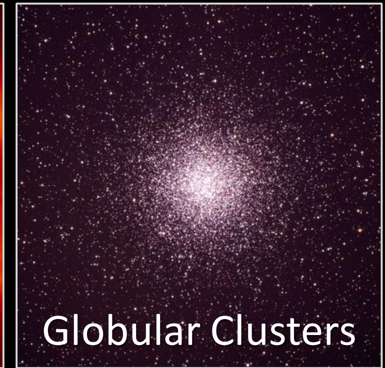
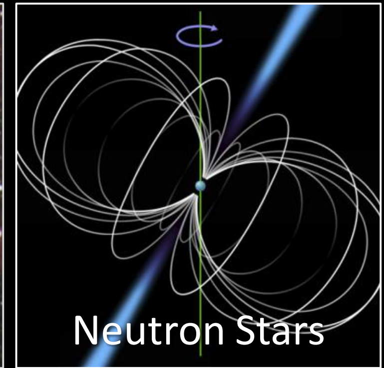
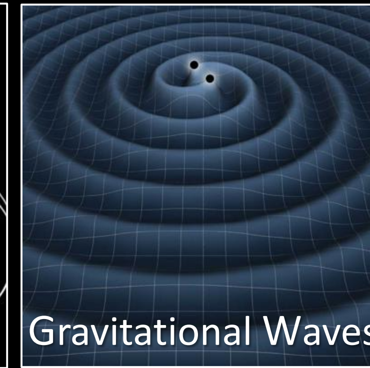






Axions and the Stars

Old Ideas and New Developments

Cosmic Wispers, Lecce, 11 Sept 2023

ORIGINS Excellence Cluster

COSMIC WISPERS CA21106

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

SFB 1258 | Neutrinos Dark Matter Messengers

Georg G. Raffelt, Max-Planck-Institut für Physik, München

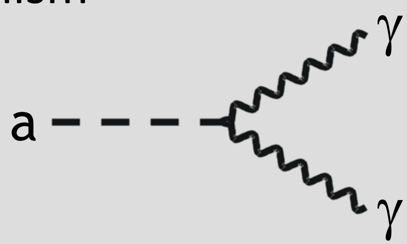
Axion Physics in a Nut Shell

Particle-Physics Motivation

CP conservation in QCD by Peccei-Quinn mechanism

$\rightarrow$ Axions $a \sim \pi^0$

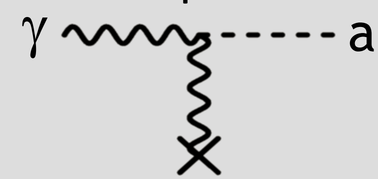
$m_\pi f_\pi \approx m_a f_a$



For $f_a \gg f_\pi$ axions are “invisible” and very light

Solar and Stellar Axions

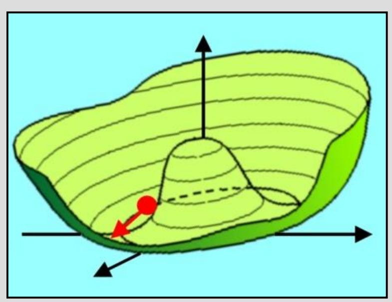
Axions thermally produced in stars, e.g. by Primakoff production



- Limits from avoiding excessive energy drain
- Solar axion searches (CAST, IAXO)

Cosmology

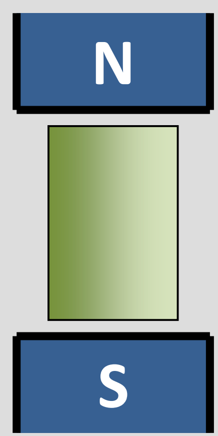
In spite of small mass, axions are born non-relativistically (non-thermal relics)



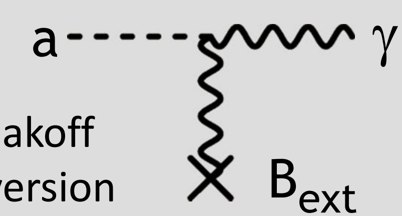
Cold dark matter candidate

$m_a \sim 10\ \mu\mathrm{eV}$ (or much smaller or larger)

Search for Axion Dark Matter



Microwave resonator (1 GHz = 4 μeV)



Primakoff conversion

ADMX, CAPP, MADMAX, …

Raffelt, from an old talk

Axion Physics in a Nut Shell

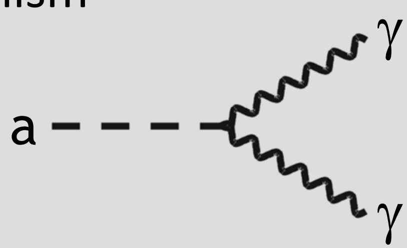
Tuesday

…hysics Motivation

…ervation in QCD by Peccei-Quinn mechanism

→ Axions $a \sim \pi^0$

$m_\pi f_\pi \approx m_a f_a$



For $f_a \gg f_\pi$ axions are "invisible" and very light

Monday

…Stellar Axions

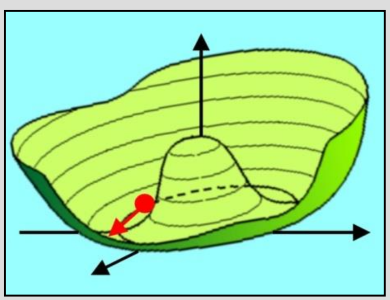
A…ons …rmally produced in stars, e.g. by Primakoff production

- Limits from avoiding excessive energy drain
- Solar axion searches (CAST, IAXO)

Wednesday

…mology

…all mass, axions are born non-relativistically (non-thermal relics)

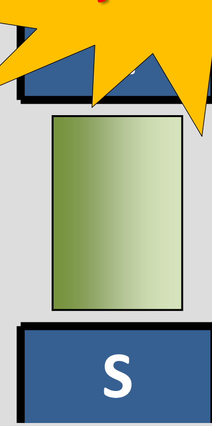


Cold dark matter candidate

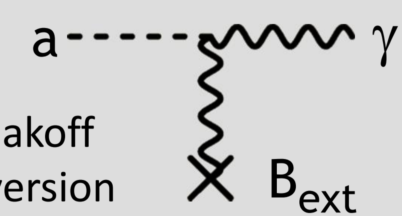
$m_a \sim 10\ \mu eV$ (or much smaller or larger)

Thursday

…Dark Matter



Microwave resonator (1 GHz = 4 μeV)

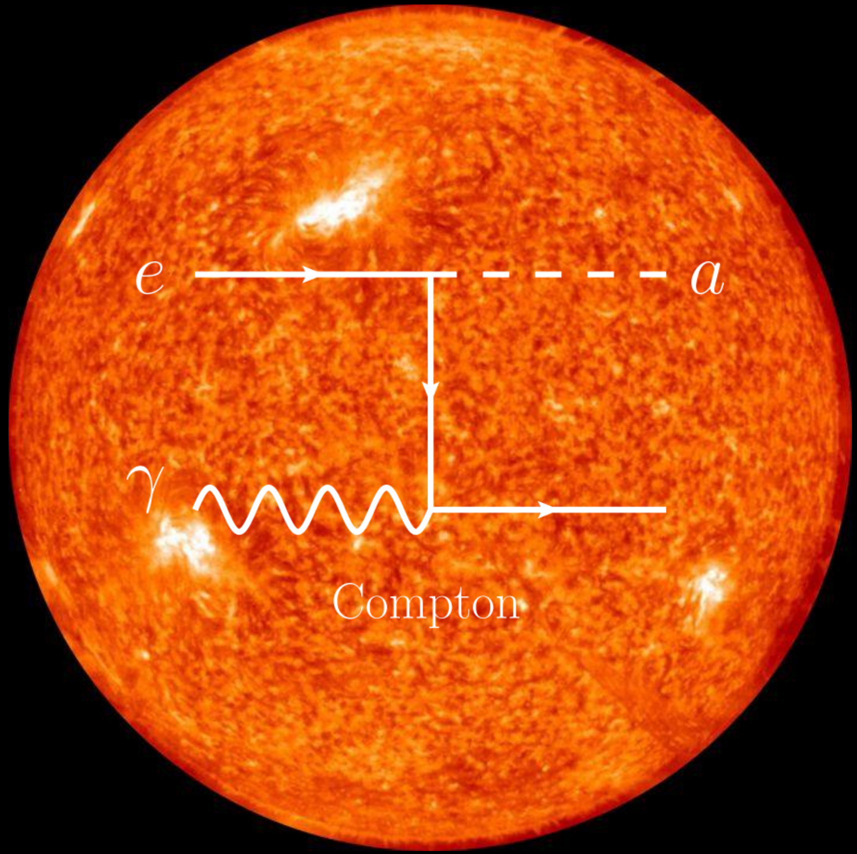


Primakoff conversion

ADMX, CAPP, MADMAX, …

Raffelt, from an old talk

Particles and Stars



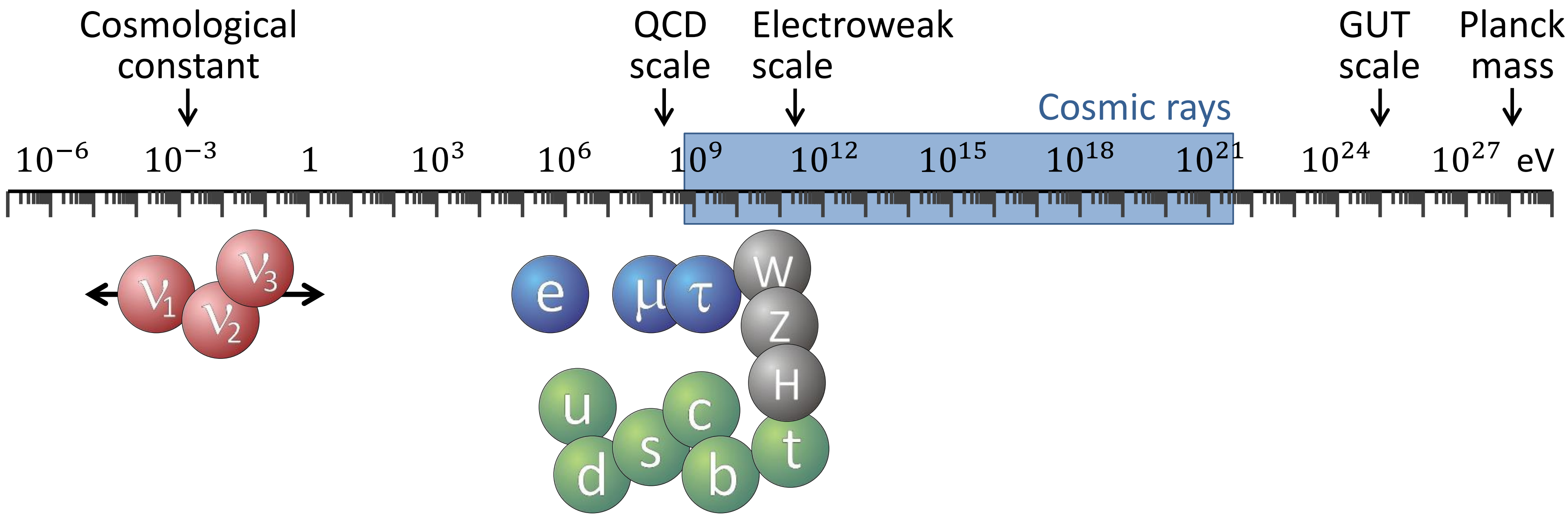
Low-mass particles are produced in stellar interiors

- **Detection opportunity (Sun or Supernovae)**
- **Backreaction on stellar properties**

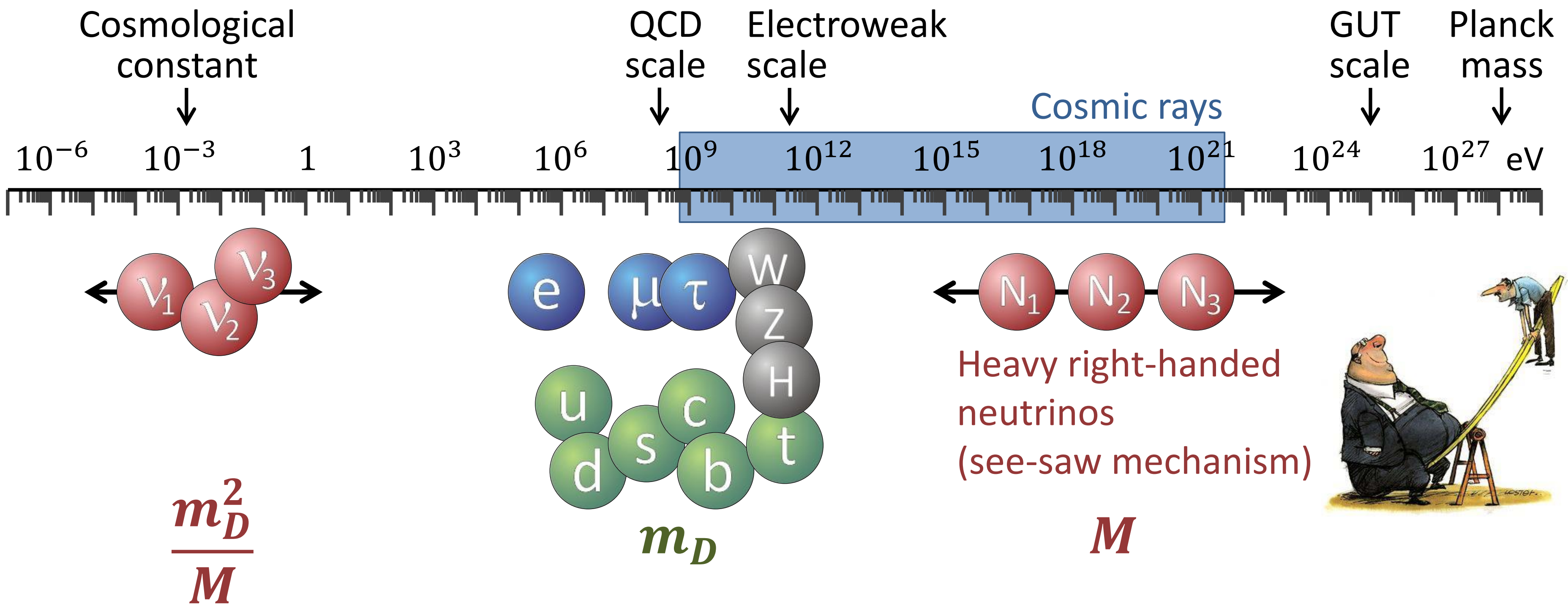
→ Which particles?

→ Which stars?

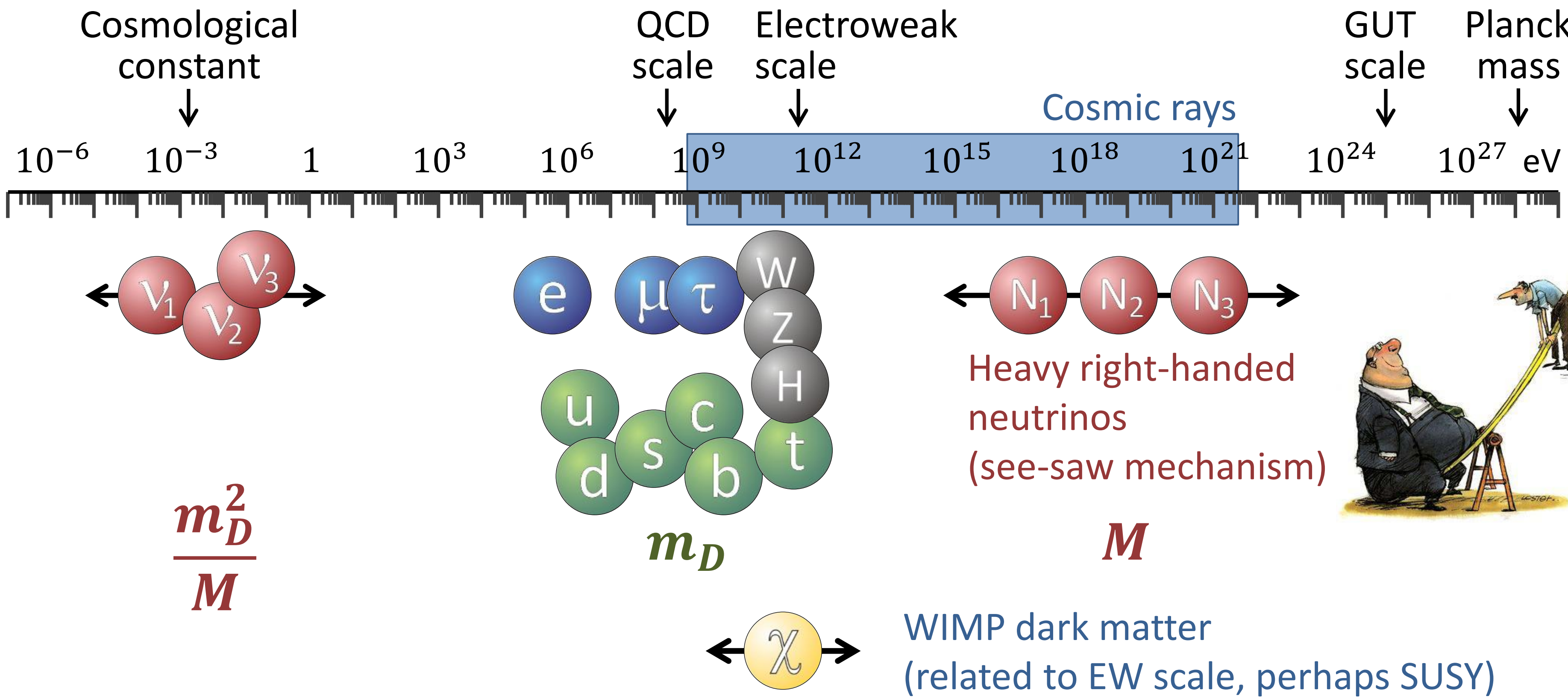
High- and Low-Energy Frontiers in Particle Physics



High- and Low-Energy Frontiers in Particle Physics



High- and Low-Energy Frontiers in Particle Physics



High- and Low-Energy Frontiers in Particle Physics

Cosmological constant ↓ — QCD scale ↓ — Electroweak scale ↓ — GUT scale ↓ — Planck mass ↓

Cosmic rays

10^{-6} 10^{-3} 1 10^{3} 10^{6} 10^{9} 10^{12} 10^{15} 10^{18} 10^{21} 10^{24} 10^{27} eV

ν_1 ν_2 ν_3

$$\frac{m_D^2}{M}$$

e μ τ W Z H u d s c b t

$$m_D$$

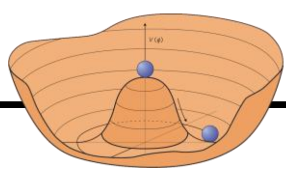
N_1 N_2 N_3

Heavy right-handed neutrinos (see-saw mechanism)

$$M$$

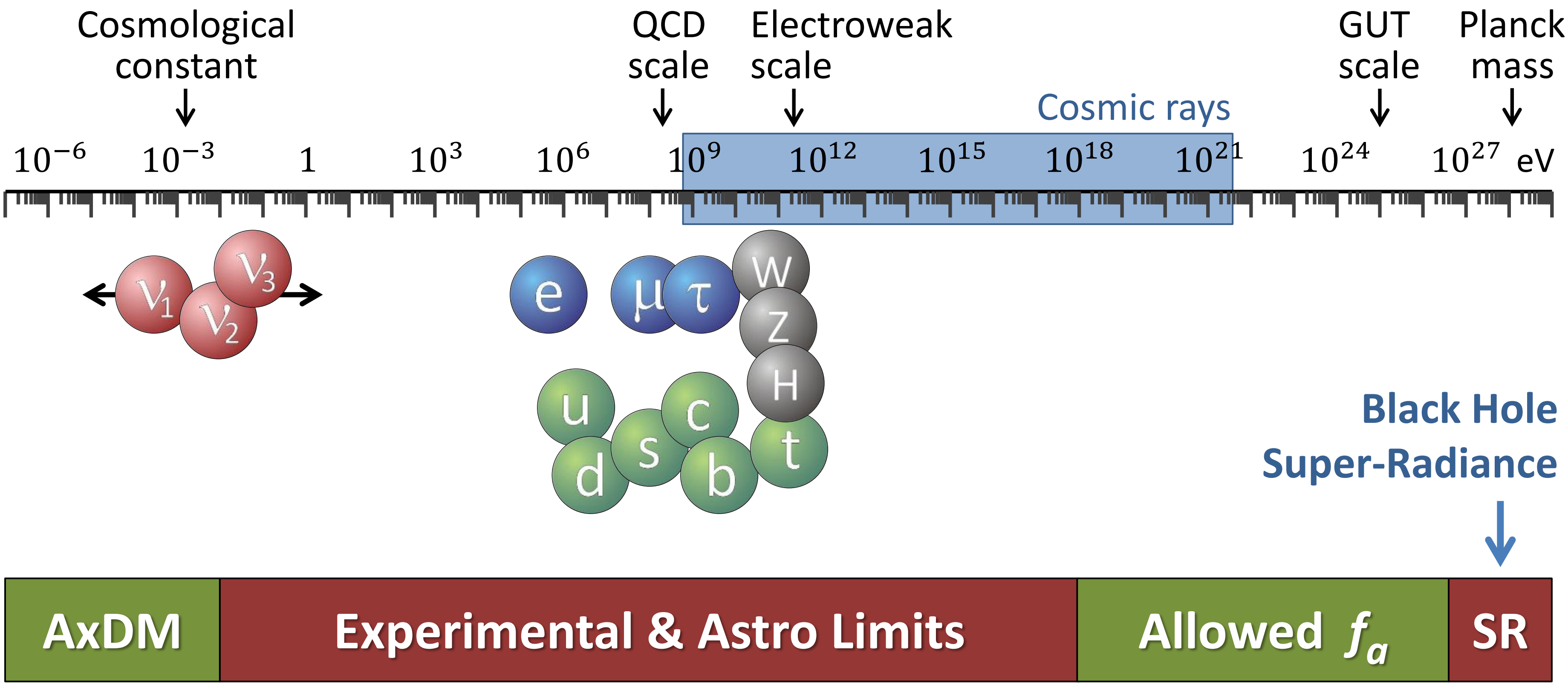
χ WIMP dark matter (related to EW scale, perhaps SUSY)

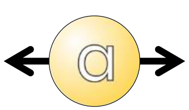
a Axion dark matter (related to Peccei-Quinn symmetry)



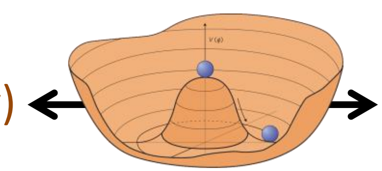
$$m_a \sim \frac{m_\pi f_\pi}{f_a} \qquad m_\pi, f_\pi \qquad f_a$$

High- and Low-Energy Frontiers in Particle Physics





Axion dark matter (related to Peccei-Quinn symmetry)

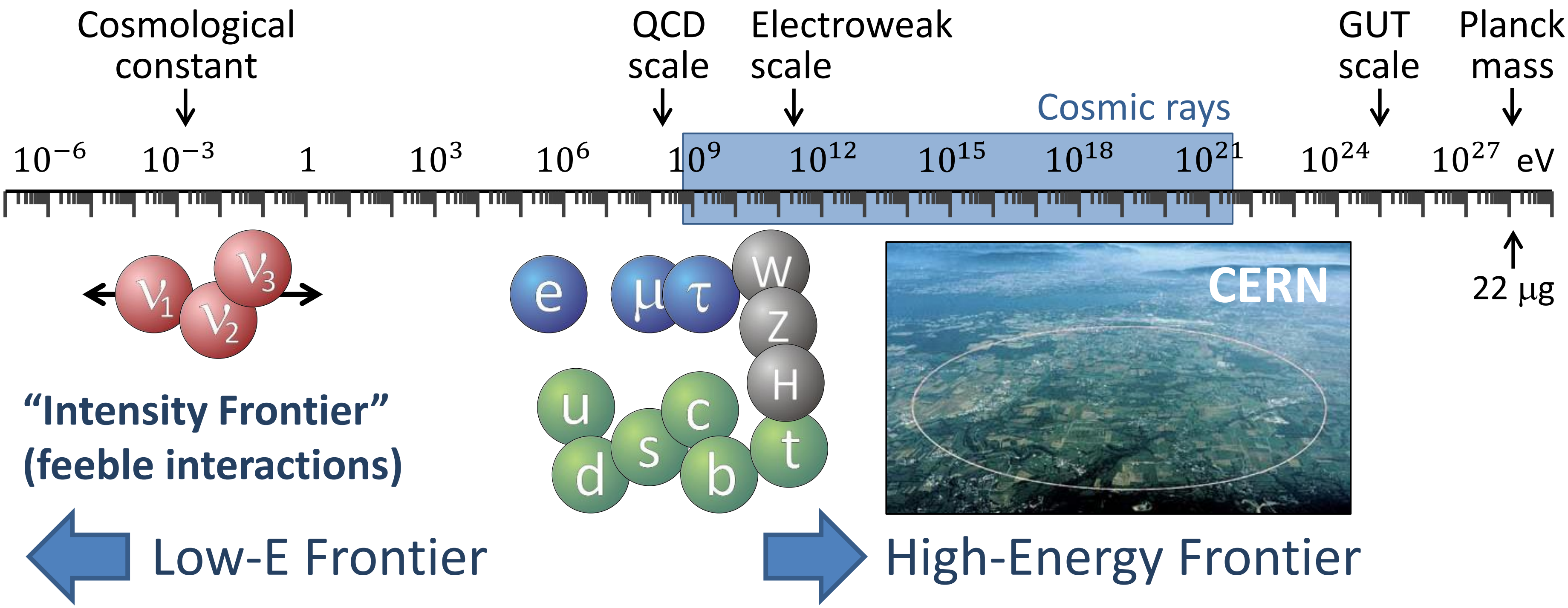


$$m_a \sim \frac{m_\pi f_\pi}{f_a}$$

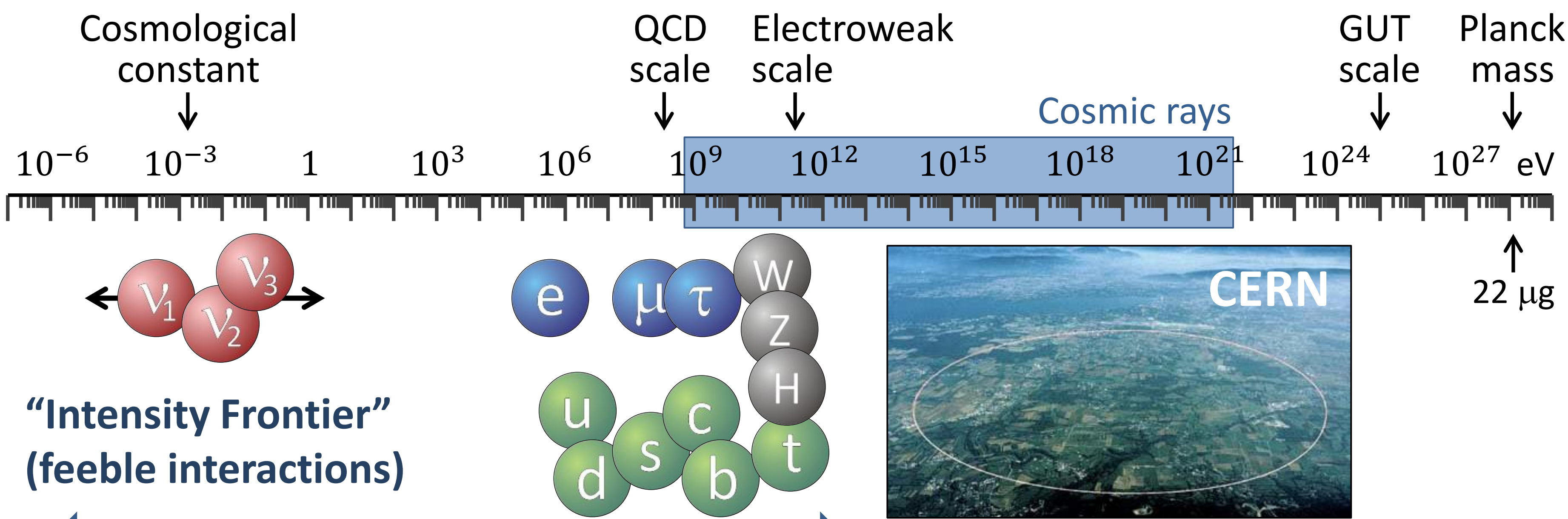
$$m_\pi, f_\pi$$

$$f_a$$

High- and Low-Energy Frontiers in Particle Physics



High- and Low-Energy Frontiers in Particle Physics



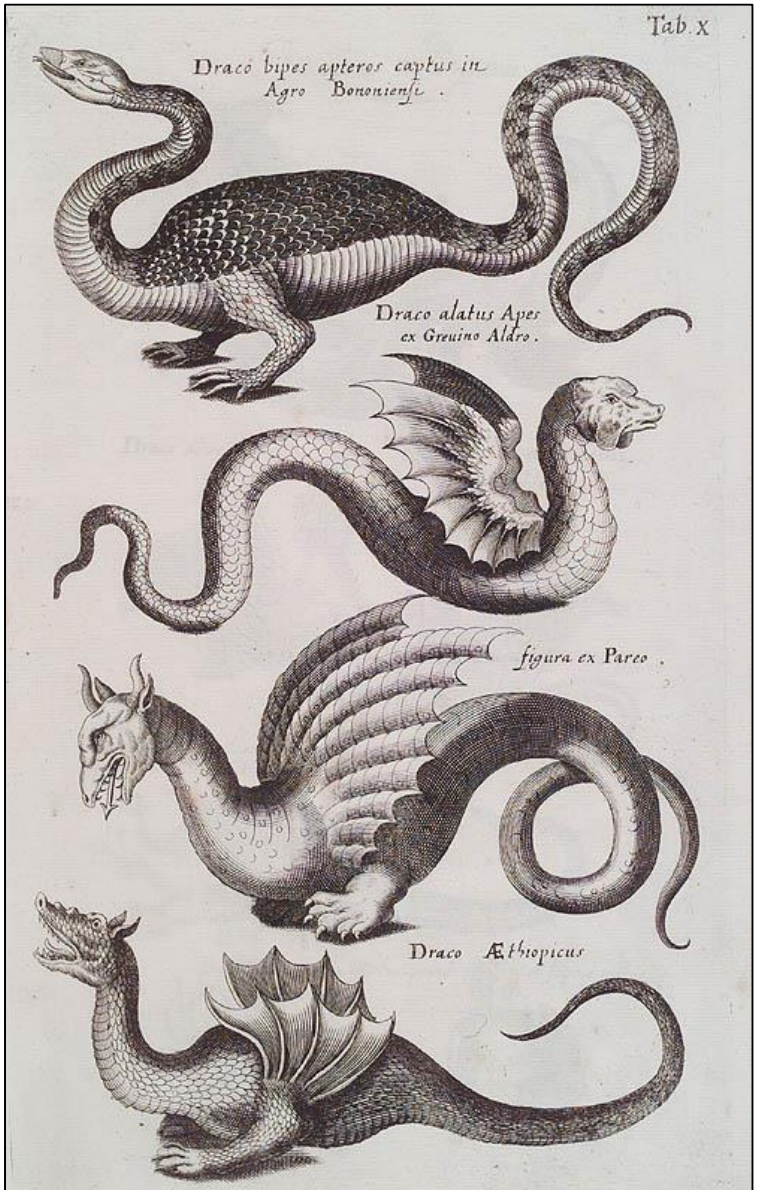
Low-E Frontier

High-Energy Frontier

Neutrinos (active & sterile)
Axions & friends
Dark photons, fuzzy dark matter,
muon-philic bosons, …

Feebly-interacting particles (FIPs)
(e.g. CERN 2022 workshop report
arXiv:2305.01715)

Bestiarium of Low-Mass Bosons



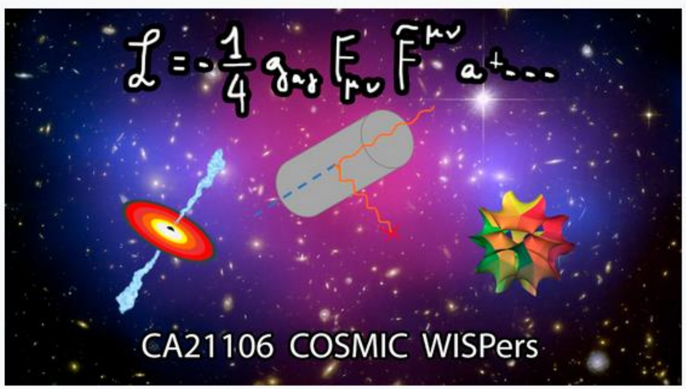
Weakly Interacting Sub-eV Particles (WISPs)

- **Axions** (1 parameter family $m_a f_a \sim m_\pi f_\pi$)
  Solves strong CP problem
  Could be dark matter
- **Axion-like particles (ALPs)**
  Generic two-photon vertex, could be dark matter
  (2 parameters m_a and $g_{a\gamma}$)
- **String axions**
  (almost massless pseudoscalars in string theory)
  One of them may solve CP problem
- **Hidden photons**
  Low-mass gauge bosons from $U'(1)$
  (kinetic mixing parameter χ and mass $m_{\gamma'}$)
- **Fifth force, fuzzy dark matter, ULAs,**
  all sorts of FIPs, WISPs, ALPs, …

COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

COSMIC WISPERS CA21106

COSMIC WISPers in the Dark Universe: Theory, astrophysics and experiments



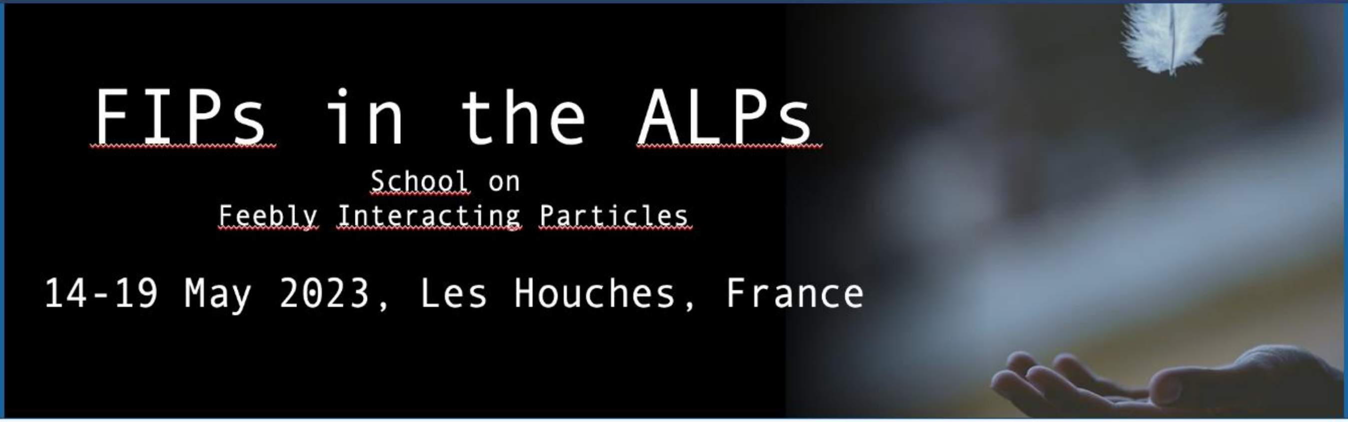
COSMIC WISPers is a COST Action **CA21106** focusses on very weakly interacting slim (m<GeV) particles (WISPs) which emerge in several extensions of the Standard Model of Particle Physics. The aim of this Action is an exhaustive study of these WISPs, notably axions, axion-like particles and dark photons, ranging from their theoretical underpinning, over their indirect observational consequences in astrophysics, to their search at colliders and beam-dump and their direct detection in laboratory experiments.

The main aim of the COSMIC WISPers Action is to promote the formation of a team of scientists with different and complementary expertise to carry on WISP studies on a systematic and coherent basis in the intersecting and interdisciplinary area of particle physics, astrophysics and cosmology. Our main goals are the following:

Funded by the European Union

Participants

Francesca Chadha-Day



May 14 – 19, 2023
Europe/Zurich timezone

Enter your search term

Overview
Registration
Practical Information
How to get to Les Houches
Directions to Hostel/Meeting room
Accommodation
Access to Les Houches computing network
Participant List

Contacts
gaia.lanfranchi@lnf.infn.it
houches-secretariat@un...

FIPs in the ALPs is the first edition of a foreseen series of schools fully dedicated to the physics of feebly-interacting particles and aims to gathering together highly renowned experts from collider, beam dump, fixed target experiments, as well as from astroparticle, cosmology, axion/ALP, ultra-light particle searches, and dark matter direct and indirect detection communities along with a set of young and brilliant physicists to discuss progress in experimental searches and underlying theory models for FIP physics.

The school is organized by the FIP Physics Centre of the Physics Beyond Colliders study group at CERN: https://pbc.web.cern.ch/fpc-mandate

The aim of the school is to embedding a new generation of physicists into the activities of the study group.

The School is organized along three main directions:

1. **MeV-GeV Dark Matter** and its searches at accelerator, direct and indirect detection experiments;
2. **Heavy neutral leptons** and their connection to active neutrino physics;
3. **Ultra-light (< 1 eV) FIPs** in particle physics, astroparticle, and cosmology.

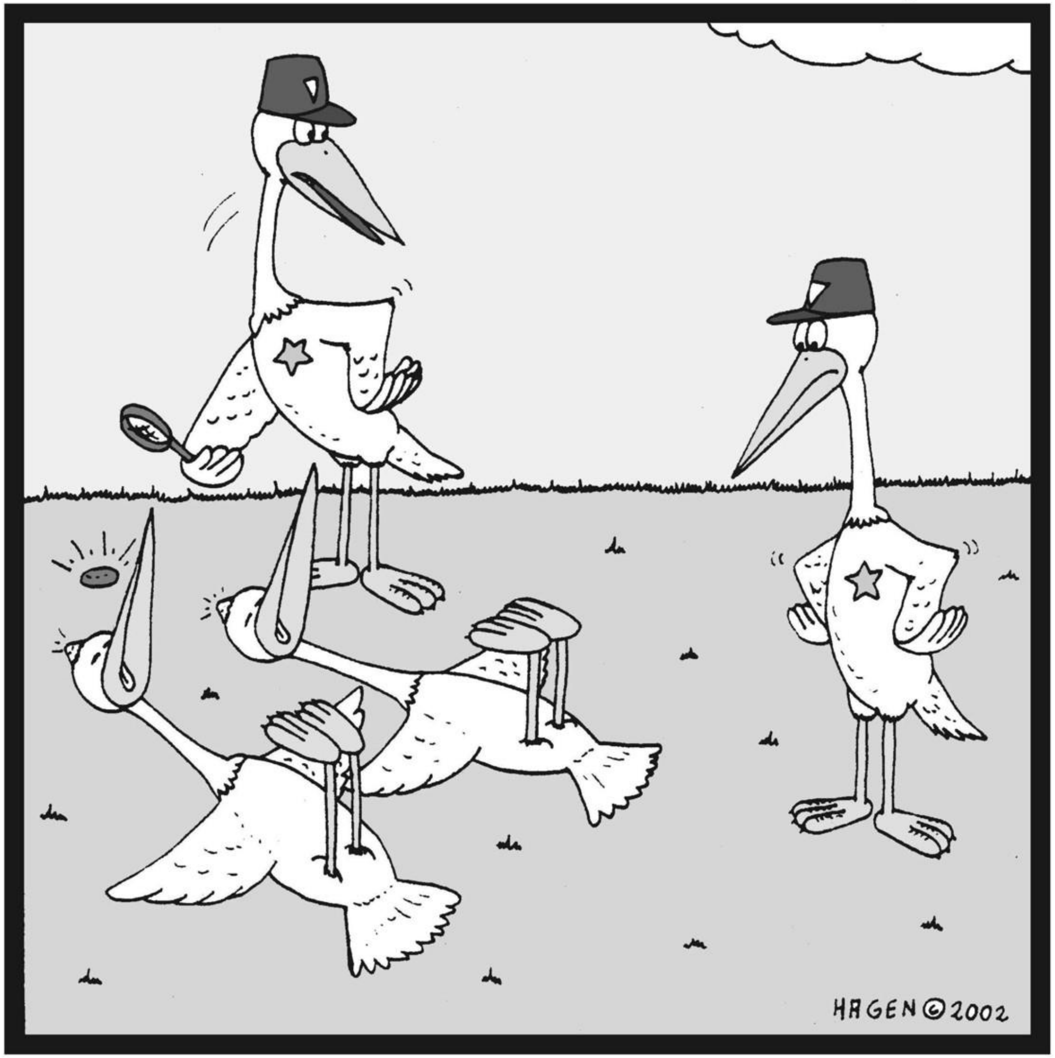
Advanced PhD students and PostDocs are strongly encouraged to apply.

The Organizers:

The FIP Physics Centre of the Physics Beyond Colliders at CERN.

https://pbc.web.cern.ch/fpc-mandate

Killing Two Birds With One Stone

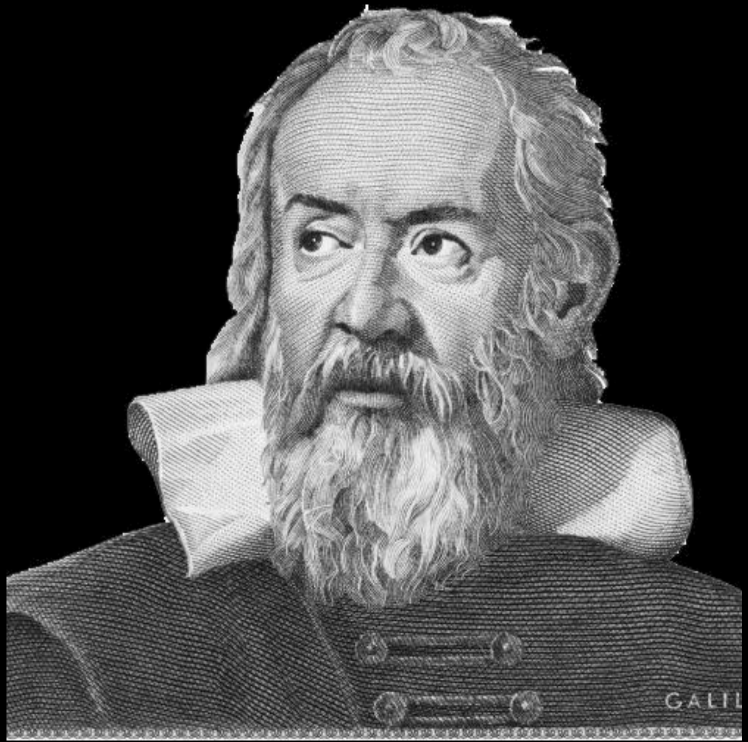


Unbelievable! It looks like they've
both been killed by the same stone...

Peccei-Quinn mechanism
- Solves strong CP problem
- May provide dark matter in the form of axions

More agnostic view today,
following Galileo’s Advice

Measure what can be measured, and make measurable what cannot be.



Some Early Papers on Stellar Particle Physics

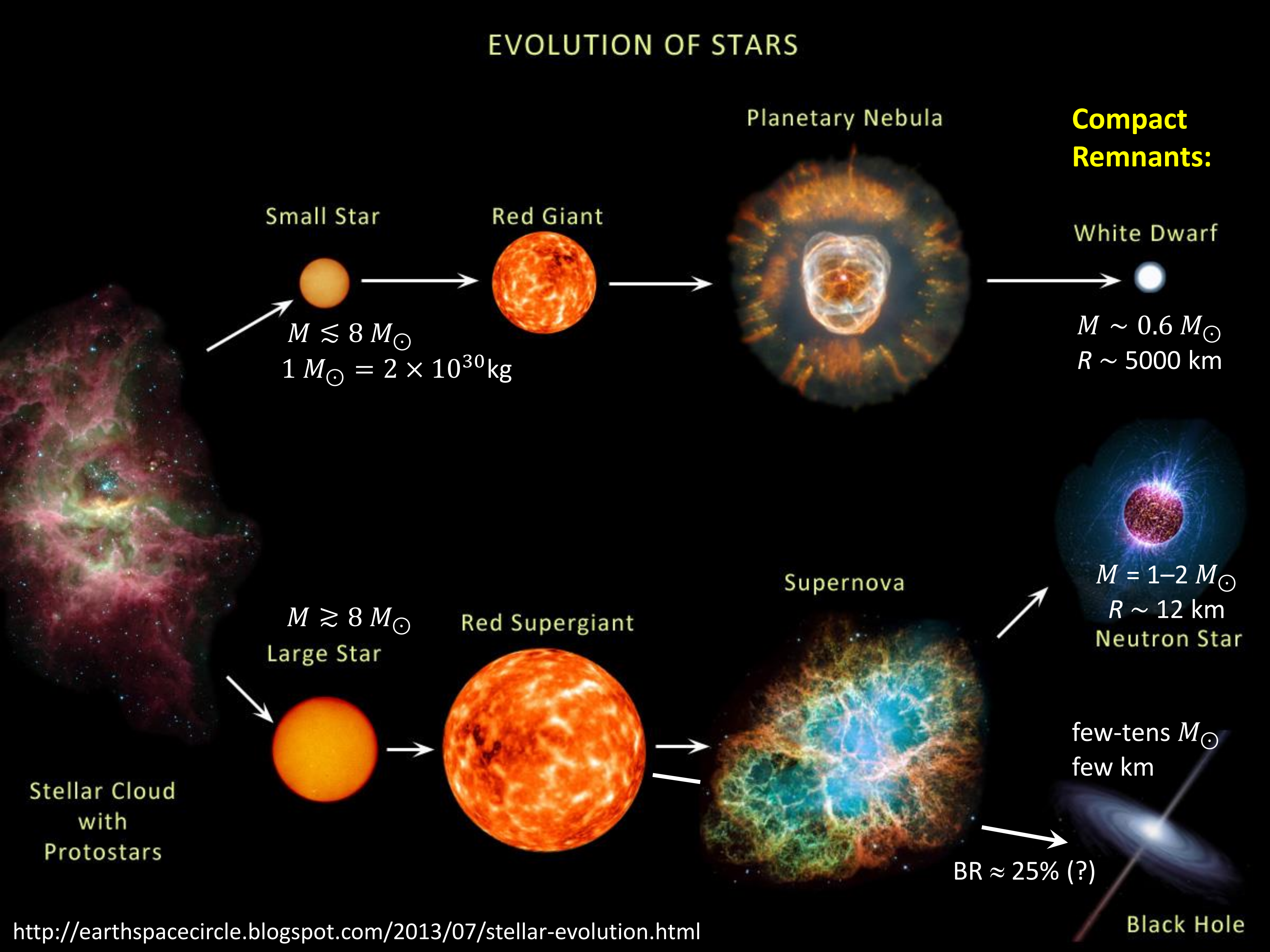
Neutrinos (since 1960s)

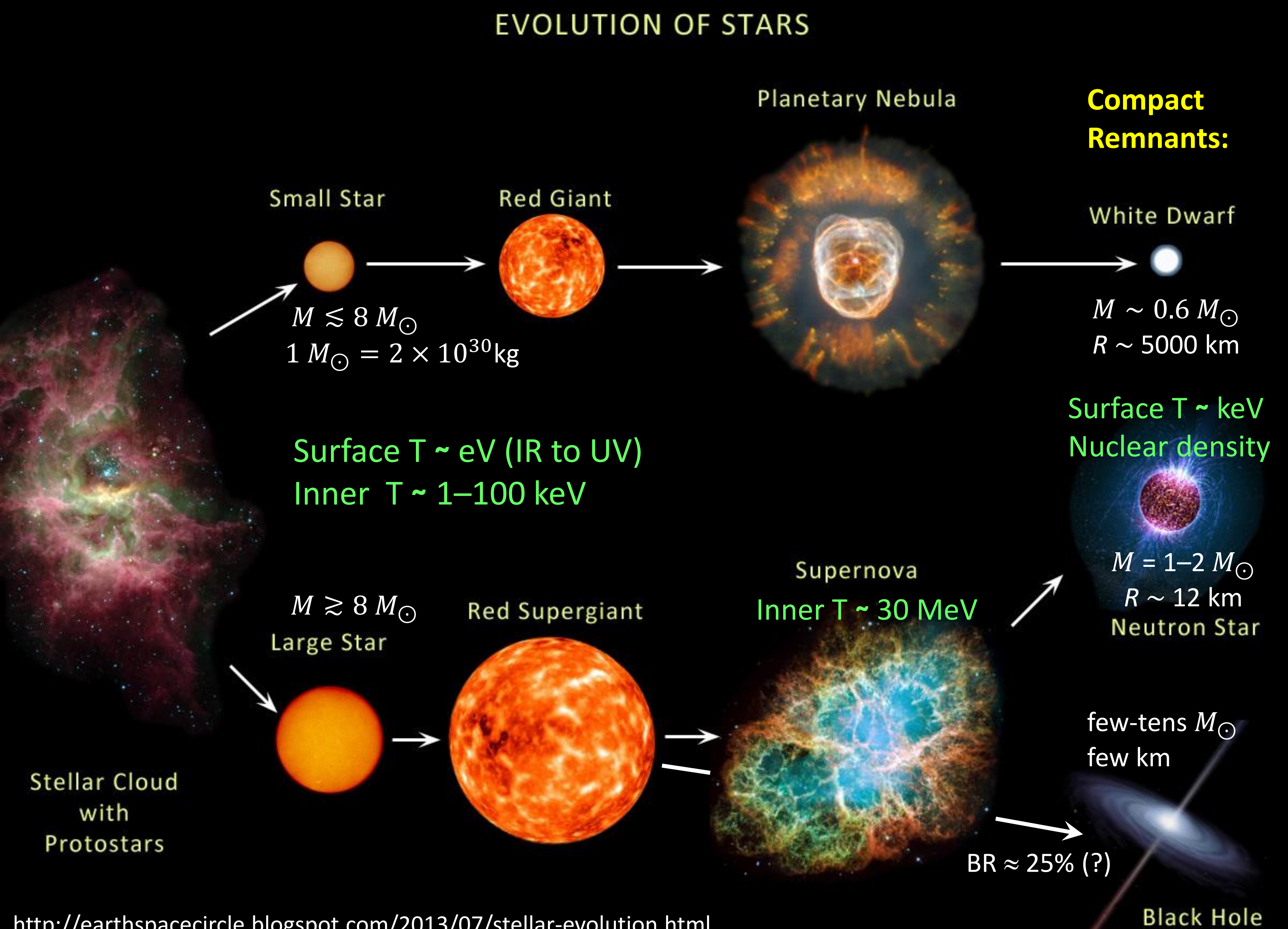
- Bernstein, Ruderman & Feinberg:
  Electromagnetic properties of the neutrino, Phys. Rev. 132 (1963) 1227
- Gribov & Pontecorvo:
  Neutrino astronomy and lepton charge, PLB 28 (1969) 493
- Cowsik:
  Limits on the radiative decay of neutrinos, PRL 39 (1978) 511
- Falk & Schramm:
  Limits from supernovae on neutrino radiative lifetimes, PLB 79 (1978) 511

Flavor oscillations!

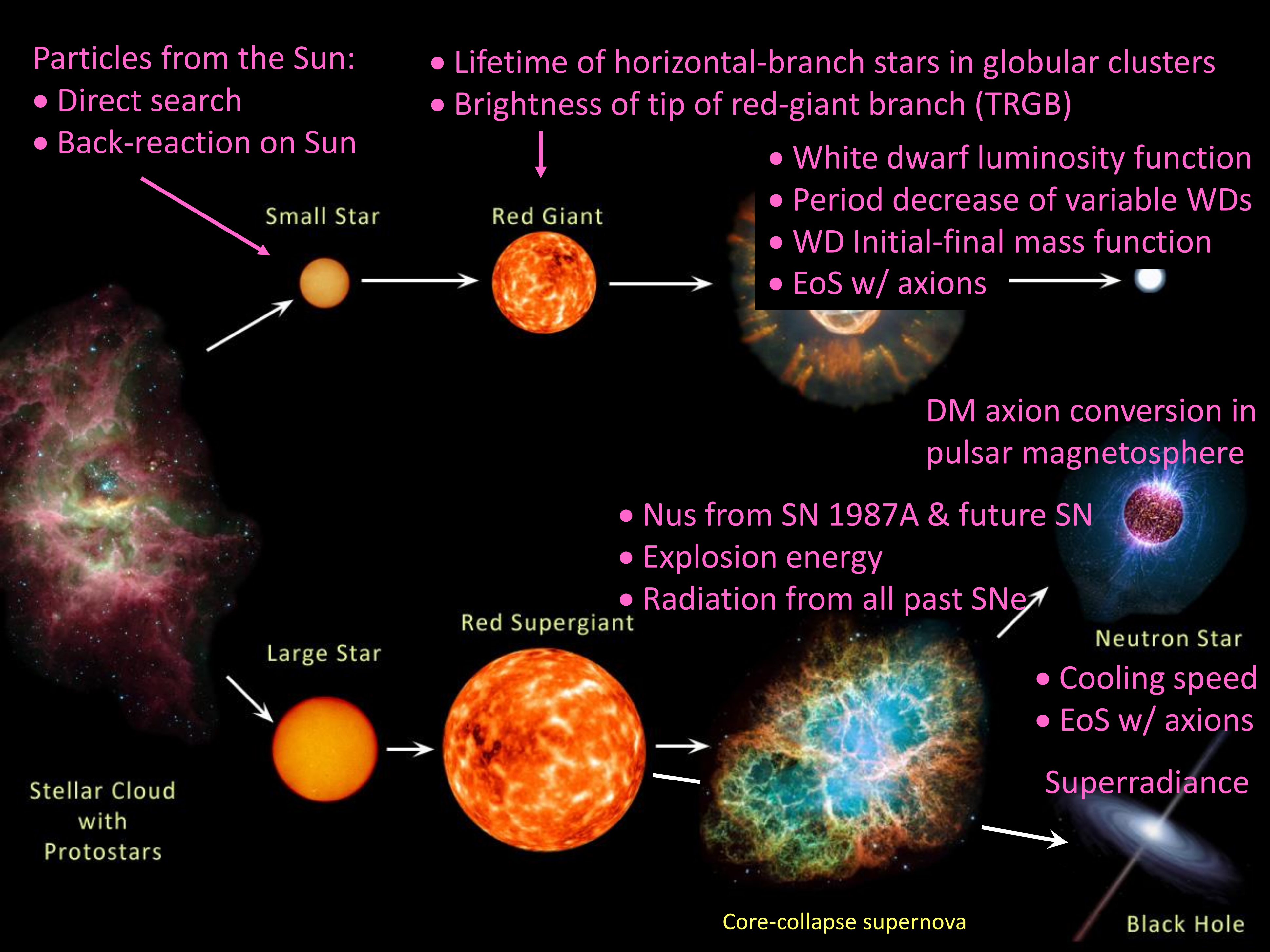
Axions & light Higgs (ca 1978)

- Vysotsky, Zeldovich, Khlopov & Chechetkin:
  Some astrophysical limitations on the axion mass,
  Pisma Zh. Eksp. Teor. Fiz. 27 (1978) 533 [JETP Lett. 27 (1978) 502]
- Dicus, Kolb, Teplitz & Wagoner:
  Astrophysical bounds on the masses of axions and Higgs particles, PRD 18 (1978) 1829
- K. O. Mikaelian: Astrophysical implications of new light Higgs bosons, PRD 18 (1978) 3605
- K. Sato: Astrophysical constraints on the axion mass and the number of quark flavors,
  Prog. Theor. Phys. 60 (1978) 1942


EVOLUTION OF STARS
Planetary Nebula
Compact Remnants:
Small Star
Red Giant
White Dwarf
$M \lesssim 8\ M_\odot$
$1\ M_\odot = 2 \times 10^{30}$kg
$M \sim 0.6\ M_\odot$
$R \sim 5000$ km
Supernova
$M = 1–2\ M_\odot$
$R \sim 12$ km
$M \gtrsim 8\ M_\odot$
Red Supergiant
Large Star
Neutron Star
few-tens $M_\odot$
few km
Stellar Cloud with Protostars
BR ≈ 25% (?)
Black Hole
http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html



http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html

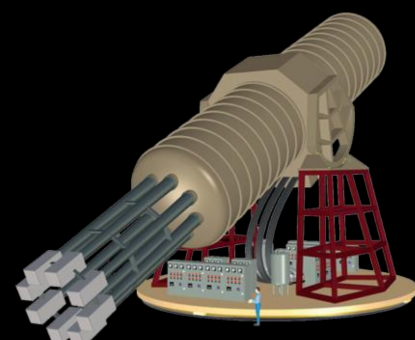


Particles from the Sun:
• Direct search
• Back-reaction on Sun
• Lifetime of horizontal-branch stars in globular clusters
• Brightness of tip of red-giant branch (TRGB)
• White dwarf luminosity function
• Period decrease of variable WDs
• WD Initial-final mass function
• EoS w/ axions
Small Star
Red Giant
DM axion conversion in
pulsar magnetosphere
• Nus from SN 1987A & future SN
• Explosion energy
• Radiation from all past SNe
Neutron Star
• Cooling speed
• EoS w/ axions
Red Supergiant
Large Star
Superradiance
Stellar Cloud
with
Protostars
Core-collapse supernova
Black Hole

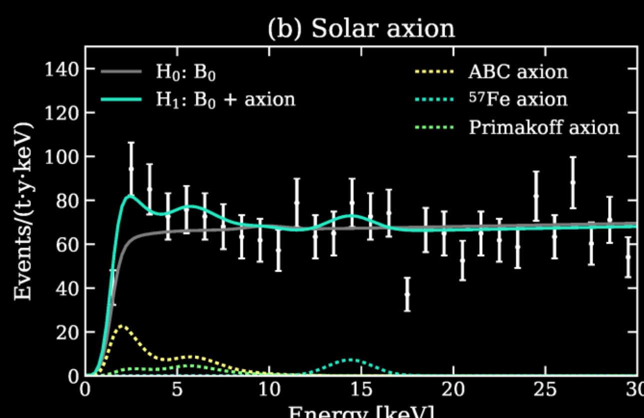
Particles from the Sun

2002 Solar Neutrinos (R.Davis, M.Koshiba)

2015 Solar Nu Oscillations (A.McDonald)

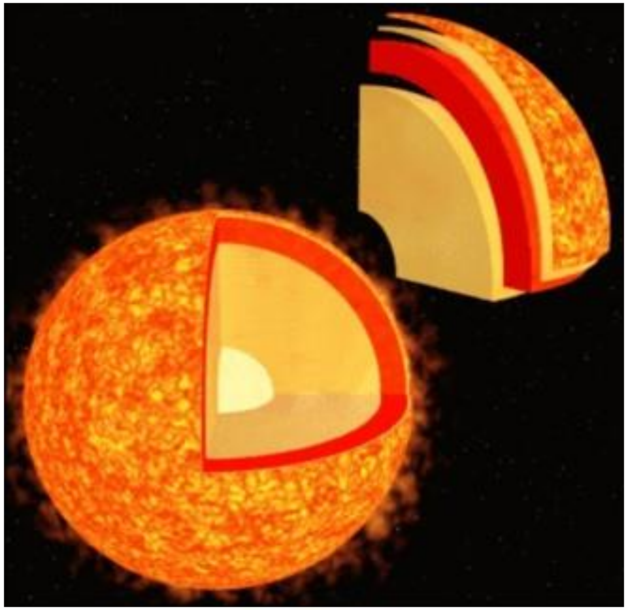


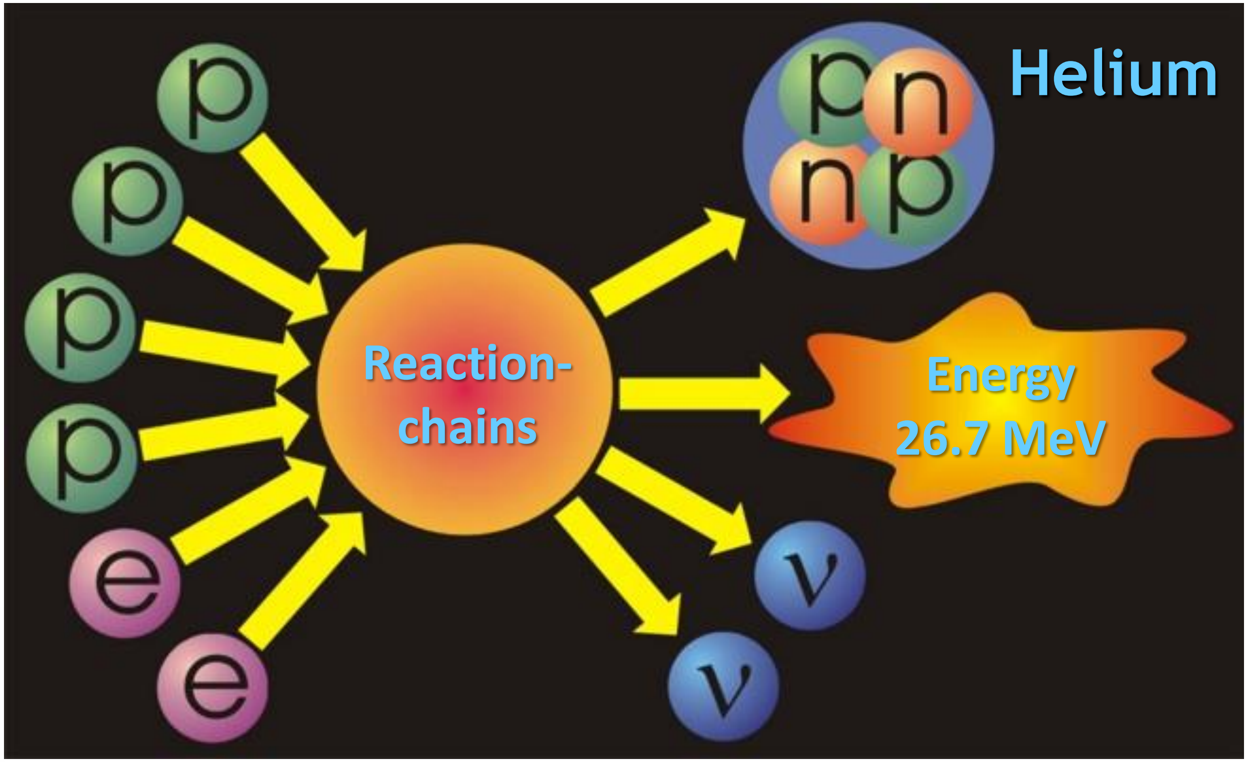
Search for solar axions
with CAST and future IAXO



Excess events in
XENON1T DM search.
Solar axions?
arXiv:2006.09721
XENONnT: no signal
arXiv:[2207.11330](2207.11330)

Neutrinos from the Sun

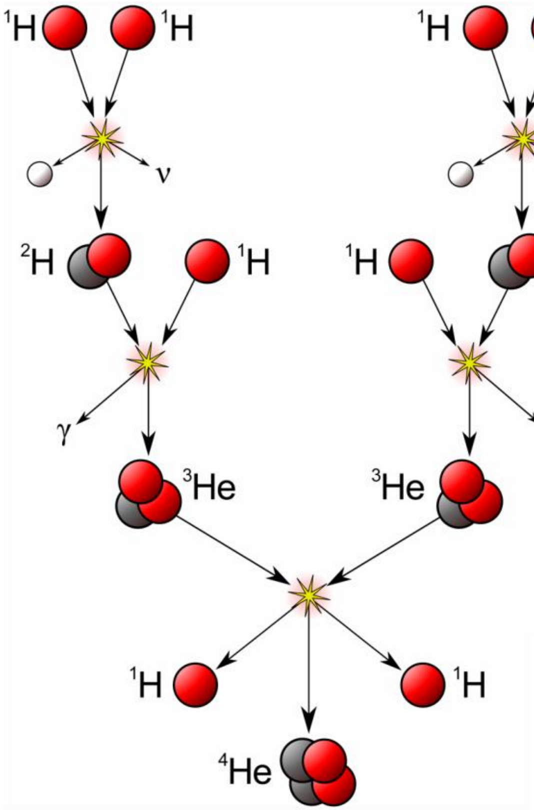




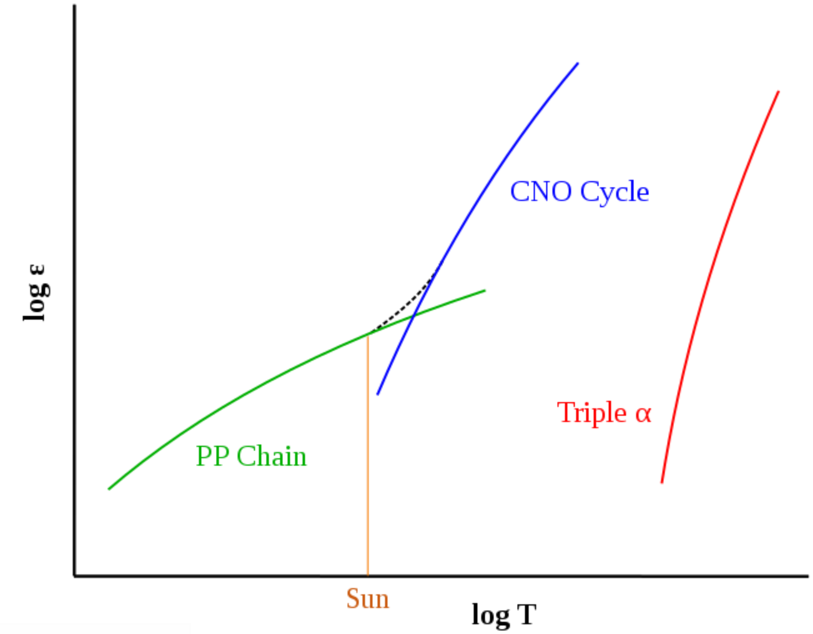
Solar radiation: 98 % light (photons)
2 % neutrinos
At Earth 66 billion neutrinos/cm^2 sec

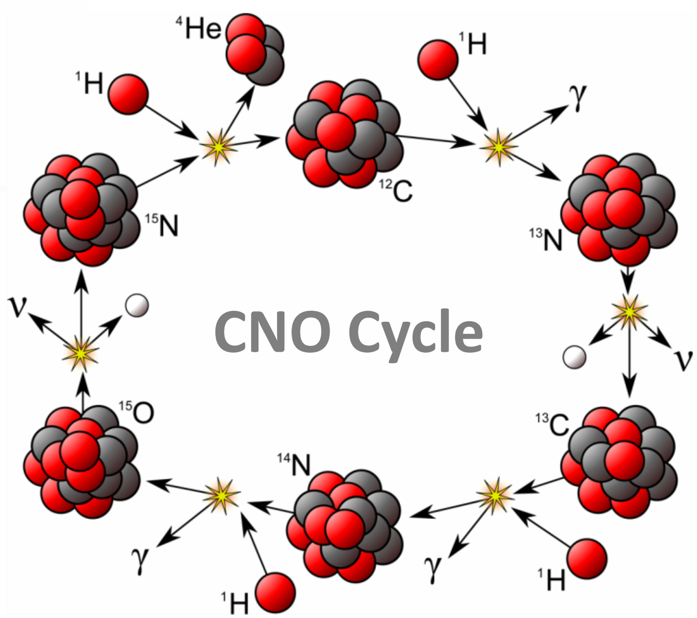
Hans Bethe (1906–2005, Nobel prize 1967)
Thermonuclear reaction chains (1938)

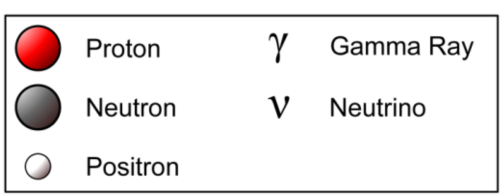
Hydrogen Burning in Stars



pp-I Chain



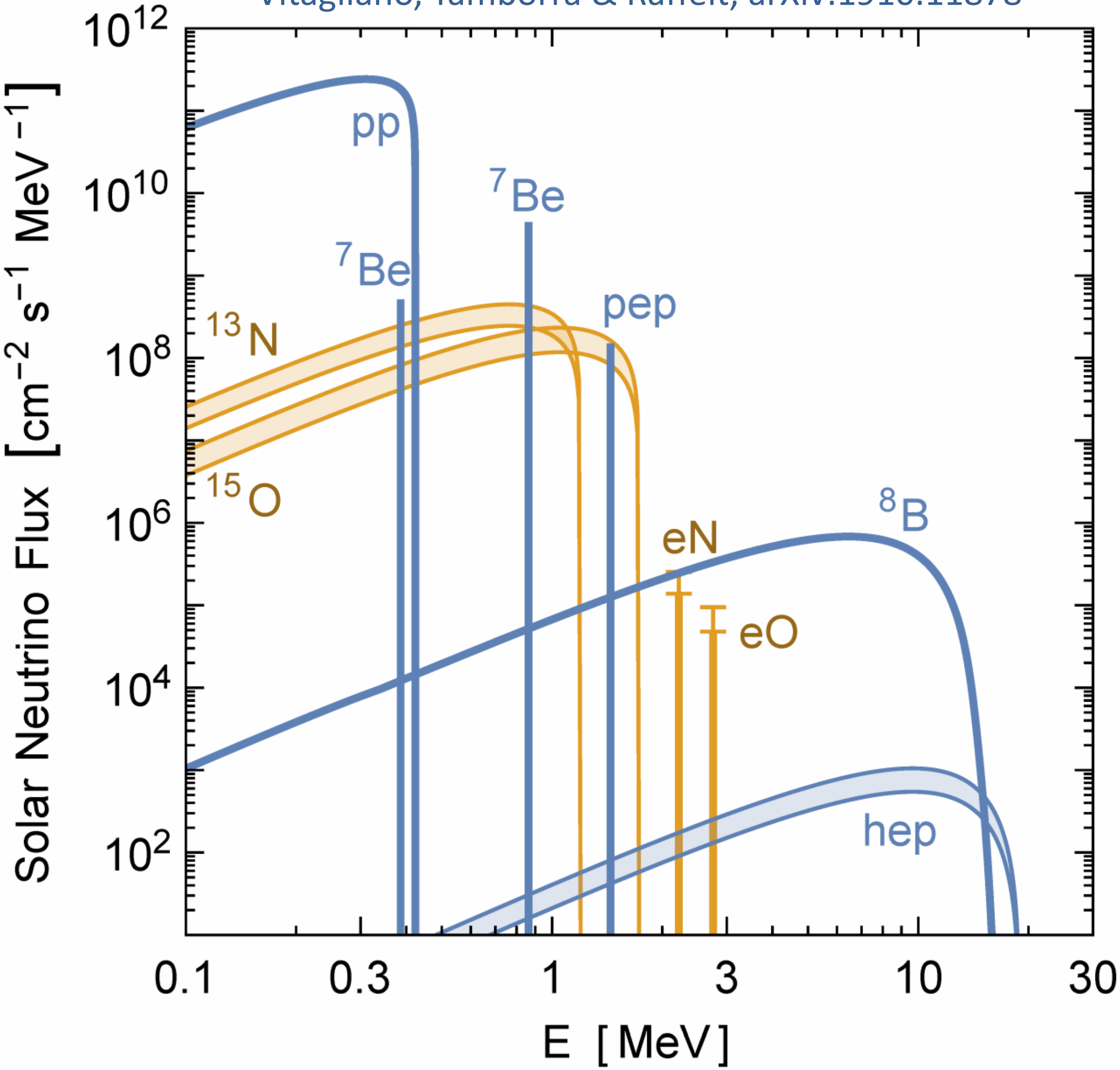




Picture credit Wikipedia

Solar Neutrinos from Nuclear Reactions

Vitagliano, Tamborra & Raffelt, arXiv:1910.11878



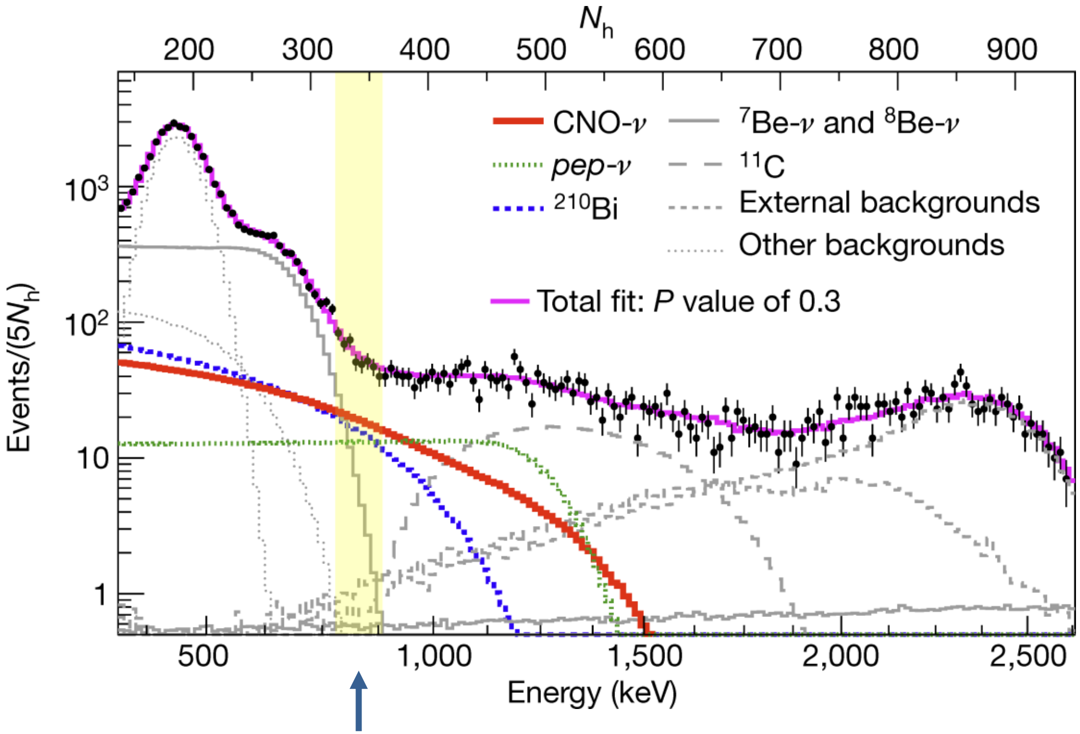
All components of pp chains (blue) have been measured

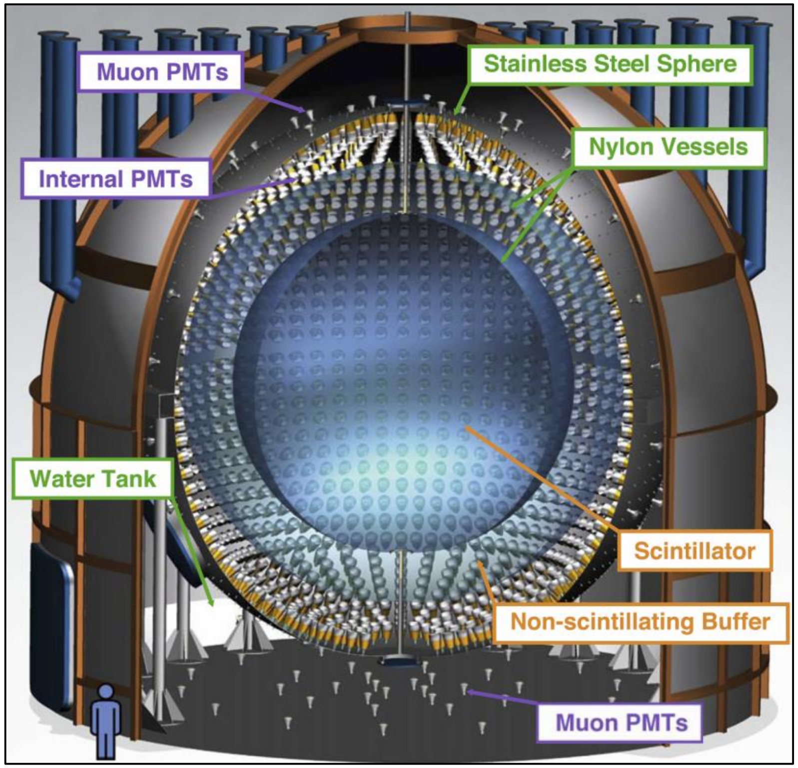
Very recently direct experimental evidence for CNO fluxes (orange) in Borexino
arXiv:2006.15115 (06/2020)
Nature 587 (2020) 577
and arXiv:2205.15975

Favors higher flux, and thus “high” CNO abundance

Borexino
has for the first time
observed
solar neutrinos
from the CNO
hydrogen fusion cycle

Solar Neutrino Spectroscopy with Borexino





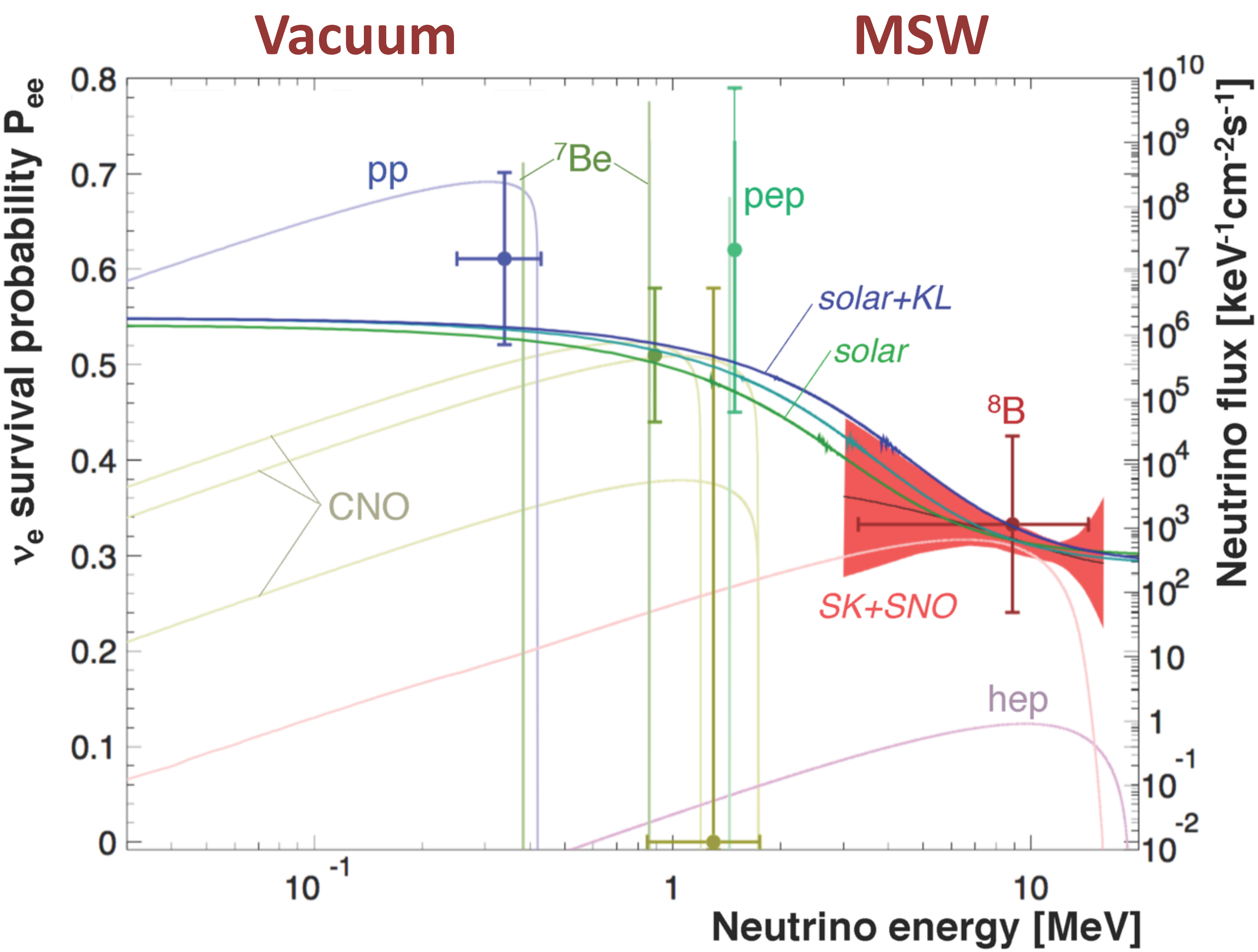
Region of interest:
Crucial background beta decay of ^{210}Bi

$$^{210}\mathrm{Pb} \xrightarrow[22.3\,\mathrm{yr}]{\beta^-} {}^{210}\mathrm{Bi} \xrightarrow[5\,\mathrm{d}]{\beta^-} {}^{210}\mathrm{Po} \xrightarrow[138.4\,\mathrm{d}]{\alpha} {}^{206}\mathrm{Pb}$$

Reduction and stabilization by controlling convective flows in scintillator

Borexino Collaboration:
Experimental evidence of neutrinos produced in the CNO fusion cycle in the Sun
Nature 587 (2020) 577
Latest: arXiv:2205.15975

Borexino now decommissioned



Energy-dependent flavor conversion probability confirms neutrino refraction in matter!

M.Wurm, Solar Neutrino Spectroscopy, arXiv:1704.06331

"Nuclear" vs. Thermal Neutrinos

- **Hydrogen burning**
  Effectively proton-neutron conversion
  $$4p + 2e \to {}^{4}\mathrm{He} + 2\nu_e$$
  Charged-current electron-neutrino production
  Other flavors (or sterile) by flavor conversion

- **Advanced burning phases**
  Effectively combine alpha particles (${}^{4}\mathrm{He}$) to larger nuclei, eg helium burning
  $$3\alpha \to {}^{12}\mathrm{C}$$
  No proton-neutron conversion necessary, no "nuclear" neutrinos

- **Neutrinos from neutral-current processes in pairs of all flavors**
  eg photo production
  $$\gamma + e \to e + \nu + \overline{\nu}$$

- **Analogous for axions or other particles**
  $$\gamma + e \to e + a$$

Thermal Neutrinos: Production Processes

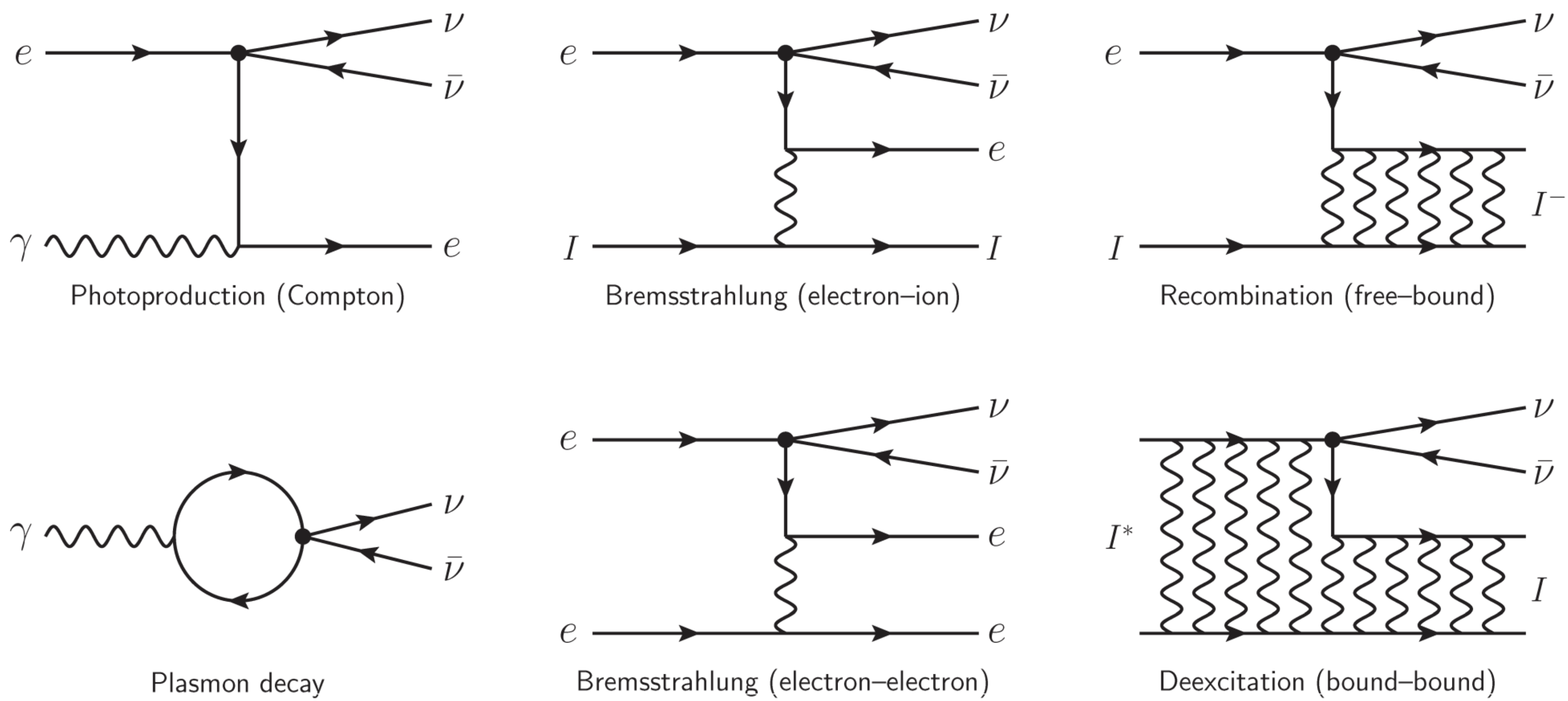


Figure 1. Processes for thermal neutrino pair production in the Sun.

Vitagliano, Redondo & Raffelt, arXiv:1708.02248

Thermal Axions: Production Processes

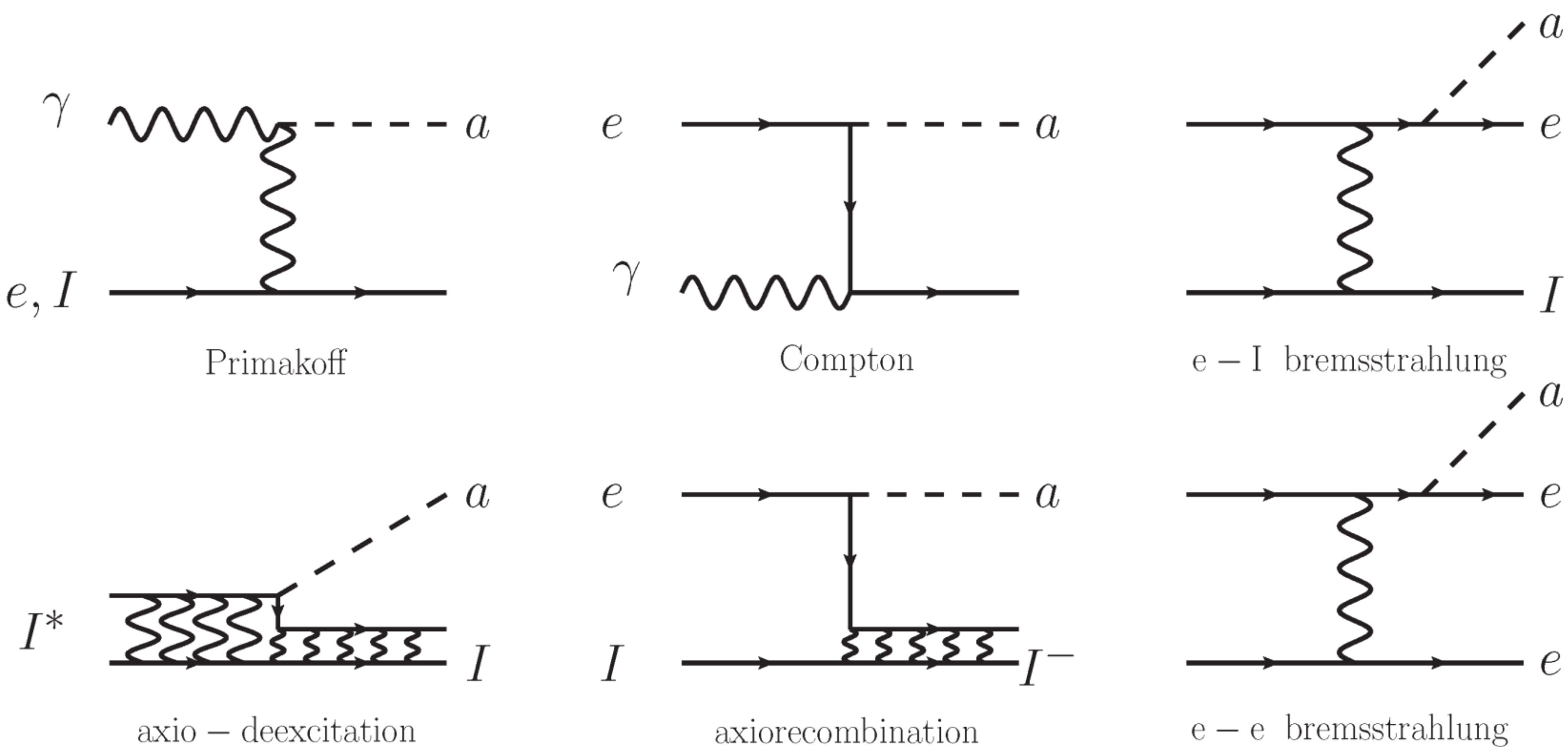
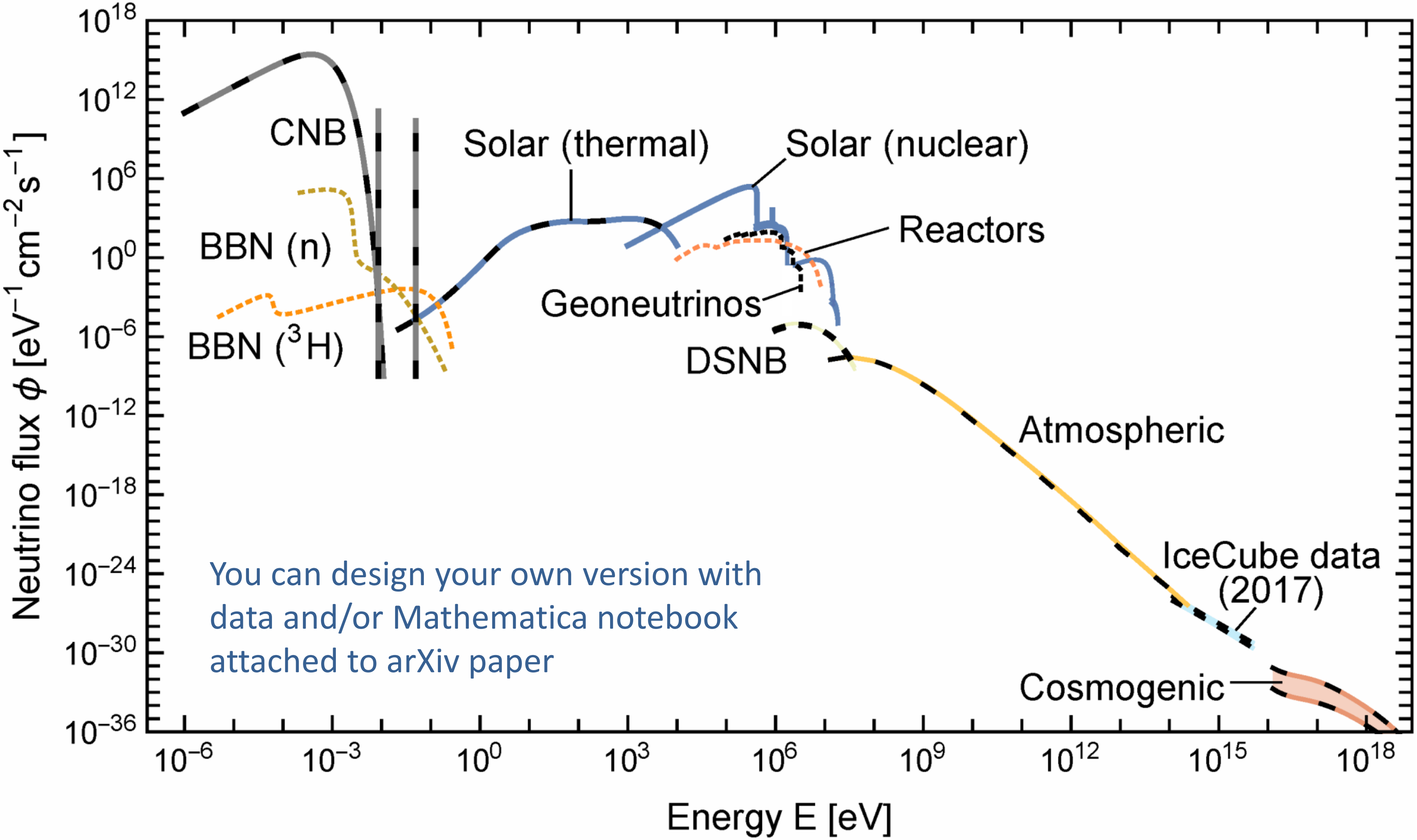


Figure 1. ABC reactions responsible for the solar axion flux in non-hadronic axion models.

Redondo, arXiv:1310.0823

Grand Unified Neutrino Spectrum (GUNS) at Earth

Vitagliano, Tamborra & Raffelt, arXiv:1910.11878



You can design your own version with data and/or Mathematica notebook attached to arXiv paper

Temperature in the Sun

Virial Theorem $\langle E_{\rm kin}\rangle = -\frac{1}{2}\langle E_{\rm grav}\rangle$

Approximate Sun as a homogeneous sphere with

Mass $M_{\rm sun} = 1.99\times 10^{33}{\rm g}$

Radius $R_{\rm sun} = 6.96\times 10^{10}{\rm cm}$

Gravitational potential energy of a proton near center of the sphere

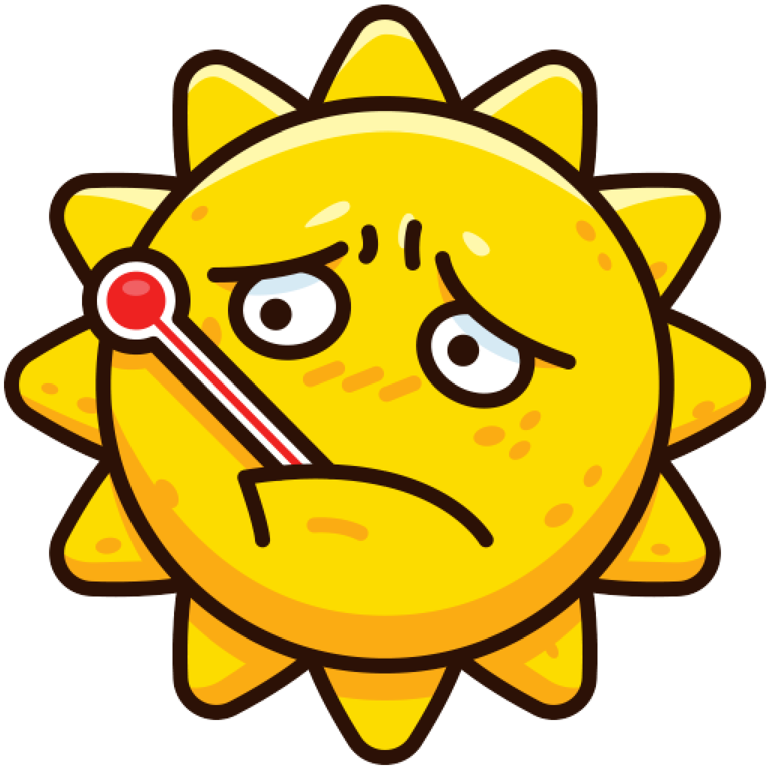
$$\langle E_{\rm grav}\rangle = -\frac{3}{2}\frac{G_N M_{\rm sun} m_p}{R_{\rm sun}} = -3.2\ {\rm keV}$$

Thermal velocity distribution

$$\langle E_{\rm kin}\rangle = \frac{3}{2}k_{\rm B}T = -\frac{1}{2}\langle E_{\rm grav}\rangle$$

Estimated temperature

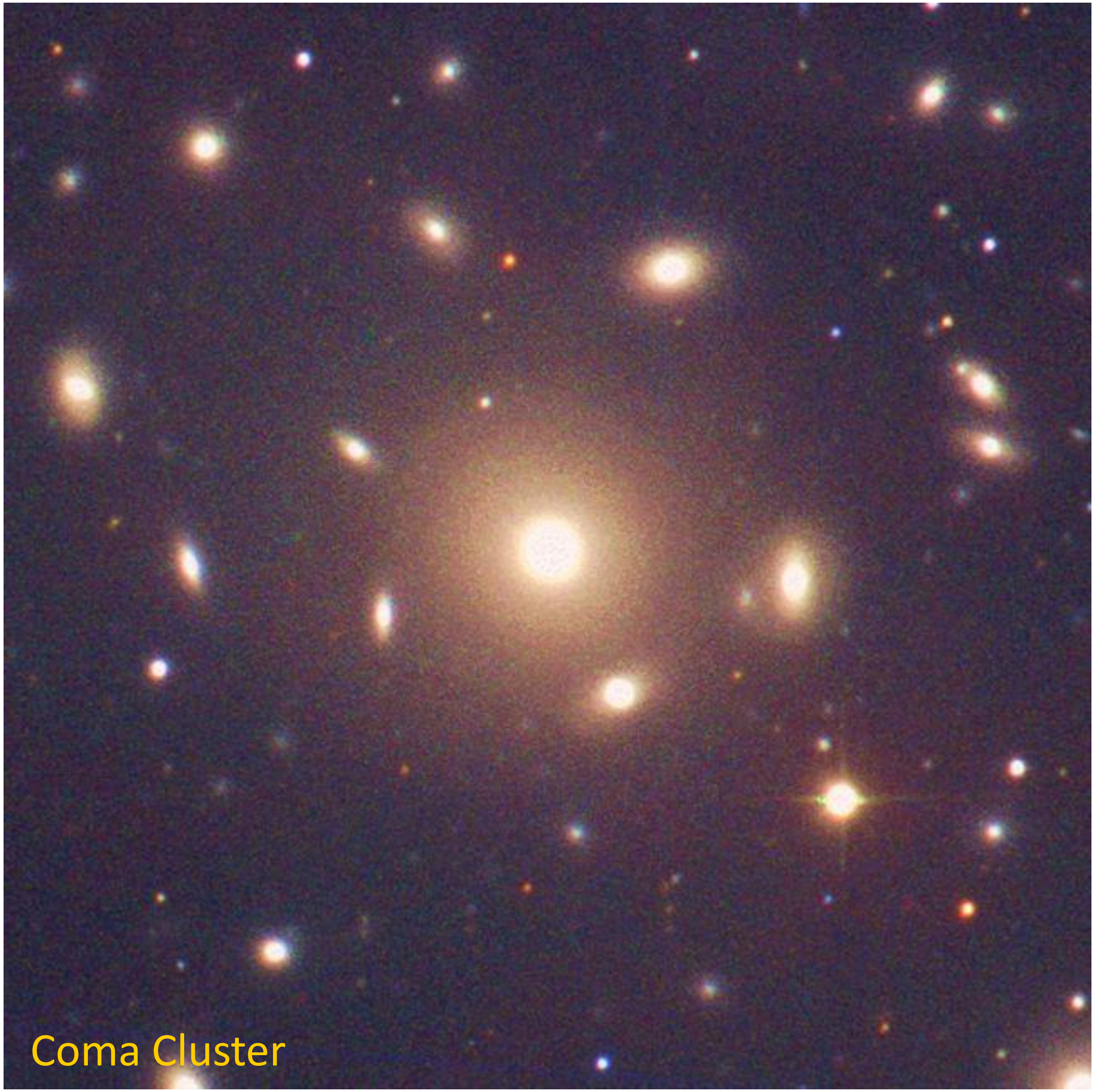
$T = 1.1\ {\rm keV}$



Central temperature from standard solar models

$T_{\rm c} = 1.56\times 10^7{\rm K} = 1.34\ {\rm keV}$

Virial Theorem – Dark Matter in Galaxy Clusters



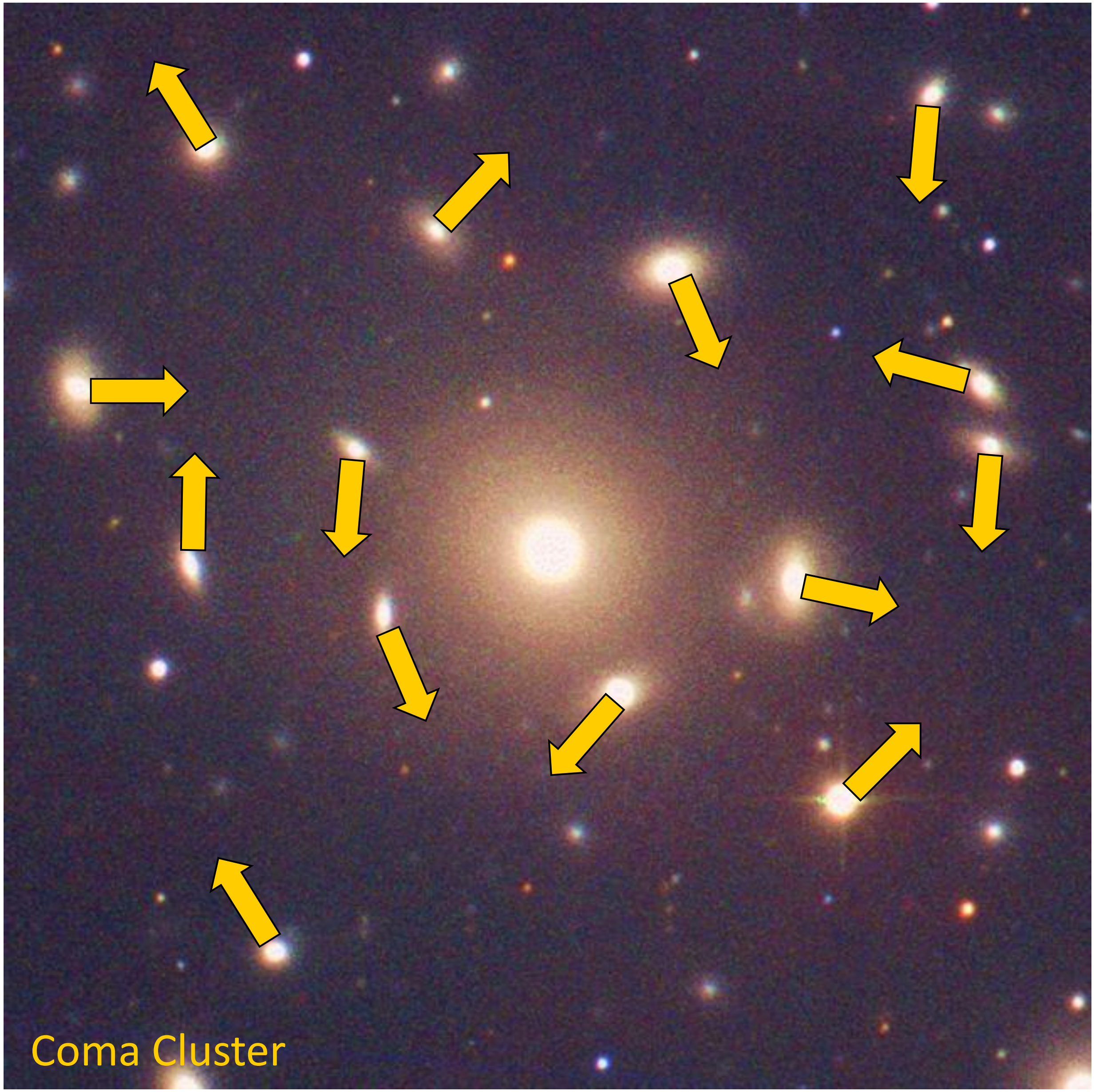
A gravitationally bound system of many particles obeys the virial theorem

$$2\langle E_{\rm kin}\rangle = -\langle E_{\rm grav}\rangle$$

$$2\left\langle\frac{mv^2}{2}\right\rangle = \left\langle\frac{G_N M_r m}{r}\right\rangle$$

$$\langle v^2\rangle \approx G_N M_r \langle r^{-1}\rangle$$

Virial Theorem – Dark Matter in Galaxy Clusters



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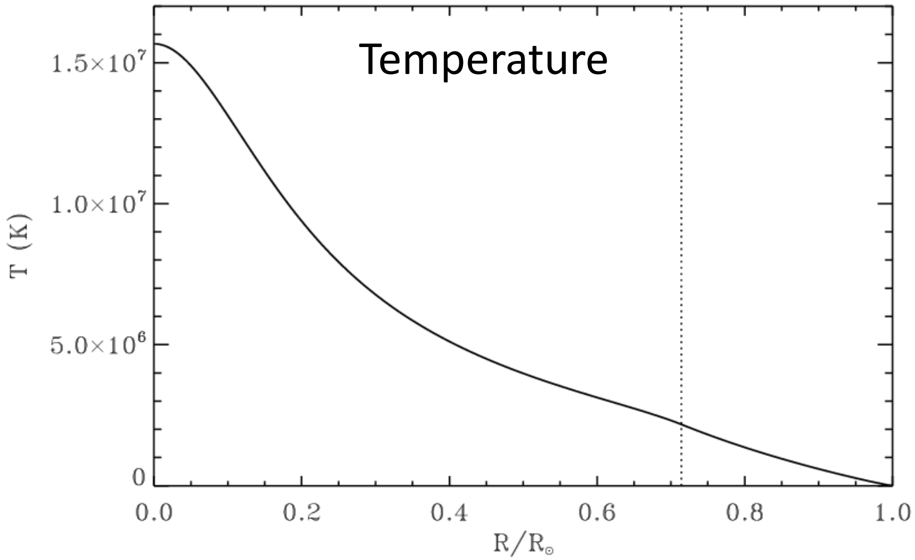
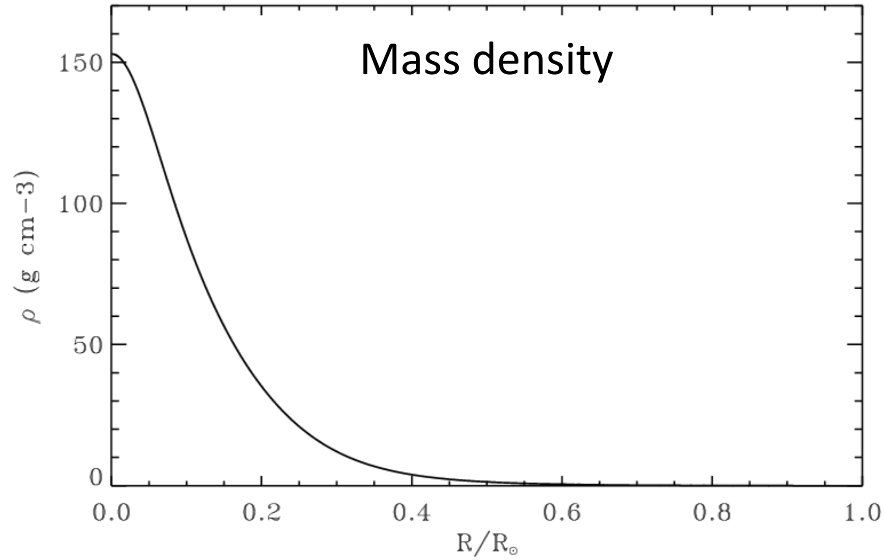
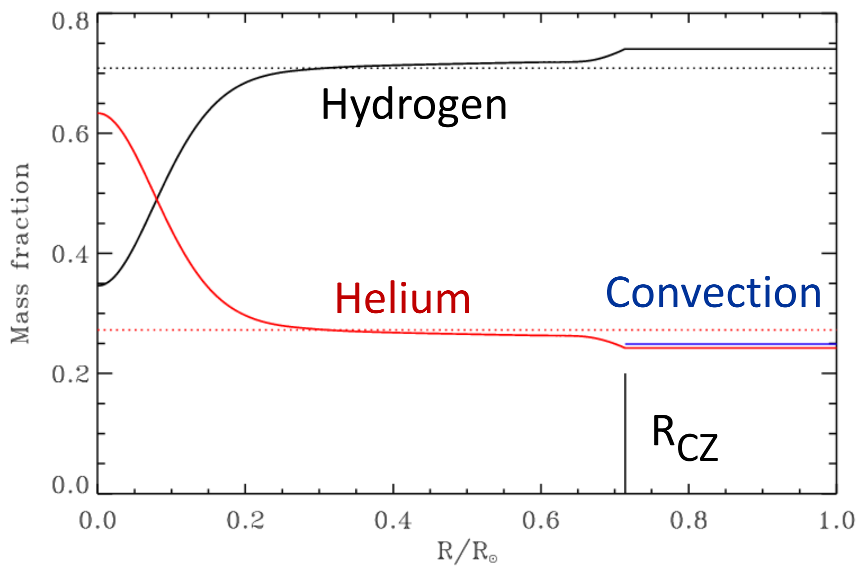
Velocity dispersion from Doppler shifts and geometric size

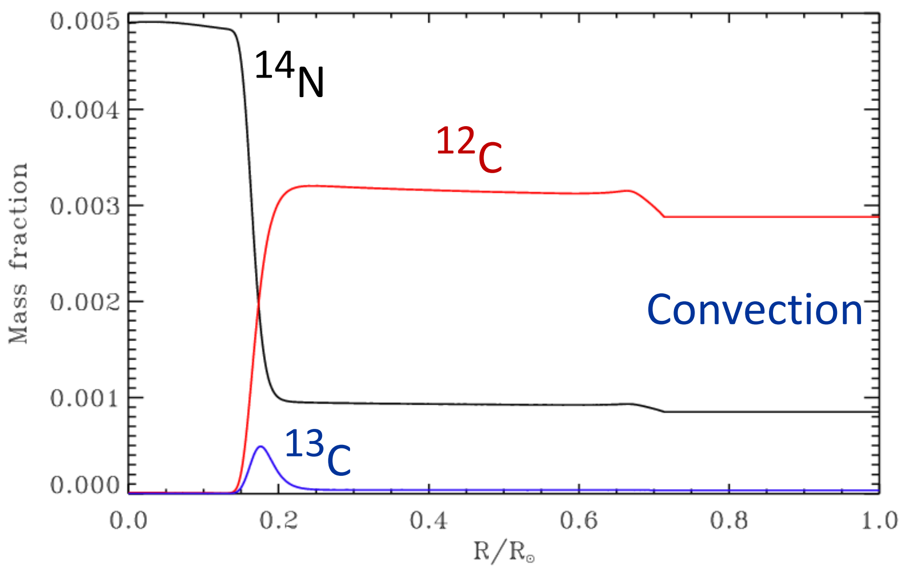
Total Mass

Standard Solar Model: Internal Structure



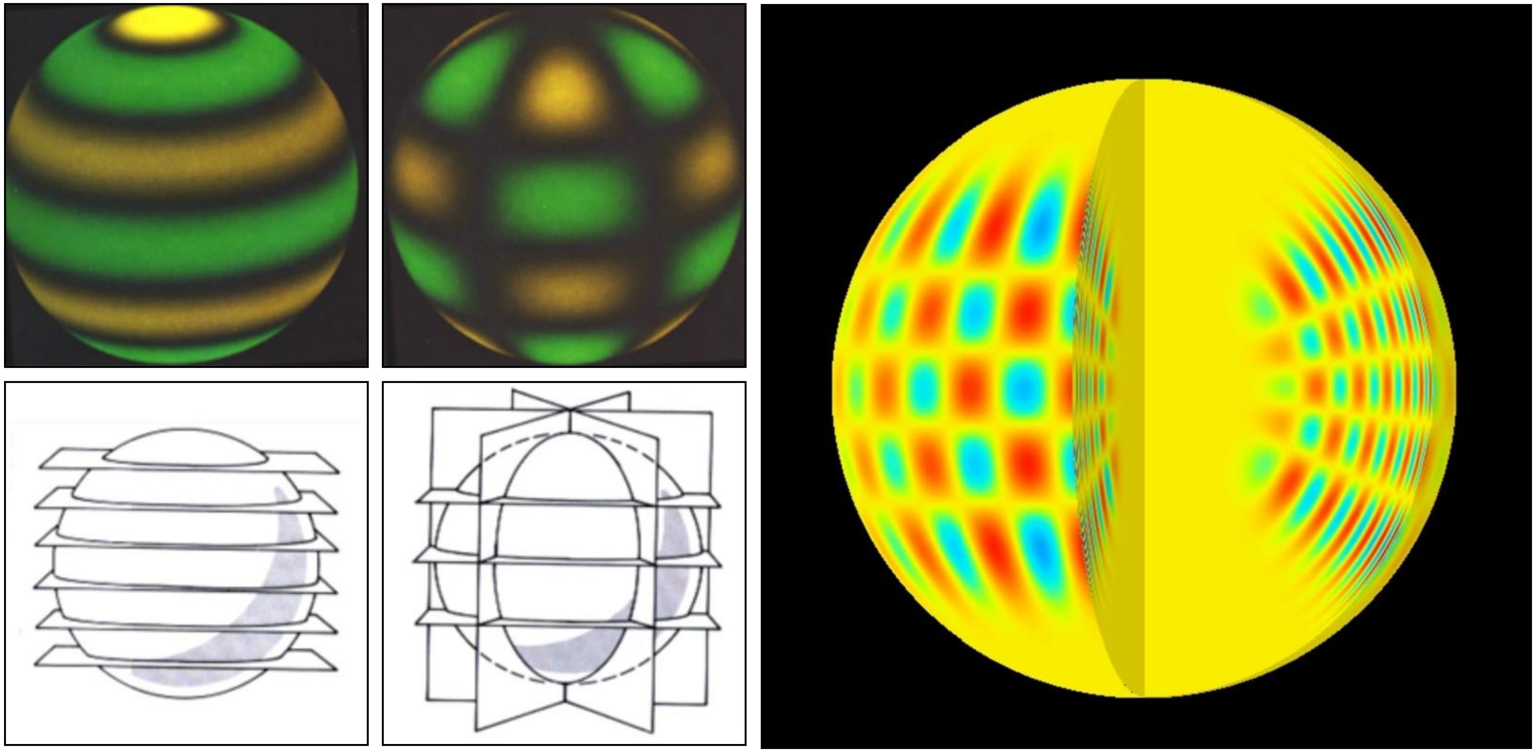






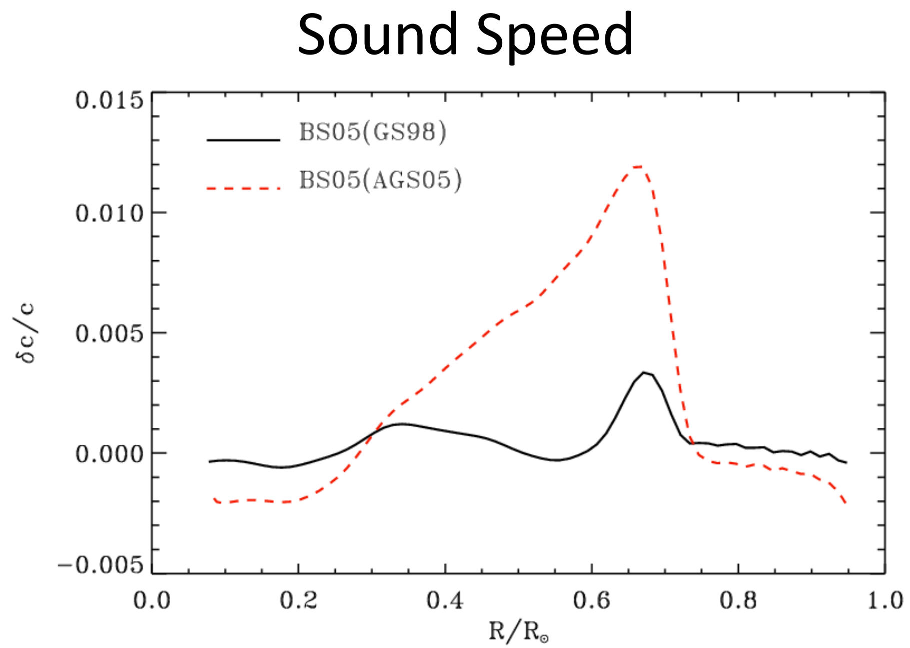
Helioseismology: Sun as a Pulsating Star

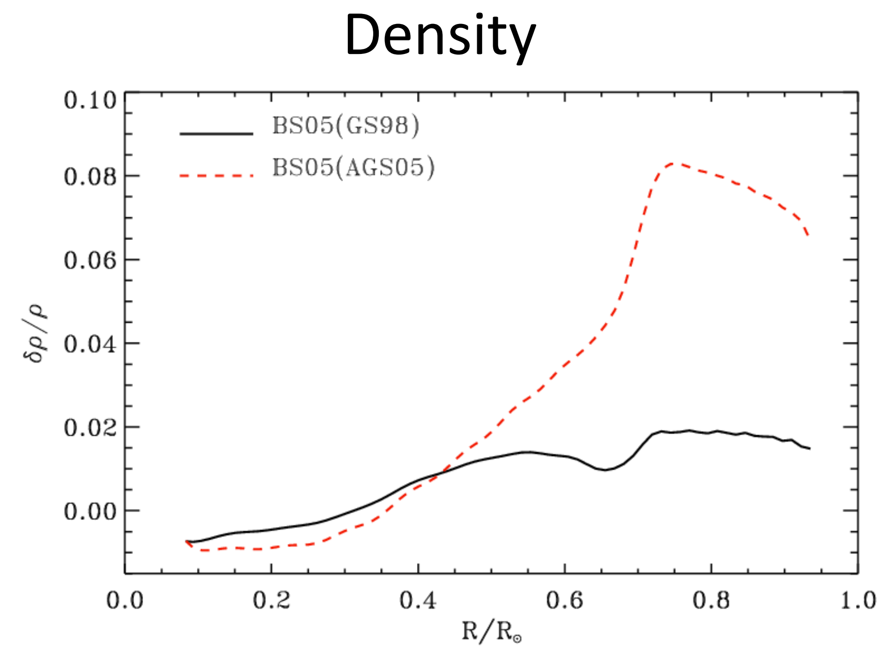
- Discovery of oscillations: Leighton et al. (1962)
- Sun oscillates in > 10^5 eigenmodes
- Frequencies of order mHz (5-min oscillations)
- Individual modes characterized by radial n, angular ℓ and longitudinal m numbers



Adapted from A. Serenelli's lectures at Scottish Universities Summer School in Physics 2006

Standard Solar Model 2005: Old and New Opacity





	Old: BS05 (GS98)	New: BS05 (ASG05)	Helioseismology
R_{CZ}	0.713	0.728	0.713 ± 0.001
Y_{SURF}	0.243	0.229	0.2485 ± 0.0035
$\langle\delta c\rangle$	0.001	0.005	—
$\langle\delta r\rangle$	0.012	0.044	—

Adapted from A. Serenelli's lectures at Scottish Universities Summer School in Physics 2006

PHYSICAL REVIEW D VOLUME 18, NUMBER 6 15 SEPTEMBER 1978

Astrophysical bounds on the masses of axions and Higgs particles

Rocky Kolb's PhD work

Duane A. Dicus and Edward W. Kolb*
Center for Particle Theory, The University of Texas, Austin, Texas 78712
Vigdor L. Teplitz†
Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
Robert V. Wagoner
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305

(Received 27 April 1978)

Lower bounds on the mass of a light scalar (Higgs) or pseudoscalar (axion) particle are found in three ways: (1) by requiring that their effect on primordial nucleosynthesis not yield a deuterium abundance outside present experimental limits, (2) by requiring that the photons from their decay thermalize and not distort the microwave background, and (3) by requiring that their emission from helium-burning stars (red giants) not disrupt stellar evolution. The best bound is from (3); it requires the axion or Higgs-particle mass to be greater than about 0.2 MeV.

The first process considered is the Primakoff process,[16] $\gamma + Z \to \phi + Z$, shown in Fig. 2. The cross section for this process near threshold is

$$|v|\sigma = 64\pi\alpha Z^2 \frac{\omega\Gamma(\phi\to 2\gamma)}{m_\phi{}^2}\frac{(\omega^2 - m_\phi{}^2)^{1/2}(\omega - m_\phi)}{(m_\phi{}^2 - 2\omega m_\phi)^2}, \quad (7)$$

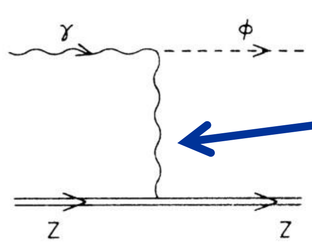


FIG. 2. $\gamma + Z \to \phi + Z$ via the Primakoff process.

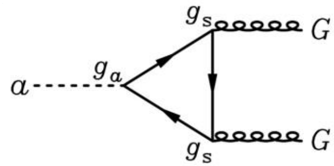
First discussion of Primakoff effect for WW axions ($m_a \gg T$)

For "invisible axions" ($m_a \ll T$)
Plasma screening effects crucial
in G.Raffelt's PhD work & PRD 33,897:1986
Still used today

Axion-Photon Coupling

Gluon coupling (generic), defines normalization of axion scale f_a

$$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi}\,\frac{a}{f_a}\,G\tilde{G}$$



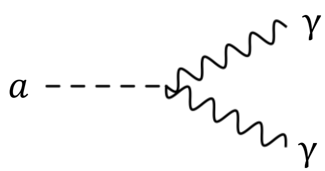
Mass (generic) depends on up/down quark masses

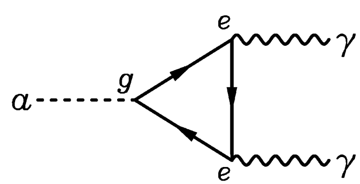
$$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d}\,\frac{m_\pi f_\pi}{f_a} = \frac{5.70\ \mu\mathrm{eV}}{f_a/10^{12}\ \mathrm{GeV}}$$

Axion-photon coupling (model dependent)

Generic from a-π-η mixing

$$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4}\,F\tilde{F}a = g_{a\gamma}\,\mathbf{E}\cdot\mathbf{B}\,a = \frac{\alpha}{2\pi}\left(\frac{E}{N} - 1.92\right)\frac{a}{f_a}\,\mathbf{E}\cdot\mathbf{B}$$



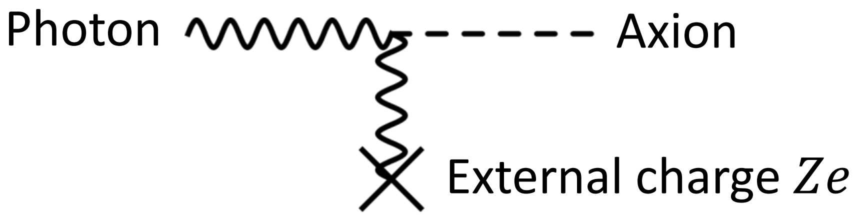


Model-dependent,
E/N = 0 (KSVZ), 8/3 (DFSZ), many others

$$g_{a\gamma} = \left(\frac{E}{N} - 1.92\right)\frac{0.203\ m_a}{\mathrm{GeV}^2} = \left(\frac{E}{N} - 1.92\right) 2.03 \times 10^{-16}\ \mathrm{GeV}^{-1}\,\frac{m_a}{1\mu\mathrm{eV}}$$

The QCD axion, precisely, Grilli di Cortona+, [1511.02867](1511.02867)

Primakoff Production



$$\mathcal{L} = g_{a\gamma} a\, \boldsymbol{E} \cdot \boldsymbol{B}$$

- **Differential scattering cross section**

$$\frac{d\sigma_{\gamma\to a}}{d\Omega} = \frac{g_{a\gamma}^2 Z^2 \alpha}{8\pi} \frac{\left|\boldsymbol{k}_\gamma \times \boldsymbol{k}_a\right|^2}{\left|\boldsymbol{k}_\gamma - \boldsymbol{k}_a\right|^4}$$

Coulomb divergence in the forward direction, to be augmented with screening factor $\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + k_S^2}$

$\boldsymbol{q} = \boldsymbol{k}_\gamma - \boldsymbol{k}_a$

- **Screening scale (Debye-Hückel scale)**

$$k_S^2 = 4\pi\alpha \sum_i \frac{Z_i^2 n_i}{T}$$

Static electric field of a test charge falls off as $\frac{e^{-k_S r}}{r^2}$ as if photons had a mass $m_\gamma = k_S$

- **Photon conversion rate**

$$\Gamma_{\gamma\to a} = \frac{g_{a\gamma}^2 T k_S^2}{32\pi} \left[\left(1 + \frac{k_S^2}{4\omega^2}\right) \log\left(1 + \frac{4\omega^2}{k_S^2}\right) - 1\right]$$

Photon Dispersion and Screening

- **Effective photon mass (non-relativistic plasma as in the Sun)**

  Summation over charged particle species with charge $Z_i e$

  Fine structure constant $\alpha = e^2/4\pi$

$$\omega_\mathrm{p}^2 = 4\pi\alpha \sum_i \frac{Z_i^2 n_i}{m_i} \approx \frac{4\pi\alpha\, n_e}{m_e}$$

  Photons propagate as if they had a mass $m_\gamma = \omega_\mathrm{p}$

- **Screening scale (Debye-Hückel scale)**

$$k_\mathrm{S}^2 = 4\pi\alpha \sum_i \frac{Z_i^2 n_i}{T}$$

$$\frac{k_\mathrm{S}}{\omega_\mathrm{p}} \approx \sqrt{\frac{m_e}{T}}$$

O(1) in a relativistic plasma

  Static electric field of a test charge falls off as $\dfrac{e^{-k_\mathrm{S} r}}{r^2}$

  as if photons had a mass $m_\gamma = k_\mathrm{S}$

- **Sun (center)**

  $T = 1.3\ \mathrm{keV}$ $\qquad \omega_\mathrm{p} = 0.3\ \mathrm{keV} \ll T$ $\qquad k_\mathrm{S} = 9\ \mathrm{keV} \gg T$

Primakoff Energy Loss Rate

- **Photon conversion rate**

$$\Gamma_{\gamma\to a}=\frac{g_{a\gamma}^2 T k_S^2}{32\pi}\left[\left(1+\frac{k_S^2}{4\omega^2}\right)\log\left(1+\frac{4\omega^2}{k_S^2}\right)-1\right]$$

- **Energy loss rate per unit volume (in erg/cm³ s)**

$$\mathrm{Q}_{\gamma\to a}=\int 2\frac{d^3\mathbf{k}_\gamma}{(2\pi)^3}\Gamma_{\gamma\to a}\frac{\omega}{e^{\omega/T}-1}=\frac{g_{a\gamma}^2 T^7}{4\pi}F(\kappa^2)$$

$$\kappa^2=\left(\frac{k_S}{2T}\right)^2\propto\frac{n_e}{T^3}$$

$$F(\kappa^2)=\frac{\kappa^2}{2\pi^2}\int_0^\infty dx\left[(x^2+\kappa^2)\log\left(1+\frac{x^2}{\kappa^2}\right)-x^2\right]\frac{x}{e^x-1}$$

- **Sun:** $\kappa^2\approx 12$ within $\pm 15\%$ throughout the Sun

$$L_a=\left(\frac{g_{a\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}}\right)^2 1.85\times 10^{-3}L_\odot$$

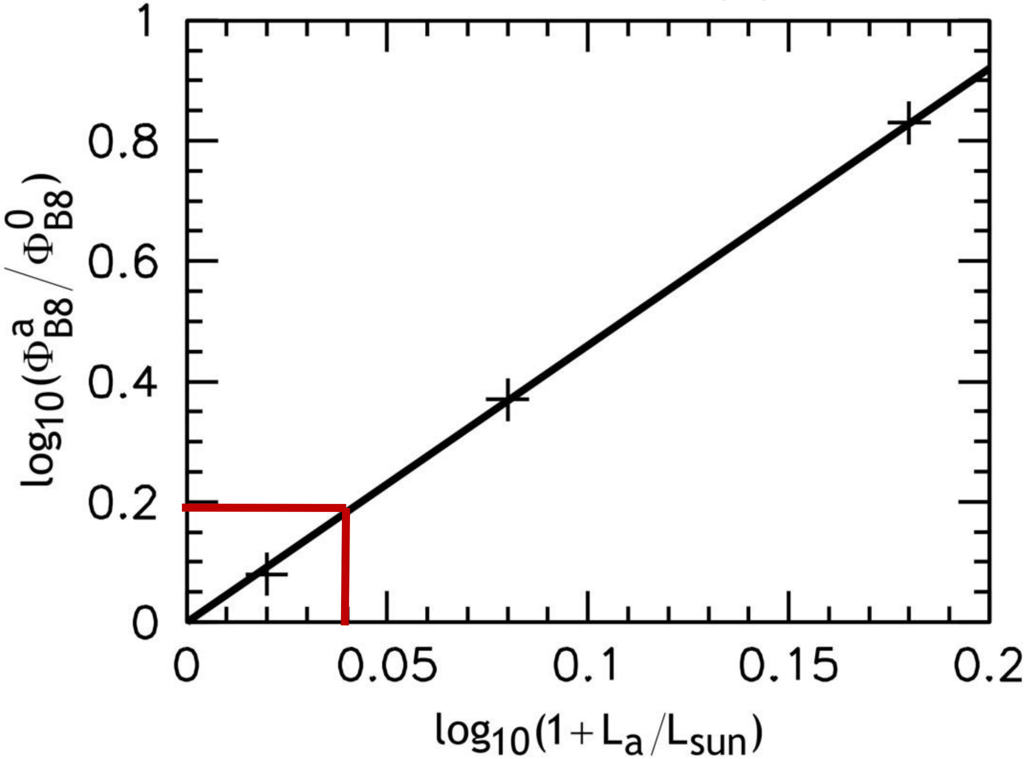
$$L_\odot=3.84\times 10^{33}\mathrm{erg/s}$$

Primakoff luminosity of the Sun

Solar Neutrino Limit on Solar Energy Losses

Self-consistent models of the present-day Sun provide a simple power-law connection between a new energy loss L_a (e.g. axions) and the solar neutrino flux from B^8

Schlattl, Weiss & Raffelt, hep-ph/9807476



Gondolo & Raffelt, arXiv:0807.2926

$$T_{c,a} = T_{c,0}\left(\frac{L_\odot + L_a}{L_\odot}\right)^{0.22}$$

$$\Phi_{\mathrm{B8}} \propto T_c^{18}$$

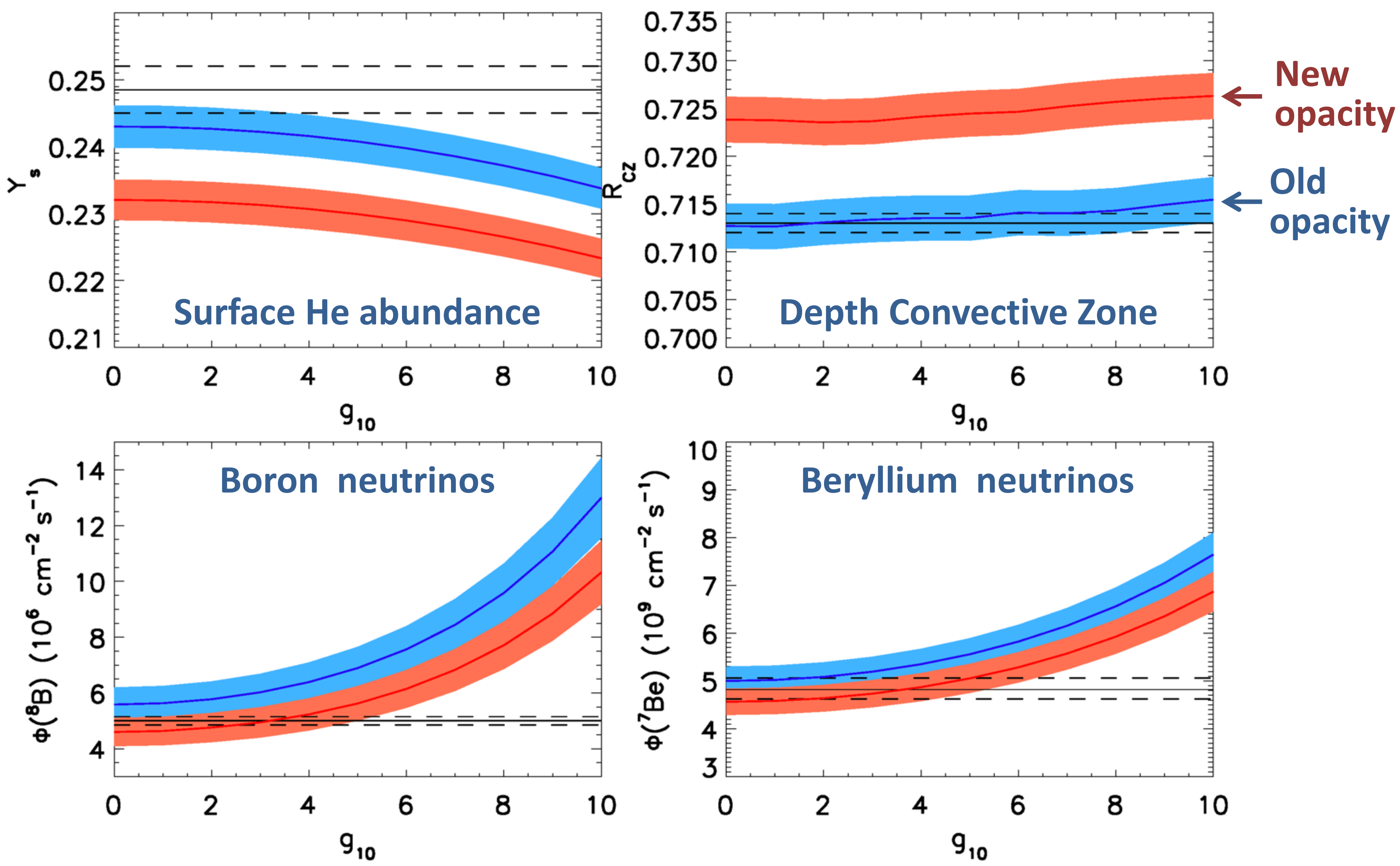
$$\Phi_{\mathrm{B8},a} = \Phi_{\mathrm{B8},a}\left(\frac{L_\odot + L_a}{L_\odot}\right)^{4.6}$$

Solar models with SNO all-flavor measurements imply roughly

$$L_a \lesssim 0.1\, L_\odot$$

$$L_a = \left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2 1.85\times 10^{-3} L_\odot \;\Rightarrow\; g_{a\gamma} \lesssim 7\times 10^{-10}\mathrm{GeV}^{-1}$$

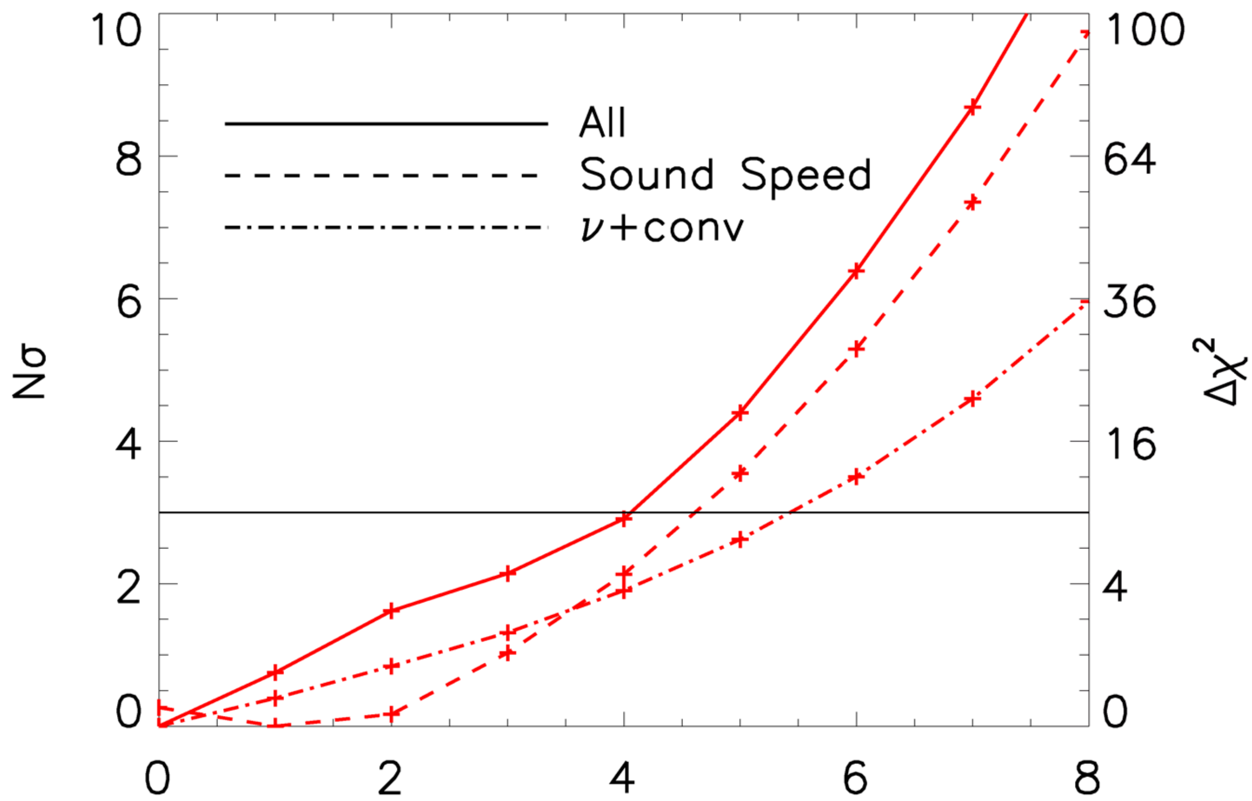
Solar Observables Modified by Axion Losses



Vinyoles, Serenelli, Villante, Basu, Redondo & Isern, arXiv:1501.01639

Global Fit from Solar Observables

Allow all input parameters to float, including chemical composition, and marginalize except for axion losses



$$g_{10} = g_{a\gamma} \times 10^{10}\ \mathrm{GeV}$$

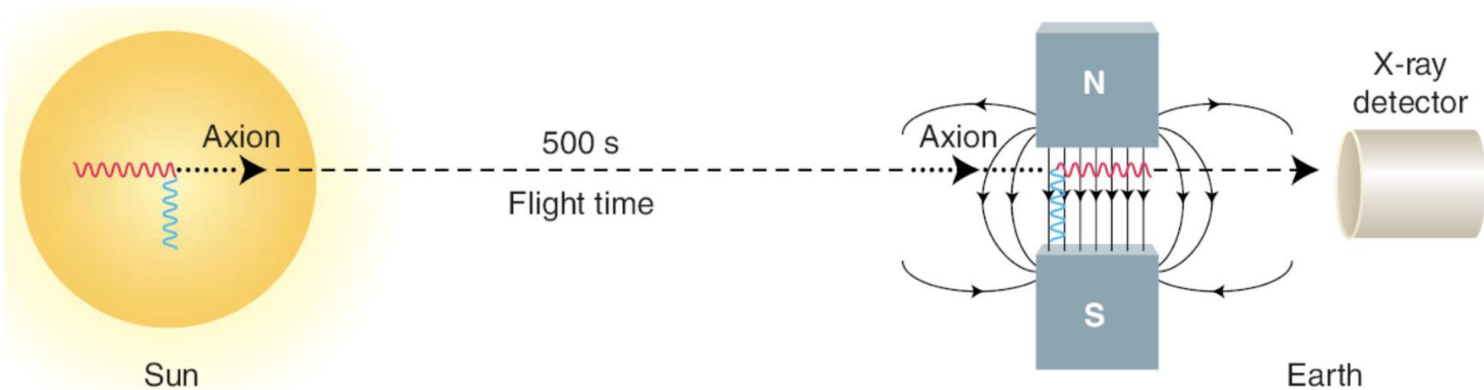
Vinyoles, Serenelli, Villante, Basu, Redondo & Isern, arXiv:1501.01639

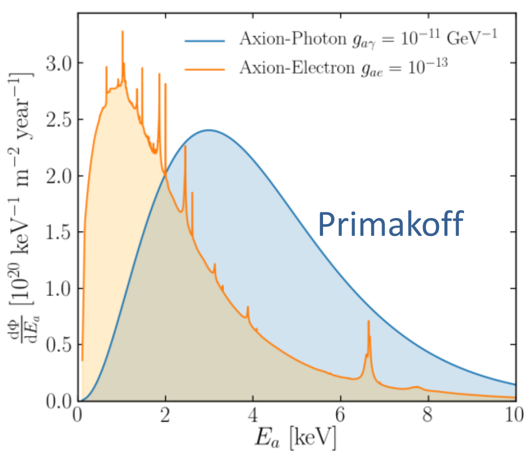
VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

Experimental Tests of the "Invisible" Axion

P. Sikivie
Physics Department, University of Florida, Gainesville, Florida 32611
(Received 13 July 1983)

Experiments are proposed which address the question of the existence of the "invisible" axion for the whole allowed range of the axion decay constant. These experiments exploit the coupling of the axion to the electromagnetic field, axion emission by the sun, and/or the cosmological abundance and presumed clustering of axions in the halo of our galaxy.





- Large coherence length overcomes small coupling
- Axion-photon conversion in B-field similar to neutrino flavor oscillation, PRD 37 (1988) 1237
- Can be enhanced with gas filling van Bibber+ PRD 39 (1989) 2089

https://cajohare.github.io/IAXOmass/

Let's point a magnet
at the sun…

© Sebastian Baum

…and look for X-Rays!

Rochester-Brookhaven-FermiLab

Lazarus+ PRL 69 (1992) 2333

Few hours of data, fixed magnet

$G_{a\gamma\gamma} < 0.77 \times 10^{-8}\ \mathrm{GeV}^{-1}$

Tokyo Helioscope (Sumico)

Fully stearable, 2.3 m long, 4 Tesla

Moriyama+ [hep-ex/9805026]

$G_{a\gamma\gamma} < 0.60 \times 10^{-9}\ \mathrm{GeV}^{-1}$

See also Ohta+ [1201.4622]

CAST (1998–2021)

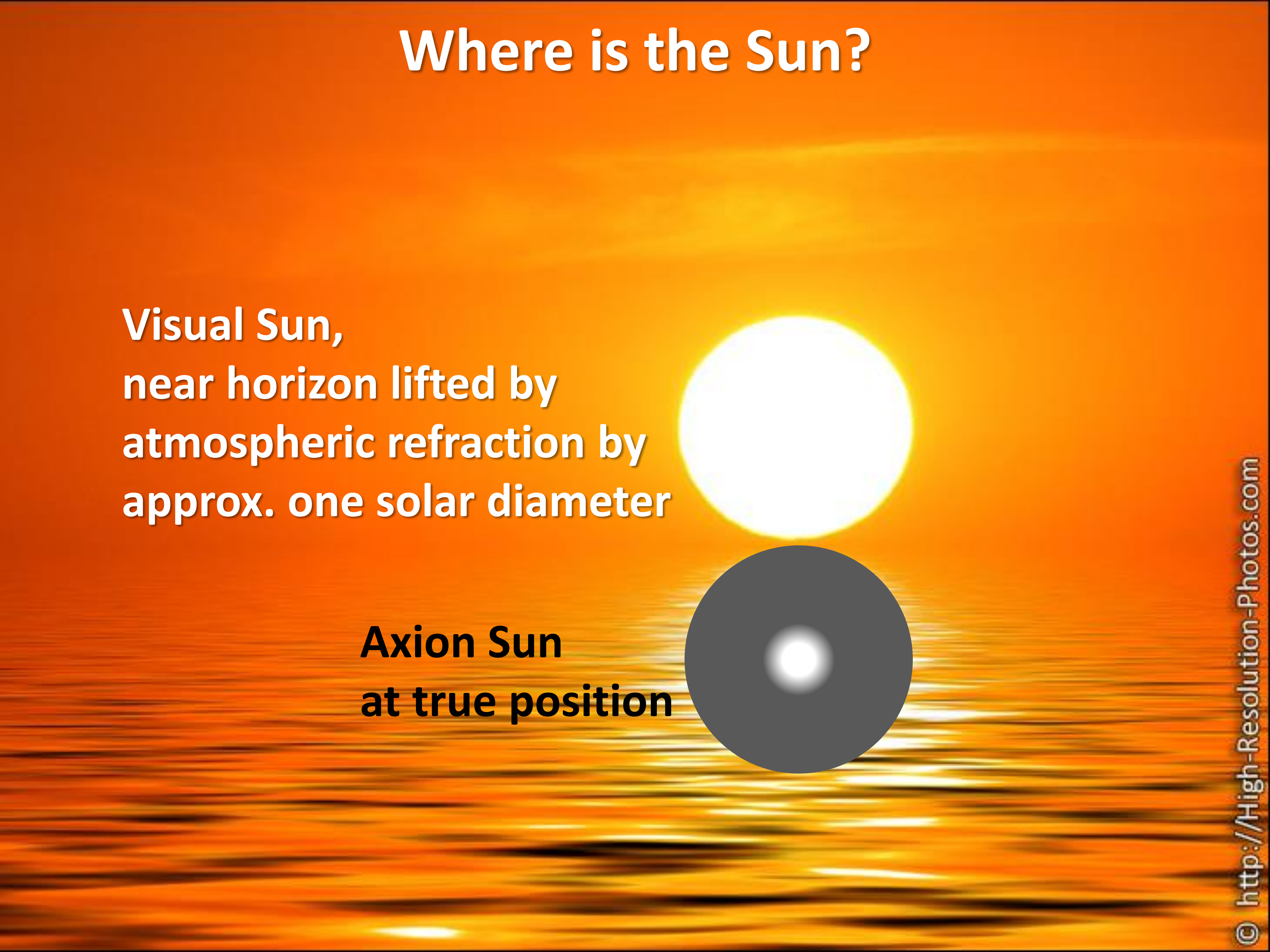
Stearable, 9.26 m long, 9 Tesla

Anastassopoulos+ [1705.02290]

$G_{a\gamma\gamma} < 0.66 \times 10^{-10}\ \mathrm{GeV}^{-1}$

CAST Movie on YouTube

https://youtu.be/XY2lFDXz8aQ


Where is the Sun?
Visual Sun,
near horizon lifted by
atmospheric refraction by
approx. one solar diameter
Axion Sun
at true position
© http://High-Resolution-Photos.com

Axion-Photon-Transitions as Particle Oscillations

Raffelt & Stodolsky, PRD 37 (1988) 1237

Photon refractive and birefringence effects
(Faraday rotation, Cotton-Mouton-effect)

Stationary Klein-Gordon equation for coupled a-γ-system

$$\left[\omega^2 + \nabla^2 + 2\omega^2 \begin{pmatrix} n_\perp - 1 & n_F & 0 \\ n_F & n_\parallel & \frac{g_{a\gamma} B}{2\omega} \\ 0 & \frac{g_{a\gamma} B}{2\omega} & -\frac{m_a^2}{2\omega^2} \end{pmatrix}\right] \begin{pmatrix} A_\perp \\ A_\parallel \\ a \end{pmatrix} = 0$$

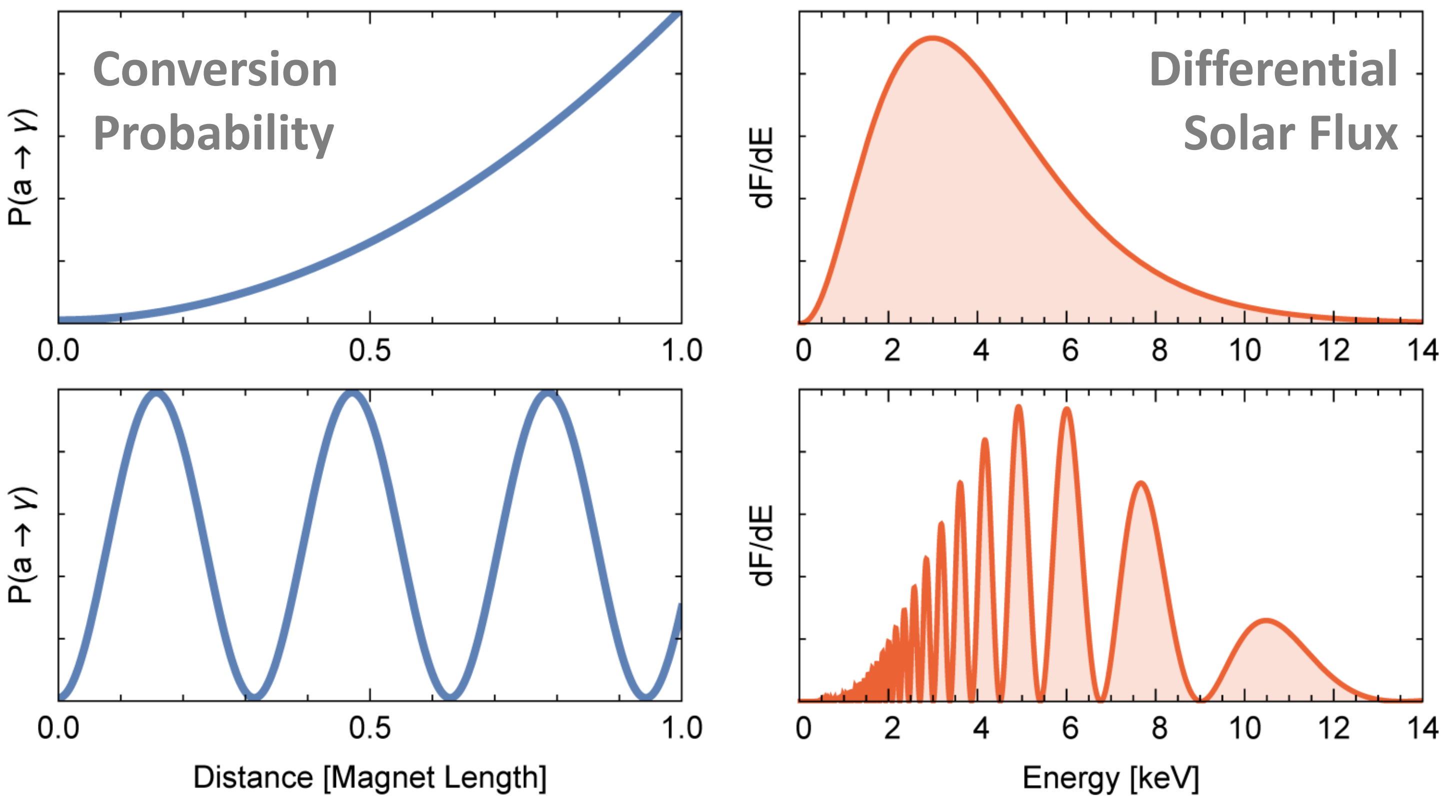
Axion-photon transitions

- Axions roughly like another photon polarization state
- In a homogeneous or slowly varying B-field, a photon beam develops a coherent axion component

Axion-Photon Conversion in CAST

$$P(a\to\gamma)=\left(\frac{g_{a\gamma}BL}{2}\,\frac{\sin(qL/2)}{qL/2}\right)^2=\left(\frac{g_{a\gamma}B}{2}\right)^2\times\begin{cases}L^2 & \text{for } qL\ll 1\\ 1/2q^2 & \text{for } qL\gg 1\end{cases}$$

Momentum transfer $q=(m_a^2-m_\gamma^2)/2\omega$

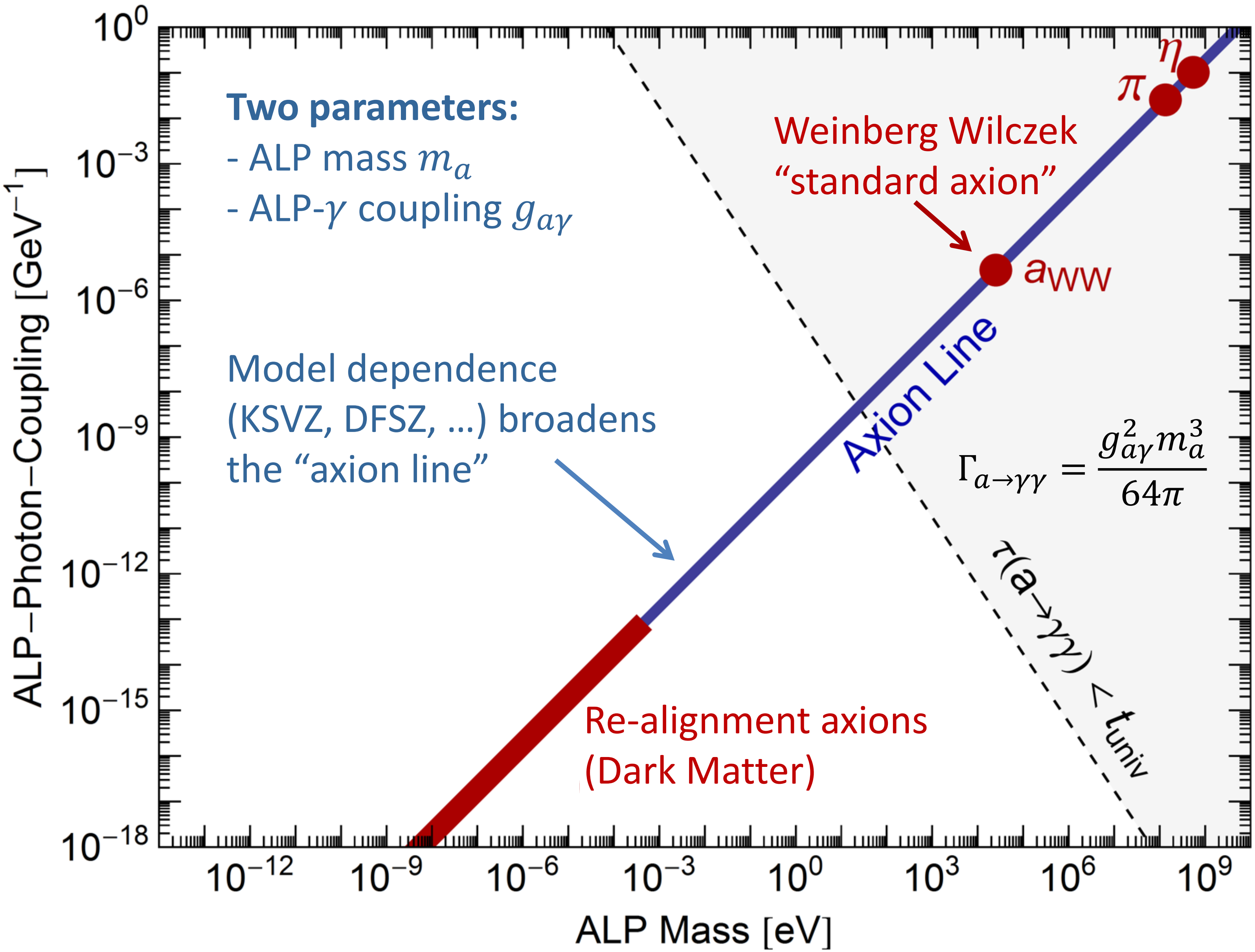


Small mass ("coherent")

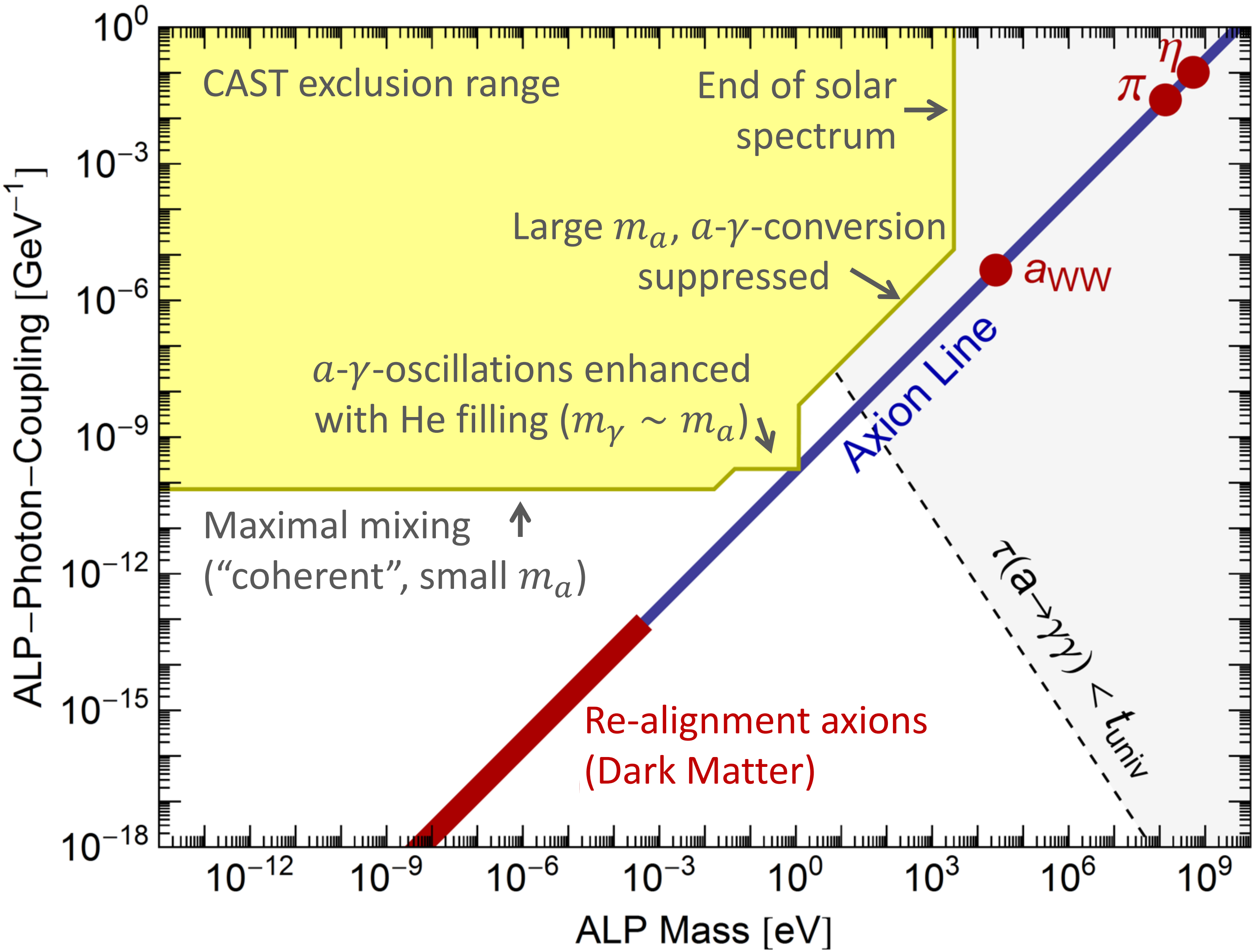
Large mass ("incoherent")

Can "weigh" axions arXiv:1811.09290

Parameter Space for Axion-Like Particles (ALPs)



Parameter Space for Axion-Like Particles (ALPs)



Extending to higher mass values with gas filling

Axion-photon transition probability

$$P_{a\to\gamma} = \left(\frac{g_{a\gamma}B}{q}\right)^2 \sin^2\left(\frac{qL}{2}\right)$$

Axion-photon momentum transfer

$$q = \left|\frac{m_a^2 - m_\gamma^2}{2E}\right|$$

Transition is suppressed for $qL \gtrsim 1$

Gas filling: Give photons a refractive mass to restore full transition strength

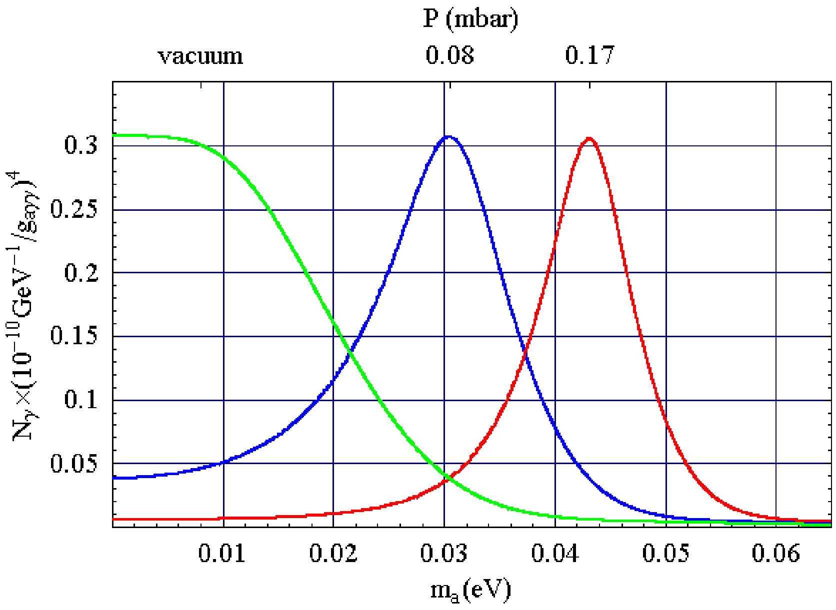
$$m_\gamma^2 = \frac{4\pi\alpha}{m_e}\, n_e$$

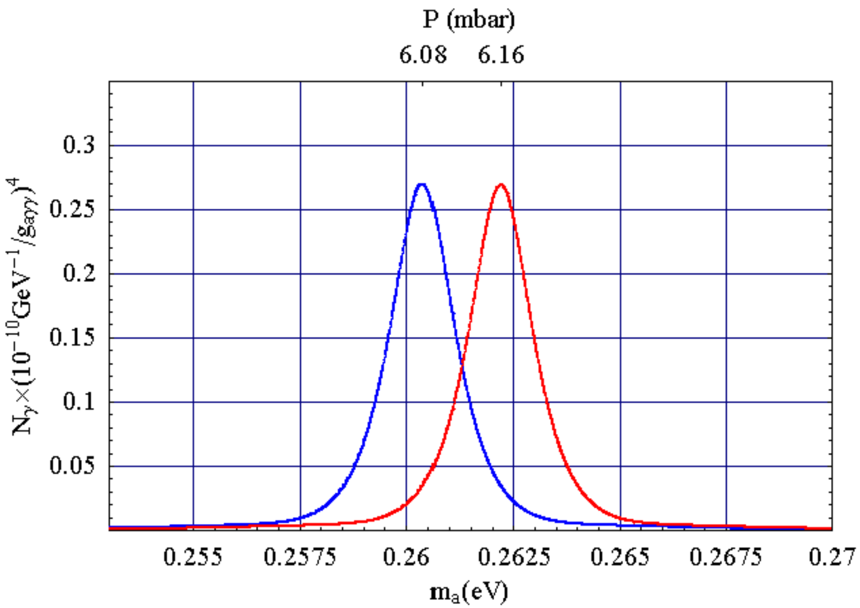
$$m_\gamma = 28.9\ \mathrm{eV} \left(\frac{Z}{A}\,\rho_{\mathrm{gas}}\right)^{1/2}$$

He-4 vapour pressure at 1.8 K is

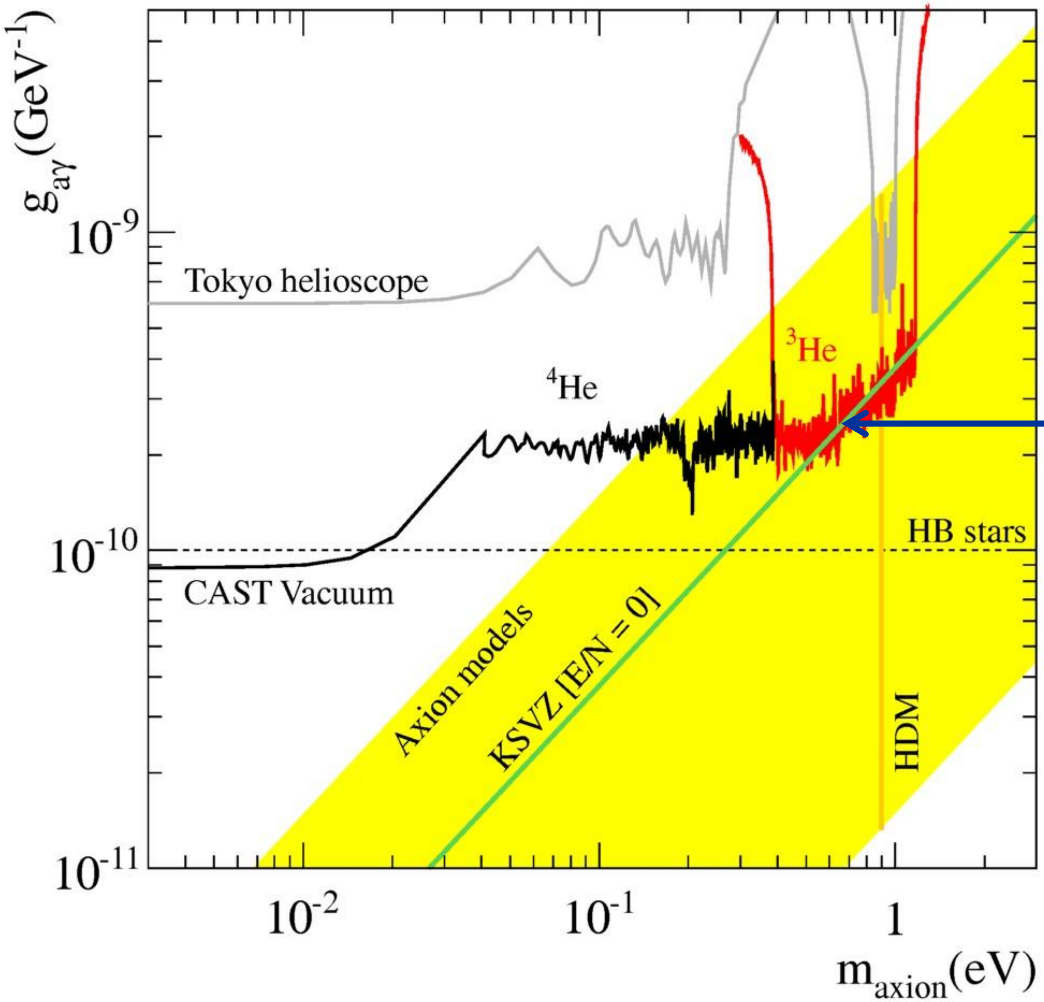
$$\rho \approx 0.2 \times 10^{-3}\ \mathrm{g\,cm^{-3}}$$

$$m_\gamma = 0.4\ \mathrm{eV}$$





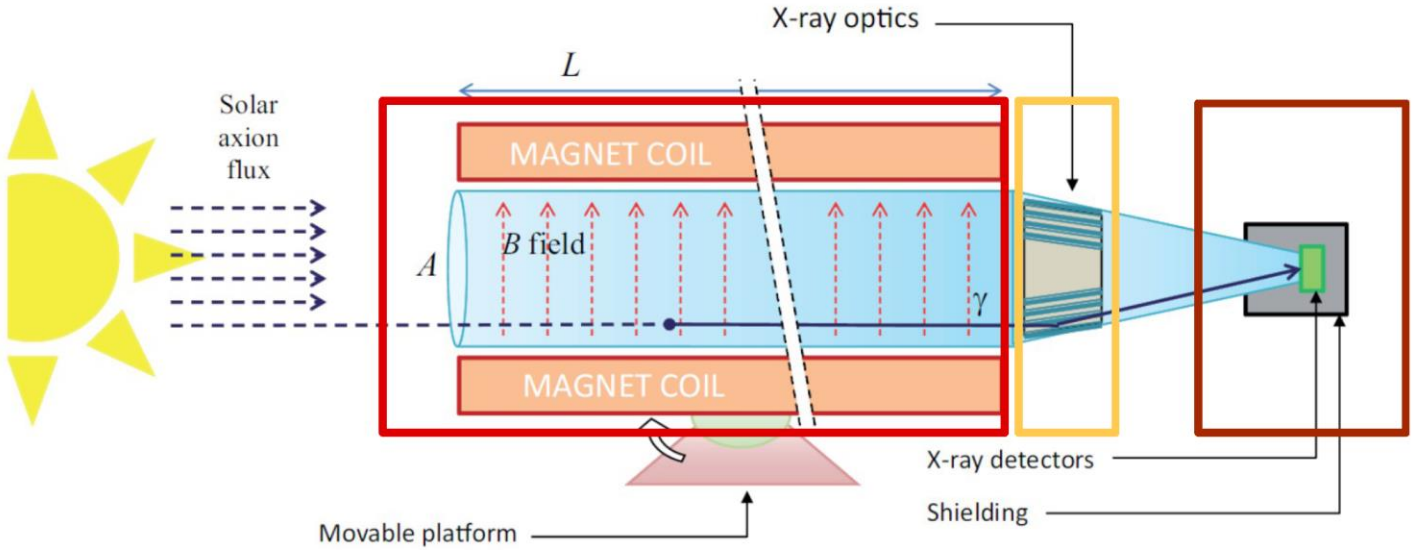
Helioscope Limits



First experimental crossing of the KSVZ line

CAST-I results: PRL 94:121301 (2005) and JCAP 0704 (2007) 010
CAST-II results (He-4 filling): JCAP 0902 (2009) 008
CAST-II results (He-3 filling): PRL 107: 261302 (2011) and PRL 112, 091302 (2014)

Advanced Helioscope



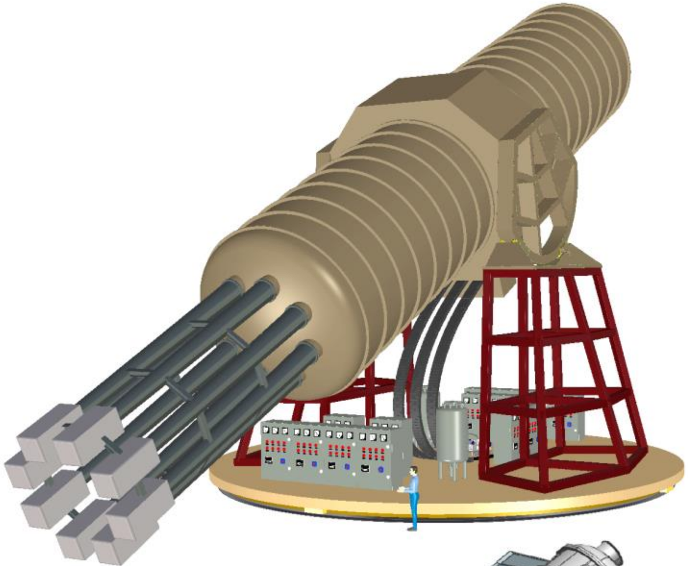
Sensitivity to axion-photon coupling

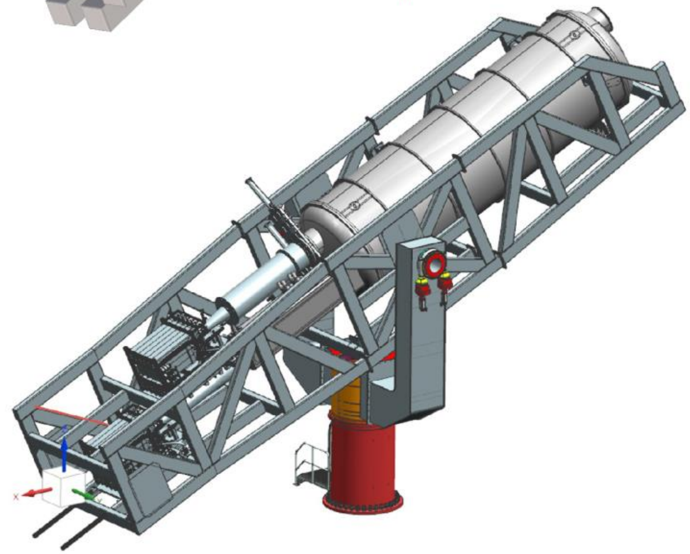
$$g_{a\gamma}^4 \propto \boxed{B^2 L^2 A} \cdot \boxed{\varepsilon_o \alpha^{-1/2}} \cdot \boxed{\varepsilon_d b^{-1/2}} \cdot \boxed{\varepsilon_t t^{-1/2}}$$

Magnet Optics Detector Time

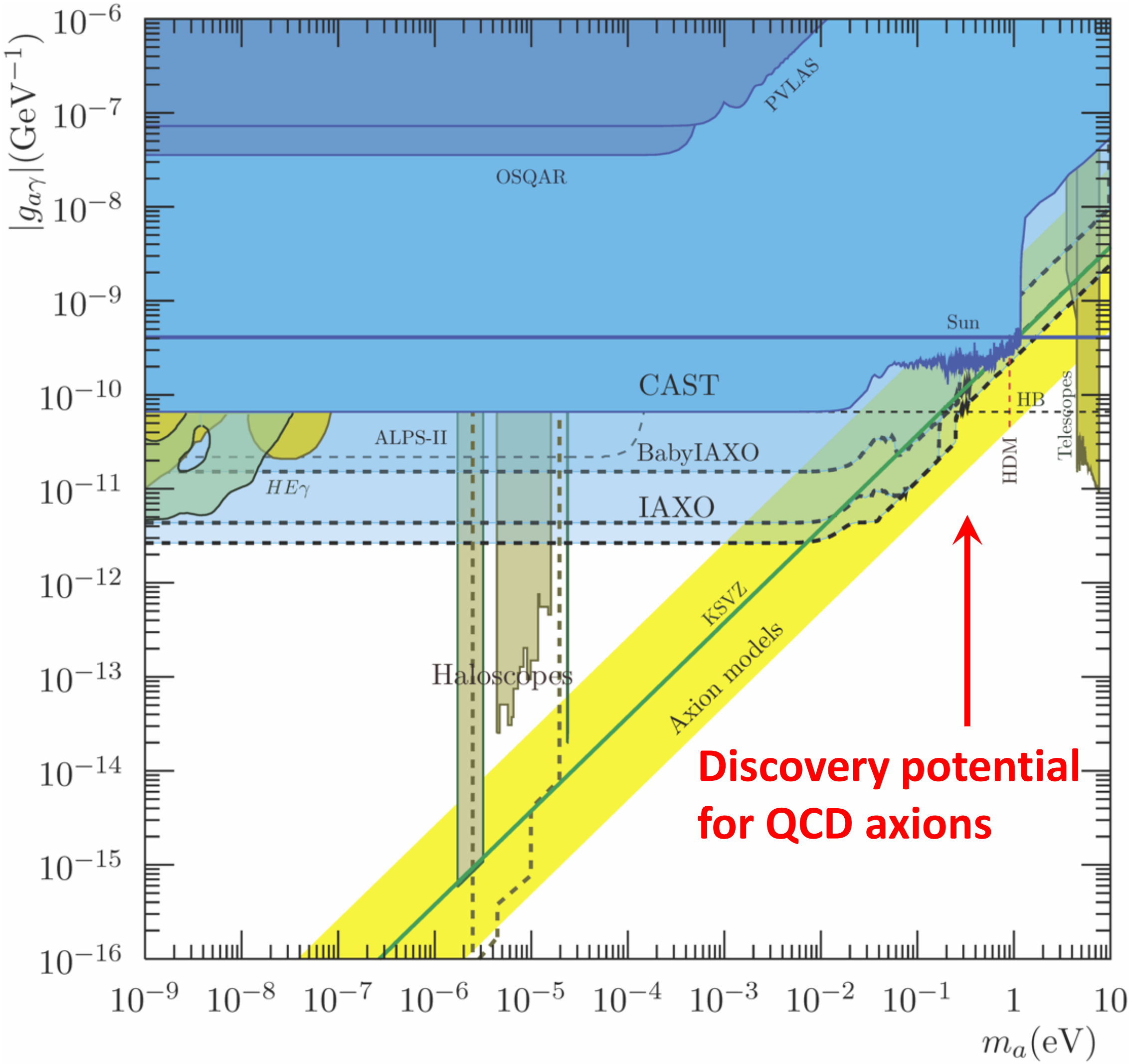
CAST, BabyIAXO, IAXO

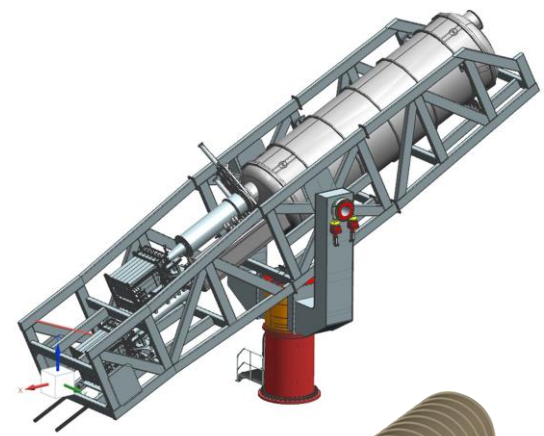
- 20 years experience from CAST
- IAXO will have a 300 times better magnet Figure of merit (FoM)
- BabyIAXO an intermediate state technology demonstrator
- BabyIAXO will be built at DESY (Hamburg)

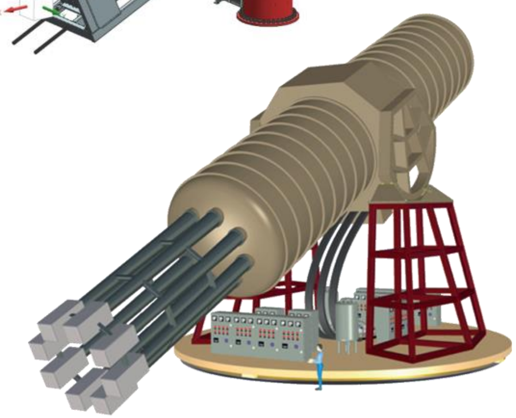




(Baby) IAXO Sensitivity Forecast

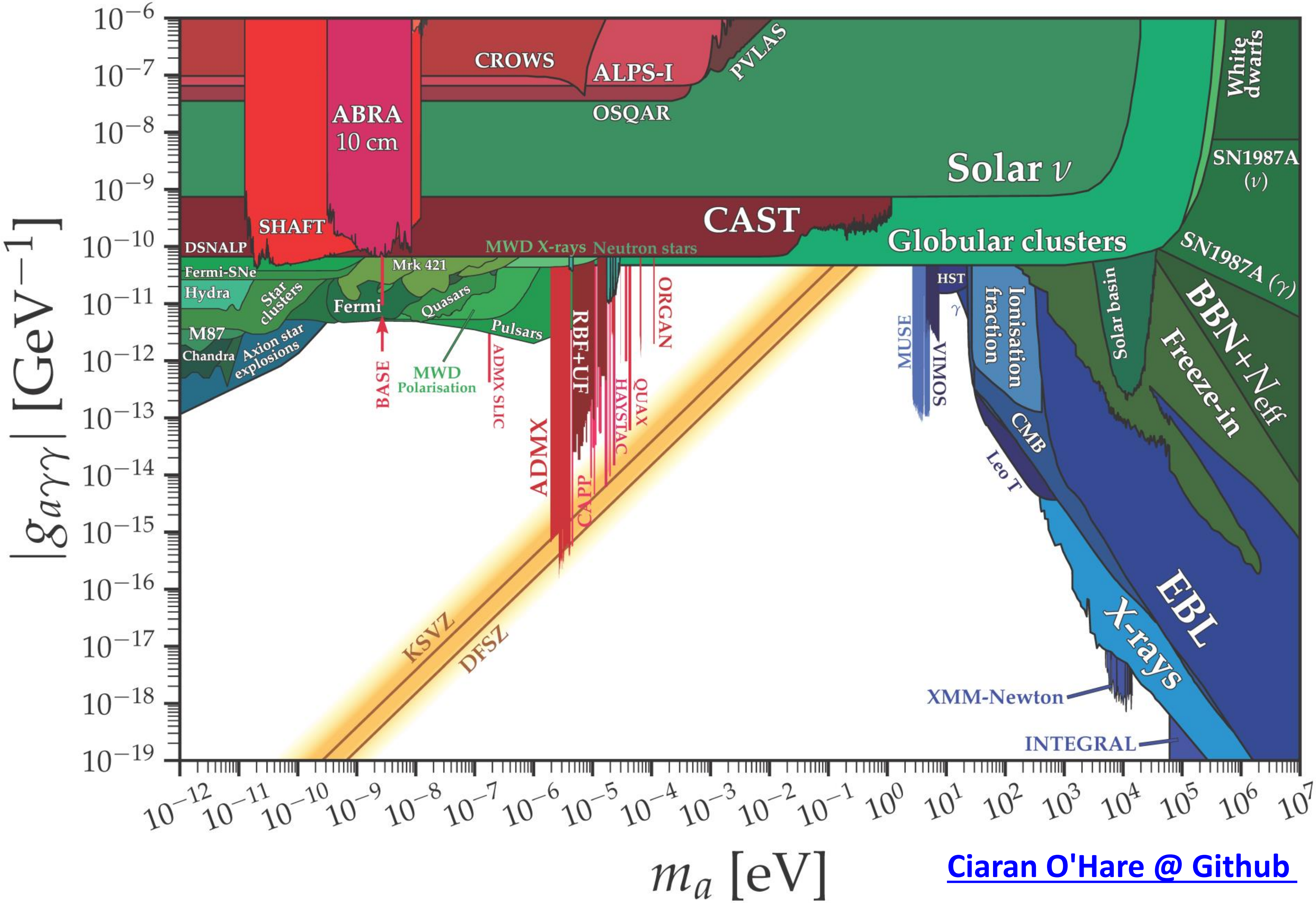






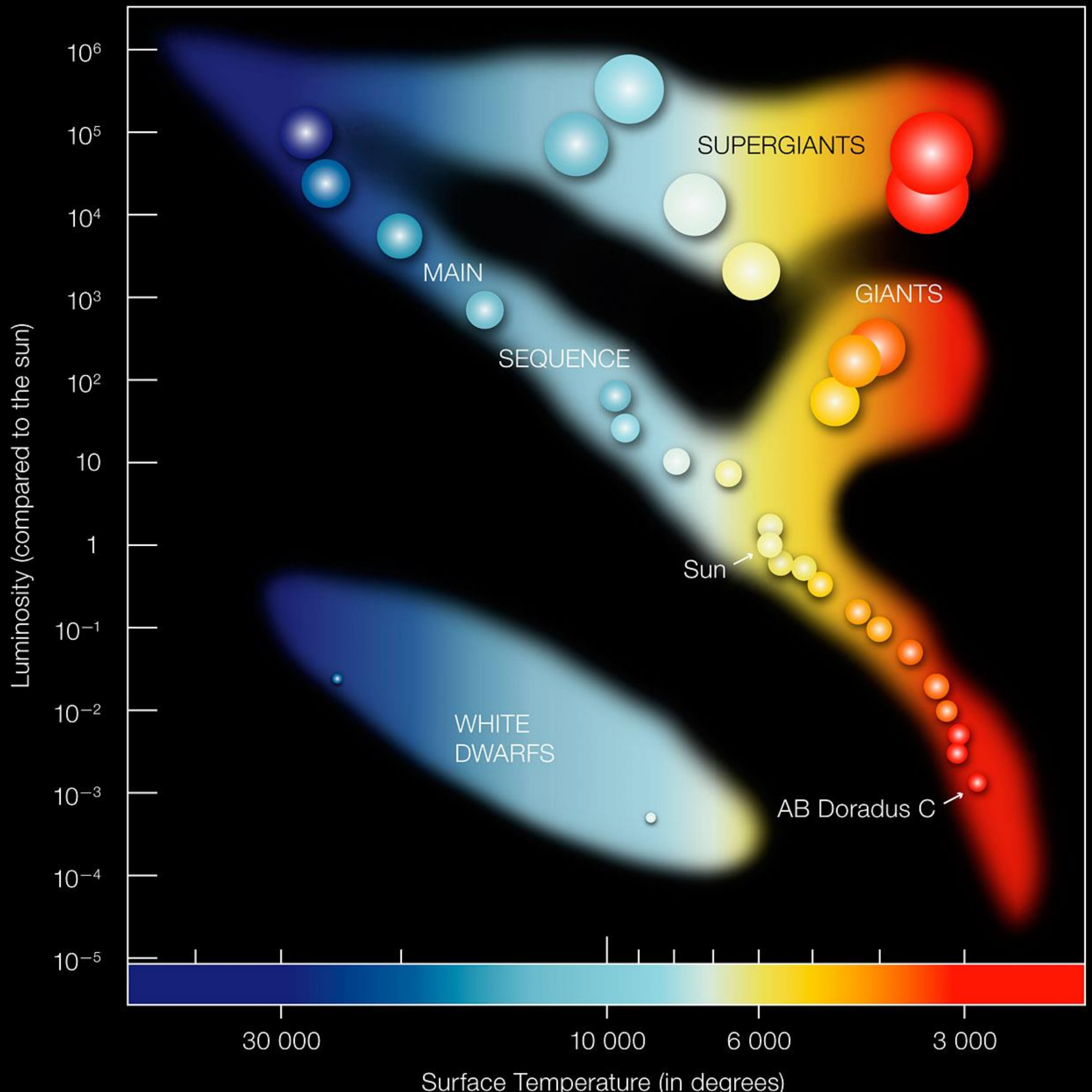
Physics potential of the International Axion Observatory (IAXO)
JCAP 1906 (2019) 047, arXiv:1904.09155

Grand Unified ALP Scape



[Ciaran O'Hare @ Github]

Axion Emission – Backreaction on Stars



Hertzsprung Russell Diagram

https://www.eso.org/public/images/eso0728c/

Equations of Stellar Structure

Assume spherical symmetry and static structure (neglect kinetic energy)
Excludes: Rotation, convection, magnetic fields, supernova-dynamics, …

Hydrostatic equilibrium

$$\frac{dP}{dr} = -\frac{G_N M_r \rho}{r^2}$$

Energy conservation

$$\frac{dL_r}{dr} = 4\pi r^2 \epsilon \rho$$

Energy transfer

$$L_r = \frac{4\pi r^2}{3\kappa\rho} \frac{d(aT^4)}{dr}$$

Literature

- Clayton: Principles of stellar evolution and nucleosynthesis (Univ. Chicago Press 1968)
- Kippenhahn & Weigert: Stellar structure and evolution (Springer 1990)

r Radius from center

P Pressure

G_N Newton's constant

ρ Mass density

M_r Integrated mass up to r

L_r Luminosity (energy flux)

ϵ Local rate of energy generation $[\mathrm{erg\,g^{-1}s^{-1}}]$

$$\epsilon = \epsilon_{\rm nuc} + \epsilon_{\rm grav} - \epsilon_\nu$$

κ Opacity

$$\kappa^{-1} = \kappa_\gamma^{-1} + \kappa_{\rm c}^{-1}$$

κ_γ Radiative opacity

$$\kappa_\gamma \rho = \langle\lambda_\gamma\rangle_{\rm Rosseland}^{-1}$$

$\kappa_{\rm c}$ Electron conduction

Convection in Main-Sequence Stars

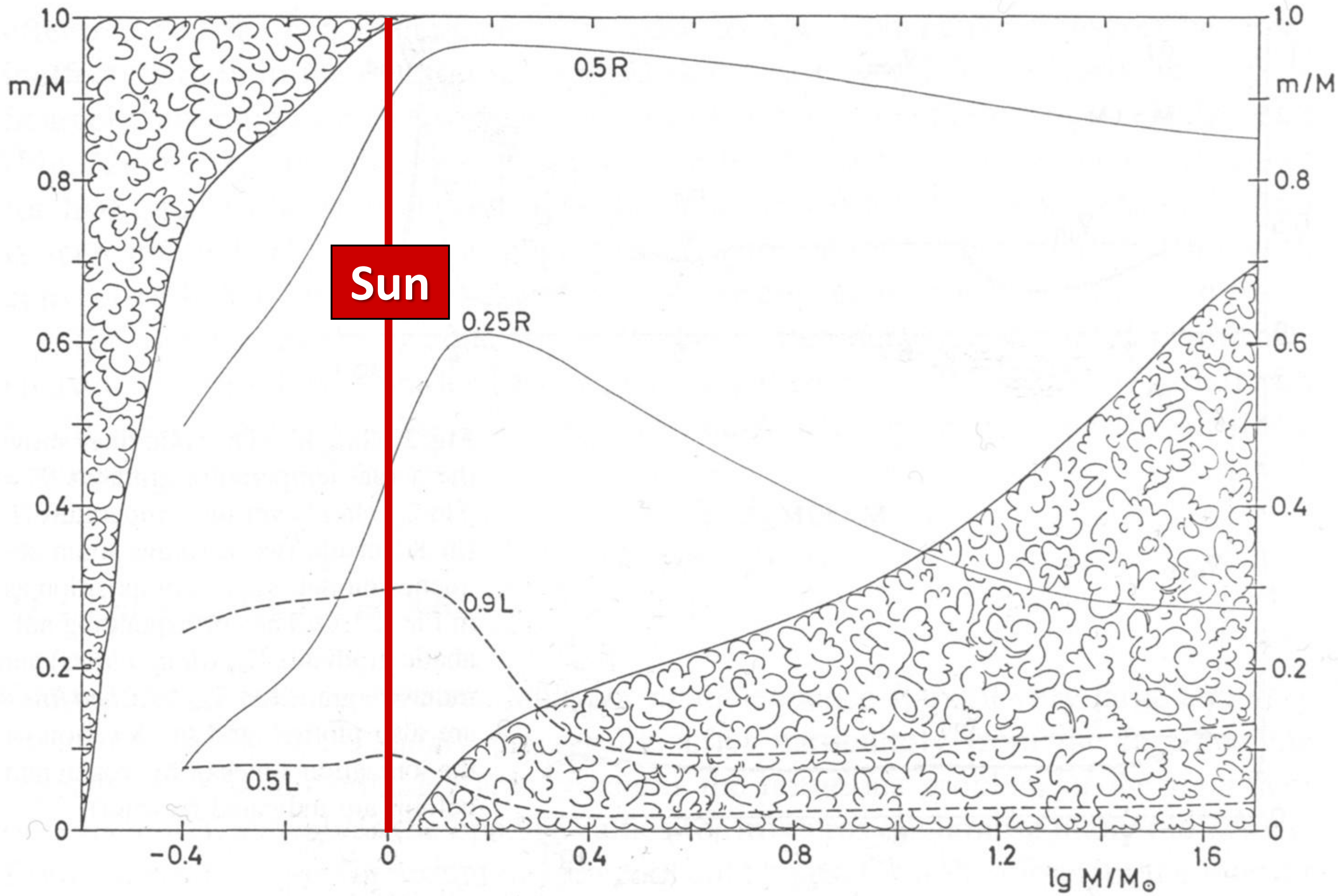
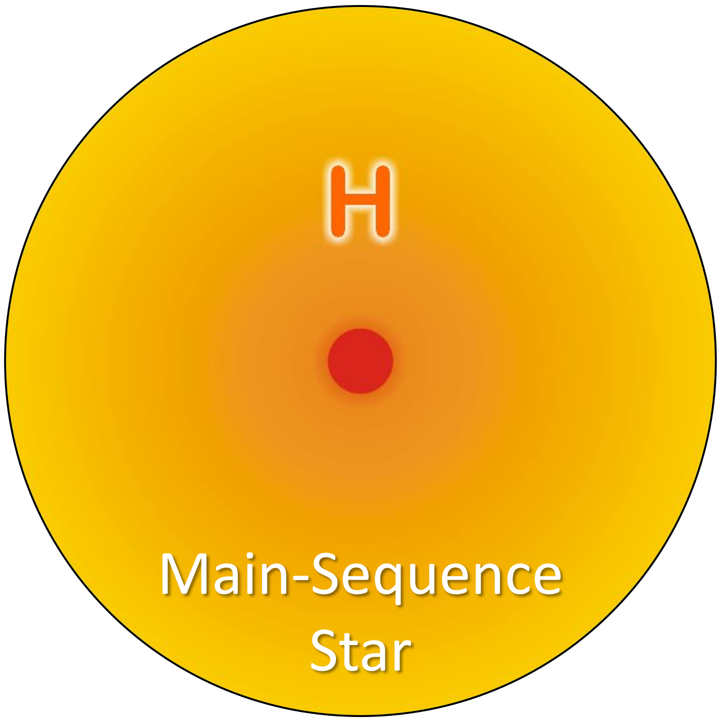


Fig. 22.7. The mass values m from centre to surface are plotted against the stellar mass M for the same zero-age main-sequence models as in Fig. 22.1. "Cloudy" areas indicate the extension of convective zones inside the models. Two solid lines give the m values at which r is 1/4 and 1/2 of the total radius R. The dashed lines show the mass elements inside which 50% and 90% of the total luminosity L are produced

Kippenhahn & Weigert, Stellar Structure and Evolution

Self-Regulated Nuclear Burning



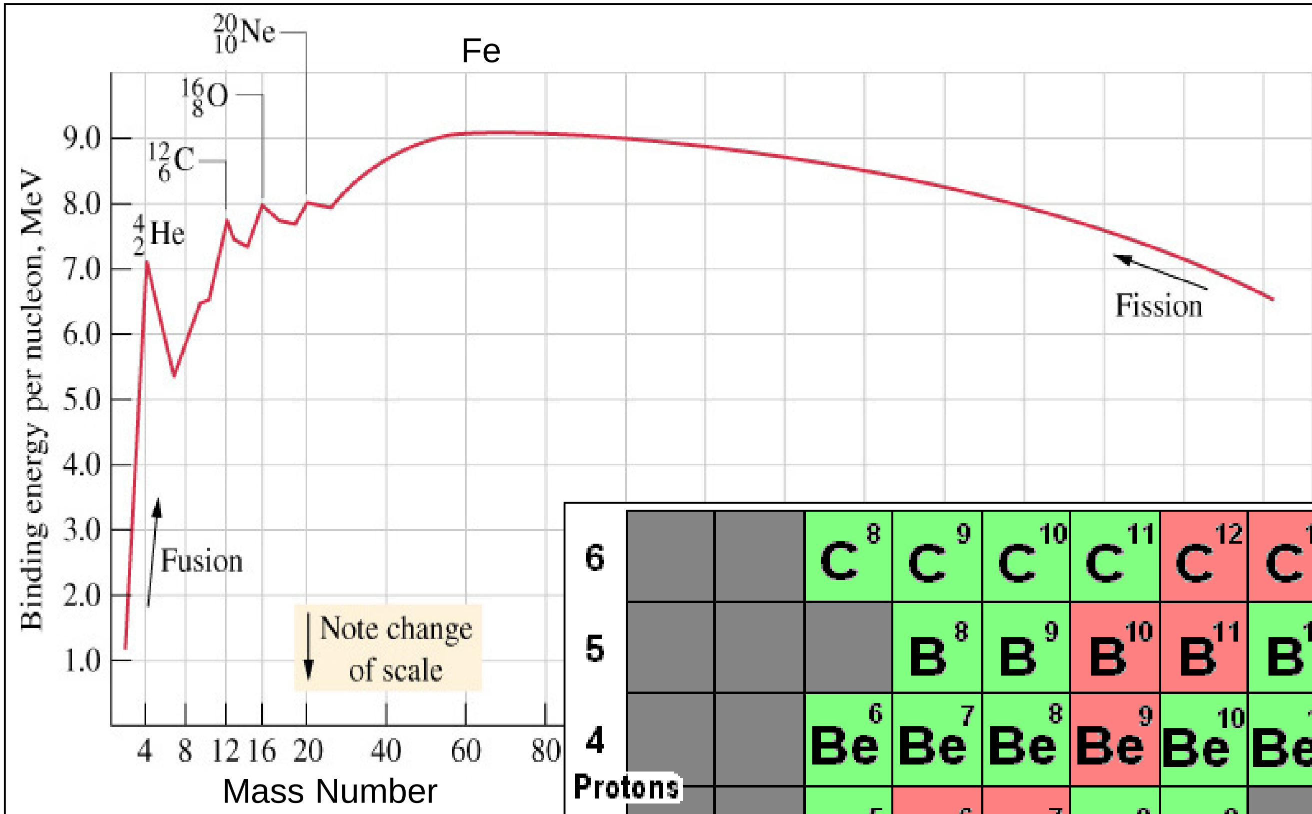
Virial Theorem: $\langle E_{\rm kin}\rangle = -\frac{1}{2}\langle E_{\rm grav}\rangle$

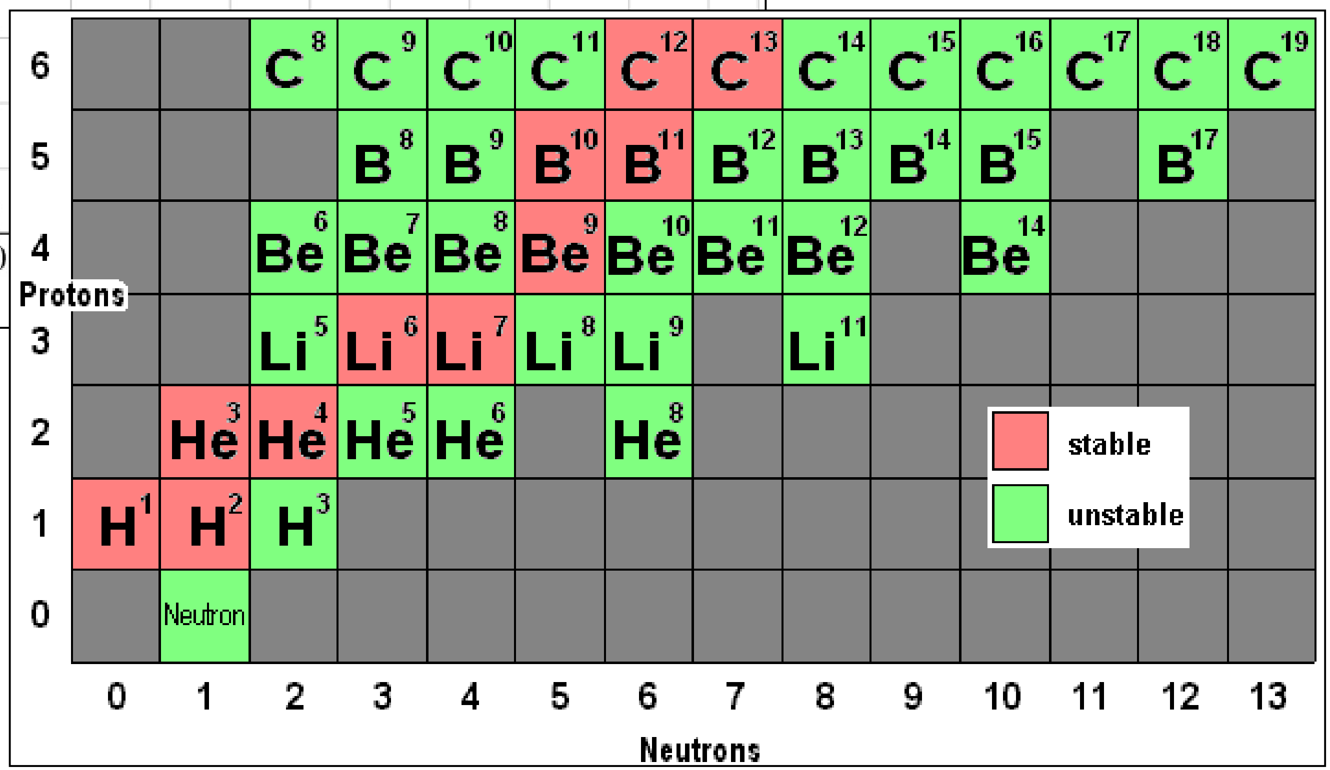
Small Contraction
$\rightarrow$ Heating
$\rightarrow$ Increased nuclear burning
$\rightarrow$ Increased pressure
$\rightarrow$ Expansion

Additional energy loss ("cooling")
$\rightarrow$ Loss of pressure
$\rightarrow$ Contraction
$\rightarrow$ Heating
$\rightarrow$ Increased nuclear burning

Hydrogen burning at nearly fixed T
$\rightarrow$ Gravitational potential nearly fixed:
$G_{\rm N}M/R \sim \text{constant}$
$\rightarrow$ $R \propto M$ (More massive stars bigger)

Nuclear Binding Energy





Thermonuclear Reactions and Gamow Peak

Coulomb repulsion prevents nuclear reactions, except for Gamow tunneling

Tunneling probability

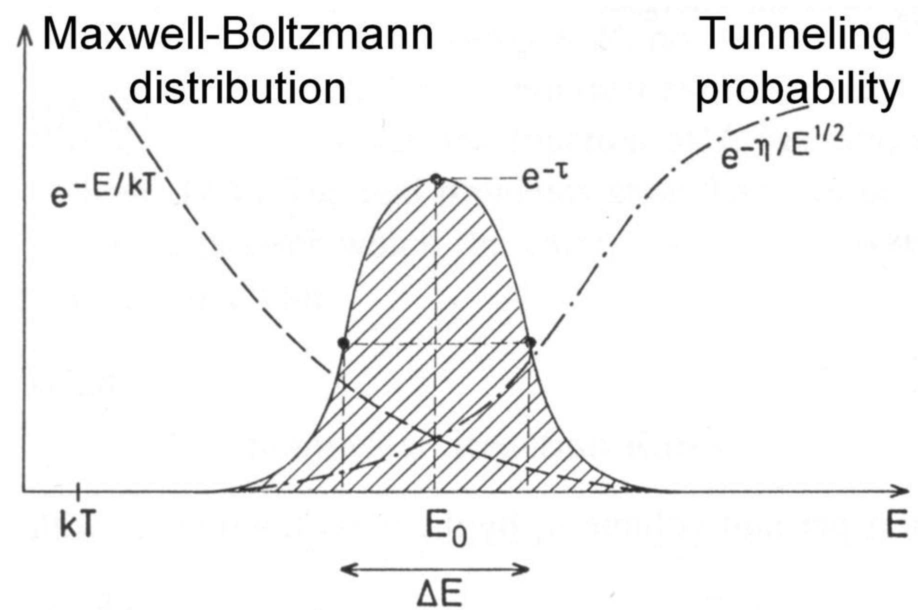
$$p \propto E^{-1/2} e^{-2\pi\eta}$$

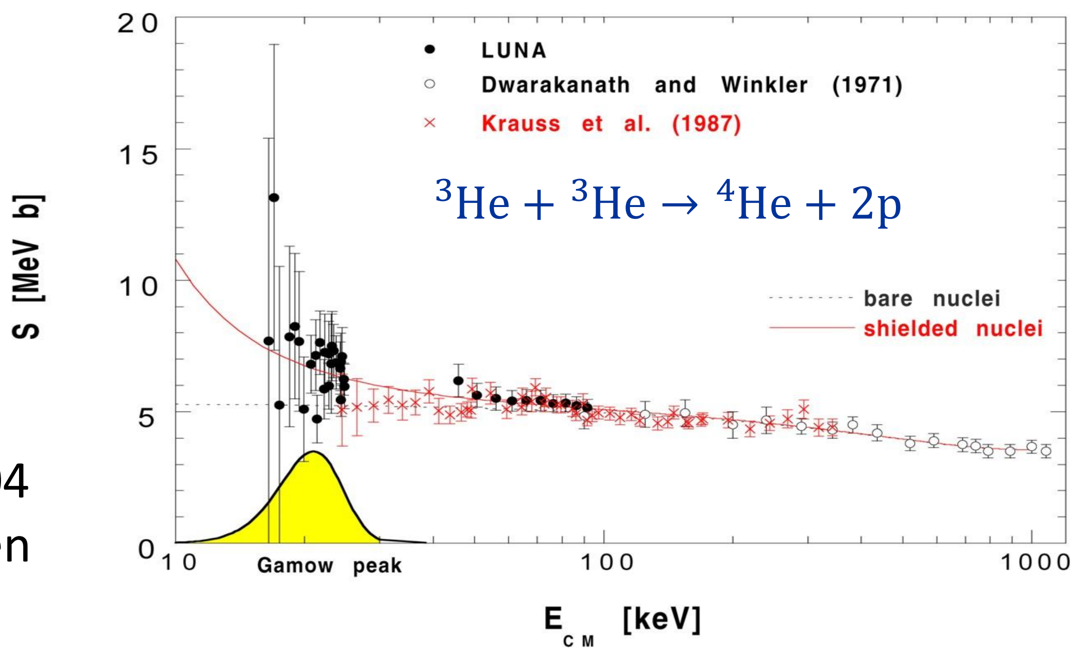
where the Sommerfeld parameter is

$$\eta = \left(\frac{m}{2E}\right)^{1/2} Z_1 Z_2 e^2$$

Parameterize cross section with astrophysical S-factor

$$S(E) = \sigma(E)\, E\, e^{2\pi\eta(E)}$$





LUNA Collaboration, nucl-ex/9902004
many more measurements since then

Main Nuclear Burning Stages

Hydrogen burning $4p + 2e^- \to {}^4\mathrm{He} + 2\nu_e$

- Proceeds by pp chains and CNO cycle
- No higher elements are formed because no stable isotope with mass number 8
- Neutrinos from $p \to n$ conversion
- Typical temperatures: 10^7 K (~1 keV)

Helium burning

$$ {}^4\mathrm{He} + {}^4\mathrm{He} + {}^4\mathrm{He} \leftrightarrow {}^8\mathrm{Be} + {}^4\mathrm{He} \to {}^{12}\mathrm{C} $$

"Triple alpha reaction" because ${}^8\mathrm{Be}$ unstable, builds up with concentration $\sim 10^{-9}$

$$ {}^{12}\mathrm{C} + {}^4\mathrm{He} \to {}^{16}\mathrm{O} $$
$$ {}^{16}\mathrm{O} + {}^4\mathrm{He} \to {}^{20}\mathrm{Ne} $$

Typical temperatures: 10^8 K (~10 keV)

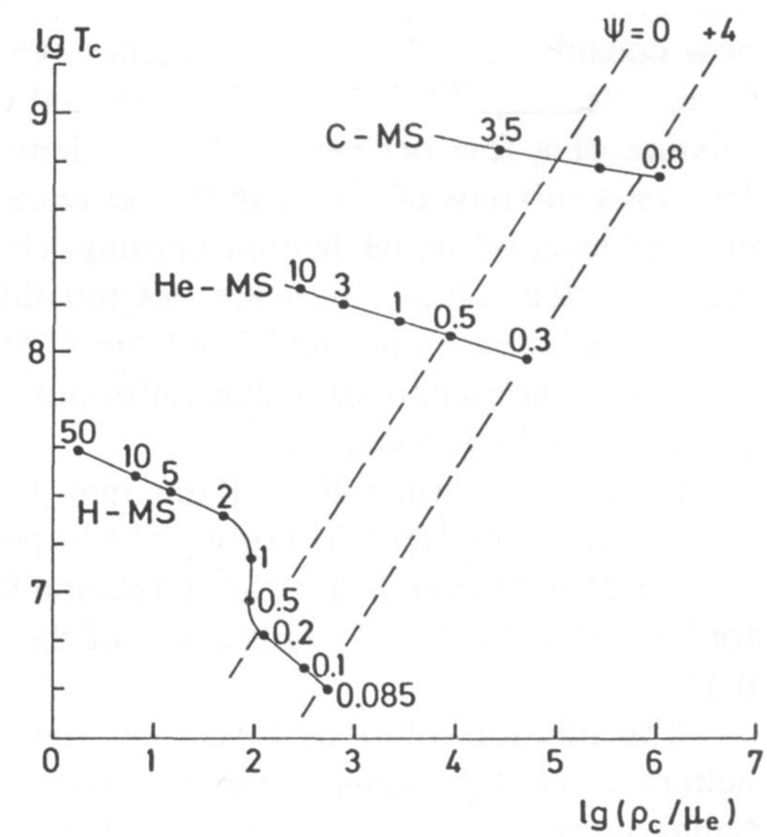
Carbon burning

Many reactions, for example

$$ {}^{12}\mathrm{C} + {}^{12}\mathrm{C} \to {}^{23}\mathrm{Na} + p \text{ or } {}^{20}\mathrm{Ne} + {}^4\mathrm{He} \text{ etc} $$

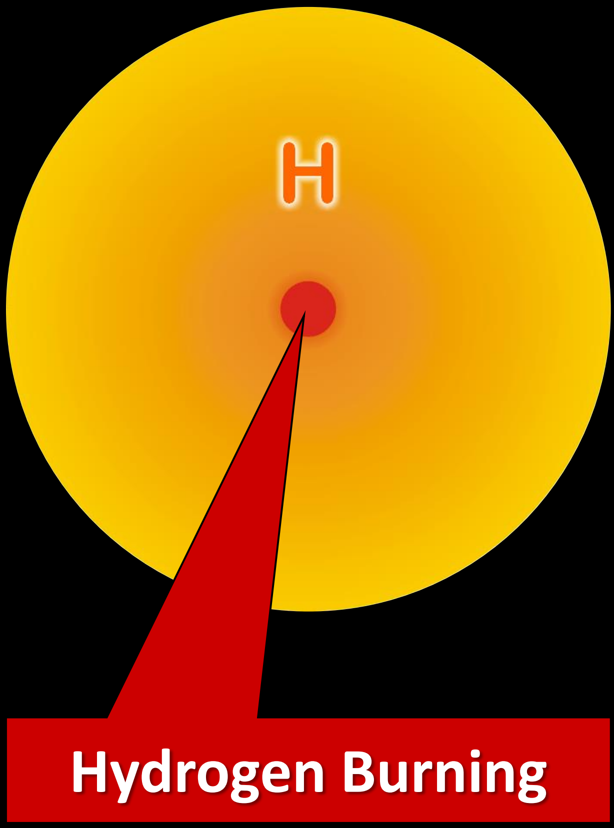
Typical temperatures: 10^9 K (~100 keV)

- Each type of burning occurs at a very different T but a broad range of densities
- Never co-exist in the same location

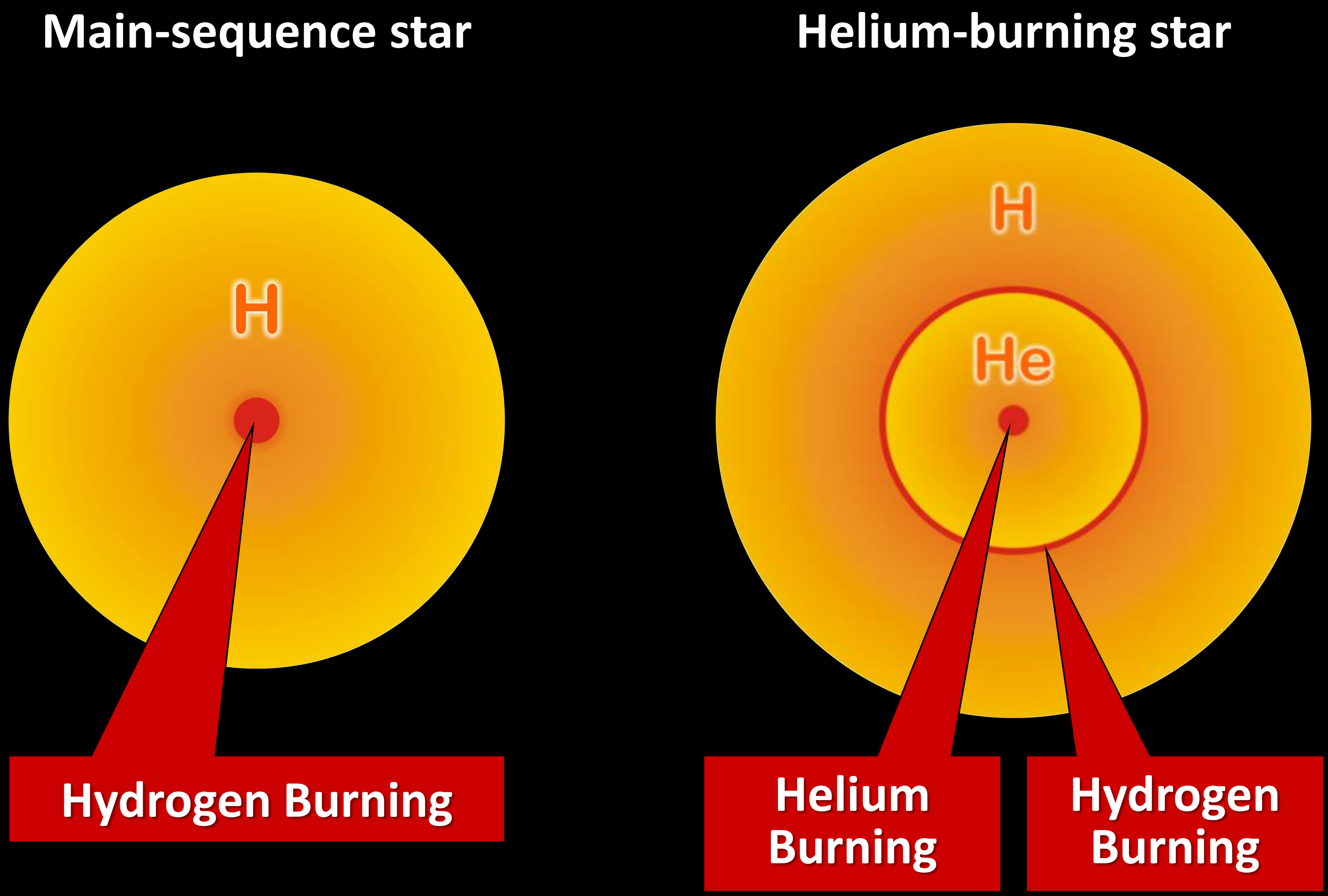


Hydrogen Exhaustion

Main-sequence star



Hydrogen Exhaustion



Burning Phases of a 15 Solar-Mass Star

Burning Phase		Dominant Process	T_c [keV]	ρ_c [g/cm^3]	L_γ [10^4 L_{sun}]	L_ν/L_γ	Duration [years]
	Hydrogen	$H \rightarrow He$	3	5.9	2.1	–	1.2×10^7
	Helium	$He \rightarrow C, O$	14	1.3×10^3	6.0	1.7×10^{-5}	1.3×10^6
	Carbon	$C \rightarrow Ne, Mg$	53	1.7×10^5	8.6	1.0	6.3×10^3
	Neon	$Ne \rightarrow O, Mg$	110	1.6×10^7	9.6	1.8×10^3	7.0
	Oxygen	$O \rightarrow Si$	160	9.7×10^7	9.6	2.1×10^4	1.7
	Silicon	$Si \rightarrow Fe, Ni$	270	2.3×10^8	9.6	9.2×10^5	6 days

Degenerate Stars ("White Dwarfs")

Assume temperature very small
$\rightarrow$ No thermal pressure
$\rightarrow$ Electron degeneracy is pressure source

Pressure ~ Momentum density × Velocity

- Electron density $n_e = p_{\mathrm{F}}^3/(3\pi^3)$
- Momentum p_{F} (Fermi momentum)
- Velocity $v \propto p_{\mathrm{F}}/m_e$
- Pressure $P \propto p_{\mathrm{F}}^5 \propto \rho^{5/3} \propto M^{5/3}R^{-5}$
- Density $\rho \propto MR^{-3}$

Hydrostatic equilibrium

$$\frac{dP}{dr} = -\frac{G_{\mathrm{N}}M_r\rho}{r^2}$$

With $dP/dr \sim -P/R$ we have

$$P \propto G_{\mathrm{N}}M\rho R^{-1} \propto G_{\mathrm{N}}M^2R^{-4}$$

Inverse mass radius relationship

$$R \propto M^{-1/3}$$

$$R = 10{,}500\ \mathrm{km}\left(\frac{0.6\ M_\odot}{M}\right)^{1/3}(2Y_e)^{5/3}$$

(Y_e electrons per nucleon)

For sufficiently large stellar mass M, electrons become relativistic

- Velocity = speed of light
- Pressure

$$P \propto p_{\mathrm{F}}^4 \propto \rho^{4/3} \propto M^{4/3}R^{-4}$$

No stable configuration

Chandrasekhar mass limit

$$M_{\mathrm{Ch}} = 1.457\ M_\odot\,(2Y_e)^2$$

Chandrasekhar Mass for Particle Physicists

Degeneracy pressure balances gravity

- N nucleons, nucleon mass m_N
- $M_{\rm star} = N\, m_N$
- Semirelativistic particles (mass m):
- Degeneracy energy:
- Number density:

$$E_{\rm deg} \simeq -E_{\rm grav} \simeq \frac{GM_{\rm star}^2}{R_{\rm star}} \simeq \frac{N^2 m_N^2}{m_{\rm Planck}^2 R_{\rm star}}$$

$$E_{\rm F} \simeq p_{\rm F} \simeq m$$

$$E_{\rm deg} \simeq Nm$$

$$n \simeq p_{\rm F}^3 \simeq m^3$$

$$R_{\rm star} \simeq \frac{m_{\rm Planck}}{m_N m}$$

$$M_{\rm star} \simeq m_N n \simeq \frac{m_{\rm Planck}^3}{m_N^2} = 3.75\times 10^{33}\,{\rm g} \simeq M_\odot$$

$$M_\odot = 2\times 10^{33}\,{\rm g}$$

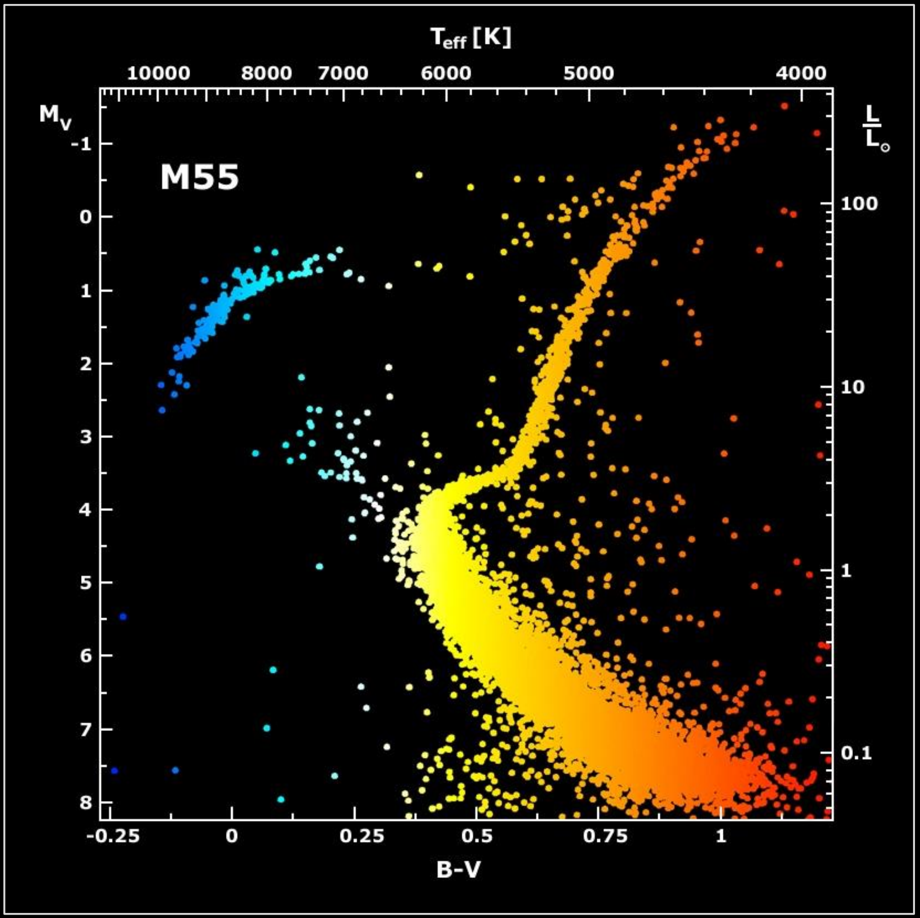
- **Neutron Star (NS):**
  Degenerate particle: Nucleon, $m = m_N$

$$R_{\rm NS} \simeq \frac{m_{\rm Planck}}{m_N^2} = 2.8\ {\rm km}$$ (in reality 12–14 km)

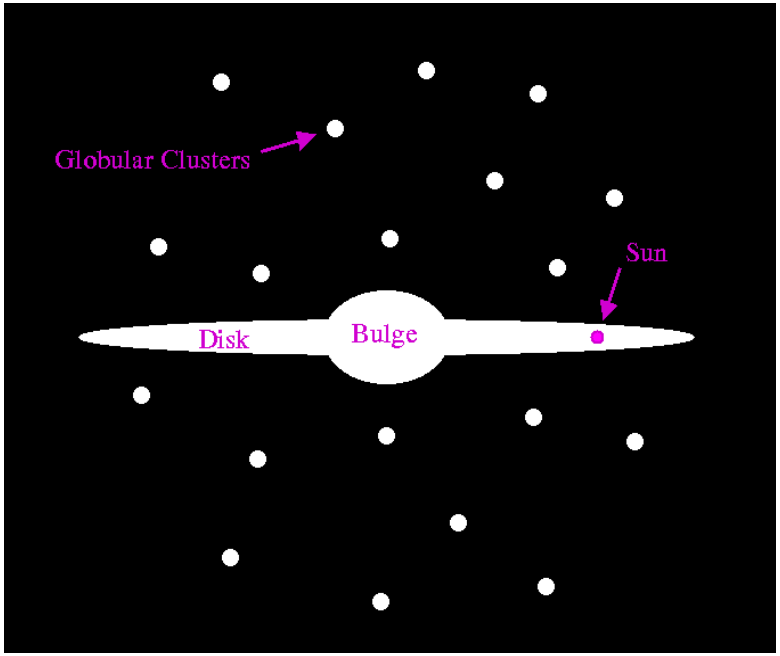
- **White Dwarf (WD):**
  Degenerate particle: Electron, $m = m_e \simeq m_N/2000$

$$R_{\rm WD} \simeq \frac{m_{\rm Planck}}{m_e m_N} = \frac{m_N}{m_e} R_{\rm NS} = 5000\ {\rm km}$$

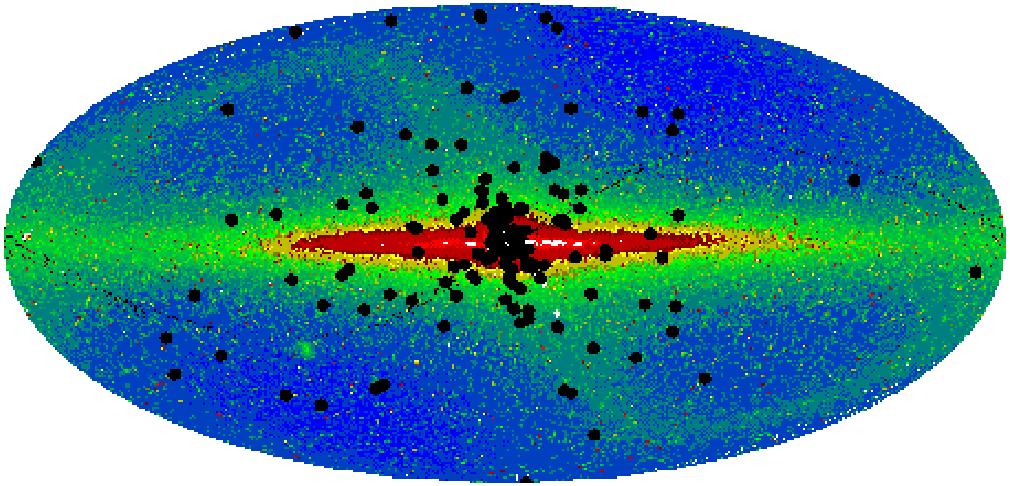
Galactic Globular Cluster M55



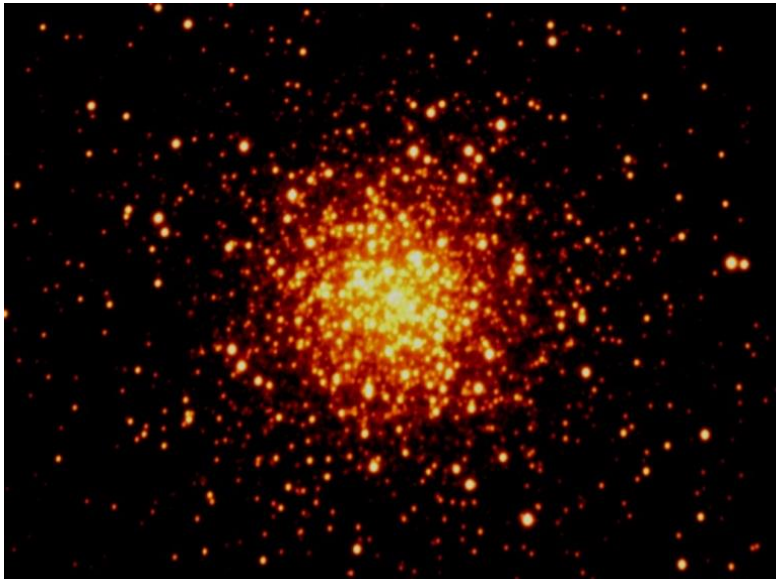
Globular Clusters of the Milky Way



Globular clusters on top of the
FIRAS 2.2 micron map of the Galaxy

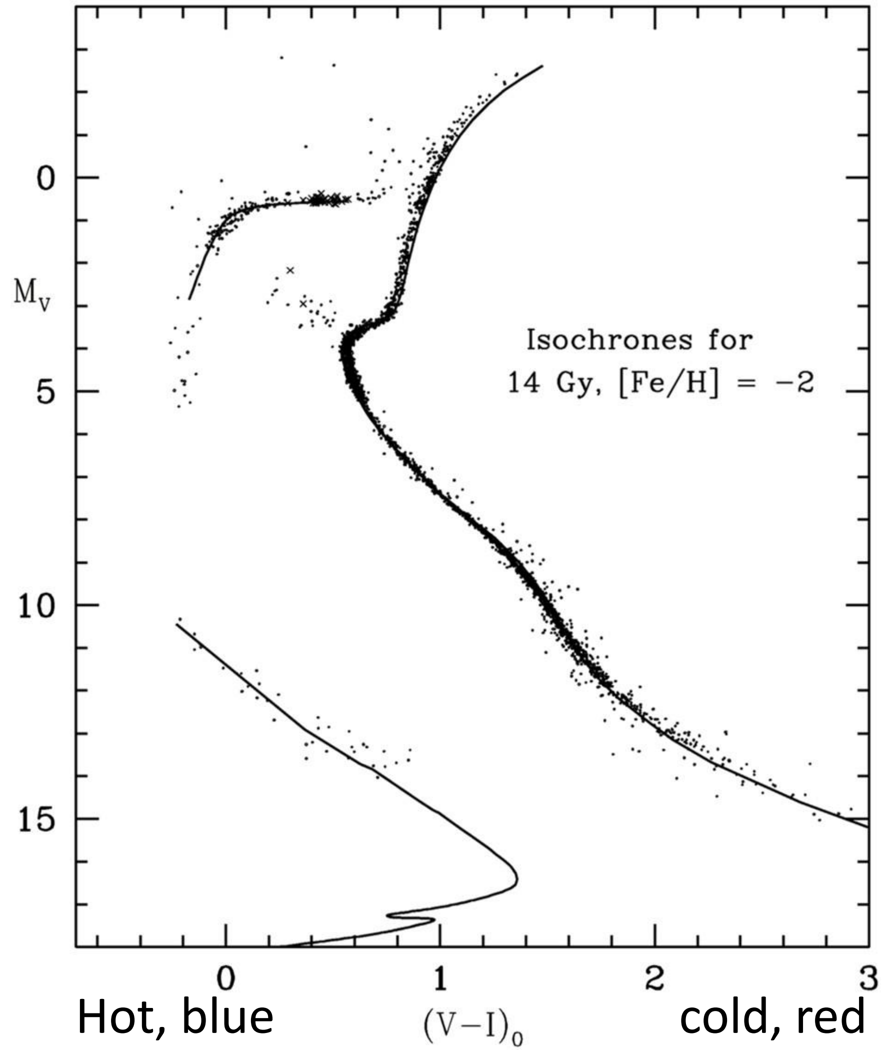


http://www.dartmouth.edu/~chaboyer/mwgc.html



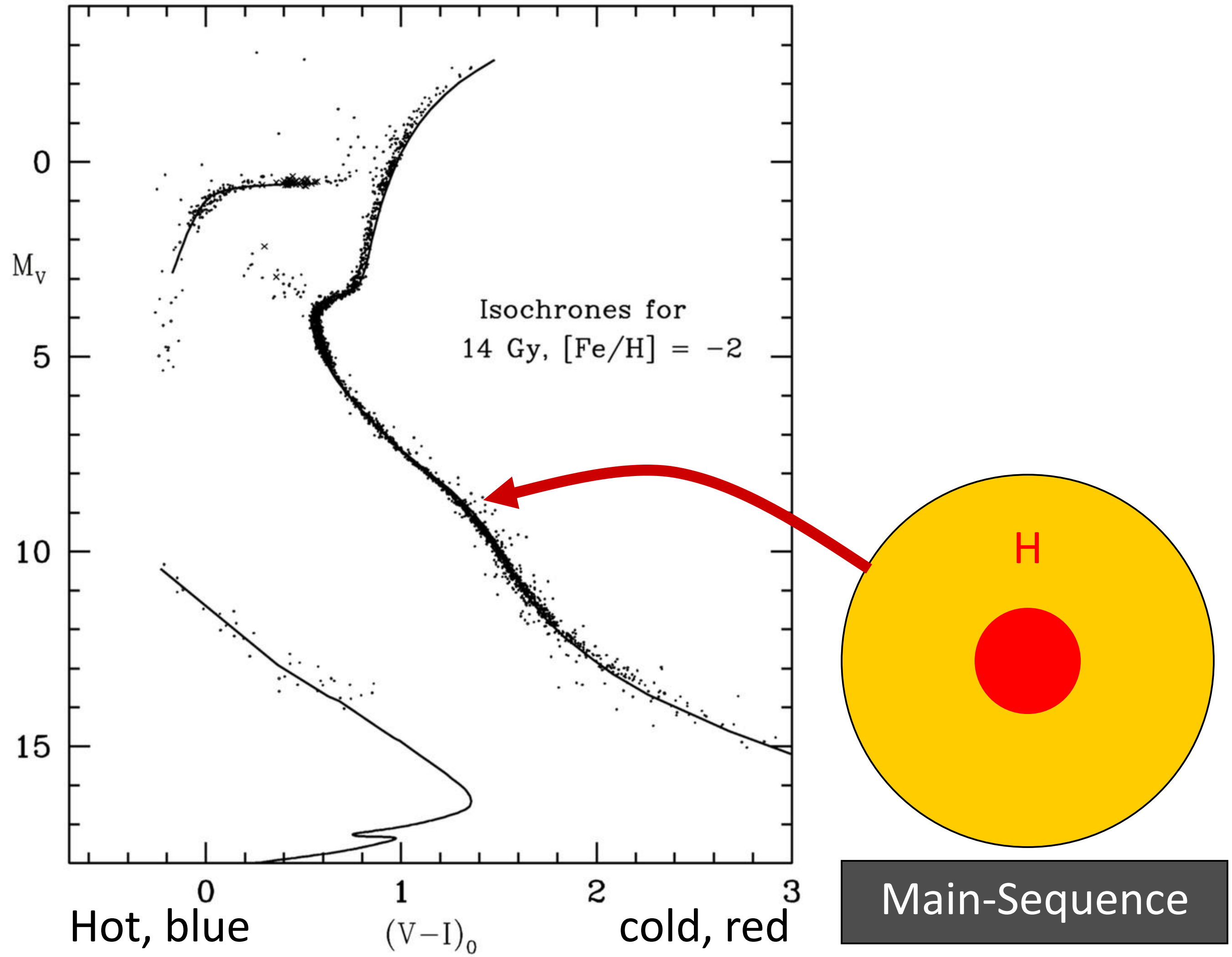
The galactic
globular cluster M3

Color-Magnitude Diagram for Globular Clusters



Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

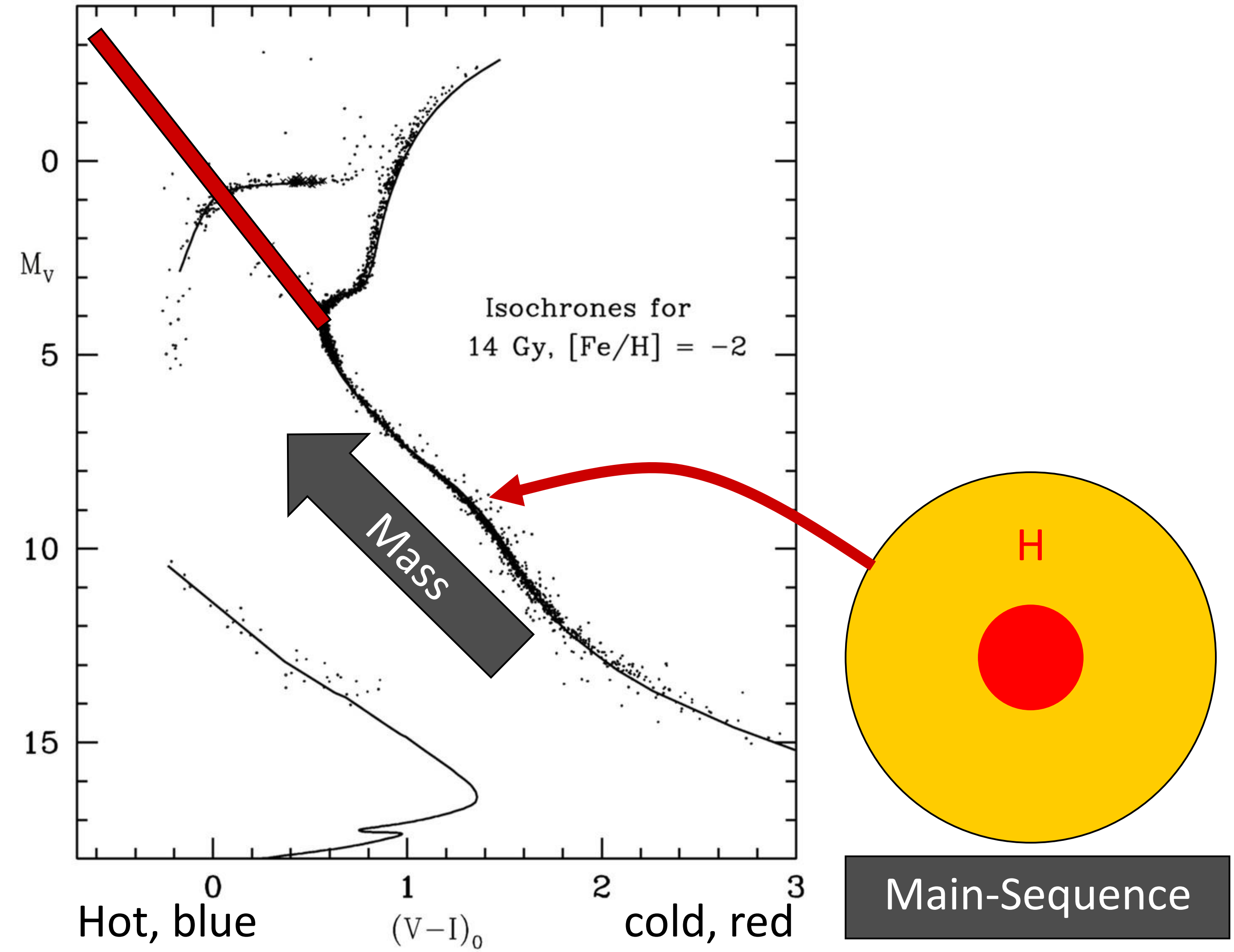
Color-Magnitude Diagram for Globular Clusters



Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

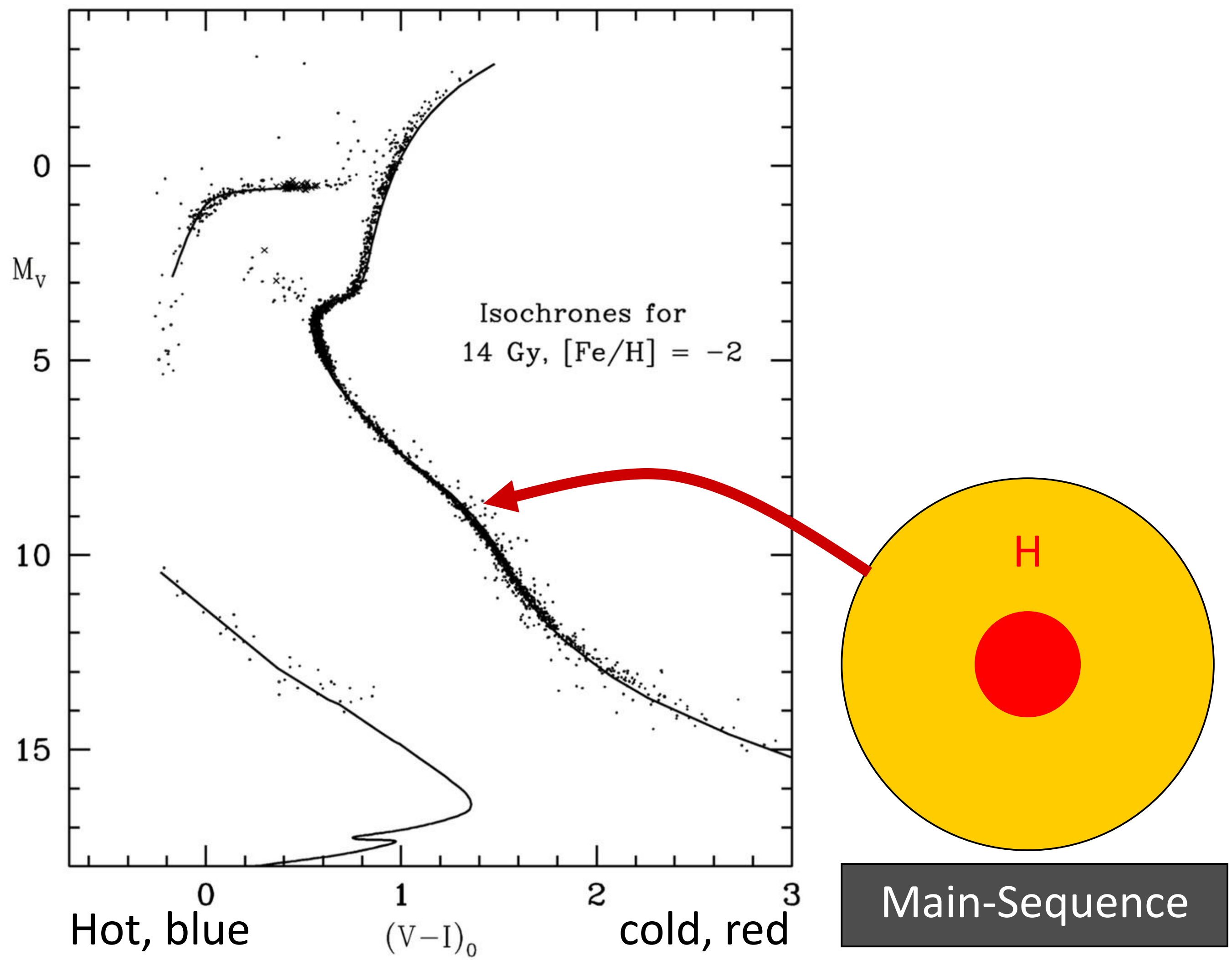
Color-Magnitude Diagram for Globular Clusters

- Stars with M so large that they have burnt out in a Hubble time
- No new star formation in globular clusters



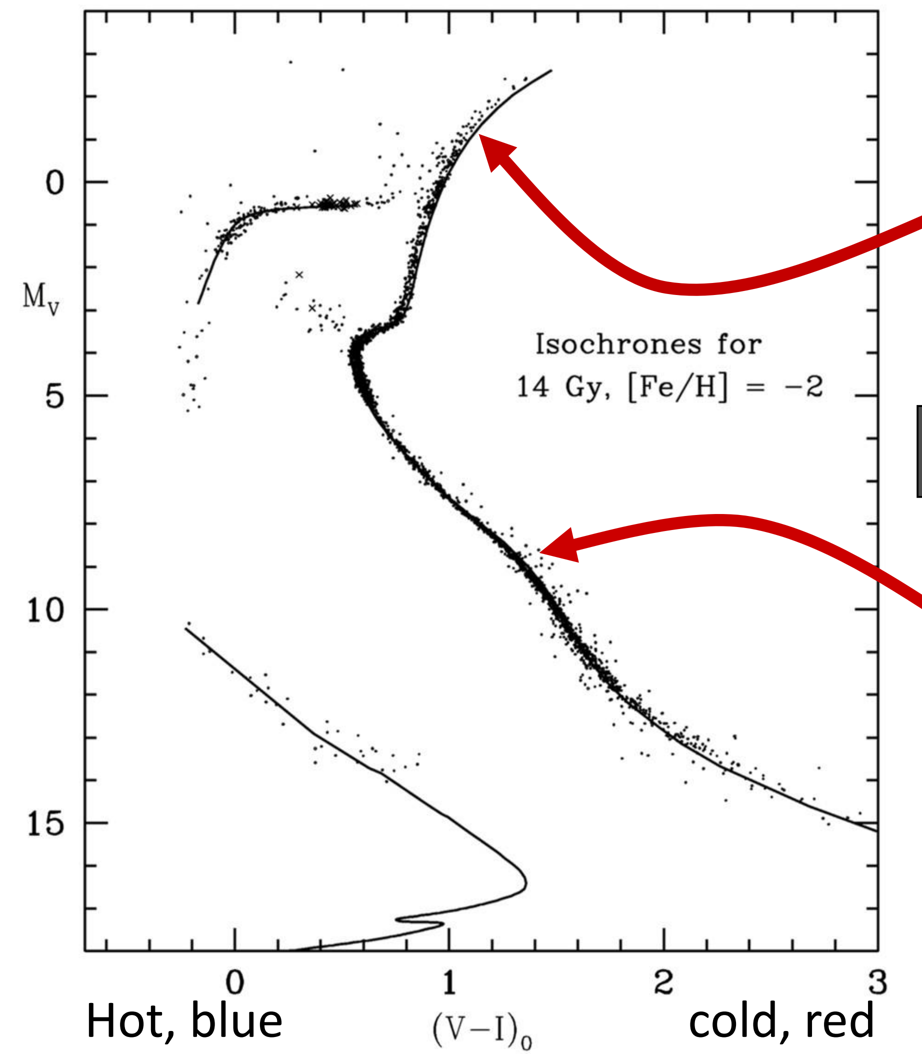
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

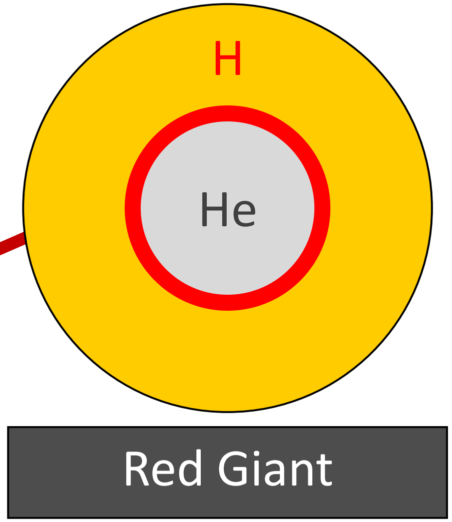
Color-Magnitude Diagram for Globular Clusters

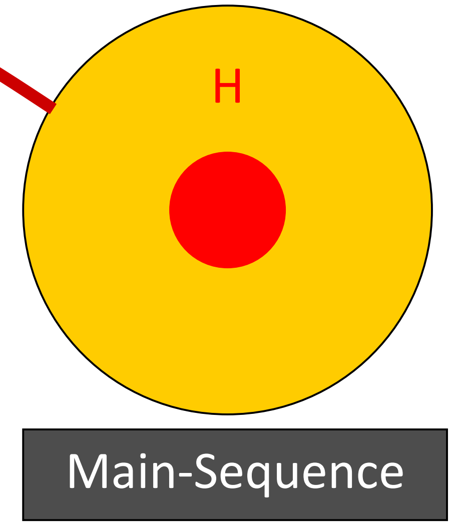


Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Color-Magnitude Diagram for Globular Clusters







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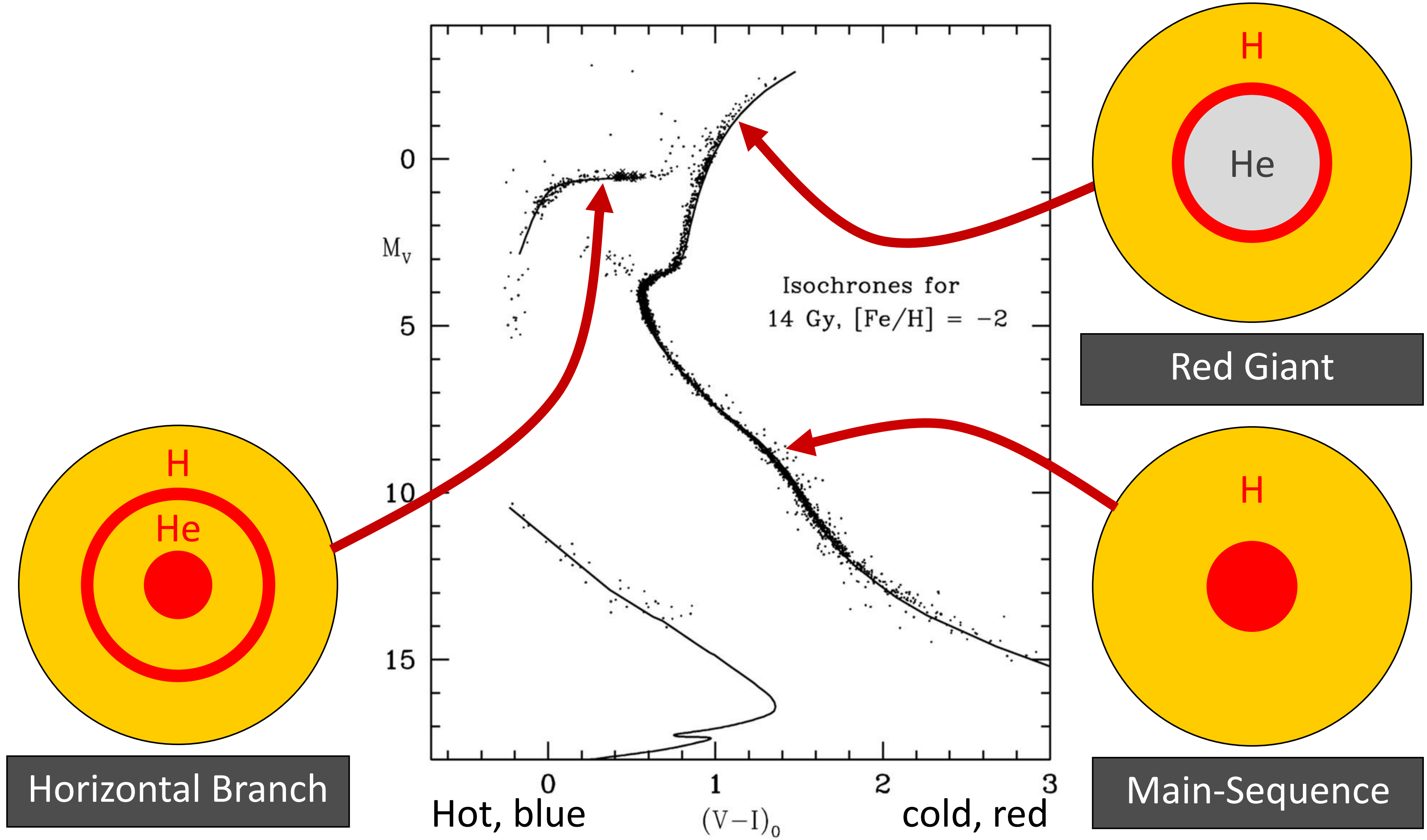
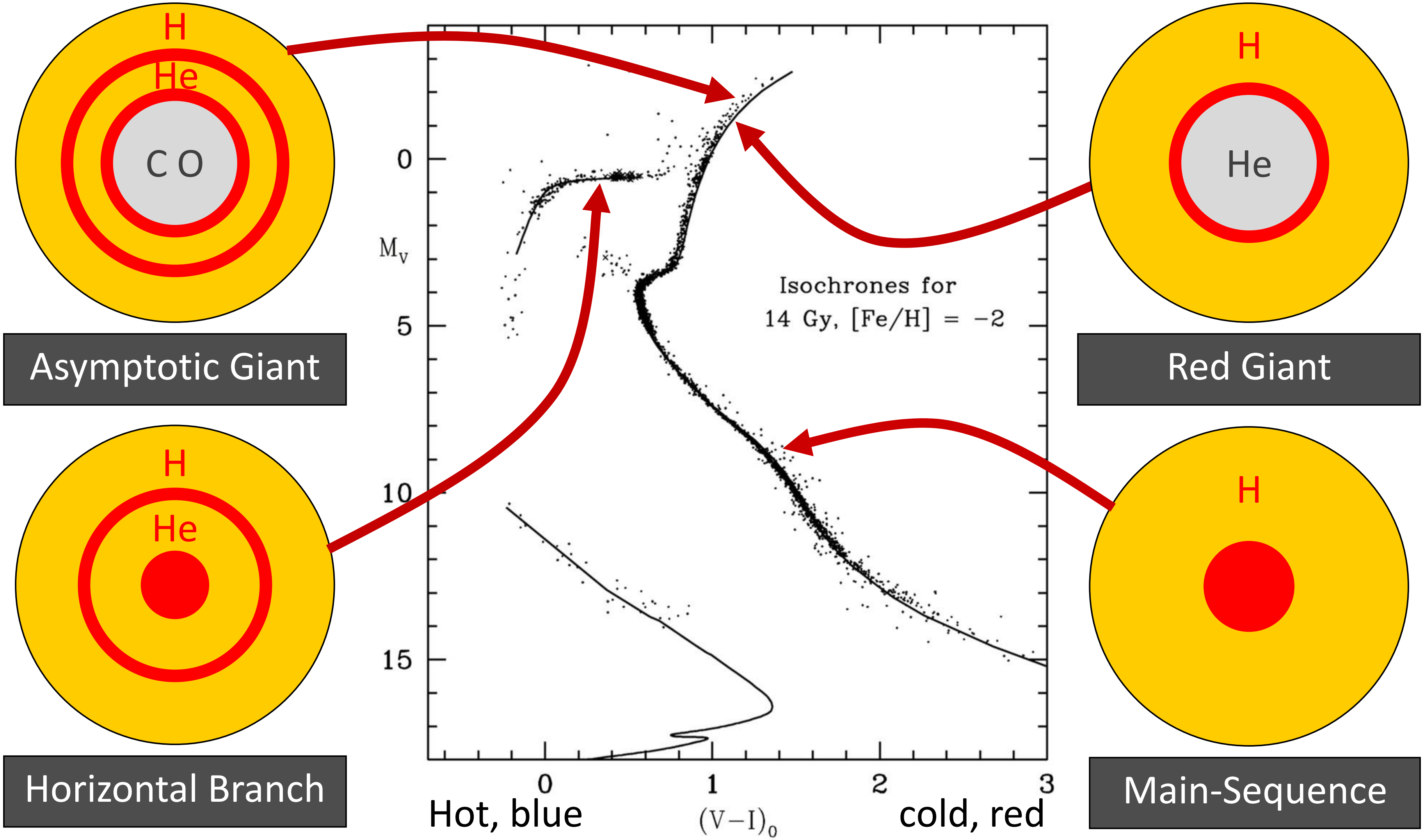
Color-Magnitude Diagram for Globular Clusters



Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Color-Magnitude Diagram for Globular Clusters



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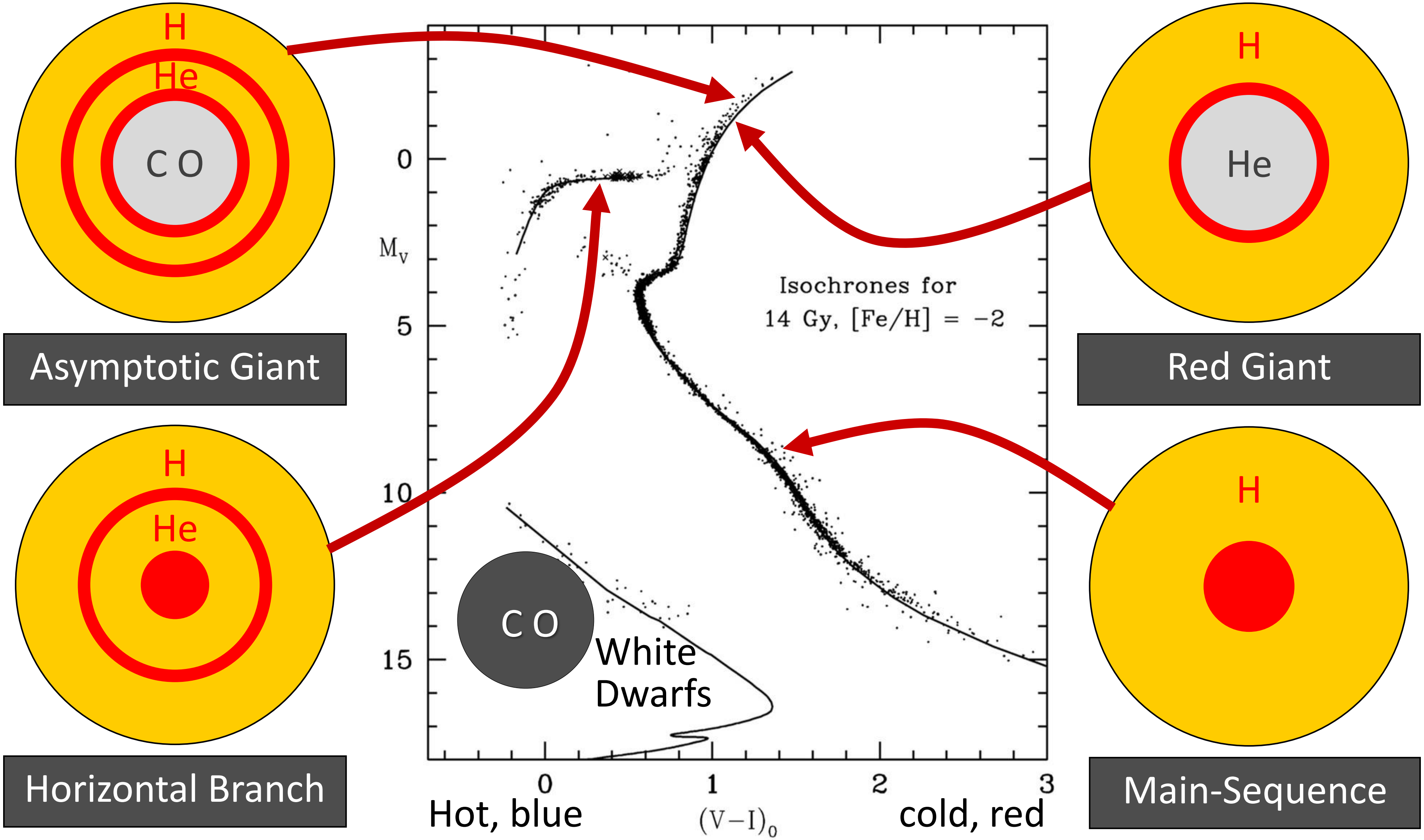

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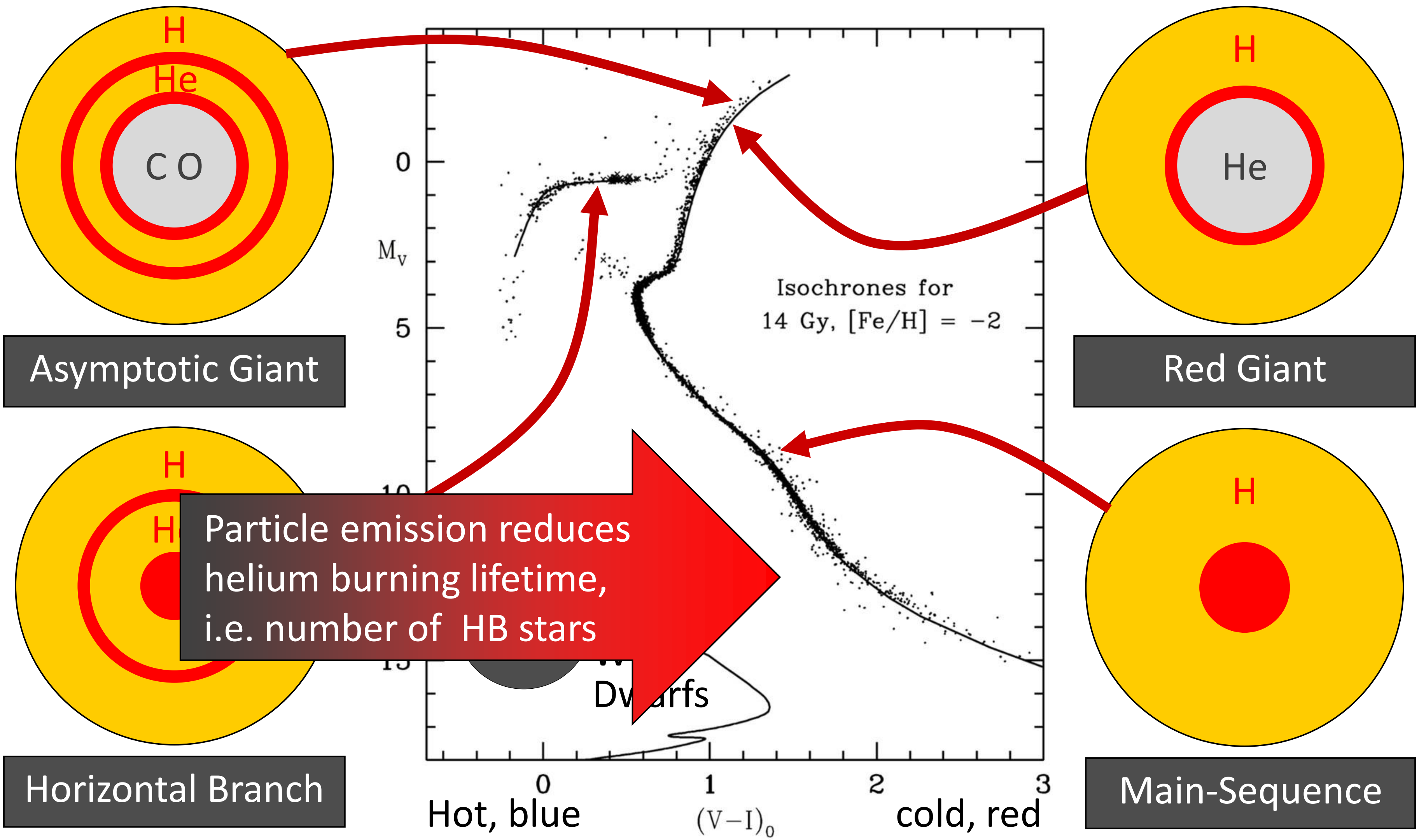


Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Thermal Axions: Production Processes

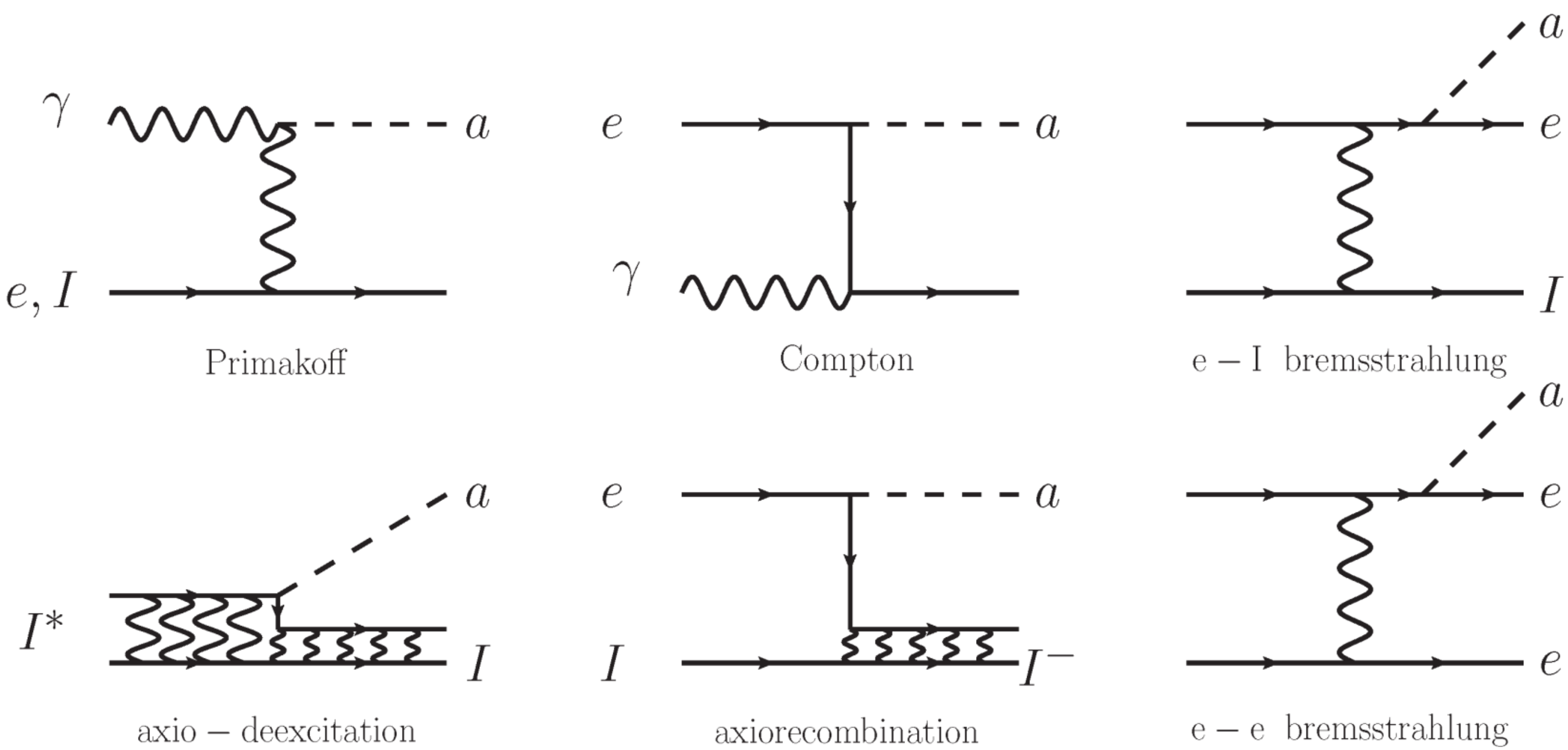
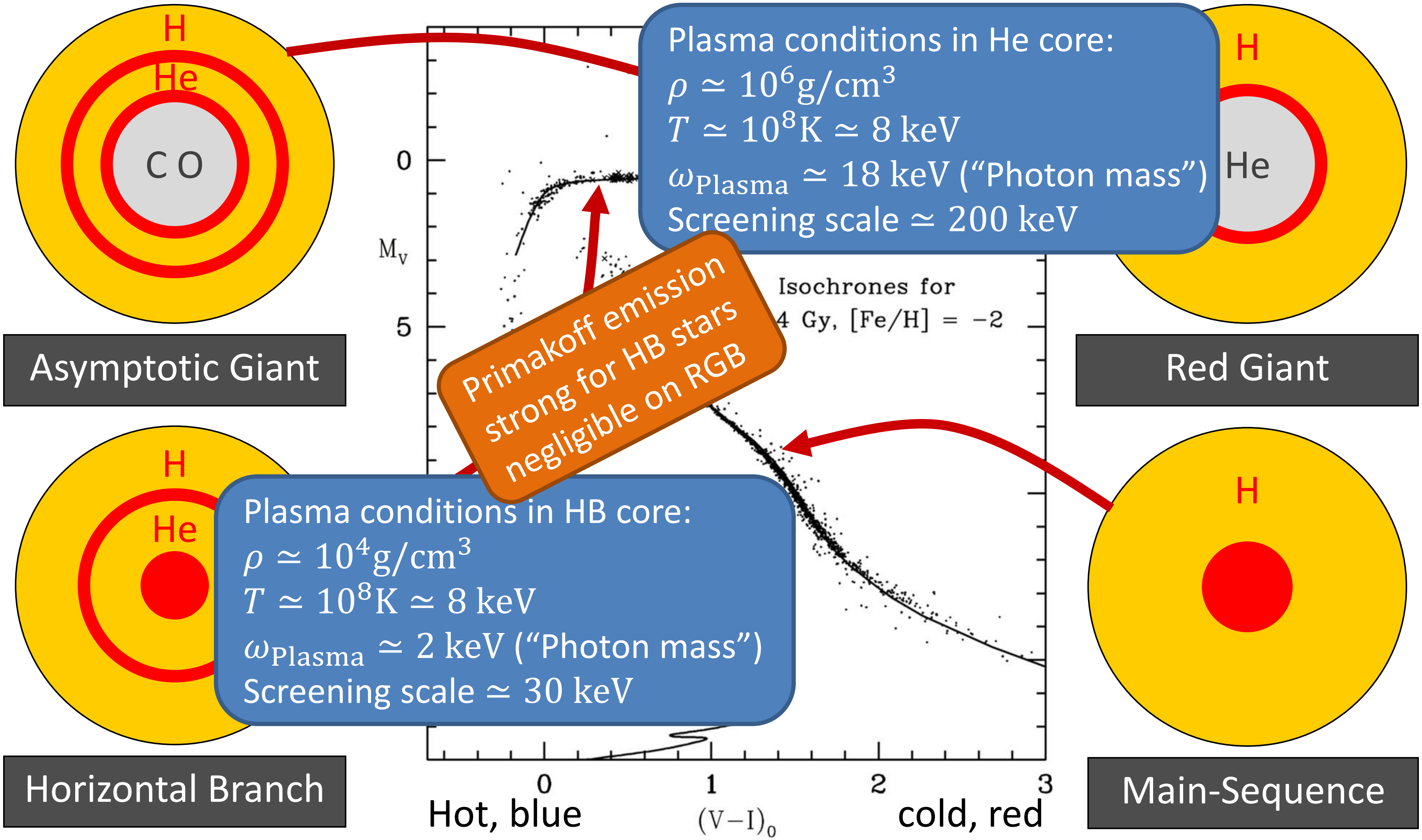


Figure 1. ABC reactions responsible for the solar axion flux in non-hadronic axion models.

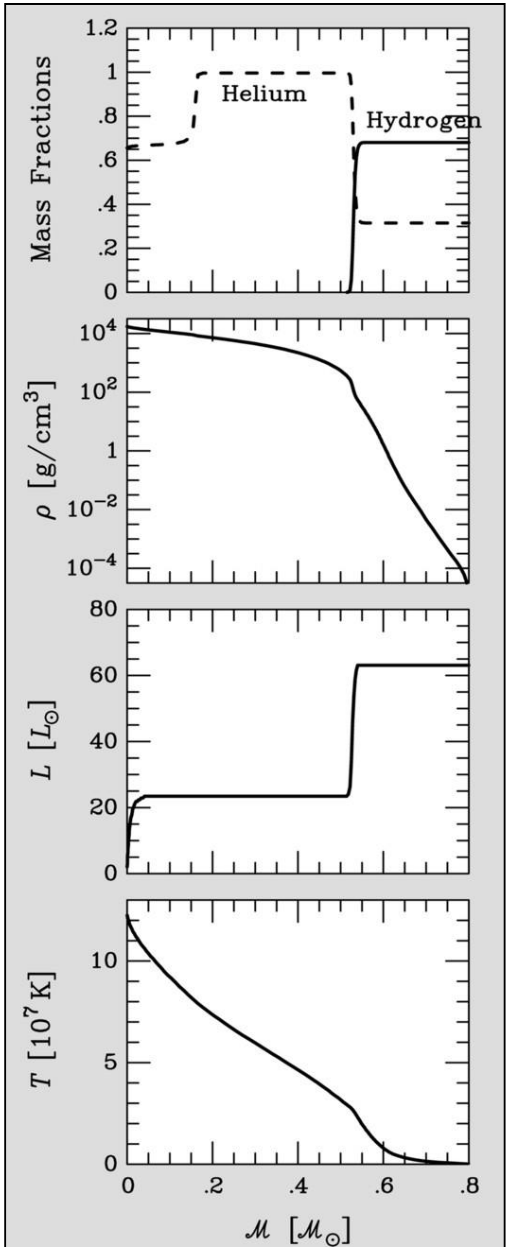
Redondo, arXiv:1310.0823

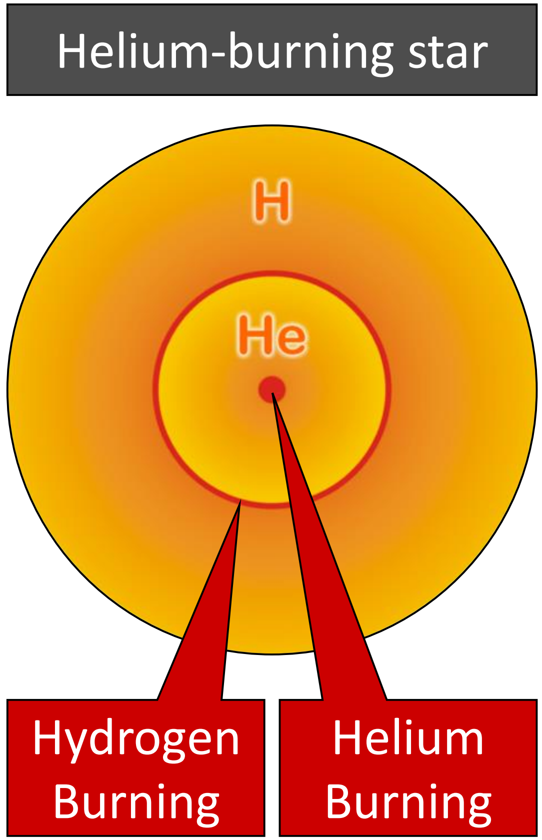
Color-Magnitude Diagram for Globular Clusters



Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Globular-Cluster Limit on Axion-Photon Coupling





- Helium-burning luminosity
  $L_{3\alpha} \sim 20\ L_{\rm sun}$
  $T \sim 10\ \mathrm{keV}$
  $\rho \sim 10^4 \mathrm{g\ cm^{-3}}$
- Core-averaged nuclear energy generation rate
  $\epsilon_{3\alpha} \sim 80\ \mathrm{erg\ g^{-1}\ s^{-1}}$
- Core-averaged Primakoff emission rate
  $\epsilon_{\rm Primakoff} \sim g_{10}^2\ 30\ \mathrm{erg\ g^{-1}\ s^{-1}}$
- Reduction of helium-burning lifetime
  $$\frac{\tau}{\tau_0} \sim \frac{1}{1 + 0.4\ g_{10}^2}$$
- Adopt nominal limit $g_{10} < 1$
  (More restrictive limit if using 10% precision for helium burning lifetime)

Helium Burning Lifetime: R-Method

Number ratio ("R") of HB/RGB fixes He-burning lifetime
(if RGB not affected by new energy loss)

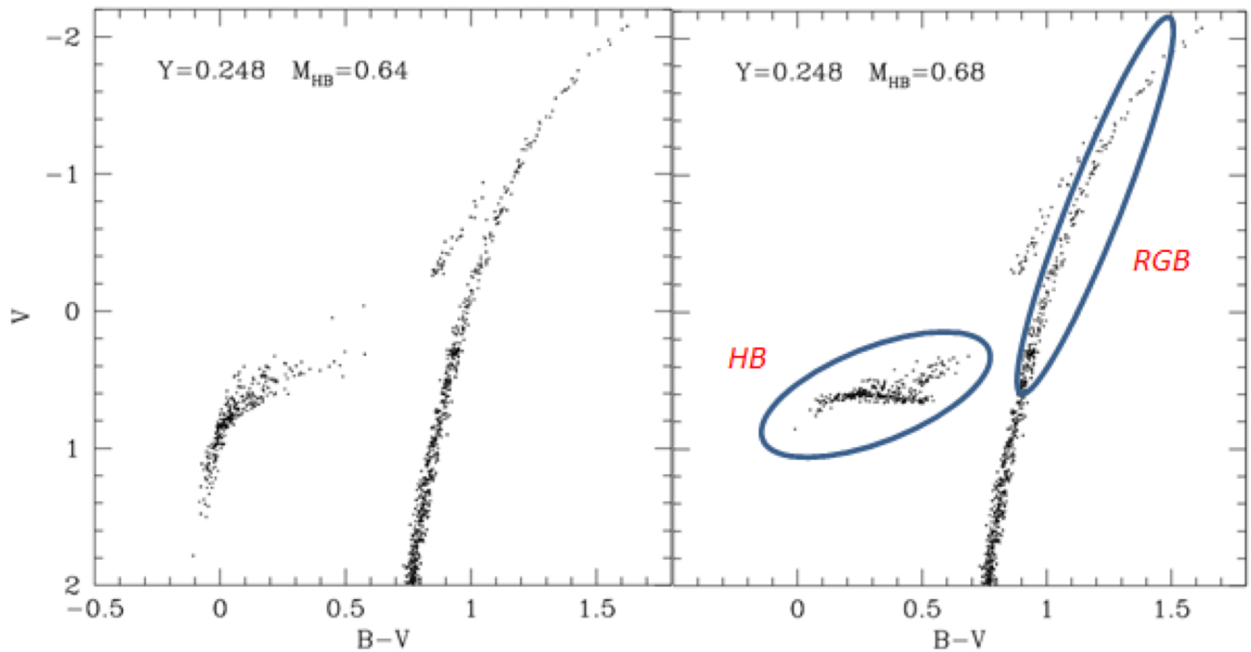
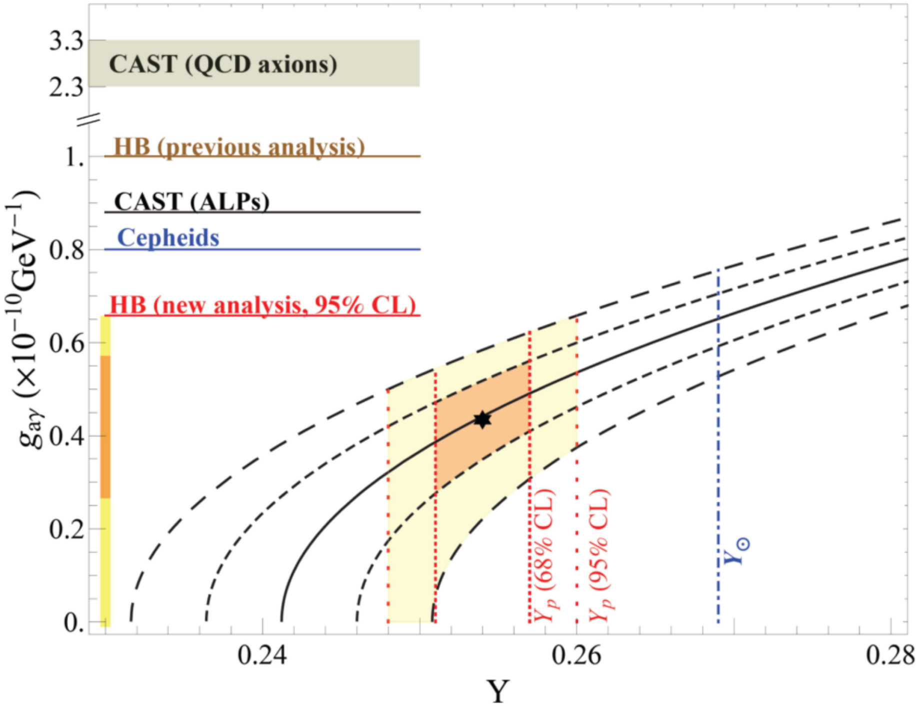


Figure 1: Example of synthetic CM diagrams. The diagram in the left panel has been obtained by assuming a stronger average mass loss rate during the RGB. As a result, the mean mass of HB stars (M_{HB}) is lower than that of the diagram in the right panel. The HB and the RGB portions used in the calculation of the R parameter are surrounded by ellipses.

Straniero, Ayala, Giannotti, Mirizzi & Domínguez,
doi:10.3204/DESY-PROC-2015-02/straniero_oscar

ALP Limits from Globular Clusters



Helium abundance and energy loss rate from modern number counts HB/RGB in 39 globular clusters R = 1.39 ± 0.03

$$R_{\rm th} = 1.48 + 6.26(Y - 0.255) - 0.41 g_{10}^2$$

$$g_{a\gamma} < \mathbf{0.66 \times 10^{-10} GeV^{-1}}$$ **(95% CL)**

Same as CAST limit within 2 digits ☺

Parameter	error	Reference
^{14}N$(p,\gamma)^{15}$O	7%	[1]
^{4}He$(2\alpha,\gamma)^{12}$C	10%	[2]
^{12}C$(\alpha,\gamma)^{16}$O	20%	[6]
R	1.39 ± 0.03	[4]
Y	0.255 ± 0.002	[5],[3]

Small “cooling hint” almost certainly systematics (as usual in astrophysics) eg nuclear reaction rates
Need more systematic exploration of systematics!

Ayala, Dominguez, Giannotti, Mirizzi & Straniero, arXiv:1406.6053
doi:10.3204/DESY-PROC-2015-02/straniero_oscar
Update including ALP masses: Lucente, Straniero, Carenza, Giannotti & Mirizzi, arXiv:2203.01336

AGB/HB Counts in 48 Globular Clusters

NGC	[Fe/H]	$L1$	$L2$	Piotto et al. (2002) $n_{\rm HB}$	Piotto et al. (2002) $n_{\rm AGB}$	Piotto et al. (2002) R_2	Sarajedini et al. (2007) $n_{\rm HB}$	Sarajedini et al. (2007) $n_{\rm AGB}$	Sarajedini et al. (2007) R_2	Sandquist (2000) $n_{\rm HB}$	Sandquist (2000) $n_{\rm AGB}$	Sandquist (2000) R_2
104	-0.72	0.078	0.068	358	53	0.148	591	82	0.139	368	38	0.103
362	-1.26	0.086	0.608	238	40	0.168	318	43	0.135	94	14	0.149
1261	-1.27	0.088	0.644	94	22	0.234	233	34	0.146	148	26	0.176
1851	-1.18	0.098	0.679	272	37	0.136	411	49	0.119	209	24	0.115
1904	-1.60	...	...	163	11	0.067	...	...	...	122	16	0.131
2419	-2.15	0.192	0.852	225	22	0.098	...	...	...	...	...	...
2808	-1.14	0.094	0.904	809	61	0.075	1200	104	0.087	247	22	0.089
4833	-1.85	0.287	0.538	94	10	0.106	...	...	...	...	...	...
5024	-2.10	0.158	0.602	224	18	0.080	360	44	0.122	302	39	0.129
5272	-1.50	0.150	0.613	...	...	...	323	40	0.124	562	65	0.116
5634	-1.88	...	...	130	15	0.115	...	...	...	...	...	...
5694	-1.98	...	...	222	26	0.117	...	...	...	56	14	0.250
5824	-1.91	...	...	463	63	0.136	...	...	...	...	...	...
5904	-1.29	0.150	0.681	162	21	0.130	280	52	0.186	555	94	0.169
5927	-0.49	0.043	0.062	201	12	0.060	...	...	...	134	20	0.149
6093	-1.75	0.464	0.447	162	31	0.191	341	51	0.150	170	39	0.229
6139	-1.65	...	...	282	35	0.124	...	...	...	114	24	0.211
6171	-1.02	0.100	0.513	...	...	...	56	10	0.179	117	29	0.248
6205	-1.53	0.527	0.441	192	20	0.104	390	48	0.123	90	12	0.133
6218	-1.47	0.561	0.299	...	...	...	82	11	0.134	91	12	0.132
6229	-1.18	...	...	278	34	0.122	...	...	...	92	19	0.207
6254	-1.26	0.588	0.260	...	...	...	157	18	0.115	69	13	0.188
6266	-1.18	...	...	446	40	0.090	...	...	...	114	18	0.158
6284	-1.26	...	...	127	16	0.126	...	...	...	...	...	...
6304	-0.45	0.062	0.060	99	8	0.081	...	...	...	...	...	...
6341	-2.31	0.261	0.542	...	...	...	245	33	0.135	140	20	0.143
6356	-0.40	...	...	362	25	0.069	...	...	...	...	...	...
6362	-0.59	0.122	0.621	38	6	0.158	...	...	...	...	...	...
6388	-0.55	0.057	0.836	1347	176	0.131	...	...	...	...	...	...
6402	-1.28	...	...	349	29	0.083	...	...	...	...	...	...
6441	-0.46	0.048	0.904	1380	154	0.112	...	...	...	...	...	...
6539	-0.63	...	...	114	15	0.132	...	...	...	...	...	...
6541	-1.81	0.563	0.347	...	...	...	248	41	0.165	...	...	...
6569	-0.76	...	...	166	30	0.181	...	...	...	...	...	...
6584	-1.50	0.102	0.558	55	8	0.145	...	...	...	...	...	...
6624	-0.44	0.077	0.085	121	9	0.074	188	20	0.106	126	30	0.238
6637	-0.64	0.078	0.065	135	25	0.185	244	43	0.176	127	21	0.165
6638	-0.95	...	...	101	28	0.277	...	...	...	...	...	...
6652	-0.81	0.073	0.080	61	5	0.082	83	9	0.108	75	20	0.267
6681	-1.62	0.558	0.334	100	9	0.090	...	...	...	82	8	0.098
6723	-1.10	0.127	0.704	102	11	0.108	194	22	0.113	101	15	0.149
6752	-1.54	0.378	0.578	...	...	...	173	20	0.116	225	13	0.058
6864	-1.29	...	...	363	69	0.190	...	...	...	55	12	0.218
6934	-1.47	0.097	0.678	149	18	0.121	99	17	0.172	...	...	...
6981	-1.42	0.142	0.570	61	7	0.115	188	36	0.191	45	10	0.222
7078	-2.37	0.174	0.713	376	48	0.128	537	57	0.106	153	23	0.150
7089	-1.65	0.150	0.790	167	18	0.108	702	100	0.142	...	...	...
7099	-2.27	0.462	0.261	89	6	0.067	...	...	...	202	11	0.054

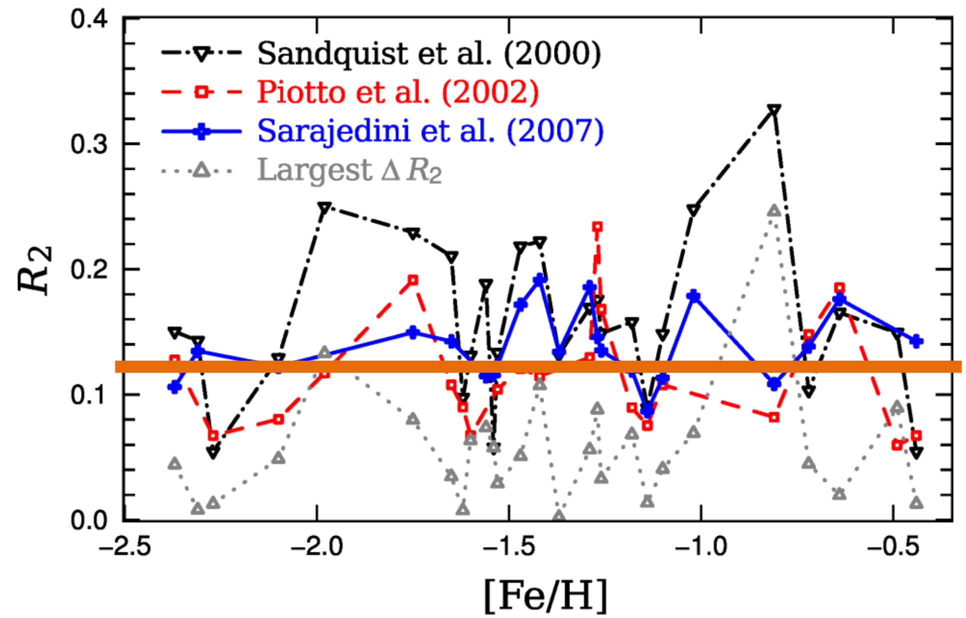


Figure 1. Comparison of R_2 for clusters shown in Table 1, limited to those with at least two different sources of photometry. The R_2 determined from the Sandquist (2000), Piotto et al. (2002), and Sarajedini et al. (2007) data are shown in black dash-dots, red dashes, and a blue solid line, respectively. The dotted grey line shows the maximum difference between R_2 determinations from different photometry.

$$R_2 = N_{\rm AGB}/N_{\rm HB} = 0.117 \pm 0.005$$

The treatment of mixing in core helium burning models II. Constraints from cluster star counts

Constantino, Campbell, Lattanzio & van Duijneveldt, arXiv:1512.04845

Predicting the Axion-Modified Ratios

M.J. Dolan, F.J. Hiskens & R.R. Volkas, arXiv:2207.03102

$g_{a\gamma} < 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1}$ $g_{a\gamma} < 0.47 \times 10^{-10}\,\mathrm{GeV}^{-1}$

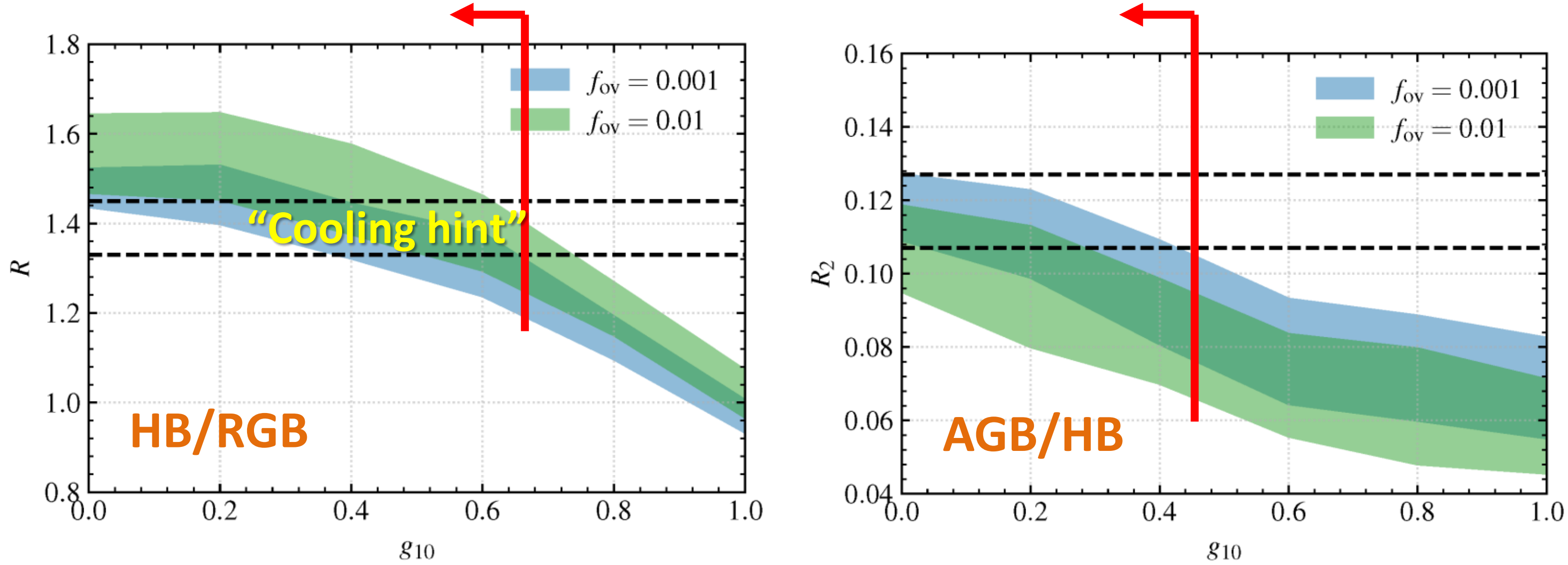
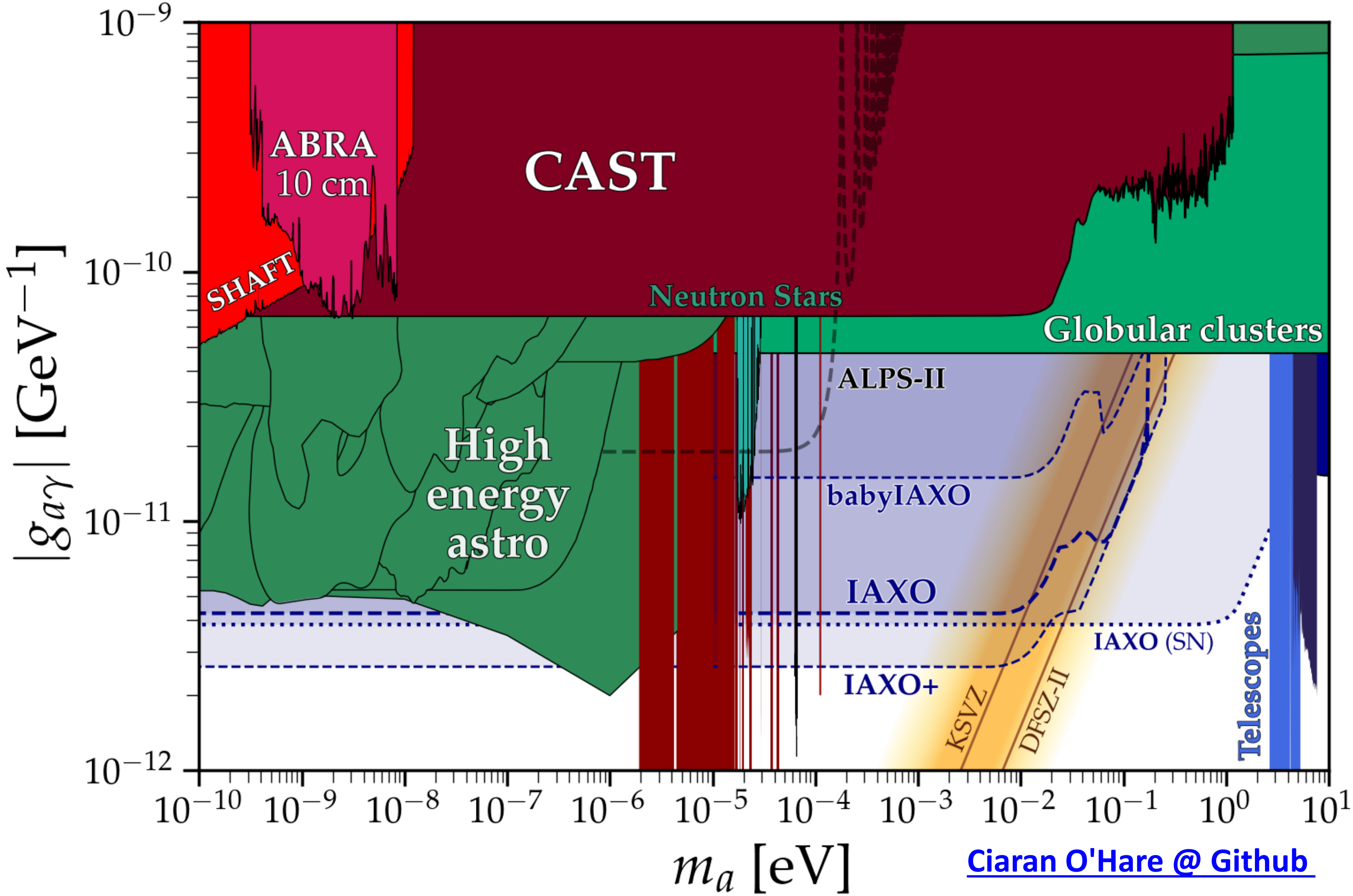


Figure 2. (Left panel): Predicted values of R as a function of g_{10} given standard convective core overshoot with $f_{\rm ov} = 0.001$ (blue) and $f_{\rm ov} = 0.01$ (green). The observed limit on R is indicated by the region between the dashed black lines (95% C.I.). (Right panel): The full range of R_2 values predicted as functions of g_{10} given standard overshoot with $f_{\rm ov} = 0.001$ (blue) and $f_{\rm ov} = 0.01$ (green). The observed limit is again shown by the dashed black lines.

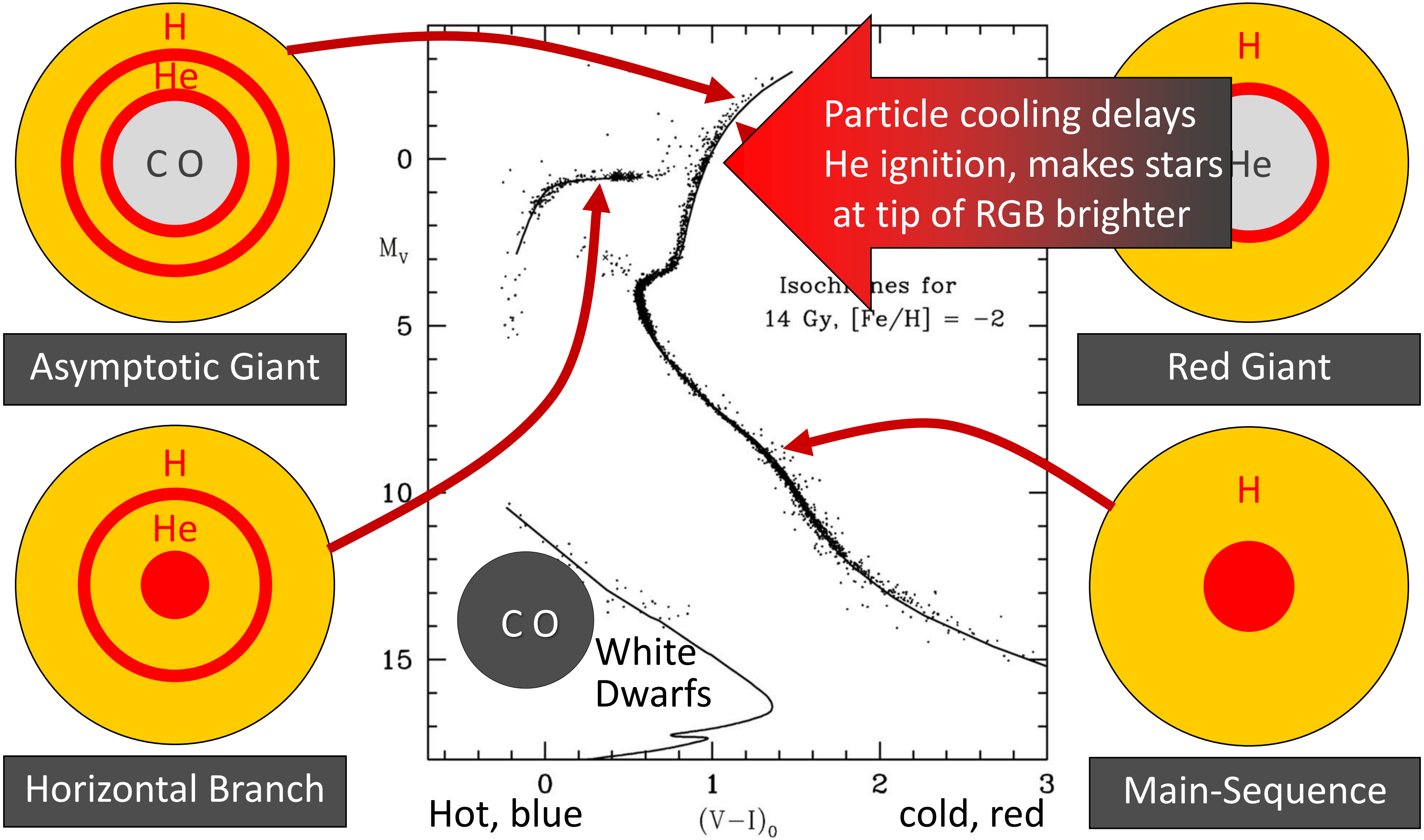
Probably one should analyze GCs for all observables simultaneously using modern high-statistics (GAIA) data

ALP Scape: Helioscope Close-Up



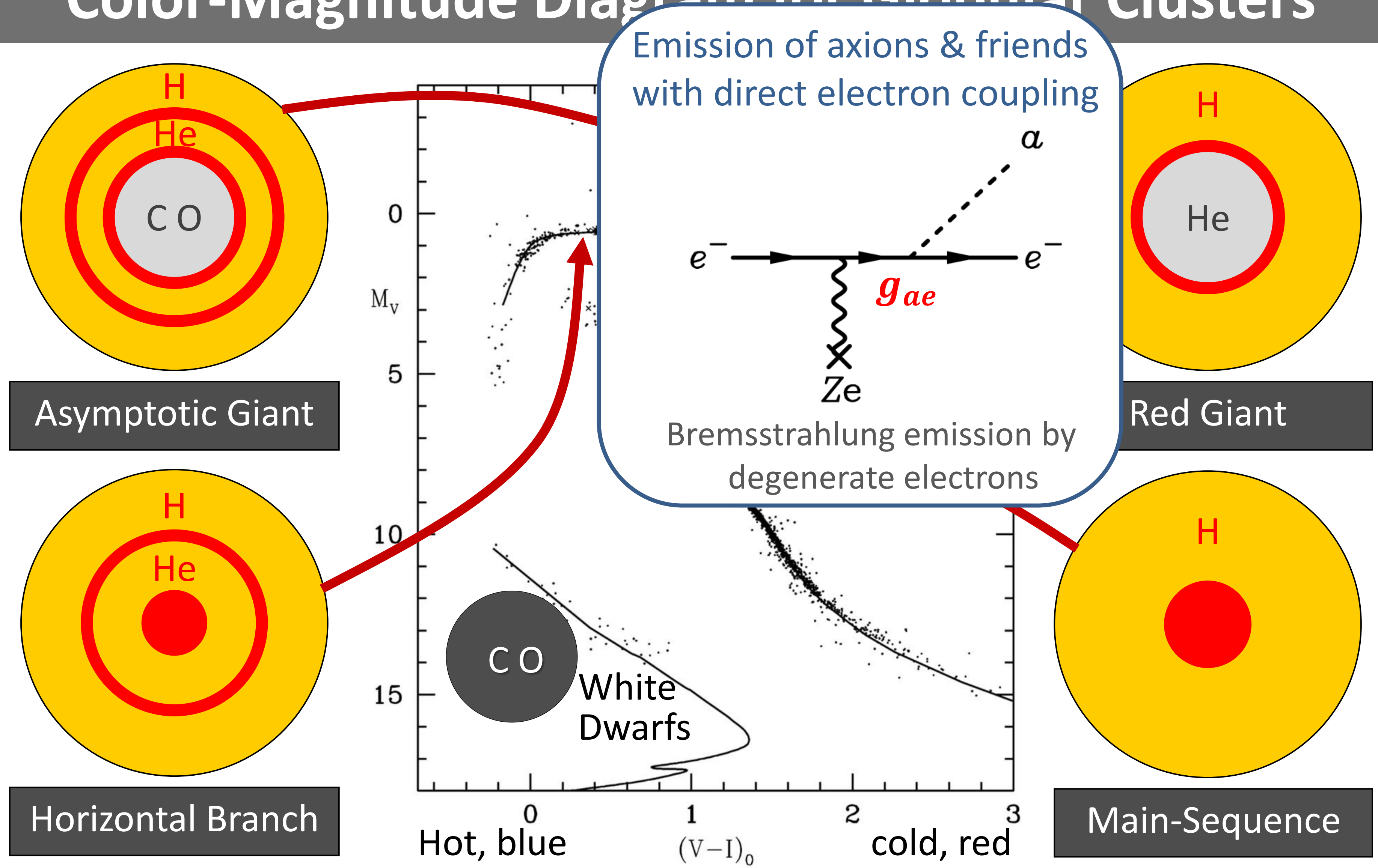
Ciaran O'Hare @ Github

Color-Magnitude Diagram for Globular Clusters



Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Color-Magnitude Diagram for Globular Clusters



Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

TRGB in 46 Globular Clusters [Cerny+ 2012.09701]

Brightness and Core Mass at TRGB

Raffelt & Weiss, Astron. Astrophys. 264 (1992) 536

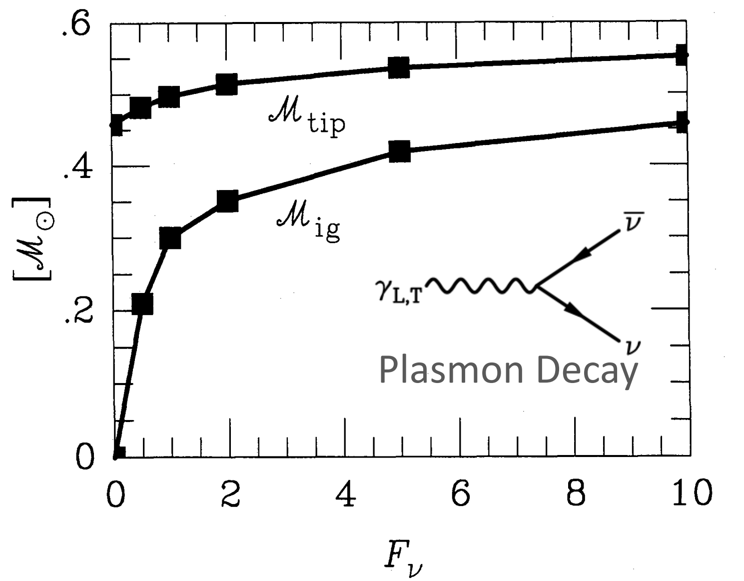


Fig. 2. Core mass at helium flash, $\mathcal{M}_{\rm tip}$, and mass-coordinate of the ignition point, $\mathcal{M}_{\rm ig}$, as a function of F_ν for $\mathcal{M} = 0.80$, $Z = 10^{-4}$, and $Y_0 = 0.22$ (see Table 2).

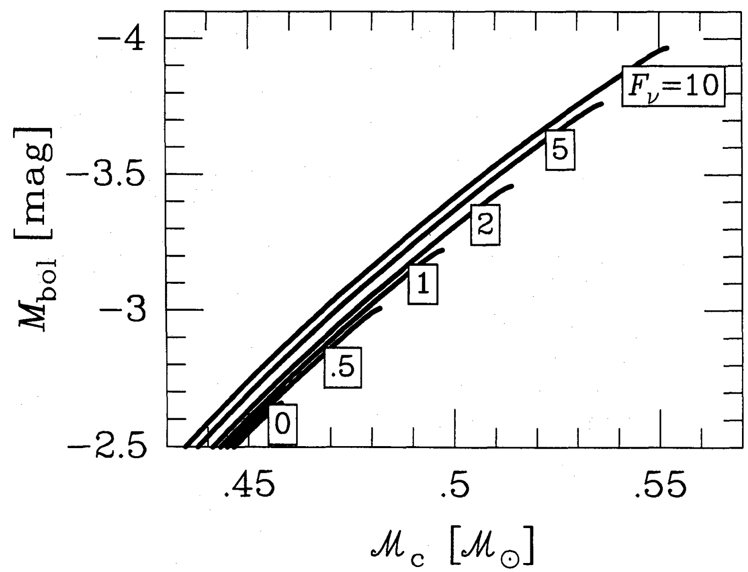


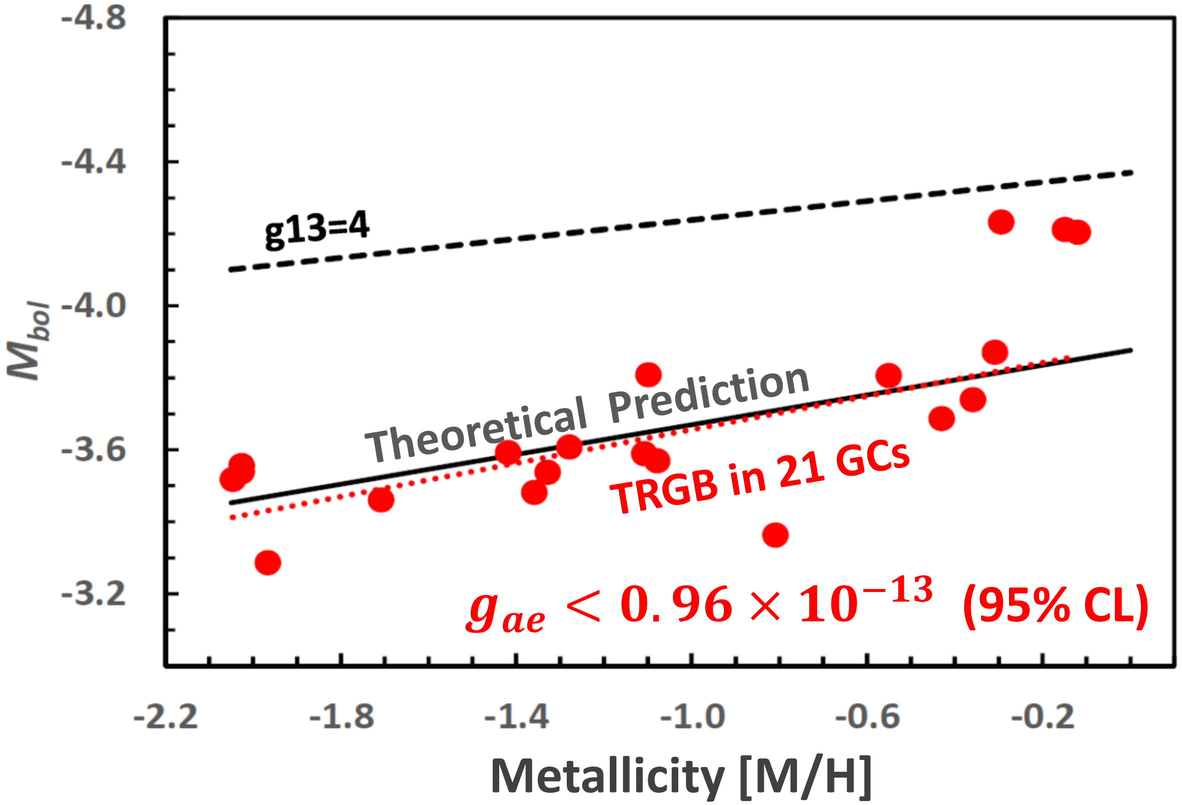
Fig. 3. Absolute surface brightness as a function of core mass for the $Z = 10^{-4}$ runs of Table 2. The curves are marked with the relevant F_ν values.

Parametric study: Vary standard neutrino losses with a fudge factor F_ν
($F_\nu = 1$ standard, $F_\nu = 0$ no losses at all, etc.)

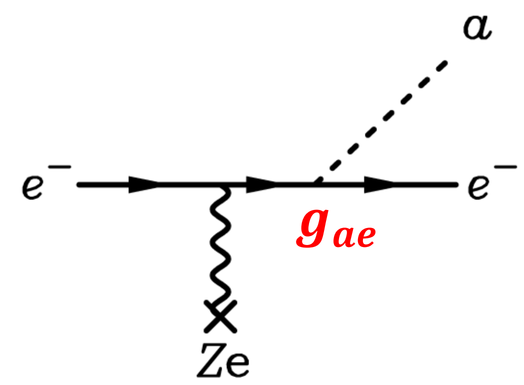
- Helium ignition point (mass coordinate $\mathcal{M}_{\rm ig}$) moves away from center
- Core mass at ignition $\mathcal{M}_{\rm tip}$ grows
- Bolometric brightness at ignition $M_{\rm tip}$ increases

New TRGB Calibration from 21 Globular Clusters

Straniero+ arXiv:2010.03833 and https://www.ggi.infn.it/talkfiles/slides/slides6554.pdf



Emission of axions & friends with direct electron coupling



Bremsstrahlung emission by degenerate electrons

DFSZ Axions

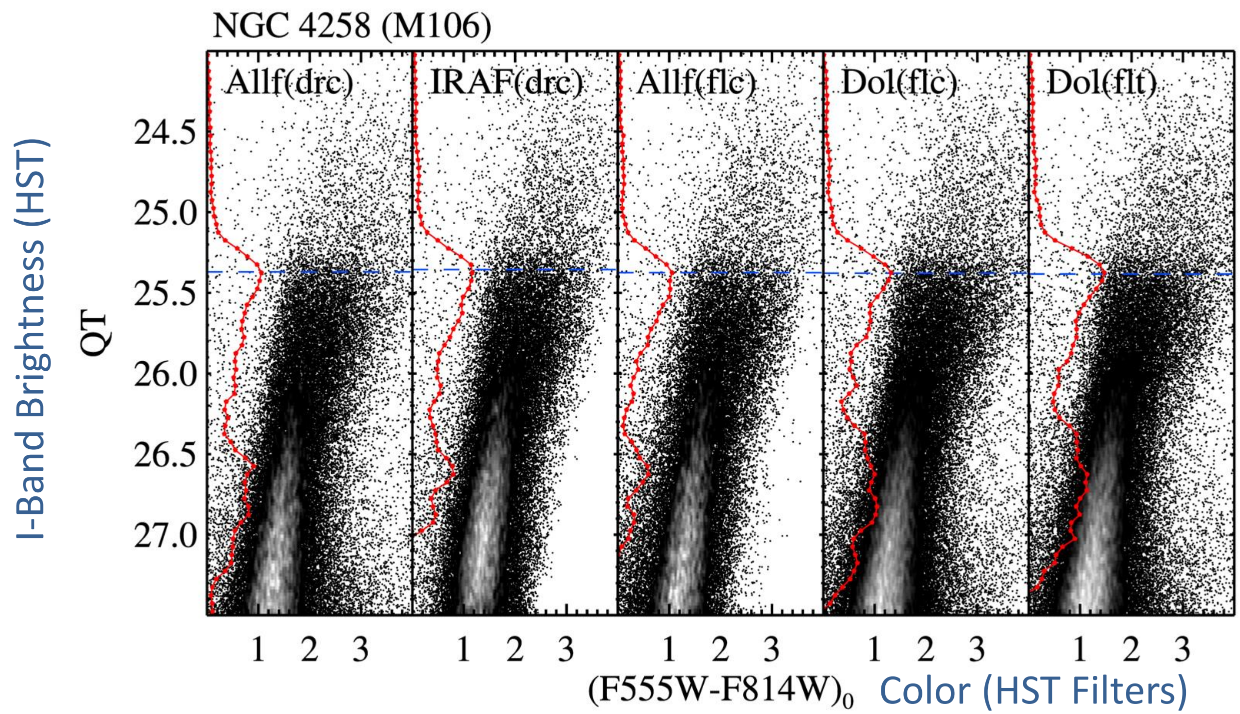
$$m_a = 6\ \mathrm{meV}\,\frac{10^9\,\mathrm{GeV}}{f_a} \qquad g_{\mathrm{ae}} = \frac{m_e C_e}{f_a}$$

$$\mathcal{L}_{\mathrm{ae}} = \frac{C_e}{2f_a}\bar{e}\gamma^\mu\gamma_5 e\,\partial_\mu a \qquad C_e = \frac{\cos^2\beta}{3}$$

$$\frac{f_a}{\cos^2\beta} > 1.8 \times 10^9\ \mathrm{GeV}$$

Tip of the Red-Giant Branch in the Galaxy NGC 4258

The Astrophysical Journal, 835:28 (17pp), 2017 January 20 Jang & Lee



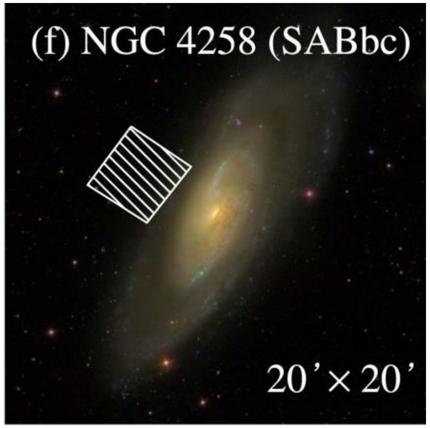
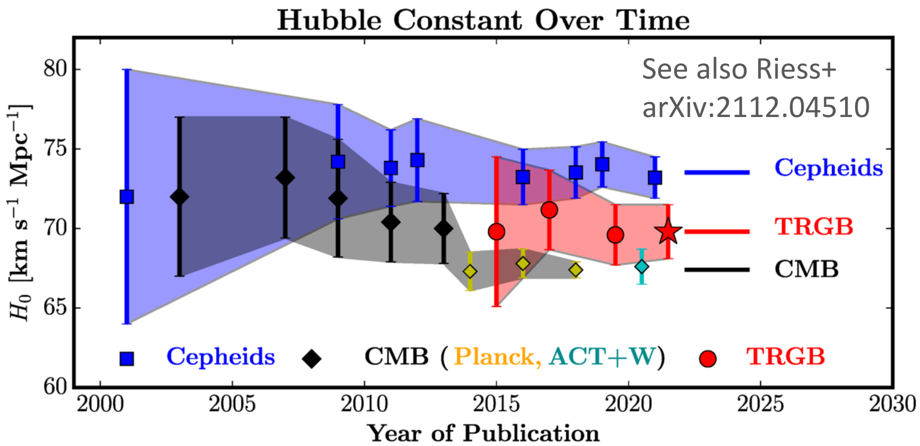
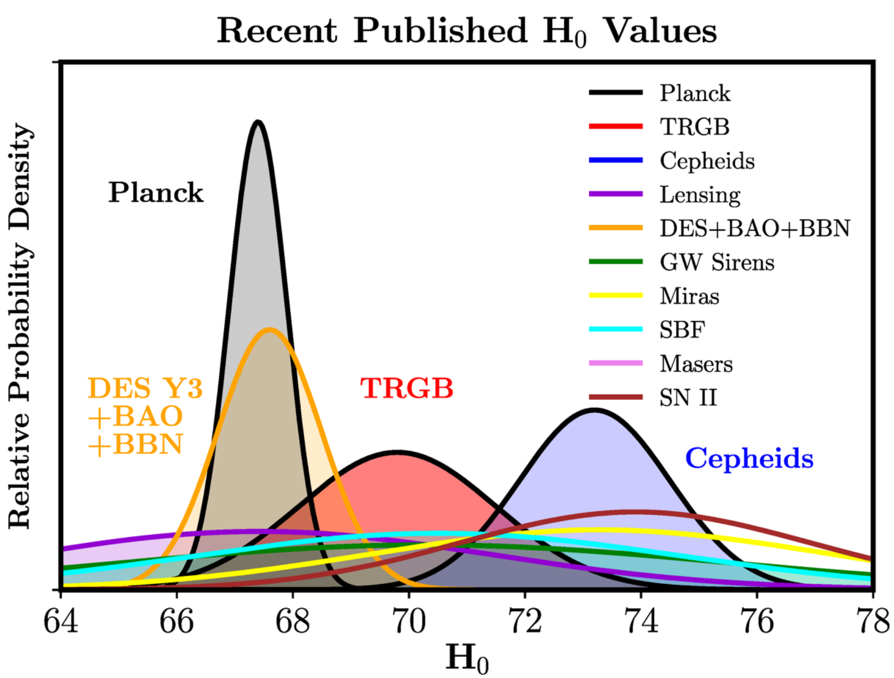


Figure 7. QT − (F555W − F814W)$_0$ CMDs of NGC 4258 from five different reduction methods : ALLFRAME on drc, IRAF/DAOPHOT on drc, ALLFRAME on flc, DOLPHOT on flc, and DOLPHOT on flt (from left to right). Edge detection responses are shown by the solid lines. Note that the estimated TRGB magnitudes (dashed lines) agree very well.

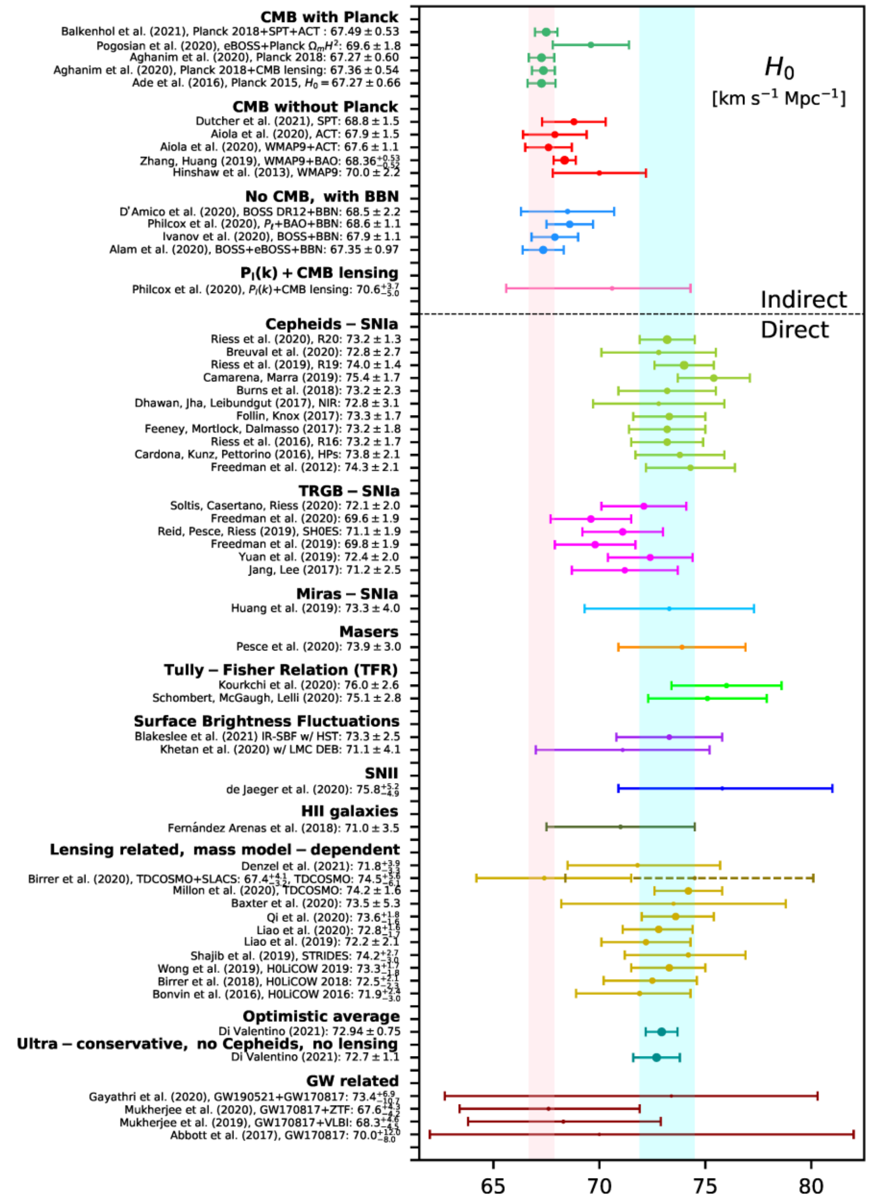
NGC 4258 hosts a water megamaser
→ Quasi-geometric distance determination
→ Among the best absolute TRGB calibrations

Hubble Tension



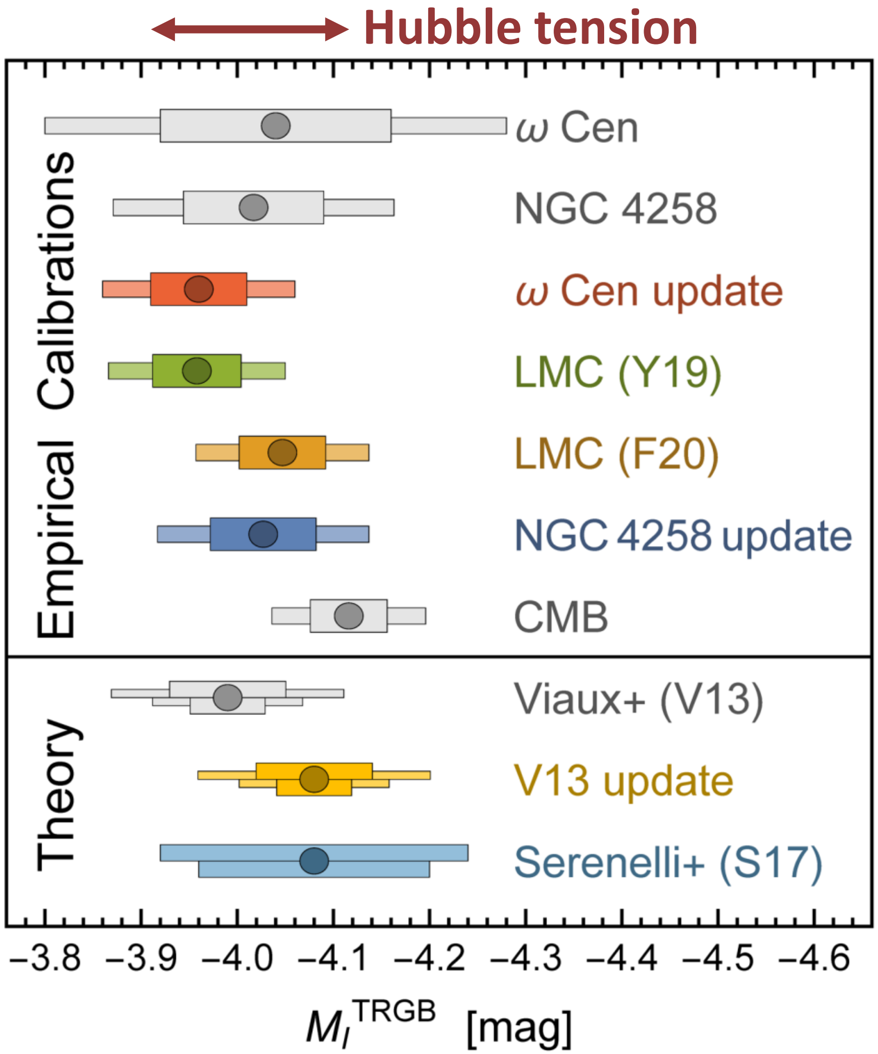


Freedman ApJ 919 (2021) 16 [2106.15656]



Di Valentino+ arXiv:2103.01183

Axion Bounds from TRGB Calibrations



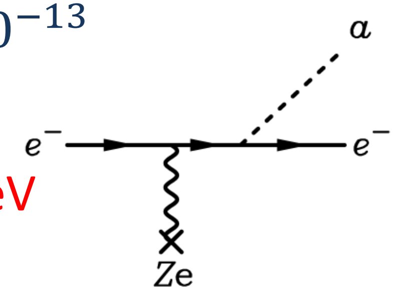
Updated TRGB Calibrations
Capozzi & Raffelt, arXiv:2007.03694

Bounds from "water megamaser" galaxy NGC 4258, compared with stellar evolution theory (95% CL)

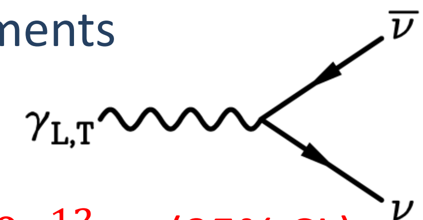
$$g_{ae} < 1.6 \times 10^{-13}$$

DFSZ-axions

$$\frac{f_a}{\cos^2\beta} > 1.1 \times 10^9 \text{ GeV}$$



Neutrino Dipole Moments

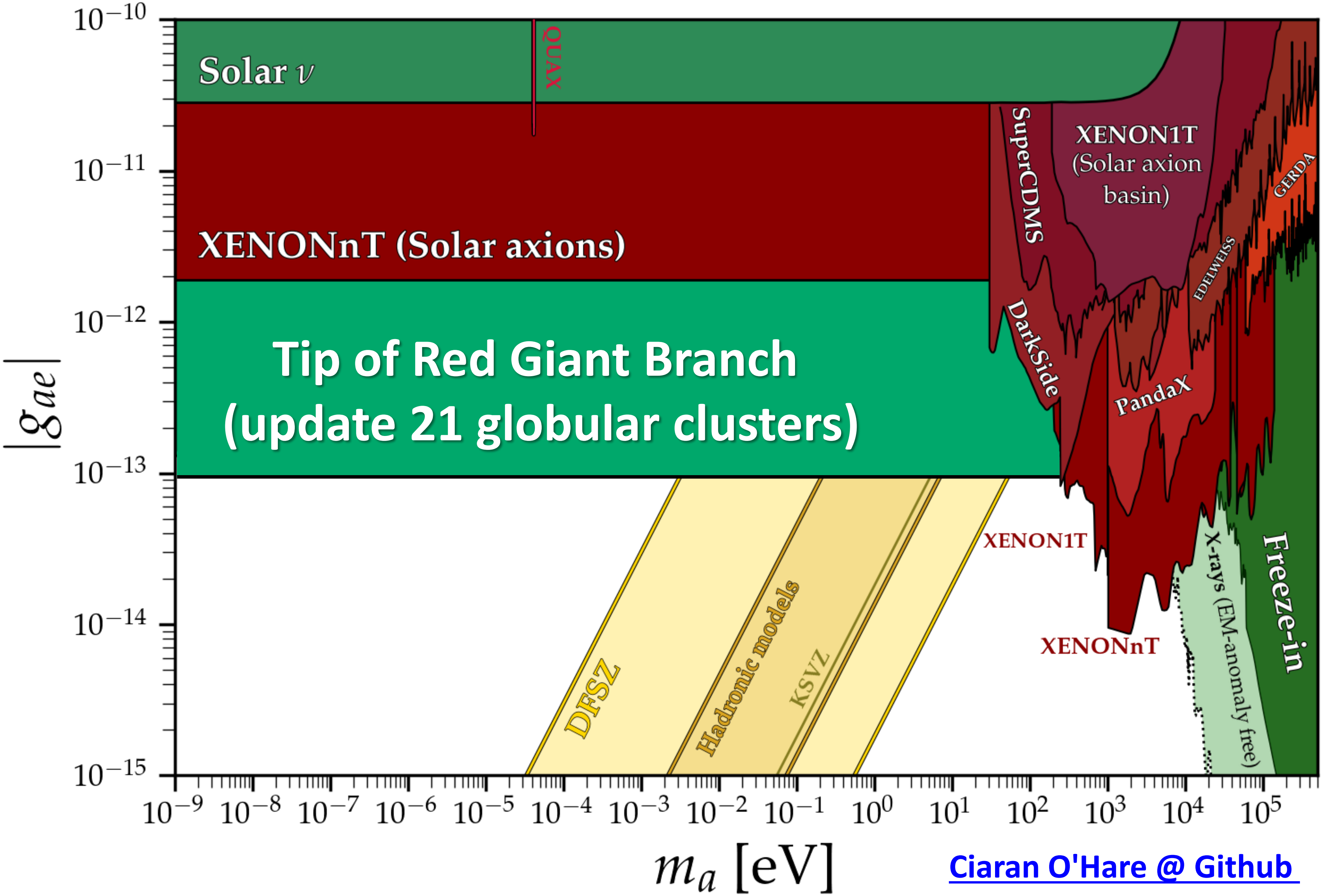


$$\sqrt{\textstyle\sum_i |\mu_i|^2} < 1.5 \times 10^{-12}\mu_{\rm B} \text{ (95\% CL)}$$

Neutrino-electron scattering (Borexino)

$$\mu_\nu^{\rm eff} < 28 \times 10^{-12}\mu_{\rm B} \text{ (90\% CL)}$$

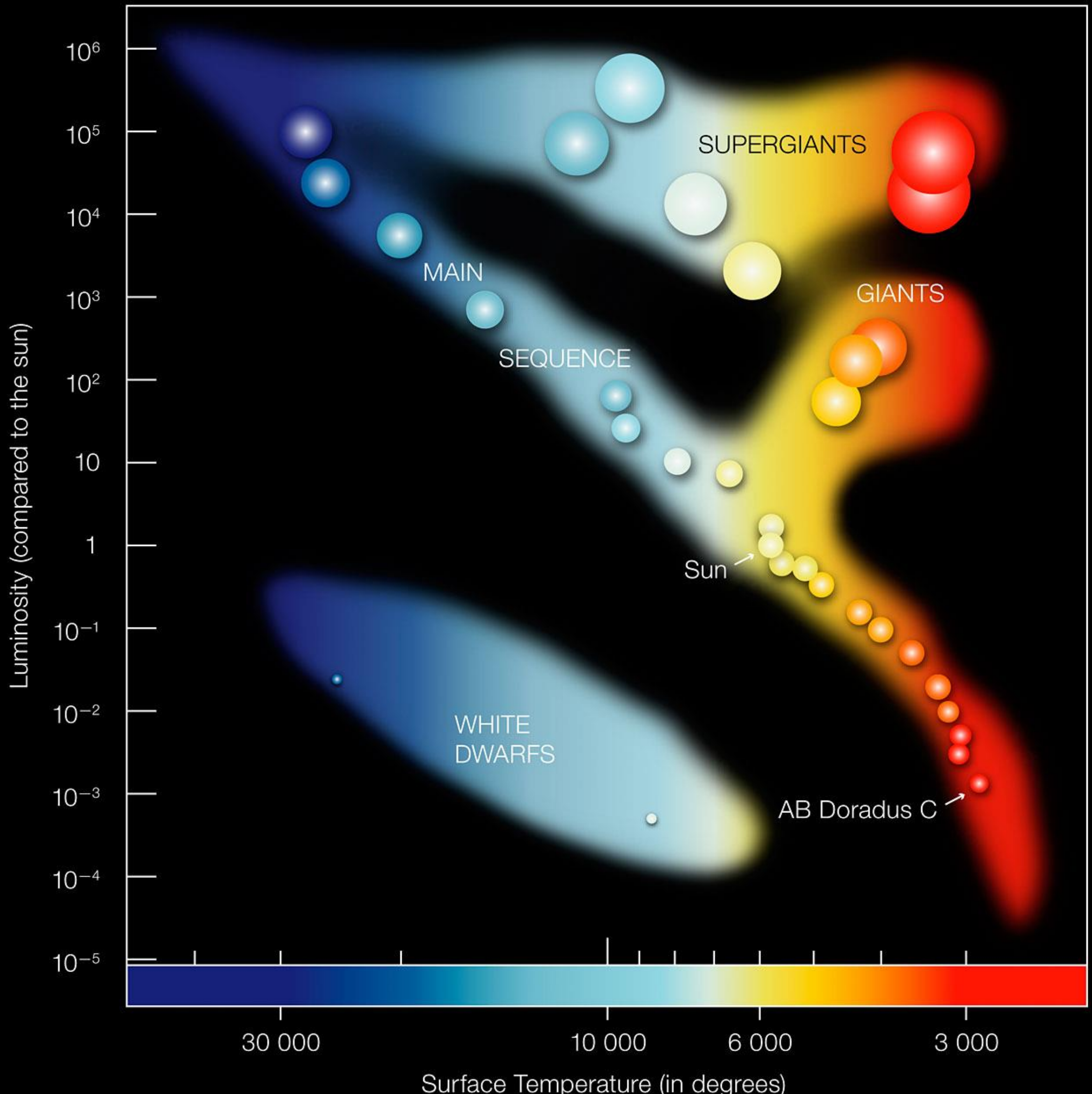
Axion-Electron Coupling



Ciaran O'Hare @ Github

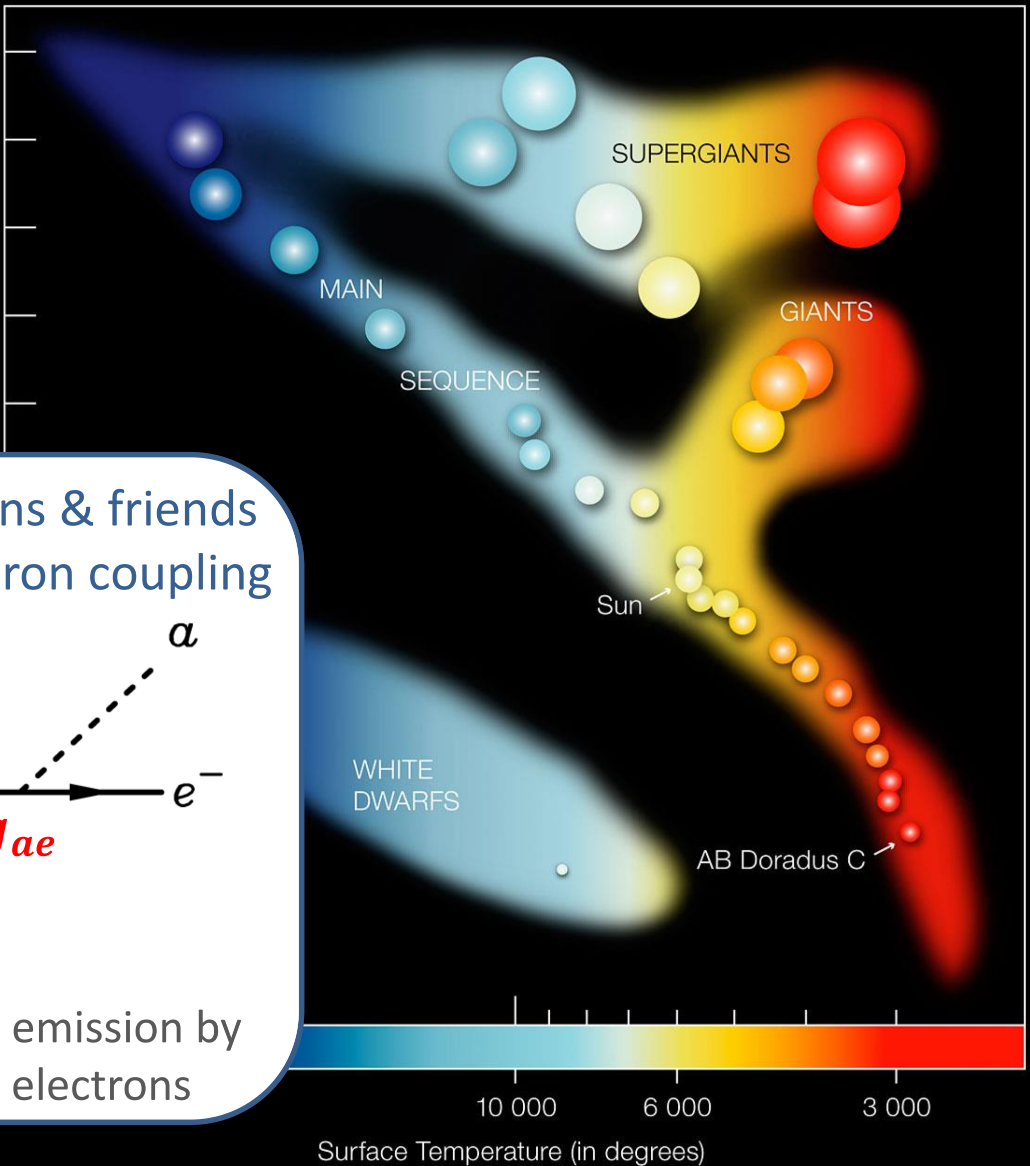
Bonus Topics

White Dwarfs

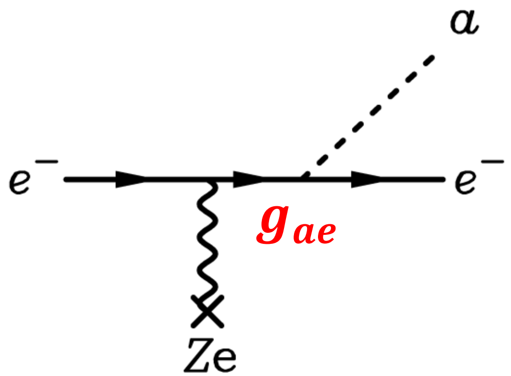


https://www.eso.org/public/images/eso0728c/

White Dwarfs



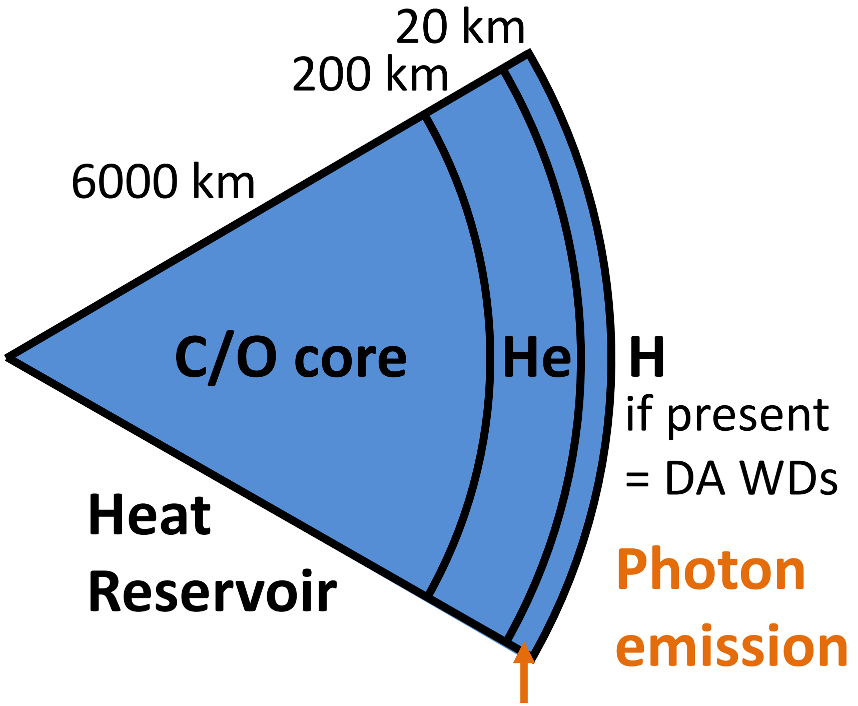
Emission of axions & friends with direct electron coupling



Bremsstrahlung emission by degenerate electrons

https://www.eso.org/public/images/eso0728c/

White Dwarfs



Energy flux control

Cooling much slower for DA type (with H layer)

$R \quad \simeq 6000$ km (Size of the Earth)

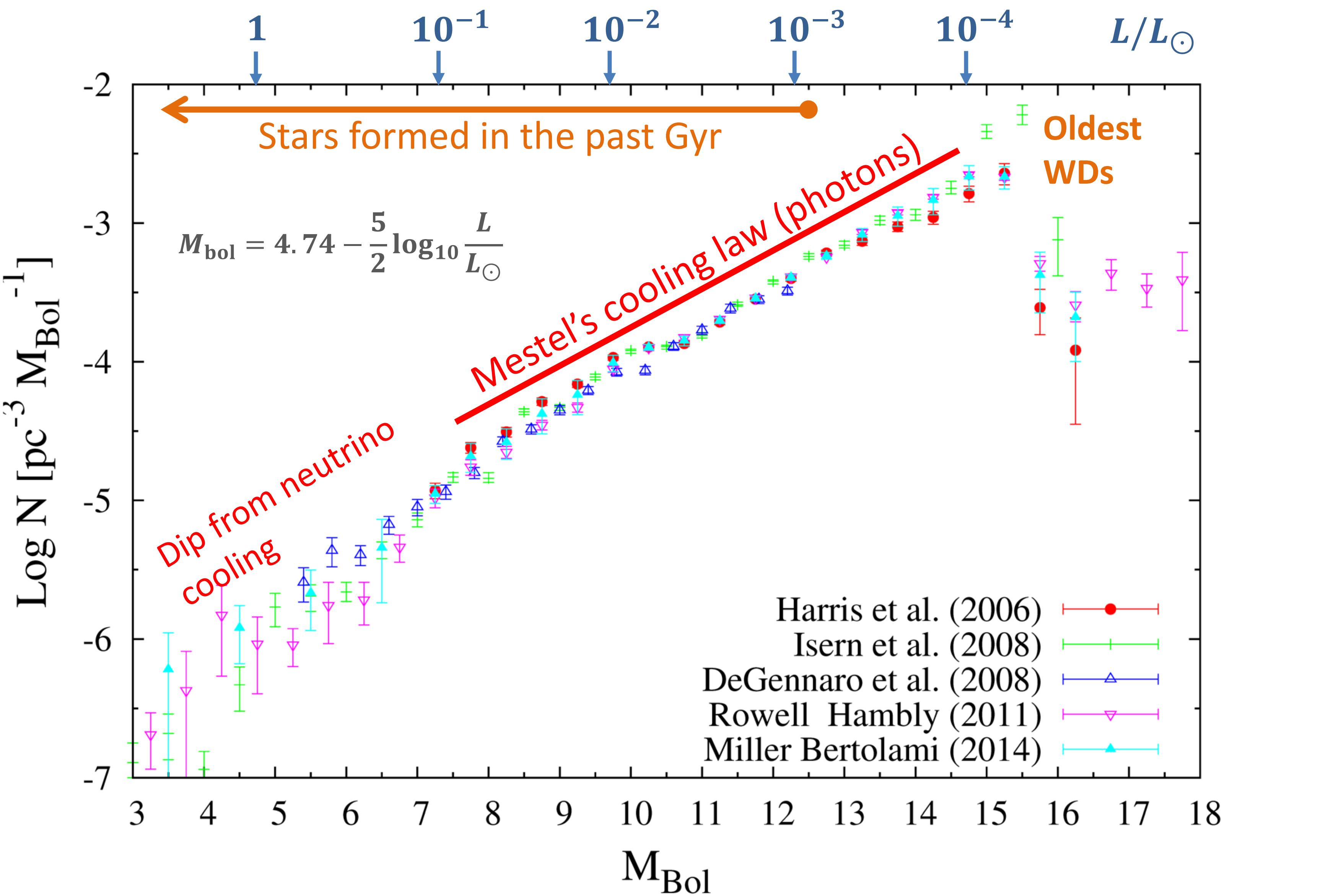
$T_{\rm eff} \simeq 10{,}000\text{–}30{,}000\mathrm{K}$ (Sun 6000 K)

$L \quad \simeq 10^{-4}\text{–}10^{-1} L_\odot$

$M \quad \simeq 0.5\text{–}0.8 M_\odot$

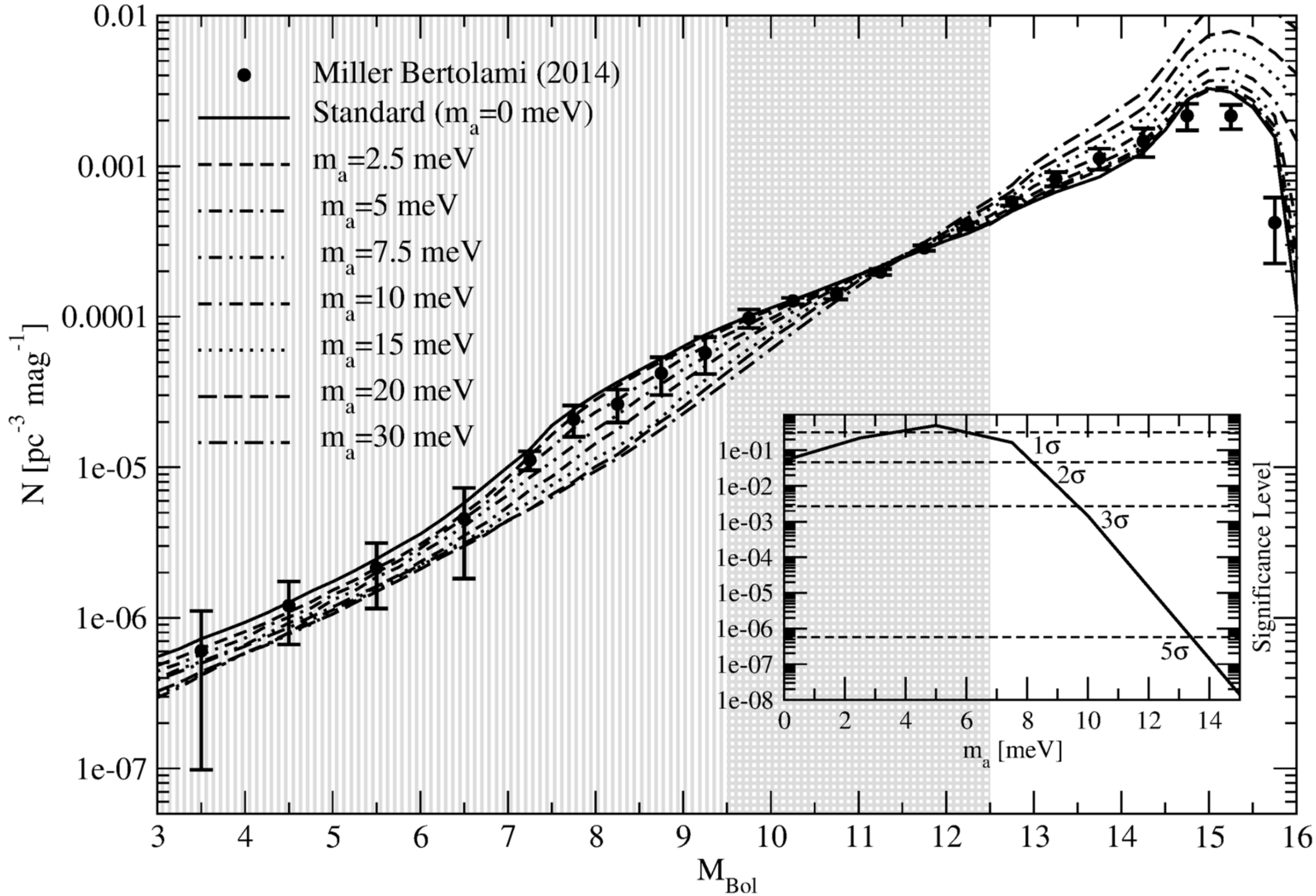
$\rho \quad \simeq 10^6 \mathrm{g/cm^3}$ (very degenerate)

White Dwarf Luminosity Function (WDLF)



Miller Bertolami, Melendez, Althaus & Isern, arXiv:1406.7712

Axion Bounds from WD Luminosity Function



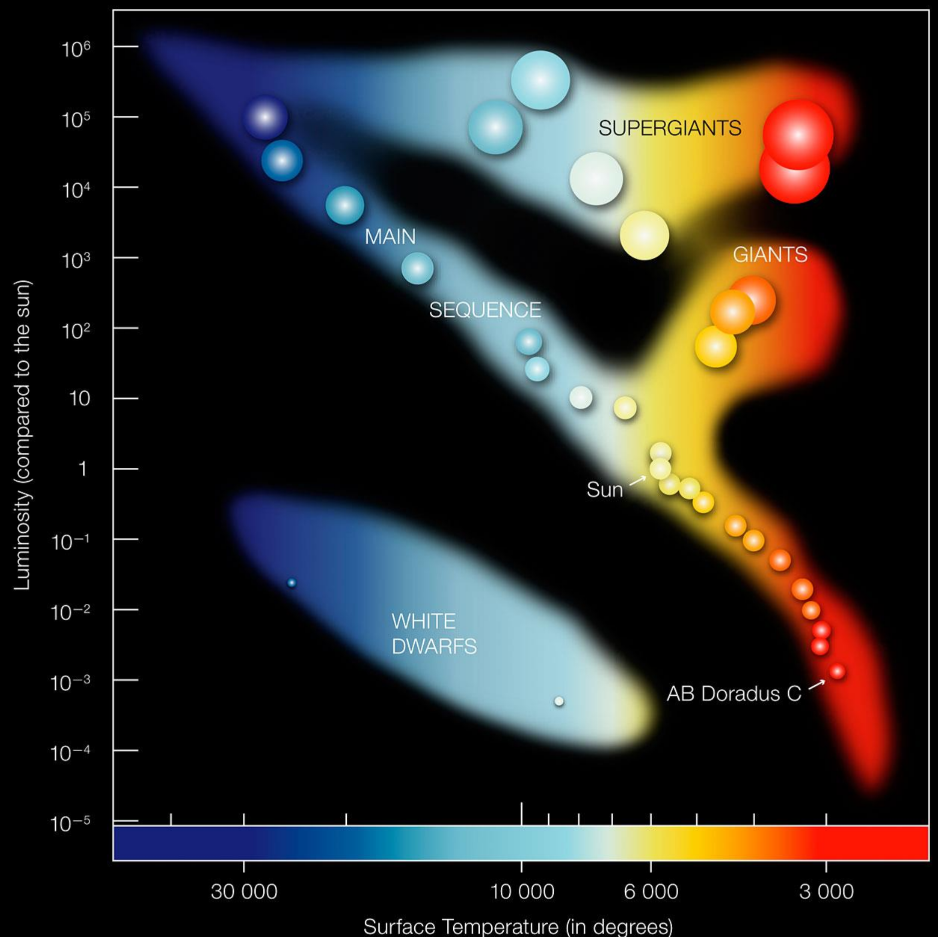
Limits on axion-electron coupling and mass limit in DFSZ model:

$g_{ae} \lesssim 3 \times 10^{-13}$ $\qquad$ $m_a \cos^2\beta \lesssim 10\ \mathrm{meV}$

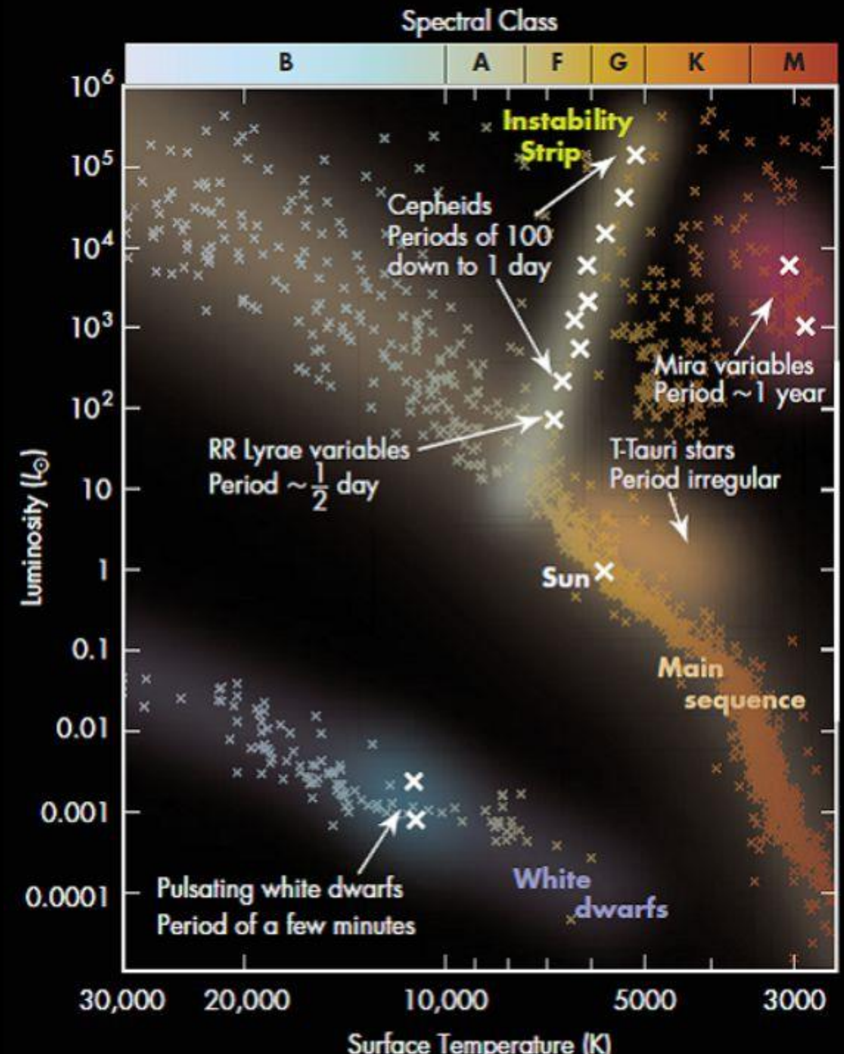
Miller Bertolami, Melendez, Althaus & Isern, arXiv:1406.7712, 1410.1677

For extensions and review see: Isern, arXiv:2002.08069

Pulsating Stars

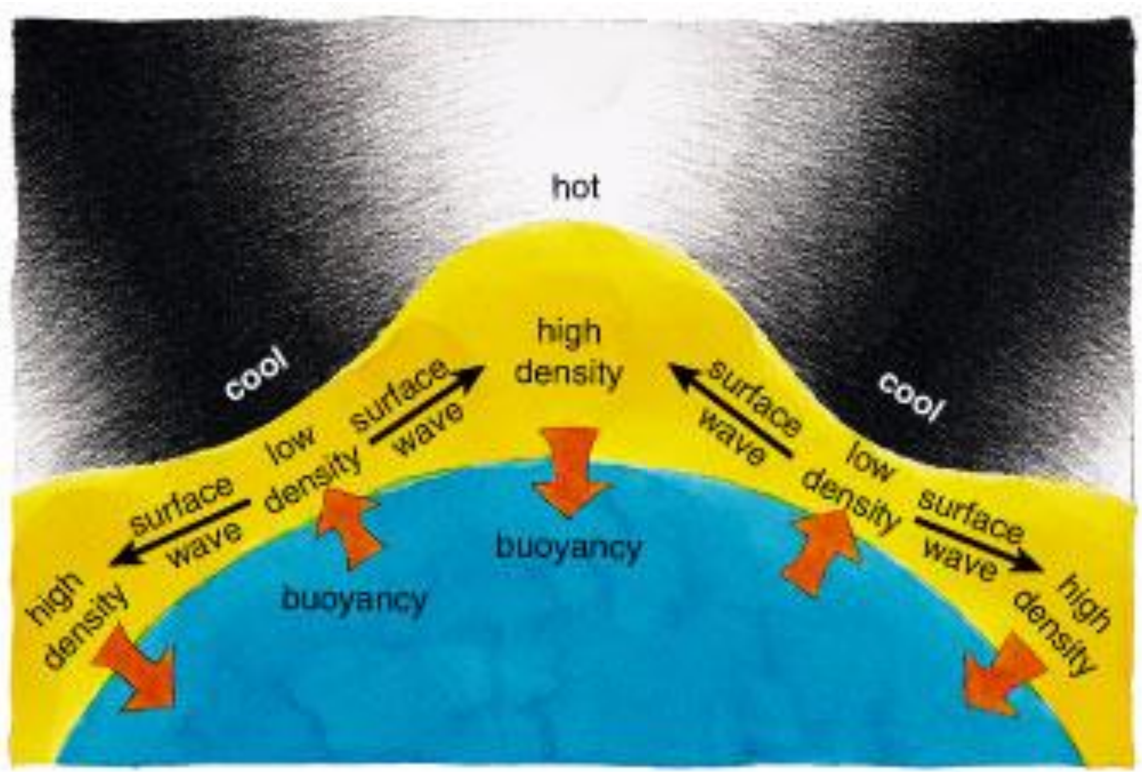


https://www.eso.org/public/images/eso0728c/



https://scienceatyourdoorstep.com/2021/01/04/what-are-variable-stars/

Non-Radial g-Modes



From a talk by J. Isern

- Long period waves (100 – 1000 s)
- Gravity is the restoring force

$$\frac{d\log\Pi}{dt} \propto -\frac{d\log T}{dt}$$

- Period decreases as the star cools
- Characteristic rate $10^{-15}\ s/s$
- Measures cooling speed of a single star

Kepler+ ApJ 254 (1982) 676

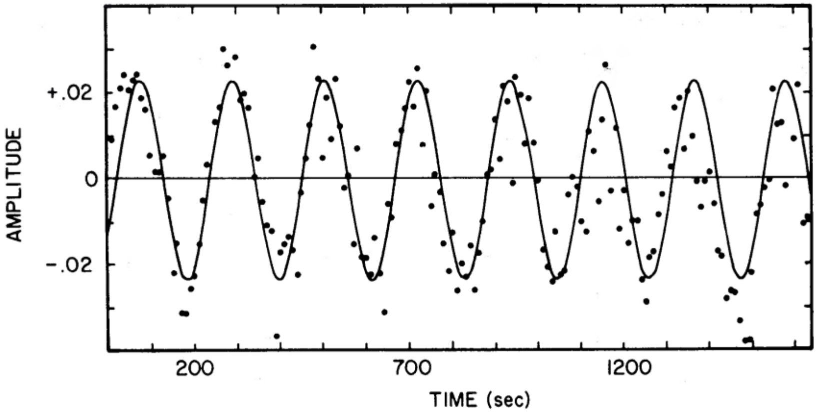


FIG. 1.—A portion of the light curve of G117−B15A in unfiltered light during run 2075. The light curve has been normalized so that the time-averaged brightness of G117−B15A is equal to 1.00, and then 1.00 has been subtracted from the light curve. The solid line is a sine curve with a period of 215.19 s and a semiamplitude of 0.022 mag.

Kepler+ ApJ 906 (2021) 7

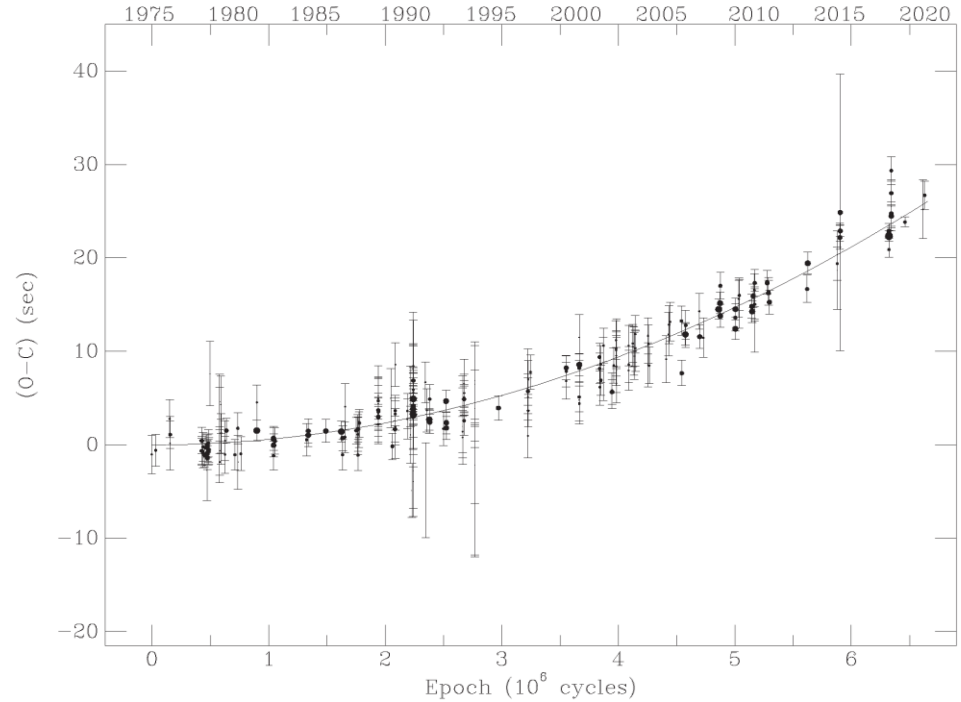


Figure 1. ($O - C$): observed minus calculated times of maxima for the 215 s pulsation of G 117-B15A. The size of each point is proportional to its weight, i.e., inversely proportional to the uncertainty in the time of maxima squared. We show $\pm 1\sigma$ error bars for each point, and the line shows our best-fit parabola to the data. The fact that the line does not overlap these error bars is a demonstration that they are underestimated. Note that as the period of pulsation is 215.1973882 s, the observed total change in phase is only 50 deg.

$D = 57.5 \pm 0.1$ pc
$T = 12{,}400$ K
$M = 0.69\ M_\odot$
Period 215.2 s

"Most stable optical clock", slipped by 26 s (of 215.2 s period) in 45 years

$$\dot{P}/P = (5.12 \pm 0.82) \times 10^{-15}\ \mathrm{s/s}$$

G117–B15A Period Decrease: Hint for Axion Cooling?

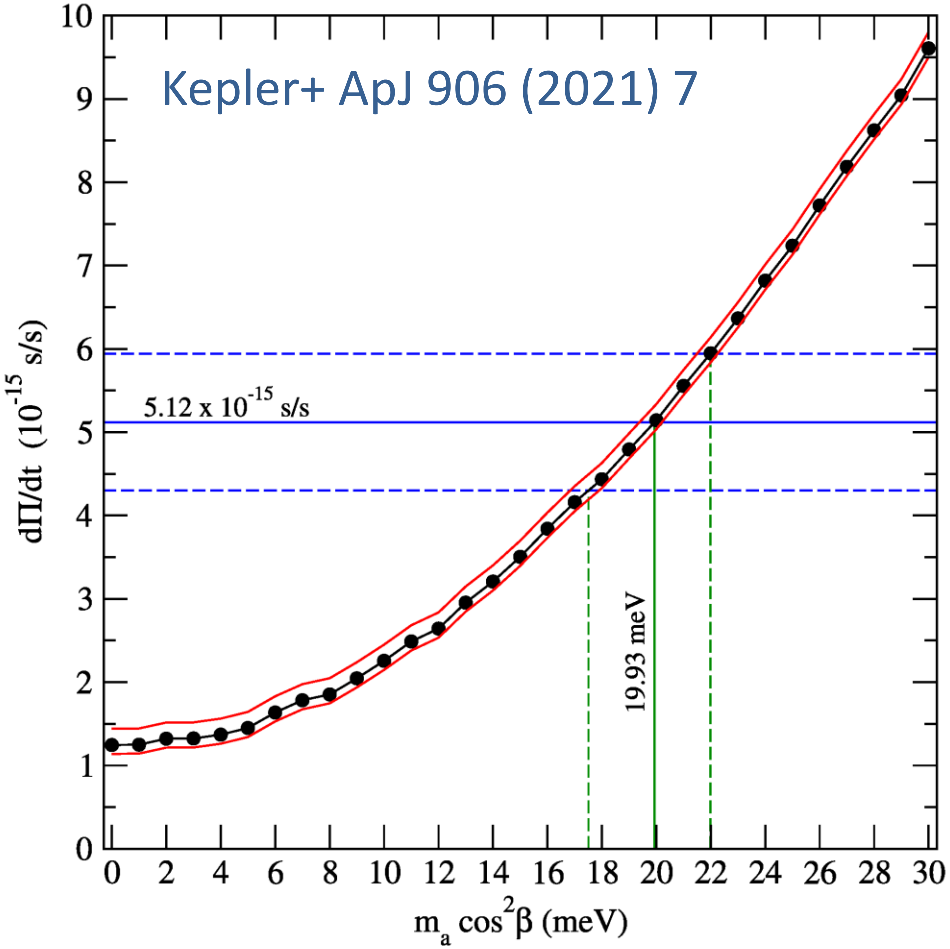
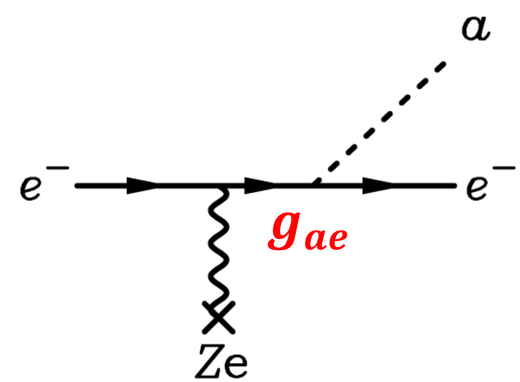


Figure 2. The rate of period change for the mode with $\ell = 1$ and $k = 2$, corresponding to a period of ∼215 s in terms of the axion mass (black circles). Dashed lines represent the uncertainties in the value in the observed $\dot{P}$ and the axion mass, while the red curves represent the internal uncertainties in $\dot{P}$ due to modeling.

$$\dot{P}/P = (5.12 \pm 0.82) \times 10^{-15}\ \mathrm{s/s}$$

Emission of axions & friends with direct electron coupling



Bremsstrahlung emission by degenerate electrons

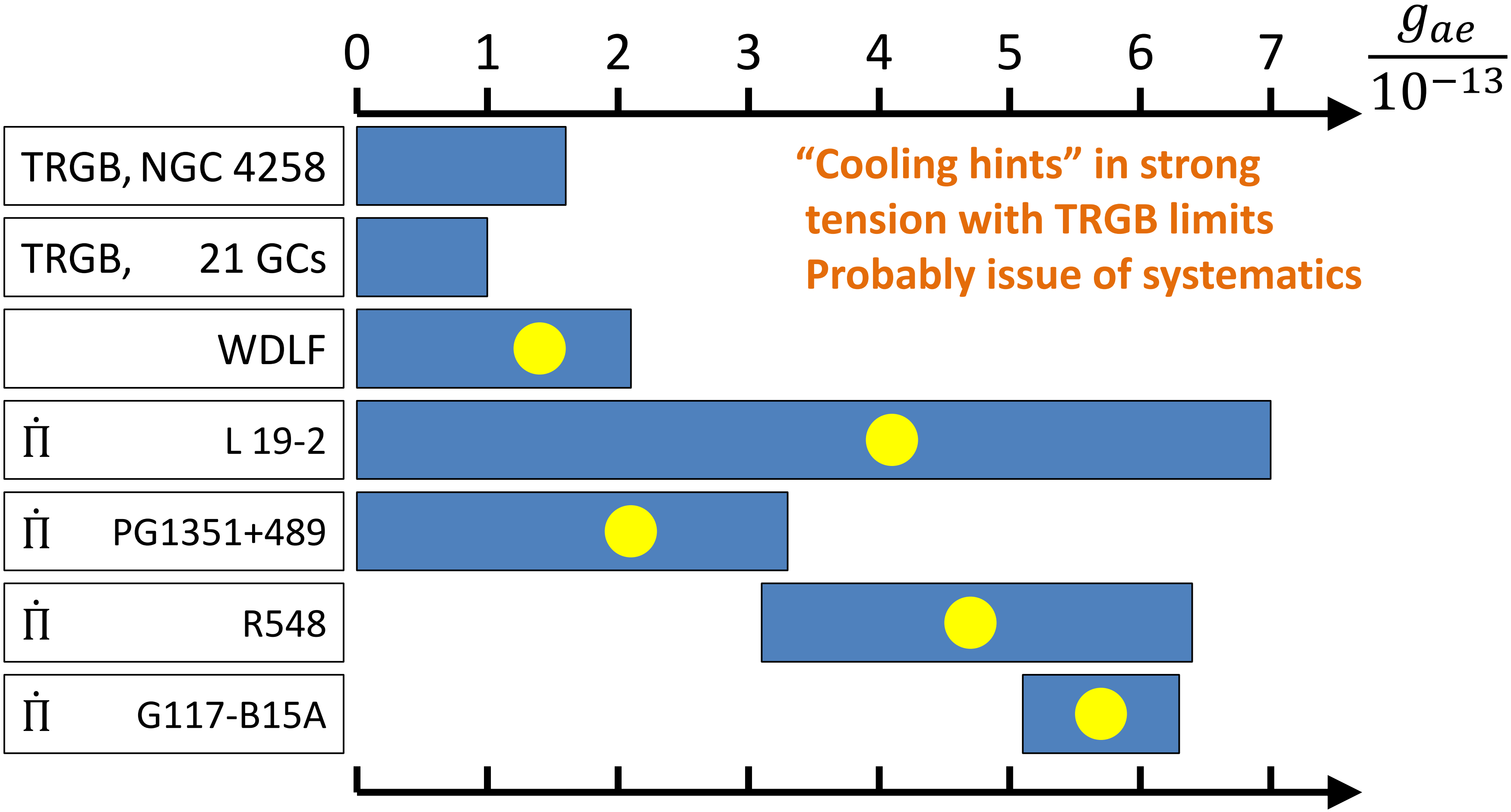
Case of DFSZ Axion

$$g_{ae} = 0.28 \times 10^{-13}\ \frac{m_a \cos^2\beta}{\mathrm{meV}}$$

Nominal cooling signal

$$g_{ae} = (5.7 \pm 0.6) \times 10^{-13}$$

White-Dwarf Bounds on Axion-Electron Coupling



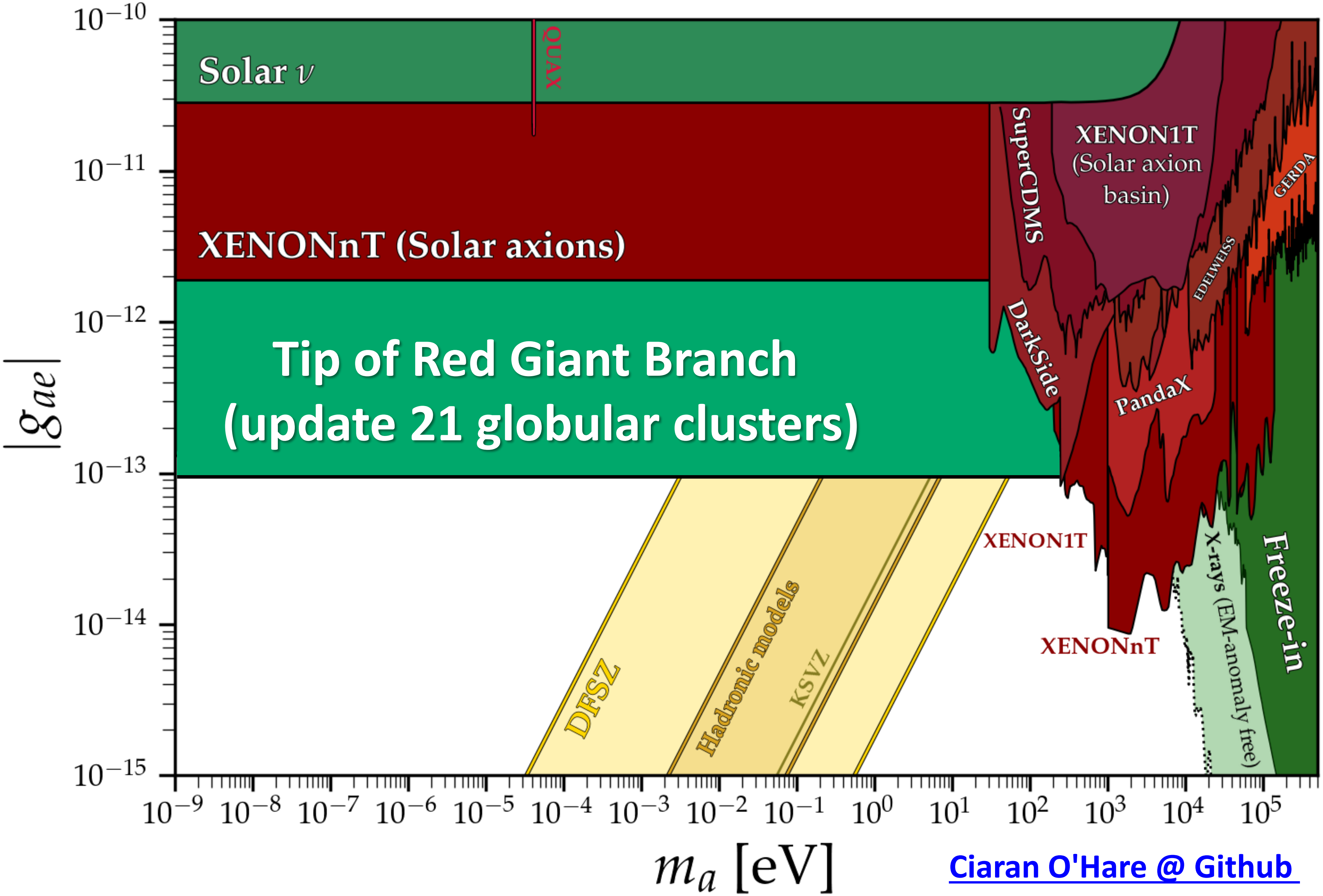
White Dwarfs as Physics Laboratories: Lights and Shadows, arXiv:2202.02052

J. Isern, S. Torres & A. Rebassa-Mansergas

Stellar Evolution Confronts Axion Models, arXiv:2109.10368

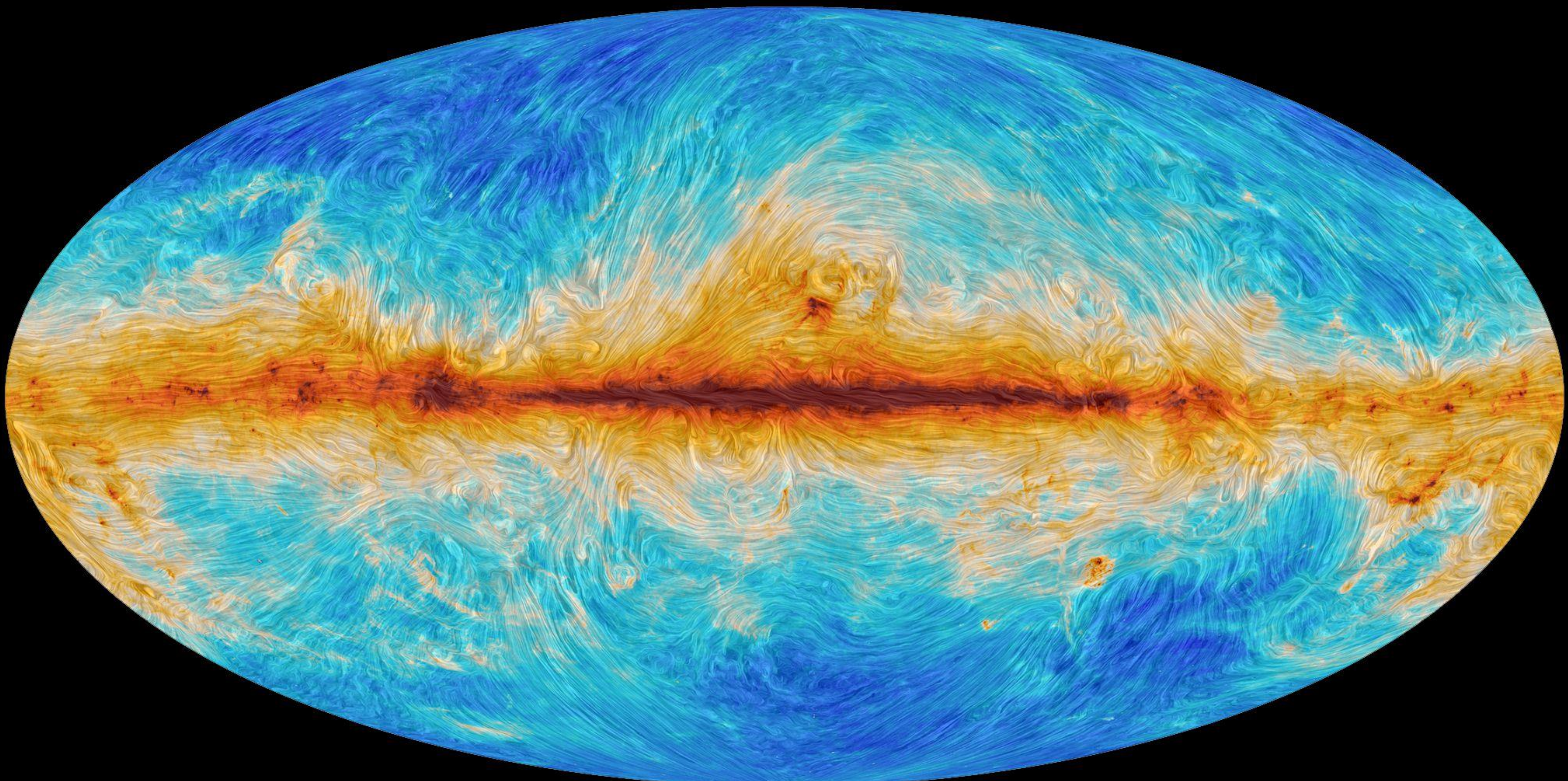
L. Di Luzio, M. Fedele, M. Giannotti, F. Mescia & E. Nardi

Axion-Electron Coupling



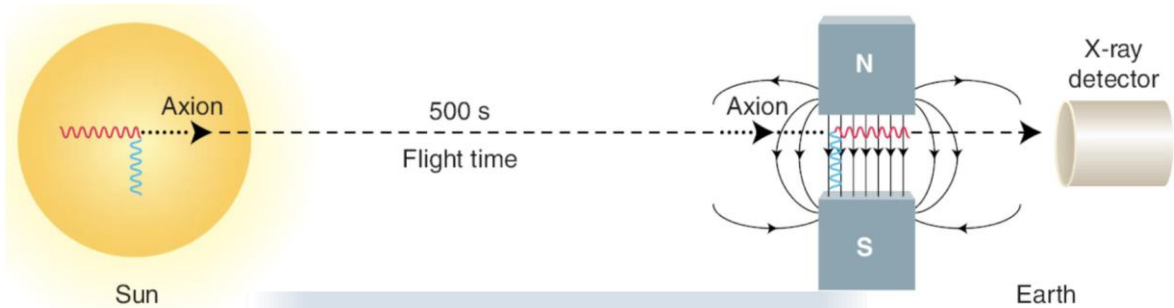
Ciaran O'Hare @ Github

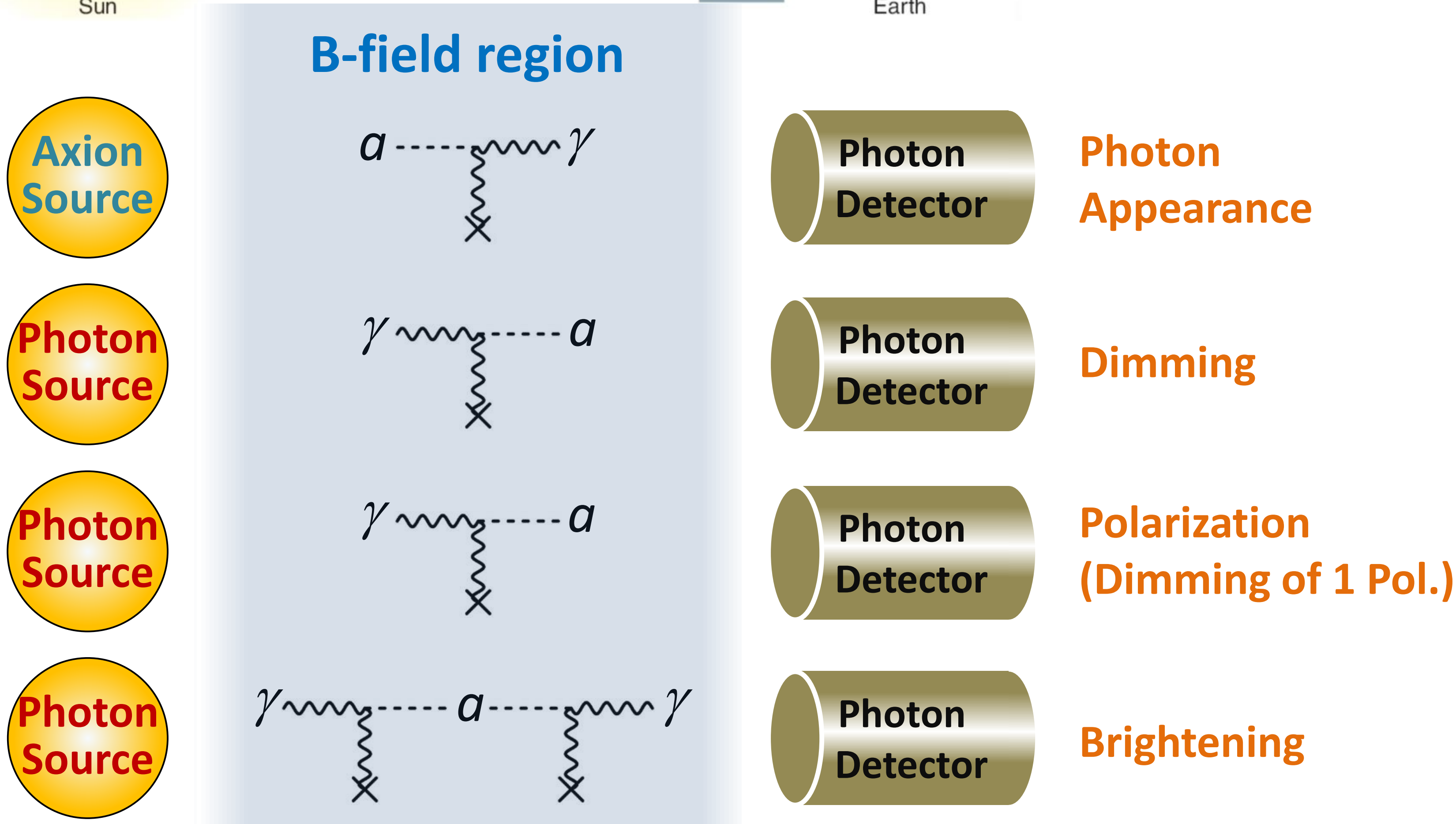
Axion-Photon Conversion in the Sky



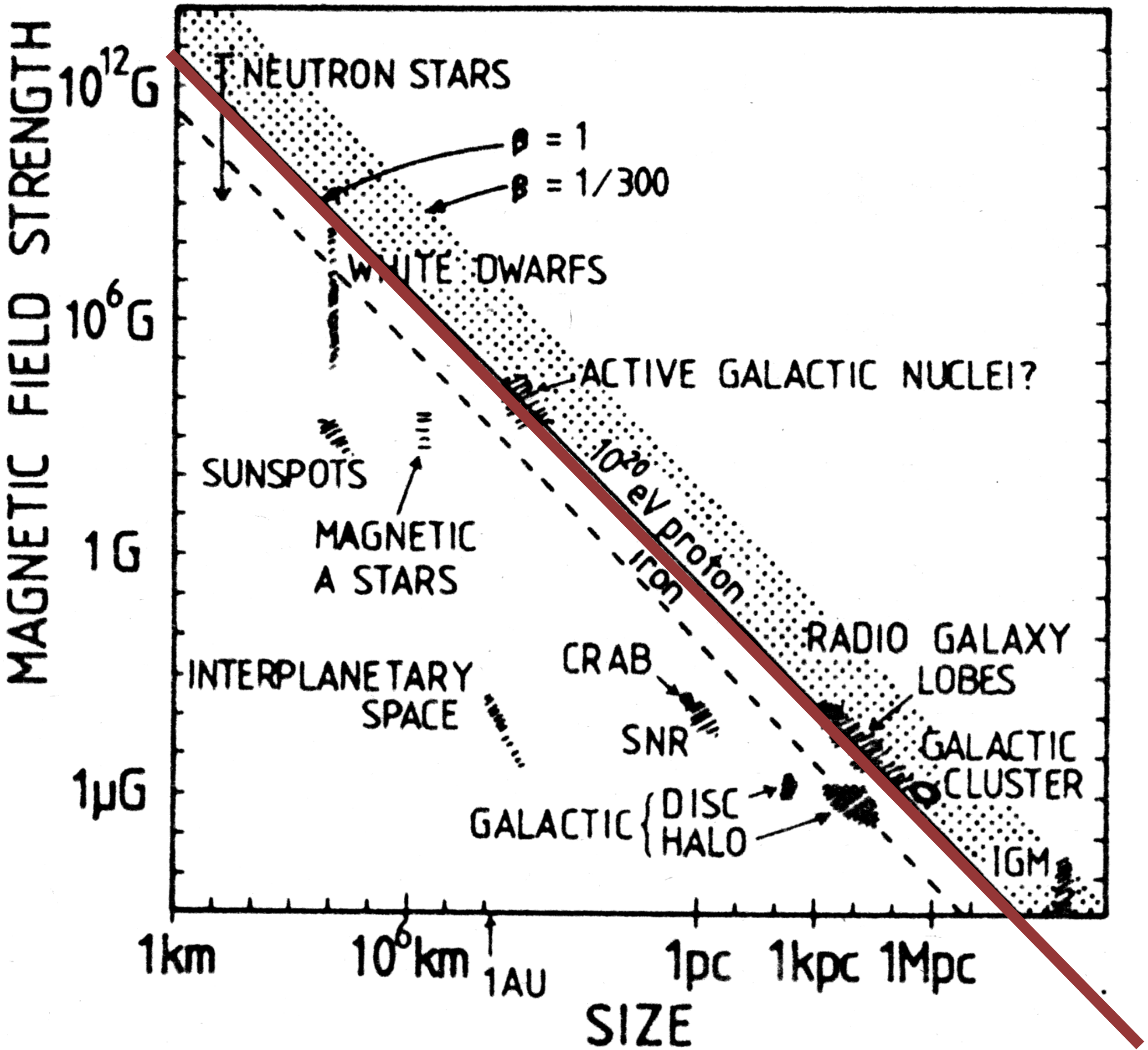
Planck: Galactic magnetic field lines traced by synchrotron radiation at 30 GHz
https://www.cosmos.esa.int/web/planck/picture-gallery

CAST in the Sky





Hillas Plot



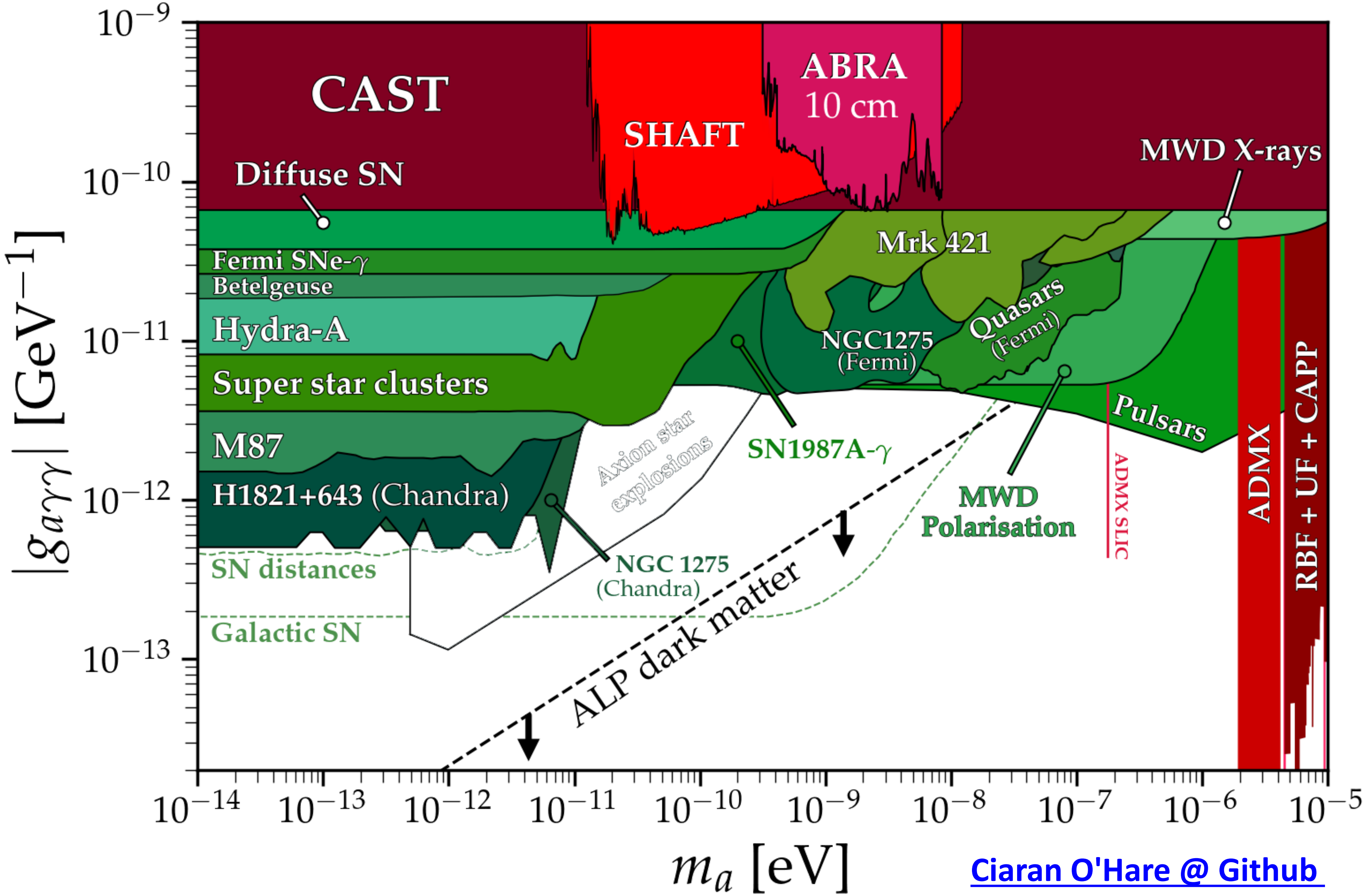
A. M. Hillas
Ann. Rev. Astron. Astrophys. 22, 425 (1984)

Size and B field strength of possible sites for particle acceleration. Objects below the line cannot accelerate protons to 10^{20} eV

ALP-γ conversion

$$\frac{g_{a\gamma}}{10^{12}\mathrm{GeV}} BL \sim 1$$

ALP Scape – High-Energy Closeup



[Ciaran O'Hare @ Github]()

ALP Constraints from Cosmic Distance Measurements

Manuel A. Buen-Abad, JiJi Fan, Chen Sun, arXiv:2011.05993

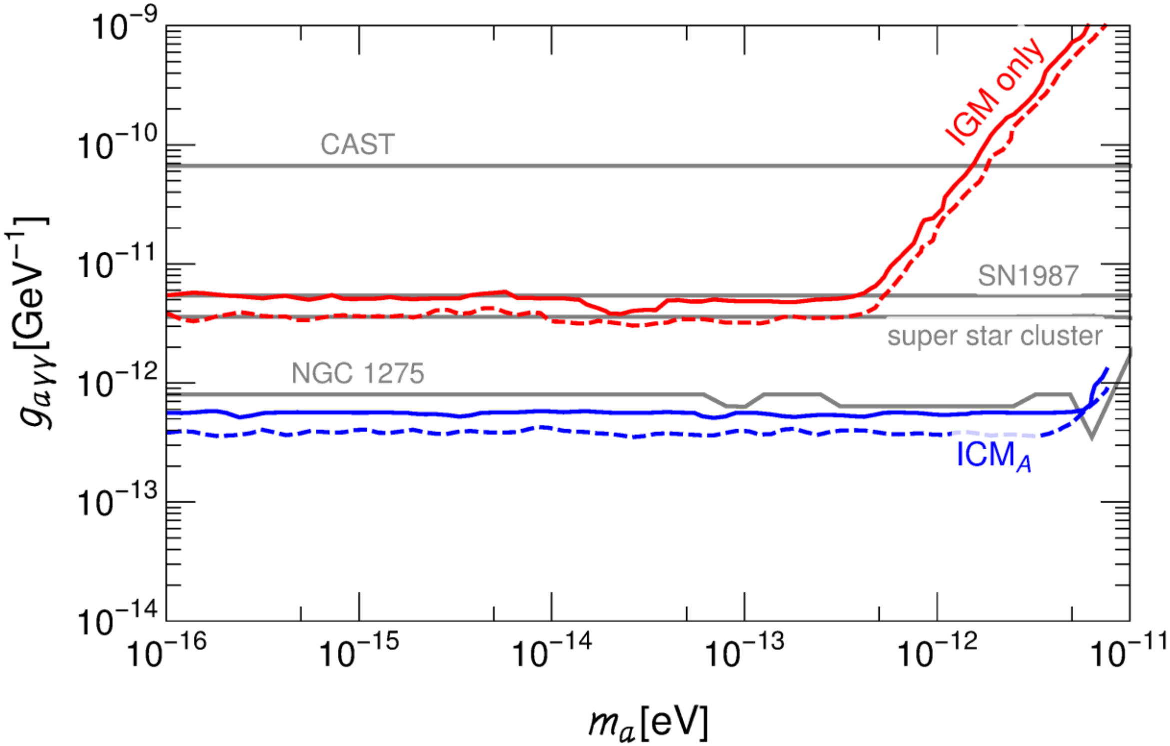
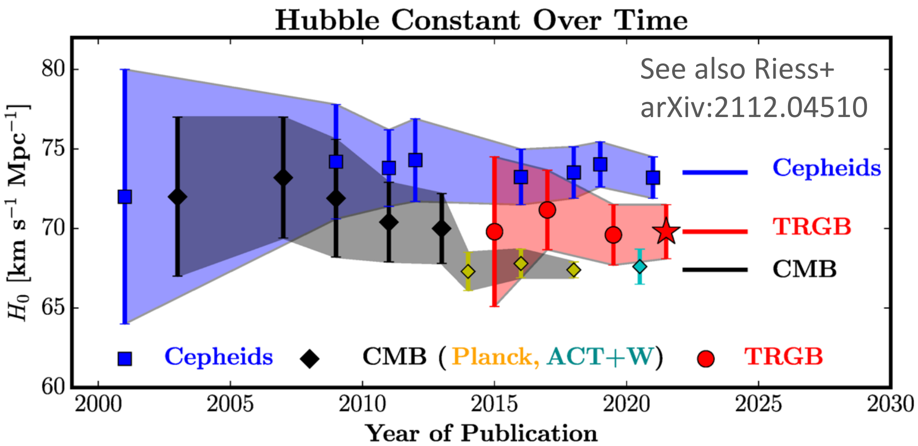
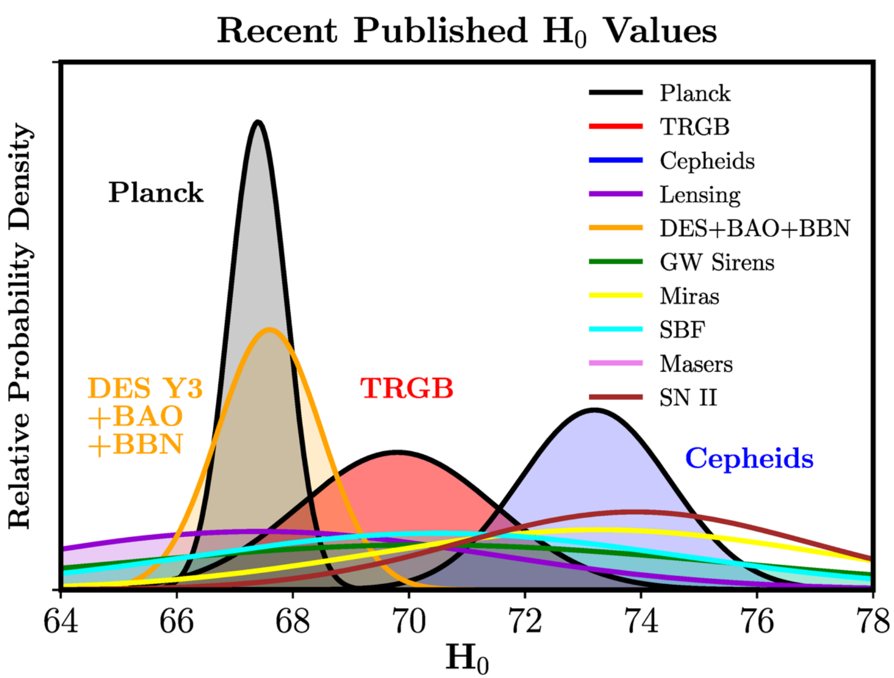


Figure 5. 95% C.L. upper limits on $g_{a\gamma\gamma}$ as a function of m_a. The solid curves are from $\mathcal{L}_{\rm late}$ while the dashed curves are from $\mathcal{L}_{\rm early}$, assuming $B_{\rm IGM} = 1$ nG and $s_{\rm IGM} = 1$ Mpc. To avoid clumsiness, we only show the upper limits from either assuming no ICM conversion effects on the galaxy cluster data (top red curves) or assuming model A in Eq. (2.10) for the effect (lower blue curves). The upper limits for model B and C in Eqs. (2.11) and (2.12) are in between them. We also show several existing bounds (grey lines) for comparison: CAST [72]; SN1987a [63]; X-ray searches from super star cluster [74] and X-ray spectroscopy from AGN NGC 1275 [57].

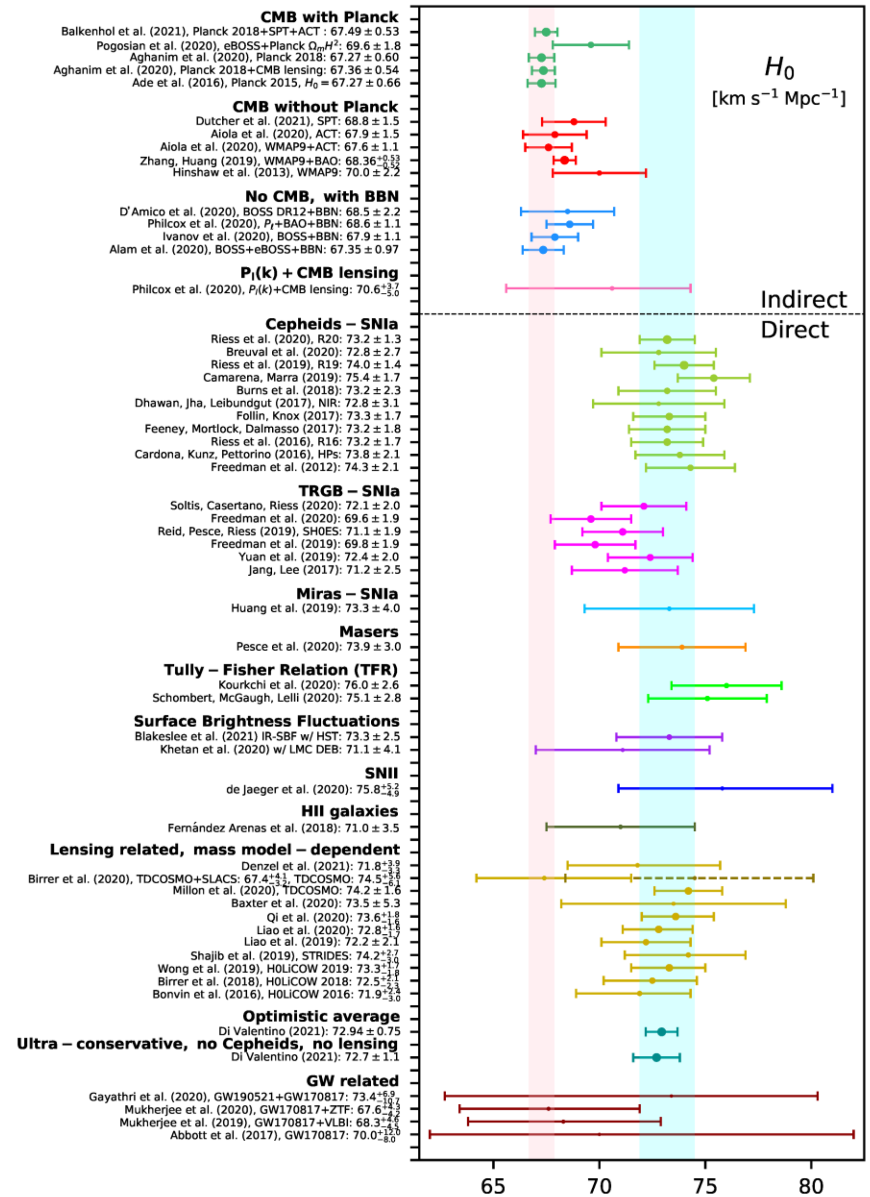
Avoid excessive dimming of distant sources by photon-ALP conversion

Hubble Tension





Freedman ApJ 919 (2021) 16 [2106.15656]



Di Valentino+ arXiv:2103.01183

Solving Hubble Tension with ALPs?

- Twenty years ago:
  Dimming of distant SNe Ia by ALP-photon conversion
  to avoid cosmic acceleration
  Csáki, Kaloper & Terning (2001), arXiv:hep-ph/0111311
  (but difficult to make consistent)

- Today:
  Brightening of distant SNe Ia by ALP-photon conversion
  to avoid Hubble tension

  - Impossible with simple models
  - Need to emit as many ALPs as photons from source

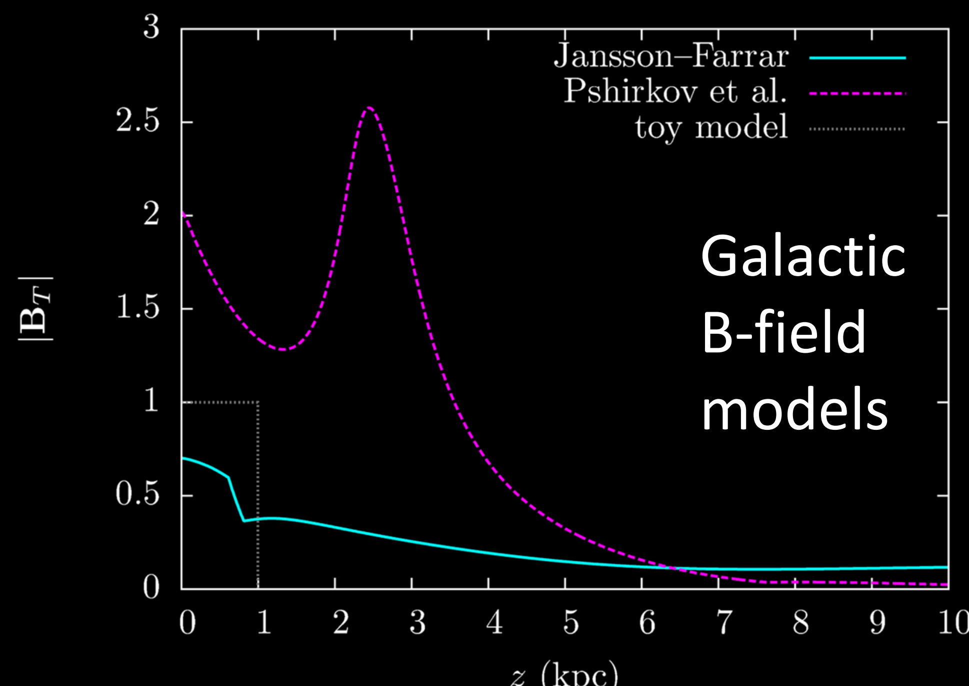
In summary, to have axions brighten SNIa, we need resonant conversions inside or near SN in order to generate an initial axion flux as large as the initial photon flux. We also need more axions converting into photons in the IGM rather than the other way around. Yet as we show above by considering some simple necessary conditions for the scenario to work, the two requirements mentioned point towards very different axion mass ranges.

Manuel A. Buen-Abad, JiJi Fan, Chen Sun, Appendix of arXiv:2011.05993

Axion-Photon-Conversion from SN 1987A

Axion-photon conversion
in transverse galactic B-field

Primakoff
production
in SN core

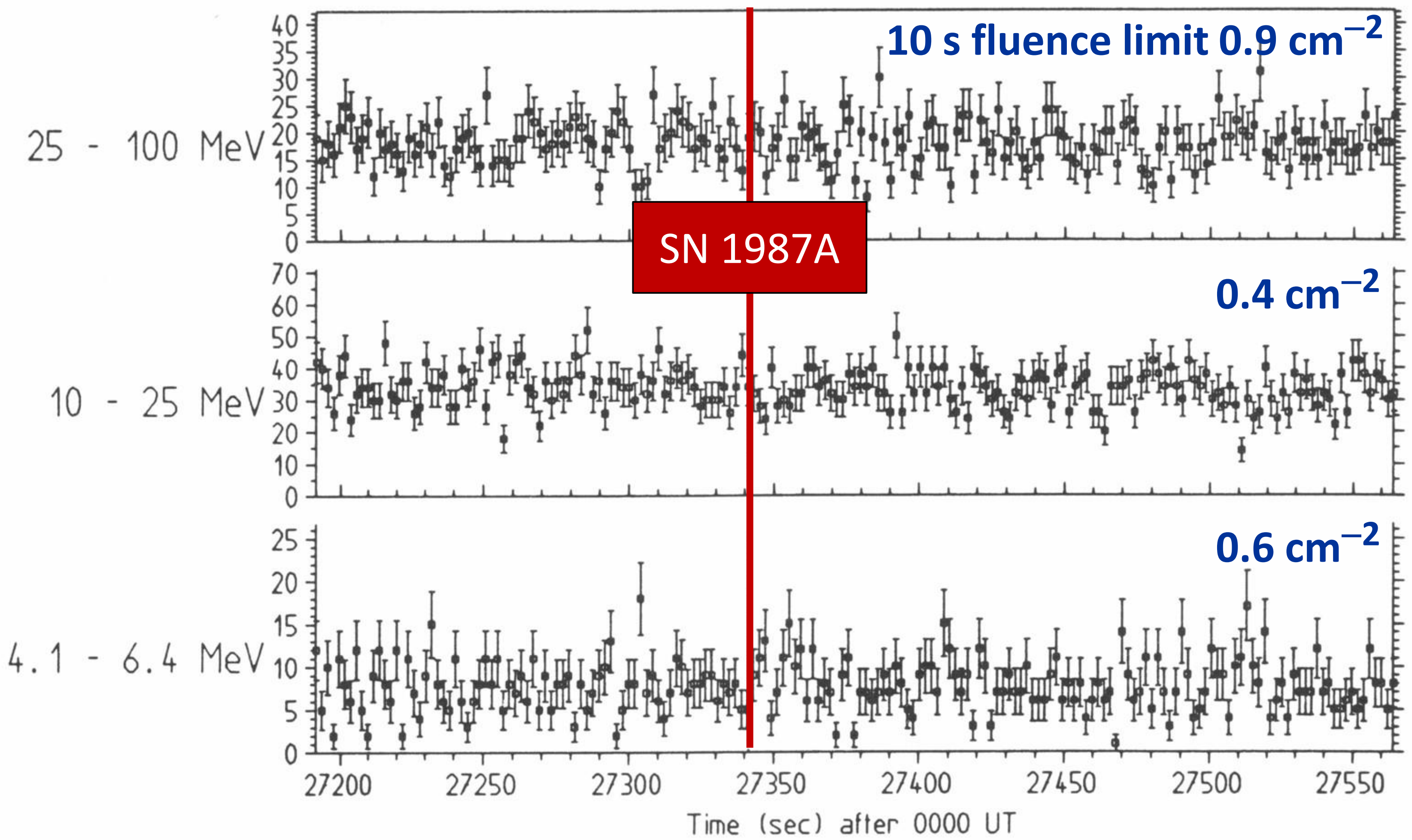


No excess γ rays
in coincidence
with SN 1987A

Payez, Evoli, Fischer, Giannotti, Mirizzi & Ringwald, arXiv:1410.3747

Gamma-Ray Observations of SMM Satellite

Counts in the GRS instrument on the Solar Maximum Mission Satellite

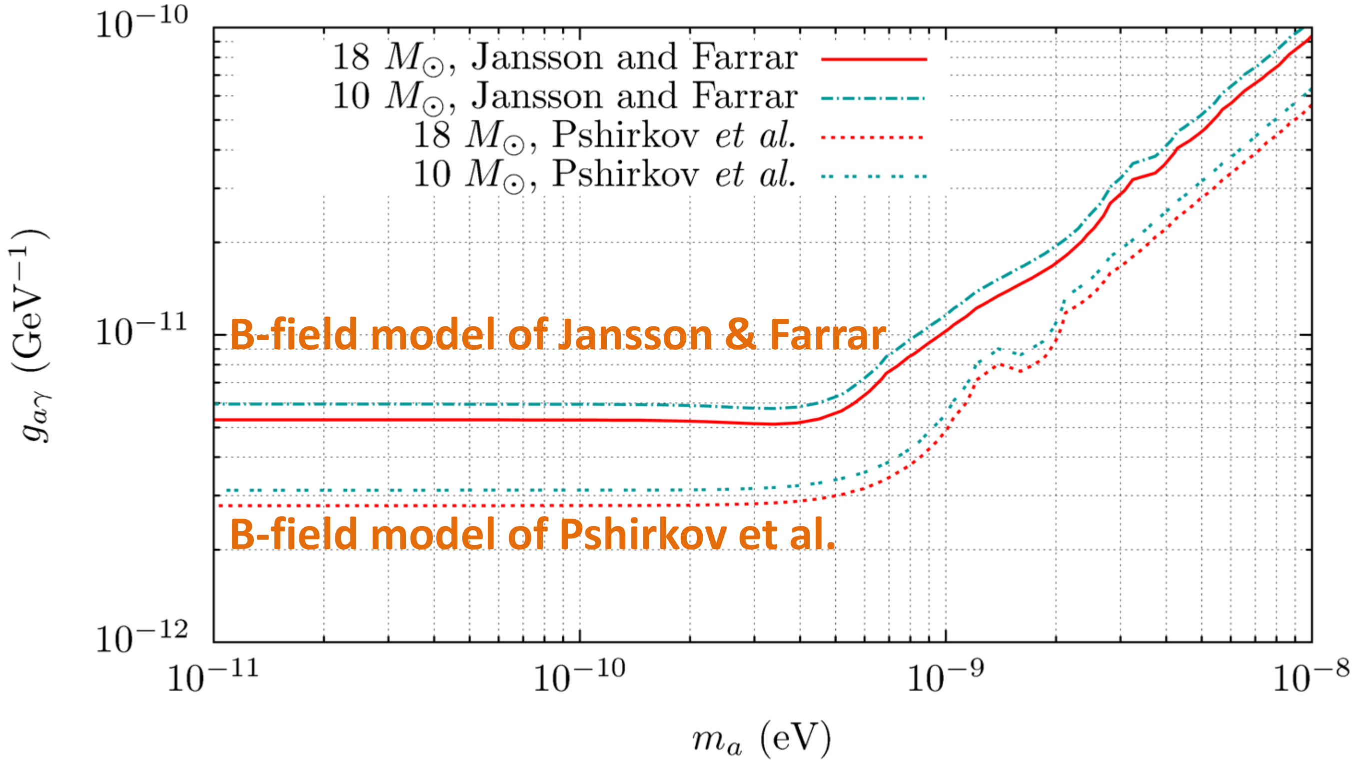


SN 1987A neutrino fluence $\sim 10^{10}\,\mathrm{cm}^{-2}$

$< 10^{-10}$ of neutrinos have decayed to photons on their way to Earth

SN 1987A Limits from Axion-Photon Conversion

- Primakoff production in SN core, several numerical models (fairly insensitive)
- Propagation in galactic B-field (main uncertainty)
- Non-detection of excess gamma rays in SMM satellite coincident with SN 1987A

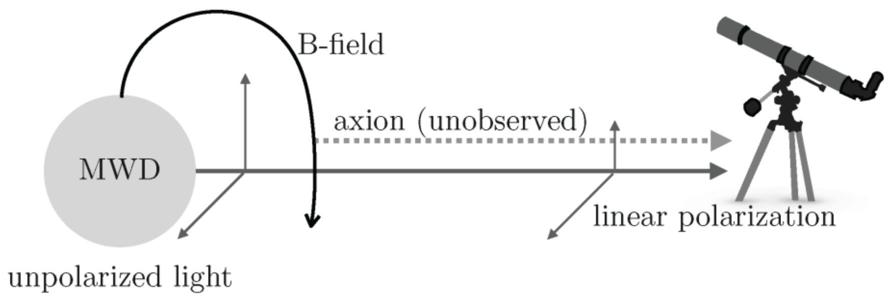


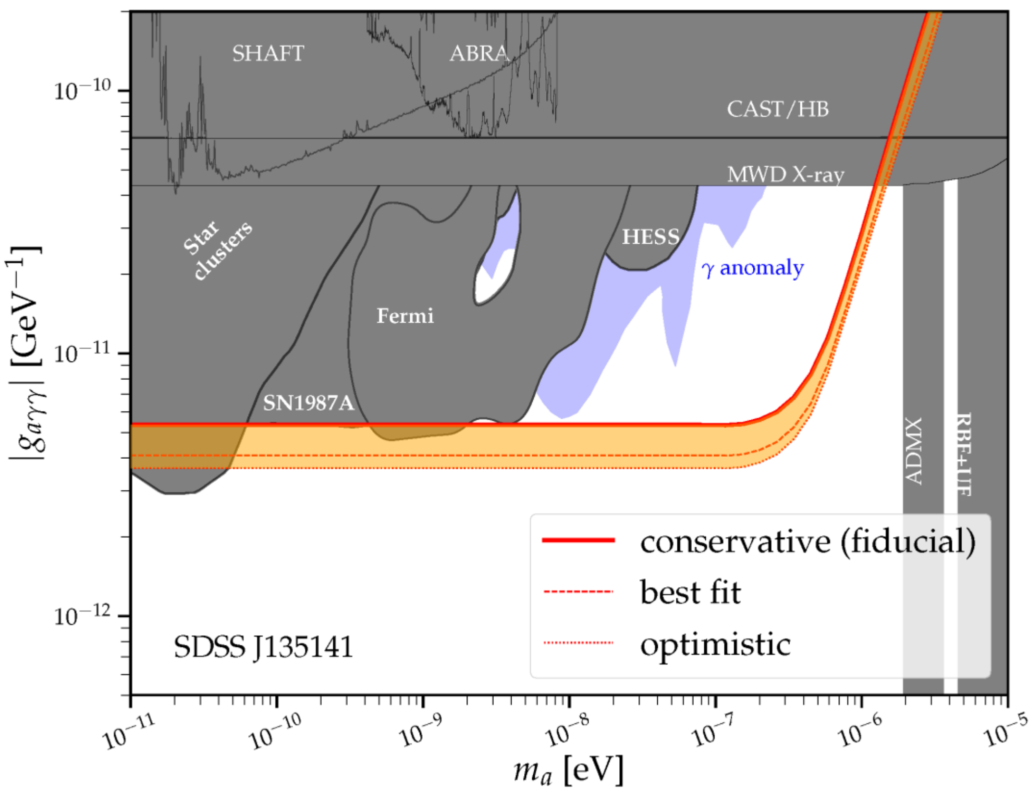
Payez, Evoli, Fischer, Giannotti, Mirizzi & Ringwald: arXiv:1410.3747

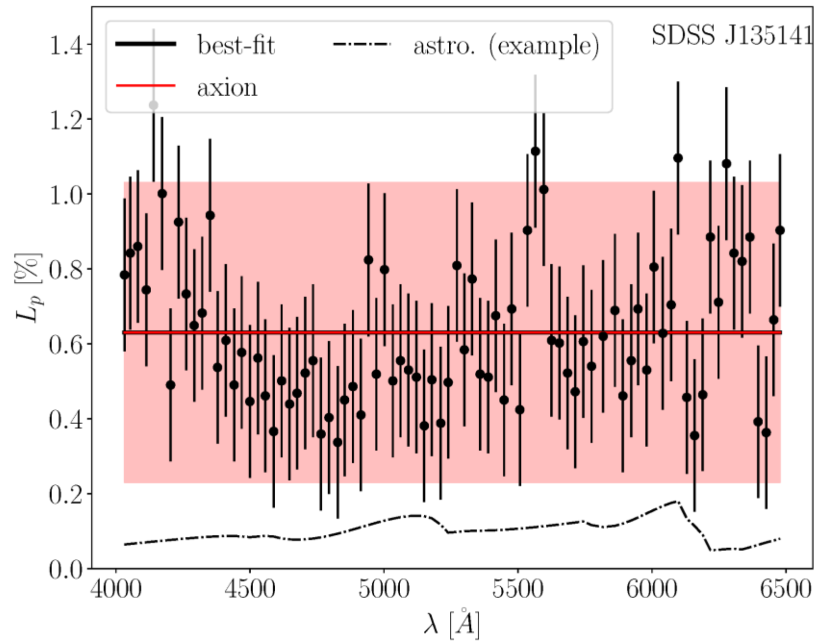
More recent analysis: Hoof & Schulz arXiv:2212.09764

Upper limit on the axion-photon coupling from magnetic white dwarf polarization

Christopher Dessert,[1,2,3] David Dunsky,[1,2] and Benjamin R. Safdi[1,2] arXiv:2203.04319

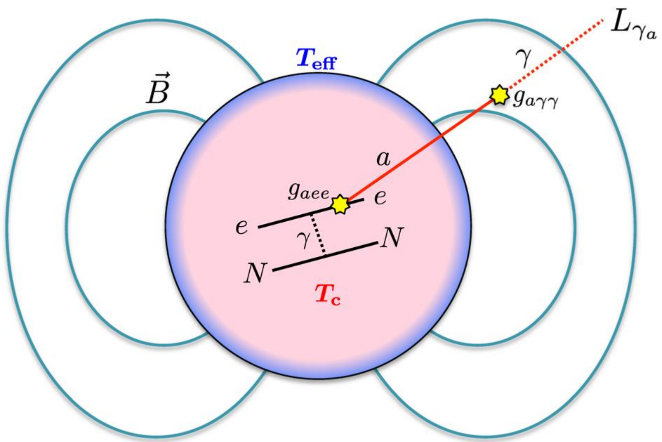


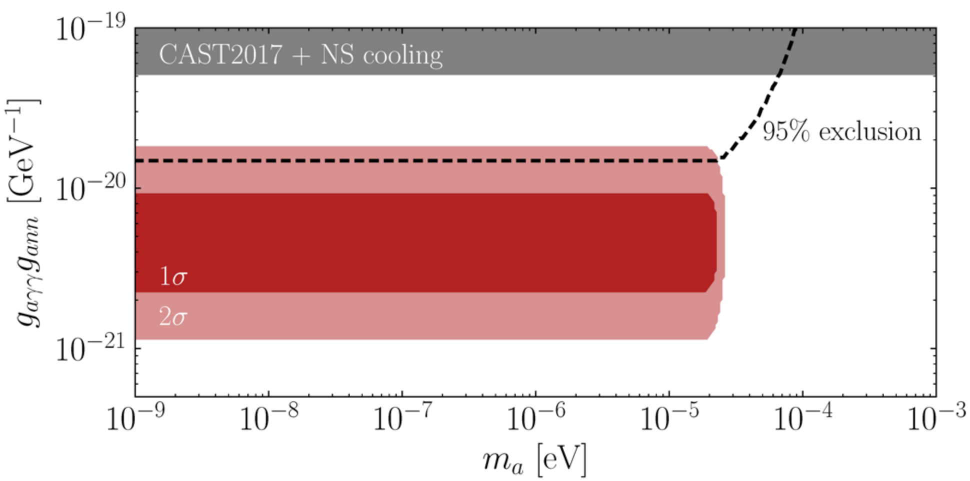




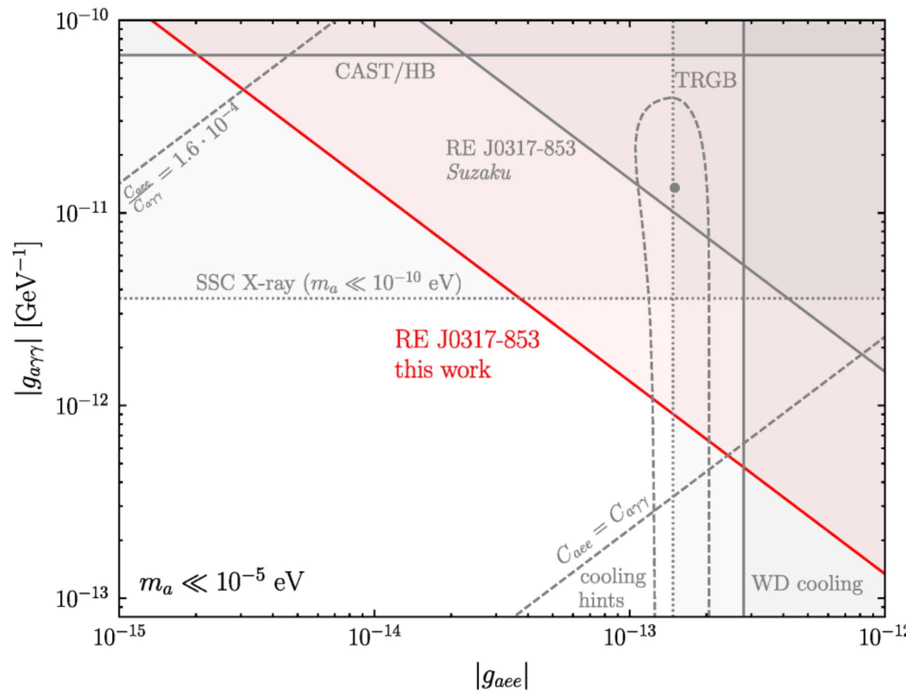
Measured polarization of MWD SDSS J135141

Axion Bounds from Magnetic WDs and NSs





Magnetic White Dwarf



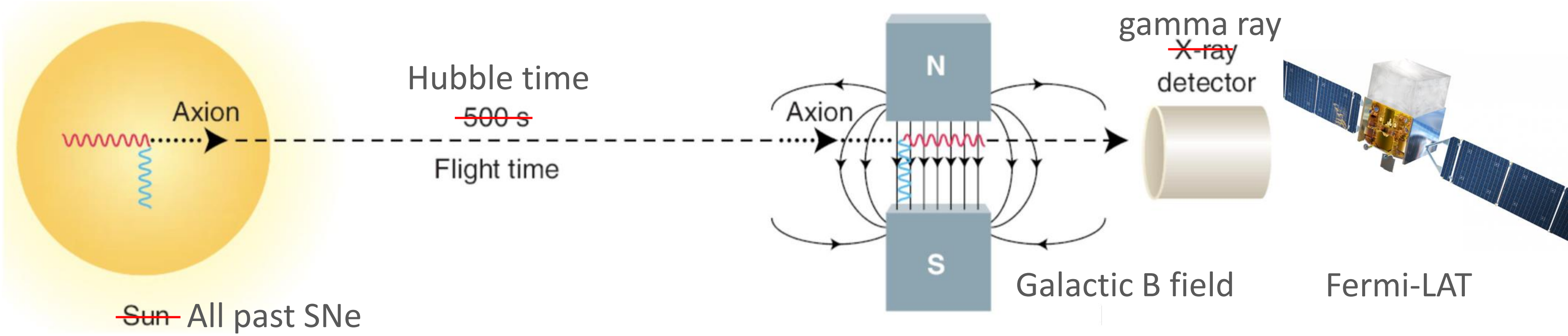
Magnificent Seven Neutron Stars
X-Ray limits and excess

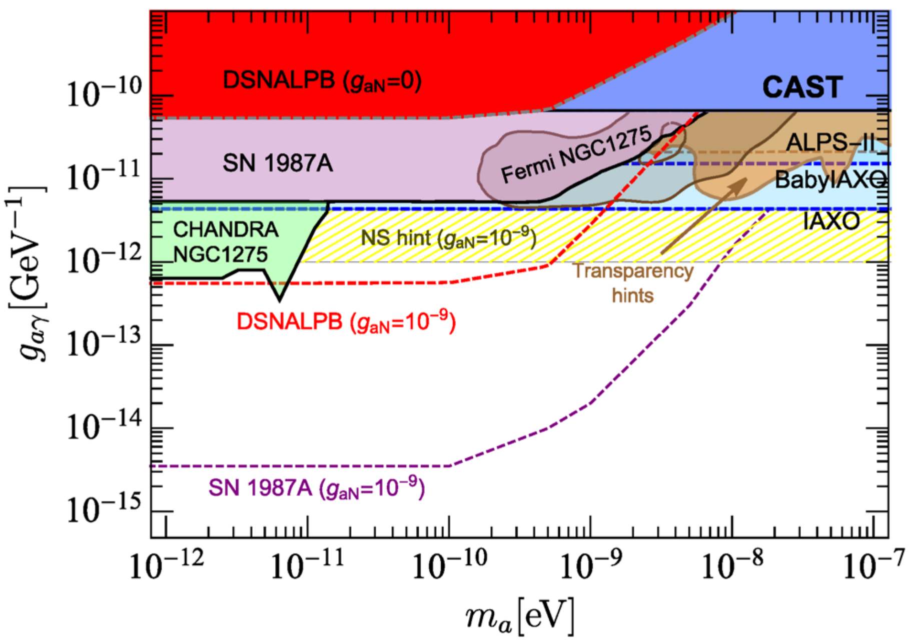
- Axion Emission Can Explain a New Hard X-ray Excess from Nearby Isolated Neutron Stars, Buschmann, Co, Dessert & Safdi, arXiv:1910.04164
- No Evidence for Axions from Chandra Observation of the Magnetic White Dwarf RE J0317-853 Dessert, Long & Safdi, arXiv:2104.12772

PHYSICAL REVIEW D **102**, 123005 (2020) arXiv:2008.11741
2110.03679

Bounds on axionlike particles from the diffuse supernova flux

Francesca Calore,[1,*] Pierluca Carenza,[2,3,†] Maurizio Giannotti,[4,‡] Joerg Jaeckel,[5,§] and Alessandro Mirizzi[2,3,‖]





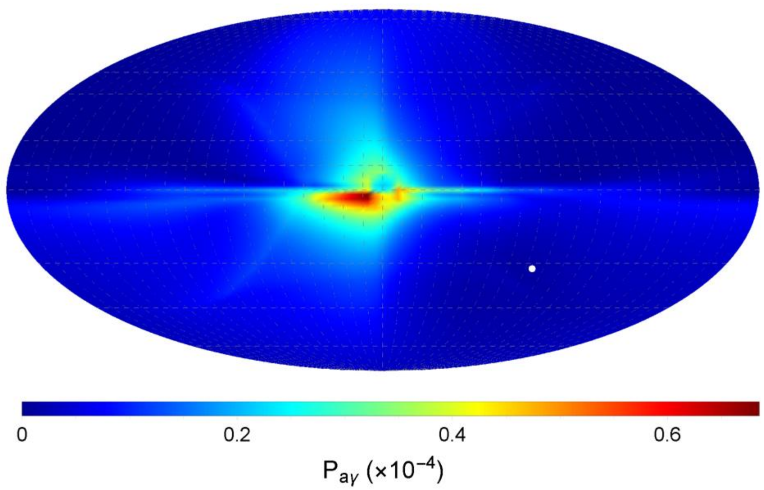


FIG. 3. Sky map in Galactic coordinates of the $a \to \gamma$ conversion probability, starting from a pure ALPs beam at the outside boundary of the Galaxy, for the Jansson and Farrar magnetic field model derived in [36]. We have taken the energy to be $E = 50$ MeV, the coupling $g_{a\gamma} = 3 \times 10^{-13}\mathrm{GeV}^{-1}$

Shining TeV Gamma Rays through the Universe

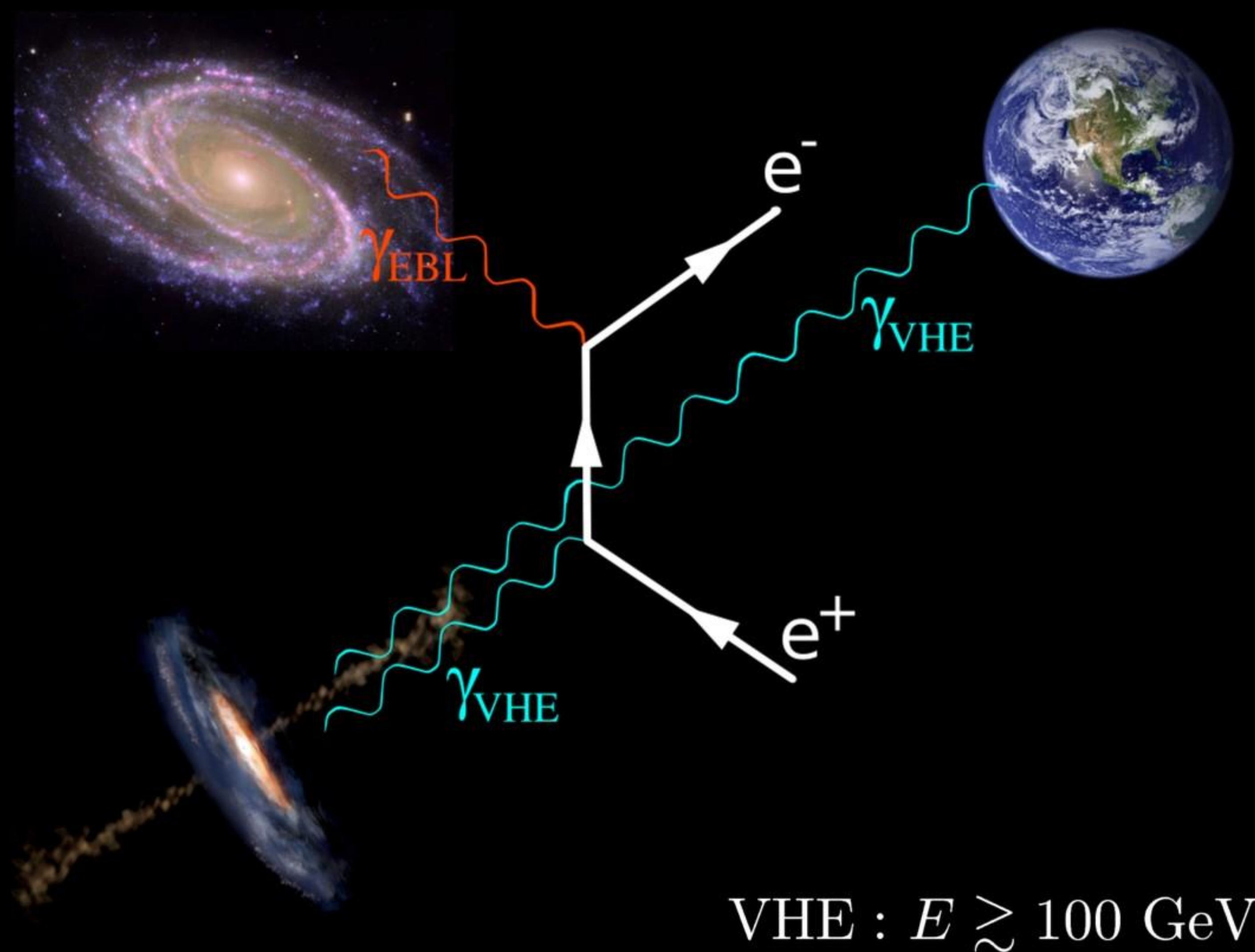


Figure from a talk by Manuel Meyer (Univ. Hamburg)

Shining TeV Gamma Rays through the Universe

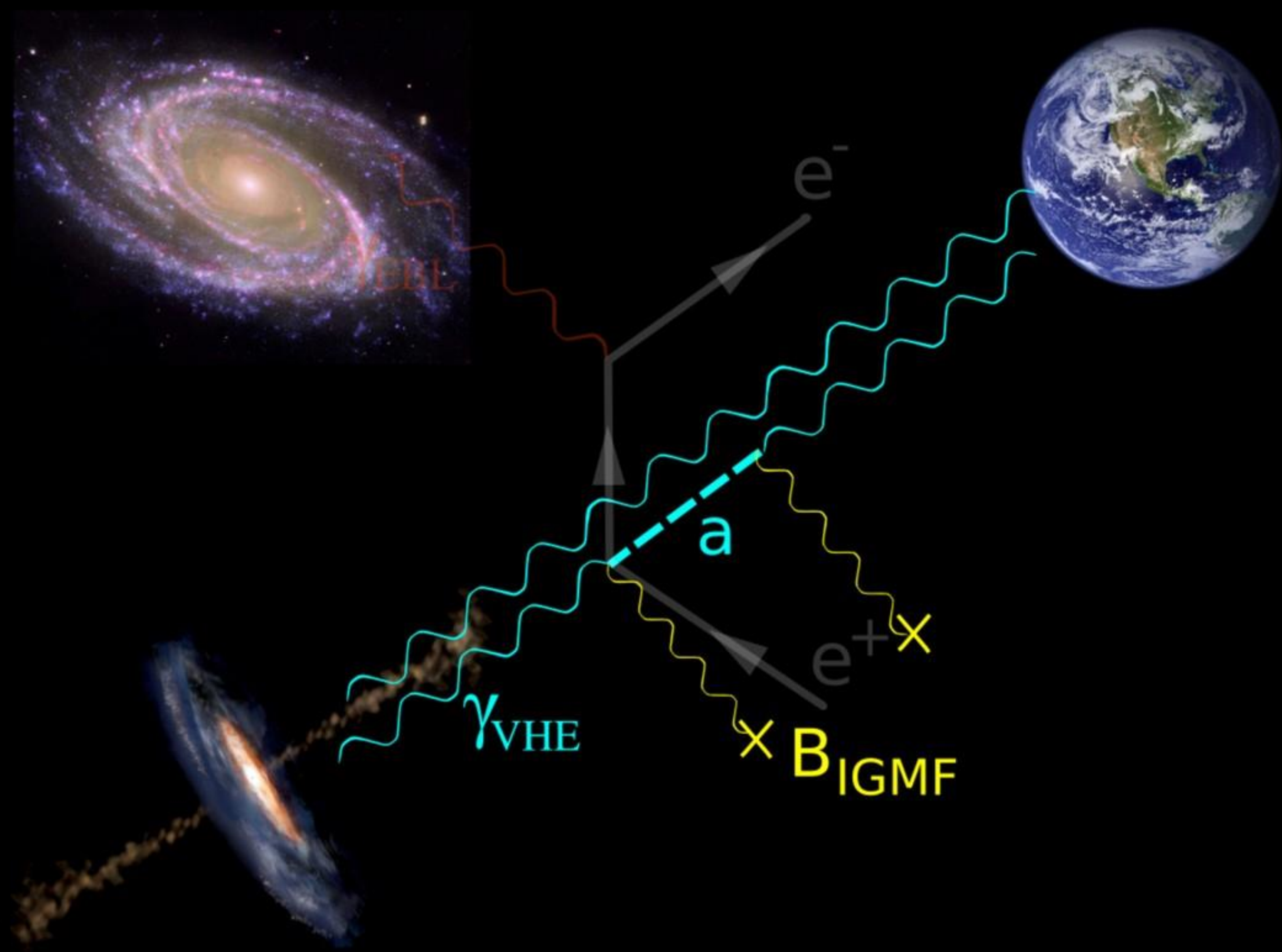
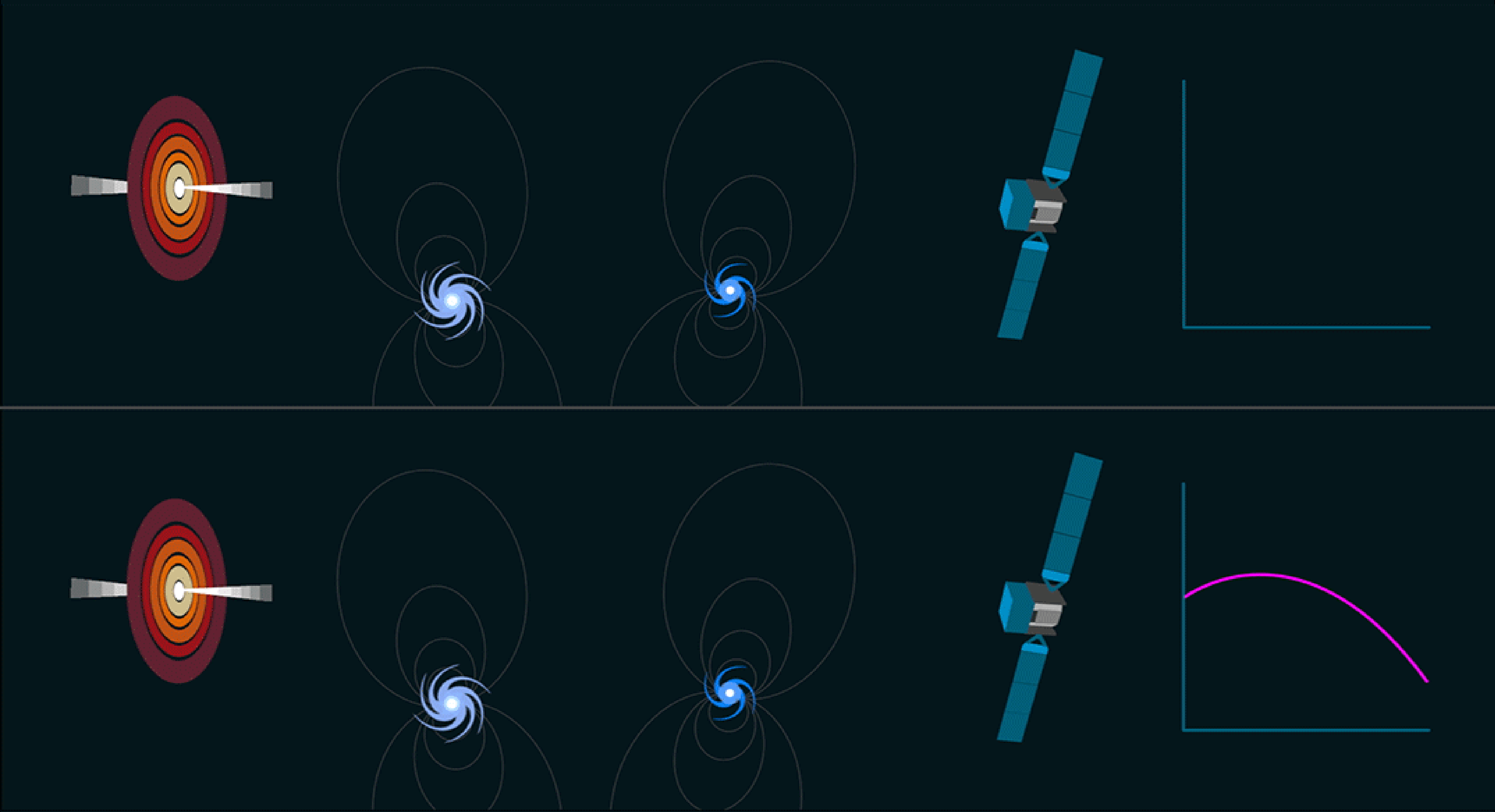


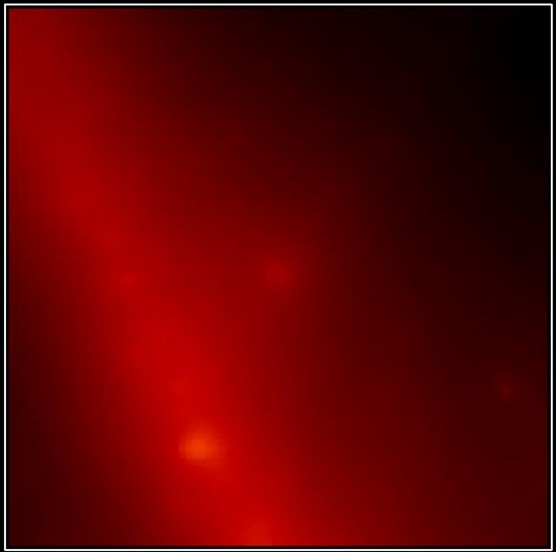
Figure from a talk by Manuel Meyer (Univ. Hamburg)

Gamma-ALP Conversion in Astrophysical B-Fields

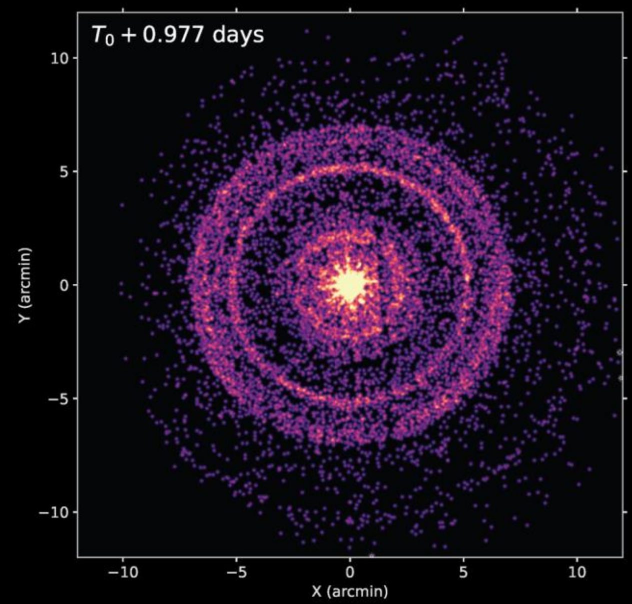


Credit: SLAC National Accelerator Laboratory/Chris Smith
https://www.nasa.gov/sites/default/files/thumbnails/image/alp_2_sequences.gif

GRB 221009A (BOAT – Brightest Of All Times)



Ten-hour timelapse of Fermi Gamma-Ray Space Telescope



X-ray afterglow (Swift) arXiv:2302.03642

LHAASO
Large High-Altitude Air-Shower Observatory
5000 photons in 2000 sec
0.5 < E < 18 TeV
1 event at 18 TeV (±40%)

Paper submitted
Not yet publicly available

Redshift z = 0.151
Optical depth for 18 TeV photon 9.4–27.1
depending on EBL modeling

ALP-photon interpretation

Galanti+	arXiv:2210.05659
Baktash+	arXiv:2210.07172
Troitsky	arXiv:2210.09250
Nakagawa+	arXiv:2210.10022
Zhang+	arXiv:2210.13120
Carenza+	arXiv:2211.02010

GRB 221009A – ALP-Boosting 18 TeV Photon

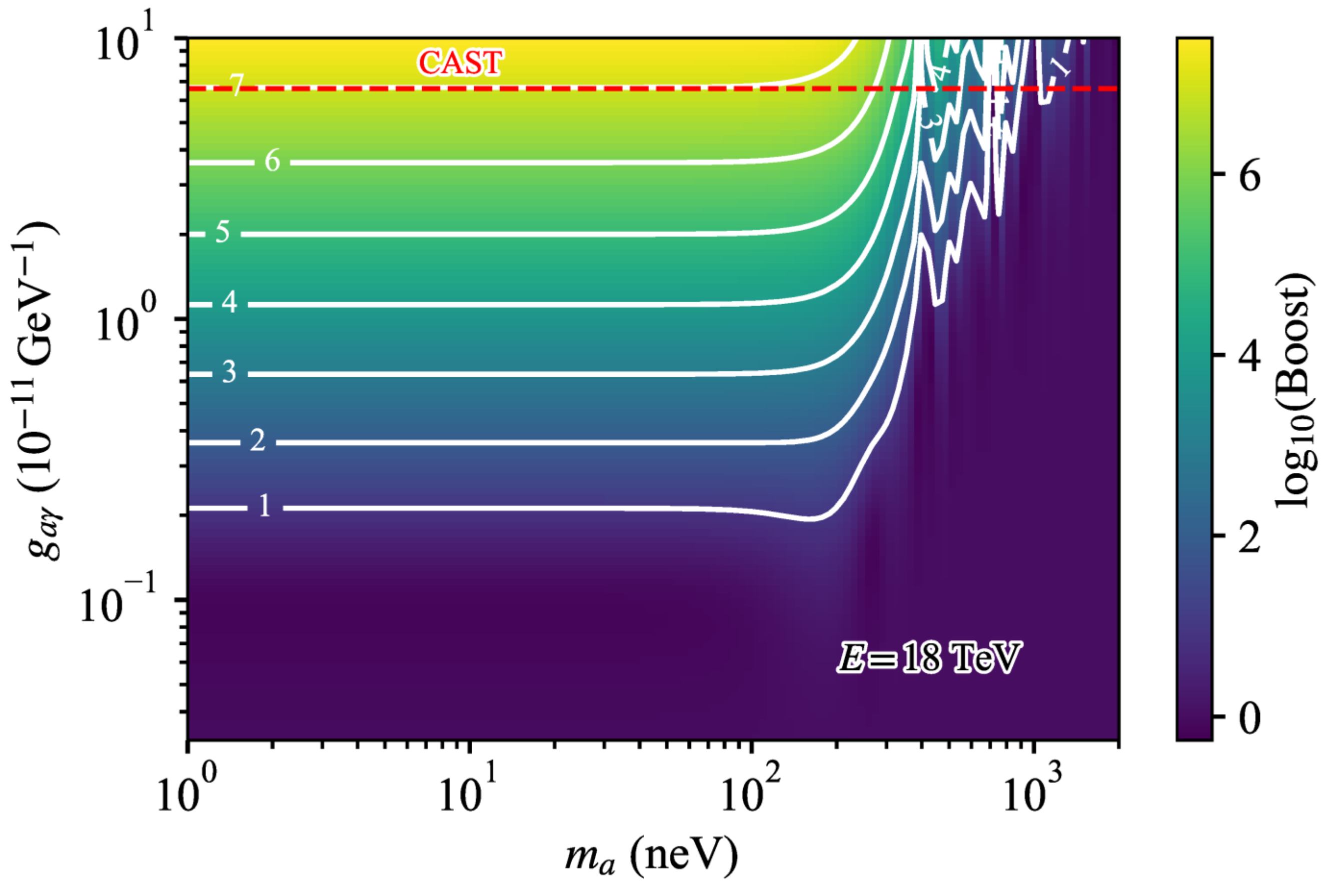
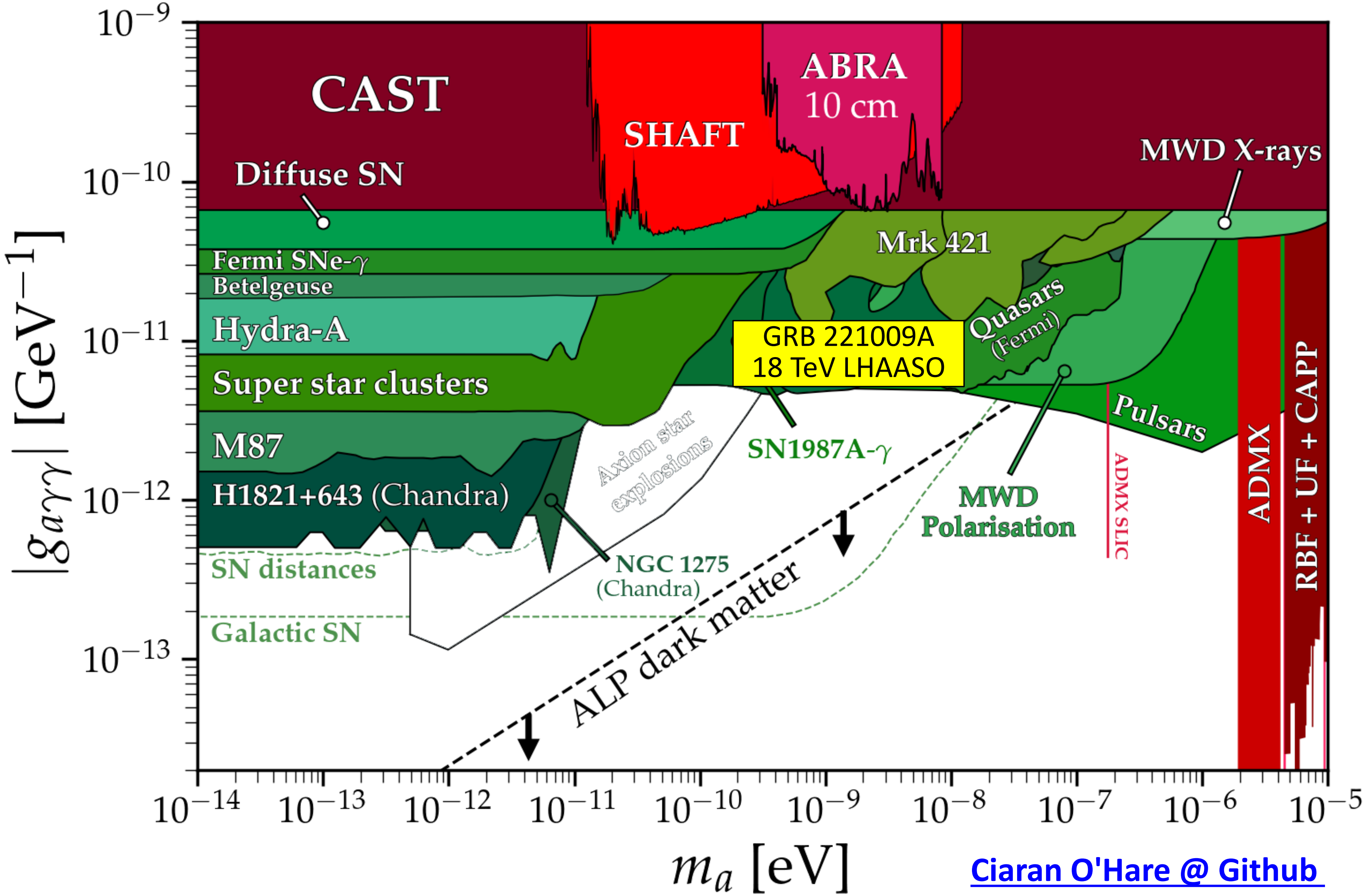


Figure 3. The logarithm of the boost factor of the photon flux over a grid of ALP parameters at $E_\gamma = 18\,\mathrm{TeV}$. The Do2011 EBL model is assumed. Parameters above the red dashed line are excluded by CAST.

Baktash, Horns & Meyer, Interpretation of multi-TeV photons from GRB221009A, arXiv:2210.07172

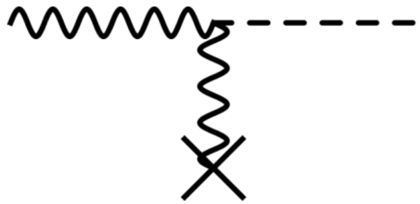
ALP Scape – High-Energy Closeup



[Ciaran O'Hare @ Github]

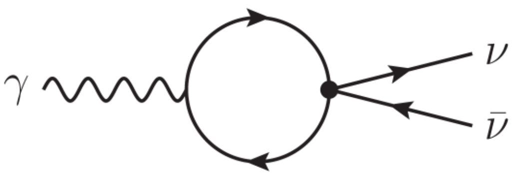
Particle Dispersion and Correlation

Reaction and Dispersion Modifications in Media



Coulomb processes become finite

- Axion Primakoff production
- Dipole-induced nu scattering
- Nuclear burning

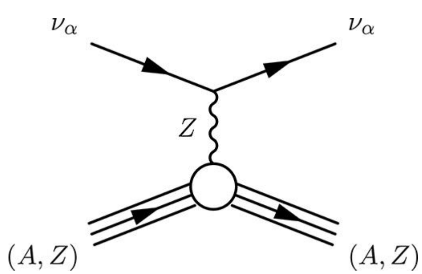


Modified kinematics and/or couplings

- Plasmon decay
- $\nu \to \overline{\nu} + \text{Majoron}$
- Neutrino flavor conversion
- Collective nu conversion

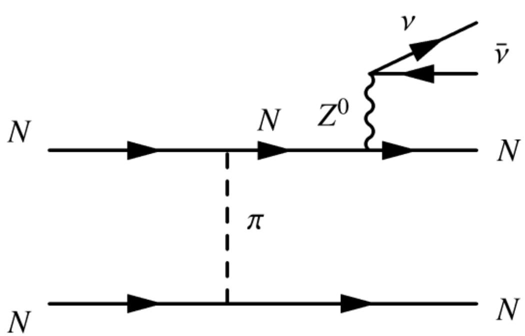
Particle mixing

- Resonant hidden γ production



Coherence in scattering

- Nu trapping in SNe
- CENNS in reactor experiments
- DM and nu detection
- Screening effects



Large modifications of nuclear processes in SNe and NSs

- Nuclear Equation of State
- Neutrino and axion processes
- Pions: Abundance and role
- Meson condensates, Hyperons

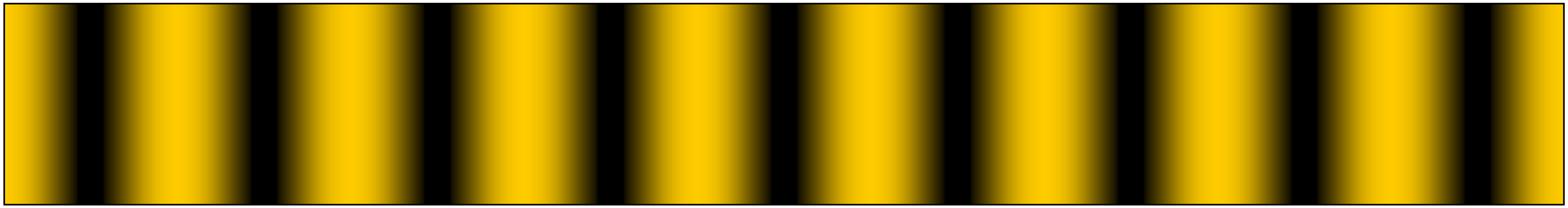
Particle Dispersion in Media

Vacuum	Most general Lorentz-invariant dispersion relation $\omega^2 - k^2 = m^2$ ω = frequency, k = wave number, m = mass Gauge invariance implies $m = 0$ for photons and gravitons
Medium	Particle interaction with medium breaks Lorentz invariance so that $\omega^2 - k^2 = \pi(\omega, k)$ Implies a relationship between ω and k (dispersion relation) Often written in terms of • Refractive index n $k = n\,\omega$ • Effective mass (note that $m_{\rm eff}^2$ can be negative, "tachyonic" case) $\omega^2 - k^2 = m_{\rm eff}^2$ • Effective potential (natural for neutrinos with m the vacuum mass) $(\omega - V)^2 - k^2 = m^2$ Which form to use depends on convenience

Refraction and Forward Scattering

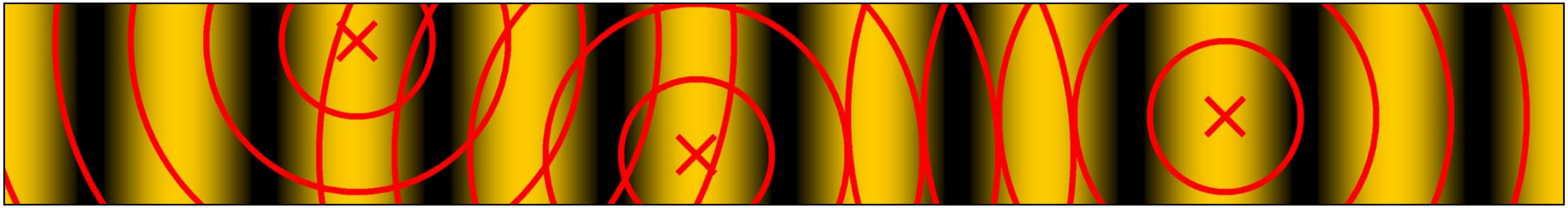
Plane wave in vacuum

$$\Phi(\boldsymbol{r},t) \propto e^{-i\omega t+i\boldsymbol{k}\cdot\boldsymbol{r}}$$



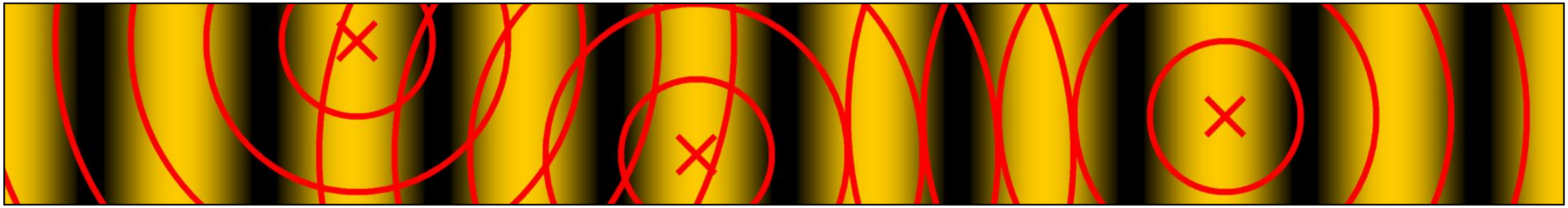
Refraction and Forward Scattering

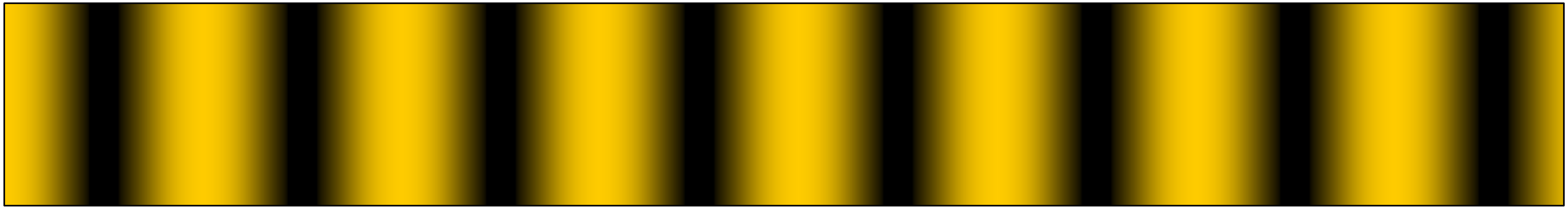
Plane wave in vacuum	$\Phi(\boldsymbol{r},t) \propto e^{-i\omega t+i\boldsymbol{k}\cdot\boldsymbol{r}}$
With scattering centers	$\Phi(\boldsymbol{r},t) \propto e^{-i\omega t}\left[e^{ik\cdot r} + f(\omega,\theta)\frac{e^{ik\cdot r}}{r}\right]$



Refraction and Forward Scattering

Plane wave in vacuum	$\Phi(\boldsymbol{r},t) \propto e^{-i\omega t + i\boldsymbol{k}\cdot\boldsymbol{r}}$
With scattering centers	$\Phi(\boldsymbol{r},t) \propto e^{-i\omega t}\left[e^{ik\cdot r} + f(\omega,\theta)\,\dfrac{e^{ik\cdot r}}{r}\right]$
In forward direction, adds coherently to a plane wave with modified wave number	$k = n_{\rm refr}\,\omega$ $n_{\rm refr} = 1 + \dfrac{2\pi}{\omega^2}\,N\,f(\omega,0)$ N = number density of scattering centers $f(\omega,0)$ = forward scattering amplitude





Photon Dispersion and Thomson Cross Section

- **Photon refractive index (non-relativistic plasma as in the Sun)**

$$n_{\rm refr} = 1 + \frac{2\pi}{\omega^2} n_e f_0(\omega)$$

- **Differential scattering cross section and scattering amplitude**

$$\frac{d\sigma}{d\Omega} = |f(\theta)|^2$$

- **Thomson scattering**

$$\left.\frac{d\sigma}{d\Omega}\right|_0 = \frac{\alpha^2}{m_e^2} = |f_0|^2$$

- **Up to a sign follows**

$$n_{\rm refr} = 1 - \frac{2\pi\alpha}{\omega^2 m_e} n_e = \frac{k}{\omega} = \frac{\sqrt{\omega^2 - m_\gamma^2}}{\omega} \simeq 1 - \frac{m_\gamma^2}{2\omega^2}$$

$$m_\gamma^2 = \frac{4\pi\alpha}{m_e} n_e = \omega_{\rm p}^2 \text{ Plasma frequency}$$

Electromagnetic Polarization Tensor

Klein-Gordon-Equation in Fourier space

$$(-K^2 g^{\mu\nu} + K^\mu K^\nu + \Pi^{\mu\nu})A_\nu = 0$$

Polarization tensor (self-energy of photon)

Gauge invariance and current conservation

$$\Pi^{\mu\nu}K_\mu = \Pi^{\mu\nu}K_\nu = 0$$

Vacuum: $\Pi^{\mu\nu} = a g^{\mu\nu} + b K^\mu K^\nu$
$\rightarrow a = b = 0$ (photon massless)

Medium: Four-velocity U available to construct Π

QED Plasma

$$\Pi^{\mu\nu}(K) =$$

$$16\pi\alpha \int \frac{d^3\boldsymbol{p}}{2E(2\pi)^3} f_e(\boldsymbol{p}) \frac{(PK)^2 g^{\mu\nu} + K^2 P^\mu K^\nu - PK(P^\mu K^\nu + K^\mu P^\nu)}{(PK)^2 - \frac{1}{4}(K^2)^2}$$

Photon: $K = (\omega, \boldsymbol{k})$ Electron/positron: $P = (E, \boldsymbol{p})$ with $E = \sqrt{\boldsymbol{p}^2 + m_e^2}$

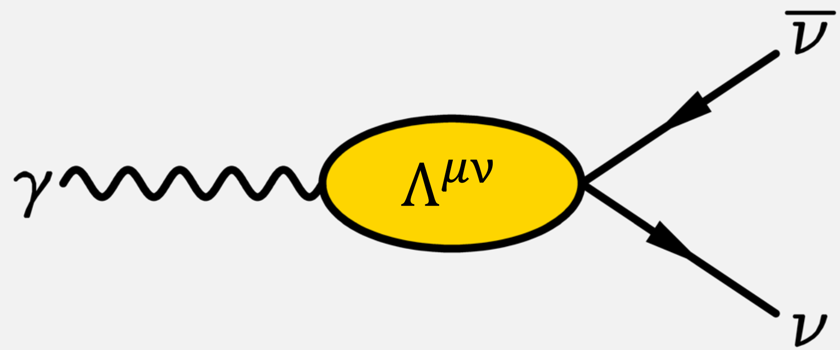
Electron/positron phase-space distribution with chemical potenial μ_e

$$f_e(\boldsymbol{p}) = \frac{1}{e^{\frac{E-\mu_e}{T}} + 1} + \frac{1}{e^{\frac{E+\mu_e}{T}} + 1}$$

Neutrino-Photon-Coupling in a Plasma

Neutrino effective in-medium coupling

$$L_{\rm eff} = -\sqrt{2} G_{\rm F} \overline{\Psi} \gamma_\alpha \frac{1}{2}(1-\gamma_5)\Psi \Lambda^{\alpha\beta} A_\beta$$



For vector current it is analogous
to photon polarization tensor

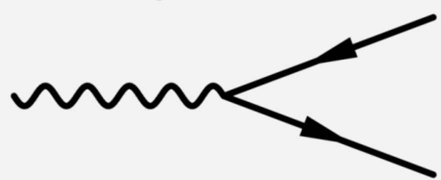
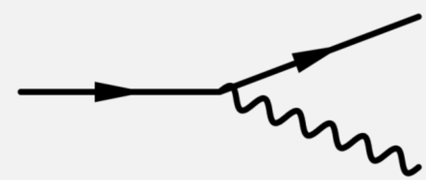
$$\Lambda_{\rm V}^{\mu\nu}(K) = 4eC_{\rm V}\int \frac{d^3\mathbf{p}}{2E(2\pi)^3}[f_e(\mathbf{p})+f_{\overline{e}}(\mathbf{p})]\,\frac{(PK)^2 g^{\mu\nu} + K^2 P^\mu P^\nu - PK(P^\mu K^\nu + K^\mu P^\nu)}{(PK)^2 - \frac{1}{4}(K^2)^2}$$

$$= \frac{C_{\rm V}}{e}\,\Pi_{\rm V}^{\mu\nu}(K)$$

$$\Lambda_{\rm A}^{\mu\nu}(K) = 2ieC_{\rm A}\epsilon^{\mu\nu\alpha\beta}\int \frac{d^3\mathbf{p}}{2E(2\pi)^3}[f_e(\mathbf{p})-f_{\overline{e}}(\mathbf{p})]\,\frac{K^2 P_\alpha K_\beta}{(PK)^2 - \frac{1}{4}(K^2)^2}$$

Usually negligible

Plasmon Decay vs. Cherenkov Effect

Photon dispersion in a medium can be	"Time-like" $\omega^2 - k^2 > 0$	"Space-like" $\omega^2 - k^2 < 0$
Refractive index n ($k = n\,\omega$)	$n < 1$	$n > 1$
Example	• Ionized plasma • Normal matter for large photon energies	Water ($n \approx 1.3$), air, glass for visible frequencies
Allowed process that is forbidden in vacuum	Plasmon decay to neutrinos $\gamma \to \nu\bar{\nu}$ 	Cherenkov effect $e \to e + \gamma$ 

Neutrinos from Thermal Processes

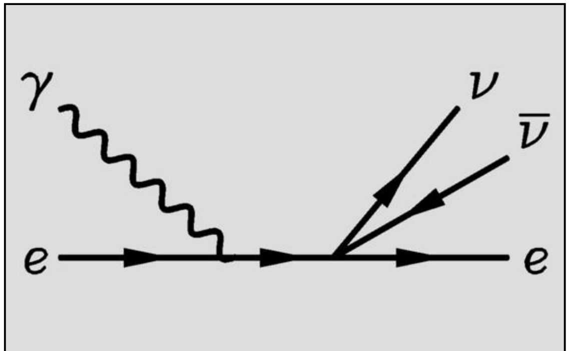
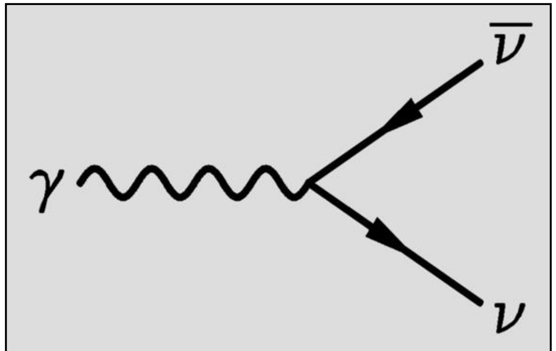
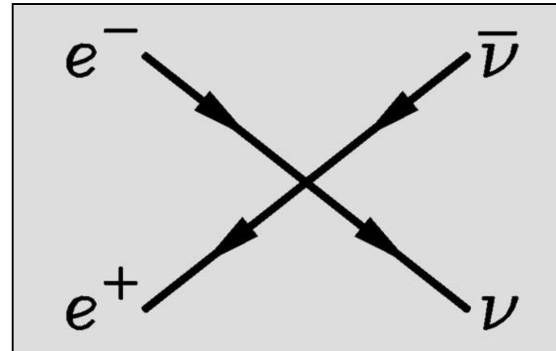


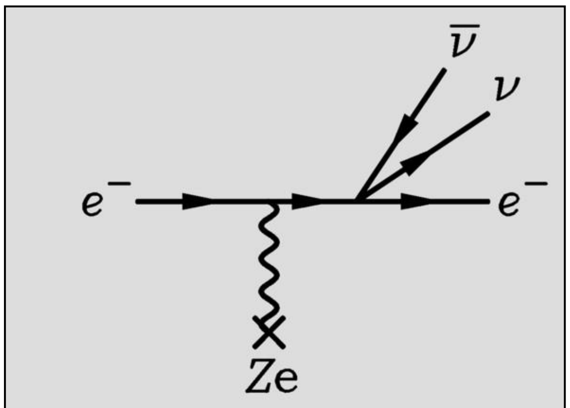
Photo (Compton)



Plasmon decay

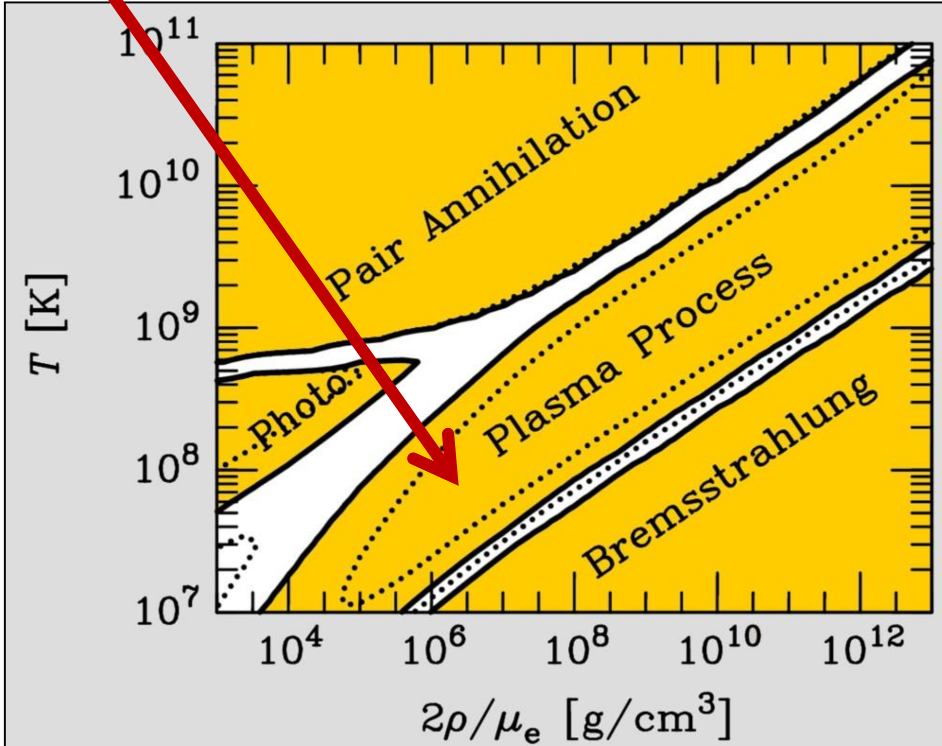


Pair annihilation



Bremsstrahlung

These processes were first discussed in 1961–63 after V–A theory



Plasmon Decay and Stellar Energy Loss Rates

Photon dispersion relation like a massive particle (nonrelativistic plasma)

$$E_\gamma^2 - p_\gamma^2 = \omega_{\rm p}^2 = \frac{4\pi\alpha n_e}{m_e}$$

Photon decay rate (transverse plasmon) with energy E_γ

$$\Gamma(\gamma\to\nu\bar\nu) = \frac{4\pi}{3E_\gamma}\times\begin{cases} \alpha_\nu\,(\omega_{\rm p}^2/4\pi) & \text{Millicharge}\\ (\mu_\nu^2/2)\,(\omega_{\rm p}^2/4\pi)^2 & \text{Dipole moment}\\ (C_{\rm V}^2G_{\rm F}^2/\alpha)\,(\omega_{\rm p}^2/4\pi)^3 & \text{Standard model}\end{cases}$$

$C_{\rm V}^2 = \pm\frac{1}{2} + \sin^2\Theta_W \approx 0.93\ (\nu_e)$ or $0.012\ (\nu_{\mu,\tau})$

Summed over flavors: $C_{\rm V}^2 \approx 1$

Energy-loss rate of stellar plasma

$$Q(\gamma\to\nu\bar\nu) = \int\frac{2d^3\mathbf{p}}{(2\pi)^3}\frac{E_\gamma\Gamma_{\gamma\to\nu\bar\nu}}{e^{E_\gamma/T}-1} = \frac{8\zeta_3T^3}{3\pi}\times\begin{cases} \alpha_\nu\,(\omega_{\rm p}^2/4\pi)\\ (\mu_\nu^2/2)\,(\omega_{\rm p}^2/4\pi)^2\\ (G_{\rm F}^2/\alpha)\,(\omega_{\rm p}^2/4\pi)^3\end{cases}$$

$$\frac{Q_{\rm dipole}}{Q_{\rm SM}} \approx \frac{2\pi\alpha\mu_\nu^2}{G_{\rm F}^2\omega_{\rm p}^2} = 0.30\left(\frac{\mu_\nu}{10^{-12}\mu_{\rm B}}\right)^2\left(\frac{10\ \text{keV}}{\omega_{\rm p}}\right)^2$$

RG before He ignition: Assume neutrino emission known within 10%, $\omega_{\rm p}\approx 20$ keV

$\boldsymbol{\mu_\nu \lesssim 10^{-12}\mu_{\rm B}}$ (Scale of the bound to be expected)

PHYSICAL REVIEW VOLUME 132, NUMBER 3 1 NOVEMBER 1963

Electromagnetic Properties of the Neutrino

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(Received 11 June 1963)

In this note we make a detailed survey of the experimental information on the neutrino charge, charge radius, and magnetic moment. Both weak-interaction data and astrophysical results can be used to give precise limits to these quantities, independent of the supposition that the weak interactions are charge conserving.

I. INTRODUCTION

MOST physicists now accept the prospect that there are two neutrinos—ν_e and ν_μ—identical except for interaction (ν_e couples weakly with electrons and ν_μ with muons) and that these neutrinos have the simplest properties compatible with existing experimental evidence; i.e., zero mass, charge, electric, and magnetic dipole moments. However, the weak interactions have produced so many surprises that it is worthwhile, from time to time, to study the *experimental* limits that have been set on these quantities. In this note we present a systematic survey of the properties of the two neutrinos that can be inferred from experiment.

II. PROPERTIES

We begin by listing the properties of the neutrinos to

tritium experiments give

$$m_{\nu_e} < 200 \text{ eV}, \tag{2}$$

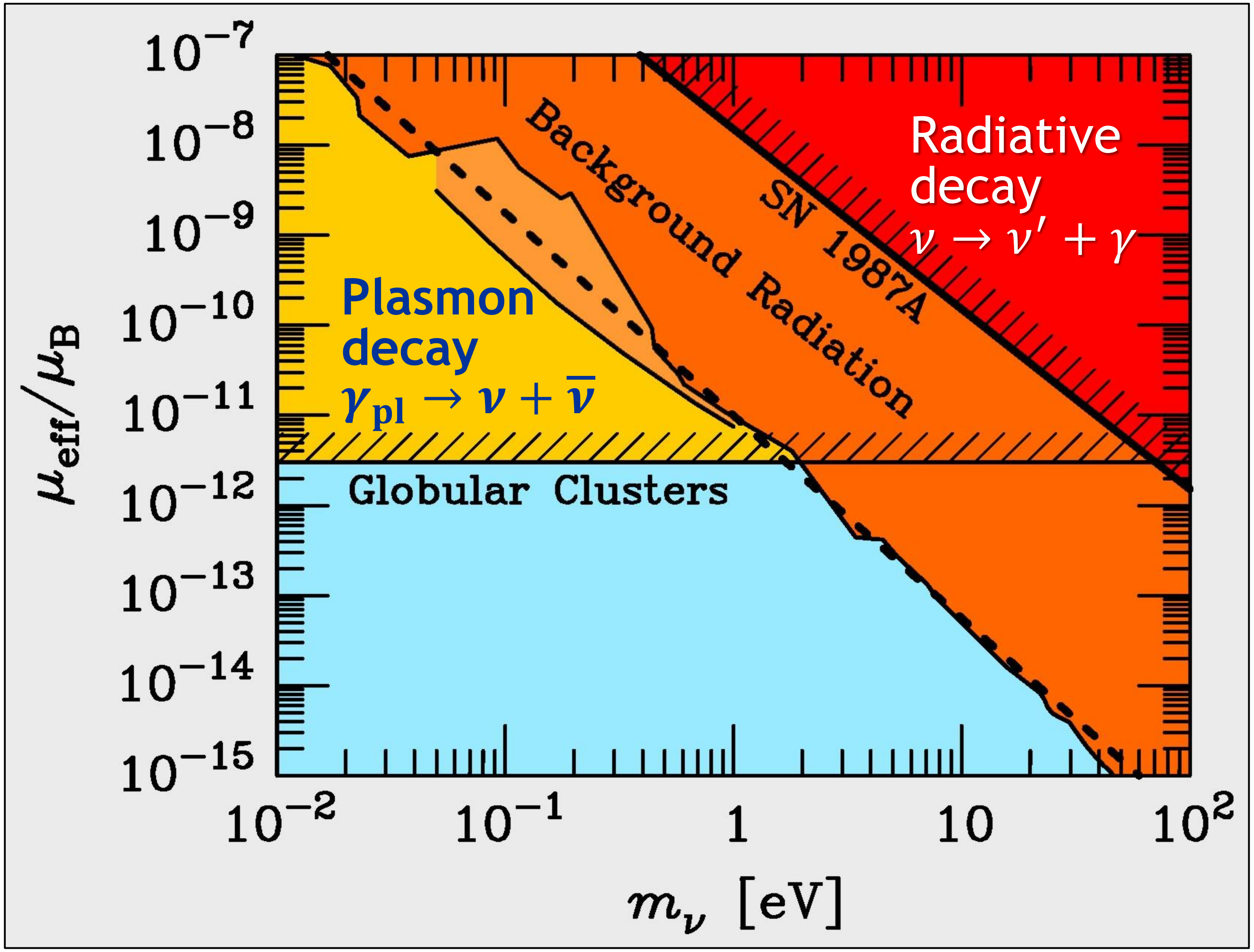
and the experiments are consistent with $m_{\nu_e}=0$.

(2) ν_μ: The mass of the muon neutrino is the least well known of the parameters associated with either neutrino. The best measurements of it come from the energy-momentum balance in π decay. The experiment of Barkas *et al.*[3] gives[4]

$$m_{\nu_\mu} < 3.5 \text{ MeV}. \tag{3}$$

The reason for this uncertainty lies in the kinematic fact that the small neutrino mass is given as the difference between measured quantities of order 1. In the $\pi \to \mu + \nu$ decay, the accuracy with which the neutrino mass can be determined is given by

Neutrino Radiative Lifetime Limits



$$\Gamma_{\nu\to\nu'\gamma} = \frac{\mu_{\rm eff}^2}{8\pi}\, m_\nu^3$$

$$\Gamma_{\gamma\to\nu\overline{\nu}} = \frac{\mu_{\rm eff}^2}{24\pi}\, \omega_{\rm pl}^3$$

arXiv:astro-ph/9808299

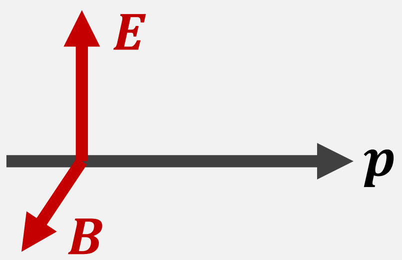
Today GC bounds more restrictive

For low-mass neutrinos, plasmon decay in globular cluster stars yields the most restrictive limits

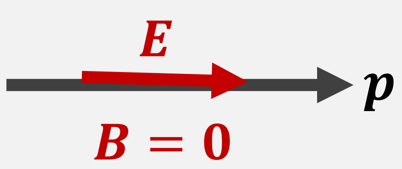
Transverse and Longitudinal "Plasmons"

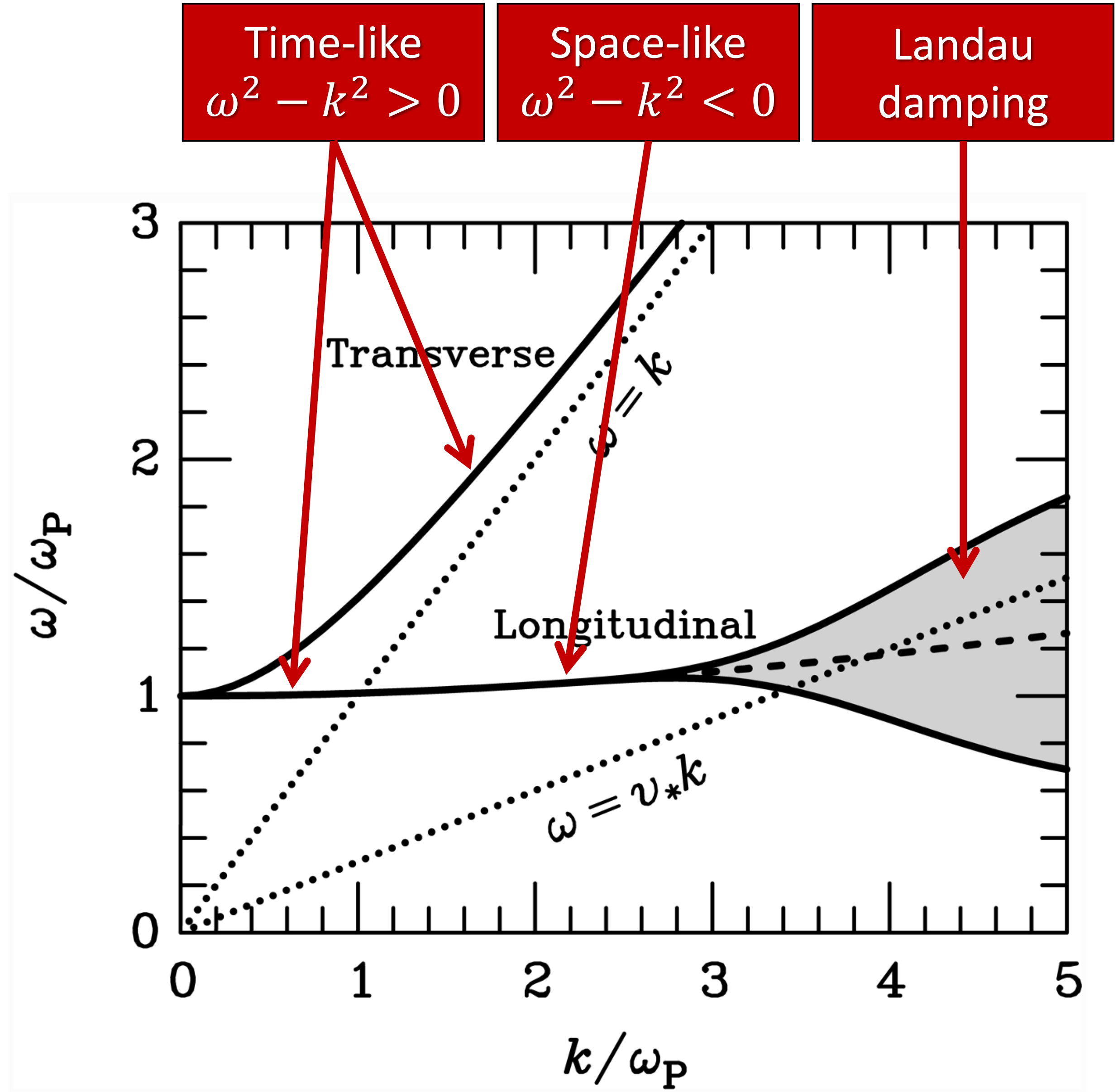
Dispersion relation in a non-relativistic, non-degenerate plasma

Transverse Excitation



Longitudinal Excitation (oscillation of electrons against positive charges)





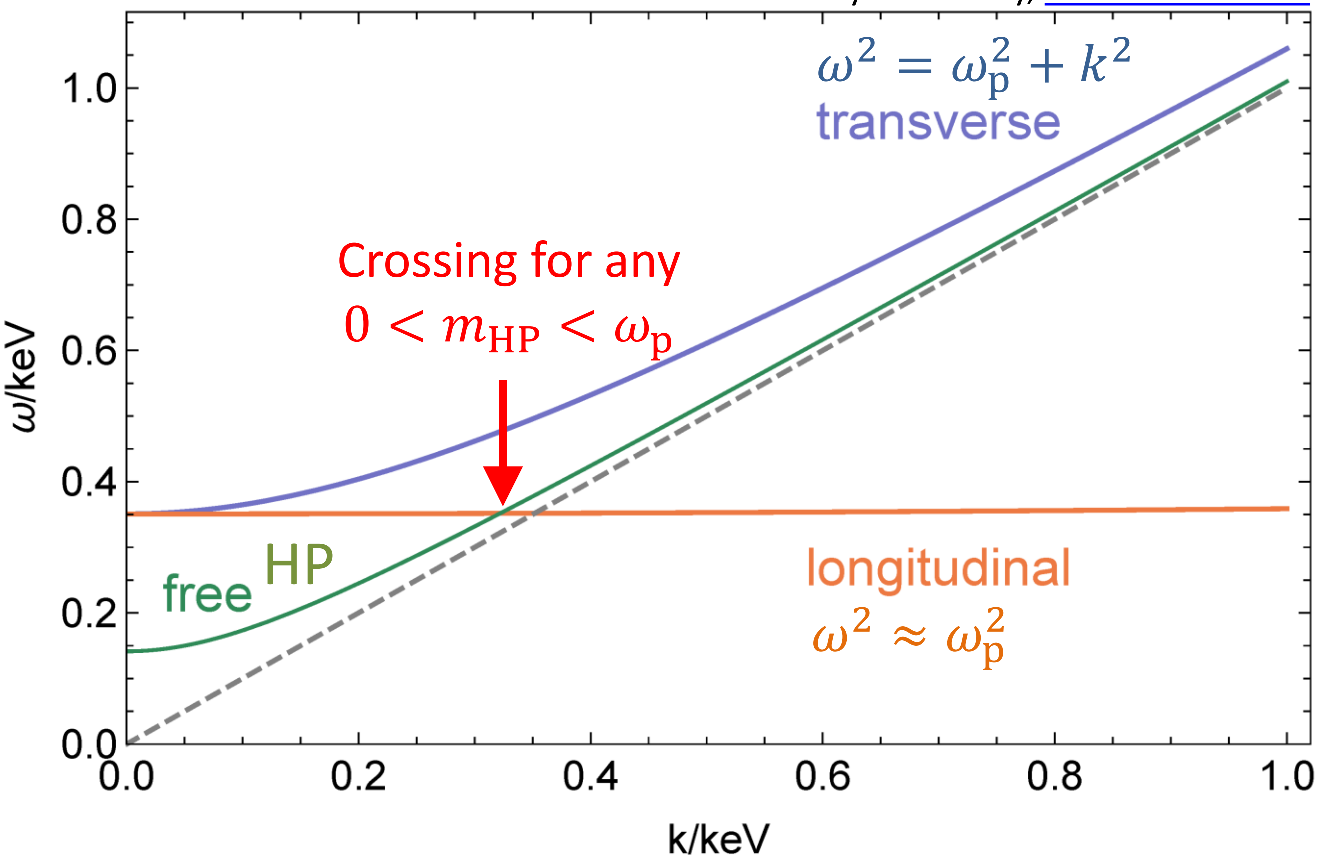
Resonant Hidden Photon Production

Hidden (dark) photons – a generic BSM conjecture and FIP dark matter candidate

$$\mathcal{L} = -\frac{1}{4}A_{\mu\nu}A^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{m_{\rm HP}^2}{2}B_\mu B^\mu - \frac{\chi}{2}A_{\mu\nu}B^{\mu\nu}$$

Photon field HP field HP mass kinetic mixing

Hardy & Lasenby, arXiv:1611.05852



Nonrelativistic plasma (Sun, globular cluster stars)

Resonant Hidden Photon Production

Damping rate to equilibrium Γ of a boson distribution function vs. self energy Π

$$\mathrm{Im}\,\Pi = -\omega\,\Gamma$$

$\Gamma = \Gamma_{\mathrm{abs}} - \Gamma_{\mathrm{prod}}$ and from detailed balance $\Gamma_{\mathrm{prod}} = e^{-\omega/T}\,\Gamma_{\mathrm{abs}}$

$$\Gamma_{\mathrm{prod}} = -\frac{\mathrm{Im}\,\Pi}{\omega(e^{\omega/T}-1)}$$

$$\Pi_{\mathrm{B}} = m^2 + \chi m^2 \frac{1}{K^2 - \Pi_A(K)} \chi m^2$$

For L plasmons, $K^2 = Z_L^{-1}\omega^2$, residue factor Z_L for canonical pole structure

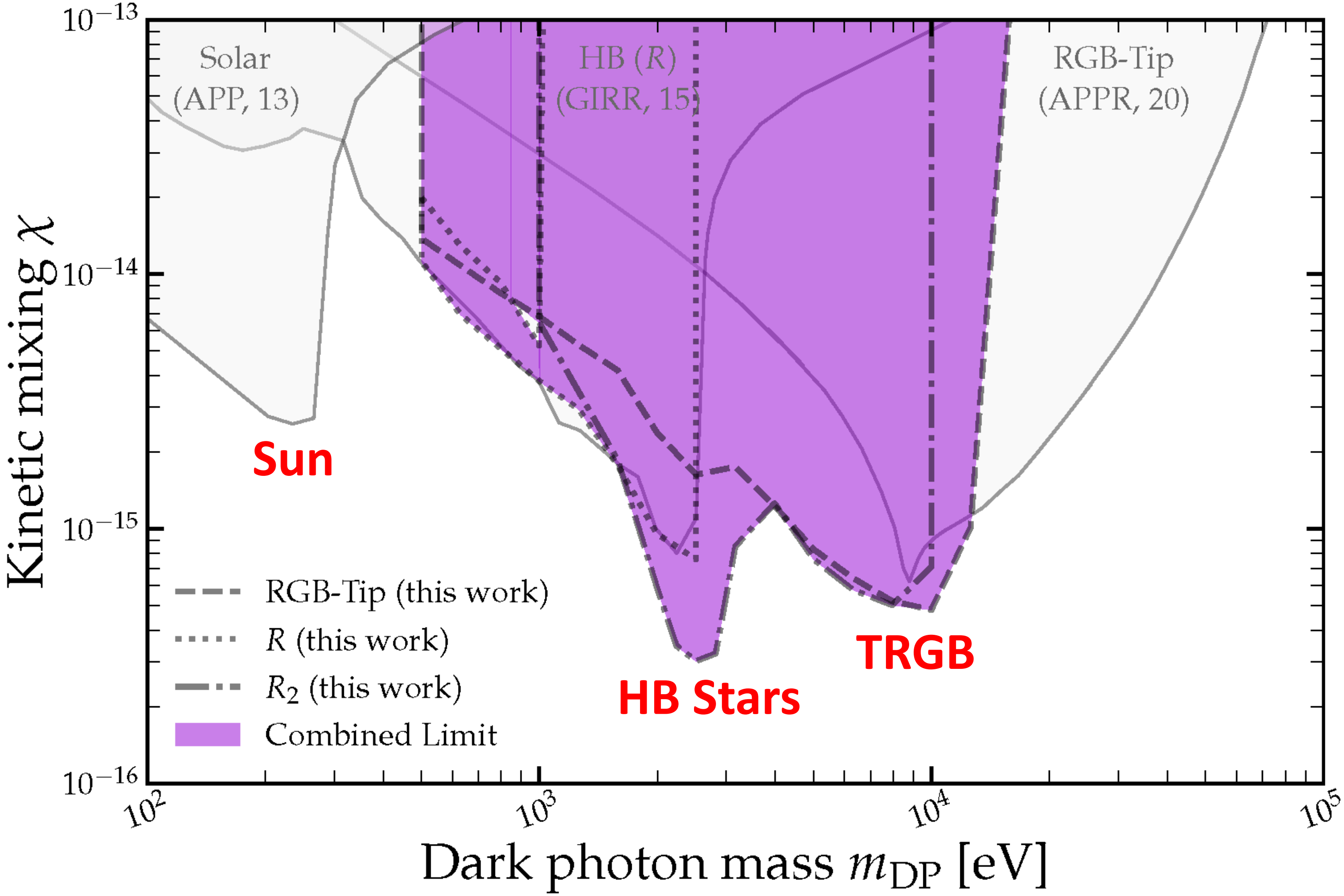
$$\mathrm{Im}\,\Pi_B = \chi^2 m^4\,\mathrm{Im}\frac{Z_{\mathrm{L}}}{\omega^2 - \omega_{\mathrm{p}}^2 - iZ_{\mathrm{L}}\mathrm{Im}\Pi_{\mathrm{L}}^A}$$

$$\Gamma_B^{\mathrm{prod}} = \frac{\chi^2 m^2}{e^{\omega/T}-1}\,\frac{\omega^2\Gamma_{\mathrm{L}}}{\left(\omega^2-\omega_{\mathrm{p}}^2\right)^2 - (\omega\Gamma_{\mathrm{L}})^2} \approx \frac{\chi^2 m^2}{e^{\omega/T}-1}\frac{\pi}{2}\delta(\omega-\omega_{\mathrm{p}})$$

Resonant conversion depends only on χ and m

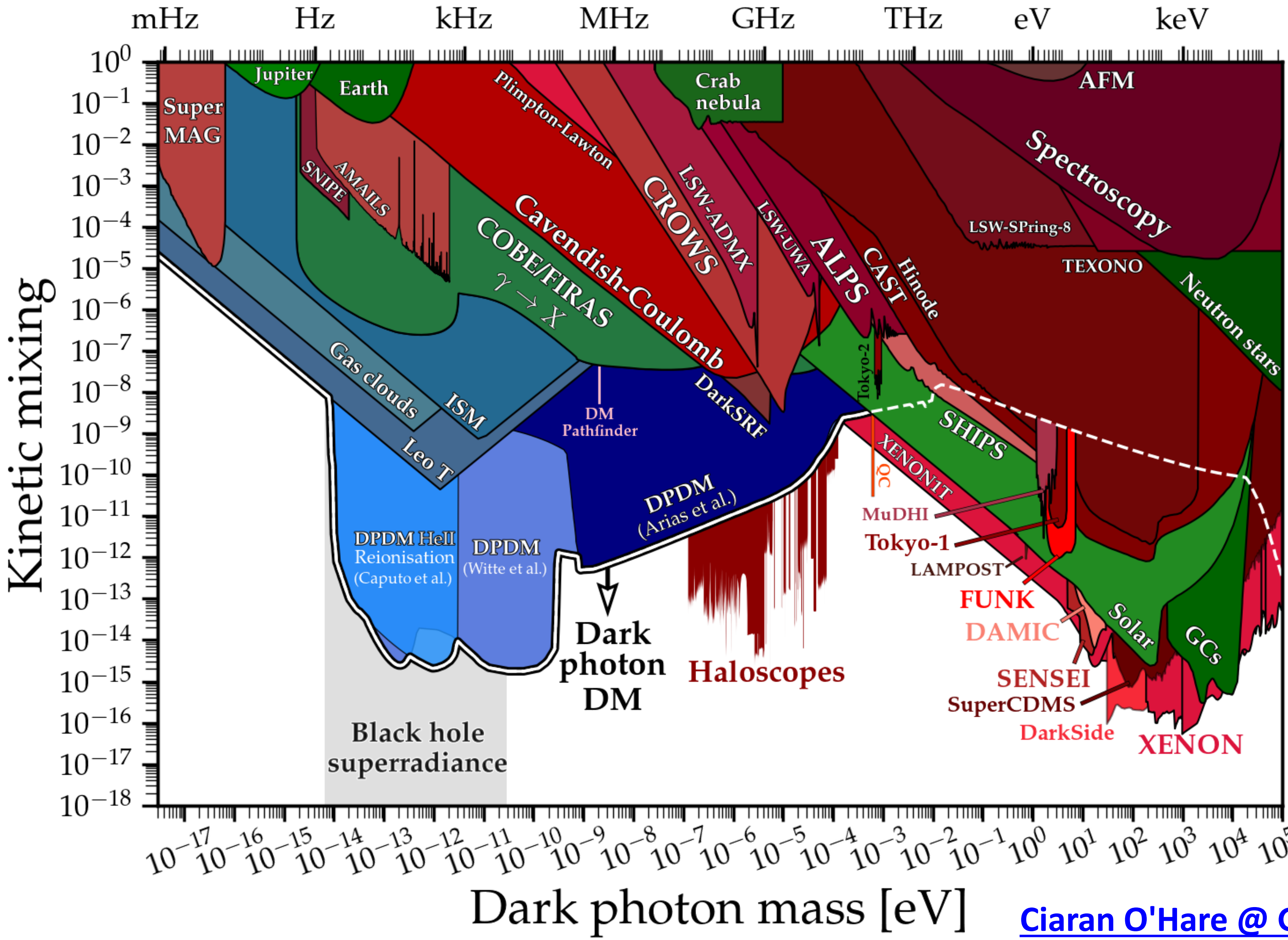
An, Pospelov & Pradler, arXiv:1302.3884 Redondo & Raffelt, arXiv:1305.2920

Hidden Photon Limits



Dolan, Hiskens & Volkas, arXiv:2306.13335

Global Hidden Photon Limits



Ciaran O'Hare @ Github

Electron (Positron) Dispersion Relation

In a relativistic medium

$$m_{\text{eff}}^2 = \frac{\alpha}{2\pi}(\mu_e^2 + \pi^2 T^2)$$

valid for $m_e \ll m_{\text{eff}}$

In a SN core

$\mu_e = 200\ \text{MeV}$

$T \ = 30\ \text{MeV}$

$m_{\text{eff}} \simeq 8\ \text{MeV} \gg m_e$

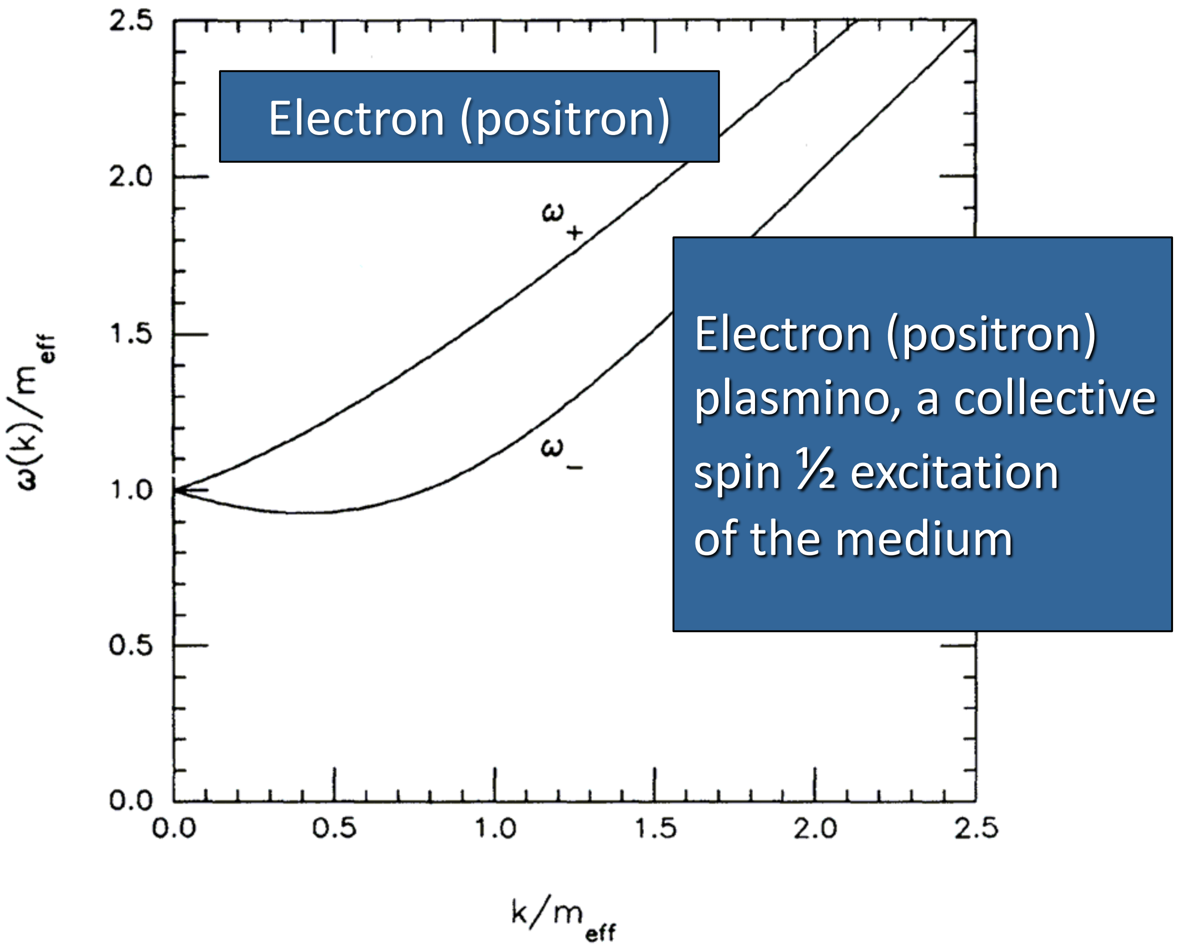


FIG. 1.—Ultrarelativistic dispersion relations for the electron or positron $[\omega_+(k)]$ and for the electron plasmino or positron plasmino $[\omega_-(k)]$.

E. Braaten, Neutrino emissivity of an ultrarelativistic plasma from positron and plasmino annihilation, Astrophys. J. 392 (1992) 70

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6000 citations

Neutrino oscillations in matter

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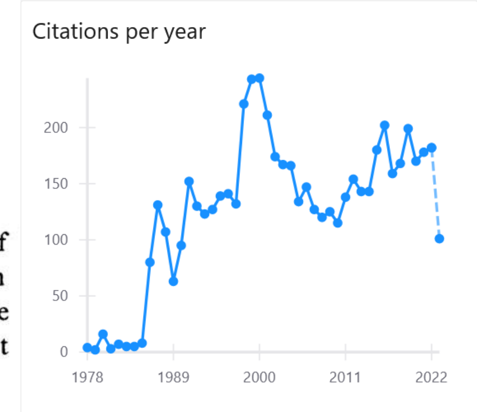
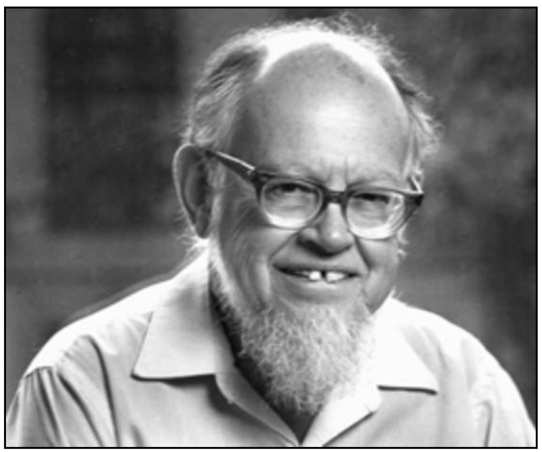
(Received 6 October 1977; revised manuscript received 5 December 1977)

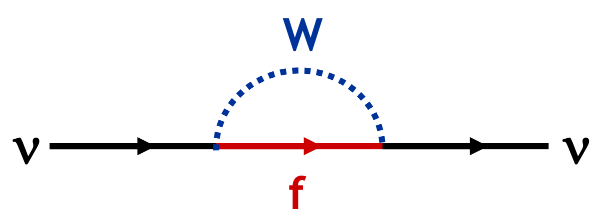
The effect of coherent forward scattering must be taken into account when considering the oscillations of neutrinos traveling through matter. In particular, for the case of massless neutrinos for which vacuum oscillations cannot occur, oscillations can occur in matter if the neutral current has an off-diagonal piece connecting different neutrino types. Applications discussed are solar neutrinos and a proposed experiment involving transmission of neutrinos through 1000 km of rock.

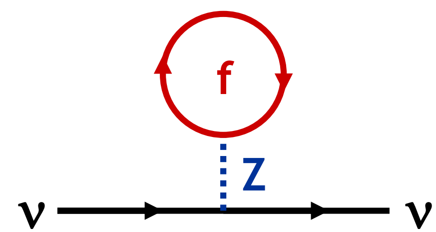




Lincoln Wolfenstein

Neutrinos in a medium suffer flavor-dependent refraction





$$V_{\rm weak} = \sqrt{2}G_{\rm F} \times \begin{cases} n_{\rm e} - n_{\rm n}/2 & \text{for } \nu_{\rm e} \\ -n_{\rm n}/2 & \text{for } \nu_\mu \end{cases}$$

Typical density of Earth: 5 g/cm^3

$$\Delta V_{\rm weak} \approx 2\times 10^{-13}\ {\rm eV} = 0.2\ {\rm peV}$$

Neutrino Majoron Decay

Majorana neutrinos with a coupling to a massless pseudoscalar (Majoron χ)

$$\mathcal{L} = ih\,\overline{\nu}\gamma_5\nu\,\chi$$

Helicity-flipping decay $\nu \to \overline{\nu} + \chi$ possible in medium.

Neutrino potential for ν_e

$$V = \sqrt{2}\,G_F\left(n_e - \frac{n_n}{2}\right)$$

Dispersion relation for $\pm$helicity neutrinos

$$E_\pm = \sqrt{m^2 + p^2} \mp V$$

Decay rate for $m = 0$

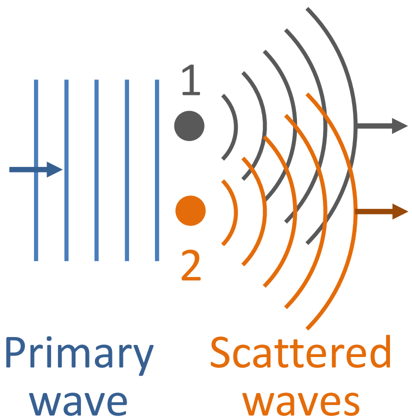
$$\Gamma_{\nu_- \to \nu_+ \chi} = \frac{h^2}{8\pi} V$$

Same decay rate for $\chi \to \nu\overline{\nu}$

Correlation Effects

Scattering processes on many targets (eg stellar medium)

For example photo production $\gamma + e \to e + a$



Scattering rate proportional to

$$|f_1|^2 + |f_2|^2 + 2|f_1 f_2^*| \cos(\boldsymbol{q} \cdot \boldsymbol{r}_{12})$$

For a target of multiple scatterers:

"Form factor" $F(q)$ multiplies $d\sigma/d\Omega$

"Static structure factor" $S(q)$ in bulk medium

Uncorrelated distribution of N scatterers:

$\sigma_{\text{tot}} = N\sigma$ (interference averages to zero)

N unresolved scatterers

$\sigma_{\text{tot}} = N^2\sigma$ (coherent enhancement)

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

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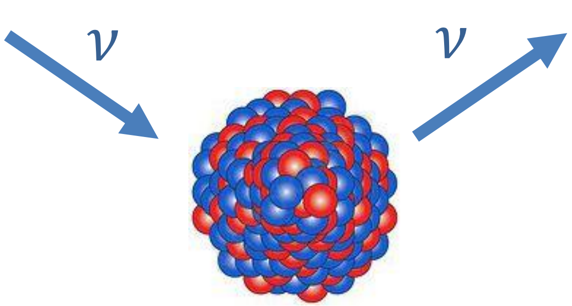
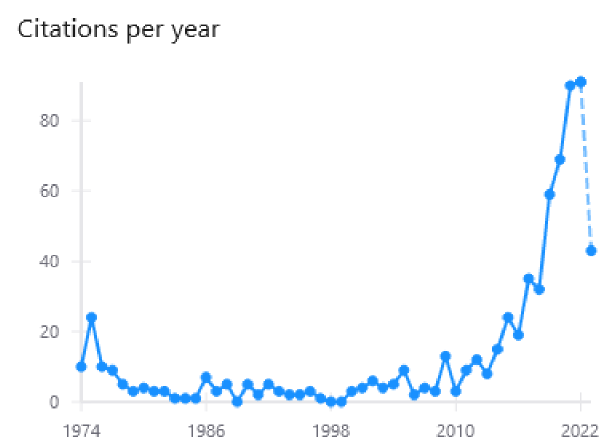
(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.



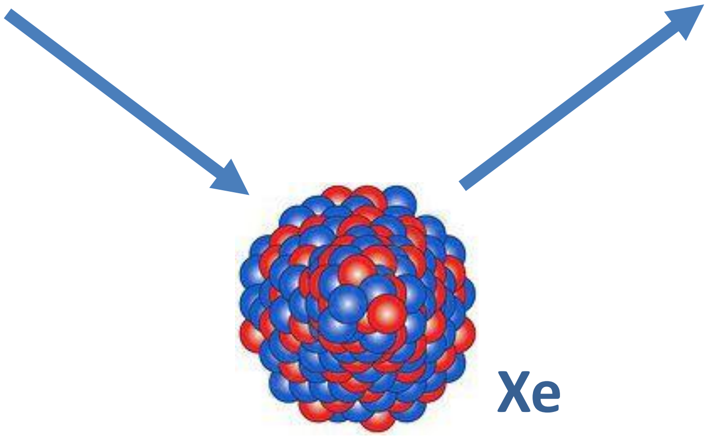
Enhancement by
$N^2 + Z^2(1 - 4\sin^2\Theta_W)$



Coherent Elastic Neutrino Nucleus Scattering (CENNS=CEνNs)
now a major industry with reactor $\overline{\nu}_e$ (eg arXiv:2203.07361)

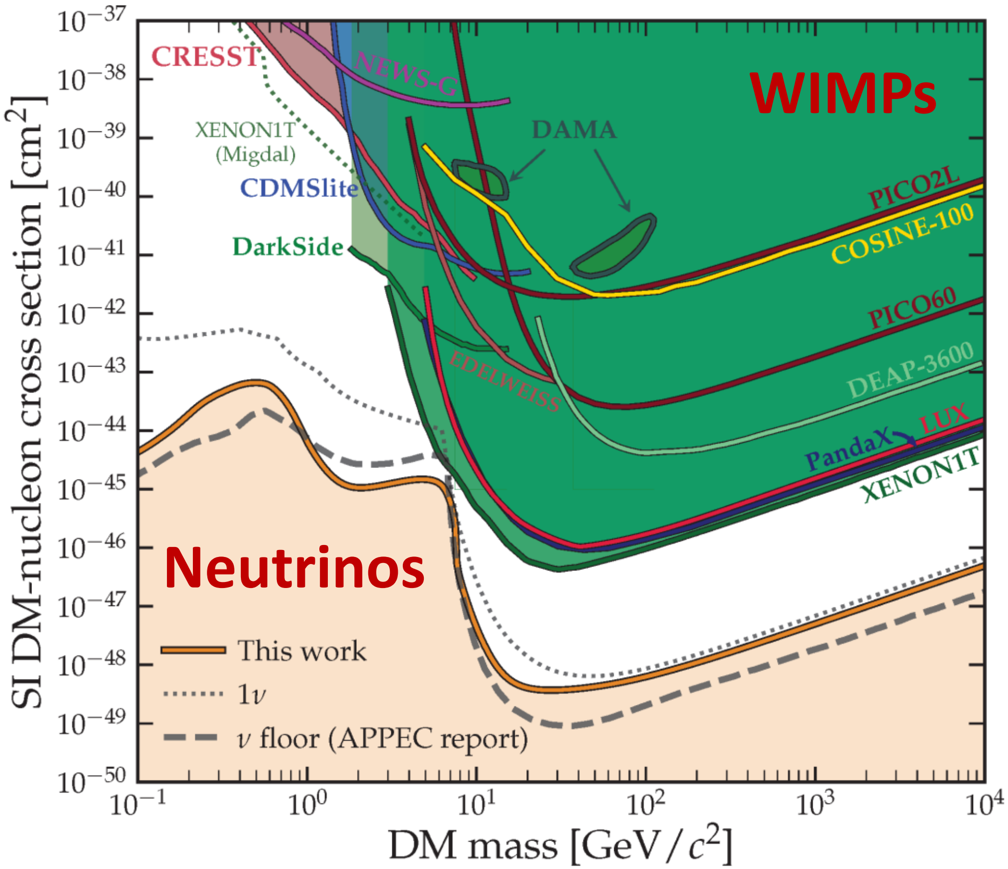
Coherent Neutrino and WIMP Scattering

Nuclear recoil



Dark-matter WIMPs

Coherent scattering of
10 MeV solar neutrinos



Neutrino fog (formerly “floor”)
O’Hare, arXiv:2109.03116

Debye-Hückel Correlation

- Probability for finding ion (electron) near another

$$p_{ij}(r) = \frac{1}{V}\left(1 - \frac{Z_i Z_j \alpha}{T}\frac{e^{-k_S r}}{r}\right)$$

$$k_S^2 = \sum_i k_i^2 \quad \text{with} \quad k_i^2 = \frac{4\pi\alpha}{T} n_i$$

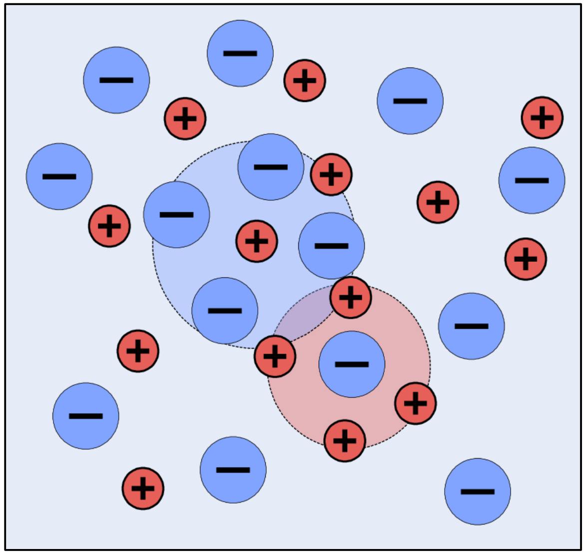


Image credit Wikipedia

- Electron correlation eg for $\gamma + e \to e + a$

  Static structure factor to multiply $d\sigma/d\Omega$

$$S(q) = 1 - \frac{k_e^2}{q^2 + k_S^2}$$

  Reduction of Compton rate by “screening” (anti-correlation), in practice small effect

- Primakoff scattering

  Static structure factor to multiply $d\sigma/d\Omega$

$$S(q) = 1 - \frac{k_S^2}{q^2 + k_S^2} = \frac{q^2}{q^2 + k_S^2}$$

  Removes forward divergence