Neutrino Astrophysics

Dark Matter and Neutrinos, IHP, Paris, 5–9 May 2025

ORIGINS Excellence Cluster

COSMIC WISPERS CA21106

MAX-PLANCK-INSTITUT FÜR PHYSIK

SFB 1258 Neutrinos Dark Matter Messengers

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

I. Neutrinos and the Stars

II. Supernova neutrinos

III. Neutrinos in cosmology

Demystifying the ghost particles

Flavor oscillations, New properties, …

Masses (limits, toward cosmo measurement)

Astrophysical messengers

Solar interior, Geonus & Reactors, Supernovae

Cosmic-ray sources, Dark matter annihilation

Workers in astrophysics & cosmology

Stellar cooling, Supernova explosions

Big-bang nucleosynthesis, Leptogenesis

Hot dark matter

Role model

Axions and other feebly interacting particles

(FIPs, WISPs, ALPs, …) can do similar things

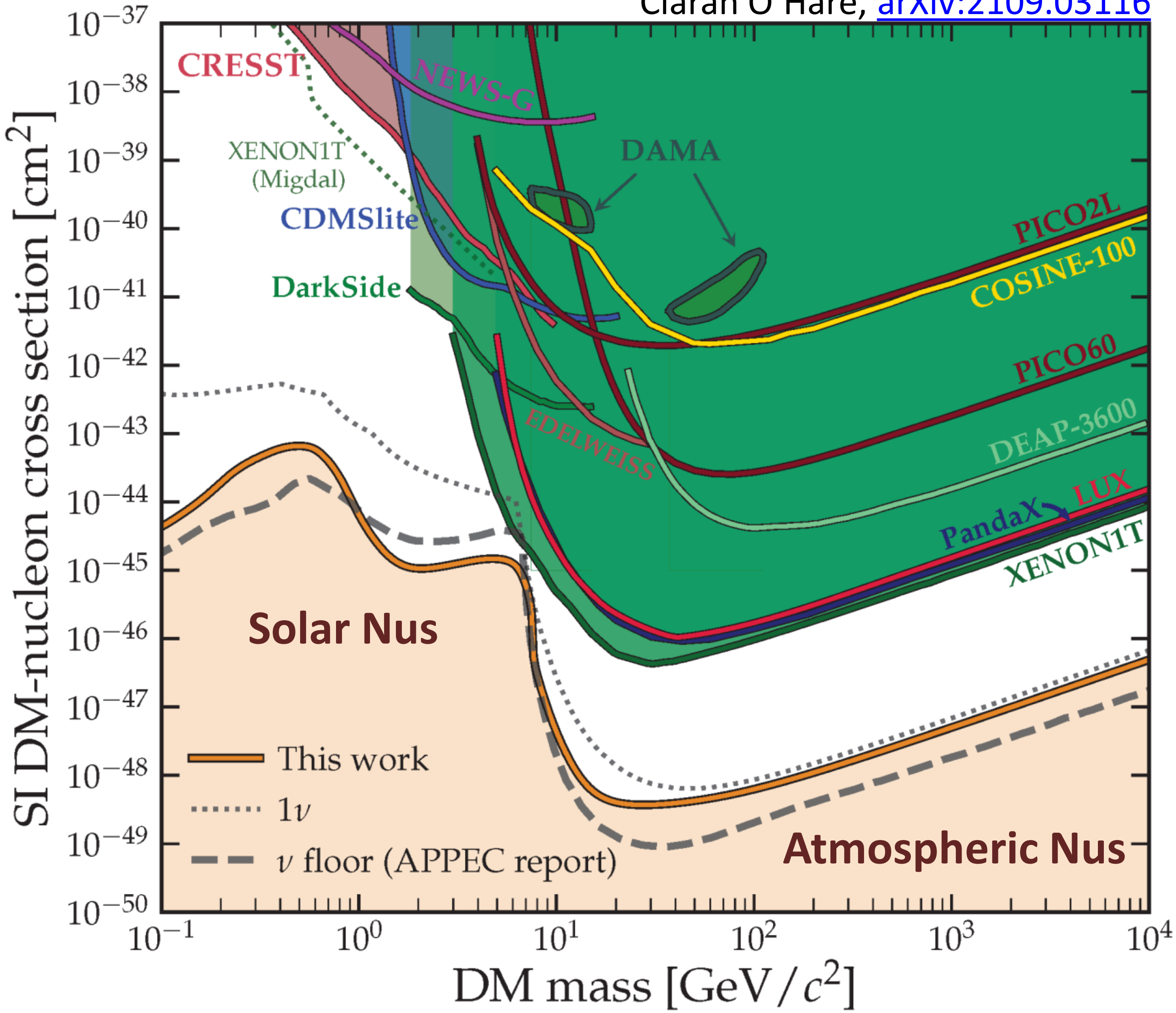
Astrophysical constraints

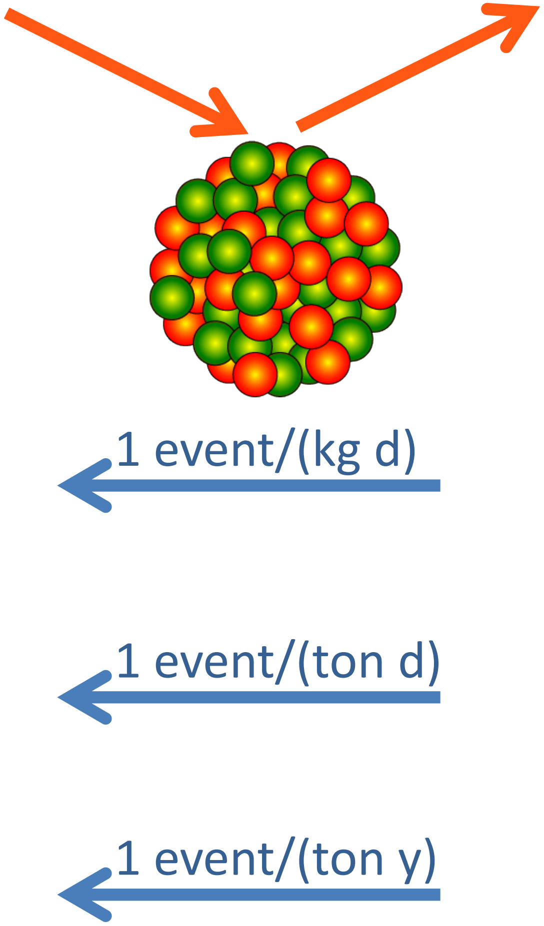
Pest

Background for dark matter searches

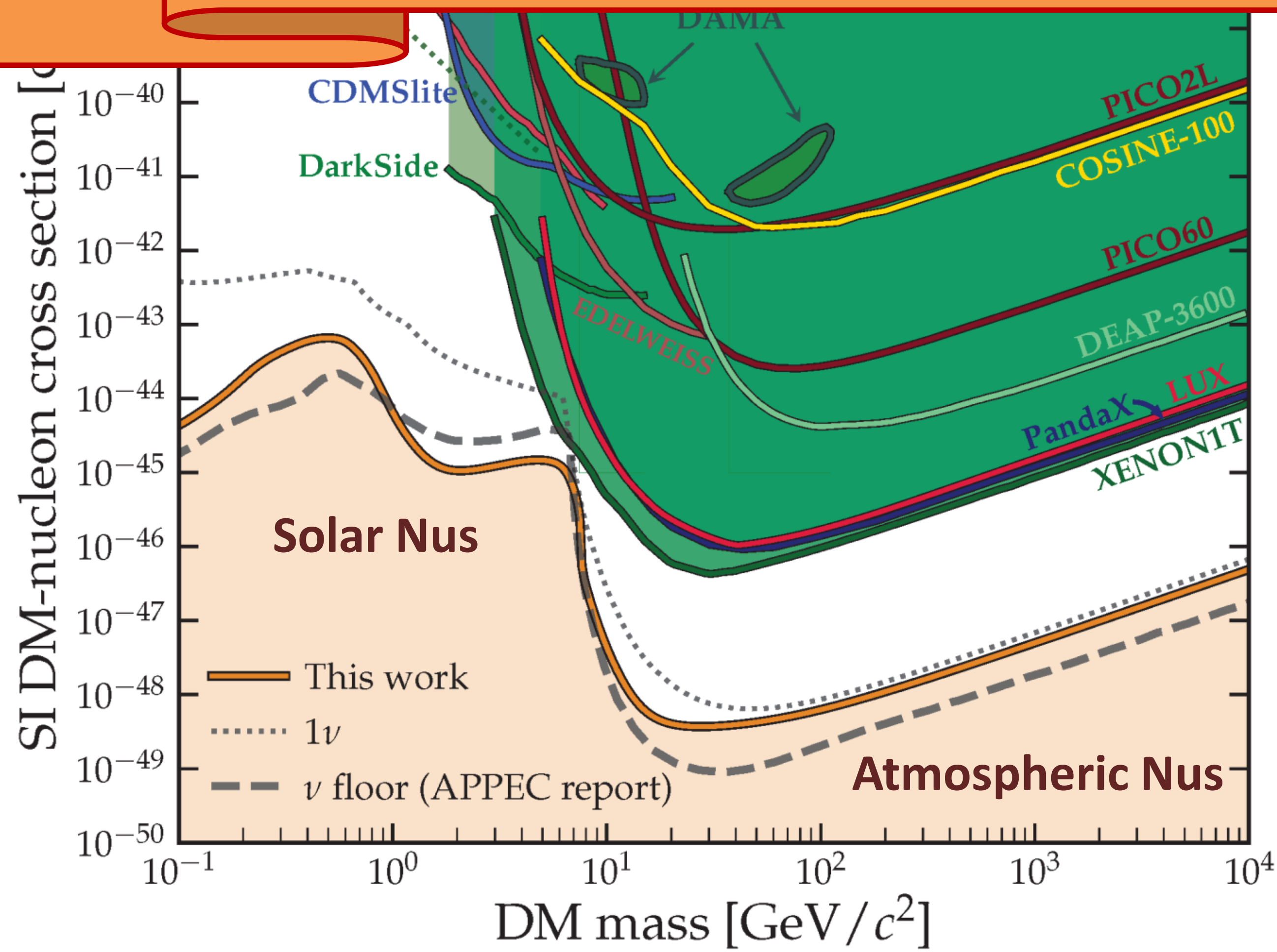
Neutrino Fog for WIMP Dark Matter Detection

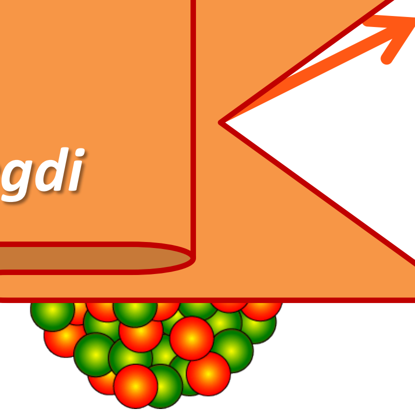
Ciaran O'Hare, arXiv:2109.03116





Yesterday's sensation
is today's calibration ***—R.Feynman***
… and tomorrow's background ***—V.Telegdi***





1 event/(kg d)

1 event/(ton d)

1 event/(ton y)

Aprile+, Xenon Collaboration, arXiv:2408.02877

XENON

清華大學
Tsinghua University

First Measurement of Coherent Elastic Neutrino Nucleus Scattering of Solar ^{8}B Neutrinos in XENONnT

Fei Gao, Tsinghua University
on behalf of the XENON Collaboration

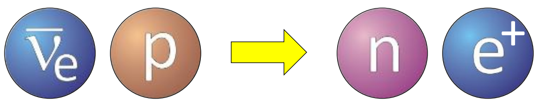
15th International Workshop on the Identification of Dark Matter
July 8-12, 2024, L'Aquila

How feebly do neutrinos interact?

Neutron decay (β decay)

$$\frac{1}{\tau} = G_{\rm F}^2 \frac{|V_{ud}|^2(1+3\,C_A^2)}{\pi} Q^5 \frac{f_{\rm Phase-Space}}{2\pi} \simeq \frac{1}{15\ \rm min}$$

Inverse β decay (IBD)



$$\sigma = G_{\rm F}^2 \frac{|V_{ud}|^2(1+3\,C_A^2)}{\pi} E_e p_e \simeq 9.5\times 10^{-44}{\rm cm}^2 \left(\frac{E_\nu - Q}{\rm MeV}\right)^2$$

$$Q = m_n - m_p$$
$$= 1.297\ \rm MeV$$

Mean free path of $\overline{\nu}_e$ (5 MeV) in water

$\boldsymbol{\lambda \simeq 1\times 10^{14}\ \rm km \simeq 12\ light\ years}$

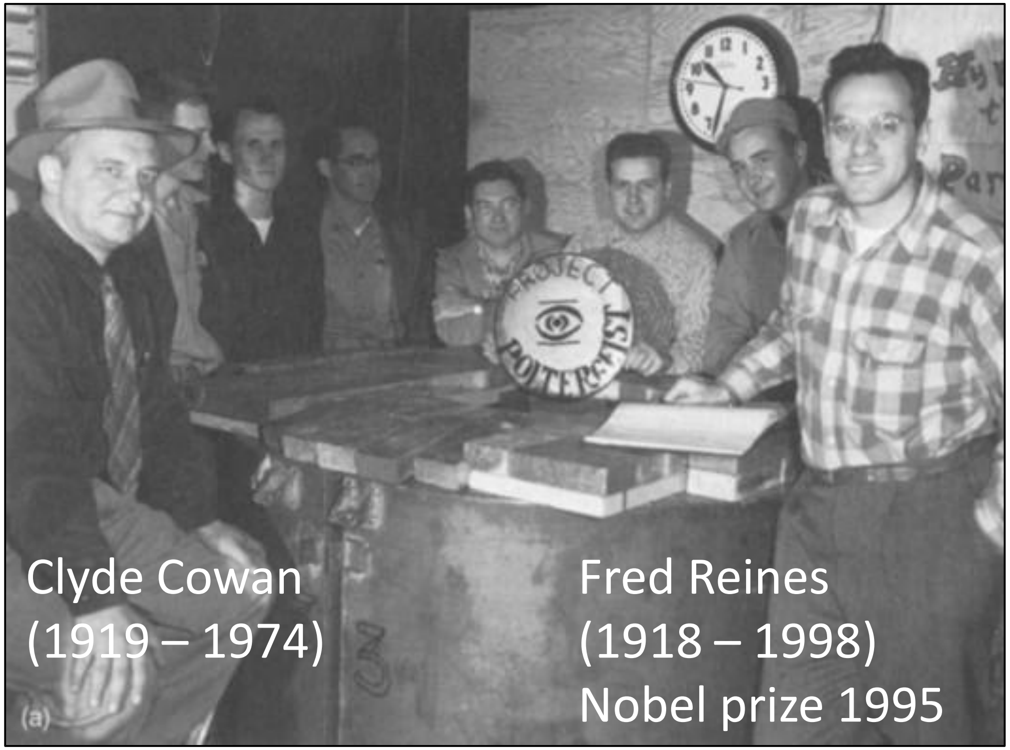
Rudolf Peierls
1907–1995

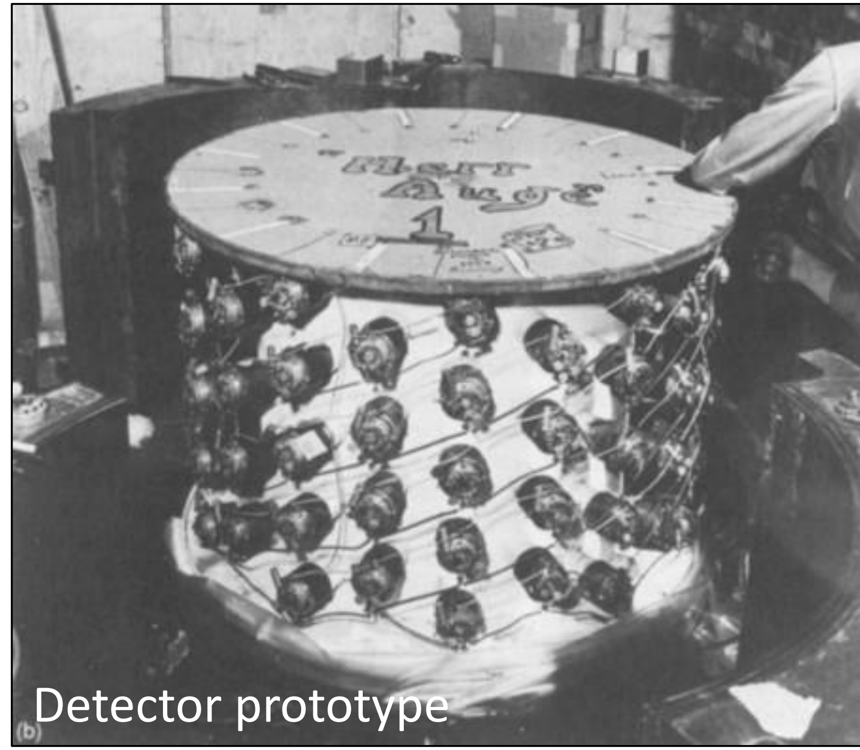
Hans Bethe
1906–2005

Bethe & Peierls
The "Neutrino"
Nature 133 (1934) 532

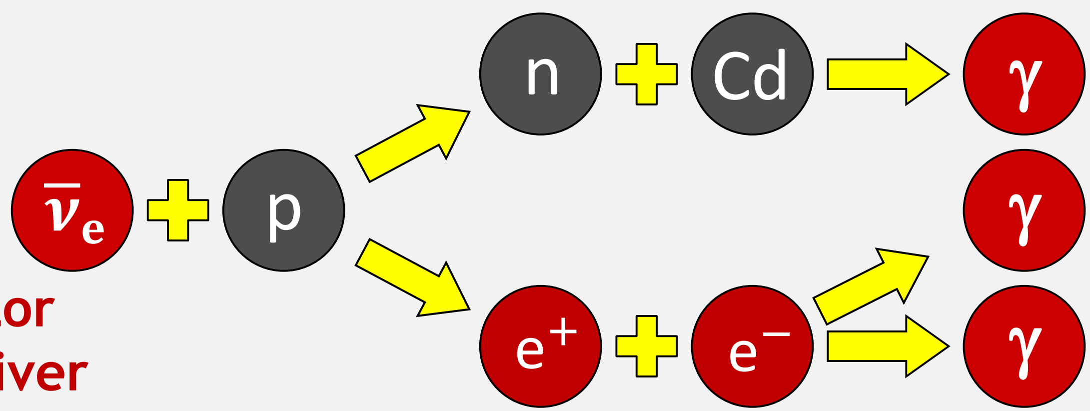
If, therefore, the neutrino has no interaction with other particles besides the processes of creation and annihilation mentioned—and it is not necessary to assume interaction in order to explain the function of the neutrino in nuclear transformations—one can conclude that there is no practically possible way of observing the neutrino.

First Detection (1954 – 1956)



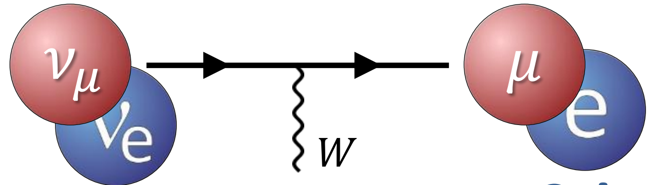


Anti-Electron Neutrinos from Hanford Nuclear Reactor & Savannah River



3 Gammas in coincidence

How do we see neutrinos? Let there be light!

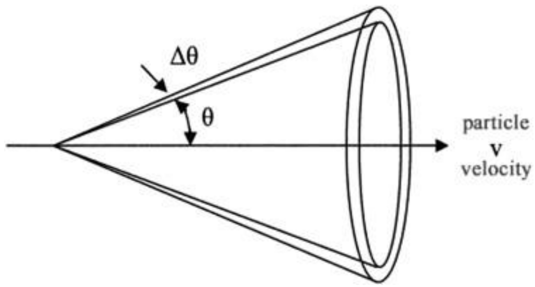


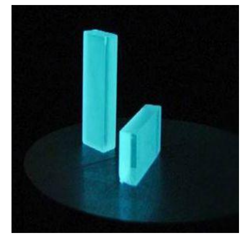
Cherenkov Light

Scintillation Light

In water, air, …

- $v_\gamma^{\text{phase}} < v_\mu$
- $\mu^- \to \mu^- + \gamma$

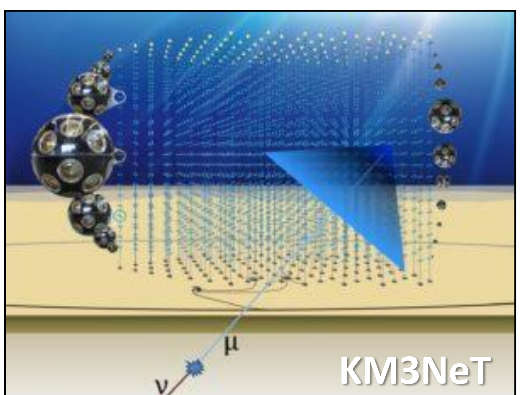




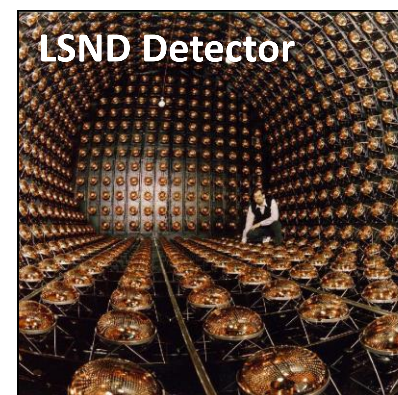
Ionizing radiation:
Some materials “scintillate”
Organic compounds dissolved
in mineral oil → Large volume

- Directional information
- Distinguish $e^\pm$ and $\mu^\pm$
- Good for large energies
- Large bodies of water or ice (> km^3)

- More light (better energy resolution)
- No directional information
- Low-energy nus (reactor, geo, solar)
- JUNO (20 kt) commissioning (2025)



(Water-based scintillator and
combining with Cherenkov
under development)



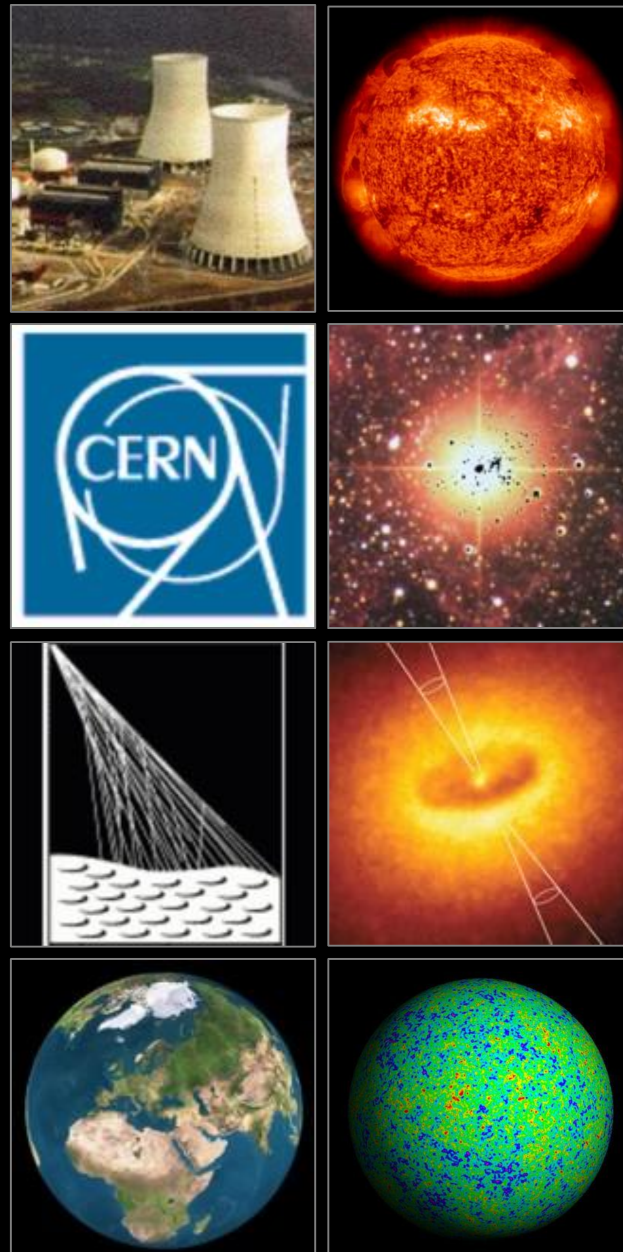
Where do Neutrinos Appear in Nature?

✓ Nuclear Reactors

✓ Particle Accelerators

✓ Earth Atmosphere (Cosmic Rays)

✓ Earth Crust (Natural Radioactivity)



Ordinary stars
Indirect Evidence

Sun ✓

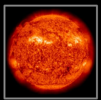
Supernovae (Stellar Collapse)
SN 1987A ✓

Astrophysical Accelerators ✓

Cosmic Big Bang (Today 330 ν/cm^3)
Indirect Evidence

How are Neutrinos Produced?

Nuclear transmutation (stars, reactors, Earth)



Fusion (H burning stars)

$4p \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e$

$e^- + p \rightarrow n + \nu_e$

Fission (Reactors, Earth)

$n + {}^{235}\mathrm{U} \rightarrow {}^{90}\mathrm{Kr} + {}^{143}\mathrm{Ba} + 3n$

$n \rightarrow p + e^- + \overline{\nu}_e$

β decay of neutron-rich isotopes

Few percent of energy
- ν_e (Sun)
- $\overline{\nu}_e$ (Reactors, Earth)

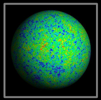
MeV range

Pair production ("thermal" neutrinos from stars)

Bremsstrahlung

$N + N \rightarrow N + N + \nu + \overline{\nu}$

$e^- + \mathrm{ion} \rightarrow \mathrm{ion} + e^- + \nu + \overline{\nu}$



Pair annihilation

$e^- + e^+ \rightarrow \nu + \overline{\nu}$

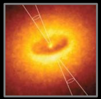
Neutrinos (all flavors) dominant energy loss

sub-MeV – tens MeV

Pion decay (from high-energy primary protons)

$p + \mathrm{target} \rightarrow \mathrm{X} + \mathrm{pions}\ (\pi^0, \pi^\pm)$ $(m_\pi = 135\ \mathrm{MeV})$

$\pi^0 \rightarrow 2\gamma$



$\pi^- \rightarrow \mu^- + \overline{\nu}_\mu \rightarrow e^- + \overline{\nu}_e + \nu_\mu + \overline{\nu}_\mu$ $(m_\mu = 106\ \mathrm{MeV})$

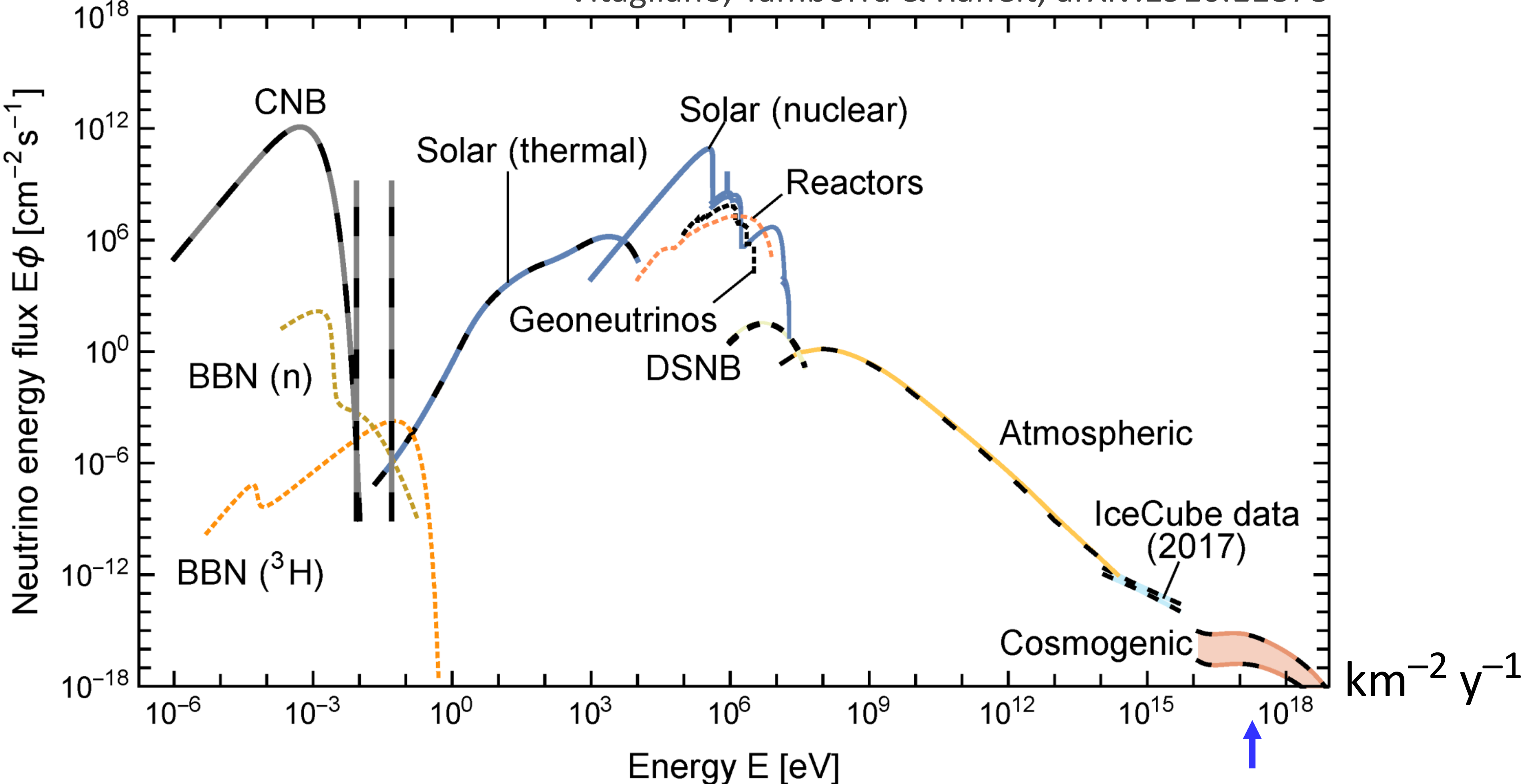
$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \nu_\mu + \overline{\nu}_\mu$

Neutrinos ~ Photons
- 2 $\overline{\nu}_\mu$ or ν_μ
- 1 $\overline{\nu}_e$ or ν_e

Up to 10^{20} eV from cosmic rays

Grand Unified Neutrino Spectrum (GUNS) at Earth

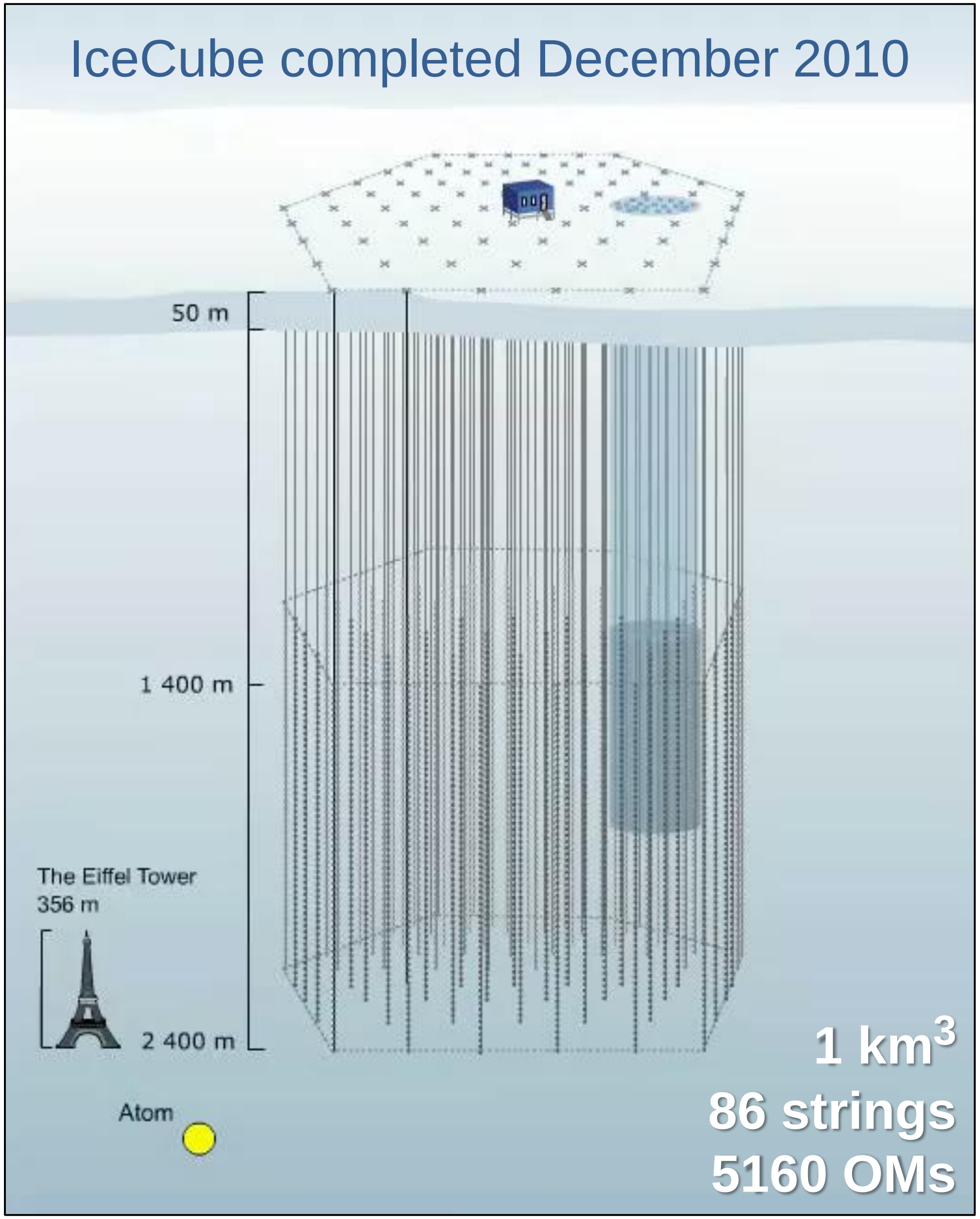
Vitagliano, Tamborra & Raffelt, arXiv:1910.11878



200 PeV

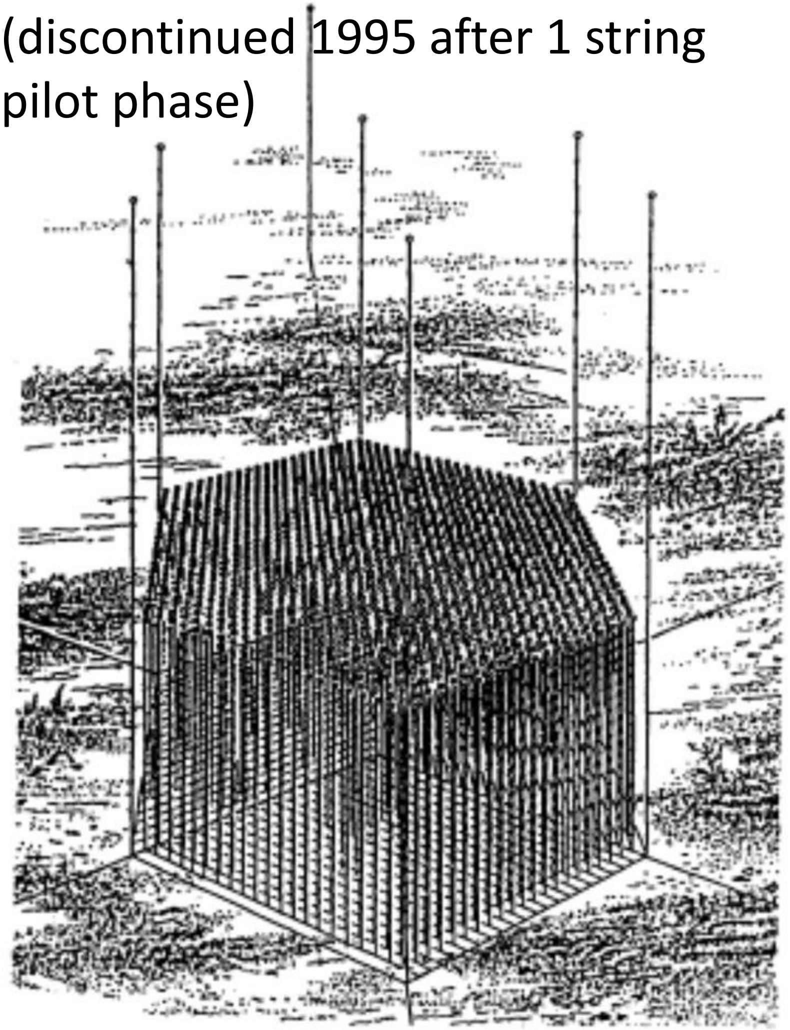
Neutrino with largest-ever energy
13 Feb 2023, KM3-230213A

IceCube Neutrino Telescope at the South Pole

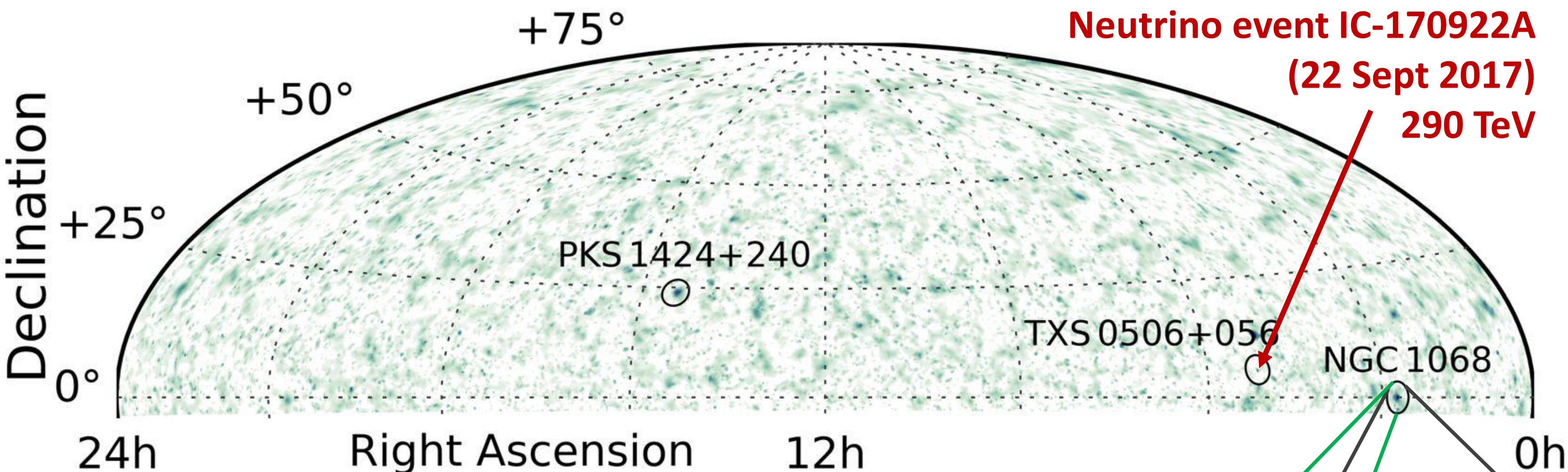


Idea for DUMAND under sea Cherenkov detector (1978)

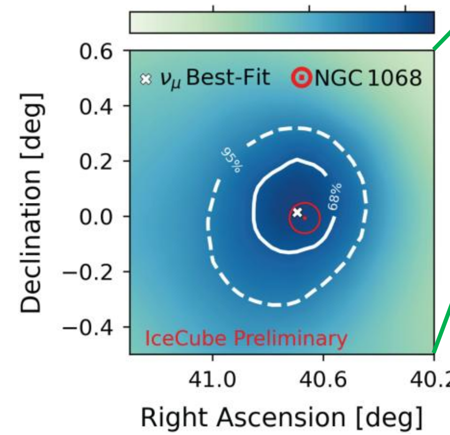
1.26 km^3, 22 698 Optical Modules (discontinued 1995 after 1 string pilot phase)



First Astrophysical Point Sources at IceCube



Neutrino emission from the nearby Active Galaxy NGC 1068 (14.4 Mpc)
AGN obscured by accretion torus



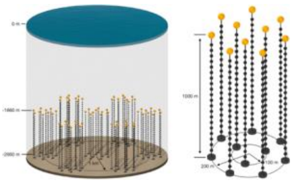
NGC 1068

Hot spot at NGC 1068
Global Significance 4.0 σ
~ 80 excess events, 13 years data

IceCube @ Neutrino 2024
Update of Science 378 (2022) 538

Cherenkov High-Energy Neutrino Telescopes

P-ONE

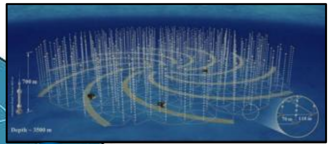


Pathfinder string

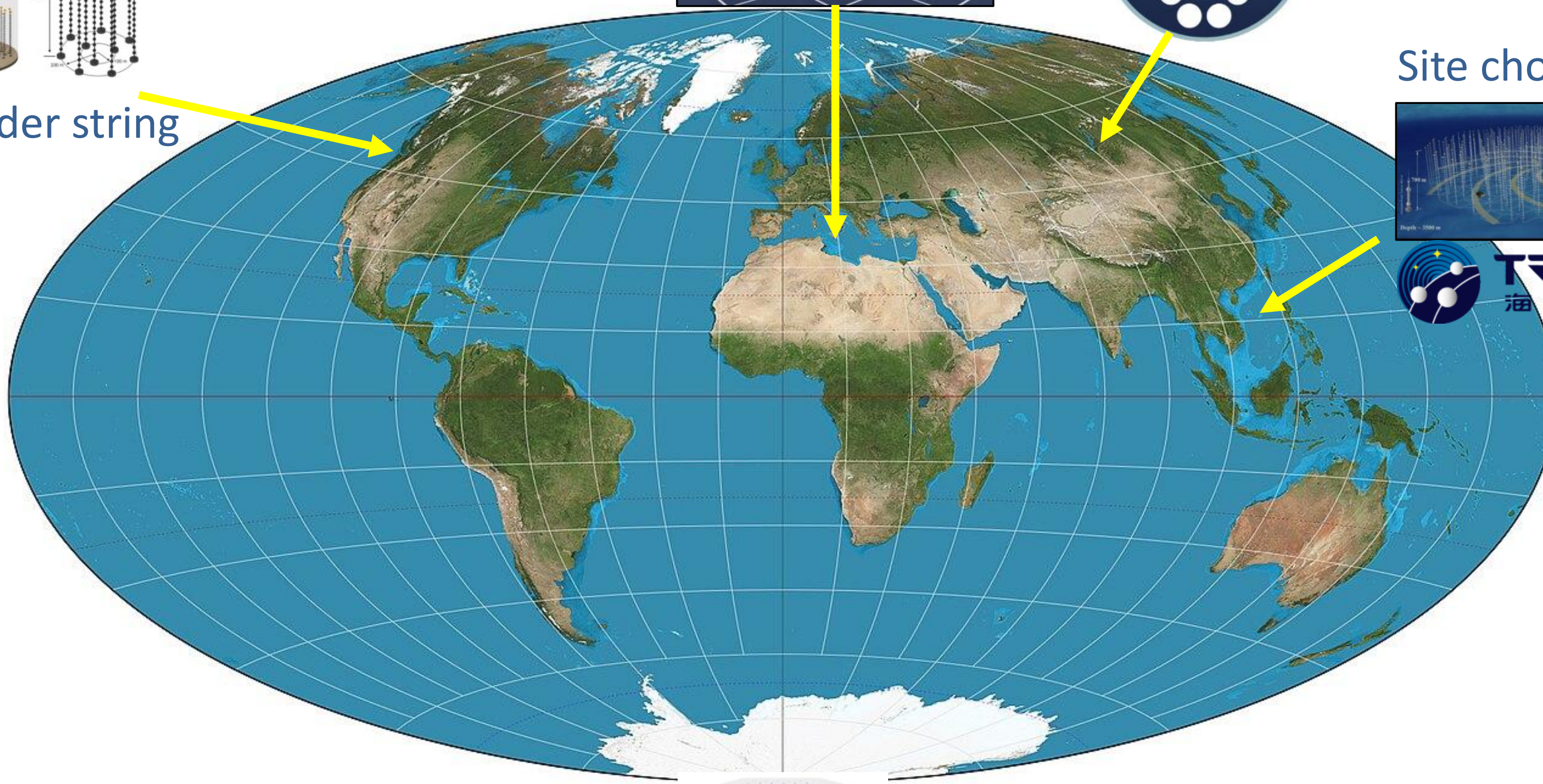
Growing
200 PeV event
13 Feb 2023

Baikal-GVD
Growing

Site chosen



TRIDENT
海 | 铃 | 计 | 划



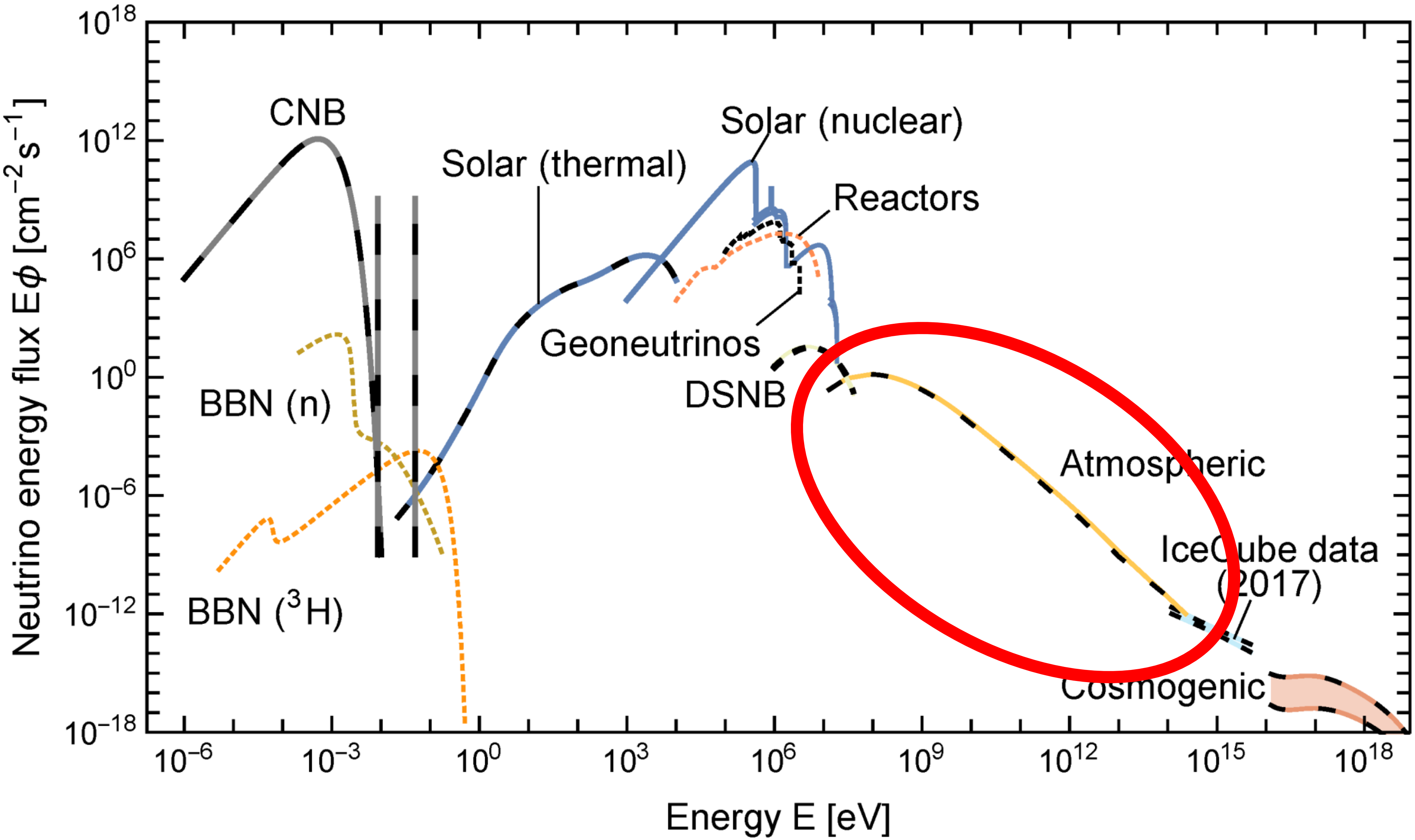
Per year about $100\ \nu_\mu^{\mathrm{astro}}$
$8 \times 10^4\ \nu_\mu^{\mathrm{atm}}$
$7 \times 10^{10}\ \mu^{\mathrm{atm}}$

ICECUBE

- Full size since 2010
- Diffuse flux (2013), first sources
- Extension planned (Gen2)

Grand Unified Neutrino Spectrum (GUNS) at Earth

Vitagliano, Tamborra & Raffelt, arXiv:1910.11878



Predicting Atmospheric Neutrinos (1936)

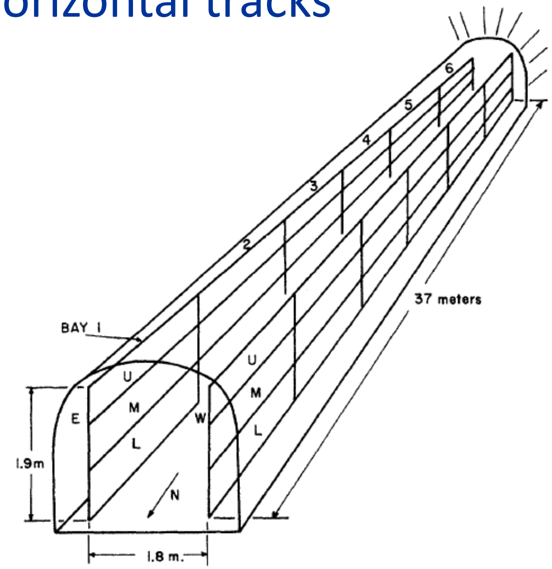
Instead [of protons and neutrons] Pauli's hypothetical 'neutrinos' should contribute substantially to the penetrating radiation. This is because in each shower ... neutrinos should be generated which then would lead to the generation of small secondary showers. The cross section for the generation of these secondary showers would likely not be much smaller than 10^{-26} cm². Contrary to the low-energy neutrinos from β decay one should be able to detect the energetic neutrinos from cosmic rays via their interactions.

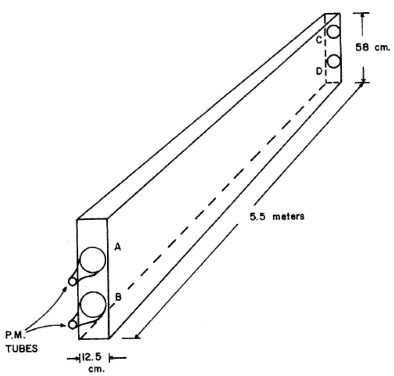
Werner Heisenberg
Zur Theorie der Schauerbildung in der Höhenstrahlung
Zeitschrift für Physik 101 (1936) 533

Detection of First Atmospheric Neutrinos 1965

Chase-Witwatersrand-Irvine (CWI) Coll.
Mine in South Africa, 8800 mwe

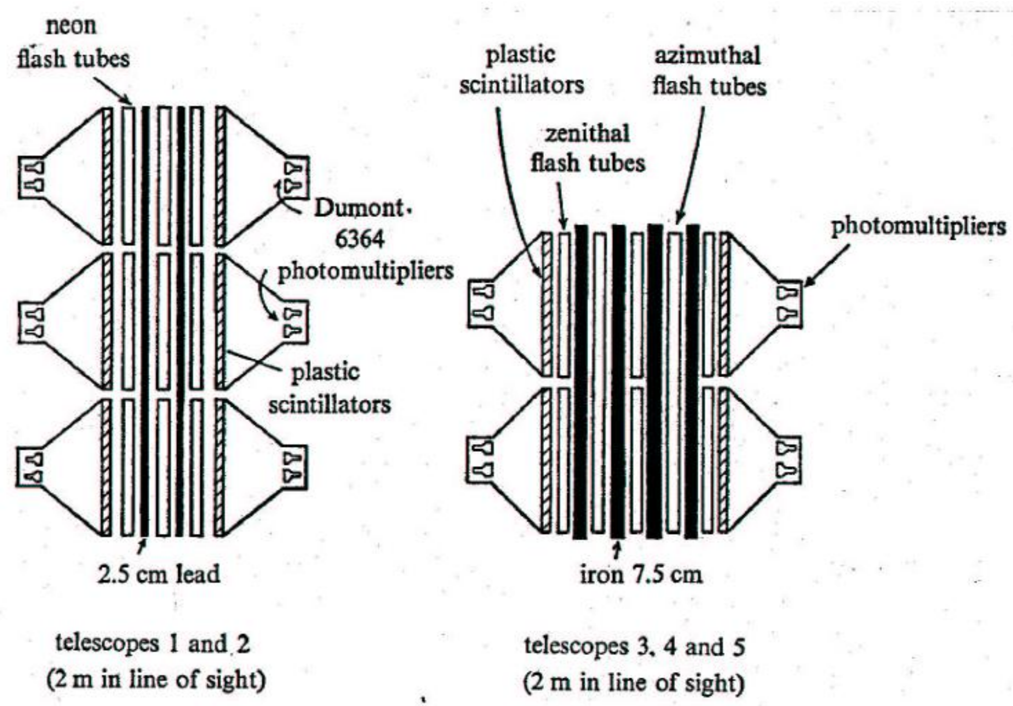
- Liquid scintillator
- Horizontal tracks



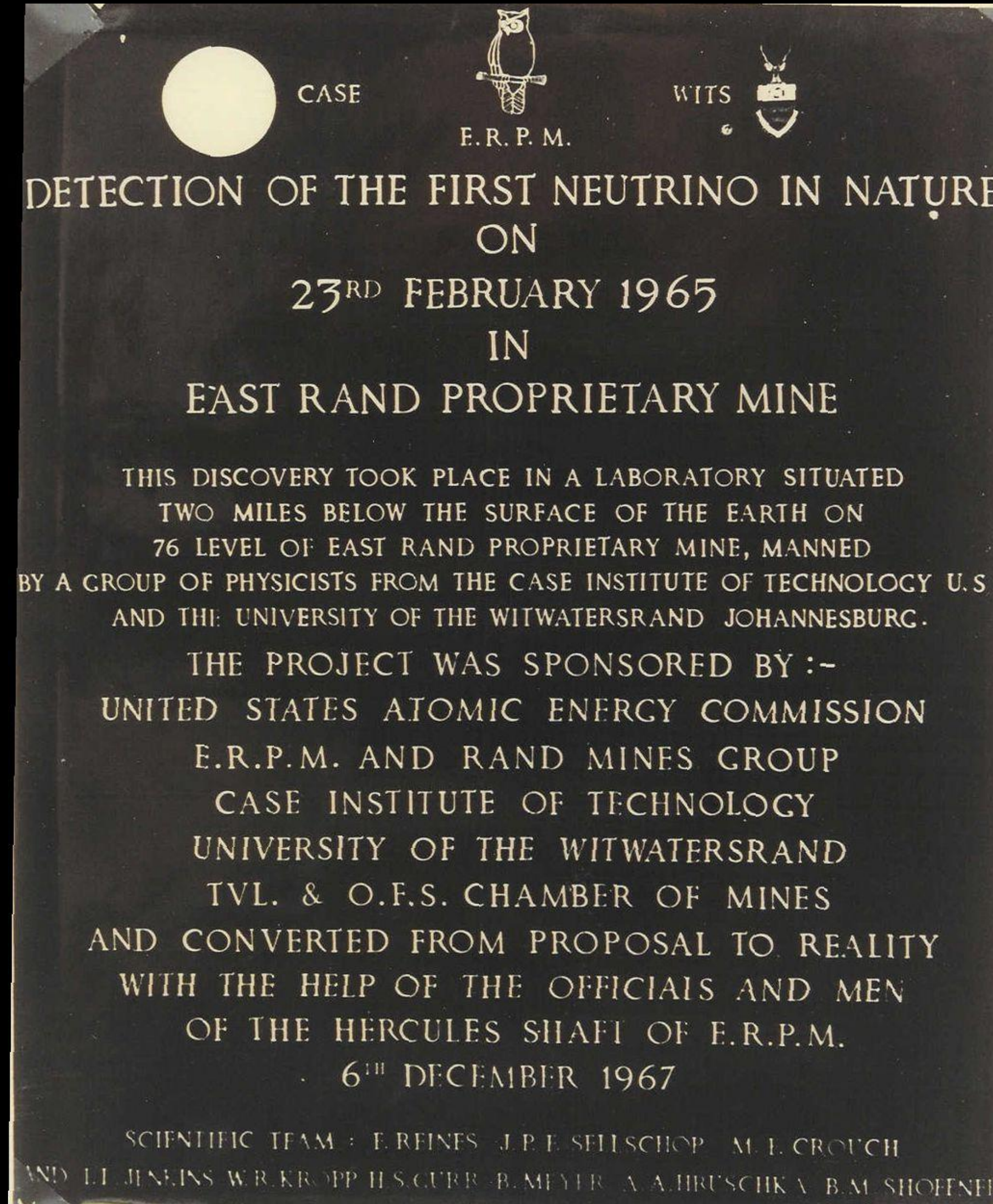


Kolar Gold Field (KGF) Collaboration
(Japan-India-UK group), 7500 mwe

- Plastic scintillator
- Flash tubes

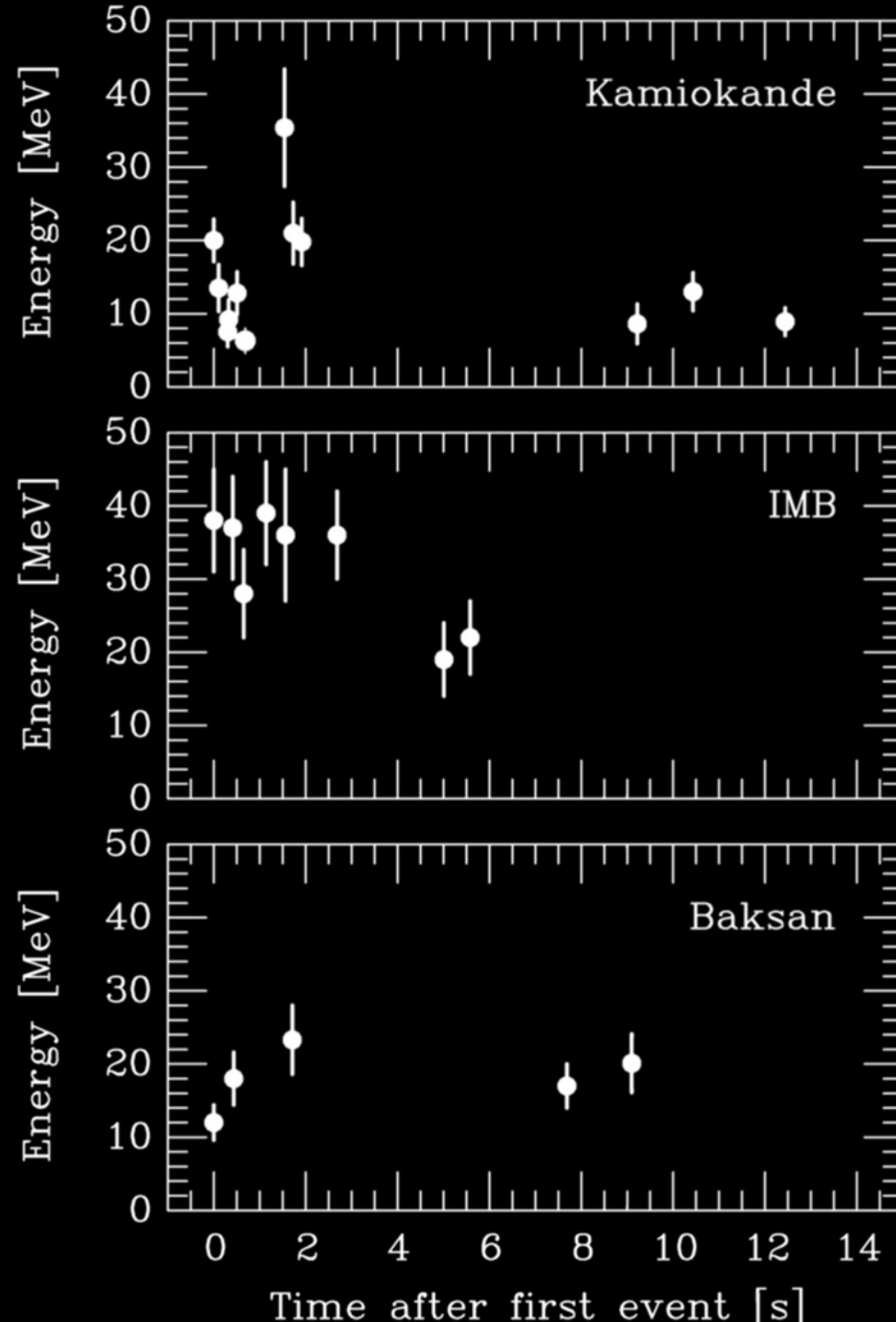


Slide adapted from Christian Spiering


CASE
E.R.P.M.
WITS
DETECTION OF THE FIRST NEUTRINO IN NATURE
ON
23RD FEBRUARY 1965
IN
EAST RAND PROPRIETARY MINE
THIS DISCOVERY TOOK PLACE IN A LABORATORY SITUATED
TWO MILES BELOW THE SURFACE OF THE EARTH ON
76 LEVEL OF EAST RAND PROPRIETARY MINE, MANNED
BY A GROUP OF PHYSICISTS FROM THE CASE INSTITUTE OF TECHNOLOGY U.S.A.
AND THE UNIVERSITY OF THE WITWATERSRAND JOHANNESBURG.
THE PROJECT WAS SPONSORED BY :-
UNITED STATES ATOMIC ENERGY COMMISSION
E.R.P.M. AND RAND MINES GROUP
CASE INSTITUTE OF TECHNOLOGY
UNIVERSITY OF THE WITWATERSRAND
TVL. & O.F.S. CHAMBER OF MINES
AND CONVERTED FROM PROPOSAL TO REALITY
WITH THE HELP OF THE OFFICIALS AND MEN
OF THE HERCULES SHAFT OF E.R.P.M.
6TH DECEMBER 1967
SCIENTIFIC TEAM : F. REINES J.P.F. SELLSCHOP M.F. CROUCH
AND T.L. JENKINS W.R. KROPP H.S. GURR B. MEYER A.A. HRUSCHKA B.M. SHOFFNER

Supernova 1987A

23 February 1987



MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York

(Received September 7, 1938)

The combination of four protons and two electrons can occur essentially only in two ways. The first mechanism starts with the combination of two protons to form a deuteron with positron emission, *viz.*

$$H+H=D+\epsilon^+. \quad (1)$$

The deuteron is then transformed into He^4 by further capture of protons; these captures occur very rapidly compared with process (1). The second mechanism uses carbon and nitrogen as catalysts, according to the chain reaction

$$\begin{aligned} &C^{12}+H=N^{13}+\gamma, \qquad N^{13}=C^{13}+\epsilon^+ \\ &C^{13}+H=N^{14}+\gamma, \\ &N^{14}+H=O^{15}+\gamma, \qquad O^{15}=N^{15}+\epsilon^+ \\ &N^{15}+H=C^{12}+He^4. \end{aligned} \quad (2)$$

Hans Bethe
1906–2005

- First mention of neutrino emission from stars
- Neutrino losses discussed, although overestimated

Dark Matter and Neutrinos, IHP, Paris, 5–9 May 2025

Neutrinos and the Stars

ORIGINS Excellence Cluster

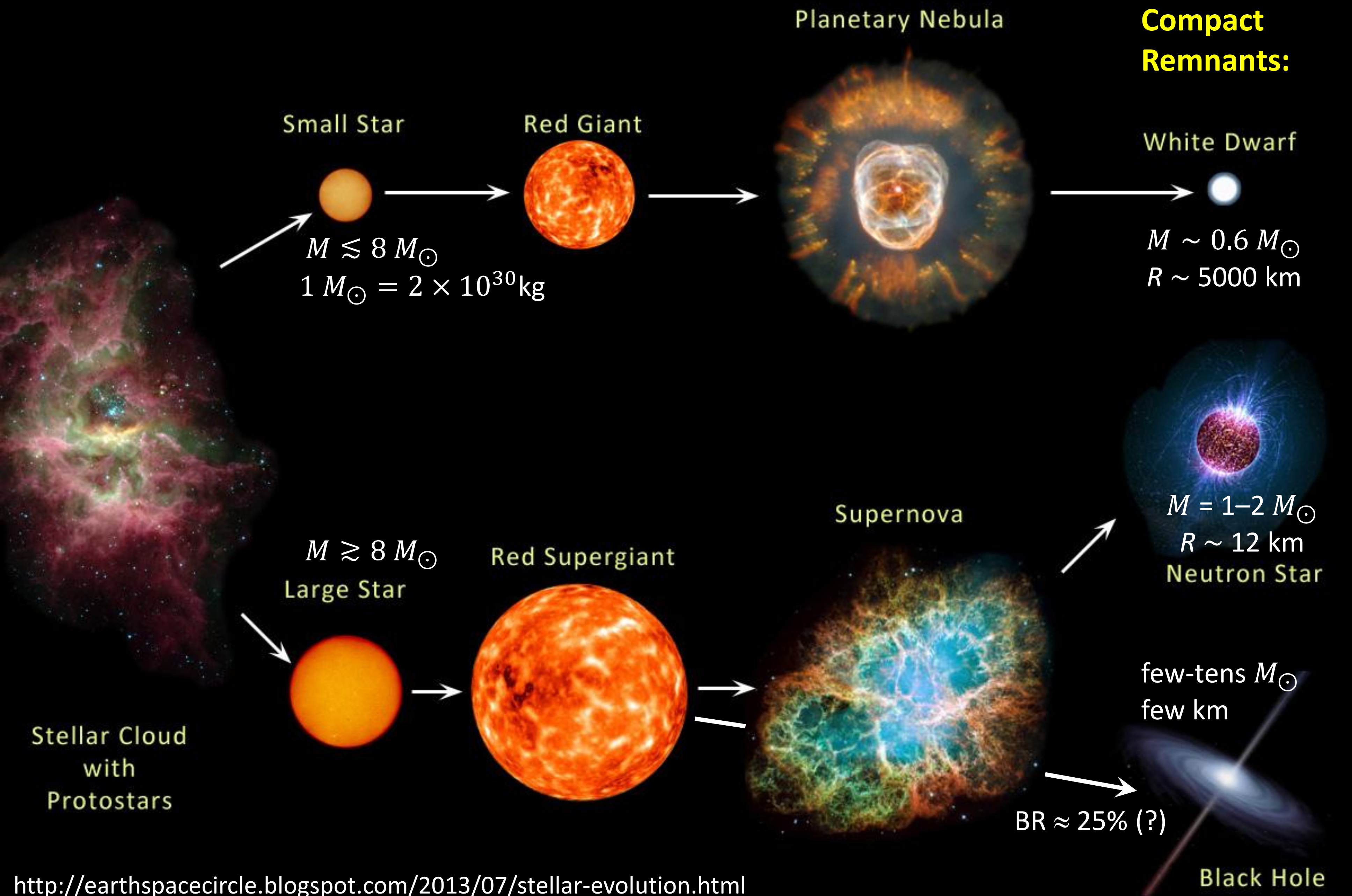
COSMIC WISPERS CA21106

MAX-PLANCK-INSTITUT FÜR PHYSIK

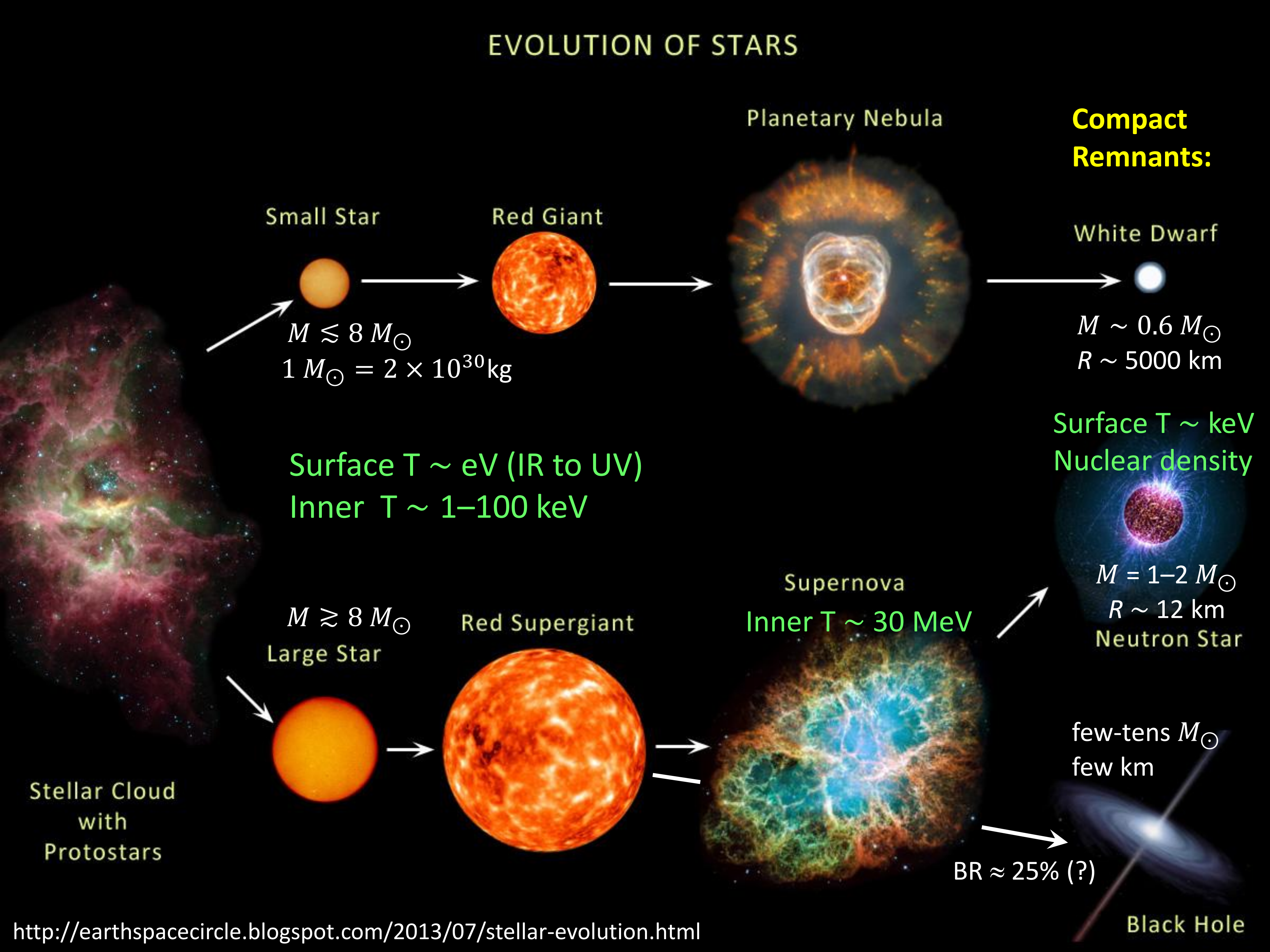
SFB 1258 Neutrinos Dark Matter Messengers

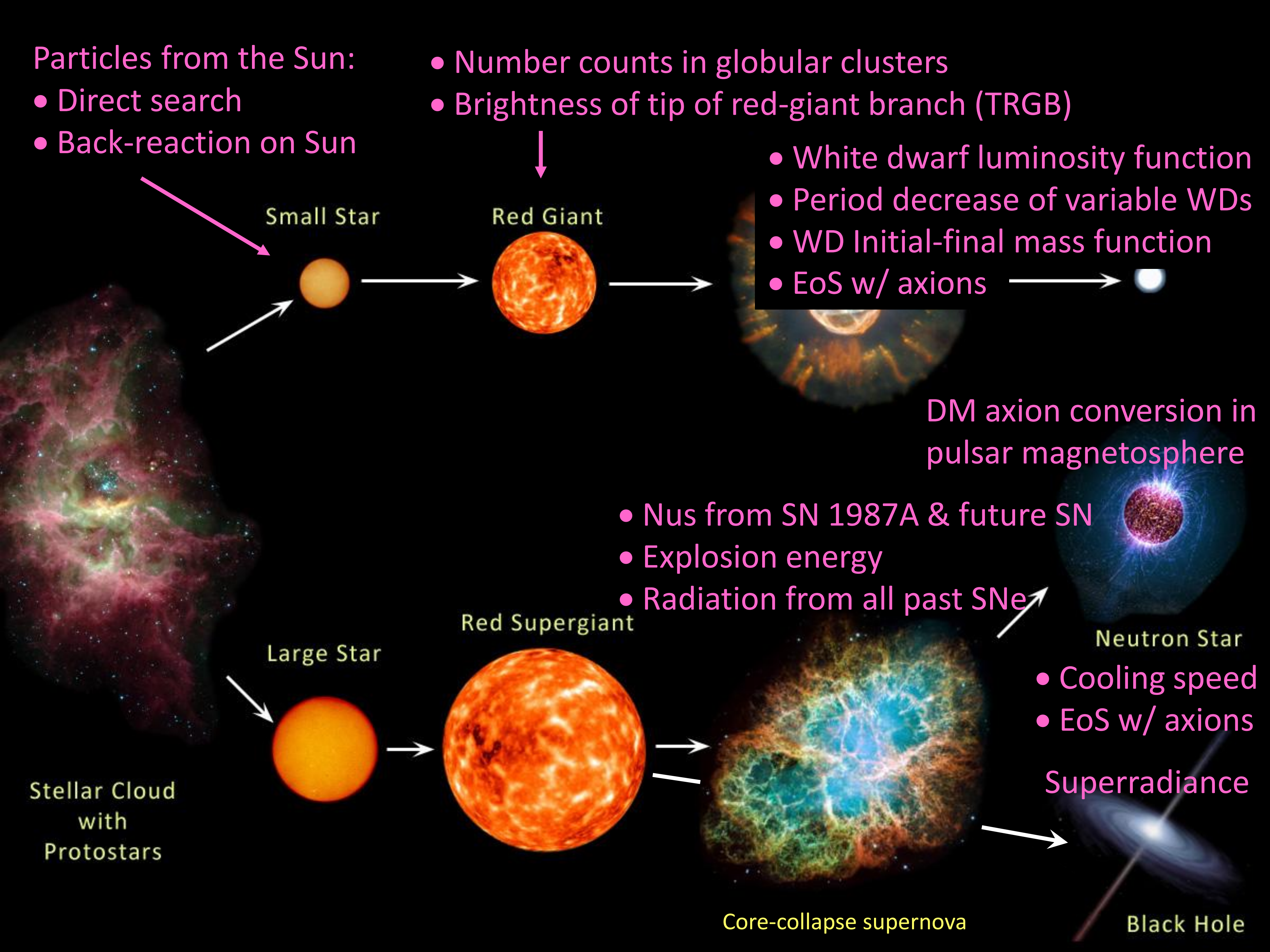
Georg G. Raffelt, Max-Planck-Institut für Physik, Garching

EVOLUTION OF STARS



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

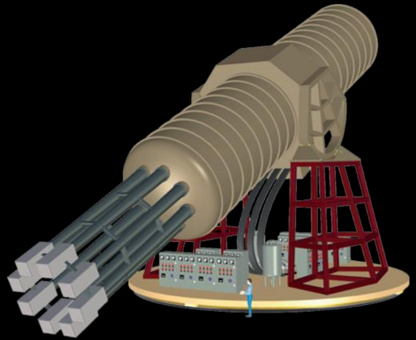

EVOLUTION OF STARS
Planetary Nebula
Compact Remnants:
Small Star
Red Giant
White Dwarf
$M \lesssim 8\,M_\odot$
$1\,M_\odot = 2 \times 10^{30}$kg
$M \sim 0.6\,M_\odot$
$R \sim 5000$ km
Surface T ~ keV
Nuclear density
Surface T ~ eV (IR to UV)
Inner T ~ 1–100 keV
Supernova
$M = 1$–$2\,M_\odot$
$R \sim 12$ km
Neutron Star
$M \gtrsim 8\,M_\odot$
Large Star
Red Supergiant
Inner T ~ 30 MeV
few-tens $M_\odot$
few km
Stellar Cloud with Protostars
BR ≈ 25% (?)
Black Hole
http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html


Particles from the Sun:
• Direct search
• Back-reaction on Sun
• Number counts 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
Red Supergiant
Large Star
Neutron Star
• Cooling speed
• EoS w/ axions
Superradiance
Stellar Cloud with Protostars
Core-collapse supernova
Black Hole

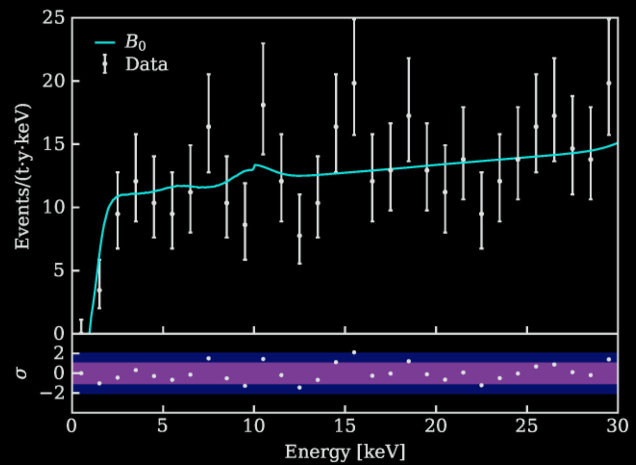
Particles from the Sun

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

2015 Solar Nu Oscillations (A.McDonald)

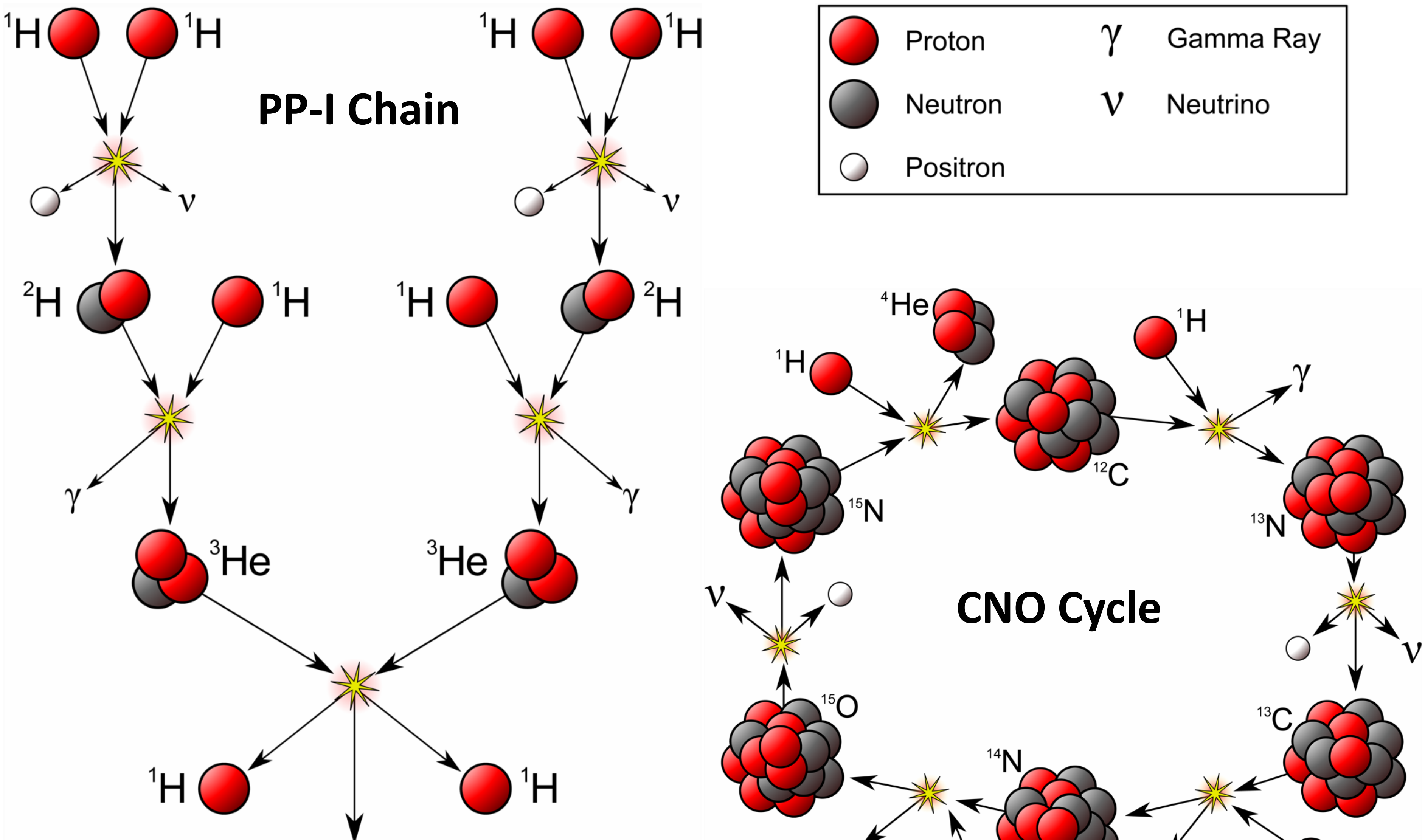


Search for solar axions
with CAST and future IAXO



No excess in XENONnT
arXiv:2207.11330
Bounds on axions,
dark photons, neutrino
dipole moments

Hydrogen Burning

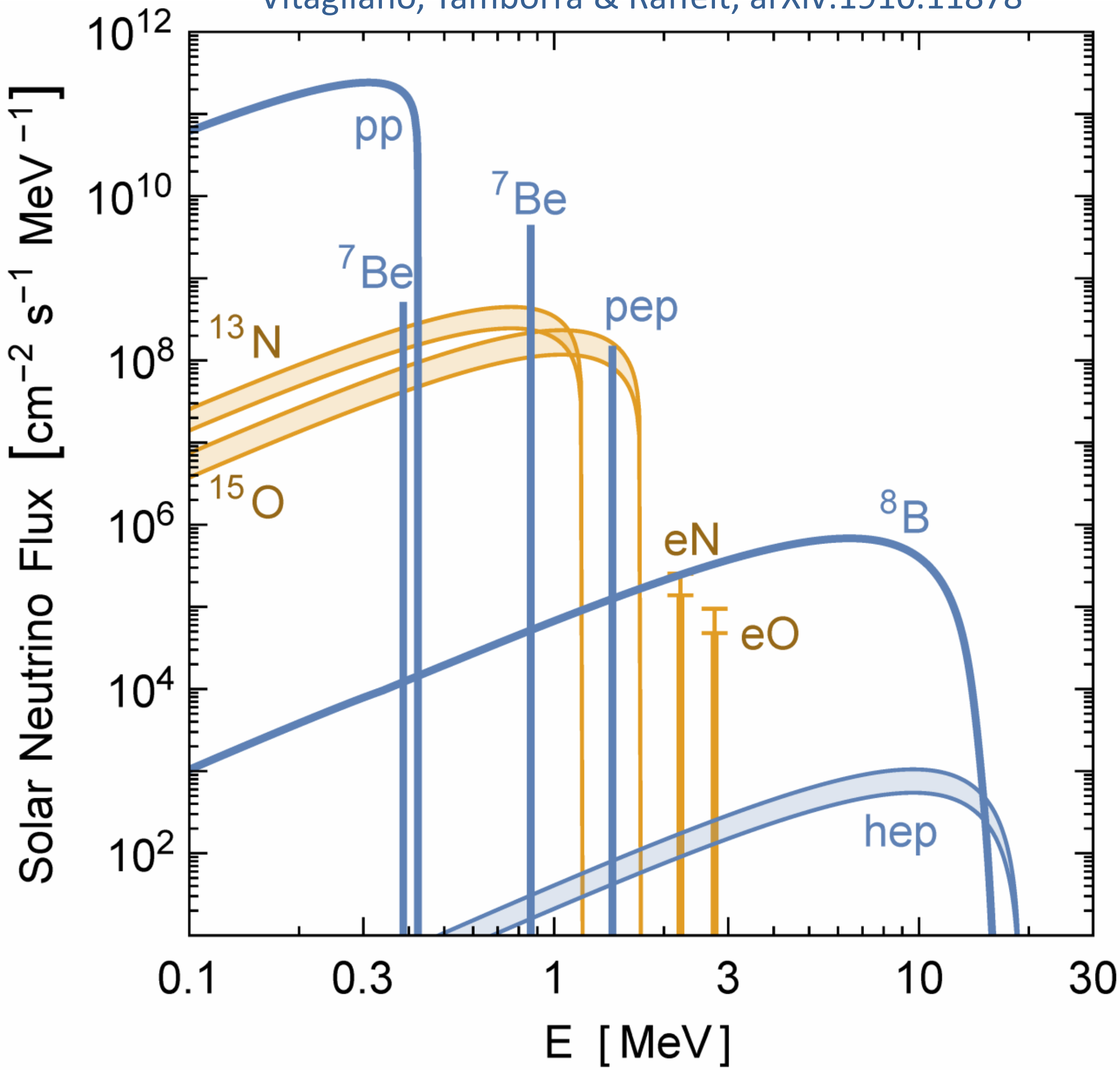


$4p + 2e \rightarrow {}^{4}He + 2\nu_e + 26.7\ \text{MeV}$

Image 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

“Nuclear” vs. Thermal Neutrinos

- **Hydrogen burning**
  Effectively proton-neutron conversion
  $$4p + 2e \rightarrow {}^{4}\mathrm{He} + 2\nu_e$$
  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
  $$3\alpha \rightarrow {}^{12}\mathrm{C}$$
  No proton-neutron conversion necessary, no “nuclear” neutrinos

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

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

Thermal Neutrinos: Production Processes

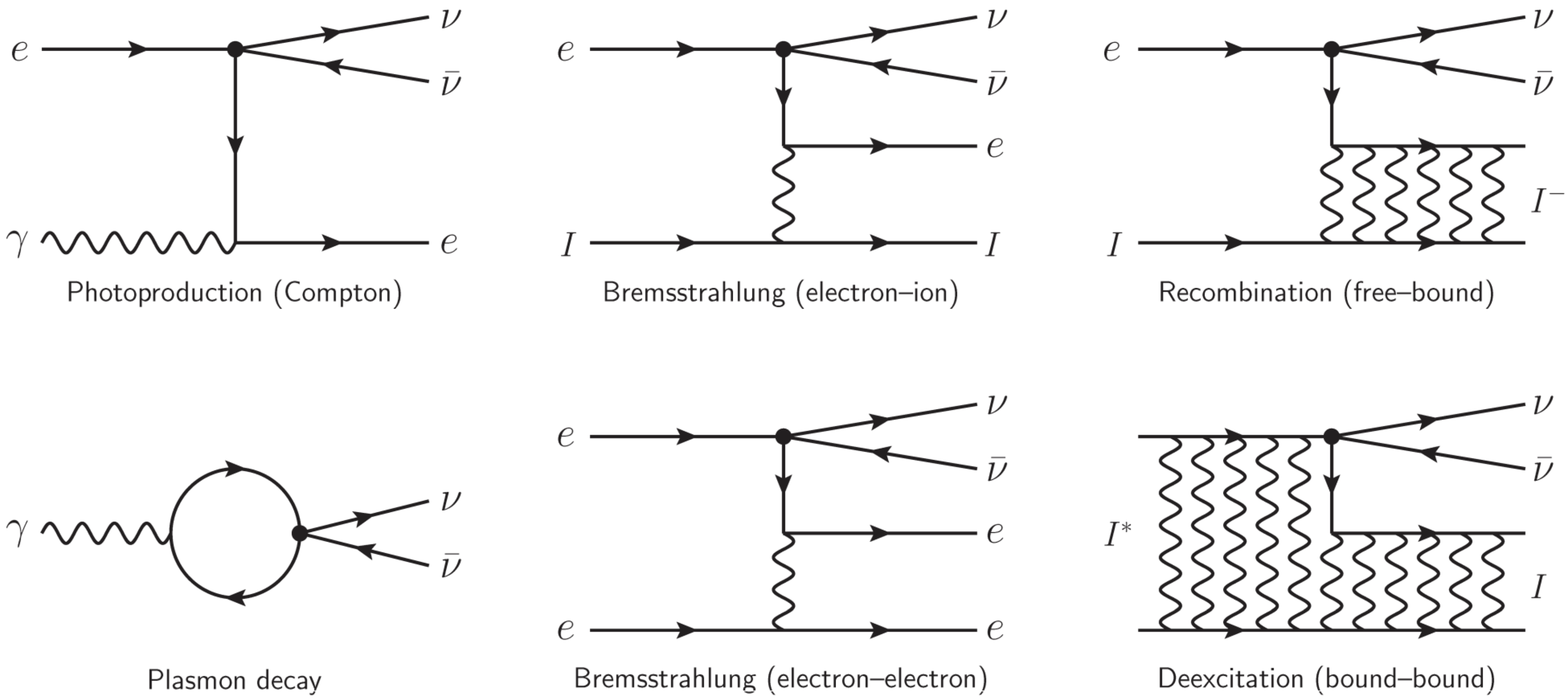
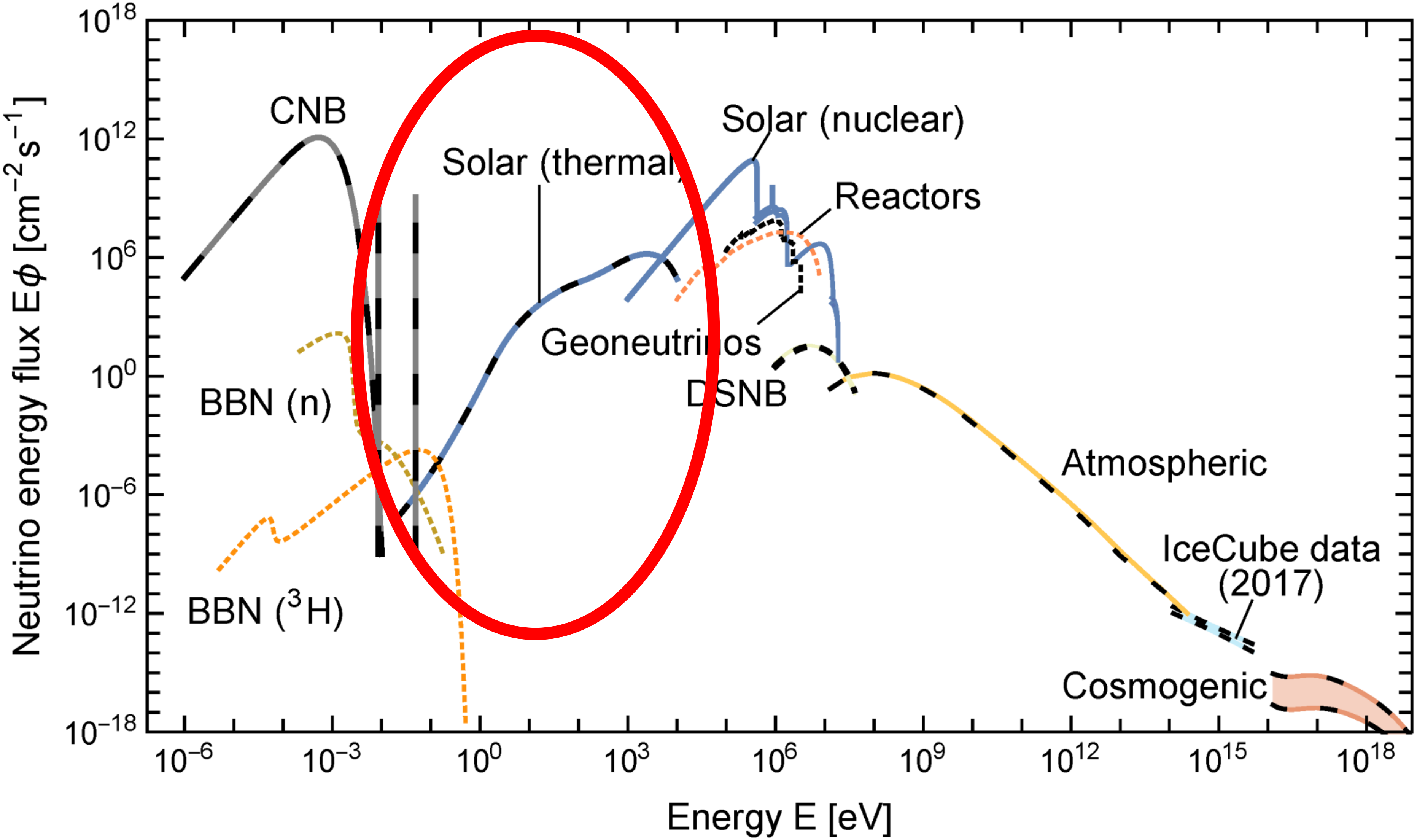


Figure 1. Processes for thermal neutrino pair production in the Sun.

Vitagliano, Redondo & Raffelt, arXiv:1708.02248

Grand Unified Neutrino Spectrum (GUNS) at Earth

Vitagliano, Tamborra & Raffelt, arXiv:1910.11878



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

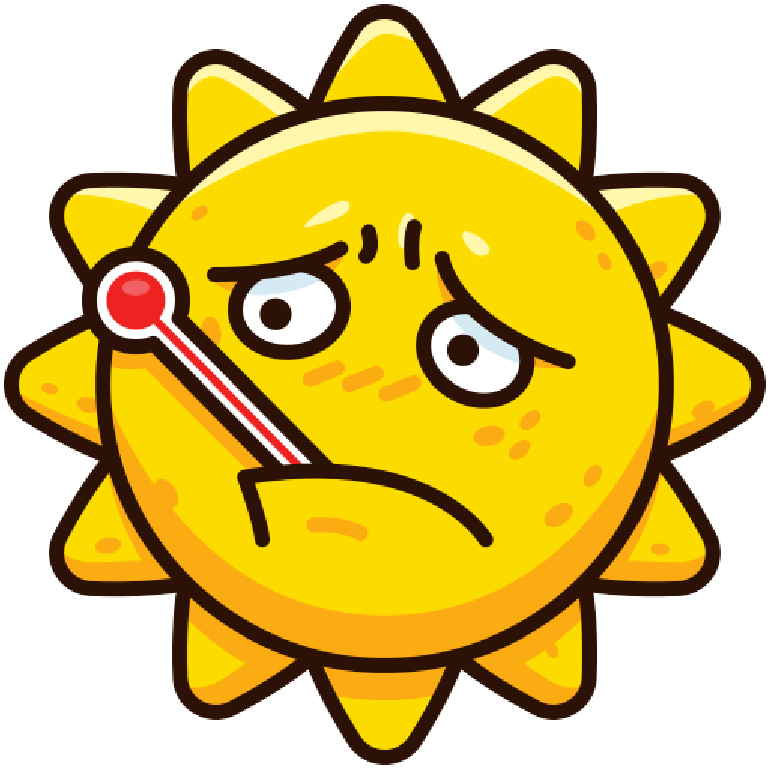
$$\langle E_{\rm grav}\rangle = -\frac{3}{2}\frac{G_N M_{\rm sun} m_p}{R_{\rm sun}} = -3.2\ {\rm keV}$$

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

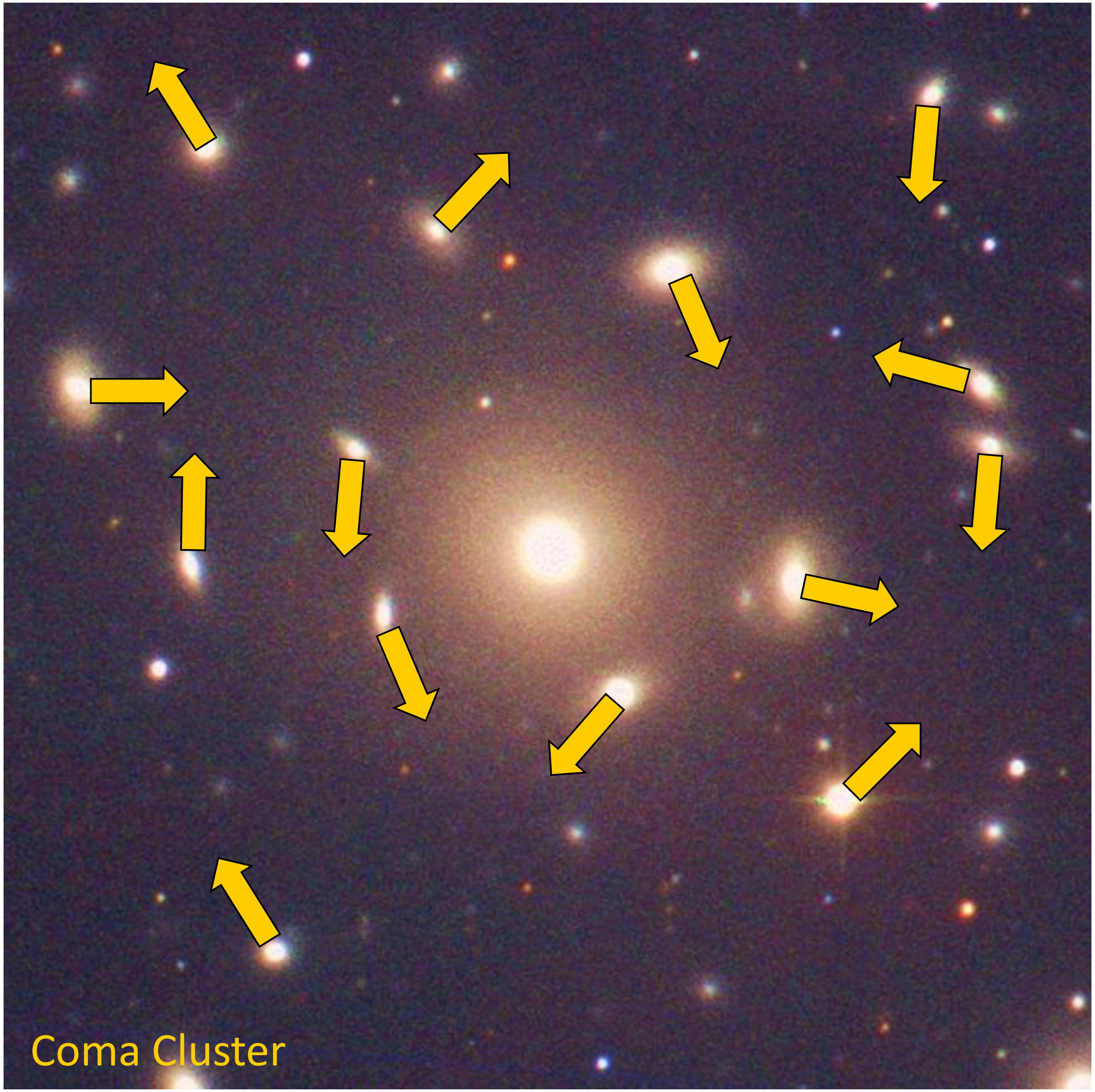
$T = 1.1\ {\rm keV}$



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

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

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

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

Velocity dispersion from Doppler shifts and geometric size

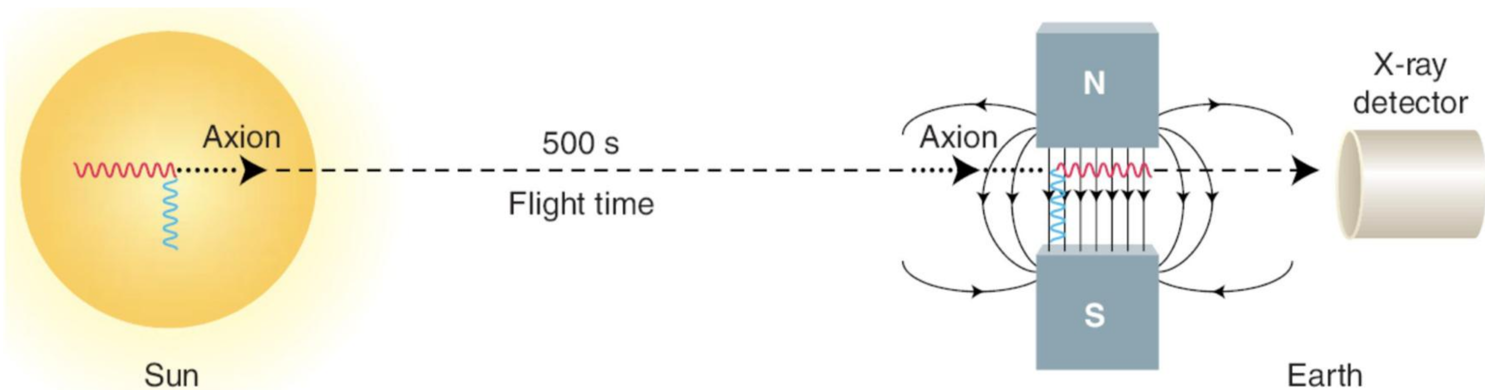
Total Mass

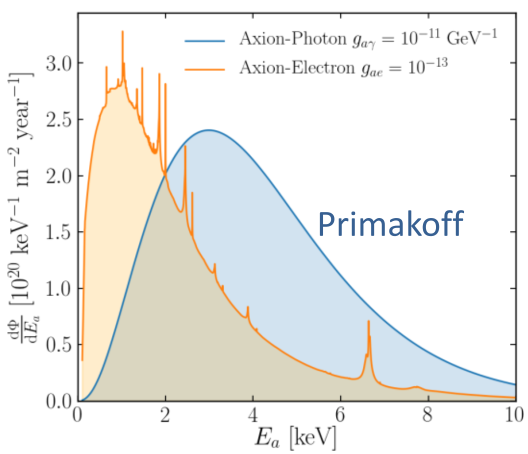
VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

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

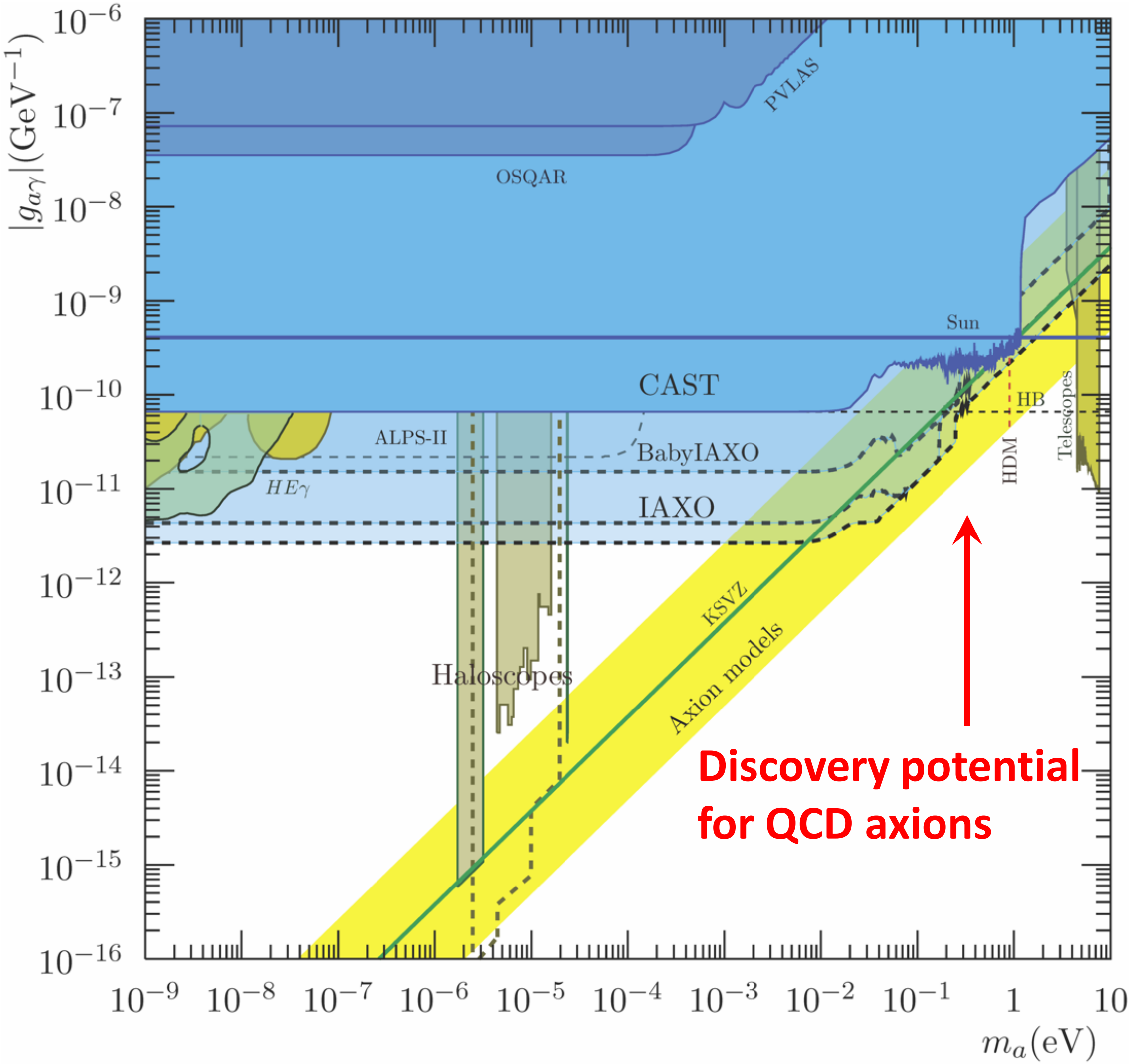
Anastassopoulos+ [1705.02290]

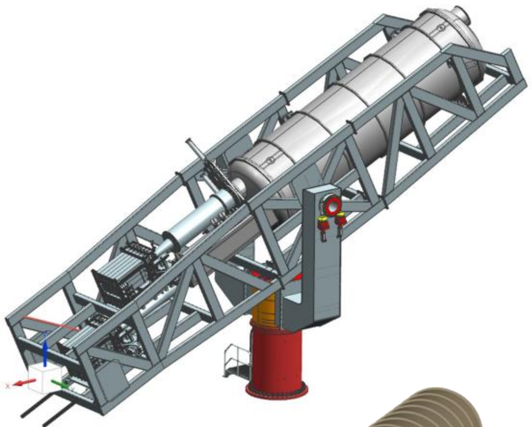
$G_{a\gamma\gamma} < 0.66 \times 10^{-10}\ \mathrm{GeV}^{-1}$

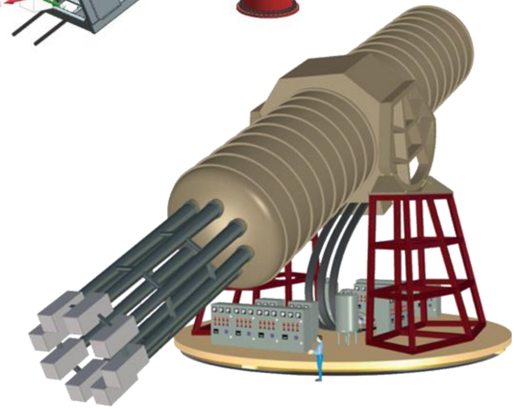
CAST Movie on YouTube

https://youtu.be/XY2lFDXz8aQ

(Baby) IAXO Sensitivity Forecast





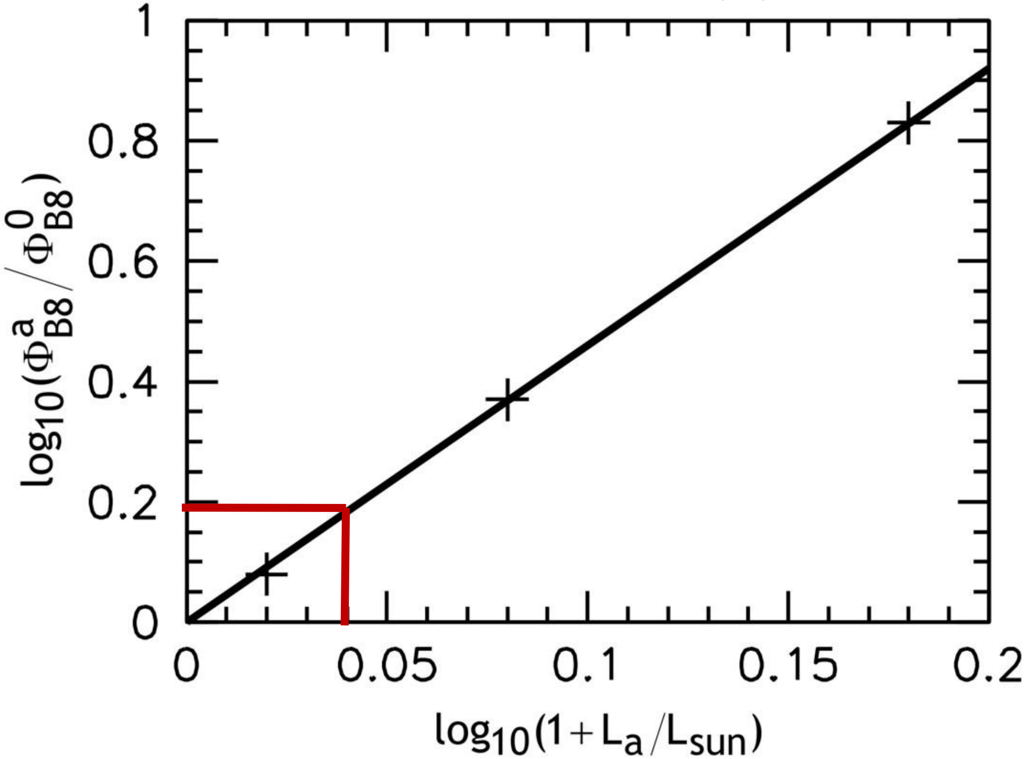


Physics potential of the International Axion Observatory (IAXO)
JCAP 1906 (2019) 047, arXiv:1904.09155

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

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

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

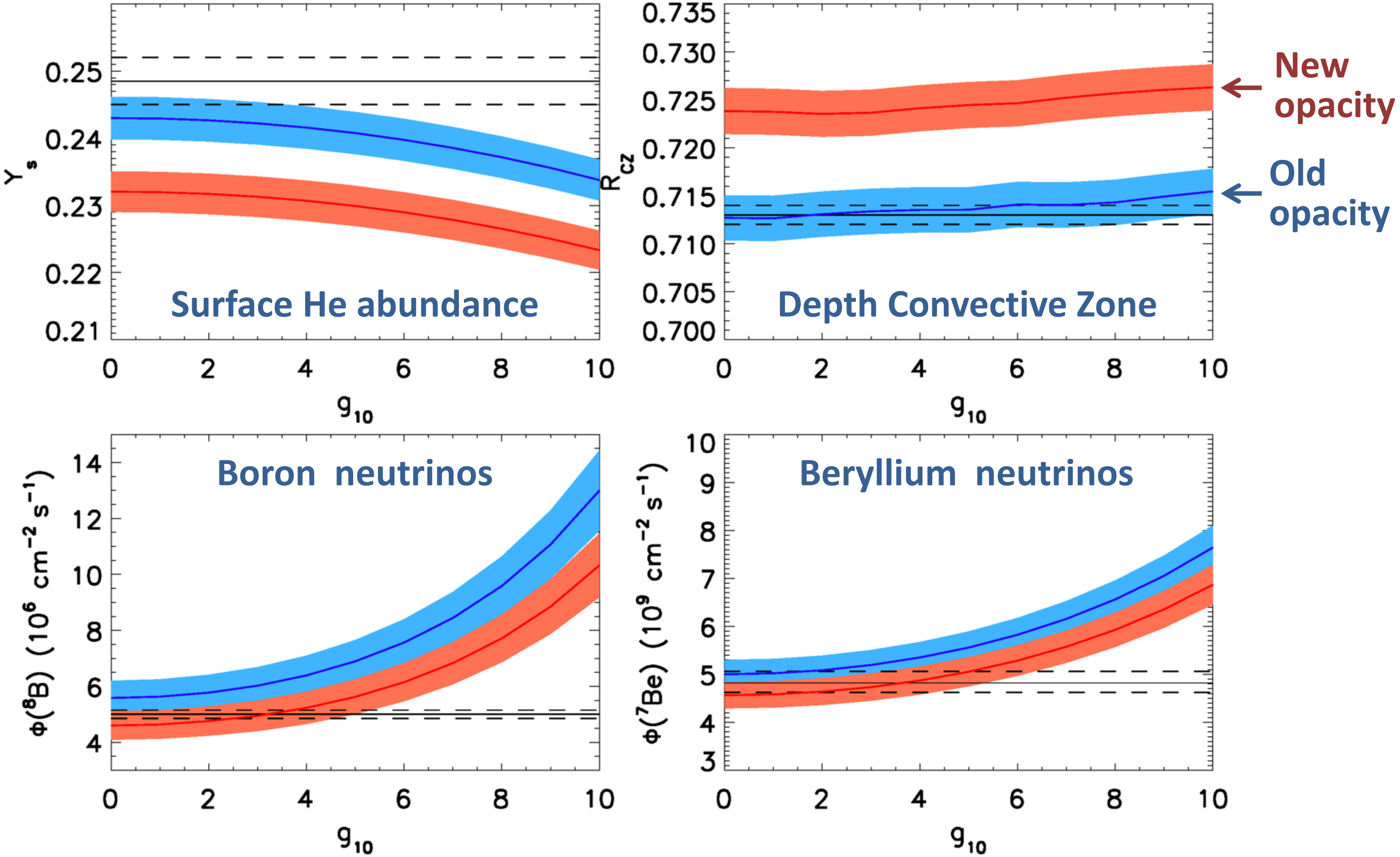
$$\Phi_{B8,a} = \Phi_{B8,a}\left(\frac{L_\odot + L_a}{L_\odot}\right)^{4.6}$$

Solar models with SNO all-flavor measurements imply roughly

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

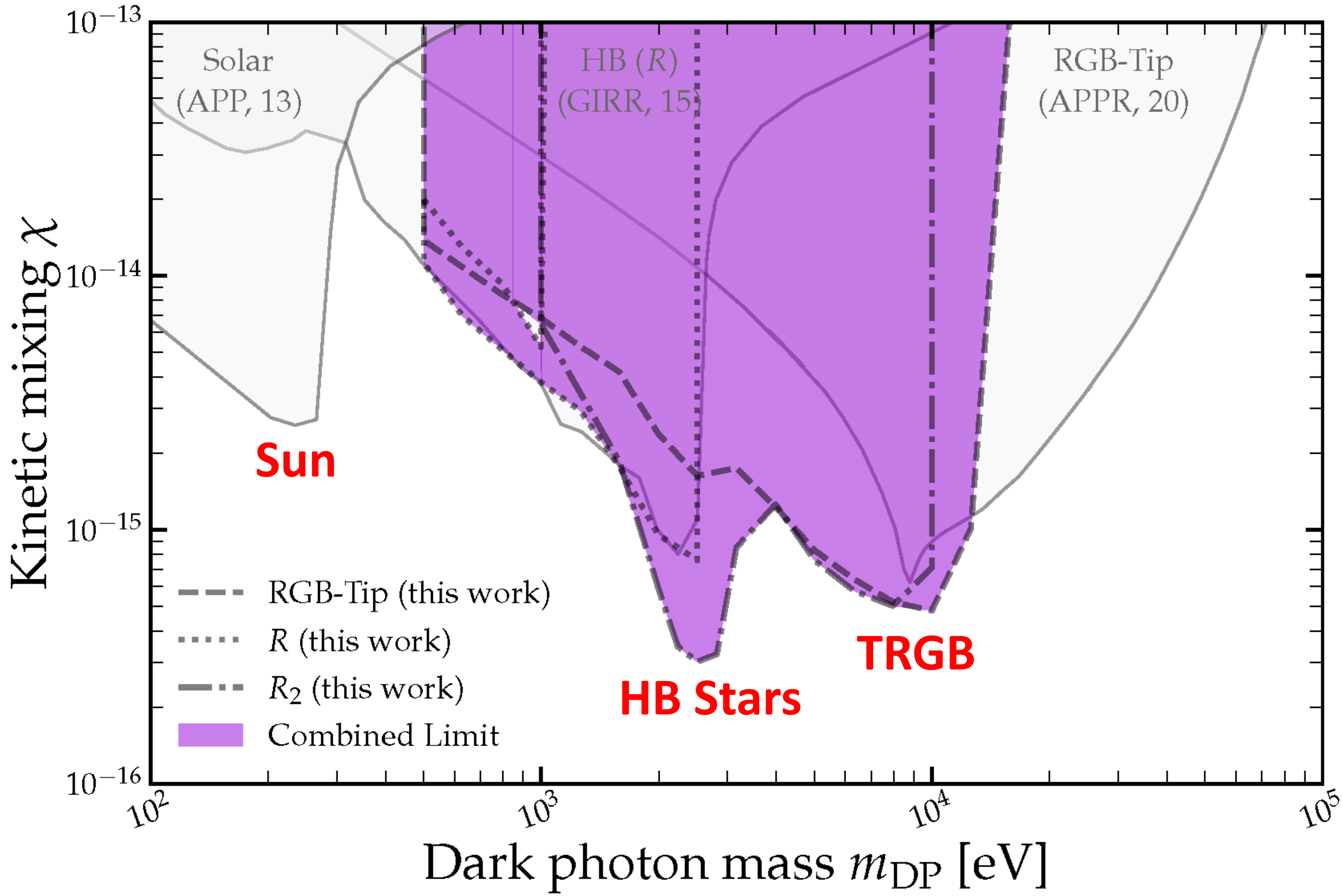
$$L_a = \left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2 1.85\times 10^{-3} L_\odot \;\Rightarrow\; g_{a\gamma} \lesssim 7\times 10^{-10}\mathrm{GeV}^{-1}$$

Solar Observables Modified by Axion Losses



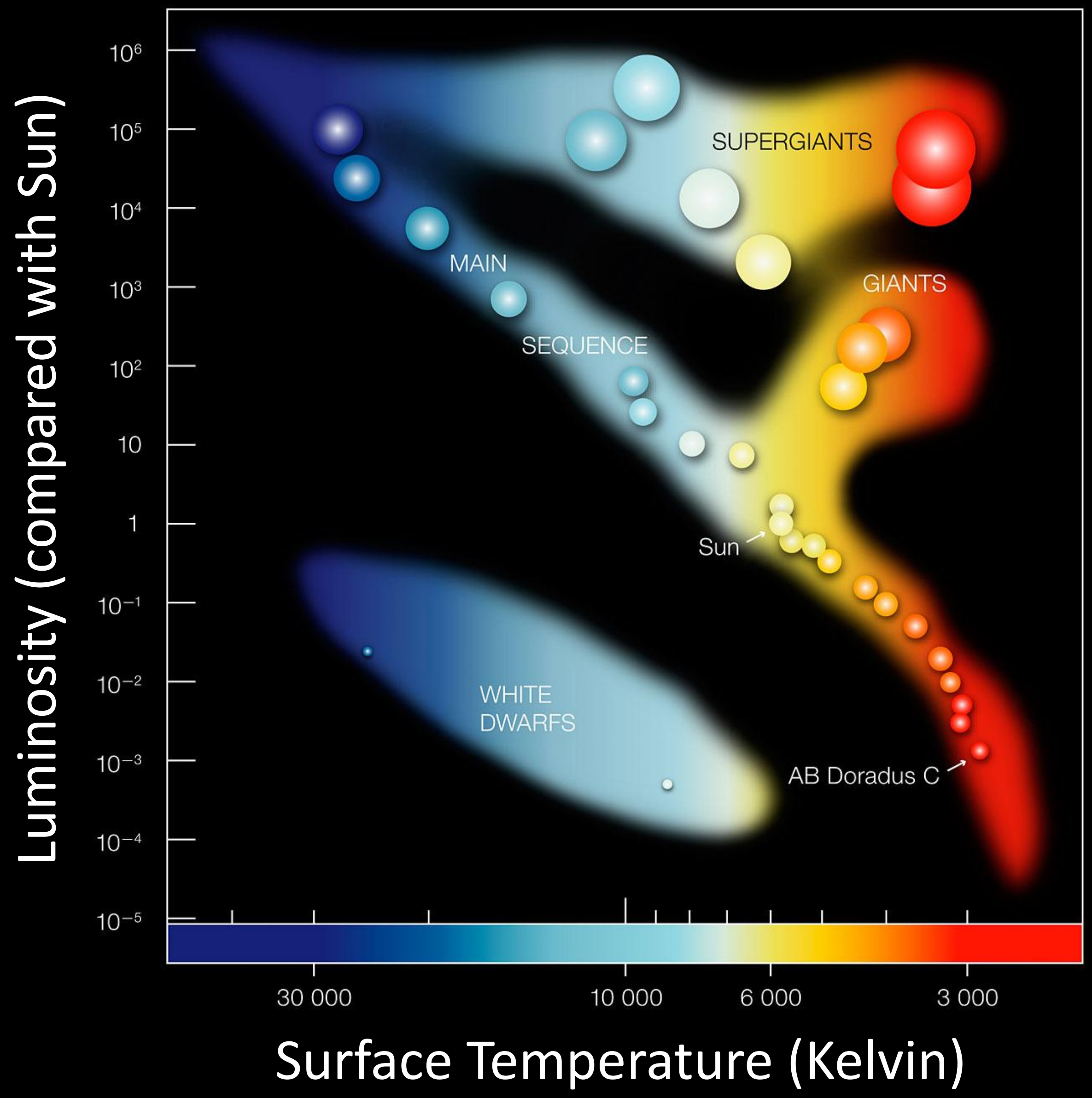
Vinyoles, Serenelli, Villante, Basu, Redondo & Isern, arXiv:1501.01639

Hidden Photon Limits



Dolan, Hiskens & Volkas, arXiv:2306.13335

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

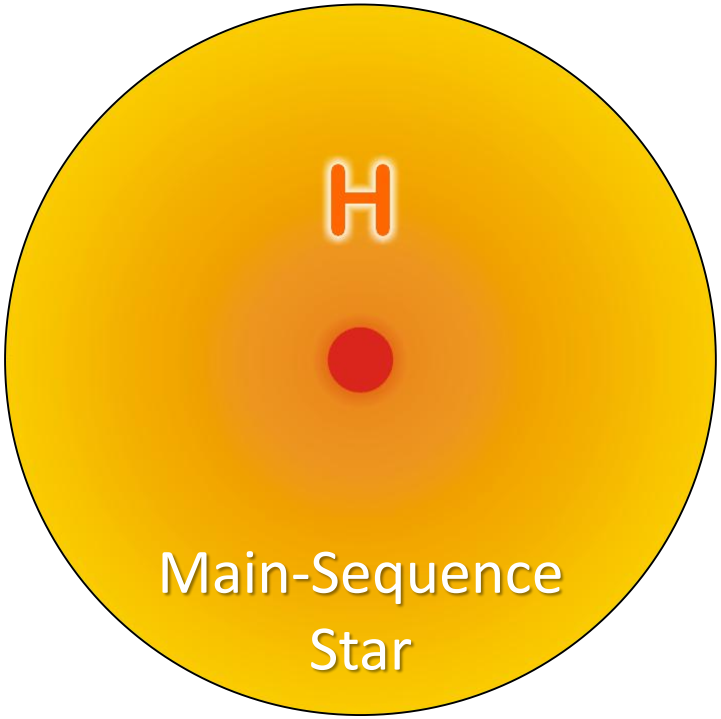
$$L_r = \frac{4\pi r^2}{3\kappa\rho}\frac{d(aT^4)}{dr}$$

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 $\kappa_\gamma \rho = \langle\lambda_\gamma\rangle^{-1}_{\rm Rosseland}$
$\kappa_{\rm c}$	Electron conduction

Self-Regulated Nuclear Burning



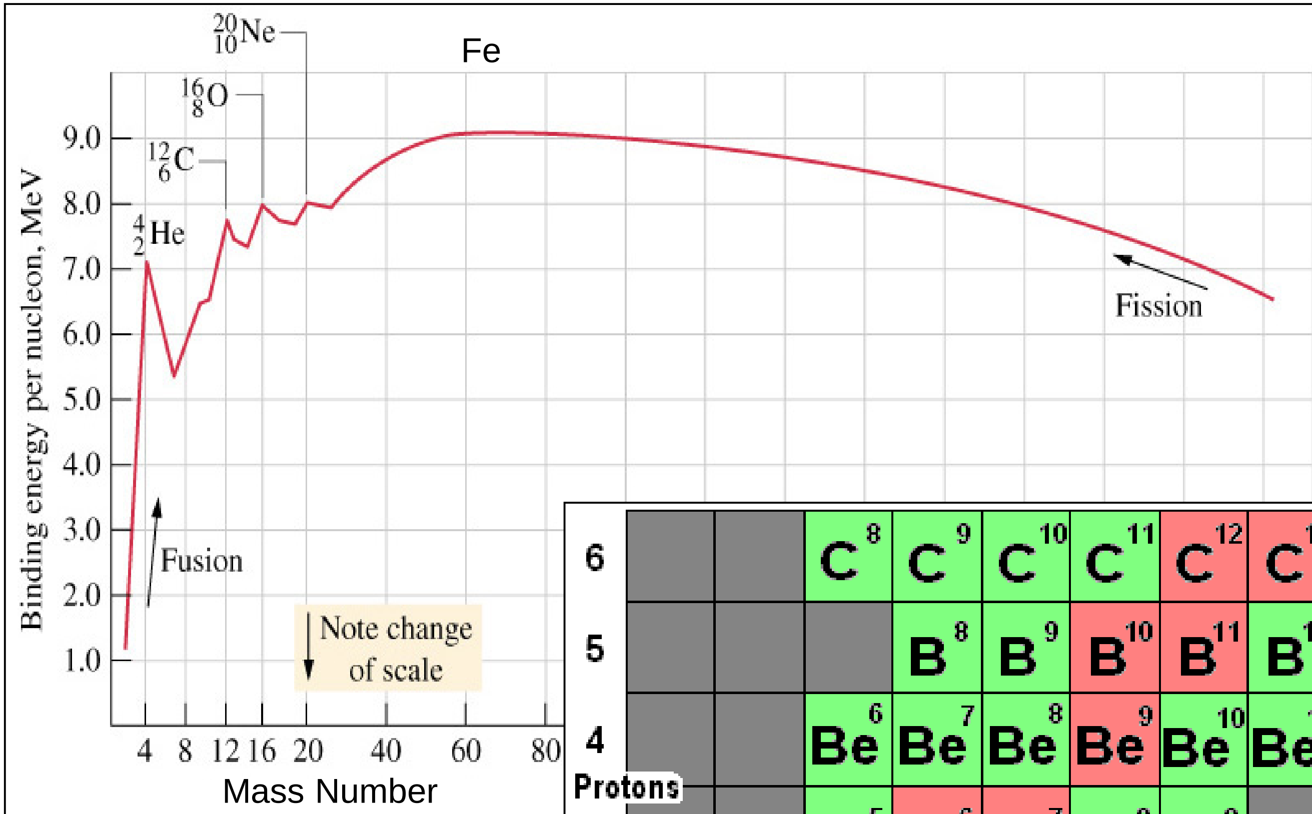
Virial Theorem: $\langle E_{\mathrm{kin}} \rangle = -\frac{1}{2} \langle E_{\mathrm{grav}} \rangle$

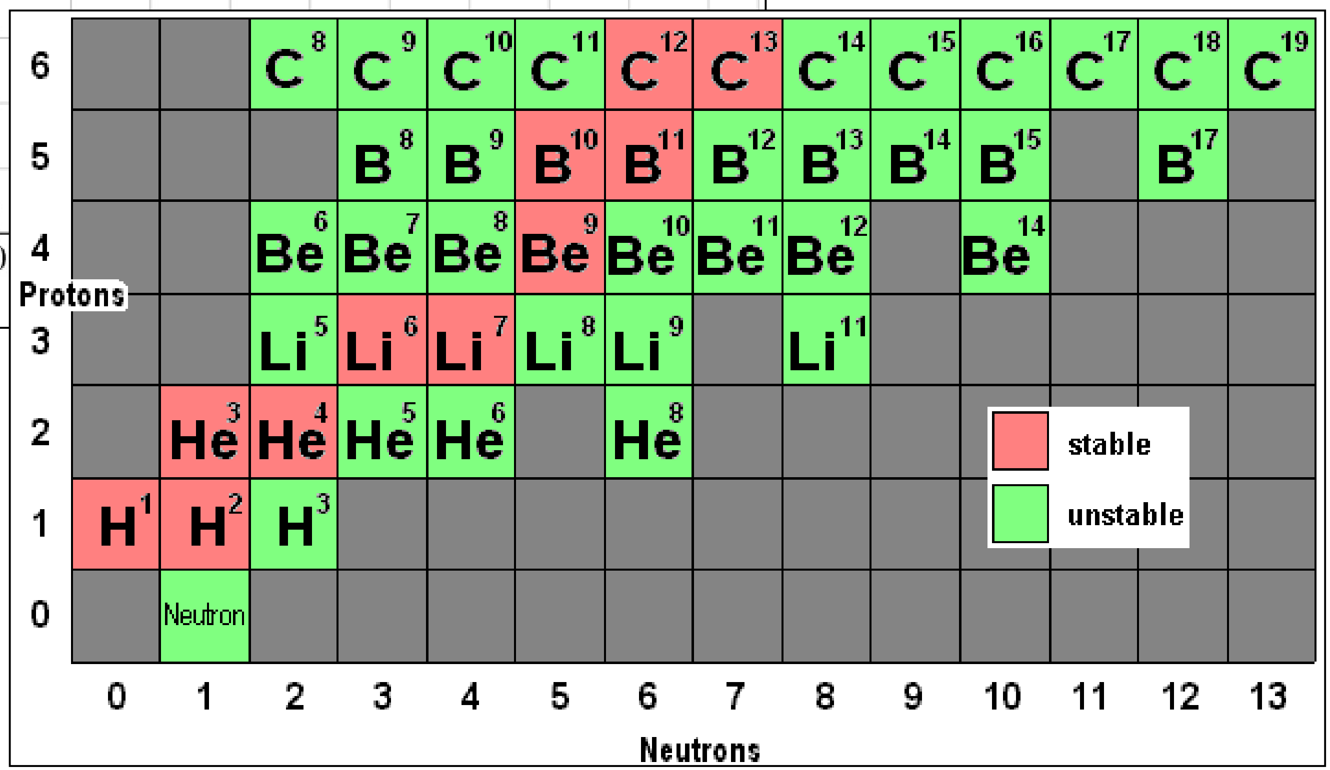
Small Contraction
$\rightarrow$ Heating
$\rightarrow$ Increased nuclear burning
$\rightarrow$ Increased pressure
$\rightarrow$ Expansion

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

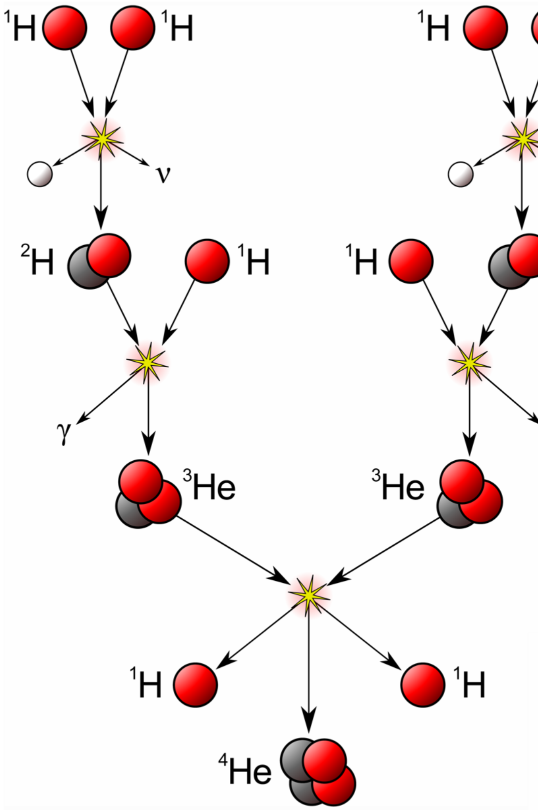
Hydrogen burning at nearly fixed T
$\rightarrow$ Gravitational potential nearly fixed:
$G_{\mathrm{N}} M/R \sim \mathrm{constant}$
$\rightarrow$ $R \propto M$ (More massive stars bigger)

Nuclear Binding Energy

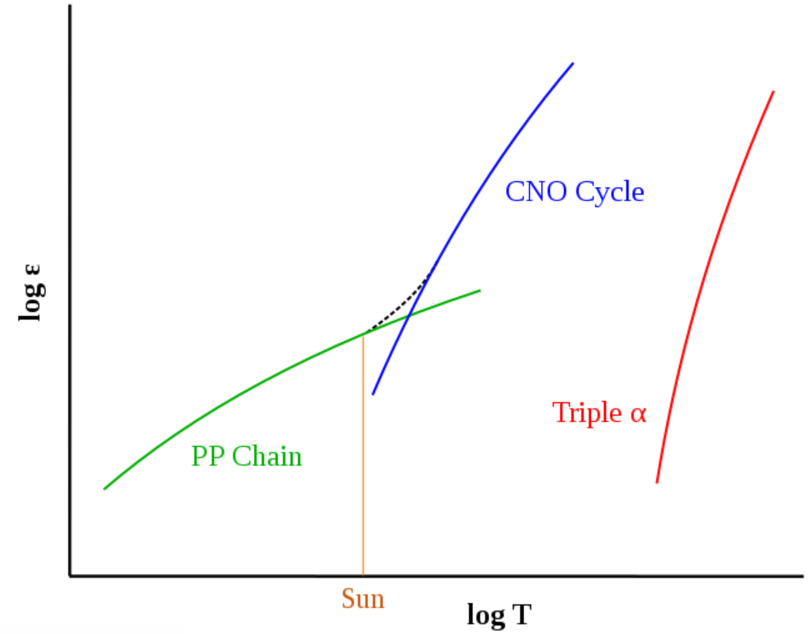


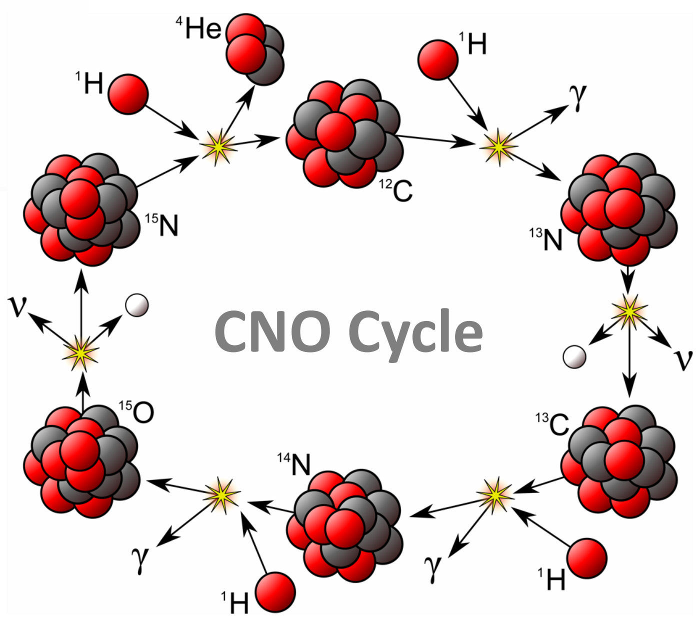


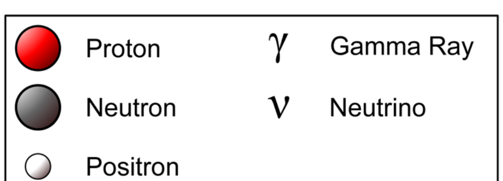
Hydrogen Burning in Stars



pp-I Chain







Picture credit Wikipedia

Thermonuclear Reactions and Gamow Peak

Coulomb repulsion prevents nuclear reactions, except for Gamow tunneling

Tunneling probability

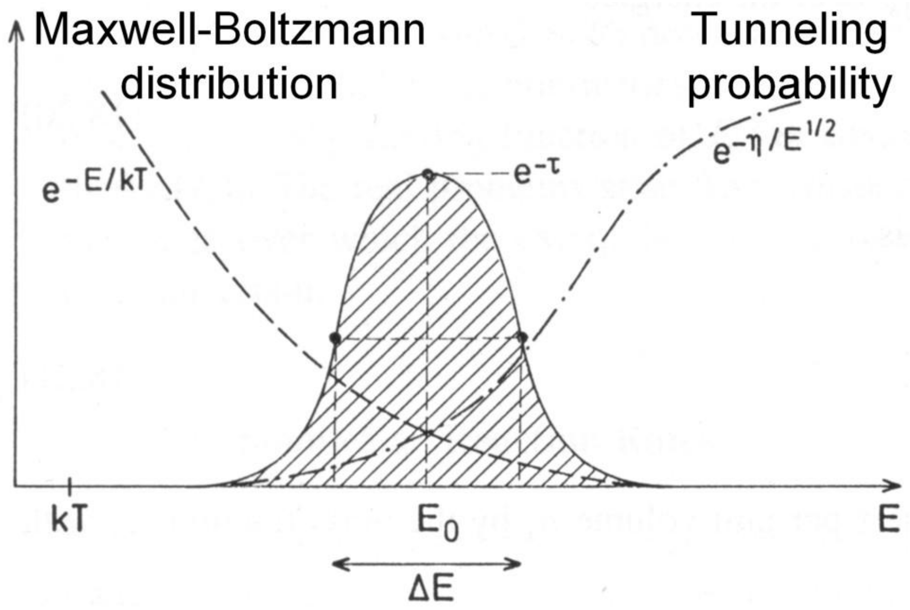
$$p \propto E^{-1/2} e^{-2\pi\eta}$$

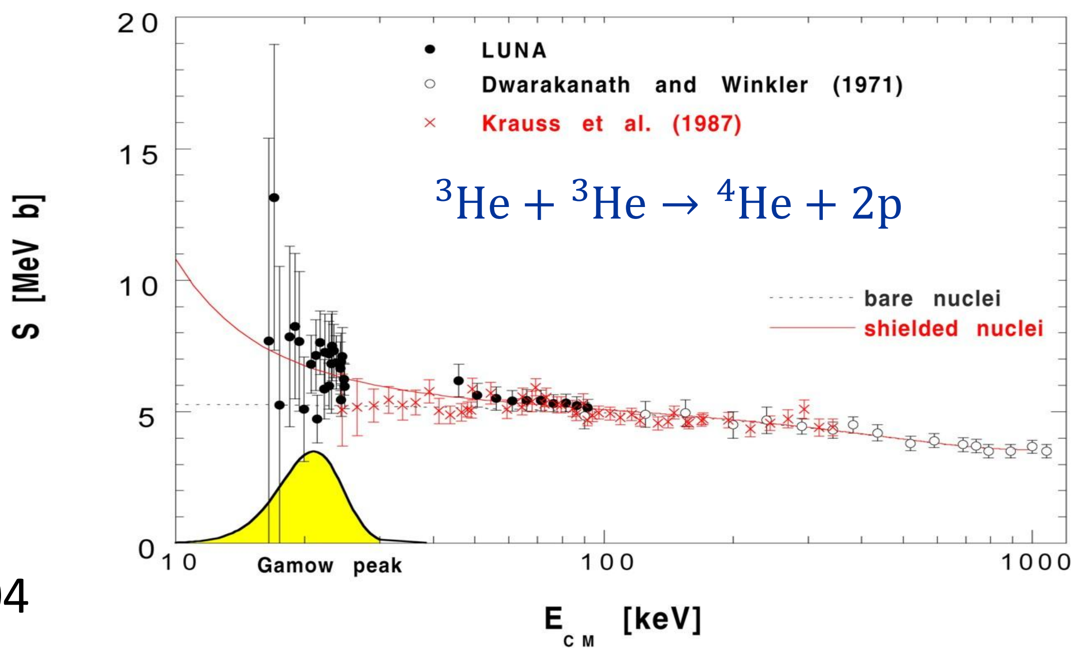
where the Sommerfeld parameter is

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

Parameterize cross section with astrophysical S-factor

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





LUNA Collaboration, nucl-ex/9902004

Main Nuclear Burning Stages

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

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

Helium burning

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

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

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

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

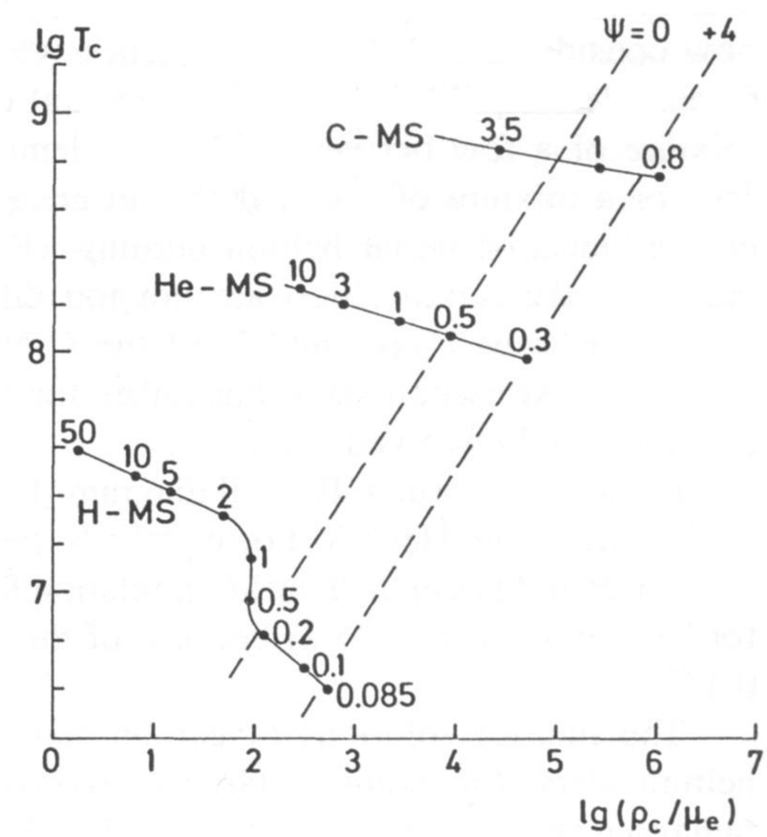
Carbon burning

Many reactions, for example

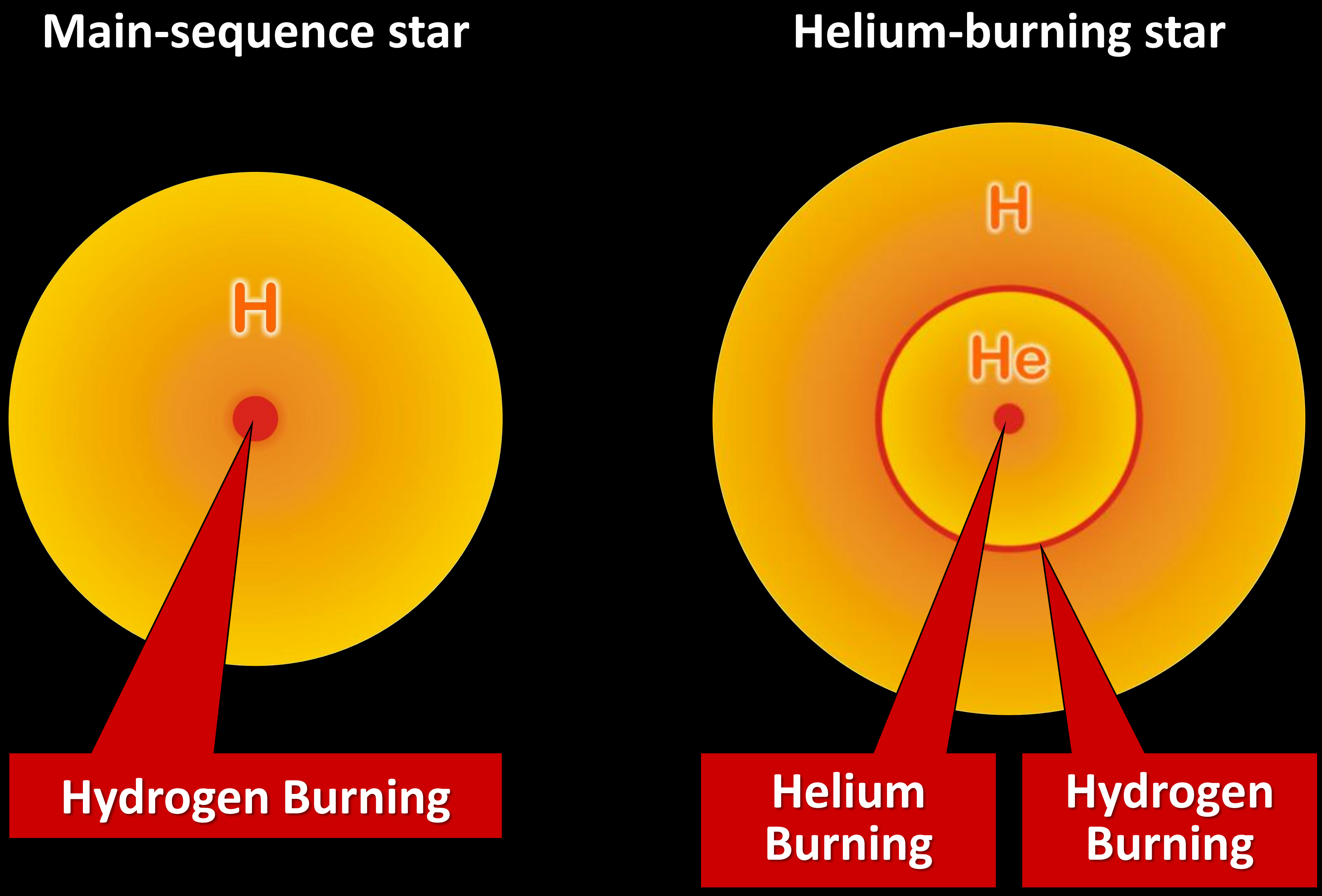
${}^{12}C + {}^{12}C \rightarrow {}^{23}Na + p$ or ${}^{20}Ne + {}^4He$ etc

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

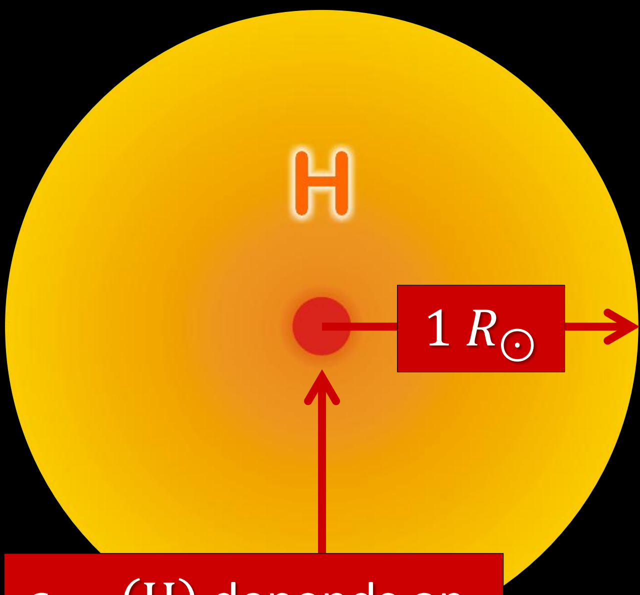


Hydrogen Exhaustion



Giant Stars

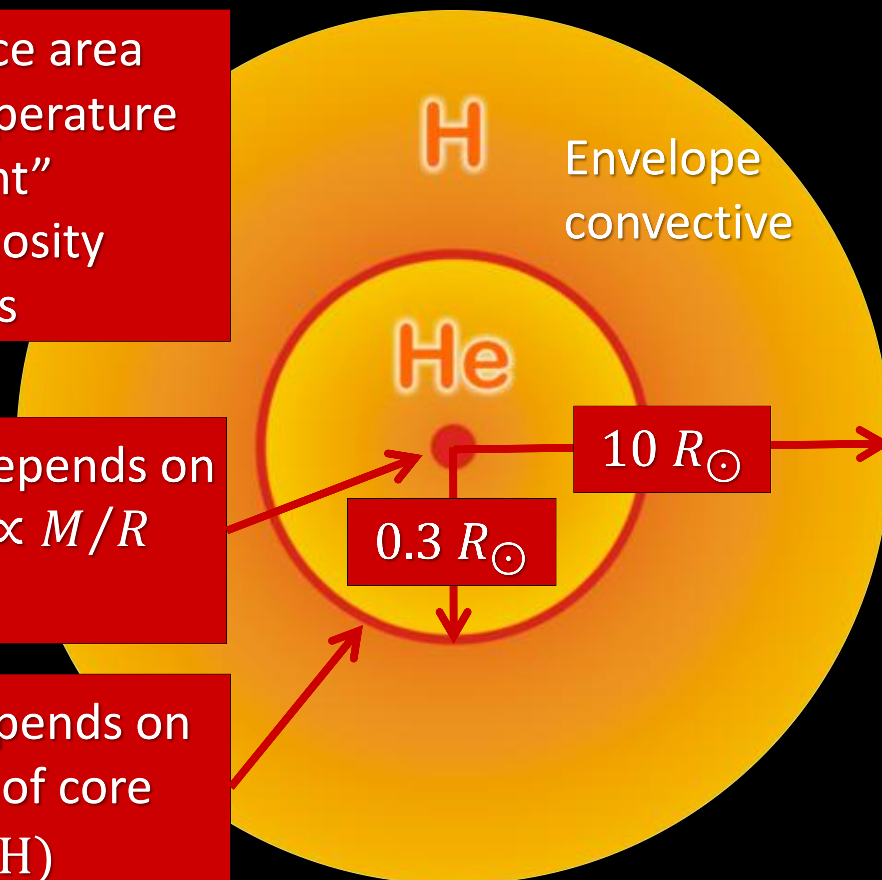
Main-sequence star $1M_\odot$ (Hydrogen burning)



$\epsilon_{\rm nuc}(\rm H)$ depends on
$T \propto \Phi_{\rm grav} \propto M/R$
of entire star

Helium-burning star $1M_\odot$

Large surface area
→ low temperature
→ "red giant"
Large luminosity
→ mass loss



$\epsilon_{\rm nuc}(\rm He)$ depends on
$T \propto \Phi_{\rm grav} \propto M/R$
of core

$\epsilon_{\rm nuc}(\rm H)$ depends on
$T \propto \Phi_{\rm grav}$ of core
→ huge $L(\rm H)$

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

Neutrinos from Thermal Processes

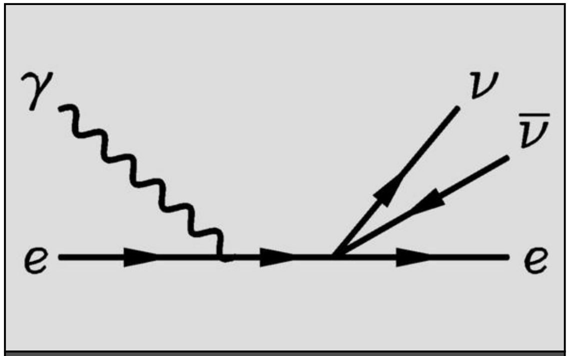
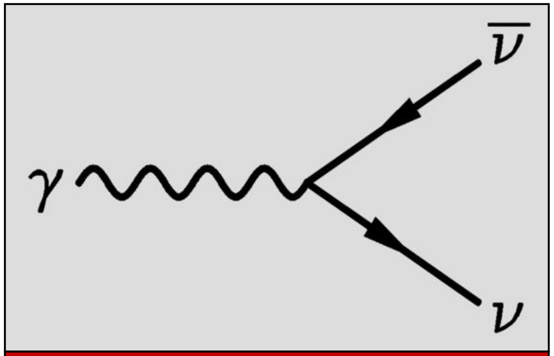
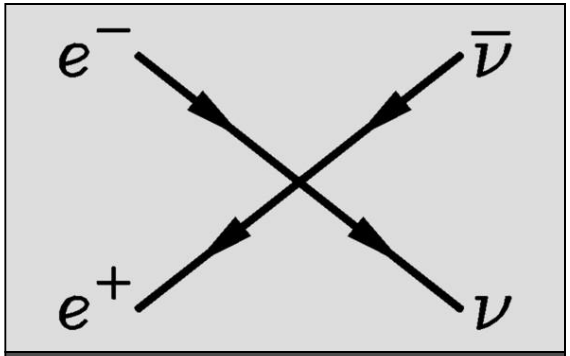


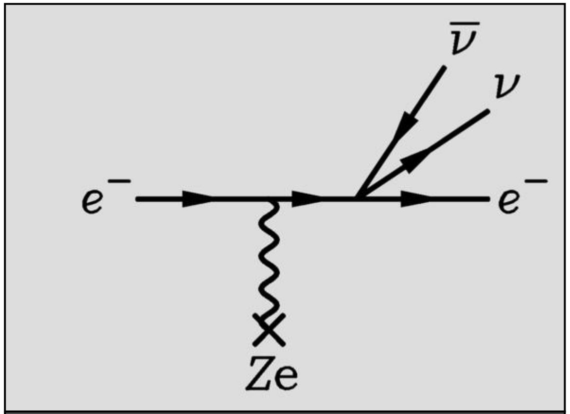
Photo (Compton)



Plasmon decay

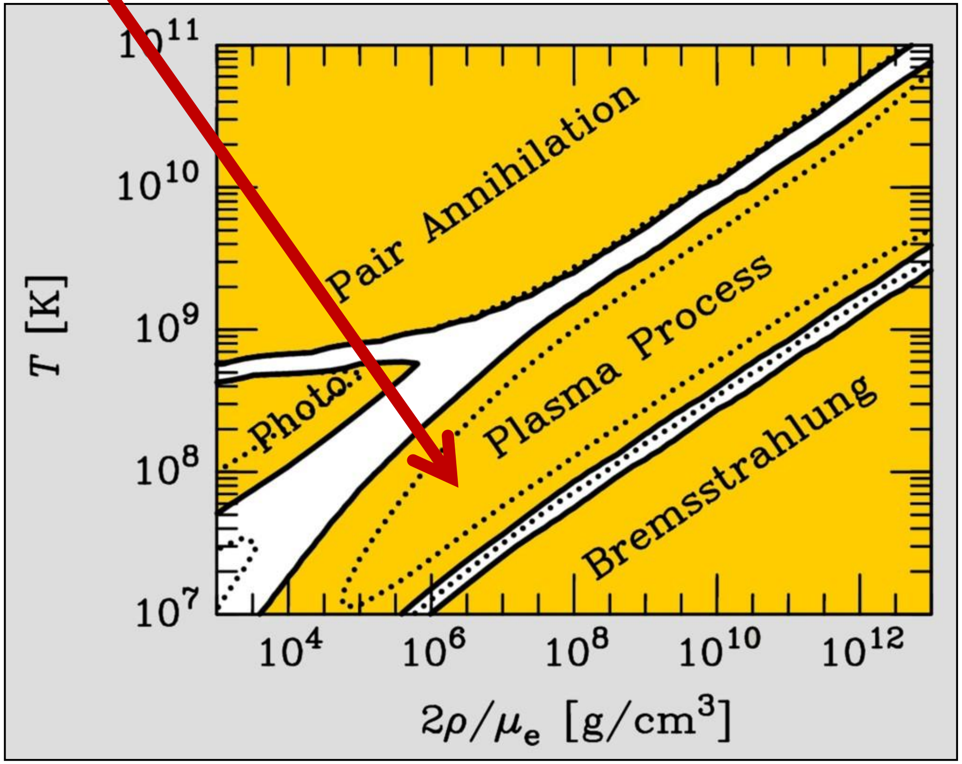


Pair annihilation

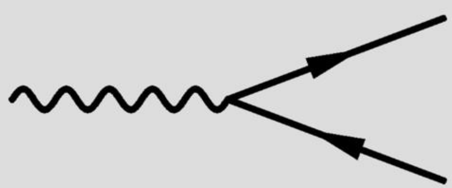
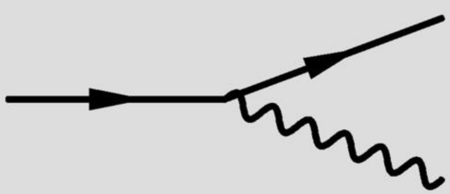


Bremsstrahlung

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

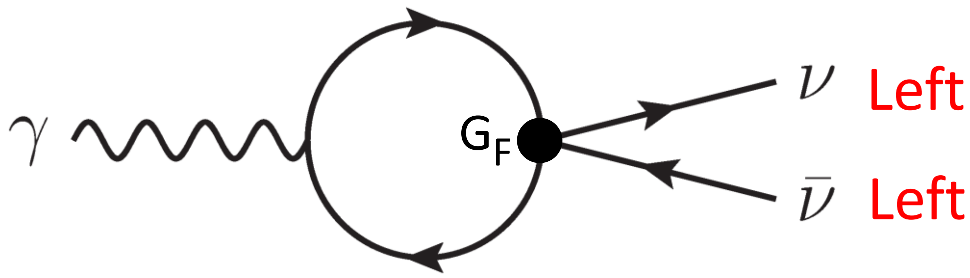


Plasmon Decay vs. Cherenkov Effect

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 $e \to e + \gamma$ 

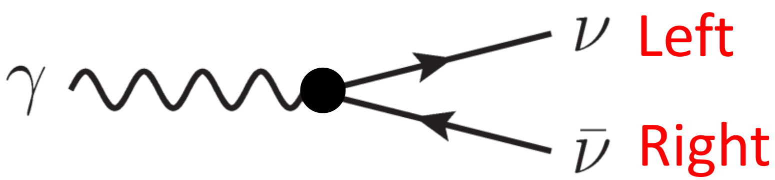
Enhanced Plasmon Decay by Dipole Moments

Standard Plasmon Decay



- Photons “shake” electrons of the medium
- These emit neutrino pairs

Neutrino dipole moment



- No direct photon coupling
- Dipole μ_ν moment possible
- Enhances plasmon decay

Neutrino Electromagnetic Form Factors

Effective coupling of electromagnetic field to a neutral fermion

$$L_{\rm eff} = -F_1 \overline{\Psi}\gamma_\mu \Psi\, A^\mu - G_1 \overline{\Psi}\gamma_\mu\gamma_5 \Psi\, \partial_\nu F^{\mu\nu} - \frac{1}{2} F_2\, \overline{\Psi}\sigma_{\mu\nu}\Psi\, F^{\mu\nu} - \frac{1}{2} G_2\, \overline{\Psi}\sigma_{\mu\nu}\gamma_5\Psi\, F^{\mu\nu}$$

Charge $e_\nu = F_1(0) = 0$

Anapole moment $G_1(0)$

Magnetic dipole moment $\mu = F_2(0)$

Electric dipole moment $\boldsymbol{\varepsilon} = G_2(0)$

- Charge form factor $F_1(q^2)$ & anapole $G_1(q^2)$ are short-range if charge $F_1(0) = 0$
- Connect states of equal helicity
- In the standard model they represent radiative corrections to weak interaction

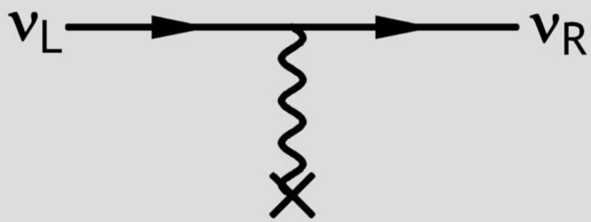
- Dipole moments connect states of opposite helicity
- Violation of individual flavor lepton numbers (neutrino mixing)
  $\rightarrow$ Magnetic or electric dipole moments can connect different flavors or different mass eigenstates ("Transition moments")
- Usually measured in "Bohr magnetons" $\mu_B = e/2m_e$

Giunti et al., Neutrino electromagnetic properties, arXiv:2411.03122

Giunti & Studenikin, Neutrino electromagnetic interactions: a window to new physics, arXiv:1403.6344

Consequences of Neutrino Dipole Moments

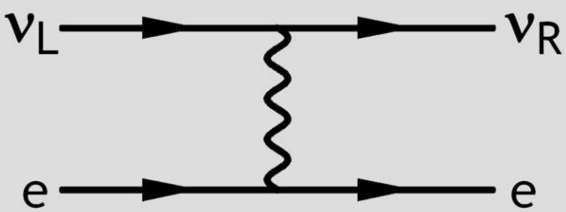
Spin precession in external E or B fields



$$\mathrm{i}\,\frac{\partial}{\partial t}\begin{pmatrix}\nu_L\\ \nu_R\end{pmatrix}=\begin{pmatrix}0 & \mu_\nu B_\perp\\ \mu_\nu B_\perp & 0\end{pmatrix}\begin{pmatrix}\nu_L\\ \nu_R\end{pmatrix}$$

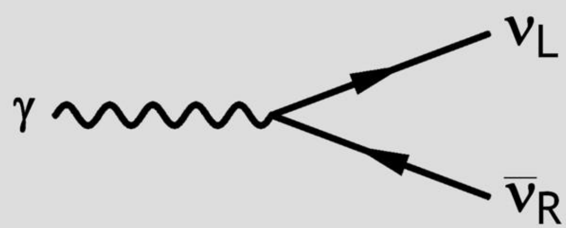
Scattering

$$\frac{d\sigma}{dT}=\frac{G_F^2 m_e}{2\pi}\left[(C_\mathrm{V}+C_\mathrm{A})^2+(C_\mathrm{V}-C_\mathrm{A})^2\left(1-\frac{T}{E}\right)^2+(C_\mathrm{V}^2-C_\mathrm{A}^2)\frac{m_e T}{E^2}\right]+\alpha\mu_\nu^2\left(\frac{1}{T}+\frac{1}{E}\right)$$



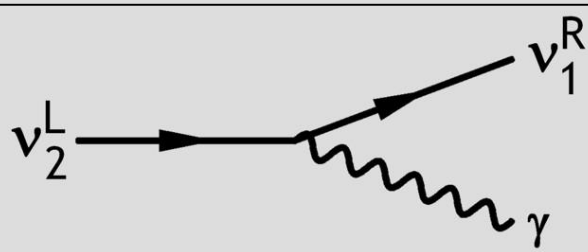
T electron recoil energy

Plasmon decay in stars



$$\Gamma=\frac{\mu_\nu^2}{24\pi}\,\omega_\mathrm{pl}^3$$

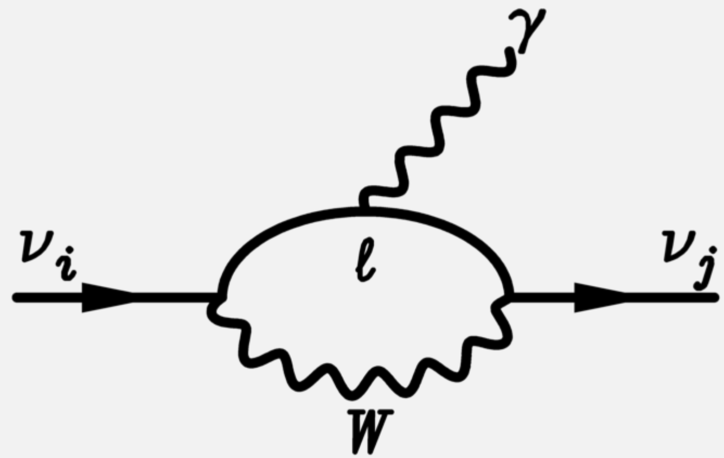
Decay or Cherenkov effect



$$\Gamma=\frac{\mu_\nu^2}{8\pi}\left(\frac{m_2^2-m_1^2}{m_2}\right)^3$$

Standard Dipole Moments for Massive Neutrinos

Standard electroweak model:
Neutrino dipole and
transition moments
are induced at higher order



Massive neutrinos ν_i $(i = 1, 2, 3)$
mixed to form weak eigenstates

$$\nu_\ell = \sum_{i=1}^{3} U_{\ell i} \nu_i$$

Explicitly for Dirac neutrinos
- Magnetic moments μ_{ij}
- Electric moments ϵ_{ij}

$$\mu_{ij} = \frac{e\sqrt{2}G_\mathrm{F}}{(4\pi)^2}(m_i + m_j) \sum_{\ell=e,\mu,\tau} U_{\ell j} U_{\ell i}^* \, f\left(\frac{m_\ell}{m_W}\right)$$

$$\epsilon_{ij} = \ldots (m_i - m_j) \ \ldots$$

$$f\left(\frac{m_\ell}{m_W}\right) = -\frac{3}{2} + \frac{3}{4}\left(\frac{m_\ell}{m_W}\right)^2 + \mathcal{O}\left(\frac{m_\ell}{m_W}\right)^4$$

Standard Dipole Moments for Massive Neutrinos

Diagonal case:
Magnetic moments
of Dirac neutrinos

$$\mu_{ii} = \frac{3e\sqrt{2}G_\mathrm{F}}{(4\pi)^2} m_i = 3.20 \times 10^{-19} \mu_\mathrm{B} \frac{m_i}{\mathrm{eV}} \qquad \mu_\mathrm{B} = \frac{e}{2m_e}$$

$$\epsilon_{ii} = 0$$

Off-diagonal case
(Transition moments)

First term in $f(m_\ell/m_W)$ does not contribute:
“GIM cancellation”

$$\mu_{ij} = \frac{3e\sqrt{2}G_\mathrm{F}}{4(4\pi)^2}(m_i+m_j)\left(\frac{m_\tau}{m_W}\right)^2 \sum_{\ell=e,\mu,\tau} U_{\ell j}U^*_{\ell i}\left(\frac{m_\ell}{m_\tau}\right)^2$$

$$= 3.96 \times 10^{-23} \mu_\mathrm{B} \frac{m_i + m_j}{\mathrm{eV}} \sum_{\ell=e,\mu,\tau} U_{\ell j}U^*_{\ell i}\left(\frac{m_\ell}{m_\tau}\right)^2$$

Largest neutrino mass eigenstate $0.05~\mathrm{eV} < m < 0.2~\mathrm{eV}$
For Dirac neutrino expect
$1.6 \times 10^{-20} \mu_B < \mu_\nu < 6.4 \times 10^{-20} \mu_B$

Plasmon Decay and Stellar Energy Loss Rates

Photon dispersion relation like a massive particle (nonrelativistic plasma)

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

Photon decay rate (transverse plasmon) with energy E_γ

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

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

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

Energy-loss rate of stellar plasma

$$Q(\gamma \to \nu\bar{\nu}) = \int \frac{2d^3\mathbf{p}}{(2\pi)^3} \frac{E_\gamma \Gamma_{\gamma\to\nu\bar{\nu}}}{e^{E_\gamma/T} - 1} = \frac{8\zeta_3 T^3}{3\pi} \times \begin{cases} \alpha_\nu \left(\omega_\mathrm{p}^2/4\pi\right) \\ (\mu_\nu^2/2)\left(\omega_\mathrm{p}^2/4\pi\right)^2 \\ \left(G_\mathrm{F}^2/\alpha\right)\left(\omega_\mathrm{p}^2/4\pi\right)^3 \end{cases}$$

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

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

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

PHYSICAL REVIEW VOLUME 132, NUMBER 3 1 NOVEMBER 1963

Electromagnetic Properties of the Neutrino

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AND

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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

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

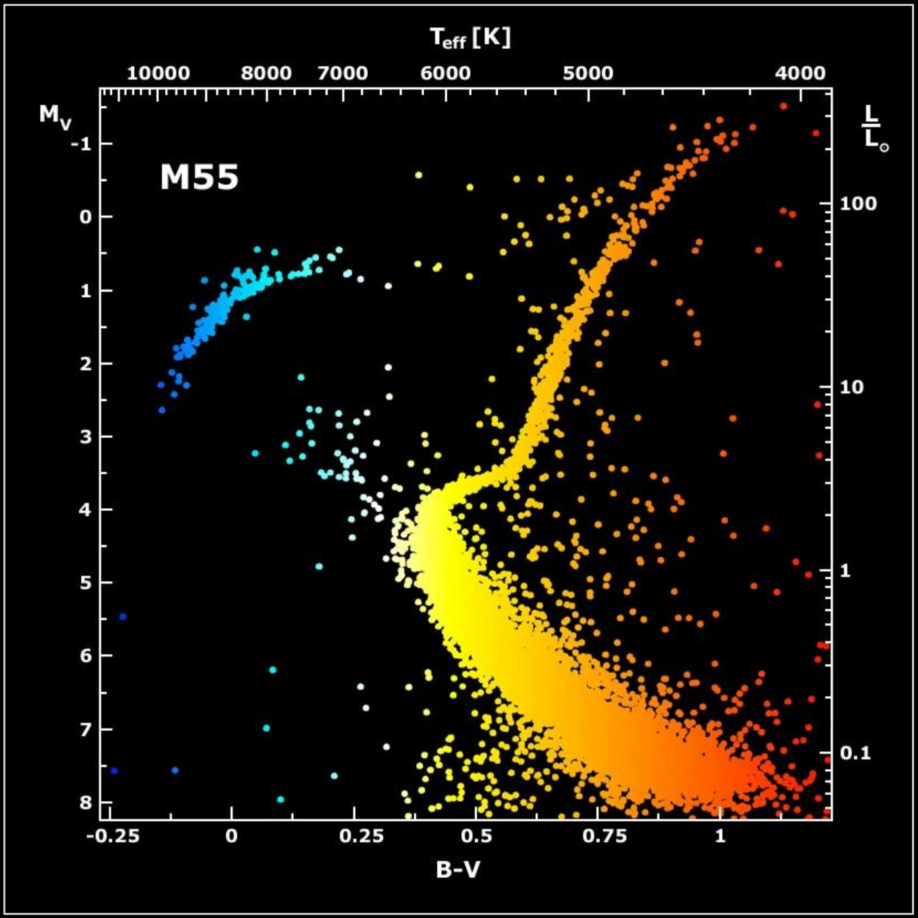
and the experiments are consistent with $m_{\nu_e} = 0$.

(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]

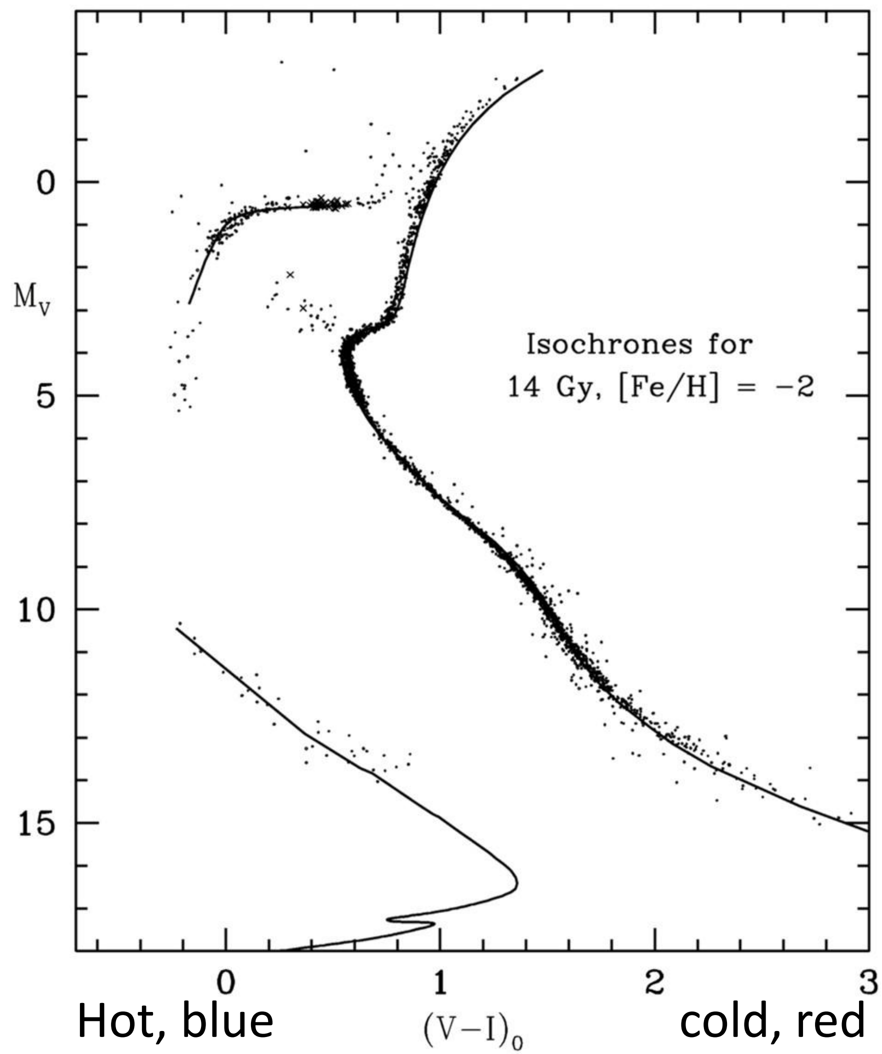
$$m_{\nu_\mu} < 3.5 \text{ MeV}. \tag{3}$$

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

Galactic Globular Cluster M55

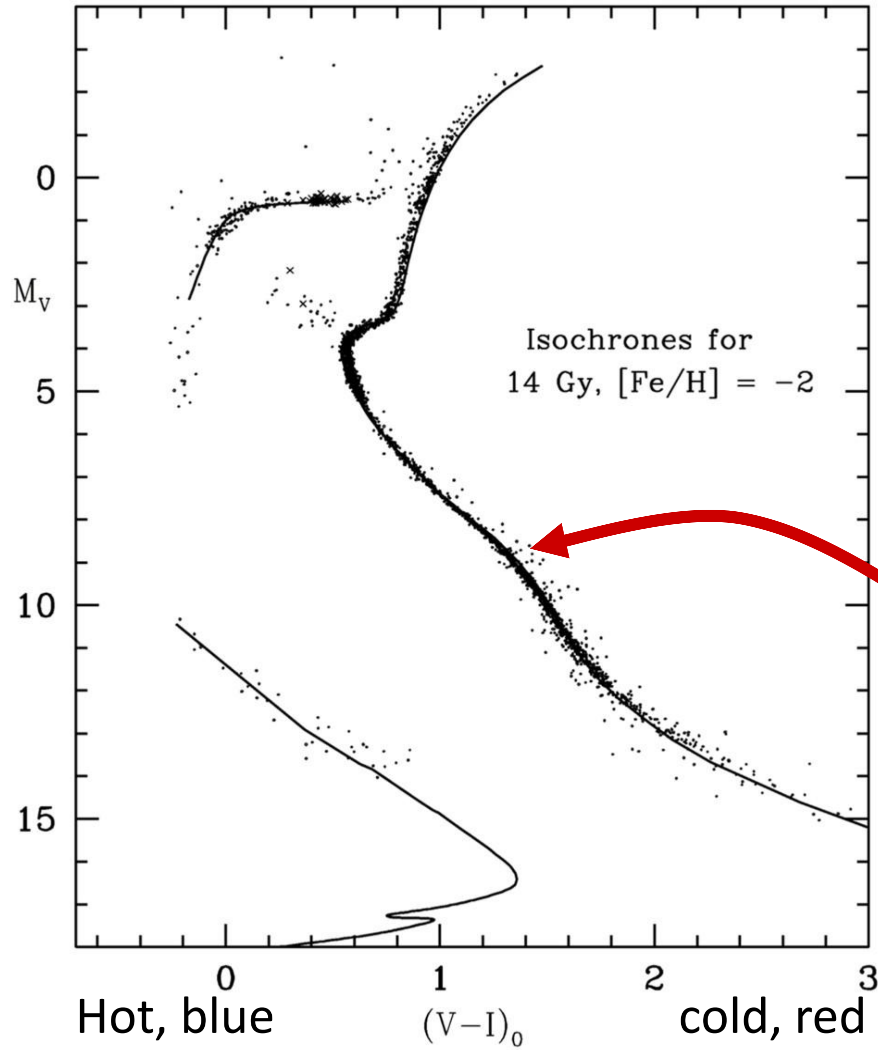


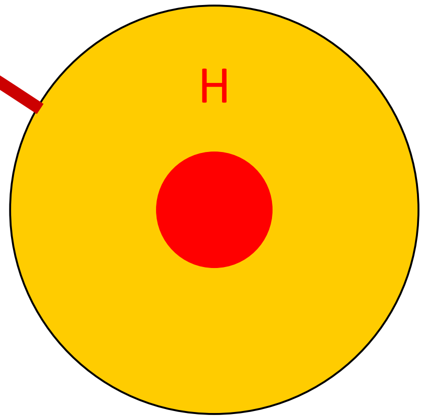
Color-Magnitude Diagram for Globular Clusters



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

Color-Magnitude Diagram for Globular Clusters

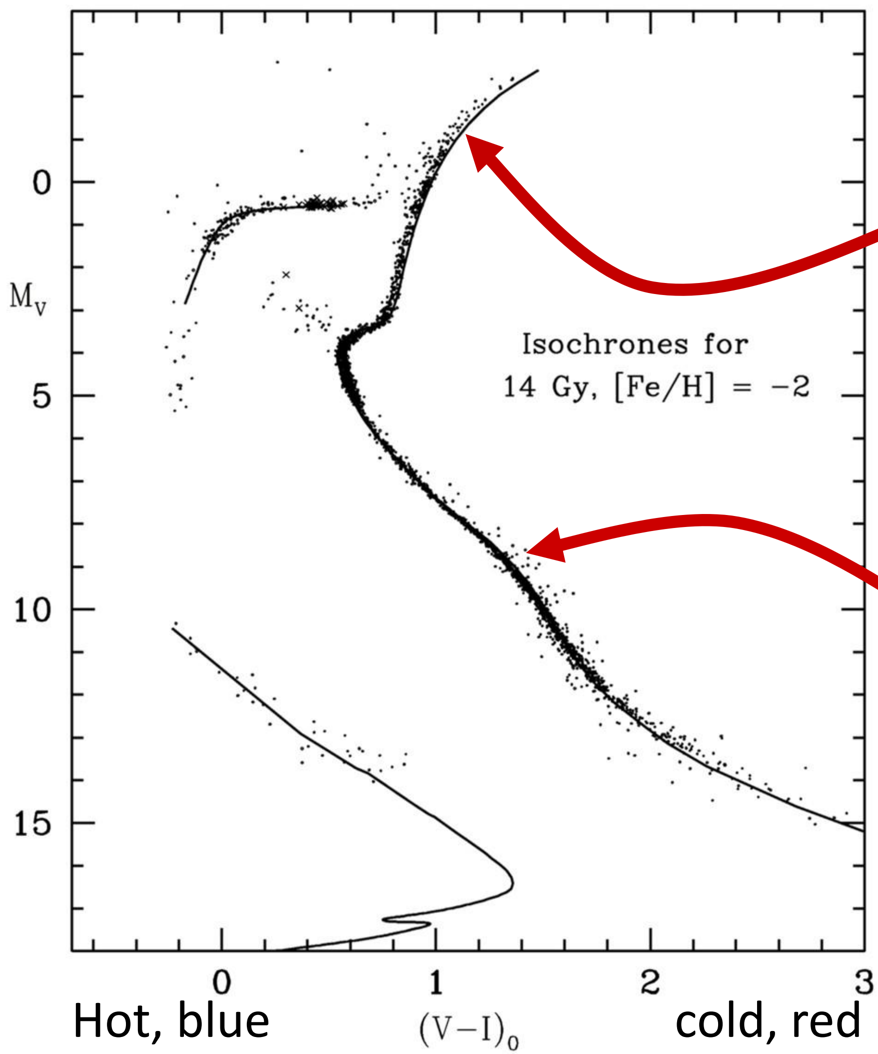


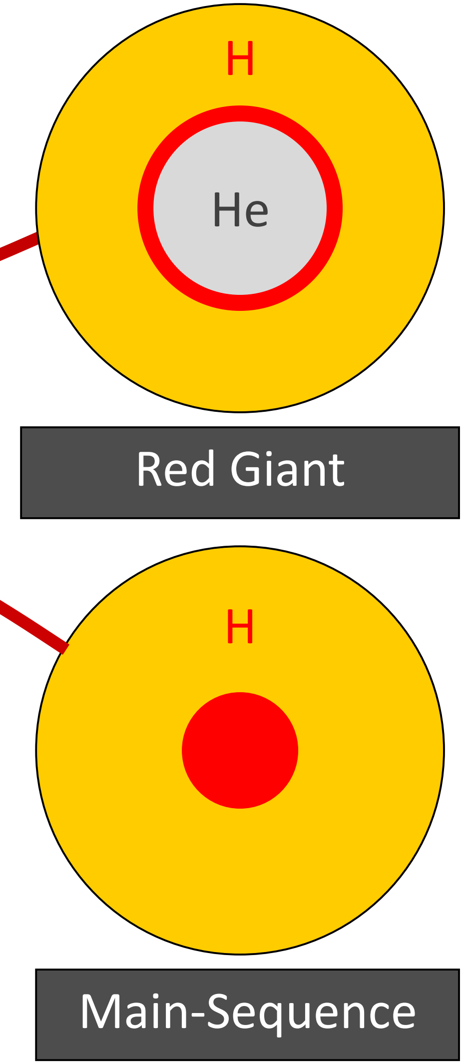


Main-Sequence

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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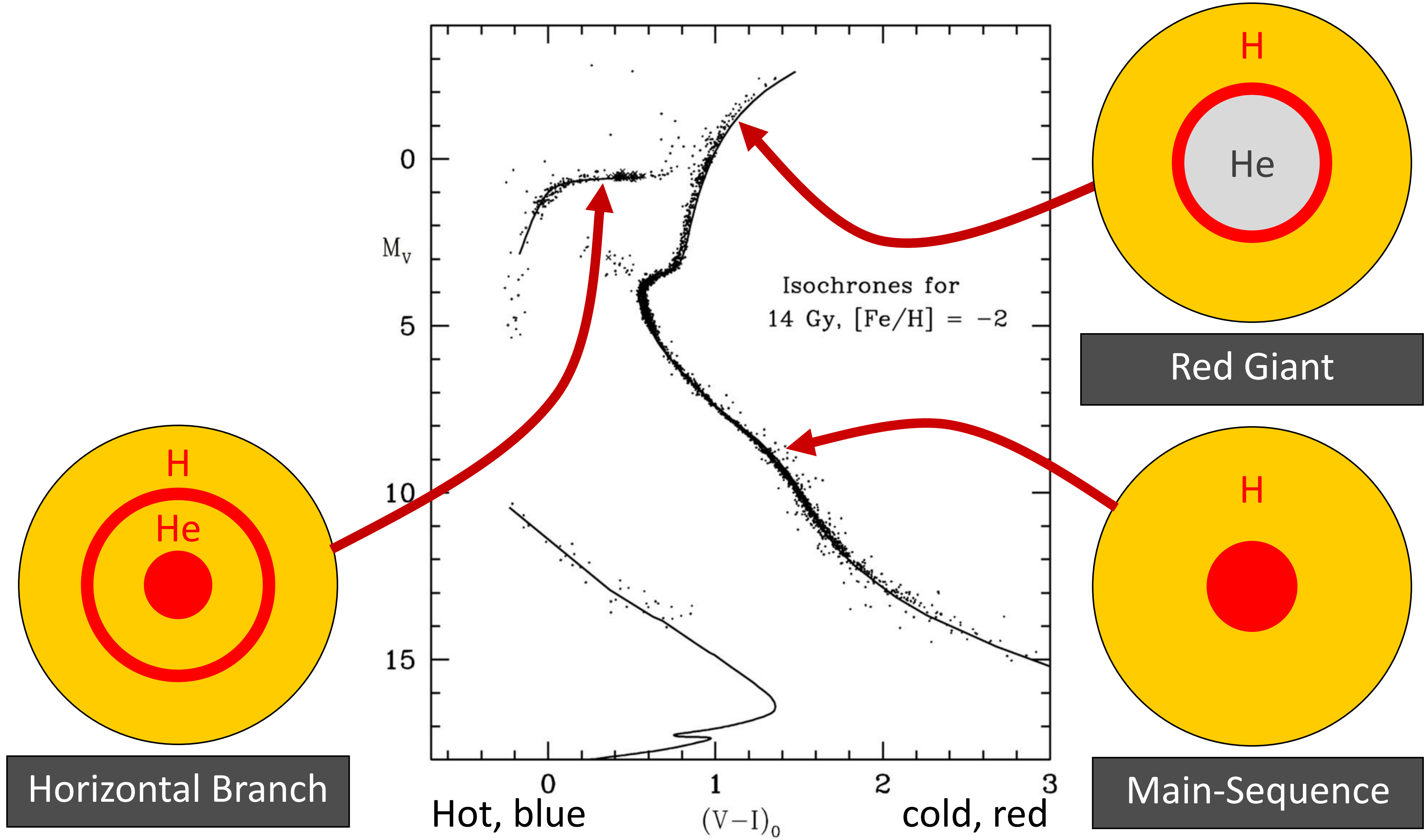

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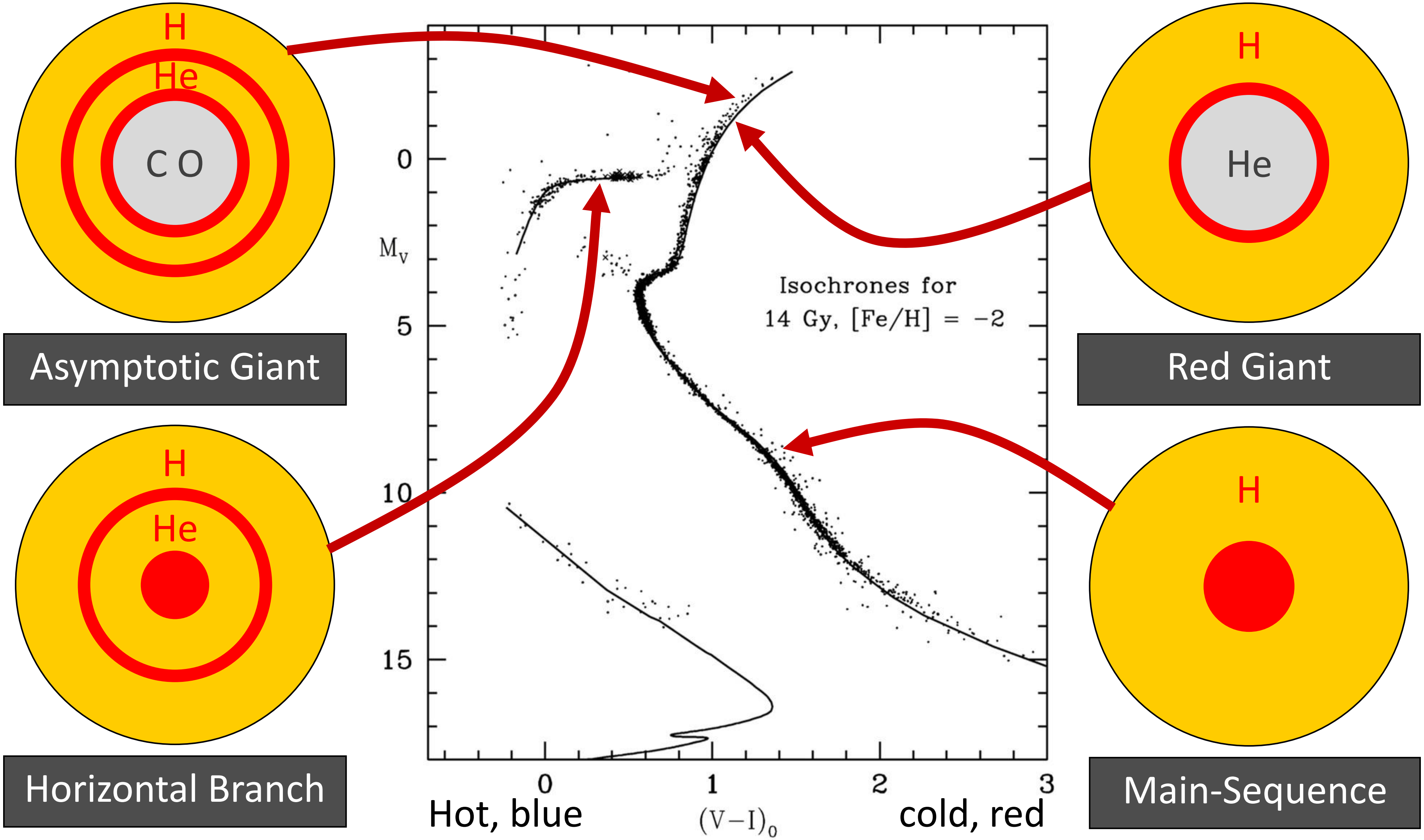

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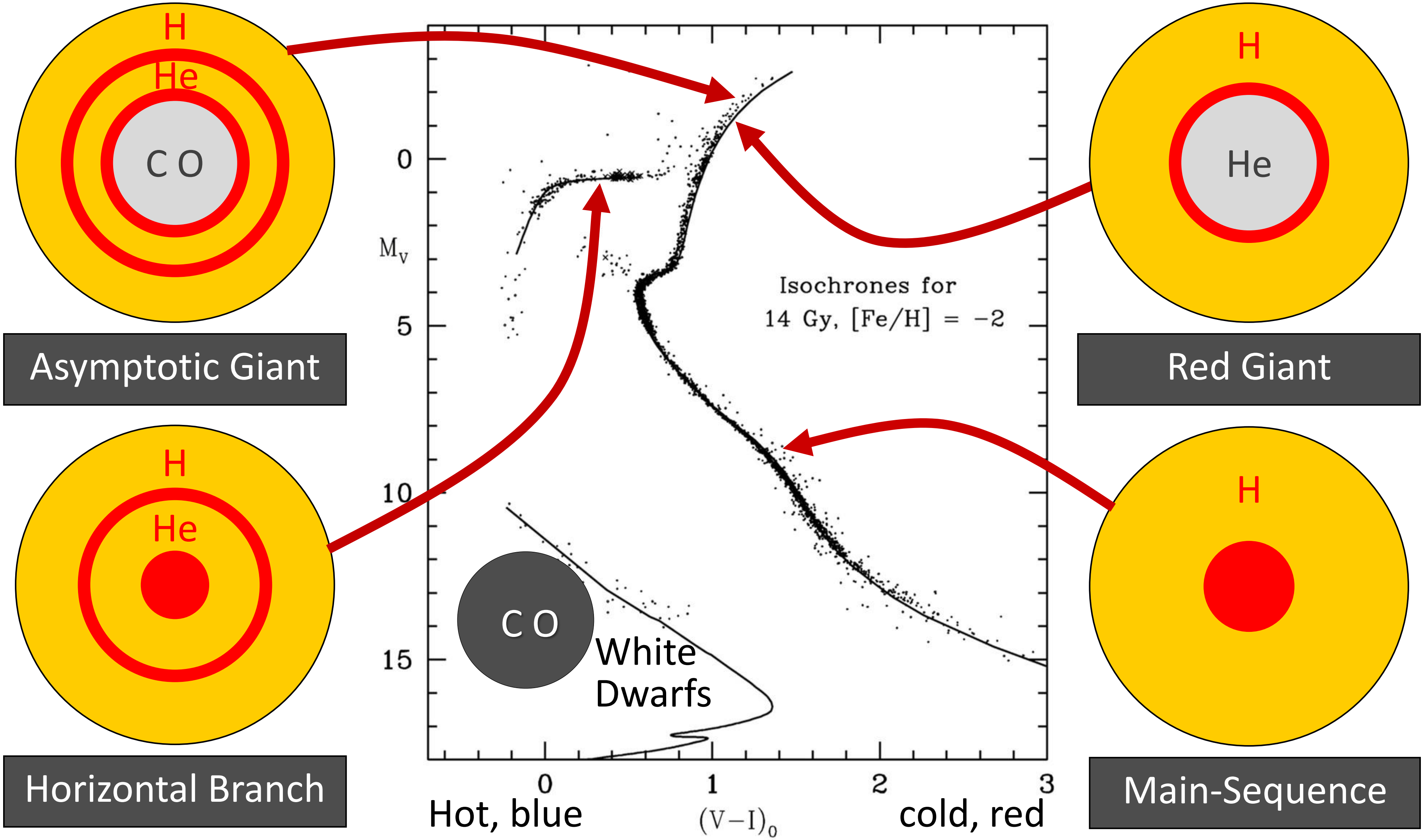
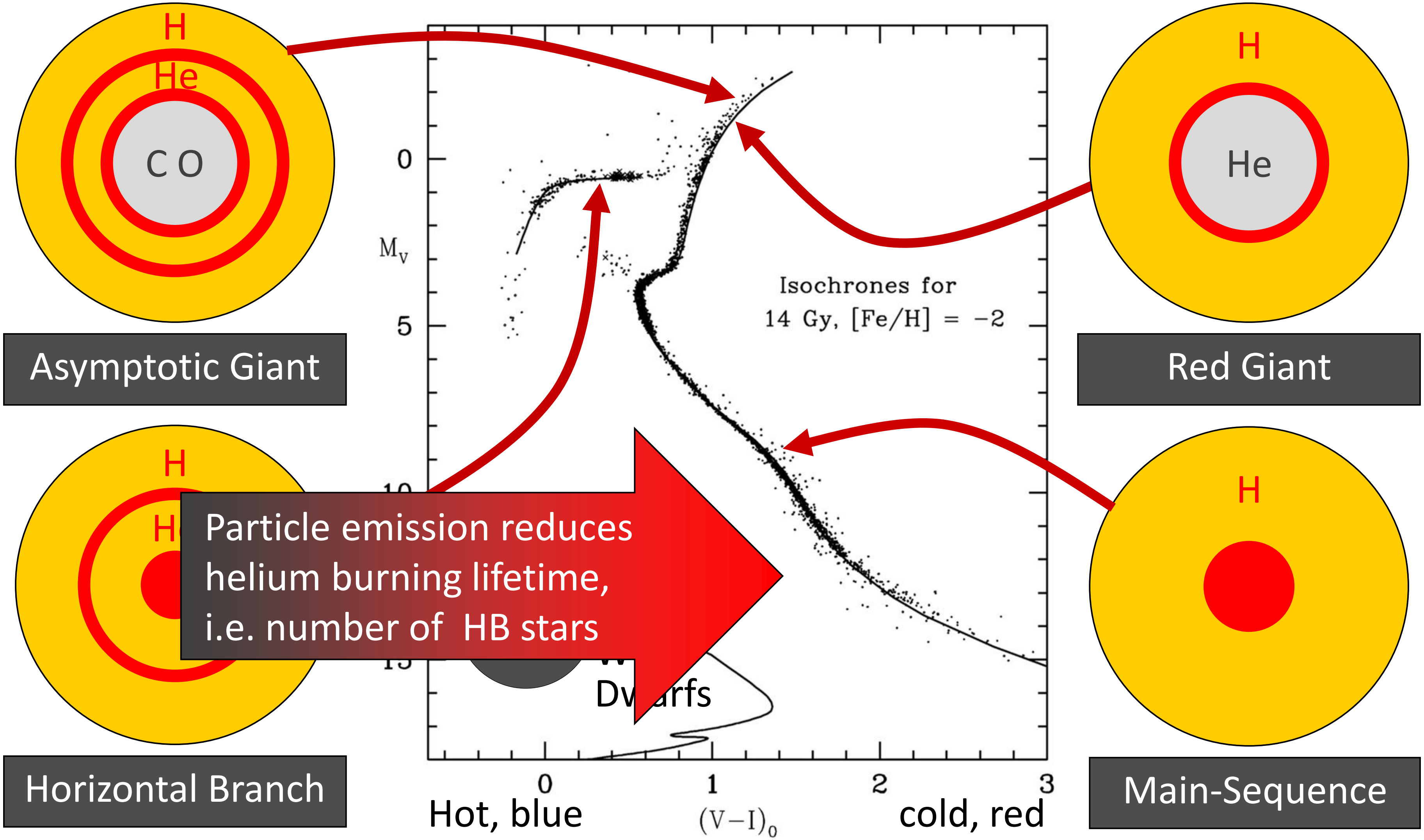


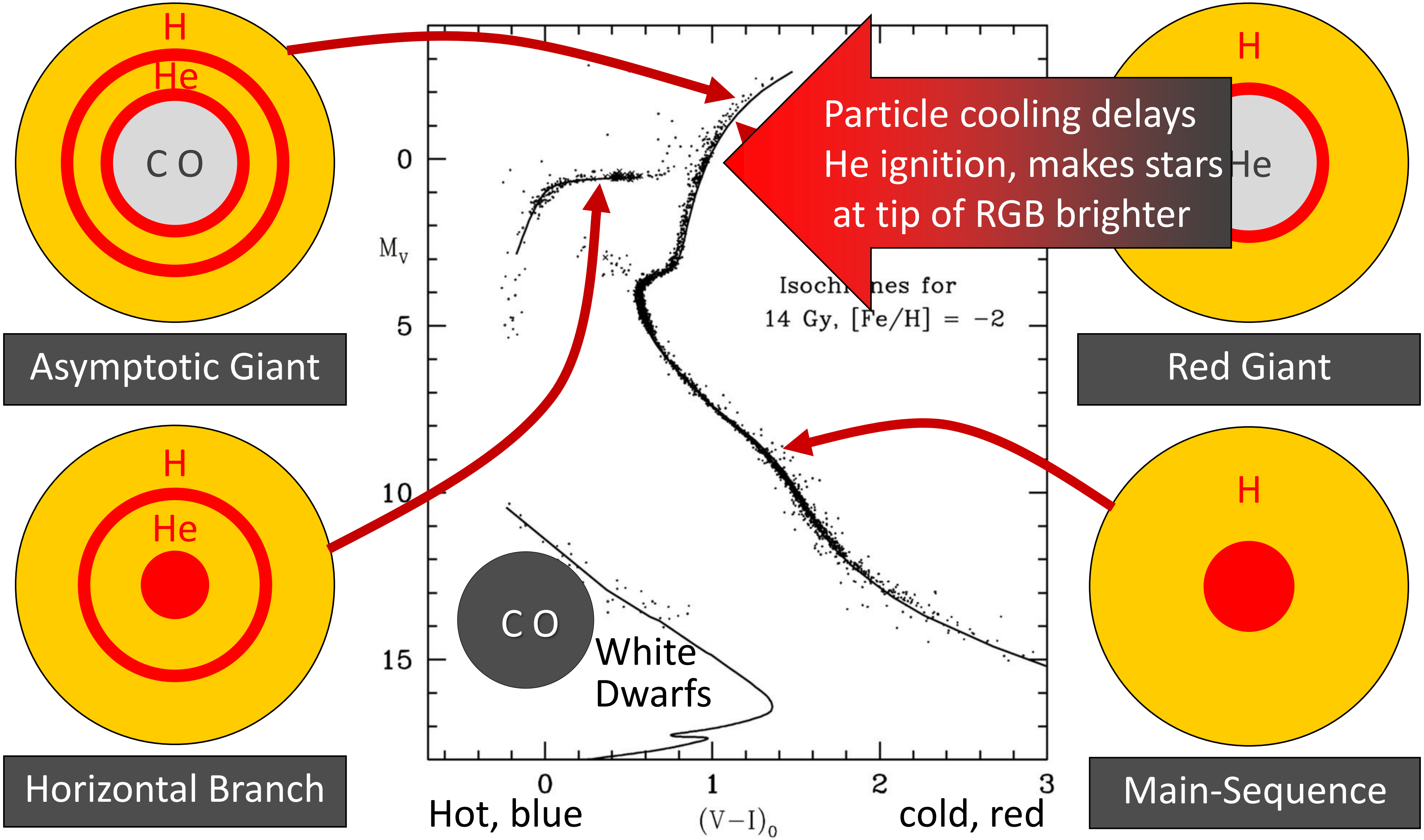
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Color-Magnitude Diagram for Globular Clusters



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

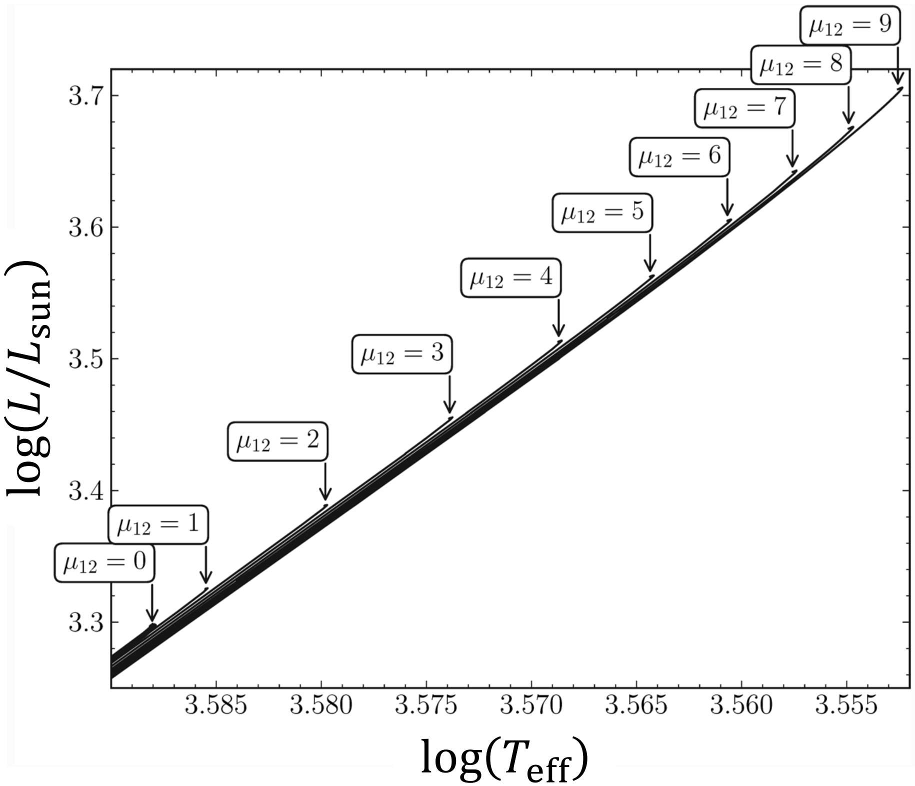
Color-Magnitude Diagram for Globular Clusters

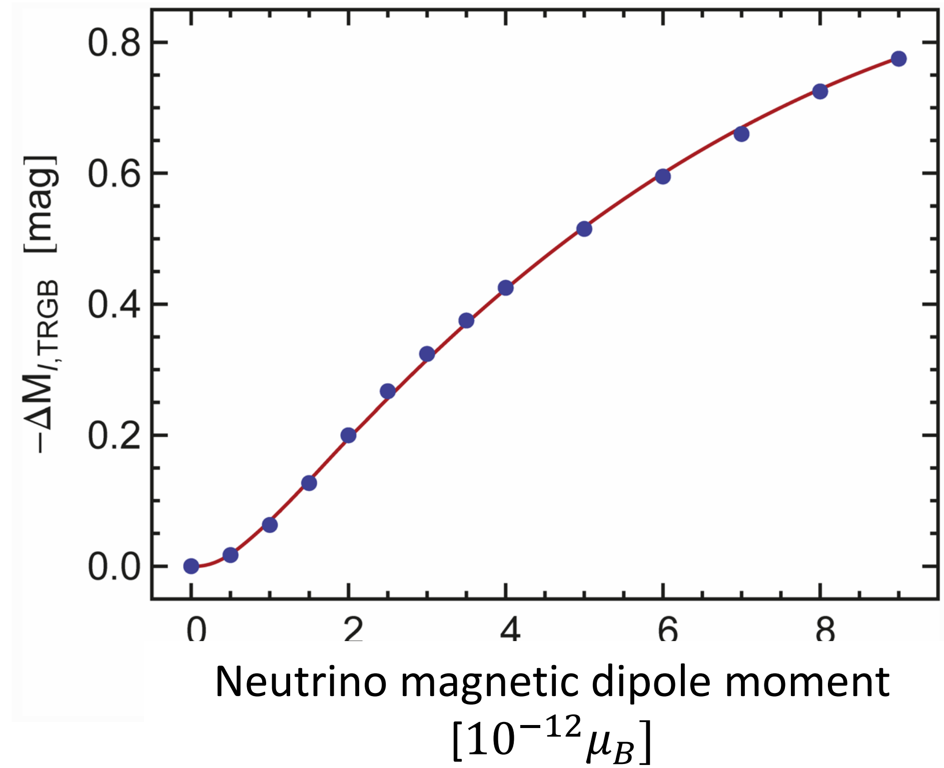


Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Helium Ignition for Low-Mass Red Giants

Brightness increase at He ignition by nonstandard neutrino losses



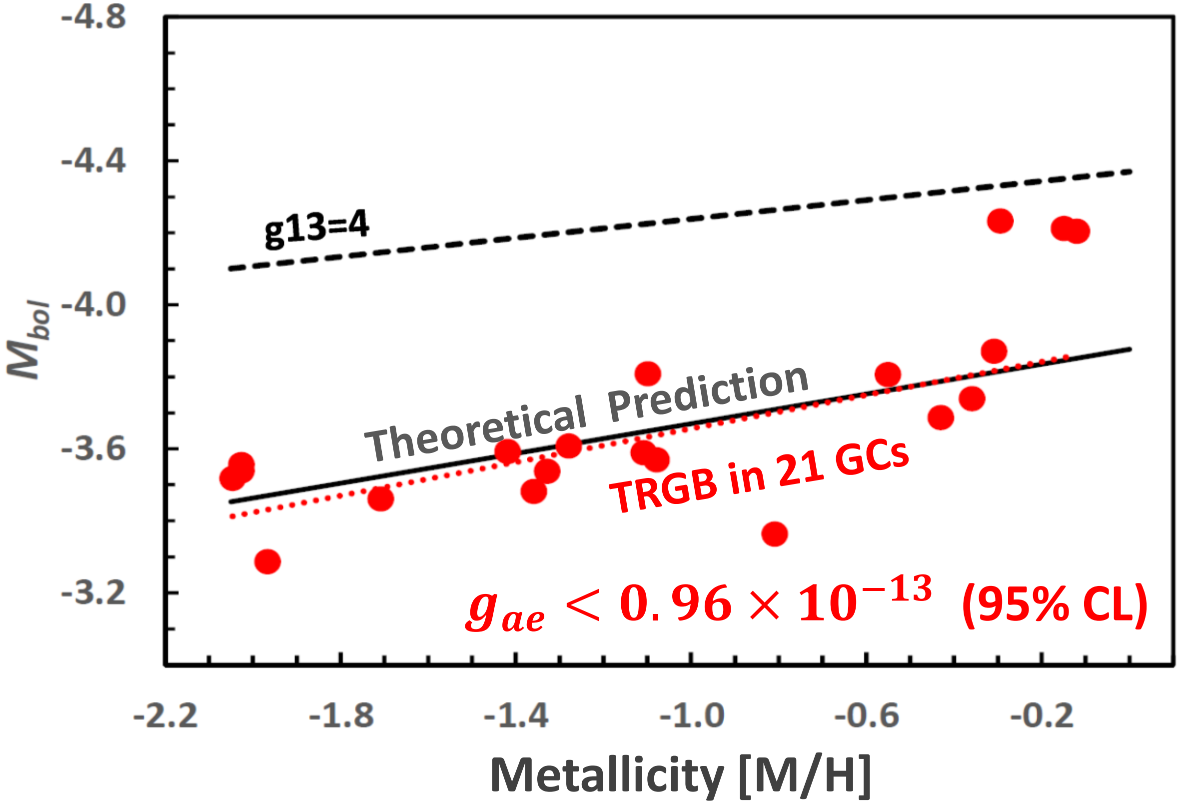


Viaux, Catelan, Stetson, Raffelt, Redondo, Valcarce & Weiss, arXiv:1308.4627

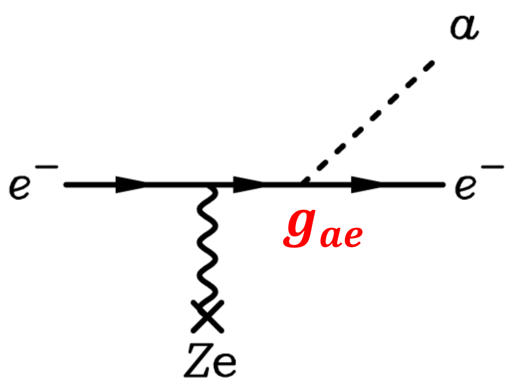
TRGB in 46 Globular Clusters [Cerny+ 2012.09701]

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

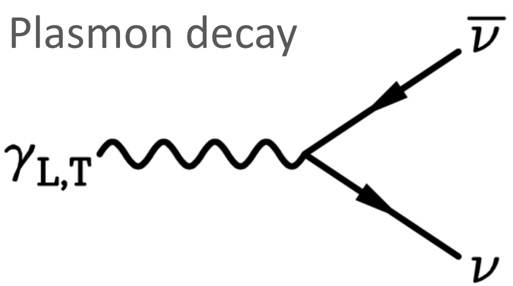


Bremsstrahlung emission by degenerate electrons

Estimated bound for neutrino dipole moments

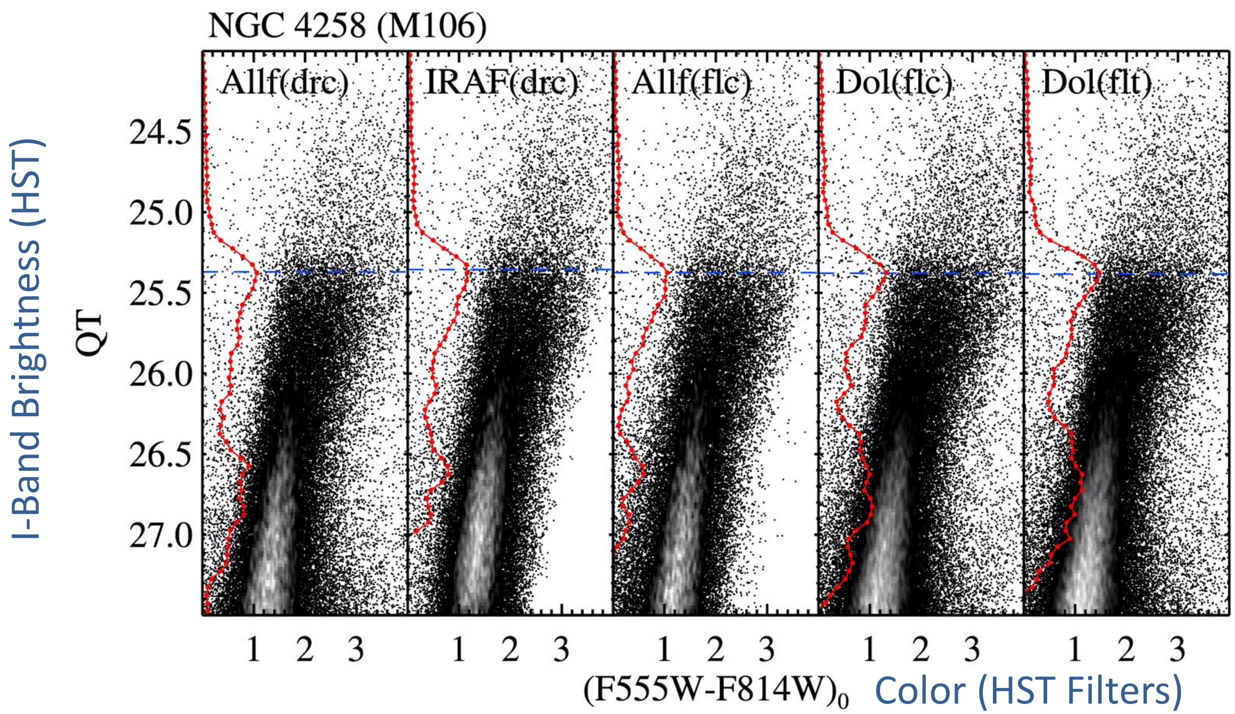
$$\sqrt{\sum_i |\mu_i|^2} < 0.92 \times 10^{-12} \mu_B \text{ (95\% CL)}$$

Plasmon decay



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

THE ASTROPHYSICAL JOURNAL, 835:28 (17pp), 2017 January 20 JANG & LEE



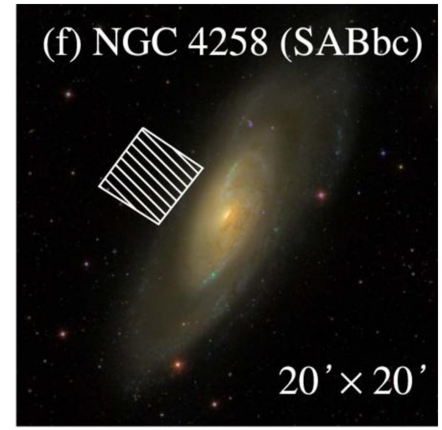


Figure 7. *QT* − (F555W − F814W)$_0$ CMDs of NGC 4258 from five different reduction methods : ALLFRAME on drc, IRAF/DAOPHOT on drc, ALLFRAME on flc, DOLPHOT on flc, and DOLPHOT on flt (from left to right). Edge detection responses are shown by the solid lines. Note that the estimated TRGB magnitudes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

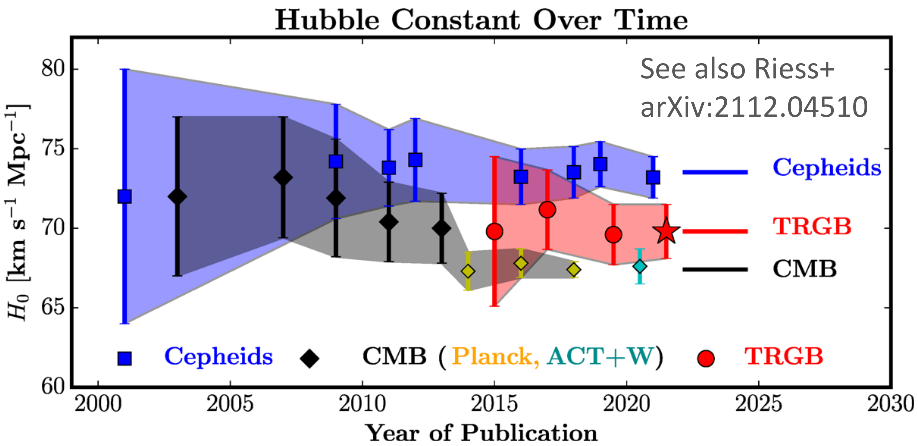
NGC 4258 hosts a water megamaser

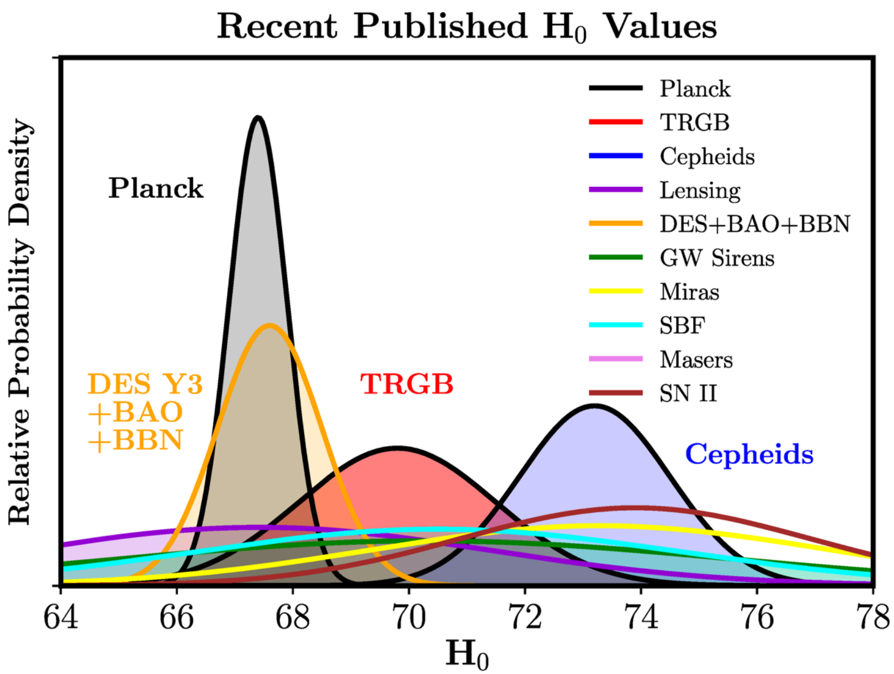
→ Quasi-geometric distance determination

→ Among the best absolute TRGB calibrations

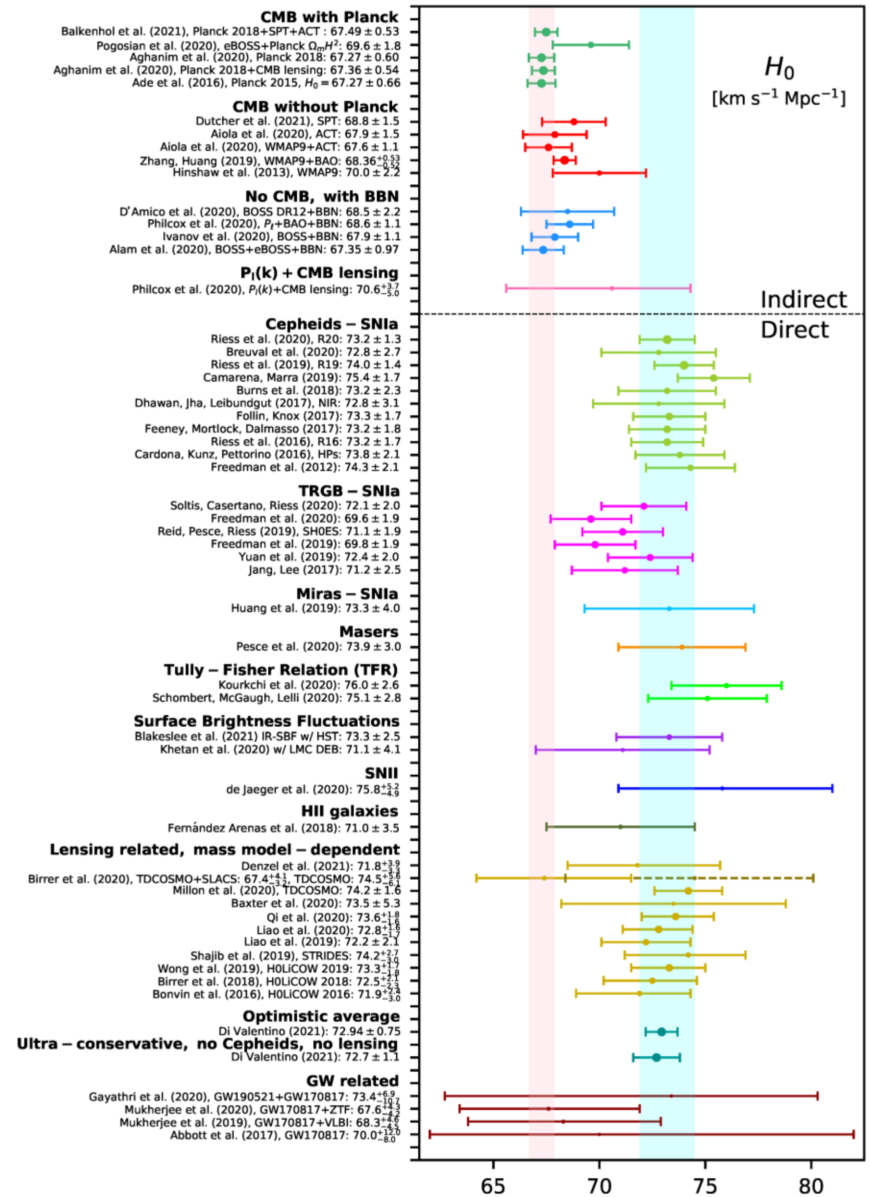
→ One rung in cosmic distance ladder

Hubble Tension



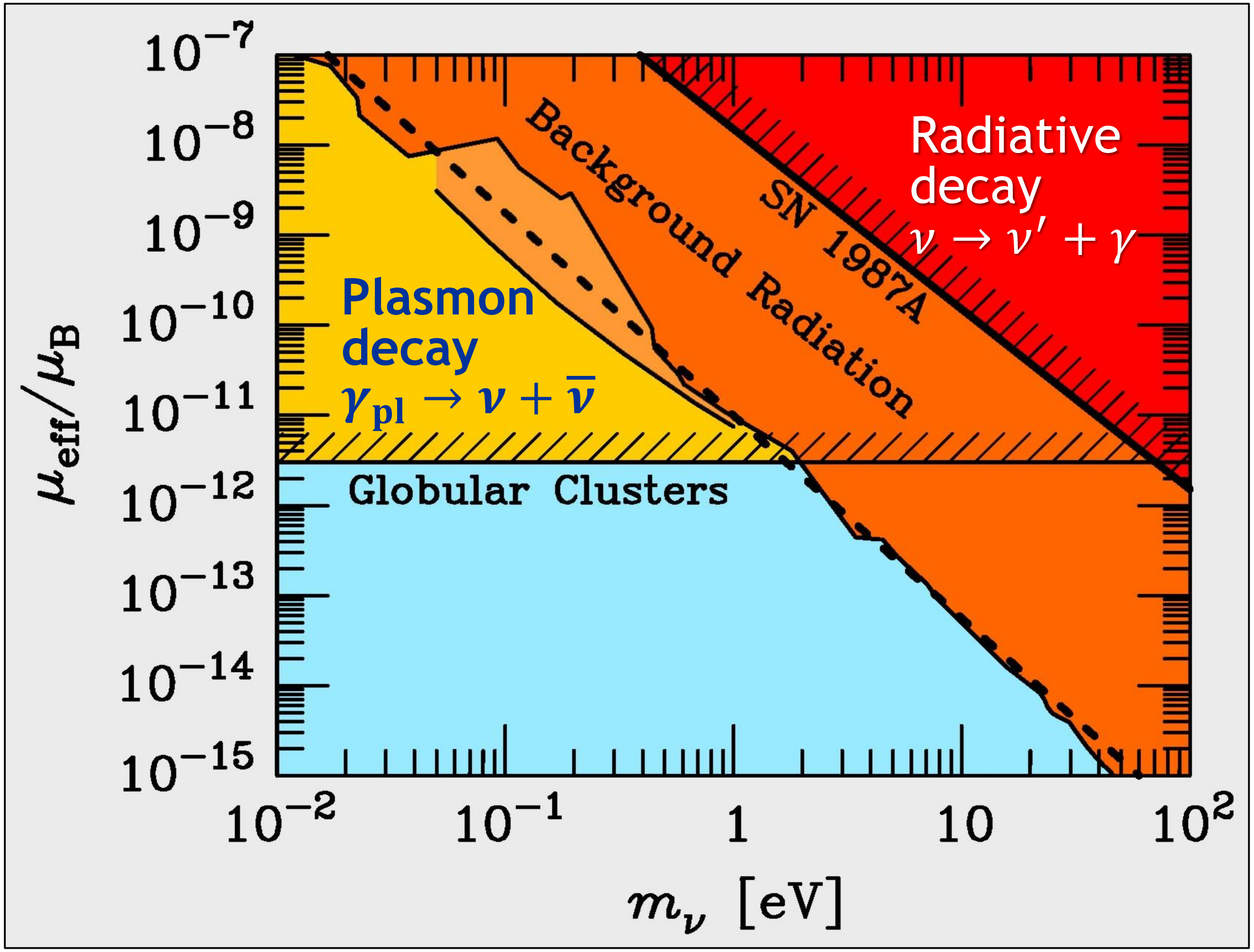


Freedman ApJ 919 (2021) 16 [2106.15656]



Di Valentino+ arXiv:2103.01183

Neutrino Radiative Lifetime Limits



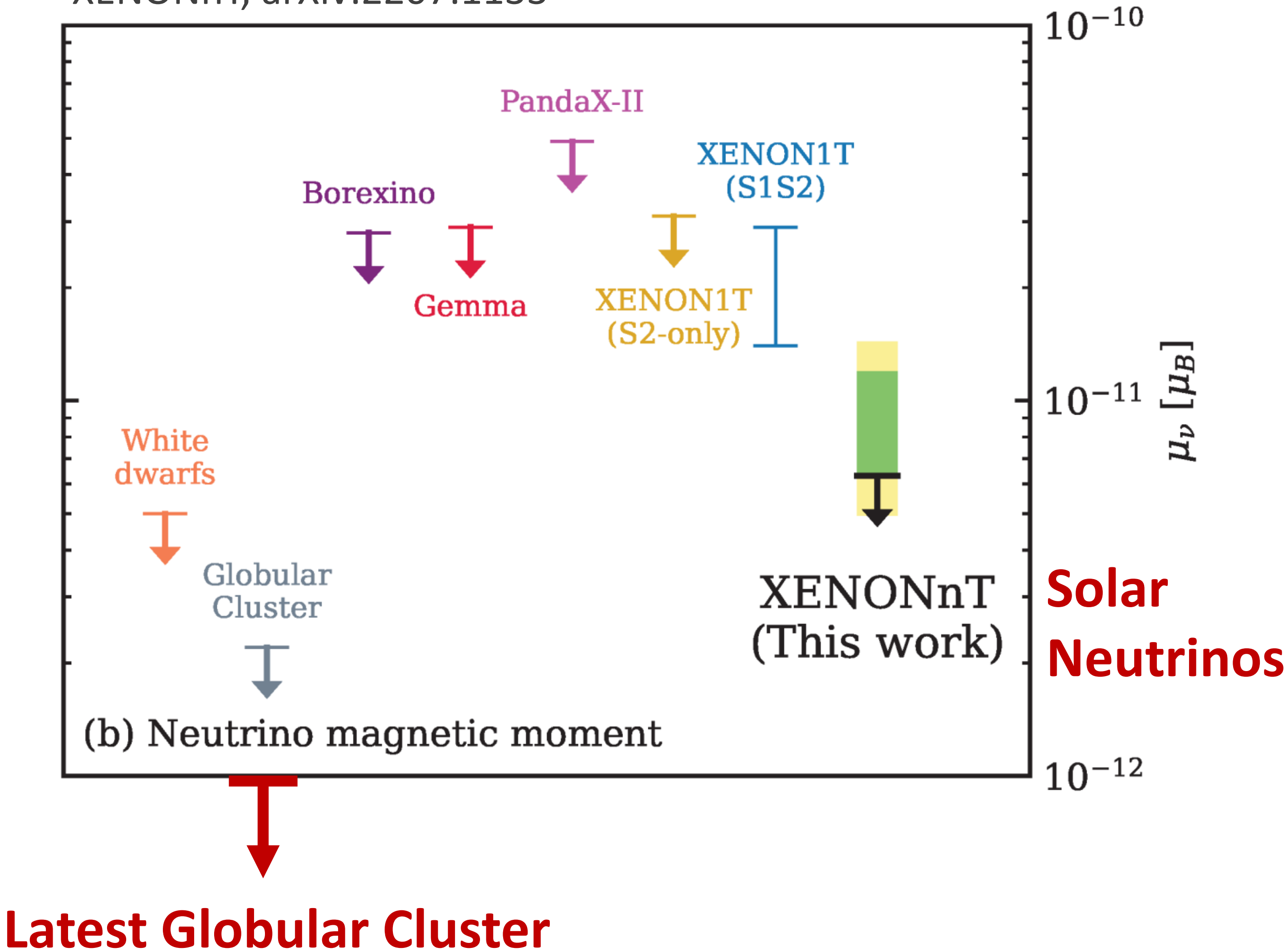
$$\Gamma_{\nu\to\nu'\gamma} = \frac{\mu_{\rm eff}^2}{8\pi}\, m_\nu^3$$

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

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

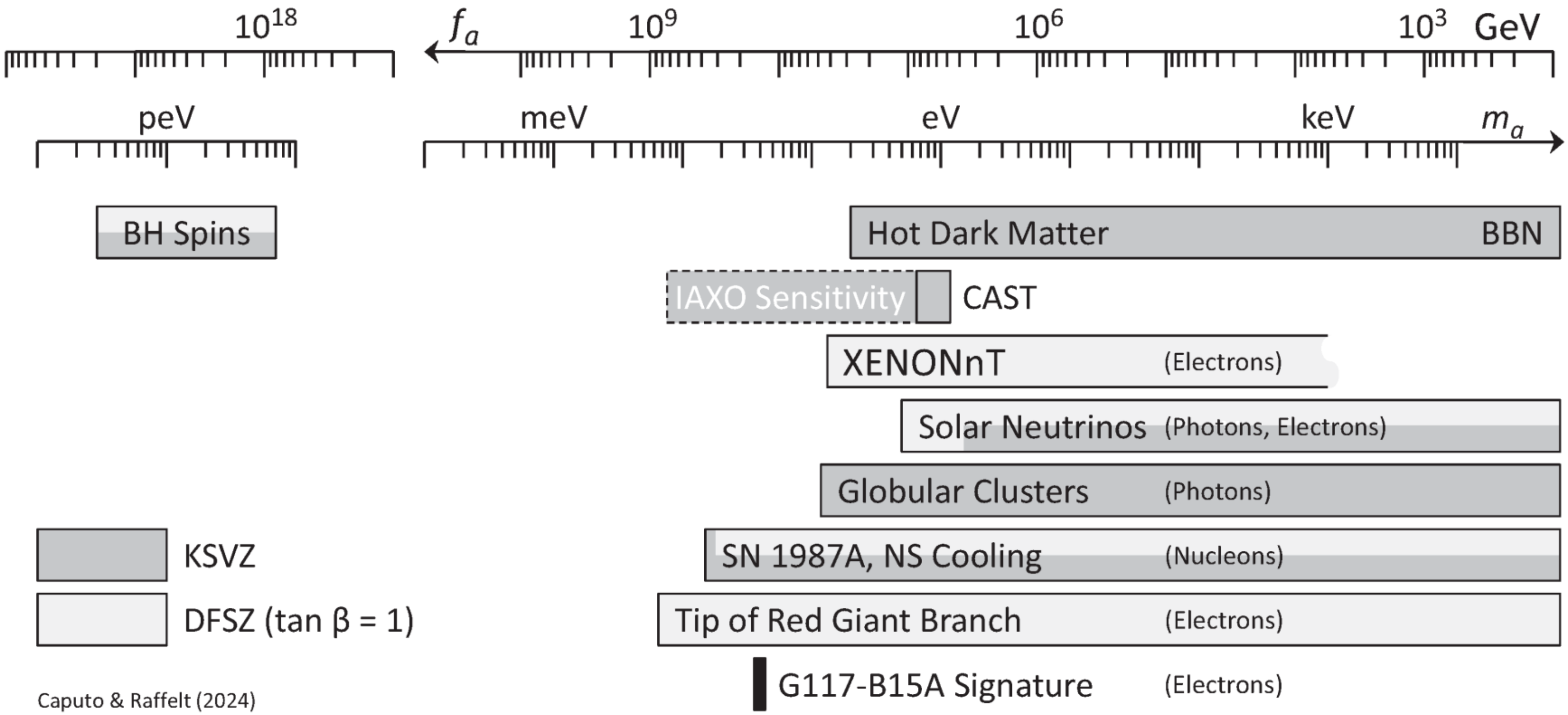
Bounds on neutrino dipole moments

XENONnT, arXiv:2207.1133



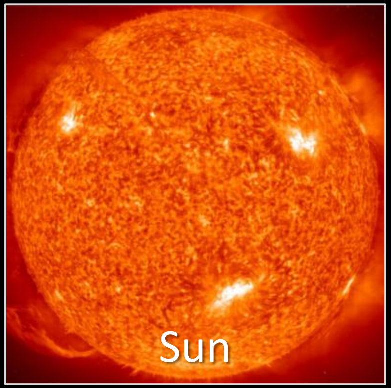
Astrophysical Axion Bounds

The 2024 Edition, Caputo & Raffelt, arXiv:2401.13728, 24 Jan 2024



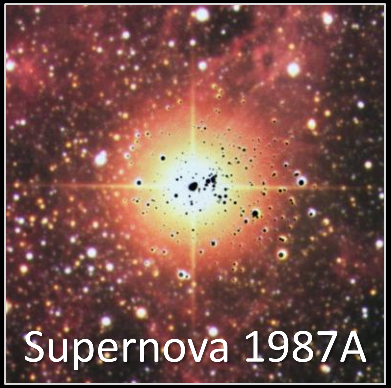
- Many improvements over the years, but overall picture the same
- Specific QCD axion signatures hard to expect from cooling effects
- Best stellar detection opportunity probably (Baby)IAXO

Neutrinos and the Stars



- Strongest local neutrino flux
- Long history of detailed measurements
- Crucial for flavor oscillation physics
- Resolve solar metal abundance problem in future?
- Use Sun as source for other particles (especially axions)

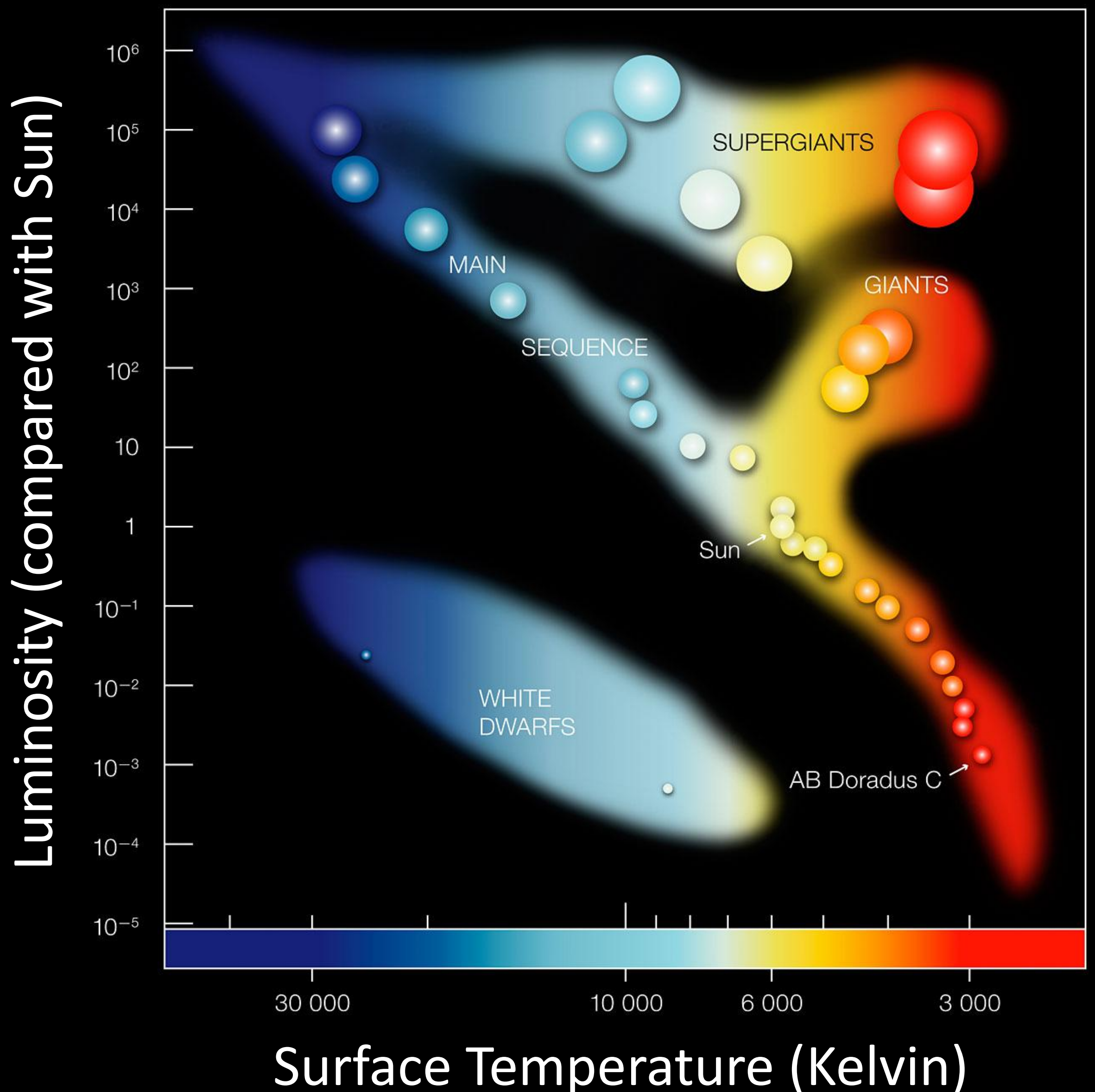
- Neutrino energy loss crucial in stellar evolution theory
- Backreaction on stars provides limits,
  e.g. neutrino magnetic dipole moments
  and other particles, notably axions



- Collapsing stars most powerful neutrino sources
- Once observed from SN 1987A
- Provides well-established particle-physics constraints
- Next galactic supernova: learn about astrophyiscs of core collapse
- Diffuse Supernova Neutrino Background (DSNB) is detectable

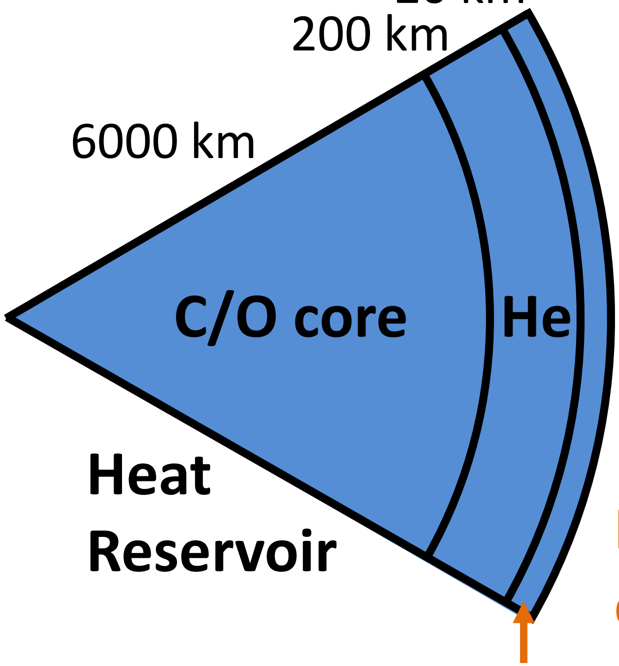
Bonus Topics

White Dwarfs



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

White Dwarfs



$R \simeq 6000\ \mathrm{km}$ (Size of the Earth)

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

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

$M \simeq 0.5\text{–}0.8 M_\odot$

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

Degenerate Stars ("White Dwarfs")

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

Pressure ~ Momentum density × Velocity

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

Hydrostatic equilibrium

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

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

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

Inverse mass radius relationship

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

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

(Y_e electrons per nucleon)

For sufficiently large stellar mass M, electrons become relativistic

- Velocity = speed of light
- Pressure

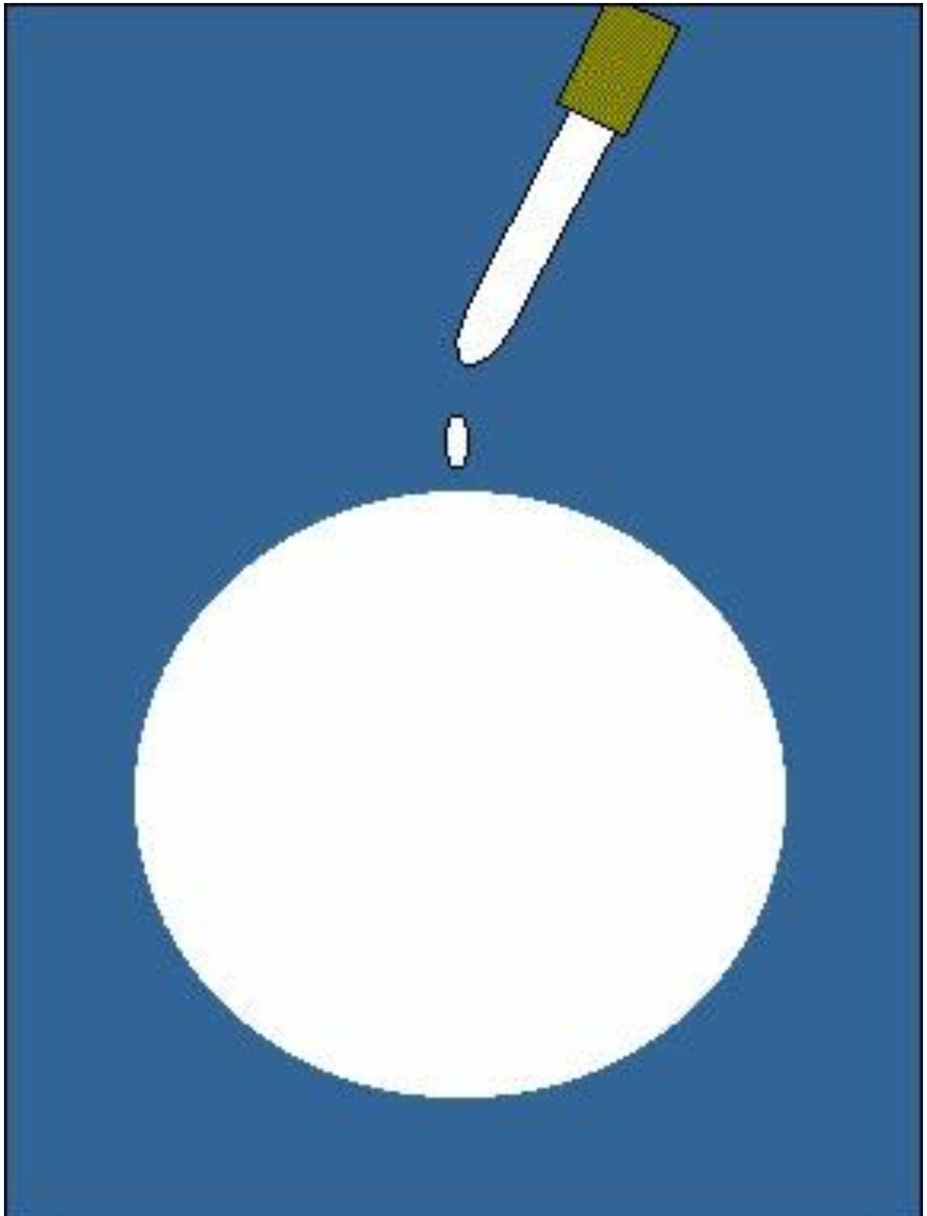
$$P \propto p_{\rm F}^4 \propto \rho^{4/3} \propto M^{4/3}R^{-4}$$

No stable configuration

Chandrasekhar mass limit

$$M_{\rm Ch} = 1.457~M_\odot~(2Y_e)^2$$

Degenerate Stars (“White Dwarfs”)



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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:

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

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

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

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

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

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

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

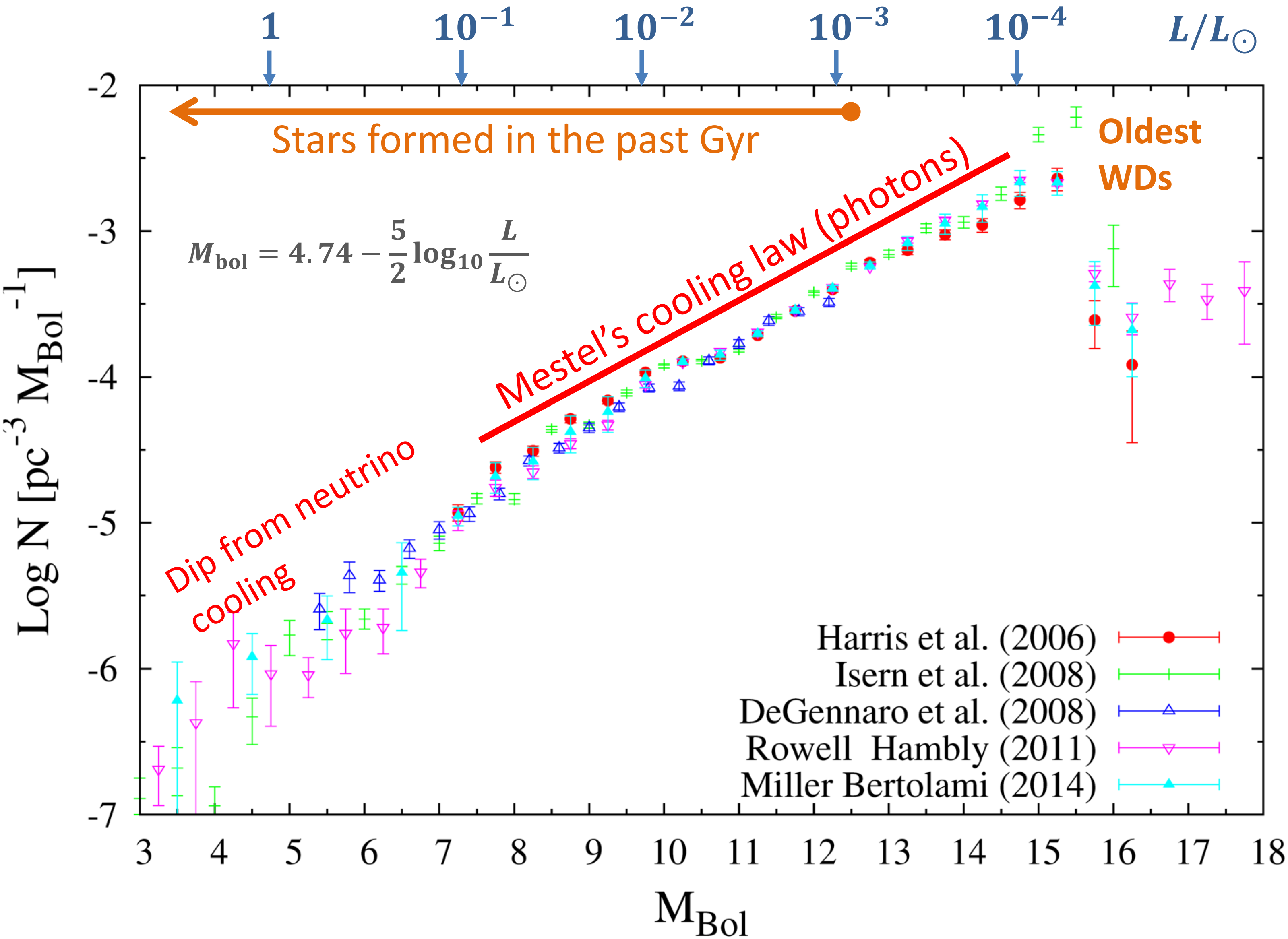
- **Neutron Star (NS):**
  Degenerate particle: Nucleon, $m = m_N$

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

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

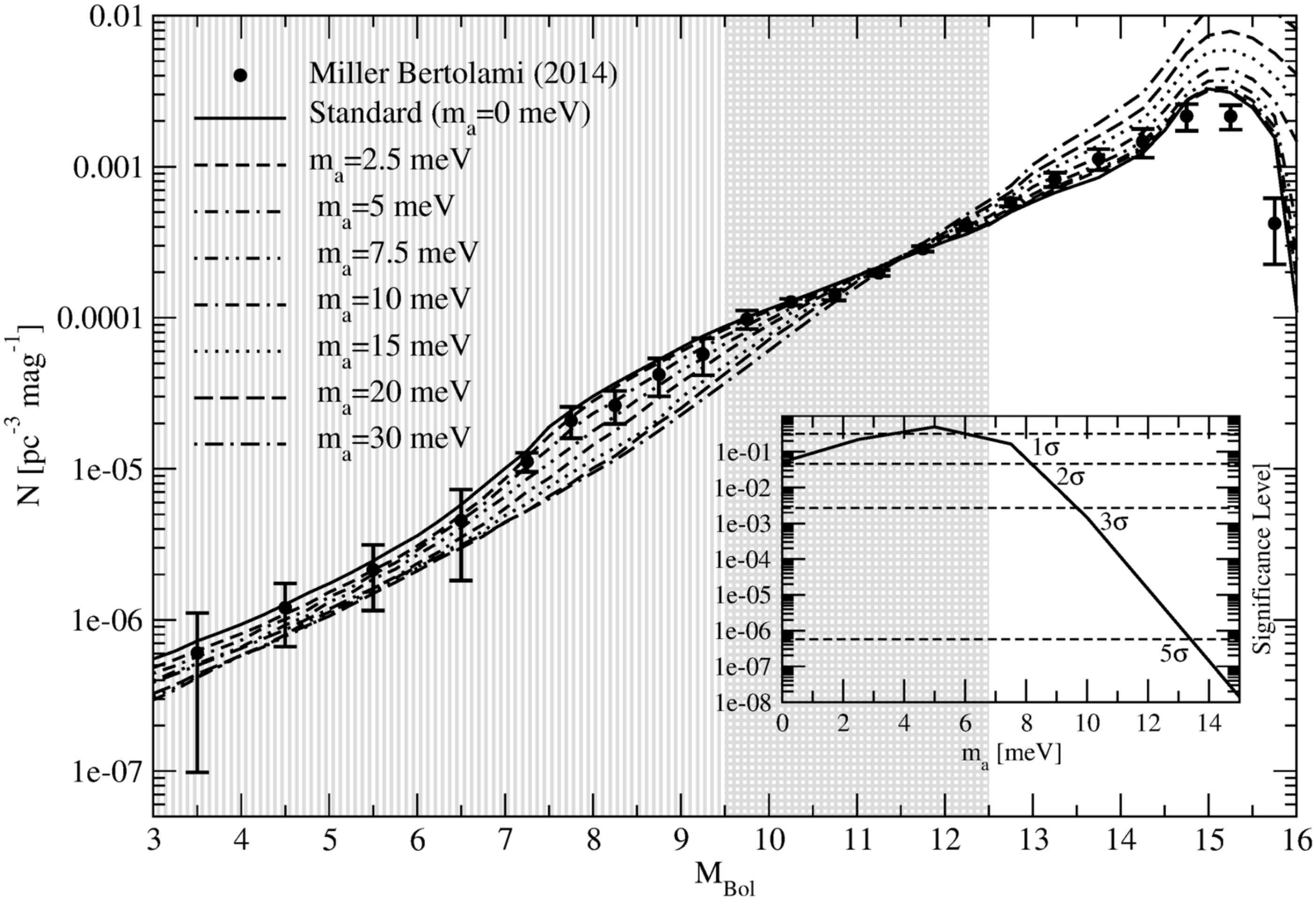
$$R_{\rm WD} \simeq \frac{m_{\rm Planck}}{m_e m_N} = \frac{m_N}{m_e} R_{\rm NS} = 5000~{\rm km}$$

White Dwarf Luminosity Function (WDLF)



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

Axion Bounds from WD Luminosity Function



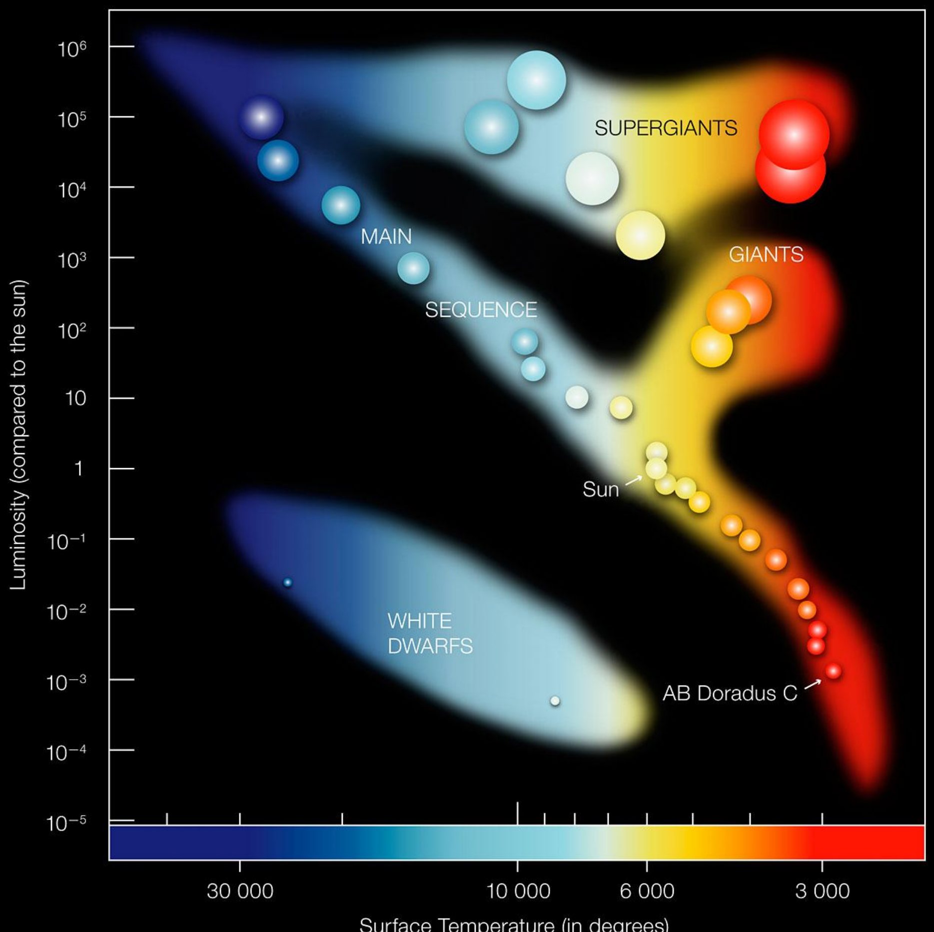
Limits on axion-electron coupling and mass limit in DFSZ model:

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

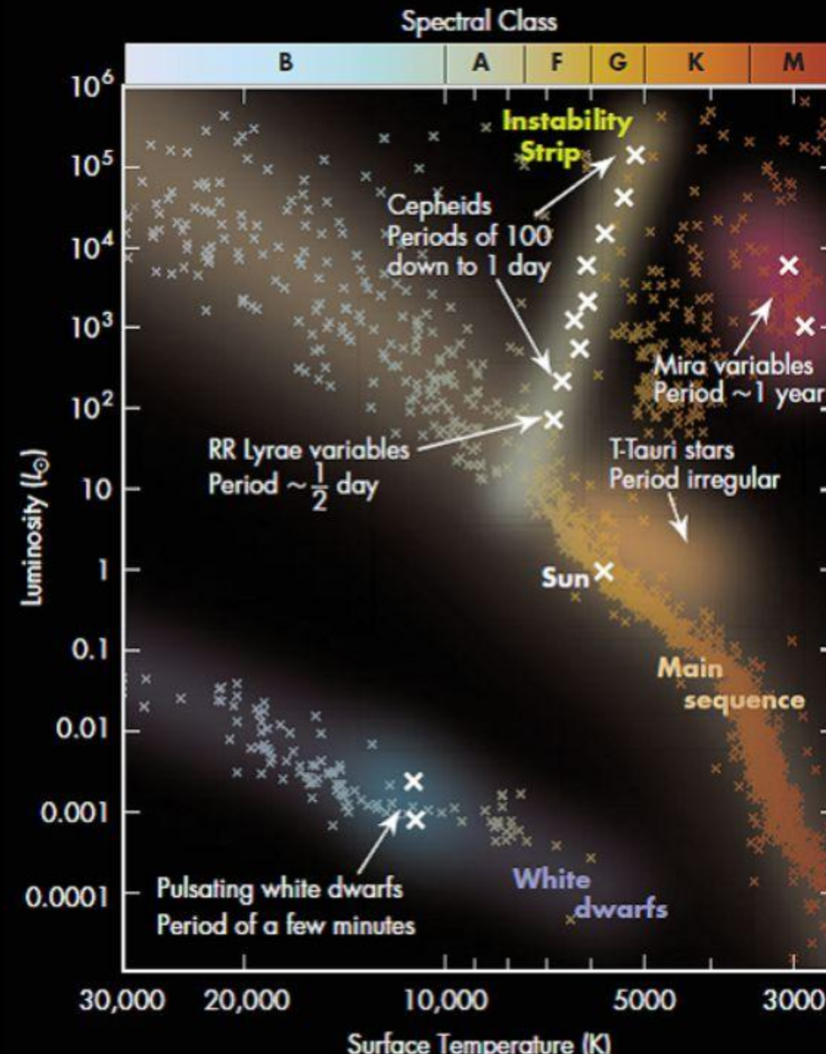
Miller Bertolami, Melendez, Althaus & Isern, arXiv:1406.7712, 1410.1677

For extensions and review see: Isern, arXiv:2002.08069

Pulsating Stars

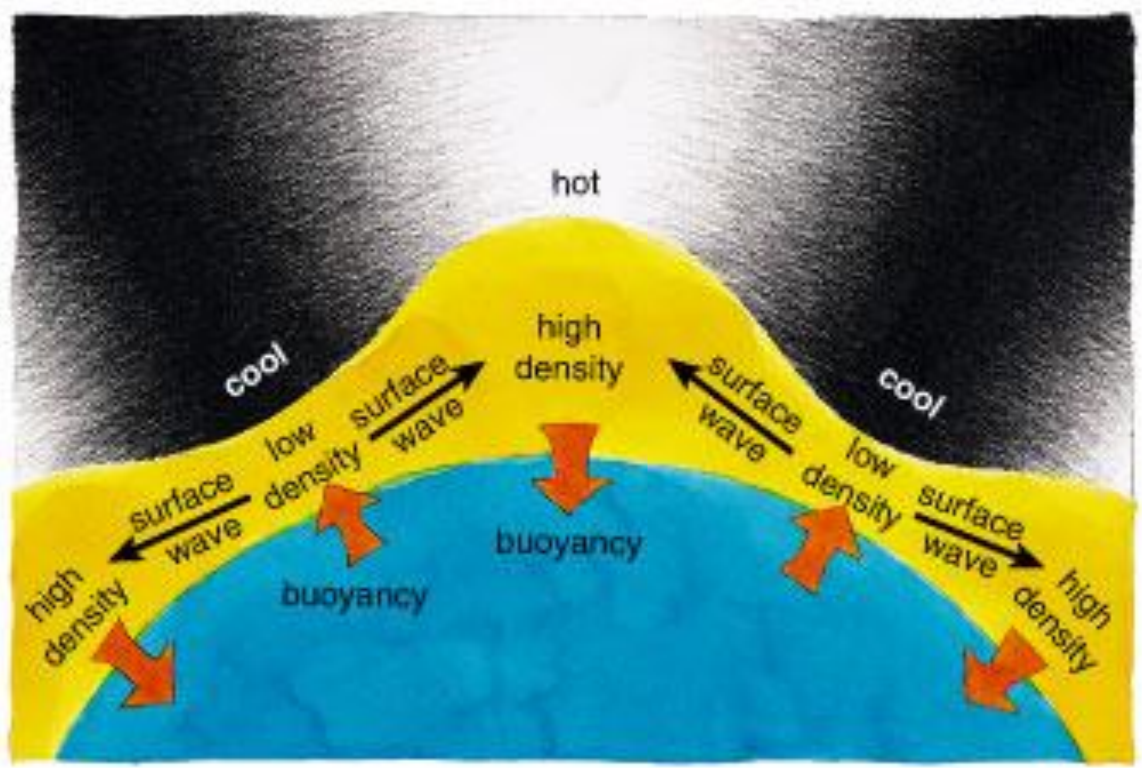


https://www.eso.org/public/images/eso0728c/



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

Pulsating White Dwarf G117–B15A

Kepler+ ApJ 254 (1982) 676

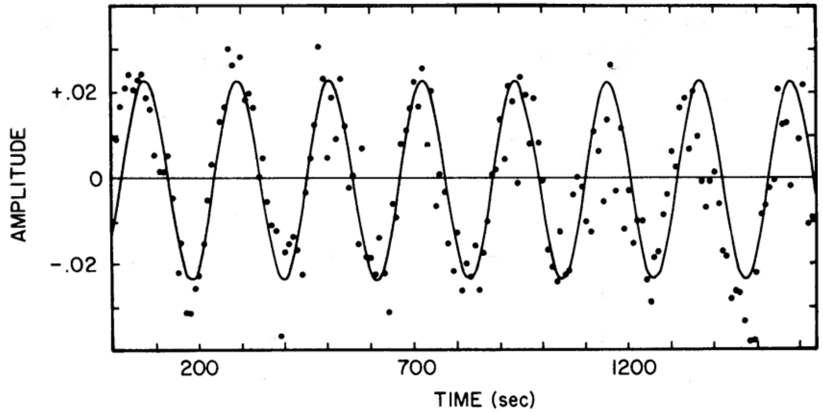


FIG. 1.—A portion of the light curve of G117−B15A in unfiltered light during run 2075. The light curve has been normalized so that the time-averaged brightness of G117−B15A is equal to 1.00, and then 1.00 has been subtracted from the light curve. The solid line is a sine curve with a period of 215.19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

Kepler+ ApJ 906 (2021) 7

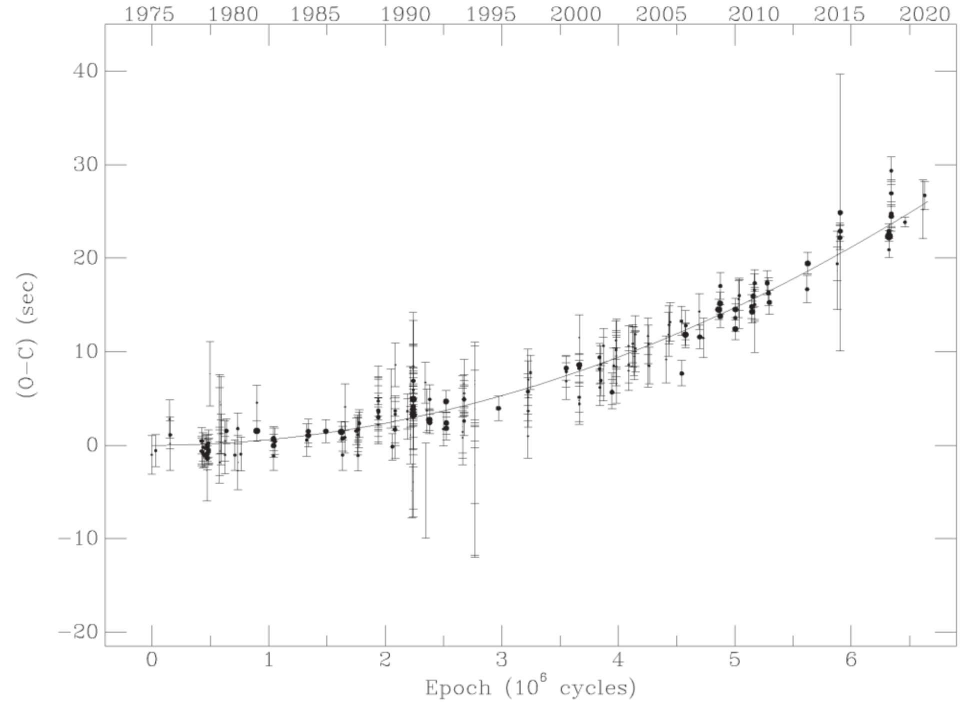


Figure 1. ($O - C$): observed minus calculated times of maxima for the 215 s pulsation of G 117-B15A. The size of each point is proportional to its weight, i.e., inversely proportional to the uncertainty in the time of maxima squared. We show $\pm 1\sigma$ error bars for each point, and the line shows 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?

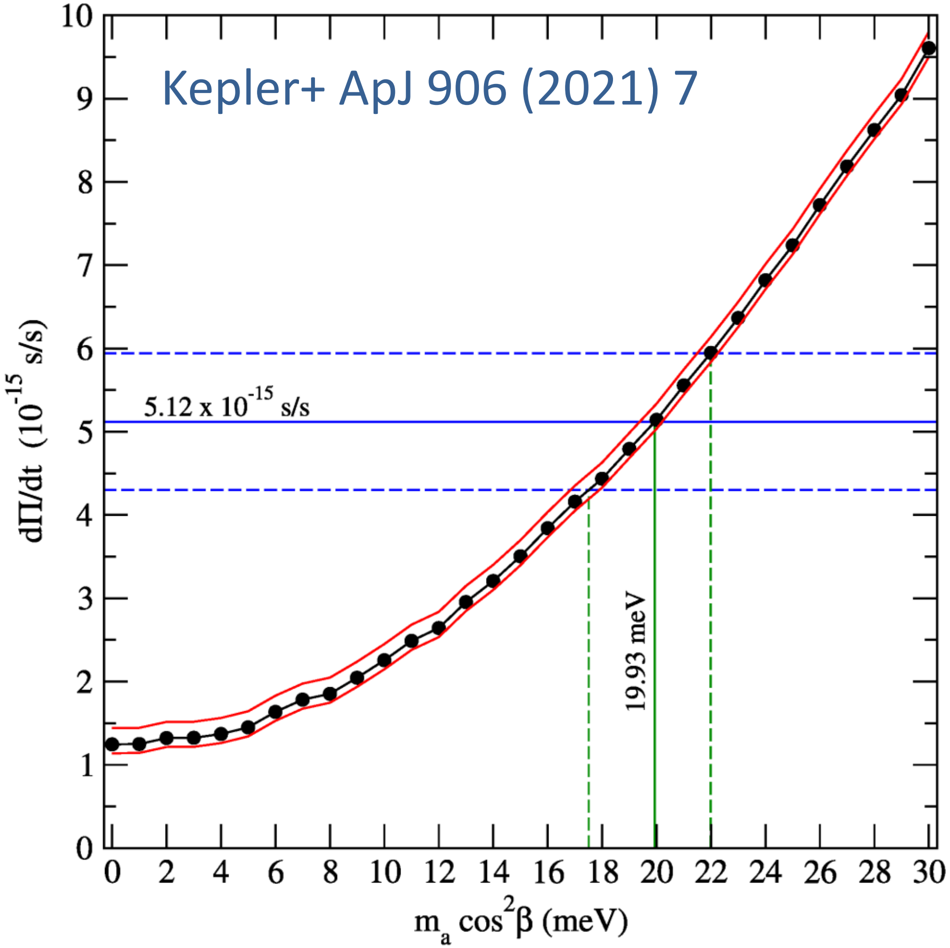
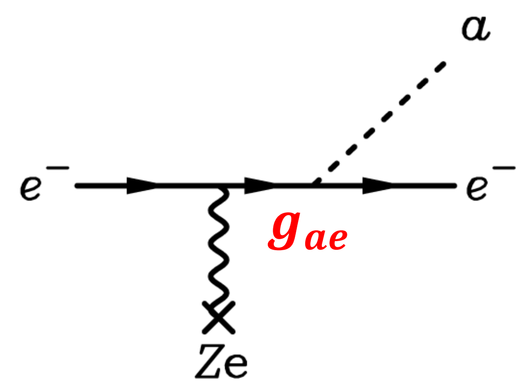


Figure 2. The rate of period change for the mode with $\ell = 1$ and $k = 2$, corresponding to a period of ~215 s in terms of the axion mass (black circles). Dashed lines represent the uncertainties in the value in the observed $\dot{P}$ and the axion mass, while the red curves represent the internal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

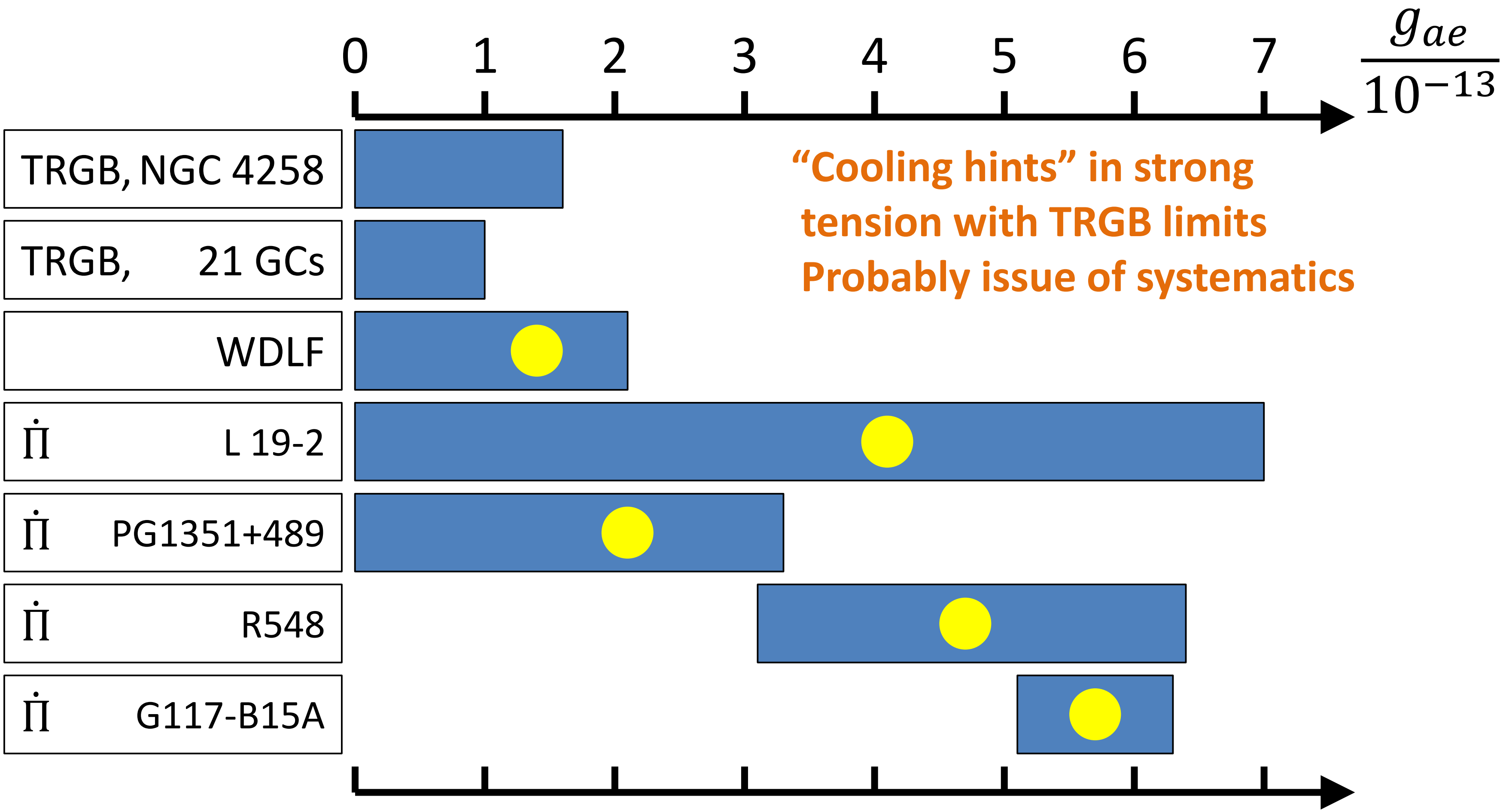
Case of DFSZ Axion

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

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

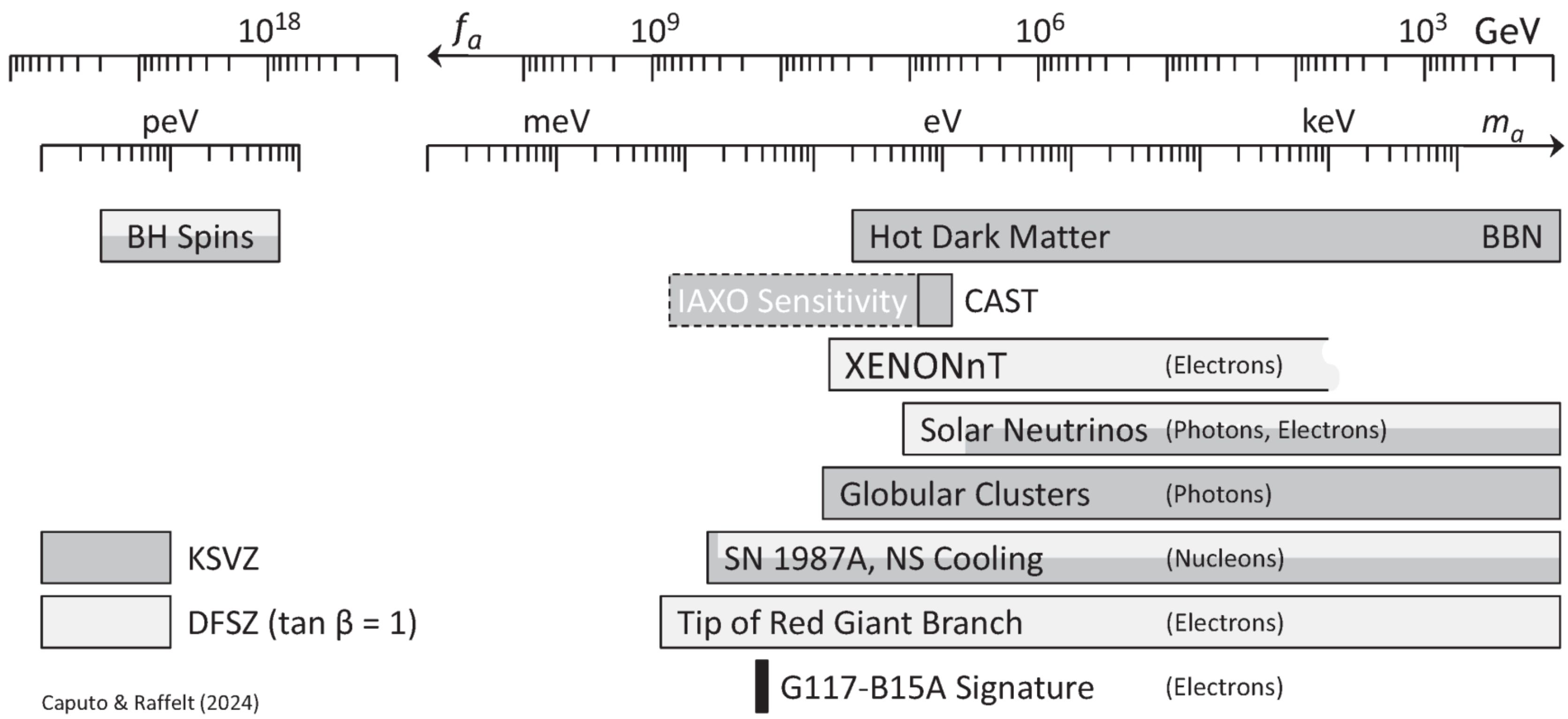
J. Isern, S. Torres & A. Rebassa-Mansergas

Stellar Evolution Confronts Axion Models, arXiv:2109.10368

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

Astrophysical Axion Bounds

The 2024 Edition, Caputo & Raffelt, arXiv:2401.13728, 24 Jan 2024



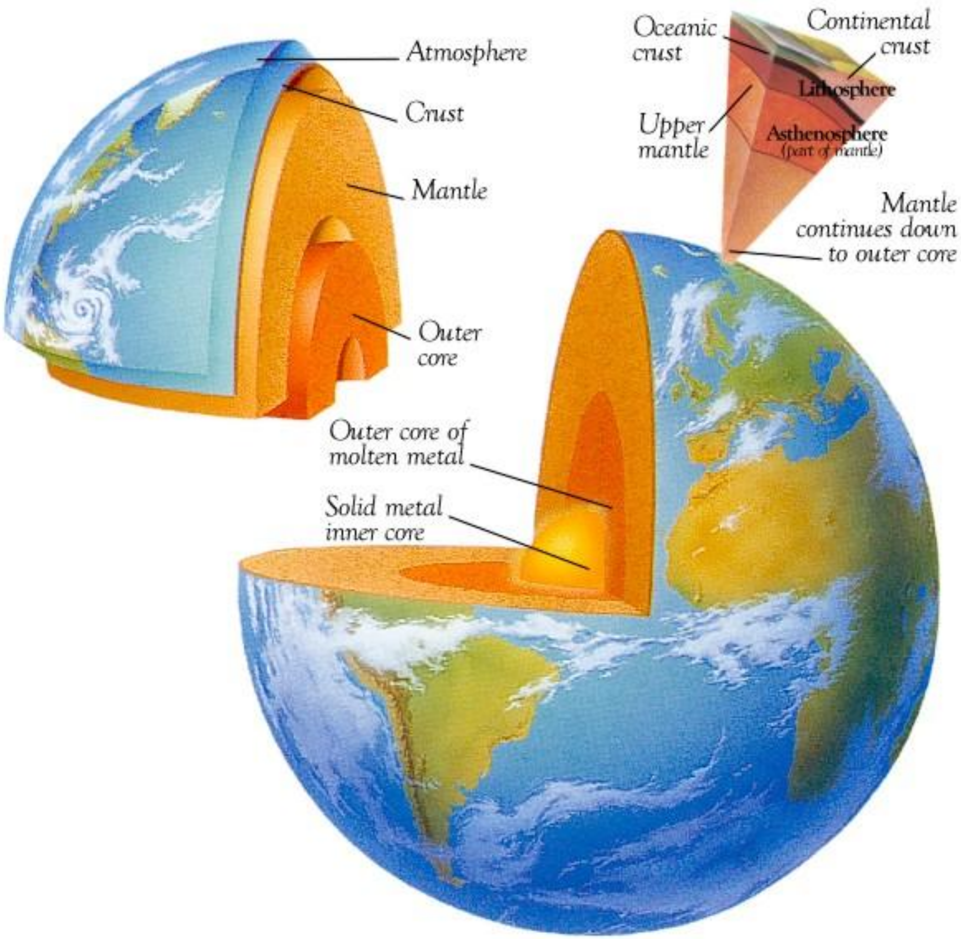
- Many improvements over the years, but overall picture the same
- Specific QCD axion signatures hard to expect from cooling effects
- Best stellar detection opportunity probably (Baby)IAXO

Geo-Neutrinos

Geo Neutrinos: What is it all about?

We know surprisingly little about the Earth's interior

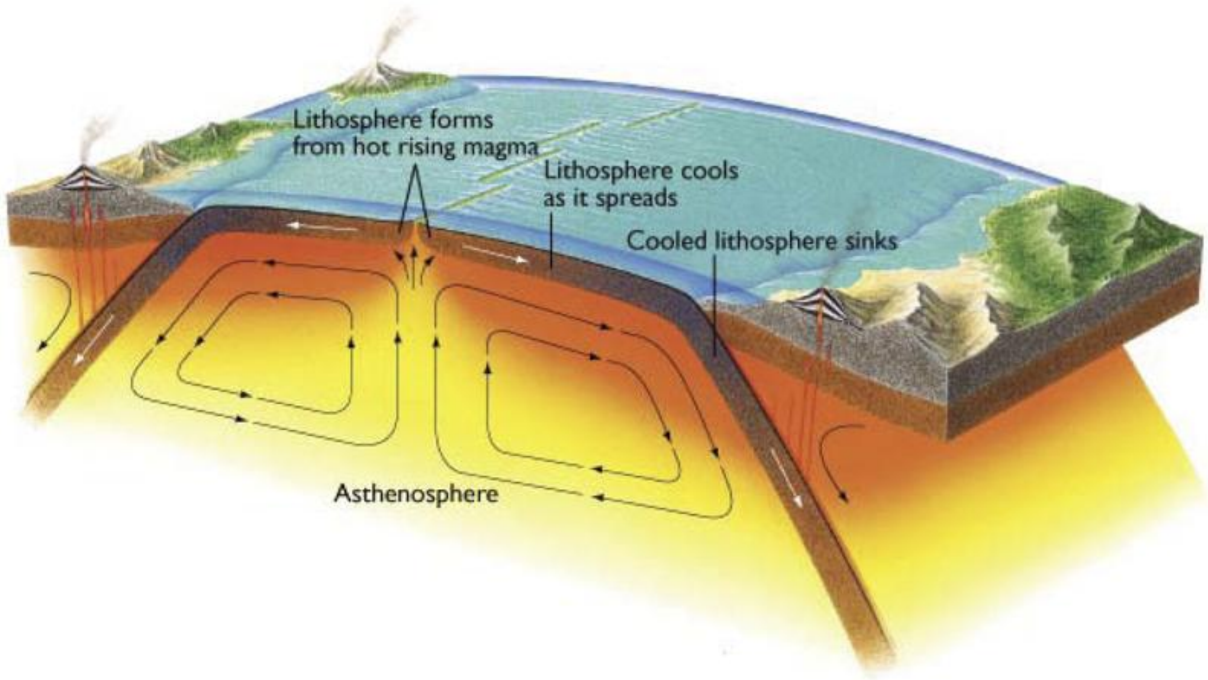
- **Deepest drill hole ~ 12 km**
- **Samples of crust for chemical analysis available (e.g. vulcanoes)**
- **Reconstructed density profile from seismic measurements**
- **Heat flux from measured temperature gradient 45–50 TW**

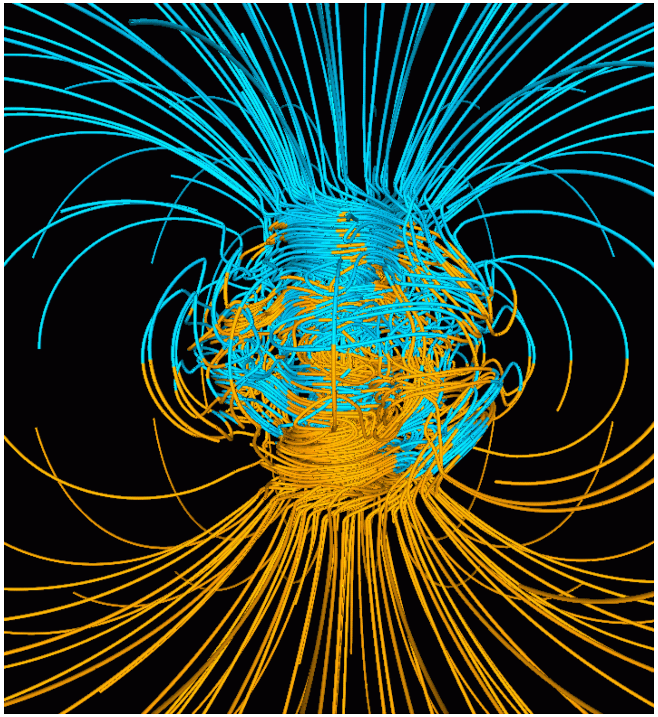


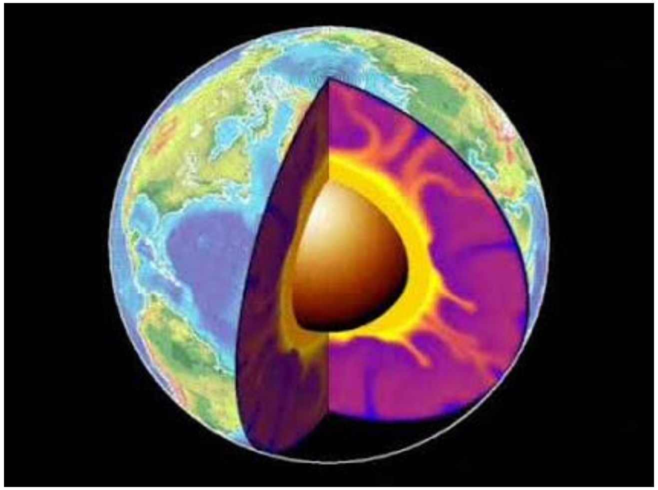
- **Neutrinos escape unscathed**
- **Carry information about chemical composition, radioactive energy production or even a hypothetical reactor in the Earth's core**

Plate Tectonics, Convection, Geo-Dynamo

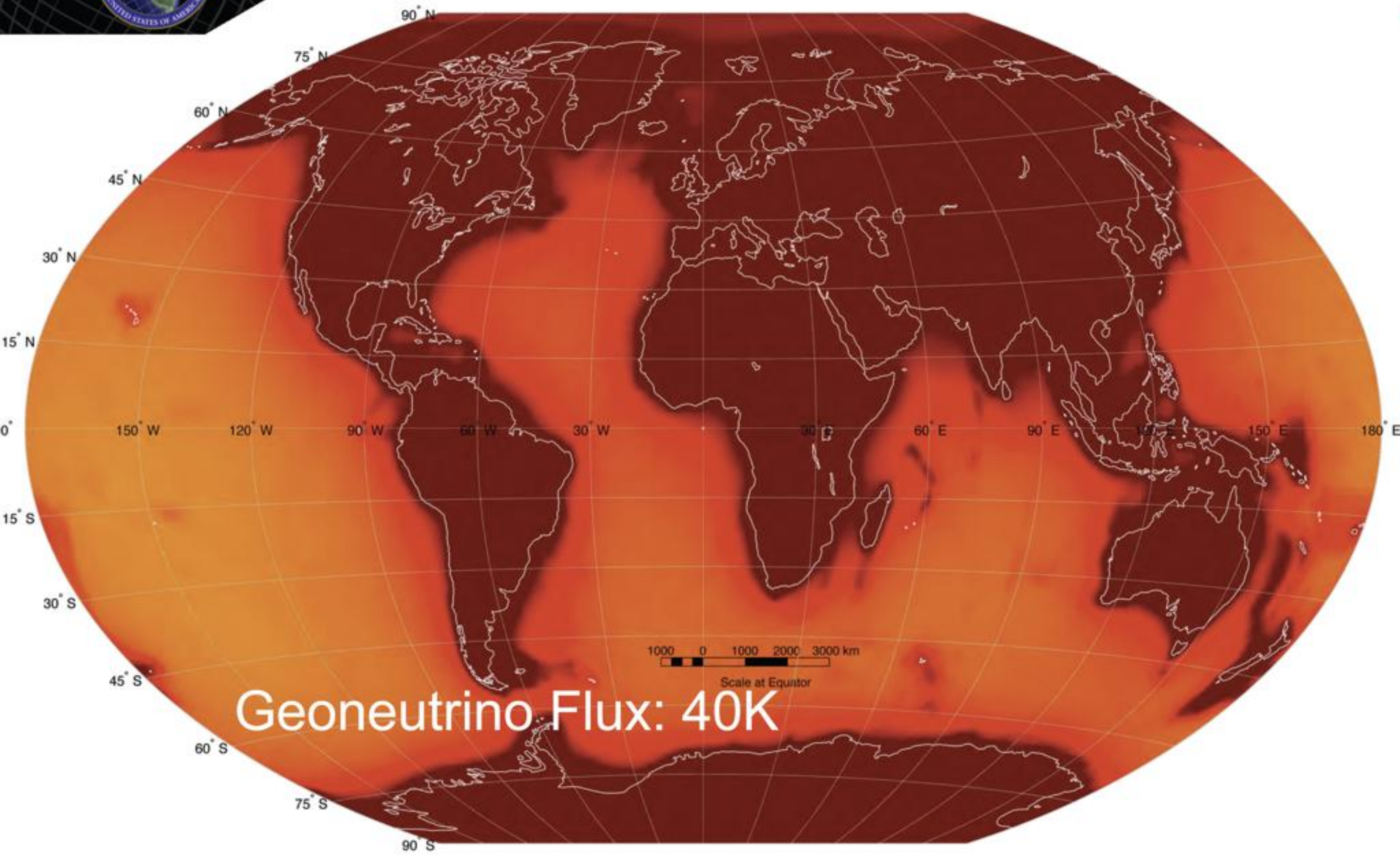
- Potassium-40 (Half life 1.25 billion years)
- Thorium-232 (14 billion years)
- Uranium-238 (4.5 billion years)





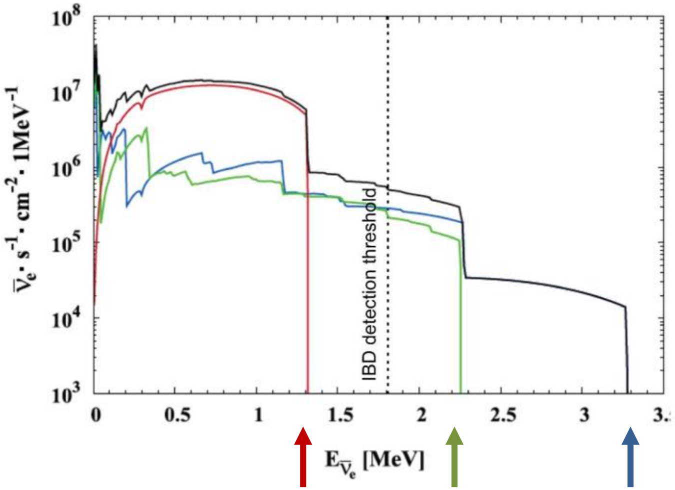


Radioactive decays provide the engine!

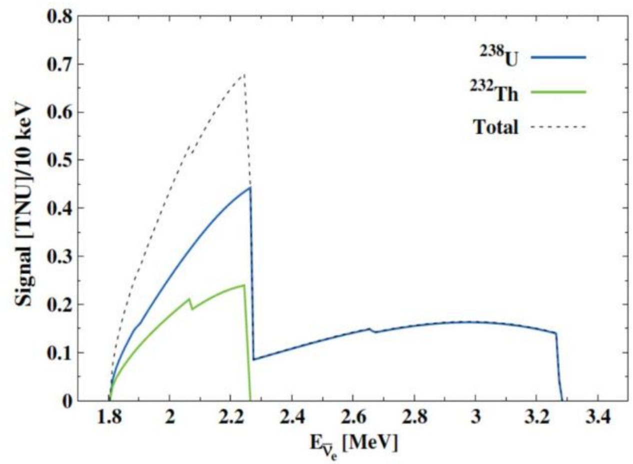

Geoneutrino Flux: 40K
90° N
75° N
60° N
45° N
30° N
15° N
0°
15° S
30° S
45° S
60° S
75° S
90° S
150° W
120° W
90° W
60° W
30° W
30° E
60° E
90° E
150° E
180° E
1000 0 1000 2000 3000 km
Scale at Equator

Geoneutrino Spectrum at Gran Sasso (LNGS)

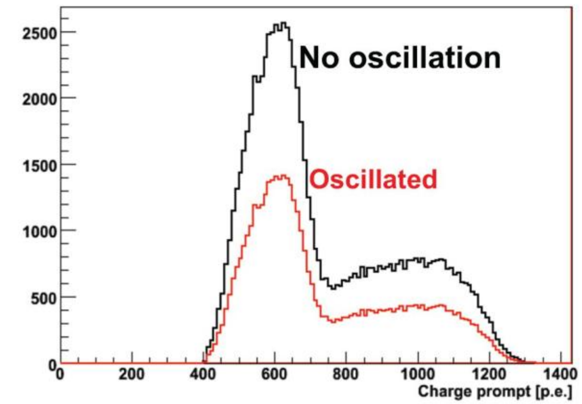
$\overline{\nu}_e$ flux $[\mathrm{s}^{-1}\mathrm{cm}^{-2}\,\mathrm{MeV}^{-1}]$



IBD Signal $\overline{\nu}_e + p \rightarrow n + e^+$



Reduction by flavor conversion



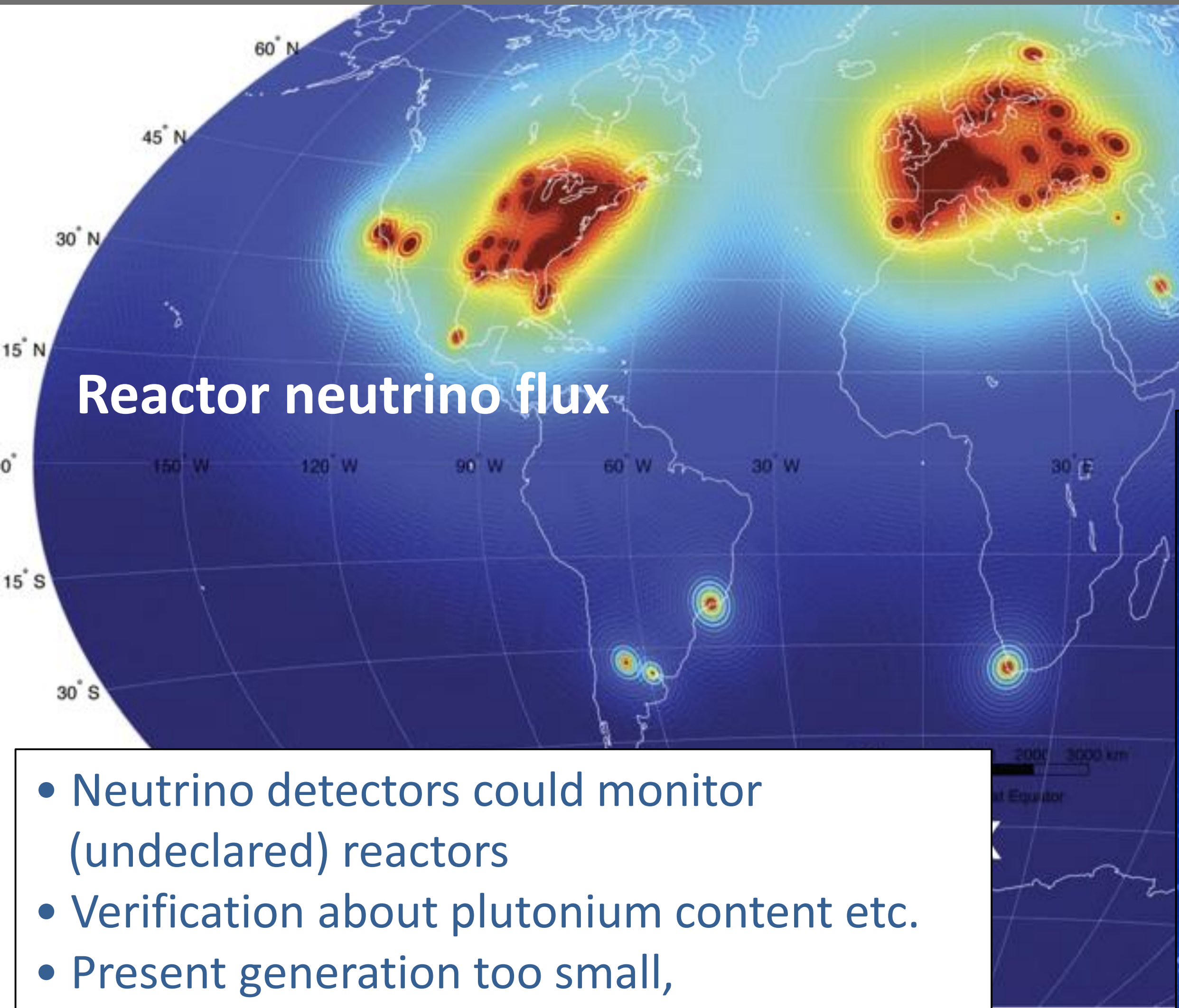
500 p.e. ~ 1 MeV

Potassium-40	Thorium-232	Uranium-238
Half life 1.3 billion years	14 billion years	4.5 billion years

- ^{40}K geoneutrinos can not be detected by IBD
- ^{238}U and ^{232}Th distinguished by different end points
- Flavor oscillation for 3 MeV antineutrinos ~100 km
- In detection range, no relevant deformation

L.Ludhova, Geoneutrinos, Plenary @ Neutrino 2024

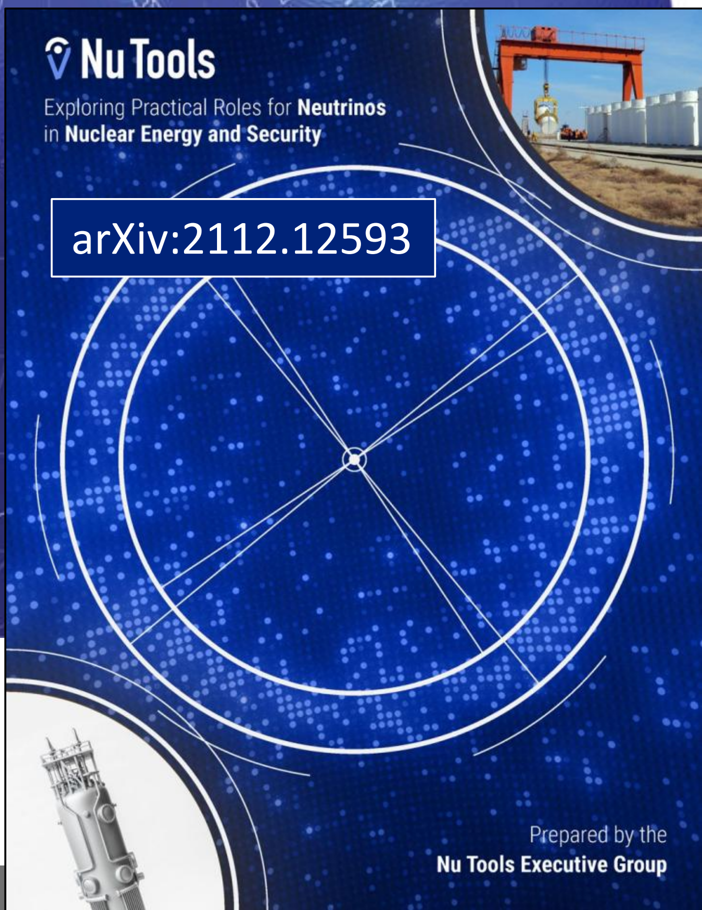
Neutrinos for Peace



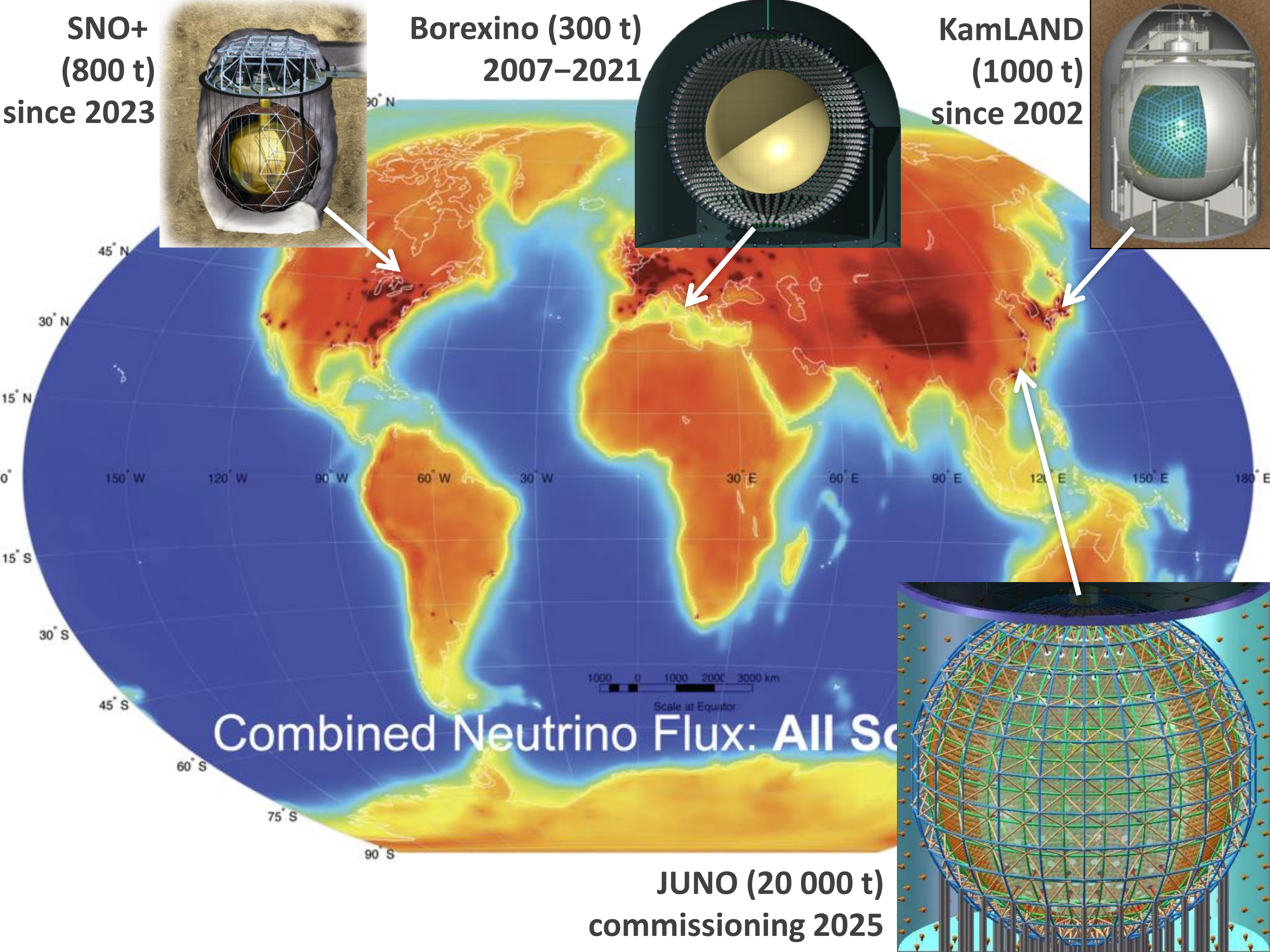
Reactor neutrino flux

- Neutrino detectors could monitor (undeclared) reactors
- Verification about plutonium content etc.
- Present generation too small, but eg *Watchman* development

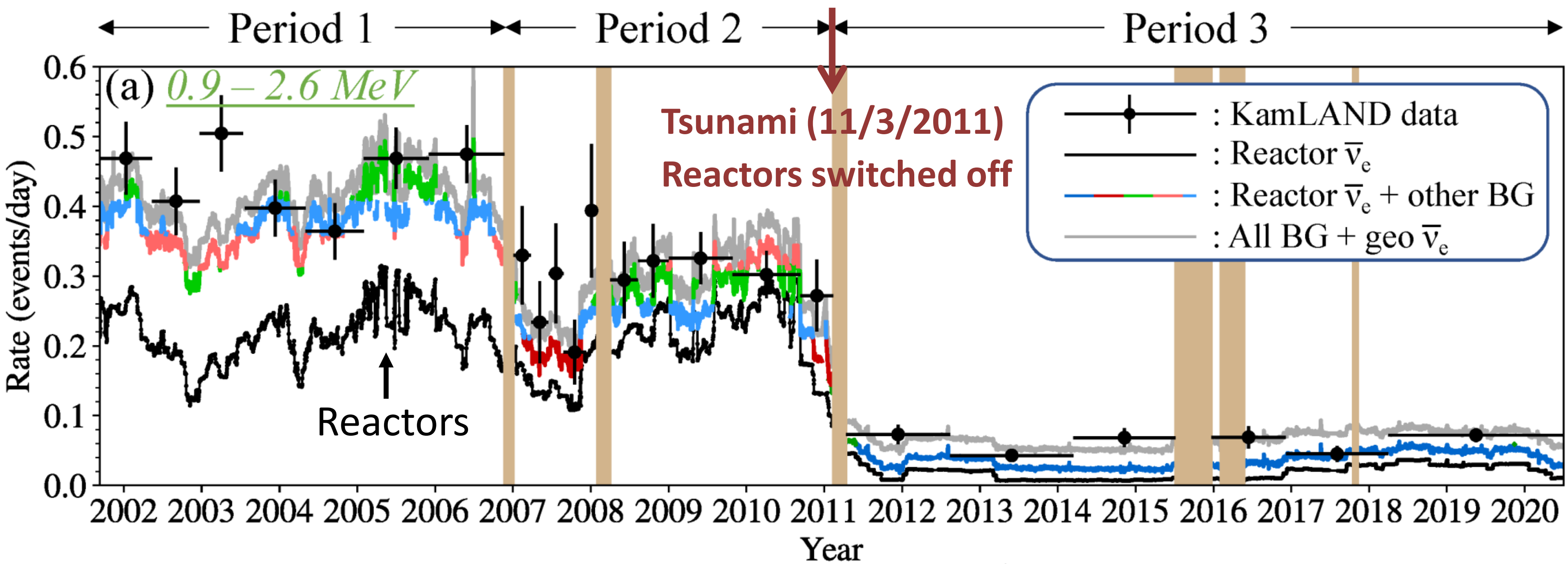
Bernstein+, *Neutrino Detectors as Tools for Nuclear Security*, arXiv:1908.07113



arXiv:2112.12593


SNO+
(800 t)
since 2023
Borexino (300 t)
2007–2021
KamLAND
(1000 t)
since 2002
JUNO (20 000 t)
commissioning 2025
Combined Neutrino Flux: All Sc
90° N
45° N
30° N
15° N
0°
15° S
30° S
45° S
60° S
75° S
90° S
150° W
120° W
90° W
60° W
30° W
30° E
60° E
90° E
120° E
150° E
180° E
1000 0 1000 2000 3000 km
Scale at Equator

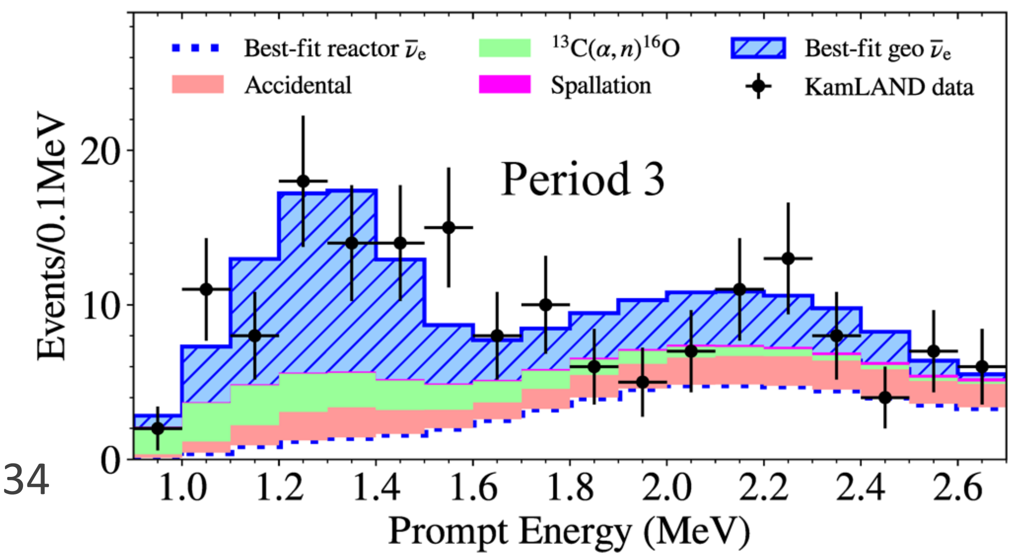
Reactor and Geoneutrinos in KamLAND (Japan)



Exposure (~14 years)
6.39×10^{32} proton-years

183^{+29}_{-28} Geoneutrinos
Total $\bar{\nu}_e$ flux $3.4^{+0.5}_{-0.5} \times 10^6\ \mathrm{cm^{-2}\ s^{-1}}$

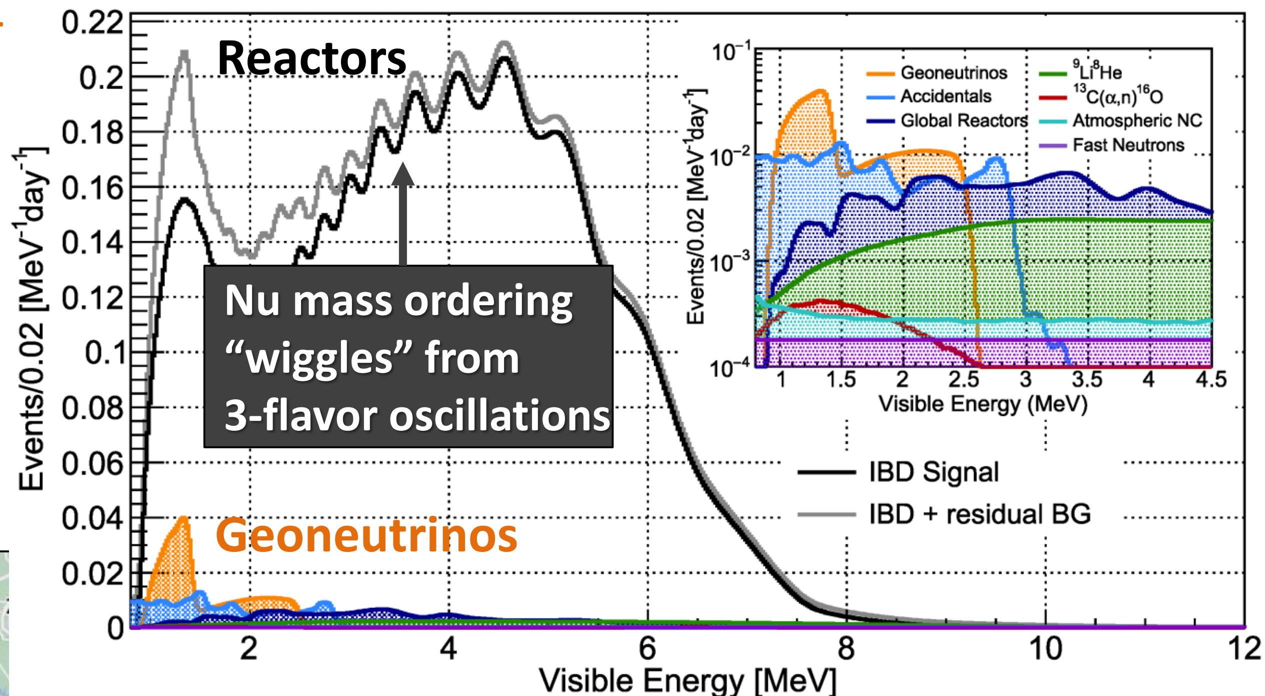
KamLAND Collaboration, arXiv:2205.14934



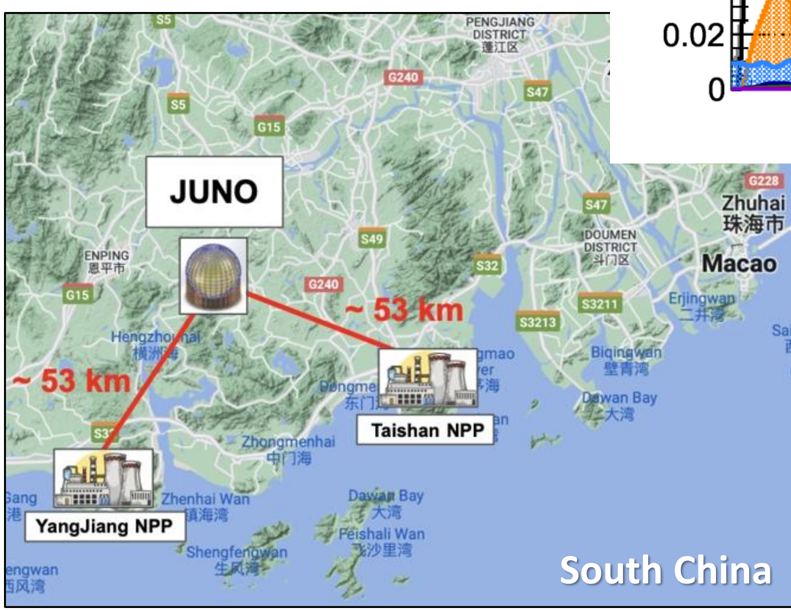
Expected Geoneutrino Signal at JUNO

Geoneutrinos	**1.2 day^{-1}**
Reactors (53 km)	43.2
Reactors world	1
Accidentals	0.8

JUNO Collaboration, arXiv:2204.13249



20 kt Scintillator Detector
Commissioning 2025



Expected precision 10 years

232-Th	35%
238-U	30%
sum	15% (anticorrelation!)
ratio	55%

C.Morales, Neutrino 2024