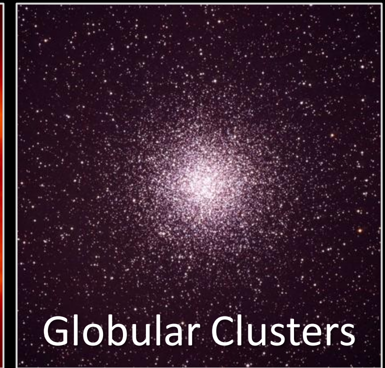
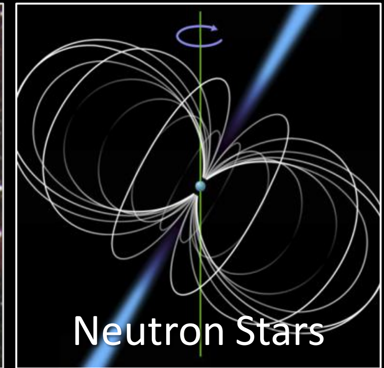
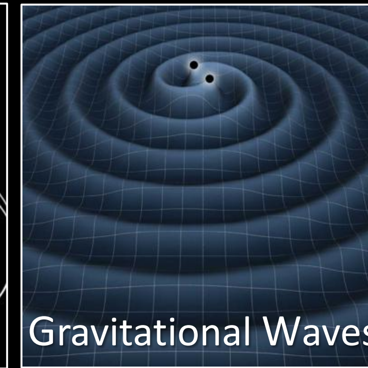






Axions and the Stars

Old Ideas and New Developments

Ringberg Castle, IMPRS Workshop, 4 June 2024

ORIGINS Excellence Cluster

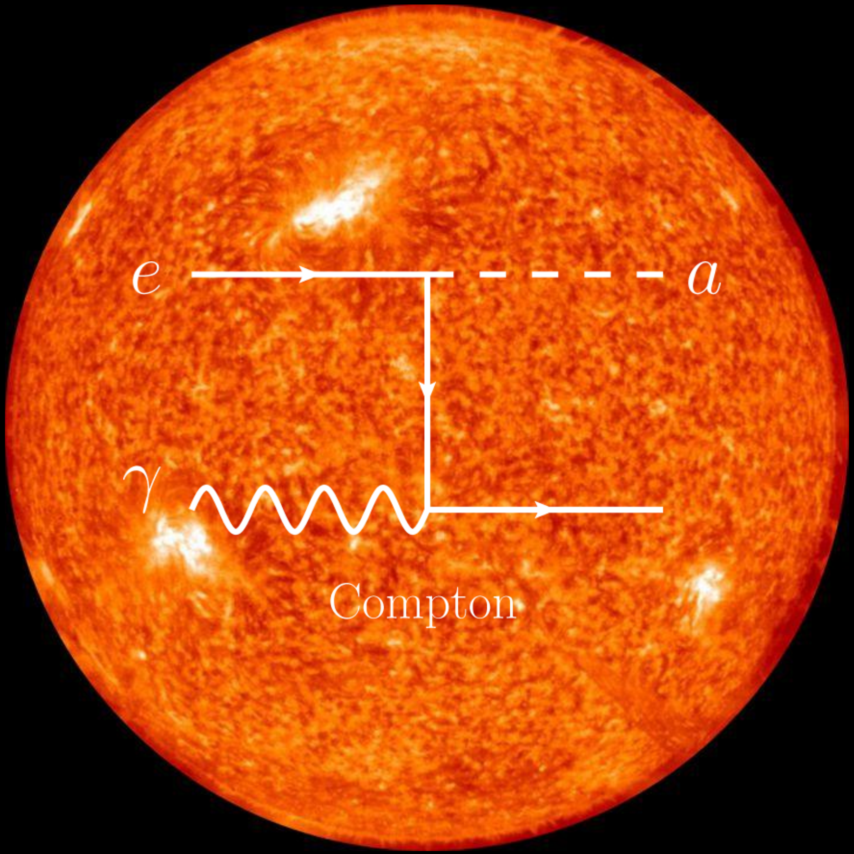
COSMIC WISPERS CA21106

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

SFB 1258 | Neutrinos Dark Matter Messengers

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

Particles and Stars



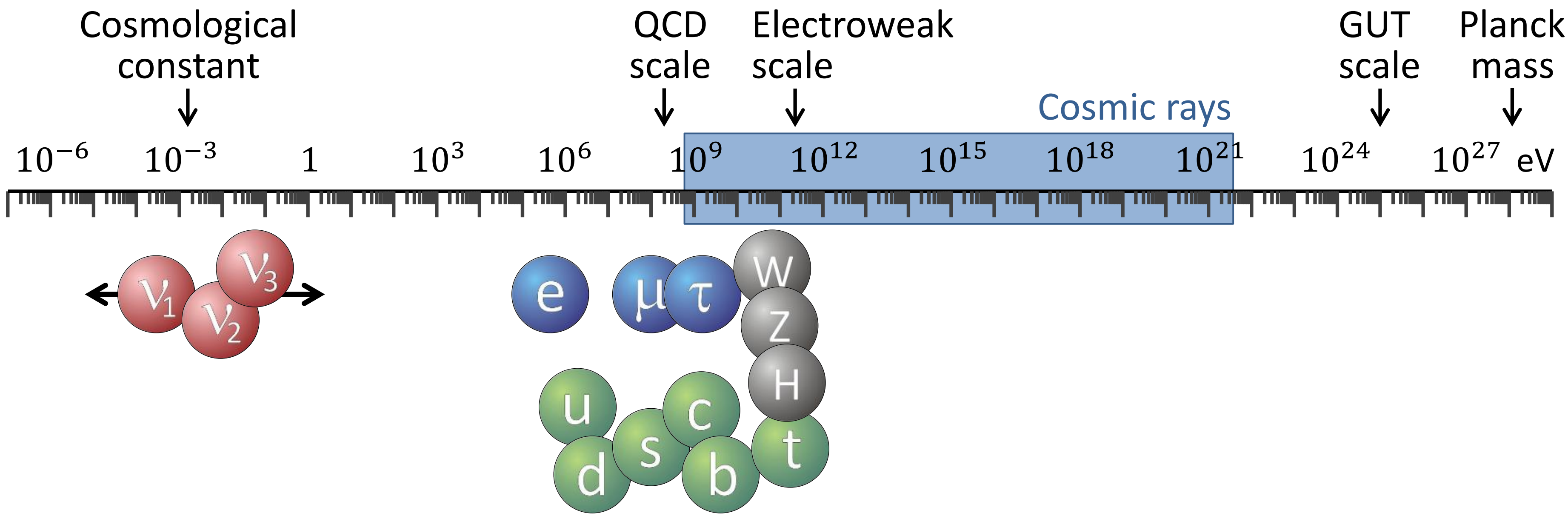
Low-mass particles are produced in stellar interiors

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

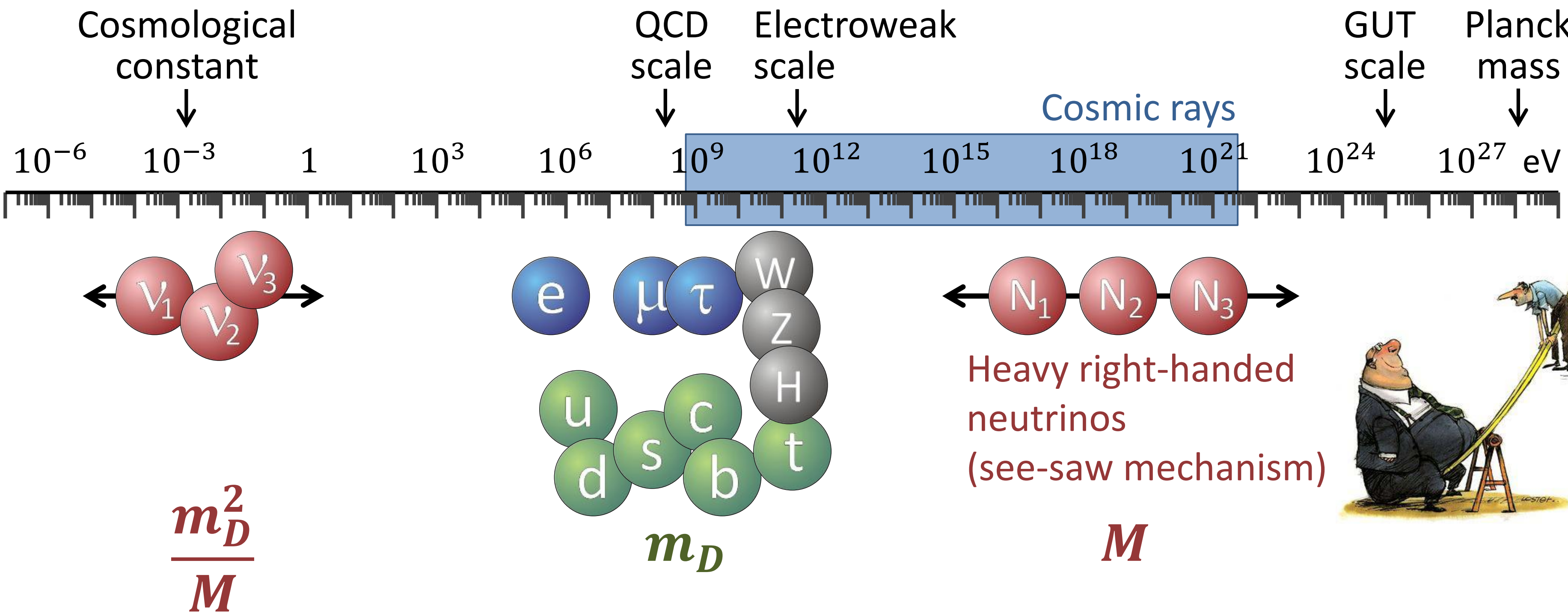
→ **Which particles?**

→ **Which stars?**

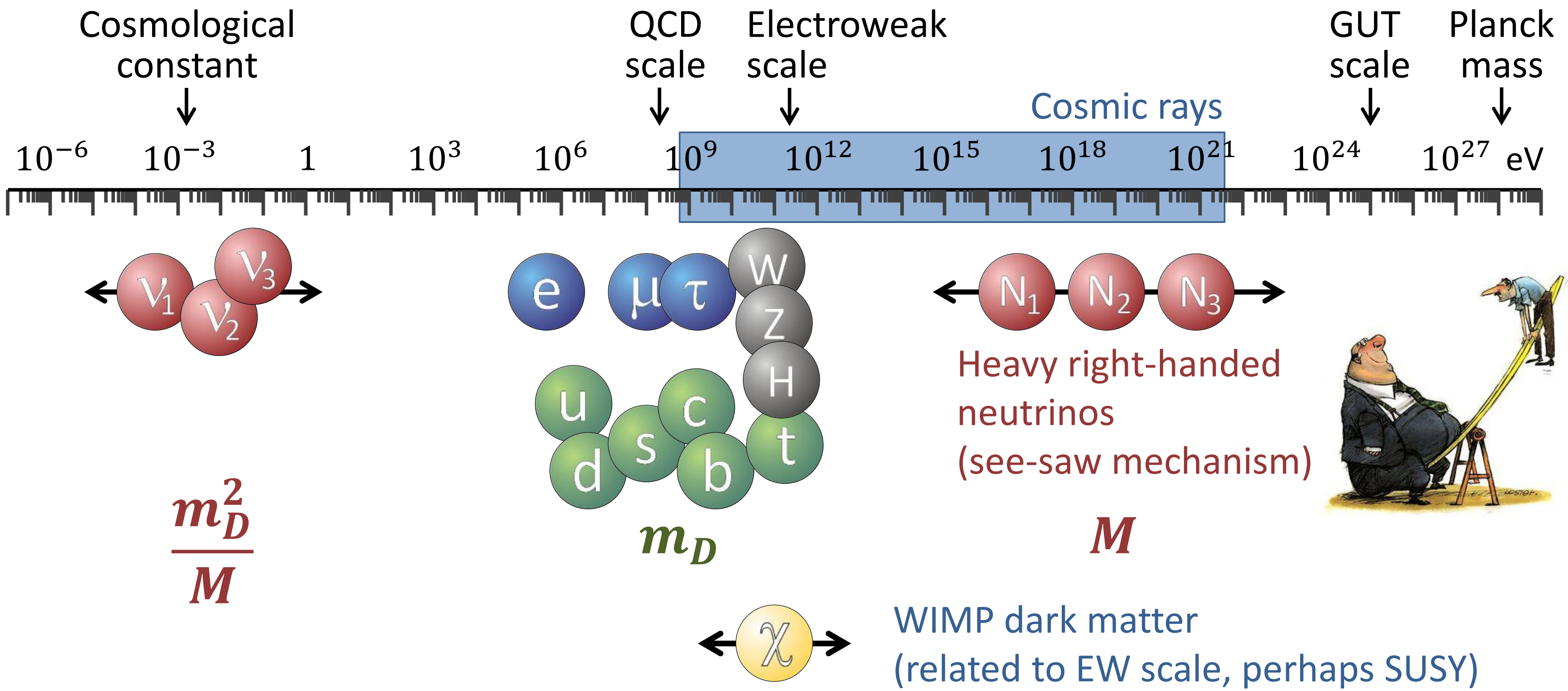
High- and Low-Energy Frontiers in Particle Physics



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 ↓ | Cosmic rays | GUT scale ↓ | Planck mass ↓

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 c s d b t

$$m_D$$

N_1 N_2 N_3

Heavy right-handed neutrinos (see-saw mechanism)

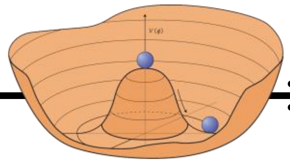
$$M$$

χ

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

a

Axion dark matter (related to Peccei-Quinn symmetry)

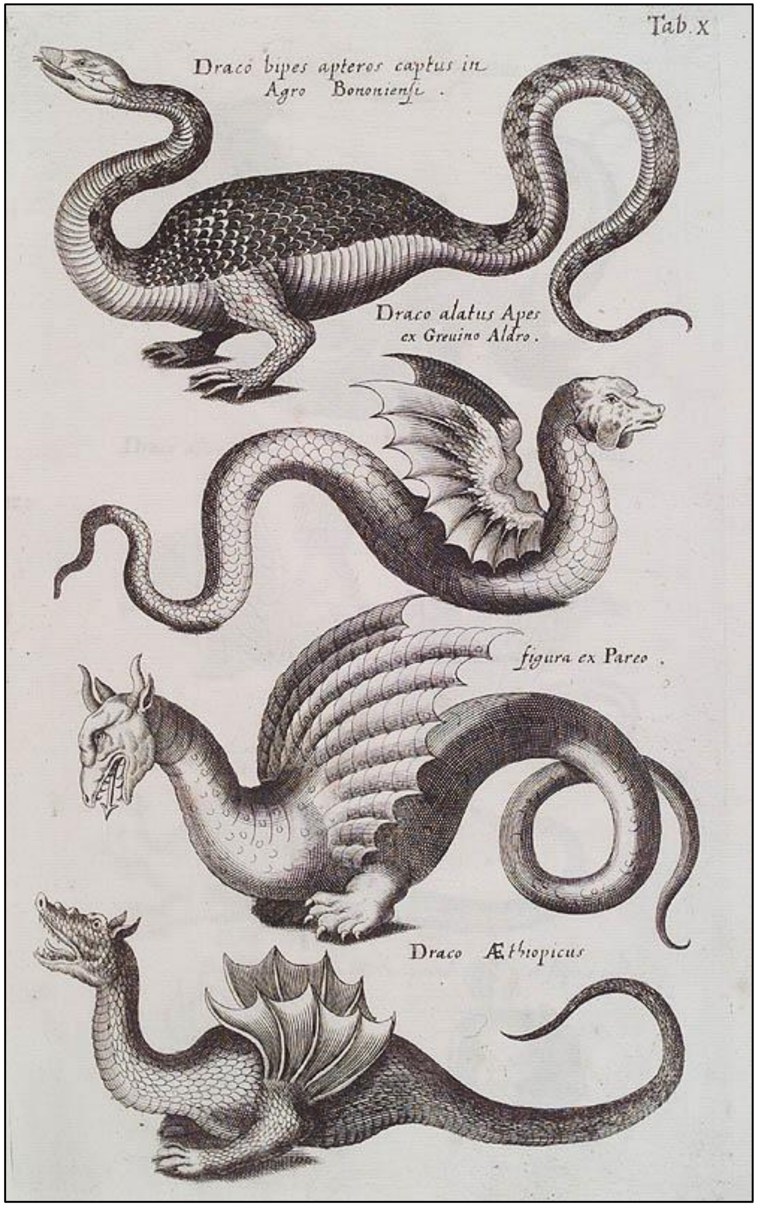


$$m_a \sim \frac{m_\pi f_\pi}{f_a}$$

$$m_\pi, f_\pi$$

$$f_a$$

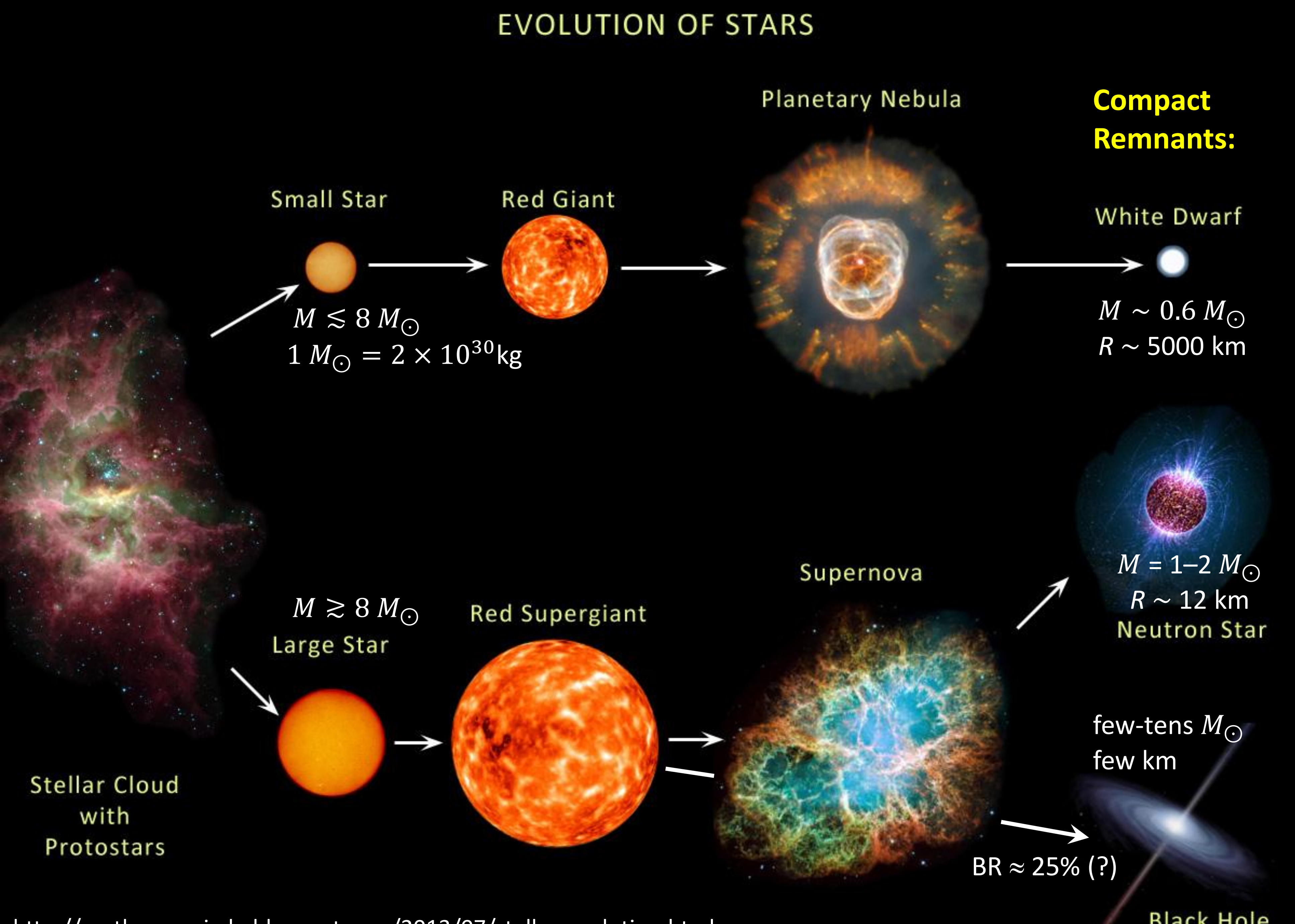
Bestiarium of Low-Mass Bosons



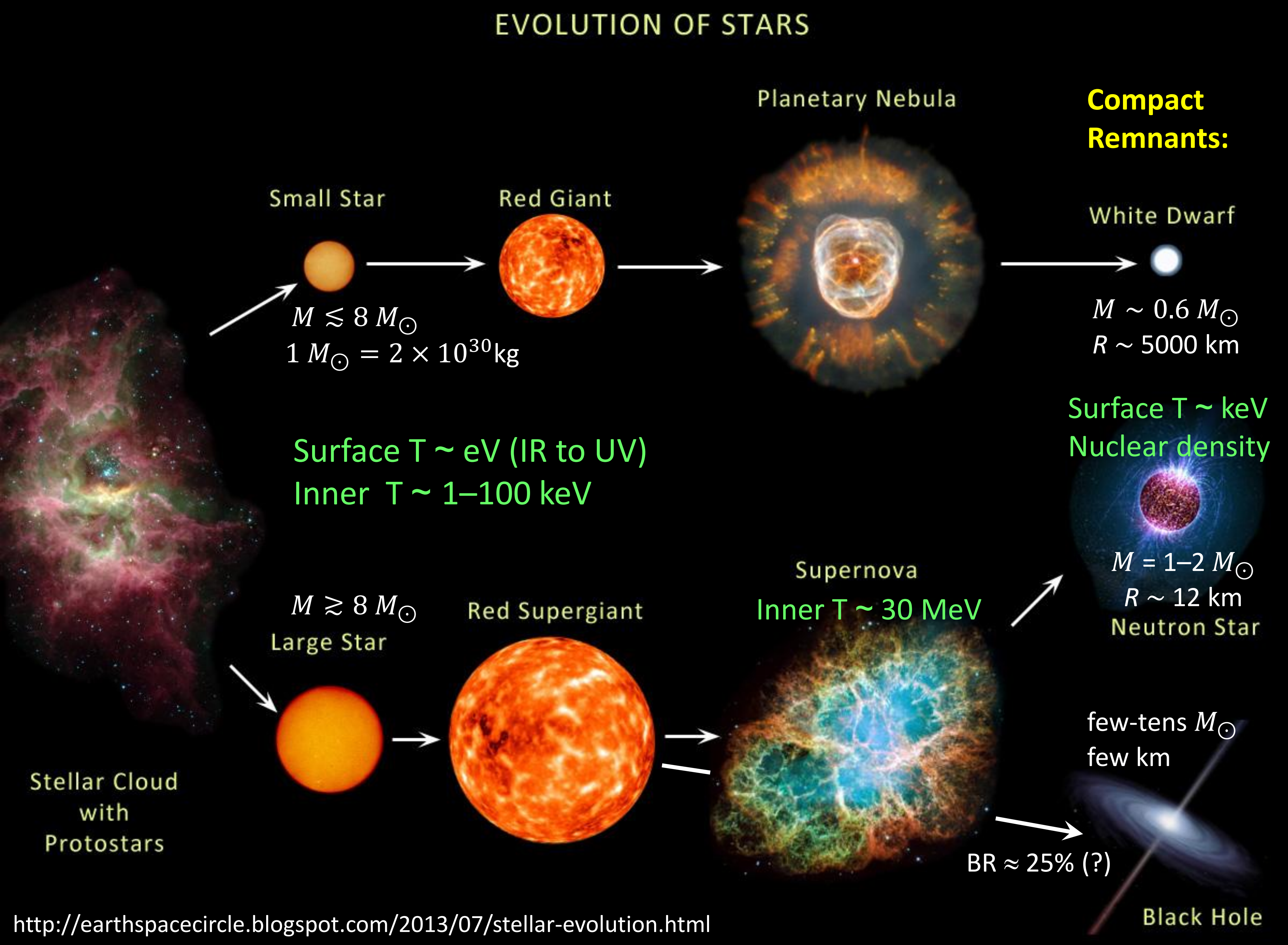
Weakly Interacting Sub-eV Particles (WISPs)

- **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, …

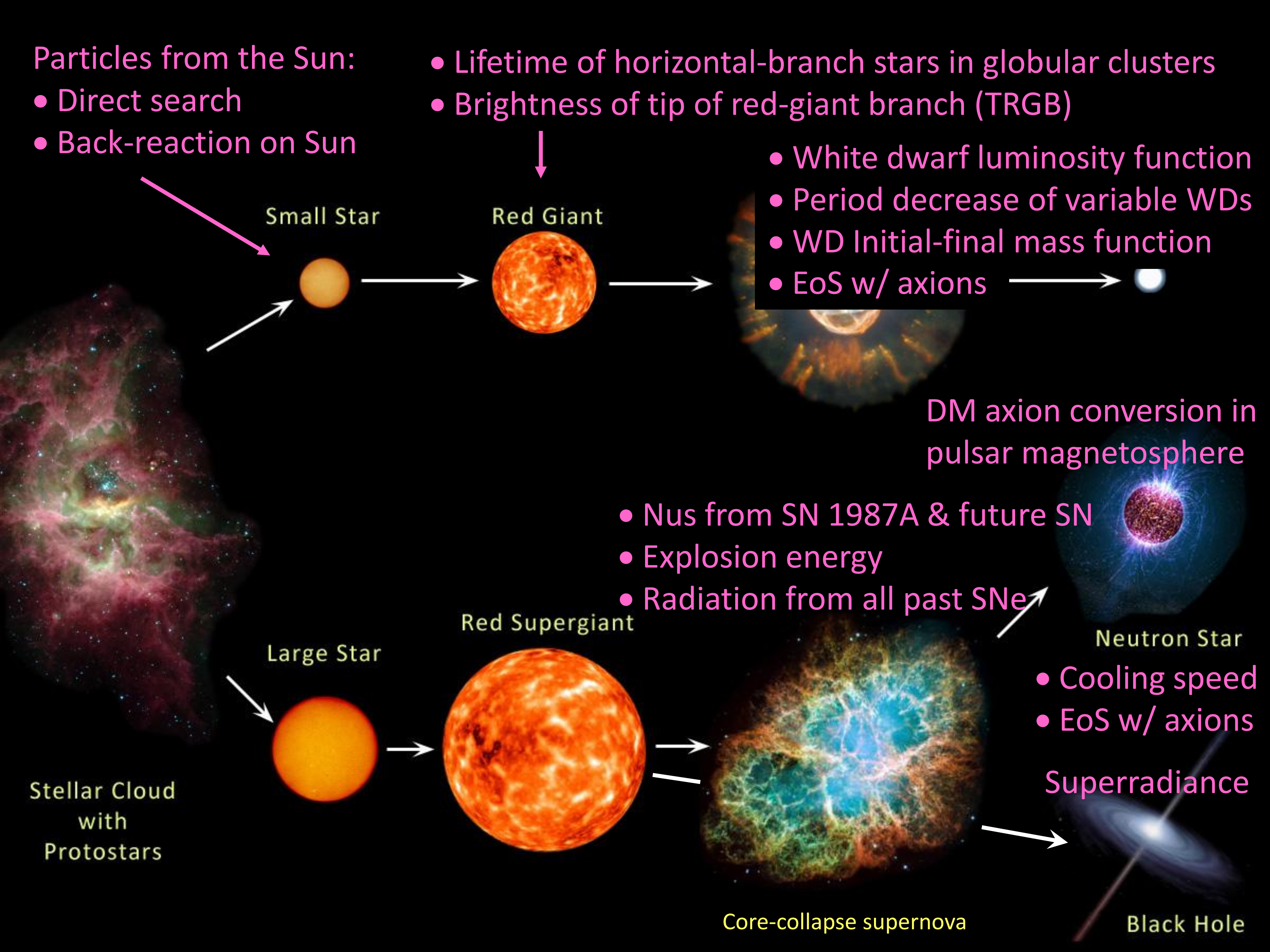
e.g. CERN 2022 workshop report, arXiv:2305.01715



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



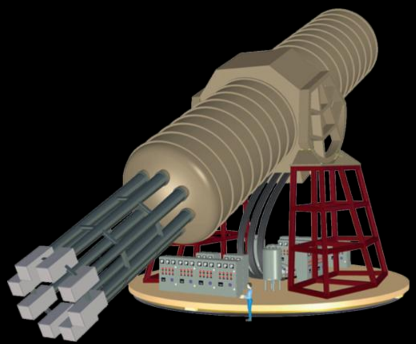
http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html


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
Red Supergiant
Large Star
Neutron Star
• Cooling speed
• EoS w/ axions
Superradiance
Stellar Cloud with Protostars
Core-collapse supernova
Black Hole

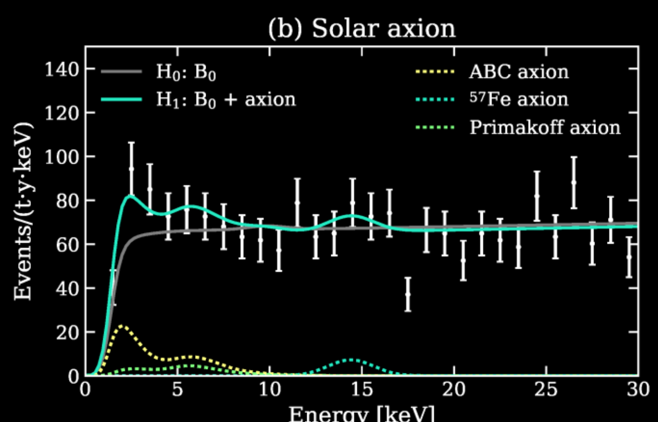
Particles from the Sun

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

2015 Solar Nu Oscillations (A.McDonald)

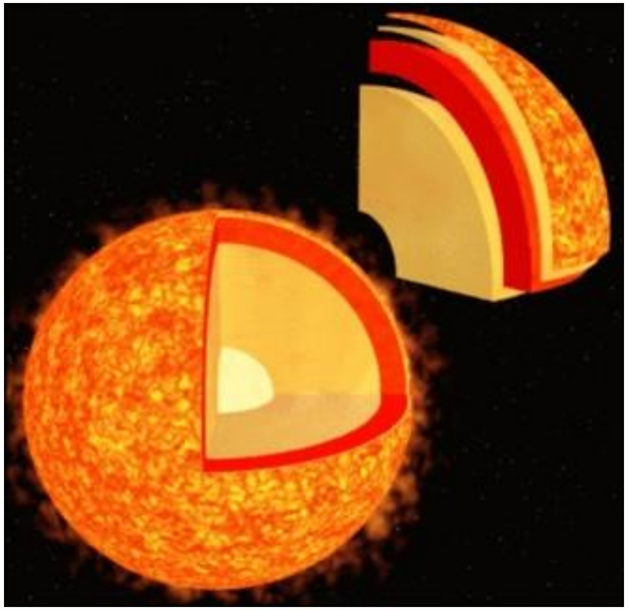


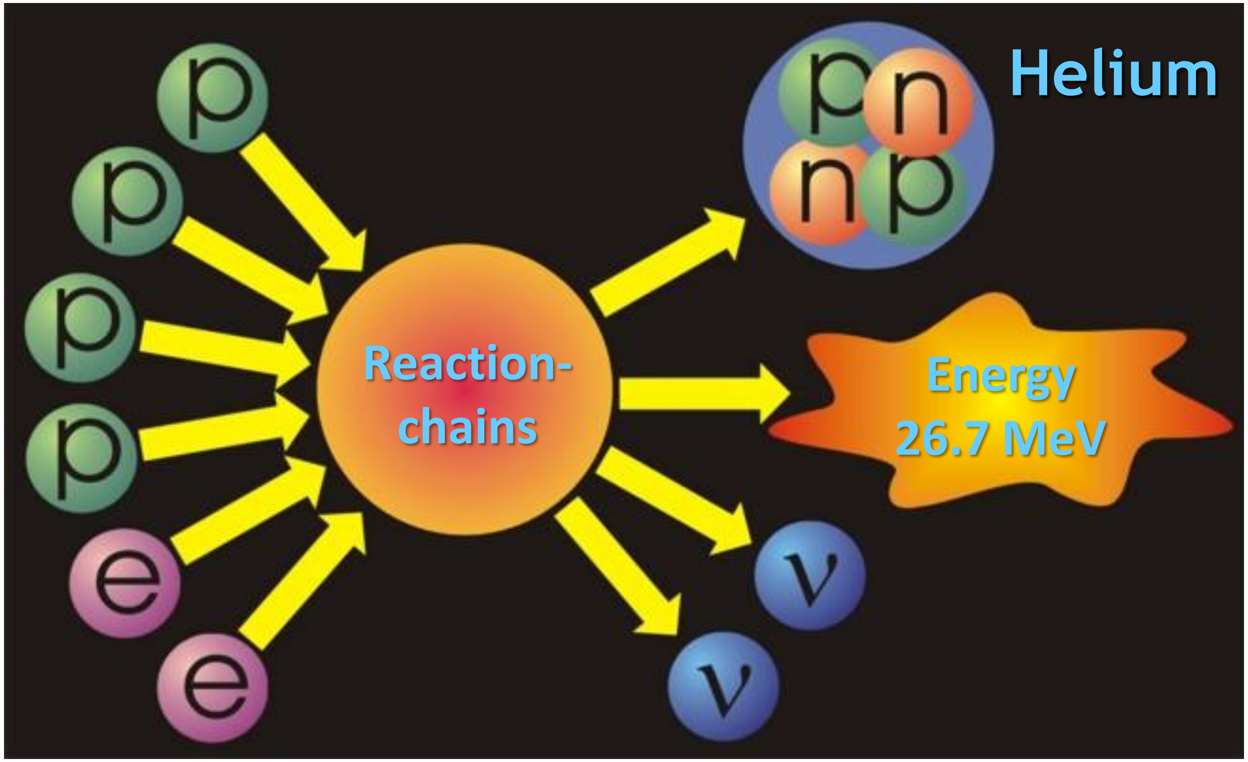
Search for solar axions
with CAST and future IAXO



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

Neutrinos from the Sun



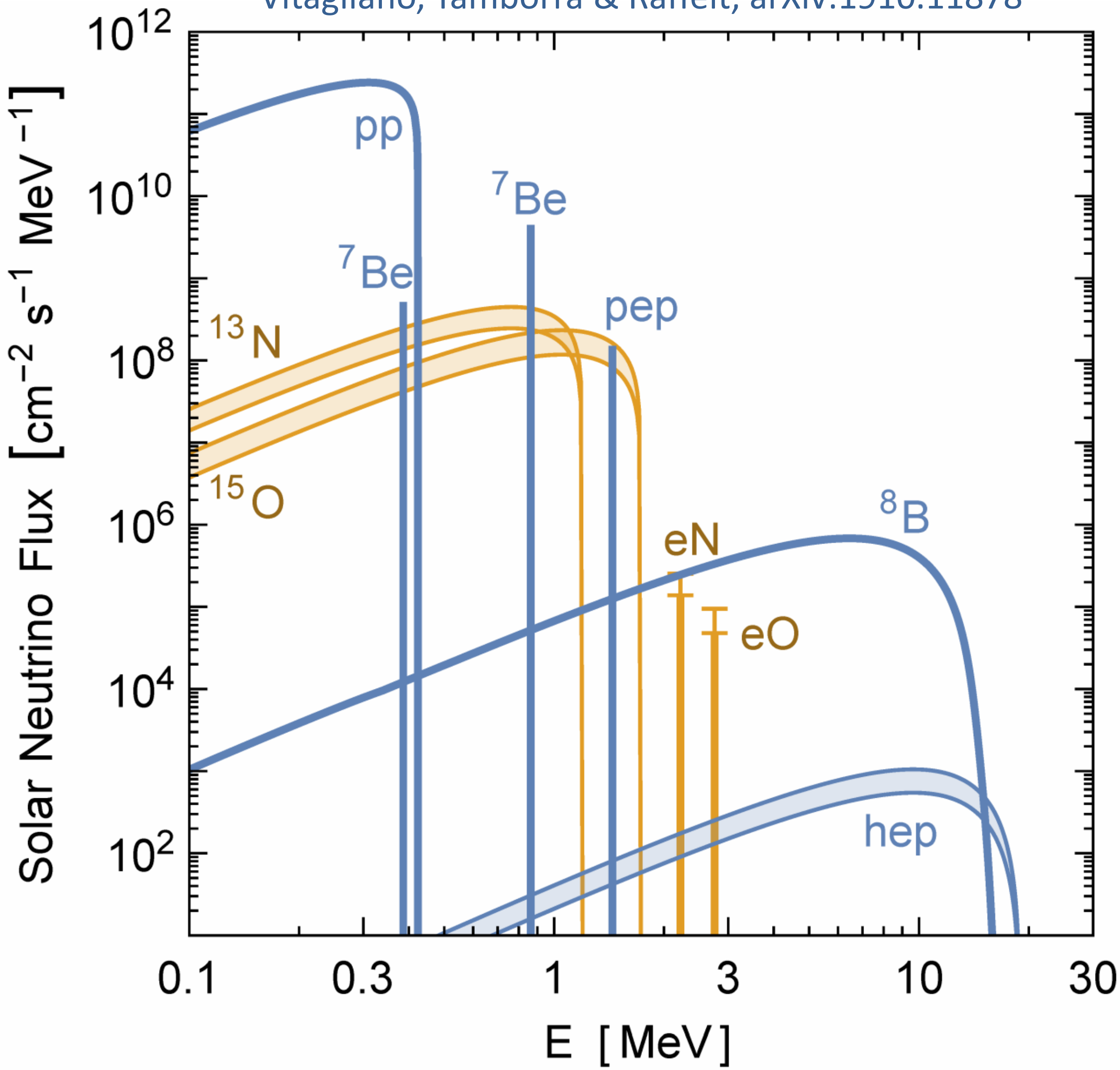


Solar radiation: 98 % light (photons)
2 % neutrinos
At Earth 66 billion neutrinos/cm^2 sec

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

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

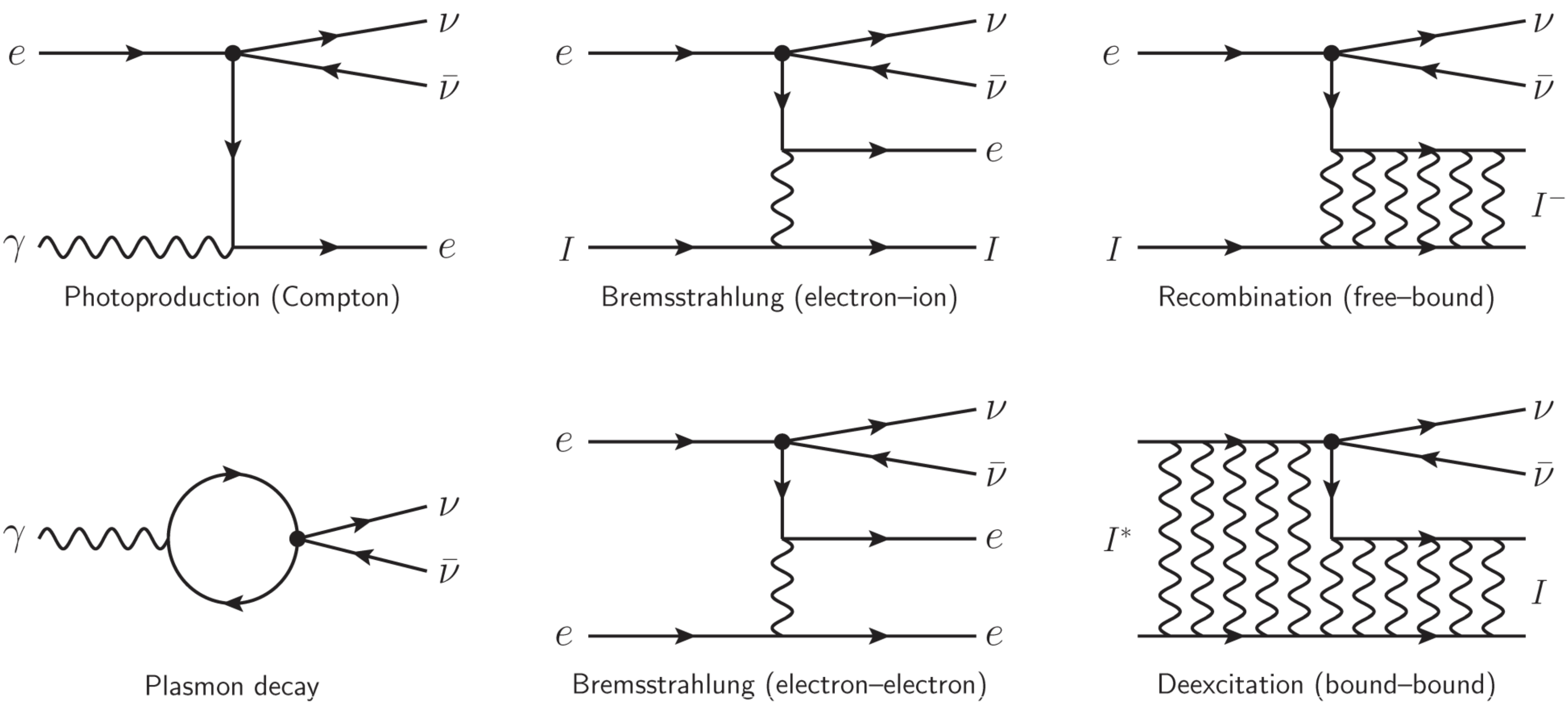
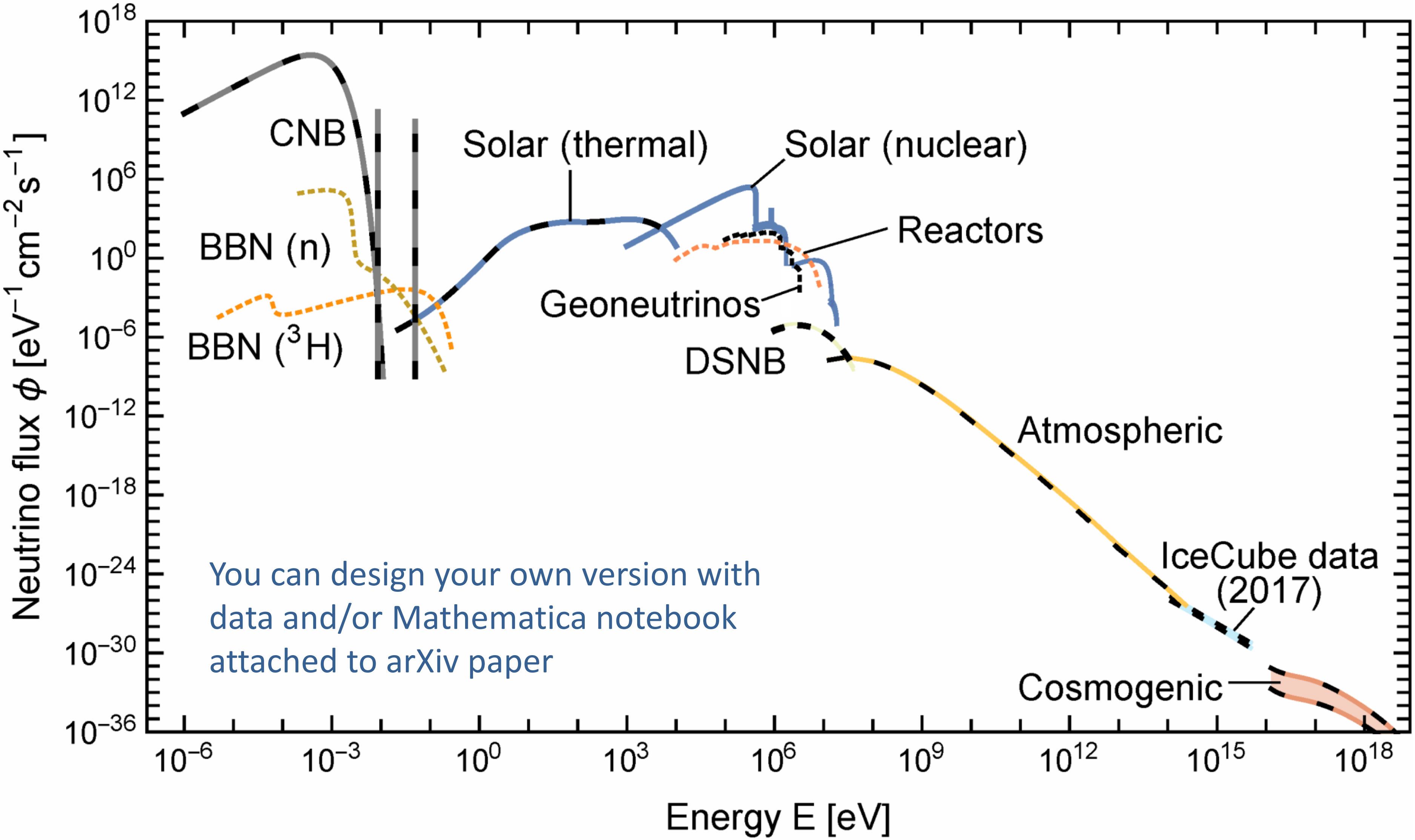


Figure 1. Processes for thermal neutrino pair production in the Sun.

Vitagliano, Redondo & Raffelt, arXiv:1708.02248

Grand Unified Neutrino Spectrum (GUNS) at Earth

Vitagliano, Tamborra & Raffelt, arXiv:1910.11878



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

Temperature in the Sun

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

Approximate Sun as a homogeneous sphere with

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

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

Gravitational potential energy of a proton near center of the sphere

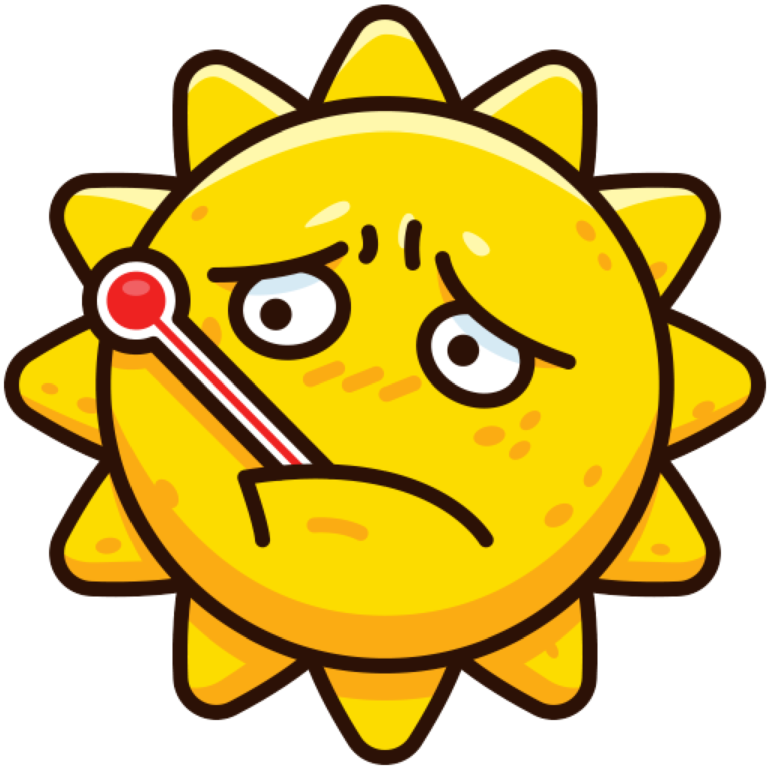
$$\langle E_{\mathrm{grav}} \rangle = -\frac{3}{2}\frac{G_N M_{\mathrm{sun}} m_p}{R_{\mathrm{sun}}} = -3.2\ \mathrm{keV}$$

Thermal velocity distribution

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

Estimated temperature

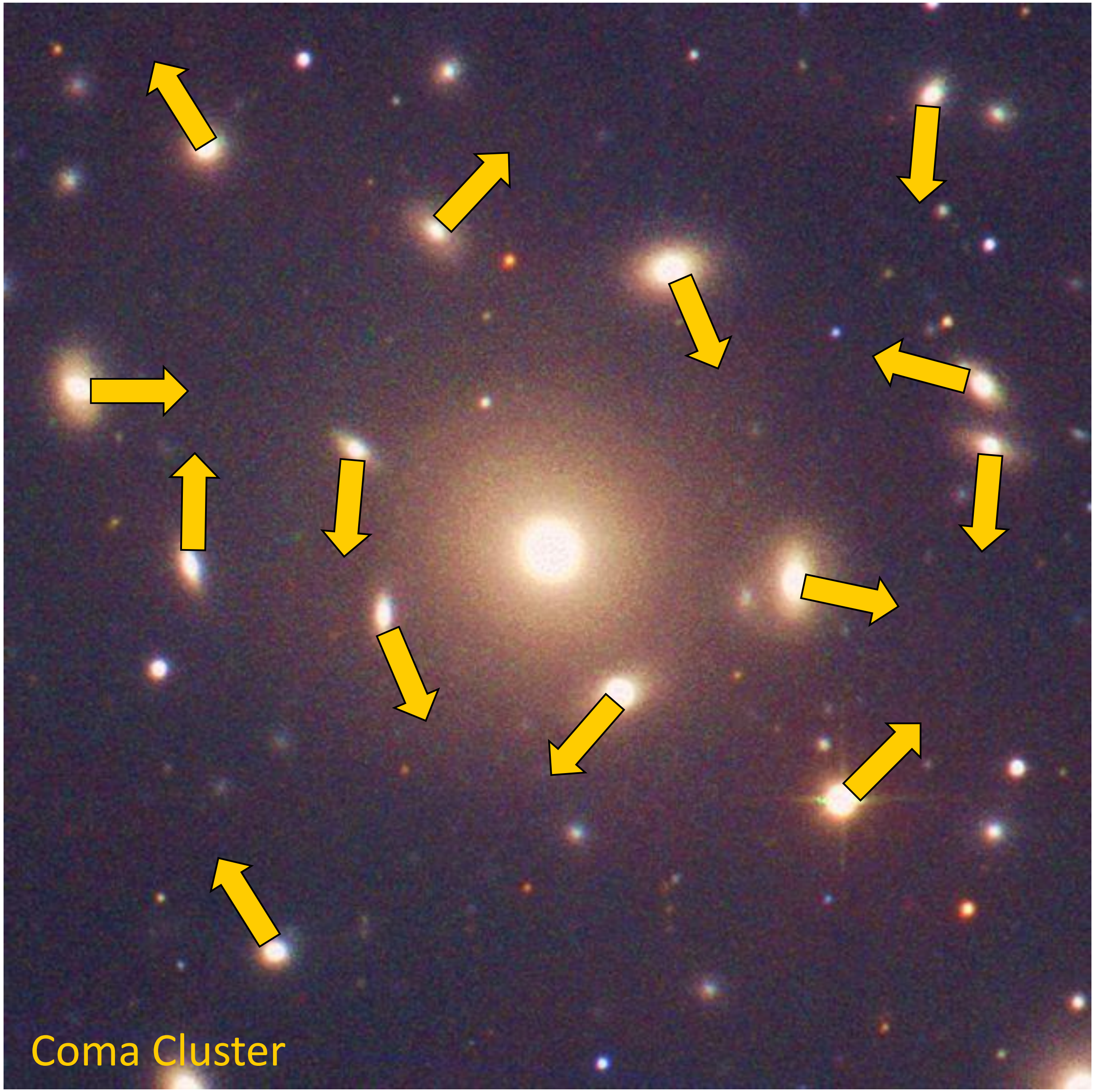
$T = 1.1\ \mathrm{keV}$



Central temperature from standard solar models

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

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

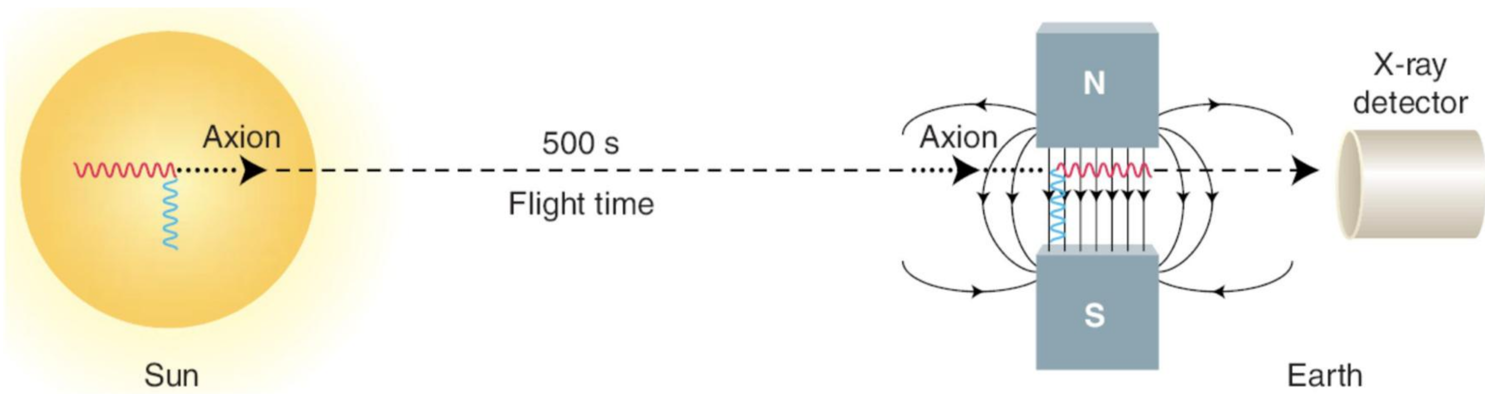
Volume 51, Number 16 PHYSICAL REVIEW LETTERS 17 October 1983

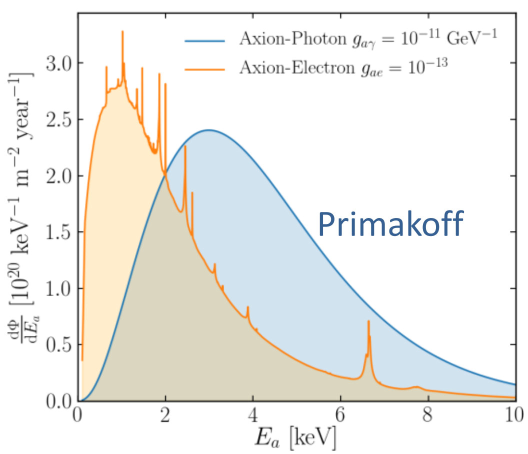
Experimental Tests of the "Invisible" Axion

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

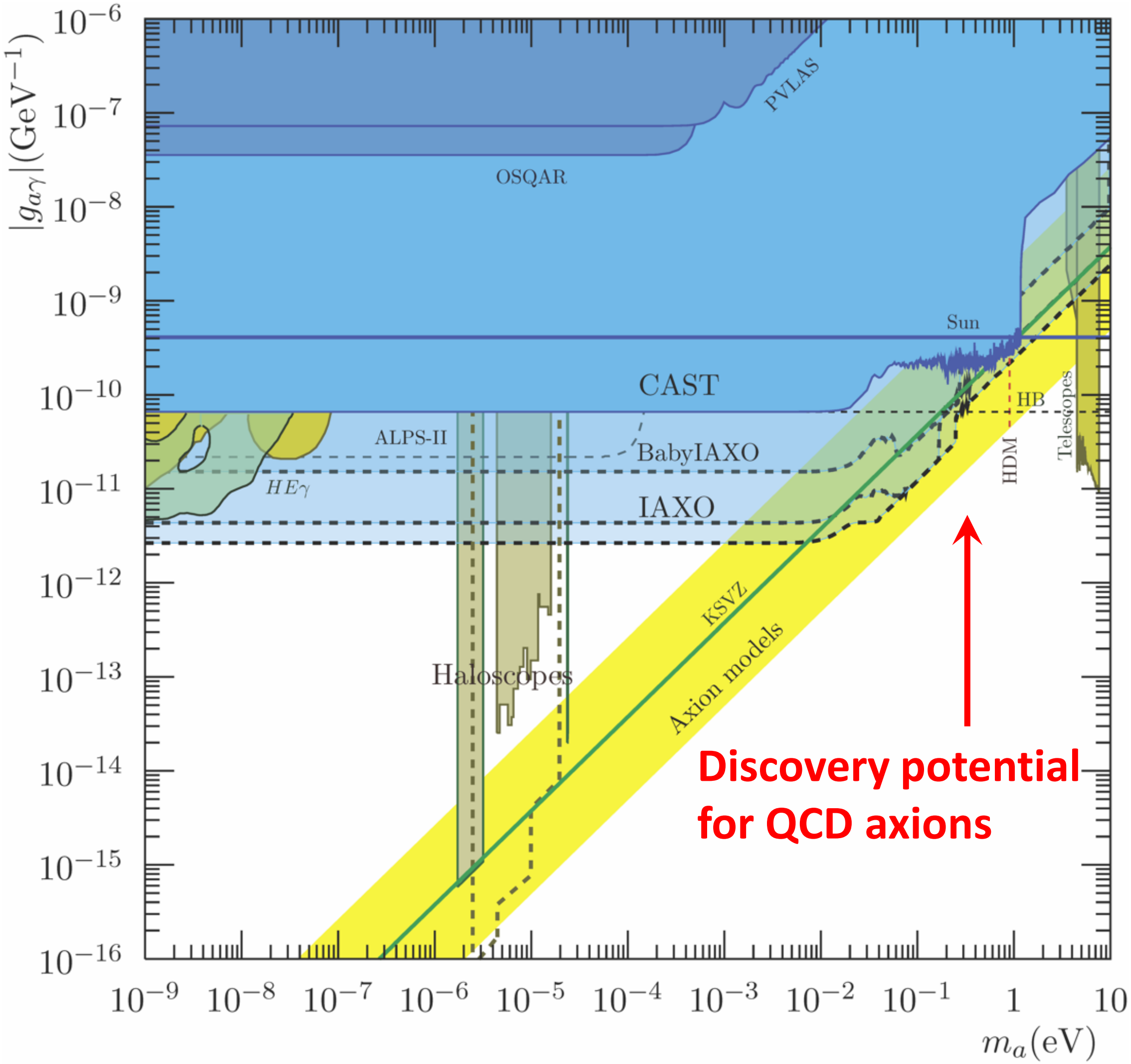
Anastassopoulos+ [1705.02290]

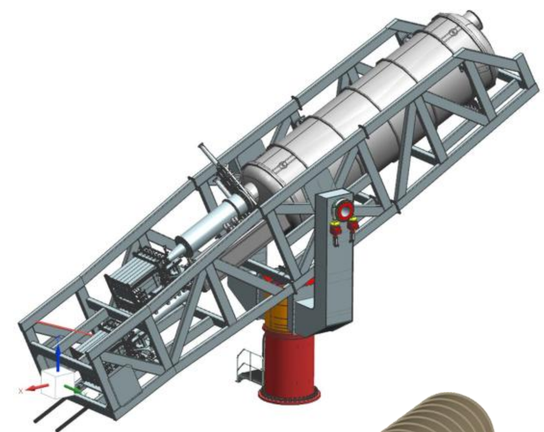
$G_{a\gamma\gamma} < 0.66 \times 10^{-10}\ \mathrm{GeV}^{-1}$

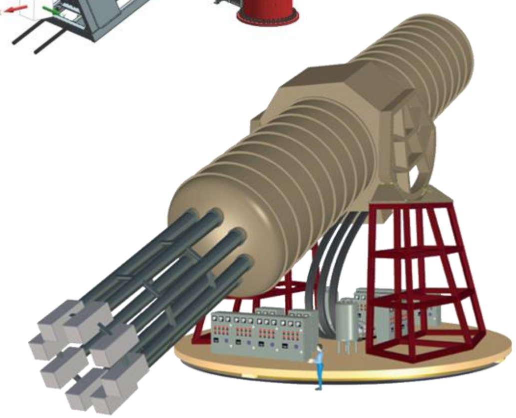
CAST Movie on YouTube

https://youtu.be/XY2lFDXz8aQ

(Baby) IAXO Sensitivity Forecast

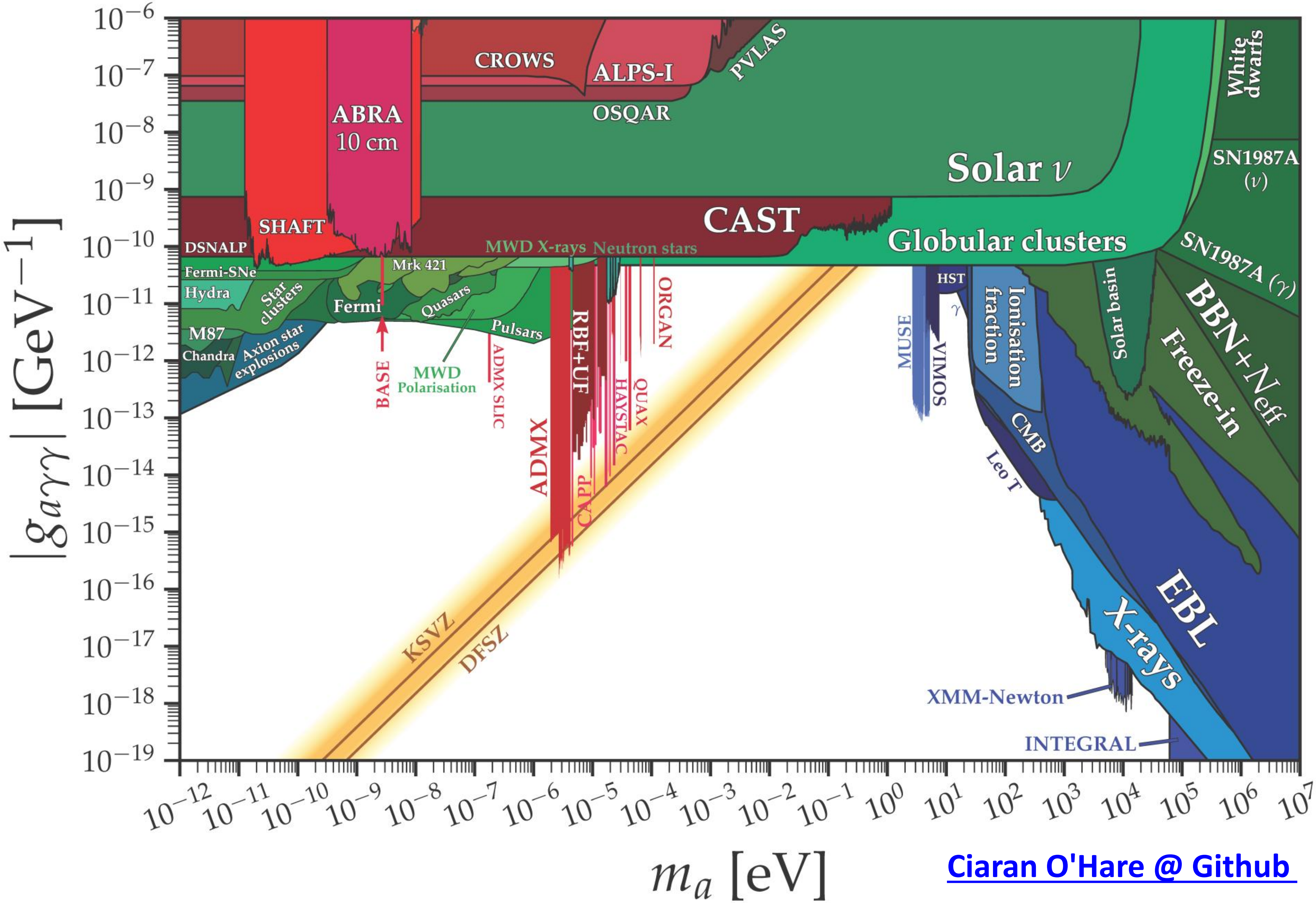






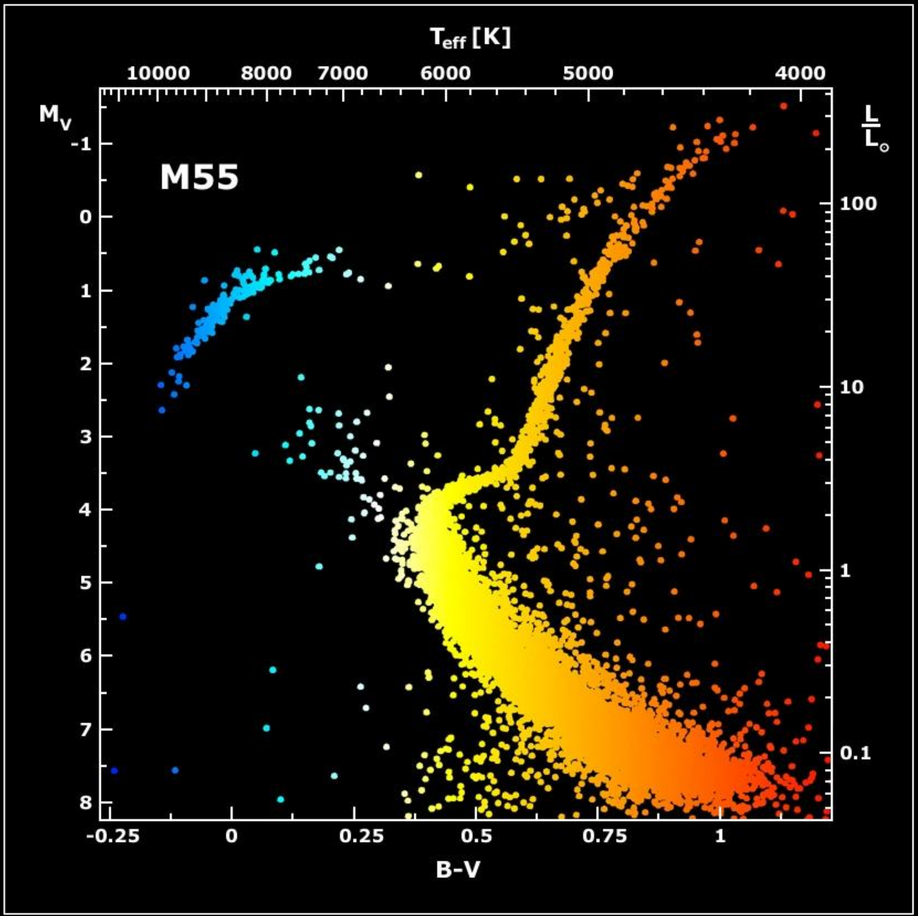
Physics potential of the International Axion Observatory (IAXO)
JCAP 1906 (2019) 047, arXiv:1904.09155

Grand Unified ALP Scape

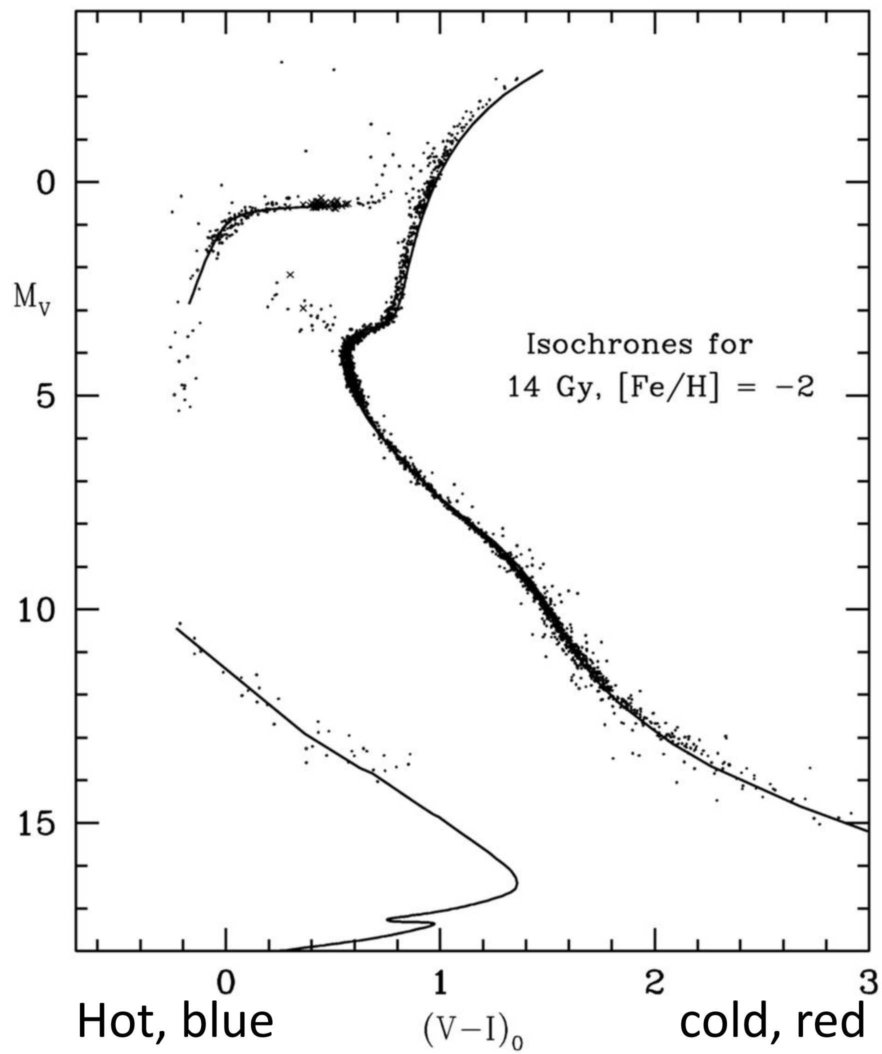


[Ciaran O'Hare @ Github](https://github.com/cajohare/AxionLimits)

Galactic Globular Cluster M55

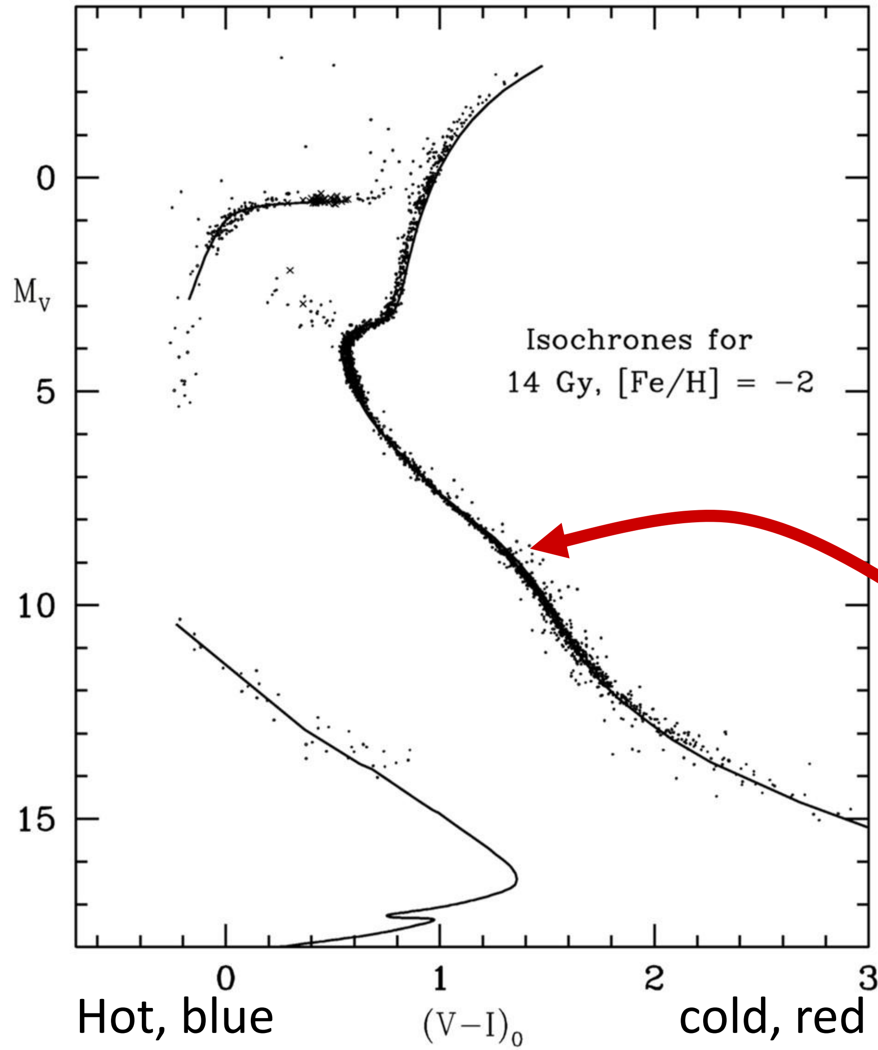


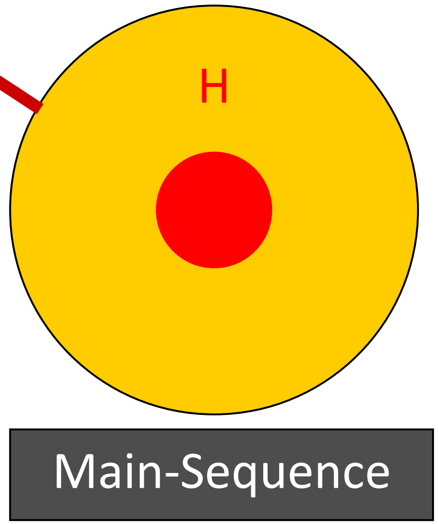
Color-Magnitude Diagram for Globular Clusters



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

Color-Magnitude Diagram for Globular Clusters

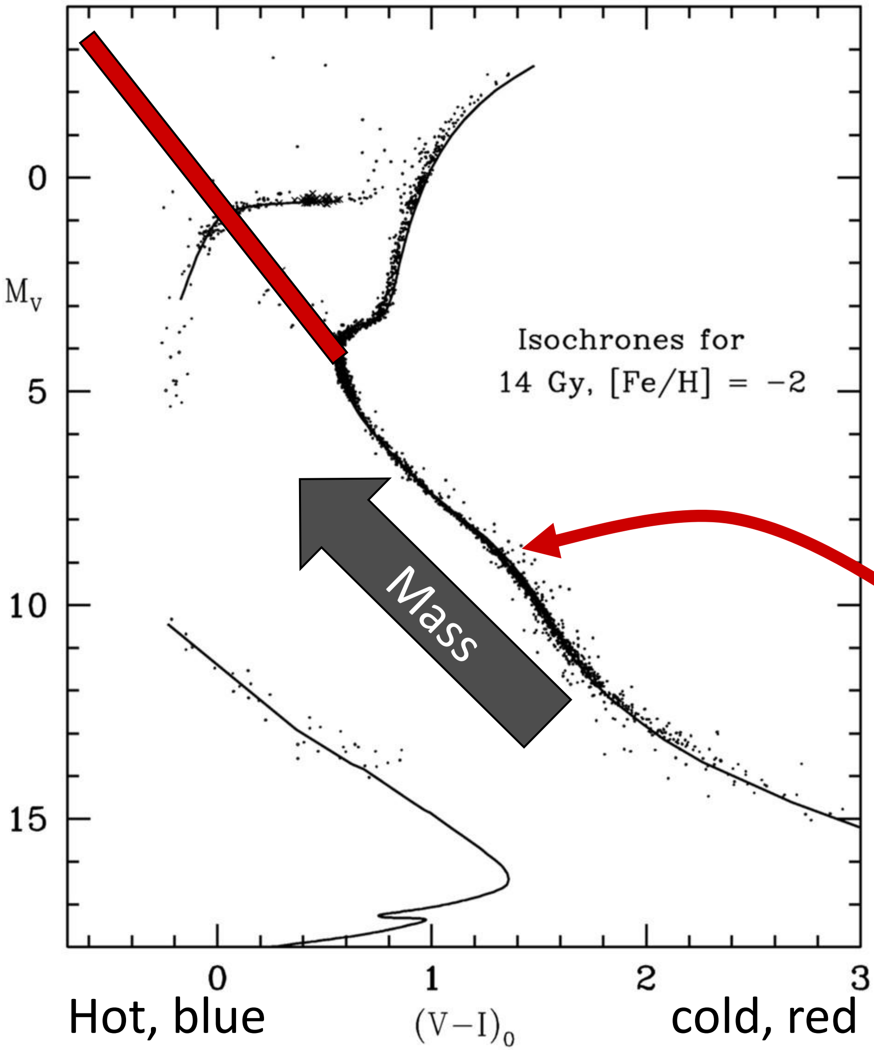


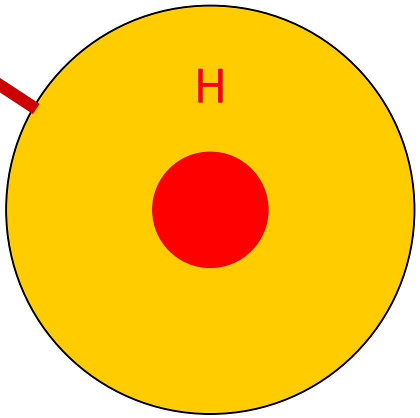


Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

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

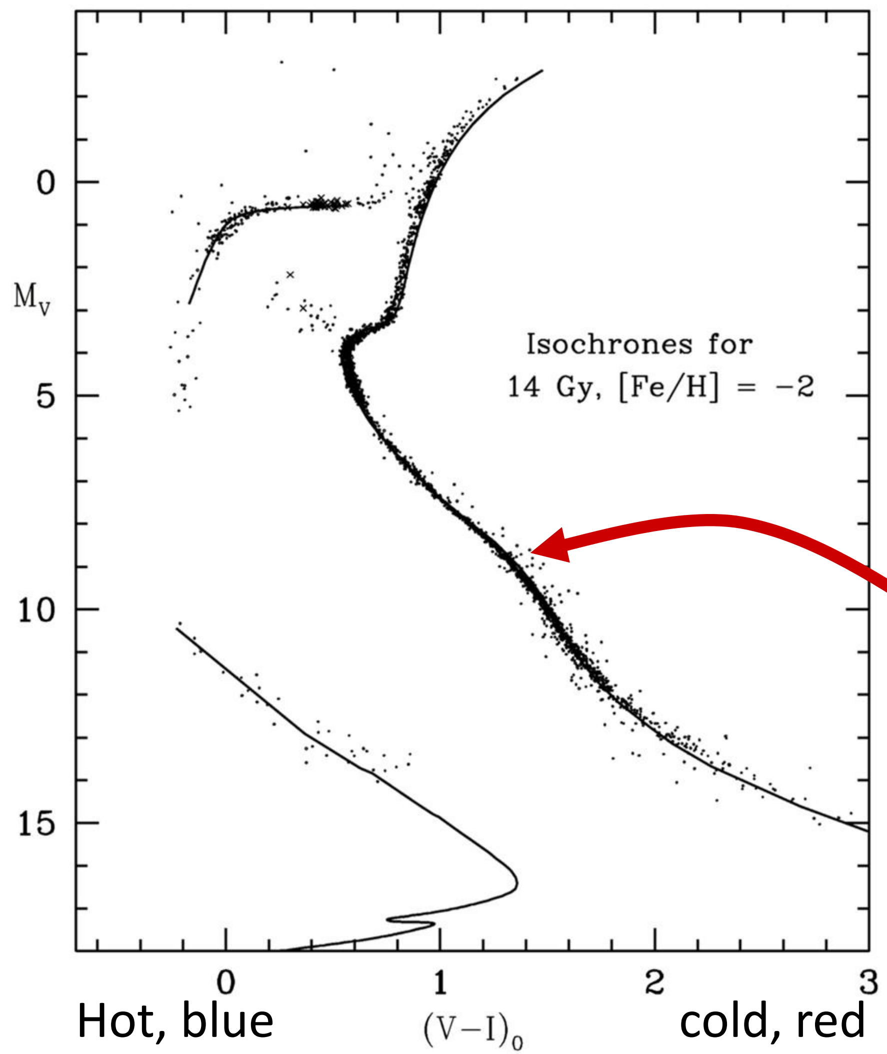


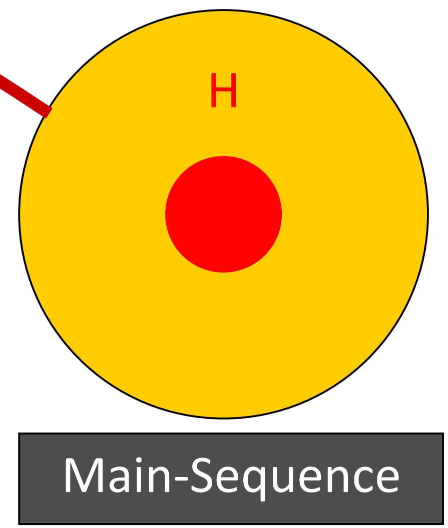


Main-Sequence

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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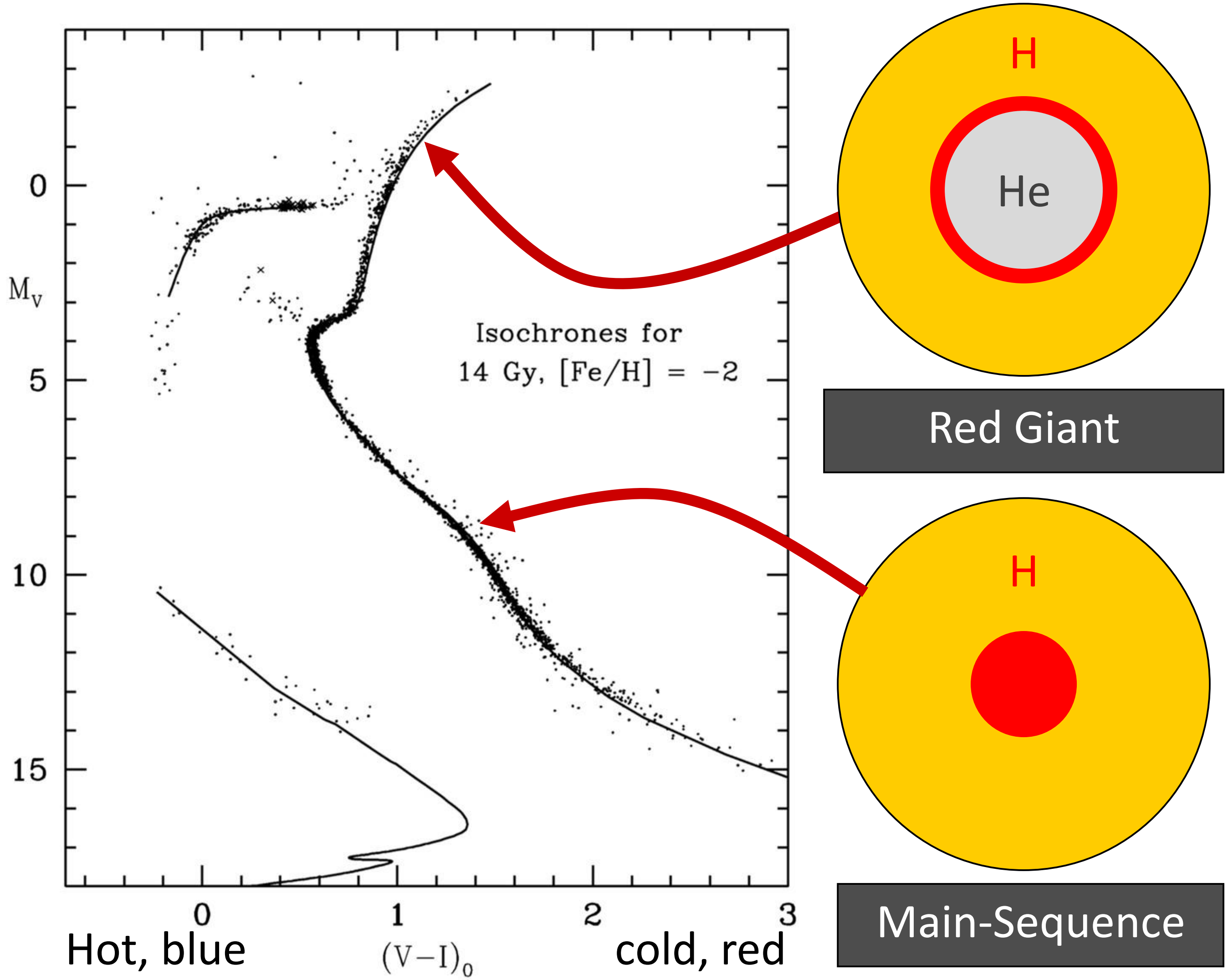

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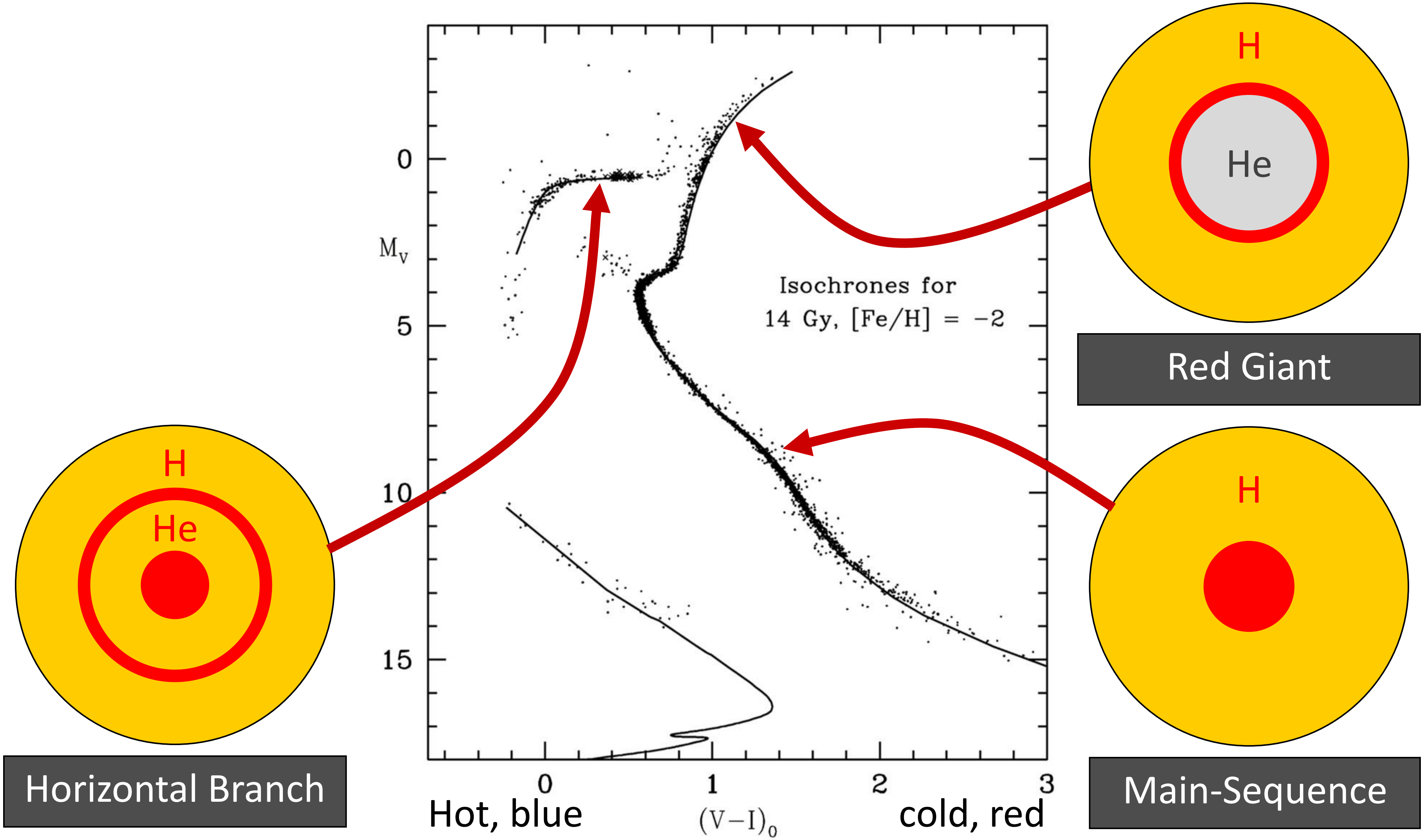

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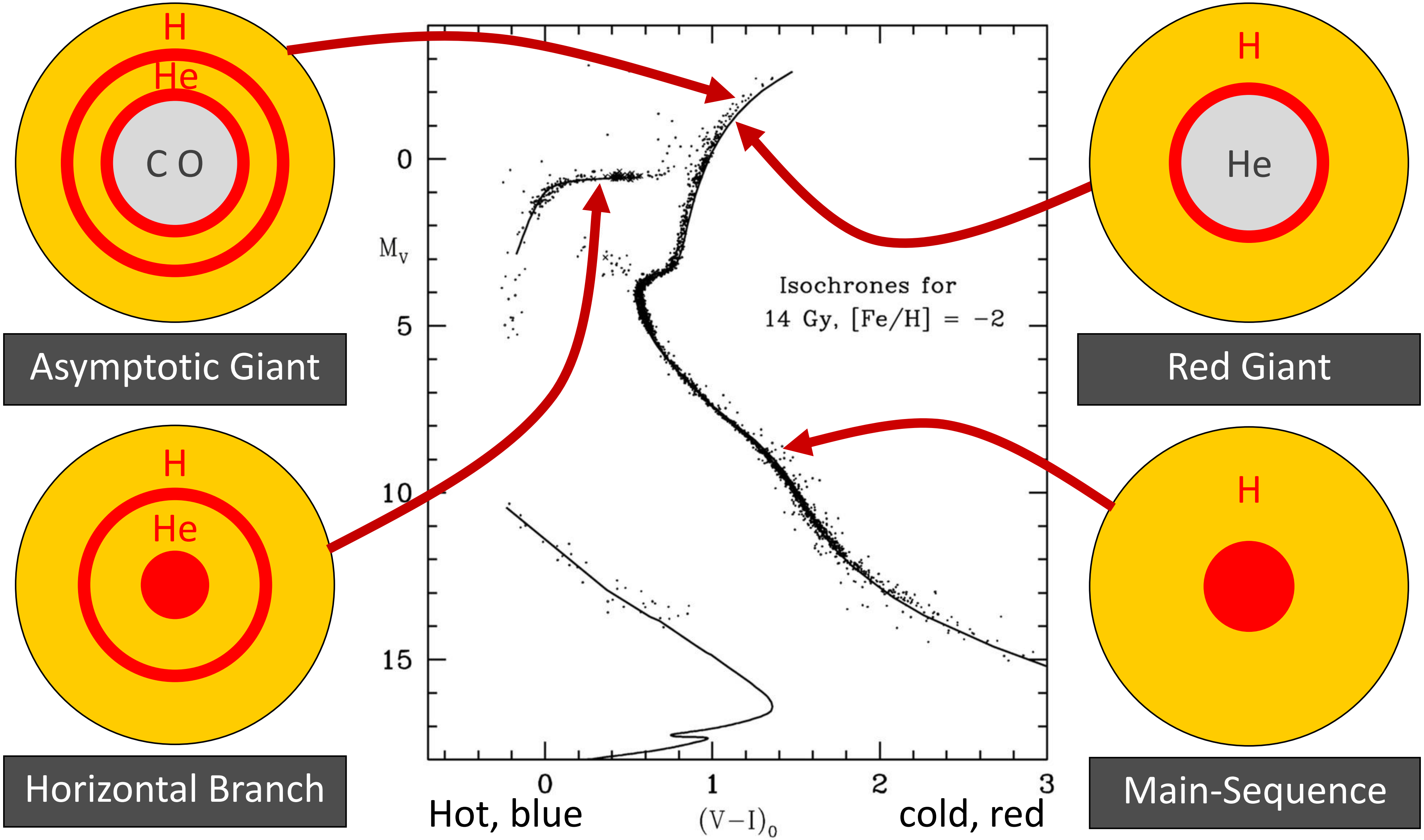

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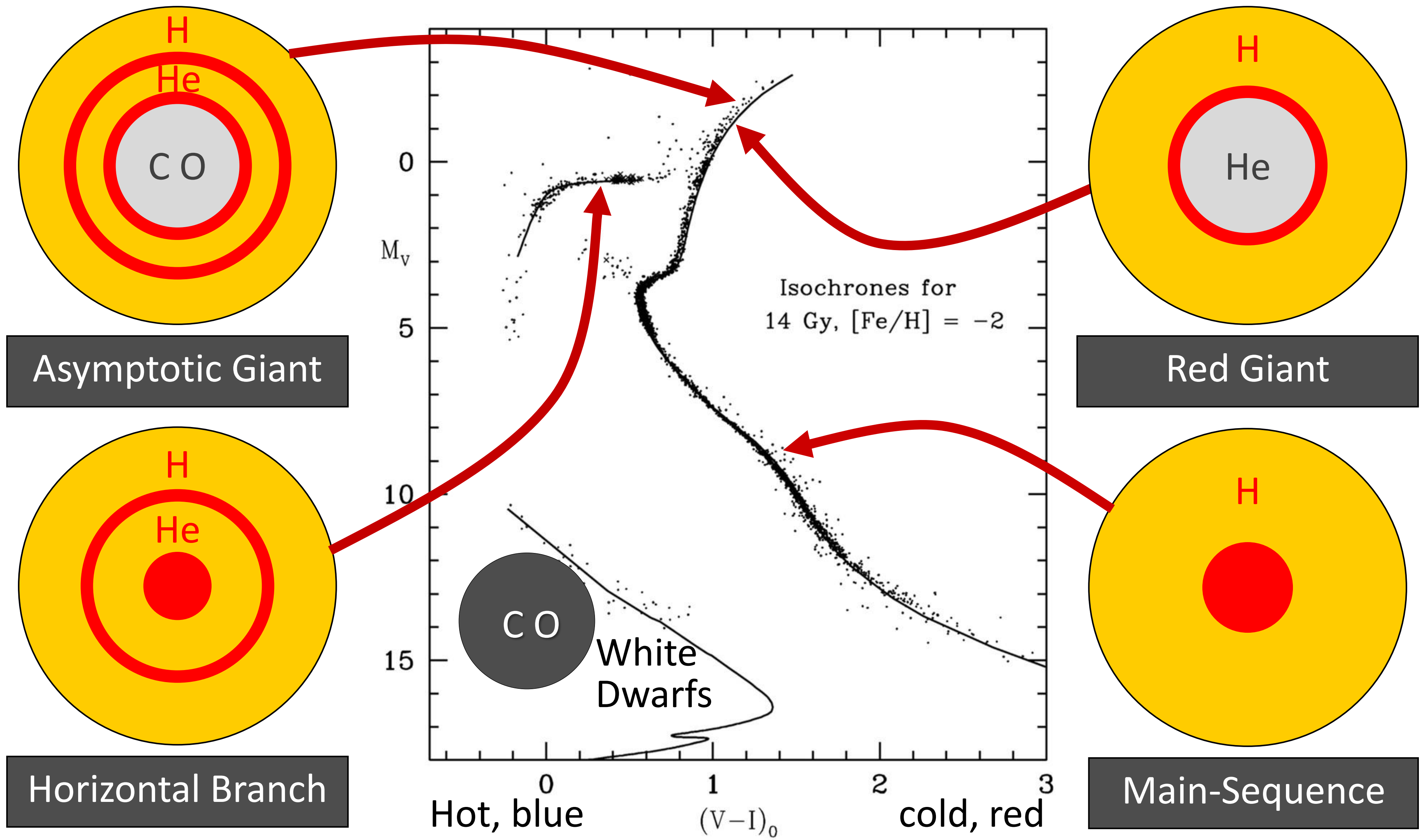

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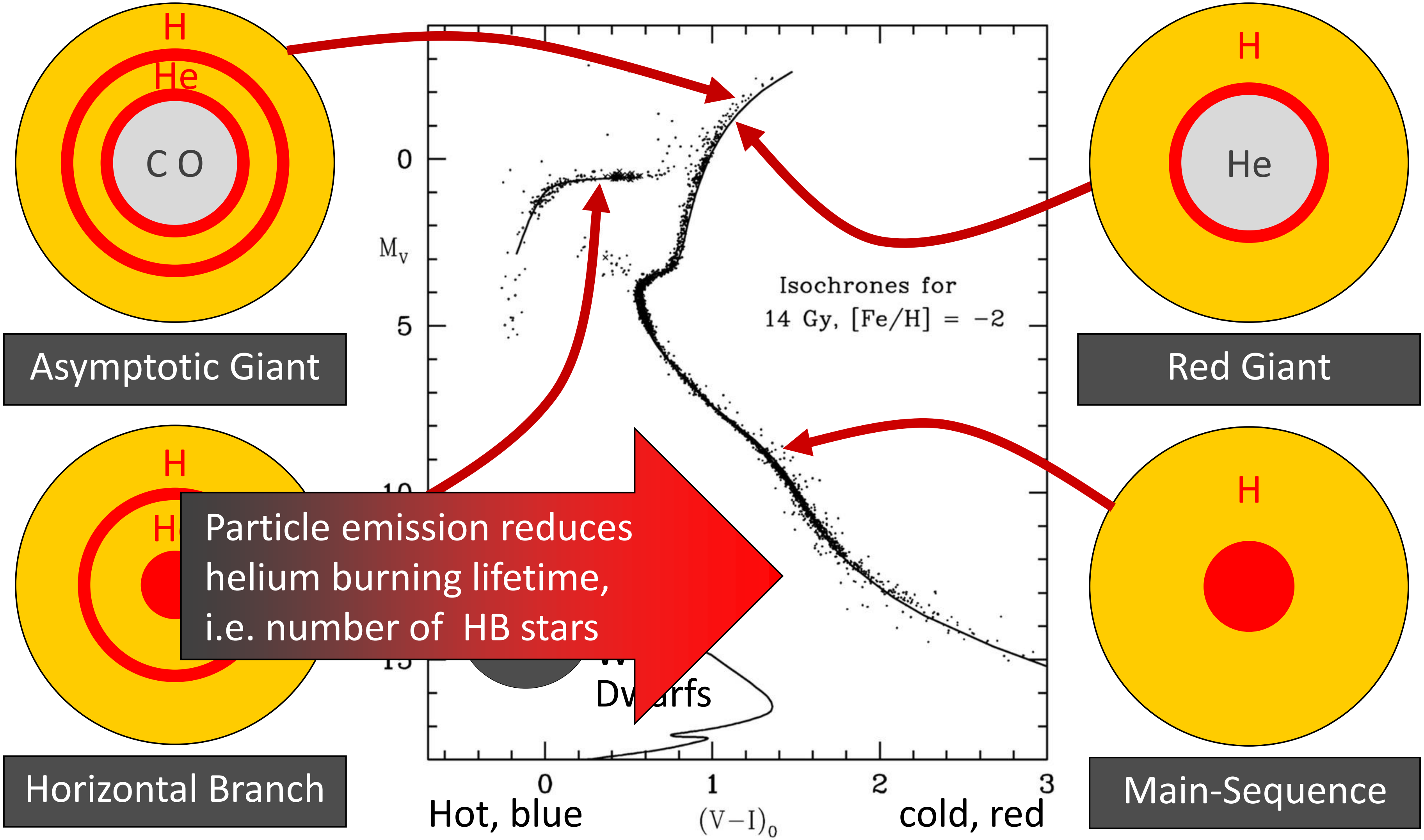

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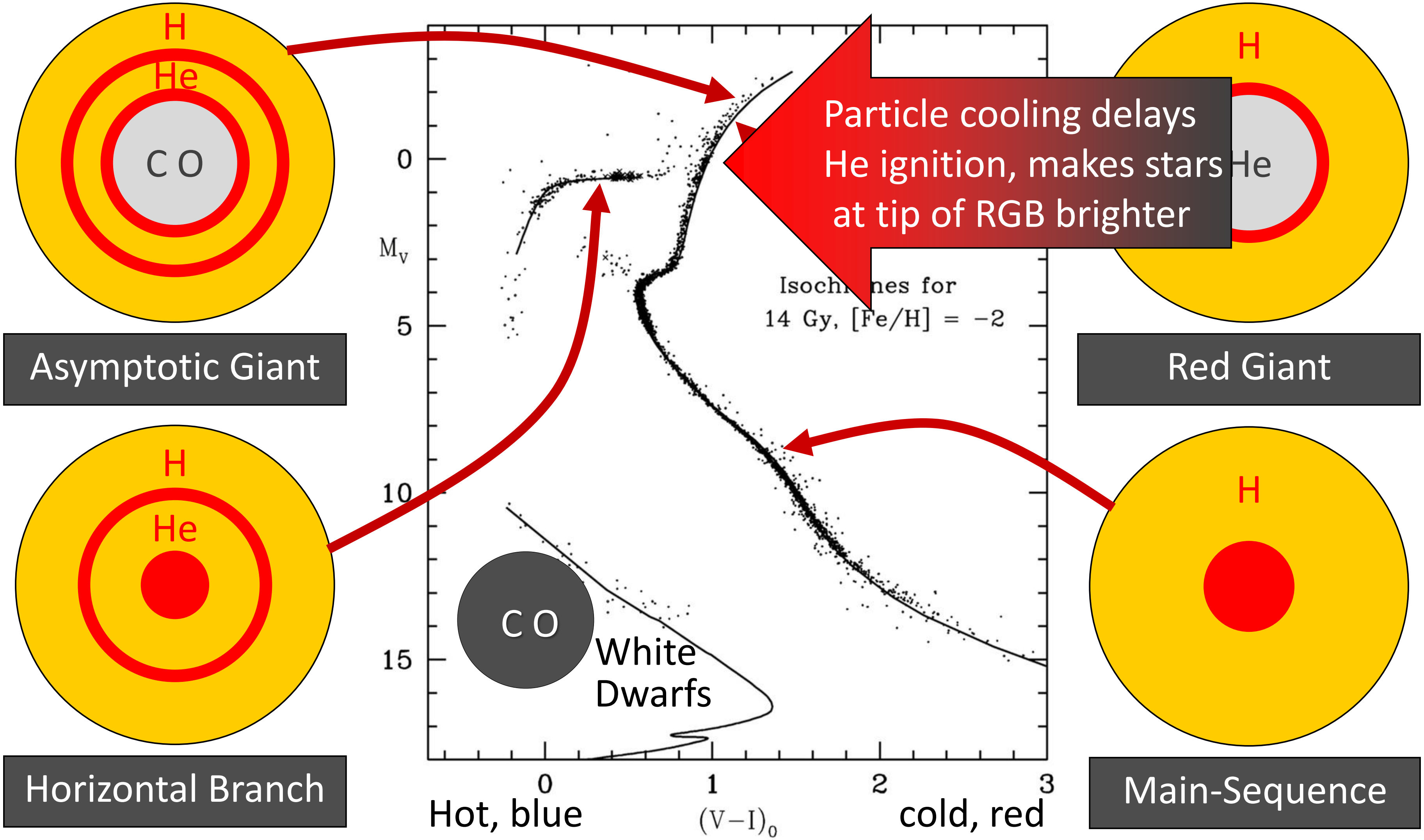
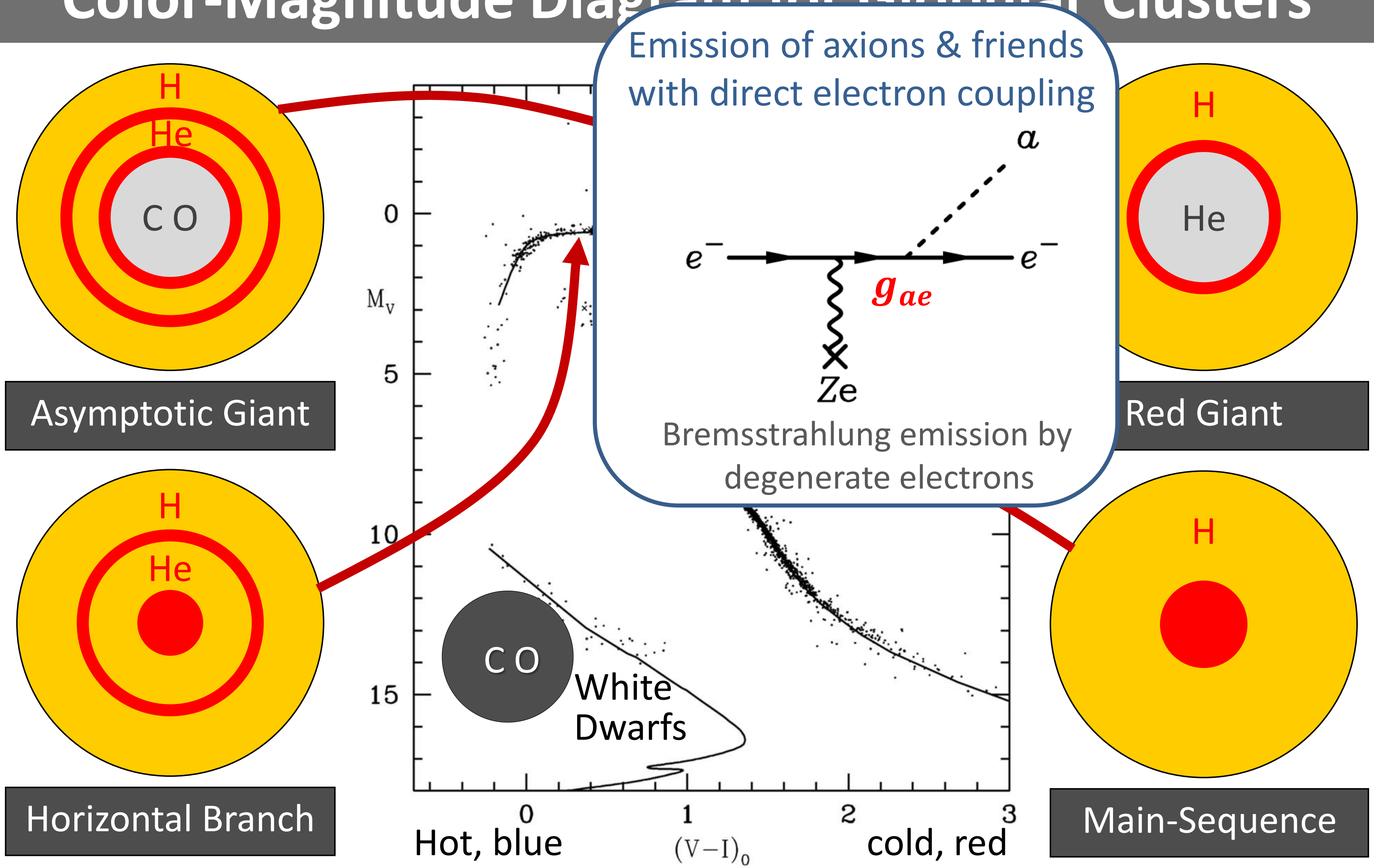
Color-Magnitude Diagram for Globular Clusters



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

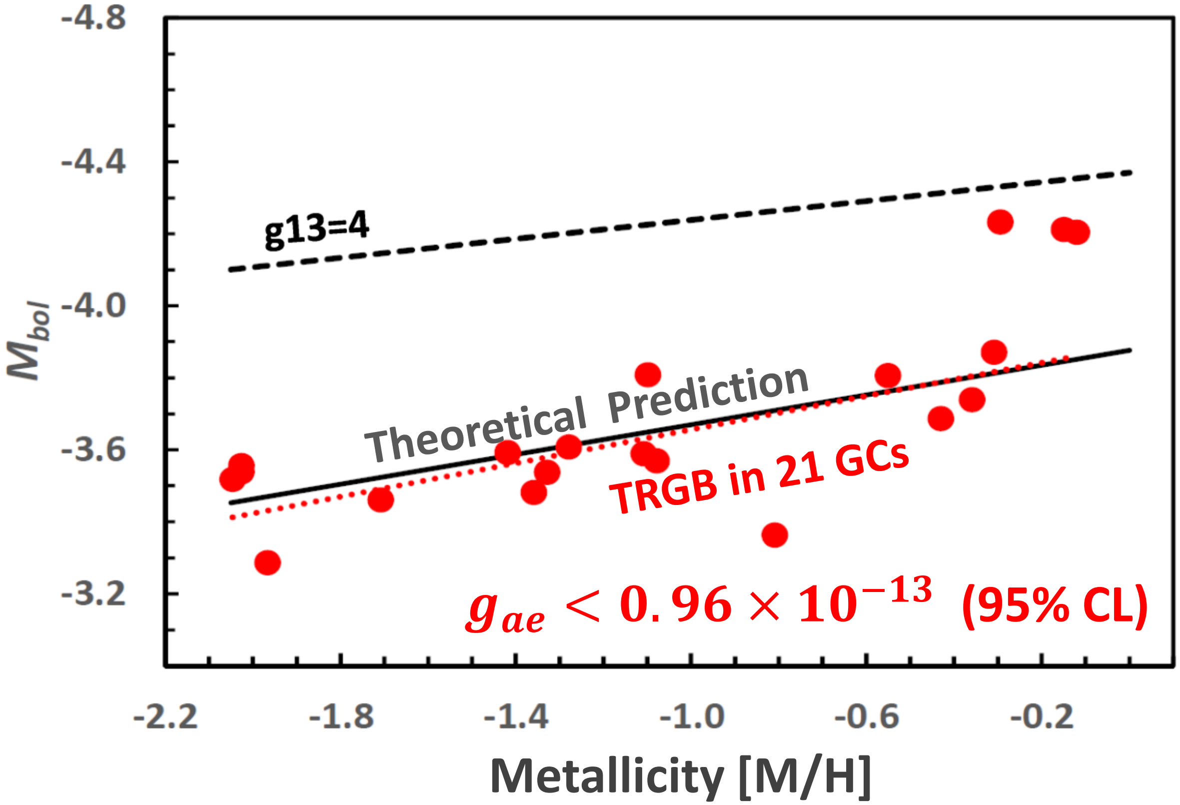
Color-Magnitude Diagram for Globular Clusters



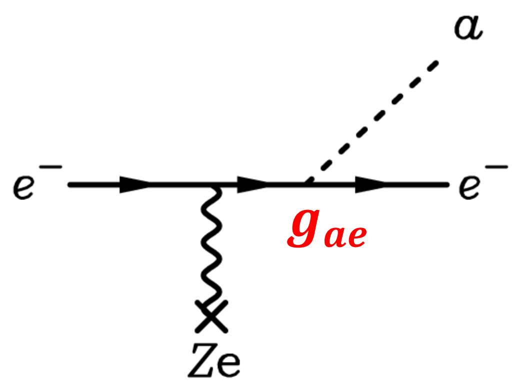
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

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

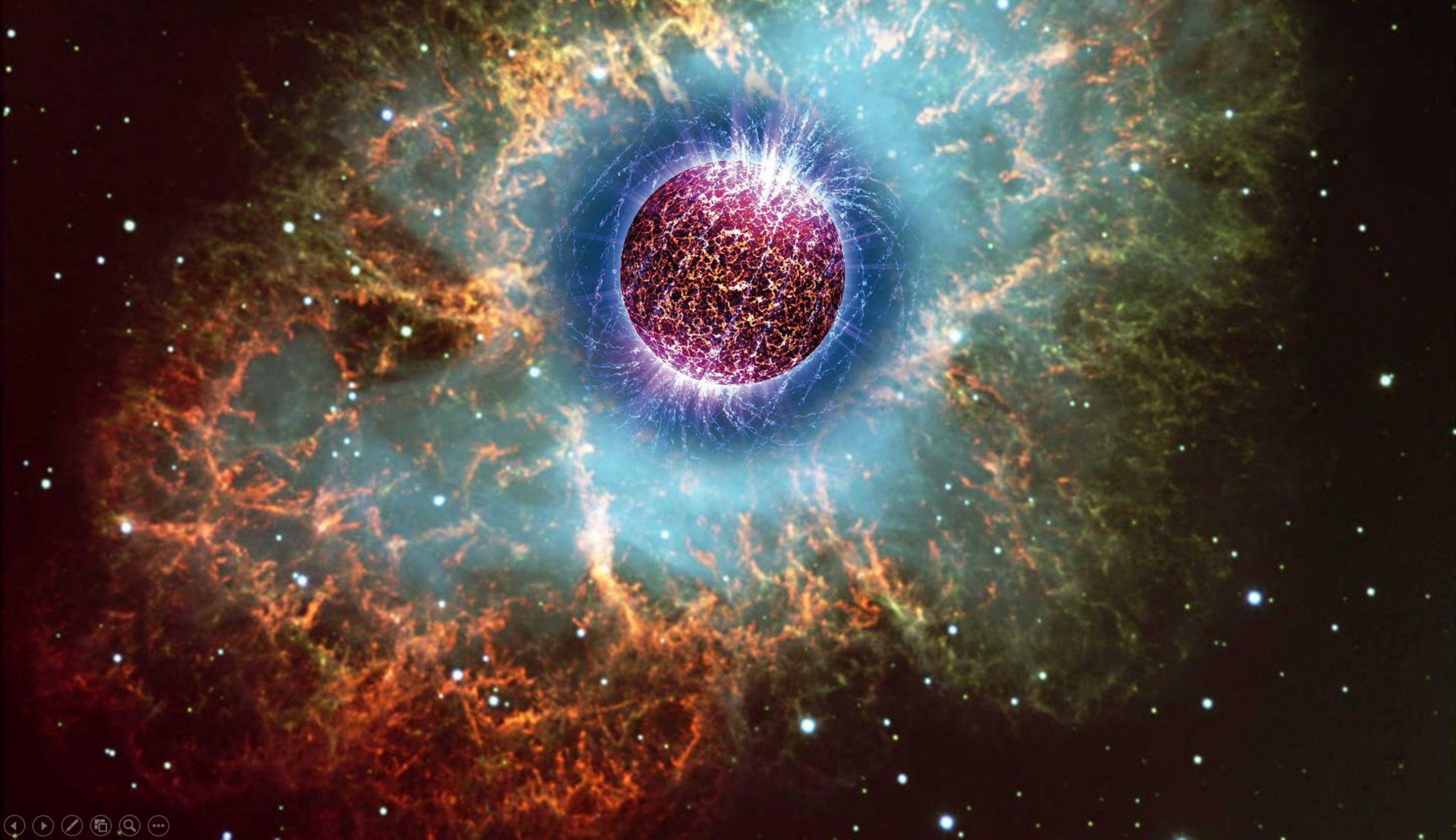
DFSZ Axions

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

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

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

Supernovae and Neutron Stars

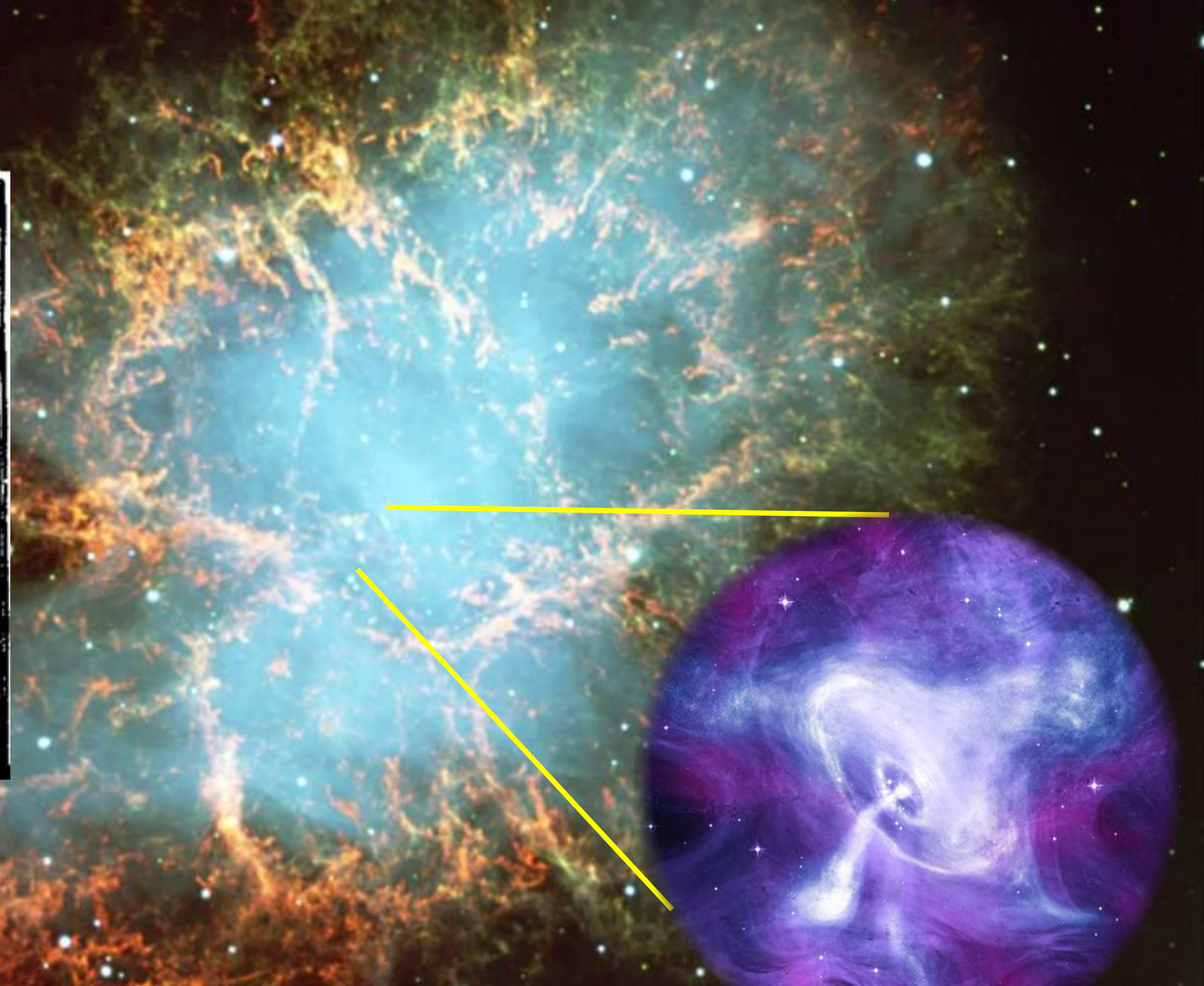


Crab Nebula – Remnant of SN 1054

凡十一日没三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次将歷屏星西北凡七十五日入濁没明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日没至和元年五月己丑出天關東南可數寸歲餘
稍没熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

Crab Nebula – Remnant of SN 1054



凡十一日没三年三月乙巳出東南方大中祥符四
年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅
前星西北大如桃速行經軒轅太星入太微垣掩右執
法犯次將歷屏星西北凡七十五日入濁没明道元
年六月乙巳出東北方近濁有芒彗至丁巳凡十三
日没至和元年五月己丑出天關東南可數寸歲餘
稍没熙寧二年六月丙辰出箕度中至七月丁卯犯
箕乃散三年十一月丁未出天囷元祐六年十一月
辛亥出參度中犯掩側星壬子犯九游星十二月癸
酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史志卷九

Crab Pulsar
Chandra X-ray composite image

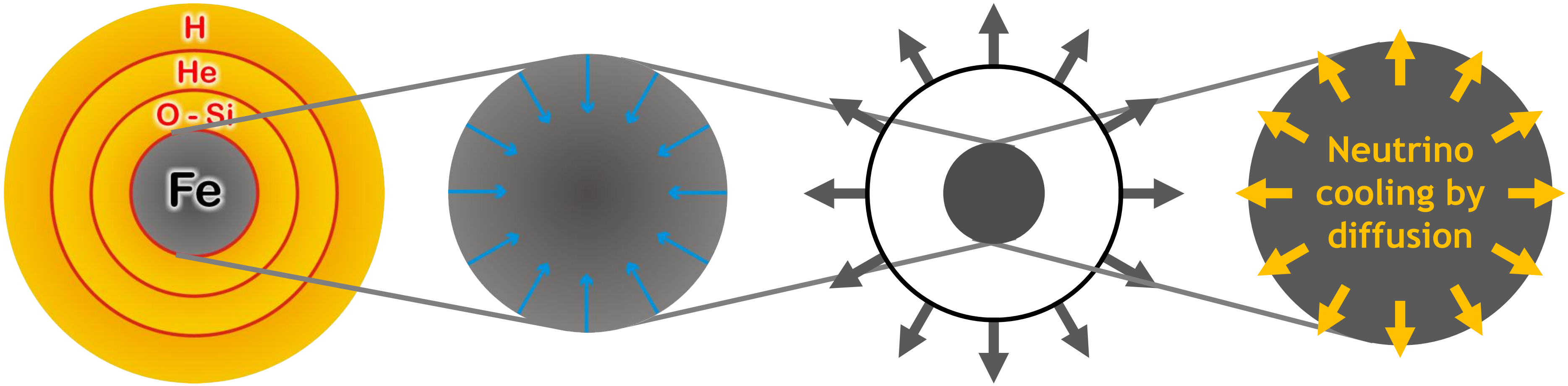
Core-Collapse Supernova Explosion

End state of a massive star
$M \gtrsim 8\, M_\odot$

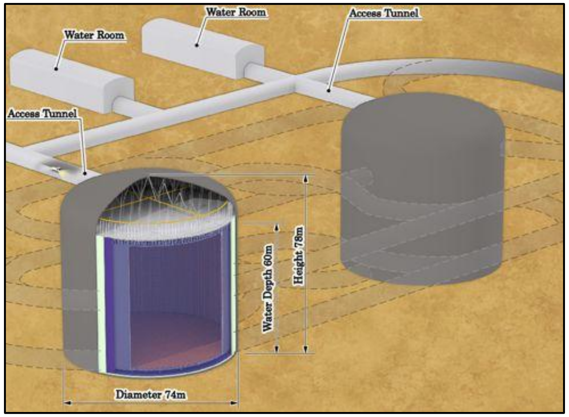
Collapse of degenerate core

Bounce at $\rho_{\rm nuc}$
Shock wave forms explodes the star

Grav. binding E
$\sim 3 \times 10^{53}$ erg
emitted as nus of all flavors

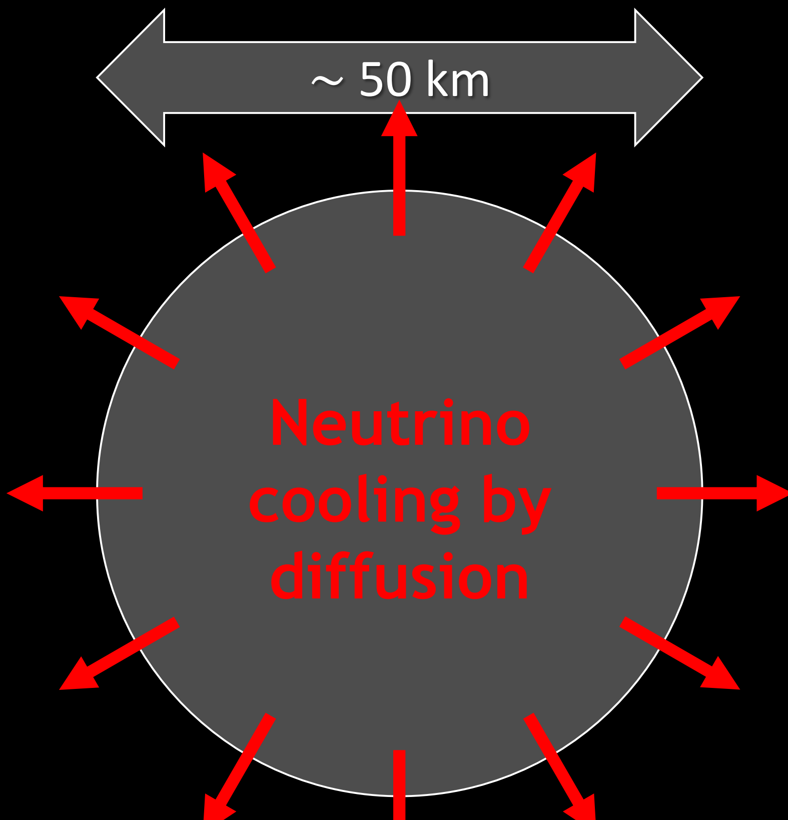


- **Huge rate of low-E neutrinos (tens of MeV) over few seconds in large-volume detectors**
- **A few core-collapse SNe in our galaxy per century**
- **Once-in-a-lifetime opportunity**



Stellar Collapse and Supernova Explosion

Newborn Neutron Star



Proto-Neutron Star

$\rho \sim \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \sim 10\ \mathrm{MeV}$

Gravitational binding energy

$$E_b \approx 3 \times 10^{53}\ \mathrm{erg} \approx 17\%\ M_{SUN}\, c^2$$

This shows up as

99% Neutrinos

1% Kinetic energy of explosion

0.01% Photons, outshine host galaxy

Neutrino luminosity

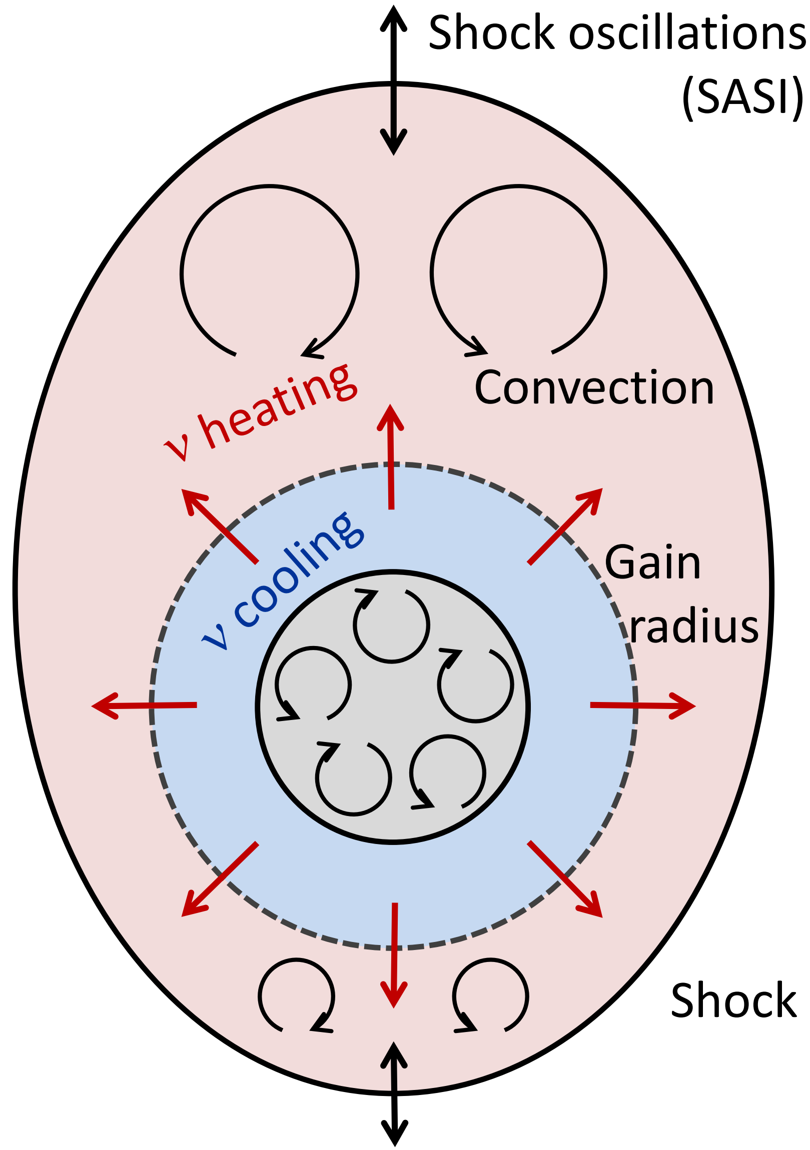
$$L_\nu \sim 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$$
$$\sim 3 \times 10^{19}\ L_{SUN}$$

While it lasts, outshines the entire visible universe

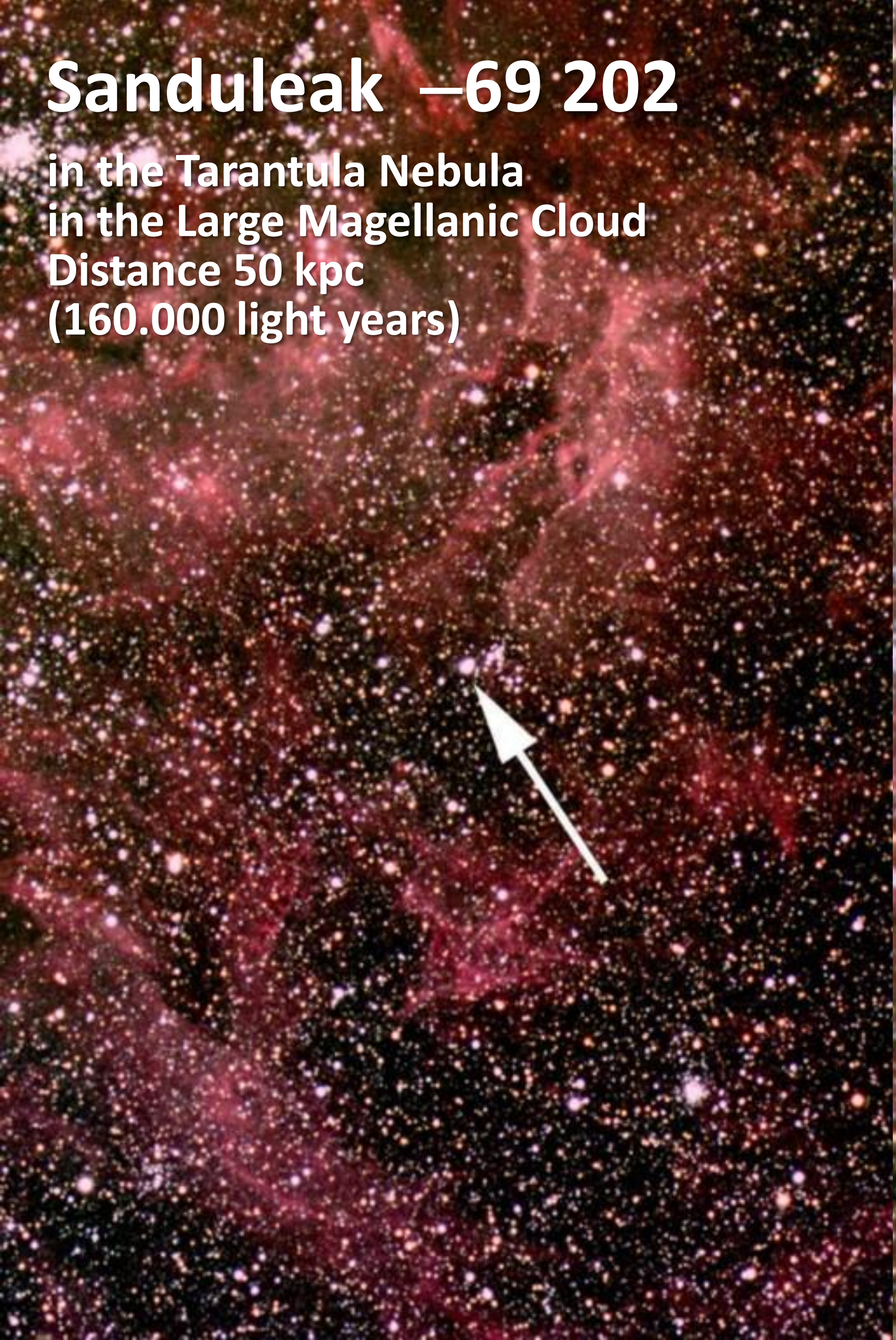
Neutrino-Driven Mechanism – Modern Version

- Stalled accretion shock pushed out to ~150 km as matter piles up on the PNS
- Heating (gain) region develops within some tens of ms after bounce
- Convective overturn & shock oscillations (SASI) enhance efficiency of ν-heating, finally revives shock
- Successful explosions in 1D and 2D for different progenitor masses
- Details important (treatment of GR, ν interaction rates, etc.)
- Self-consistent 3D studies are performed, successful explosions

→ 3D Model of Princeton Group:
https://youtu.be/i-Ly8aCoF7E



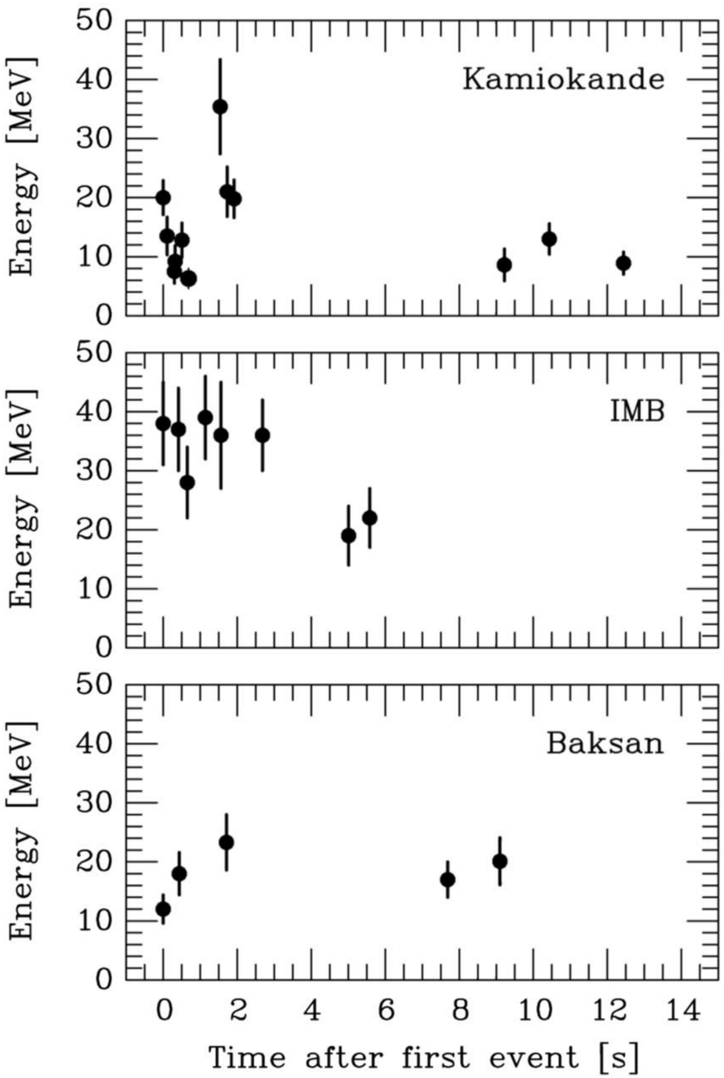
Adapted from B. Müller

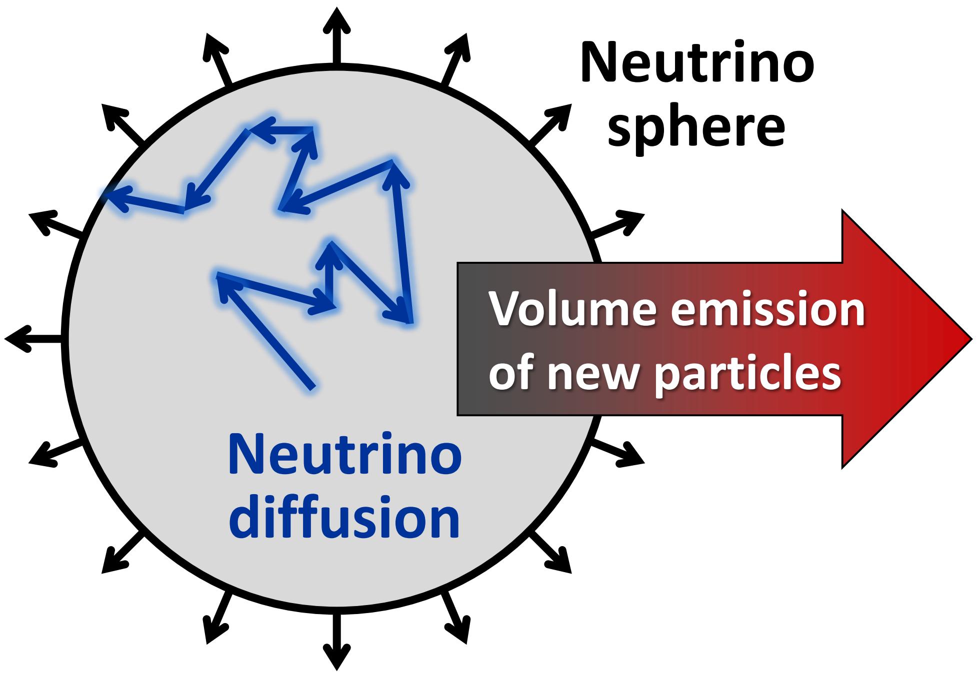

Sanduleak –69 202
in the Tarantula Nebula
in the Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)


Supernova 1987A
23 February 1987

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal





Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

New Interest in SN 1987A as Particle Lab

Bounds on Exotic Particle Interactions from SN 1987a

Georg Raffelt (UC, Berkeley, Astron. Dept. and LLNL, Livermore), David Seckel (UC, Santa Cruz)

Sep, 1987

10 pages

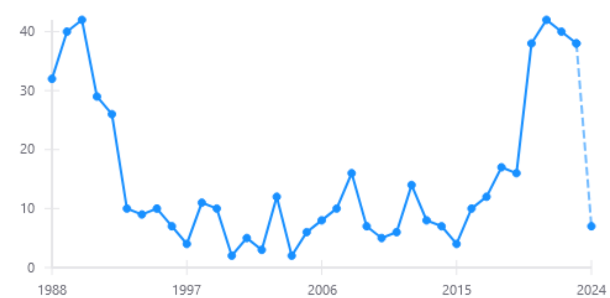
Published in: *Phys.Rev.Lett.* 60 (1988) 1793
DOI: 10.1103/PhysRevLett.60.1793

PDG: Invisible A0 (Axion) MASS LIMITS from Astrophysics and Cosmology

Report number: SCIPP-87/107

View in: OSTI Information Bridge Server

Citations per year



Axions from SN 1987a

Michael S. Turner (Fermilab and Chicago U., EFI and Chicago U., Astron. Astrophys. Ctr.)

Nov, 1987

9 pages

Published in: *Phys.Rev.Lett.* 60 (1988) 1797
DOI: 10.1103/PhysRevLett.60.1797

Report number: FERMILAB-PUB-87-202-A

View in: OSTI Information Bridge Server, ADS Abstract Service, KEK scanned document

Citations per year

Constraints on Axions from SN 1987a

Ron Mayle (LLNL, Livermore), James R. Wilson (LLNL, Livermore), John R. Ellis (CERN), Keith A. Olive (Minnesota U.), David N. Schramm (Chicago U., Astron. Astrophys. Ctr. and Fermilab) Show All(6)

Dec, 1987

9 pages

Published in: *Phys.Lett.B* 203 (1988) 188-196
Published: 1988
DOI: 10.1016/0370-2693(88)91595-X

Report number: FERMILAB-PUB-87-225-A, EFI-87-104-CHICAGO, UMN-TH-637-87, CERN-TH-4887-87

View in: CERN Document Server

Citations per year

SN 1987A Signal Duration Too Long?

Fiorillo+ [arXiv:2308.01403](https://arxiv.org/abs/2308.01403)

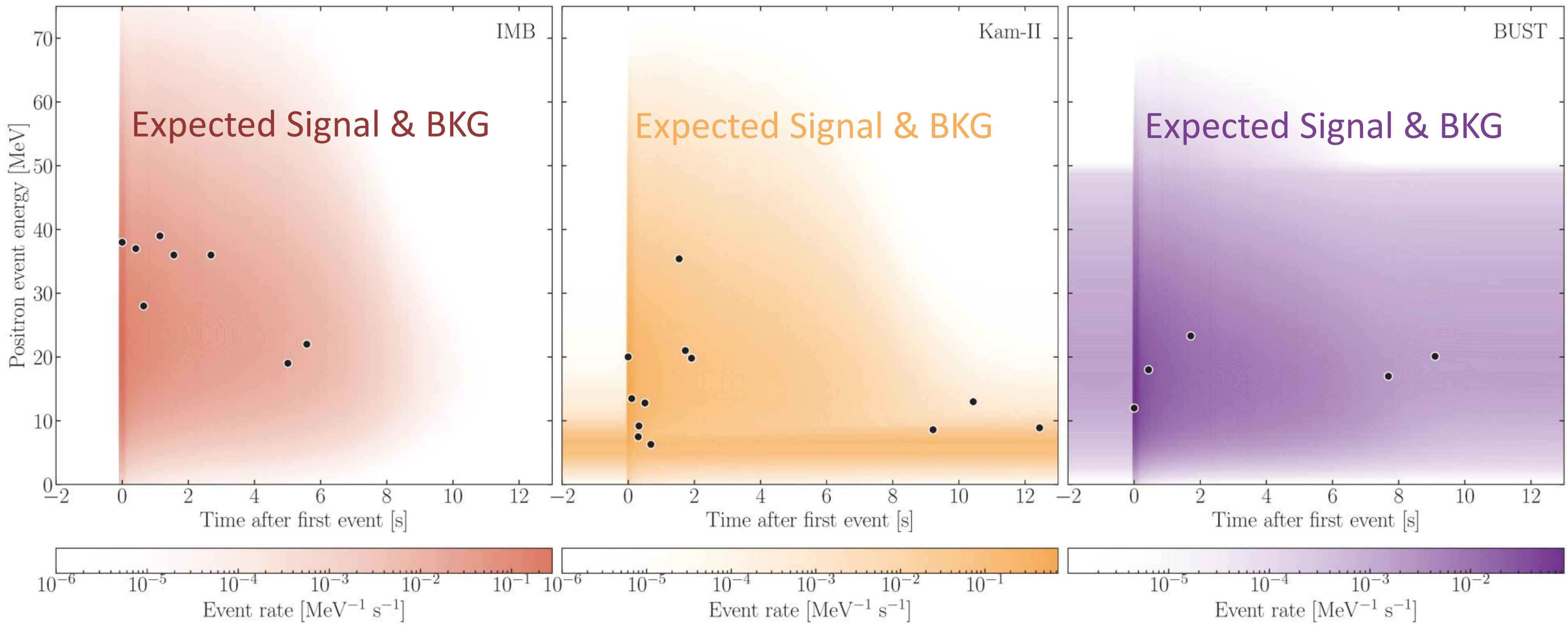


FIG. 17. Differential event distribution (signal and background) at each experiment, compared with the observations. Results are shown for model 1.44-SFHo without flavor swap; the offset time for each experiment is chosen as the best-fit value reported in Table VII.

- **In a suite of Garching models (no axions), expected signal always too short (PNS convection!)**
- **Deserves dedicated study**

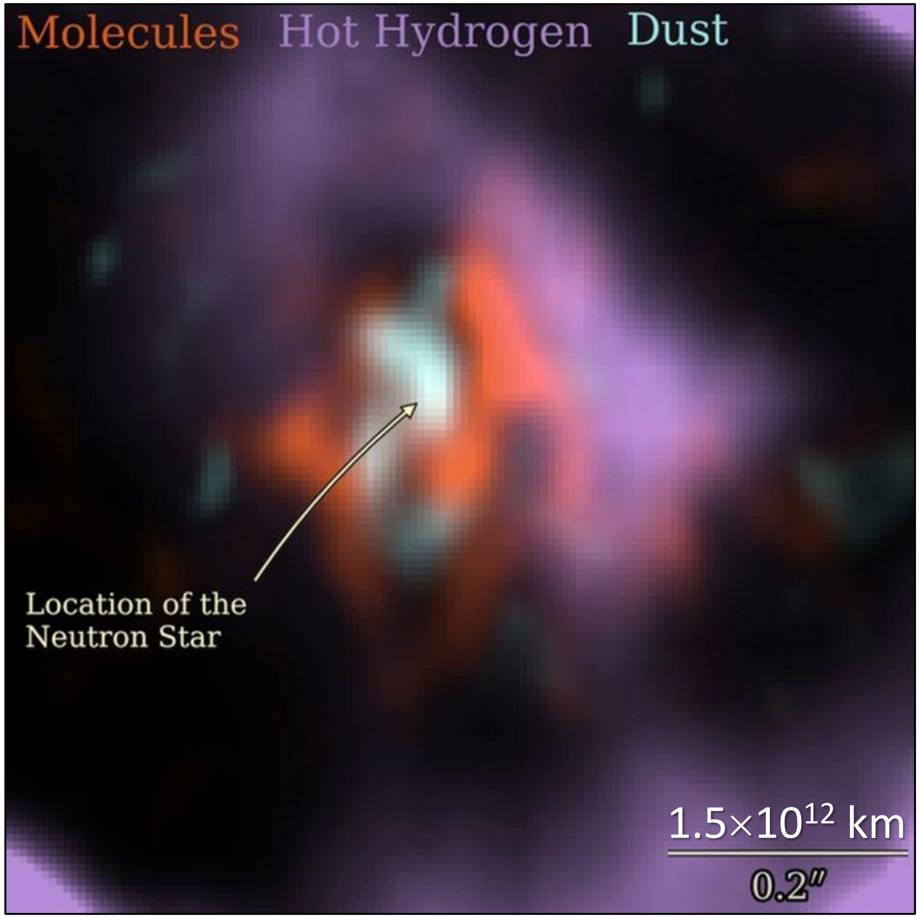
Where is the Neutron Star of SN 1987A?

No pulsar or neutron star has been seen until now (35 years later)

- Infra-red excess observed by ALMA: In "the blob" strong indication for NS
  Expected position, remnant hidden by dust [Cigan+ arXiv:1910.02960]
- Most plausible model: Thermally cooling non-pulsar NS [Page+ arXiv:2004.06078]

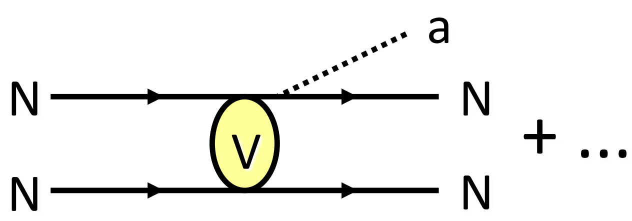
https://www.bbc.com/news/science-environment-50473482

Atacama Large Millimeter/Submillimeter Array (ALMA) at ESO in Chile



Axion Emission from a Nuclear Medium

Axion-nucleon interaction: $\mathcal{L}_{\rm int} = \frac{C_N}{2f_a}\,\overline{\Psi}_N\gamma_\mu\gamma_5\Psi_N\partial^\mu a = \frac{C_N}{2f_a} J^A_\mu \partial^\mu_a$



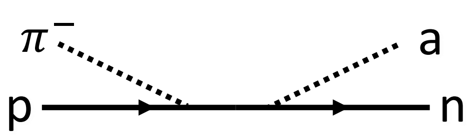
Nucleon-Nucleon
Bremsstrahlung

Axial-vector interaction implies dominance of spin-dependent process

- Interaction potential (one-pion exchange OPE often used, but too simplistic)
- In-medium coupling constants
- In-medium effective nucleon properties
- Correlation effects (static and dynamical spin-spin correlations)

→ **For latest discussion see Carenza et al. arXiv:1906.11844**

Thermal π^- contribute significant (dominant?)

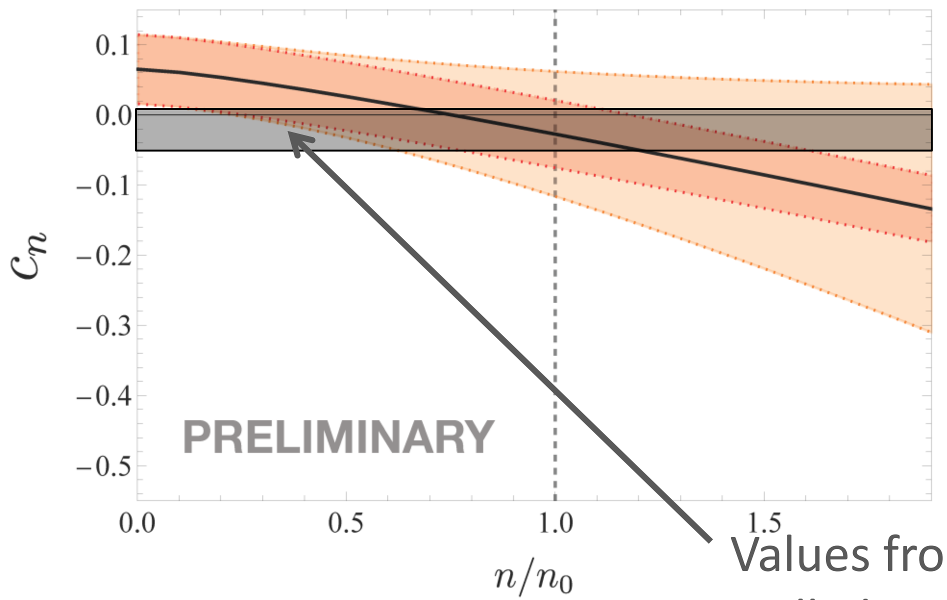


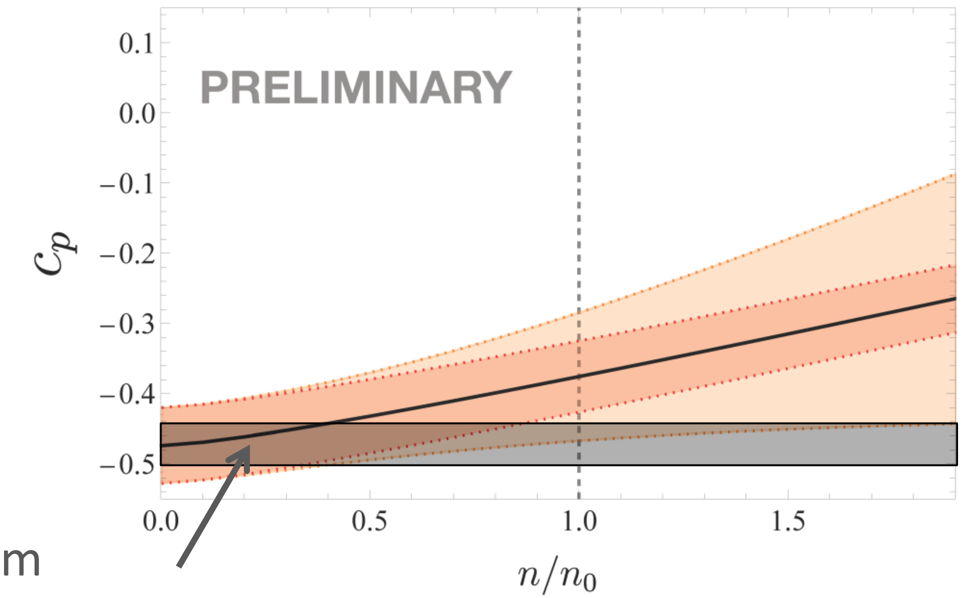
→ **For latest discussion see Carenza et al. arXiv:2010.02943**

Axion Couplings in Dense Nuclear Medium

Brand New

KSVZ Axions





Values from
Grilli di Cortona et al.
arXiv:1511.02867

S. Stelzl, Cosmic Wispers Workshop, Bari

Work in preparation, Balkin, Serra, Springmann, Stadlbauer, Stelzl & Weiler

SN 1987A Axion Limits from Burst Duration

- Raffelt, Lect. Notes Phys. 741 (2008) 51 hep-ph/0611350
  Burst duration calibrated by early numerical studies
  "Generic" emission rates inspired by OPE rates
  $f_a \gtrsim 4 \times 10^8$ GeV and $m_a \lesssim 16$ meV (KSVZ, based on proton coupling)

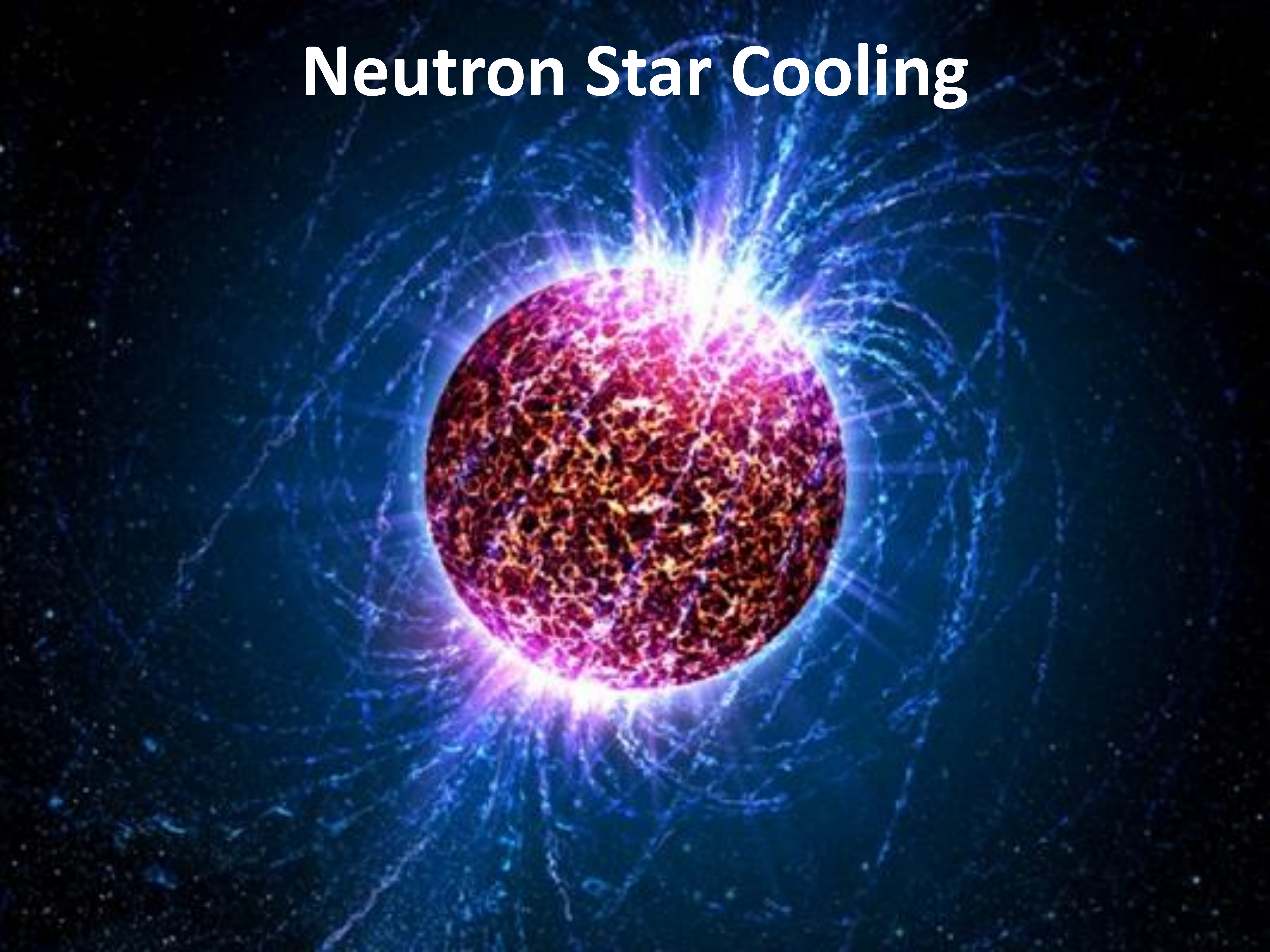
- Chang, Essig & McDermott, JHEP 1809 (2018) 051 1803.00993
  Various correction factors to emission rates, specific SN core models
  $f_a \gtrsim 1 \times 10^8$ GeV and $m_a \lesssim 60$ meV (KSVZ, based on proton coupling)

- Carenza, Fischer, Giannotti, Guo, Martínez-Pinedo & Mirizzi,
  JCAP 10 (2019) 016 & Erratum 1906.11844
  Beyond OPE emission rates, specific SN core models: similar to Chang et al.
  $f_a \gtrsim 4 \times 10^8$ GeV and $m_a \lesssim 15$ meV (KSVZ, based on proton coupling)

- Carenza, Fore, Giannotti, Mirizzi & Reddy 2010.02943
  Including thermal pions $\pi^- + p \to n + a$ (factor 3 larger emission)
  $f_a \gtrsim 5 \times 10^8$ GeV and $m_a \lesssim 11$ meV (KSVZ, based on proton coupling)

- Bar, Blum & D'Amico, Is there a supernova bound on axions? 1907.05020
  Alternative picture of SN explosion (thermonuclear event)
  Observed signal not PNS cooling. SN1987A neutron star (or pulsar) not yet found.
  (but see "NS 1987A in SN 1987A", Page et al. arXiv:2004.06078)

Neutron Star Cooling



Cooling Simulations of Five Neutron Stars

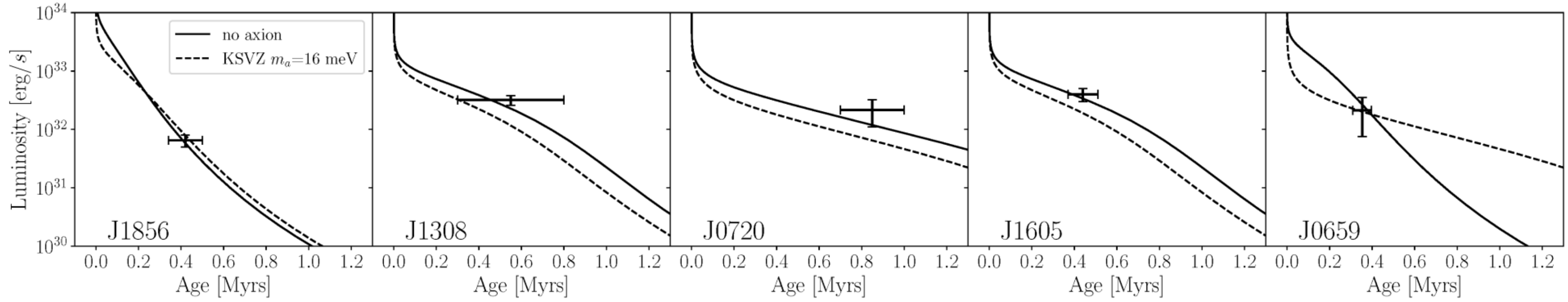
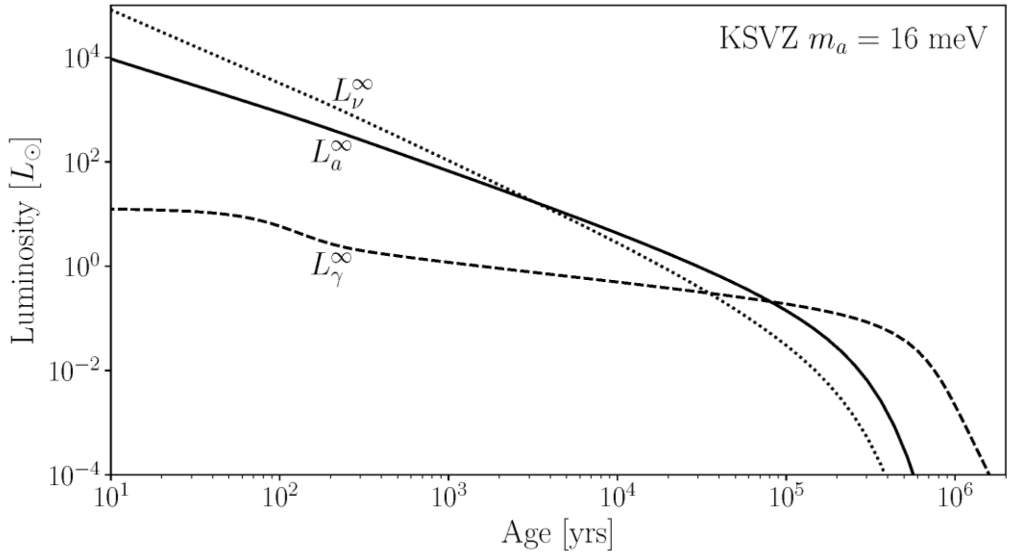


Figure 1. The luminosity and age data for each of the NSs considered in this work (see Tab. I). We show the best-fit cooling curves computed in this work for each of these NSs under the null hypothesis and with the axion mass fixed to $m_a = 16$ meV, which is our 95% upper limit on the QCD axion mass in the context of the KSVZ model.



Cooling of J1605 with KSVZ axions, BSk22 EOS, SBF-0-0 superfluidity model, $M_{\rm NS} = 1.0\ M_\odot$

Bounds similar to SN1987A

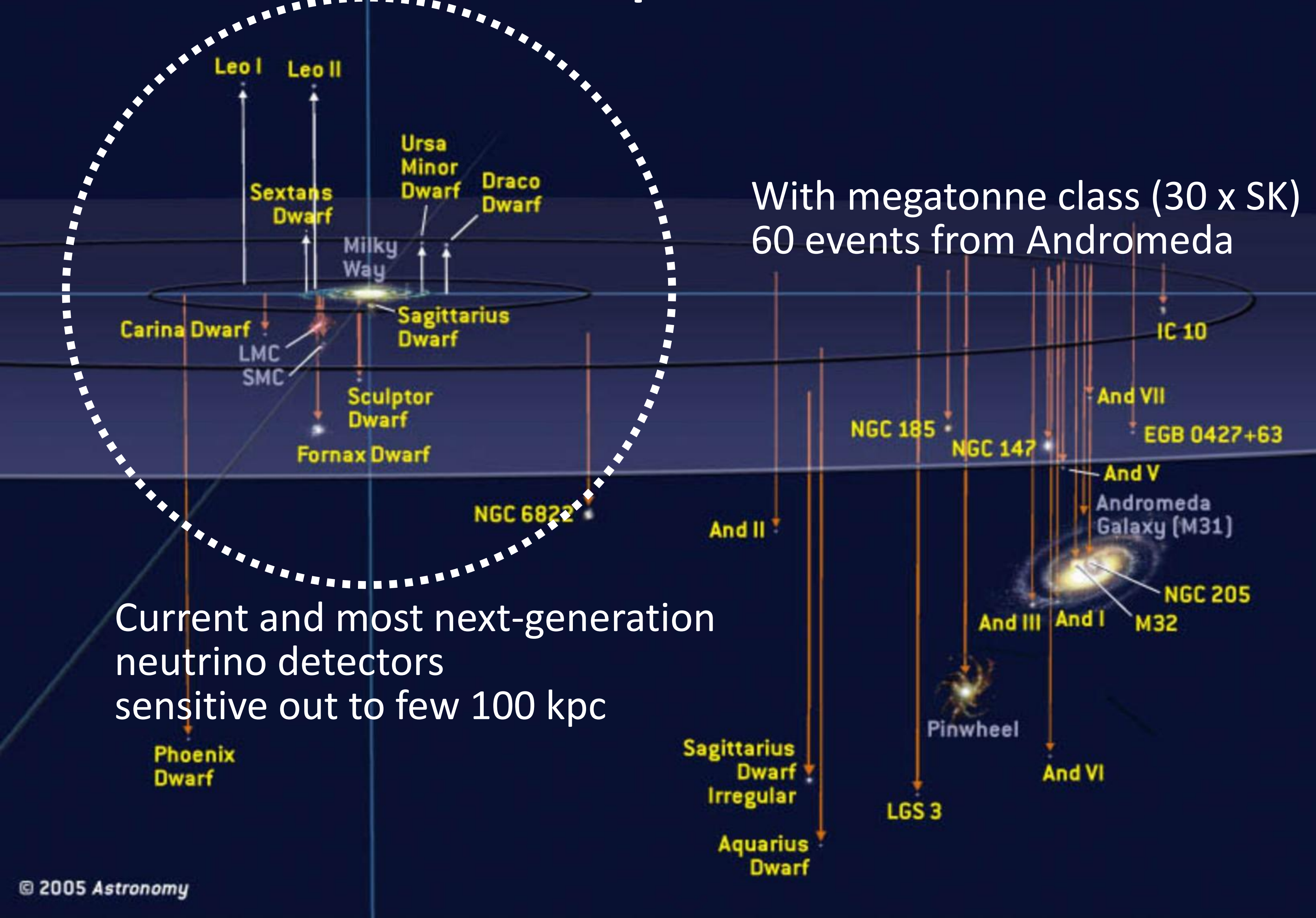
$m_a < 10 - 20$ meV

Upper Limit on the QCD Axion Mass from Isolated Neutron Star Cooling

Buschmann, Dessert, Foster, Long & Safdi, 2111.09892

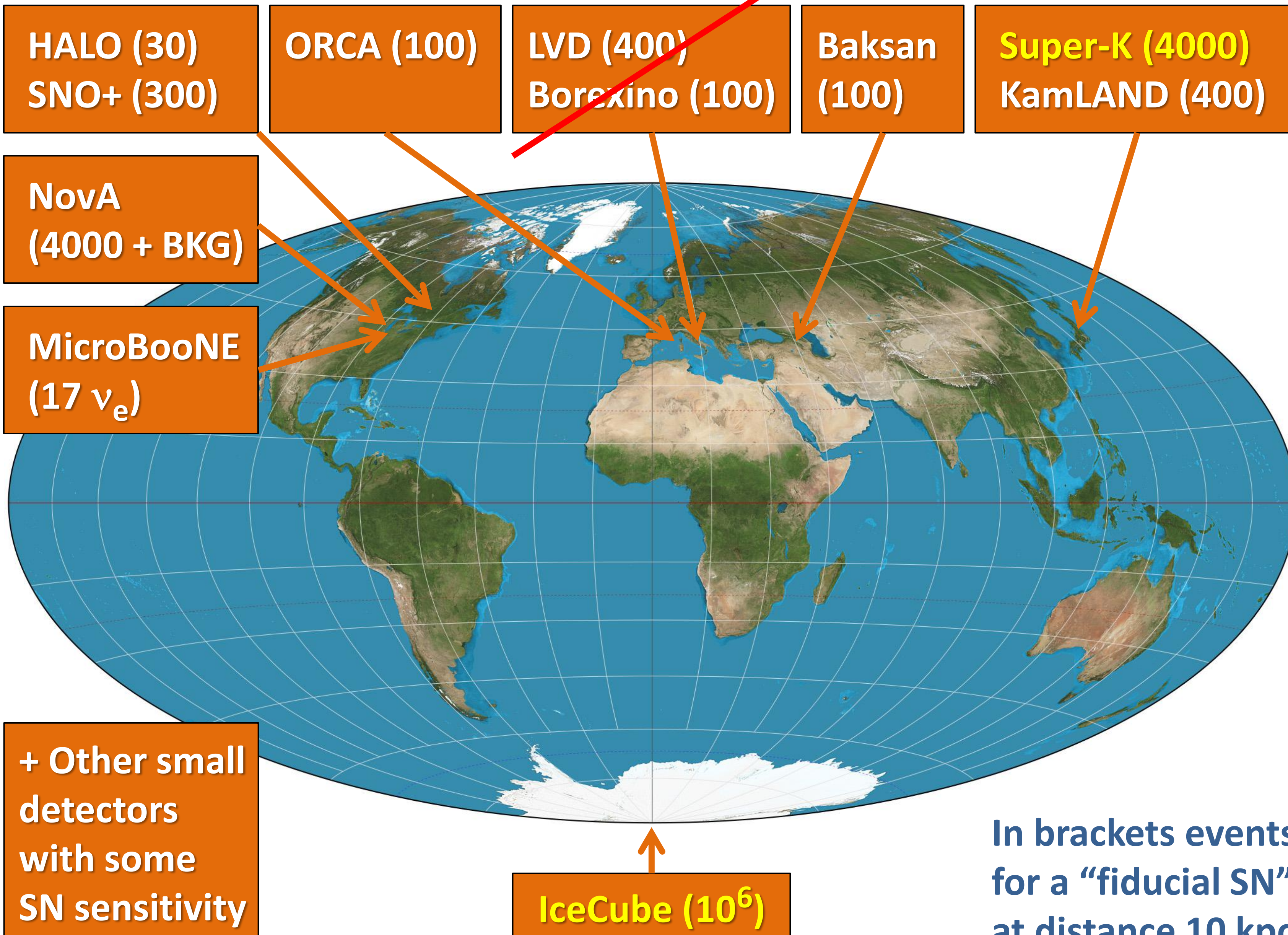
Local Group of Galaxies

With megatonne class (30 x SK)
60 events from Andromeda



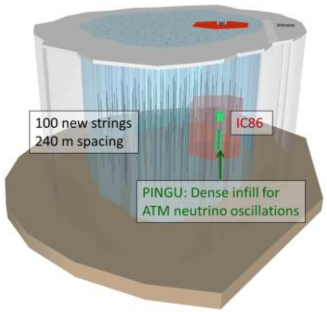
Current and most next-generation neutrino detectors
sensitive out to few 100 kpc

Operational Detectors for Supernova Neutrinos

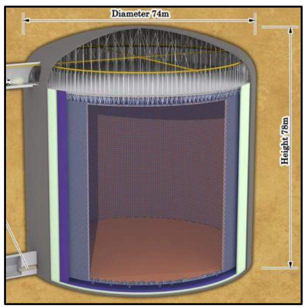


In brackets events for a “fiducial SN” at distance 10 kpc

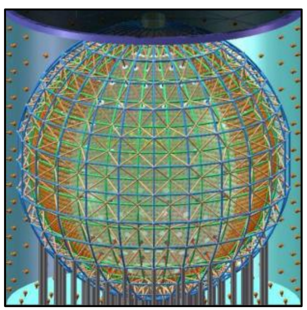
Next Generation Very-Large-Scale Detectors (2020+)



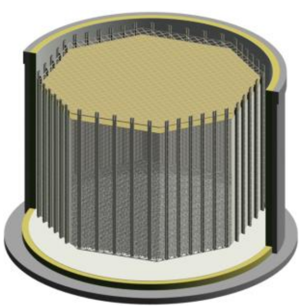
IceCube Gen-2
- Dense infill (PINGU)
- Larger volume (statistics for high-E events)
Doubling the number of optical modules



Megaton-class water Cherenkov detector
Notably Hyper-Kamiokande
SN neutrino statistics comparable to IceCube,
but with event-by-event energy information

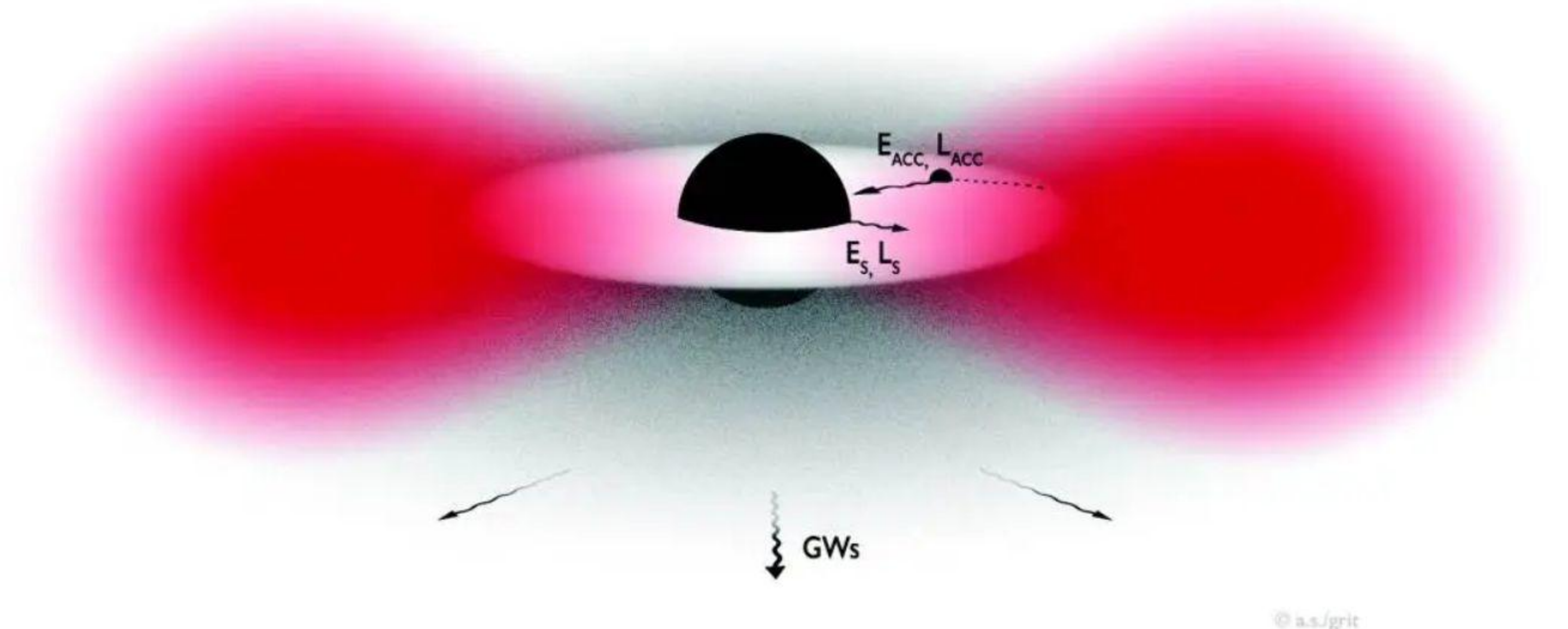


Scintillator detectors (20 kilotons)
- JUNO in China for reactor nus (construction)
- RENO-50 in Korea for reactor nus (plans)
- Baksan Large Volume Scintillator Detector
  (discussions in Russia)



Liquid argon time projection chamber
For long-baseline oscillation experiment DUNE
- Unique SN capabilities (CC ν_e signal)
- But cross sections poorly known

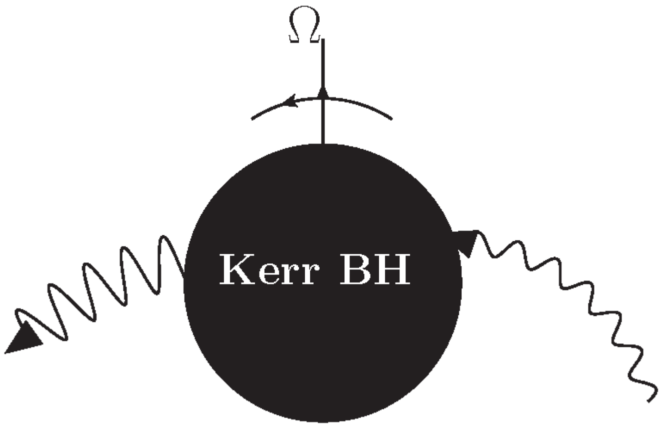
Superradiance



Superradiance: New Frontiers in Black Hole Physics (2020 edition)
R. Brito, V. Cardoso & P. Pani, 1501.06570v8 (8 Jan 2021)

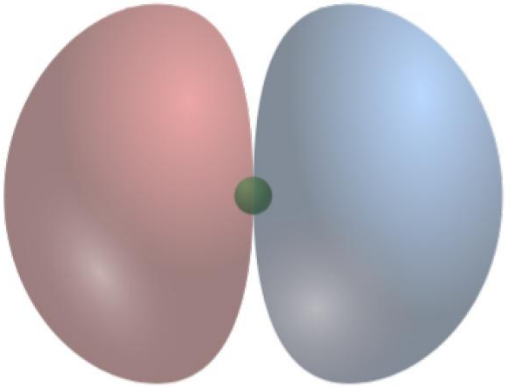
Superradiance

Extraction of rotational energy from spinning object by low-frequency modes $\omega < \Omega$ of an external bosonic field



$m\Omega > \omega$

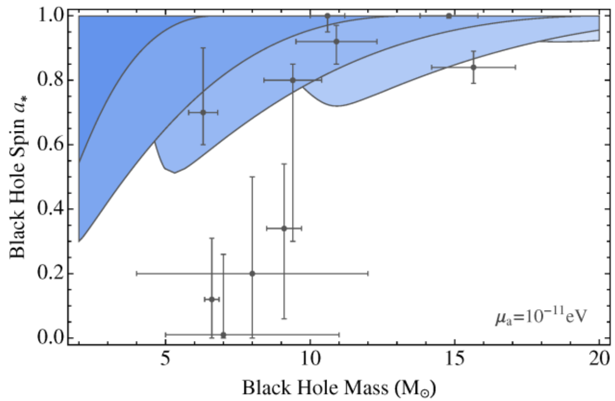
- Bosons with mass get gravitationally bound
- Superradiant run-away mode $\phi = Y_{lm}(\theta, \phi)\psi_{lmn}(r)e^{\Gamma t}$
- "Bosonic atom"
- Transitions → Gravitational waves



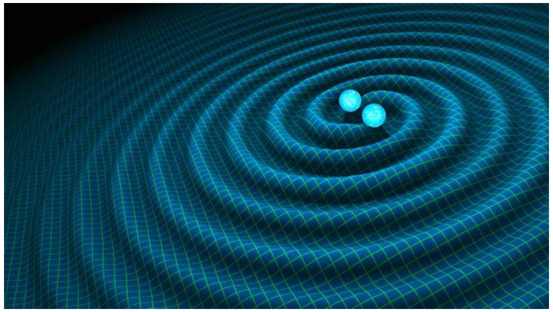
Superradiance: New Frontiers in Black Hole Physics (2020 edition)
R. Brito, V. Cardoso & P. Pani, [1501.06570v8](1501.06570v8) (8 Jan 2021)

- **Constraints on light particles from BH spin**

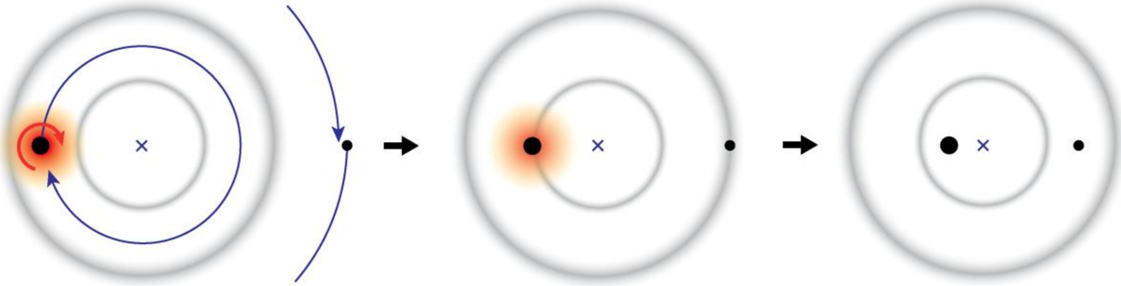
  Exploring the string axiverse with precision black hole physics
  Arvanitaki & Dubovsky, [1004.3558]
  Discovering the QCD axion with black holes and gravitational waves, Arvanitaki, Baryakhtar & Huang, [1411.2263]



- **Gravitational waves from "atomic transitions"**

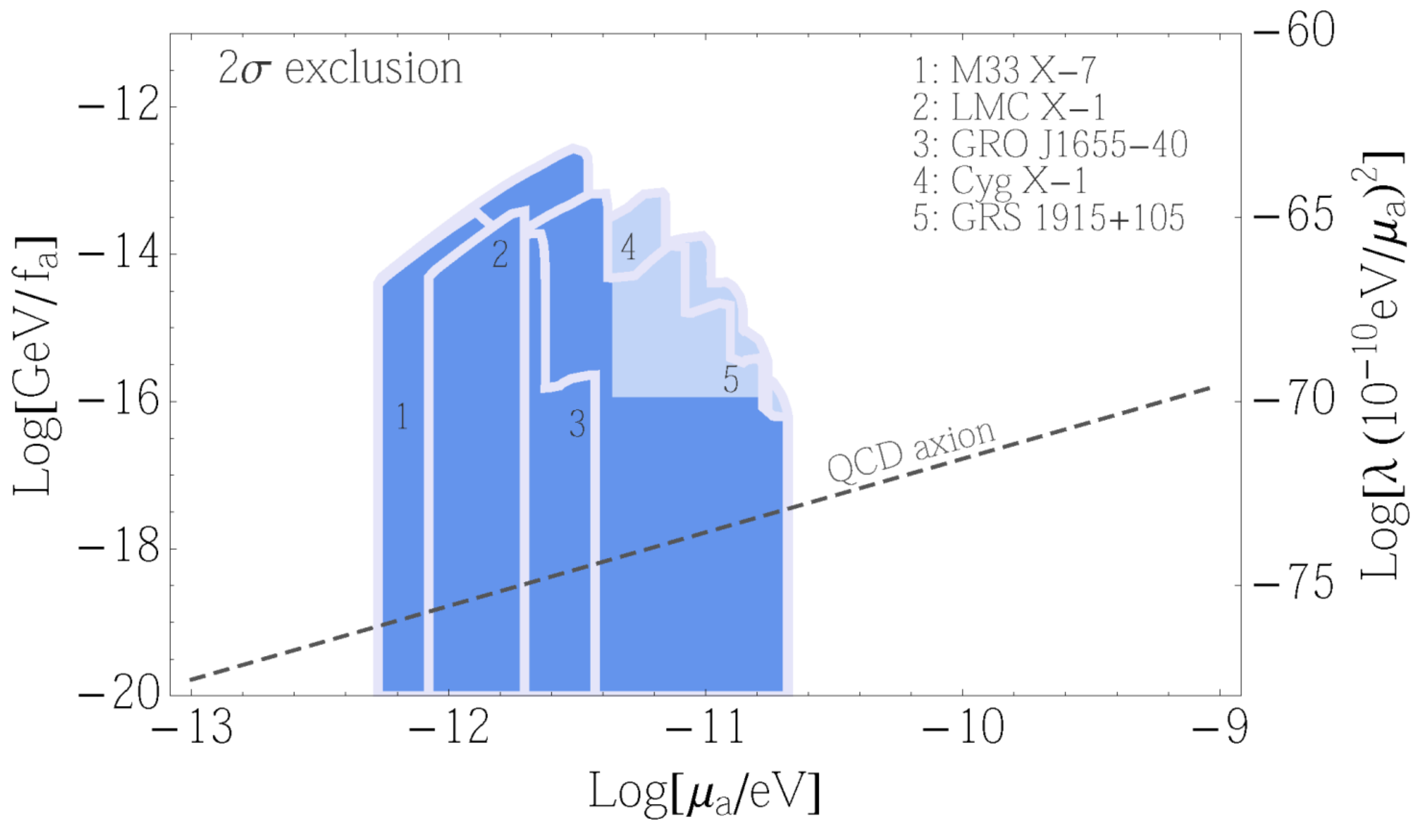


- **Effects on binaries**



Probing Ultralight Bosons with Binary Black Holes
Baumann, Chia & Porto, [1804.03208]

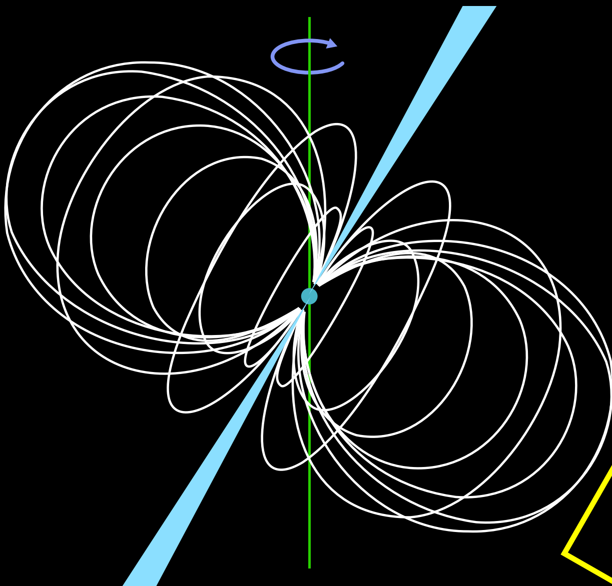
Constraints from Black Hole Spins



#	Object	Mass ($M_\odot$)	Spin	Age (yrs)	Period (days)	$M_{\text{comp. star}}$ ($M_\odot$)	$\dot{M}/\dot{M}_E$
1	M33 X-7	15.65 ± 1.45	$0.84^{+.10}_{-.10}$[51]	3×10^6 [52]	3.4530 [53]	$\gtrsim 20$ [53]	$\gtrsim 0.1$[53]
2	LMC X-1	10.91 ± 1.4	$0.92^{+.06}_{-.18}$ [54]	5×10^6 [52]	3.9092 [55]	31.79 ± 3.48 [55]	0.16 [55]
3	GRO J1655-40	6.3 ± 0.5	$0.72^{+.16}_{-.24}$ [51]	3.4×10^8 [56]	2.622 [56]	2.3 - 4 [56]	$\lesssim 0.25$ [57]
4	Cyg X-1	14.8 ± 1.0	> 0.99 [58]	4.8×10^6[59]	5.599829 [52]	17.8 [52]	0.02[52]
5	GRS1915+105	10.1 ± 0.6	> 0.95 [51, 60]	4×10^9 [61]	33.85 [62]	0.47 ± 0.27 [62]	$\gtrsim 1$ [62].

Arvanitaki, Baryakhtar & Huang, 1411.2263

Dark Matter Axion-Photon Conversion in Neutron Star Magnetospheres



Dark matter axions
$m_a \sim \mu\text{eV},\ v_a \sim 10^{-3}c$

Very narrow radio line

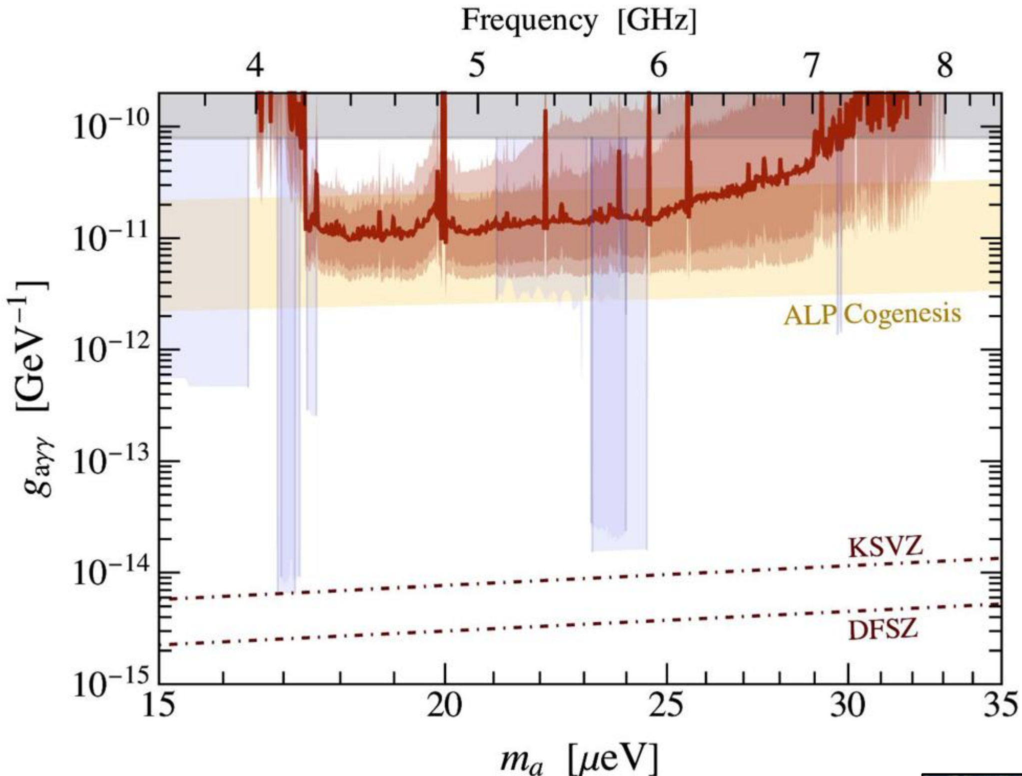
Pshirkov & Popov 2007
arXiv:0711.1264
Many papers recently

Axion mass and plasma frequency
Degenerate near NS surface
→ Resonant conversion

Extraterrestrial Axion Search with the Breakthrough Listen Galactic Center Survey

Joshua W. Foster,[1,*] Samuel J. Witte,[2,†] Matthew Lawson,[3,4] Tim Linden,[3]
Vishal Gajjar,[5] Christoph Weniger,[2] and Benjamin R. Safdi[6,7,‡]

2202.08274

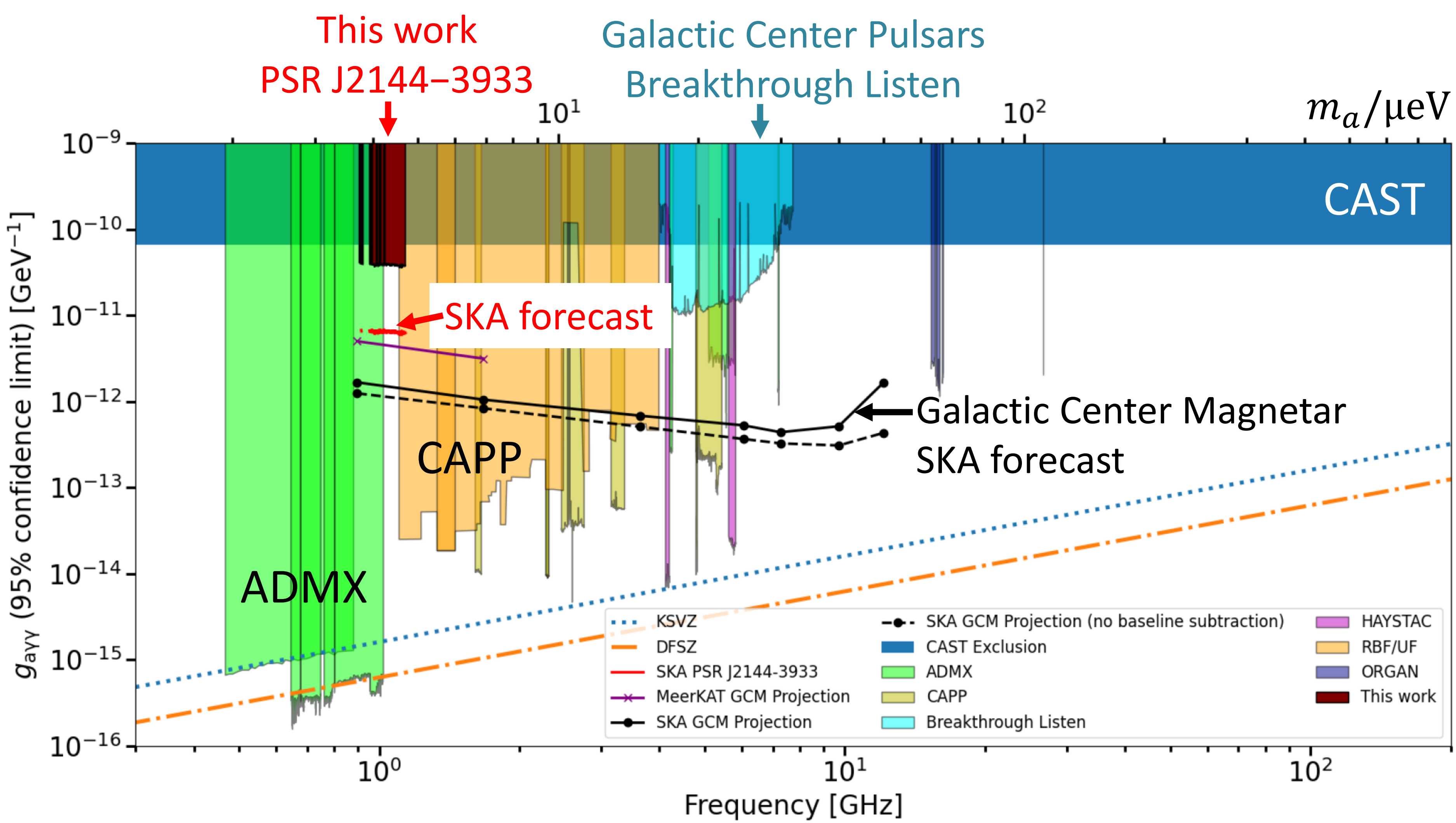


- Green Bank Telescope Archival Data
- Breakthrough Listen Project (Search for ET Life)
- State-of-the-art ray tracing simulations
- Galactic Center Region
  - Many pulsars
  - Enhanced dark matter density

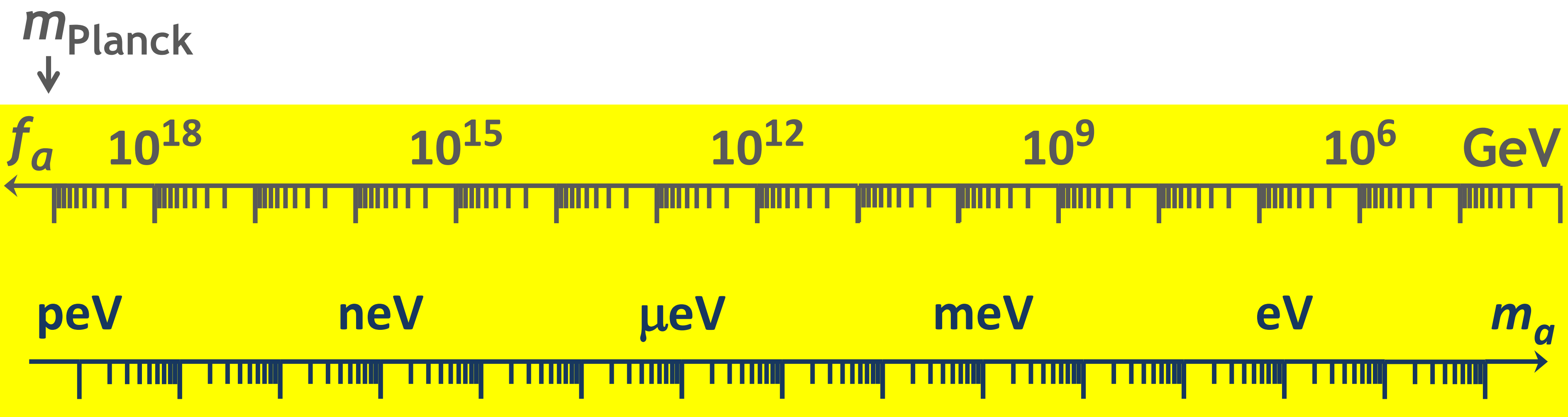
Searching for Time-Dependent Axion Dark Matter Signals in Pulsars

R. A. Battye,[1,*] M. J. Keith,[1,†] J. I. McDonald,[2,‡] S. Srinivasan,[1,§] B. W. Stappers,[1,¶] and P. Weltevrede[1,**]

2303.11792



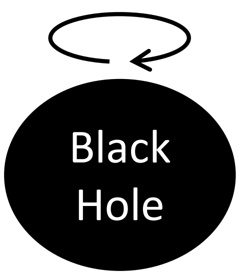
Astrophysical Axion Bounds and Opportunities

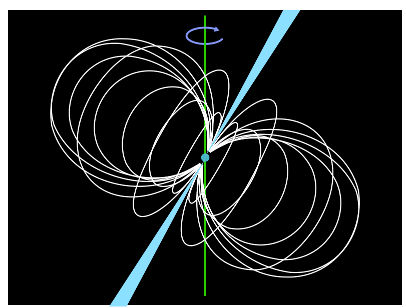


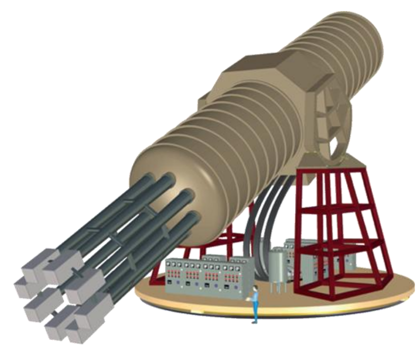
Super Radiance

Opportunities for detection

Astrophysical Bounds (Energy loss of stars)





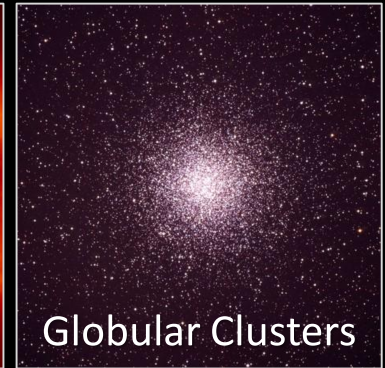


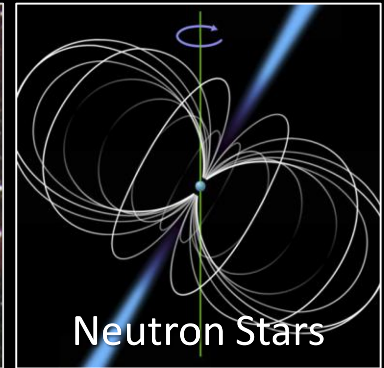
IAXO Solar Axion Telescope

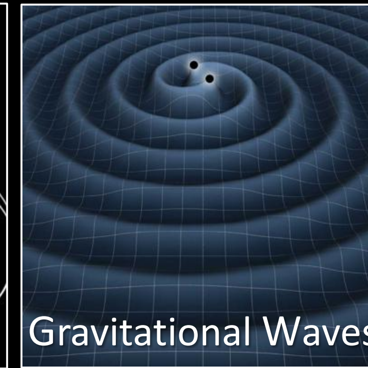
Axion conversion in neutron star magnetospheres

Particles from Stars: What to expect?

- **New Ideas ...**
- Extension & refinements of existing arguments
  (ordinary stars, Red Giants, (variable) white dwarfs, neutron star cooling, ...)
- Search for solar axions: (baby) IAXO, XENON n tonne, ...
- Search for magnetically converted ALPs
  from magnetic white dwarfs & neutron stars (x-ray satellites)
- Radio search for axion dark matter conversion in neutron star magnetospheres
  (new detetectors SKA, ...)
- Next galactic supernova observation **(3% chance every year!)**
- Theoretical developments in collective neutrino flavor evolution
- Diffuse Supernova Neutrino Background observation **(Super-K (Gd), JUNO)**
- Gravitational-wave evidence for superradiance from black holes







Some Literature

Axion Reviews: Theory & Cosmology

- **Axion Dark Matter (Snowmass 2021 White Paper), 2203.14923**
  C.B. Adams, et al.
- **Axion dark matter: What is it and why now? 2105.01406**
  F. Chadha-Day, J. Ellis & D.J.E. Marsh
- **Recent Progress in the Physics of Axions and Axion-Like Particles, 2012.05029**
  K. Choi, S.H. Im & C.S. Shin
- **The Landscape of QCD Axion Models, 2003.01100**
  L. Di Luzio, M. Giannotti, E. Nardi & L. Visinelli
- **Small-Scale Structure of Fuzzy and Axion-Like Dark Matter, 1912.07064**
  J.C. Niemeyer
- **Axion Cosmology, 1510.07633**
  D.J.E. Marsh
- **Axions: Theory and Cosmological Role, 1301.1123**
  M. Kawasaki & K. Nakayama
- **Axions and the Strong CP Problem, 0807.3125**
  J.E. Kim & G. Carosi

Axion Reviews: Experiments & Searches

- **The Search for Ultralight Bosonic Dark Matter,** doi:10.1007/978-3-030-95852-7
  D.F. Jackson Kimball & K. van Bibber (eds.), (Springer, 2023, open access)

- **Invisible Axion Search Methods,** 2003.02206
  P. Sikivie

- **New Experimental Approaches in the Search for Axion-Like Particles,** 1801.08127
  I.G. Irastorza & J. Redondo

- **Experimental Searches for the Axion and Axion-Like Particles,** 1602.00039
  P.W. Graham, I.G. Irastorza, S.K. Lamoreaux, A. Lindner & K.A. van Bibber

- **Searches for astrophysical and cosmological axions,**
  doi:10.1146/annurev.nucl.56.080805.140513
  S.J. Asztalos, L.J. Rosenberg, K. van Bibber, P. Sikivie & K. Zioutas (2006)

- **Microwave cavity searches for dark-matter axions,** doi:10.1103/RevModPhys.75.777
  R. Bradley, J. Clarke, D. Kinion, L.J. Rosenberg, K. van Bibber, S. Matsuki,
  M. Mück & P. Sikivie (2003)

- **Searches for invisible axions,** doi:10.1016/S0370-1573(99)00045-9
  L.J. Rosenberg & K.A. van Bibber (2000)

Axion Reviews: Astrophysical Methods

Stellar Evolution

- **White Dwarfs as Physics Laboratories: Lights and Shadows, 2202.02052**
  J. Isern, S. Torres & A. Rebassa-Mansergas
- **Stellar Evolution Confronts Axion Models, 2109.10368**
  L. Di Luzio, M. Fedele, M. Giannotti, F. Mescia & E. Nardi
- **Astrophysical Axion Bounds: The 2024 Edition, 2401.13728**
  A. Caputo & G. Raffelt
- **Stars as Particle Physics Laboratories, (Univ. Chicago Press, 1996)**
  G. Raffelt

Brand New

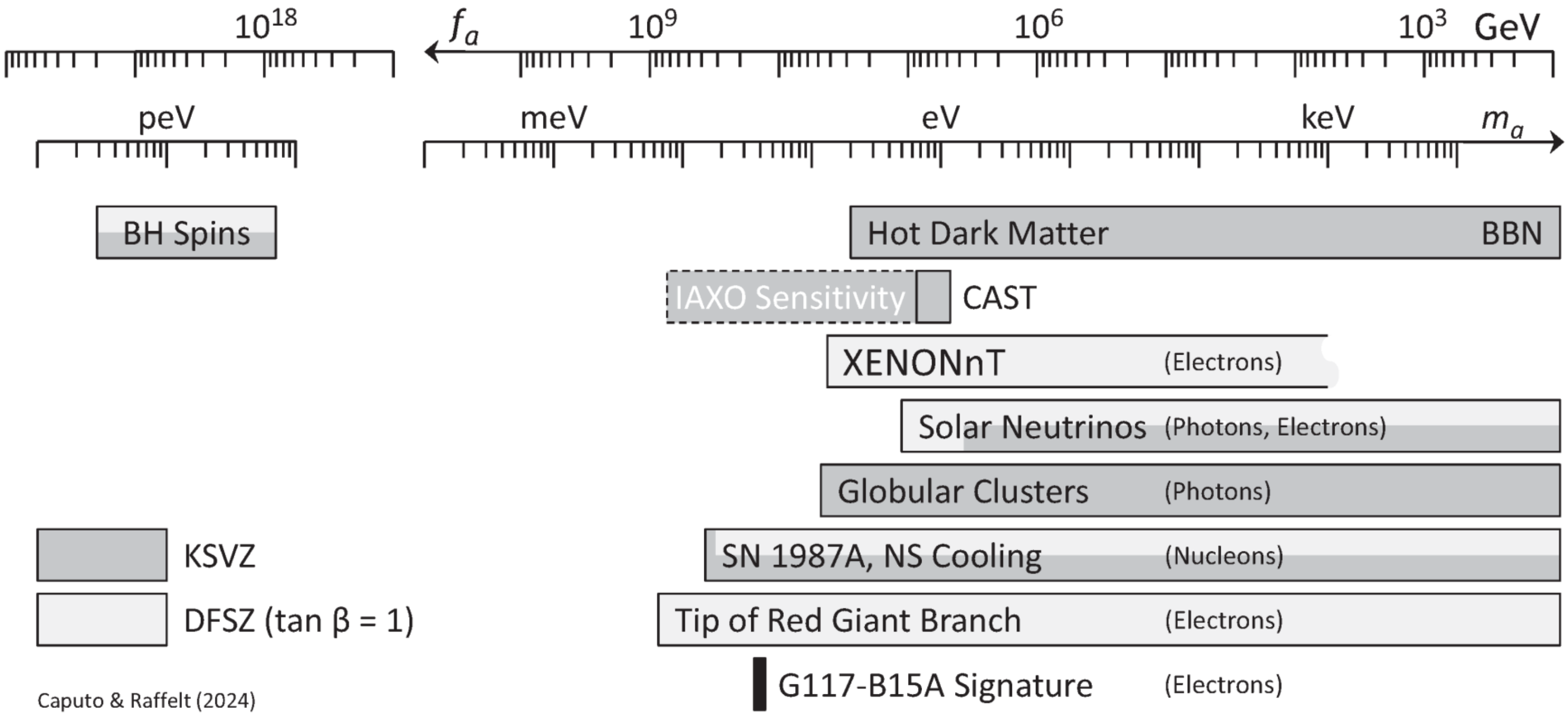
CAST in the Sky (Axion-Photon Conversion in B-fields)

- **Axion-Like Particles Implications for High-Energy Astrophysics, 2205.00940**
  G. Galanti & M. Roncadelli
- **Axion-Like Particle Searches with IACTs, 2106.03424**
  I. Batković, A. De Angelis, M. Doro & M. Manganaro

Astrophysical Axion Bounds

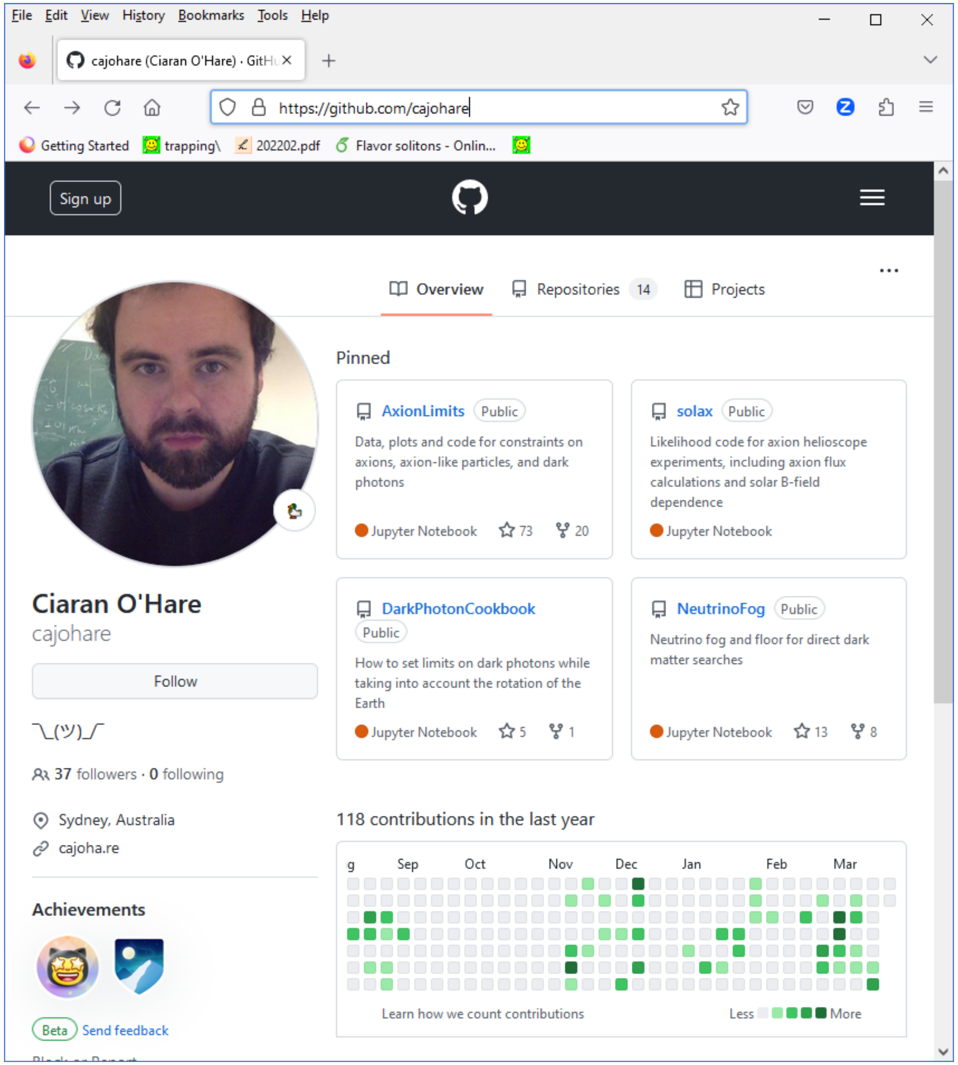
Brand New

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

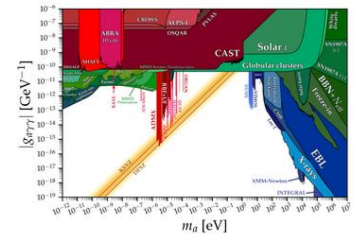
Bounds on Low-Mass Bosons



https://github.com/cajohare

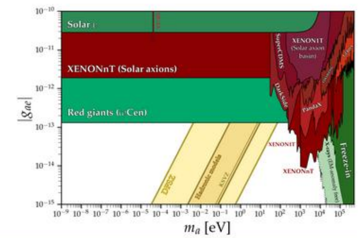
Axion-photon coupling

Data files
Plot (pdf, png)
Plot with projections (pdf, png)
Plot of dimensionless coupling (pdf, png)
Plot of dimensionless coupling with projections (pdf, png)



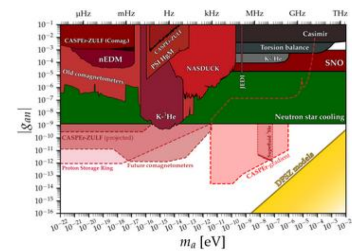
Axion-electron coupling

Data files
Plot (pdf, png)
Plot with projections (pdf, png)



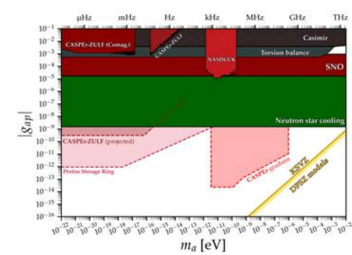
Axion-neutron coupling

Data files
Plot (pdf, png)
Plot with projections (pdf, png)



Axion-proton coupling

Data files
Plot (pdf, png)
Plot with projections (pdf, png)



Many constraint plots and the latest references

Some Reviews on Supernova Neutrinos

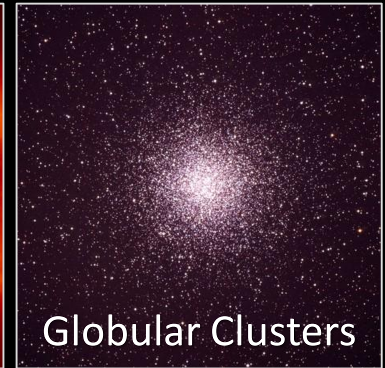
- Mirizzi, Tamborra, Janka, Saviano & Scholberg:
  Supernova Neutrinos: Production, Oscillations and Detection
  → arXiv:1508.00785

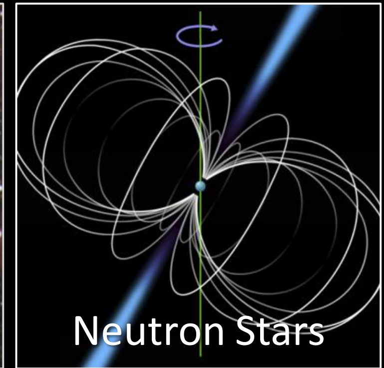
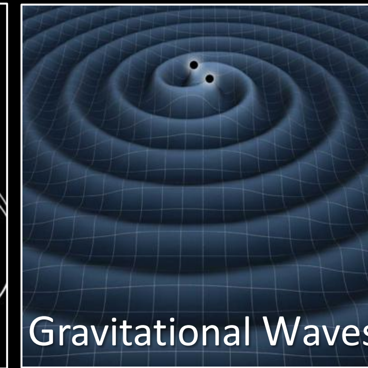
- Burrows & Vartanyan: **Core-Collapse Supernova Explosion Theory**
  → arXiv:2009.14157

- Janka: **Neutrino Emission from Supernovae**
  → arXiv:1702.08713

- Beacom: **The Diffuse Supernova Neutrino Background**
  → arXiv:1004.3311

- Himmel & Scholberg: **Supernova Neutrino Detection**
  → arXiv:1205.6003


Solar Axions

Globular Clusters

Supernova 1987A

Neutron Stars

Gravitational Waves

Thanks!