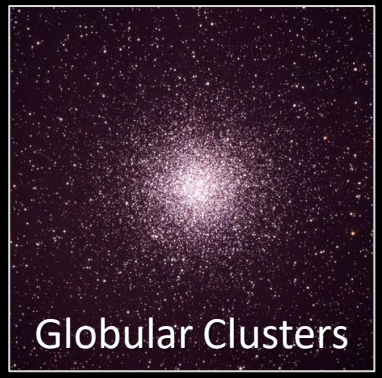
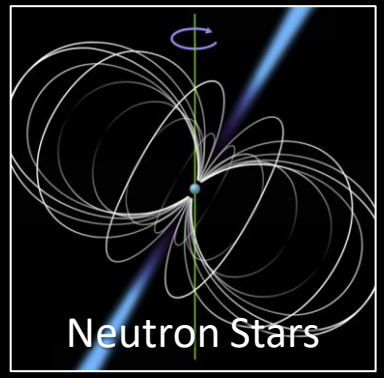
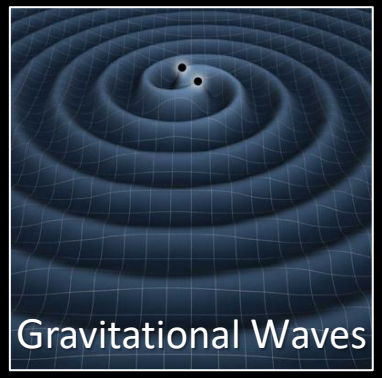






Stars as Laboratories for New Particles

Invisibles Workshop, CERN, 1 Sept 2025

ORIGINS Excellence Cluster

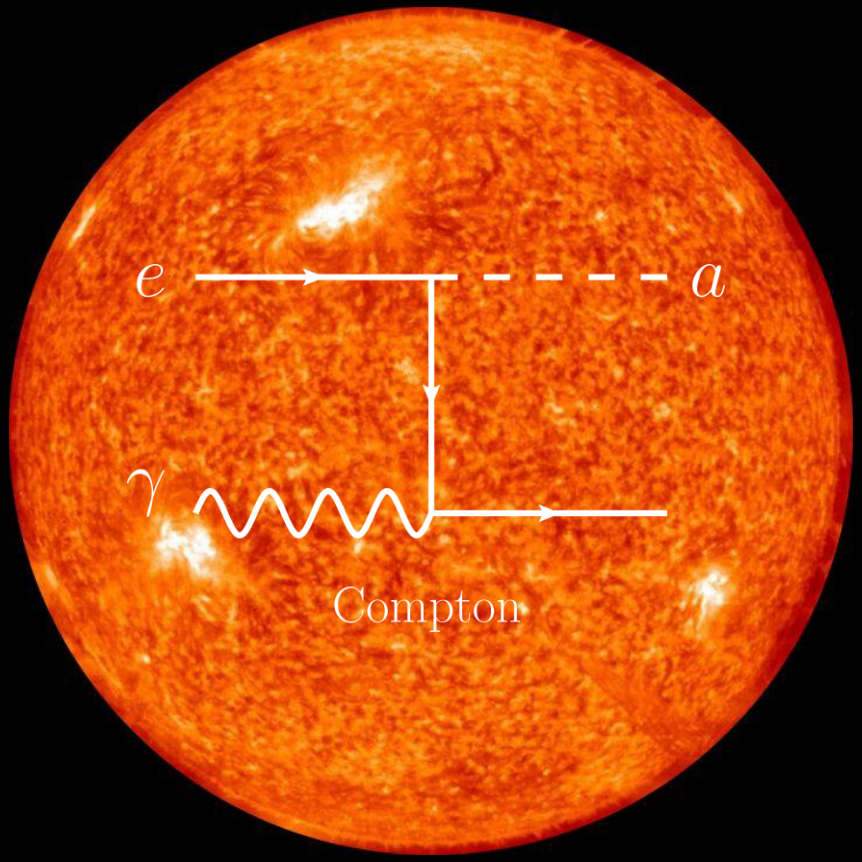
COSMIC WISPERS CA21106

MAX-PLANCK-INSTITUT FÜR PHYSIK

SFB 1258 Neutrinos Dark Matter Messengers

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

Particles and Stars

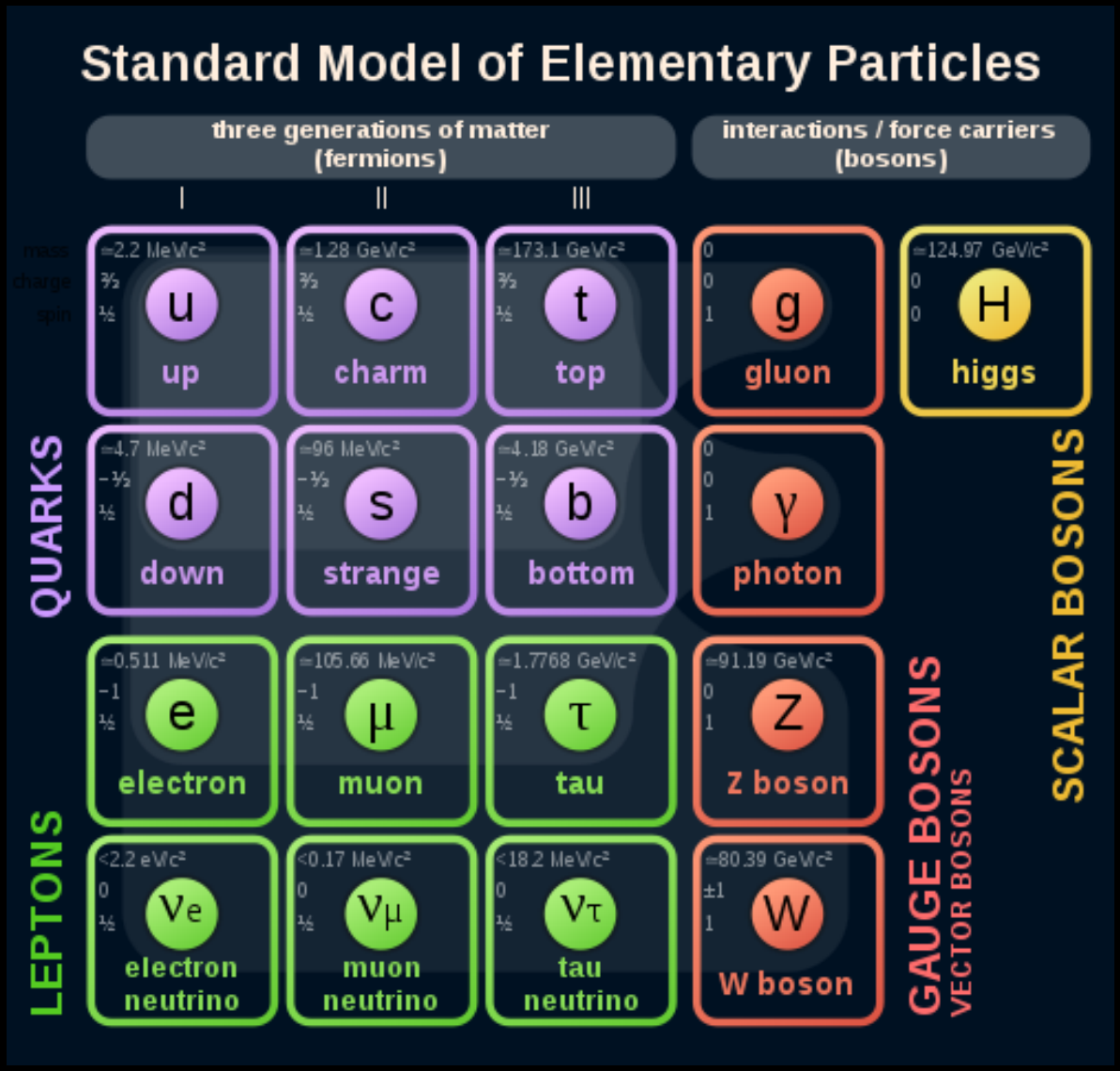


Low-mass particles are produced in stellar interiors

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

→ Which particles?

→ Which stars?

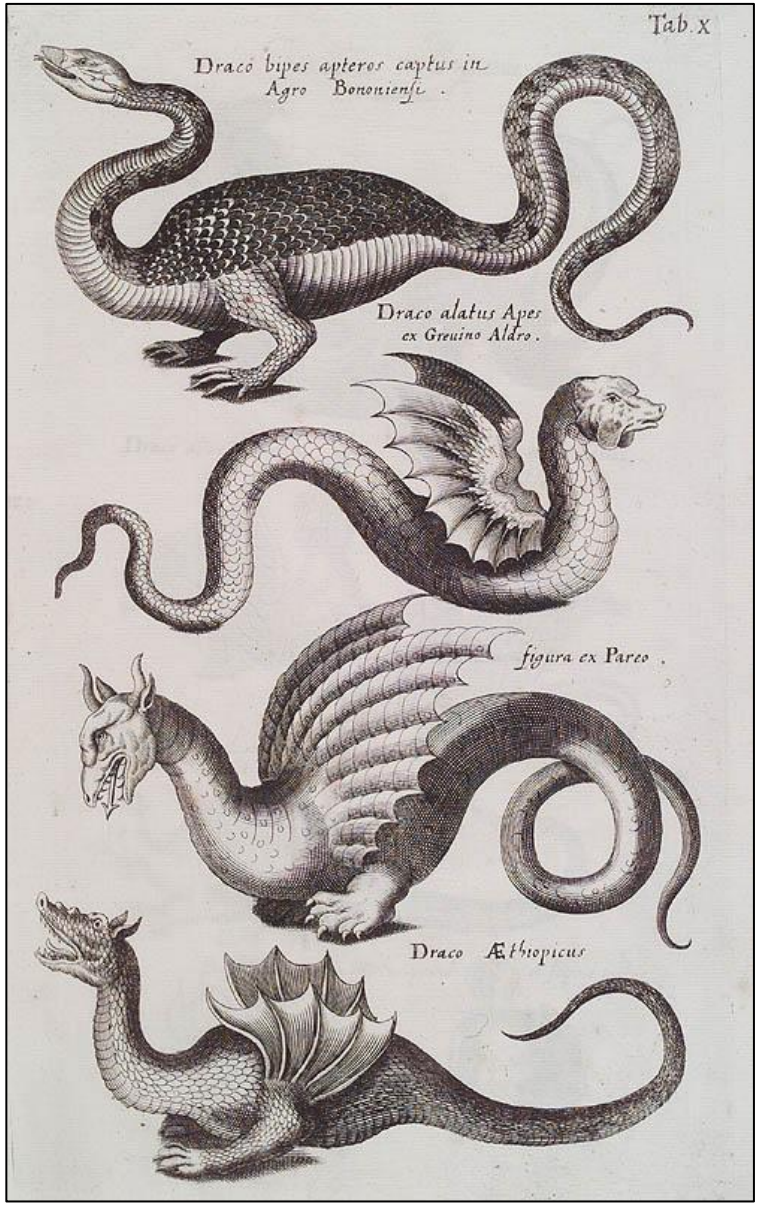


What else is there to know?

Urgent Particle-Physics Questions

- **Neutrino properties**
  - Two or four components? (Dirac vs Majorana)
  - Electromagnetic properties?
- **Dark matter of the universe**
  - WIMPs (heavy neutrino-like particles)
  - Axions (very low-mass π^0 like particles)
  - Many other options
- **Matter-antimatter asymmetry in the universe**
- **What drives cosmic inflation?**

Bestiarium of Low-Mass Bosons



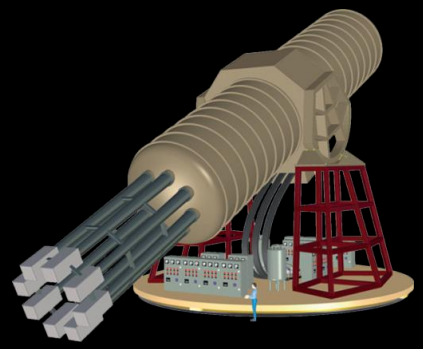
Weakly Interacting Sub-eV Particles (WISPs)

- **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, mediators, majorons, ...**

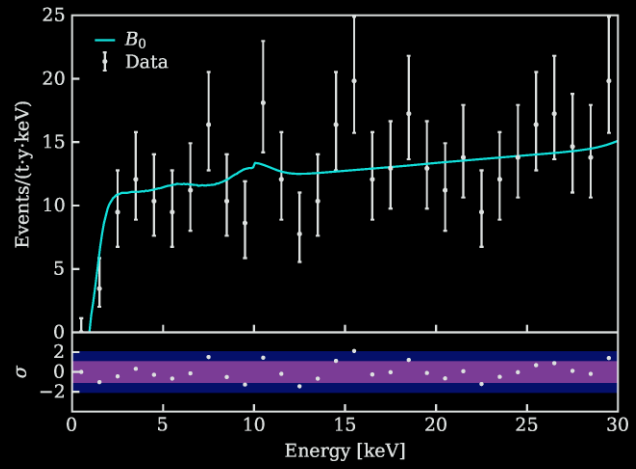
Particles from the Sun

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

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.*

$$H+H=D+\epsilon^{+}. \qquad (1)$$

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

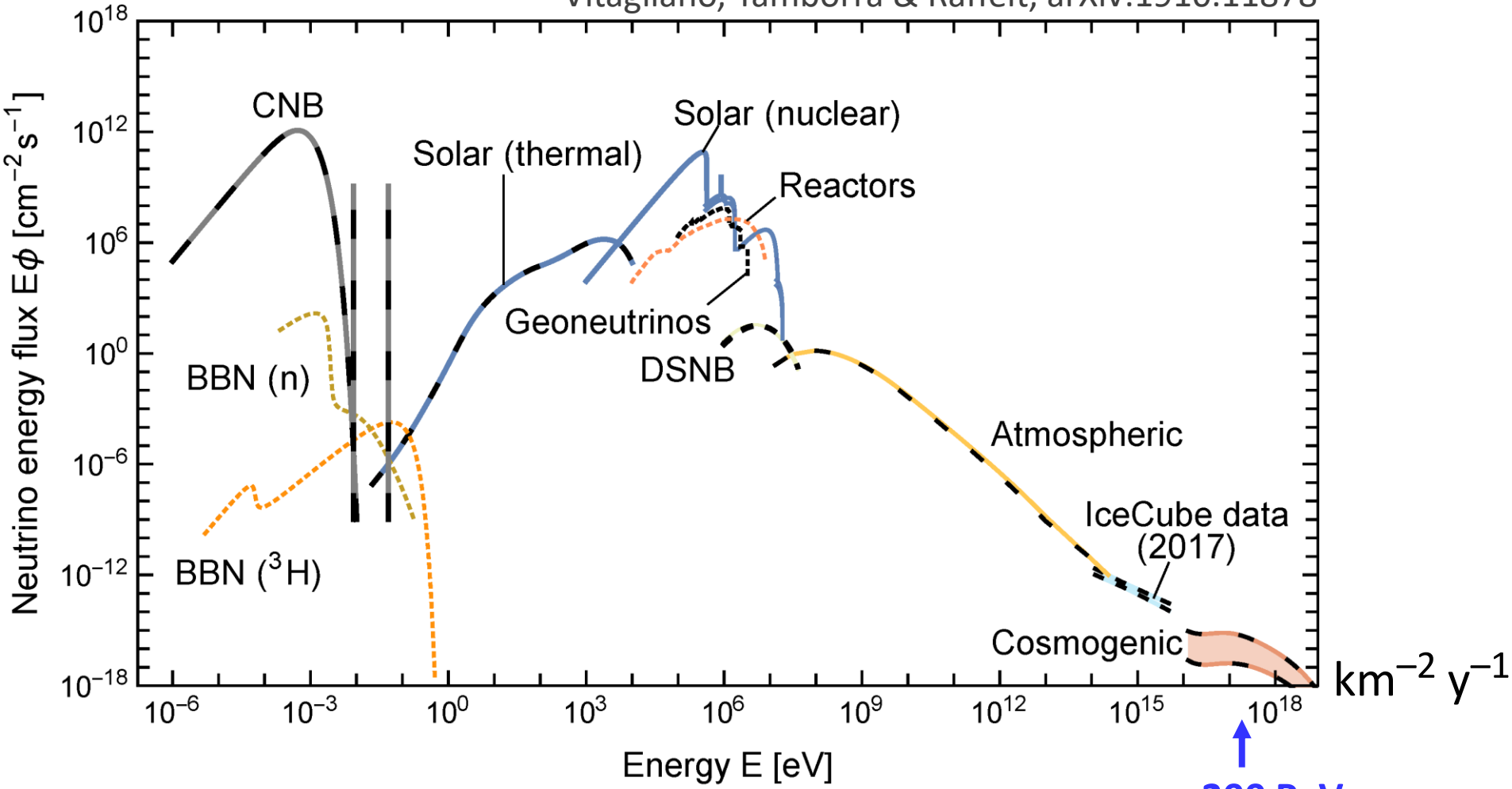
$$\begin{aligned} &C^{12}+H=N^{13}+\gamma, && N^{13}=C^{13}+\epsilon^{+} \\ &C^{13}+H=N^{14}+\gamma, && \\ &N^{14}+H=O^{15}+\gamma, && O^{15}=N^{15}+\epsilon^{+} \\ &N^{15}+H=C^{12}+He^{4}. && \end{aligned} \qquad (2)$$

Hans Bethe
1906–2005

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

Grand Unified Neutrino Spectrum (GUNS) at Earth

Vitagliano, Tamborra & Raffelt, arXiv:1910.11878



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

Nuclear vs. Thermal Particles from the Sun

Neutrinos from nuclear transformation

Effectively proton-neutron conversion

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

$L_\nu \simeq 2\%$ of $L_\odot = 3.8 \times 10^{26}$ Watts

At Earth $66 \times 10^9\ \nu\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Sub-MeV to 18 MeV energies

Set by nuclear interactions

Thermal neutrinos

Photon conversion, bremsstrahlung, ...

$$\gamma + e \rightarrow e + \nu + \bar{\nu}$$

$$e + p \rightarrow p + e + \nu + \bar{\nu}$$

At Earth $6.2 \times 10^6\ \nu\bar{\nu}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

Average energy 2.5 keV

Set by thermal energies in solar core

Thermal gravitons

Bremsstrahlung, ...

$$e + p \rightarrow p + e + \mathrm{graviton}$$

$L_{\mathrm{graviton}} \simeq 10^{-19}\ L_\odot \simeq 40\ \mathrm{MW}$

Undetectable

Thermal Axions, ALPs, Dark Photons, ...

Various thermal processes

L_a depends on coupling strength

Allows for axion detection?

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

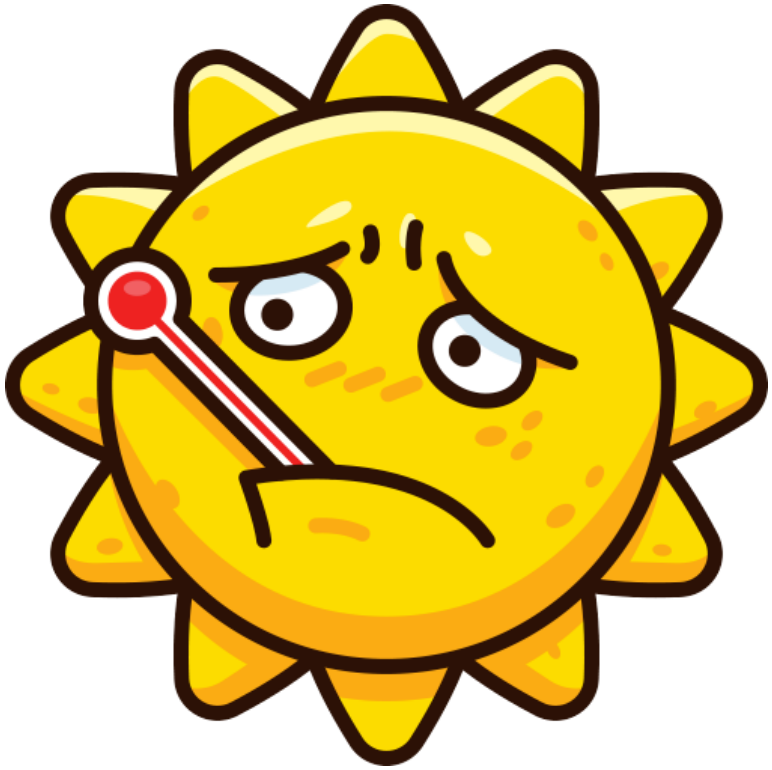
$$\langle E_{\rm grav}\rangle = -\frac{3}{2}\frac{G_N M_{\rm sun} m_p}{R_{\rm sun}} = -3.2\ {\rm keV}$$

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

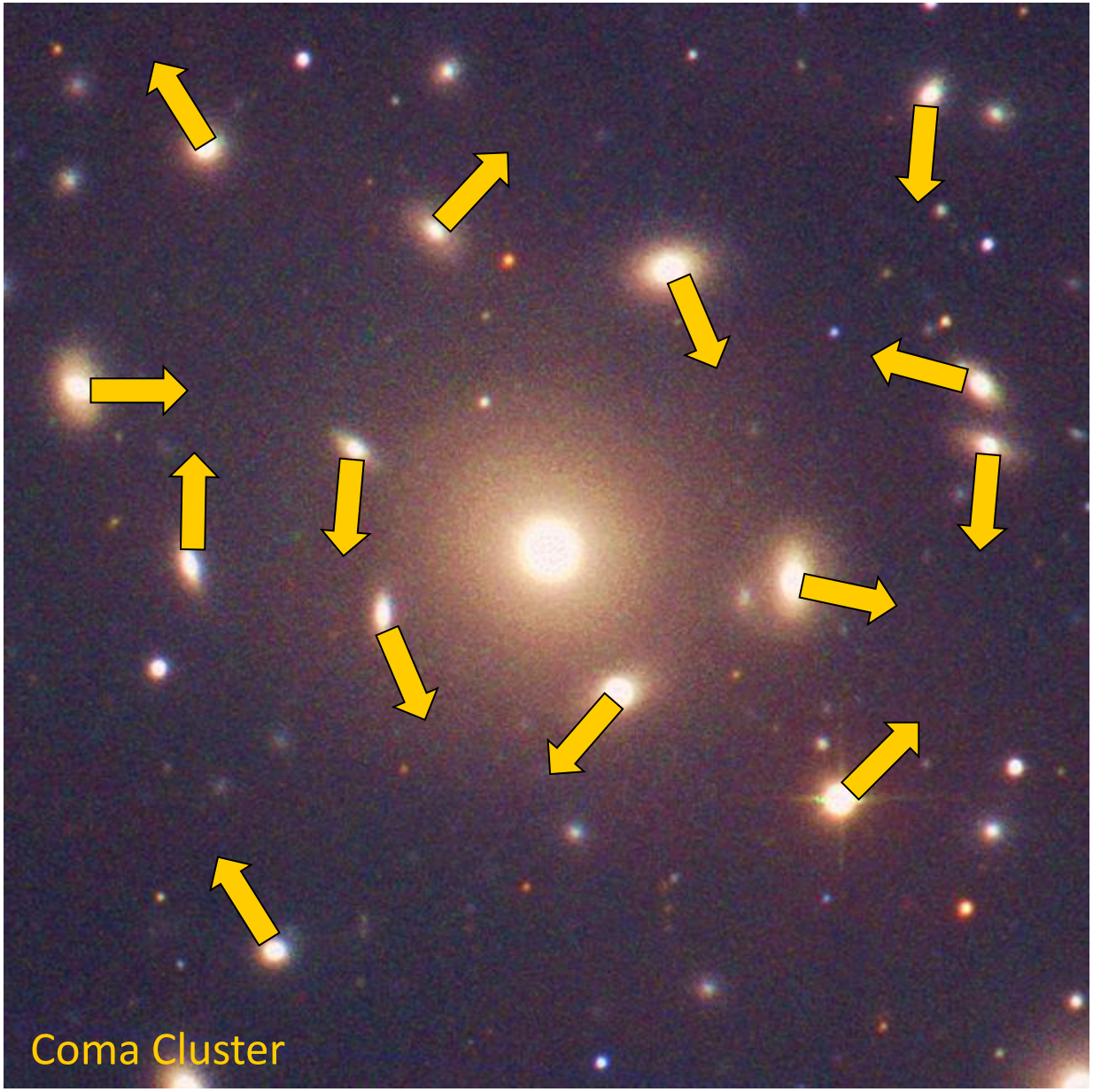
$T = 1.1\ {\rm keV}$



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

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

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

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

Velocity dispersion from Doppler shifts and geometric size

↓

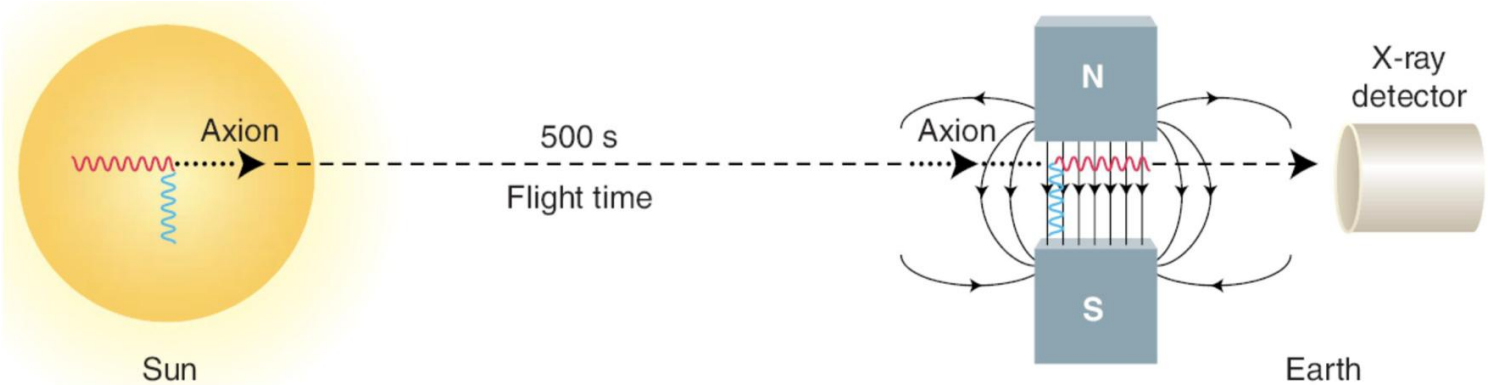
Total Mass

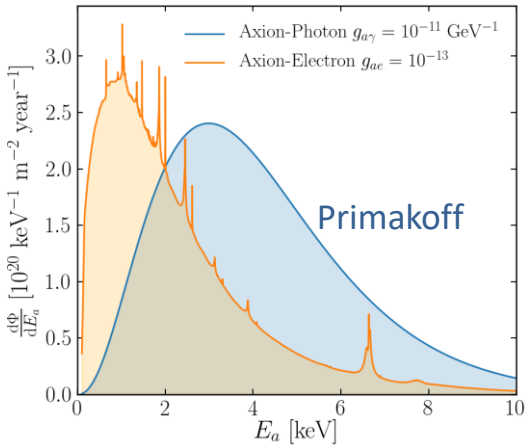
VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

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/

PHYSICAL REVIEW D VOLUME 18, NUMBER 6 15 SEPTEMBER 1978

Astrophysical bounds on the masses of axions and Higgs particles

Rocky Kolb's PhD work

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

(Received 27 April 1978)

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

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

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

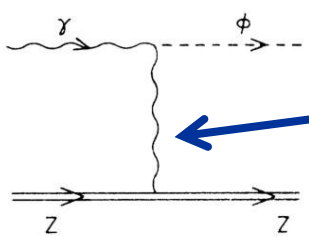


FIG. 2. $\gamma + Z \to \phi + Z$ via the Primakoff process.

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

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

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

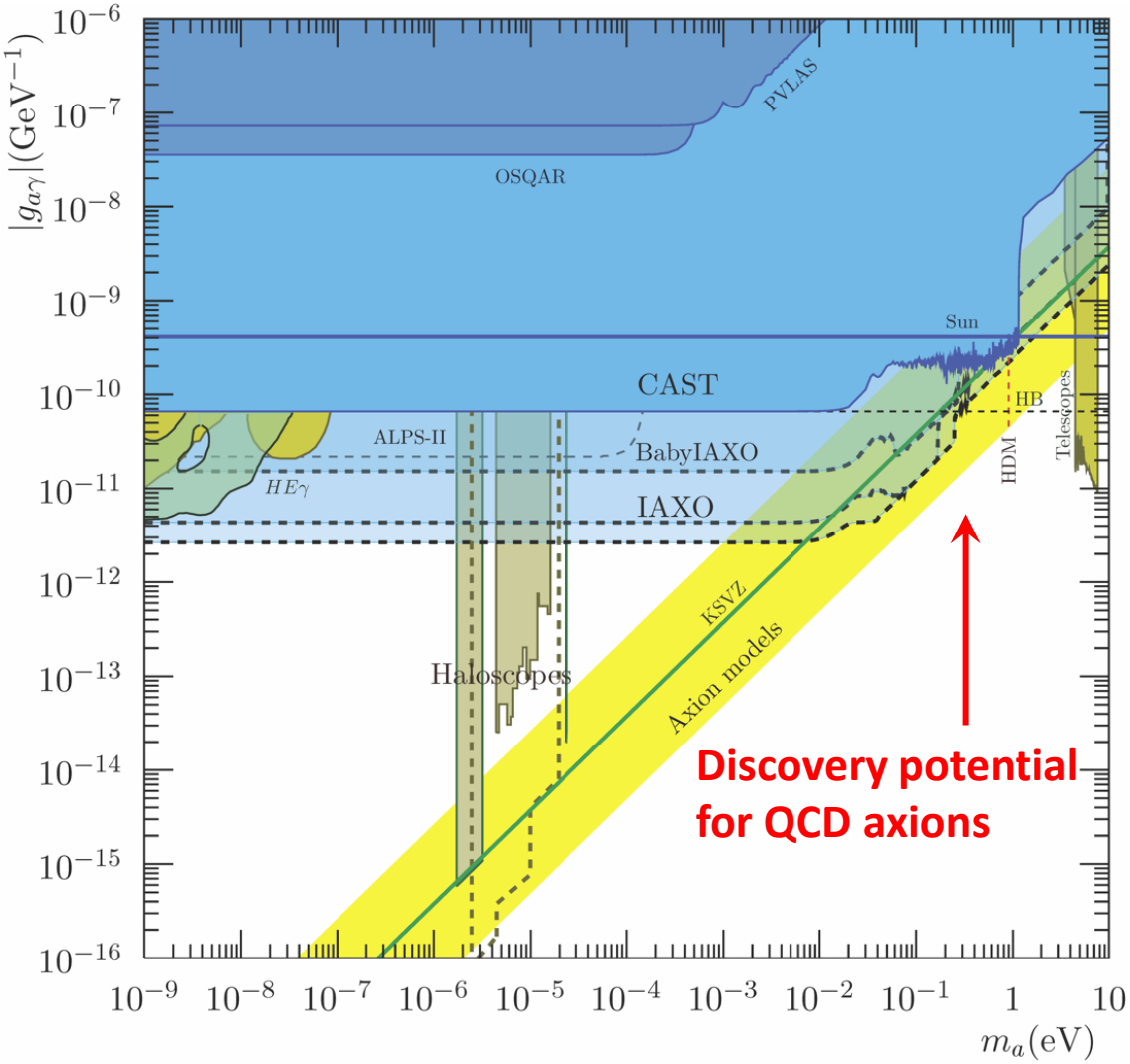
CAST Collaboration [2406.16840]

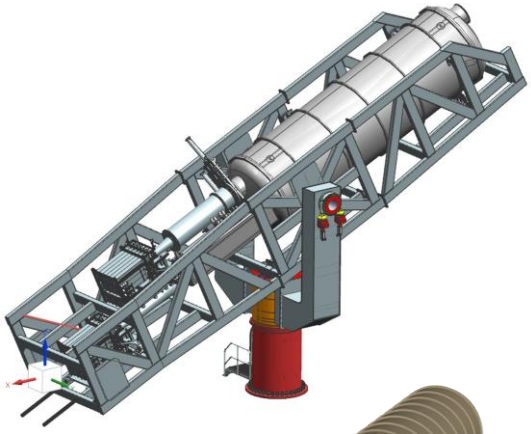
$G_{a\gamma\gamma} < 0.58 \times 10^{-10}\ \mathrm{GeV}^{-1}$

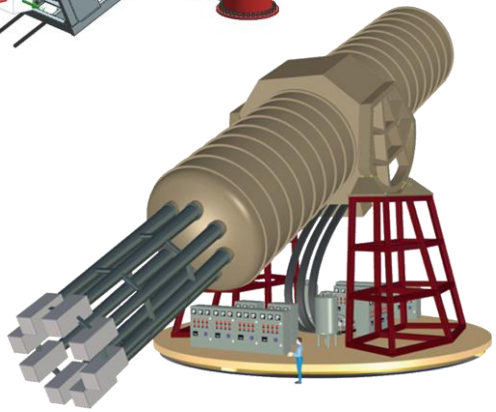
CAST Movie on YouTube

https://youtu.be/XY2lFDXz8aQ

(Baby) IAXO Sensitivity Forecast

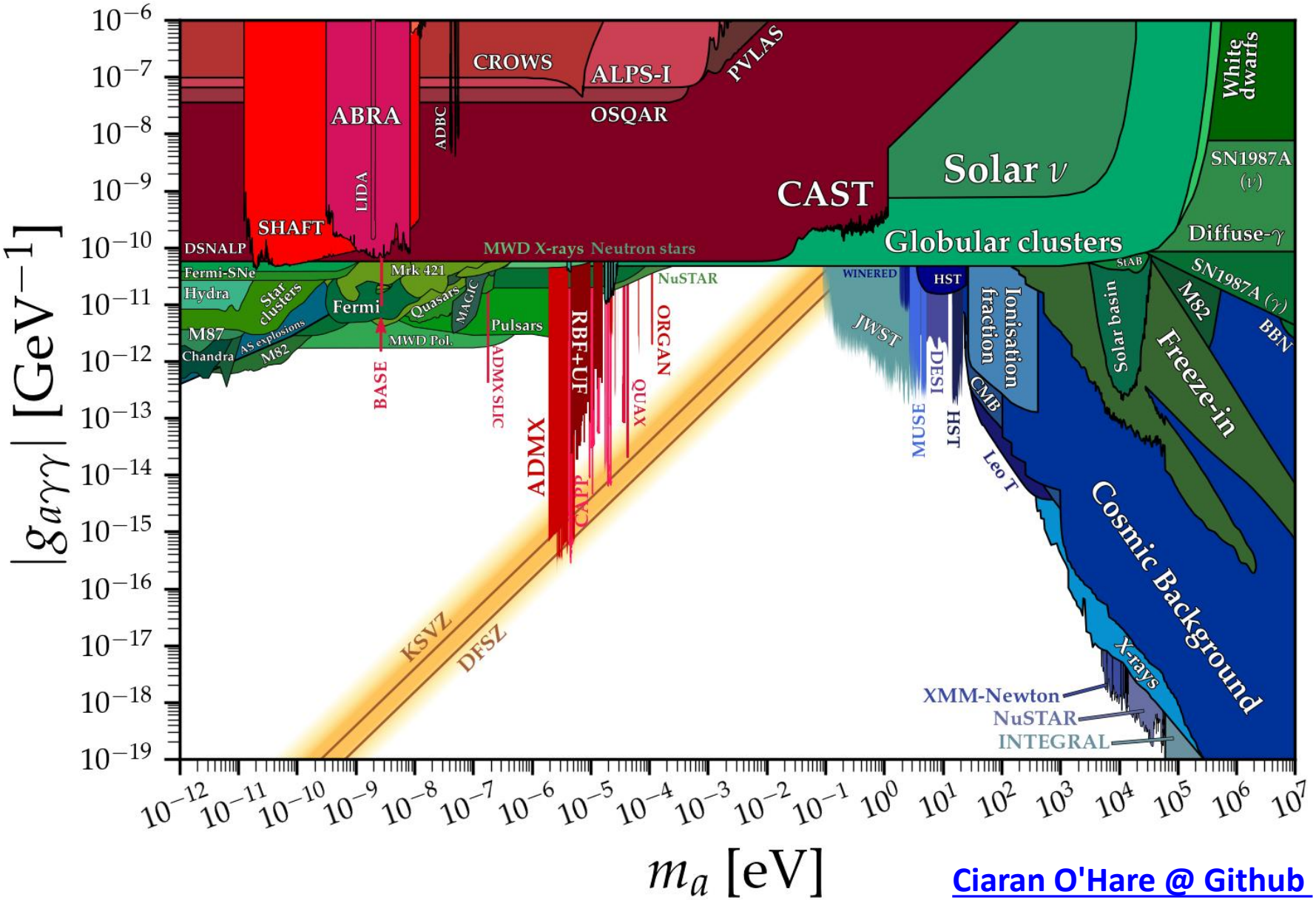




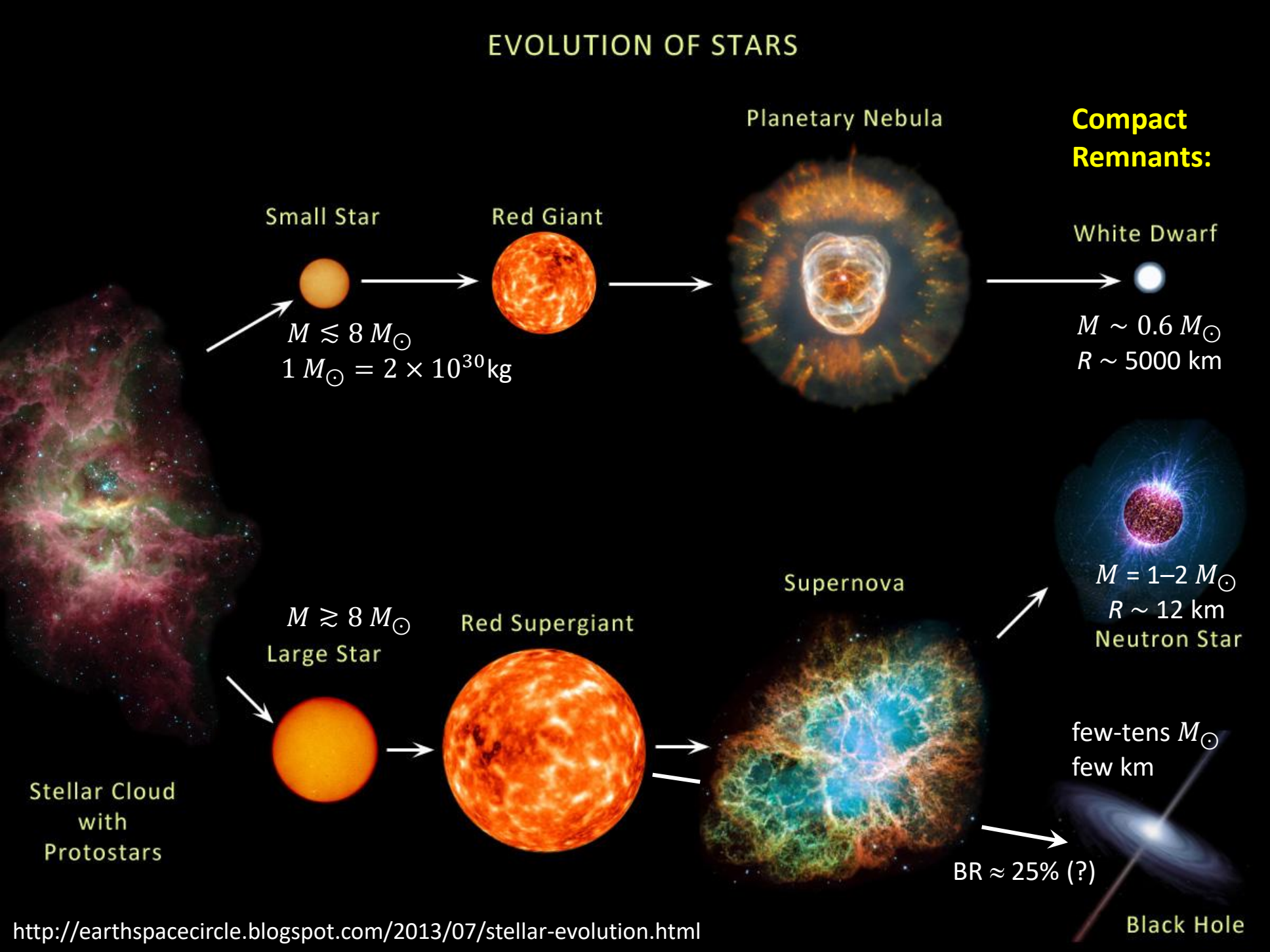


Physics potential of the International Axion Observatory (IAXO)
JCAP 1906 (2019) 047, arXiv:1904.09155

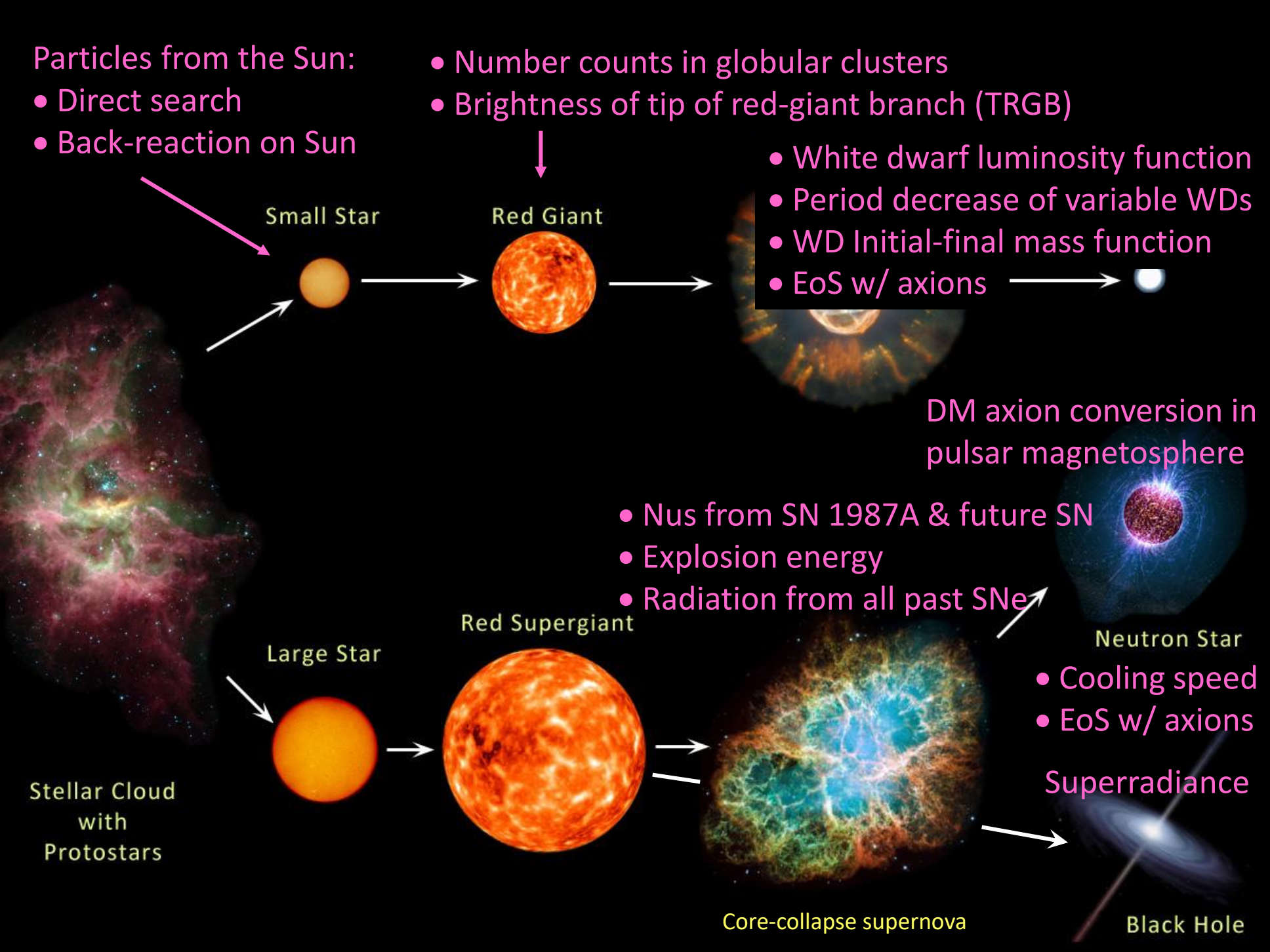
Grand Unified ALP Scape



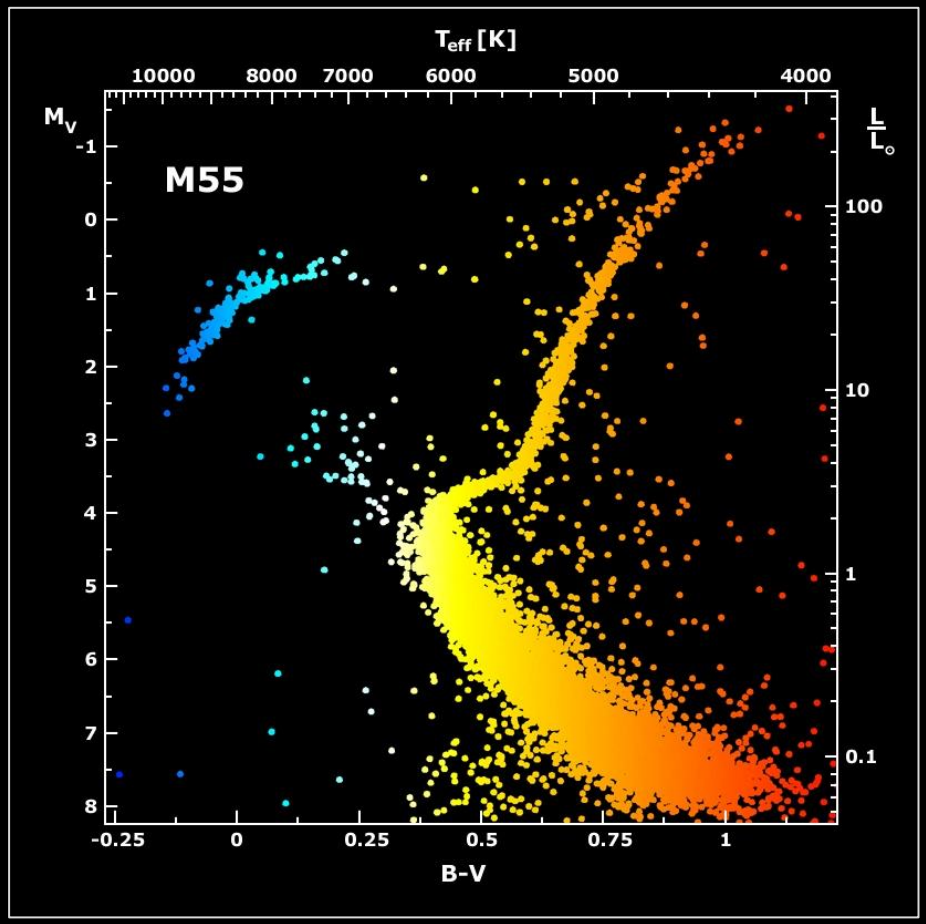
Ciaran O'Hare @ Github



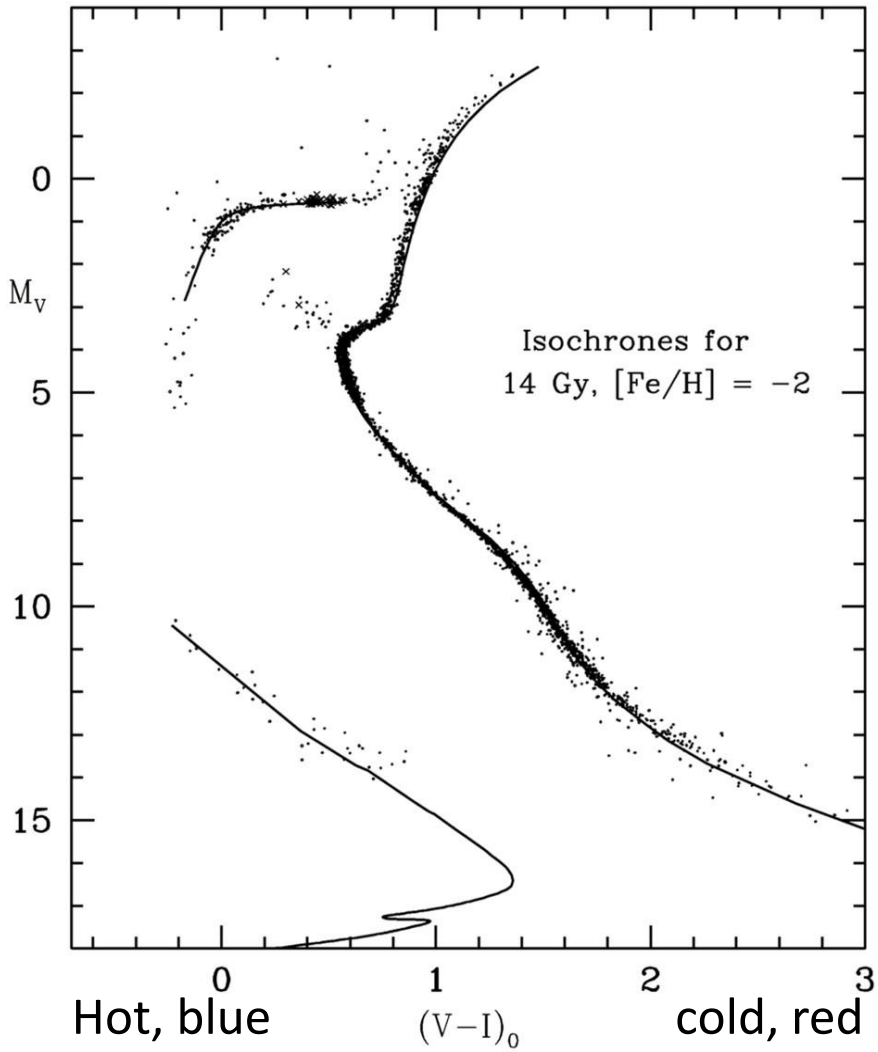
http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html


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

Galactic Globular Cluster M55

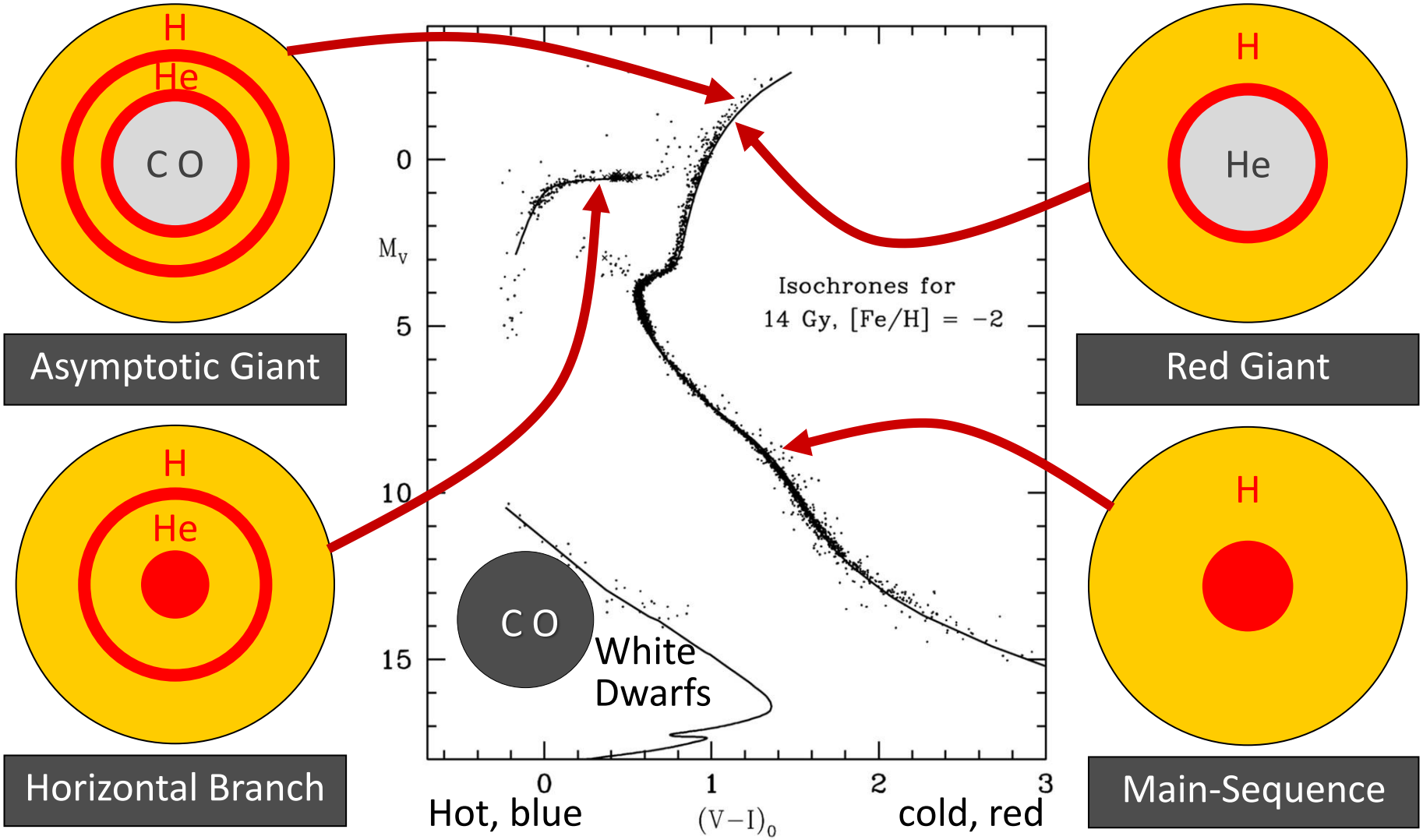


Color-Magnitude Diagram for Globular Clusters



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

Color-Magnitude Diagram for Globular Clusters



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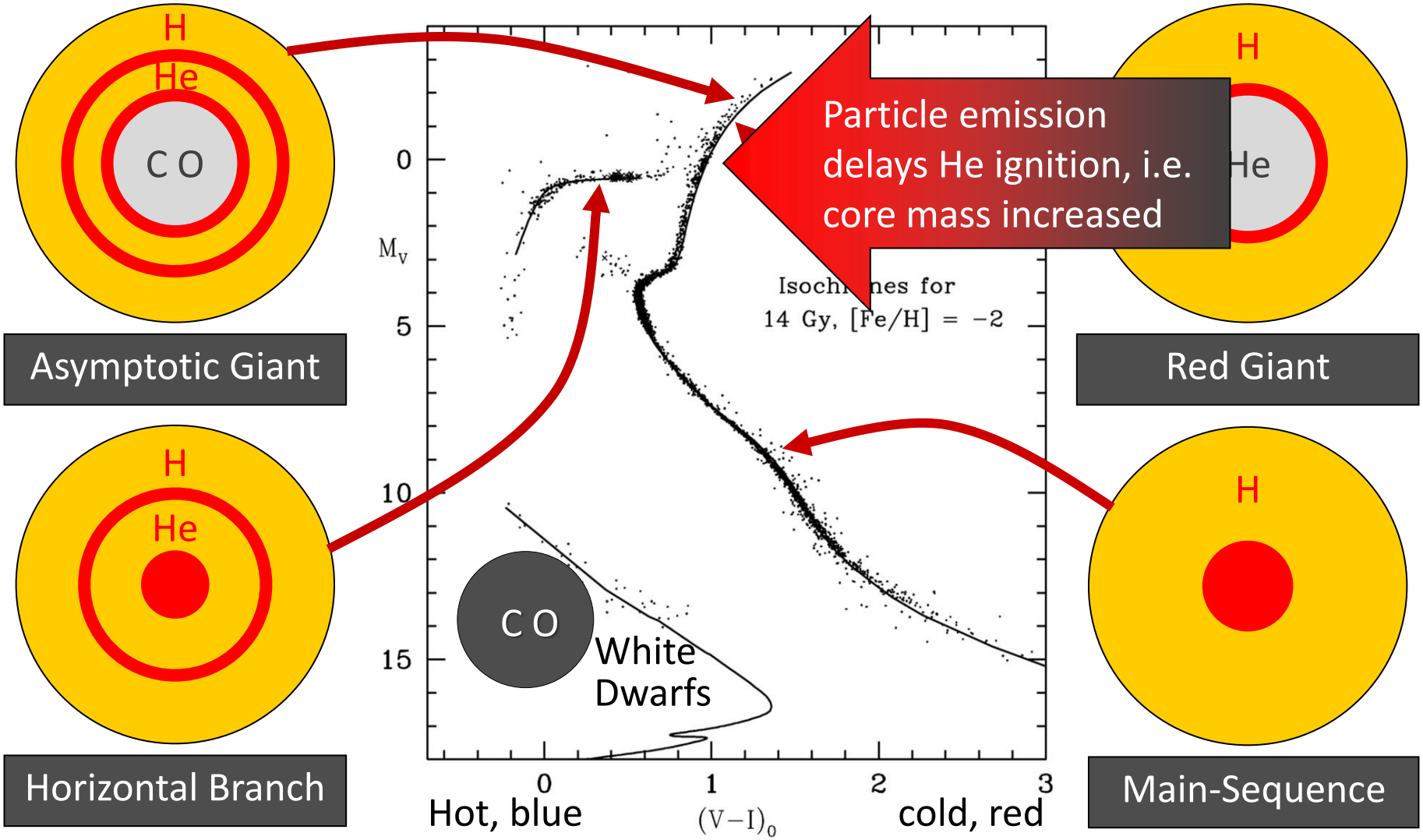
Color-Magnitude Diagram for Globular Clusters

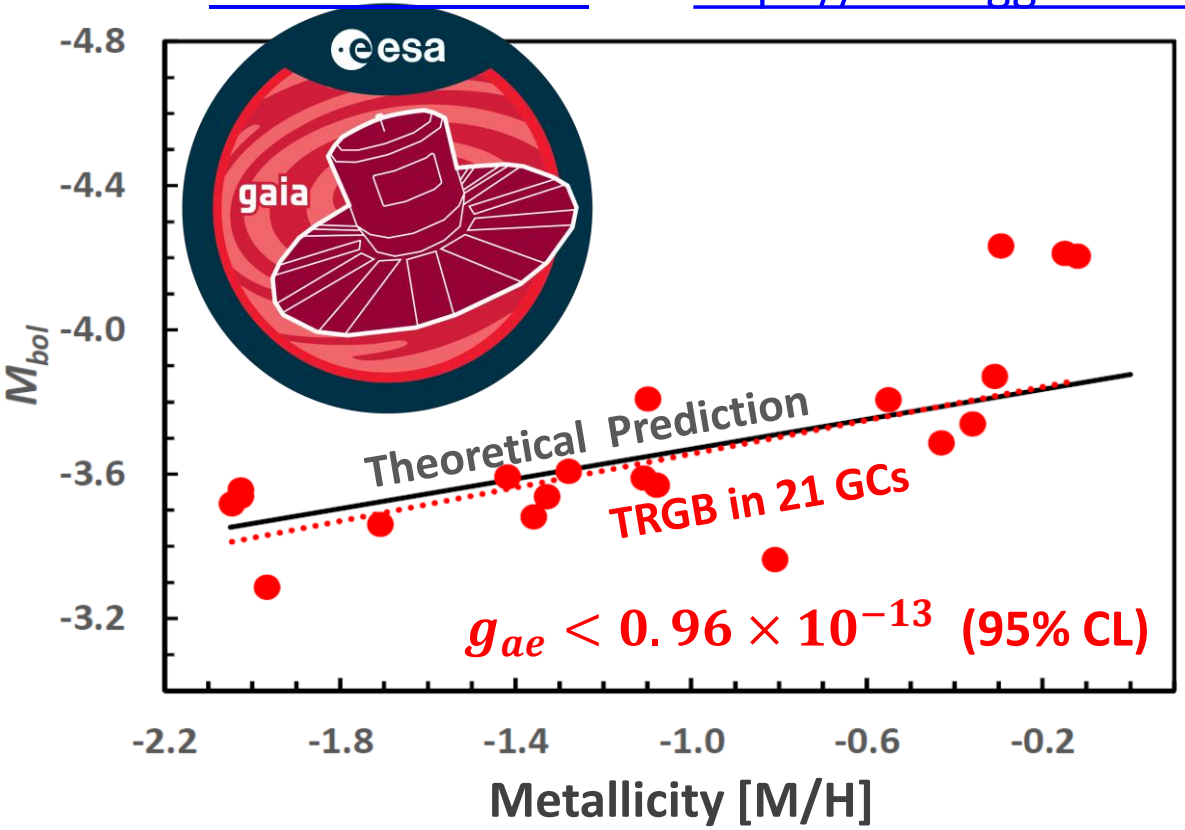


Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

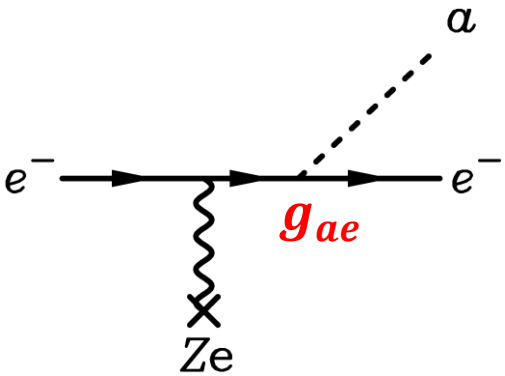
TRGB in 46 Globular Clusters [Cerny+ 2012.09701]

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

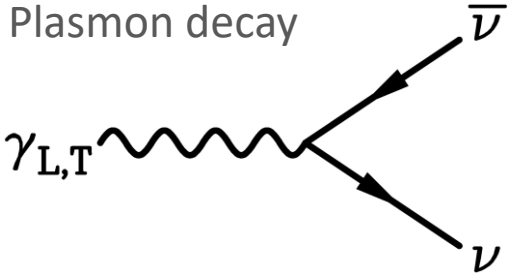


Bremsstrahlung emission by degenerate electrons

Estimated bound for neutrino dipole moments

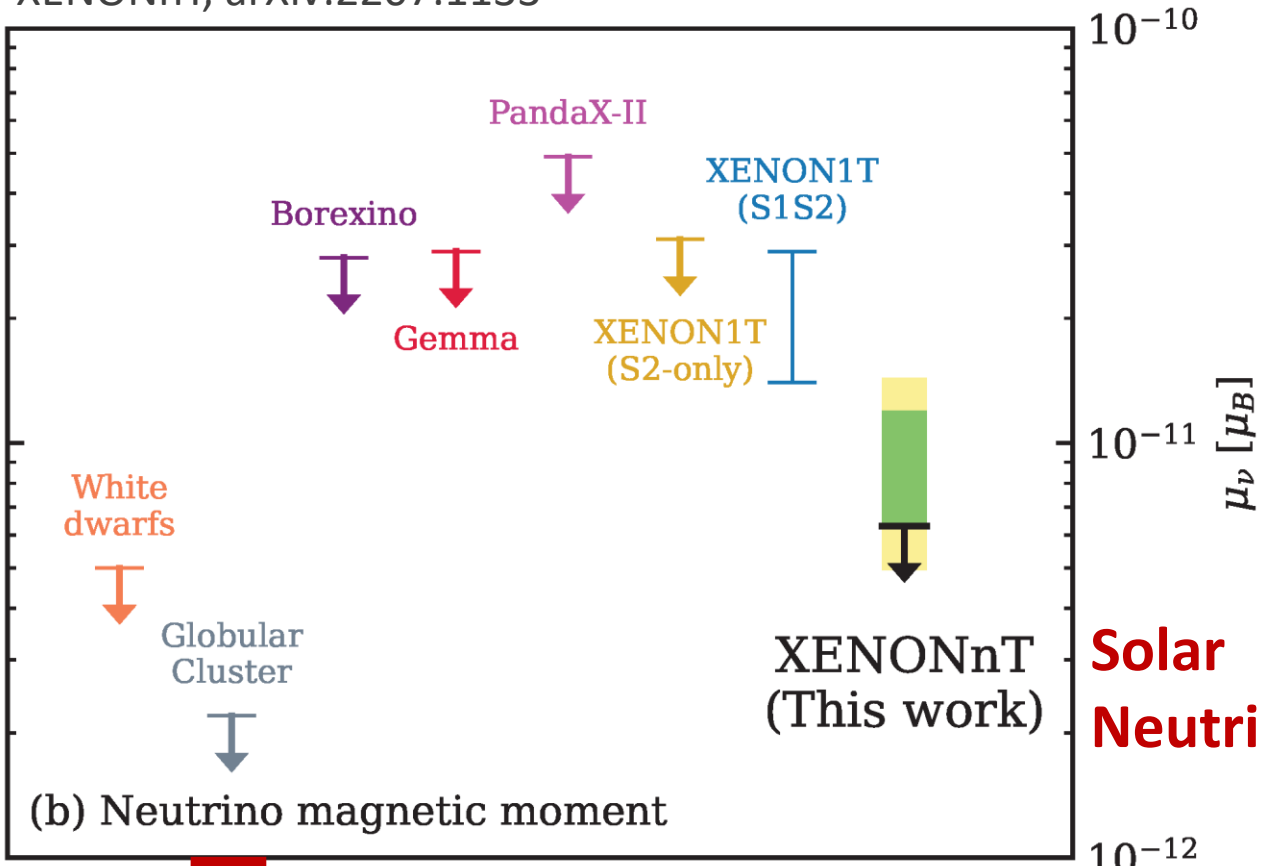
$$\sqrt{\sum_i |\mu_i|^2} < 0.92 \times 10^{-12} \mu_B \text{ (95\% CL)}$$

Plasmon decay

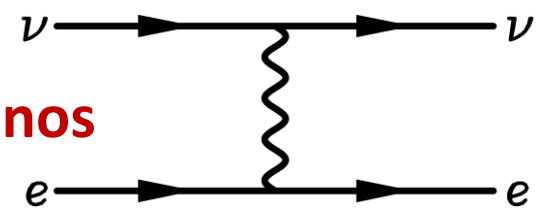


Bounds on neutrino dipole moments

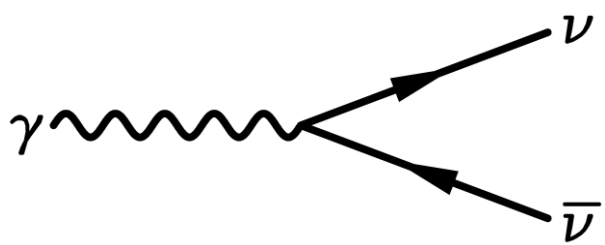
XENONnT, arXiv:2207.1133



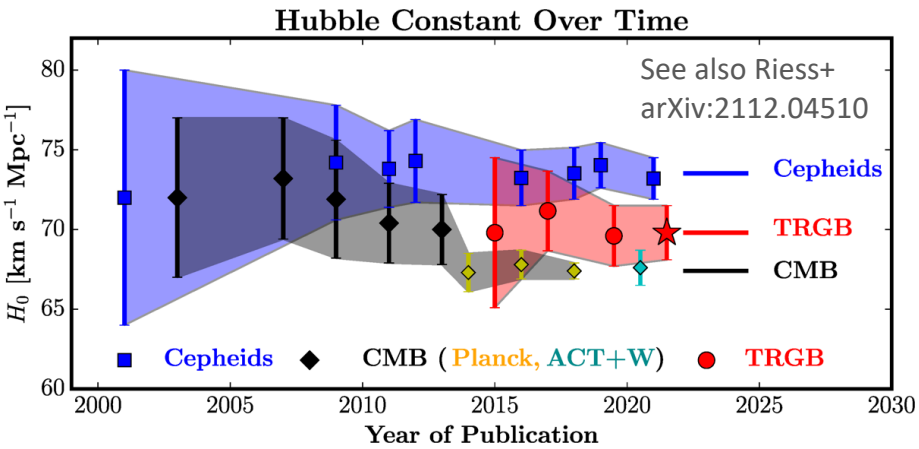
Solar Neutrinos

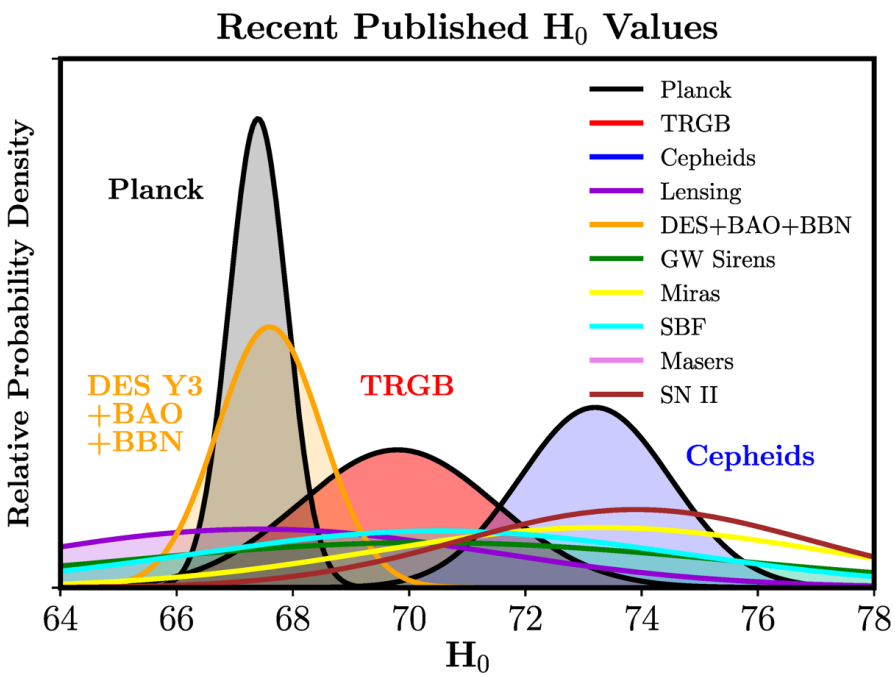


Latest Globular Cluster

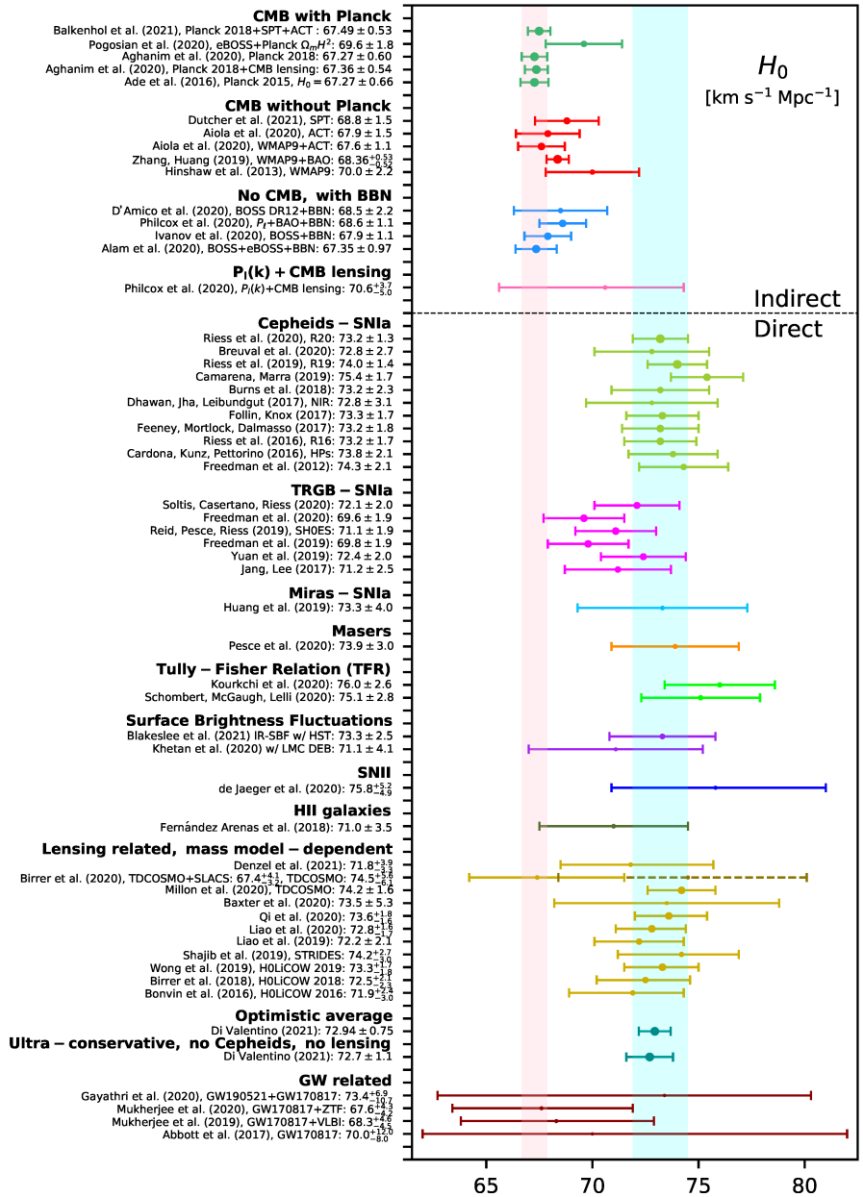


Hubble Tension





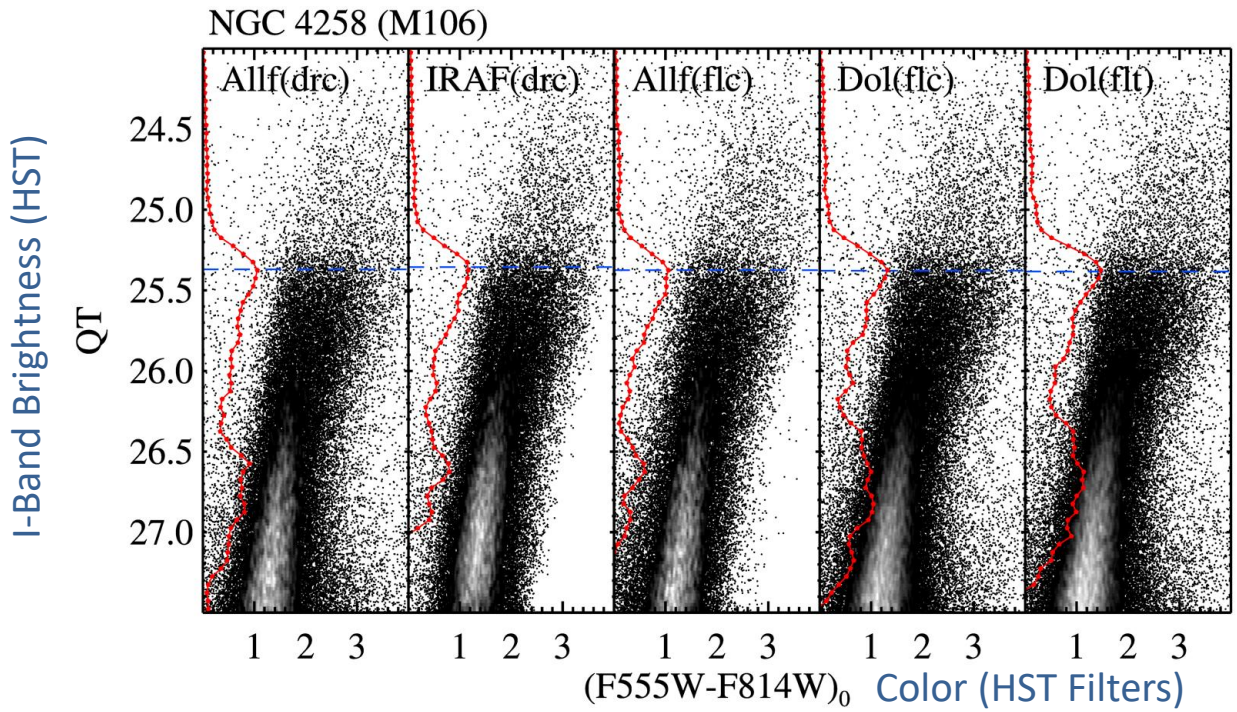
Freedman ApJ 919 (2021) 16 [2106.15656]



Di Valentino+ arXiv:2103.01183

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

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



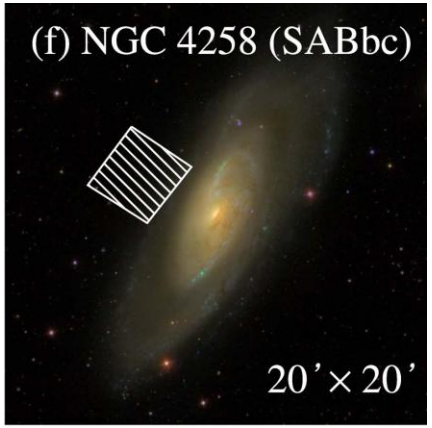


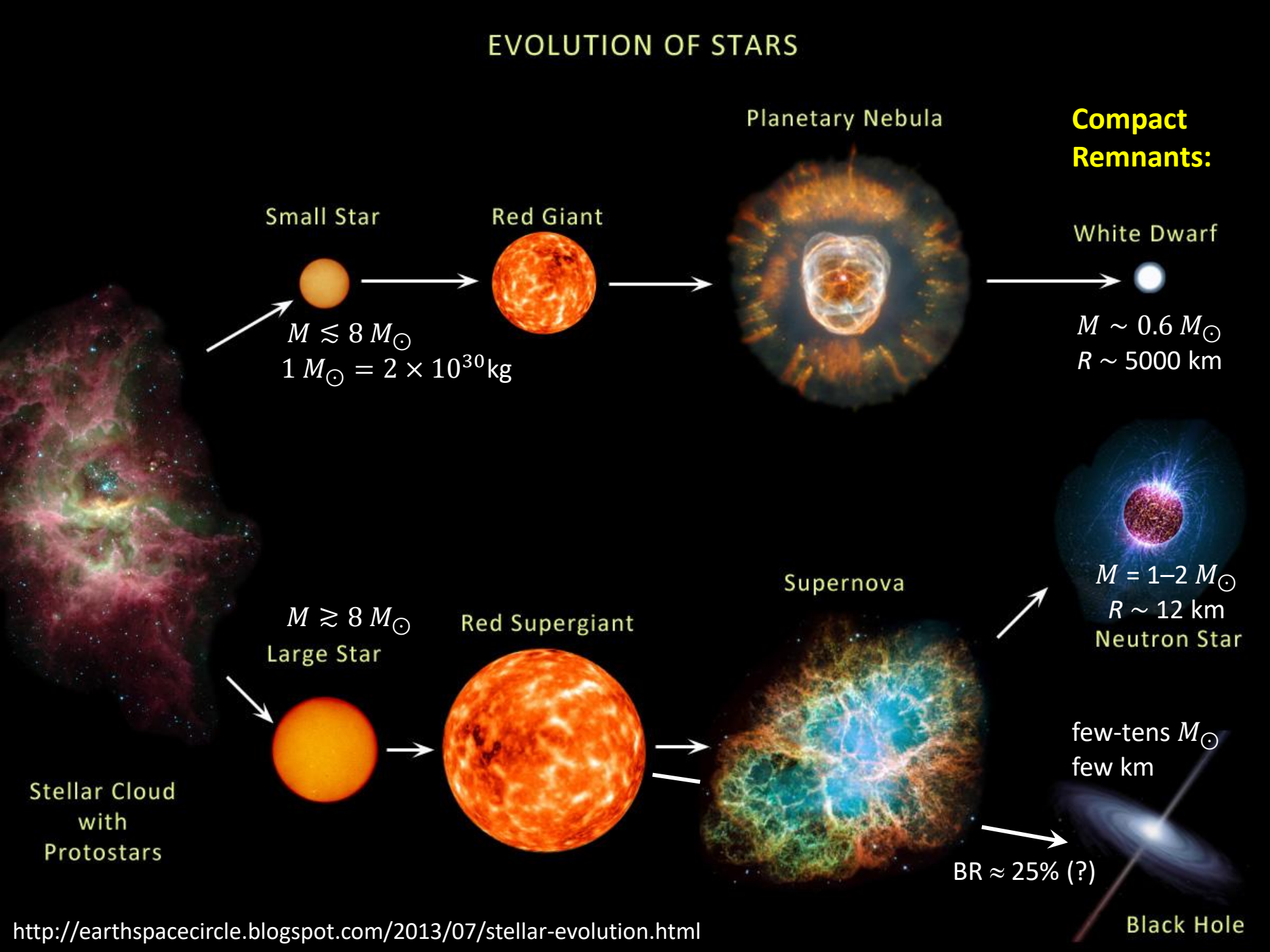
Figure 7. $QT - (F555W - F814W)_0$ CMDs of NGC 4258 from five different reduction methods : ALLFRAME on drc, IRAF/DAOPHOT on drc, ALLFRAME on flc, DOLPHOT on flc, and DOLPHOT on flt (from left to right). Edge detection responses are shown by the solid lines. Note that the estimated TRGB magnitudes (dashed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

NGC 4258 hosts a water megamaser

→ Quasi-geometric distance determination

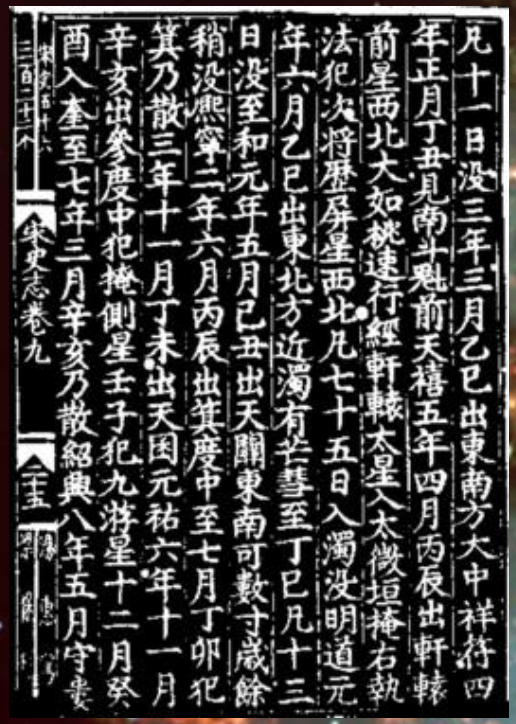
→ Among the best absolute TRGB calibrations

→ One rung in cosmic distance ladder



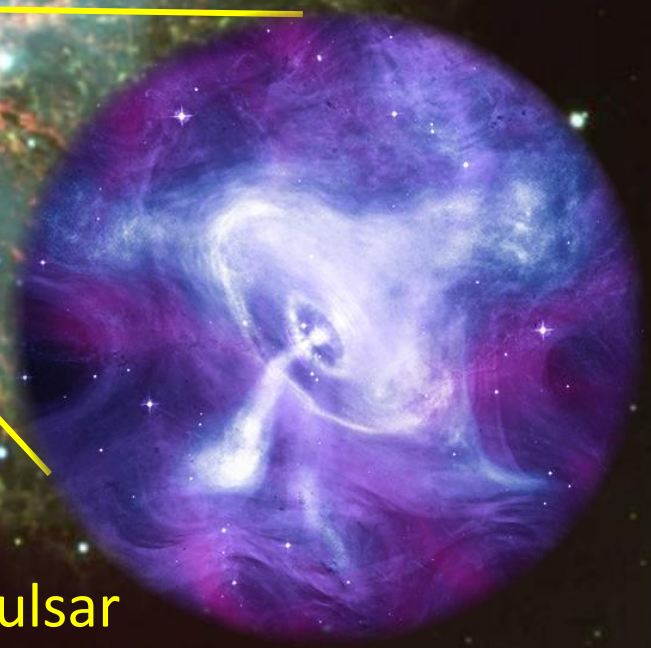
http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html

Crab Nebula – Remnant of SN 1054



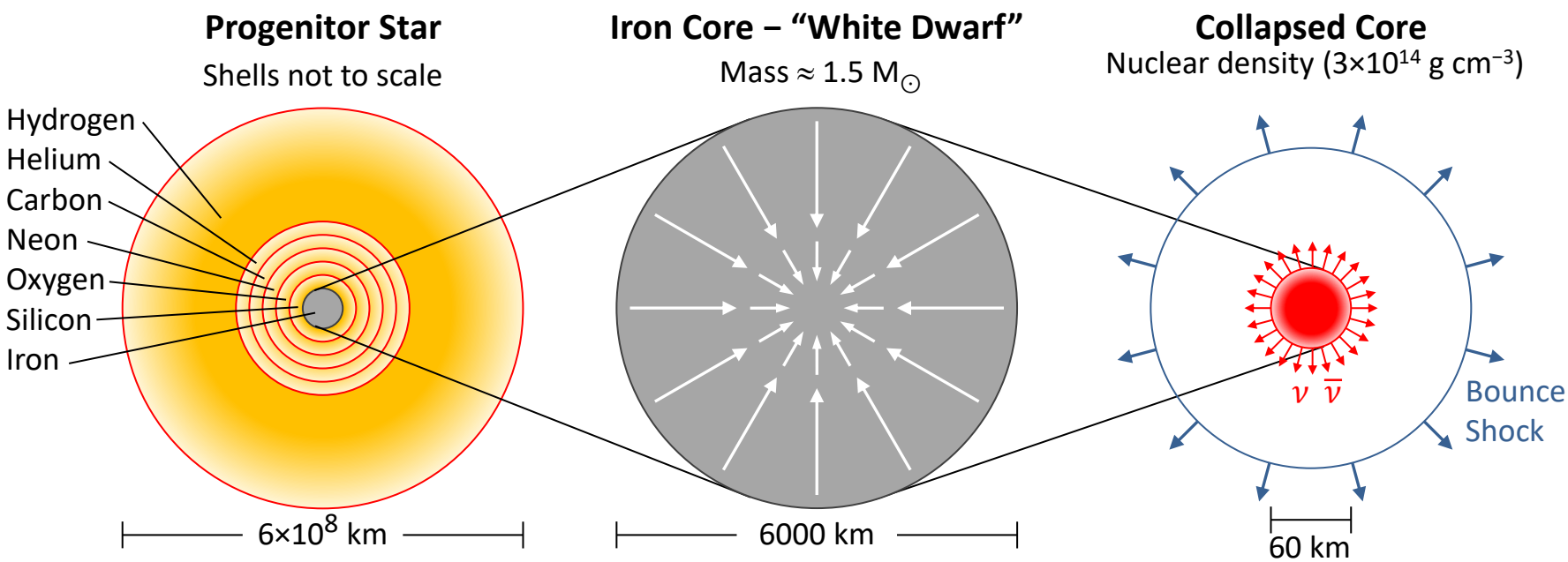
凡十一日沒三年三月乙巳出東南方大中祥符四年正月丁丑見南斗魁前天禧五年四月丙辰出軒轅前星西北大如桃速行經軒轅太星入太微垣掩右執法犯次將歷屏星西北凡七十五日入濁沒明道元年六月乙巳出東北方近濁有芒彗至丁巳凡十三日沒至和元年五月己丑出天關東南可數寸歲餘稍沒熙寧二年六月丙辰出箕度中至七月丁卯犯箕乃散三年十一月丁未出天囷元祐六年十一月辛亥出參度中犯掩側星壬子犯九游星十二月癸酉入奎至七年三月辛亥乃散紹興八年五月守婁

宋史卷五十五 三百二十八 宋史志卷九 三十五



Crab Pulsar
Chandra X-ray composite image

Stellar Collapse and Explosion



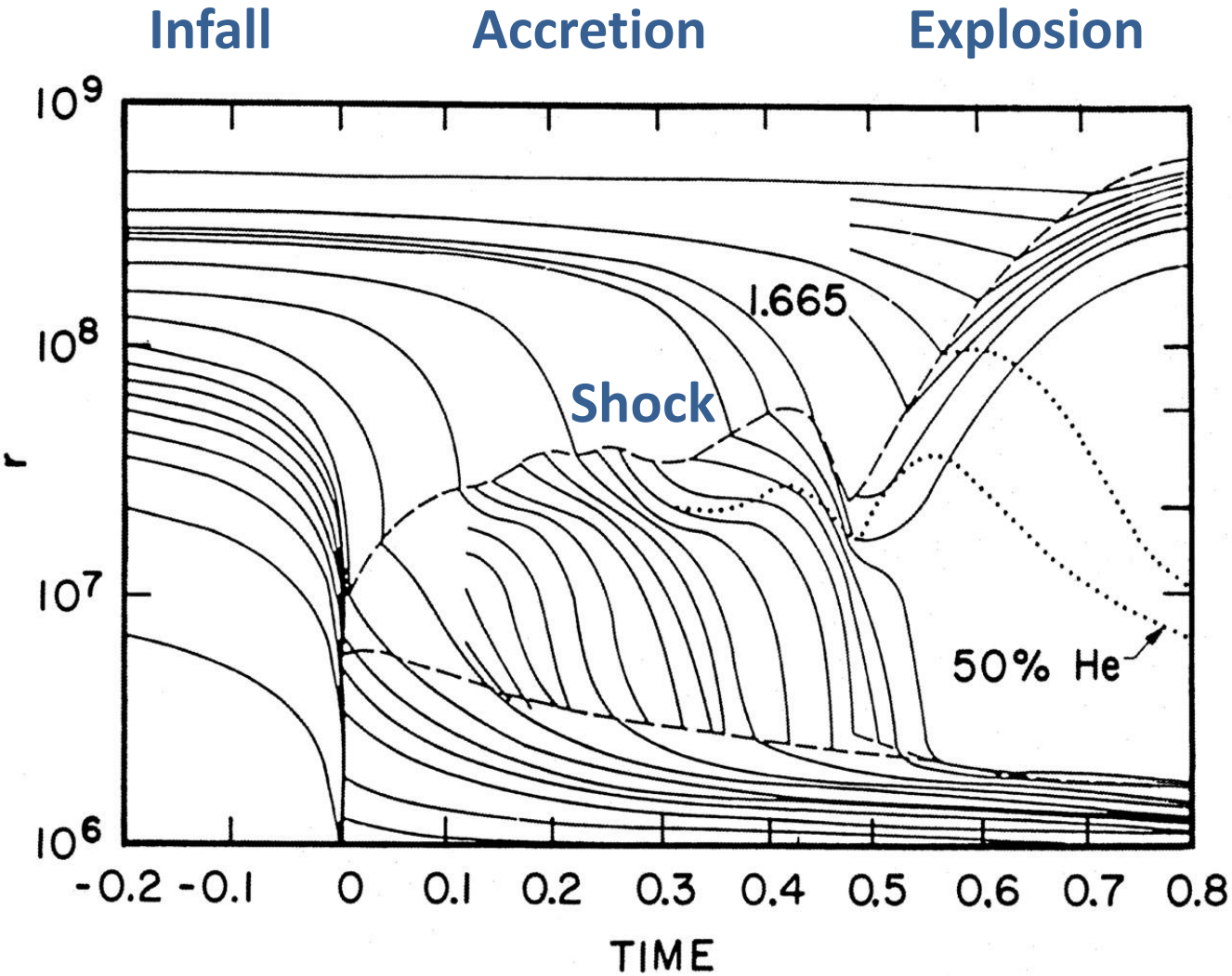
Gravitational binding energy

$$E_b \approx 3 \times 10^{53}\ \text{erg} \approx 15\%\ M_{SUN}\, c^2$$

This shows up as

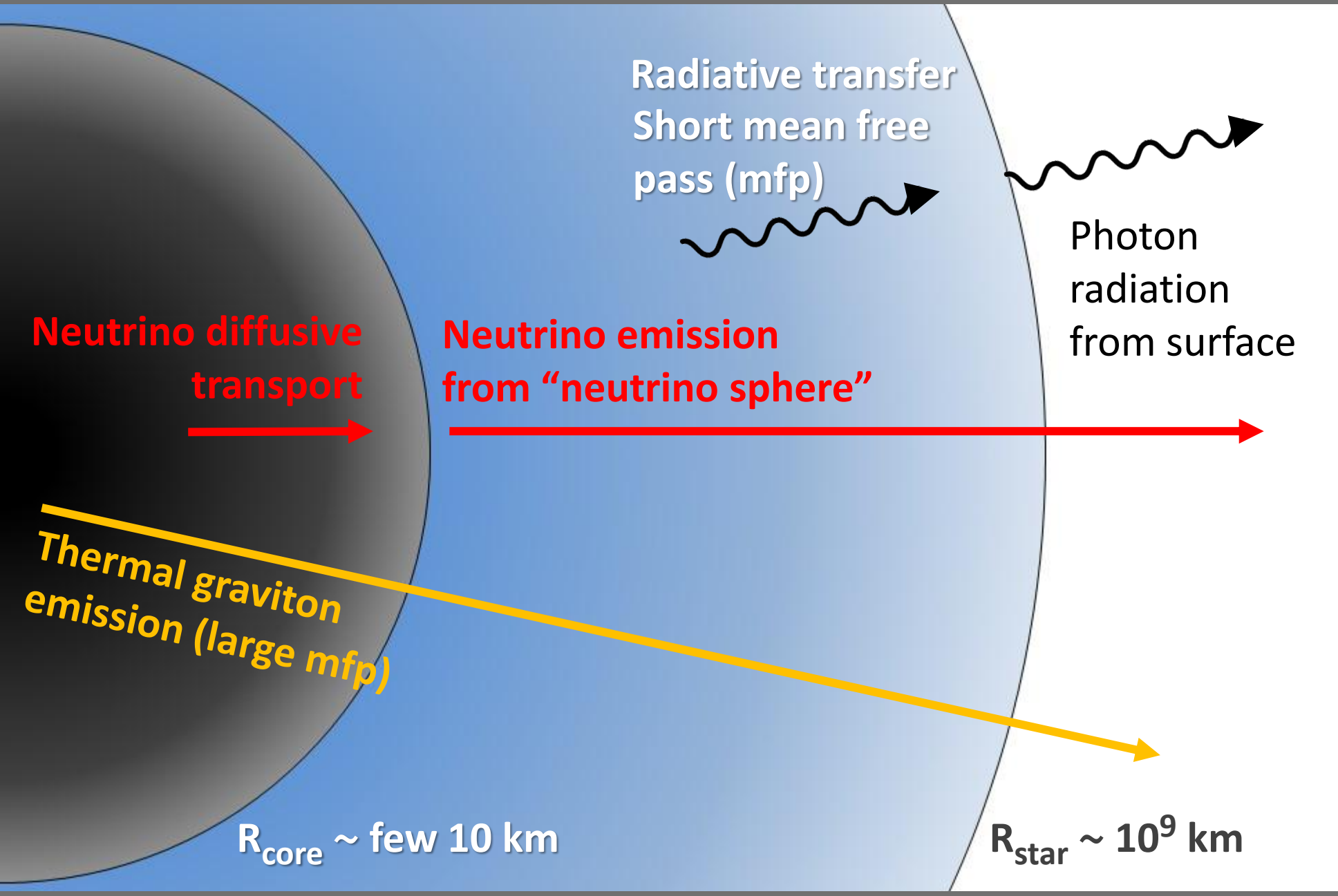
99%	Neutrinos
1%	Kinetic energy of explosion
0.01%	Photons, outshine host galaxy

Delayed (Neutrino-Driven) Explosion

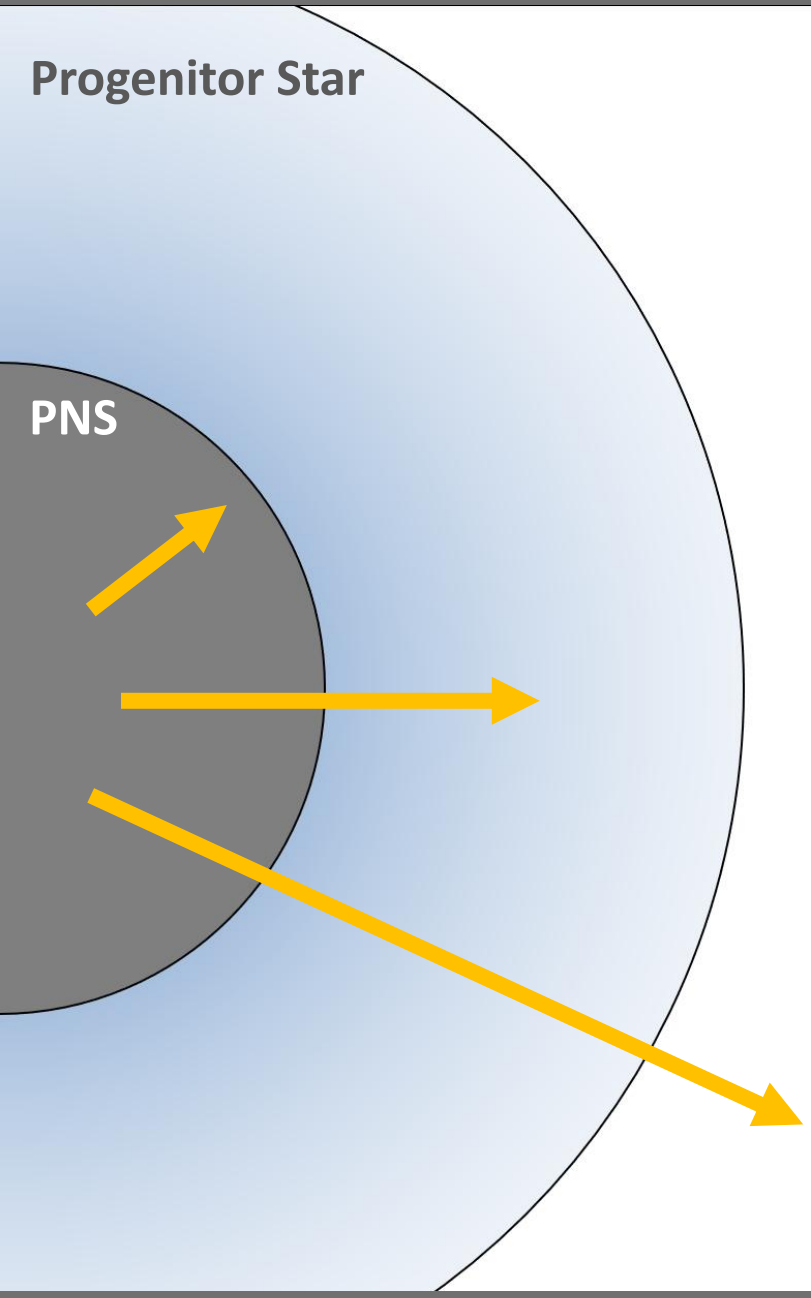


Wilson, Proc. Univ. Illinois Meeting on Num. Astrophys. (1982)
Bethe & Wilson, ApJ 295 (1985) 14

Roles of Different Forms of Radiation



Impact of New Particles



Energy and lepton transport within PNS

Energy transport beyond neutrino sphere (directly or decay products)

- **Explosion**
- **Nucleosynthesis**

Detection (direct or decay products)

- **SN 1987A, next nearby SN**
- **Diffuse background from all past SNe**

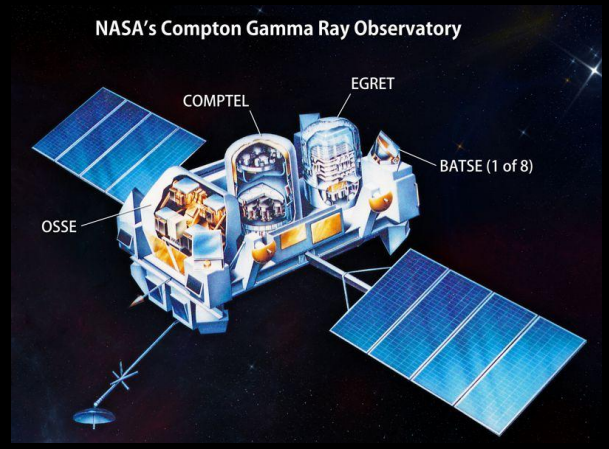
Supernova Bounds on Radiative Particle Decays

Low-E SNe provide best constraints Caputo+ arXiv:2201.09890

Adds to Explosion energy

Collapsed SN core

Progenitor mantle

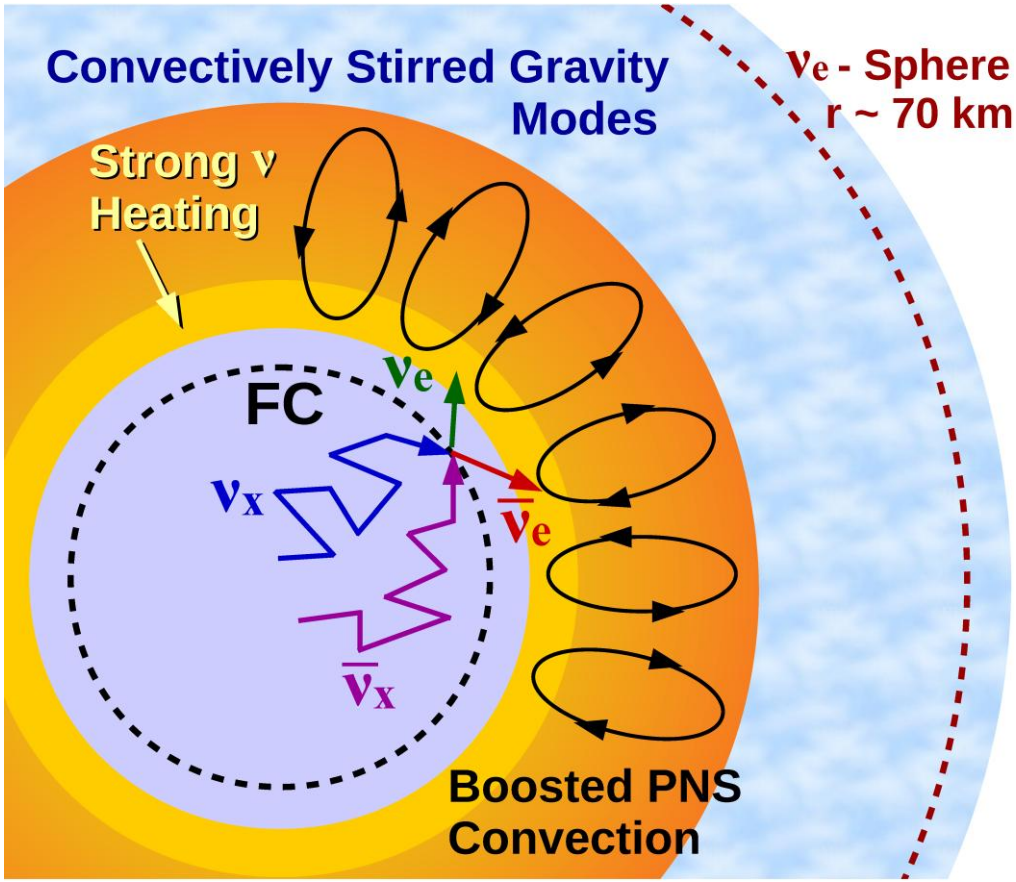


Cosmic gamma ray background from all past supernovae

Solar Maximum Mission

No excess gamma rays @ SN 1987A neutrino burst

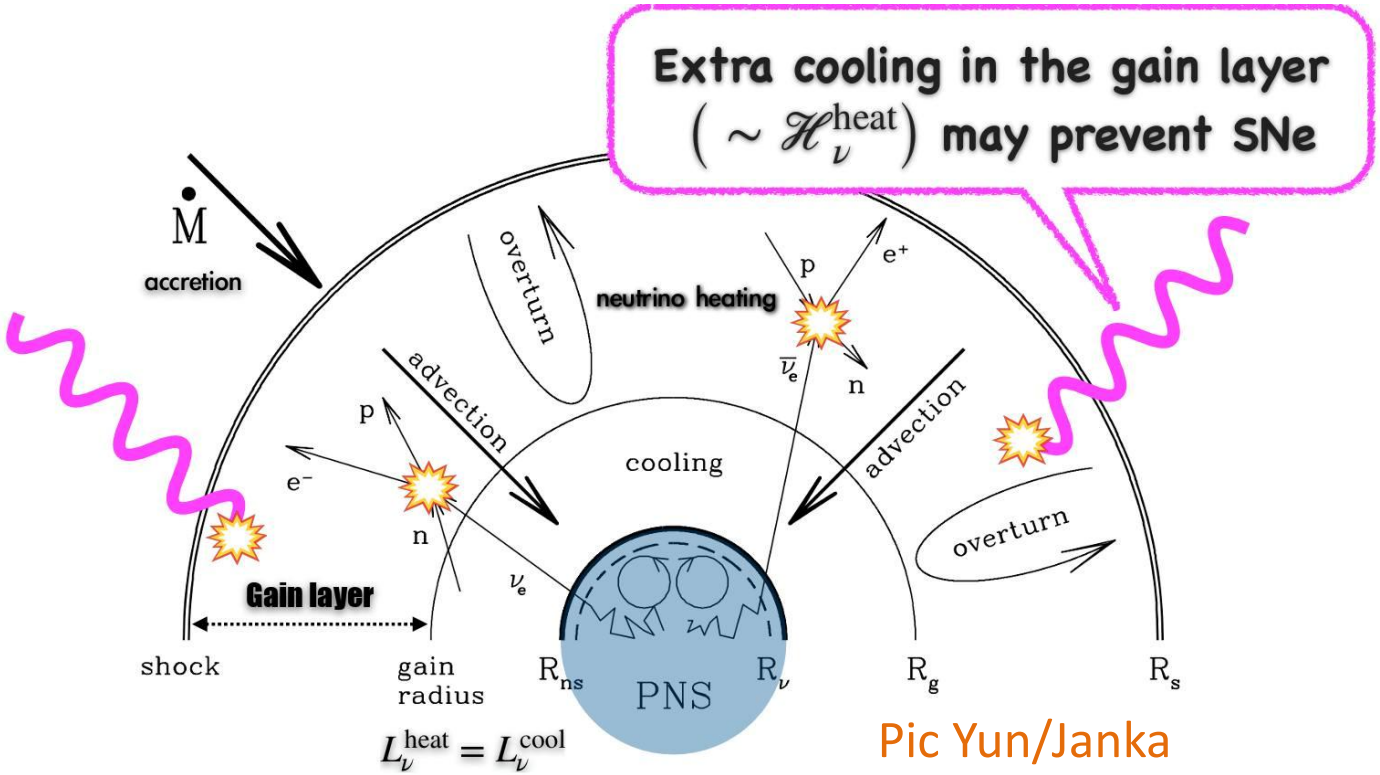
Gravitational-Wave Signatures of New Energy Transfer



- PNS convection stimulated by novel heating at bottom of convection layer
- Causes GW emission during otherwise quiescent phase shortly after core bounce
- Testing BSM forms of energy transfer with GWs from next SN

Ehring, Abbar, Janka, Raffelt, Nakamura & Kotake, arXiv:2412.02750

Cooling the Shock: SN Bounds on Dark Photons



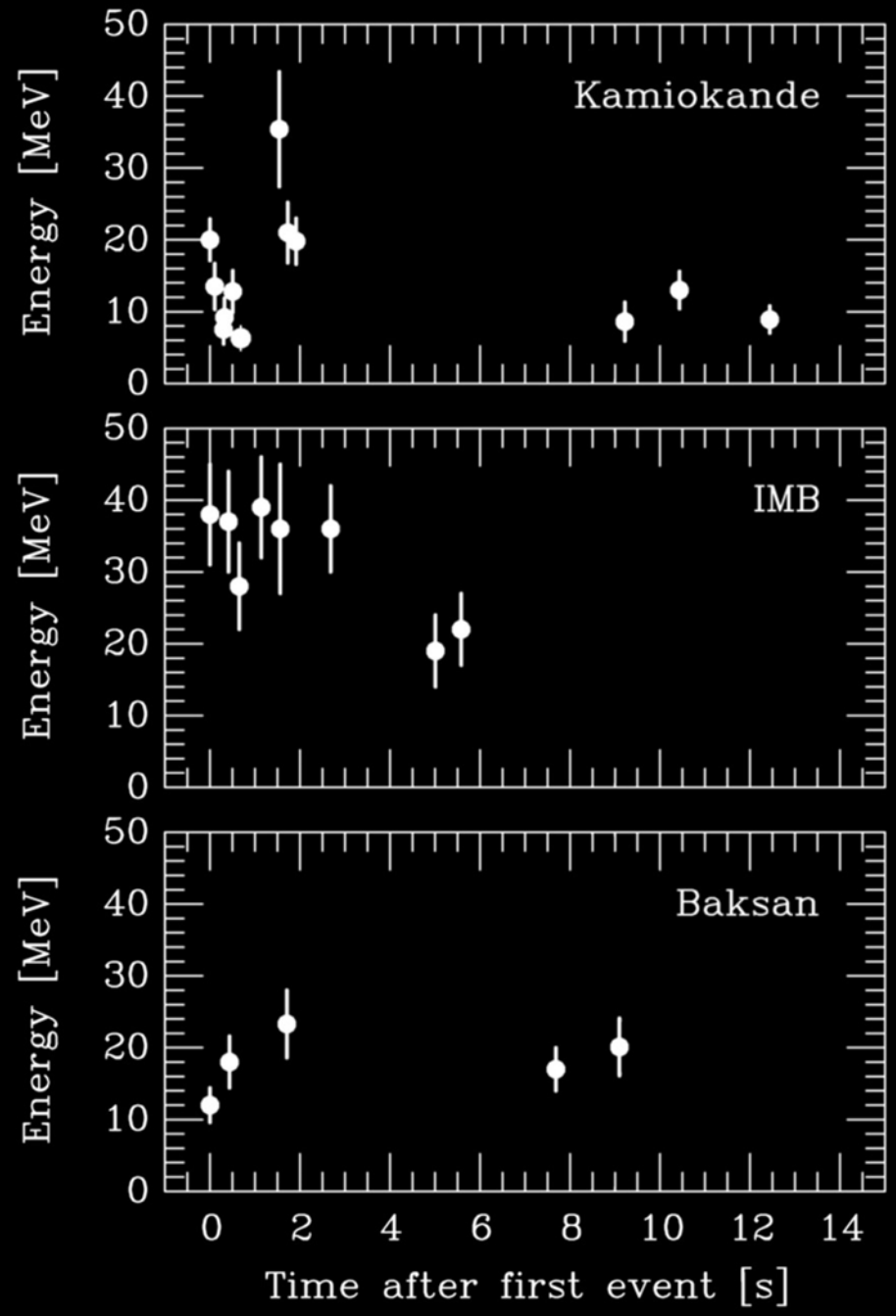
Pic Yun/Janka

- Plasma frequency in “gain layer” 100–400 keV
- Resonant conversion Plasmon → Hidden Photon
- Drains energy from “gain” layer

Caputo, Janka, Raffelt & Yun, PRL, arXiv:2502.01731

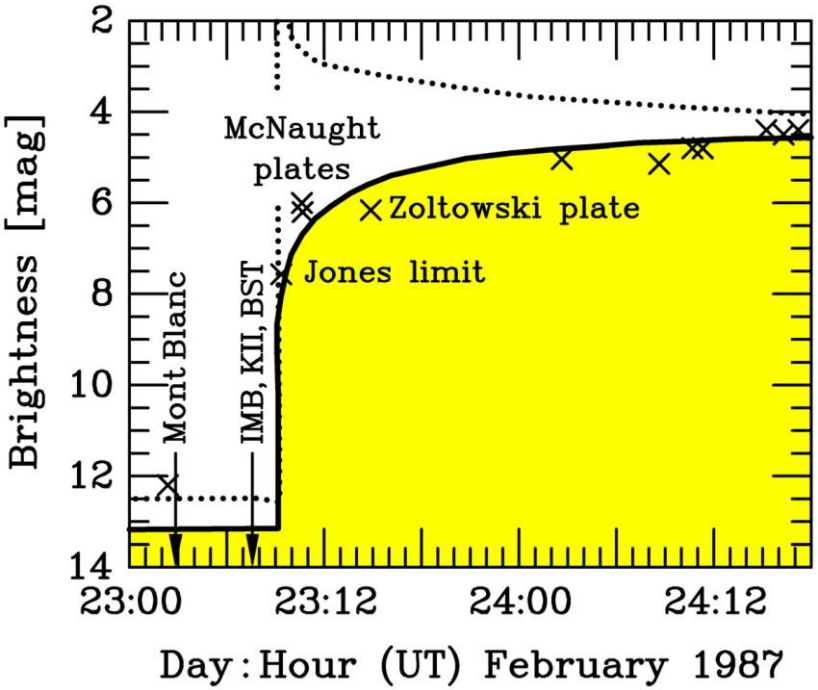
Supernova 1987A

23 February 1987



Do Neutrinos Gravitate?

Early light curve of SN 1987A



- Neutrinos arrived several hours before photons (as expected)
- Transit time for ν and γ same (160.000 yr) within a few hours

Shapiro time delay for particles moving in a gravitational potential

$$\Delta t = -2 \int_A^B dt\, \Phi[r(t)]$$

For trip from LMC to us, depending on galactic model,

$$\Delta t \approx 1\text{–}5 \text{ months}$$

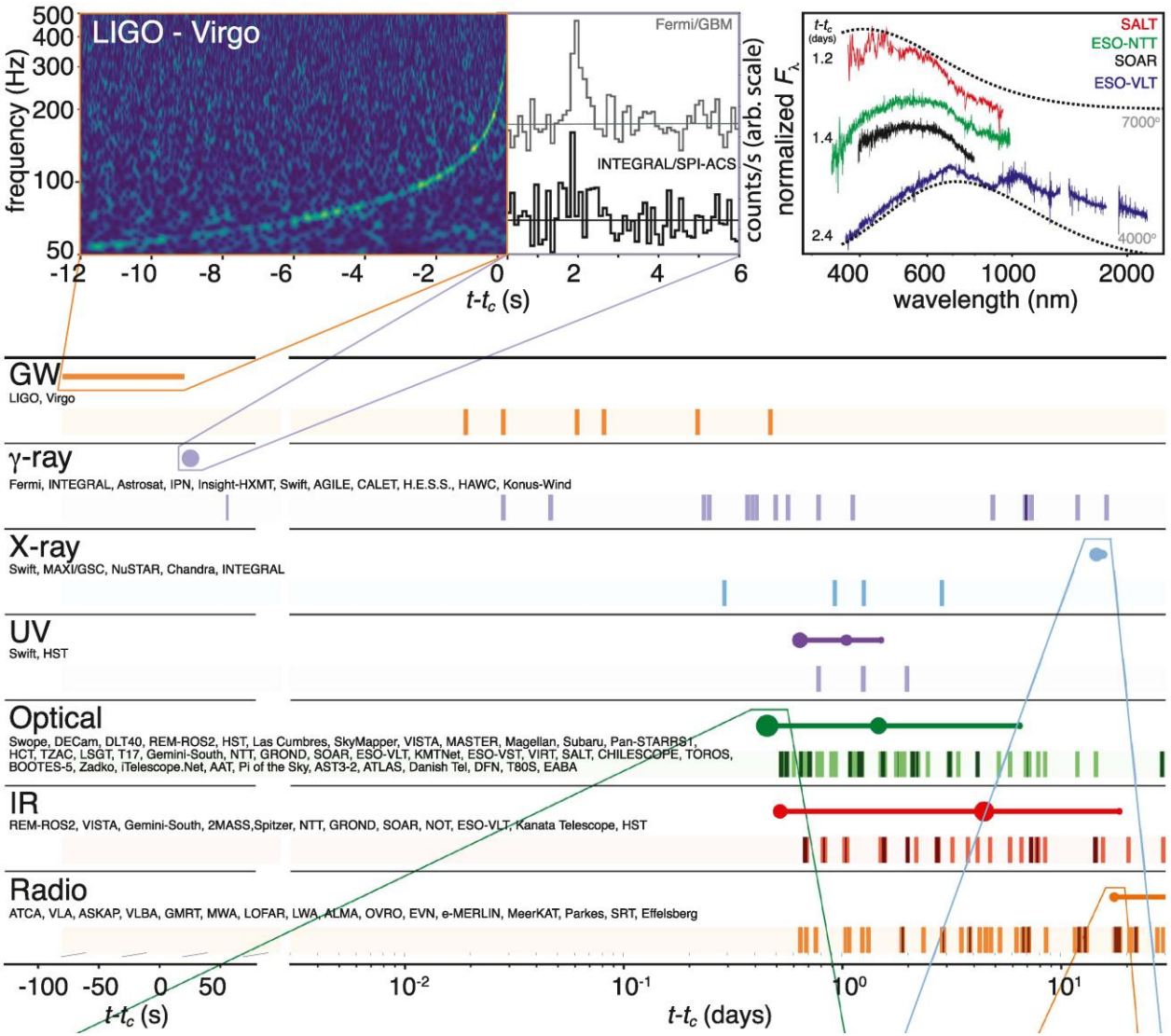
Neutrinos and photons respond to gravity the same to within

$$1\text{–}4 \times 10^{-3}$$

Longo, PRL 60:173, 1988
Krauss & Tremaine, PRL 60:176, 1988

GW vs Gamma-Ray Shapiro Time Delay

ApJ Lett. 848 (2017) L12



NS-NS Merger

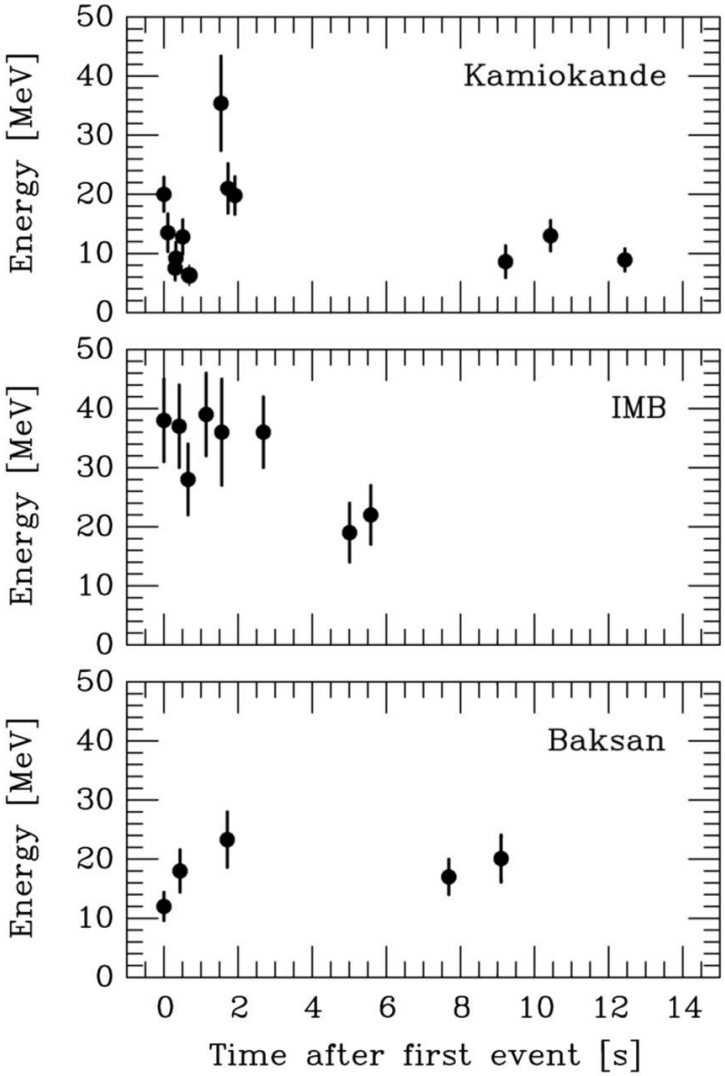
- **GW170817**
- **GRB 170817A**

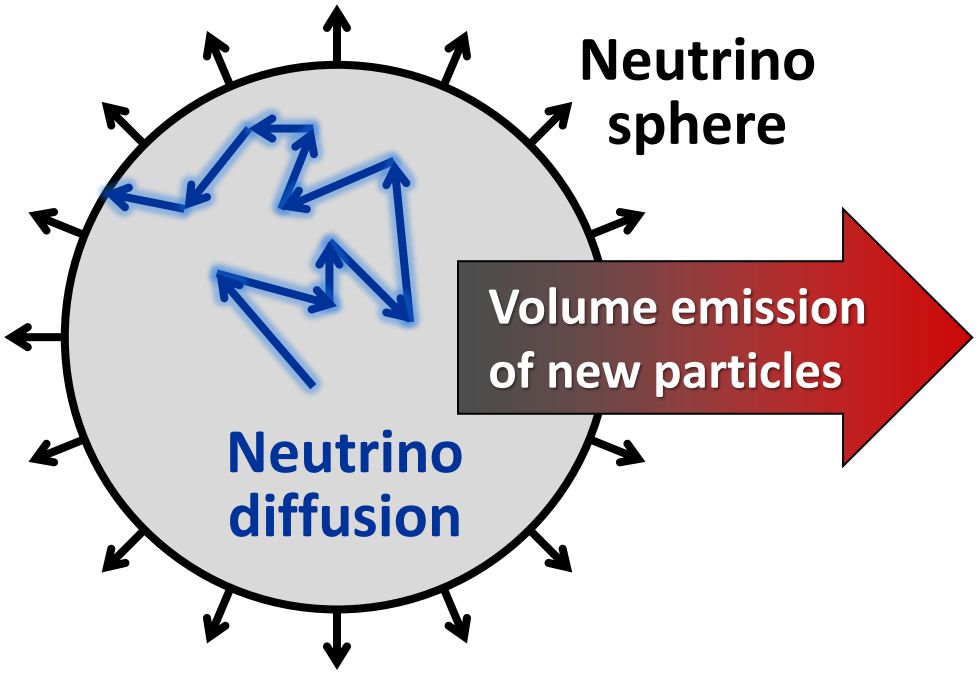
GWs & γ arrive within 2 s
Equal Shapiro time delay within $\sim 10^{-7}$

(Shoemaker & Murase arXiv:1710.06427)

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal



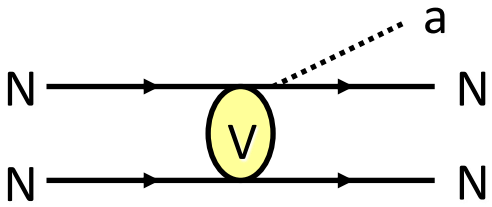


Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

Axion Emission from a Nuclear Medium

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



+ …

Nucleon-Nucleon Bremsstrahlung

Axial-vector interaction implies dominance of spin-dependent process

- Interaction potential (one-pion exchange OPE was often used, but too simplistic) → **Carenza+** arXiv:1906.11844
- In-medium coupling constants → **Springmann+** arXiv:2410.10945
- In-medium effective nucleon properties
- Correlation effects (static and dynamical spin-spin correlations)
- Thermal π^- contribute significantly (dominantly?) → **Carenza+** arXiv:2010.02943

Axion emission is a complicated nuclear physics problem, for several issues see Fiorillo, Gil Muyor, Janka, Raffelt & Vitagliano, work in progress

SN 1987A Axion Limits from Burst Duration

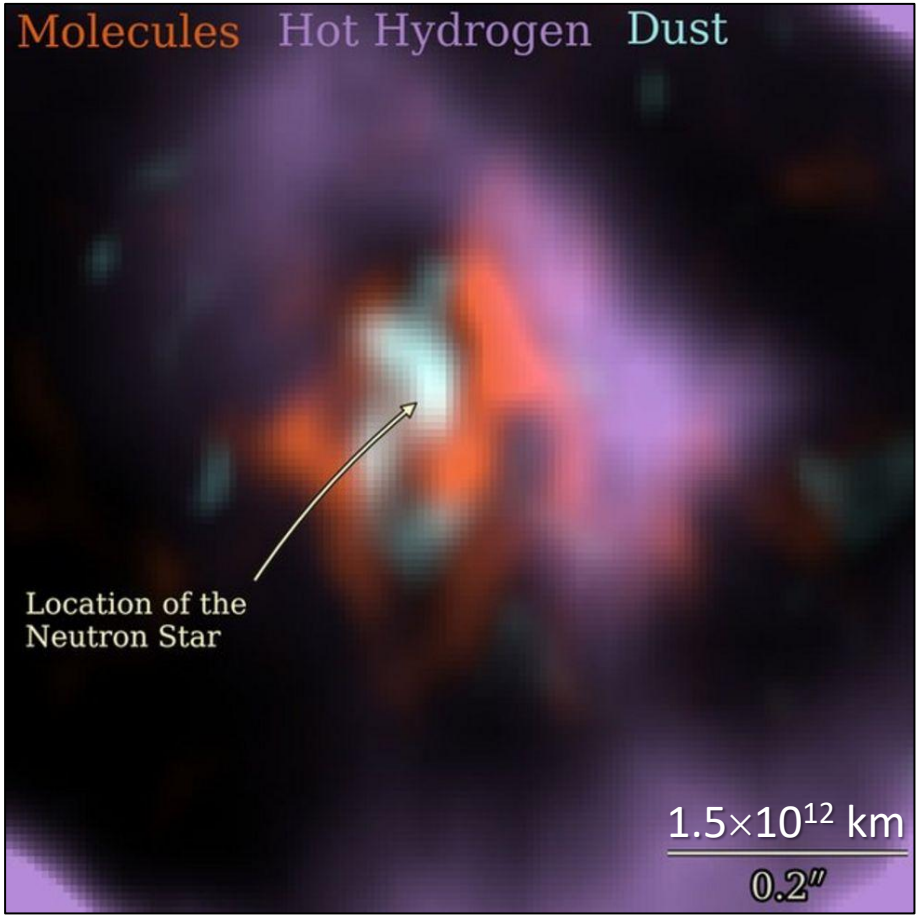
- Raffelt, Lect. Notes Phys. 741 (2008) 51 hep-ph/0611350
  Burst duration calibrated by early numerical studies
  "Generic" emission rates inspired by OPE rates
  $f_a \gtrsim 4 \times 10^8$ GeV and $m_a \lesssim$ **16 meV** (KSVZ, based on proton coupling)
- Chang, Essig & McDermott, JHEP 1809 (2018) 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)

Where is the Neutron Star of SN 1987A?

No pulsar or neutron star has been seen until now (38 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

SN 1987A Signal Duration Too Long?

Fiorillo+ arXiv:2308.01403

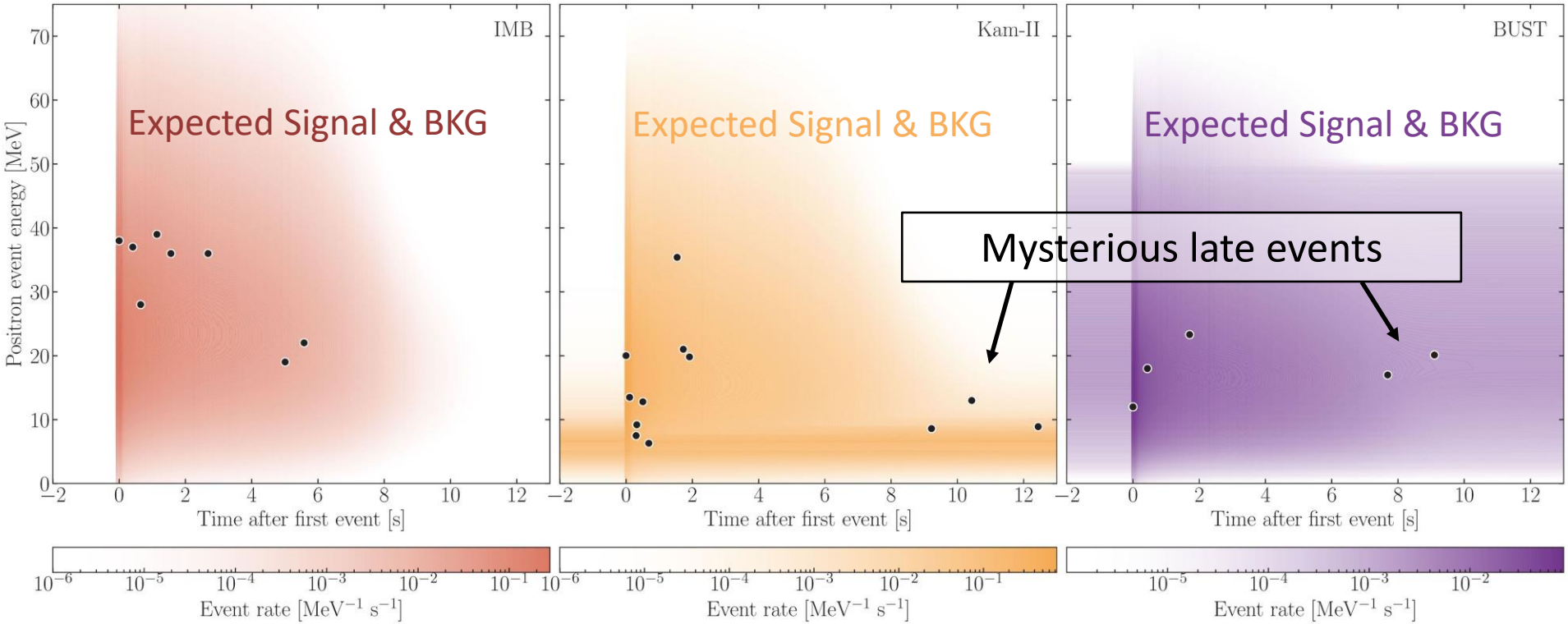
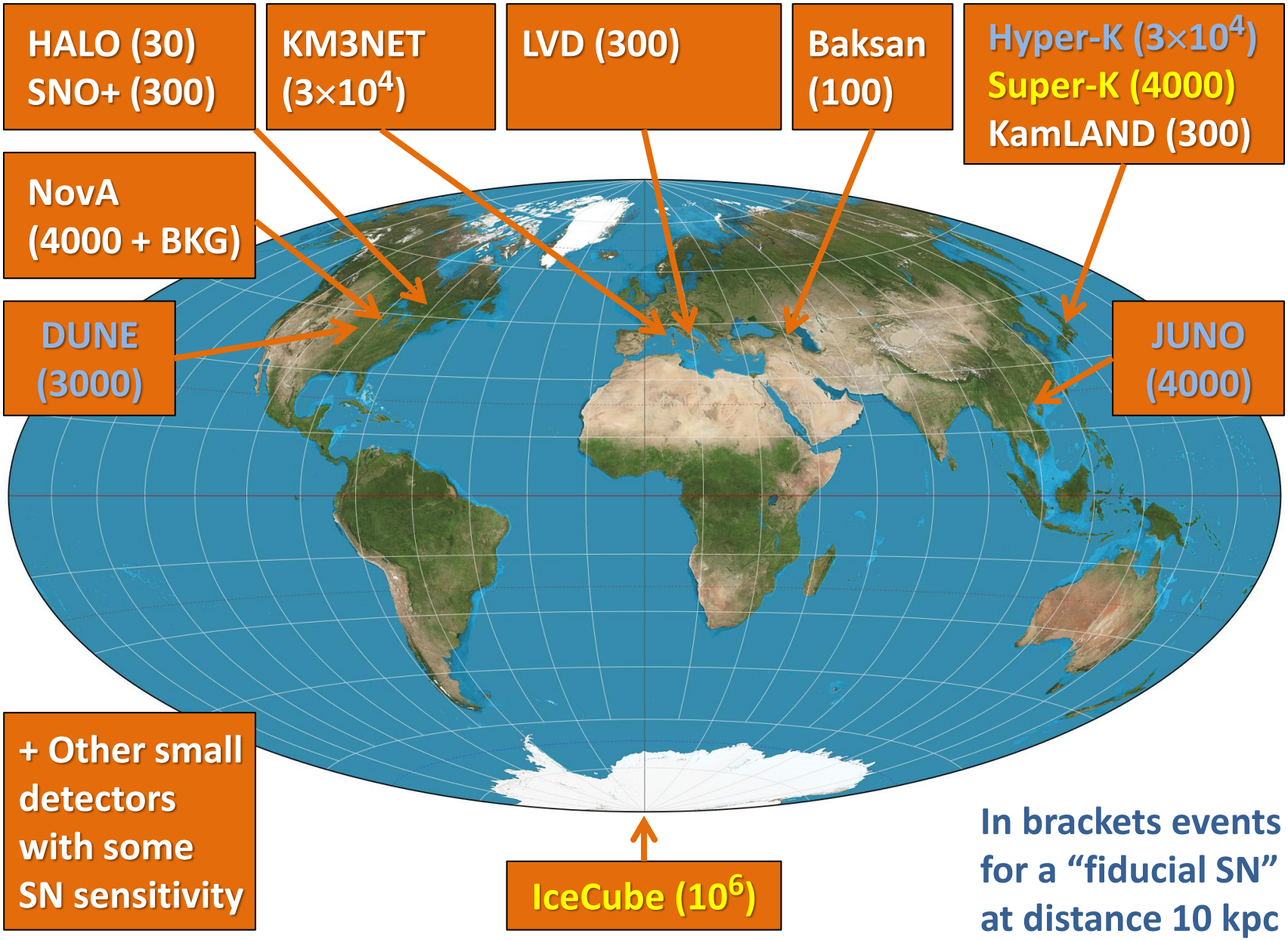


FIG. 17. Differential event distribution (signal and background) at each experiment, compared with the observations. Results are shown for model 1.44-SFHo without flavor swap; the offset time for each experiment is chosen as the best-fit value reported in Table VII.

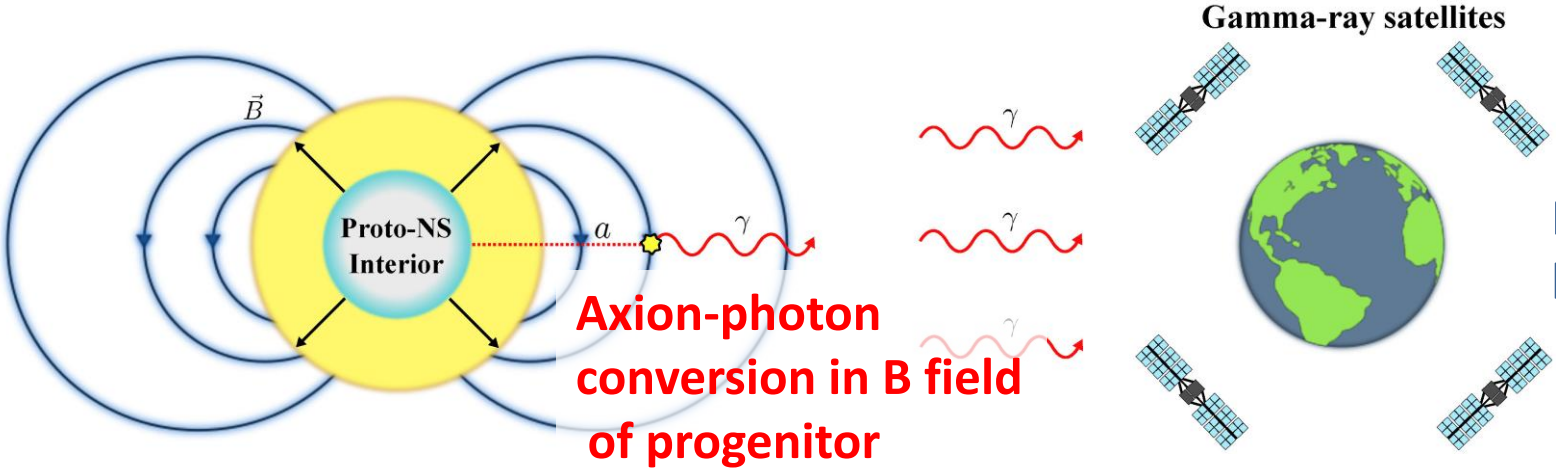
- **In a suite of Garching models (no axions), expected signal always too short (PNS convection and reduced opacities by correlations!)**
- **Deserves dedicated study**

(Near) Operational Detectors for Next SN Neutrinos



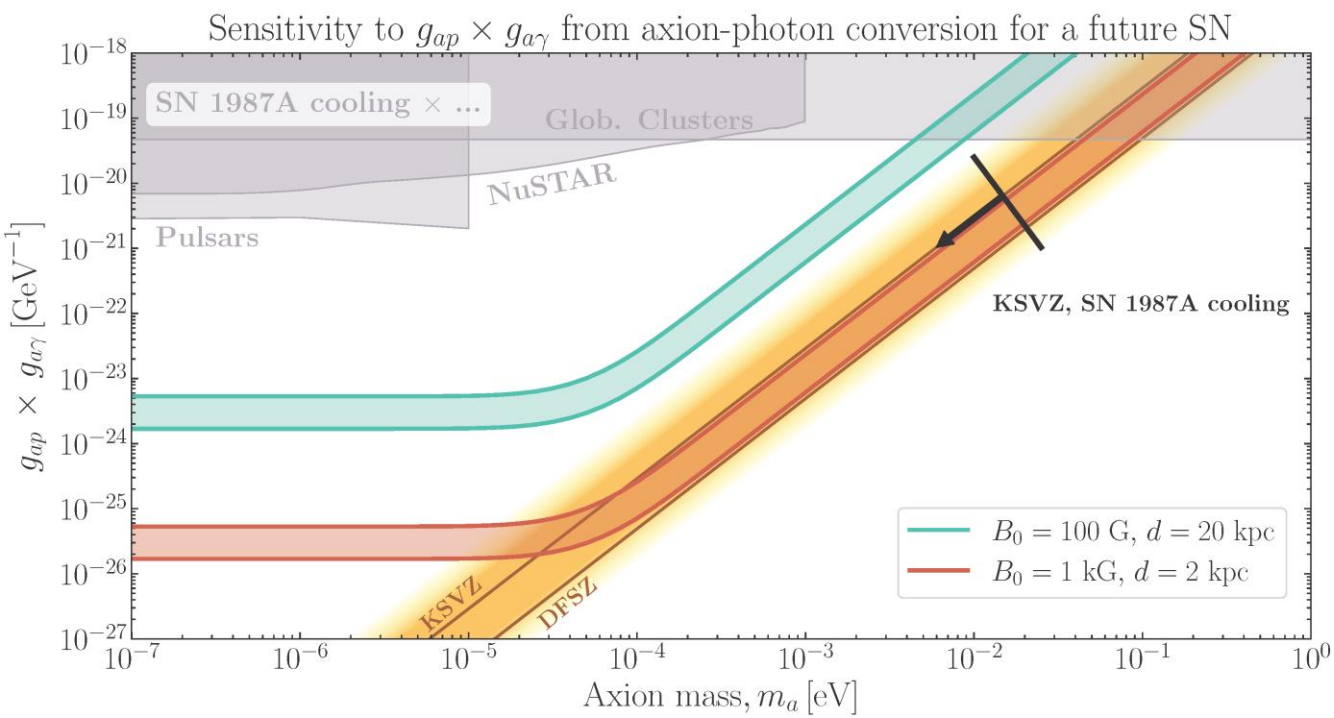
In brackets events for a "fiducial SN" at distance 10 kpc

Detecting Axions with Next Galactic Supernova?



Axion-photon conversion in B field of progenitor

Fermi-LAT like satellites



Manzari+ arXiv:2405.19393

This figure: Fiorillo, Gil Muyor, Janka, Raffelt, and Vitagliano, in progress

For optimistic SN assumptions (distance, B field) QCD axion parameters reachable

BSM Signature from the Next Galactic SN

Smoking gun signature:

Nearly any event in nearly any detector coincident with neutrino burst

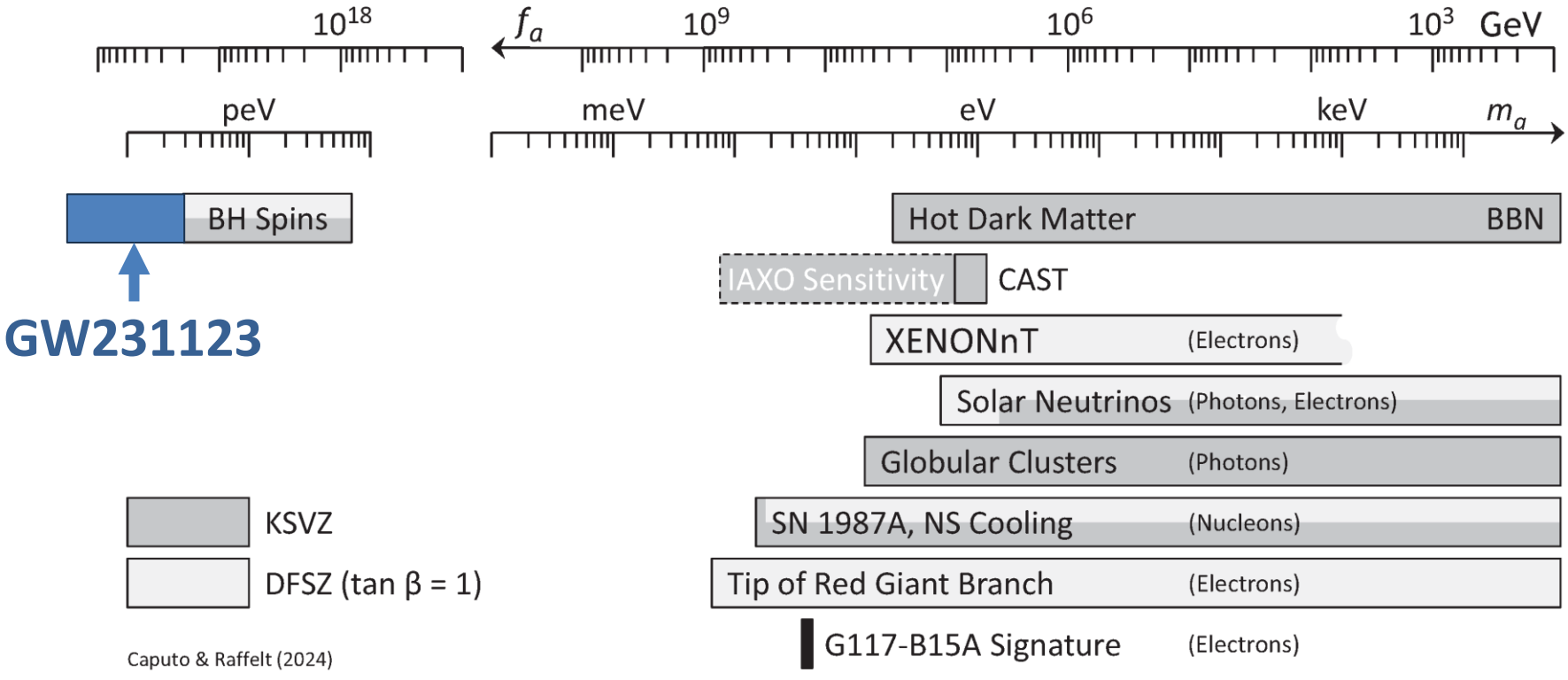
"Sneaking out directly from SN core"

- Gamma-rays (from decay or conversion)
- 100-MeV-range neutrinos
- Gravitational waves during quiescent phase
- Something unexpected

Astrophysical Axion Bounds

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

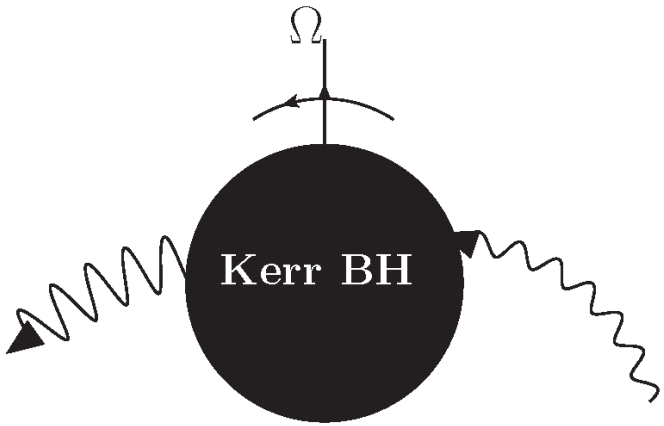
See also Carenza, Giannotti, Isern, Mirizzi & Straniero, arXiv:2411.02492



- Many improvements over the years, but overall picture the same
- Specific QCD axion signatures cannot come from cooling effects
- Best stellar detection opportunity probably (Baby)IAXO

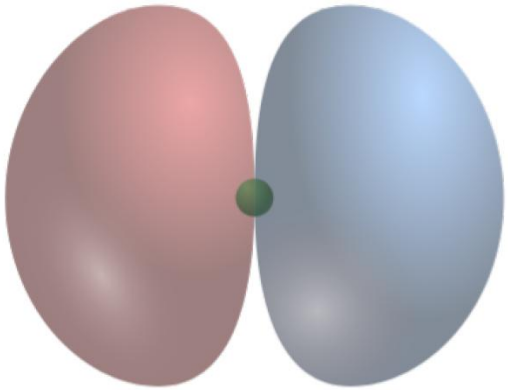
Superradiance

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



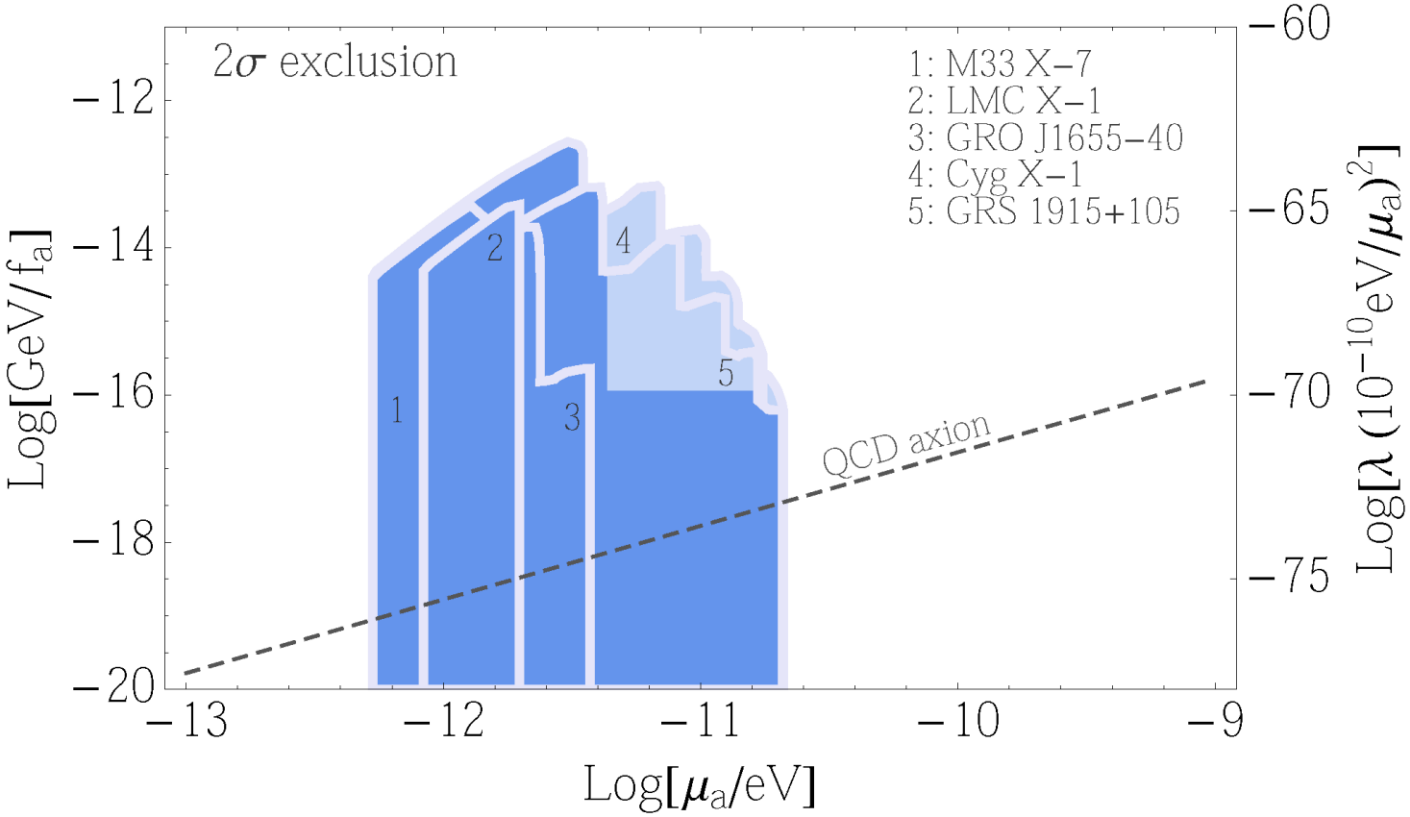
$m\Omega > \omega$

- **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 (8 Jan 2021)

Constraints from Black Hole Spins

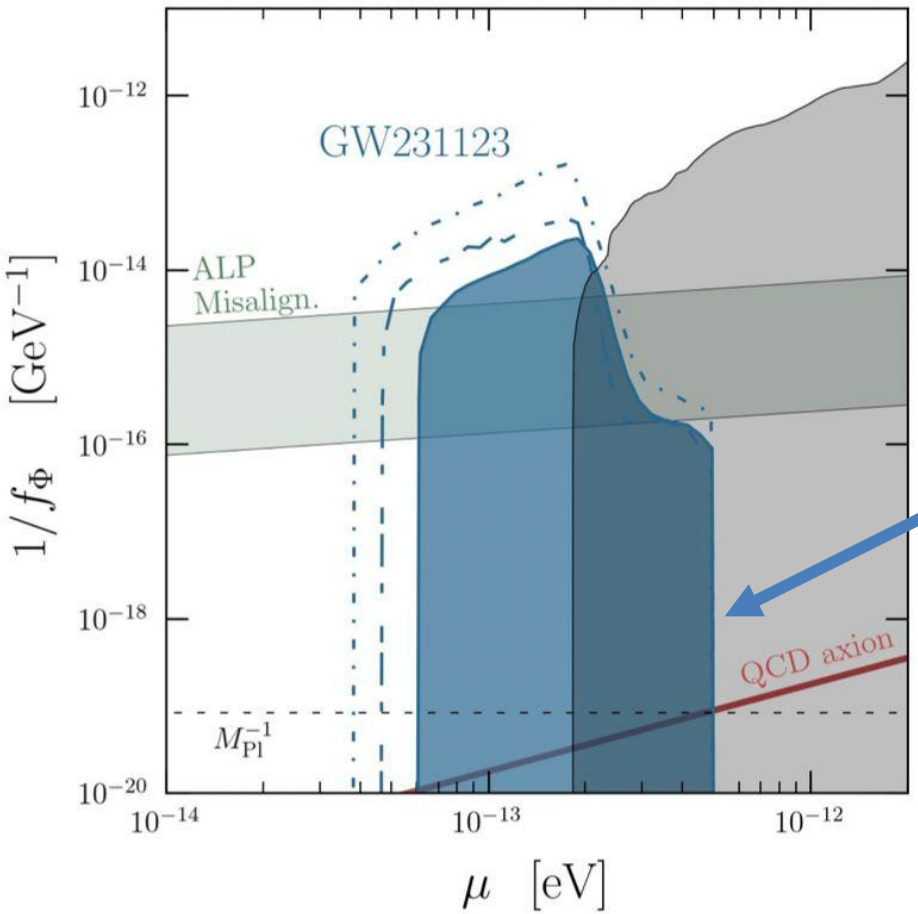


#	Object	Mass ($M_\odot$)	Spin	Age (yrs)	Period (days)	$M_{\text{comp. star}}$ ($M_\odot$)	$\dot{M}/\dot{M}_E$
1	M33 X-7	15.65 ± 1.45	$0.84^{+.10}_{-.10}$[51]	3×10^6 [52]	3.4530 [53]	$\gtrsim 20$ [53]	$\gtrsim 0.1$[53]
2	LMC X-1	10.91 ± 1.4	$0.92^{+.06}_{-.18}$ [54]	5×10^6 [52]	3.9092 [55]	31.79±3.48 [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

BH Spins from Binary Merger GW231123

LIGO-Virgo-KAGRA observed GWs from BH-BH merger GW231123
$137^{+22}_{-17} M_\odot$ and $103^{+20}_{-52} M_\odot$ with large spins

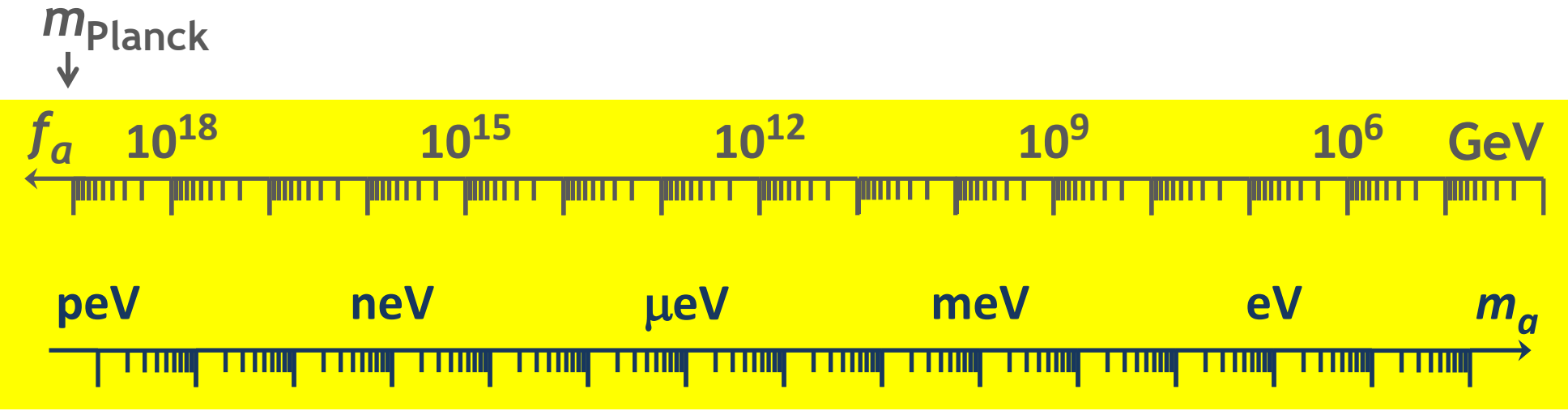


New super-radiance bounds on scalar boson masses

Caputo, Franciolini & Witte
arXiv:2507.21788 (29 July 2025)

Aswathi, East, Siemonsen, Sun & Jones
arXiv:2507.20979 (28 July 2025)

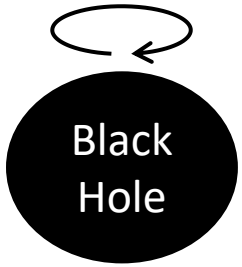
Astrophysical Axion Bounds and Opportunities

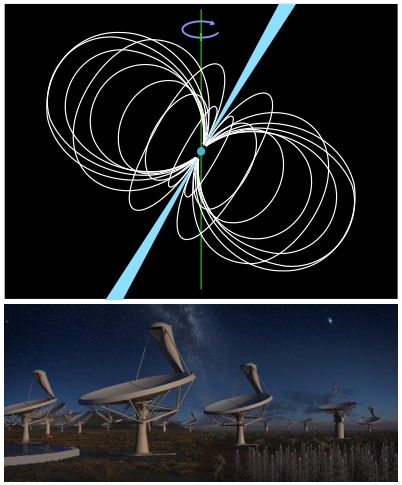


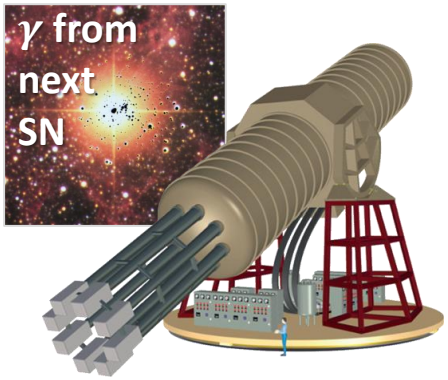
Super Radiance

Opportunities for detection

Astrophysical Bounds (Energy loss of stars)



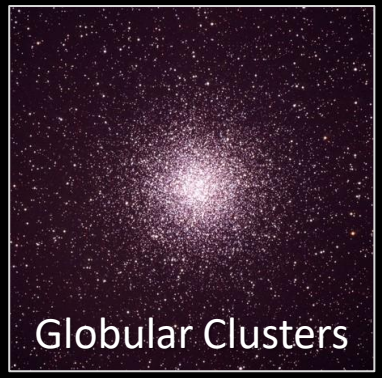




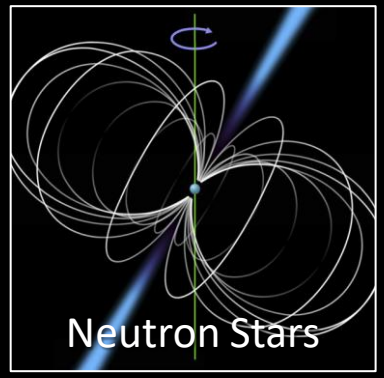
IAXO Solar Axion Telescope

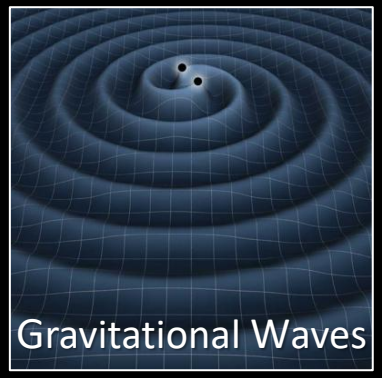
Axion conversion in neutron star magnetospheres

Solar Axions


Globular Clusters

Supernova 1987A


Neutron Stars

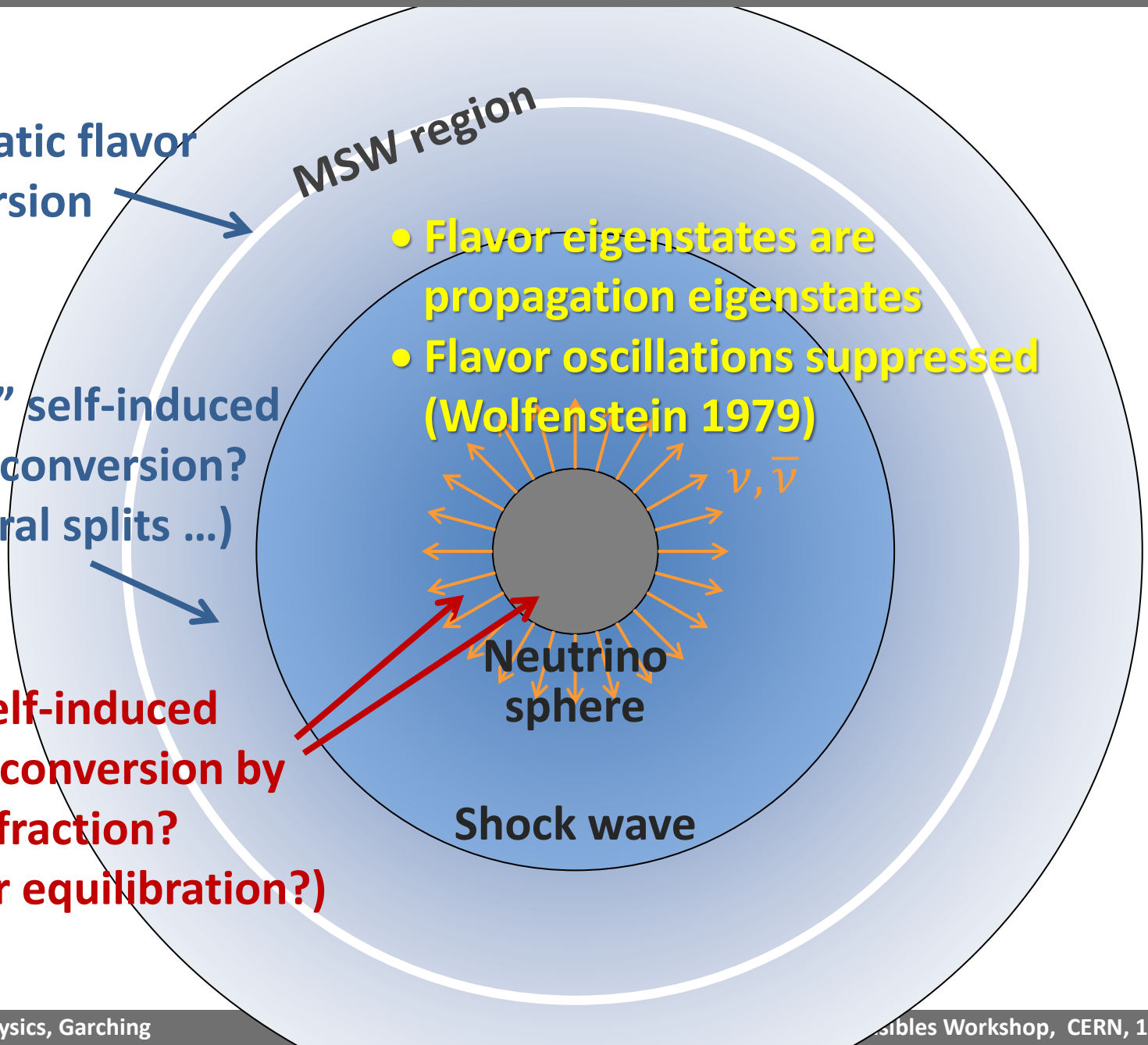

Gravitational Waves

Thanks!

Bonus Topics

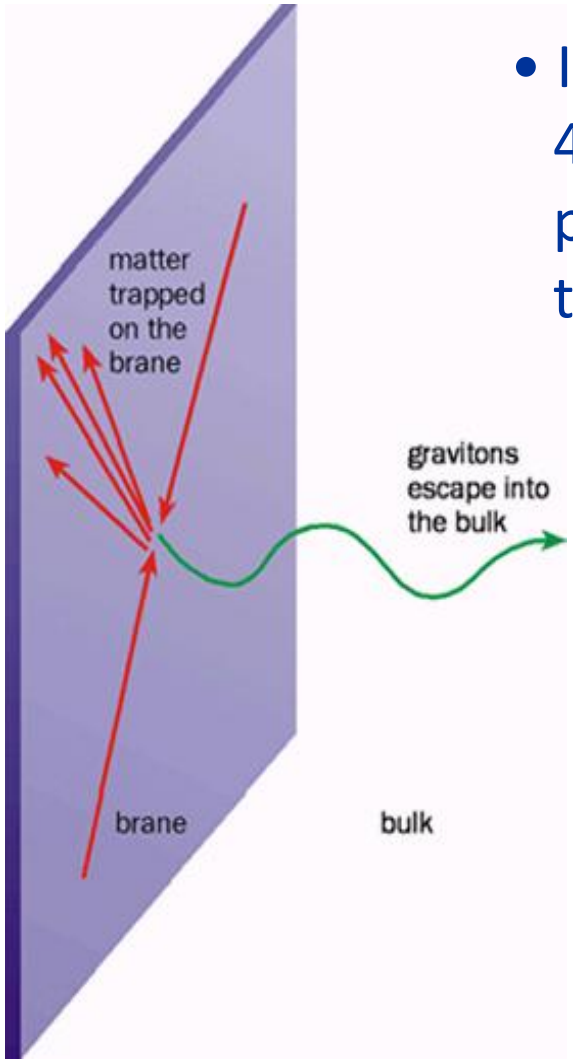
Flavor Conversion in Core-Collapse Supernovae

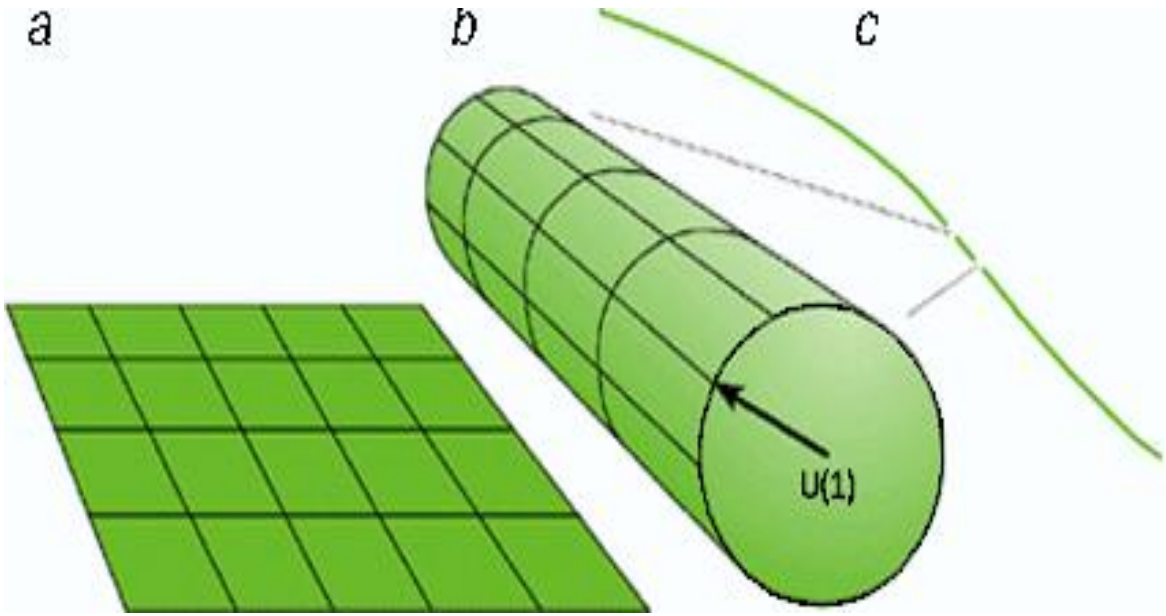
- Adiabatic flavor conversion
- "Slow" self-induced flavor conversion? (Spectral splits …)
- Fast self-induced flavor conversion by ν-ν refraction? (Flavor equilibration?)



Large Extra Dimensions

- Fundamentally, space-time can have more than 4 dimensions (e.g. 10 or 11 in string theories)
- If standard model fields are confined to 4D brane in (4+n) D space-time, and only gravity propagates in the (4+n) D bulk, the compactification scale could be macroscopic





Supernova 1987A Limit on Large Extra Dimensions

Cullen & Perelstein, hep-ph/9904422, Hanhart et al., nucl-th/0007016

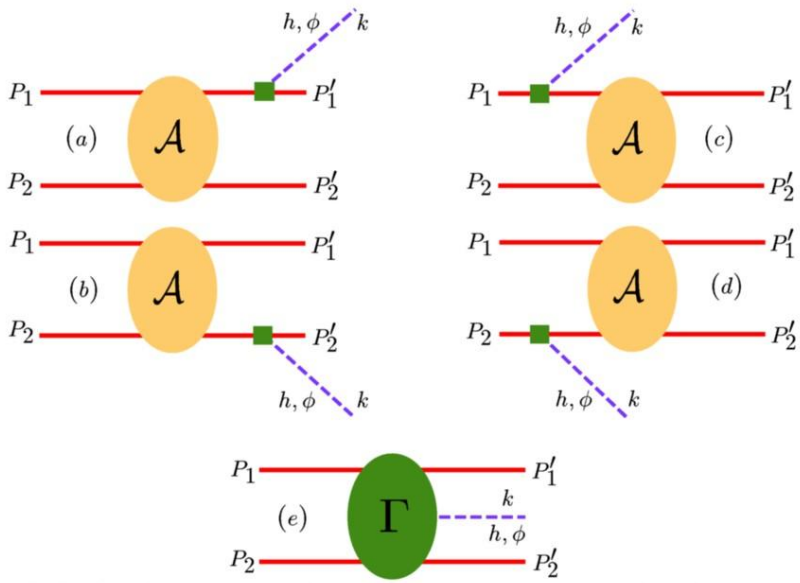


FIG. 1. *The leading diagrams contributing to processes $NN \to NNh$ and $NN \to NN\phi$. Nucleons are denoted by solid lines and the KK-modes h or ϕ are denoted by dashed lines. Solid squares denote an insertion of the single-nucleon energy-momentum tensor, while solid ovals containing $\mathcal{A}$ denote an insertion of the full NN scattering amplitude. The solid oval containing Γ denotes the non-pole vertex required for the sum of diagrams to satisfy $\partial_\mu M^{\mu\nu} = 0$.*

SN core emits large flux of KK gravity modes by nucleon-nucleon bremsstrahlung

$$\text{Rate} \propto M_{\text{Pl}}^{-2}$$

Large multiplicity of modes

$$RT \sim 10^{11}$$

for R ~ 1 mm, T ~ 30 MeV

$$\text{Rate} \propto \frac{(RT)^n}{M_{\text{Pl}}^2} \propto \frac{T^n}{M_{\text{Pl}}^{2+n}}$$

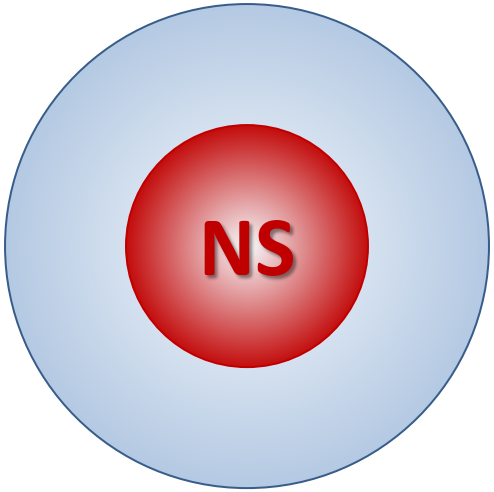
SN 1987A energy-loss argument:

R < 1 mm, M > 9 TeV (n = 2)

R < 1 nm, M > 0.7 TeV (n = 3)

Originally the most restrictive limit on such theories, except for cosmological arguments. Other restrictive limits from neutron stars.

Bounds from KK Decays



Gravitationally trapped KK cloud

Decays:

- Gammas constrained by observations
- All decays keep old neutron stars hot

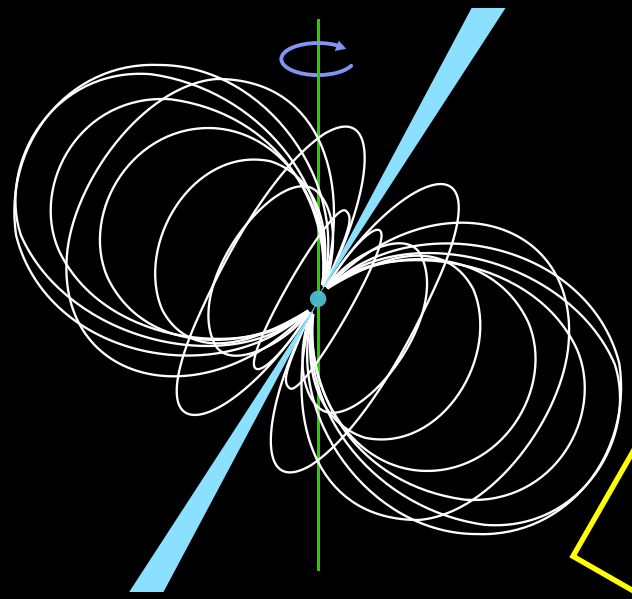
TABLE V: Upper limits on the compactification radius R (in meters) from our arguments.

n	1	2	3	4	5	6	7
Neutrino Signal							
SN 1987A	4.9×10^{2}	1.0×10^{-6}	1.1×10^{-9}	3.8×10^{-11}	4.9×10^{-12}	1.2×10^{-12}	4.4×10^{-13}
EGRET γ-ray limits							
All cosmic SNe	4.9	1.0×10^{-7}	2.5×10^{-10}	1.2×10^{-11}	1.9×10^{-12}	5.6×10^{-13}	2.3×10^{-13}
Cas A	5.3×10^{3}	1.3×10^{-6}	9.2×10^{-10}	2.6×10^{-11}	3.1×10^{-12}	7.6×10^{-13}	2.8×10^{-13}
RX J185635–3754	16.	6.7×10^{-8}	1.2×10^{-10}	5.6×10^{-12}	9.0×10^{-13}	2.7×10^{-13}	1.1×10^{-13}
Neutron-star excess heat							
PSR J0953+0755	8.3	5.9×10^{-8}	1.3×10^{-10}	5.9×10^{-12}	9.4×10^{-13}	2.8×10^{-13}	1.2×10^{-13}

Hannestad & Raffelt, arXiv:hep-ph/0304029v3 (April 2025)

Large correction, important for viability for recent interest in theories with 1 extra dimension, should be reexamined

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

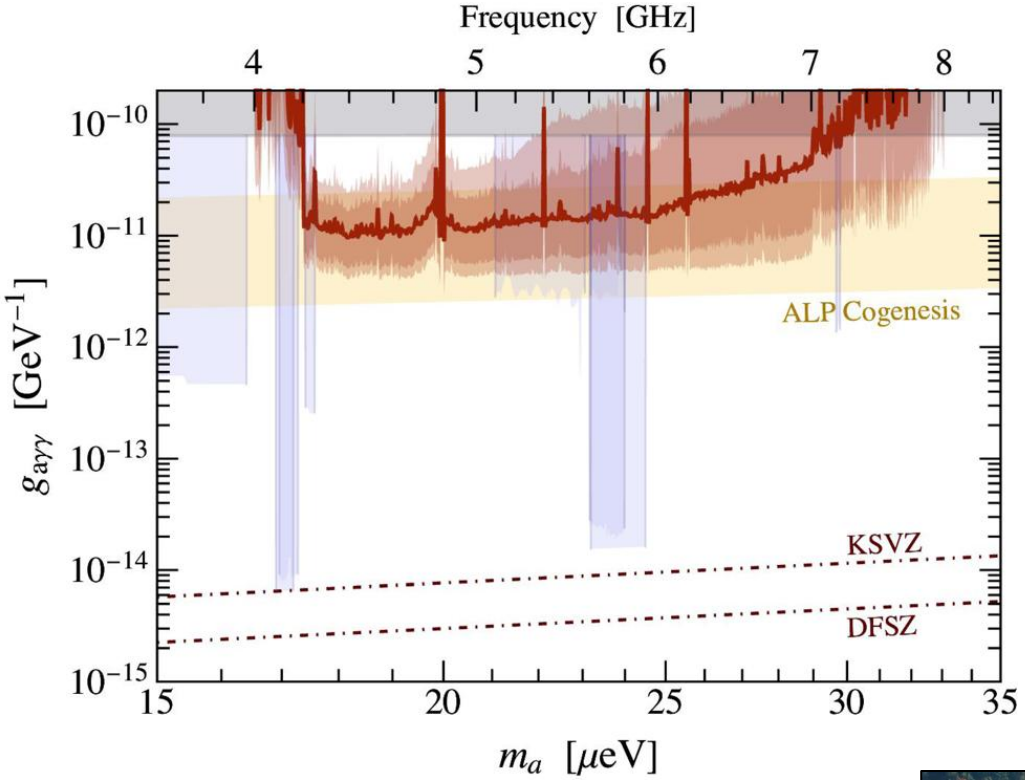
Pshirkov & Popov 2007
arXiv:0711.1264
Many papers recently

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

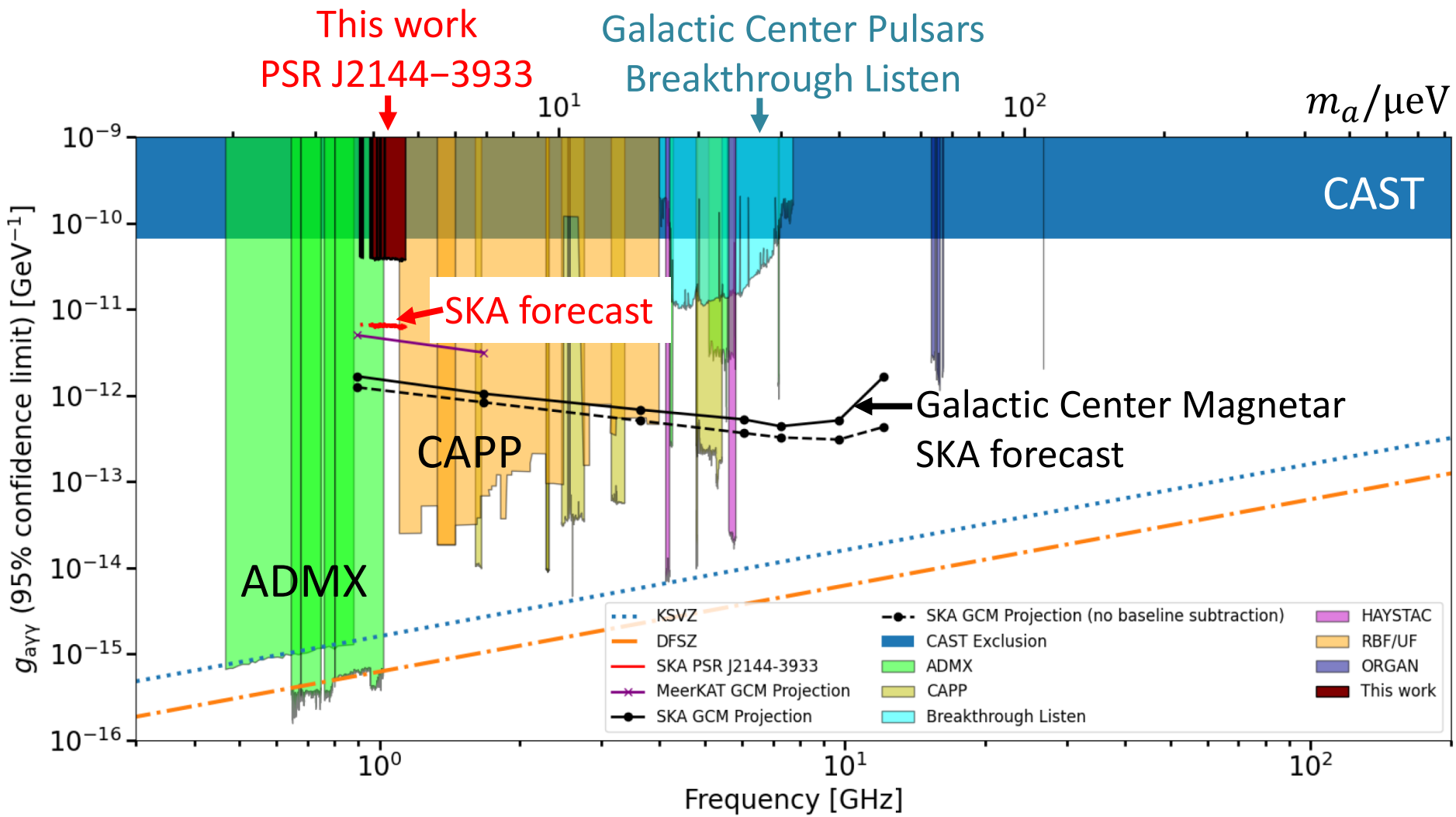


- Green Bank Telescope Archival Data
- Breakthrough Listen Project (Search for ET Life)
- State-of-the-art ray tracing simulations
- Galactic Center Region
  - Many pulsars
  - Enhanced dark matter density

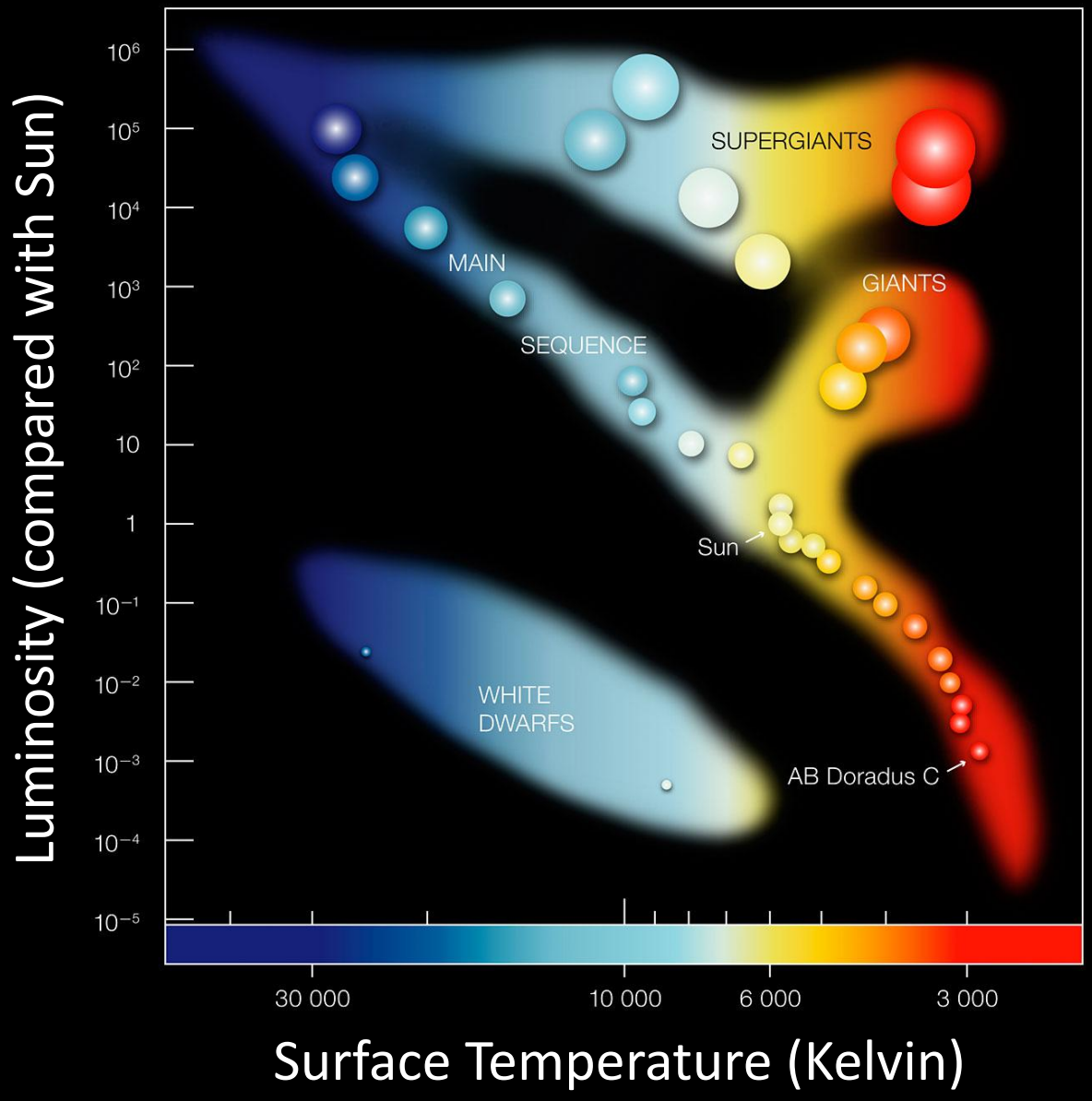
Searching for Time-Dependent Axion Dark Matter Signals in Pulsars

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

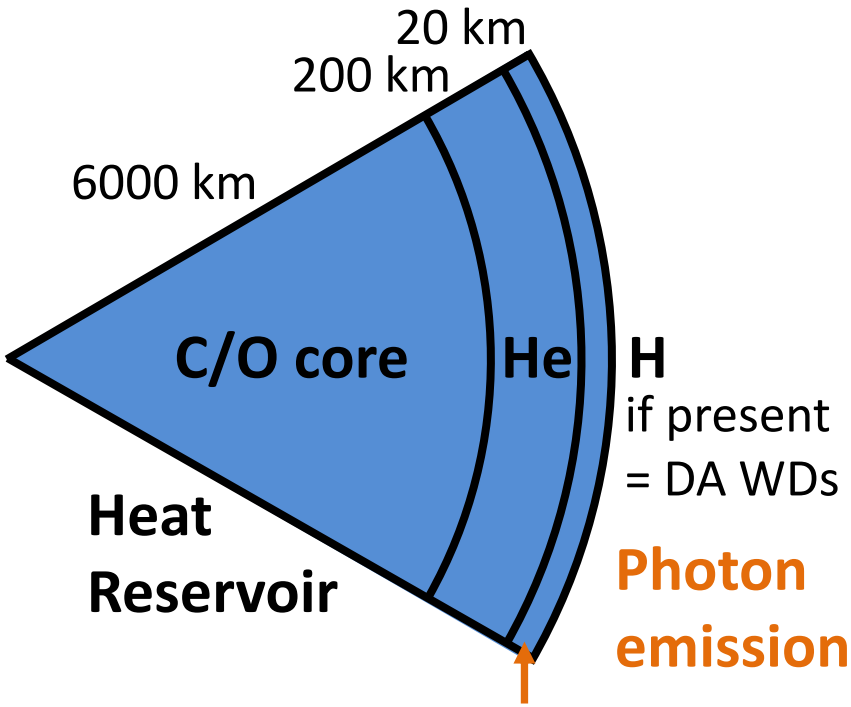


White Dwarfs



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

White Dwarfs



Energy flux control

Cooling much slower for DA type (with H layer)

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

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

$L \simeq 10^{-4}$–$10^{-1} L_\odot$

$M \simeq 0.5$–$0.8 M_\odot$

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

Degenerate Stars ("White Dwarfs")

Assume temperature very small
→ No thermal pressure
→ Electron degeneracy is pressure source

Pressure ~ Momentum density × Velocity

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

Hydrostatic equilibrium

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

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

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

Inverse mass radius relationship

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

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

(Y_e electrons per nucleon)

For sufficiently large stellar mass M, electrons become relativistic

- Velocity = speed of light
- Pressure

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

No stable configuration

Chandrasekhar mass limit

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

Chandrasekhar Mass for Particle Physicists

Degeneracy pressure balances gravity

- N nucleons, nucleon mass m_N
- $M_{\rm star} = N\, m_N$
- Semirelativistic particles (mass m): $E_{\rm F} \simeq p_{\rm F} \simeq m$
- Degeneracy energy: $E_{\rm deg} \simeq Nm$
- Number density: $n \simeq p_{\rm F}^3 \simeq m^3$

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

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

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

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

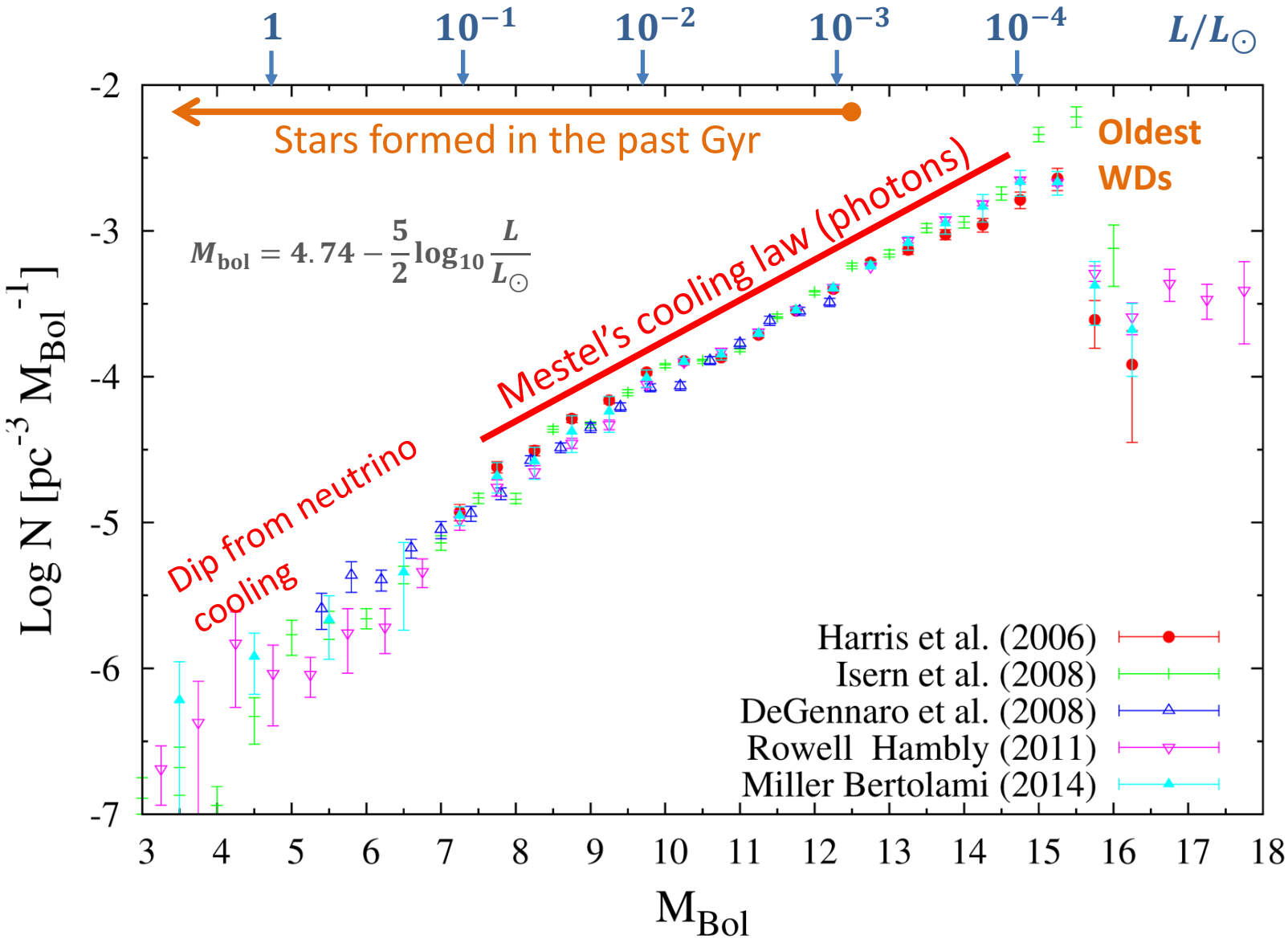
- **Neutron Star (NS):**
  Degenerate particle: Nucleon, $m = m_N$

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

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

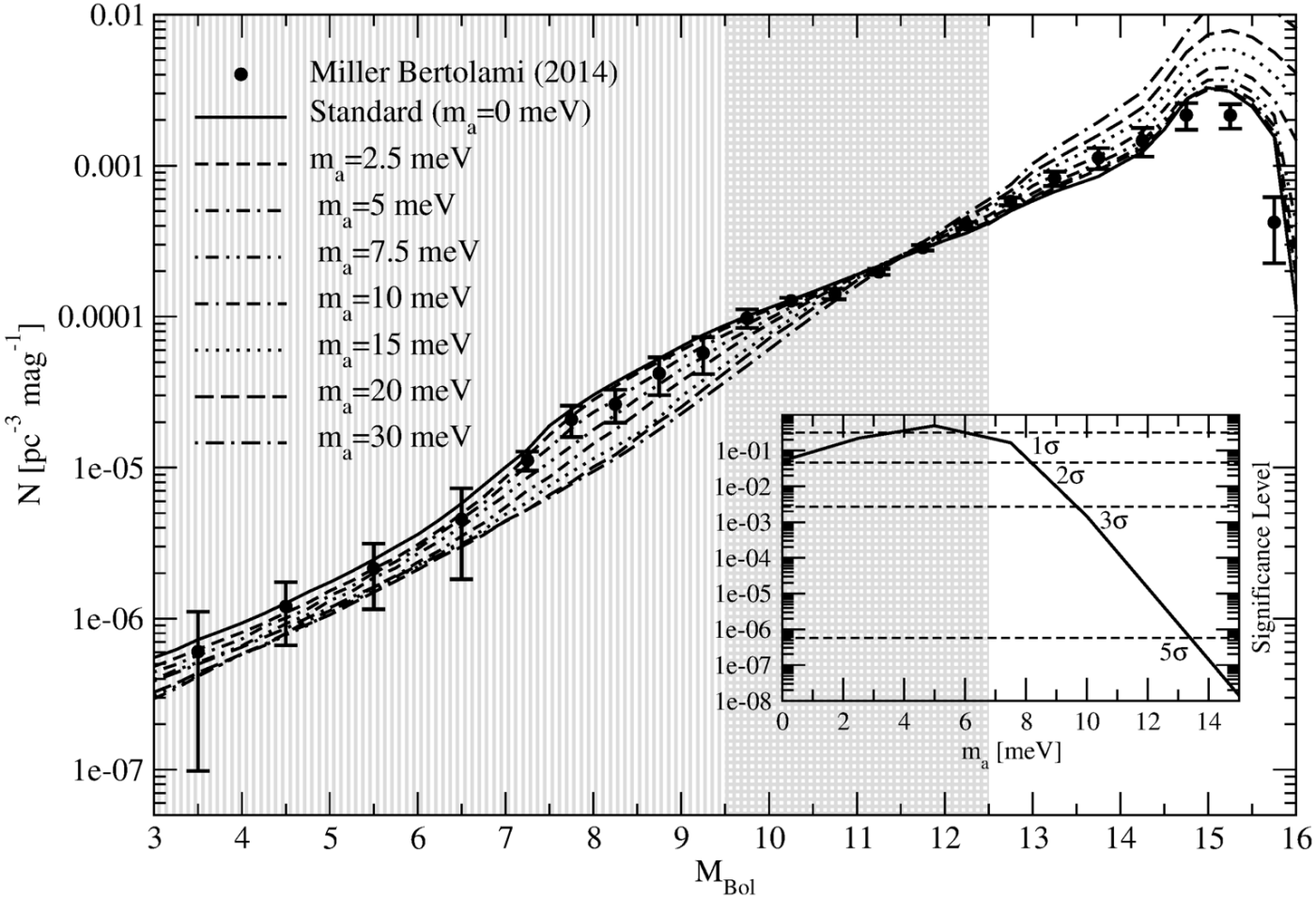
$$R_{\rm WD} \simeq \frac{m_{\rm Planck}}{m_e m_N} = \frac{m_N}{m_e} R_{\rm NS} = 5000\ {\rm km}$$

White Dwarf Luminosity Function (WDLF)



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

Axion Bounds from WD Luminosity Function



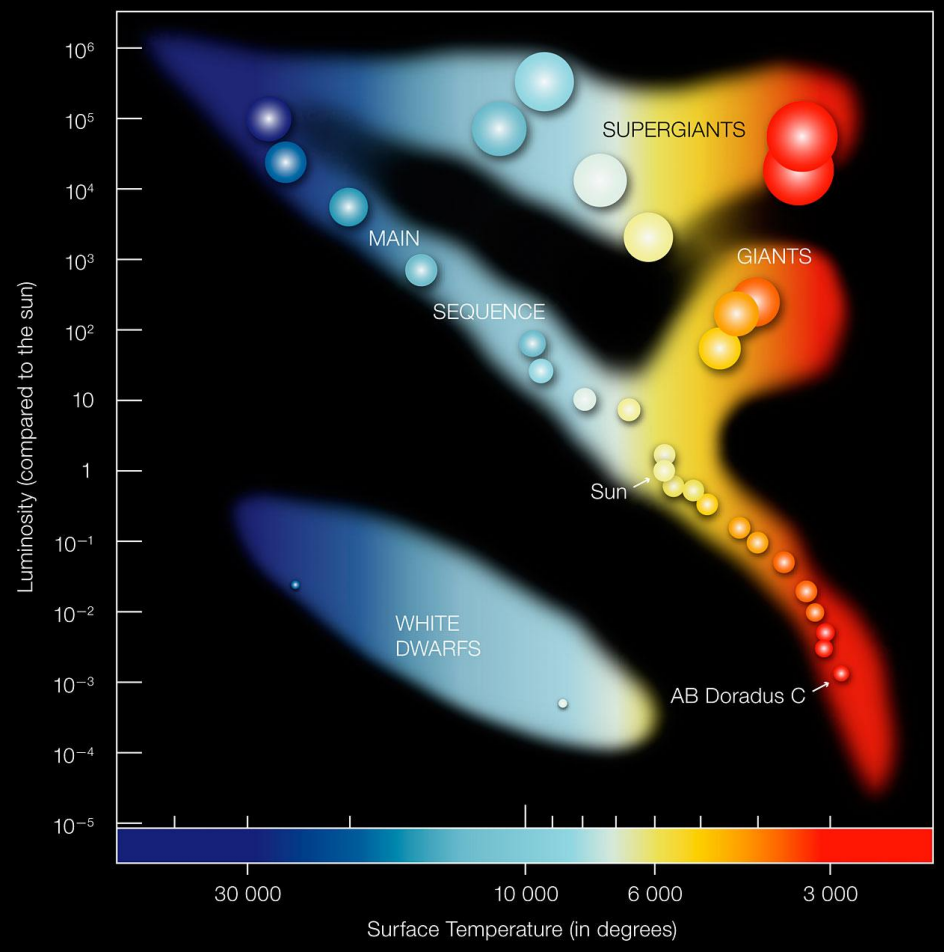
Limits on axion-electron coupling and mass limit in DFSZ model:

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

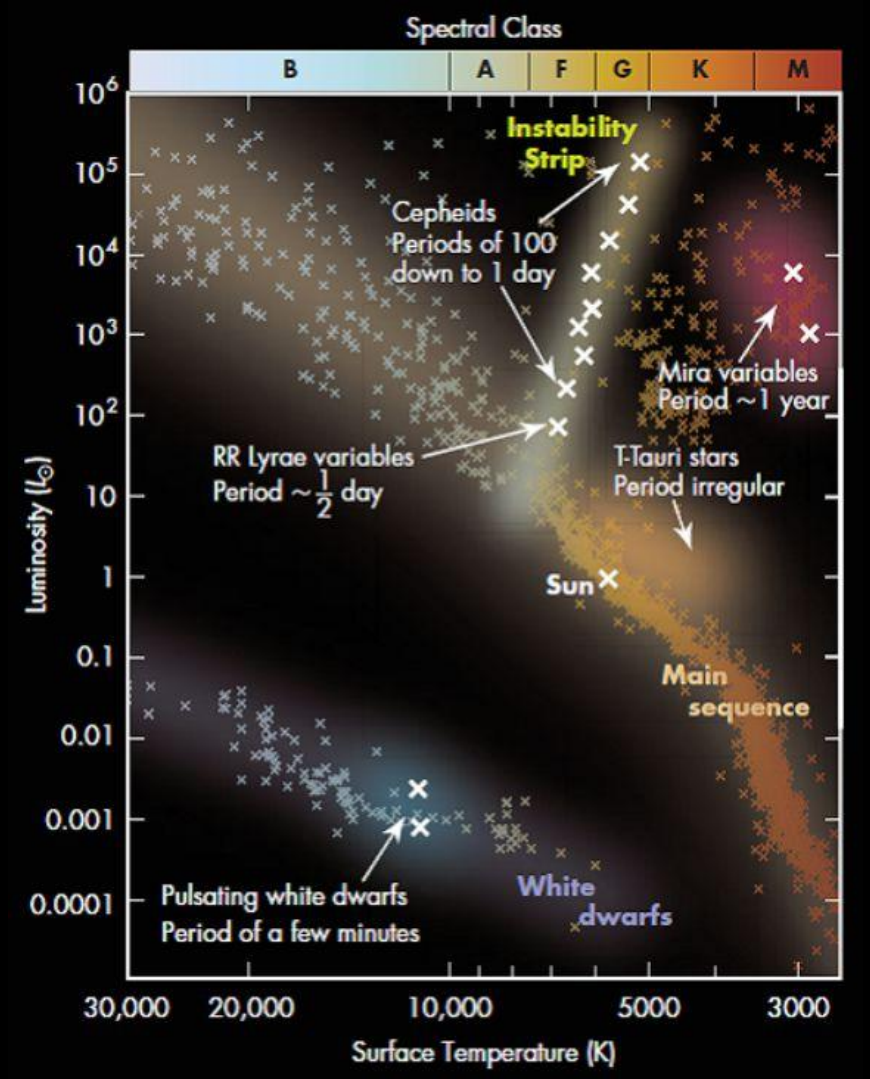
Miller Bertolami, Melendez, Althaus & Isern, arXiv:1406.7712, 1410.1677

For extensions and review see: Isern, arXiv:2002.08069

Pulsating Stars

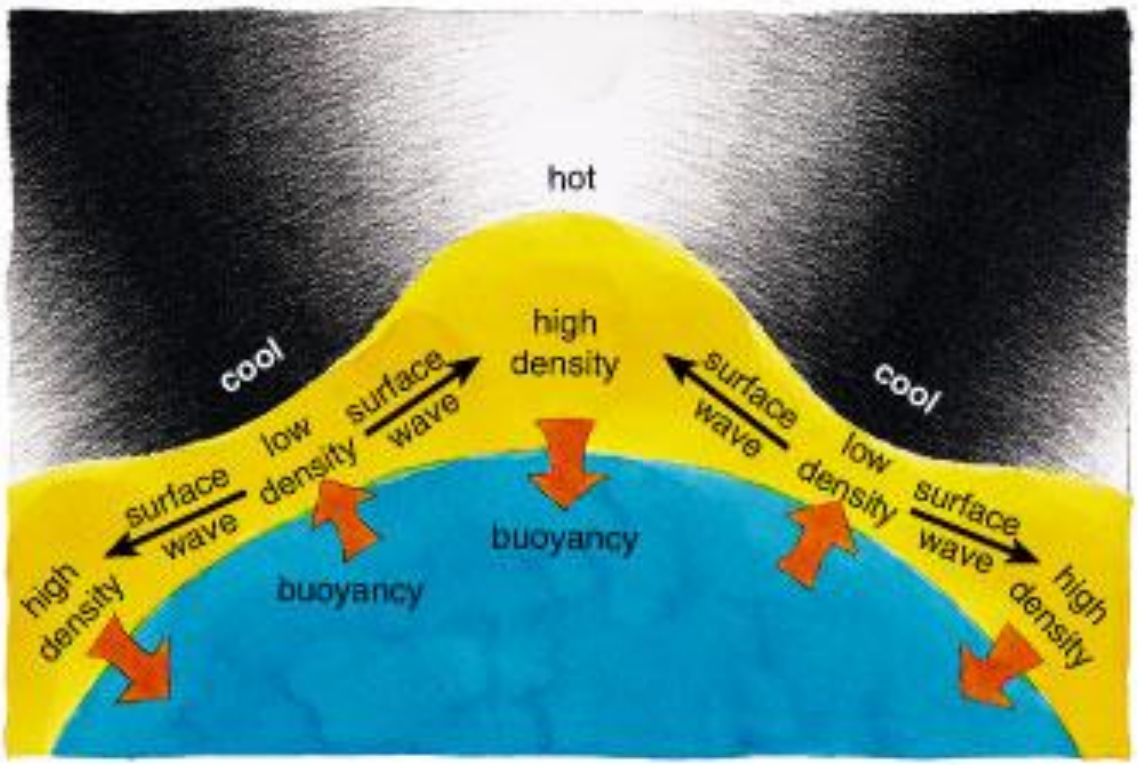


https://www.eso.org/public/images/eso0728c/



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

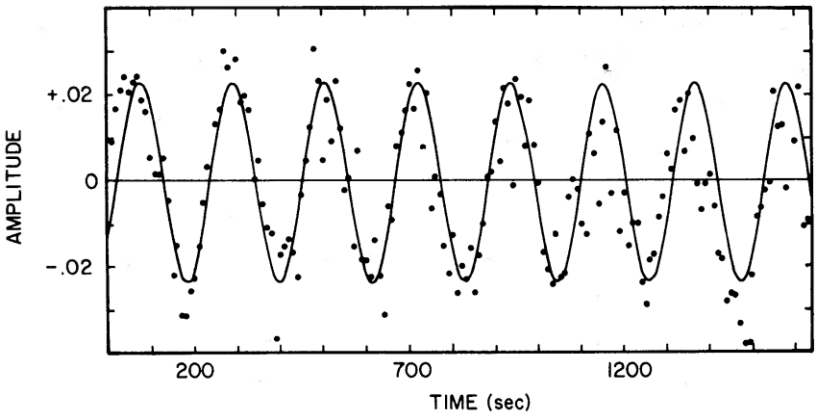


FIG. 1.—A portion of the light curve of G117−B15A in unfiltered light during run 2075. The light curve has been normalized so that the time-averaged brightness of G117−B15A is equal to 1.00, and then 1.00 has been subtracted from the light curve. The solid line is a sine curve with a period of 215.19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

$D = 57.5 \pm 0.1$ pc

$T = 12{,}400$ K

$M = 0.69\ M_\odot$

Period 215.2 s

Kepler+ ApJ 906 (2021) 7

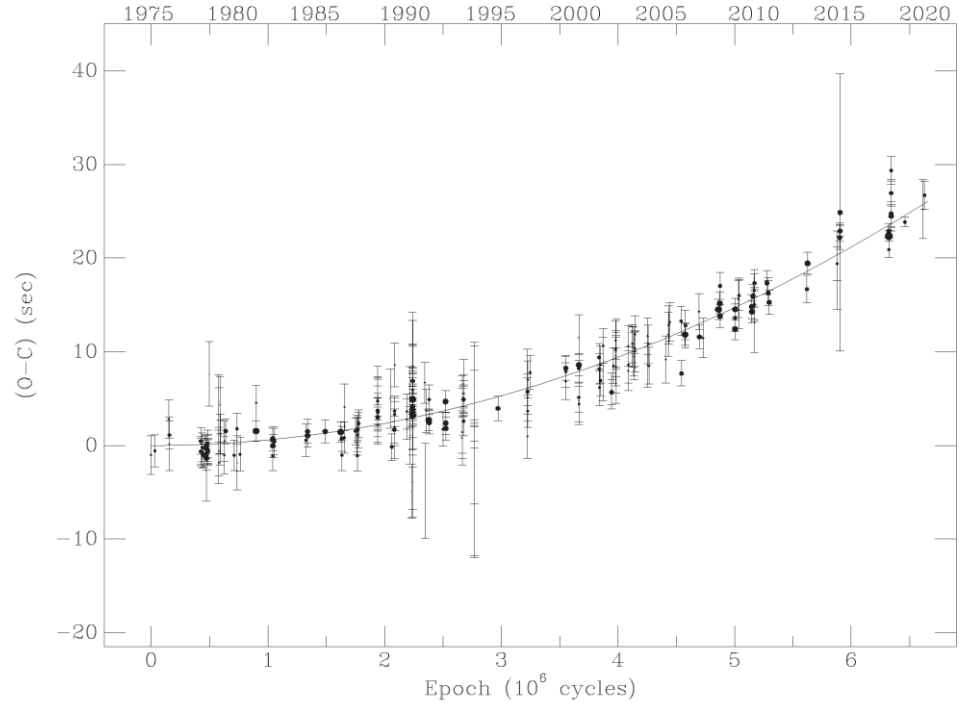


Figure 1. $(O - C)$: observed minus calculated times of maxima for the 215 s pulsation of G 117-B15A. The size of each point is proportional to its weight, i.e., inversely proportional to the uncertainty in the time of maxima squared. We show $\pm 1\sigma$ error bars for each point, and the line shows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

"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?

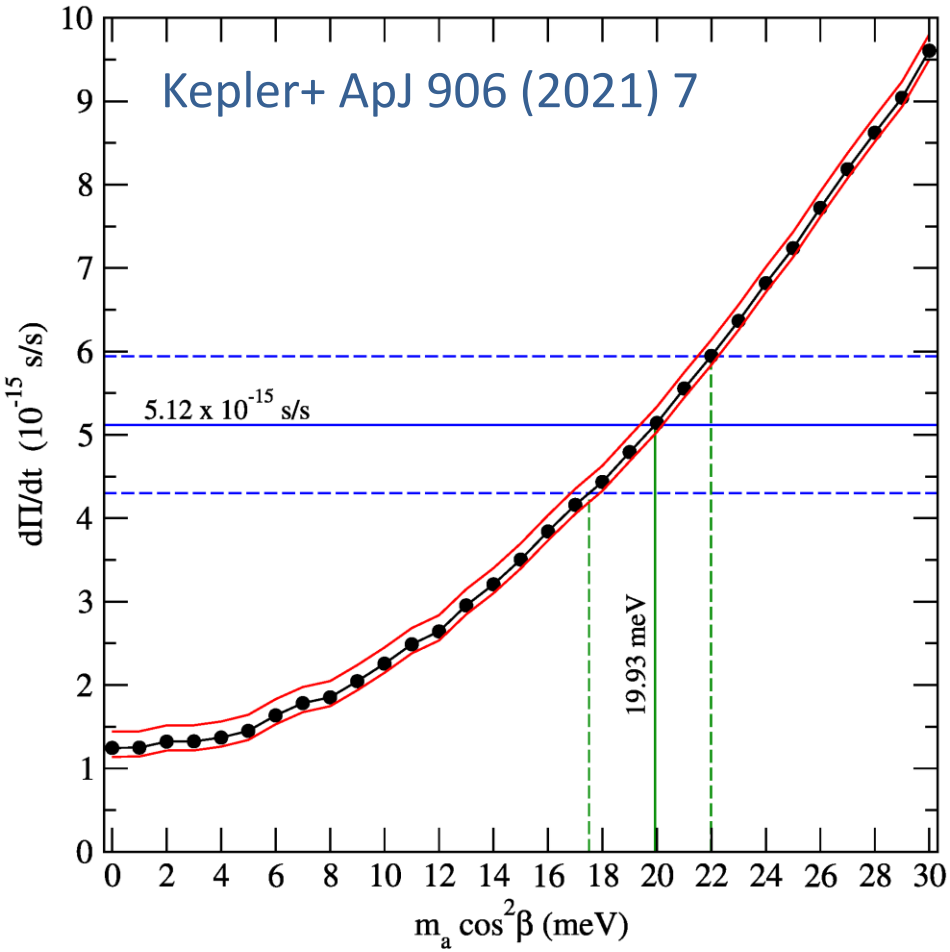
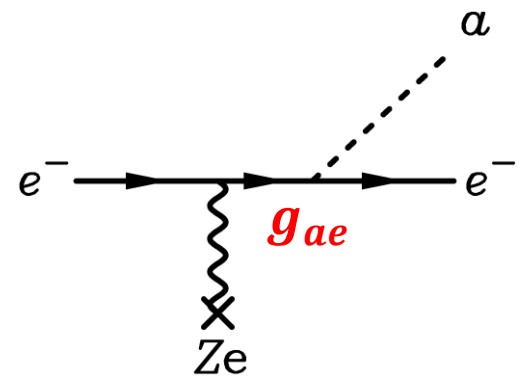


Figure 2. The rate of period change for the mode with $\ell = 1$ and $k = 2$, corresponding to a period of ~215 s in terms of the axion mass (black circles). Dashed lines represent the uncertainties in the value in the observed $\dot{P}$ and the axion mass, while the red curves represent the internal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

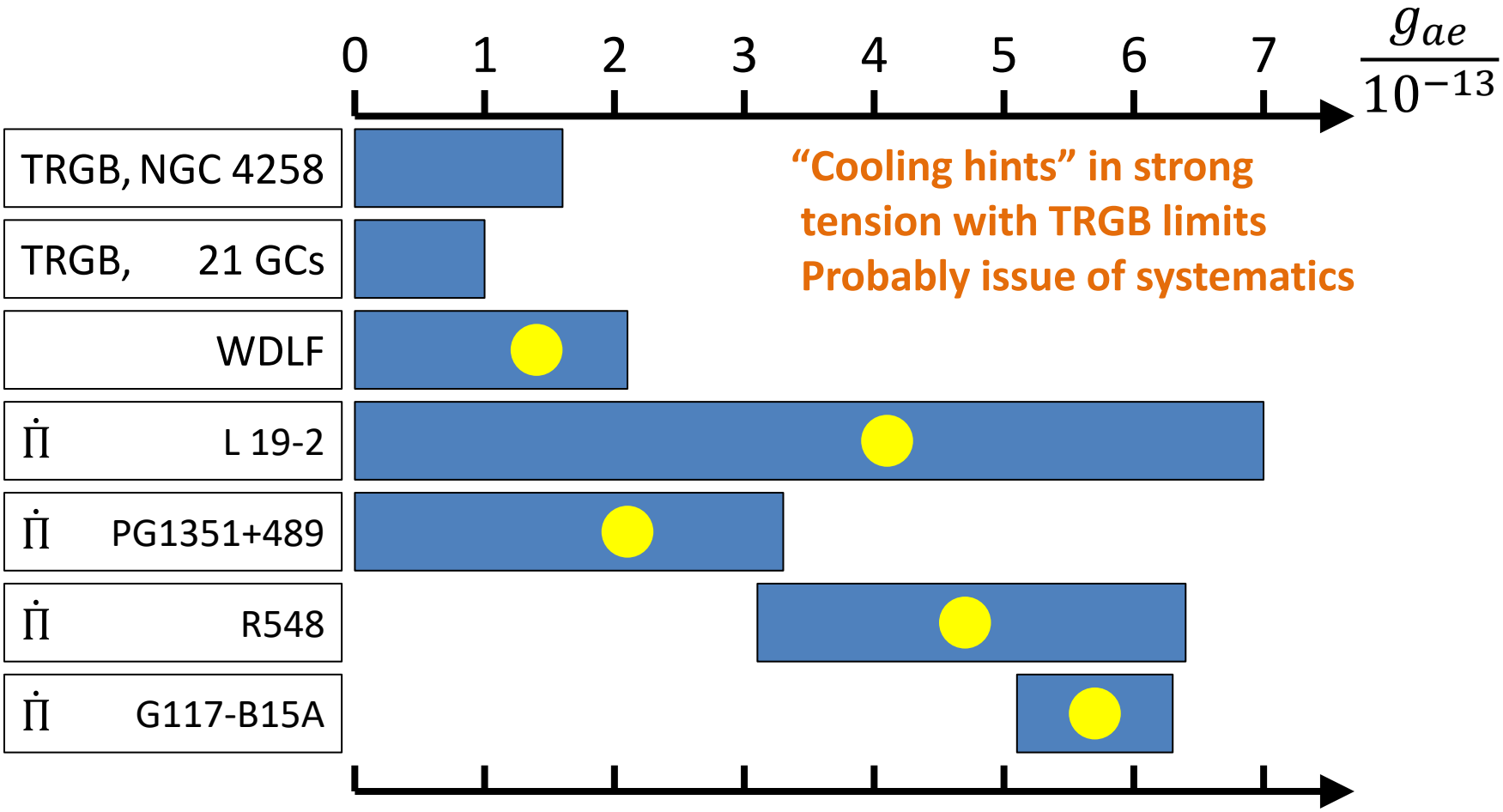
Case of DFSZ Axion

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

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