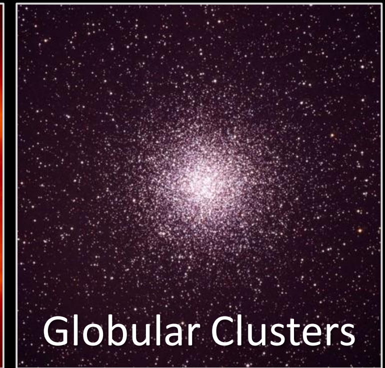
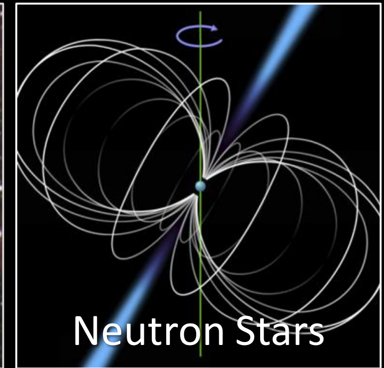
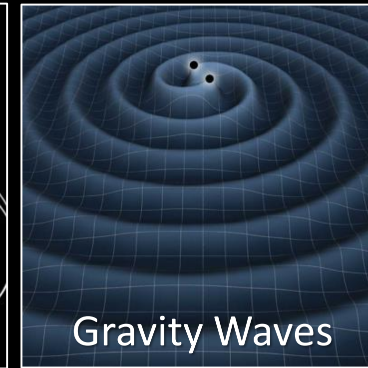






Stars as Particle-Physics Laboratories

Old Ideas and New Developments

ORIGINS Excellence Cluster

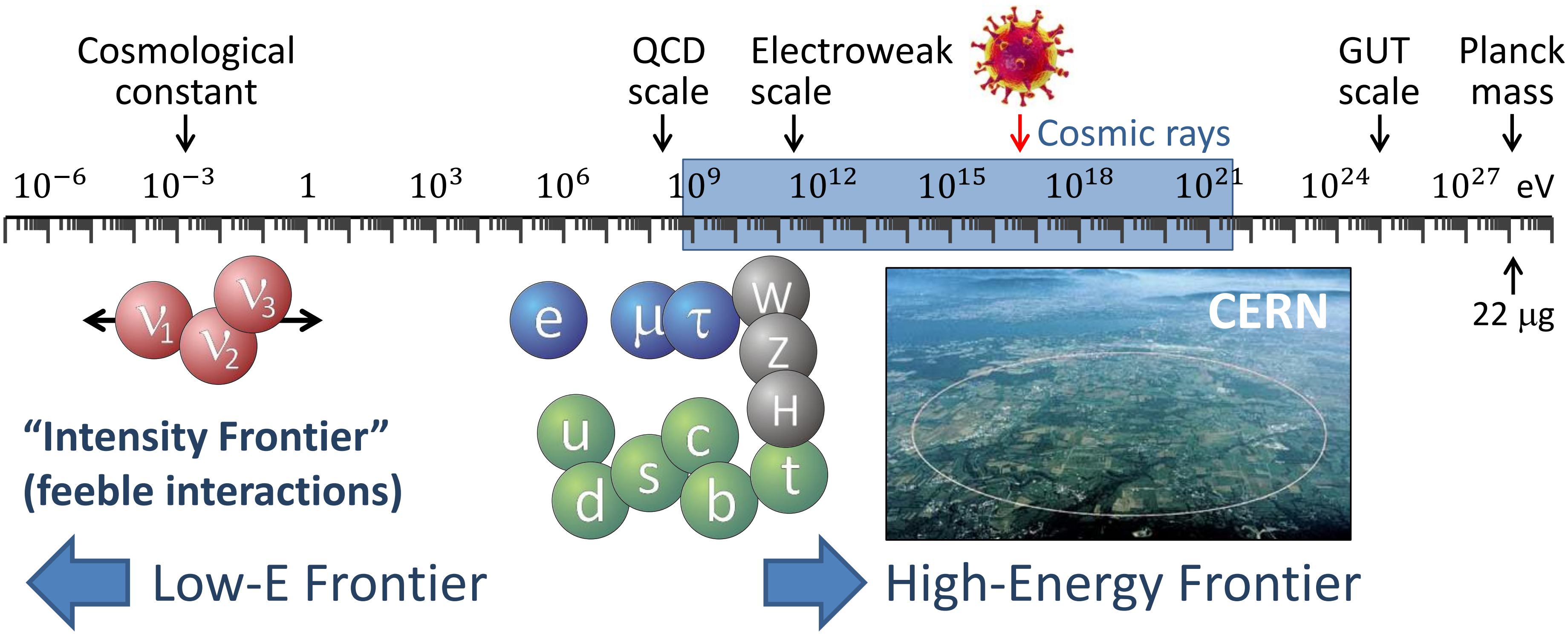
MAX-PLANCK-GESELLSCHAFT

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

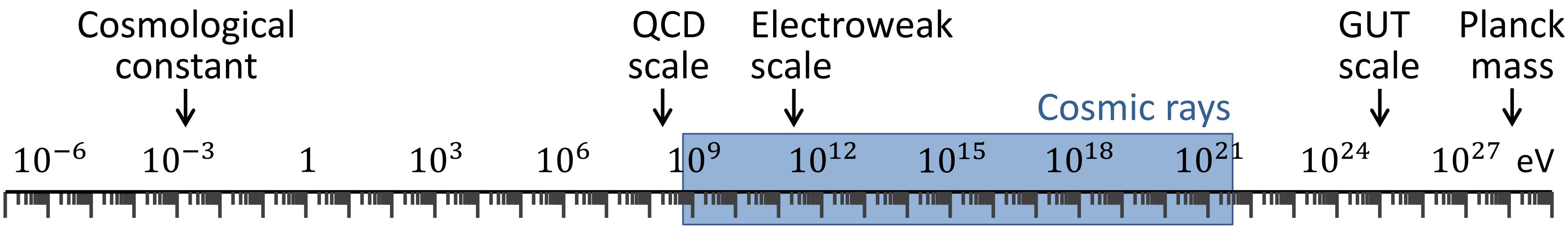
SFB 1258 Neutrinos Dark Matter Messengers

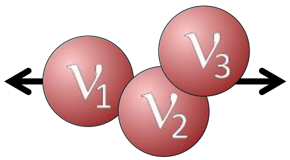
Georg G. Raffelt, Max-Planck-Institut für Physik, München

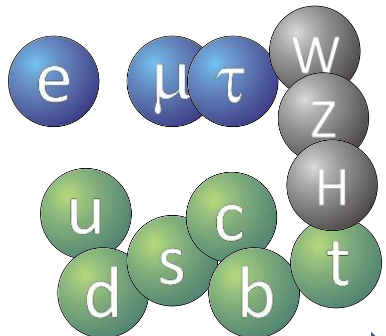
High- and Low-Energy Frontiers in Particle Physics



High- and Low-Energy Frontiers in Particle Physics







"Intensity Frontier"
(feeble interactions)

Low-E Frontier

High-Energy Frontier

Muons in SN cores
and neutron stars

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

} Feebly-interacting particles (FIPs)
(e.g. CERN 2020 workshop report
arXiv:2102.12143)

Some Early Papers on Stellar Particle Physics

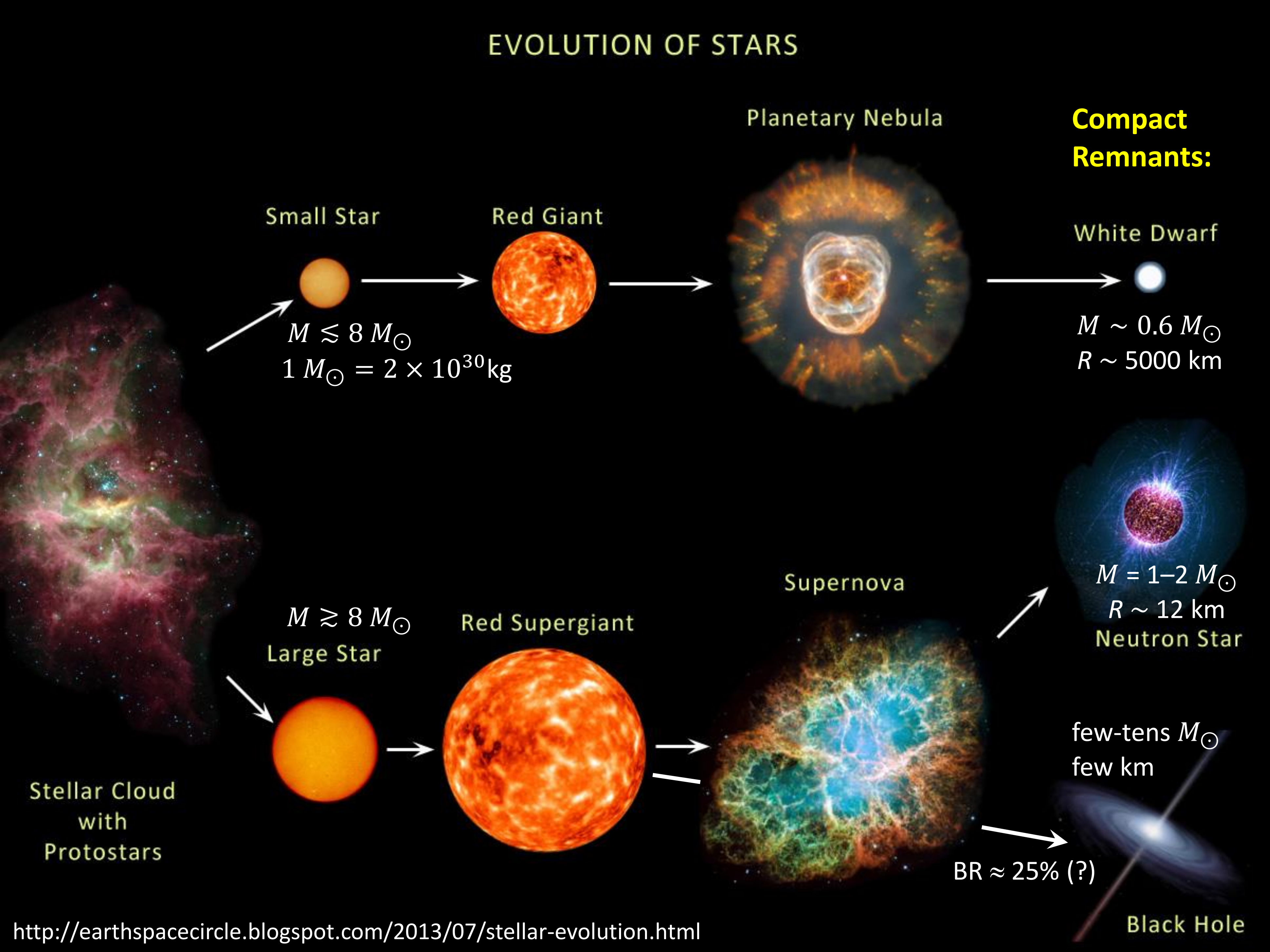
Neutrinos

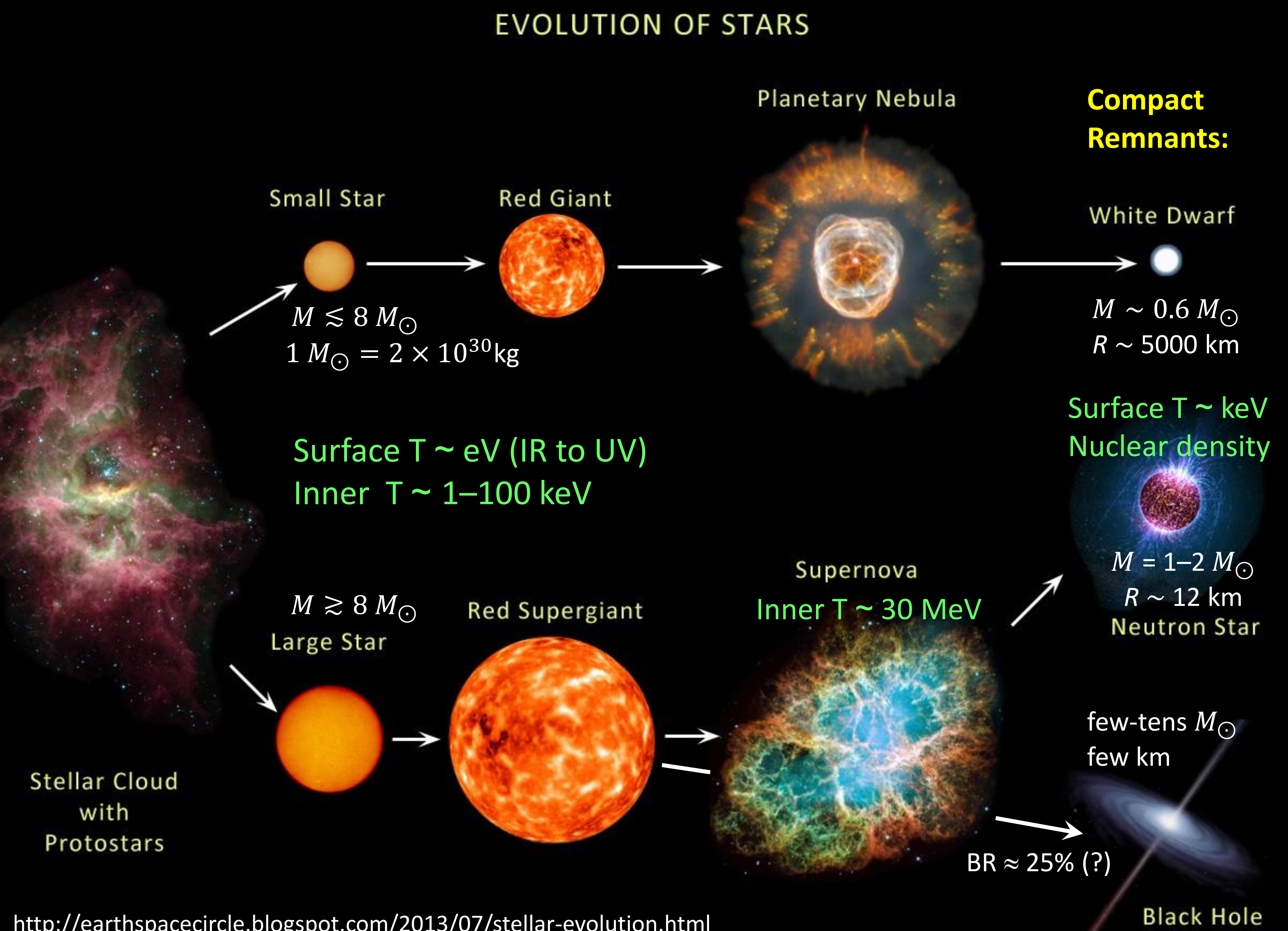
- Bernstein, Ruderman & Feinberg:
  Electromagnetic properties of the neutrino, Phys. Rev. 132 (1963) 1227
- Gribov & Pontecorvo:
  Neutrino astronomy and lepton charge, PLB 28 (1969) 493
- Cowsik:
  Limits on the radiative decay of neutrinos, PRL 39 (1978) 511
- Falk & Schramm:
  Limits from supernovae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

Flavor oscillations!

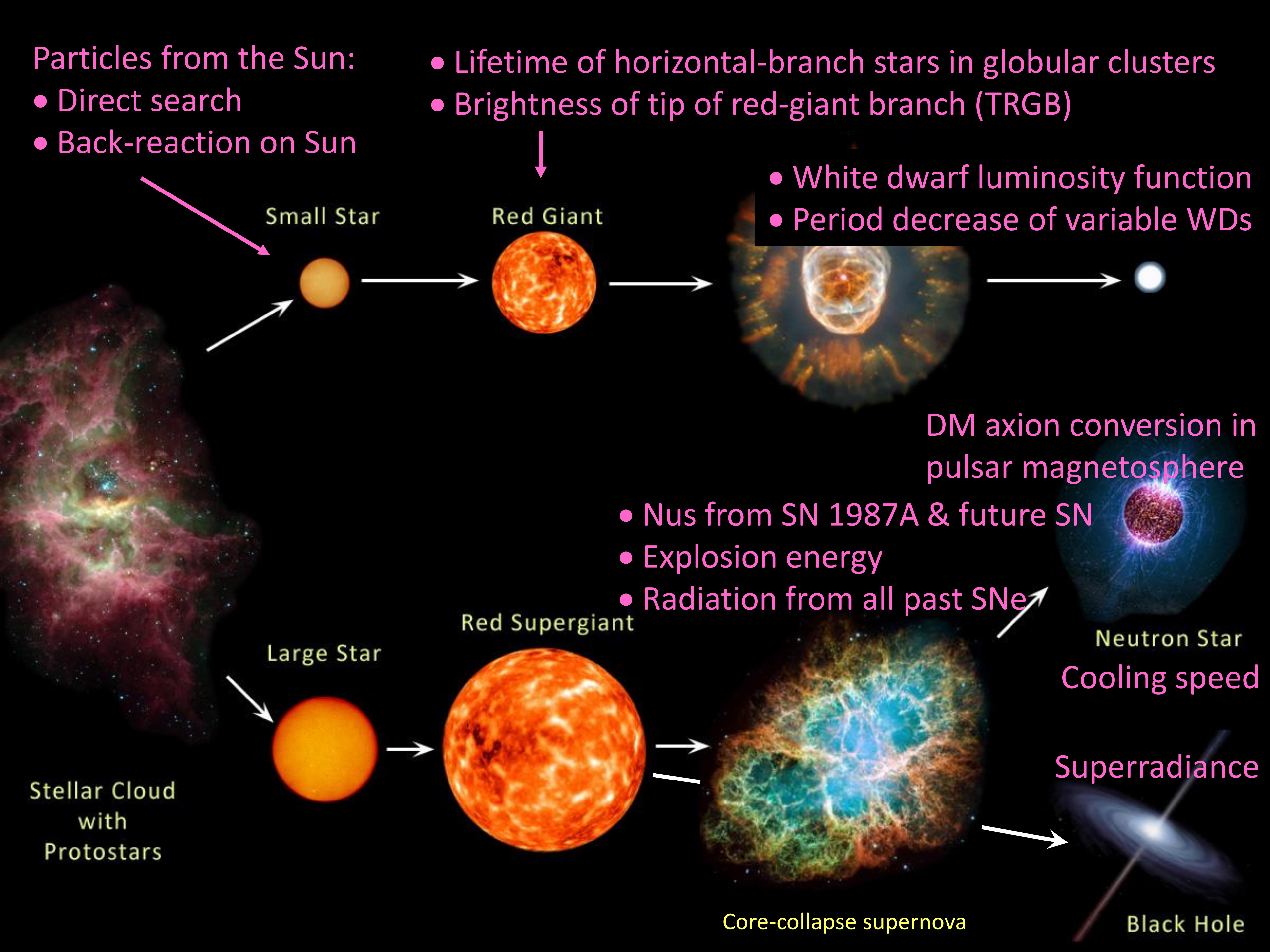
Axions & light Higgs (ca 1978)

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


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



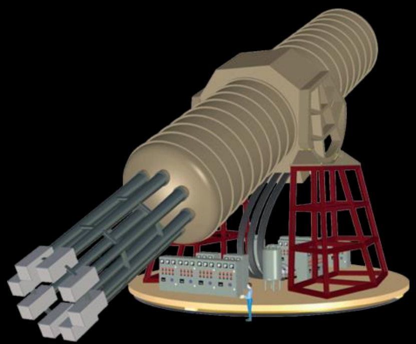
http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html


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

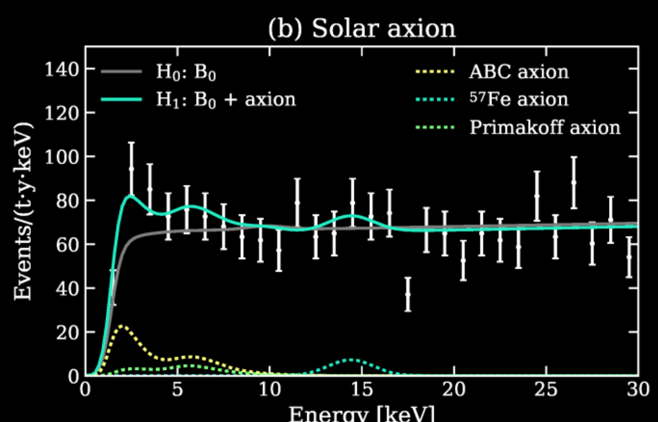
Particles from the Sun

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

2015 Solar Nu Oscillations (A.McDonald)



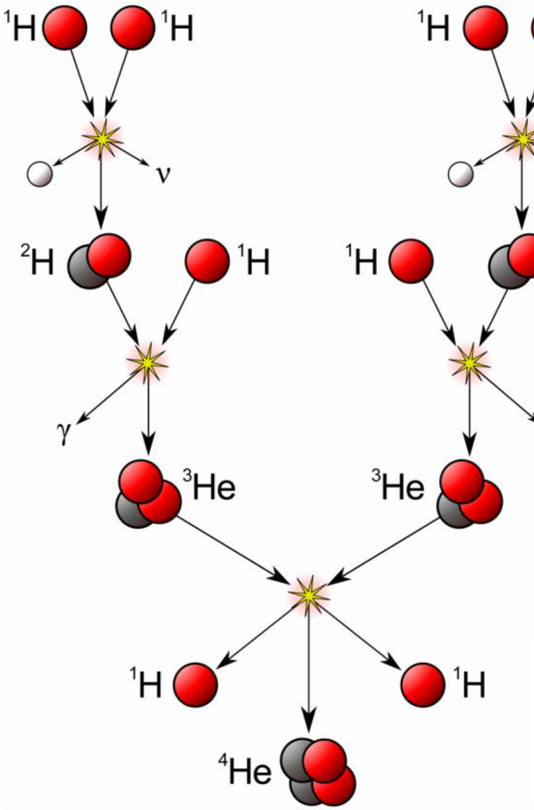
Search for solar axions
with CAST and future IAXO



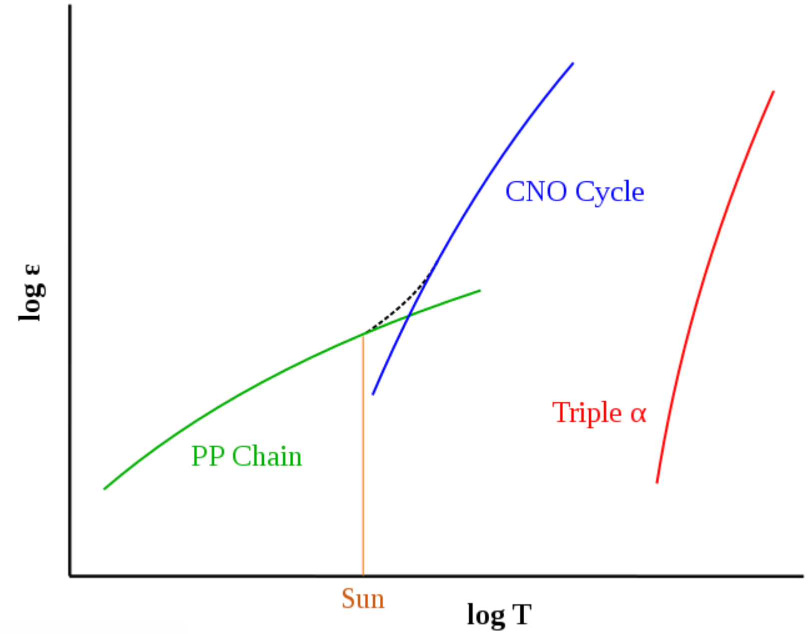
Excess events in
XENON1T DM search.
Solar axions?
arXiv:2006.09721

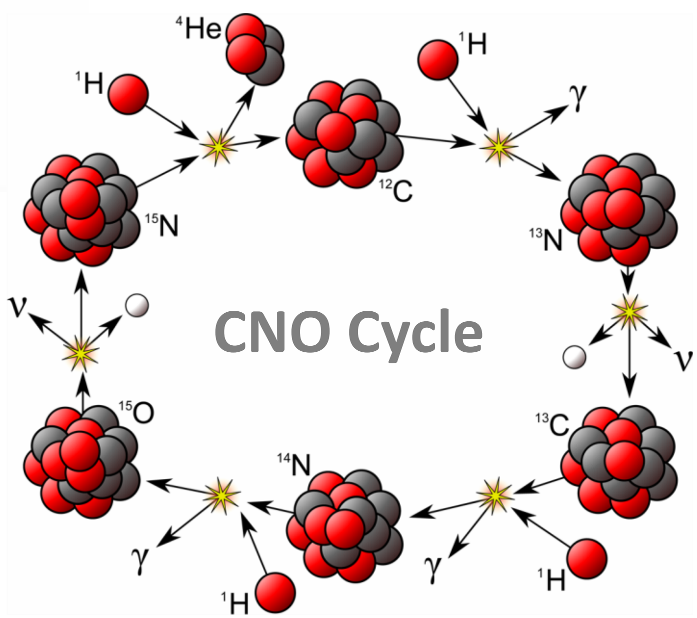
Borexino
has for the first time
observed
solar neutrinos
from the CNO
hydrogen fusion cycle

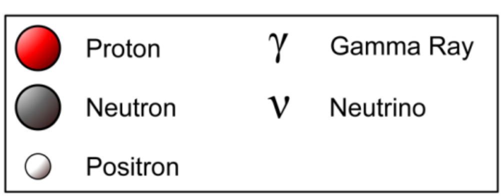
Hydrogen Burning in Stars



pp-I Chain

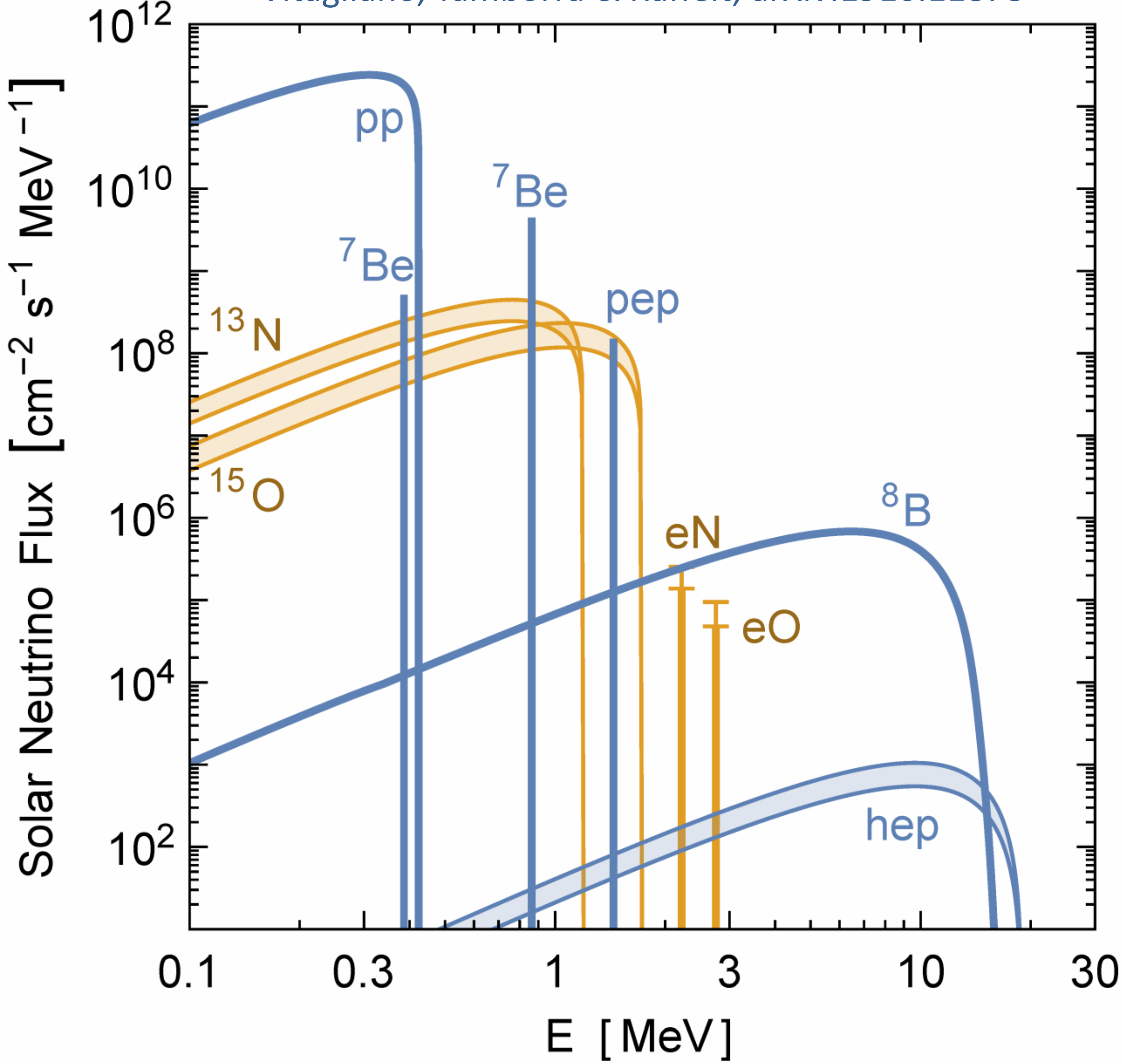






Picture credit Wikipedia

Vitagliano, Tamborra & Raffelt, arXiv:1910.11878

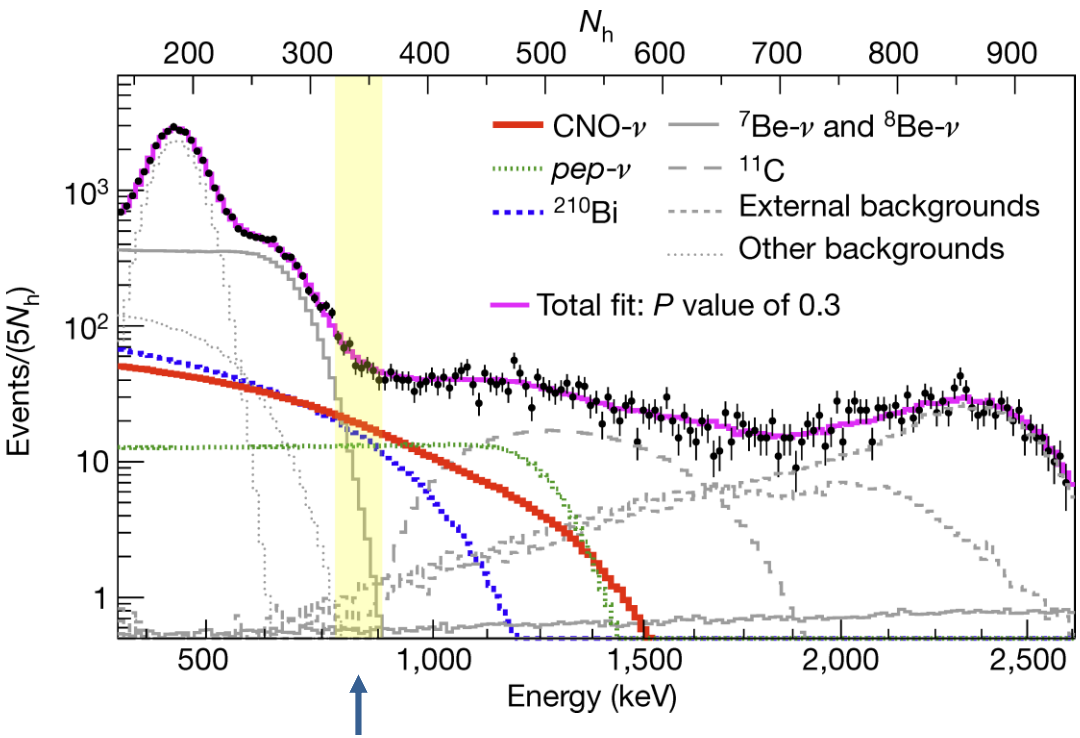


All components of pp chains (blue) have been measured

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

Favors higher flux, but cannot decide between "high" and "low" CNO abundance

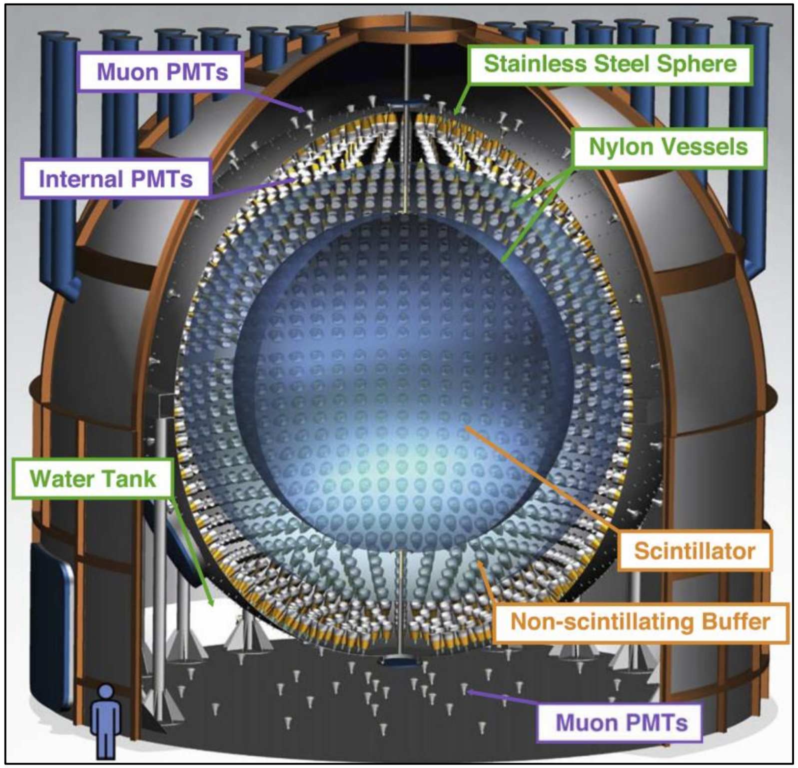
Solar Neutrino Spectroscopy with Borexino



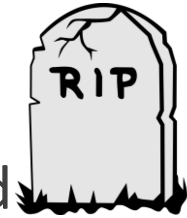
Region of interest:
Crucial background beta decay of ^{210}Bi

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

Reduction and stabilization by controlling convective flows in scintillator



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



Borexino now being decommissioned

Thermal Neutrinos: Production Processes

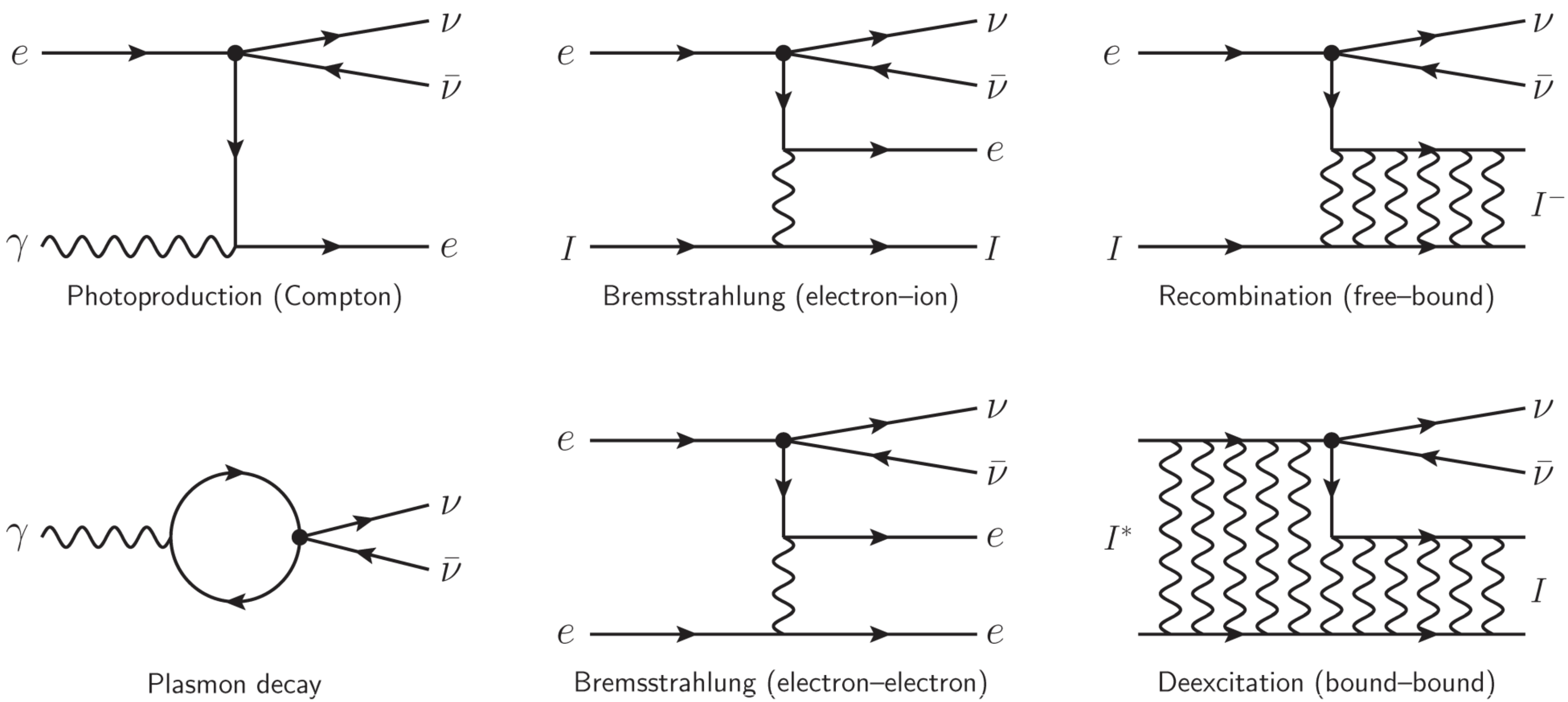
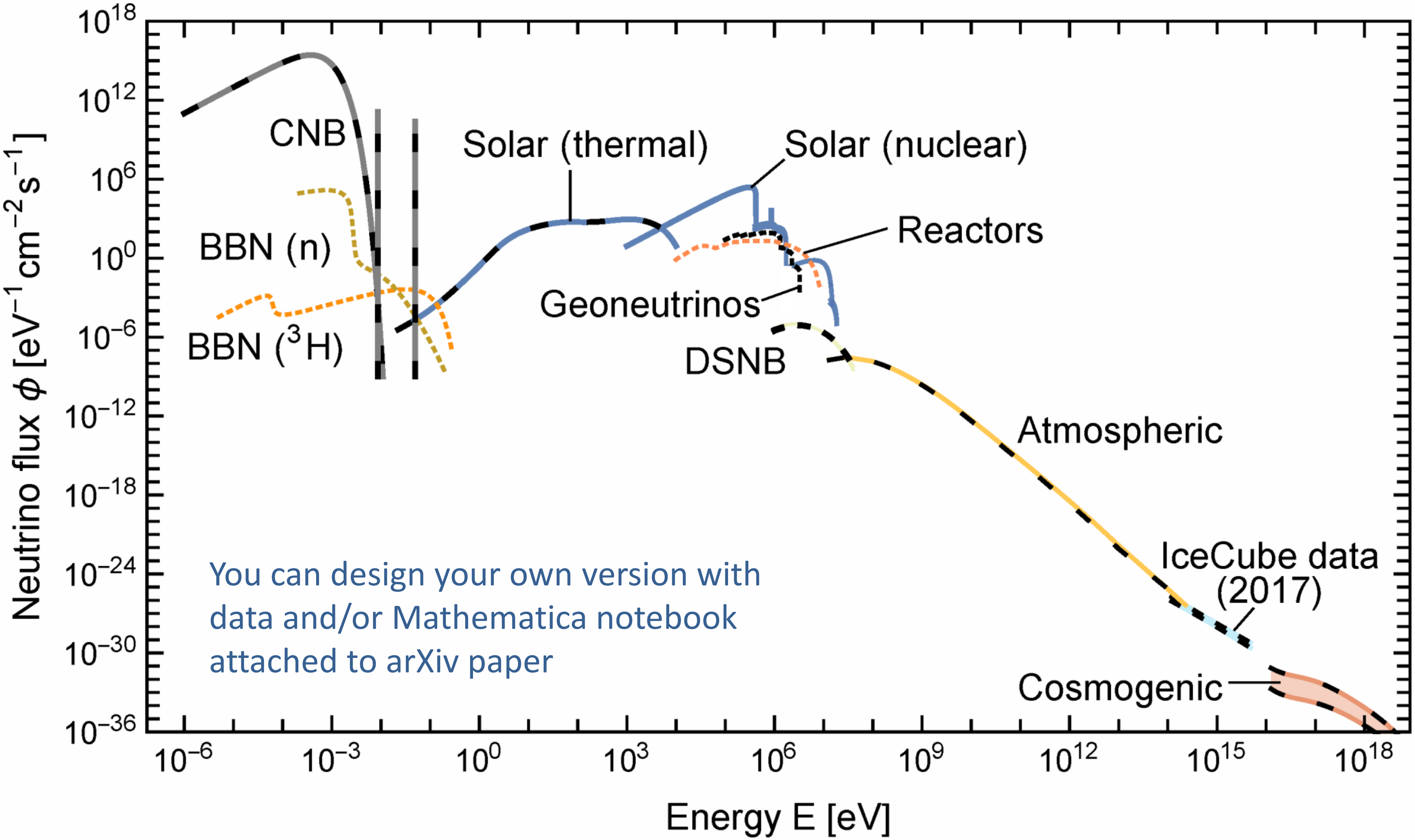


Figure 1. Processes for thermal neutrino pair production in the Sun.

Vitagliano, Redondo & Raffelt, arXiv:1708.02248

Grand Unified Neutrino Spectrum (GUNS) at Earth

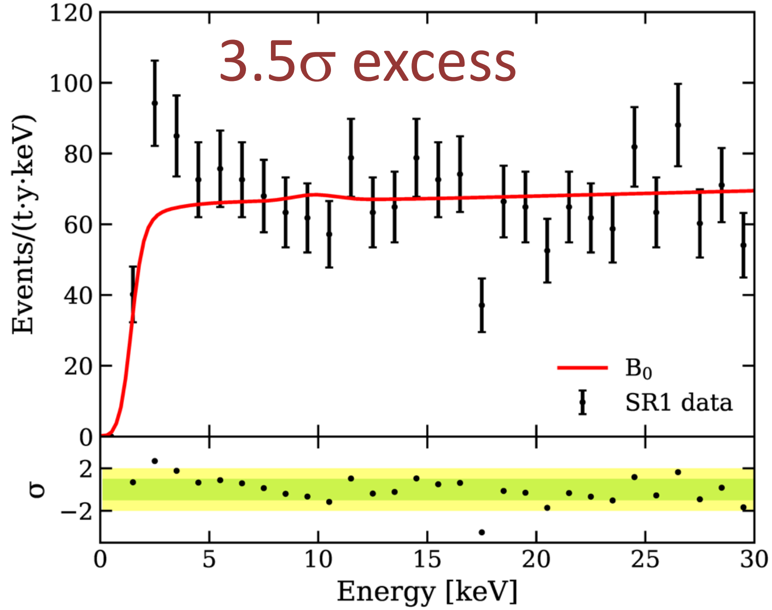
Vitagliano, Tamborra & Raffelt, arXiv:1910.11878

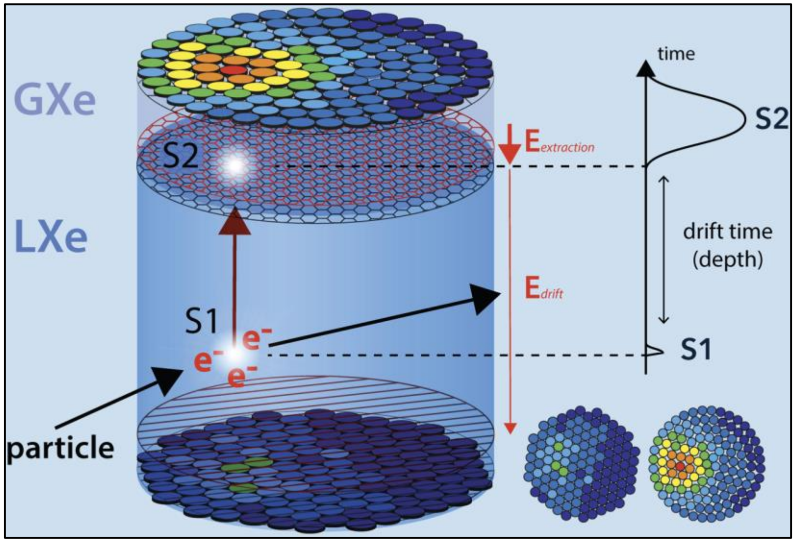


You can design your own version with data and/or Mathematica notebook attached to arXiv paper

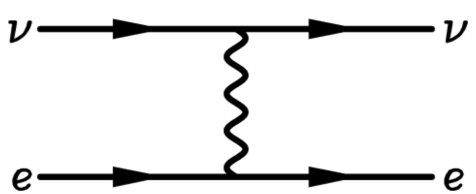
Observation of Excess Electronic Recoil Events in XENON1T

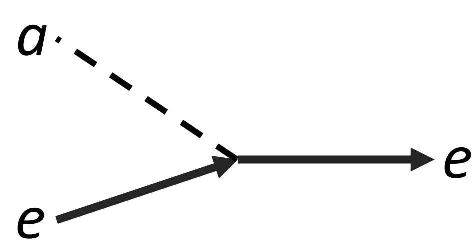
arXiv:2006.09721 (17 June 2020), ~ 370 citations inSPIRE (Jan 2022)





Caused by solar neutrinos or axions from the Sun?





Solar neutrinos with dipole moments
$\mu_\nu = 14 - 29 \times 10^{-12} \mu_B$ **(90% CL)**
(Astro bound $\mu_\nu < 1.5 \times 10^{-12} \mu_B$**)**

Solar axions (keV energies)
(Also violates astro bounds)

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

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

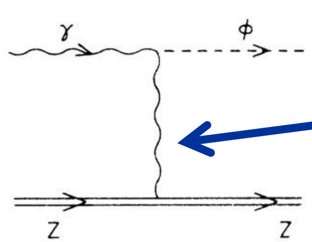


FIG. 2. $\gamma + Z \to \phi + Z$ via the Primakoff process.

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

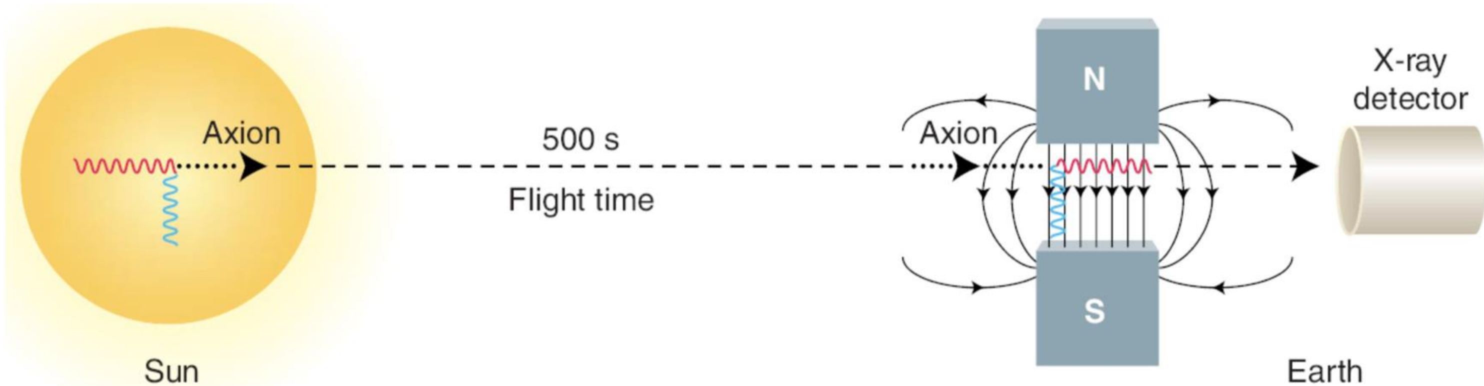
VOLUME 51, NUMBER 16 PHYSICAL REVIEW LETTERS 17 OCTOBER 1983

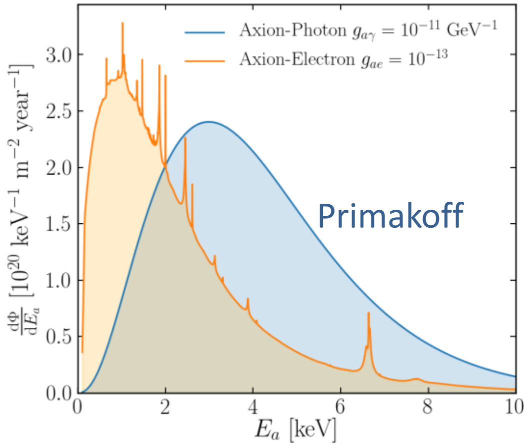
Experimental Tests of the "Invisible" Axion

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…

…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

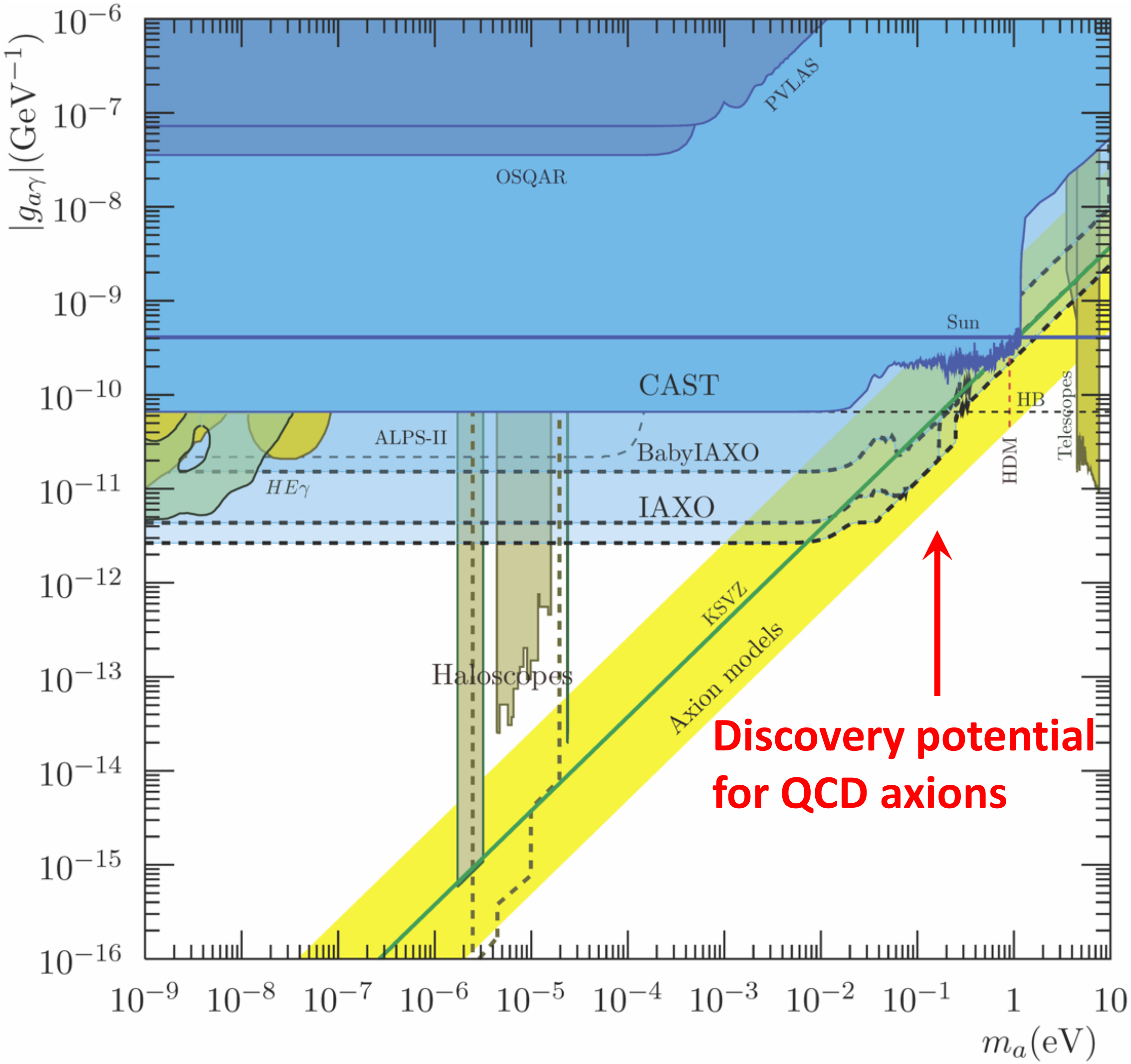
Anastassopoulos+ [1705.02290]

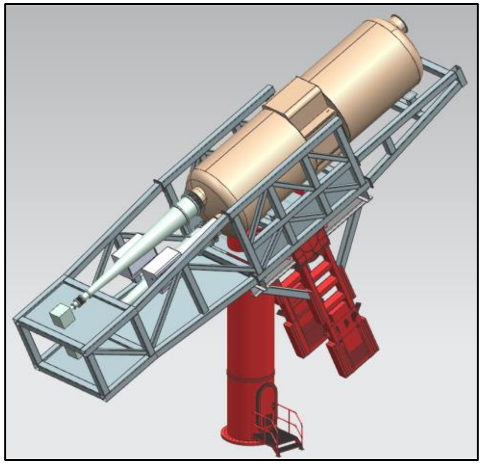
$G_{a\gamma\gamma} < 0.66 \times 10^{-10}\ \mathrm{GeV}^{-1}$

CAST Movie on YouTube

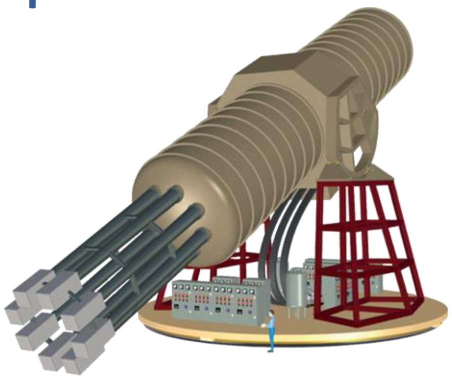
https://youtu.be/XY2lFDXz8aQ

(Baby) IAXO Sensitivity Forecast



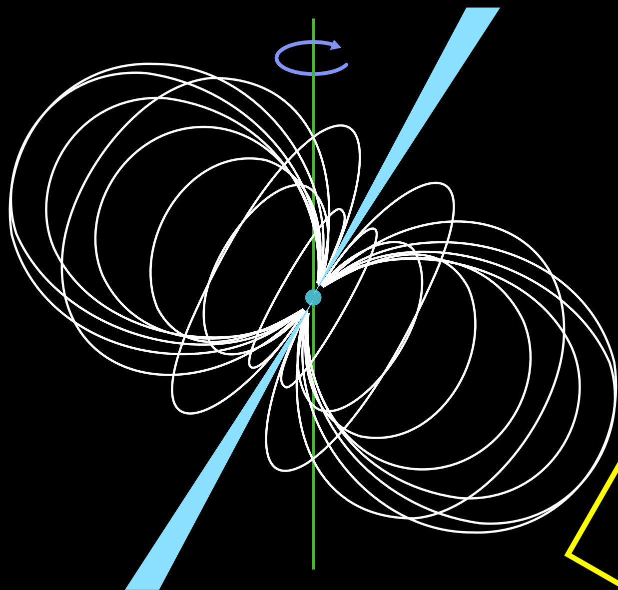


Baby IAXO @ DESY
Operation 2024+



- Conceptual Design of the International Axion Observatory (IAXO), arXiv:1401.3233
- Conceptual Design of BabyIAXO, arXiv:2010.12076

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

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

PHYSICAL REVIEW LETTERS **125,** 171301 (2020)

Featured in Physics

arXiv:2004.00011

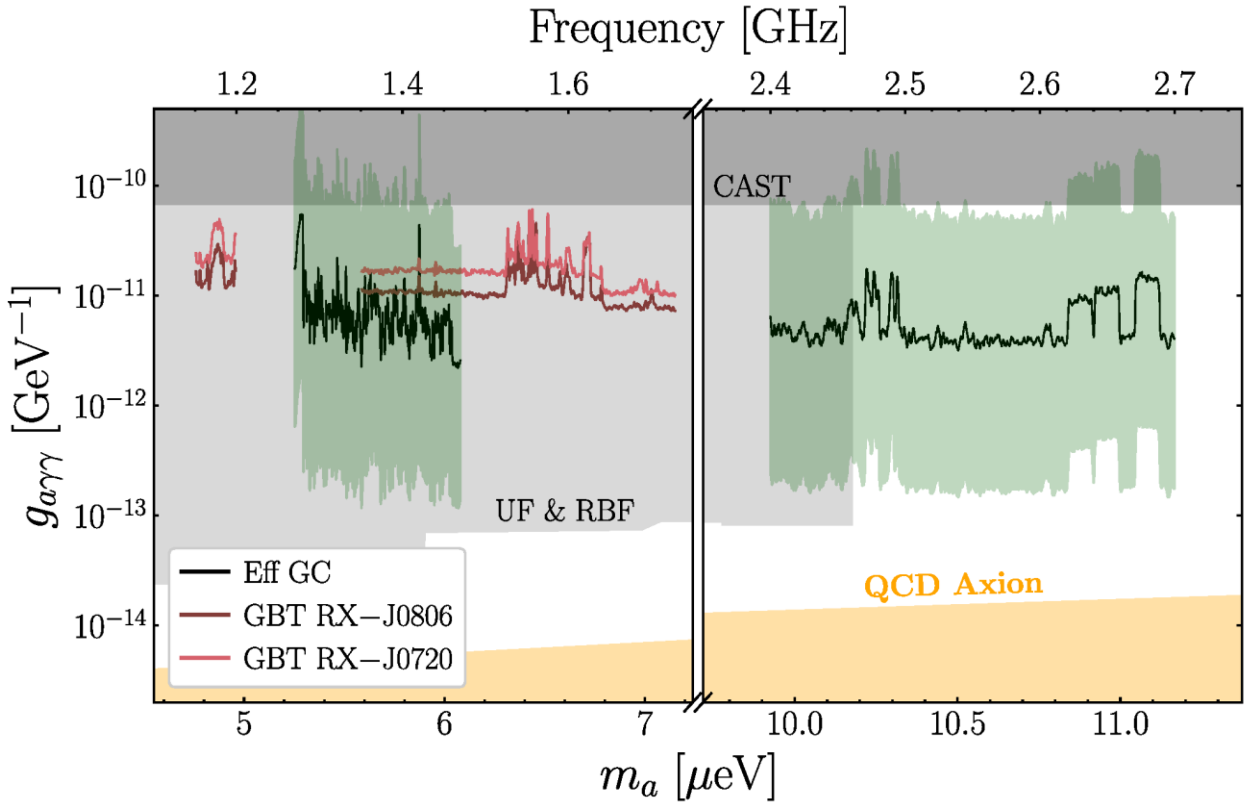
See also Battye+ 2107.01225

Green Bank and Effelsberg Radio Telescope Searches for Axion Dark Matter Conversion in Neutron Star Magnetospheres

Joshua W. Foster,[1,*] Yonatan Kahn,[2] Oscar Macias,[3,4] Zhiquan Sun,[1] Ralph P. Eatough,[5,6] Vladislav I. Kondratiev,[7,8] Wendy M. Peters,[9] Christoph Weniger,[4,†] and Benjamin R. Safdi[1,‡]

Green Bank

Effelsberg



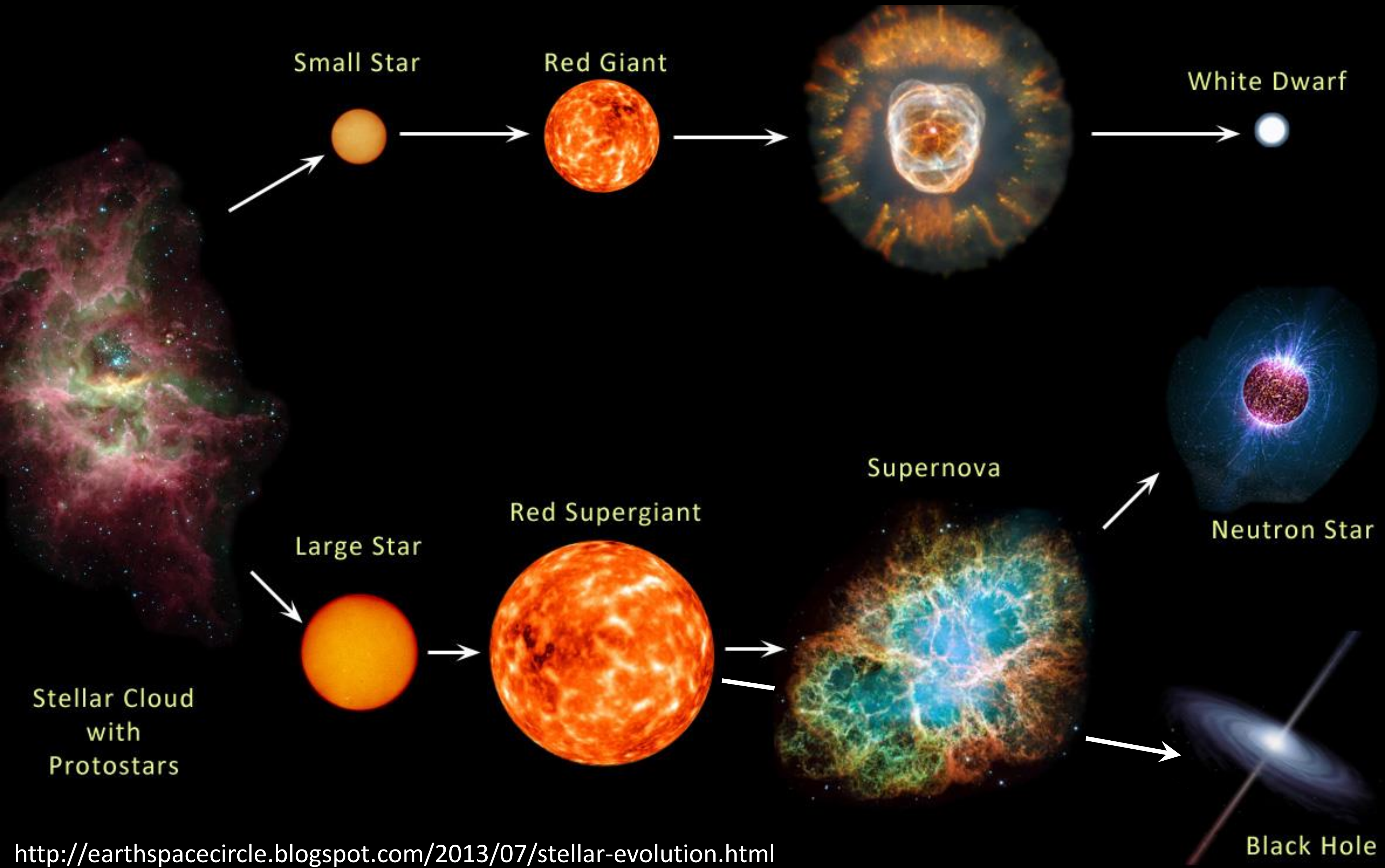
Detecting QCD axions requires more observation time and/or larger telescopes (FAST, SKA)


NEW
Thermal Imaging Scopes
AXION XQ
PULSAR
AXION


PULSAR AXION KEY XM 22

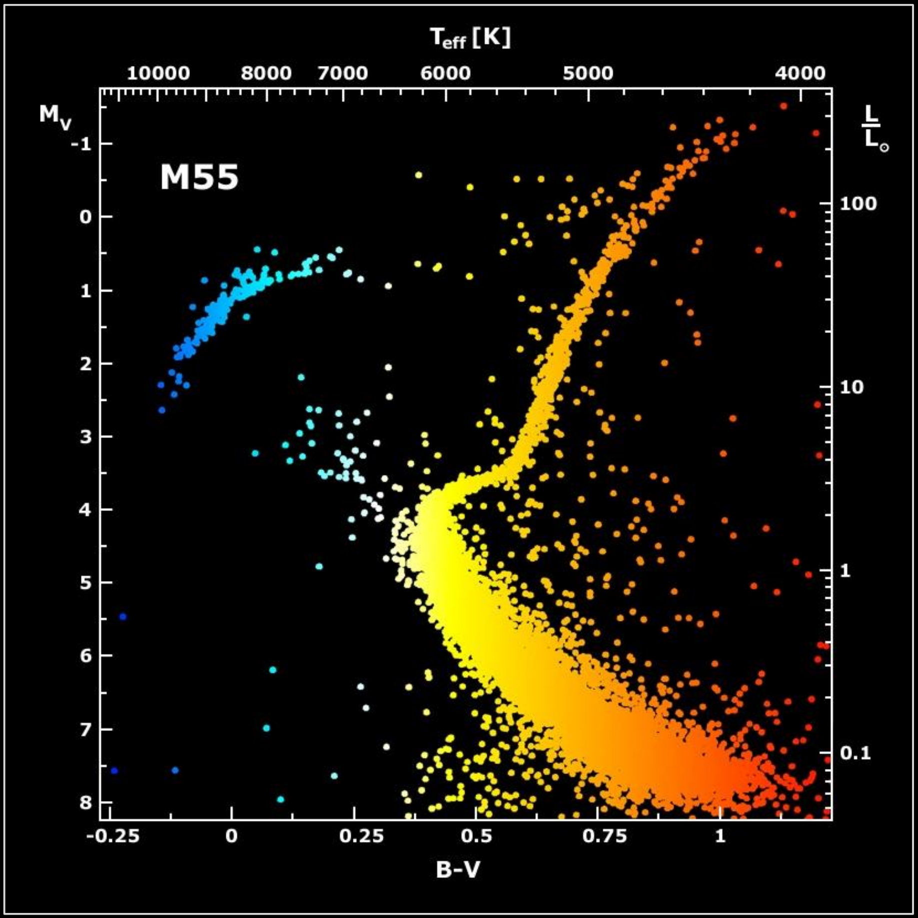
EVOLUTION OF STARS

What can we learn from this discontinuous evolution?

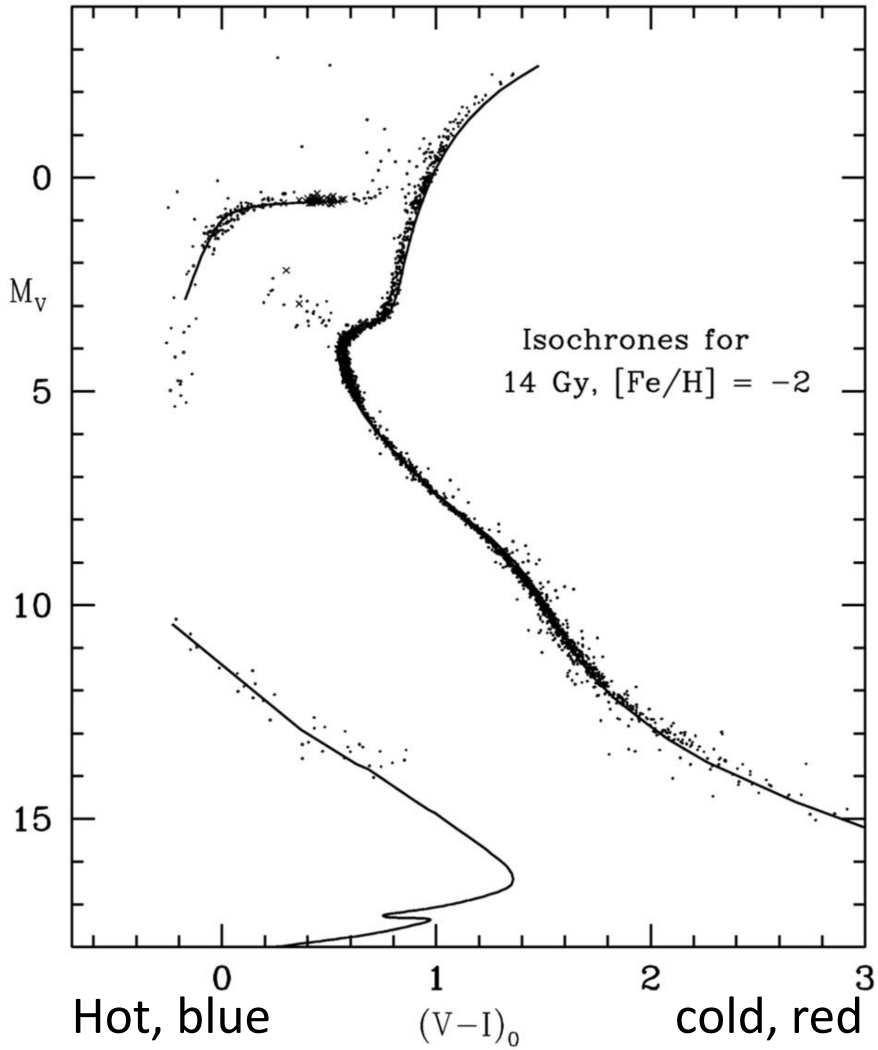


http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html

Galactic Globular Cluster M55

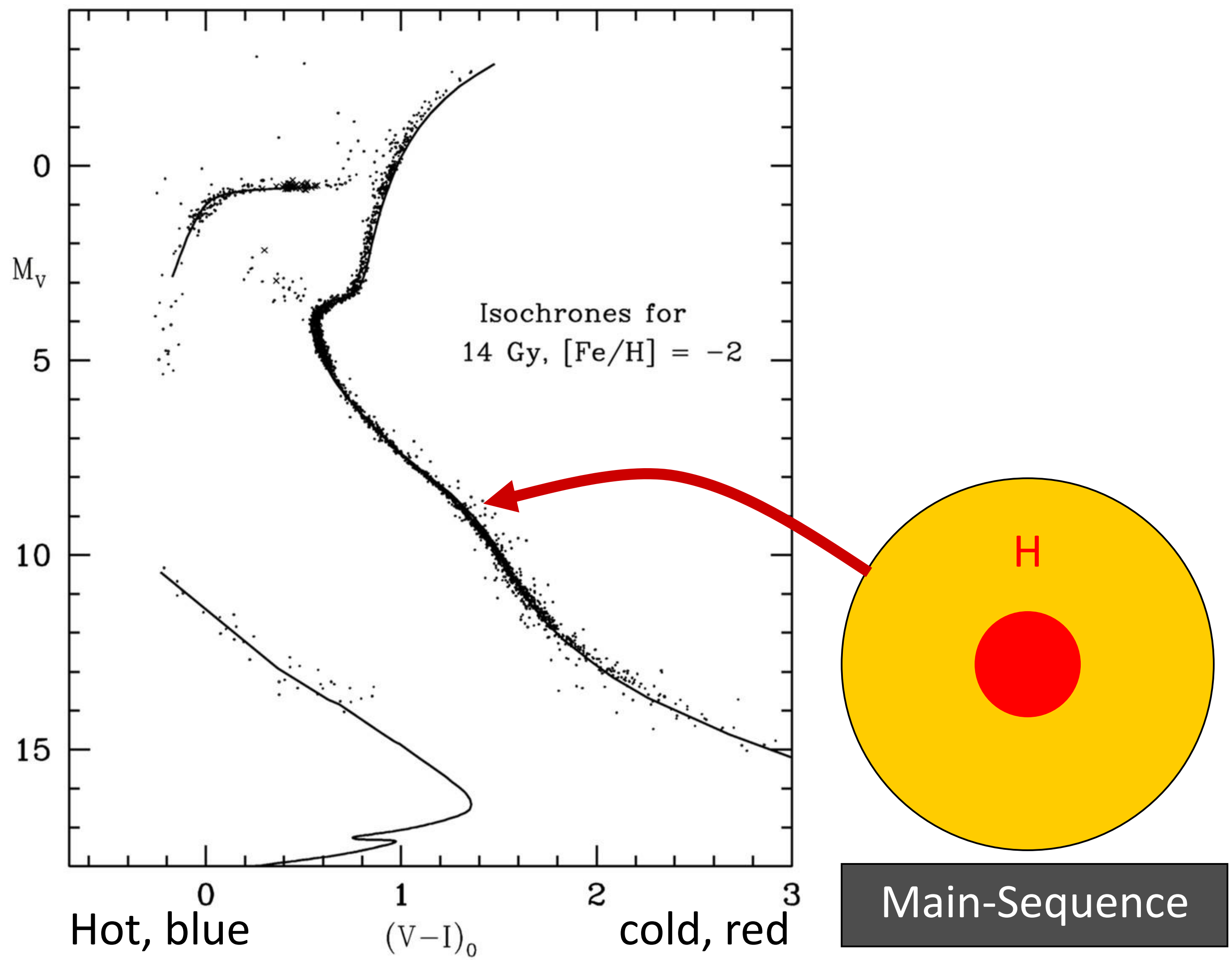


Color-Magnitude Diagram for Globular Clusters



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

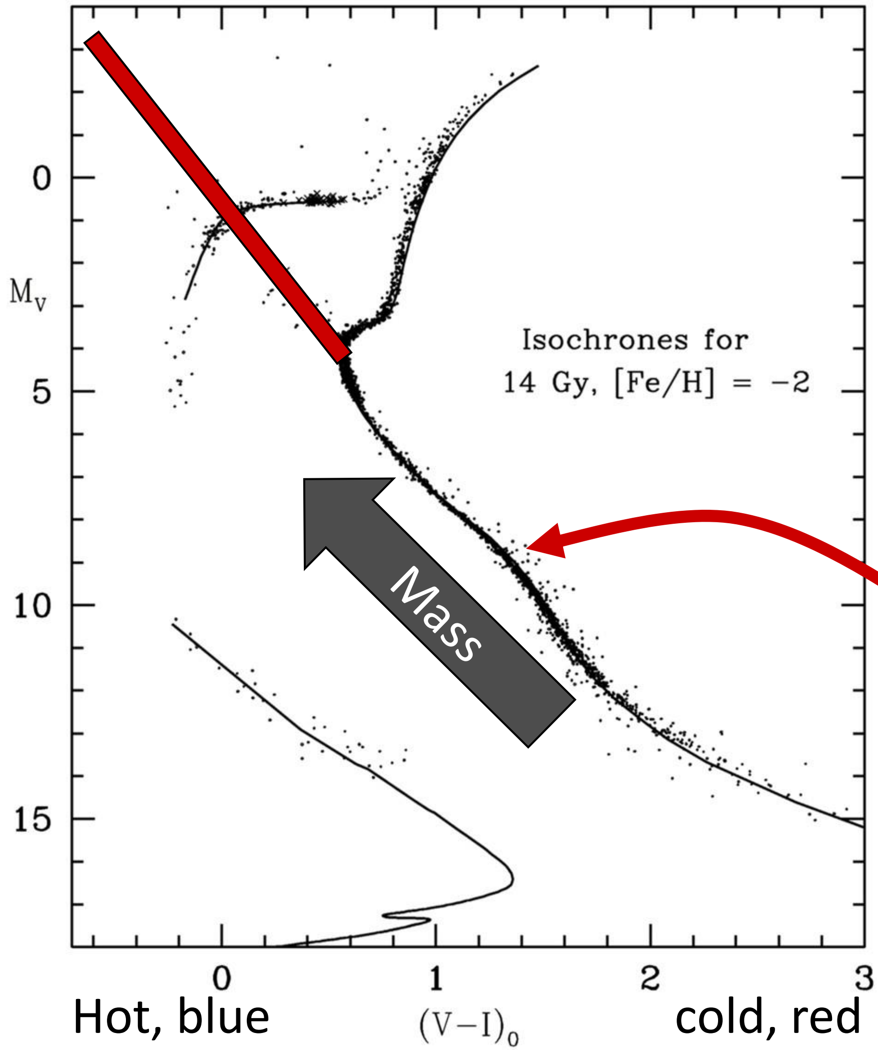
Color-Magnitude Diagram for Globular Clusters

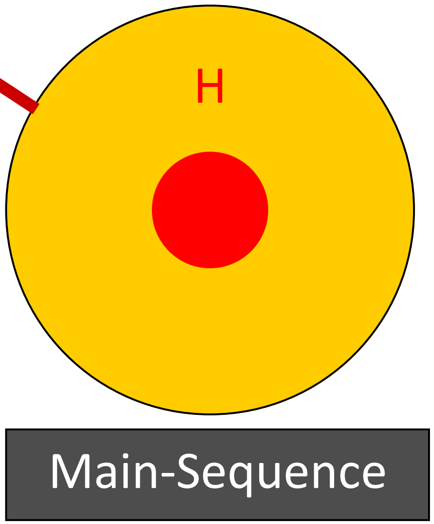


Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

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





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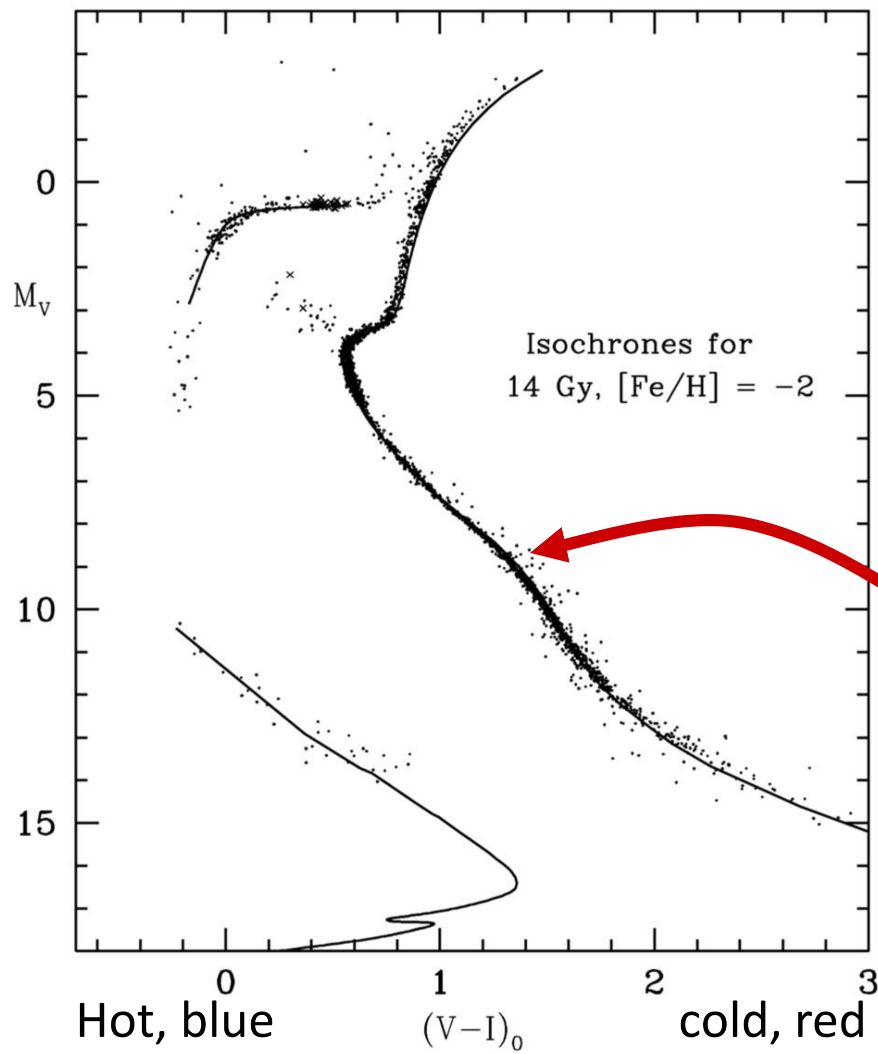

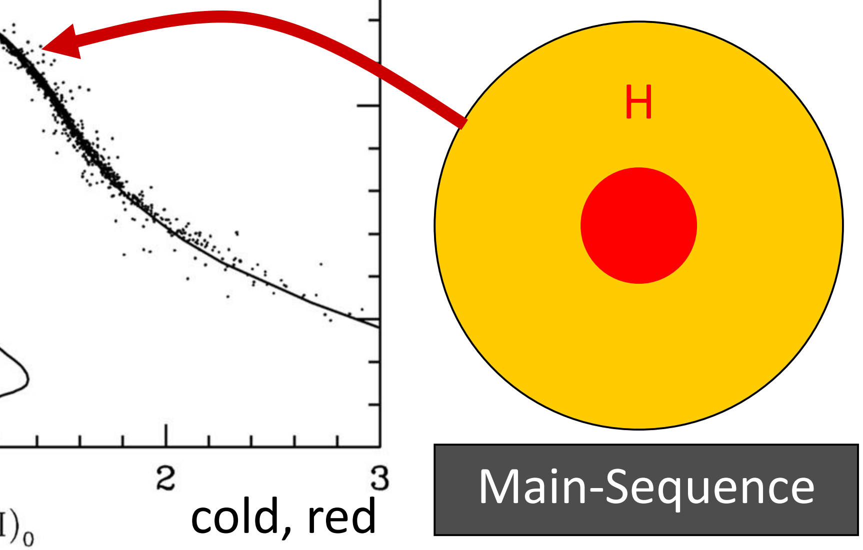

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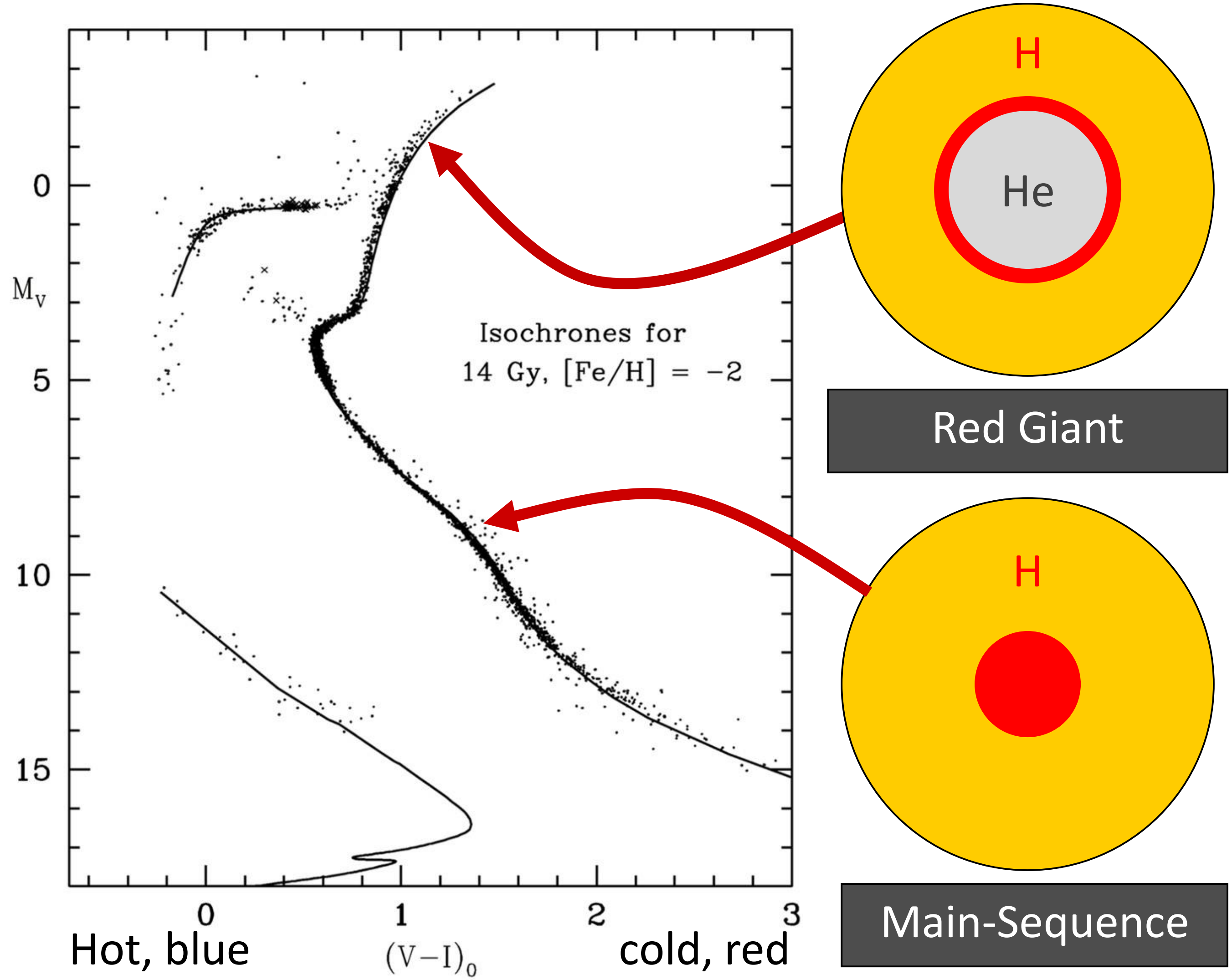

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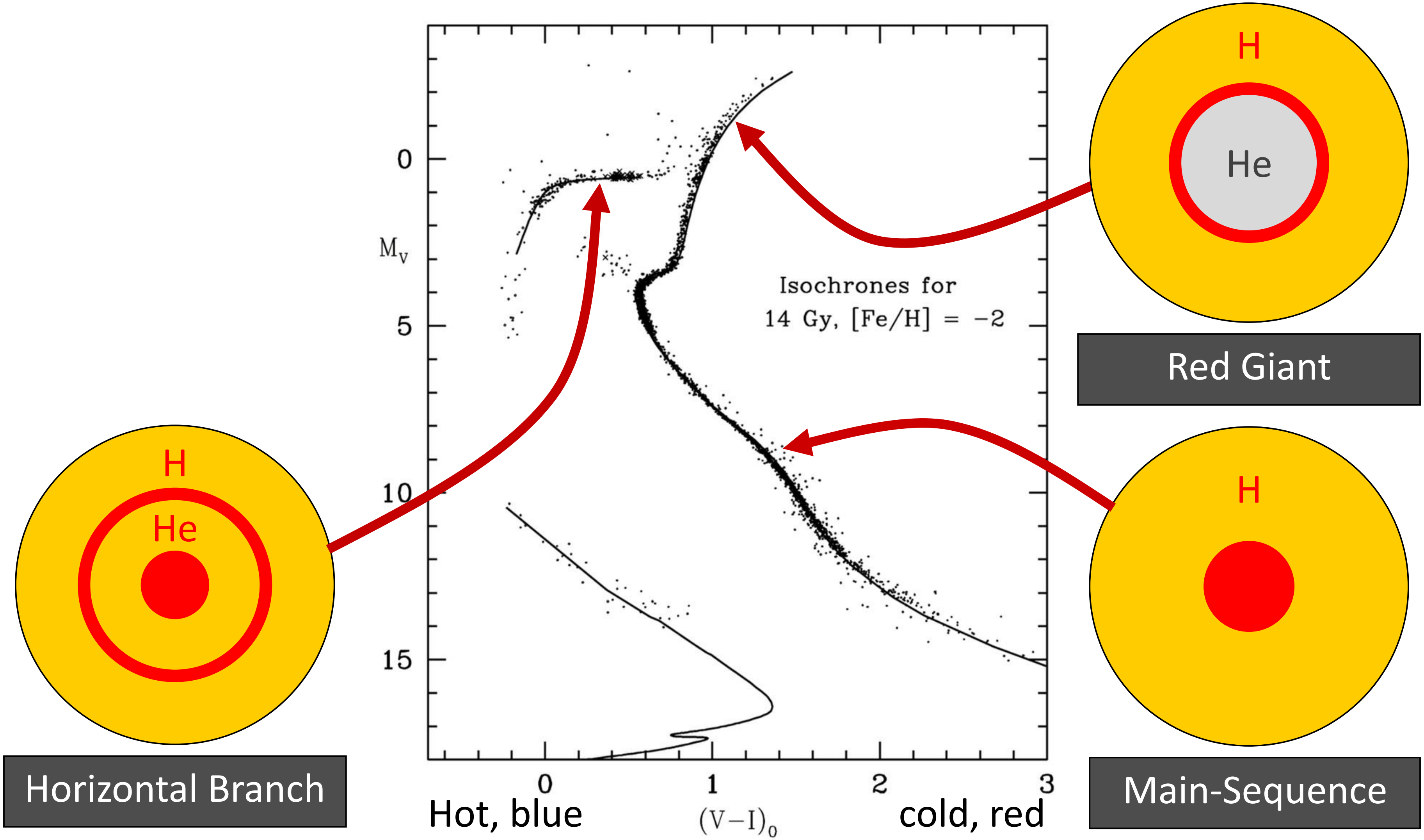

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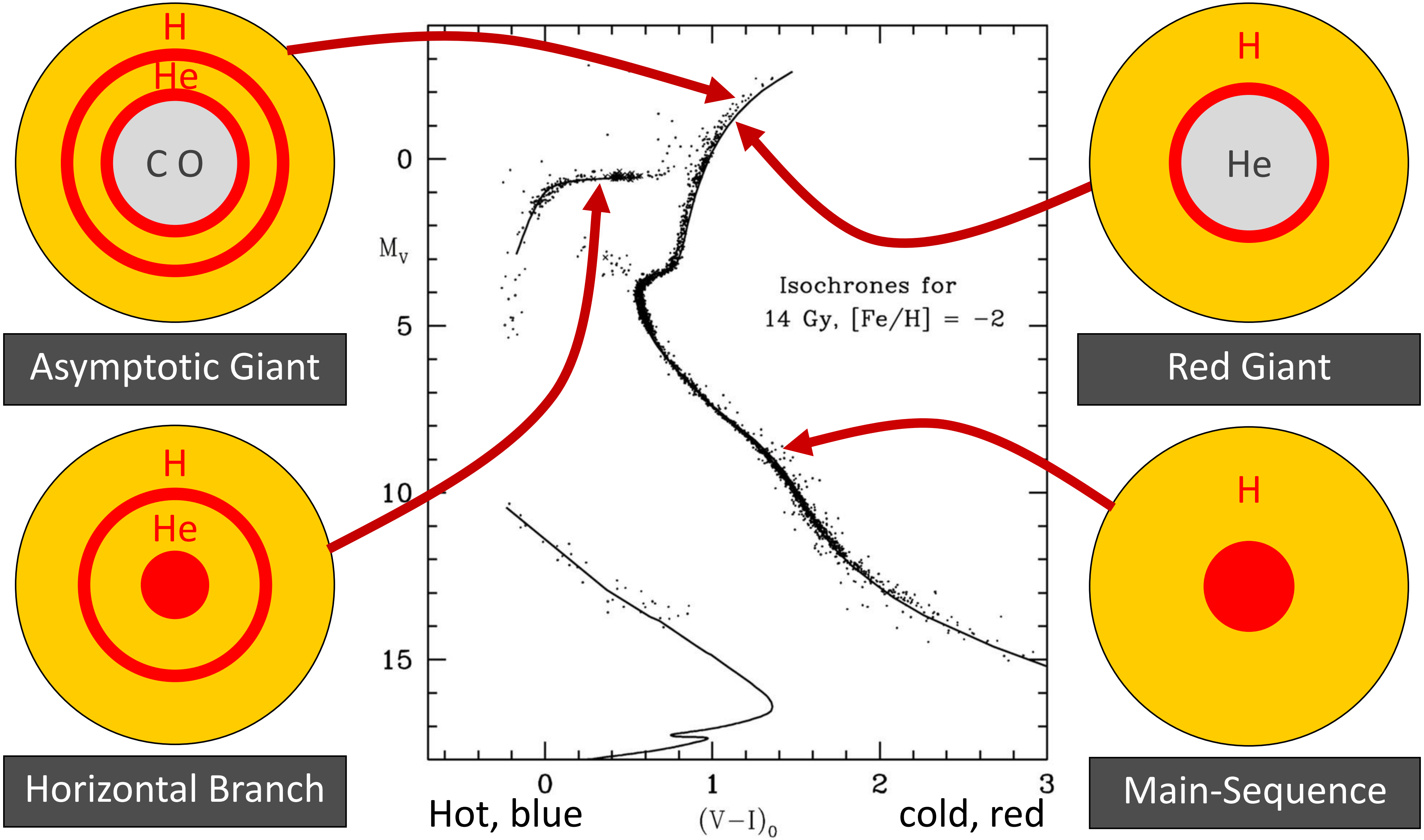

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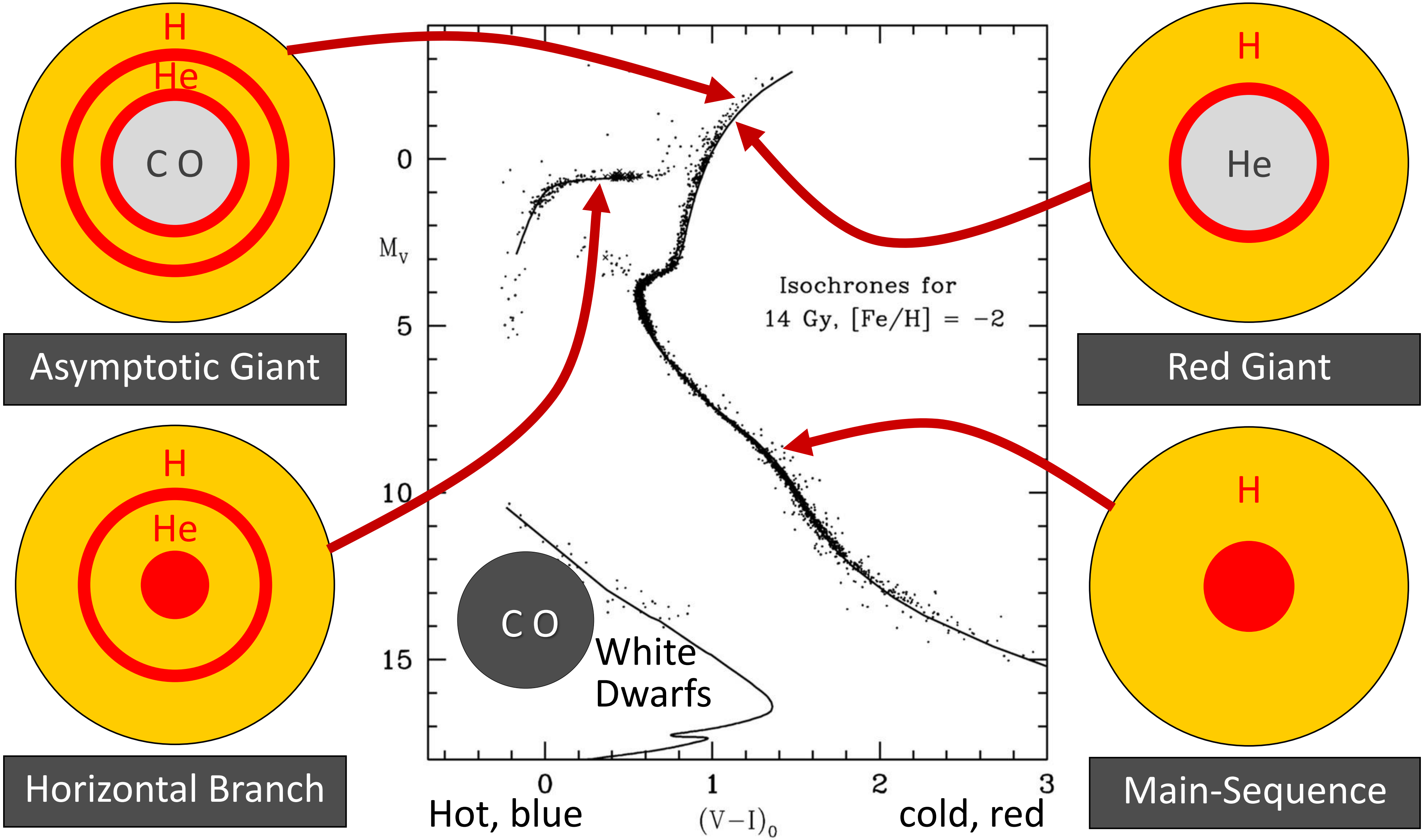
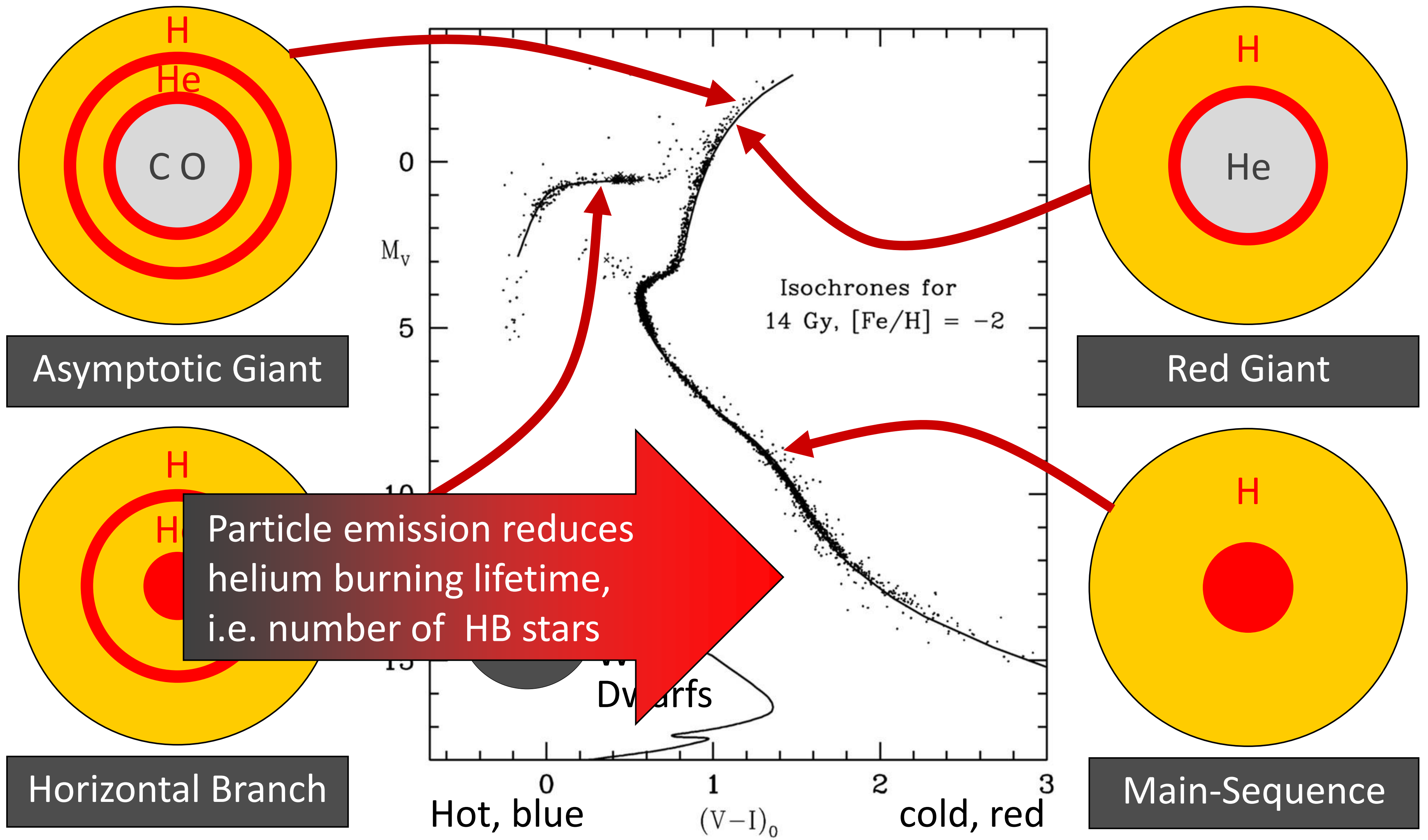


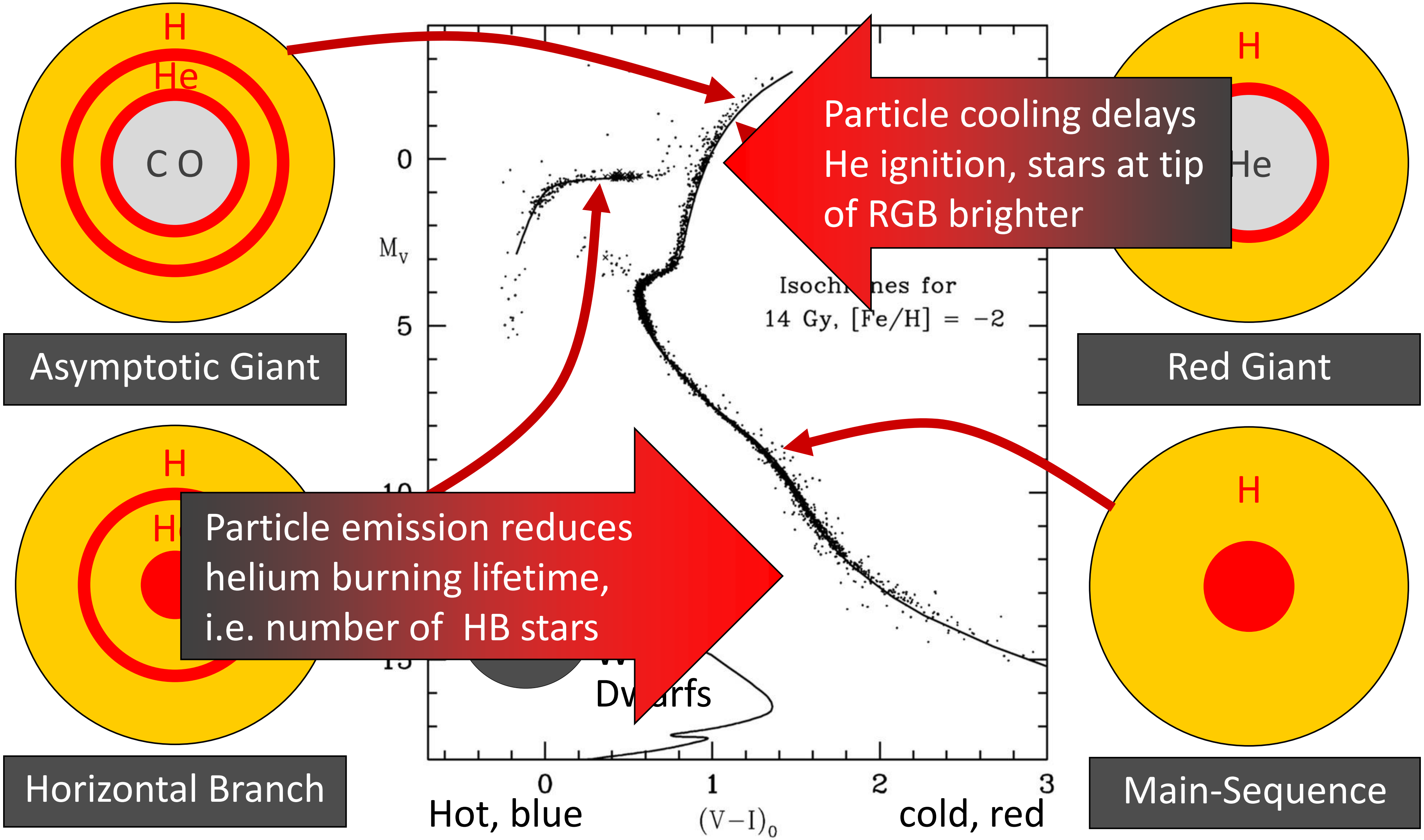
Color-magnitude diagram synthesized from several low-metallicity globular clusters and compared with theoretical isochrones (W.Harris, 2000)

Color-Magnitude Diagram for Globular Clusters



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

Color-Magnitude Diagram for Globular Clusters



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

TRGB in 46 Globular Clusters [Cerny+ 2012.09701]

Brightness and Core Mass at TRGB

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

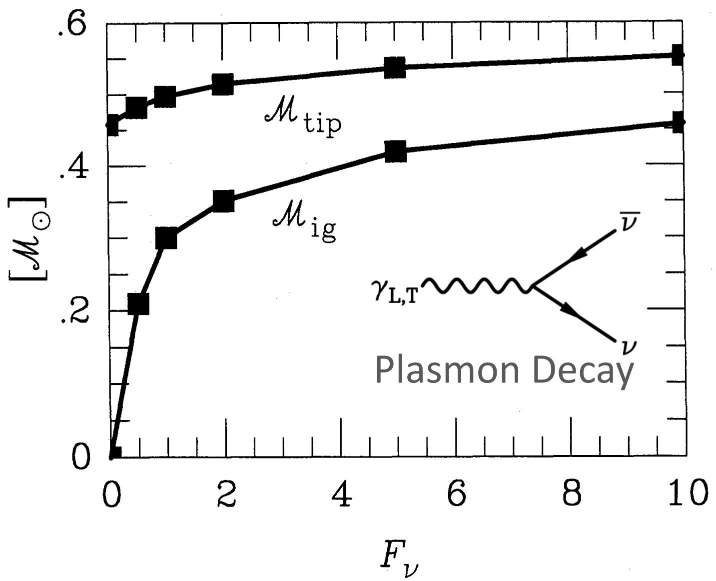


Fig. 2. Core mass at helium flash, $\mathcal{M}_{\rm tip}$, and mass-coordinate of the ignition point, $\mathcal{M}_{\rm ig}$, as a function of F_ν for $\mathcal{M} = 0.80$, $Z = 10^{-4}$, and $Y_0 = 0.22$ (see Table 2).

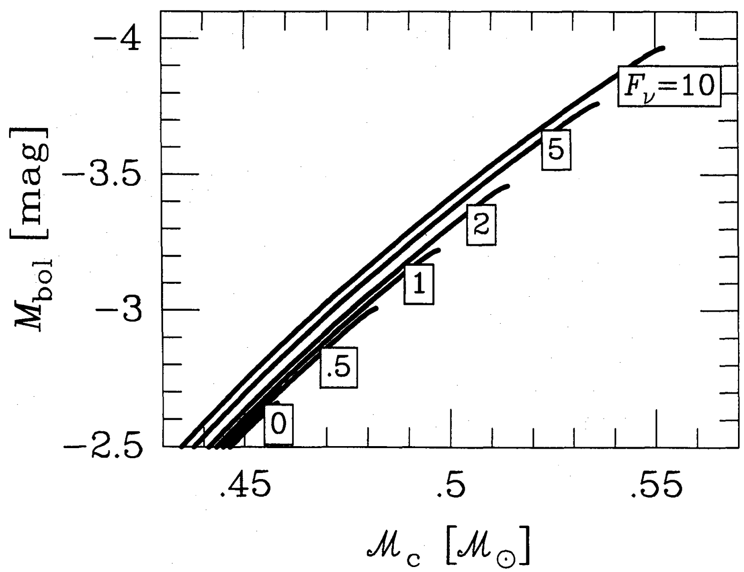


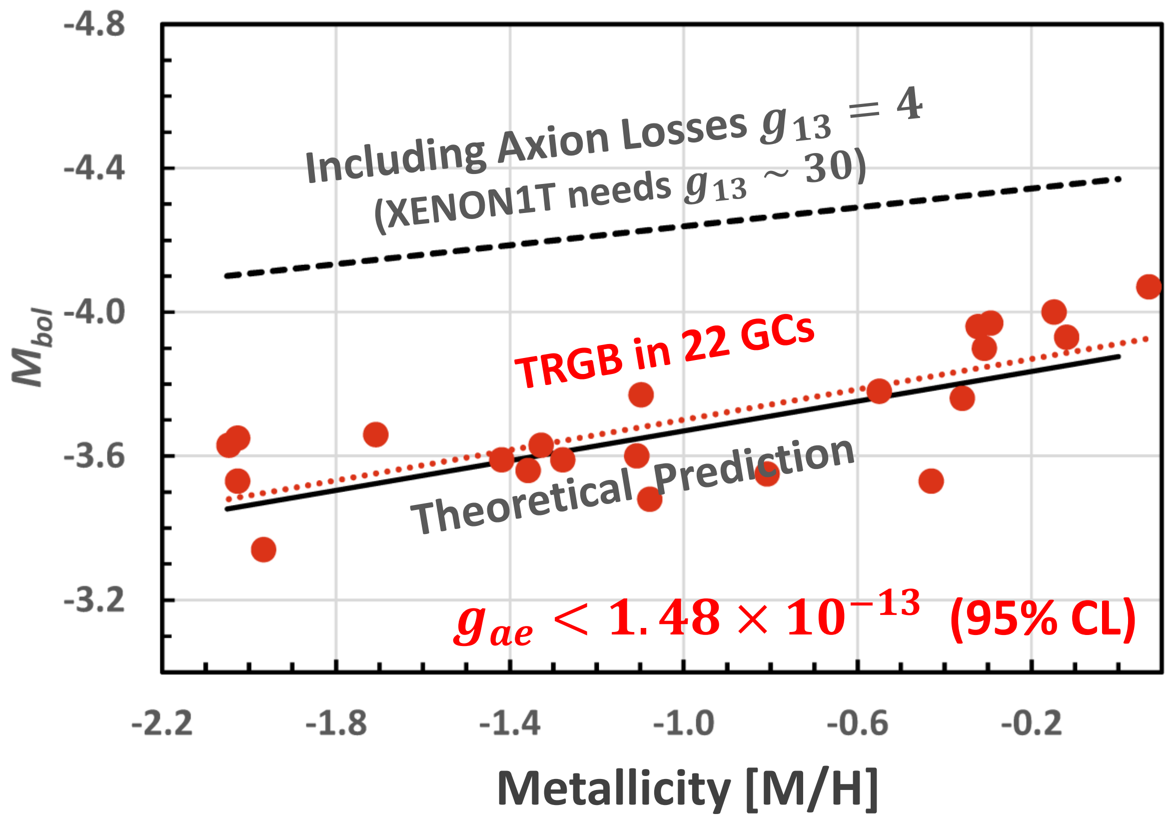
Fig. 3. Absolute surface brightness as a function of core mass for the $Z = 10^{-4}$ runs of Table 2. The curves are marked with the relevant F_ν values.

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

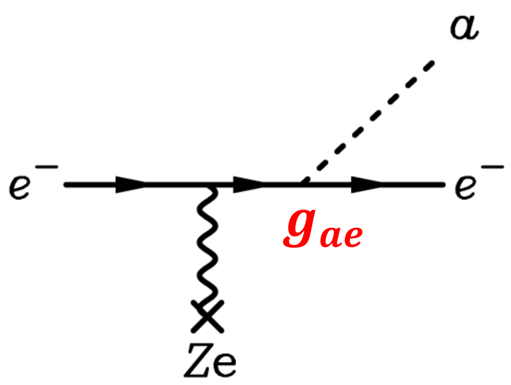
- Helium ignition point (mass coordinate $\mathcal{M}_{ig}$) moves away from center
- Core mass at ignition $\mathcal{M}_{tip}$ grows
- Bolometric brightness at ignition M_{tip} increases

New TRGB Calibration from 22 Globular Clusters

Straniero+ arXiv:2010.03833 (8 Oct. 2020)



Emission of axions & friends with direct electron coupling



Bremsstrahlung emission by degenerate electrons

DFSZ Axions

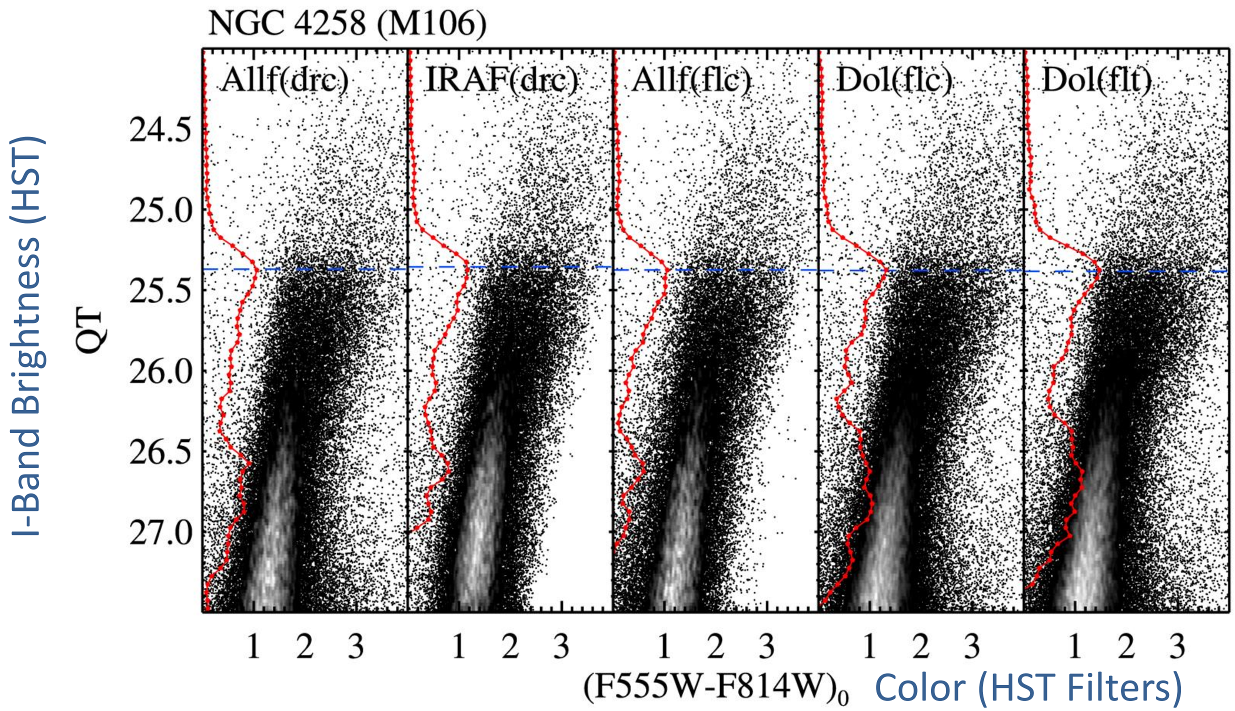
$$m_a = 6\ \text{meV}\,\frac{10^9\text{GeV}}{f_a} \qquad g_{ae} = \frac{m_e C_e}{f_a}$$

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

$$\frac{f_a}{\cos^2\beta} > 1.15 \times 10^9\ \text{GeV}$$

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

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



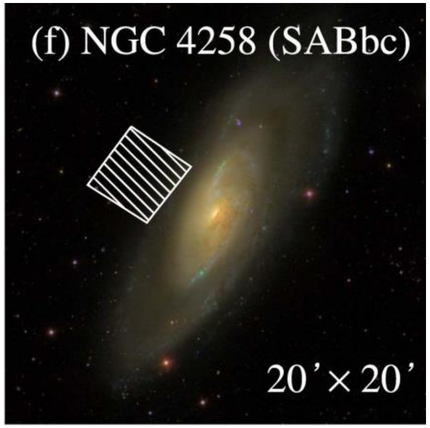
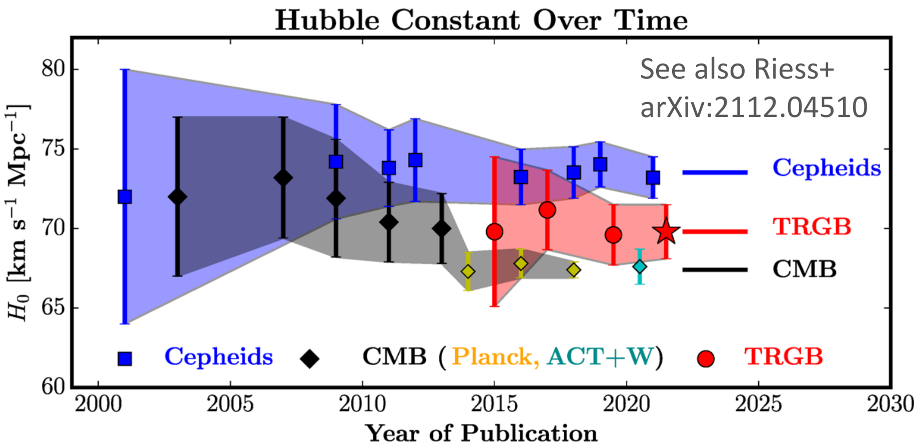
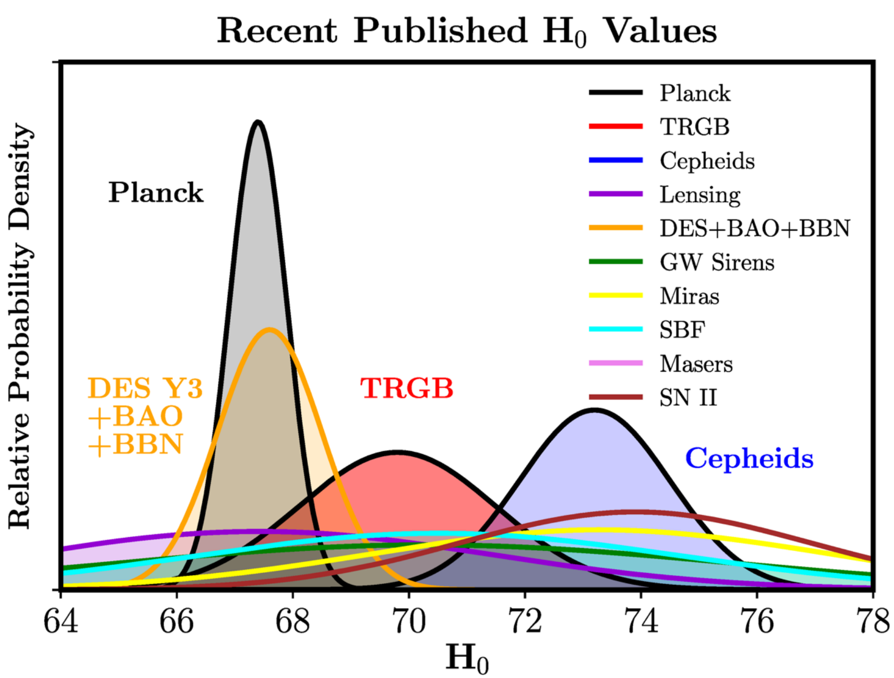


Figure 7. QT − (F555W − F814W)$_0$ CMDs of NGC 4258 from five different reduction methods : ALLFRAME on drc, IRAF/DAOPHOT on drc, ALLFRAME on flc, DOLPHOT on flc, and DOLPHOT on flt (from left to right). Edge detection responses are shown by the solid lines. Note that the estimated TRGB magnitudes (dashed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

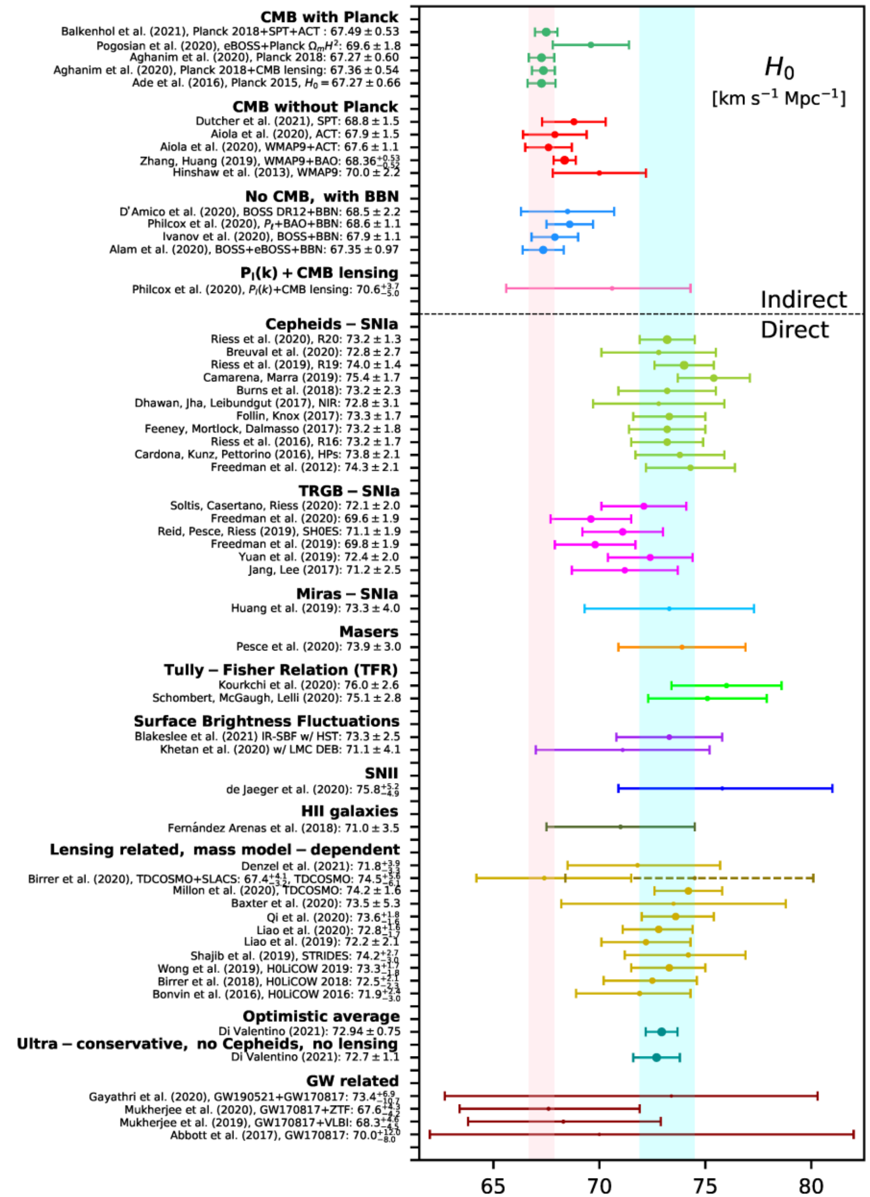
NGC 4258 hosts a water megamaser
→ Quasi-geometric distance determination
→ Among the best absolute TRGB calibrations

Hubble Tension



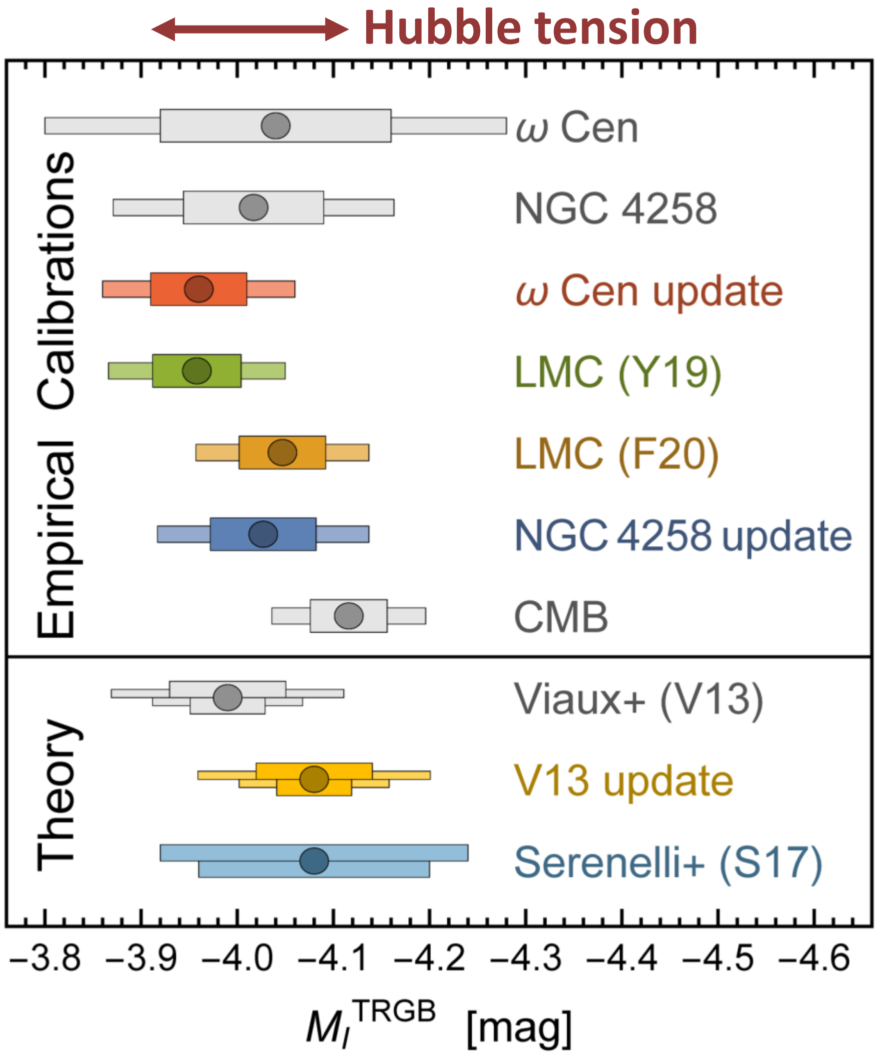


Freedman ApJ 919 (2021) 16 [2106.15656]



Di Valentino+ arXiv:2103.01183

Axion Bounds from TRGB Calibrations



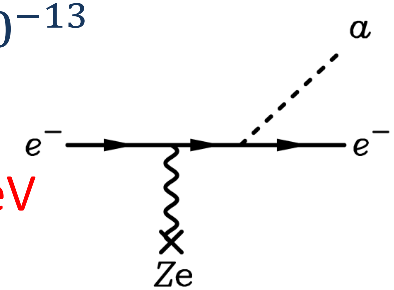
Updated TRGB Calibrations
Capozzi & Raffelt, arXiv:2007.03694

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

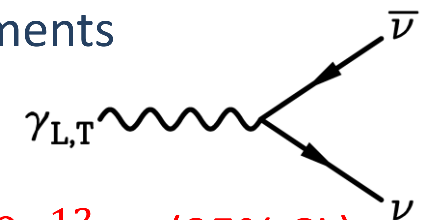
$$g_{ae} < 1.6 \times 10^{-13}$$

DFSZ-axions

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



Neutrino Dipole Moments

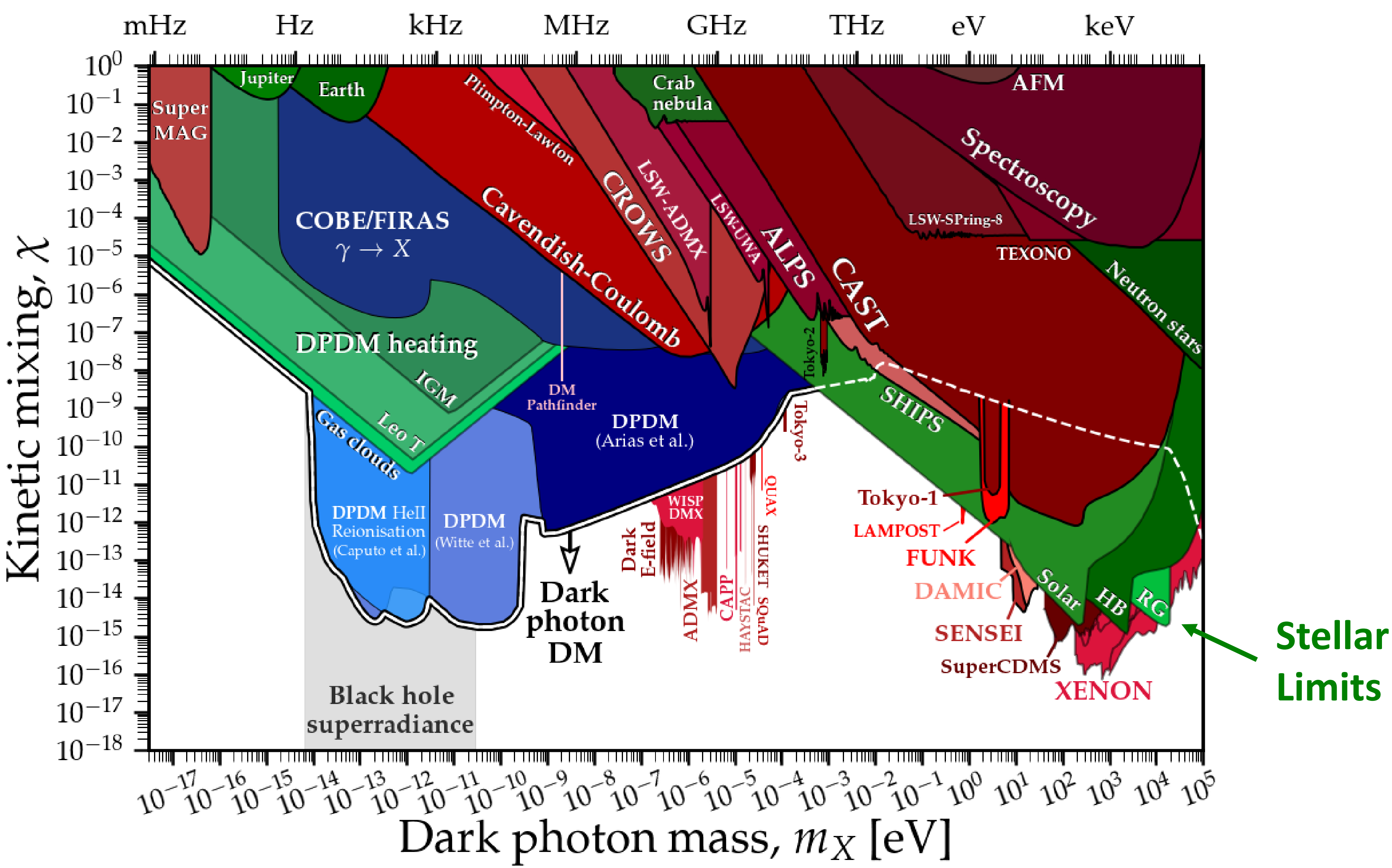


$$\sqrt{\textstyle\sum_i |\mu_i|^2} < 1.5 \times 10^{-12}\mu_{\rm B} \text{ (95\% CL)}$$

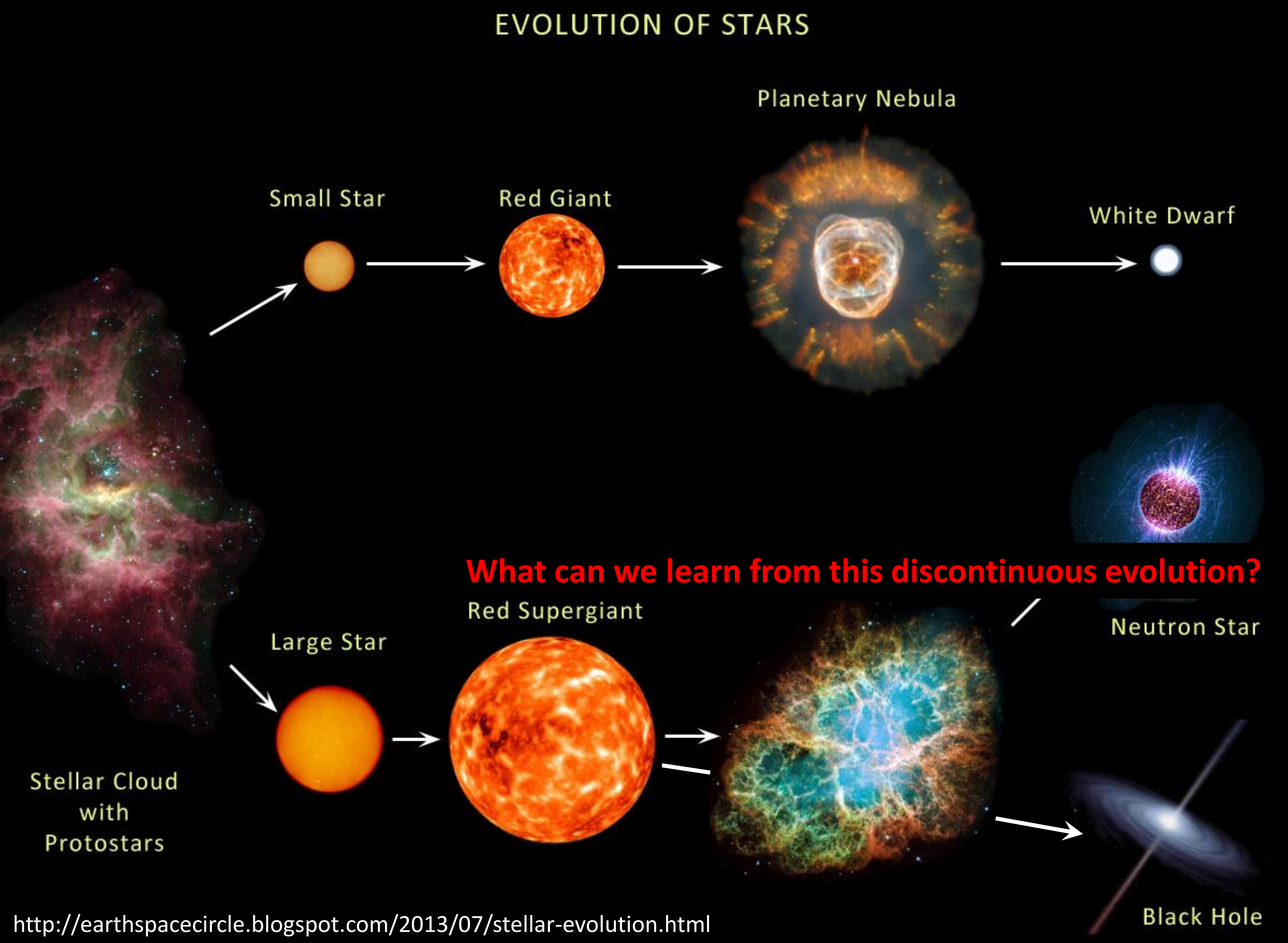
Neutrino-electron scattering (Borexino)

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

Dark Photon Limits



Caputo, Millar, O'Hare & Vitagliano, arXiv:2105.04565



What can we learn from this discontinuous evolution?

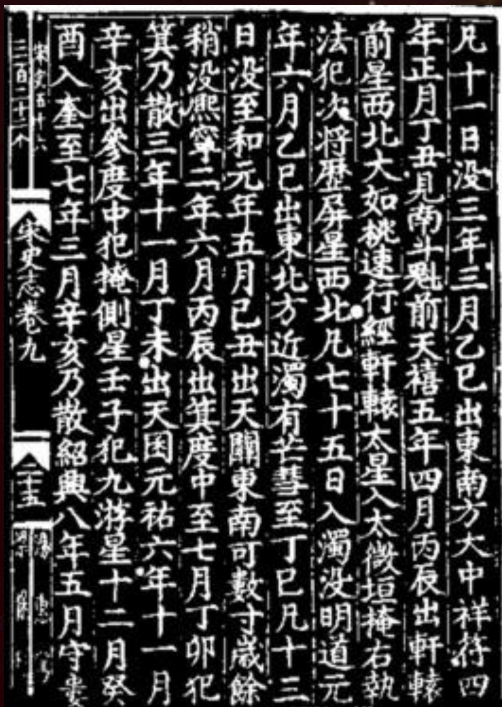
http://earthspacecircle.blogspot.com/2013/07/stellar-evolution.html

Crab Nebula – Remnant of SN 1054

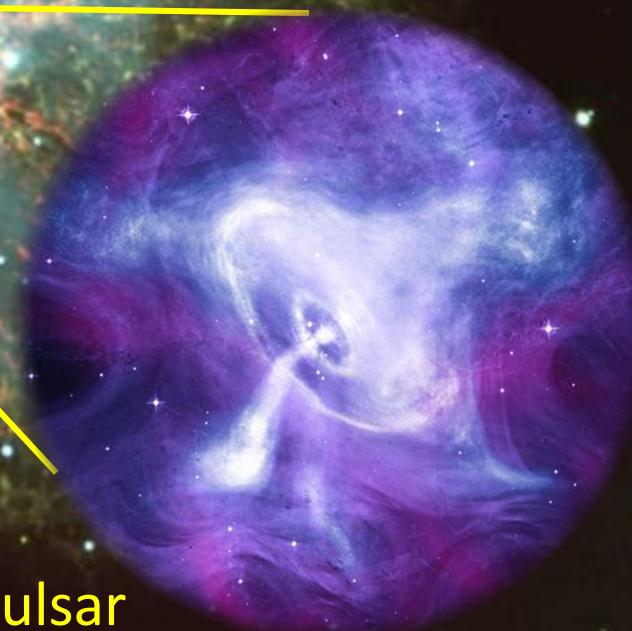
Crab Nebula – Remnant of SN 1054


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
法犯次將歷屛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
宋史志卷九

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

宋史志卷九



Crab Pulsar
Chandra X-ray composite image

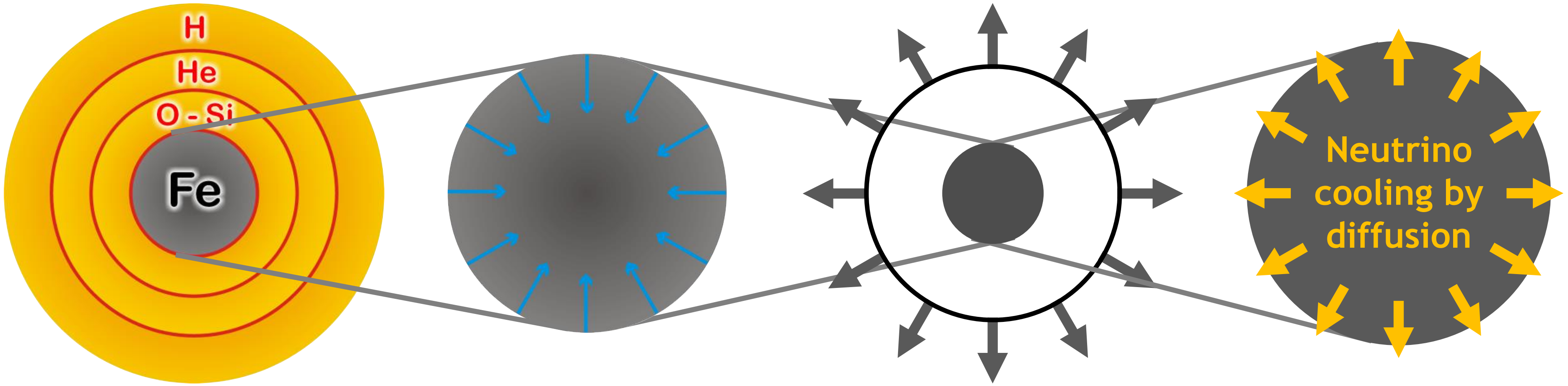
Core-Collapse Supernova Explosion

End state of a massive star $M \gtrsim 6\text{–}8\ M_\odot$

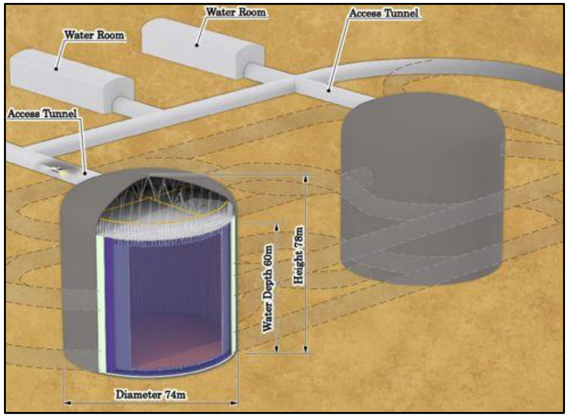
Collapse of degenerate core

Bounce at ρ_{nuc}
Shock wave forms explodes the star

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



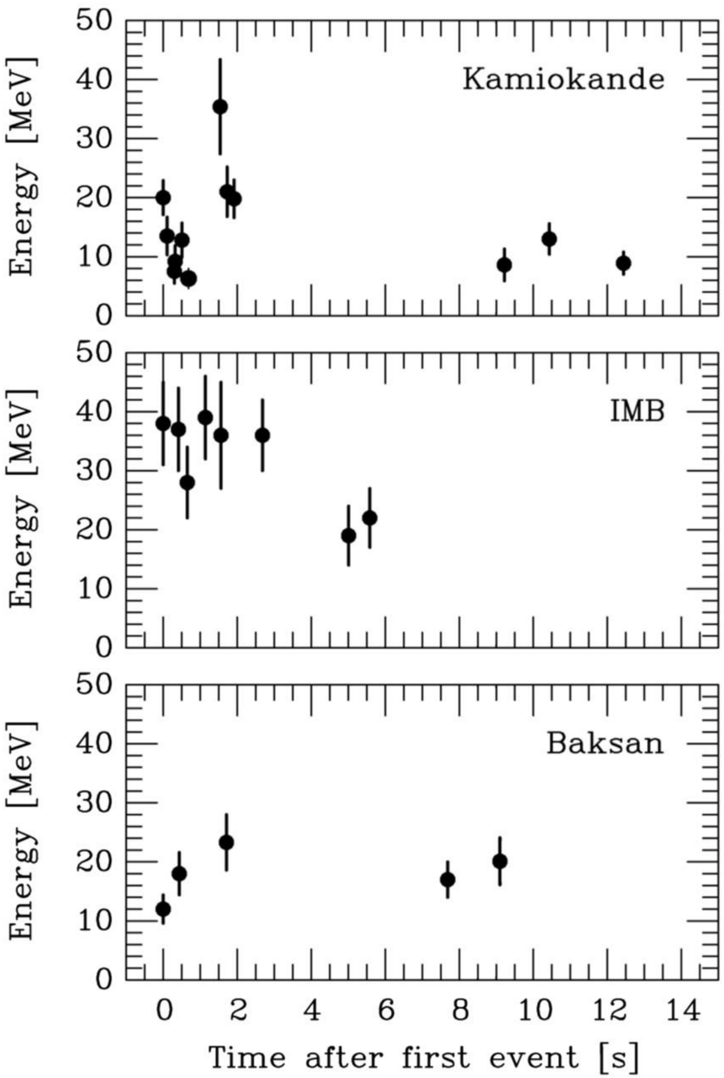
- Huge rate of low-E neutrinos (tens of MeV) over few seconds in large-volume detectors
- A few core-collapse SNe in our galaxy per century
- Once-in-a-lifetime opportunity

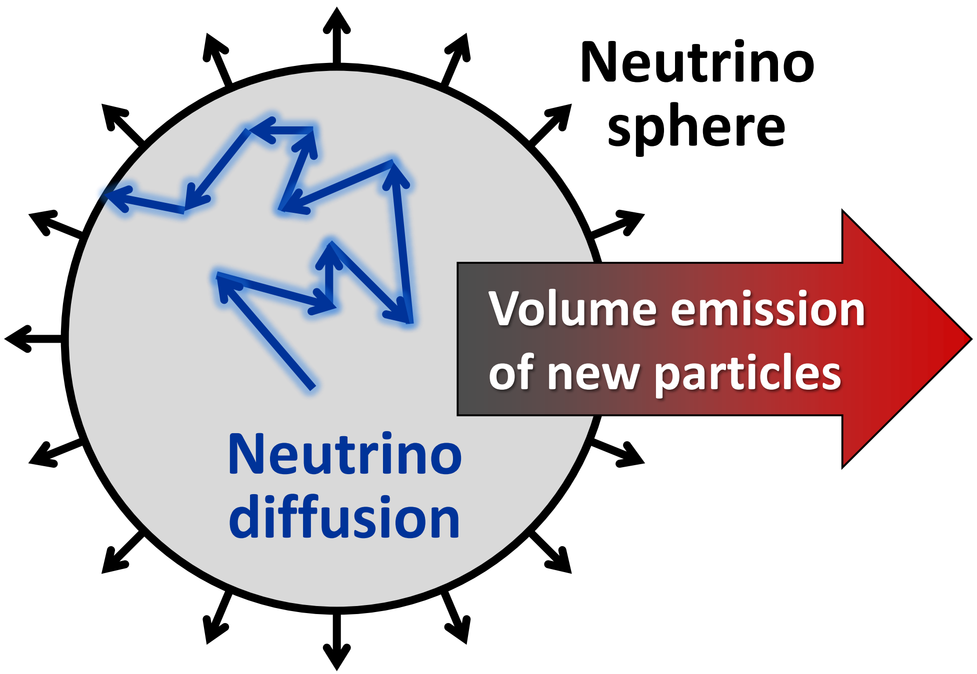



Sanduleak –69 202
in the Tarantula Nebula
in the Large Magellanic Cloud
Distance 50 kpc
(160.000 light years)
Supernova 1987A
23 February 1987

Supernova 1987A Energy-Loss Argument

SN 1987A neutrino signal

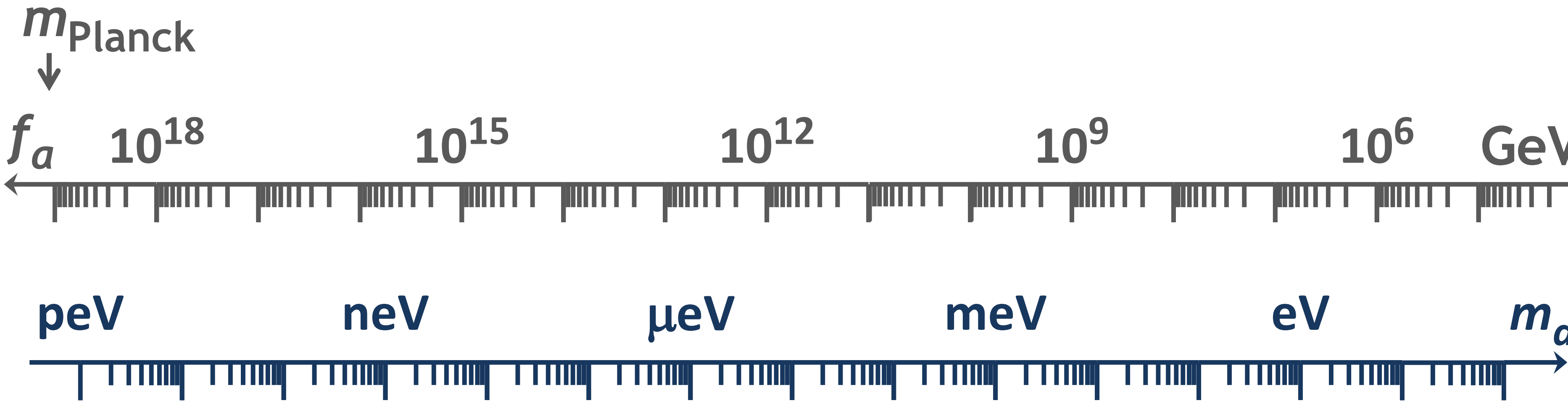




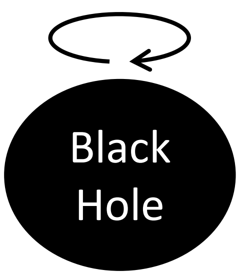
Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.
(Early neutrino burst powered by accretion, not sensitive to volume energy loss.)

Late-time signal most sensitive observable

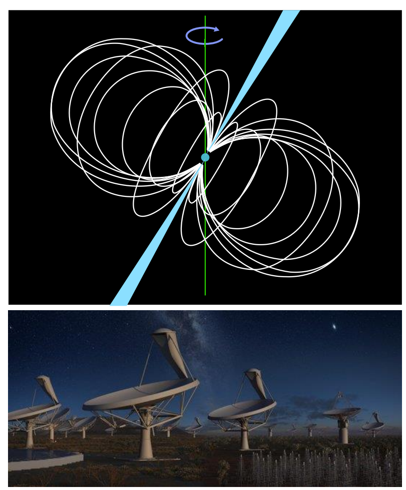
Axion Detection Opportunities from Stars



Super Radiance

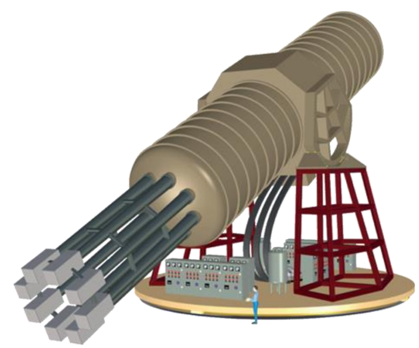


Opportunities for detection



Axion conversion in neutron star magnetospheres

Astrophysical Bounds (Energy loss of stars)



IAXO Solar Axion Telescope

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
  $f_a \gtrsim 4 \times 10^8\ \mathrm{GeV}$ and $m_a \lesssim 16\ \mathrm{meV}$ (KSVZ, based on proton coupling)

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

- Carenza, Fischer, Giannotti, Guo, Martínez-Pinedo & Mirizzi,
  JCAP 10 (2019) 016 & Erratum [1906.11844v3]
  Beyond OPE emission rates, specific SN core models: similar to Chang et al.
  $f_a \gtrsim 4 \times 10^8\ \mathrm{GeV}$ and $m_a \lesssim 15\ \mathrm{meV}$ (KSVZ, based on proton coupling)

- Carenza, Fore, Giannotti, Mirizzi & Reddy [arXiv:2010.02943]
  Including thermal pions $\pi^- + p \to n + a$ (factor 3 larger emission)
  $f_a \gtrsim 5 \times 10^8\ \mathrm{GeV}$ and $m_a \lesssim 11\ \mathrm{meV}$ (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)

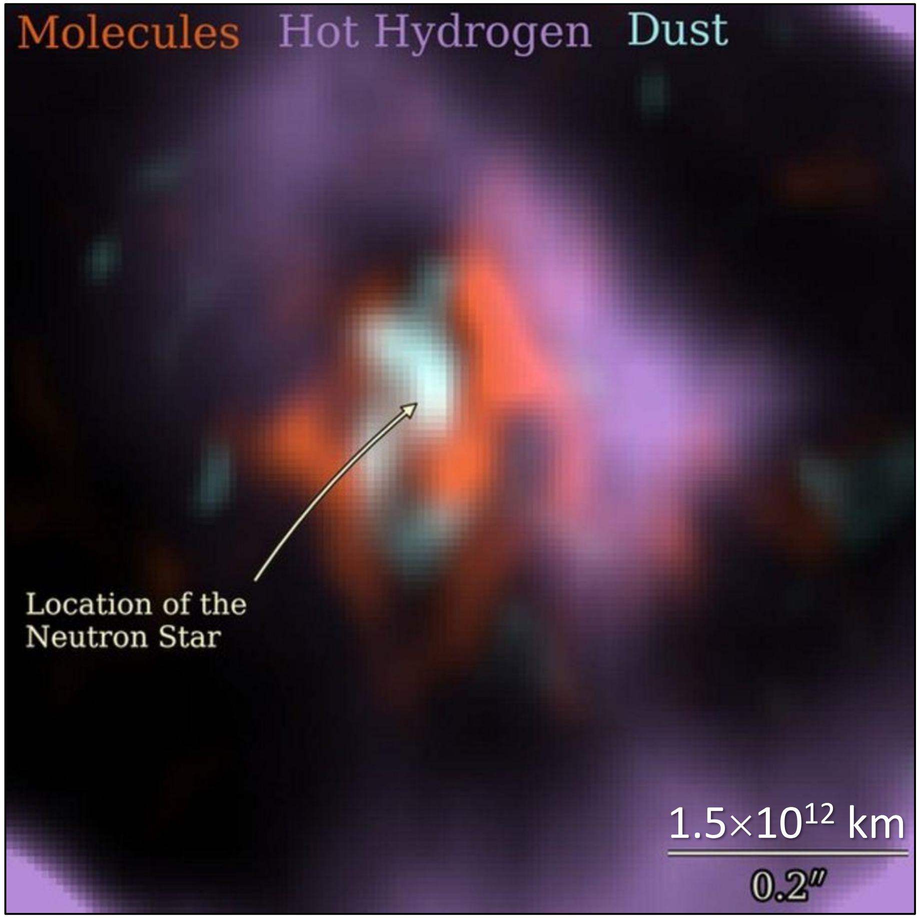
Where is the Neutron Star of SN 1987A?

No pulsar or neutron star has been seen until now (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



Operational Detectors for Supernova Neutrinos

HALO (30)
SNO+ (300)

ORCA (100)

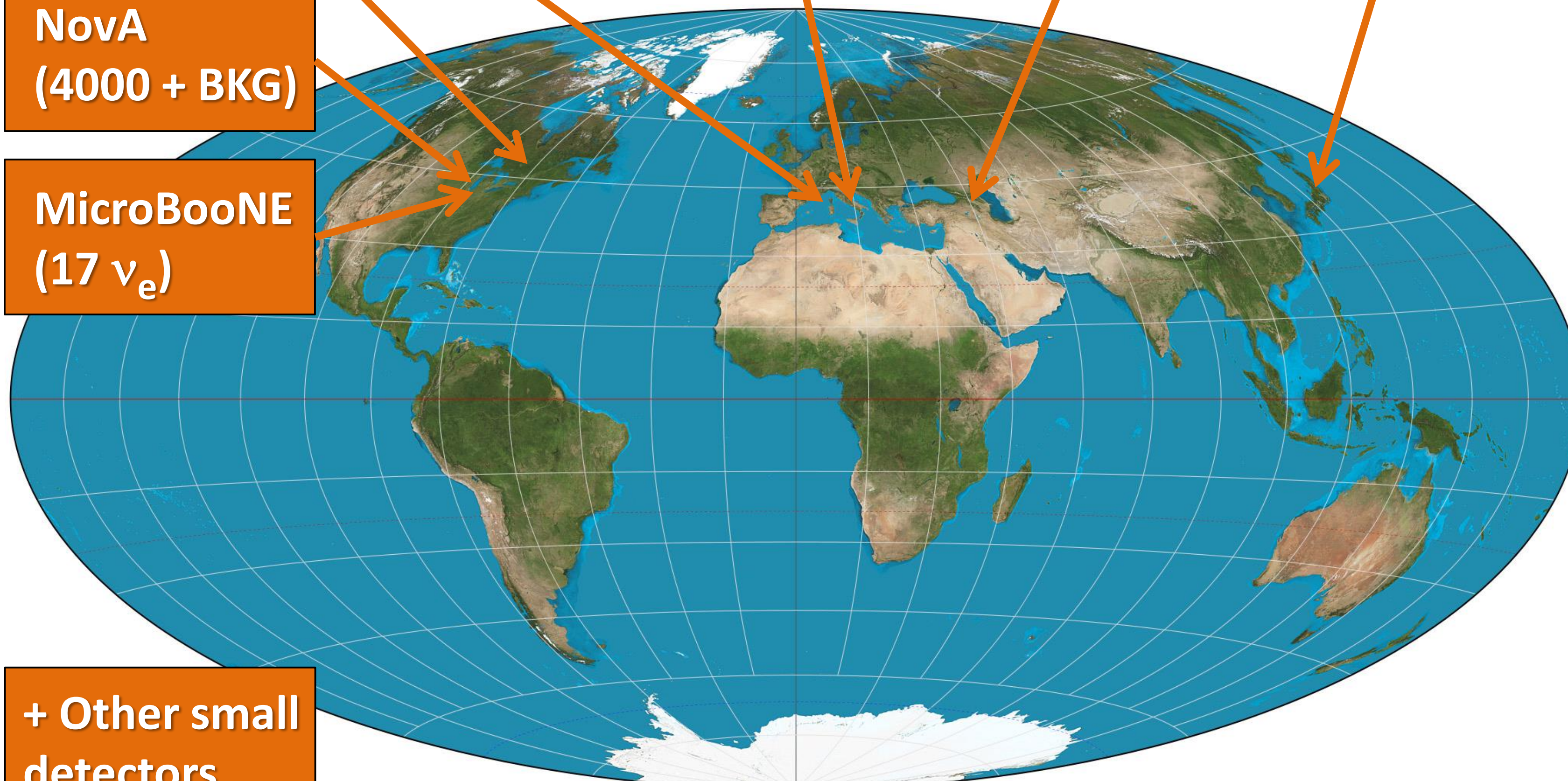
LVD (400)
Borexino (100)

Baksan
(100)

Super-K (4000)
KamLAND (400)

NovA
(4000 + BKG)

MicroBooNE
(17 ν_e)

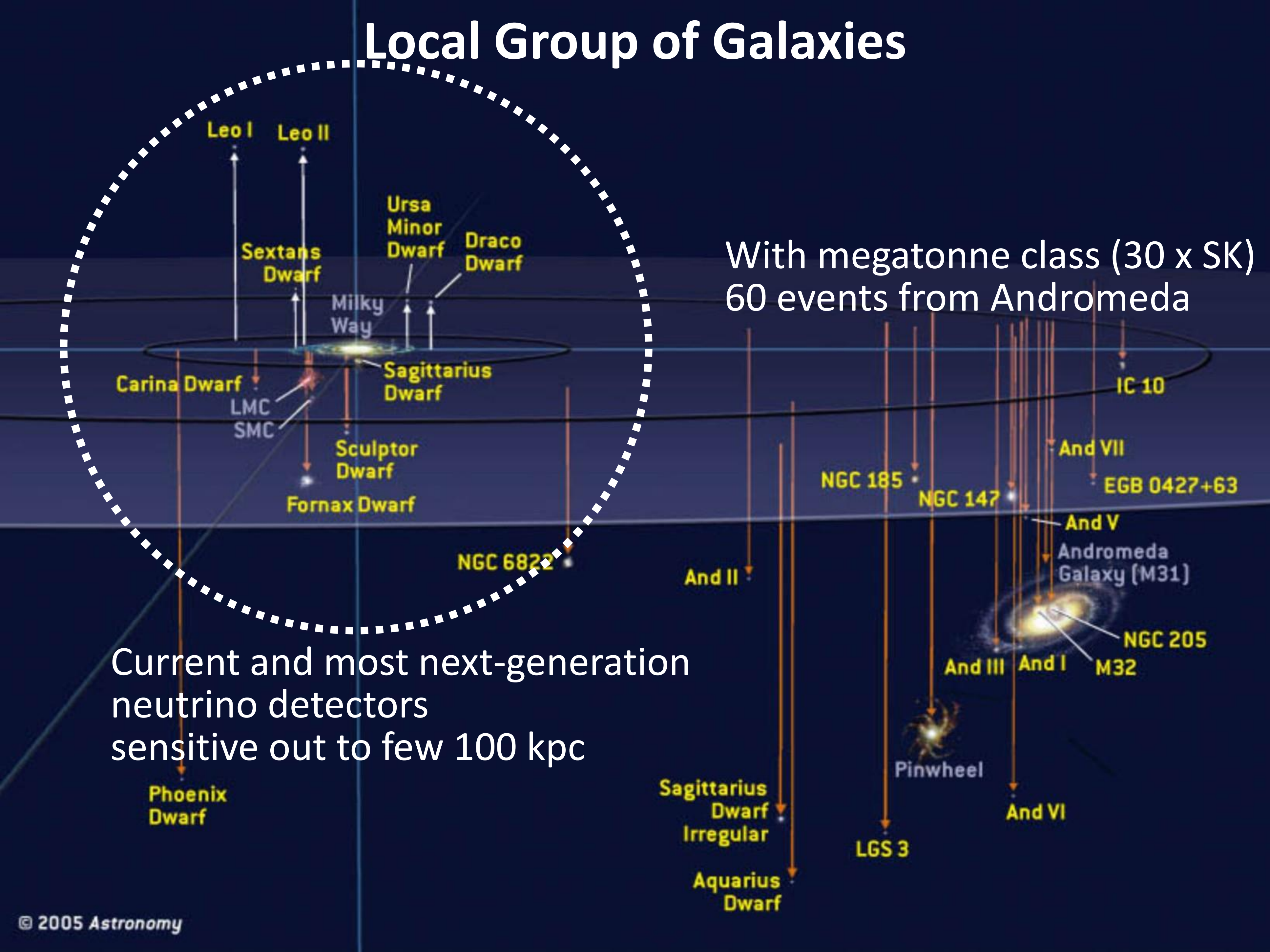


+ Other small detectors with some SN sensitivity

IceCube (10^6)

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

Local Group of Galaxies



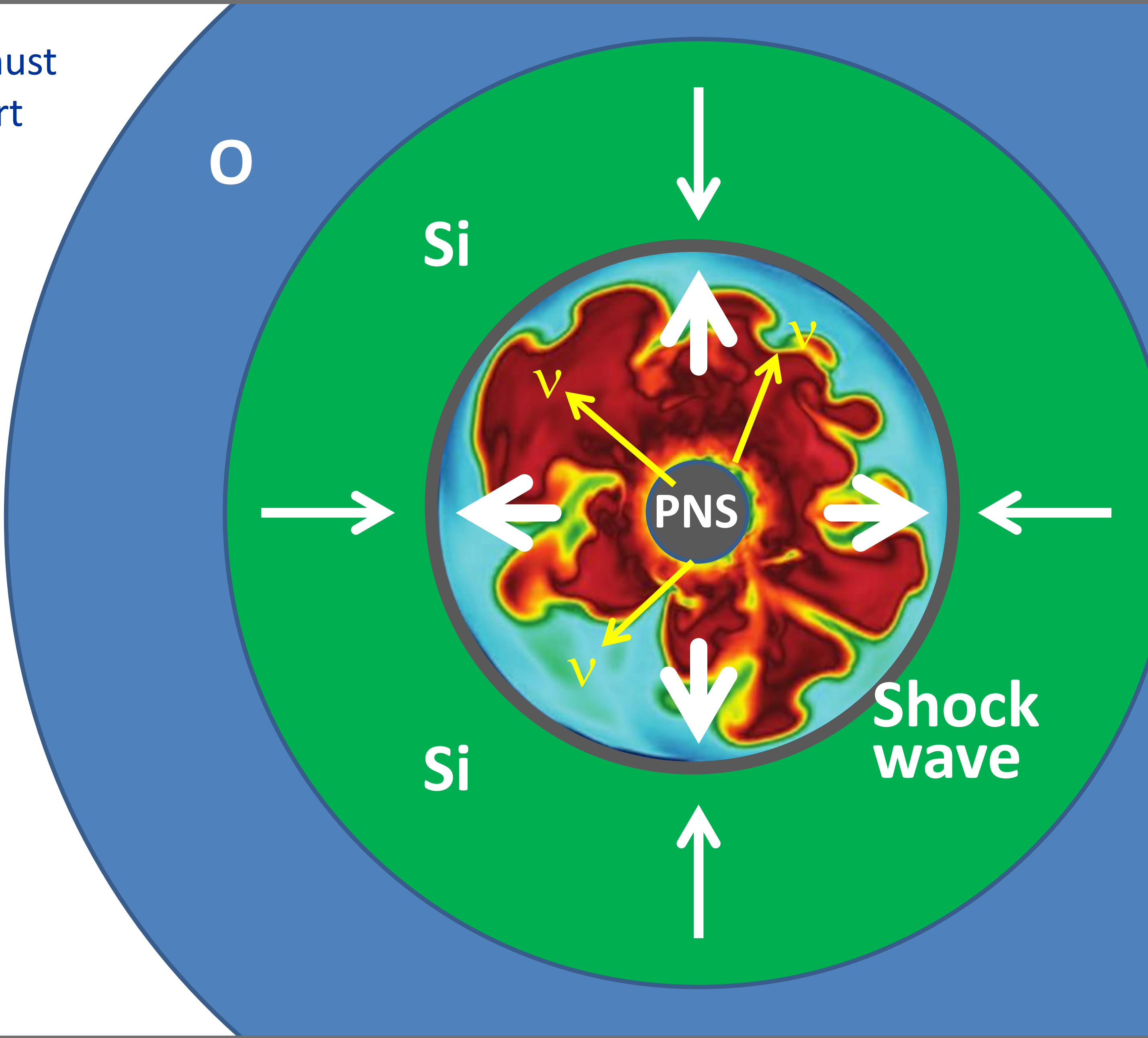
With megatonne class (30 x SK)
60 events from Andromeda

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

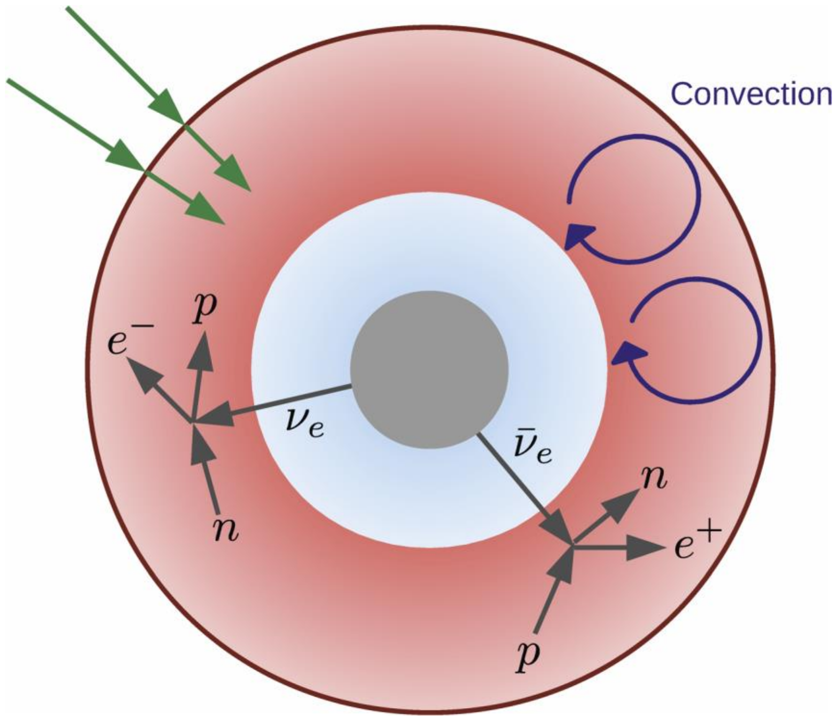
Shock Revival by Neutrinos

Stalled shock wave must receive energy to start re-expansion against ram pressure of infalling stellar core

Shock can receive fresh energy from neutrinos!

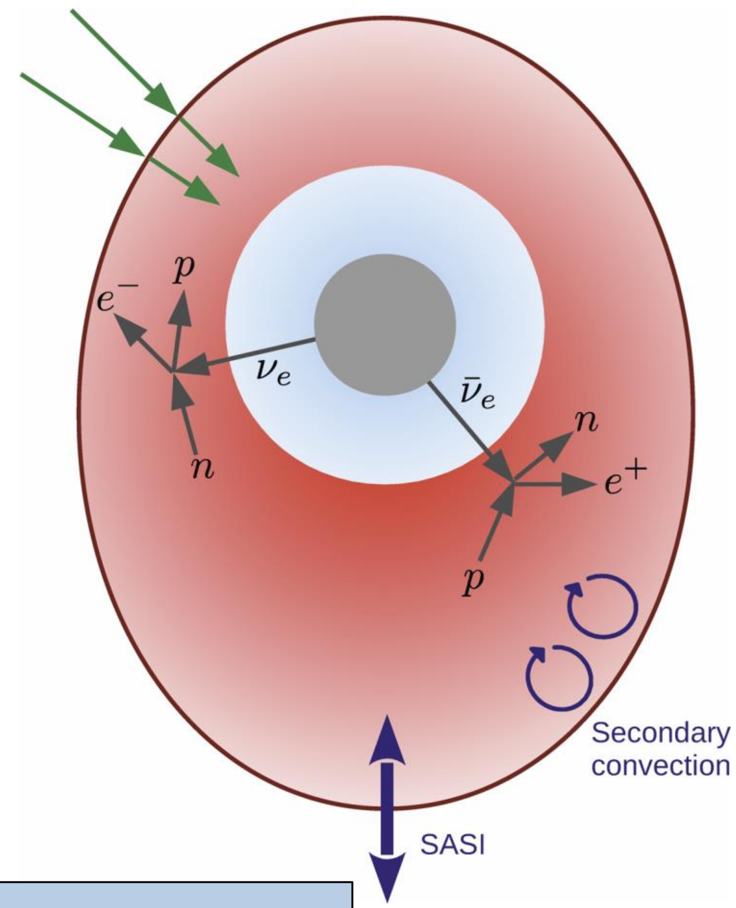


Convection



SASI

Standing accretion shock instability

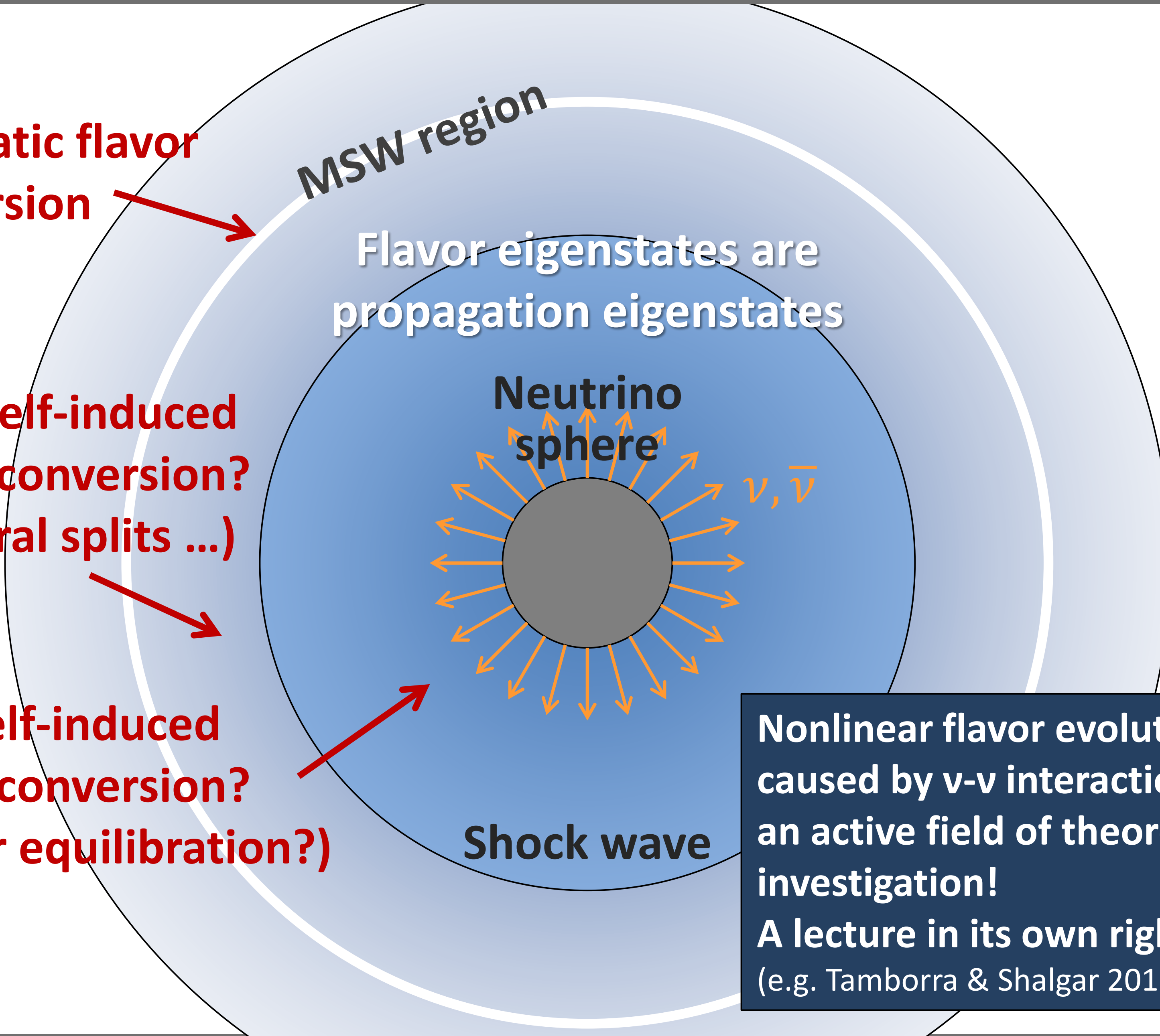


Images: Tobias Melson

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

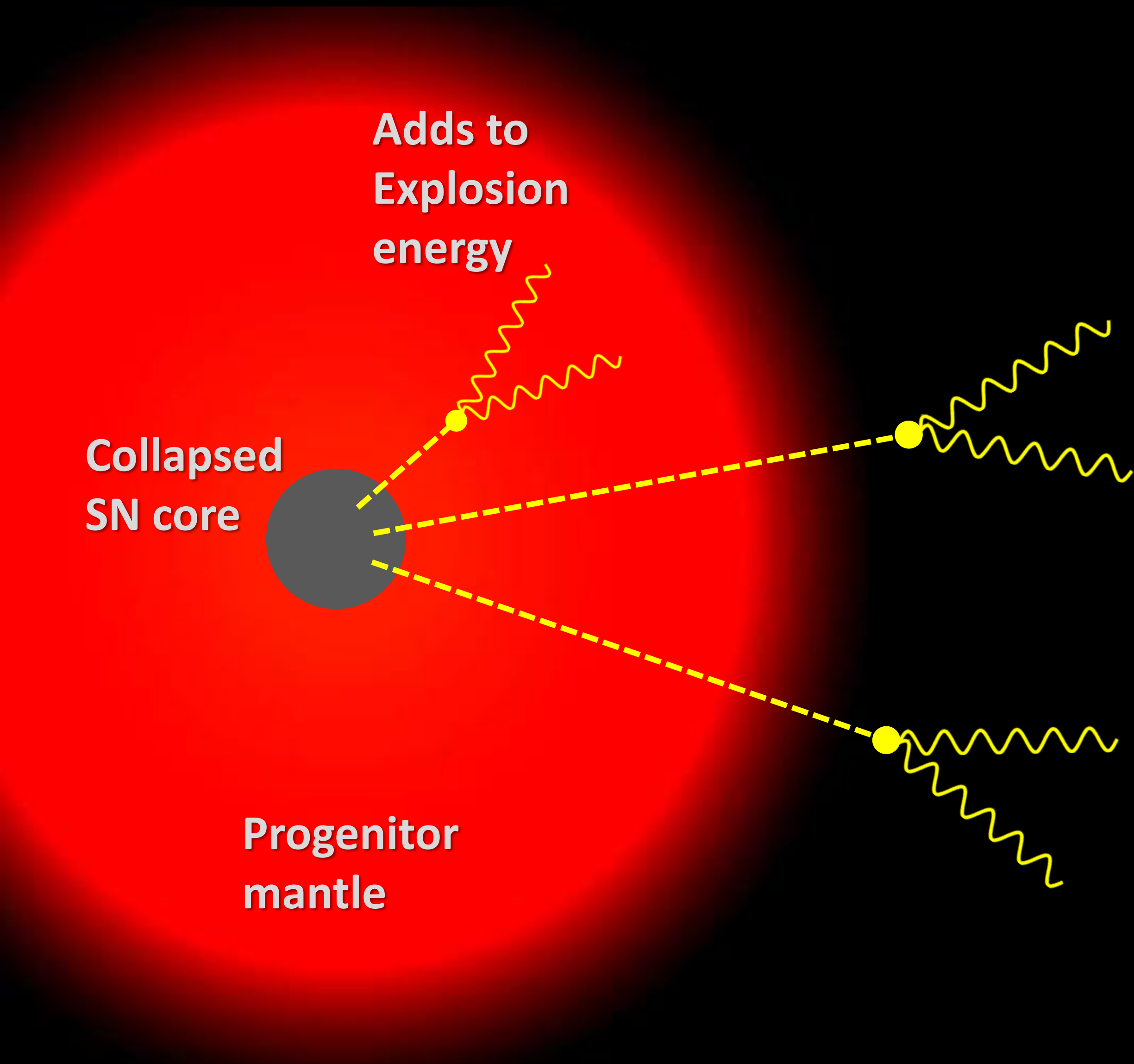
Flavor Conversion in Core-Collapse Supernovae

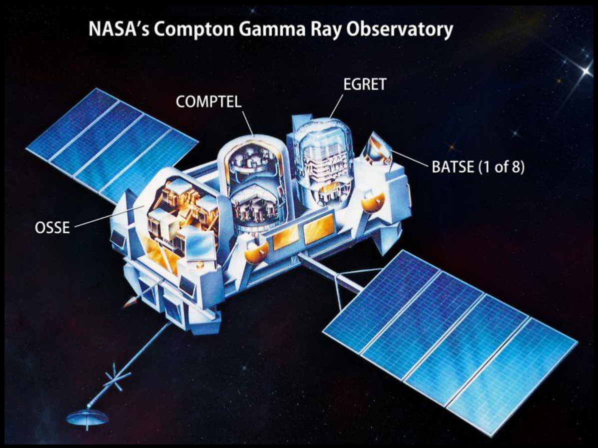
- Adiabatic flavor conversion
- Slow self-induced flavor conversion? (Spectral splits …)
- Fast self-induced flavor conversion? (Flavor equilibration?)



Nonlinear flavor evolution caused by ν-ν interaction an active field of theoretical investigation!
A lecture in its own right!
(e.g. Tamborra & Shalgar 2011.01948)

Supernova Bounds on Radiative Particle Decays





Cosmic gamma ray background from all past supernovae

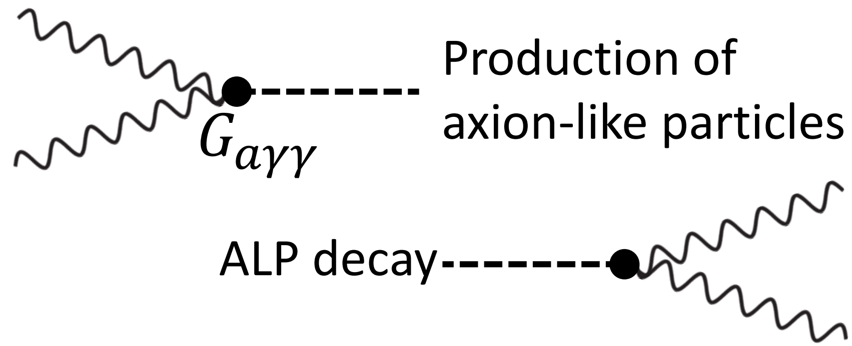
Solar Maximum Mission

No excess gamma rays @ SN 1987A neutrino burst

Low-Energy Supernovae Severely Constrain Radiative Particle Decays

Andrea Caputo,[1,2] Hans-Thomas Janka,[3] Georg Raffelt,[4] and Edoardo Vitagliano[5]

arXiv:2201.09890 (24 Jan 2022)

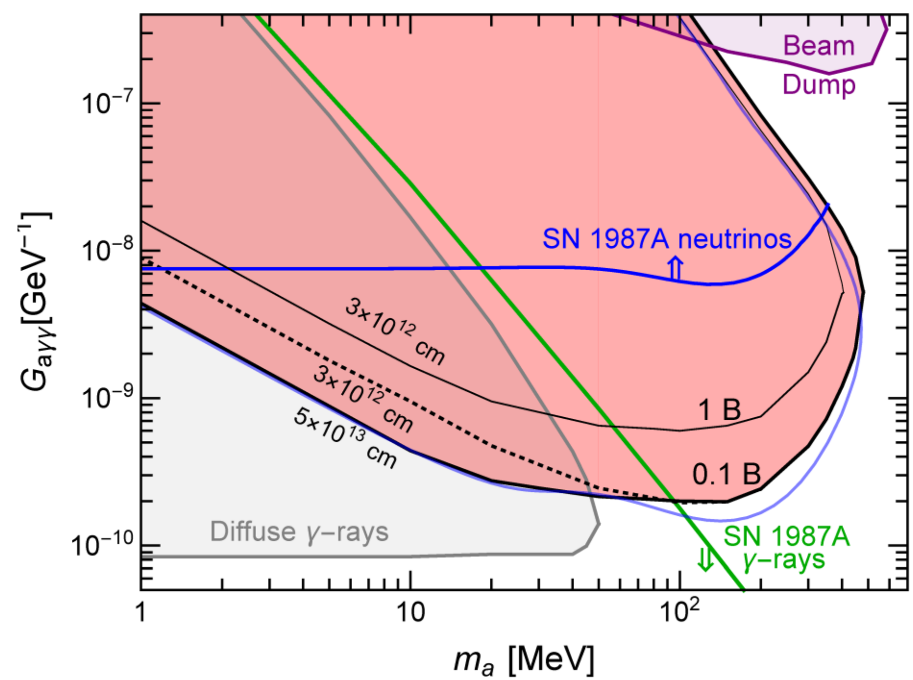


Typical SN explosion energy 1–2 B

Some SNe have very small observed explosion energies < 0.1 B
(e.g. subluminous type II-P SNe)

Restrictive limits on energy deposition in progenitor star by particle decays!

1 B (bethe) = 10^{51} erg
Neutron-star binding energy 200–400 B
(0.11–0.22 M_{SUN})



Muon-Philic Bosons from Supernovae

Diffuse 100 MeV gamma rays
from SN 1987A
and from all past supernovae

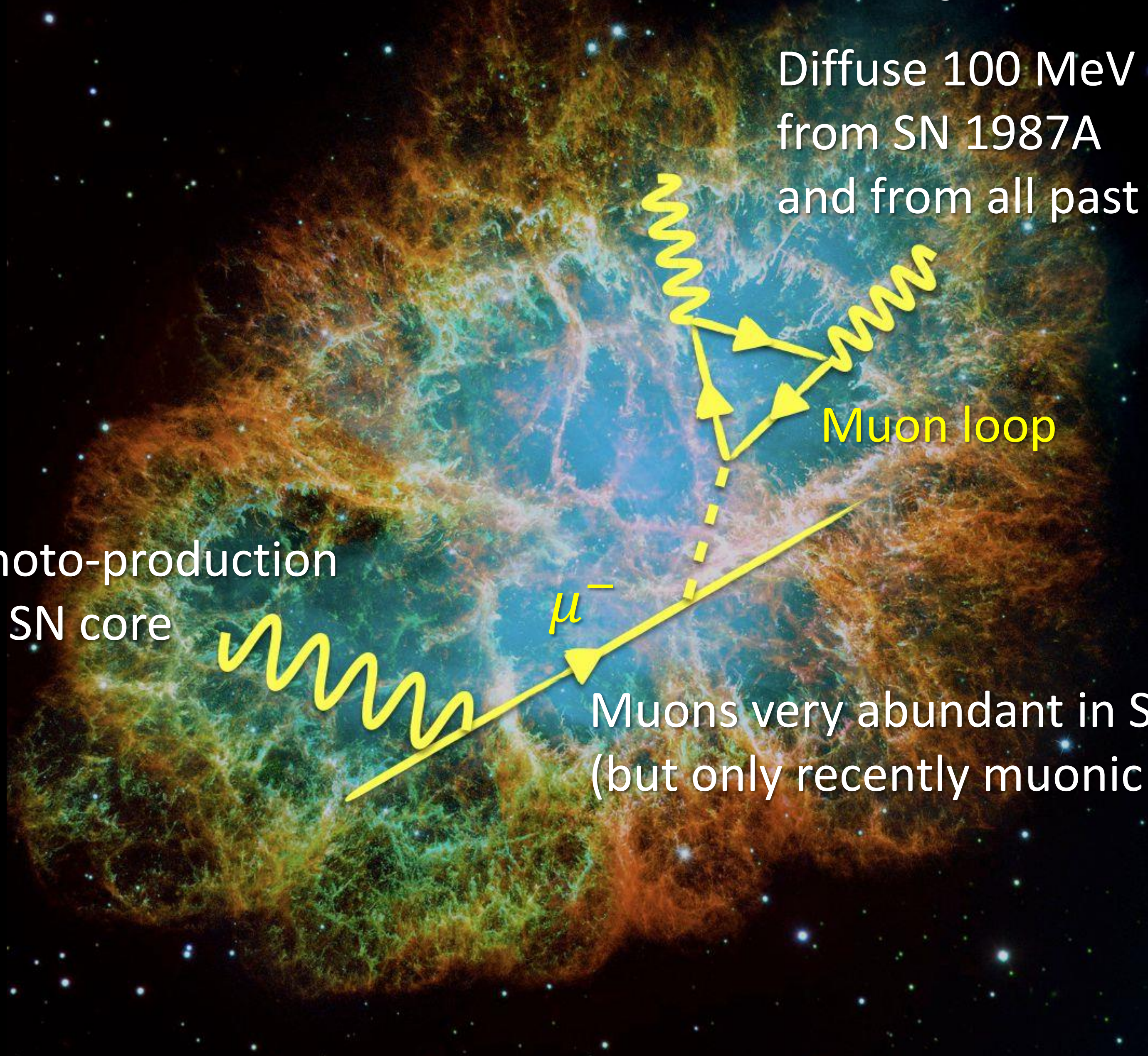
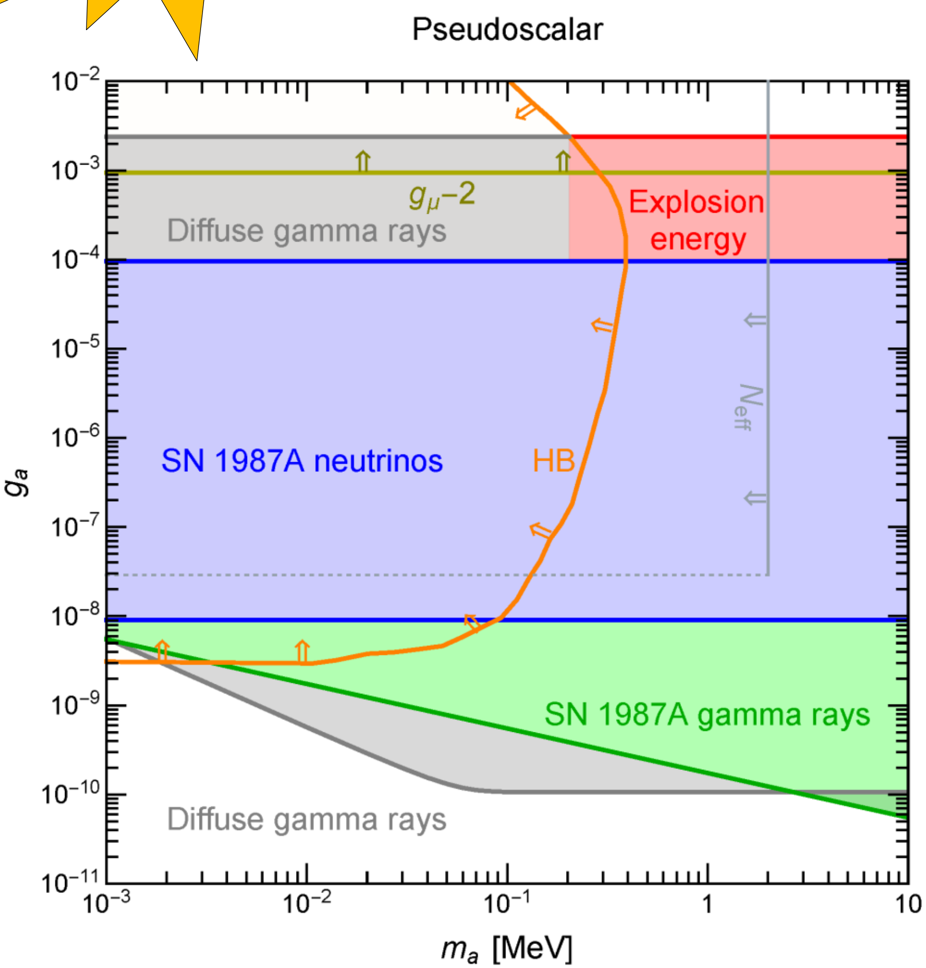


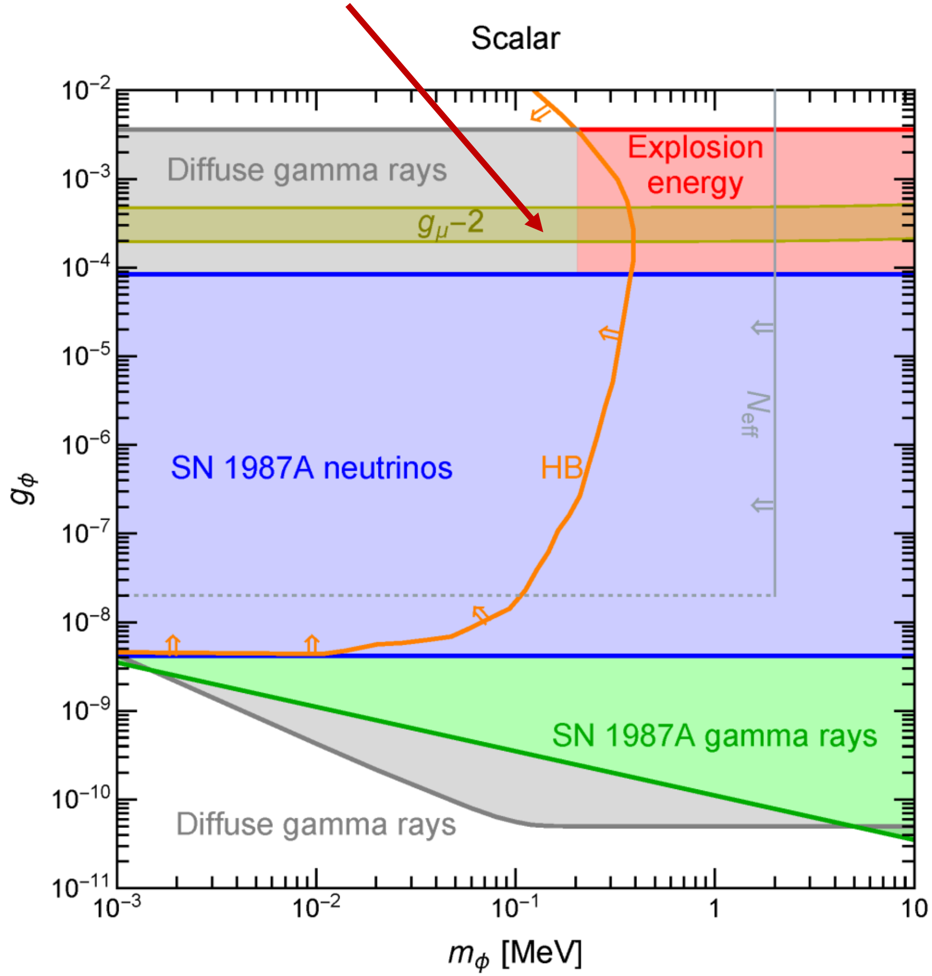
Photo-production
in SN core

Muons very abundant in SN core!
(but only recently muonic SN models)

Brand New

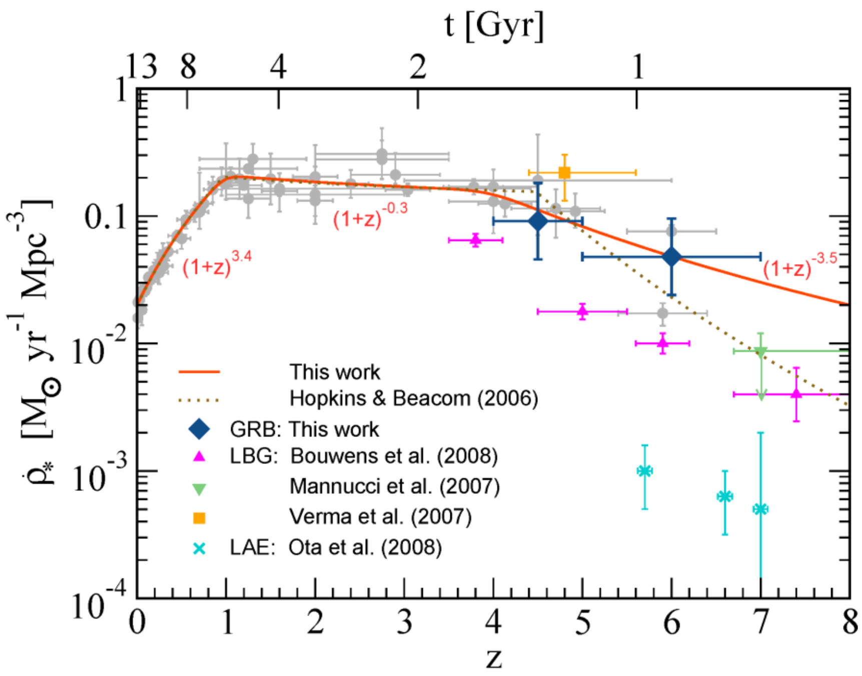
Excludes explanation of muon magnetic-moment anomaly by a scalar-boson (muon-philic boson) contribution





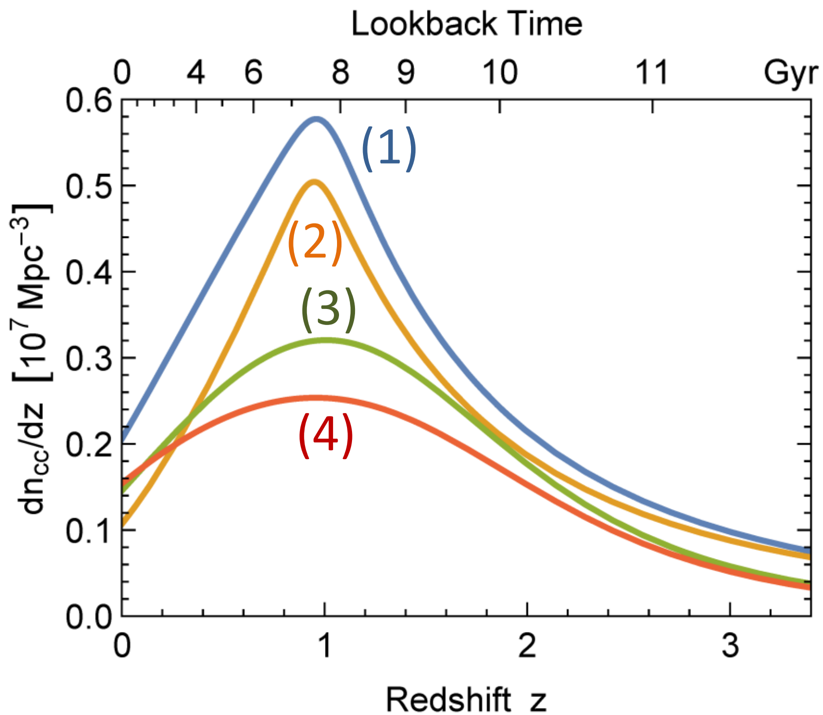
Caputo, Raffelt & Vitagliano, arXiv:2109.03244 (30 pages)

Star-formation rate (1)



(1) Yüksel+ arXiv:0804.4008
(2) Mathews+ arXiv:1405.0458
(3) Robertson+ arXiv:1502.02024
(4) Madau+ arXiv:1403.0007

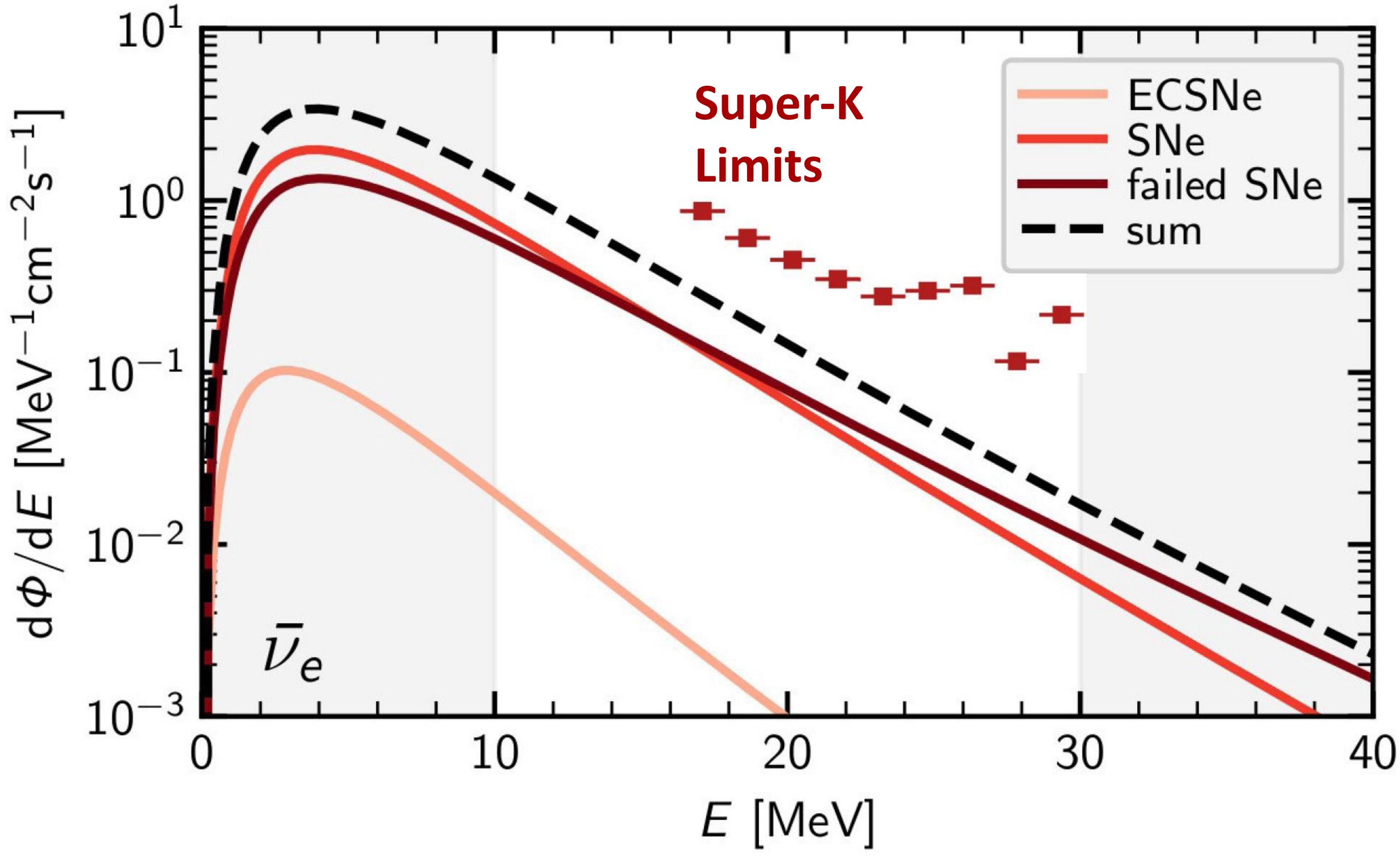
Core-collapse distribution



Total cc density
$0.6 - 1 \times 10^7\ \mathrm{Mpc}^{-3}$

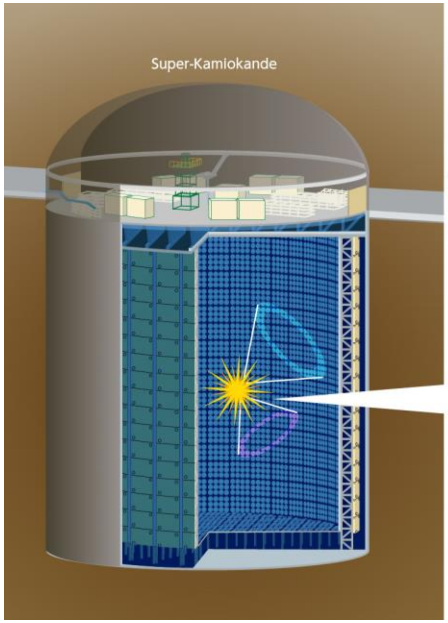
Kresse+, arXiv:2010.04728

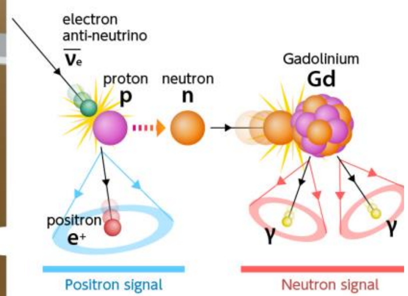
For latest Super-K limits see arXiv:2109.11174



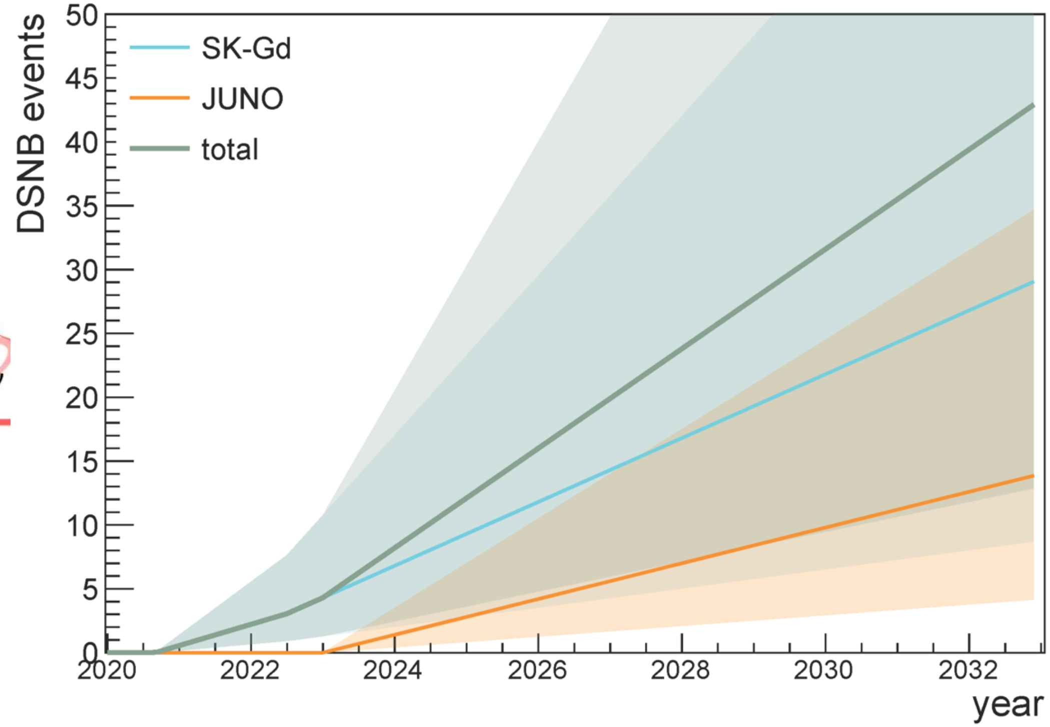
In the detection window, essentially $\frac{d\Phi}{dE} \propto e^{-E/E_0}$

Search for the Diffuse SN Neutrino Background





Water Cherenkov
22.5 kt fiducial
Sk-Gd since 2020

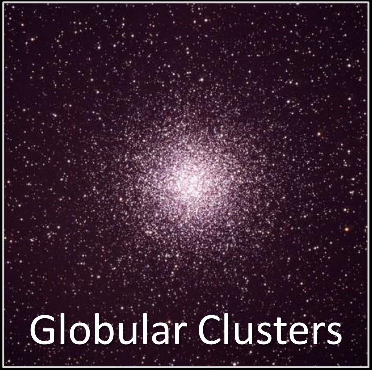
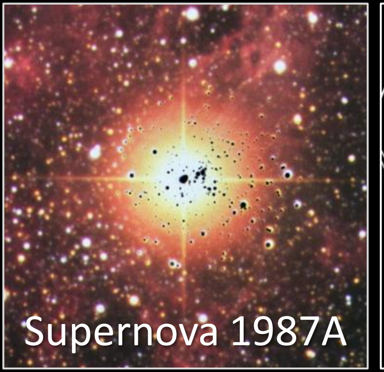
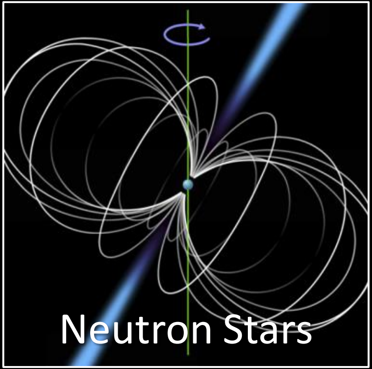
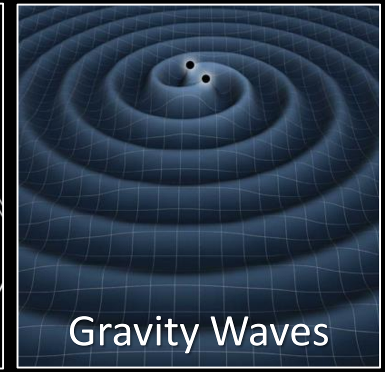


Li, Vagins & Wurm:
Prospects for the detection of the DSNB with the experiments SK-Gd and JUNO
arXiv:2201.12920

JUNO
Liquid Scintillator
17 kt fiducial
Data taking 2023

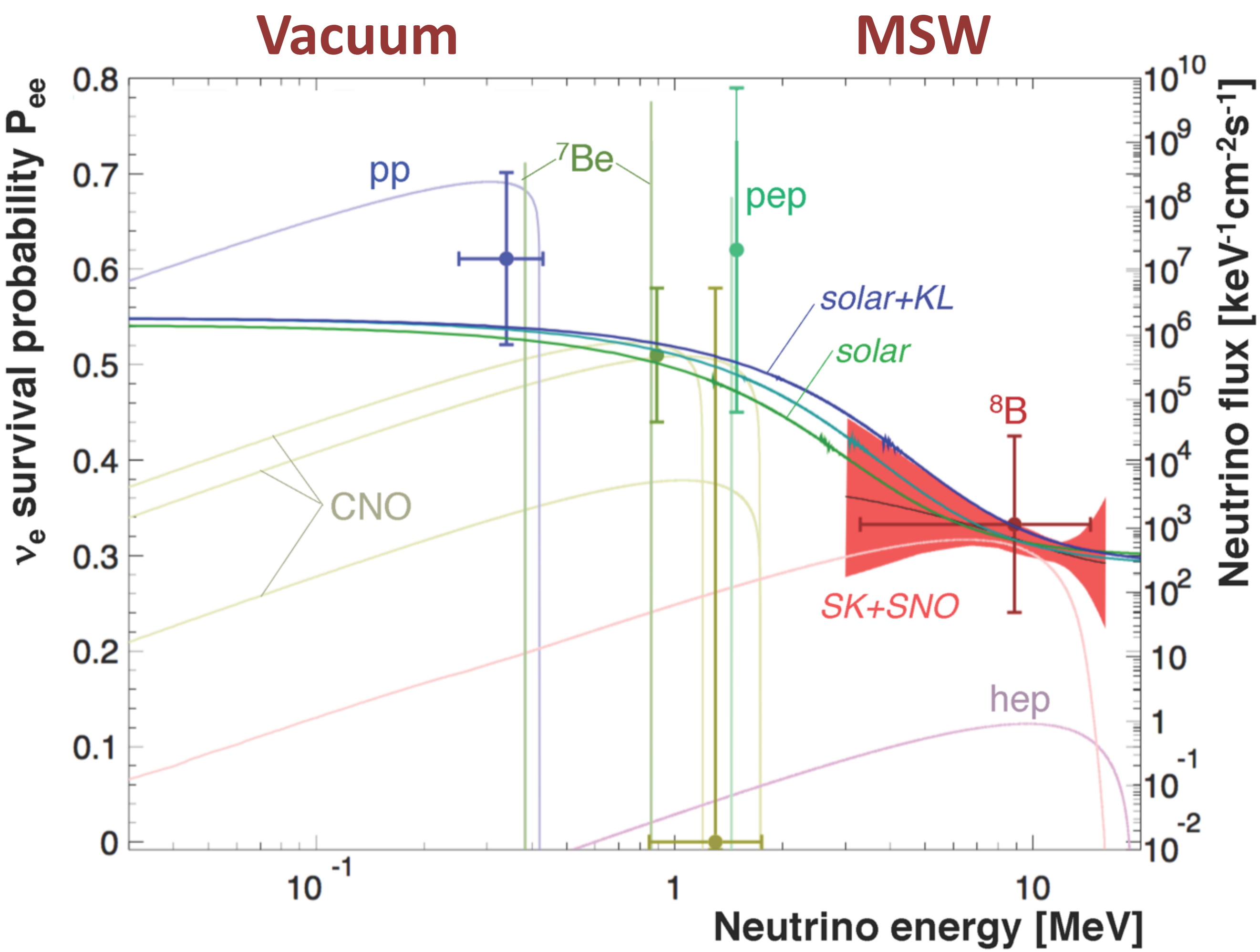
Particles from Stars: What to expect?

- 😀 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
- 😀 Gravitational-wave evidence for superradiance from black holes


Solar Axions

Globular Clusters

Supernova 1987A

Neutron Stars

Gravity Waves

Thanks!

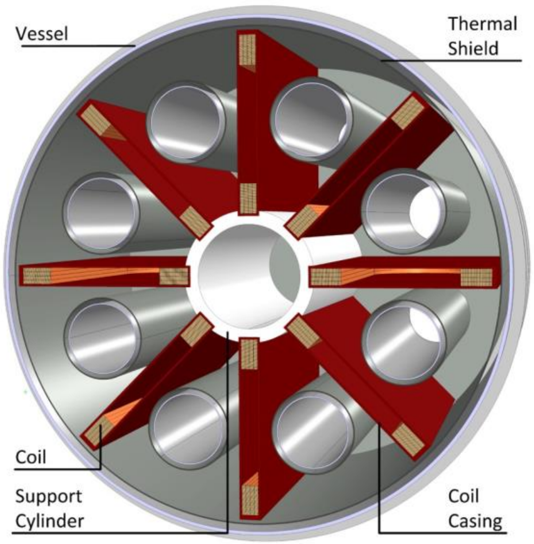
Solar Neutrino Spectroscopy with Borexino

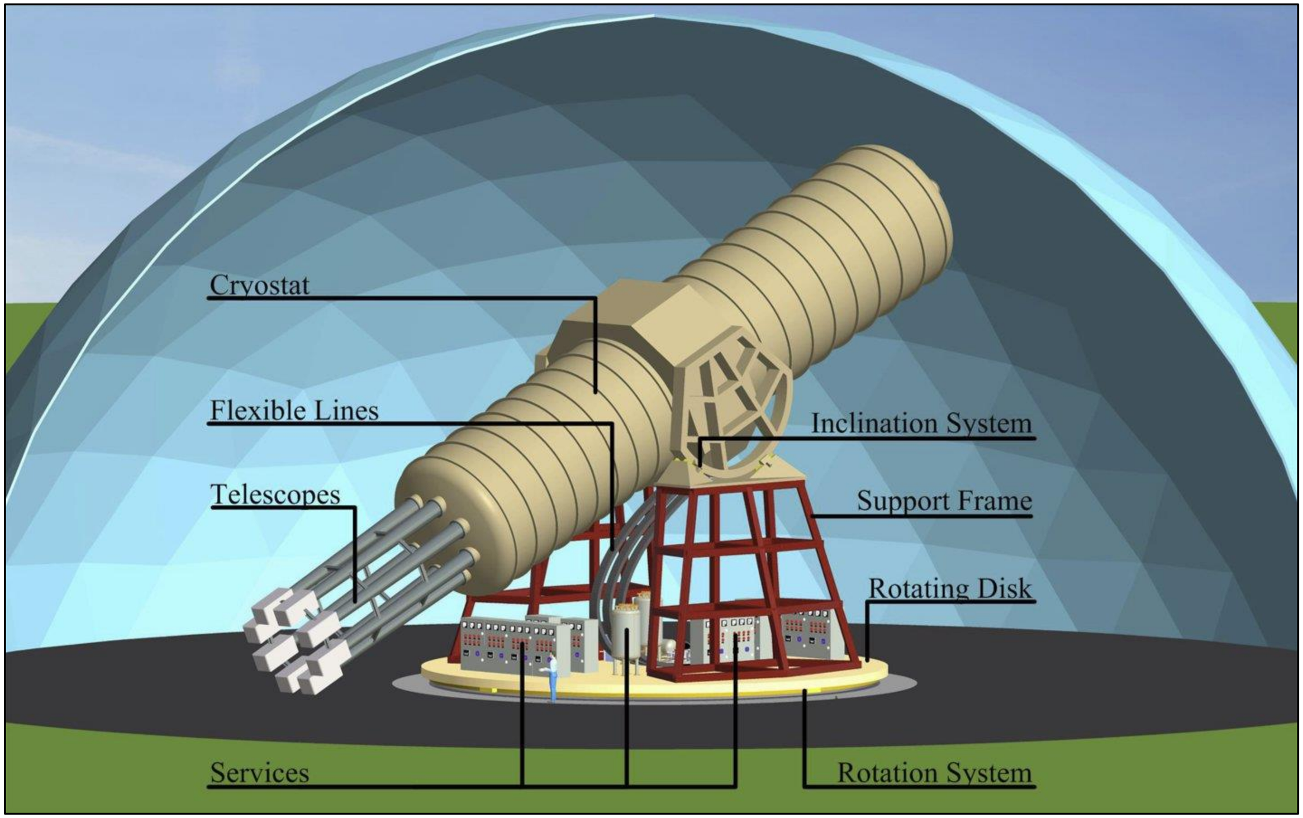


Energy-dependent flavor conversion probability confirms neutrino refraction in matter!

M.Wurm, Solar Neutrino Spectroscopy, arXiv:1704.06331

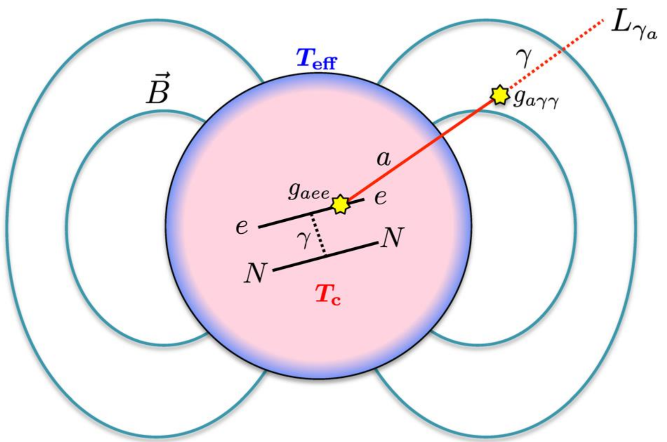
Next Generation Axion Helioscope (IAXO)



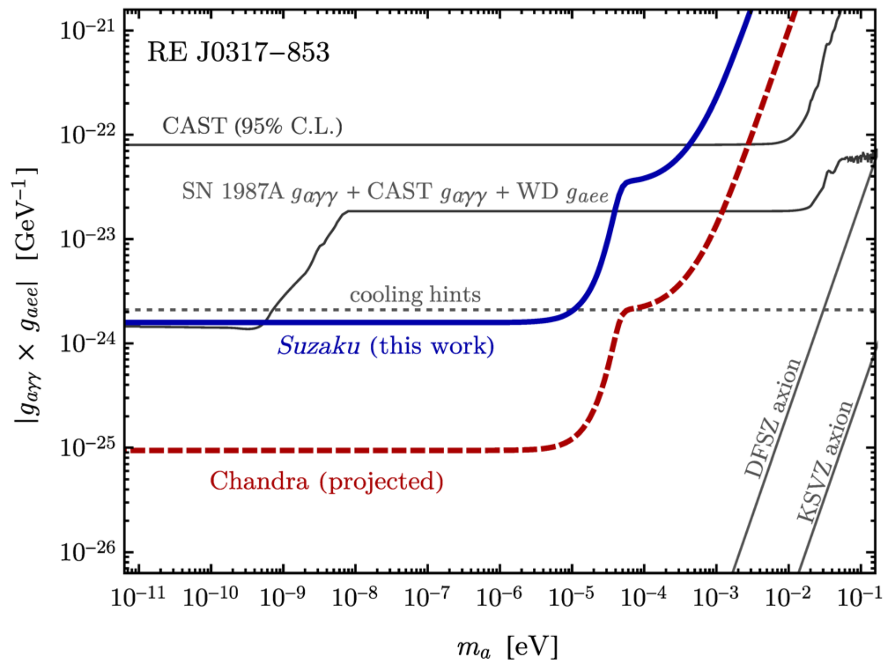


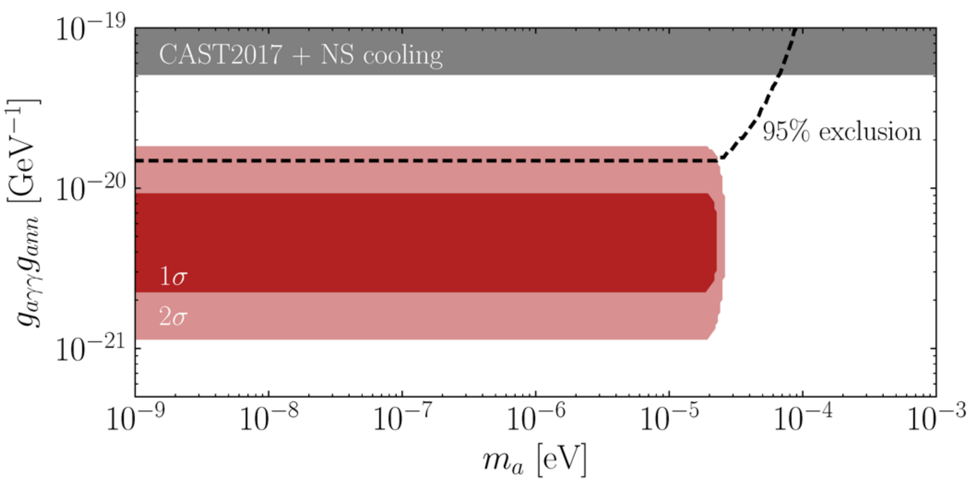
Need new magnet w/
– Much bigger aperture: $\sim 1\ \mathrm{m}^2$ per bore
– Lighter (no iron yoke)
– Bores at T_{room}

- Conceptual Design of the International Axion Observatory (IAXO), arXiv:1401.3233
- Physics potential of the International Axion Observatory (IAXO), arXiv:1904.09155



Magnetic White Dwarf



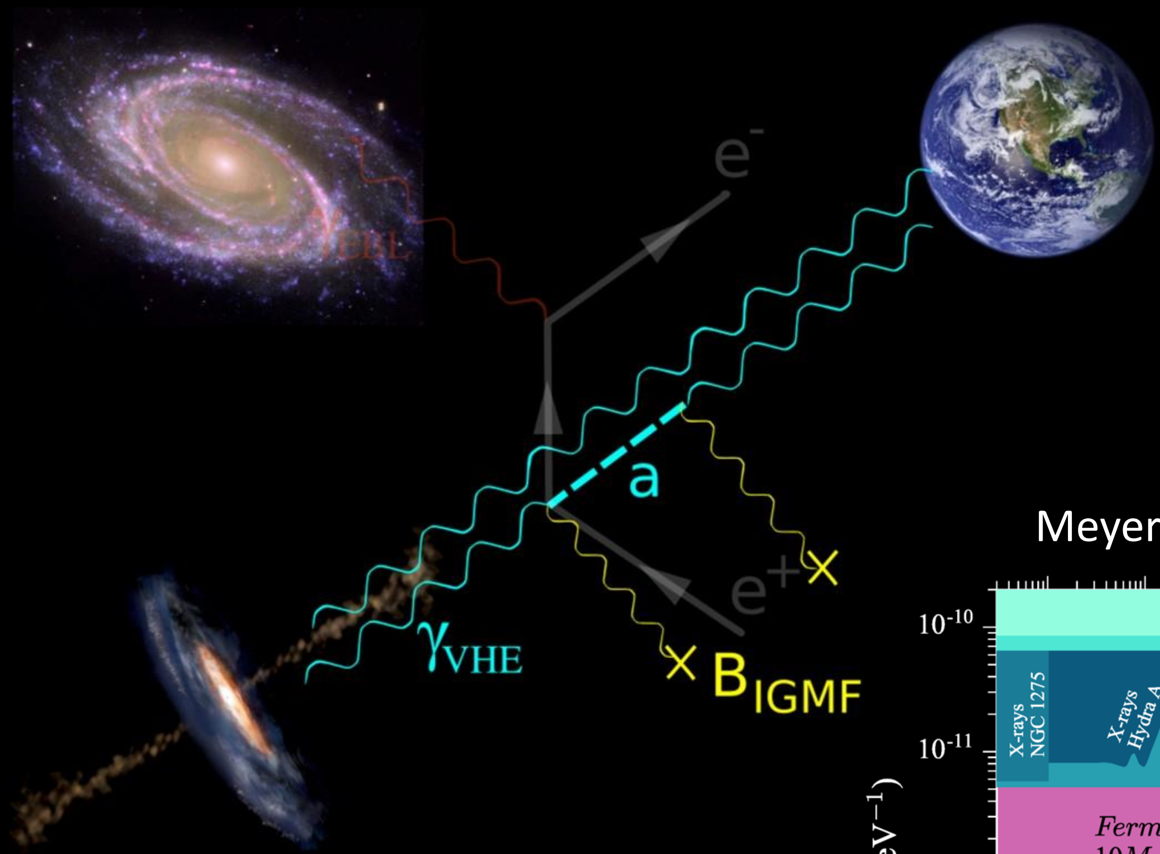


Magnificent Seven Neutron Stars
X-Ray limits and excess

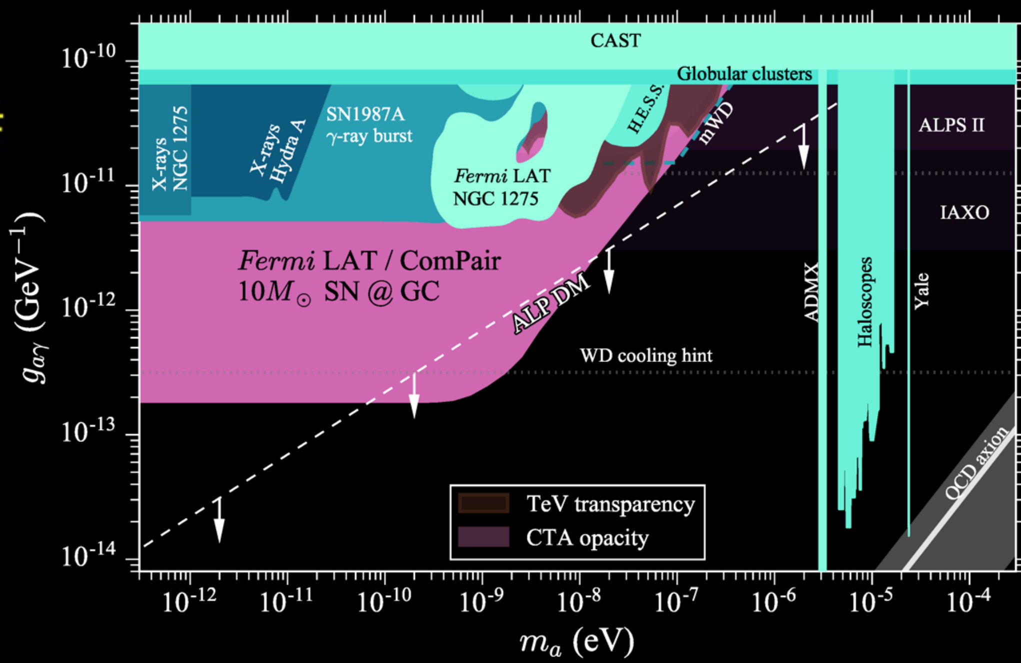
- Buschmann, Co, Dessert & Safdi: *X-Ray Search for Axions from Nearby Isolated Neutron Stars*, arXiv:1910.04164
- Dessert, Long & Safdi: *X-Ray Signatures of Axion Conversion in Magnetic White Dwarf Stars*, PRL 123 (2019) 061104, arXiv:1903.05088, see also Dessert+ arXiv:2104.12772, 26 Apr 2021

Shining TeV Gamma Rays through the Universe

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



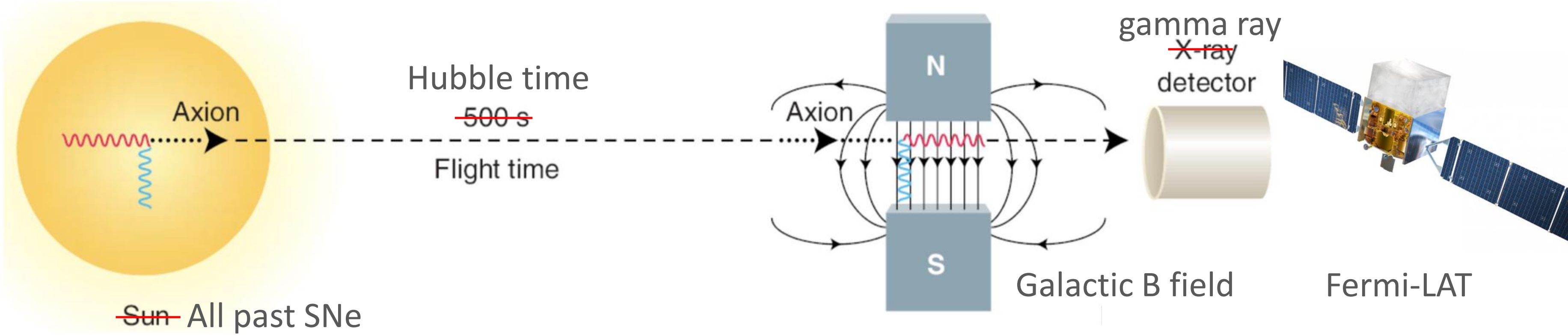
Meyer (Fermi-LAT Coll.) arXiv:1611.07784

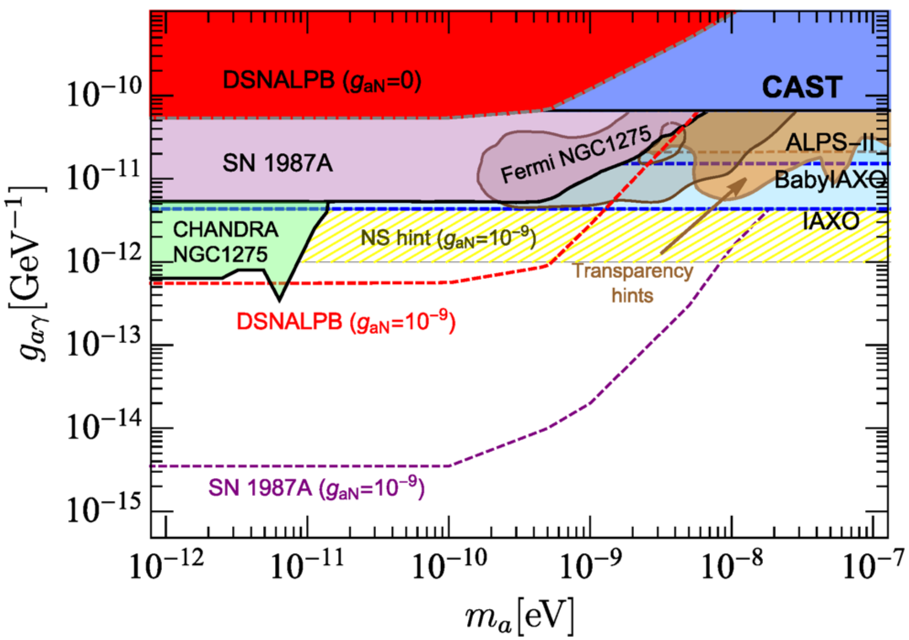


See also Biteau & Meyer:
Gamma-Ray Cosmology and Tests of Fundamental Physics [arXiv:2202.00523]

Bounds on axionlike particles from the diffuse supernova flux

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





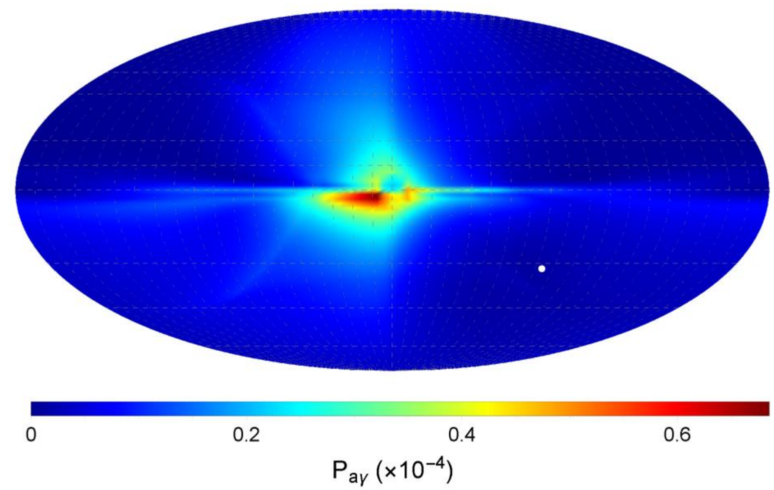
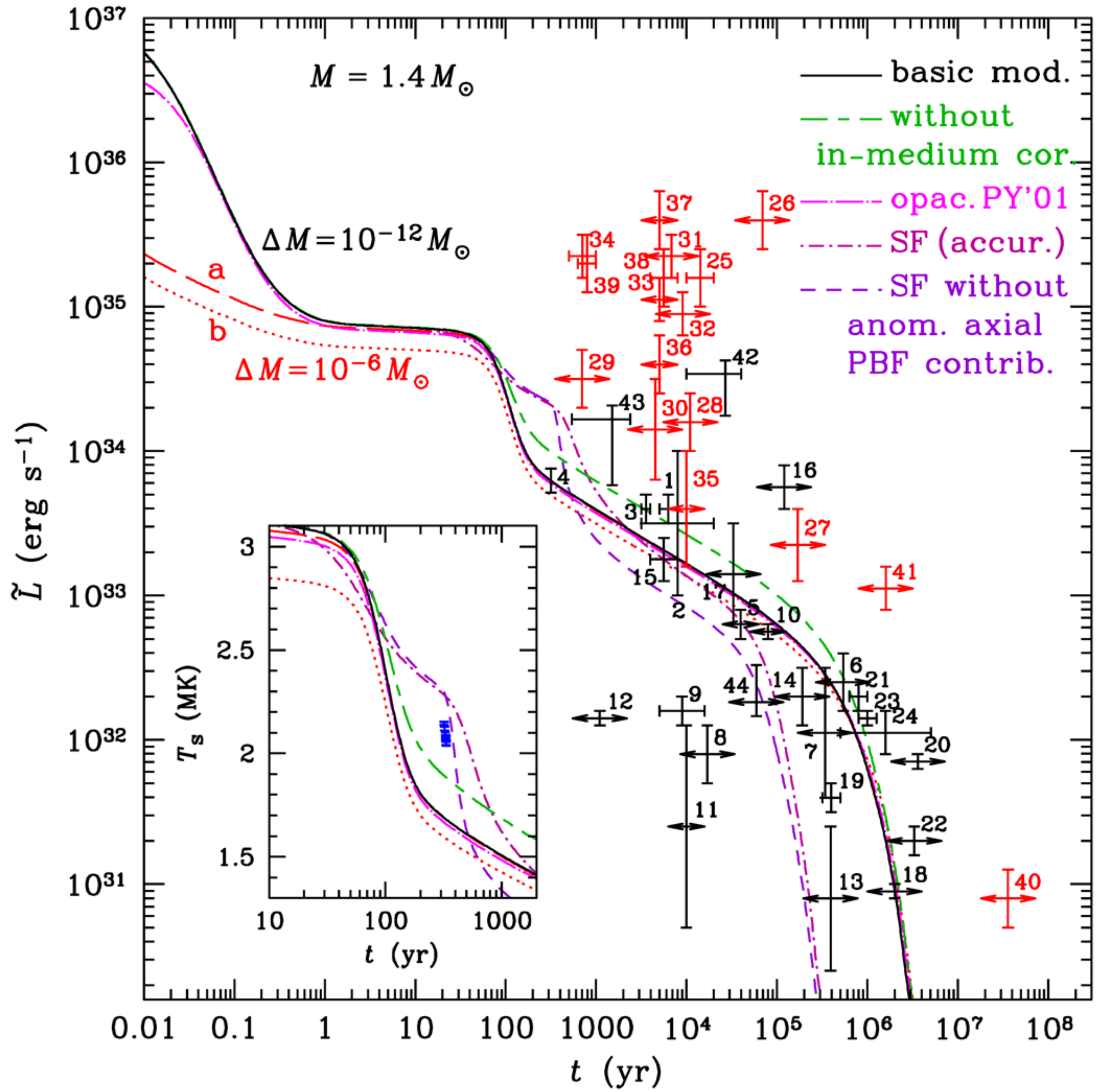


FIG. 3. Sky map in Galactic coordinates of the $a \to \gamma$ conversion probability, starting from a pure ALPs beam at the outside boundary of the Galaxy, for the Jansson and Farrar magnetic field model derived in [36]. We have taken the energy to be $E = 50$ MeV, the coupling $g_{a\gamma} = 3 \times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



Potekhin & Chabrier: Magnetic neutron star cooling and microphysics [1711.07662]

Axion Limits from Neutron Star Cooling

Selection of pulsars at different age:

- Umeda, Iwamoto, Tsuruta, Qin & Nomoto, astro-ph/9806337
- A. Sedrakian, arXiv:1512.07828 (hadronic axions)
- A. Sedrakian, arXiv:1810.00190 (non-hadronic axions)

Supernova Remnant Cas A (320 years)

- Leinson, arXiv:1405.6873
- Hamaguchi, Nagata, Yanagi & Zheng, arXiv:1806.07151

Supernova Remnant HESS J1731-347 (27 kyears)

- Beznogov, Rrapaj, Page & Reddy, arXiv:1806.07991
  $g_{an}^2 < 0.77 \times 10^{-19}$
- Leinson, arXiv:1909.03941 $C_n m_a \lesssim 2\ \mathrm{meV}$
  $g_{an}^2 < 1.1 \times 10^{-19}$

Magnificent Seven & PSR J0659 (ages $> 10^5$ years)

- Buschmann et al. arXiv:2111.09892
  $m_a < 16\ \mathrm{meV}$ (95% CL) for KSVZ axions

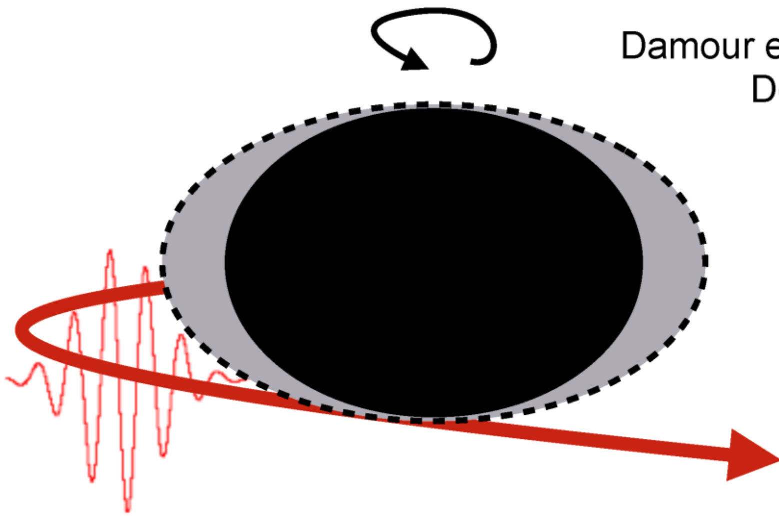
Limits broadly comparable to SN 1987A bounds (m_a tens of meV range) with different systematics

Superradiance

Initially slow particle scattering in the ergoregion speeds up by extracting angular momentum and energy from the BH;

Waves similarly increase in amplitude

Particles/waves trapped in orbit around the BH repeat this process continuously



Damour et al; Zouros & Eardley; Detweiler; Gaina

Superradiance condition:

Angular velocity of particle slower than angular velocity of BH horizon

$$\frac{\omega_a}{m} < \Omega_{BH}$$

(m = magnetic quantum number)

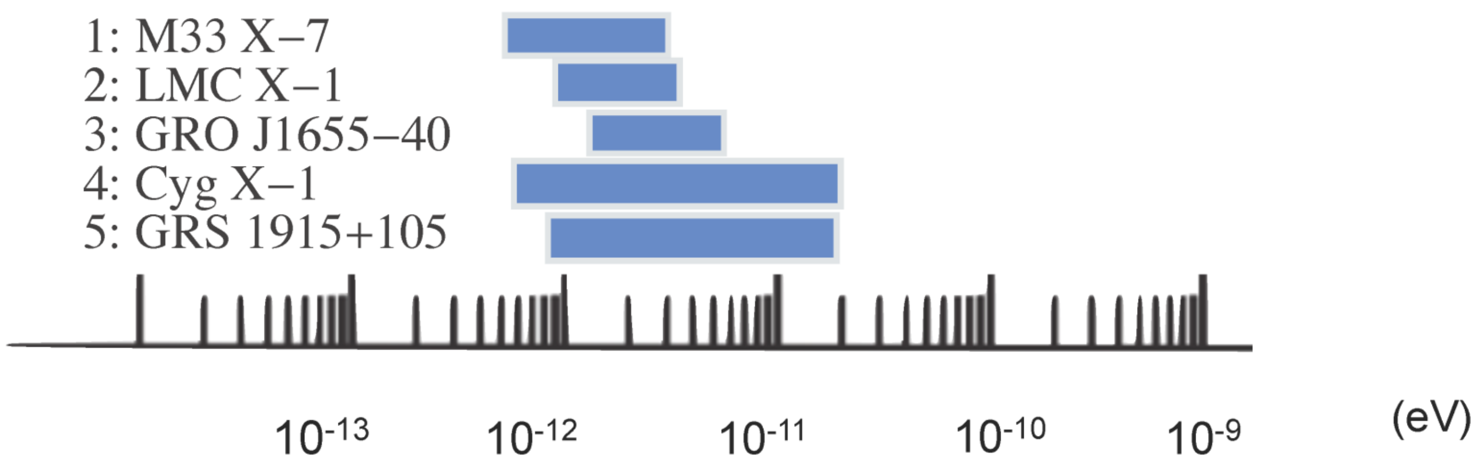
Particles in orbits that satisfy the SR condition are amplified:
"Black hole bomb"

Kinematic, not resonant condition

Black Hole Spins

Five currently measured black holes combine to set limit:

$$2 \times 10^{-11} > \mu_a > 6 \times 10^{-13}\ \text{eV}$$
$$3 \times 10^{17} < f_a < 1 \times 10^{19}\ \text{GeV}$$

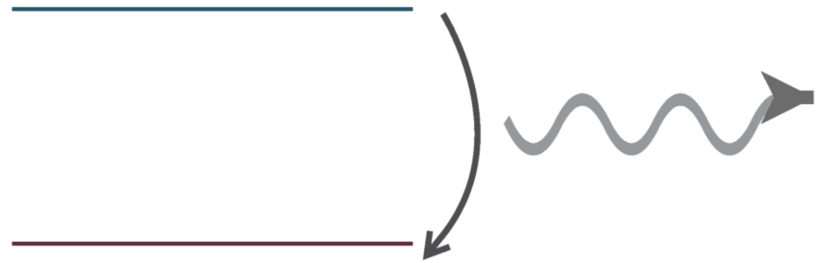


Arvanitaki , Baryakhtar & Huang, arXiv:1411.2263, PRD 91 (2015) 084011

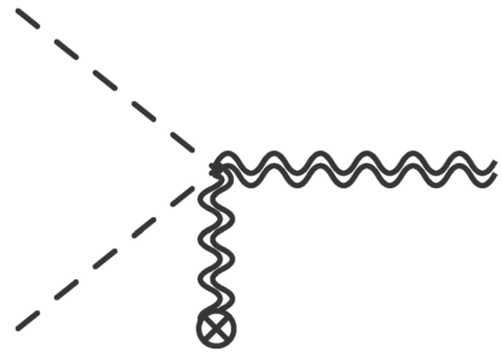
But see Fernandez, Ghalsasi & Profumo, arXiv:1911.07862

Gravitational Wave Signals

- Transitions between levels



- Annihilations to gravitons



Arvanitaki, Baryakhtar, Dimopoulos, Dubovsky & Lasenby, arXiv:1604.03958

→ arXiv:1501.06570

Superradiance

→ Latest Bounds on low-mass bosons

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[2] *CENTRA, Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049 Lisboa, Portugal.*

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Abstract

Superradiance is a radiation enhancement process that involves dissipative systems. With a 60 year-old history, superradiance has played a prominent role in optics, quantum mechanics and especially in relativity and astrophysics. In General Relativity, black-hole superradiance is permitted by the ergoregion, that allows for energy, charge and angular momentum extraction from the vacuum, even at the classical level. Stability of the spacetime is enforced by the event horizon, where negative energy-states are dumped. Black-hole superradiance is intimately connected to the black-hole area theorem, Penrose process, tidal forces, and even Hawking radiation, which can be interpreted as a quantum version of black-hole superradiance. Various mechanisms (as diverse as massive fields, magnetic fields, anti-de Sitter boundaries, nonlinear interactions, etc...) can confine the amplified radiation and give rise to strong instabilities. These "black-hole bombs" have applications in searches of dark matter and of physics beyond the Standard Model, are associated to the threshold of formation of new black hole solutions that evade the no-hair theorems, can be studied in the laboratory by devising analog models of gravity, and might even provide a holographic description of spontaneous symmetry breaking and superfluidity through the gauge-gravity duality. This work is meant to provide a unified picture of this multifaceted subject. We focus on the recent developments in the field, and work out a number of novel examples and applications, ranging from fundamental physics to astrophysics.