LECTURE: Astrophysical Aspects

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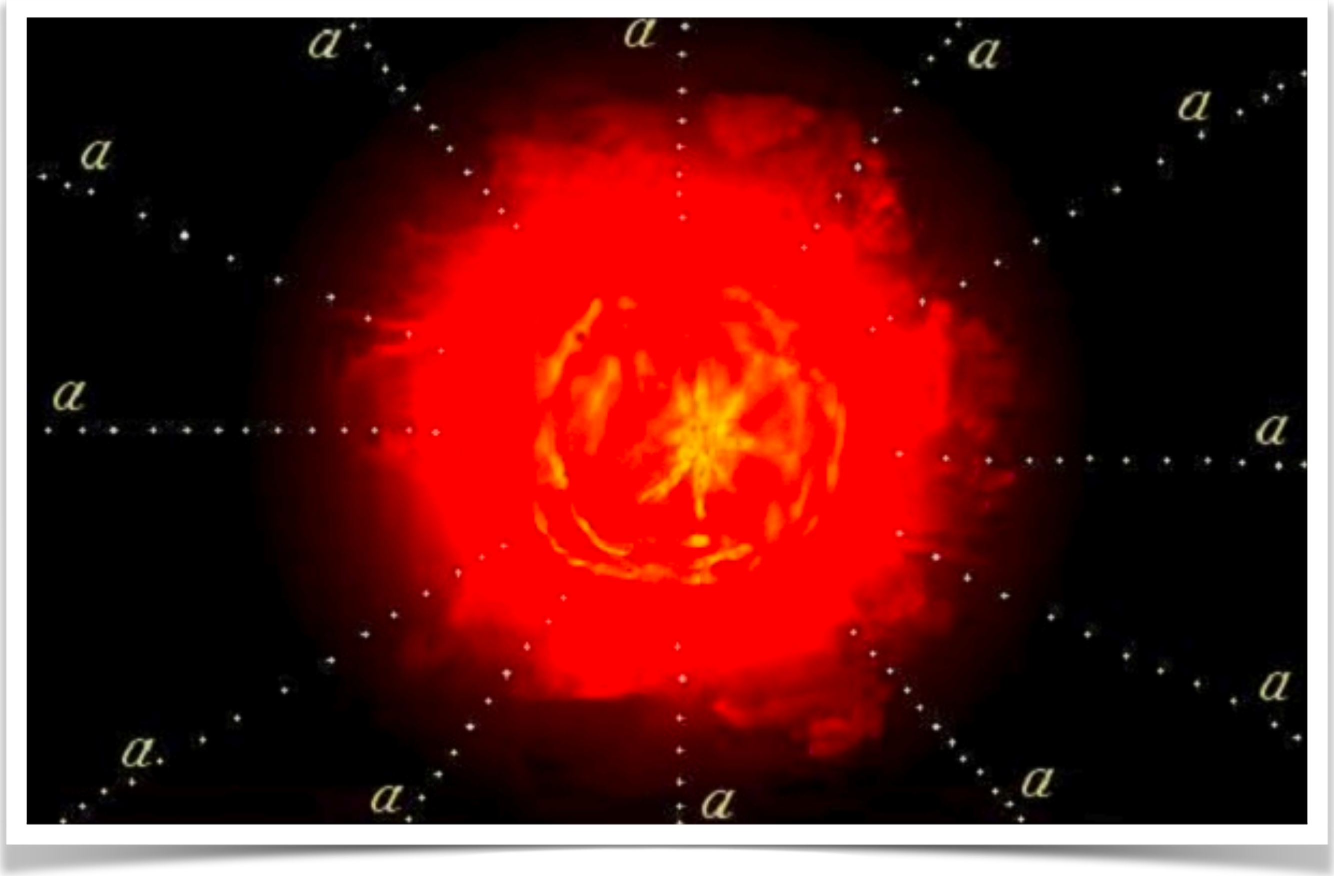


Axion ++,
Annecy, September 25-28, 2023

Summary

- *Some important facts about Stars*
- *Feebly Interactive Particles (FIPs) and Stars*
- *Exploring the sky with axions?*

Part 1: Stars

Stars as Labs for Very Rare Processes

D. D. Clayton, "Principles of Stellar Evolution and Nucleosynthesis", Chicago (1984)

Example: the SM process

$$e^+ \, e^- \rightarrow \bar{\nu} \, \nu$$

has a branching ratio 10^{-19} times smaller than the process

$$e^+ \, e^- \rightarrow \gamma \, \gamma$$

Yet, it controls the late evolution of massive stars.

Another very rare process, $\gamma \rightarrow \bar{\nu}\nu$, controls the stellar evolution during the RGB.

Stars: An intuitive picture…

Stars are self-gravitating bound systems, which radiates energy supplied by an internal (nuclear) source

→ D. Prialnik (2009)

As the gas compresses, under the effect of gravity, temperature and density increase.

Eventually, at $T \sim$ 1keV, hydrogen is ignited.

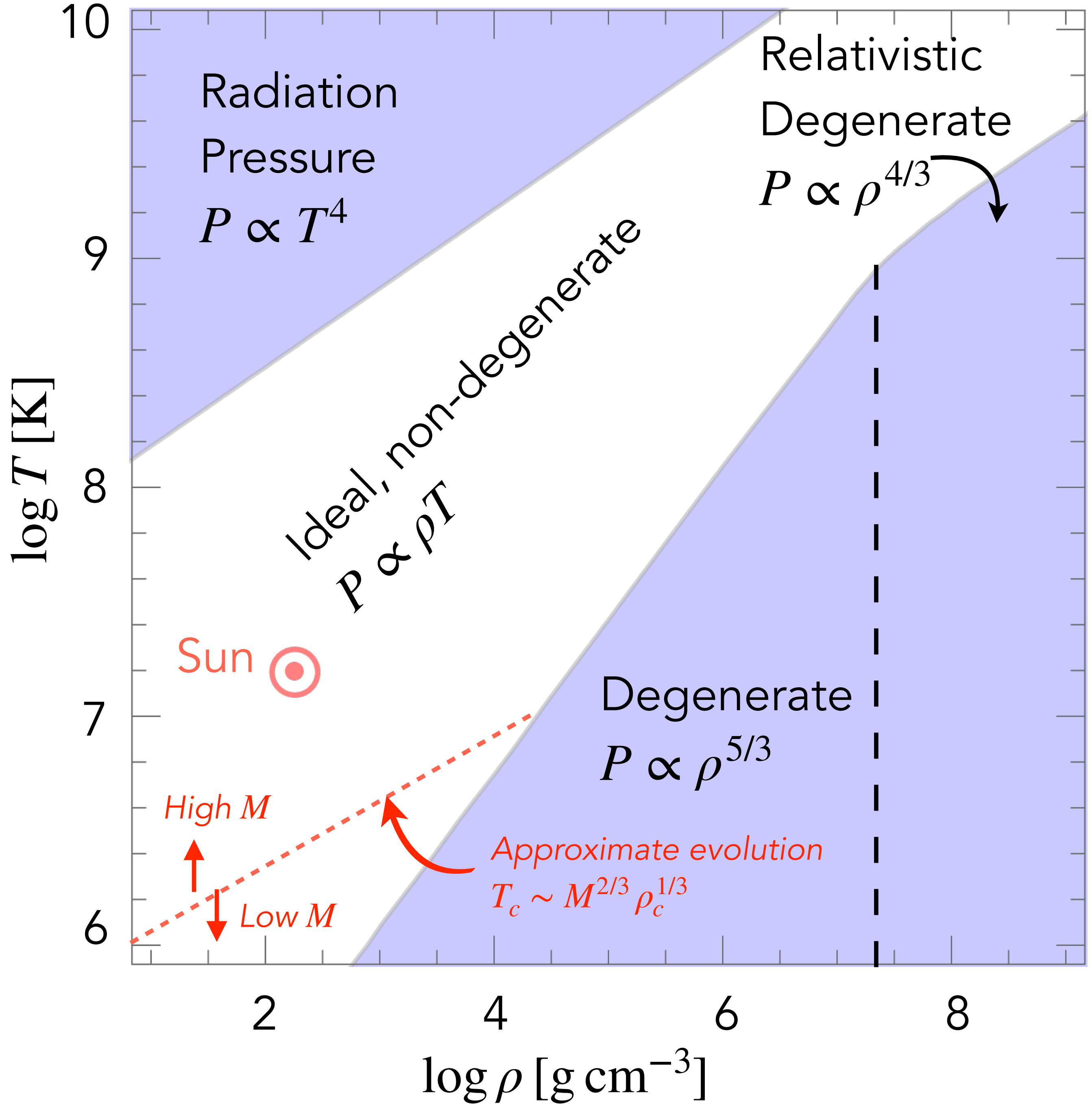
➡ We have a star!

Note: in most cases the gas can be described as an ***ideal gas*** *even at the very high density typical of the stellar cores!!* → See Backup Notes

Limitation 1: Onset of Degeneracy

Degeneracy pressure has a stronger dependence on the density!

→ *if we keep increasing the density, eventually we reach degeneracy: density is no longer dependent on the temperature.*



$$T \sim A\, M^{2/3} \rho^{1/3} - B\, \rho^{2/3}$$

e.g. → Padmanabhan, invitation to astrophysics (2006)

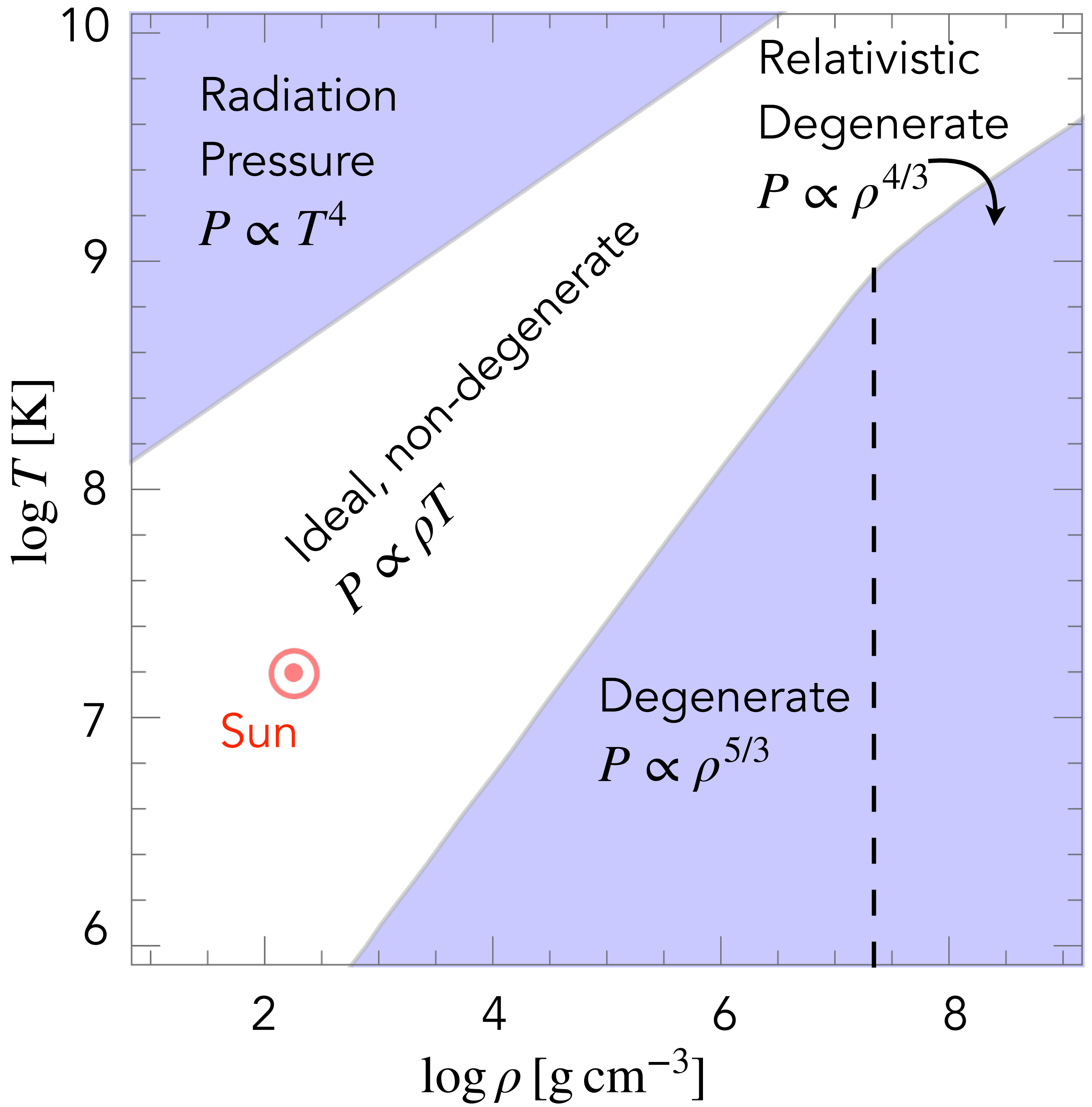
There is a maximal temperature (dependent on M).

For the cloud to become star it is required to ignite H

→ $M \gtrsim 0.1\, M_\odot$

Limitation 2: Radiation Pressure

Radiation pressure opposes gravity



For very large mass, the radiation pressure may be so large that it prevents the formation of a bound state.

$\rightarrow\ M \lesssim 100\, M_\odot$

The stellar mass range is relatively narrow

$$0.1\, M_\odot \lesssim M \lesssim 100\, M_\odot$$

A more detailed picture: Energy

Energy equation: $\dot{E}_{\rm tot} = L_{\rm nuc} - L$

Change in energy

Energy produced

Energy lost

Internal energy

$$E_{\rm tot} = U_{\rm int} + \Omega = \frac{1}{2}\Omega$$

Gravitational energy

Virial Theorem:

$$U_{\rm int} = -\frac{1}{2}\Omega$$

Notes:

1. Since $\Omega < 0$ also $E_{\rm tot} < 0$ (bound state)
2. If we add also radiation,

   $$E_{\rm tot} = \frac{1}{2}\left(\Omega + U_{\rm rad}\right)$$

   → Radiation acts as a (positive) gravitational potential energy. If too large ⇒ no bound state.

→ *D. Prialnik (2009)*

… A more detailed picture: Stability

Energy: $\dot{E}_{\rm tot} = L_{\rm nuc} - L$

Equilibrium: $L_{\rm nuc} = L$. We can use the viral theorem (hydrostatic equilibrium). Ignore $U_{\rm rad}$. A small perturbation from equilibrium:

$L_{\rm nuc} > L \;\rightarrow\; \dot{E}_{\rm tot} > 0 \;\rightarrow\; \dot{\Omega} > 0 \;\rightarrow$ Expansion → Pressure decrease:

… A more detailed picture: Stability

Energy: $\dot{E}_{\mathrm{tot}} = L_{\mathrm{nuc}} - L$

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Ideal, Non-degenerate gas:

$P \propto T \;\Rightarrow\; T$ decreases as well, and L_{nuc} is suppressed → Self-regulating system. Equilibrium! Nuclear reactions can be sustained (and so the star can go on living in a stable configuration) for as long as there is nuclear fuel

At this point *the configuration is determined entirely by the stellar mass*, aside from a small influence of the metal content.

… A more detailed picture: Stability

Energy: $\dot{E}_{\text{tot}} = L_{\text{nuc}} - L$

Equilibrium: $L_{\text{nuc}} = L$. We can use the viral theorem (hydrostatic equilibrium). Ignore U_{rad}. A small perturbation from equilibrium:

$L_{\text{nuc}} > L \;\rightarrow\; \dot{E}_{\text{tot}} > 0 \;\rightarrow\; \dot{\Omega} > 0 \;\rightarrow$ Expansion → Pressure decrease:

Degenerate Gas:

More in Backup Slides

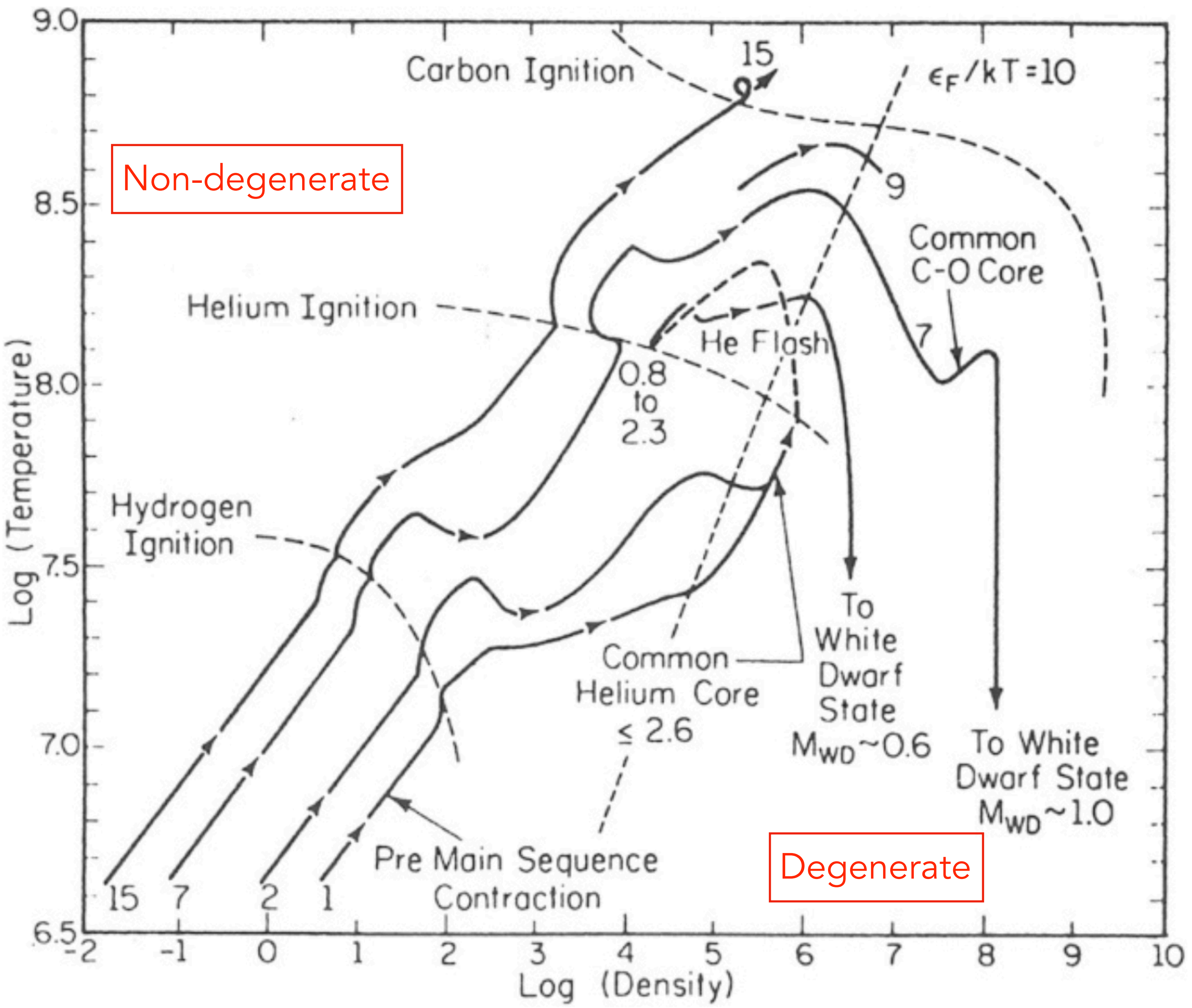
→ P is (almost) independent from T.

→ The system is not self-regulated. Unstable system. Nuclear reactions lead to runaway. Expansion may lead to restoration of non-deg. conditions

Summary: Stellar Evolution

Key Features:

- Approximate evolution of central conditions:
  $T_c \sim M^{2/3} \rho_c^{1/3}$
- Nuclear burning stable only in non-deg. conditions.
- Nuclear reactions very sensitive to T. Implies, onion structure for advanced stages.

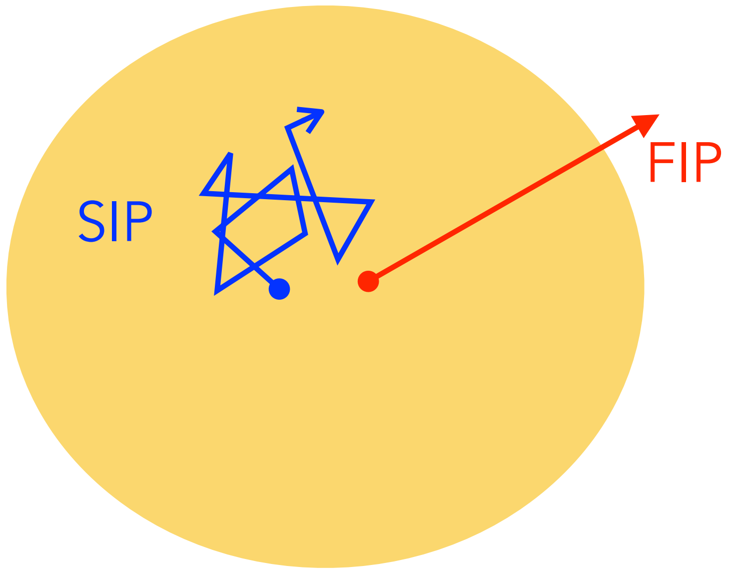


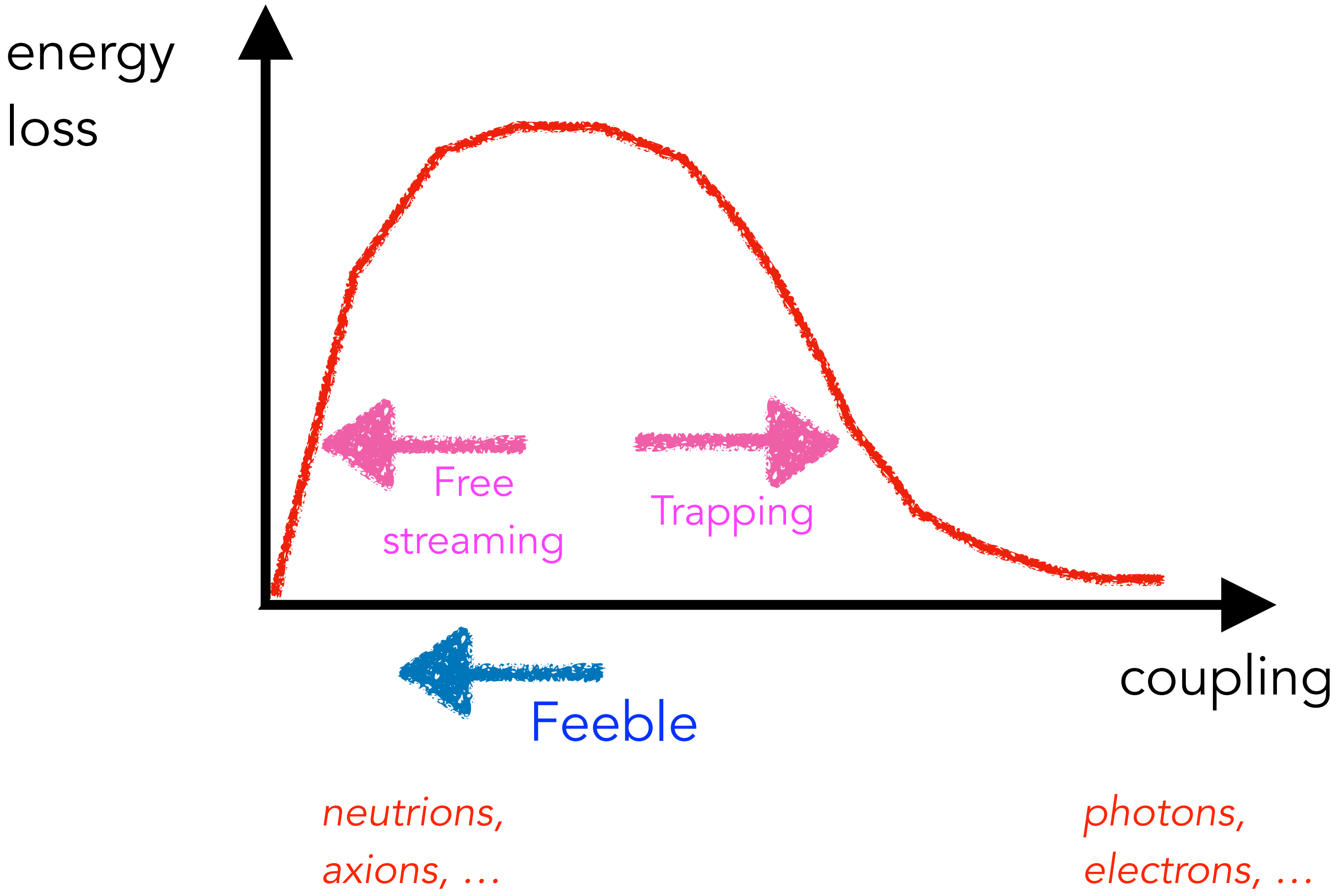
From from Iben (1985). Fig 2.12 in Hansen, Kawaler, Trimble, Stellar Interiors (2004)

Part 2:
FIPs & Stars

The Role of FIPs in Stars

Light particles, $m \lesssim T$, can be efficiently thermally produced in stellar core…

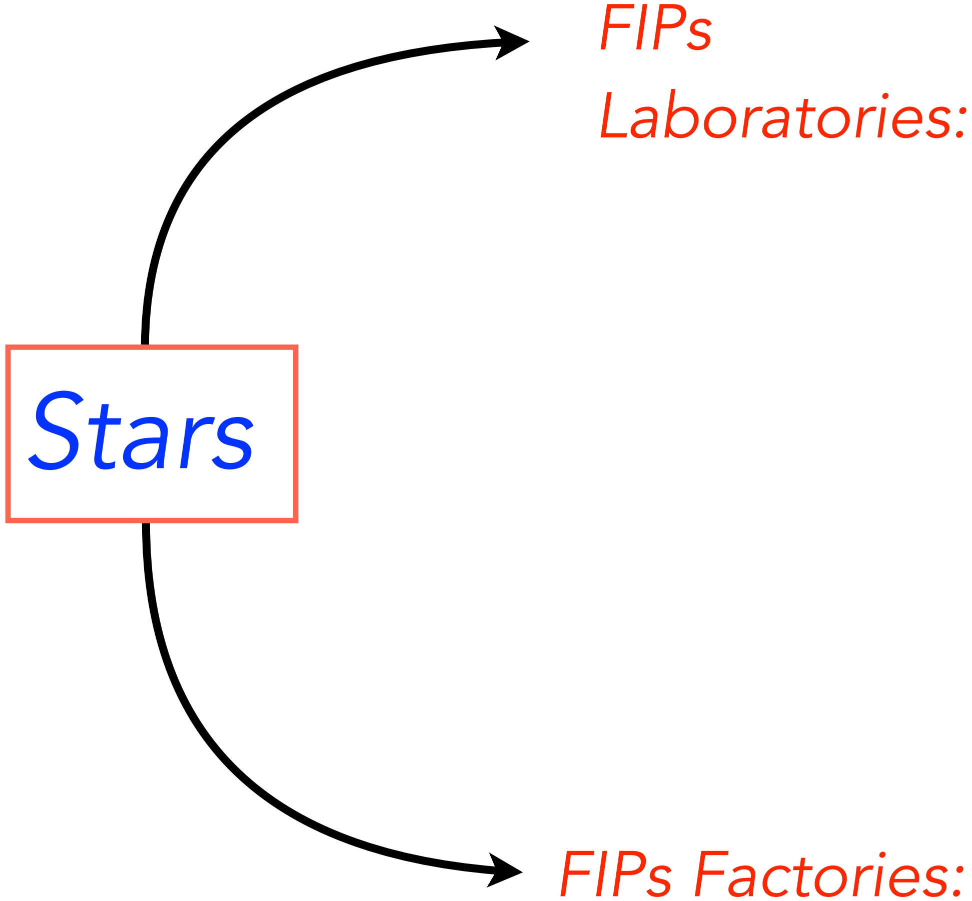




… and can efficiently contribute to the energy transport (L), especially if weakly coupled

This is often known (not always correctly) as FIPs cooling

FIPs and Stars



Stars

FIPs Laboratories:

FIP production may cause:

1. *Quantitative Changes (e.g., modify the evolutionary times of some phases)*

2. *Qualitative changes (e.g., modify the evolution of a star, prevent some phases from happening…)*

FIPs Factories:

Stars produce FIPs which might be detectable (directly or indirectly)

The Role of FIPs in Stars

Energy considerations: $\dot{E}_{\text{tot}} = L_{\text{nuc}} - L$

Energy Produced

Energy Lost

Equilibrium:

$$L_{\text{nuc}} = L.$$

Suppose, now we add a weakly coupled FIP

→ L increases and hence L_{nuc} increases.

The Role of FIPs in Stars

Ideal, Non-degenerate gas:

Increasing L $\Rightarrow$

→ Higher $L_{\rm nuc}$

→ faster use of fuel.

→ faster evolution.

Can be tested !

The enormous majority of stellar bounds on FIPs is found using this method.

There are, however, many other ways that could be used to test new physics with stars. We should explore new possibilities

The Role of FIPs in Stars

A counterintuitive result:

Ideal, Non-degenerate gas:

Higher $L_{\rm nuc}$ → Higher T (nuclear burning is a steep function of T)

→ exotic FIPs energy loss heats up the system!!

→ We can constrain FIPs by measuring the core temperature of the star!!

(Not easy, see → S. Hoof talk, Wed. @ 15:55)

Example, the solar temperature is well measured by the flux of neutrinos from B8 is extremely sensitive to the temperature ($\phi_{B8} \sim T_c^{18}$)

⇒ axion constraint → P. Gondolo and G. Raffelt, Phys. Rev. D 79 (2009)

The Role of FIPs in Stars

Degenerate gas:

If $L_{\rm nuc} \approx 0 \;\rightarrow \dot{E}_{\rm tot} < 0$ → The star cools down

Add FIPs

→ more efficient cooling (faster evolution) of degenerate systems (e.g., WDs)

→ modify rate of period change in some degenerate systems:

E.g. for WD Variables $\frac{\dot{P}}{P} \propto \left|\frac{\dot{T}}{T}\right|$

The Role of FIPs in Stars

There are other less (or not at all) studied effects of FIPs on Stars, e.g., modify the evolution, impact on convection, impact on nucleosynthesis, or even modification of the Equation of State (EOS)

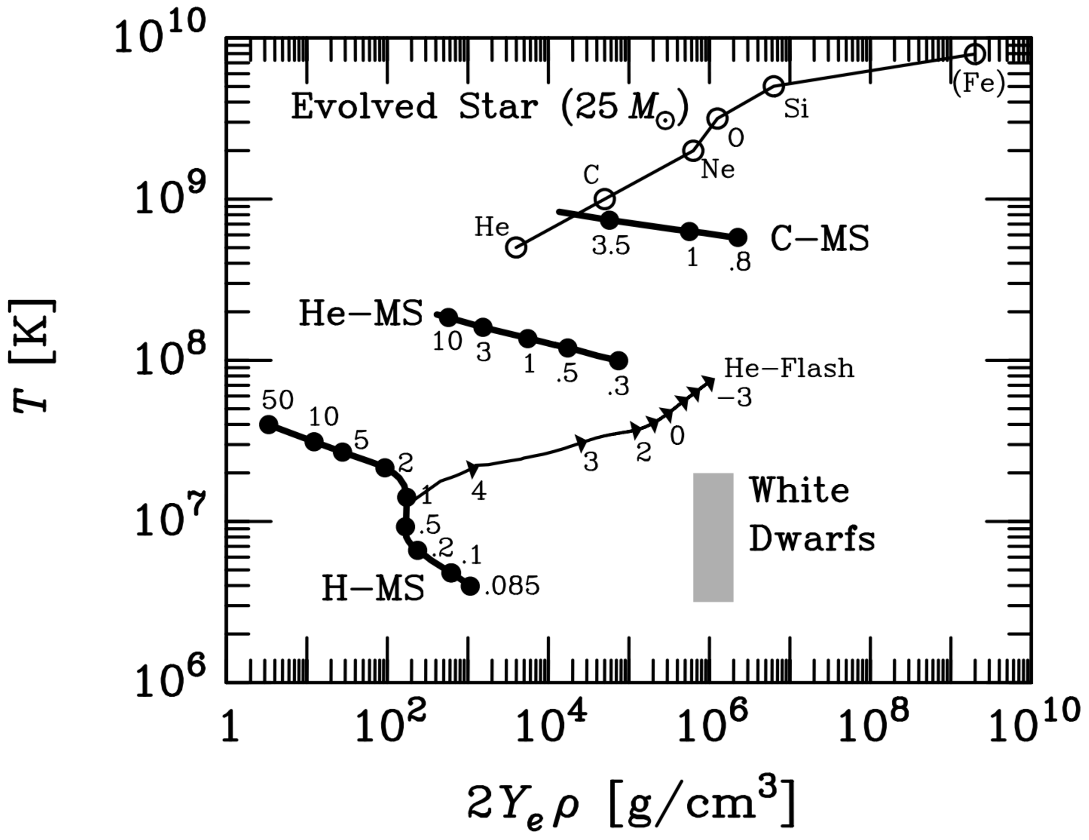
➡ Some additional info in Backup Material

Observing the Stars

We can observe (almost) only the surface of stars

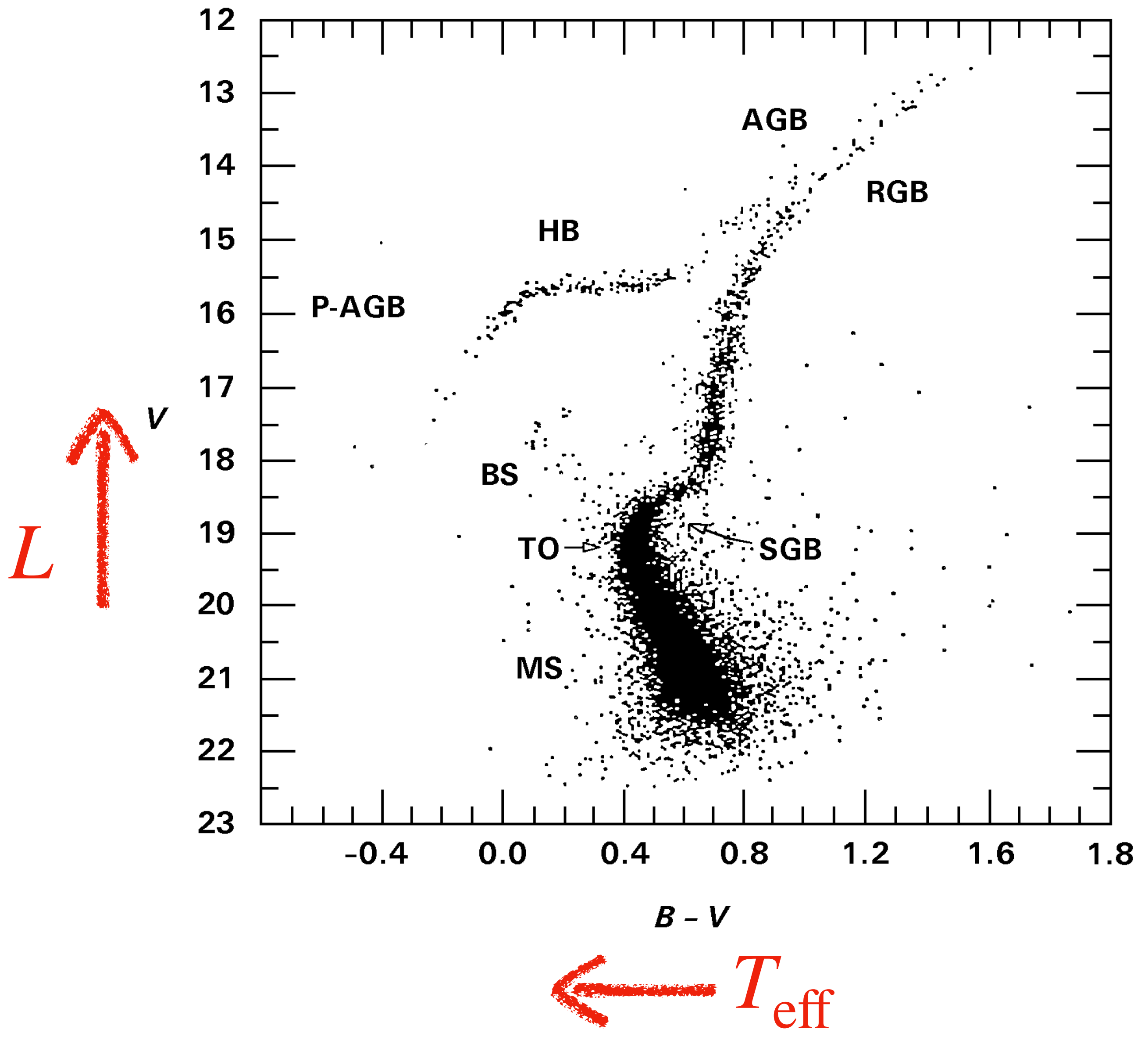
Numerical codes provide the link with core properties

Core

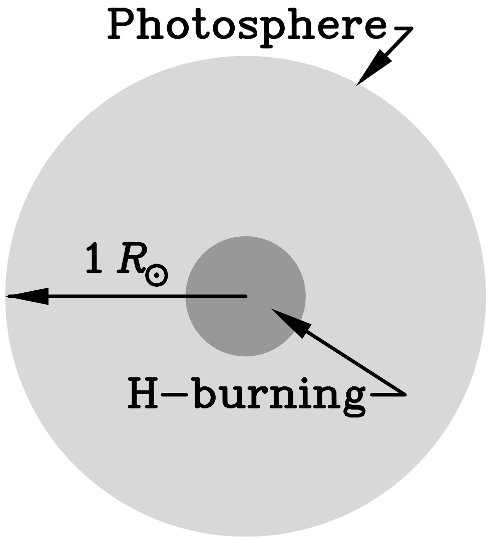


G. Raffelt, Stars as Laboratories (1996).

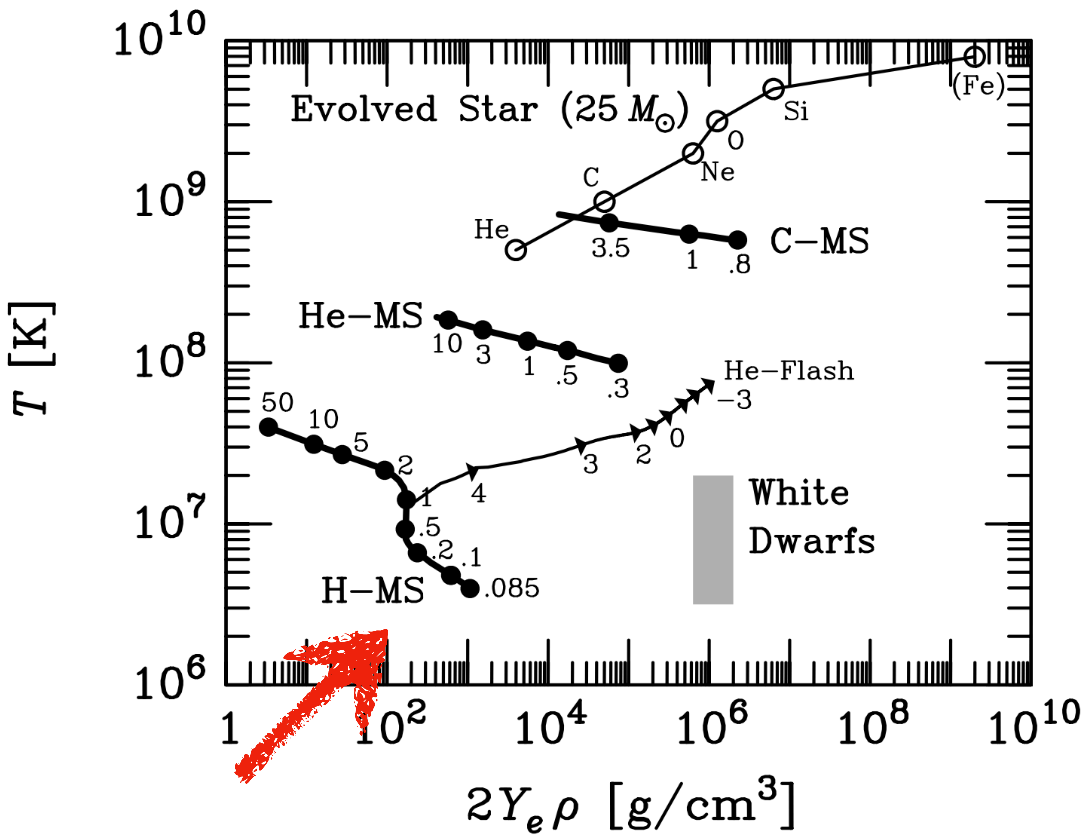
Surface

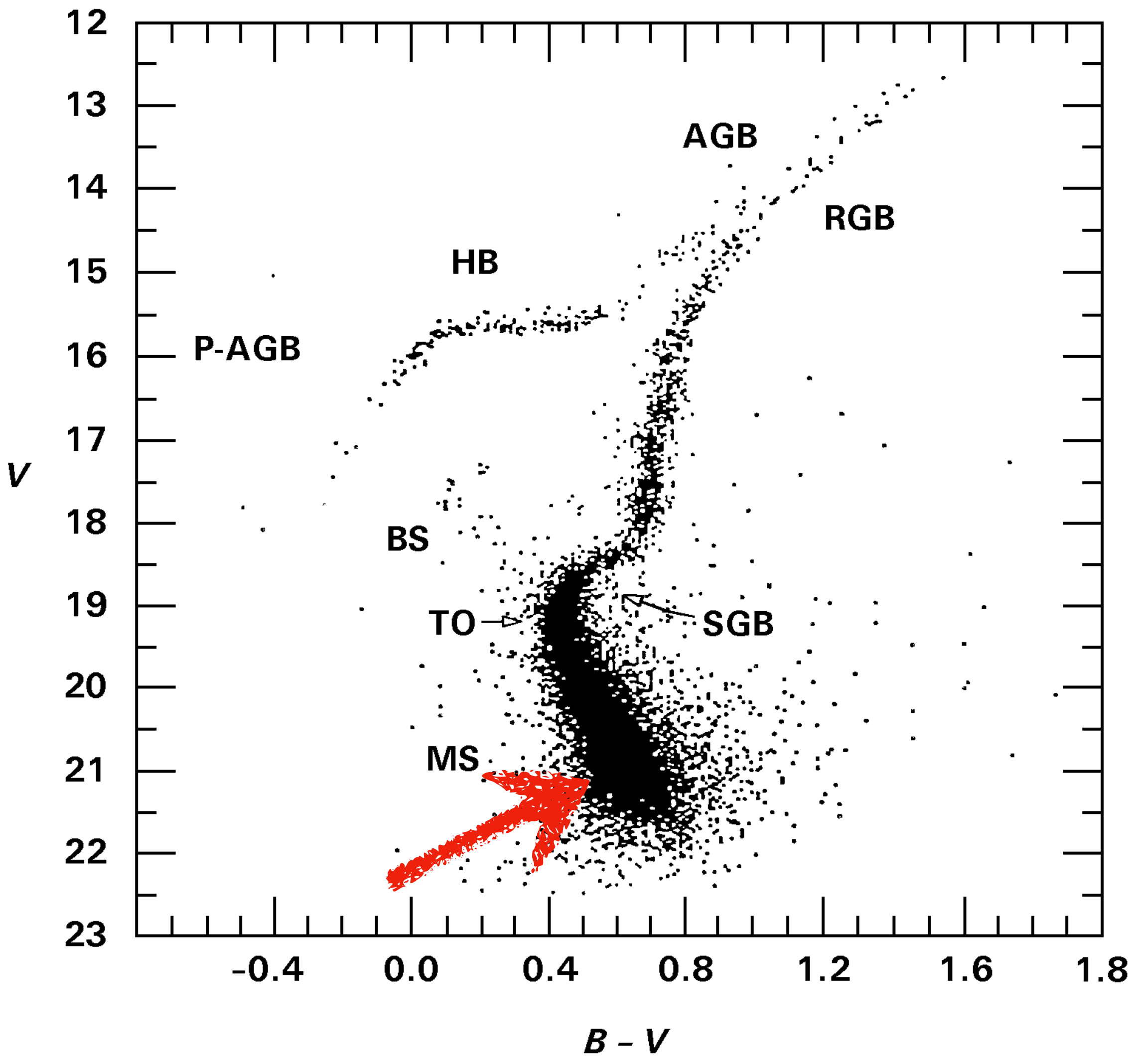


Stellar Evolution → Main Sequence Stars



Most of the stellar life is spent burning H into He in the core





G. Raffelt, Stars as Laboratories (1996).

Solar bounds on axions

The sun is a good (not excellent) lab for axions.

The flux of neutrinos from B8 is extremely sensitive to the temperature $\phi_{B8} \sim T_c^{18}$

→ $g_{a\gamma} < 7 \cdot 10^{-10}\,\mathrm{GeV}^{-1}$ $(3\,\sigma)$

P. Gondolo and G. Raffelt,
Phys. Rev. D 79 (2009)

A more complete analysis gives

$$\boxed{\rightarrow \quad g_{a\gamma} < 4.1 \cdot 10^{-10}\,\mathrm{GeV}^{-1} \quad (3\,\sigma)}$$

Vinyoles, Serenelli, Villante, Basu,
Redondo & Isern, JCAP 10 (2015) 015

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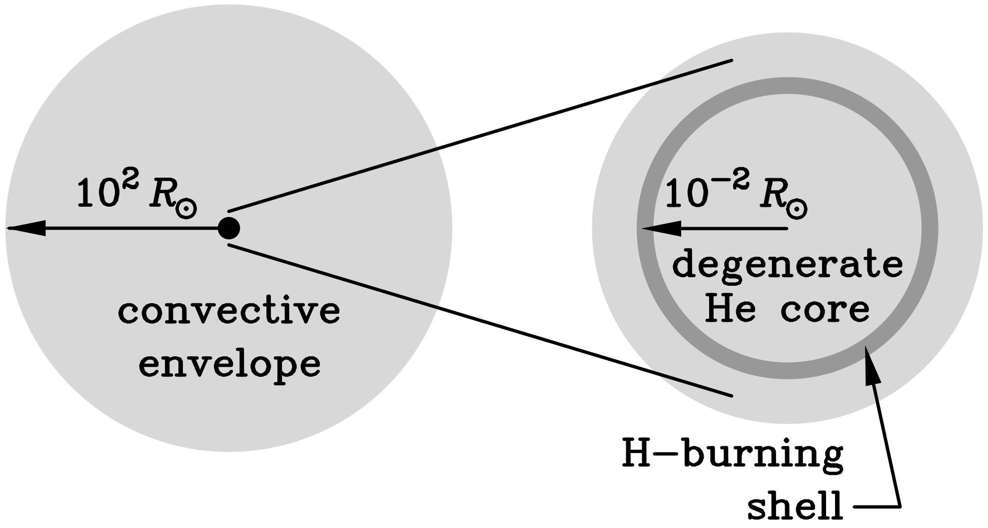
$\sim 6 \times 10^{12}\,\mathrm{axions\ cm^{-2}\,s^{-1}}$

on Earth, peaked at ~ keV.

Allowed by astrophysics, but excluded by experimental searches

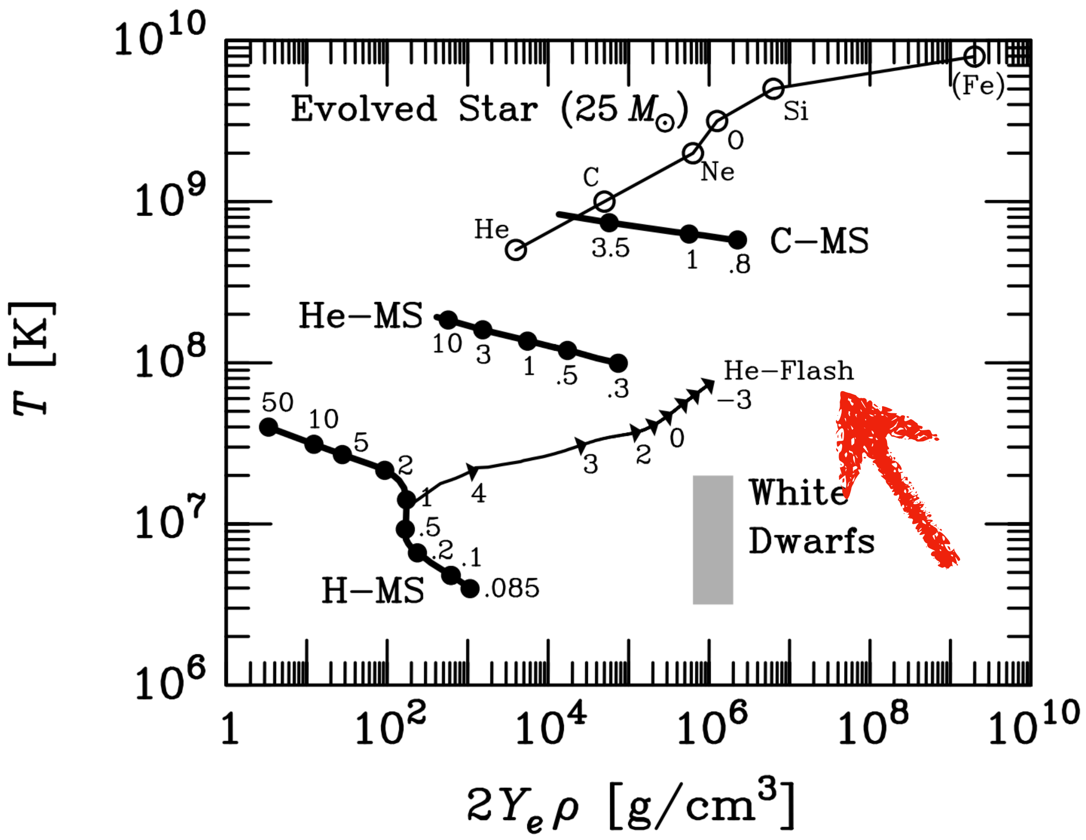
→ Julia Vogel's talk

Stellar Evolution → Red Giant Branch

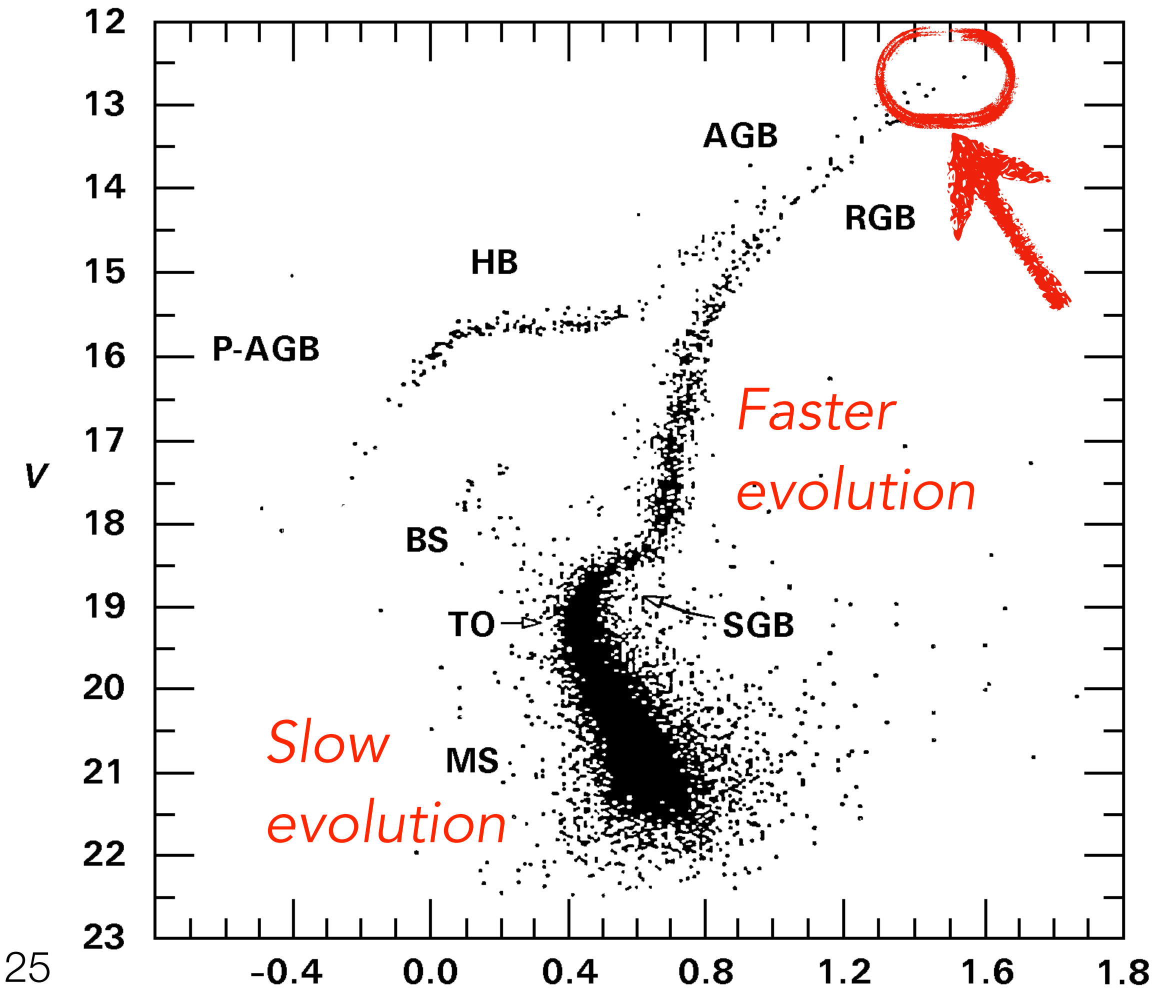


After the H in the core is exhausted, a light star star moves in the RGB.

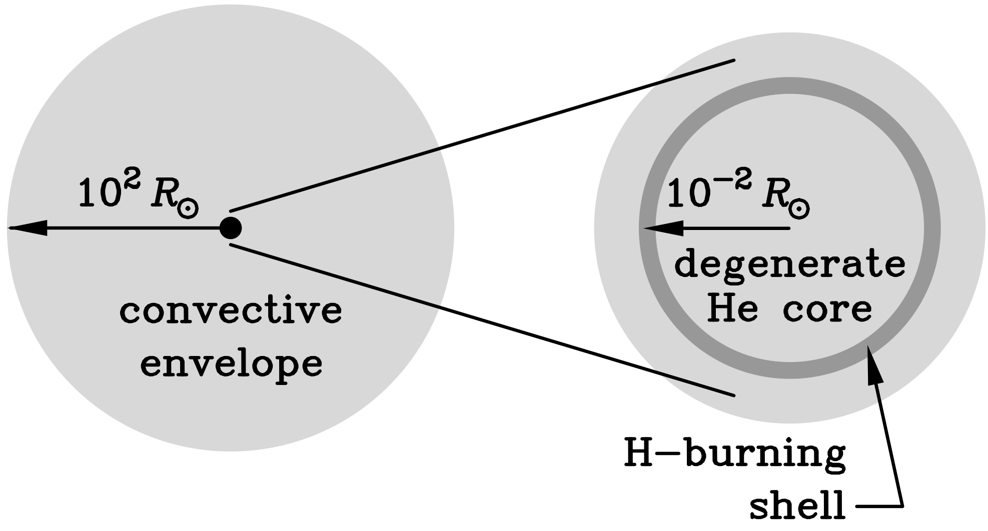
No Core Burning! Core looks like a WD surrounded by H-burning shell.



G. Raffelt, Stars as Laboratories (1996).



Stellar Evolution → Red Giant Branch

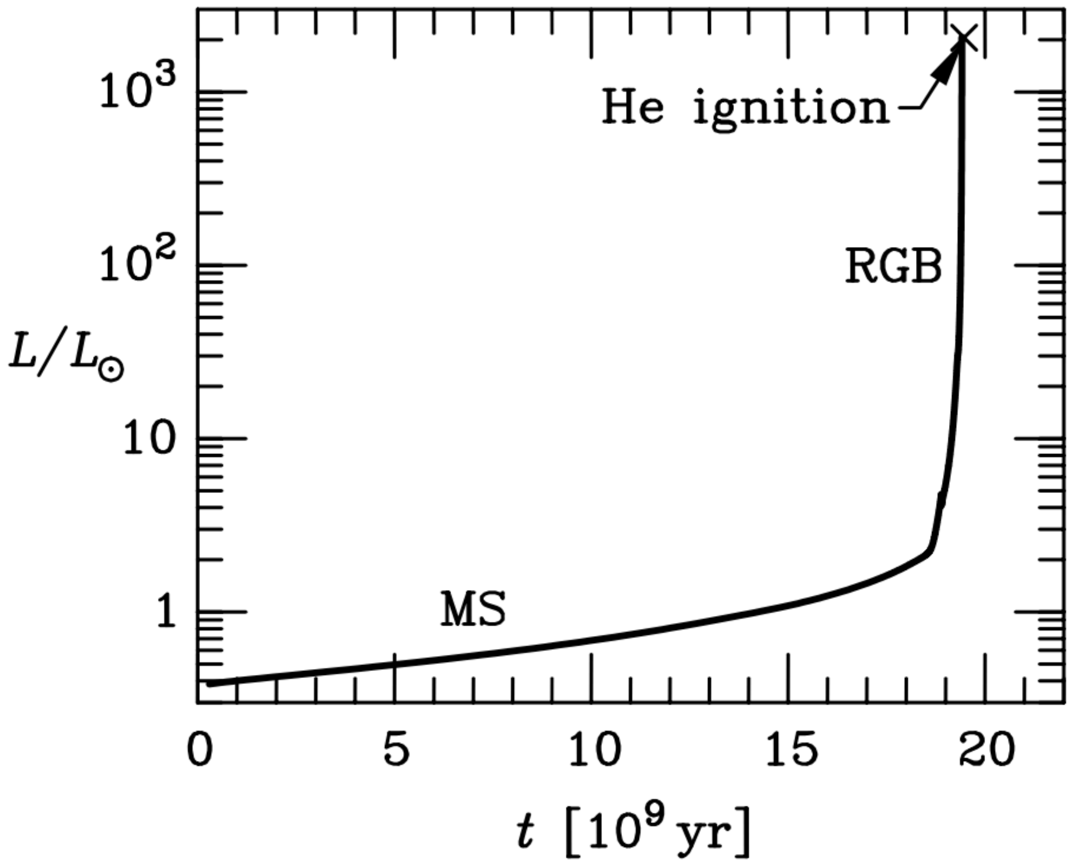


When the core becomes degenerate,
→ $R \propto M^{-1/3}$
→ The core shrinks from the shell ashes
→ The envelop expands and cools (Red Giant)

The gravitational energy from the core heats up the shell → the luminosity increases

The physics is driven by the core mass, not by the total mass (as in MS phase)

The evolution is much faster than the self-regulating MS phase.



G. Raffelt, Stars as Laboratories (1996).

Stellar Evolution → Red Giant Branch

FIPs (including neutrinos) → COOLING (degenerate medium)

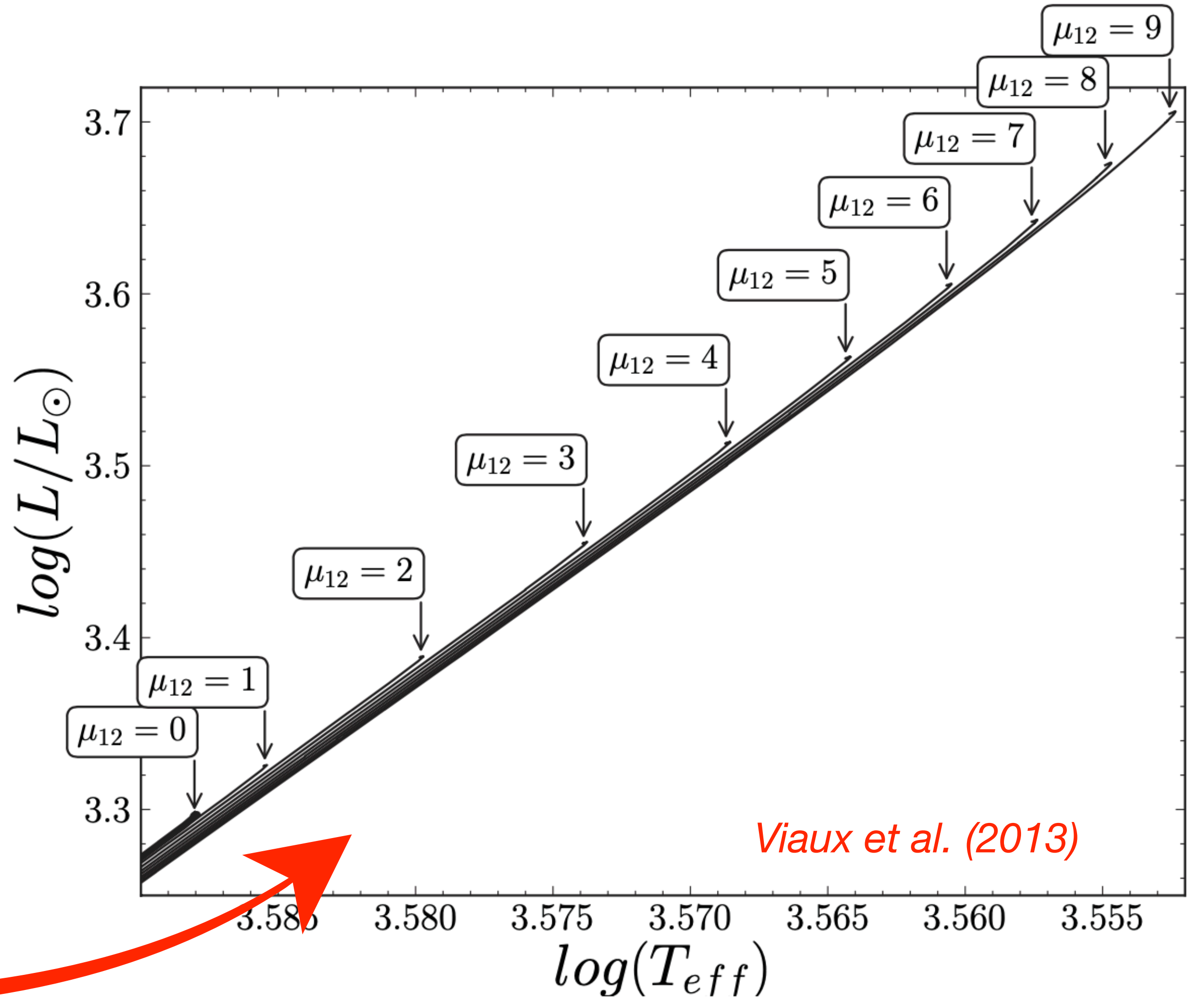
→ *Prevent the core from reaching the temperature required to ignite He*

→ *The core has time to grow more.*

Higher core mass

→ *hotter shell*

→ *higher luminosity*



Viaux et al. (2013)

Note. The analysis in this figure is somewhat outdated and should serve only as a qualitative example.

Stellar Evolution → Red Giant Branch

Currently, the RGB Tip analysis provides the strongest bounds on:

Axion-electron coupling:

$$g_{ae} \sim 0.60^{+0.32}_{-0.58} \times 10^{-13},$$

$$\boxed{g_{ae} \leq 1.48 \times 10^{-13} \quad (95\,\%\ \mathrm{C.L.})}$$

O. Straniero et al., Astron.Astrophys. 644 (2020)

and on the neutrino magnetic moment:

$$\boxed{\mu_\nu < 1.5 \times 10^{-12} \mu_B \quad (95\,\%\ \mathrm{CL})}$$

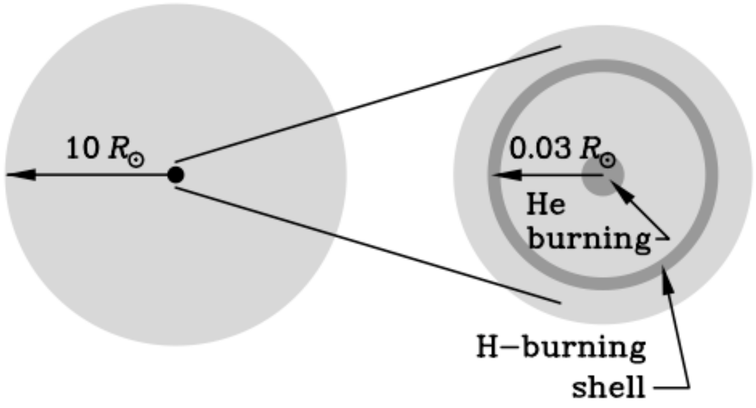
F. Capozzi, G. Raffelt, Phys.Rev.D 102 (2020) 8

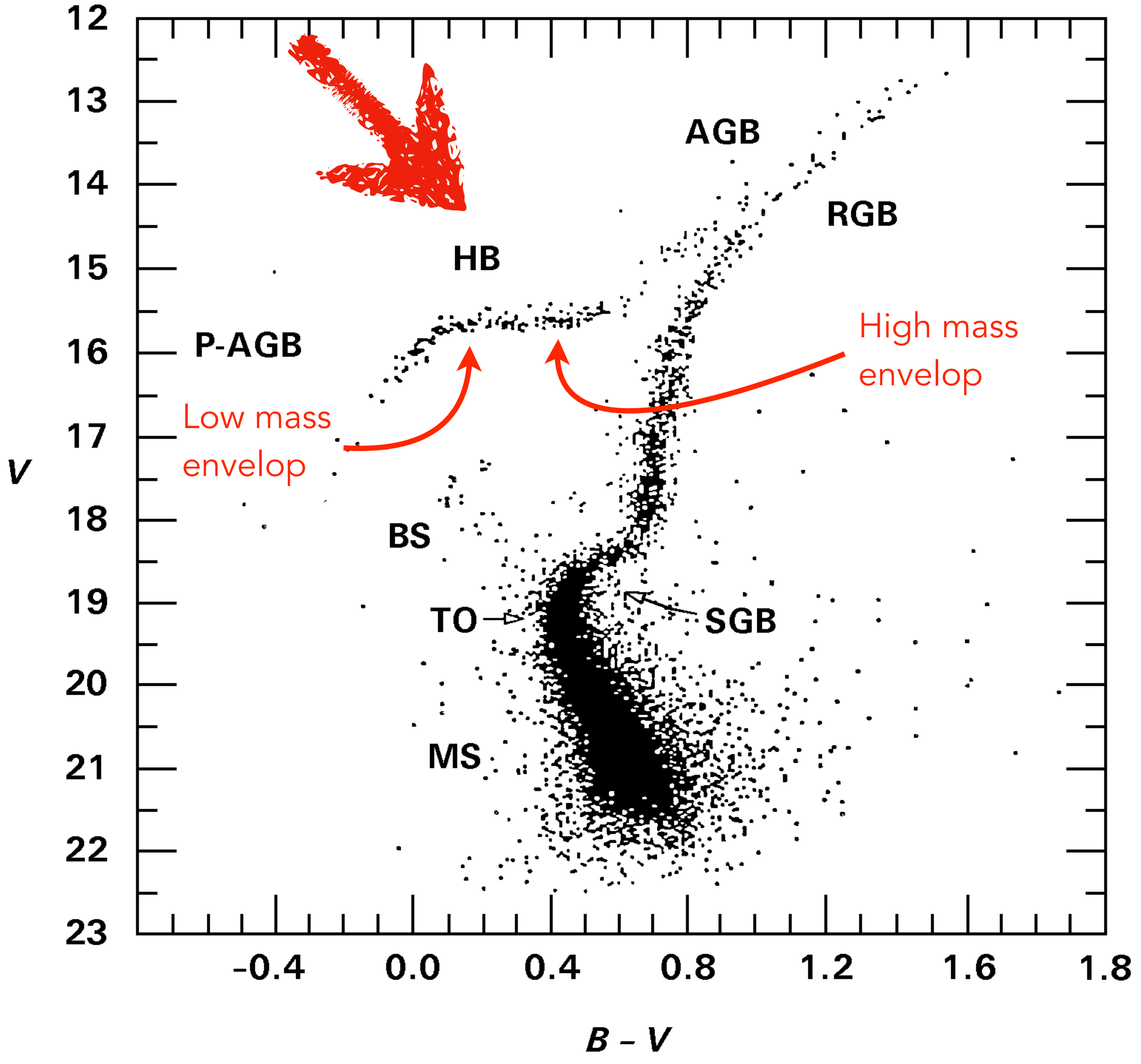
Recently, the bounds from RGB have been questioned in two publications

- N Franz, M Dennis, J Sakstein, arXiv:2307.13050
- M Dennis, J Sakstein, arXiv:2305.03113

The criticism is that the uncertainties are much larger than those used in the papers which derived the bonds. However, the uncertainties proposed in seem largely inflated.

Stellar Evolution → Horizontal Branch



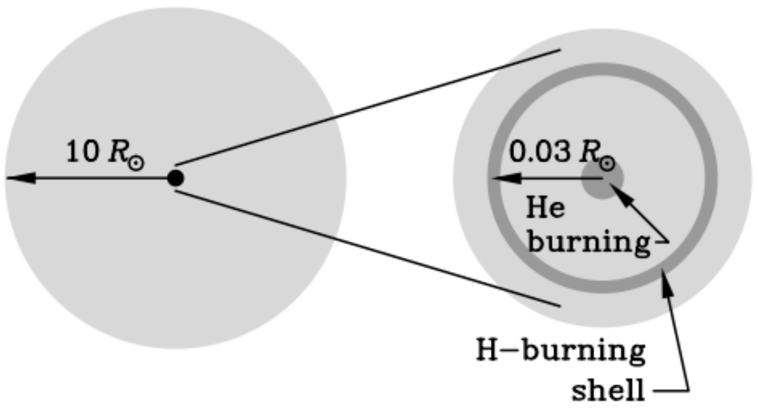


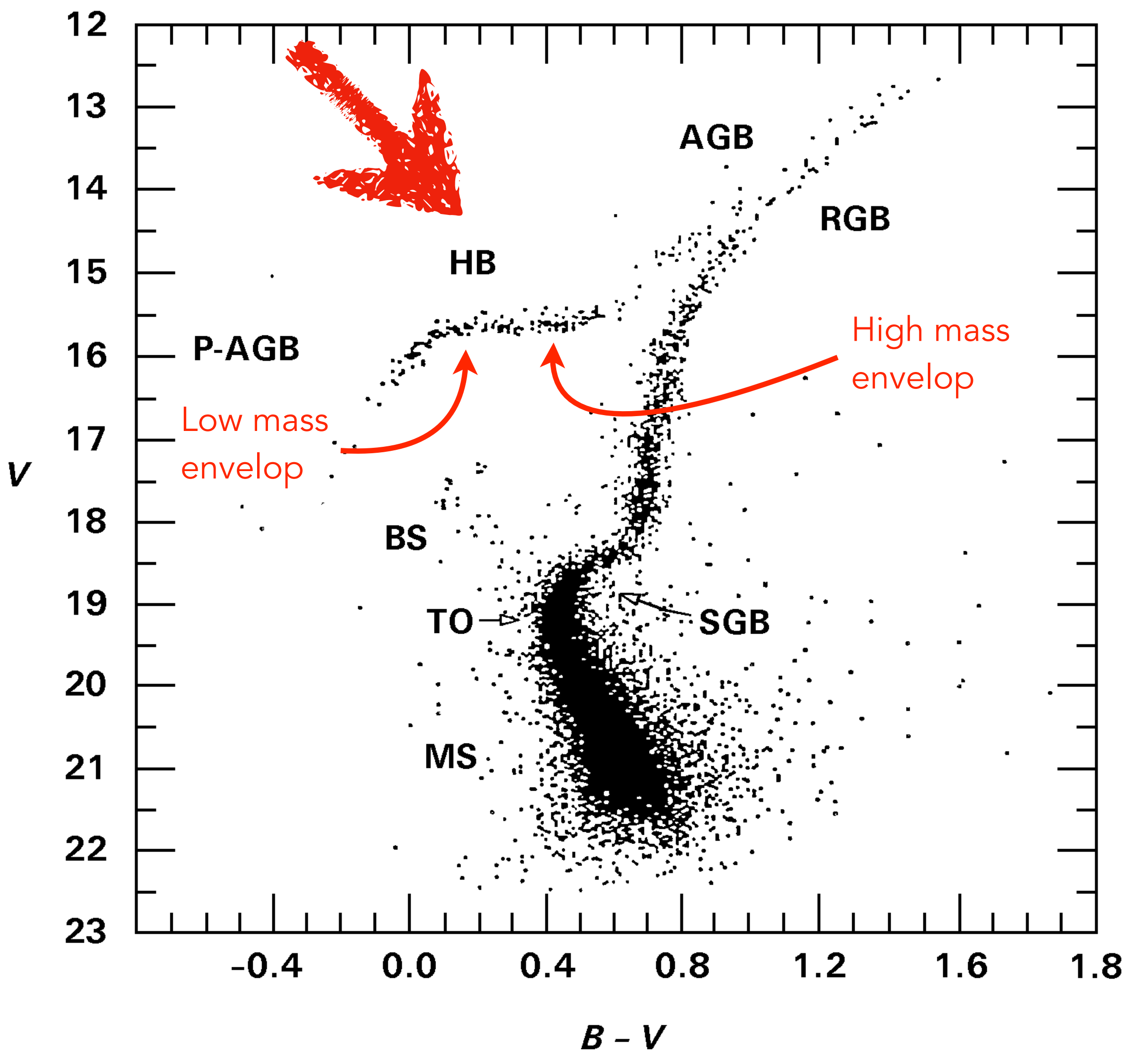
<u>Becoming a HB stars.</u>

→ The unstable nuclear ignition in the degenerate core triggers a passage back to the non-degenerate regime and the contraction stops.

→ The star envelope shrinks and cools down.

Stellar Evolution → Horizontal Branch





Becoming a HB stars.

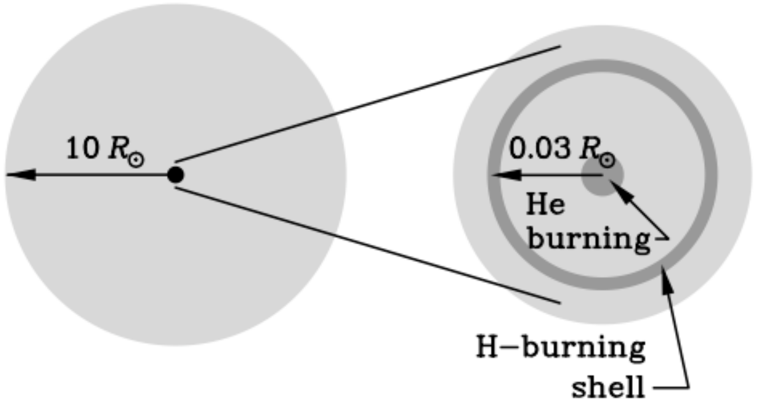
→ The unstable nuclear ignition in the degenerate core triggers a passage back to the non-degenerate regime and the contraction stops.
→ The star envelope shrinks and cools down.

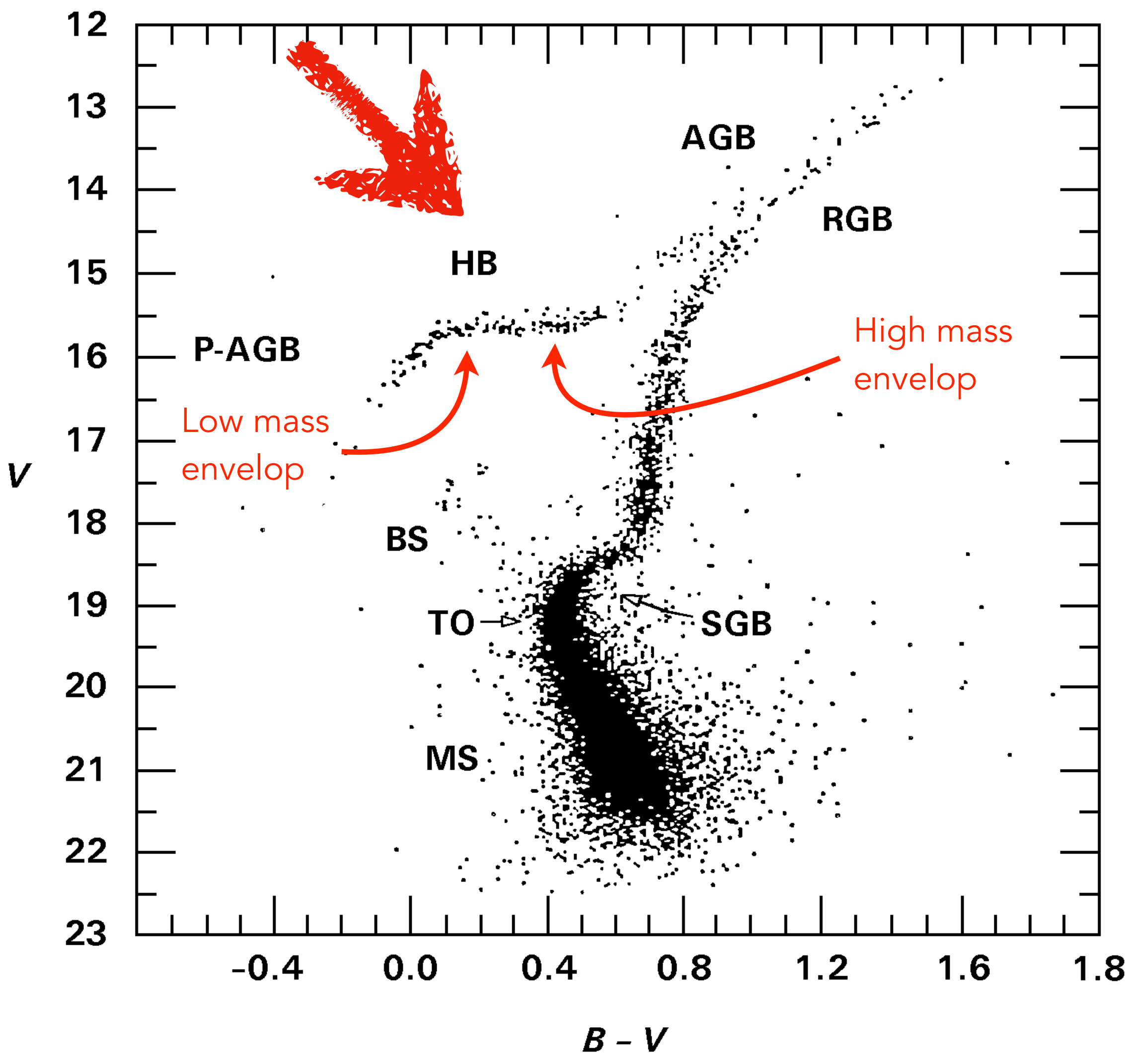
With the onset of a new and strongly temperature-dependent source of energy, the **core expands**.

Although the hydrogen-burning shell remains the dominant source of the star's luminosity, **the expansion of the core pushes the hydrogen-burning shell outward, cooling it** and causing the rate of energy output of the shell to decrease

→ abrupt **decrease in the luminosity** of the star.

Stellar Evolution → Horizontal Branch





<u>The star moves to the HB region</u>, at lower luminosity

The final luminosity is fixed only by the core mass and hence by the He-ignition temperature → HB-stars lay on a line with constant L and different $T_{\rm eff}$.

$L \approx$ constant since this depends only on the He mass core, which is set by the He-flash.

Mass loss during giant phase
→ HB distribution in $T_{\rm eff}$

High mass loss → small radius → bluer
$(L \propto R^2 T_{\rm eff}^4 = \text{const})$

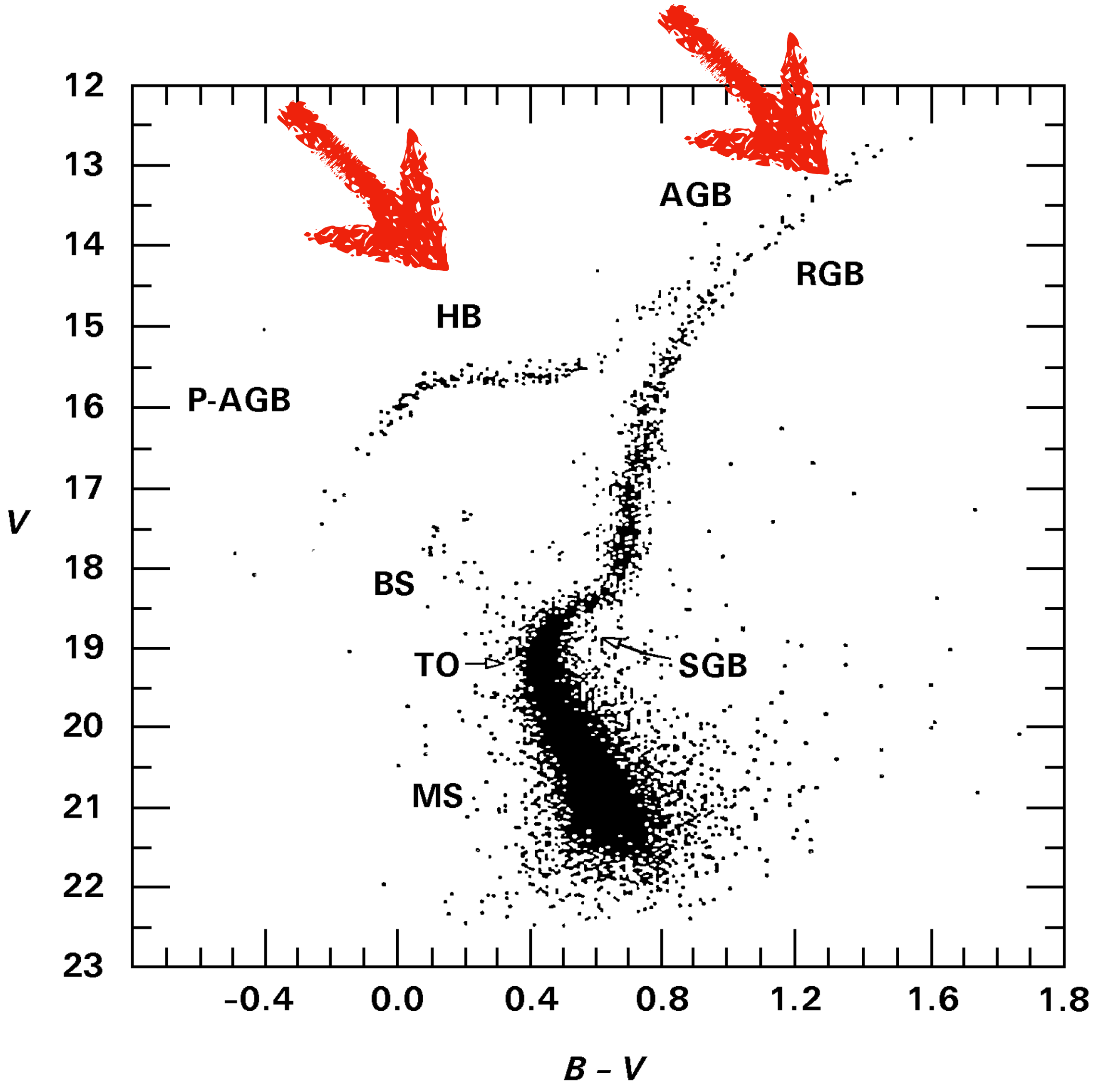
NOTE: *The apparent bending in the blue region is a filter effect → e.g., Raffelt, Stars as Labs (1996), fn. 5*

Stellar Evolution → Horizontal Branch

R-parameter: number ratio of HB and RGB

$$R = \frac{N_{\rm HB}}{N_{\rm RGB}}$$

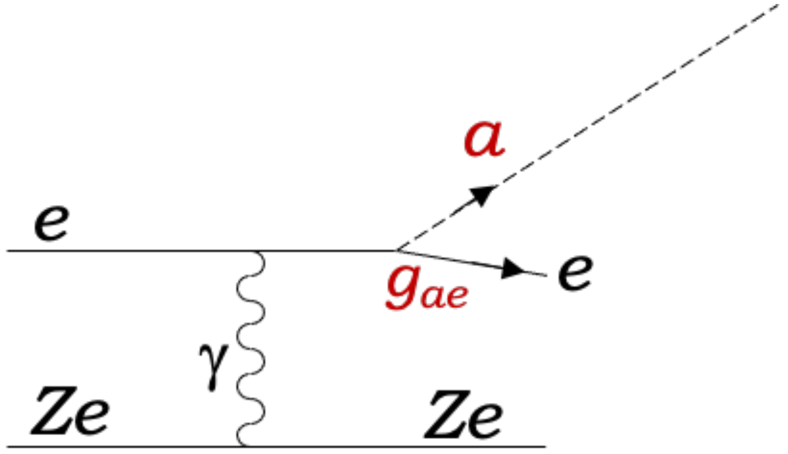
Test new physics

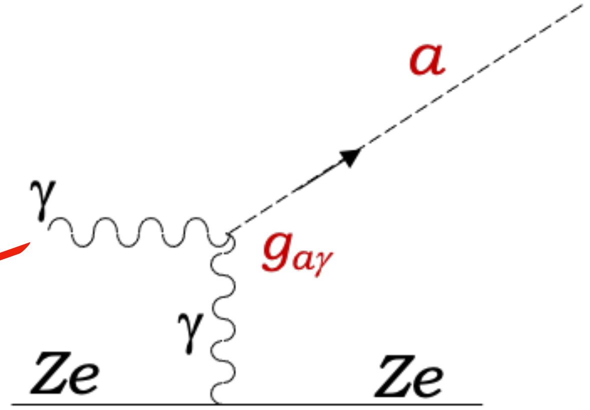


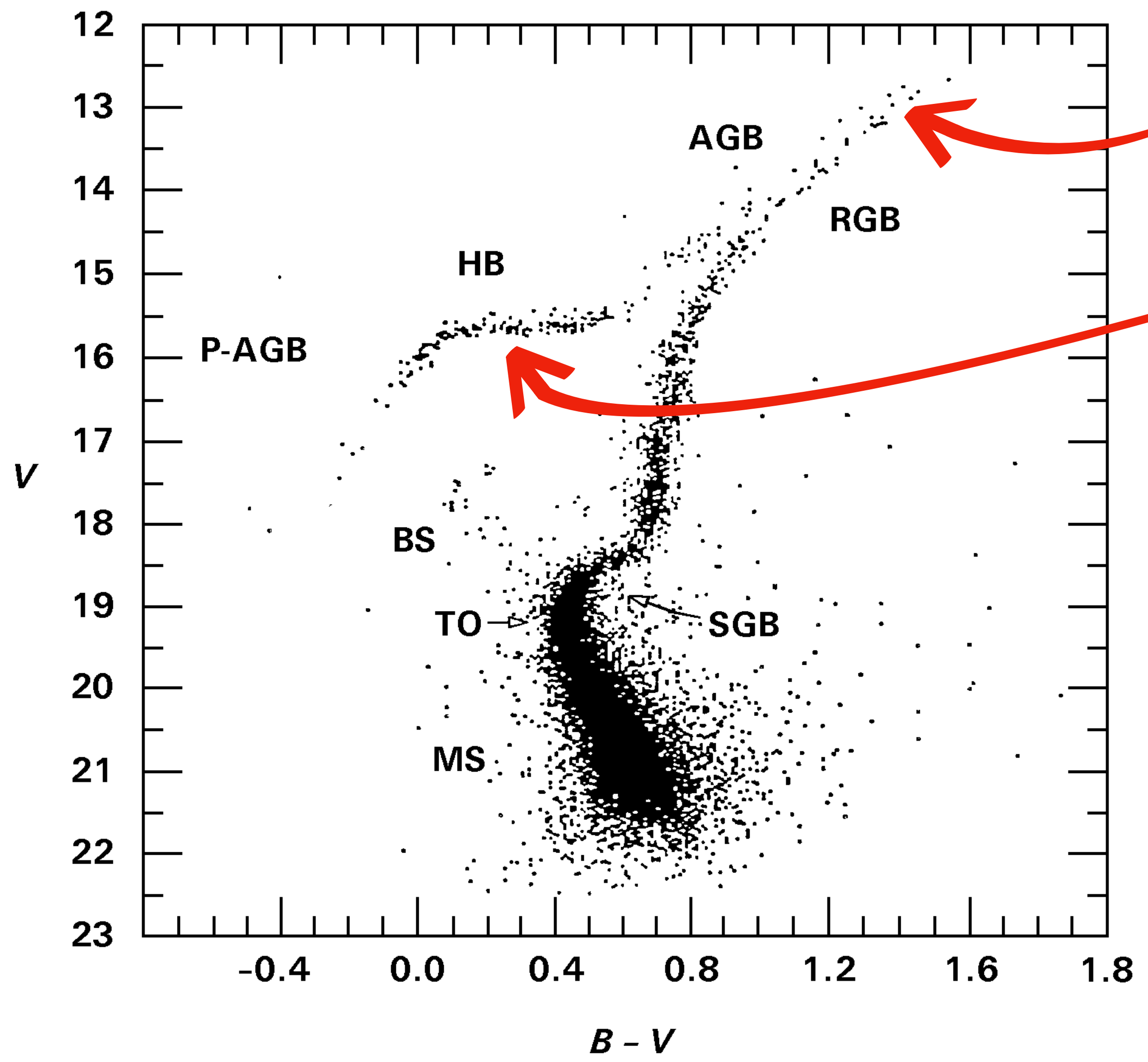
The ratio depends on the efficiency of the energy loss in the two evolutionary stages

Stellar Evolution → Horizontal Branch

R-parameter: number ratio of HB and RGB







$$R = R_0(Y) - F_{a\gamma}\left(g_{\gamma 10}\right) - F_{ae}\left(g_{e13}\right)$$

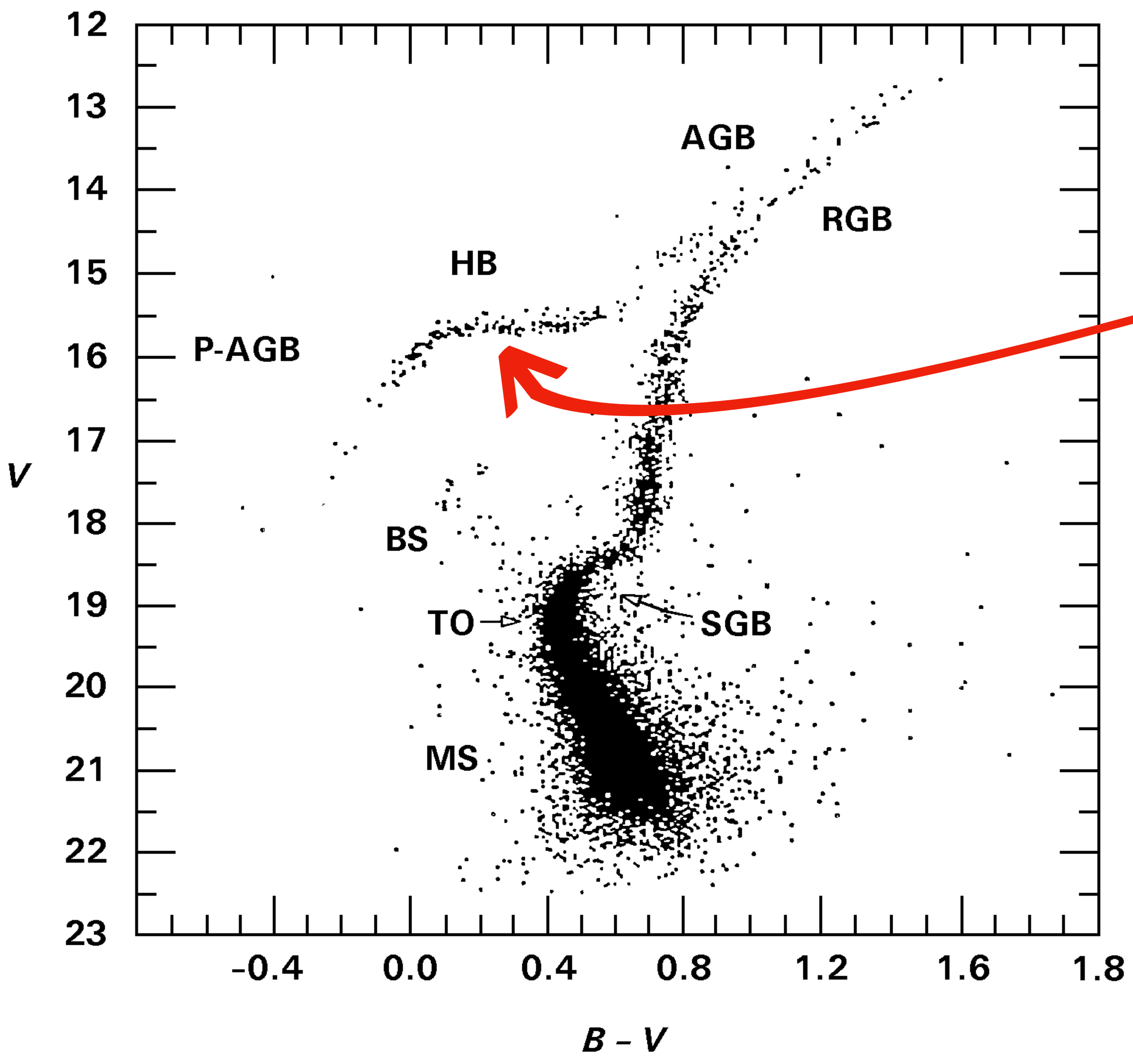
with

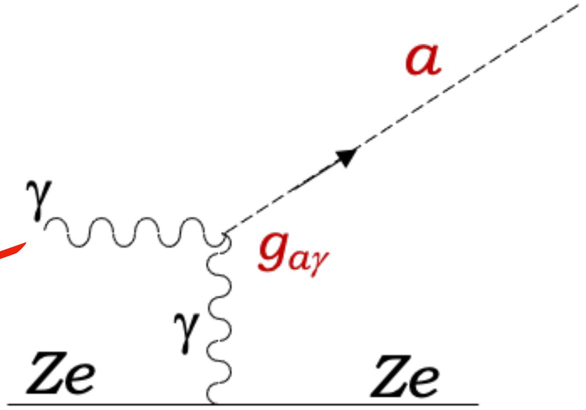
$$R_0(Y) = 0.02 + 7.33Y$$
$$F_{a\gamma}(x) = 0.095\sqrt{21.86 + 21.08x}$$
$$F_{ae}(x) = 0.0053x^2 + 0.039\left(\sqrt{1.2^2 + x^2} - 1.2 - 0.14x^{3/2}\right)$$

MG. +, JCAP 05 (2016)

Stellar Evolution → Horizontal Branch

R-parameter: number ratio of HB and RGB





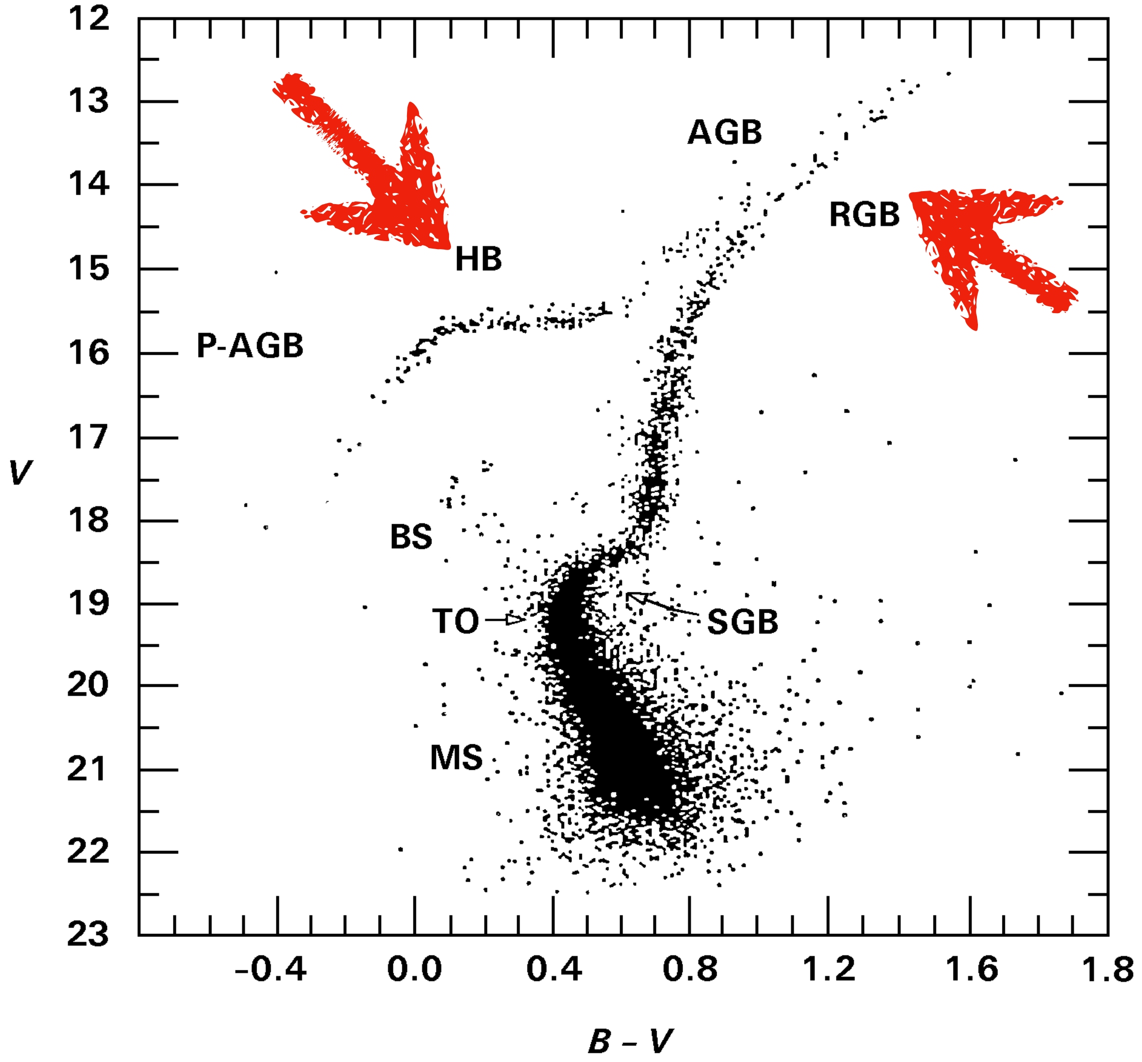
Keeping only the axion-photon coupling:

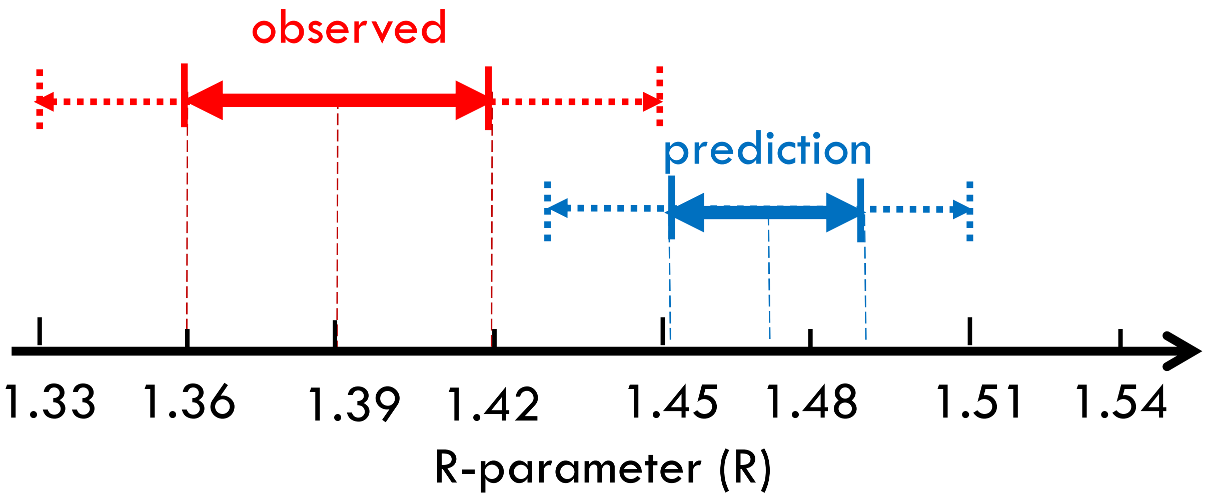
$$\boxed{g_{a\gamma} \leq 6.5 \cdot 10^{-11}\,\mathrm{GeV}^{-1}}$$

Ayala, Dominguez, M.G., Mirizzi, Straniero, PRL 113 (2014)

Stellar Evolution → Horizontal Branch

The latest analysis showed a slight discrepancy between the predicted and observed R-parameter.



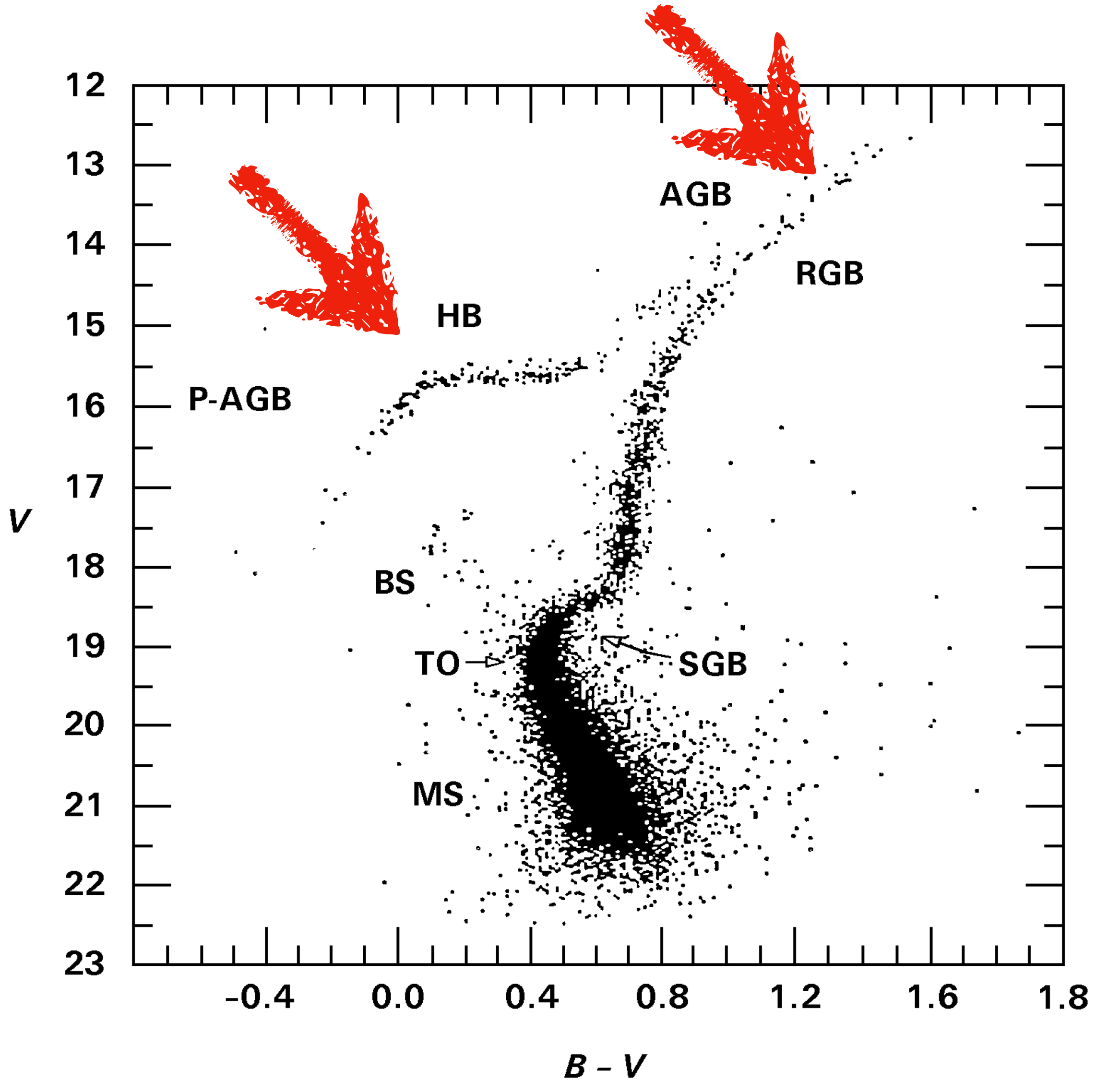


Ayala, Dominguez, M.G., Mirizzi, Straniero, PRL 113 (2014)

Stellar Evolution → AGB and R2

The number ratio of AGB over HB
is the R_2-parameter

$$R_2 = \frac{N_{\mathrm{AGB}}}{N_{\mathrm{HB}}}$$



AGB stars have a He-burning shell which is hotter and less dense than the core of HB stars.

→ it will lose more energy in axions, since the rate scales as T^7/ρ.

Stellar Evolution → AGB and R2

Recent determination

$$R_2 = 0.117 \pm 0.005,$$

based on the Hubble Space Telescope photometry of 48 globular clusters.

Constantino et al., MNRAS 456, 4 (2015)

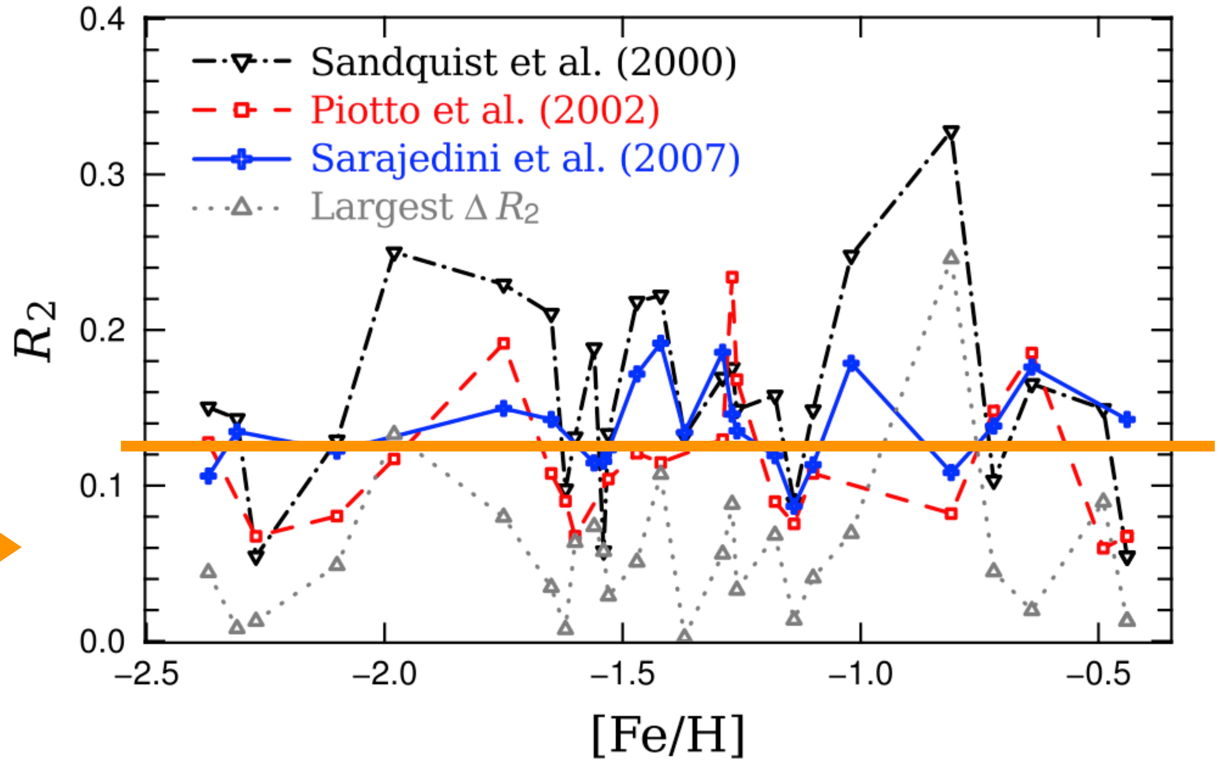


Figure 1. Comparison of R_2 for clusters shown in Table 1, limited to those with at least two different sources of photometry. The R_2 determined from the Sandquist (2000), Piotto et al. (2002), and Sarajedini et al. (2007) data are shown in black dash-dots, red dashes, and a blue solid line, respectively.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

$$\boxed{g_{a\gamma} \leq 4.7 \cdot 10^{-11}\,\mathrm{GeV}^{-1}}$$

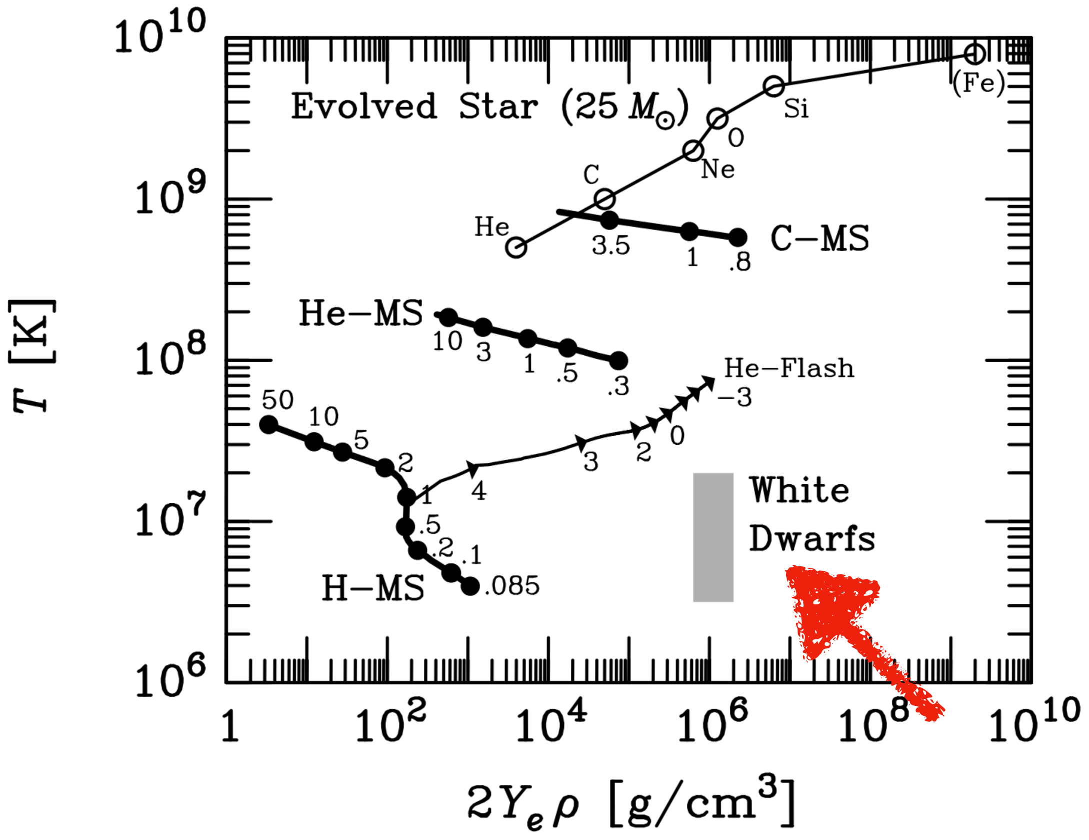
Axions → M.J. Dolan, F.J. Hiskens & R.R. Volkas, JCAP 10 (2022)

Dark Photons → Dolan, Hiskens, Volkas, e-Print: 2306.13335

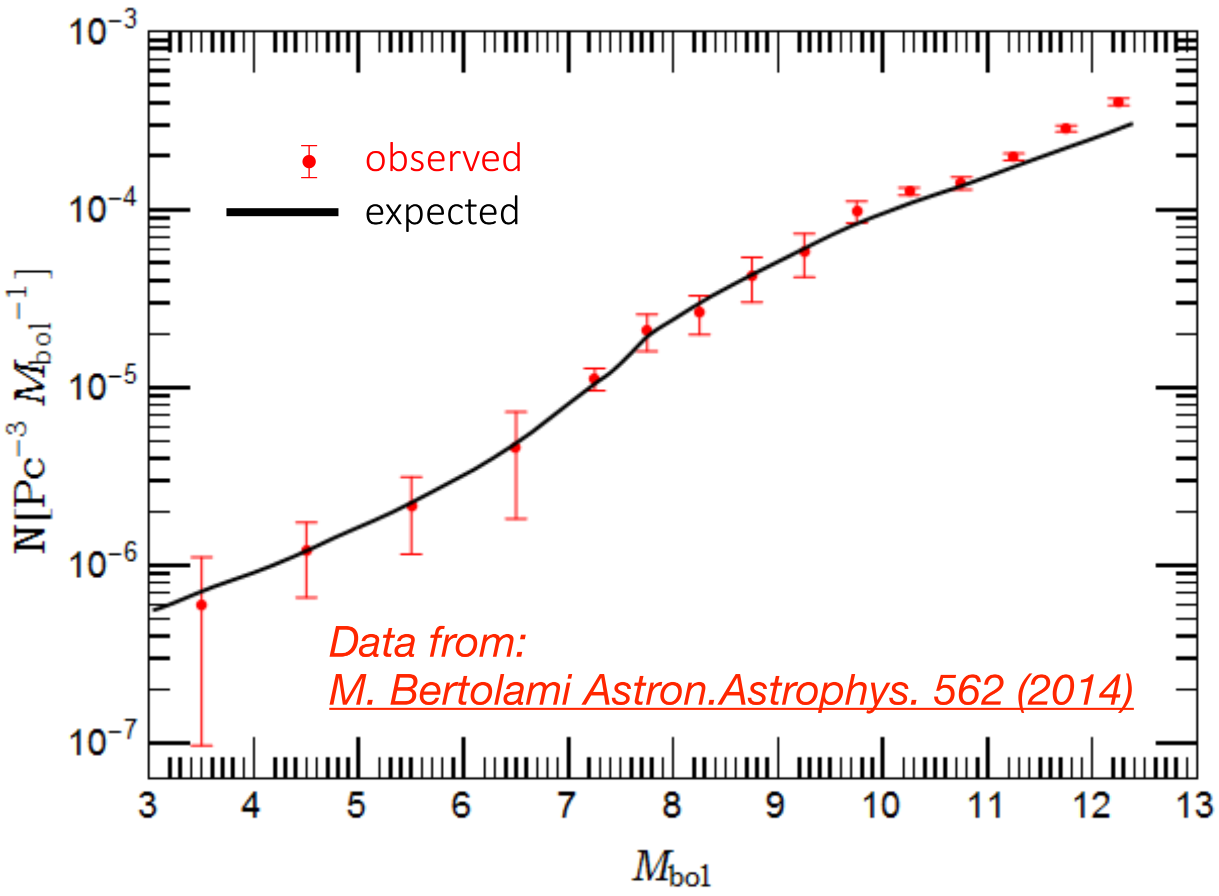
No evidence for the hint from R-parameters analysis

Stellar Evolution → White Dwarfs

Lighter stars go to the AGB at the end of the central He, and end up as CO White Dwarfs.



G. Raffelt, Stars as Laboratories (1996).



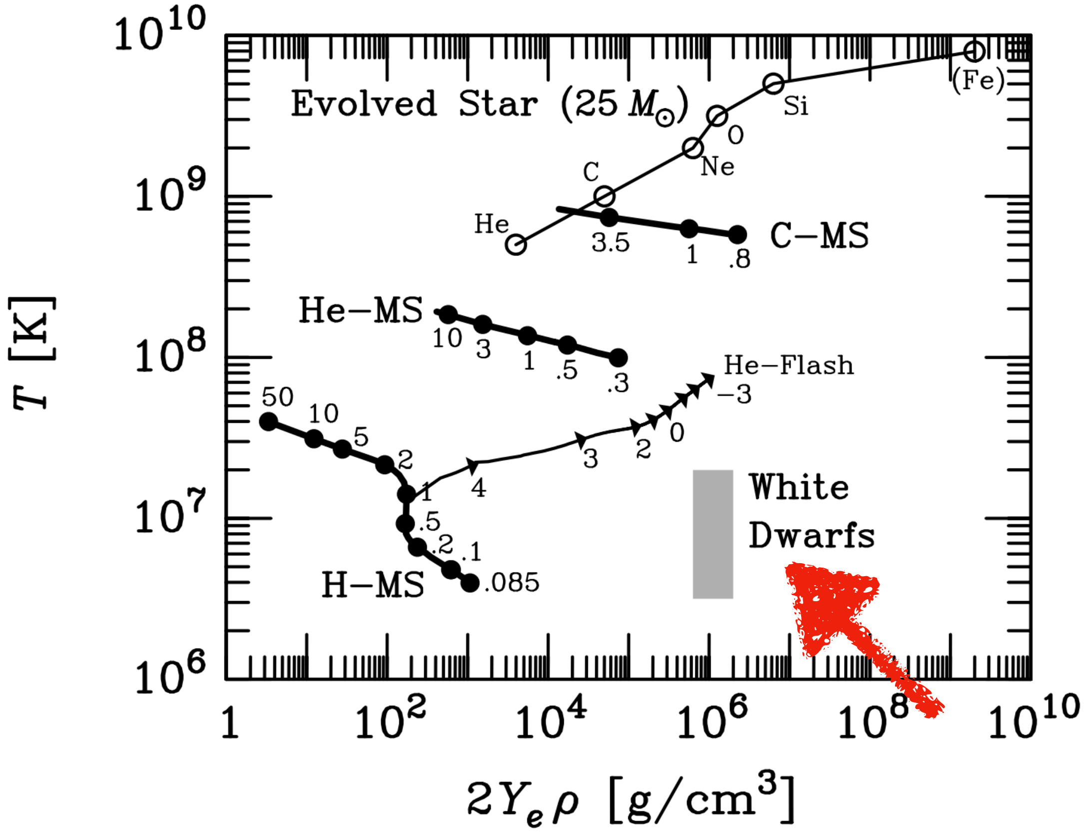
Data from:
M. Bertolami Astron.Astrophys. 562 (2014)

The WDLF is a powerful way to measure the cooling efficiency

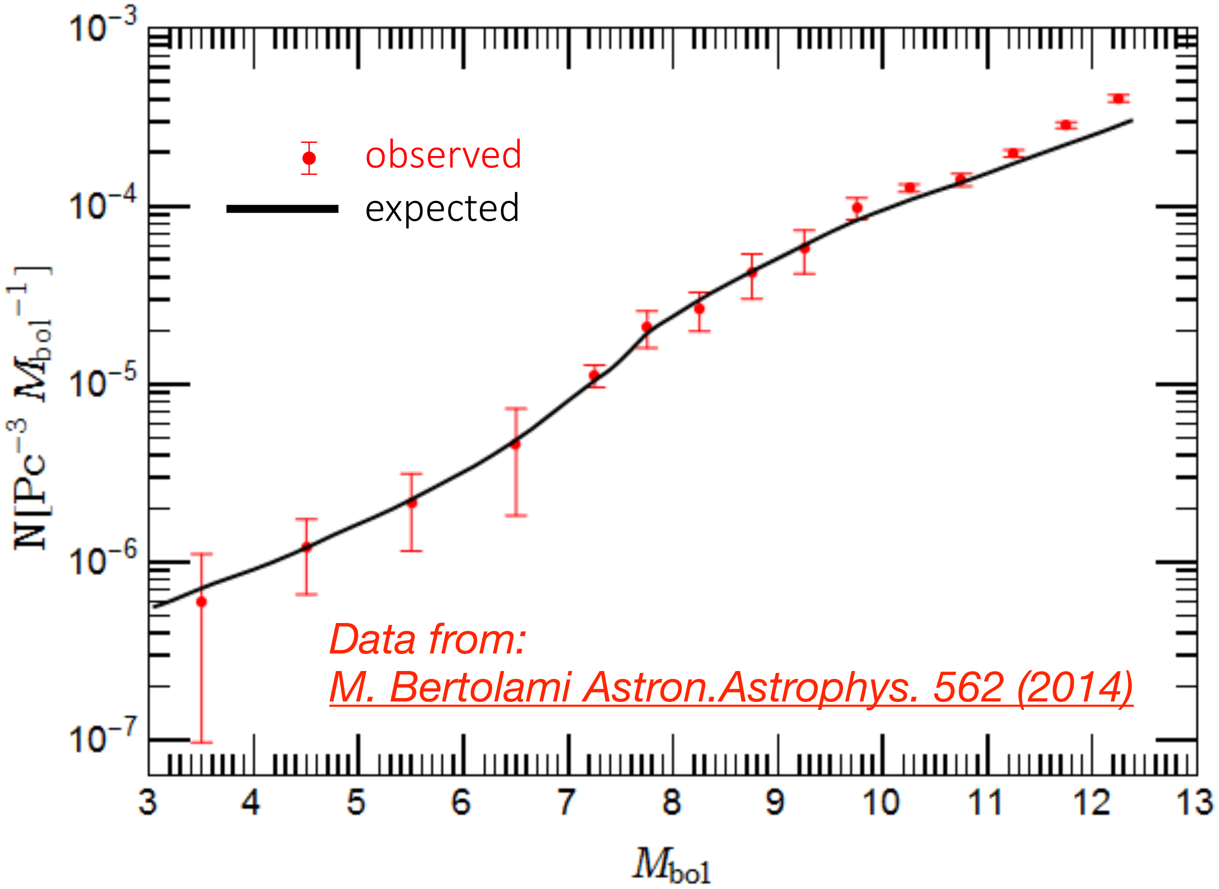
$$\frac{dN_{\rm WD}}{dV\,dL} \propto \frac{1}{L_\gamma + L_\nu + L_x}$$

Stellar Evolution → White Dwarfs

The shape of the WDLF shows specific contributions to cooling, e.g., neutrinos!



G. Raffelt, Stars as Laboratories (1996).



Data from:
M. Bertolami Astron.Astrophys. 562 (2014)

- The data showed a ~2σ hint for additional cooling

M. Bertolami et. al. (2014)

- The cooling shows the T-dependence of axion-bremsstrahlung

MG., Irastorza, Redondo, Ringwald JCAP 05 (2016)

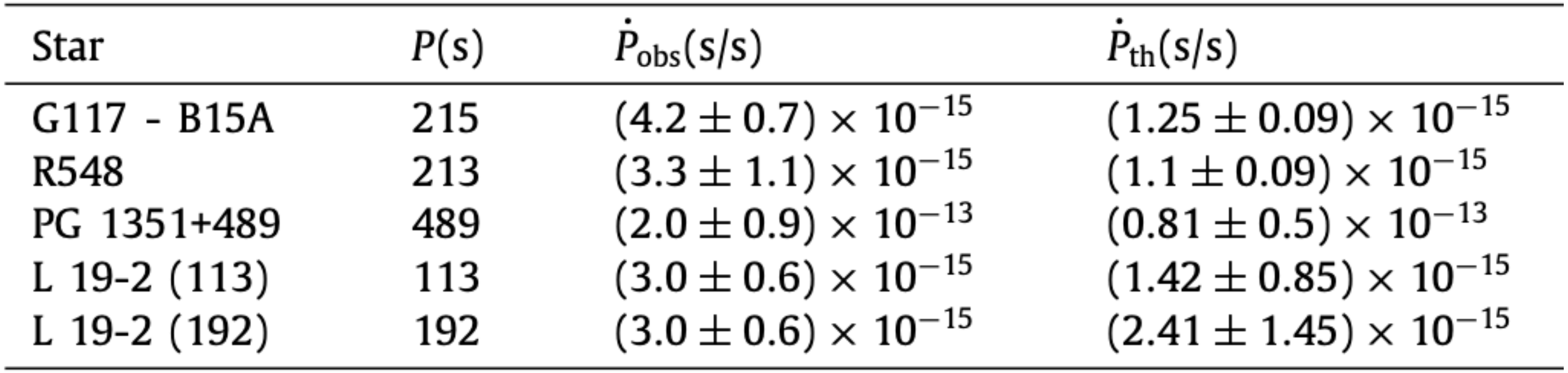
Old analysis. Needs revision!

Stellar Evolution: WD

WD Variables (WDV)

Measures of the period change rate in WD variables offer a way to test the cooling of WDs

$$|\dot{P}/P| \propto \dot{T}/T$$



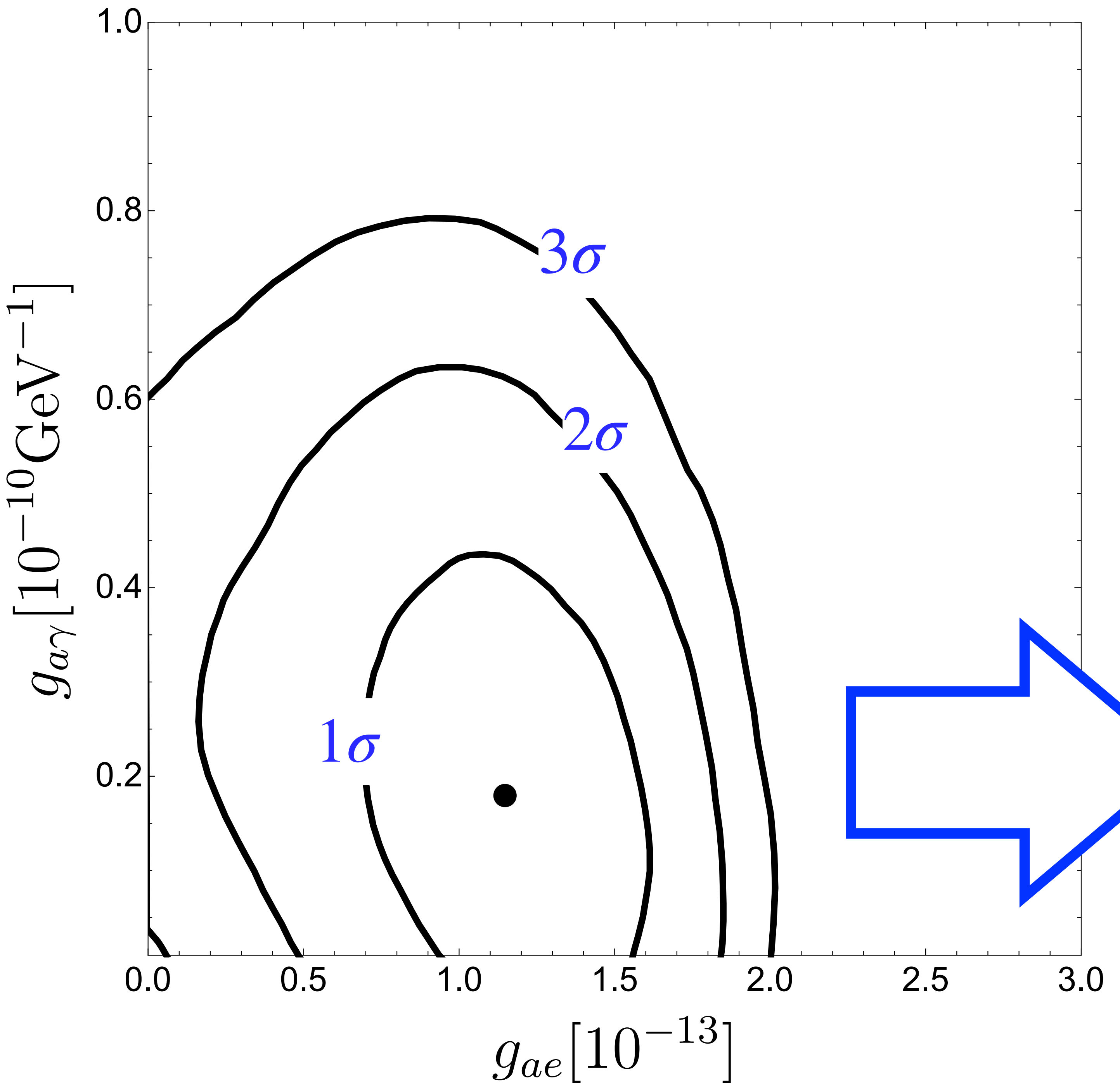
Star	$P(\mathrm{s})$	$\dot{P}_{\mathrm{obs}}(\mathrm{s/s})$	$\dot{P}_{\mathrm{th}}(\mathrm{s/s})$
G117 - B15A	215	$(4.2 \pm 0.7) \times 10^{-15}$	$(1.25 \pm 0.09) \times 10^{-15}$
R548	213	$(3.3 \pm 1.1) \times 10^{-15}$	$(1.1 \pm 0.09) \times 10^{-15}$
PG 1351+489	489	$(2.0 \pm 0.9) \times 10^{-13}$	$(0.81 \pm 0.5) \times 10^{-13}$
L 19-2 (113)	113	$(3.0 \pm 0.6) \times 10^{-15}$	$(1.42 \pm 0.85) \times 10^{-15}$
L 19-2 (192)	192	$(3.0 \pm 0.6) \times 10^{-15}$	$(2.41 \pm 1.45) \times 10^{-15}$

L. Di Luzio, M.G., E. Nardi, L. Visinelli, Phys.Rept. 870 (2020)

Observations over the past ~30 yr showed consistently $\dot{P}_{\mathrm{obs}} > \dot{P}_{\mathrm{th}}$, which seems to imply an overly efficient cooling.

- *Many works starting form Isern, Hernanz, Garcıa-Berro (1992).*
- *Latest result from Kepler+ ApJ 906 (2021) 7. Confirms the anomaly*

Stellar Global Fits



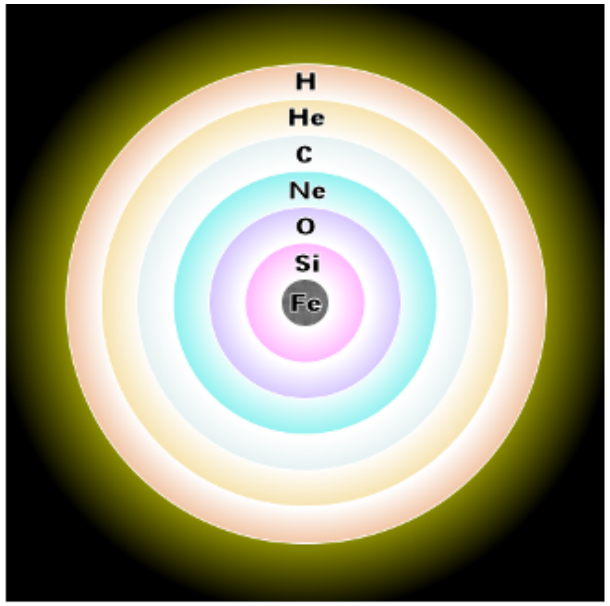
Many recent results from stars

Global analysis of WDs, RGB and HB stars shows a ***preference for finite axion couplings*** *with electrons and photons*

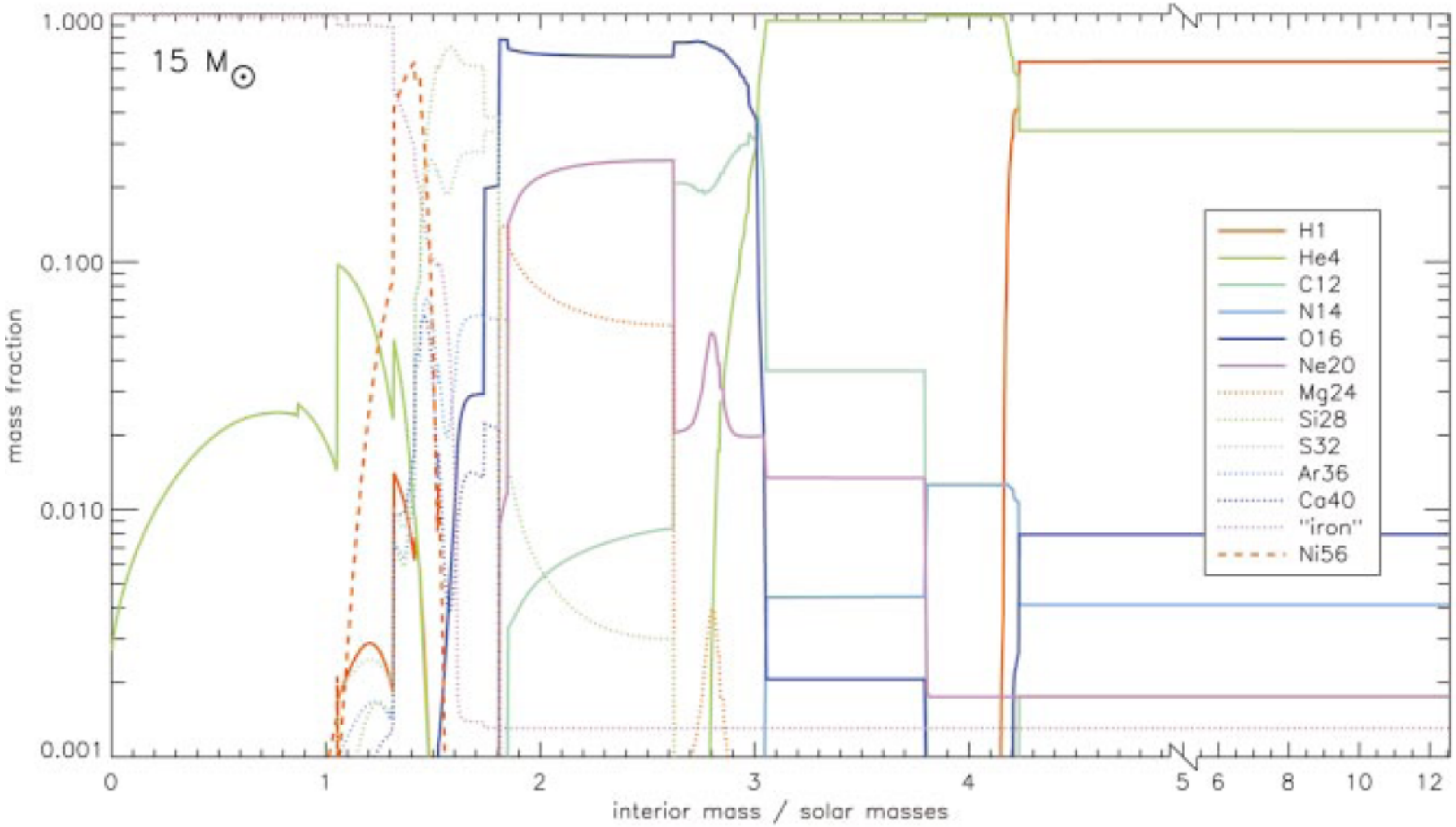
For QCD models →
meV to ~100 meV mass region

Di Luzio, Fedele, M.G., Mescia, Nardi, JCAP 02 (2022) 02, 035

Later Evolutionary Stages

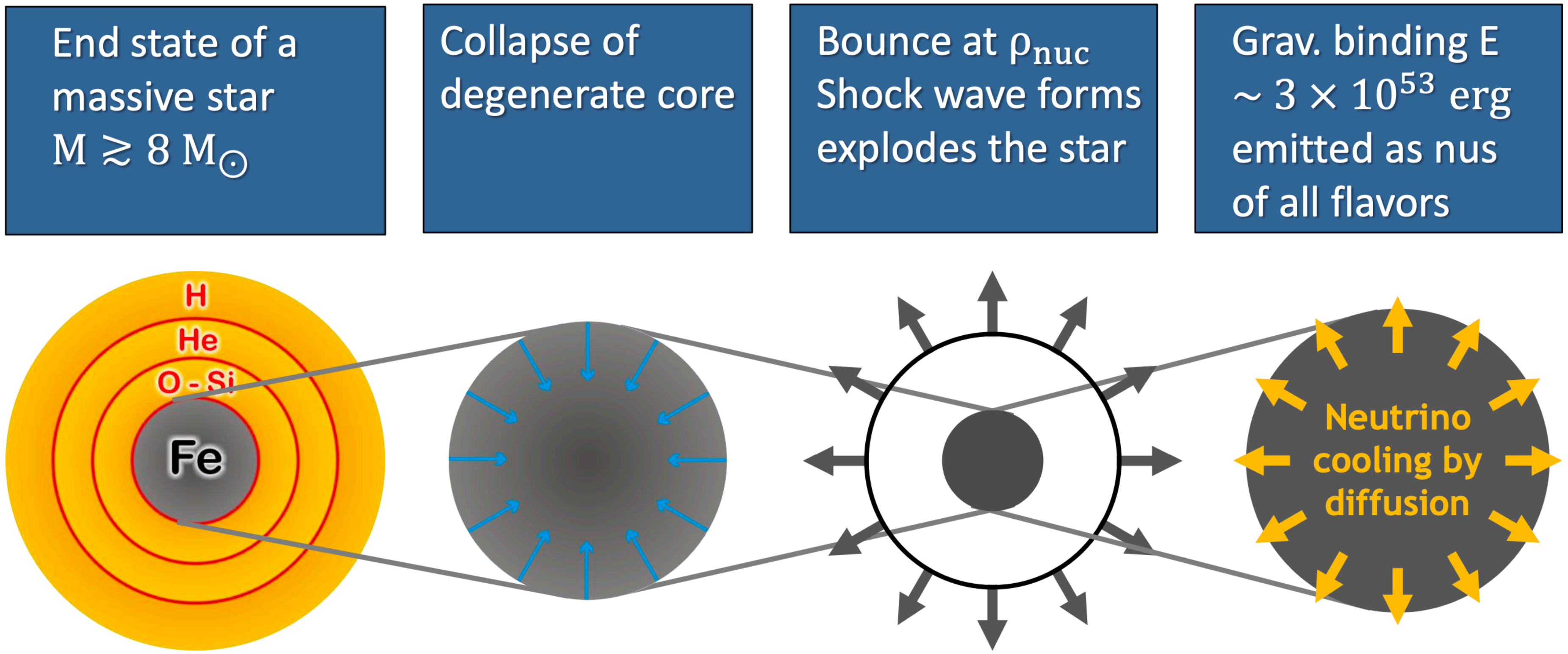


Stars with $M \gtrsim 8\,M_\odot$ go on burning until they develop a iron core



From Woosley, Heger, Weaver, Rev Mod Phys, 74, 1015 (2002)

Core Collaps Supernova



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

Collapse of degenerate core

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

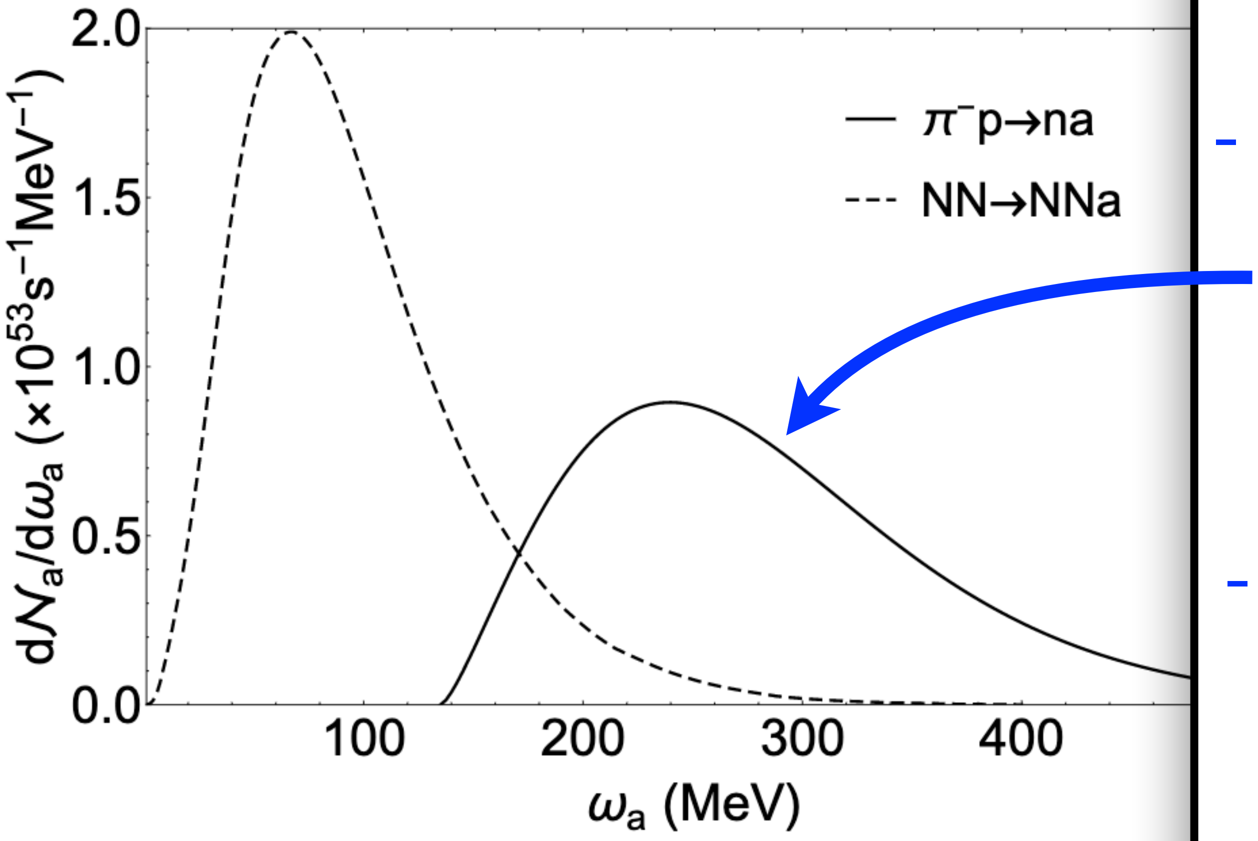
Grav. binding E $\sim 3 \times 10^{53}$ erg emitted as nus of all flavors

→ See G. Raffelt, Astro Lecture 2, Axion Beyond Boundaries Workshp, GGI 2023

Neutrino signal associated with SN 1987A at Kamiokande-II, Irvine-Michigan-Brookhaven, and Baksan Scintillator Telescope confirmed several expectation about CC SN.

Bounds on new physics. Roughly, $L_x \lesssim L_\nu$

Supernova axions



Significant theoretical progress in last 2 years

- Pions in SN: Larger than expected fraction of π^-

  B. Fore and S. Reddy, Phys.Rev.C 101 (2020);
  B. Fore et al., arXiv:2301.07226 (2023)

- Significance of the $\pi + N \rightarrow N + a$ processes. Dominates the axion emission rate. Harder spectrum.

  P. Carenza et al., Phys.Rev.Lett. 126 (2021);
  A. Lella et al, *Phys.Rev.D* 107 (2023) 10

- Inclusion of the axion-pion contact interaction. Significant contribution to $\pi + N \rightarrow N + a$. Irrelevant contribution to $N + N \rightarrow N + N + a$

  K. Choi et al., *JHEP* 02 (2022) 143

- Inclusion of the Δ resonance contribution in pion process

  Ho, Kim, Ko, Park, *Phys.Rev.D* 107 (2023) 7

- Direct detection of SN axions

  Ge, Hamaguchi, Ichimura, Ishidoshiro, Kanazawa, JCAP 11 (2020);
  Vonk, Guo, Meißner, *Phys.Rev.D 105 (2022)*

Supernova Axion Bounds

- Raffelt, Lect. Notes Phys. 741 (2008) OPE rates.

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

- Chang, Essig & McDermott, JHEP 1809 (2018) Semiquantitative, various correction factors

$f_a \gtrsim 1 \times 10^8\,\mathrm{GeV} \quad (m_a \lesssim 60\,\mathrm{meV})$ (KSVZ, proton coupling)

- Carenza, Fischer, MG, Guo, Martínez-Pinedo & Mirizzi, JCAP 10 (2019), Beyond OPE,

$f_a \gtrsim 4 \times 10^8\,\mathrm{GeV} \quad (m_a \lesssim 15\,\mathrm{meV})$ (KSVZ, proton coupling)

- Carenza, Fore, MG, Mirizzi & Reddy, Phys.Rev.Lett. 126 (2021),

Including thermal pions $\pi^- + p \to n + a$

$f_a \gtrsim 5 \times 10^8\,\mathrm{GeV} \quad (m_a \lesssim 11\,\mathrm{meV})$ (KSVZ, proton coupling)

Talk by Alessandro Lella, Wednesday @ 14:15

Neutron Stars

The cooling of a NS can be observed through many years. Exotic cooling would modify these observations.

Significant recent progress

- L. B. Leinson, *JCAP* 08 (2014), Cas A

Hint at $g_{an}^2 \approx 1.6 \times 10^{-19}$

- K. Hamaguchi et al. *Phys.Rev.D* 98 (2018) 10, Cas A,

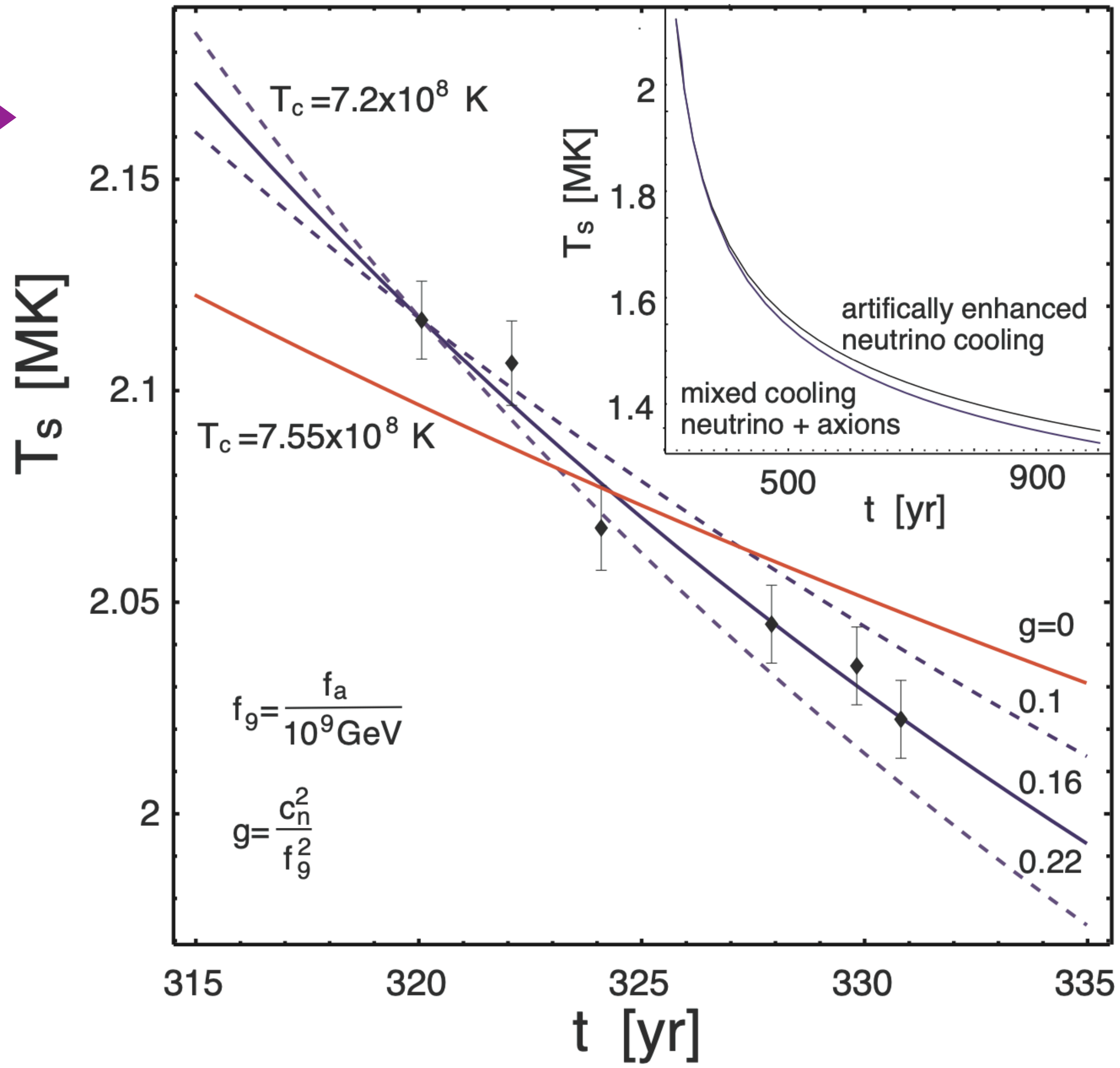
$g_{ap}^2 + 1.6 g_{an}^2 \leq 1.1 \times 10^{-18}$

- D M. Beznogov et al. *Phys.Rev.C* 98 (2018) 3, NS in HESS J1731-347

$g_{an}^2 \leq 0.77 \times 10^{-19}$

- L. B. Leinson, JCAP 11 (2019), NS in HESS J1731-347

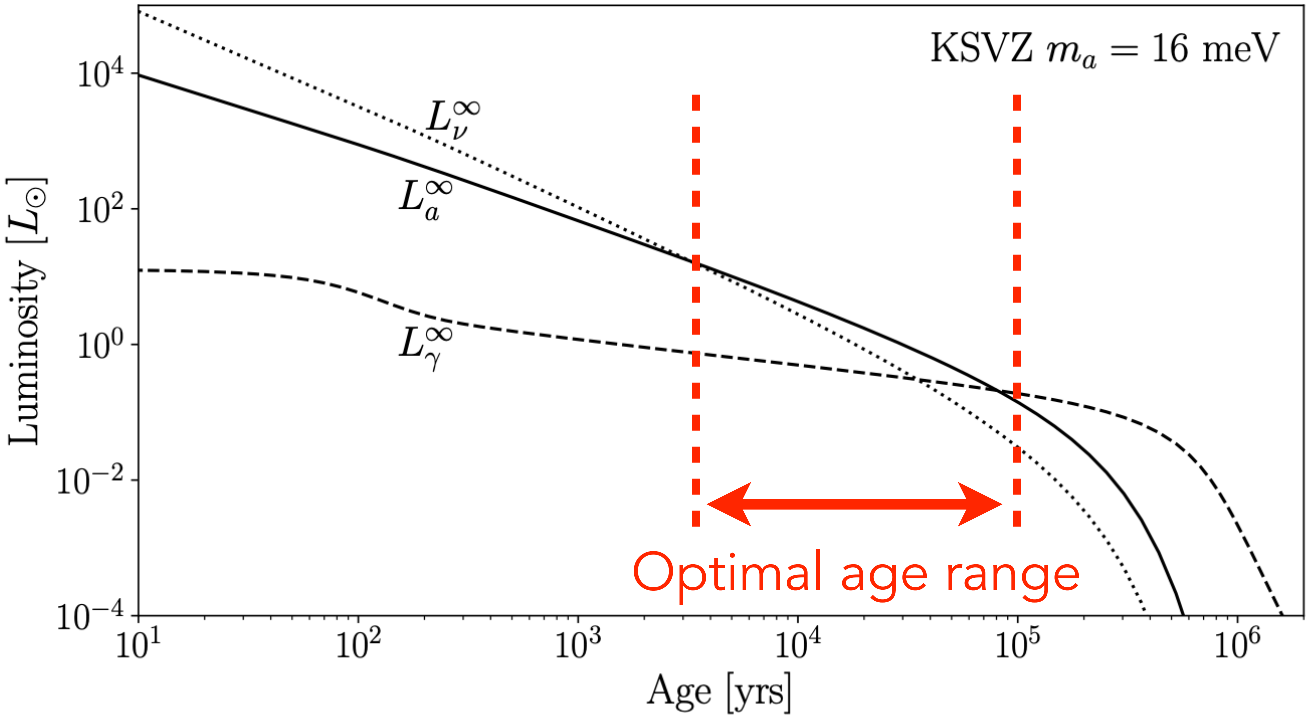
$g_{an}^2 \leq 1.1 \times 10^{-19}$

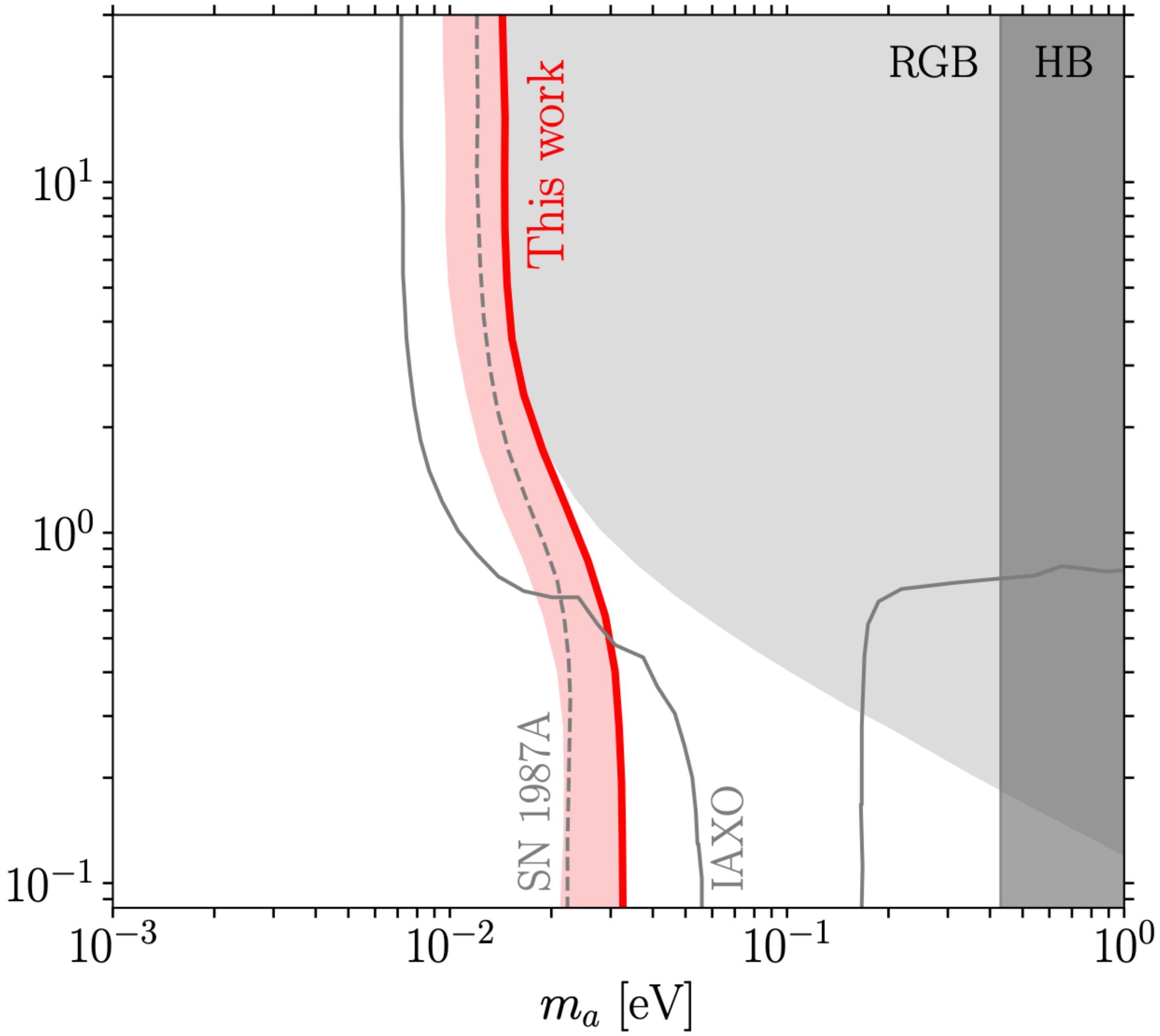


→ Correspond to $m_a \approx 30$ MeV, similar to SN1987A

Neutron Stars

M. Buschmann et al., Phys.Rev.Lett. 128 (2022), study of a set of NS with age O(0.1) Myr



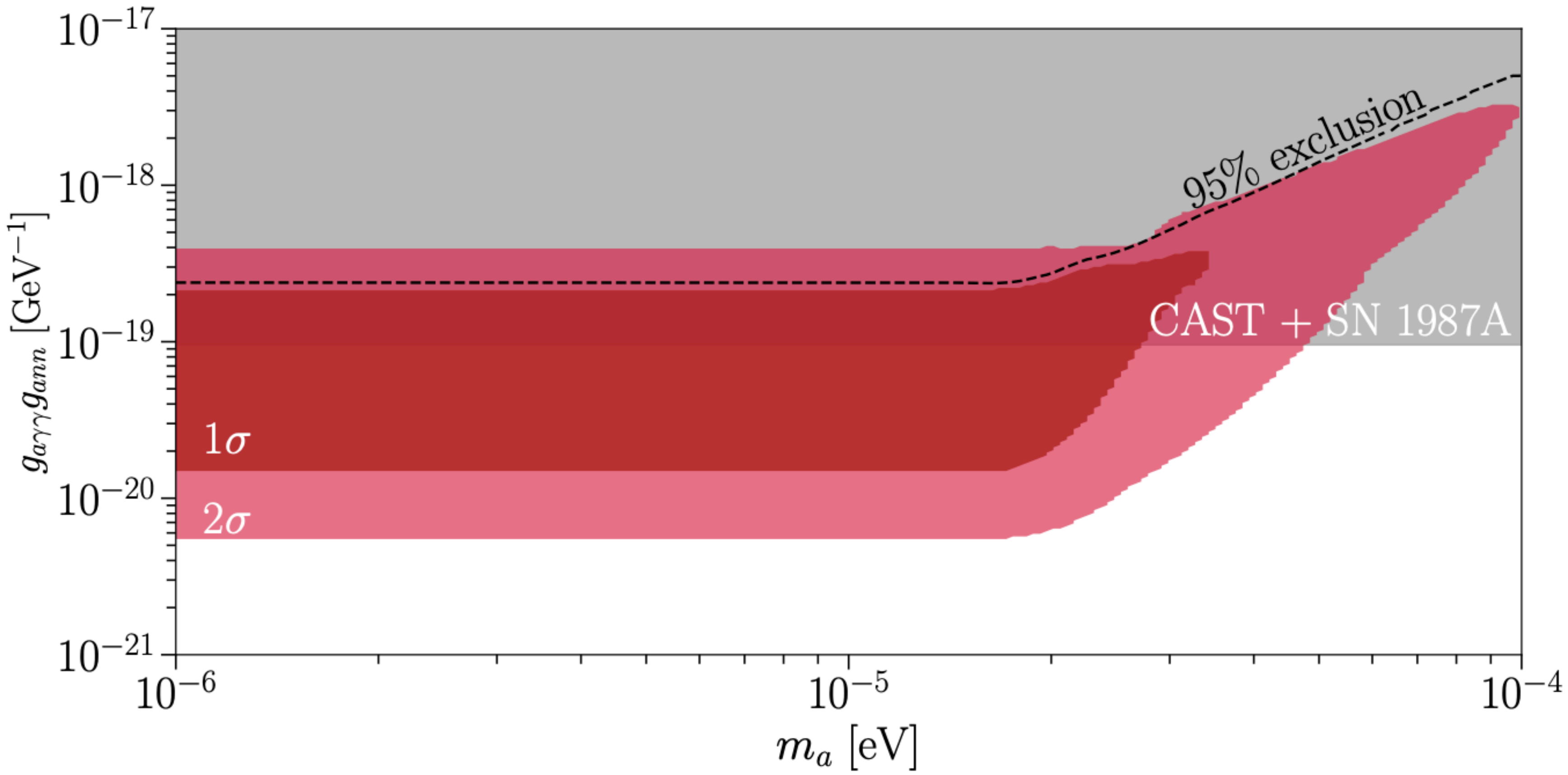


See M. Buschmann & J. Foster@GGI 2023, for many more details

Axion Hint from Neutron Stars?

Excess of X-ray emission (XMM-Newton + Chandra) in the 2 - 8 keV energy range from the nearby Magnificent Seven isolated NS

Buschmann, Co, Dessert, Safdi, Phys.Rev.Lett. 126 (2021)



ALPs still a viable option.

Compatibility with other astro bounds requires electro-phobia.

$g_{a\gamma} g_{an}$ is quite large at those masses. Yet, QCD axion models that explain it exist

→ Darmé, Di Luzio, MG, Nardi, Phys.Rev.D 103 (2021)

See B. Safdi talk @ GGI 2023

Black Holes as Axion Labs?

Black hole superradiance.

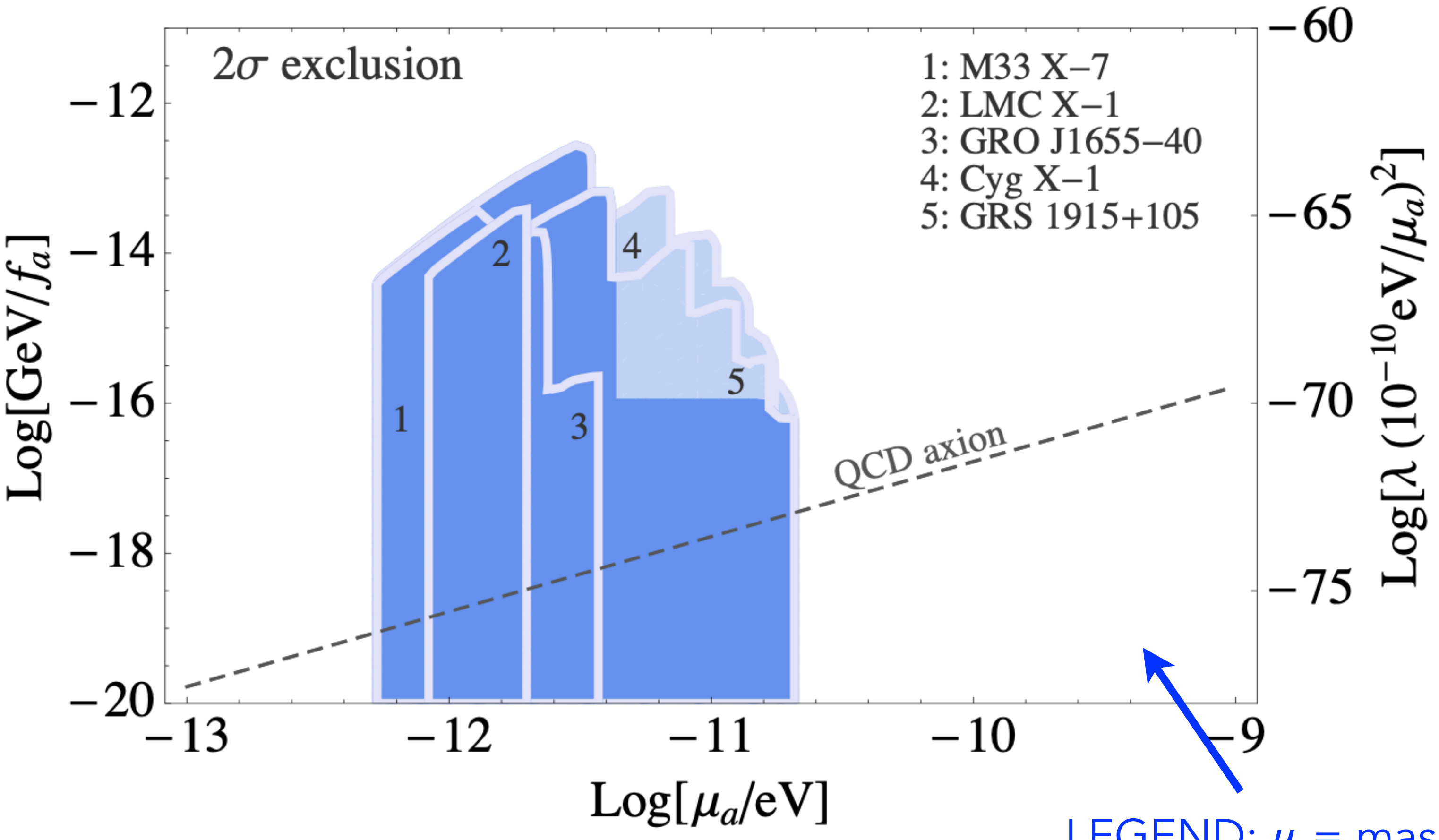
Build up boson population near BH. Non thermal mechanism.

Axion Factory!

No need for an initial axion

Subtract spin from rotating BH

A. Arvanitaki, M. Baryakhtar,
X. Huang, Phys.Rev.D 91 (2015)



LEGEND: μ_a= mass.
λ measures interaction
term $\mathscr{L} \supset \lambda\phi^4/4!$

+ Expected GW signals

See Francesca Day Wed.@13:15 and Yifan Chen Wed.@2:55

Part 3:
The Hunt for Stellar Axions

Axion Telescopes?

Axions could be excellent astrophysics messengers.
They could be far superior to photons and neutrinos to study some aspects of stellar evolution.

Dedicated axion experiments could be used to access the solar core and to learn about various solar properties:

- Solar magnetic field

  C. A. J. O'Hare, A. Caputo, A. J. Millar, E. Vitagliano Phys.Rev.D 102 (2020) 4

- Solar temperature profile

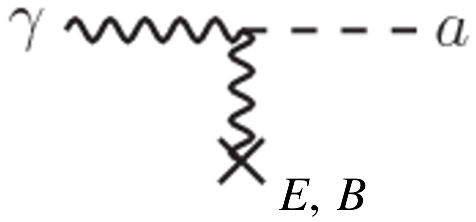
  S. Hoof, J. Jaeckel, L. J. Thormaehlen, arXiv:2306.00077

- Solar chemical composition

  J. Jaeckel, L. J. Thormaehlen, Phys.Rev.D 100 (2019) 12

➡ *S. Hoof Talk, Wed@15:35*

The Sun as Axion Factory: Summary

Coupling	Process	Energy
$g_{a\gamma}$	Primakoff (E) 	$\sim (3-4)\,\mathrm{keV}$
	Primakoff (B)	$\sim (10-200)\,\mathrm{eV}$ (LP) $\lesssim 1\,\mathrm{keV}$ (TP)
g_{ae}	ABC e.g., $e + Z_e \to Ze + e + a$	$\sim 1\,\mathrm{keV}$
g_{aN}	nuclear reactions $p + d \to {}^3\mathrm{He} + a$	$5.5\,\mathrm{MeV}$
	Nuclear de-excitation ${}^{57}\mathrm{Fe}^* \to {}^{57}\mathrm{Fe} + a$	$14.4\,\mathrm{keV}$
	${}^{7}\mathrm{Li}^* \to {}^{7}\mathrm{Li} + a$	$0.478\,\mathrm{MeV}$
	${}^{83}\mathrm{Kr}^* \to {}^{83}\mathrm{Kr} + a$	$9.4\,\mathrm{keV}$

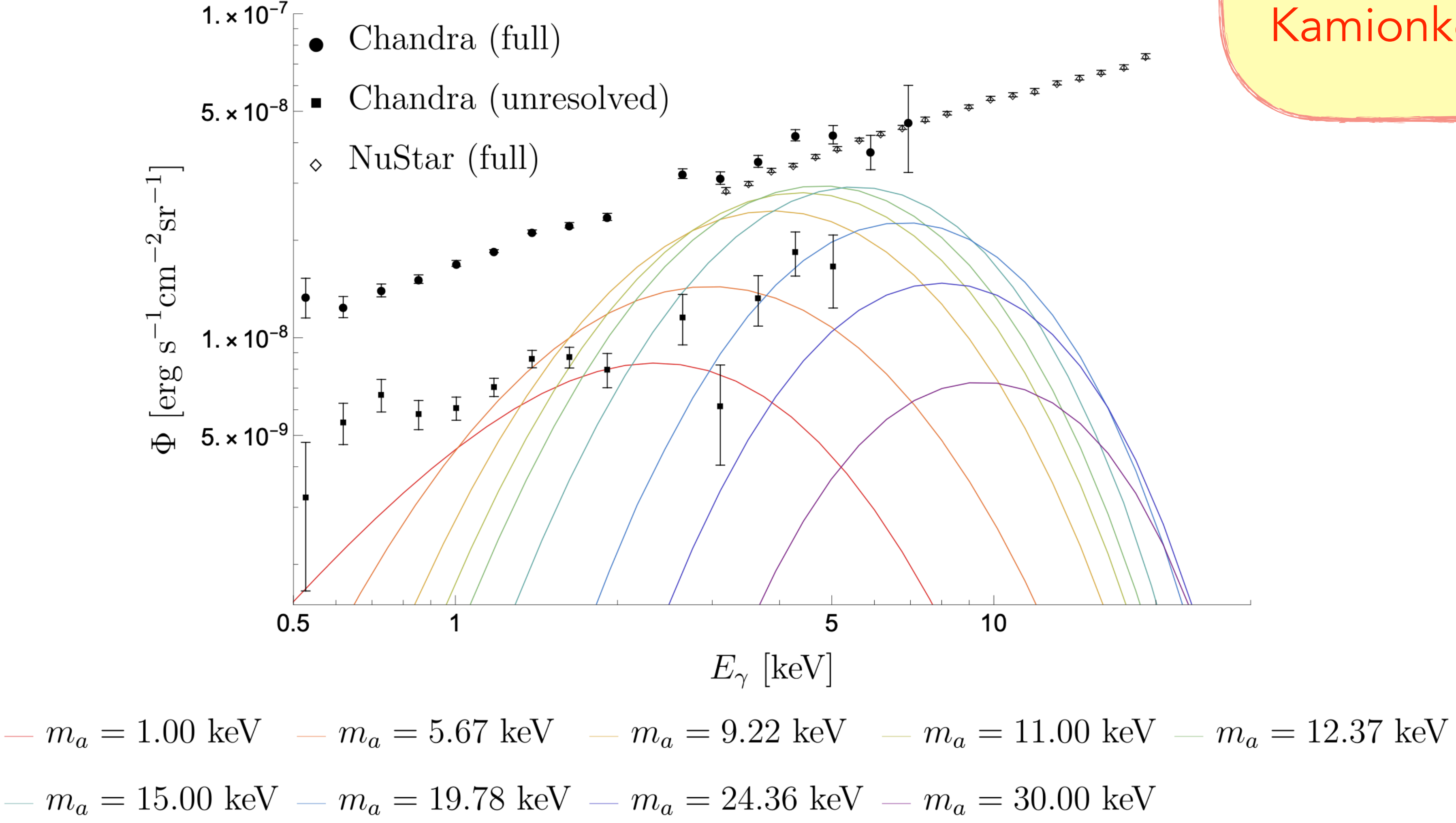
Other MS stars?

Other MS have solar-like properties but are much further away. Less interesting.

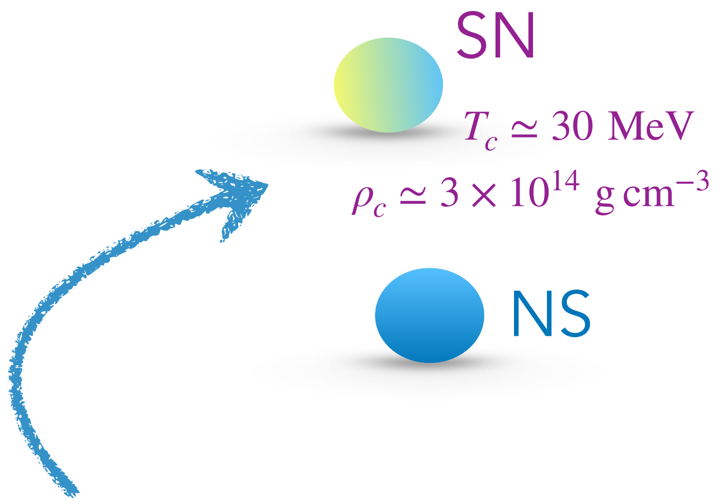
Yet, there are many of them.

Diffuse axion flux recently calculated

If ALPs are sufficiently heavy, their decay produces an x-ray diffuse background:
N. H. Nguyen, E. H. Tanin, M. Kamionkowski arXiv:2307.11216



Other stars?

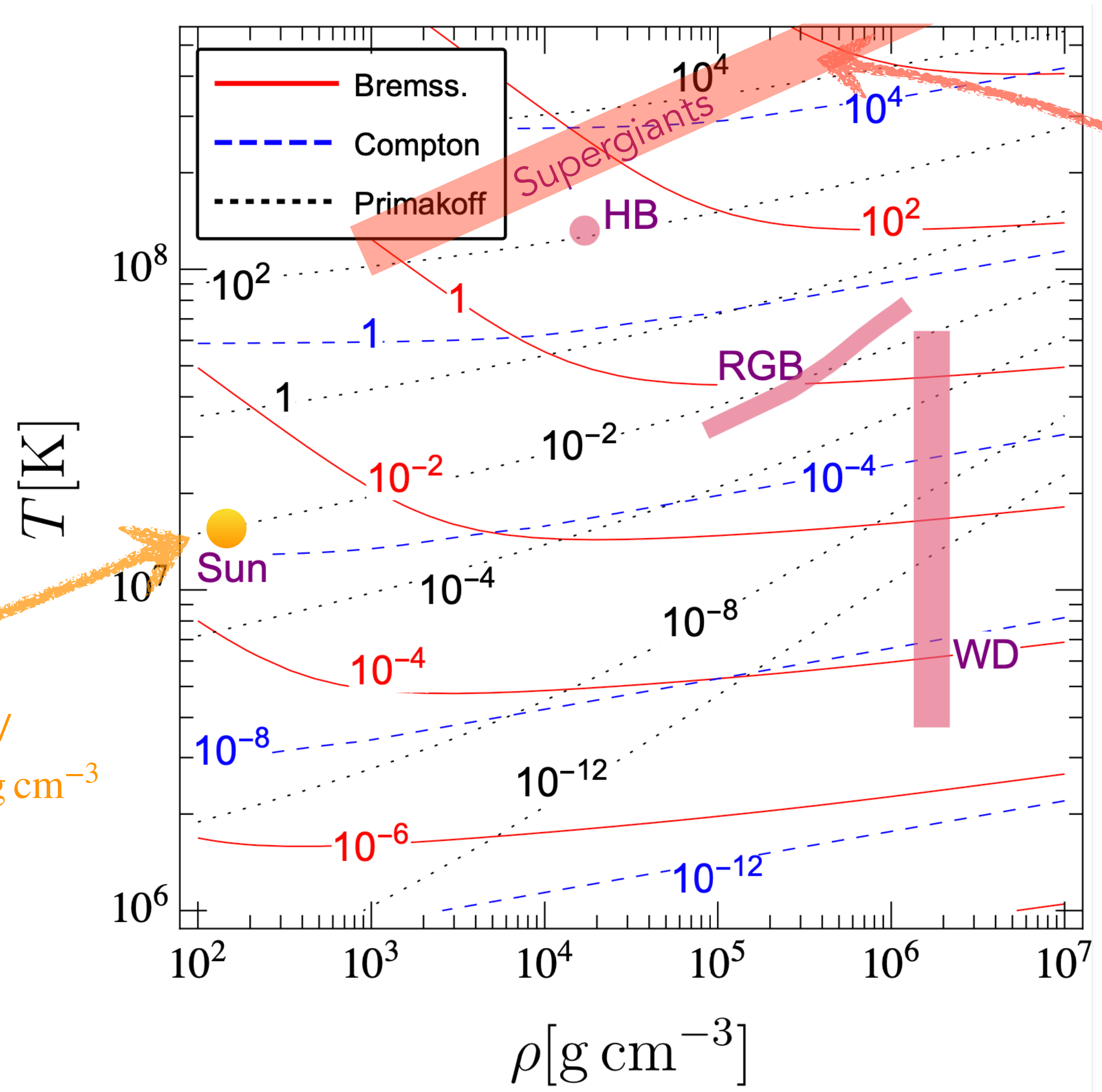


$T_c \simeq 30$ MeV

$\rho_c \simeq 3 \times 10^{14}$ g cm^{-3}

Monster Stars

(See talk by A. Lella)



Supergiants:

T_c and ρ_c depend on mass and evolutionary stage

Sun:

$T_c \sim 1$ keV

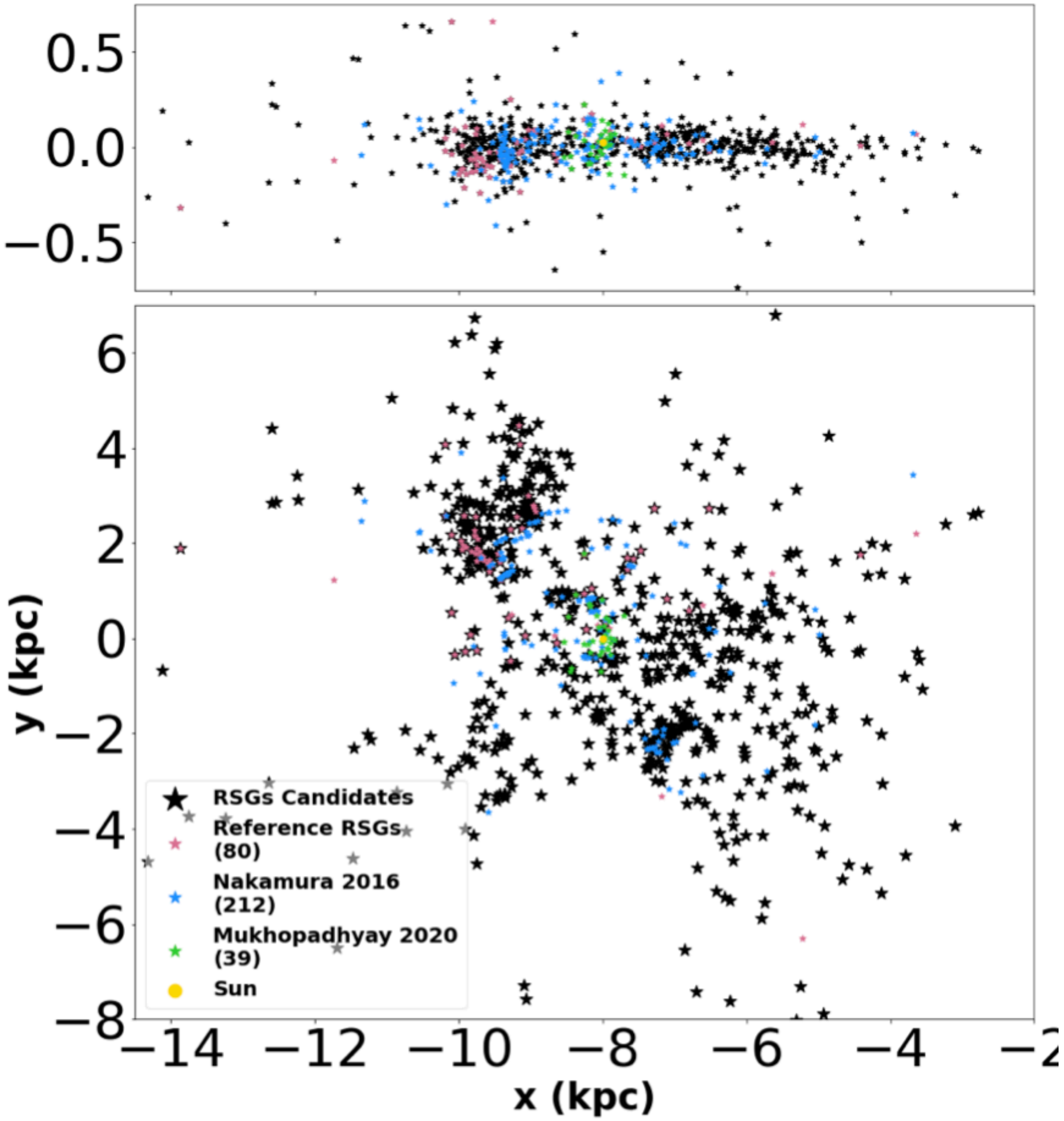
$\rho_c \sim 10^2$ g cm^{-3}

The sun is quite an unremarkable star… but yet, likely, our best bet

Di Luzio, MG, Nardi, Visinelli, Phys.Rept. 870 (2020)

Supergiants

Brand new catalog of Red SG, Sarah Healy et al., arXiv:2307.08785



Many candidates at a few kpc from the Sun.

See also
→ M. Mukhopadhyay et al., Astrophys.J. 899 (2020)

A Telescope for Supergiants

			Photons		Axions		
Model	Phase	$t_{\rm cc}$ [yr]	$\log_{10}(L_{\rm eff}/L_\odot)$	$\log_{10}(T_{\rm eff}/{\rm K})$	C	E_0 [keV]	β
0	He burning	155000	4.90	3.572	1.36	50	1.95
1	before C burning	23000	5.06	3.552	4.0	80	2.0
2	before C burning	13000	5.06	3.552	5.2	99	2.0
3	before C burning	10000	5.09	3.549	5.7	110	2.0
4	before C burning	6900	5.12	3.546	6.5	120	2.0
5	in C burning	3700	5.14	3.544	7.9	130	2.0
6	in C burning	730	5.16	3.542	12	170	2.0
7	in C burning	480	5.16	3.542	13	180	2.0
8	in C burning	110	5.16	3.542	16	210	2.0
9	in C burning	34	5.16	3.542	21	240	2.0
10	between C/Ne burning	7.2	5.16	3.542	28	280	2.0
11	in Ne burning	3.6	5.16	3.542	26	320	1.8
12	beginning of O burning	1.4	5.16	3.542	27	370	1.8

Axion spectrum

$$\frac{d\dot{N}_a}{dE} = \frac{10^{42} C g_{11}^2}{\text{keV s}} \left(\frac{E}{E_0}\right)^{\beta} e^{-(\beta+1)E/E_0}$$

can pin down t_{cc} from $\sim 10^{-5}$ yr

Constant photon spectrum for the last 10^5 yr

Axions are sensitive to all late evolutionary stages. Surface photons are not.

M. Xiao et al., Phys.Rev.Lett. 126 (2021); M. Xiao et al., Phys. Rev. D 106 (2022)

Axion telescopes for massive stars. Is it feasible?

Very small axion flux, even at ~100 pc

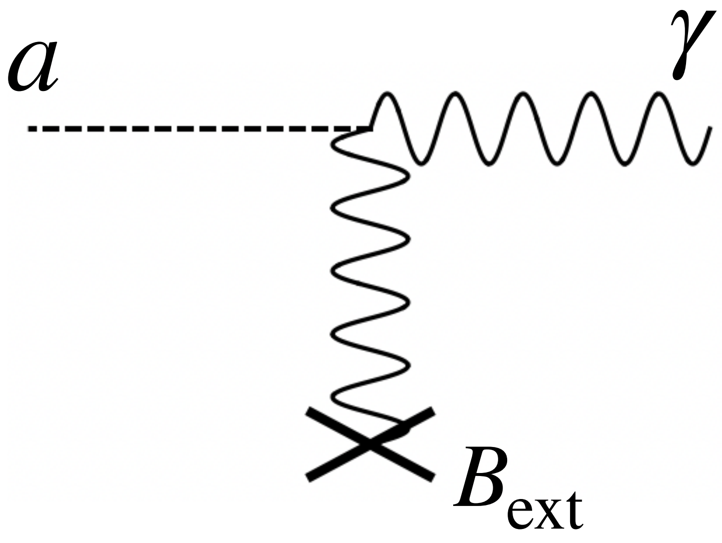
Axions can convert into photons in the magnetic field between us and the star

$$P_{a\gamma} = 8.7 \times 10^{-6} g_{11}^2 \left(\frac{B_\mathrm{T}}{1\ \mu\mathrm{G}}\right)^2 \left(\frac{d}{197\ \mathrm{pc}}\right)^2 \frac{\sin^2 qd}{(qd)^2}$$

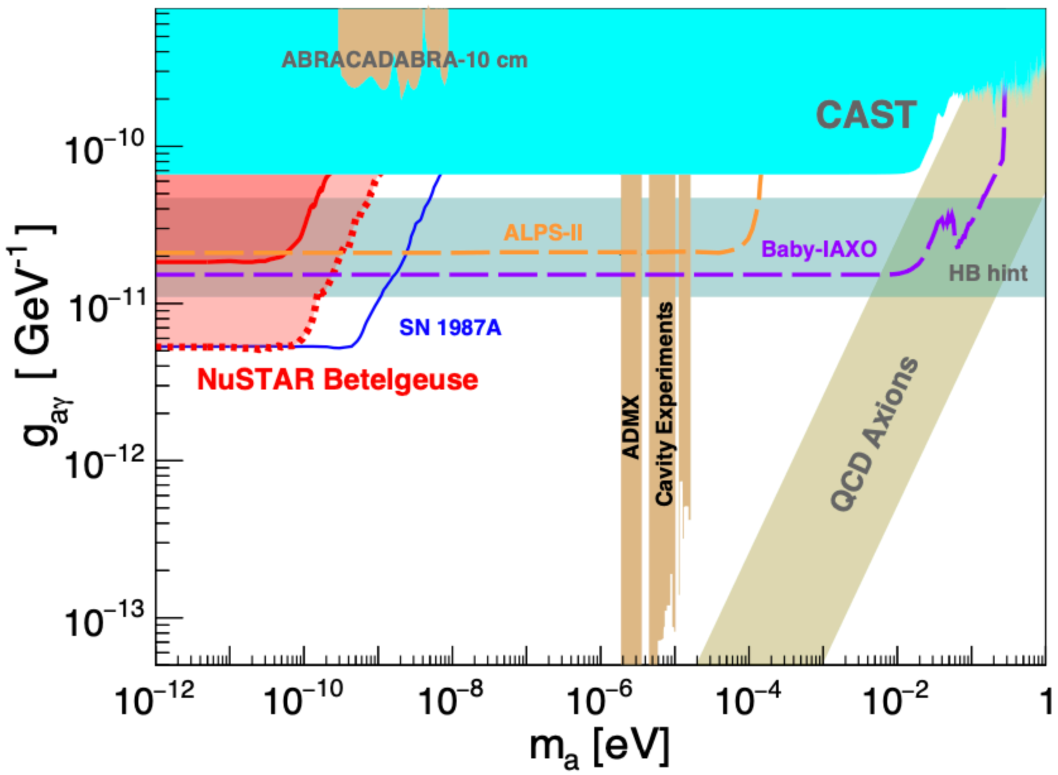
(Assuming B uniform)

$g_{11} \leq 6.5$ from helioscope (CAST) bound

Limits sensitivity at high mass



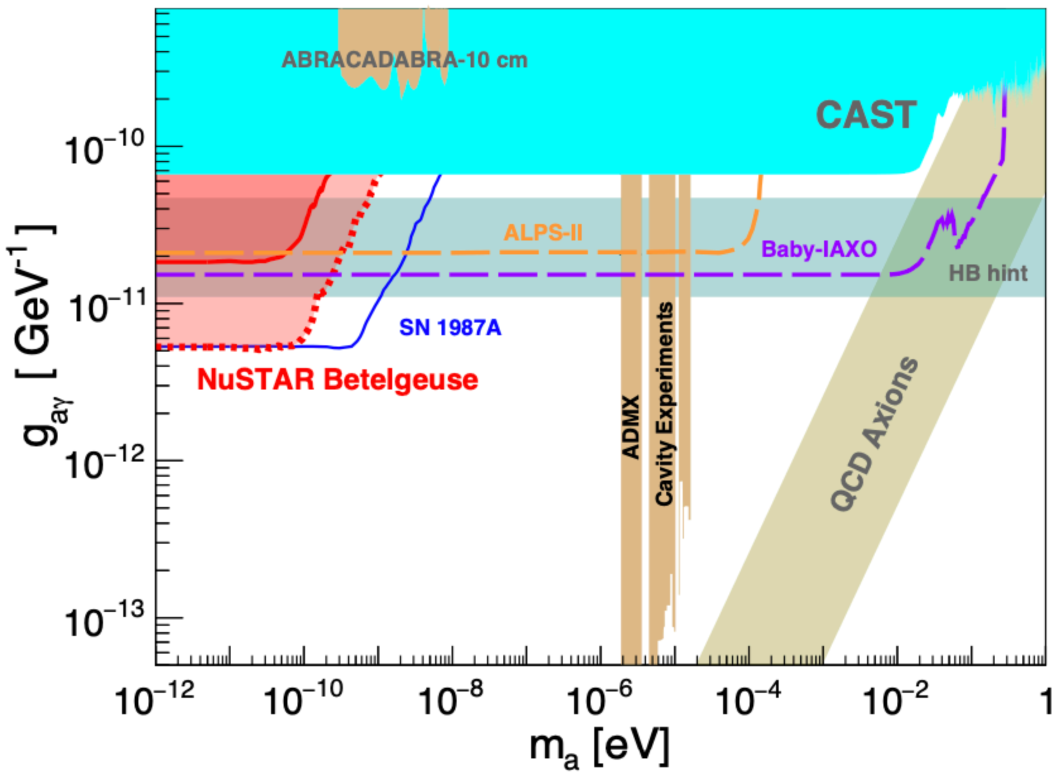
Betelgeuse, a case study



First hard X-ray observations of Betelgeuse (with NuSTAR)… no trace of Axions

- *Xiao, Perez, M.G., Straniero, Mirizzi, Grefenstette, Roach, Nynka, Phys.Rev.Lett. 126 (2021)*
- *Xiao, Carenza, M.G., Mirizzi, Perez, Straniero, Grefenstette Phys.Rev.D 106 (2022)*

… and Super Star Clusters



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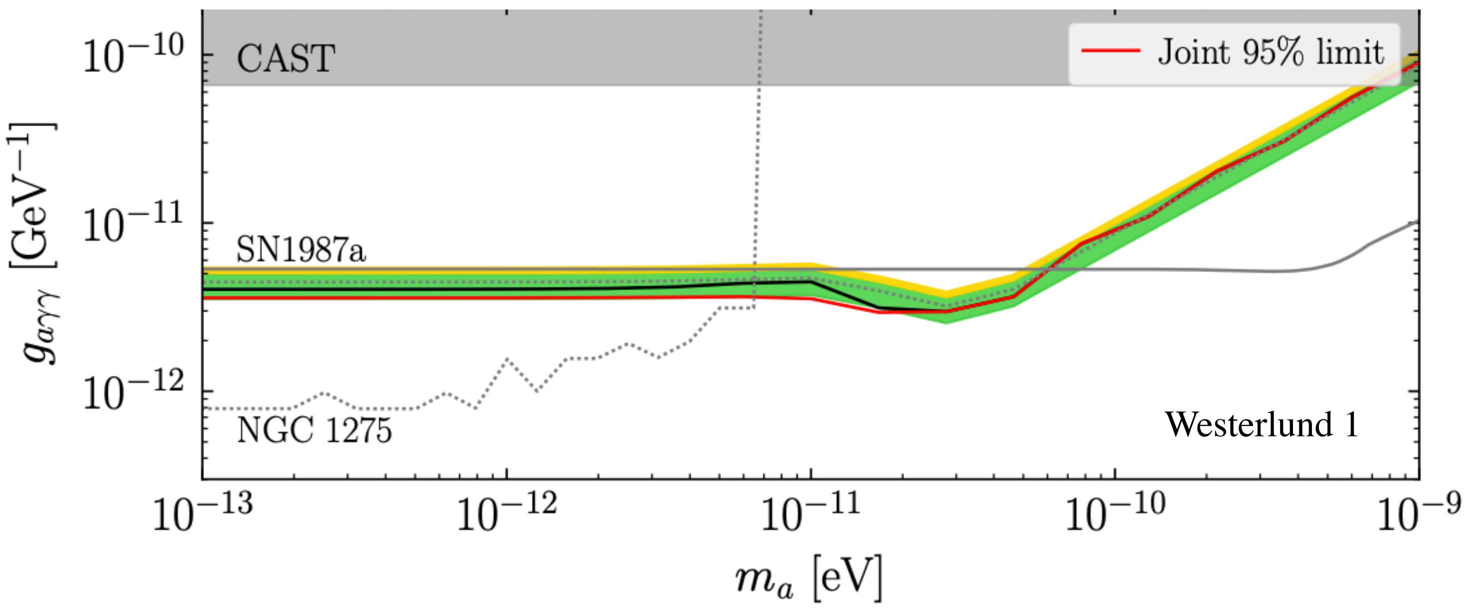
- *Xiao, Carenza, M.G., Mirizzi, Perez, Straniero, Grefenstette Phys.Rev.D 106 (2022)*

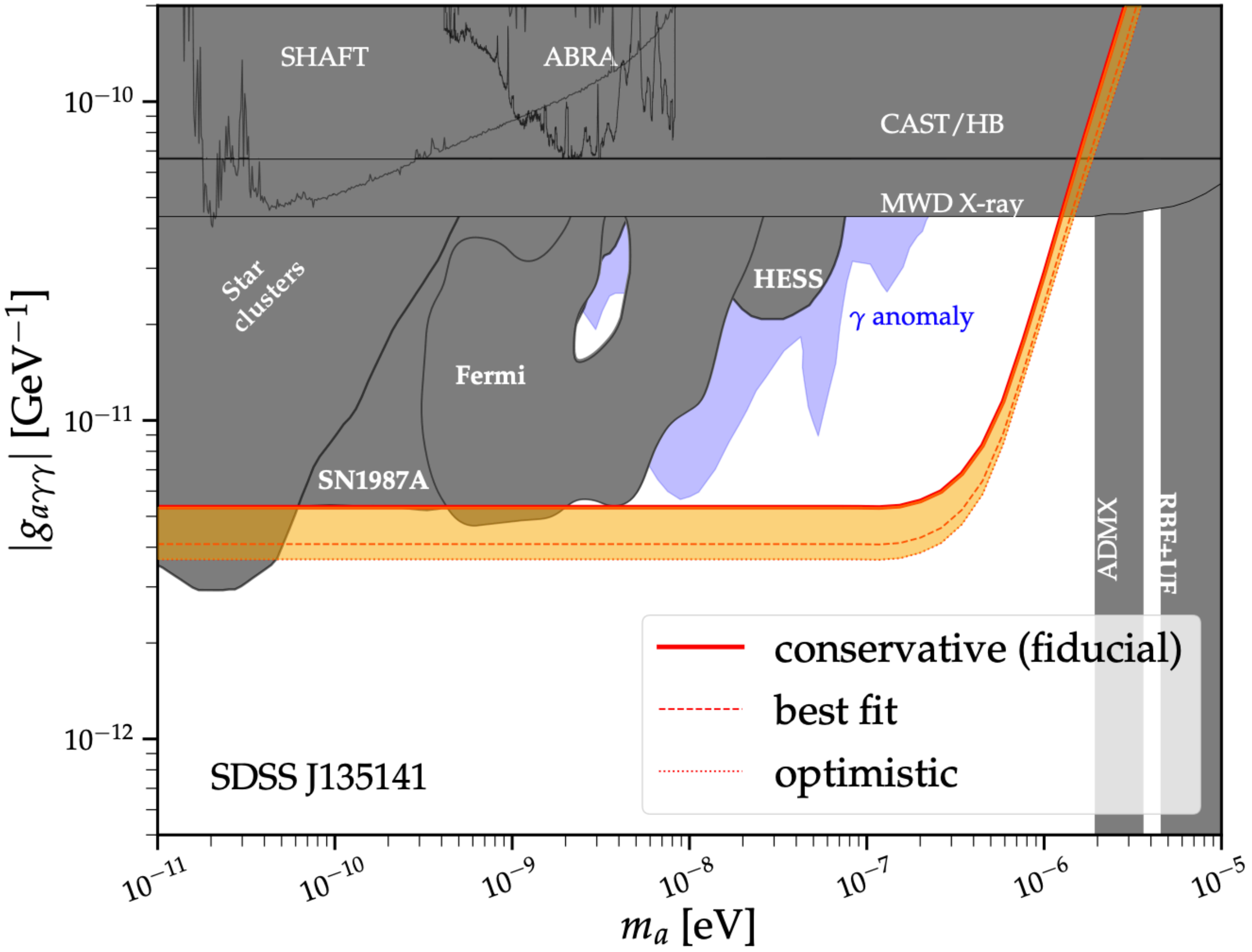
Similar result from observations of Super Star Clusters

Dessert, Foster, Safdy, Phys.Rev.Lett. 125 (2020)



Polarization Effects

A different proposal:
→ look at polarization of light from MWD



C. Dessert talk, Wed. @17:30

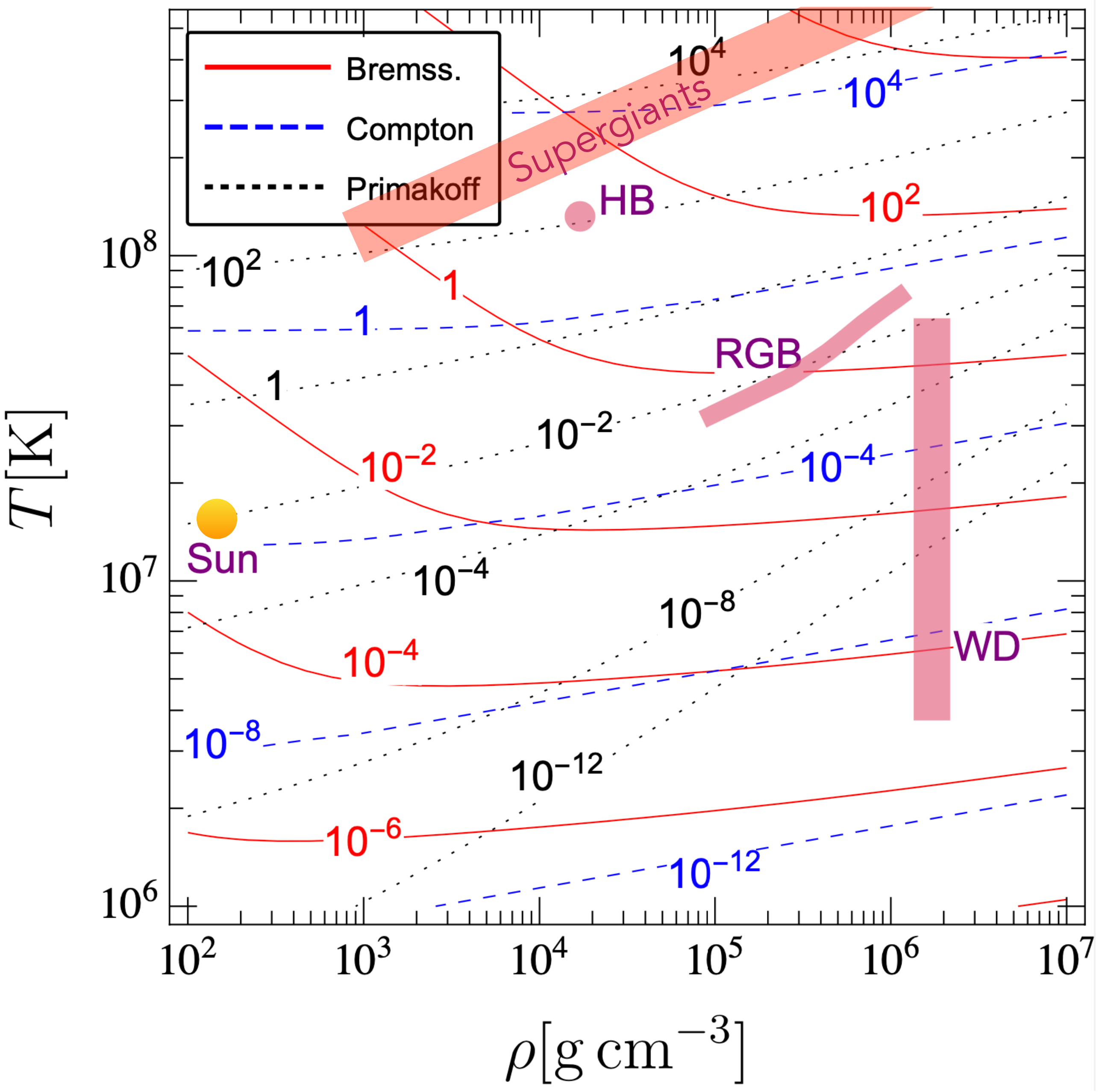
C. Dessert, D. Dunsky, B. Safdi, Phys.Rev.Lett. 128 (2022) 9

Supernova axions

SN

$T_c \simeq 30\ \mathrm{MeV}$

$\rho_c \simeq 3 \times 10^{14}\ \mathrm{g\,cm^{-3}}$



General criterion (Raffelt) from observed ν-signal form SN 1987A:

$$\varepsilon_x \lesssim 10^{19}\,\mathrm{erg\,g^{-1}s^{-1}}$$

$$@\quad \rho = 3 \times 10^{14}\,\mathrm{g\,cm^{-3}},\ T = 30\,\mathrm{MeV}$$

Corresponds to $\sim 10^{56}\,\mathrm{axions/\,s}$.

About $\sim 10^{13}\,\mathrm{cm^{-2}\,s^{-1}}$ axions on Earth from Betelgeuse

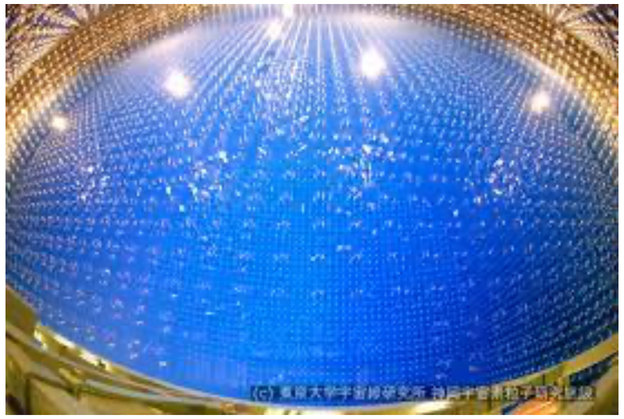
Huge flux… but short!

Detecting SN axions

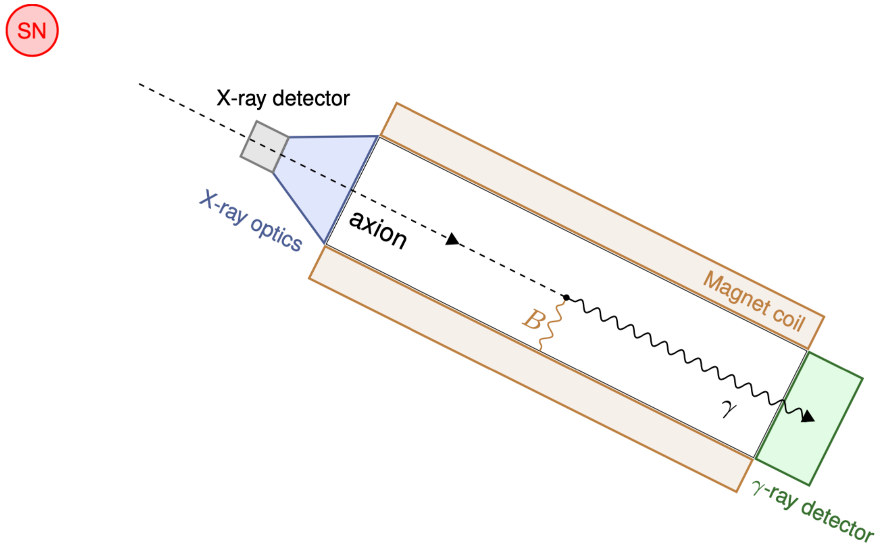
Direct Detection:

→ **Cherenkov**

- A. Lella et al., arXiv:2306.01048;
- Vonk, Guo, Meißner, Phys.Rev.D 105 (2022)
- P. Carenza et al., arXiv:2306.17055



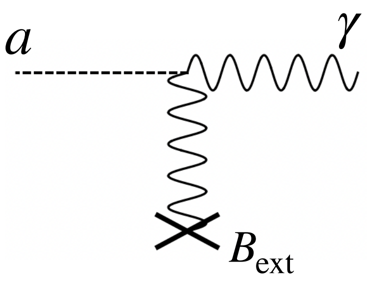
→ **Heliscopes**

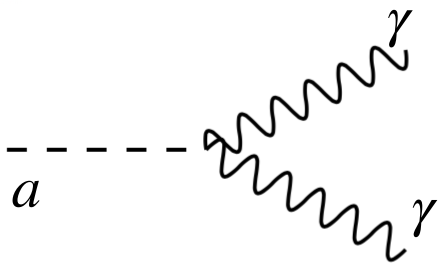


Ge, Hamaguchi, Ichimura, Ishidoshiro, Kanazawa, JCAP 11 (2020);

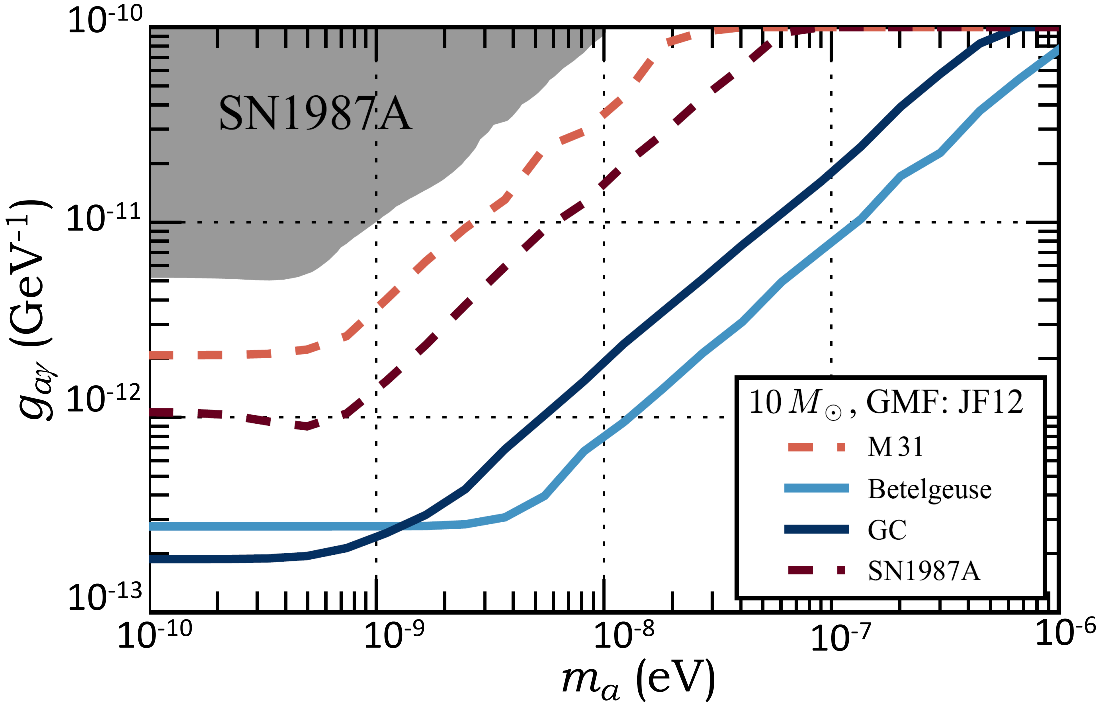
Indirect detection

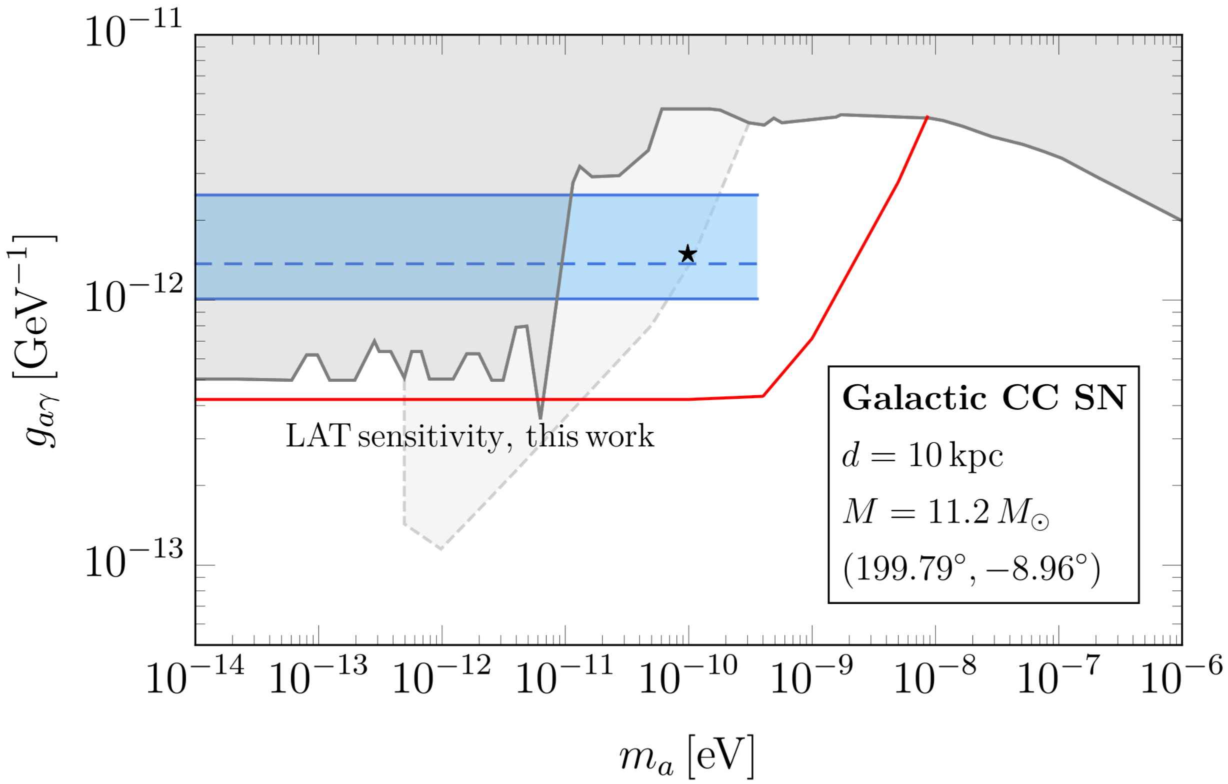
Through photon oscillations of decay. Many ideas





Fermi LAT as Axion SN-Scope





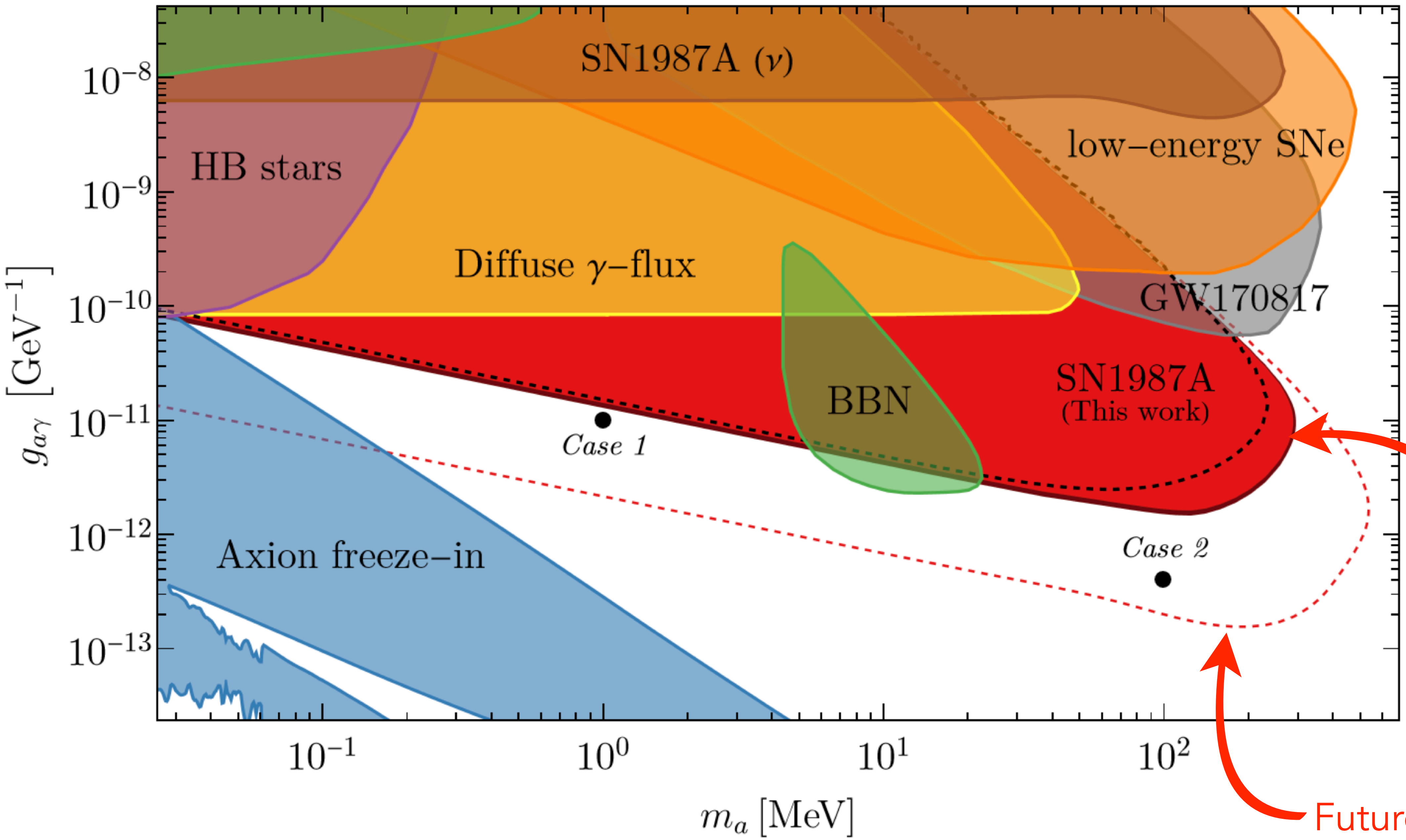
M. Meyer , M. G., A. Mirizzi, J. Conrad, M.A. Sánchez-Conde, Phys.Rev.Lett. 118 (2017)

Calore, Carenza, Eckner, M. G., Lucente, Mirizzi, Sivo et al. arXiv:2306.03925

New analysis
→ slightly reduced sensitivity. But…

Significant opportunities to study axions and the SN itself if $g_{a\gamma} \gtrsim 10^{-12}\,\mathrm{GeV}^{-1}$

High Mass SN ALPs @ Fermi LAT

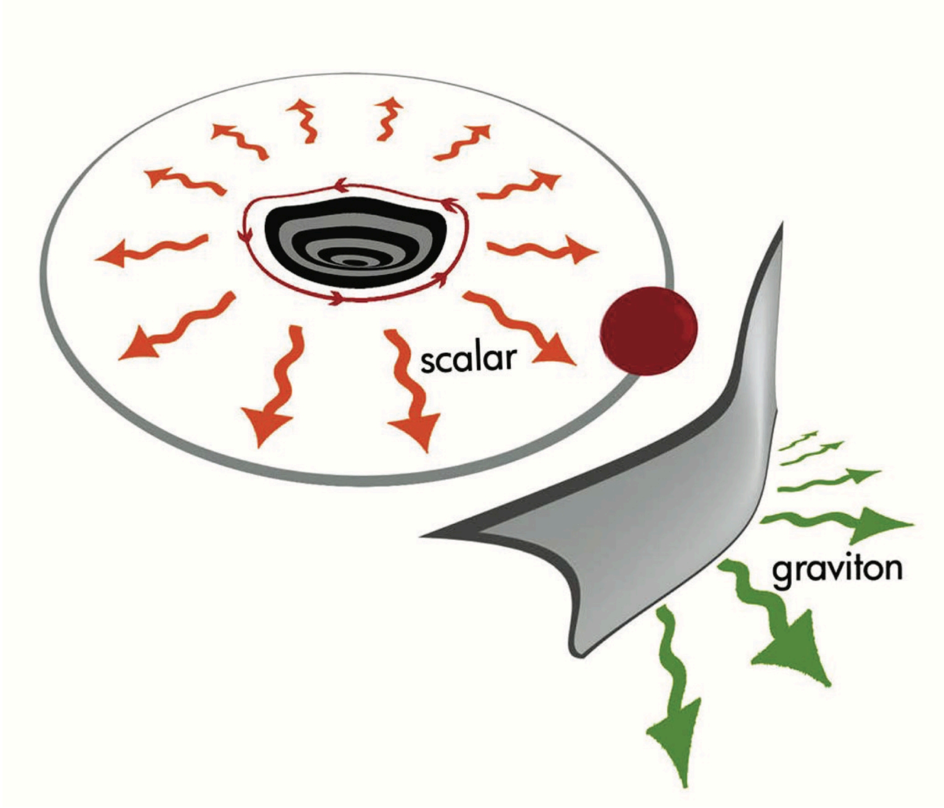


Current bound

Future galactic SN

Eike Müller, Francesca Calore, Pierluca Carenza,
Christopher Eckner, M.C. David Marsh, arXiv:2304.01060

Black Holes Axions



Brito, Cardoso, Pani, arXiv:1501.06570

Black hole superradiance.
Detectable GW from axion cloud around a BH.

Axion Factory! No need for an initial axion

However, no direct axion detection

Advanced Ligo as axion telescope

Active searches going on

- *C. Palomba et al. Phys.Rev.Lett. 123 (2019)*
- *L. Sun, R. Brito, M. Isi, Phys.Rev.D 101 (2020)*

Limitations: geometrical factor limit the boson mass to very small values:
axion Compton wavelength ~ BH size $\Rightarrow m_a < 10^{-11}\,\mathrm{eV}$

➡ *See Francesca Day Wed.@13:15 and Yifan Chen Wed.@2:55*

Will we detect Stellar Axions with Next Gen. Experiments?

Sun	● High potential to detect ALPs (including QCD axions) if $m_a \lesssim 100\,\mathrm{meV}$ and $g_{a\gamma} \sim$ stellar bounds ● Possibility to explore solar magnetic field through $g_{a\gamma}$ but likely not in next generation experiments ● Unlikely axions discover through g_{ae} in the near future ● Higher masses may be accessed through g_{aN}, but in large part in tension with SN1987A
Other stars	● Production can be much larger than in the Sun ● Require magnetic fields to compensate for large distance $\Longrightarrow$ Explore mostly very low mass region but sensitive to very small couplings
SN	● Huge production but for short time. Several close by candidates ● Direct detection may be possible but more studies are required ● At very low mass, strong potential for detection with γ-ray observatories (e.g., Fermi LAT) ● At high mass, possible detection of decay products (e.g., Fermi LAT)
NS	● Keep an eye at the excess from Magnificent 7. NuSTAR?

References

- Essential → G. Raffelt: *Stars as Laboratories for Fundamental Physics*, (1996)

- L. Di Luzio, M.G., E. Nardi, L. Visinelli, *The landscape of QCD axion models*, Phys.Rept. 870 (2020). It has a fairly updated section on stellar bounds

- *Feebly Interacting Particles: FIPs 2022 workshop report*, updated to early 2023

- *G. Raffelt lectures at GGI-2023* (2 lectures), clear and updated

- J. Isern, S. Torres & A. Rebassa-Mansergas, White Dwarfs as Physics Laboratories:

Background information:

- D. D. Clayton, *Principles of Stellar Evolution and Nucleosynthesis*, Chicago (1984)

- D. Prialnik, *An Introduction to the Theory of Stellar Structure and Evolution*, Cambridge (2009). Extremely clear. Very nice discussion of instabilities.

- R. Kippenhahn, A. Weigert, A. Weiss, *Stellar Structure and Evolution*, Springer (2012). Very detailed.

Conclusions and final comments

- Stars are excellent labs and factories for axions and other FIPs
- New interesting ideas are popping out and many things are still unexplored
- Much more about stellar axions (and other FIPs) than what I covered (Apologies!)

Backup Slides

Stars: An intuitive picture…

Stars are self-gravitating bound systems, which radiates energy supplied by an internal (nuclear) source

→ D. Prialnik (2009)

1. → Stars are spherical (or, almost spherical)

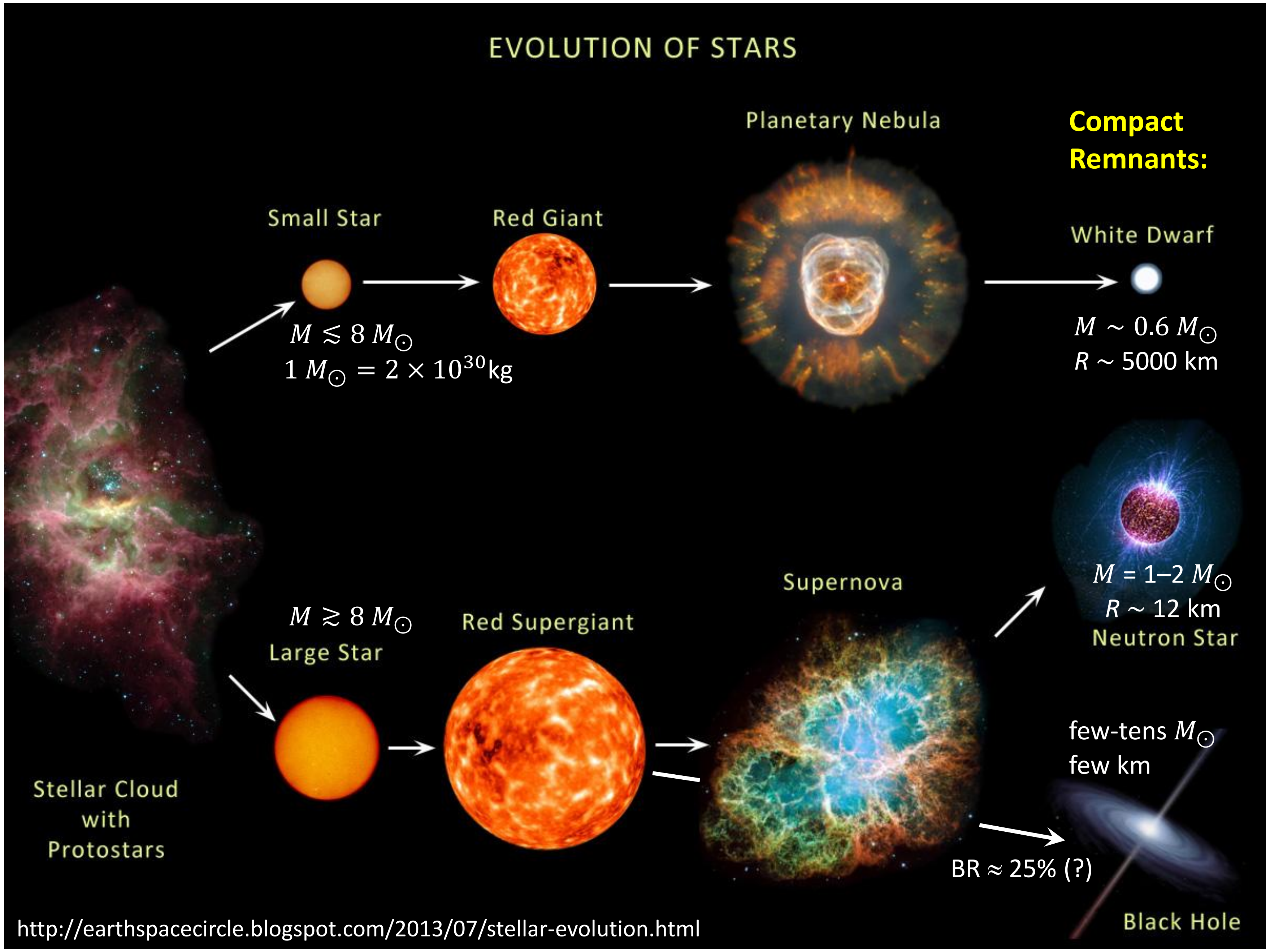
   1D codes are very efficient at describing stars

2. → No need for GR (in most cases)

3. → The core density of stars is very high, for Earth standards. Yet, (in most cases) the **ideal gas** approximation works well

Backup Material

Stars and Stellar Evolution



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

Stars have a large variety of characteristics.

A lot of their evolution depends on the initial mass, with some less dependence on the initial composition.

Surface temperatures ~ 1 eV (~visible); core temperatures ~ several keV (x-ray)

SNe and NS: surface temperature ~ x-rays and core is several MeV (gamma rays)

Stars are Spherical

Stars are self-gravitating bound systems, which radiates energy supplied by an internal (nuclear) source

→ *Prialnik (2009)*

Gravity dominates over sufficiently large systems, since it is not screened. Assuming $\epsilon_c \approx (0.1 - 1)\mathrm{eV}$ and a standard density, we can see that $\epsilon_g \gg \epsilon_c$ for $R \gg R_g \approx 1000\ \mathrm{km}$

→ Planets are spherical
→ Rocks and meteorites are not spherical (chemical binding → short range → anisotropic).

→ Stars are spherical (or, almost spherical)

The kinetic energy of rotation relative to the gravitational binding energy is of the order

$$\frac{M\omega^2 R^2}{GM^2/R} = \frac{\omega^2 R^3}{GM} \sim 2 \times 10^{-5} \ll 1$$

Anisotropies due to the magnetic field are, typically, even smaller.

→ *1D codes are very efficient at describing stars*

Compactness and GR

For a spherical object we can define (unambiguously) the compactness

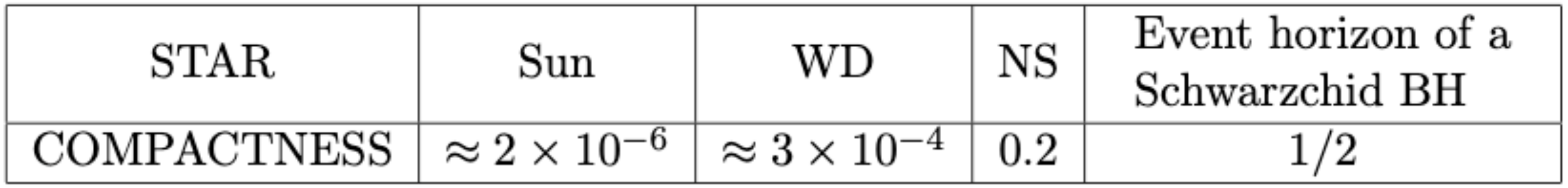
$$C = \frac{GM}{c^2R}$$

Note: compares escape velocity with c

To get an intuition of how large this parameter is, notice that

$$\frac{GM_\odot}{c^2R} \simeq 1.47\ \mathrm{km}^{-1}$$

A large compactness ($C \sim 1$) indicates that General Relativity effects are important.



STAR	Sun	WD	NS	Event horizon of a Schwarzchid BH
COMPACTNESS	$\approx 2 \times 10^{-6}$	$\approx 3 \times 10^{-4}$	0.2	1/2

GR is not required (in most cases)

Special relativity and quantum mechanics are essential

Ideal Gas Approximation?

Stellar cores are very dense and so atoms are tightly packed.

The solar core is about 150 $\mathrm{g\,cm^{-3}}$, which should be compared with the density $\rho = 22.6\,\mathrm{g\,cm^{-3}}$ of Osmium, the densest stable element.

Yet, the ideal gas is a good approximation to describe the stellar interior.

The reason is duplex.

1. In most cases, the stellar interior conditions are such that **matter is highly ionized** and ionized matter can be compressed to extremely high values while still keeping the ideal gas properties.

2. the **Coulomb potential energy**, normally $\sim \mathrm{eV}$, is considerably **lower than the thermal energies**, normally $\sim \mathrm{keV}$ or higher

→ *e.g., D.D. Clayton (1984)*

… A more detailed picture: Stability

Now, let's look at this a little more quantitatively.

From **Hydrostatic equilibrium**: $$\frac{dP_c}{P_c} = \frac{4}{3}\frac{d\rho_c}{\rho_c}$$

Equation of state: $P \propto \rho^a T^b \quad \rightarrow \quad \frac{dP_c}{P_c} = a\frac{d\rho_c}{\rho_c} + b\frac{dT_c}{T_c}$

Combining the two equations

$$\left(\frac{4}{3} - a\right)\frac{d\rho_c}{\rho_c} = b\frac{dT_c}{T_c}$$

- **Non-degenerate gas**: $a = b = 1$. Compression (caused by energy loss) ⇒ temperature increase and viceversa. Negative Heat Capacitance and self-regulating system.

- **Degenerate Gas**: $4/3 \leq a \leq 5/3$, $b \ll 1$. No self-regulation.

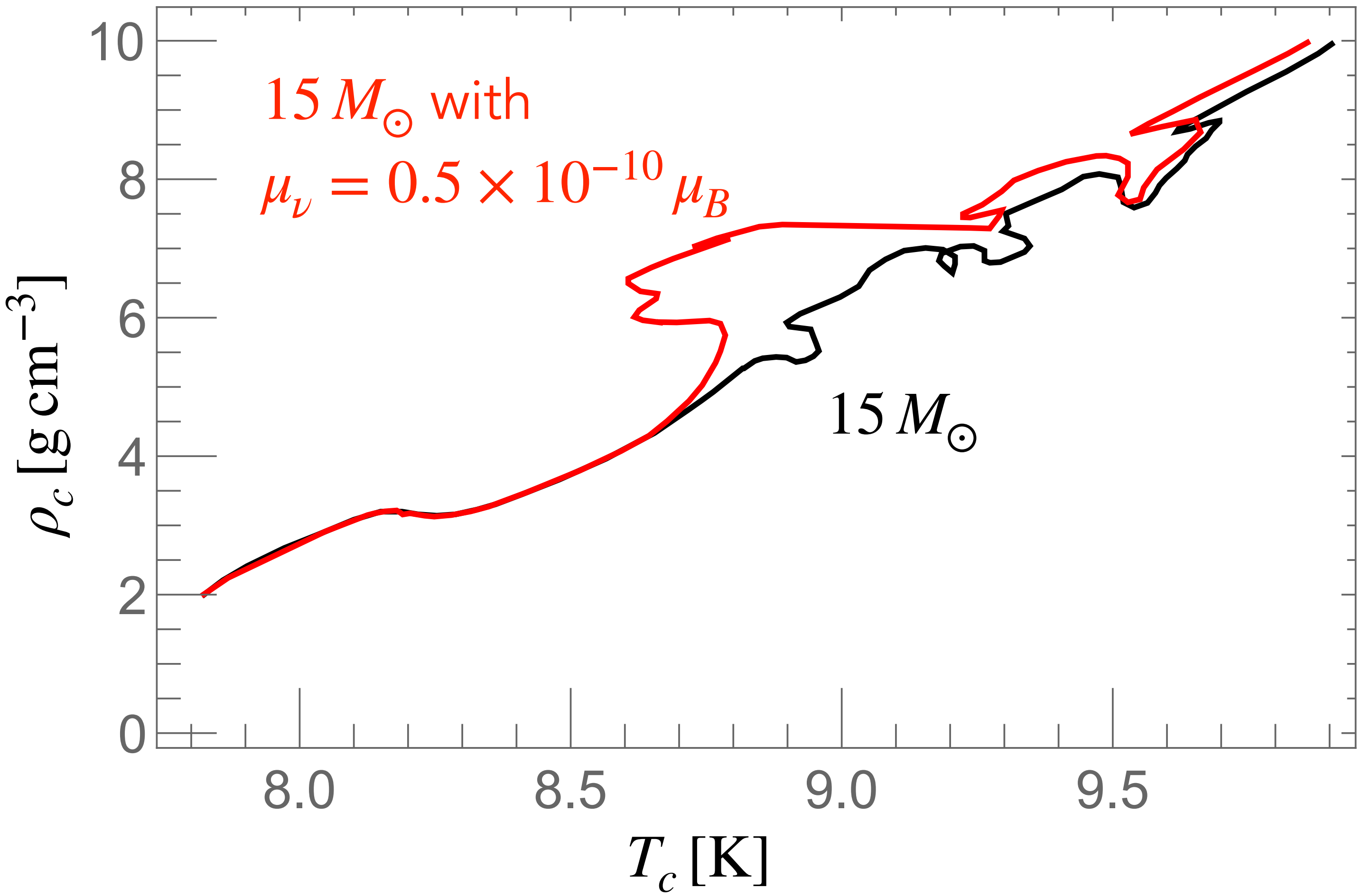
The Role of FIPs in Stars: Degeneracy Effects

If $L_{\text{nuc}} \approx 0 \ \rightarrow \dot{E}_{\text{tot}} < 0$ → The star cools down

→ accelerated evolution of degenerate systems (e.g., WDs)

→ shorten rate of period change in some degenerate systems: WDs $\dot{P}/P \propto |\dot{T}/T|$

→ Drive partially degenerate systems into deeper degeneracy. Qualitative change



The core departures from the standard trajectory between the He- and the C-burning stages, as soon as the neutrino cooling becomes more important than the radiation energy loss.

A. Heger, A. Friedland, M.G., V. Cirigliano, APJ. 696 (2009)

The Role of FIPs in Stars: Stellar Instabilities

Something that has not been studied very much, so far, is the role of FIPs in driving a star into or out of an instability region.

Example:

→ convection is driven by a very strong temperature gradient $\left|\frac{dT}{dr}\right|$.

→ An efficient additional energy transport may reduce $\left|\frac{dT}{dr}\right|$, and drive the star out of a convection zone.

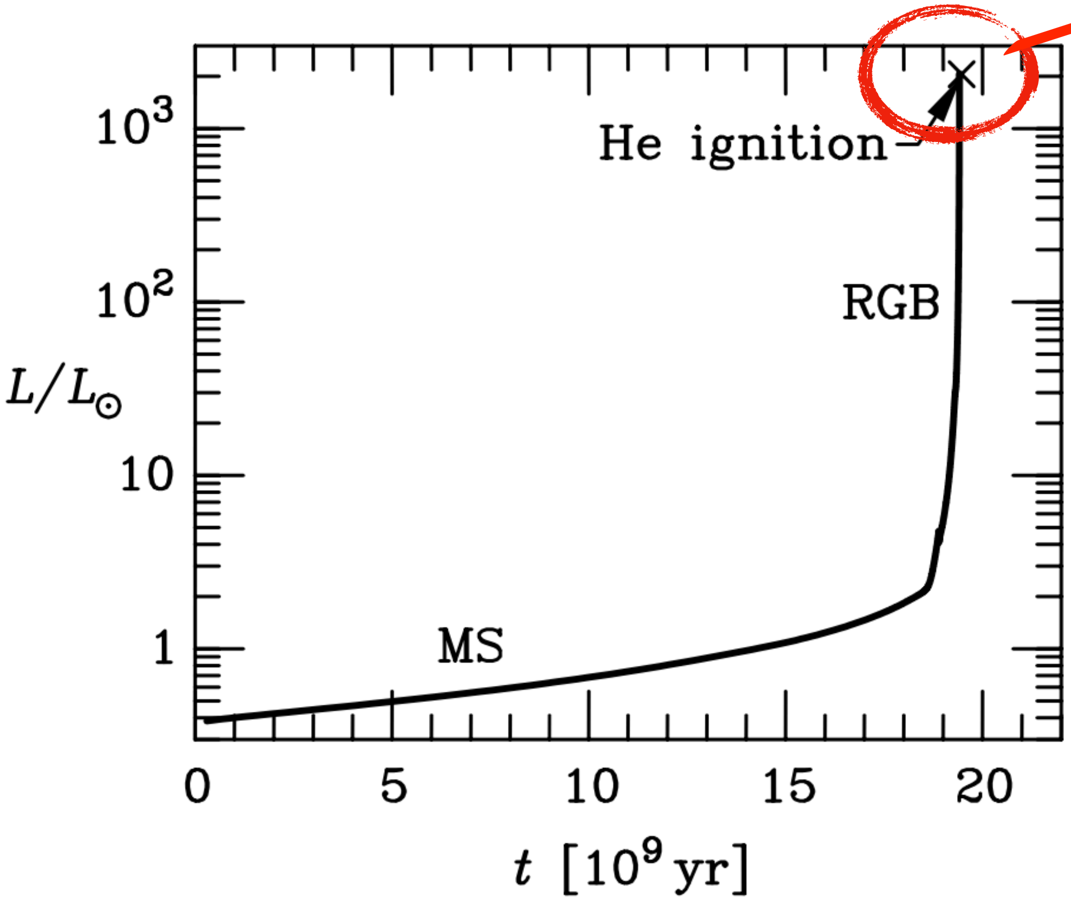
→ Convection can be observed (asteroseismiology) and plays a significant role on chemical mixing.

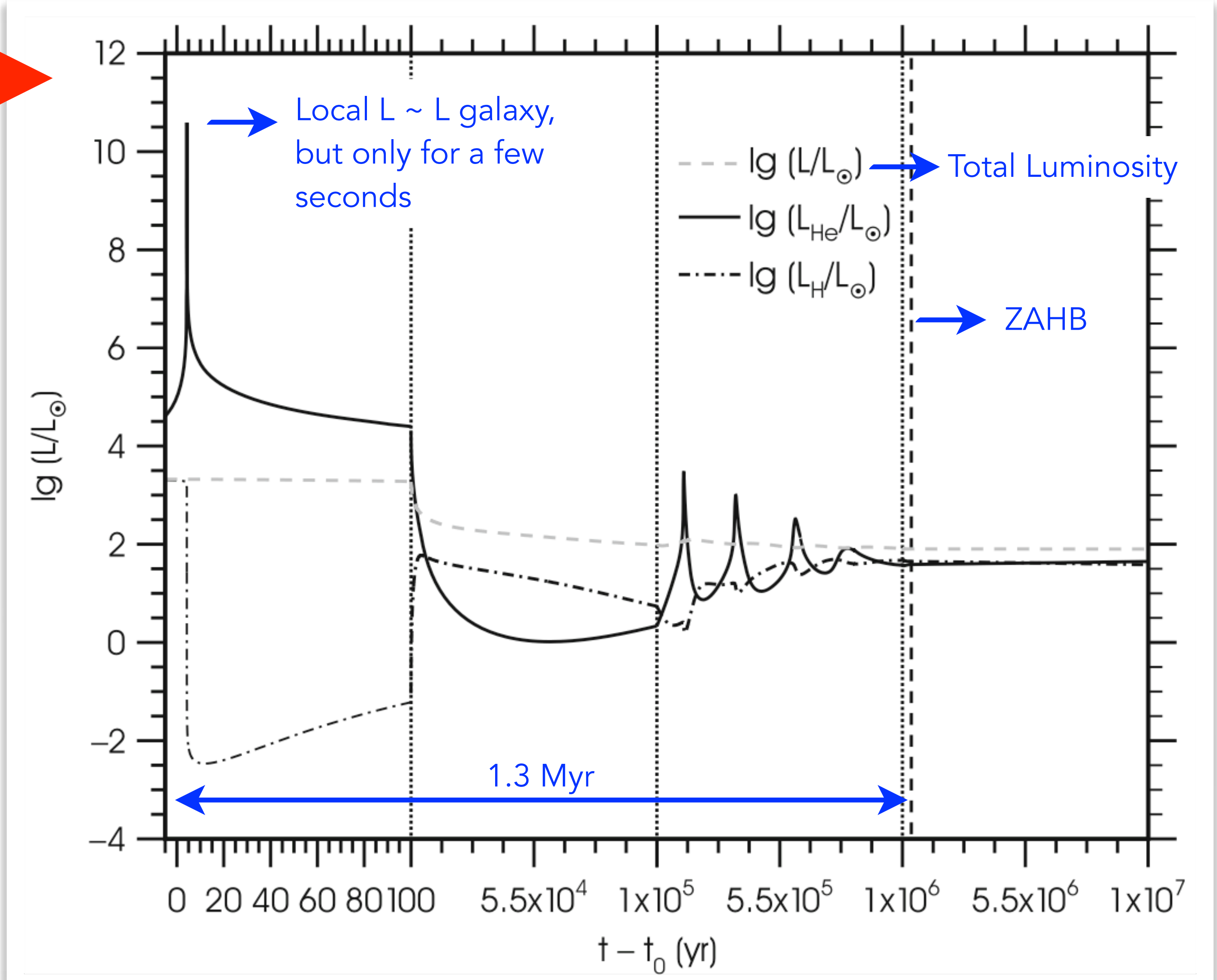
→ Can the role of FIPs be identified ?

Stellar Evolution → Red Giant Branch

Core RGB evolution of a $0.85\,M_\odot$ star
→ Kippenhahn, Weigert, Weiss (2012)

The process continues till He-ignition ($T \sim 10^8$ K, $M_c \approx 0.5\,M_\odot$)





Local L ~ L galaxy, but only for a few seconds

Total Luminosity

ZAHB

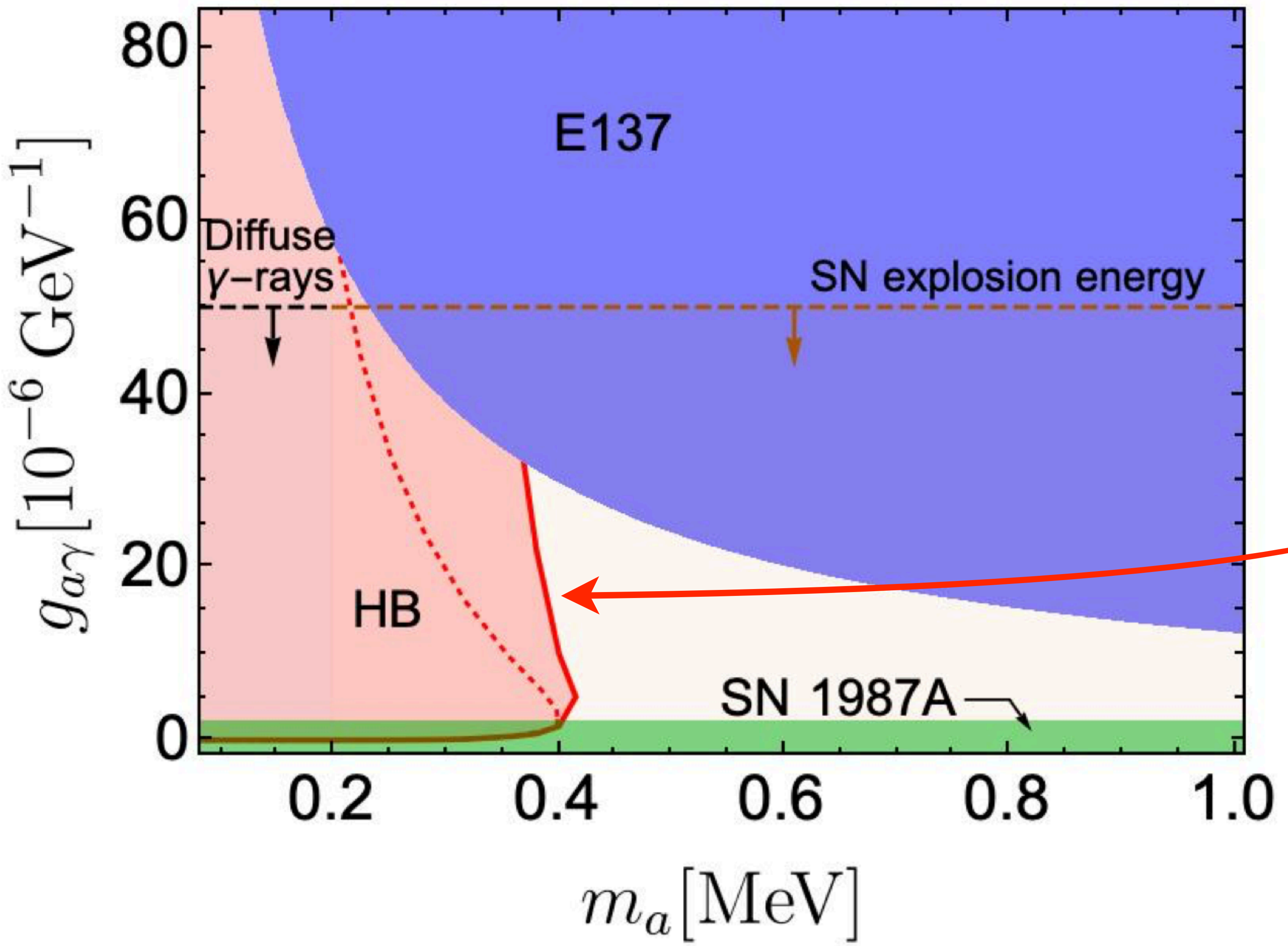
1.3 Myr

Fig. 33.9 Changes in total (L), hydrogen (L_H), and helium (L_He) luminosity with time during the helium flash in the $0.85\,M_\odot$ star of Fig. 33.5. $t = 0$ is defined for the moment when $L_\mathrm{He}/L_\odot = 5$, and the zero-age horizontal branch is reached 1.325×10^6 years later. This is defined as the point of minimal total thermal energy and indicated by the *vertical dashed line*. *Vertical dotted lines* delimit ranges of different scale for the time axis

G. Raffelt, Stars as Laboratories (1996).

Stellar Evolution → Horizontal Branch

Generalization at large mass.



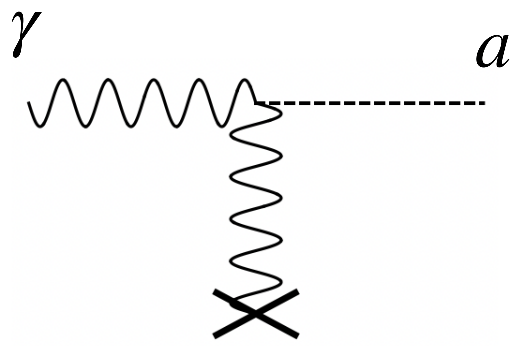
Exotic energy transport compete with convection

G. Lucente et al., [Phys.Rev.Lett. 129 (2022) 1, 011101]

Supernova axions

Talk by Alessandro Lella, Wednesday @ 14:15

Extreme environment $\rho \sim 3 \times 10^{14}\,\mathrm{g\,cm^{-3}}$, $T \sim 30$ MeV.

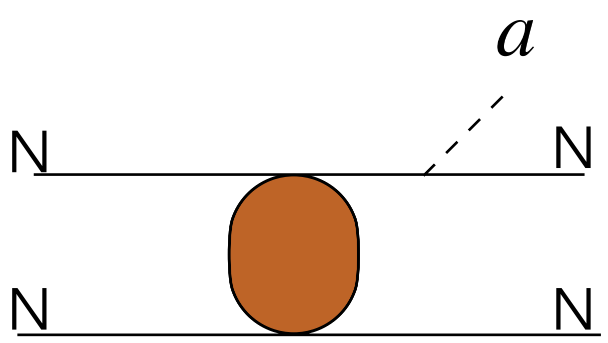


Primakoff requires $\propto g_{a\gamma}^2$

J. Brockway, E. Carlson, G. Raffelt, Phys. Lett. B 383, 439 (1996);

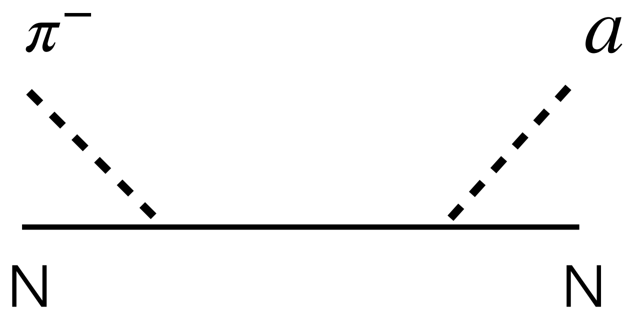
J. Grifols, E. Masso, R. Toldra, Phys. Rev. Lett. 77, 2372 (1996)

A. Payez, C. Evoli, T. Fischer, M. G., A. Mirizzi, A. Ringwald, JCAP 1502 (2015).



Bremsstrahlung $\propto g_{aN}^2$

P. Carenza et al., JCAP 10 (2019) 10, 016



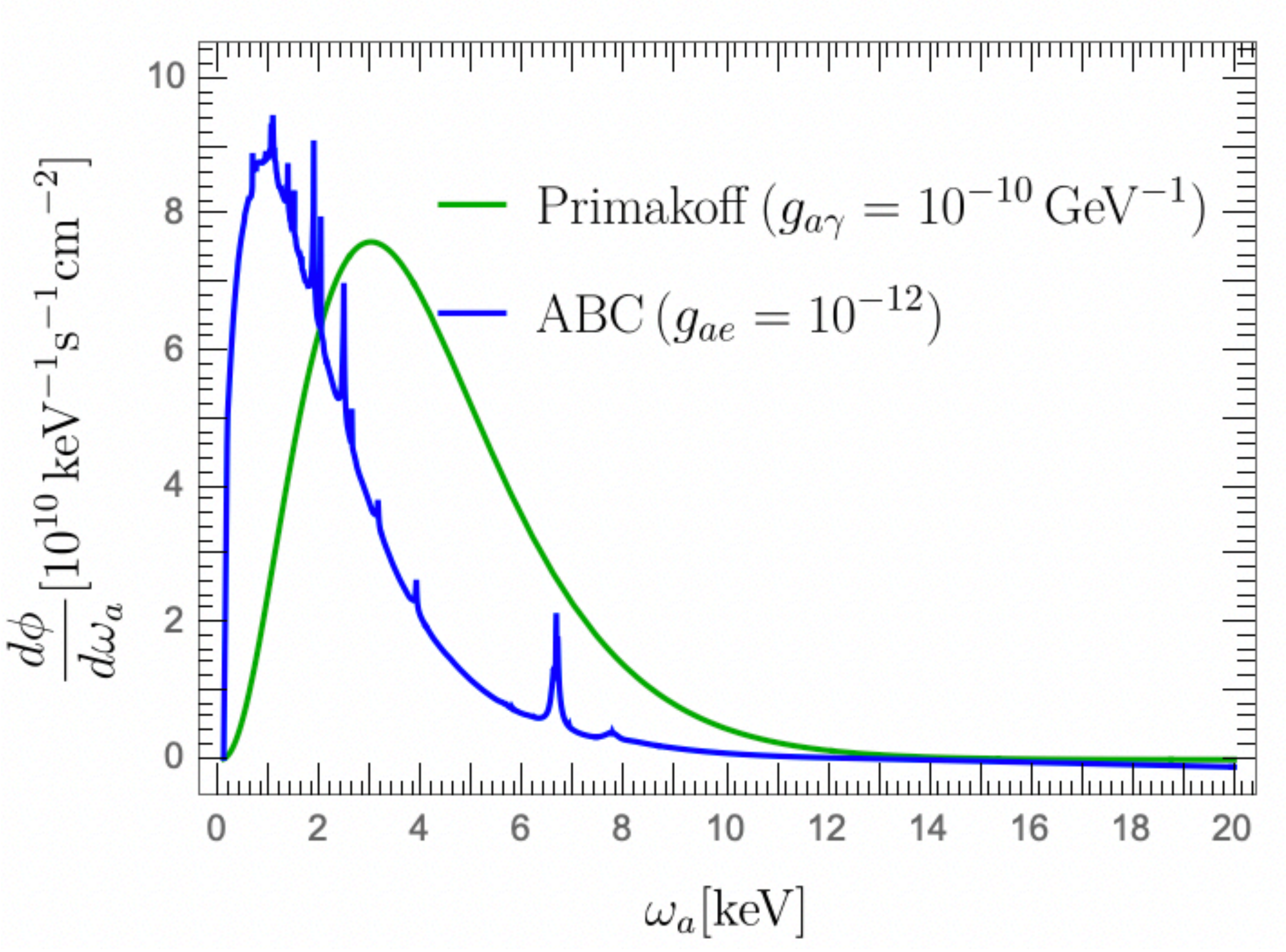
Pion induced $\propto g_{aN}^2$

P. Carenza, B. Fore, M.G., A. Mirizzi, S. Reddy, Phys.Rev.Lett. 126 (2021)

Pion abundance was underestimated. Breakthrough result in
B. Fore and S. Reddy, Phys. Rev. C 101, 035809 (2020)

The Sun as Axion Factory

$$\frac{dN_a}{dt} = 1.1 \times 10^{39} \left[\left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}} \right)^2 + 0.7 \left(\frac{g_{ae}}{10^{-12}} \right)^2 \right] \mathrm{s}^{-1}$$



up to $\sim 10^{39}$ axions/s
($\Rightarrow 10^{11}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ axions on Earth), peaked at $\sim$ keV

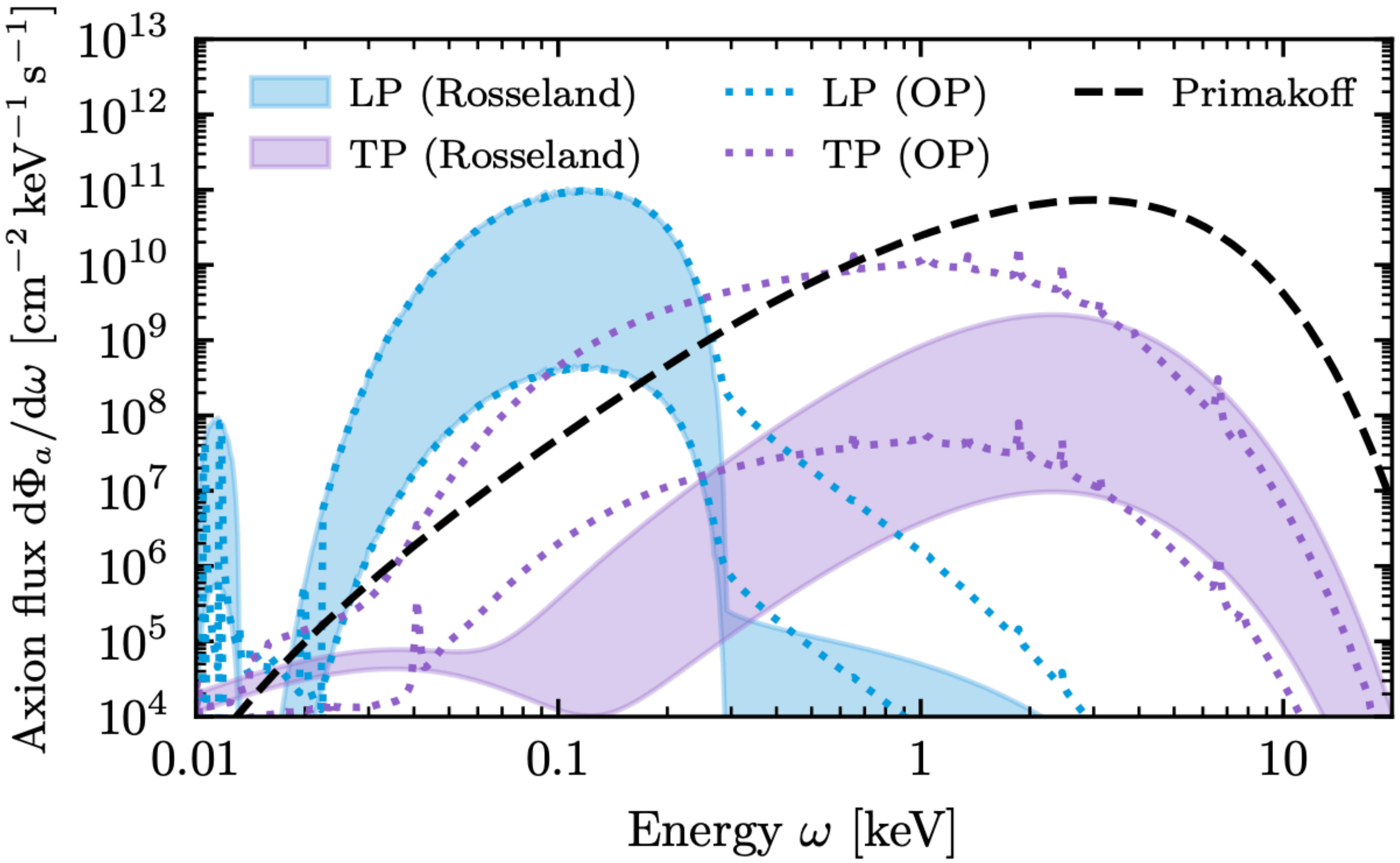
We can observe this flux with the Next Gen. Axion Helioscopes (See Julia Vogel's talk)

J. Redondo, JCAP 1312 (2013)

The Sun as Axion Factory

Furthermore, axions can be produced in conversion in the solar magnetic field

Very clear presentation of the Solar axion flux:
→ S. Hoof, J. Jaeckel, L. J. Thormaehlen, JCAP 09 (2021) 006



→ Sebastian Hoof talk, Wed. @ 15:55

Solar axions from Nuclear Reactions

Recent progress in the search for axions from nuclear reactions in the Sun. Important examples:

$p + d \rightarrow {}^{3}\mathrm{He} + a$

- Searched by CAST *JCAP* 03 (2010)
- Borexino *Phys.Rev.D* 85 (2012)
- and using previous SNO data Phys.Rev.Lett. 126 (2021)
- Recent analysis of the JUNO sensitivity shows potential to search in unexplored regions G. Lucente, N. Nath, F. Capozzi, MG, A. Mirizzi, Phys.Rev.D 106 (2022)
- HP case in F. D'Eramo, G. Lucente, N. Nath, S. Yun (2023)

${}^{57}\mathrm{Fe}^{*} \rightarrow {}^{57}\mathrm{Fe} + a$

- Searched by CAST *JCAP 12 (2009)*
- BabyIAXO potential studied in *Eur.Phys.J.C 82 (2022)*

${}^{7}\mathrm{Li}^{*} \rightarrow {}^{7}\mathrm{Li} + a$

- Searched by Borexino *Eur.Phys.J.C 54 (2008)*
- CAST *JCAP* 03 (2010)

Comprehensive discussion in R. Massarczyk, P.H. Chu, S.R. Elliott, Phys.Rev.D 105 (2022)

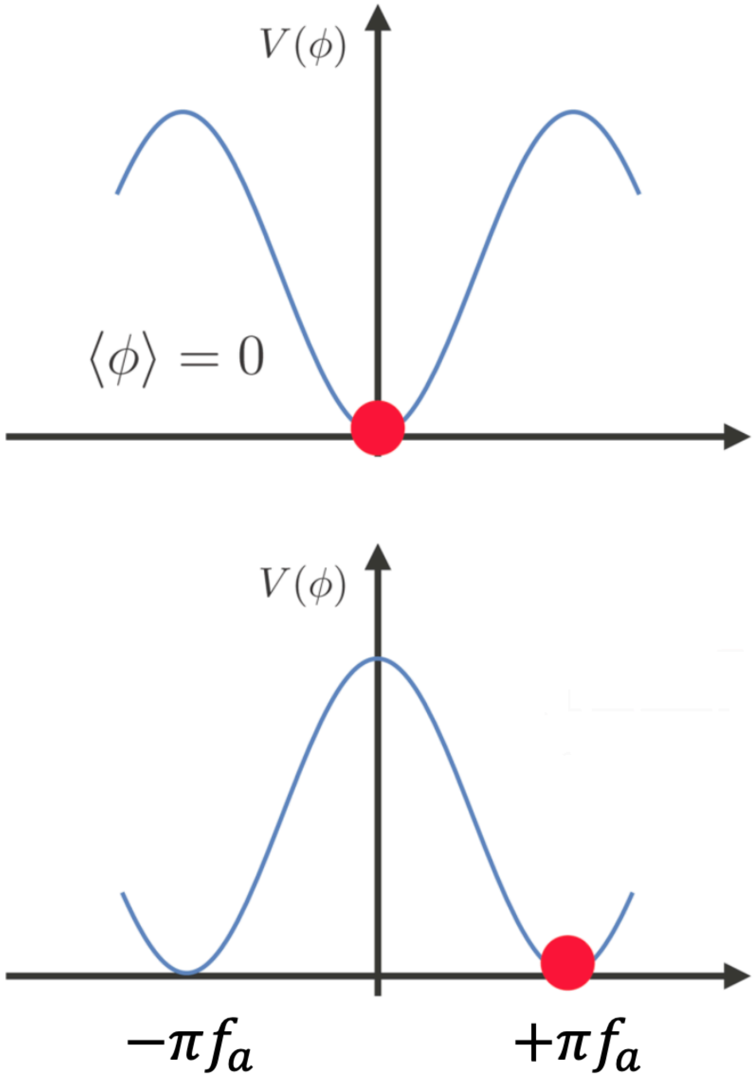
Axions Impact on EOS

Nuclear chiral perturbation theory with QCD axion leads to non-derivative nucleon couplings

$\sigma_{\pi N} \simeq 50$ MeV

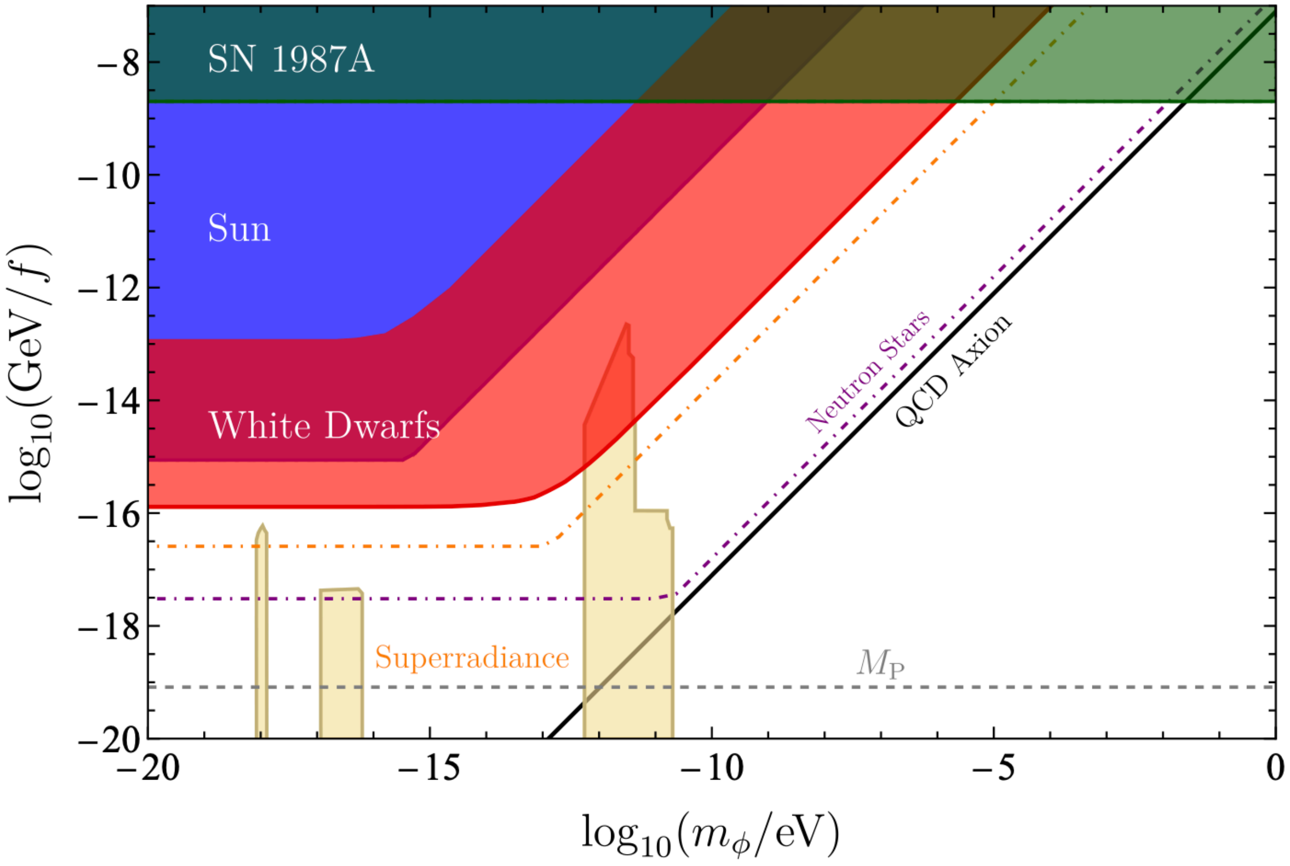
$$V(\phi) = -\frac{m_\pi^2 f_\pi^2}{4}\left(1 - \underbrace{\frac{4\sigma_{\pi N} n_N}{m_\pi^2 f_\pi^2}}_{\mathcal{O}(1)\text{ at nuclear density}}\right)\left(\cos\frac{\phi}{f_a} - 1\right)$$

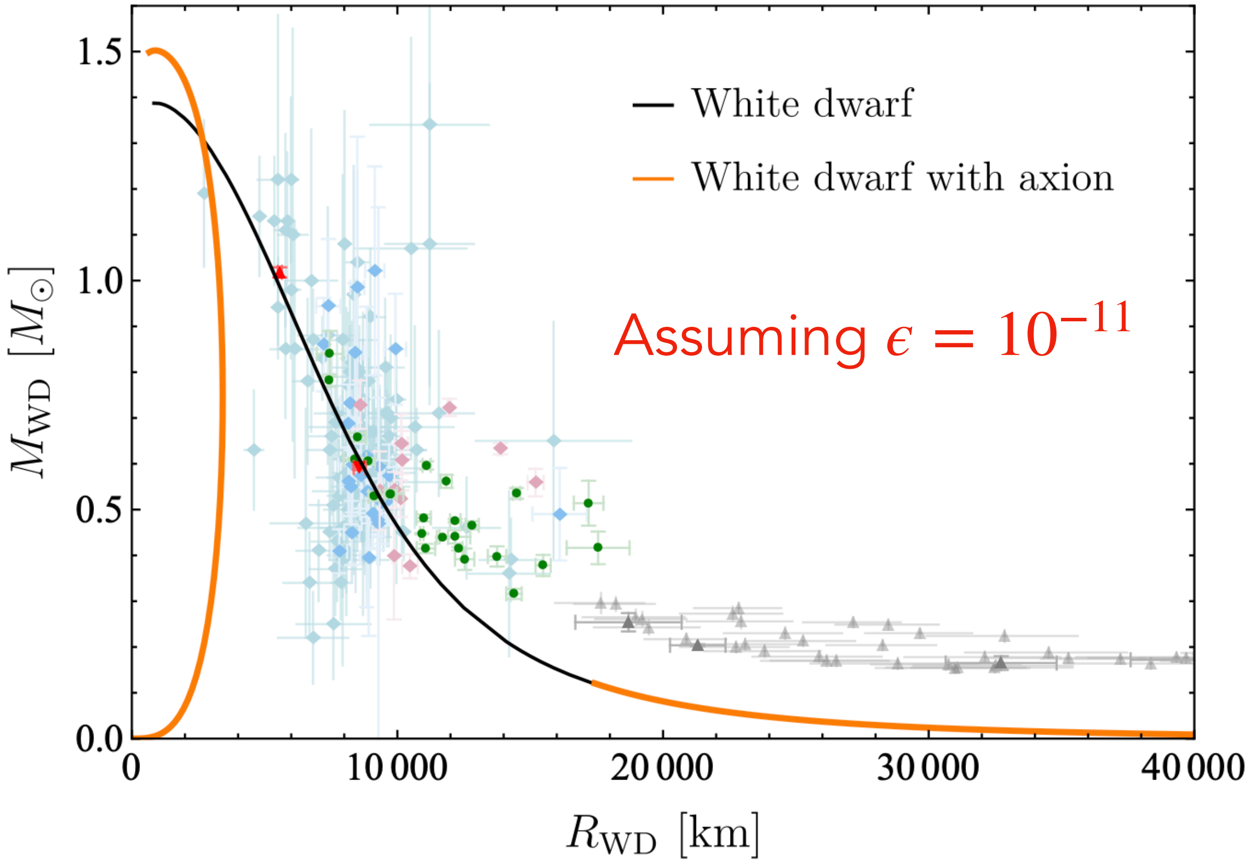
In models in which the expected mass is reduced ($1 \to \epsilon$), the additional term may be sufficient for shifting the min of the axion potential from 0 to πf_a



- *Hook & Huang 1708.08464,*
- *Balkin+ 2105.13354*

Axions Impact on EOS: WD Mass-Radius Relation





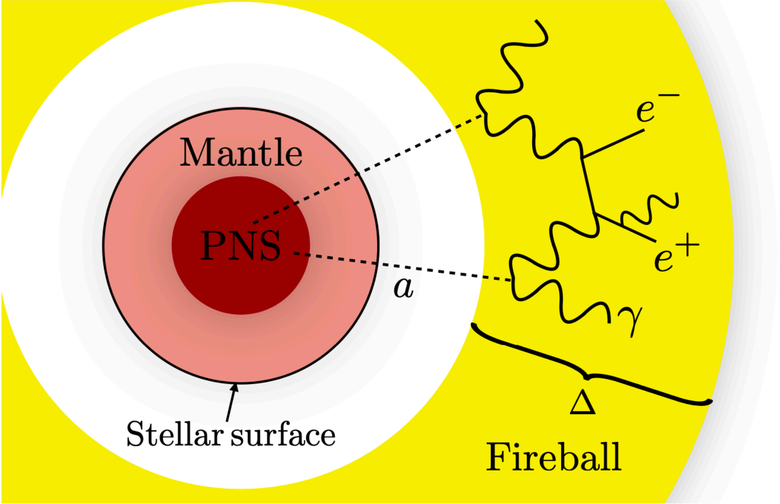
Assuming $\epsilon = 10^{-11}$

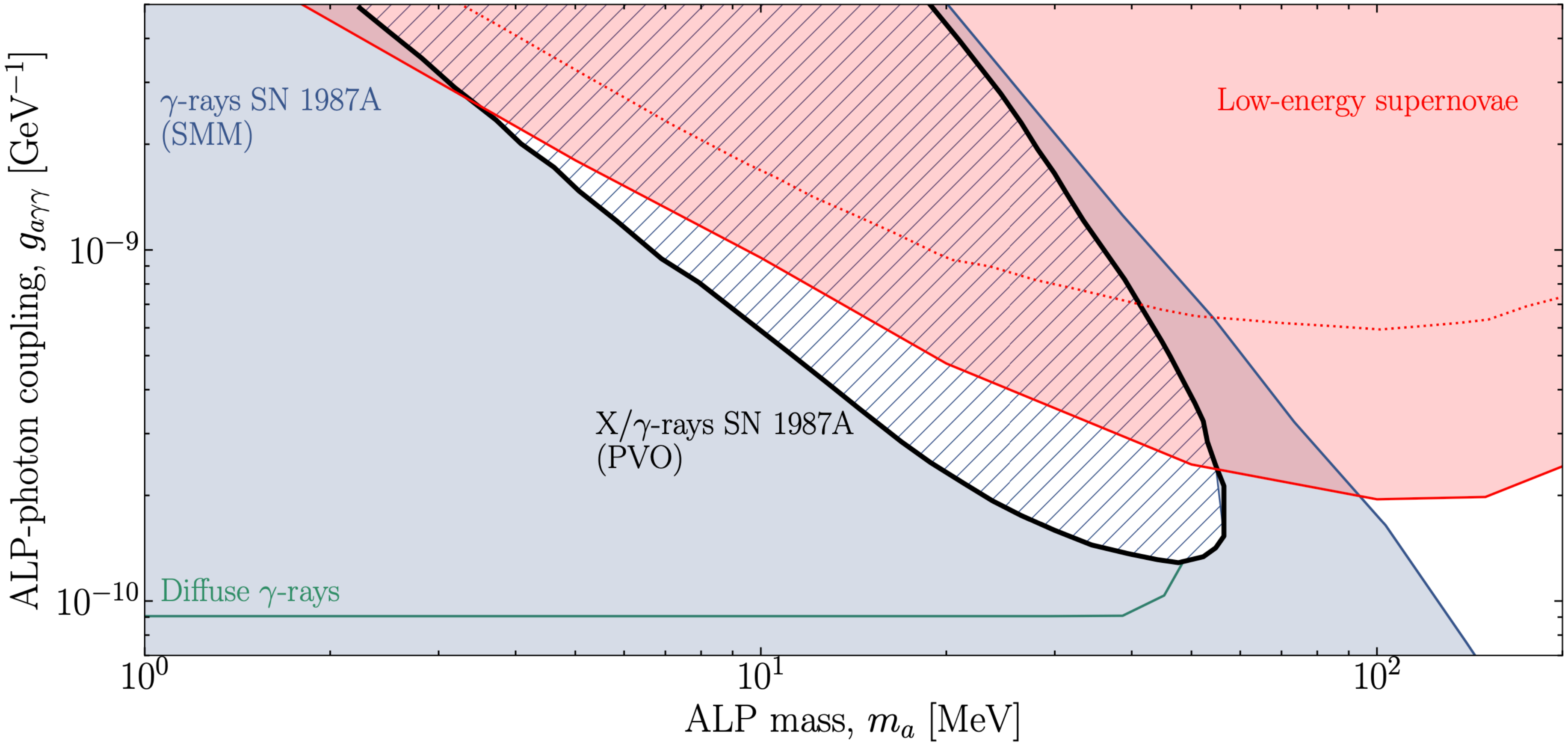
R. Balkin, J. Serra, K. Springmann, S. Stelzl & A. Weiler, e-Print: 2211.02661

→ Nice recent presentation in Stefan Stelzl talk at COST 2023

SN axions and Fiereball Formation

- Massive ALPs, $a \rightarrow \gamma\gamma$: fireball formation outside progenitor star
- The photon energy is downgrades from ~100 MeV to sub-eV

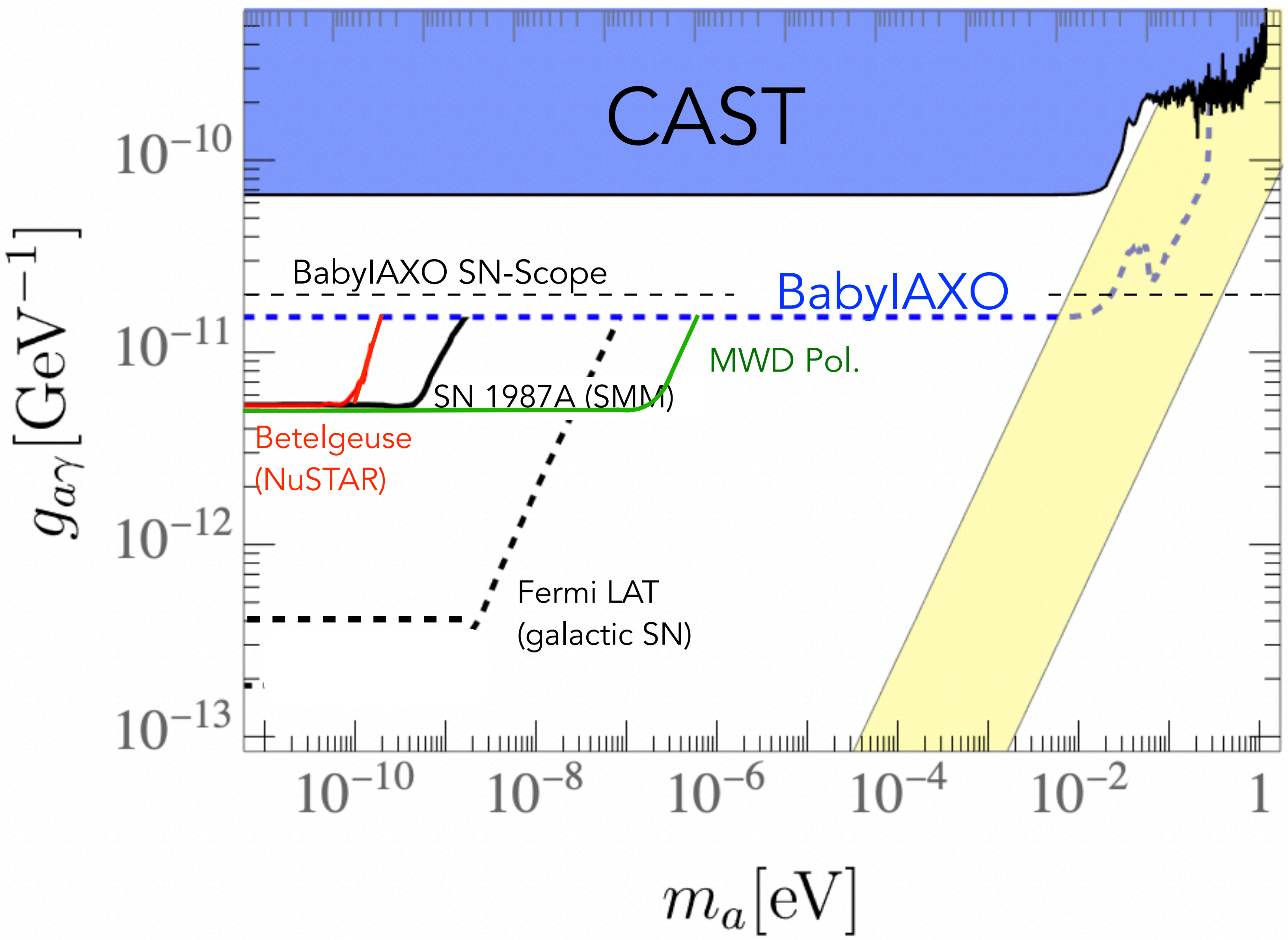




Bound from Pioneer Venus Orbiter (PVO) from SN 1987A. The exclusion window remains

→ Diamond, Fiorillo, Marques-Tavares, Vitagliano, Phys.Rev.D 107 (2023)

Summary: Detecting Stellar Axions



Legend:

Solar Axion

Pre-SN Axions

SN Axions

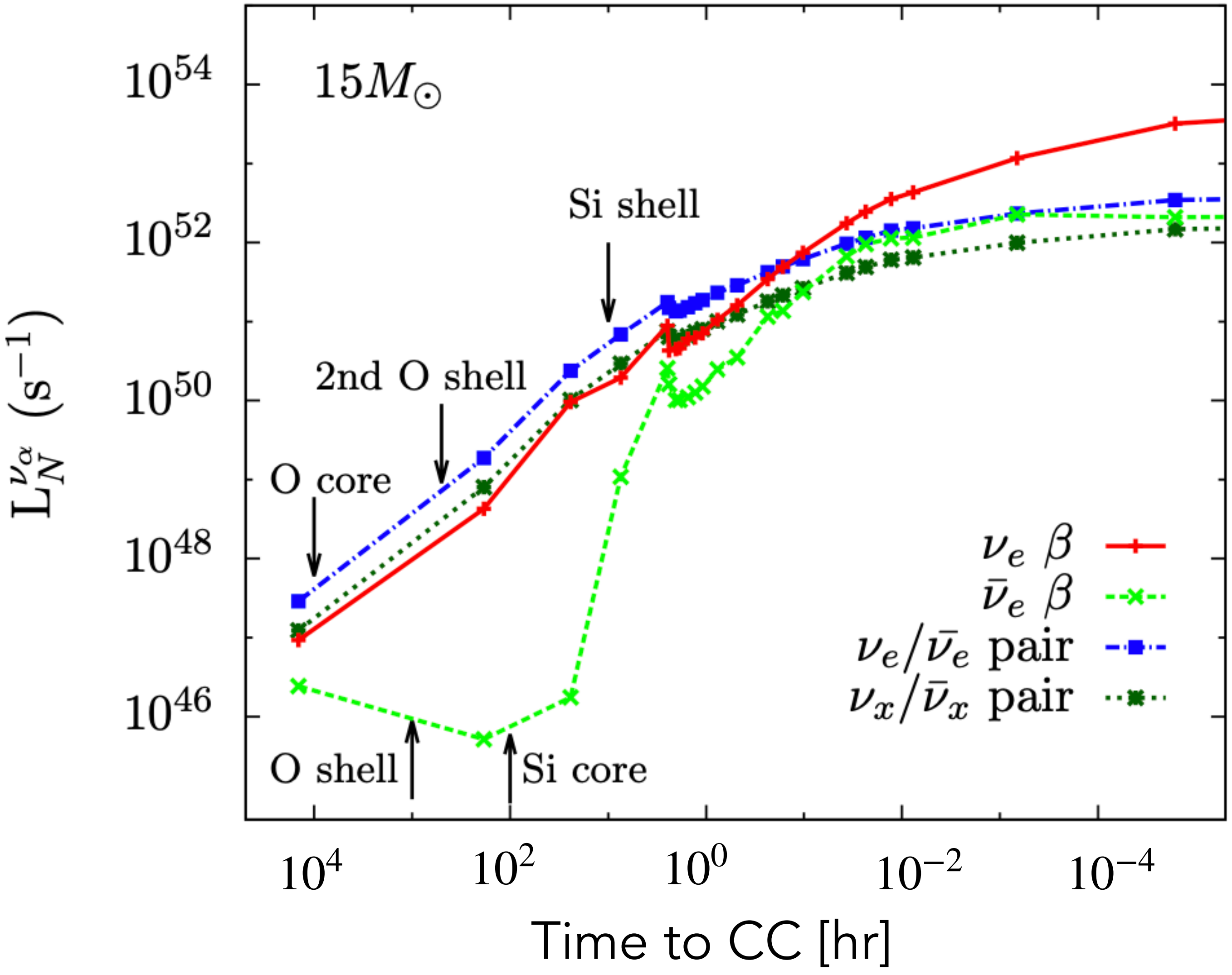
— Current bounds

- - - - Estimated sensitivities

🟨 Benchmark QCD models

Pre-SN signal

Neutrinos are produced from thermal and beta processes.

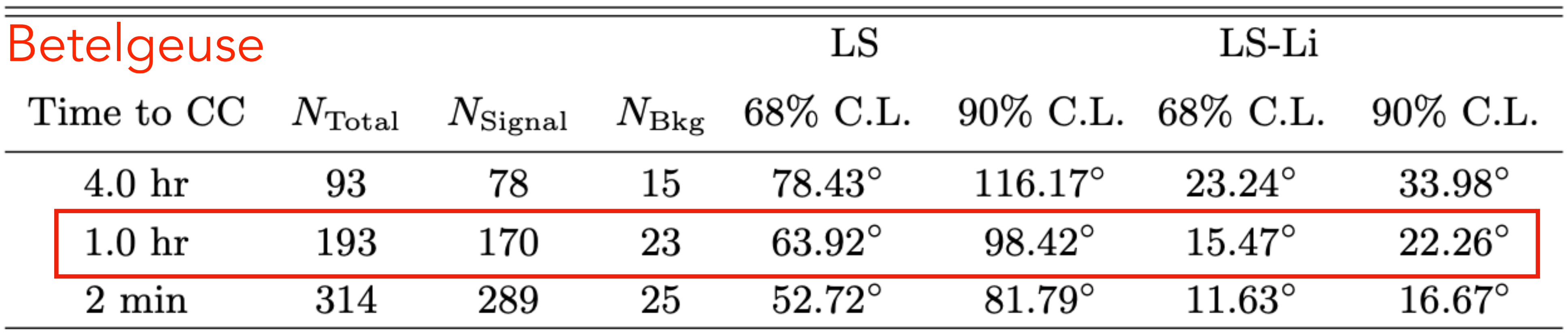


K .M. Patton. C. Lunardini, R. Farmer and F. X. Timmes, ApJ 851 (2017)

Pre-SN signal

Major difficulty: angular resolution.
Improves with use of Liquid Scintillator (LS) detector with a Lithium compound dissolved (LS-Li)

Tanaka & Watanabe (2014)



Betelgeuse				LS		LS-Li	
Time to CC	N_{Total}	N_{Signal}	N_{Bkg}	68% C.L.	90% C.L.	68% C.L.	90% C.L.
4.0 hr	93	78	15	78.43°	116.17°	23.24°	33.98°
1.0 hr	193	170	23	63.92°	98.42°	15.47°	22.26°
2 min	314	289	25	52.72°	81.79°	11.63°	16.67°

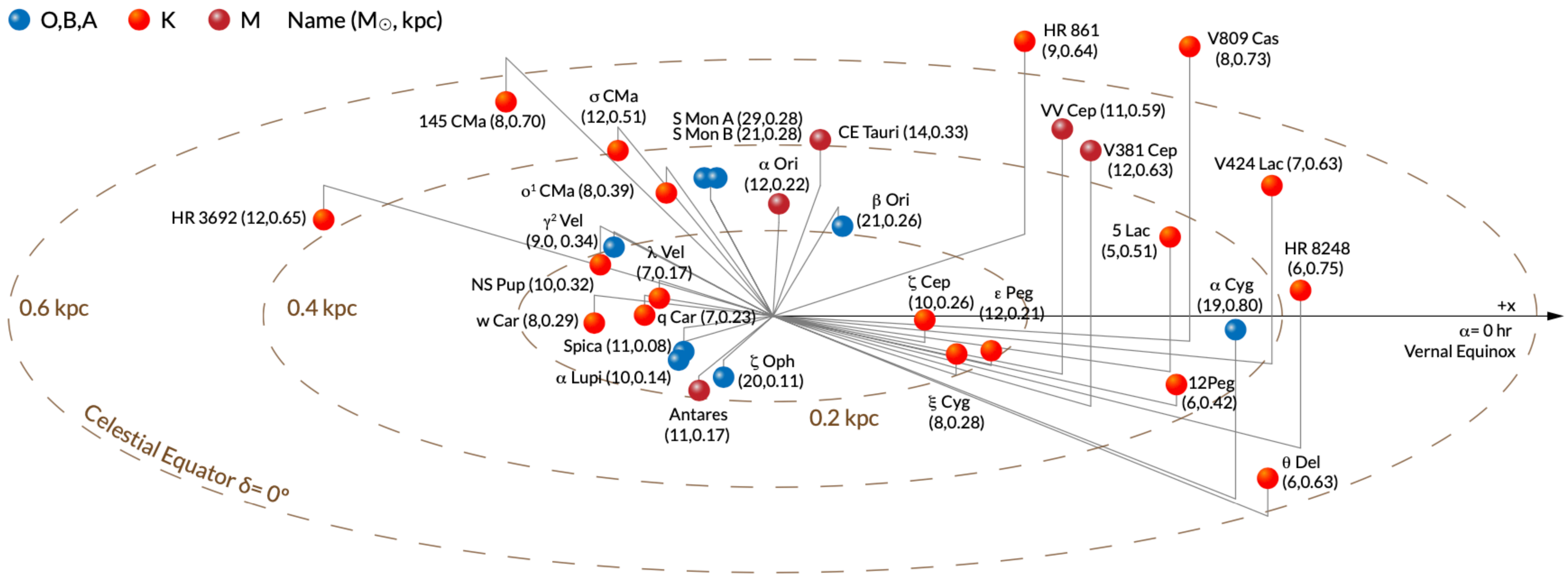
Adapted from: M. Mukhopadhyay, C. Lunardini, F.X. Timmes, K. Zuber, Astrophys.J. 899 (2020)

✴ Betelgeuse is 11.6° from S Monoceros A, B (~280 pc)

Where should we look ?

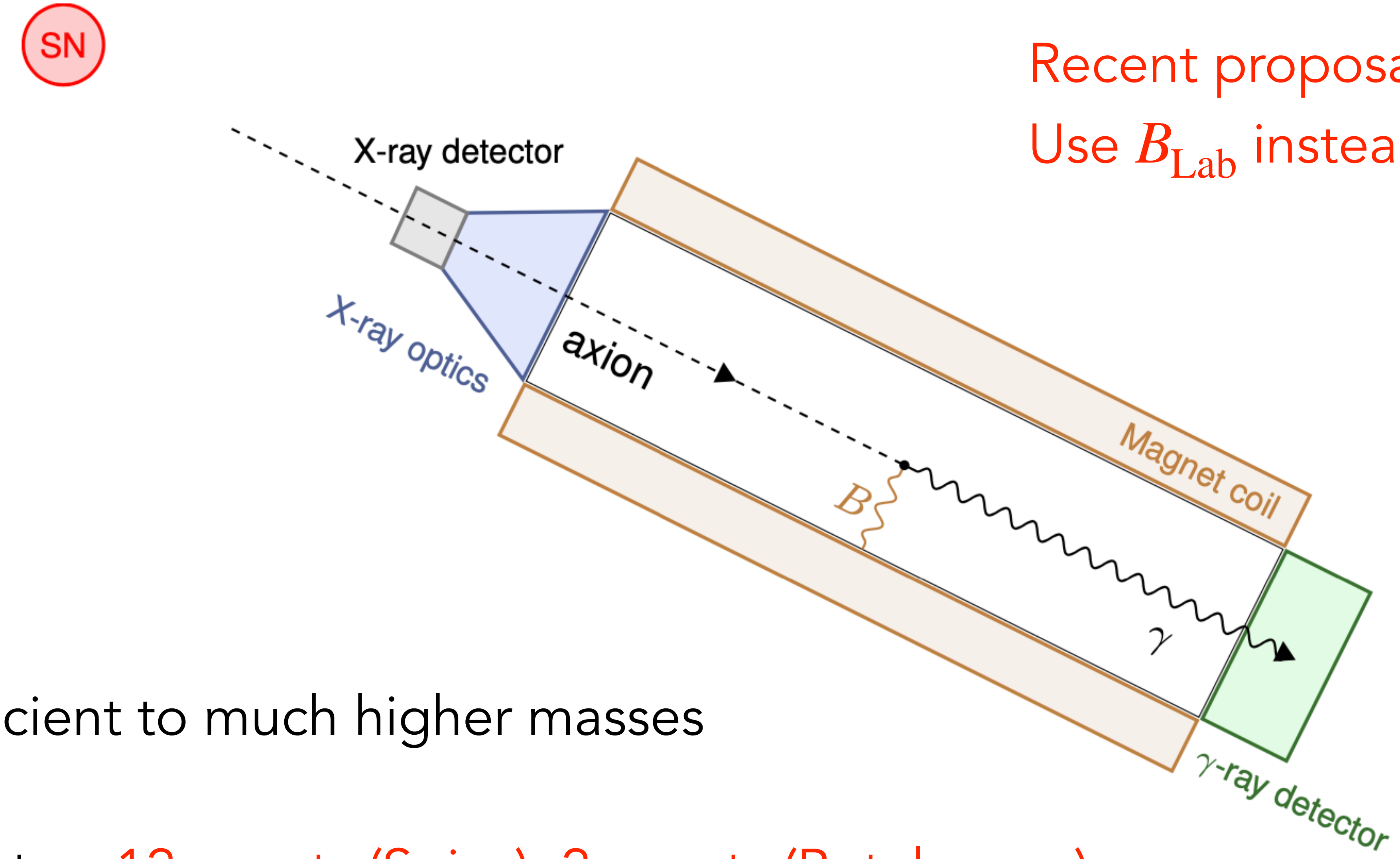
Very comprehensive recent analysis on identification of (near) SN from pre-SN neutrinos

M. Mukhopadhyay, C. Lunardini, F.X. Timmes, K. Zuber, Astrophys.J. 899 (2020)



31 candidates within 1 kpc from the sun.

Helioscopes as Axion SN-Scopes



Recent proposal.

Use B_{Lab} instead of B_{galactic}

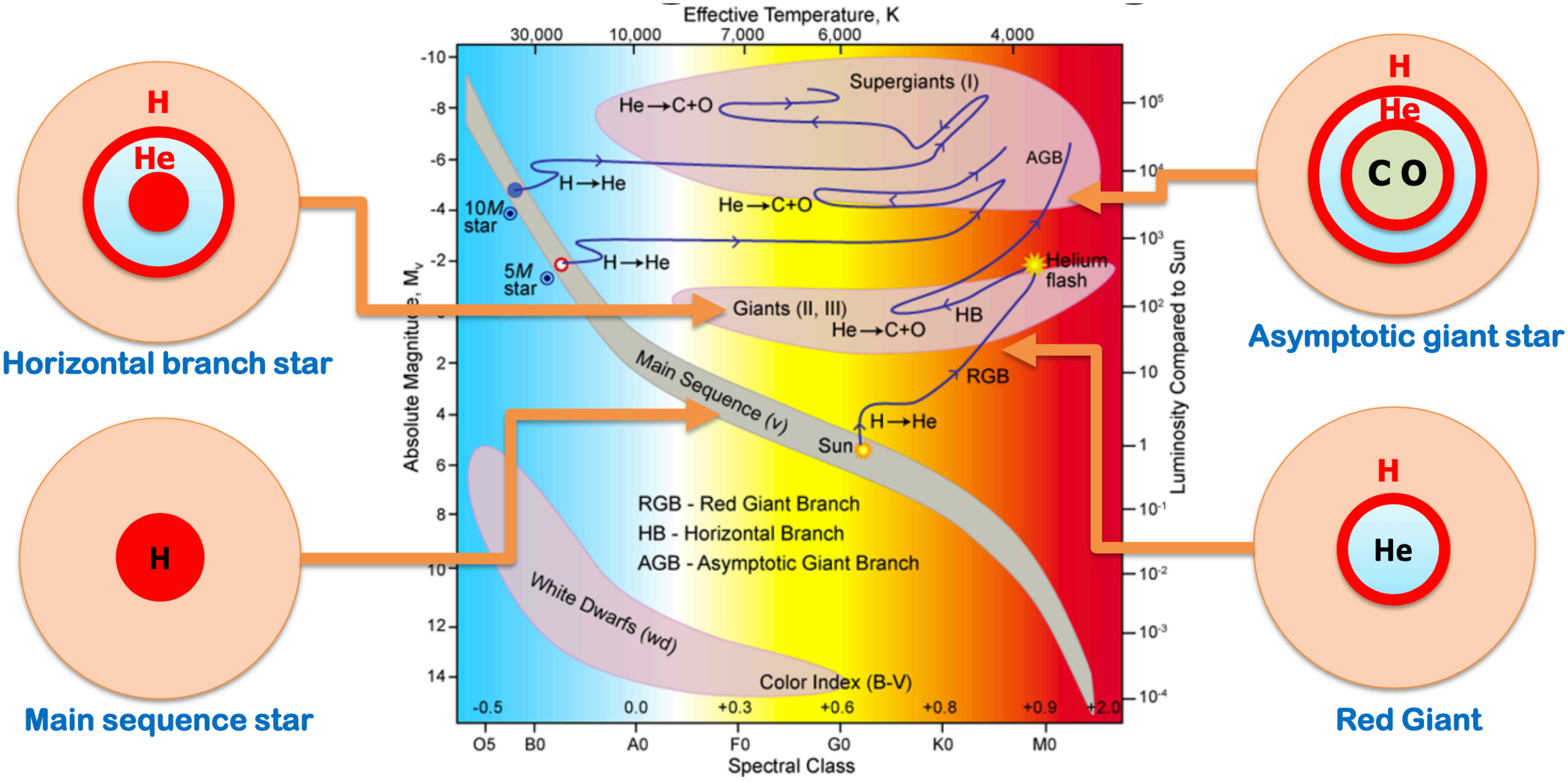
Axion helioscope
turned around

Efficient to much higher masses

Up to ~12 events (Spica), 2 events (Betelgeuse)
with BabyIAXO setup

Ge, Hamaguchi, Ichimura, Ishidoshiro, Kanazawa (2020) [arXiv:2008.03924]

Color Magnitude Diagram



Horizontal branch star

Main sequence star

Asymptotic giant star

Red Giant