Next Frontiers in the Search for Dark Matter
GGI, Florence, 23-27 September 2019

ASTROPHYSICAL AXION BOUNDS/HINTS

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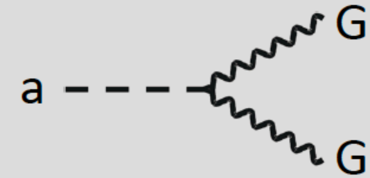
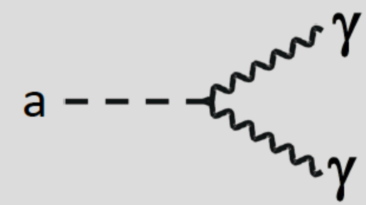
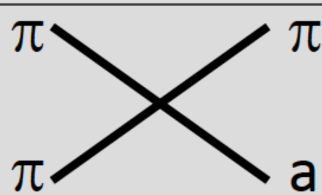
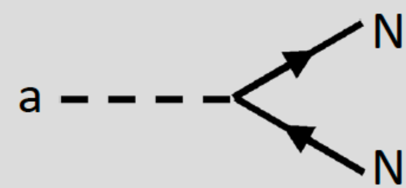
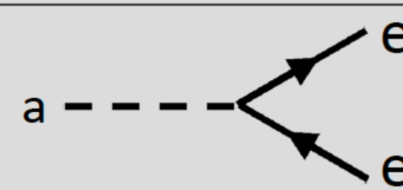
OUTLINE

- Axion interactions and models
- Energy-loss arguments
- Axion bounds and hints from normal stars (GC, WD)
- Revisiting the SN 1987A axion bound
- Conclusions

AXION PROPERTIES

Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} \, G\tilde{G}a$	
Mass (generic)	$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d} \frac{m_\pi}{f_\pi f_a} \approx \frac{6\ \mu\text{eV}}{f_a/10^{12}\ \text{GeV}}$	
Photon coupling	$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	
Pion coupling	$\mathcal{L}_{a\pi} = \frac{C_{a\pi}}{f_\pi f_a}\left(\pi^0\pi^+\partial_\mu\pi^- + \cdots\right)\partial^\mu a$	
Nucleon coupling (axial vector)	$\mathcal{L}_{aN} = \frac{C_N}{2f_a} \overline{\Psi}_N \gamma^\mu \gamma_5 \Psi_N \partial_\mu a$	
Electron coupling (optional)	$\mathcal{L}_{ae} = \frac{C_e}{2f_a} \overline{\Psi}_e \gamma^\mu \gamma_5 \Psi_e \partial_\mu a$	

MAIN AXION MODELS

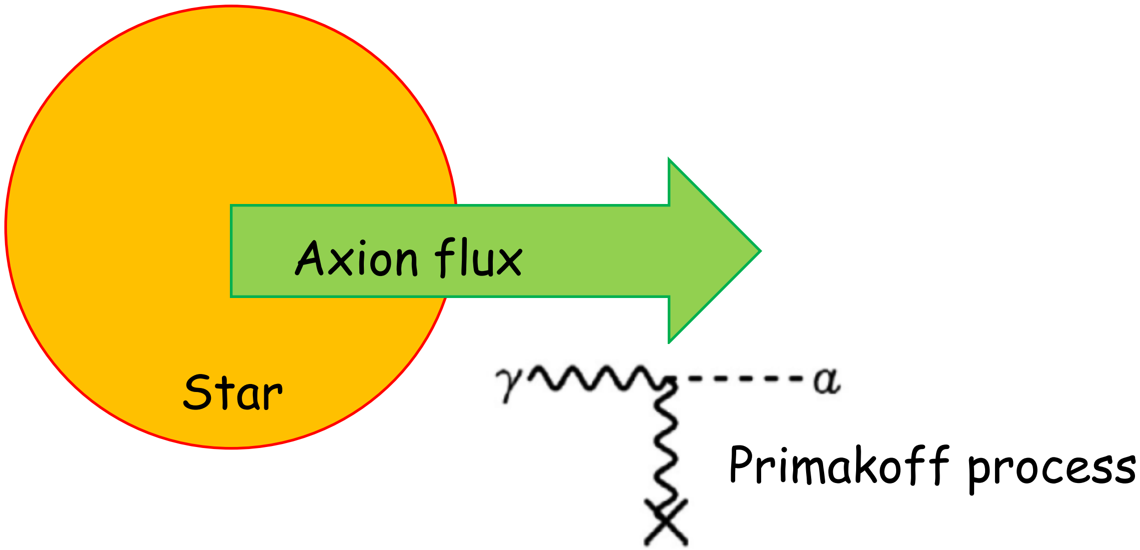
- DFSZ (Dine, Fischler, Srednicki, Zhitniskii) model

  ✓ Axions coupling to fermions and photons

- KSVZ (Kim, Shifman, Vainshetein, Zakharov) model (hadronic axions)

  ✓ tree-level coupling to quarks and leptons suppressed
  ✓ Nucleon and photon couplings still possible
  ✓ Evades bounds of DFSZ model

ENERGY-LOSS ARGUMENT

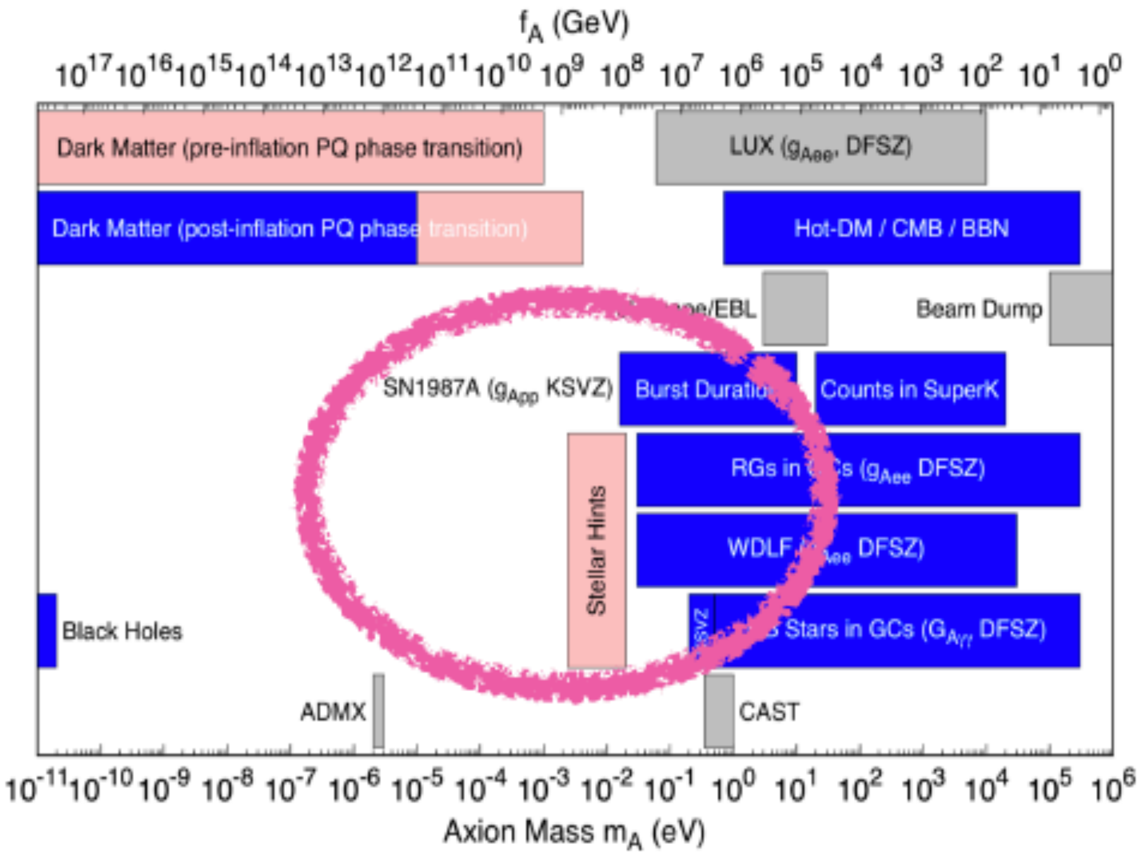


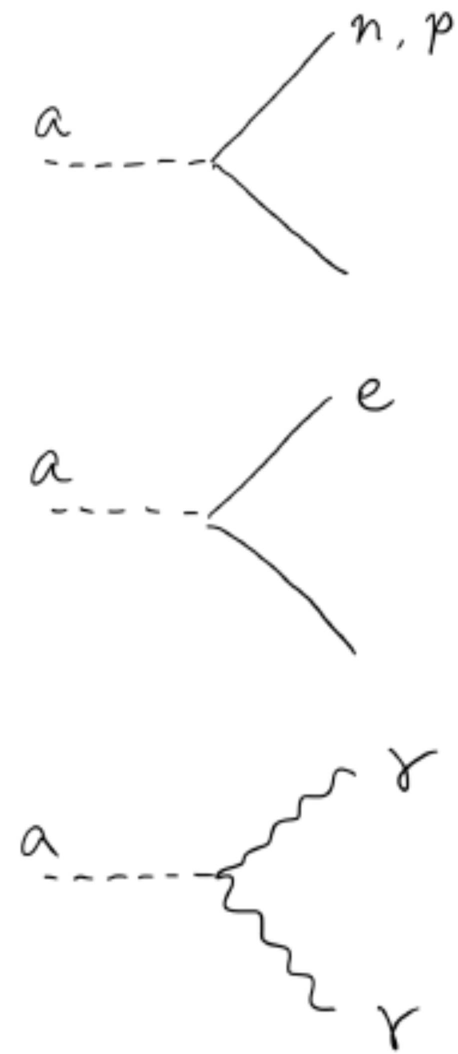
- Axions have very small mass
- Emission from stellar plasma not suppressed by threshold effect
- New energy-loss channel
- Back-reaction on stellar properties and evolution

Additional energy loss ("cooling")

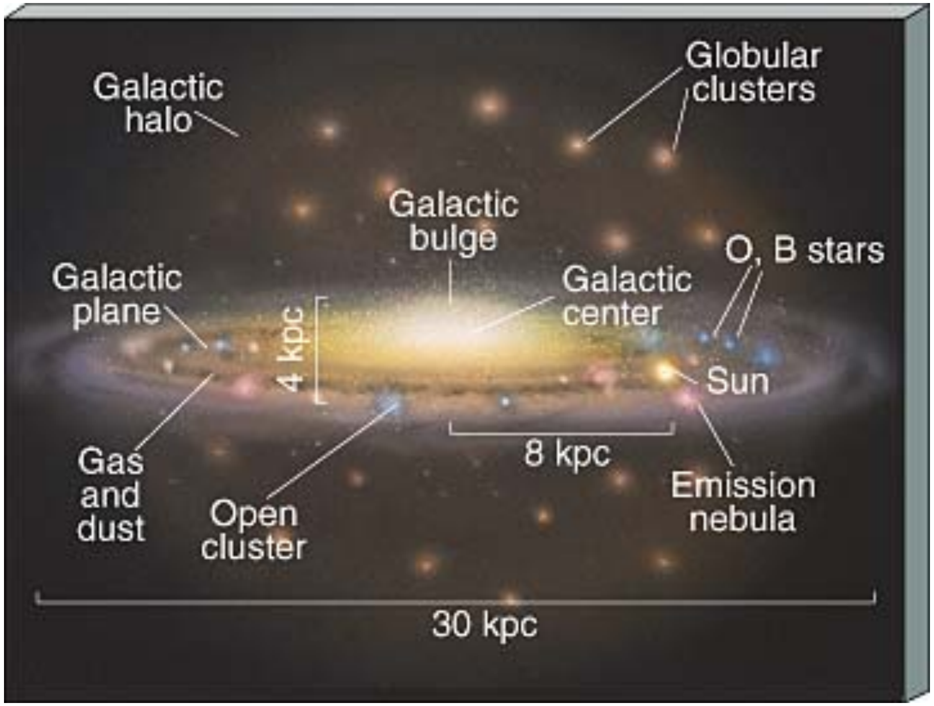
- Loss of pressure
- Contraction
- Heating
- Increased nuclear burning

$$\mathcal{O}(10^8)\ \mathrm{GeV} < f_a < \mathcal{O}(10^{12})\ \mathrm{GeV}$$



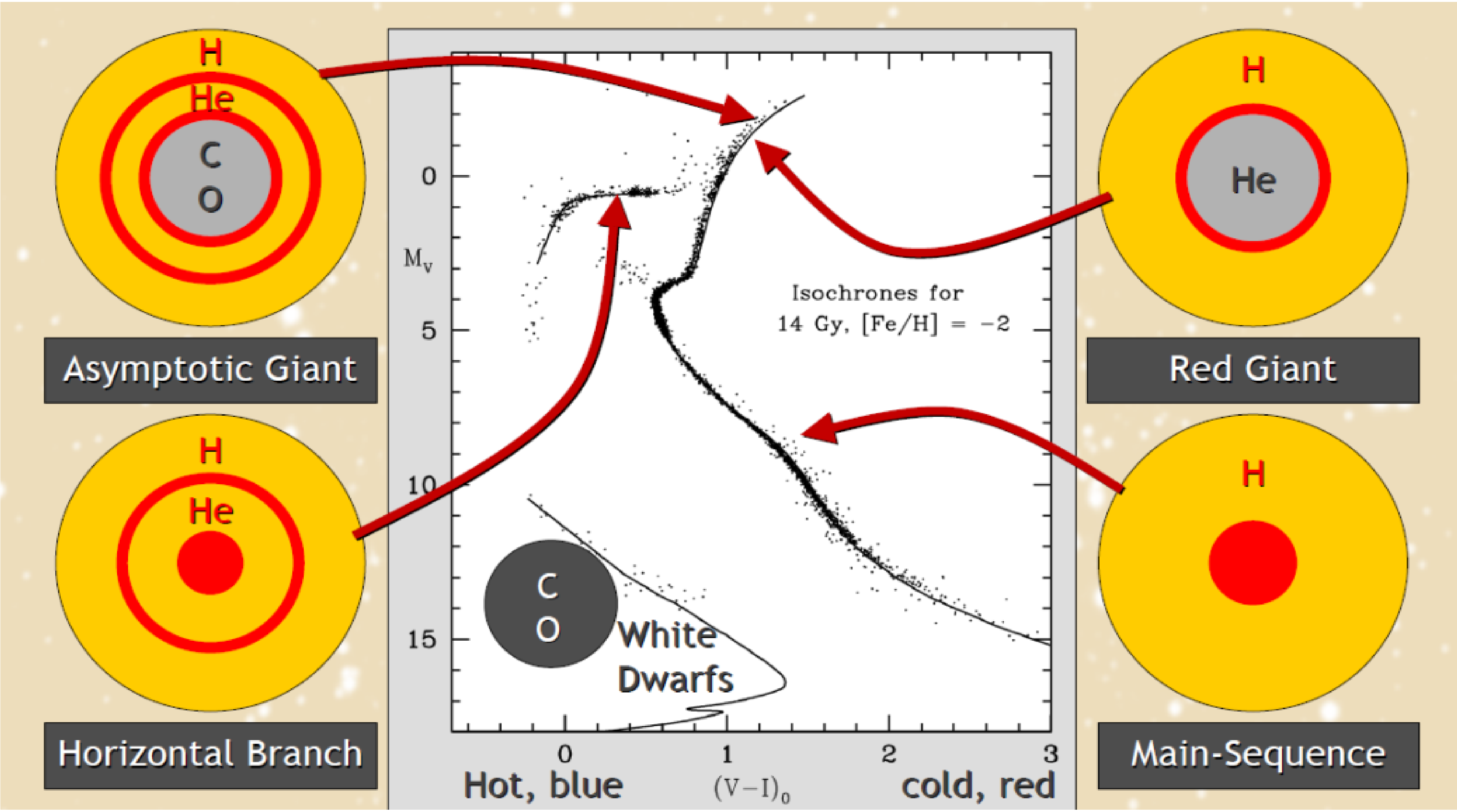


GLOBULAR CLUSTERS



- Globular clusters are gravitationally bound associations of typically 10^6 stars
- The low metallicity is one indicator for their great age
- All stars in a given cluster are coeval; they differ only in their mass

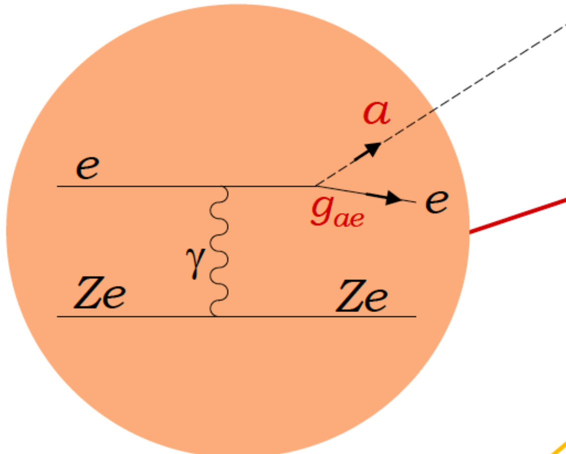
COLOR MAGNITUDE DIAGRAM FOR GLOBULAR CLUSTER



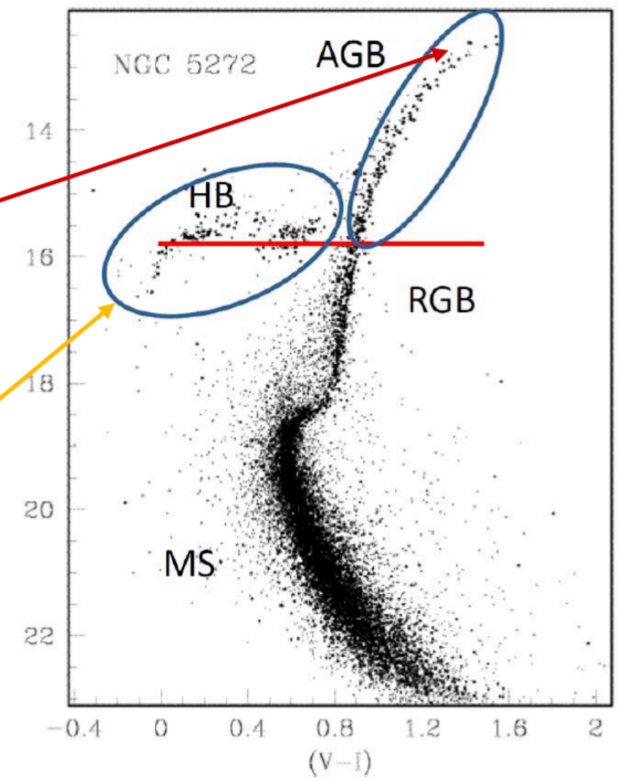
The color-magnitude diagram of a globular cluster represents an "isochrone" of a stellar population. Locus of coeval stars with different initial masses.

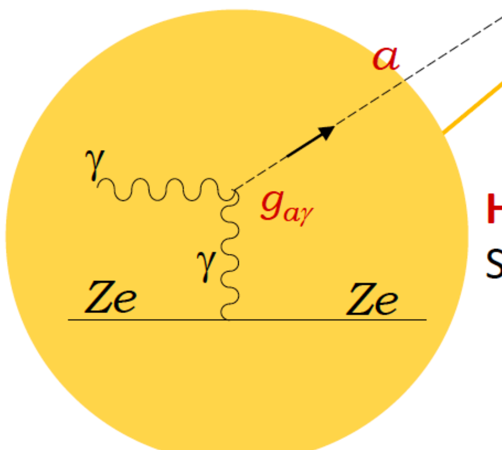
SENSITIVITY TO AXION EMISSION

$R = N_{HB}/N_{RG}$



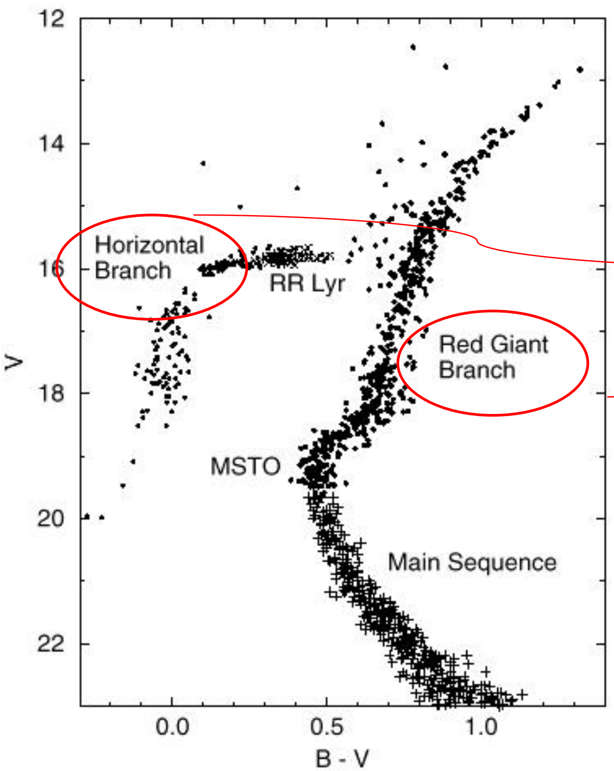
RGB: Very dense.
Sensitive to g_{ae}

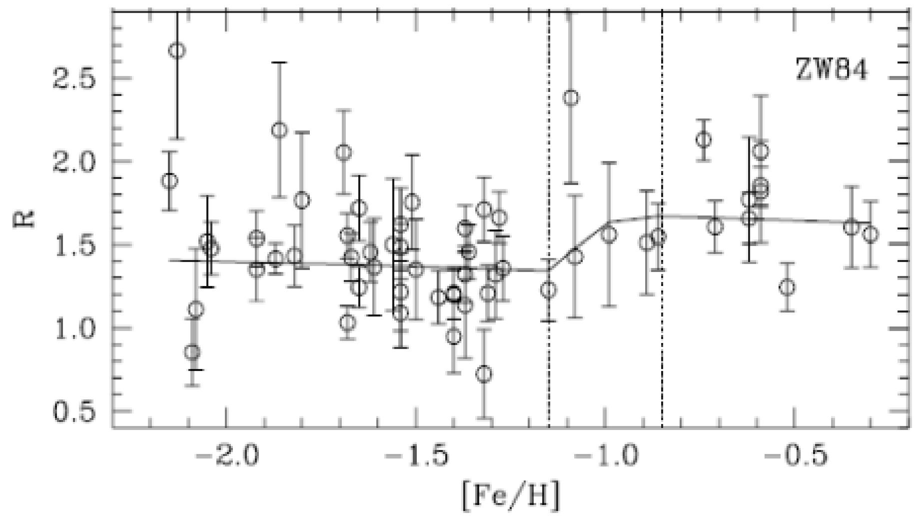




HB: Not very dense.
Sensitive to $g_{a\gamma}$

HELIUM BURNING LIFETIME OF HB STARS





[Salaris et al., astro-ph/0403600]
57 GCs

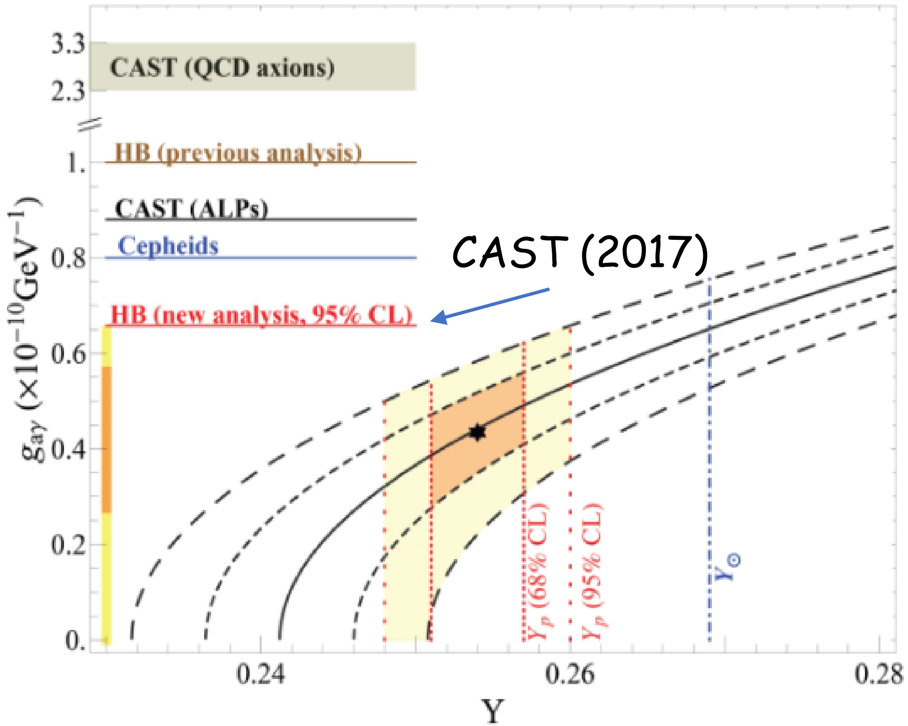
$$R = \frac{N_{HB}}{N_{RGB}}$$

Well reproduced, within 30 %, by models of GC without axions

Axions would reduce the lifetime of stars in HB, while producing negligible change in RGB evolution (Primakoff rate suppressed in degenerate RGB core).
[Raffelt & Deaborn, PRD 36, 2211 (1987)]

NEW AXION BOUND FROM HB

[*Ayala, Dominguez, Giannotti, A.M., Straniero, 1406.6053*]



Helium abundance and energy loss rate from modern number counts HB/RGB in 39 globular clusters

Taking as benchmark the direct determination of Helium fraction by Izotov et al. (1308.2100) Y_p=0.254±0.003 we find

$$g_{a\gamma} < 0.66 \times 10^{-10} GeV^{-1} \quad (95\ \%\ CL)$$

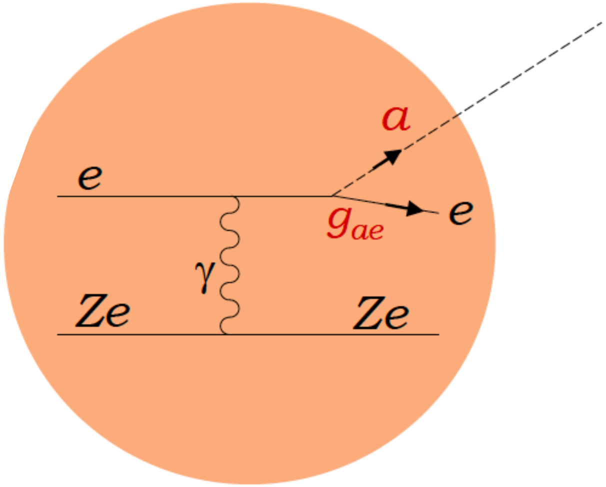
The strongest bound on $g_{a\gamma}$ comparable with CAST one

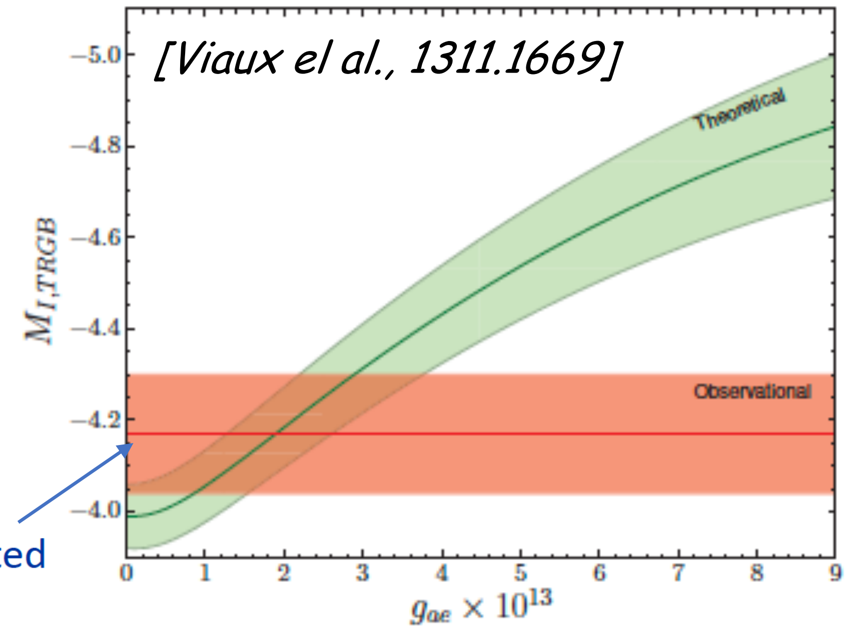
RED GIANT COOLING

Particle emission delays He ignition, i.e. core mass increased

A particularly useful observable is the brightness of the tip of the RG branch.
Additional cooling would give rise to a brighter RGB tip

RGB: Very dense. Sensitive to g_{ae}

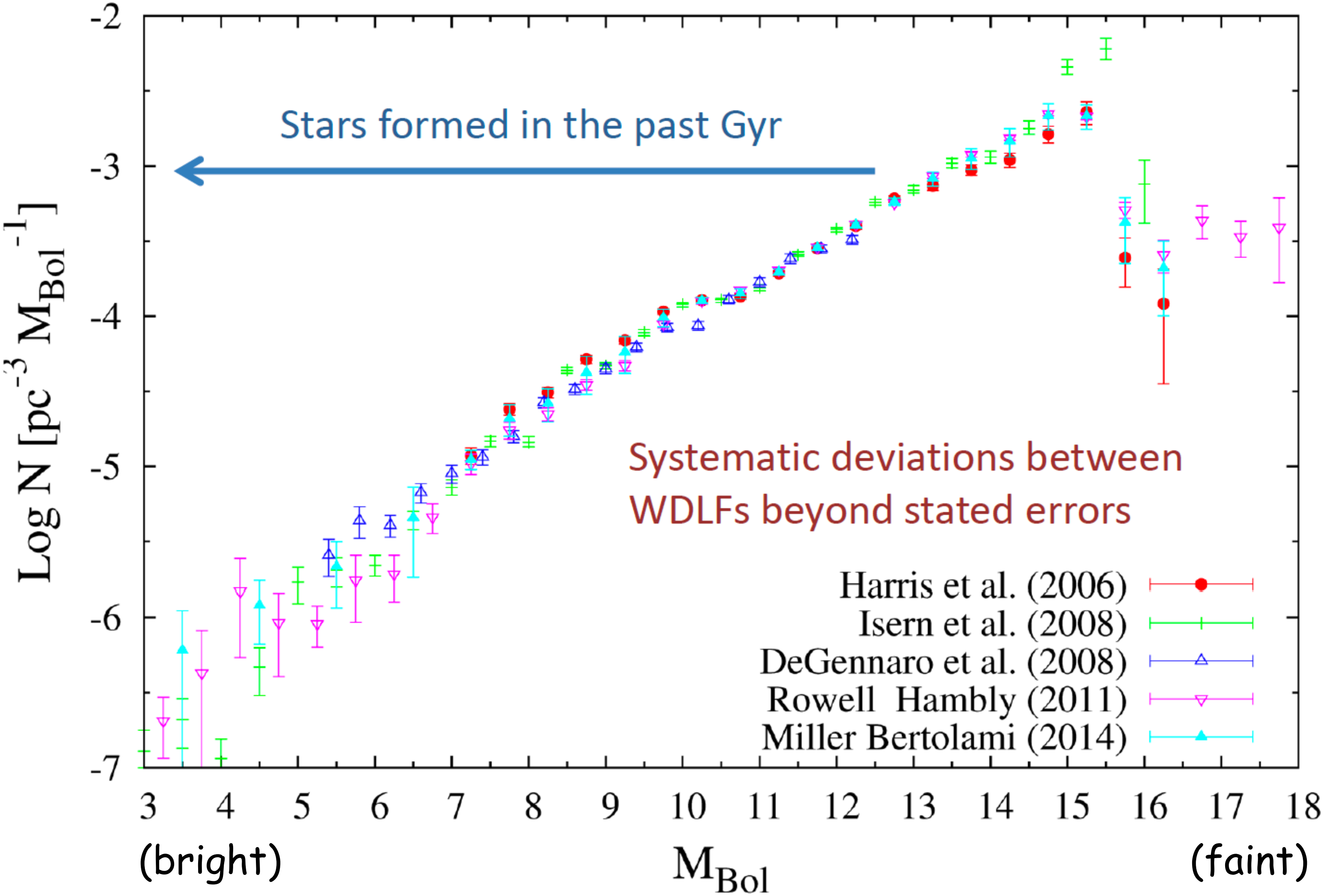




- Uncertainty dominated by distance
- Can be improved in future (GAIA mission)

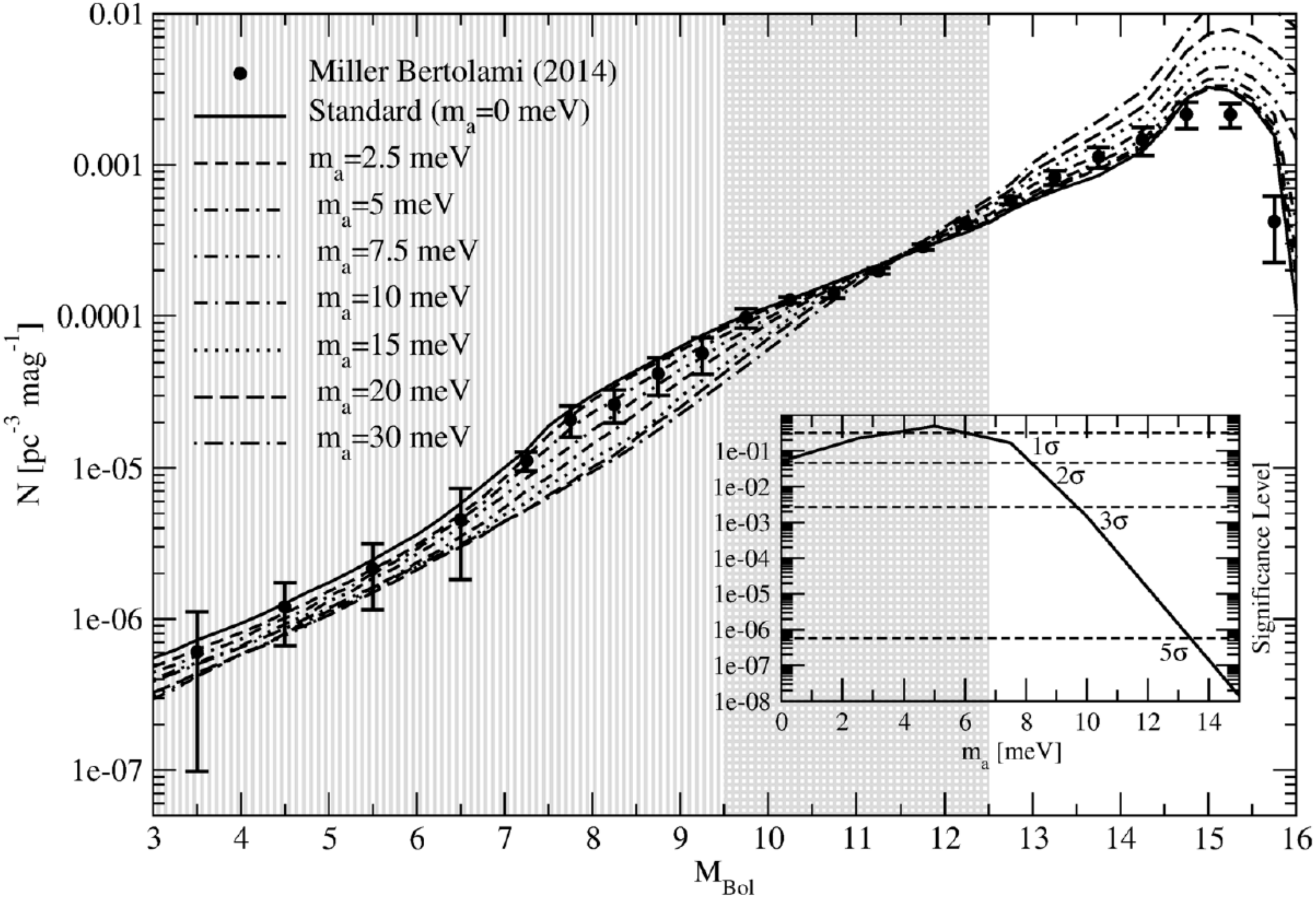
$$g_{ae} < 4.3 \times 10^{-13}$$

WHITE DWARF LUMINOSITY FUNCTION



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

AXION BOUNDS FROM WD LUMINOSITY FUNCTION



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

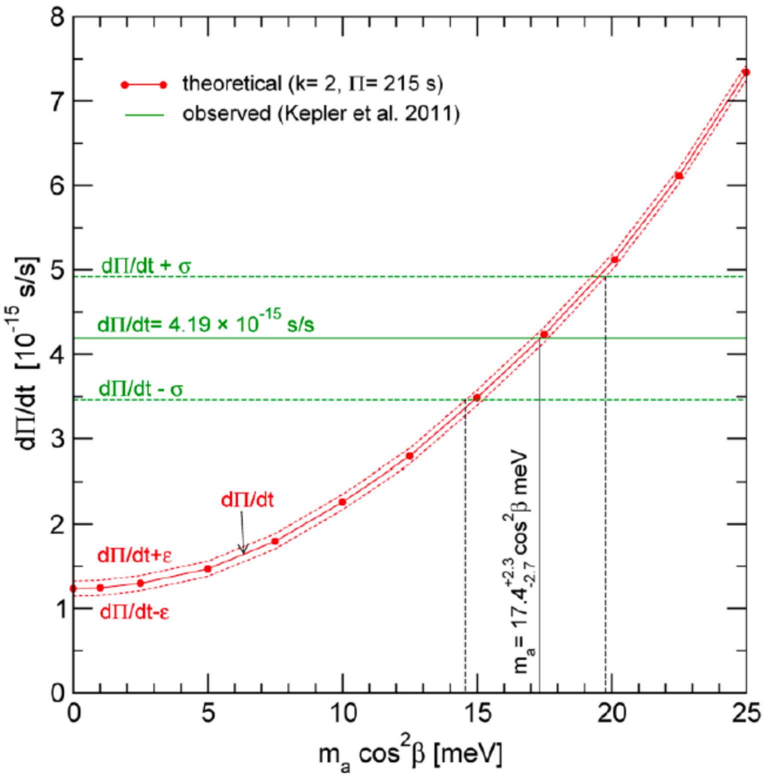
$g_{ae} \lesssim 3 \times 10^{-13}$ $\qquad$ $m_a \cos^2\beta \lesssim 10$ meV

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

WHITE DWARF PULSATING PERIOD

Period change $\dot{\Pi}$ of pulsating white darfs depends on cooling speed

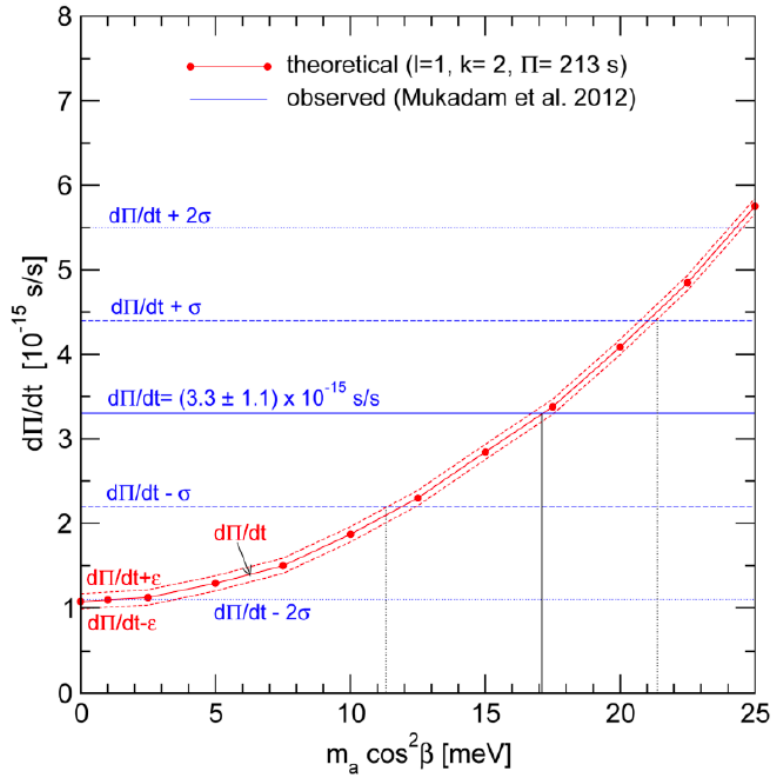
White dwarf G117−B15A



Favored by $\dot{\Pi}$

Córsico et al., arXiv:1205.6180

White dwarf R548



Favored by $\dot{\Pi}$

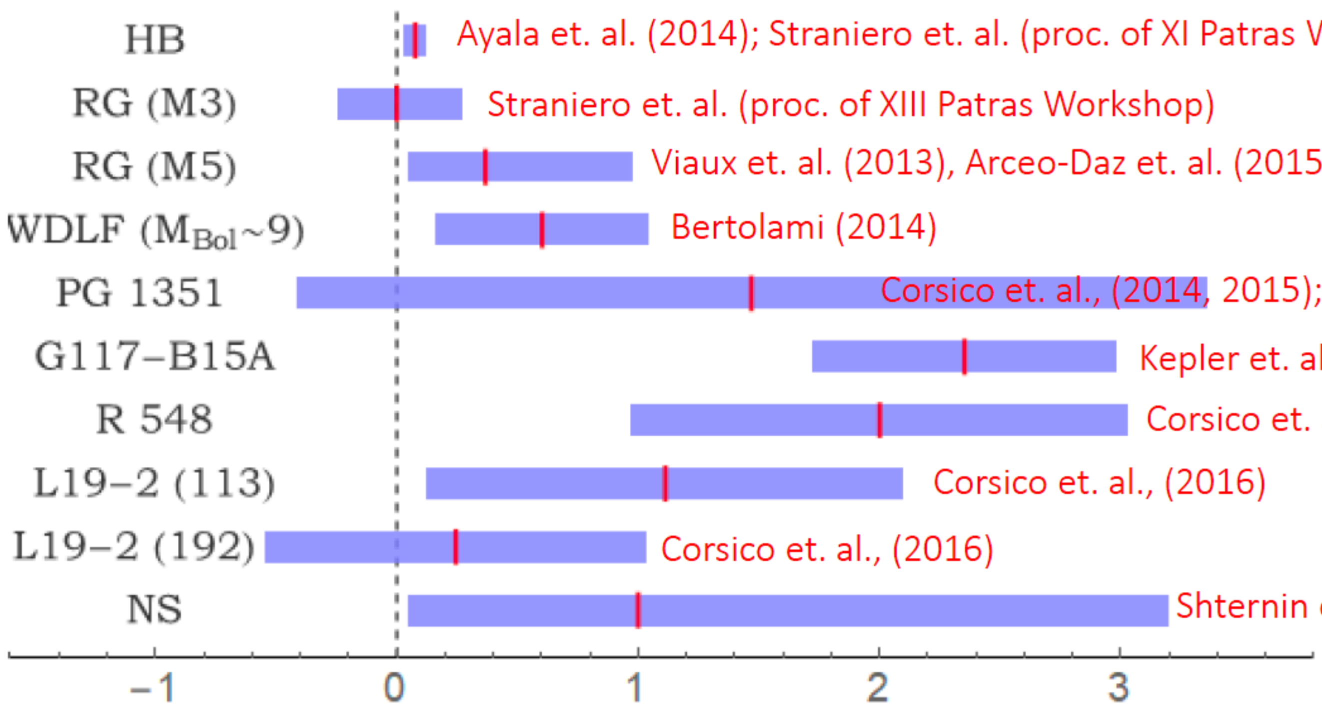
Córsico et al., arXiv:1211.3389

….sont dans les détails

HINTS OF NEW PHYSICS?

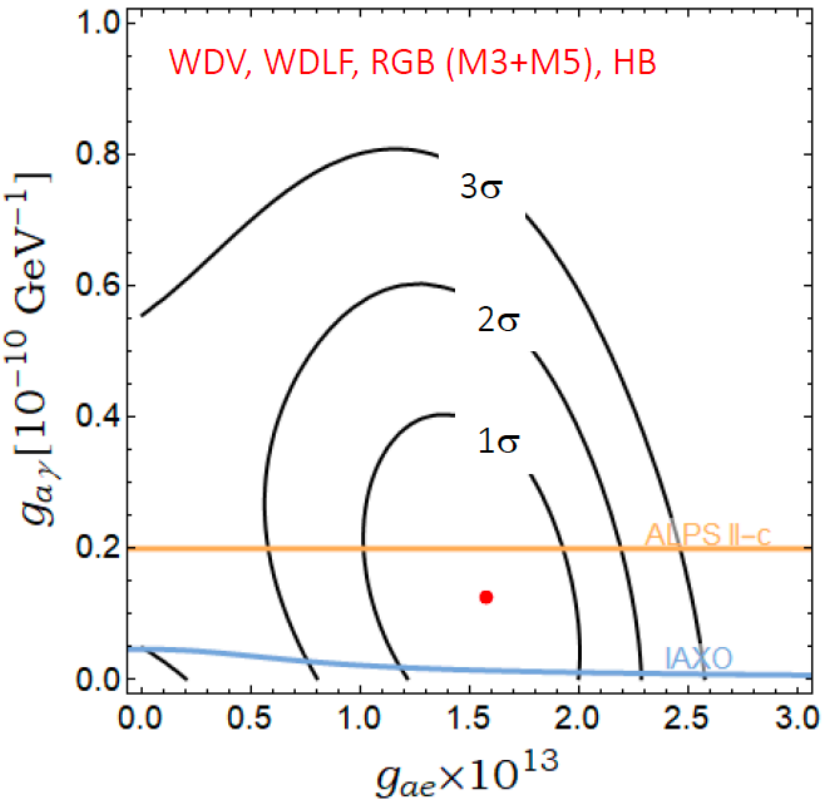
Several stellar systems seem to be cooling faster than predicted by the models *[Giannotti et al., 1512.08108]*, perhaps hinting to new physics

Though these hints should be taken carefully, they could show a systematic problem in our understanding of stellar evolution



ALP INTERPRETATION

Stellar cooling shows a mild preference for a small coupling to photons and electrons



[Giannotti el al., 1708.02111]

Best fit

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

$$g_{a\gamma} = 0.12\times 10^{-10}\,\mathrm{GeV}^{-1}$$

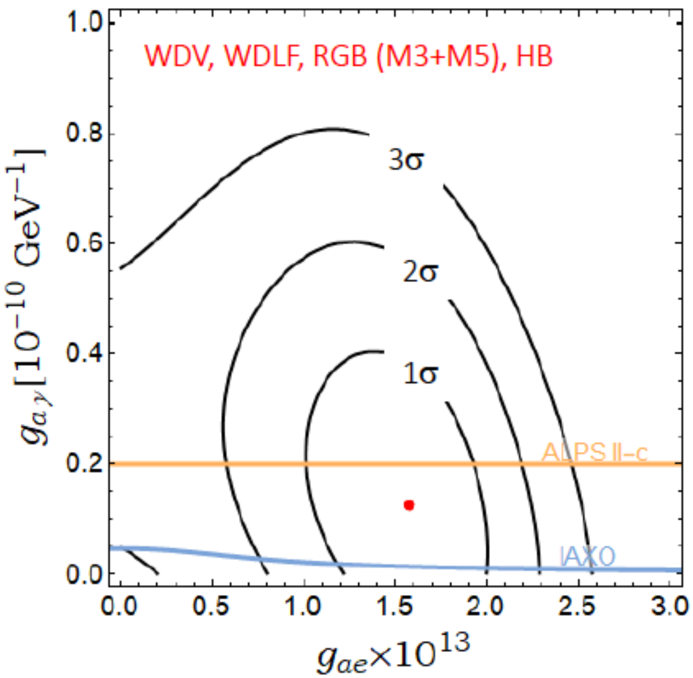
$$g_{ae} = m_e \frac{C_{ae}}{f_a} \qquad g_{a\gamma} = \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a}$$

best fit corresponds to:

$$\frac{C_{ae}}{C_{a\gamma}} \approx 2.7\times 10^{-2}$$

ALP interpretation

Stellar cooling shows a mild preference for a small coupling to photons and electrons



M.G., I. Irastorza, J. Redondo, A. Ringwald, K. Saikawa, JCAP **1710** (2017)

For the DFSZ I (II) model, this means a preference for a small (large) tan β

DFSZ I: $C_e = \frac{\cos^2\beta}{3};\ C_{a\gamma} = \frac{8}{3} - 1.92$

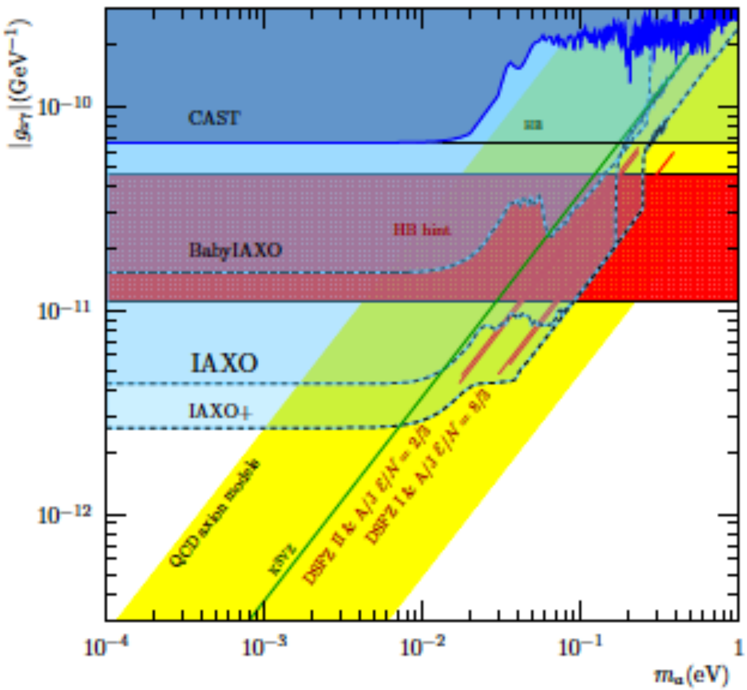
DFSZ II: $C_e = \frac{\sin^2\beta}{3};\ C_{a\gamma} = \frac{2}{3} - 1.92$

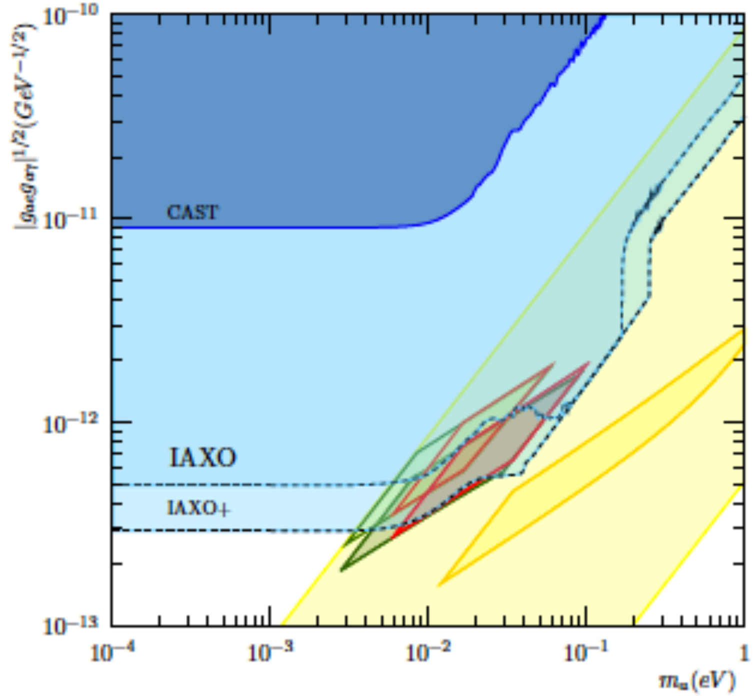
Both DFSZ I and II explain fairly well the combined observations

$\chi^2_{min}/\mathrm{d.o.f.} \approx 1$

EXPERIMENTAL SENSITIVITY

[Armengaud et al., 1904.09155]

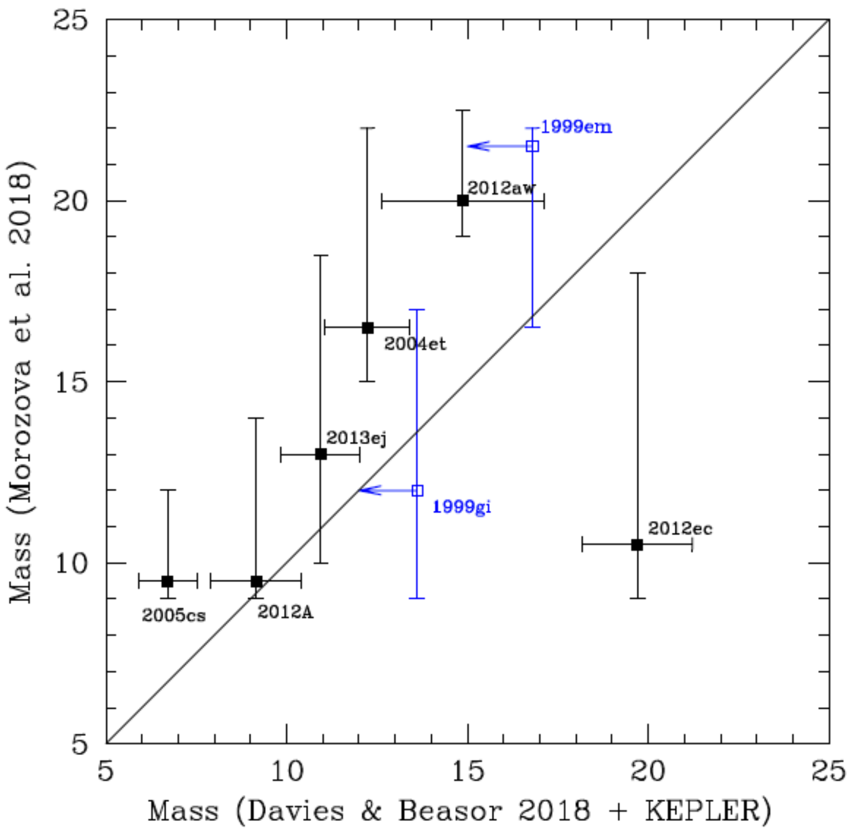




MASS AND LUMINOSITY OF TYPE II SN PROGENITOR

Extant estimates of the progenitor (initial) masses are based on:

- Pre-explosive luminosity
- Properties of the light-curves



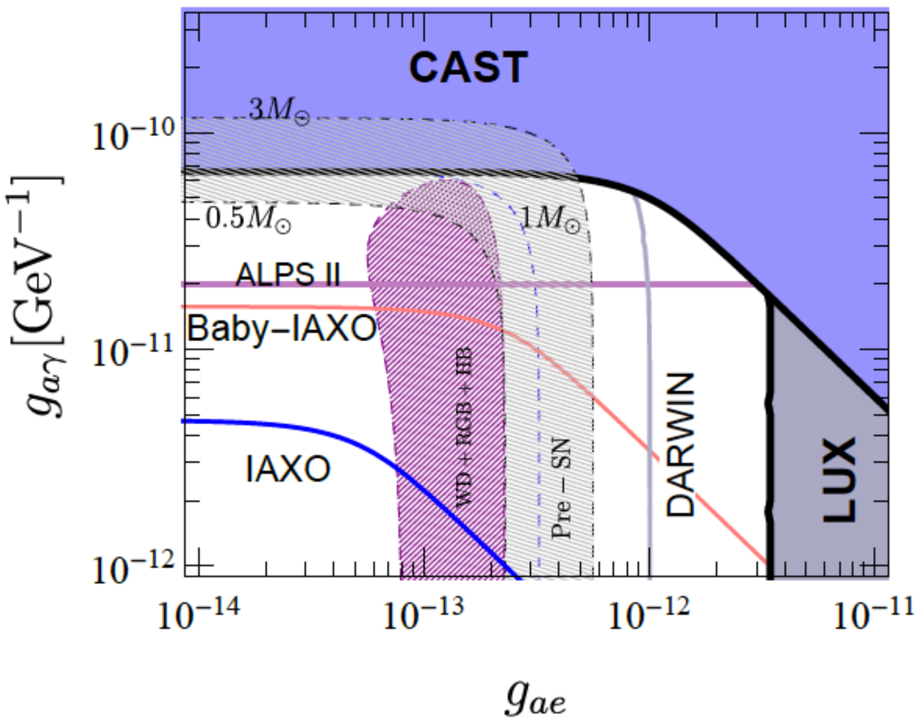
Excluding SN 2012ec, the masses estimated from the luminosity curves are $2.9 \pm 0.8\, M_{sun}$ higher than those derived from the progenitor luminosity!

Progenitors appear fainter than expected

NEW HINT OF AXIONS?

[Straniero, Dominguez, Piersanti, Giannotti, A.M., 1907.06367]

Fainter progenitor might point to an additional energy loss channel on top of neutrinos



Axions may account for the missing contribution to the stellar energy-loss

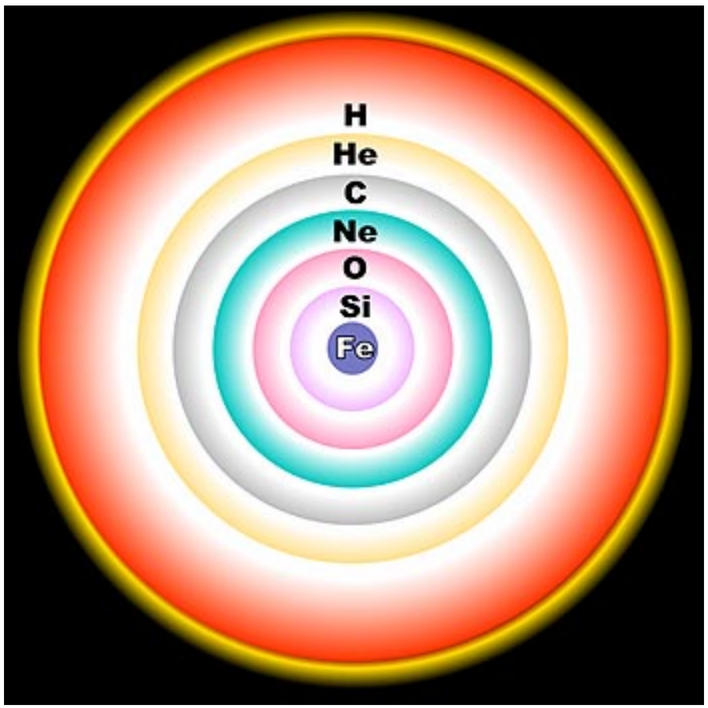
SUPERNOVAE

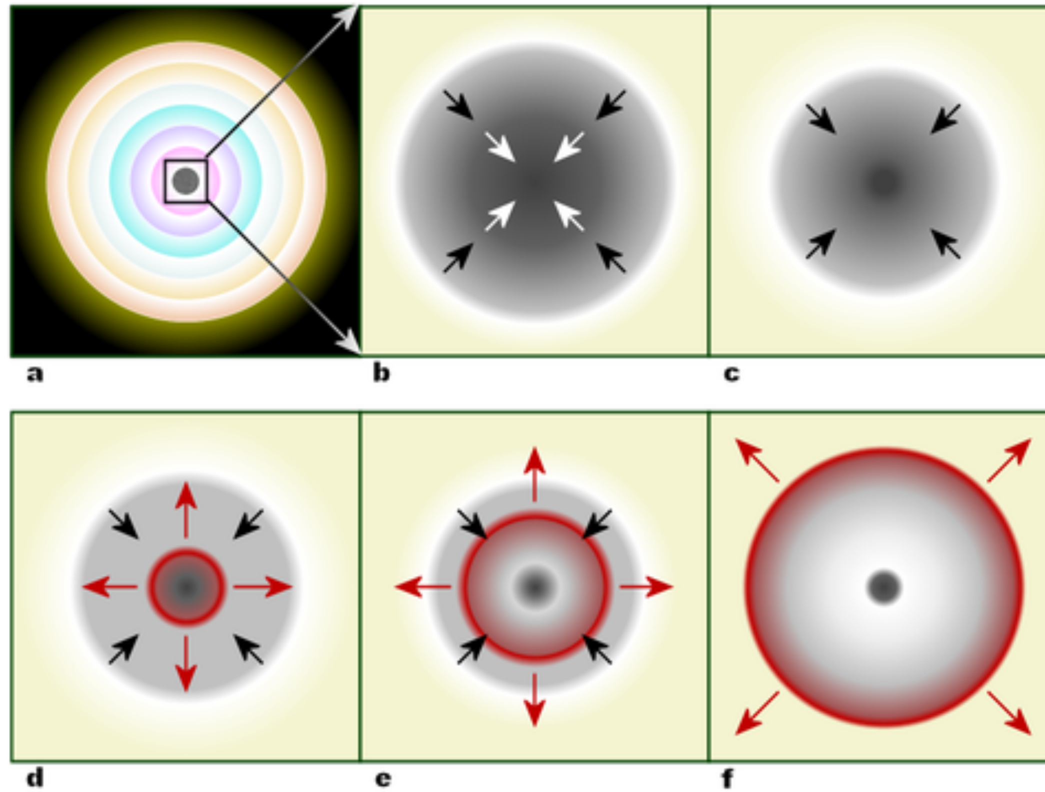
Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8\, M_\odot$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.

- **ENERGY SCALES:** 99% of the released energy (~ 10^{53} erg) is emitted by ν and $\bar{\nu}$ of all flavors, with typical energies E ~ O(15 MeV).
- **TIME SCALES:** Neutrino emission lasts **~10 s**
- **EXPECTED:** **1-3 SN/century** in our galaxy (d ≈ $\mathcal{O}$(10) kpc).

LIFE AND DEATH OF A MASSIVE STAR

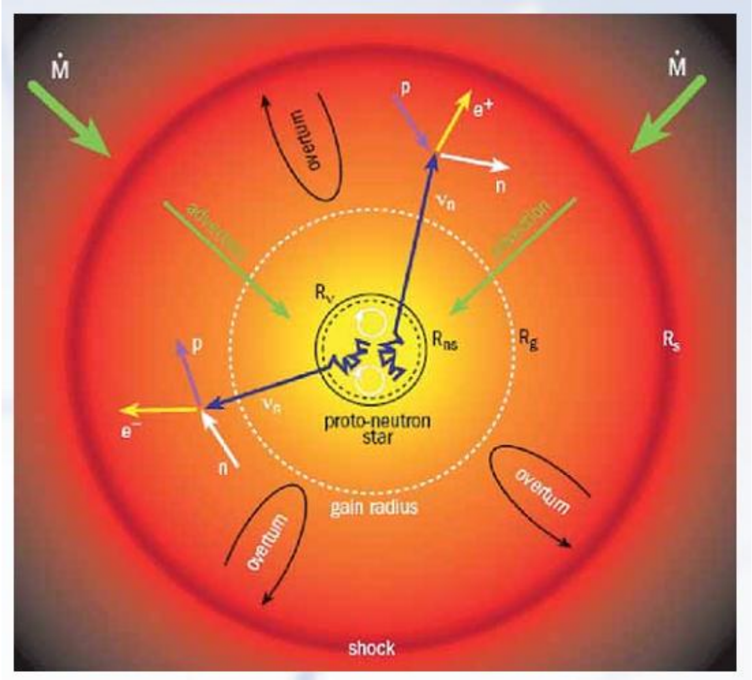
Onion-like layers of a massive, evolved star just before core collapse.





NEUTRINOS AND EXPLOSION MECHANISM

Paradigm: Explosions by the convectively supported neutrino-heating mechanism



- "Neutrino-heating mechanism": Neutrinos "revive" stalled shock by energy deposition *[Colgate & White, 1966, Wilson, 1982, Bethe & Wilson, 1985]*
- Convective processes & hydrodynamic instabilities enhance the heating mechanism *[Herant et al. 1992, 1994; Burrows et al. 1995, Janka & Müller 1994, 1996; Fryer & Warren 2002, 2004; Blondin et al. 2003; Scheck et al. 2004,06,08]*

THREE PHASES OF NEUTRINO EMISSION

[Figure adapted from *Fischer et al. (Basel group), arXiv: 0908.1871*]

10. 8 M_{sun} progenitor mass

(spherically symmetric with Boltzmnann ν transport)

Neutronization burst

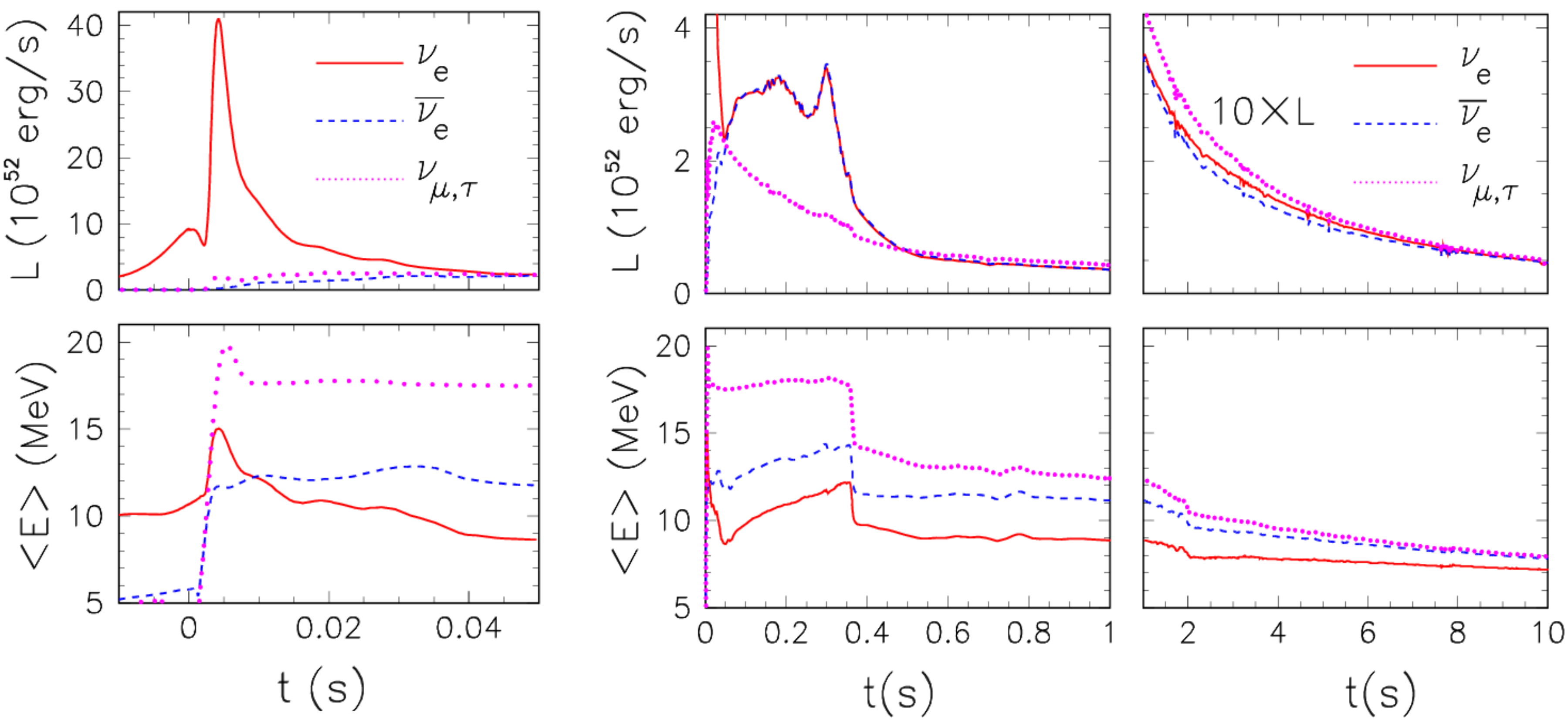
- Shock breakout
- De-leptonization of outer core layers

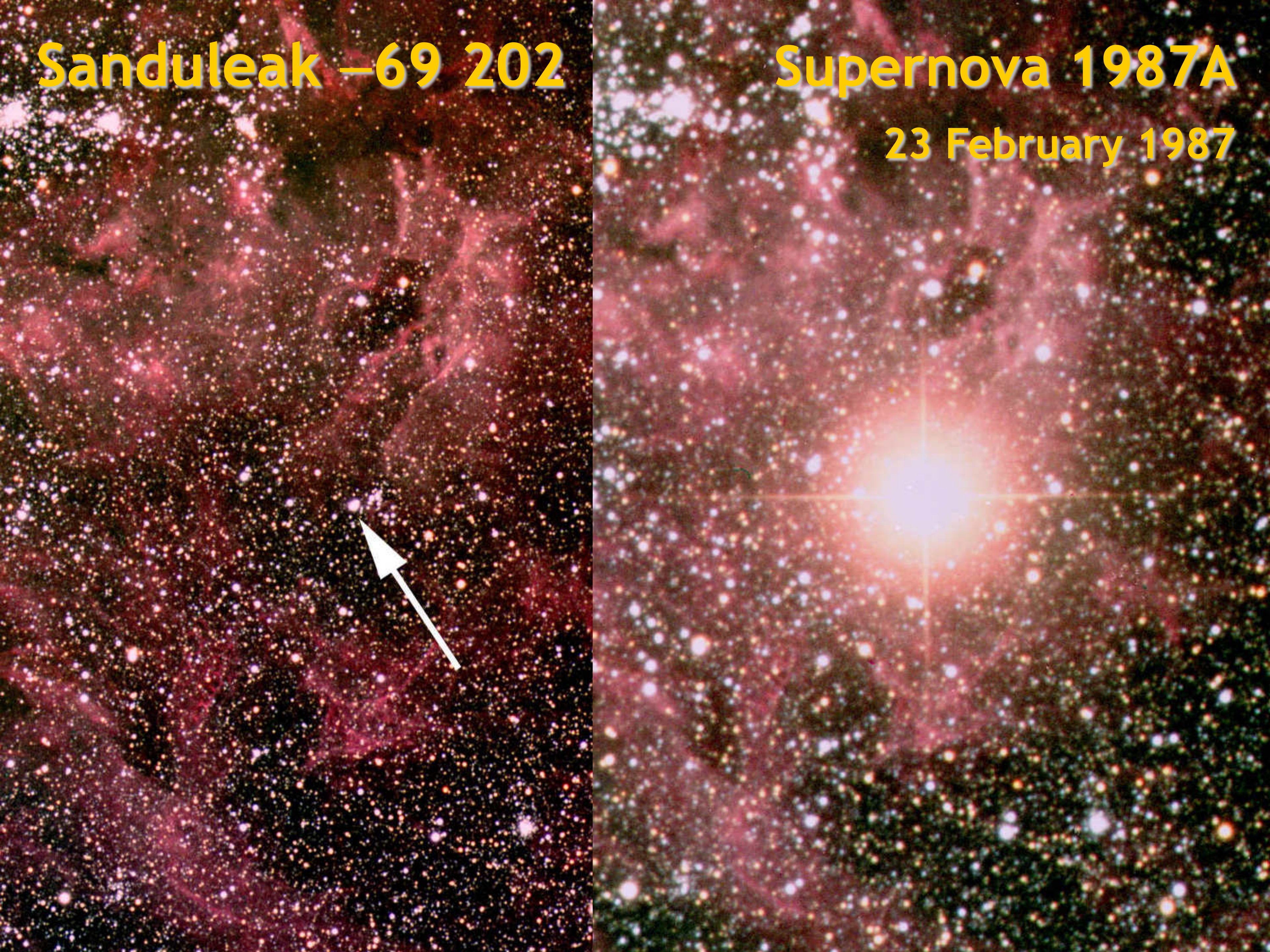
Accretion

- Shock stalls ~ 150 km
- ν powered by infalling matter

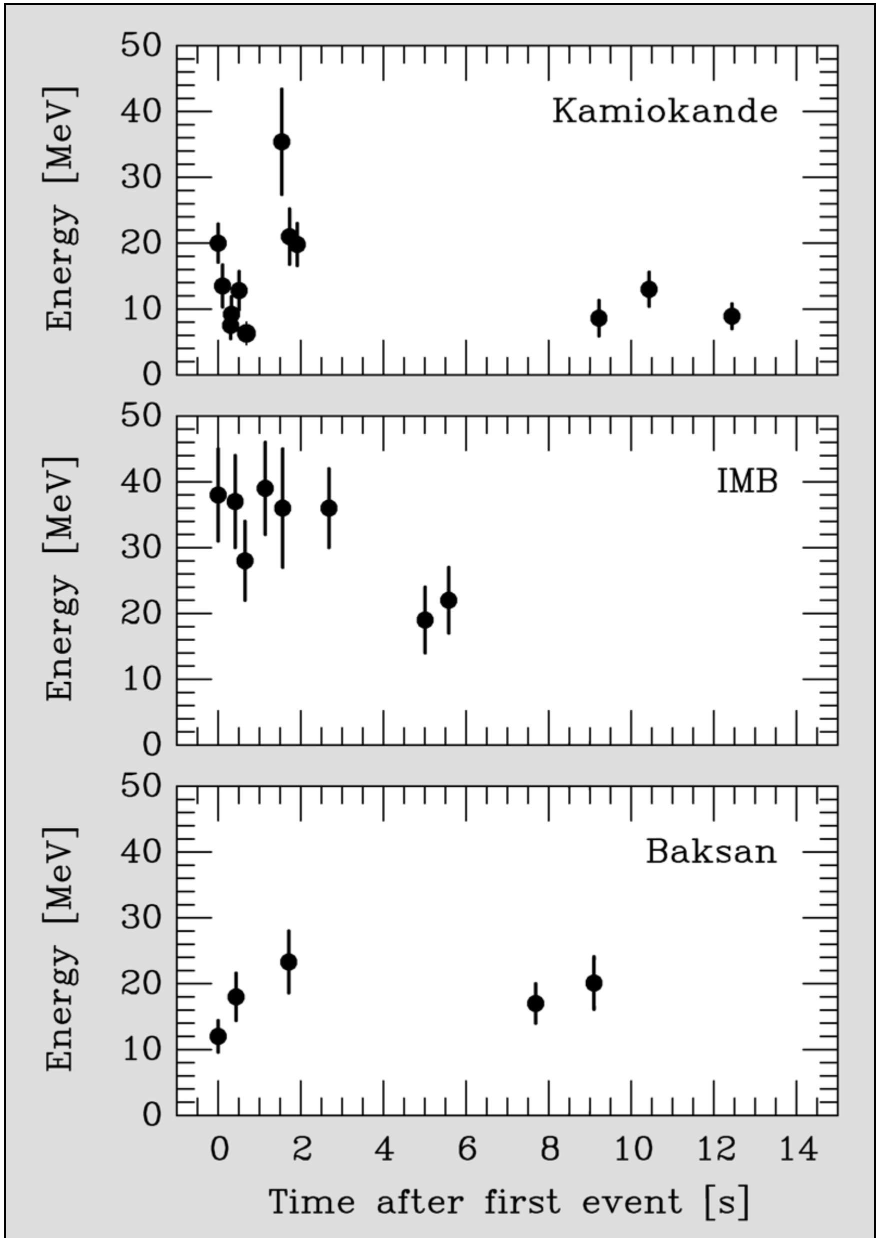
Cooling

- Cooling on ν diffusion time scale




Sanduleak −69 202
Supernova 1987A
23 February 1987

NEUTRINO SIGNAL OF SUPERNOVA 1987A



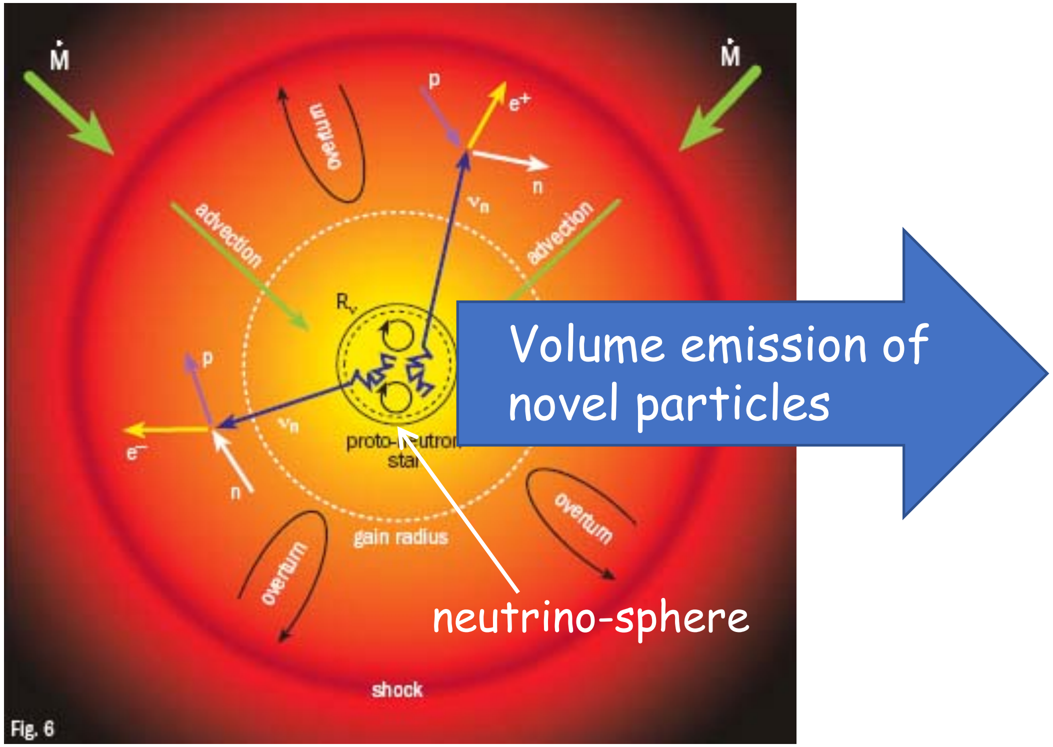
Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties,
signals are contemporaneous

ENERGY-LOSS ARGUMENT



Emission of very weakly interacting particles would "steal" energy from the neutrino burst and shorten it.

Assuming that the SN 1987A neutrino burst was not shortened by more than ~½ leads to an approximate requirement on a novel energy-loss rate of

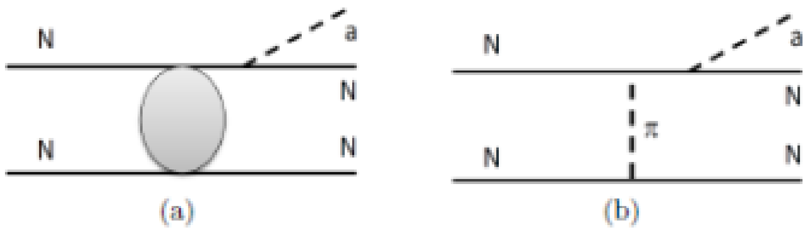
$$\varepsilon_X < 10^{19}\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

for $\rho \approx 3 \times 10^{14}$ g cm^{-3} and $T \approx 30$ MeV

AXION EMISSION FROM A NUCLEAR MEDIUM

$$NN \to NNa$$

nucleon-nucleon bremsstrahlung



Bulk nuclear interaction   One pion exchange

$$L_{aN} = \frac{g_{aN}}{2m_N} \bar{N} \gamma_\mu \gamma_5 N \partial^\mu a$$

$$g_{aN} = C_N \frac{m}{f_a}$$

Non-degenerate energy-loss rate $\varepsilon_a = g_{aN}^2 \, 2 \times 10^{39} \, \mathrm{erg\,g^{-1}\,s^{-1}} \rho_{15} T_{30}^{3.5}$

$$\begin{pmatrix} T_{30} = T / 30 \, \mathrm{MeV} \\ \rho_{15} = \rho / 10^{15} \, \mathrm{g\,cm^{-3}} \end{pmatrix}$$

$$\langle \rho_{15} \rangle \approx 0.4$$

$$\langle T_{30}^{3.5} \rangle \approx 1.4$$

$$\Rightarrow \quad g_{aN} < 9 \times 10^{-10}$$

RELAXING SN 1987A AXION LIMITS

[Chang, Essig & Mc Dermatt, arXiv: 1803.00993]

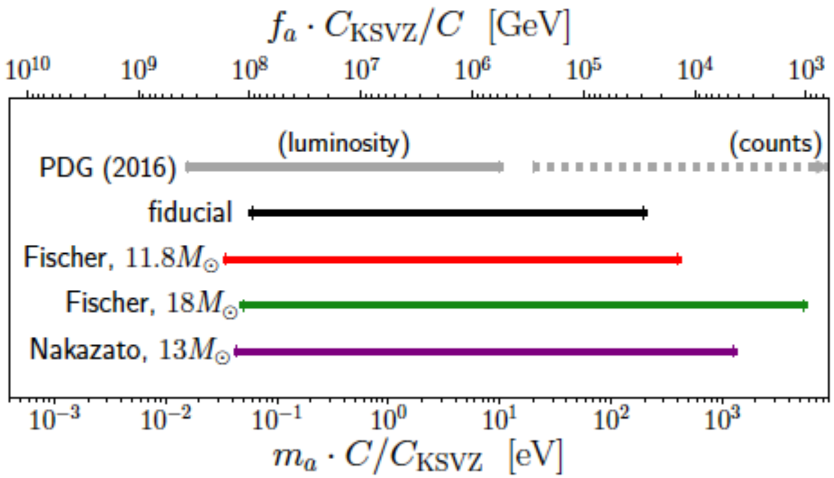


Figure 11. Constraints on the QCD axion mass and axion decay constant for various supernova temperature and density profiles. The "canonical" bound from the PDG [35, 115] is shown with a solid gray line, while the bound labelled "counts" comes from [123]. Our bounds close the gap between these constraints, known as the "hadronic axion window".

Including corrections to axion emissivity, the bound might be relaxed by factor ~ 4-5

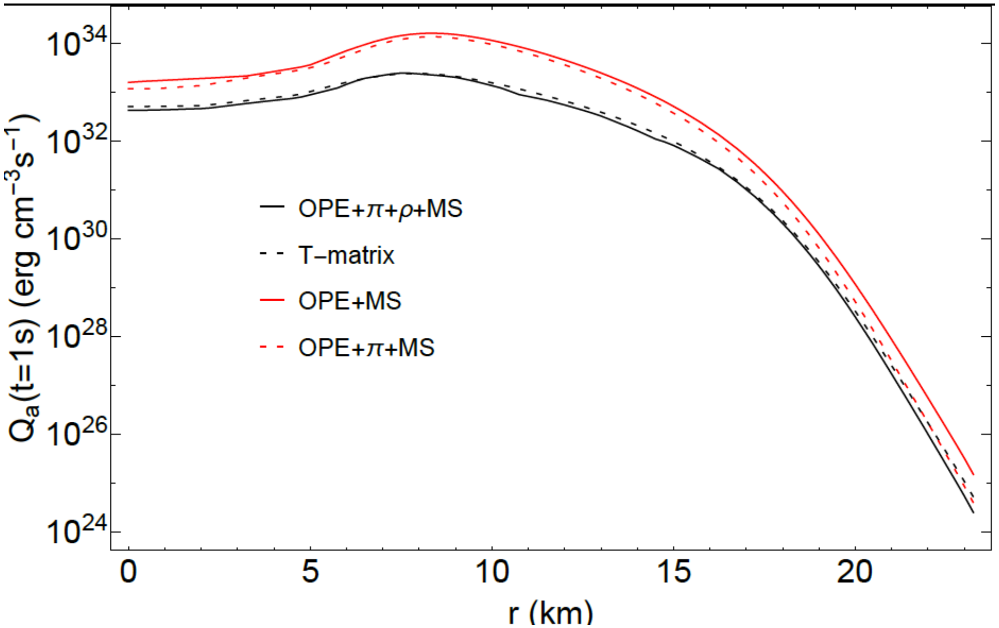
How robust is the new bound?

OUR IMPROVEMENT OF AXION EMISSIVITY BEYOND OPE

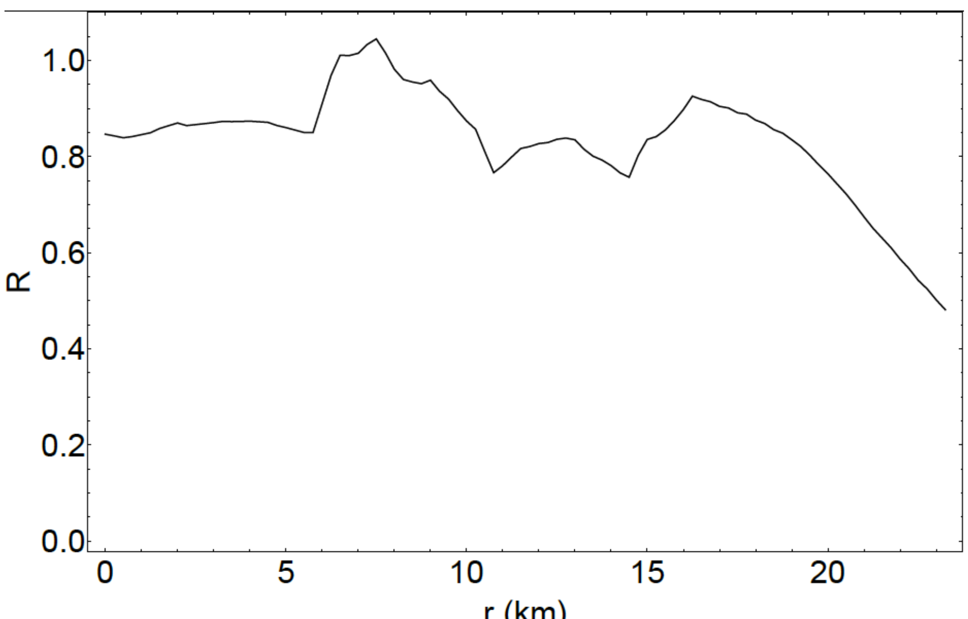
[Carenza, Giannotti,Gang,Fischer, Martinez-Pinedo,A.M., 1906.11844, v2]

- Non-zero pion mass in the propagator→ $\sqrt{3 m_N T} \sim m_\pi$
- Two-pions exchange→ Important around $2\mathrm{fm} \simeq 1.5 {m_\pi}^{-1}$
- Effective nucleon mass→ $m_N^*(\rho)$
- Multiple nucleon scatterings→ Nucleon spin fluctuations

COMPARISON WITH T-MATRIX



We compared our modified OPE prescription with results of T-matrix based on NN scattering data



In the region relevant for axion production we find differences < 20 %.

The SN axion bound

G. Raffelt, Lect. Notes Phys. **741** (2008) 51

The SN1987A neutrino burst lasted $\sim 10\,\mathrm{s}$, then

$$L_\mathrm{a} < 2 \times 10^{52}\,\mathrm{erg\,s}^{-1}$$

The axion luminosity for our model at $t = 1\,\mathrm{s}$ is

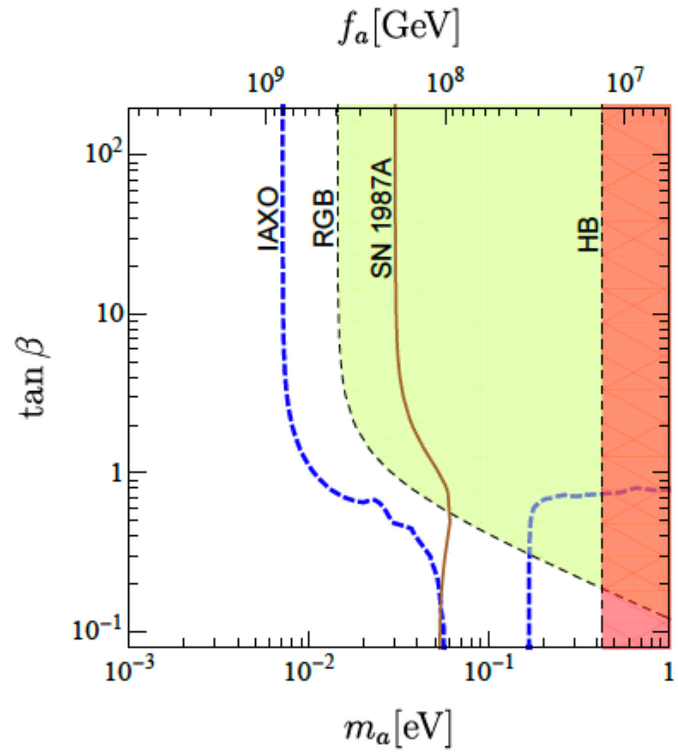
$$L_a \simeq 6.15 \times 10^{69}\ \mathrm{erg}\ \mathrm{s}^{-1}(g_{an}^2 + 0.29 g_{ap}^2 + 0.27 g_{an} g_{ap})$$

KVSZ AXION BOUND

Table 2. Bounds on axion couplings and mass for KVSZ model in our SN model at $t_{\mathrm{pb}} = 1$ s.

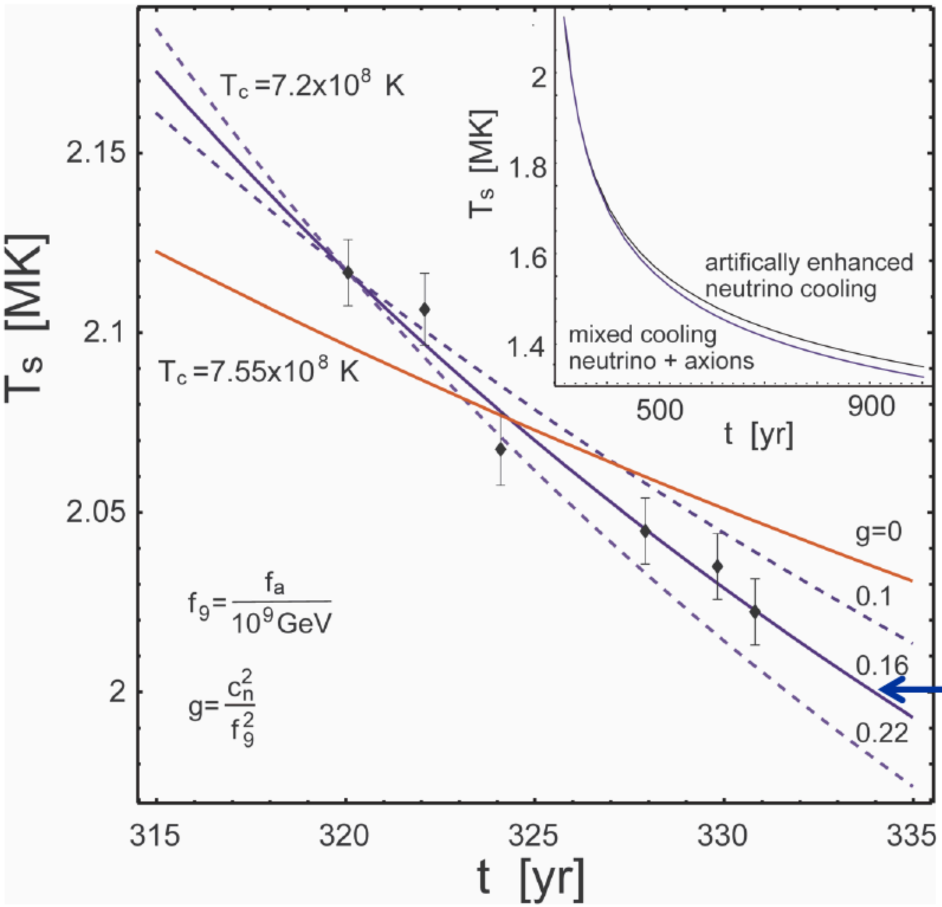
$C_{ap} = -0.47\,; C_{an} = 0$	g_{ap} $(\times 10^{-10})$	m_a (meV)	$f_a(\times 10^8$ GeV)
OPE	8	10	5.5
OPE+MS	9	11	4.9
OPE+corr. (no MS)	32	42	1.4
OPE+corr.+MS	33	43	1.3

DFSZ AXION BOUND

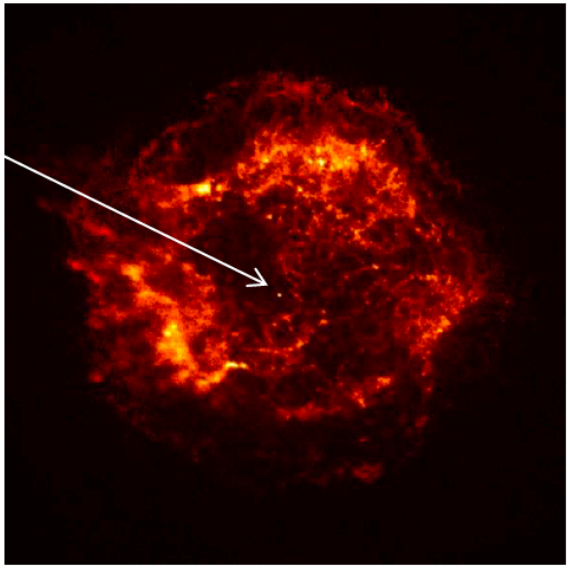


- Our analysis indicates a mass bound m_a < 40-50 meV
- Except for small values of $\tan\beta$ the SN 1987A is less stringent than the RGB one
- There is still part of parameter space available for next generation experiments, like IAXO

COOLING OF NS IN CAS A



Chandra x-ray image of non-pulsar compact remnant



$C_n m_a \sim 2.4$ meV

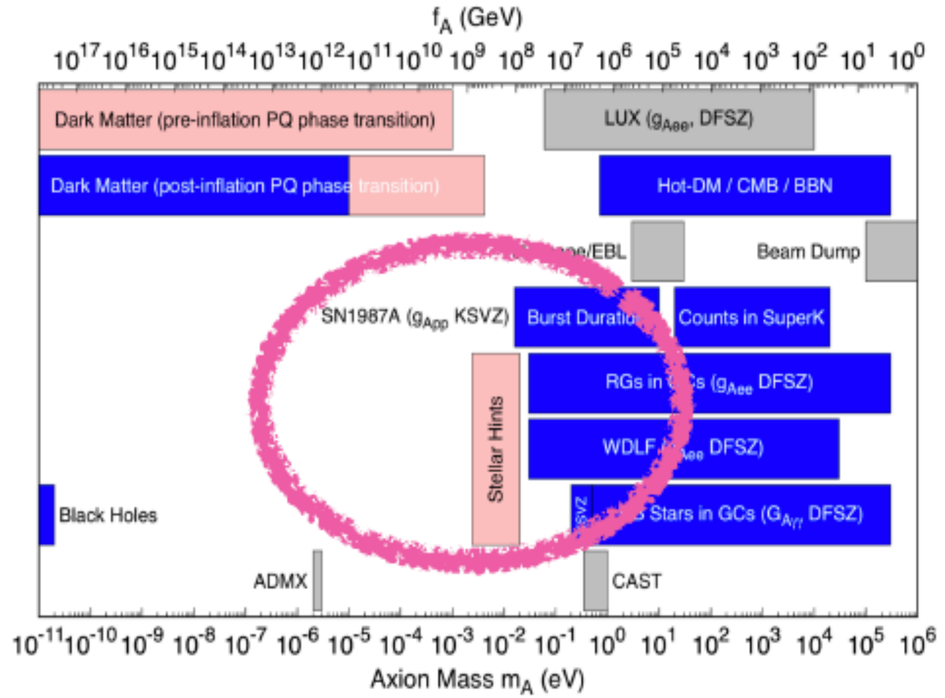
Measured surface temperature over 10 years reveals unusually fast cooling rate

- Neutron Cooper pair breaking and formation (PBF) as neutrino emission process?
- Evidence for extra cooling (by axions)?

Leinson, arXiv:1405.6873

No evidence in Hamaguci *et al.*, 1806.07151

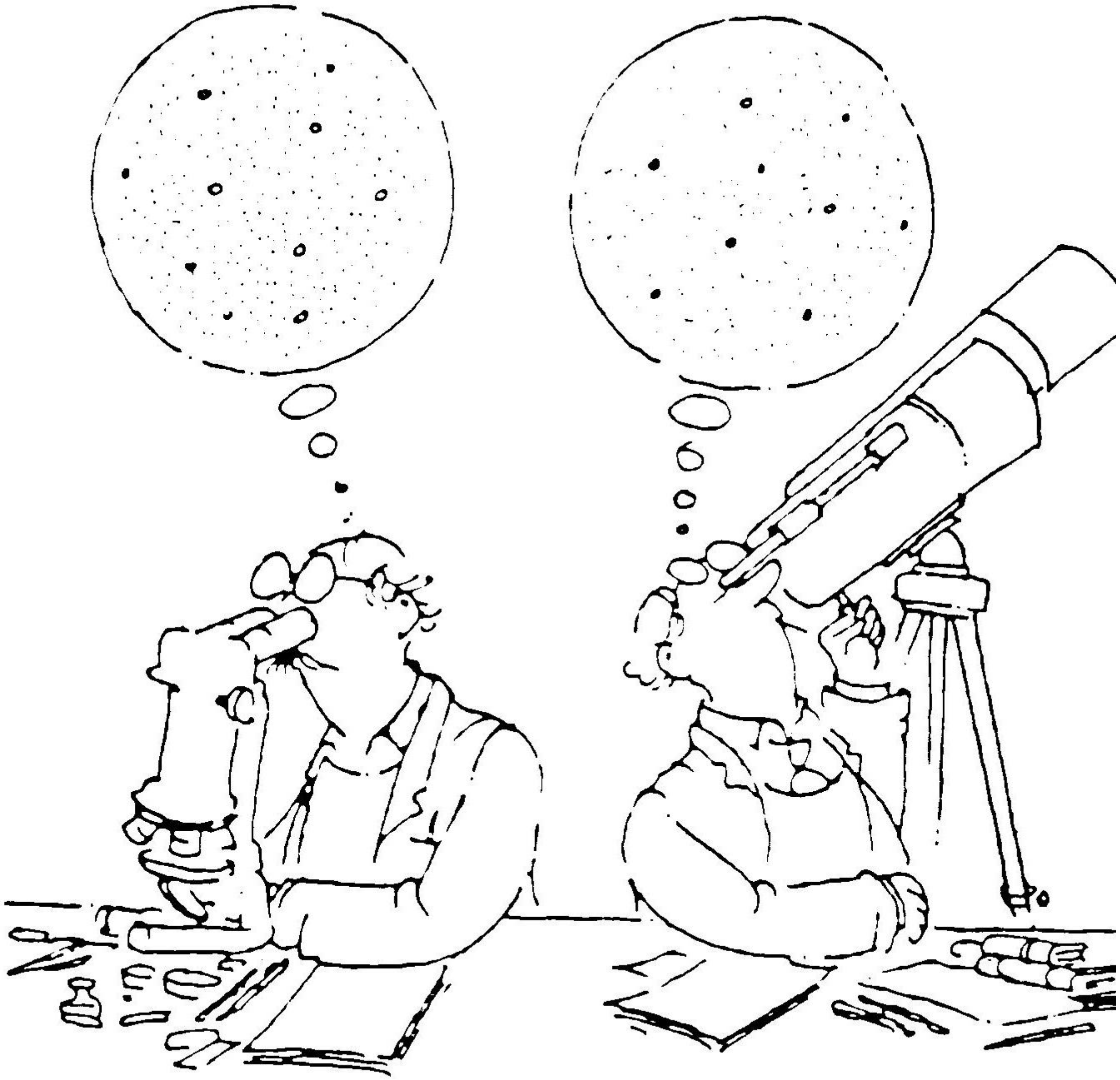
CONCLUSIONS



- Astrophysical observations from different stellar systems (GCs, WDs, SNe, NS) offer bounds and intriguing hints on axions

- Stellar hints would be probed by next generation lab experiments, like IAXO and ALPS II

Future astrophysical data and lab experiments would give a definitive verdict on axions.



Stay tuned !