Low-energy Supernovae constraints on ALPs

Andrea Caputo

University of Tel Aviv and Weizmann Institute

PADUA 2022

A.C., H.T. Janka, G. Raffelt, E. Vitagliano, arXiv 2201.09890 (PRL 2022)

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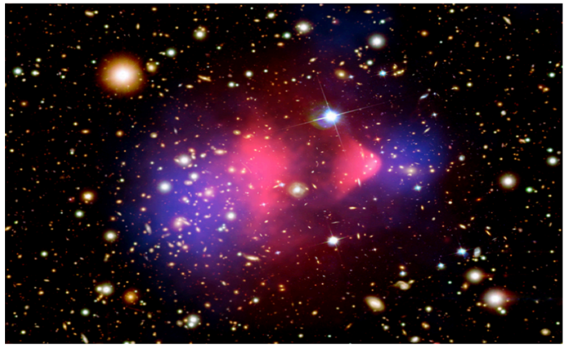
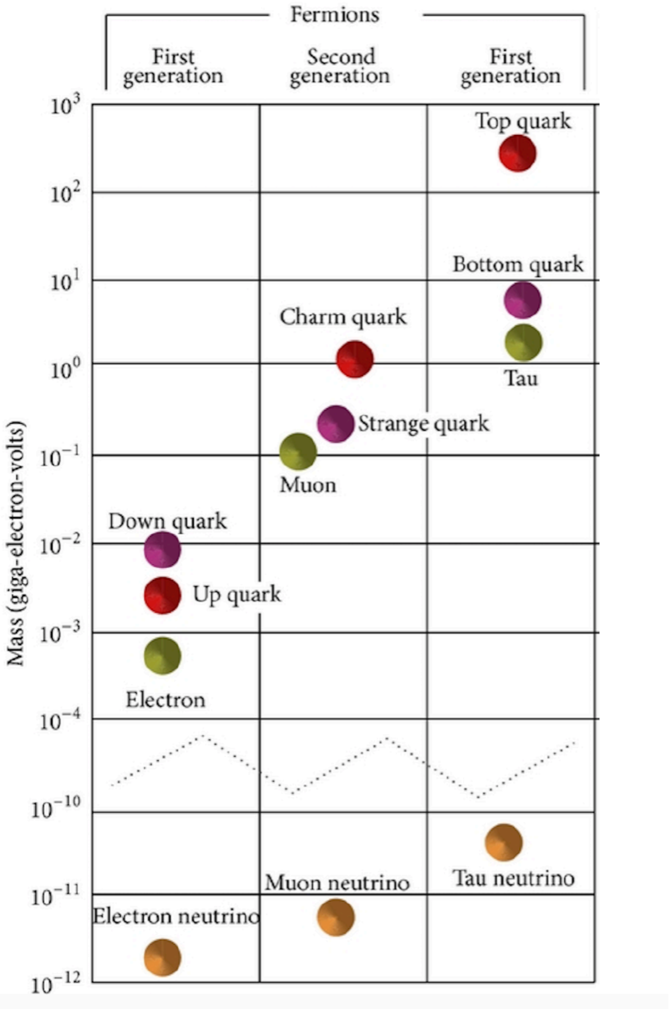
We have a lot of evidences for physics beyond the Standard Model

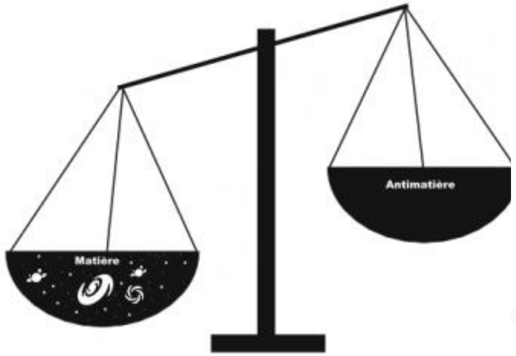
Dark Matter



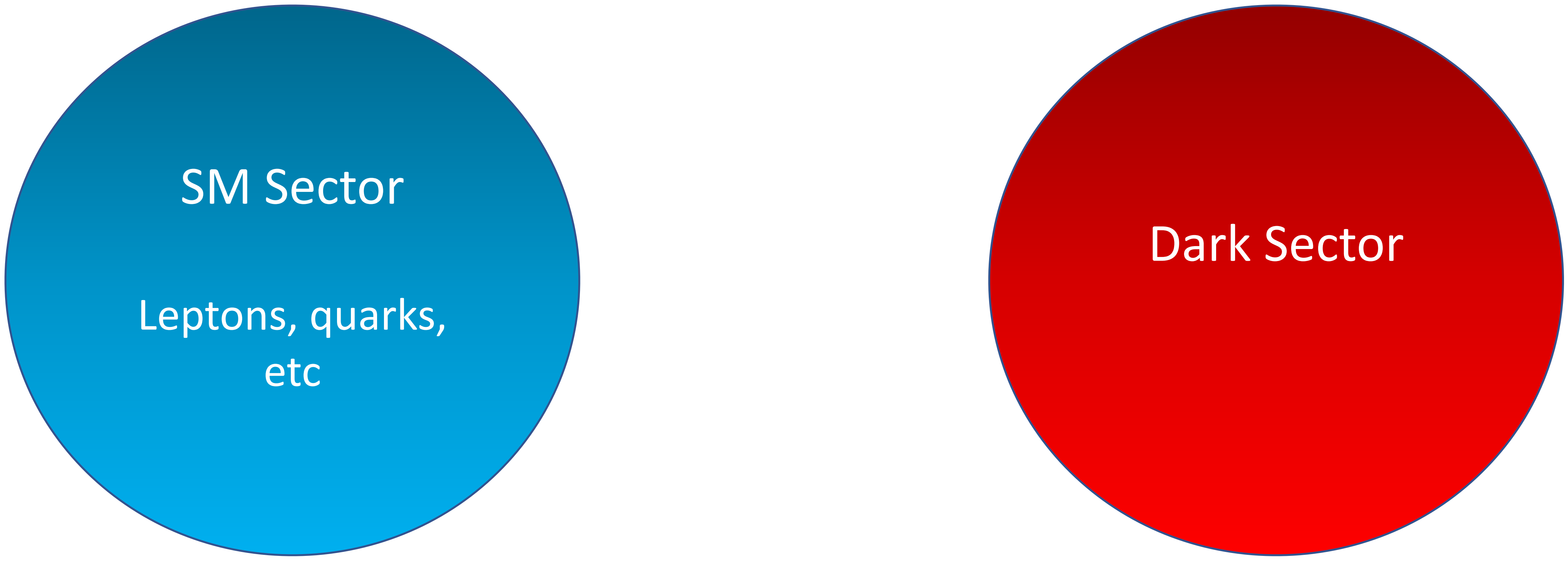
Neutrino Masses



Matter Antimatter asymmetry



We therefore have many open questions and what we do usually is to introduce a Dark Sector, that is to say new particles which can be connected in different ways to the SM particles



How to look for new particles?

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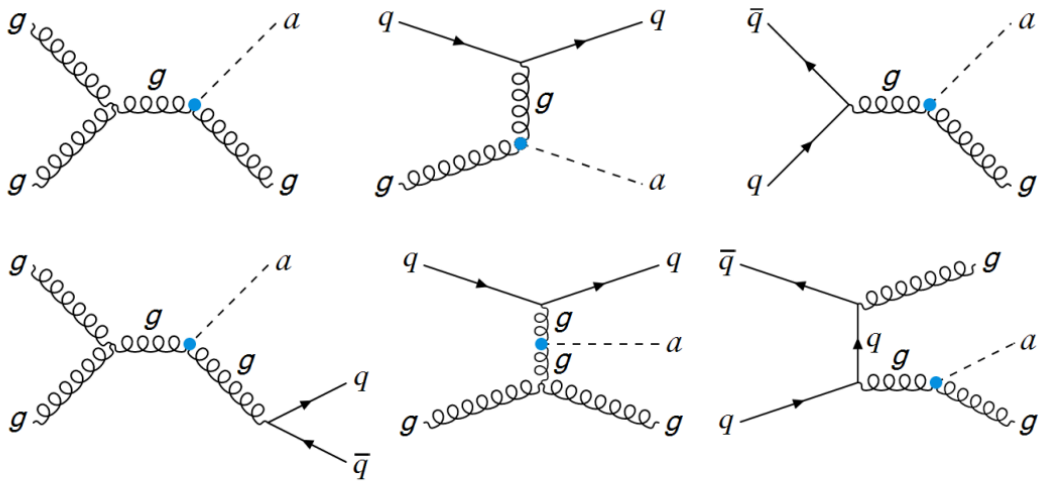
- Collider searches. We have been doing this successfully for decades, however is more and more difficult to reach high energies



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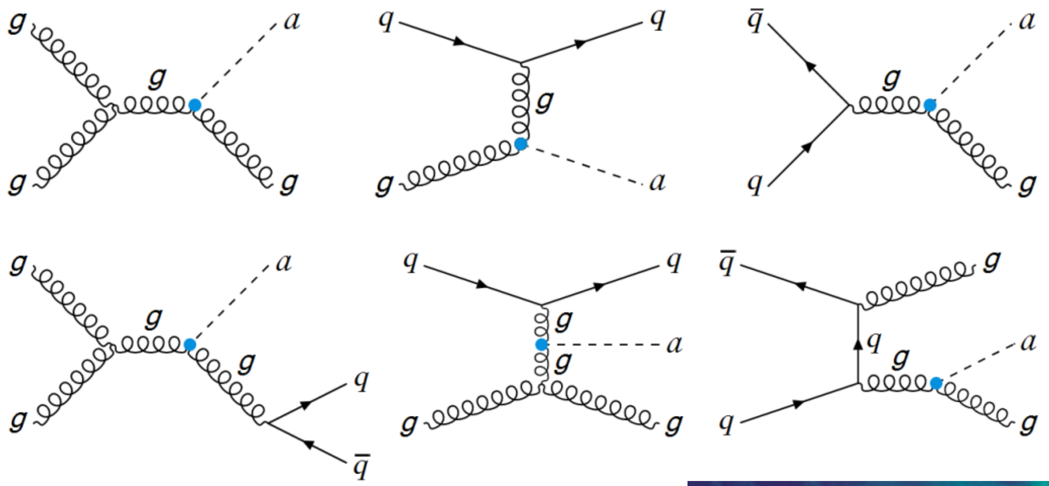
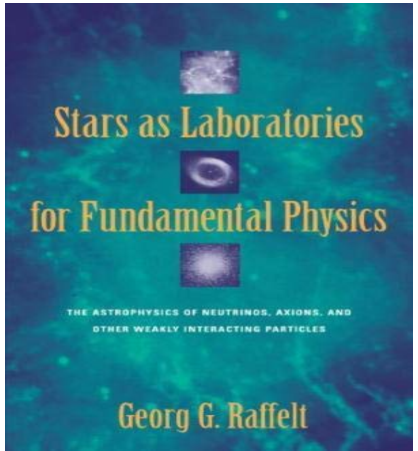
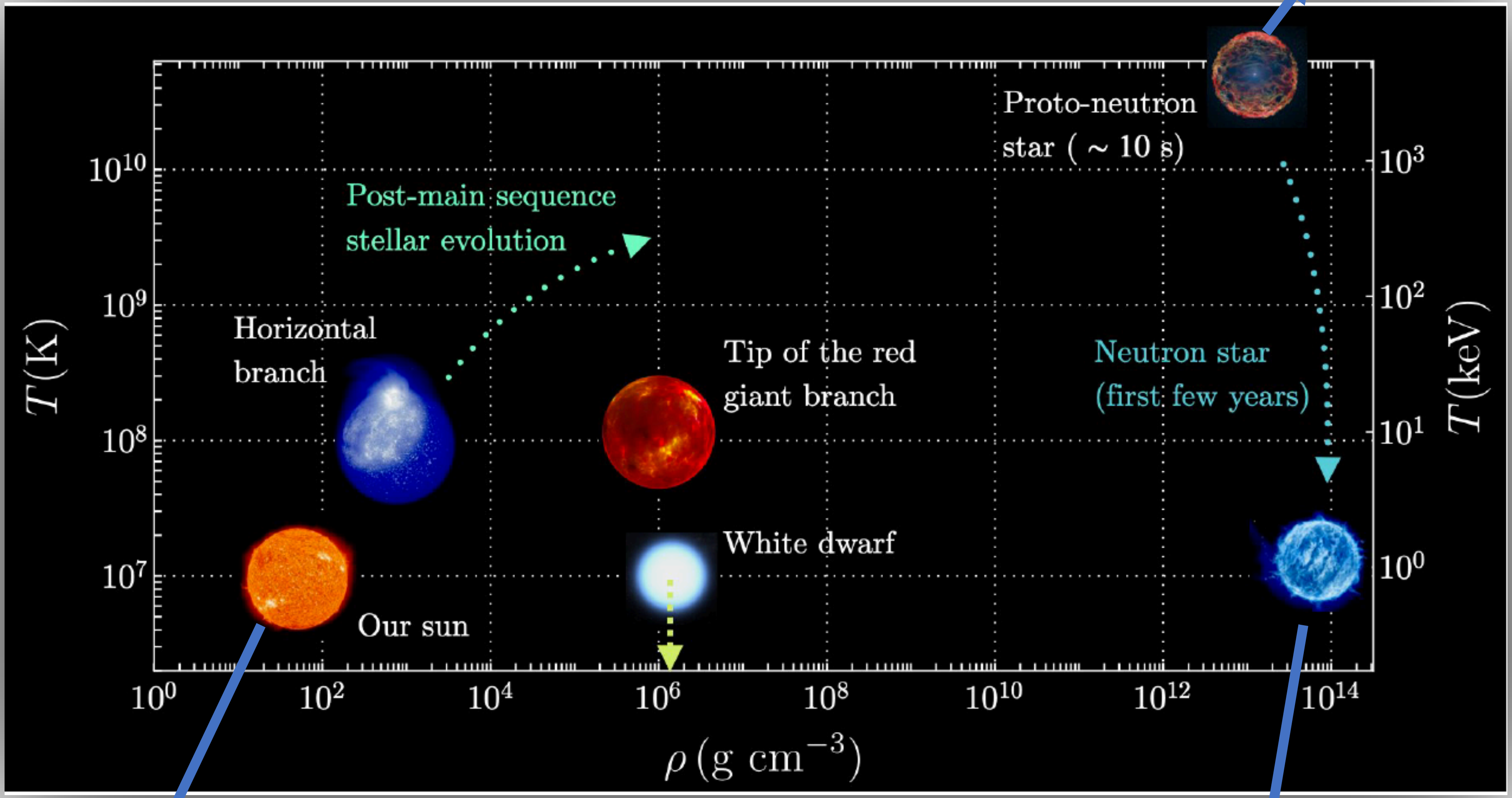


- Be creative and use astrophysical objects!



A.C, P. Carenza et al, *Phys.Rev.Lett.* 127 (2021) 18, 181102
A.C, H.T. Janka, G.Raffelt and E.Vitagliano, arXiv 2201.09890

Djuna Croon, Light Dark World 2020



C.O'Hare, **A.C**, A. Miller, E. Vitagliano, *Phys.Rev.D* 102 (2020) 4, 043019
A.C, A. Miller, E. Vitagliano, *Phys.Rev.D* 101 (2020) 12, 123004

A.C, L. Sberna et al, *Phys.Rev.D* 100 (2019) 6, 063515
A.C, J.Zavala and D.Blas, *Phys.Dark Univ.* 19 (2018) 1-11

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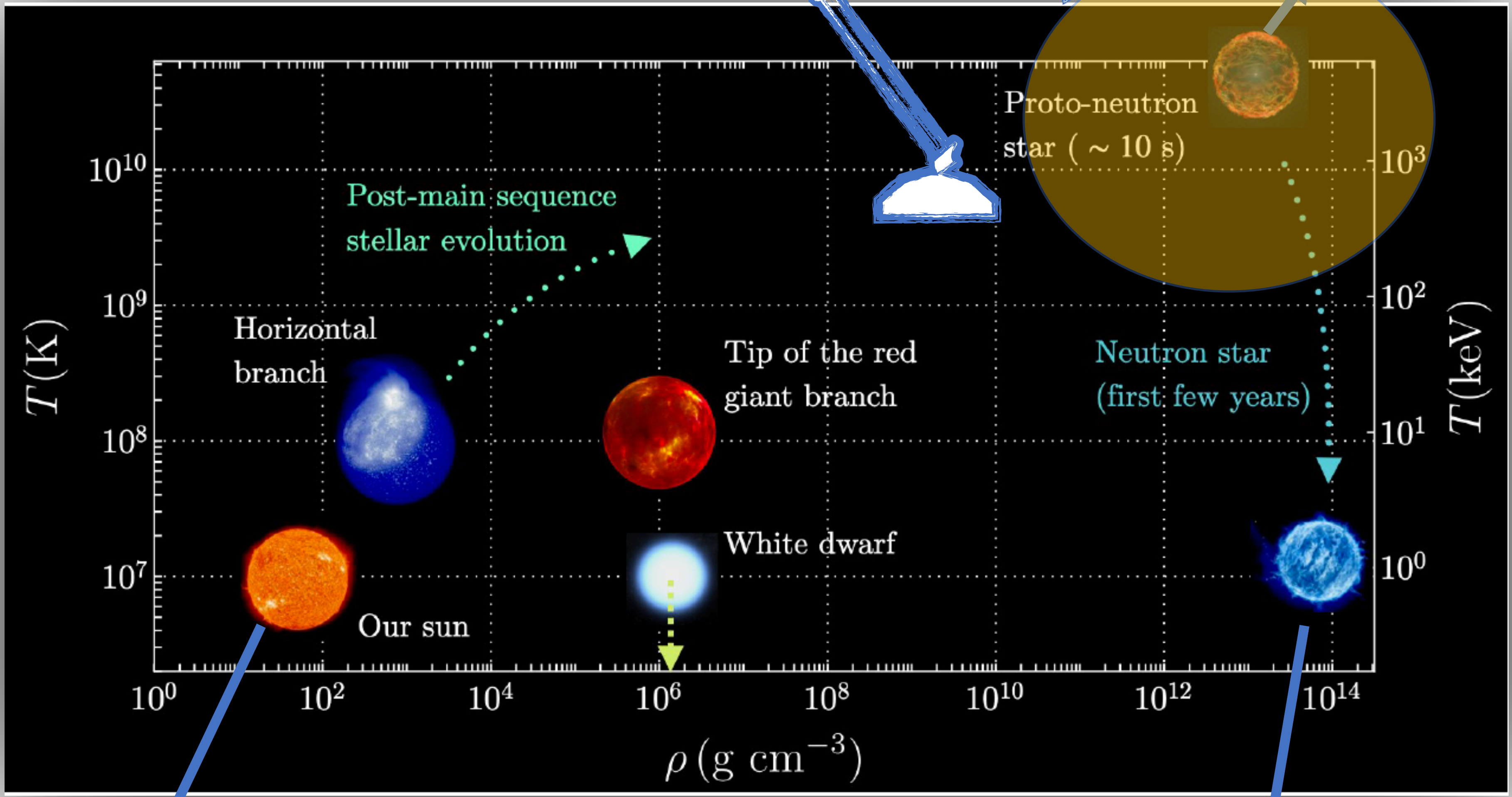

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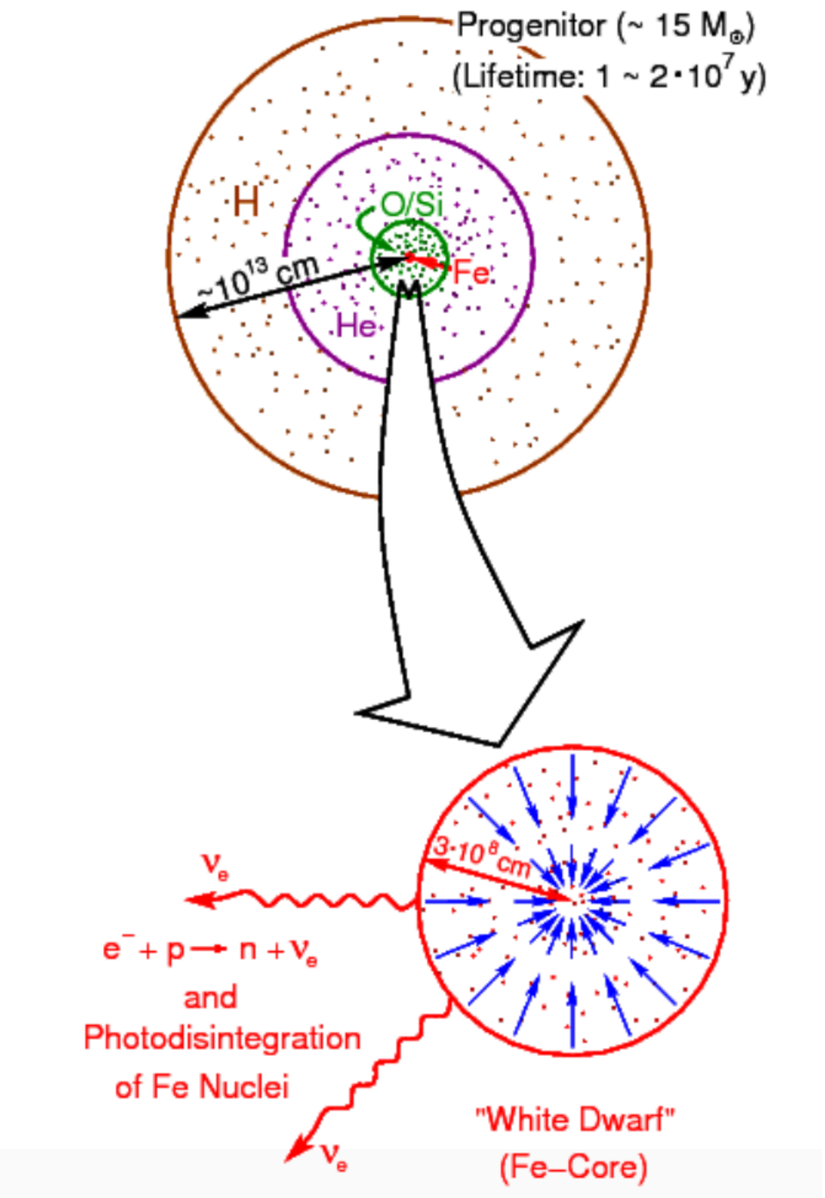
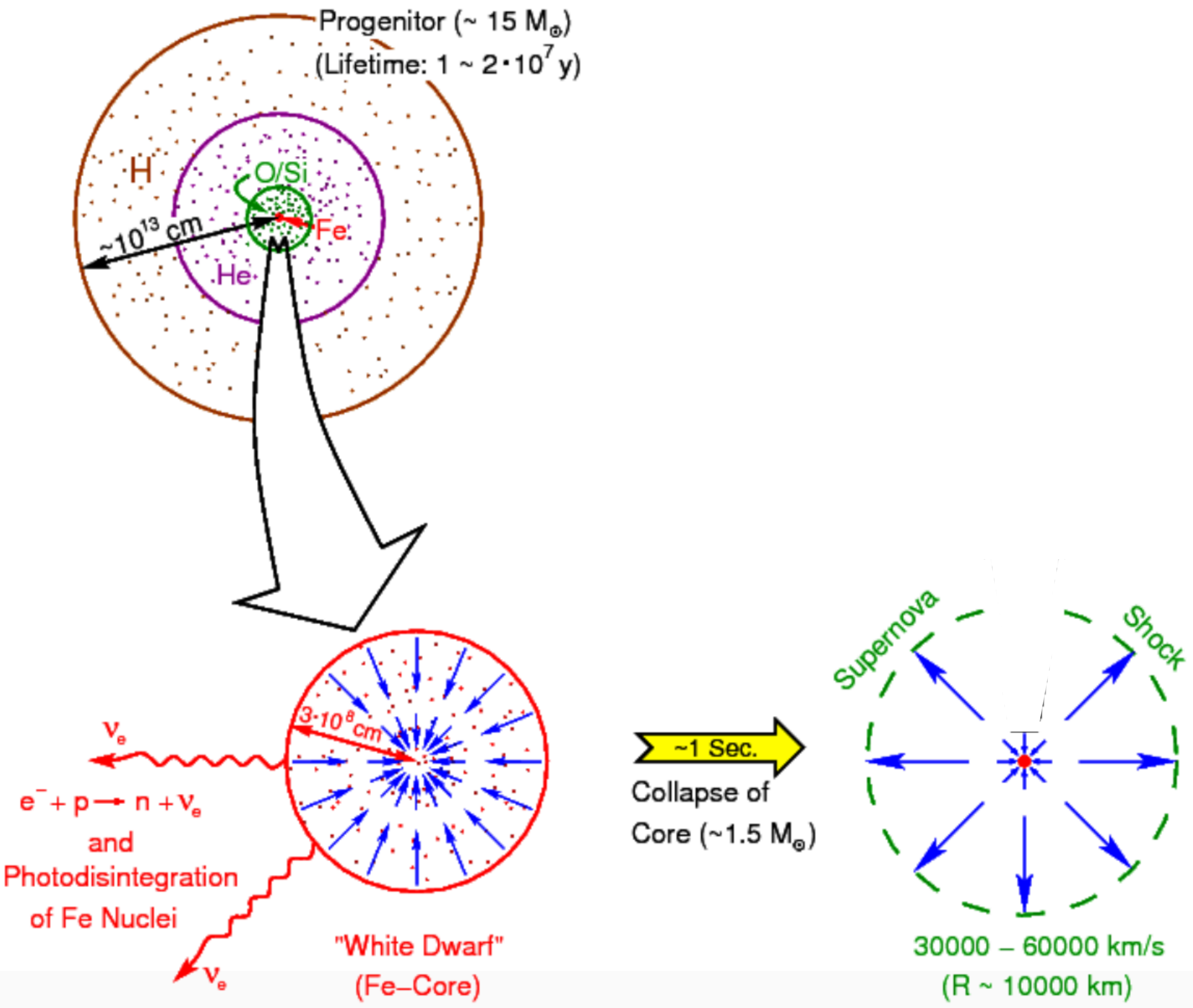
In this talk I will use Low Energy Supernovae (LESNe) to constrain new physics

A little bit of SN Physics



See T. Janka Cern Colloquium
https://indico.cern.ch/event/1037035/

A little bit of SN Physics



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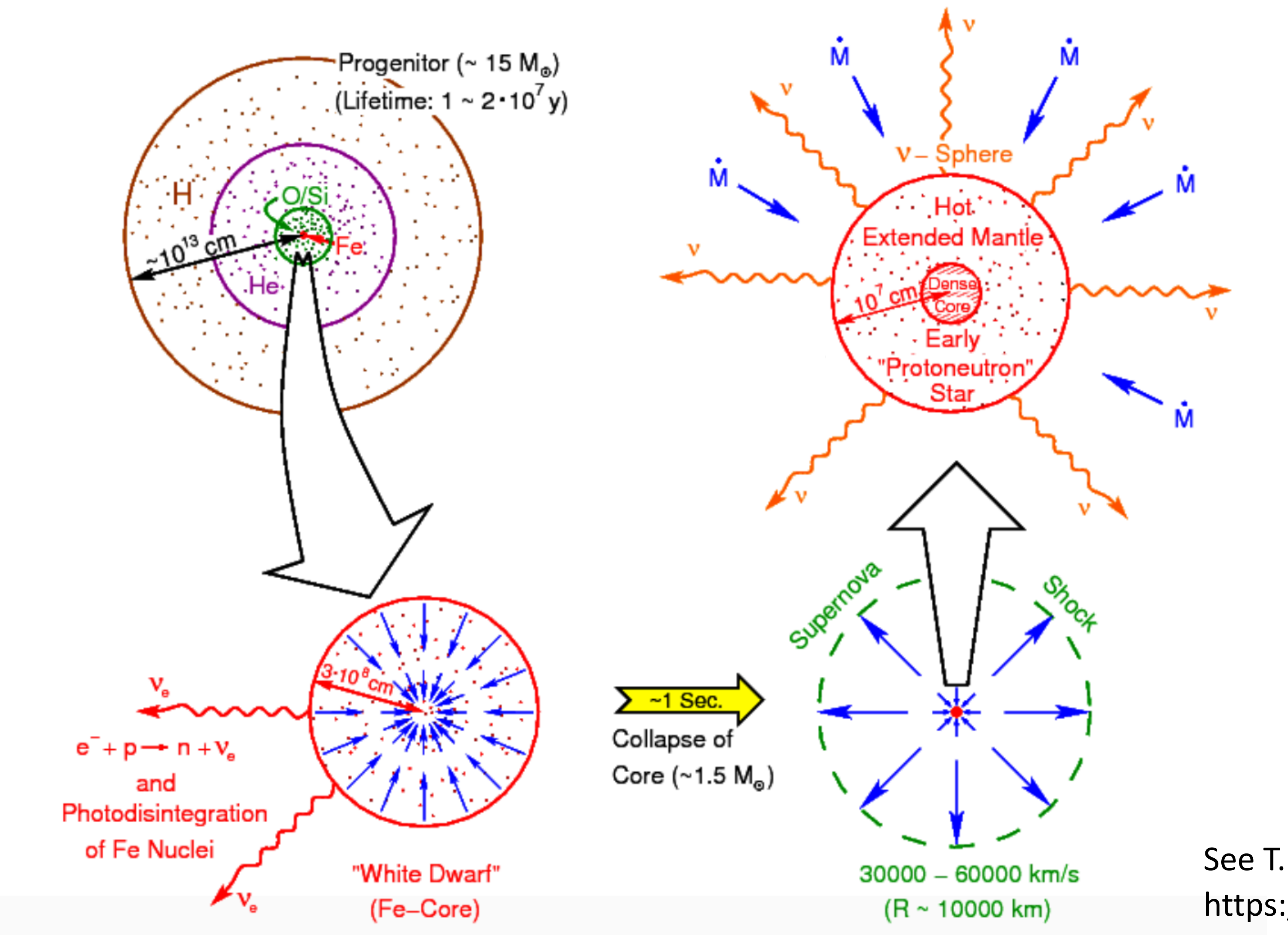

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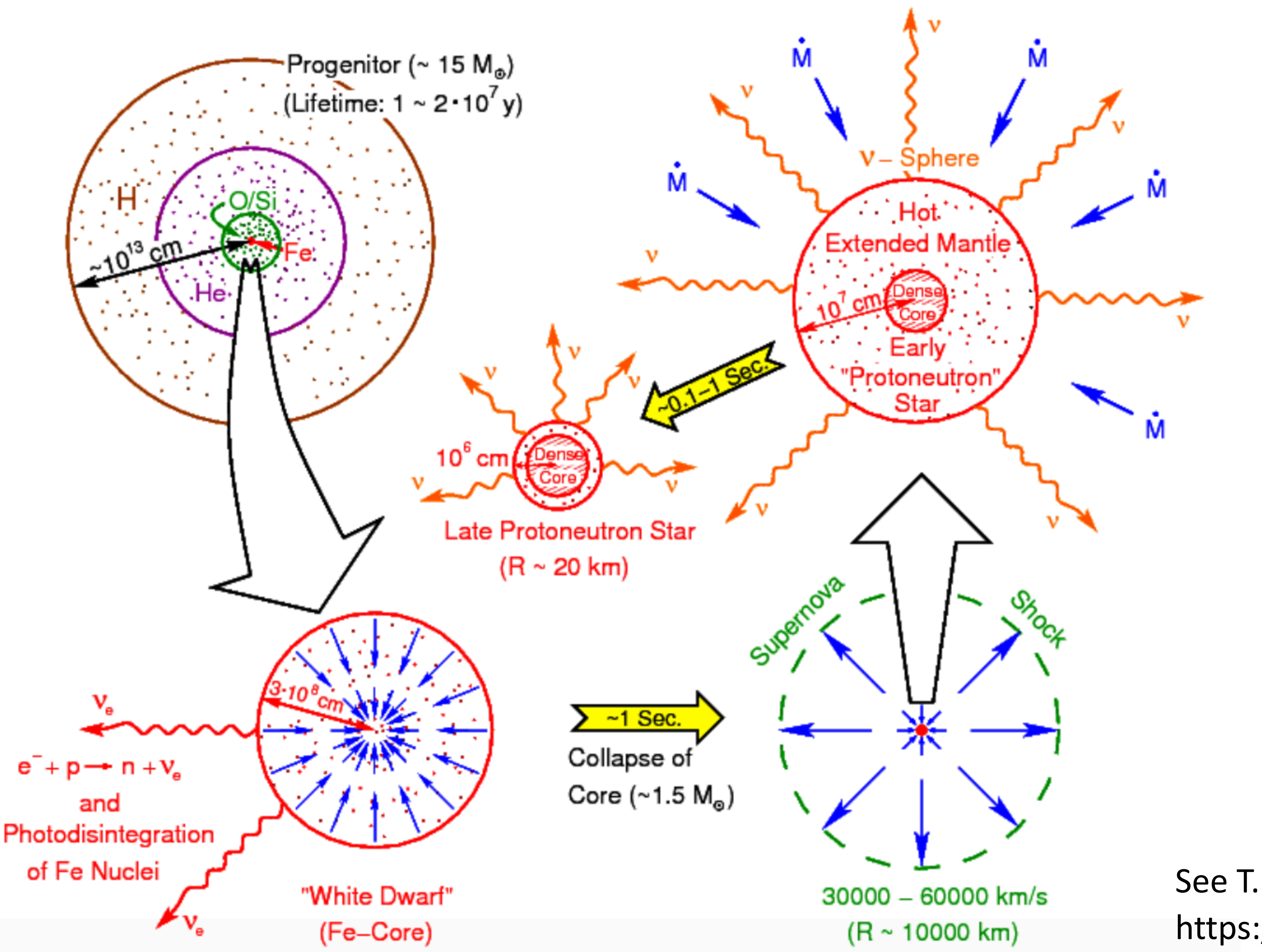

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PNS: protoneutron star

- $r \approx 10\ km$
- T $\approx 40\ MeV$
- Nuclear density

Neutrino emitted from the "neutrino sphere", cooling the PNS in $\sim 10s$

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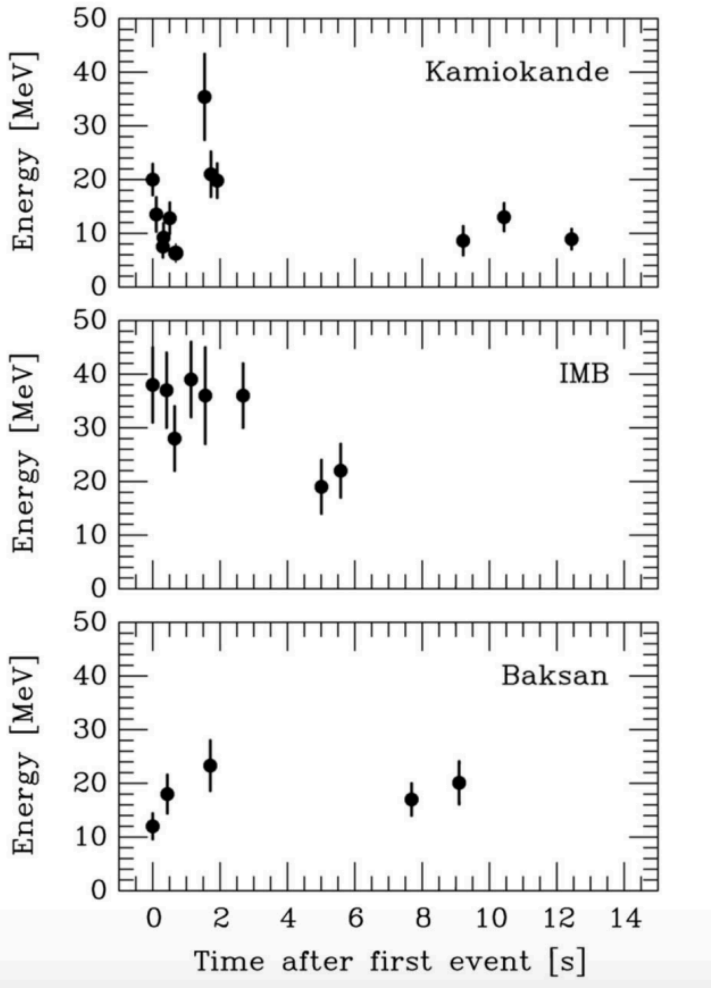
SN 1987A neutrino signal



$$E_b \approx \frac{3}{5}\frac{G_N \mathcal{M}^2}{R} = 1.60\times 10^{53}\,\mathrm{erg}\left(\frac{\mathcal{M}}{\mathcal{M}_\odot}\right)^2\left(\frac{10\,\mathrm{km}}{R}\right)$$

$$T = \tfrac{2}{3}\langle E_{\mathrm{kin}}\rangle \approx 17\,\mathrm{MeV}$$

$$t_{\mathrm{diff}} \approx R^2/\lambda$$

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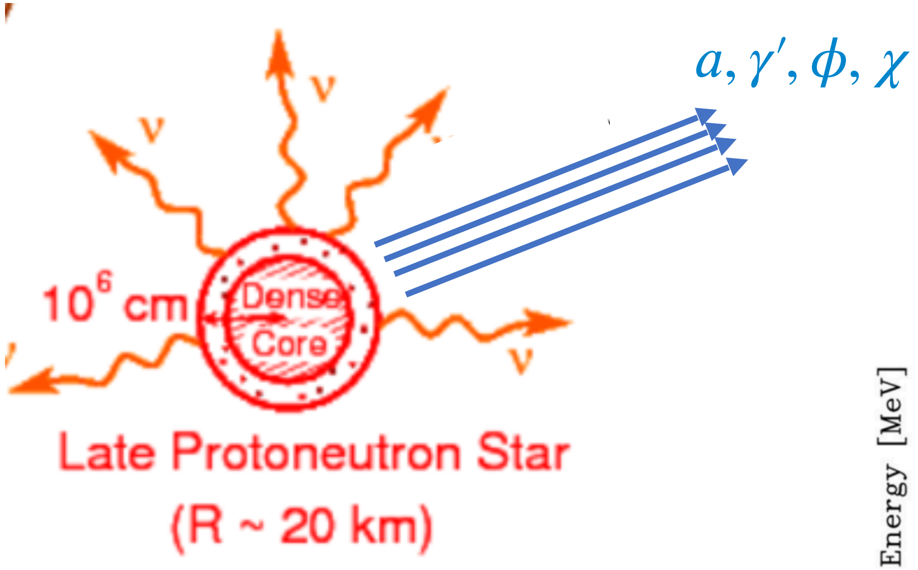

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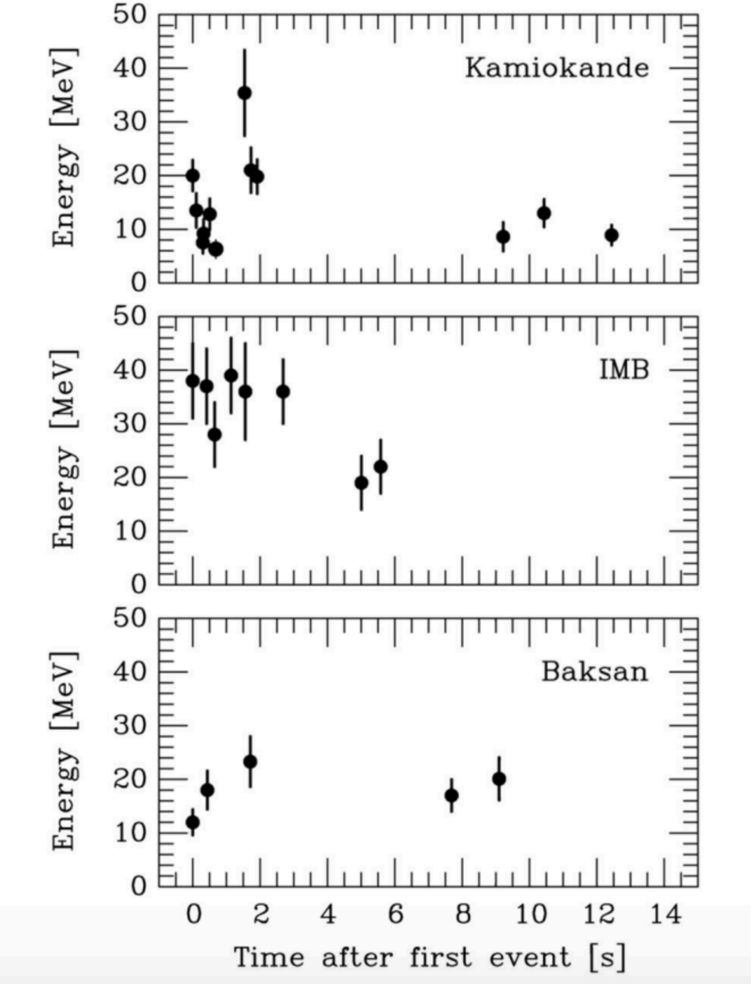
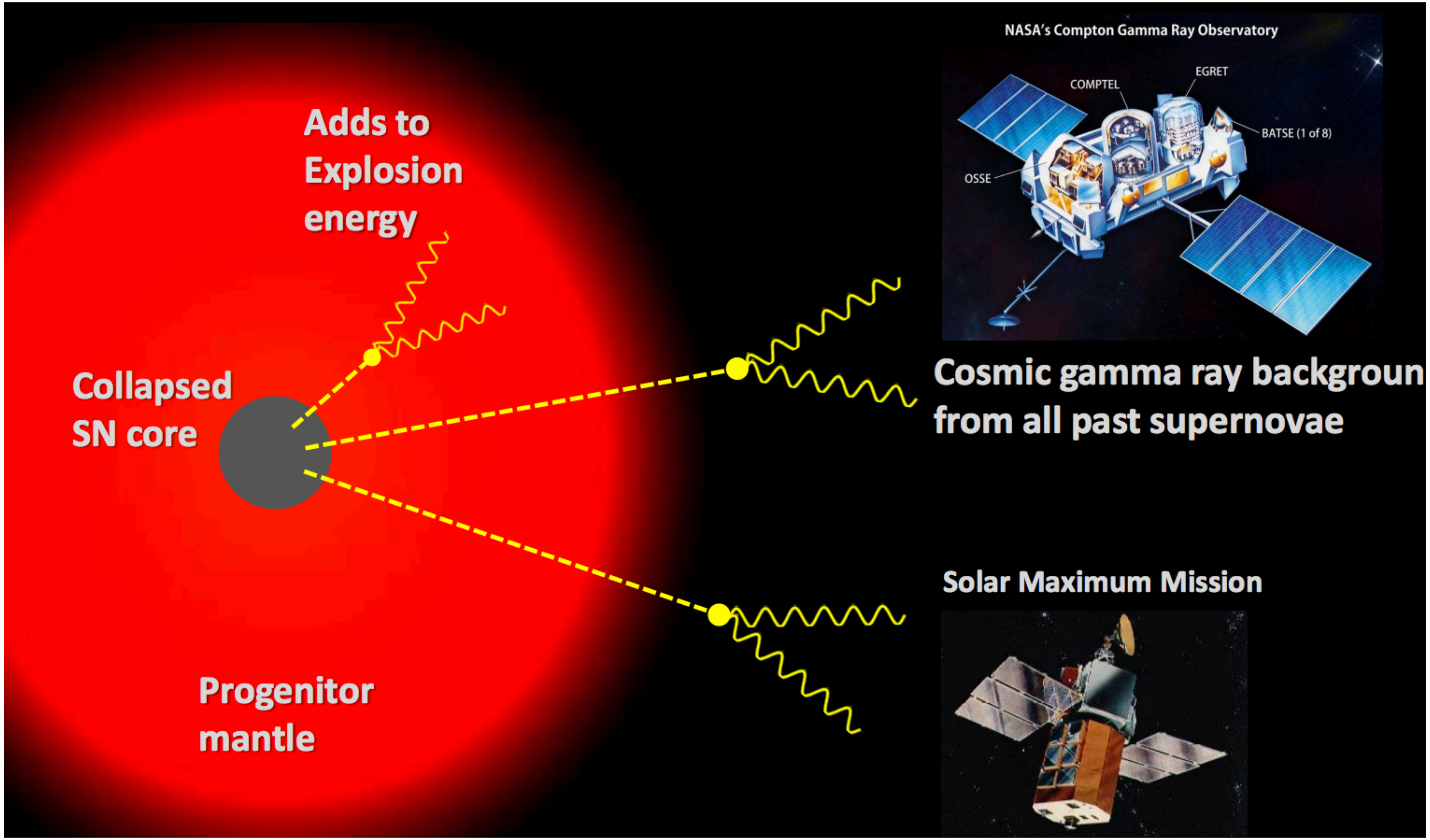


Use SNe to get a bound on exotic particles which decay into SM relics



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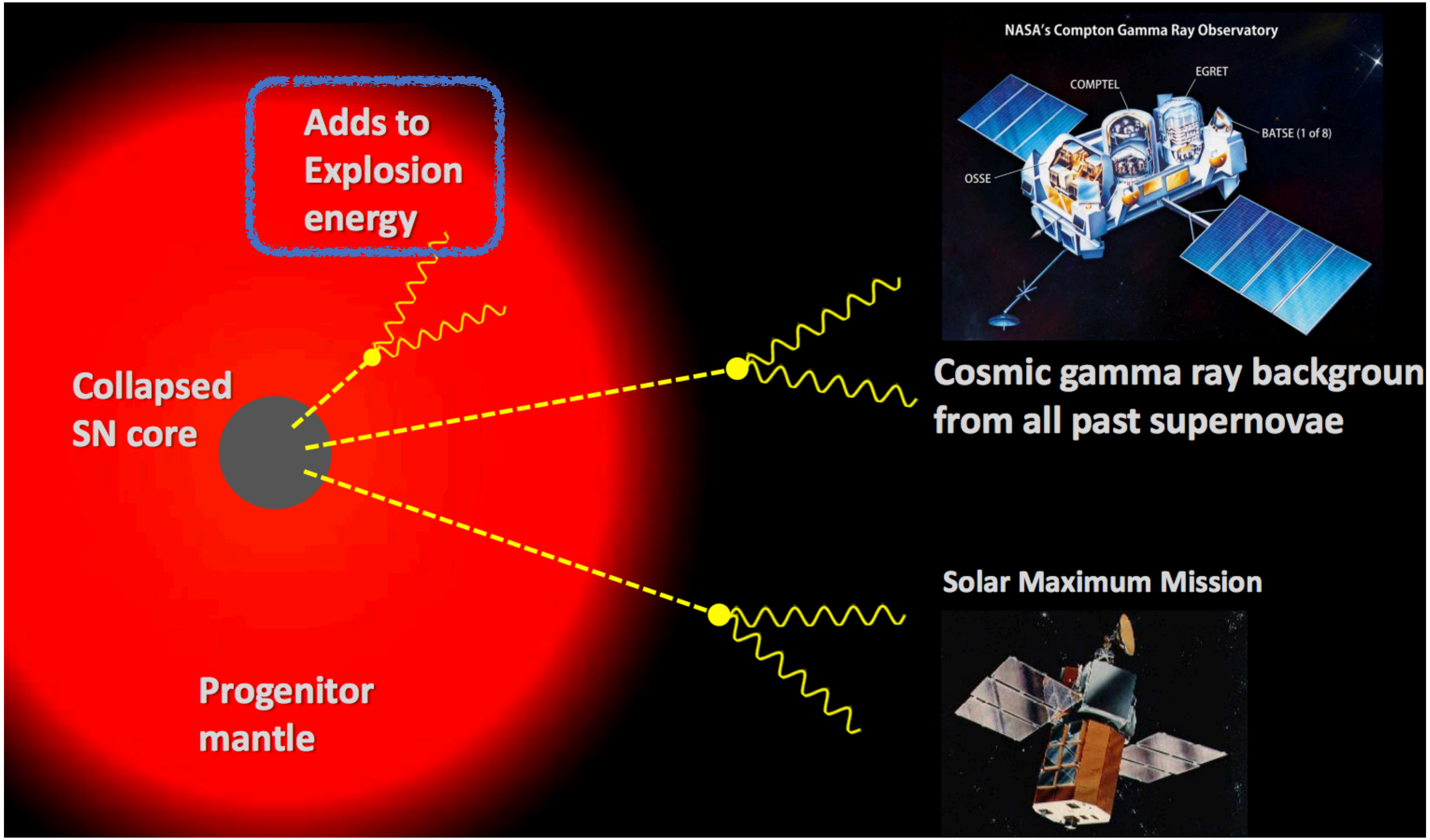

Low Luminous Supernovae (LLSNe)

Low-energy Supernovae (LESNe)

- 10–100 times dimmer than normal core-collapse SNe (CCSNe)
- 2–3 times lower photospheric expansion velocities
- Observations point to **0.1 B** (or smaller) explosion energies

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A low-energy core-collapse supernova without a hydrogen envelope

S. Valenti, A. Pastorello, E. Cappellaro, S. Benetti, P. A. Mazzali, J. Manteca, S. Taubenberger, N. Elias-Rosa, R. Ferrando, A. Harutyunyan, V. P. Hentunen, M. Nissinen, E. Pian, M. Turatto, L. Zampieri & S. J. Smartt

Low-luminosity Type II supernovae: spectroscopic and photometric evolution

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S. Benetti,[2] D. Branch,[5] E. Baron,[5] F. Patat,[6] M. Armstrong,[7] C
M. Salvo[8] and M. Riello[2,1]

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[8]Australian National University, Mount Stromlo Observatory, Cotter Road, Weston ACT 2611, Australia

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MNRAS **439**, 2873–2892 (2014) doi:10.1093/mnras/stu156
Advance Access publication 2014 February 21

Low luminosity Type II supernovae – II. Pointing towards moderate mass precursors

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Radiation-hydrodynamical modelling of underluminous Type II plateau supernovae

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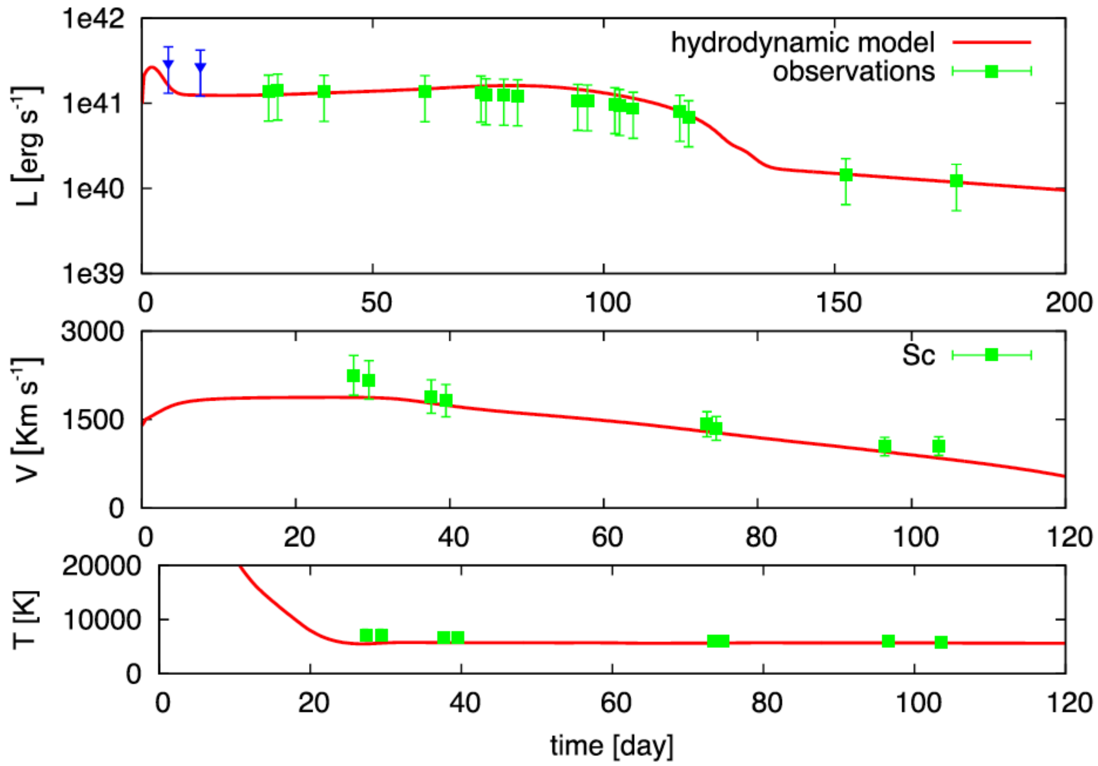
ABSTRACT

With the aim of improving our knowledge about the nature of the progenitors of low-luminosity Type II plateau supernovae (LL SNe IIP), we made radiation-hydrodynamical models of the well-sampled LL SNe IIP 2003Z, 2008bk and 2009md. For these three SNe, we infer explosion energies of 0.16–0.18 foe, radii at explosion of 1.8–3.5 × 10^{13} cm and ejected masses of 10–11.3 $M_{\odot}$. The estimated progenitor mass on the main sequence is in the range ~13.2–15.1 $M_{\odot}$ for SN 2003Z and ~11.4–12.9 $M_{\odot}$ for SNe 2008bk and 2009md, in agreement with estimates from observations of the progenitors. These results together with those for other



Radiation
supernova

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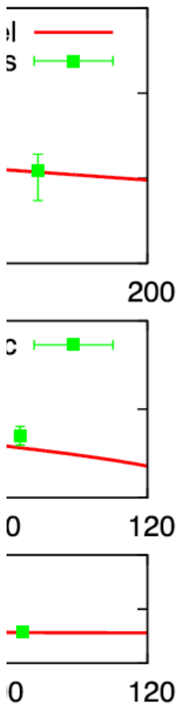
Accepted 2016 Octol

Since the spectral energy distribution of SN2008ha is very similarity to that of SN2005hk, we used this object as a reference and add a bolometric correction to the R-band flux (taking also in to account the different time evolution of the two supernovae). Fitting the pseudo-bolometric light curve with a toy-model based on Arnett's equations (Ref. 18) (see Ref. 33 for details on the toy-model) we estimated for SN2008ha an ejected mass between 0.1 and 0.5 solar masses, a kinetic energy of 1-5 x 10^{49} erg, a nickel mass of 0.003-0.005 solar masses and an JD ~ 2454773 as explosion time. Even though these values should be confirmed by detailed models, such a small ejected mass is consistent with the fast luminosity and spectral evolution of SN2008ha, and makes the thermonuclear explosion of a degenerate white dwarf of 1.4 solar masses (i.e. a normal SNe Ia), very unlikely.



If new particles, let's call them axions, are produced in the SN core and they then **decay in the SN mantle**, they can **dump energy** which should then show up either in **kinetic energy or radiation energy**.

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Luminosity of the new particles

$$E_{\rm mantle} = \int dt \int_0^{R_{\rm NS}} dR \int_{m'_a(R)}^{\infty} dE_a \, \frac{dL_a(R, E_a, t)}{dR\, dE_a}$$
$$\times \left\{\exp[-(R_{\rm NS} - R)/\lambda_a] - \exp[-(R_* - R)/\lambda_a]\right\},$$

Proto-neutron star radius

Progenitor radius

Axion mean free path (boosted, energy-dependent)

A.C., H.T. Janka, G. Raffelt, E. Vitagliano, arXiv 2201.09890

Example model: axion coupling to photons

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma} a \tilde{F}^{\mu\nu} F_{\mu\nu}$$

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$$Q_a = \int \frac{2d^3\mathbf{k}}{(2\pi)^3} \frac{\omega}{e^{\omega/T} - 1} \hat{n}\sigma_{\mathrm{P}} \qquad \sigma_{\mathrm{P}} = \frac{Z^2 \alpha G_{a\gamma\gamma}^2}{2} f_{\mathrm{P}}$$

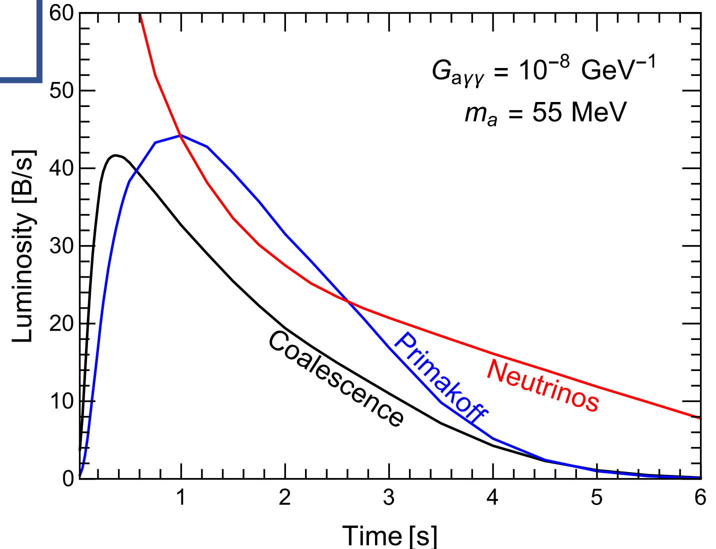
$$= \hat{n}\, \alpha G_{a\gamma\gamma}^2 \frac{\pi^2 T^4}{30} \langle f_{\mathrm{P}} \rangle, \qquad \langle f_{\mathrm{P}} \rangle = 20 \frac{m_a^2 + 3 m_a T + 3T^2}{\pi^4 T^2} e^{-m_a/T}$$

Primakoff

$$Q_a = \int \frac{d^3\mathbf{p}}{(2\pi)^3} \omega\, e^{-\omega/T} \Gamma_{\mathrm{A}} = \frac{G_{a\gamma\gamma}^2 T^3 m_a^4}{128\pi^3} F(m_a/T)$$

$$F(\mu) = \int_\mu^\infty dx\, x \sqrt{x^2 - \mu^2}\, e^{-x} f_{\mathrm{B}}$$

Coalescence



The axions get produced and then can decay back into photons!

$$\lambda_{a\to 2\gamma} = \frac{64\pi}{G^2_{a\gamma\gamma}} \frac{\sqrt{E_a^2 - m_a^2}}{m_a^4} \simeq \frac{4.0 \times 10^{13}\,\mathrm{cm}}{G_9^2} \frac{E_{100}}{m_{10}^4}$$

Gamma ray photons **quickly absorbed** by pair production on nuclei and electrons

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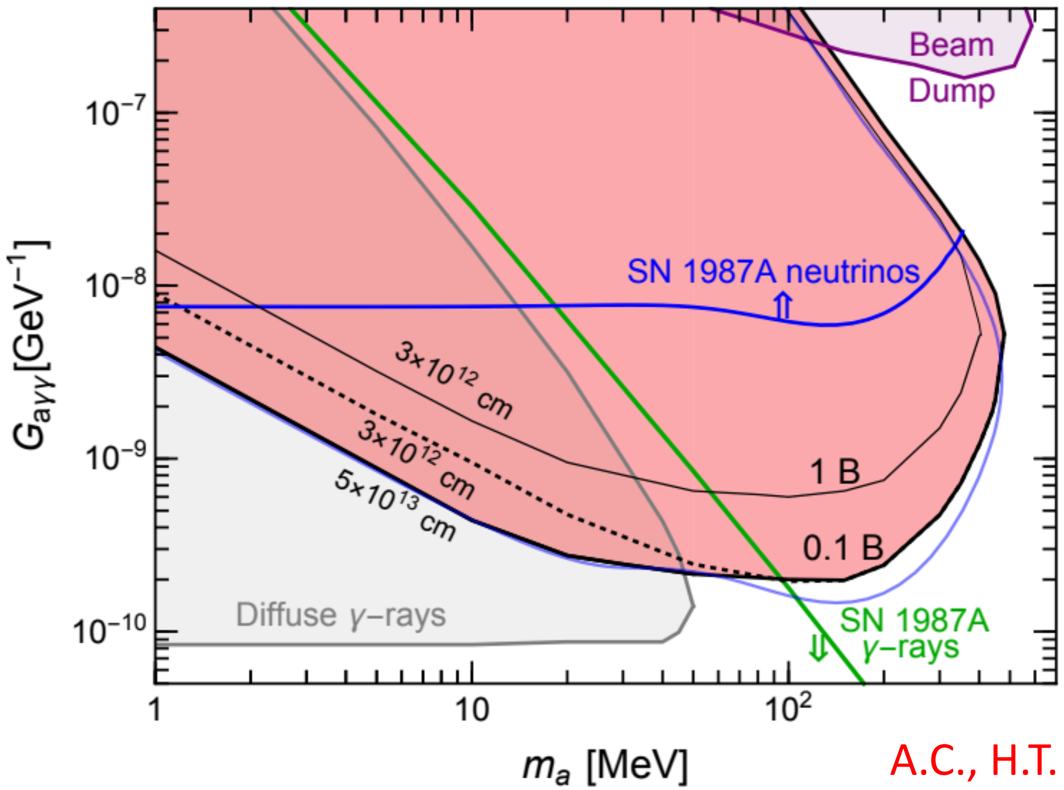

Imposing the **energy deposit in the mantle** is not too big gives very strong bounds.

A.C., H.T. Janka, G. Raffelt, E. Vitagliano, arXiv 2201.09890 (PRL 2022)

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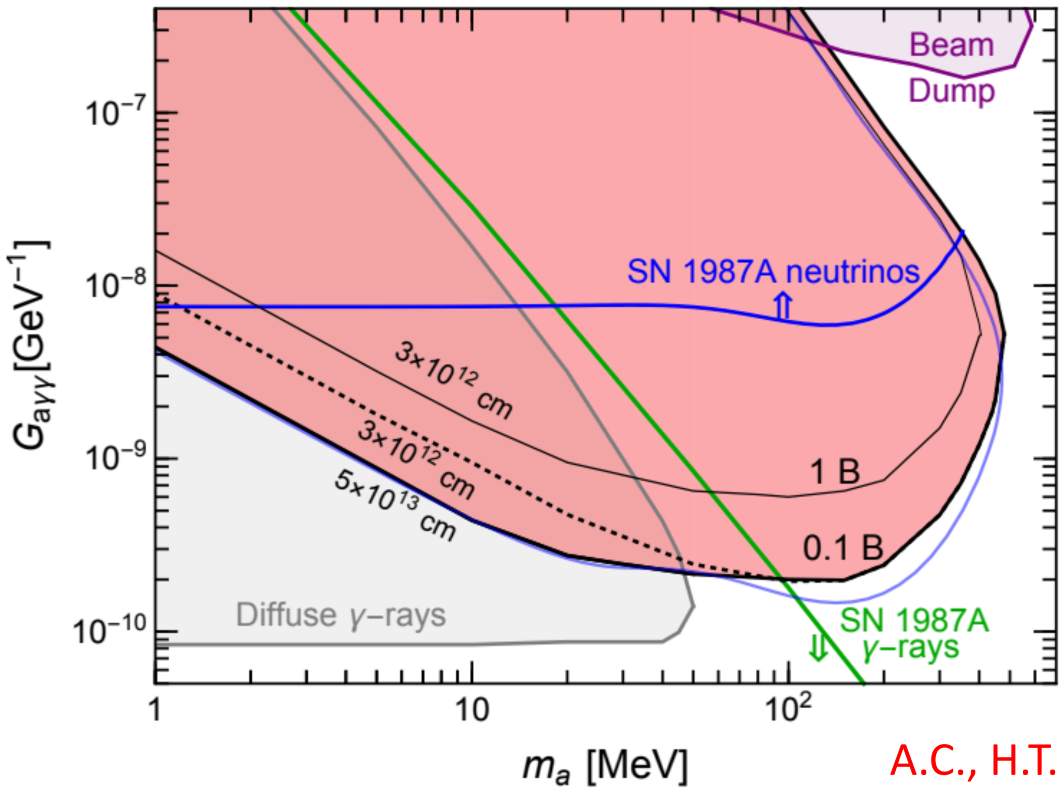


Imposing the **energy deposit in the mantle** is not too big gives very strong bounds.

Cute **one zone** model:

$$R_{NS} = 12.9\ km; T = 30\ MeV;\ \rho = \frac{3\times 10^{14} g}{cm^3}; t_{em} = 3\ s$$

A.C., H.T. Janka, G. Raffelt, E. Vitagliano, arXiv 2201.09890 (PRL 2022)

Conclusions

- The interplay between particle physics and astrophysics will be crucial in the next years.

- SN physics, for example, can place very strong constraints on new interactions via various phenomena:

1. Cooling arguments;
2. Gamma-ray signals;
3. Explosion energy (LESNe).

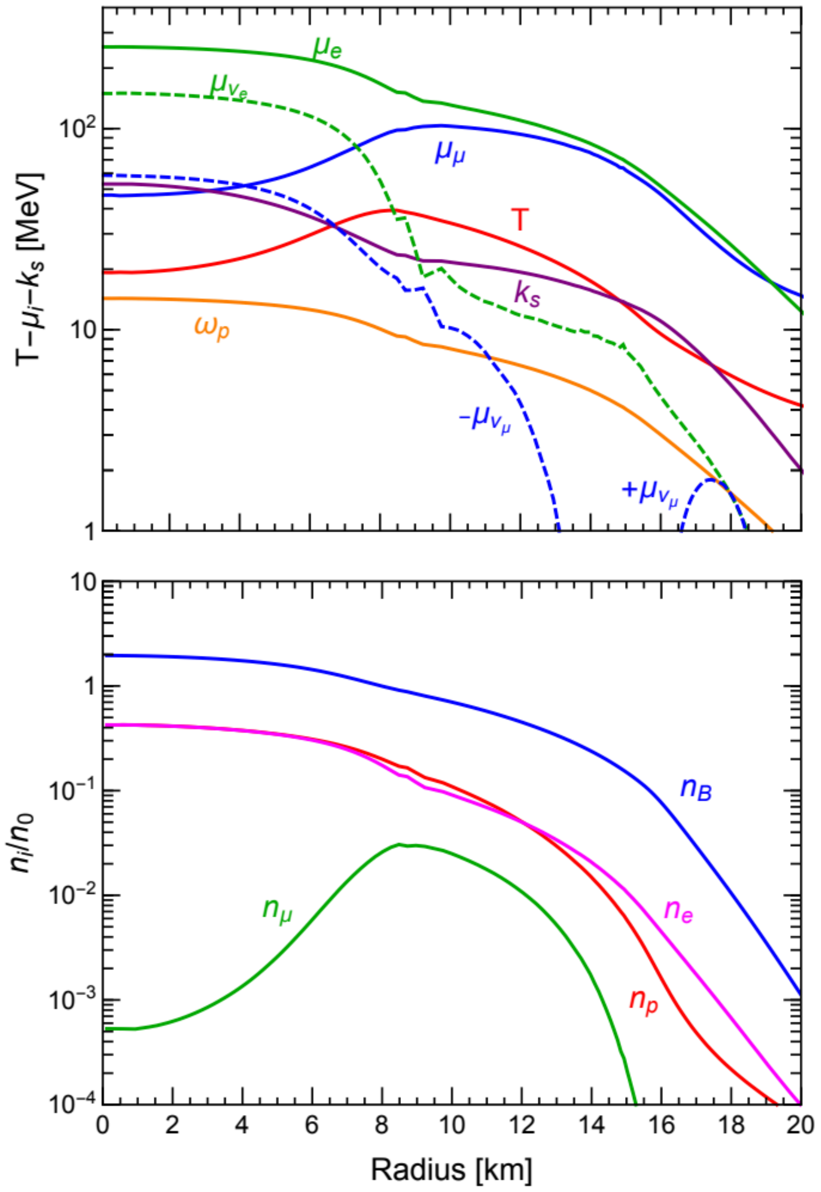
- In the future:

1. Radiative transport and light curves;
2. Next galactic SN?

Thanks for the attention!

Back up slides

Garching SN model

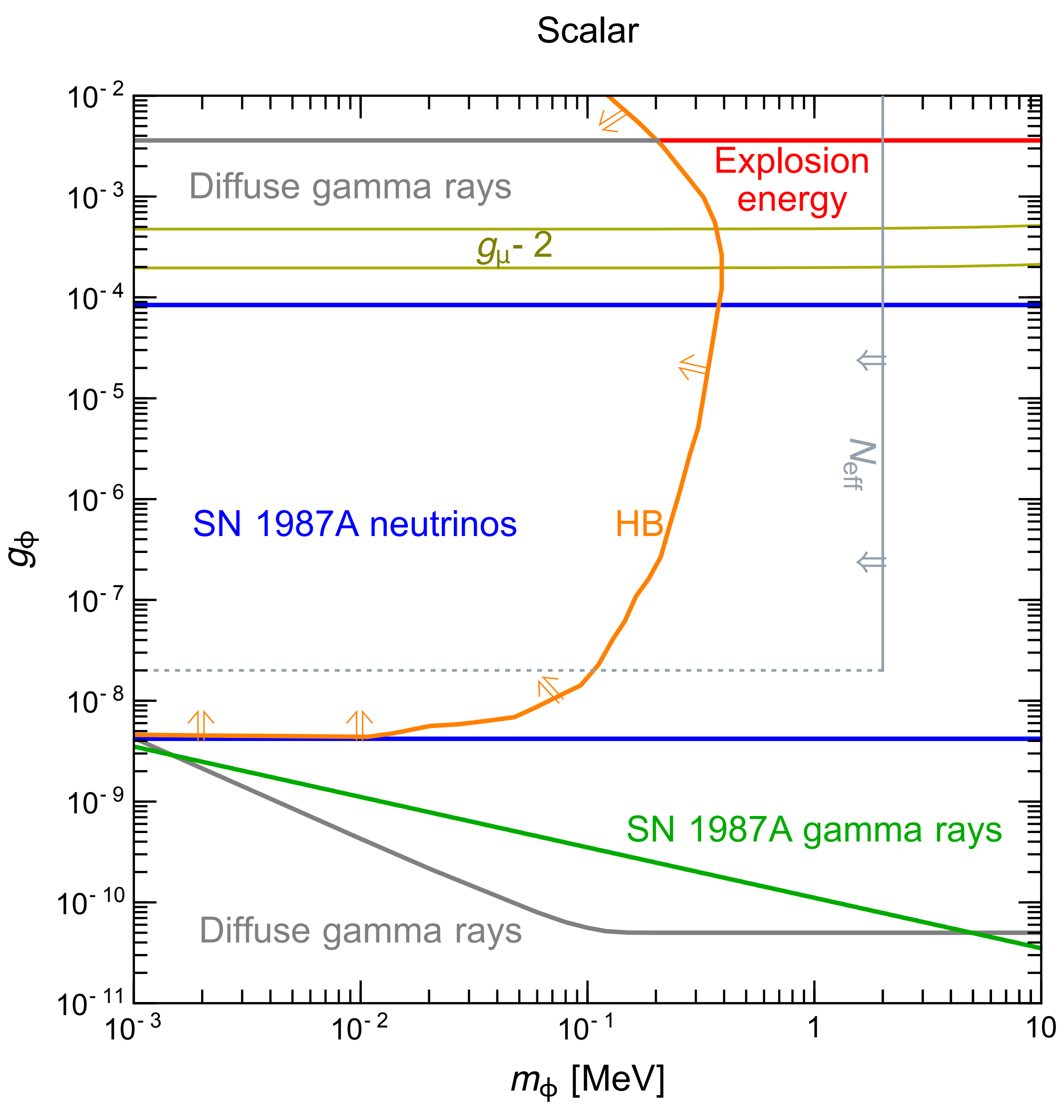


Cosmological bounds

$$\rho_{\rm rad} = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_{\rm CMB}$$

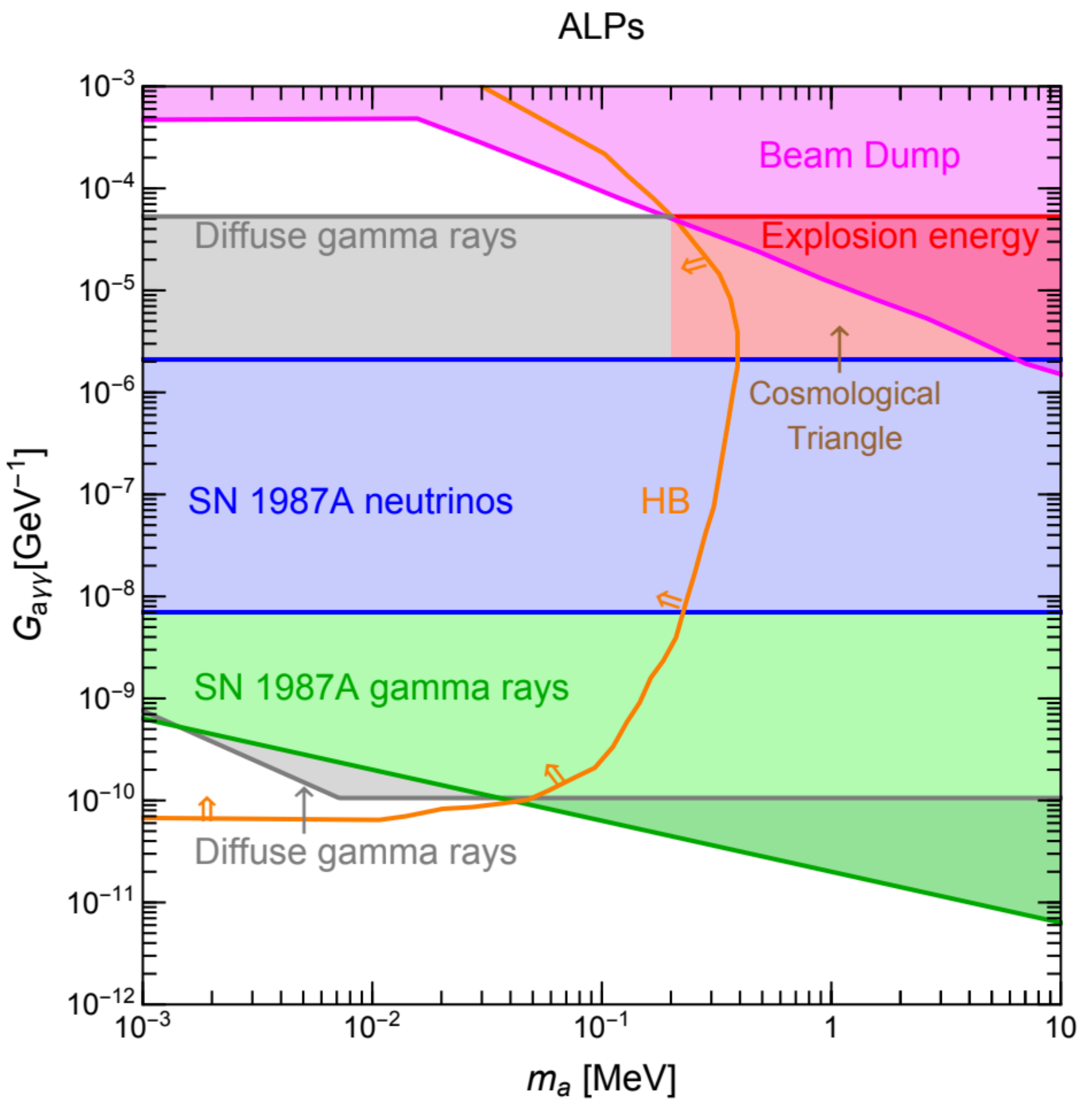
New particles usually add to N_{eff}, our case is different and reduces it. Early on, the new bosons are in equilibrium with muons, providing more radiation. However, if they decay radiatively after neutrino decoupling, they will heat the photons so that later the CNB will yet colder than the CMB, an effect that reduces N_{eff}.

This arguments exclude masses below 2 MeV, for couplings that are large enough to get the boson thermalized with the SM.

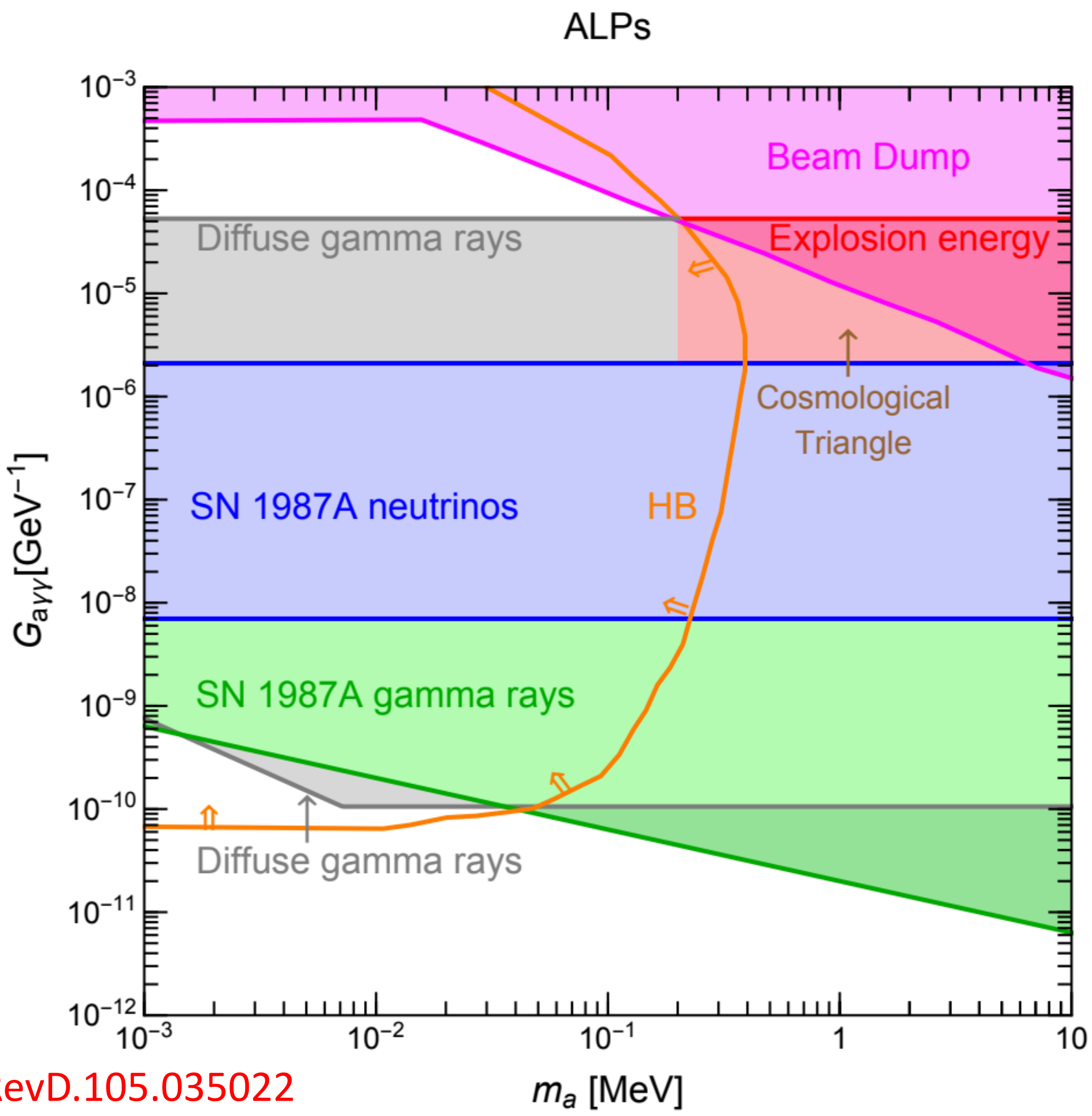


Collider bounds

For masses above 1–10 MeV, muonphilic particles can also be efficiently probed at colliders. In particular, electron beam-dump experiments, such as the SLAC E137 experiment or the planned Jefferson Lab BDX experiment provide an excellent source of secondary muons, which can then be used to look for muonic (pseudo)scalars.



We close the cosmological triangle for ALPs!



PhysRevD.105.035022

Recently some efforts have been dedicated to close the cosmological triangle for ALP using future accelerator-based neutrino experiments (V. Brdar et al., Phys. Rev. Lett. 126, 201801 (2021)) and also CERN Gamma Factory (R. Balkin et al., *Annalen Phys.* (2021)).

It seems that SN physics already closes up the allowed parameter space! Once again astrophysical probe turns out to be quite powerful.