A fresh look on the limit on light ALPs from SN1987A

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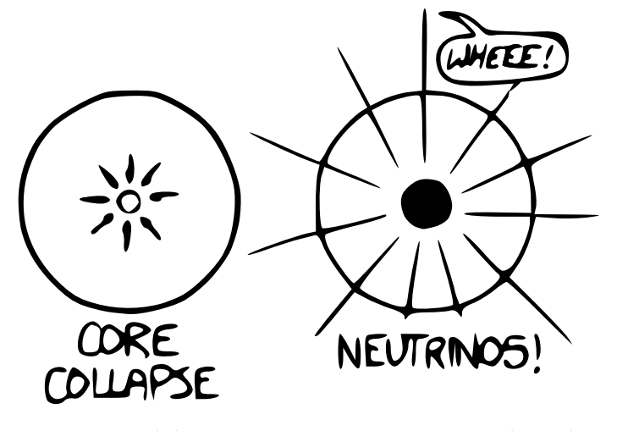
Reminder

When a very massive star undergoes a core-collapse, lots of neutrinos are quickly radiated by the proto-neutron star, leading to a short, intense ν burst (hours before the optical flash).



http://what-if.xkcd.com/73/

Such supernova (SN) explosions are also an ideal place to search for extremely light axion-like particles (ALPs) a with a generic two-photon interaction, of effective coupling $g_{a\gamma}$:

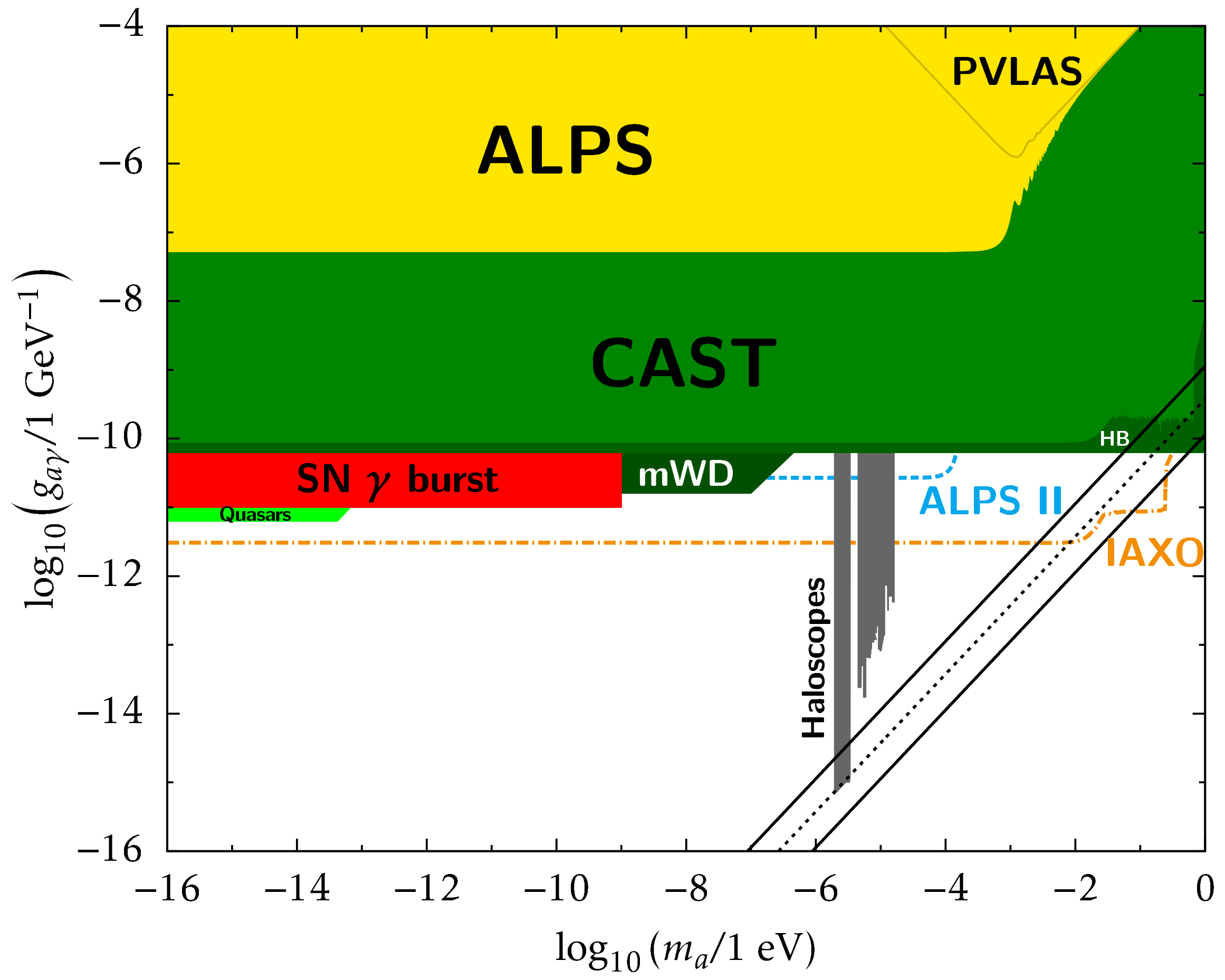
$$\mathcal{L}_{a\gamma} = \frac{1}{4}\, g_{a\gamma} F_{\mu\nu}\tilde{F}^{\mu\nu} a. \qquad (1)$$

Produced with typical energies related to the core temperature, these spinless particles should convert in the Galactic magnetic field into γ-ray photons, coincidental with the ν burst [1, 2].

SN1987A, in the Large Magellanic Cloud (only 50 kpc away)

- ν burst detected (Kamiokande, IMB, Baksan)
- 3σ upper limit on the γ signal during the ν burst (~ 10 s) from the Gamma Ray Spectrometer (SMM satellite):

$$\text{total fluence } < 0.6\ \gamma\ \mathrm{cm}^{-2} \text{ in the range } 25\text{–}100\ \mathrm{MeV}. \qquad (2)$$



Objectives

Our aim is to obtain a more precise bound, using:

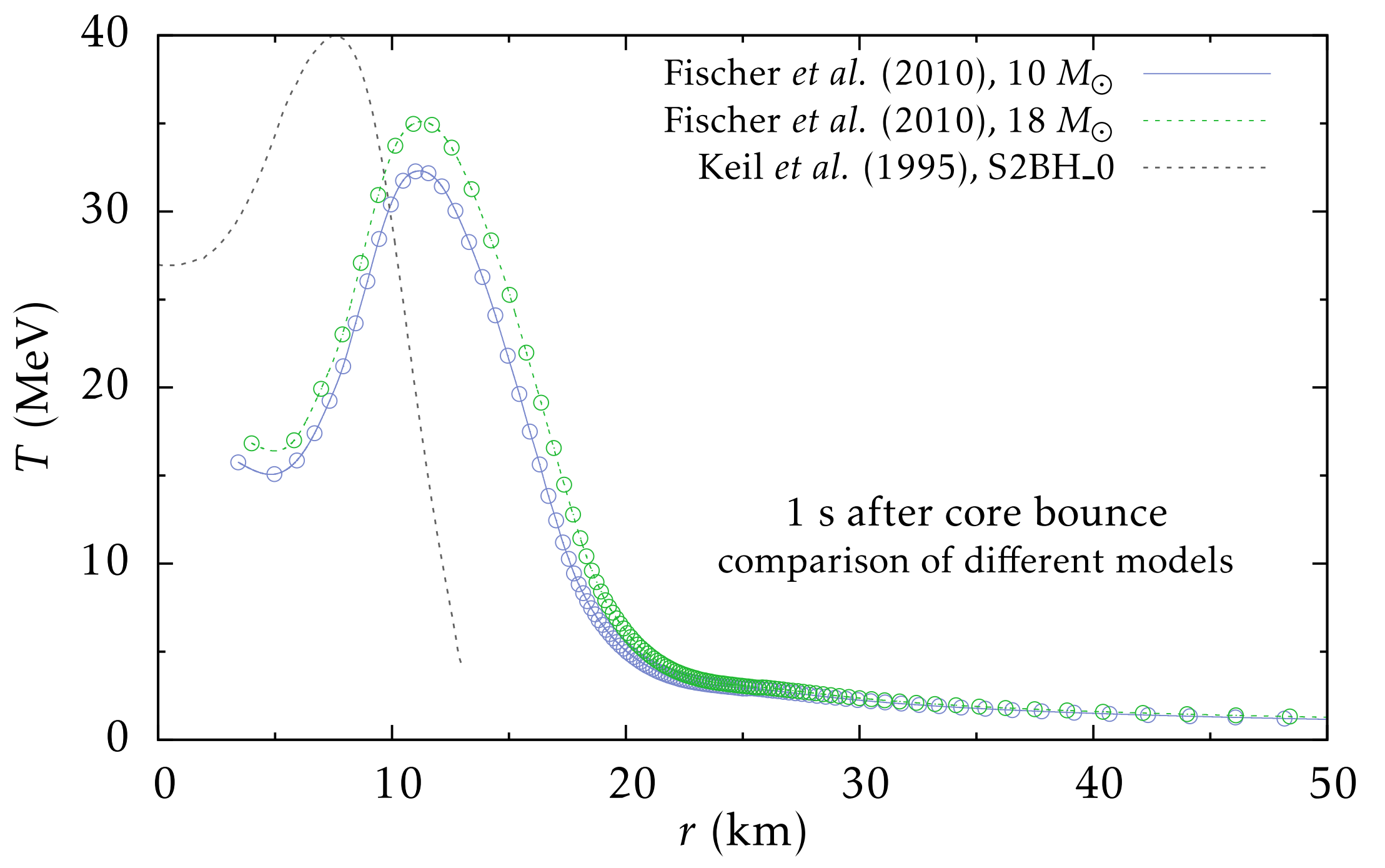
- recent SN simulations, with a good time resolution;
- a modern model of the Galactic magnetic field;
- give the ALP-mass dependence of the limit;
- include degeneracy & mass-reduction effects;
- investigate the dependence on the progenitor mass.

I. Supernova Simulations & Time Resolution

The original analysis [1] was based on simulation data for three values of the after-bounce time: 1 s, 5 s, and 10 s.

Updated spherically symmetric model [3] for a progenitor of 18 $M_\odot$ (resp. 10 $M_\odot$), with simulations up to 21 s (resp. 10 s) after bounce, described by ~ 600 snapshots in both cases.

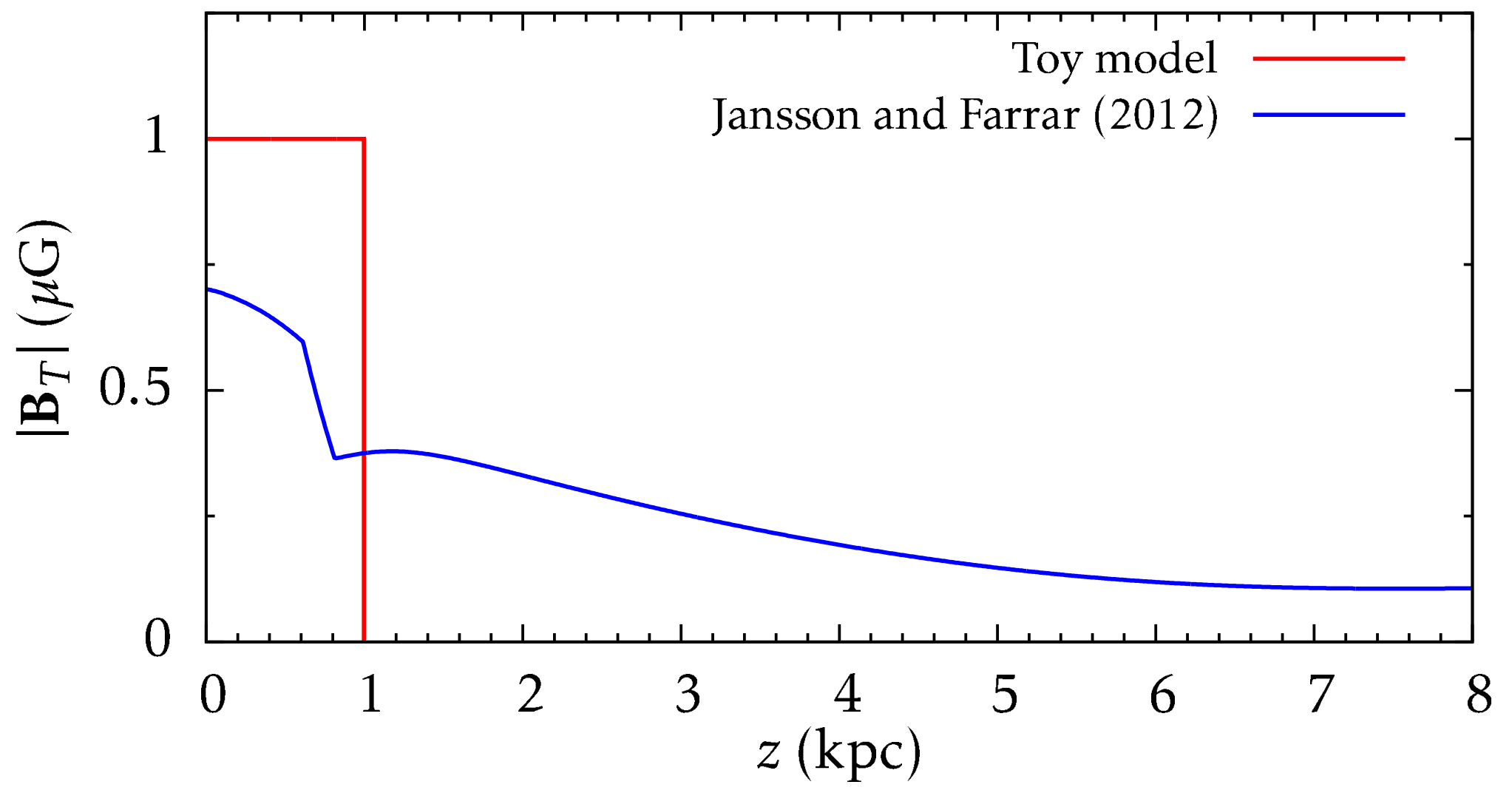
We have a collection of snapshots at different times of the profiles of various physical quantities inside the protoneutron star as a function of the radius.



II. Magnetic Field & Conversion Probability

We make a great improvement for the description of the magnetic field, as it used to be a slab of constant magnetic field.

We now use the recent Jansson–Farrar model of the Galactic magnetic field [4]. In the direction of SN1987A, the field strength $|\mathbf{B}_T|$, in each case, evolves schematically as follows:



Both the original papers [1, 2] also used an approximate expression of the conversion probability, valid in the massless limit:

$$P_{a\gamma} = \sin^2(2\theta)\sin^2\!\left(\frac{\Delta\mu^2 L}{4E}\right) \sim \frac{1}{4}\, g_{a\gamma}^2 B_T^2 L^2, \qquad (3)$$

and estimated to hold for $m_a \le 10^{-9}$ eV in this problem.

Here, we have the full conversion probability and are therefore able give the precise mass dependence of the limit.

III. Degeneracy & High Density

In the conditions of the SN core:

- e^- are relativistic and their phase space is Pauli blocked;
- p^+ are non-relativistic and partially degenerate.

ALPs are produced via the Primakoff effect on p^+ [1, 2]:

$$p^+ + \gamma \to p^+ + a \qquad (4)$$

with a volume production rate per unit energy

$$\frac{\mathrm{d}\dot{n}_a}{\mathrm{d}E} = \frac{g_{a\gamma}^2 \xi^2 T^3 E^2}{8\pi^3\left(e^{E/T}-1\right)}\left[\left(1+\frac{\xi^2T^2}{E^2}\right)\ln\left(1+\frac{E^2}{\xi^2T^2}\right)-1\right], \qquad (5)$$

where $\xi^2 \equiv \kappa^2/4T^2$ and κ is the inverse screening length.

Original analysis: consider only $t \ge 1$ s, neglect the degeneracy. We modify the Primakoff cross section to include the effect of partial p^+ degeneracy on the number of available targets for the ALP production, but also on the screening length, which is then between the Debye and the Thomas–Fermi regimes.

Moreover, due to the extremely high density during the first seconds ($\rho \sim 10^{14}\ \mathrm{g\ cm^{-3}}$), the p^+ effective mass can go down to about 50% of its value in the vacuum. We further take this mass reduction into consideration, and use the updated EOS tables (2010, 2011) based on [6].

Take-Home Message

With these improvements, the bound is slightly more stringent. The results are very stable over a variety of changes mostly because the limit on $g_{a\gamma}$ essentially goes as the fourth root of the fluence.

Discussion

The total production rate $\frac{\mathrm{d}\dot{N}_a}{\mathrm{d}E}$ is obtained by integrating Eq. (5) over the SN volume (no extrapolation at low r), for radii up to 50 km, to be fully consistent with the EOS of [6].

- the degeneracy diminishes the production slightly;
- mass effects are needed to get the correct number of targets;
- there is a stronger conversion (mostly due to the halo).

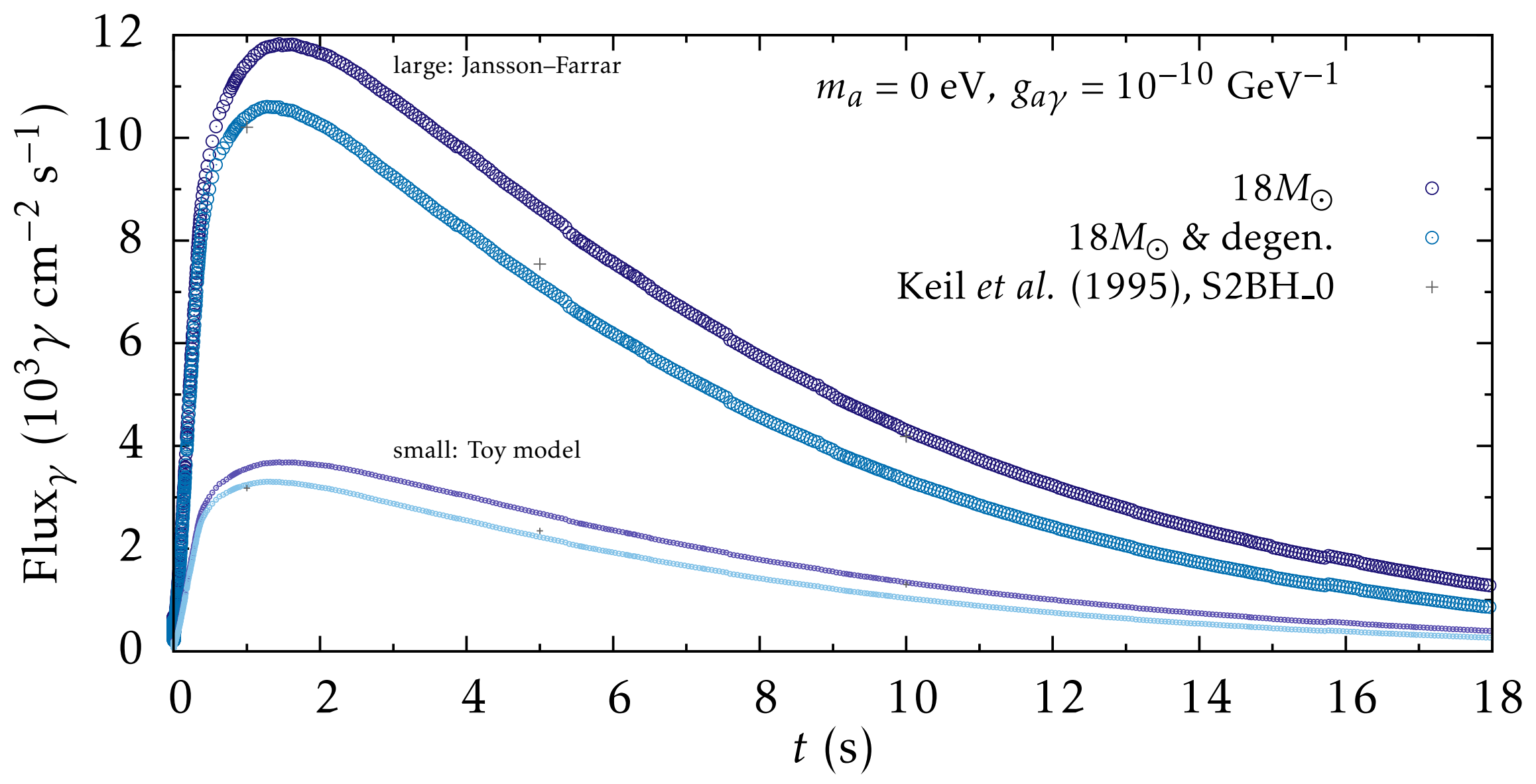
The gamma flux at Earth is then obtained by integrating

$$\frac{\mathrm{dFlux}_\gamma}{\mathrm{d}E} = \frac{1}{4\pi d^2}\frac{\mathrm{d}\dot{N}_a}{\mathrm{d}E}P_{a\gamma} \qquad (6)$$

in the energy range 25–100 MeV (SMM), with d the distance from Earth to SN1987A. The time integral of the flux over the neutrino burst duration gives us the fluence that we need.

The limit on $g_{a\gamma}$ goes as the fourth root of the fluence; it does not change very much, even with different progenitor masses. We also investigate the stability of our results under many changes, including another magnetic field model [5].

Flux

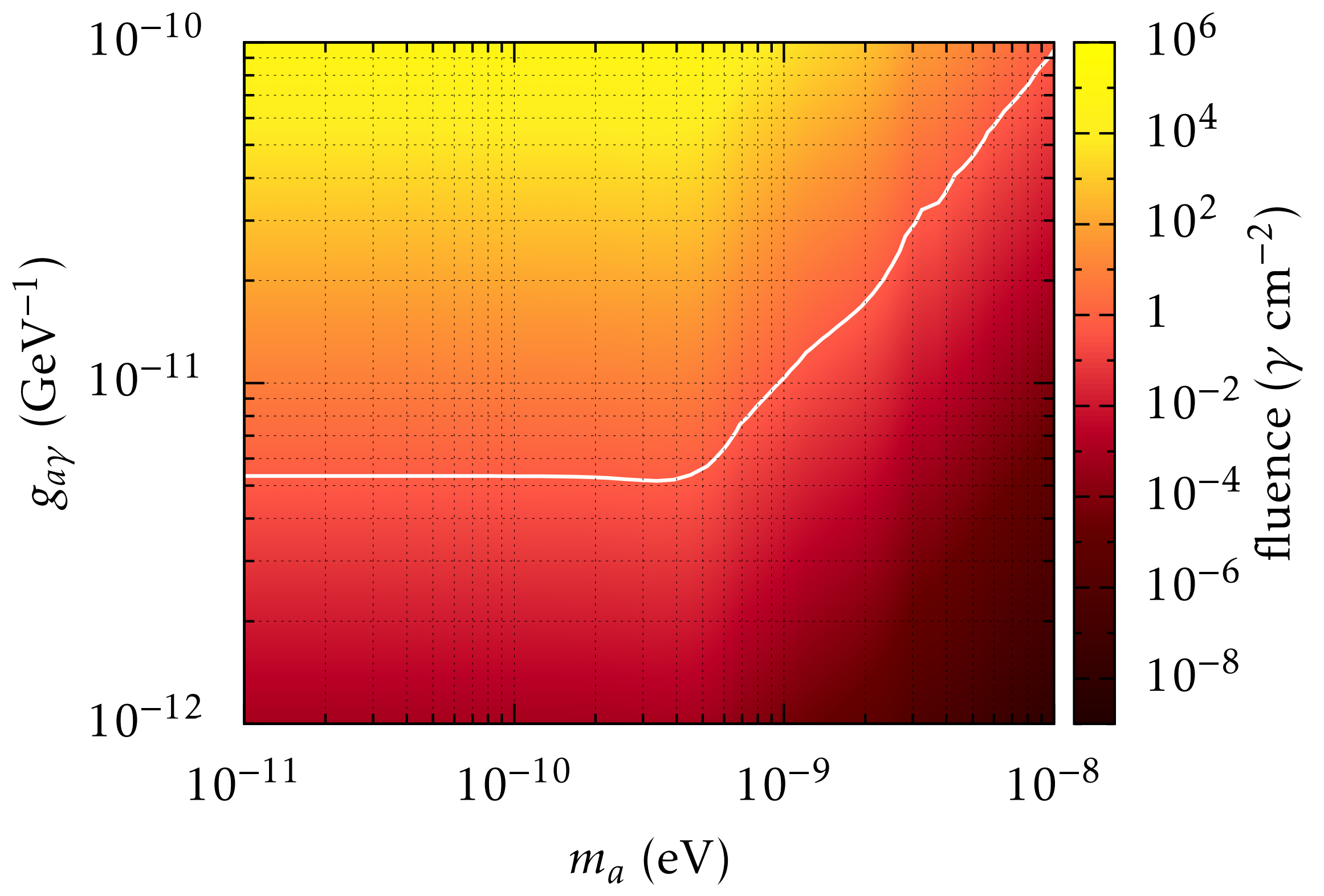


Maybe surprisingly at first, the largest effect of degeneracy on the flux is not at times $t < 1$ s. This is because ALPs are mostly produced where the temperature is the highest.

In the proto-neutron star, the temperature is affected by neutrino processes (which completely dominate the energy loss): at early times, the maximum of temperature is a few km from the SN center, and moves towards the center as time evolves. Initially, it is therefore not where the degeneracy is the largest.

Fluence & New Bound

Our updated upper limit on $g_{a\gamma}$ (18 $M_\odot$ and Jansson–Farrar):



In the event of a similar close-by SN explosion in the near future, with the Fermi-LAT sensitivity above 100 MeV, we might reach values of $g_{a\gamma}$ even lower than 10^{-12} GeV^{-1}.

References

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