New Bounds on Axions from Supernovae

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Based on:

New constraints for heavy axion-like particles from supernovae, JCAP 1101:015,2011.

In collaboration with:
L.Duffy, *Los Alamos National Laboratory*, R.Nita, *Florida Tech*

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Summary

- Axions: Theory, phenomenology, and experimental bounds

- "Standard" and "non-standard" axion models

-Supernovae constraints on heavy axion models

- Conclusions

The Axion

Axions are hypothetical particles whose existence is related to the Peccei-Quinn (PQ) solution of the Strong CP problem.

R. Peccei and H. Quinn (1977)

The PQ solution, considered the most elegant solution of this problem, predicts the existence of a new (pseudo)scalar particle, the axion. Today, axions are also considered strong CDM candidates.

S. Weinberg (1978), F. Wilczek (1978)

If it were found, the axion would be the first spin zero elementary particle to be discovered, it would confirm the PQ solution of the strong CP problem, and, possibly, it would explain the origin of the CDM component of the universe.

After being hunted (unsuccessfully) for more that 30 years, today the research in axion is experiencing a revival in terms of new experimental efforts for its detection, and new theoretical ideas and models. About 100 papers were published in 2010 about axions, and many have already been published this year.

The Axion: General Considerations

The axion properties depend on the

PQ-constant → f_a

$$g_{a\gamma} \approx \frac{\alpha_{em}}{2\pi \ f_a}$$

Photons

Interactions

$$L_{\text{int}} = -i\,\frac{C_i m_i}{f_a}\, a\,\overline{\psi}\gamma_5\psi - \frac{1}{4}\; g_{a\gamma}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Matter (fermions)

Mass

(Standard Axion)

$$m_a \approx \frac{6\,\text{eV}}{f_a/10^6\,\text{GeV}}$$

In order to escape detection, the axion must be very weakly coupled. That is why it is know as the *invisible axion.*

Why Invisible ? The astrophysical argument

Early terrestrial experiments showed that, in order to escape detection, $f_a > 10^4$ GeV

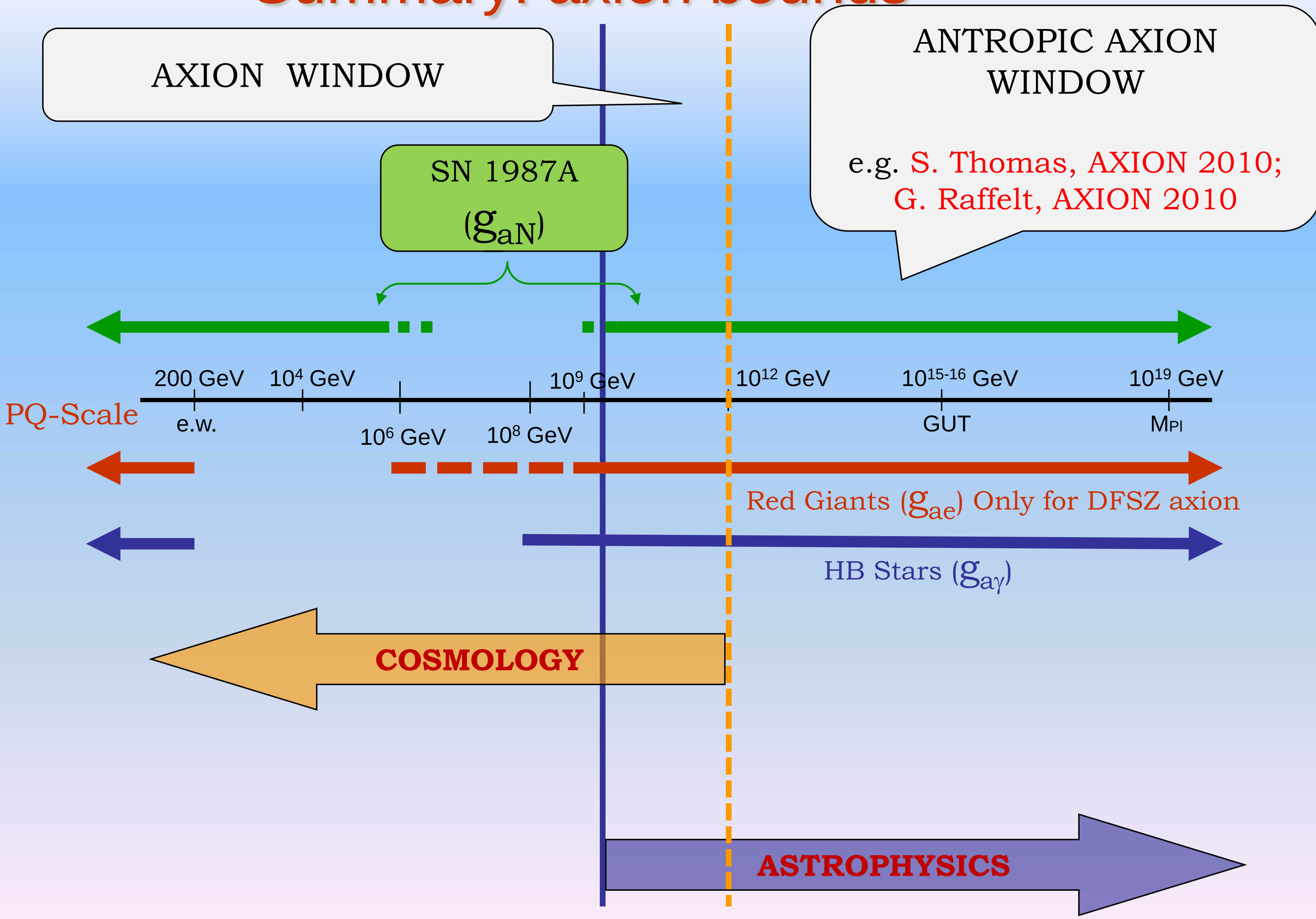
$$m_a \approx \frac{6\,\mathrm{eV}}{f_a/10^6\,\mathrm{GeV}} \Rightarrow m_a < 0.6\,\mathrm{keV}$$

So, the axion is light

Over-production in stars:
The emission of light particles would lead to an *overly efficient energy drain*, inconsistent with observations.
Unless
the axion interactions are strongly reduced:

$f_a > 10^9$ GeV

Summary: axion bounds



Non-standard Axions

If the standard relation between the axion mass and the PQ constant

$$m_a \approx \frac{6\,\mathrm{eV}}{f_a / 10^6\,\mathrm{GeV}}$$

is relaxed, the axion window opens up. Several models predict the existence of axion-like particles (ALPs), for which the above relation is not verified. In some cases, the ALPs are very light. In some other cases, they are heavy.

Today, the general approach to study this sector of particle physics is phenomenological: No relation is assumed between the axion mass and couplings, and the full axion parameter space is studied.

For light ALP, the stellar energy loss argument is still valid.

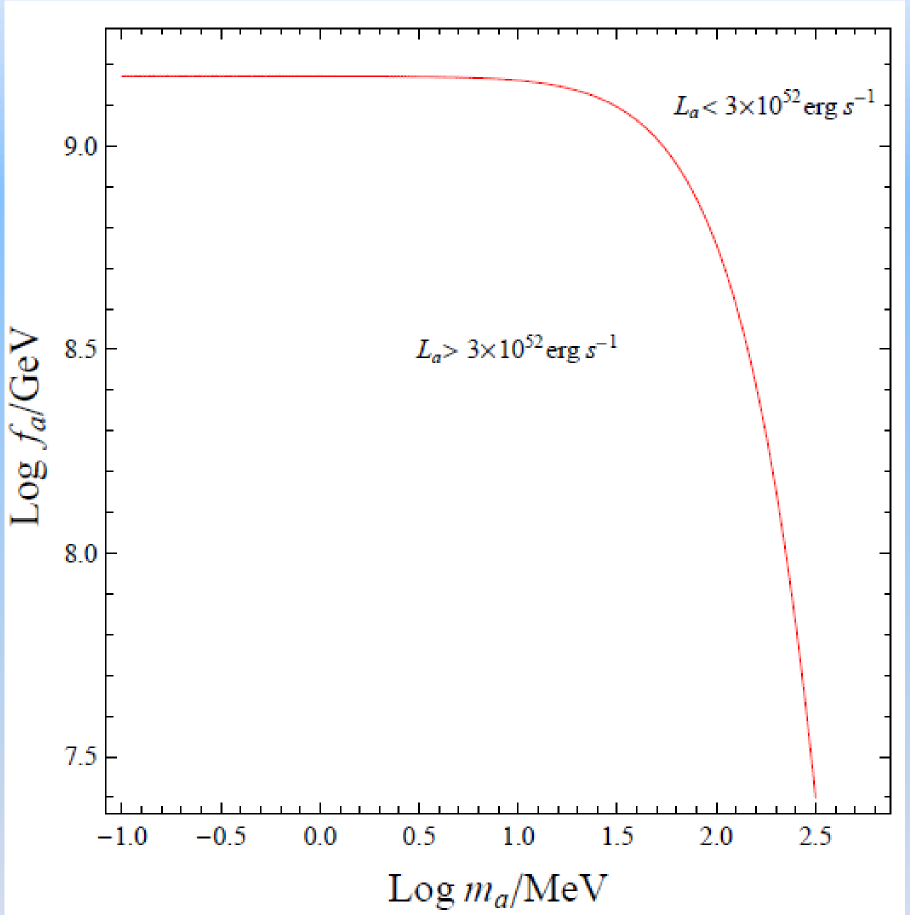
Can astrophysics offer good arguments also for heavy axions?

Bounds on the PQ constant for heavy Axions

If axions are heavier than a few times the core temperature of a star, the production rate is dumped. So, the bounds from stellar cooling are, in general, independent from the axion mass, up to a certain mass, and then they become very weak.

From low mass stars, we cannot expect to derive constraints on axions heavier than 100 keV or so.

The figure shows how the axion bound from SN 1987A is dumped when axions are heavier than the core temperature ~30 MeV.



From M.G. L.Duffy, R.Nita JCAP (2011), axion OPE production from M.G., F. Nesti (2005)

Heavy Axion Like Particles (HALPs)

Several models predict heavy (~1keV to 1 GeV), weakly coupled axions

V. Rubakov (1995), to overcome the problems from the Planck scale induced terms;

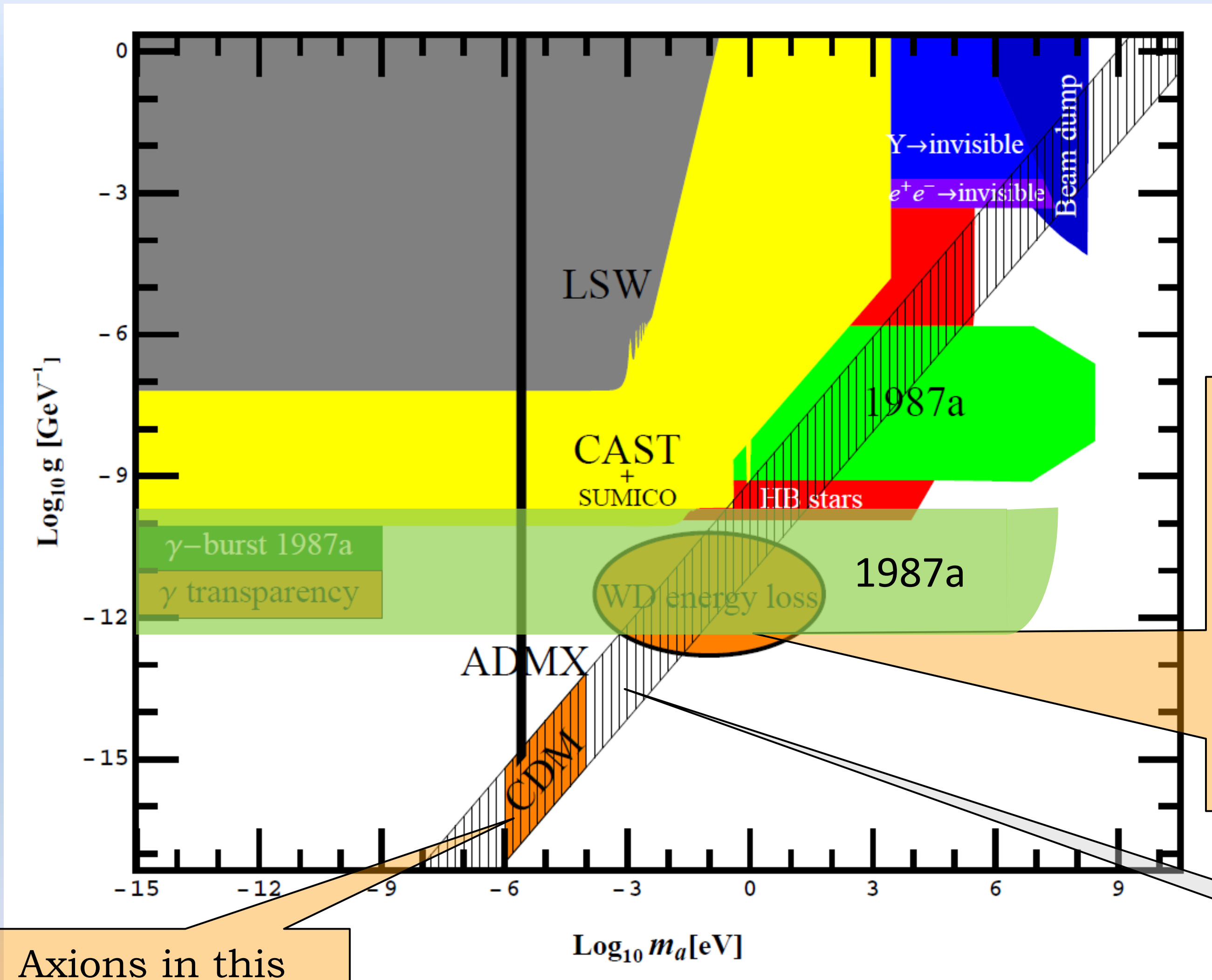
A.Berezhiani, Drago (1999), to explain some features of GRBs;

K.R.Dines, E.Dudas,T.Gherghetta (2000); L. Di Lella, A. Pilaftis, G. Raffelt, K. Zioutas (2000), KK-modes of the standard axions. Might help explain the value of f_a.

Z. Berezhiani, L. Gianfagna, M.G (2004); L. Gianfagna, M.G, F. Nesti (2004), axions from hidden sector. For GRBs and Planck induced terms.

In the models of axions interacting with a hidden sector, the axion still solves the strong CP.

Axion-Like Particles



Bounds on axion-photon coupling

$$g_{a\gamma} \approx \frac{8\times 10^{-4}}{f_a}$$

Some anomalous energy loss in WD could be explained by axions with this mass and coupling.

→ J.Isern, E.Garcia-Berro, S. Torres, S. Catalan (2008, 2010)

Axions in this region of the parameter space would be CDM

From J. Jaeckel and A. Ringwald, The Low-Energy Frontier of Particle Physics, (2010).

Standard axion

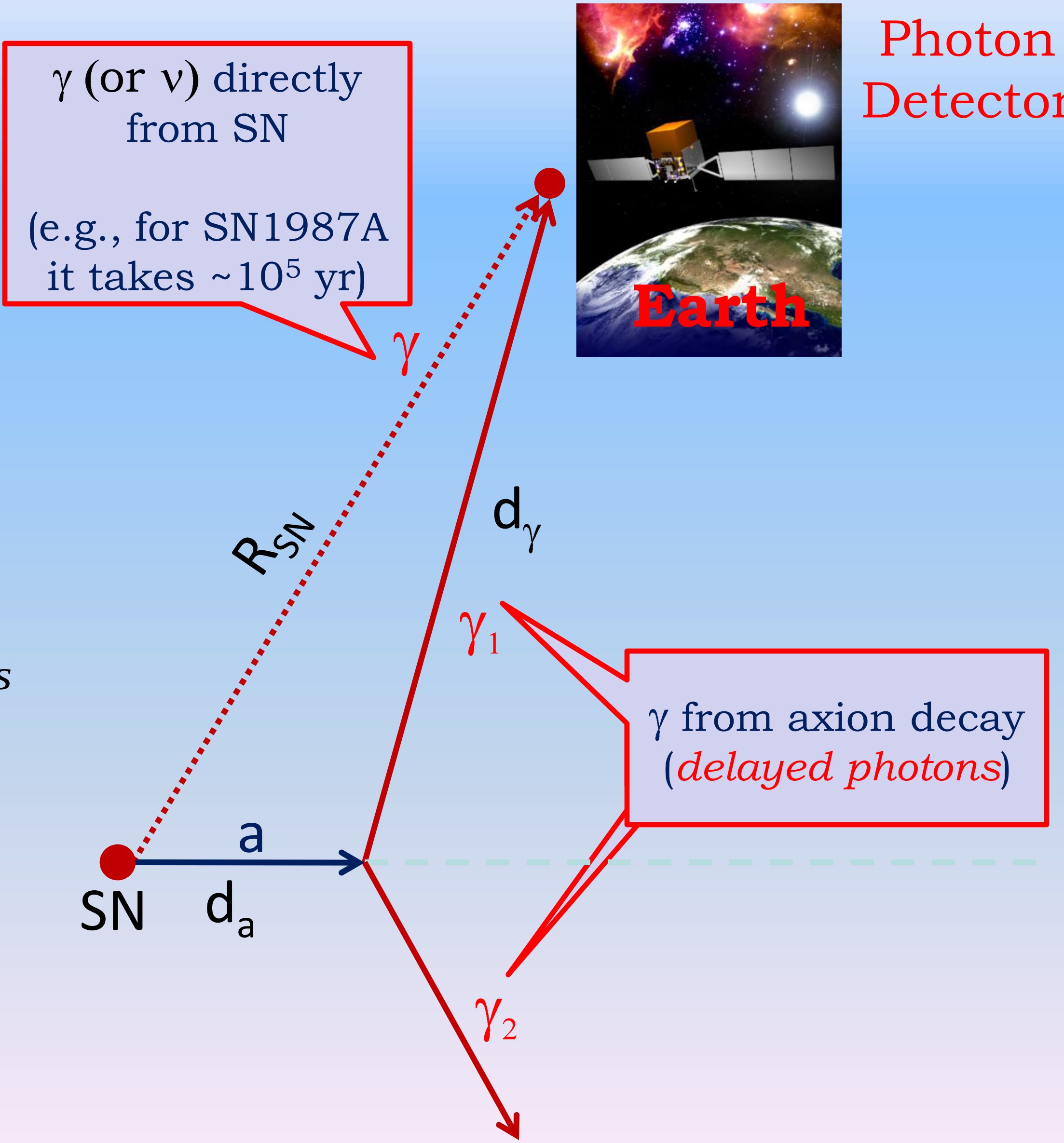
Hunting the Invisible Particle

- The axions produced in the SN core travel in space and after a certain time t_a they decay into 2 photons (γ).

- The number of axions which decay after a time t_a can be expressed in terms of the axion lifetime.

$$\tau_a \approx 1.7\times 10^{17}\left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{2}\left(\frac{m_a}{1\mathrm{MeV}}\right)^{-3} s$$

- The spectrum of photons arriving today can be calculated in terms of the time from the SN event, the axion mass, and the PQ constant.

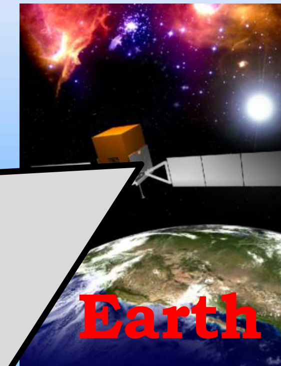


Hunting the Invisible Particle

Photon Detector:
The Fermi Large Area Telescope (Fermi-LAT)

The Fermi Large Area Telescope is a detector designed to detect high-energy gamma-rays up to 300GeV.

The point source sensitivity of the Fermi-LAT, at the latitudes of the SNe we are considering, is $< 6 \times 10^{-9}$ photons cm^{-2}s^{-1} for photons of energies $\omega_\gamma \geq 100$ MeV.



Photon Detector

γ

γ from axion decay
(*delayed photons*)

γ_2

the

PQ constant.

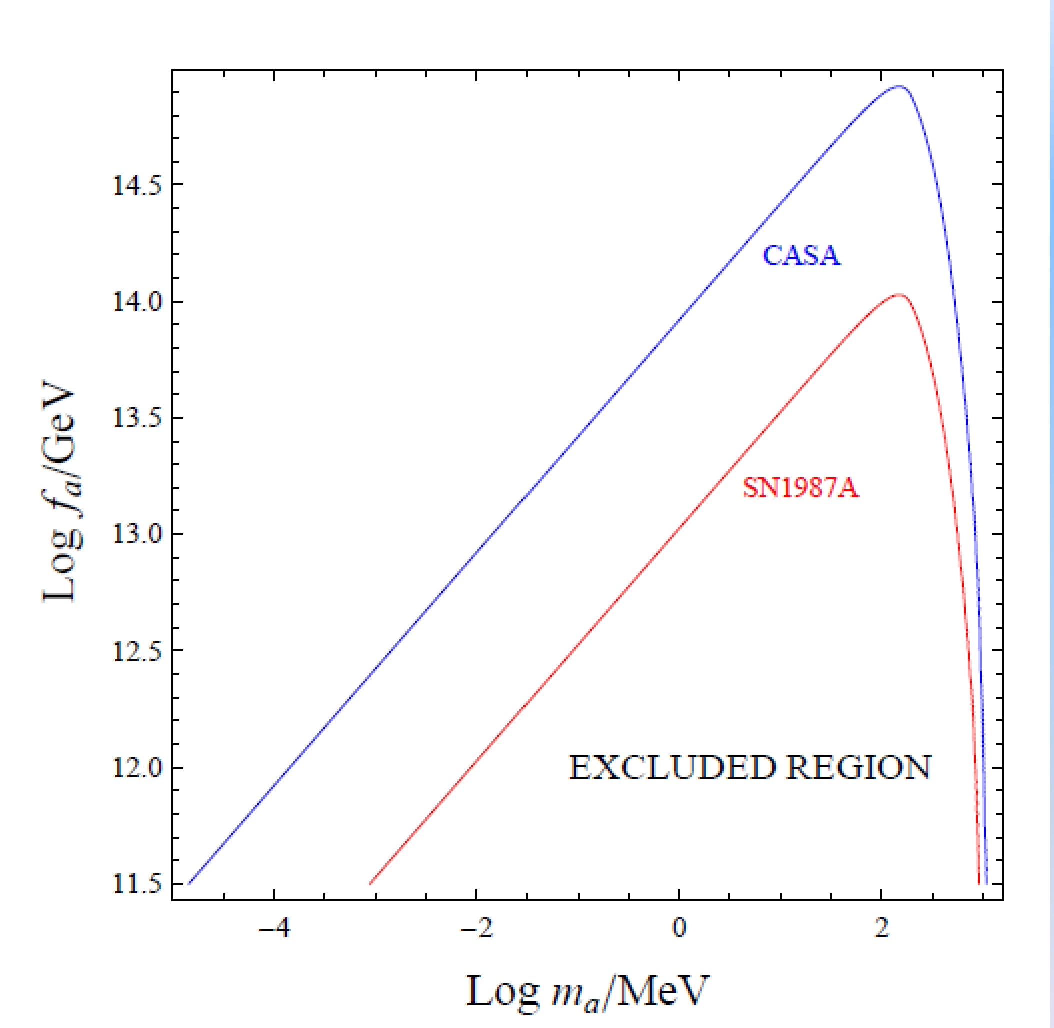
Bounds from Fermi-LAT

We can calculate the flux of photons with energy > 100MeV, and compare with the data from the Fermi Large Area Telescope.

Our bounds, from the analysis of SN1987A and Cassiopeia A are shown on the side.

These constraints translate into bounds on the axion-photon coupling by using

$$g_{a\gamma} \approx \frac{8\times 10^{-4}}{f_a}$$



From M.G. L.Duffy, R.Nita, JCAP (2011)

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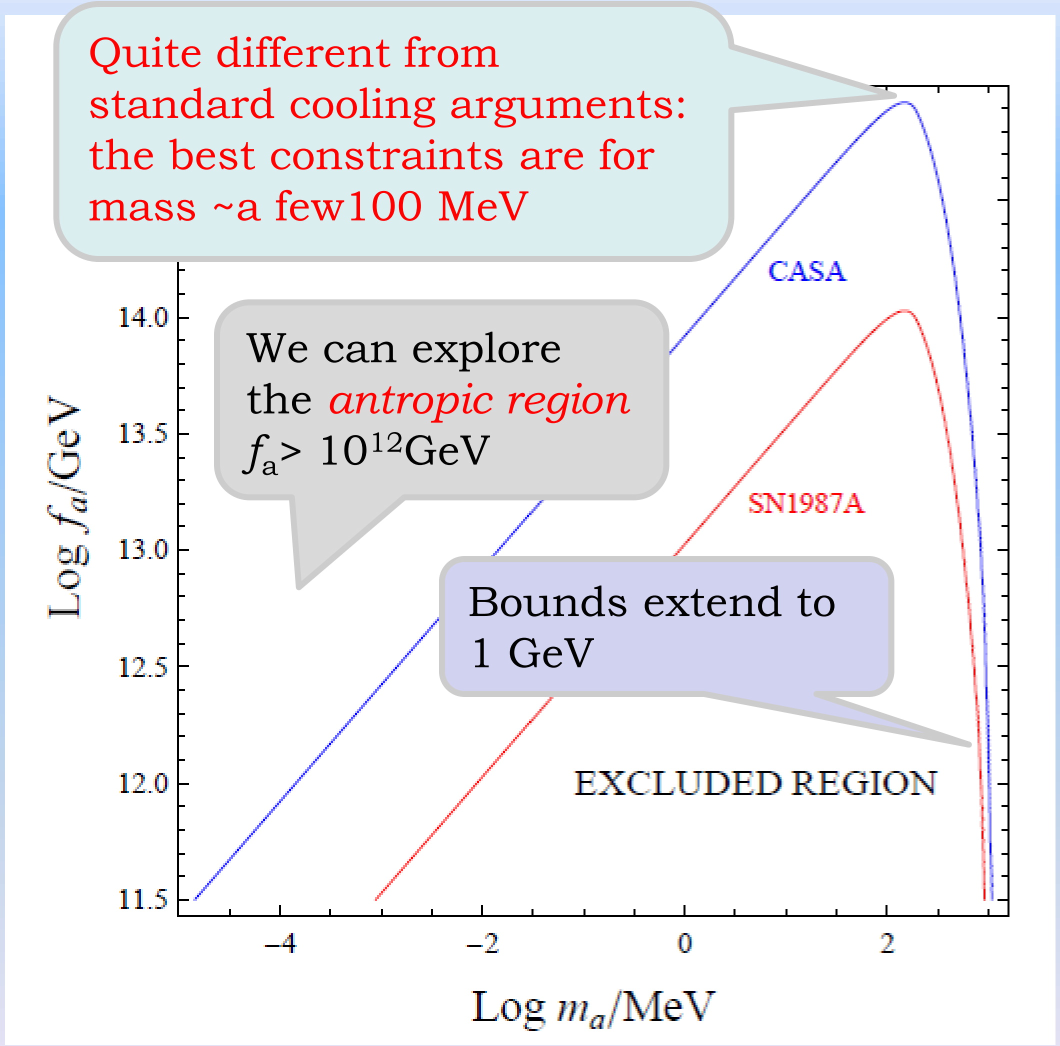
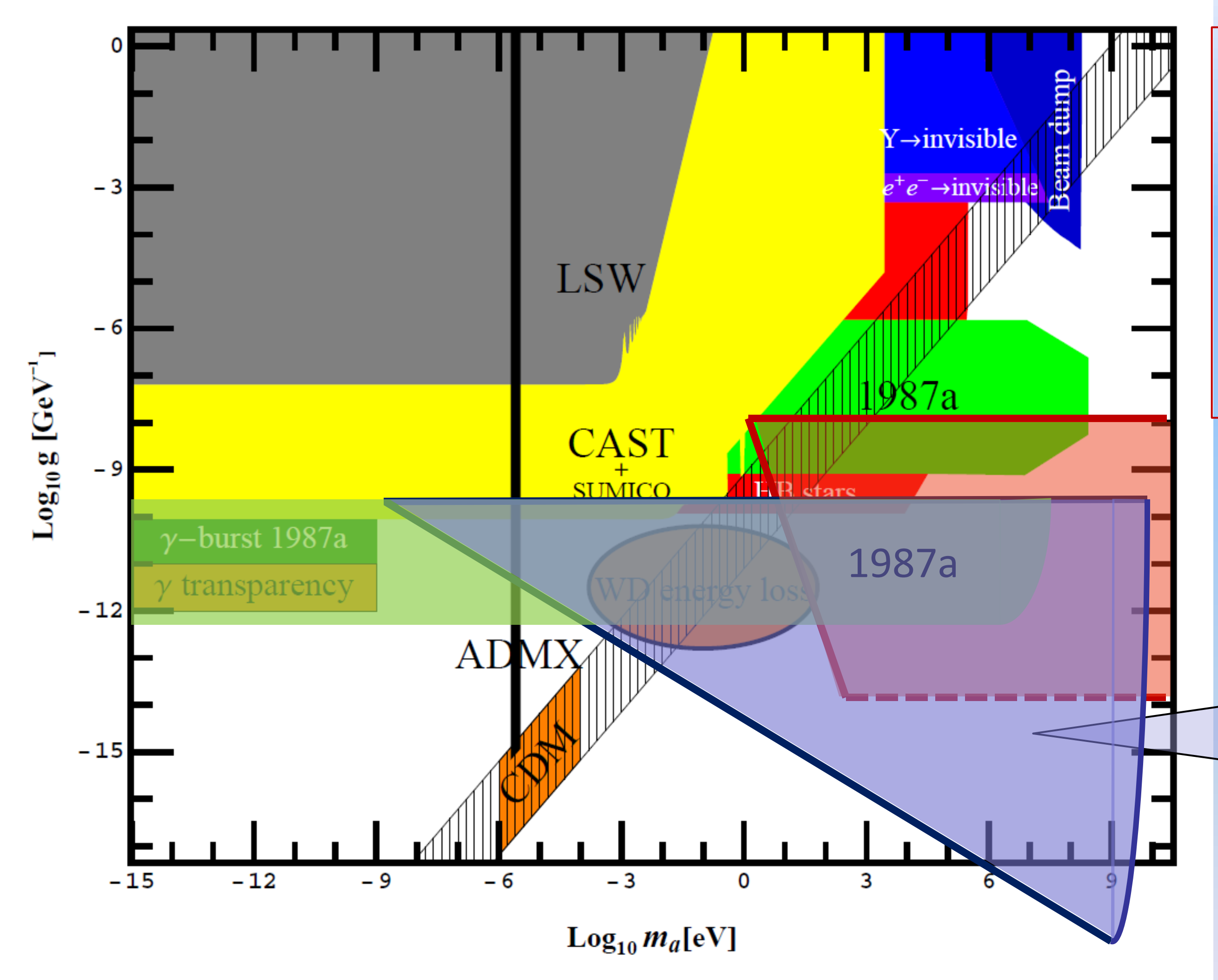


From M.G. L.Duffy, R.Nita JCAP (2011)

New Constraints on Axion-Like Particles



Bounds on axion-photon coupling

$$g_{a\gamma} \approx \frac{8\times 10^{-4}}{f_a}$$

Constraints from *delayed photons* from SN → M.G., L.Duffy, R.Nita (2011)

Conclusions

- Astrophysics, and in particular stellar astrophysics, is a very powerful tool to constrain physics beyond the standard model

- We have analyzed the photon flux expected today from the decay of axion-like particles produced in the SN core, and compared the results of our analysis with the data from the Fermi Large Area Telescope (Fermi-LAT).

  The results of our analysis provide very strong constraints in an unexplored region of the axion parameter space, and new constraints for standard axion models.

- Improving the (gamma) photon detection could provide an indirect way to detect axions.

- Future perspectives:
  - Apply to existing models, e.g. to axions from large extra dimensions
  - Generalize the idea to other hypothetical particles coupled to photons
  - ?


Thank
You