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GAMMA-RAY LIMIT ON AXION-LIKE PARTICLES FROM SUPERNOVAE

Alessandro MIRIZZI
University of BARI & INFN BARI, Italy

OUTLINE

- Introduction to SN & ALPs

- ALPs bound from SN 1987A

[Payez, Evoli, Fischer, Giannotti, A.M. & Ringwald, 1410.3747]

- FERMI-LAT as SN ALPscope

[Meyer, Giannotti, A.M., Conrad & Sanchez-Conde, to appear soon]

- Conclusions

PLEIADVM CONSTELLATIO.

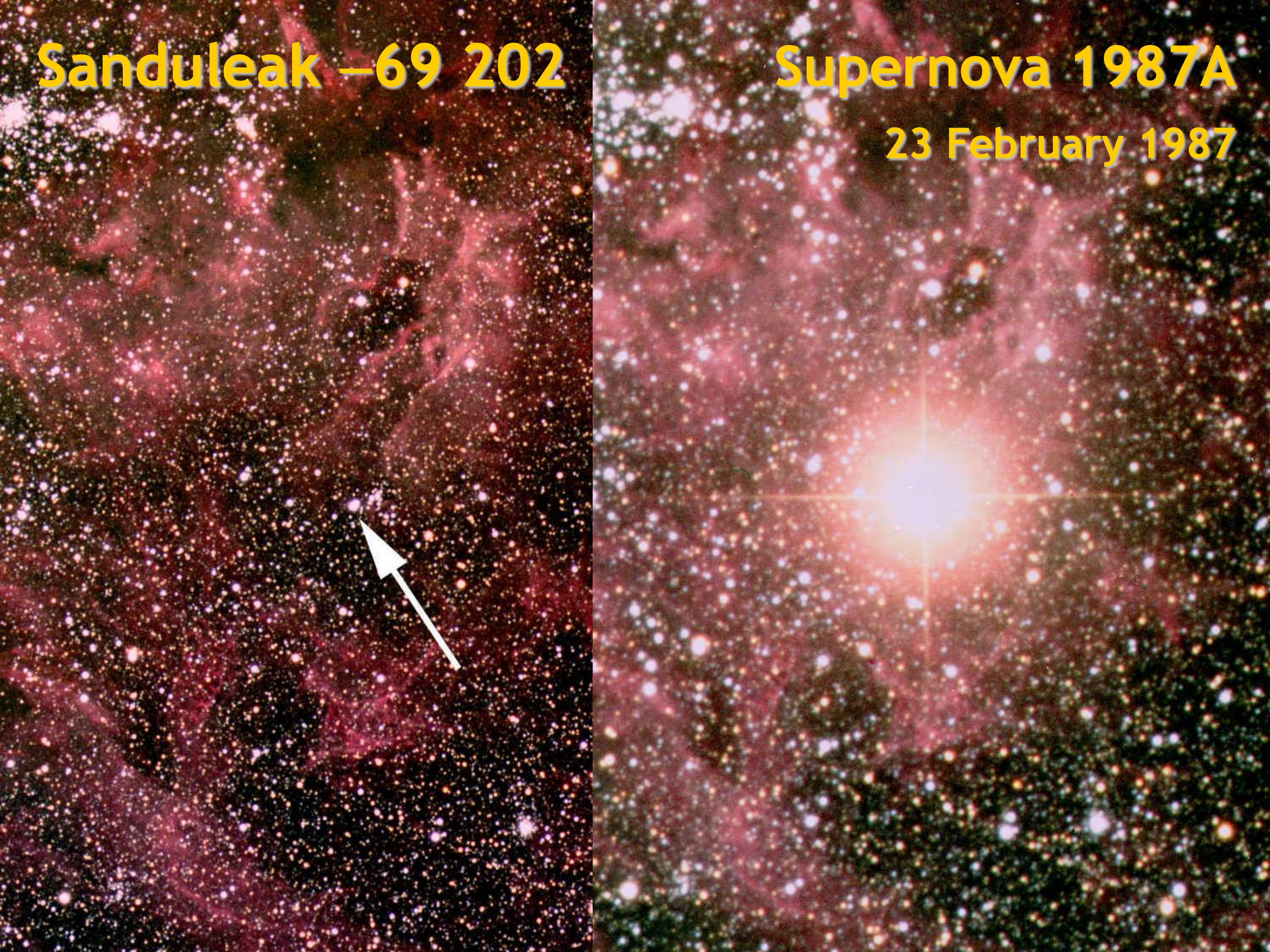
Quod tertio loco à nobis fuit obſeruatum, eſt ipſiuſmet LACTEI Circuli eſſentia, ſeu materies, quam Perſpicilli beneficio adeò ad ſenſum licet intueri, vt & altercationes omnes, quæ per tot ſæcula Philoſophos excruciarunt ab oculata certitudine dirimantur, noſque à verboſis diſputationibus liberemur. Eſt enim GALAXYA nihil aliud, quam innumerarum Stellarum coaceruatim conſitarum congeries; in quamcunq; enim regionem illius Perſpicillum dirigas, ſtatim Stellarum ingens frequentia ſe ſe in conſpectum profert, quarum complures ſatis magnæ, ac valde conſpicuæ videntur, ſed exiguarum multitudo prorſus inexplorabilis eſt.

At cum non tantum in GALAXYA lacteus ille candor, veluti albicantis nubis ſpectetur, ſed complures conſimilis coloris areolæ ſparſim per æthera ſubfulgeant, ſi in illarum quamlibet Specillum conuertas Stellarum conſtipatarum cętum

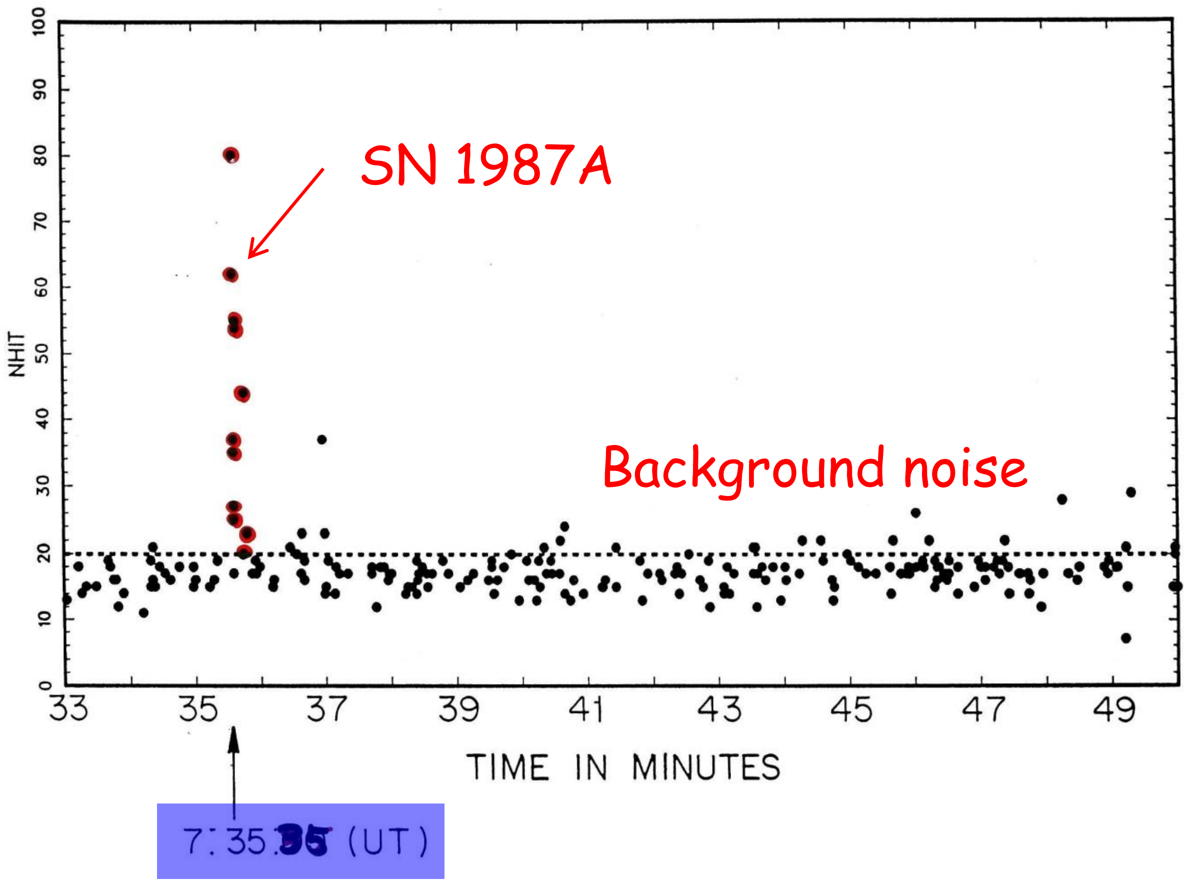
SUPERNOVAE

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 $E \sim O(15\ \text{MeV})$.
- **TIME SCALES:** Neutrino emission lasts **~10 s**
- **EXPECTED:** **1-3 SN/century** in our galaxy ($d \approx O(10)$ kpc).

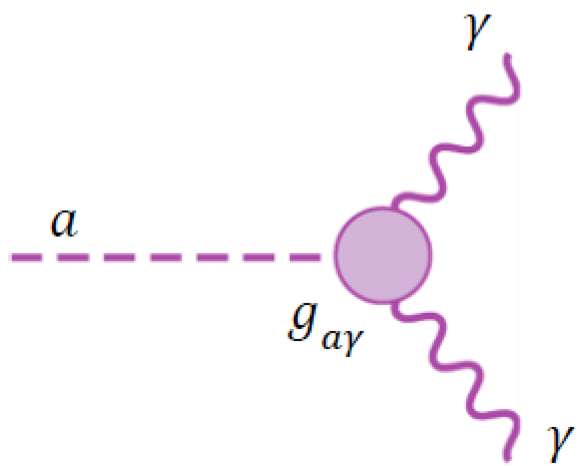

Sanduleak −69 202
Supernova 1987A
23 February 1987

NEUTRINO SIGNAL OF SN 1987A IN KAMIOKANDE



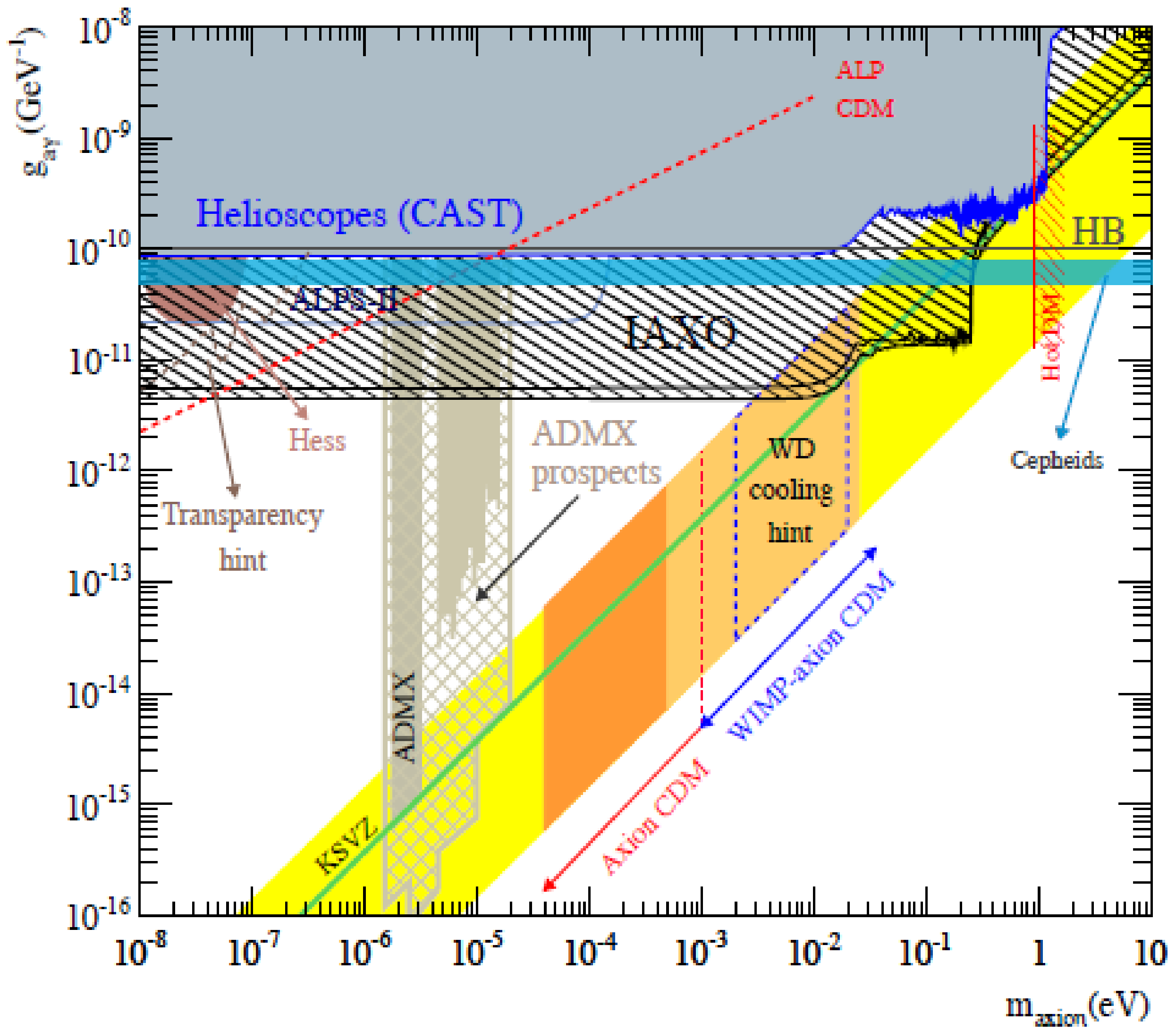
AXION-LIKE PARTICLES (ALPs)

$$L_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}_{\mu\nu} a = g_{a\gamma} \vec{E} \cdot \vec{B} a$$

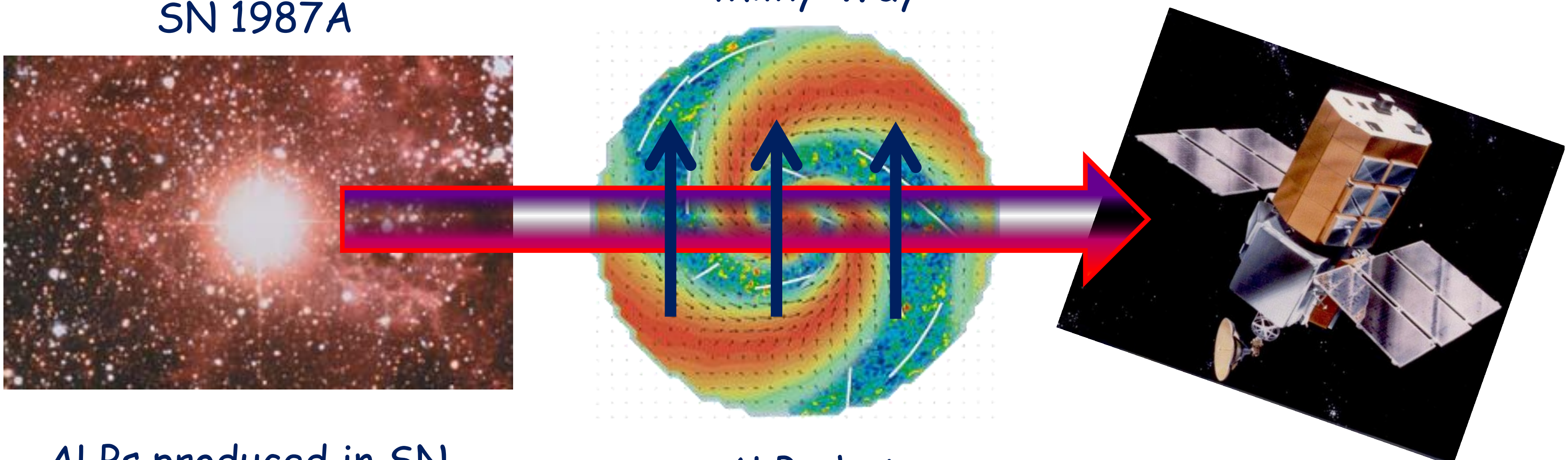


- Primakoff process: Photon-ALP transitions in external static E or B field
- Photon-ALP conversions in macroscopic B-fields

SEARCHING FOR ALPS USING THEIR ELECTROMAGNETIC COUPLING



ALPs CONVERSIONS FOR SN 1987A



ALPs produced in SN core by Primakoff process

ALP-photon conversions in the Galactic B-fields

No excess gamma-rays in coincidence with SN 1987A

- Extremely stringent upper limit [*Brockway, Carlson, Raffelt, astro-ph/9605197, Masso and Toldra, astro-ph/9606028*]

$$g_{a\gamma} \leq 10^{-11} GeV^{-1} \text{or } g_{a\gamma} \leq 3 \times 10^{-12} GeV^{-1} \text{ for } m_a \leq 10^{-9} \text{eV}$$

However…

OUR WORK

…. Criticism found in the literature; this bound has sometimes been objected.

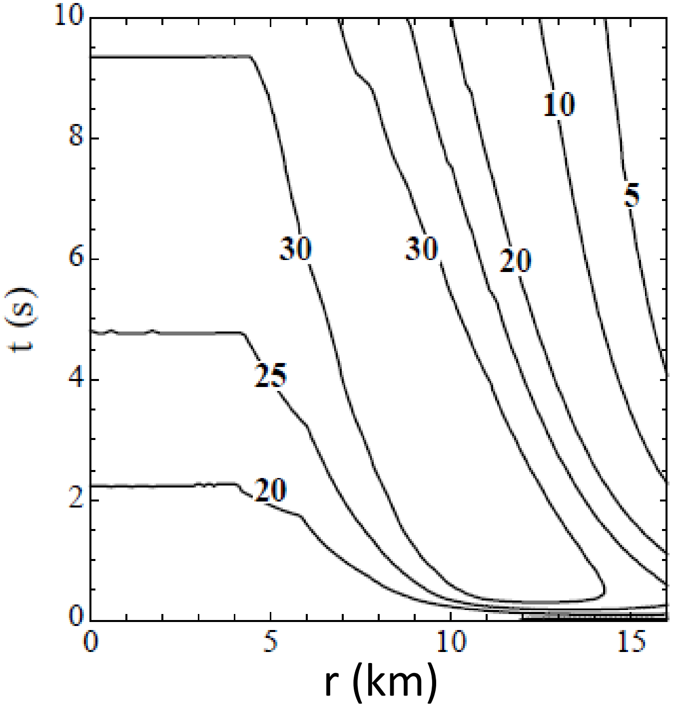
In [*Payez, Evoli, Fischer, Giannotti, A.M. & Ringwald, 1410.3747*] we updated the argument, to obtain a more precise bound using

- state-of-art models for SNe
- accurate microscopic description of the SN plasma
- state-of-art models for Galactic B-fields

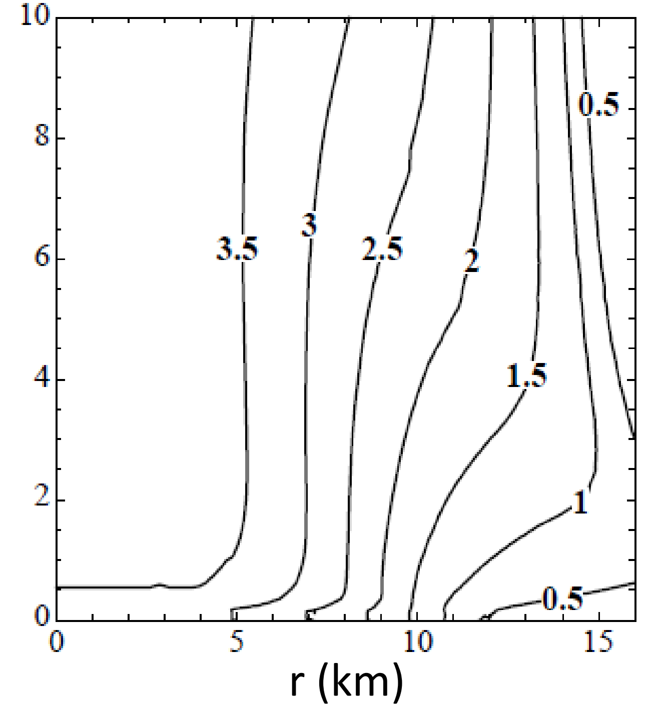
SN SIMULATIONS AND TIME RESOLUTION

[Fischer et al. (2010)]

Temperature in MeV



Density in units of 10^{14} g cm^{-3}



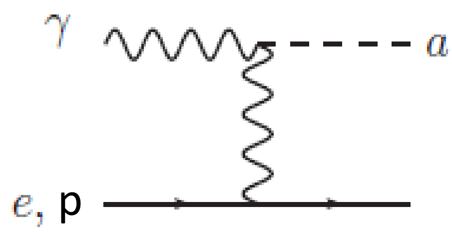
- Updated spherically symmetric model for a 18 $M_{\odot}$ (resp. 10 $M_{\odot}$) progenitor

~ 600 snapshots describing the interior up to ~21 s (resp. 10 s) after the bounce

Original analysis: data only for 1, 5 , 10 s after bounce *[Keil et al. (1995)]*

PRIMAKOFF PRODUCTION

ALPs are produced in SN core via the Primakoff effect on *e* and *p*



Primakoff

With such high temperatures and densities in the core:

- e^- are degenerate and their phase space is Pauli blocked ⟶ negelcted
- *p* are non-relativistic and partially degenerate (n_p ⟶ n_p^{eff})

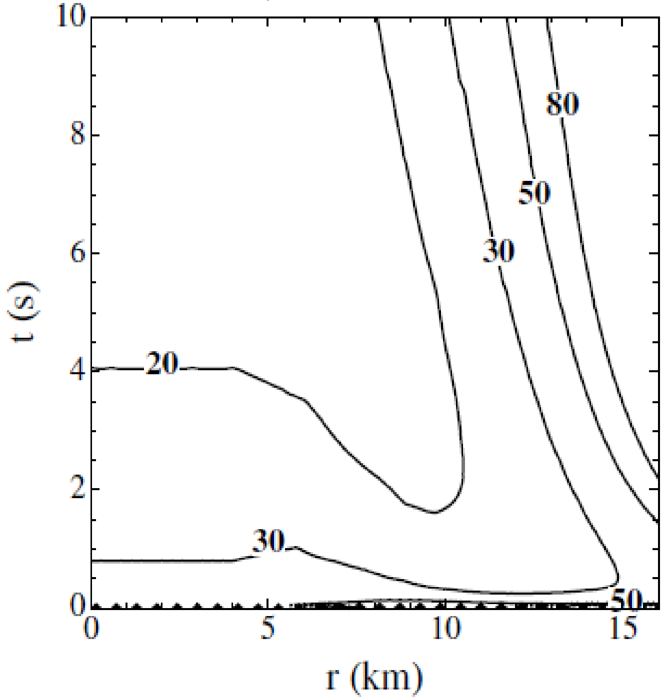
Primakoff conversion rate:

$$\Gamma = \frac{g_{a\gamma}^2\, \alpha\, n_p^{\rm eff}}{8}\left[\left(1+\frac{\kappa^2}{4E^2}\right)\ln\left(1+\frac{4E^2}{\kappa^2}\right)-1\right],$$

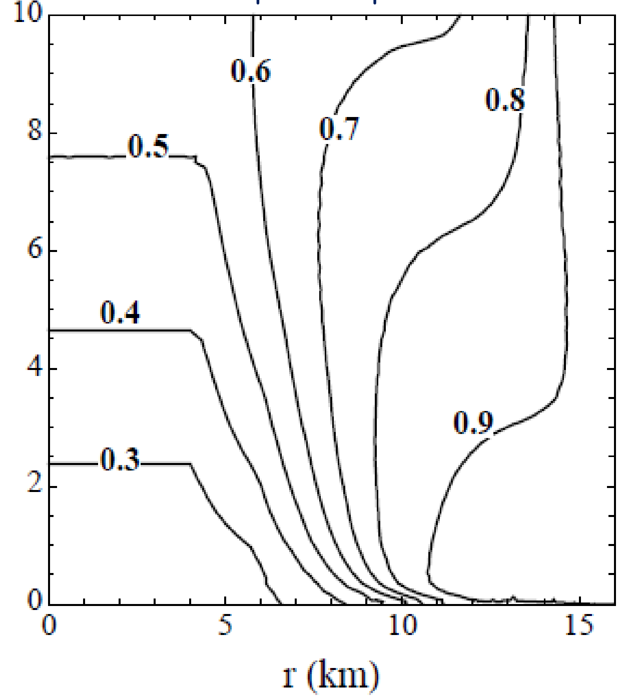
where κ is the inverse screening length (affected by *p* degeneracy: from Debye to Fermi-Thomas)

DEGENERACY AND MASS REDUCTION EFFECT

Effective proton mass over T



n_p^{eff} / n_p



- Effective proton mass $m_p \longrightarrow m_p^*$

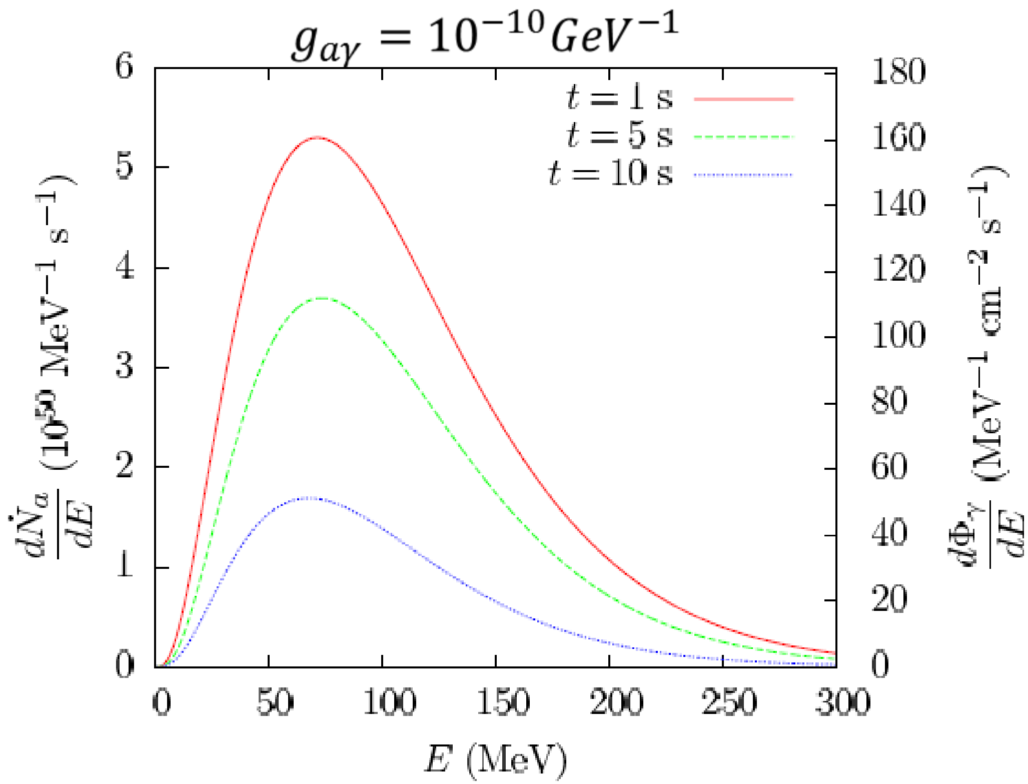
  High-density nuclear EoS *[Shen et al. (1998)]*
  - easier to be degenerate
  - more targets for a given density

ALP FLUX FOR SN 1987A

ALP production rate per unit energy via Primakoff process

$$\frac{d\dot{n}_a}{dE} = \frac{dn_\gamma}{dE} \times \Gamma$$

integrated over volume gives the total rate

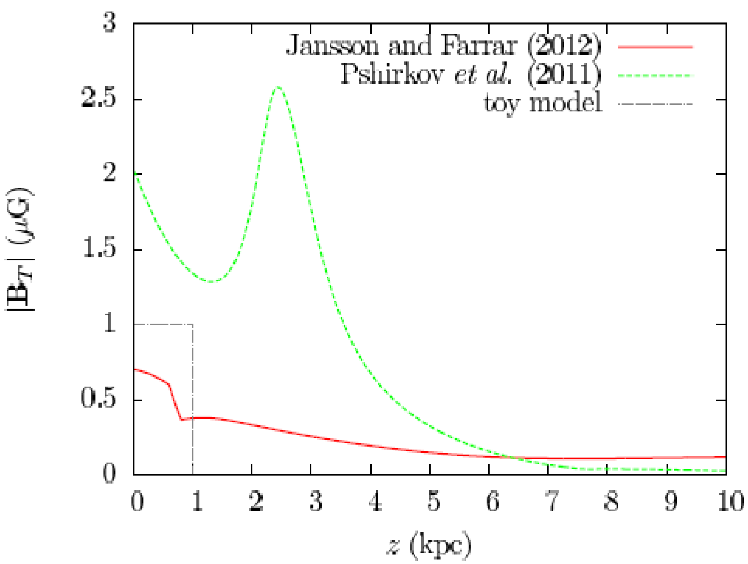


MAGNETIC FIELD AND CONVERSION PROBABILITY

- Original analysis
  - Toy model for the *B*-field (constant slab of 1 μG over 1 kpc)
  - Approximate conversion probability for massless ALPs ($m_a \lesssim 10^{-9}$ eV)

$$P_{a\gamma} \sim \frac{1}{4} g_{a\gamma}^2 B_T^2 L^2$$

Towards SN 1987A

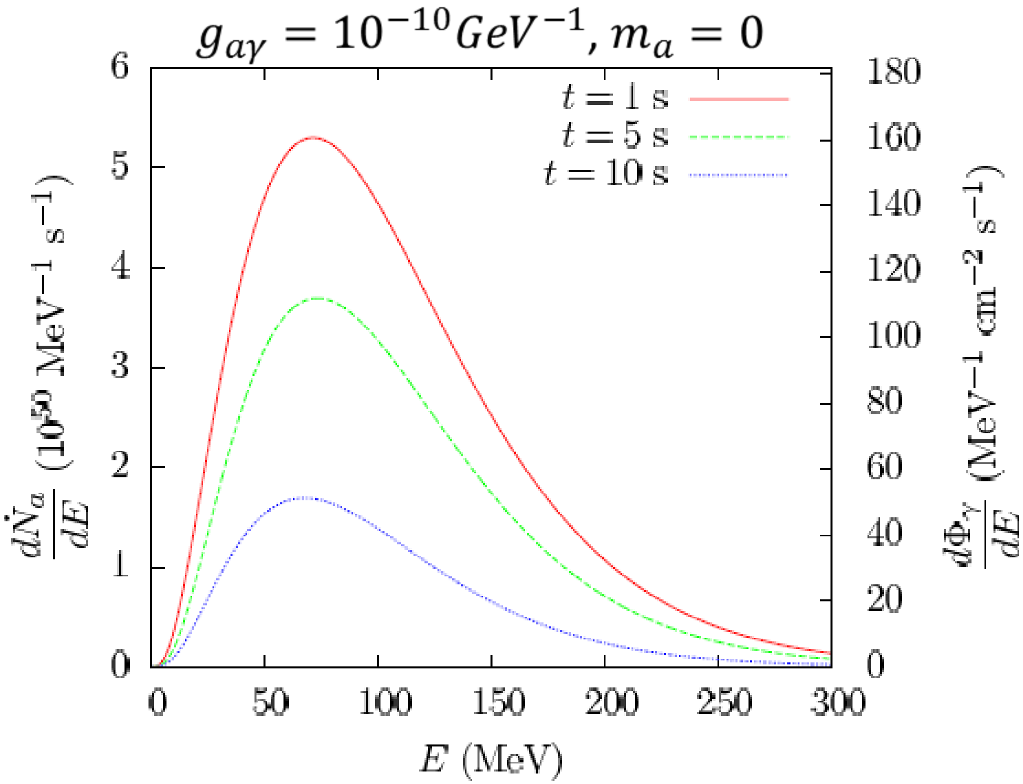


- Very significant improvements
  - modern models of the Galactic *B*-field [Jansson & Farrar (2012)], [Pshirkov et al. (2011)]
  - full conversion probability

→ precise mass dependence of the limit

- Expect a larger conversion probability
  No halo component in the toy model

PHOTON FLUX AT EARTH



Differential photon flux per unit energy

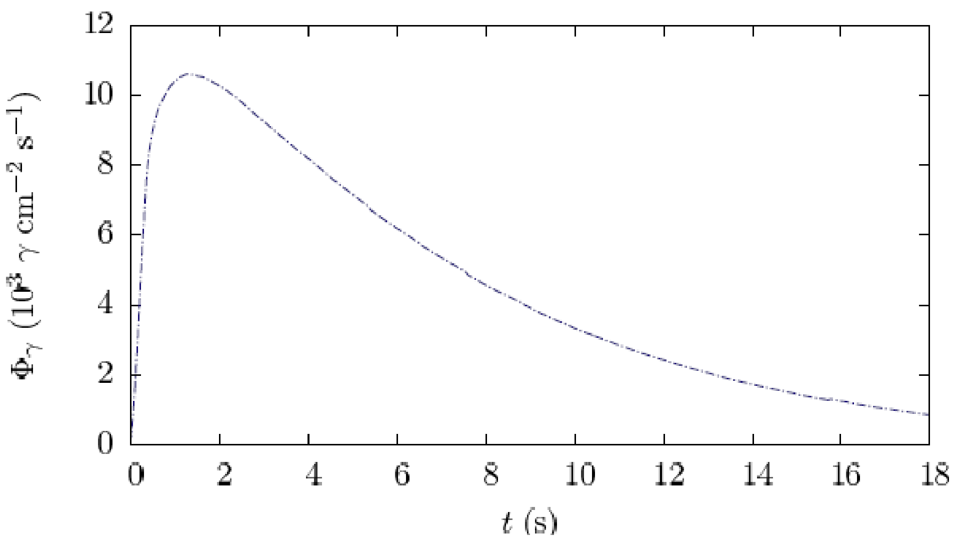
$$\frac{d\Phi_\gamma}{dE} = \frac{1}{4\pi d^2} \frac{d\dot{n}_a}{dE} \times P_{a\gamma}$$

d= 50 kpc

To compare with the GRS bound ⟶ consider only the 25-100 MeV range

PHOTON FLUX AT EARTH IN THE 25-100 MeV RANGE

We are no longer limited to 3 values of the after bounce time
Precise time evolution of the photon flux at Earth in the 25–100 MeV range

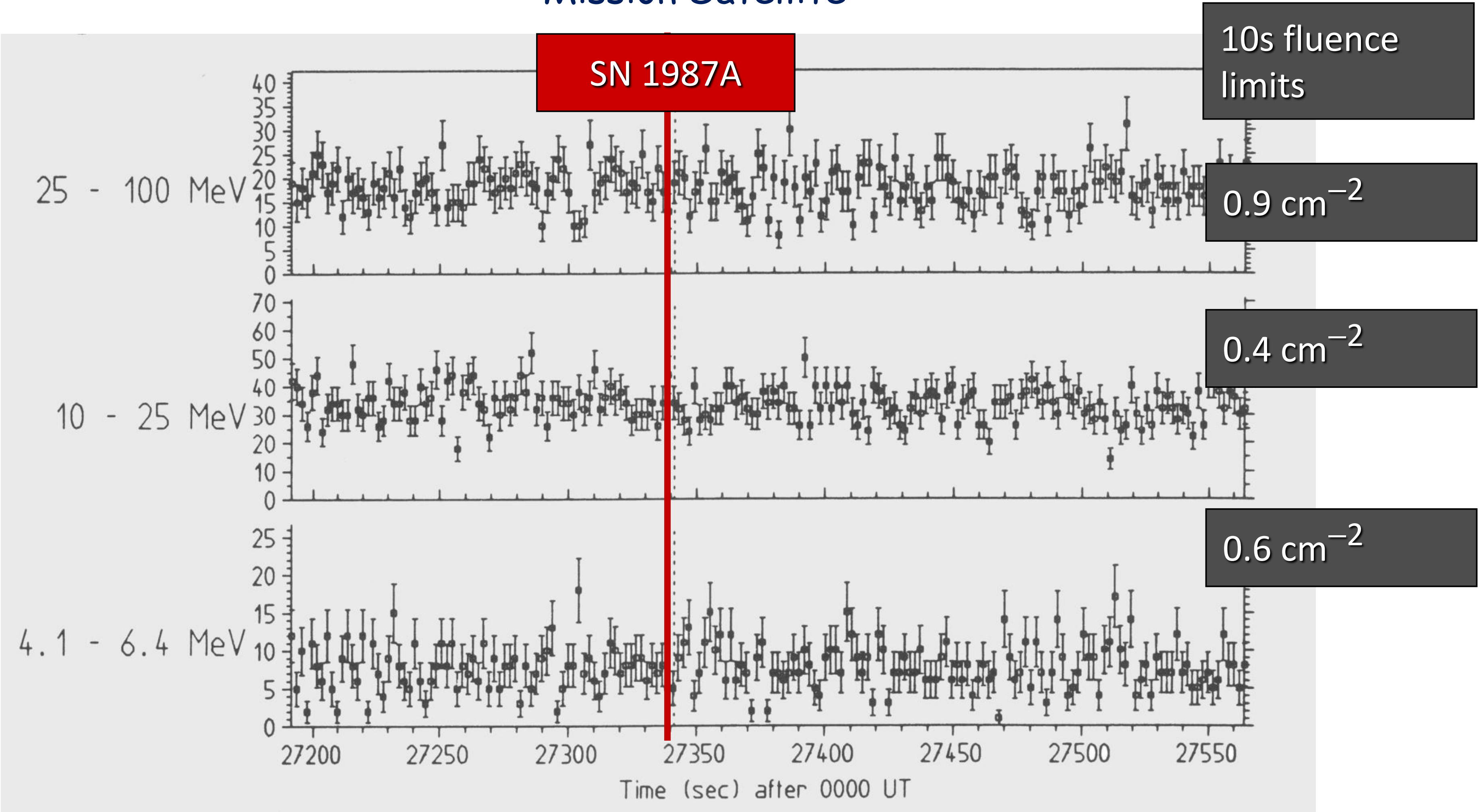


Finally, integrate until 10.24 s (burst duration) to get the fluence

- Particle mass dependence ⟶ parameter scan
  Solve the propagation in the *B*-field for each couple (m_a, $g_{a\gamma}$)

GAMMA-RAY OBSERVATION FROM SMM SATELLITE

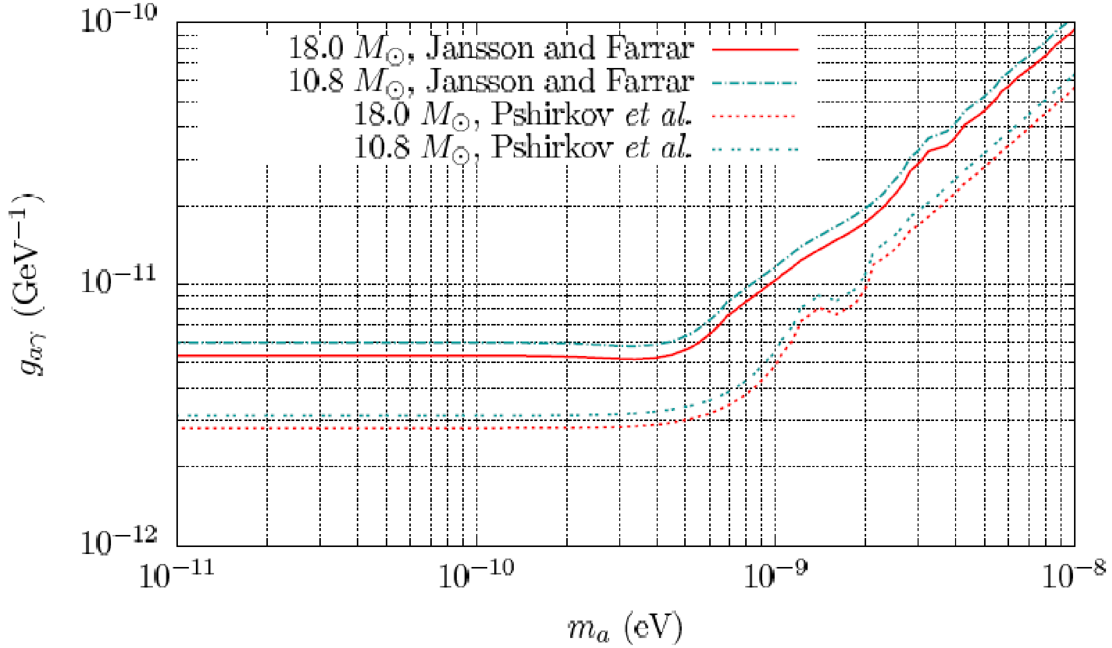
Counts in the GRS instrument on the Solar Maximum Mission Satellite



$$F(g_{a\gamma}) = 7.02 \times 10^4 \left(\frac{g_{a\gamma}}{10^{-10} GeV^{-1}}\right)^4 \gamma cm^{-2}$$

NEW BOUND ON ALPs FROM SN 1987A

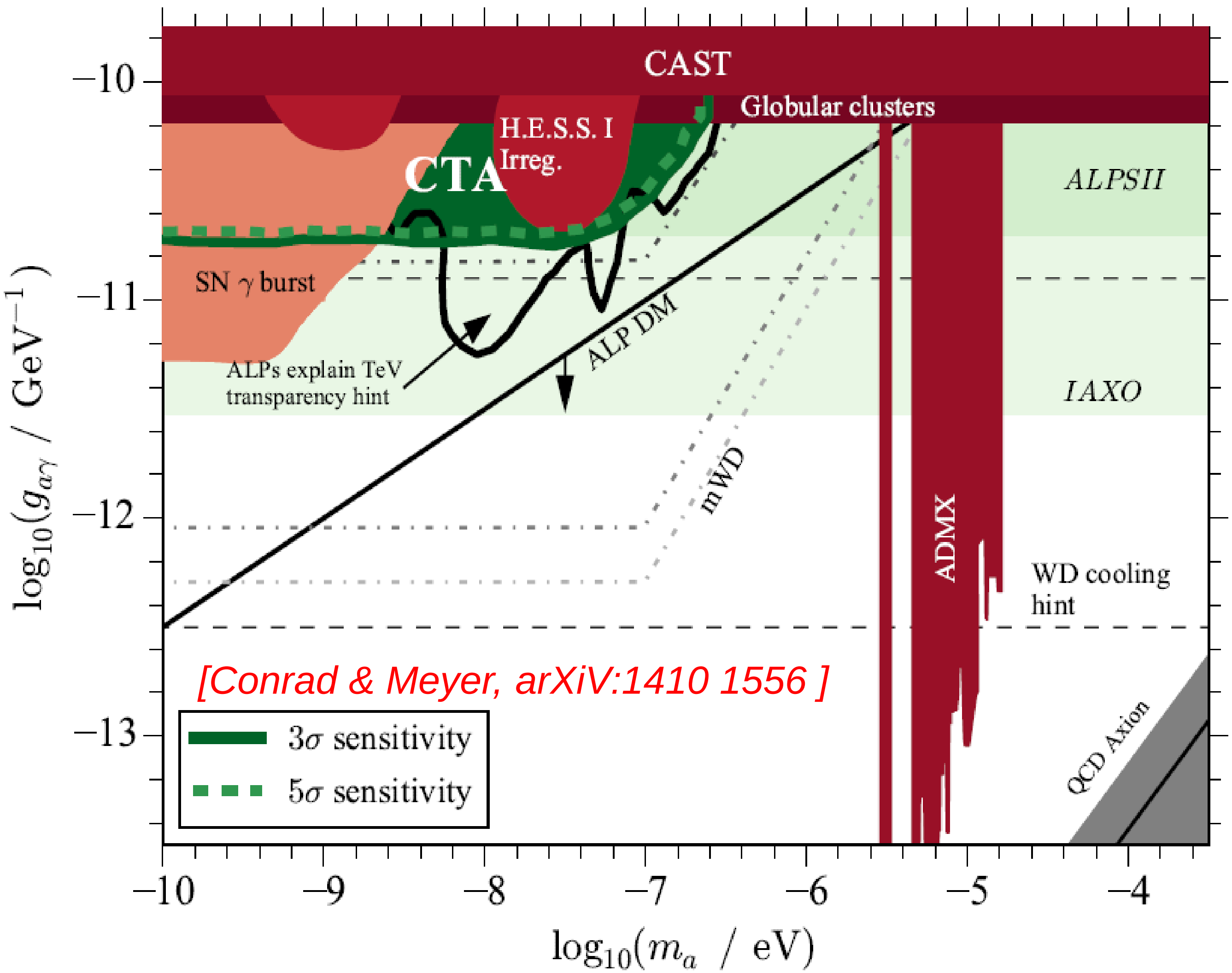
[Payez, Evoli, Fischer, Giannotti, A.M. & Ringwald, 1410.3747]



- Very stable even with progenitor of different masses
- Galactic magnetic field model: by far, the biggest remaining uncertainty

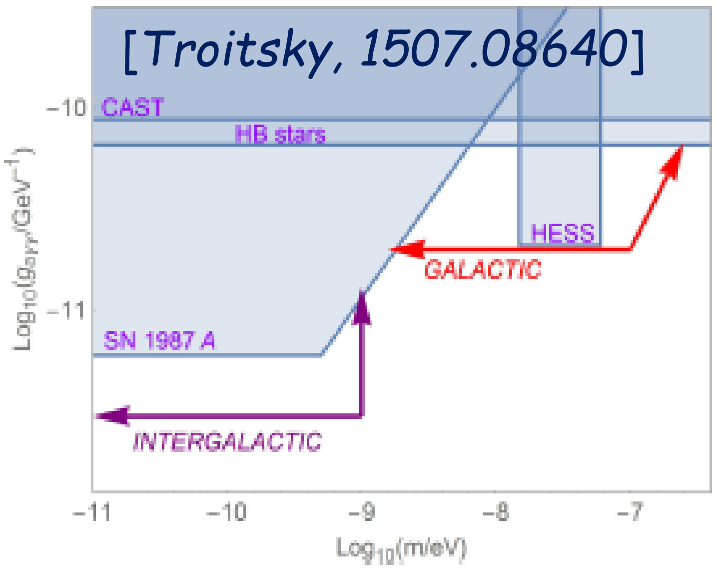
$$g_{a\gamma} \leq 5.3 \times 10^{-12}\ GeV^{-1} \quad \text{for} \quad m_a < 4.4 \times 10^{-10}\text{eV}$$

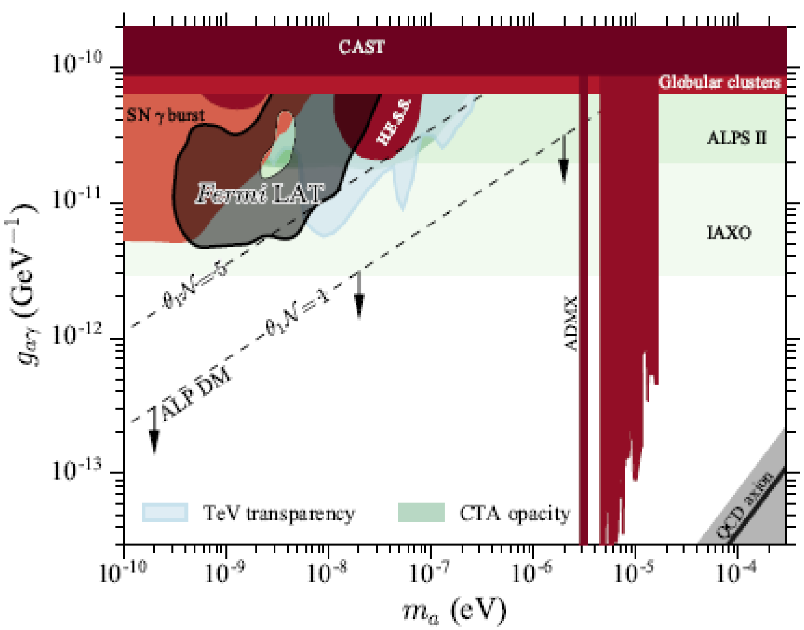
BOUND ON ALPs



SN 1987A provides the strongest bound on ALP-photon coversions for ultralight ALPs

SN 1987A BOUND & TEV PHOTONS





- ALP-photon conversions in cosmic magnetic fields have been introduced to explain the reduction of opacity for TeV photons [*e.g., intergalactic case: De Angelis, Roncadelli, Mansutti, 0707.4312, galactic case: Simet, Hooper, Serpico, 0712;2825*]

- Recent Fermi-LAT analysis of γ-spectrum of NGC 1275 in Perseus cluster + SN 1987A bound strongly constrain the parameter space for the model [*Fermi collab., 1603.06978*]

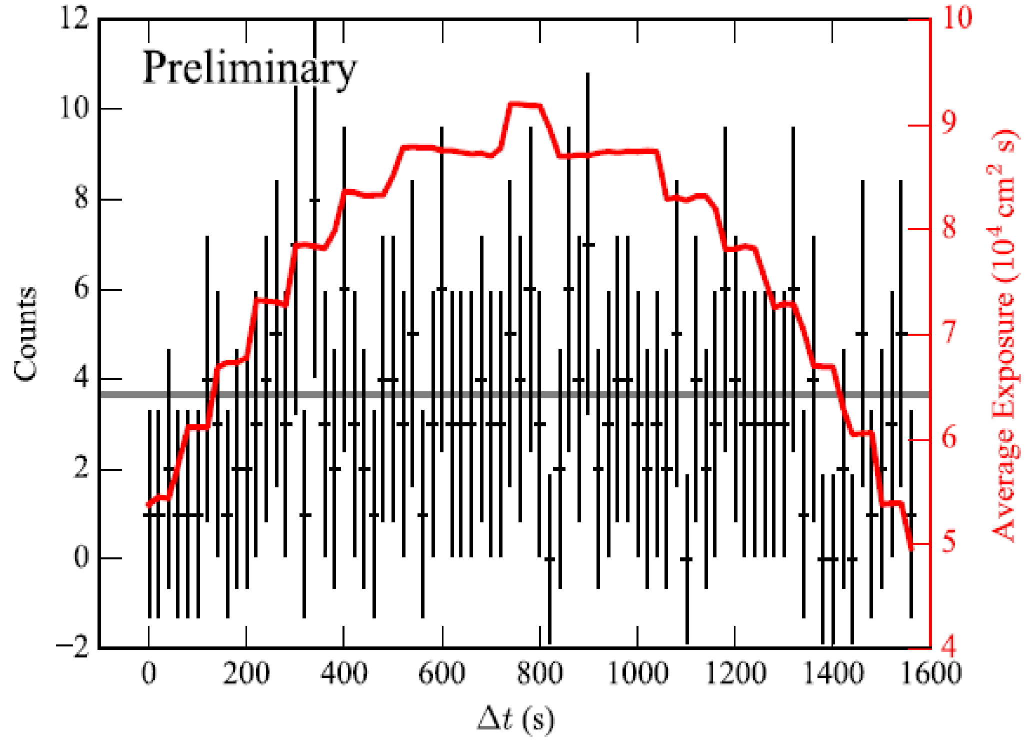
WHAT'S FROM SN 20XXA ?

FERMI-LAT AS GALACTIC SN ALP-SCOPE

[Meyer, Giannotti, A.M., Conrad & Sanchez-Conde, to appear soon]

Sensitivity Estimate: Observed Counts from Galactic Center

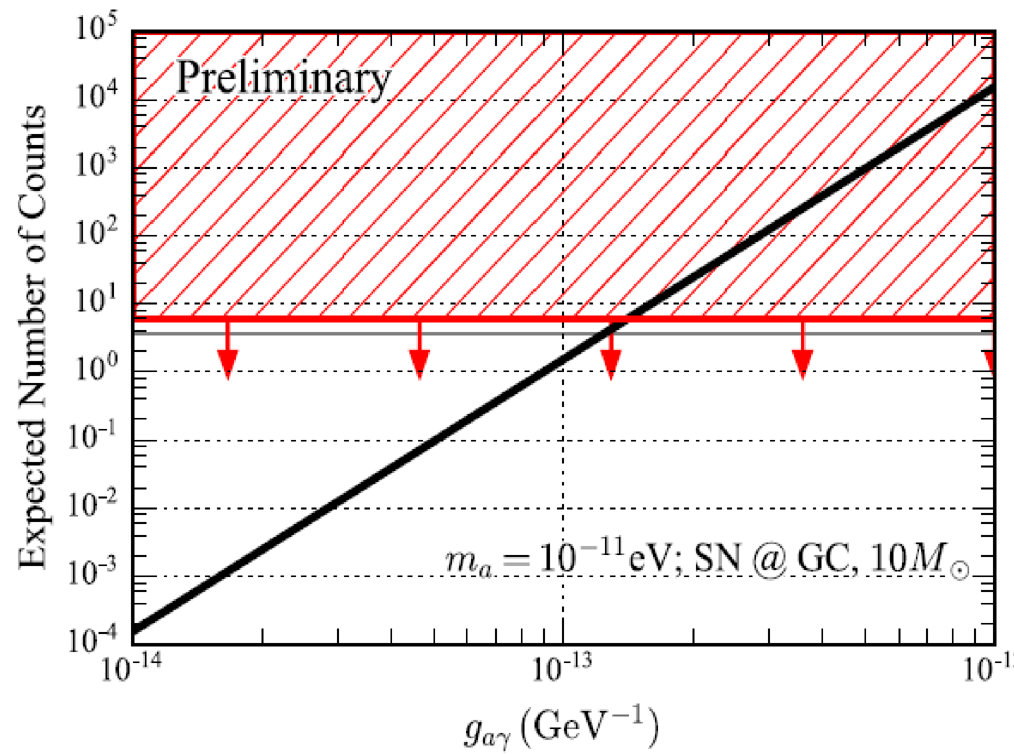
- Use **Galactic Center** as target
- Estimate number of background counts from **data**:
  - From one exposure of the Galactic Center (~1500s)
  - Energy Range: **50-500 MeV**
  - Within **68% PSF (~ 11 degrees @ 50 MeV)**
  - Use **20s time bins** (full explosion time)
- **Expected number of background counts: ~3.7**
- Compare against number of **expected counts from SN explosion**
- Use **statistical test for low-count regime** [Feldman & Cousins 1998]



Energy range	50-500 MeV
Event Class / IRF	P8R2_TRANSIENT020_V6
Zenith Angle	< 80°

Expected Number of Counts from ALP burst

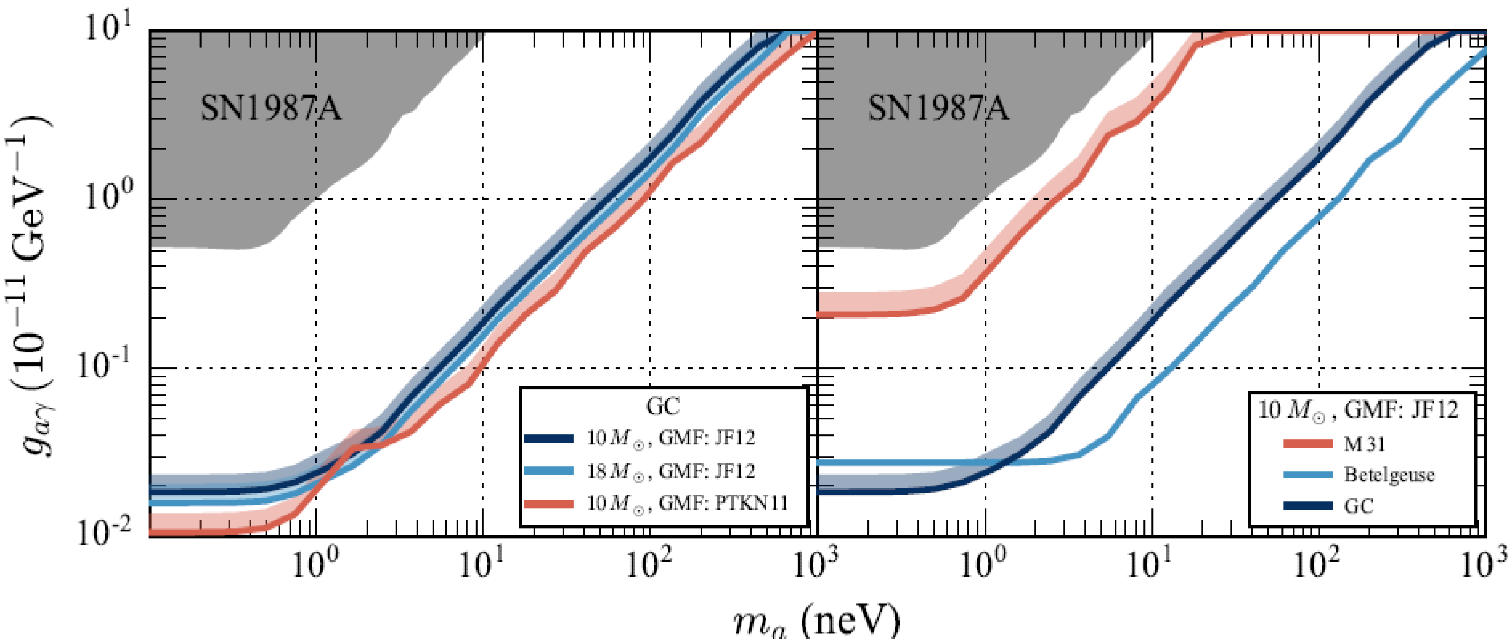
- integrated over explosion **time** (~20s)
- integrated over **energy**, 50-500 MeV
- Folded with Fermi-LAT **instrumental response function**
- Expected number of counts **~ $g_{a\gamma}^4$**
- **Little dependence** on progenitor mass



For 4 counts in time bin of explosion region → exclude ALP models with expected number of counts > 6.1 (95% C.L.)

FERMI-LAT SENSITIVITY

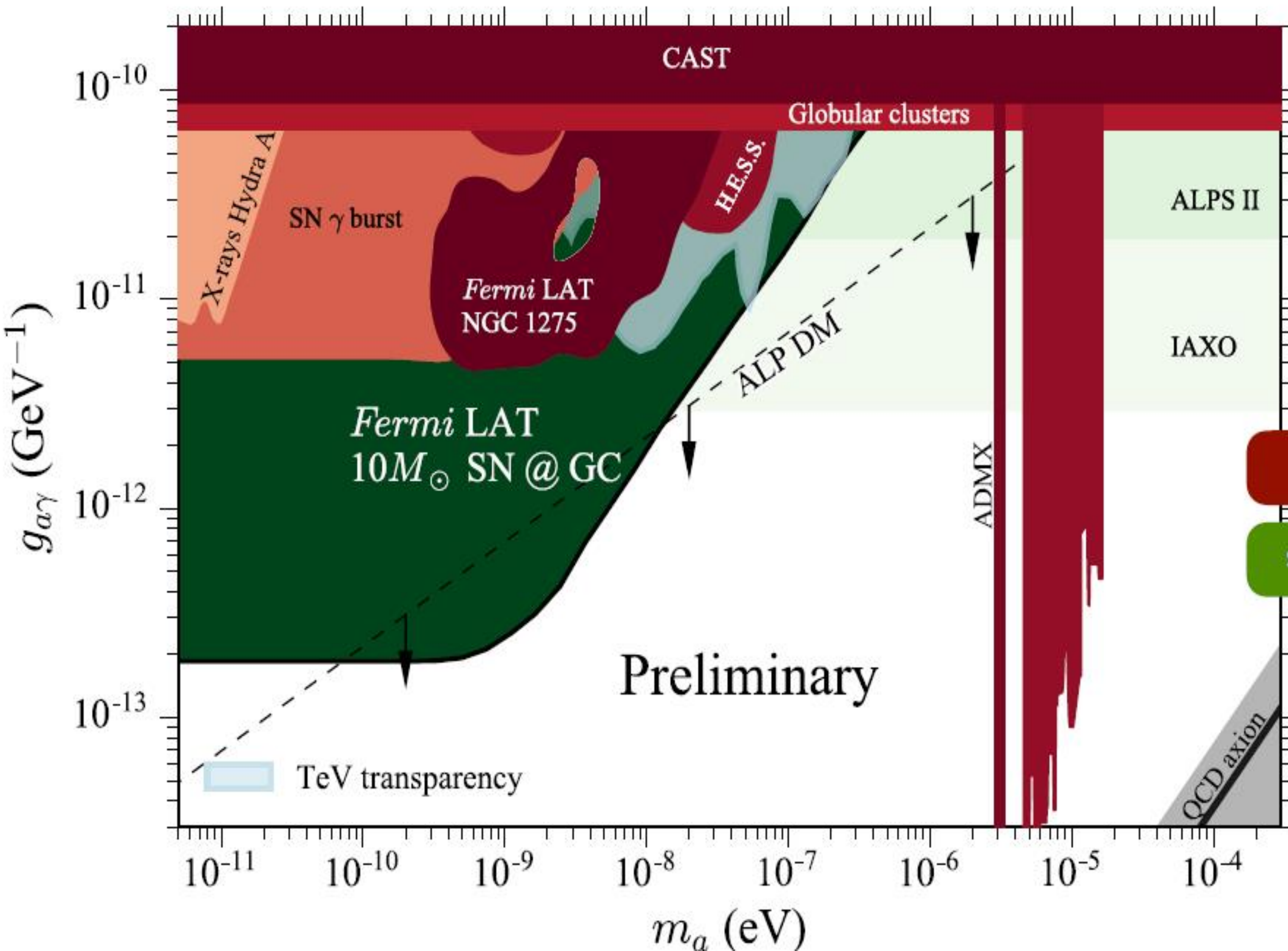
	GC	Betelgeuse	M 31
R.A. (°)	266.42	88.79	10.63
Dec. (°)	−28.99	7.41	41.30
Distance (kpc)	8.5	0.197	778



For a SN @ GC sensitivity down to

$$g_{a\gamma} \approx 2 \times 10^{-13}\ GeV^{-1} \quad \text{for} \quad m_a \leq 10^{-9}\, eV$$

Comparing the Sensitivity with other Limits



Limits

Sensitivities

CONCLUSIONS

- We have revisited the SN 1987A γ-ray limit on ultra-light ALPs using state-of-the art SN models, stellar microphysics and galactic B-field.

  We get

$$g_{a\gamma} \leq 5.3 \times 10^{-12} GeV^{-1} \text{ for } m_a \leq 4.4 \times 10^{-10} \text{eV}$$

It provides the strongest bound on ALP-photon coversions for ultralight ALPs

- A Galactic SN explosion in the field of view of FERMI-LAT would allow us to improve the SN 1987A bound by more than one order of magnitude ...

  or even detect DM ALPs !

A Galactic SN is a lifetime opportunity for ALPs