15th Patras Workshop on Axions, WIMPS and WISPS
Freiburg, 3-7 June 2019

AXIONS FROM SUPERNOVAE: BOUNDS AND DISCOVERY OPPORTUNITIES

Alessandro MIRIZZI
University of BARI & INFN BARI, Italy

OUTLINE

- Introduction to SN neutrinos
- SN 1987A neutrinos
- ALPs and axion bounds from SN 1987A
- Axion effect on future SN neutrino observations
- Conclusions

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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

SUPERNOVA NEUTRINOS

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 ($d \approx \mathcal{O}(10)$ kpc).

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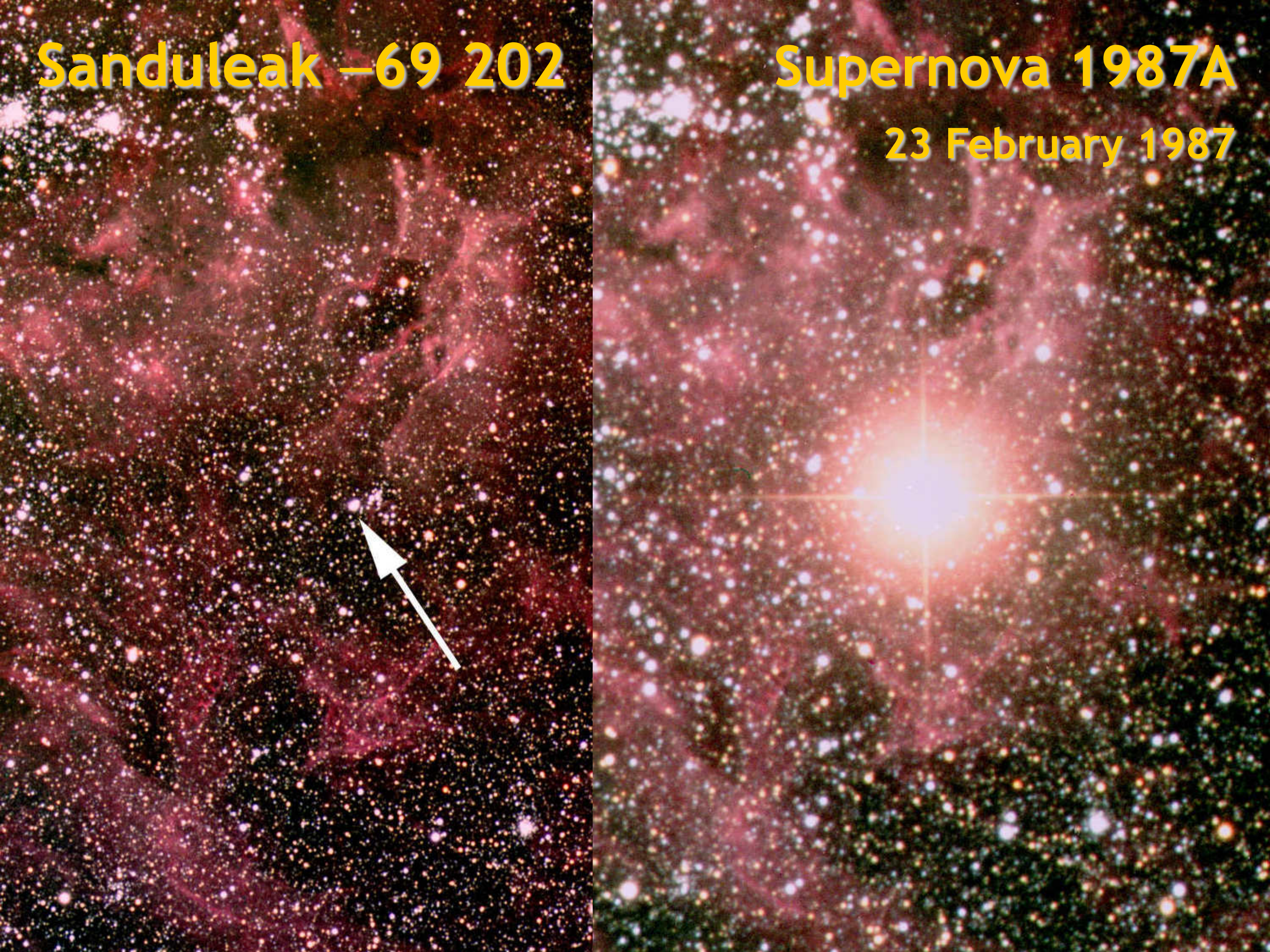
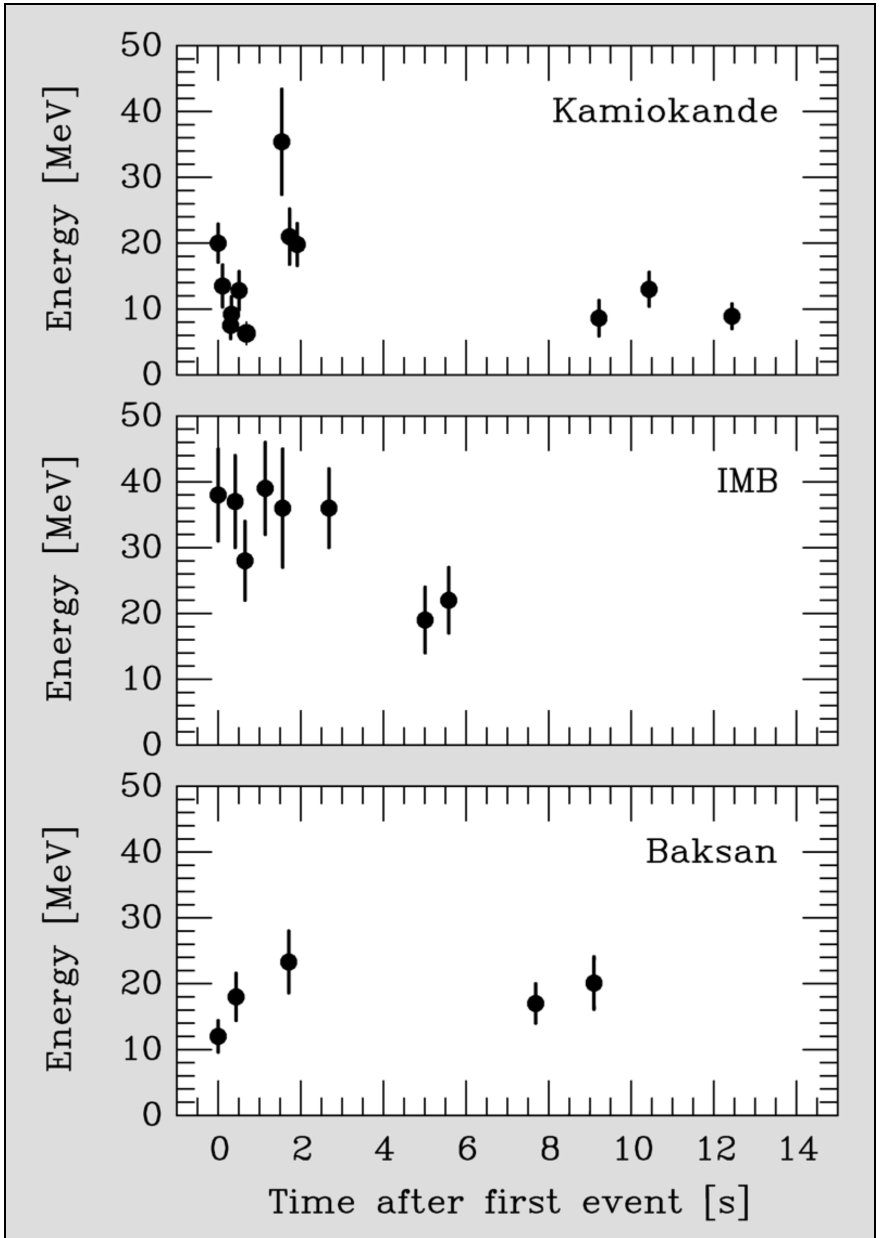

Sanduleak −69 202
Supernova 1987A
23 February 1987

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

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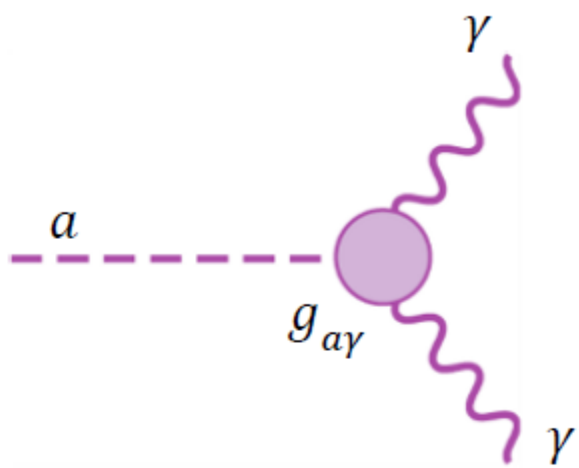
AXION BOUNDS FROM SN 1987A

- Axion-like particles
- Energy-loss and axions

AXION-LIKE PARTICLES (ALPs)

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

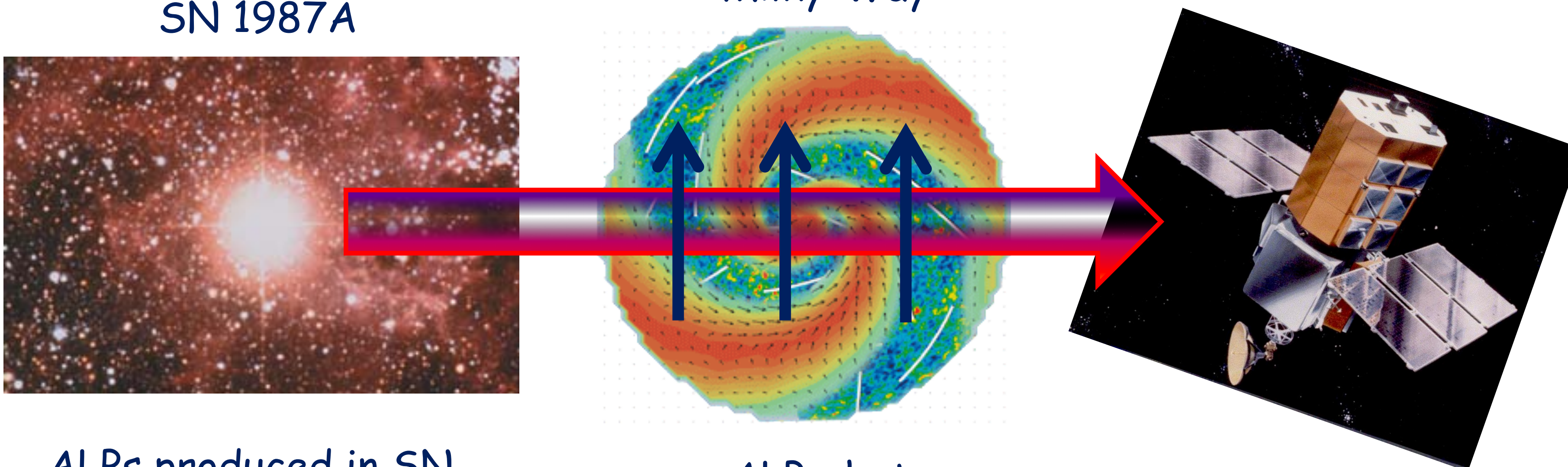


- Primakoff process: Photon-ALP transitions in external static E or B field
- Photon-ALP conversions in macroscopic B-fields

ALPs CONVERSIONS FOR SN 1987A

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

SN 1987A | Milky-Way | SMM Satellite



ALPs produced in SN core by Primakoff process

ALP-photon conversions in the Galactic B-fields

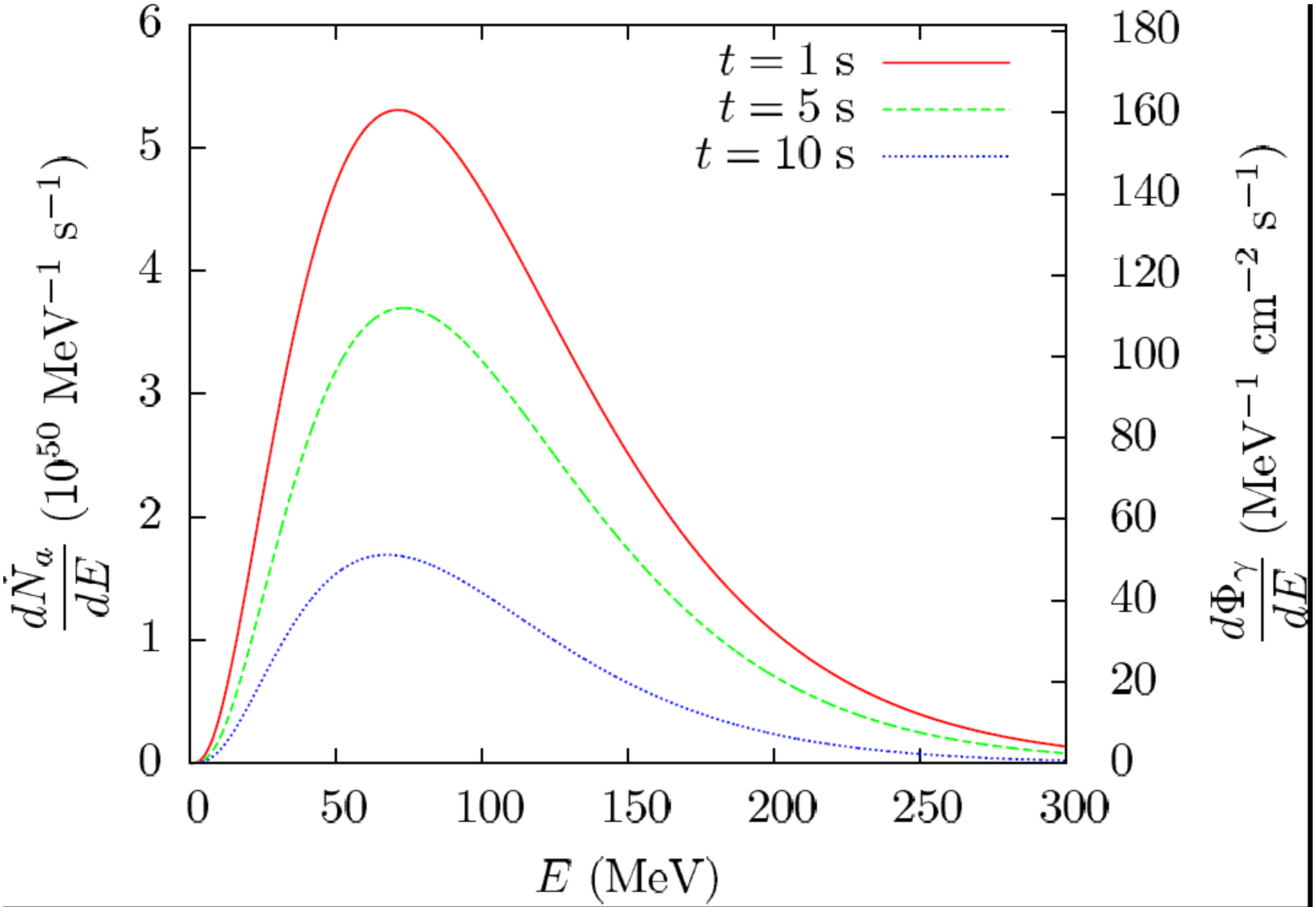
No excess gamma-rays in coincidence with SN 1987A

In [*Payez, Evoli, Fischer, Giannotti, A.M. & Ringwald, 1410.3747*] we revaluate the bound with

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

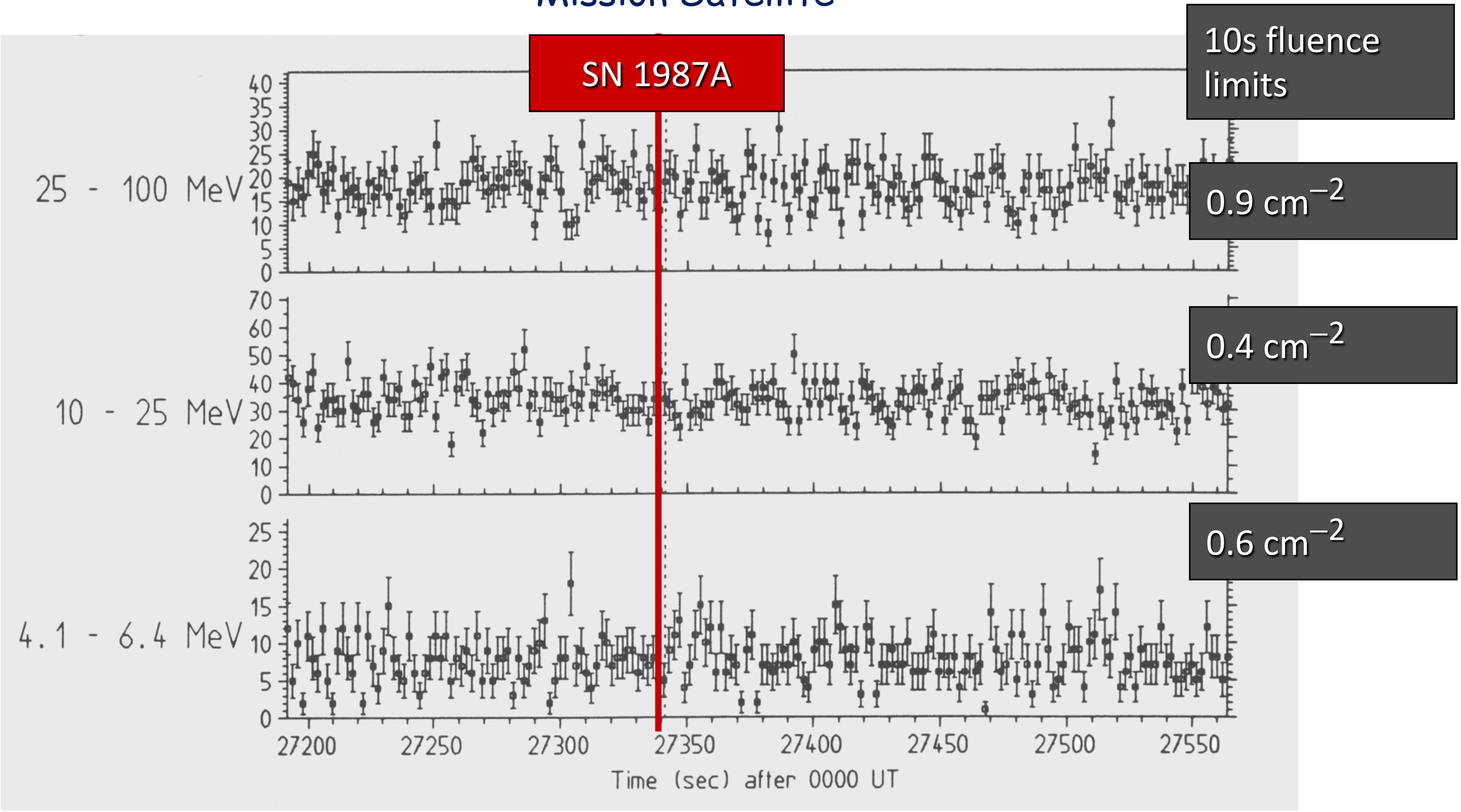
ALP-PHOTON FLUXES FOR SN 1987A

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



GAMMA-RAY OBSERVATION FROM SMM SATELLITE

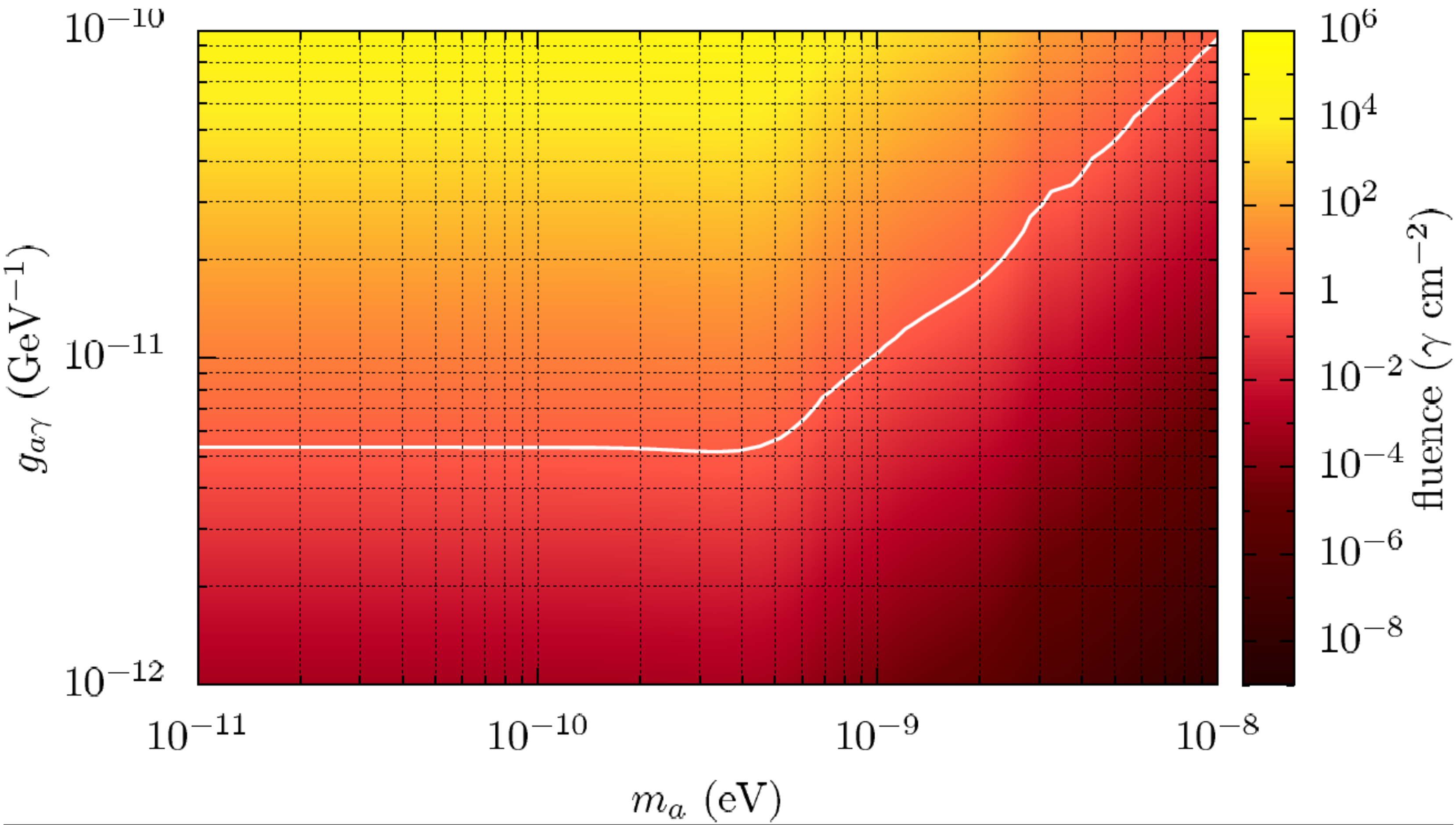
Counts in the GRS instrument on the Solar Maximum Mission Satellite



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

NEW BOUND ON ALPs FROM SN 1987A

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



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

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

Oskar Klein centre

Stockholm University

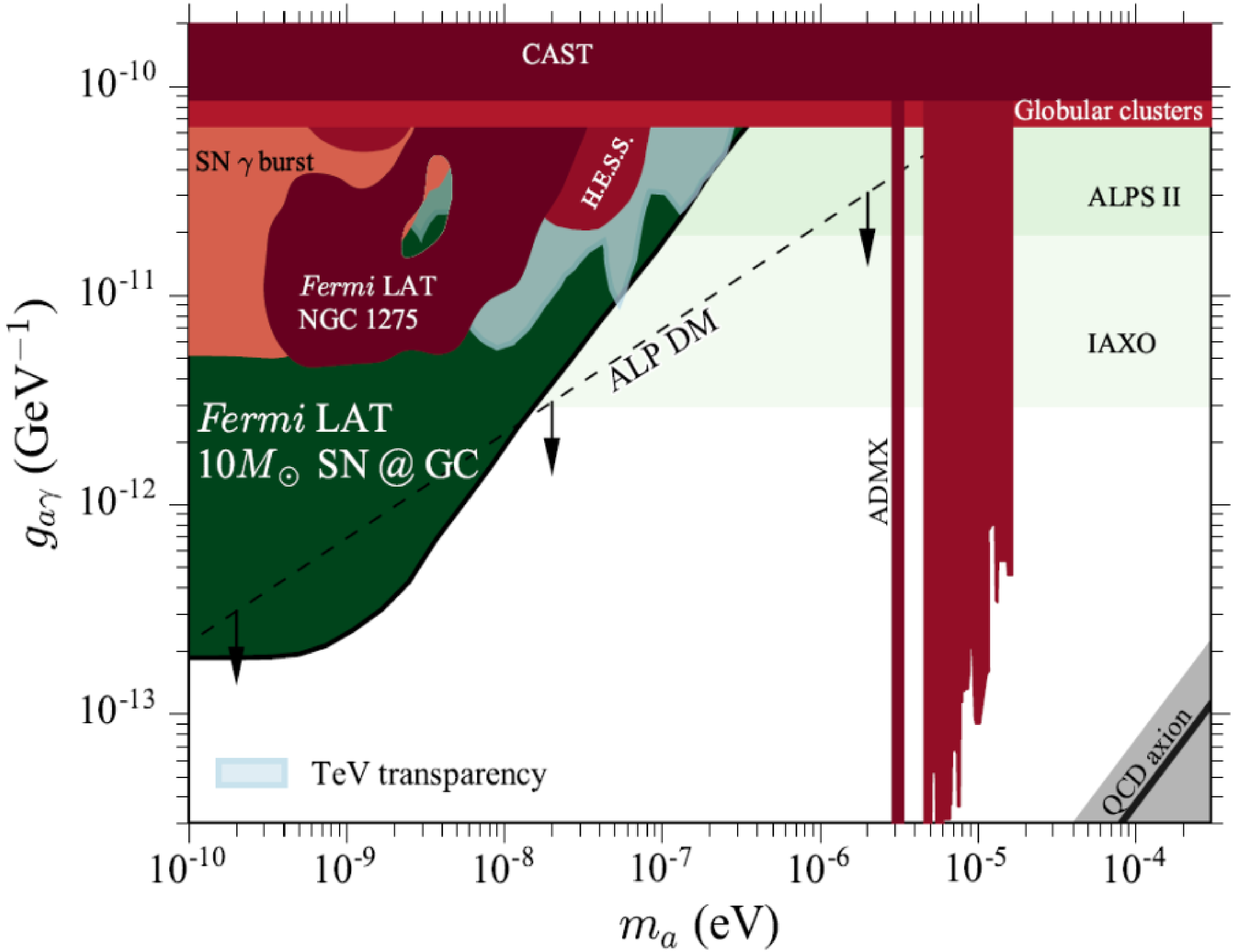
Fermi Gamma-ray Space Telescope

SENSITIVITY OF THE FERMI LAT TO THE DETECTION OF A SN GAMMA-RAY BURST DUE TO AXIONLIKE PARTICLES

Alessandro Mirizzi, Manuel Meyer, Maurizio Giannotti, Jan Conrad, Miguel Sanchez-Conde

arXiv: 1609.02350

See talk of Manuel Meyer



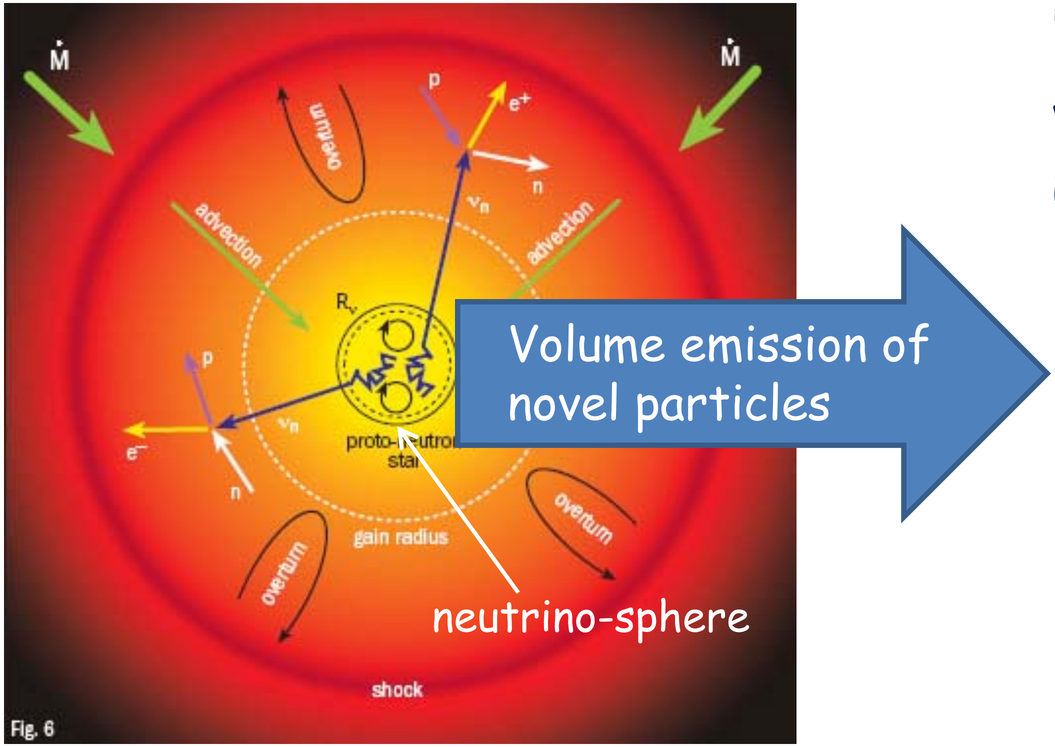
A Galactic SN explosion in the field of view of FERMI-LAT would allow us to improve the SN 1987A bound by more than one order of magnitude ...

or even detect DM ALPs !

AXION BOUNDS FROM SN 1987A

- Axion-like particles
- Energy-loss and axions

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

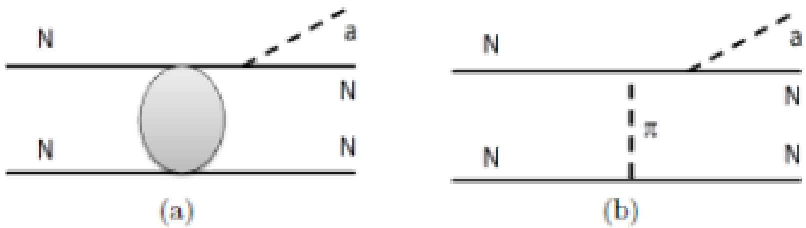
$$\varepsilon_X < 10^{19}\ \mathrm{erg\ g^{-1}\ s^{-1}}$$

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

AXION EMISSION FROM A NUCLEAR MEDIUM

$$NN \rightarrow NNa$$

nucleon-nucleon bremsstrahlung



Bulk nuclear interaction   One pion exchange

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

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

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

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

$$\langle\rho_{15}\rangle \approx 0.4$$
$$\langle T_{30}^{3.5}\rangle \approx 1.4$$

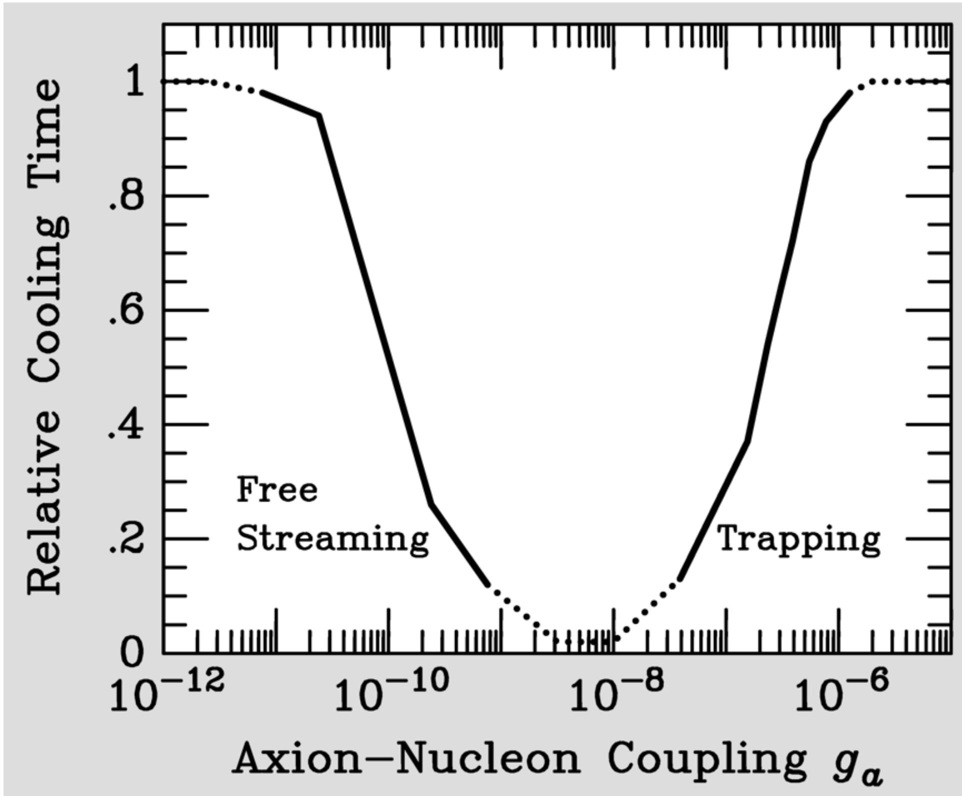
$$\Rightarrow \quad g_{aN} < 9\times 10^{-10}$$

SN 1987A AXION LIMITS

Free streaming

[Burrows, Turner & Brinkmann, PRD 39:1020,1989]

Volume emission of axions



Trapping

[Burrows, Ressell & Turner, PRD 42:3297,1990]

Axion diffusion from an "axion-sphere"

Possible detection in a water Cherenkov detector via oxygen nuclei excitation

Hadronic axion ($m_a \sim 1$ eV, $f_a \sim 10^6$ GeV) not excluded by SN 1987A. Possible hot-dark matter candidate. The "hadronic axion window" is closed by cosmological mass bounds.

RELAXING SN 1987A AXION LIMITS ?

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

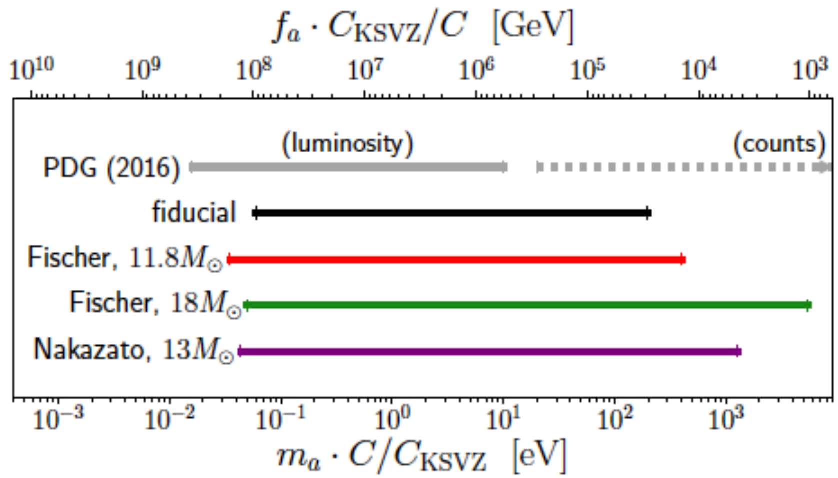


Figure 11. Constraints on the QCD axion mass and axion decay constant for various supernova temperature and density profiles. The "canonical" bound from the PDG [35, 115] is shown with a solid gray line, while the bound labelled "counts" comes from [123]. Our bounds close the gap between these constraints,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

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

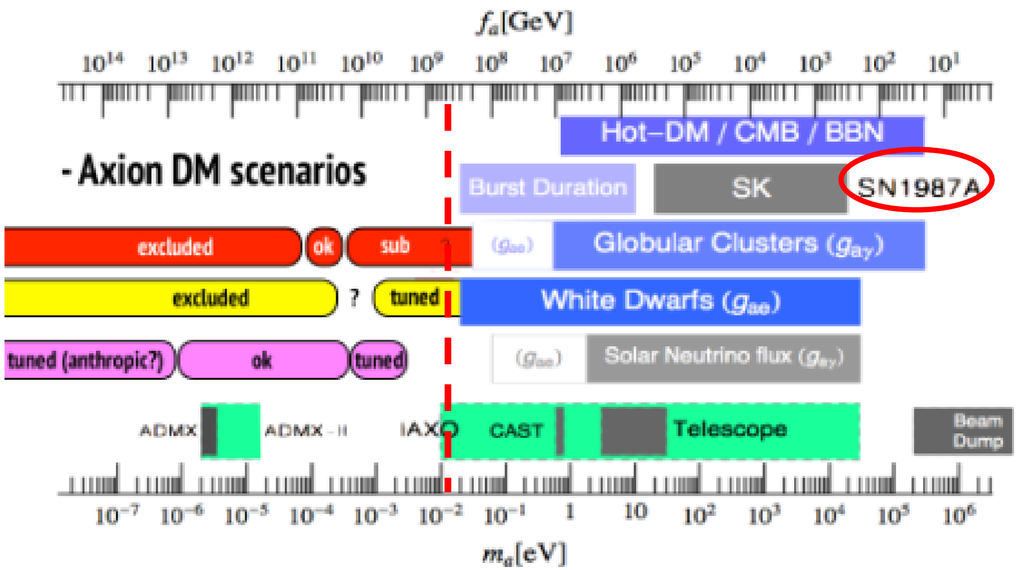
Caveat: How robust is the new bound?

See talk by Pierluca Carenza

WHAT WE LEARNT FROM SN 1987A?

- General confirmation of core-collapse paradigm (total energy, spectra, time scale)

- No unexpected energy-loss channel: Restrictive limits on axions…but we a lot of uncertainties….



- Improving Energy-Loss Limits with Next Supernova?
  Sensitivity comparable to IAXO one. Important for hadronic axions where WD bounds are absent.

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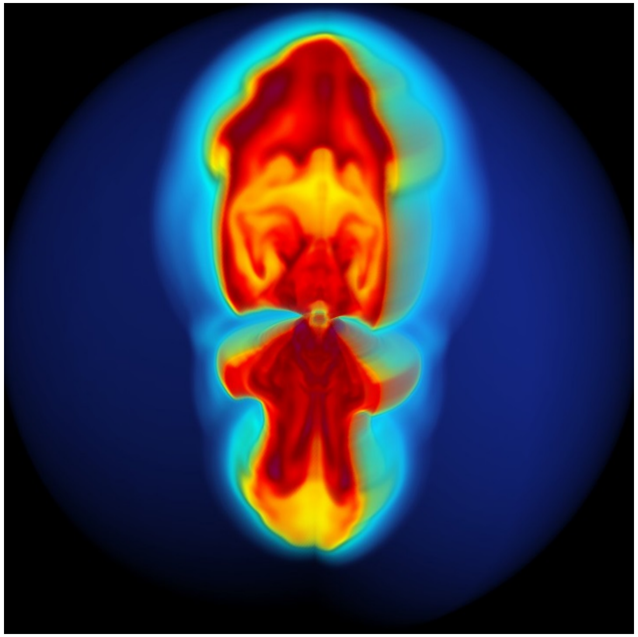
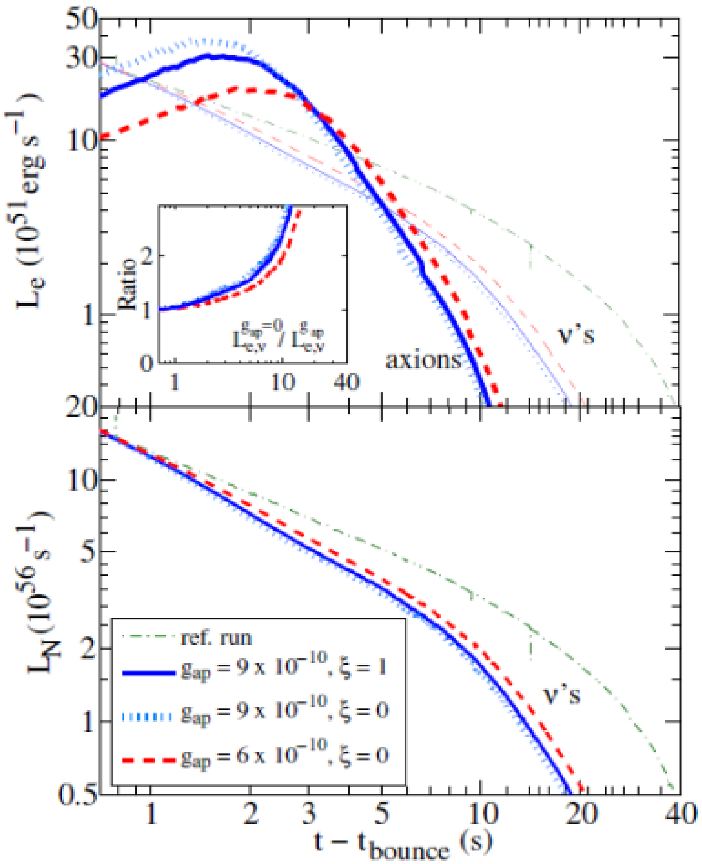


A REAPPRISAL OF AXION EMISSION WITH STATE OF ART SIMULATIONS

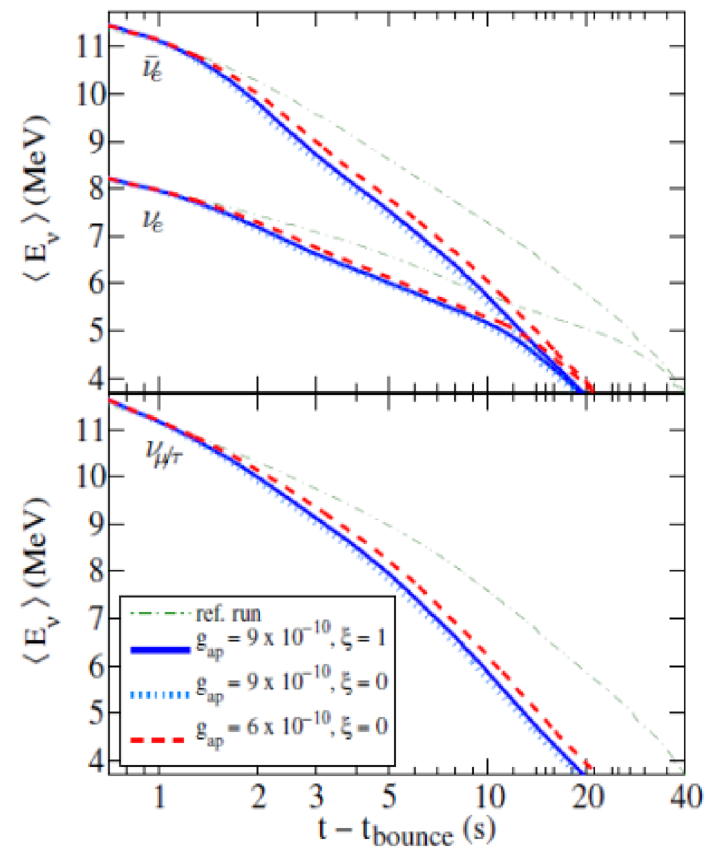
[Fischer, Chakraborty, Giannotti <u>*A.M.*</u> *, Payez & Ringwald, 1605.08780*]

18 M_{sun} progenitor mass

(spherically symmetric with Boltzmnann ν transport)



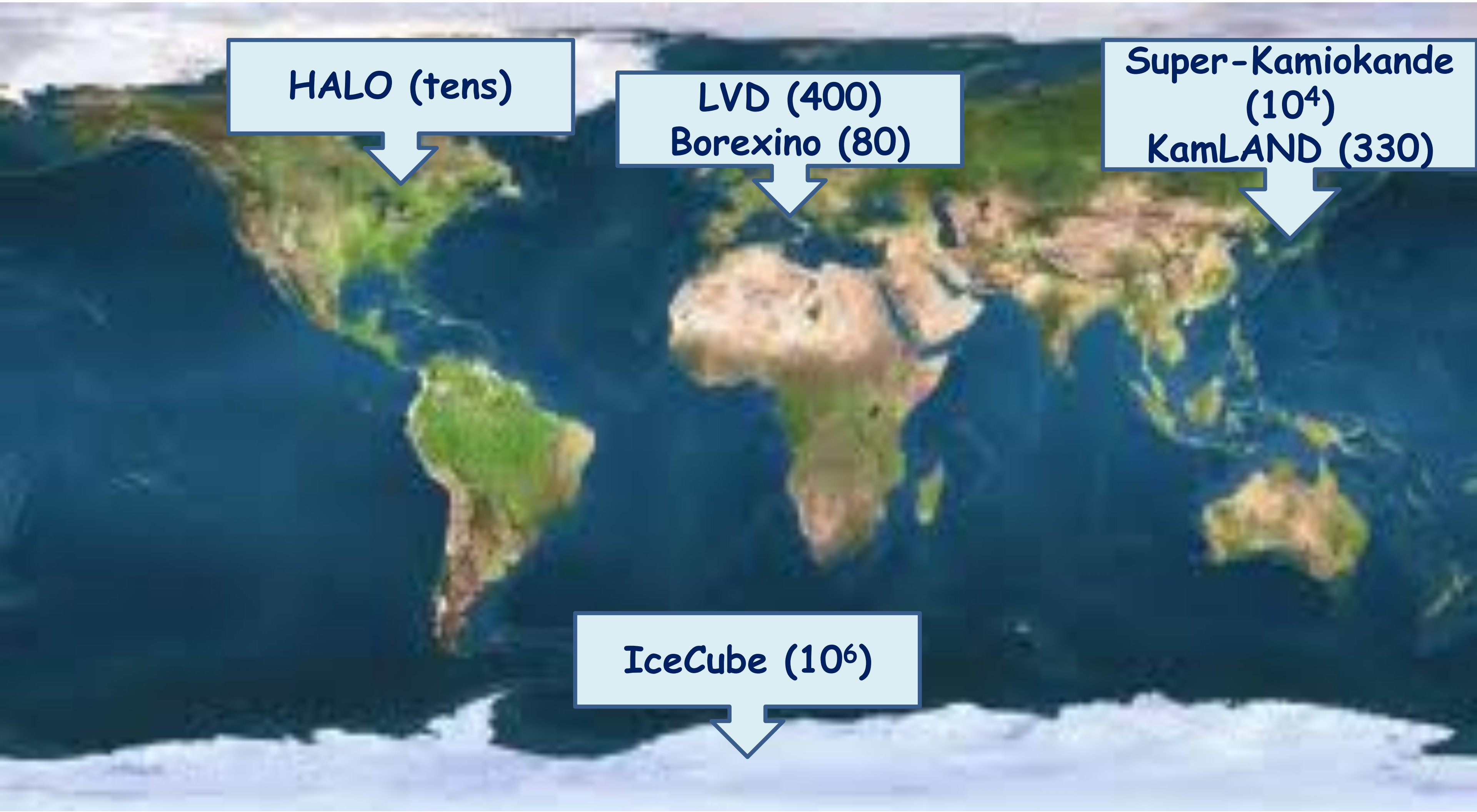
(a) Energy and number luminosities



(b) Average neutrino energies

KSVZ hadronic axion model (g_{an} =0)

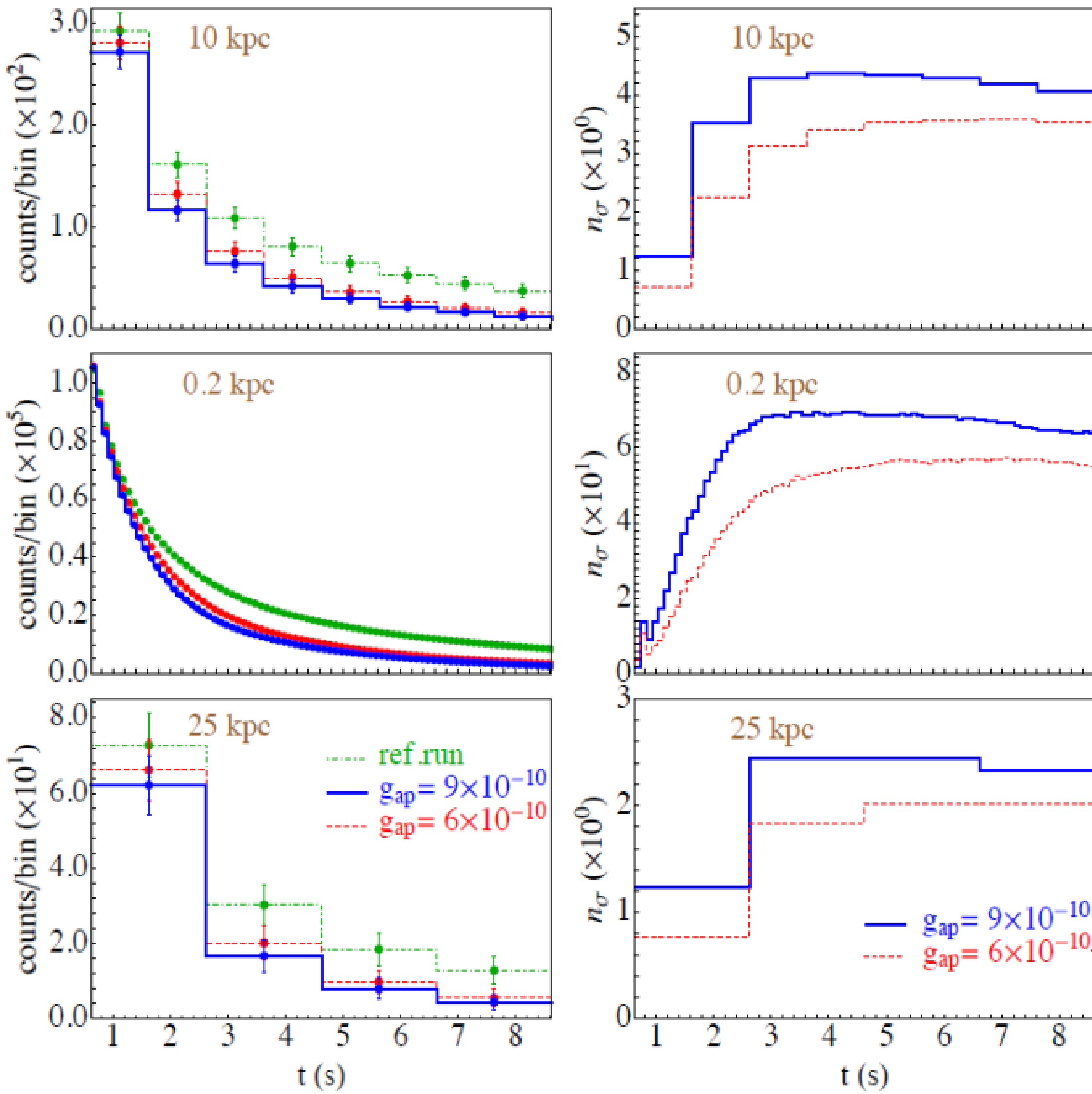
Large Detectors for Supernova Neutrinos



In brackets events for a "fiducial SN" at distance 10 kpc

IMPACT ON NEUTRINO SIGNAL

@ Super-Kamiokande



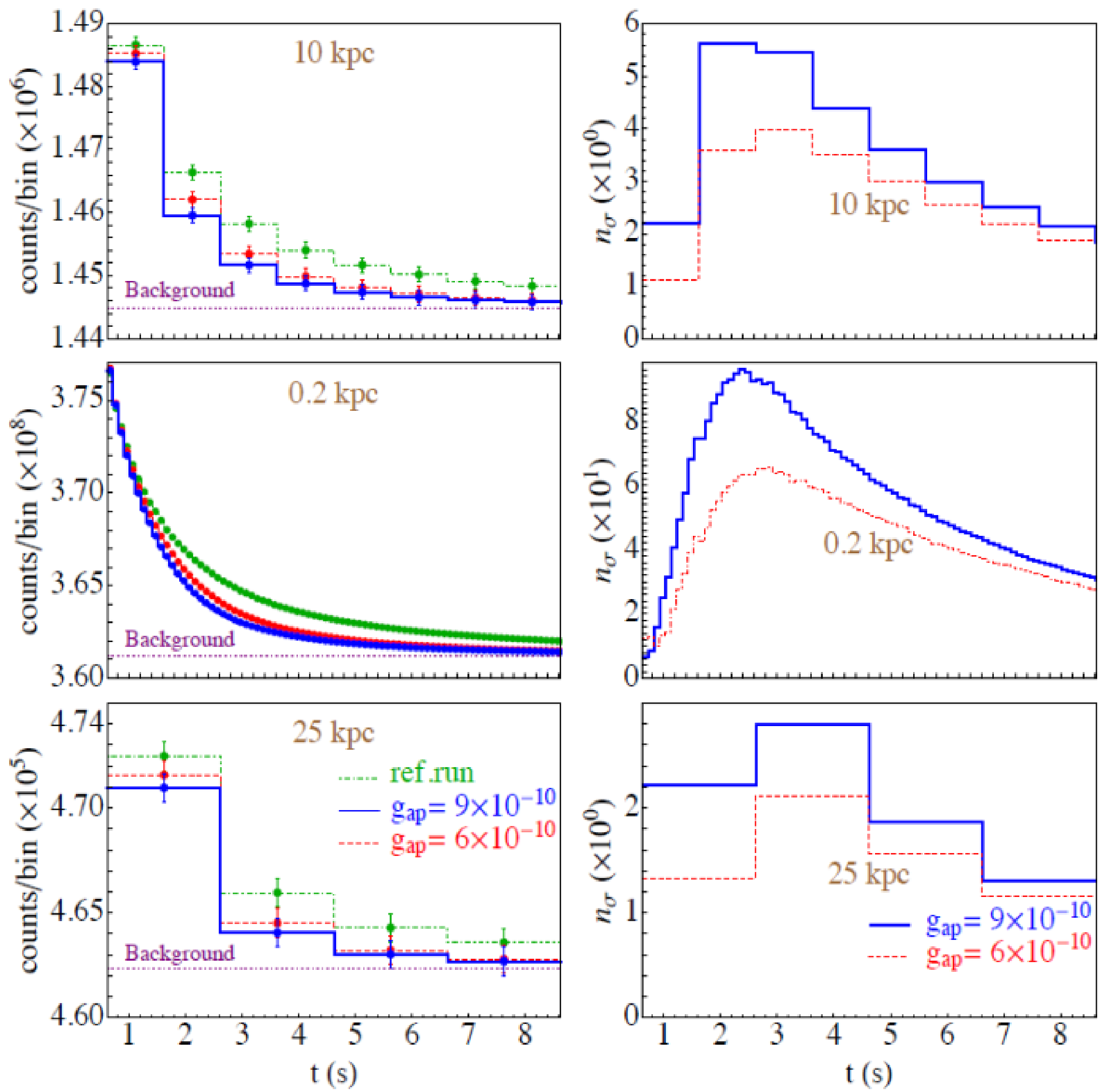
(~ GC)

(Betelgeuse)

$m_a = 3 \times 10^{-2}\, eV,$
$f_a = 4.8 \times 10^8 GeV$

$m_a = 8 \times 10^{-2}\, eV,$
$f_a = 7.3 \times 10^8 GeV$

@ Icecube



10 kpc
Background
counts/bin (×10^6)
n_σ (×10^0)
0.2 kpc
counts/bin (×10^8)
n_σ (×10^1)
25 kpc
counts/bin (×10^5)
ref.run
g_ap= 9×10^-10
g_ap= 6×10^-10
t (s)

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CONCLUSIONS

Core-collapse SNe represent powerful laboratories to constrain ALPs and axions

SN 1987A provided strong constraints which can be improved with current and planned gamma and neutrino detectors.

A Galactic SN is a lifetime opportunity for axions !

The speaker‘s attendance at this conference was sponsored by the Alexander von Humboldt Foundation.

http://www.humboldt-foundation.de