Impatiently awaited — What supernova explosions tell us about axion-like particles

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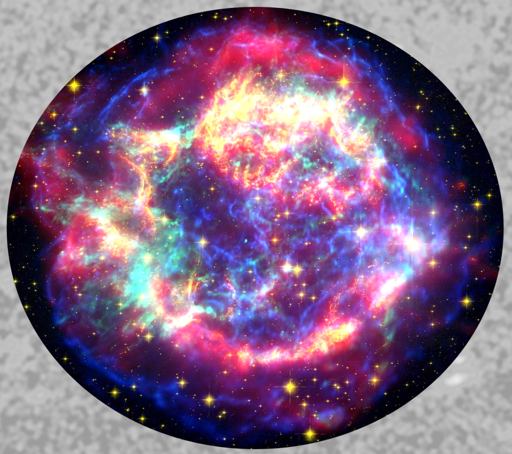
Rencontres de Physique des Particules 2024
Sorbonne Université, LPNHE, Paris



Axion(-like) particles and the Primakoff effect

Axions and axion-like particles (ALPs) may contribute (at least a fraction) to the dark matter content of the universe.

Origin/motivation:
spontaneously broken global $U(1)$-symmetry at energy scale f_a
—> axion: chiral $U(1)$-symmetry of QCD
—> ALPs: anything goes
Result: pseudo Nambu-Goldstone boson a

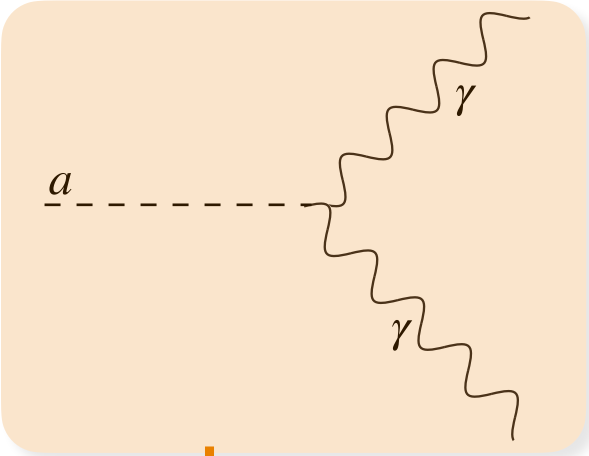
[Peccei, Quinn77; Weinberg 78; Wilczek 78; Arias et al. 12]

ALP photon coupling

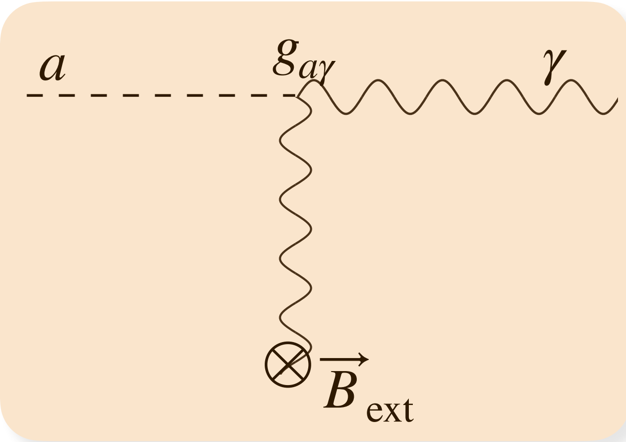
minimal scenario:

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

$$g_{a\gamma} = \frac{\alpha}{2\pi} \frac{1}{f_a} \mathcal{N}$$



decay

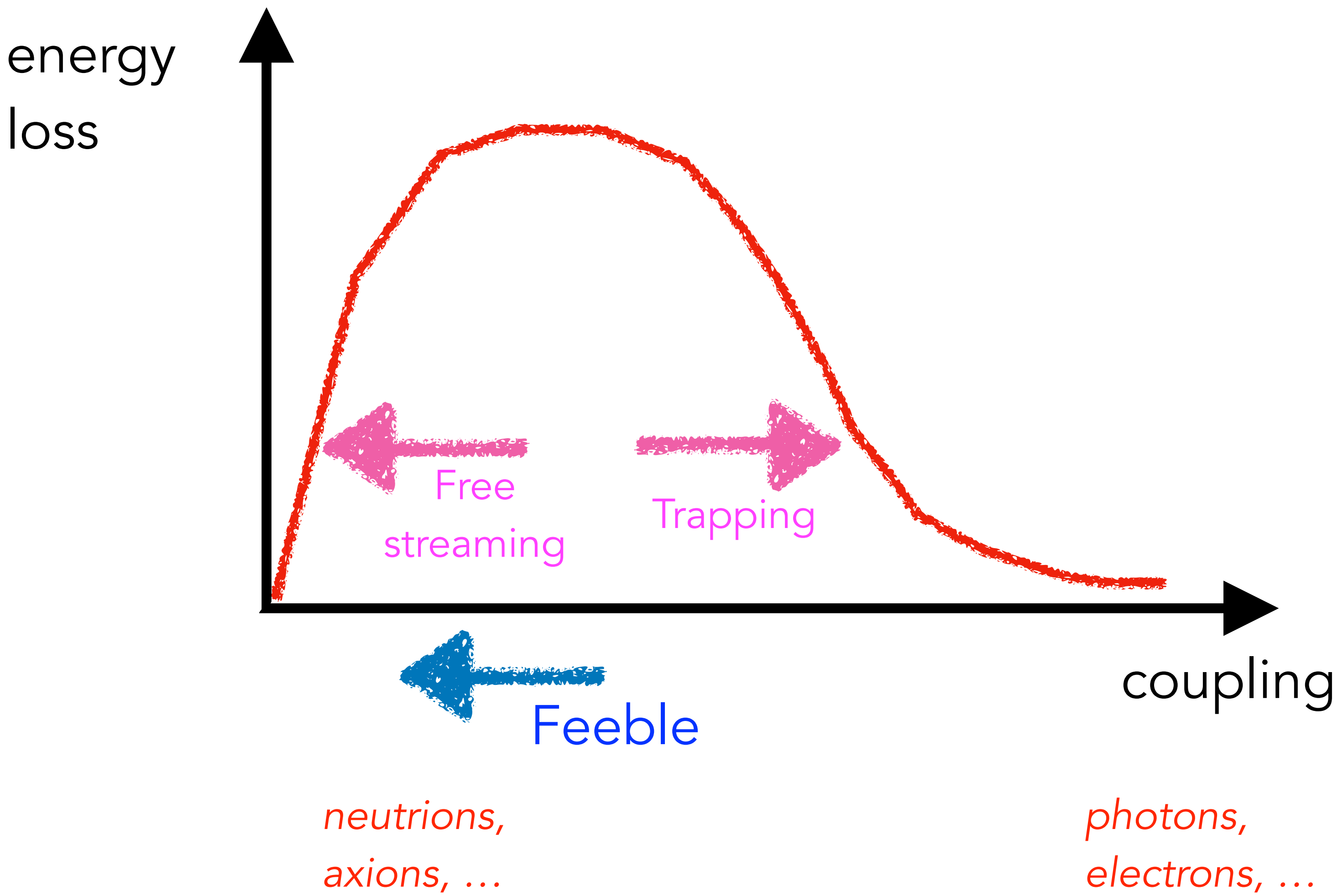


Primakoff effect

Using stellar astrophysics to probe ALPs

Let us assume ALPs are only feebly coupled to photons.

- ✦ Light particles, $m \lesssim T$, are efficiently thermally produced in the core of stellar objects.
- ✦ Almost free-streaming in stellar environment.
  - → new channel of stellar energy losses (they cool too faster)
  - → effects are observationally accessible



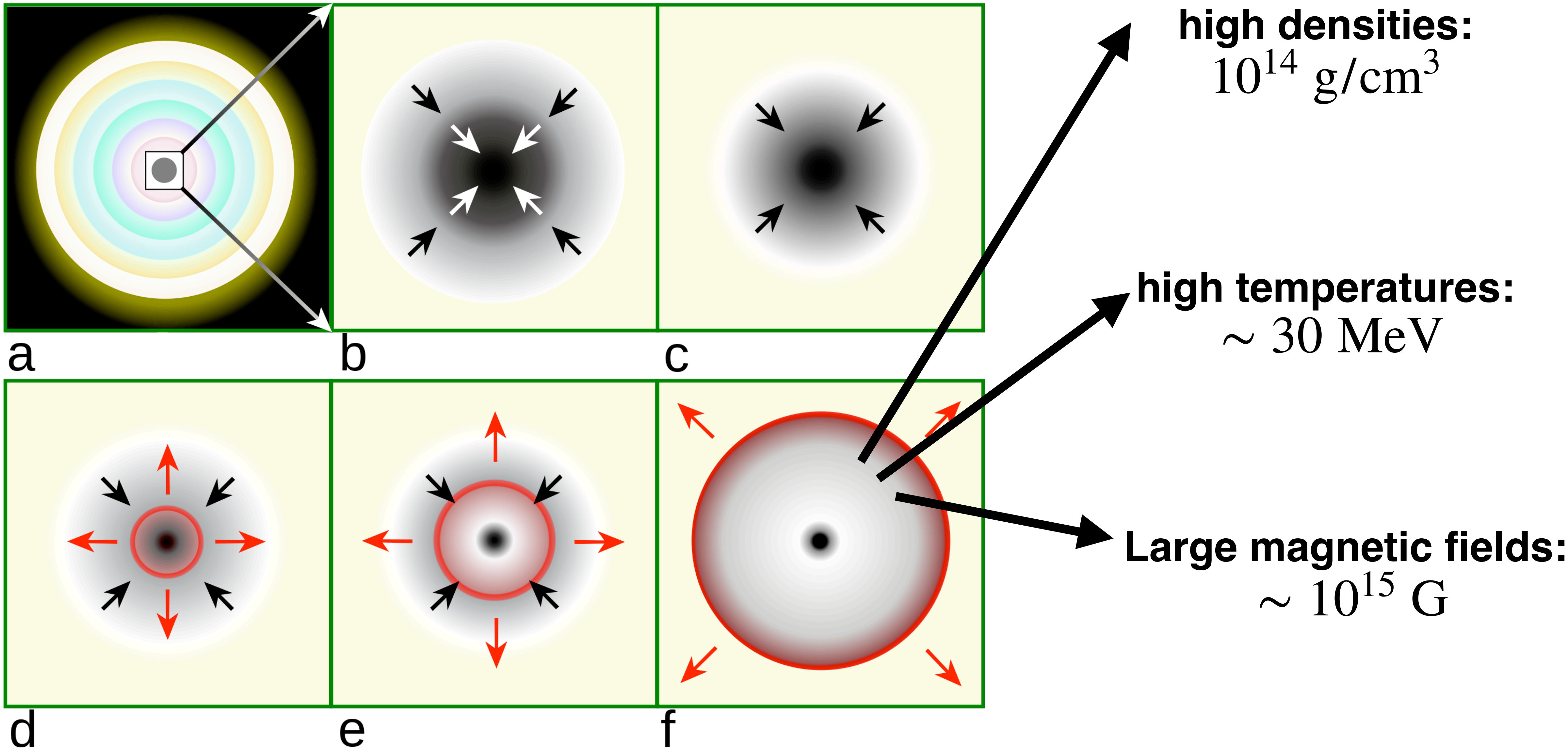
[figure credit: M. Giannotti, @FIPs '20]

Tangible example:
Hints from observations of White Dwarf cooling (period change rate too high) [Isern, Hernanz, Garcıa-Berro (1992), Córsico, Althaus, Miller Bertolami, Kepler (2019), and many other works]

Axions/ALPs may explain this discrepancy.

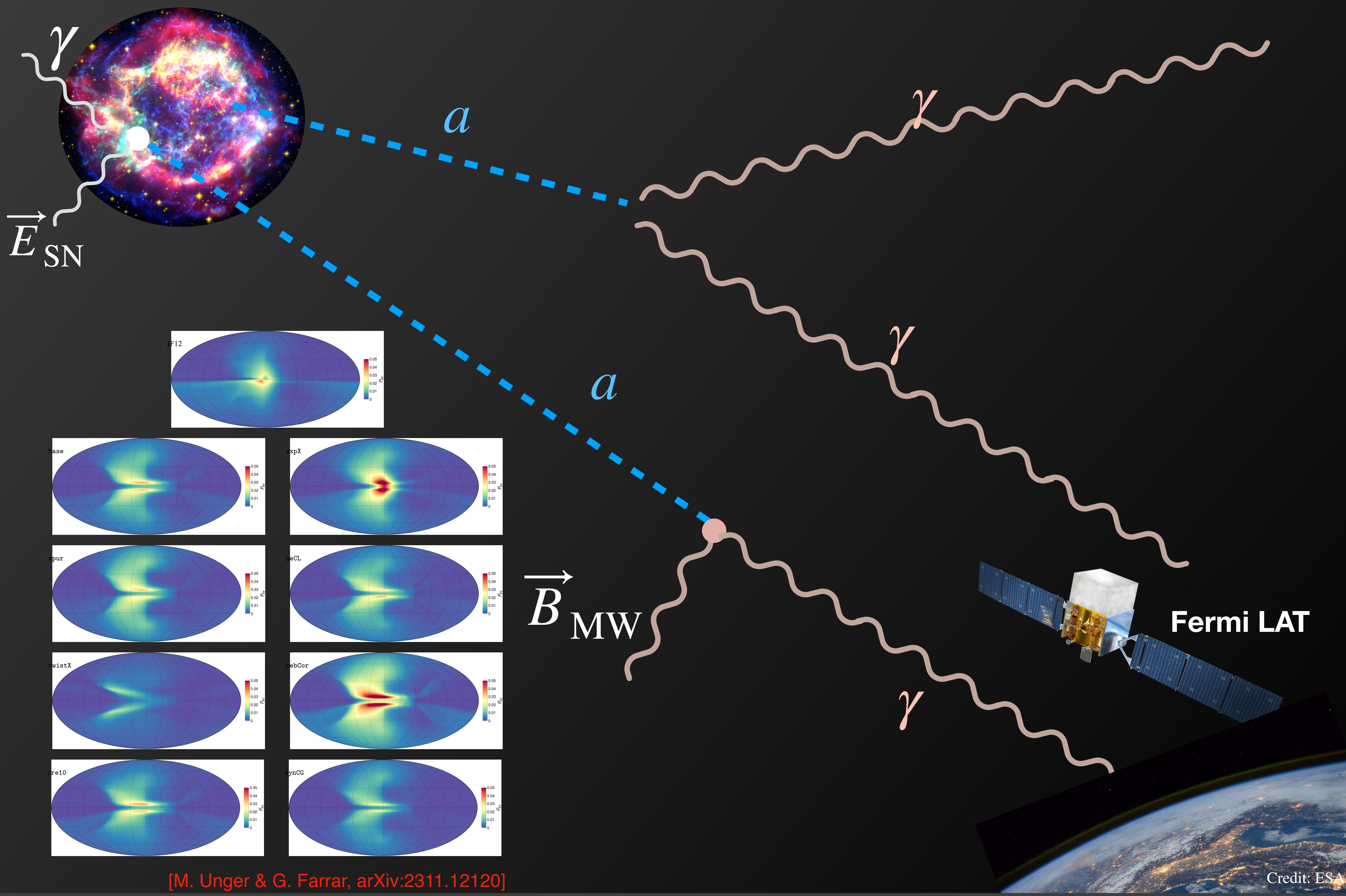
The appeal of core-collapse supernovae (SNe)

Massive stars ($> 8\,M_\odot$) burn their fuel until reaching an onion-like interior with a degenerate iron core in their centres.



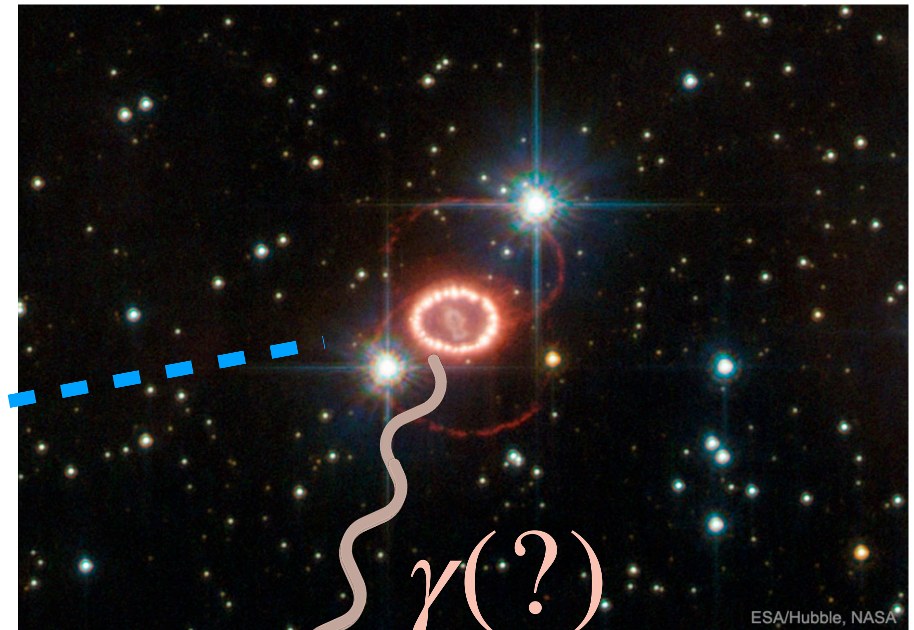
Fusing nuclei heavier than iron requires energy, thus gravity wins over the radiation pressure from the core; a rapid collapse occurs.

How to directly detect ALPs

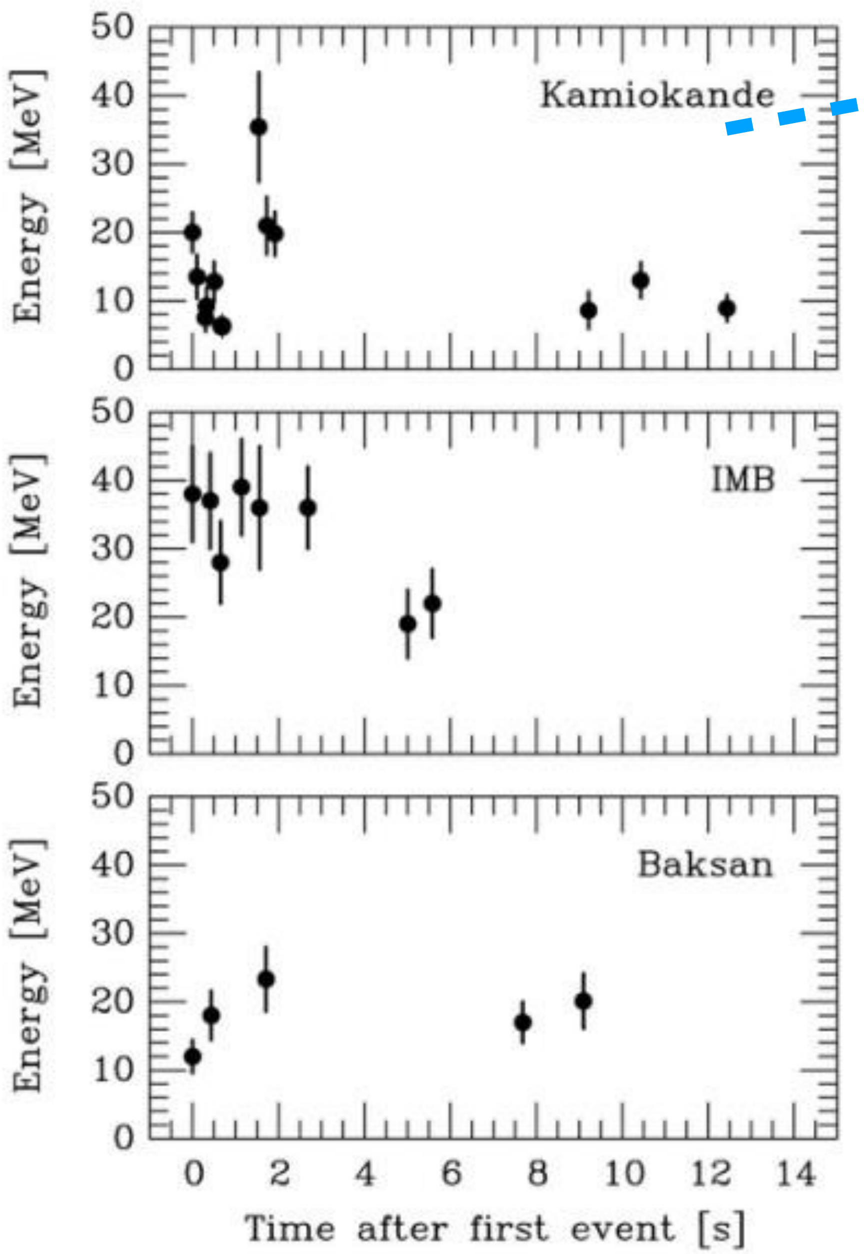


The one Galactic SN in modern times: SN 1987A

A supernova in the Large Magellanic Cloud (50 kpc distance) exploded in 1987.



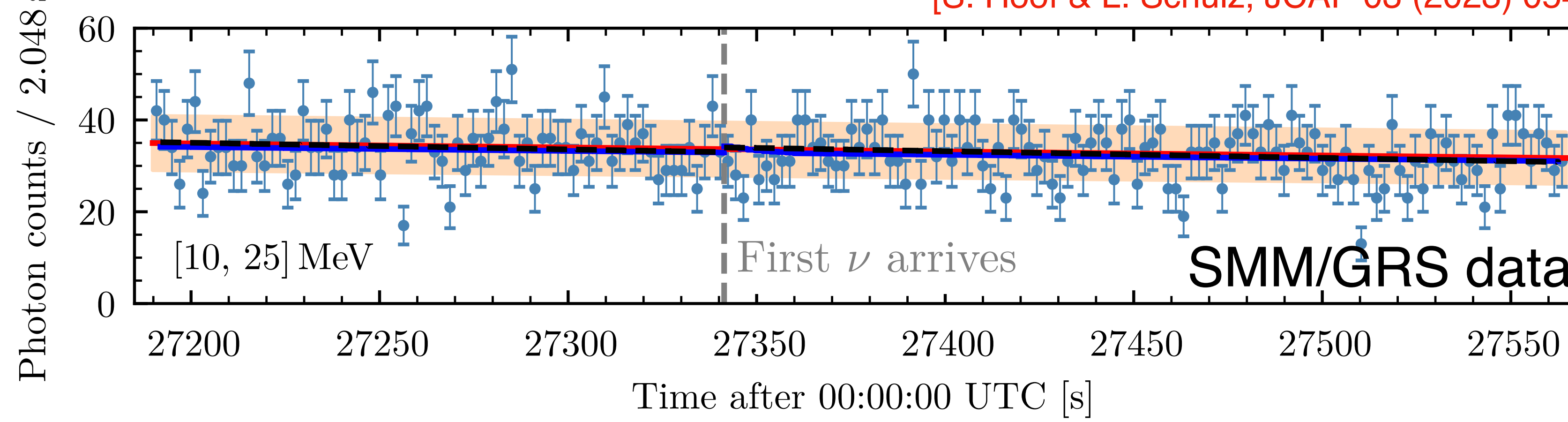
SN 1987A neutrino signal



[credit: Georg Raffelt]

Gamma-ray counts towards SN 1987A

[S. Hoof & L. Schulz, JCAP 03 (2023) 054]

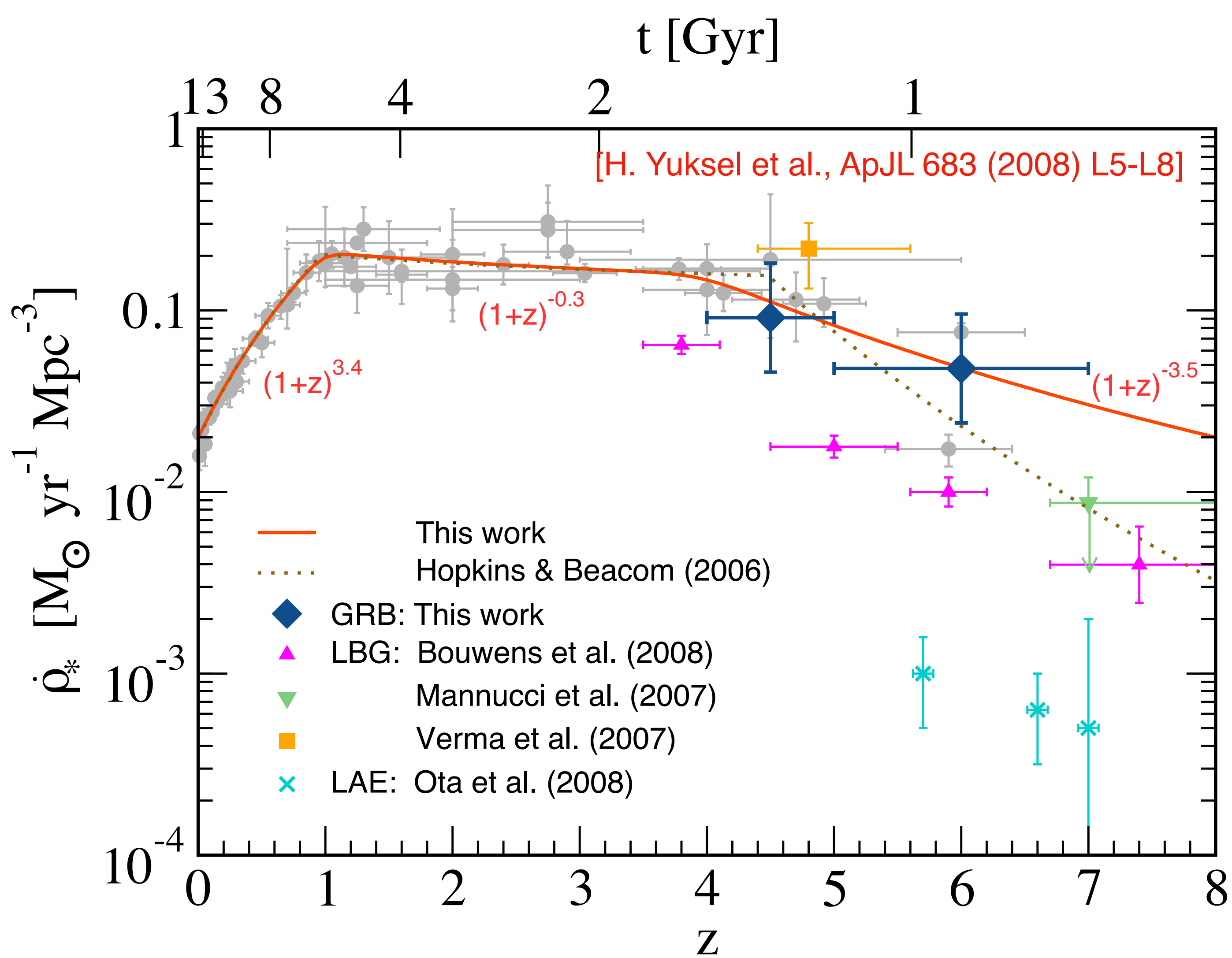


Neutrino data and non-observation of gamma rays still used to set competitive constraints on exotic new degrees of freedom! [A. Payez et al., JCAP 02 (2015) 006], [S. Hoof & L. Schulz, JCAP 03 (2023) 054], [E. Müller, **CE** et al., JCAP 07 (2023) 056], [A. Lella et al., PRD 109 (2024) 2, 023001], etc.

Extragalactic Searches

Using extragalactic supernova explosions

Supernovae are not that rare on larger scales; their rates scales with the star-formation rate in the universe.



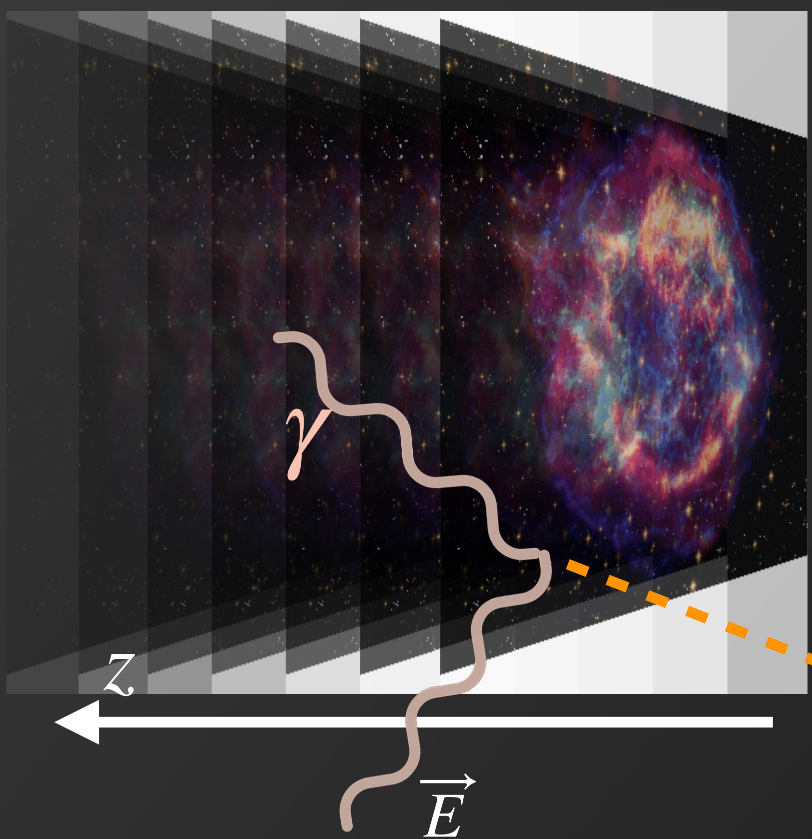
Observables:

→ **The diffuse axion-like particle background ($m_a \sim \mathcal{O}(10^{-9}\ \mathrm{eV})$),**

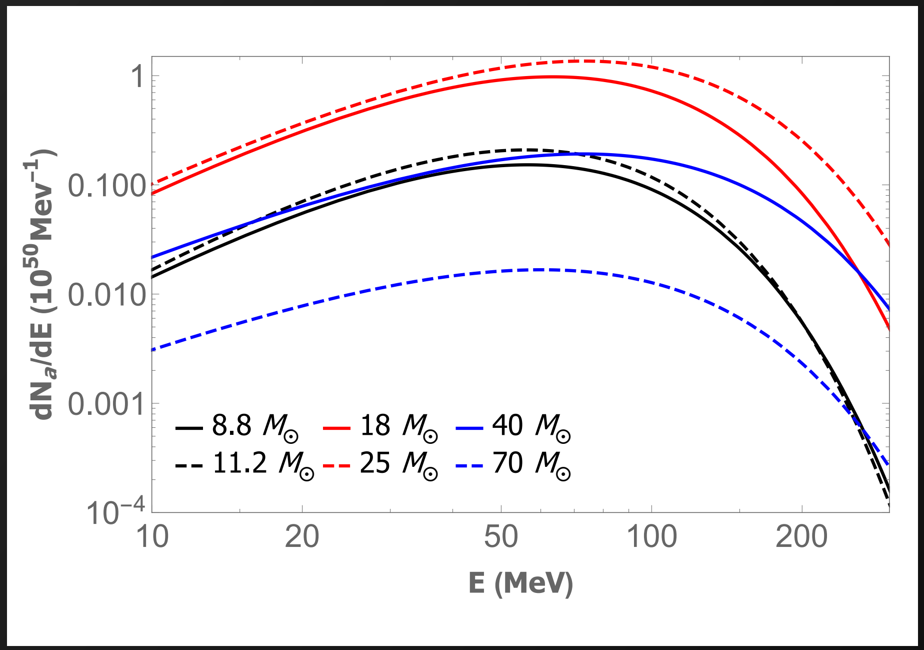
→ **individual events: SN 2023ixf ($m_a \sim \mathcal{O}(\mathrm{MeV})$).**

The Diffuse Supernova ALP Background

Cumulative cosmological SN flux



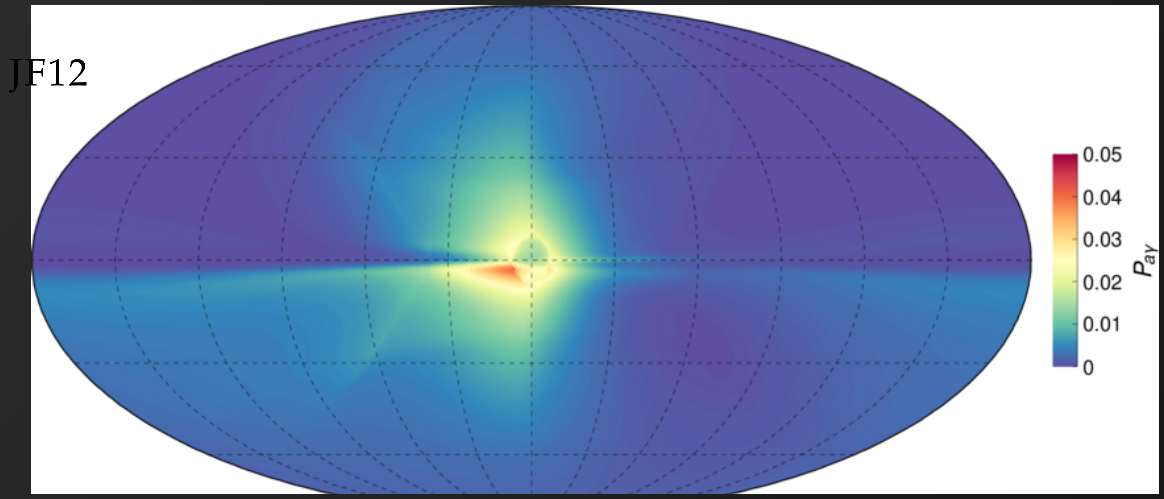
+ star-formation rate
+ numerical SN simulations for different progenitors masses

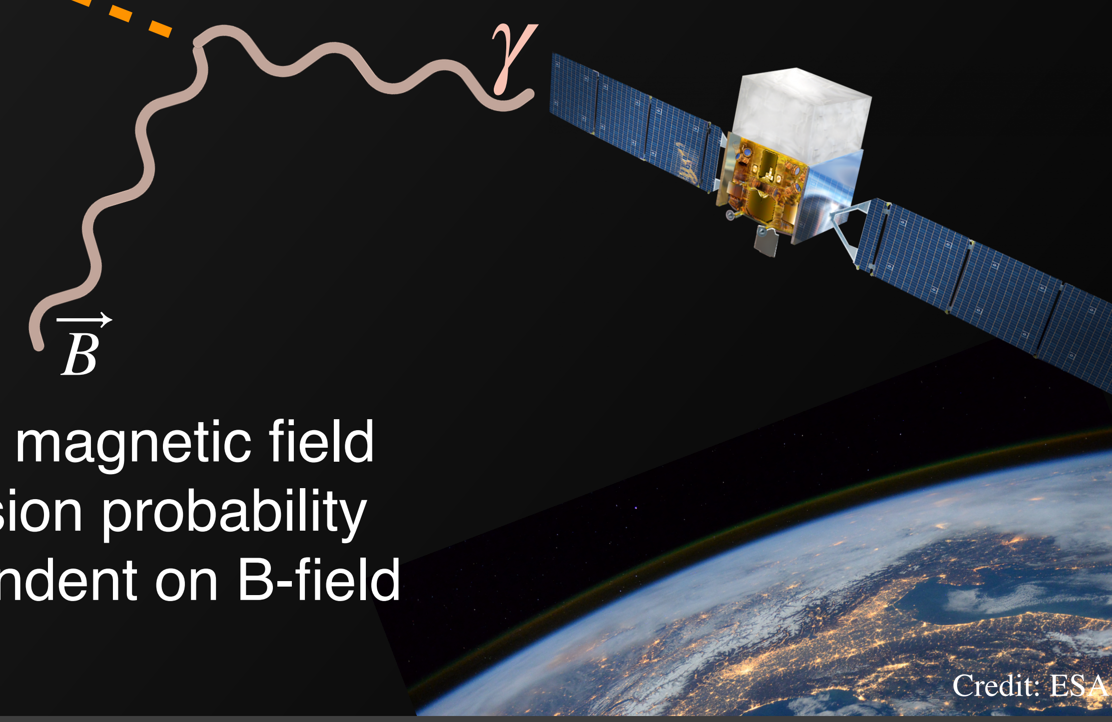


[F. Calore, **CE** et al., PRD 105 (2022) 6]

electrostatic field of ions, electrons and protons

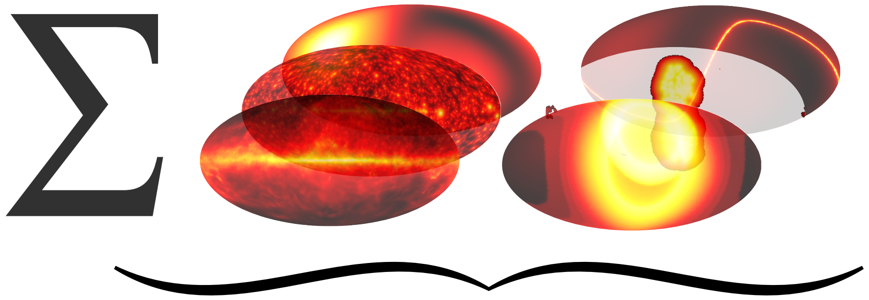
a



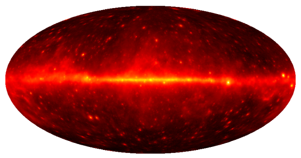


Milky Way's magnetic field —> conversion probability highly dependent on B-field structure

The bound on the ALP parameter space



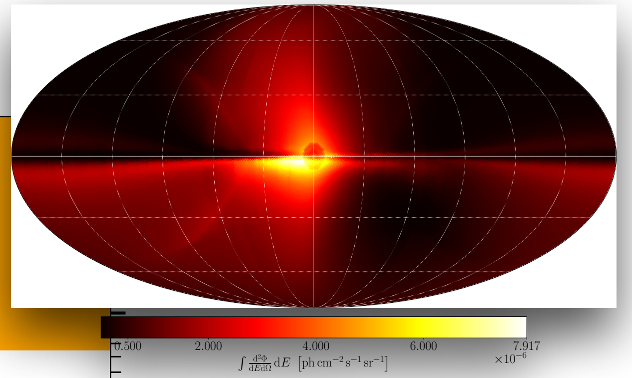
model templates

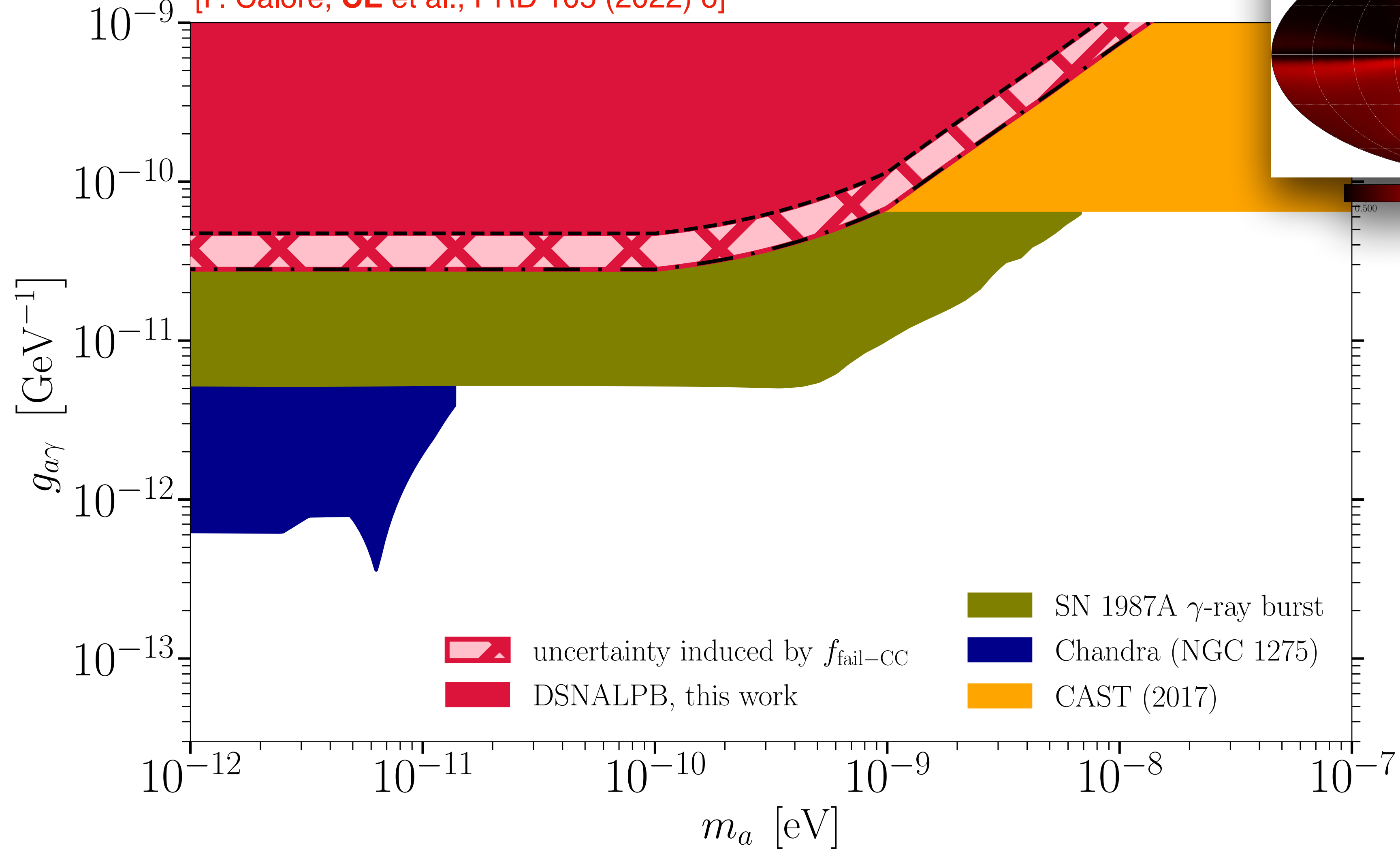


Fermi-LAT data

No detection: How much space is their to accommodate an additional signal?

ALP signal



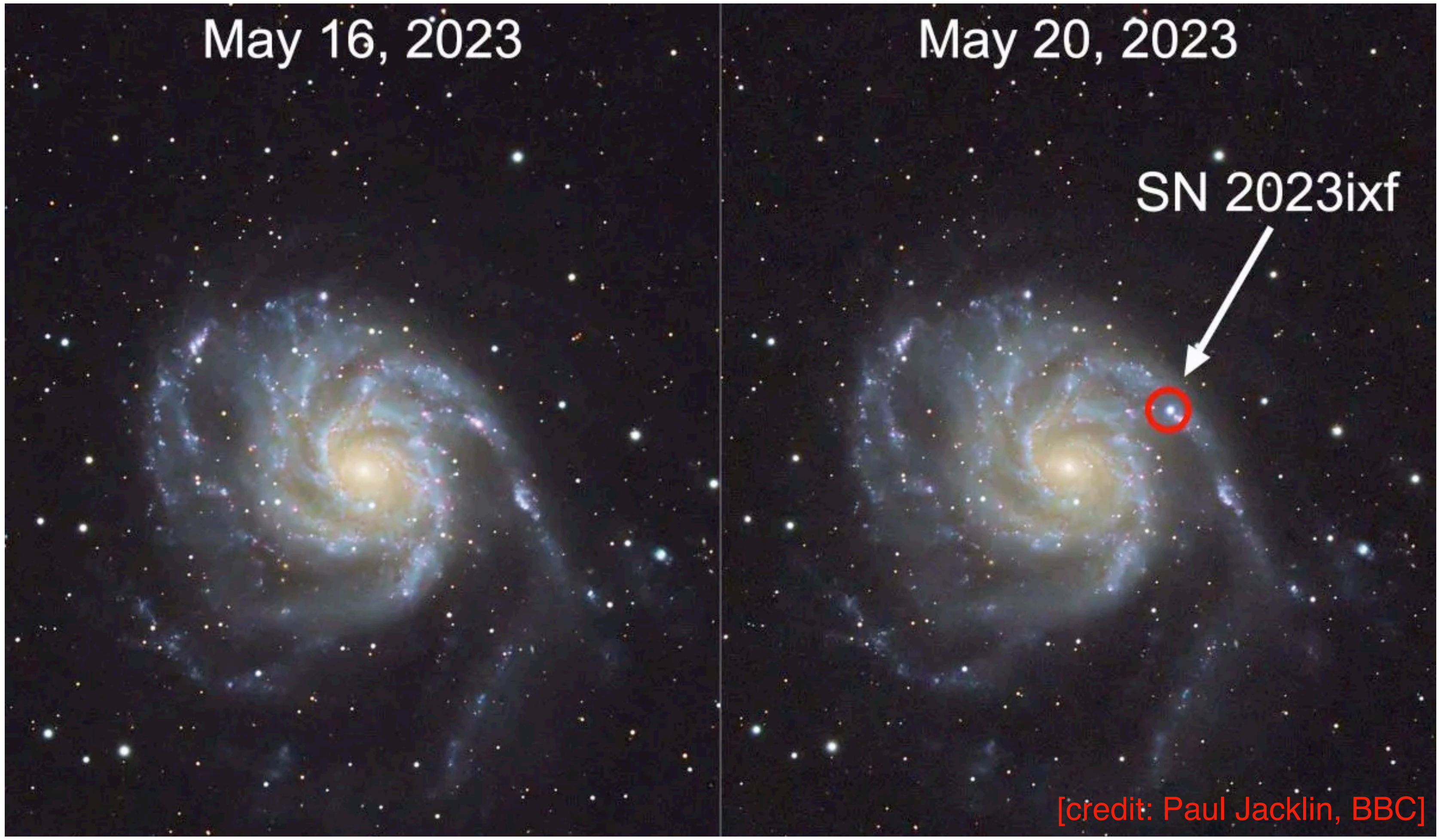


Constraints stronger than CAST (solar axion bounds) and can be improved with future gamma-ray measurements (MeV mission).

The decay of MeV-scale ALPs and SN 2023ixf

What about individual extragalactic SN events?

A recent type II supernova was optically detected in the Pinwheel galaxy (M 101, distance ~ 7 Mpc) on the 18th of May 2023 with a progenitor mass from 9 to 22 $M_\odot$.

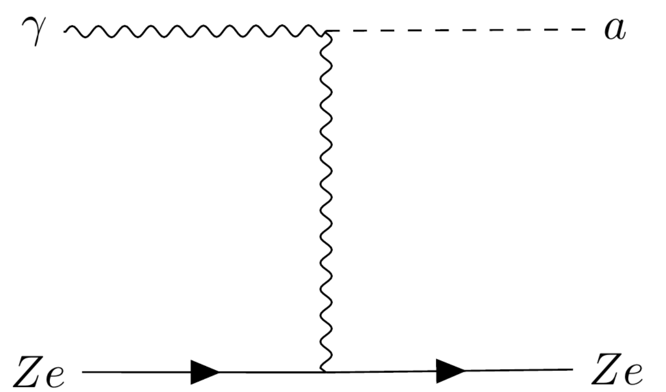


→ Large scientific and publication attention, e.g. [C. D. Kilpatrick et al., ApJL 952 (2023) 1], [L. A. Sgro et al., Res. Notes AAS 7 (2023), 141]

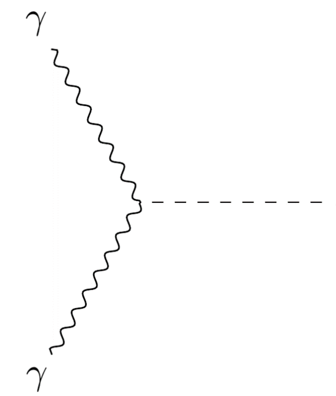
→ As individual event too faint to detect signal of light ALPs, but **MeV-scale ALPs are accessible via ALP decay**!

The decay of MeV-scale ALPs and SN 2023ixf

ALP production:
(environmental properties via numerical simulation results of 11 $M_\odot$ progenitor)



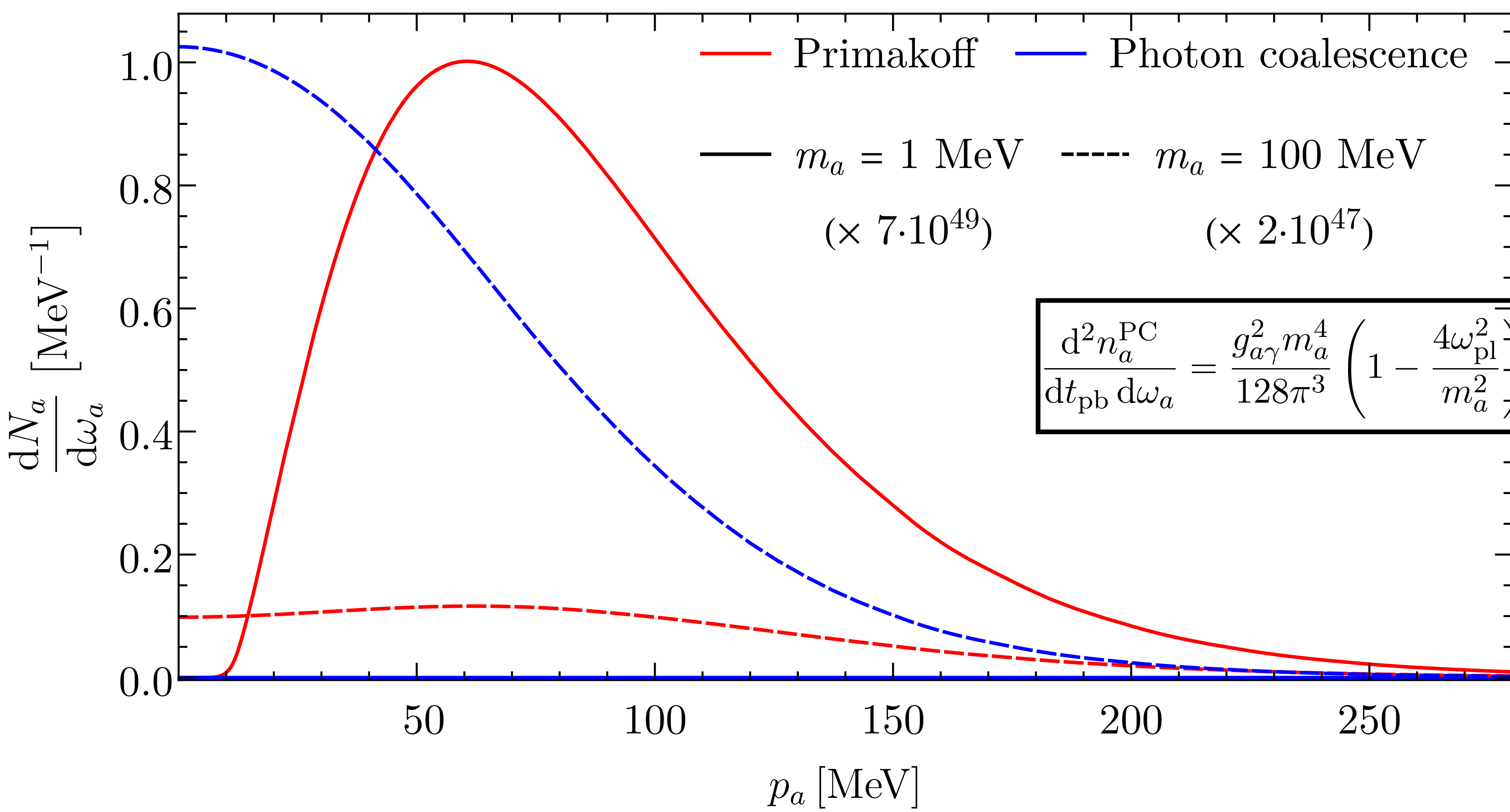
Primakoff process



inverse decay/ photon coalescence

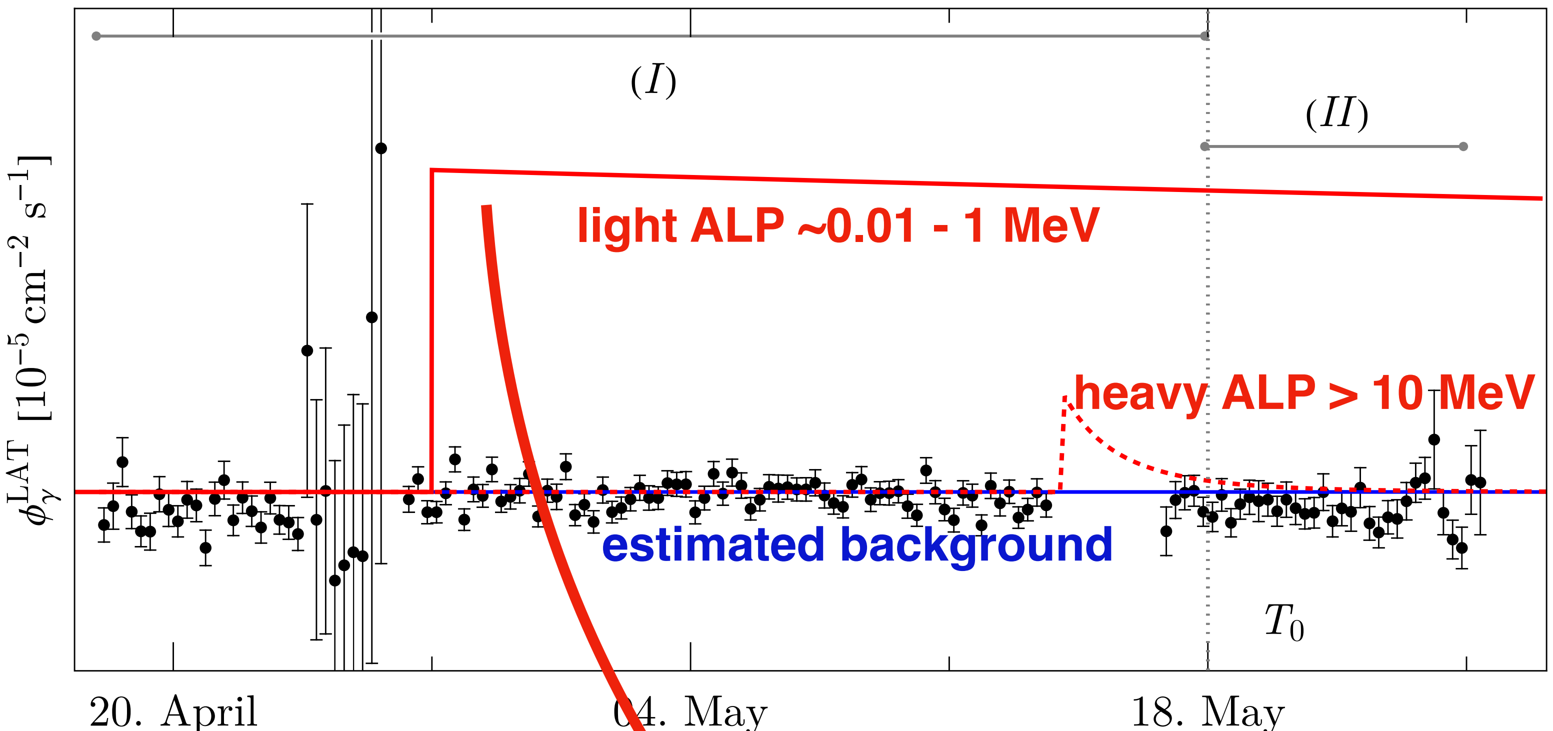
We accounted for photon coalescence was ignored in previous studies since it only becomes relevant above the MeV scale!

[E. Müller, **CE** et al., JCAP 07 (2023) 056]



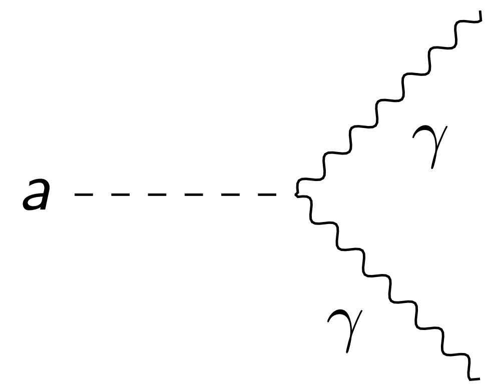
$$\frac{d^2 n_a^{PC}}{dt_{pb}\, d\omega_a} = \frac{g_{a\gamma}^2 m_a^4}{128\pi^3}\left(1-\frac{4\omega_{pl}^2}{m_a^2}\right)\int_{\omega_{min}}^{\omega_{max}} d\omega_\gamma \left[\left(e^{\omega_\gamma/T}-1\right)\left(e^{(\omega_a-\omega_\gamma)/T}-1\right)\right]^{-1}$$

The decay of MeV-scale ALPs and SN 2023ixf

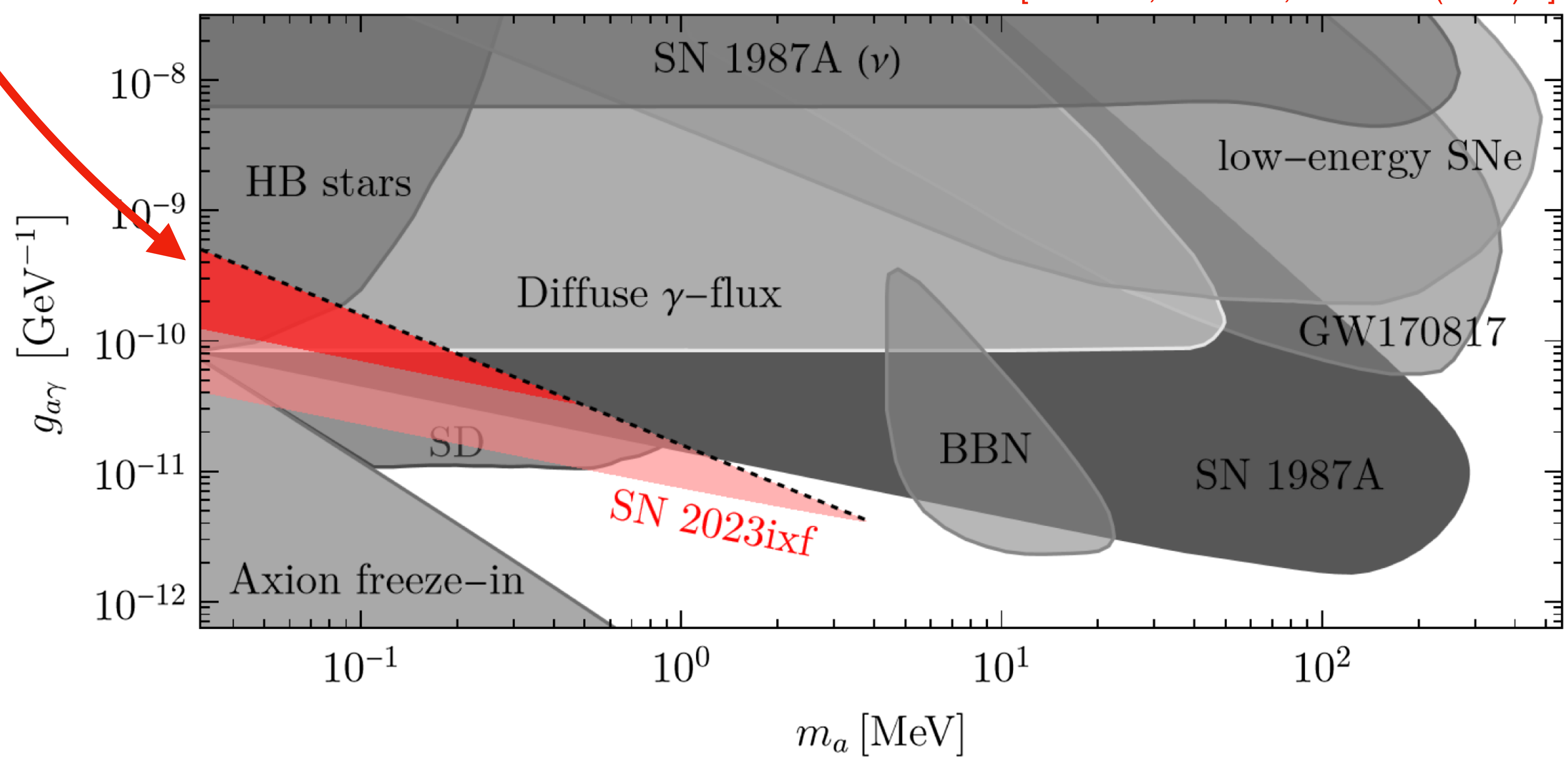


The Fermi-LAT data towards SN 2023ixf around the optical onset.

signal: ALP decay



[E. Müller, **CE** et al., PRD 109 (2024) 2]



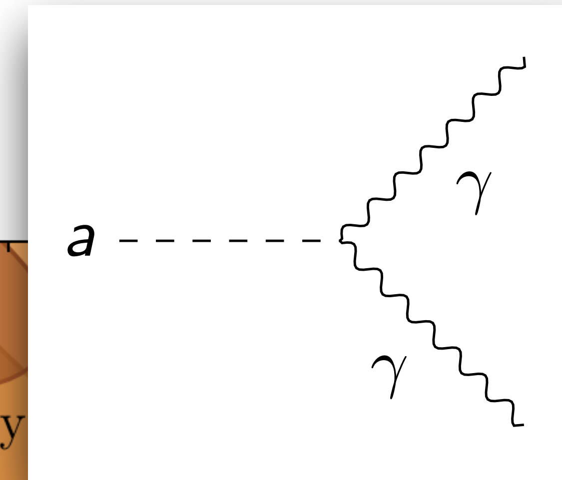
SN 2023ixf can probe unexplored parts of MeV-scale ALPs via ALP decay (within uncertainties: progenitor mass, distance and volume of the SN).

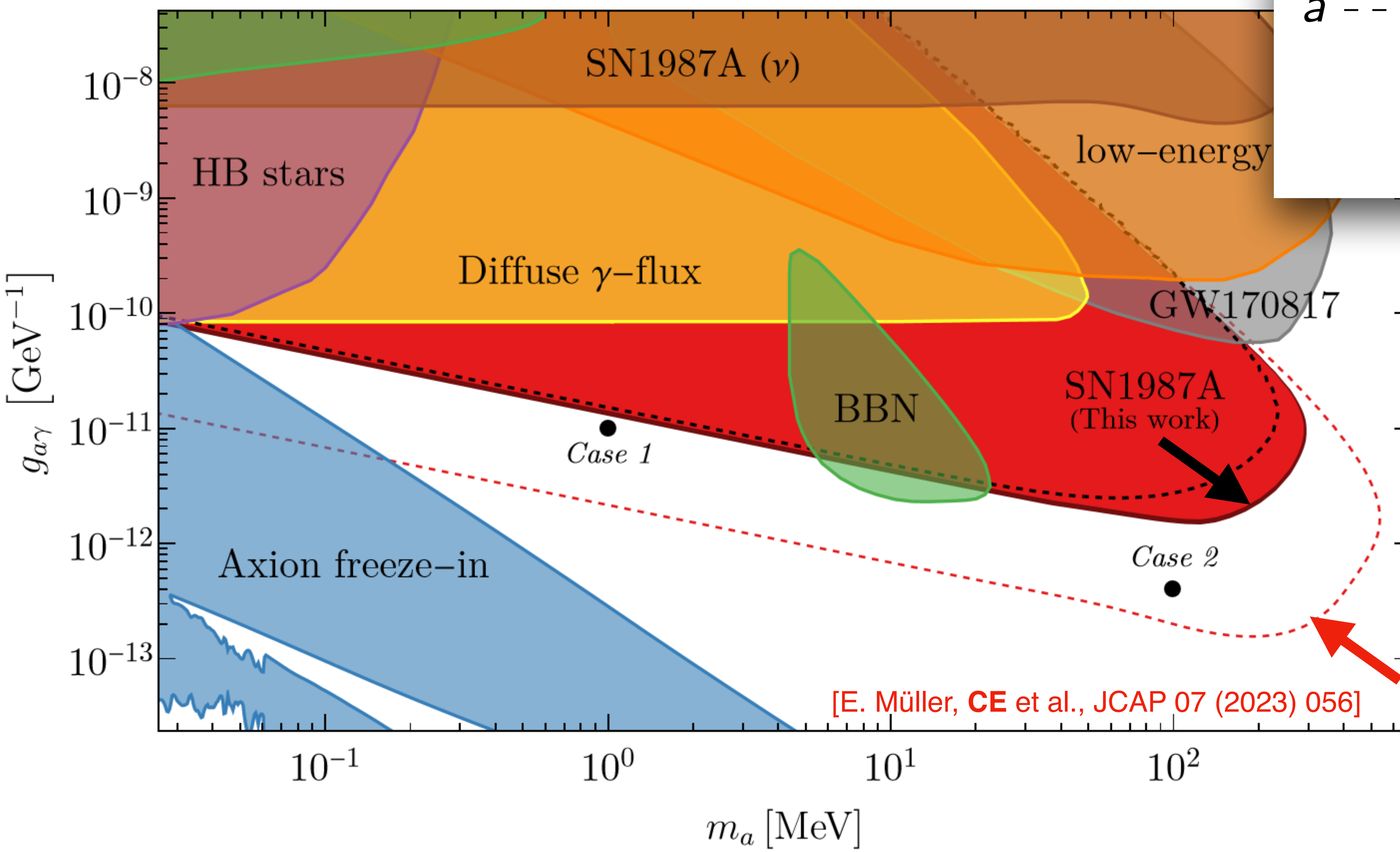
Prospects for future Galactic SNe

What if there where a Galactic supernova like 1987?

Photon coalescence was previously not accounted for when probing the parameter space of MeV-scale ALPs? Impact on constraints from ALP decay:

- → **SN 1987A**
- → **A future Galactic supernova (same distance as SN 1987A)**





Sensitivity of Fermi-LAT to a future SN at 50 kpc (Fluence 5σ over background)

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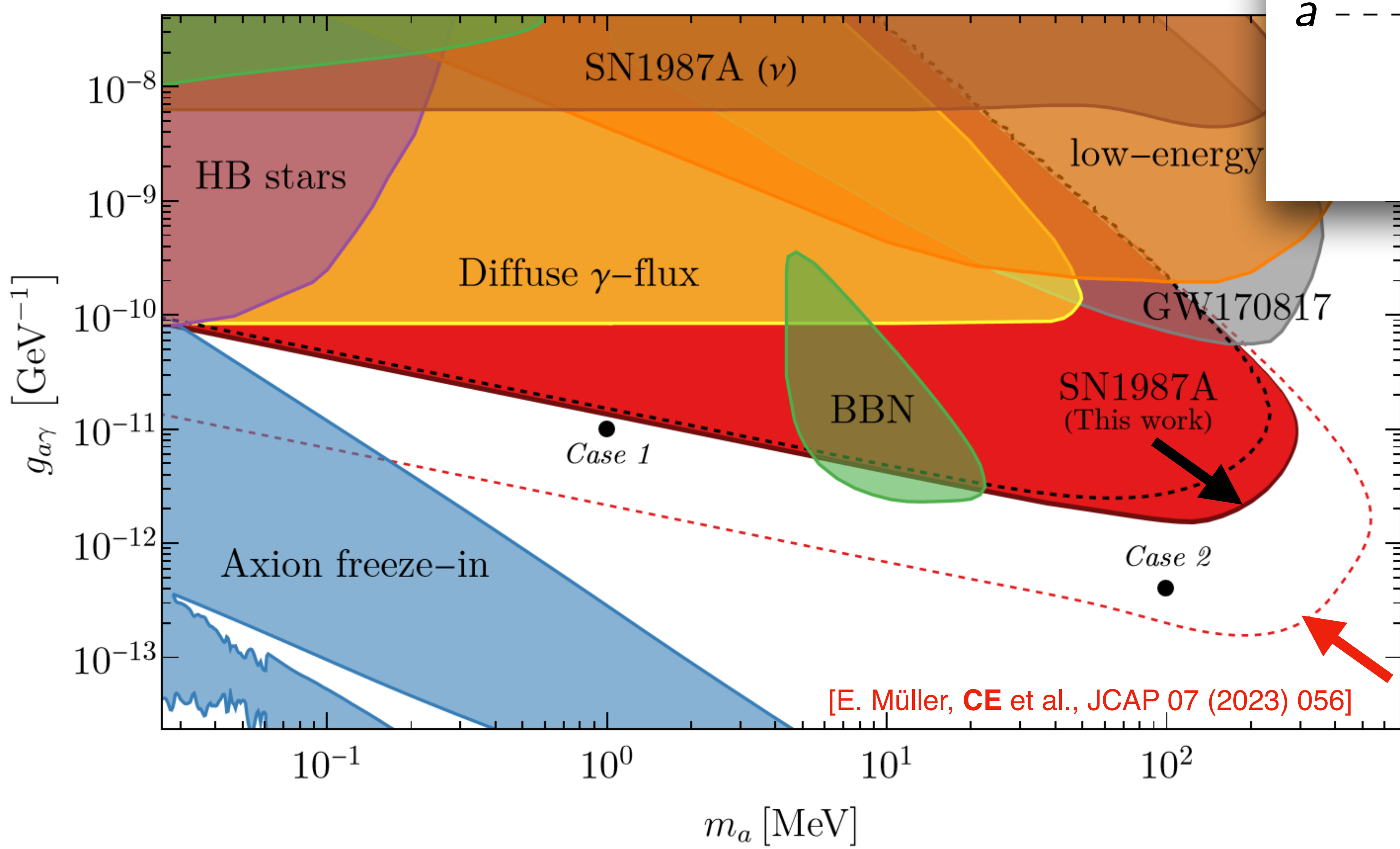
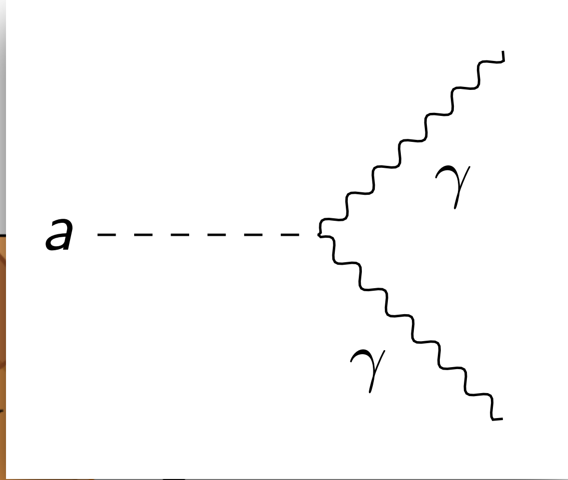




Sensitivity of Fermi-LAT to a future SN at 50 kpc (Fluence 5σ over background)

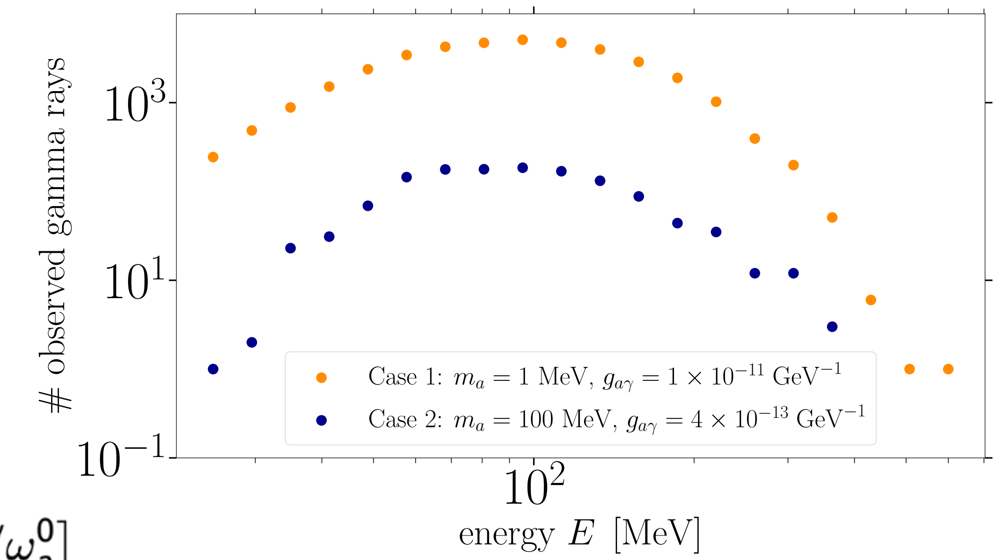
With modern instruments: Can we learn more about the ALP's properties from a future Galactic SN?

What if there where a Galactic supernova like 1987?

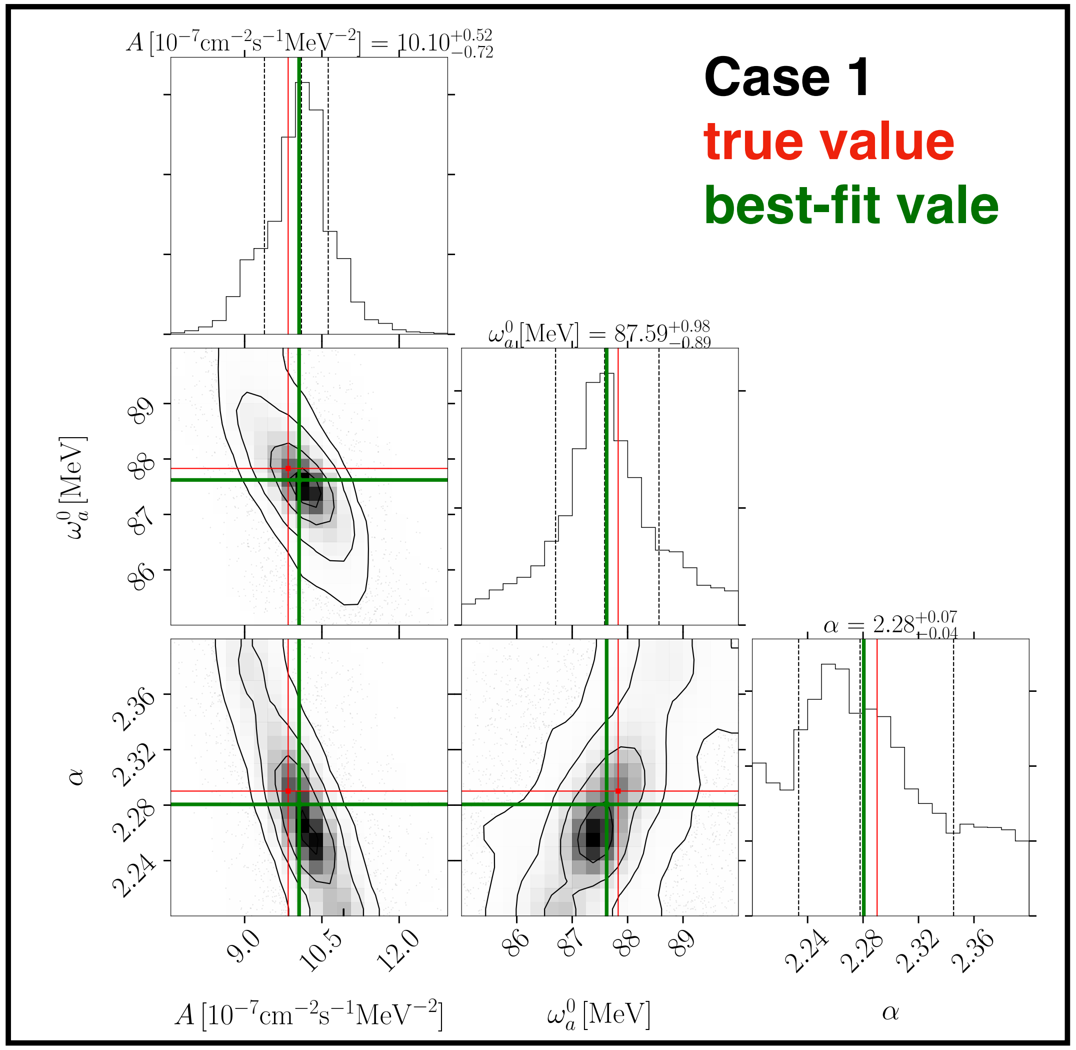
Signal shape depends on the ALP mass, can we infer the mass if a positive signal occurs?

- **Case 1:** $m_a = 1$ **MeV**
- **Case 2:** $m_a = 100$ **MeV**

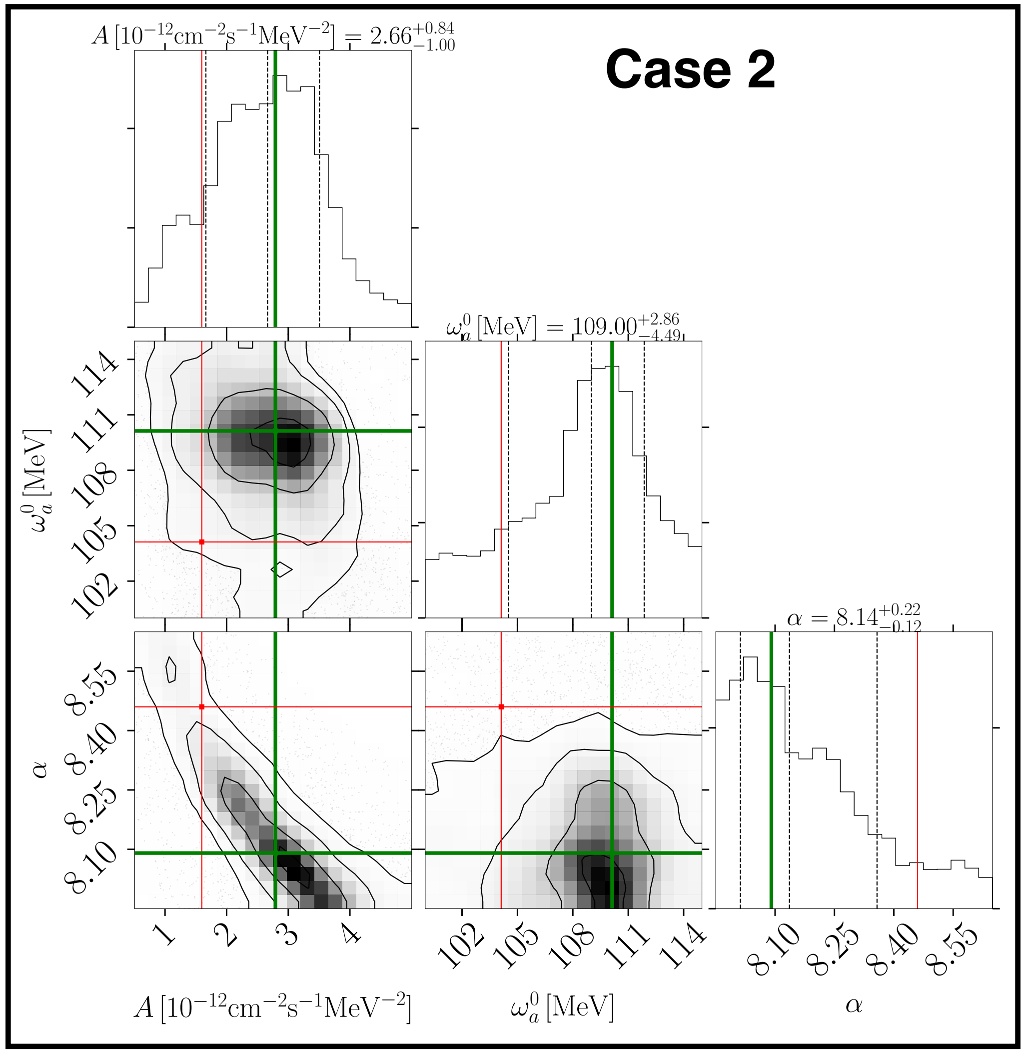
fit function: $$\left.\frac{d\Phi_\gamma}{d\omega_\gamma}\right|_{m_a<10\text{ MeV}} = A\,\omega_\gamma\,\Gamma\left[\alpha, (1+\alpha)\,\omega_a^{\min}/\omega_a^0\right]$$



[E. Müller, **CE** et al., JCAP 07 (2023) 056]

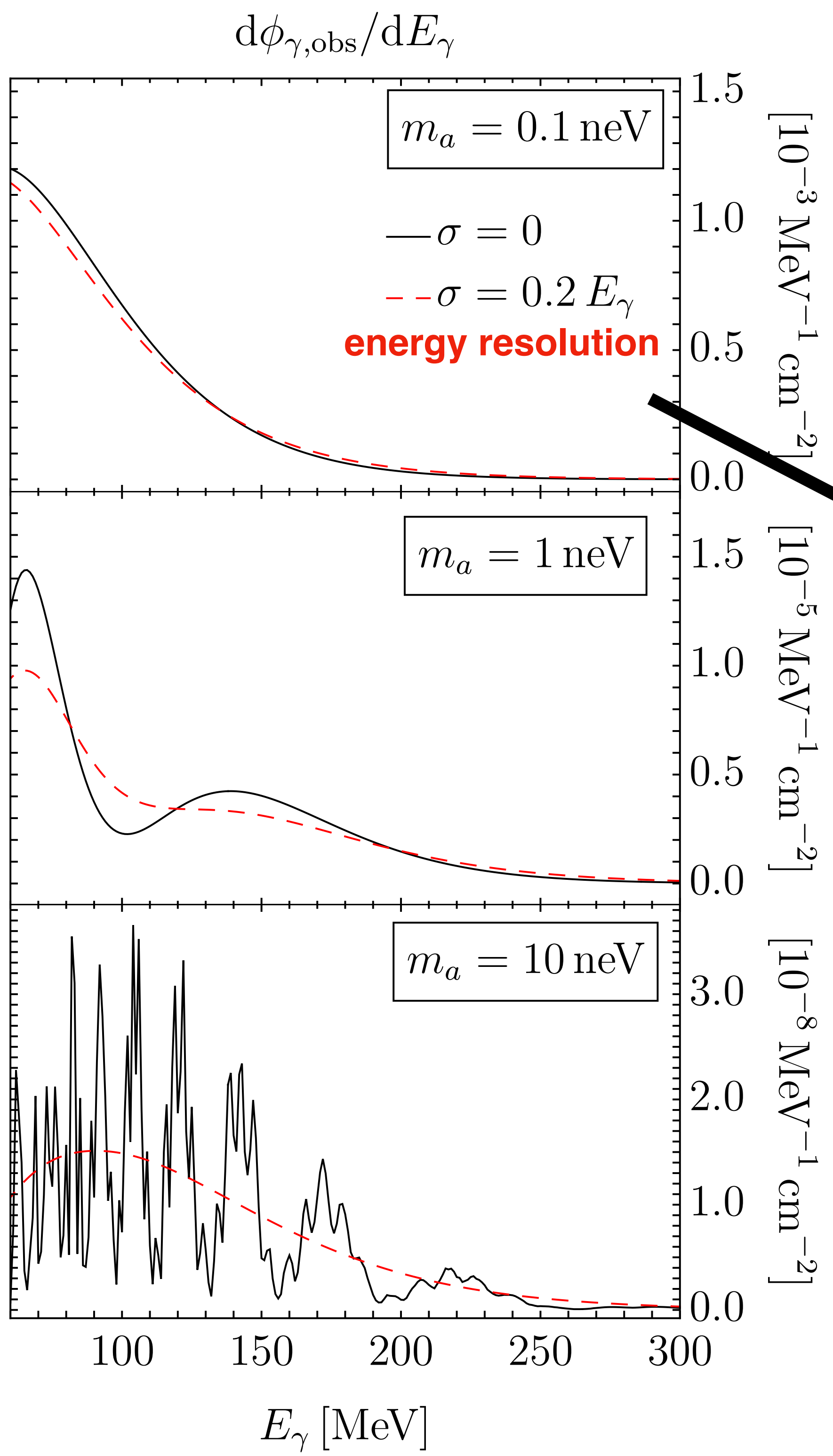


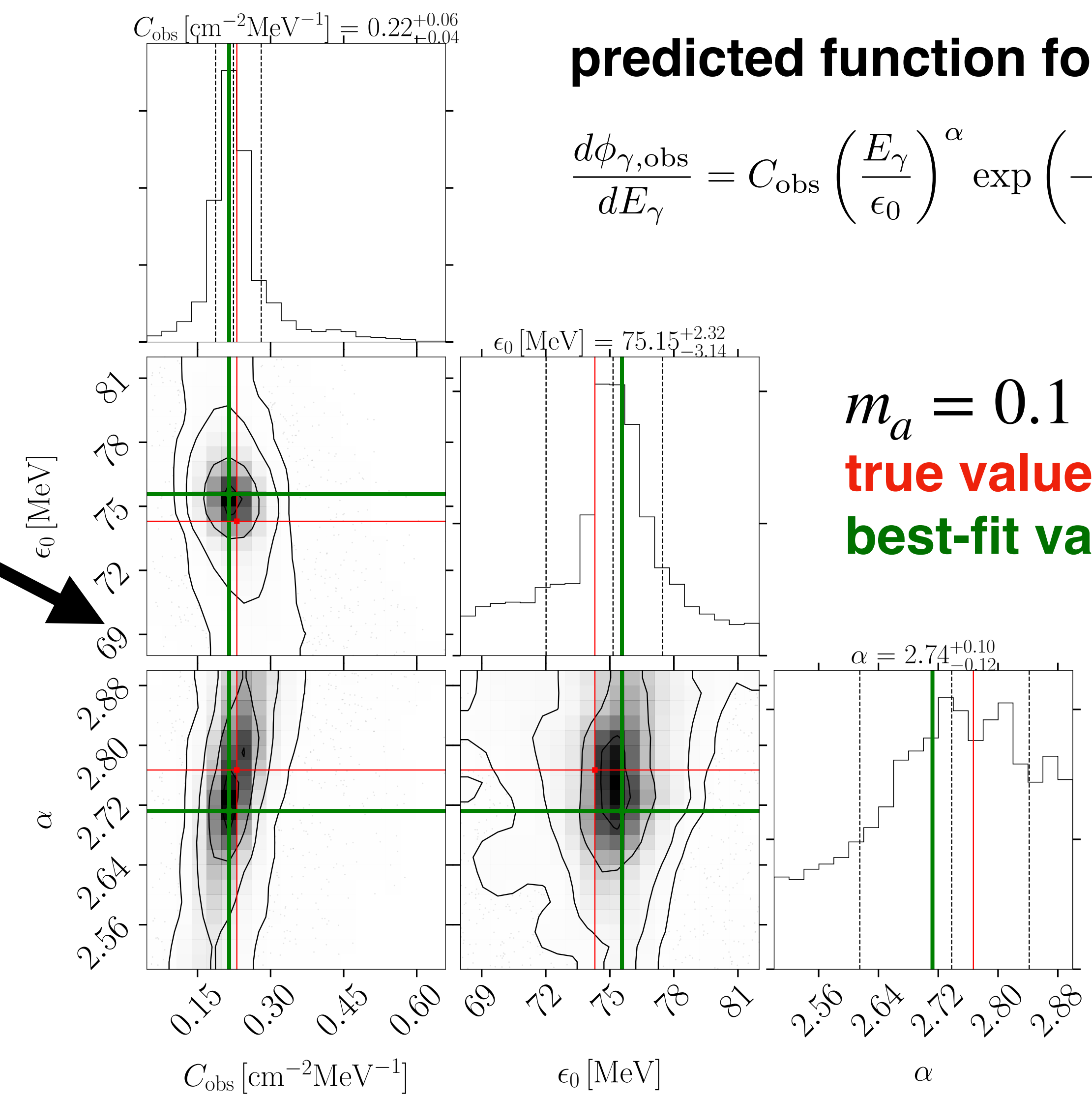
Heavy MeV-scale ALPs do not follow the assumed signal shape! Indication pointing towards $m_a > 10$ MeV.



Fermi-LAT prospects for light ALPs $\sim \mathcal{O}(\mathrm{neV})$

What can we learn from a close Galactic supernova (~10 kpc) with a progenitor resembling Betelgeuse (~11 $M_\odot$) regarding ALPs with $m_a \sim \mathcal{O}(1\ \mathrm{neV})$, i.e. Primakoff production?





predicted function form:

$$\frac{d\phi_{\gamma,\mathrm{obs}}}{dE_\gamma} = C_\mathrm{obs}\left(\frac{E_\gamma}{\epsilon_0}\right)^\alpha \exp\left(-\frac{(\alpha+1)E_\gamma}{\epsilon_0}\right)$$

$m_a = 0.1$ **neV**
true value
best-fit vale

[F. Calore, **CE** et al., arXiv:2306.03925]

Spectrum is mass-dependent: Below a threshold, no distortions due to surrounding photon plasma frequency. Fit allows us to derive ϵ_0 — connected to SN temperature.

Fermi-LAT prospects for light ALPs $\sim \mathcal{O}(\mathrm{neV})$

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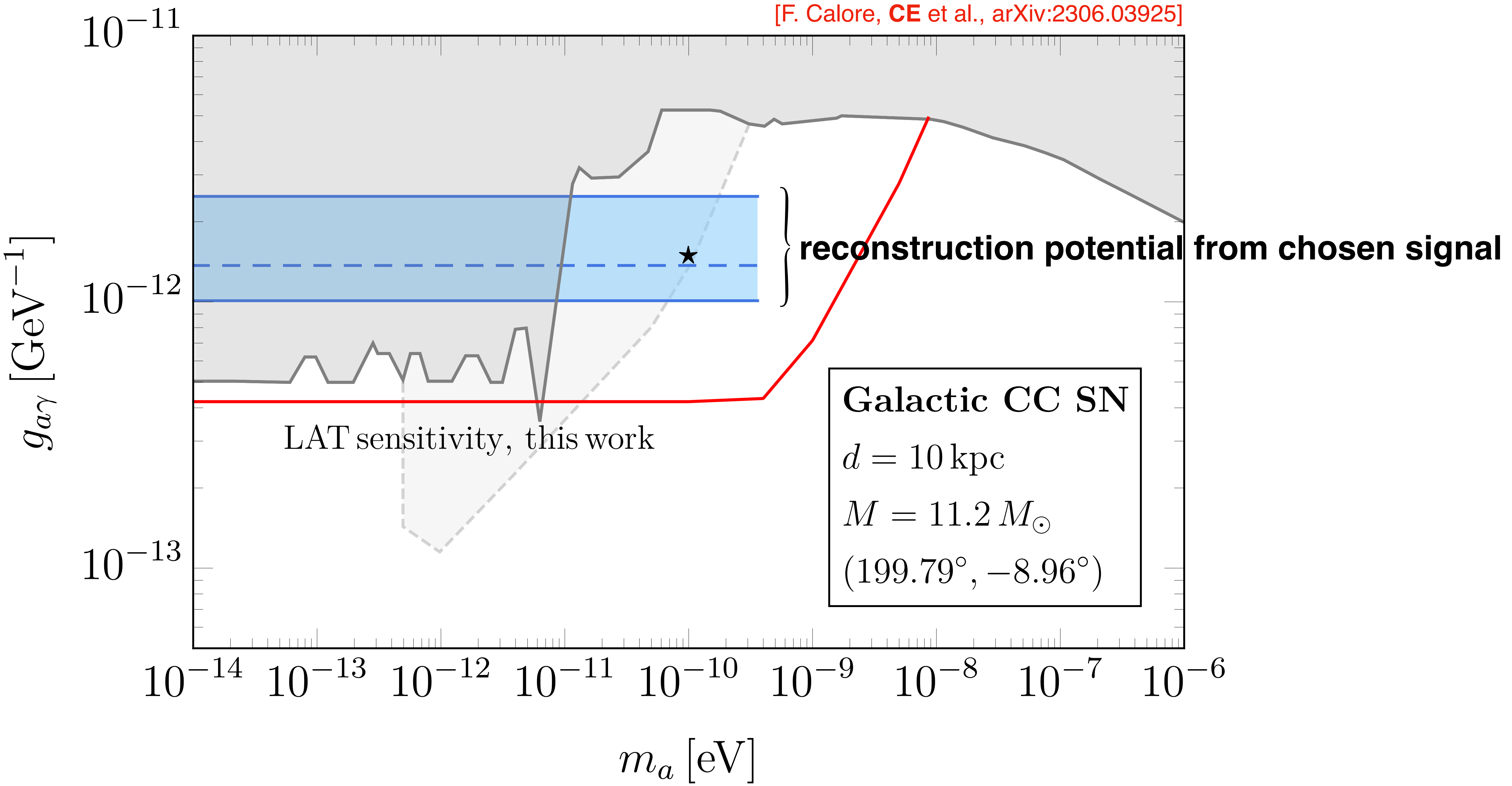


Can we extract more information by adding couplings to further Standard Model particles?

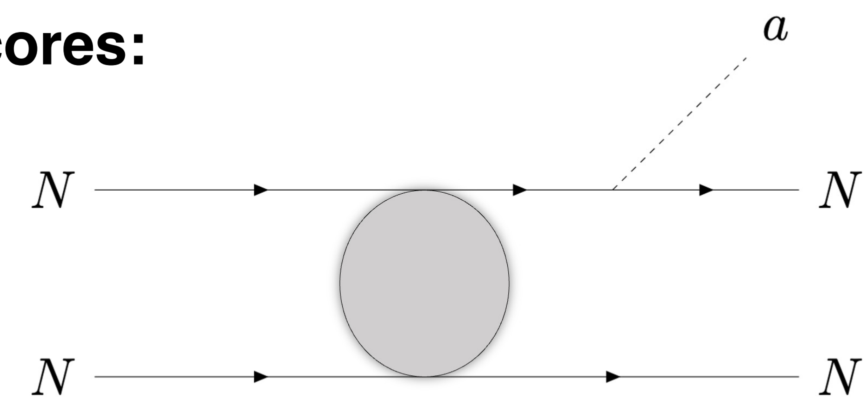
SN prospects for light ALPs with nucleon couplings

Introduction ALP couplings to mesons and hadrons introduces a rich phenomenology:

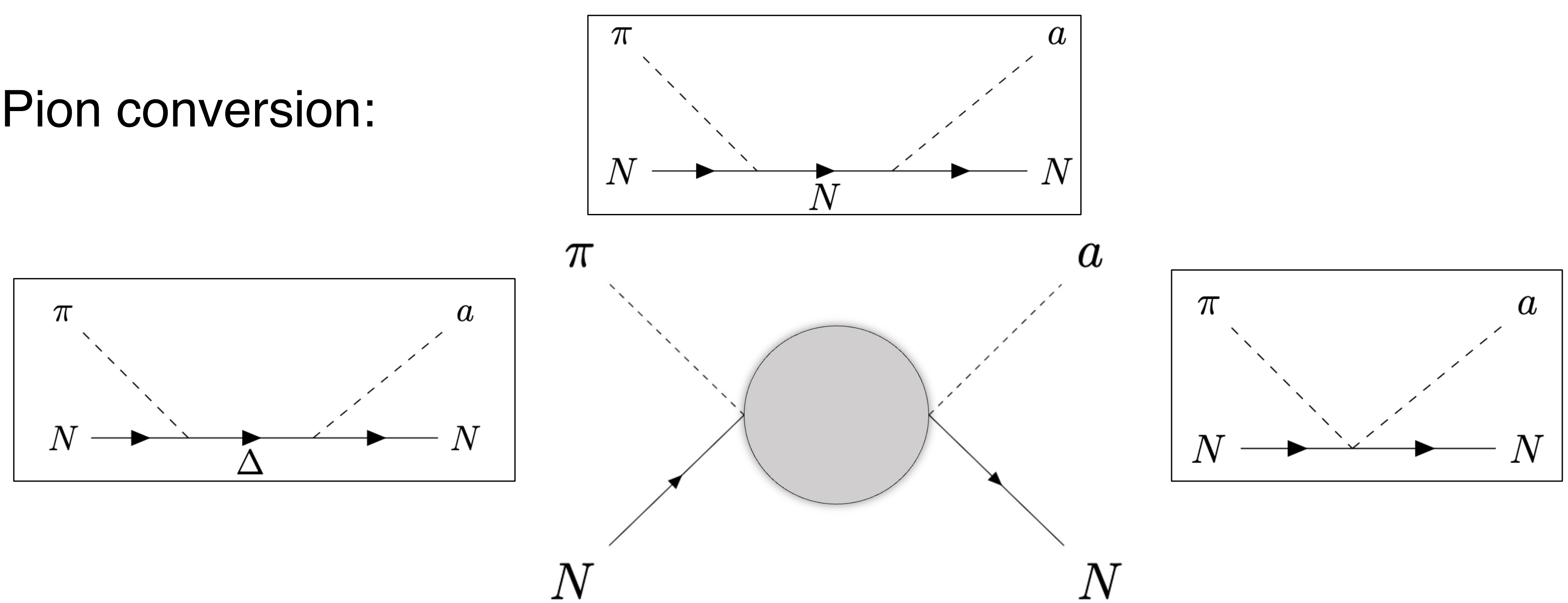
$$\mathcal{L}_{\text{int}} = g_a \frac{\partial_\mu a}{2m_N}\left[C_{ap}\bar{p}\gamma^\mu\gamma_5 p + C_{an}\bar{n}\gamma^\mu\gamma_5 n + \frac{C_{a\pi N}}{f_\pi}\left(i\pi^+\bar{p}\gamma^\mu n - i\pi^-\bar{n}\gamma^\mu p\right) + C_{aN\Delta}\left(\bar{p}\,\Delta^+_\mu + \overline{\Delta^+_\mu}\,p + \bar{n}\,\Delta^0_\mu + \overline{\Delta^0_\mu}\,n\right)\right]$$

ALP production in SN cores:

Nucleon-nucleon bremsstrahlung



Pion conversion:



Pion conversion was typically neglected in the past.

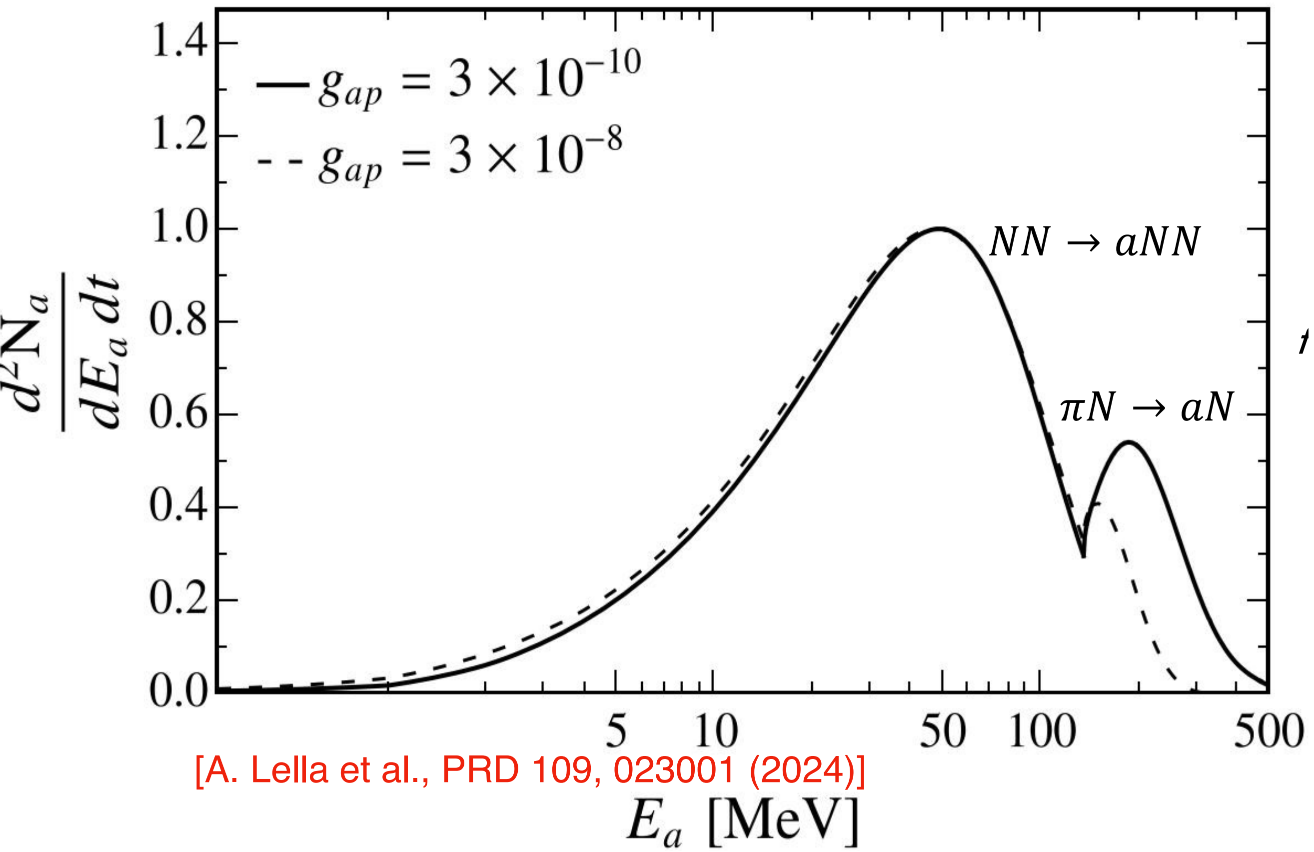
Now understood that it can even dominate the ALP production!

[B. Fore & S. Reddy, PRC 101, 035809 (2020)]

SN prospects for light ALPs with nucleon couplings

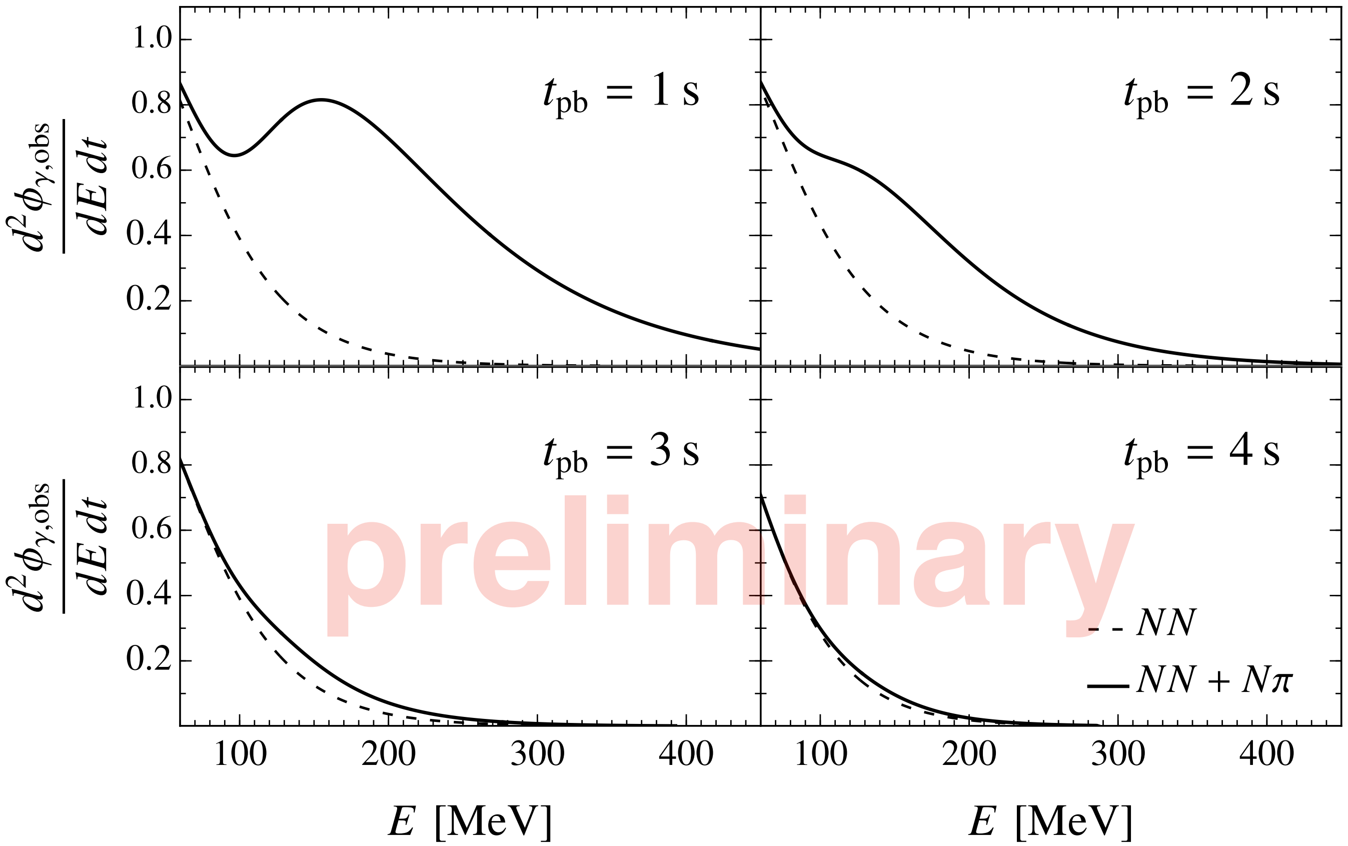
Both processes contribute at different energies and introduce a time-dependence due to the evolution of the SN core (pion density).

time-integrated ALP spectrum



[A. Lella et al., PRD 109, 023001 (2024)]

time-dependent ALP spectrum



[A. Lella, **CE** et al., in prep.]

Questions to answer:

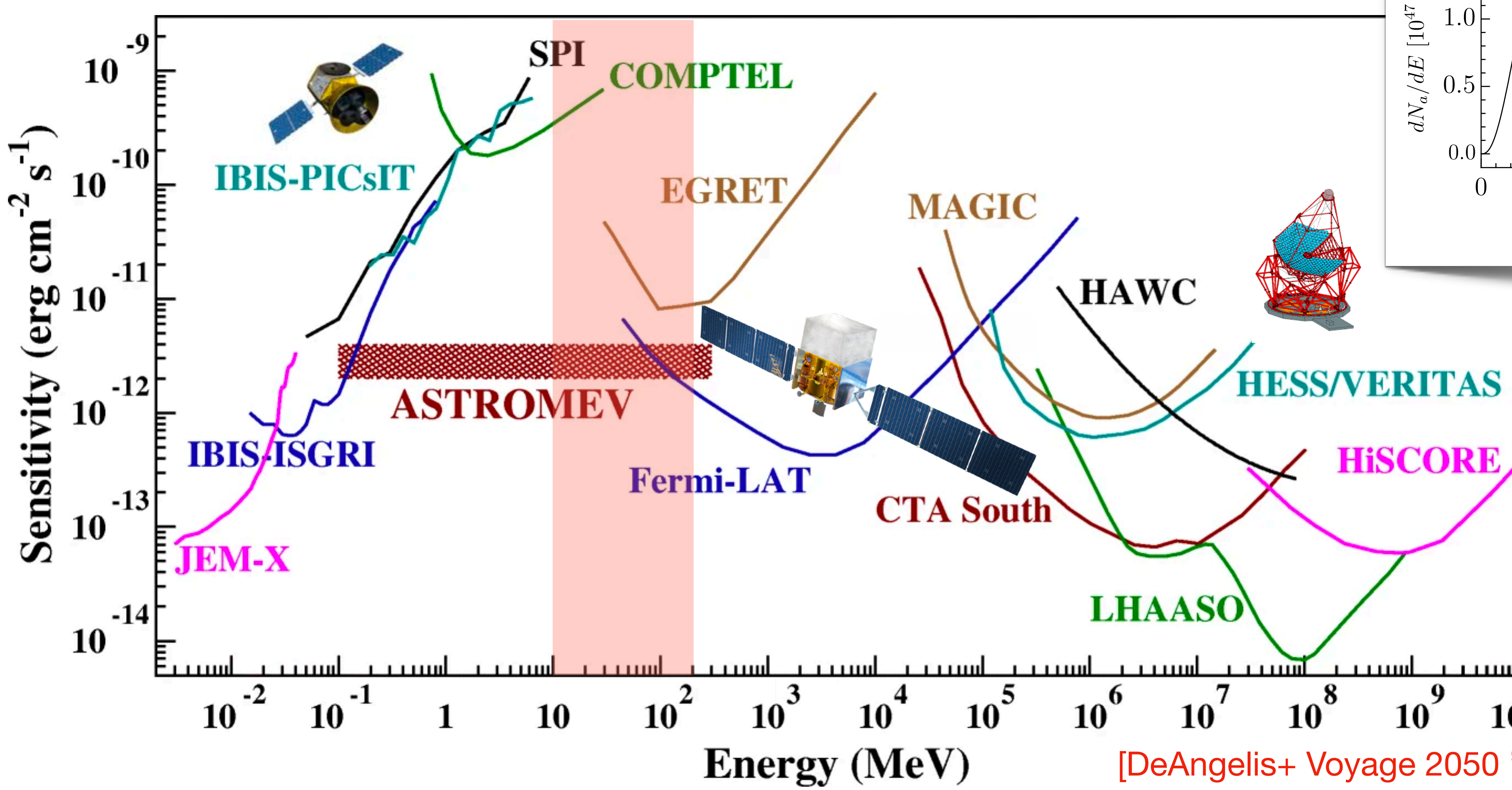
→ Is the *Fermi*-LAT energy resolution good enough to observe a two-peak spectrum?

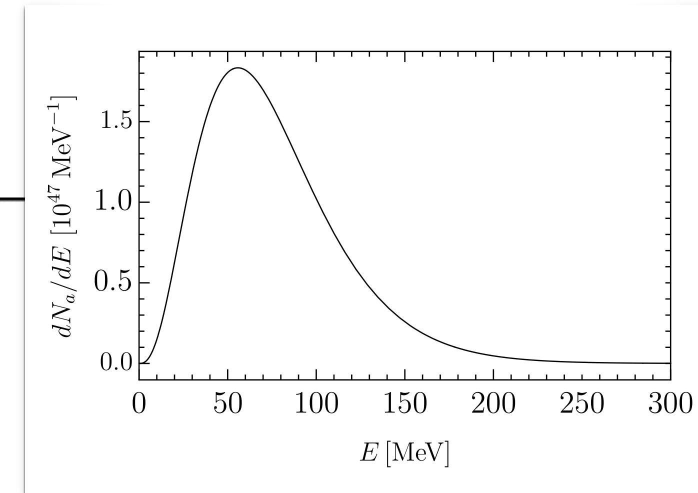
→ Can we re-construct the mean temperature of the spectrum? Tied to equation of state of SN core.

Outlook

- ✦ Lacking a Galactic SN, extragalactic SNe are capable of probing parts of the ALP parameter space.
- ✦ Observing the prompt gamma-ray emission from a future Galactic SN, allows us to study the properties of ALPs and learn about their nature.
- ✦ SN ALPs not only carry information about their own nature but also about the internal physics of the stellar progenitors.

What may be possible in the future?





[DeAngelis+ Voyage 2050 '21]

Closing the MeV gap greatly enhances the access to ALP supernova phenomenology!