Fermi listens for Cosmic WISPers

Past, Present, and the Future of *Fermi's* Axion-like Particle Searches

Image Credit: Stephanie Fowler, @designbystlight

Milena Crnogorčević (she/her)
Postdoctoral Fellow
Oskar Klein Centre/Stockholm University

11th Fermi Symposium
11 September, 2024

milena.crnogorcevic@fysik.su.se www.mcrnogor@github.io @mcrnogor

Axion/ALP Landscape: A Theorist's view

Axion/ALP Landscape: A Theorist's view

Weakly Interacting Sub-eV Particles

WISPs

Axion/ALP Landscape: A Theorist's view

Weakly Interacting Sub-eV Particles

WISPs

QCD axion

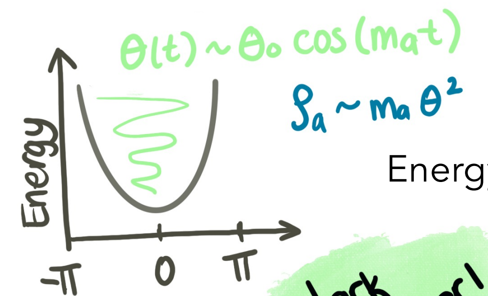
- Solution to the strong charge-parity (CP) problem
- $m_a \sim 10^{-12} - 0.01$ eV
- Minimal coupling to photons
- Produced via misalignment mechanism (early Universe)

Axion/ALP Landscape: A Theorist's view

Weakly Interacting Sub-eV Particles

WISPs → QCD axion

- Solution to the strong charge-parity (CP) problem
- $m_a \sim 10^{-12} - 0.01$ eV
- Minimal coupling to photons
- Produced via misalignment mechanism (early Universe)



Energy breaking scale $\propto 1/m_a$

dark matter!

Axion/ALP Landscape: A Theorist's view

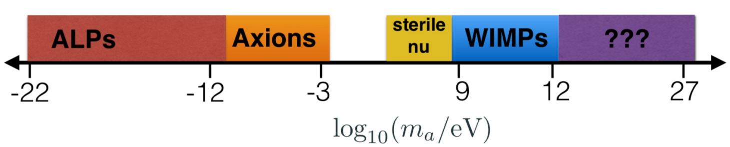
Weakly Interacting Sub-eV Particles

WISPs

Axion-like particles (ALPs)

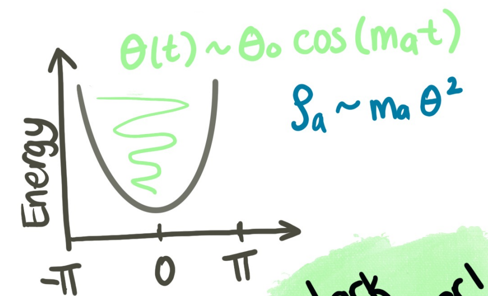
- Extension of the QCD axion
- No longer a solution to the strong CP problem
- Still very weak couplings to the Standard Model particles
- Mass ***not*** dictated by the QCD effects

→ $m_{\text{alp}} \rightarrow 10^{-22}$ eV



QCD axion

- Solution to the strong charge-parity (CP) problem
- $m_a \sim 10^{-12} - 0.01$ eV
- Minimal coupling to photons
- Produced via misalignment mechanism (early Universe)



dark matter!

Axion/ALP Landscape: A Theorist's view

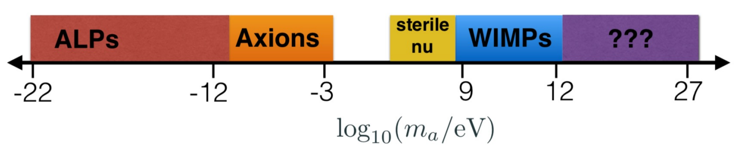
Weakly Interacting Sub-eV Particles

WISPs

Axion-like particles (ALPs)

- Extension of the QCD axion
- No longer a solution to the strong CP problem
- Still very weak couplings to the Standard Model particles
- Mass ***not*** dictated by the QCD effects

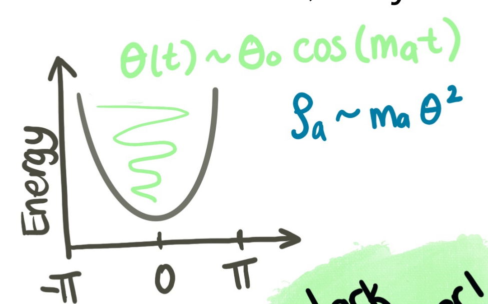
→ $m_{\mathrm{alp}} \rightarrow 10^{-22}$ eV



Hidden Photons

QCD axion

- Solution to the strong charge-parity (CP) problem
- $m_a \sim 10^{-12} - 0.01$ eV
- Minimal coupling to photons
- Produced via misalignment mechanism (early Universe)



dark matter!

Axion/ALP Landscape: A Theorist's view

Cosmology of the Invisible Axion #6

John Preskill (Harvard U.), Mark B. Wise (Harvard U.), Frank Wilczek (Santa Barbara, KITP) (Sep, 1982)

Published in: *Phys.Lett.B* 120 (1983) 127-132

DOI cite claim reference search 3,466 citations

Axion Cosmology #1

Pierre Sikivie (CERN and Florida U.) (Oct, 2006)

Published in: *Lect.Notes Phys.* 741 (2008) 19-50 • Contribution to: Joint ILIAS-CAST-CERN Axion Training at CERN, 19-50 • e-Print: astro-ph/0610440 [astro-ph]

pdf DOI cite claim reference search 474 citations

WISPy Cold Dark Matter #1

Paola Arias (DESY and Chile U., Catolica), Davide Cadamuro (Munich, Max Planck Inst.), Mark Goodsell (DESY and CERN), Joerg Jaeckel (Durham U., IPPP), Javier Redondo (Munich, Max Planck Inst.) et al. (Jan, 2012)

Published in: *JCAP* 06 (2012) 013 • e-Print: 1201.5902 [hep-ph]

pdf DOI cite claim reference search 861 citations

Axion Cosmology #1

David J. E. Marsh (King's Coll. London) (Oct 26, 2015)

Published in: *Phys.Rept.* 643 (2016) 1-79 • e-Print: 1510.07633 [astro-ph.CO]

pdf DOI cite claim reference search 1,810 citations

Cosmology of axion dark matter #2

Ciaran A.J. O'Hare (Sydney U.) (Mar 26, 2024)

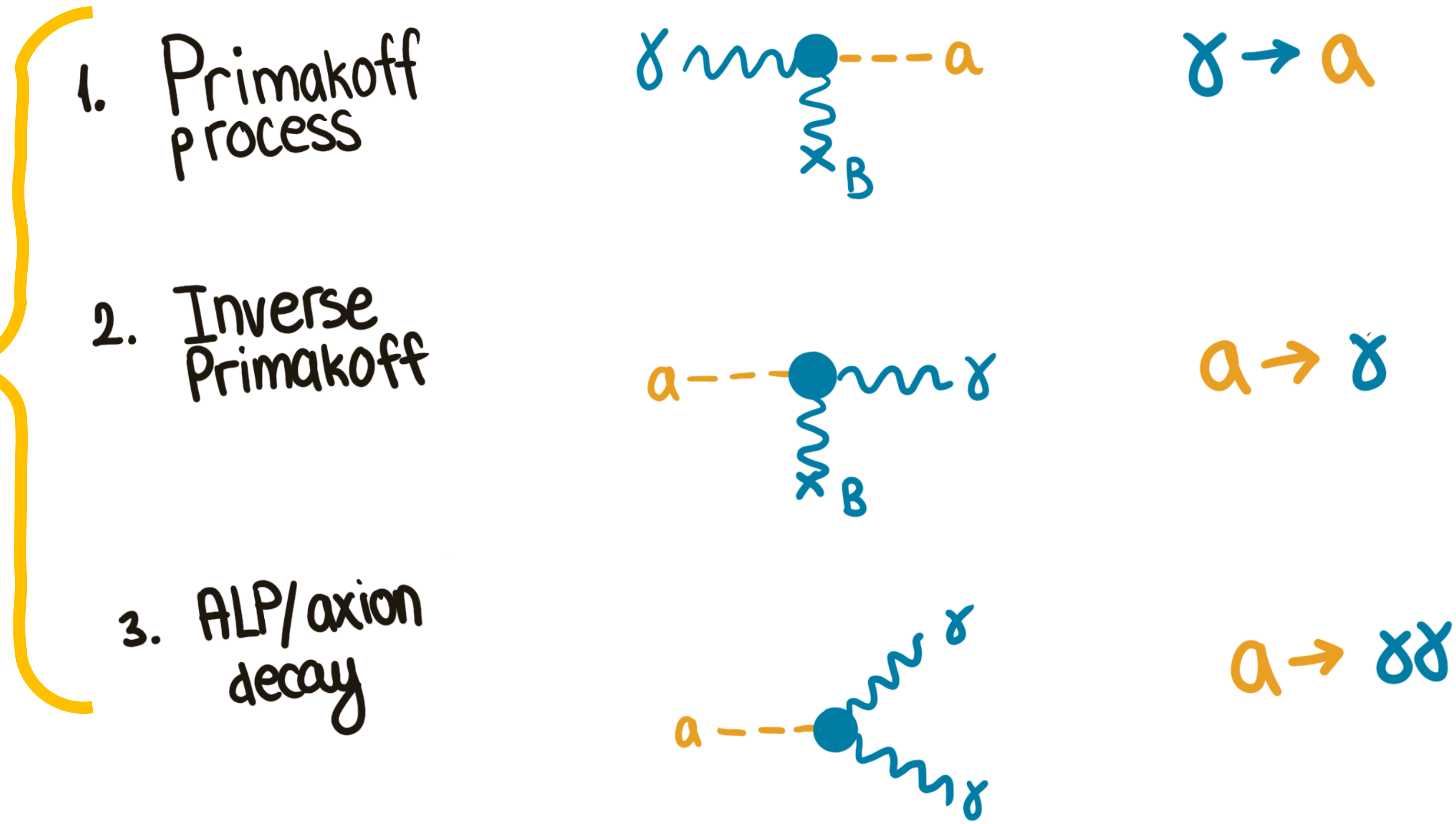
Published in: *PoS* COSMICWISPers (2024) 040 • Contribution to: COSMICWISPers, 040 • e-Print: 2403.17697 [hep-ph]

pdf DOI cite claim reference search 36 citations

Axion/ALP Landscape: An Observer's view

Axion/ALP Landscape: An Observer's view

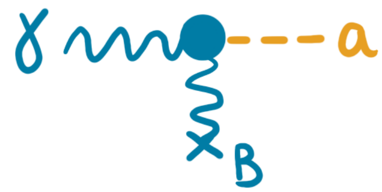
ALP/axion - photon interactions



Axion/ALP Landscape: An Observer's view

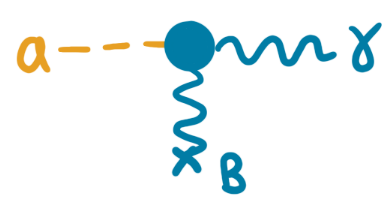
ALP/axion - photon interactions

1. Primakoff process



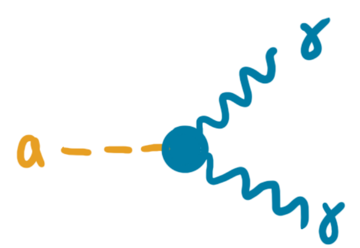
$\gamma \rightarrow a$

2. Inverse Primakoff



$a \rightarrow \gamma$

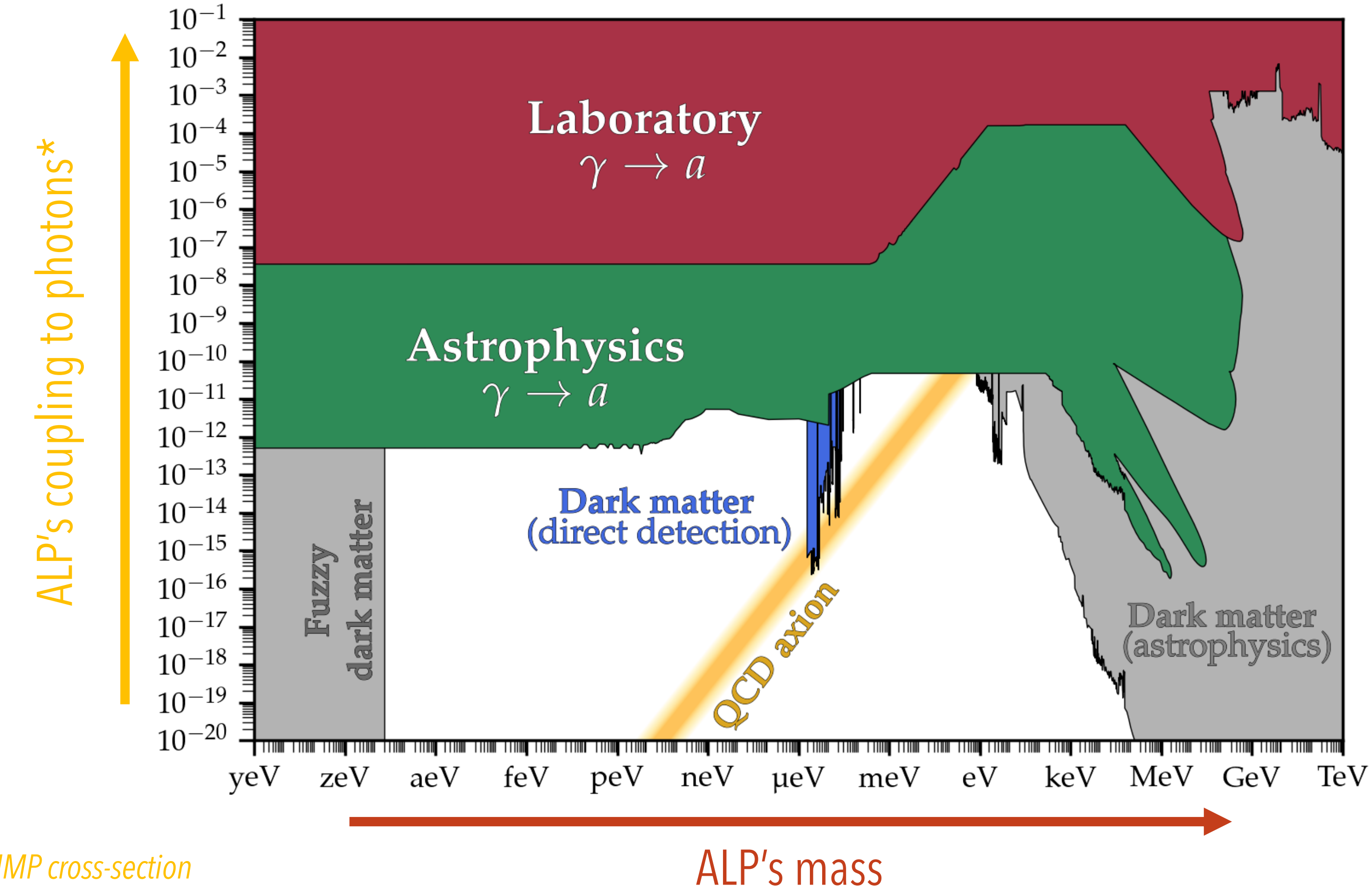
3. ALP/axion decay



$a \rightarrow \gamma\gamma$

Line searches for $m_{\rm alp} < 1$ MeV.
→ Signatures in radio, IR, and X-rays.

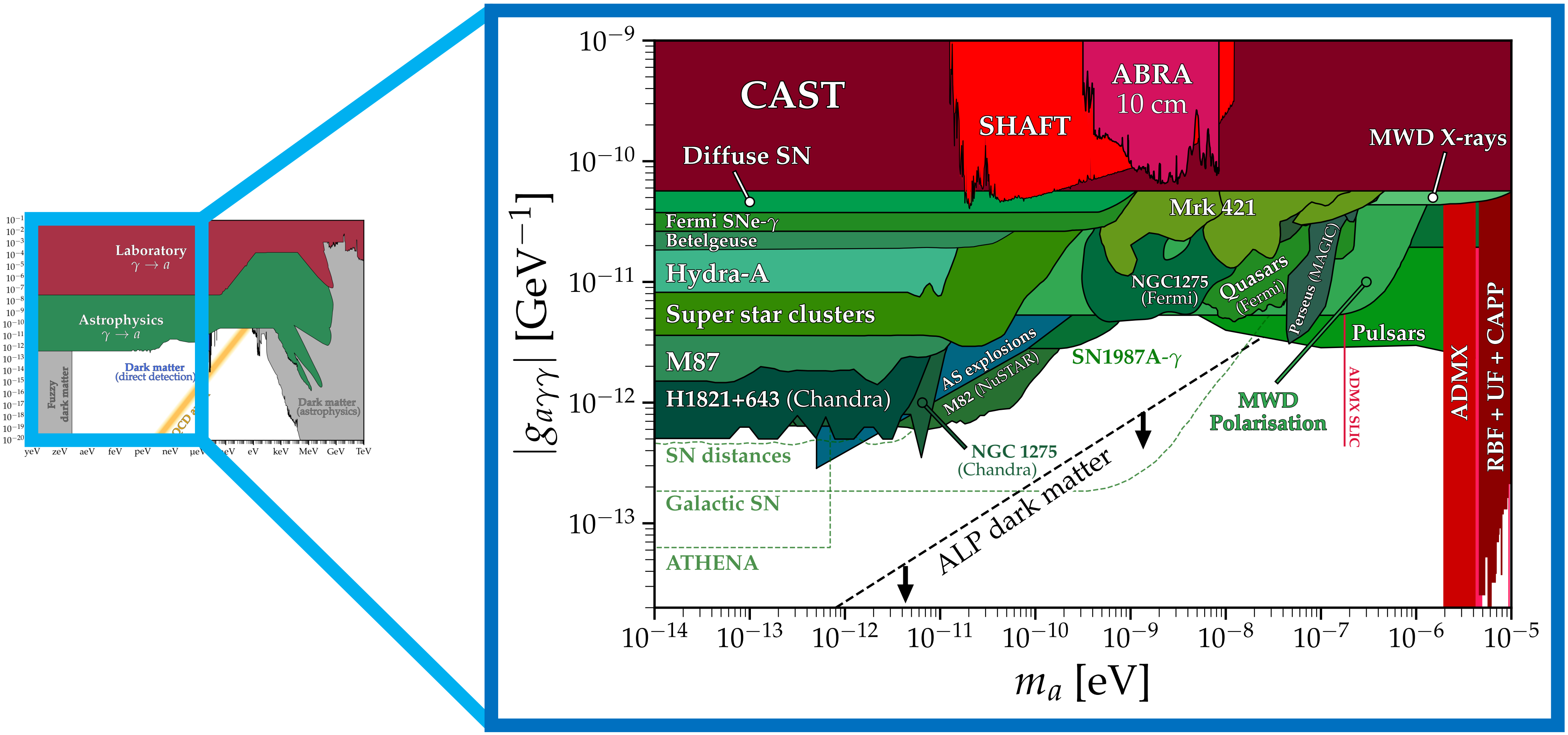
Axion/ALP Landscape: An Observer's view



Plot produced using: https://cajohare.github.io/AxionLimits/

*analogous to a WIMP cross-section

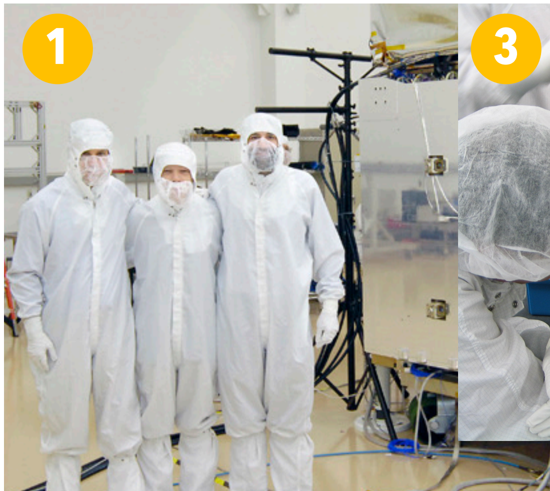
Axion/ALP Landscape: An Observer's view



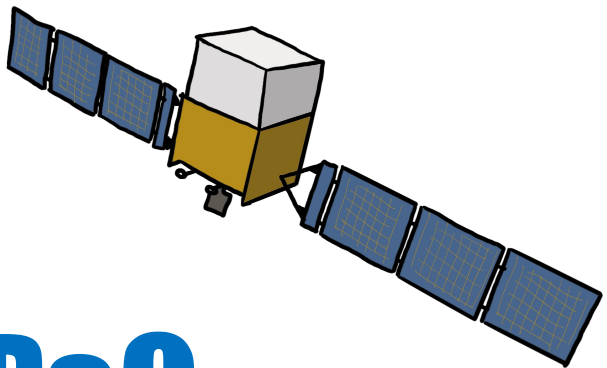
Plot produced using: https://cajohare.github.io/AxionLimits/

Axion/ALP Landscape: An Instrumentalist's View

Axion/ALP Landscape: An Instrumentalist's View

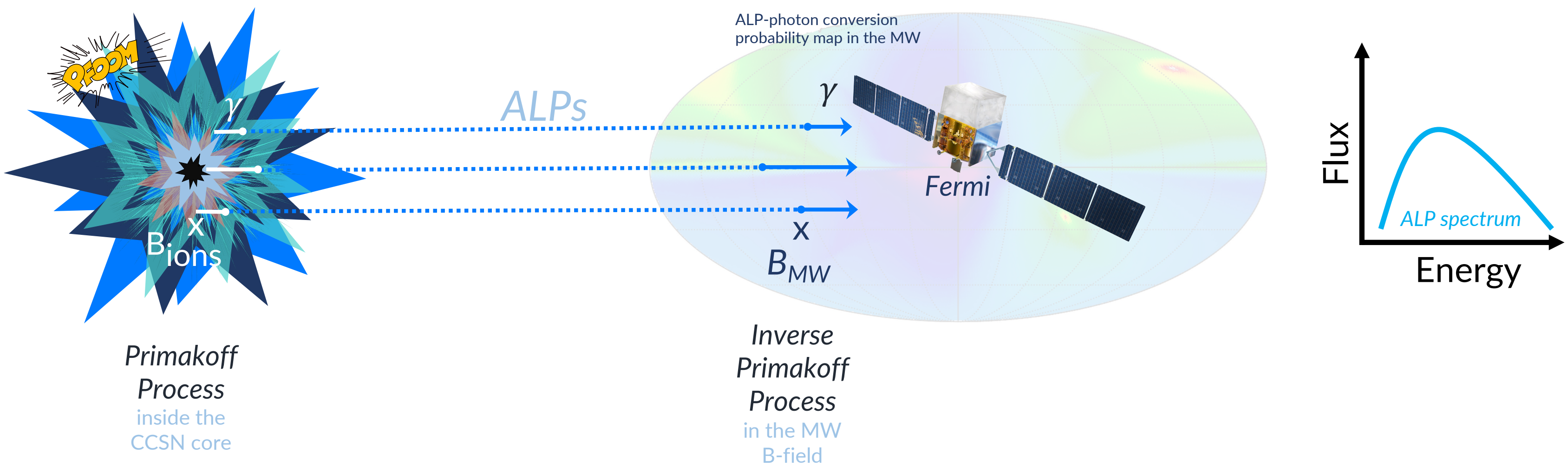


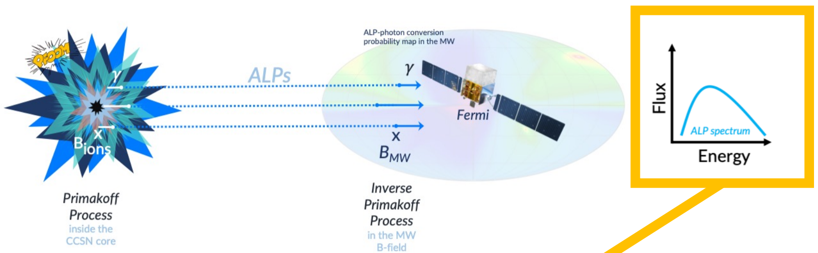
*1. From left: Fermi/LAT Principle Investigator **Peter Michelson**, Fermi/LAT co-creator **Bill Atwood** and **Steven Ritz**, project scientist at NASA. (Credit: Steven Ritz/UC Santa Cruz.) 2. **Fermi Operations team** sporting their colorful unofficial uniforms. (Courtesy Jana Thayer.) 3. Putting the Large Area Telescope together. (Photo courtesy SLAC Communications.) 4. The view of the launch from Cocoa Beach. (Courtesy SLAC Communications.) 5. **The team** that put the Large Area Telescope together at SLAC. (Courtesy SLAC Communications.)*



Where to look for ALPs?

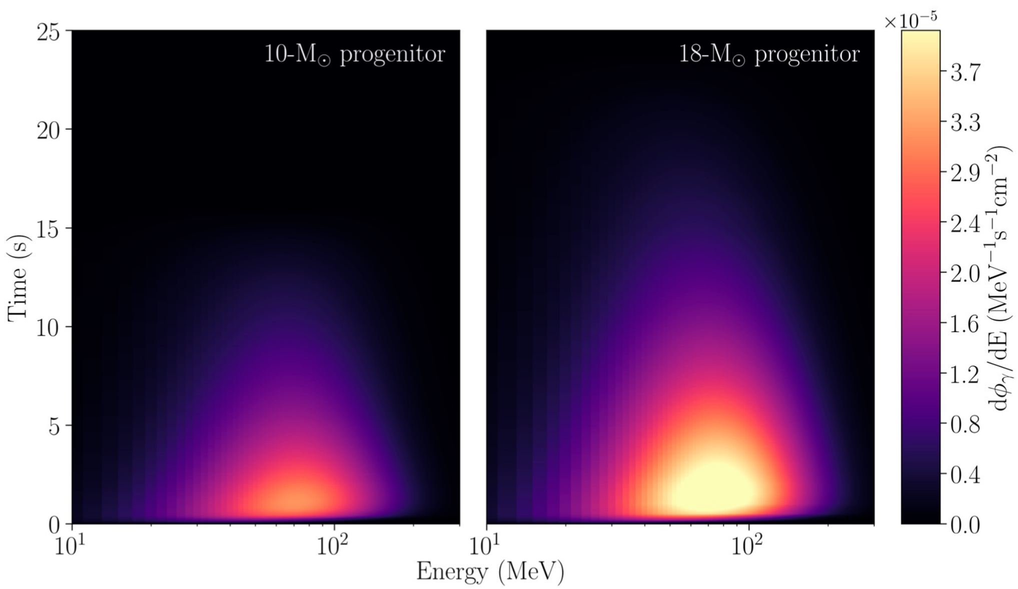
Core-Collapse Supernovae (CCSNe)



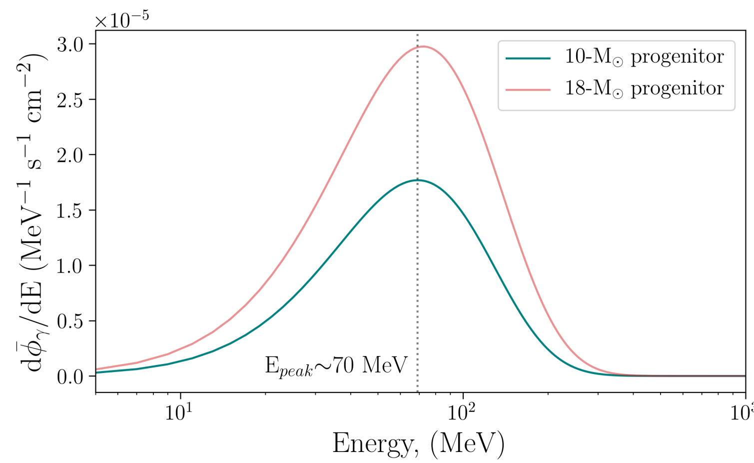


Motivation: ALPs are theorized to have a unique spectral signature in the prompt gamma-ray emission of CCSN. No other known physical processes are predicted to produce such a signature.

Crnogorčević+ PRD '20

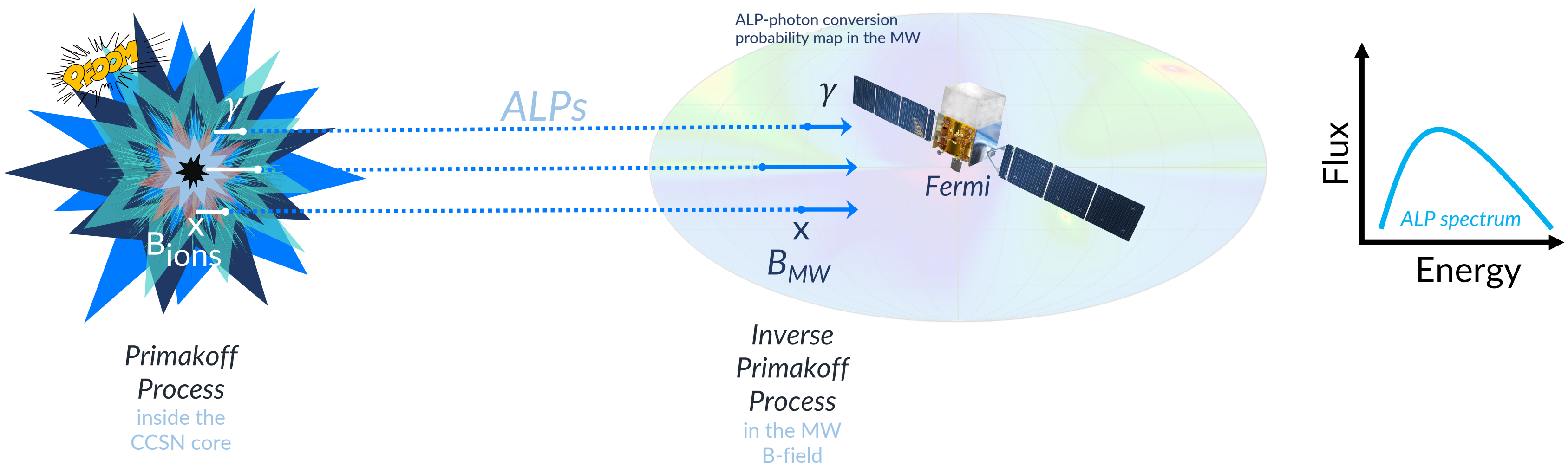


The observed evolution of the ALP-induced gamma-ray emission in time and energy in a core-collapse of a 10 and 18-M⊙ progenitor.

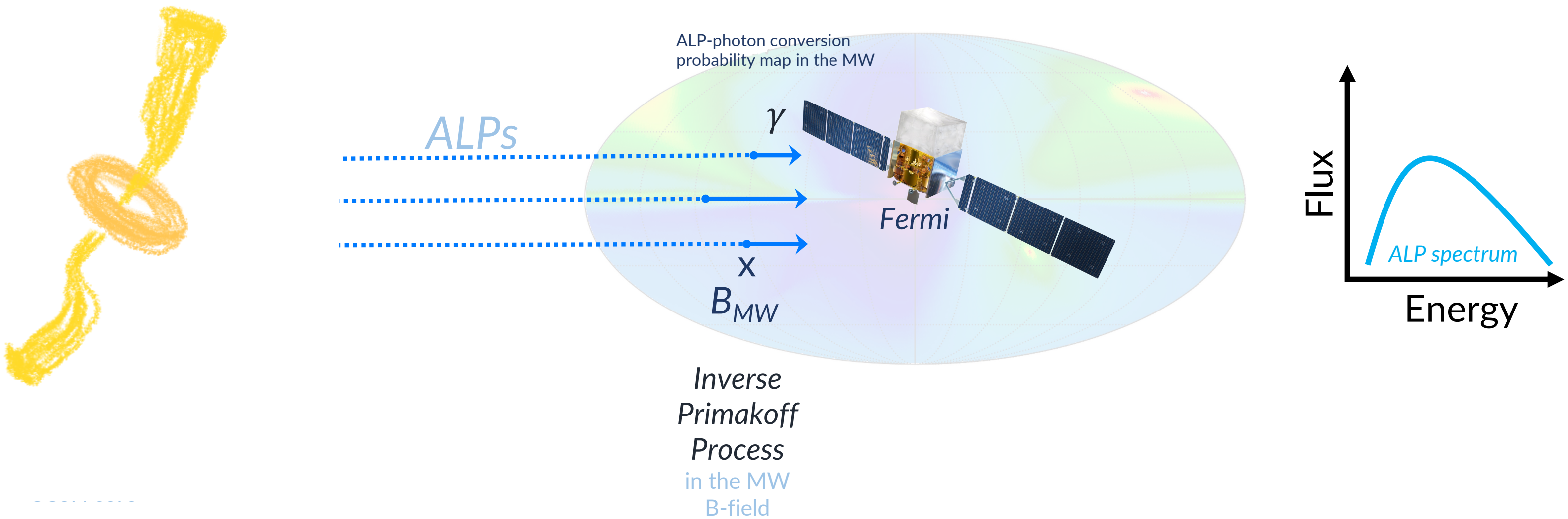


The observed ALP-induced gamma-ray spectrum for 10 and 18-M⊙ progenitors averaged over 10 seconds.

Photon from in-source conversions



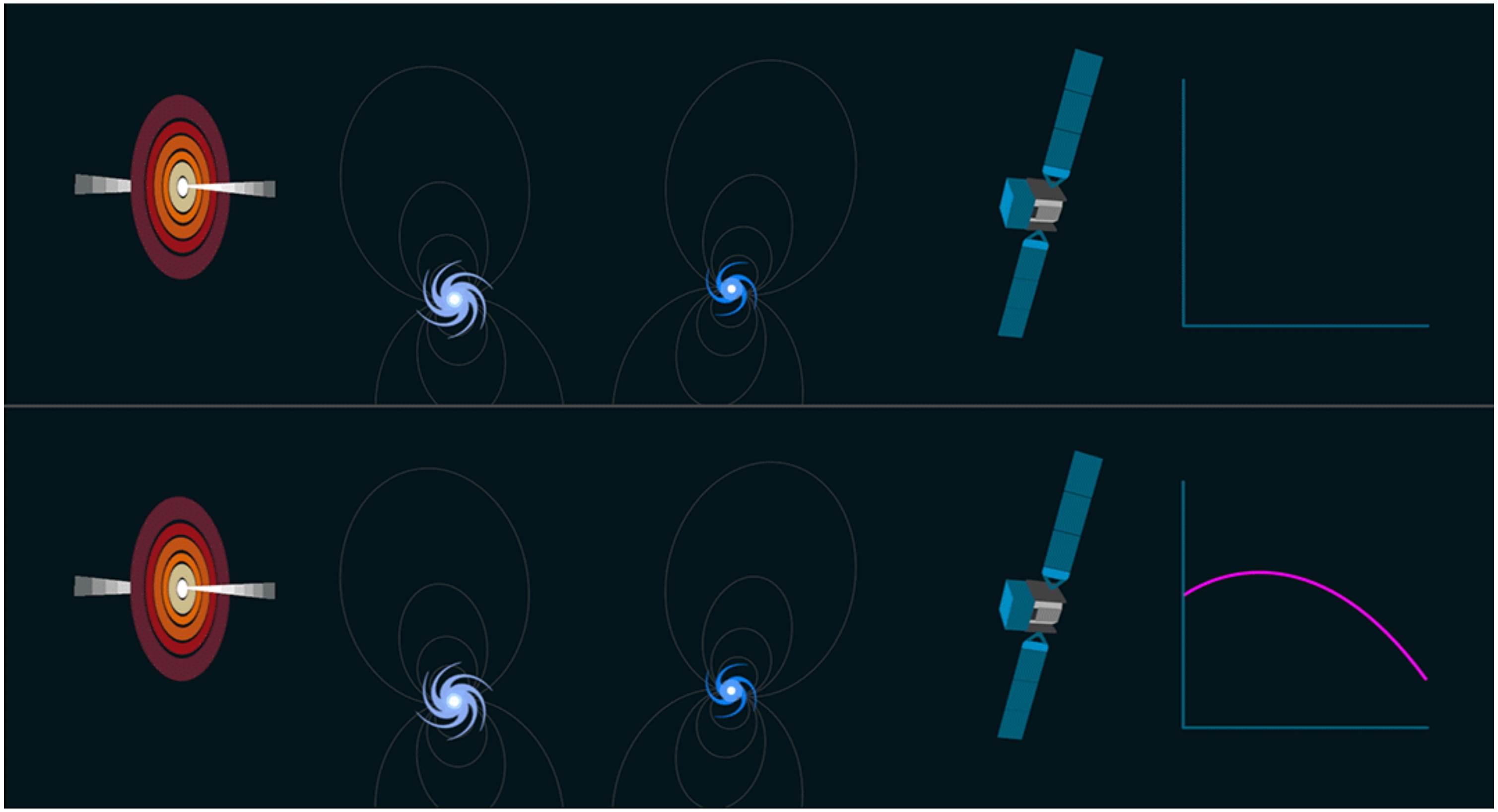
Photon from in-source conversions



AGN, blazars, etc.

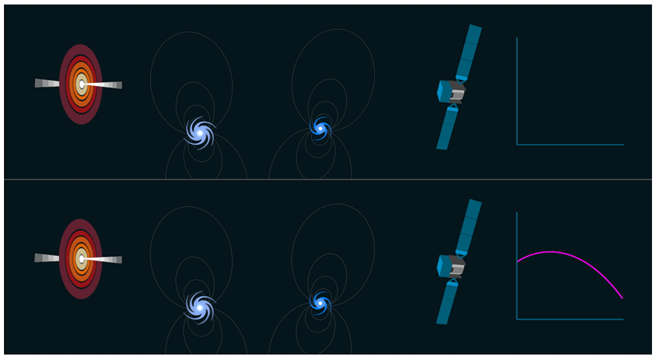
Extended Gamma-ray Sources

Active Galactic Nuclei (AGN), blazars, Star-Forming (SF) galaxies, galaxy clusters



[Credit: SLAC/Chris Smith]

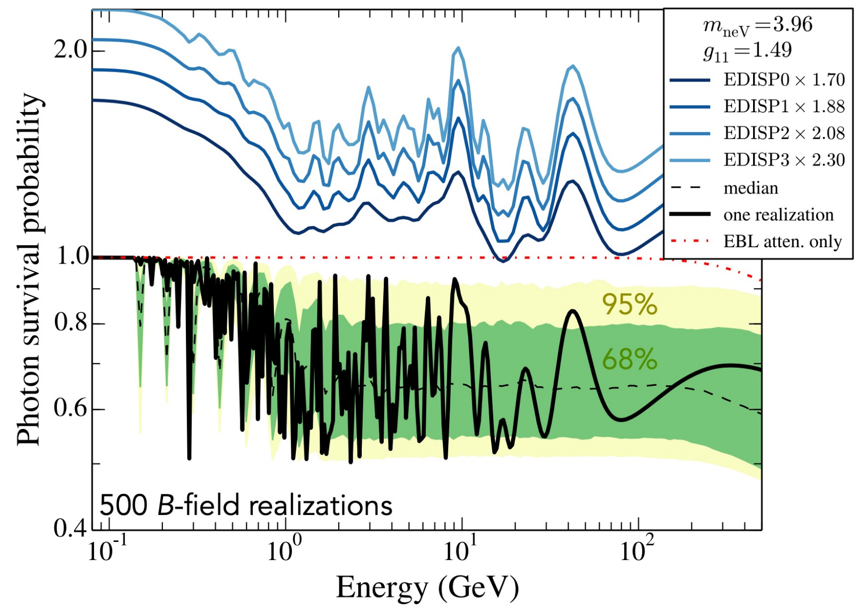
Extended Gamma-ray Sources



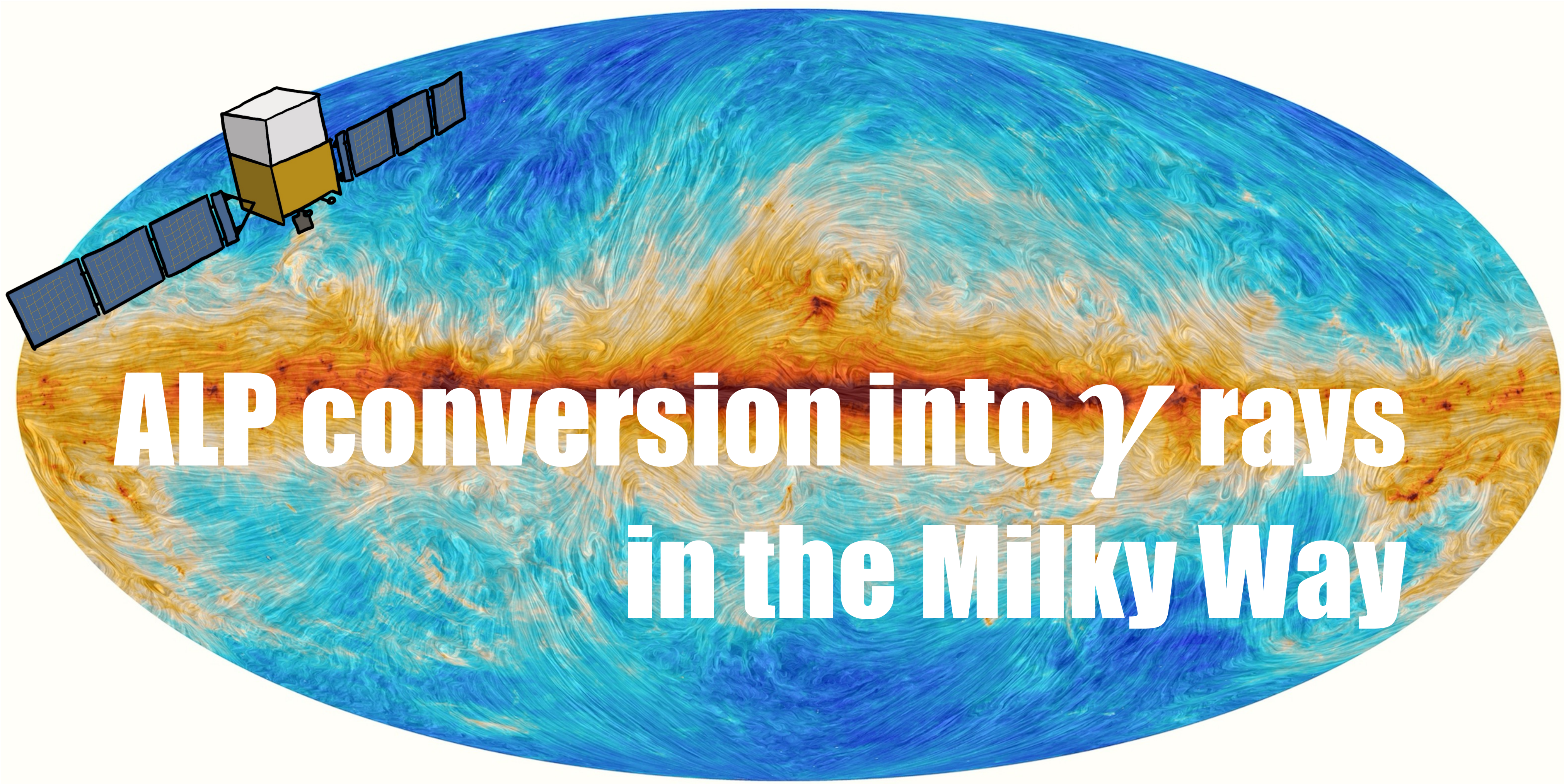
[Credit: SLAC/Chris Smith]

1. *In situ* production of photons via leptonic or hadronic processes
2. Conversion into ALPs/axions in the interstellar medium, intergalactic radiation fields, Milky way
3. Searches for deviation from the original astrophysical spectrum in the gamma-ray data

NGC 1275 [credit: Manuel Meyer]



[Hooper & Serpico '07; Fairbairn+ '11;Horns+ '12; Wouters & Brun '12, '13; Abramowski+ '13; Meyer+ '14, Meyer & Conrad '14; Ajello+ '16; Berg+ '16, *Malyshev+ '18, Cheng+ '21, Zhang+ '18, Guo+ '20, Carenza+ '21, Kachelriess+ '22,*]

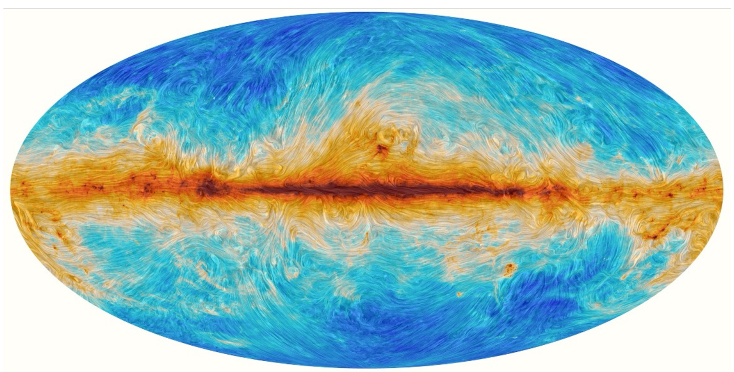

ALP conversion into γ rays
in the Milky Way

Milky Way magnetic field

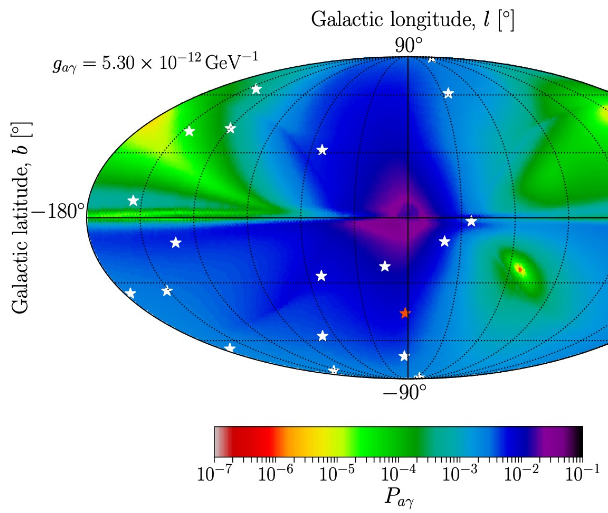
- Monochromatic photon-ALP beam propagating in a cold plasma in a homogeneous B field

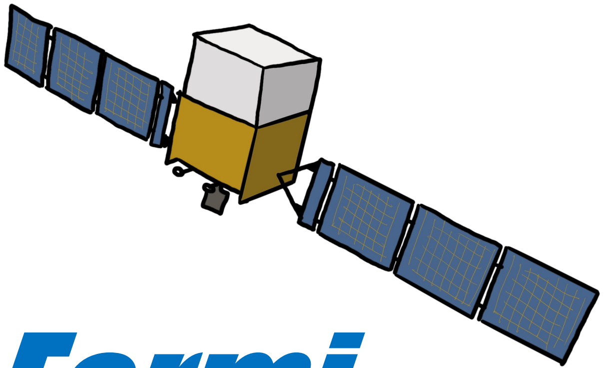
$$P_{a\gamma} = (\Delta_{a\gamma} L)^2 \frac{\sin^2(\Delta_{\rm osc} L/2)}{(\Delta_{\rm osc} L/2)^2} \rightarrow \left(\frac{g_{a\gamma} B_T}{2}\right)^2 L^2$$

for massless ALPs and low couplings [Raffelt & Stodolsky '88, Horns+ '12]



→



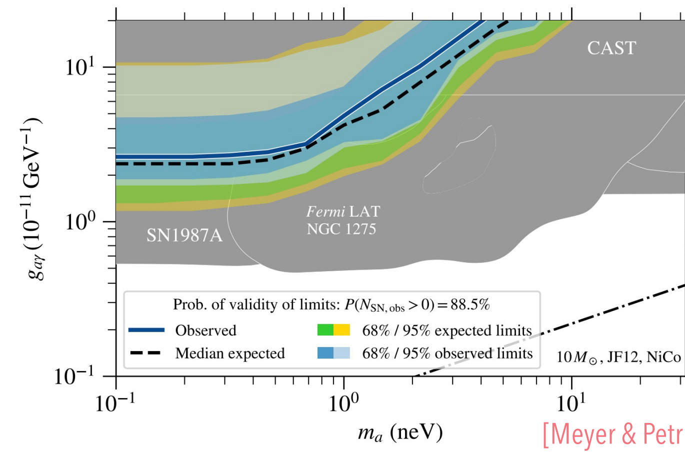


Some of the *Fermi* results

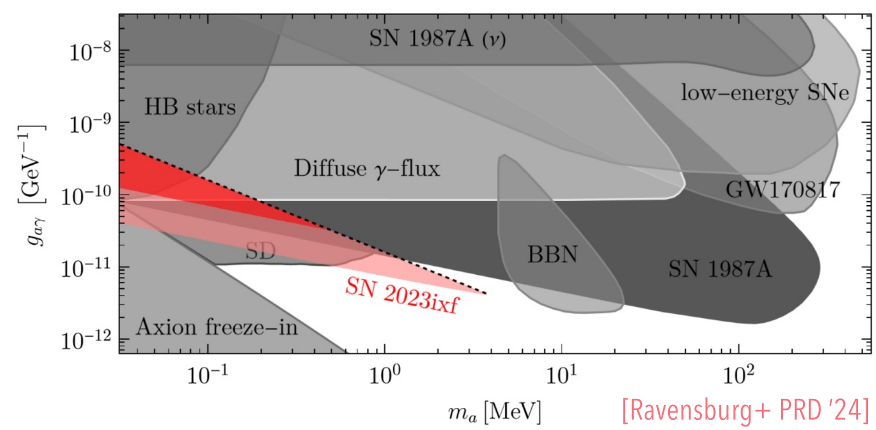
CCSNe: Individual Sources

- Nearby individual CCSNe (single & joint likelihood)
- No detection (*yet!*)
- Constraining both *light* ($\lesssim 10^{-10}$ eV) and *heavy* ALPs ($\lesssim$ 3 MeV)
- Particularly exciting venue for future searches (ZTF, Vera Rubin)
- A running MeV–GeV instrument is a paramount!

[Meyer+ PRL '17, Meyer & Petrushevska PRL '20, Crnogorčević+ PRD '21, Müller+ PRD '23, Ravensburg+ PRD '24, Calore+ PRD '24, and more]

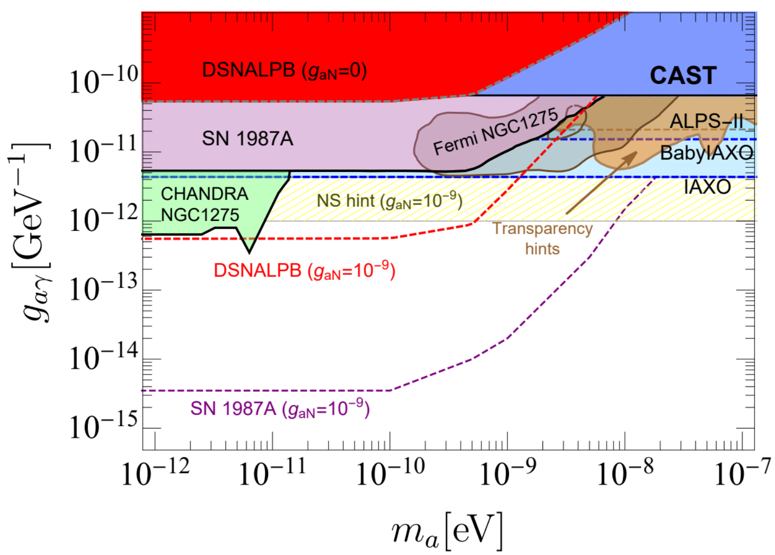


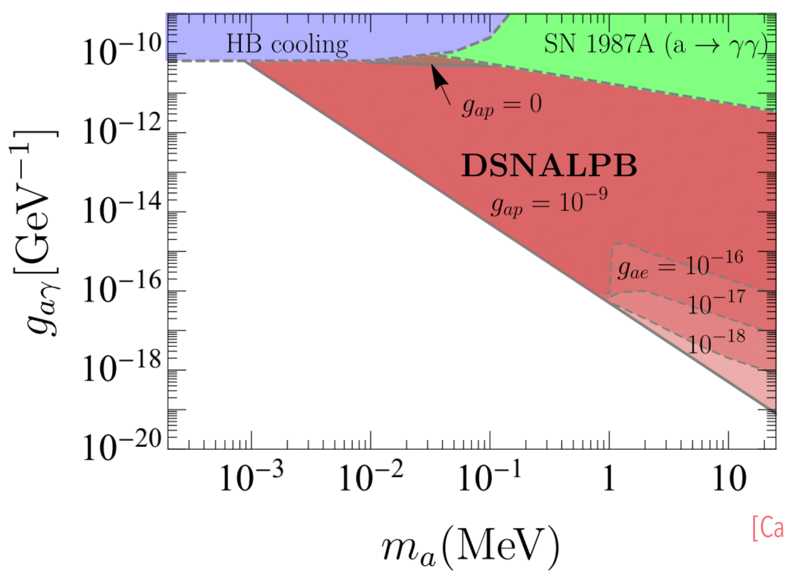
[Meyer & Petrushevska PRL '20]



[Ravensburg+ PRD '24]

CCSNe: Diffuse Emission



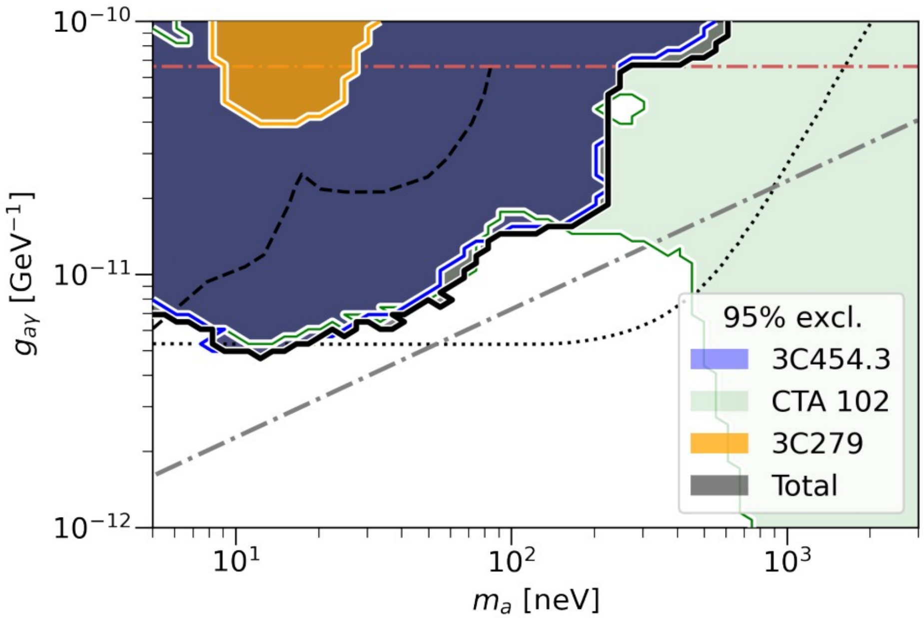


[Calore+ PRD '20]

- Improved constraints if ALPs couple to nucleons
- Heavier ALPs → significant decay in MeV gamma rays
- Future: improved characterization of backgrounds, galactic SN limits

Flaring blazars

[Davies+ '22]



Legend black dotted: WD radio polarization
black dashed: spectral irregularities
red dot-dash: CAST experiment
gray dot-dash: DM line

- Blazar jets serve as new potential ALP-photon mixing regions
- Three flaring blazars: 3C454.3, CTA 102, and 3C279
- Modeled a full photon-photon dispersion in the jet
- Slight preference for ALP signal in CTA 102, but combined results show no significant evidence for ALPs

[Ajello+ '16, Libanov & Troitsky '20, Cheng+ '21, etc.]

Extended Gamma-ray Sources

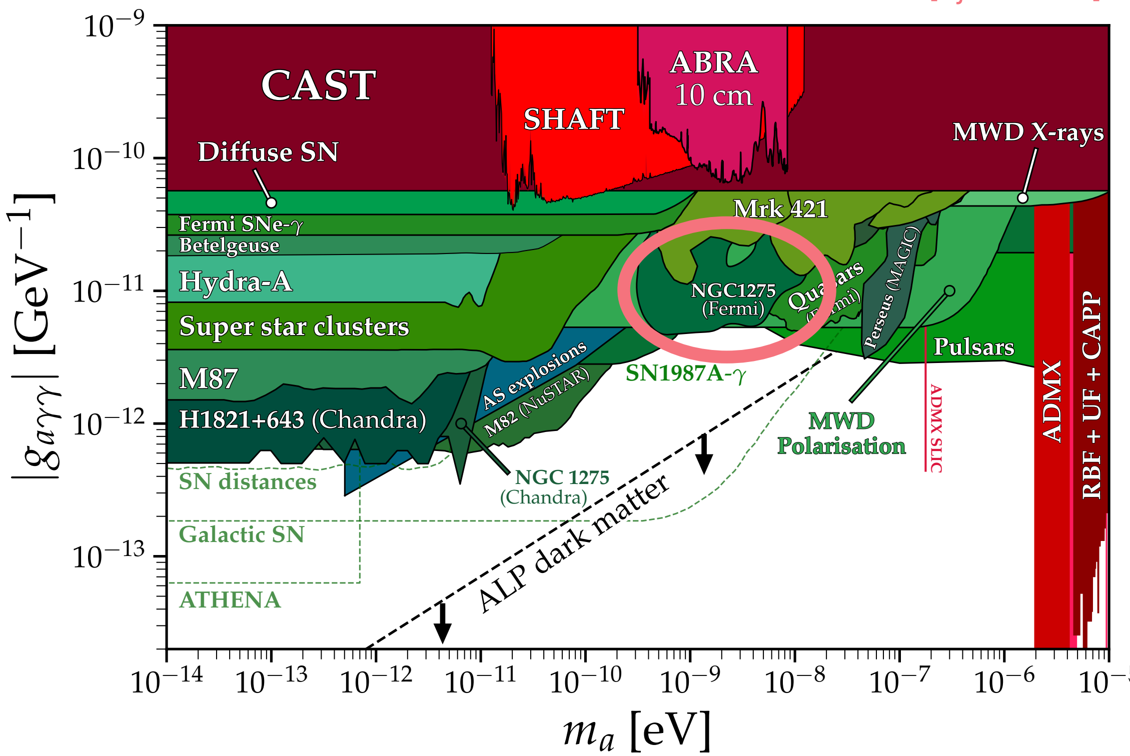
- Radio galaxy NGC 1275, also a gamma-ray source in *Fermi* [Abdo+ ‘09]
- Central region of the cool-core Persius cluster, z = 0.0176
- High central magnetic field
- ALP limits driven by the ICM modelling; popular target for ALP searches

[Ajello+ ‘16, Libanov & Troitsky ‘20, Cheng+ ‘21, etc.]

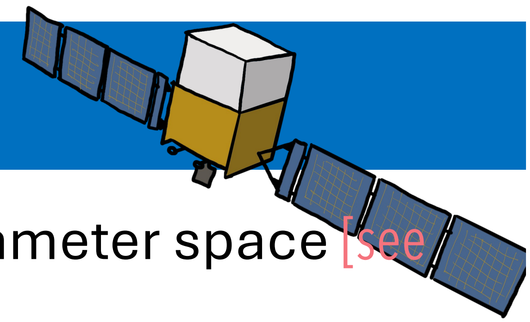
NGC 1275: spectral irregularities

- Milky Way & Persius cluster B fields
- conservative estimate of the central B field of 10μG [Aleksić+ '12]
- EBL absorption
- 6 years of data → still the most stringent constraint for $m_{alp} \sim 10^{-9}$ eV
- See [Cheng+ '21, etc] for additional B field considerations

[Ajello+ '16]

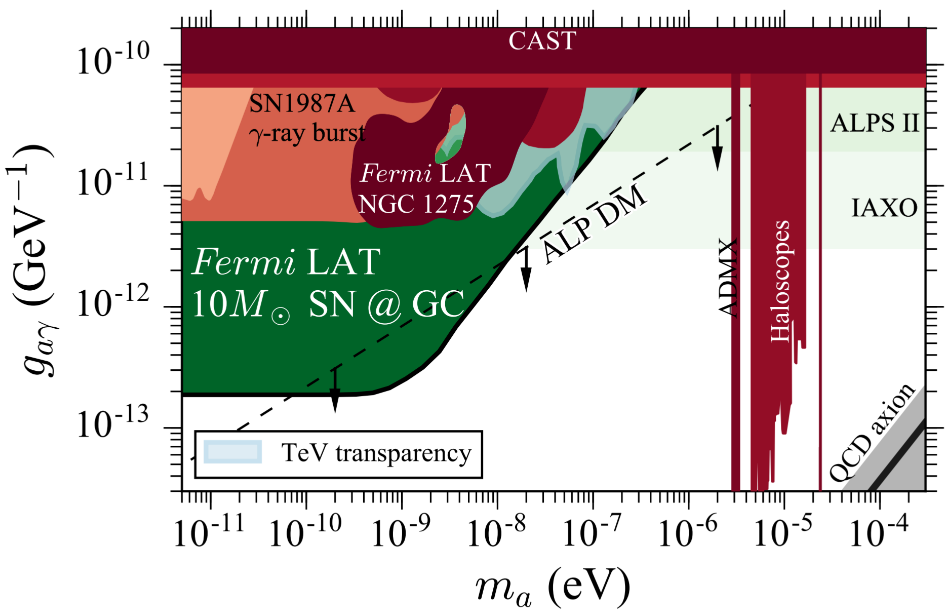


What we did not talk about…



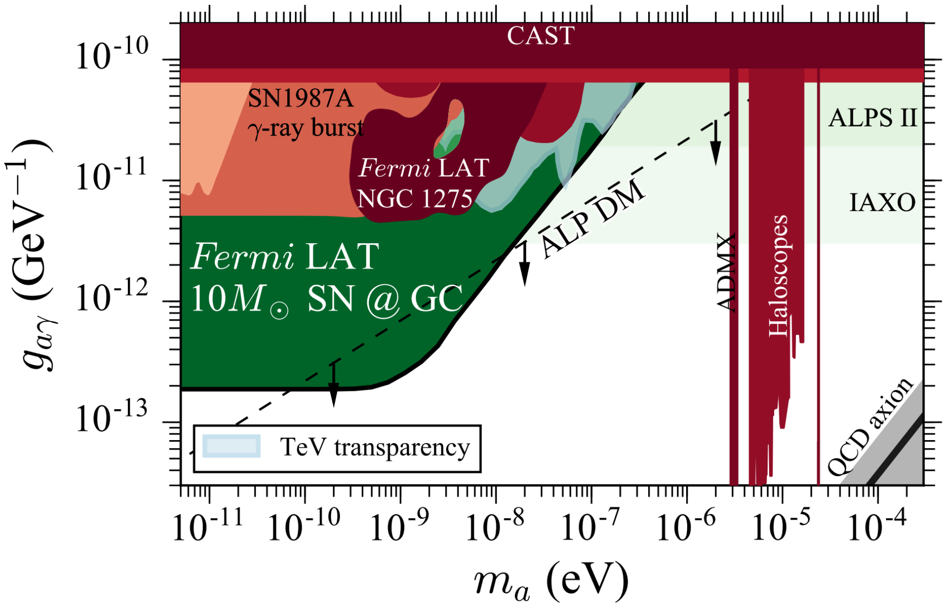
- GRB 221009A and other GRBs to constrain the ALP parameter space [see e.g. Crnogorčević+ '21, Meyer+ '23]
- Other nearby blazar sources & multiwavelength considerations (with H.E.S.S.) space [see e.g. Abramowski+ '13, Zhang+ '18, Guo+ '20, Carenza+ '21, Ecker & Calore '22, Jacobsen+ '23]
- Constraints on coupling with nucleons and electrons [see e.g. Calore+ 21]
- Axion fireballs from CCSNe [see e.g. Diamond+ 23]
- Hypermassive neutron stars ALP signatures [see e.g. Harris+ 20, Zhung+ '22]
- Resonant ALP-photon conversion around pulsars [see e.g. Pshirkov+ 07]
- Solar searches, main-sequence stars, etc.
- …

Venues for the future searches: Galactic SN

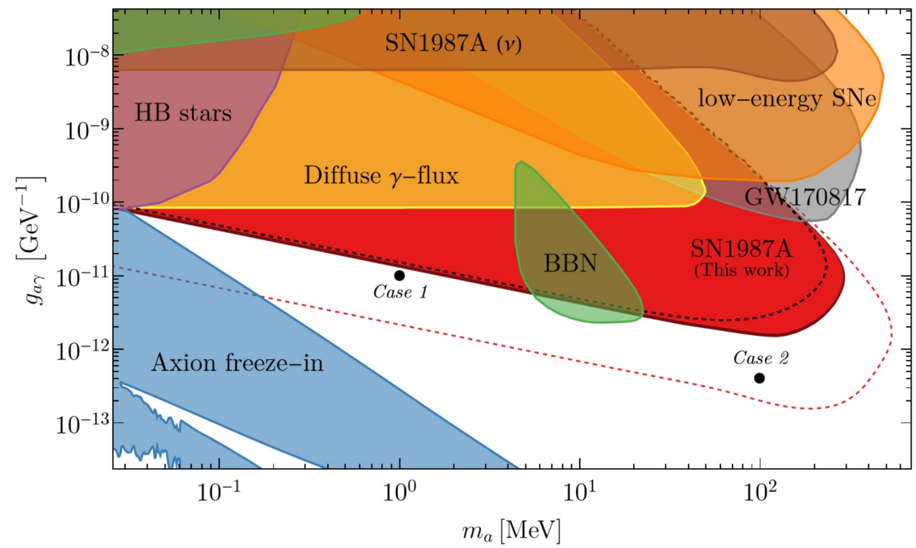


[Meyer+ ’16]

Venues for the future searches: Galactic SN



[Meyer+ '16]



[Ravensburg (née Müller)+ '16]

Venues for the future searches: MMA

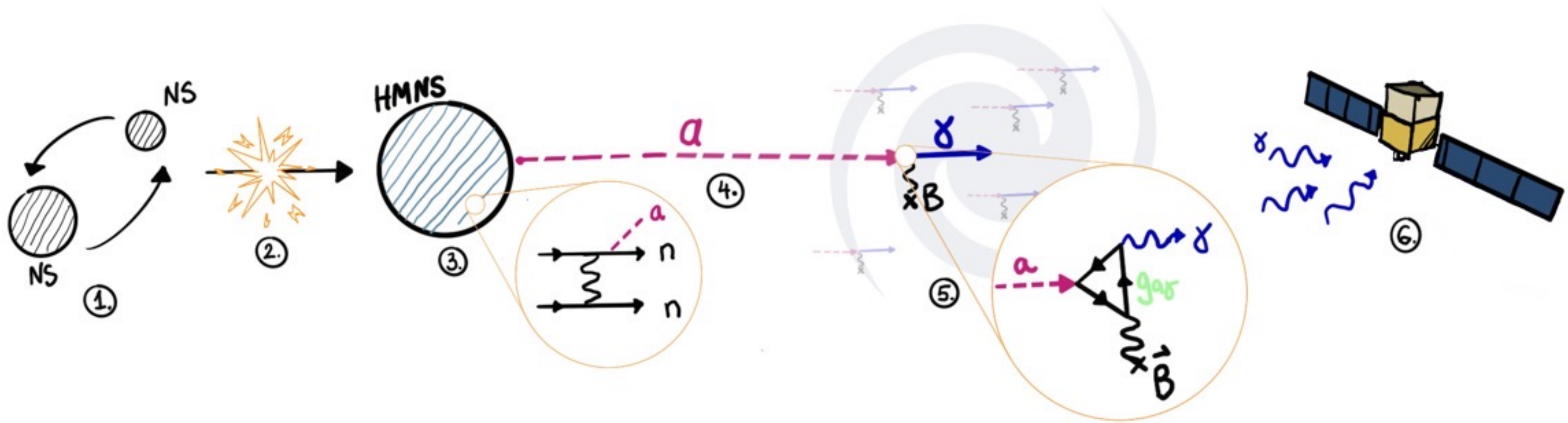
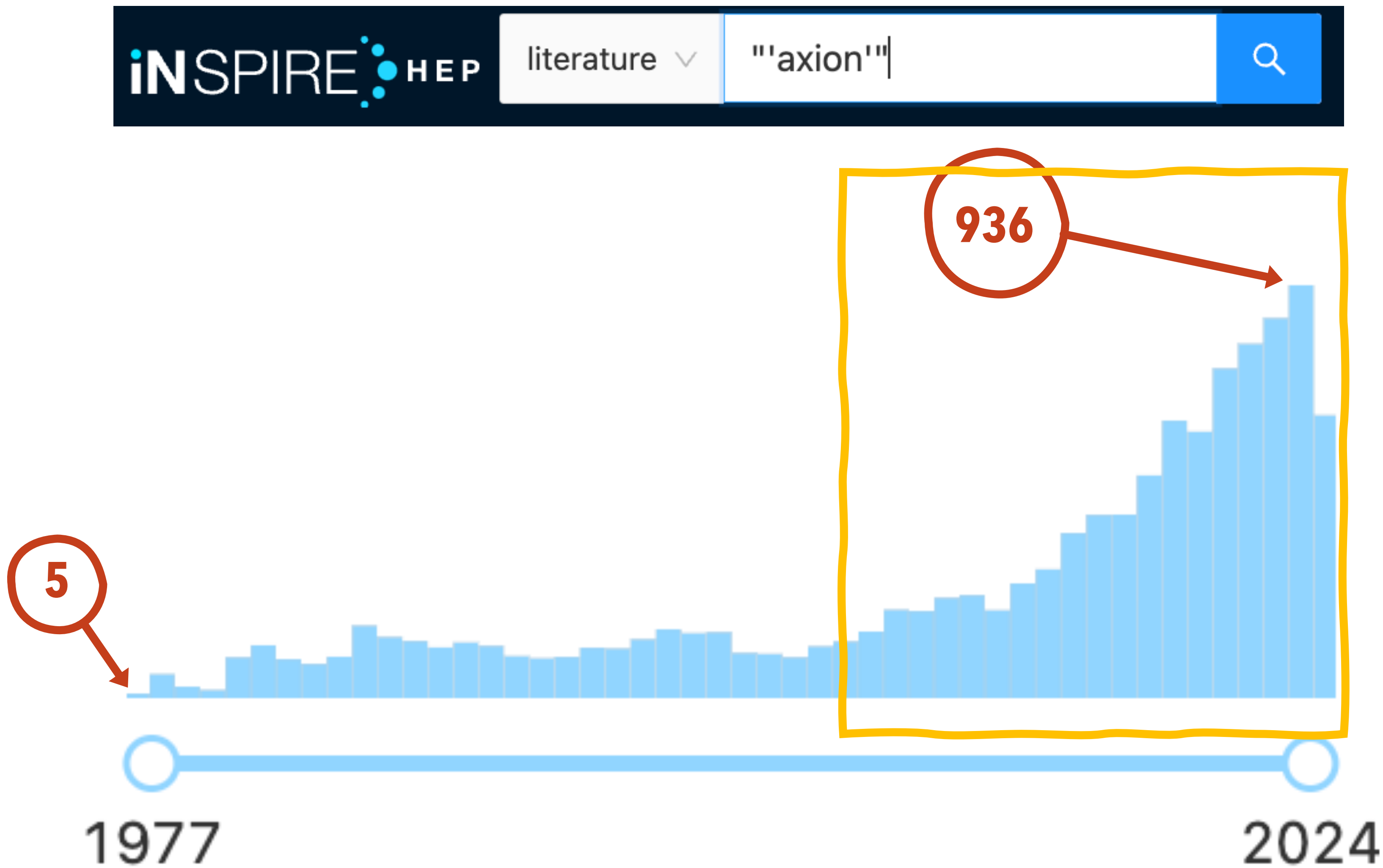
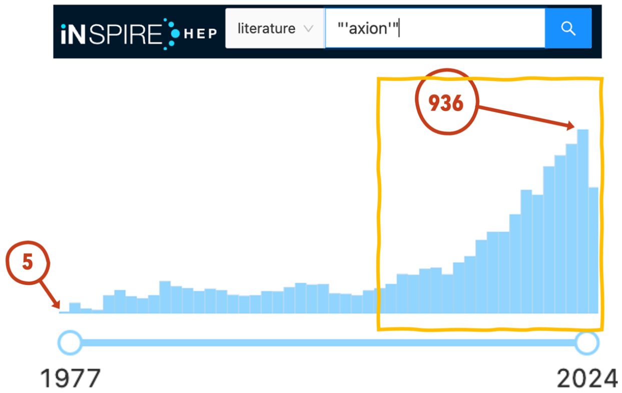


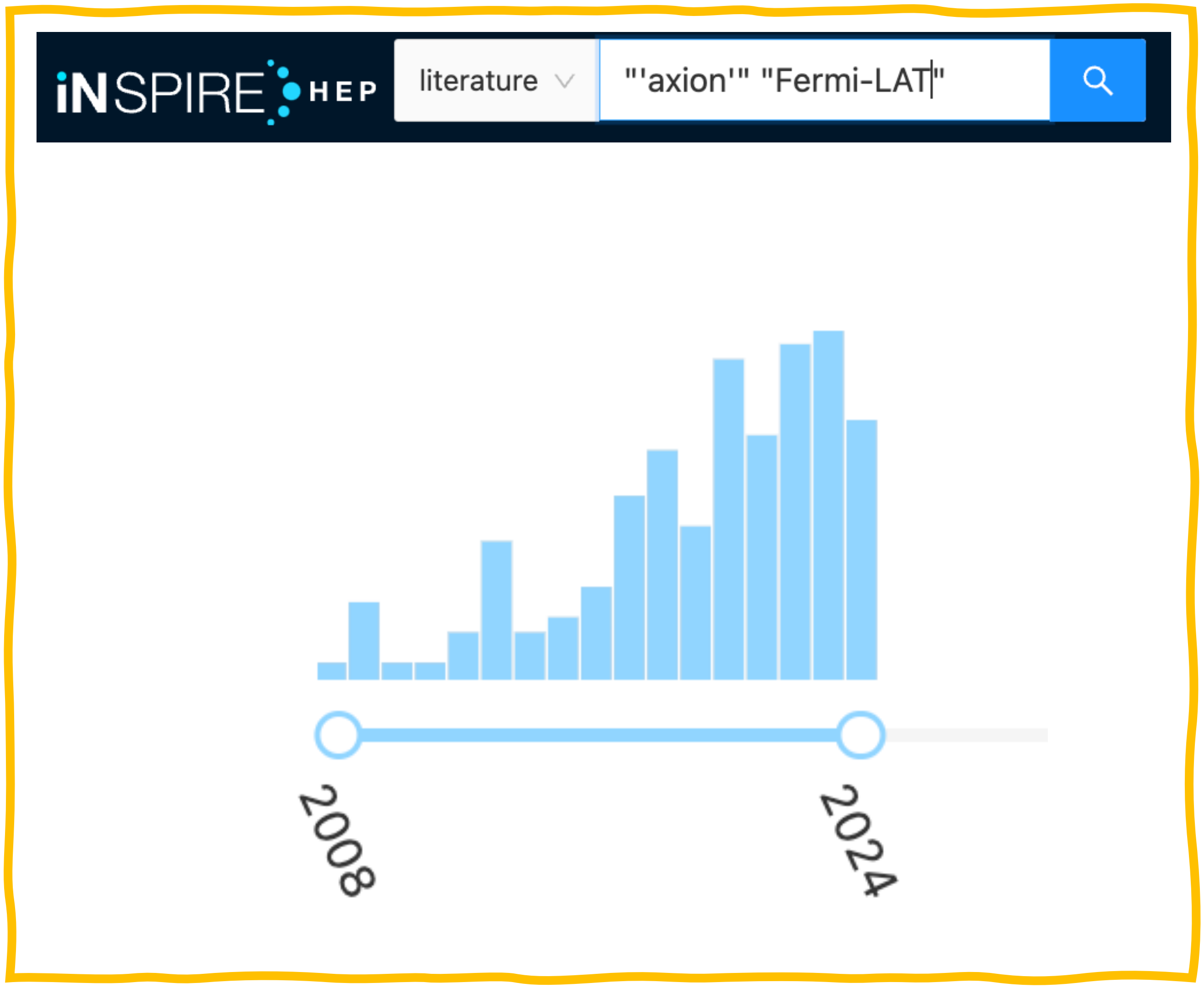
Figure description: (1) Two neutron stars (NS) orbit each other until the (2) merger, followed by (3) the formation of a hypermassive neutron star (HMNS). There, ALPs are produced via the neutron-neutron bremsstrahlung process. Once produced, ALPs travel undisturbed (4), until they reach the magnetic field of the Milky Way (5). In the Milky Way's magnetic field, ALPs convert into gamma-rays, which then can be detected by *Fermi* (6).



(accessed on September 5, 2024)

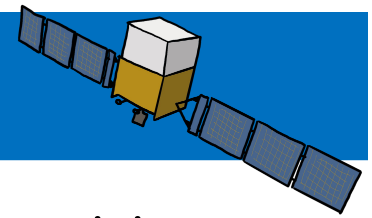


iNSPIRE HEP
literature
"'axion'"
936
5
1977
2024



iNSPIRE HEP
literature
"'axion'" "Fermi-LAT"
2008
2024

Conclusions & Outlook



- *Fermi*-LAT **continues to be** a crucial player in **uniquely** characterizing axions and ALPs, leading candidates to describe the nature of dark matter (and more).
- **No other current experiment can search for the MeV→soft GeV signatures of ALPs from astrophysical sources.**
- Probes are multiwavelength & multimessenger, as the characterization of classical physical processes is needed.
- **The future of ALPs is bright** (pun intended). We must make sure we have something to capture it. (*Fermi,* in concert with CTAs and MeV instruments.)

Thank you.