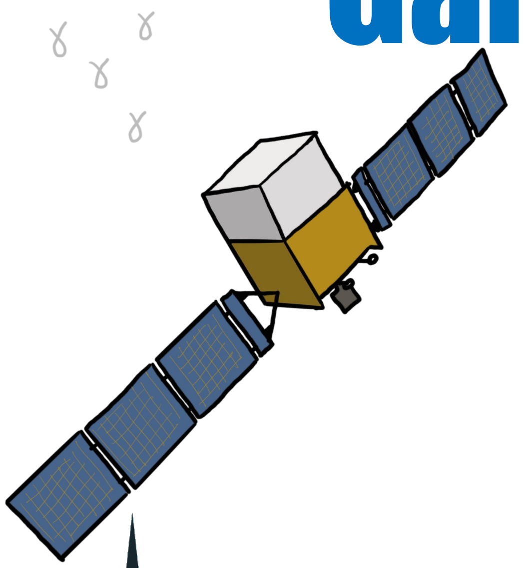
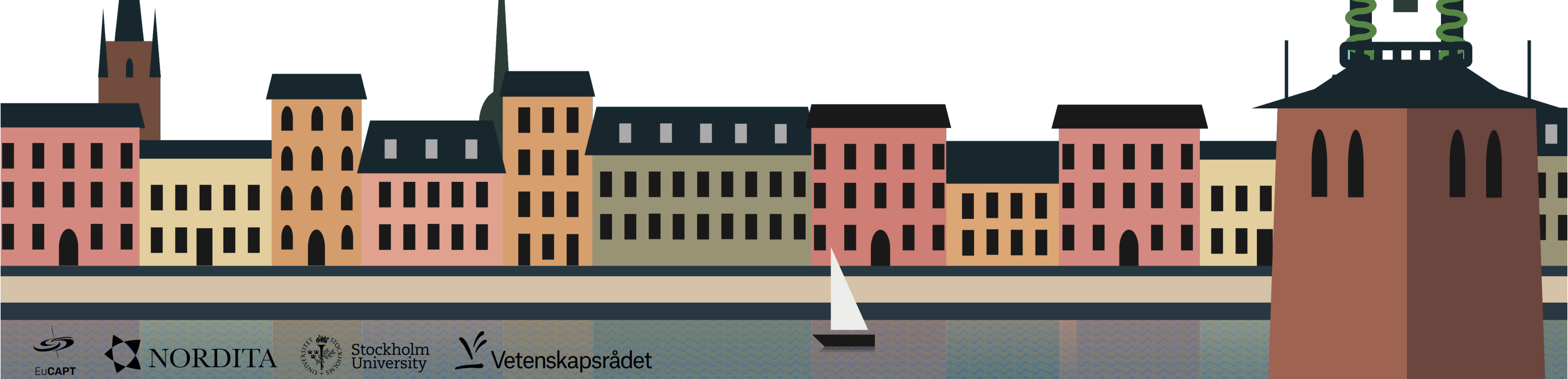


# Gamma-ray Windows into the Axion Landscape

## Current Status and Future Prospects


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

EuCAPT NORDITA Stockholm University Vetenskapsrådet

# Axion/ALP Landscape: A Theorist's View

Strong CP problem solution

Dark Matter Candidate

String Theory ubiquity

# Axion/ALP Landscape: A Theorist's View

Strong CP problem solution

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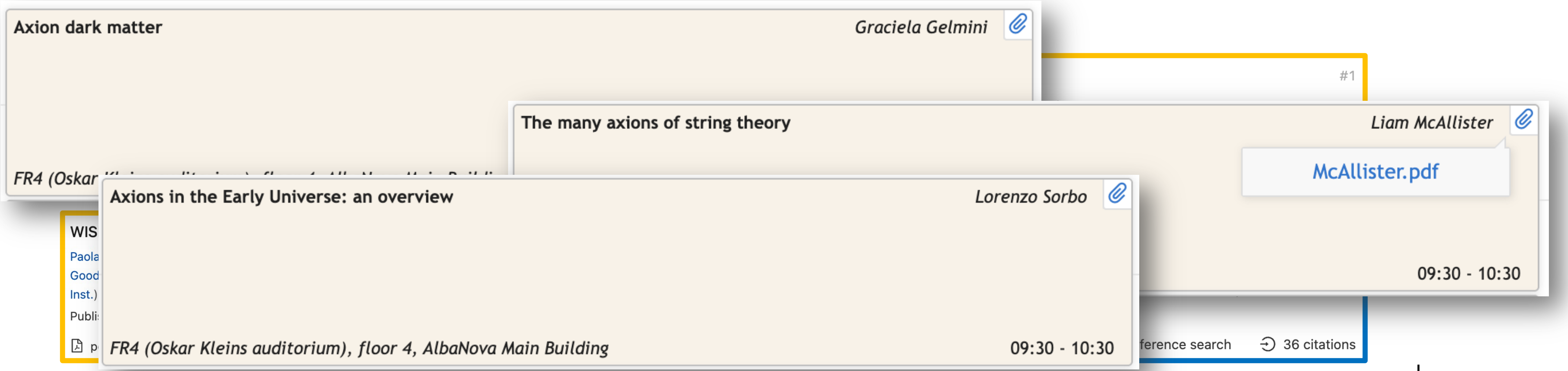



and many more…

# Axion/ALP Landscape: A Theorist's View

Strong CP problem solution

Dark Matter Candidate

String Theory ubiquity

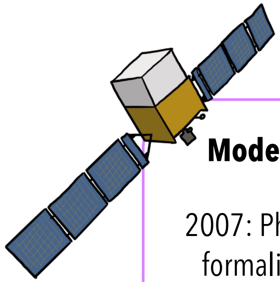
**Dynamic solution to the strong CP problem via spontaneous symmetry breaking**
Peccei & Quinn, Phys. Rev. Lett. 38, 1440 (1977)

**Axion particle prediction**
Wilczek, Phys. Rev. Lett. 40, 279 (1978); Weinberg, Phys. Rev. Lett. 40, 223 (1978)

Original **"visible" axion ruled out by experiments**; "Invisible" axion with suppressed couplings
KSVZ model (1981)
DFSZ model (1981)

**Astrophysical Axion constraints**
SN1987A neutrino observations
Raffelt & SeckelPhys. Rev. Lett. 60, 1793 (1988)

**1990s: Dark Matter Connection**
Preskill, Wise & Wilczek (1983): Axions as DM candidates
- Misalignment mechanism detailed calculations
- Cosmological axion abundance



**Modern astrophysical searches**
2007: Photon-ALP oscillation formalism (e.g., Hooper & Serpico 2007)
2008**:** Fermi-LAT launches

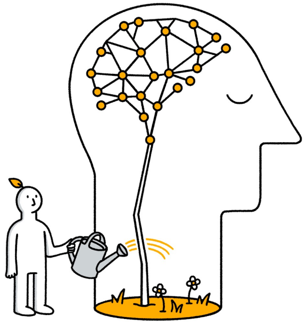
**2010s: ALP framework**
Generalization: Beyond QCD to generic ALPs
Broader parameter space
String theory

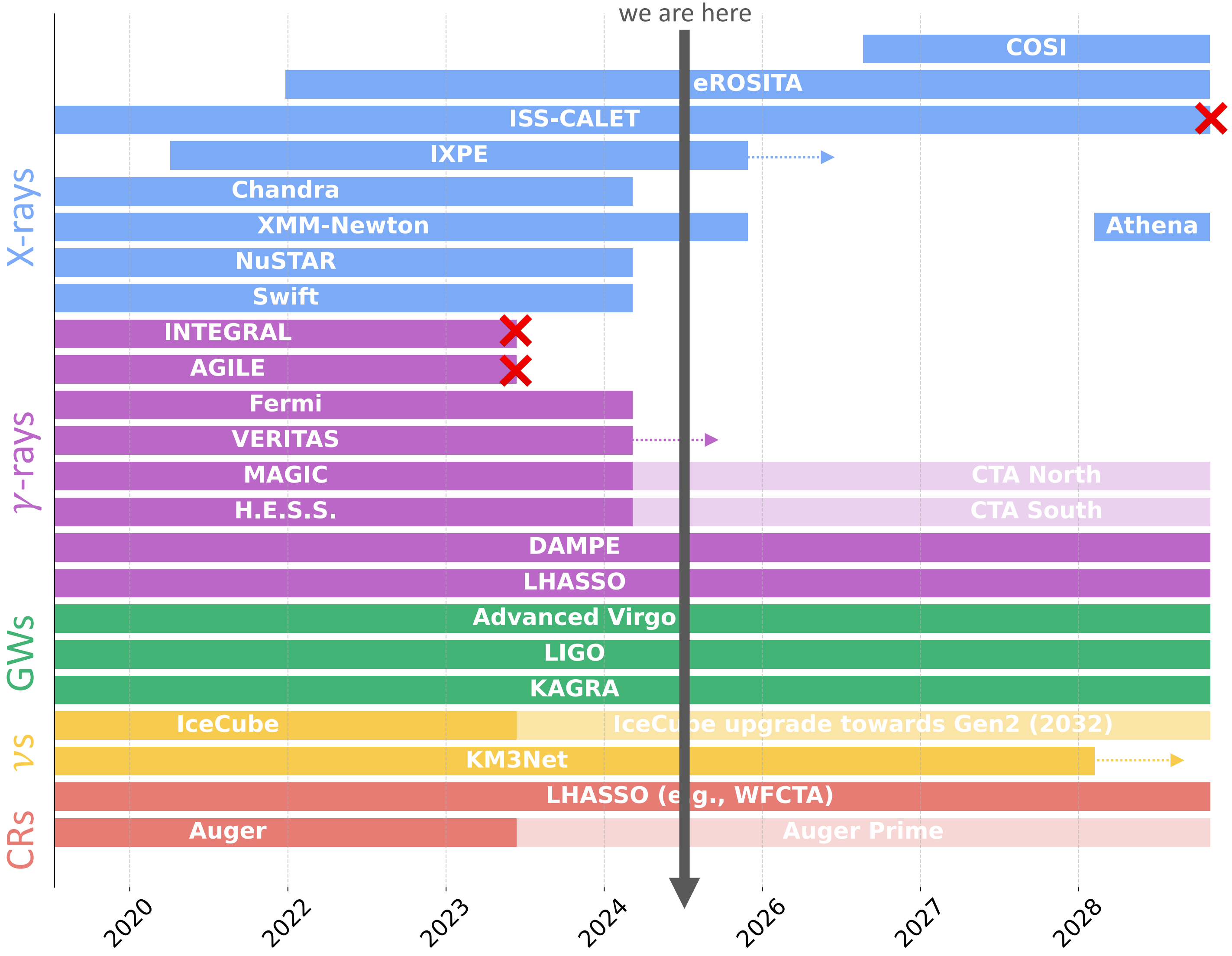
**2016 –** Fermi-LAT golden era; established gamma-ray astronomy as premier ALP probe

**2020s – Multimessenger Breakthrough**

**2022 – Laboratory-Astro Convergence**
(ADMX – DFSZ sensitivity)

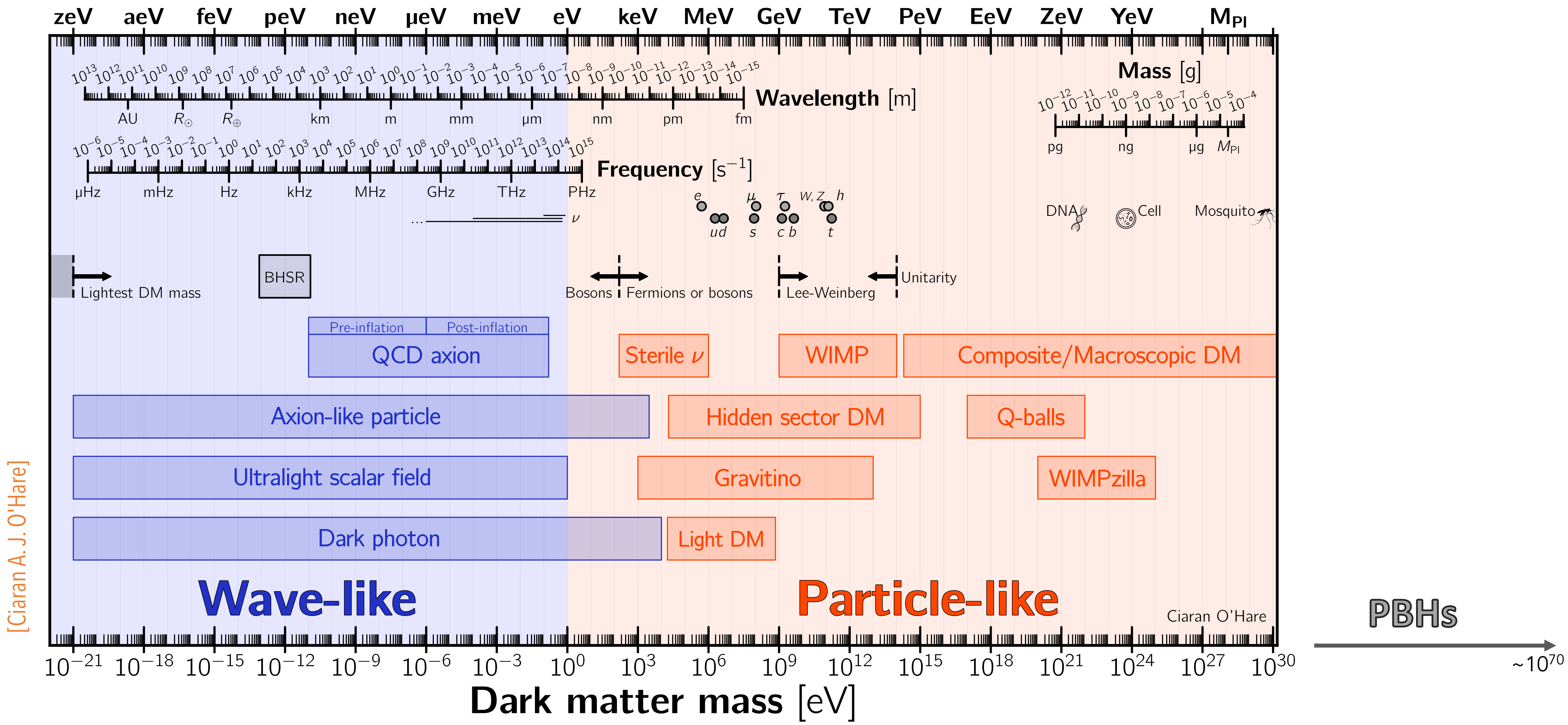
# Axion/ALP Landscape*: An Instrumentationalist's View



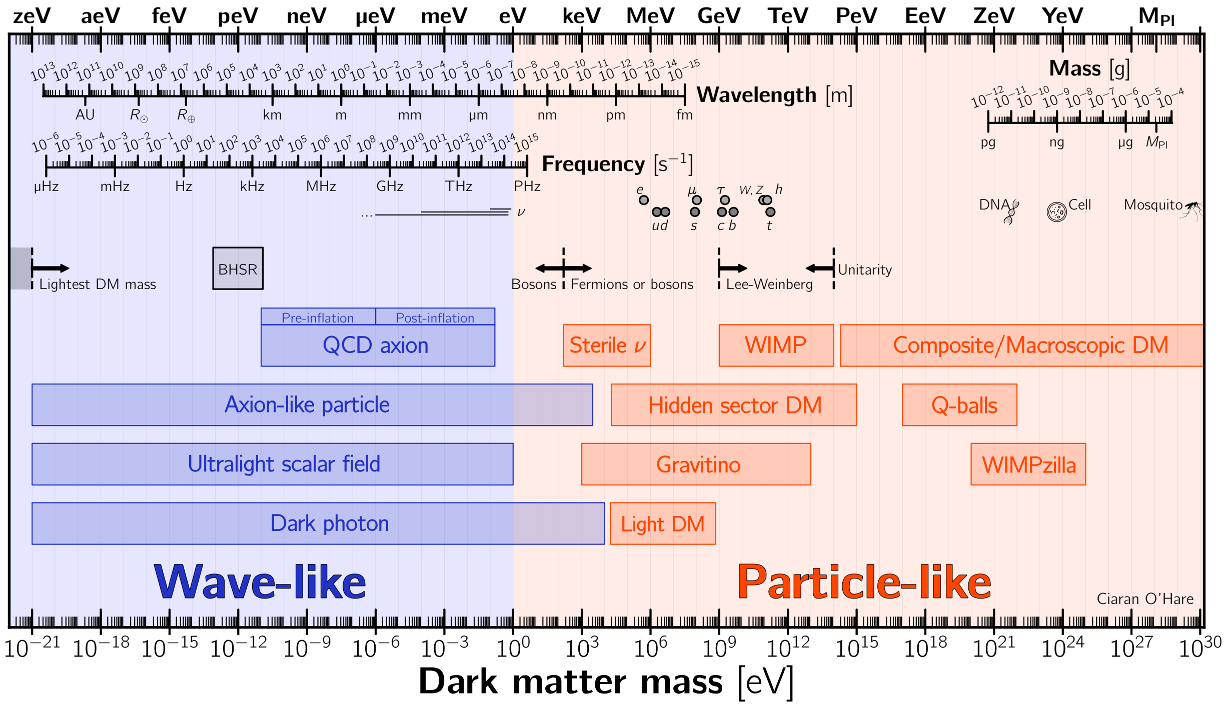



*indirect detection

# Axion/ALP Landscape: An Observer's View



# Axion/ALP Landscape: An Observer's View



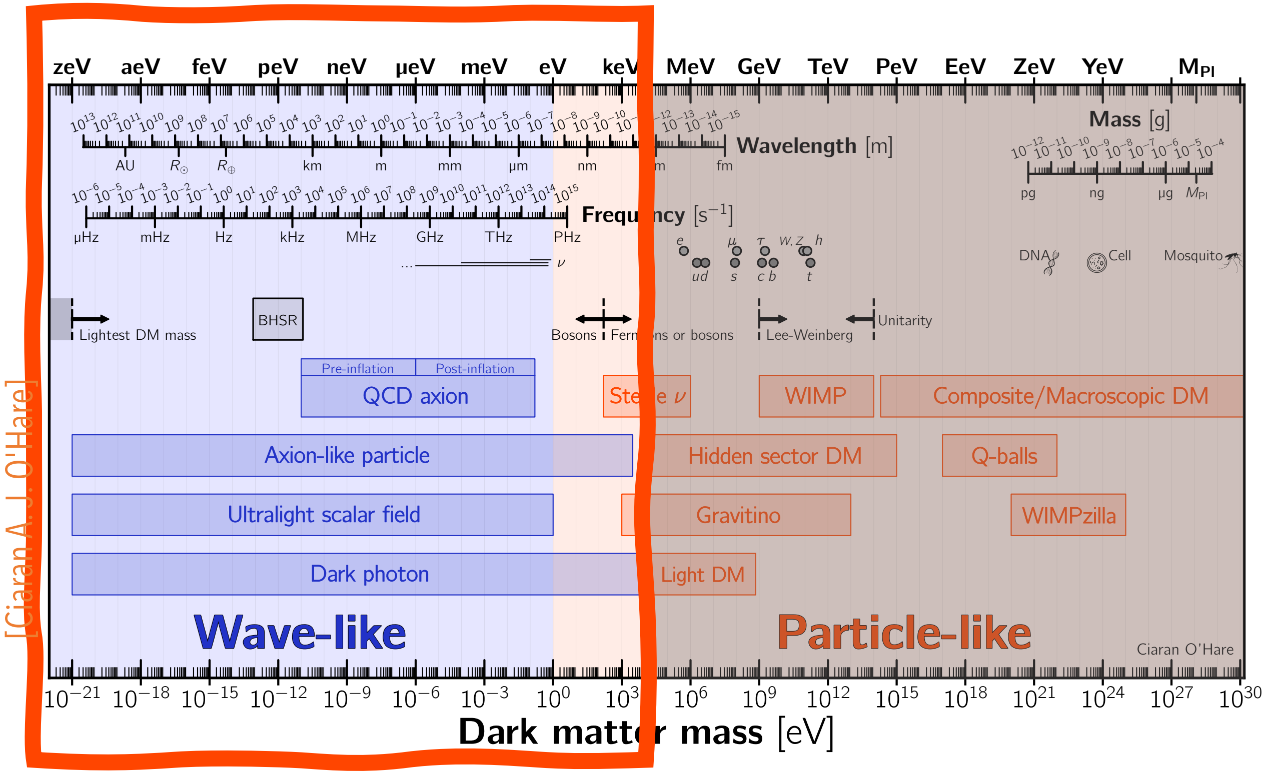

[Ciaran A. J. O'Hare]

Dark matter spans over **80 orders** of magnitude in mass (+ interaction strength)

**proton**
**m~$10^{-27}$ kg**


(c) Pablo Carlos Budassi

# Axion/ALP Landscape: An Observer's View



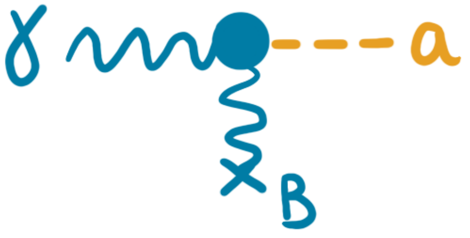

## Our search strategies are inherently *biased*

1. **model dependency bias:** theory guides our search strategies
2. **observational bias:** disparity between the data we have and the data we need
3. **identifiable signature bias:** required for observation

# Axion/ALP Landscape: An Observer's View

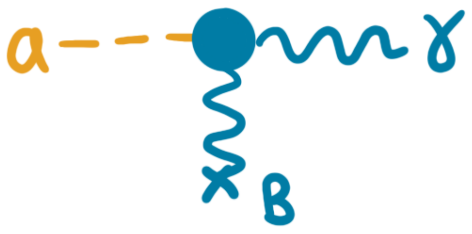
**ALP/axion - photon interactions**

1. Primakoff process



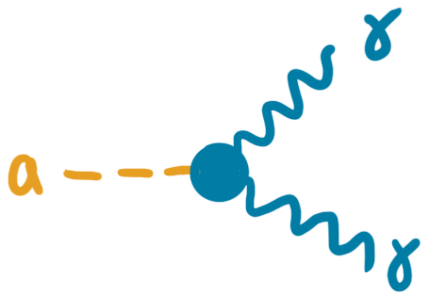

γ → a

2. Inverse Primakoff




a → γ

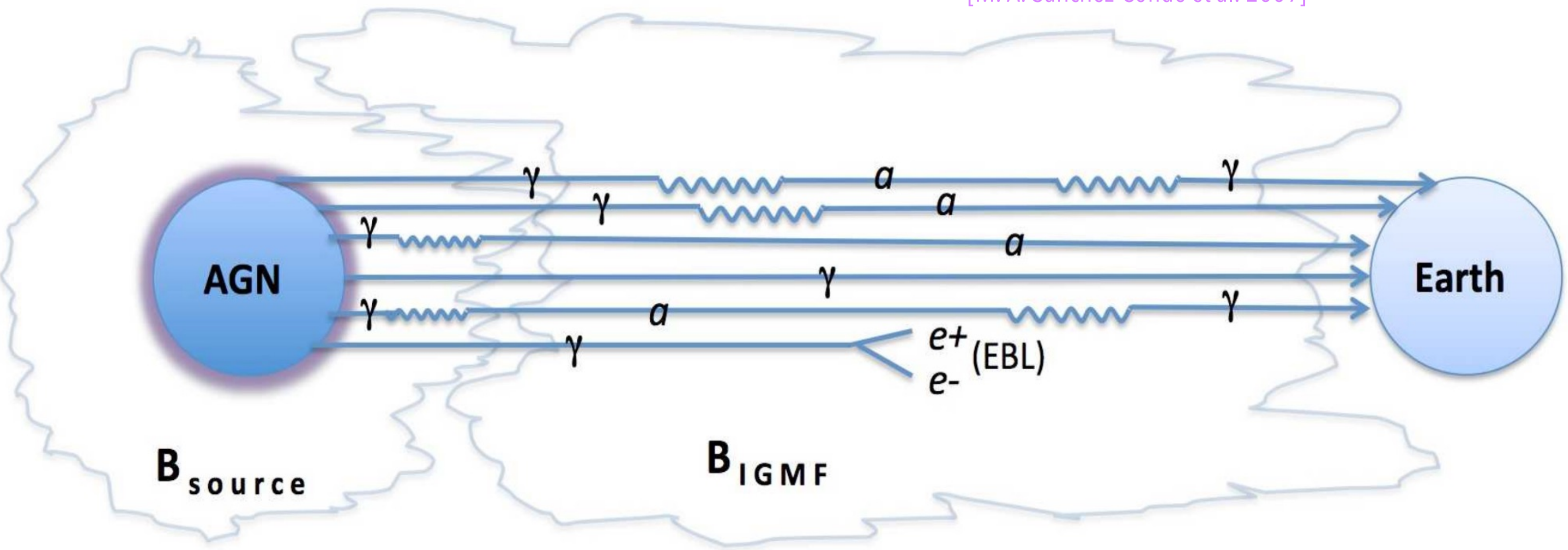
3. ALP/axion decay




a → γγ

# Photon-Axion/ALP Mixing

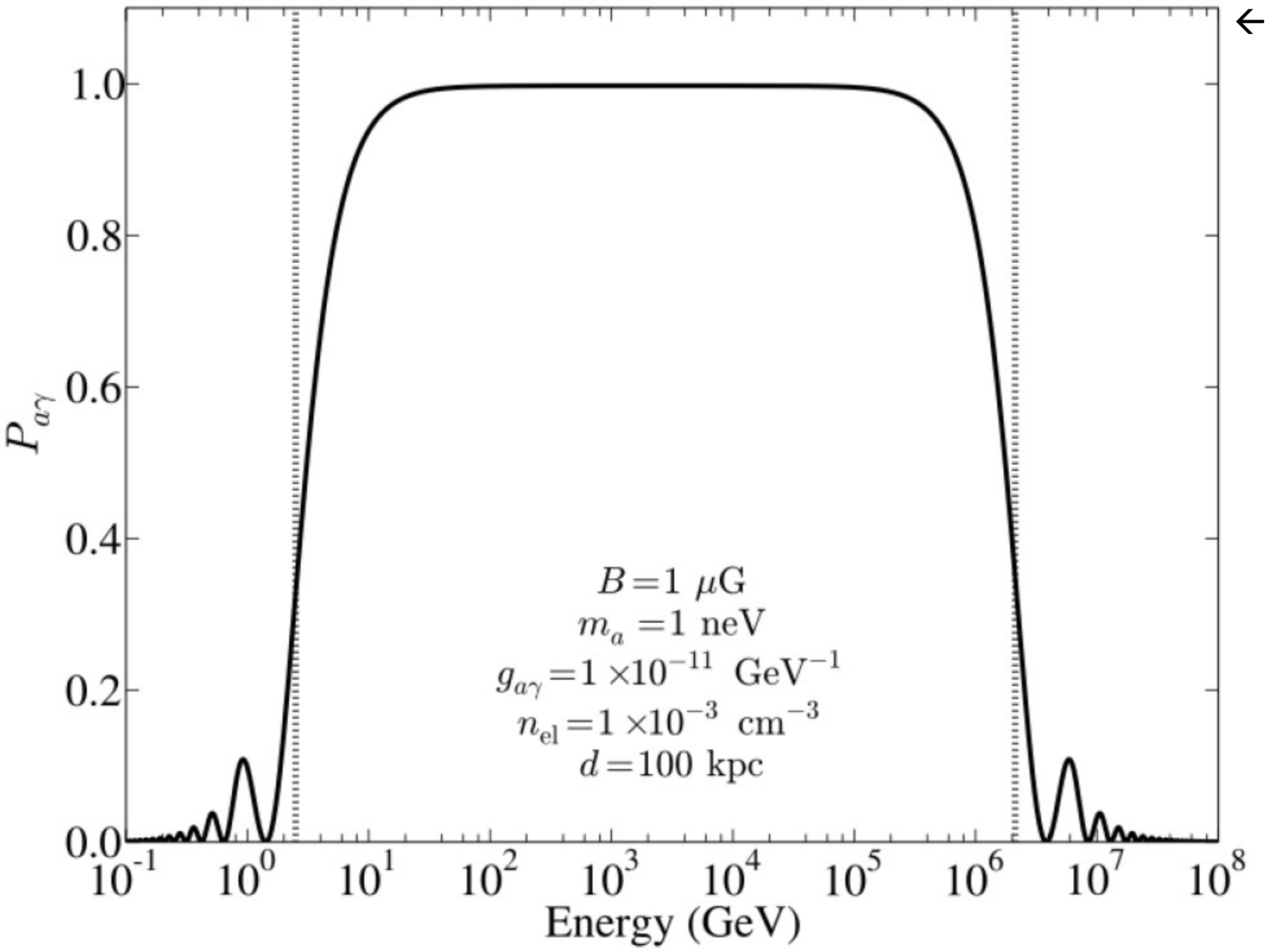
[M. A. Sánchez-Conde et al. 2009]




**Many different scenarios:**

- Mixing in the source (AGN)
- IGMF mixing
- Source + IGMF mixing
- IGMF + Galactic mixing
- Source + cluster + Galactic mixing …

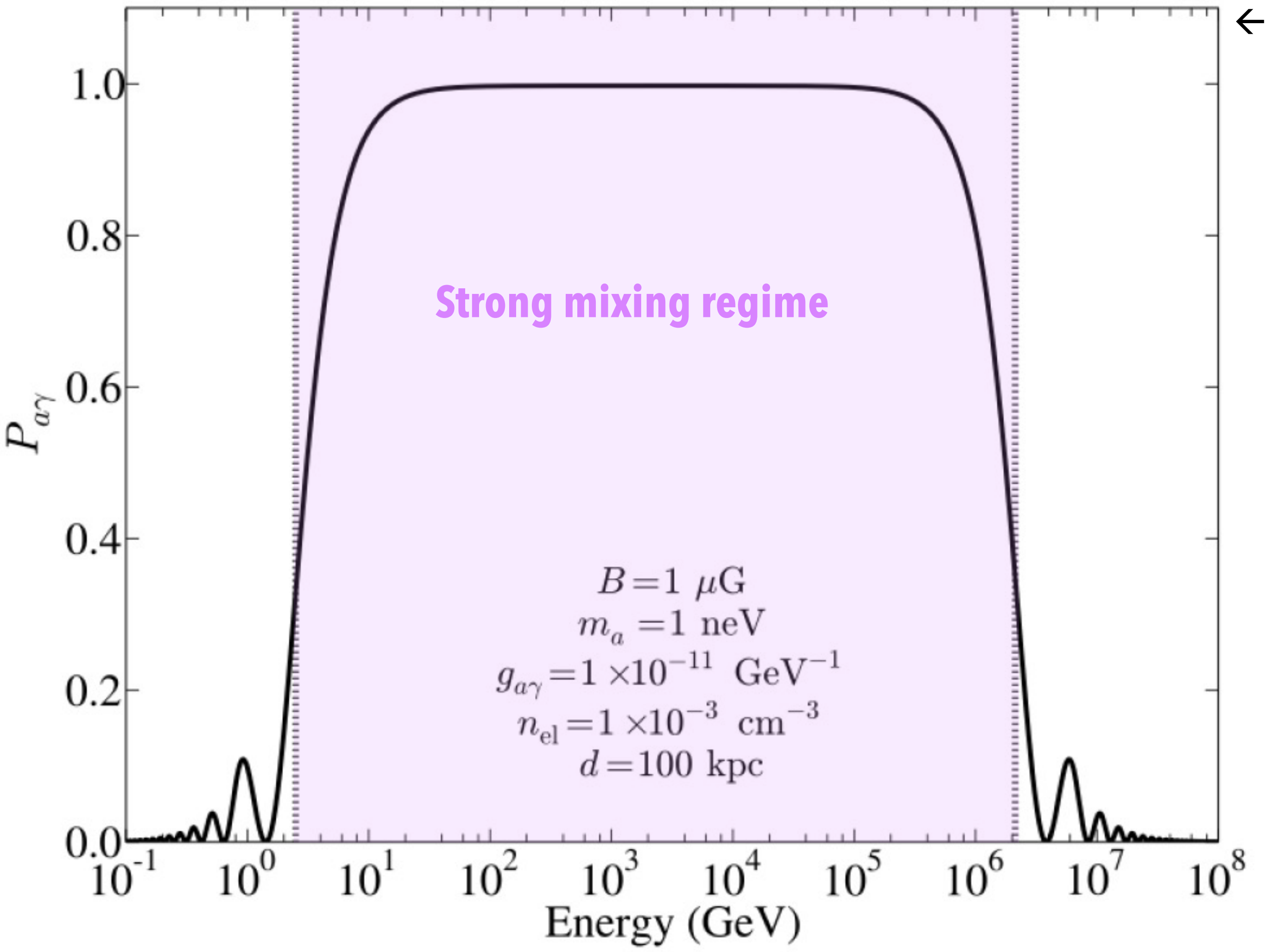
# Photon-Axion/ALP Mixing




← In a coherent magnetic field

[Raffelt & Stodolsky 1988]

# Photon-Axion/ALP Mixing

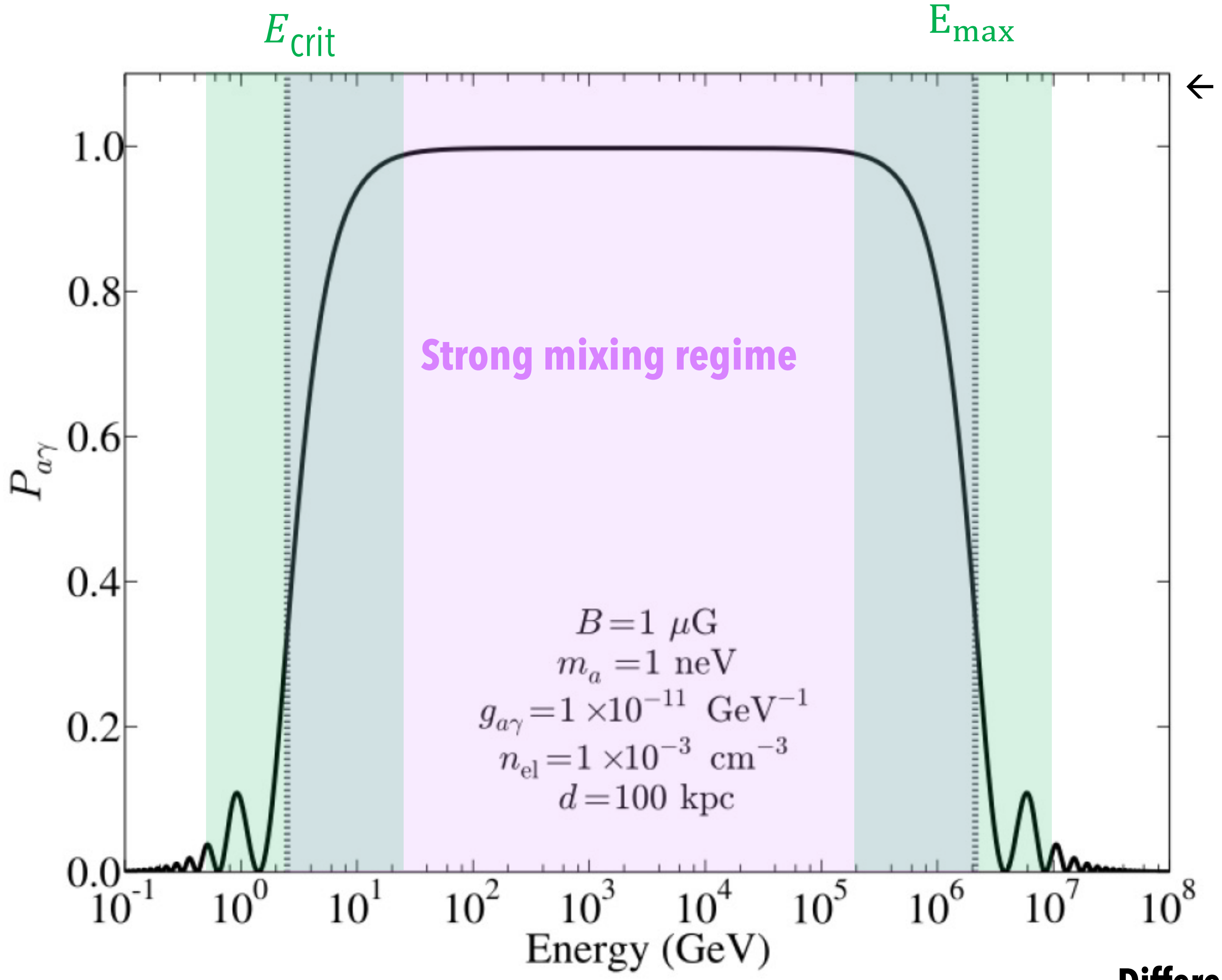



← In a coherent magnetic field

**Observable**: axions/ALPs do not get absorbed during propagation, might lead to a **boost in flux**

[Raffelt & Stodolsky 1988]

# Photon-Axion/ALP Mixing




← In a coherent magnetic field

**Observable**: axions/ALPs do not get absorbed during propagation, might lead to a **boost in flux**

**Observable**: irregularities in energy spectrum around $E_{crit}$ and $E_{max}$

$$E_{crit}\,(GeV) = 2.5\ GeV \frac{|m^2_{alp,neV} - \omega^2_{plasma,neV}|}{g_{11} B_{\mu G}}$$

$$E_{max} = 2.12\times10^6\ GeV\ g_{11}\ B^{-1}_{\mu G}$$

Gamma-ray energies

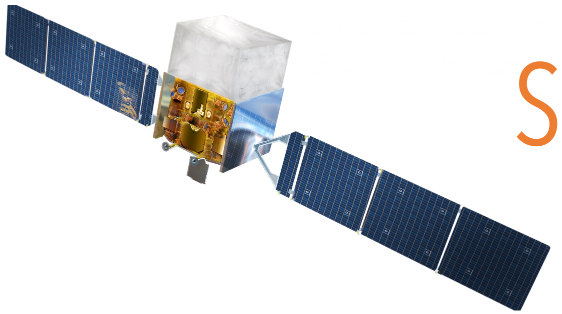
↔

Ultra-light ALPs ($\sim 10^{-9}$ eV)

**Different *E* for different astrophysical scenarios, but same ALP properties: cross-checks!**

[Raffelt & Stodolsky 1988]

# Axion/ALP Landscape: An Instrumentationalist's View



Satellite

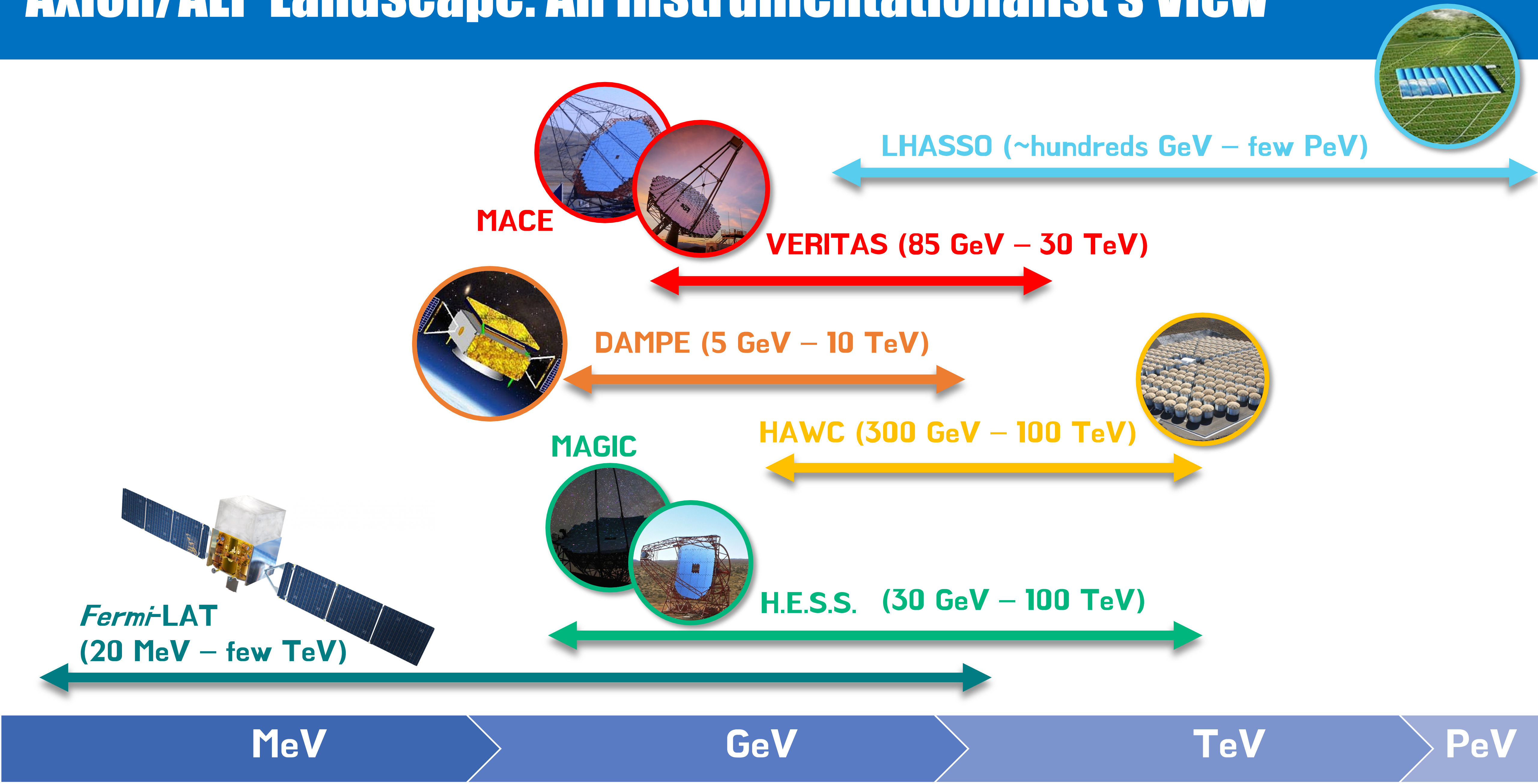
- *Fermi* Large Area Telescope (LAT), AGILE (deorbited Feb 20, '24)
- Pair-conversion instruments

Atmospheric/water Cherenkov Telescopes

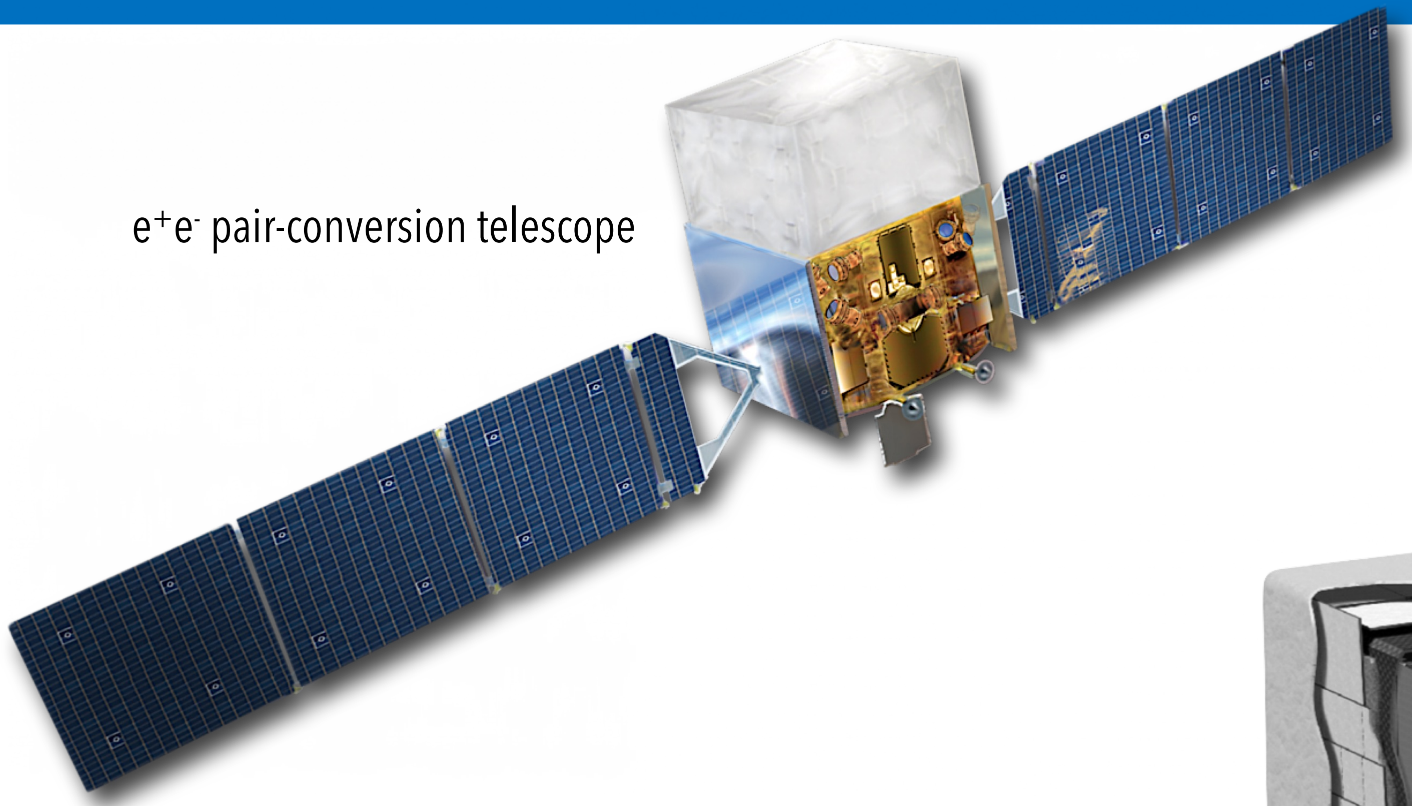
- VERITAS, MAGIC, HESS, HAWC, LHASSO
- Atmosphere/water = calorimeter, particle showers

# Axion/ALP Landscape: An Instrumentationalist's View

*approximate scale



# The *Fermi*-LAT



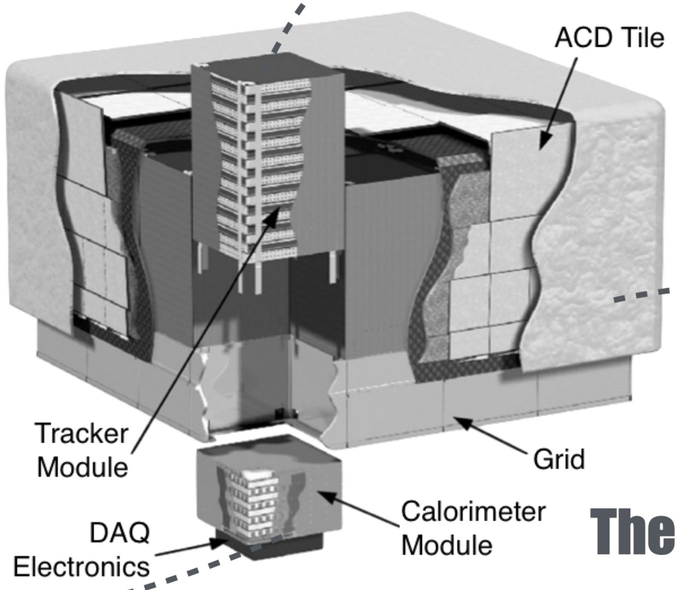
$e^+e^-$ pair-conversion telescope

individual $\gamma$ rays convert into $e^+e^-$ pairs

→ tracks (localization) & deposited energy

…it also detects electrons.

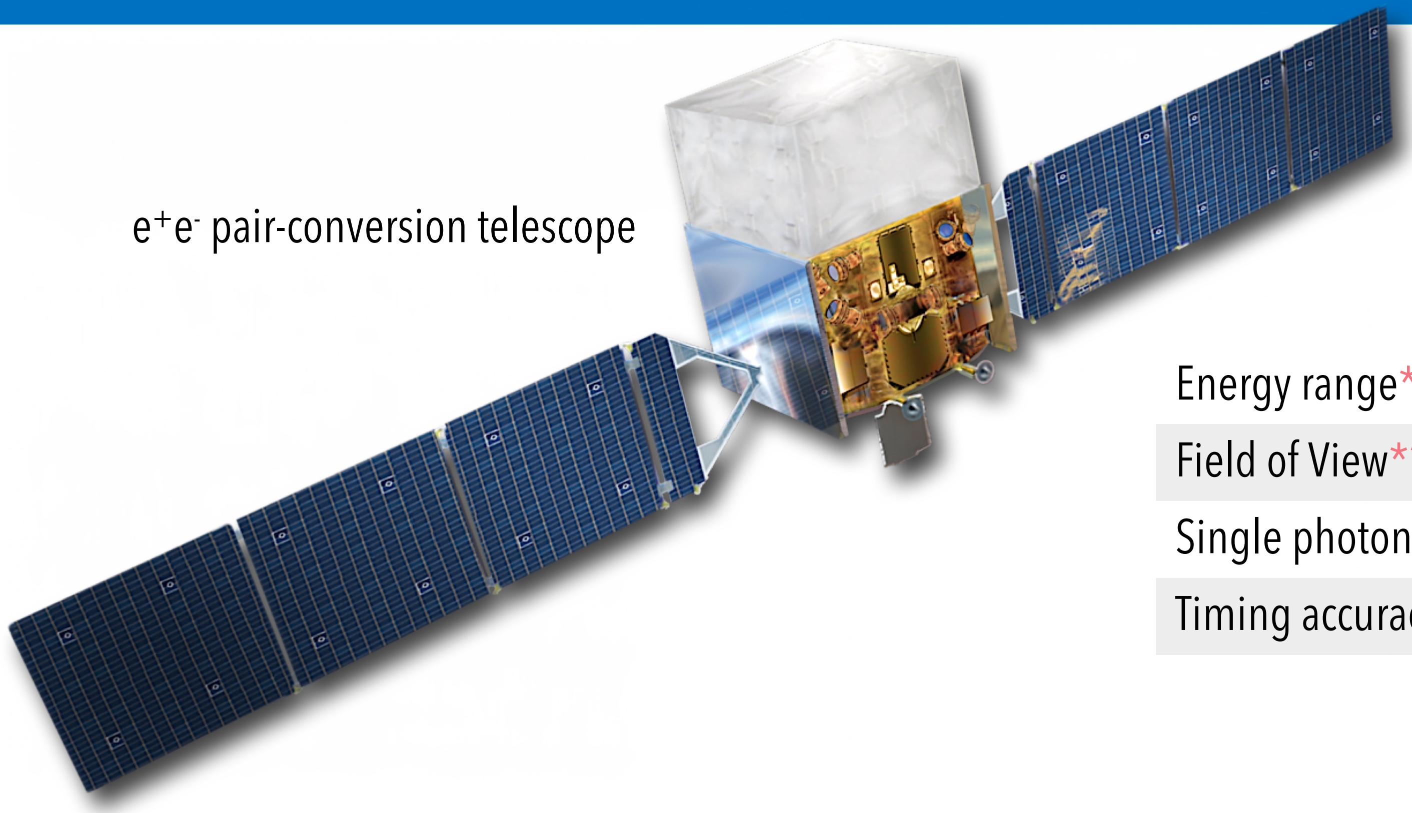
**The Tracker-converter**




**The Anti-coincidence Detector**

**The Calorimeter**

# The *Fermi*-LAT



$e^+e^-$ pair-conversion telescope

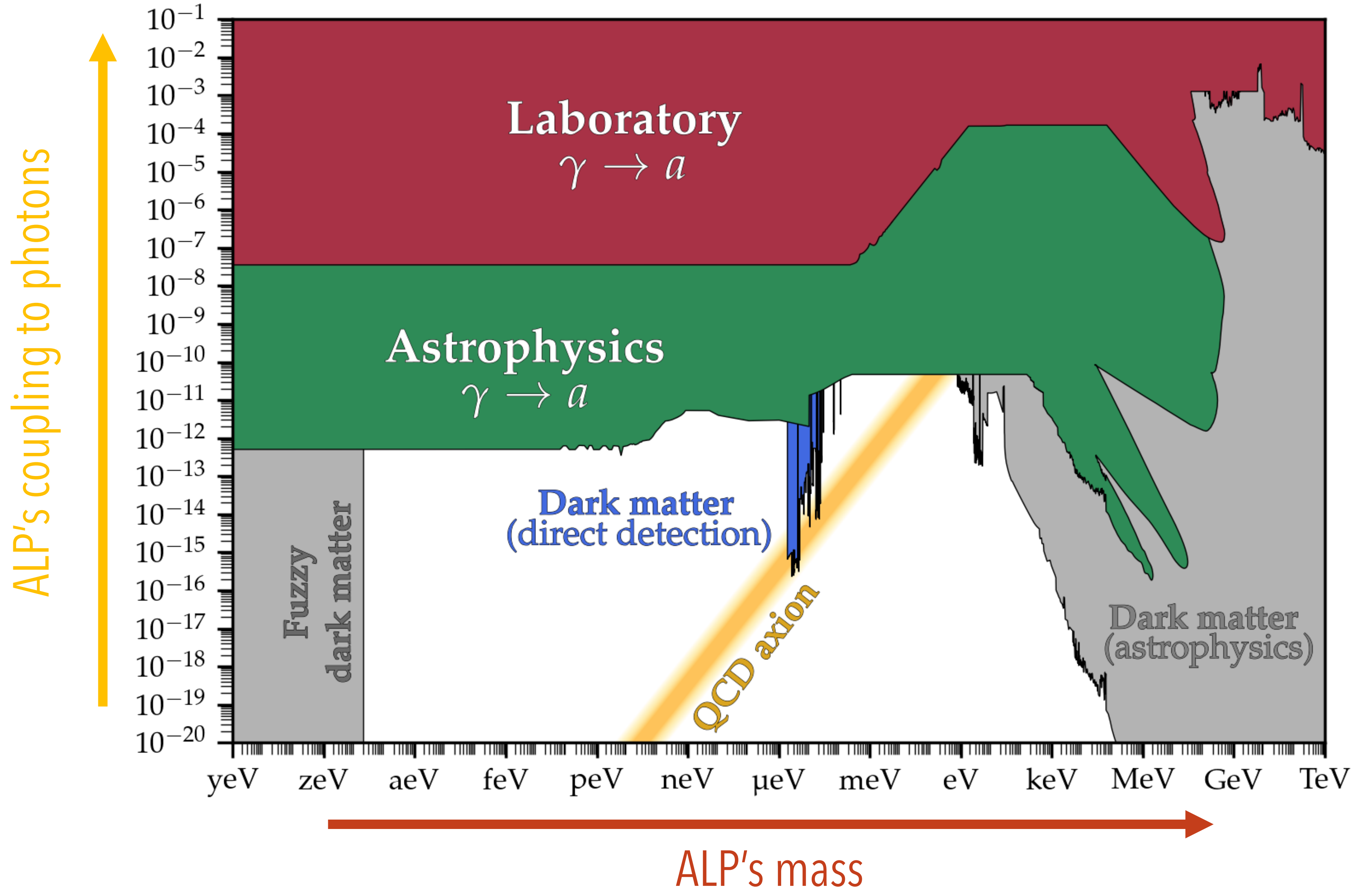
| | |
|---|---|
| Energy range* | 20 MeV to > 300 GeV |
| Field of View** | 2.4 sr (~1/5 of the whole sky) |
| Single photon angular resolution*** | < 1 deg at 1 GeV |
| Timing accuracy | 1 microsecond |

individual $\gamma$ rays convert into $e^+e^-$ pairs
→ tracks (localization) & deposited energy

*well-suited for Axion/ALP searches
**whole sky every ~3 hours
***point-source localization <0.5 arcmin

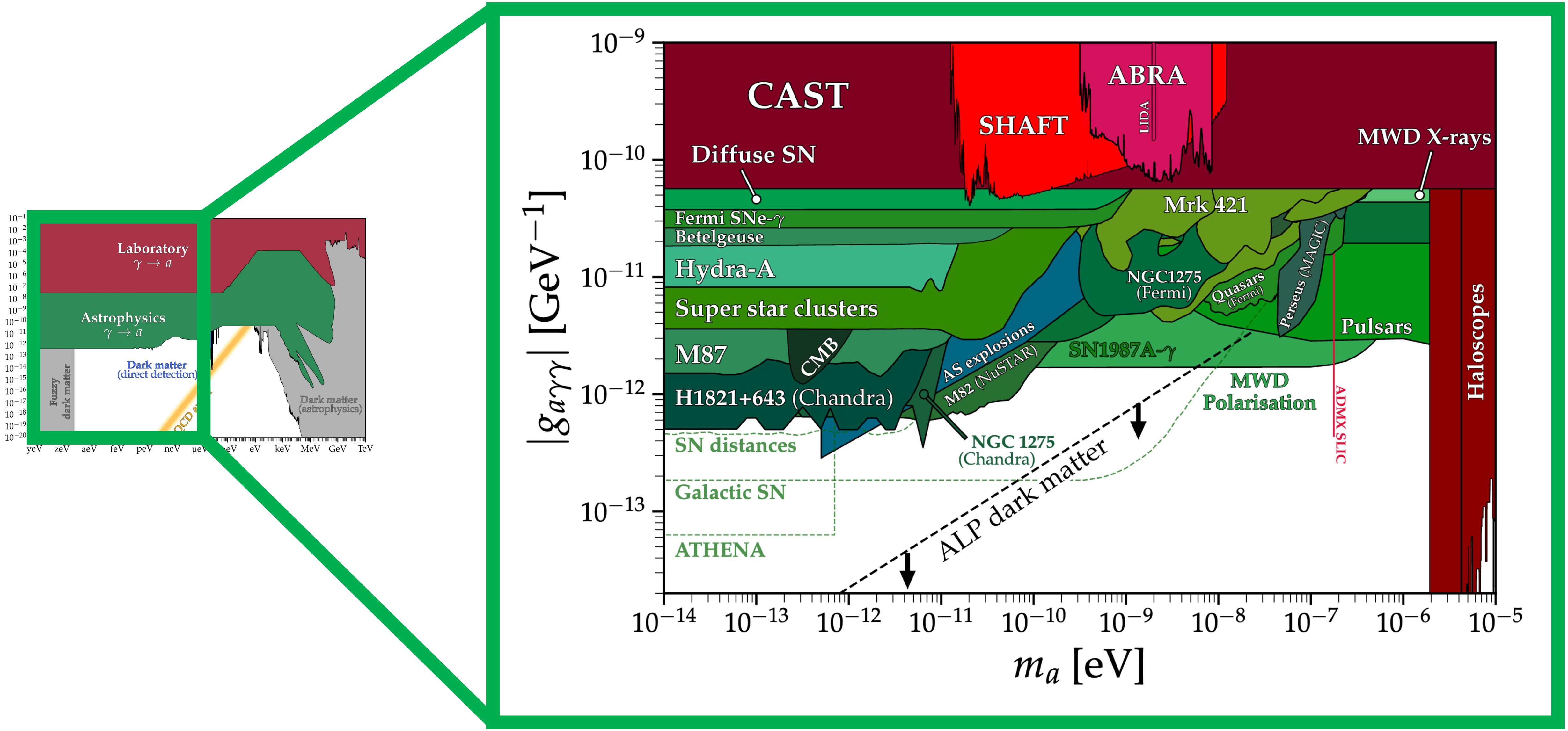
…it also detects electrons.

# Axion/ALP Landscape: An Observer's View




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

# Axion/ALP Landscape: An Observer's View

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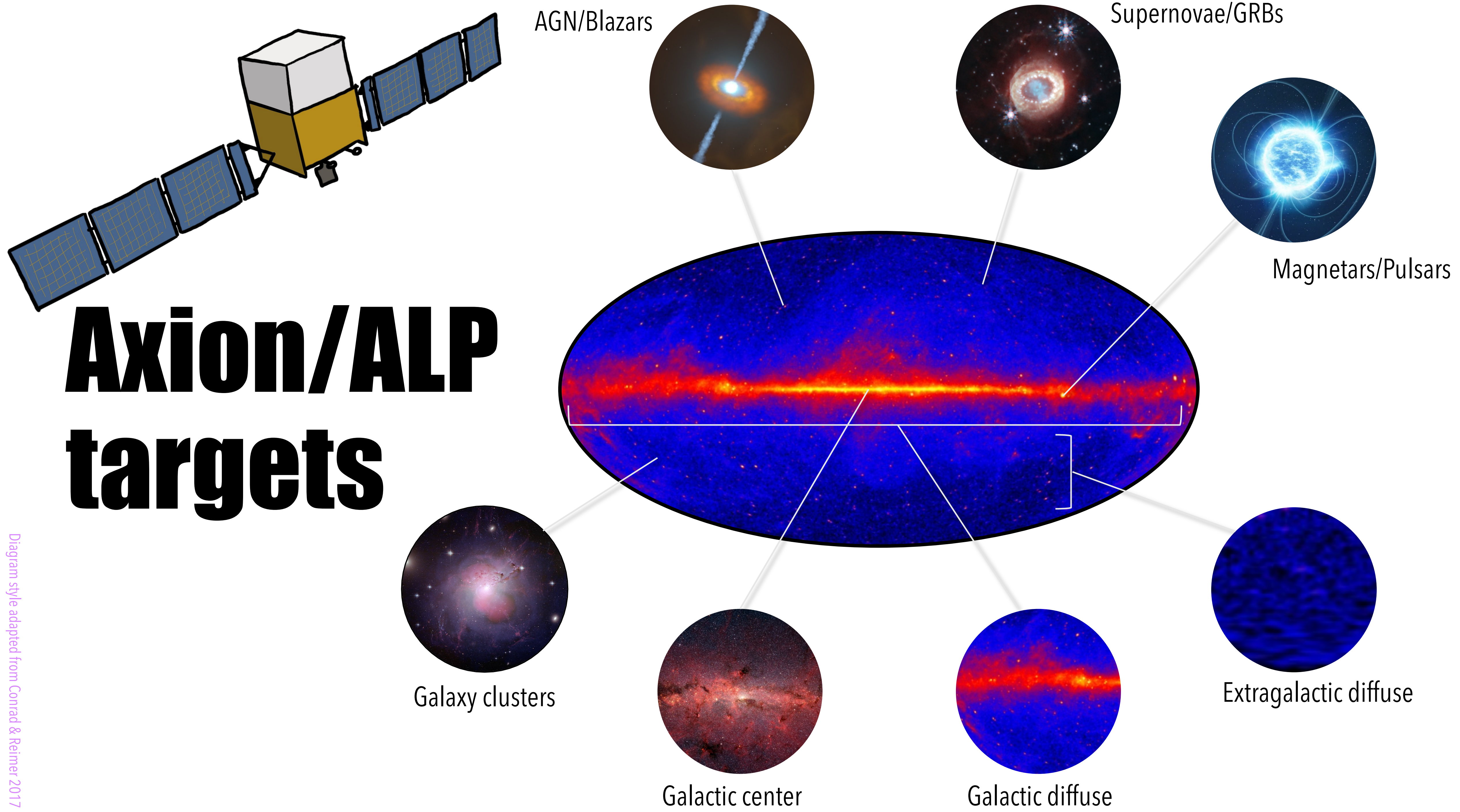
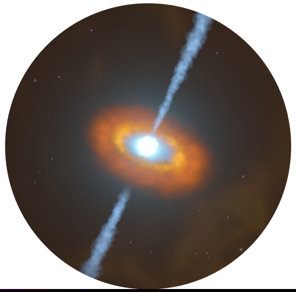
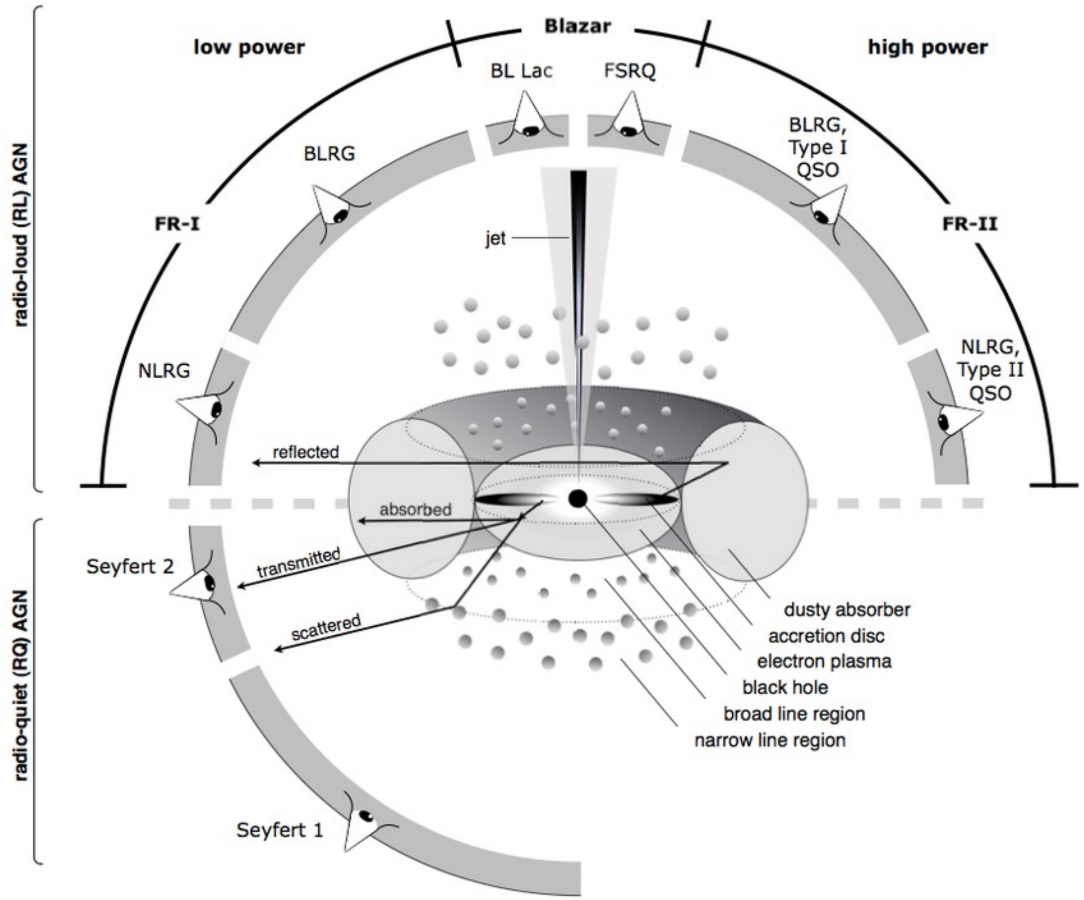


Axion/ALP targets
AGN/Blazars
Supernovae/GRBs
Magnetars/Pulsars
Galaxy clusters
Galactic center
Galactic diffuse
Extragalactic diffuse
Diagram style adapted from Conrad & Reimer 2017

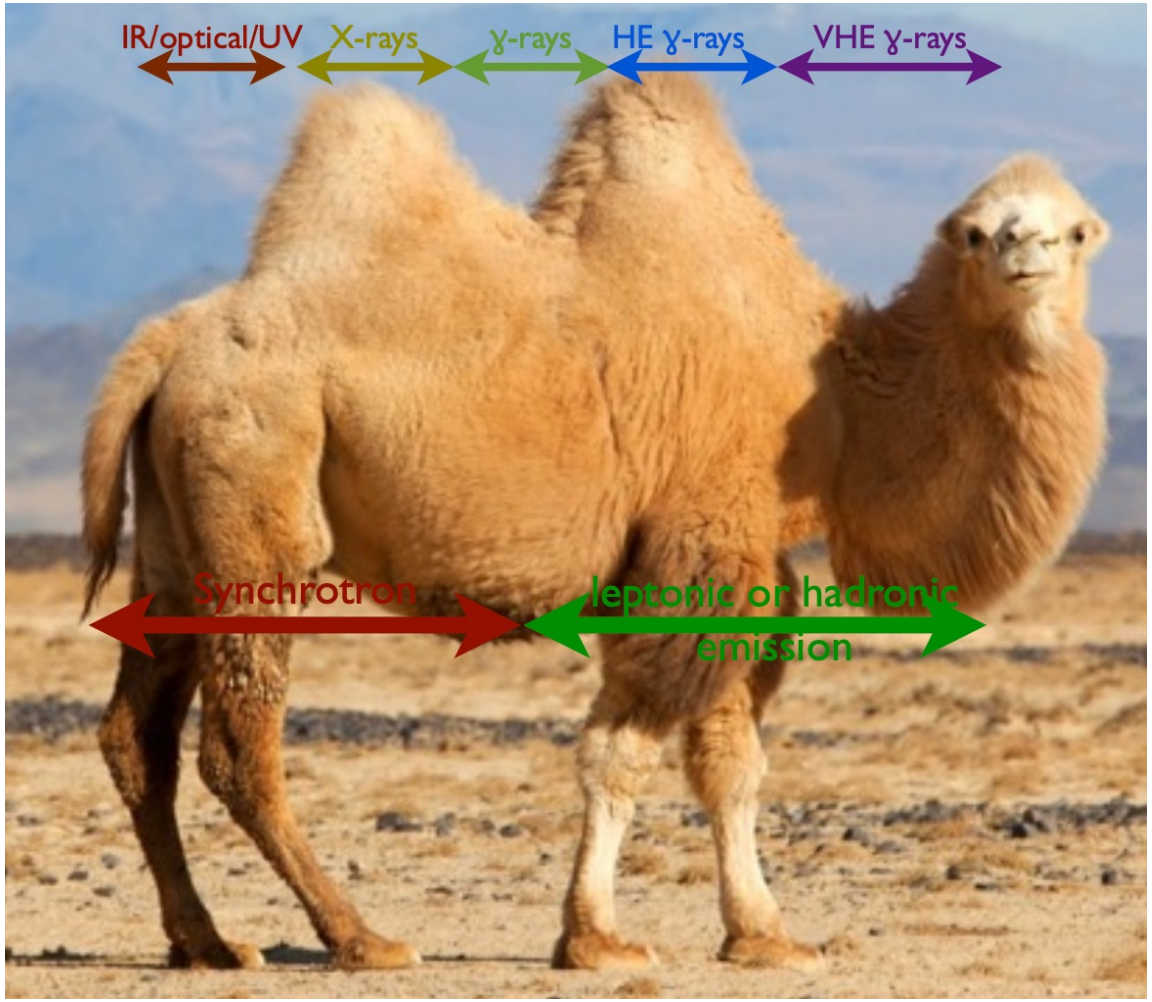
# Target 1: AGN & Blazars



# AGN & Blazars

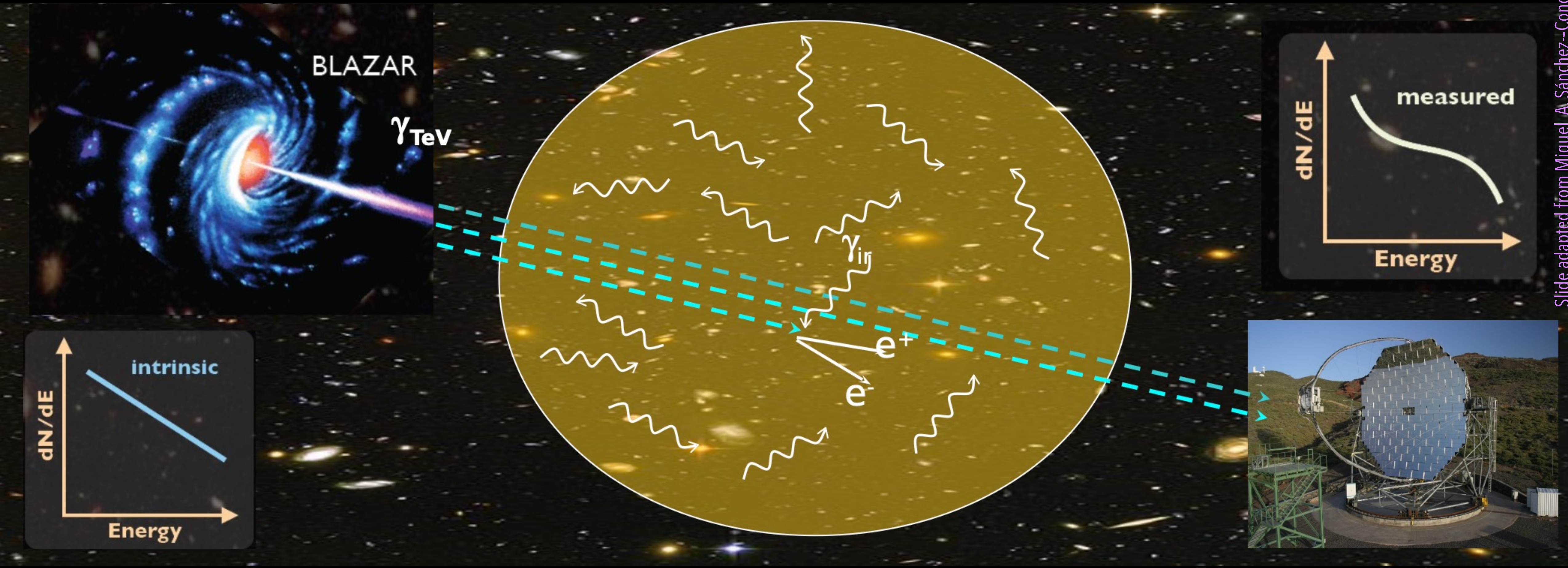



[Beckmann & Shrader 2012]




[adapted from M. Meyer]

# AGN & Blazars




Slide adapted from Miguel A. Sánchez-Conde

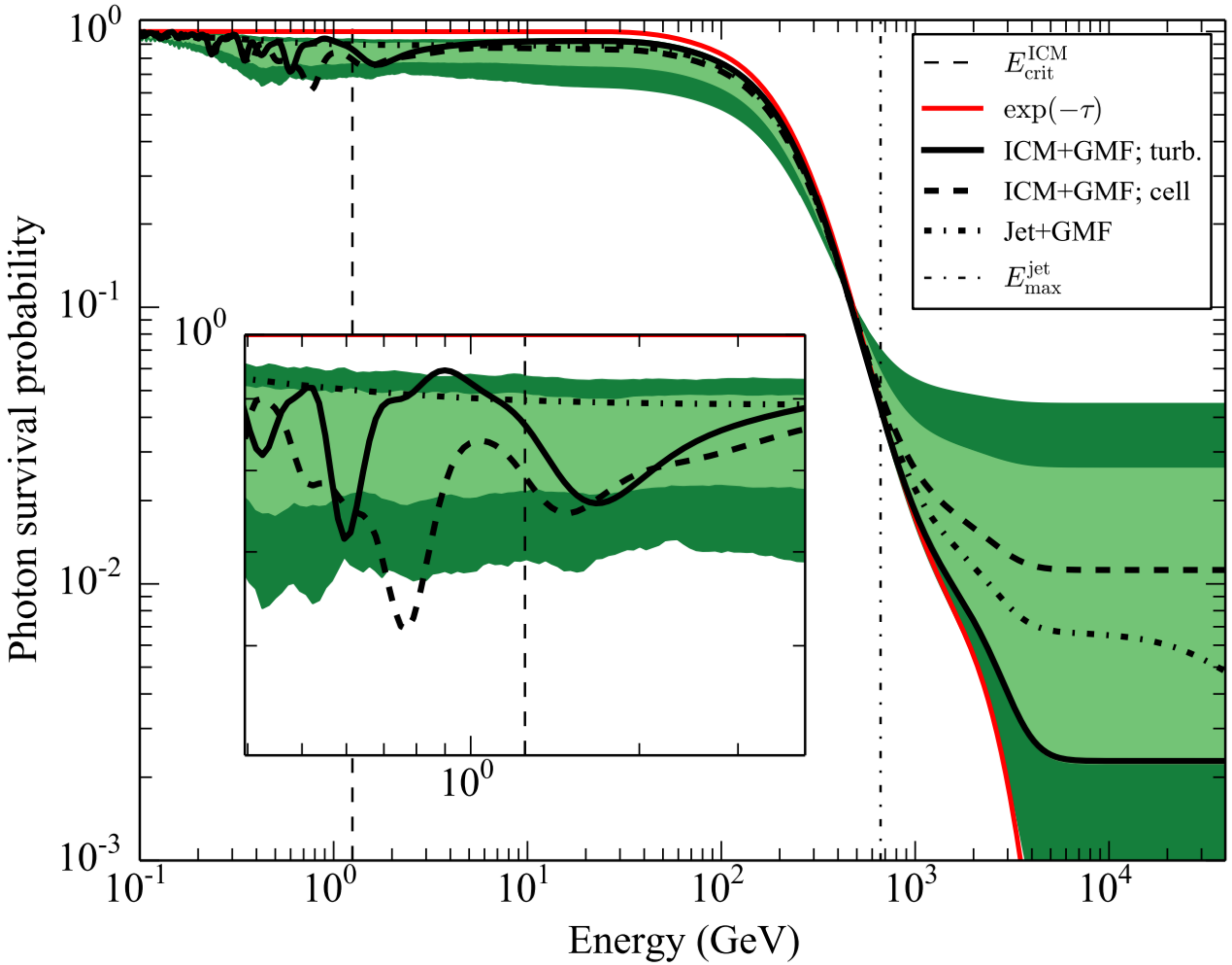
EBL ≡ Extragalactic Background light

$\tau$ ≡ optical depth

$$F_{\text{Earth}} = F_{\text{source}} \exp[-\tau(E, z)]$$

**Example: for a source at the redshift of 0.5 and at 0.5 TeV, attenuation ~2 orders of magnitude!**

# ALPs could modify spectrum of AGN!



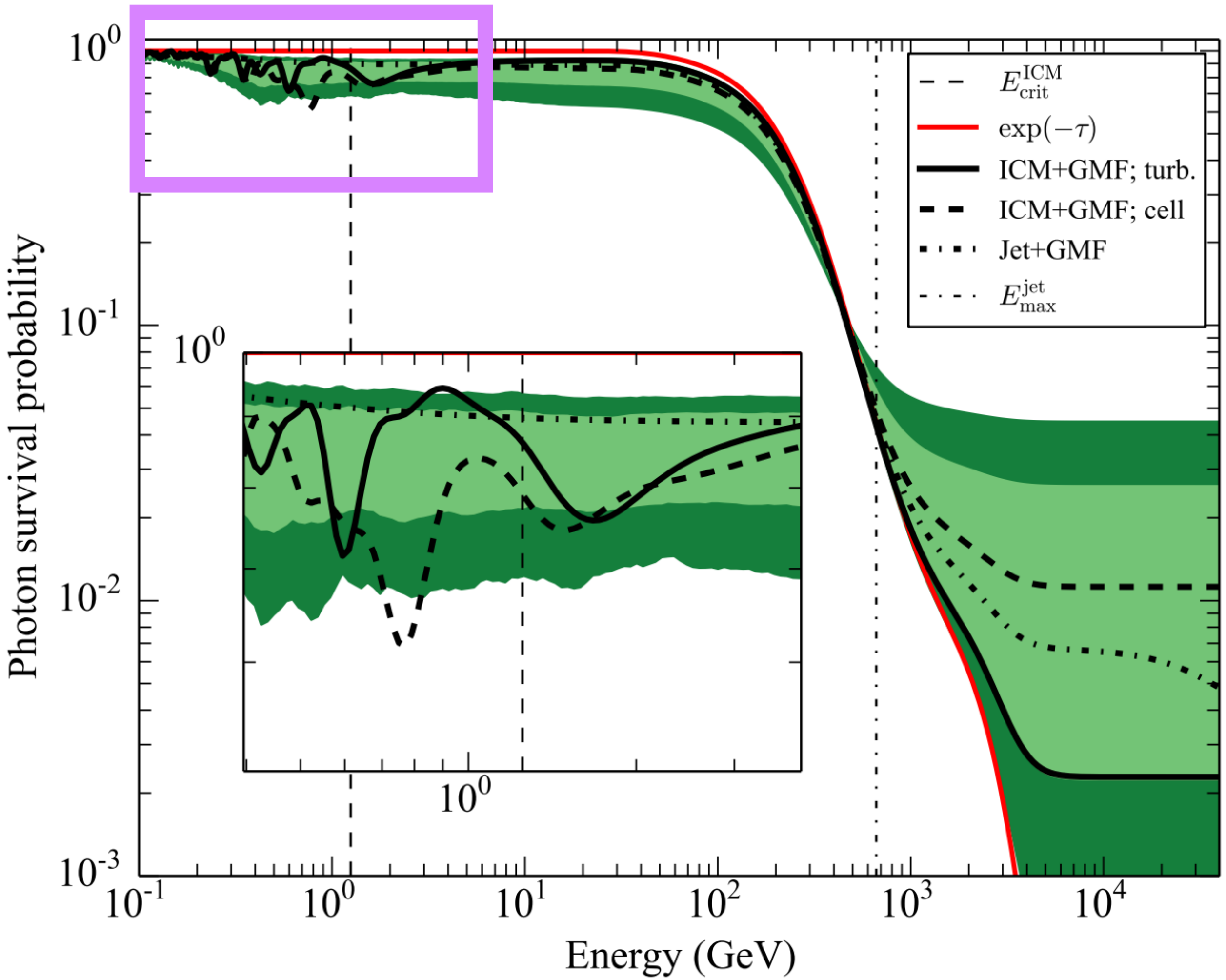

[Meyer et al. 2014]

**PG 1553+113**

z = 0.4, in a cluster, $g_{11}$= 2, M=$10^{-9}$ eV

# ALPs could modify spectrum of AGN!

irregularities

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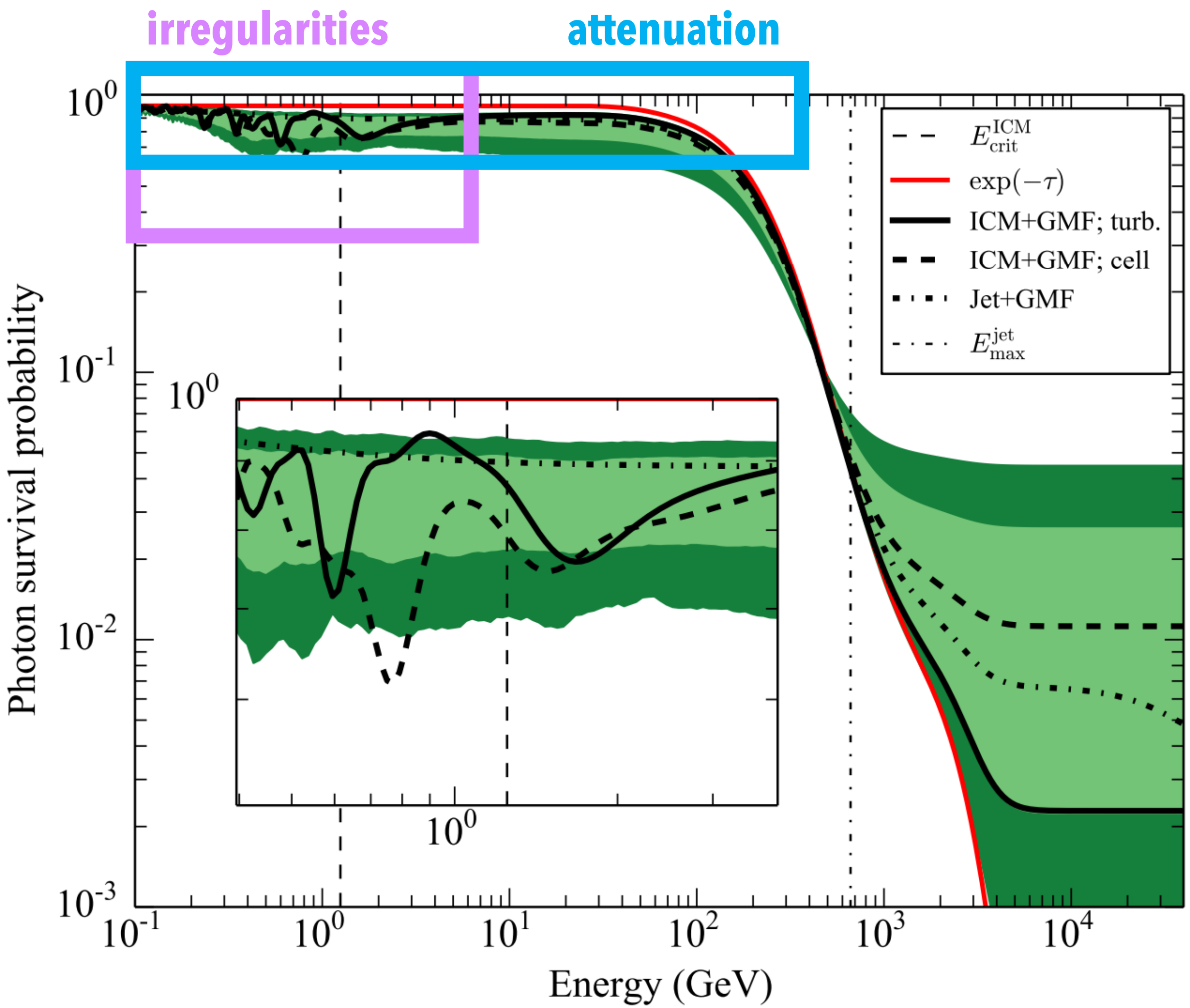


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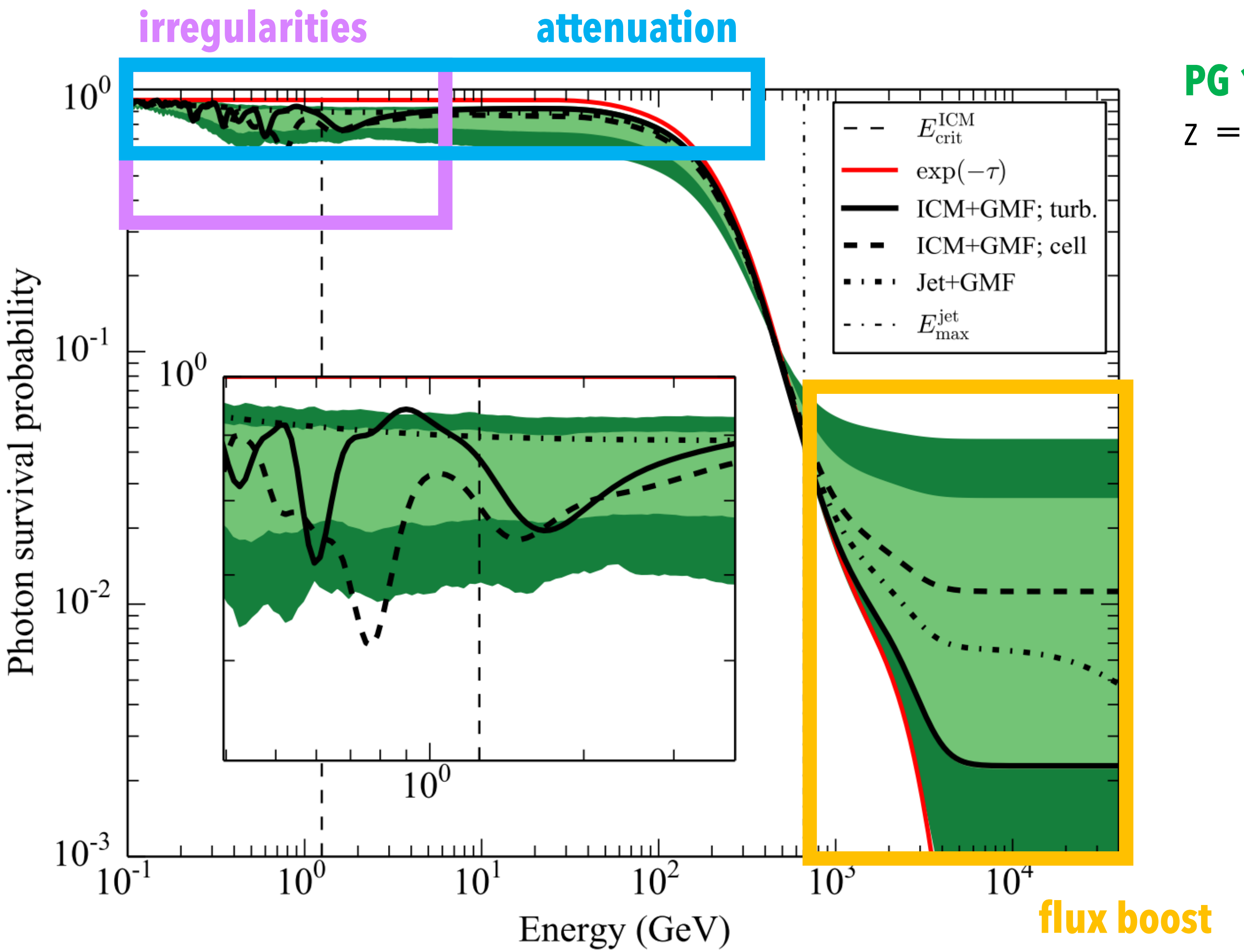


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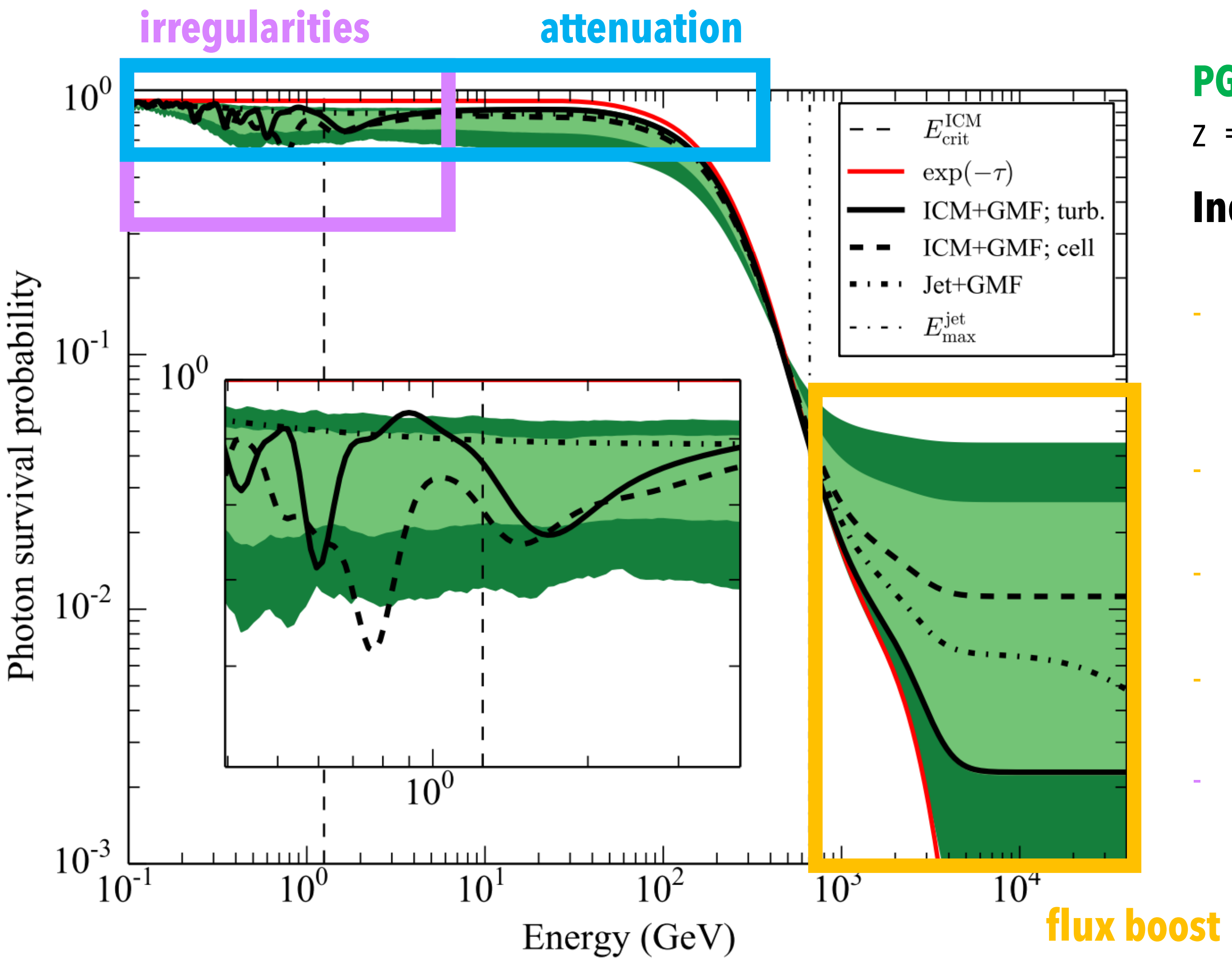



[Meyer et al. 2014]

**PG 1553+113**

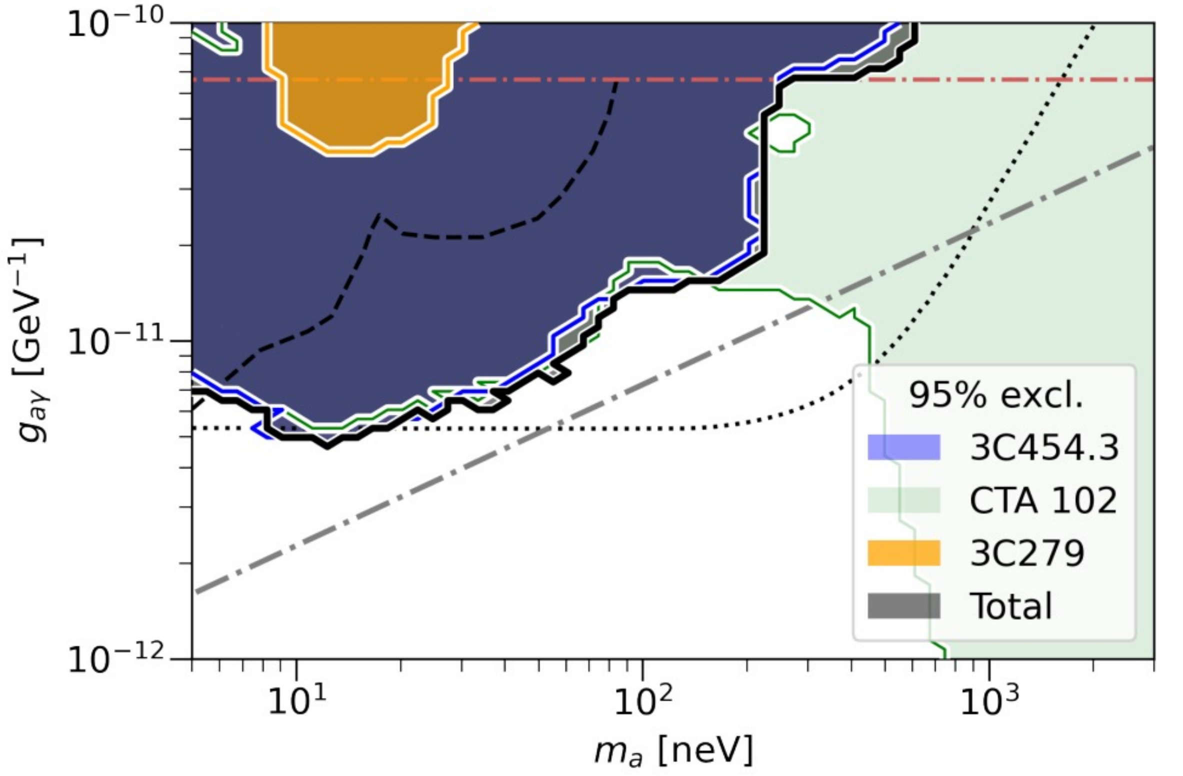
z = 0.4, in a cluster, $g_{11}$= 2, M=$10^{-9}$ eV

**Indeed, observed!**

- **Lower opacity of the Universe to gamma rays** (e.g., Aharonian et al. 2006, Albert et al. 2008, Acciari et al. 2011, DeAngelis et al. 2009, 11, 13)
- **Spectral hardening of AGNs** (e.g., Albert et al. 2008, Wagner et al. 2010, Aleksić et al. 2011, Furniss et al. 2013)
- **Intrinsic spectrum deviates from a power law (pile-up problem)** (e.g., Dominguez et al. 2012, Furniss et al. 2013)
- **Fast, intense flares in FSRQs ($\gamma\gamma$ absorption problem)** (e.g., Tavecchio et al. 2012)
- **GeV spectral breaks and dips** (e.g., Tanaka et al. 2013, Rubtsov & Troitsky 2014, Mena & Razzaque 2013)

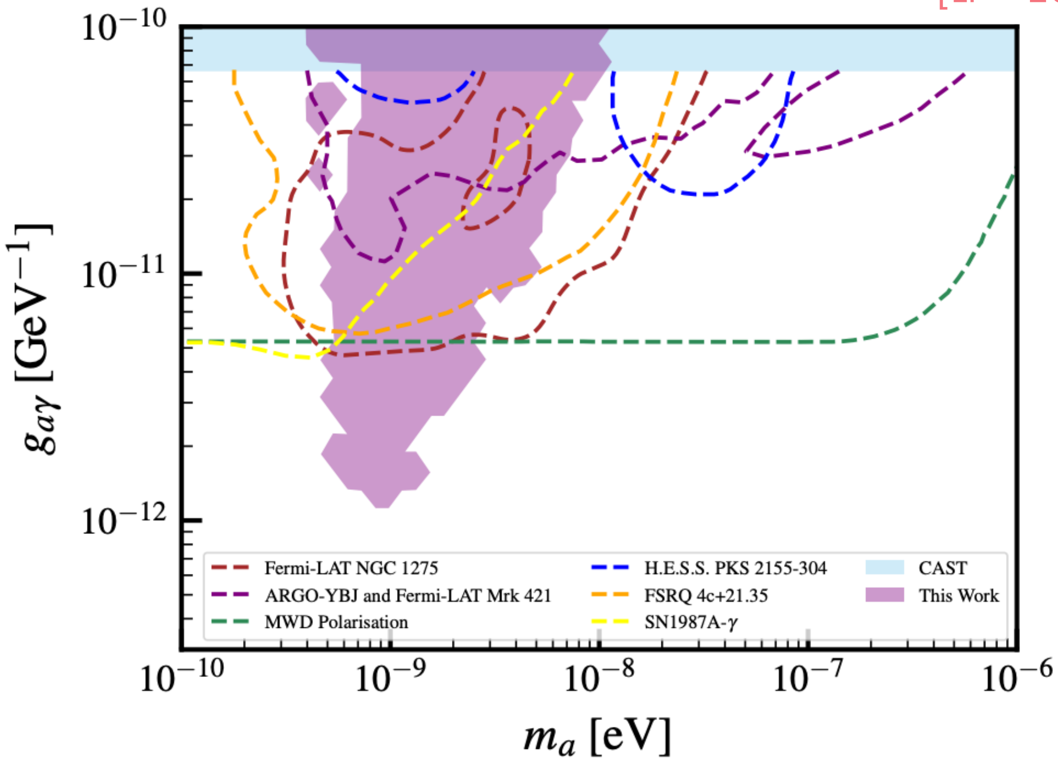
Flaring blazars

[Davies+ '22]




FSRQ Ton 599

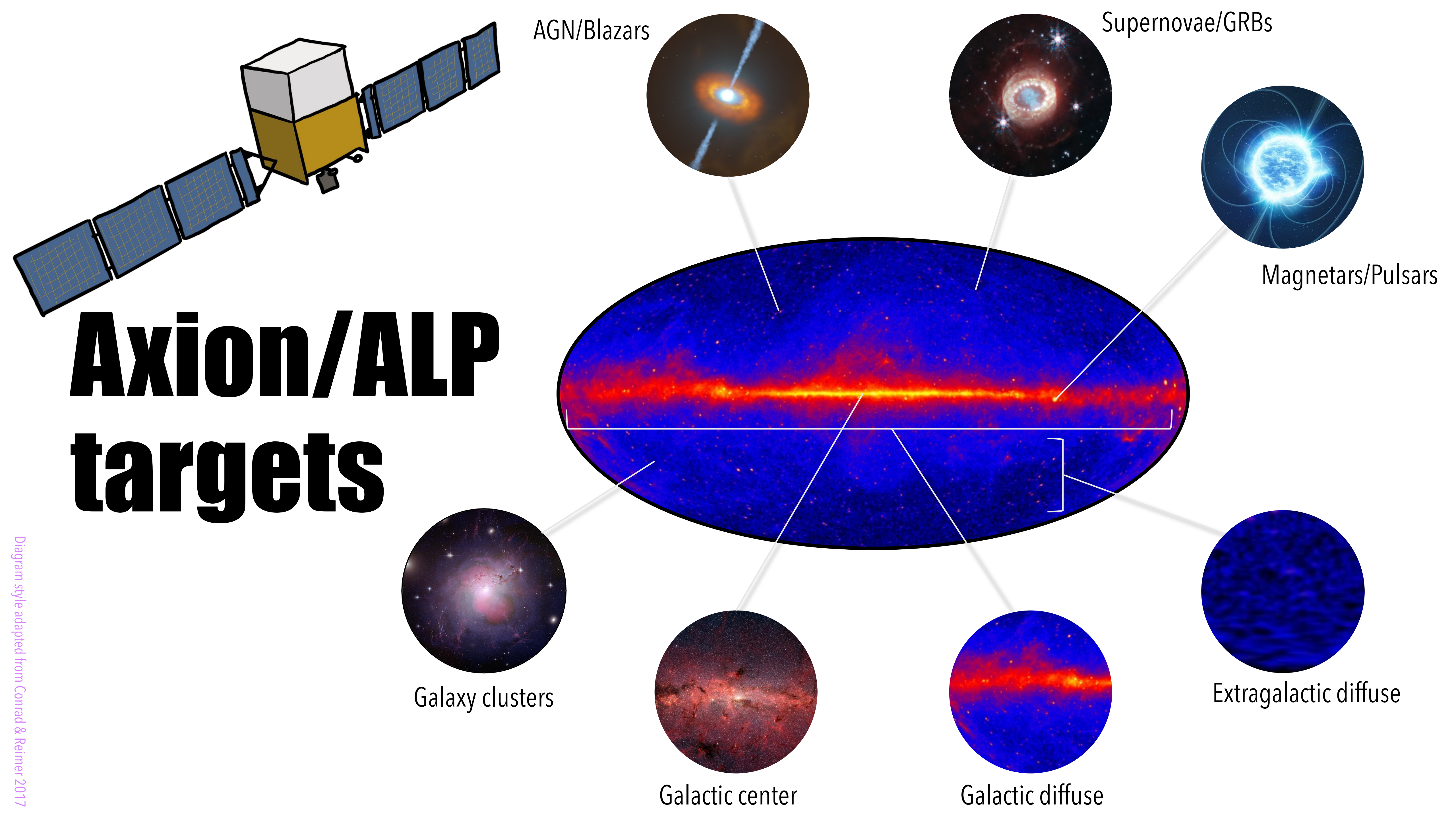
[Li+ '25]




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

**Legend** green dashed: WD radio polarization
red dashed: spectral irregularities NGC 1275
yellow dashed: SN1987A

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



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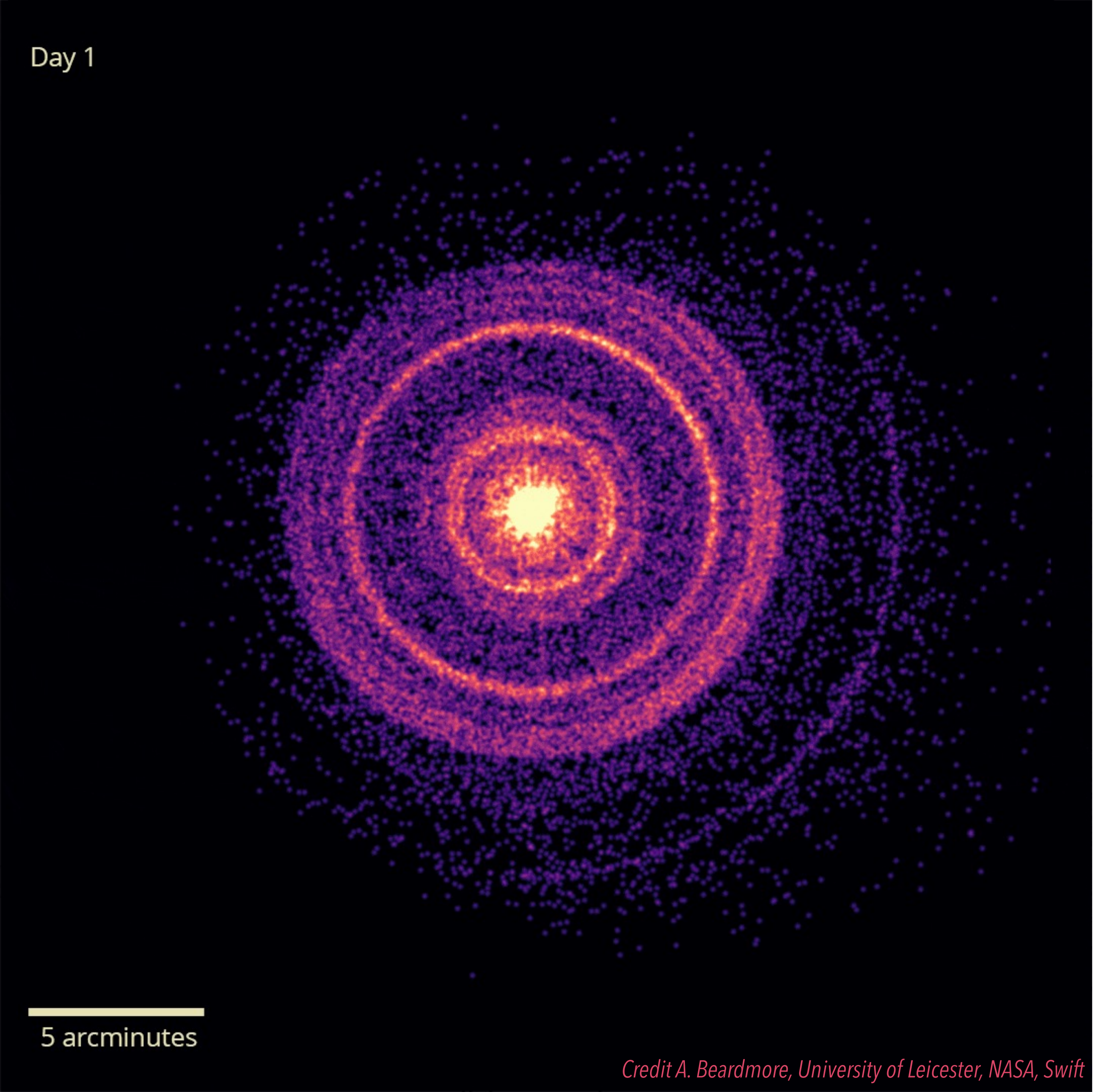
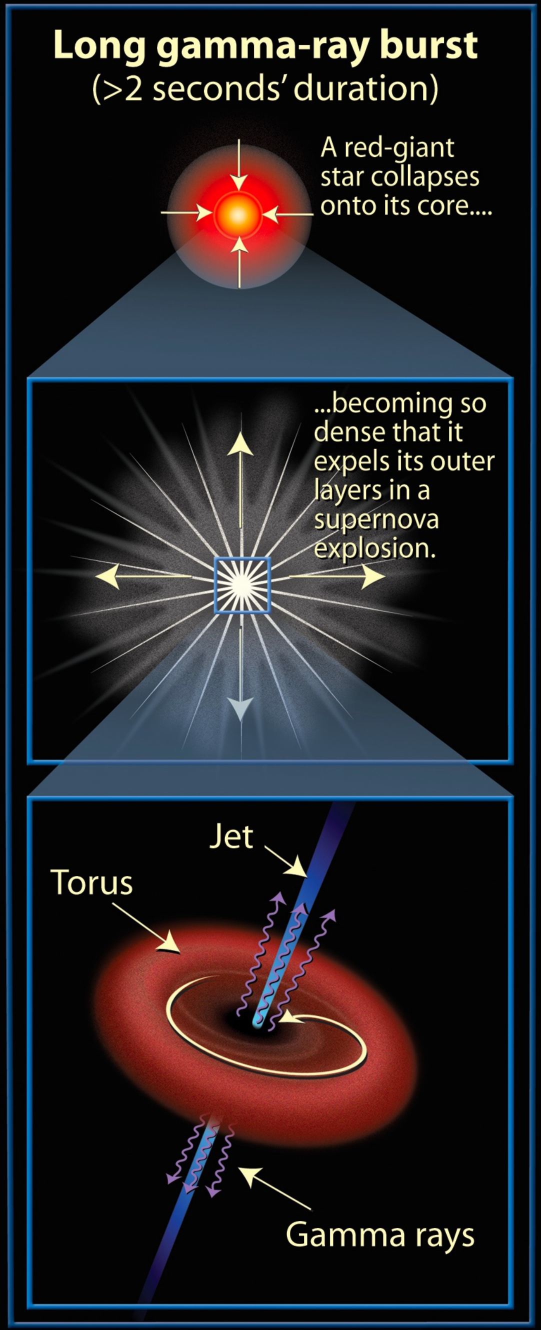
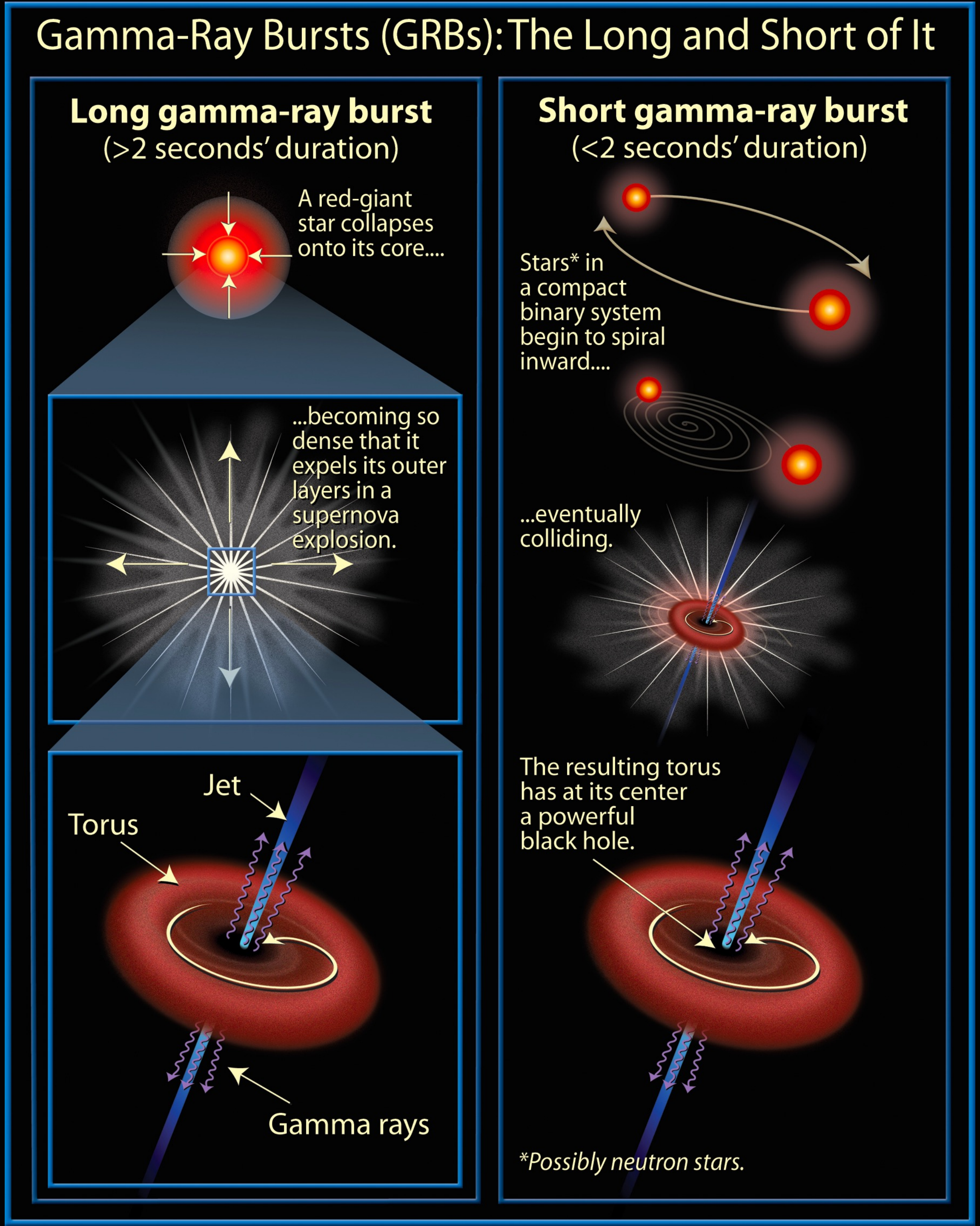


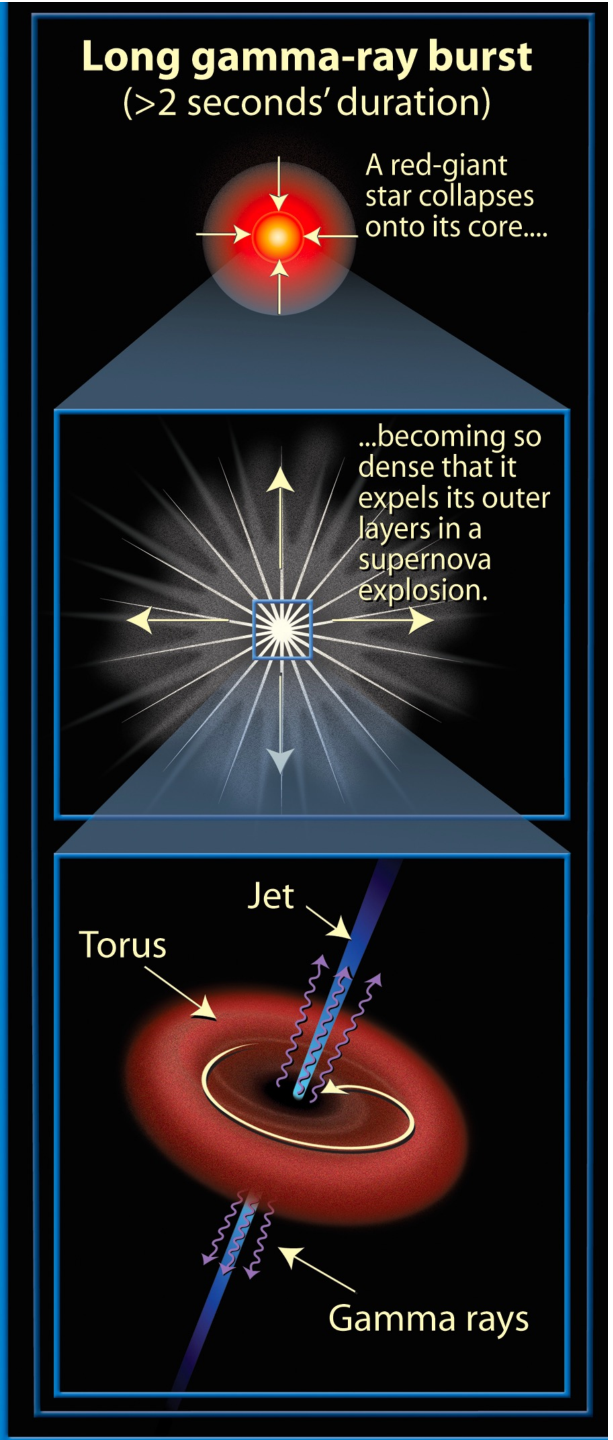

# Target 2: Gamma-ray Bursts

# Gamma-Ray Bursts (GRBs): The Long and Short of It





Gamma-Ray Bursts (GRBs): The Long and Short of It
Long gamma-ray burst
(>2 seconds' duration)
A red-giant star collapses onto its core....
...becoming so dense that it expels its outer layers in a supernova explosion.
Jet
Torus
Gamma rays
Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward....
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.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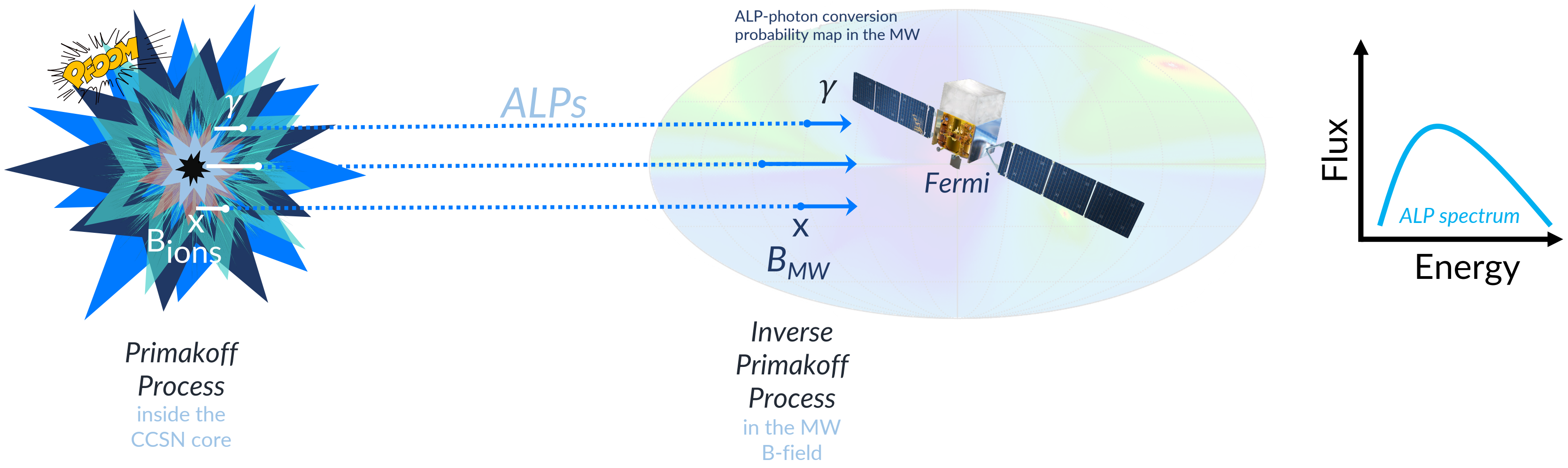
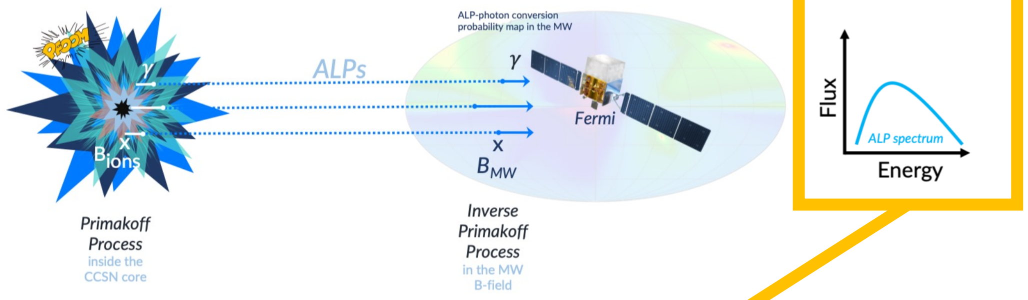
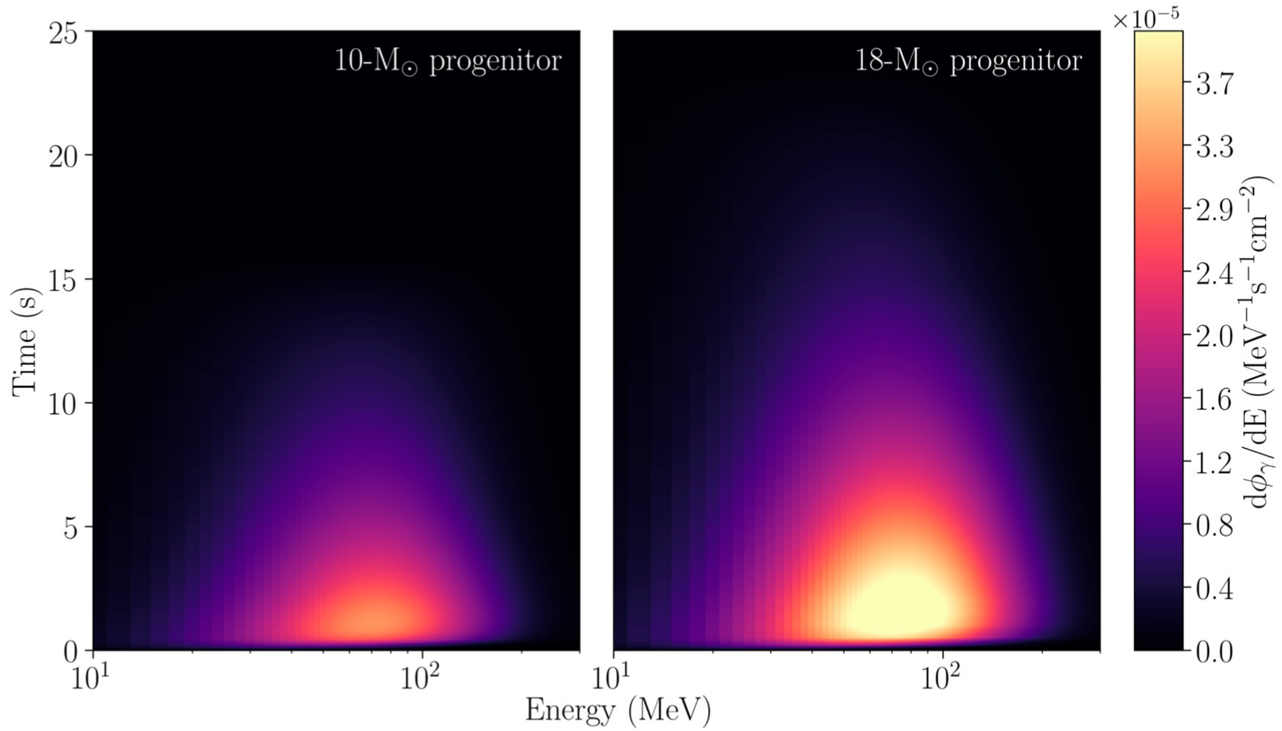
A red-giant star collapses onto its core....
...becoming so dense that it expels its outer layers in a supernova explosion.
Jet
Torus
Gamma rays

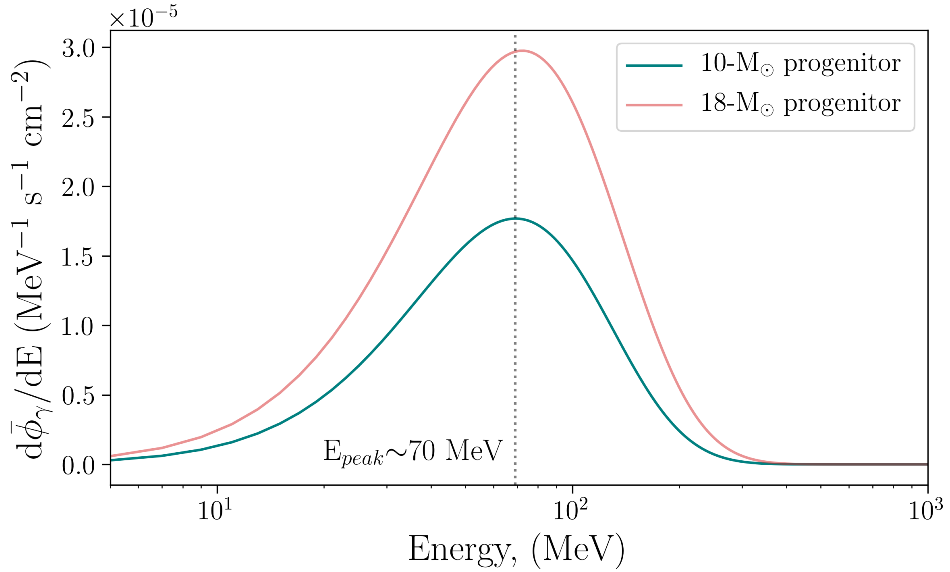

γ
x
B
ions
ALPs
ALP-photon conversion probability map in the MW
γ
Fermi
x
B MW
Primakoff Process
inside the CCSN core
Inverse Primakoff Process
in the MW B-field
Flux
ALP spectrum
Energy




**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.




The observed evolution of the ALP-induced gamma-ray emission in time and energy in a core-collapse of a 10 and 18-$M_\odot$ progenitor.



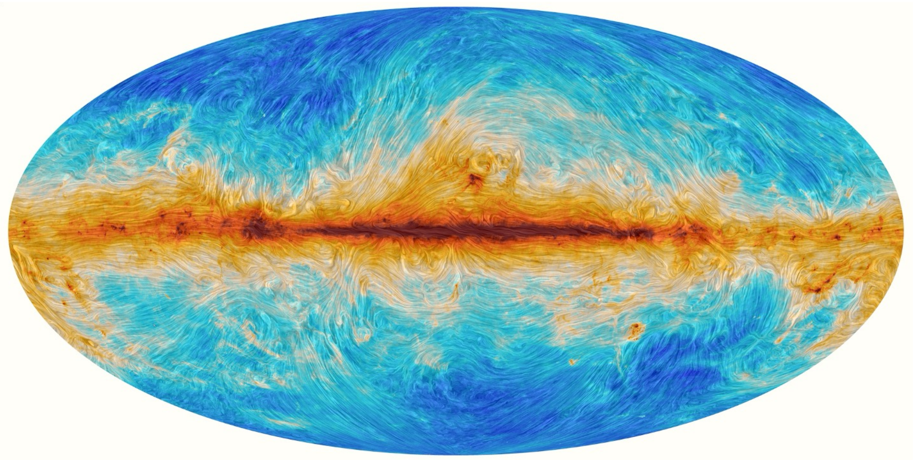

The observed ALP-induced gamma-ray spectrum for 10 and 18-$M_\odot$ progenitors averaged over 10 seconds.

# Milky Way magnetic field

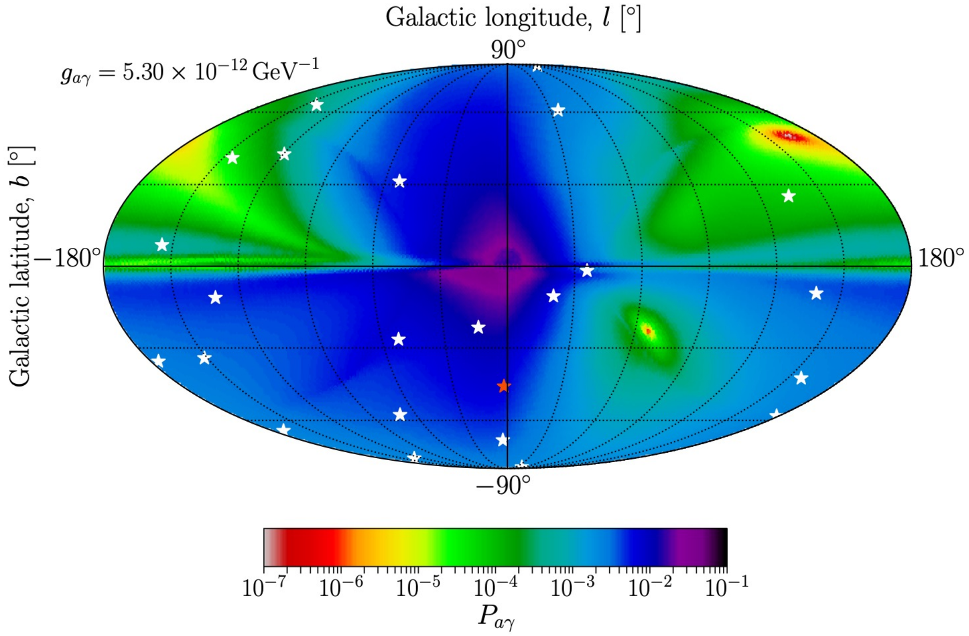
- Monochromatic photon-ALP beam propagating in a cold plasma in a homogeneous B field

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

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



→

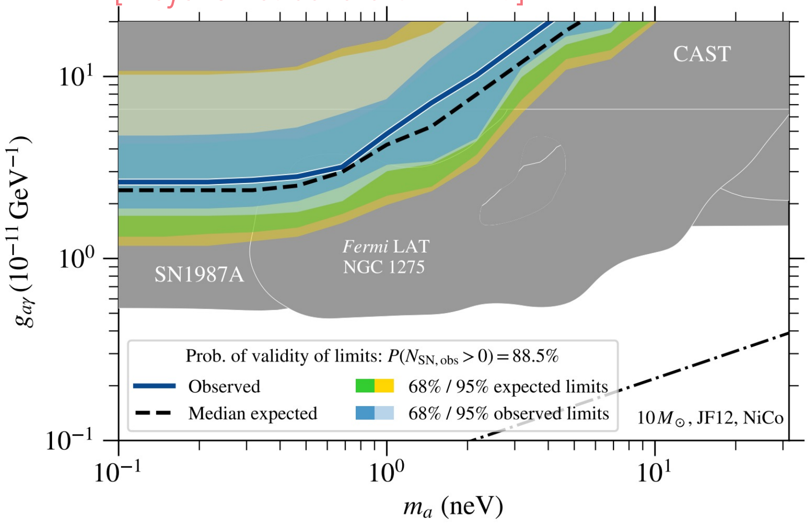


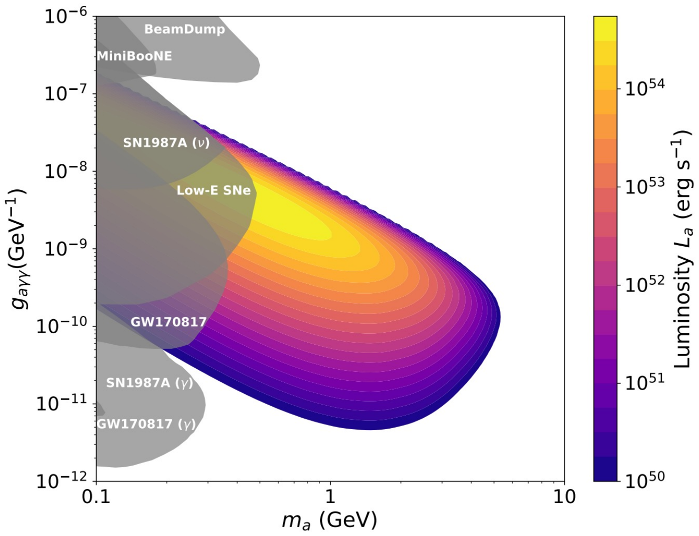
# CCSNe: Individual Sources

- 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!

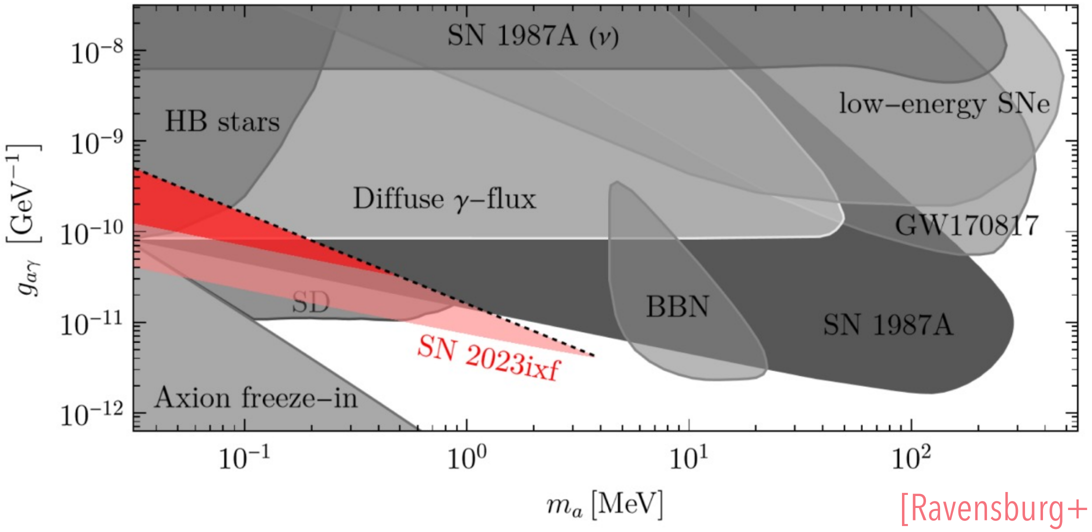
*[Meyer+ PRL '17, Meyer & Petrushevska PRL '20, Crnogorčević+ PRD '21, Müller+ PRD '23, Ravensburg+ PRD '24, Calore+ PRD '24, Ghosh + 2025, and more]*

[Meyer & Petrushevska PRL '20]




[Ghosh et al. 2025]

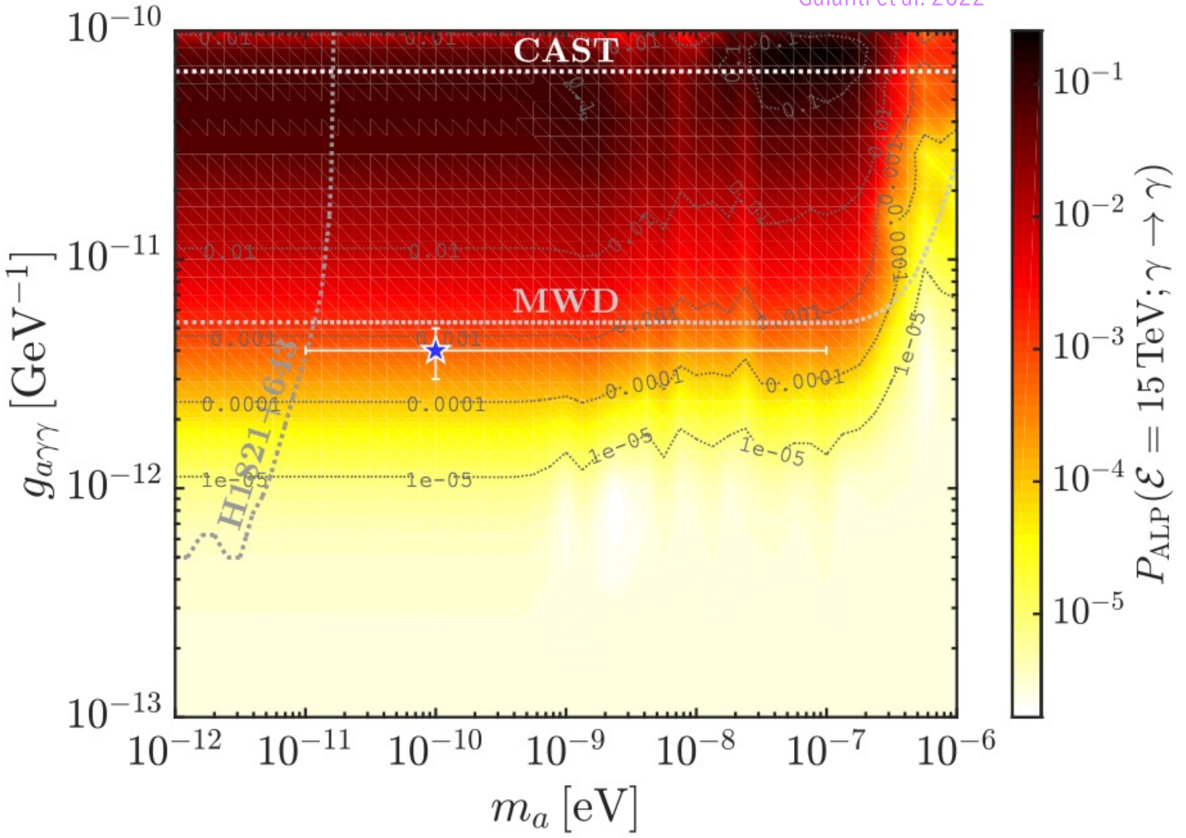



[Ravensburg+ PRD '24]

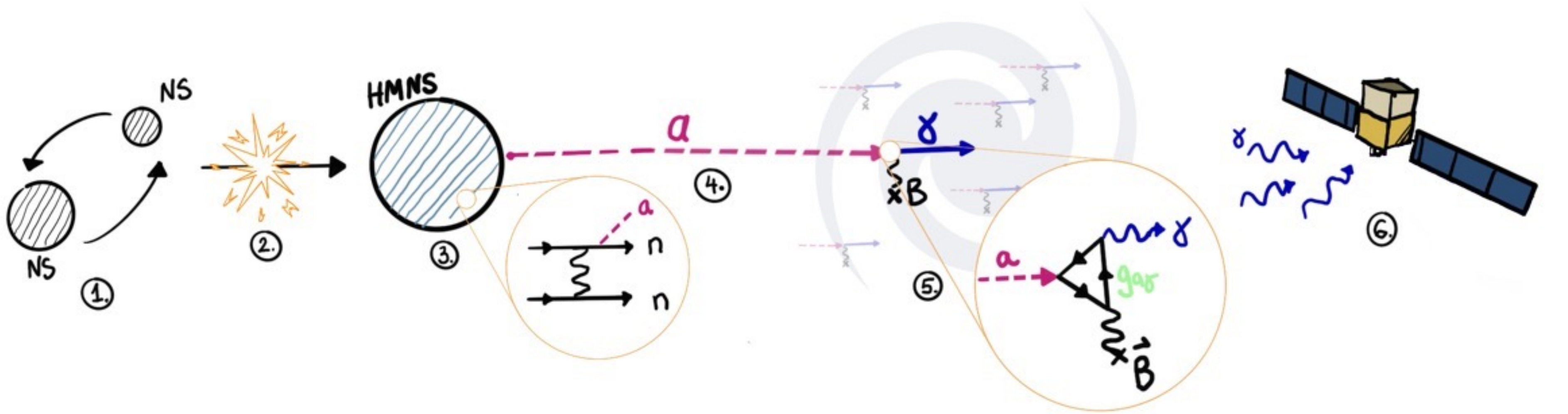
# GRB 221009A

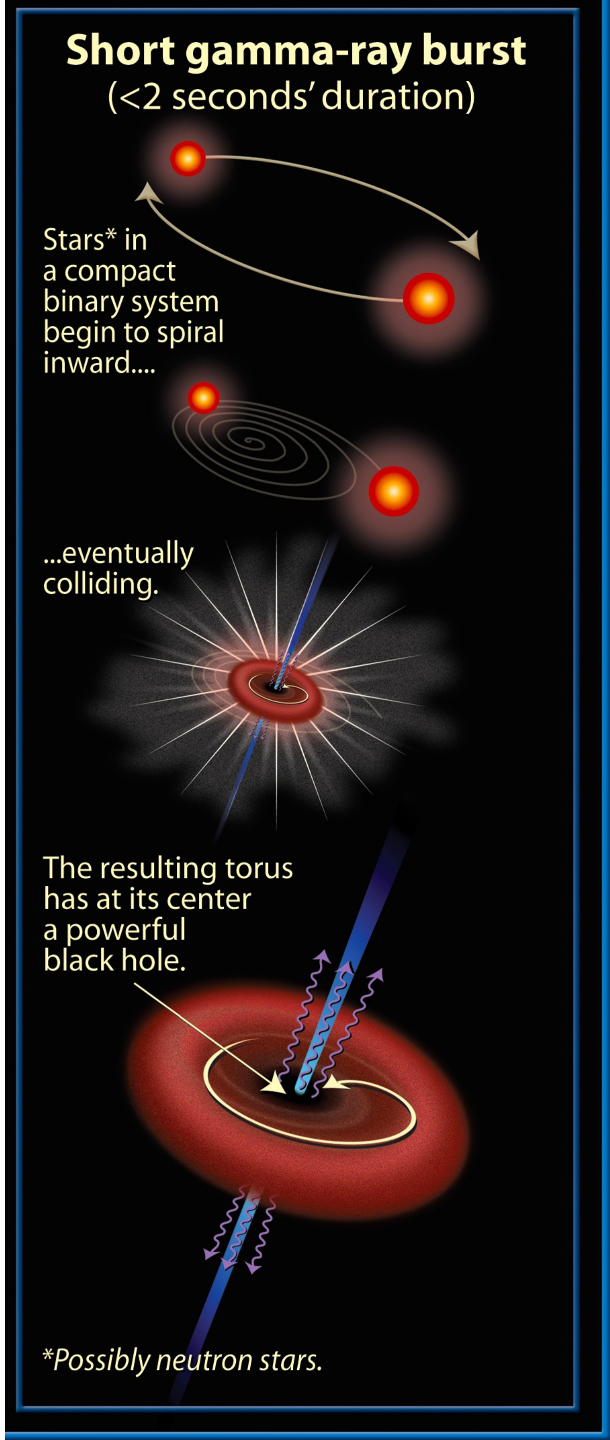
- Brightest GRB ever observed across all wavelengths (BOAT)
- Distance: z = 0.151
- Multiple peaks in light curve, duration > 1000 seconds
- LHASSO detection of photons up to 18 TeV – highest energy ever from a GRB
- These photons shouldn't be observed at these distances (~$10^{-4}$ survival probability)
- Photon → ALP → Photon oscillations!

Galanti et al. 2022

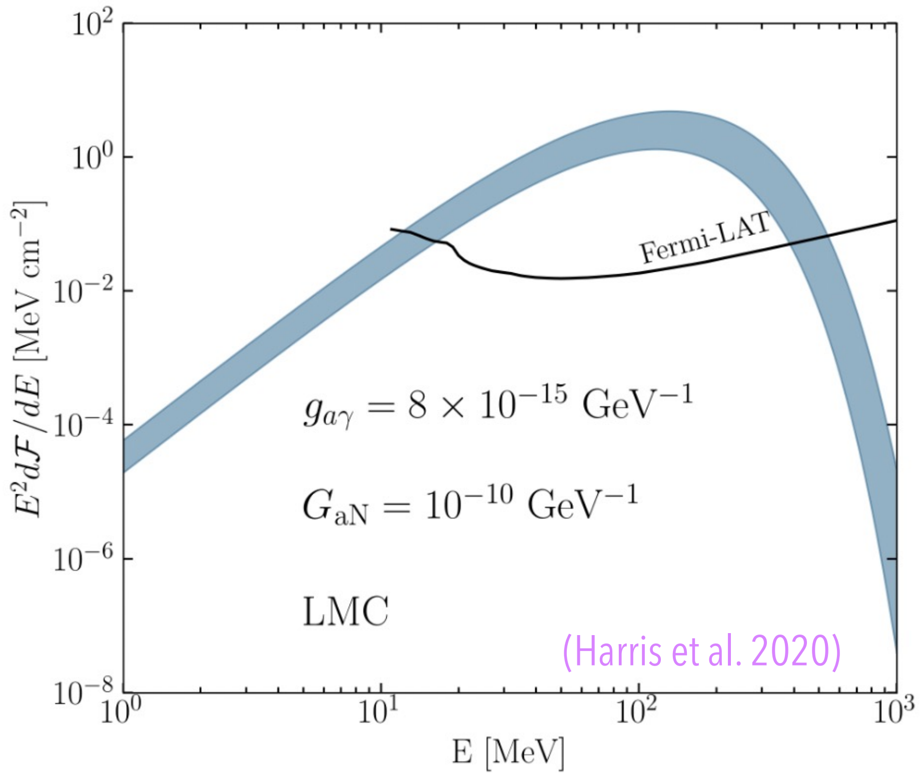



[Gonzalez et al. 2022, Baktash et al. 2022, Gao et al. 2023, Rojas et al. 2025, etc.]

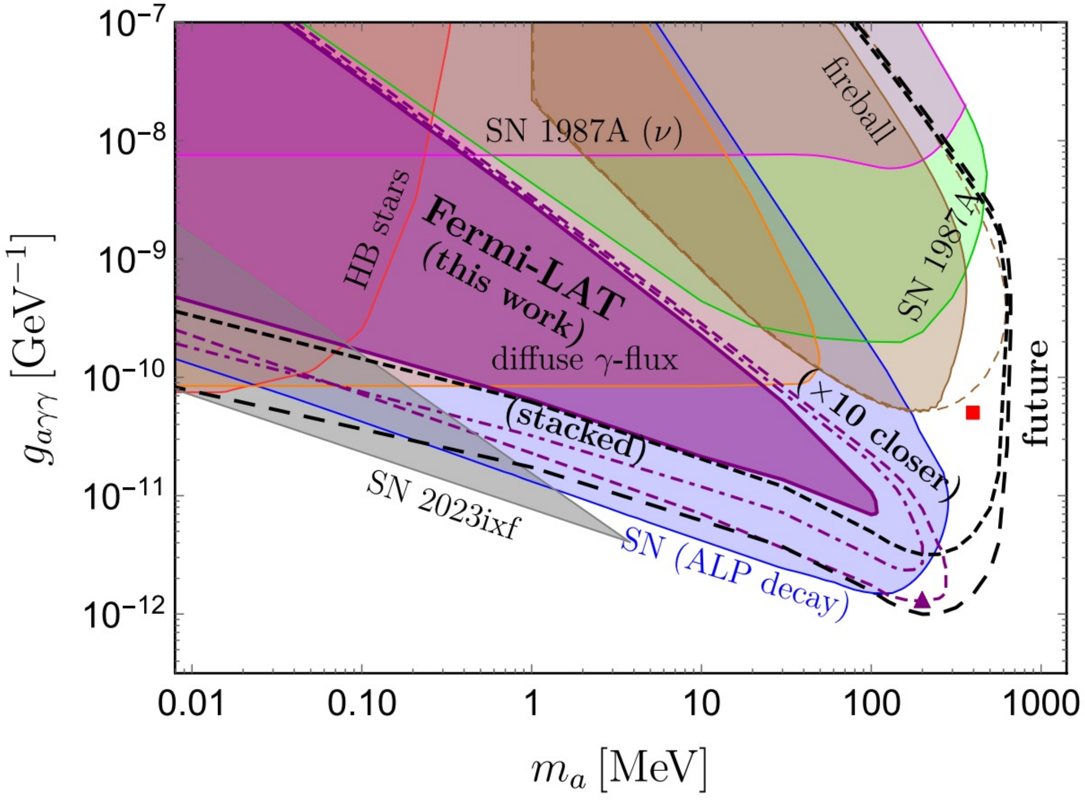

NS
NS
1.
2.
HMNS
3.
a
a
n
n
4.
γ
B
a
$g_{a\gamma}$
γ
$\vec{B}$
5.
γ
6.


Short gamma-ray burst
(<2 seconds' duration)
Stars* in a compact binary system begin to spiral inward....
...eventually colliding.
The resulting torus has at its center a powerful black hole.
*Possibly neutron stars.

# GW170817




(Harris et al. 2020)




(Dev et al. 2024, also Dekker et al 2025)

- Depends on NS temperature profile
- Duration of the "supermassive" NS phase
- MW magnetic fields

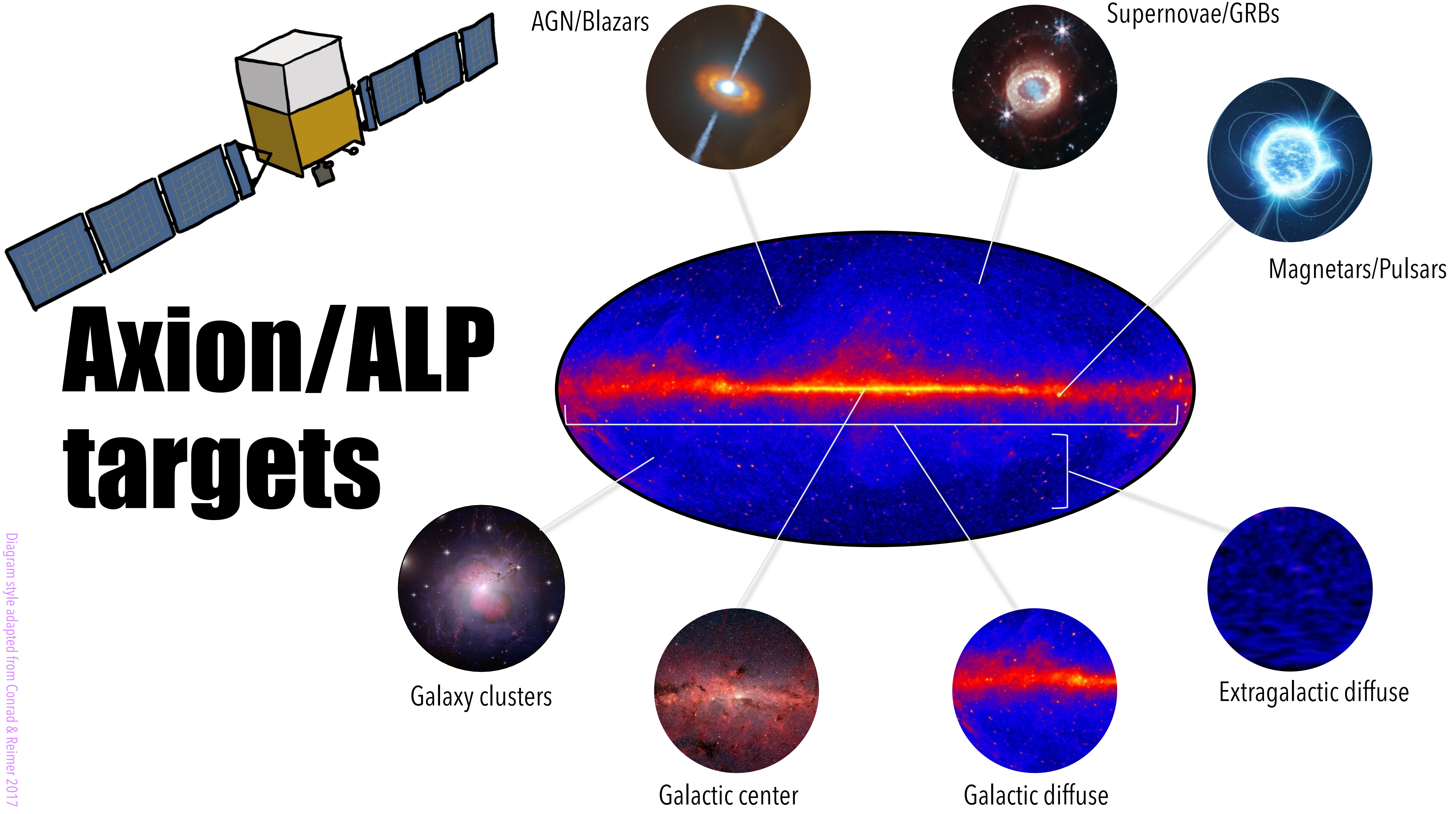
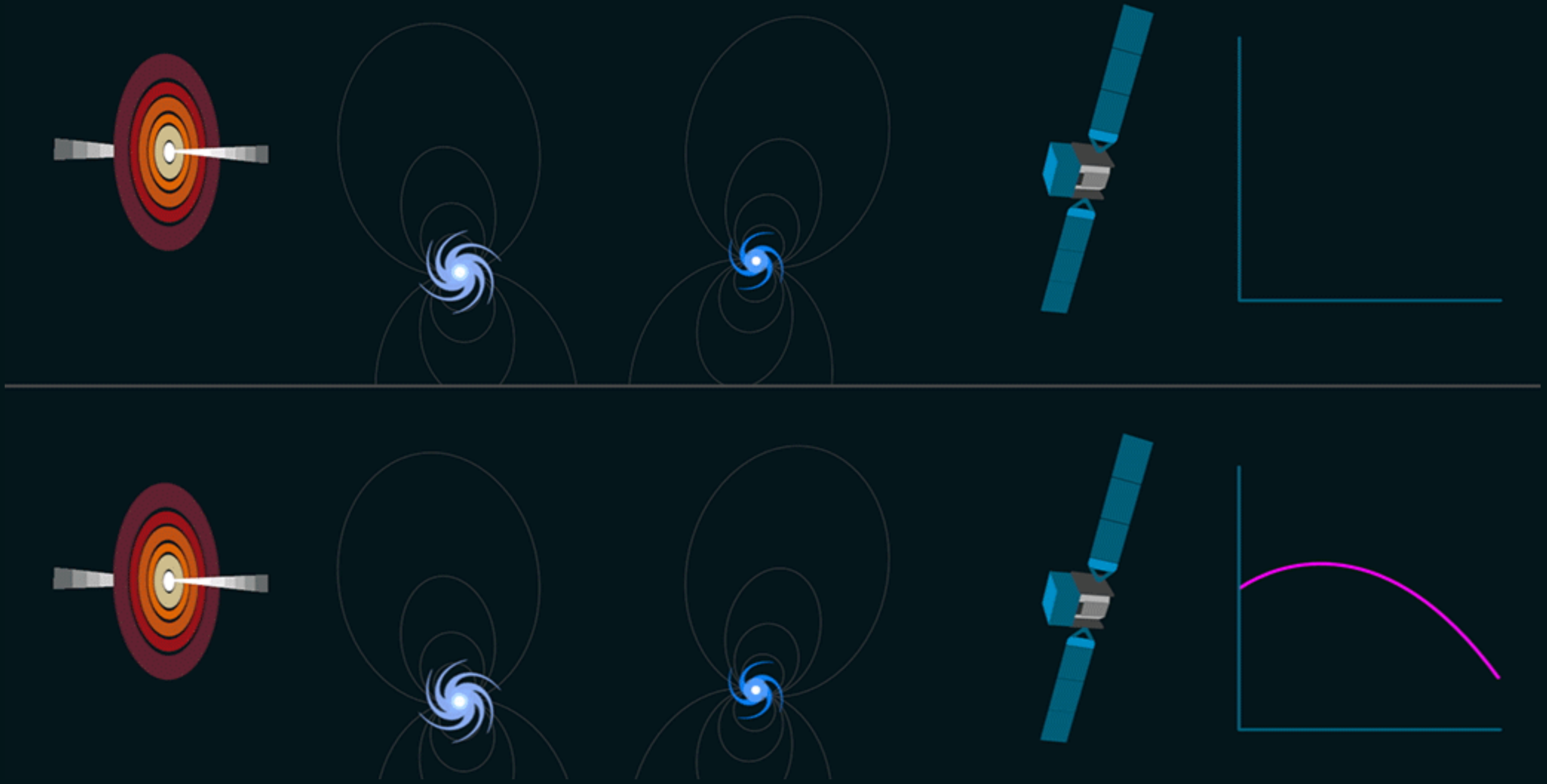


Diagram style adapted from Conrad & Reimer 2017

# Target 3: Galaxy Clusters



Credit: (SLAC National Accelerator Laboratory). (T. Wistisen/Aarhus University)

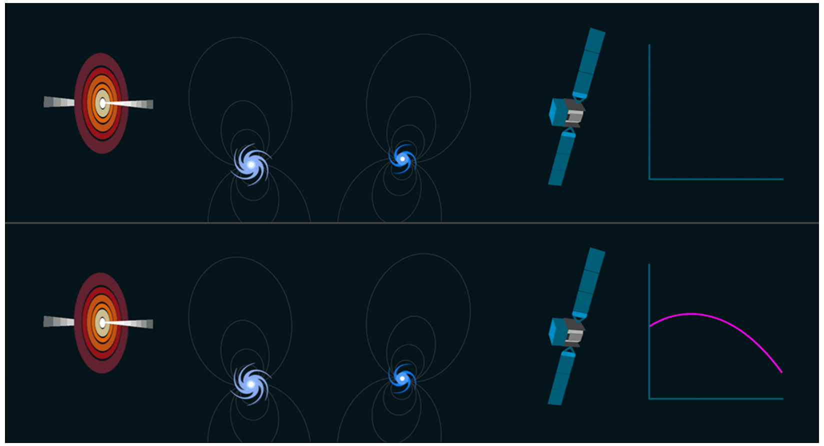
# Galaxy clusters

- 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.]

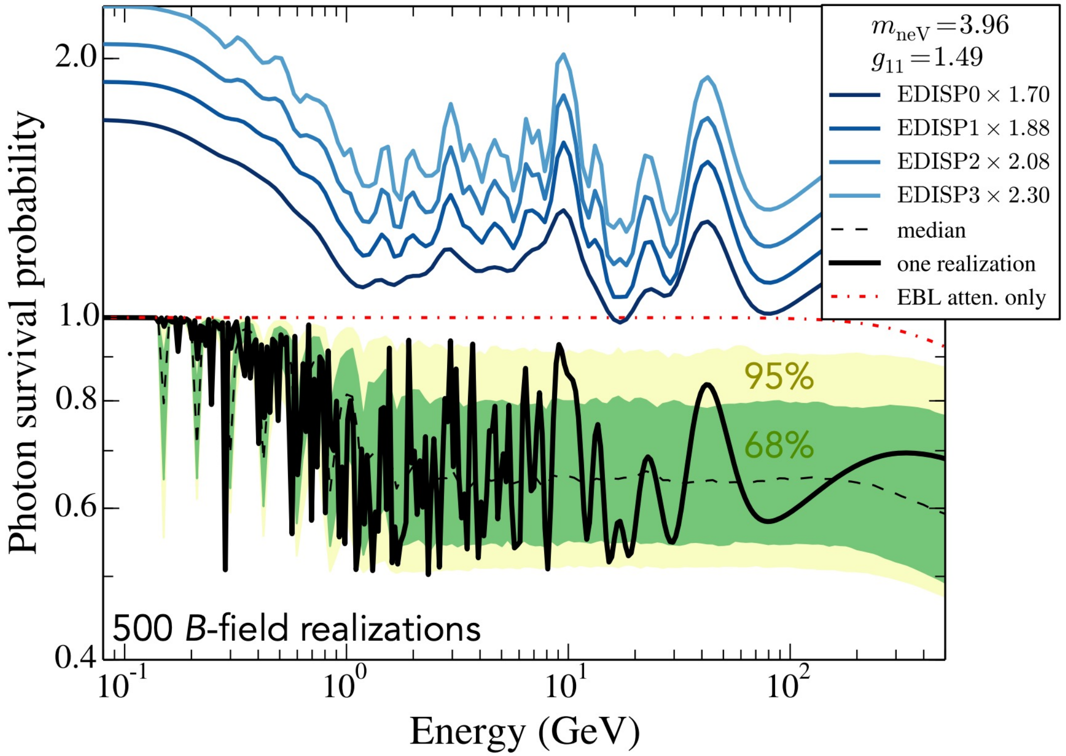
[Credit: Marie-Lou Gendron-Marsolais & Hlavacek-Larrond]

# Extended Gamma-ray Sources



[Credit: SLAC/Chris Smith]

NGC 1275 [credit: Manuel Meyer]



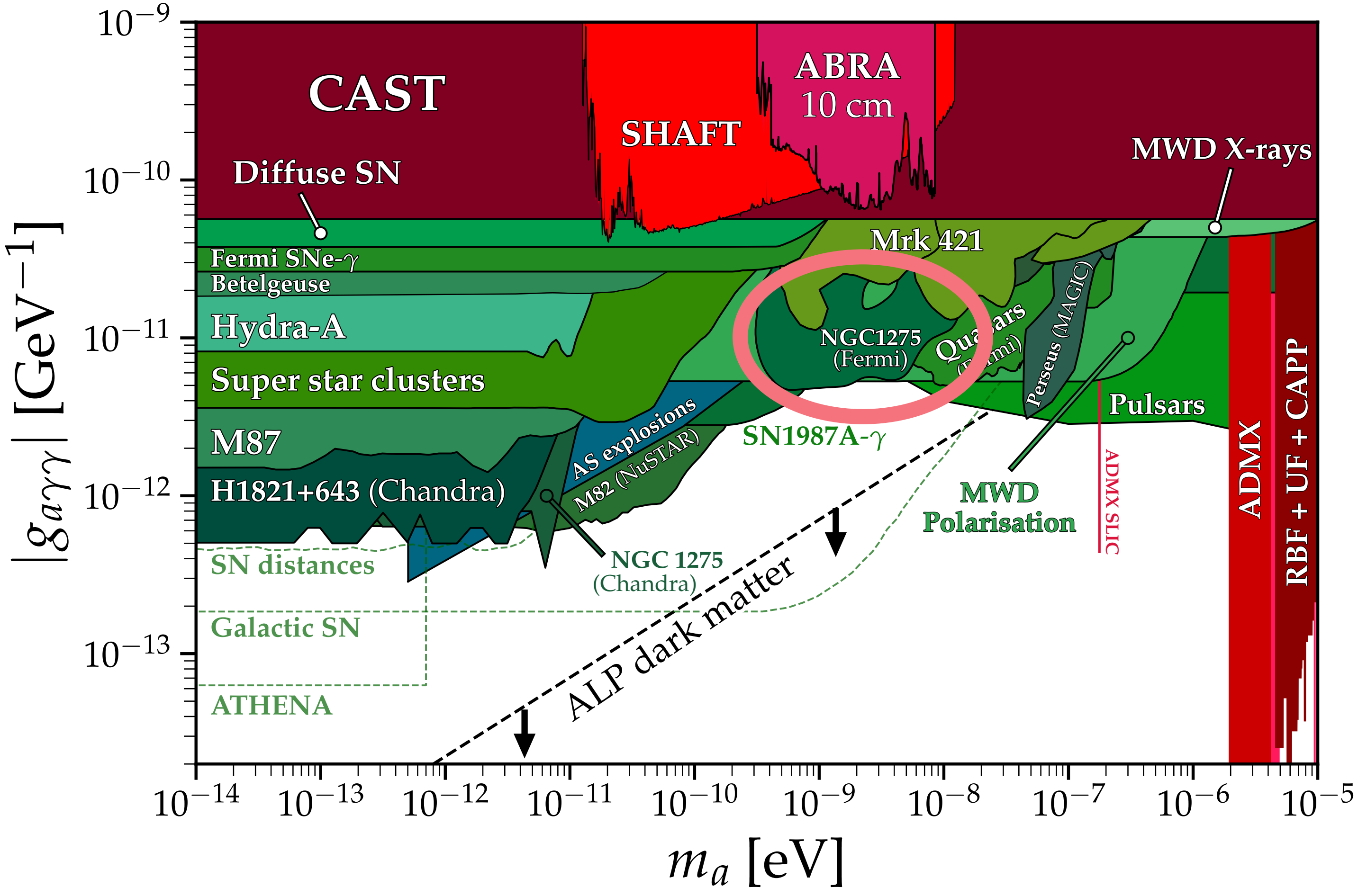

1. *In situ* production of photons via leptonic or hadronic processes
2. Conversion into ALPs/axions in the interstellar medium, intergalactic radiation fields, Milky way
3. Searches for deviation from the original astrophysical spectrum in the gamma-ray data

[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,* ]

# NGC 1275: spectral irregularities

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

[Ajello+ '16]



# NGC 1275: spectral irregularities

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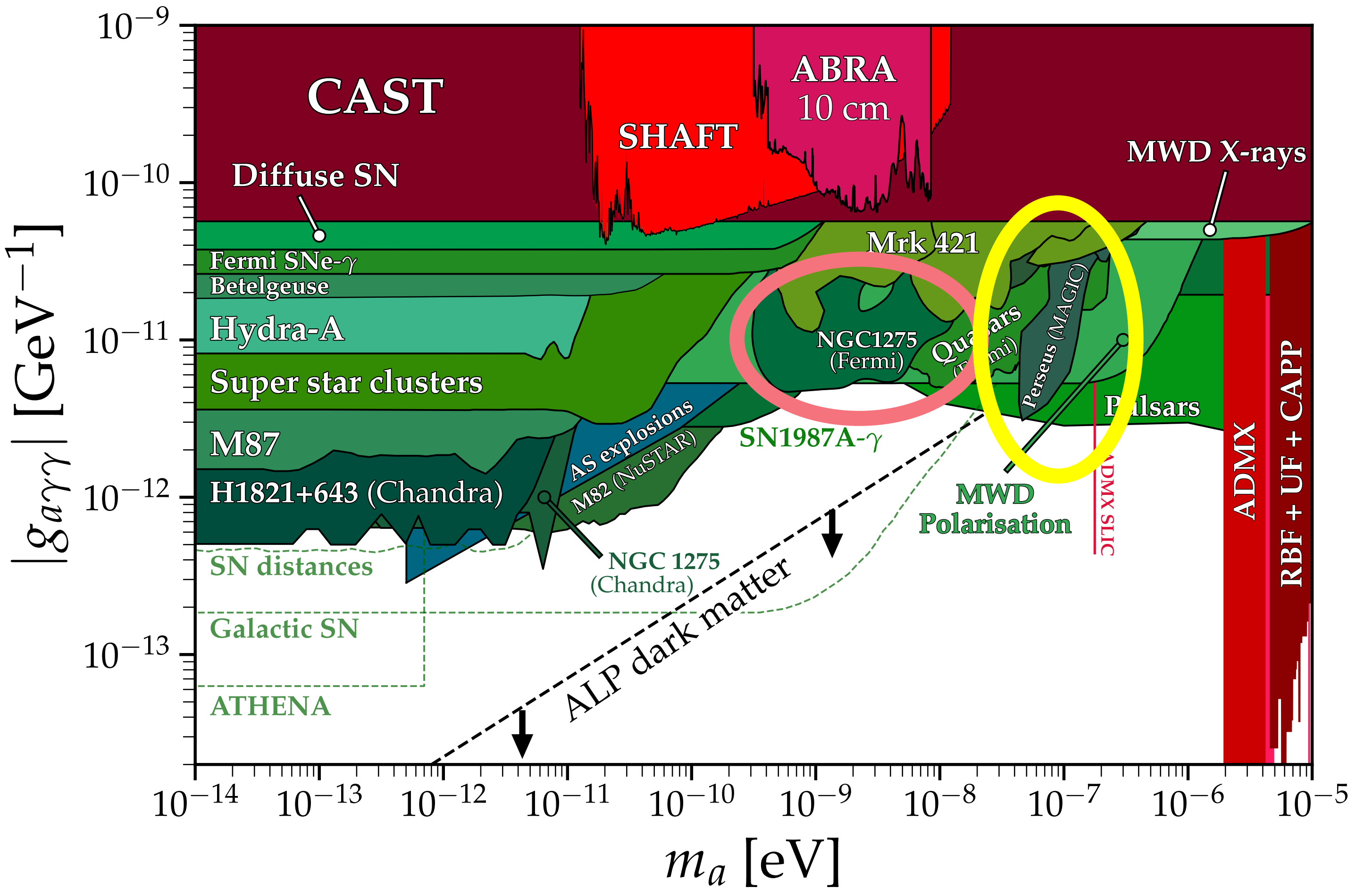
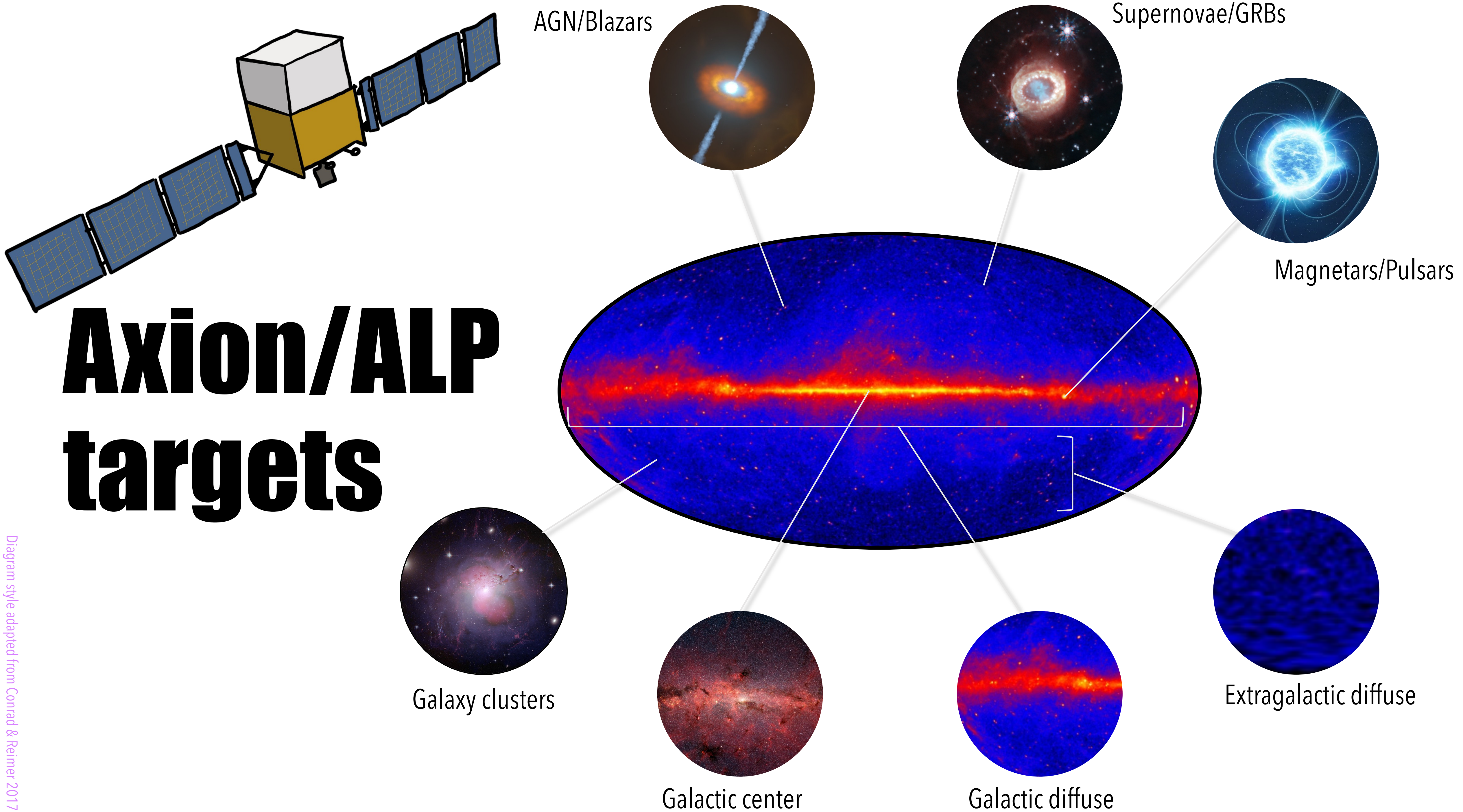
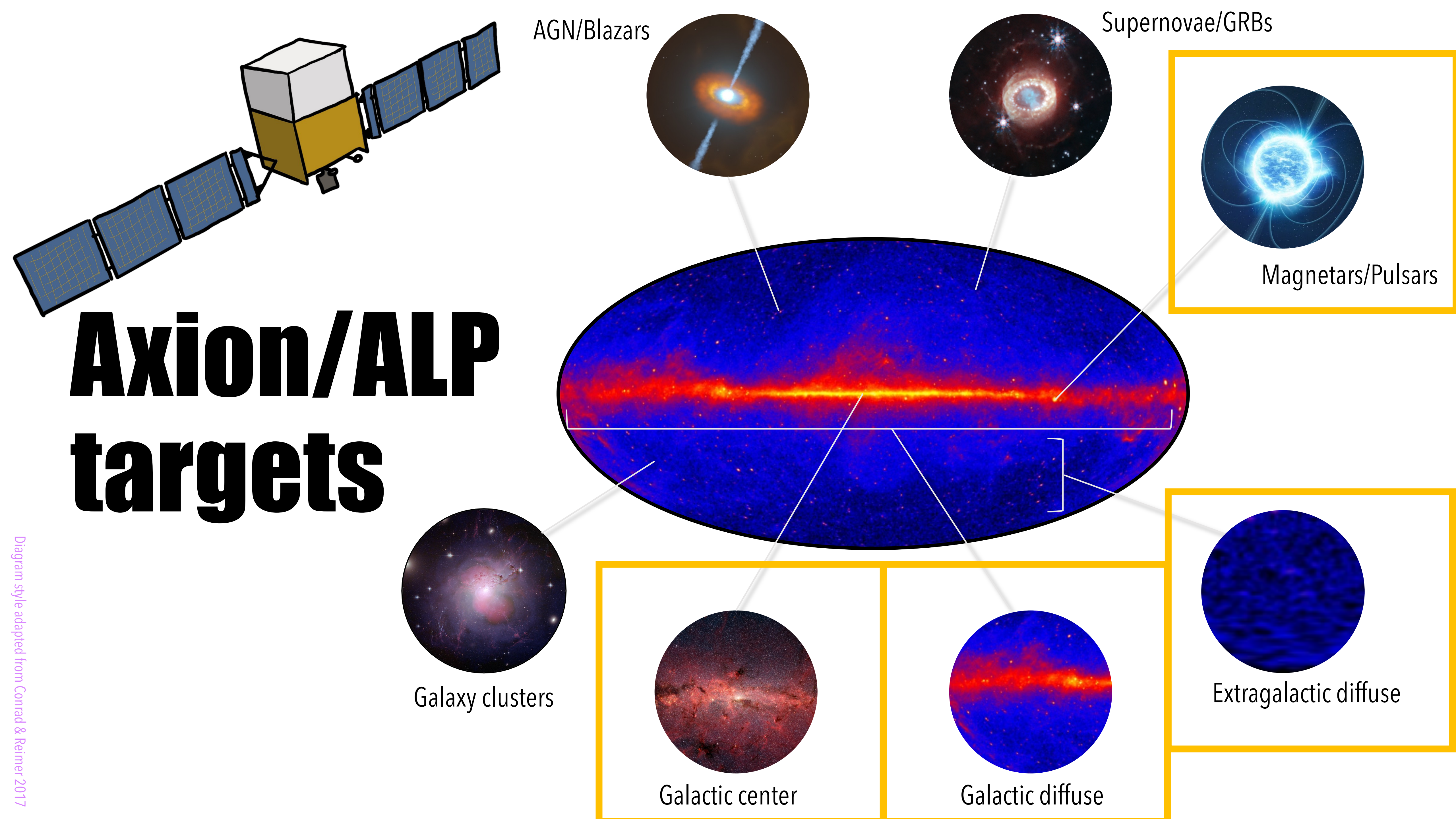
- See [Cheng+ '21, etc] for additional B field considerations

[Ajello+ '16]

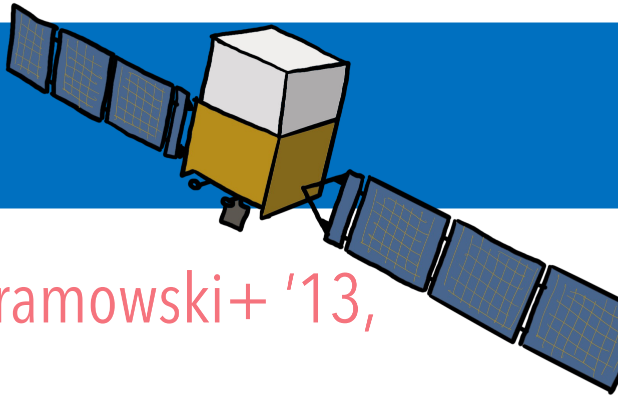



Axion/ALP targets
AGN/Blazars
Supernovae/GRBs
Magnetars/Pulsars
Galaxy clusters
Galactic center
Galactic diffuse
Extragalactic diffuse
Diagram style adapted from Conrad & Reimer 2017

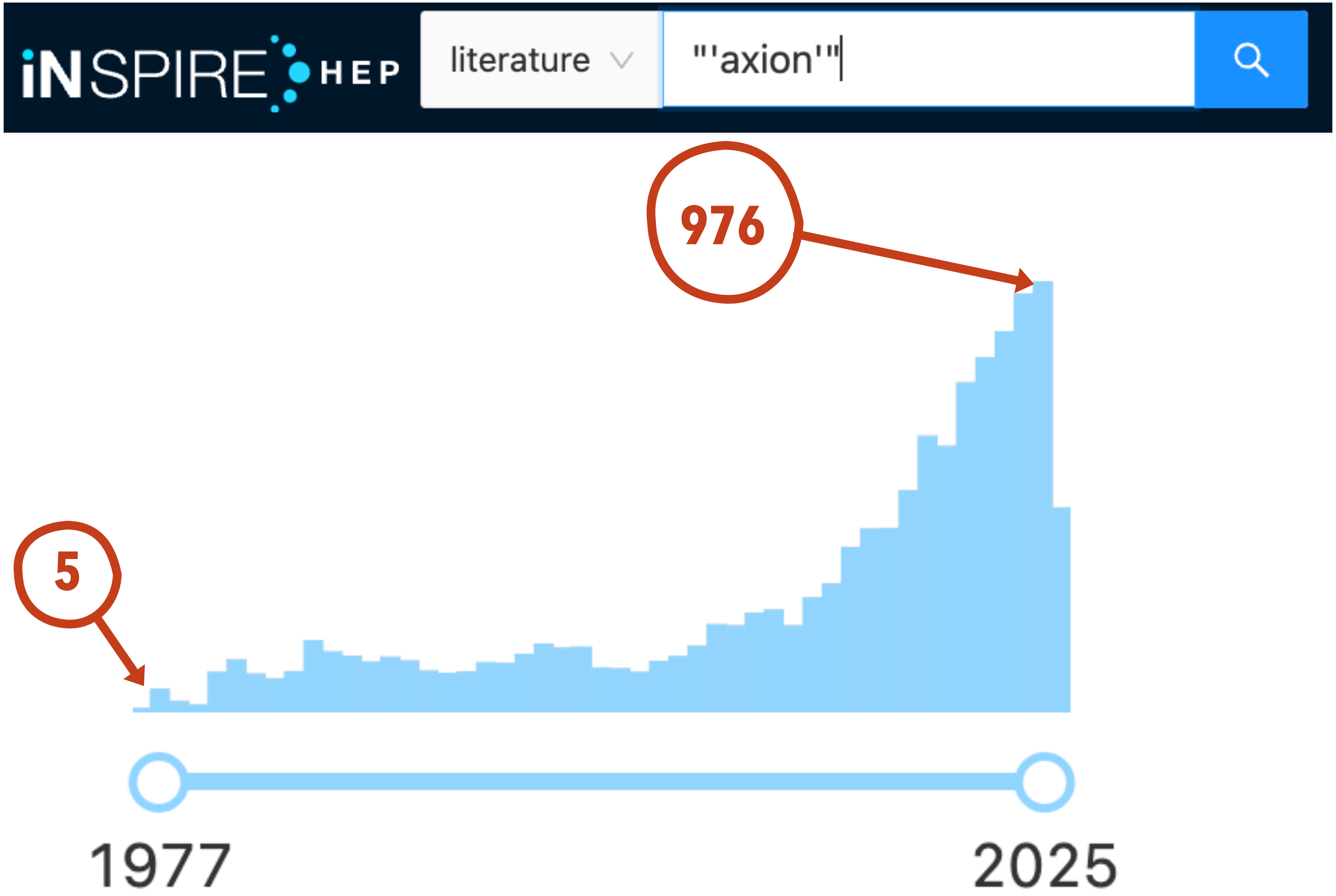


Axion/ALP targets
AGN/Blazars
Supernovae/GRBs
Magnetars/Pulsars
Galaxy clusters
Galactic center
Galactic diffuse
Extragalactic diffuse
Diagram style adapted from Conrad & Reimer 2017

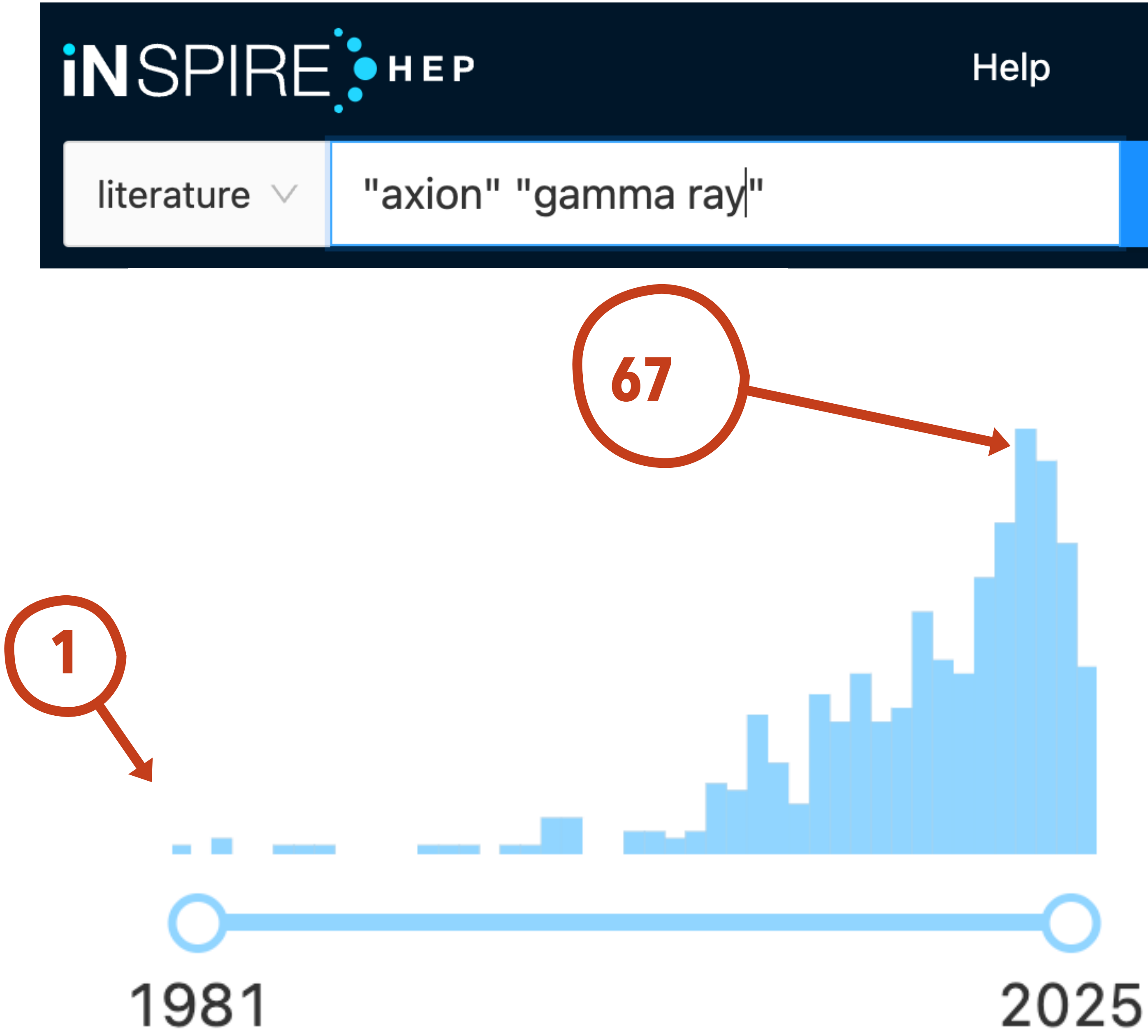
# What we did not talk about...



- Other nearby blazar sources & multiwavelength considerations [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]
- Diffuse emission from supernovae with upgraded magnetic fields [see e.g. Calore+ 2020, 2023]
- Galactic Supernovae prospects [see e.g. Meyer+ 2016]
- Polarization measurements with future instruments (in particular COSI)
- Solar searches, main-sequence stars, etc.
- …




(accessed on September 5, 2024)



iNSPIRE HEP
Help
literature
"axion" "gamma ray"
67
1
1981
2025

for some values of the ALP mass. We note that measurement uncertainties of 10% have been obtained for other Fermi-LAT sources in the 20-500 GeV energy-range, and future experiments like AMEGO [81], e-Astrogram [82] or CTAO [83] are expected to improve over Fermi-LAT precision.

demonstrates that AMEGO can probe ALP-photon coupling down to $g_{a\gamma\gamma} \sim 5 \times 10^{-14}$ GeV$^{-1}$ for $M_{\rm PBH} = 3 \times 10^{16}$ g and $m_a < 10^{-11}$ eV, improving upon current astrophysical constraints by one order of magnitude. The limit becomes weak significanlty for $m_a > 10^{-11}$ eV due to rapid decline of conversion probability within the integral region. MAST with larger effecitve area achieves more stringent limits than e-ASTROGAM, providing complementary coverage to AMEGO's results in the ALP mass range $m_a > 10^{-11}$ eV.

alerts. Nevertheless, AMEGO would detect signatures of ALPs if $m_a < 0.1\,$neV and $g_{10} > 0.01$ even without directional information since it plans all-sky surveys with the field of view of 2.5 sr and the cadence of 3 hours.

and [77–79] for more details). The binned data in the top subfigures of Figures 7 and 9 show that observatories like COSI [64], e-ASTROGAM [65,66], and AMEGO [67] may detect

current or future missions, e.g., at keV energies with Swift, at MeV energies with AMEGO and GECCO, and at TeV energies with Cherenkov Telescope Array Observatory (CTAO)[46,47], would result in a substantial extension of the derived limits to lower and higher ALP masses. This is

As a result, we can expect ALP-induced polarization effects both in the X-ray band and in the HE range, which can be detectable by observatories such as IXPE [50], eXTP [51], XL-Calibur [52], NGXP [53], XPP [54] and COSI [55], e-ASTROGAM [56, 57], AMEGO [58], respectively. In addition, we want to stress that many

*Fermi* LAT, the search for ALP-induced GRBs will be substantially improved. In particular, observatories such as AMEGO [113], with its excellent sensitivity, angular and energy resolution, low energy threshold, and a large field of view, will allow for the most stringent constraints

mass determination. The peak of axion flux is likely to produce gamma-rays in the $\leq 1$ MeV energy range and so future observations with medium energy gamma-ray missions, such as AMEGO and e-ASTROGAM, will be vital to further constrain UL $m_a$.

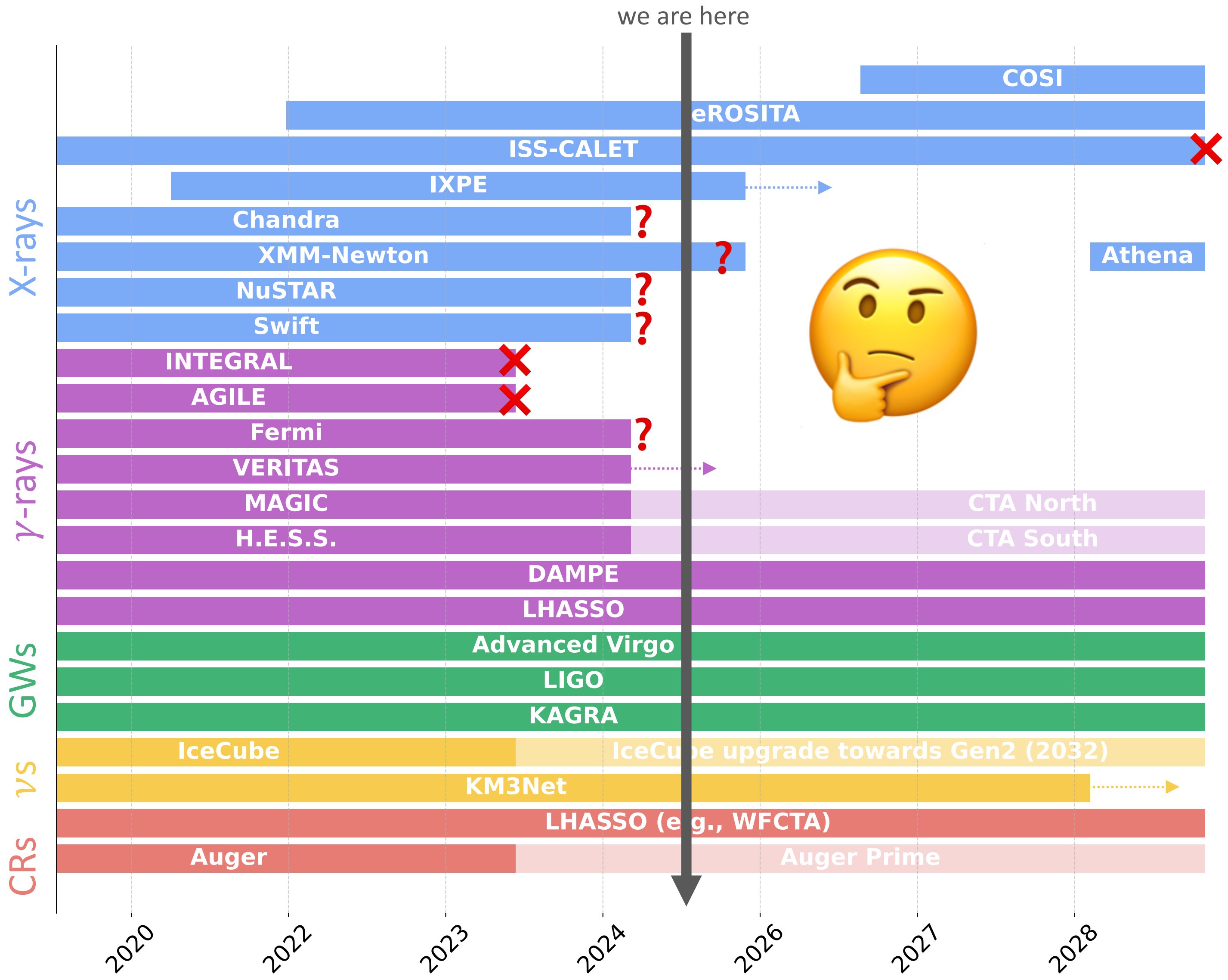
*Fermi* LAT as well as a science case for future gamma-ray satellites such as AMEGO [74].

Observatory, AMEGO/e-ASTROGAM will allow probing D$a$B and associated axion-photon couplings with unprecedented sensitivity covering a wide range of possible source energies as low as 0.1 $\mu$eV and multiple decades in axion masses. We highlight the differences between

In Sec. 4, we compare the gamma-ray spectrum with and without proper calculation of non-relativistic pion or ALP production and show that the future AMEGO-X measurement can be sensitive to the improper treatment of the scalar production. We conclude in Sec. 5.

every 20–50 years. These results highlight the importance of employment of three experiments (for instance, AMEGO-X, ...t points of the sky at the same time, it would be possible to ... of operational downtime could be considered negligible, as at least two out of the three experiments would remain operational. Under such conditions, the joint detection of a BNS event at 100 Mpc would be reduced to approximately once every 4–9 years.

# Dark Matter Landscape: An Instrumentationalist's View




e-ASTROGAM
AMEGO
AMEGO-X
...

VLAST
HERD

"Hunting for axionlike particles is a bit like waiting for sunshine in a Swedish winter: sure, it's possible, but you mostly get darkness and a lingering sense of existential disappointment. And just when you think you spot a glimmer of hope, it's swallowed up by another round of systematic uncertainties."

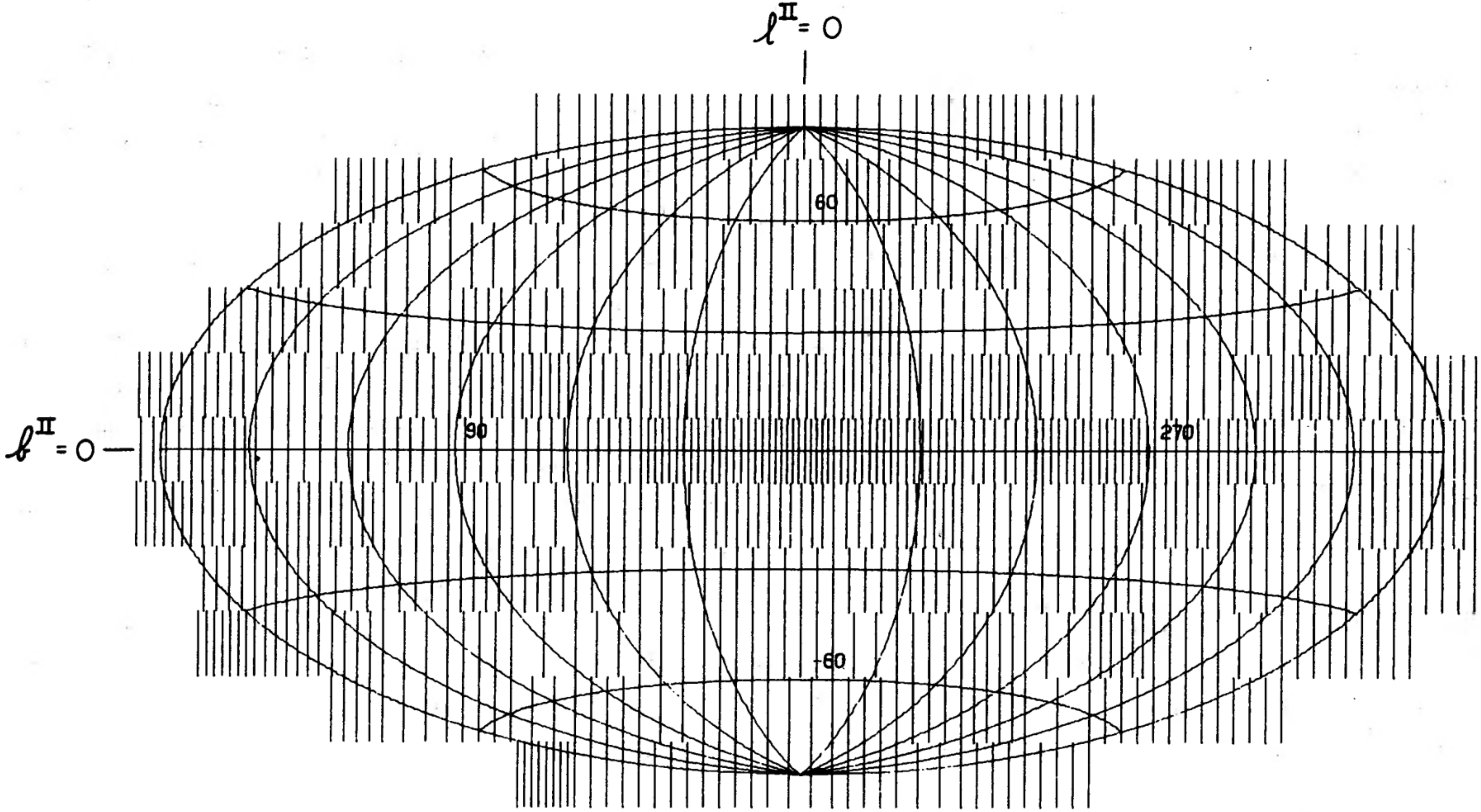
*ChatGPT, 2025*

# Future Innovations in Gamma rays

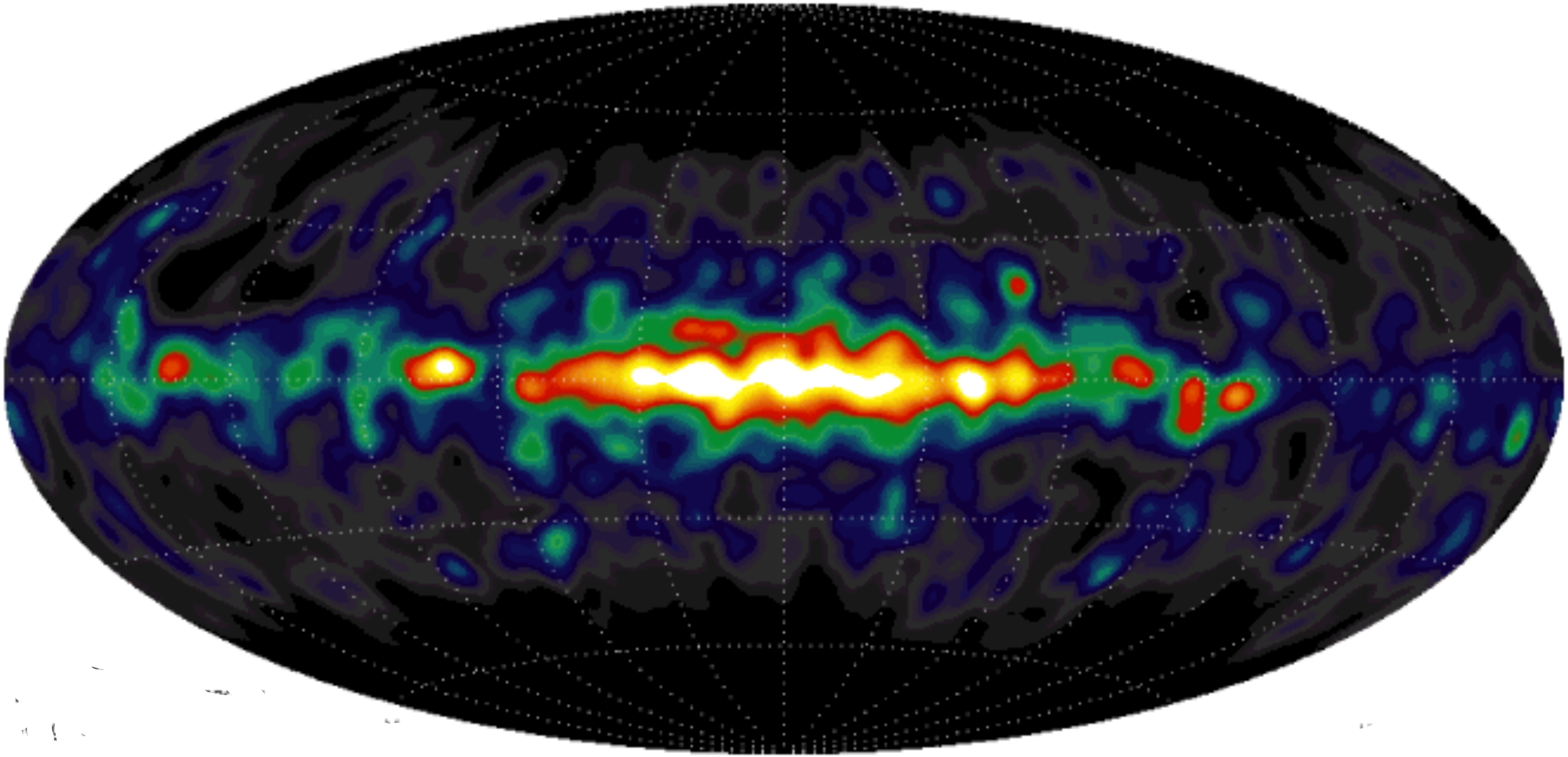
*Science Analysis Group*

… to explore gamma-ray science priorities, necessary capabilities, new technologies, and theory/modeling needs drawing on the 2020 Decadal **to inspire work toward 2040.**

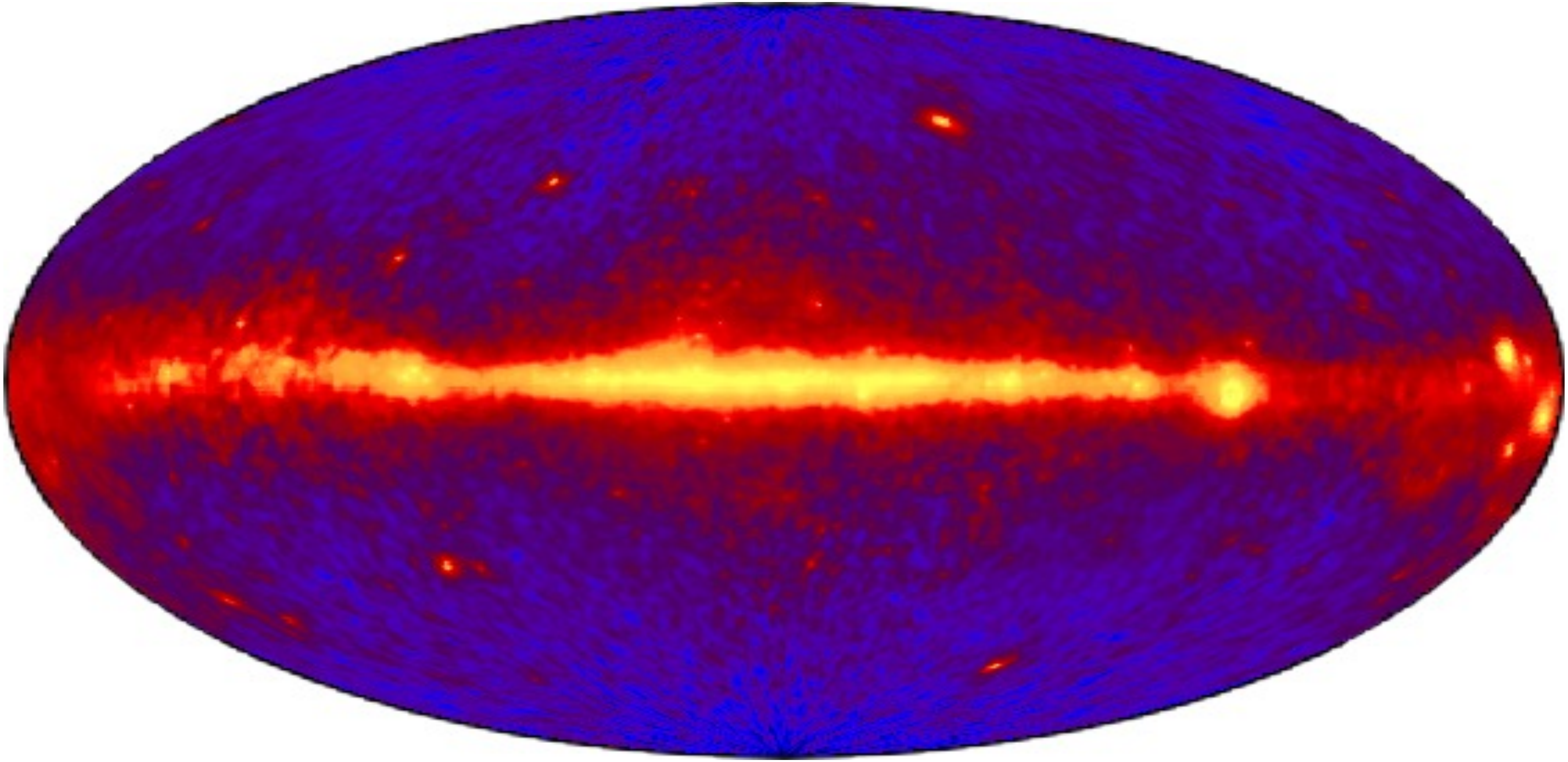
FIG-SAG



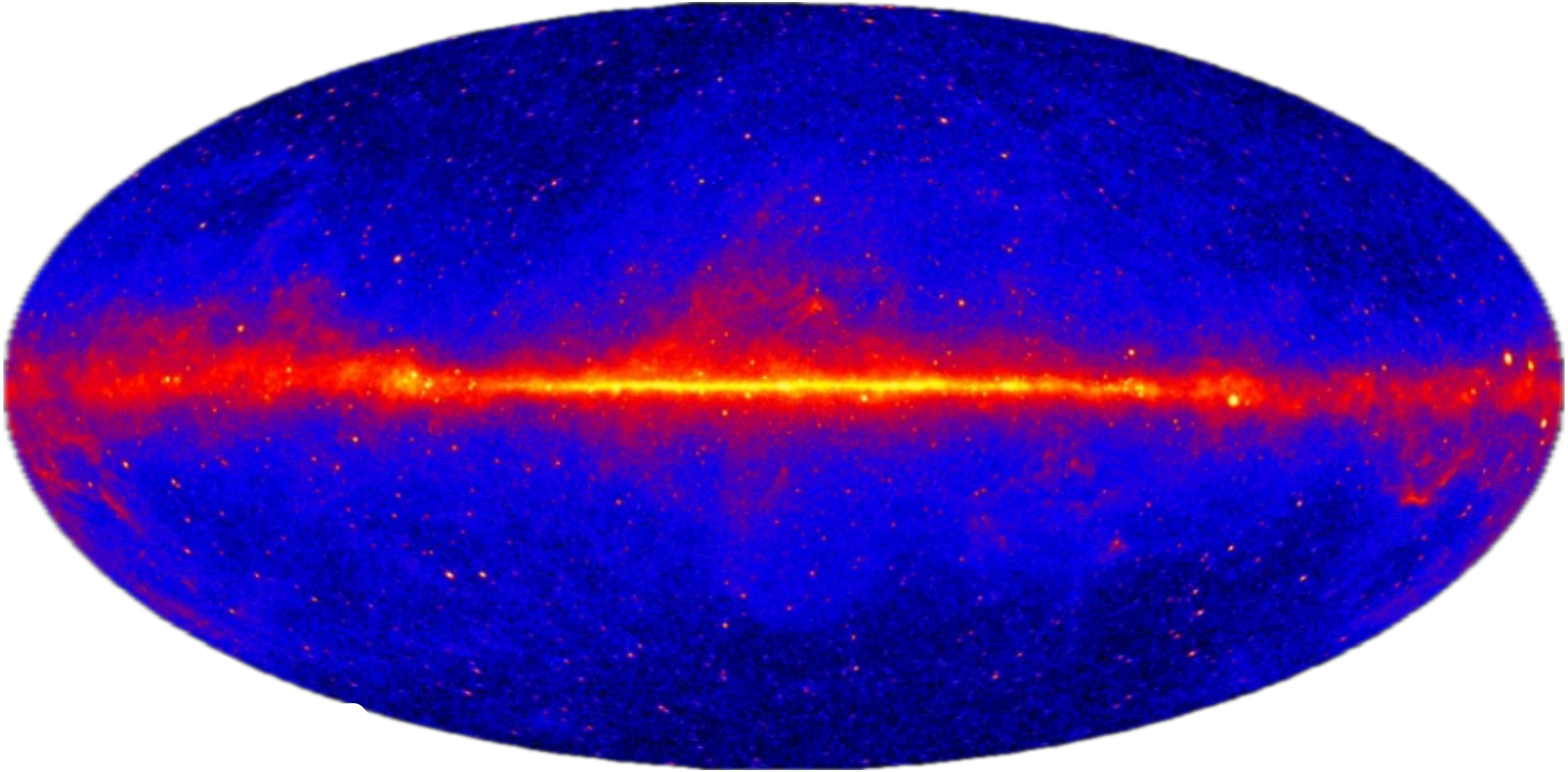

1968, Orbiting Solar Observatory, OSO-3 (~50 MeV)



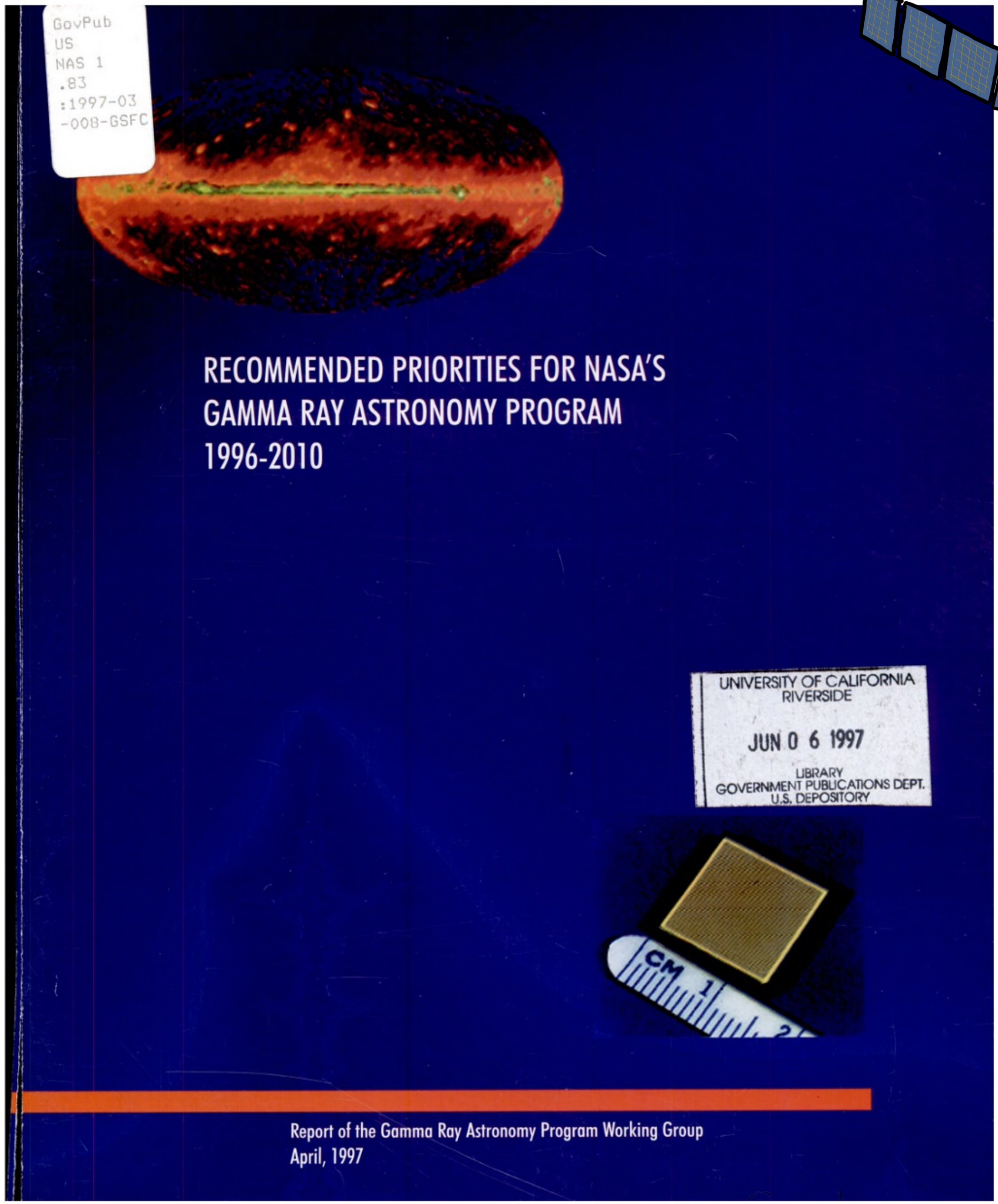
2000, COMPTEL (onboard CGRO), 1–30 MeV



2000, EGRET (onboard CGRO), above 100 MeV



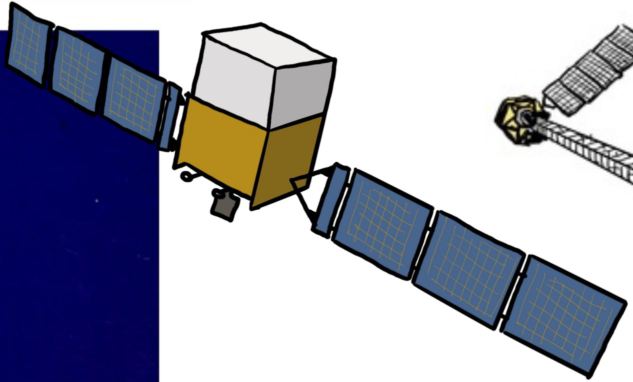
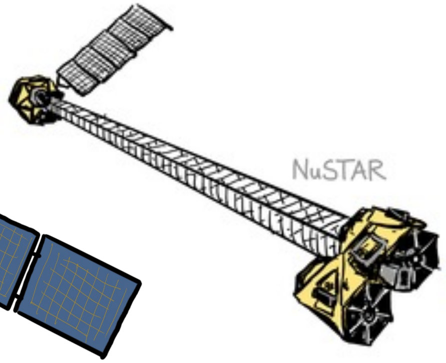
2020, LAT (onboard *Fermi* ), above 500 MeV

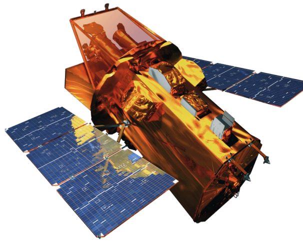



RECOMMENDED PRIORITIES FOR NASA'S
GAMMA RAY ASTRONOMY PROGRAM
1996-2010

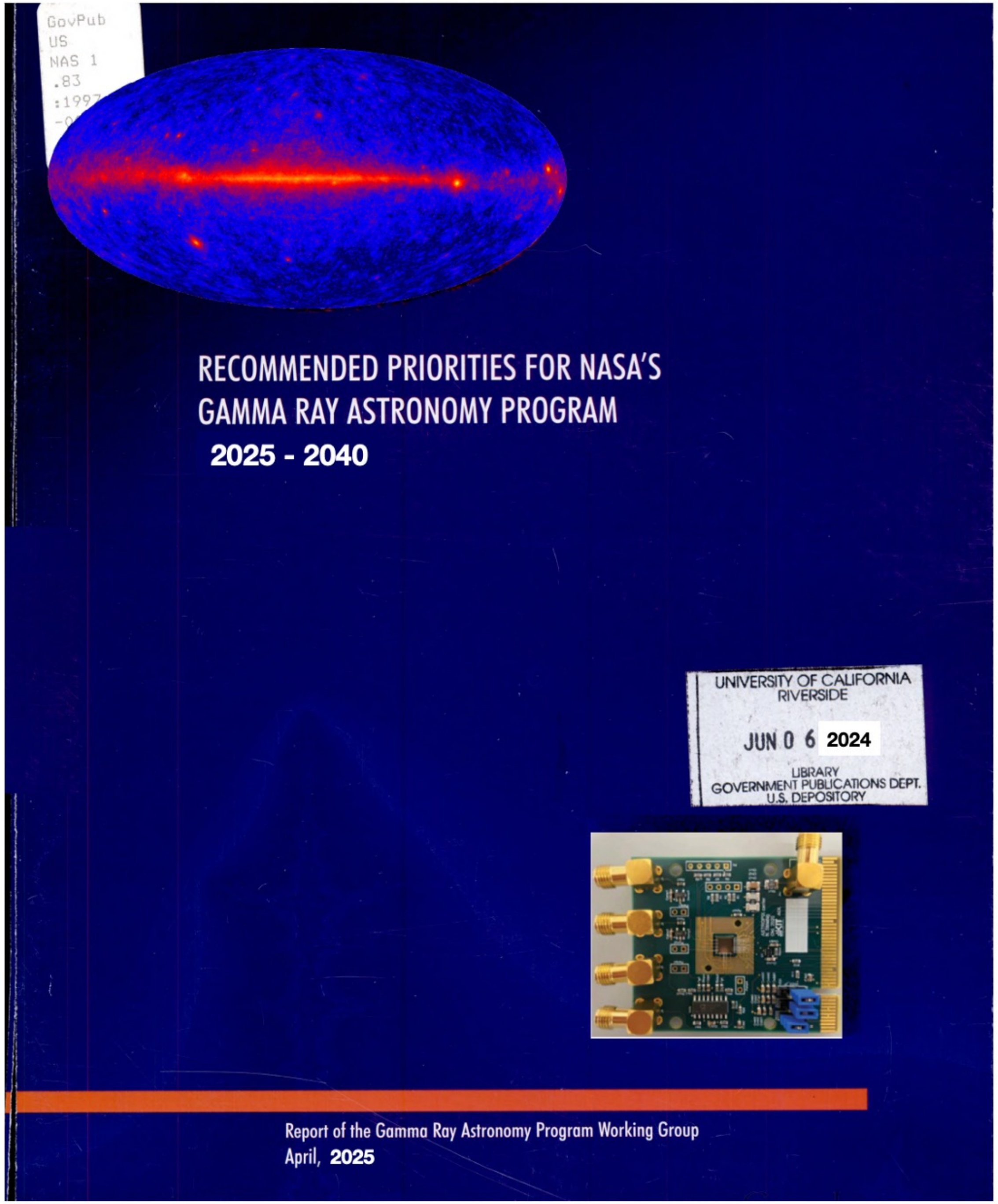


Report of the Gamma Ray Astronomy Program Working Group
April, 1997

- Intermediate Missions: Fermi, NuSTAR and now COSI
- MIDEX and SMEX: Swift and NICER
- Technology: a robust technology development program (SiPMs, new scintillators, upgraded silicon detectors, etc)
- Balloons (+ CubeSats!): long duration balloons enabled COSI, LEAP, etc.
- Data Analysis & Theory: mainly supported through GI programs
- TeV Astronomy: VERITAS, HESS, HAWC, and MAGIC.

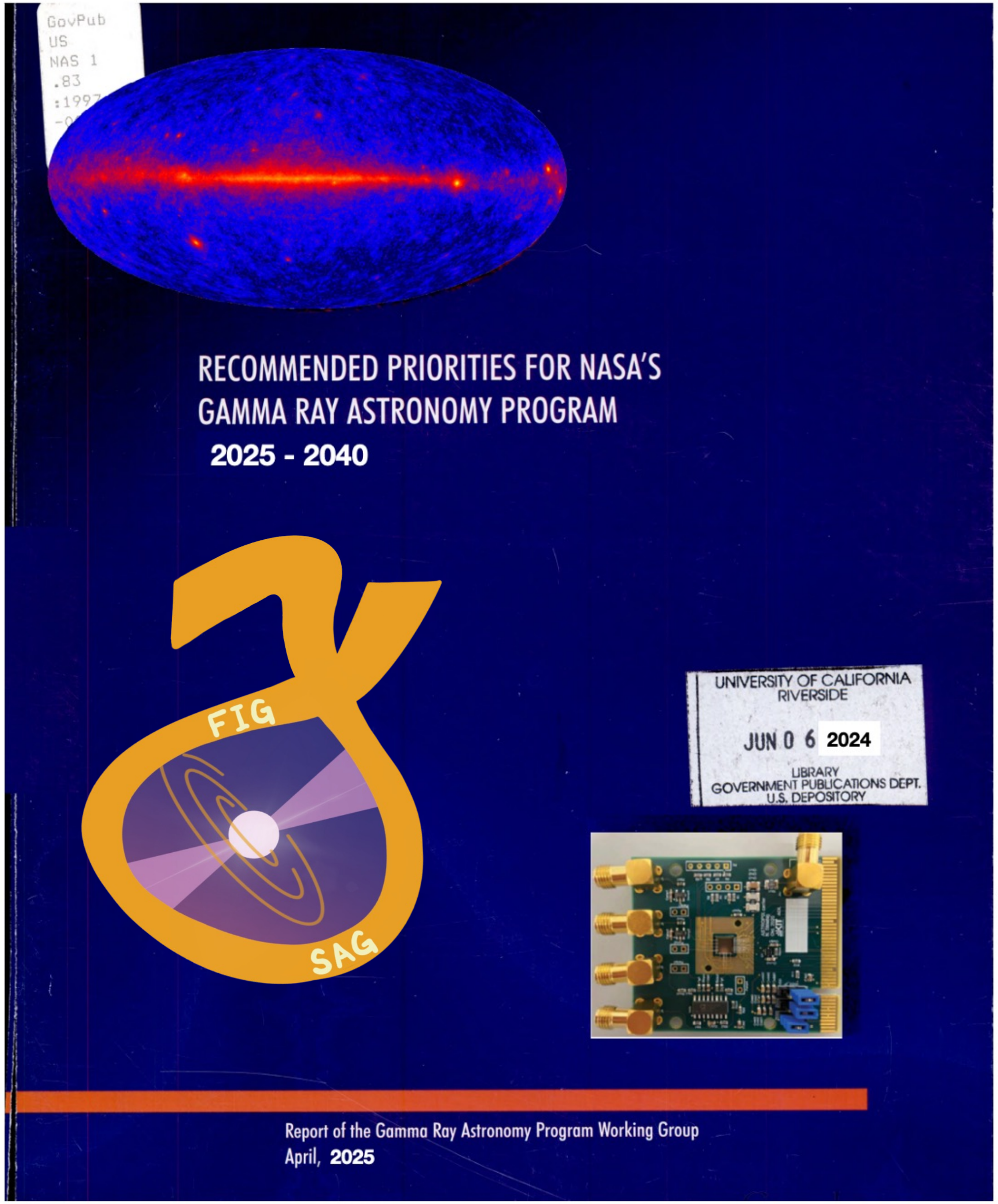



RECOMMENDED PRIORITIES FOR NASA'S
GAMMA RAY ASTRONOMY PROGRAM
2025 - 2040



Report of the Gamma Ray Astronomy Program Working Group
April, 2025

[insert your space-based gamma-ray wish list]




Submitted to the NASA Astrophysics Advisory Committee by

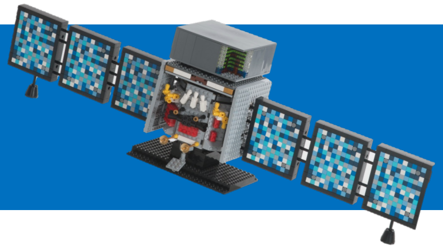
*The Future Innovations in Gamma Ray Science Analysis Group*

# Future Innovations in Gamma Rays SAG: A Report on Gamma-ray Science Objectives Beyond 2025

Chris Fryer[1], C. Michelle Hui[2], Paolo Coppi[3], Milena Crnogorcevic[4], Tiffany R. Lewis[5], Marcos Santander[6], and Zorawar Wadiasingh[7]

[1]Los Alamos National Laboratory
[2]NASA Marshall Space Flight Center
[3]Yale University
[4]Stockholm University
[5]Michigan Technological University
[6]University of Alabama, Huntsville
[7]University of Maryland, College Park

# Conclusions & Outlook

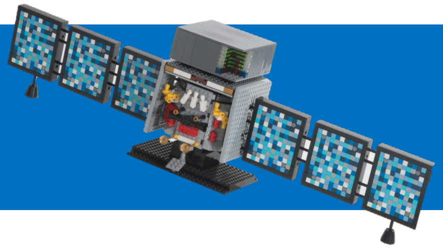


- **Gamma-ray instruments continue to be** a crucial players in **uniquely** characterizing axions and ALPs, leading candidates to describe the nature of dark matter (and more).
- **No other current experiment can search for the MeV→soft GeV signatures of ALPs from astrophysical sources.**
- Probes are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

FIG SAG

**Thank you.**

# Conclusions & Outlook



https://pcos.gsfc.nasa.gov/sags/figsag.php

FIG SAG

**Thank you.**