The Dark Matters of the Universe

Milena Crnogorčević
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Oskar Klein Centre Colloquium
March 11, 2025

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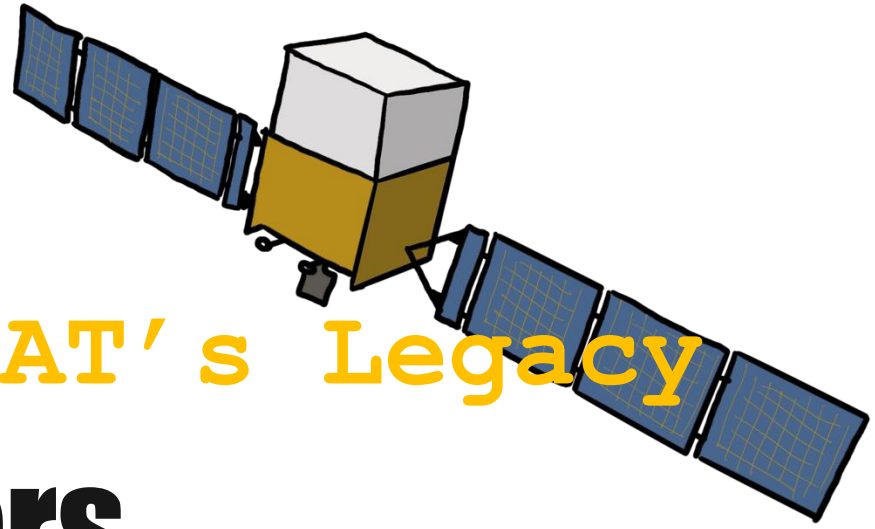

Establishing Fermi-LAT's Legacy

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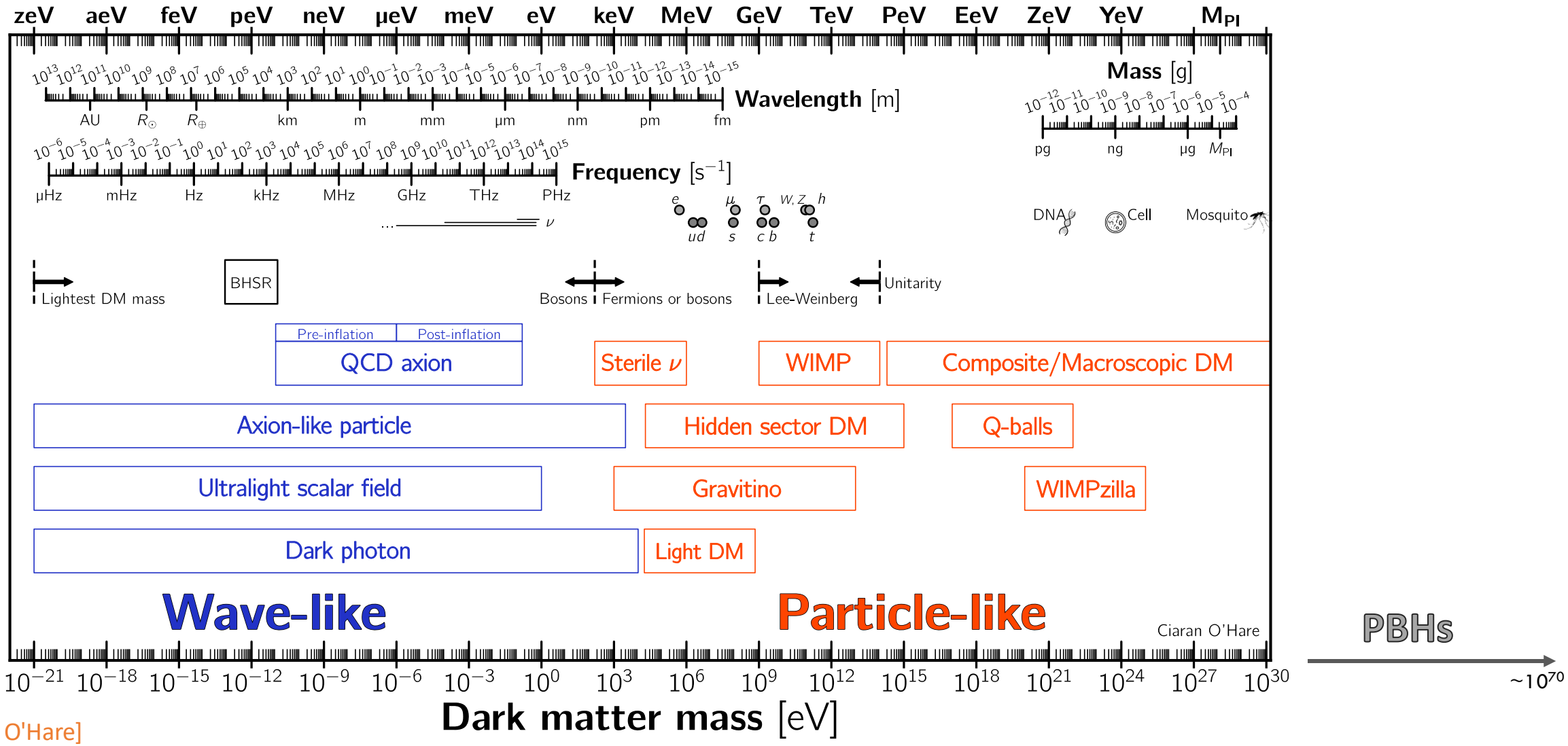
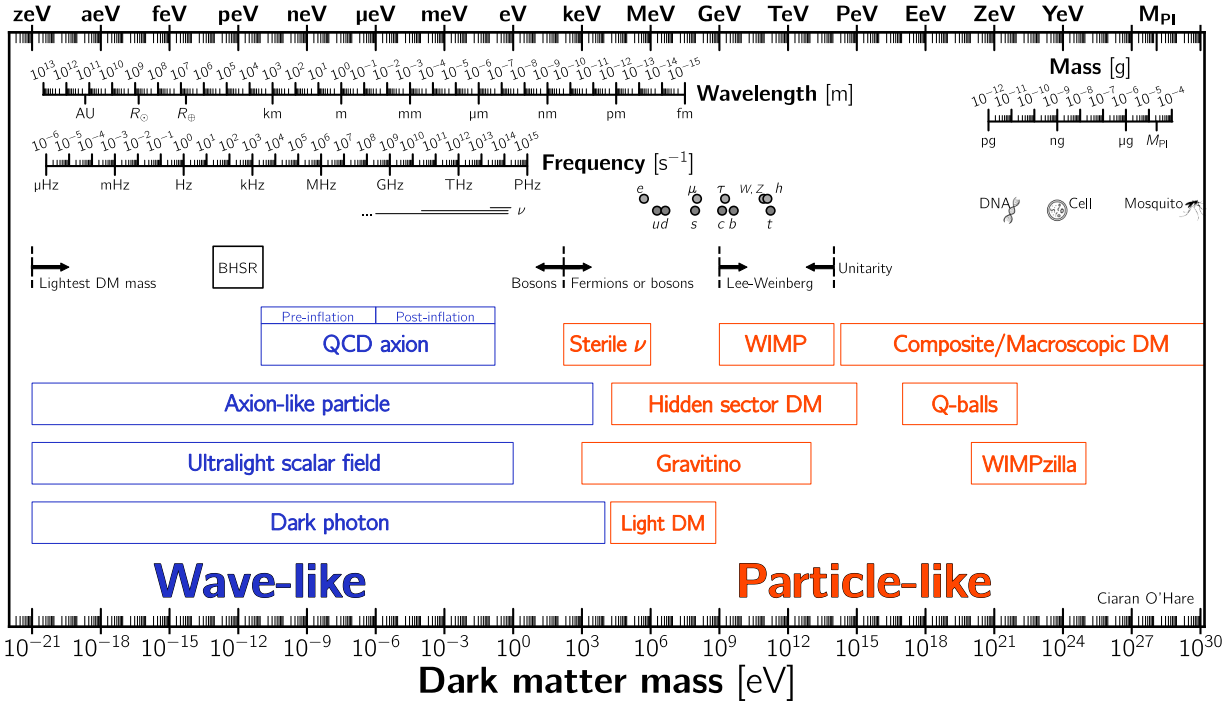
Dark Matter Landscape: A Theorist's View



[Ciaran A. J. O'Hare]

Dark Matter Landscape: A Theorist's View



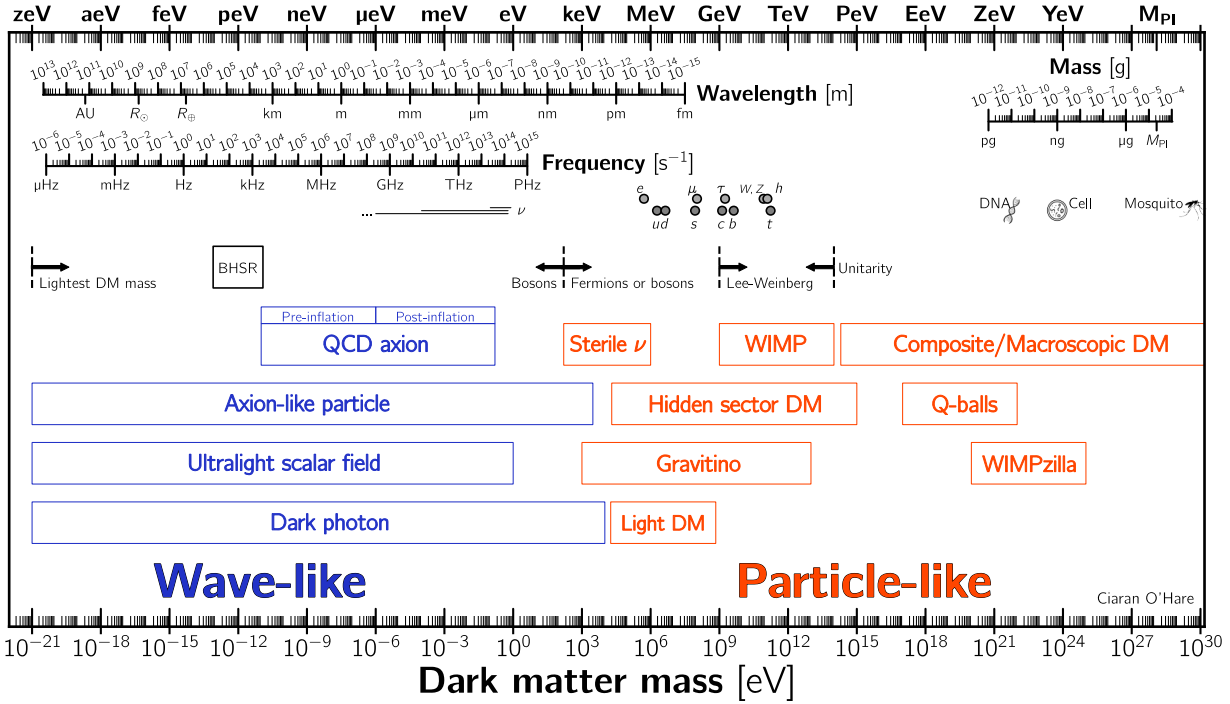
[Ciaran A. J. O'Hare]

Dark matter spans over

80 orders of magnitude in mass (+ interaction strength)

proton
$m \sim 10^{-27}$ kg

Dark Matter Landscape: A Theorist's View



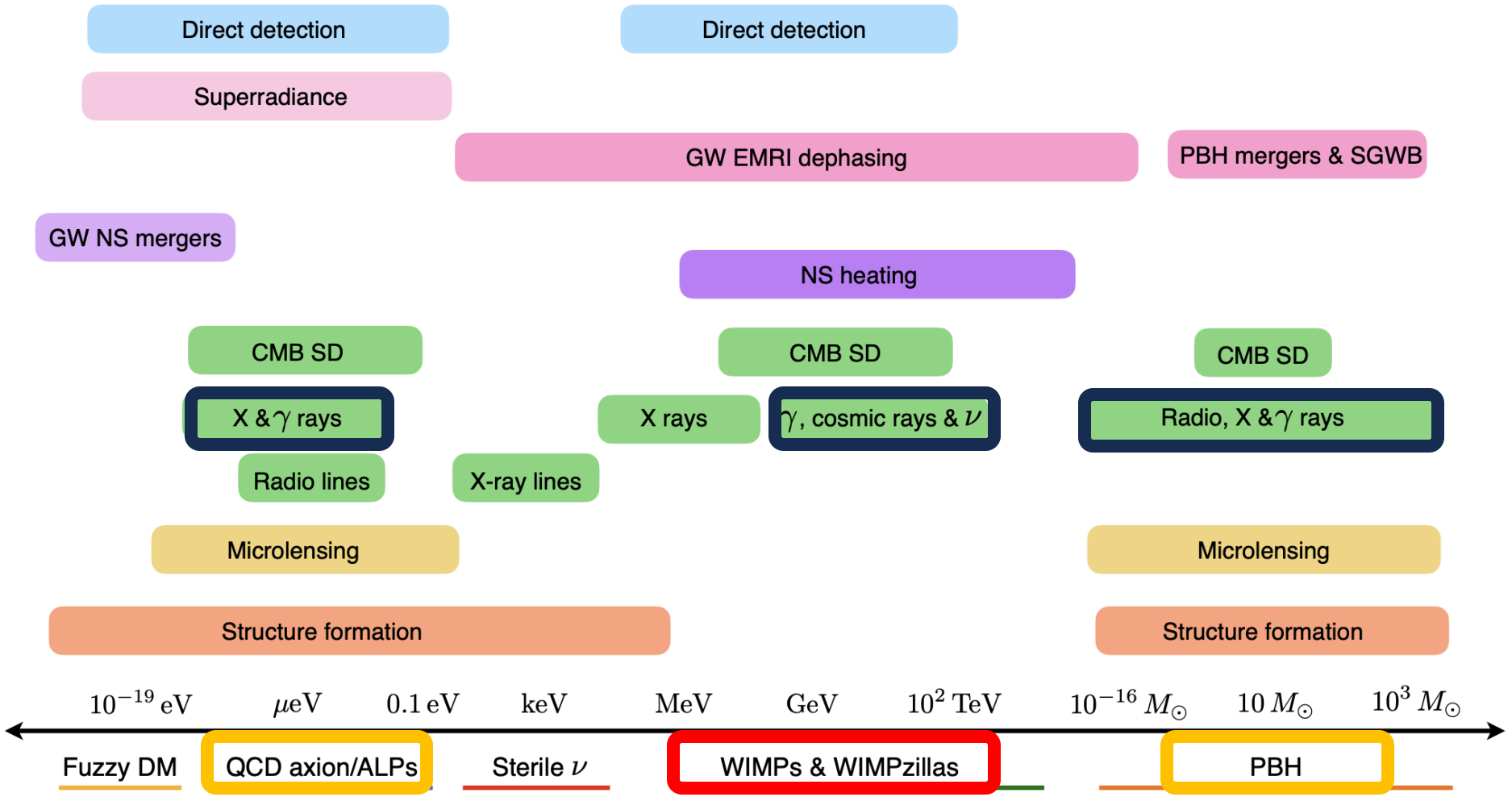
Issue: Our search strategies are inherently _biased_

- Theory guides our search strategies: **model dependency**
- Disparity between *available* and needed data: **observational biases**
- Detection requires an **identifiable signature**

… but we have to start somewhere.

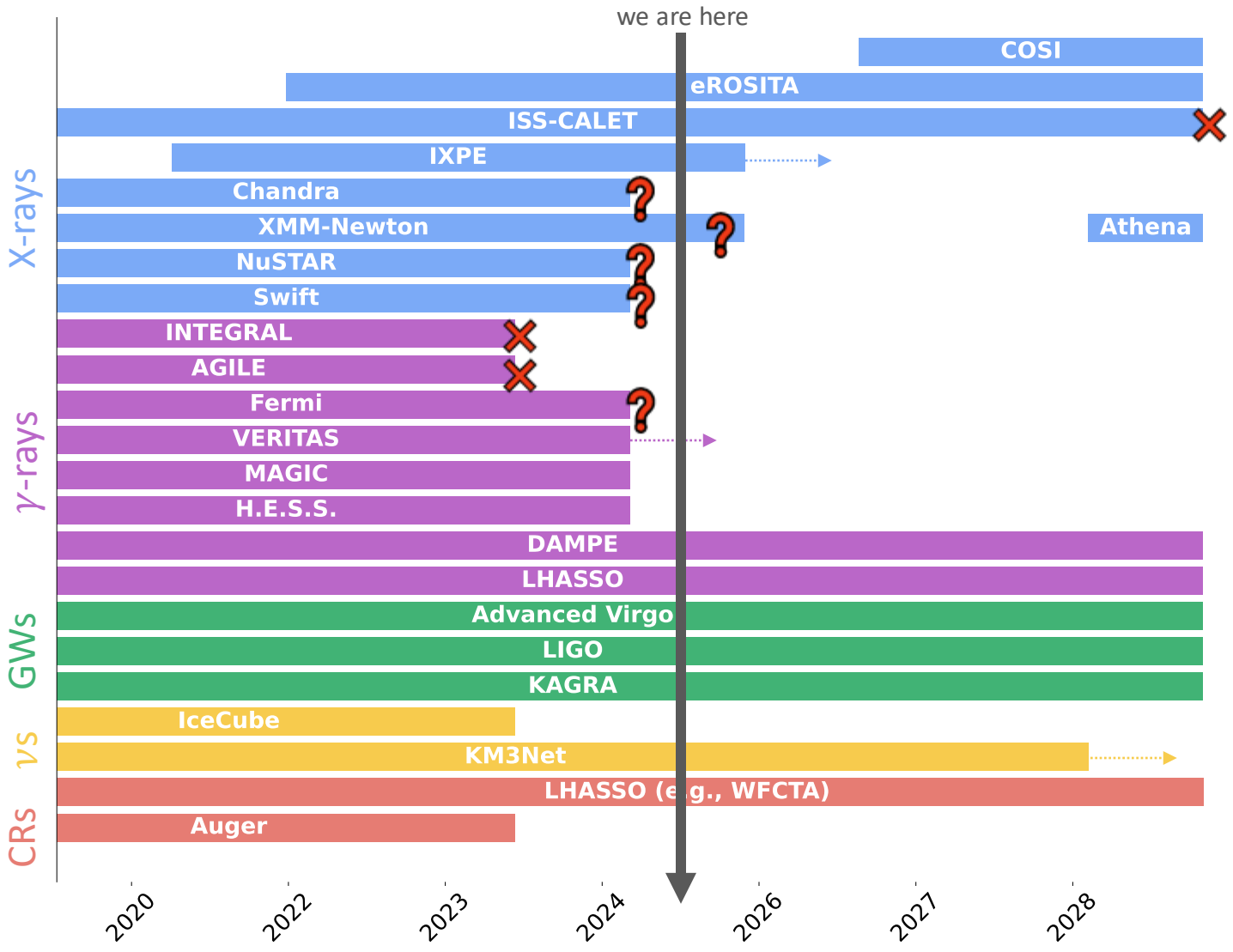
[Ciaran A. J. O'Hare]

Dark Matter Landscape: An Observer's View

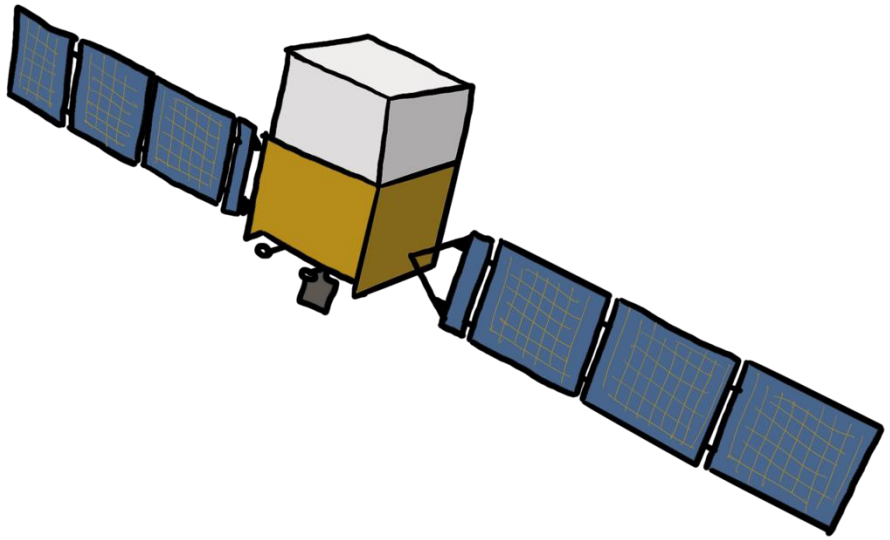


[EuCAPT WhitePaper, 2021]

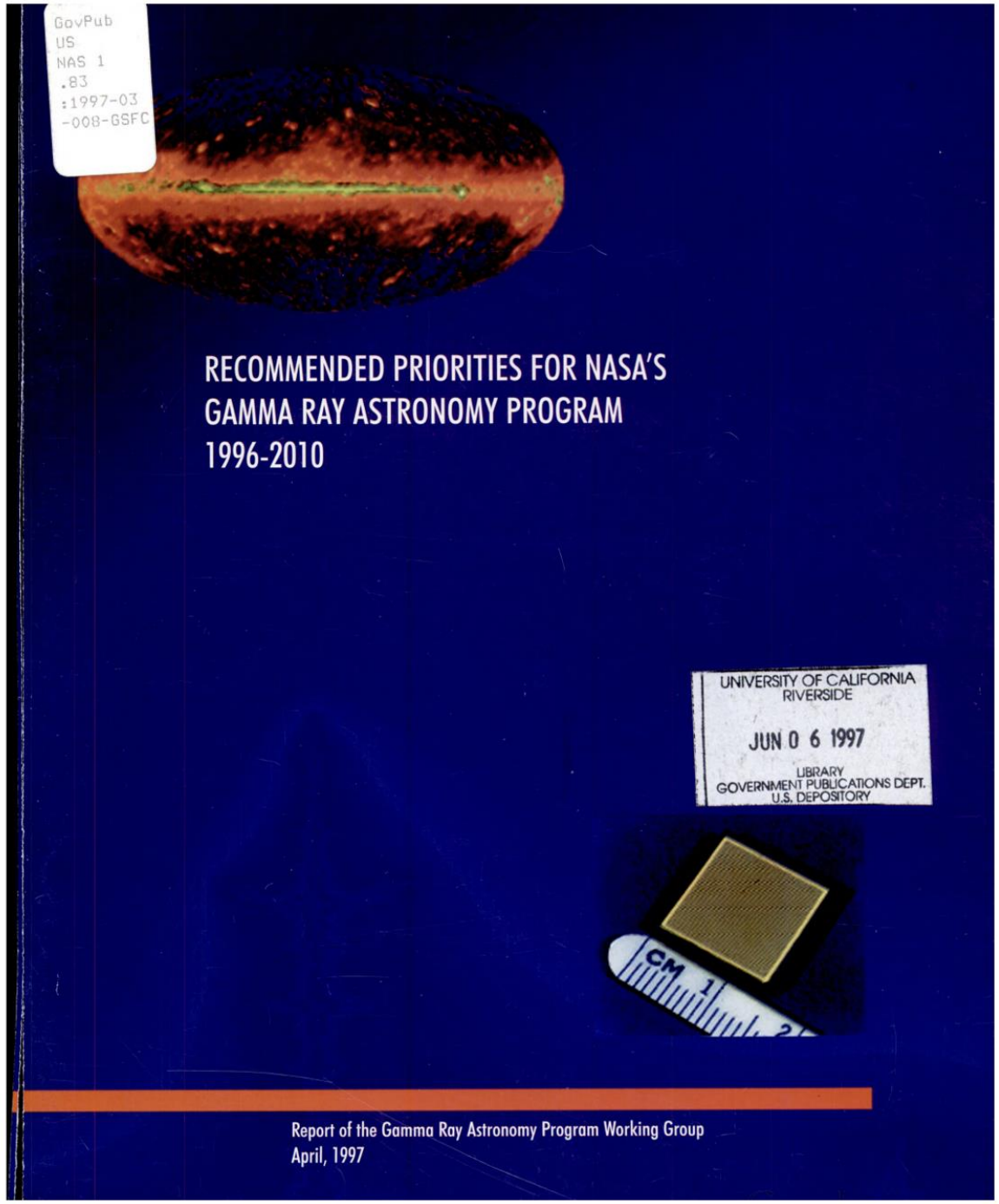
Dark Matter Landscape: An Instrumentationalist's View



Where does the story



start?



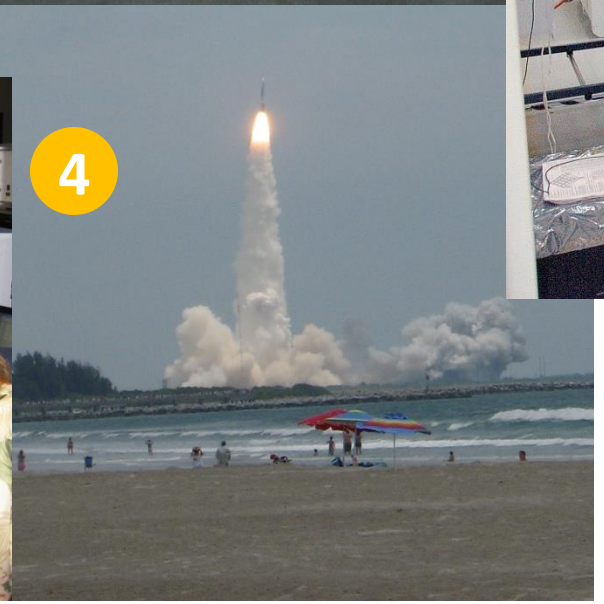
GAMMA-RAY ASTRONOMY PROGRAM WORKING GROUP MEMBERS:

Elena Aprile (Columbia)
Alan Bunner (NASA) [Ex-Officio (NASA Headquarters)]
Neil Gehrels (GSFC) [Co-Chair]
Jonathan Grindlay (Harvard)
Gerald Fishman (MSFC)
W. Neil Johnson (NRL)
Kevin Hurley (UCB/SSL)
Steve Kahn (Columbia)
Richard Lingenfelter (UCSD)
Peter Michelson (Stanford)
Thomas Prince (Caltech) [Co-Chair]
Roger Romani (Stanford)
James Ryan (UNH)
Bonnard Teegarden (GSFC)
David Thompson (GSFC)
Trevor Weekes (Harvard/Smithsonian)
Stanford Woosley (UCSC)

The highest priority recommendation:
A next-generation 10 MeV to 100 GeV gamma-ray mission (such as GLAST, now *Fermi*) with orders of magnitude improvements in sensitivity compared to previous missions (EGRET).

The full report can be found at: https://ntrs.nasa.gov/citations/199

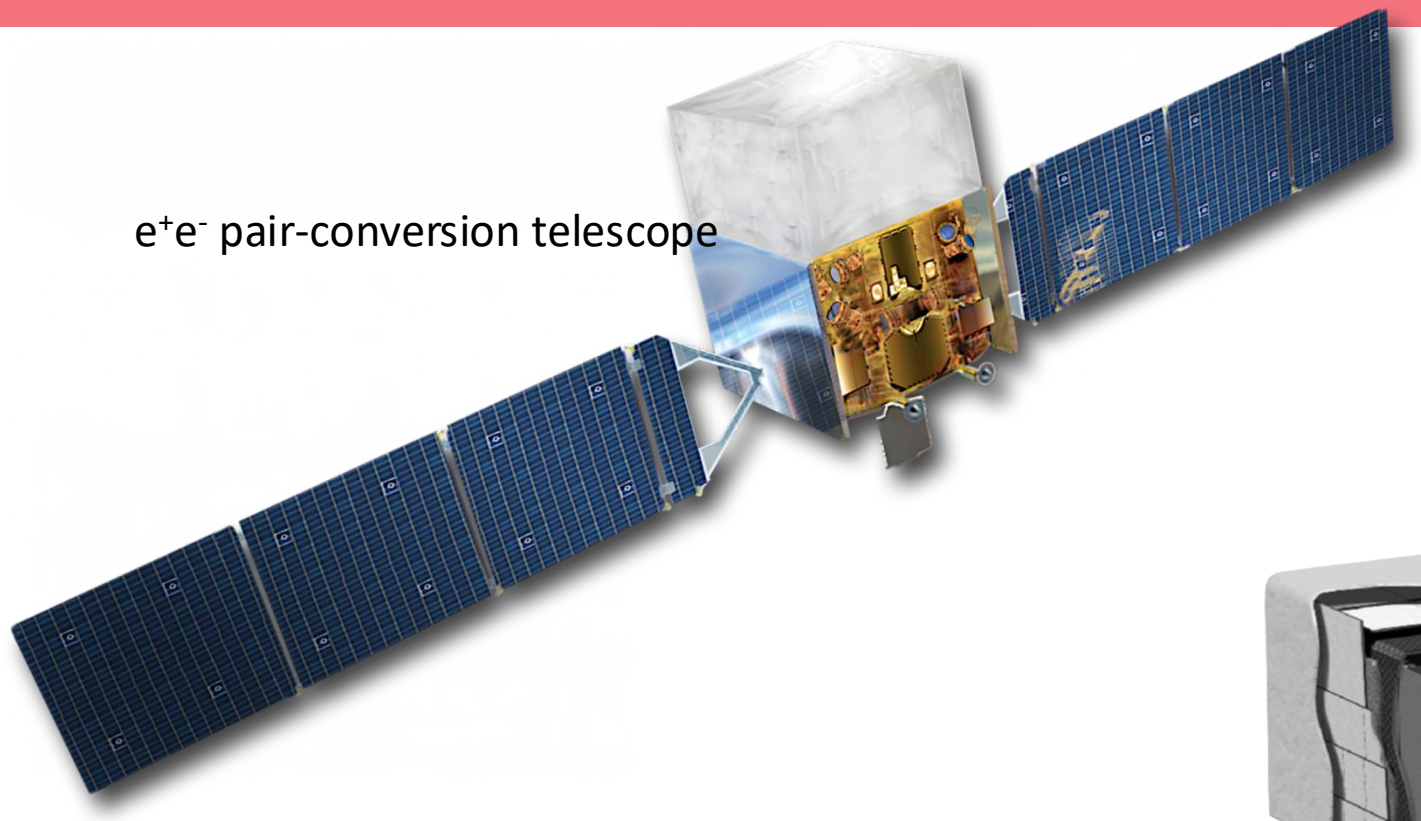
Dark Matter Landscape: An Instrumentationalist's View



*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.)*

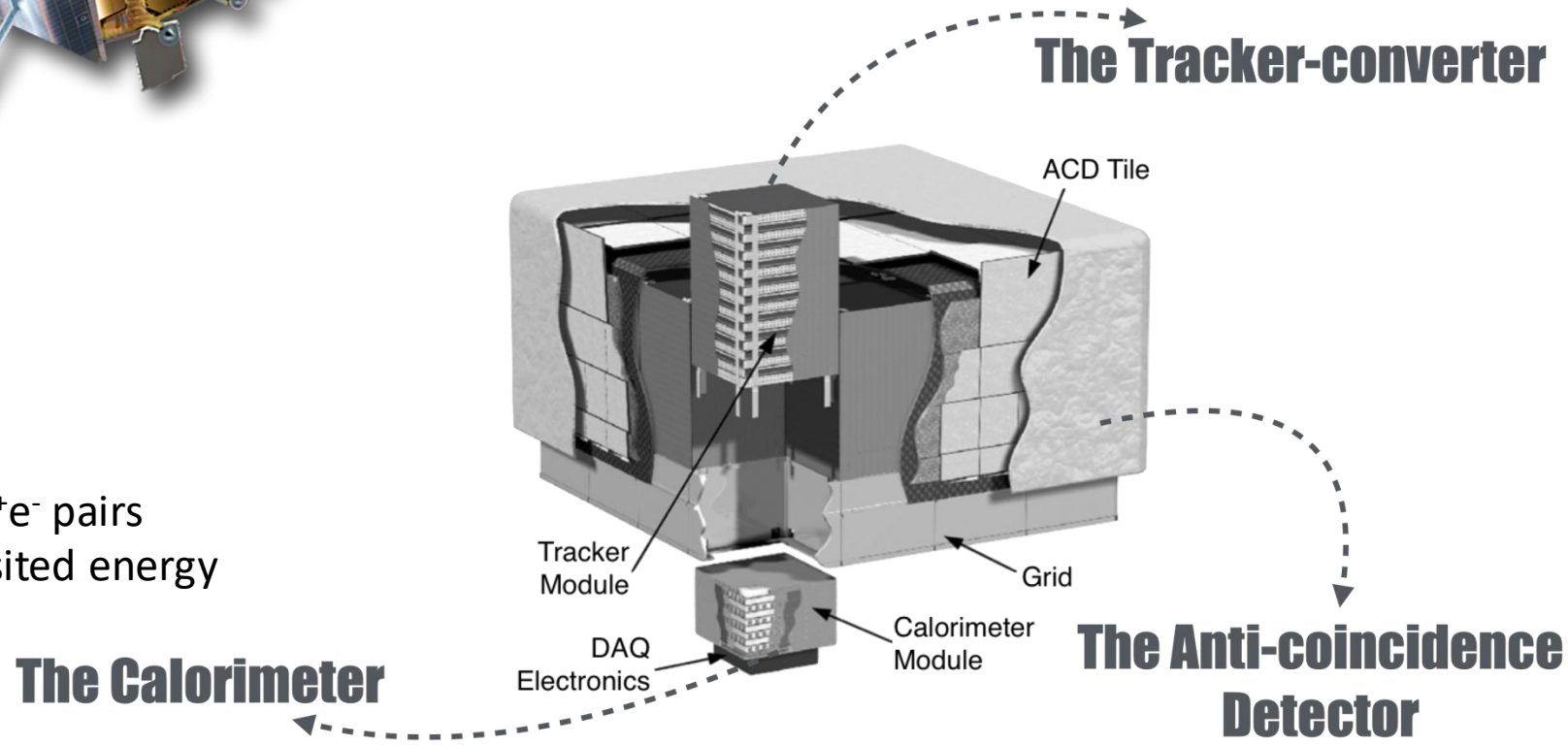
The *Fermi*-LAT

e^+e^- pair-conversion telescope

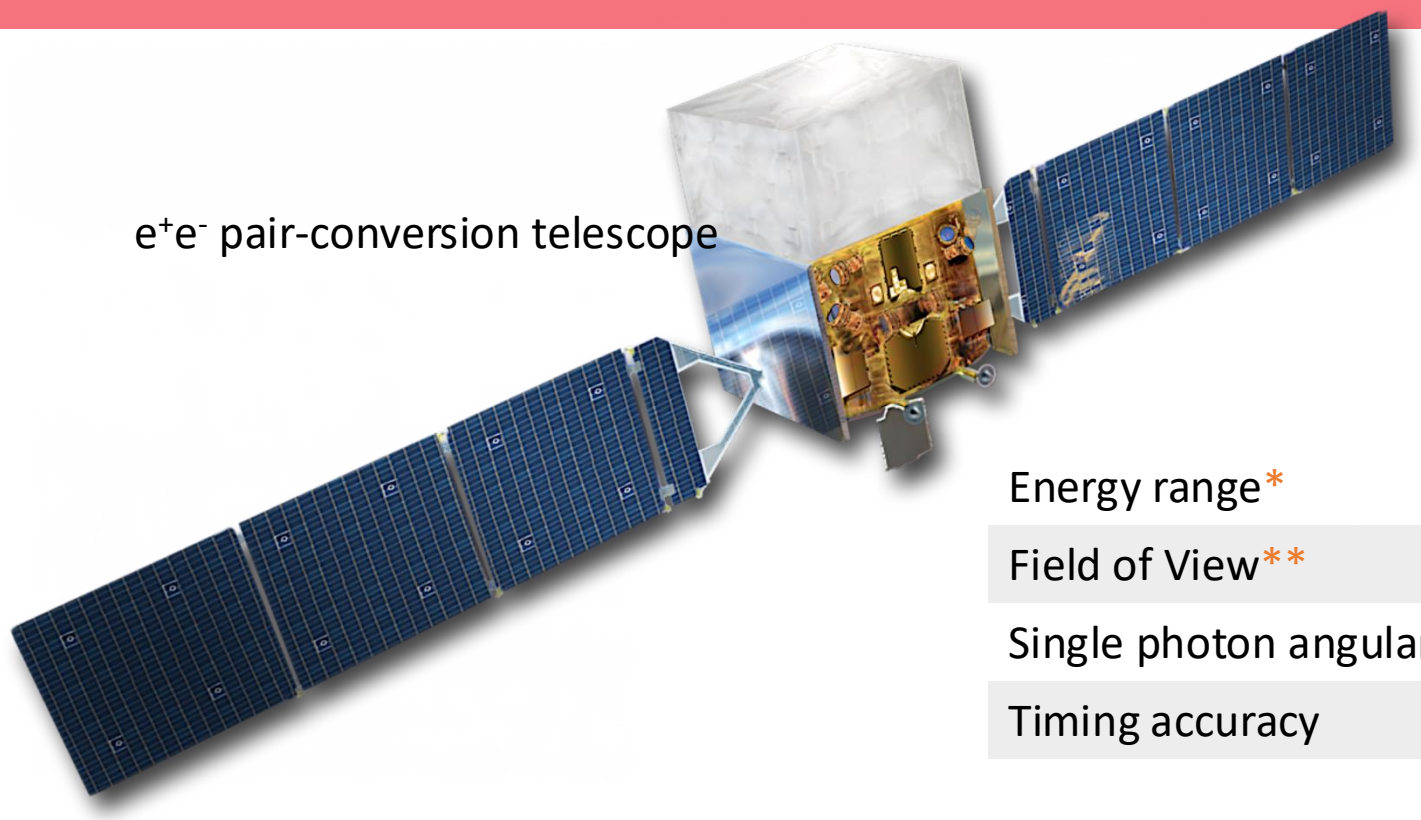


individual γ rays convert into e^+e^- pairs
→ tracks (localization) & deposited energy

…it also detects electrons.



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 γ rays convert into e^+e^- pairs
→ tracks (localization) & deposited energy

*ideally suited for WIMP searches
**whole sky every ~3 hours
***point-source localization <0.5 arcmin

…it also detects electrons.

Pre-launch estimates for GLAST sensitivity to Dark Matter annihilation signals

E. A. Baltz‡, B. Berenji‡, G. Bertone§, L. Bergström ¶, E. Bloom‡, T. Bringmann ¶, J. Chiang‡, J. Cohen-Tanugi‡, J. Conrad ¶ **, Y. Edmonds‡, J. Edsjö ¶, G. Godfrey‡, R. E. Hughes‖, R. P. Johnson+, A. Lionetto*, A. A. Moiseev♯, A. Morselli*, I. V. Moskalenko††, E. Nuss‡‡, J. F. Ormes§§, R. Rando¶¶¶, A. J. Sander‖, A. Sellerholm¶, P. D. Smith‖, A. W. Strong‖‖, L. Wai‡, P. Wang‡, B. L. Winer ‖

Abstract. We investigate the sensitivity of the Gamma-ray Large Area Space Telescope (GLAST) to indirectly detect weakly interacting massive particles (WIMPs) through the γ-ray signal that their pair annihilation produces. WIMPs are among the favorite candidates to explain the compelling evidence that about 80% of the mass in the Universe is non-baryonic dark matter (DM). They are serendipitously motivated by various extensions of the standard model of particle physics such as Supersymmetry and Universal Extra Dimensions (UED). With its unprecedented sensitivity and its very large energy range (20 MeV to more than 300 GeV) the main instrument on board the GLAST satellite, the Large Area Telescope (LAT), will open a new window of discovery. As our estimates show, the LAT will be able to detect an indirect DM signature for a large class of WIMP models given a cuspy profile for the DM distribution. Using the current state of the art Monte Carlo and event reconstruction software developed within the LAT collaboration, we present preliminary sensitivity studies for several possible sources inside and outside the Galaxy. We also discuss the potential of the LAT to detect UED via the electron/positron channel. Diffuse background modeling

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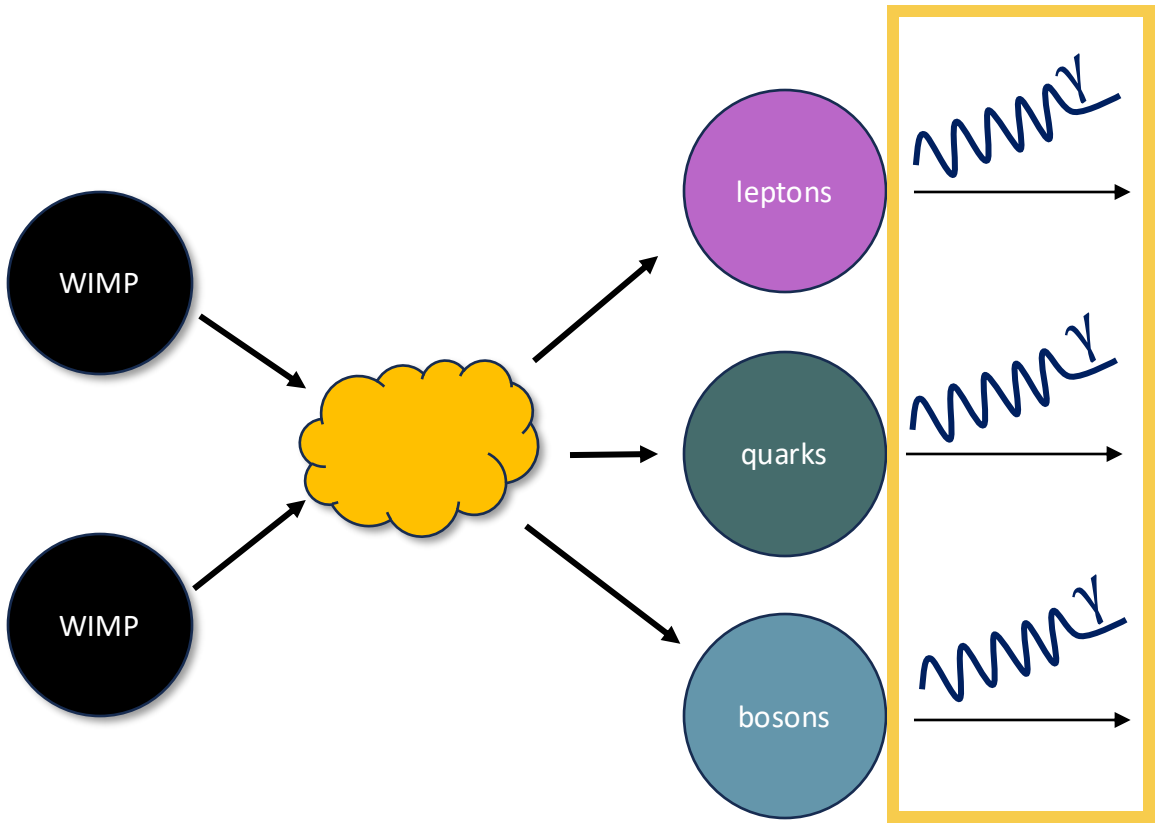
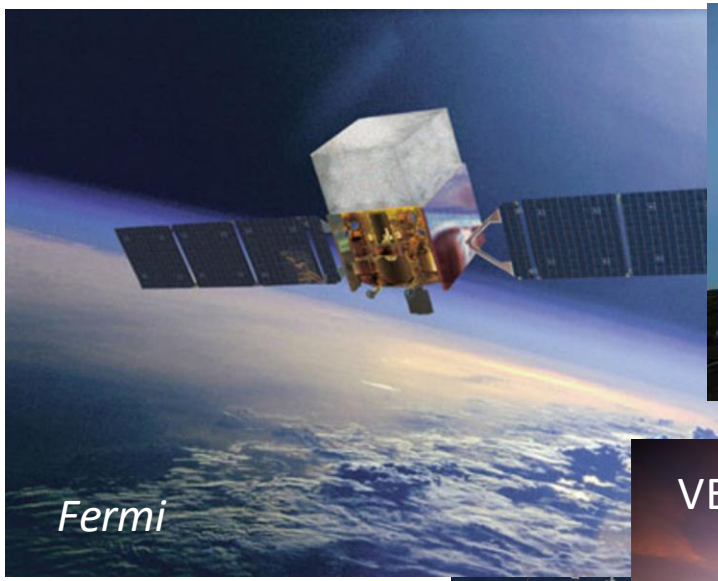
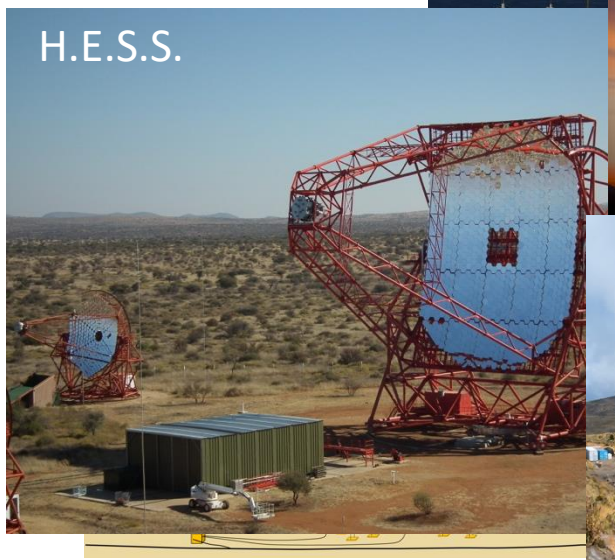
Country	Funding Agencies
United States	NASA; Department of Energy
France	Commissariat à l'Energie Atomique; CNRS/Institut National de Physique Nucléaire et de Physique des Particules
Italy	Agenzia Spaziale Italiana; Istituto Nazionale di Fisica Nucleare; Istituto Nazionale di Astrofisica
Japan	Ministry of Education, Culture, Sports, Science and Technology; High Energy Accelerator Research Organization (KEK); Japan Aerospace Exploration Agency
Sweden	K. A. Wallenberg Foundation; Swedish Research Council; National Space Board

Authors' affiliations removed for readib

As our estimates show, the LAT will be able to detect an indirect DM signature for a large class of WIMP models given a cuspy profile for the DM distribution. Using







Slide adapted from the Fermi Summer School 2020.

WIMP 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
- Atmosphere/water = calorimeter, particle showers

WIMP Landscape: An Instrumentationalist's View

HAWC
300 water Cherenkov detectors
300 GeV to 100 TeV

VERITAS
4 imaging air Cherenkov telescopes (IACT)
85 GeV to 30 TeV

H.E.S.S.
5 imaging air Cherenkov telescopes (IACT)
30 GeV to 100 TeV

MAGIC
2 imaging air Cherenkov telescopes (IACT)
30 GeV to 100 TeV

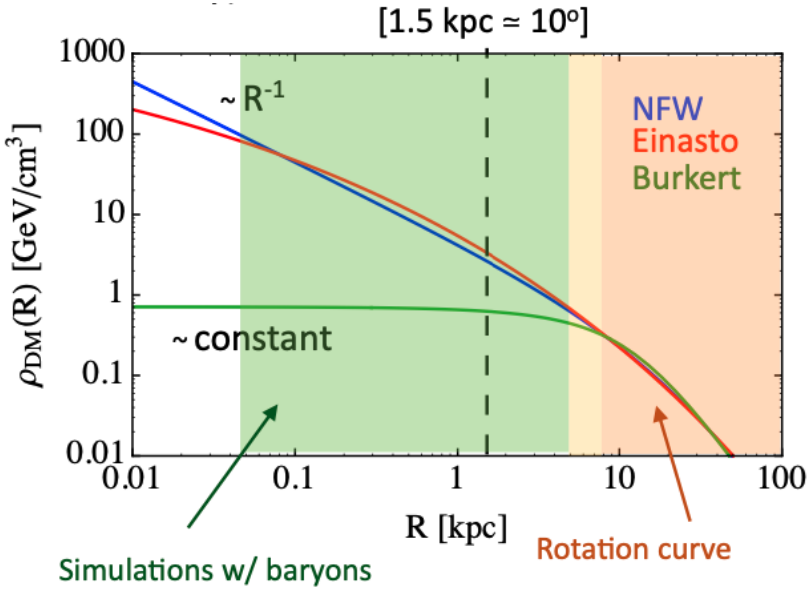
Fermi-LAT
Space telescope
20 MeV to 1 TeV

+ LHAASO

MeV GeV TeV

WIMP Landscape: A Theorist's View

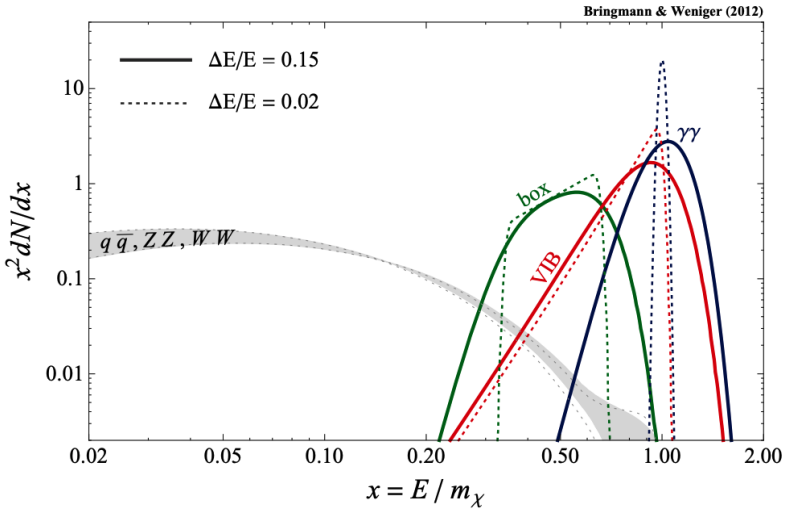
DM gamma-ray flux = $\int_{\Delta\Omega,\mathrm{los}} \rho_{DM}^2$ X $\frac{\langle\sigma v\rangle}{2M_{DM}^2}\sum B_i \frac{dN_\gamma}{dE}$



astrophysics J-factor

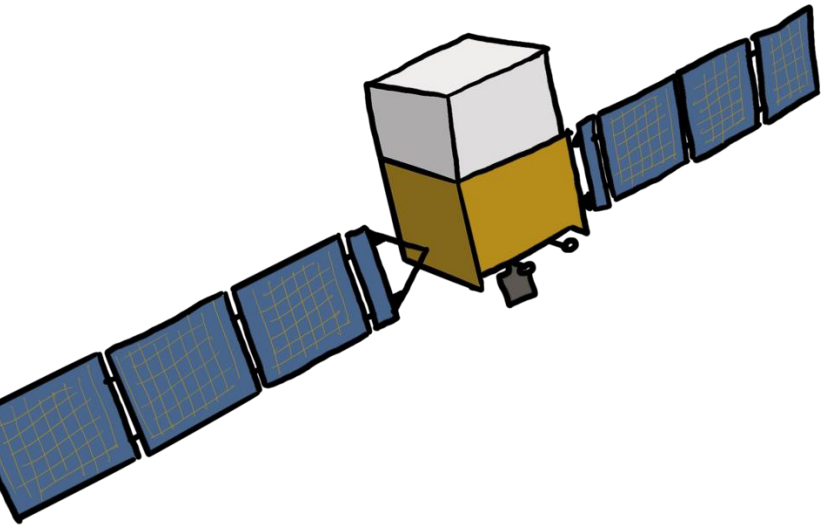
[Schaller+ '16, Calore+ '15]

Gamma-ray lines

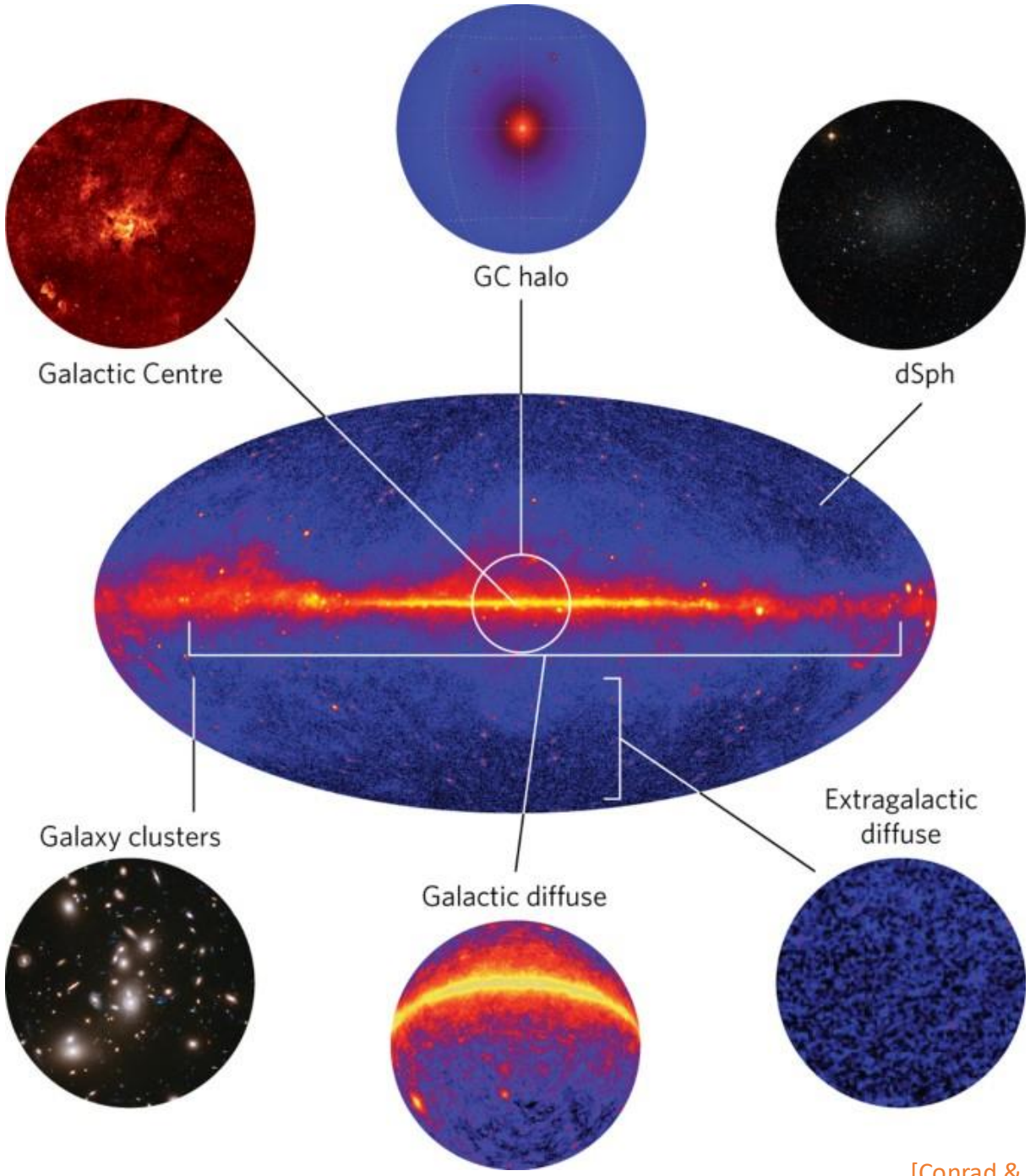


particle physics

[Iocco+ '15]

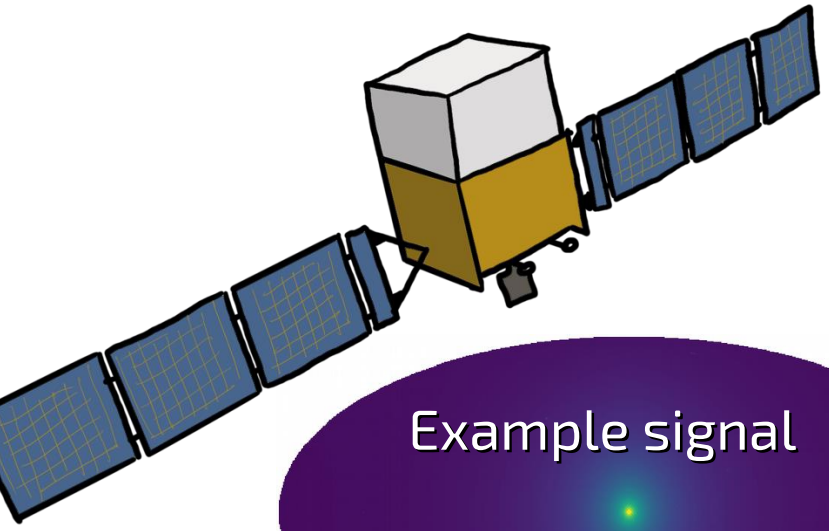


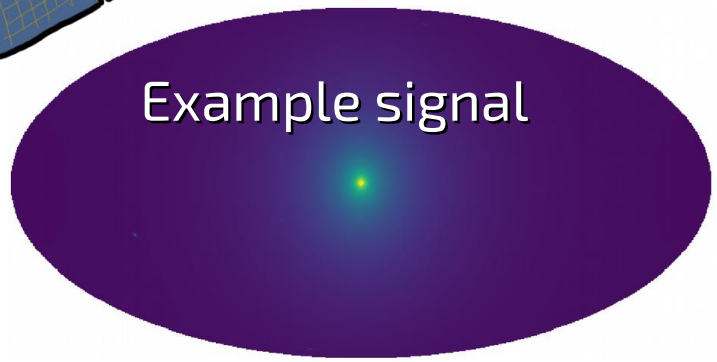
DM targets

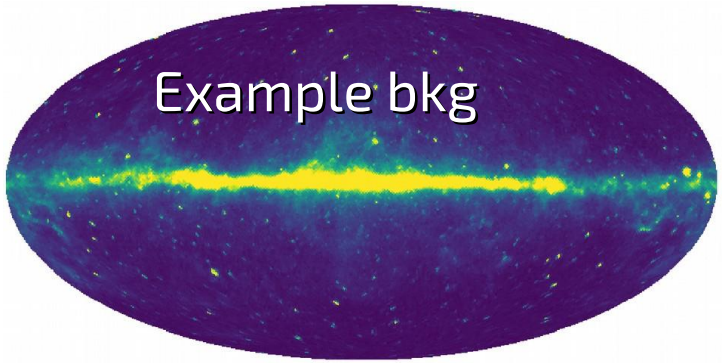


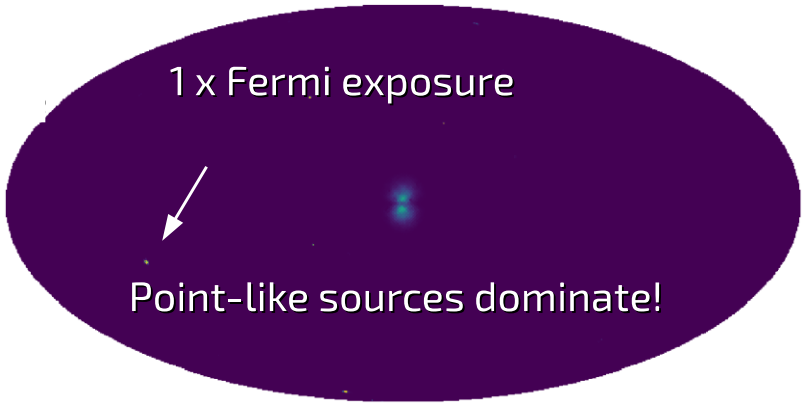
Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.
See papers by Rebecca Leane & Tim Linden

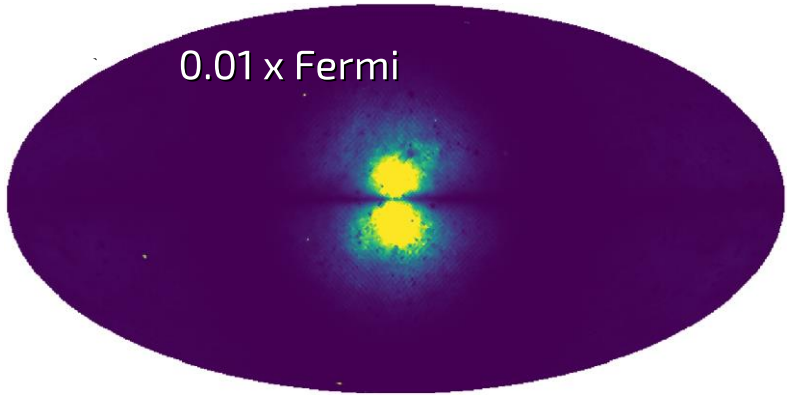
[Conrad & Reimer 201

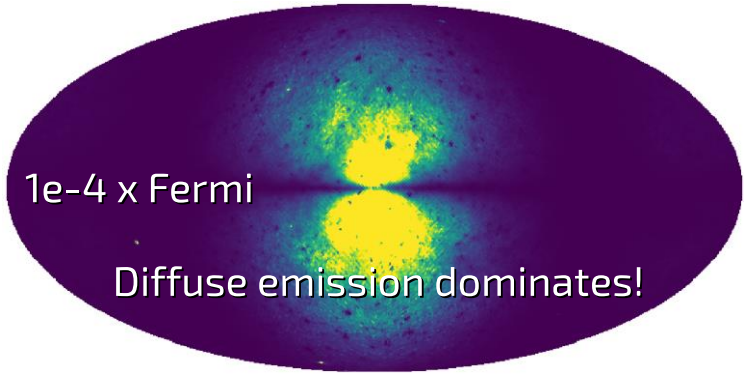






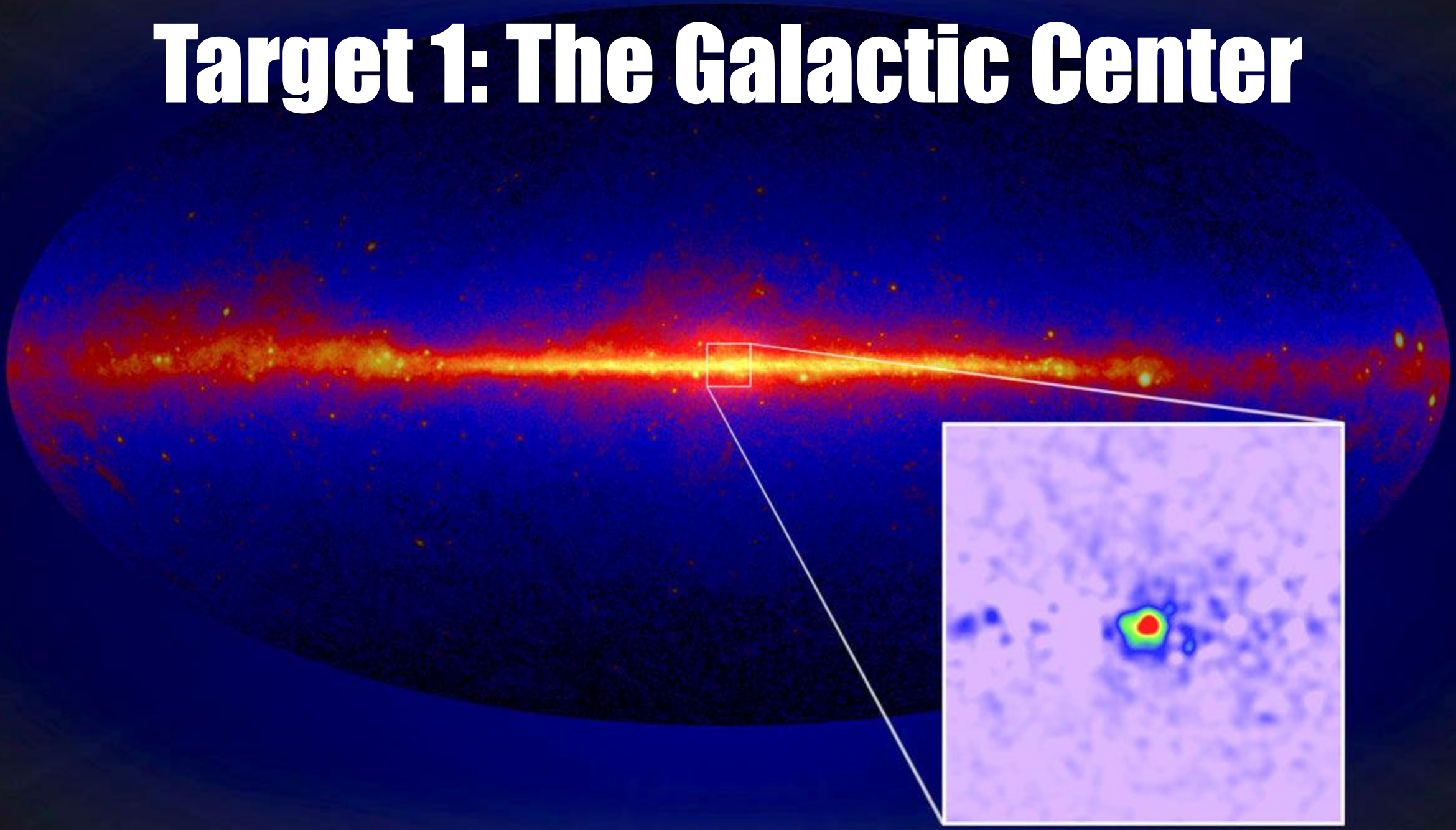






[Adapted from the *Fermi* Summer School]

Target 1: The Galactic Center



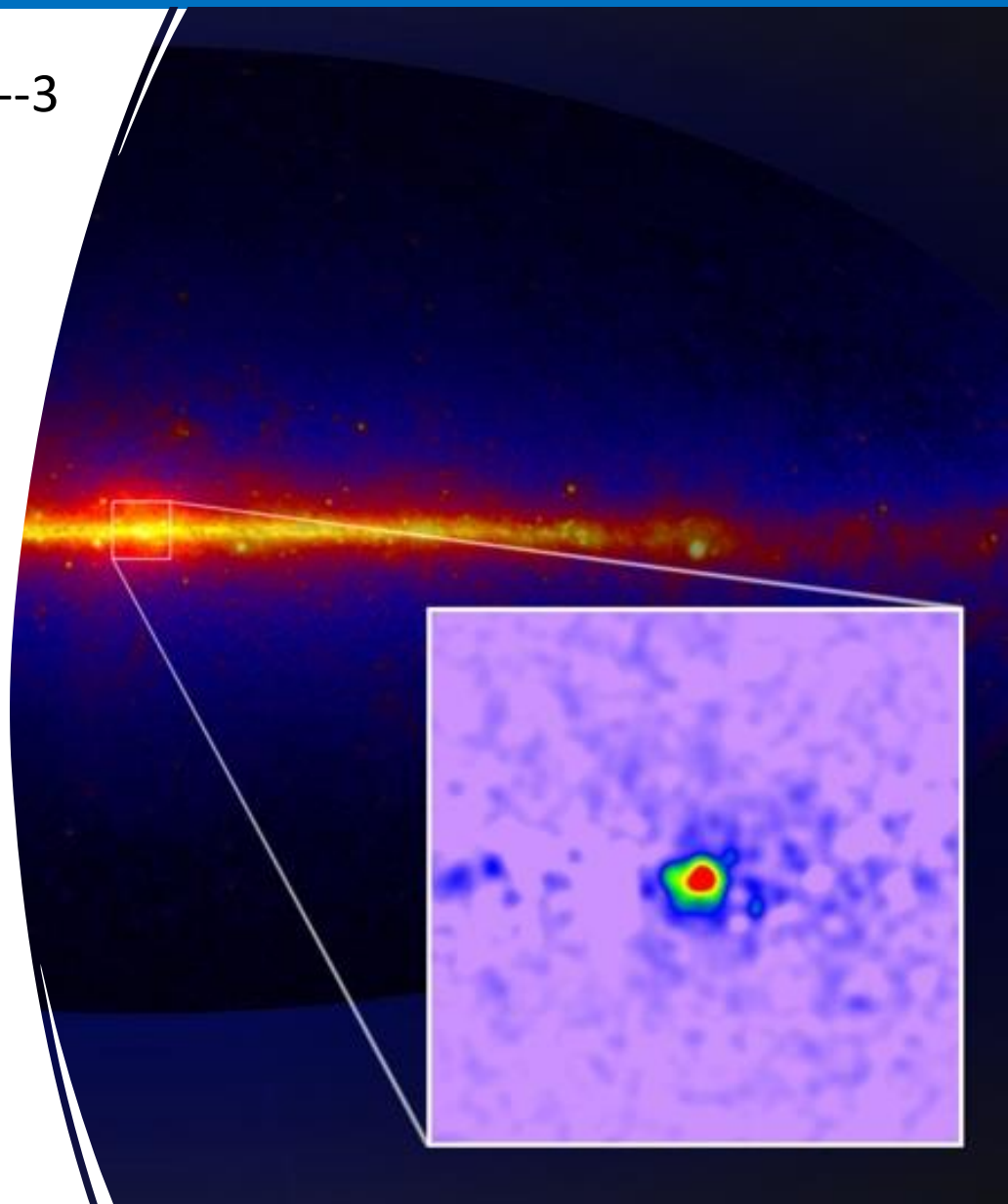
Credit: NASA/DOE/FERMI LAT COLLABORATION; T. LINDEN

Target 1: The Galactic Center

Credit: NASA/DOE/FERMI LAT COLLABORATION; T. LINDEN

Gamma rays from the Galactic Center

- Well-established bright excess in gamma rays (peaking at 1--3 GeV) detected in LAT
- Extended emission up to ~10 degrees (1.5 kpc)



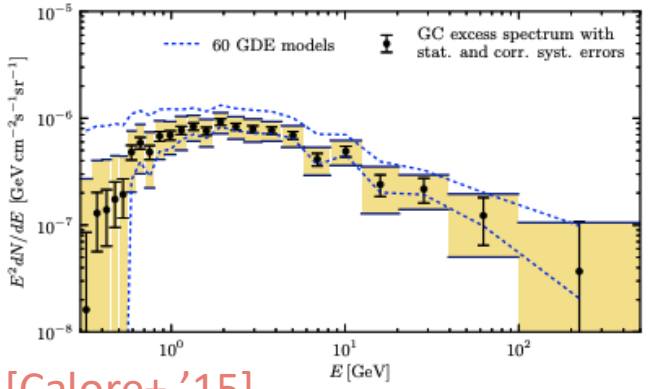
Hooper, Goodenough (2009, 2010) Hooper, Linden (2011)
Abazajian, Kaplinghat (2012) Gordon, Macias (2013) Daylan, et al. (2014)
Calore, Cholis, Weniger (2014) Murgia, et al. (2015) Ackermann et al. (2017)

Gamma rays from the Galactic Center

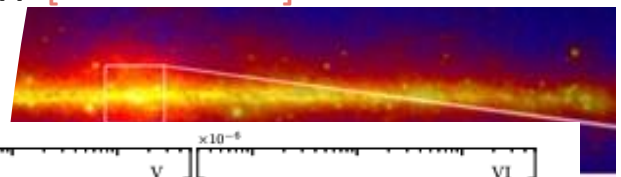
- Well-established bright excess in gamma rays (peaking at 1--GeV) detected in LAT
- Extended emission up to ~10 degrees (1.5 kpc)

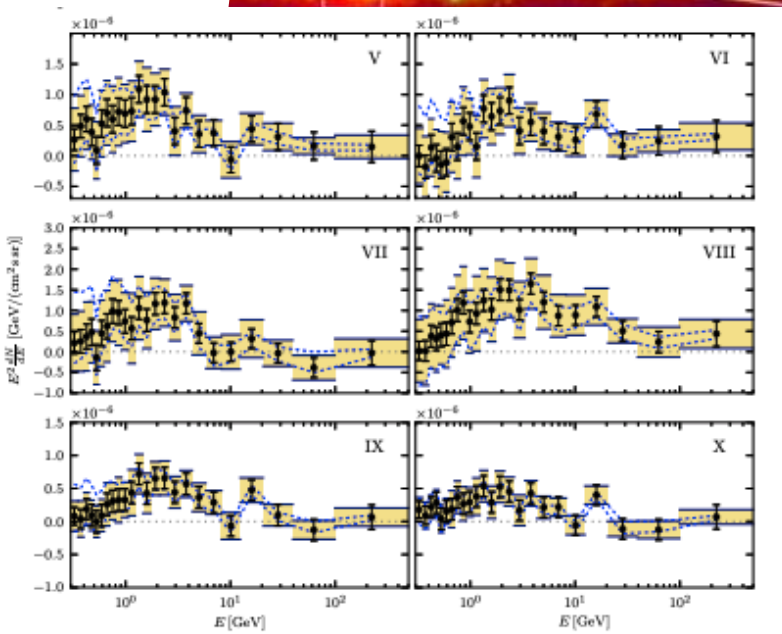
Maybe Dark Matter.

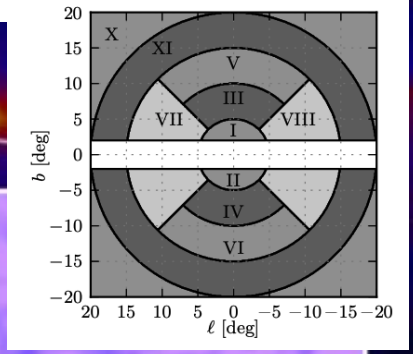
- Morphology approximately spherical, extending far out of th center
- Intensity well-fit by thermal particle dark matter
- Spectrum seemingly invariant with position and

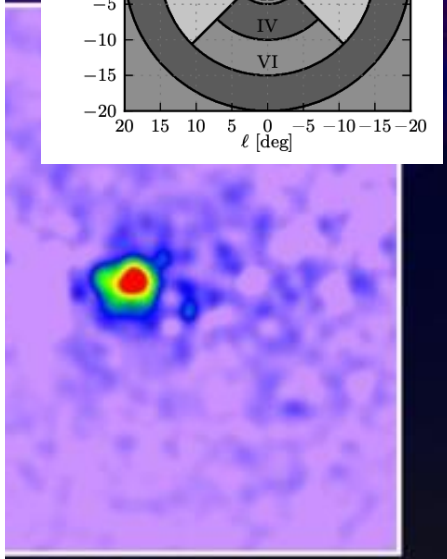


[Calore+ '15]







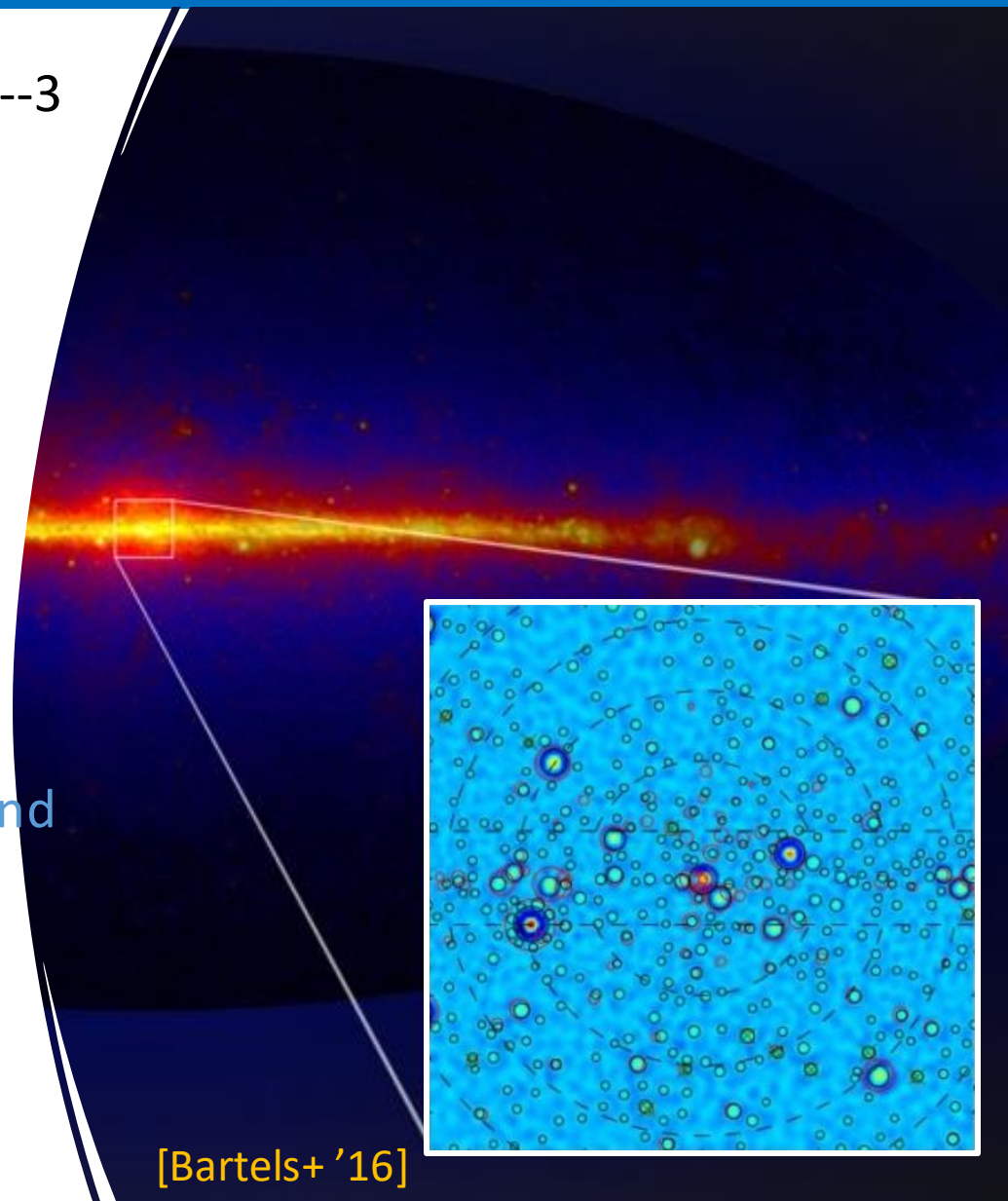


Gamma rays from the Galactic Center

- Well-established bright excess in gamma rays (peaking at 1--3 GeV) detected in LAT
- Extended emission up to ~10 degrees (1.5 kpc)

Maybe not. Milisecond Pulsars?

- Unresolved sources could collectively explain GCE
- **Dark matter is smooth.** Point sources are clumpy.
  - Non-Poissanian template fitting.
  - Wavelet transforms.
- [Lee+ ‘15, ‘16, Bartels+ ’16, Buschmann+ ‘20] and more…
- [Leane & Slatyer ’19, Zhong+ ‘19, Leane & Slatyer ’20a,b] and more…



[Bartels+ ’16]

Gamma rays from the Galactic Center

Where now?

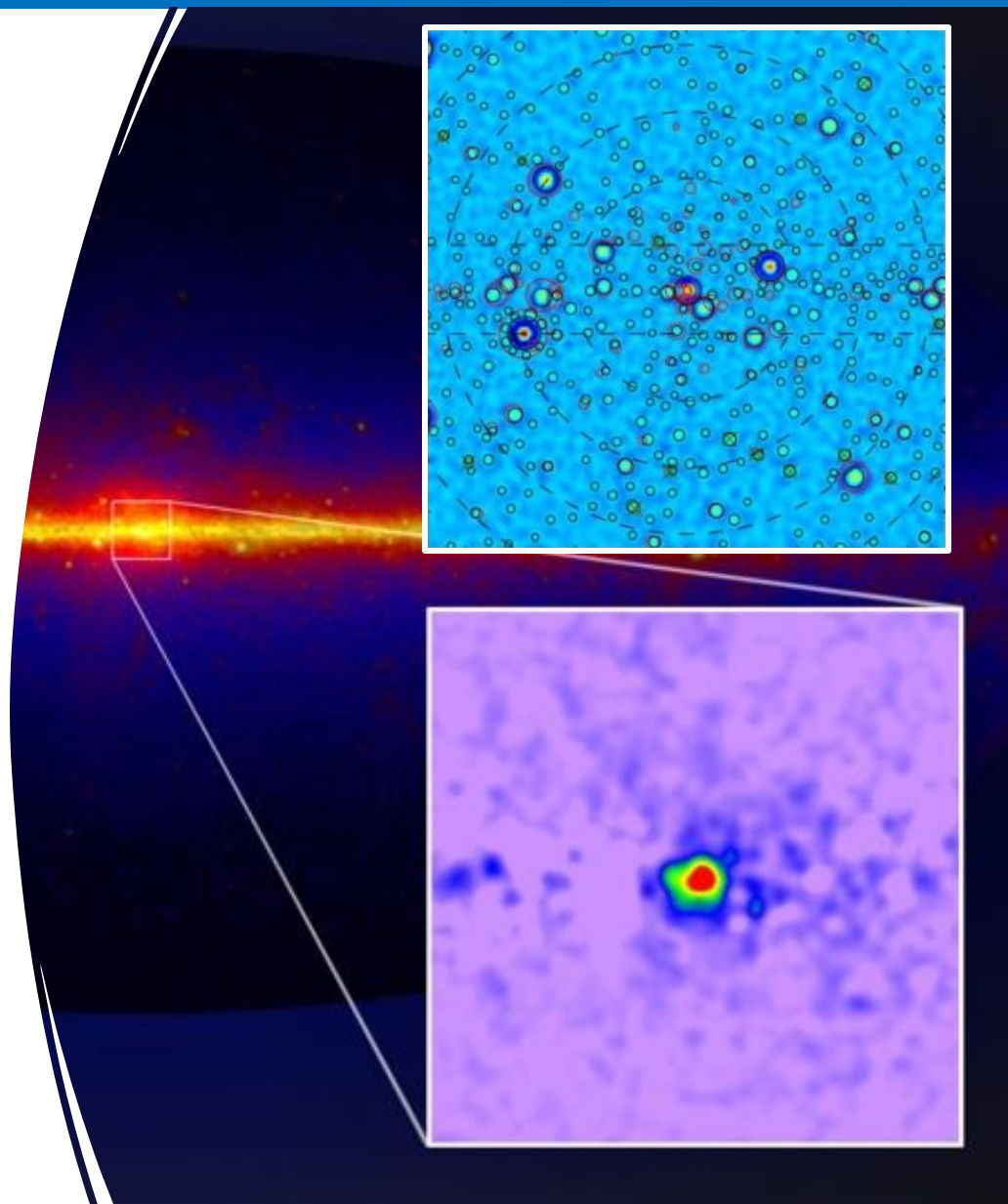
[2107.09070], [2110.06931], [2401.02481], [2402.05449], [2402.04733], [2002.12371], [1908.10874] [2211.09796] …

Questions considered in the last few months (Machine Learning approach):

-Does the total profile look like MSP or DM?

-Does it look clumpy of smooth?

-Did we reach the instrumental limits? What about theoretical models?



Gamma rays from the Galactic Center

Where now?

[2107.09070], [2110.06931], [2401.02481], [2402.05449], [2402.04733], [2002.12371], [1908.10874] [2211.09796] …

Questions considered in the last few months (Machine Learning approach):

-Does the total profile look like MSP or DM?

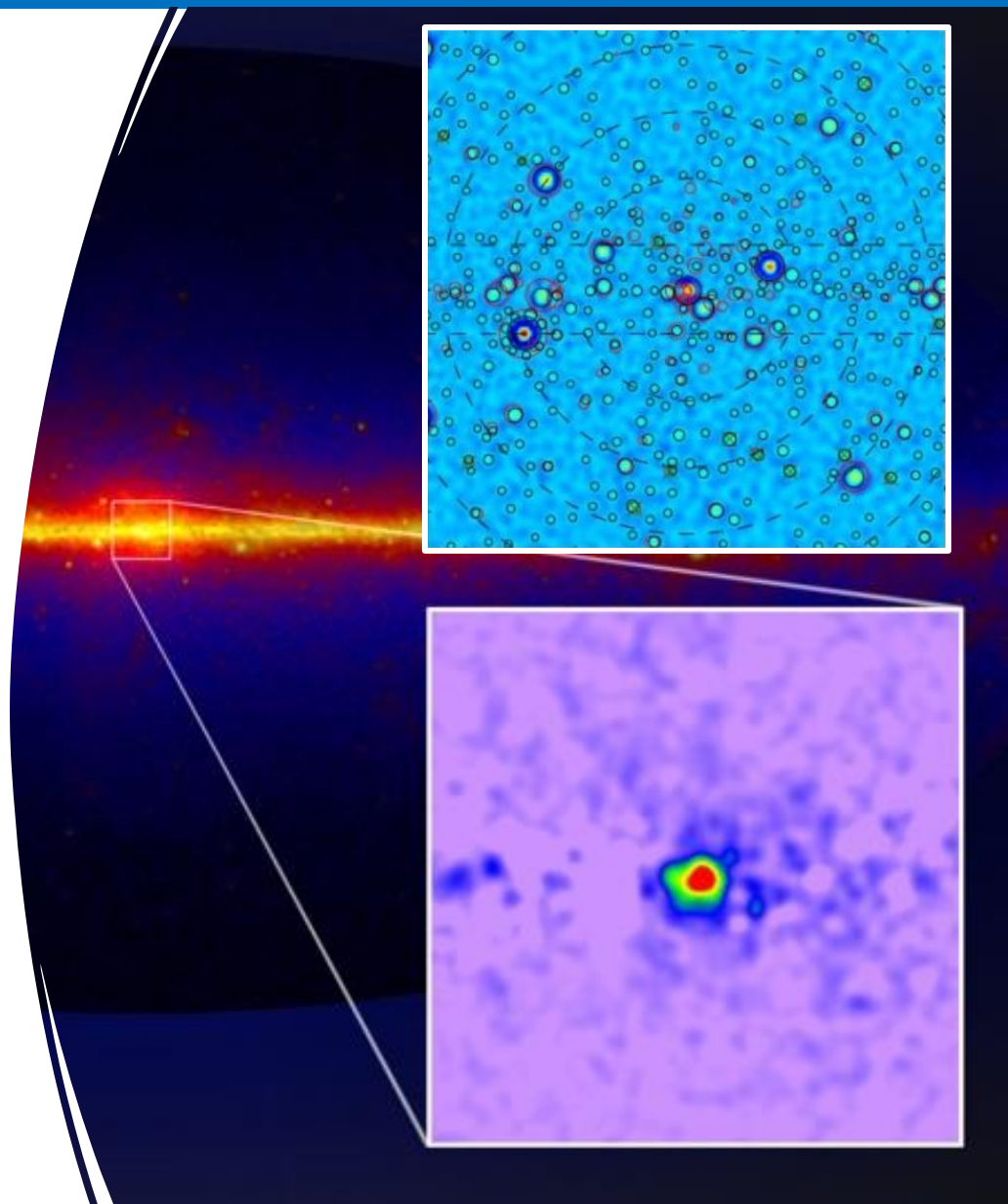
-Does it look clumpy of smooth?

-Did we reach the instrumental limits? What about theoretical models?

Diffuse models are not representative of the data

Confirming pulsars: future detections of radio emission by MeerKat and SKA

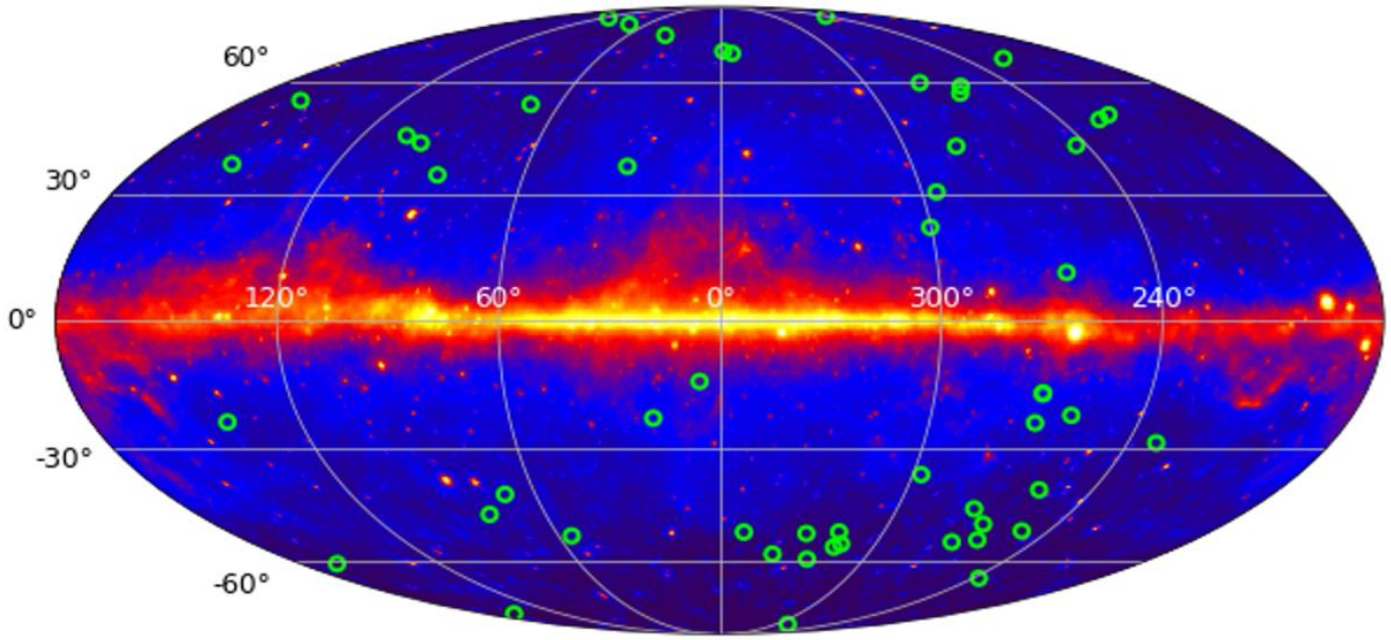
Confirming dark matter: check for signals elsewhere



Carina Dwarf Galaxy, ESO/G. Bono & CTIO

Target 2: dSphs

Dwarf Spheroidal Galaxies

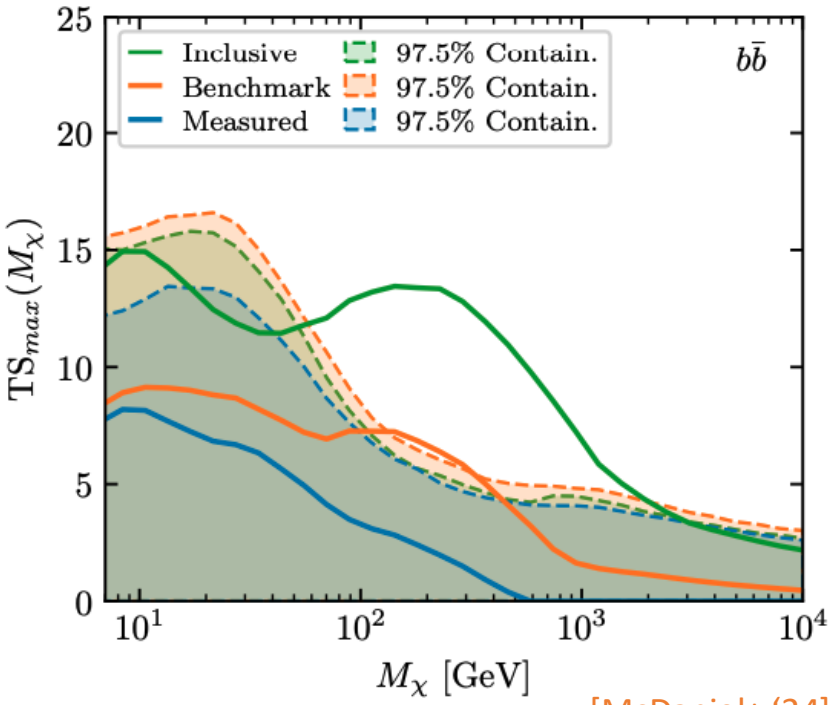


DM γ-ray flux = astrophysics J-factor x particle physics

$$\frac{d\Phi}{dE} \propto \int_{\Delta\Omega,\mathrm{los}} \rho_{DM}^2 \times \frac{\langle\sigma v\rangle}{2M_{DM}^2} \sum B_i \frac{dN_\gamma}{dE}$$

[Drlica-Wagner+ '20]

- 57 confirmed or possible dSphs)
- Variety of optical surveys, e.g. DES, PanSTARRs, other DECam surverys, Gaia, etc. (~75 % sky coverage)

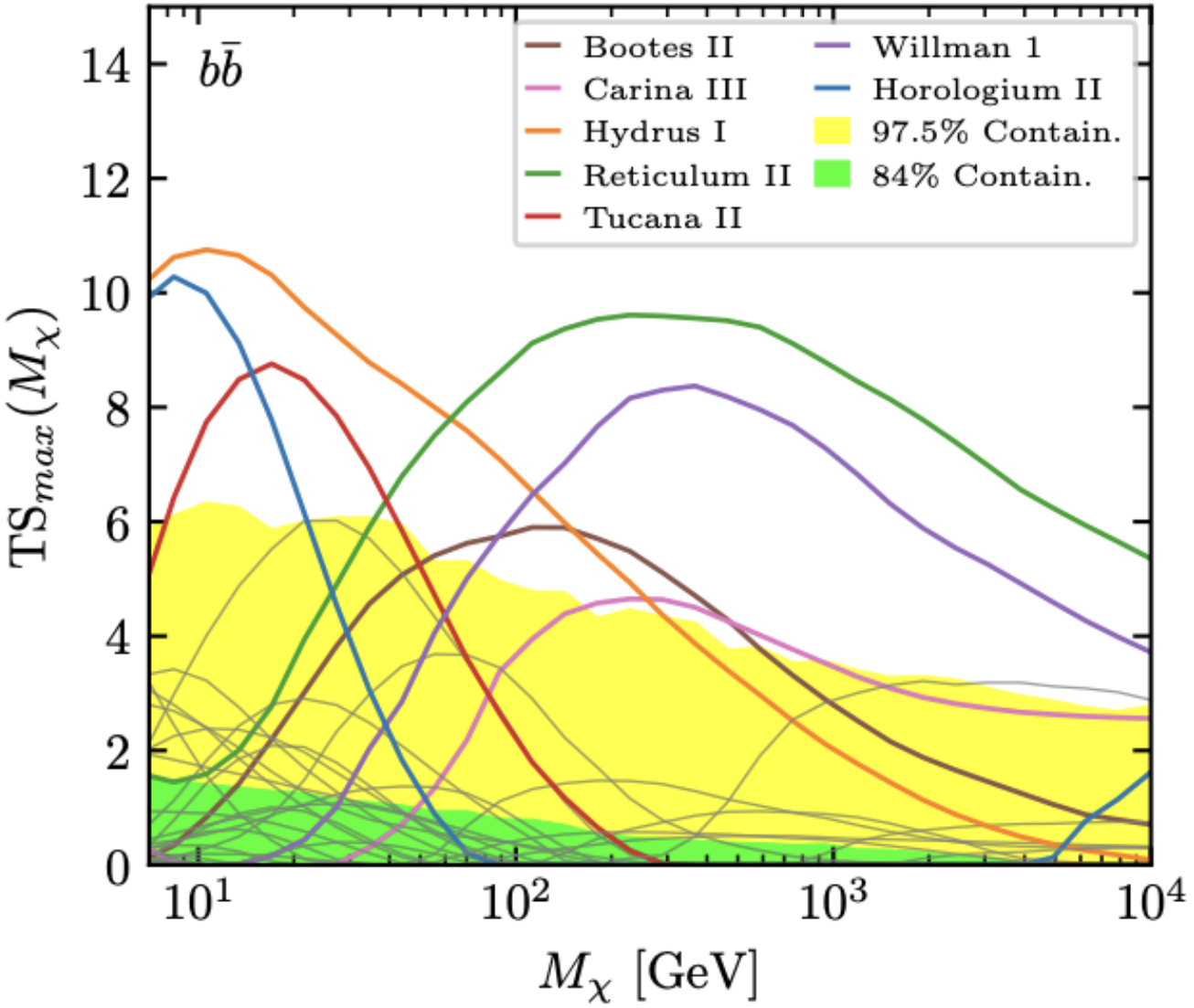


[McDaniel+ '24]

Combined dSph Analyses – 2024

7 dSphs with local significance $> 2\sigma$

… not the first time: some marginal significance reports in the past.



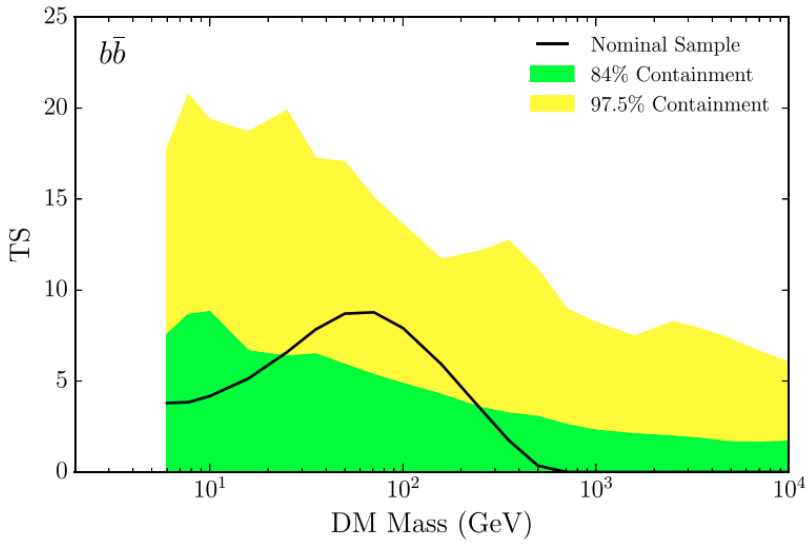
Ret II (DiMauro+ ‘21, Albert+ ‘17, Geringer-Sameth+ ‘15, Hooper & Linden ’15) Tucana II, Willman 1, Horologium II, Bootes I (DiMauro+ ‘21)

Think: $\sqrt{TS} \sim \sigma$

Combined dSph Analyses - Comparison

[Adapted from Fermi Symposium 2024]

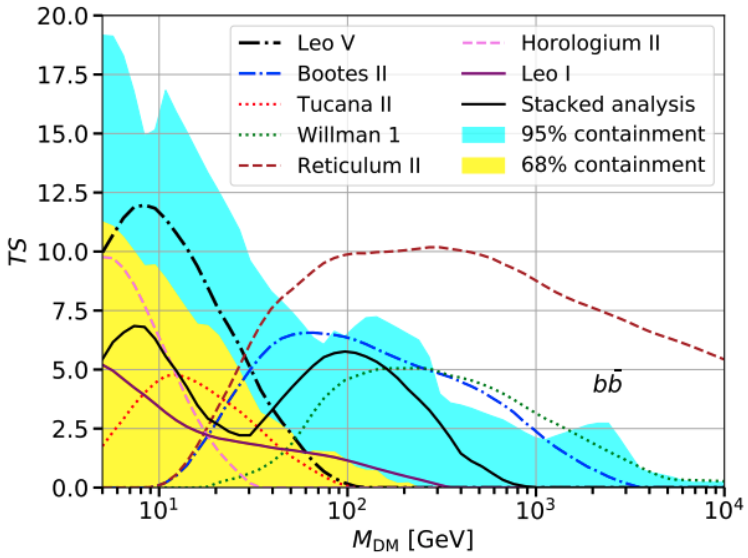
6 years



$< 2\,\sigma$

[Albert+ '17]

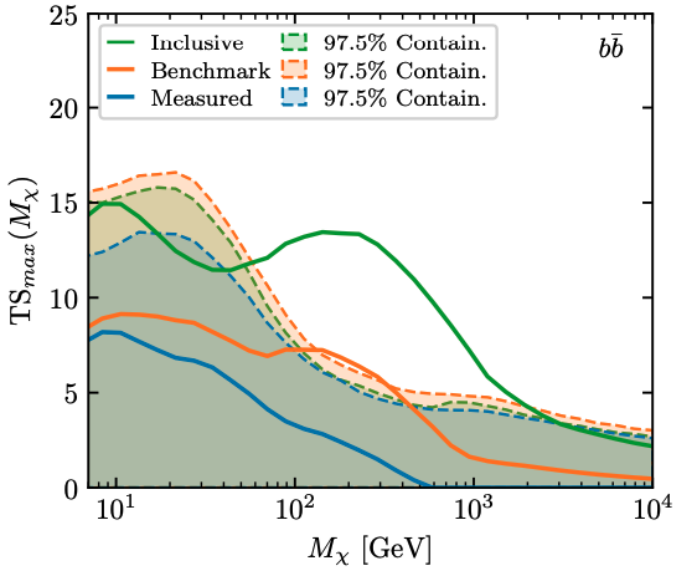
11 years



$\lesssim 2\,\sigma$

[DiMauro+ '21]

14 years



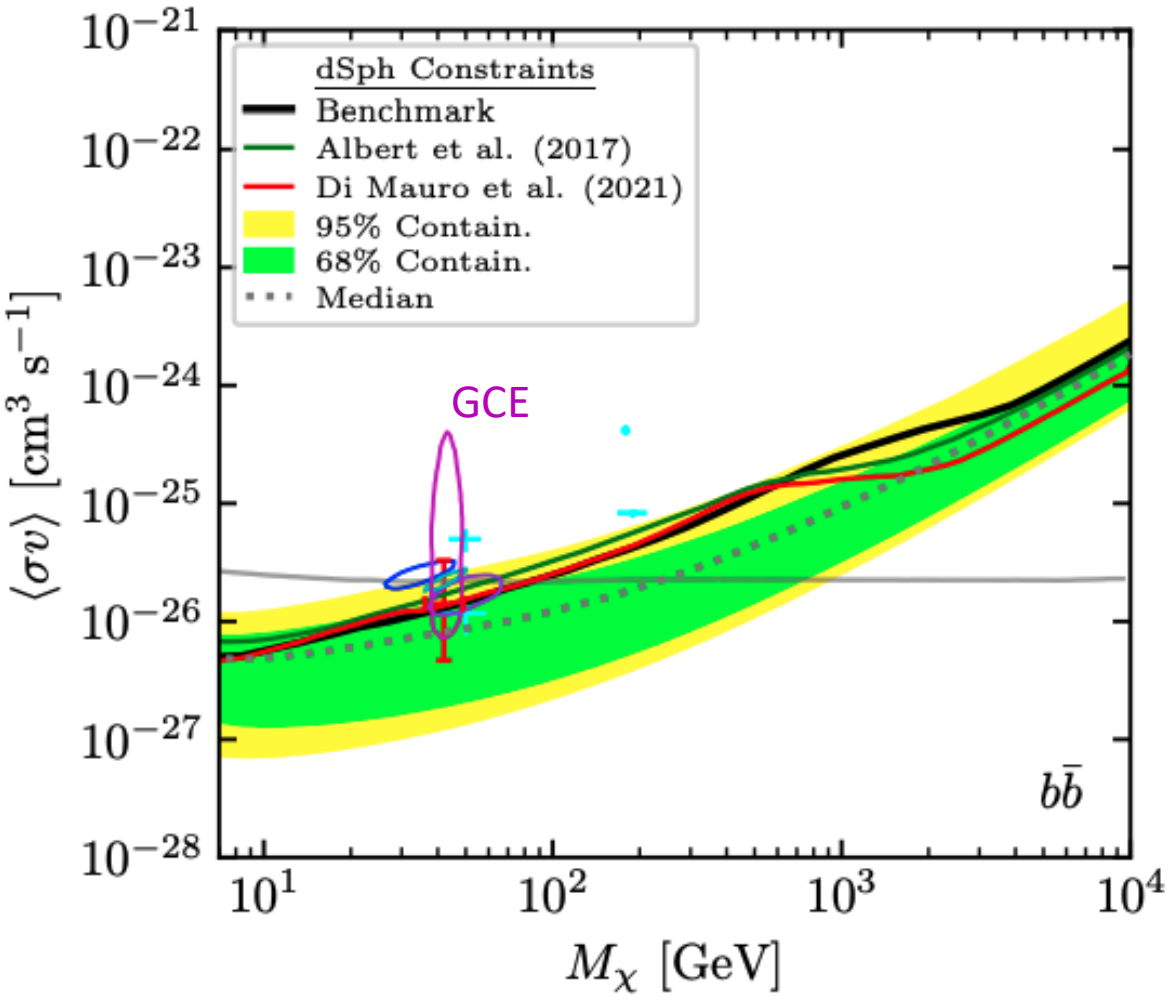
$\gtrsim 2\,\sigma$

[McDaniel+ '24]

Shaded regions: blank-field analysis

Think: $\sqrt{TS} \sim \sigma$

Limits on the parameter space



[McDaniel+ '24]

Trials factor reduces significance to 0.5 σ.

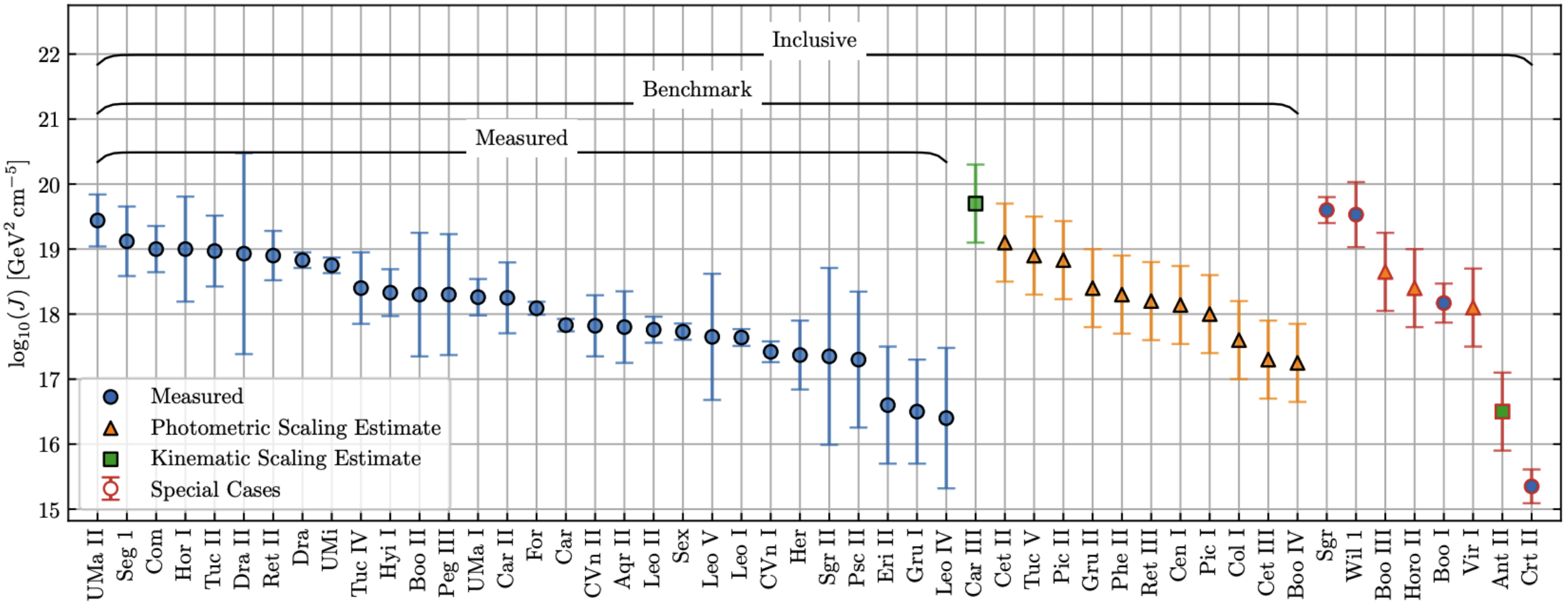
Observations:

- generally consistent with previous limits; *in tension with the GCE results*

- cannot rule out DM given the uncertainties in GC DM profile and diffuse model

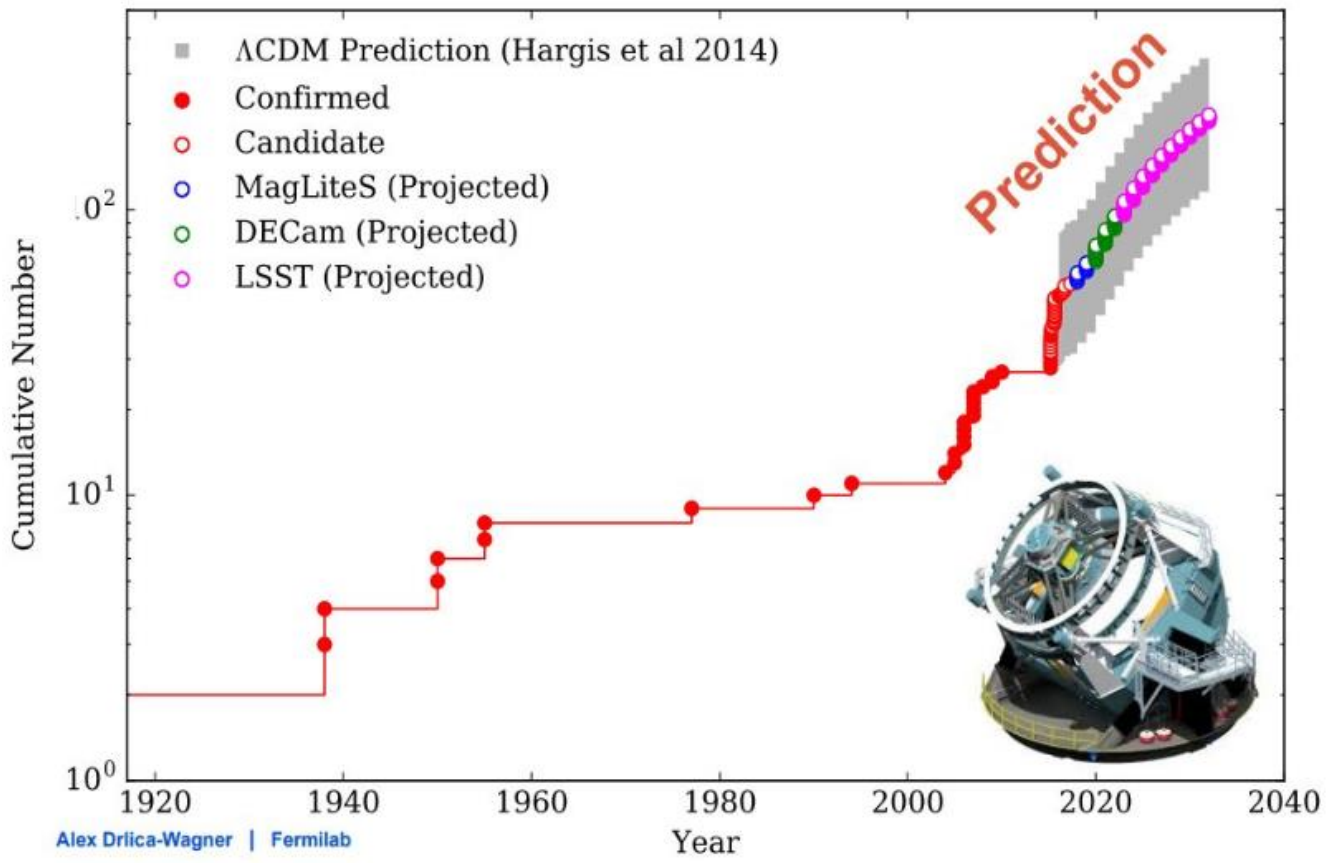
J-value calculations are... hard

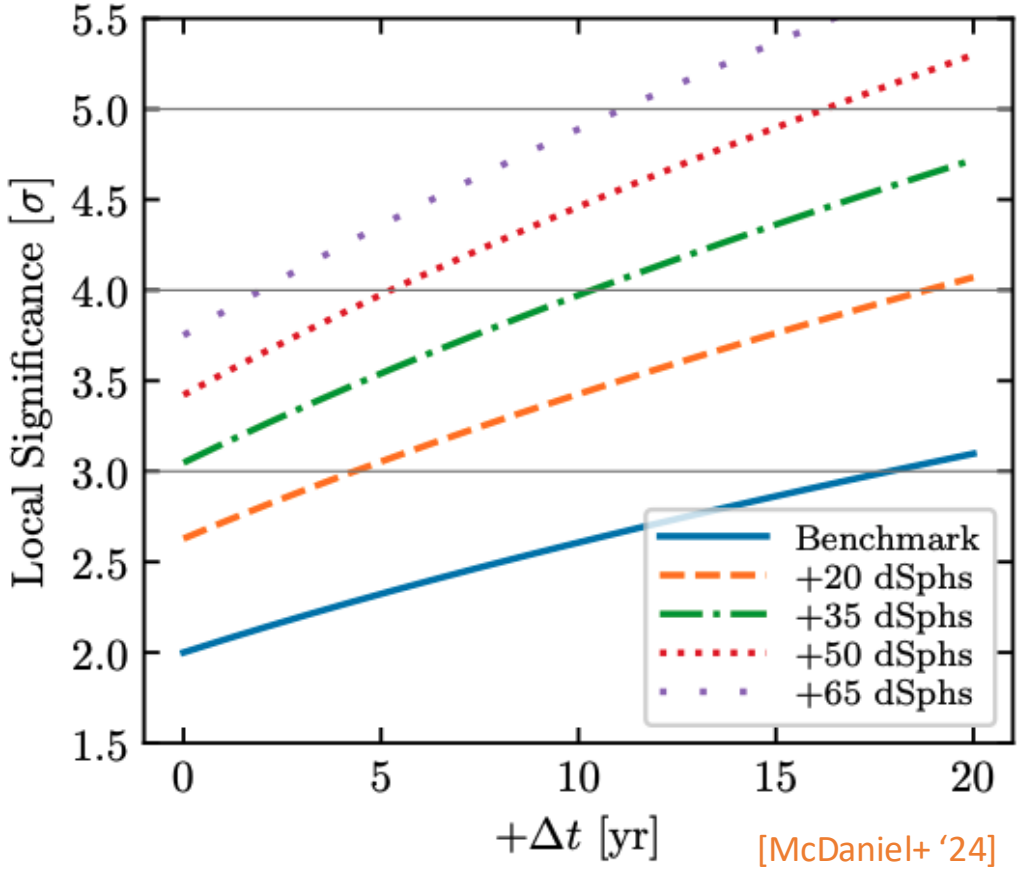
[McDaniel+ ‘24]



Many underlying assumptions: dark matter distribution models, parametric/non-parametric approaches, observational limitations – can result in at least a factor of few difference to the real value. [e.g., Bonnivard+ ‘15, Geringer-Sameth+ ’15, Hayashi+ ’16, etc.]

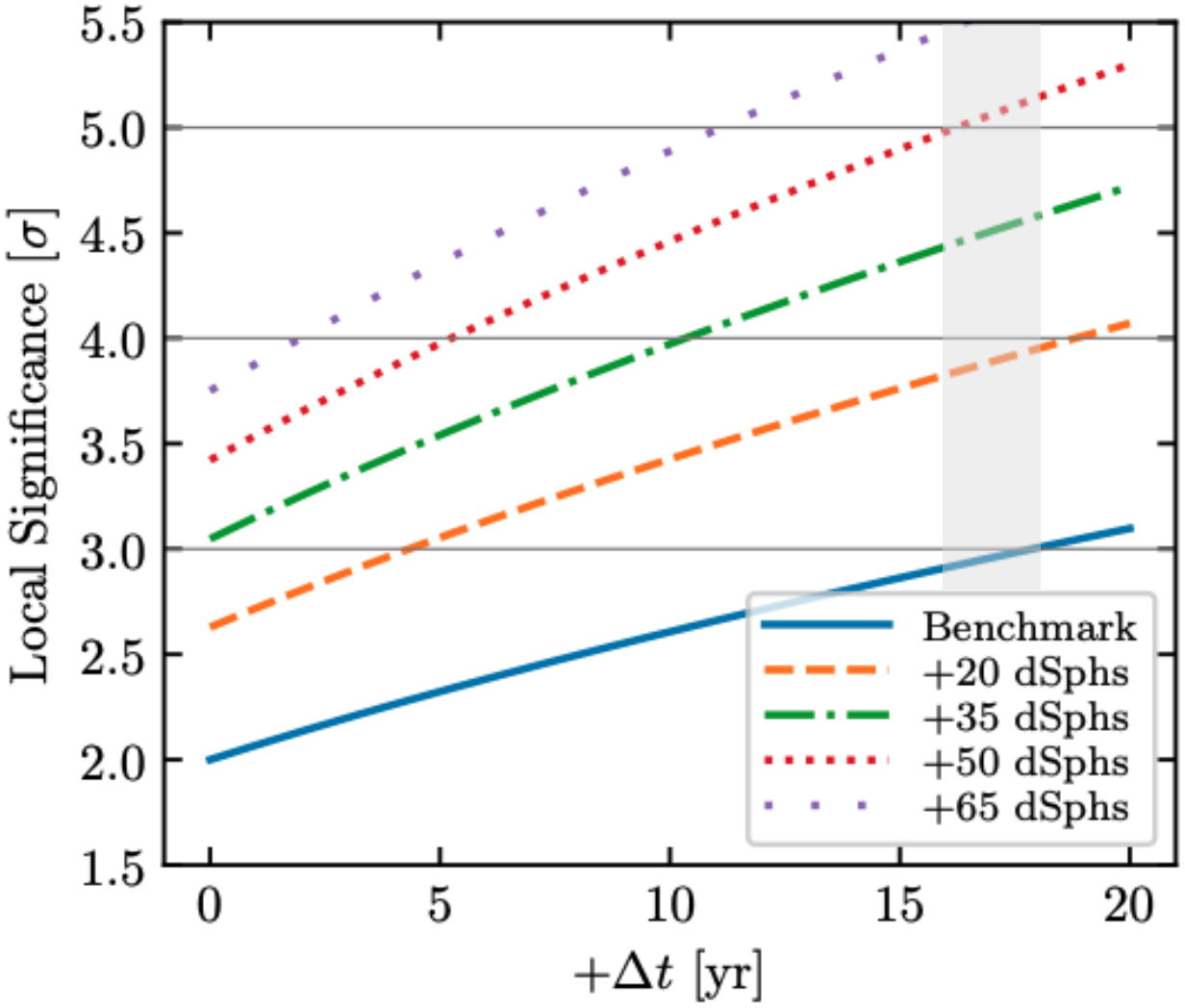
Future of dSph DM searches





[McDaniel+ '24]

Future of dSph DM searches



Sensitivity improves w/ exposure time as $\sigma \sim \sqrt{T_{\text{exp}}}$

[McDaniel+ '24]

How many dwarf galaxies do we *really* need?

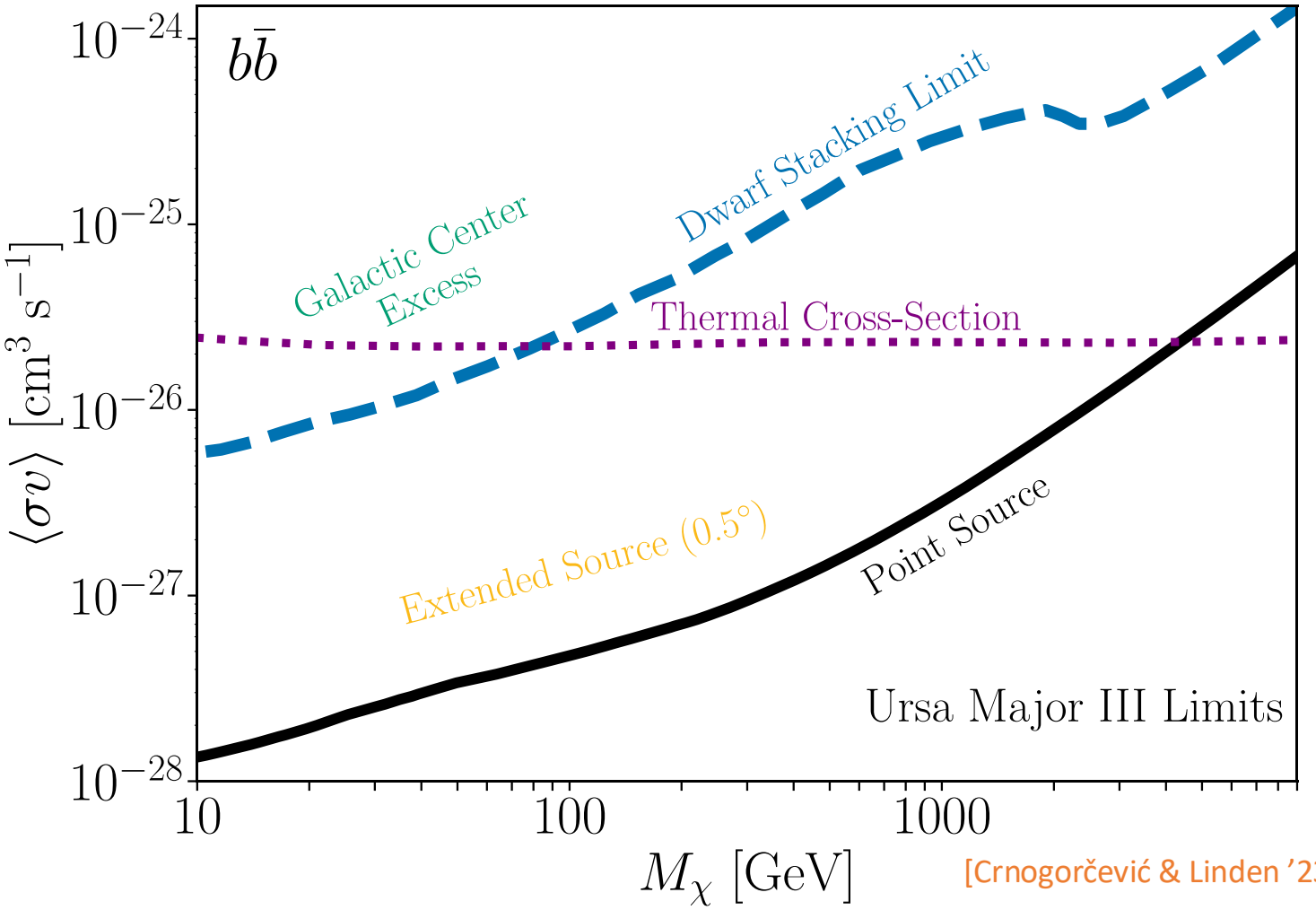
Maybe just one, but a good one?

Ursa Major III

[Discovery: Smith+ 2023]

[J-factor: Errani+ 2023]

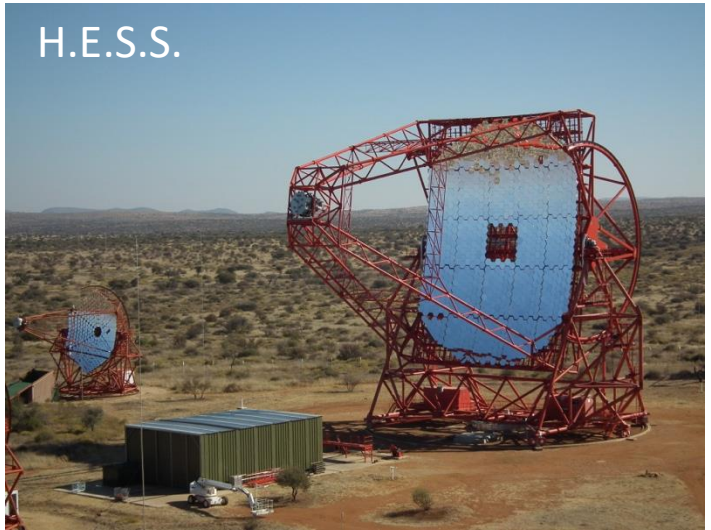
- Unstable unless large DM content
- Nearby (~10 kpc)
- Strong constraints on DM annihilation
- *Confirming the dark matt density…*



[Crnogorčević & Linden '23]

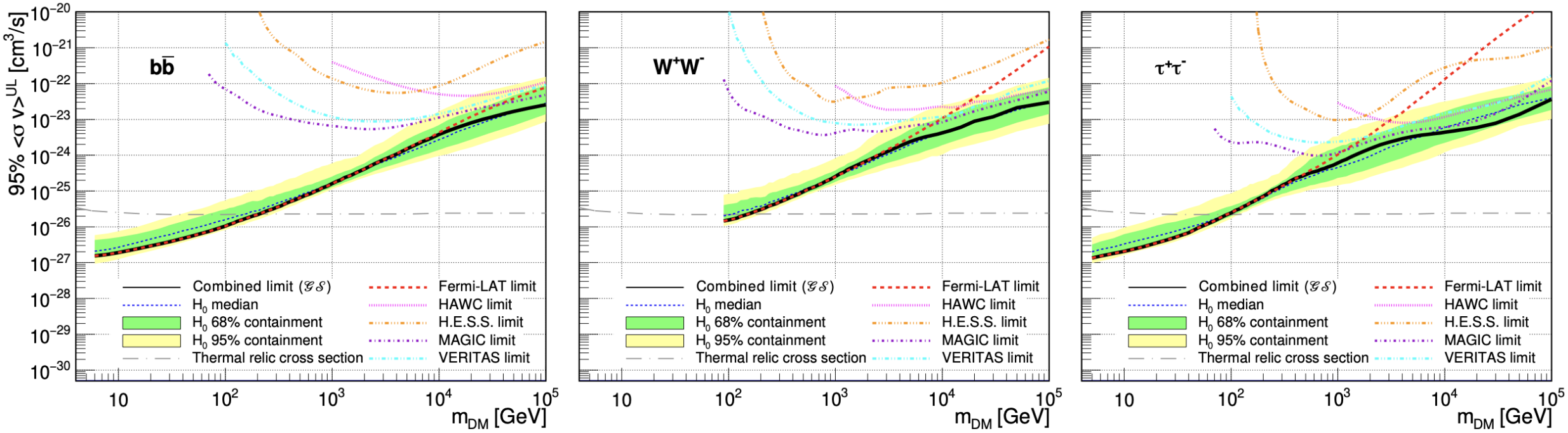
GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)

- Perform multi-instrument and multi-target analysis to obtain the most sensitive and robust results
- Joining likelihoods across instruments is challanging
- Focus: dSphs
- Limits driven by LAT sensitivity
- Legacy analysis of the current-generation gamma-ray instruments



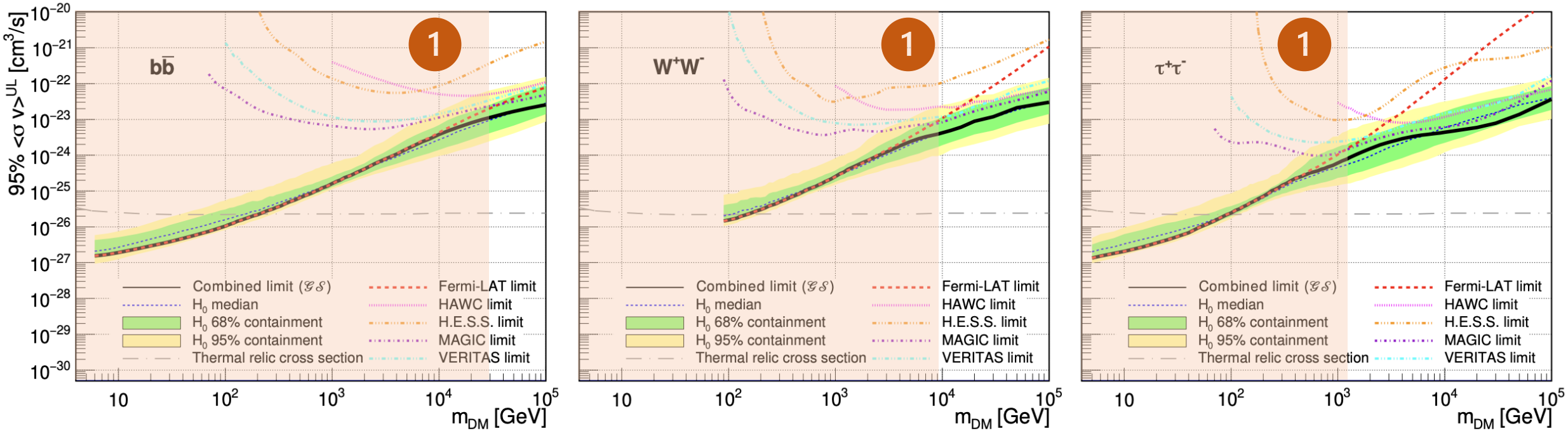
GLORY DUCK

GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)



As reported in Celina Armand TeVPA '22 talk.

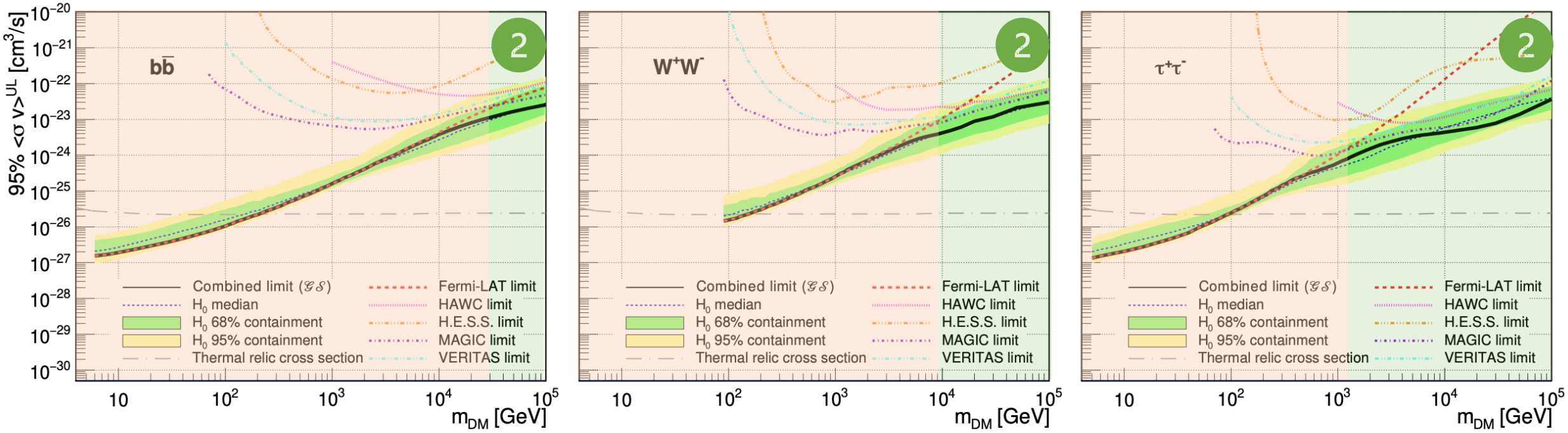
GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)



Dominated by *Fermi* LAT 1

As reported in Celina Armand TeVPA '22 talk.

GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)



HAWC, HESS, MAGIC, VERITAS take over 2

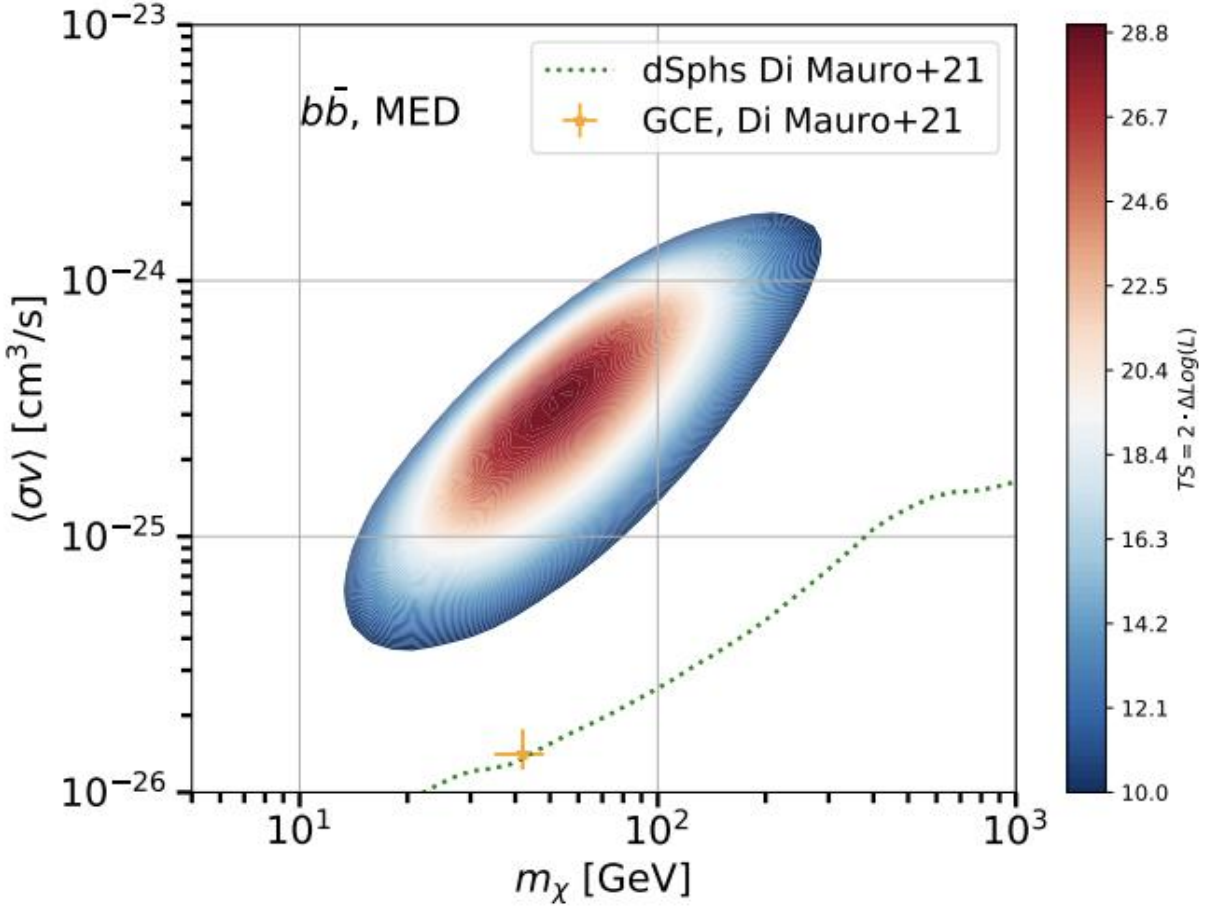
dark matter subhaloes, stellar streams, tidal disturbance/stripping of dwarfs, dark matter spikes, brown dwarfs, etc.

As reported in Celina Armand TeVPA '22 talk.

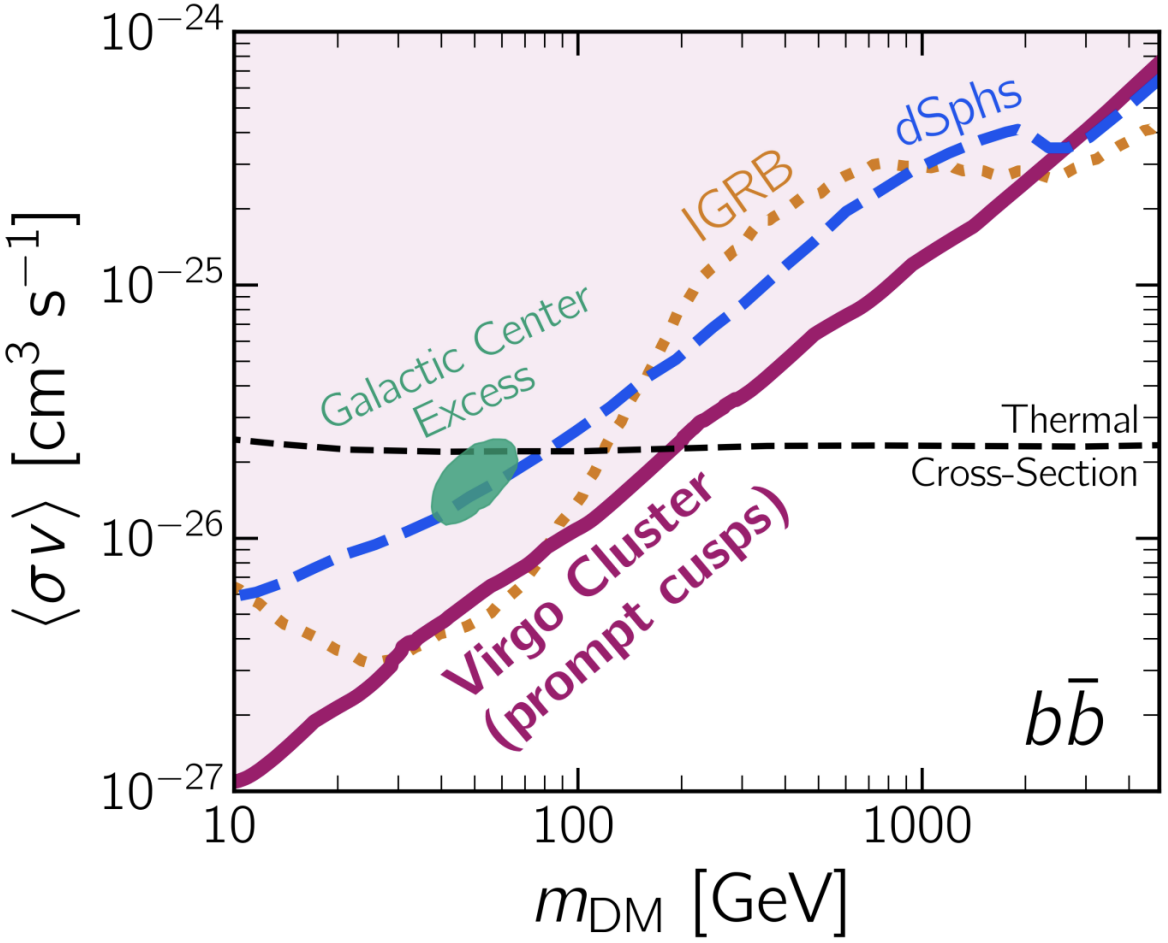
X-ray: NASA/CXC/CfA/M.Markevitch Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/

Briefly...

[DiMauro et al. 2023]



[Crnogorcevic et al. 2025]



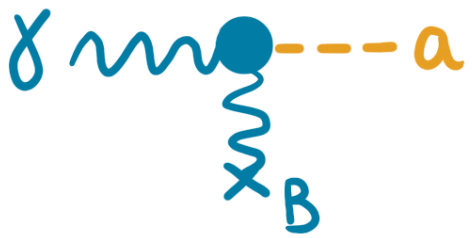

Standard Model
WIMP


Standard Model
AXION
HYPOTHETICAL ELEMENTARY PARTICLE
PROMISES TO
"CLEAN UP"
YOUR STRONG
CP PROBLEM!

Axion/ALP Landscape: An Observer's view

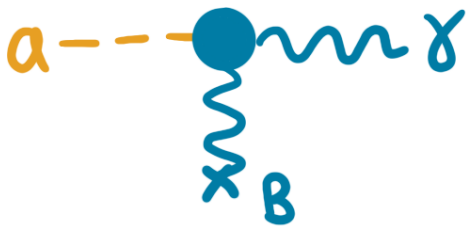
ALP/axion - photon interaction s

1. Primakoff process



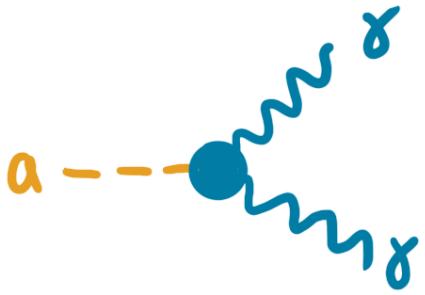
$\gamma \rightarrow a$

2. Inverse Primakoff



$a \rightarrow \gamma$

3. ALP/axion decay

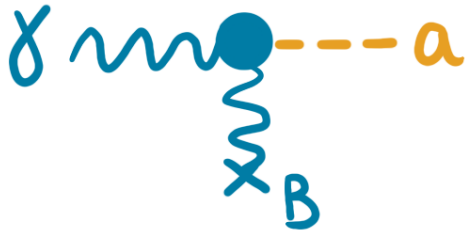


$a \rightarrow \gamma\gamma$

Axion/ALP Landscape: An Observer's view

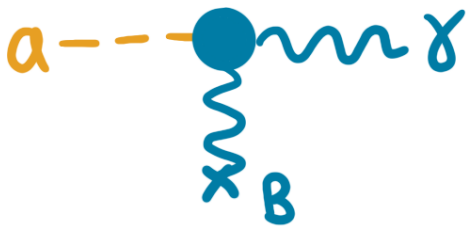
ALP/axion - photon interaction

1. Primakoff process



$\gamma \rightarrow a$

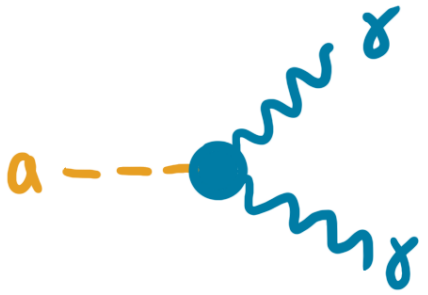
2. Inverse Primakoff



$a \rightarrow \gamma$

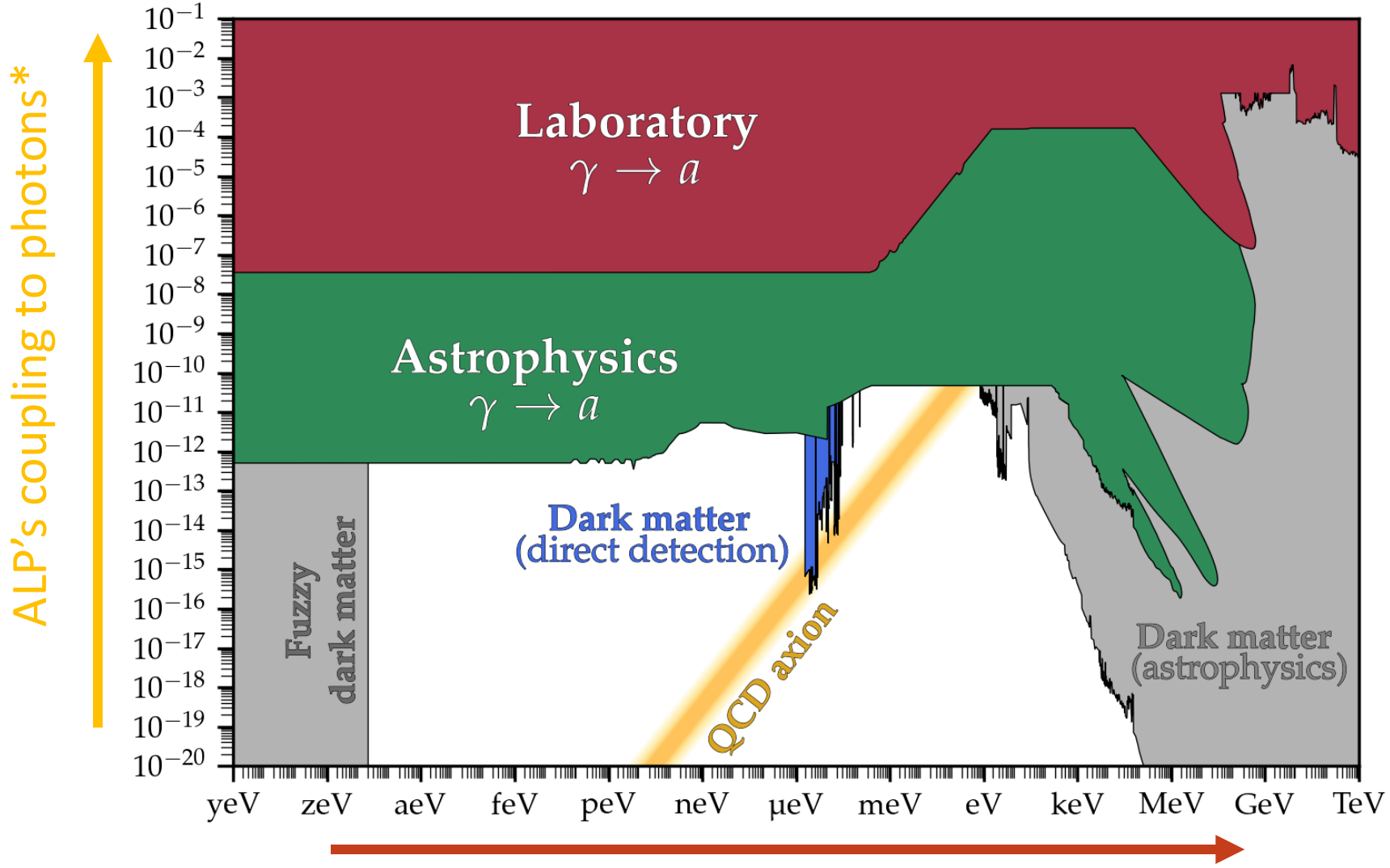
Line searches for $m_{\mathrm{alp}} < 1$ MeV.
→ Signatures in radio, IR, and X-rays.

3. ALP/axion decay



$a \rightarrow \gamma\gamma$

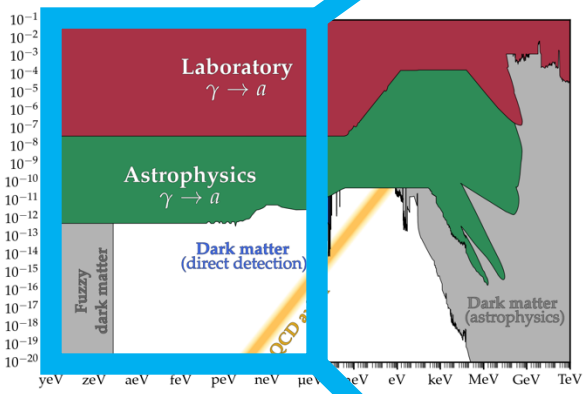
Axion/ALP Landscape: An Observer's view

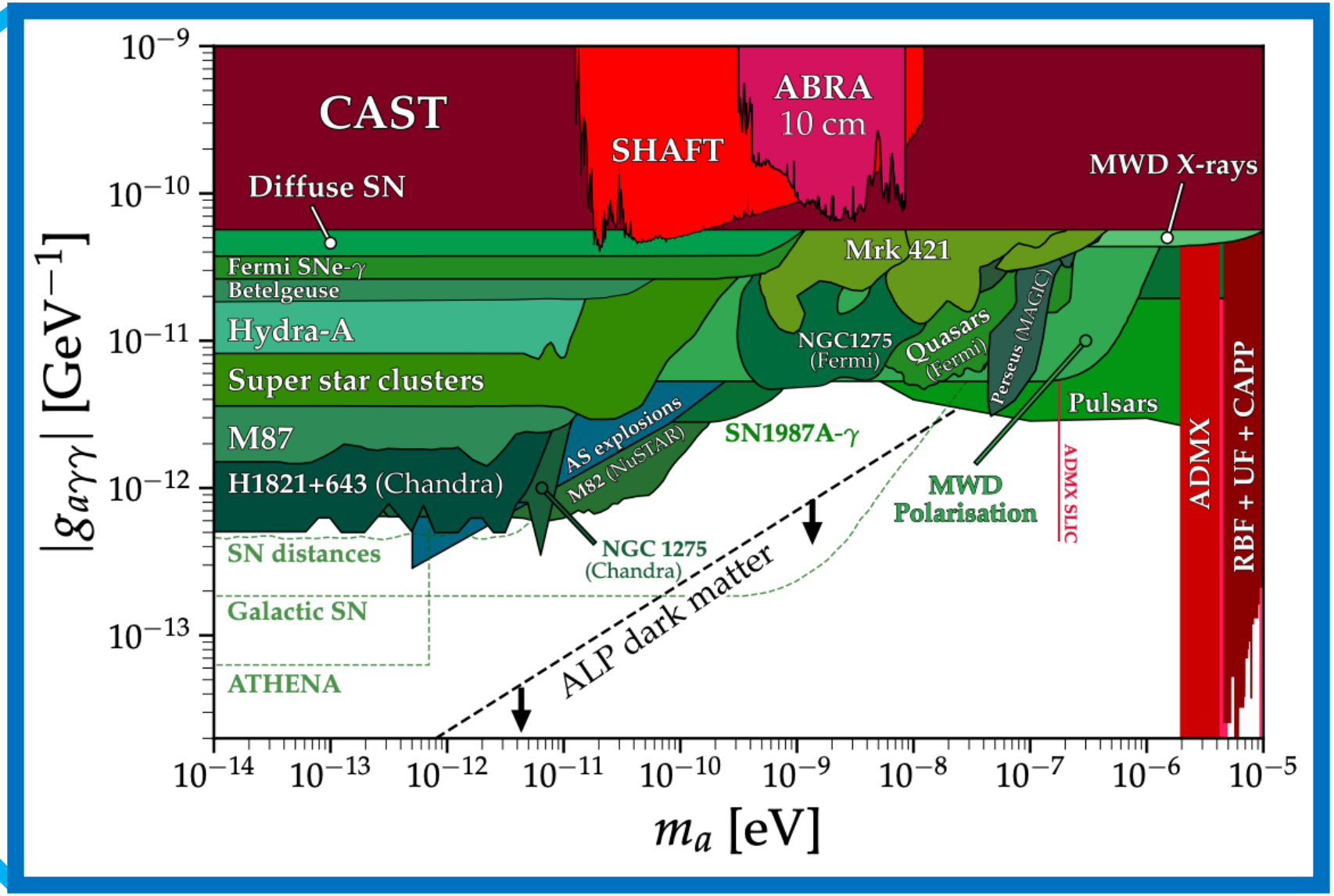


*analogous to a WIMP cross-section

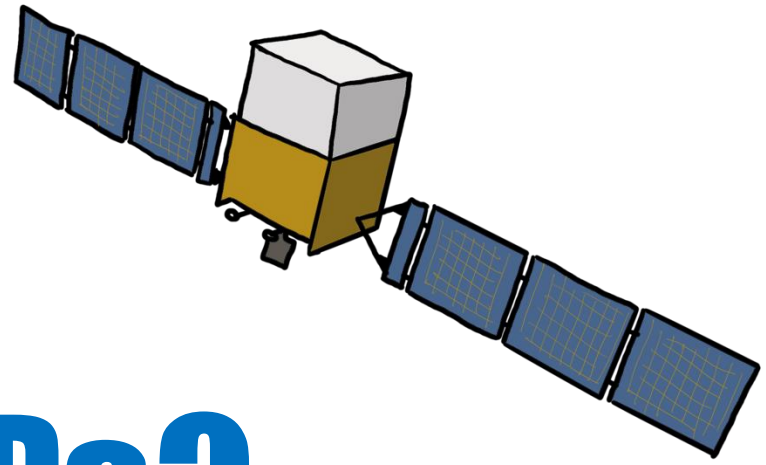
Plot produced using: https://cajohare.github.io/AxionLimits/

Axion/ALP Landscape: An Observer's view



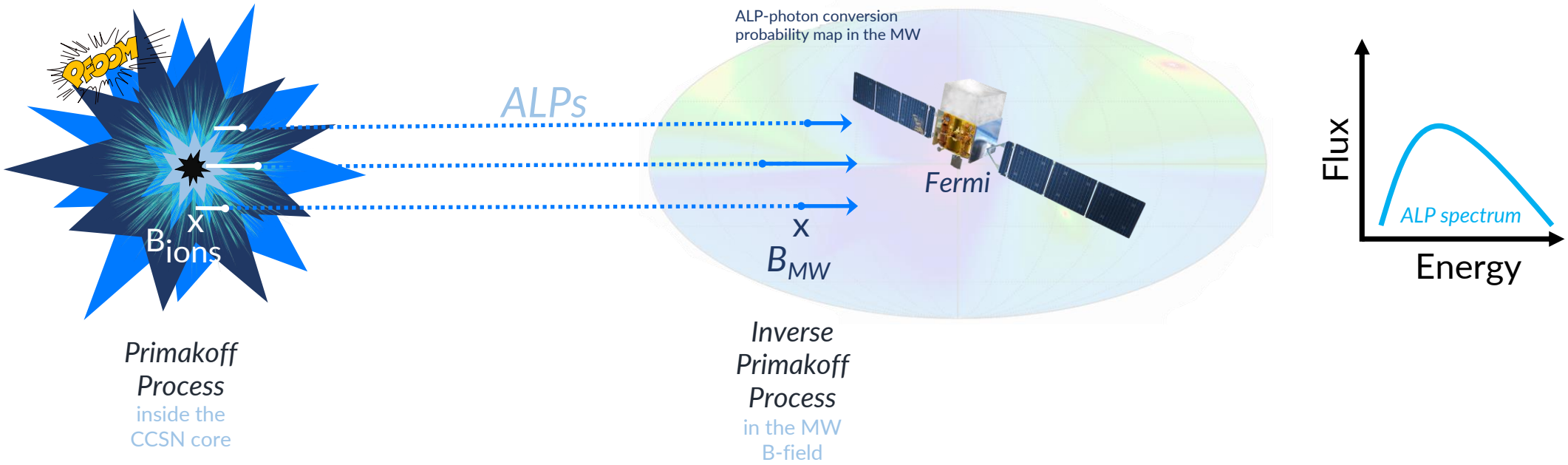


Plot produced using: https://cajohare.github.io/AxionLimits/



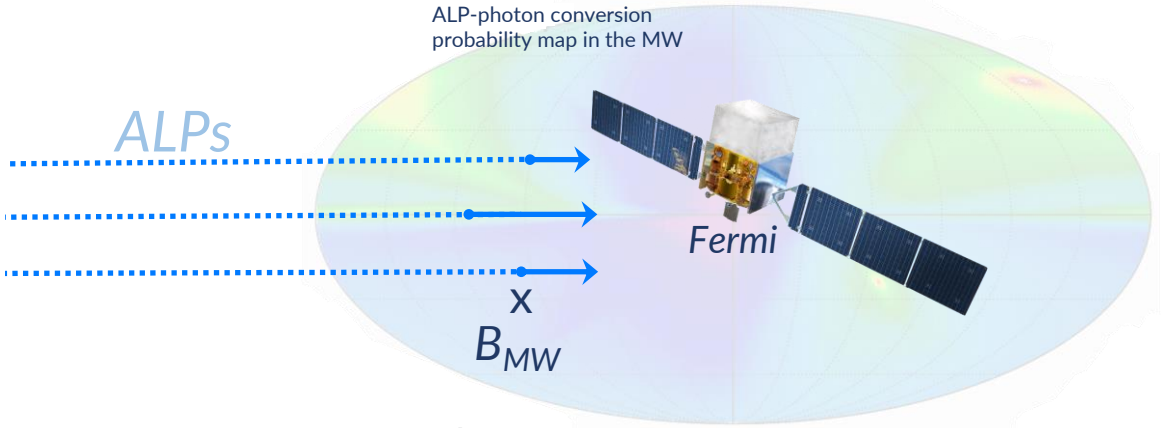
Where to look for ALPs?

Photon from in-source conversions

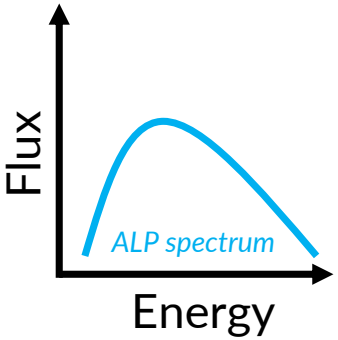


Photon from in-source conversions

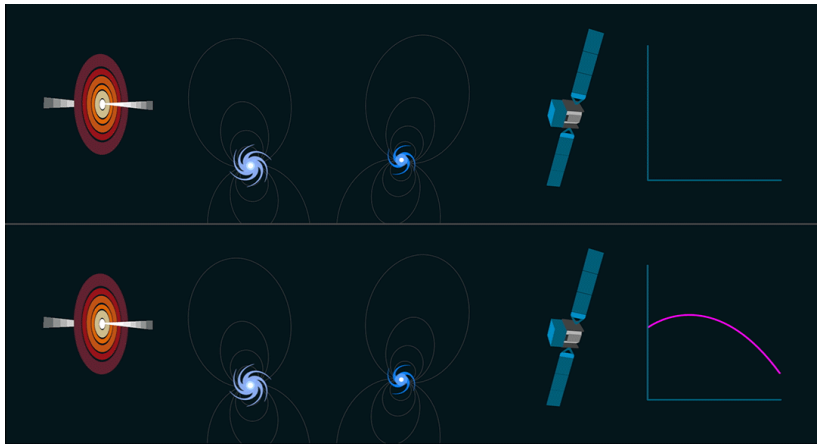
AGN, blazars, etc.



Inverse Primakoff Process in the MW B-field



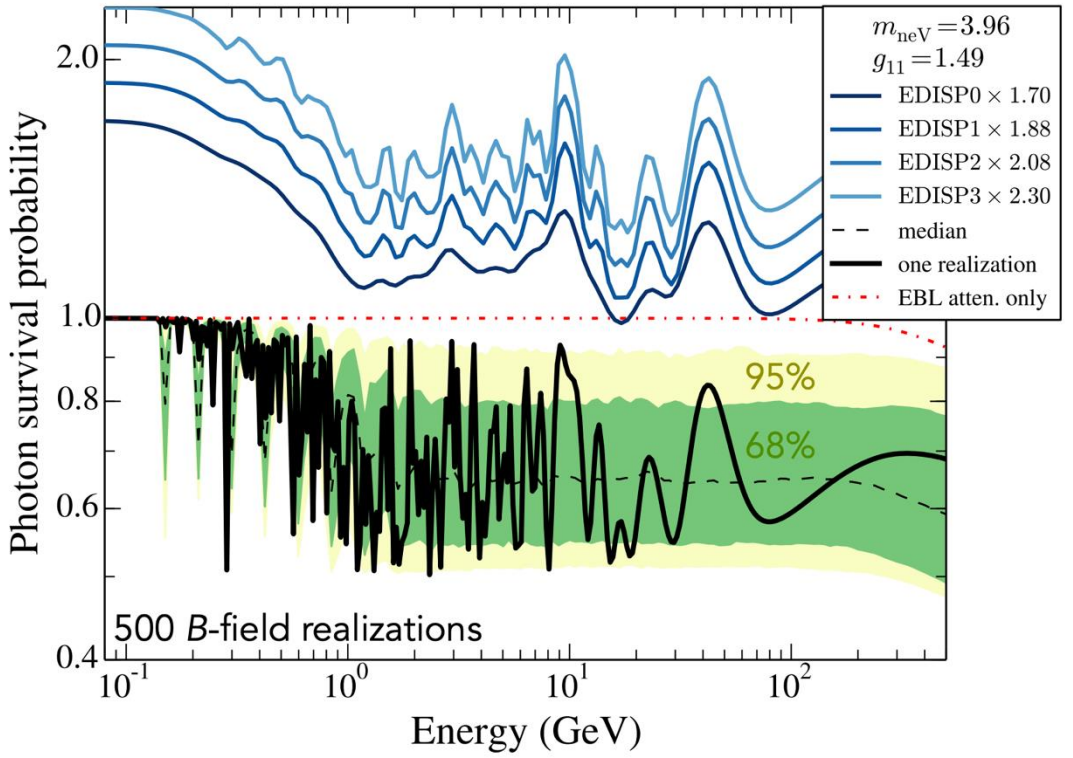
Extended Gamma-ray Sources



[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 Meye

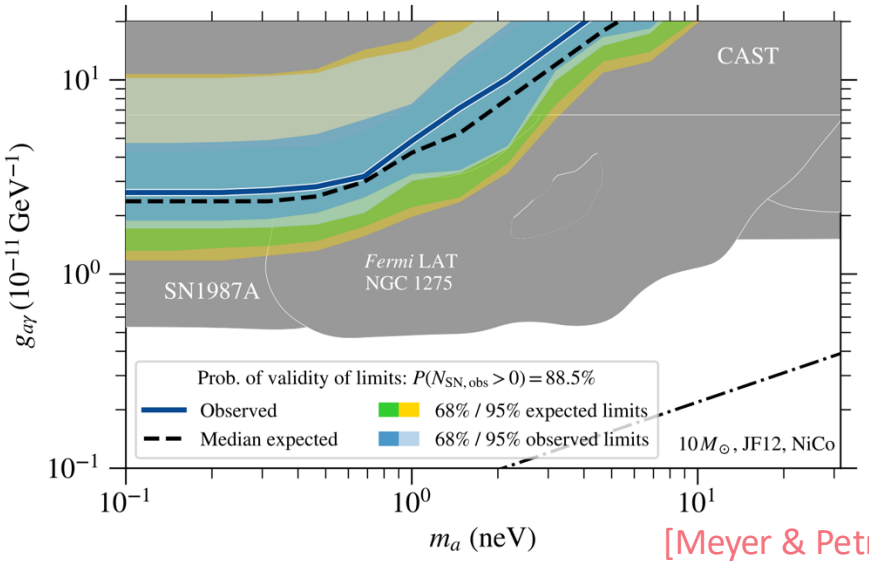


[Hooper & Serpico '07; Fairbairn+ '11;Horns+ '12; Wouters & Brun '12, '13; Abramowski+ '13; Meyer+ '14, Meyer & Conrad '14; Ajello+ '16; Berg+ '16, *Malyshev+ '18, Cheng+ '21, Zhang+ '18, Guo+ '20, Carenza+ '21, Kachelriess+ '22,*]

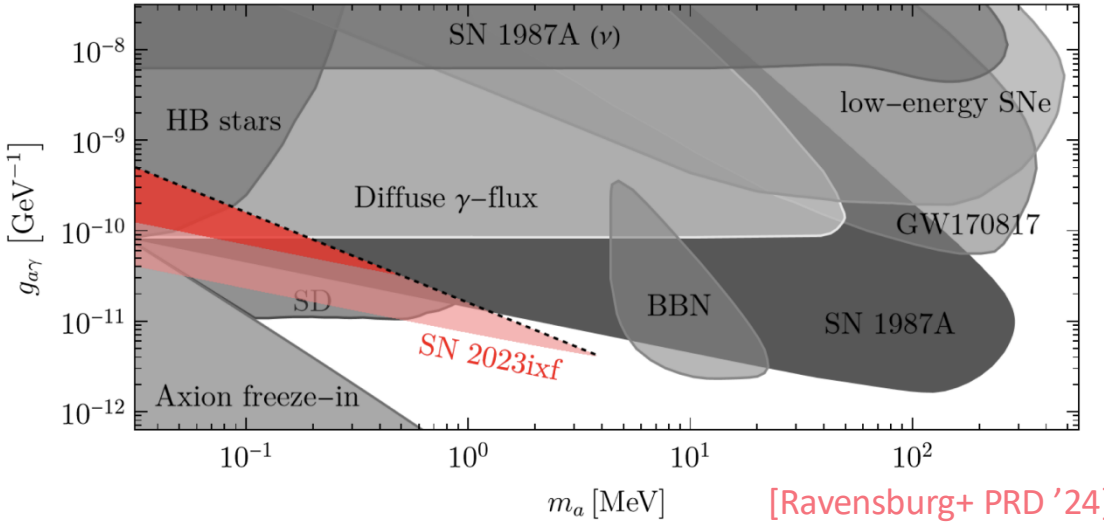
CCSNe: Individual Sources

- 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]

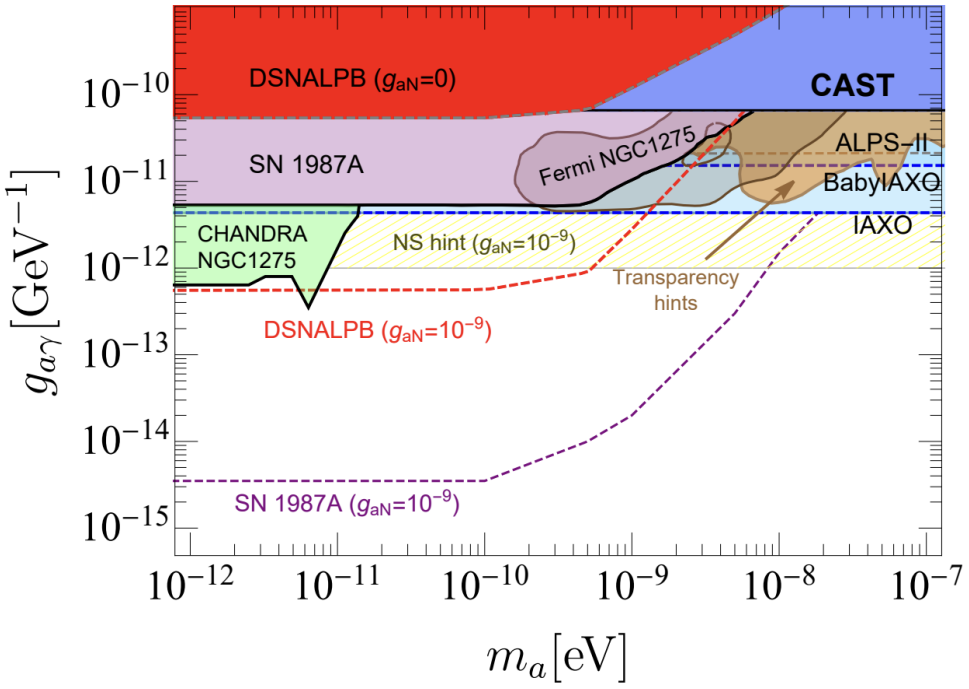


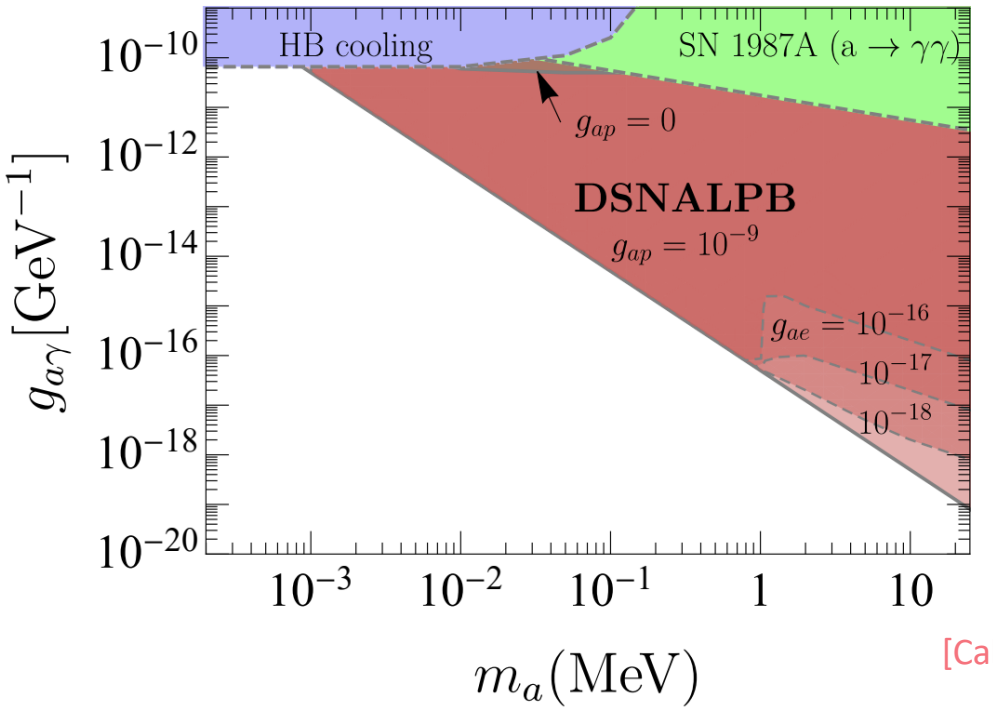
[Meyer & Petrushevska PRL '20]



[Ravensburg+ PRD '24]

CCSNe: Diffuse Emission



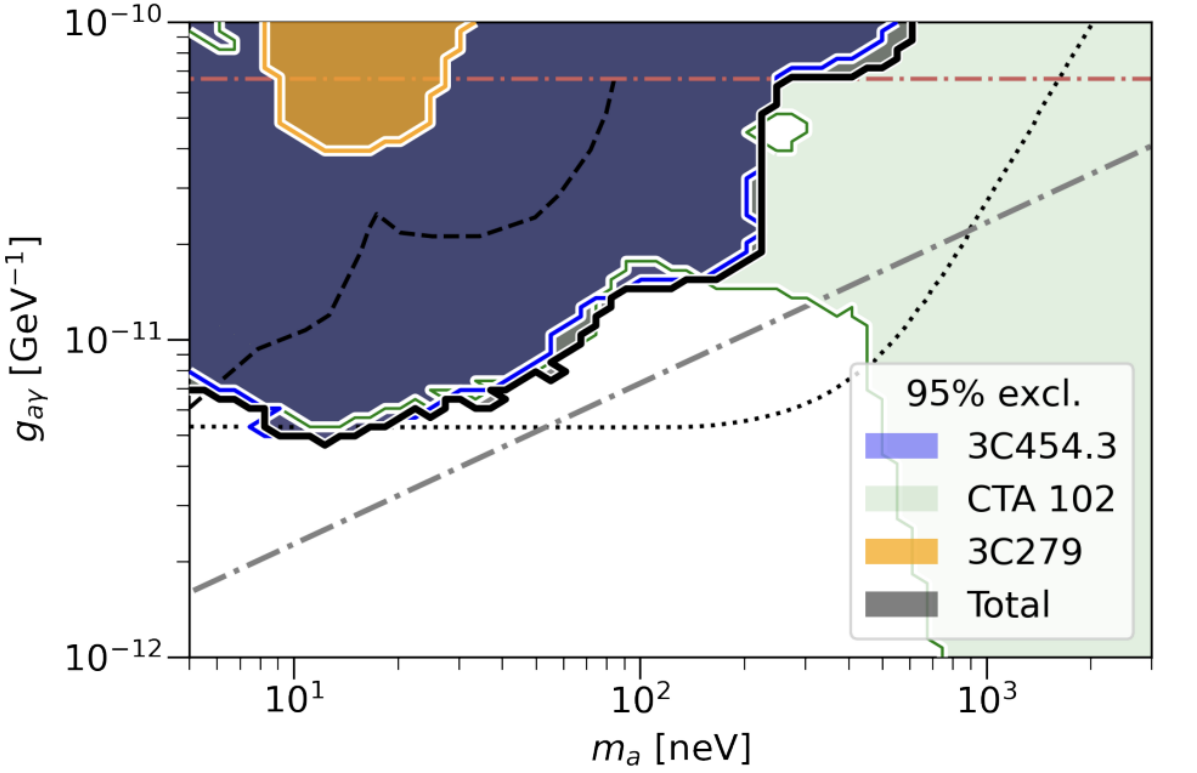


[Calore+ PRD '20]

- 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

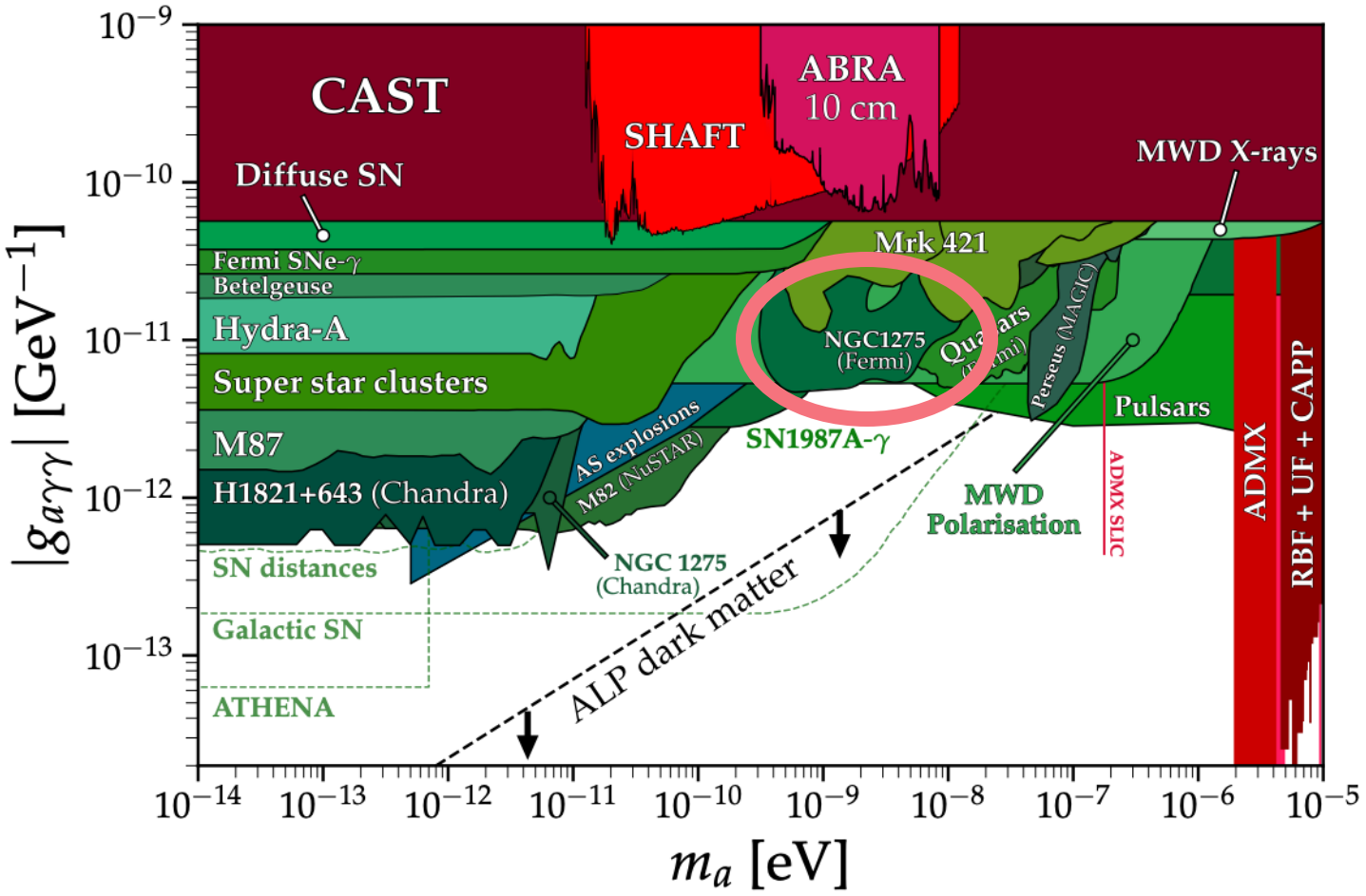
[Ajello+ ‘16, Libanov & Troitsky ‘20, Cheng+ ‘21, etc.]

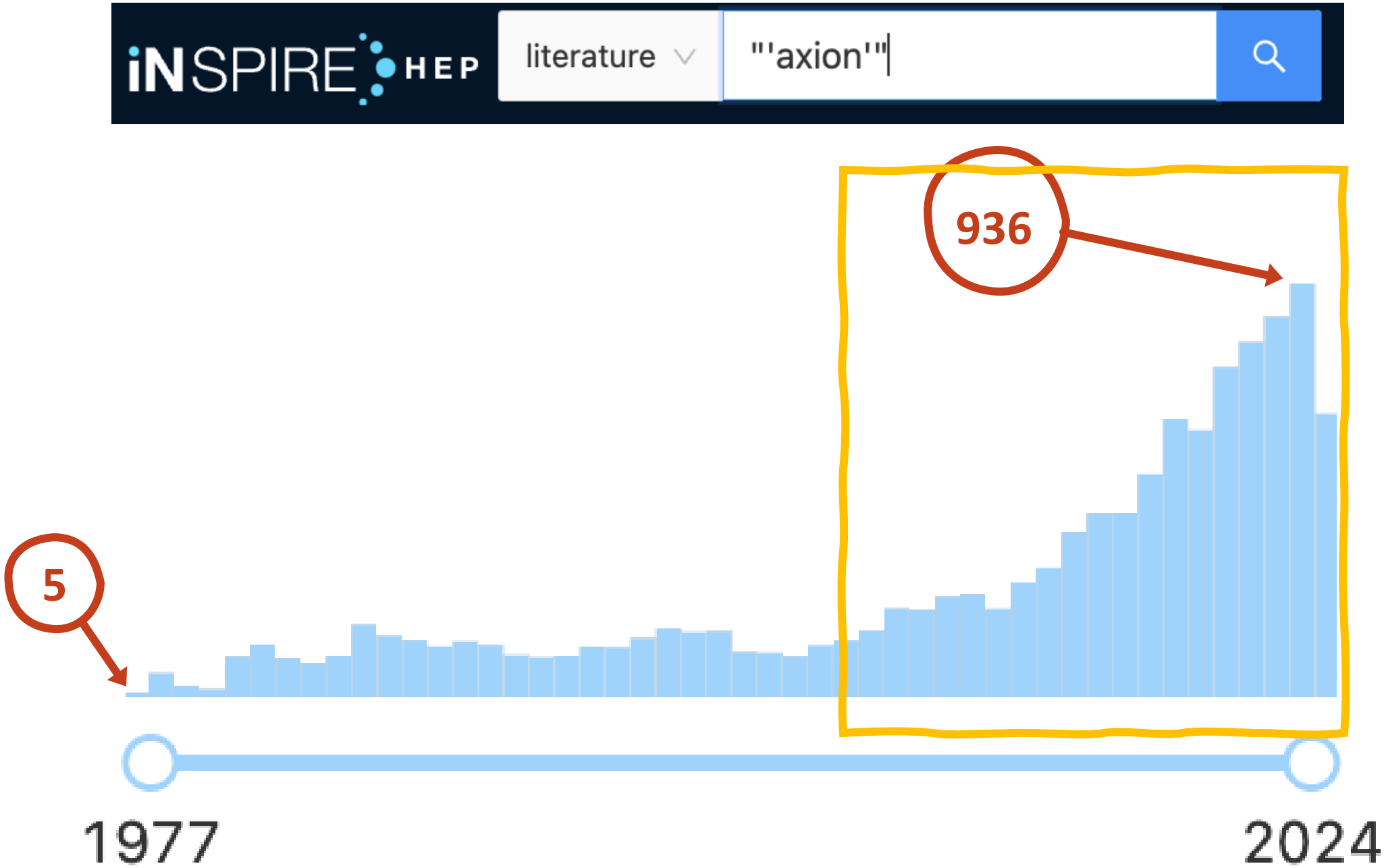
[Credit: Marie-Lou Gendron-Marsolais & Hlavacek-Larrond]

NGC 1275: spectral irregularities

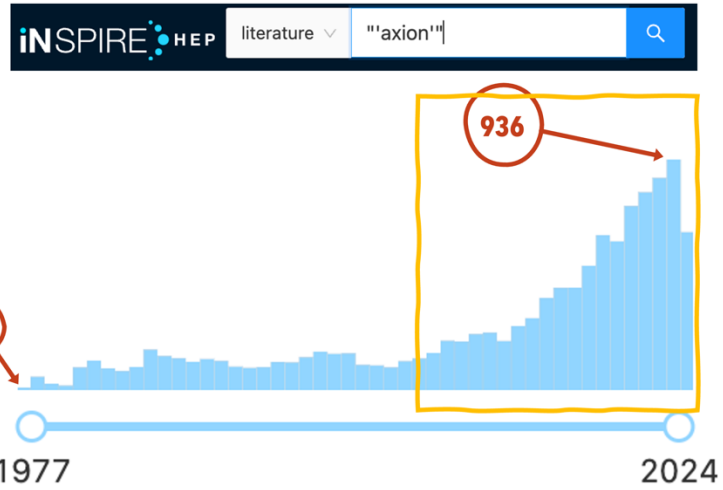
- Milky Way & Persius cluster B fields
- conservative estimate of the central B field of 10μG [Aleksić+ ‘12]
- EBL absorption
- 6 years of data → still the most stringent constraint for $m_{\rm alp} \sim 10^{-9}$ eV
- See [Cheng+ ‘21, etc] for additional B field considerations

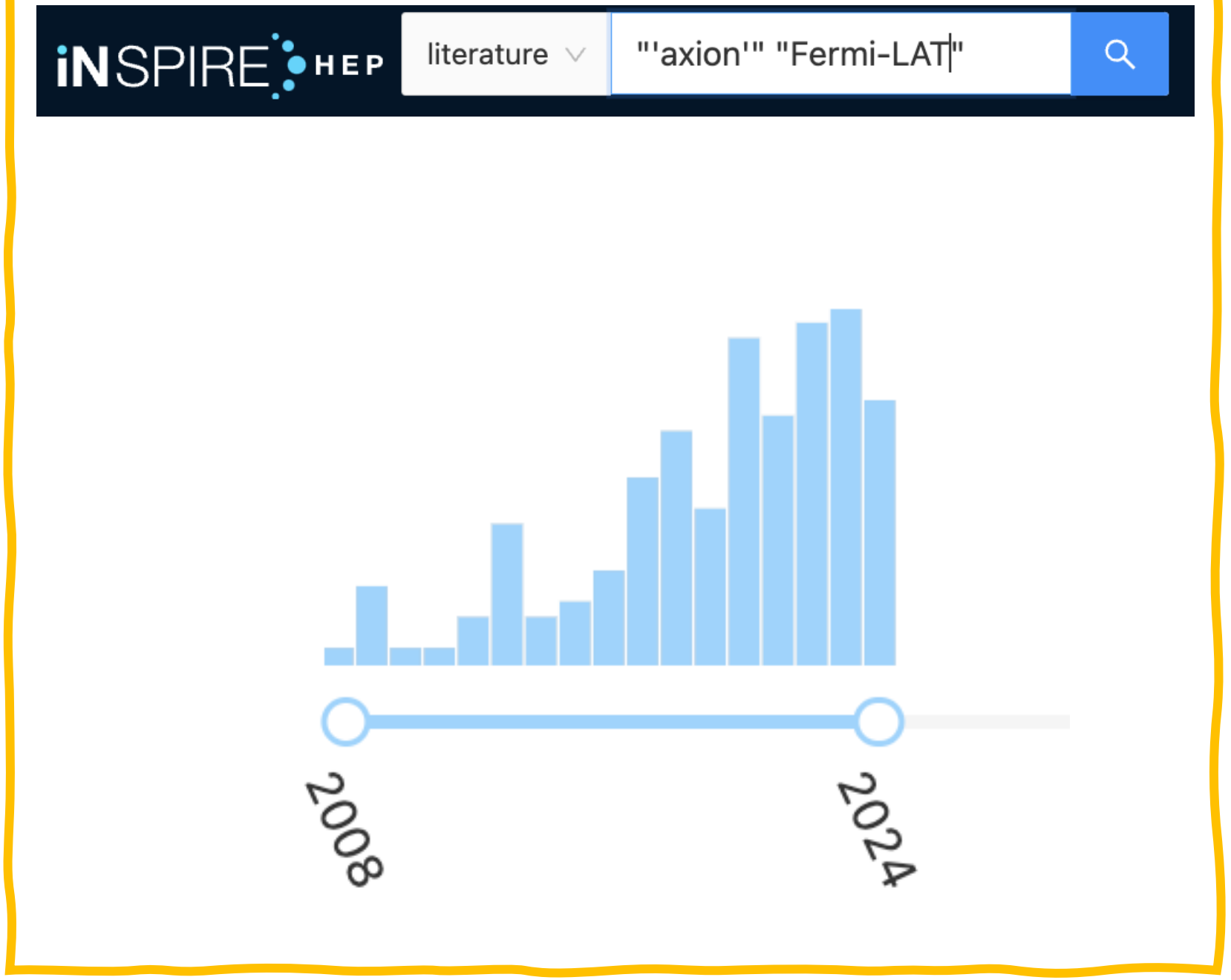
[Ajello+ ’16]





(accessed on September 5, 20


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

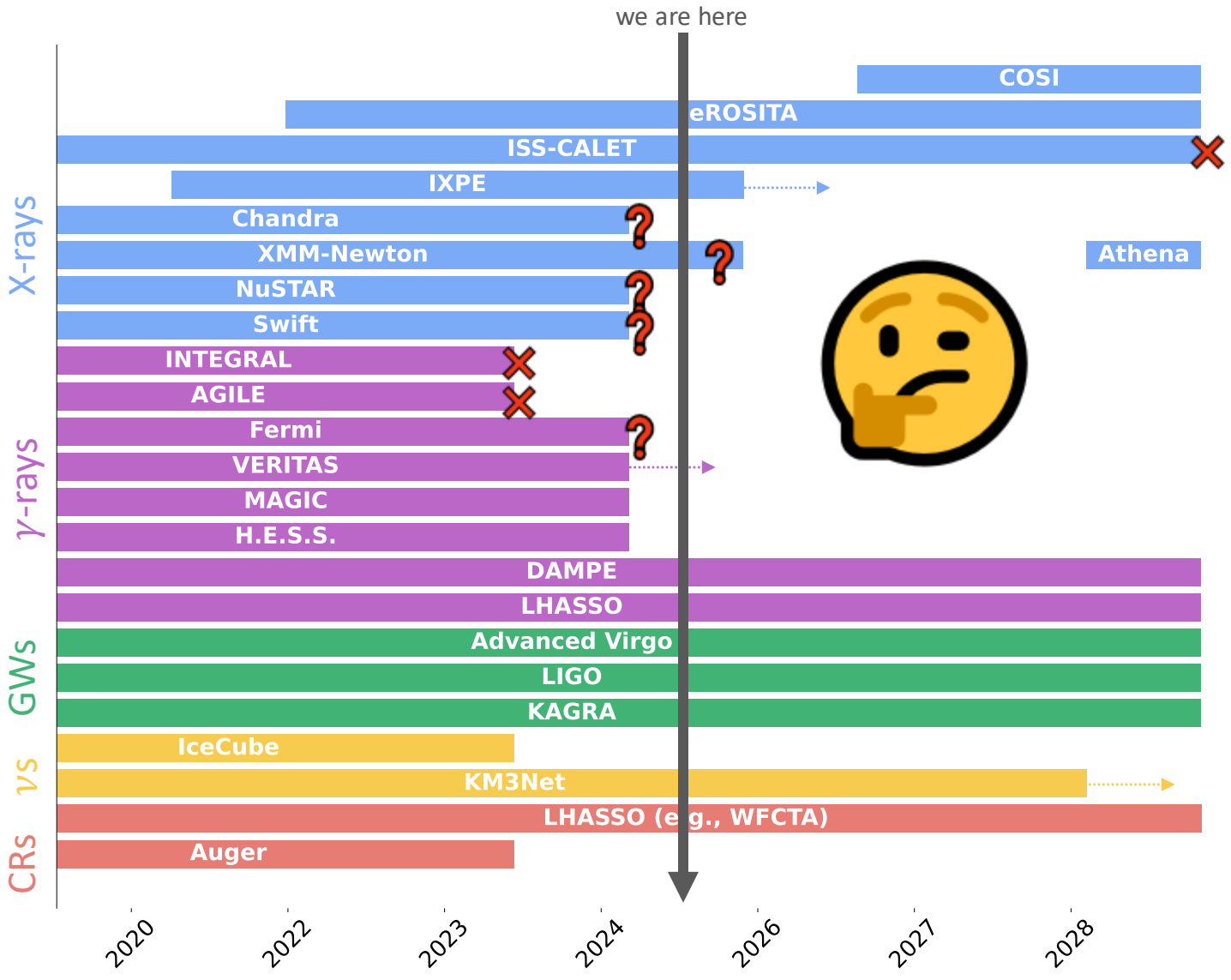

iNSPIRE HEP
literature
"'axion'" "Fermi-LAT"
2008
2024

Where next?

“Expecting to uncover dark matter in the next two decades is like waiting for the sun during a Stockholm winter—if you catch a glimpse, it’s barely enough to brighten your day before the darkness takes over again.”

ChatGPT, 2025

Dark Matter Landscape: An Instrumentationalist's View

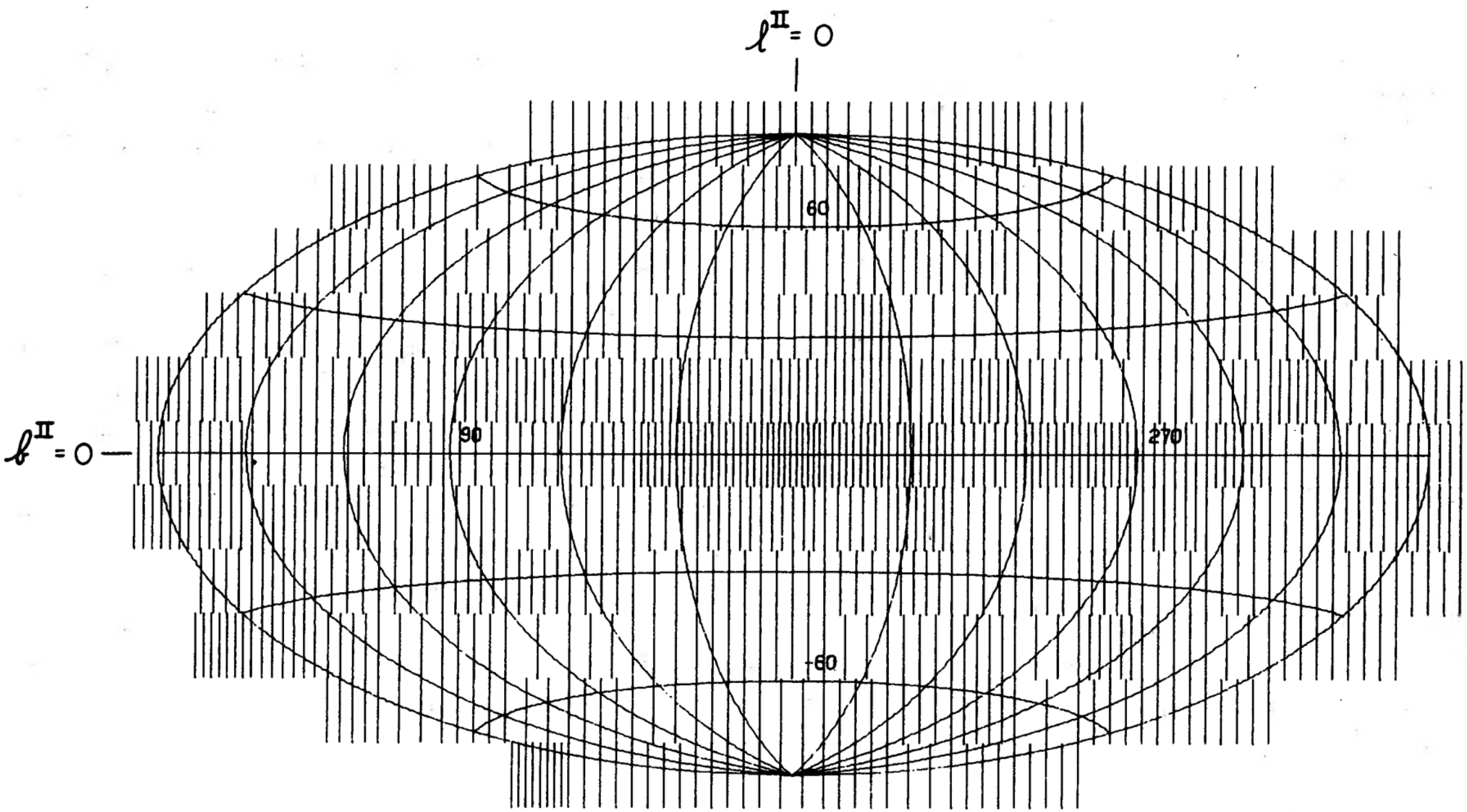


Future Innovations in Gamma rays

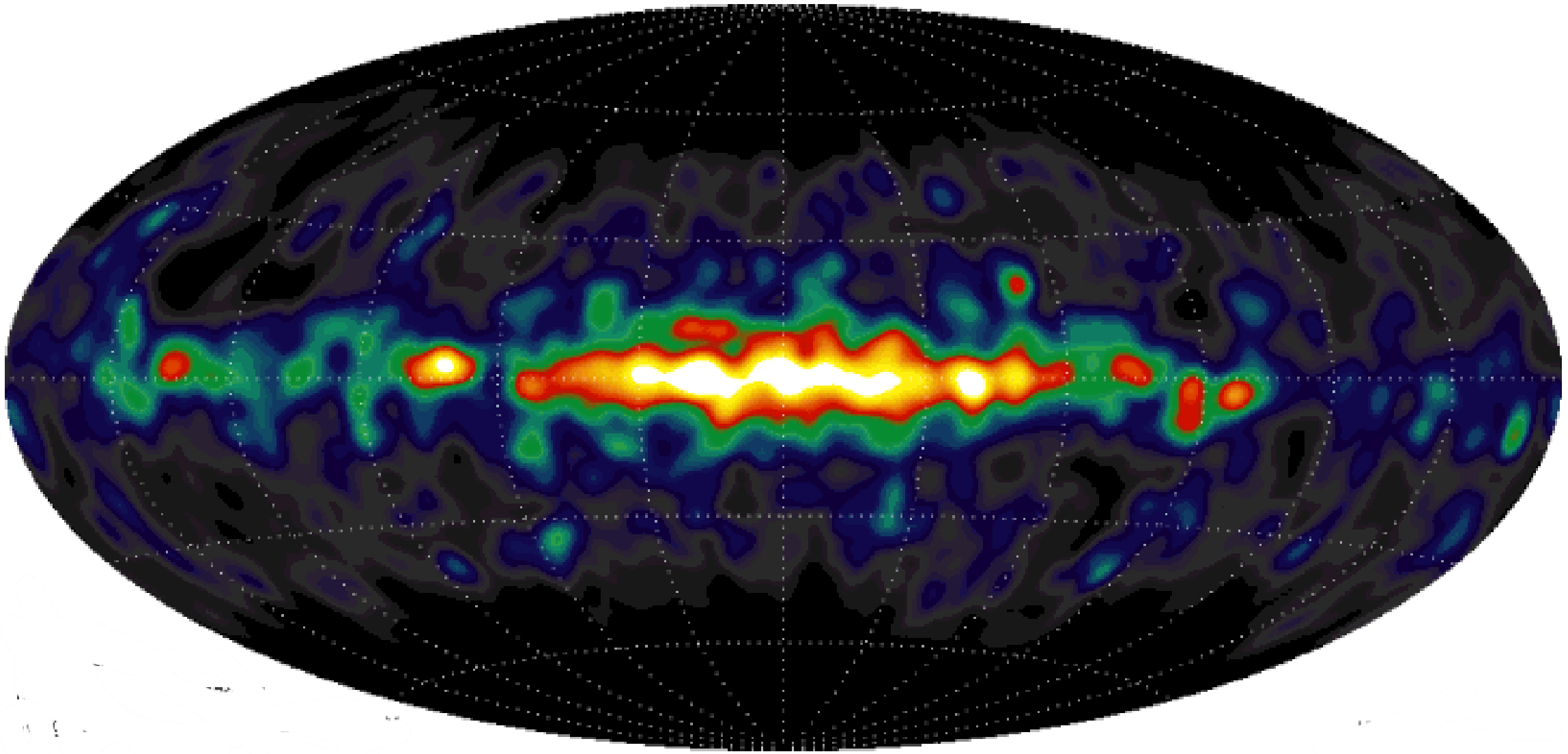
Science Analysis Group

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

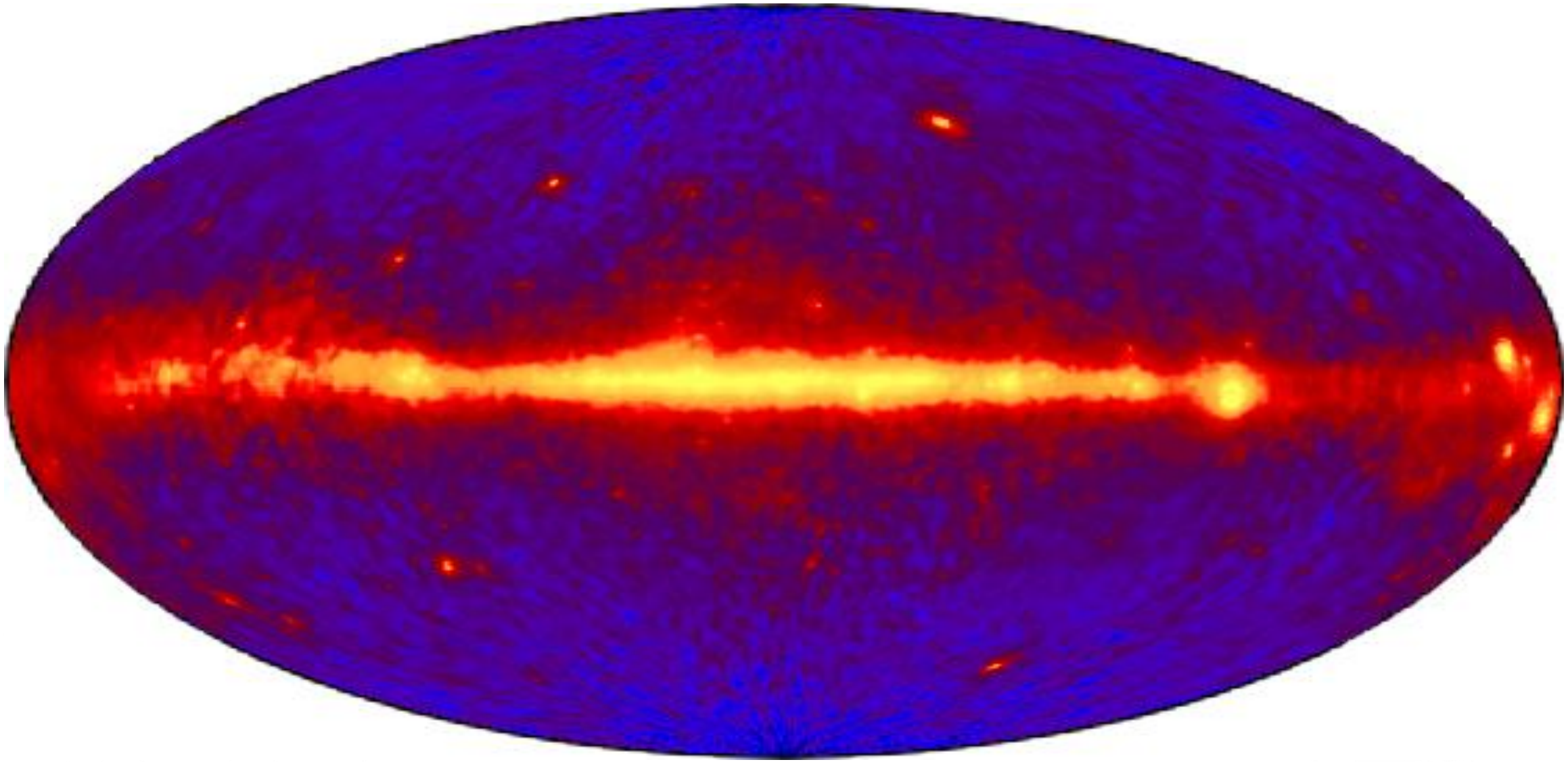
FIG-SAG



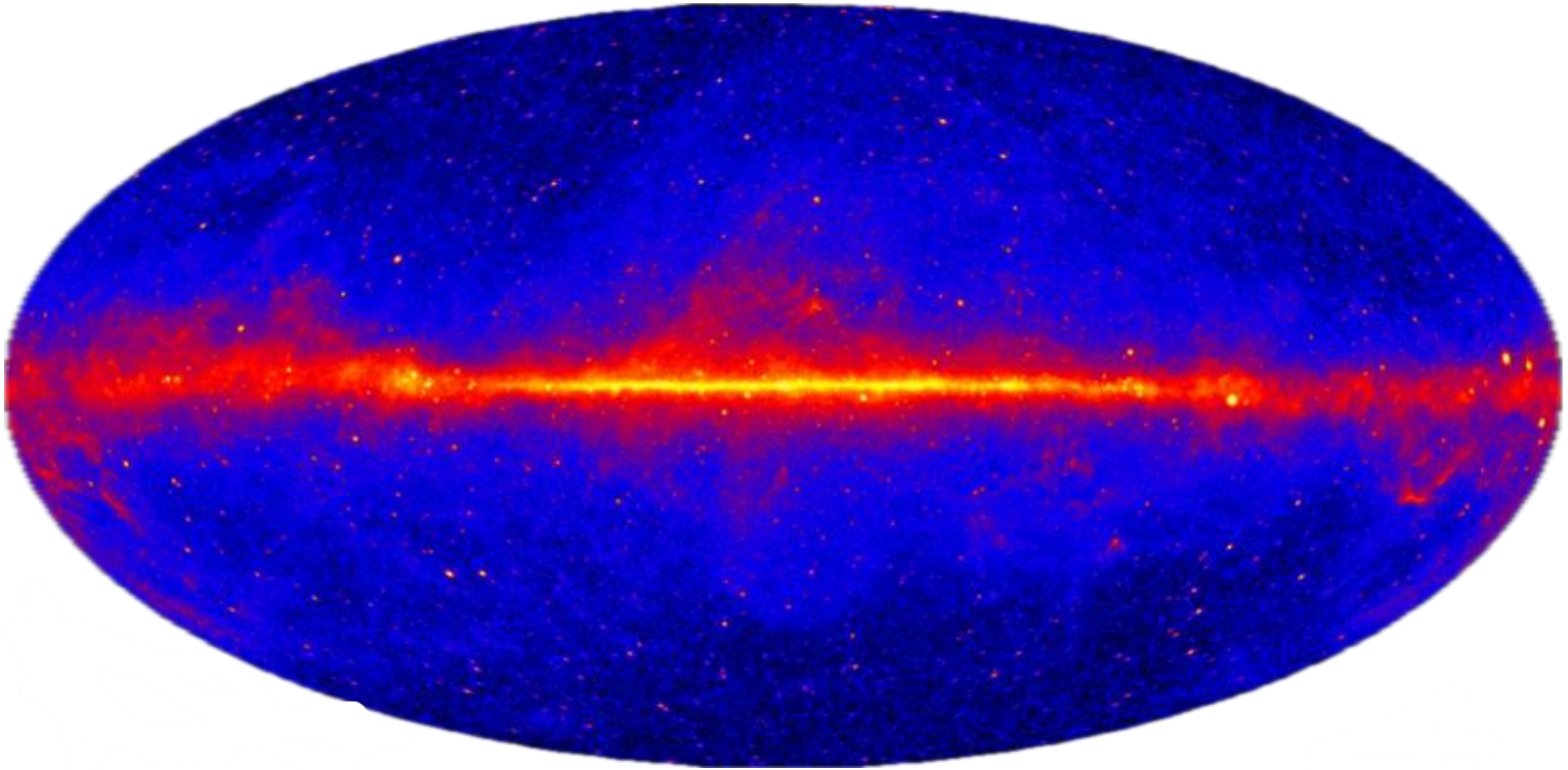
1968, Orbiting Solar Observatory, OSO-3 (~50 MeV)



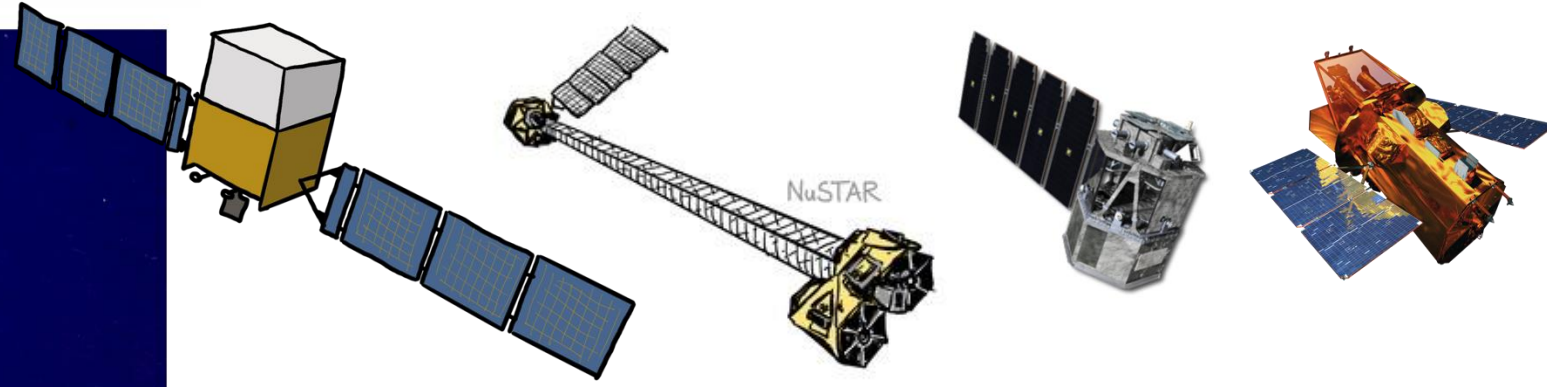
2000, COMPTEL (onboard CGRO), 1—30 MeV



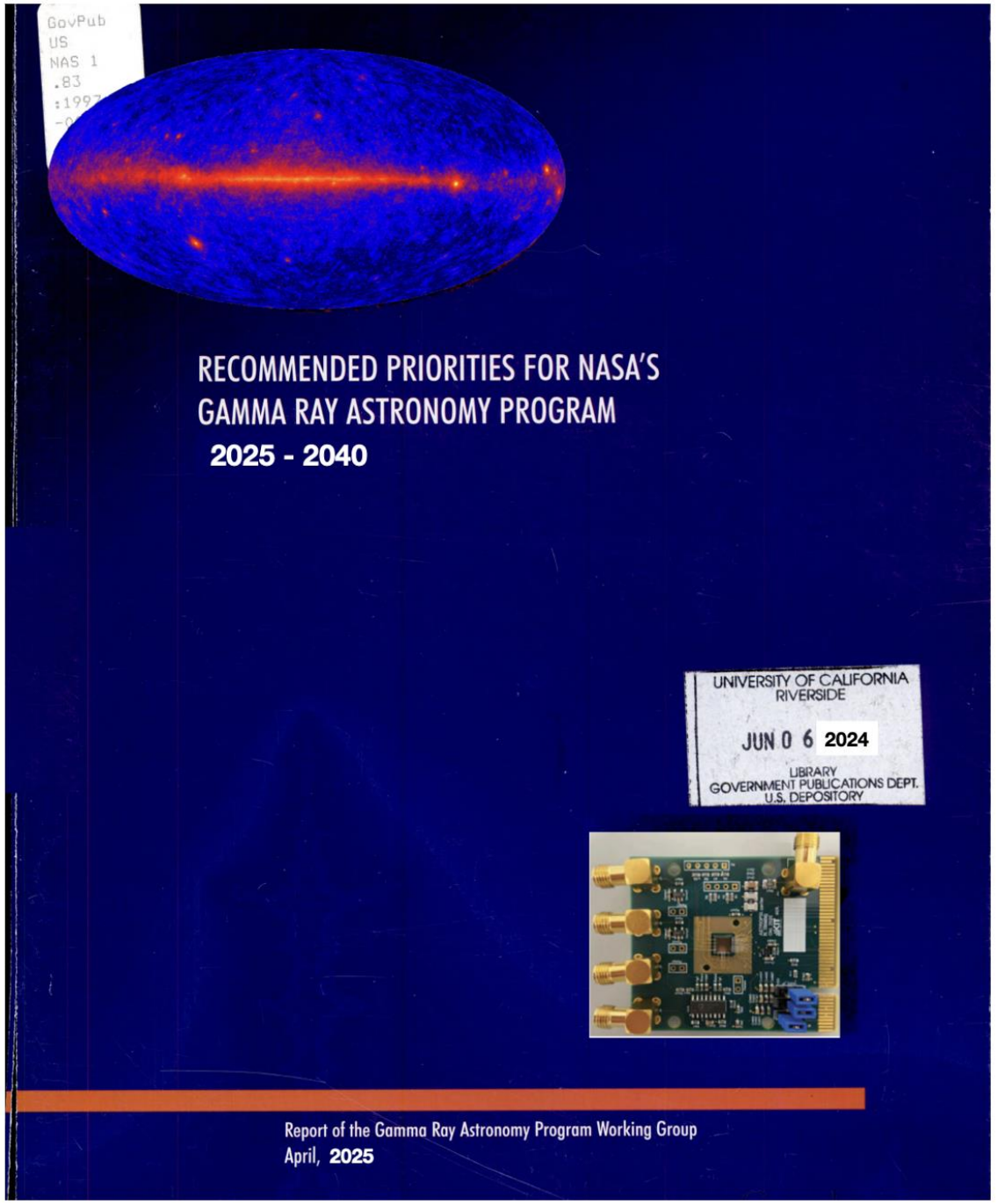
2000, EGRET (onboard CGRO), above 100 MeV



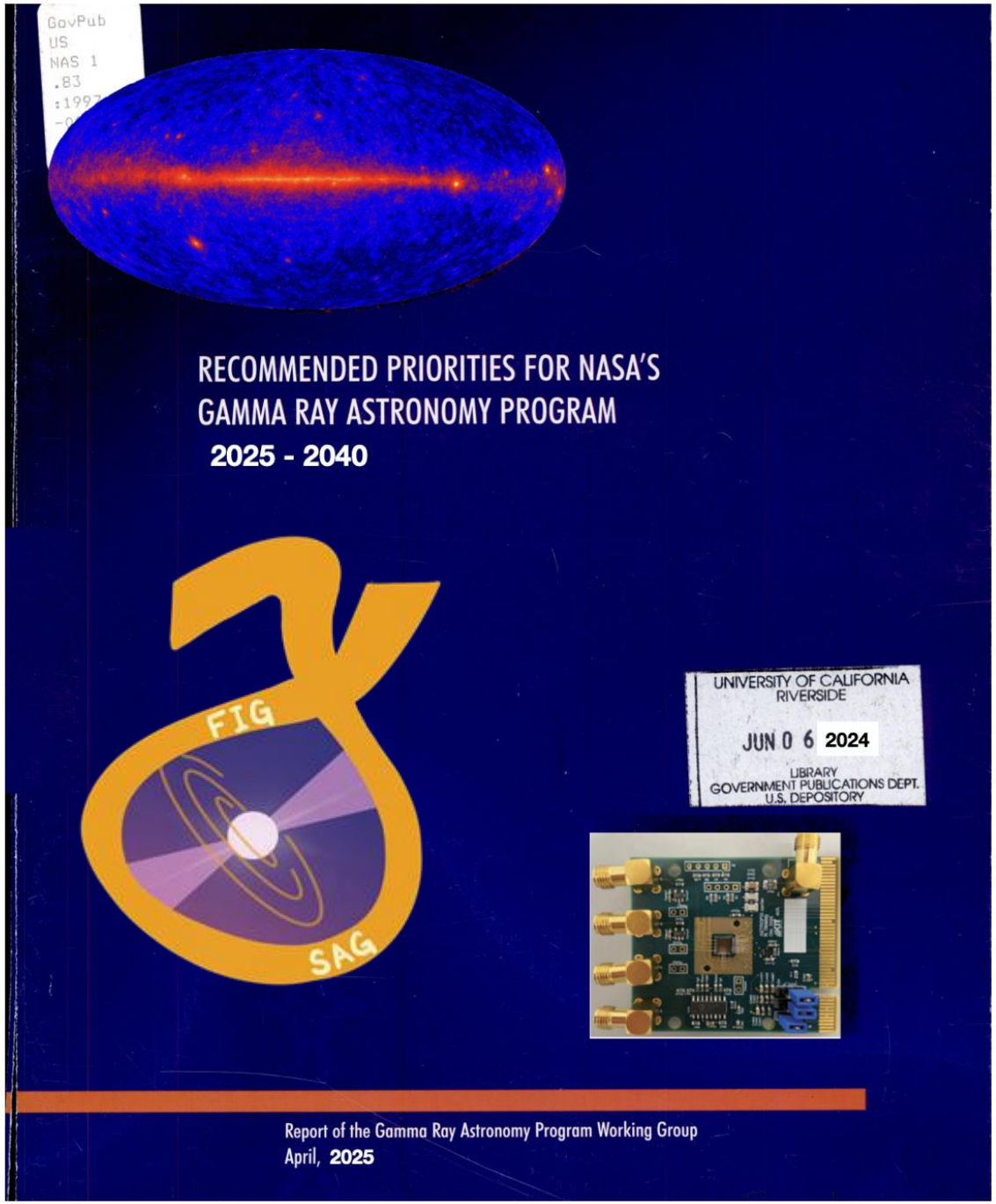
2000, LAT (onboard *Fermi*), above 500 MeV



- 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.



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



Submitted to the NASA Astrophysics Advisory Committee by

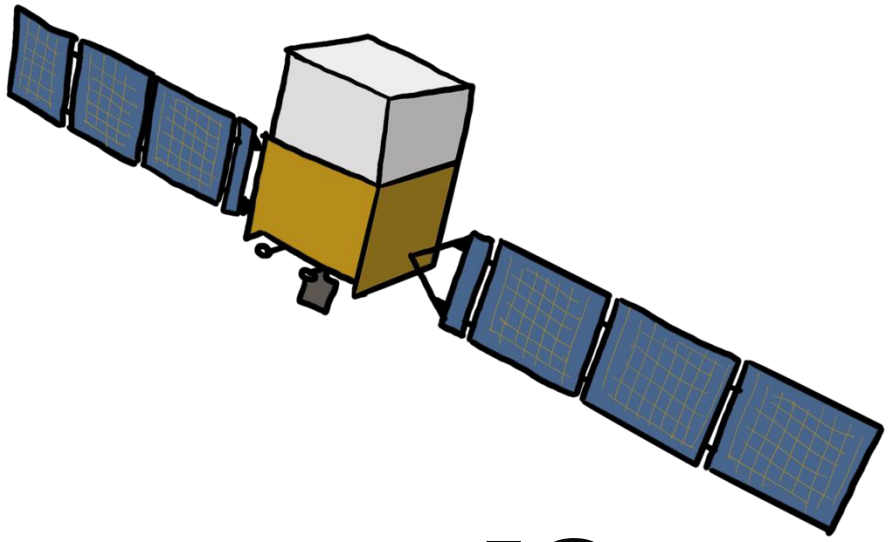
The Future Innovations in Gamma Ray Science Analysis Group

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

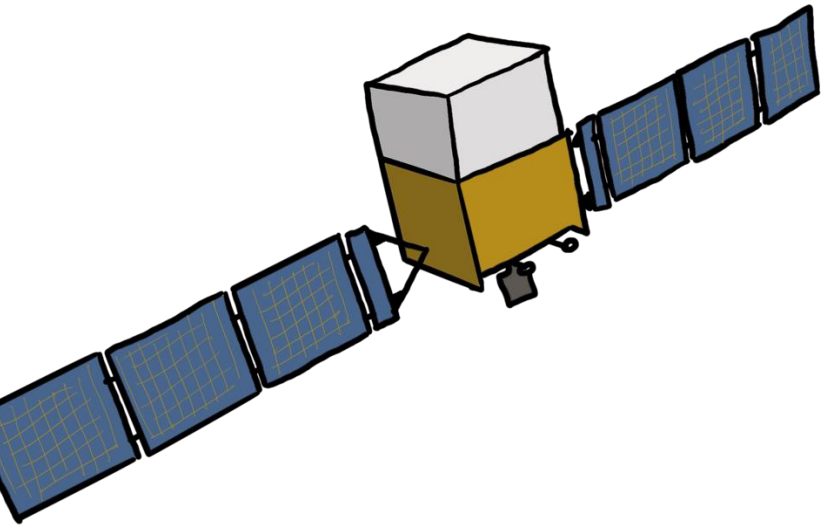
Chris Fryer[1], C. Michelle Hui[2], Paolo Coppi[3], Milena Crnogorcevic[4], Tiffany R. Lewis[5], Marcos Santander[6], and Zorawar Wadiasingh[7]

[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

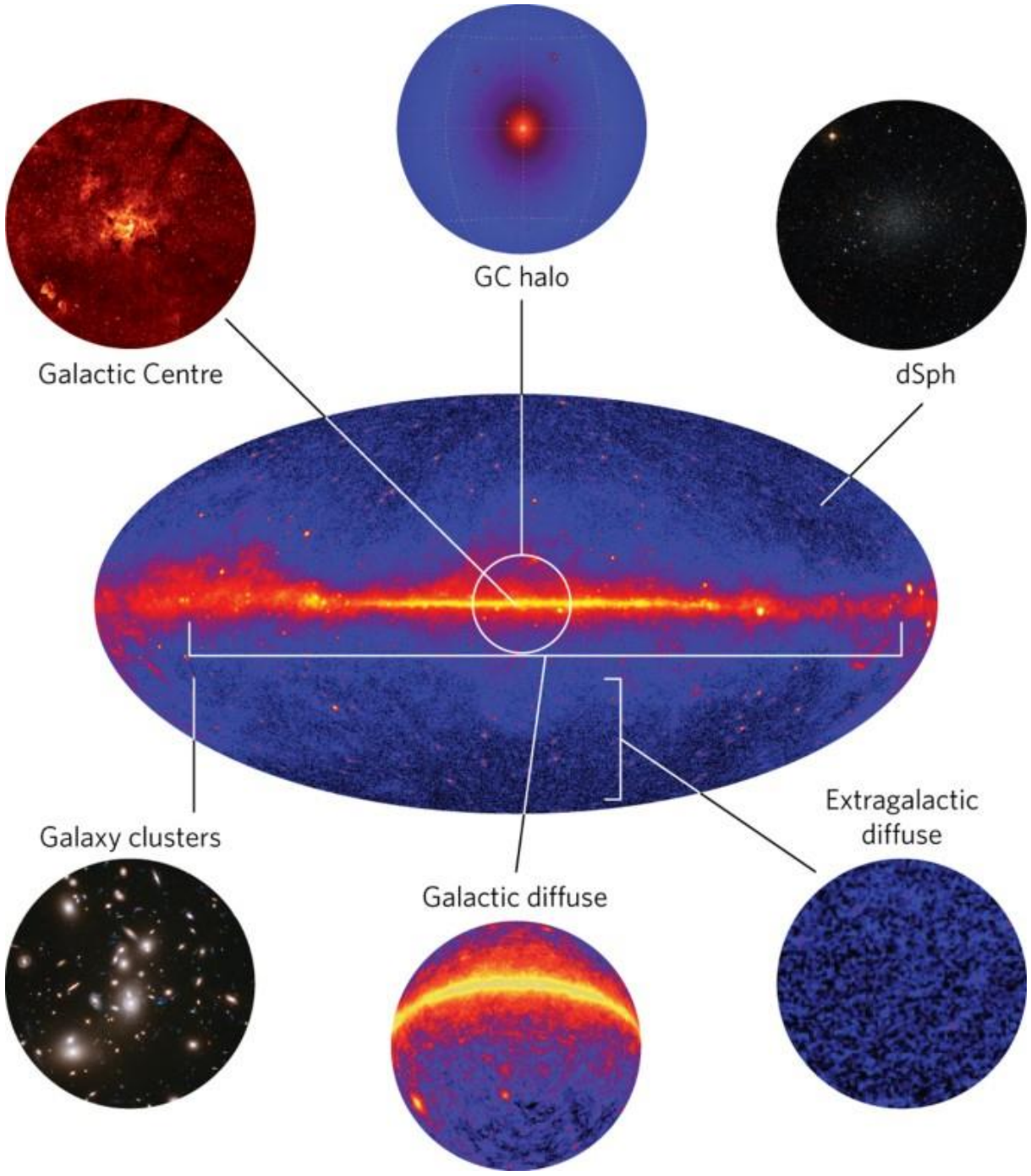
Where does the story



end?

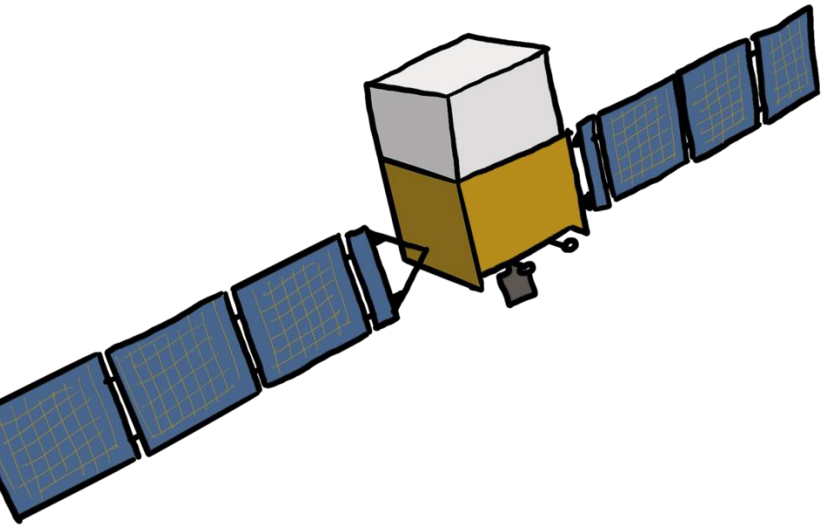


DM targets

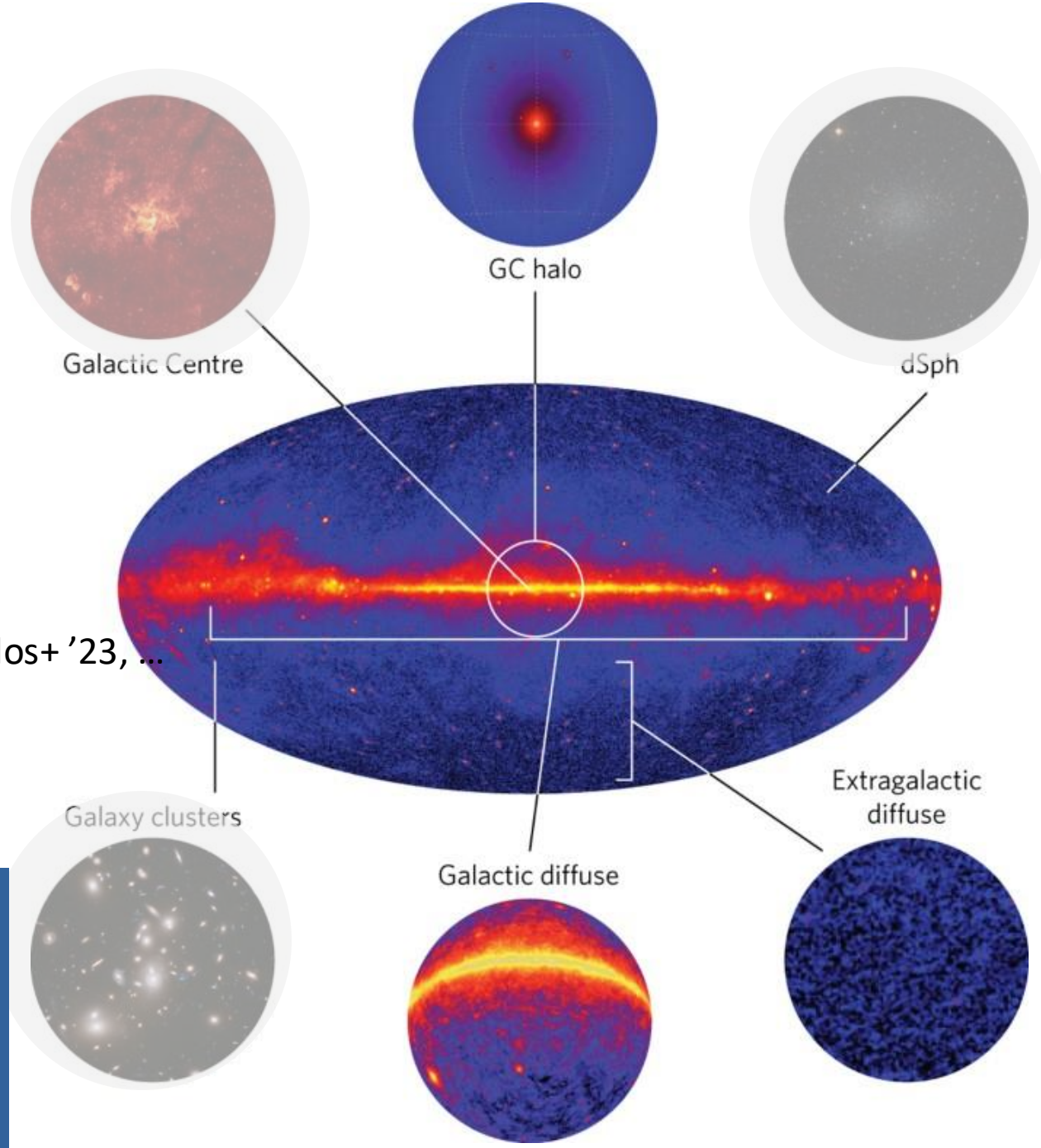


[Conrad & Reimer 2017]

Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.
See papers by Rebecca Leane & Tim Linden



Galactic halo: LAT Collaboration ’13, Karwin+ ‘21, …
Galactic diffuse: LAT Collaboration ‘12, Acero+ ‘16,
Charles+ ’16, Porter+ 17, DiMauro+ ’19, ’21, …
Extragalactic diffuse: LAT Collaboration ‘15, Ajello+ ‘15, Delos+ ’23, …
Solar System:
Axions/ALPs:
PBHs:



[Conrad & Reimer 2017]

EuCAPT Virtual Colloquia

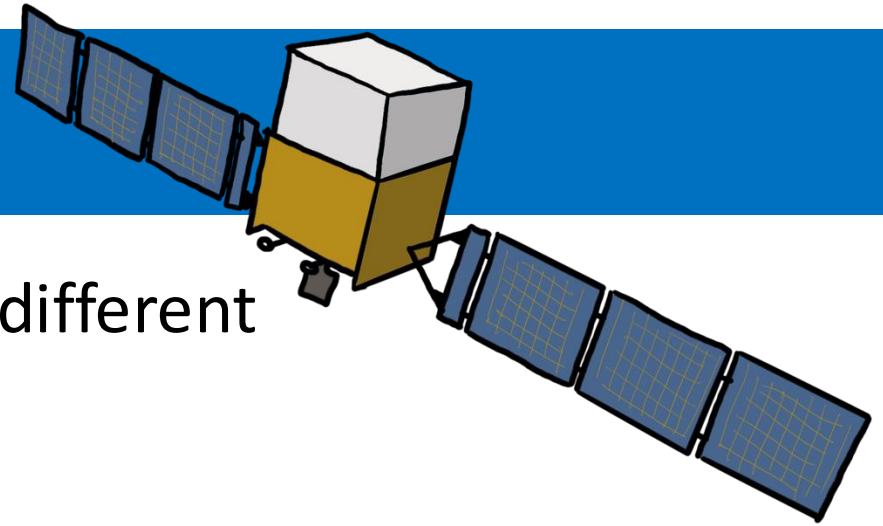
Anti-matter in Cosmic Rays as a Dark Matter probe

by Prof. Fiorenza Donato (Torino University and INFN, and CERN)

Tuesday Mar 11, 2025, 3:00 PM → 4:30 PM Europe/Zurich

On line only (CERN)

Conclusions



- Gamma-ray observations provide unique tests for different dark matter models
- Indirect detection provides stringent constraints
- Future experiment development is crucial
- Our next space gamma-ray experiment is uncertain--- ***FIG SAG as a venue to make a strong case to funding agencies***