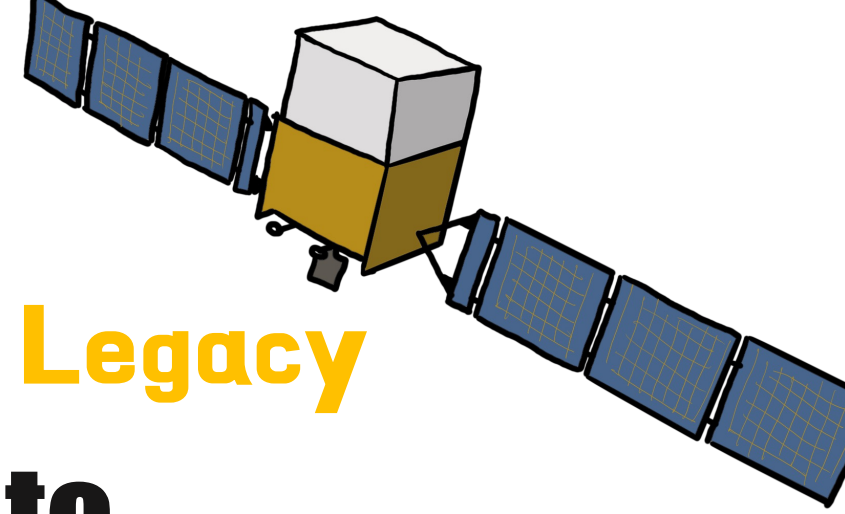


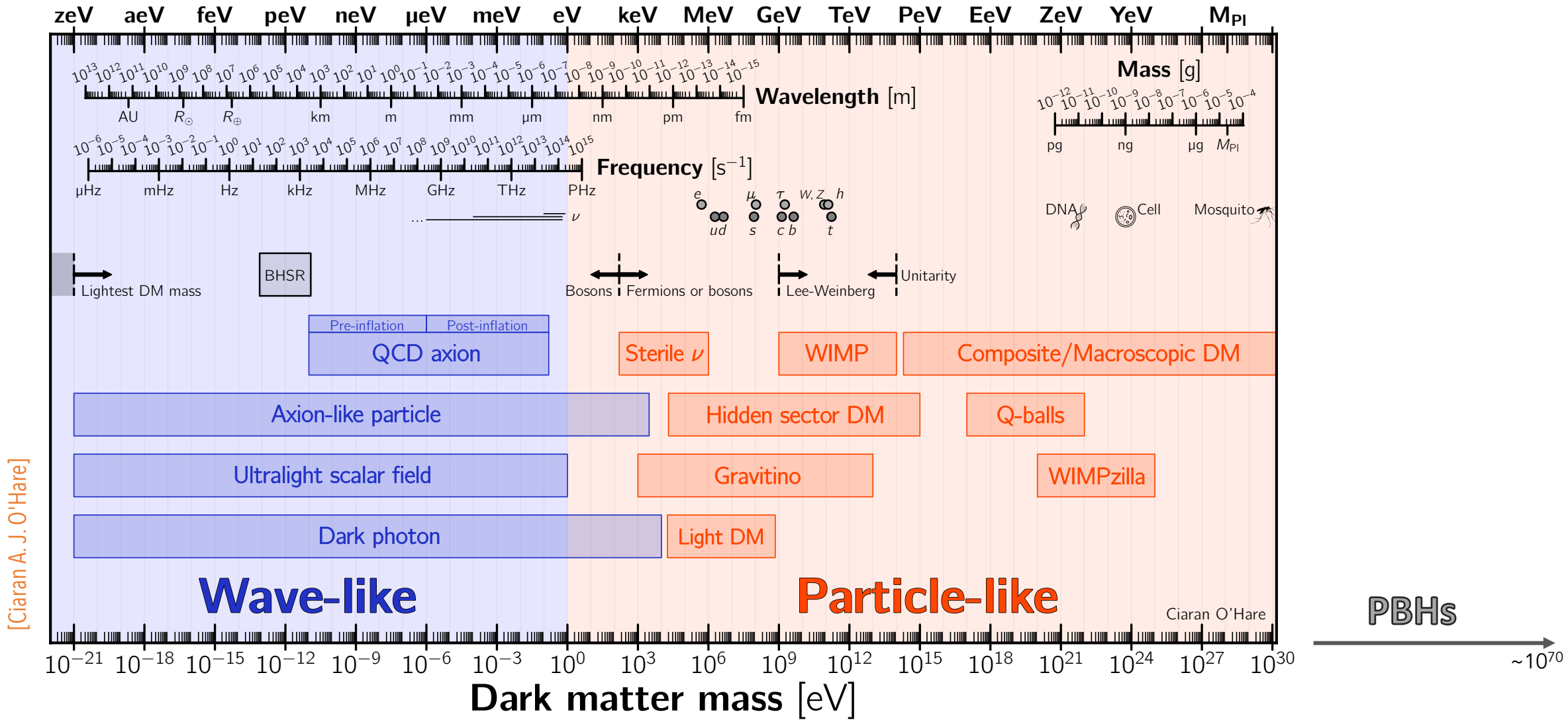
Establishing Fermi-LAT's Legacy

From gamma rays to multimessenger dark matter searches

Milena Crnogorčević
Postdoctoral Fellow at the Oskar Klein Centre
milena.crnogorcevic@fysik.su.se

Dark Matter & Neutrinos
Institut Henri Poincaré
May 23, 2025

Dark Matter Landscape: A Theorist's View



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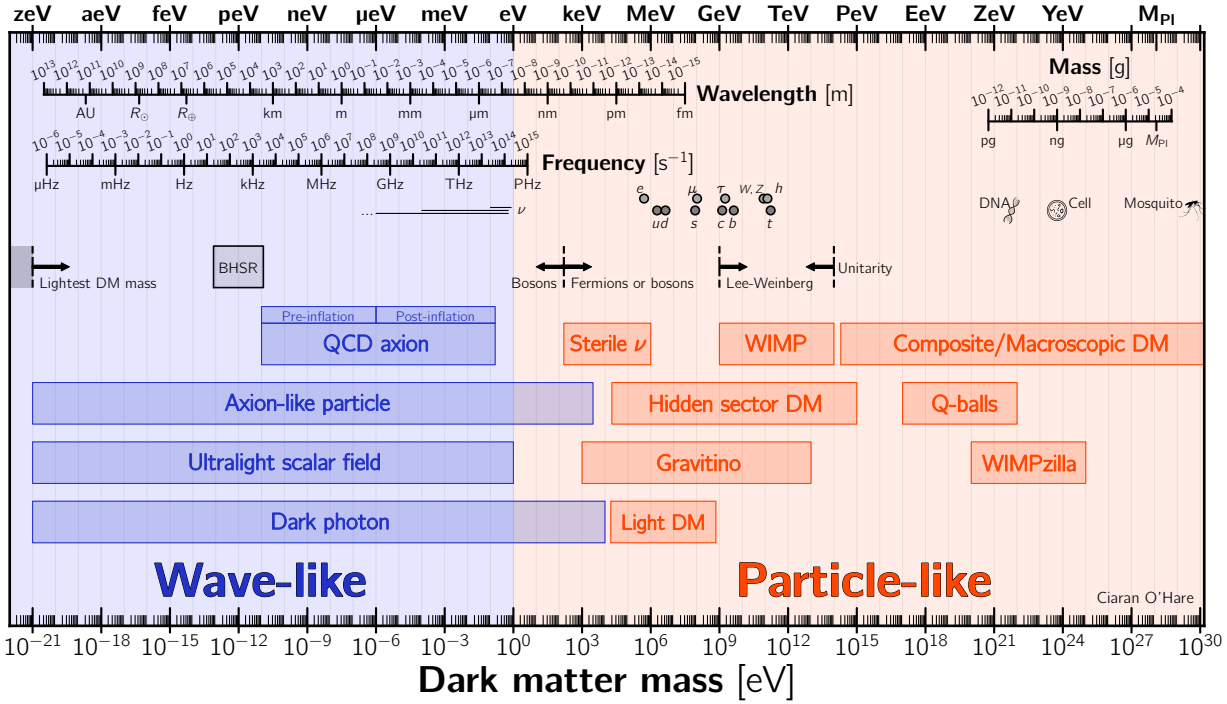


[Ciaran A. J. O'Hare]

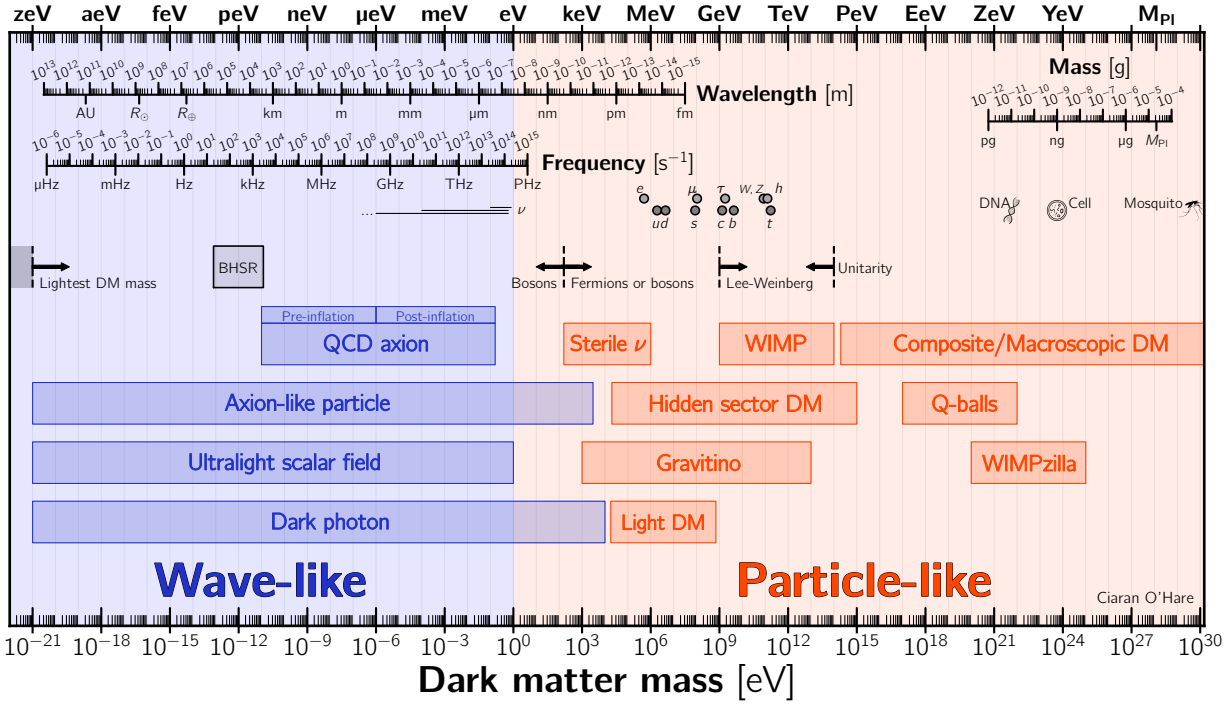
Dark matter spans over

80 orders of magnitude in mass (+ interaction strength)

proton
m ~ 10^{-27} kg

(c) Pablo Carlos Budassi

Dark Matter Landscape: A Theorist's View

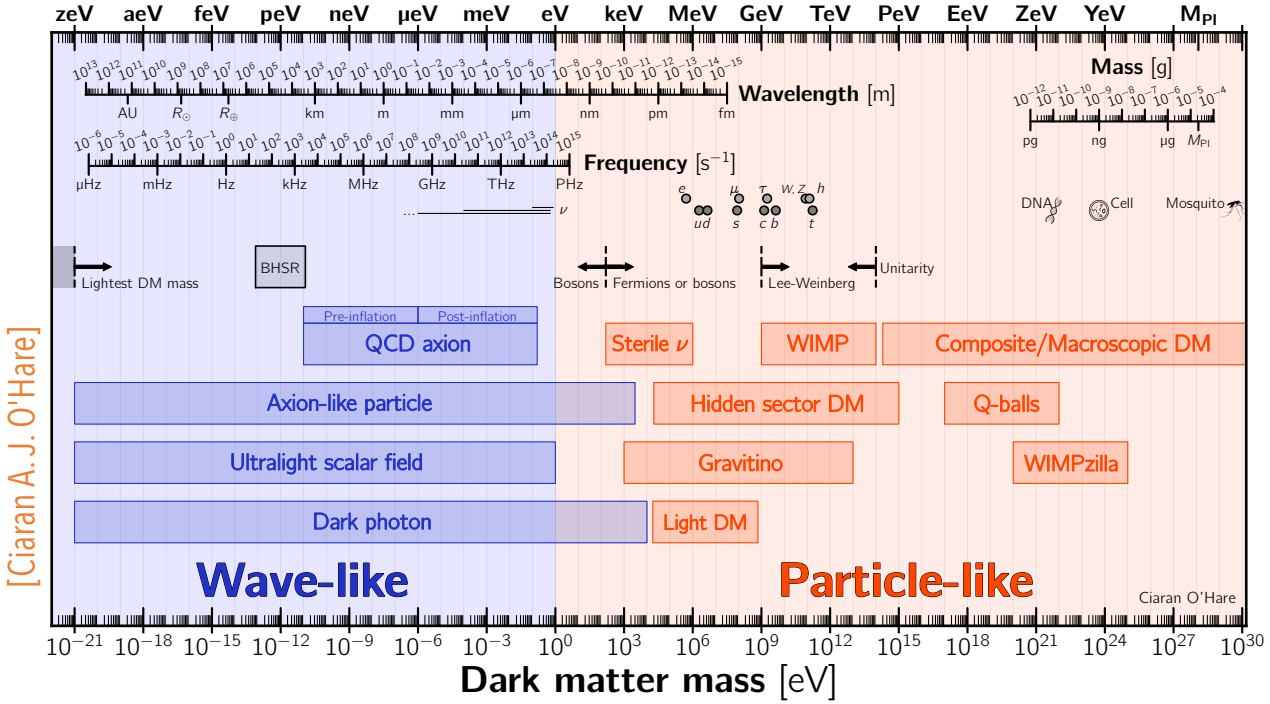


[Ciaran A. J. O'Hare]

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

Dark Matter Landscape: A Theorist's View



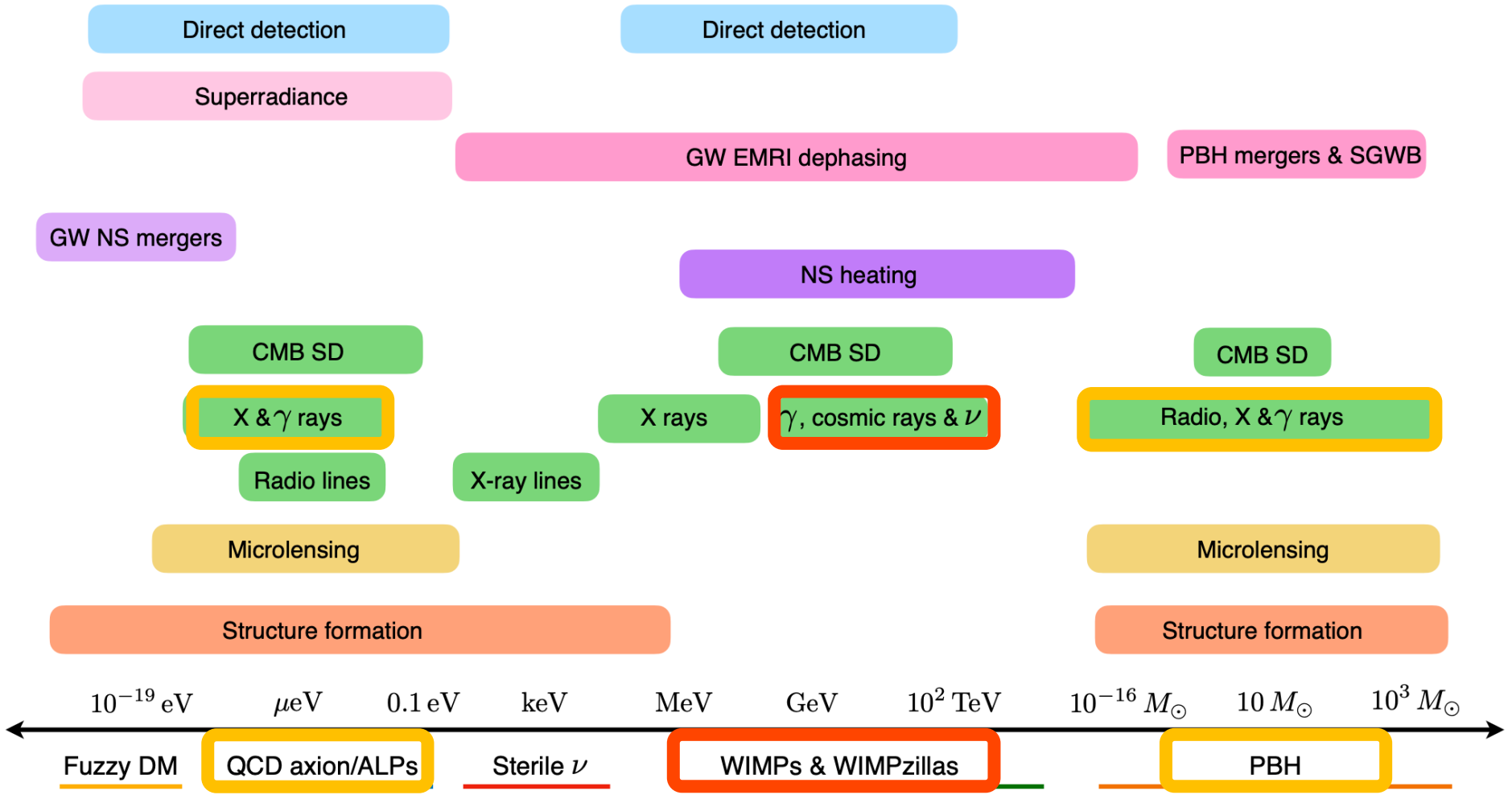
[Ciaran A. J. O'Hare]

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

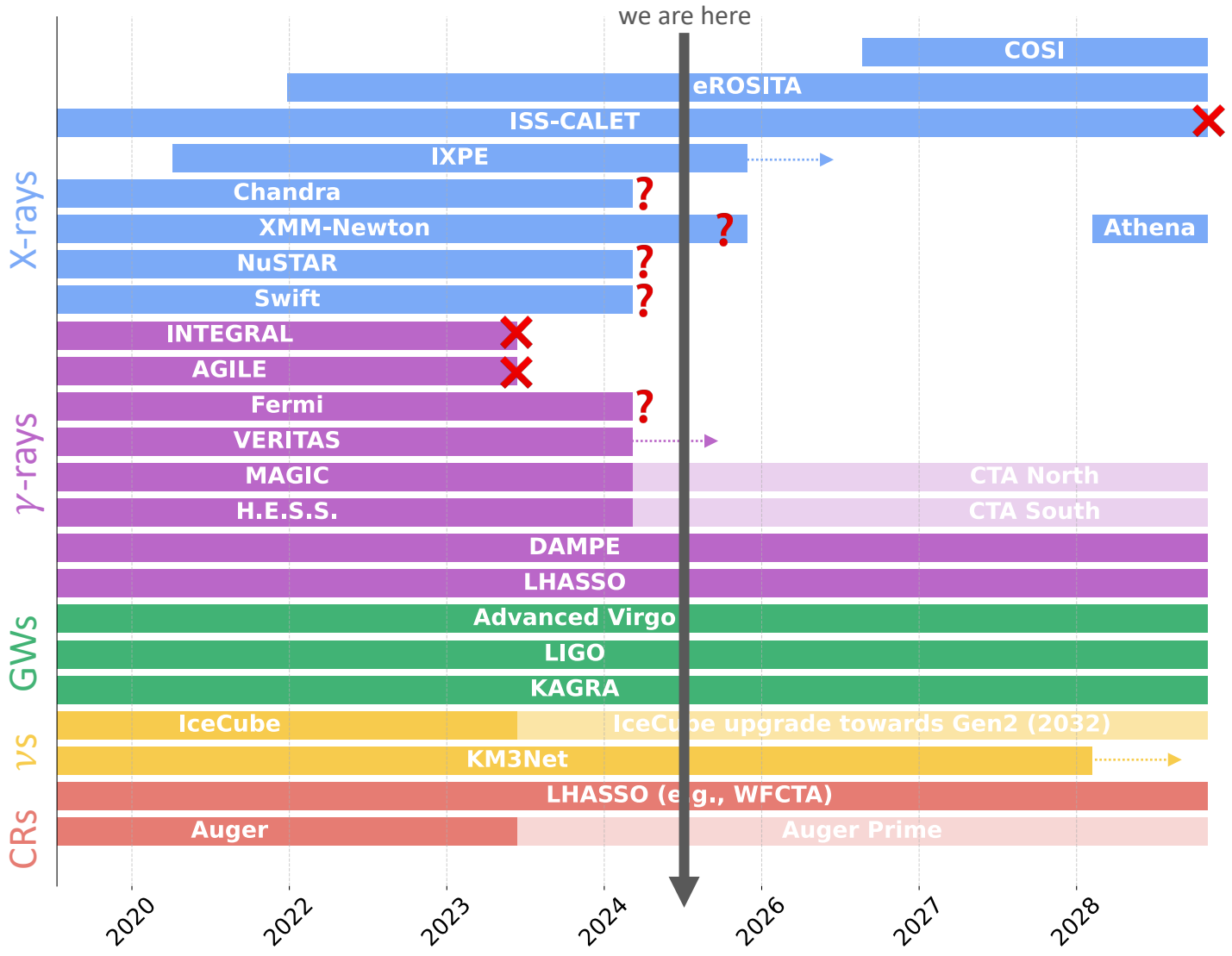
… we have to start somewhere.

Dark Matter Landscape: An Observer's View



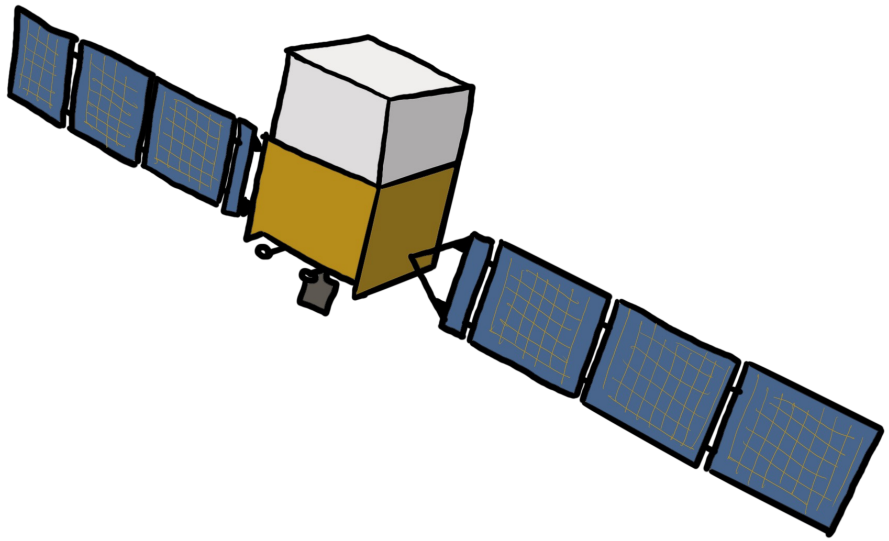
[EuCAPT WhitePaper, 2021]

Dark Matter Landscape*: An Instrumentationalist's View

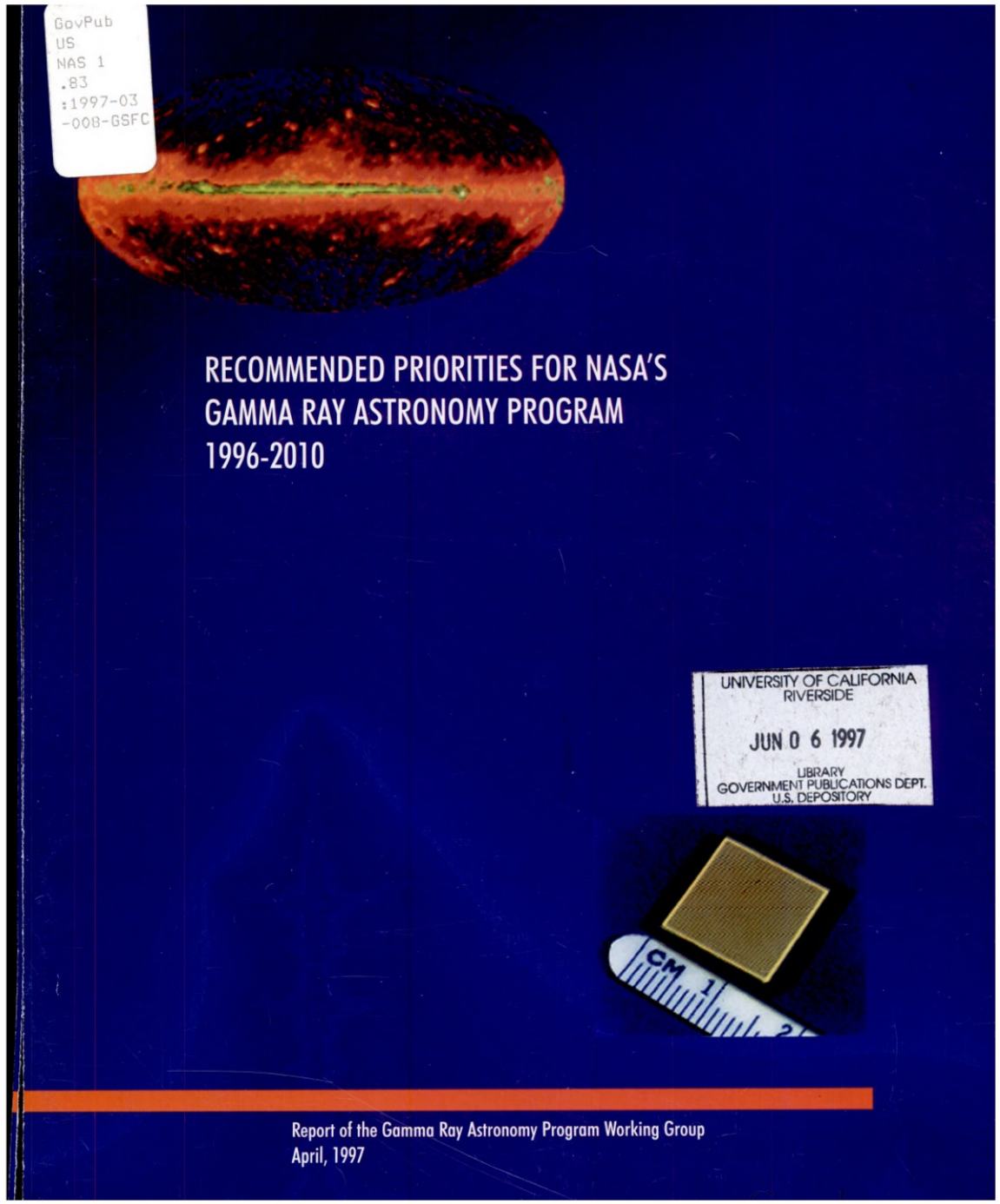


*indirect detection

Where does the story



start?

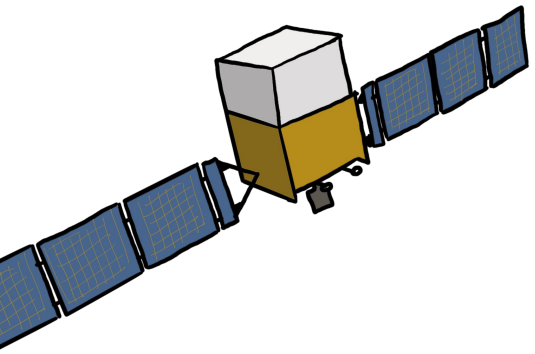


GAMMA-RAY ASTRONOMY PROGRAM WORKING GROUP MEMBERS:

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/19980017217.



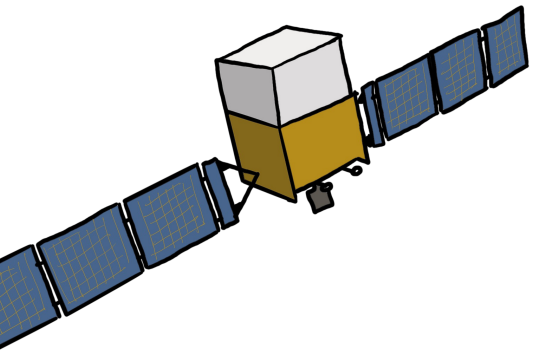
The Case of Dark Matter & *Fermi*

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

Authors' affiliations removed for readibility.



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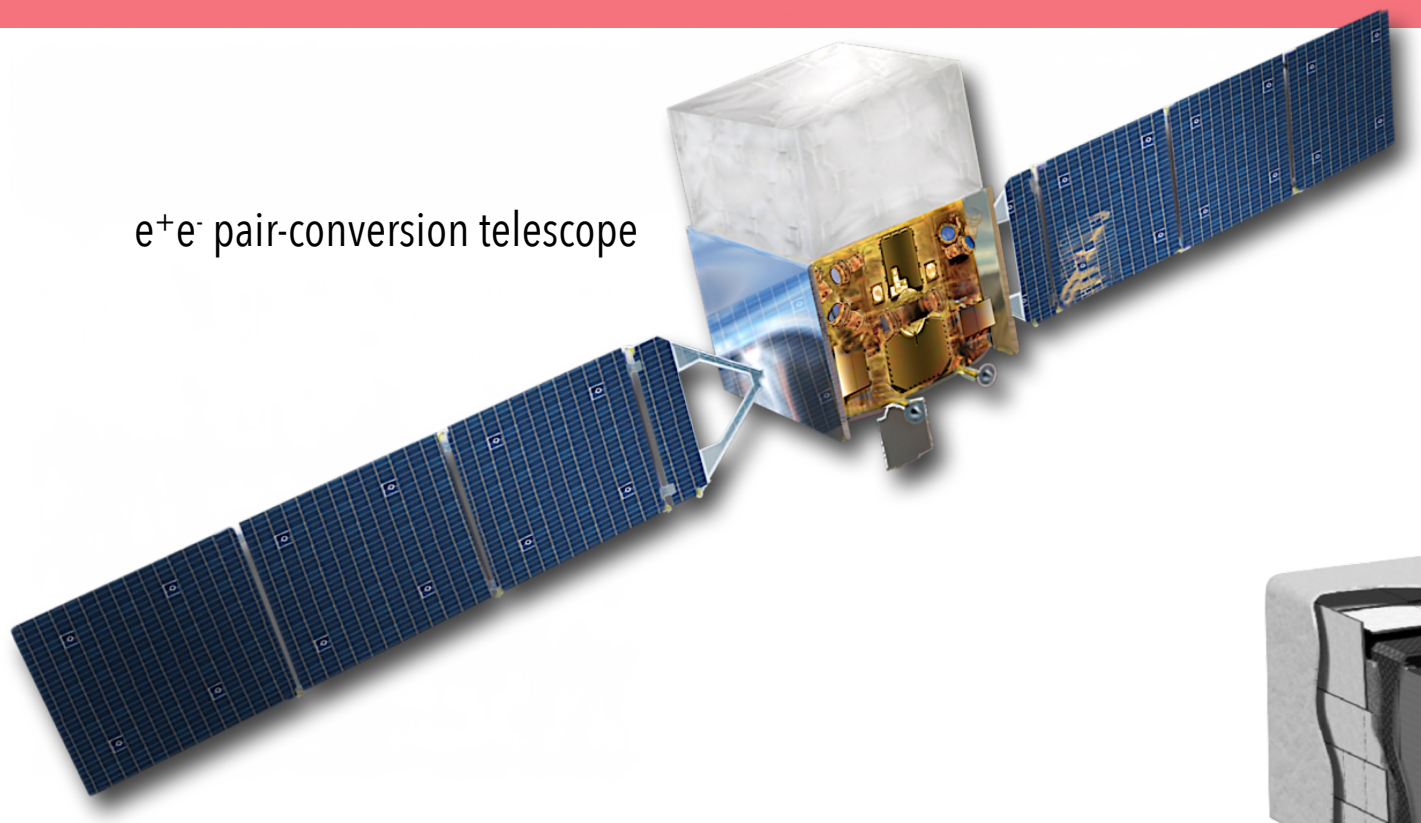
Authors' affiliations removed for readibility.

Building *Fermi*

*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.)*

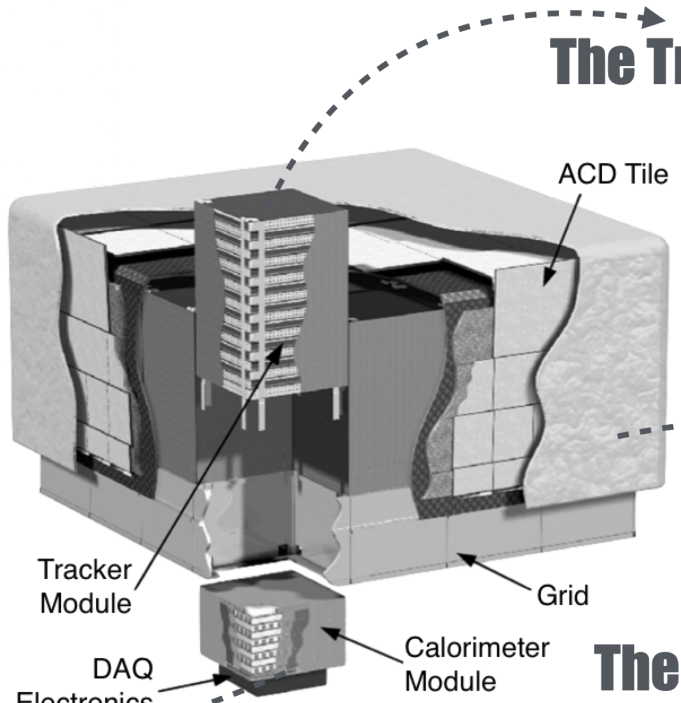
The *Fermi*-LAT

e^+e^- pair-conversion telescope

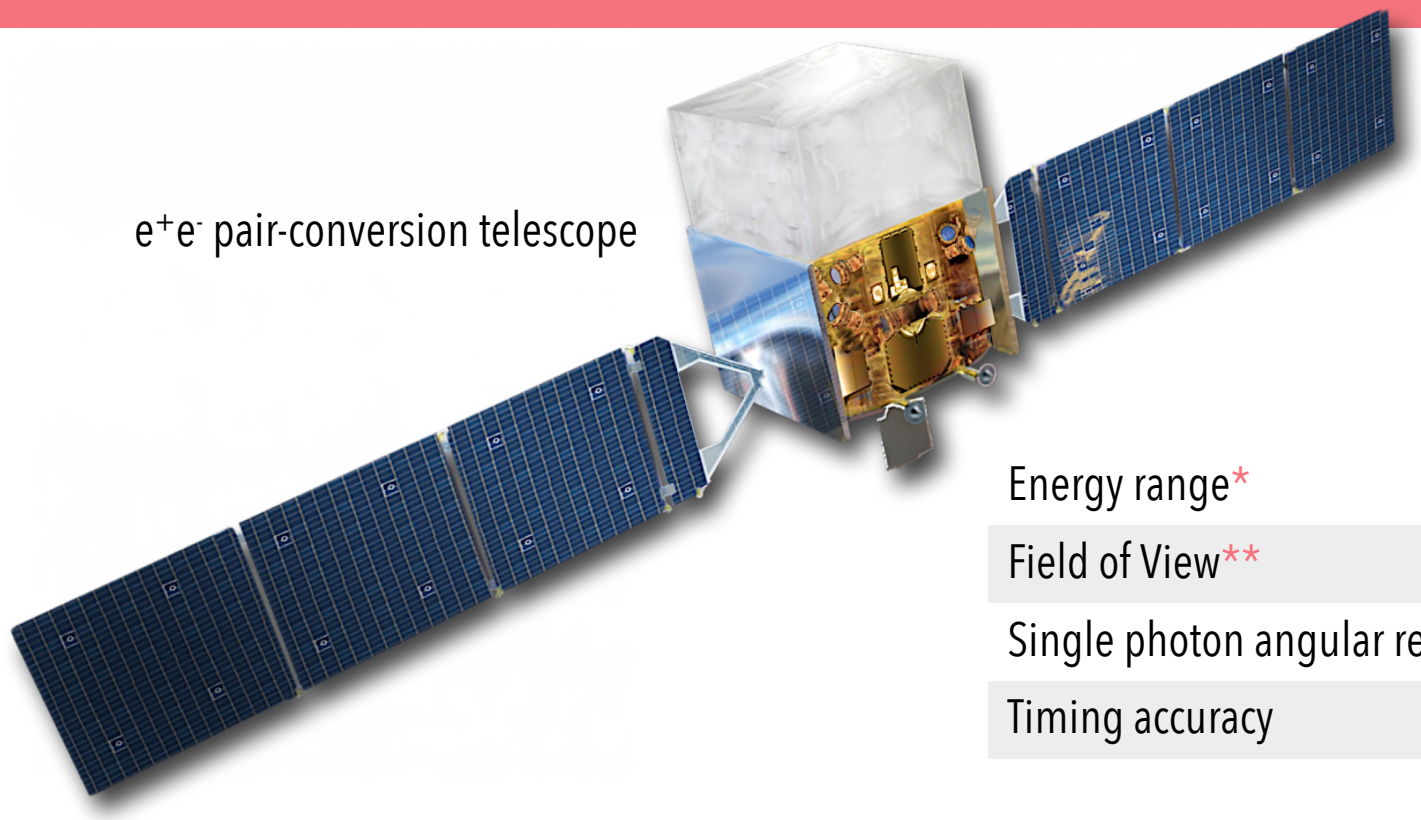


individual γ rays convert into e^+e^- pairs
→ tracks (localization) & deposited energy

…it also detects electrons.



The *Fermi*-LAT



e^+e^- pair-conversion telescope

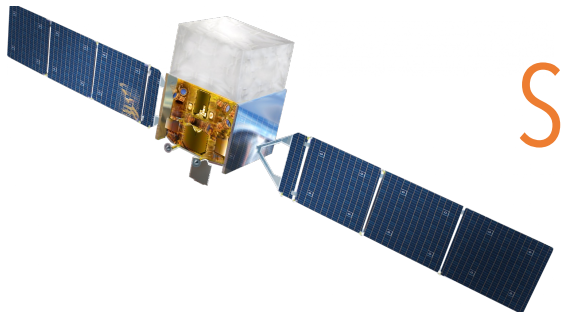
Energy range*	20 MeV to > 300 GeV
Field of View**	2.4 sr (~1/5 of the whole sky)
Single photon angular resolution***	< 1 deg at 1 GeV
Timing accuracy	1 microsecond

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.

WIMP Landscape: An Instrumentationalist's View



Satellite

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

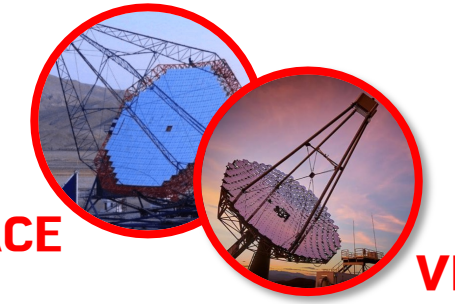
Atmospheric/water Cherenkov Telescopes

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

WIMP Landscape: An Instrumentationalist's View

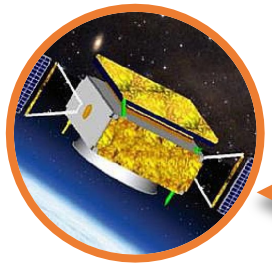
*approximate scale

LHASSO (~hundreds GeV – few PeV)



MACE

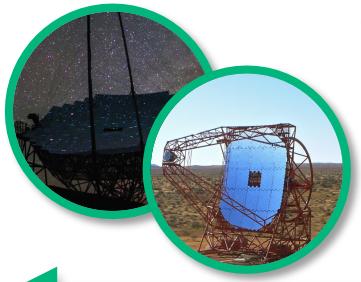
VERITAS (85 GeV – 30 TeV)



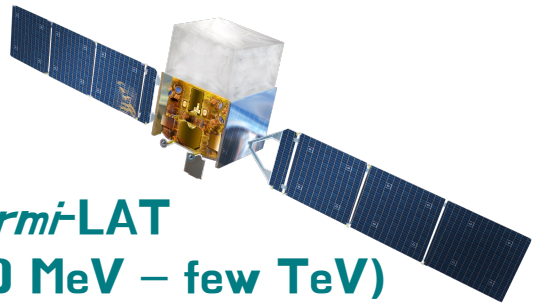
DAMPE (5 GeV – 10 TeV)

HAWC (300 GeV – 100 TeV)

MAGIC

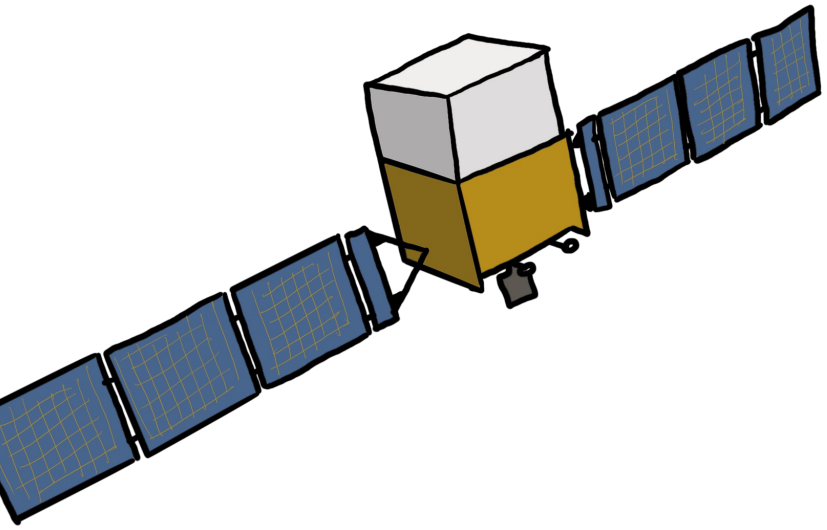


H.E.S.S. (30 GeV – 100 TeV)

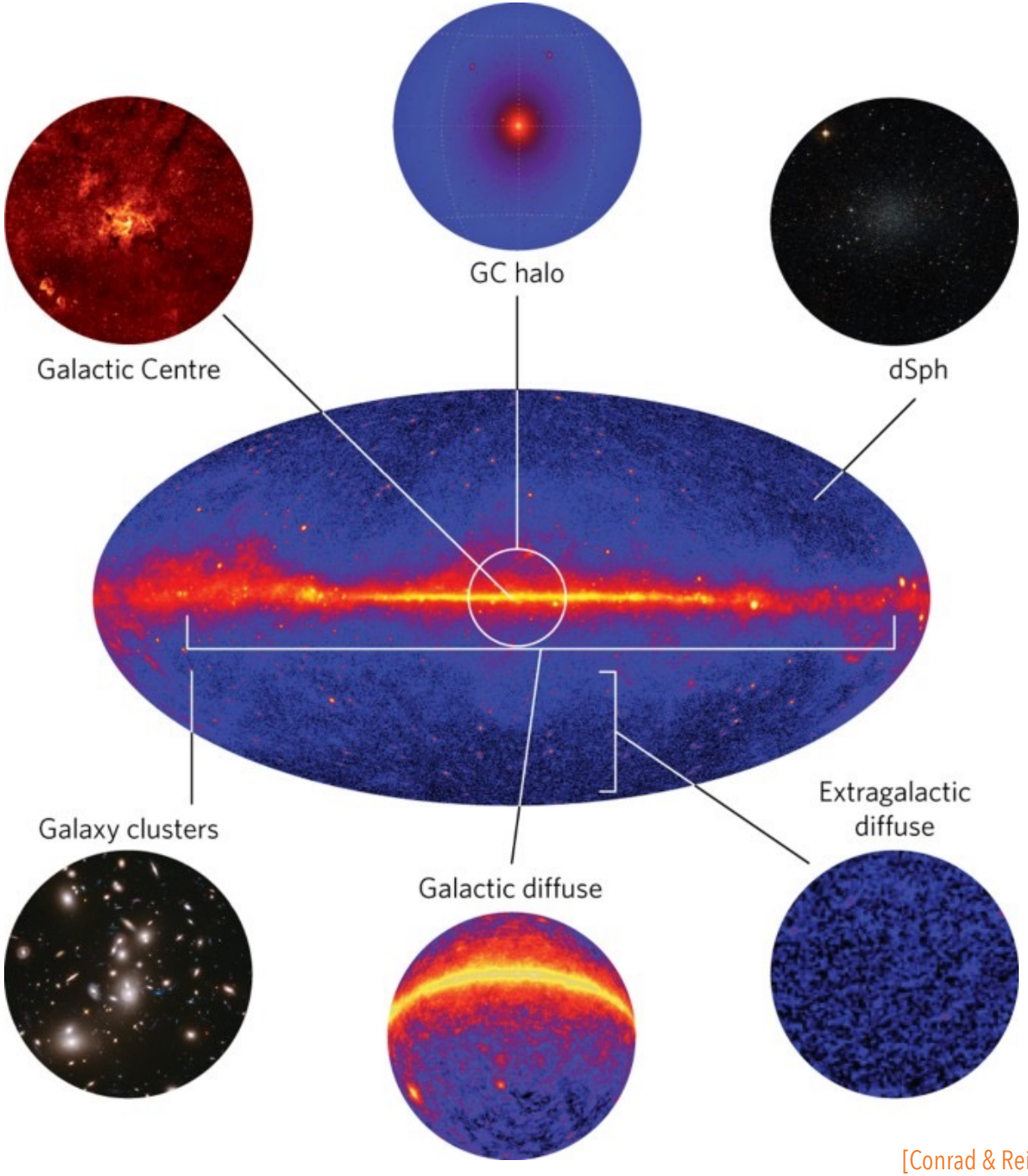


Fermi-LAT
(20 MeV – few TeV)

MeV | GeV | TeV | PeV

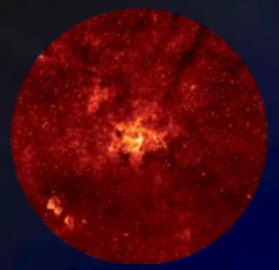


DM targets

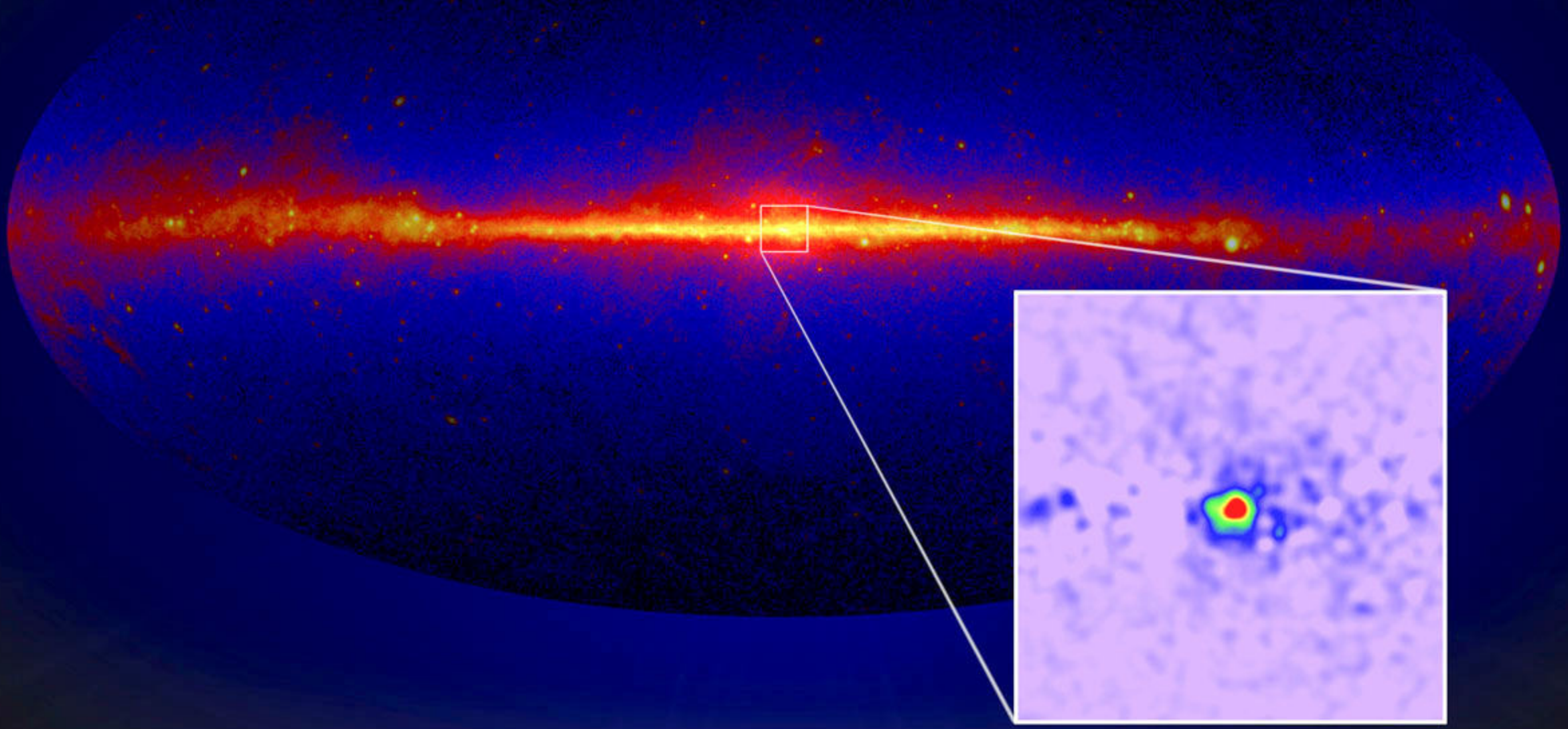


Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.
@ DM & νs: Rebecca Leane and Tim Linden

[Conrad & Reimer 2017]



Target 1: The Galactic Center



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

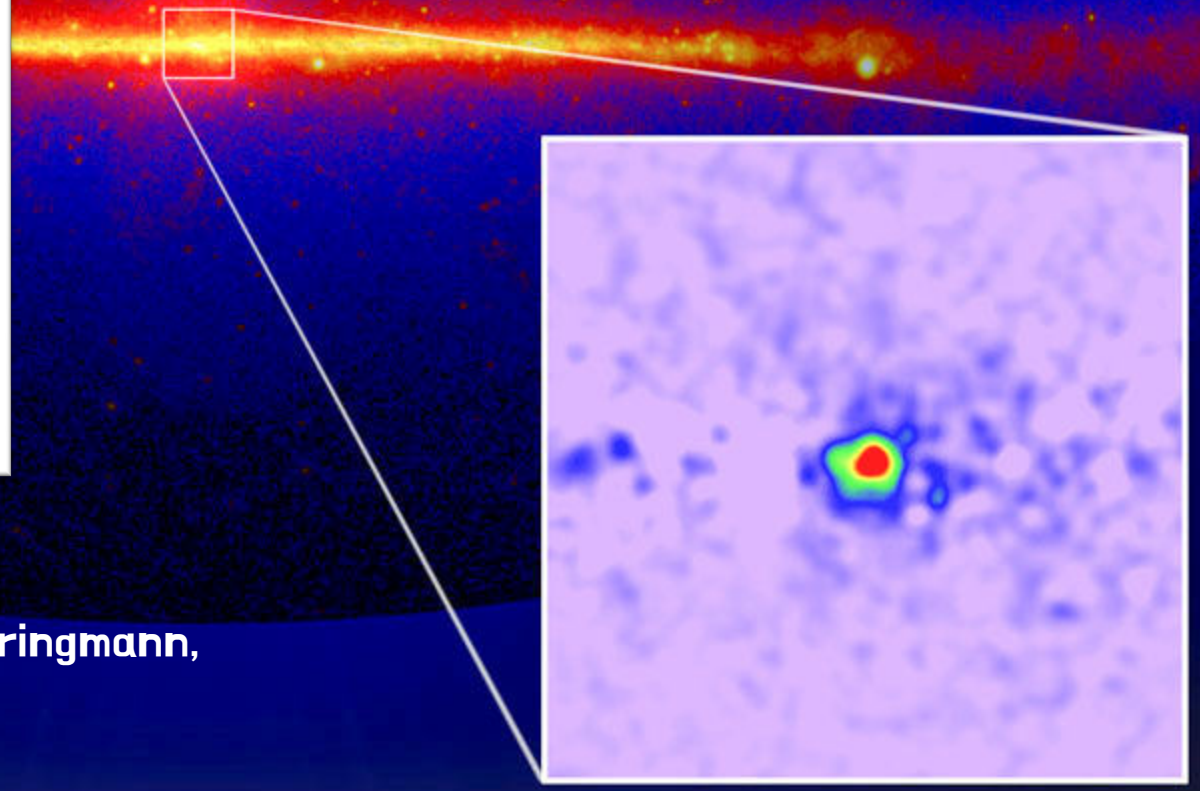
Target 1: The Galactic Center

Insights on the GeV Galactic Center Excess from the highest energies

9:30 AM - 10:00 AM

(Institut Henri Poincaré)
Bâtiment Perrin, 11, Rue Pierre et Marie Curie 75005 Paris

Presenter Silvia Manconi

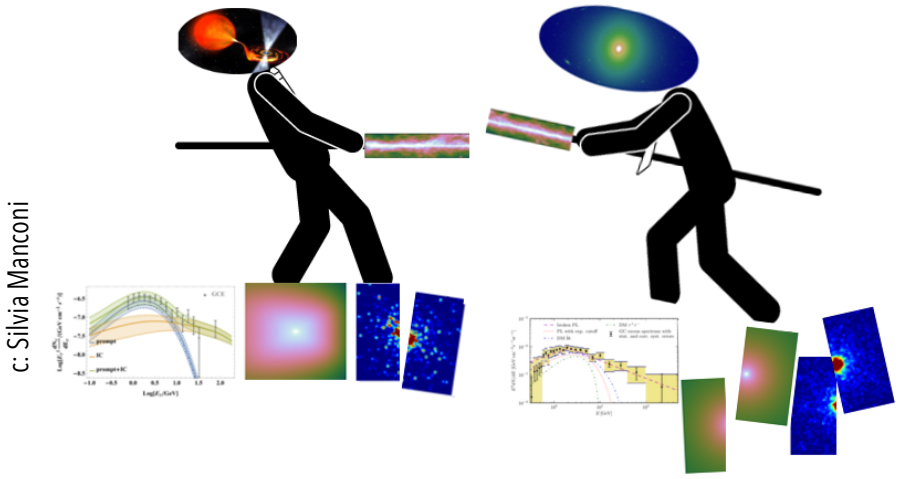


also @ DM & νs: Kevork Abazajian, Torsten Bringmann, Marco Cirelli, Rebecca Leane, Tim Linden

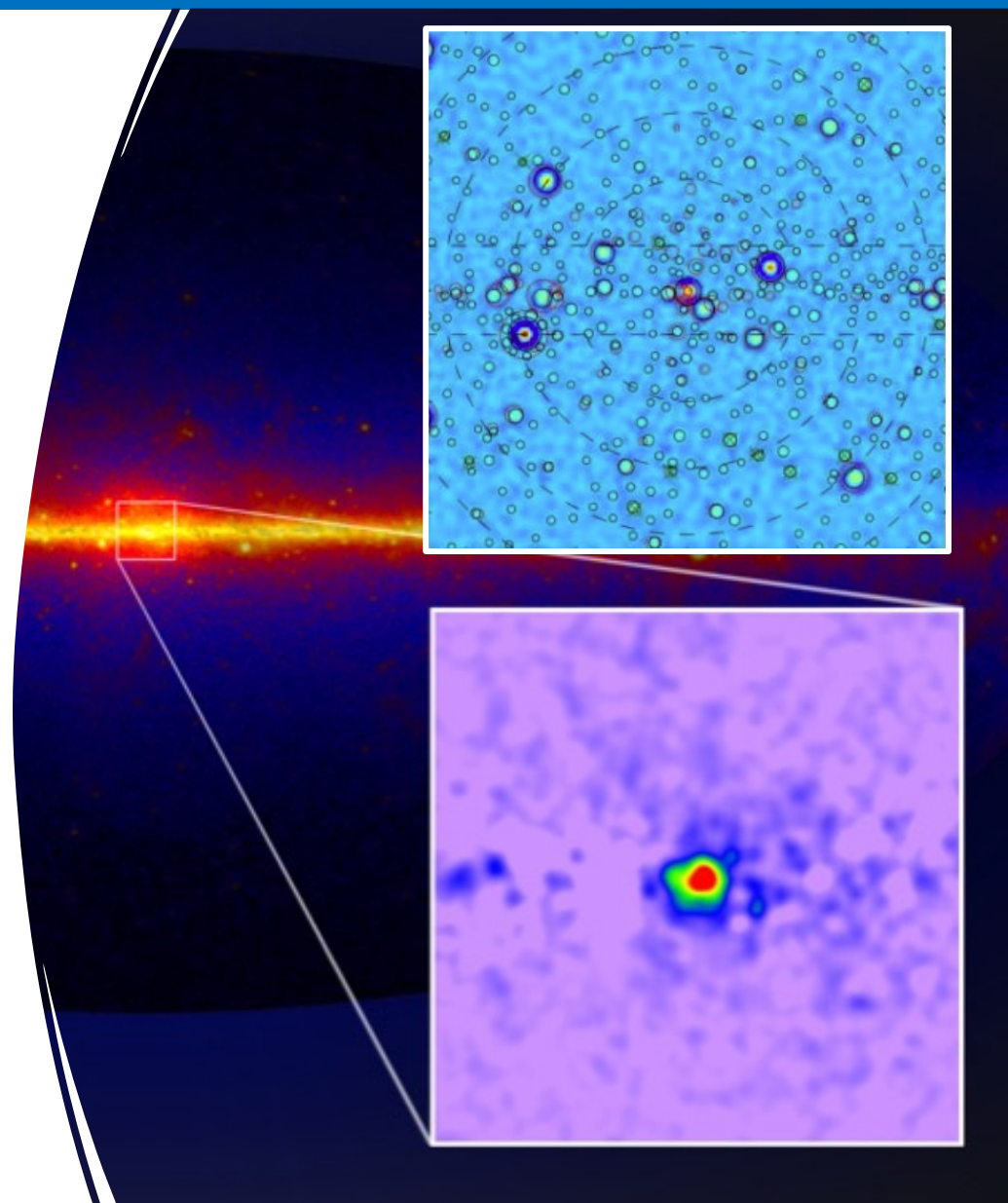
Credit: NASA/DOE/FERMI LAT COLLABORATION; T. LINDEN

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)

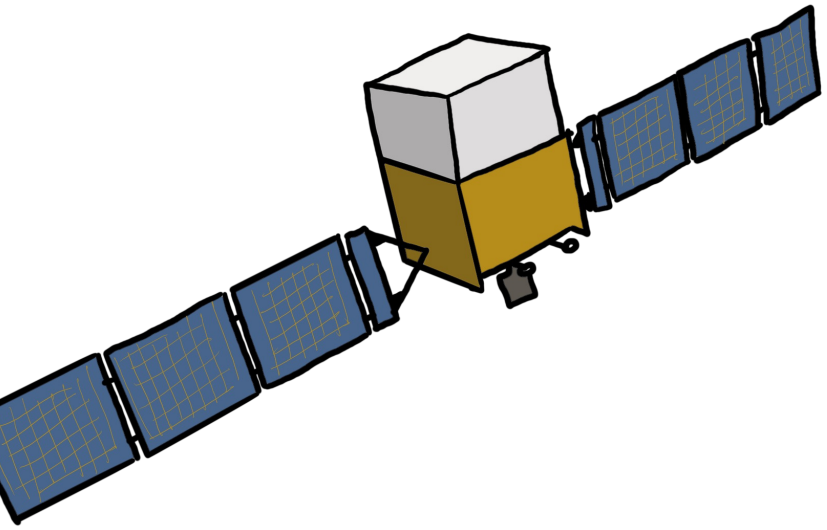


c: Silvia Manconi

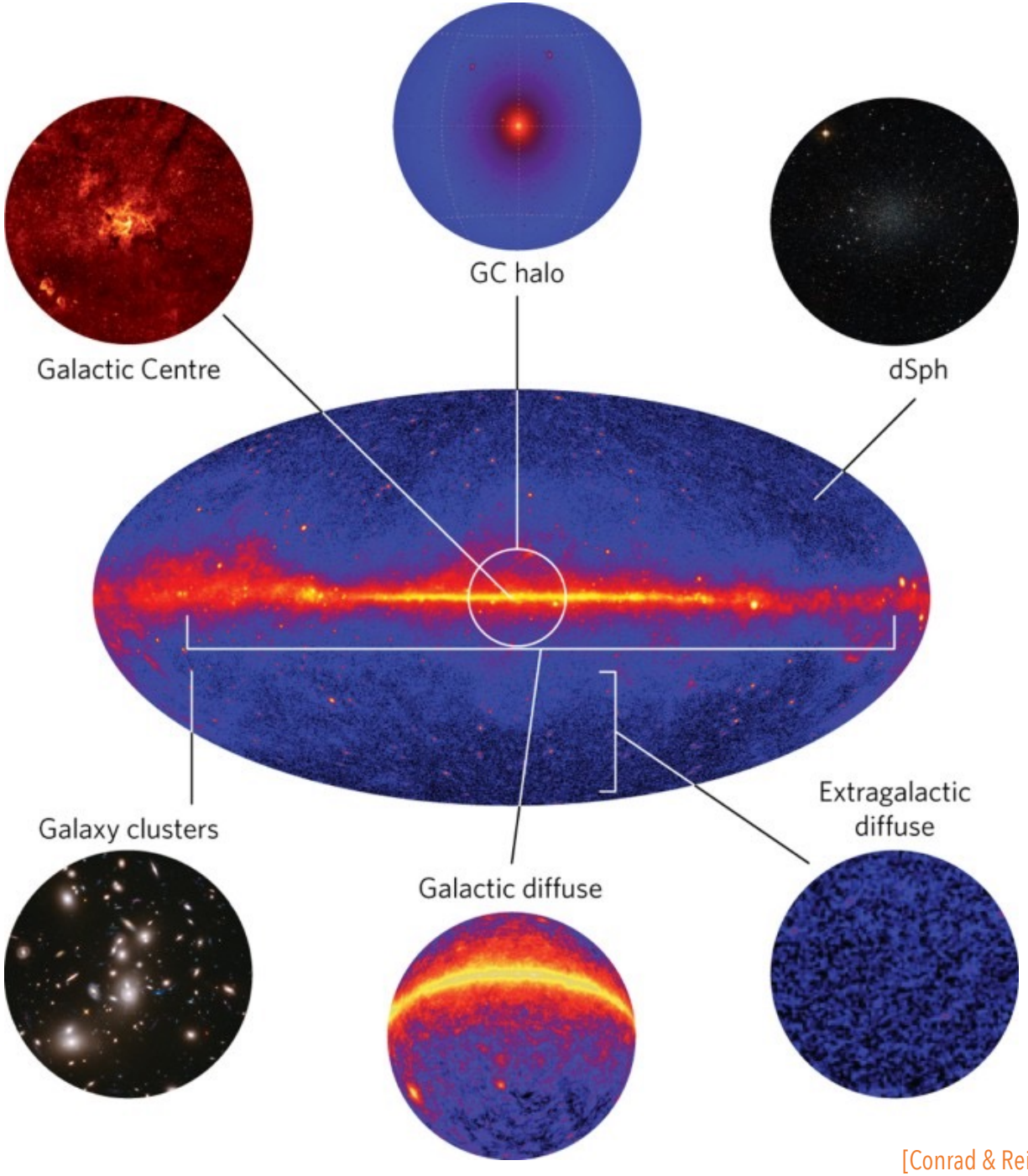


-Did we reach the instrumental limits? What about theoretical models?

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 (or build a better instrument?)



DM targets



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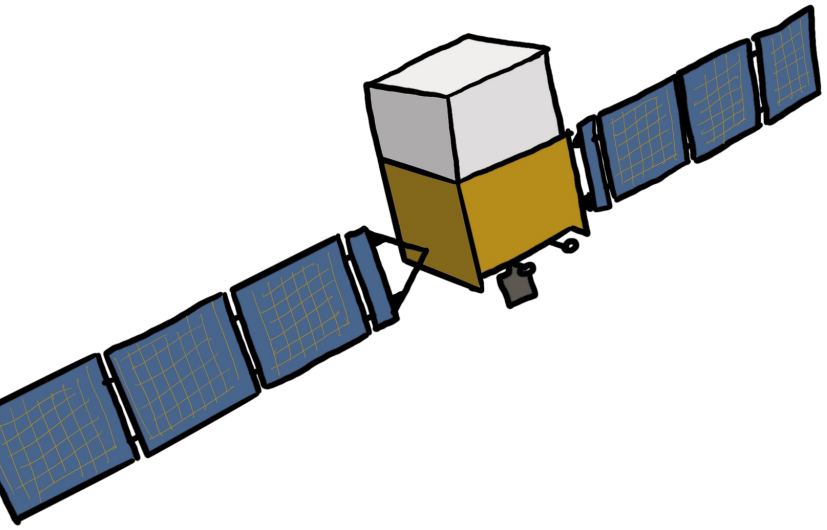
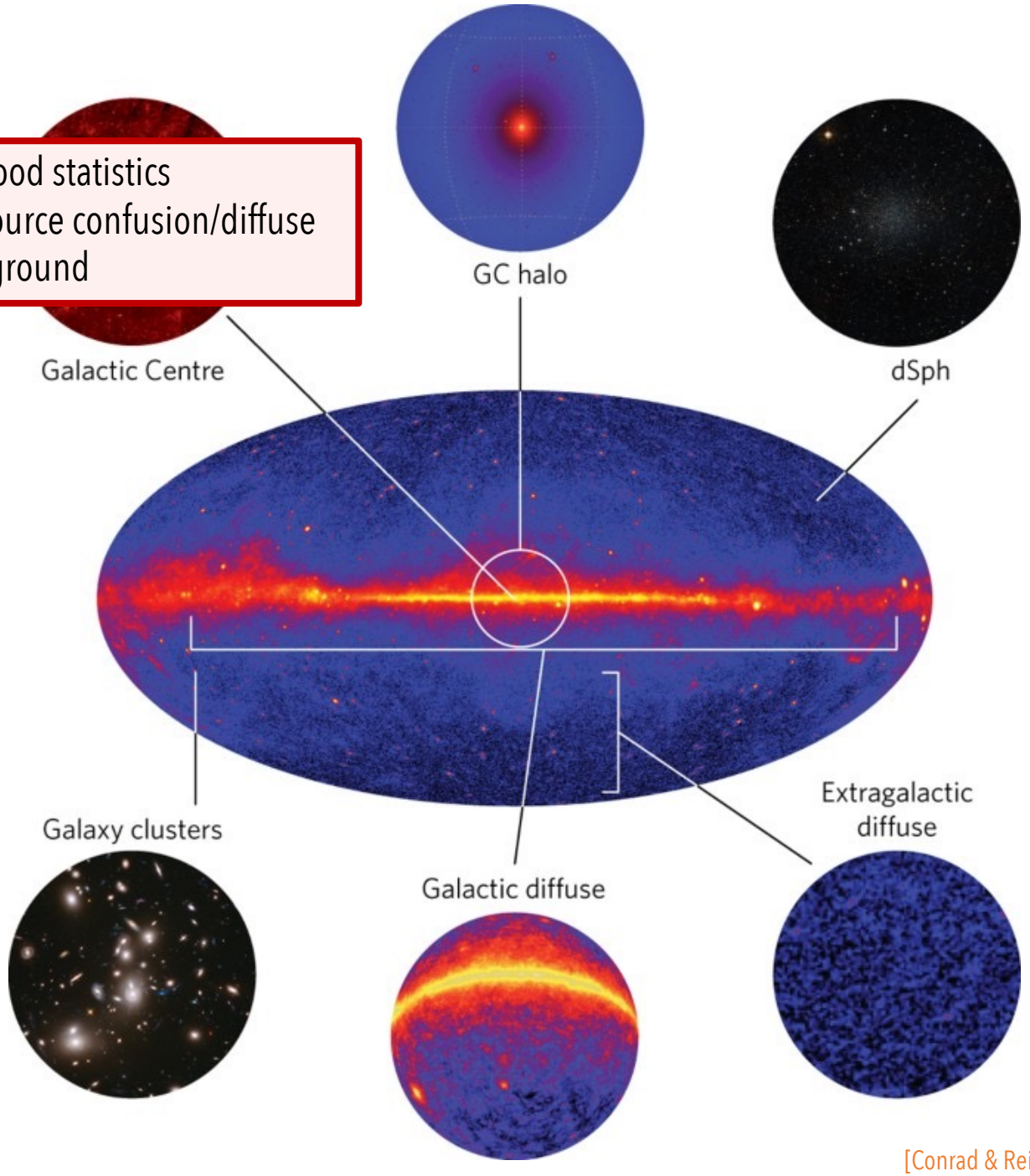
[Conrad & Reimer 2017]



DM targets

✅ Good statistics
❌ Source confusion/diffuse background



Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.
@ DM & νs: Rebecca Leane and Tim Linden

[Conrad & Reimer 2017]

Fornax Dwarf Galaxy, ESO/Sky Survey 2

Target 2: dSphs

→ most dark-matter dominated systems known in the Universe

→ 61 dwarf satellites identified so far in the Milky Way, more on the horizon

→ nearby (furthest 460 kpc), some within single-digit kpc

→ not much astrophysical background, inactive

Fornax Dwarf Galaxy, ESO/Sky Survey 2

Target 2: dSphs

Dwarf Spheroidal Galaxies

DM γ-ray flux

$$\frac{d\Phi}{dE}$$

=

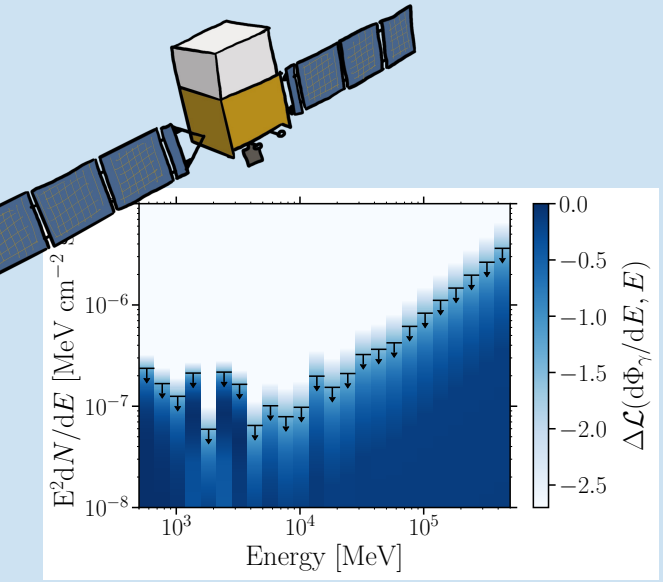
astrophysics J-factor

$$\int_{\Delta\Omega,\mathrm{los}} \rho_{DM}^2$$

×

particle physics

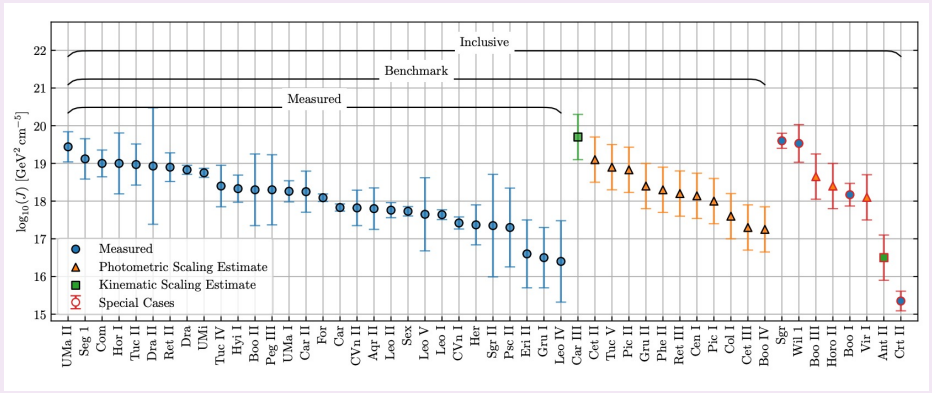
$$\frac{\langle\sigma v\rangle}{2M_{DM}^2}\sum B_i \frac{dN_\gamma}{dE}$$



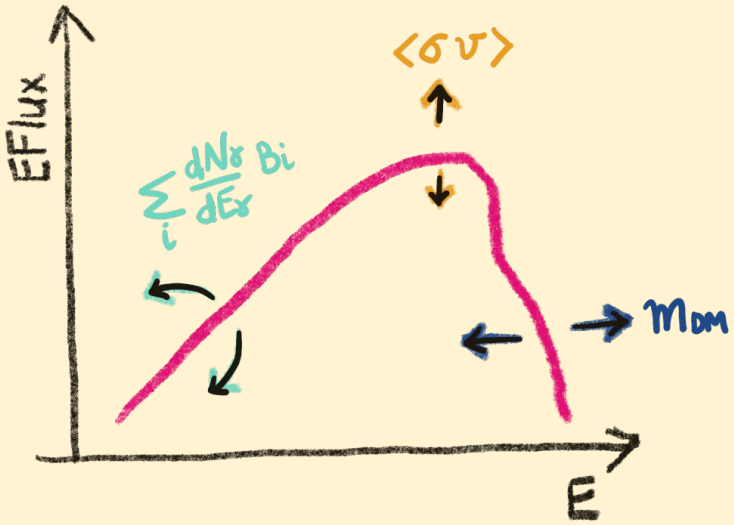
Ursa Major III [MC & Linden 2023]

Dark matter content determined from stellar velocity dispersion

- **Classical dwarfs**: spectra for several thousand stars
- **Ultra-faint dwarfs**: spectra for fewer than 100 stars

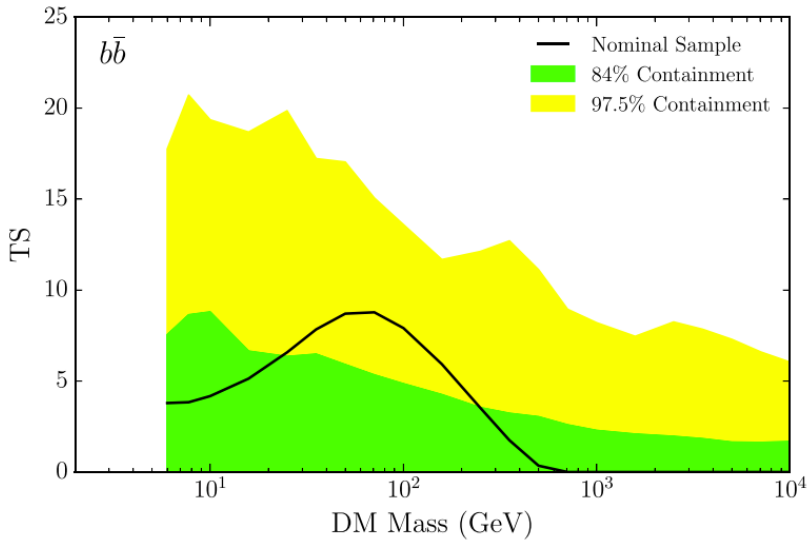


J-factors [Fermi-LAT Collaboration 2024]



Combined dSph Analyses

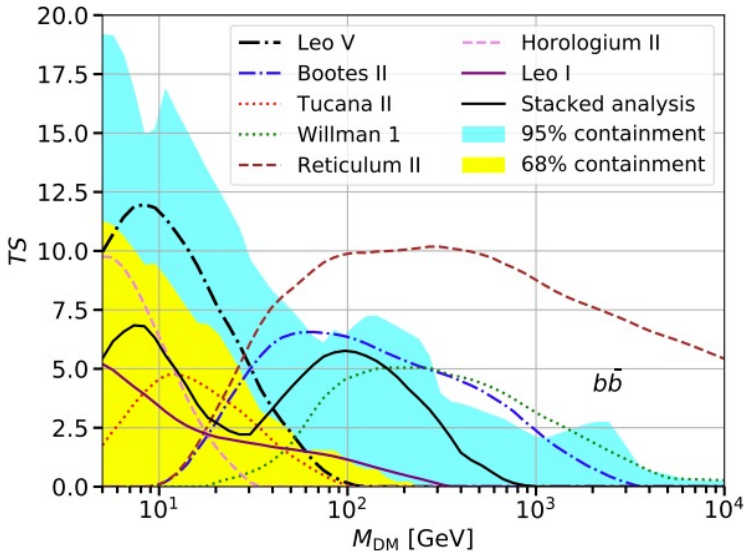
6 years



$< 2\,\sigma$

[Fermi-LAT Collaboration '17]

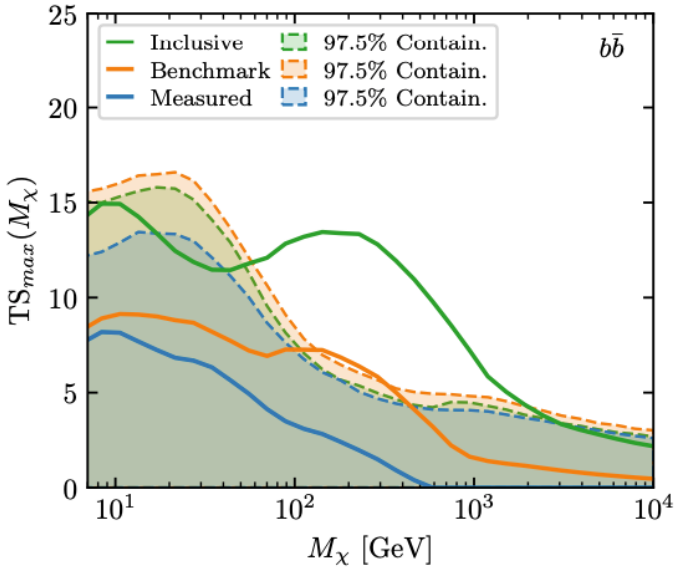
11 years



$\lesssim 2\,\sigma$

[Fermi-LAT Collaboration '21]

14 years

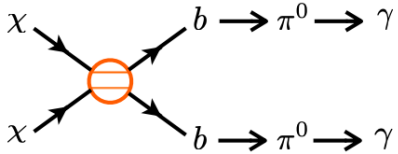


$\gtrsim 2\,\sigma$

[Fermi-LAT Collaboration+ '24]

Shaded regions: blank-field analysis

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



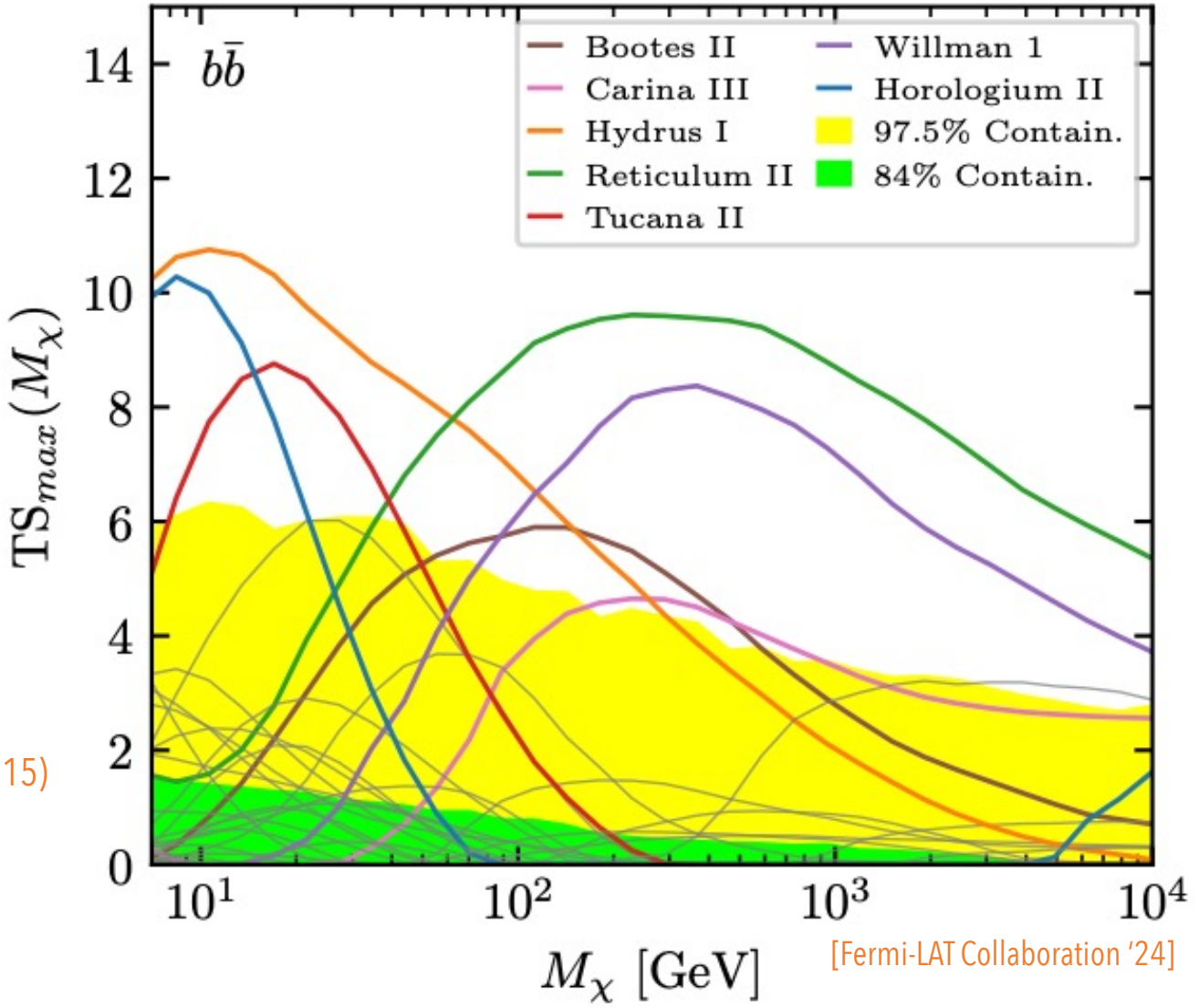
Combined dSph Analyses

(2024)

→ 7 dSphs with local significance > 2σ

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

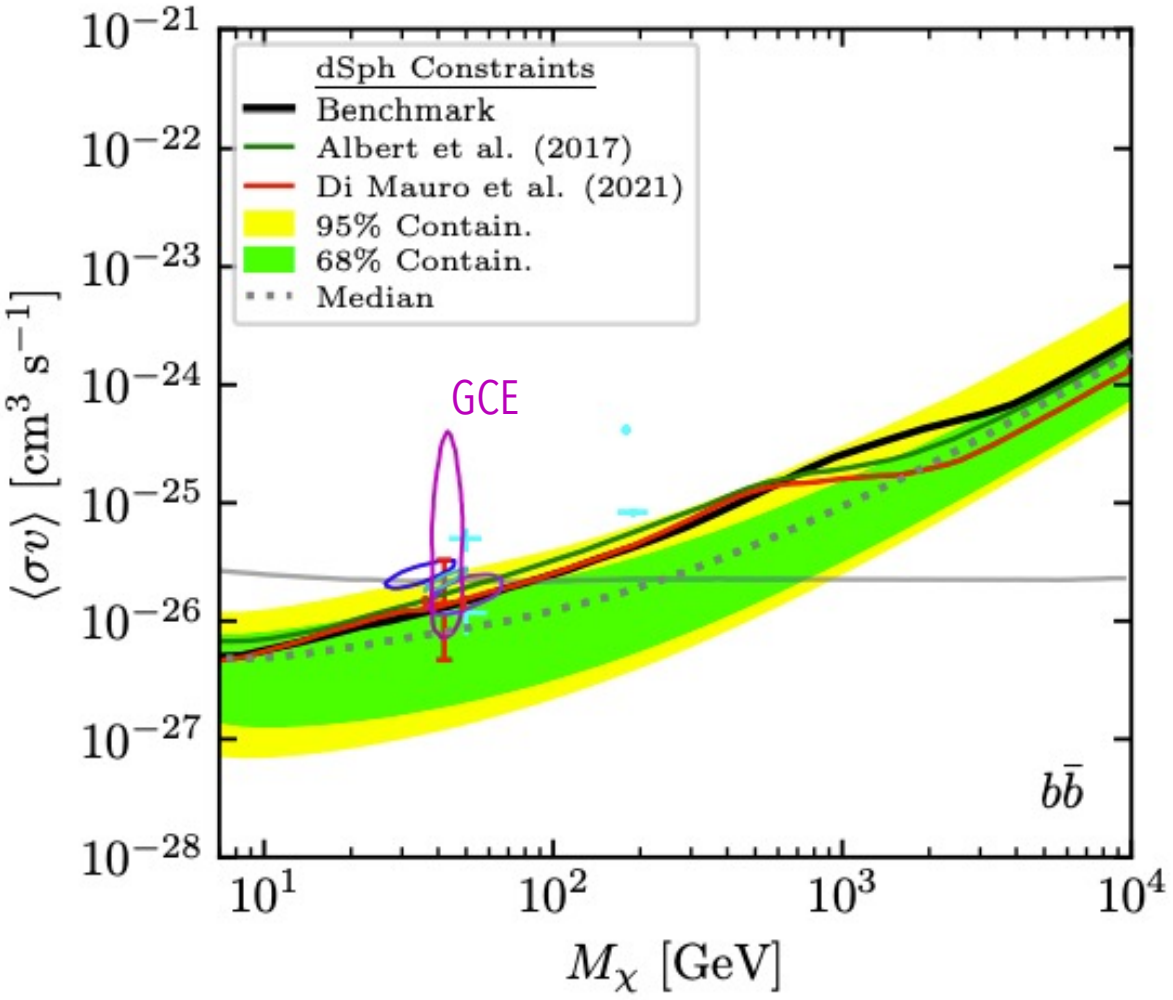
Ret II (DiMauro+ '21, Albert+ '17, Geringer-Sameth+ '15, Hooper & Linden '15)
Tucana II, Willman 1, Horologium II, Bootes I (DiMauro+ '21)



[Fermi-LAT Collaboration '24]

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

Limits on the parameter space



[Fermi-LAT Collaboration '24]

→ Trials factor reduces significance to 0.5 σ.

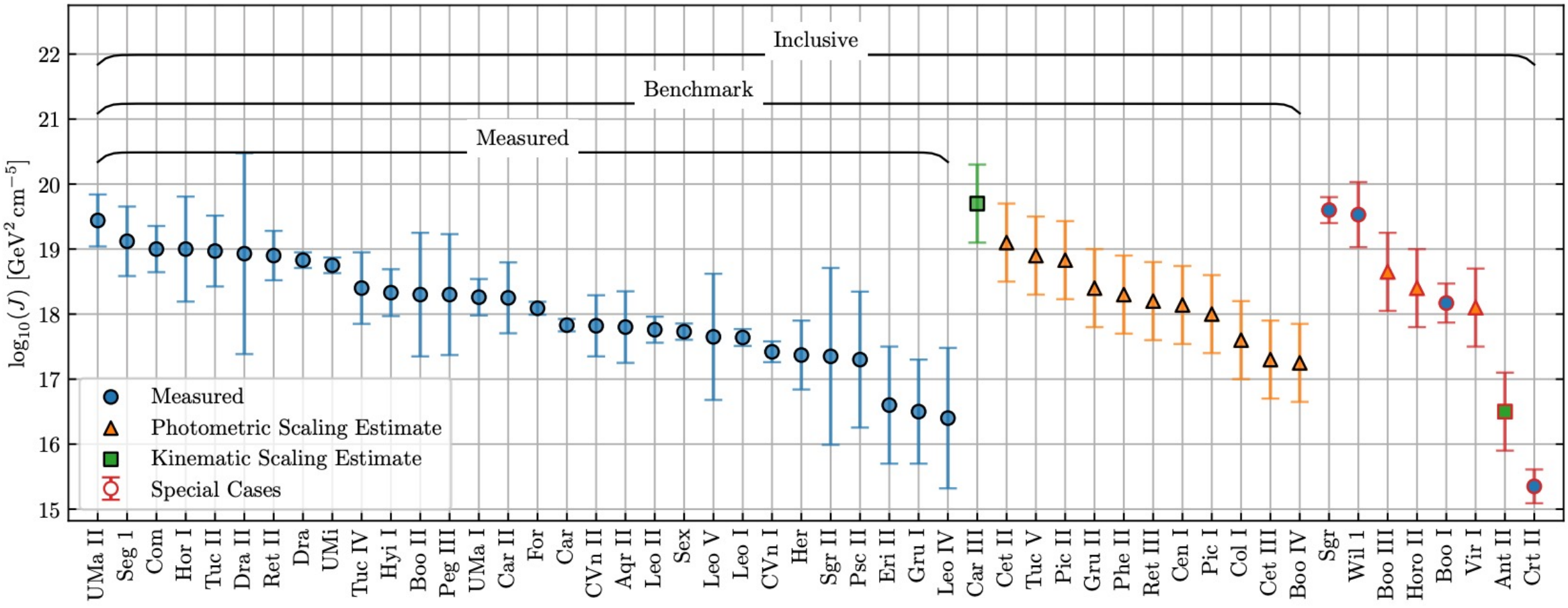
Observations:

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

→ cannot rule out DM due to the uncertainties in galactic center analysis (DM profile and interstellar diffuse model)

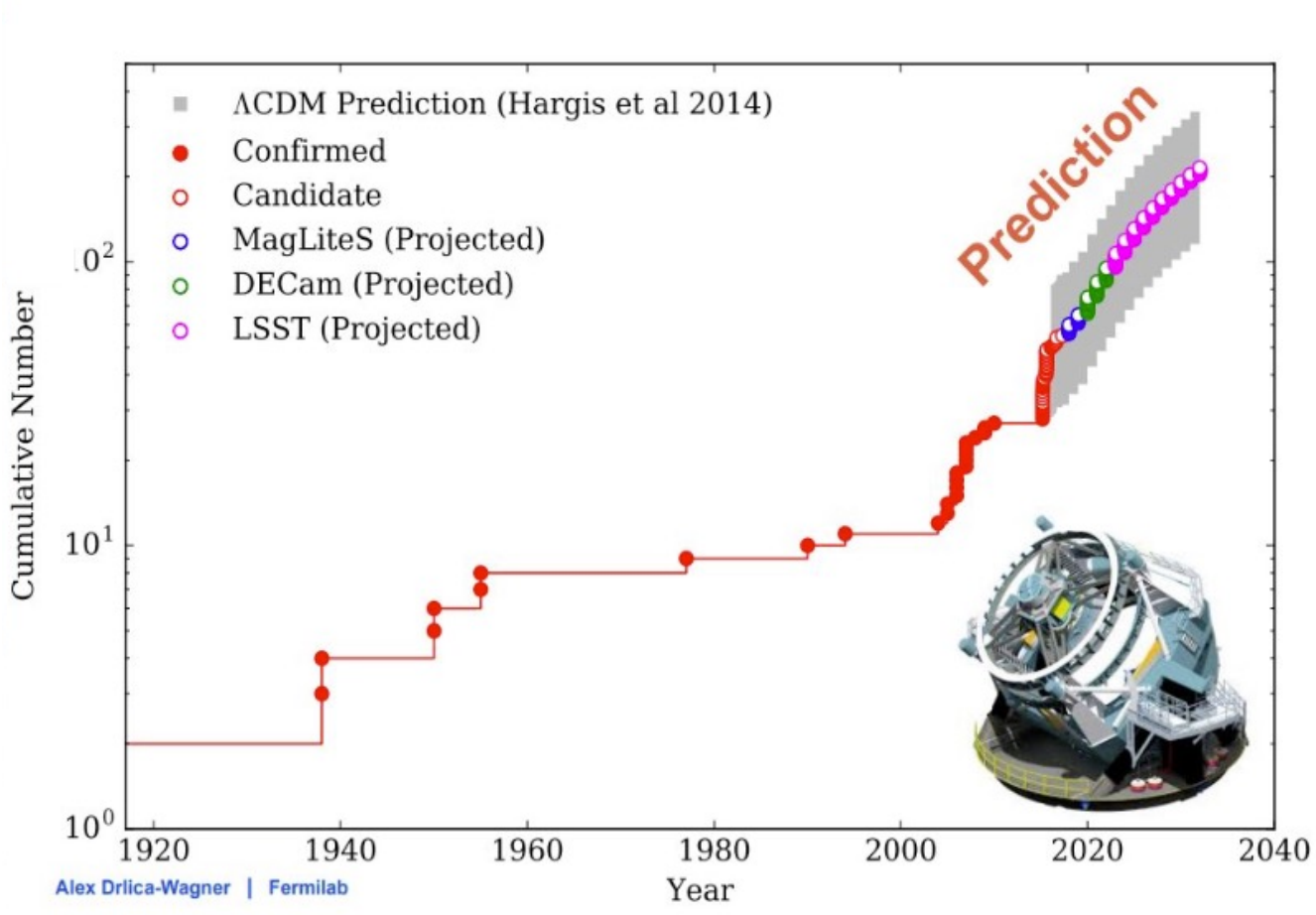
J-value calculations are... hard

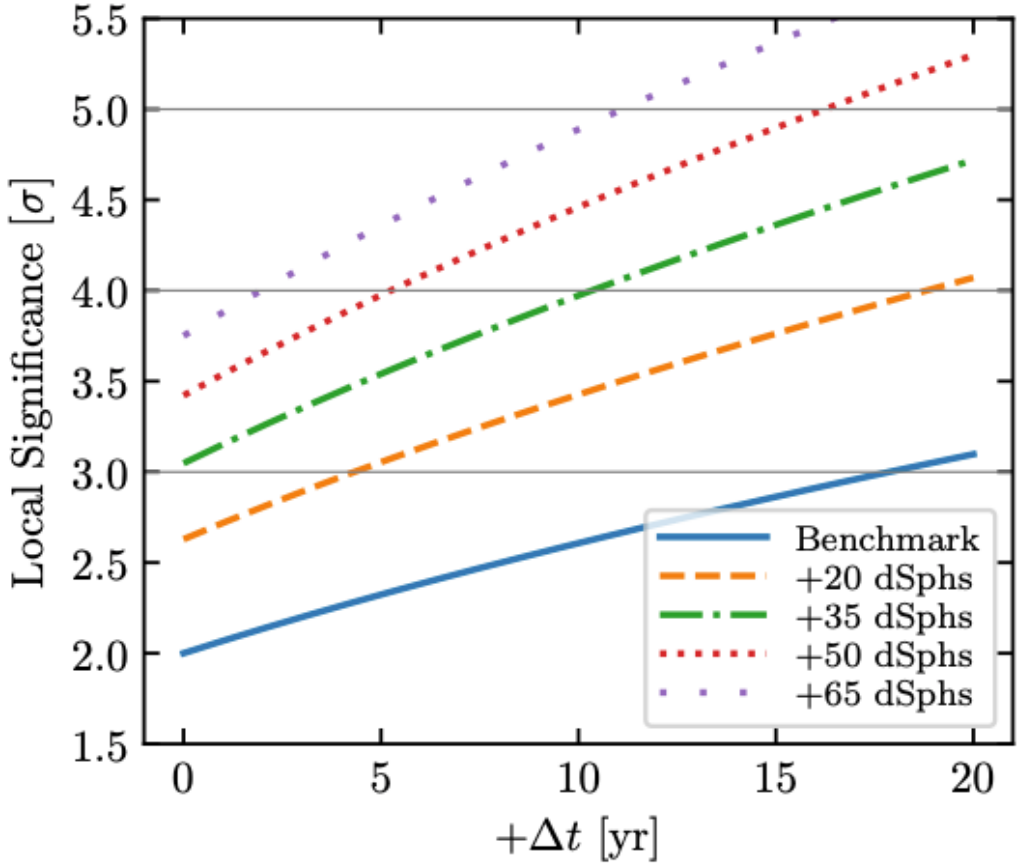
[McDaniel+ '24]



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



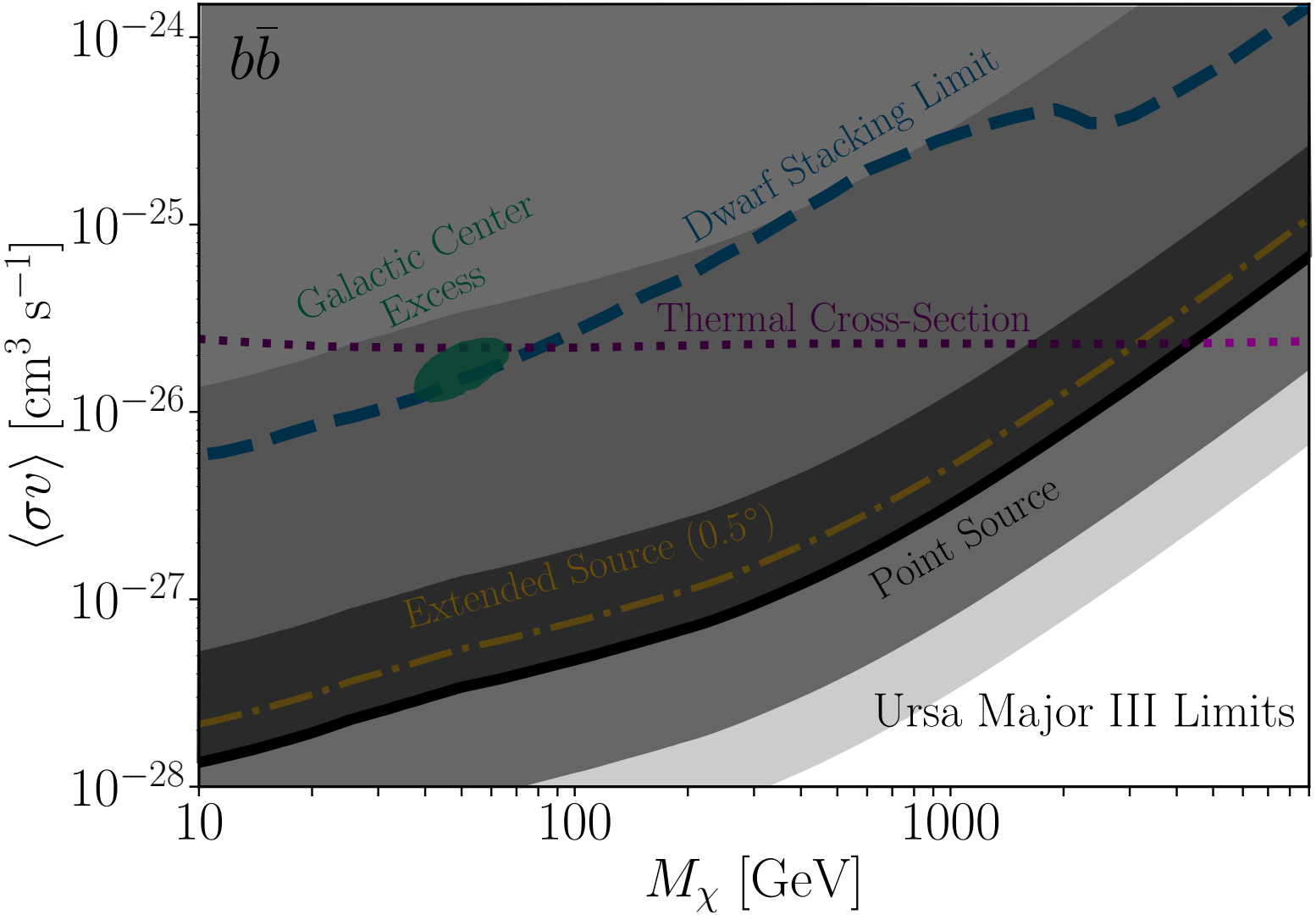


[Fermi-LAT Collaboration '24]

How many dwarf galaxies do we *really* need?

Maybe just one, but a good one?

Ursa Major III



[MC & Linden '23]

Ursa Major III

[Discovery: Smith+ 2023]

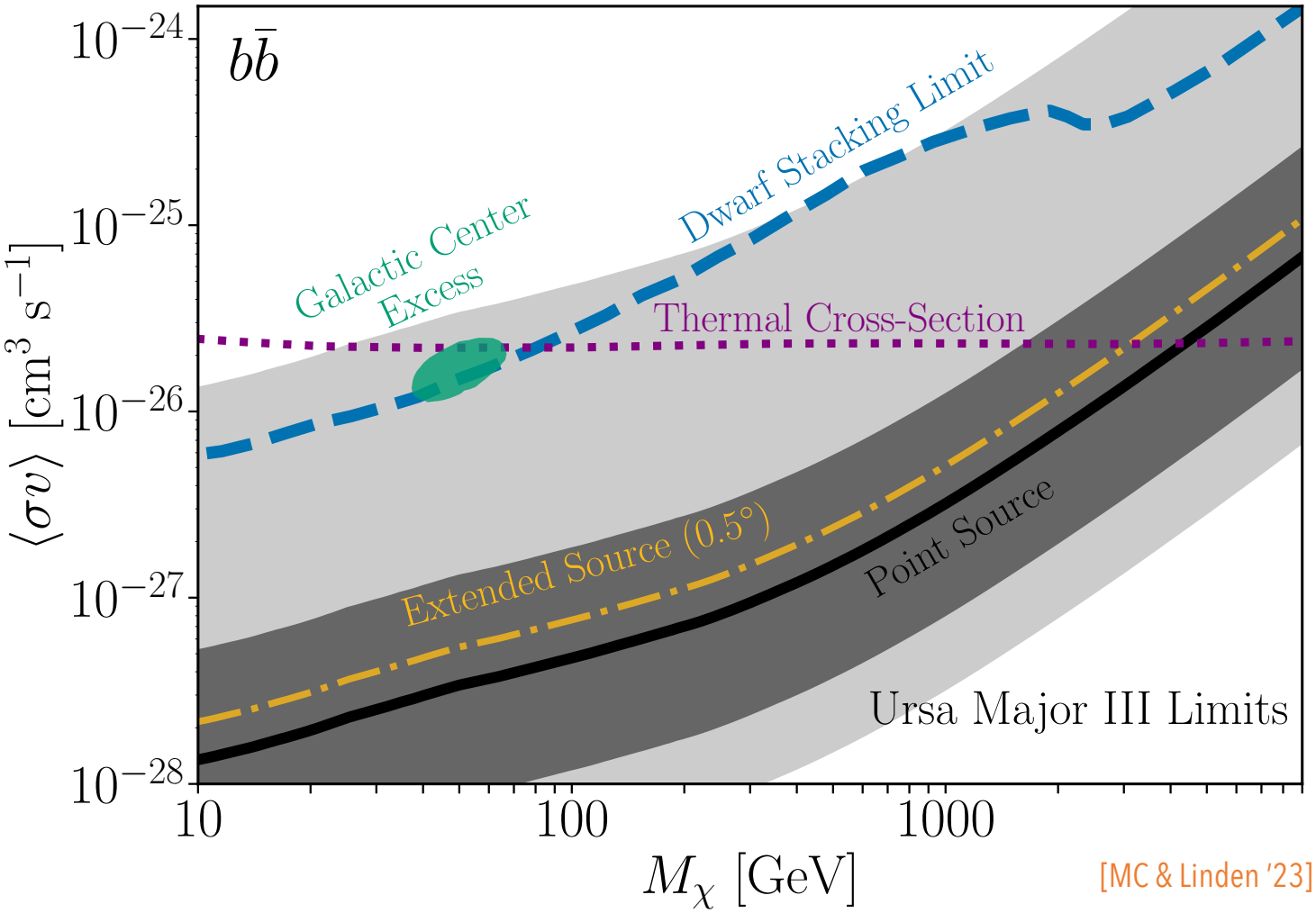
[J-factor: Errani+ 2023]

→ Unstable unless large DM content

→ Nearby (~10 kpc)

→ Strong constraints on DM annihilation

→ *Confirming the dark matter density requires deeper optical surveys*



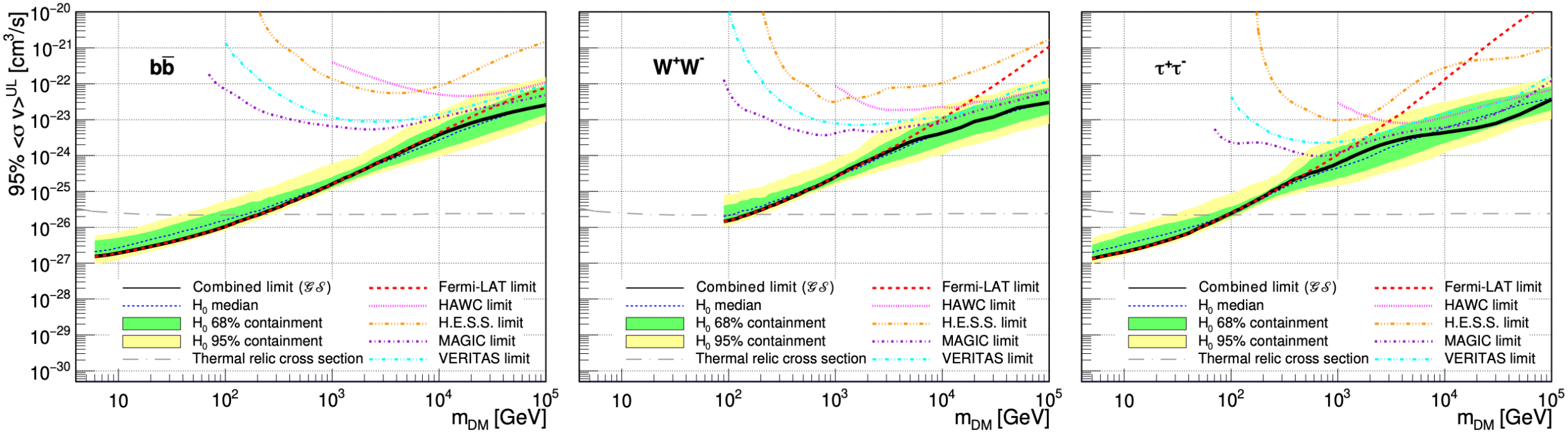
[MC & Linden '23]

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

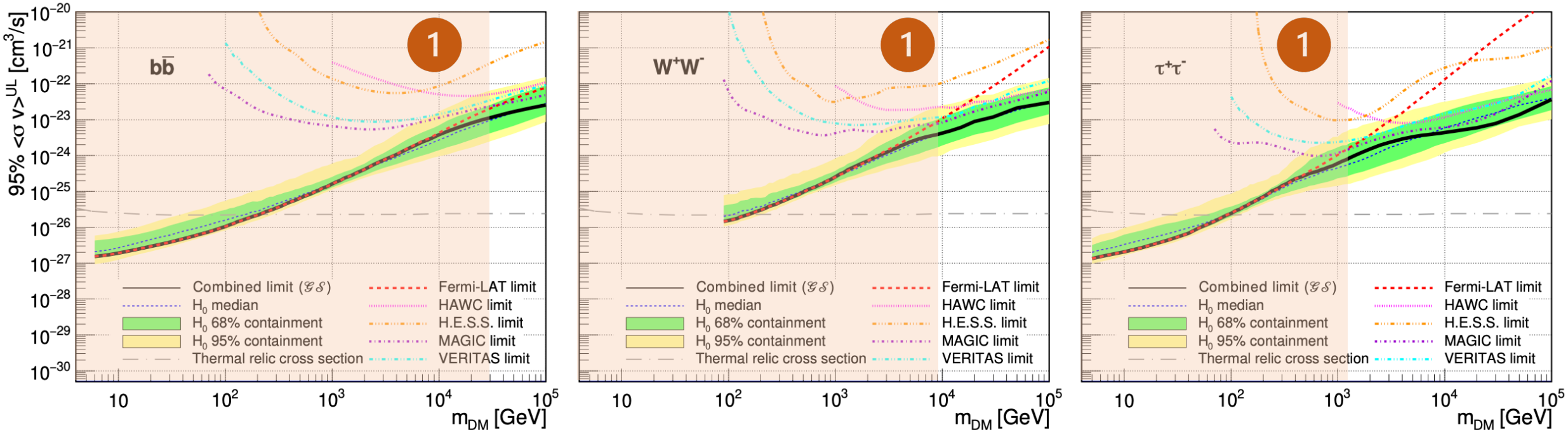
GLORY DUCK

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



As reported in Celina Armand TeVPA '22 talk.

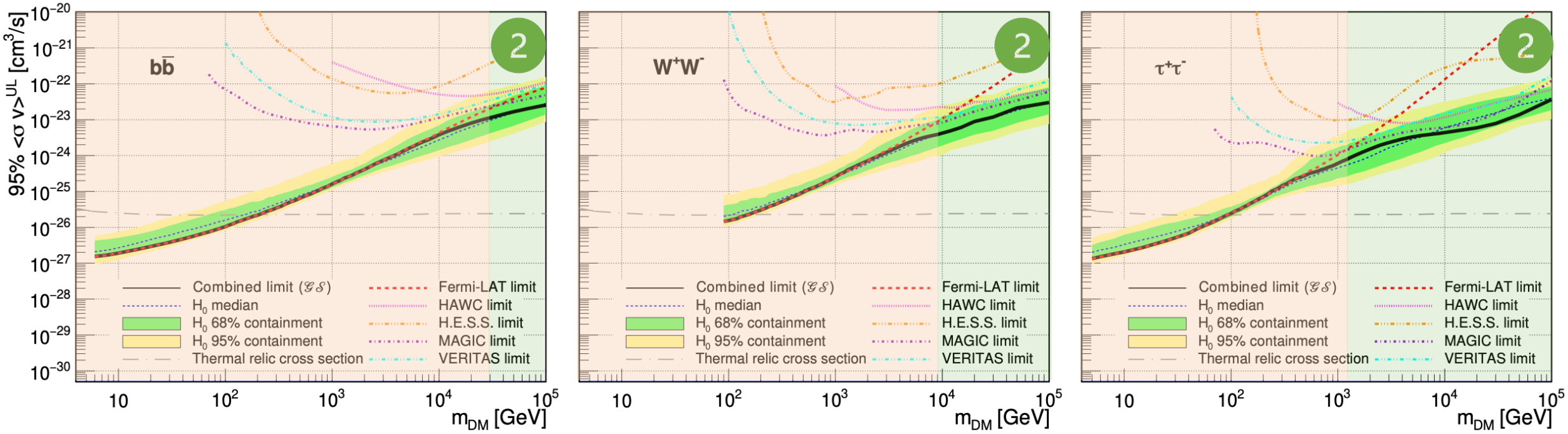
GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)



Dominated by *Fermi* LAT 1

As reported in Celina Armand TeVPA '22 talk.

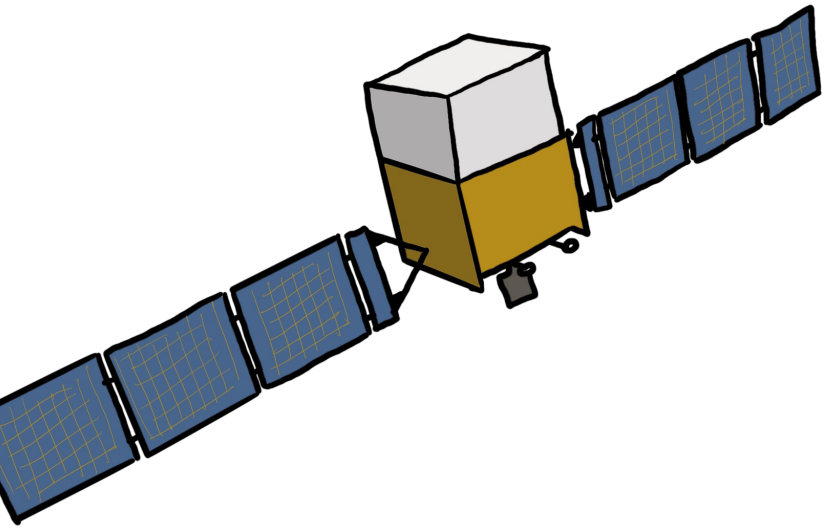
GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)



HAWC, HESS, MAGIC, VERITAS take over 2

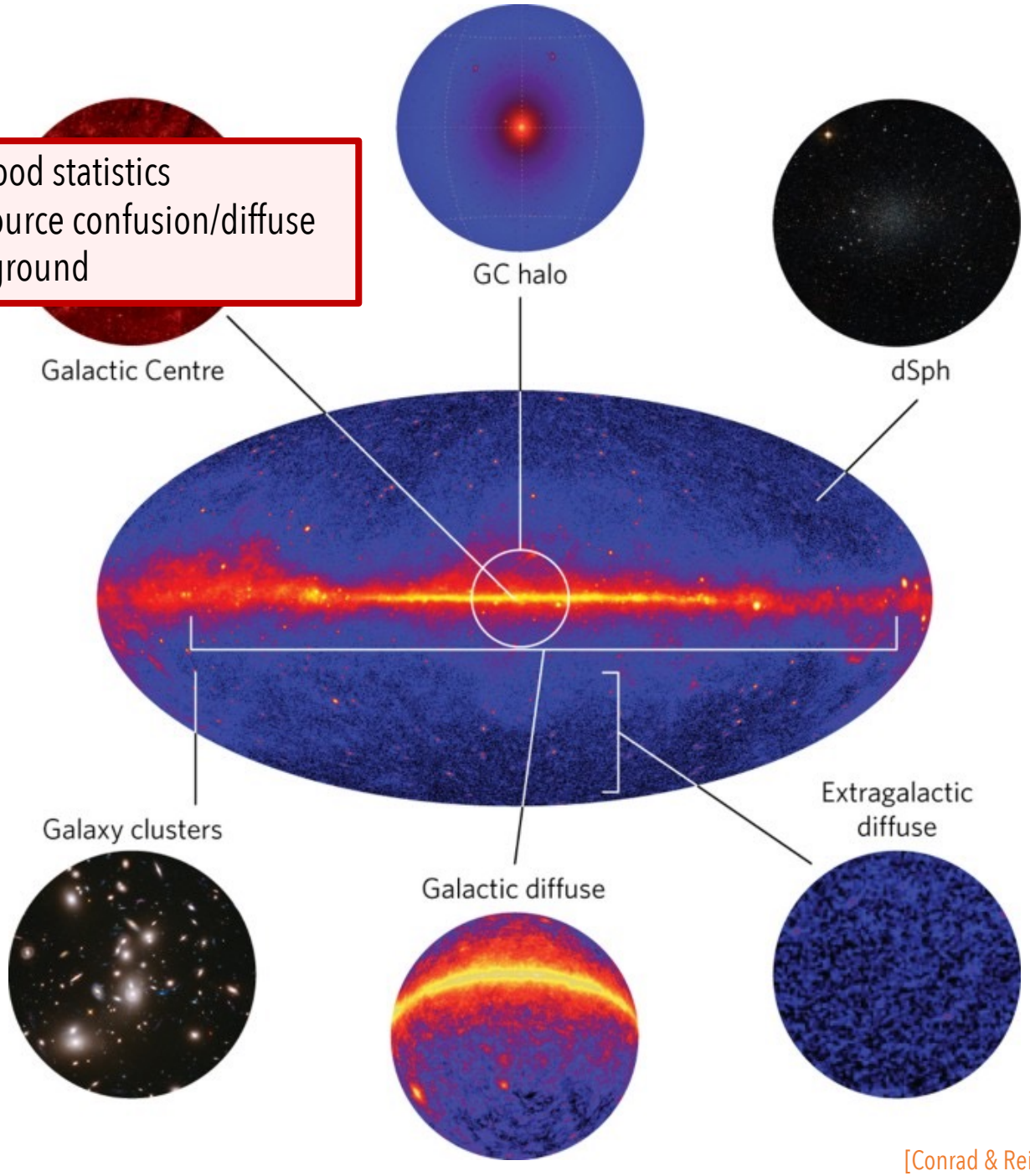
dark matter subhaloes, stellar streams, tidal disturbance/stripping of dwarfs, dark matter spikes, brown dwarfs, etc.

As reported in Celina Armand TeVPA '22 talk.



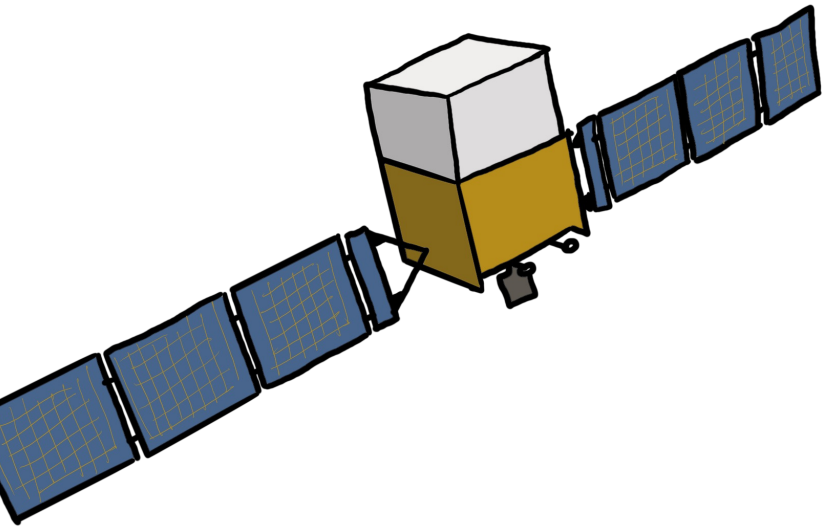
DM targets

✅ Good statistics
❌ Source confusion/diffuse background



Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.
@ DM & νs: Rebecca Leane and Tim Linden

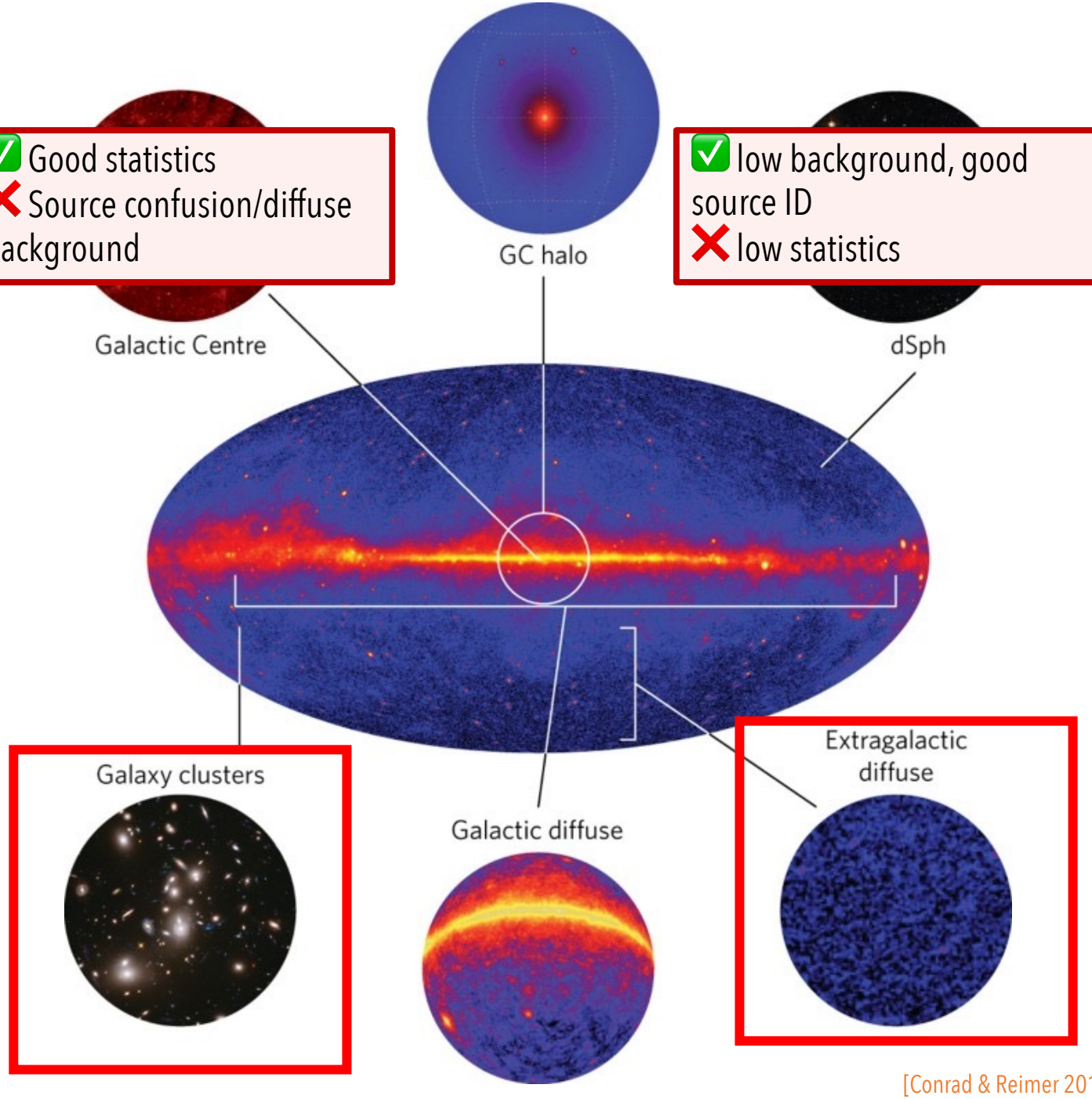
[Conrad & Reimer 2017]



DM targets

✅ Good statistics
❌ Source confusion/diffuse background

✅ low background, good source ID
❌ low statistics



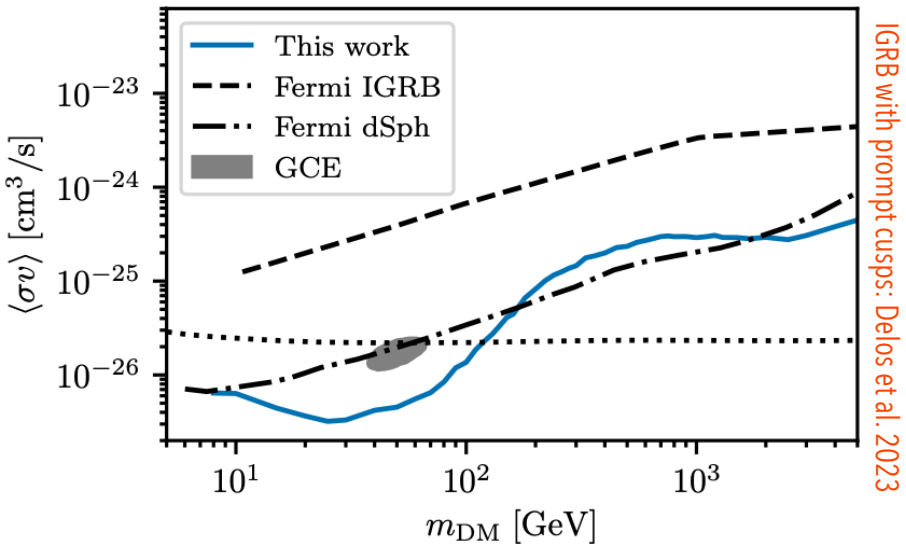
Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.
@ DM & νs: Rebecca Leane and Tim Linden

[Conrad & Reimer 2017]

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

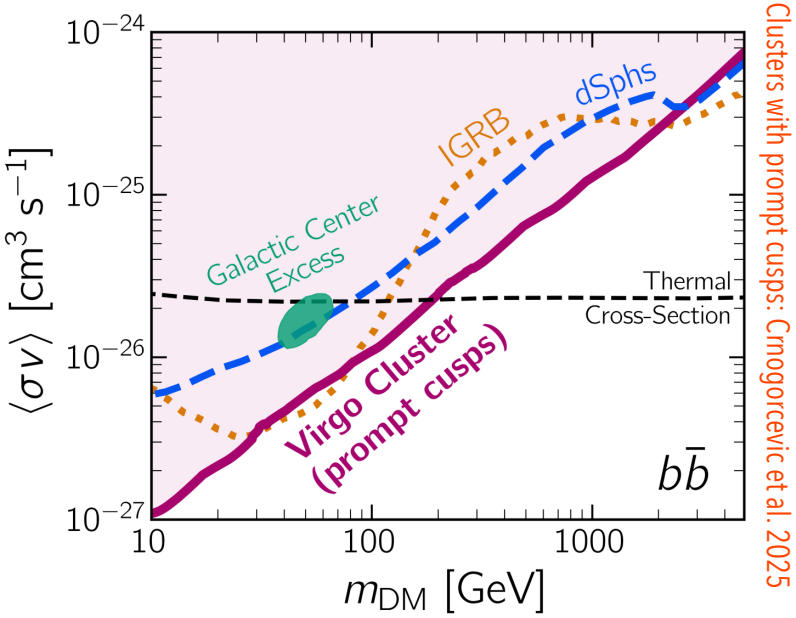
Extragalactic searches

Isotropic gamma-ray background



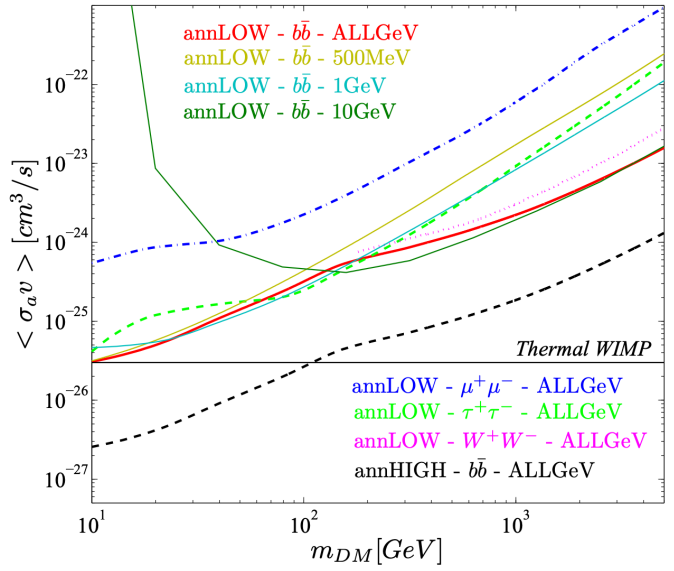
IGRB with prompt cusps: Delos et al. 2023

Galaxy clusters



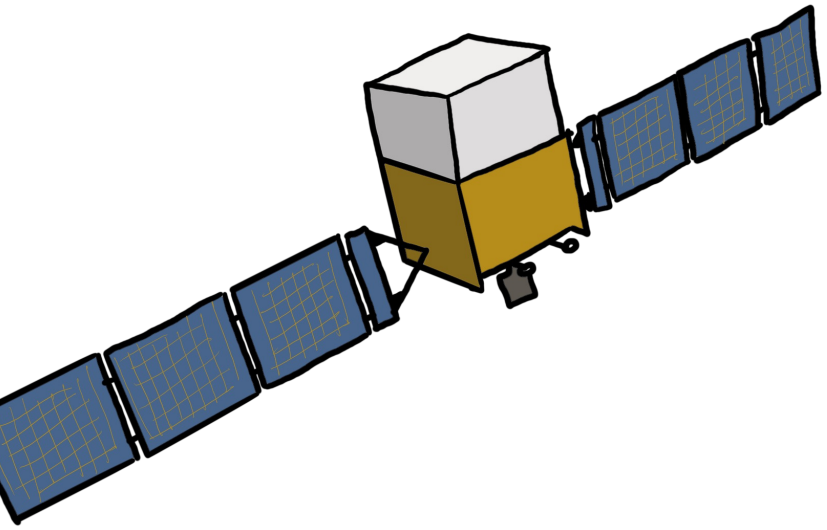
Clusters with prompt cusps: Crnogorcevic et al. 2025

Cross-correlations



2MASS x Fermi-LAT: Regis et al. 2015

Breadth of searches currently targeting signals from extragalactic halos



DM targets

✅ Good statistics
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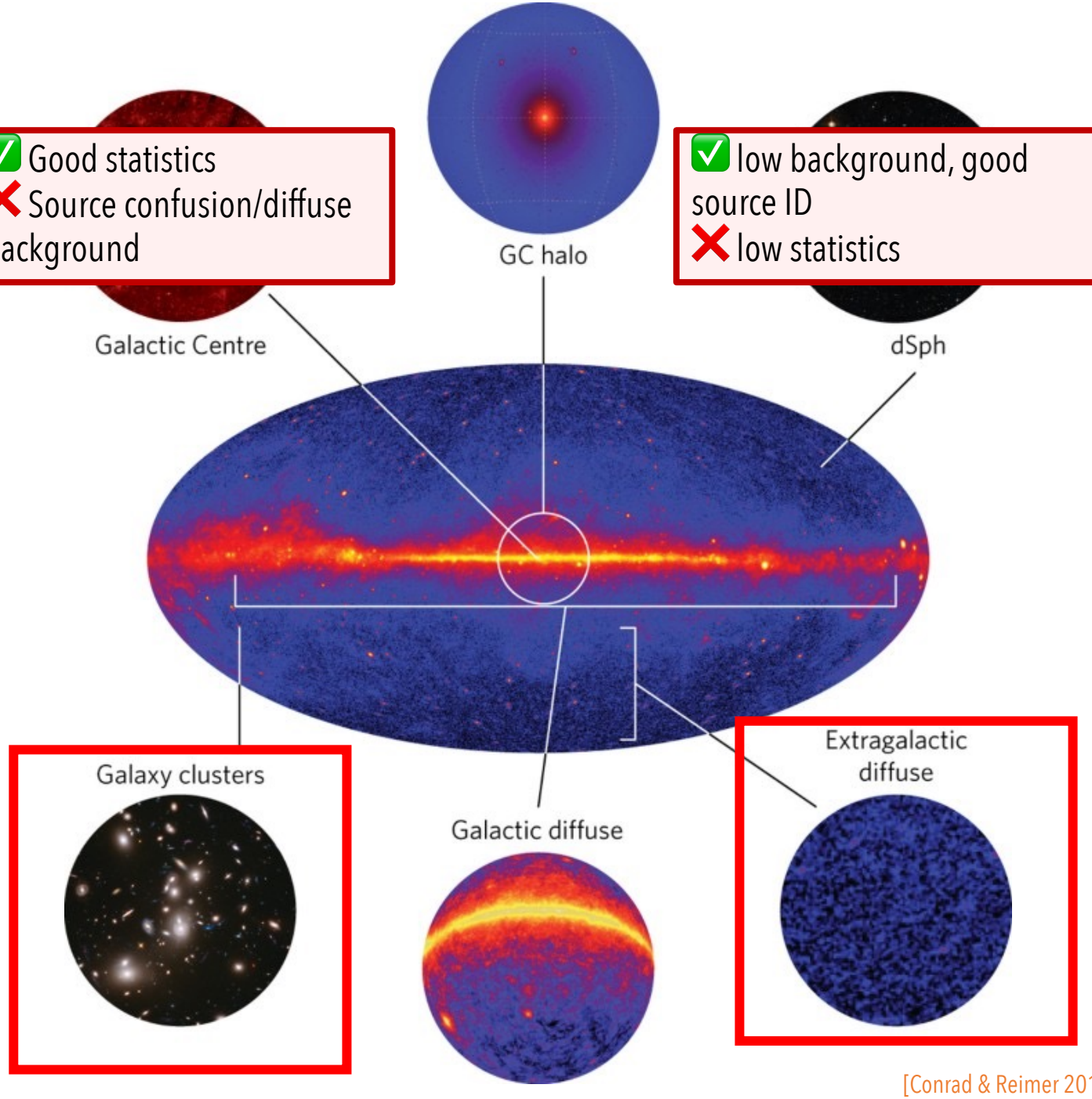
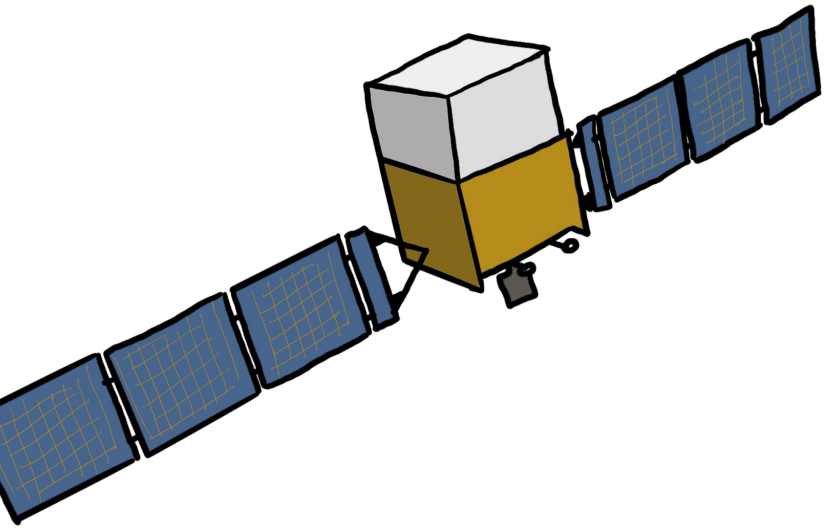
✅ low background, good source ID
❌ low statistics



Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.
@ DM & νs: Rebecca Leane and Tim Linden

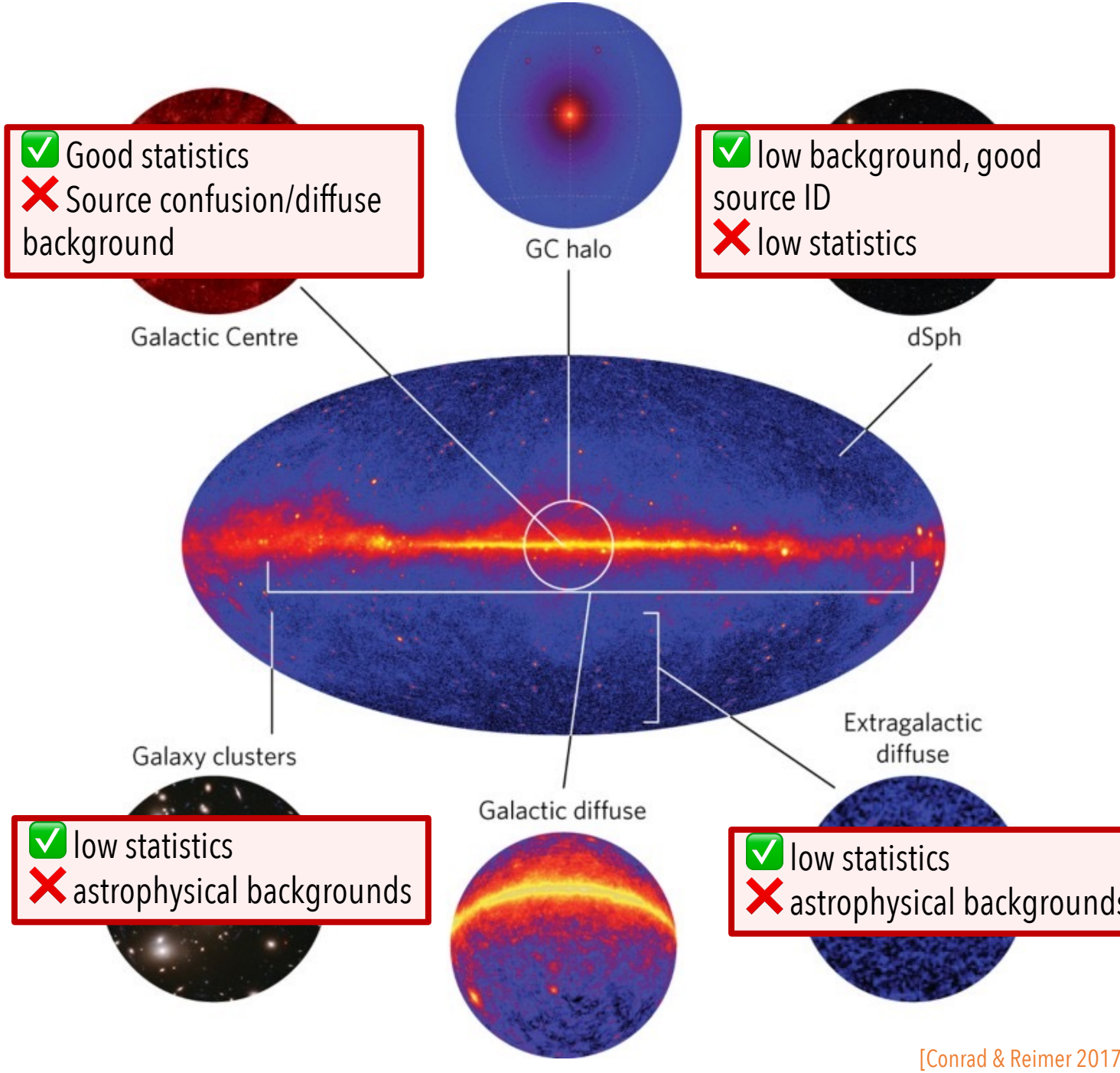
[Conrad & Reimer 2017]



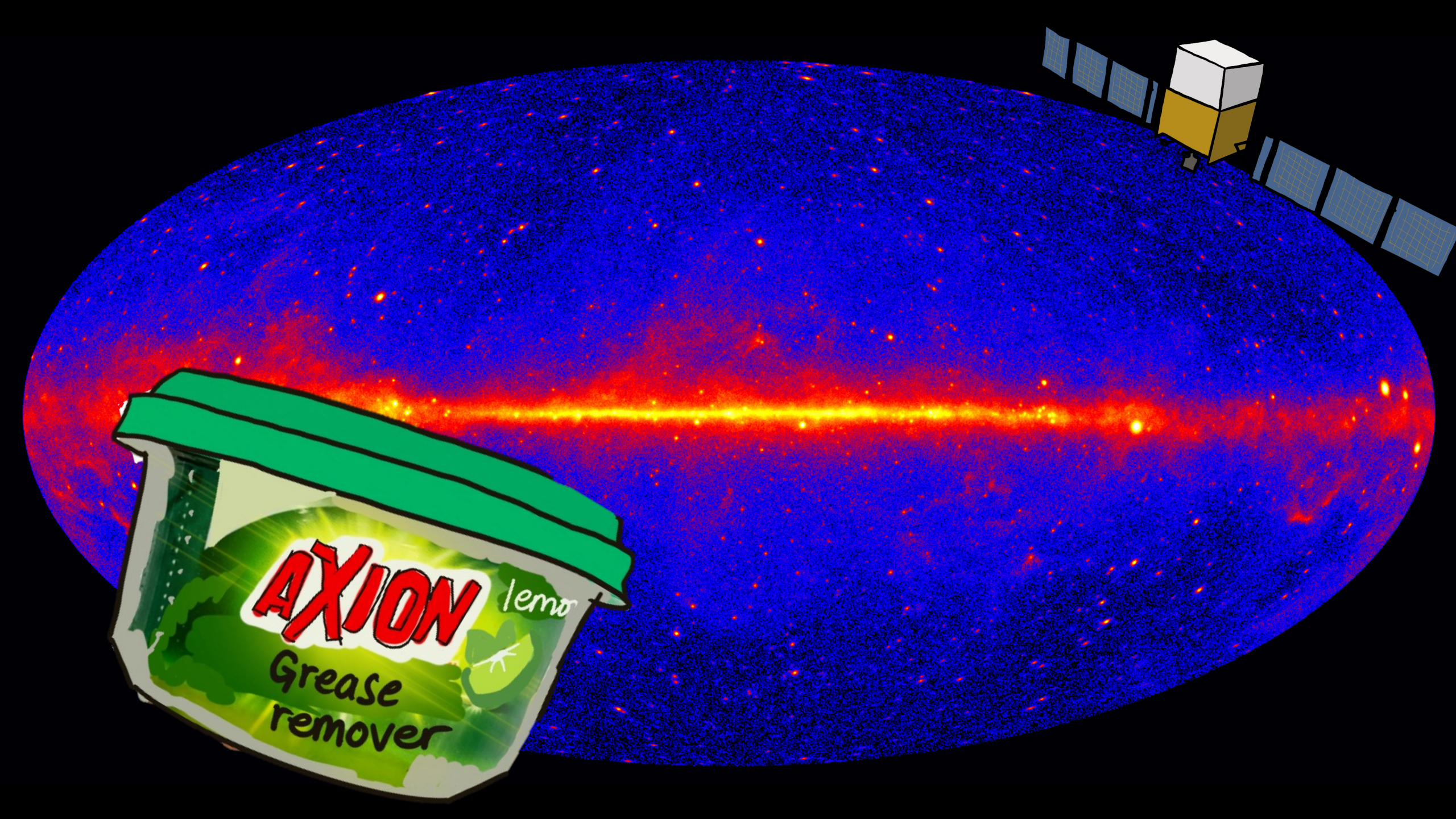
DM targets

Check e.g. Amerio et al. 2025, Fernandez-Suarez & Sanchez-Conde 2025, for some recent works on GC halo searches.

Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.
@ DM & νs: Rebecca Leane and Tim Linden



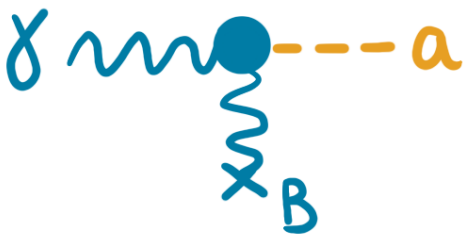
[Conrad & Reimer 2017]


AXION
lemon
Grease
remover

Axion/ALP Landscape: An Observer's view

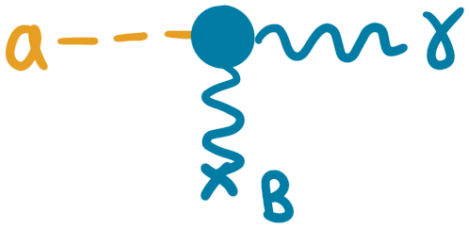
ALP/axion - photon interactions

1. Primakoff process



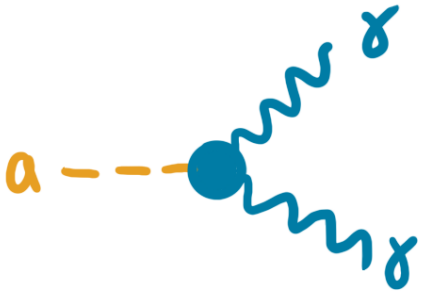
$\gamma \rightarrow a$

2. Inverse Primakoff



$a \rightarrow \gamma$

3. ALP/axion decay

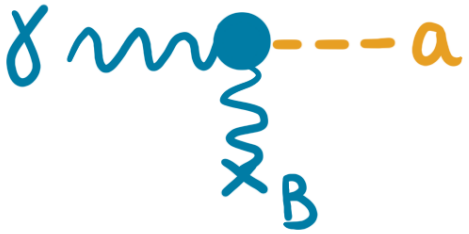


$a \rightarrow \gamma\gamma$

Axion/ALP Landscape: An Observer's view

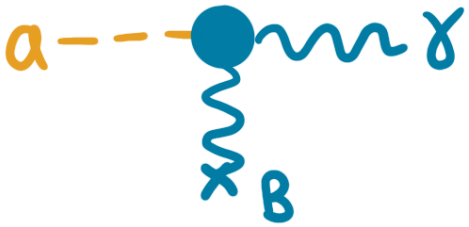
ALP/axion - photon interactions

1. Primakoff process



$\gamma \rightarrow a$

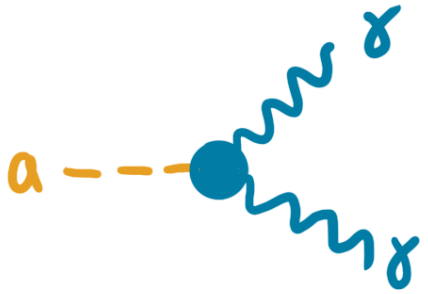
2. Inverse Primakoff



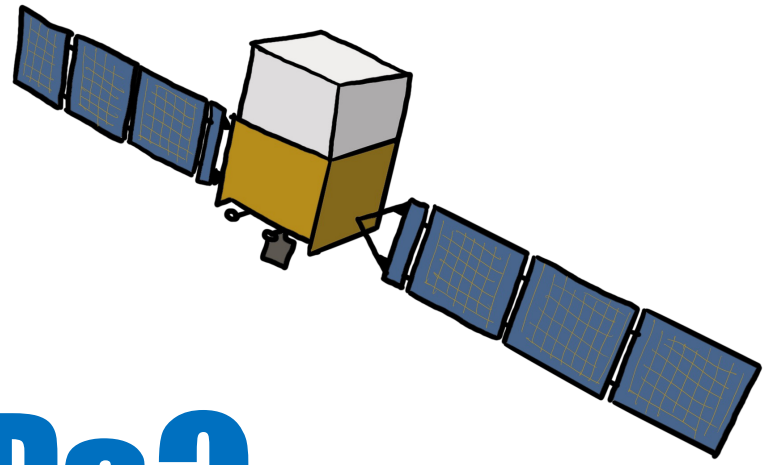
$a \rightarrow \gamma$

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

3. ALP/axion decay

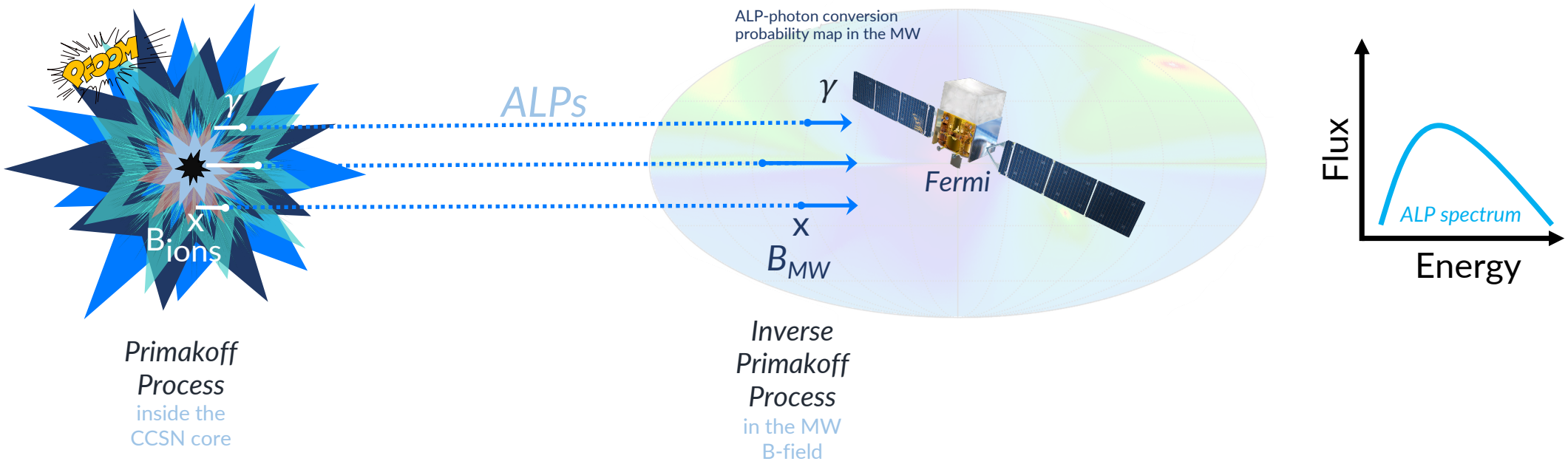


$a \rightarrow \gamma\gamma$



Where to look for ALPs?

Photon from in-source conversions

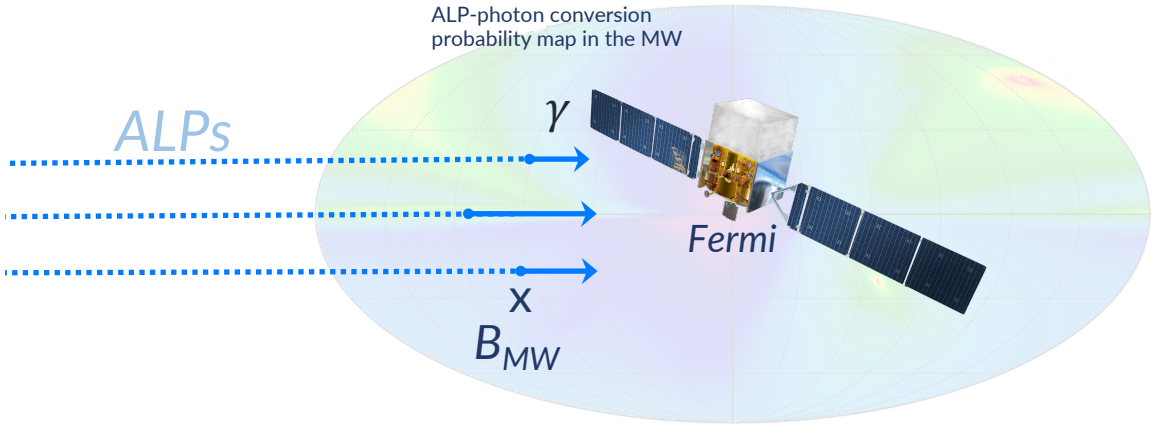


Primakoff Process inside the CCSN core

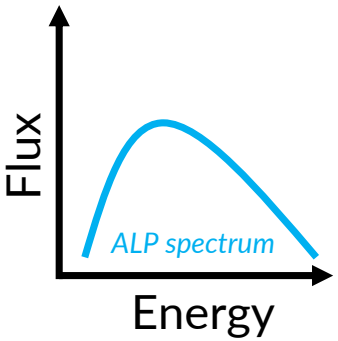
Inverse Primakoff Process in the MW B-field

Photon from in-source conversions

AGN, blazars, etc.



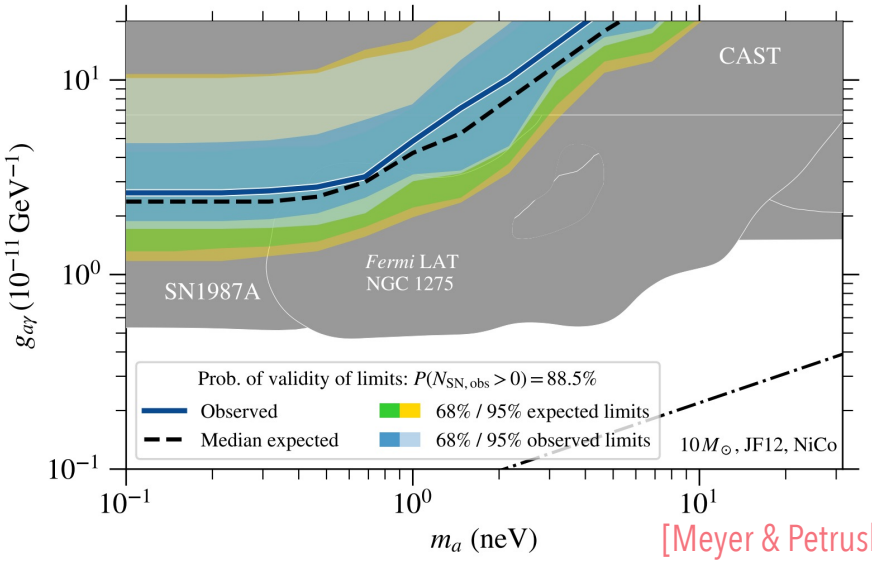
Inverse Primakoff Process in the MW B-field



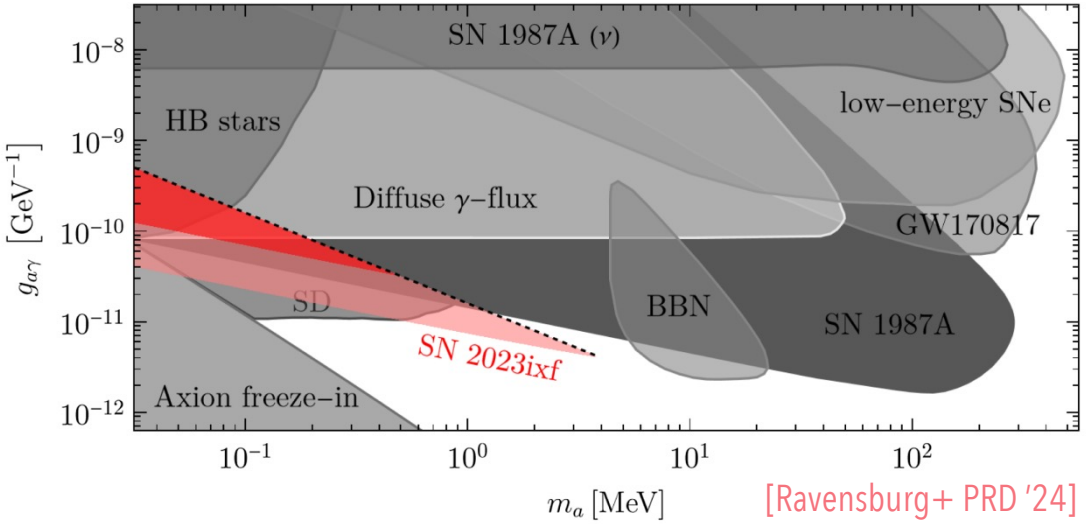
CCSNe: Individual Sources

- 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]

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

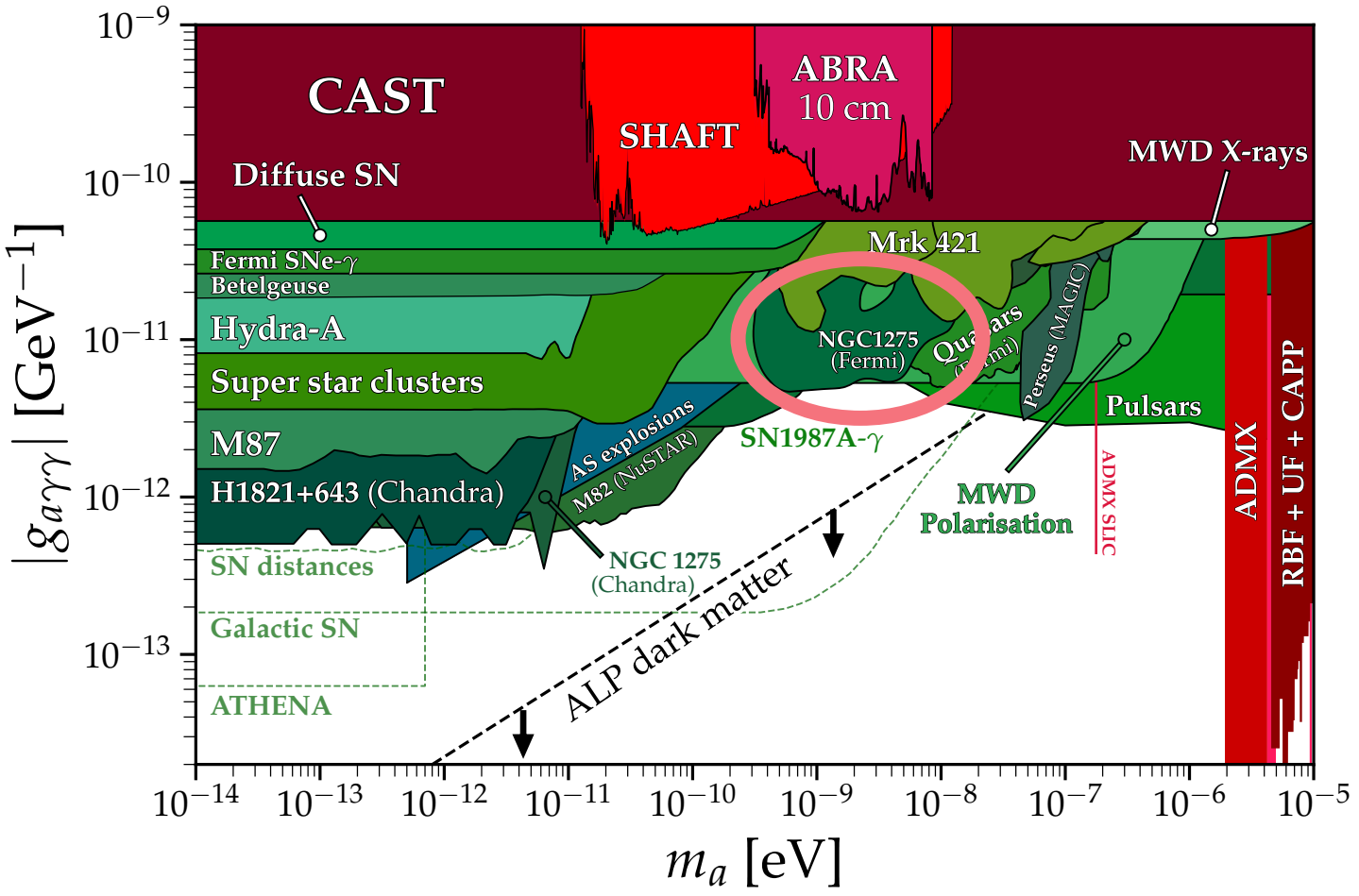
[Ajello+ '16, Libanov & Troitsky '20, Cheng+ '21, etc.]

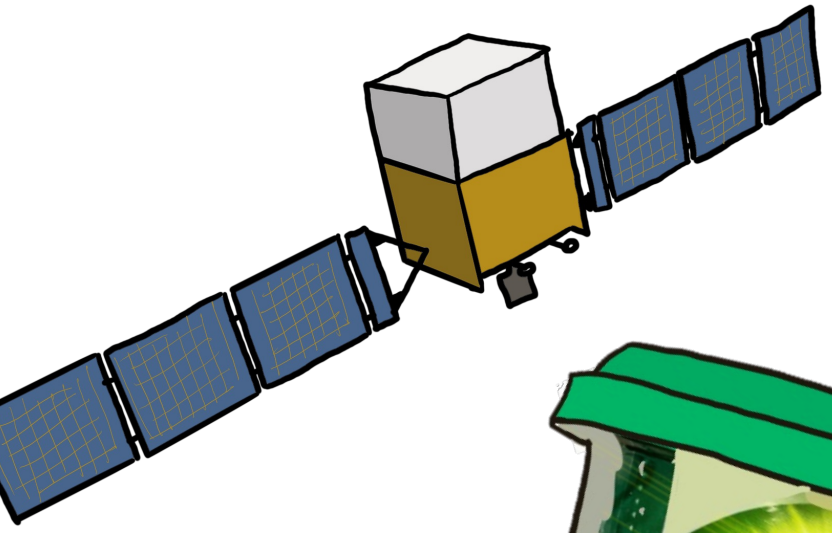
[Credit: Marie-Lou Gendron-Marsolais & Hlavacek-Larrond]

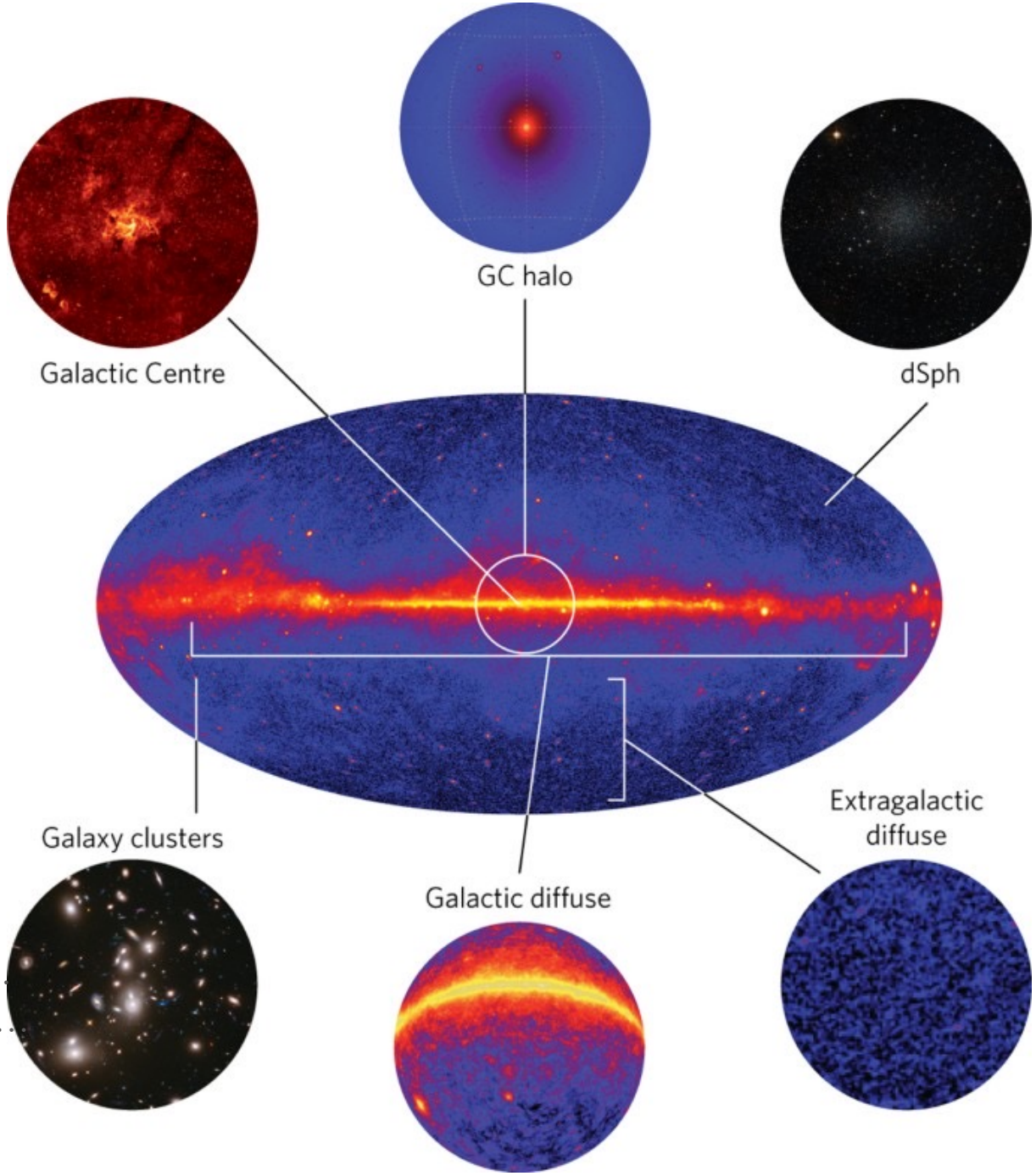
NGC 1275: spectral irregularities

- 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]



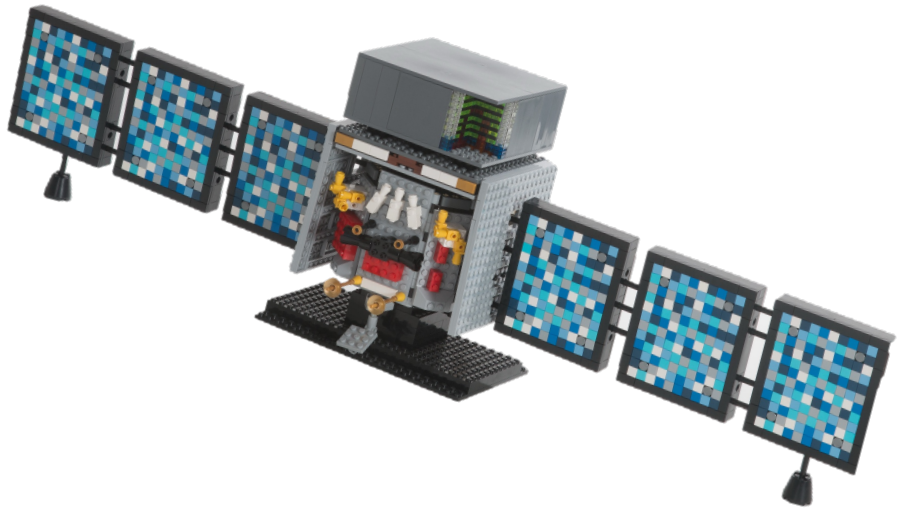




Galactic halo: LAT Collaboration '13, Karwin+ '21, …
Galactic diffuse: LAT Collaboration '12, Acero+ '16,
Charles+ '16, Porter+ 17, DiMauro+ '19, '21, …
Extragalactic diffuse: LAT Collaboration '15, Ajello+ '15, Delos+ '23, …
Solar System: Leane & Smirnov '20, Leane & Linden '21, Leane+ '21, …
Axions/ALPs: Ajello+ '16, Libanov & Troitsky '20, Cheng+ '21,
Meyer & Petrushevska '20, …
PBHs: Carr+ '10; Ballesteros+ '20; Iguaz+ '21, …

[Conrad & Reimer 2017]

Where does the story

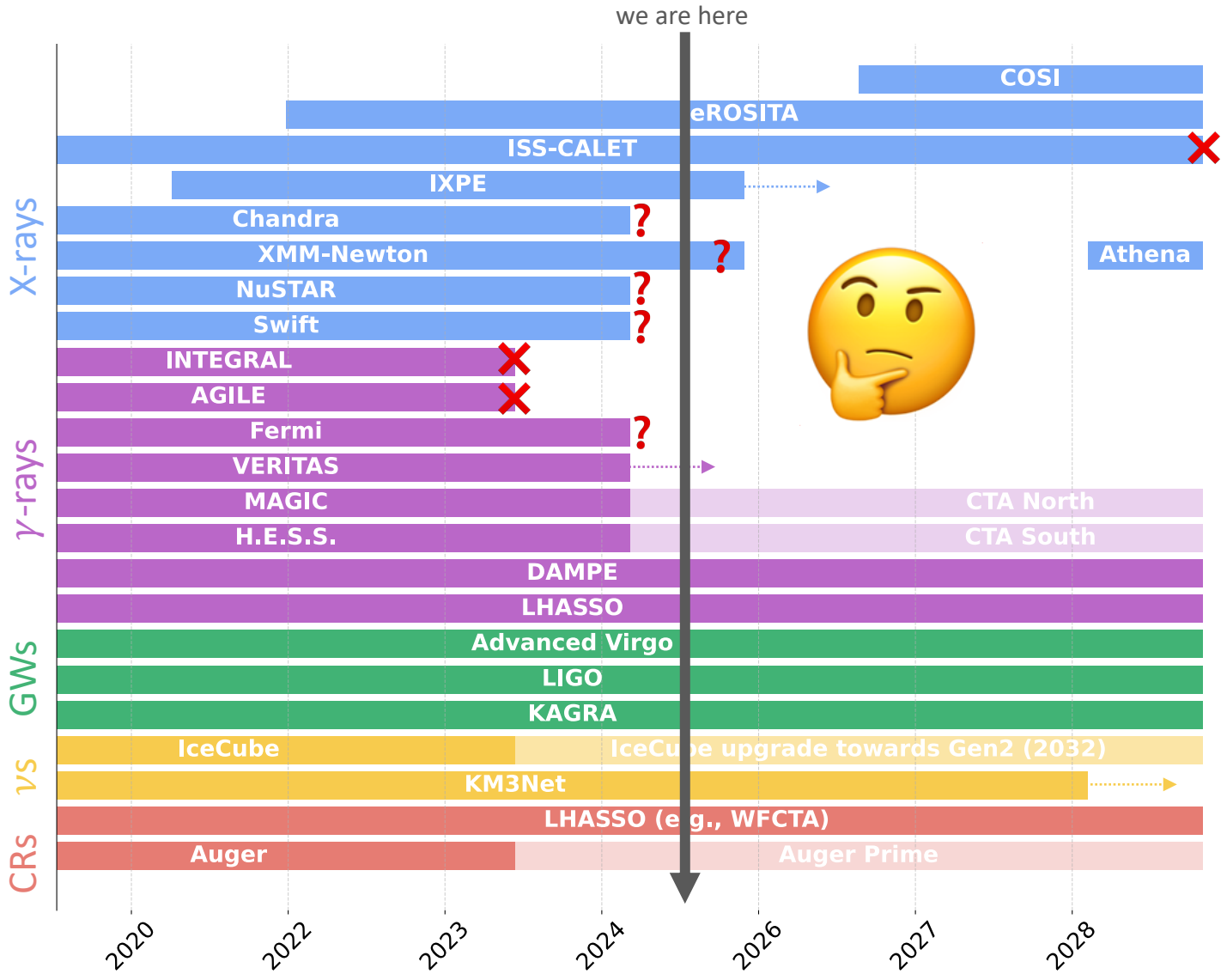


end?

"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



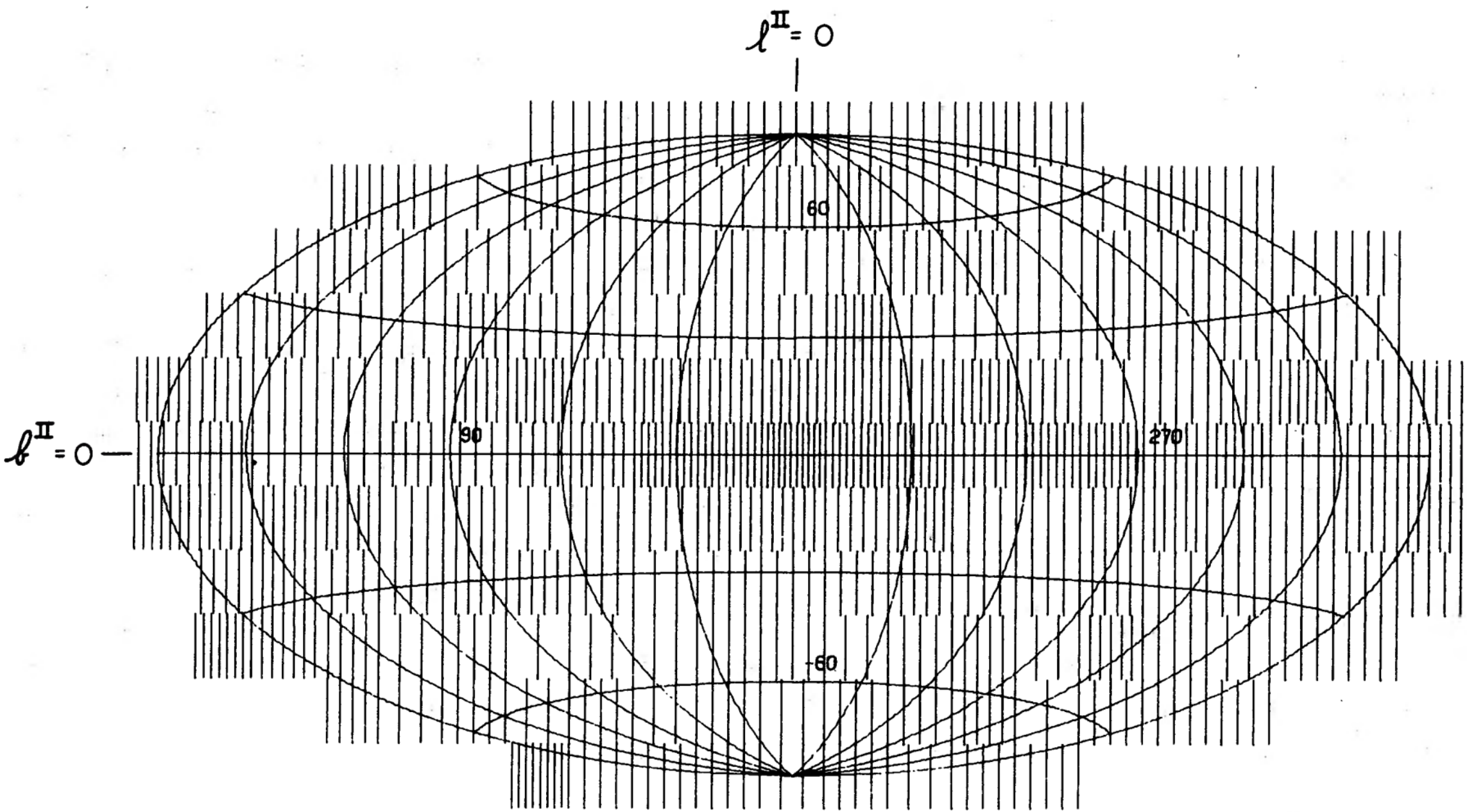
e-ASTROGAM
AMEGO
AMEGO-X
…

VLAST?

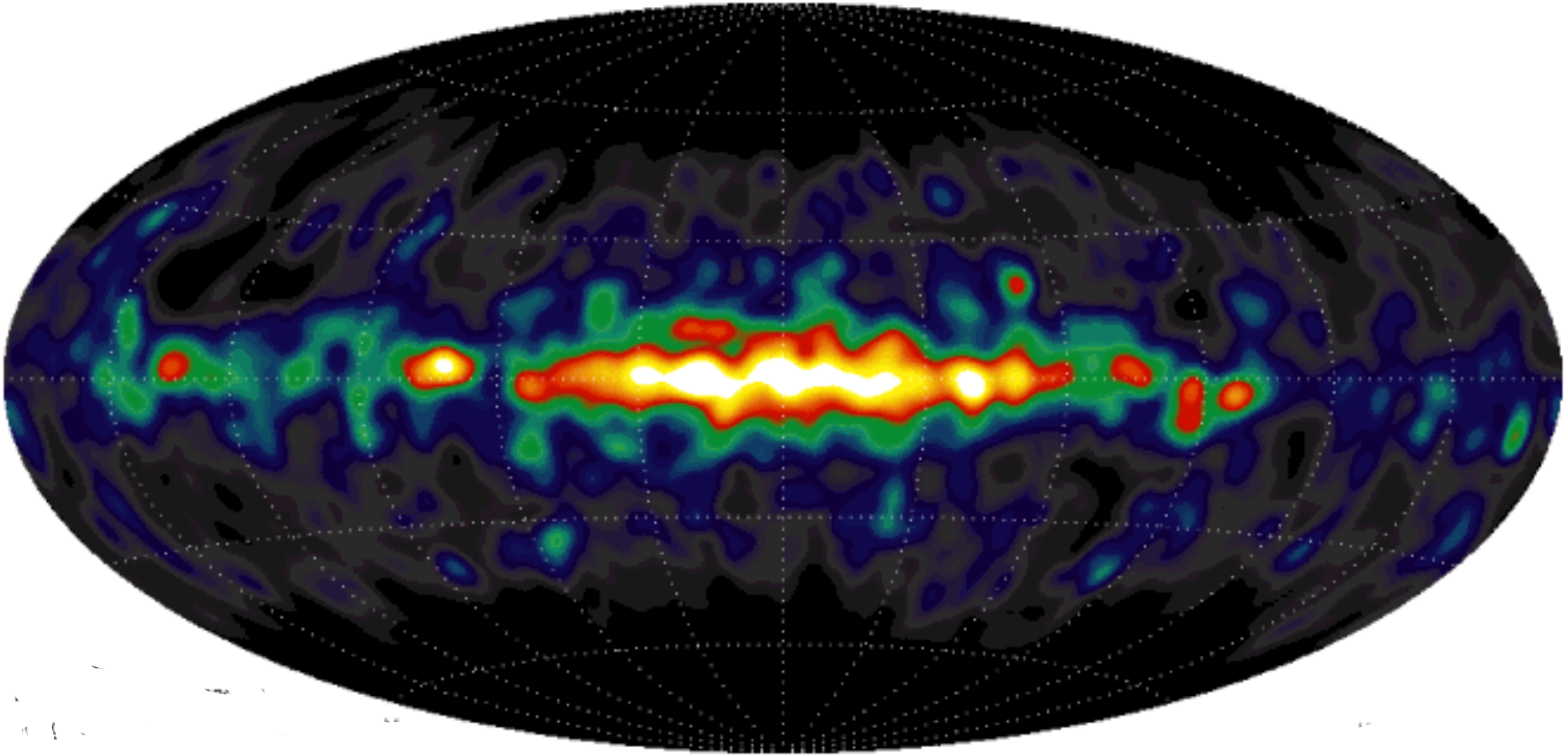
Future Innovations in Gamma rays

Science Analysis Group

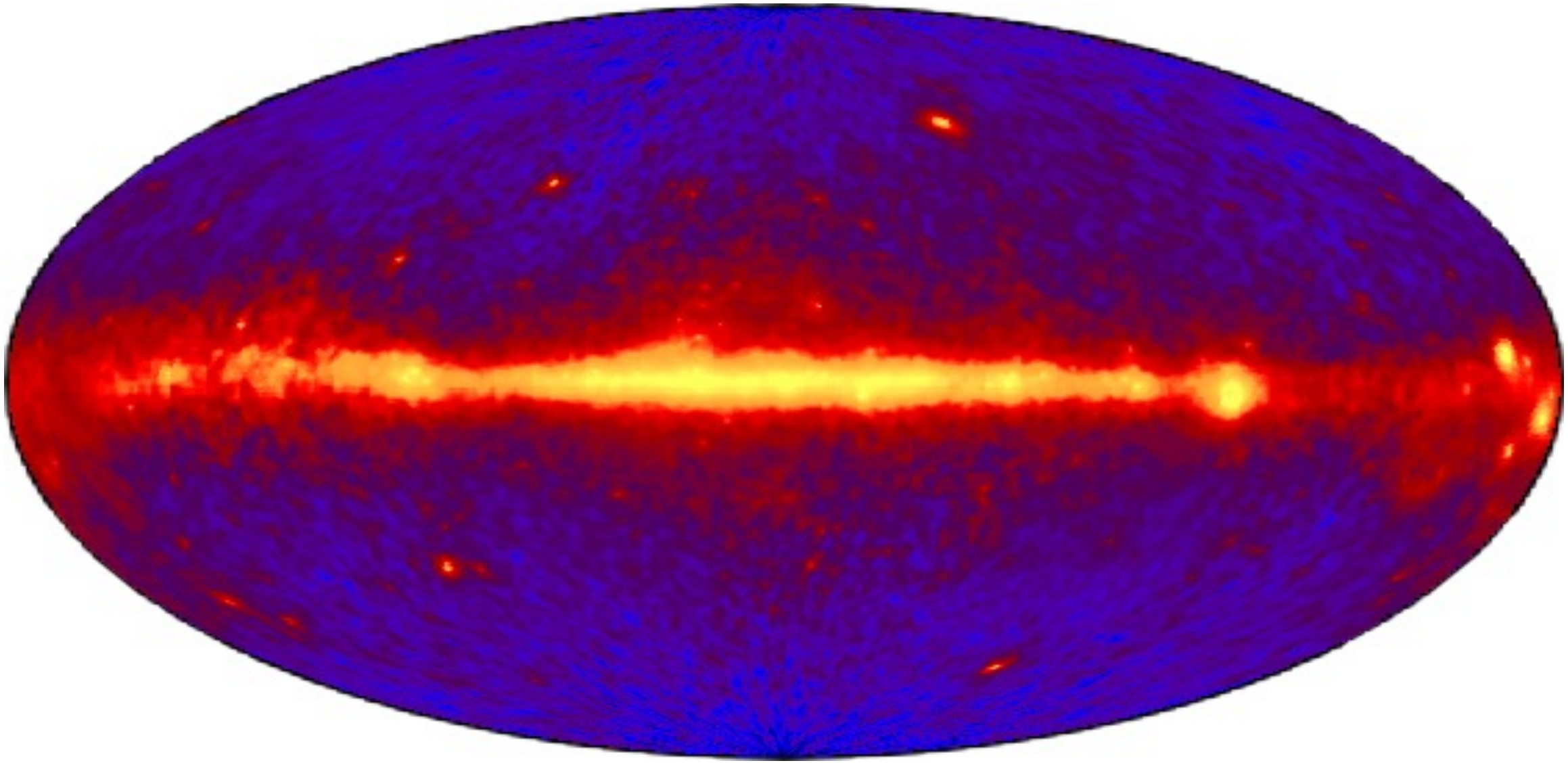
… to explore gamma-ray science priorities, necessary capabilities, new technologies, and theory/modeling needs drawing on the 2020 Decadal **to inspire work toward 2040.**



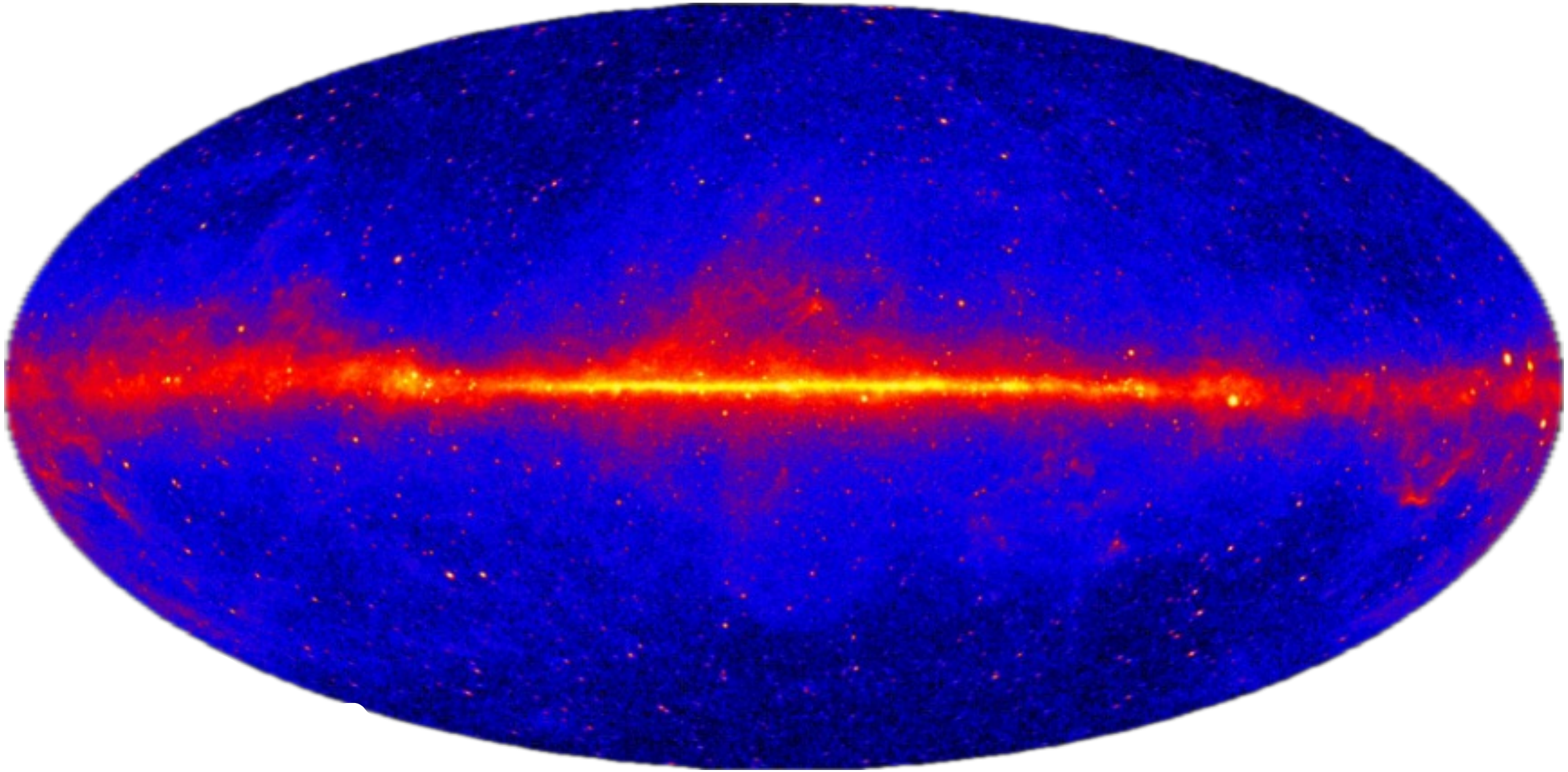
1968, Orbiting Solar Observatory, OSO-3 (~50 MeV)



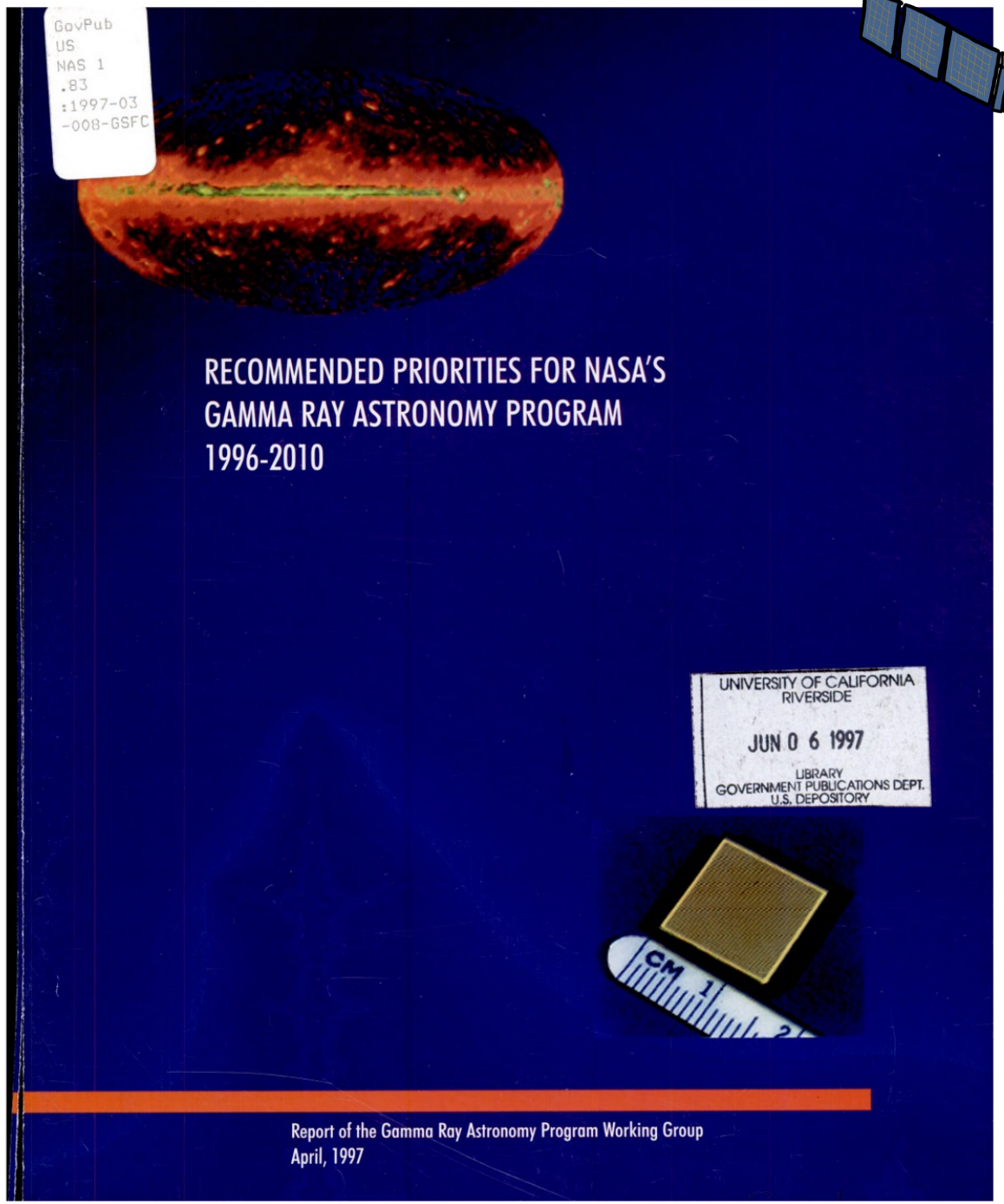
2000, COMPTEL (onboard CGRO), 1–30 MeV

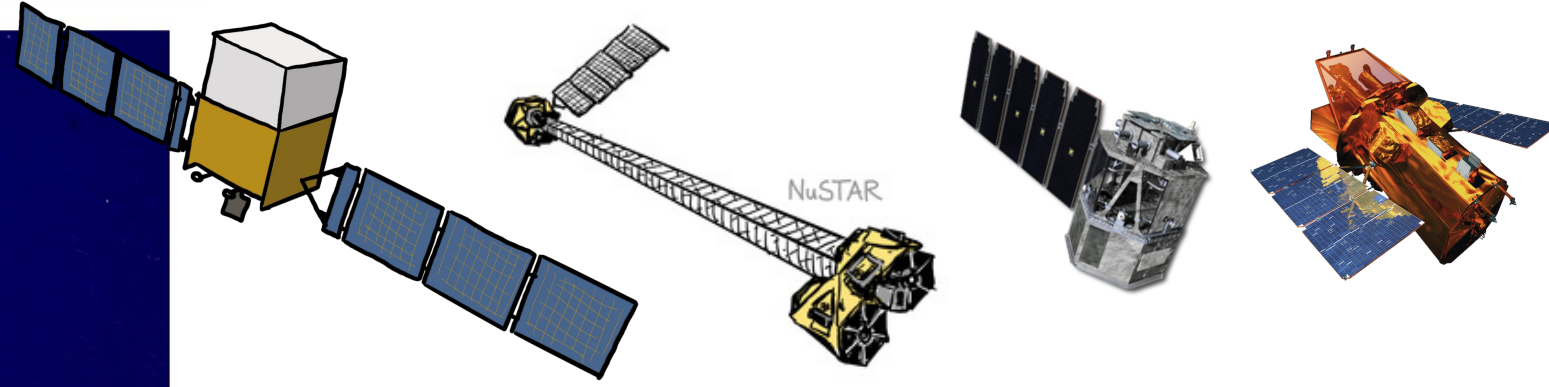


2000, EGRET (onboard CGRO), above 100 MeV

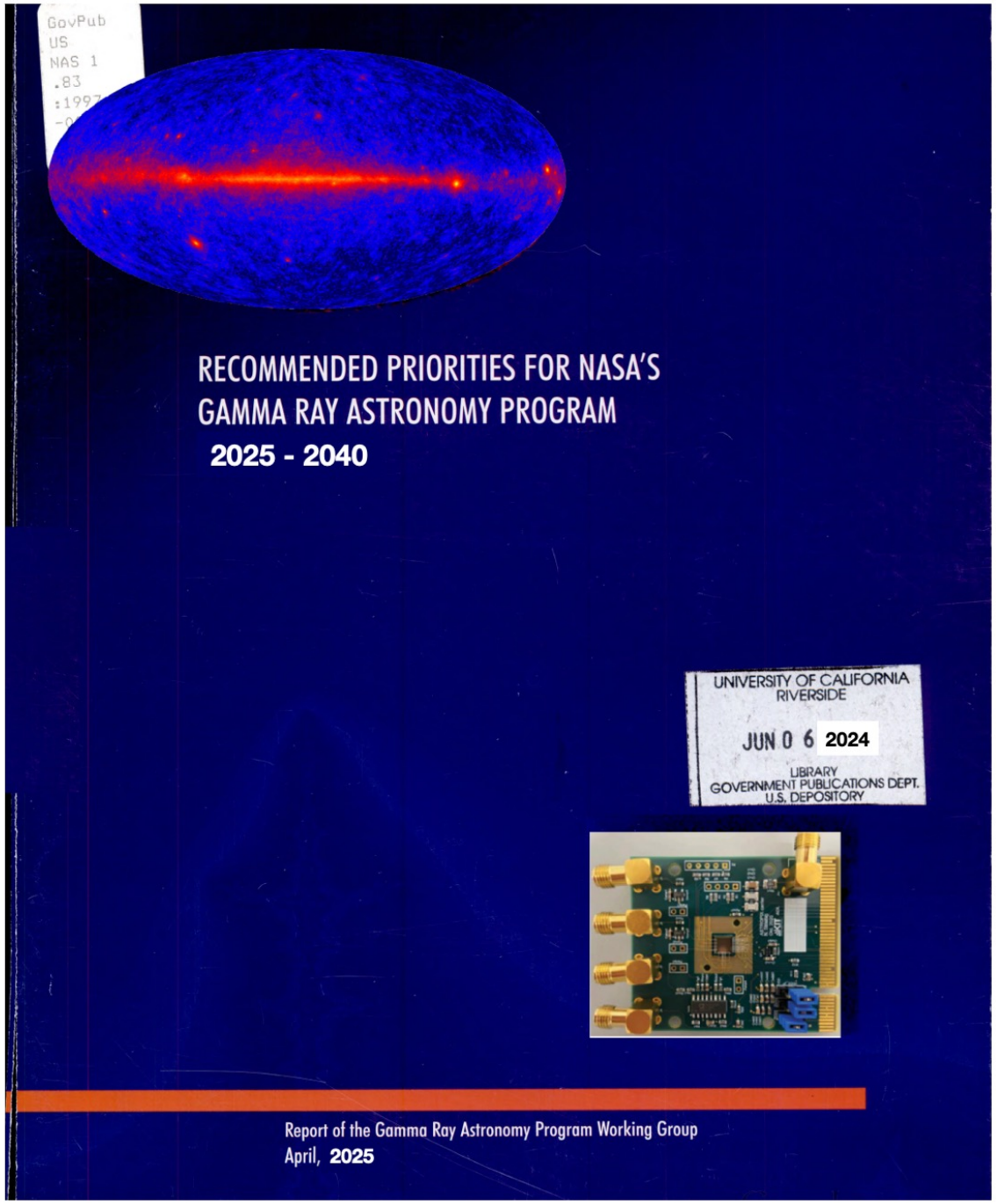


2000, LAT (onboard *Fermi*), above 500 MeV

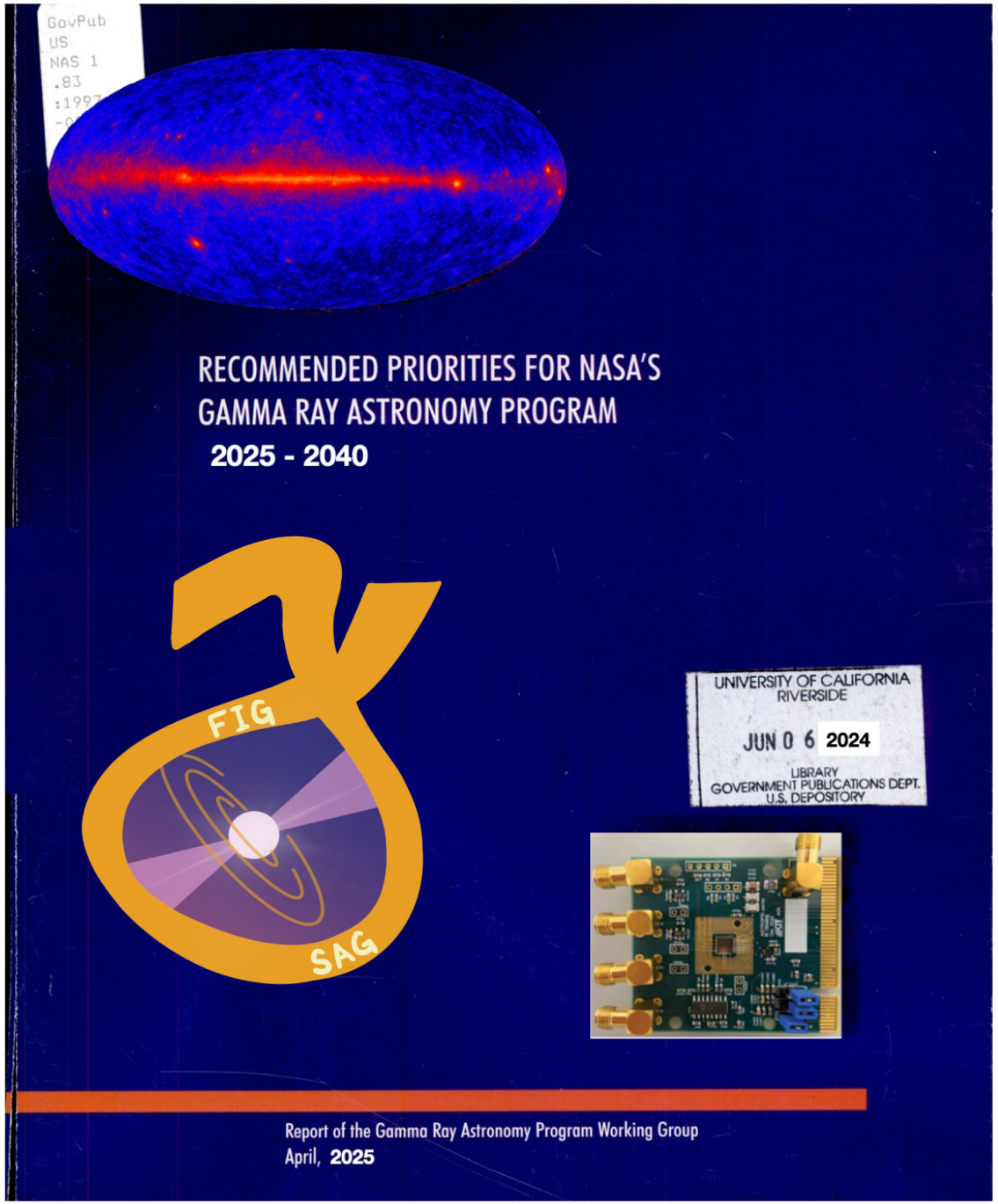




- Intermediate Missions: Fermi, NuSTAR and now COSI
- MIDEX and SMEX: Swift and NICER
- Technology: a robust technology development program (SiPMs, new scintillators, upgraded silicon detectors, etc)
- Balloons (+ CubeSats!): long duration balloons enabled COSI, LEAP, etc.
- Data Analysis & Theory: mainly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

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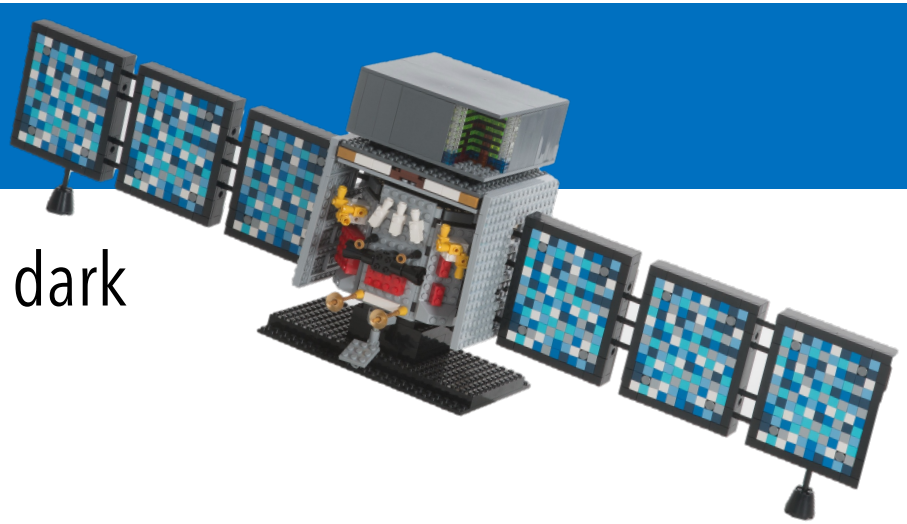
Conclusions



- 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***