

dark matter

Milena Crnogorčević

Postdoctoral Fellow at the Oskar Klein Centre
→ GRAPPA, University of Amsterdam [Fall 2026]

International School of Cosmic Ray Astrophysics 2026
Erice



dark matter

1

Dark Matter Introduction

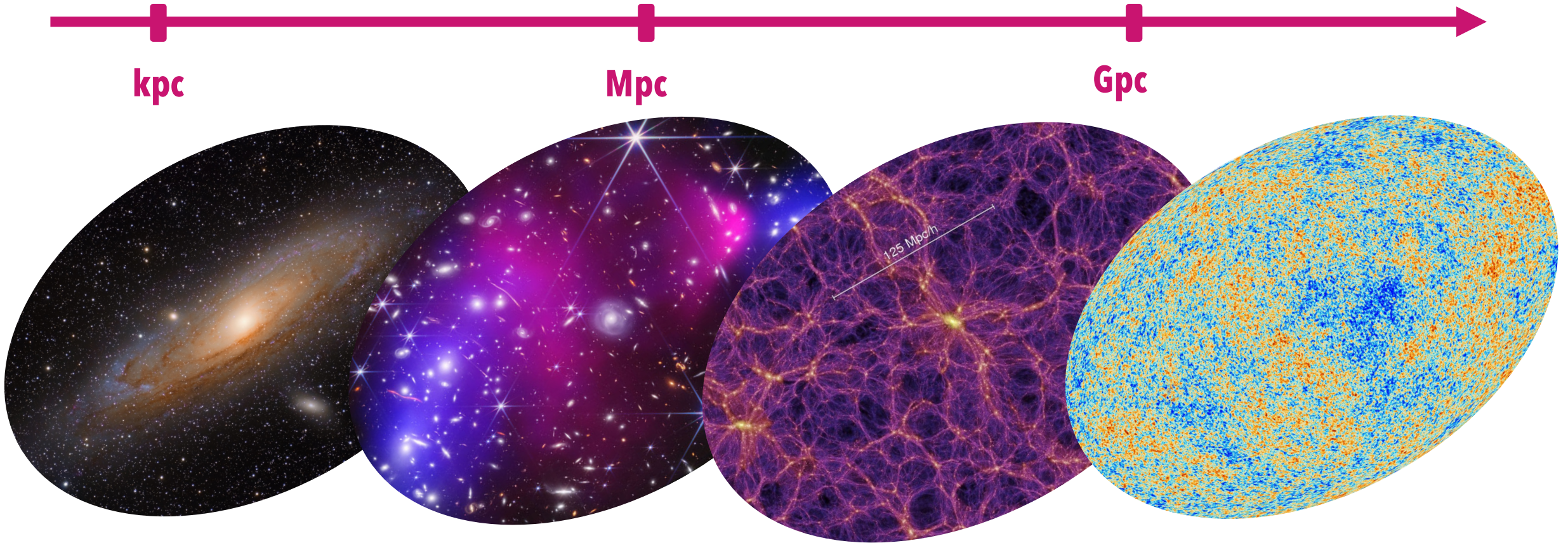
2

Dark Matter Candidates and Detection
Techniques

3

Indirect Detection

Take-home message: dark matter acting across the scales



A single non-baryonic dark-matter component consistently explains observations across these scales

dark matter

1

Dark Matter Introduction

2

**Dark Matter Candidates and
Detection Techniques**

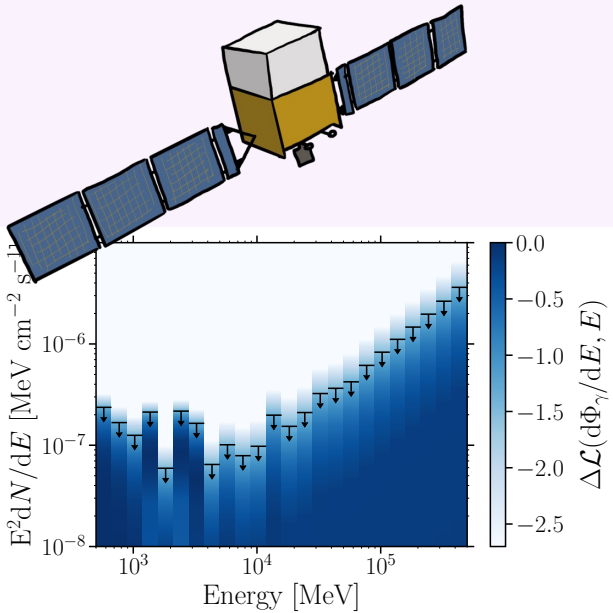
3

Indirect Detection

Take-home message

DM flux

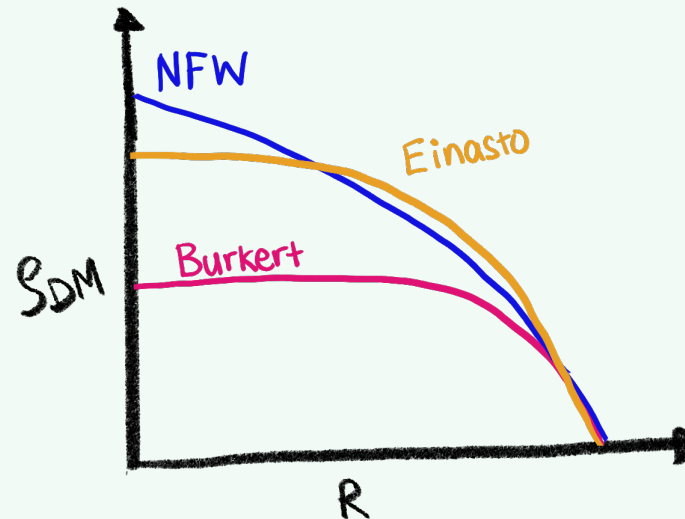
$$\frac{d\Phi}{dE}$$



=

astrophysics
J-factor

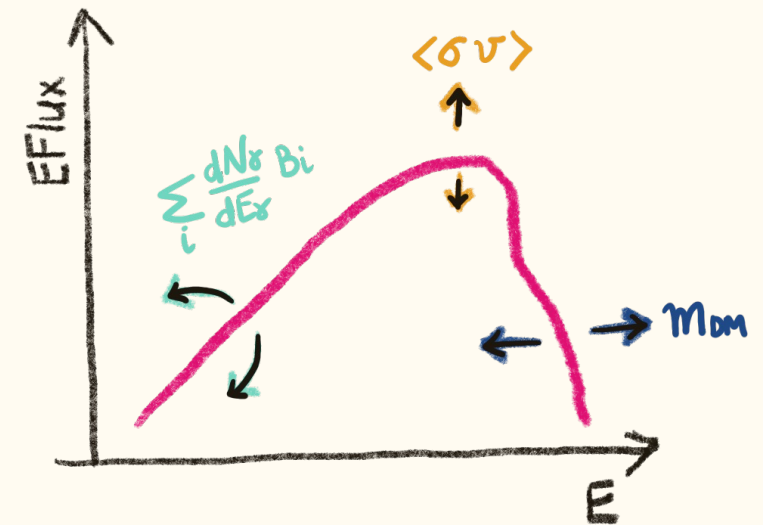
$$\int_{\Delta\Omega, \text{los}} \rho_{DM}^2$$



×

particle physics

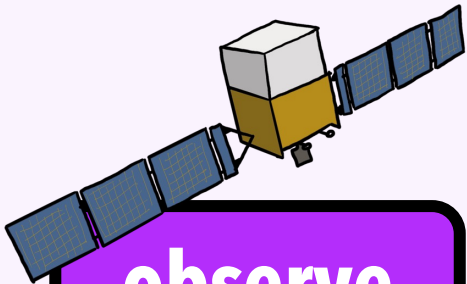
$$\frac{\langle\sigma v\rangle}{2M_{DM}^2} \sum B_i \frac{dN_\gamma}{dE}$$



Take-home message

DM flux

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



observe

=

**astrophysics
J-factor**

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

**infer from
astrophysical
data/assume**

×

particle physics

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

**measure/
constrain**

dark matter

1

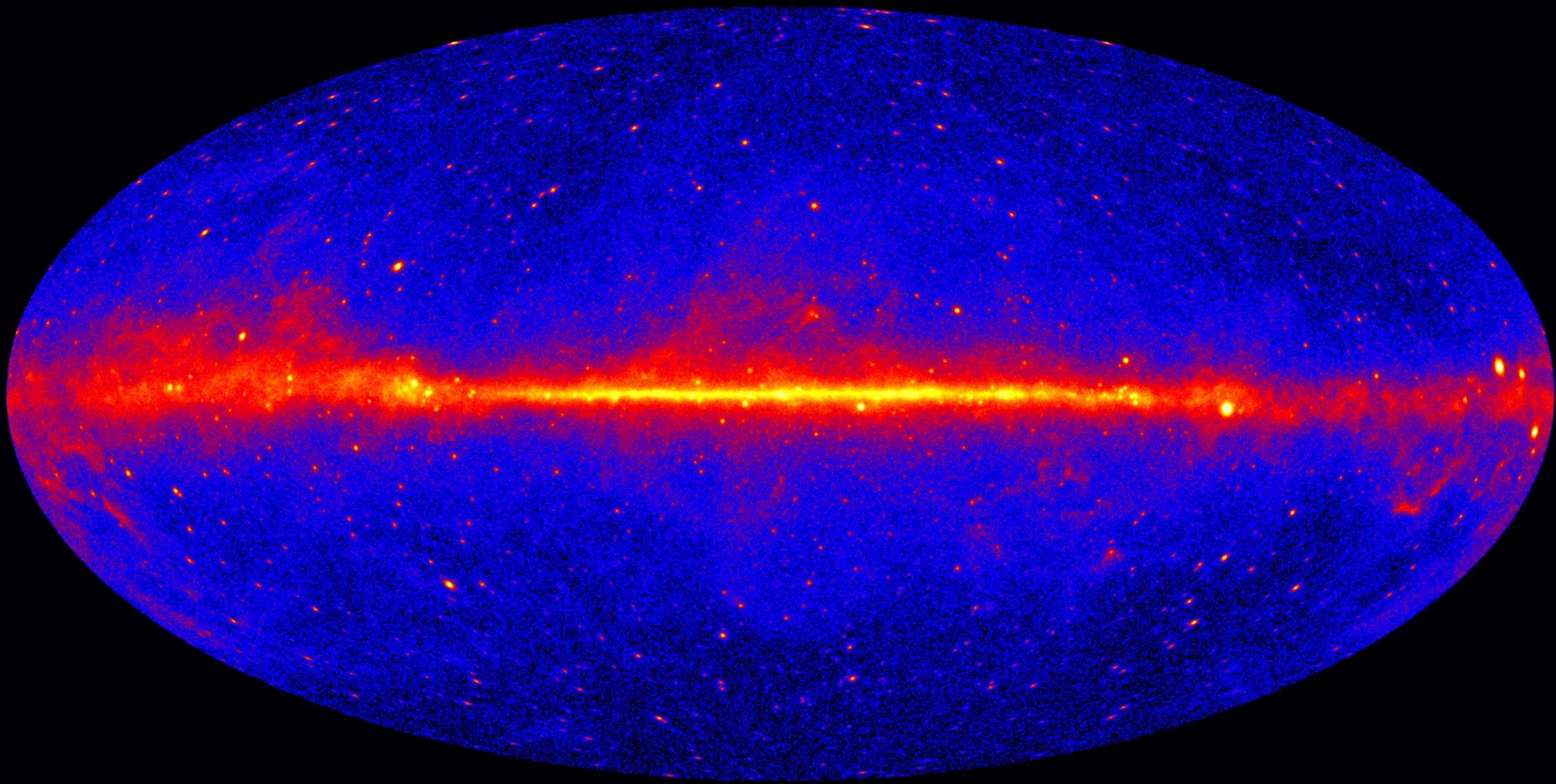
Dark Matter Introduction

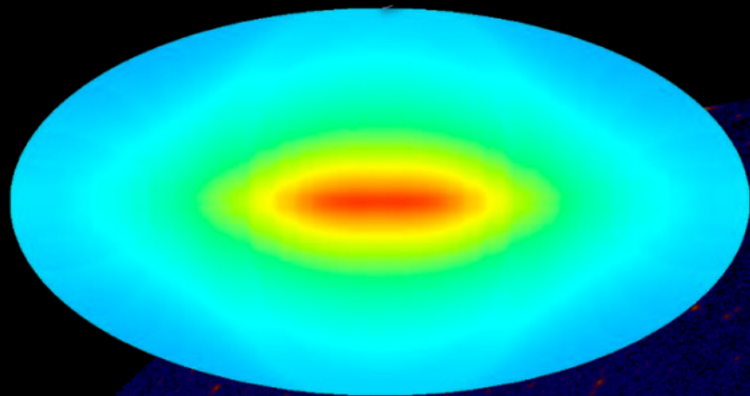
2

Dark Matter Candidates and Detection
Techniques

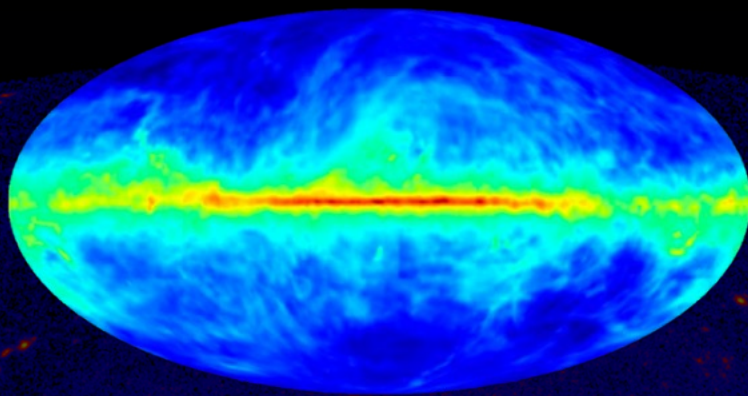
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Indirect Detection

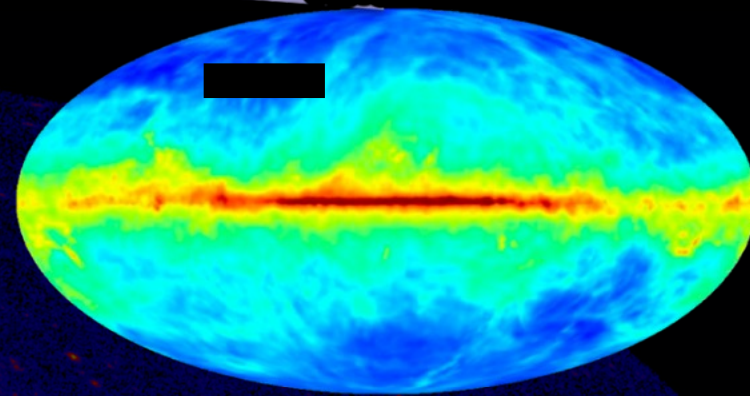




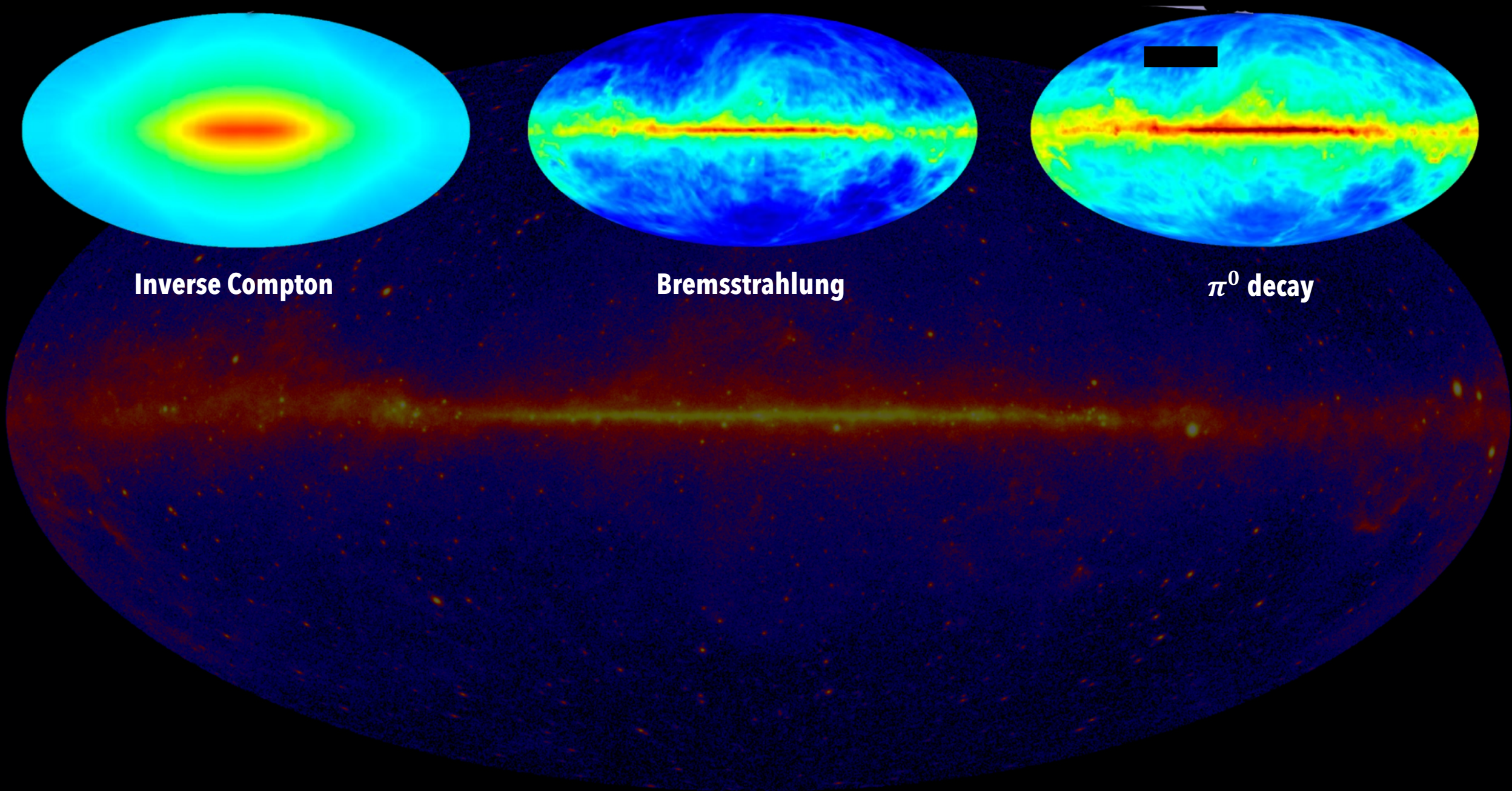
Inverse Compton

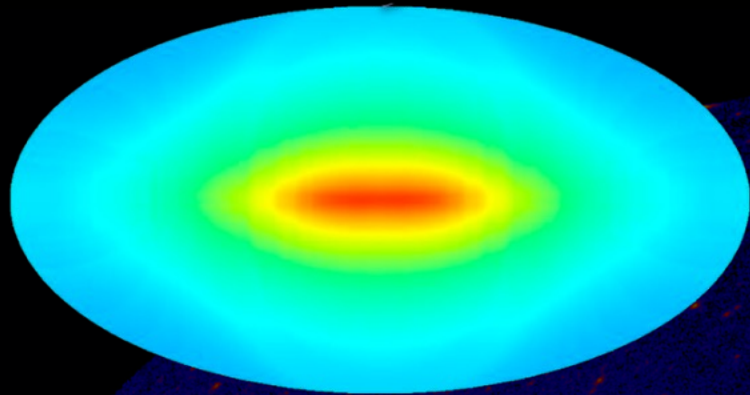


Bremsstrahlung

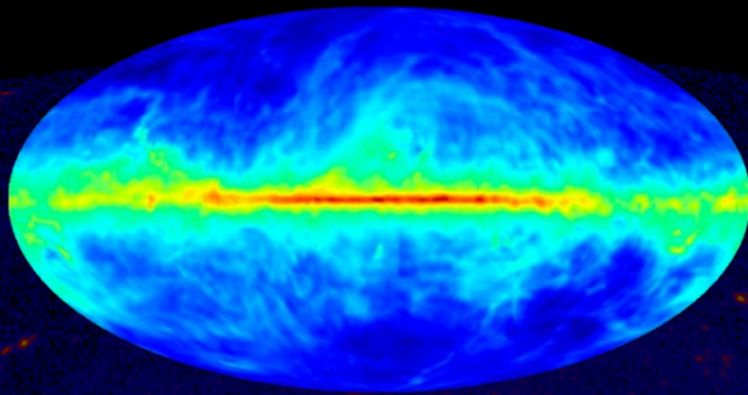


π^0 decay

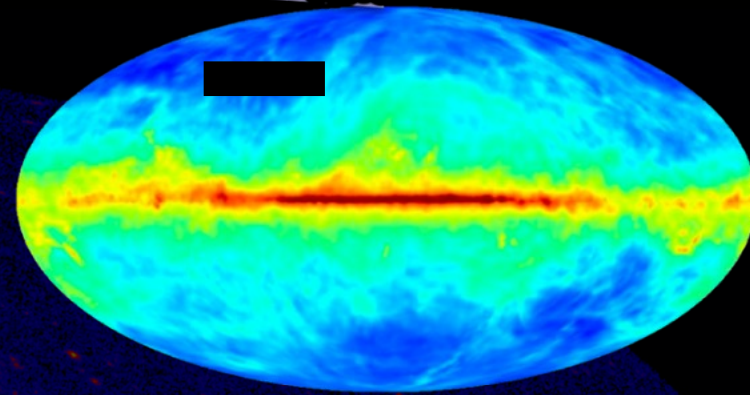




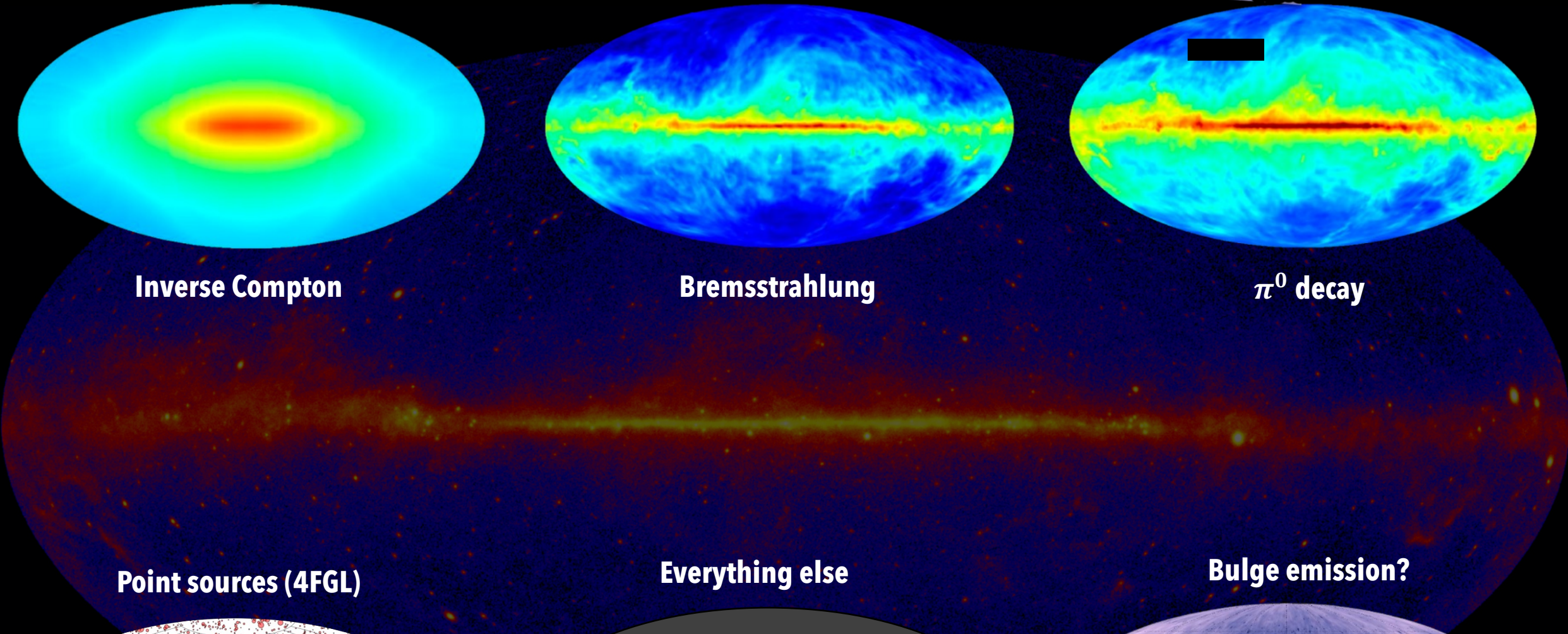
Inverse Compton



Bremsstrahlung



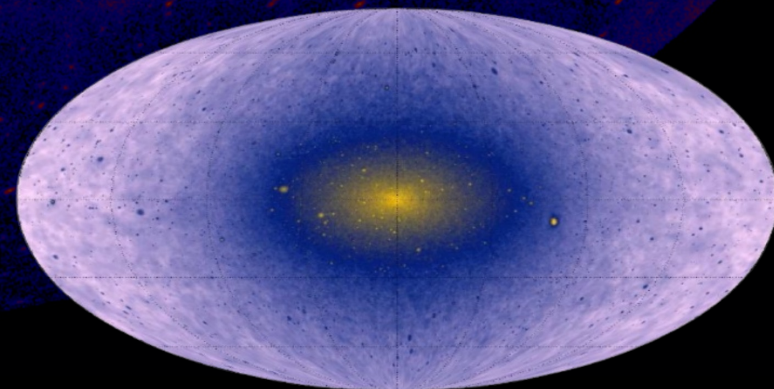
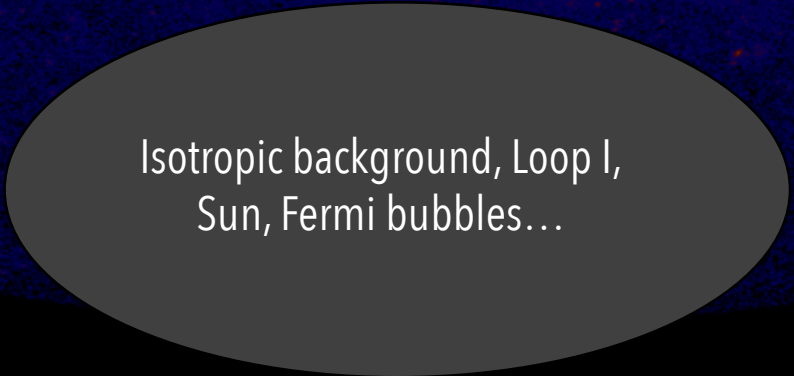
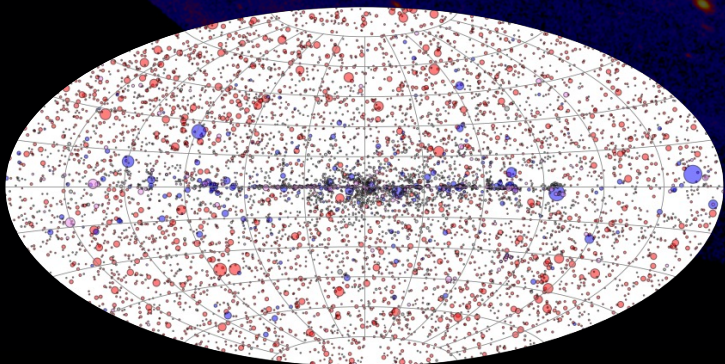
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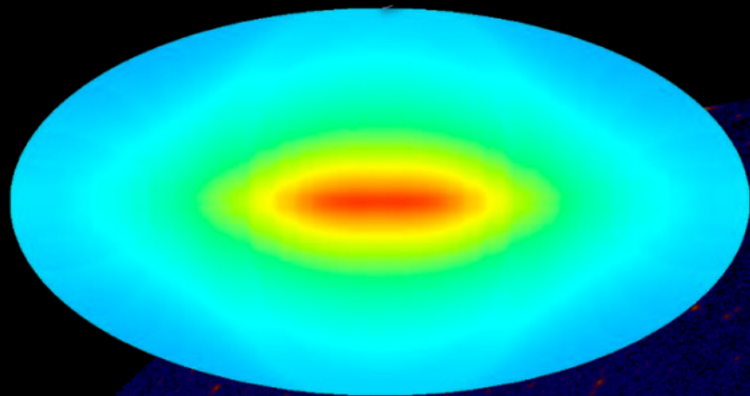


Point sources (4FGL)

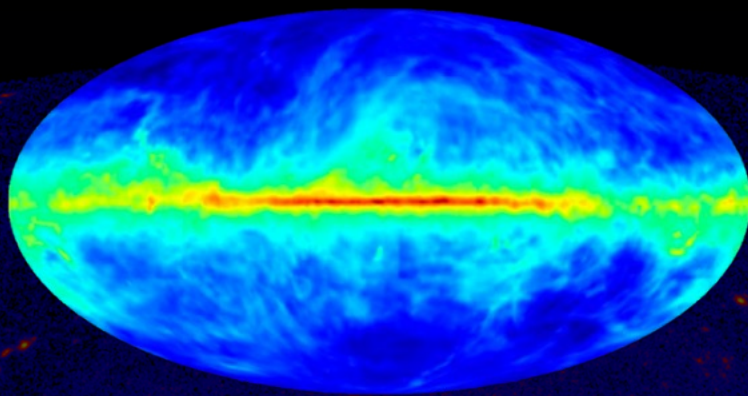
Everything else

Bulge emission?

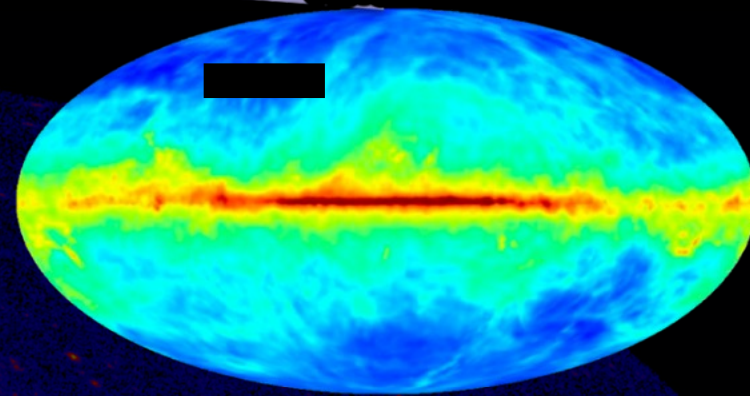




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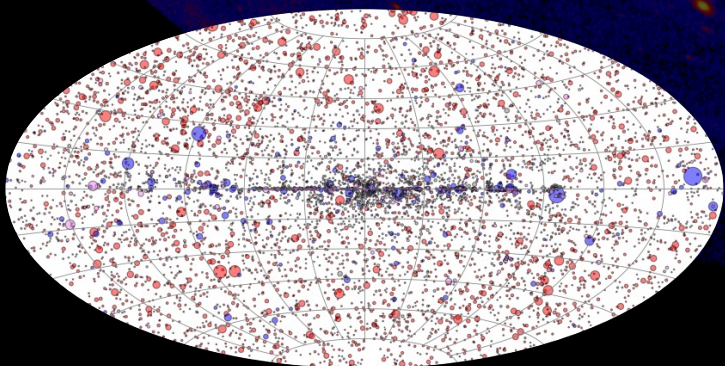
Bremsstrahlung



π^0 decay

Signal = Astrophysical backgrounds flux + DM flux

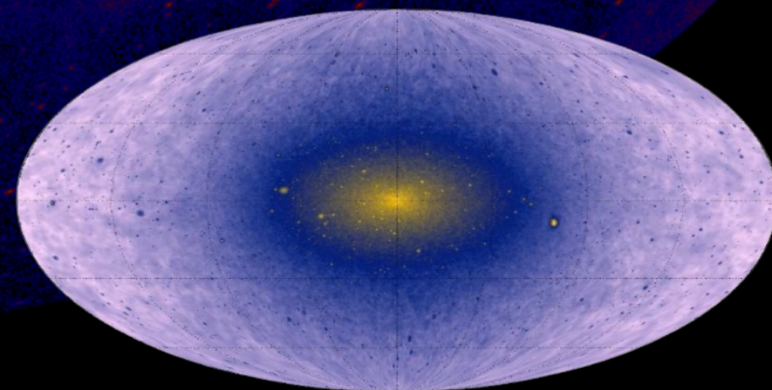
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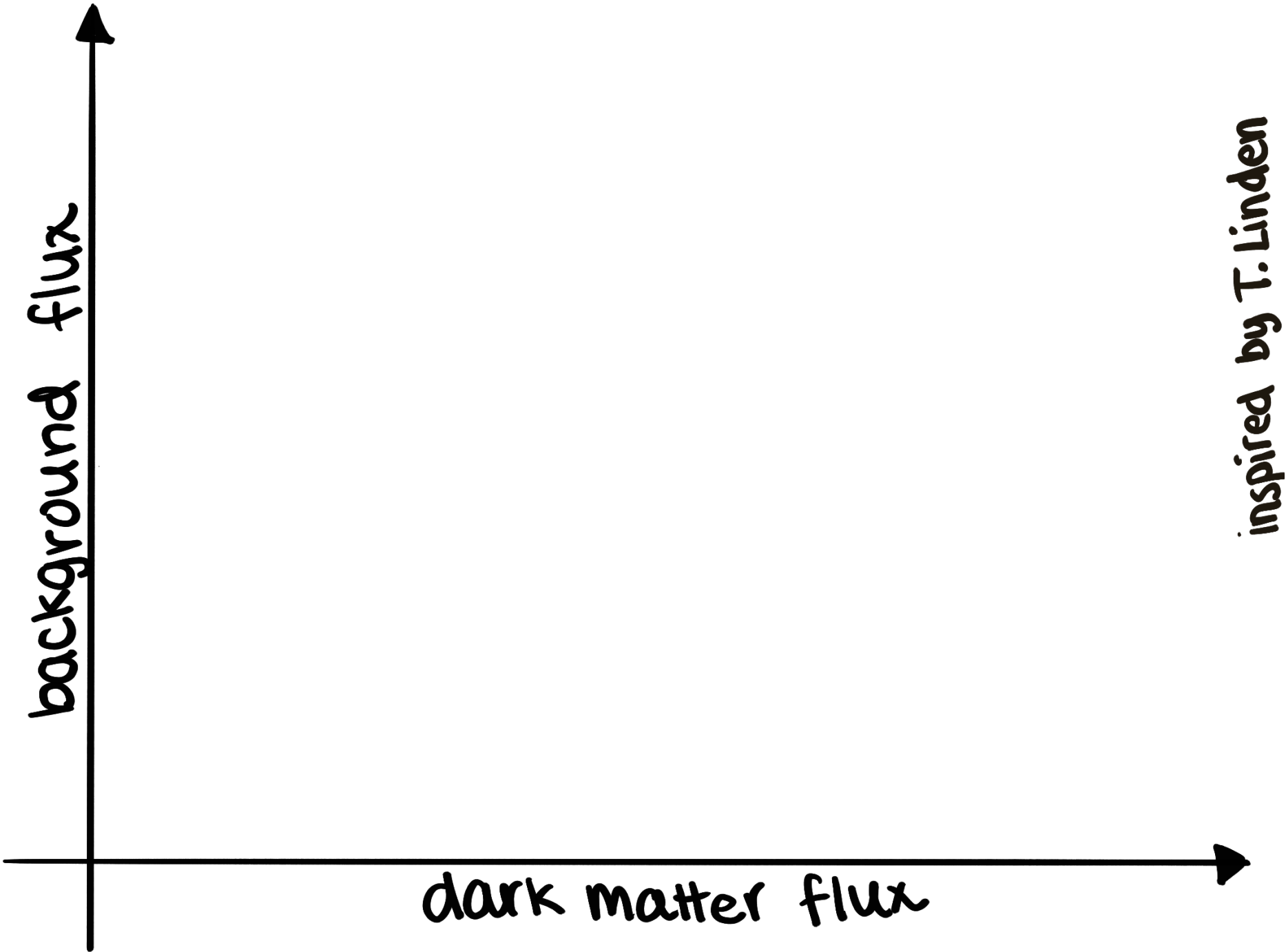


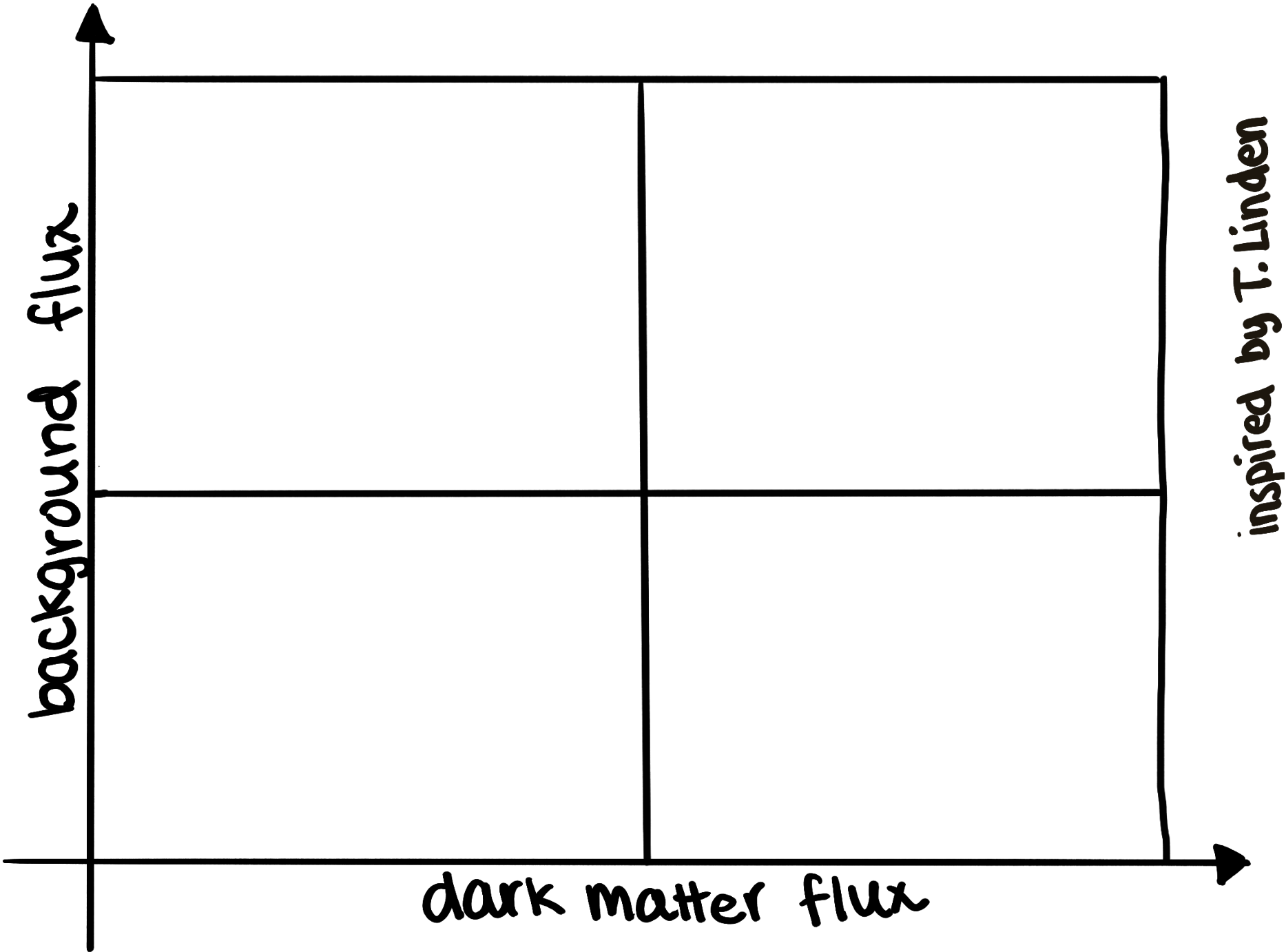
Everything else

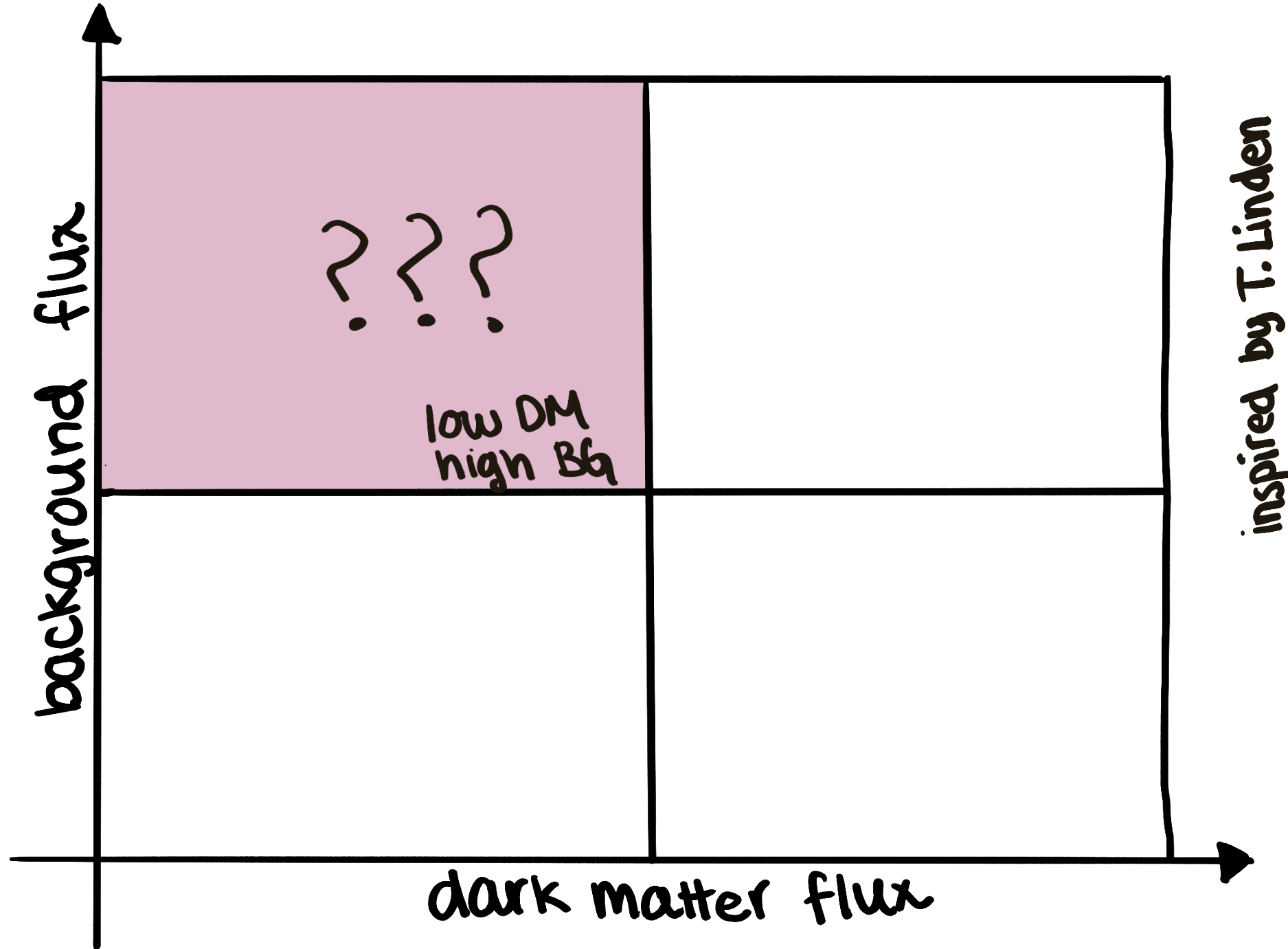
Isotropic background, Loop I,
Sun, Fermi bubbles...

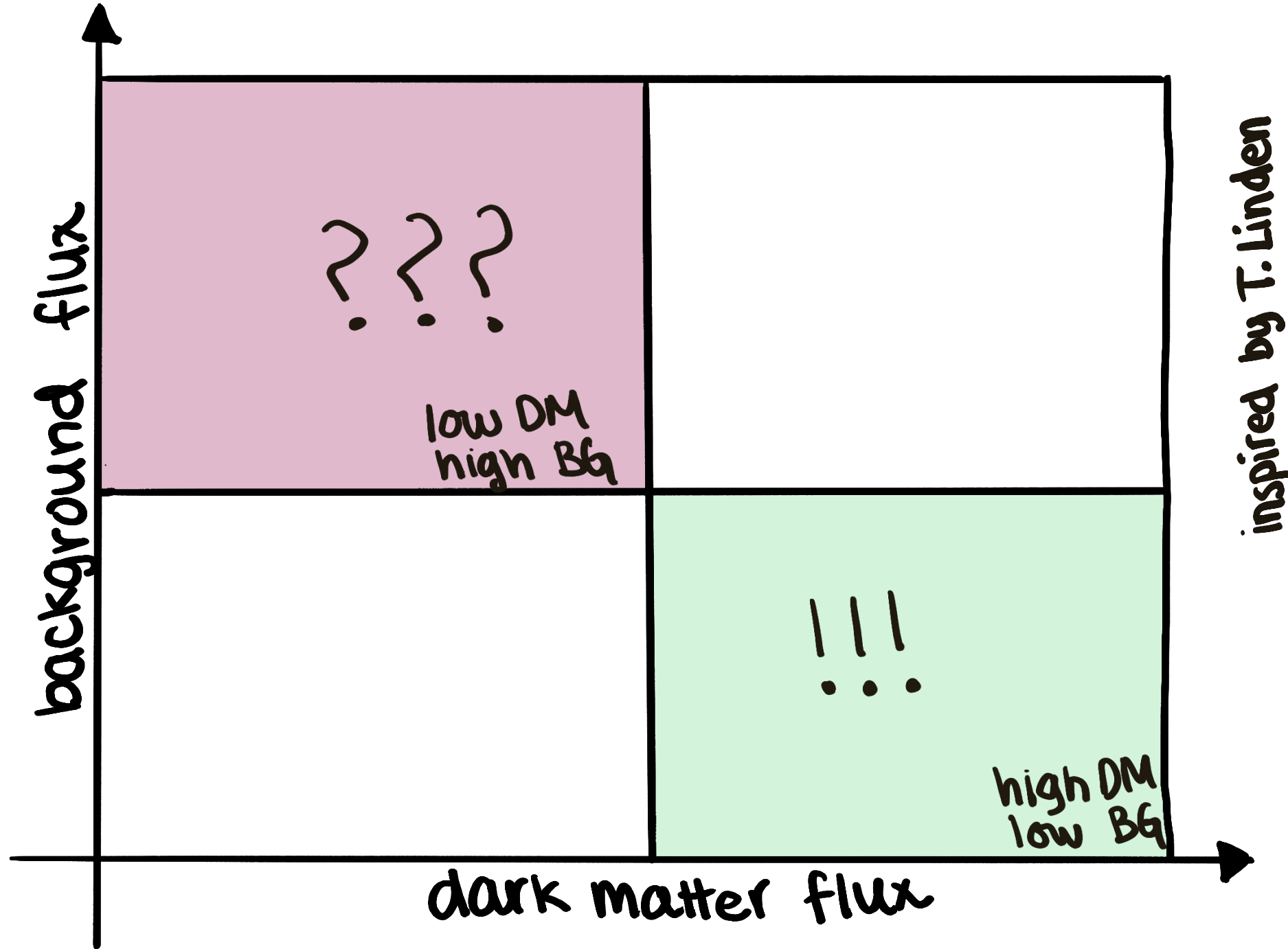
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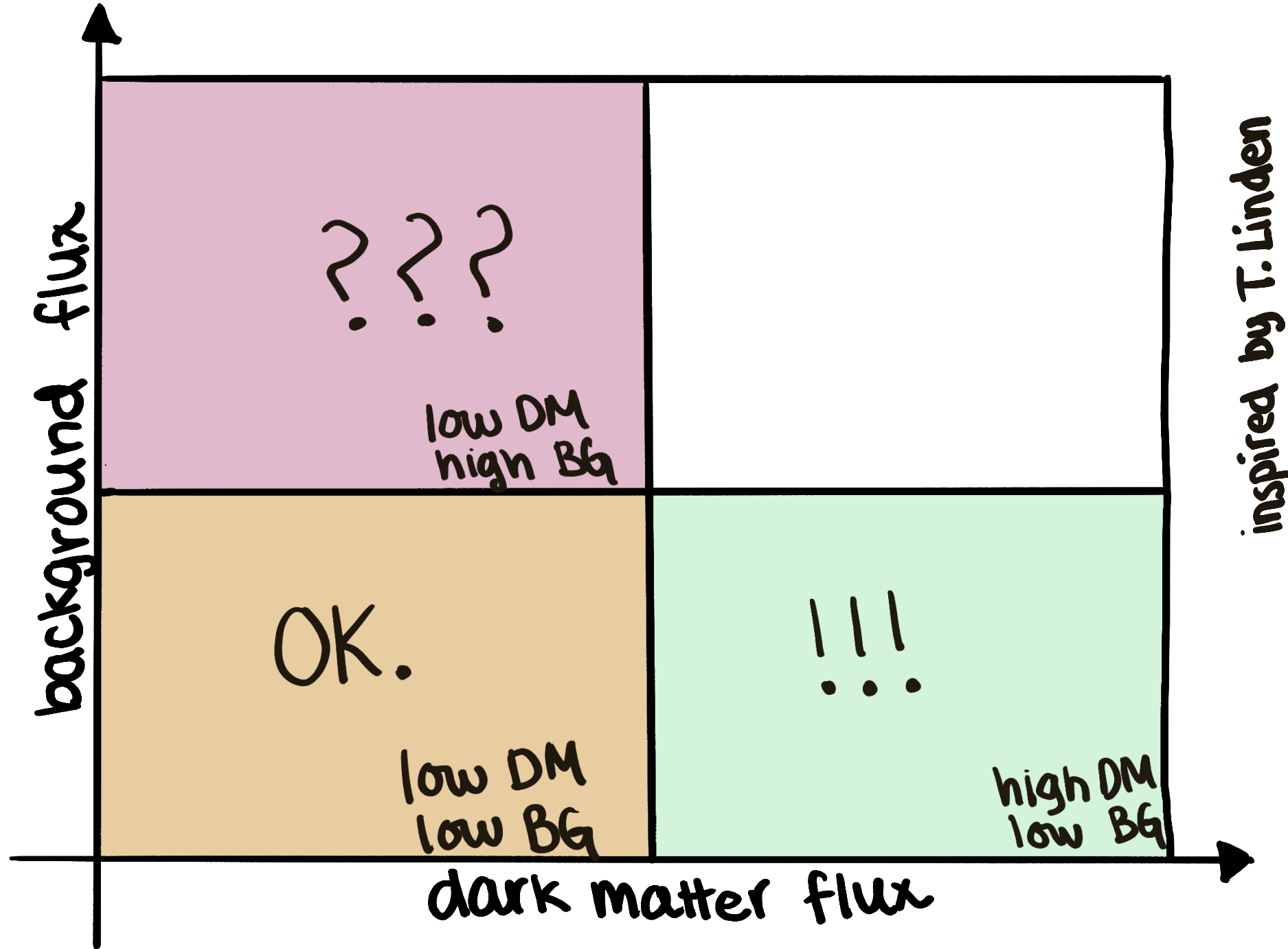


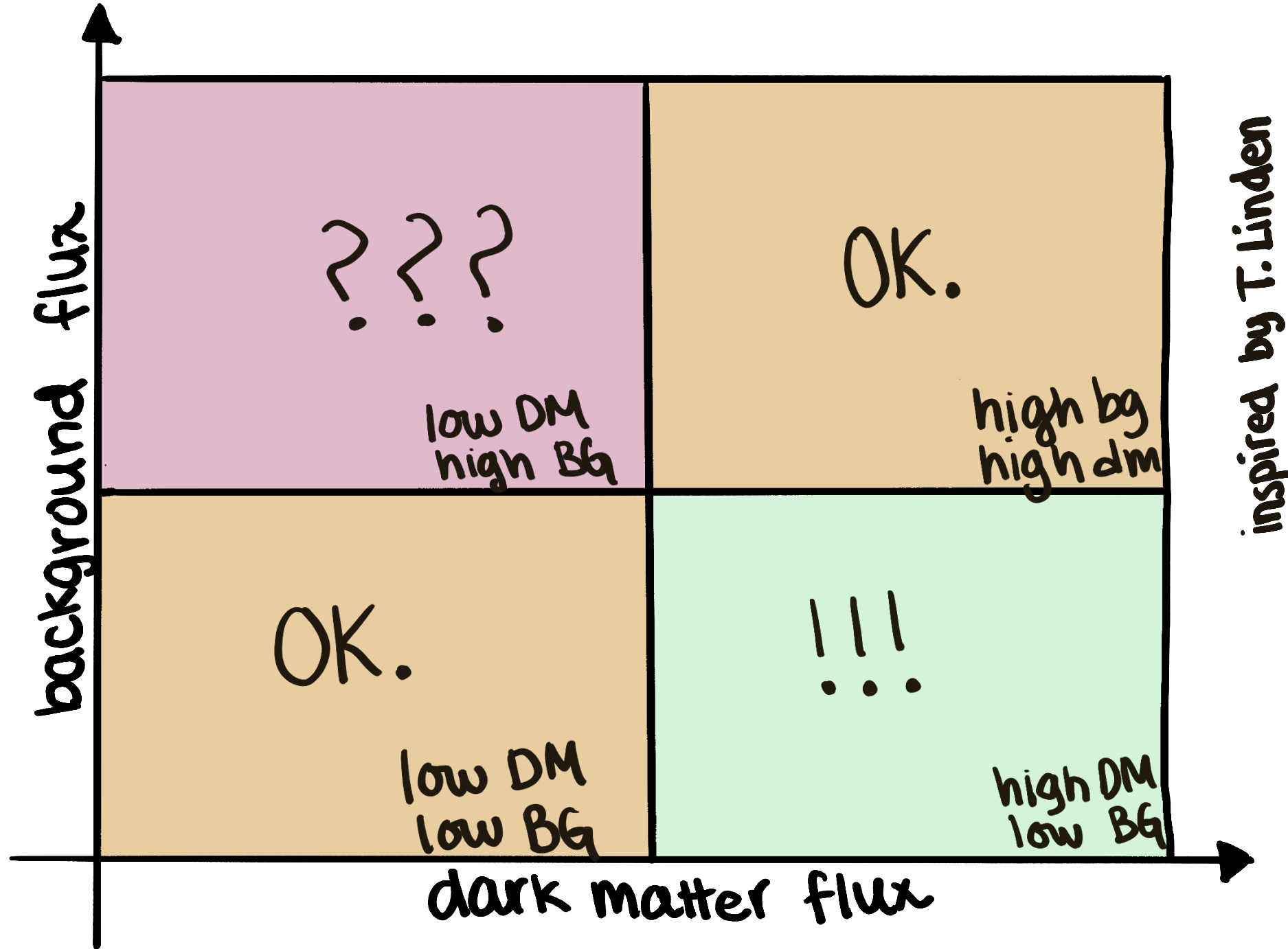


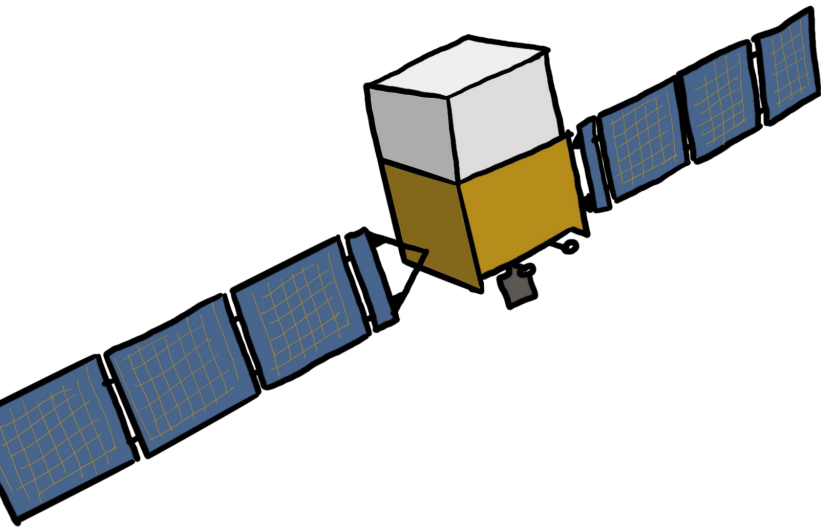




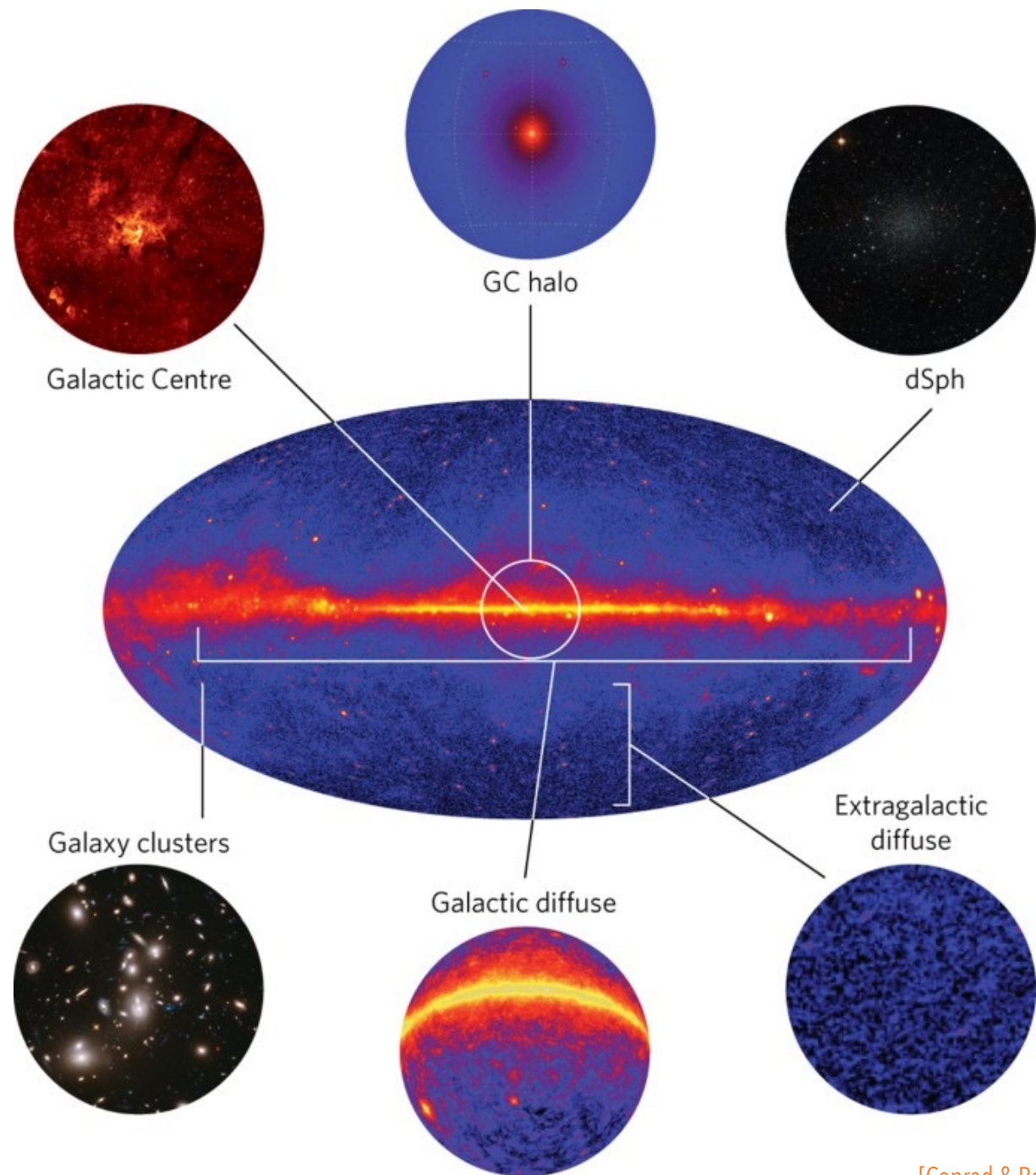






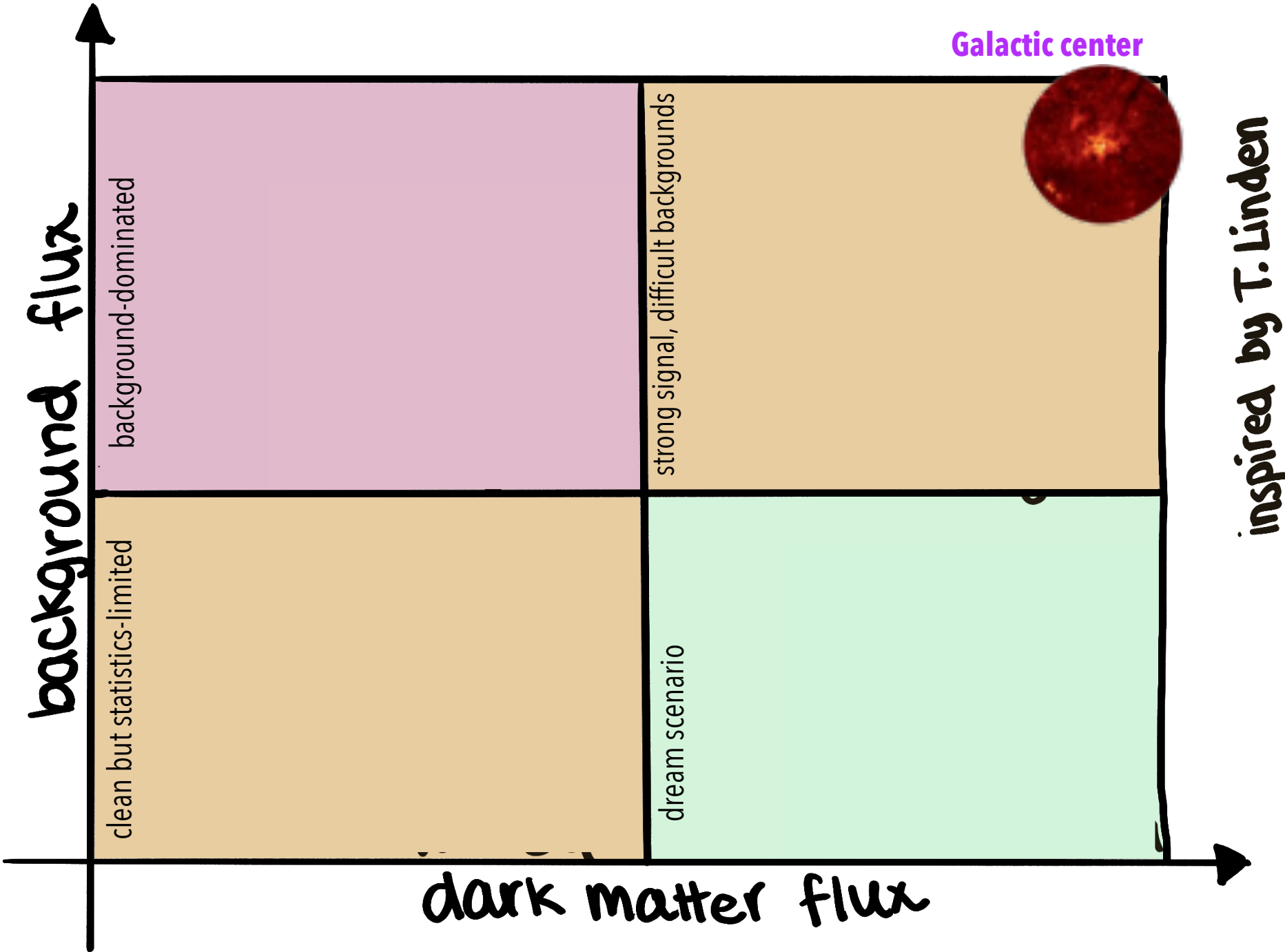


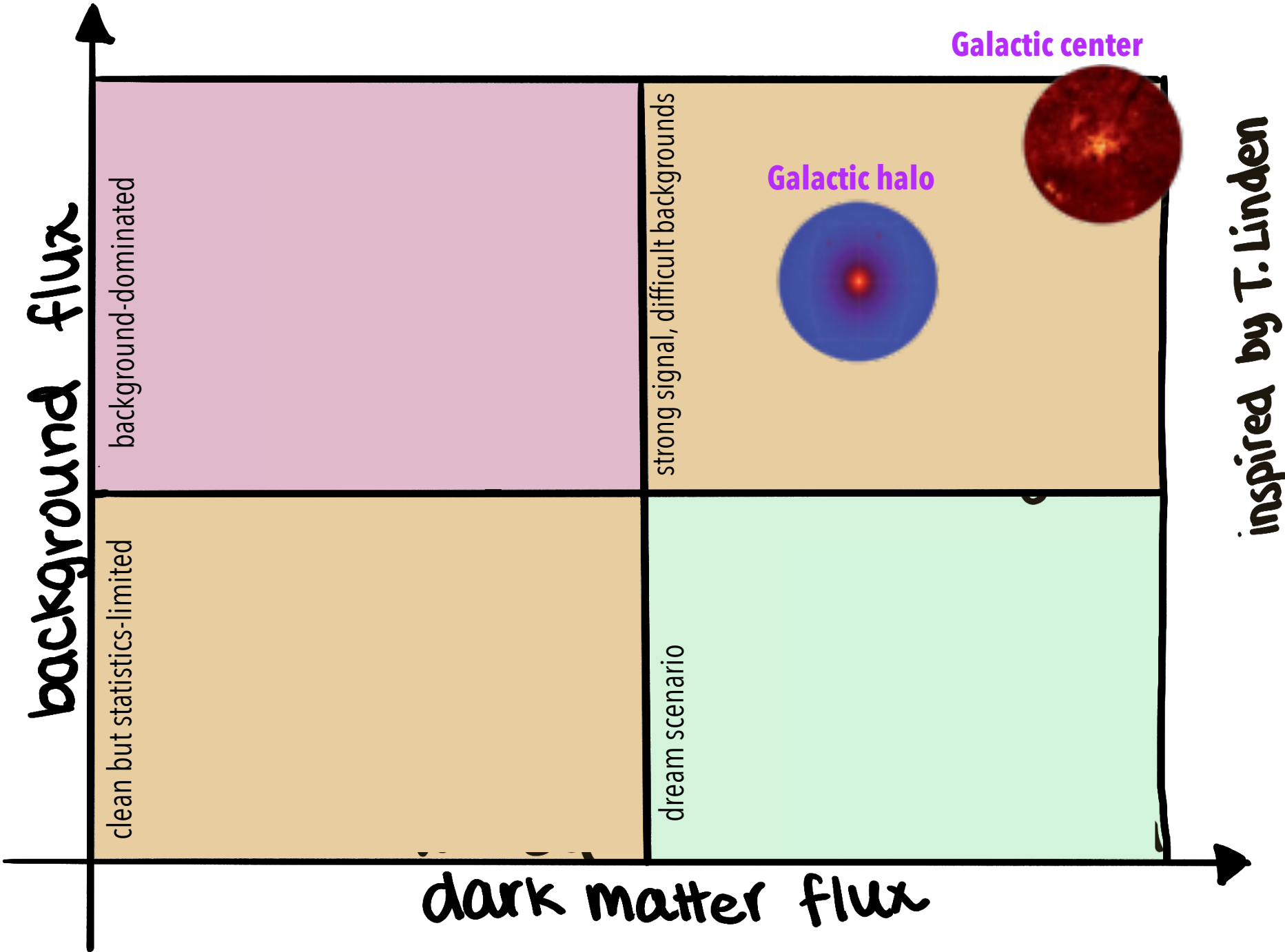
DM targets

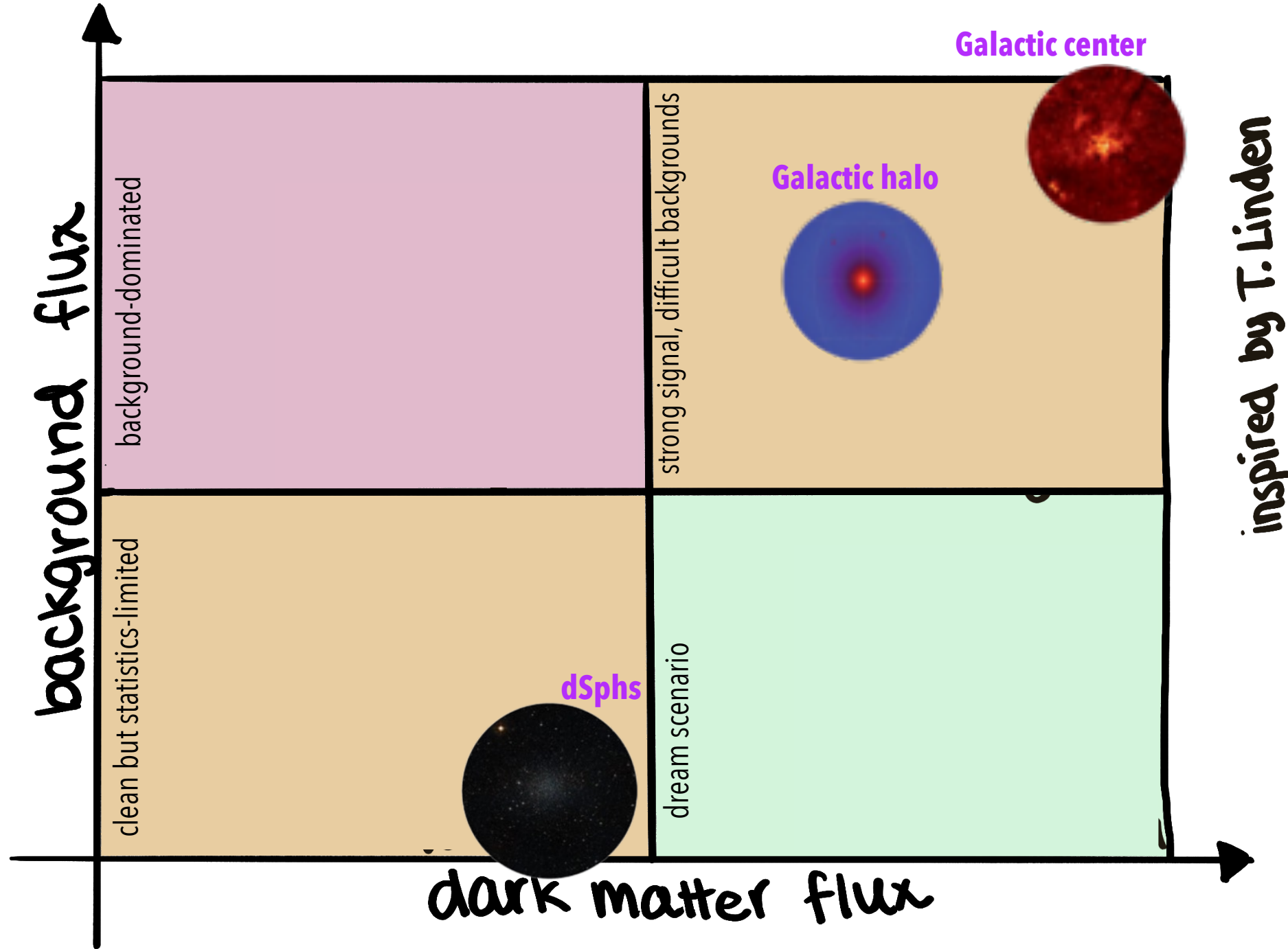


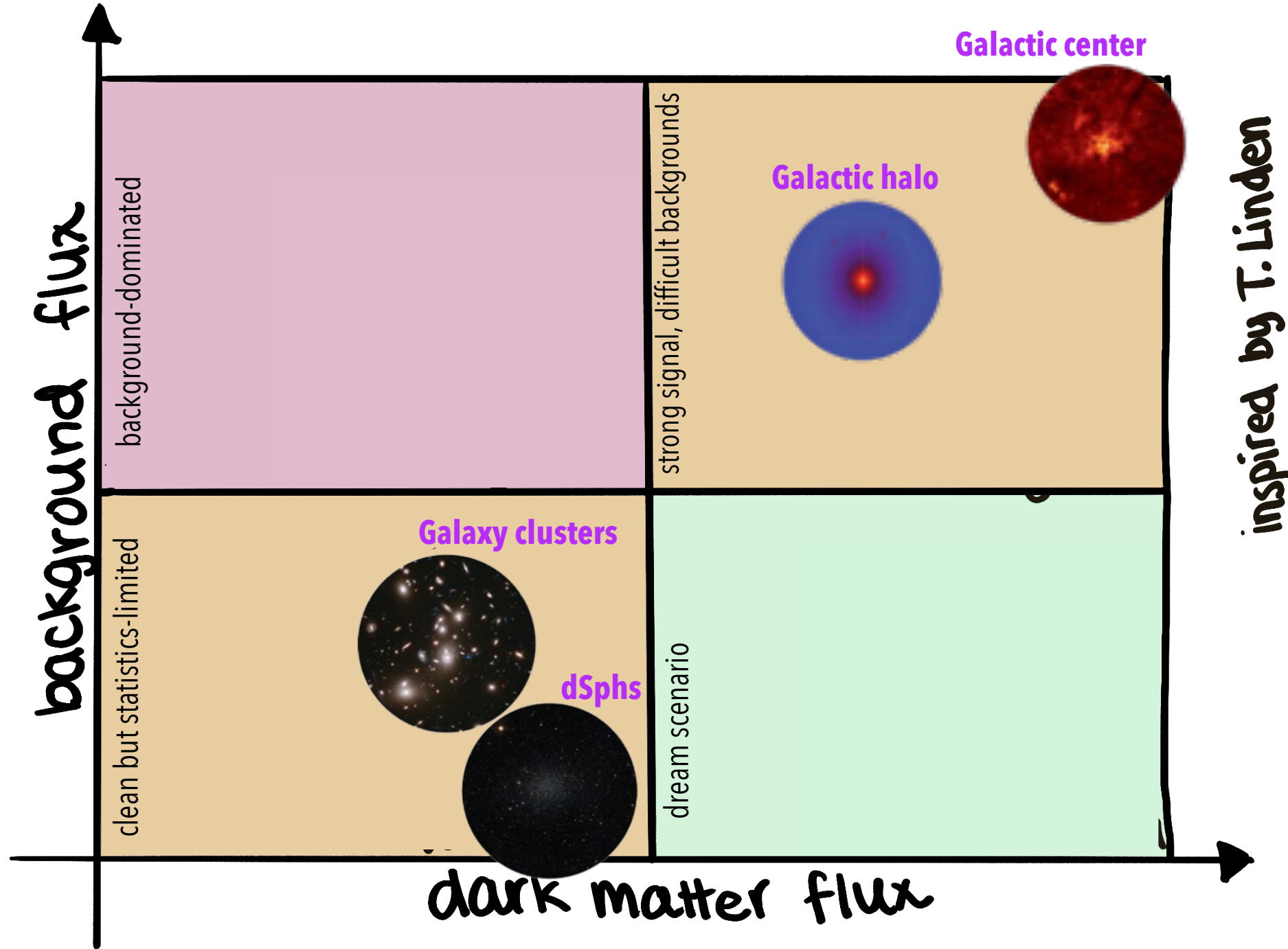
Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.
Nguyen+ 25, 26, Leane+ 23, Blanco+ 24, 25, etc.

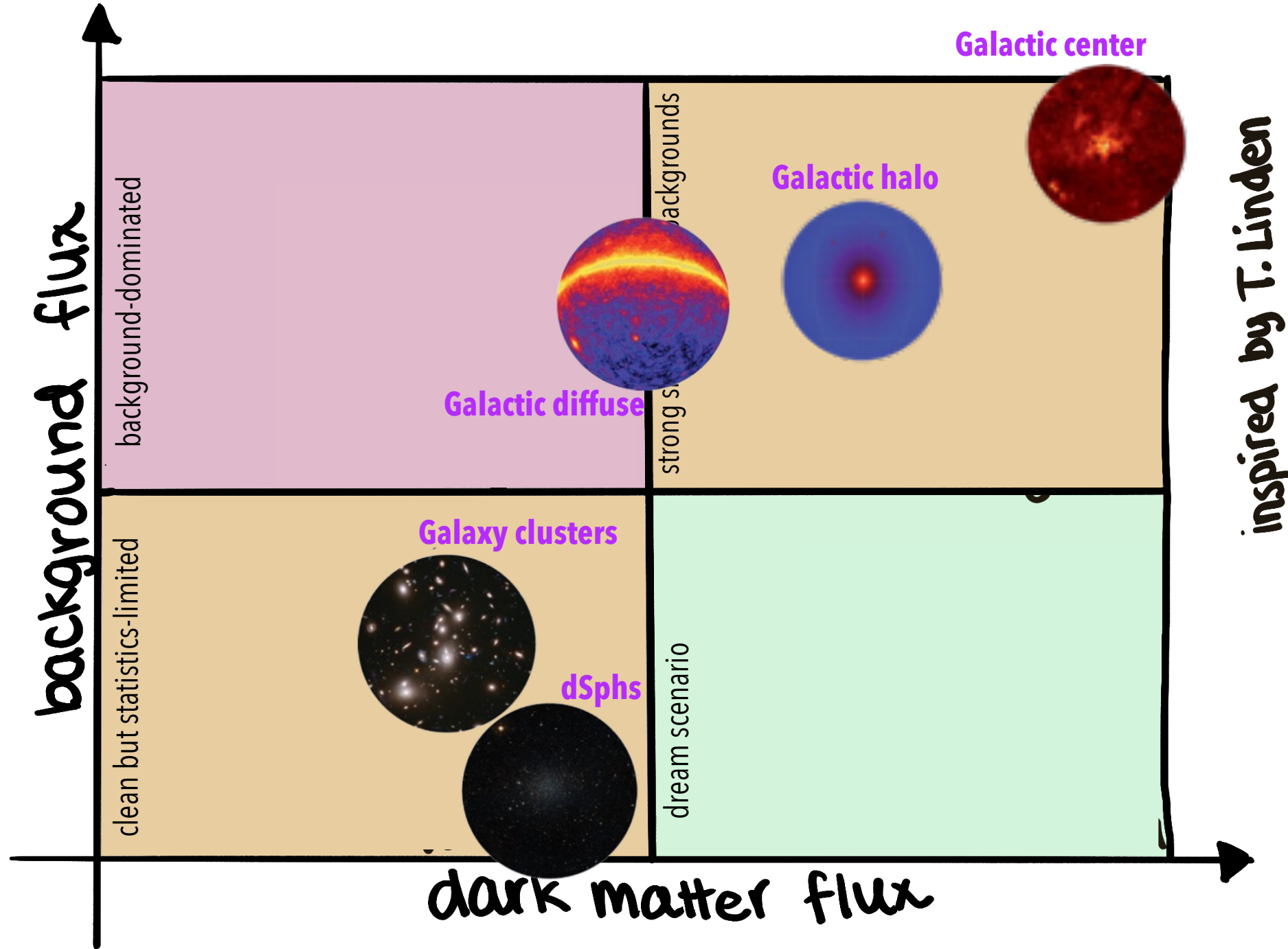
[Conrad & Reimer 2017]

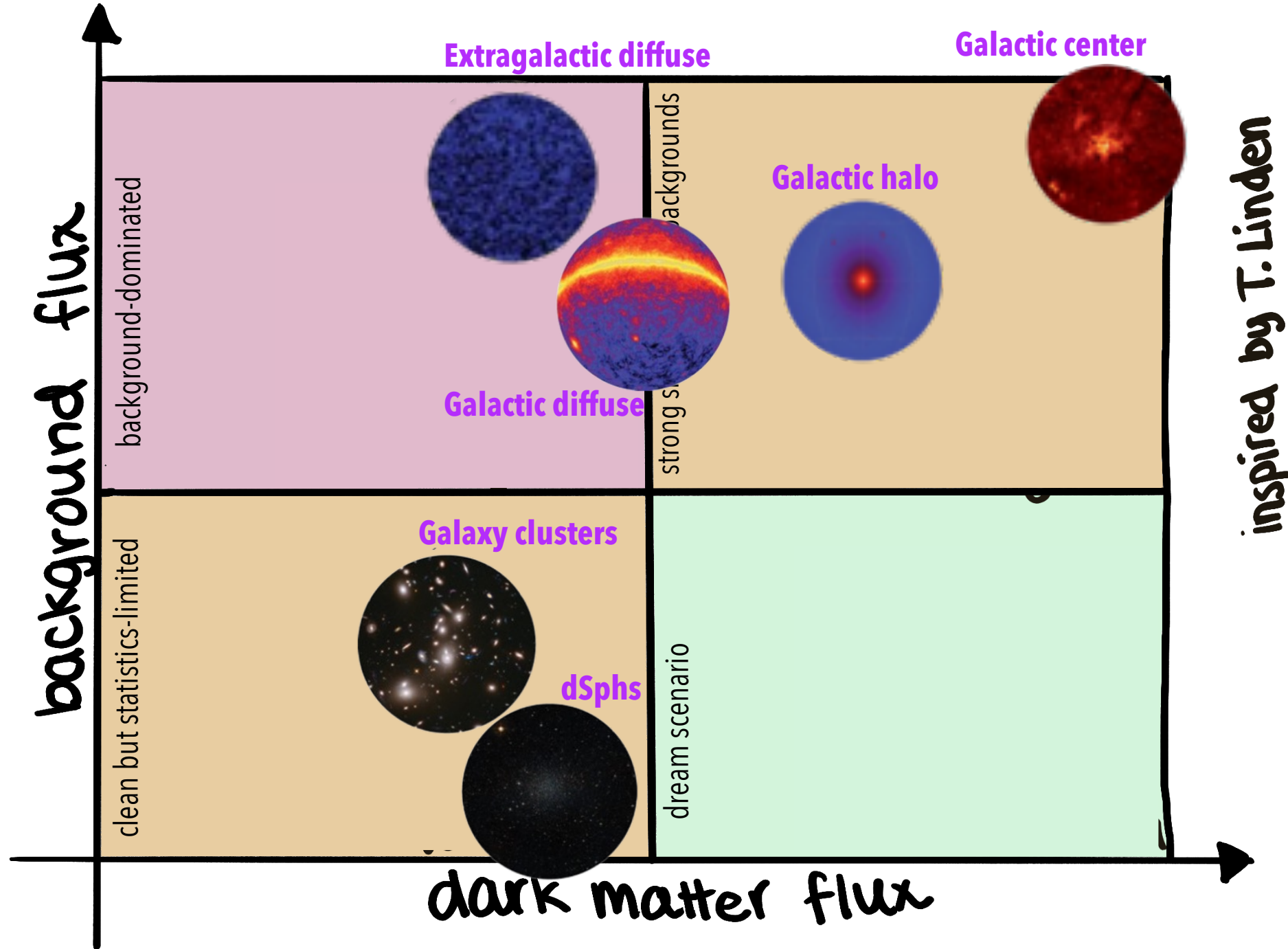




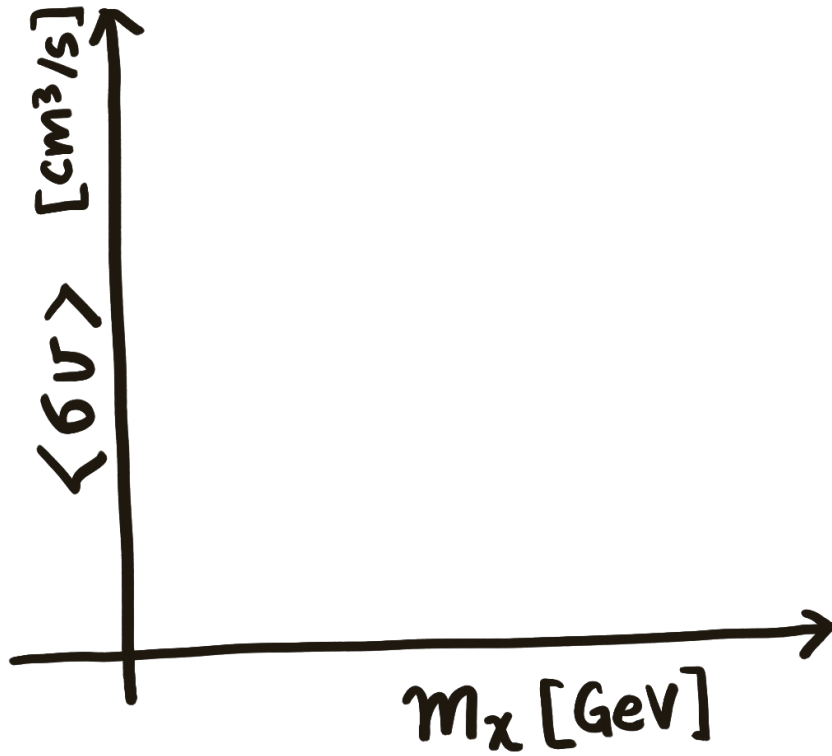




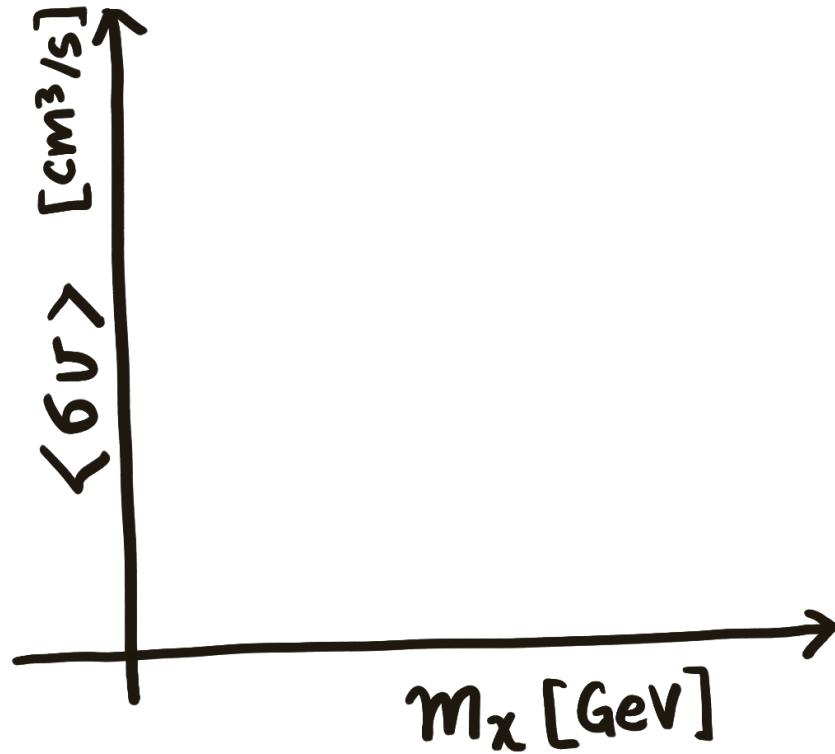




\$\$\$ plots



\$\$\$ plots

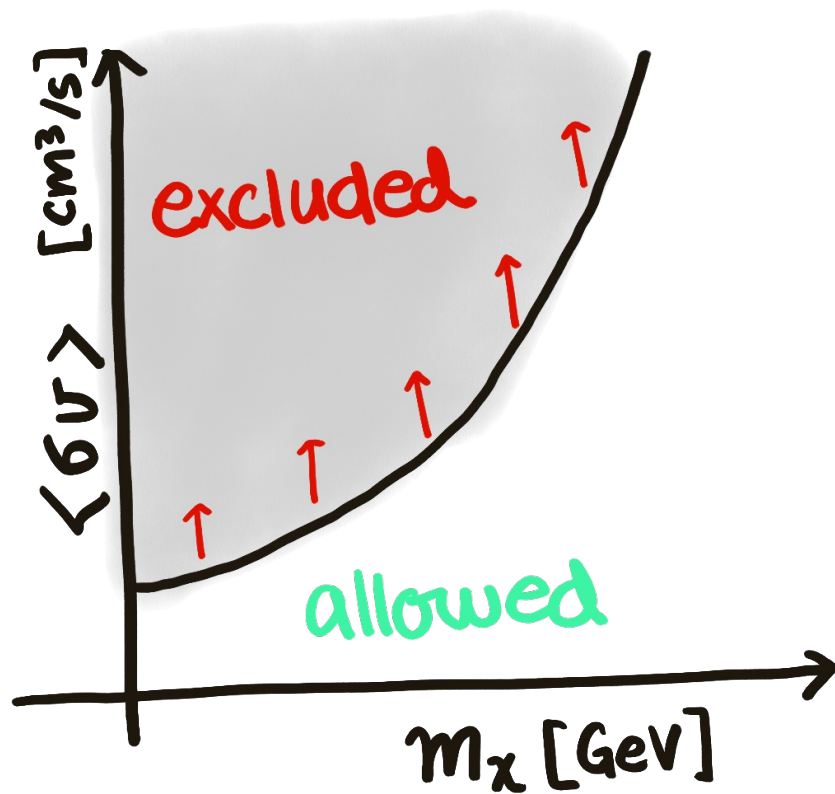


expected (theory predicted)

vs.

observed flux

\$\$\$ plots



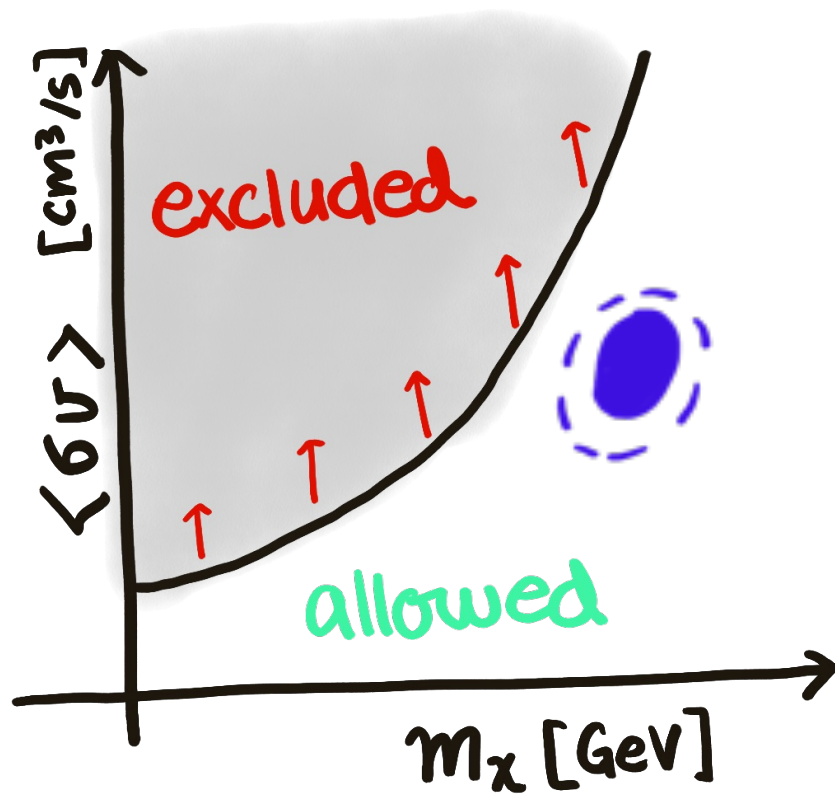
expected (theory predicted)

VS.

observed flux

Possibility 1: **No** signal detection.
→ derive upper limits

\$\$\$ plots



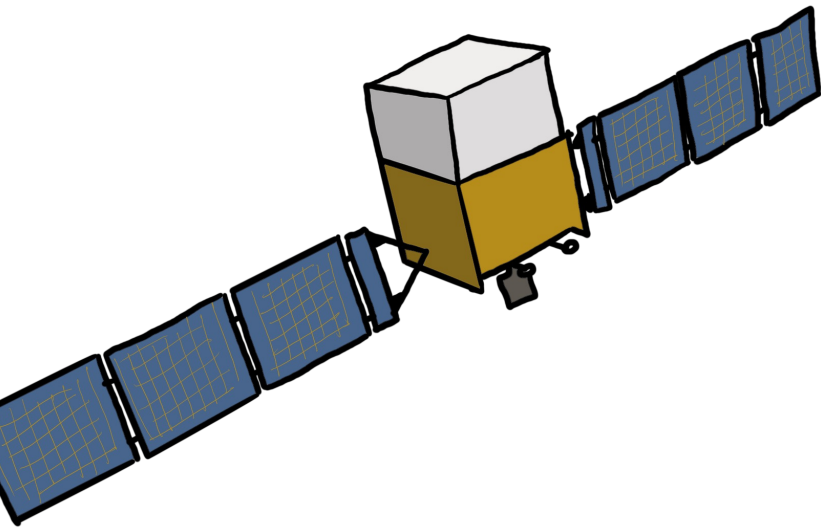
expected (theory predicted)

VS.

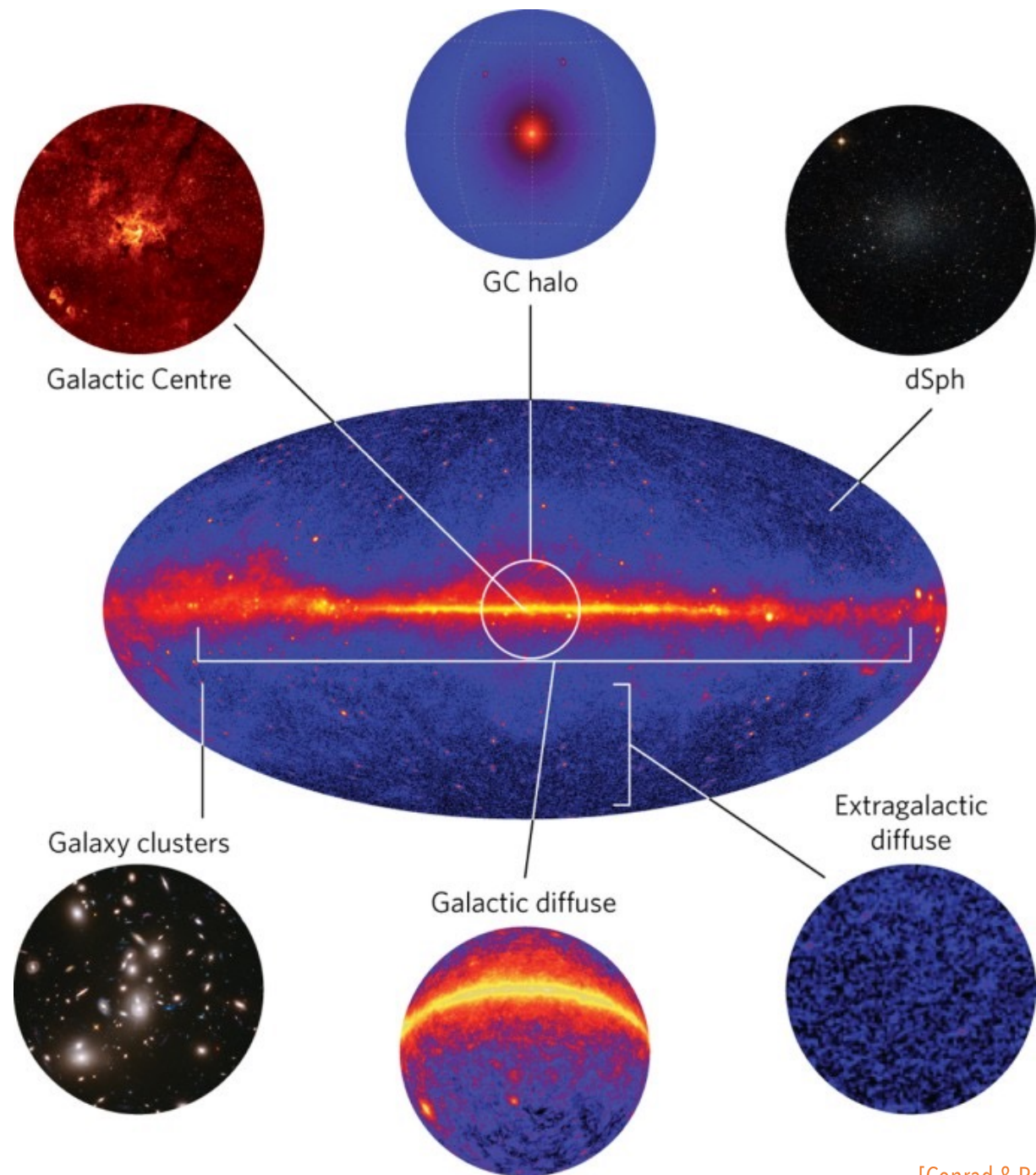
observed flux

Possibility 1: **No** signal detection.
→ derive upper limits

Possibility 2: **Signal detection.**
→ fit parameters of your DM model

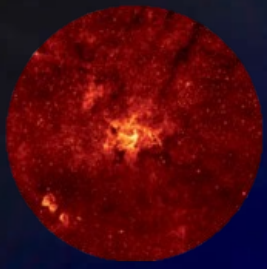


DM targets

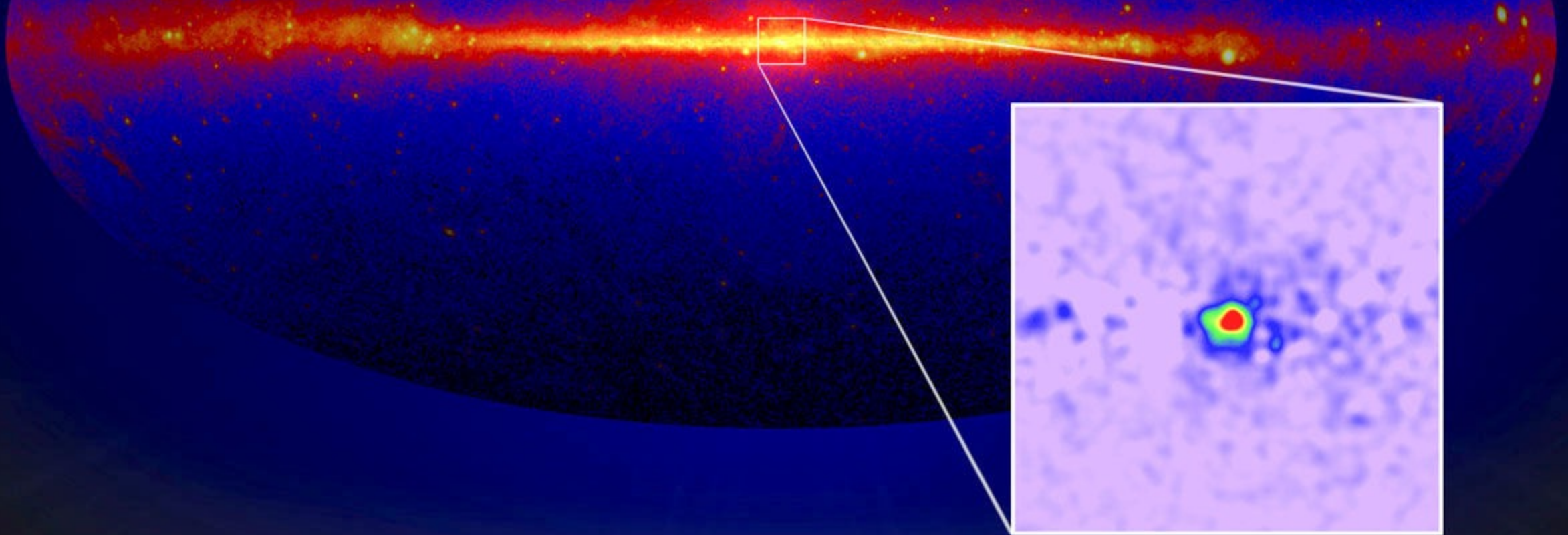


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[Conrad & Reimer 2017]



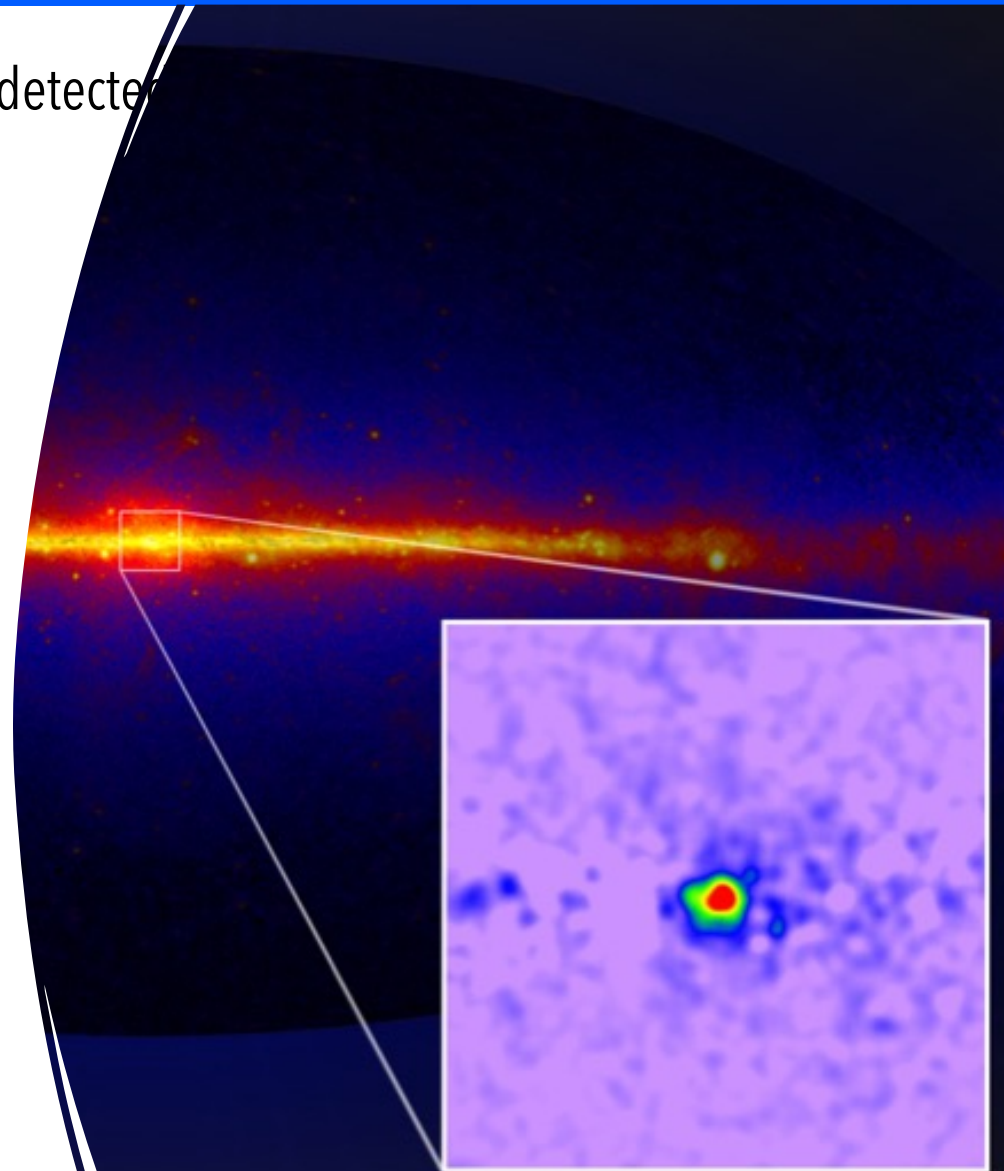
Target 1: The Galactic Center



Gamma rays from the Galactic Center

- Well-established bright excess in gamma rays (peaking at 1--3 GeV) detected
- 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)

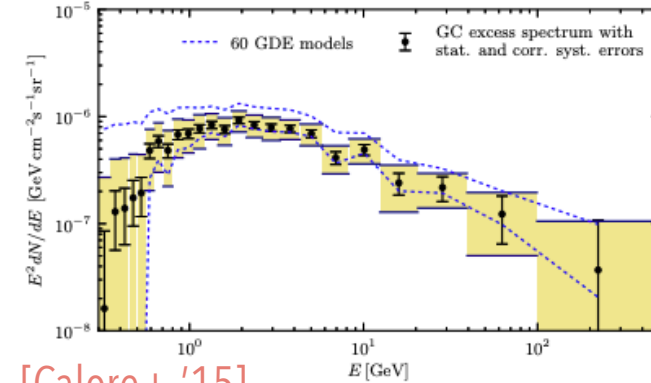


Gamma rays from the Galactic Center

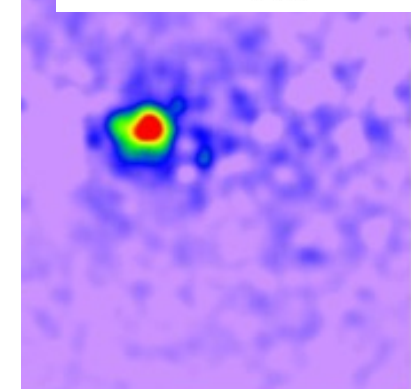
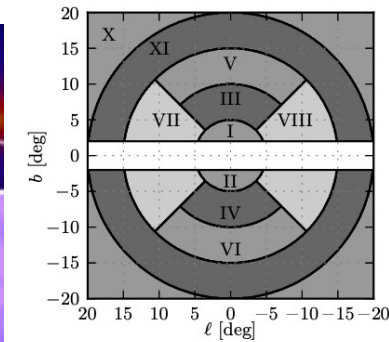
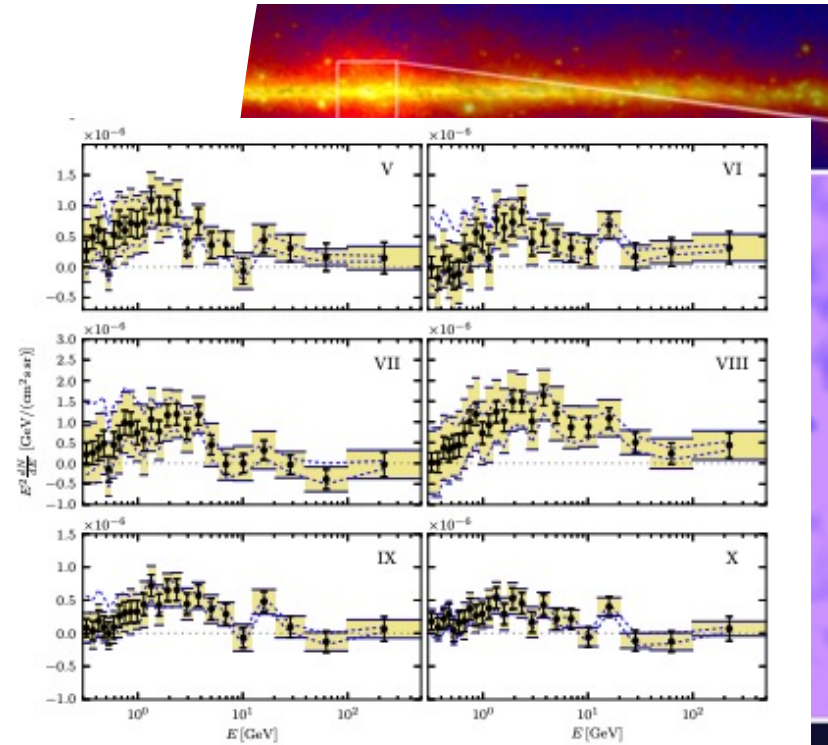
- Well-established bright excess in gamma rays (peaking at 1--3 GeV) detected in LAT
- Extended emission up to ~ 10 degrees (1.5 kpc)

Maybe Dark Matter.

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



[Calore+ '15]

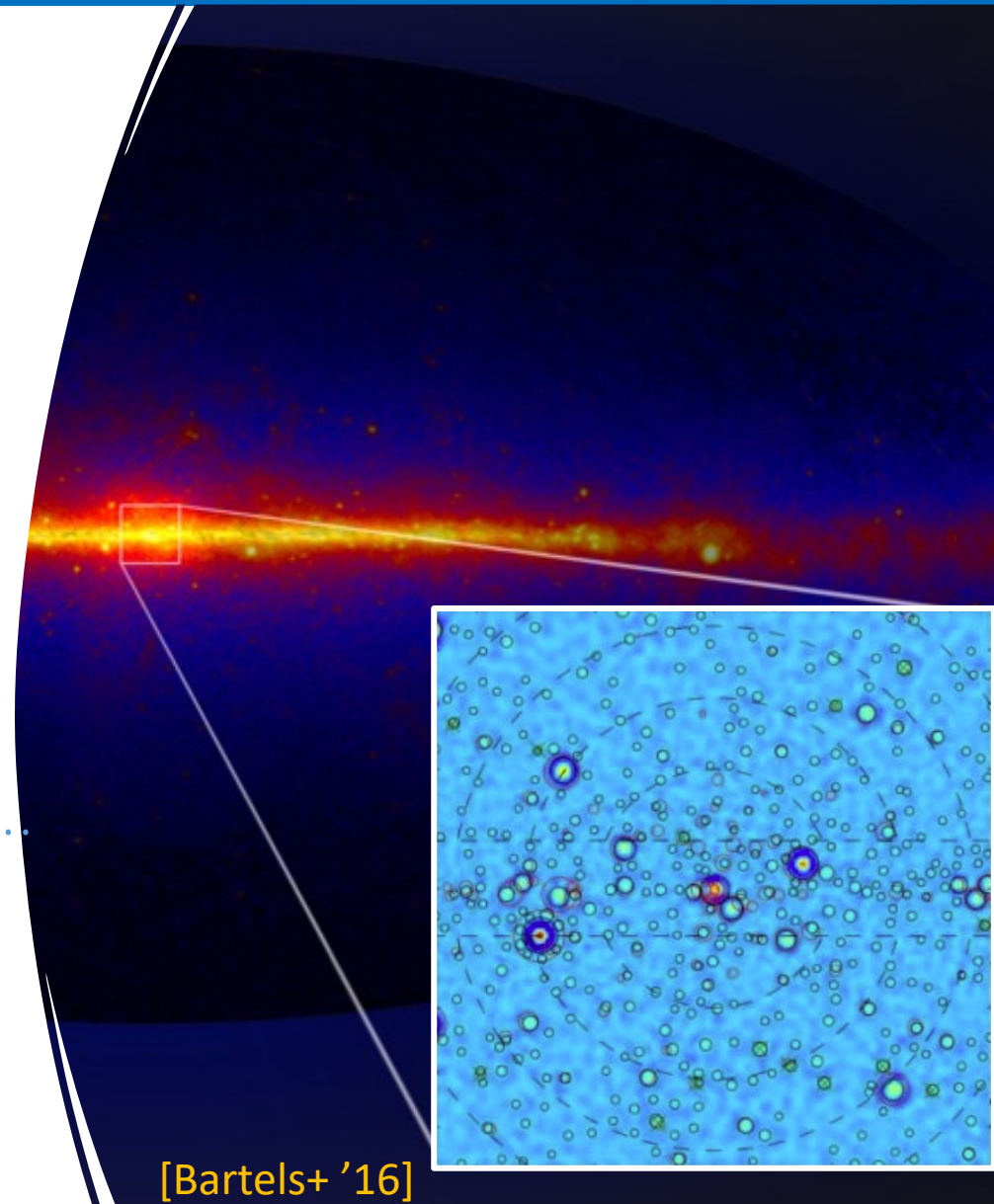


Gamma rays from the Galactic Center

- 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. Millisecond Pulsars?

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



Galactic Center Excess Flux

c. Tim Linden

Flux ($\text{GeV cm}^{-2} \text{s}^{-1}$)

10^{-6}

10^{-7}

10^{-8}

0.3

1

3

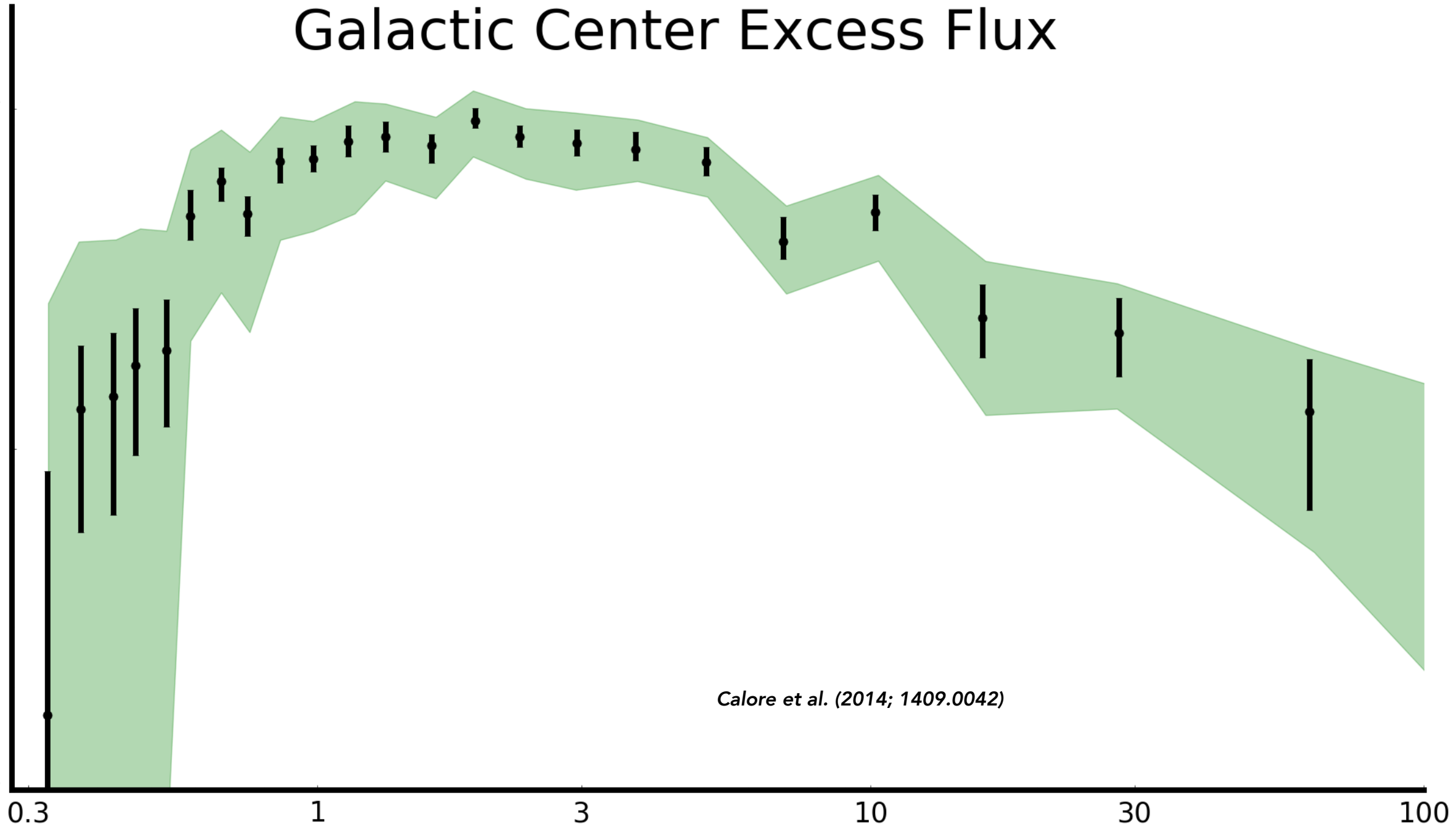
10

30

100

Energy (GeV)

Calore et al. (2014; 1409.0042)



Galactic Center Excess Flux

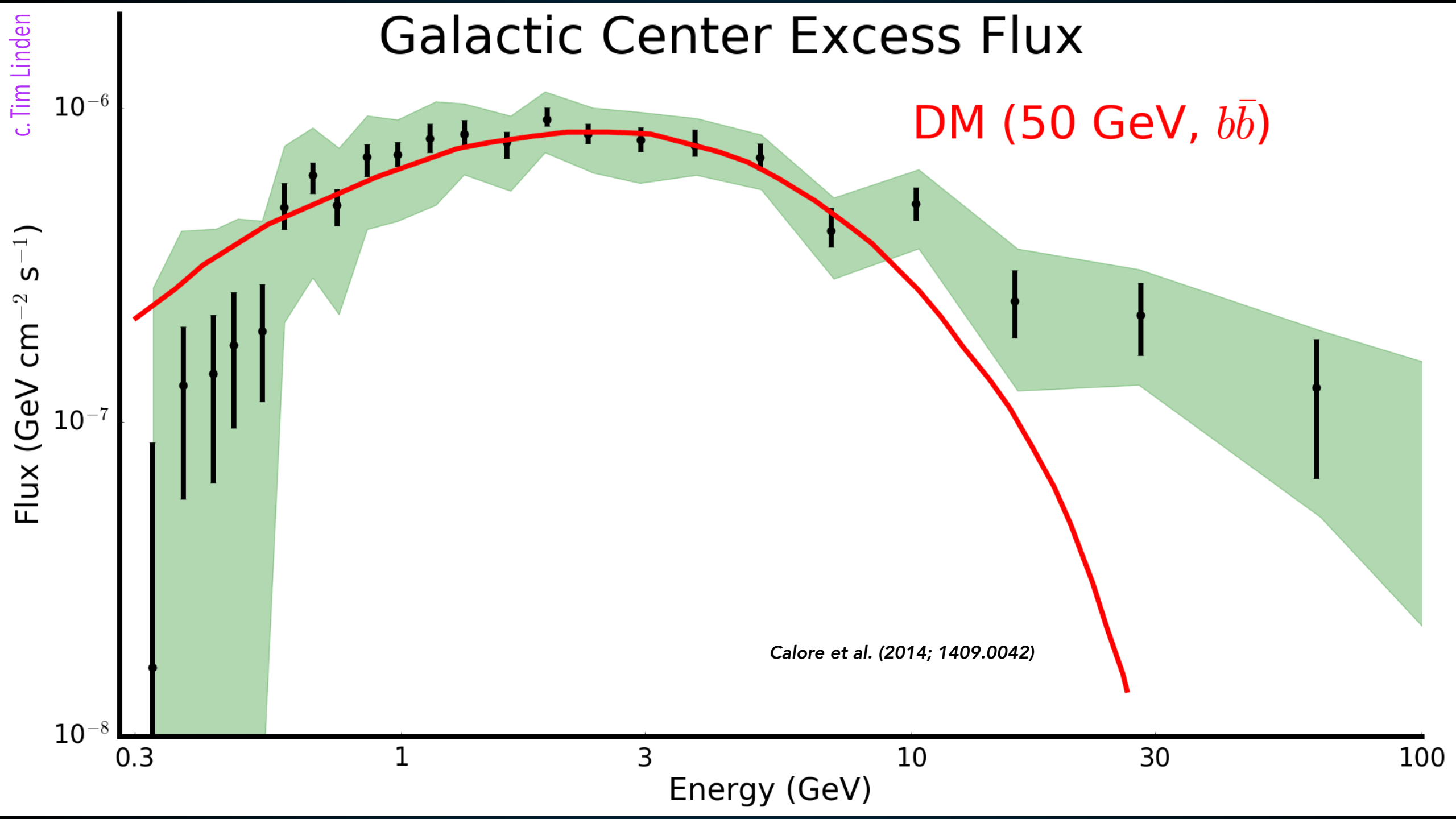
c. Tim Linden

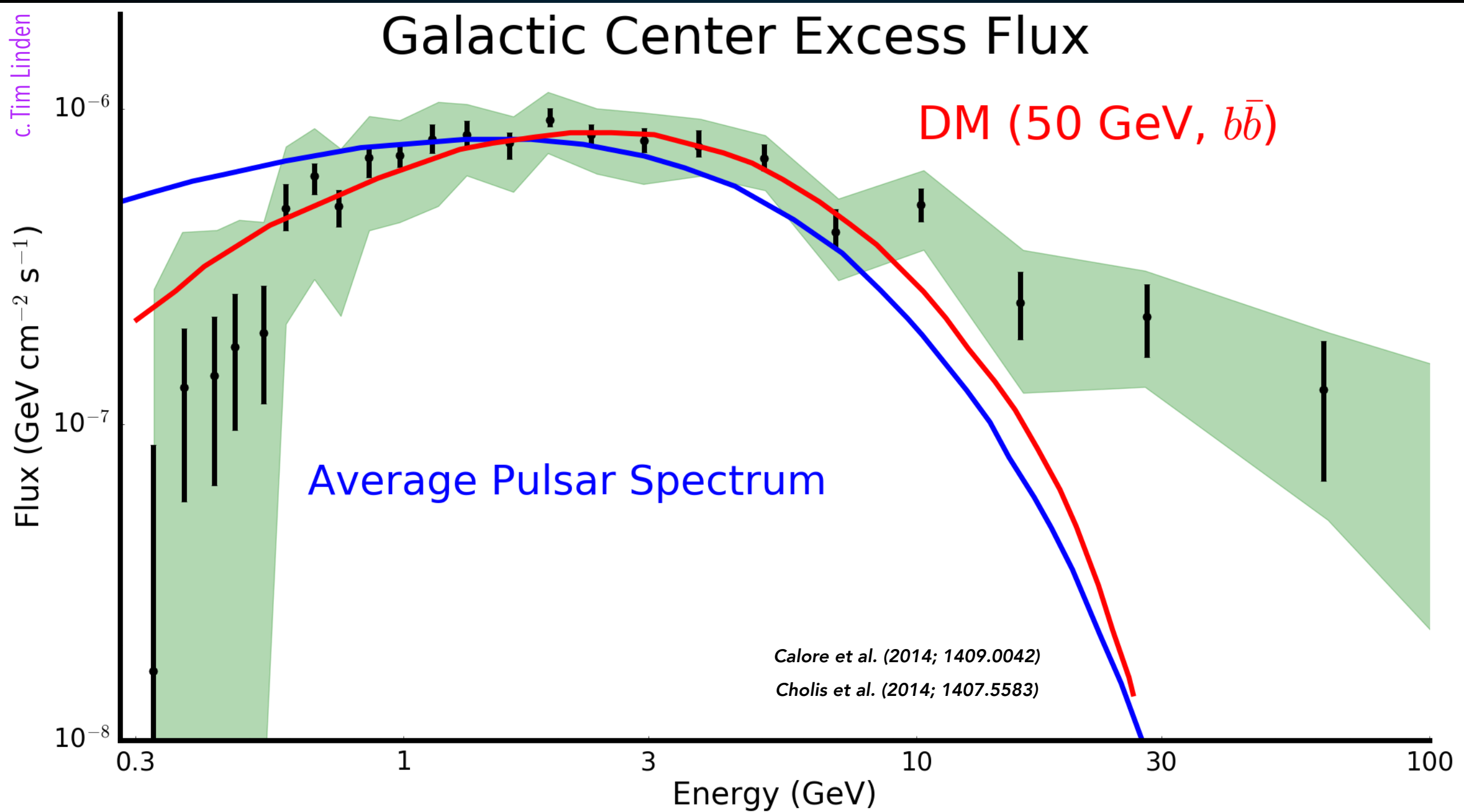
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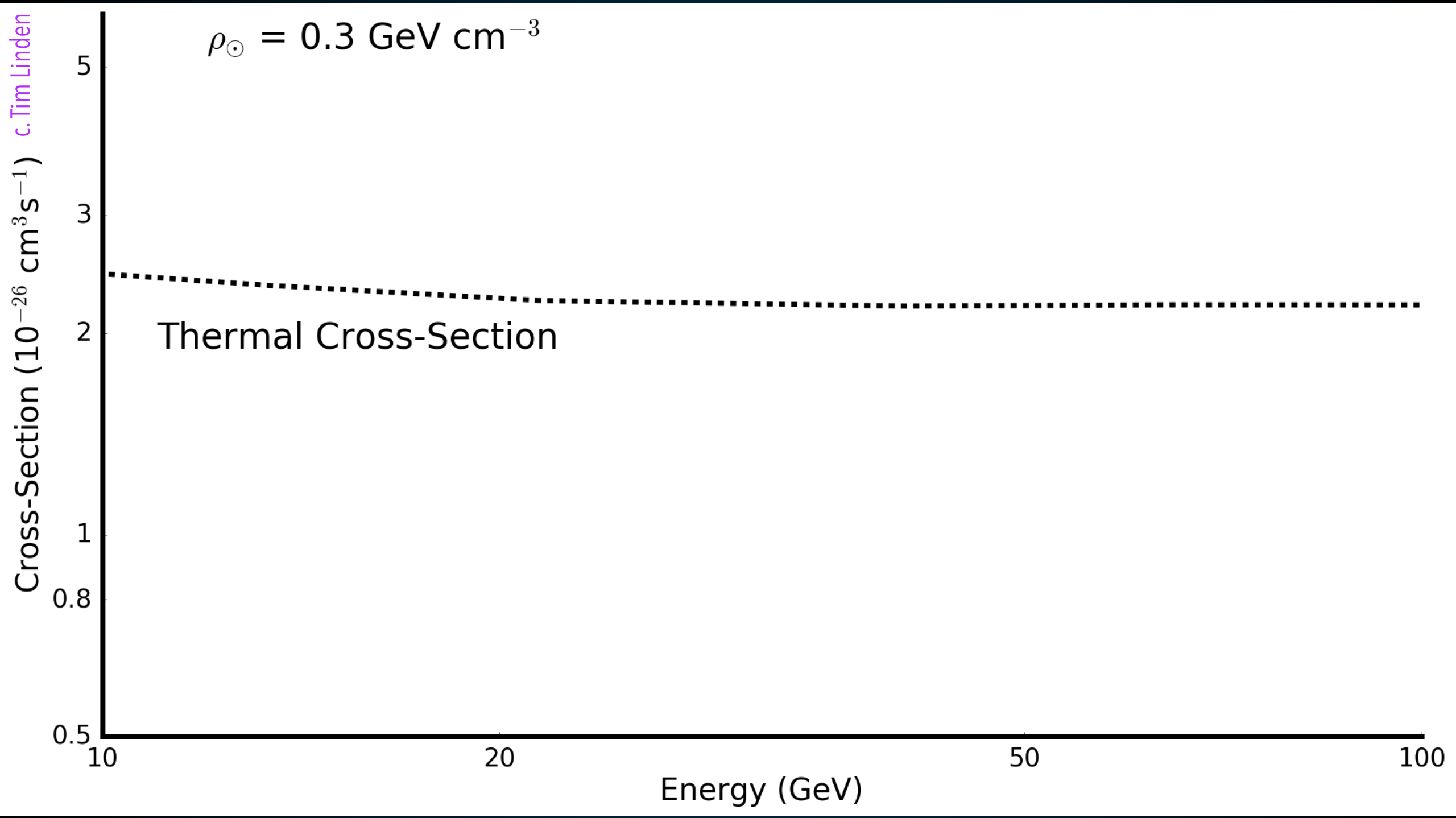
DM (50 GeV, $b\bar{b}$)

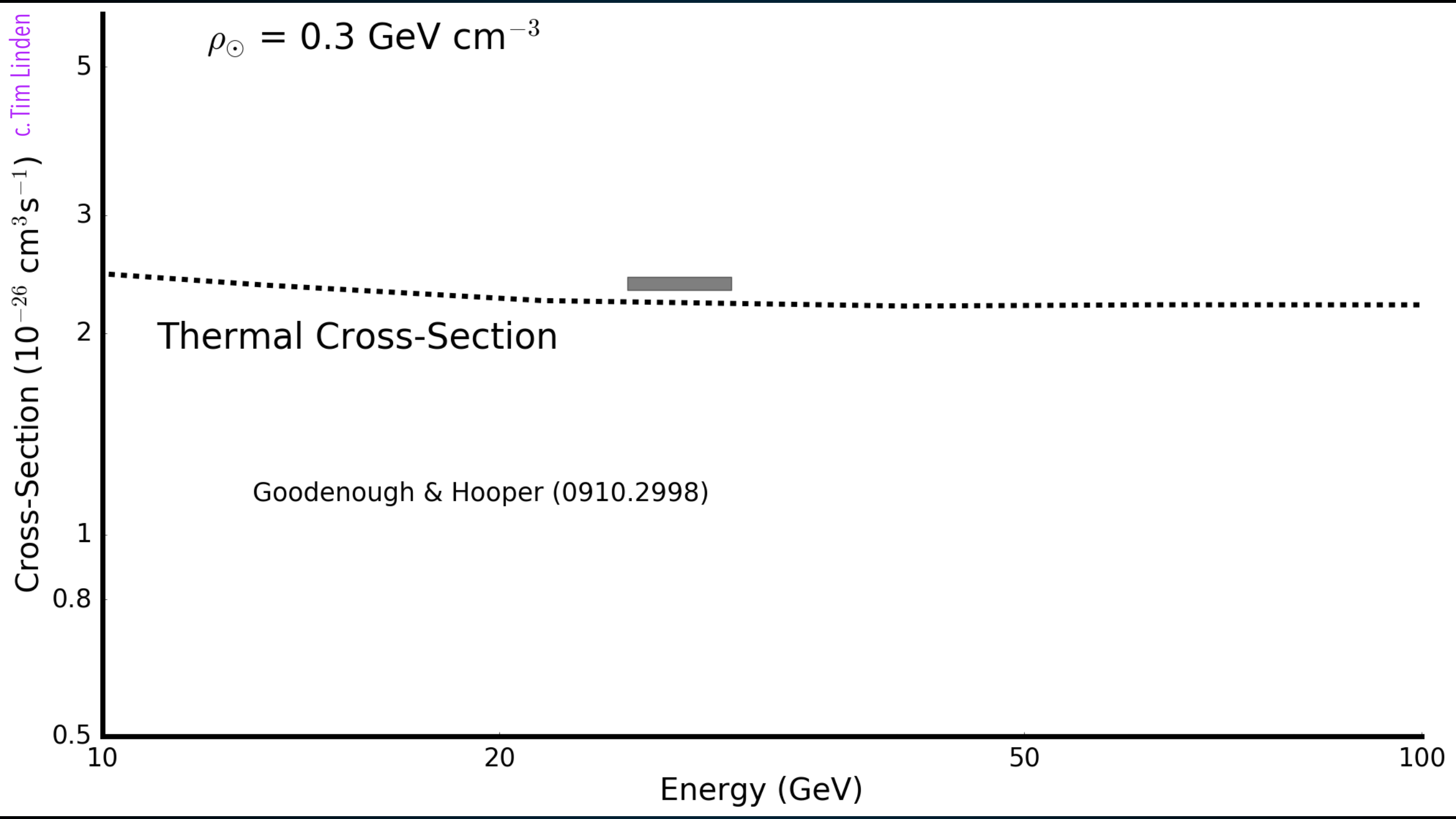
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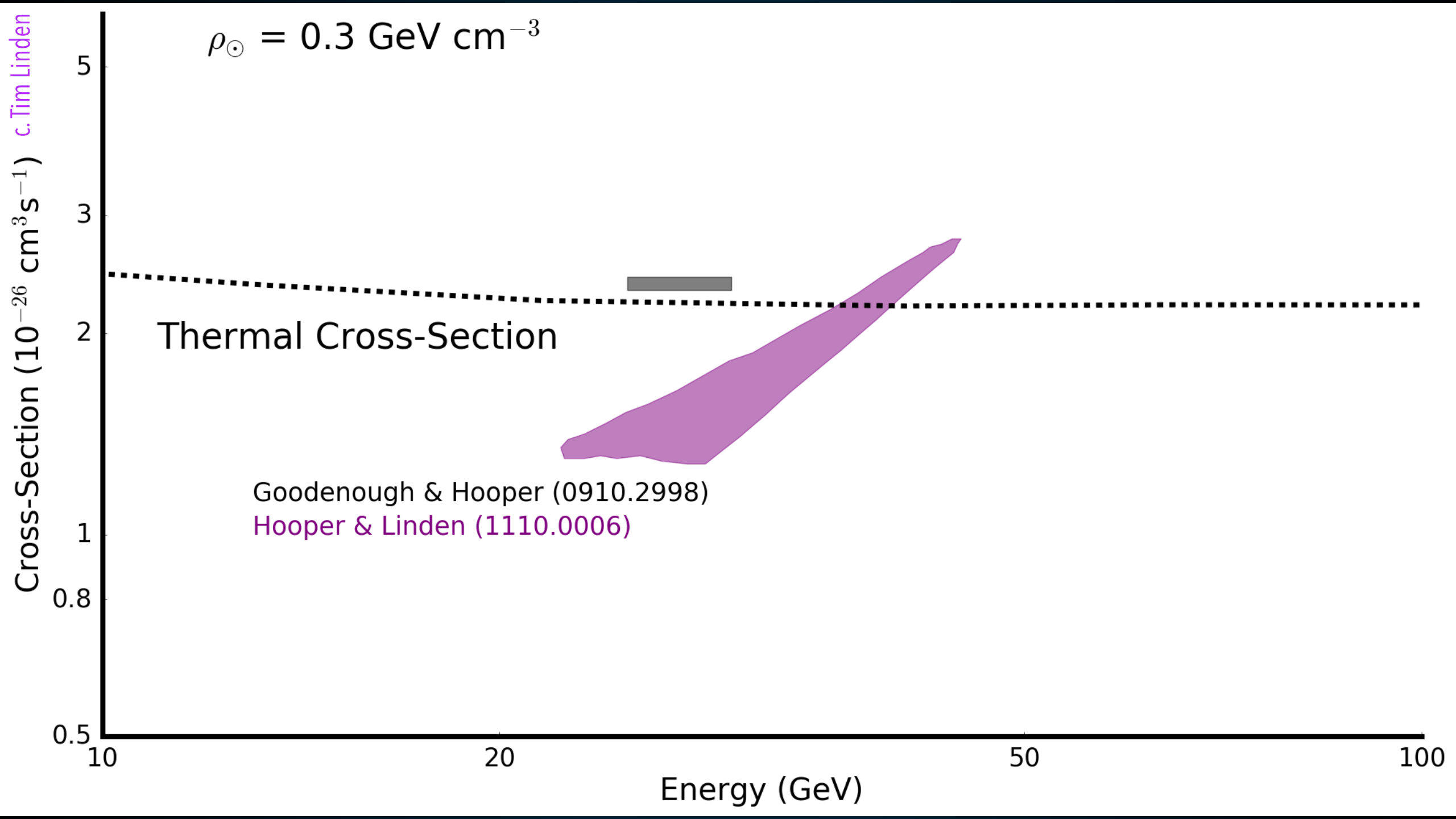
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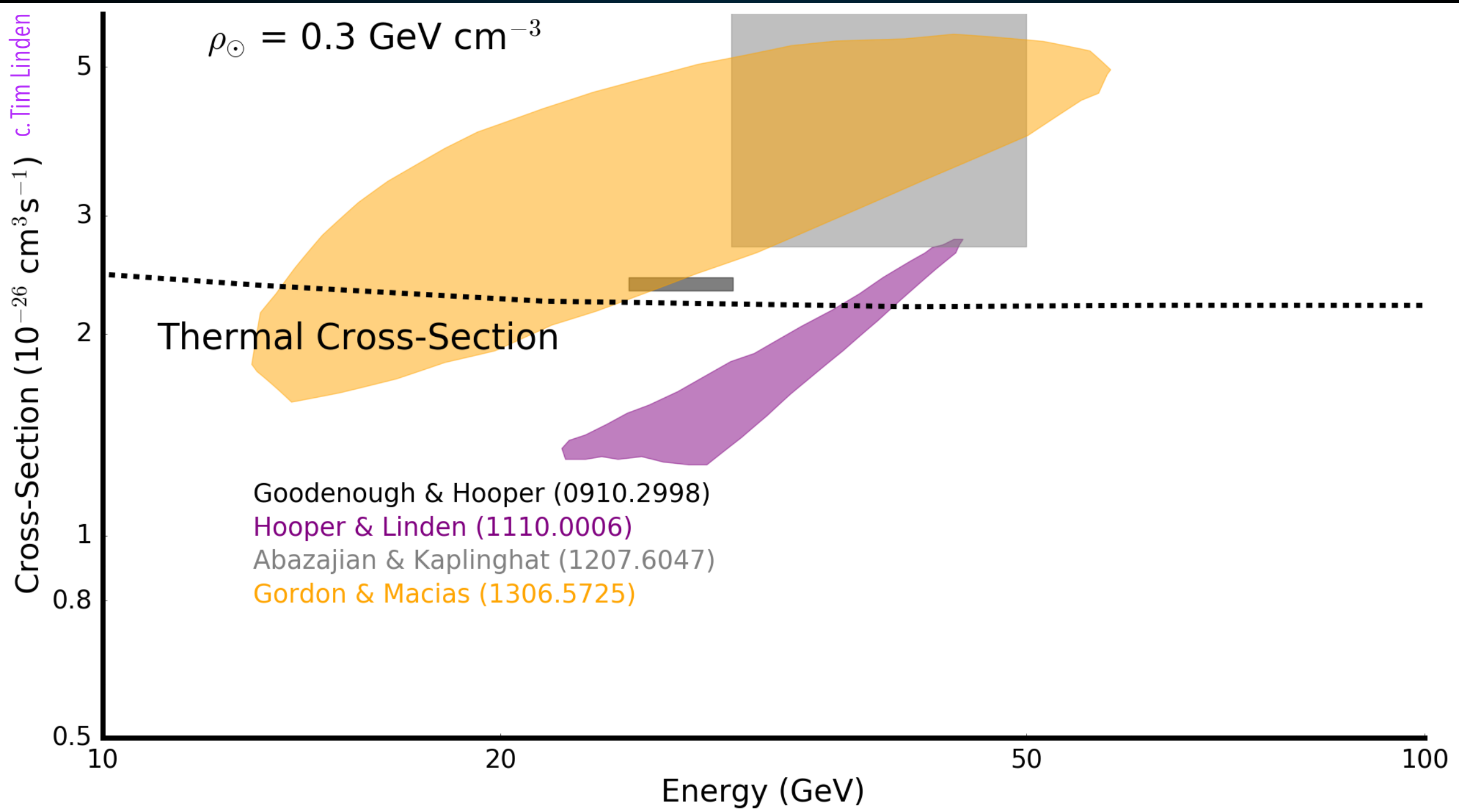


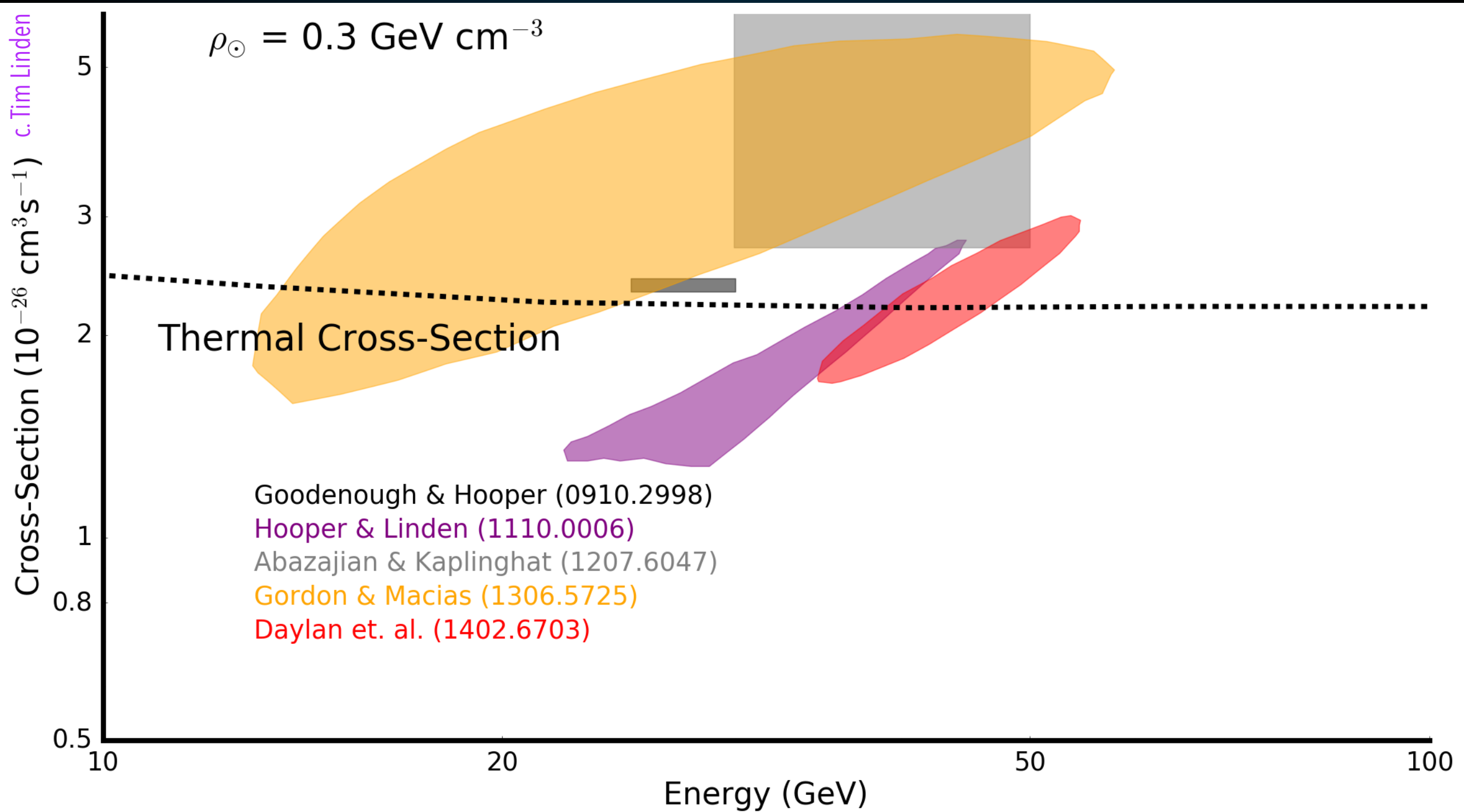


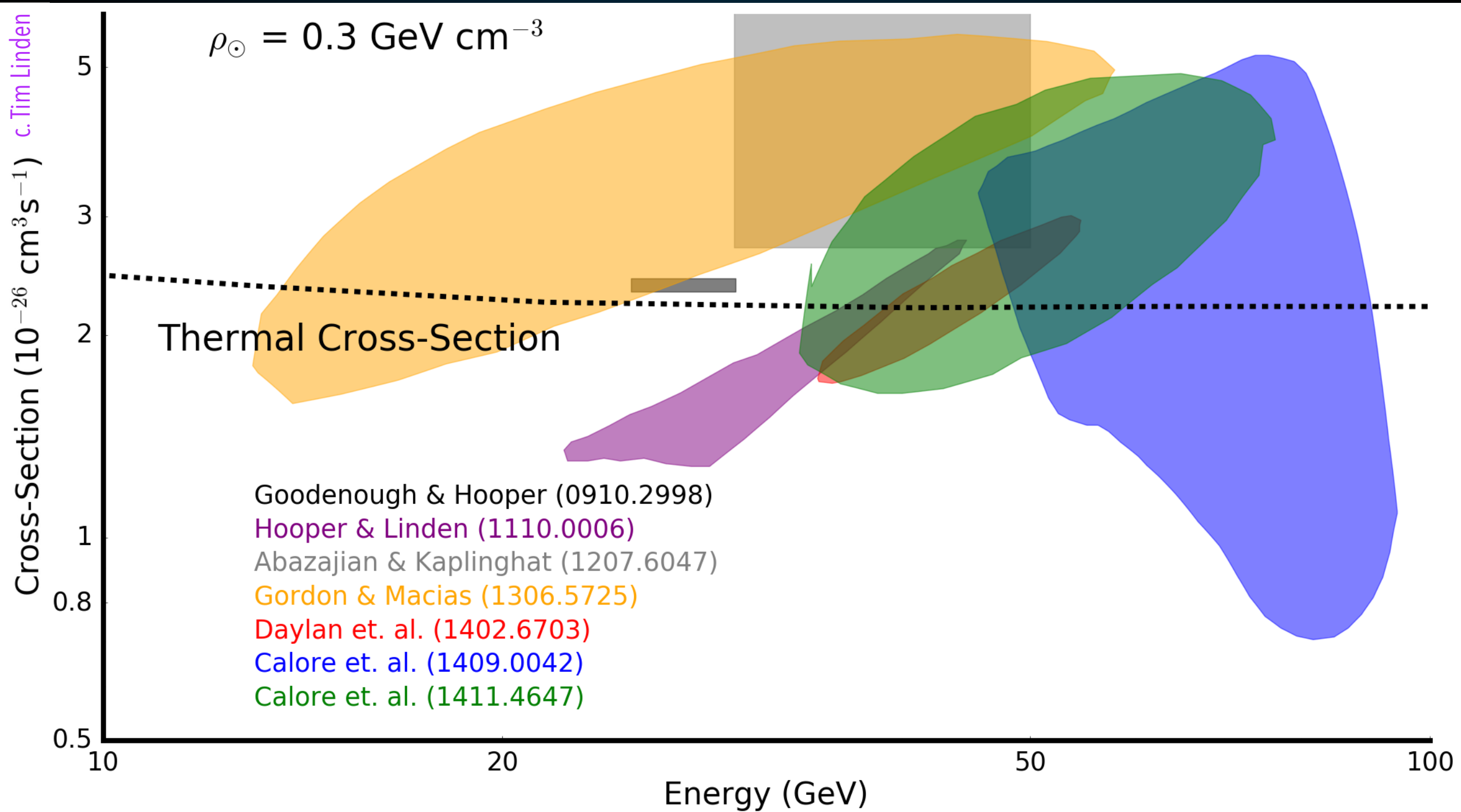






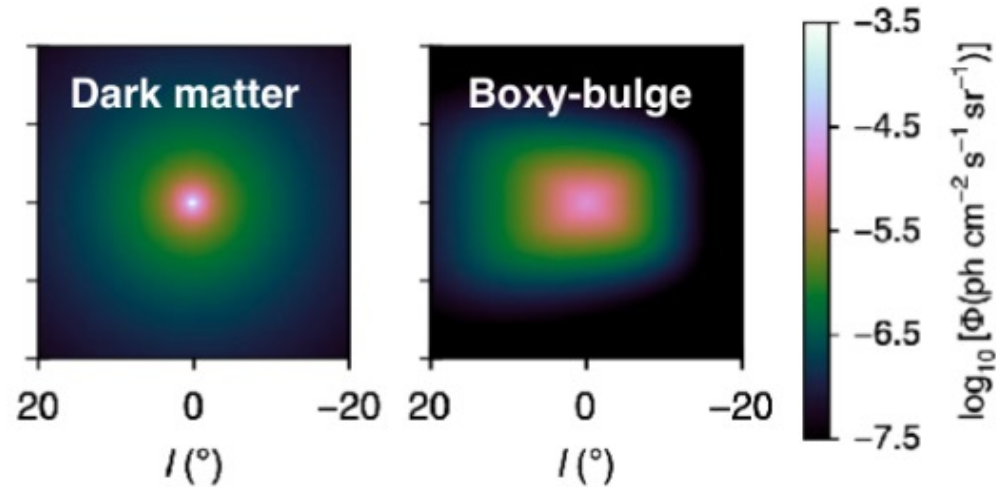






Morphology

c. Silvia Manconi

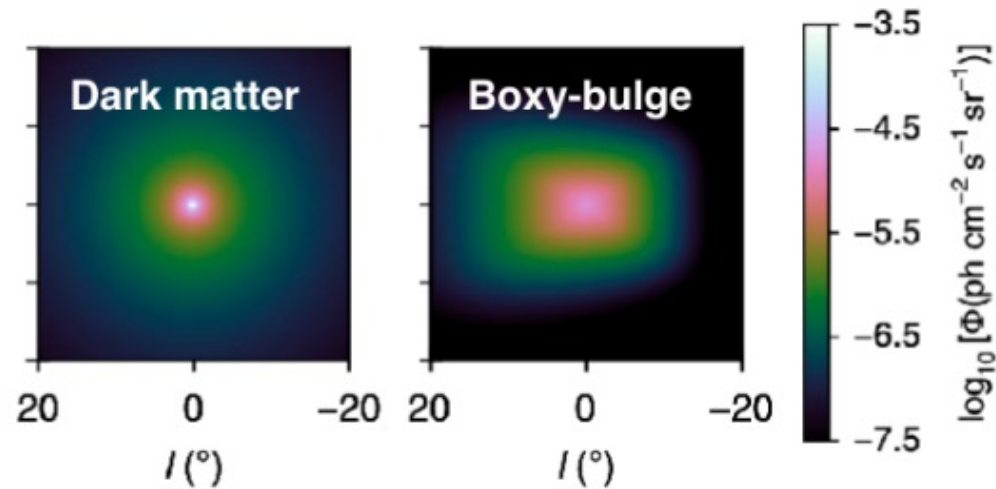


Spherical symmetric (dark matter-like)

- Early works: spherical symmetric, contracted NFW profile $\gamma = 1.26$, but often *not testing* other morphologies
- Recent works: [DiMauro PRD'20,21, Cholis+PRD'22,McDermott+22], ... using astrophysical models and varying many parameters

Morphology

c. Silvia Manconi



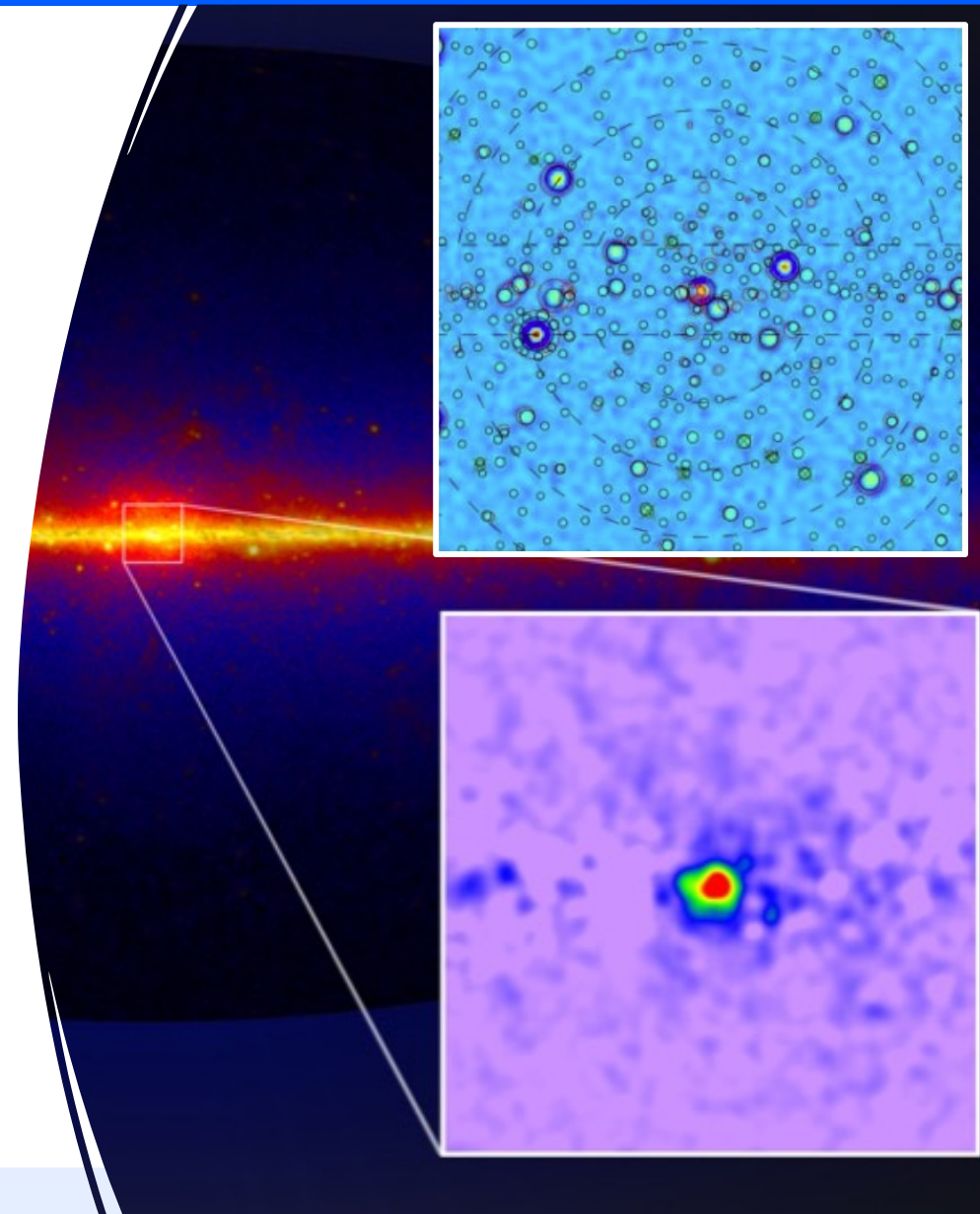
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Stellar (MSP-like)

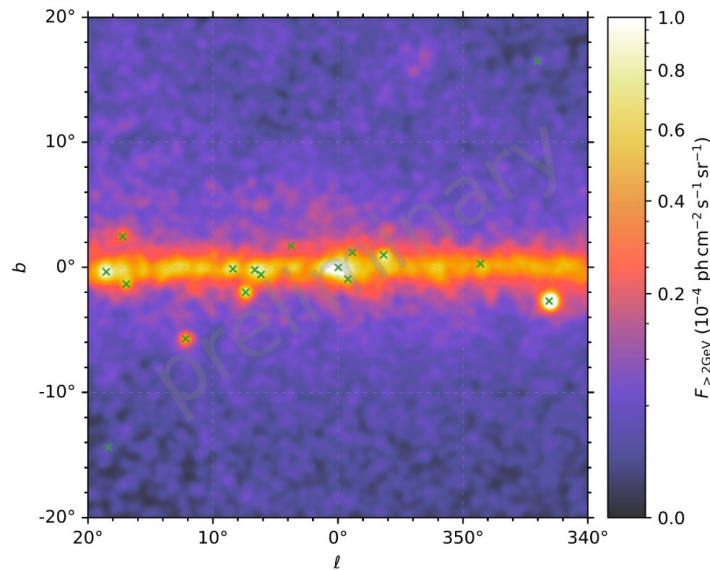
- Stellar distribution of old MSP-like objects in Galactic bulge [Coleman+MNRAS20]
- First evidence: two independent groups [Bartels+NA'18,Macias+NA'18,JCAP'19]
- Subsequent works with even more significance: [Calore,SM PRL'21,Pohl+ApJ22]

GCE ca. 2026: the debate



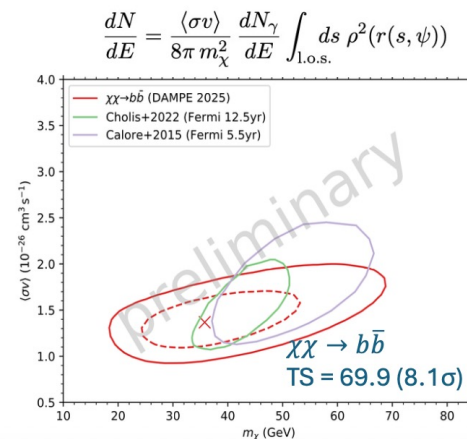
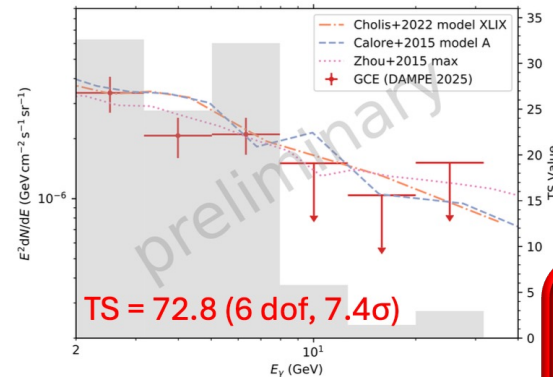
GCE ca. 2026: the debate

Excess is robust. Precise properties are not.

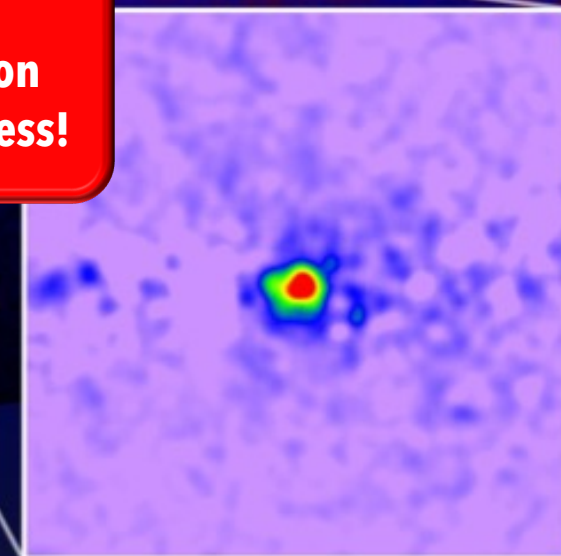
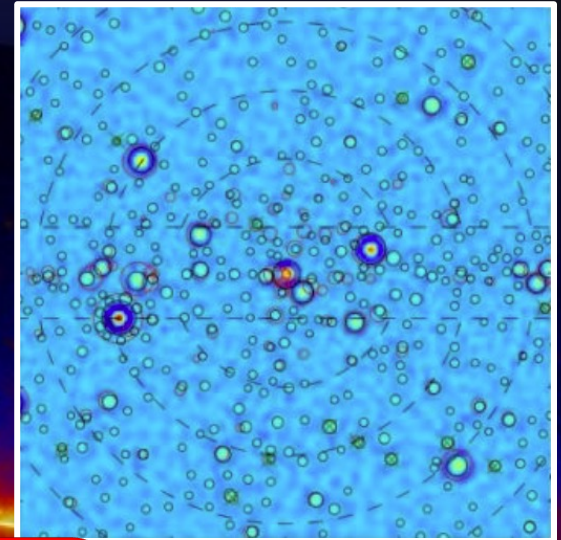


- 7.4 σ with 8.5 yr of data
- If $\chi\chi \rightarrow b\bar{b}$:
 $m_\chi = (36 \pm 9) \text{ GeV}$
 $\langle\sigma v\rangle = (1.37 \pm 0.21) \times 10^{-26} \text{ cm}^3/\text{s}$

C. Perrina [DAMPE]



DAMPE provided the first independent confirmation of the Galactic Center excess!

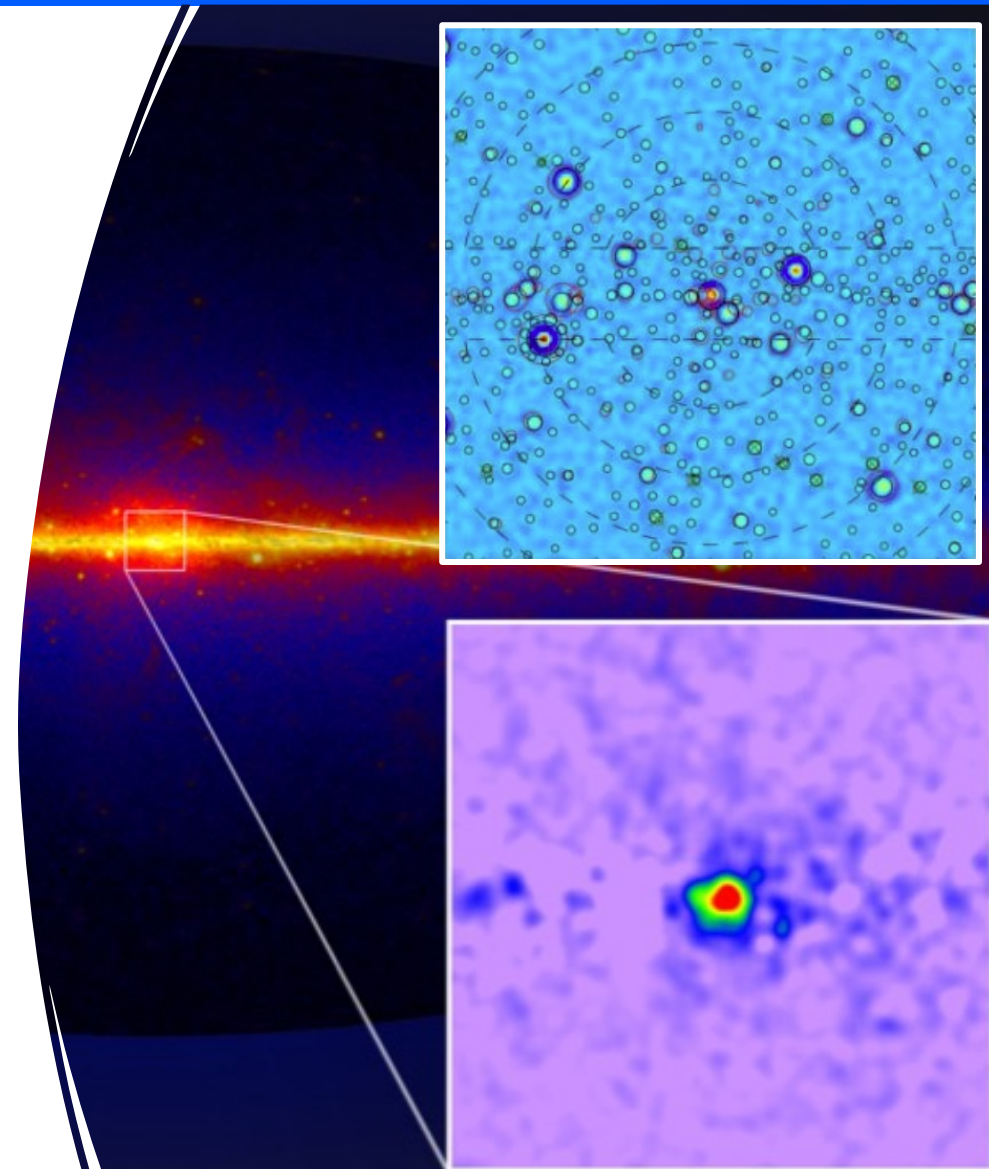


GCE ca. 2026: the debate

(e.g., Bartels+18; Macias+18; Buschmann+20; List+ 20; 21; Leane&Slatyer 20; di Mauro+21;26; Zhong+24; Song+24; Malyshev+25; Ramírez+25; Holst&Hooper 25)

Excess is robust. Precise properties are not.

- **Morphology:** spherical vs bulge-like; central battleground today.
- **Granularity:** Point-source vs smooth emission.
- **Systematics:** Role of diffuse background systematics.
- **Interpretation:** DM vs Millisecond Pulsars (MSPs) vs mixed scenario.



GCE ca. 2026: the debate

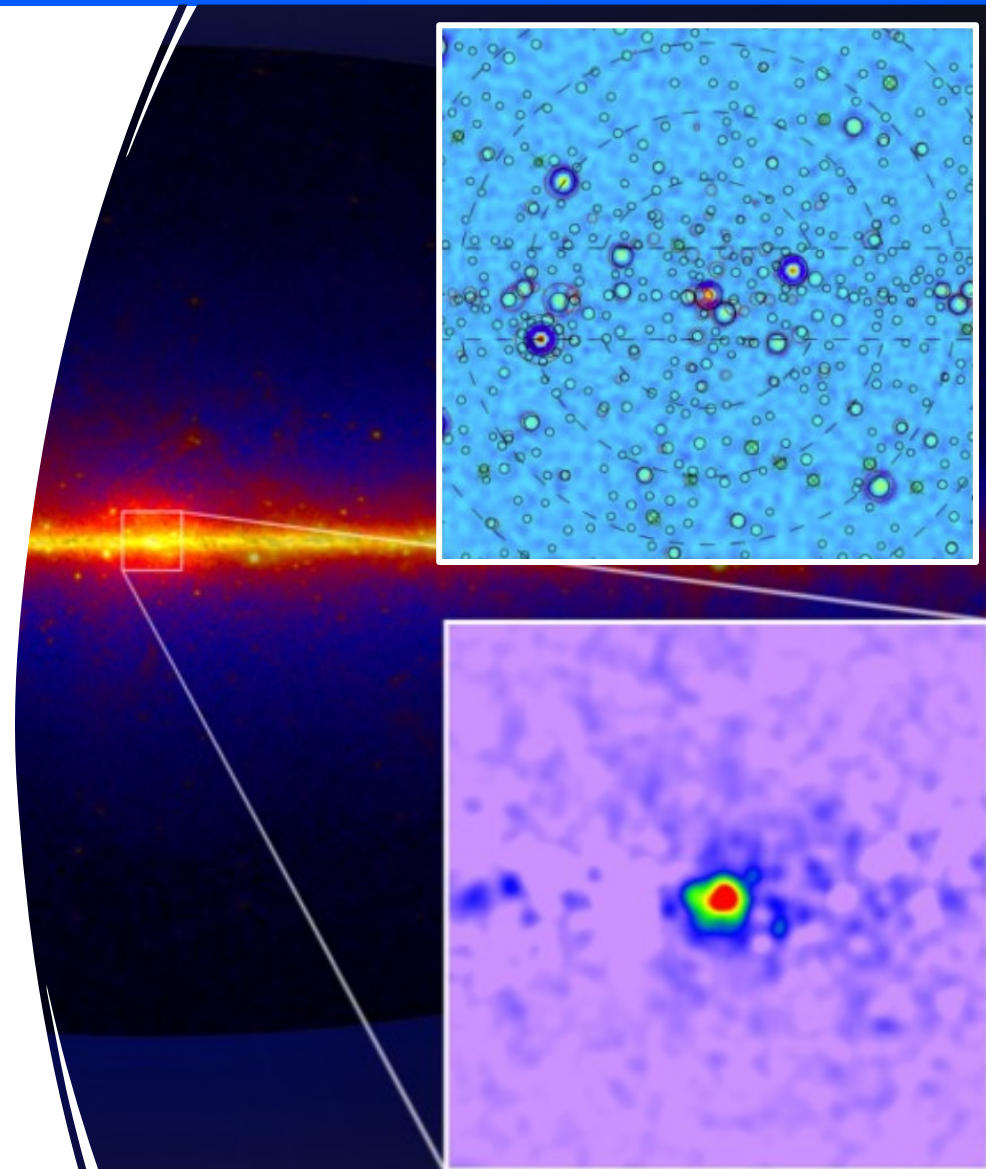
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Dark matter:

- NFW, index $\sim 1.1 - 1.3$.
- 10-100 GeV WIMPs



GCE ca. 2026: the debate

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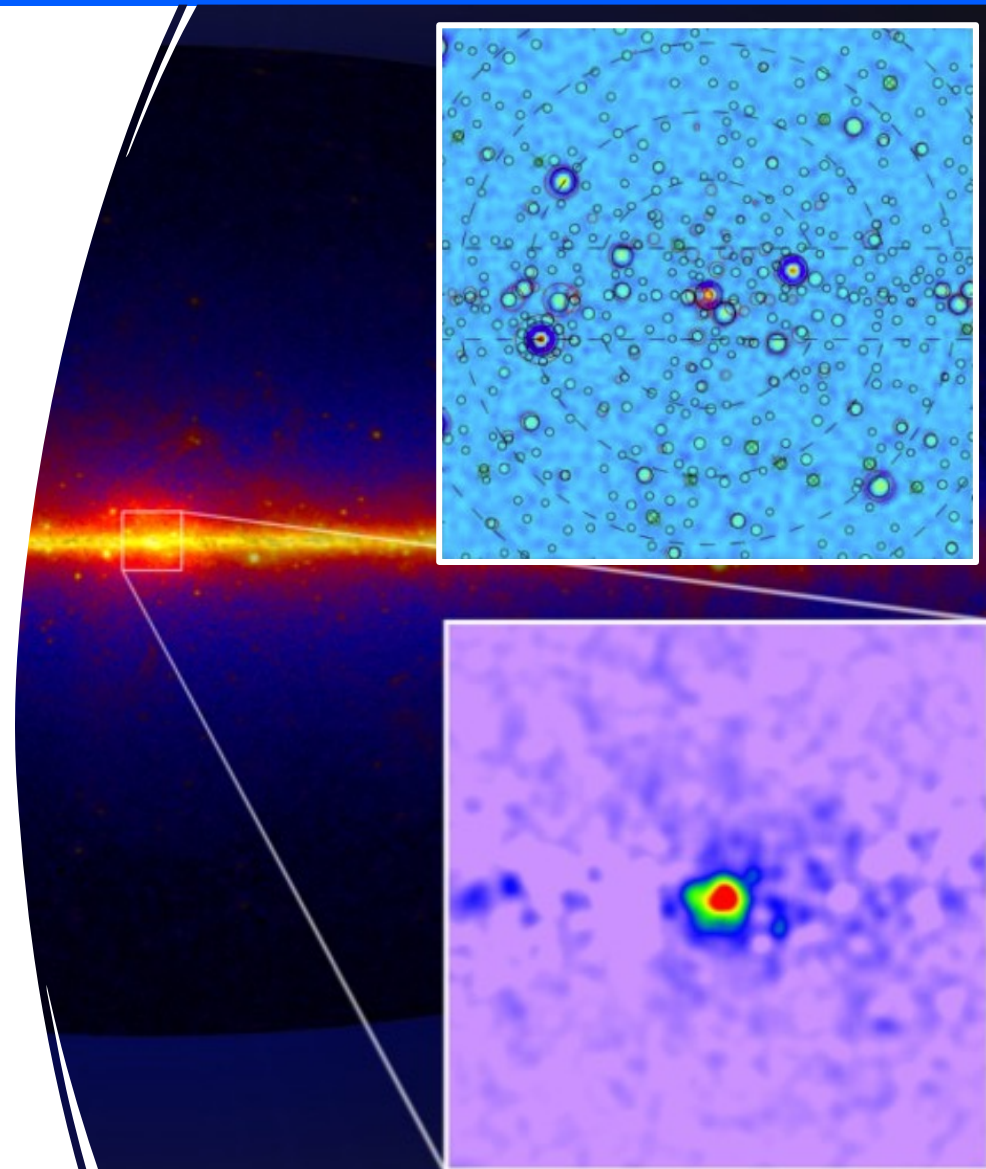
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Dark matter:

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Unresolved MSPs

- Required number may be too large, $O(10^5)$.
- Luminosity function suggests some tension.



GCE ca. 2026: the debate

(e.g., Bartels+18; Macias+18; Buschmann+20; List+ 20; 21; Leane&Slatyer 20; di Mauro+21;26; Zhong+24; Song+24; Malyshev+25; Ramírez+25; Holst&Hooper 25)

Excess is robust. Precise properties are not.

- **Morphology:** spherical vs bulge-like; central battleground today.
- **Granularity:** Point-source vs smooth emission.
- **Systematics:** Role of diffuse background systematics.
- **Interpretation:** DM vs Millisecond Pulsars (MSPs) vs mixed scenario.

Dark matter:

- NFW, index $\sim 1.1 - 1.3$.
- 10-100 GeV WIMPs

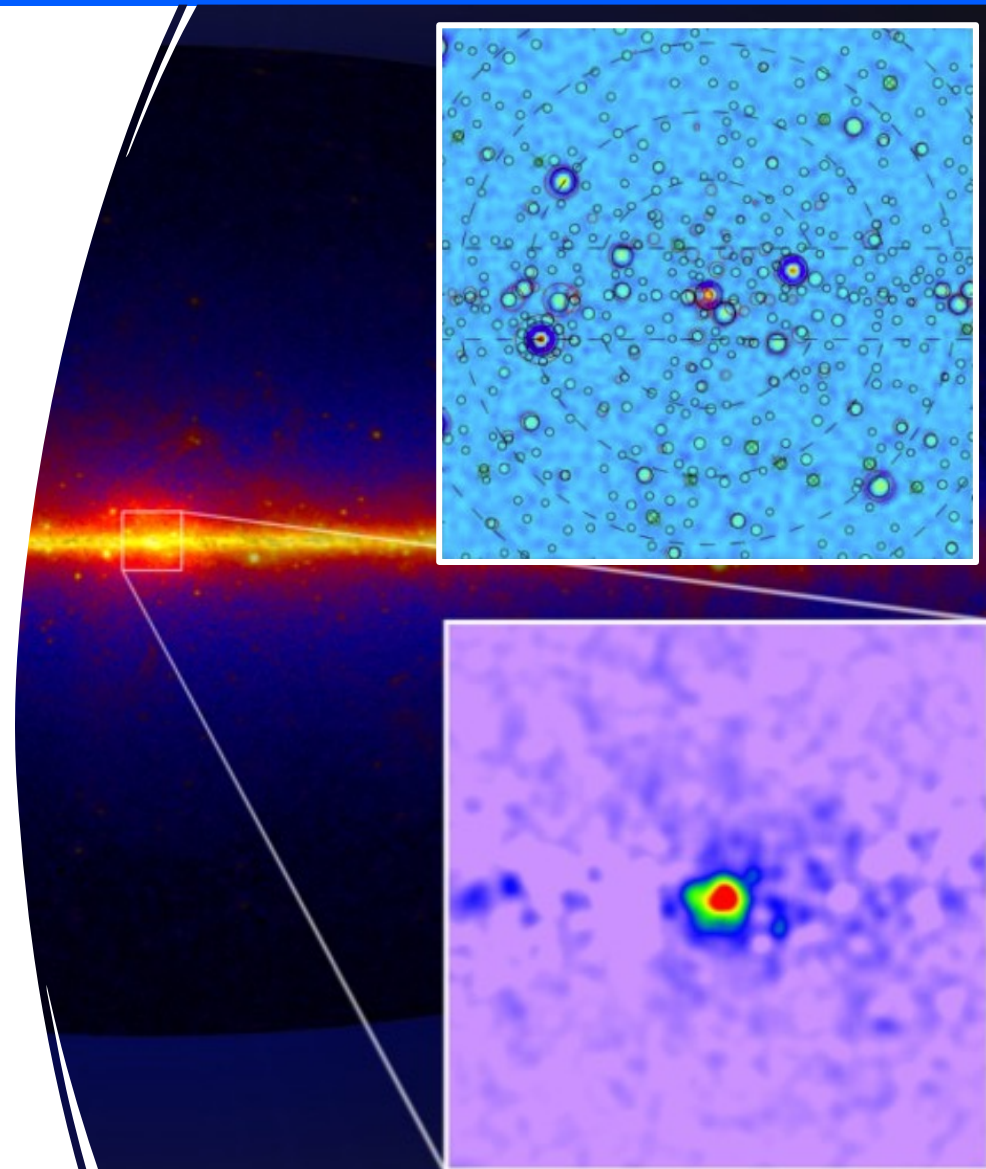
Unresolved MSPs

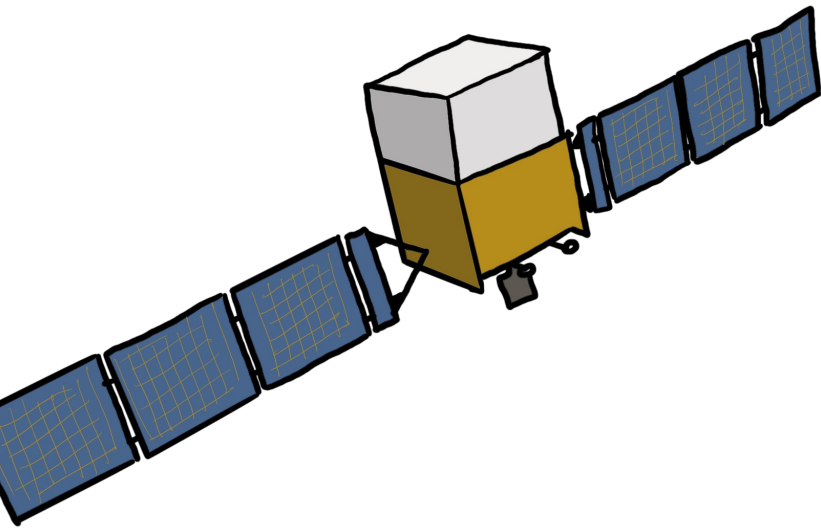
- Required number may be too large, $O(10^5)$.
- Luminosity function suggests some tension.

Diffuse models are not representative of the data

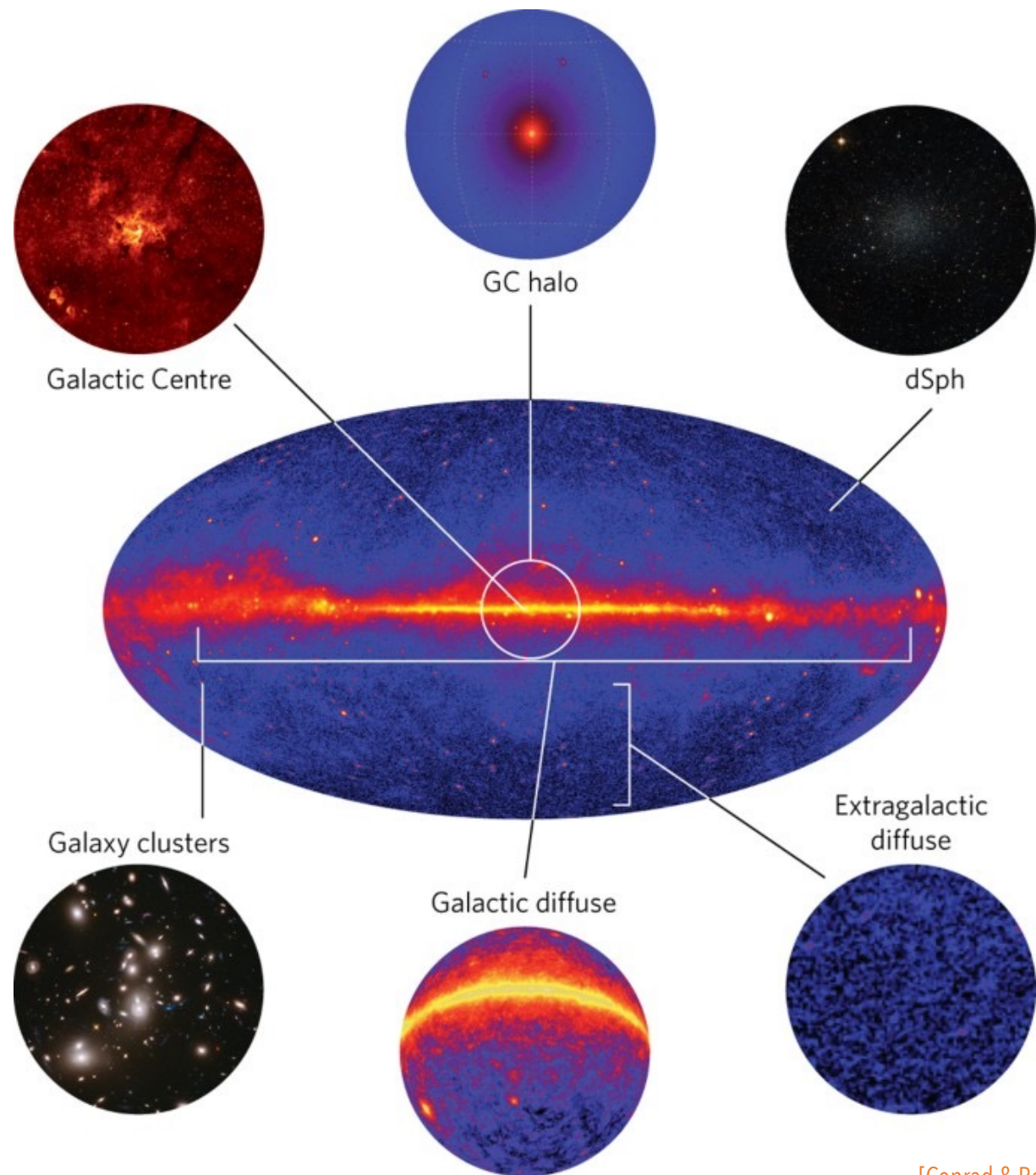
Confirming pulsars: future detections of radio emission by MeerKat and SKA

Confirming dark matter: check for signals elsewhere

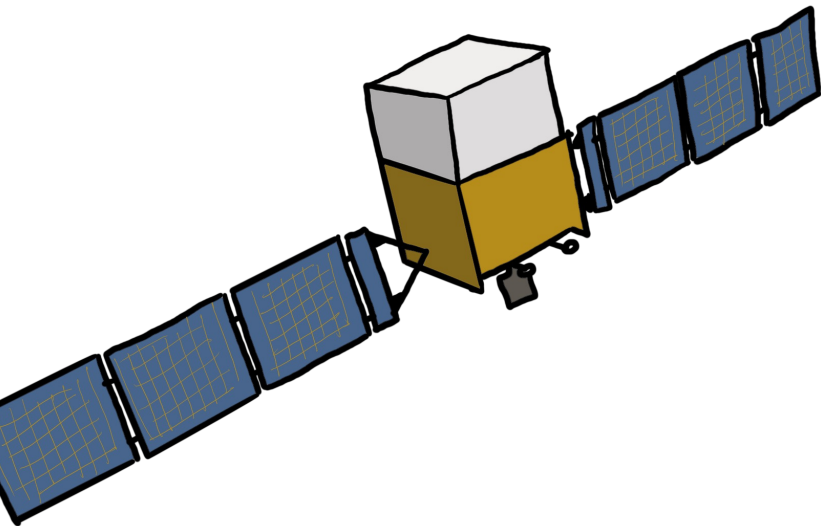




DM targets

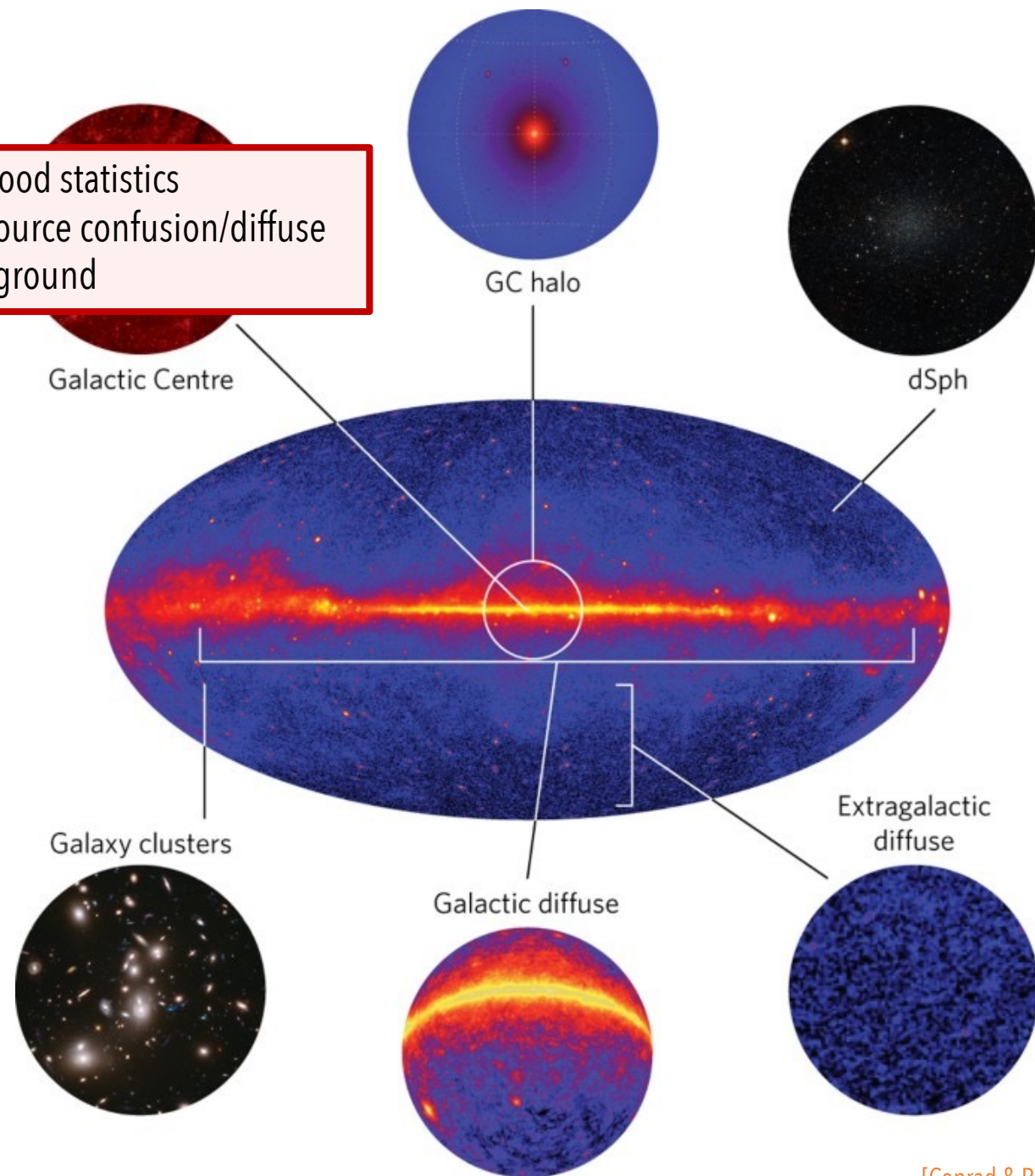


Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.



DM targets

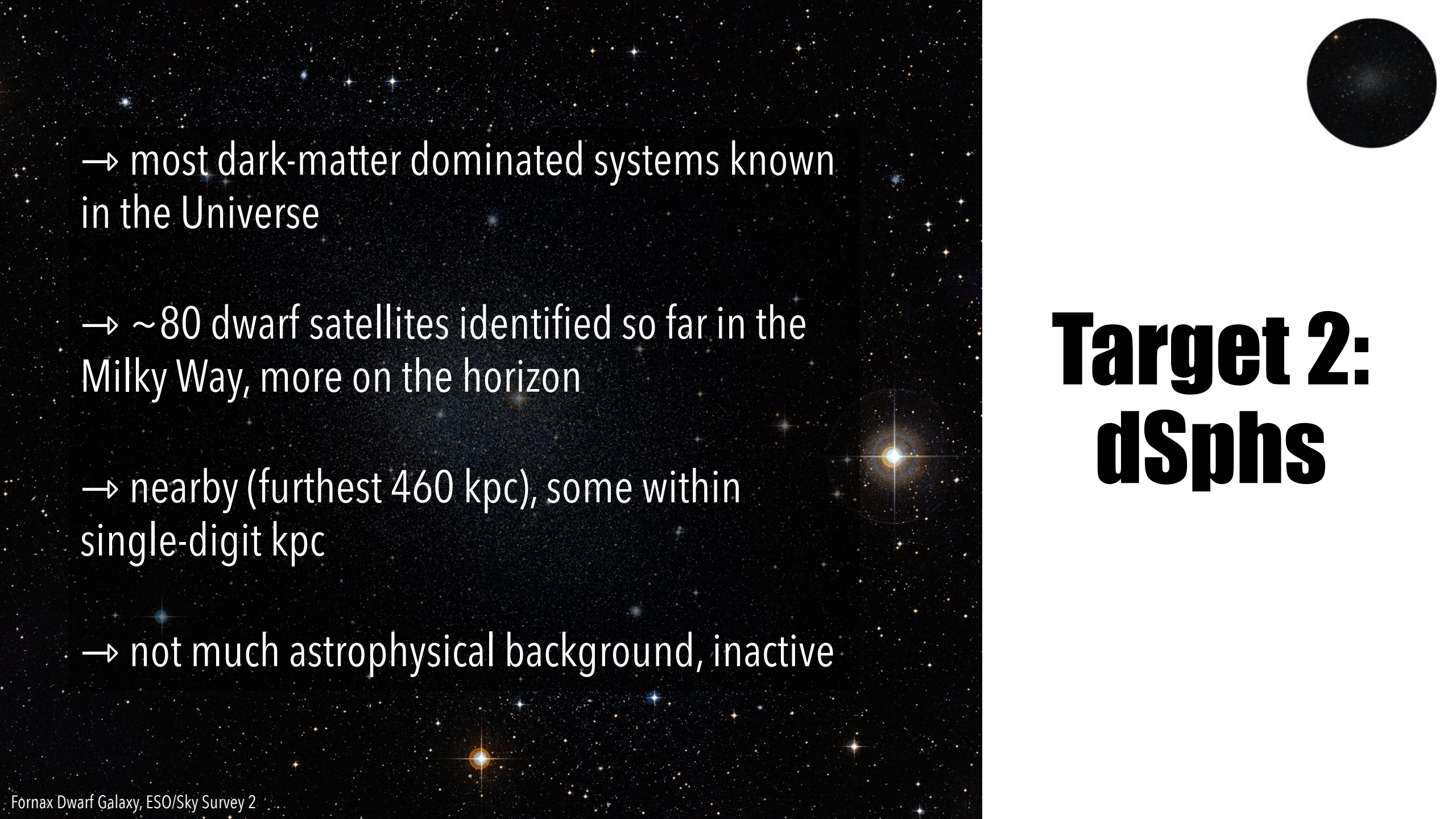
- ✓ Good statistics
- ✗ Source confusion/diffuse background



Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.



Target 2: dSphs



→ most dark-matter dominated systems known in the Universe

→ ~80 dwarf satellites identified so far in the Milky Way, more on the horizon

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

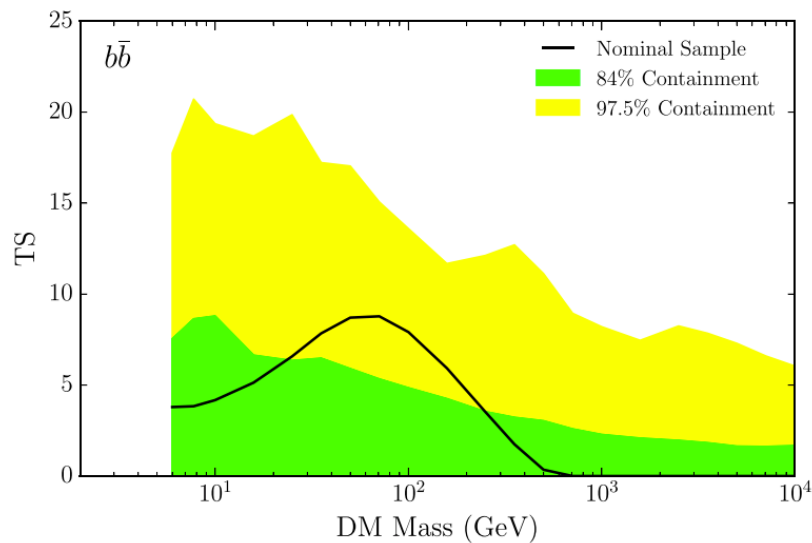
→ not much astrophysical background, inactive



Target 2: dSphs

Prolonged exposure (Fermi-LAT)

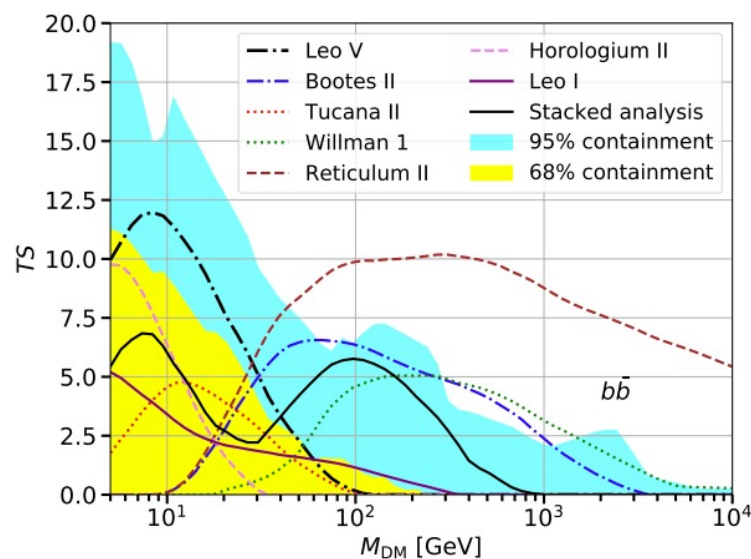
6 years



$< 2\sigma$

[Albert+ '17]

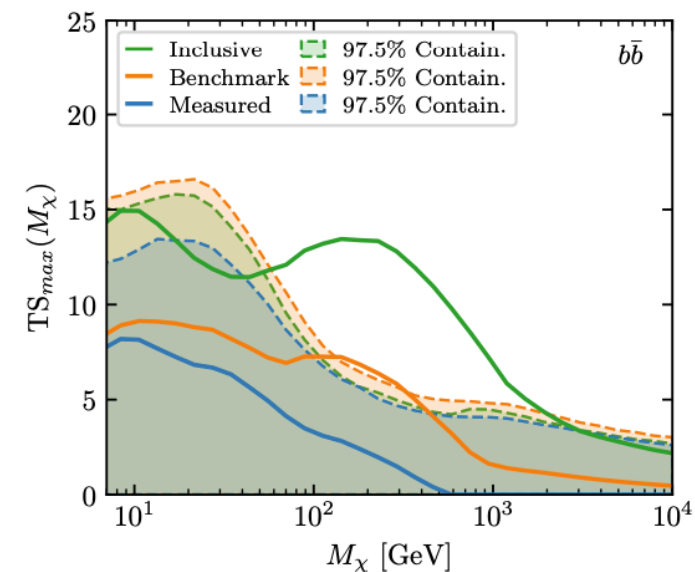
11 years



$\approx 2\sigma$

[Di Mauro & Winkler '21]

14 years



$\approx 2\sigma$

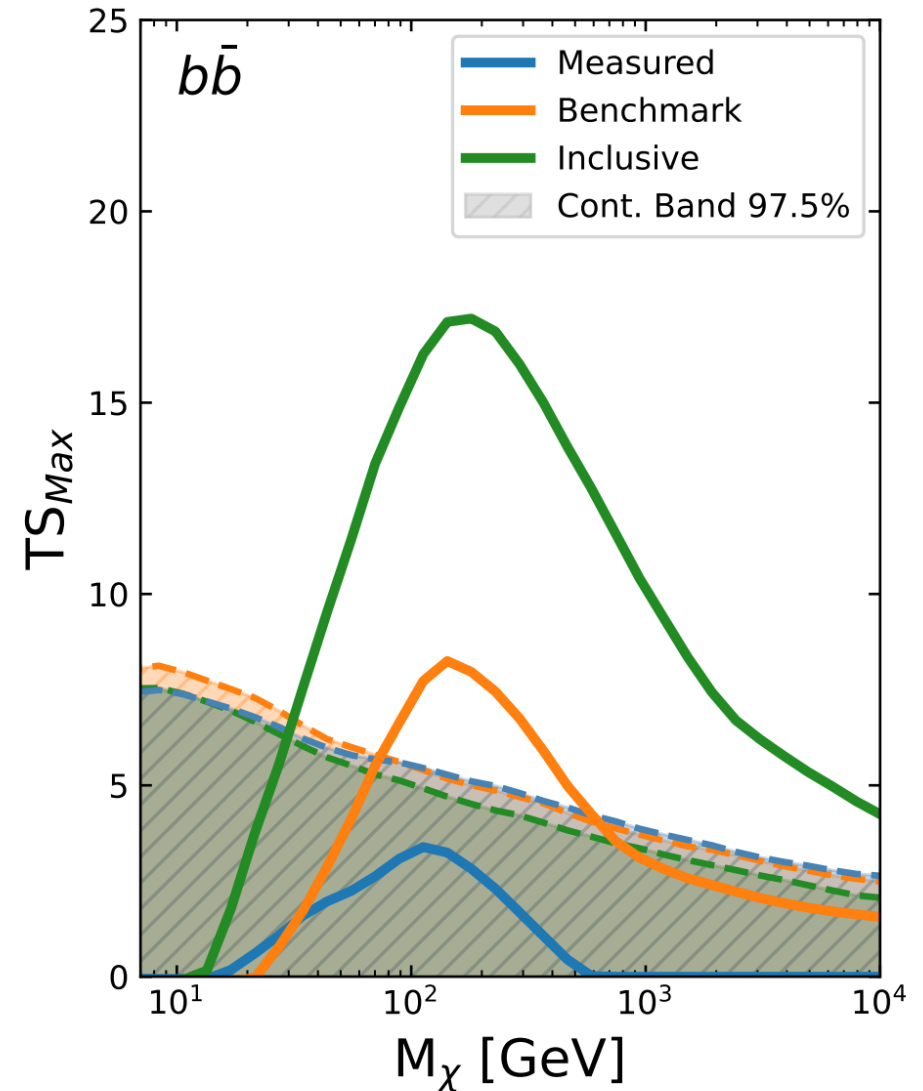
[McDaniel+ '24]

Shaded regions: blank-field analysis

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

Combined dSph Analyses: the latest

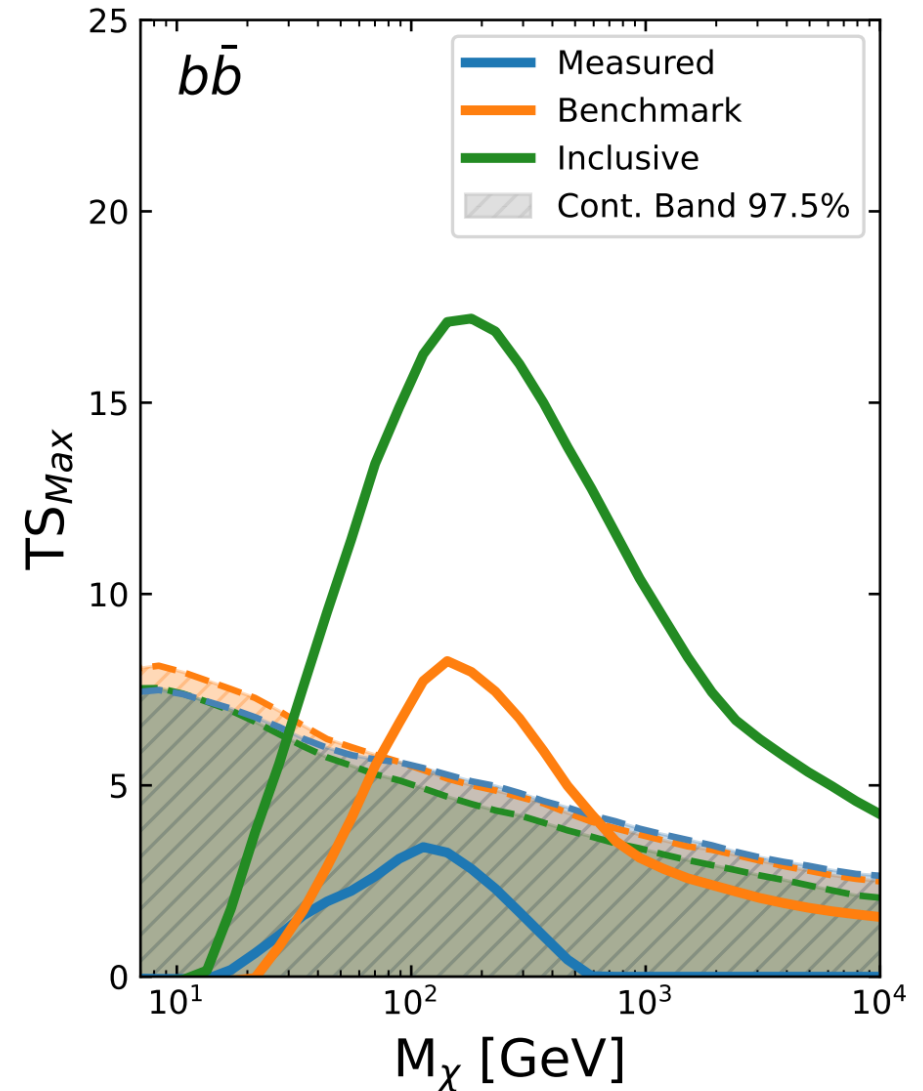
- 16 years of data
- Methodological changes to McDaniel+ '24:
 - Stricter event selection: SOURCEVETO
 - Energy threshold 2 GeV
 - 4FGL-DR4
 - **Adoptive ROI modeling (TS + PS maps)**
 - **Null model: 6500 blank sky fields**
 - DM spectra: CosmiXs instead of PPPC4DMID



[Circiello et al. '26]

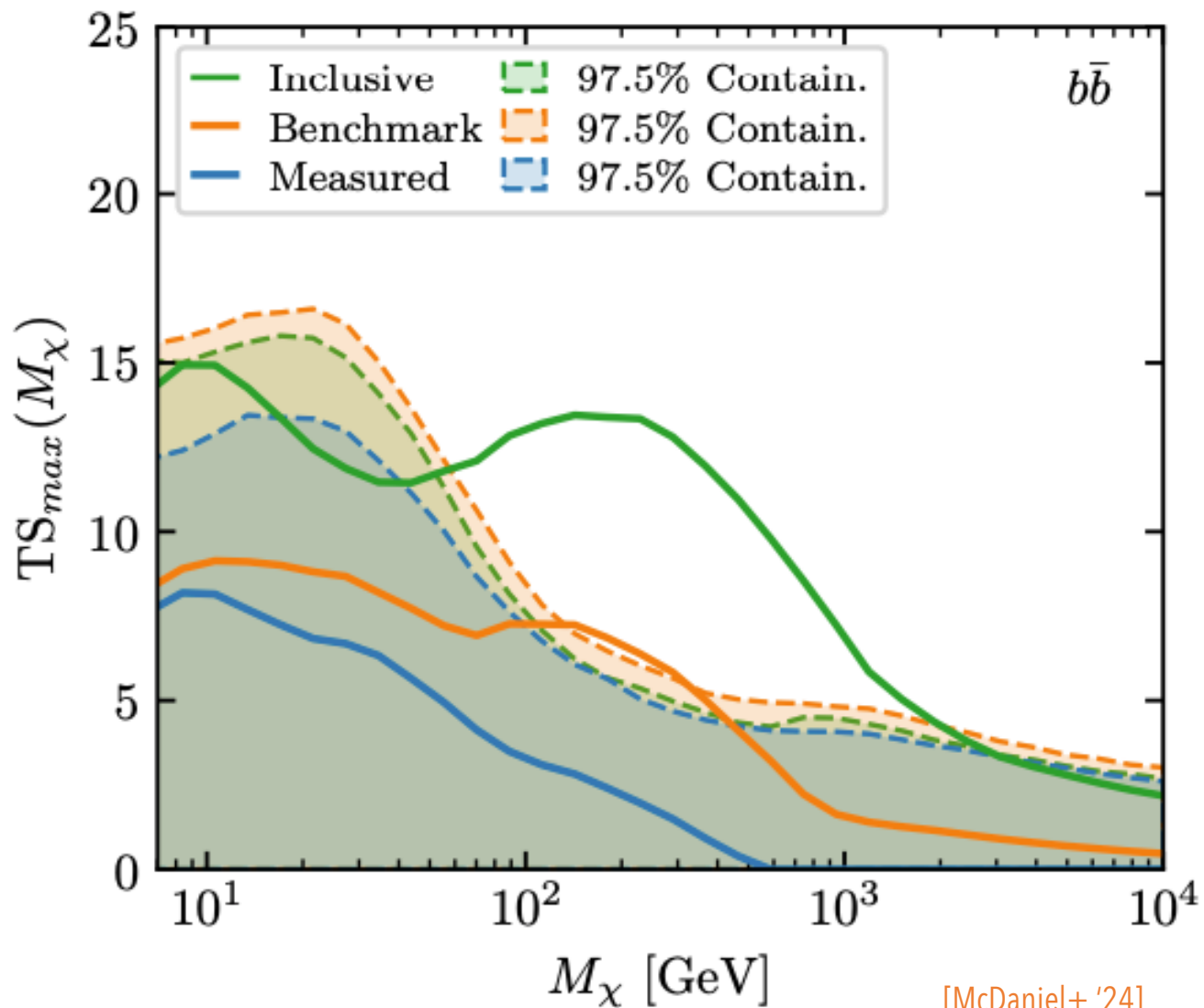
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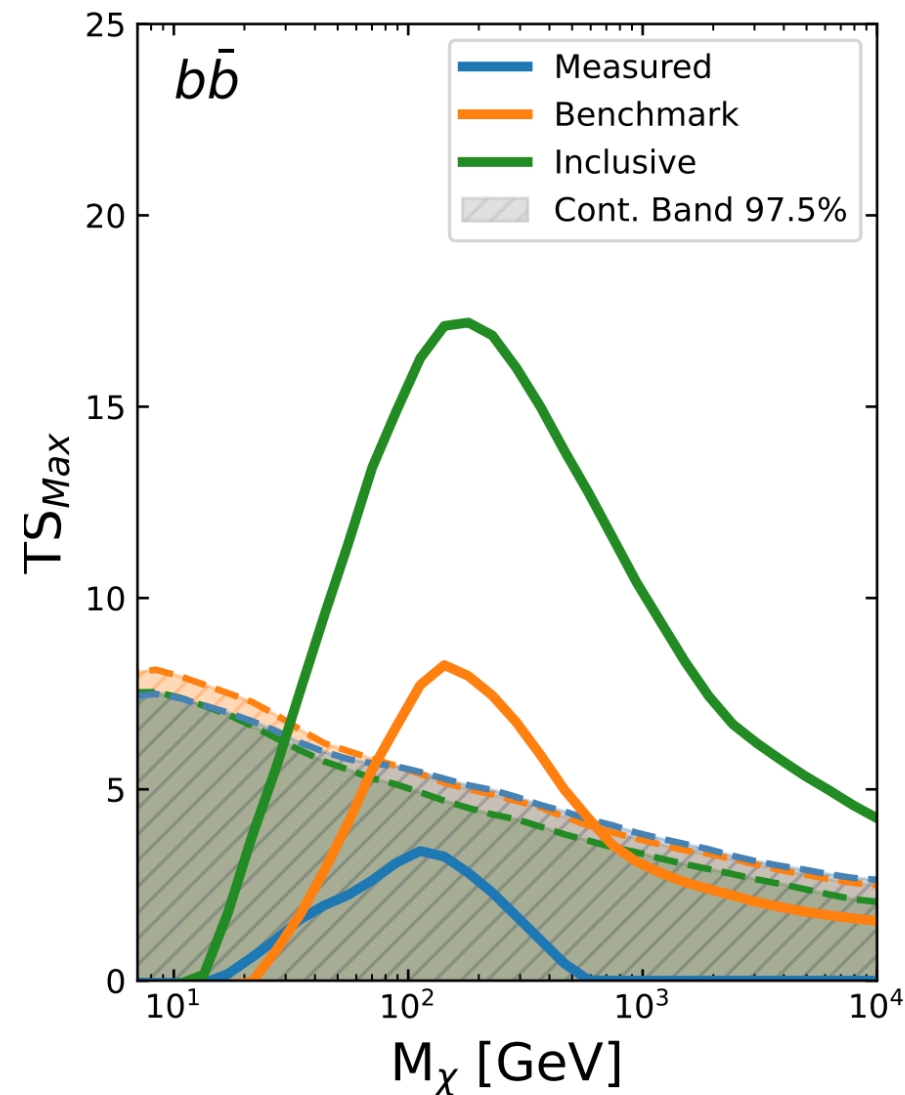


[Circiello et al. '26]

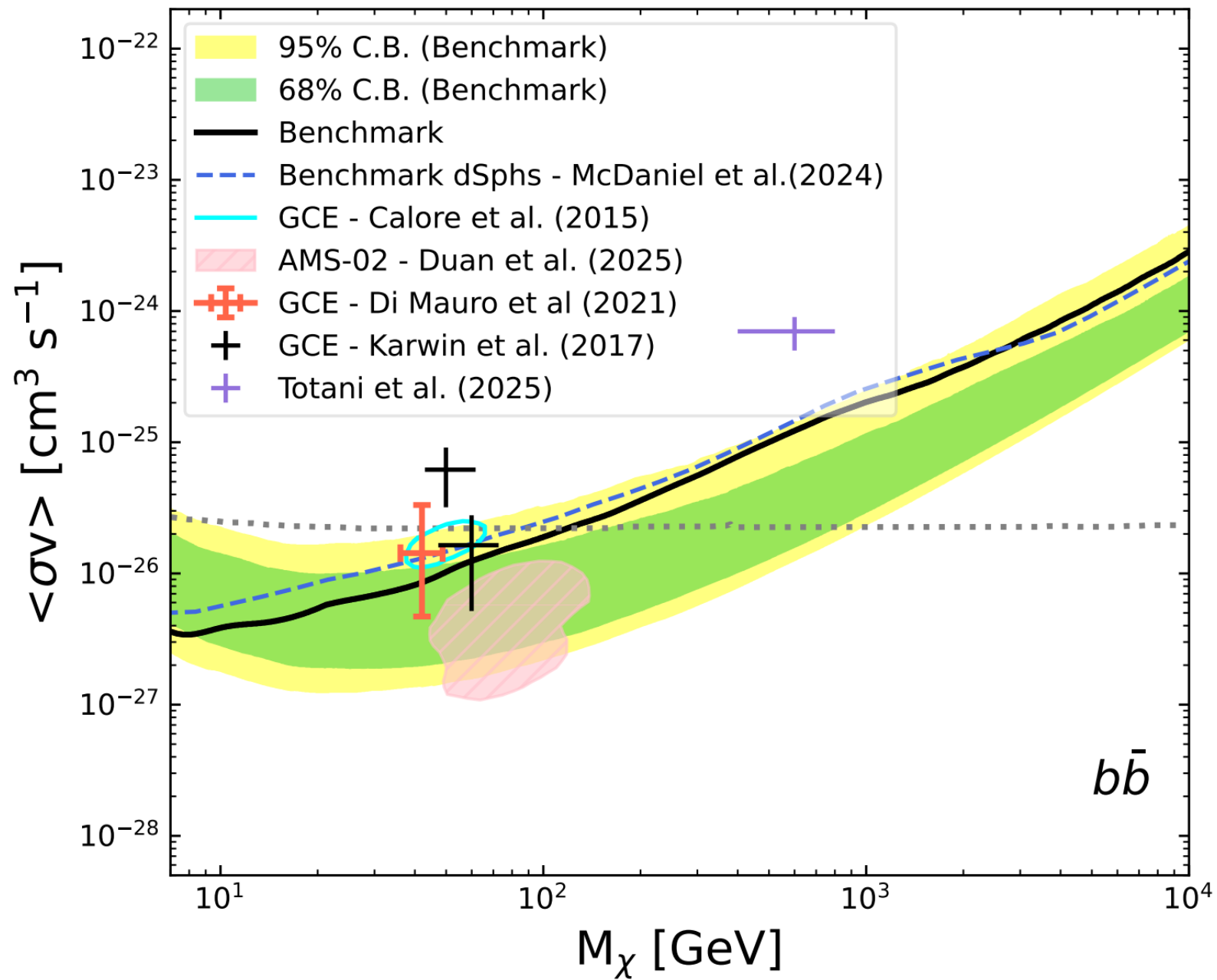
Combined dSph Analyses: the latest



[McDaniel+ '24]



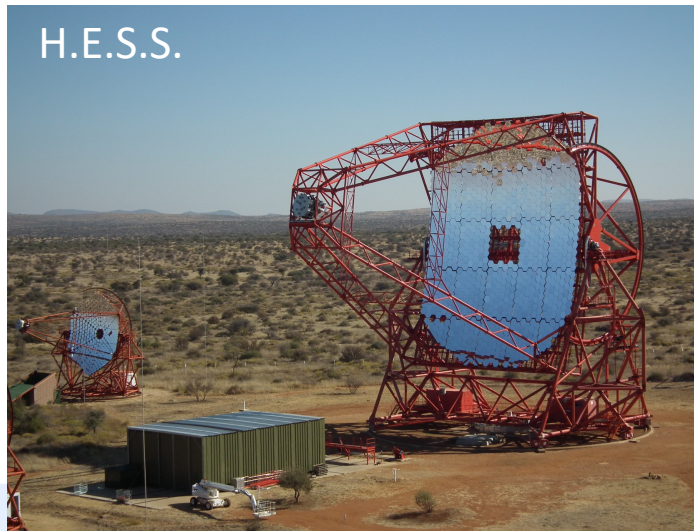
[Circiello et al. '26]



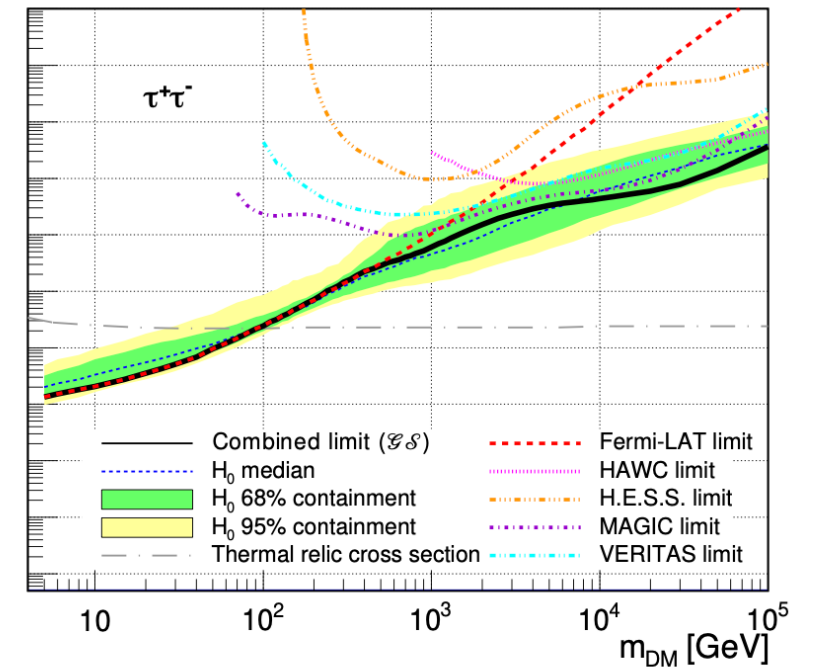
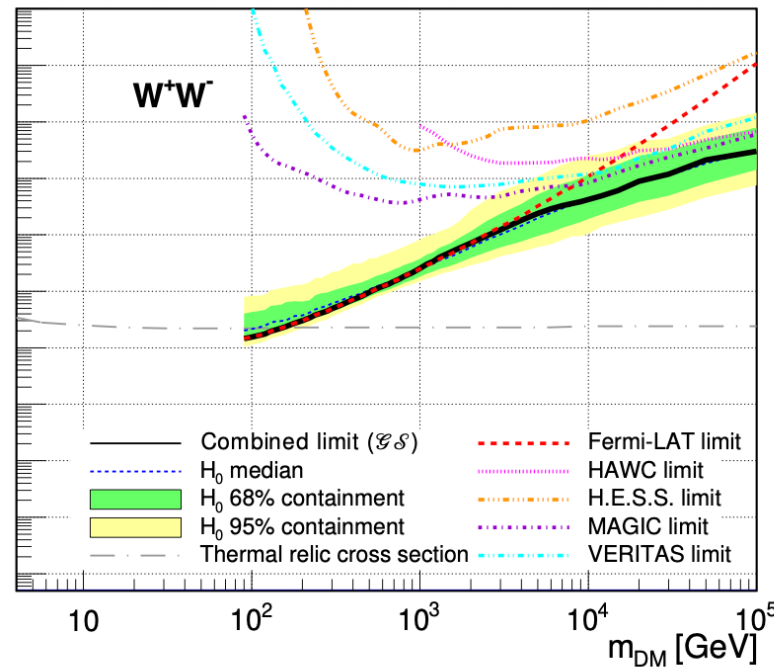
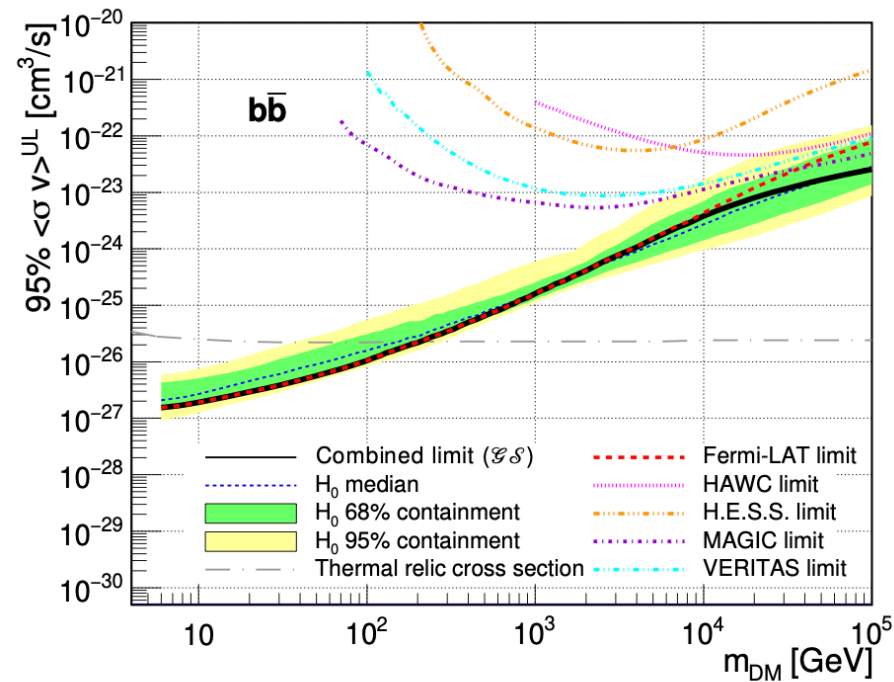


GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)

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

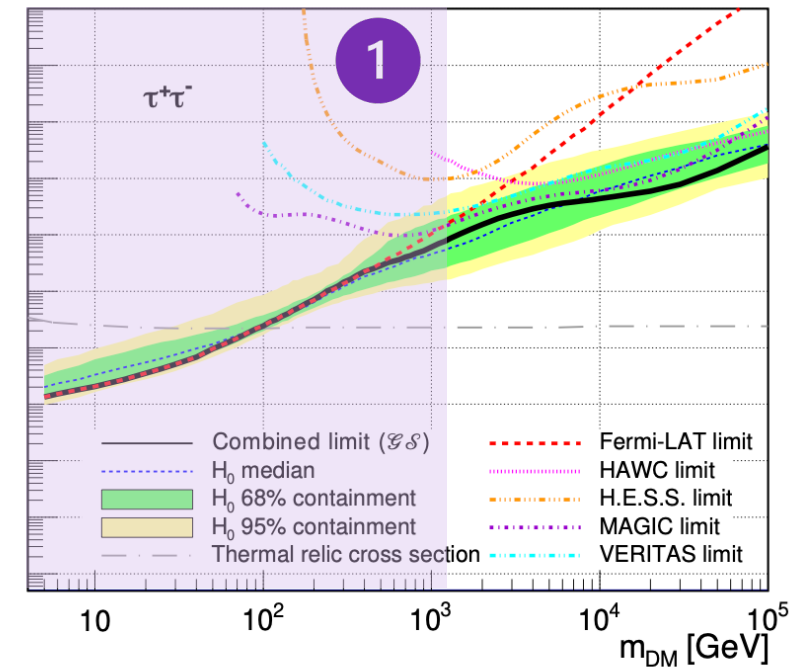
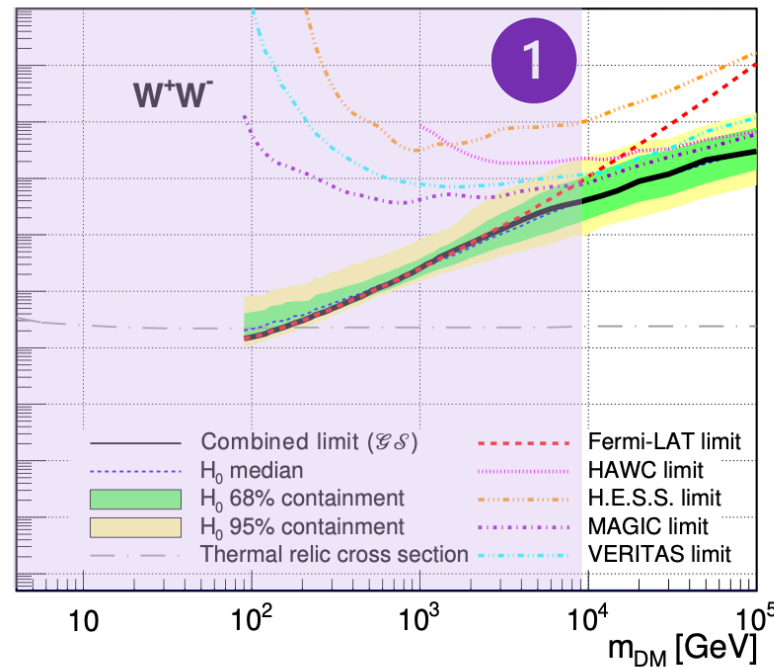
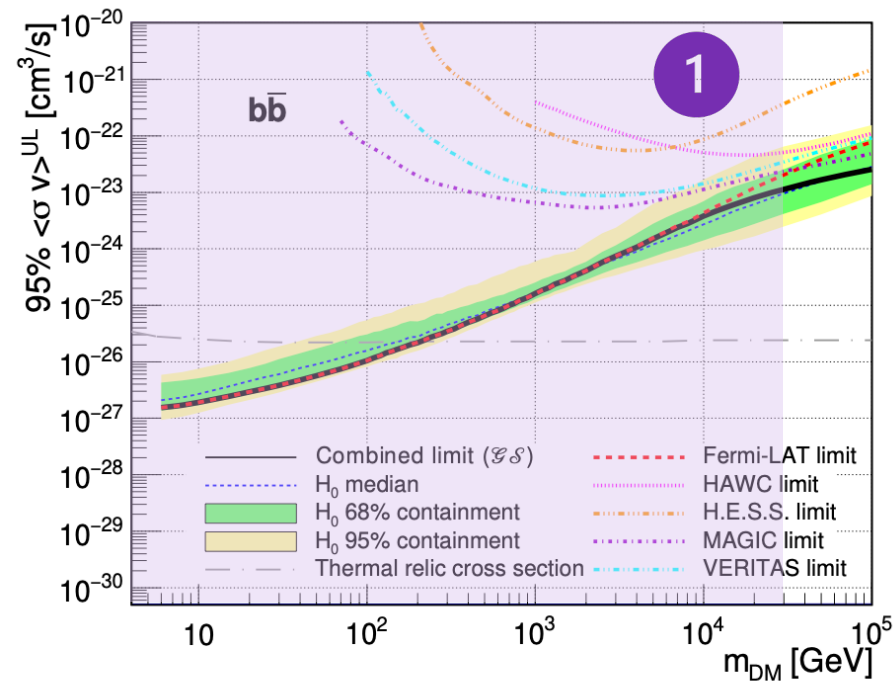


GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)



*[LAT, HAWC, H.E.S.S., MAGIC, & VERITAS, incl. **MC**, JCAP03(2026)035]

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

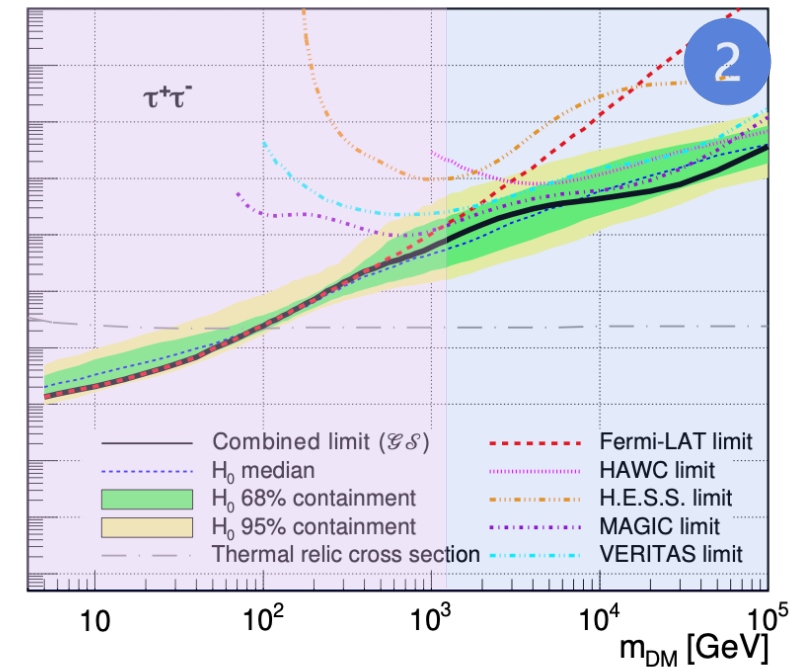
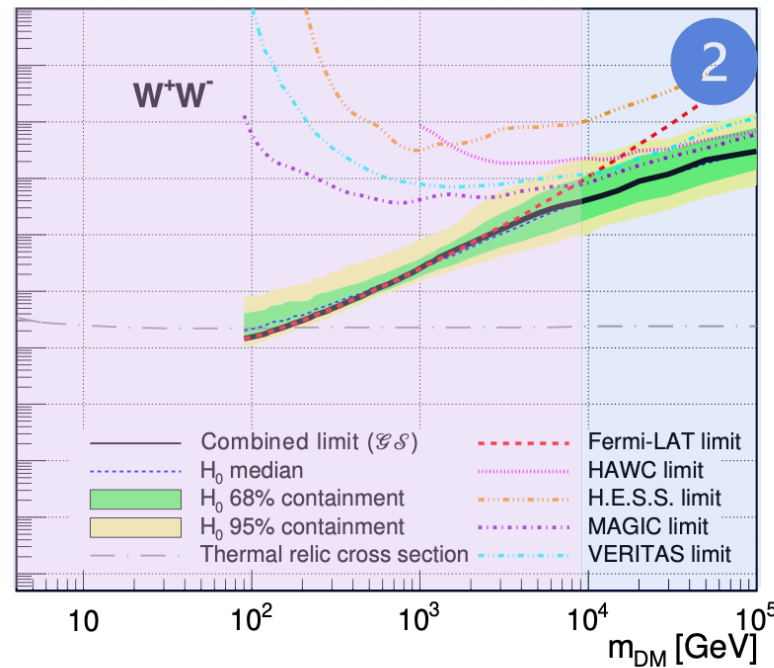
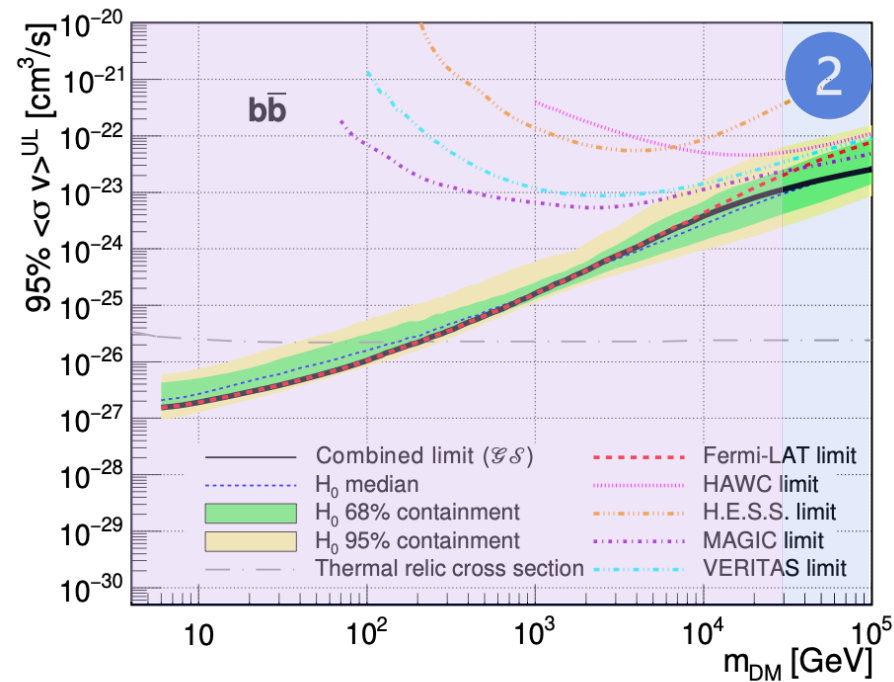


1

Dominated by *Fermi* LAT

*[LAT, HAWC, H.E.S.S., MAGIC, & VERITAS, incl. **MC**, JCAP03(2026)035]

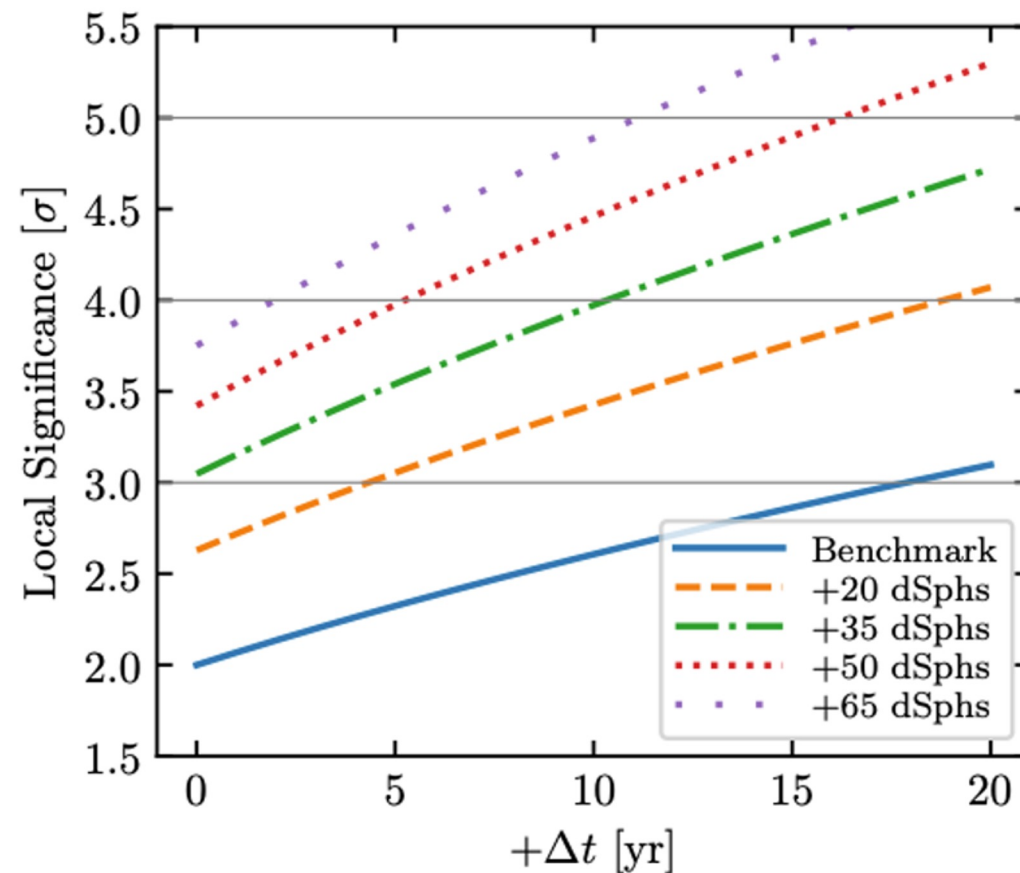
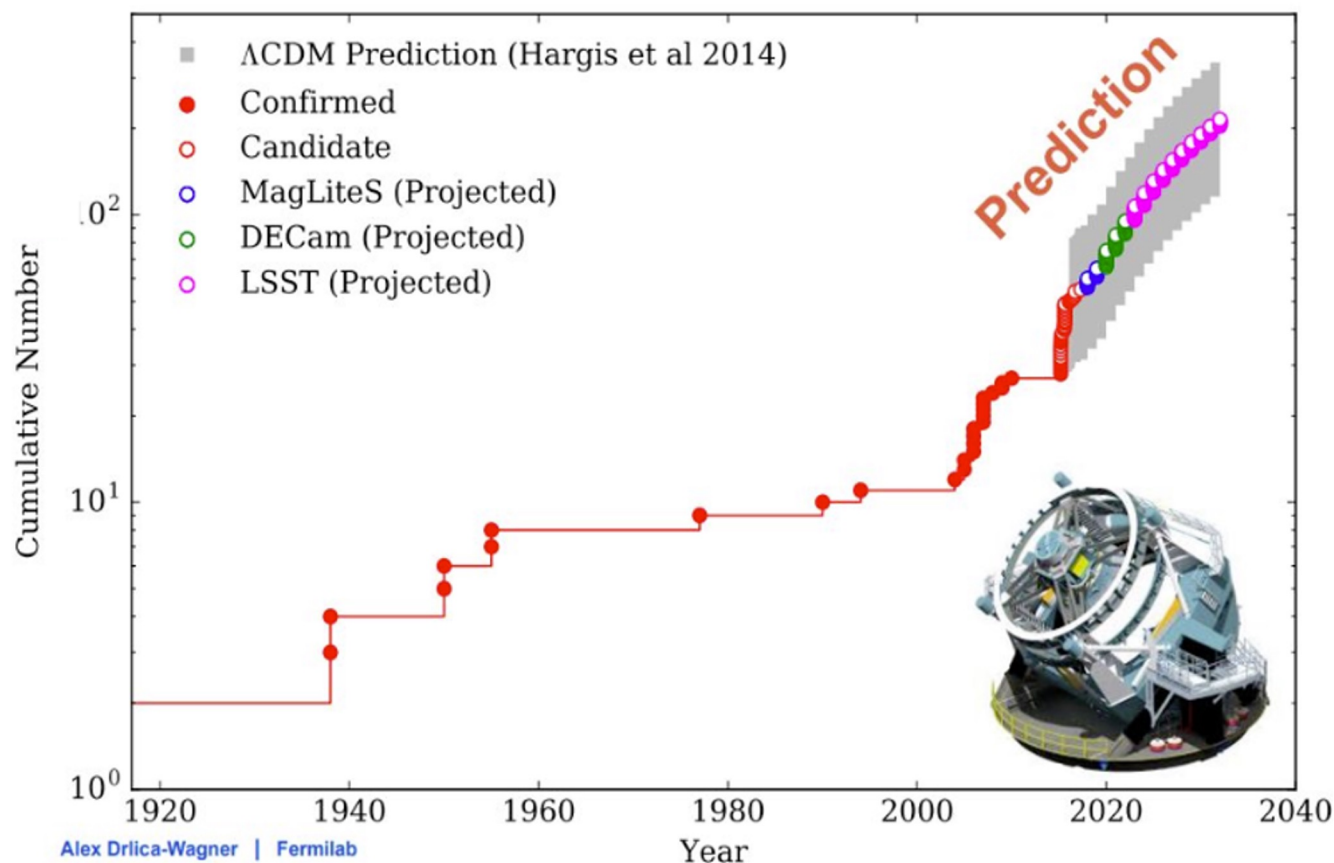
GloryDuck (LAT, HAWC, HESS, MAGIC, VERITAS)



HAWC, HESS, MAGIC, VERITAS take over

2

*[LAT, HAWC, H.E.S.S., MAGIC, & VERITAS, incl. **MC**, JCAP03(2026)035]



[Fermi-LAT Collaboration '24]

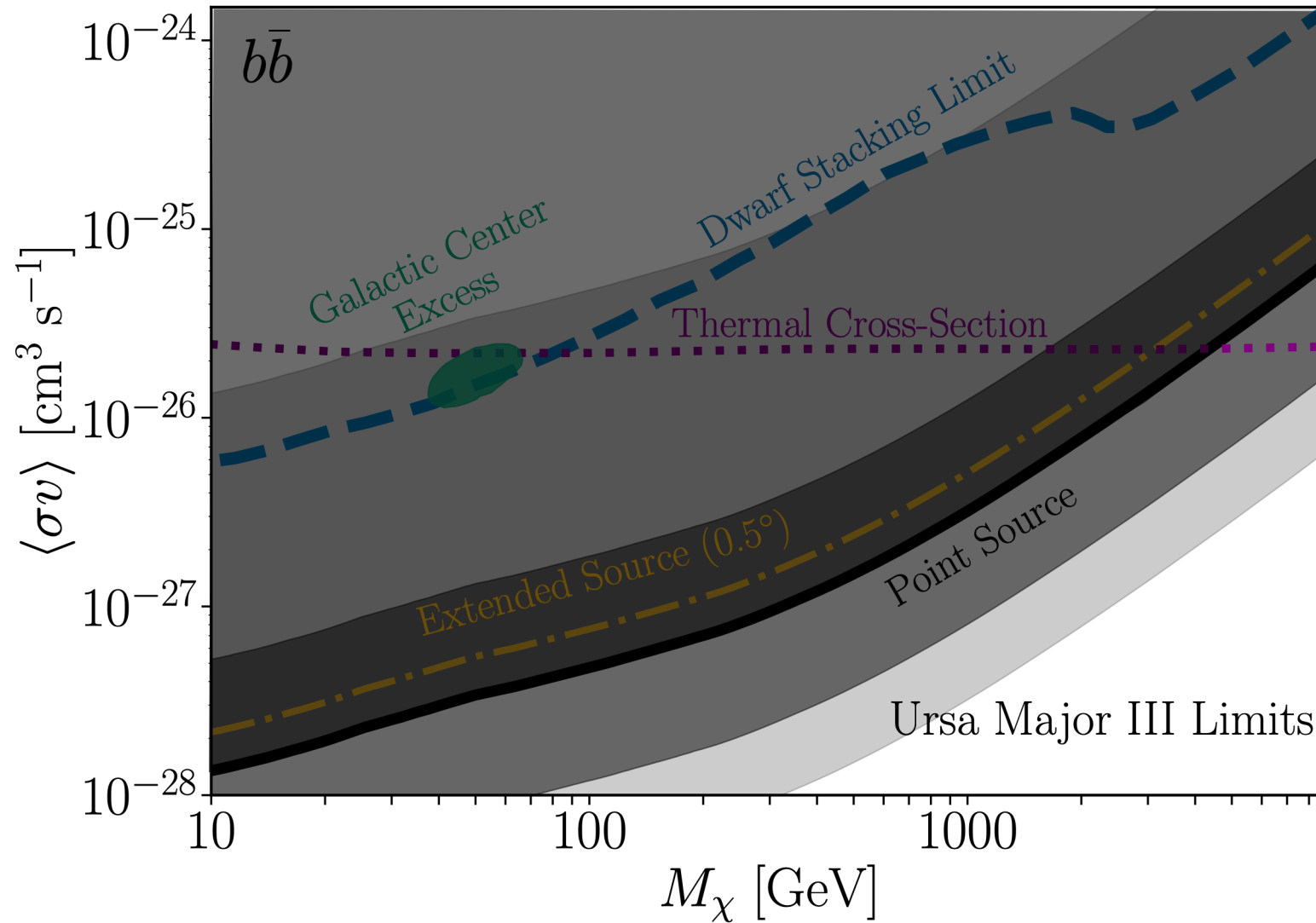
Timeline: data previews 2026–27, first full release early 2028. Roman & Euclid reach fainter, more distant systems.

Tsiane, Mau, Drlica-Wagner et al. (LSST DESC), arXiv:2504.16203 (2025), Nadler+ 2024 (Roman/Euclid)

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]

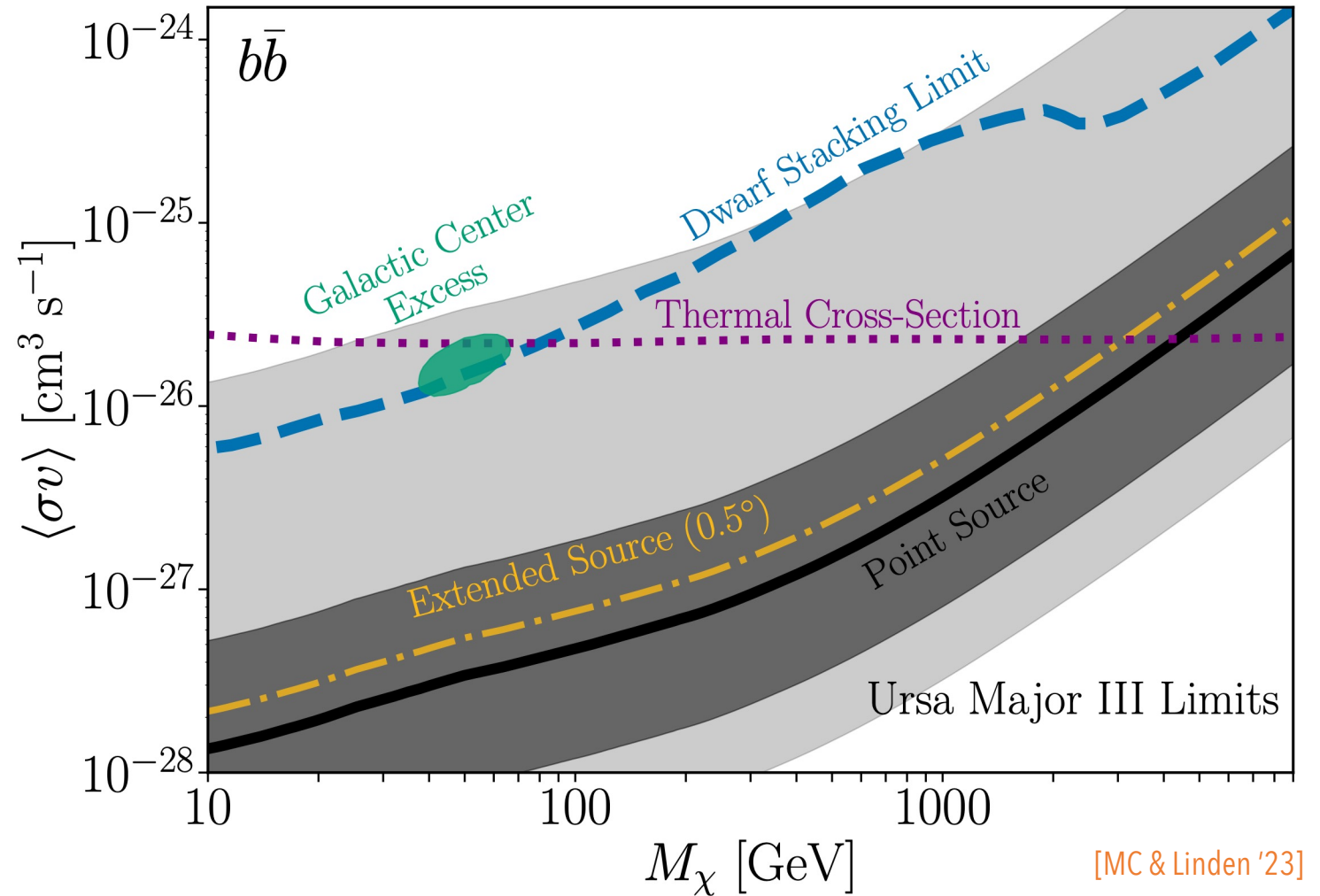
[J-factor: Errani+ 2023]

→ 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]

Ursa Major III

[Discovery: Smith+ 2023]

[J-factor: Errani+ 2023]

→ Unstable unless Λ

→ Near

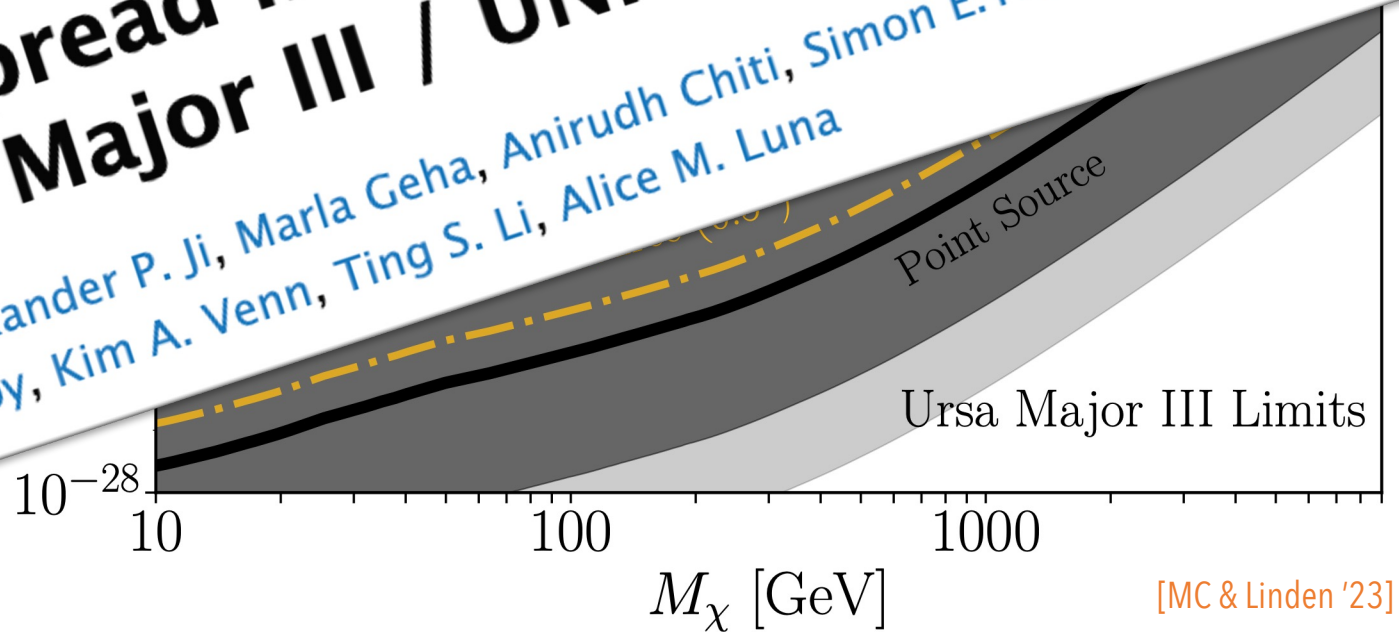
Astrophysics > Astrophysics of Galaxies

arXiv:2510.02431 (astro-ph)

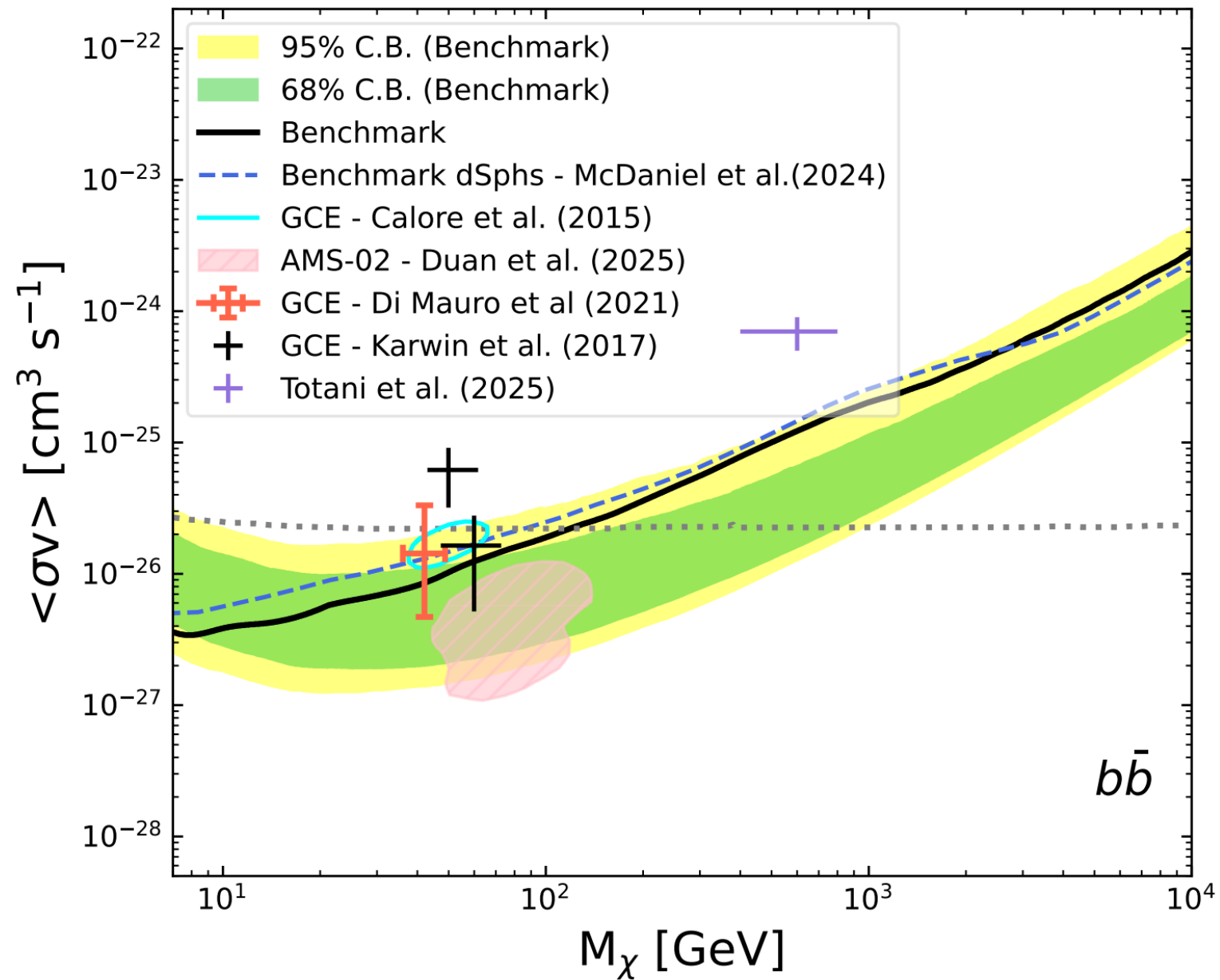
[Submitted on 2 Oct 2025 (v1), last revised 2 Dec 2025 (this version, v2)]

No Observational Evidence for Dark Matter Nor a Large Metallicity Spread in the Extreme Milky Way Satellite Ursa Major III / UNIONS 1

William Cerny, Daisy Bissonette, Alexander P. Ji, Marla Geha, Anirudh Chiti, Simon E.T. Smith, Joshua D. Simon, Andrew B. Pace, Evan N. Kirby, Kim A. Venn, Ting S. Li, Alice M. Luna

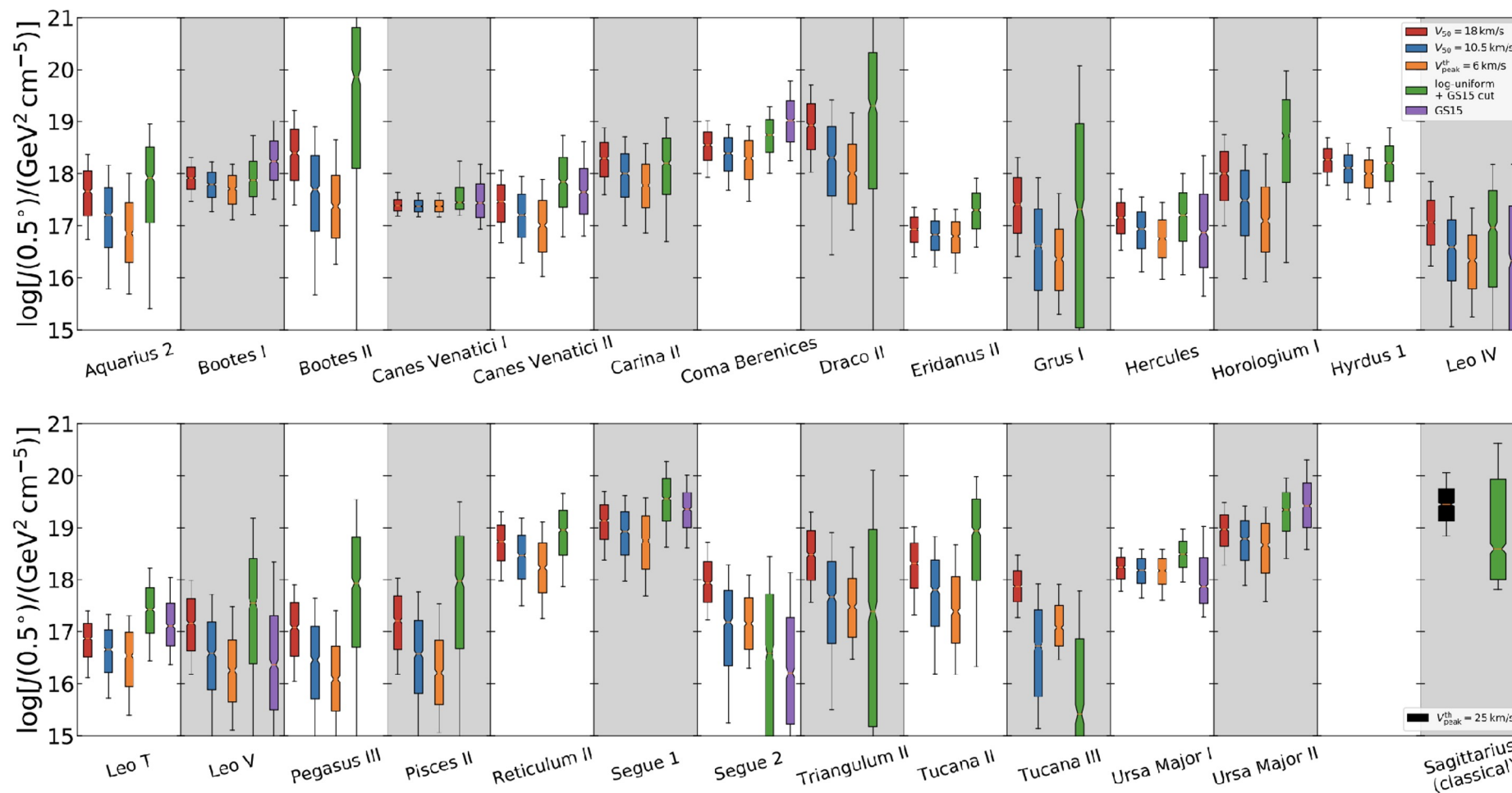


[MC & Linden '23]



J-factor uncertainties

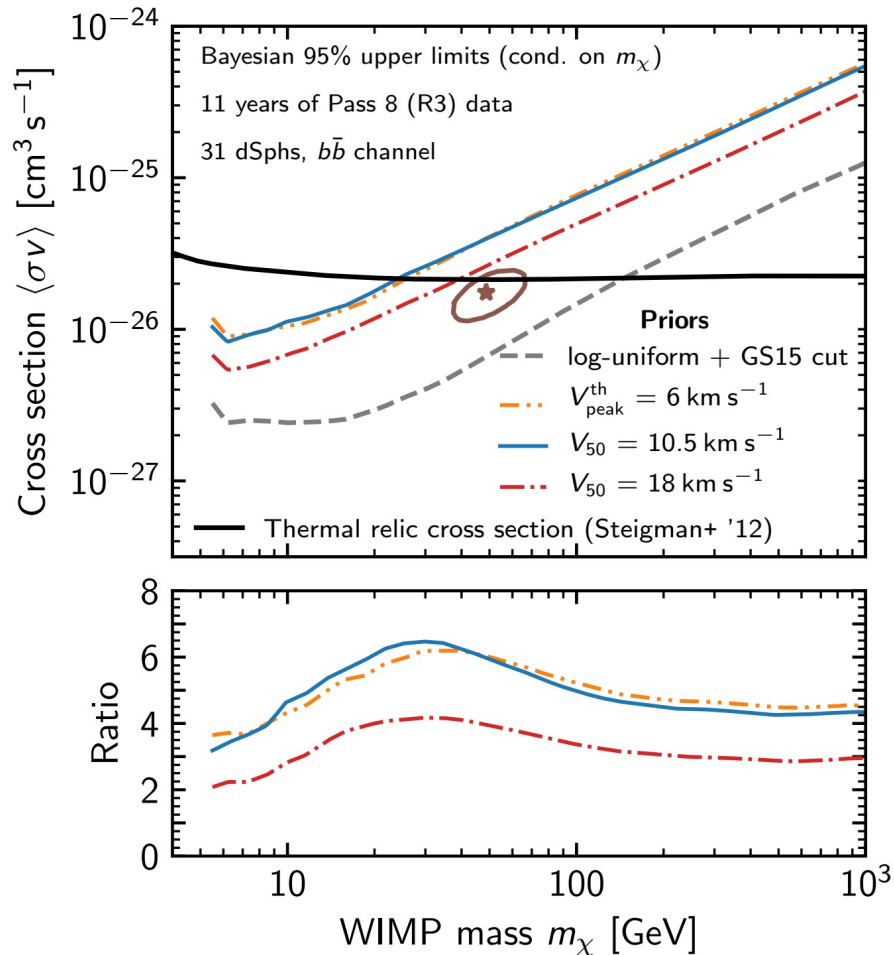
Ando+ 2020



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](#), [Ando+ '20](#), etc.]

J-factor uncertainties

Ando+ 2020



- Adopting satellite priors weaken the cross-section constraints by a factor of 2-7
- The effect is relatively insensitive to the condition of satellite formation
- Thermal cross section can be excluded only up to 20-50 GeV

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](#), [Ando+ '20](#), etc.]

Future of dwarfs: observer's view

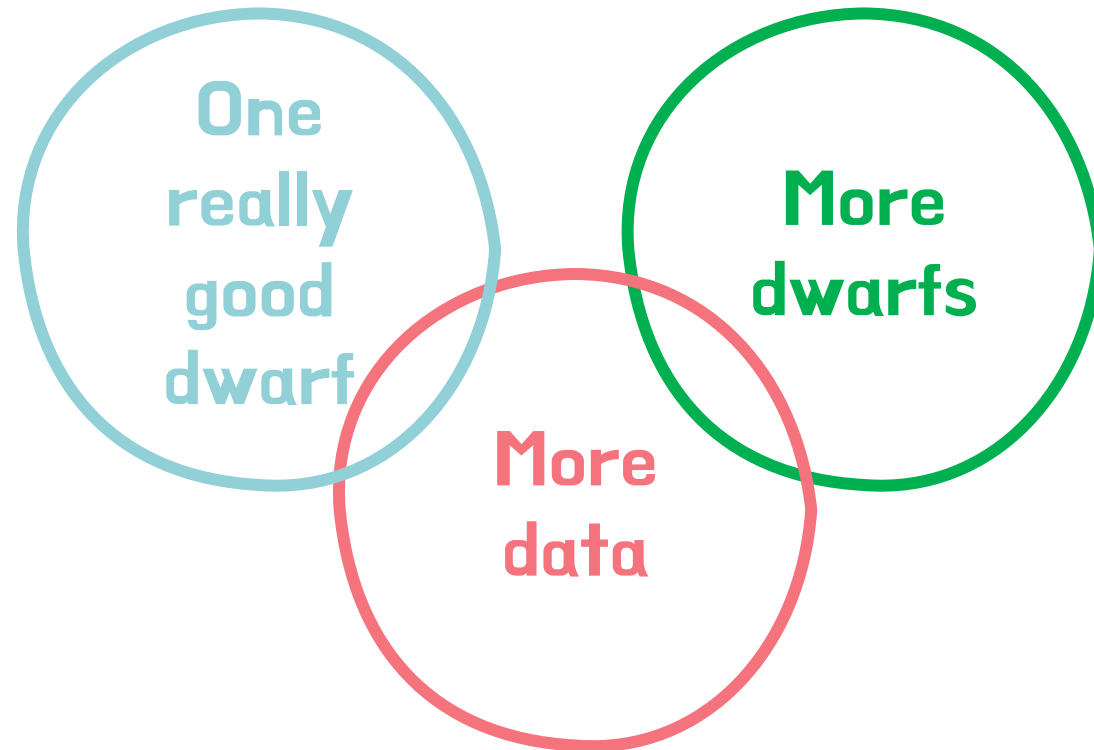


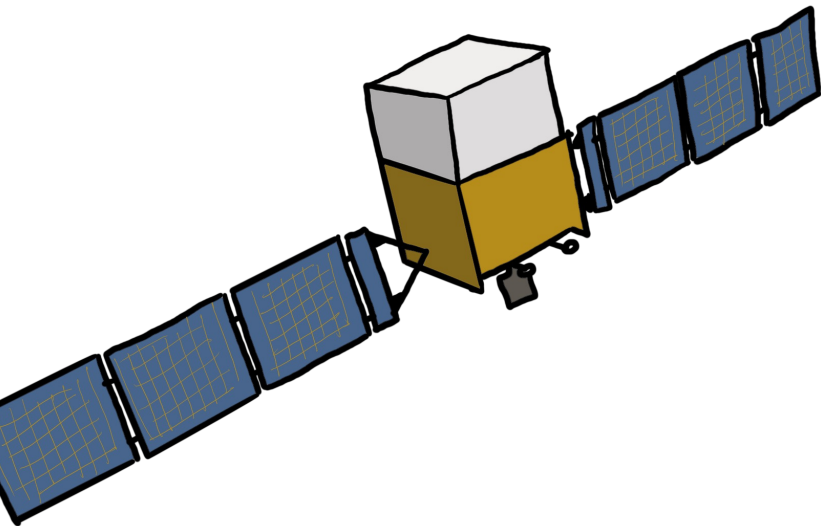
One
really
good
dwarf

Future of dwarfs: observer's view



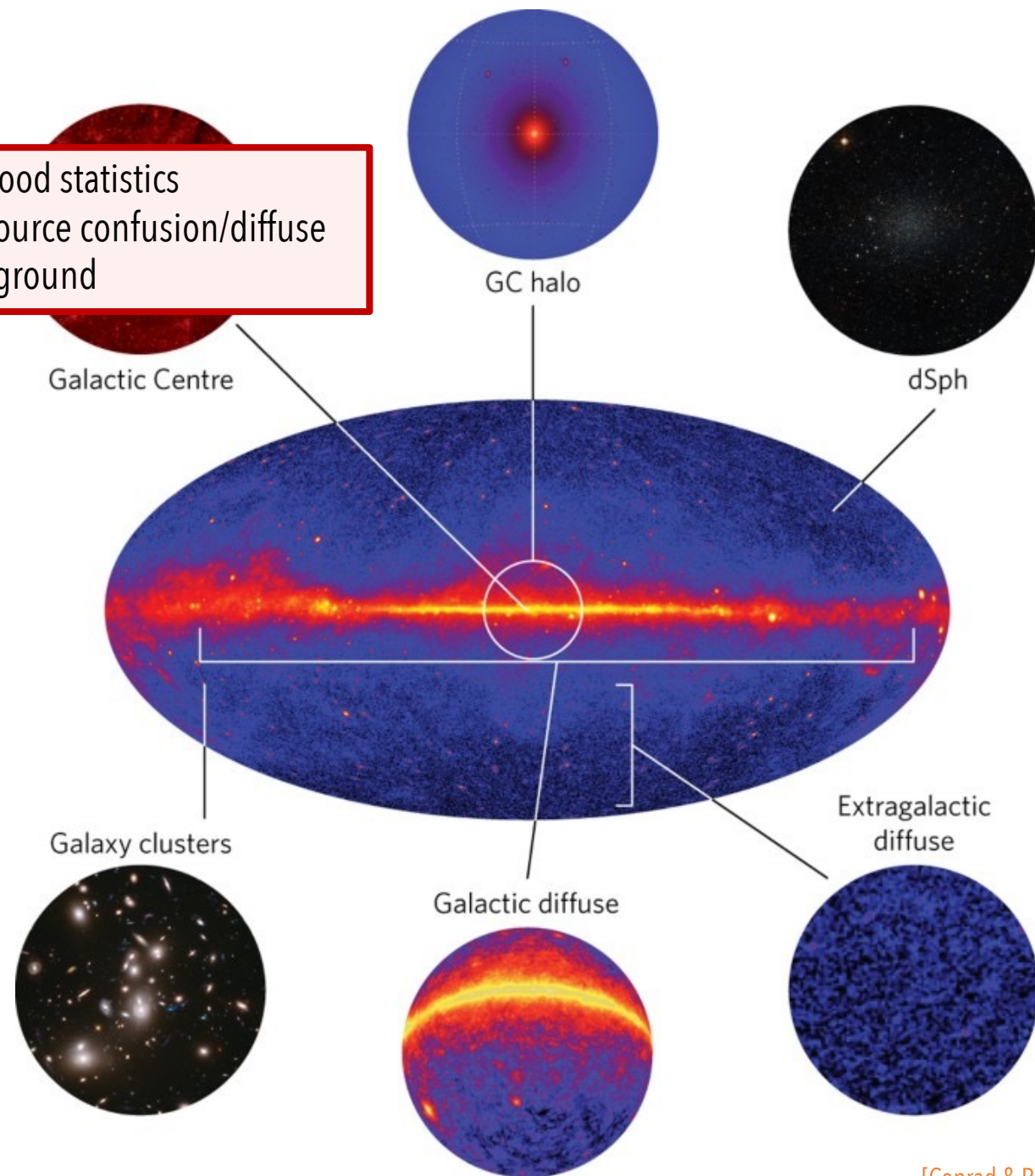
Future of dwarfs: observer's view



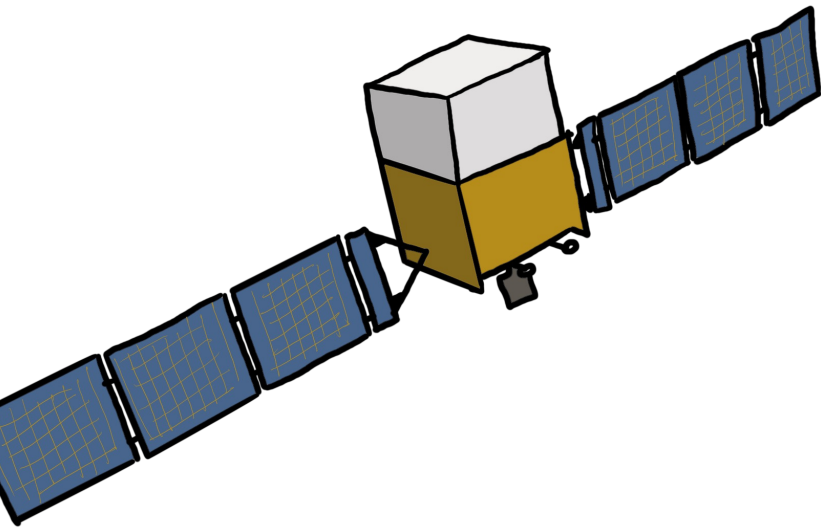


DM targets

- ✓ Good statistics
- ✗ Source confusion/diffuse background



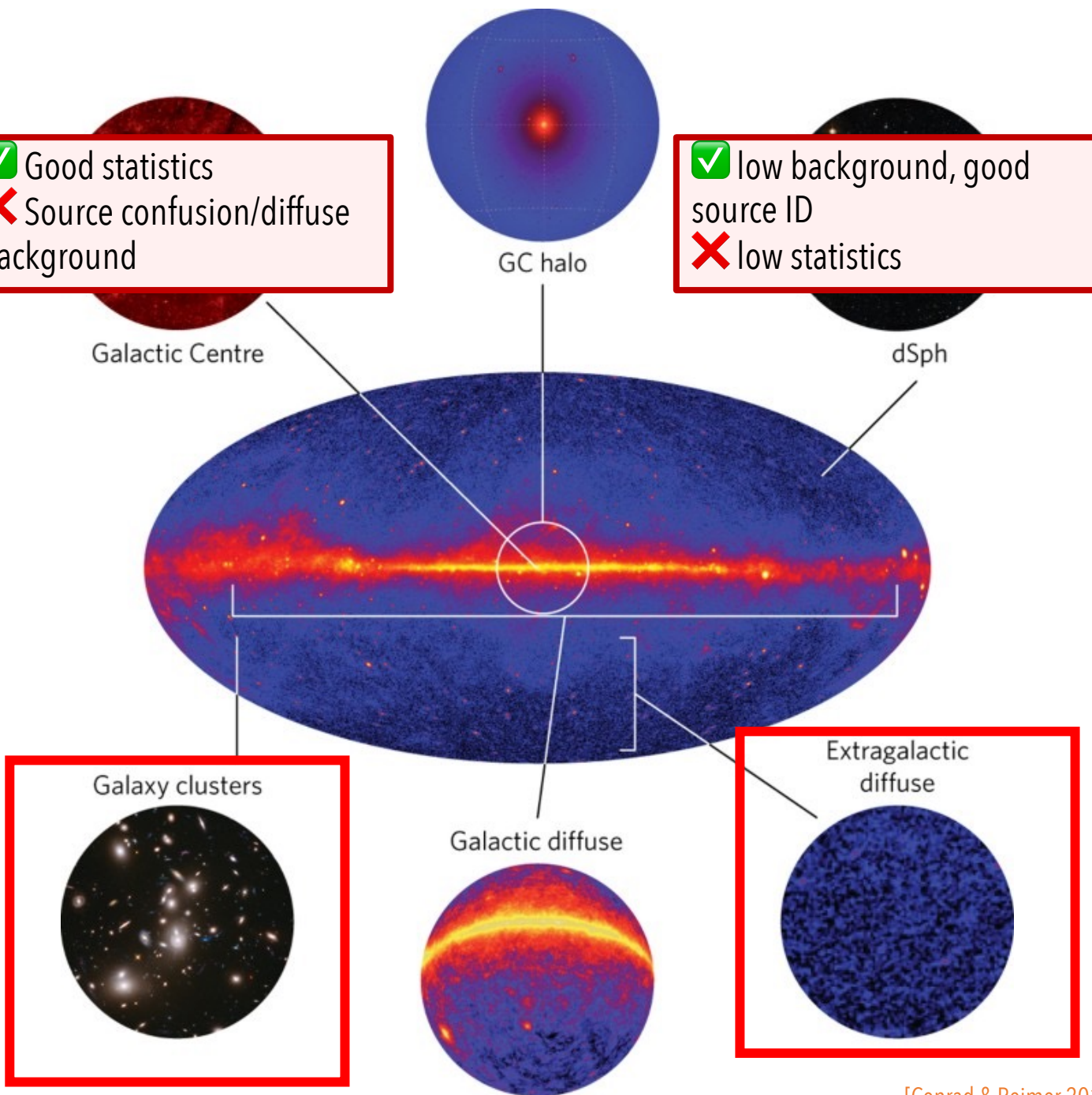
Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.



DM targets

✓ Good statistics
✗ Source confusion/diffuse background

✓ low background, good source ID
✗ low statistics



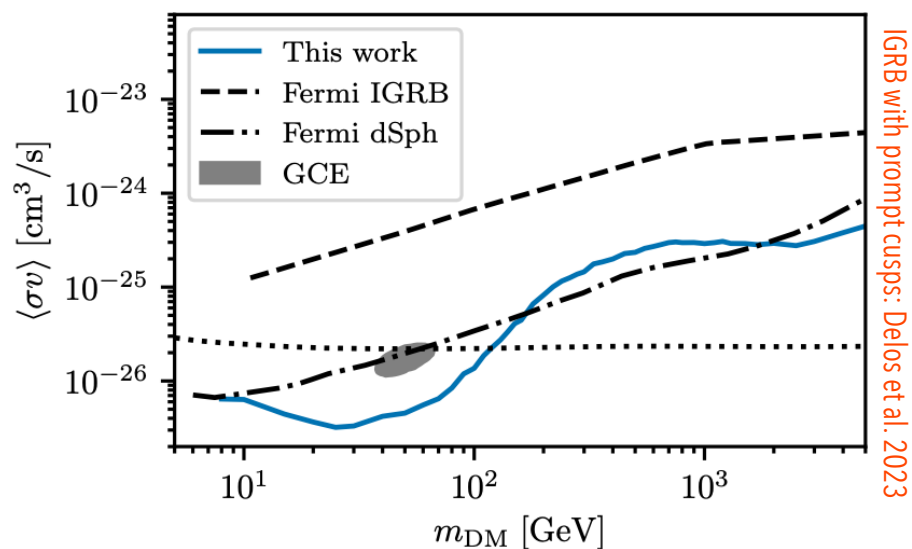
Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.



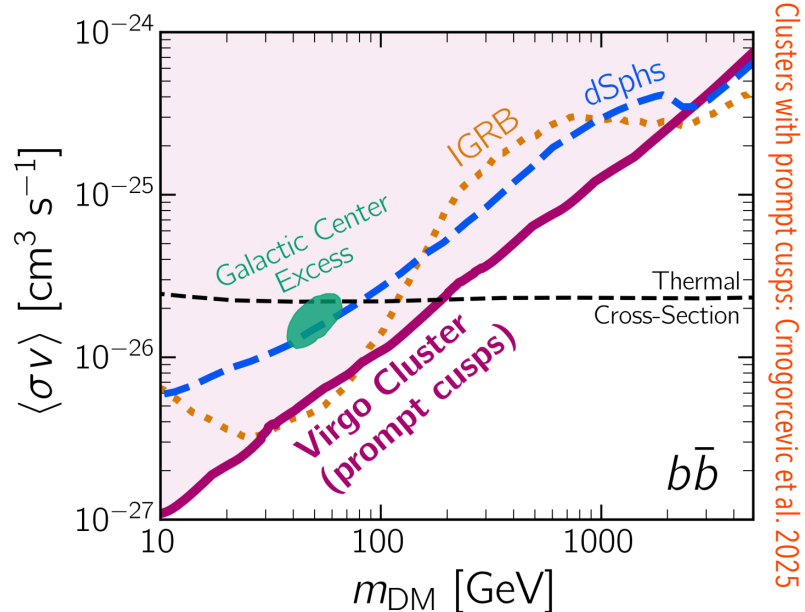
Target 3: Extragalactic Dark Matter

Extragalactic searches

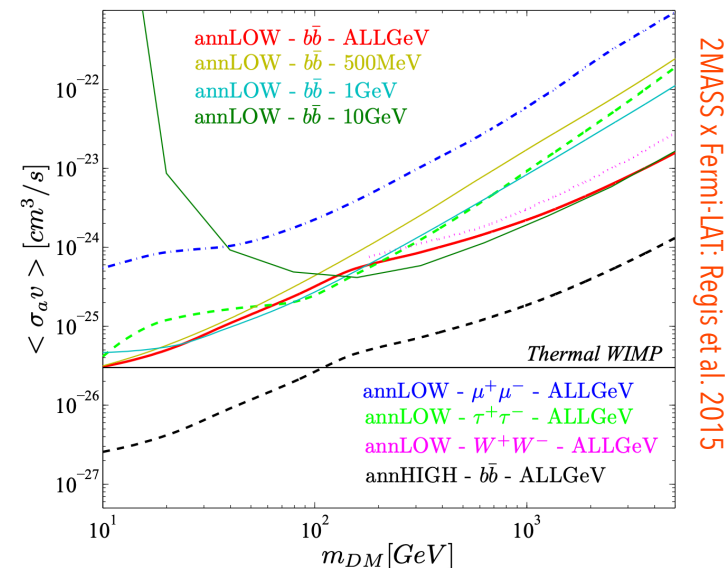
Isotropic gamma-ray background



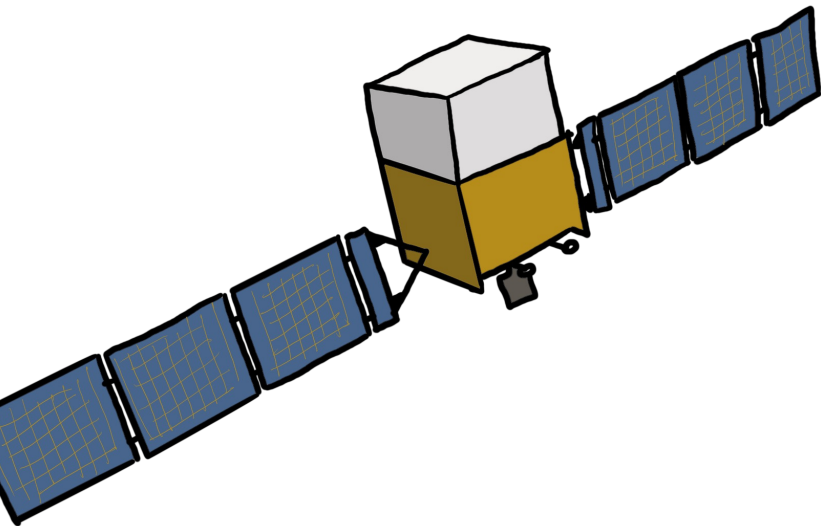
Galaxy clusters



Cross-correlations



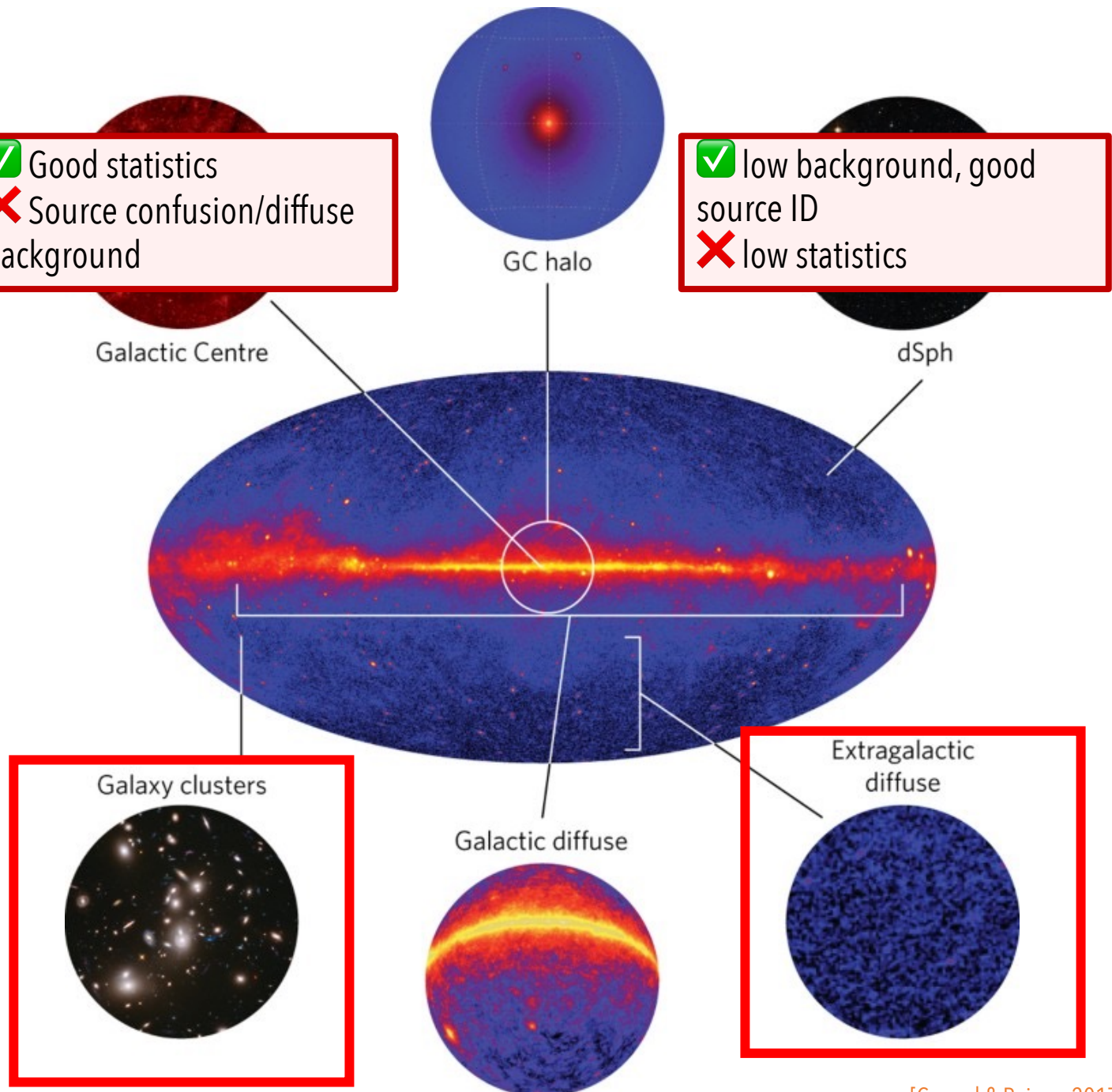
Breadth of searches currently targeting signals from extragalactic halos



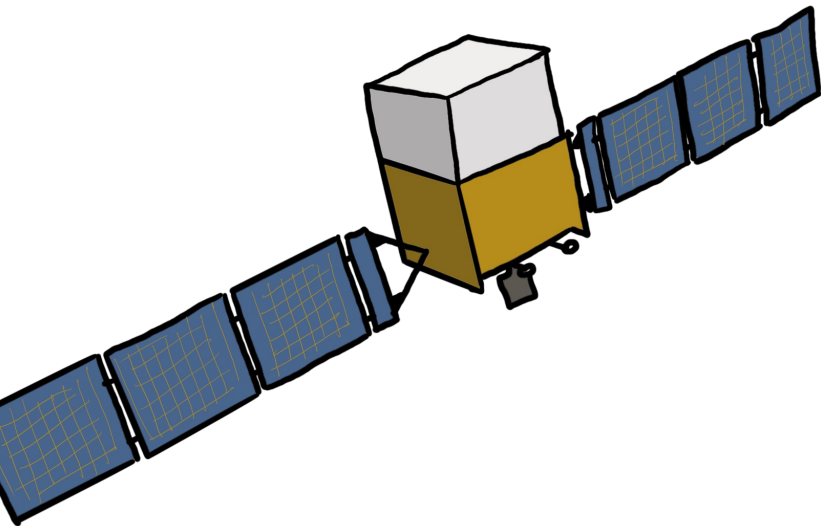
DM targets

✓ Good statistics
✗ Source confusion/diffuse background

✓ low background, good source ID
✗ low statistics



Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.



DM targets

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

✓ Good statistics
✗ Source confusion/diffuse background

✓ low background, good source ID
✗ low statistics

✓ low statistics
✗ astrophysical backgrounds

✓ low statistics
✗ astrophysical backgrounds

Galactic Centre

GC halo

dSph

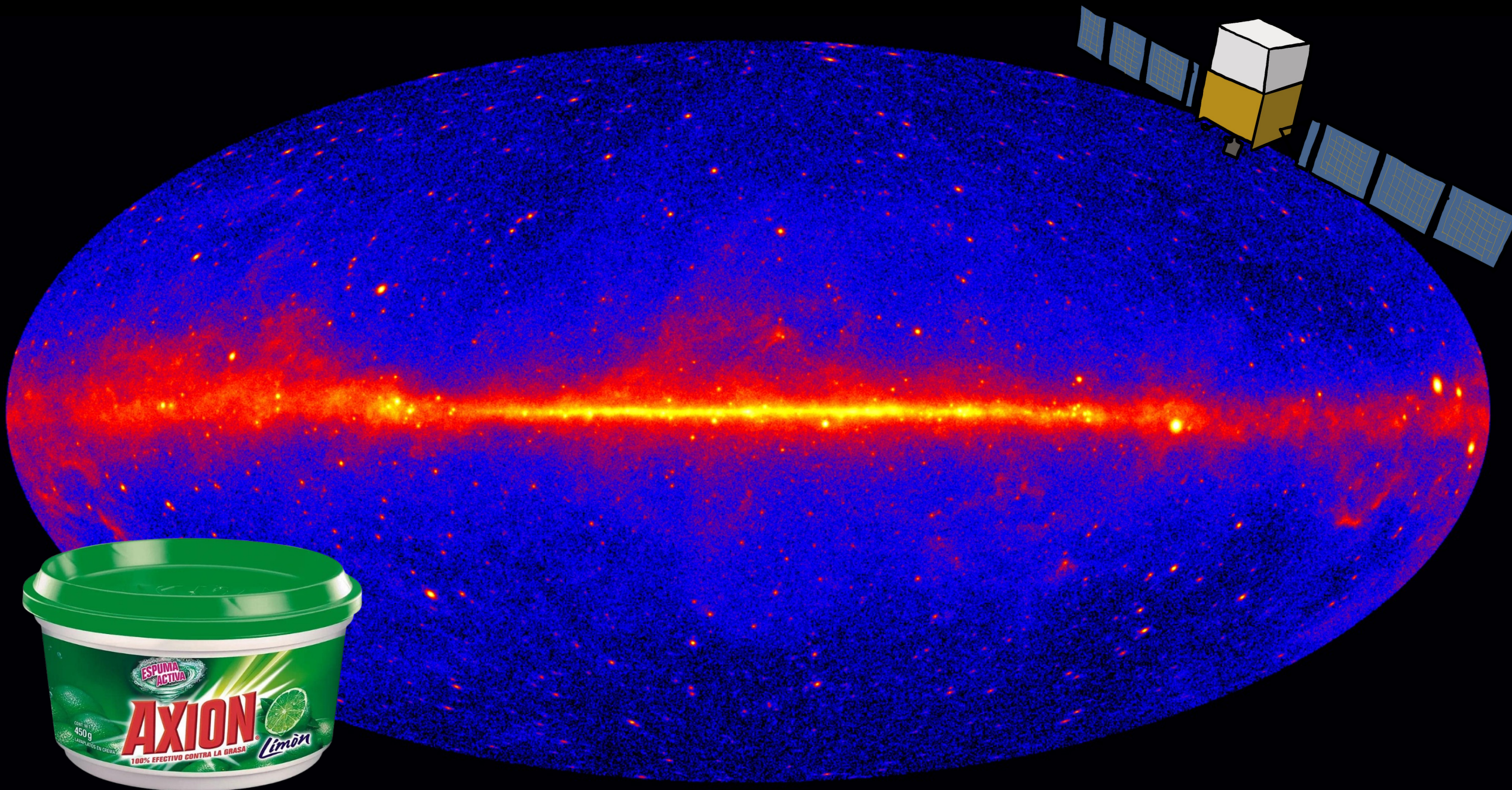
Galaxy clusters

Galactic diffuse

Extragalactic diffuse

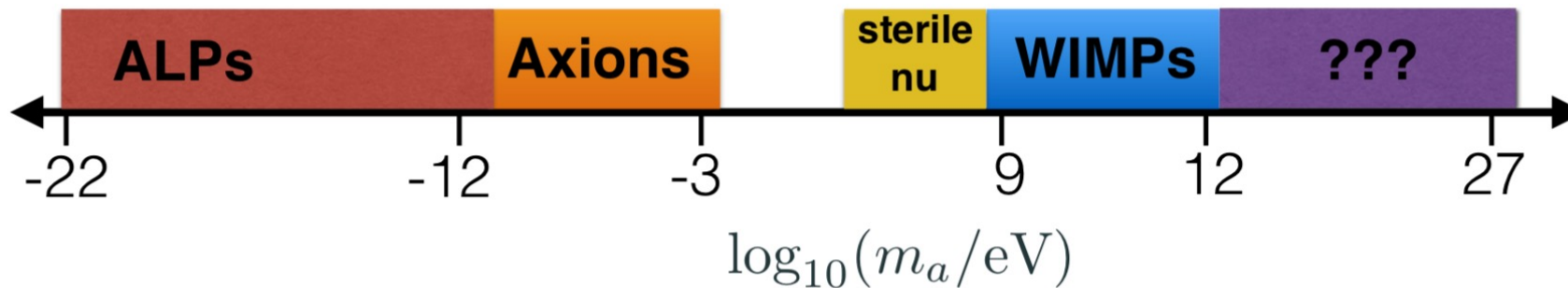
Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.

[Conrad & Reimer 2017]



Axions and ALPs

- a proposed solution of the strong charge-parity problem in QCD (ALPs extension thereof)
- **WISPs**: weakly-interacting sub-eV particles (mass $\lesssim 10^{-10}$ eV)



Axions and ALPs

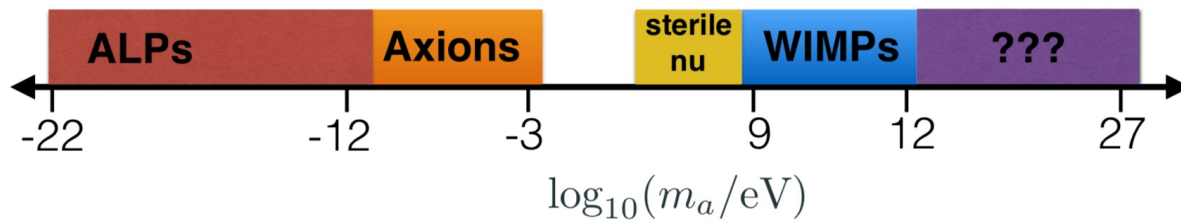
- a proposed solution of the strong charge-parity problem in QCD (ALPs extension thereof)
- **WISPs**: weakly-interacting sub-eV particles (mass $\lesssim 10^{-10}$ eV)

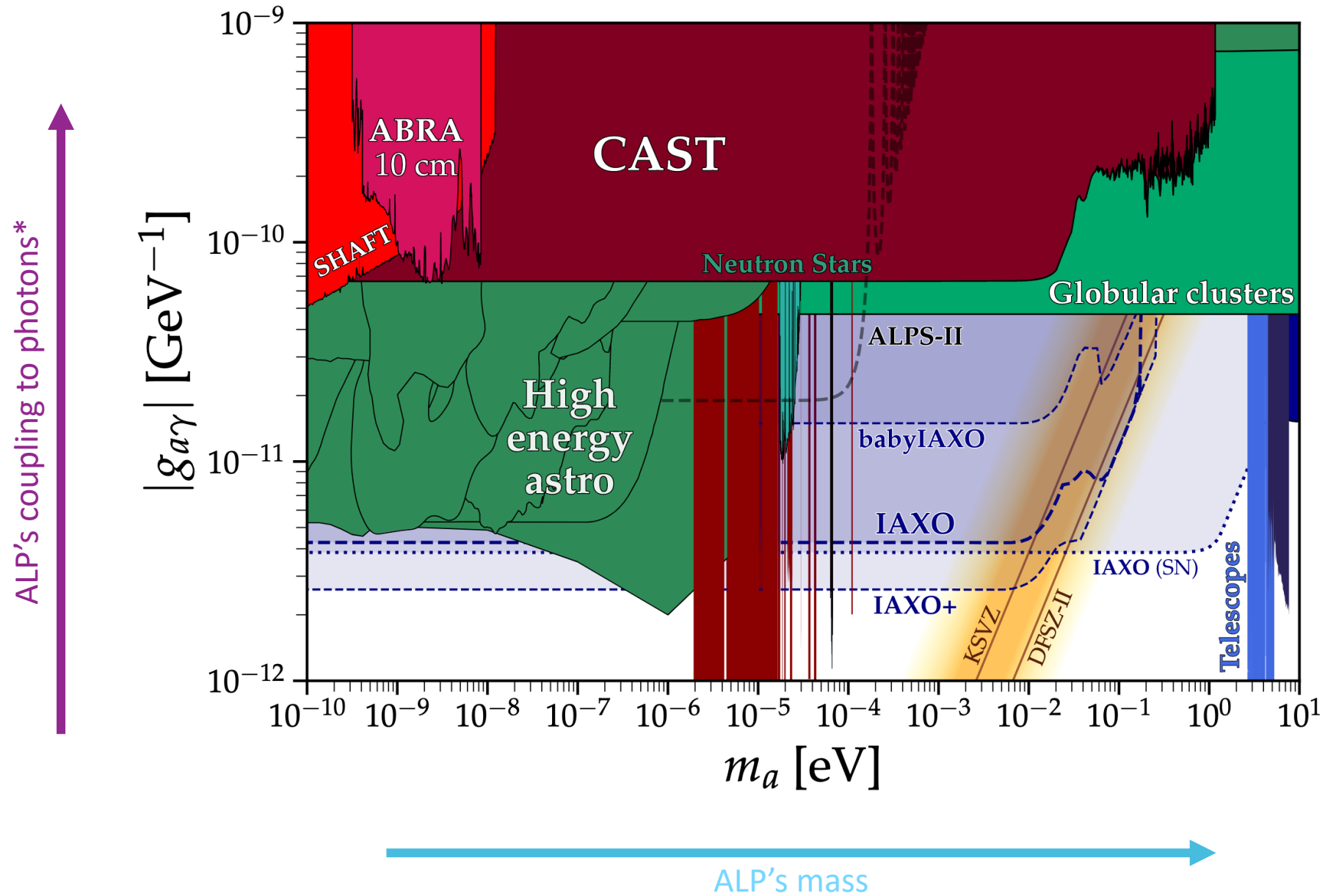
❖ **Cold** matter requirements:

- ✓ feeble interactions with standard model particles
- ✓ cosmological stability
- ✓ Non-thermal production → cold

$$\rho_{a,0} \lesssim 1 \frac{\text{keV}}{\text{cm}^3} \frac{m_a(t_0)}{\text{eV}} \left(\frac{\theta(t_1)}{53 \text{TeV}} \right)^2 \rightarrow \text{Dark Matter!}$$

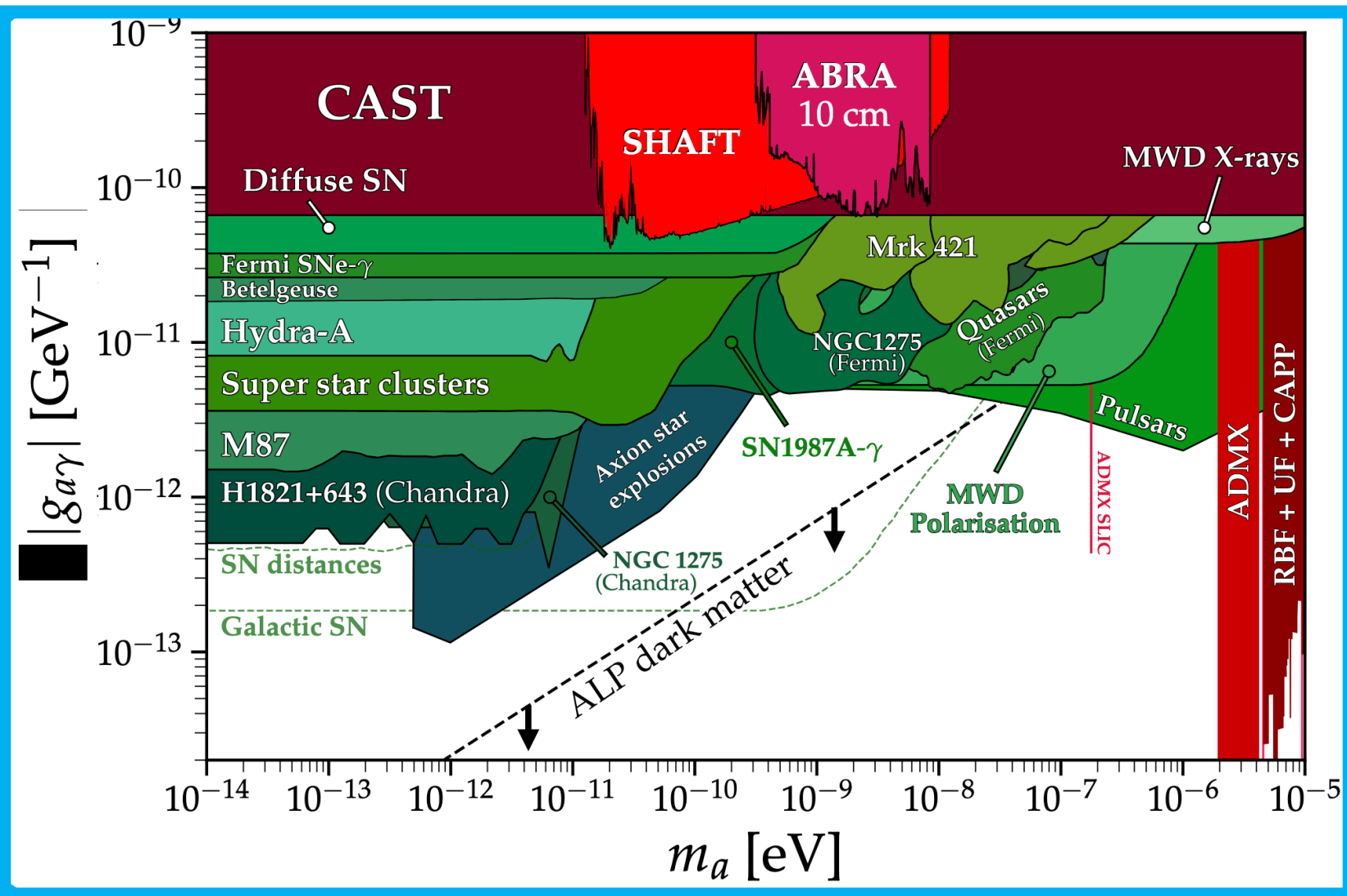
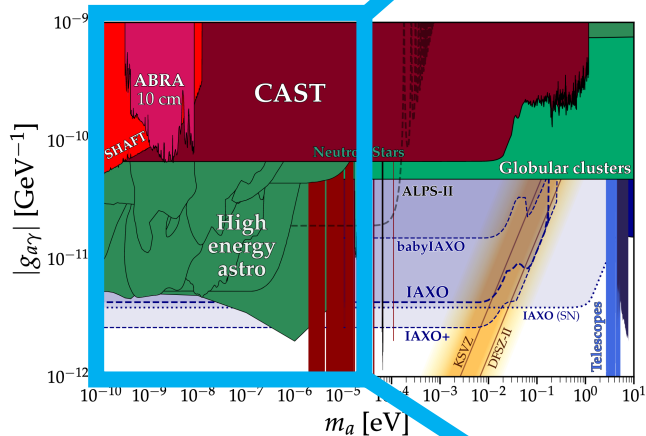
- ❖ Direct and indirect searches → limits on coupling/mass parameter space





*analogous to a WIMP cross-section

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

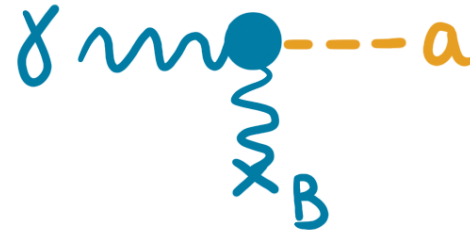


Plot produced using: <https://cajohare.github.io/AxionLimits/>

Axion/ALP Landscape: An Observer's view

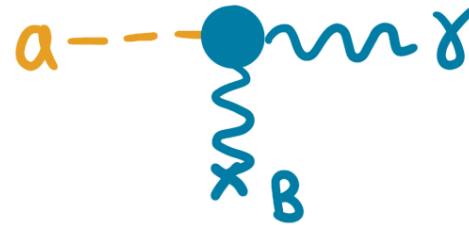
ALP/axion - photon interactions

1. Primakoff
process



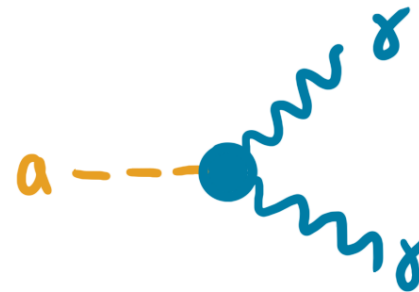
$$\gamma \rightarrow a$$

2. Inverse
Primakoff



$$a \rightarrow \gamma$$

3. ALP/axion
decay



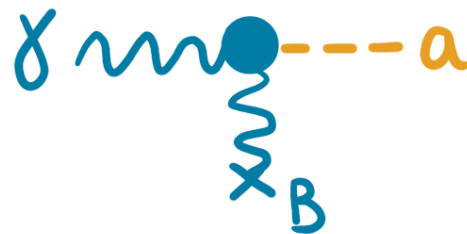
$$a \rightarrow \gamma\gamma$$

Axion/ALP Landscape: An Observer's view

ALP/axion - photon interactions

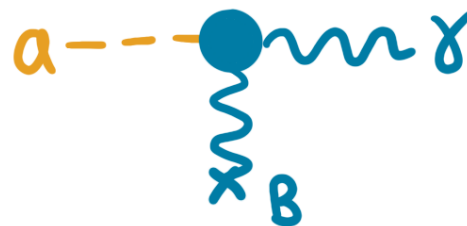
Line searches for
 $m_{\text{alp}} < 1 \text{ MeV}$.
→ Signatures in radio,
IR, and X-rays.

1. Primakoff
process



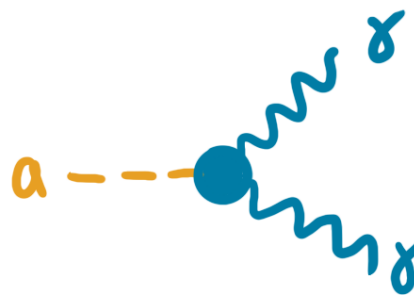
$$\gamma \rightarrow a$$

2. Inverse
Primakoff

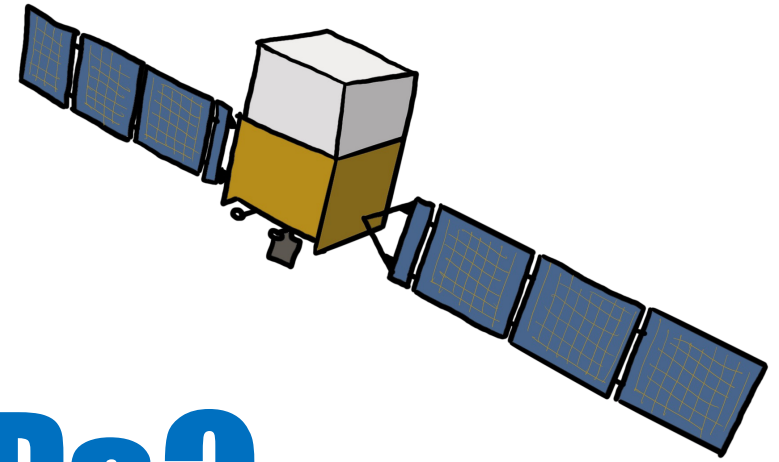


$$a \rightarrow \gamma$$

3. ALP/axion
decay

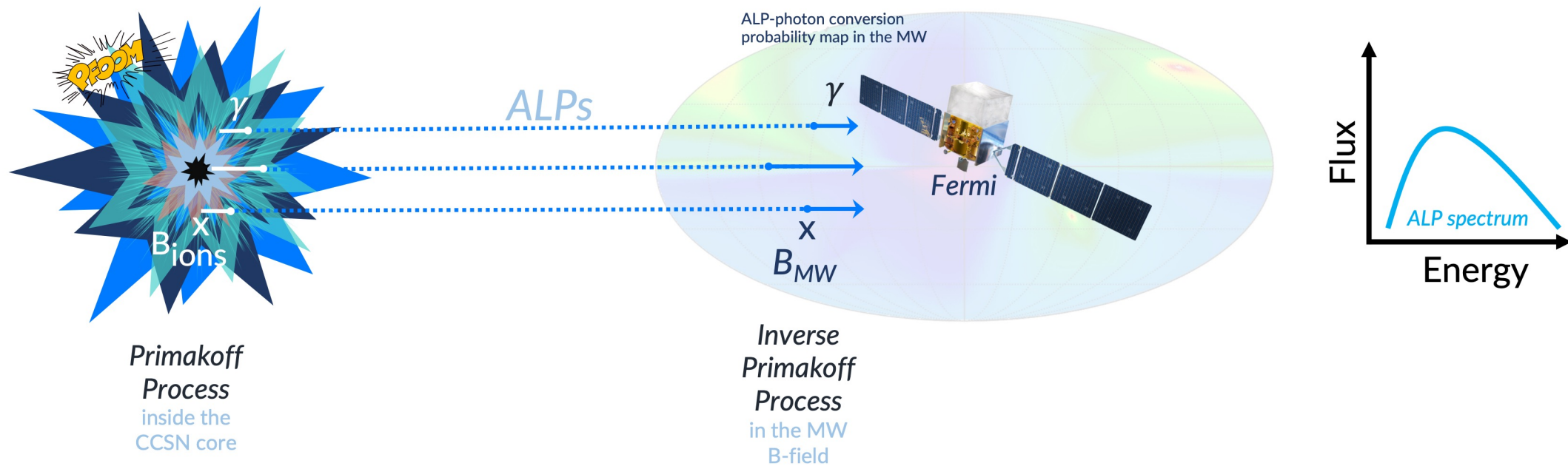


$$a \rightarrow \gamma\gamma$$

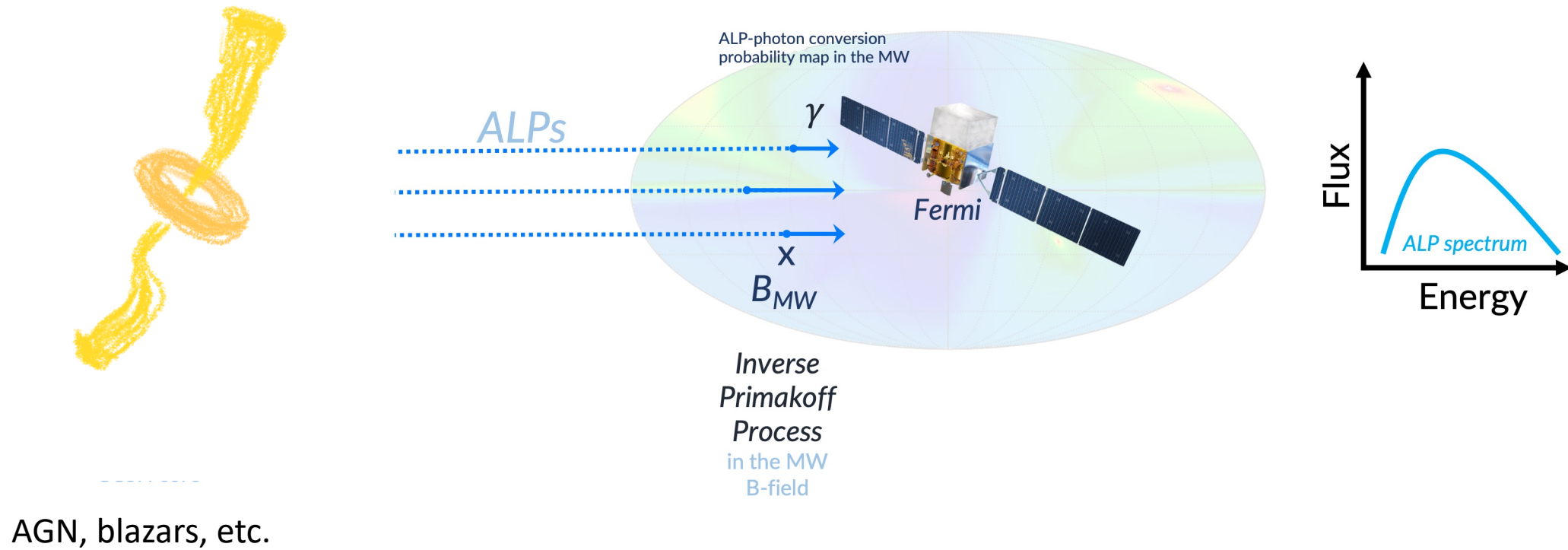


Where to look for ALPs?

Photon from in-source conversions



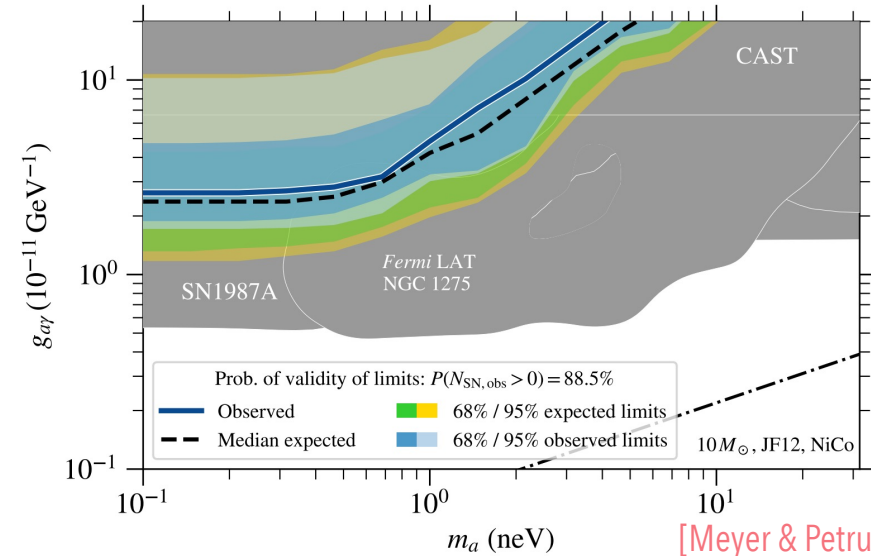
Photon from in-source conversions



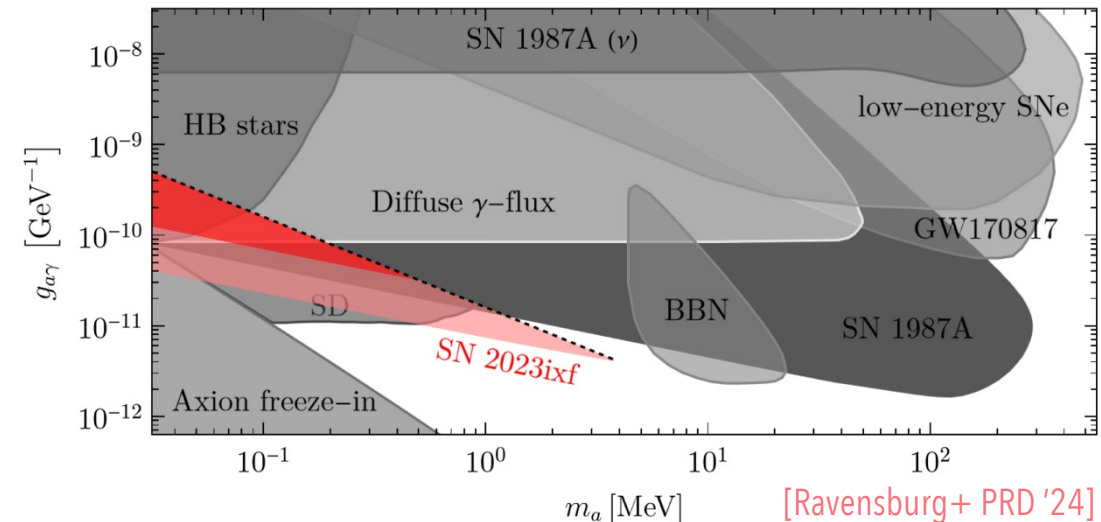
CCSNe: Individual Sources

- 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 & Petrushevskaya PRL '20, Crnogorčević+ PRD '21, Müller+ PRD '23, Ravensburg+ PRD '24, Calore+ PRD '24, and more]

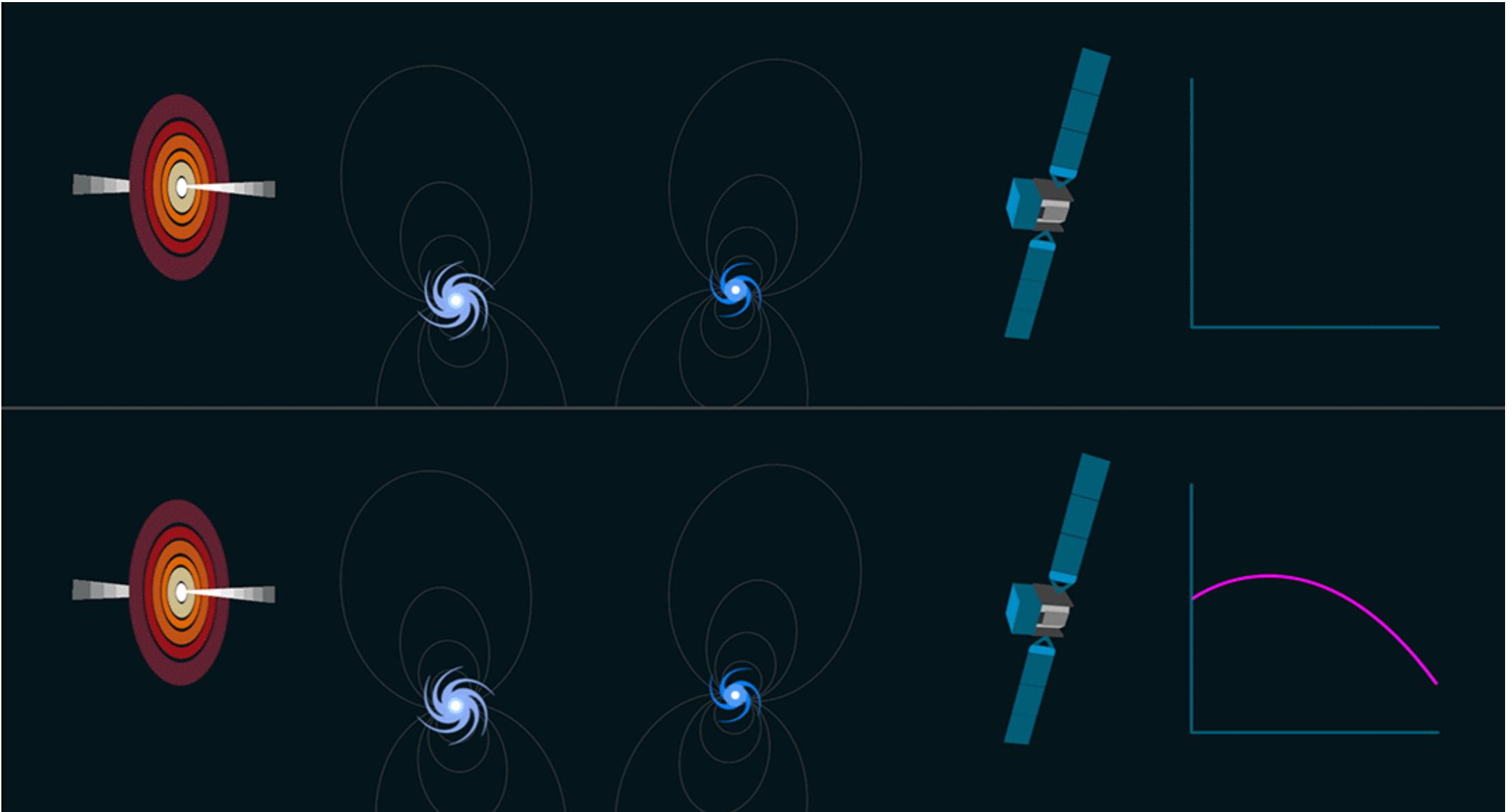


[Meyer & Petrushevskaya PRL '20]



[Ravensburg+ PRD '24]

Distortions in the astrophysical spectra



[Credit: SLAC/Chris Smith]

Distortions in the astrophysical spectra

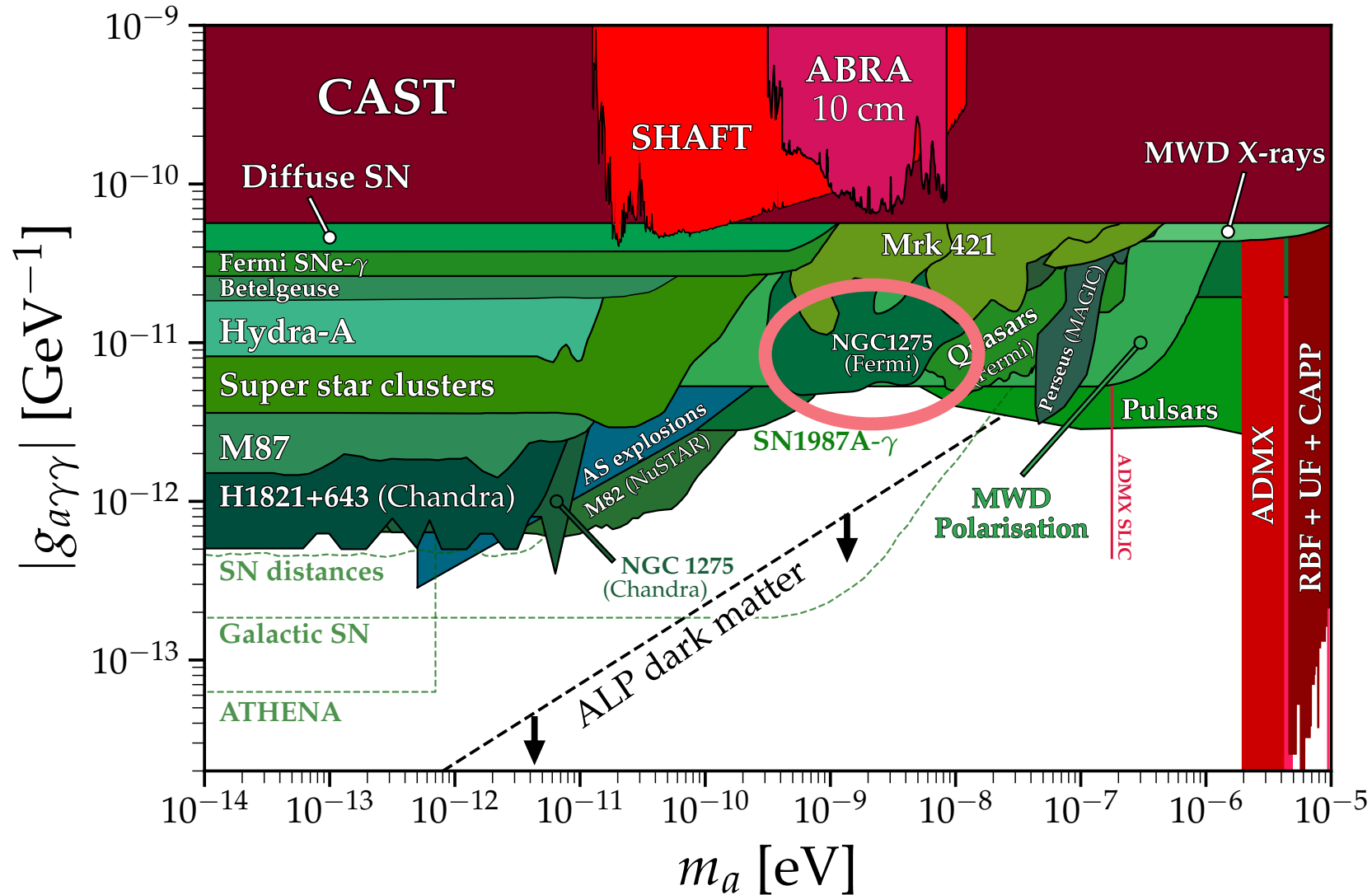
- Radio galaxy NGC 1275, also a gamma-ray source in *Fermi* [Abdo+ '09]
- Central region of the cool-core Persius cluster, $z = 0.0176$
- High central magnetic field
- ALP limits driven by the ICM modelling; popular target for ALP searches

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



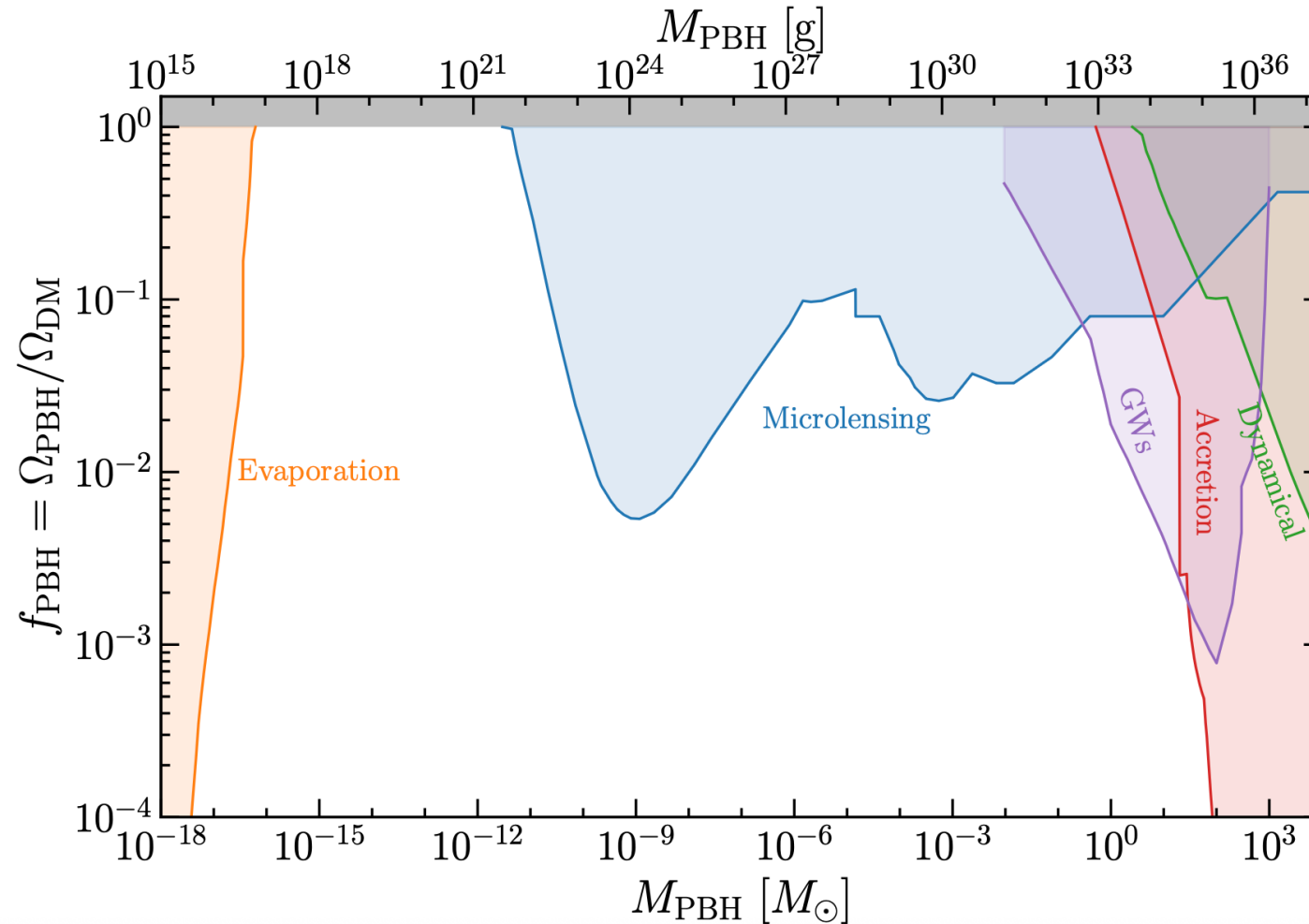
[Credit: Marie-Lou Gendron-Marsolais & Hlavacek-Larrond]

NGC 1275: spectral irregularities



Primordial black holes: sneak peak

<https://github.com/bradkav/PBHbounds>



Take-aways

Maturing experiments & shrinking parameter spaces

WIMP paradigm: diversified

Shifted from anomaly chasing to systematic, robust searches

Every major astrophysics discovery in the last decade came **from combining multiple messengers**. DM will be no different.

Future: put the dark matter into "multimessenger"



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