Dark Matter from the littlest galaxies

Gamma-ray insights from ultra-faint dwarfs and IMBHs

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ICRC 2025
July 18, 2025

ICRC 2025
The Astroparticle Physics Conference
Geneva July 15-24, 2025

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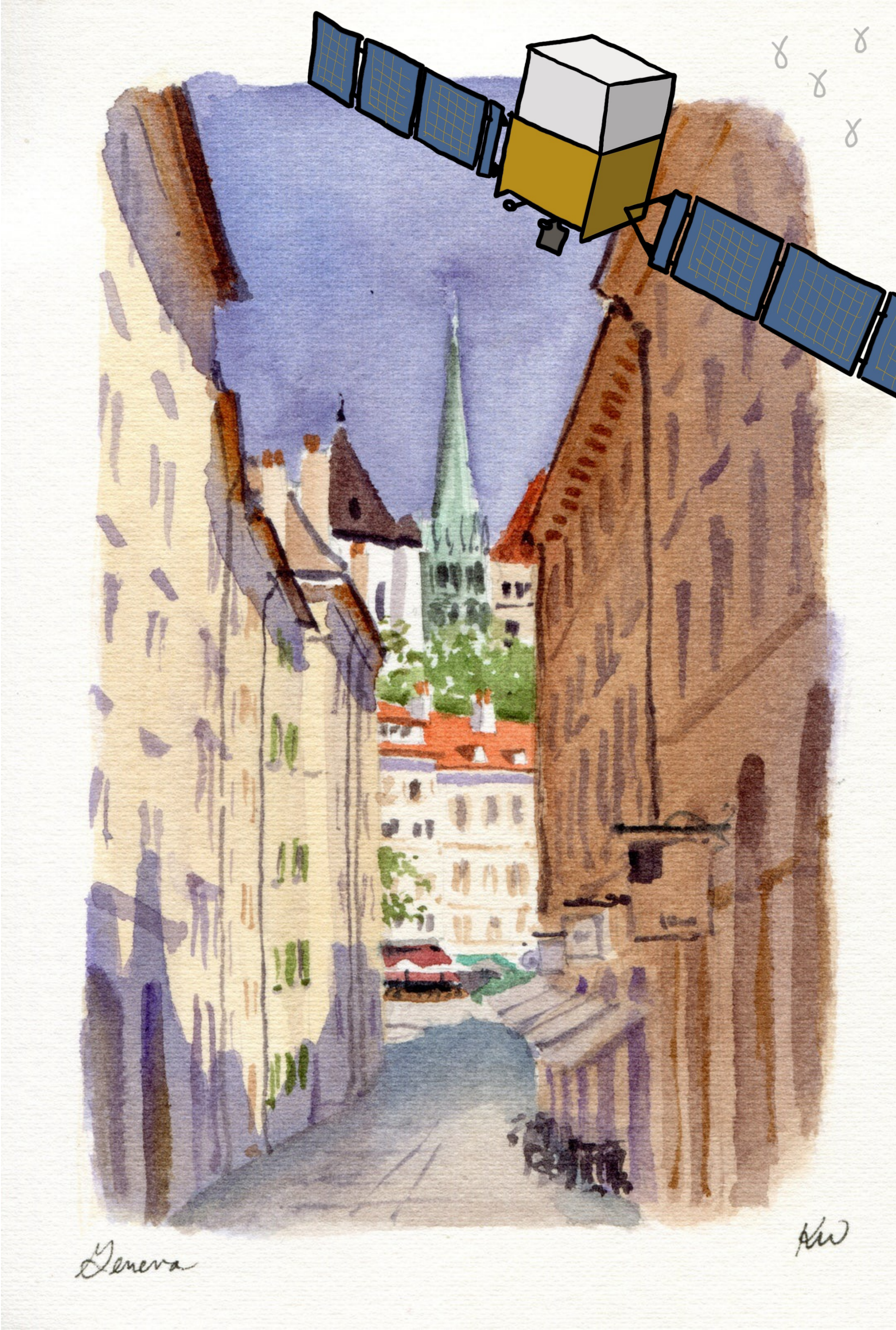

Image Credit: Katie Woodward

Target 1: dSphs

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→ 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

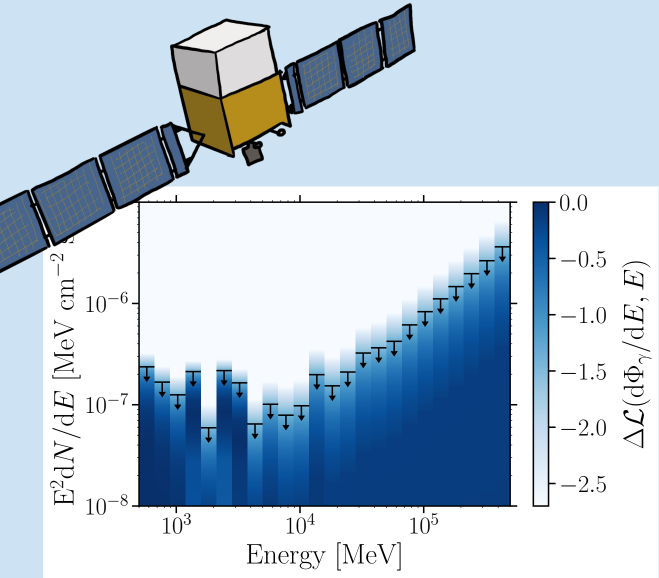
Fornax Dwarf Galaxy, ESO/Sky Survey 2

Dwarf Spheroidal Galaxies

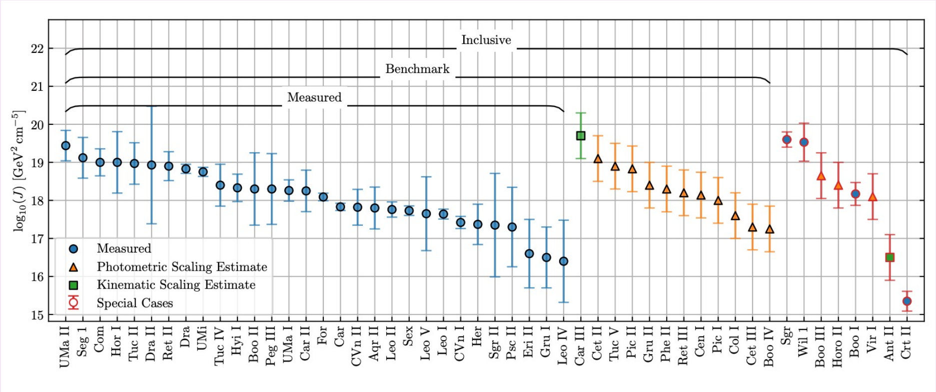
DM γ-ray flux = **astrophysics J-factor** × **particle physics**

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

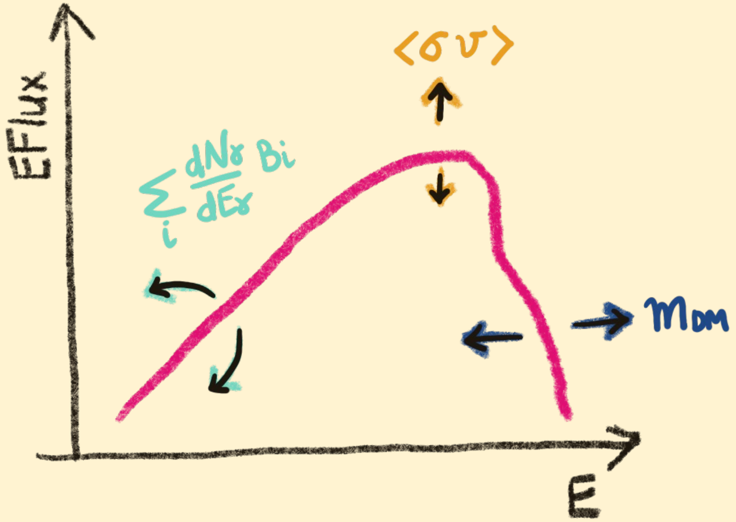
Dark matter content determined from stellar velocity dispersion
- **Classical dwarfs**: spectra for several thousand stars
- **Ultra-faint dwarfs**: spectra for fewer than 100 stars



Ursa Major III [MC & Linden 2024]

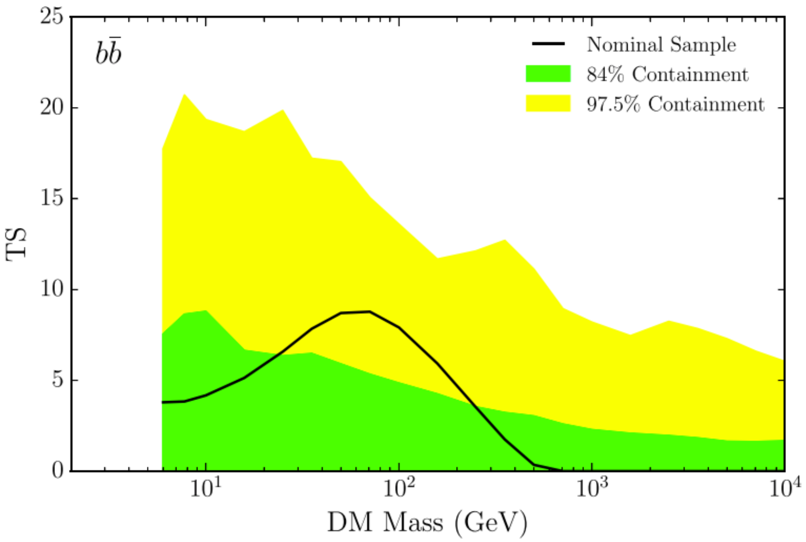


J-factors [McDaniel+ 2024]



Combined dSph Analyses

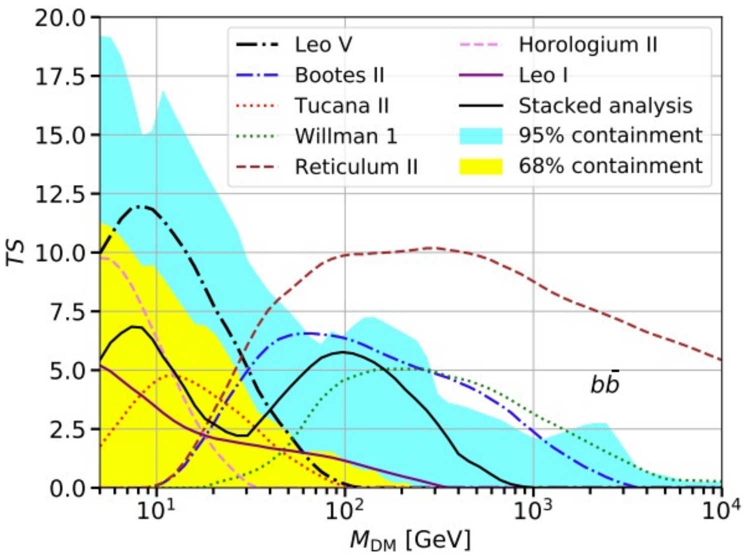
6 years



$< 2\ \sigma$

[Fermi-LAT Collaboration '17]

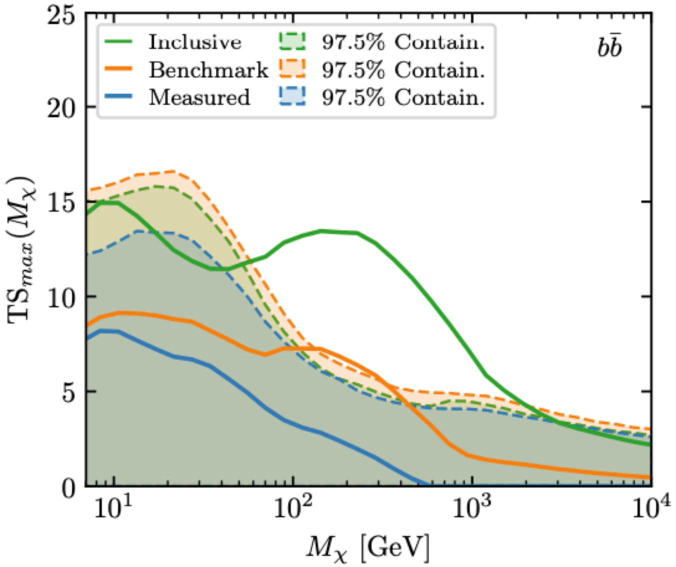
11 years



$\lesssim 2\ \sigma$

[Fermi-LAT Collaboration '21]

14 years

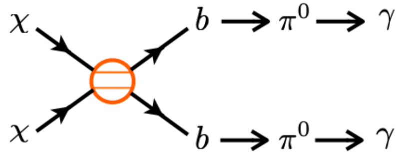


$\gtrsim 2\ \sigma$

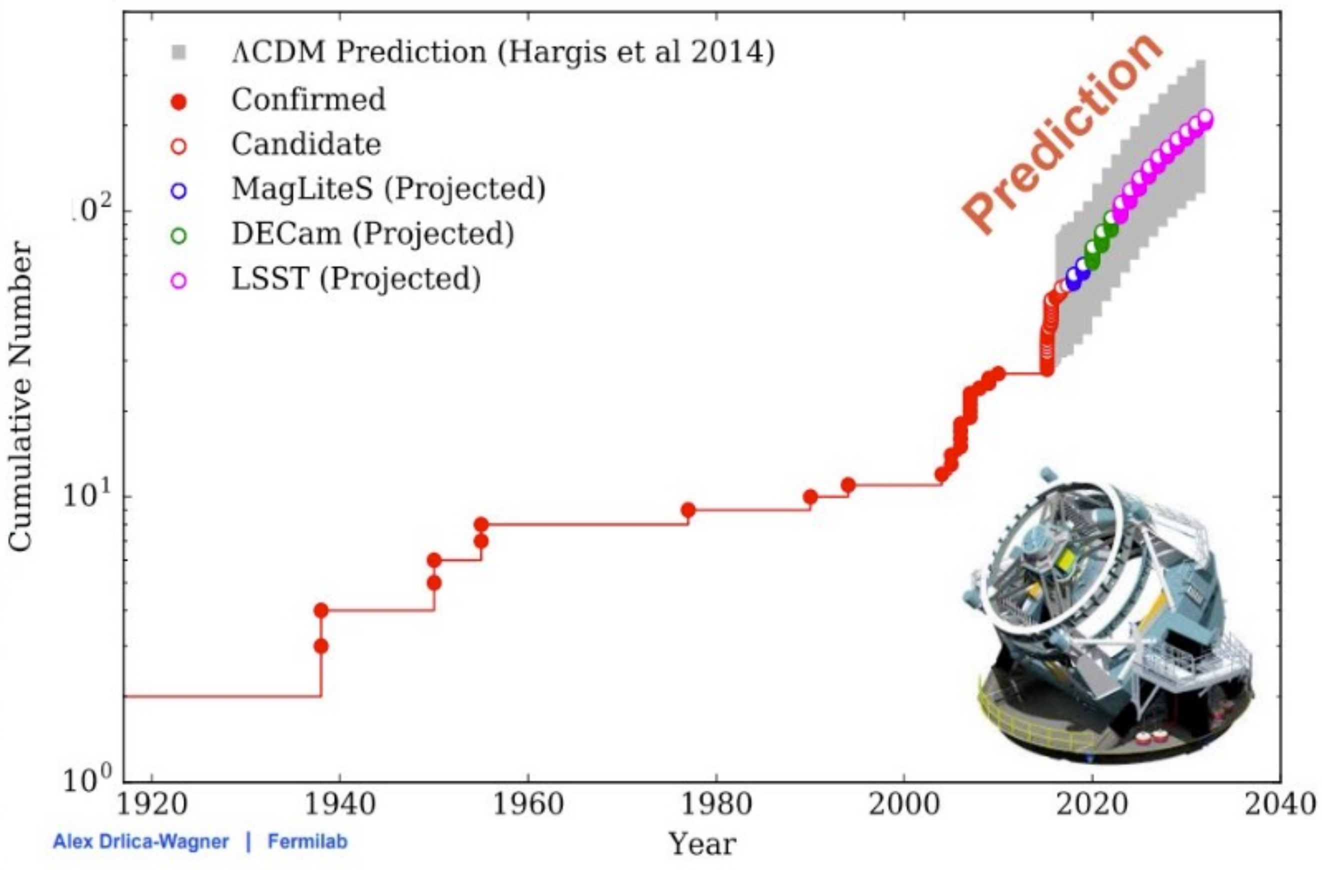
[McDaniel+ '24]

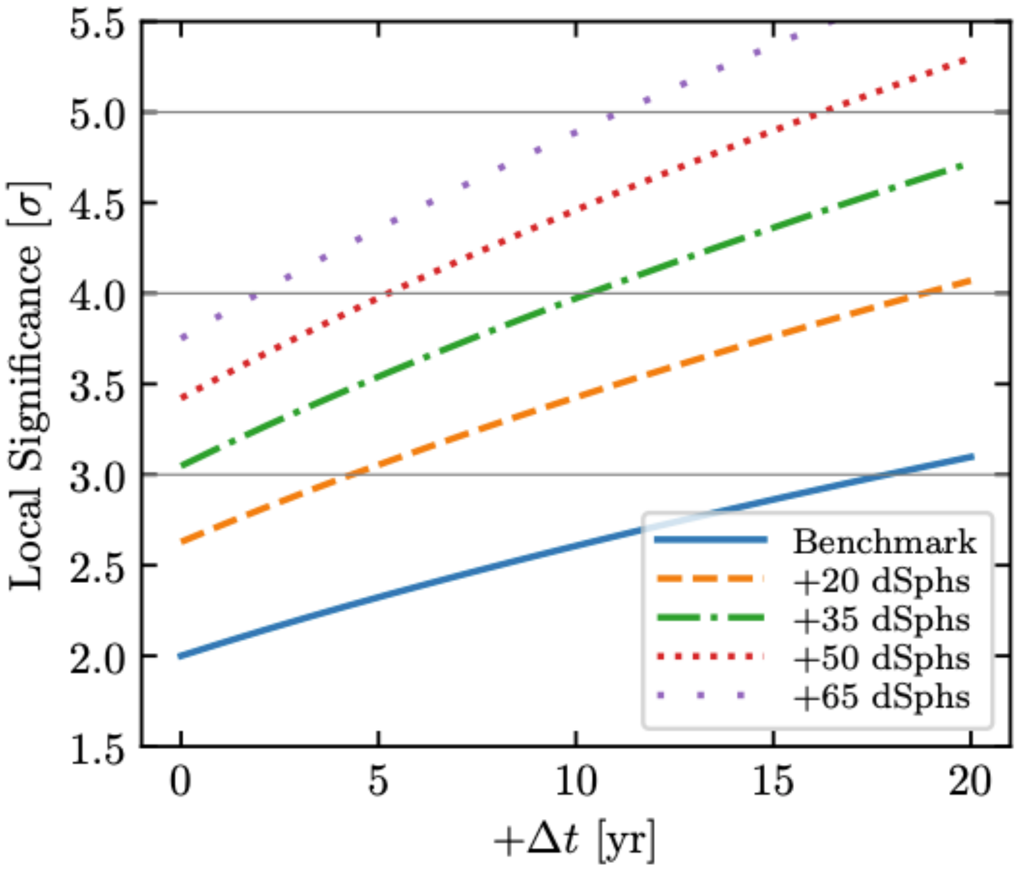
Shaded regions: blank-field analysis

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



Future of dSph DM searches





[McDaniel+'24]

How many dwarf galaxies do we *really* need?

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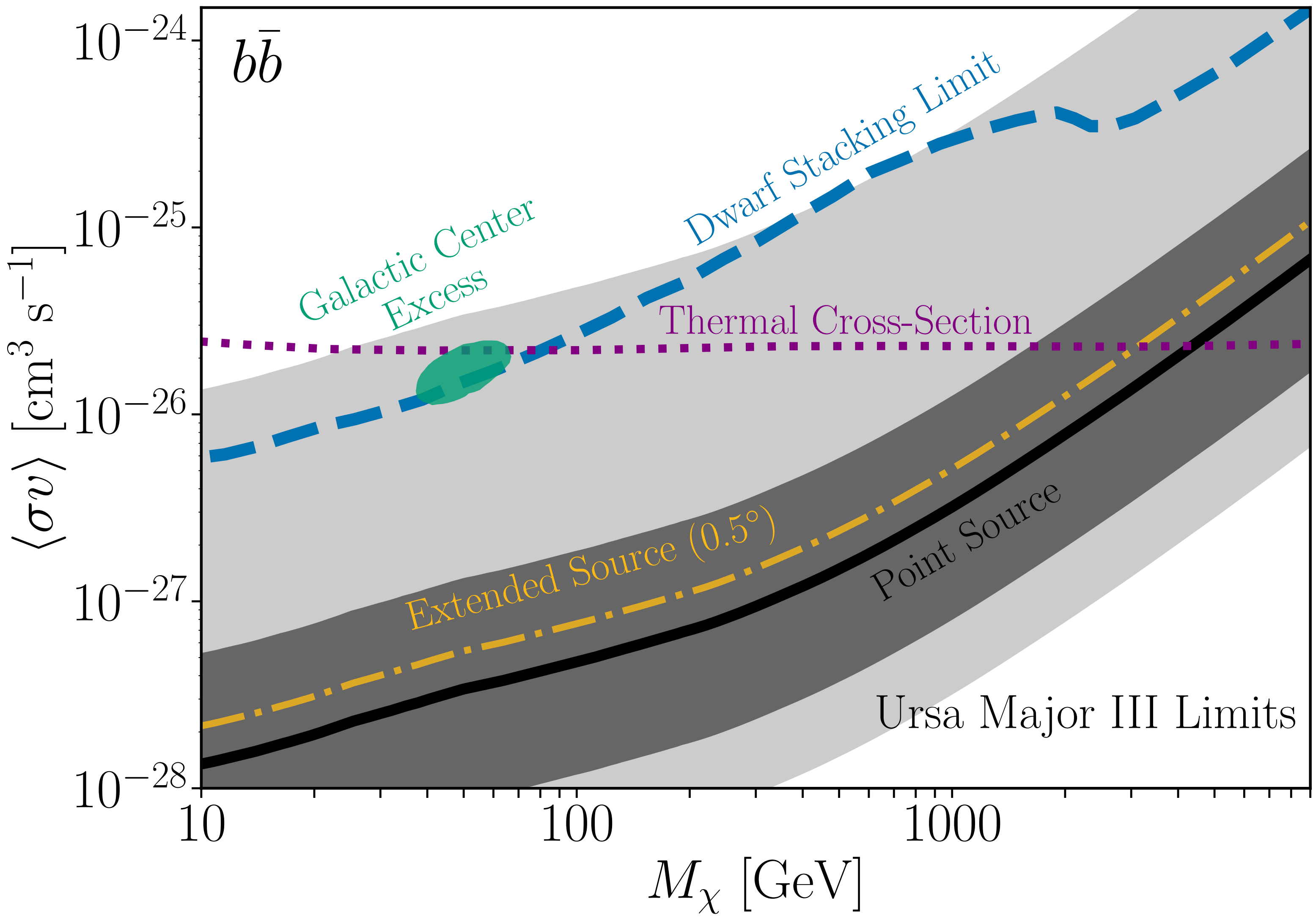
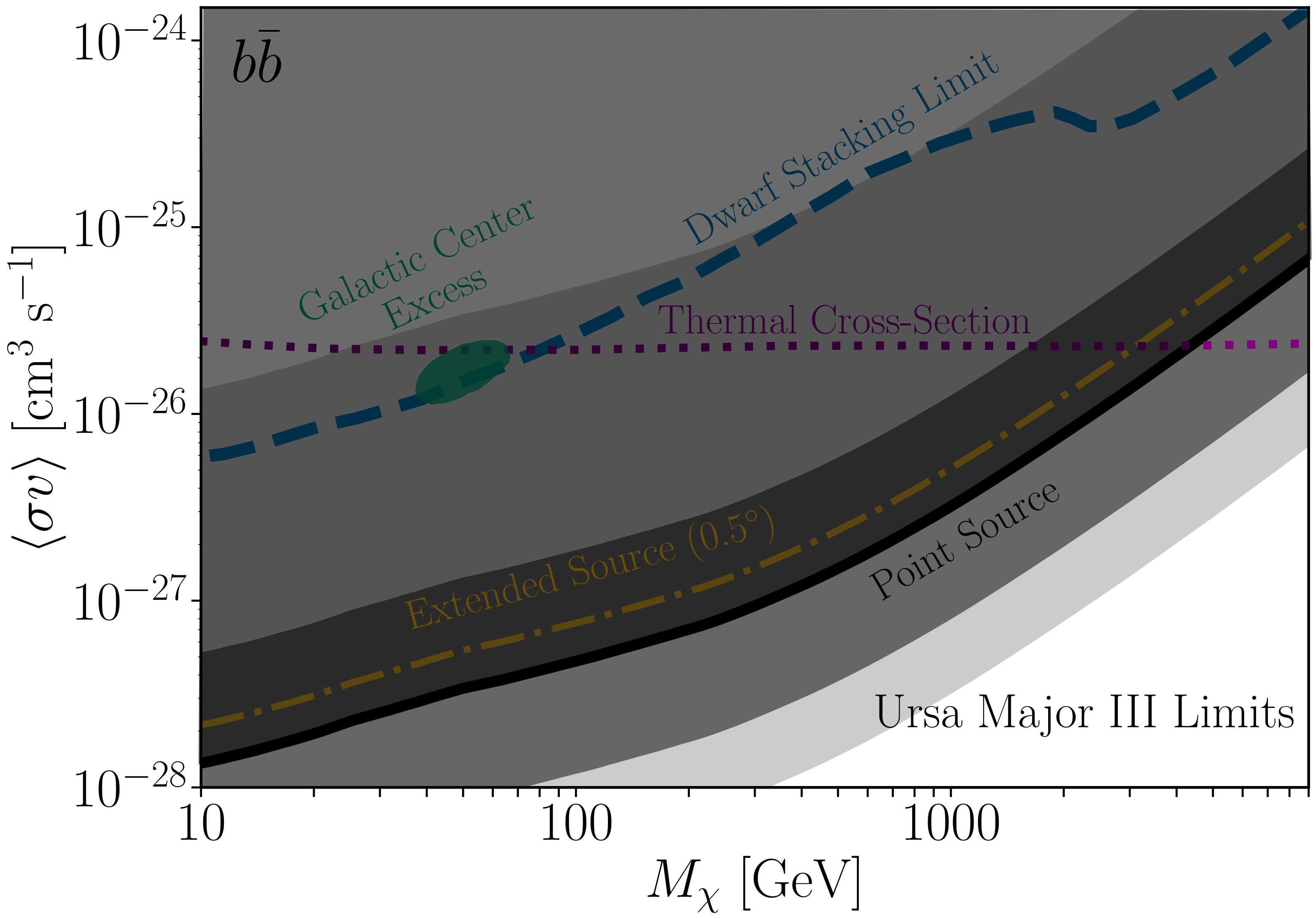
Maybe just one, but a good one?

Ursa Major III



[MC & Linden '24]

Ursa Major III



[MC & Linden '24]

Ursa Major III

[Discovery: Smith+ 2023]

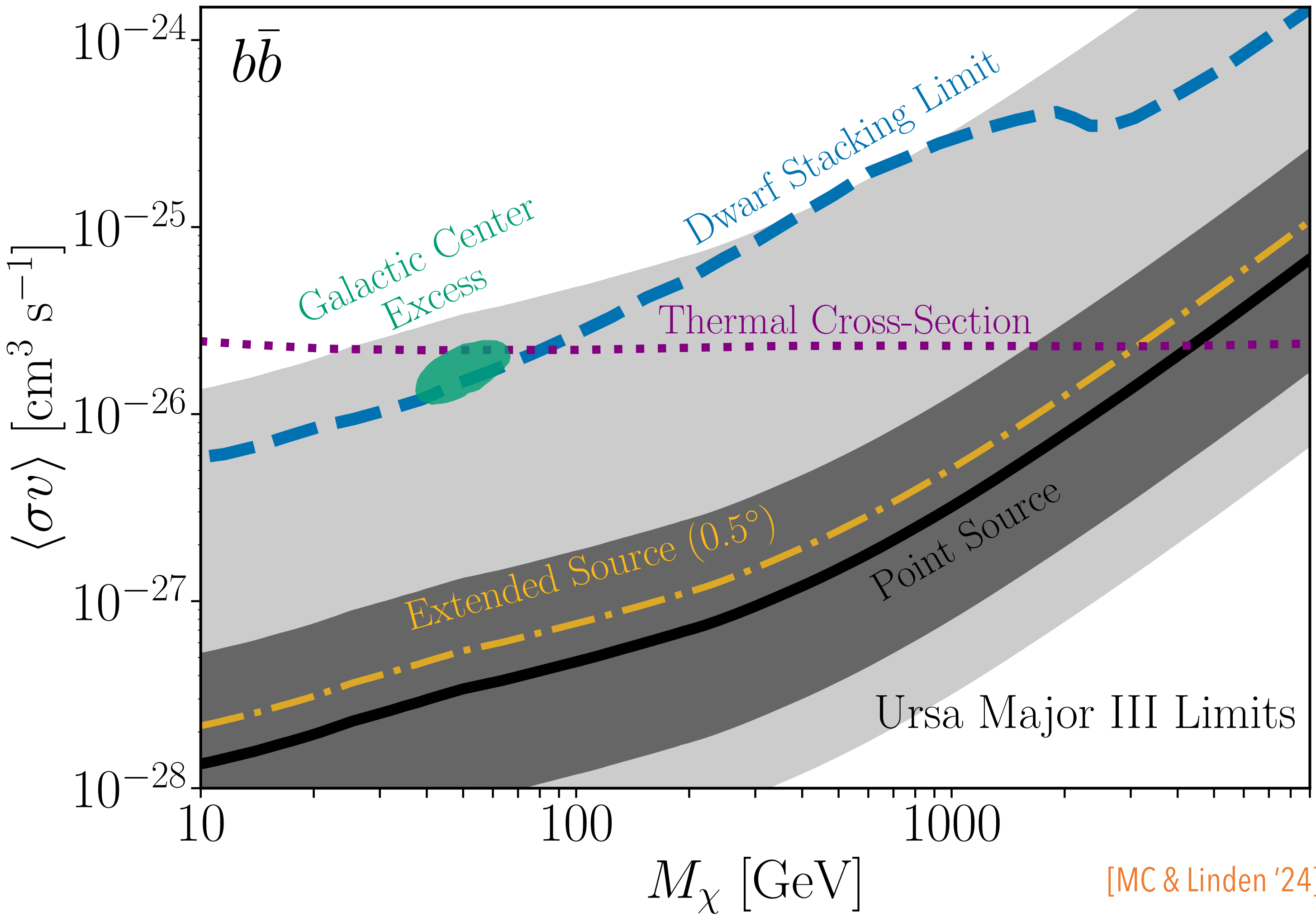
[J-factor: Errani+ 2023]

→ Unstable unless large DM content

→ Nearby (~10 kpc)

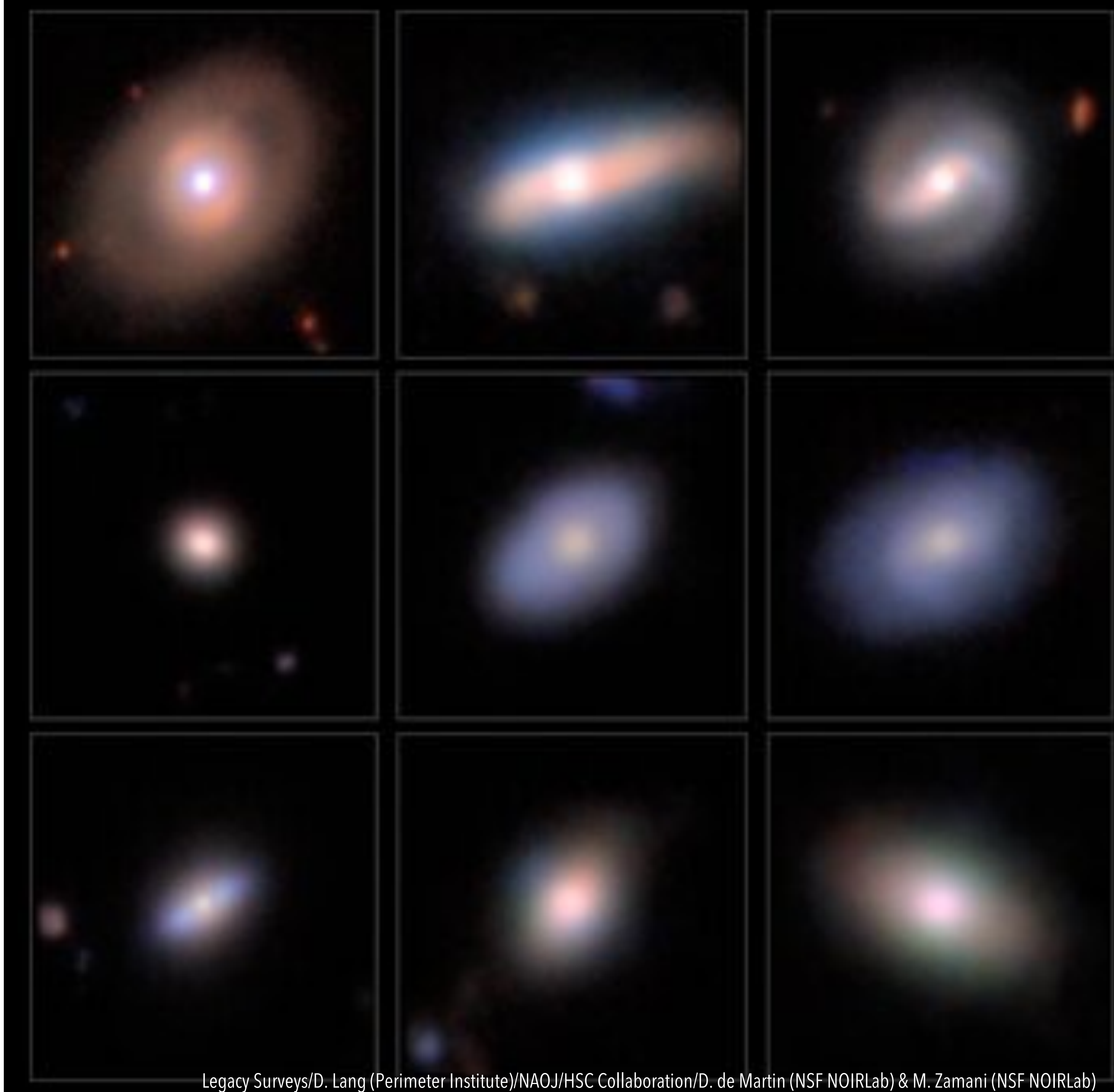
→ Strong constraints on DM annihilation

→ Confirming the dark matter density requires deeper optical surveys



[MC & Linden '24]

Target 2: dwarf AGN



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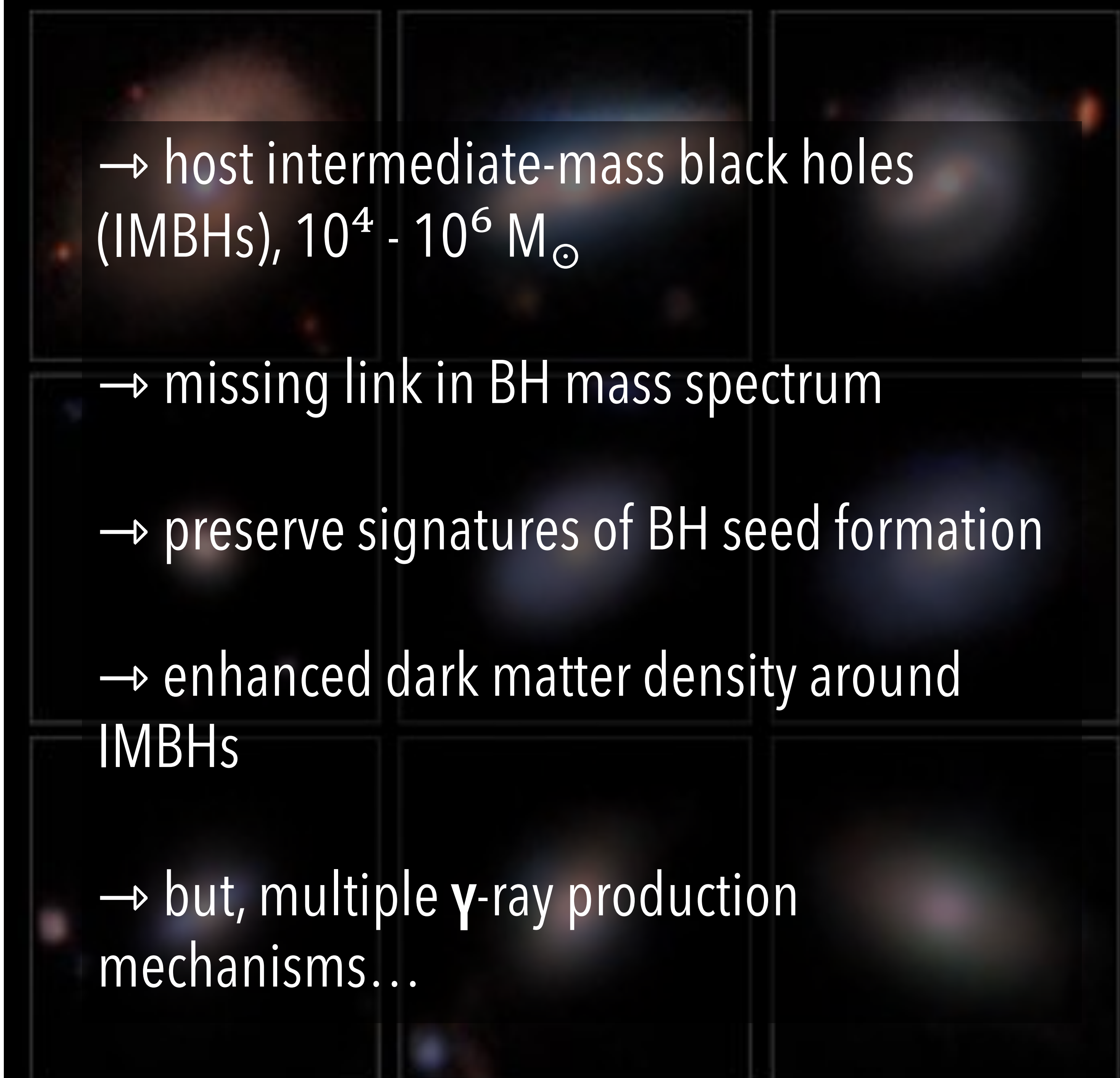


→ host intermediate-mass black holes (IMBHs), 10^4 - 10^6 $M_\odot$

→ missing link in BH mass spectrum

→ preserve signatures of BH seed formation

→ enhanced dark matter density around IMBHs

→ but, multiple **γ**-ray production mechanisms…

Legacy Surveys/D. Lang (Perimeter Institute)/NAOJ/HSC Collaboration/D. de Martin (NSF NOIRLab) & M. Zamani (NSF NOIRLab)

Alert: astrophysical backgrounds

Classical ways to produce γ-rays:

→ Accretion-related processes: Inverse Compton from corona/disk

→ Misaligned jets: Reduced Doppler boosting ⟶ softer spectra

→ Cosmic-ray interactions: Star formation/supernova activity

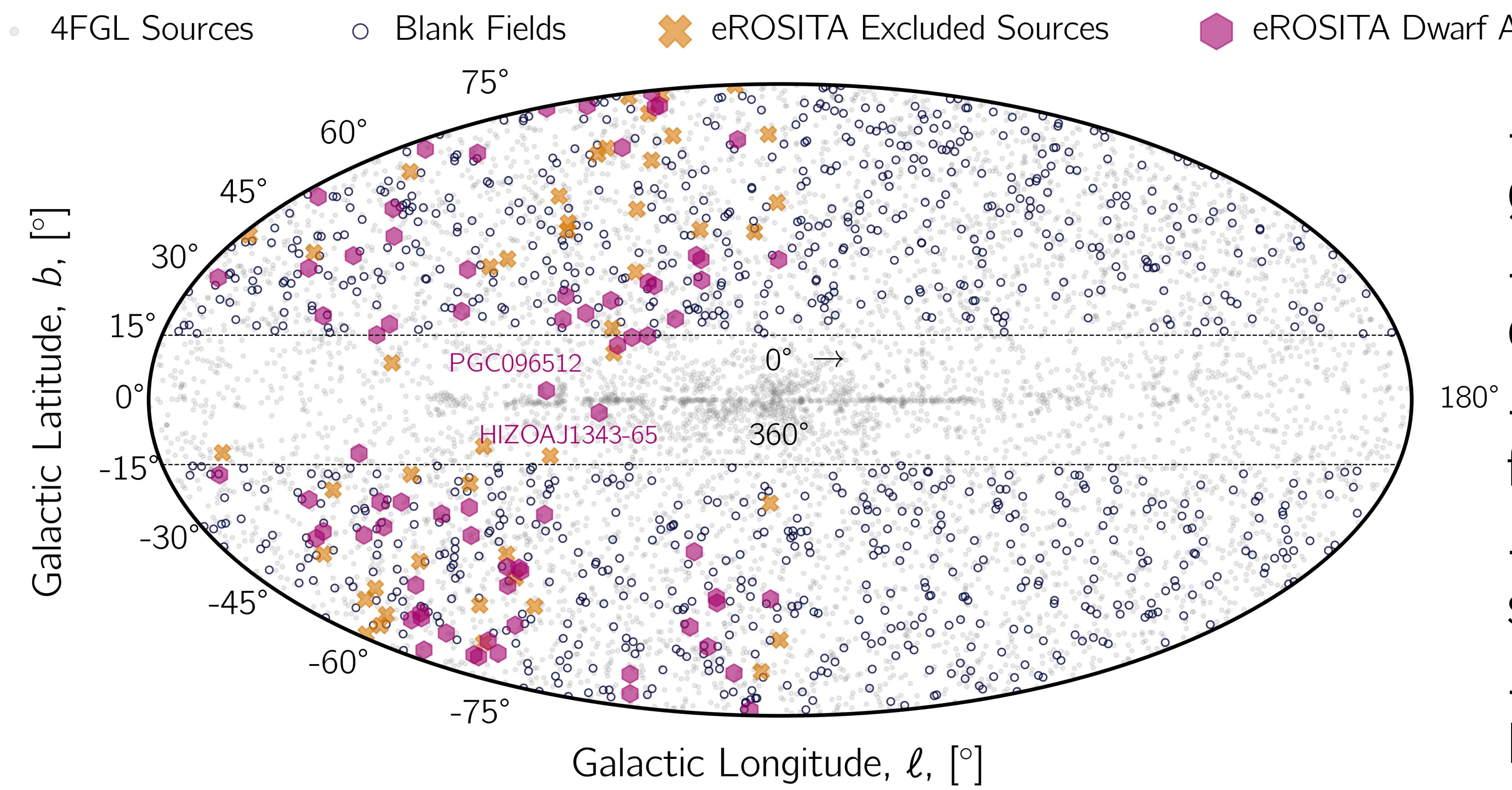
→ AGN-driven outflows: Shocks in interstellar medium

New ways to produce γ-rays:

→ Dark matter annihilation: Enhanced density around IMBHs

Multiple mechanisms likely contribute: requires multiwavelength approach to disentangle

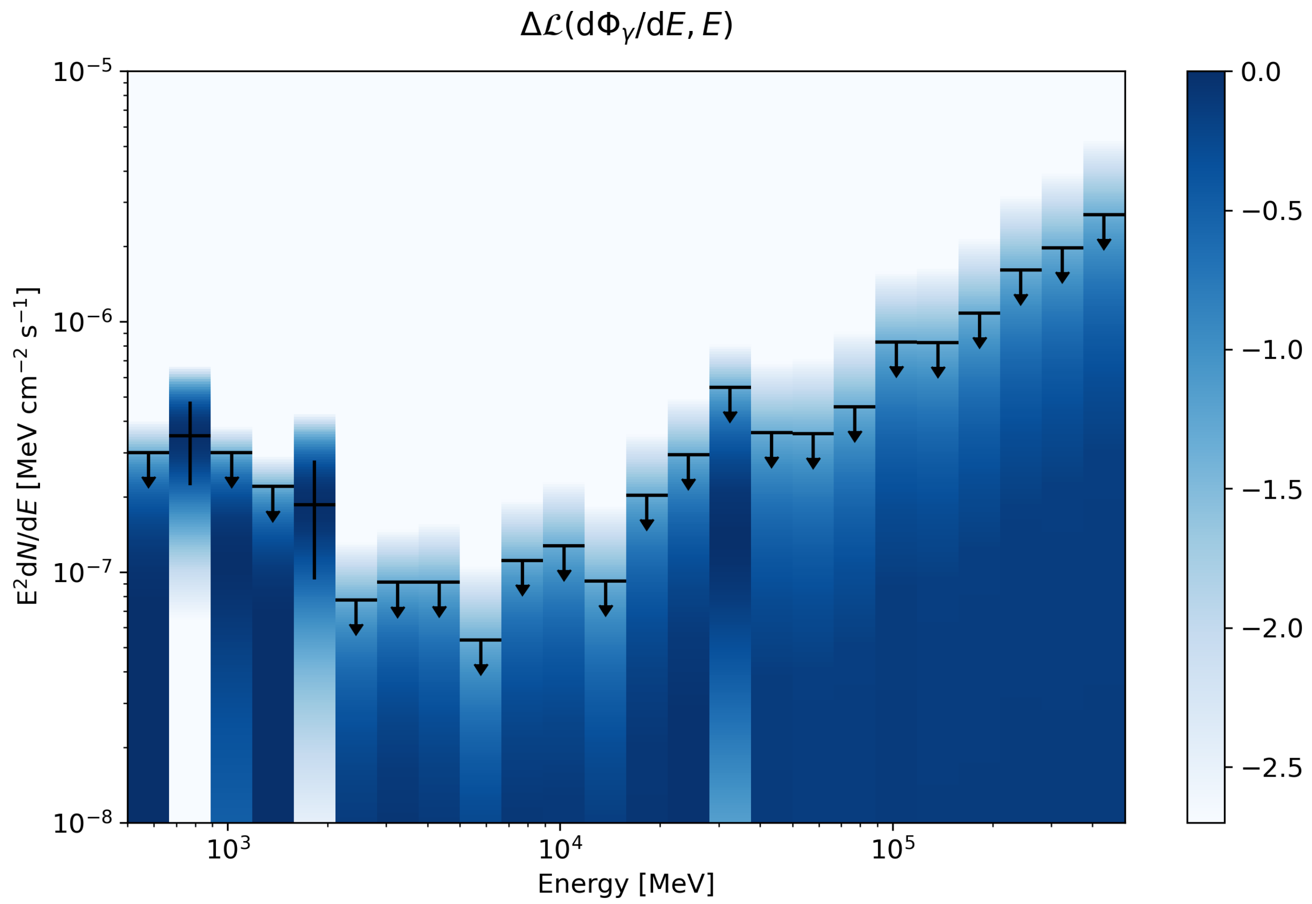
Dwarf AGN sample



- → 74 X-ray selected AGN in dwarf galaxies within 200 Mpc (eRASS1)
- → ULXs, X-ray binaries, background AGN excluded
- → ~50% are off-nuclear - displaced from galaxy centers
- → IMBH masses estimated via M--M_* scaling relations (10^4-10^6 $M_\odot$)
- → DESI found 2,444 dwarf AGN but leaves too few blank fields for statistical calibration, + contamination from SF

(Sacchi et al. 2024)

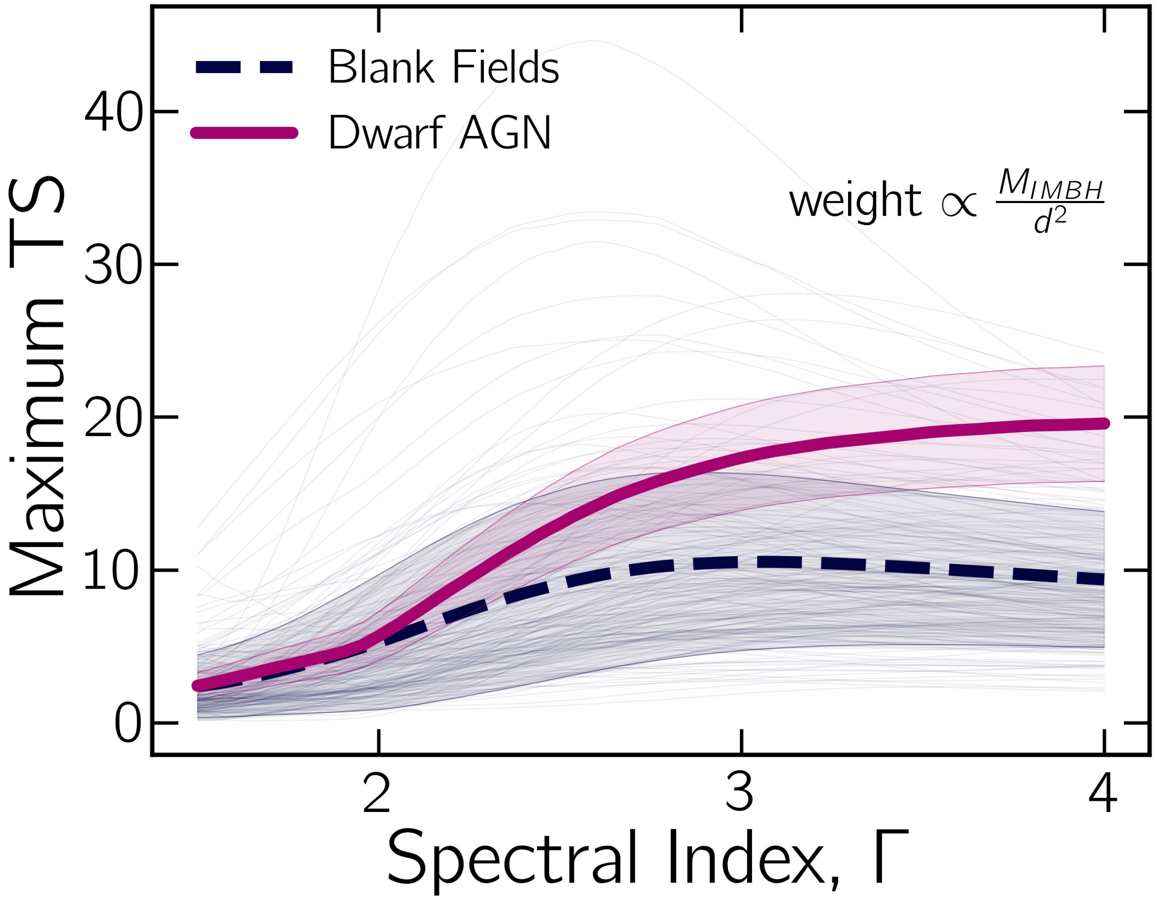
Fermi Analysis



- Standard *Fermi* analysis
- 15 years of *Fermi* data
- 500 MeV to 500 GeV
- 4FGL-DR4 Source catalog
- Construct TS profiles assuming power law
- No $>5\sigma$ detection for any of the 74 sources

Example, PGC 2077238

Joint Likelihood Analysis Results



→ Combined analysis of all 74 dwarf AGN

→ Soft spectral excess at **Γ** ~ 3.5

→ Approximately ~3σ above the null hypothesis (assuming Gaussian error propagation)

→ Weighted by M_{IMBH}/d^2

→ Soft excess remains robust down to 100 MeV

→ Spectral shape consistent across energy ranges

→ Not purely instrumental artifact

→ Suggests potential intrinsic astrophysical origin

But, should have we seen something?

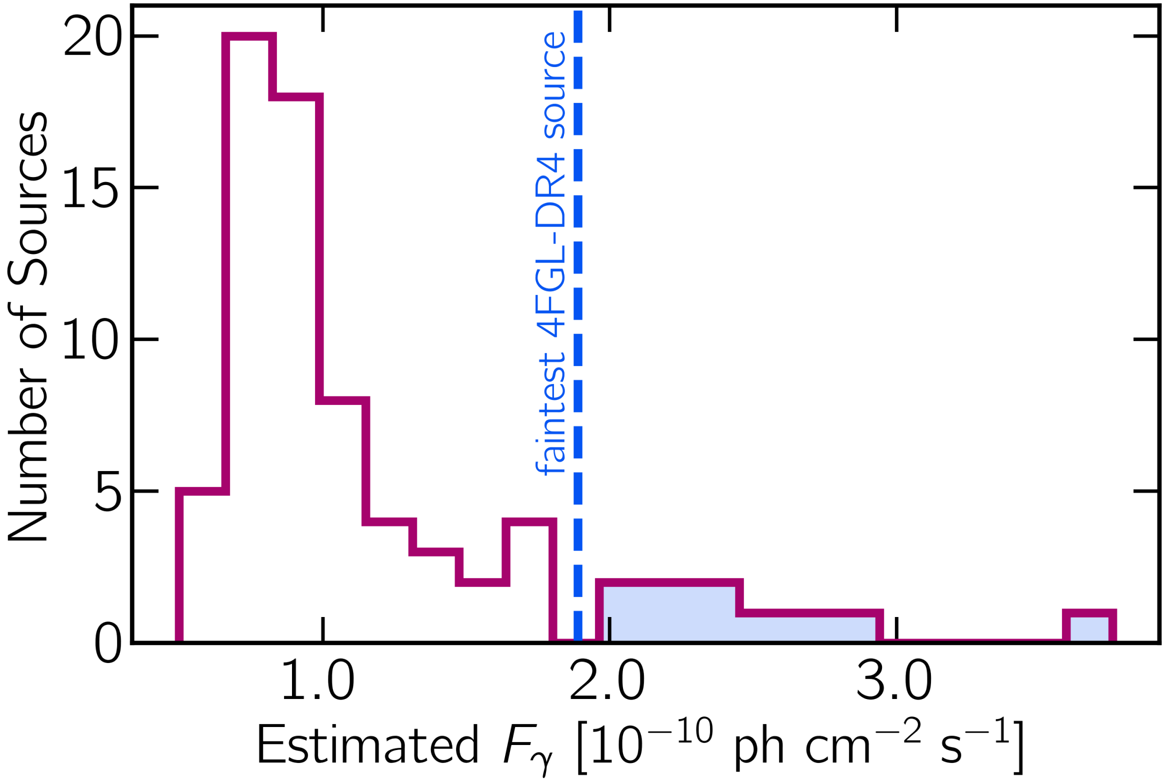
→ Applied BL Lac scaling (e.g., Li+ 2013):

$$\log L_\gamma = (0.59 \pm 0.05) \log L_X + (17.55 \pm 2.31)$$

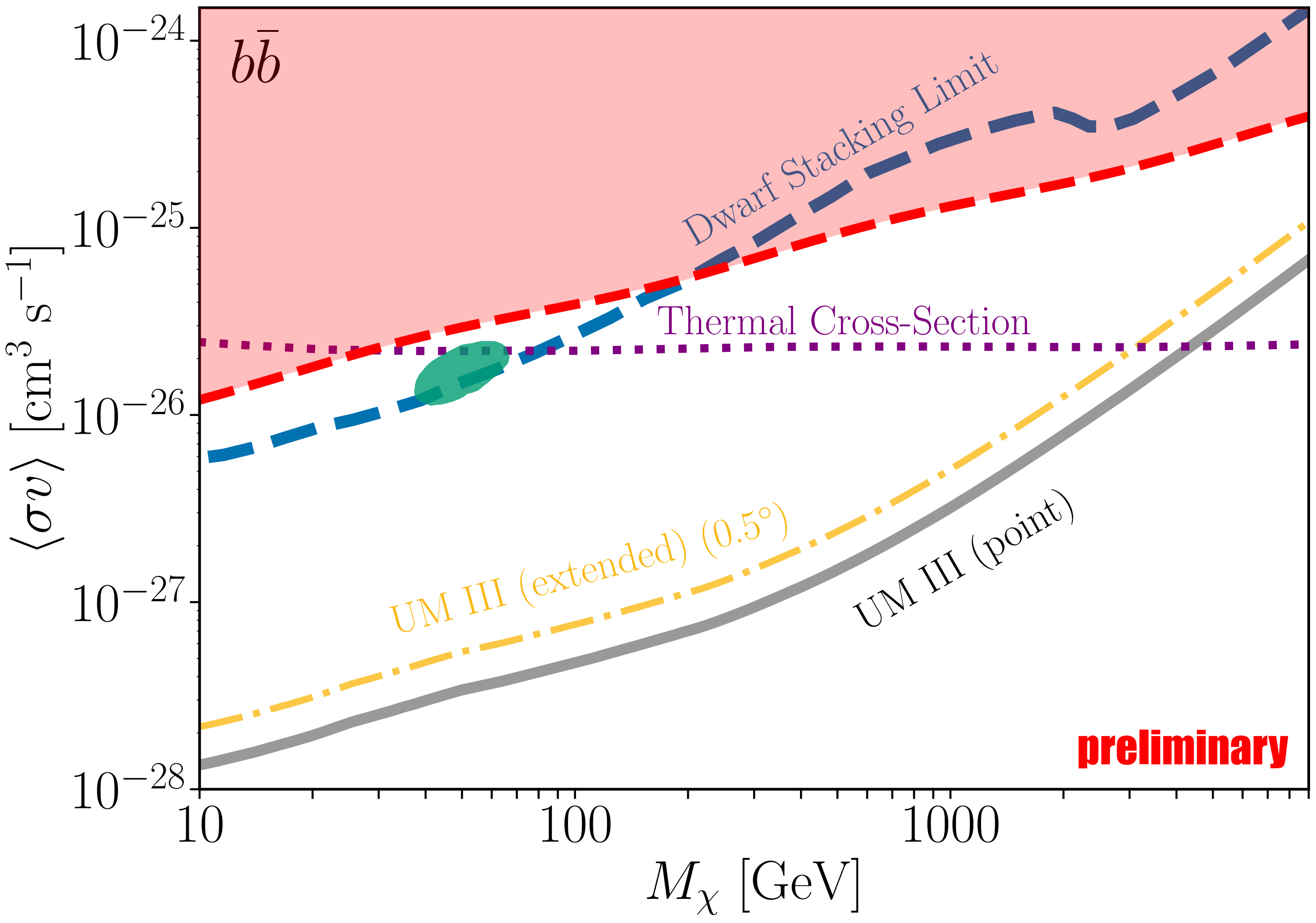
→ Most predicted fluxes just below *Fermi* threshold

→ Expected some scatter above detection limit

No firm detections suggest different physics



Dark Matter constraints

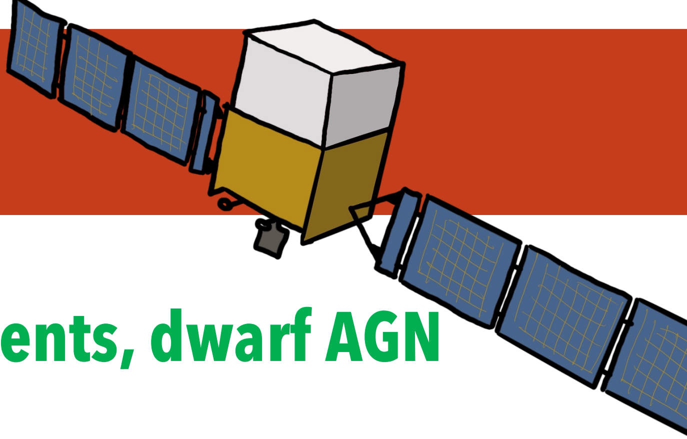


→ DM spike parameters randomly assigned from EAGLE simulation results to the IMBH AGN with similar masses (Aschersleben et al. 2024)

→ Model-dependent results - depend on assumed spike profiles (NFW) and IMBH-halo relationships

→ Currently exploring the robustness of these assumptions

Conclusions



Complementary approaches: dSphs probe "clean" DM environments, dwarf AGN probe enhanced DM densities around IMBHs

→ Ultra-faint dSphs: Ursa Major III sets the strongest individual constraints on DM annihilation from any single dwarf galaxy

→ Dwarf AGN - first systematic search: 74 eROSITA X-ray selected sources, 15 years *Fermi*-LAT data

→ **Key finding:** Intriguing $\sim 3\sigma$ soft spectral excess at $\Gamma \sim 3.5$ in joint likelihood

→ Future: eROSITA full survey (~1,350 dwarf AGN), multiwavelength follow-up, next-generation instruments (CTA, AMEGO-X)

→ results to appear following ICRC, stay tuned for arXiv:2507.xxxxx!

The littlest galaxies continue to provide the biggest insights into dark matter!