Gamma rays from the littlest galaxies

Tracing Accretion and Dark Matter in the Low-Mass Universe

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

November 5, 2025

TeV Particle Astrophysics
TeVPA
Valencia 2025

milena.crnogorcevic@fysik.su.se mcrnogor.github.io @mcrnogor

Gamma rays from the littlest galaxies

Tracing Accretion and Dark Matter in the Low-Mass Universe

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

November 5, 2025

TeV Particle Astrophysics
TeVPA
Valencia 2025

milena.crnogorcevic@fysik.su.se mcrnogor.github.io @mcrnogor

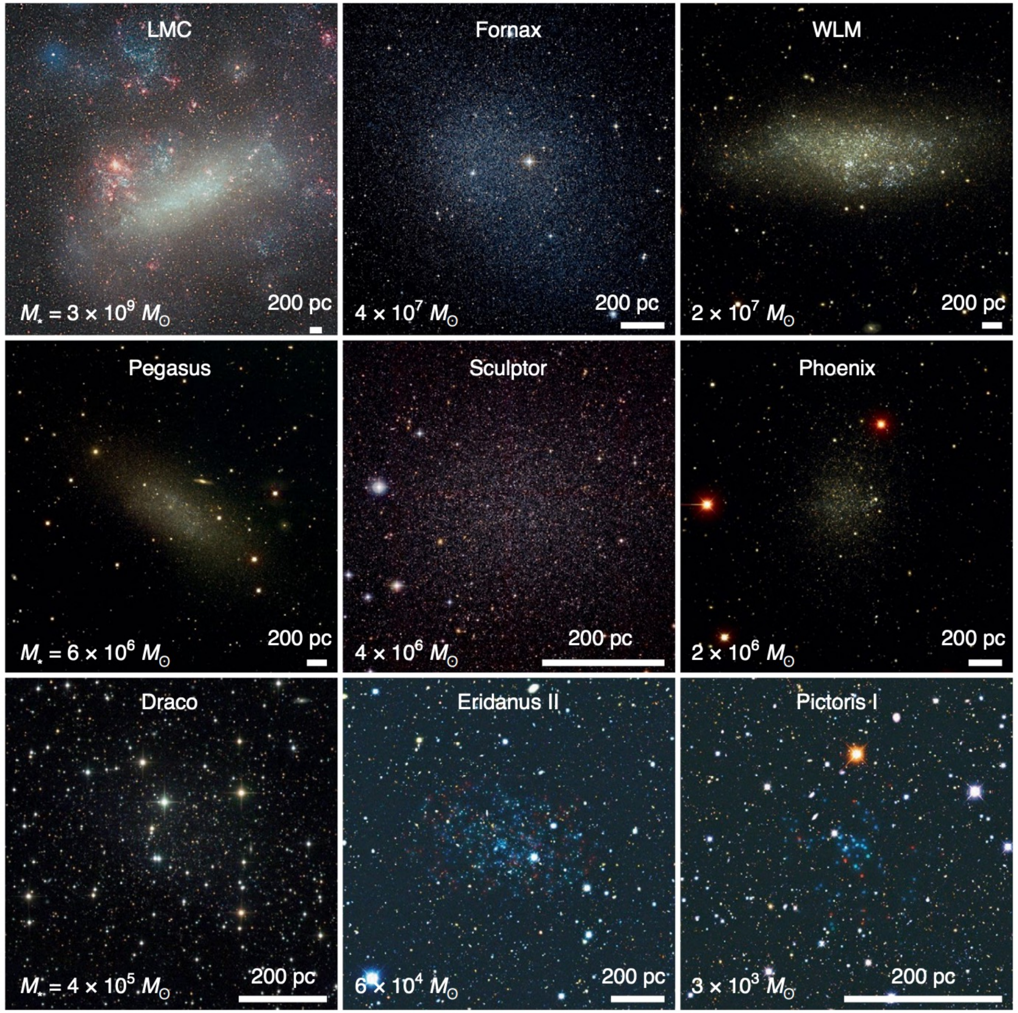
Dwarf galaxies: small but mighty

→ Low-mass galaxies:

tens of $M_{sun} < M_{stellar} < 3 \times 10^9 M_{sun}$

→ At the forefront of current/future observational efforts:

- Near-field cosmology (*Gaia*, DES, Rubin/LSST)
- Early Universe & Reionization (JWST)
- Accretion & Feedback (Athena, AXIS, SKA, ngVLA)
- Fundamental physics & dark matter (*Fermi*, IACTs, IceCube)



[Bullock & Boylan-Kolchin 2017]

Representative sample of the Local Group dwarf galaxies.

Dwarf galaxies: small but mighty

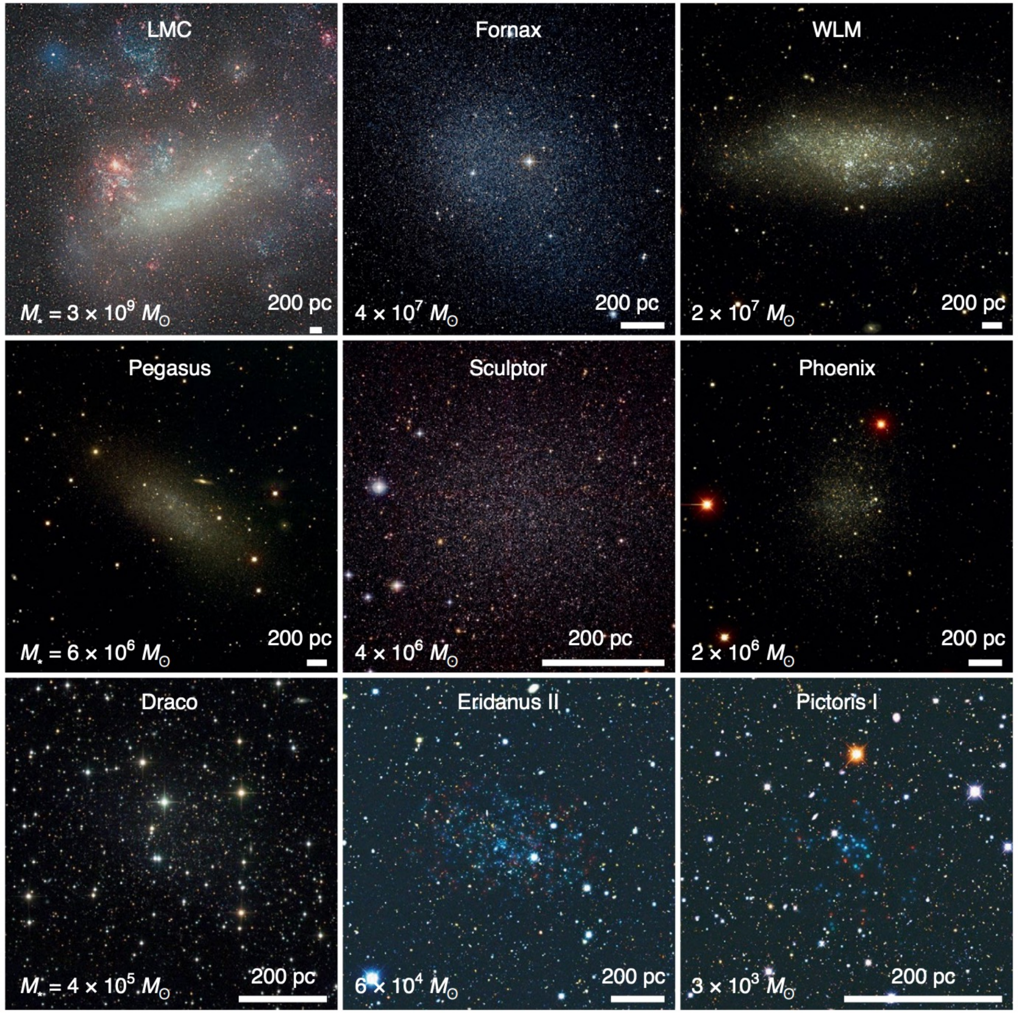
→ Low-mass galaxies:

tens of $M_{sun} < M_{stellar} < 3 \times 10^9\, M_{sun}$

→ At the forefront of current/future observational efforts:

- Near-field cosmology (*Gaia*, DES, Rubin/LSST)
- Early Universe & Reionization (JWST)
- Accretion & Feedback (Athena, AXIS, SKA, ngVLA)
- Fundamental physics & dark matter (*Fermi*, IACTs, IceCube)

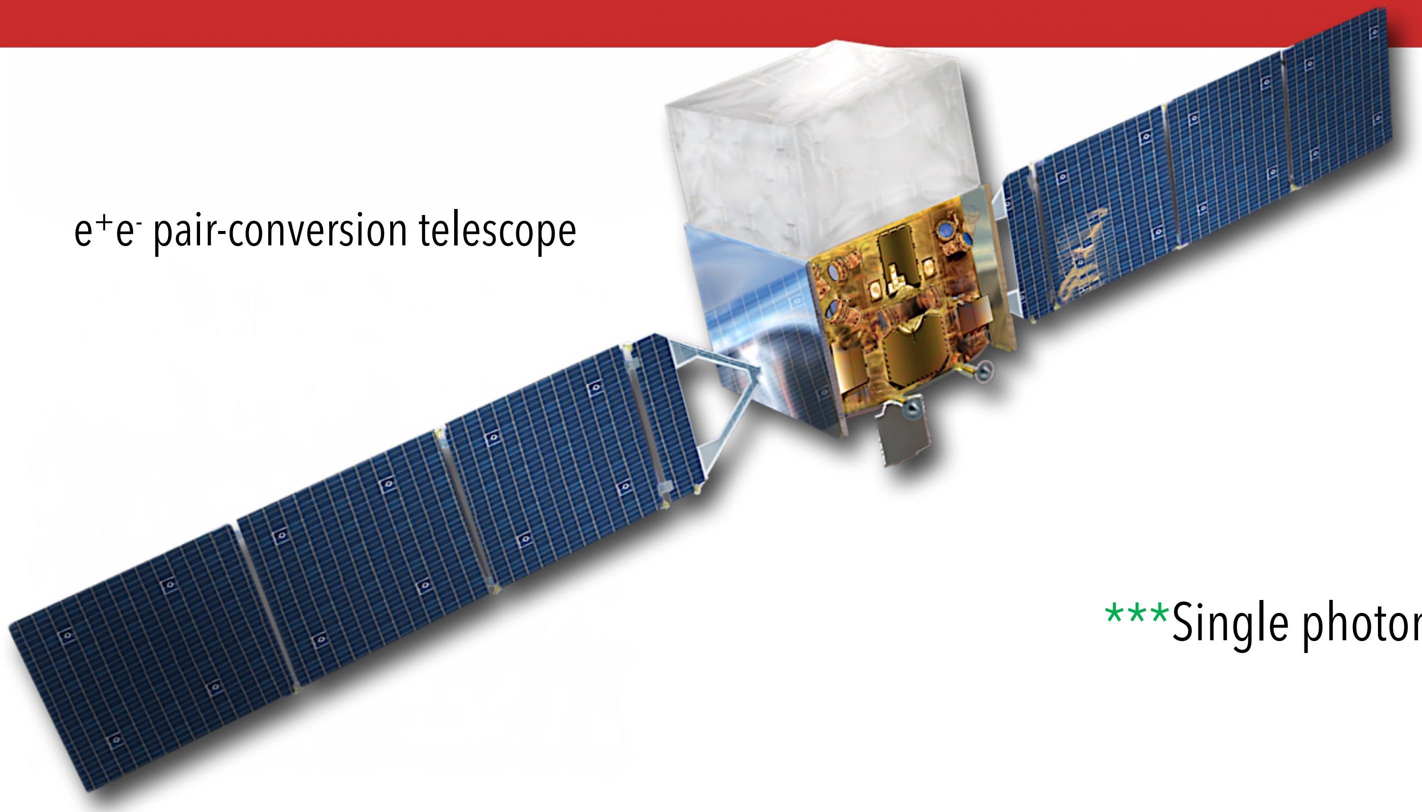
Dwarf galaxies: bridges between **large scale structure**, **galaxy formation**, & **fundamental physics**.



[Bullock & Boylan-Kolchin 2017]

Representative sample of the Local Group dwarf galaxies.

Obligatory slide on Fermi Large Area Telescope



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

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

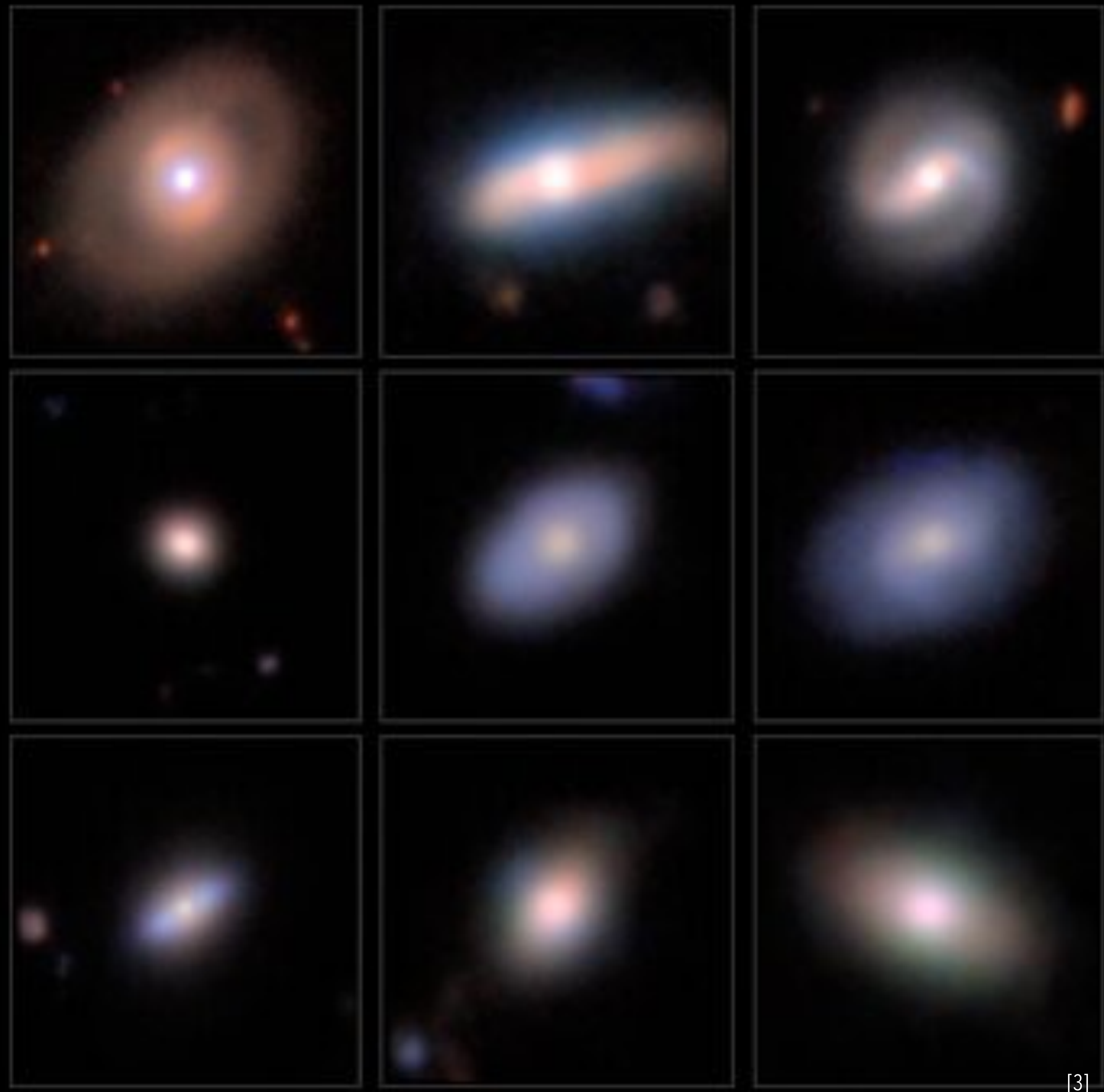
individual γ rays convert into e^+e^- pairs
→ tracks (localization) & deposited energy

…it also detects electrons.

Dwarf AGN

Based on Crnogorčević+ 2025, arXiv: **2509.18239**

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

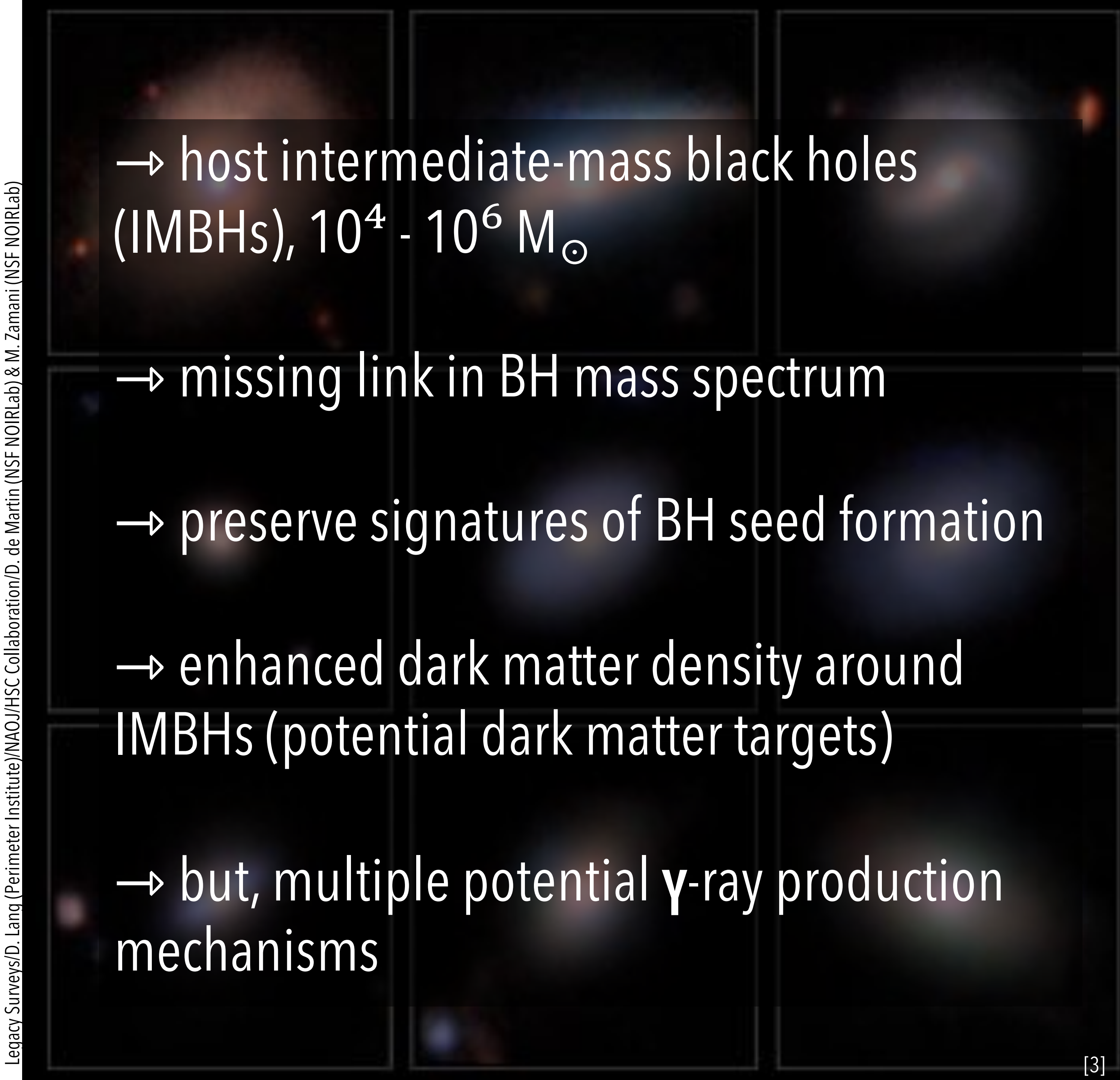


[3]

Dwarf AGN

Based on Crnogorčević+ 2025, arXiv: **2509.18239**

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



→ 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 (potential dark matter targets)

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

Gammas from AGNs

Classical ways to produce γ-rays:

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

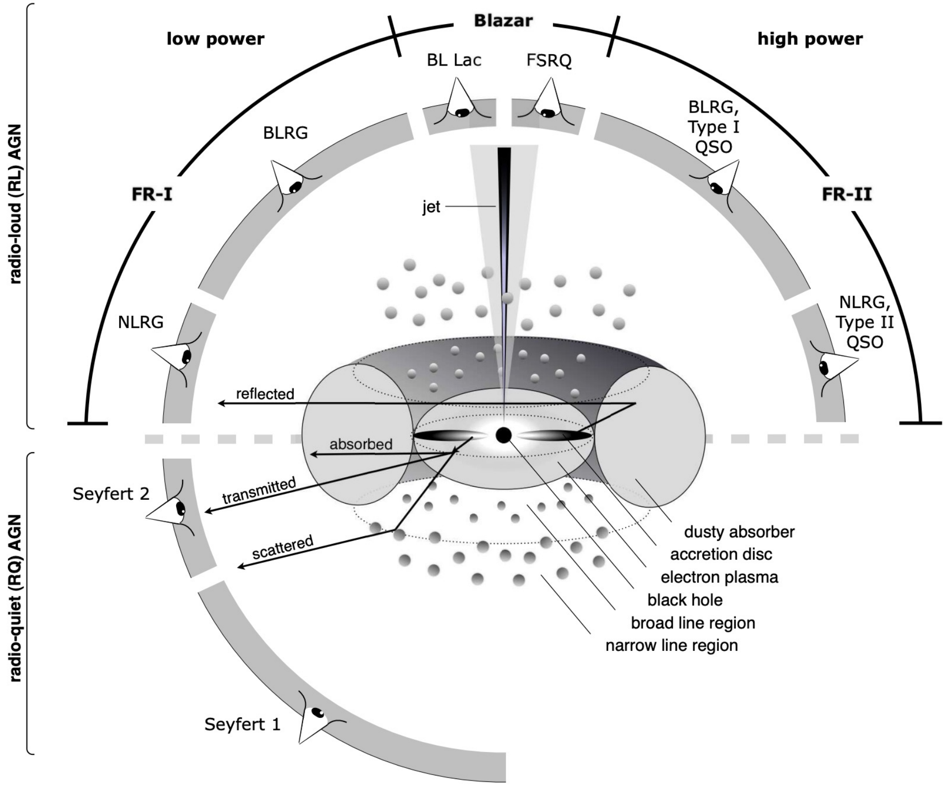
→ Misaligned jets: Reduced Doppler boosting → softer spectra

→ 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



[Beckmann & Shrader 2013]

Gammas from AGNs

Classical ways to produce γ-rays:

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

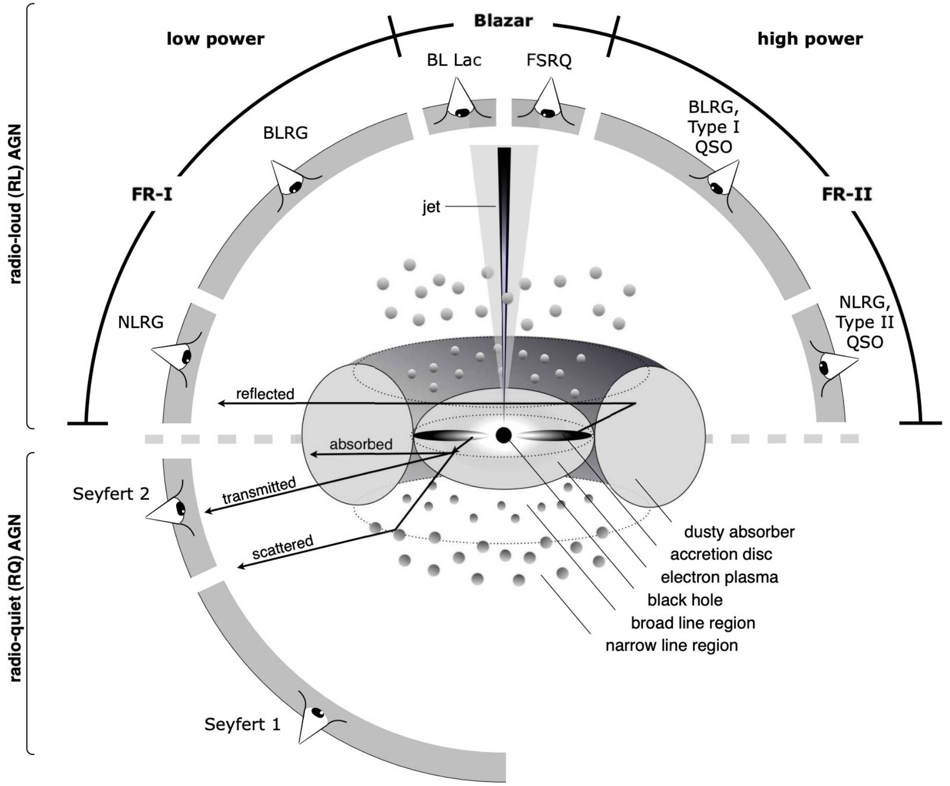
→ Misaligned jets: Reduced Doppler boosting → softer spectra

→ Cosmic-ray interactions: Star formation/supernova activity

→ AGN-driven outflows: Shocks in interstellar medium

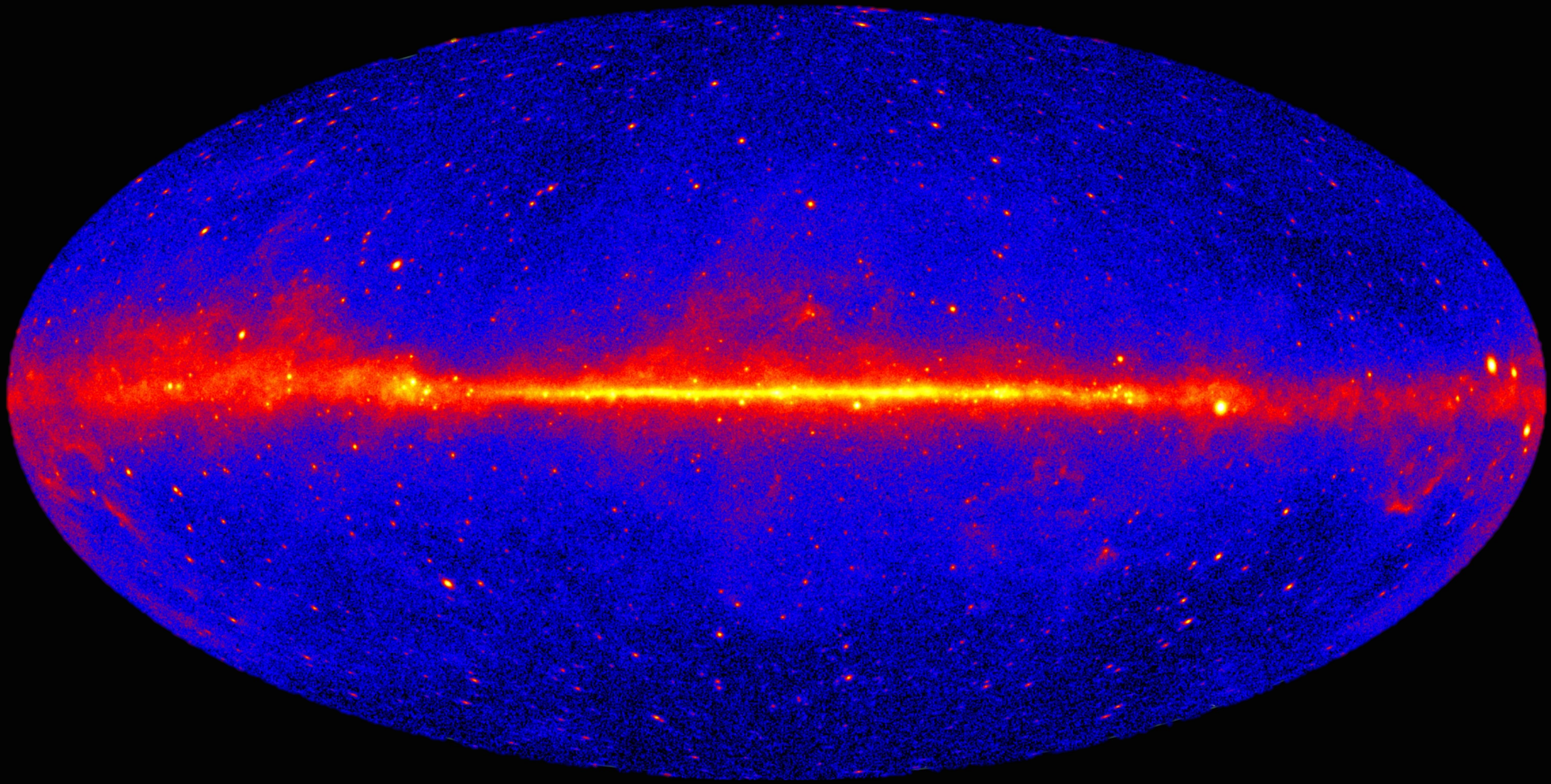
New ways to produce γ-rays:

→ Dark matter annihilation: Enhanced density around IMBHs

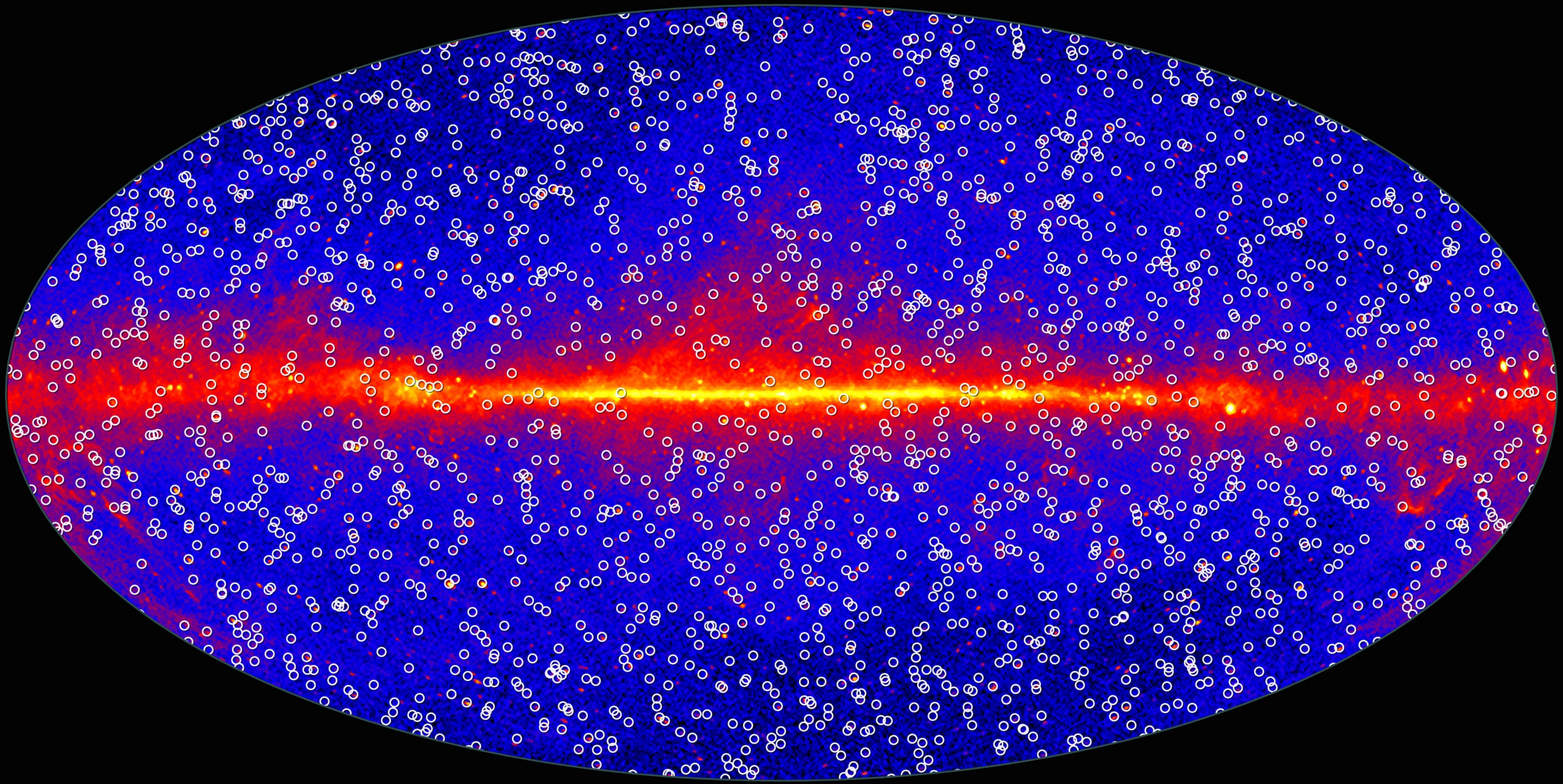


[Beckmann & Shrader 2013]

Multiple mechanisms likely contribute: requires multiwavelength approach to disentangle



Fermi-LAT Collaboration



Fermi-LAT Collaboration

Some questions you may ask...

Some questions you may ask…

→ Do gamma-ray emission mechanisms observed in massive galaxy AGN **scale down** to IMBHs?

Some questions you may ask…

→ Do gamma-ray emission mechanisms observed in massive galaxy AGN **scale down** to IMBHs?

→ How does emission efficiency depend on e.g., **black hole mass** as a proxy for accretion rate?

Some questions you may ask...

→ Do gamma-ray emission mechanisms observed in massive galaxy AGN **scale down** to IMBHs?

→ How does emission efficiency depend on e.g., **black hole mass** as a proxy for accretion rate?

→ Can gamma-ray observations distinguish between **competing emission models?**

Some questions you may ask...

→ Do gamma-ray emission mechanisms observed in massive galaxy AGN **scale down** to IMBHs?

→ How does emission efficiency depend on e.g., **black hole mass** as a proxy for accretion rate?

→ Can gamma-ray observations distinguish between **competing emission models?**

→ Are there unique signatures in IMBH systems **not seen** in SMBH-hosted AGN?

Dwarf AGN sample

MaNGA AGN dwarf galaxies (MAD) - I. A new sample of AGN in dwarf galaxies with spatially resolved spectroscopy

M. Mezcua[1,2]★, H. Domínguez Sánchez[3]

[1] *Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Magrans, 08193 Barcelona, Spain*

[2] *Institut d'Estudis Espacials de Catalunya (IEEC), Carrer Gran Capità, 08034 Barcelona, Spain*

3 *Centro de Estudios de Física del Cosmos de Aragón (CEFCA), Plaza San Juan, 1, 44001, Teruel, Spain*

Accepted 2024 January 24. Received 2024 January 8; in original form 2023 May 19

ABSTRACT

The finding of active galactic nuclei (AGN) in dwarf galaxies has important implications for galaxy evolution and supermassive black hole formation models. Yet, how AGN in dwarf galaxies form is still debated, in part due to scant demographics. We make use of the MaNGA survey, comprising ~10,000 galaxies at z < 0.15, to identify AGN dwarf galaxies using a spaxel by spaxel classification in three spatially-resolved emission line diagnostic diagrams (the [NII-, [SII]- and [OI]-BPT) and the WHAN diagram. This yields a sample of 664 AGN dwarf galaxies, the largest to date, and an AGN fraction of ~ 20% that is significantly larger than that of single-fiber-spectroscopy studies (i.e. ~ 1%). This can be explained by the lower bolometric luminosity (< 10^{42} erg s^{-1}) and accretion rate (sub-Eddington) of the MaNGA AGN dwarf galaxies. We additionally identify 1,176 SF-AGN (classified as star-forming in the [NII]-BPT but as AGN in the [SII]- and [OI]-BPT), 122 Composite, and 173 LINER sources. The offset between the optical center of the galaxy and the median position of the AGN spaxels is more than 3 arcsec for ~62% of the AGN, suggesting that some could be off-nuclear. We also identify seven new broad-line AGN with log M_{BH} = 5.0 - 5.9 $M_{\odot}$. Our results show how integral-field spectroscopy is a powerful tool for uncovering faint and low-accretion AGN and better constraining the demographics of AGN in dwarf galaxies.

Key words: Galaxies: dwarf, active, accretion

Dwarf AGN sample

MaNGA AGN dwarf galaxies (M
dwarf galaxies with spatiall

M. Mezcua[1,2]★, H
[1] Institute of Space Scien
[2] Institut d'Estudi
3 Centro

Accepted 2024

i
als
inte
bette

Key wo

DRAFT VERSION FEBRUARY 20, 2025
Typeset using LaTeX **twocolumn** style in AASTeX631

Tripling the Census of Dwarf AGN Candidates Using DESI Early Data

RAGADEEPIKA PUCHA,[1,2] S. JUNEAU,[3] ARJUN DEY,[3] M. SIUDEK,[4,5] M. MEZCUA,[6,4] J. MOUSTAKAS,[7] S. BENZVI,[8] K. HAINLINE,[2] R. HVIDING,[9,2] YAO-YUAN MAO,[1] D. M. ALEXANDER,[10,11] R. ALFARSY,[12] C. CIRCOSTA,[13,14] WEI-JIAN GUO,[15] V. MANWADKAR,[16,17] P. MARTINI,[18,19,20] B. A. WEAVER,[3] J. AGUILAR,[21] S. AHLEN,[22] D. BIANCHI,[23] D. BROOKS,[14] R. CANNING,[12] T. CLAYBAUGH,[21] K. DAWSON,[24] A. DE LA MACORRA,[25] BIPRATEEP DEY,[26,27] P. DOEL,[14] A. FONT-RIBERA,[14,28] J. E. FORERO-ROMERO,[29,30] E. GAZTAÑAGA,[6,12,4] S. GONTCHO A GONTCHO,[21] G. GUTIERREZ,[31] K. HONSCHEID,[18,32,20] R. KEHOE,[33] S. E. KOPOSOV,[34,35] A. LAMBERT,[21] M. LANDRIAU,[21] L. LE GUILLOU,[36] A. MEISNER,[3] R. MIQUEL,[37,28] F. PRADA,[38] G. ROSSI,[39] E. SANCHEZ,[40] D. SCHLEGEL,[21] M. SCHUBNELL,[41,42] H. SEO,[43] D. SPRAYBERRY,[3] G. TARLÉ,[42] AND H. ZOU[15]

ABSTRACT

Using early data from the Dark Energy Spectroscopic Instrument (DESI) survey, we search for AGN signatures in 410,757 line-emitting galaxies. By employing the BPT emission-line ratio diagnostic diagram, we identify AGN in 75,928/296,261 (≈25.6%) high-mass ($\log(M_\star/M_\odot) > 9.5$) and 2,444/114,496 (≈2.1%) dwarf ($\log(M_\star/M_\odot) \leq 9.5$) galaxies. Of these AGN candidates, 4,181 sources exhibit a broad Hα component, allowing us to estimate their BH masses via virial techniques. This study more than triples the census of dwarf AGN and doubles the number of intermediate-mass black hole (IMBH; $M_{\rm BH} \leq 10^6\ M_\odot$) candidates, spanning a broad discovery space in stellar mass ($7 < \log(M_\star/M_\odot) < 12$) and redshift ($0.001 < z < 0.45$). The observed AGN fraction in dwarf galaxies (≈2.1%) is nearly four times higher than prior estimates, primarily due to DESI's smaller fiber size, which enables the detection of lower luminosity dwarf AGN candidates. We also extend the $M_{\rm BH} - M_\star$ scaling relation down to $\log(M_\star/M_\odot) \approx 8.5$ and $\log(M_{\rm BH}/M_\odot) \approx 4.4$, with our results aligning well with previous low-redshift studies. The large statistical sample of dwarf AGN candidates from current DESI releases will be invaluable for enhancing our understanding of galaxy evolution at the low-mass end of the galaxy mass function.

Dwarf AGN sample

DRAFT VERSION FEBRUARY 4, 2025
Typeset using LaTeX **twocolumn** style in AASTeX631

X-Ray Bright Active Galactic Nuclei in Local Dwarf Galaxies: Insights from eROSITA

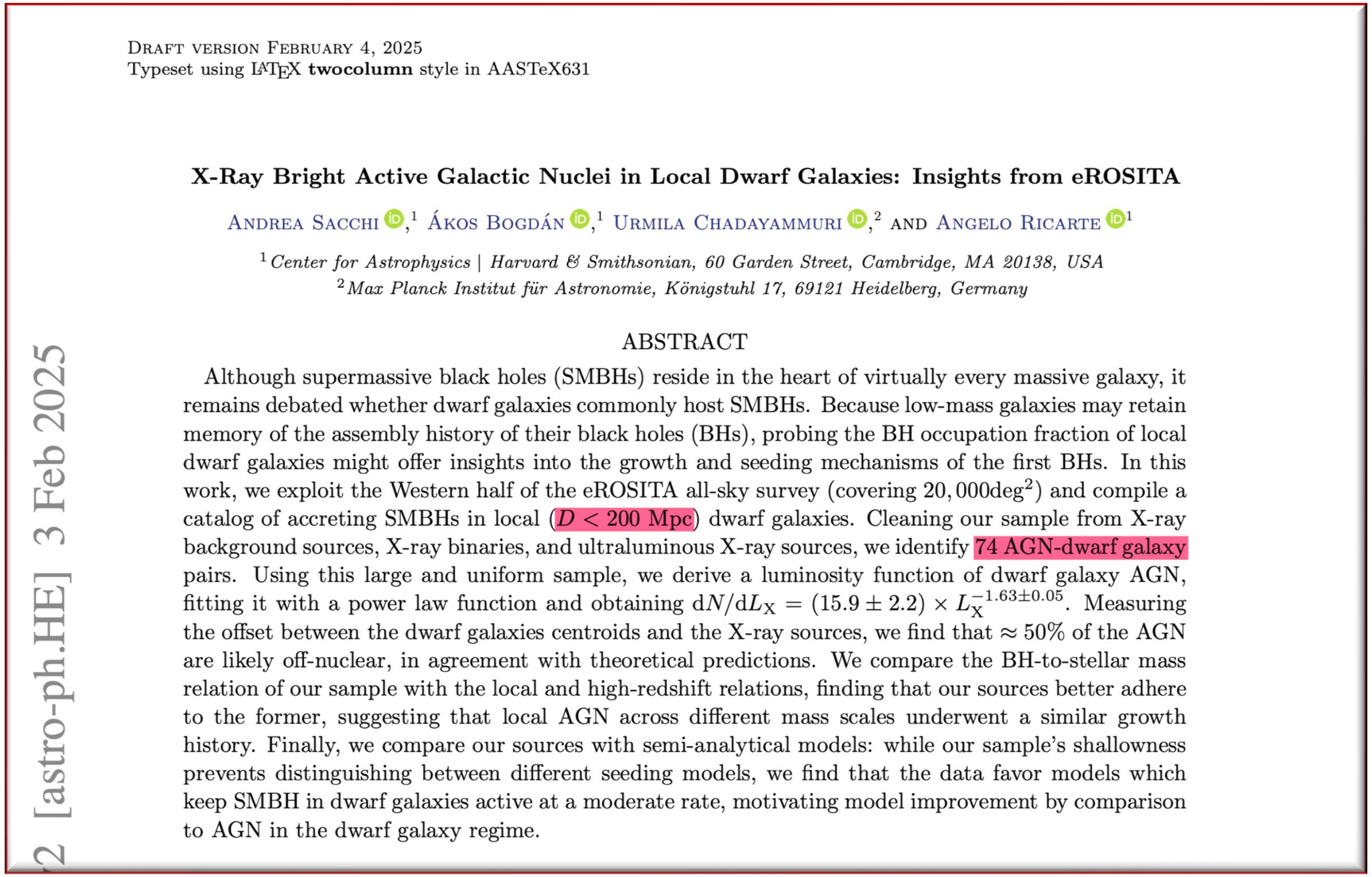
ANDREA SACCHI,[1] ÁKOS BOGDÁN,[1] URMILA CHADAYAMMURI,[2] AND ANGELO RICARTE[1]

[1] *Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 20138, USA*
[2] *Max Planck Institut für Astronomie, Königstuhl 17, 69121 Heidelberg, Germany*

ABSTRACT

Although supermassive black holes (SMBHs) reside in the heart of virtually every massive galaxy, it remains debated whether dwarf galaxies commonly host SMBHs. Because low-mass galaxies may retain memory of the assembly history of their black holes (BHs), probing the BH occupation fraction of local dwarf galaxies might offer insights into the growth and seeding mechanisms of the first BHs. In this work, we exploit the Western half of the eROSITA all-sky survey (covering 20,000deg^2) and compile a catalog of accreting SMBHs in local ($D < 200$ Mpc) dwarf galaxies. Cleaning our sample from X-ray background sources, X-ray binaries, and ultraluminous X-ray sources, we identify 74 AGN-dwarf galaxy pairs. Using this large and uniform sample, we derive a luminosity function of dwarf galaxy AGN, fitting it with a power law function and obtaining $\mathrm{d}N/\mathrm{d}L_\mathrm{X} = (15.9 \pm 2.2) \times L_\mathrm{X}^{-1.63\pm0.05}$. Measuring the offset between the dwarf galaxies centroids and the X-ray sources, we find that $\approx 50\%$ of the AGN are likely off-nuclear, in agreement with theoretical predictions. We compare the BH-to-stellar mass relation of our sample with the local and high-redshift relations, finding that our sources better adhere to the former, suggesting that local AGN across different mass scales underwent a similar growth history. Finally, we compare our sources with semi-analytical models: while our sample's shallowness prevents distinguishing between different seeding models, we find that the data favor models which keep SMBH in dwarf galaxies active at a moderate rate, motivating model improvement by comparison to AGN in the dwarf galaxy regime.

Dwarf AGN sample



Draft version February 4, 2025
Typeset using LaTeX **twocolumn** style in AASTeX631

X-Ray Bright Active Galactic Nuclei in Local Dwarf Galaxies: Insights from eROSITA

Andrea Sacchi,[1] Ákos Bogdán,[1] Urmila Chadayammuri,[2] and Angelo Ricarte[1]

[1] *Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 20138, USA*
[2] *Max Planck Institut für Astronomie, Königstuhl 17, 69121 Heidelberg, Germany*

ABSTRACT

Although supermassive black holes (SMBHs) reside in the heart of virtually every massive galaxy, it remains debated whether dwarf galaxies commonly host SMBHs. Because low-mass galaxies may retain memory of the assembly history of their black holes (BHs), probing the BH occupation fraction of local dwarf galaxies might offer insights into the growth and seeding mechanisms of the first BHs. In this work, we exploit the Western half of the eROSITA all-sky survey (covering $20,000\deg^2$) and compile a catalog of accreting SMBHs in local ($D < 200$ Mpc) dwarf galaxies. Cleaning our sample from X-ray background sources, X-ray binaries, and ultraluminous X-ray sources, we identify 74 AGN-dwarf galaxy pairs. Using this large and uniform sample, we derive a luminosity function of dwarf galaxy AGN, fitting it with a power law function and obtaining $\mathrm{d}N/\mathrm{d}L_X = (15.9 \pm 2.2) \times L_X^{-1.63\pm0.05}$. Measuring the offset between the dwarf galaxies centroids and the X-ray sources, we find that ≈ 50% of the AGN are likely off-nuclear, in agreement with theoretical predictions. We compare the BH-to-stellar mass relation of our sample with the local and high-redshift relations, finding that our sources better adhere to the former, suggesting that local AGN across different mass scales underwent a similar growth history. Finally, we compare our sources with semi-analytical models: while our sample's shallowness prevents distinguishing between different seeding models, we find that the data favor models which keep SMBH in dwarf galaxies active at a moderate rate, motivating model improvement by comparison to AGN in the dwarf galaxy regime.

→ X-rays sensitive to accretion

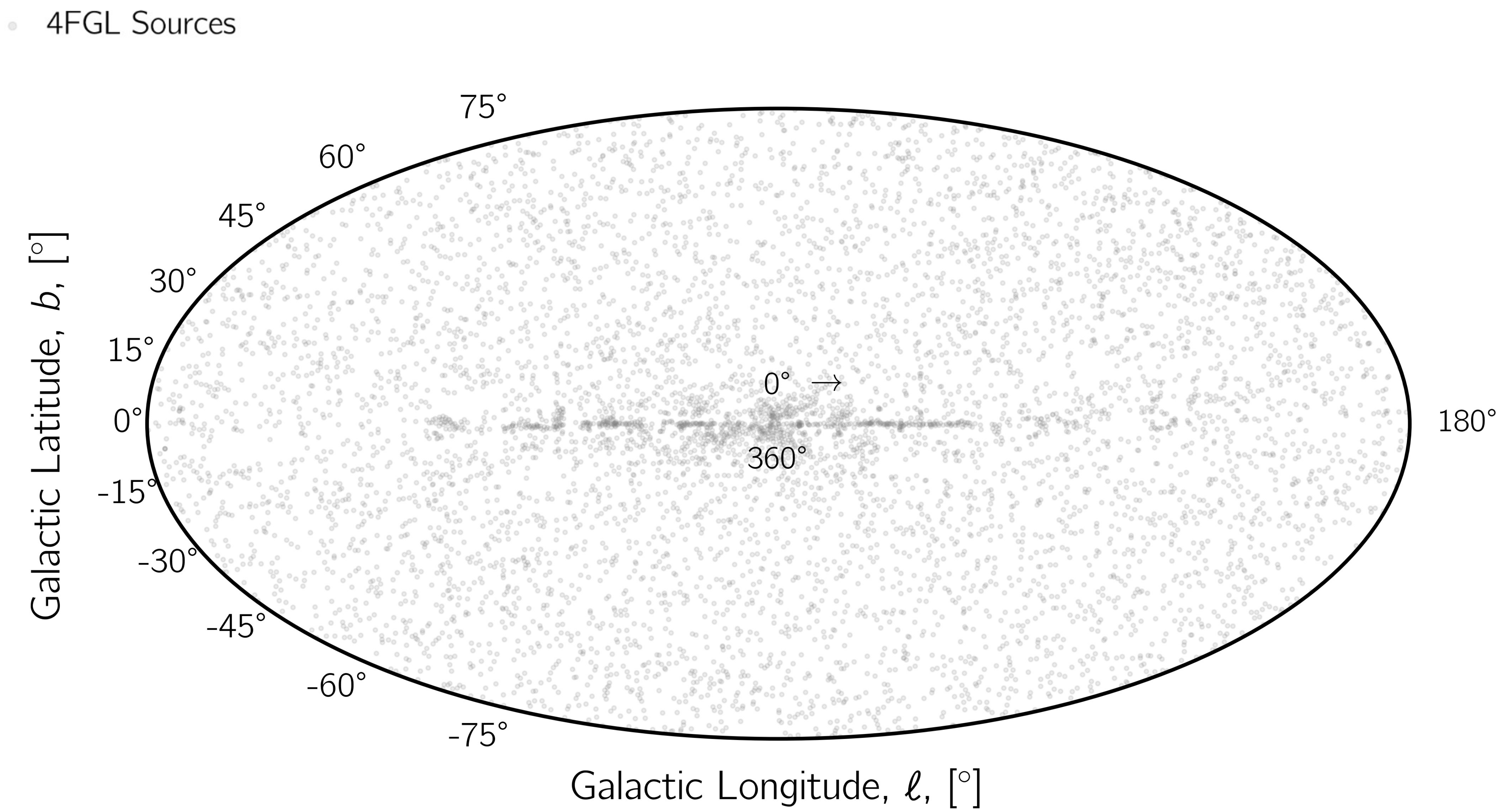
→ minimizes the contamination or line emission biases

→ unbiased to obscuration of the AGN

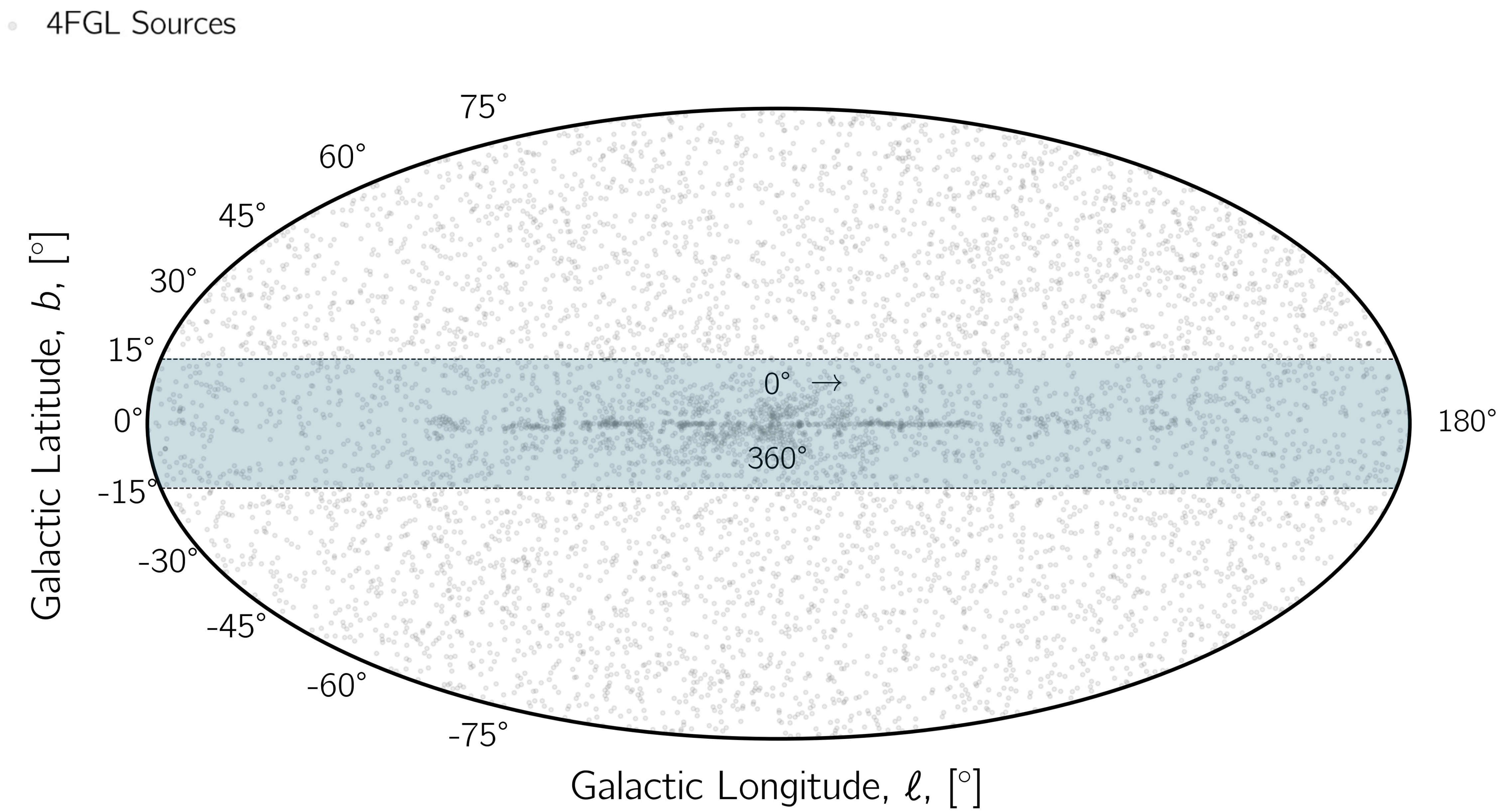
→ closest sources (D < 200 Mpc)

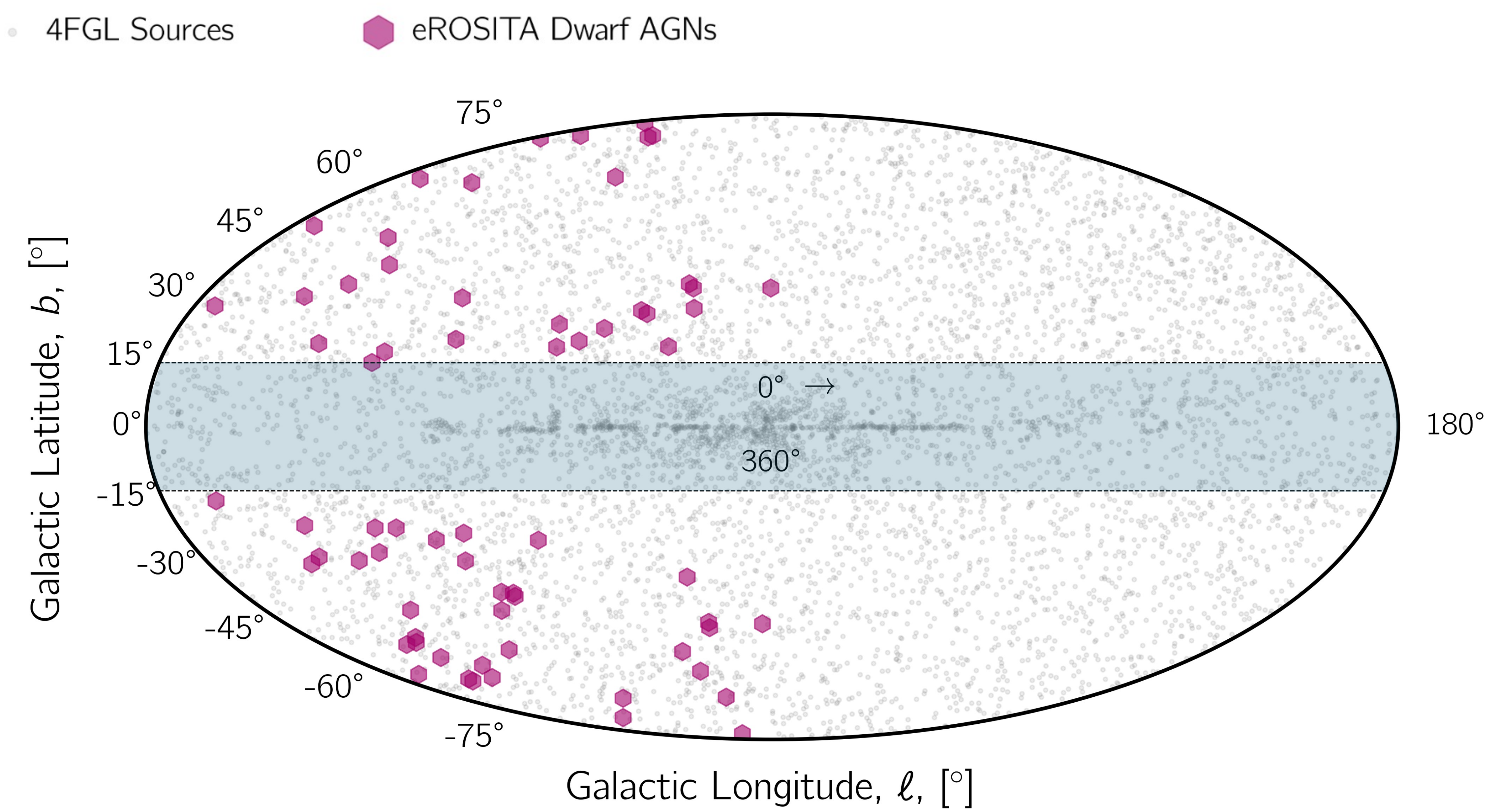
→ available control samples

→ almost… all-sky

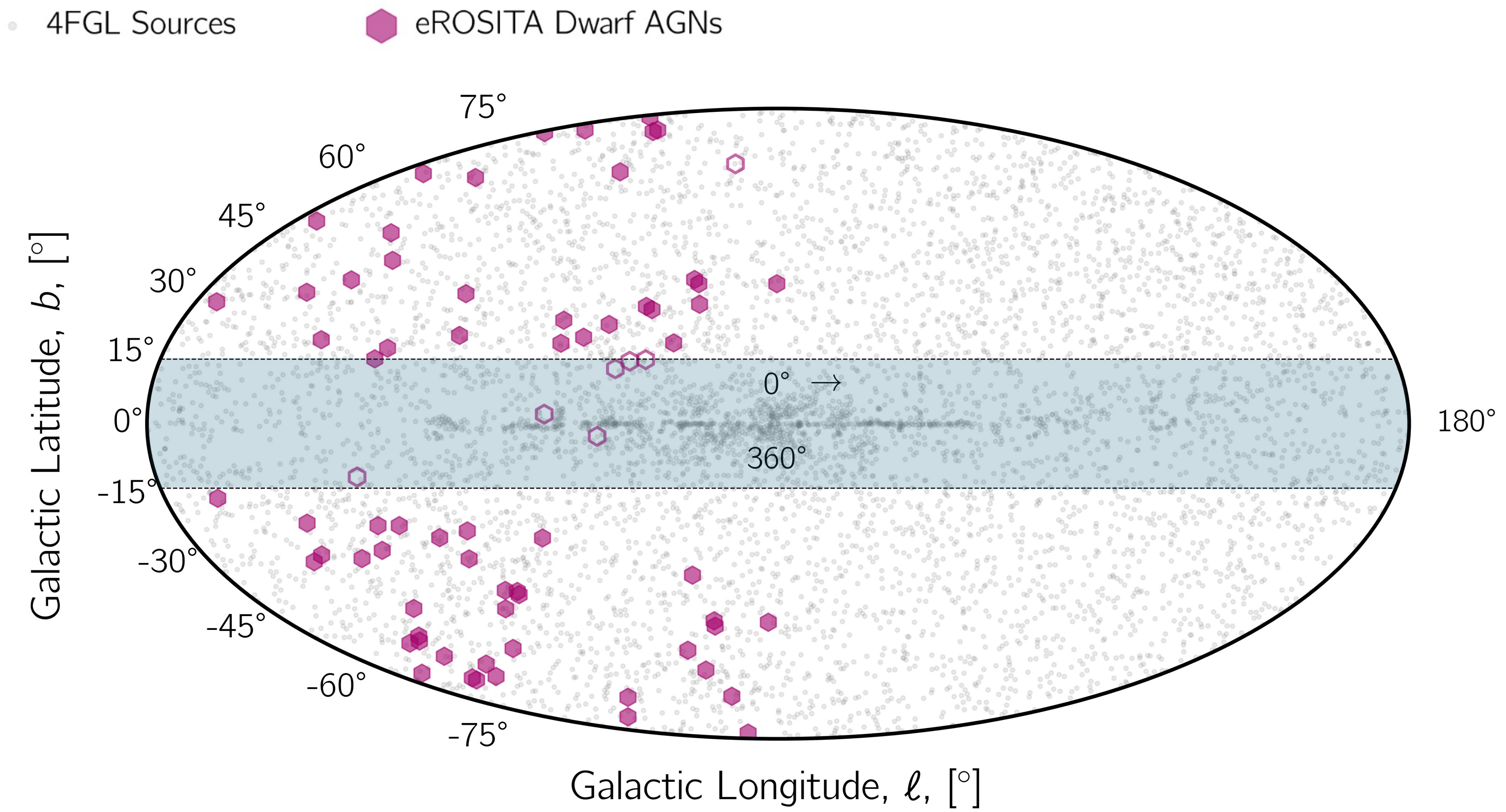


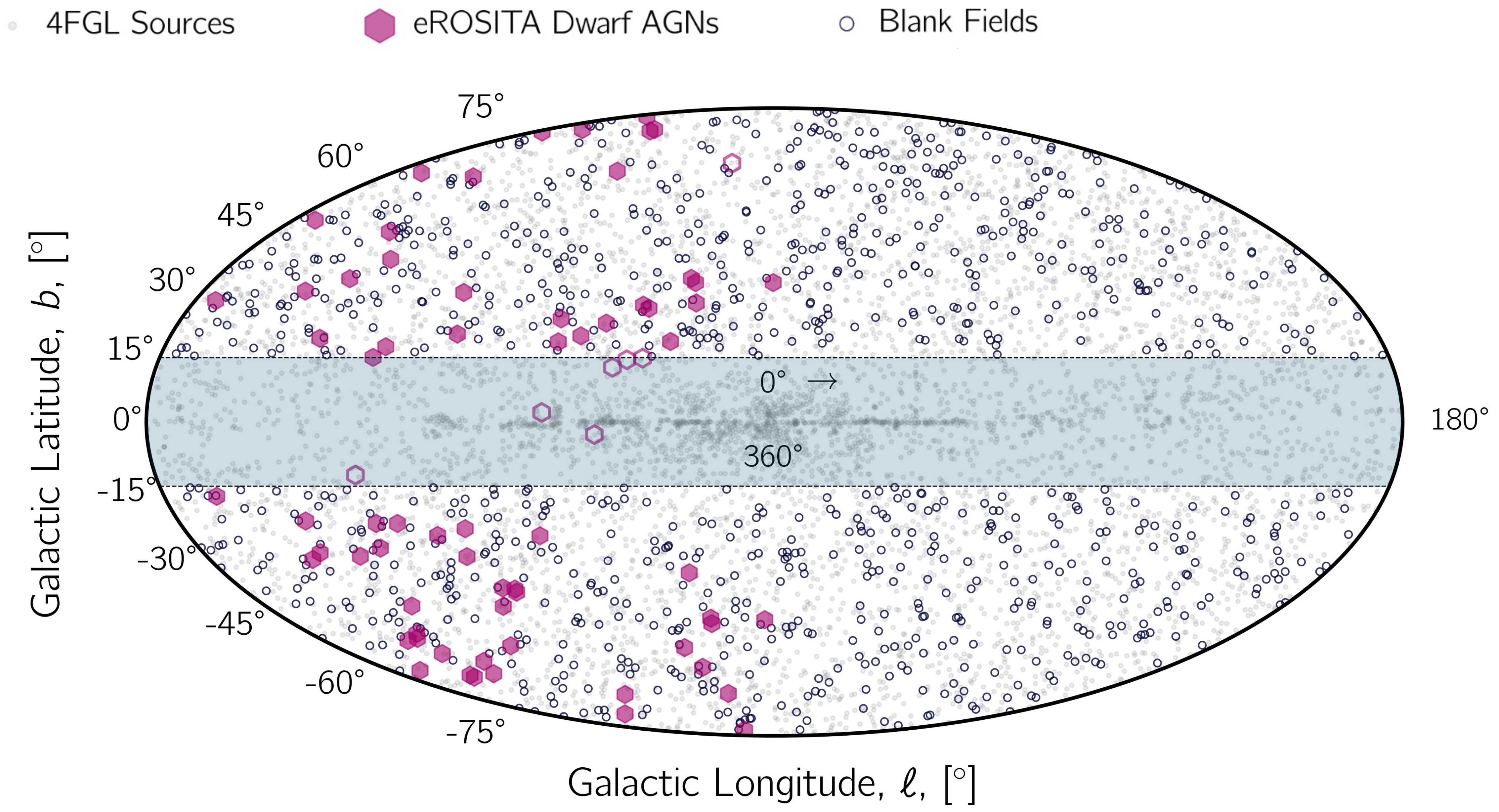
4FGL Sources
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
0° →
360°
180°
Galactic Latitude, b, [°]
Galactic Longitude, ℓ, [°]

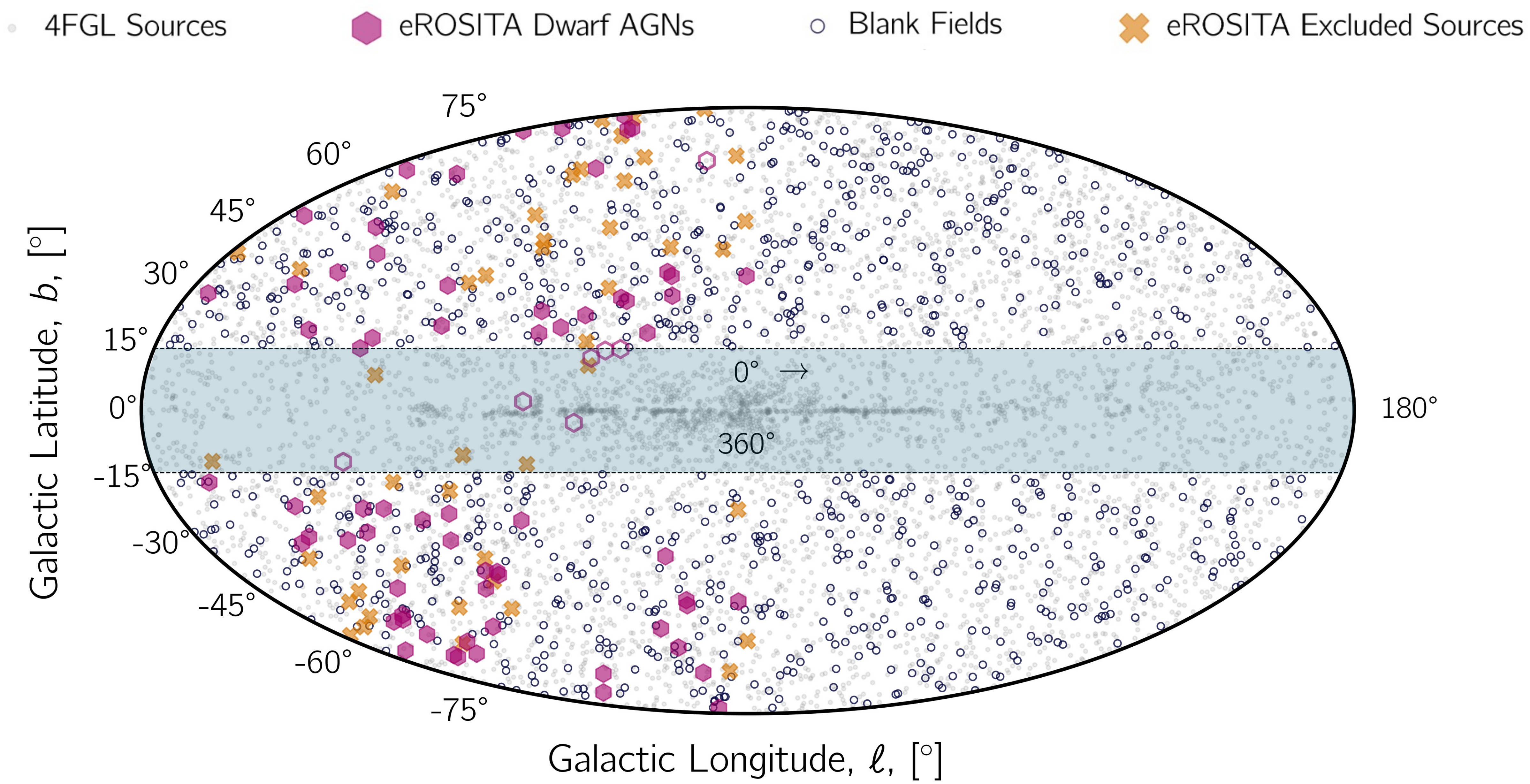

4FGL Sources
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
0° →
360°
180°
Galactic Latitude, b, [°]
Galactic Longitude, ℓ, [°]



4FGL Sources
eROSITA Dwarf AGNs
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
0° →
360°
180°
Galactic Latitude, b, [°]
Galactic Longitude, ℓ, [°]

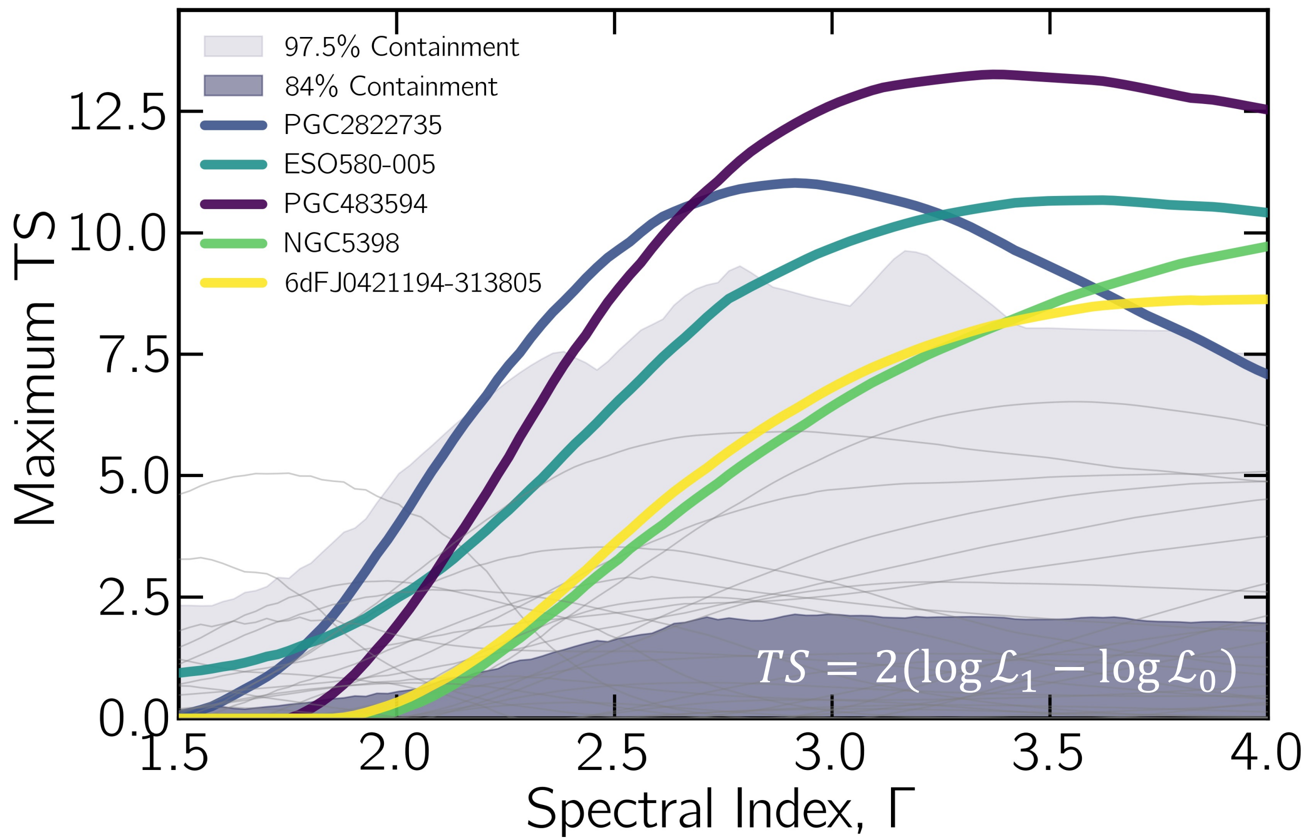

4FGL Sources
eROSITA Dwarf AGNs
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
0° →
360°
180°
Galactic Latitude, b, [°]
Galactic Longitude, ℓ, [°]


4FGL Sources
eROSITA Dwarf AGNs
Blank Fields
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
0° →
360°
180°
Galactic Latitude, b, [°]
Galactic Longitude, ℓ, [°]



4FGL Sources
eROSITA Dwarf AGNs
Blank Fields
eROSITA Excluded Sources
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
0° →
360°
180°
Galactic Latitude, b, [°]
Galactic Longitude, ℓ, [°]

Individual Source Analysis: No Detection



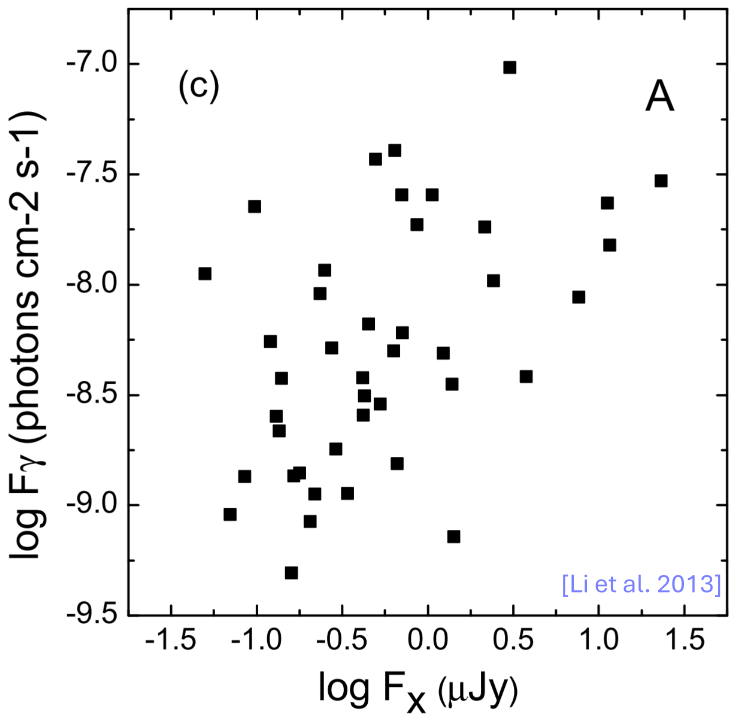
Roughly, $\sqrt{TS} \sim$ detection significance (in σ).
TS = 25 corresponds to $\sim 5\ \sigma$ detection in LAT.

- 15 years of Fermi-LAT Pass 8
- Energy range: 500 MeV – 500 GeV
- Event class: P8R3 SOURCE (evclass=128, evtype=3)
- Software: Fermipy v1.2.0 + Fermitools v2.2.0
- ROI: $10° \times 10°$ (model extended to $15° \times 15°$ for PSF spillover)
- Background sources from 4FGL-DR4
- Modeled as point source (unresolved at LAT resolution)
- Binned likelihood analysis per energy bin
- SED derived with fixed per-bin index $\mathbf{\Gamma} = 2$

What does this no detection mean?

X-ray / γ-ray Scaling

- Empirical **BL Lac relation**

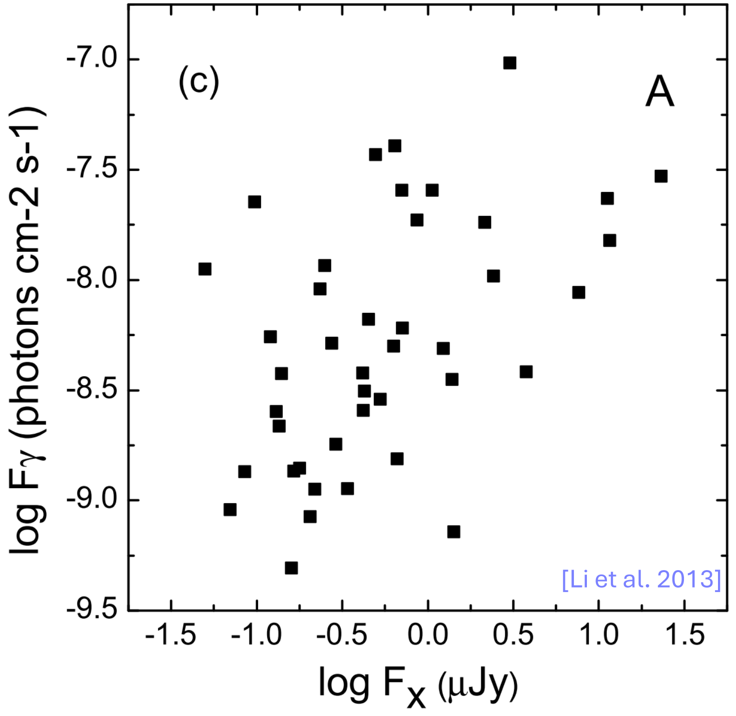


$\log F_\gamma = 0.42 \log F_X - 8.17$ (& scatter based on different states)

What does this no detection mean?

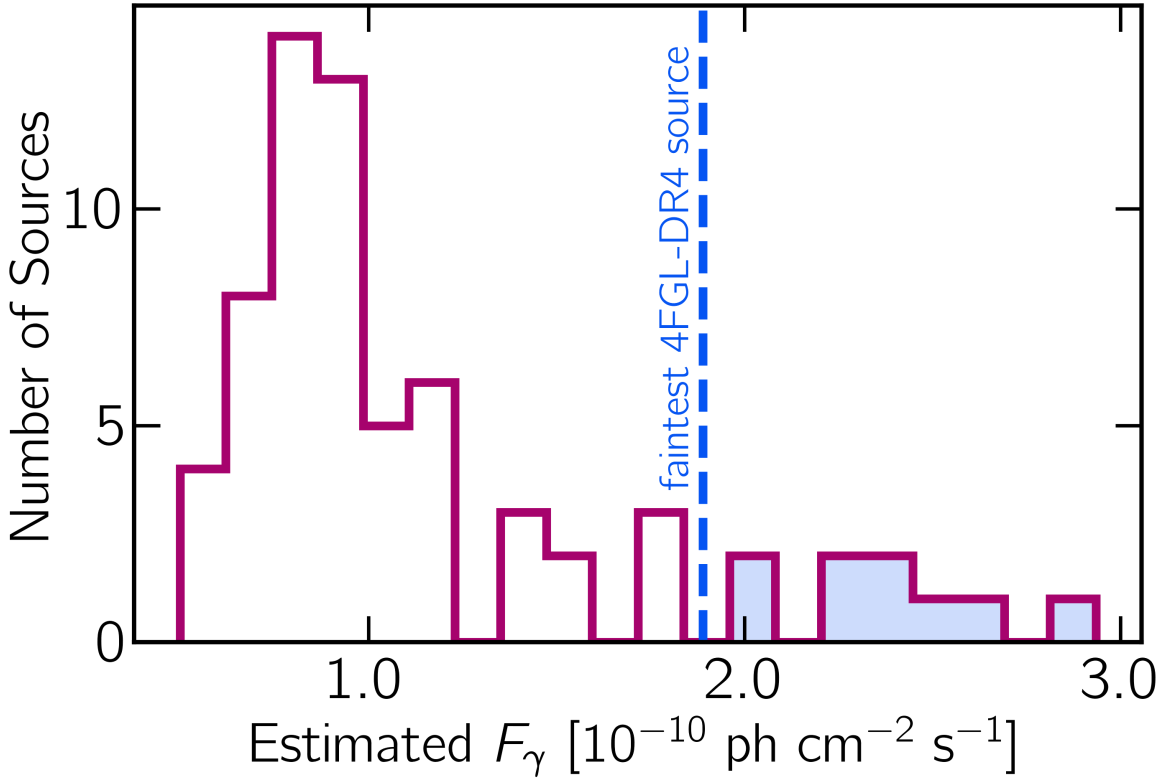
X-ray / γ-ray Scaling

- Empirical **BL Lac relation**



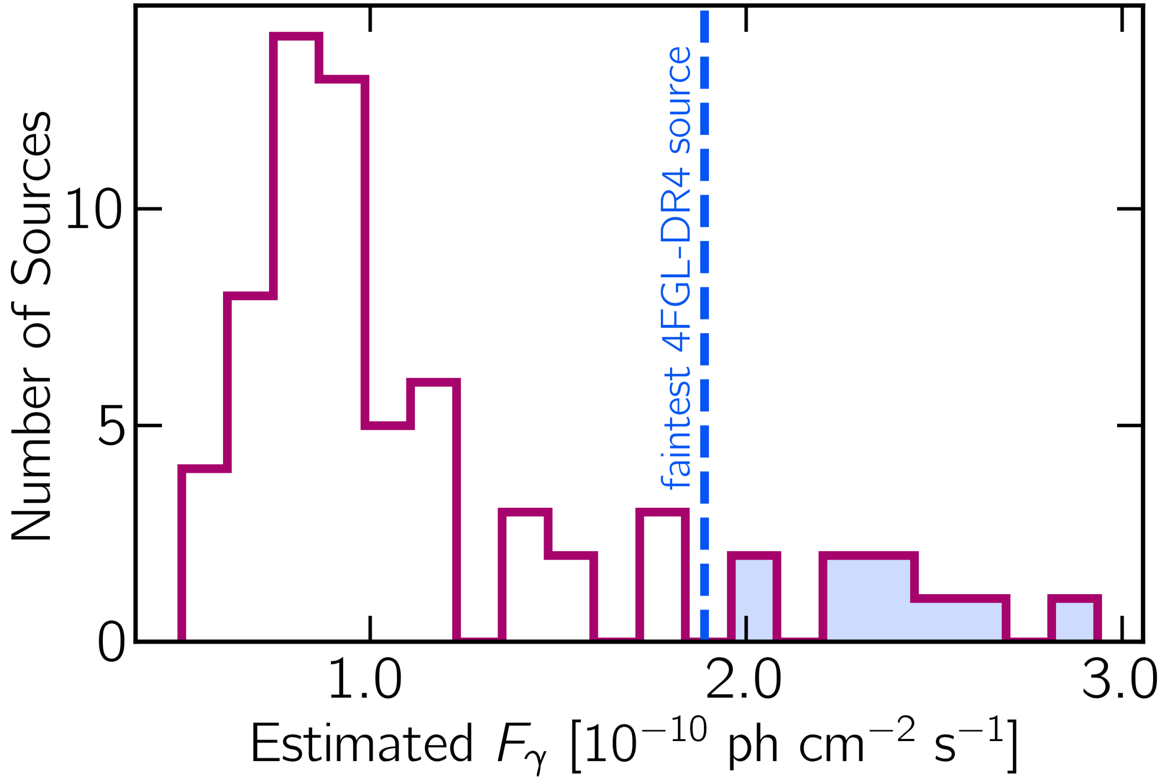
$$\log F_\gamma = 0.42 \log F_X - 8.17$$ (& scatter based on different states)

Most predicted fluxes fall just below LAT's sensitivity after 15 years



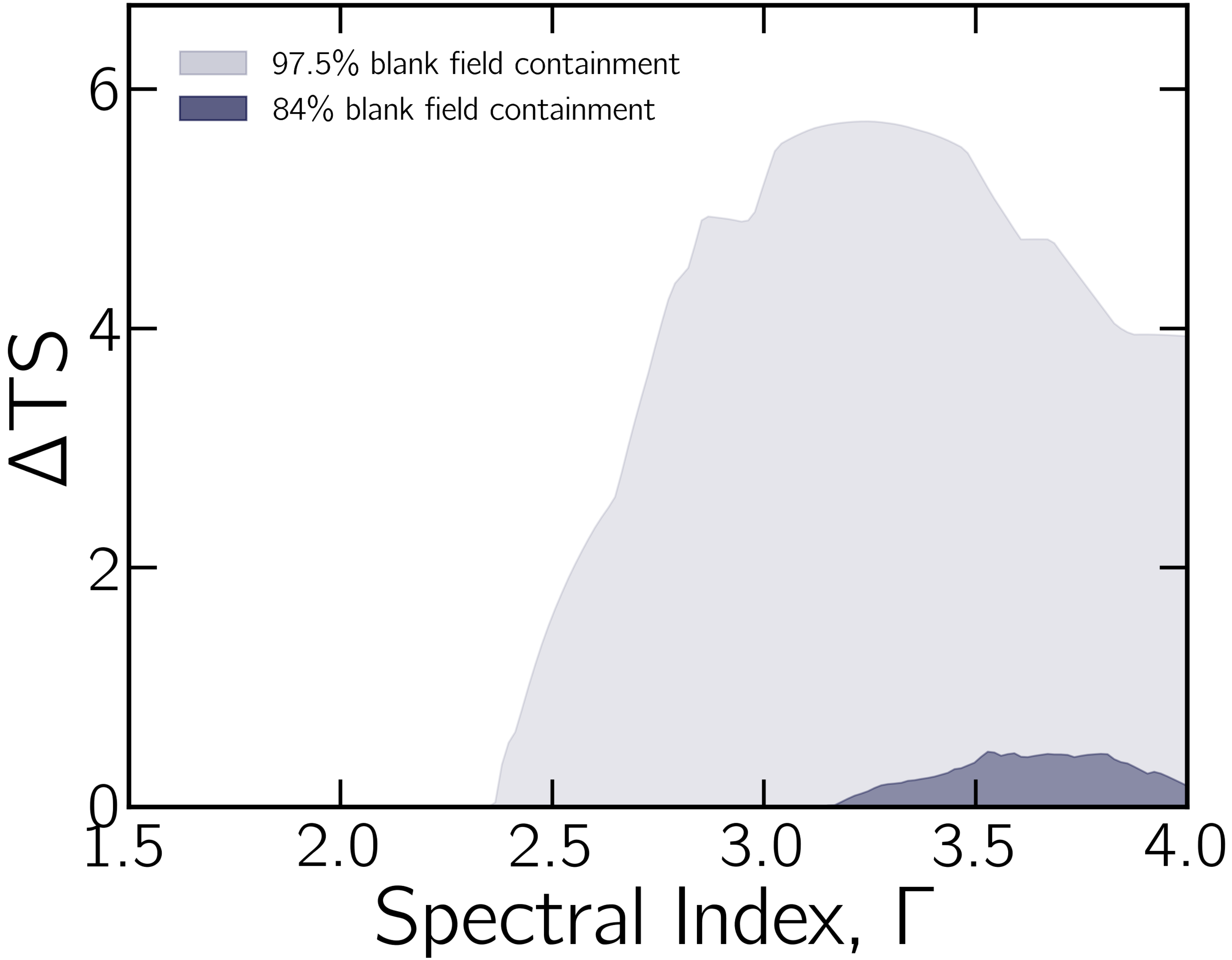
What does this no detection mean?

Most predicted fluxes fall just below LAT's sensitivity after 15 years

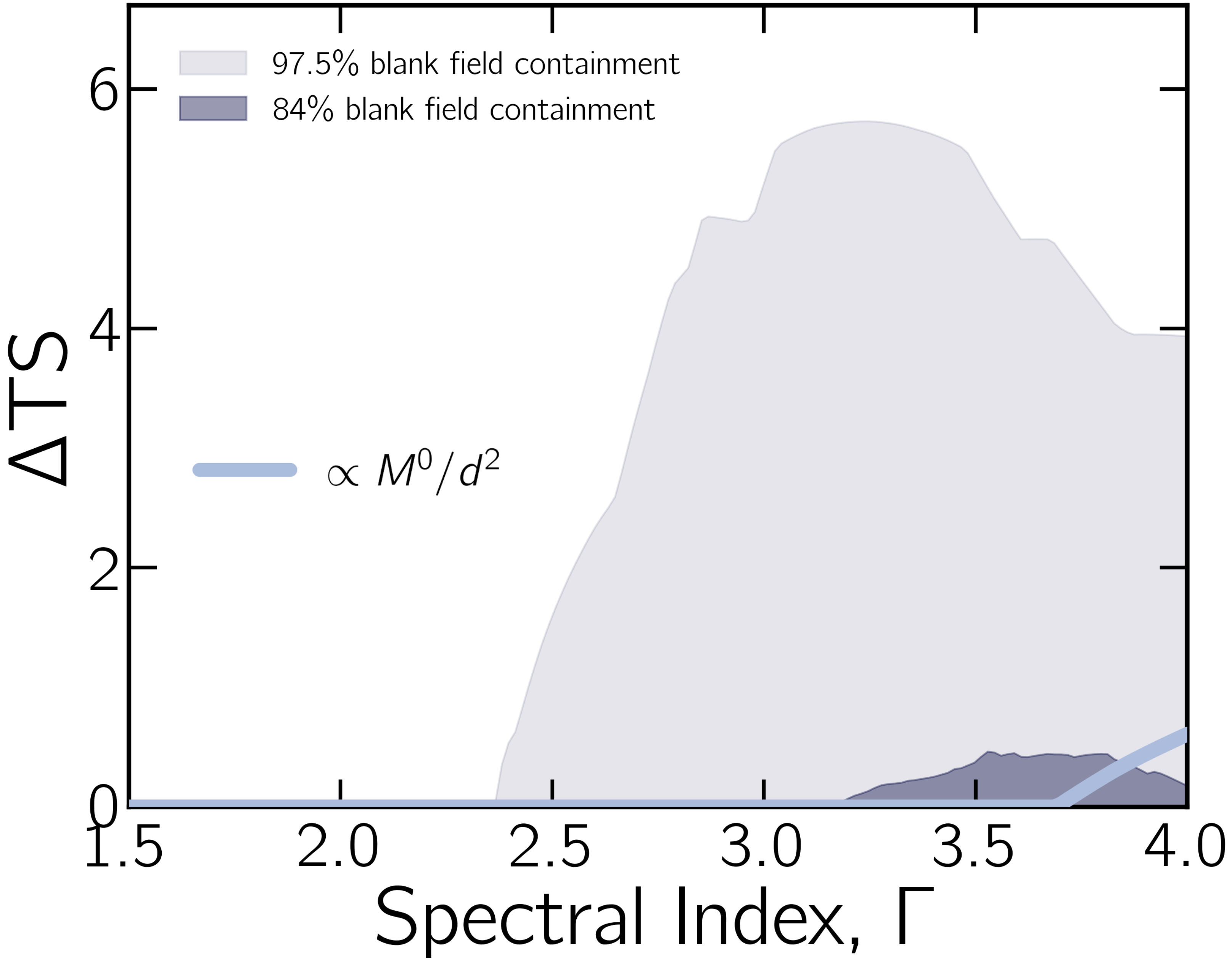


- No outliers detected → **BL Lac-like SSC emission likely suppressed**
- **Dwarf AGN are ≥ 7x less efficient** in producing gamma rays than BL Lacs (at fixed X-ray flux)
- **Possible causes:**
  - Weak or misaligned jets (less Doppler boost)
  - Weaker B fields
  - Different accretion regimes
  - $\gamma\gamma$ absorption in denser environments

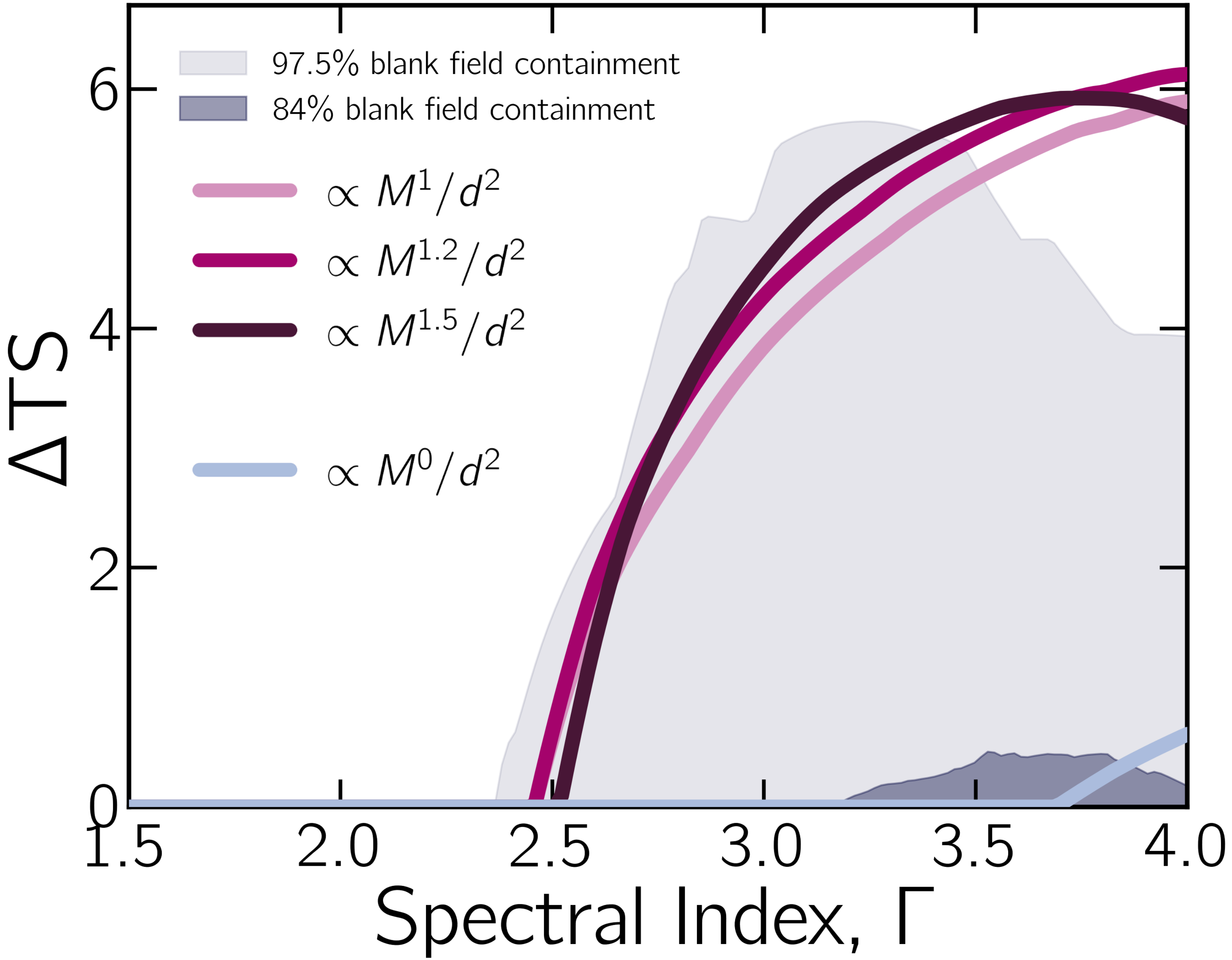
Joint likelihood analysis


97.5% blank field containment
84% blank field containment
6
4
2
0
ΔTS
1.5
2.0
2.5
3.0
3.5
4.0
Spectral Index, Γ

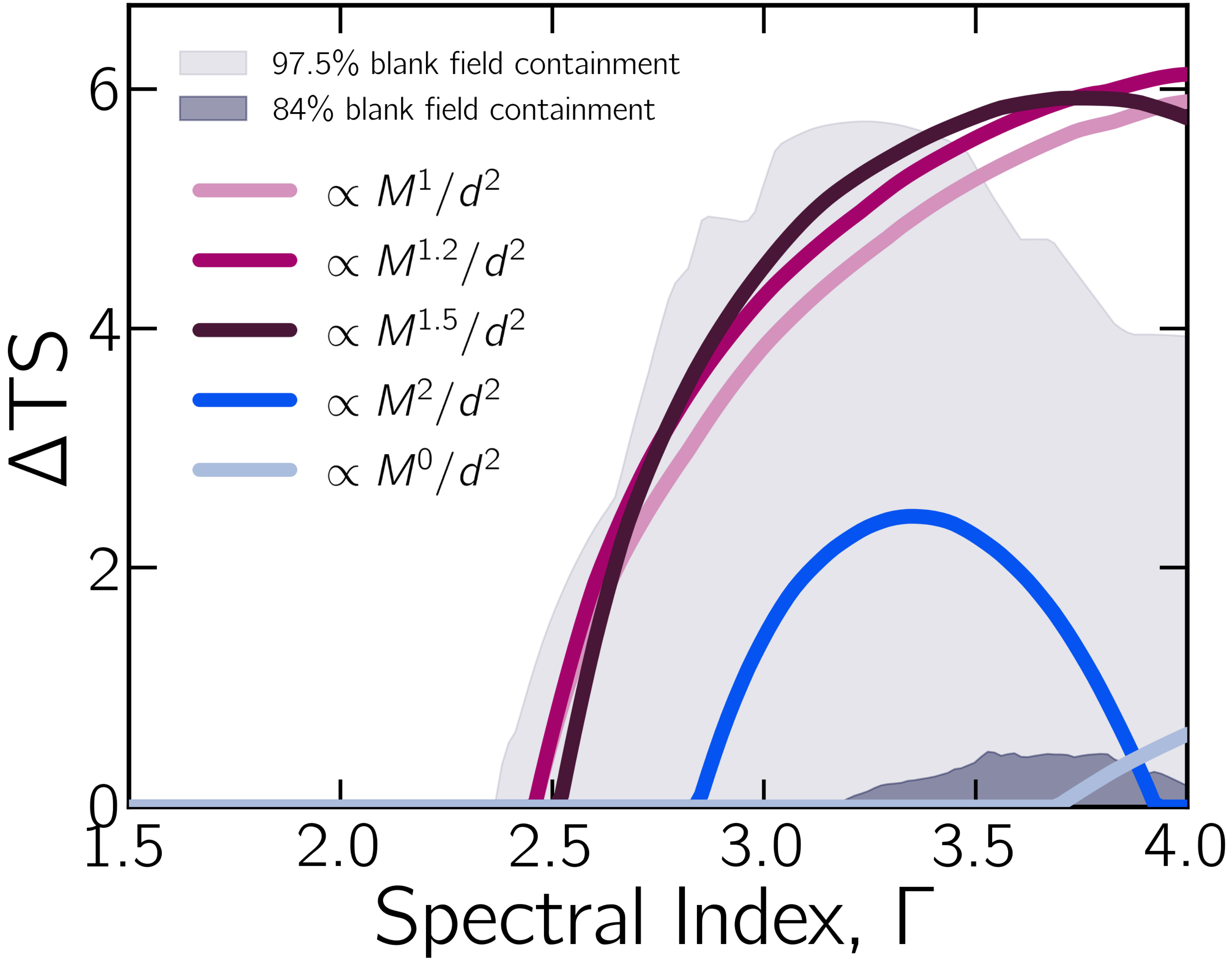
With IMBH mass derived from stellar mass–black hole mass relation (Reines & Volonteri 2015):



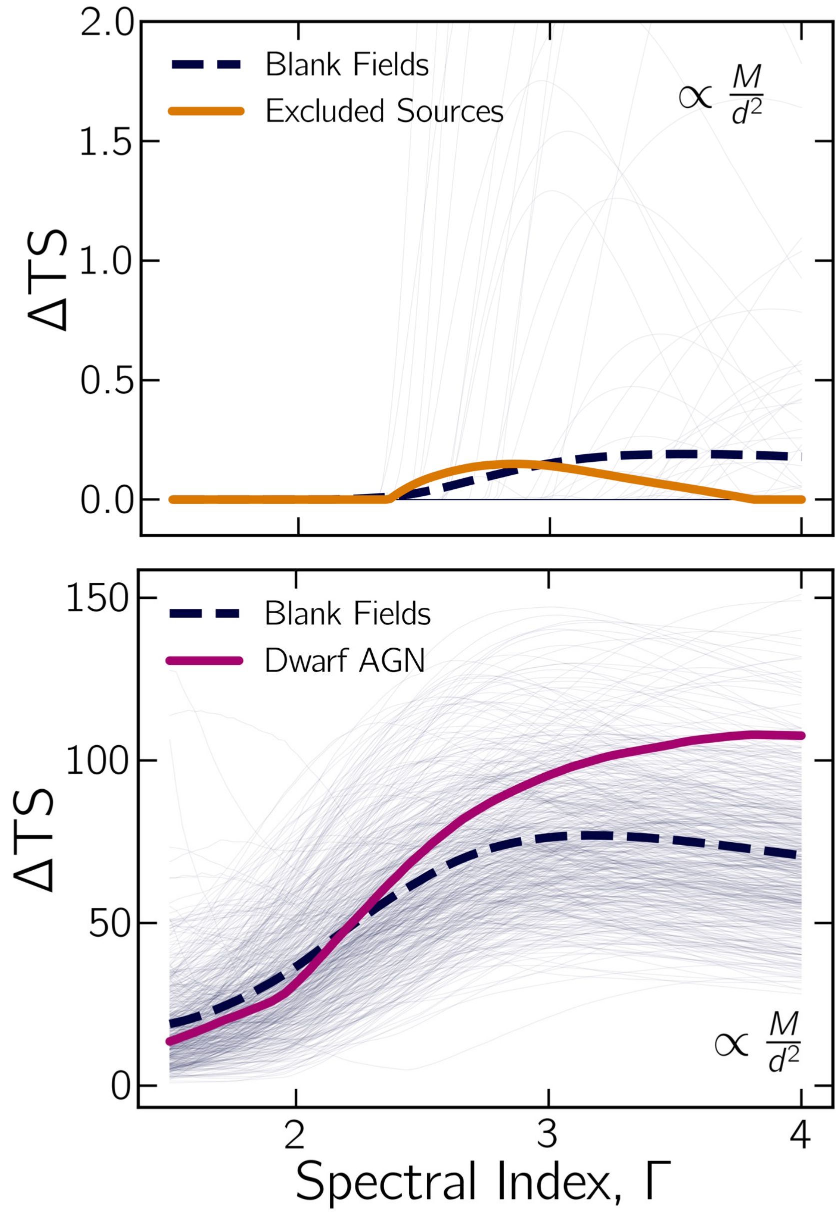
With IMBH mass derived from stellar mass–black hole mass relation (Reines & Volonteri 2015):



With IMBH mass derived from stellar mass–black hole mass relation (Reines & Volonteri 2015):



With IMBH mass derived from stellar mass–black hole mass relation (Reines & Volonteri 2015):



Interpretation:

→ Suggestive—but not conclusive—evidence that **γ**-ray emission may scale with IMBH mass

→ Spectrum significantly softer than typical blazars (**Γ** ≈ 2–2.5)

→ Possible explanations:

- Coronal or accretion-disk Comptonization
- Weak or misaligned jets
- **γγ** absorption or host star formation contamination

→ Verified against 400 blank-field ensembles and excluded-source control sample

→ Similar soft peak appears when extended down to 100 MeV (but with inflated significance ⟶ likely systematics)

Conclusions

→ **No individual detections** in 15 years of *Fermi*-LAT data
→ Joint-likelihood analysis reveals **modest (~2σ) population-level excess** at soft indices ($\Gamma \gtrsim 3.8$)
→ Signal strongest when weighted by **$\mathbf{M}^{\alpha}$/d²** with $\alpha \approx$ 1-1.5, suggesting γ-rays may scale with IMBH mass
→ Soft spectrum differs from typical AGN/blazars ($\Gamma \sim$ 2-2.5), indicating potential **different emission mechanisms**
→ Possible explanations: coronal emission, misaligned jets, host galaxy processes, $\gamma\gamma$ absorption

Future:
→ Deeper γ-ray exposures and next-generation MeV telescopes (AMEGO, e-ASTROGAM)
→ Multiwavelength follow-up to disentangle emission mechanisms
→ Theoretical modeling of γ-ray production in IMBH regime

Thank you!

TeV Particle Astrophysics
TeVPA
Valencia 2025

Back-up

Building the sample

eRASS1 (Merloni+24)
Fx (in different bands), position
~930’000 sources

+

Hecate catalogue (Kovlakas+21)
M_{gal}, SFR, z
5’775 dwarf galaxies
(1e6 $M_{\odot}$<M_{gal}<3e9 $M_{\odot}$)

↓

120 unique matches

Building the sample