Searching for dark matter subhalos with the Fermi-LAT

In collaboration with M. A. Sánchez-Conde, M. Di Mauro, N. Mirabal, A. Domínguez, E. Charles, A. Aguirre-Santaella, D. Nieto

Based on [1906.11896], [1910.14429], on behalf of the Fermi-LAT Collaboration

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Weakly Interacting Massive Particle (WIMP)

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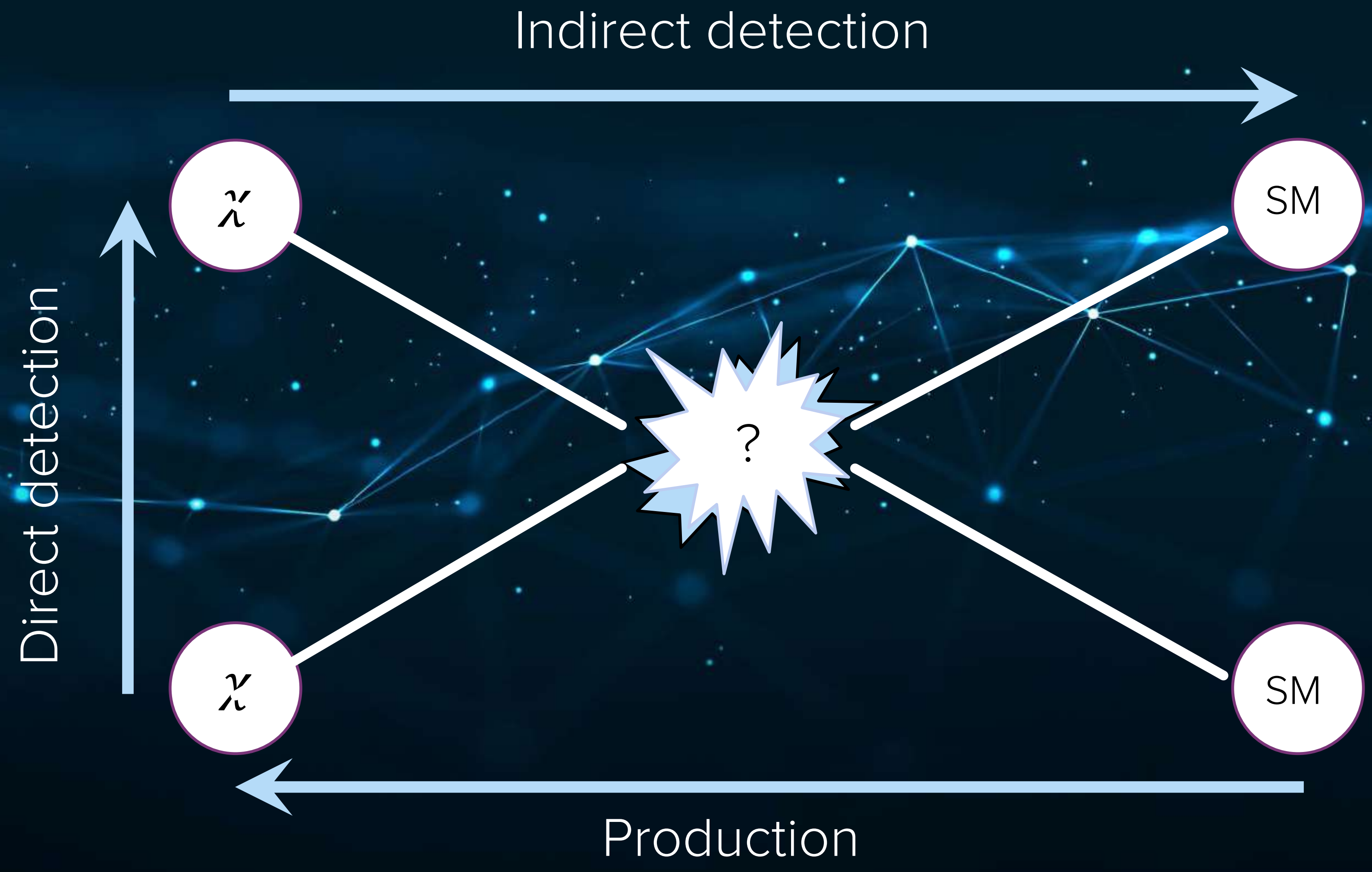
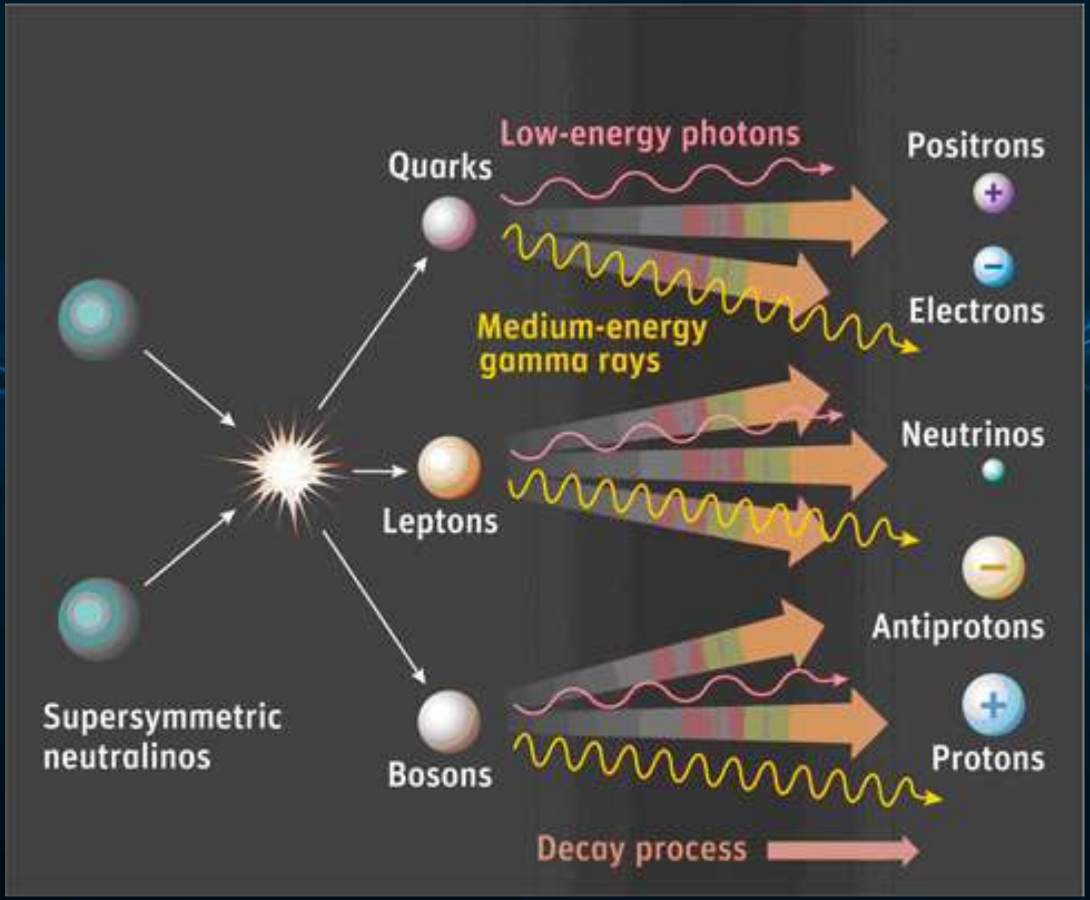


See talk by **R. Leane** for more details on WIMP phenomenology + indirect detection!

Weakly Interacting Massive Particle (WIMP)



- These particles can self-annihilate or decay into SM particles

- Some by-products of these processes are photons, neutrinos and cosmic rays

- Photons are the ‘golden channel’, as they are not deflected by magnetic fields (cosmic rays), yet they are much easier to detect than neutrinos, with no energy loses at the scales relevant for DM searches (local Universe)

Gamma-ray astrophysics

Two type of observatories: space- and ground-based

Fermi-LAT (2008-)

MAGIC (2003-)

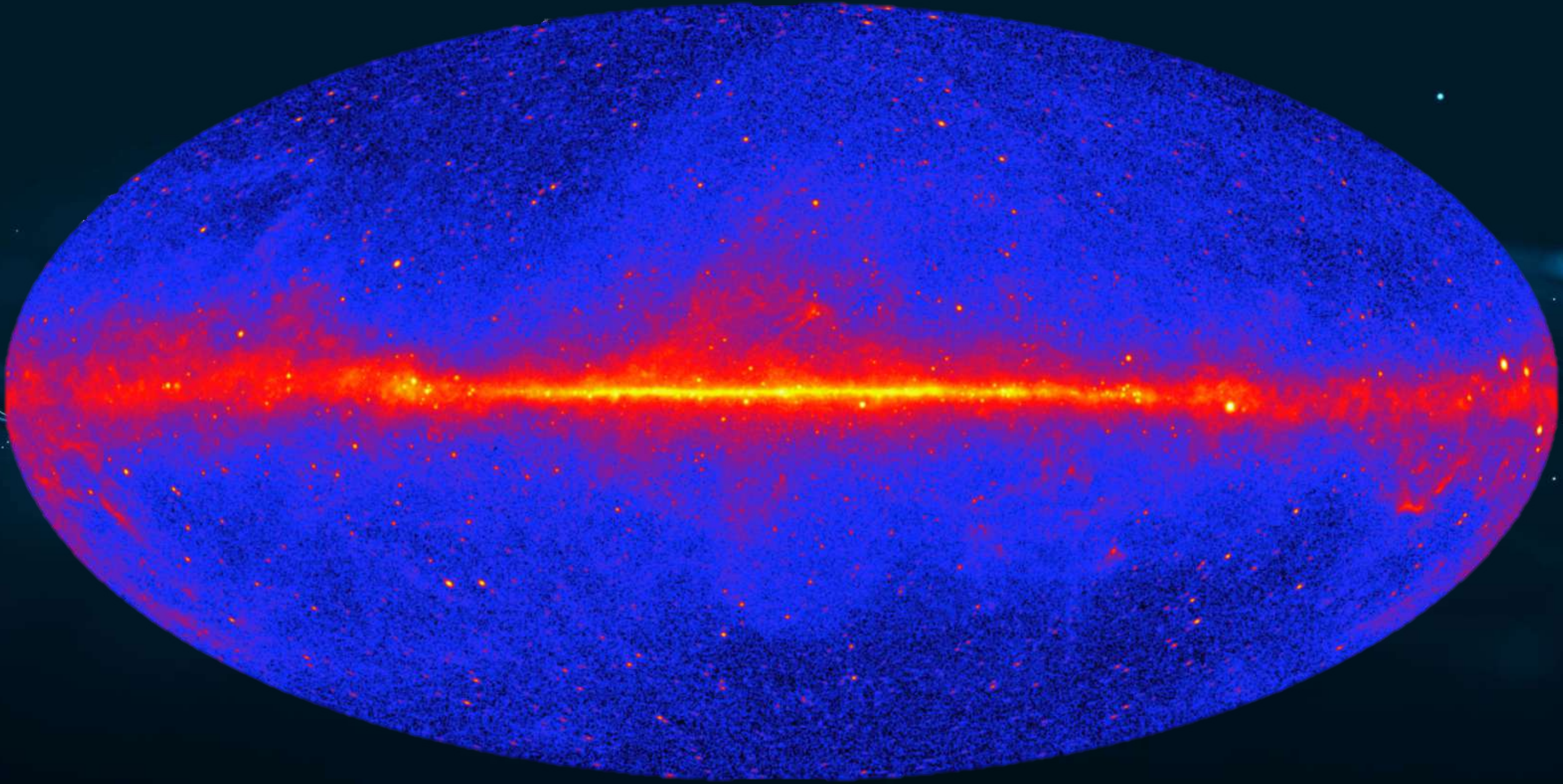
Both types complementary

Gamma-ray astrophysics

Fermi-LAT (2008-)

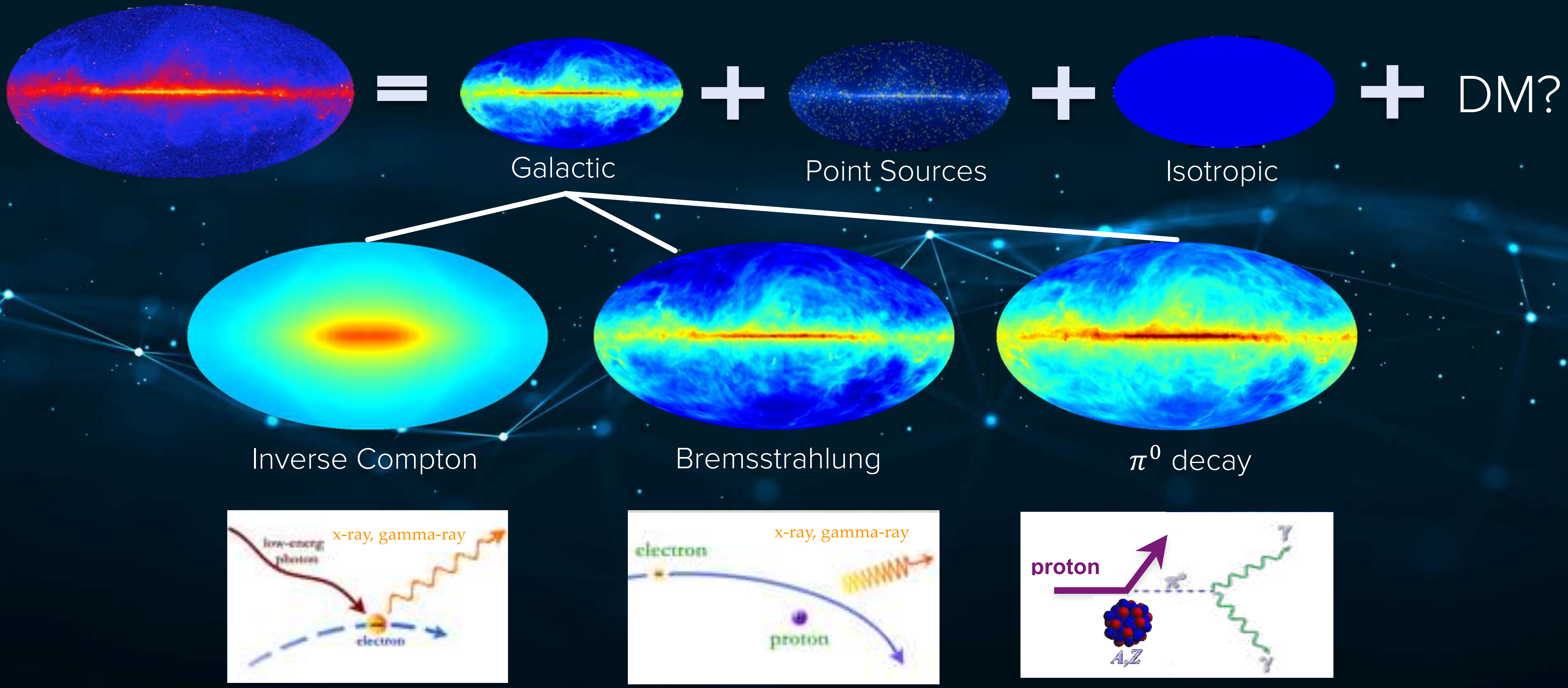
- Energy range: 20 MeV - 1 TeV
- Energy resolution: ~20% @ 1 GeV
- FoV: 2.4 sr (whole sky in ca. 3h)
- Angular resolution: ~0.1° @ 10 GeV
- Effective area: ~1 m^2

Gamma-ray astrophysics

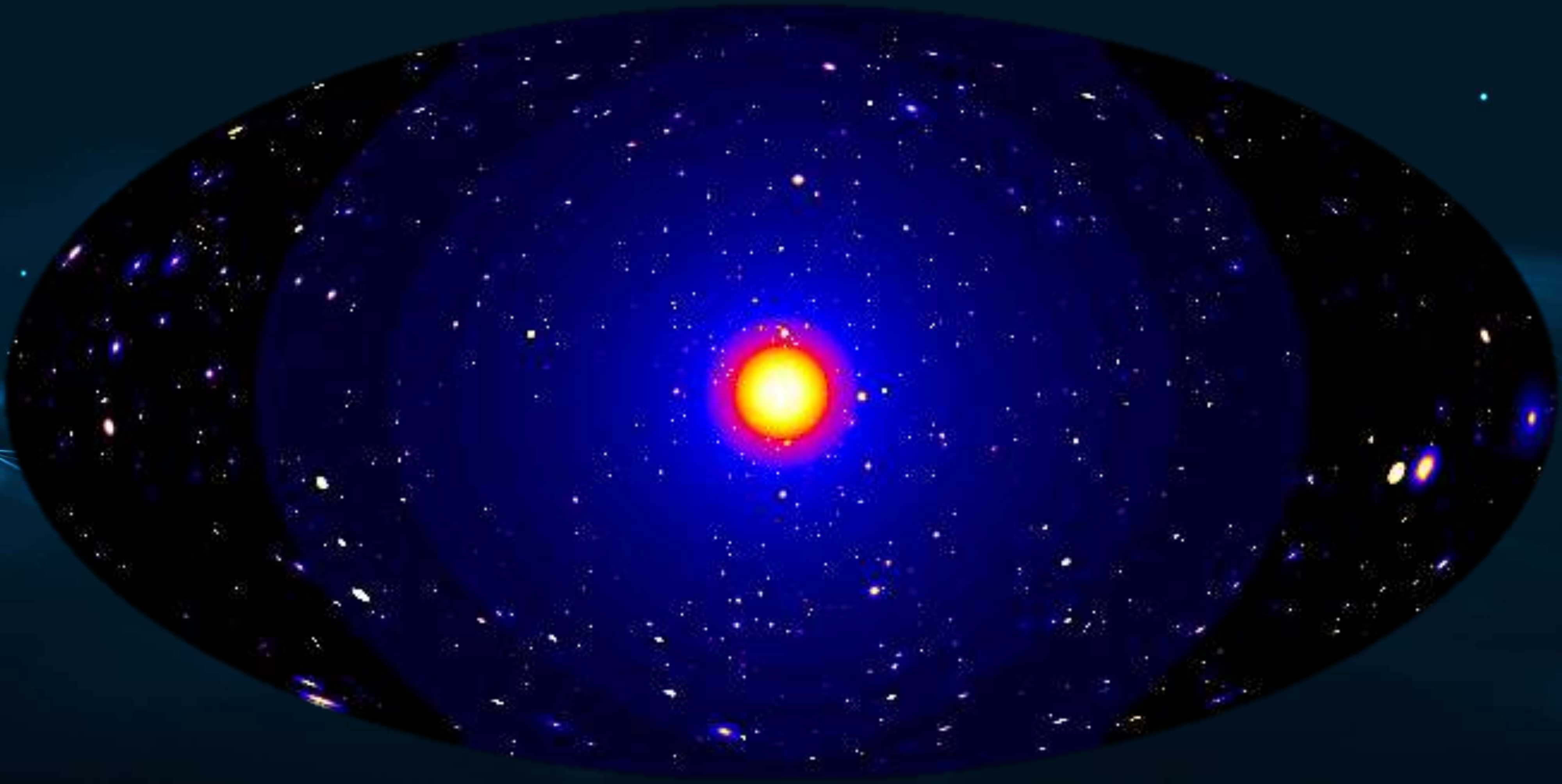


Fermi-LAT 8-year skymap

Gamma-ray astrophysics

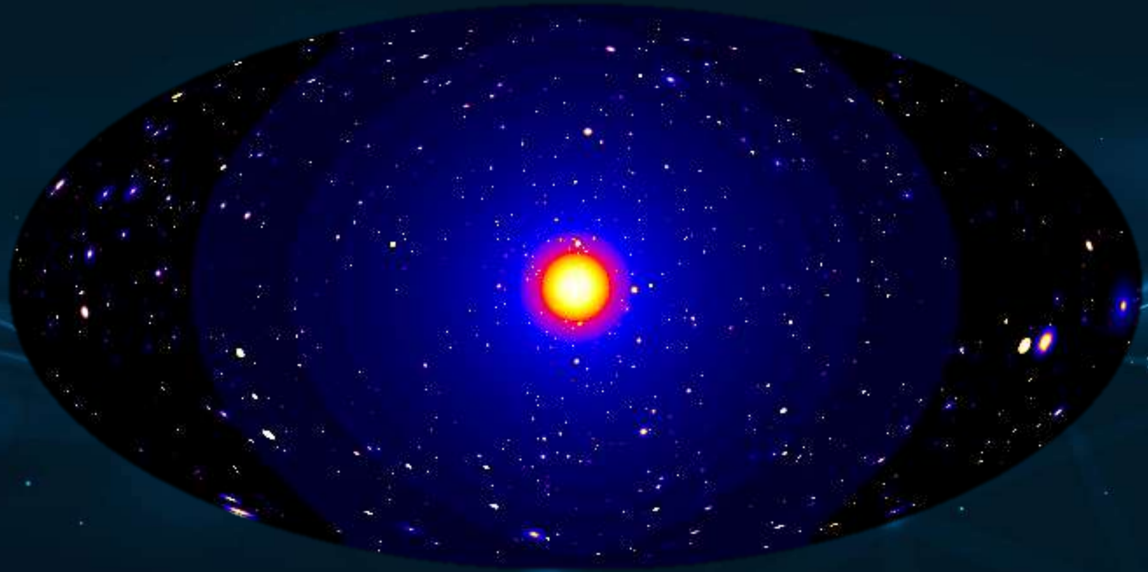


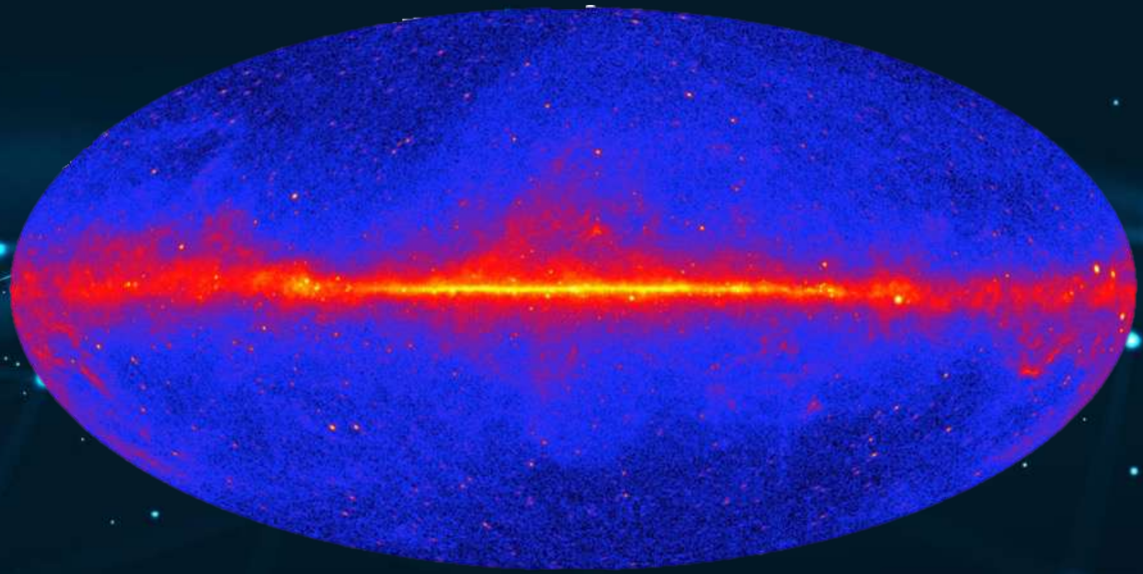
DM predictions



DM annihilation signal simulated skymap, Pieri+09 [0908.0195]

DM predictions

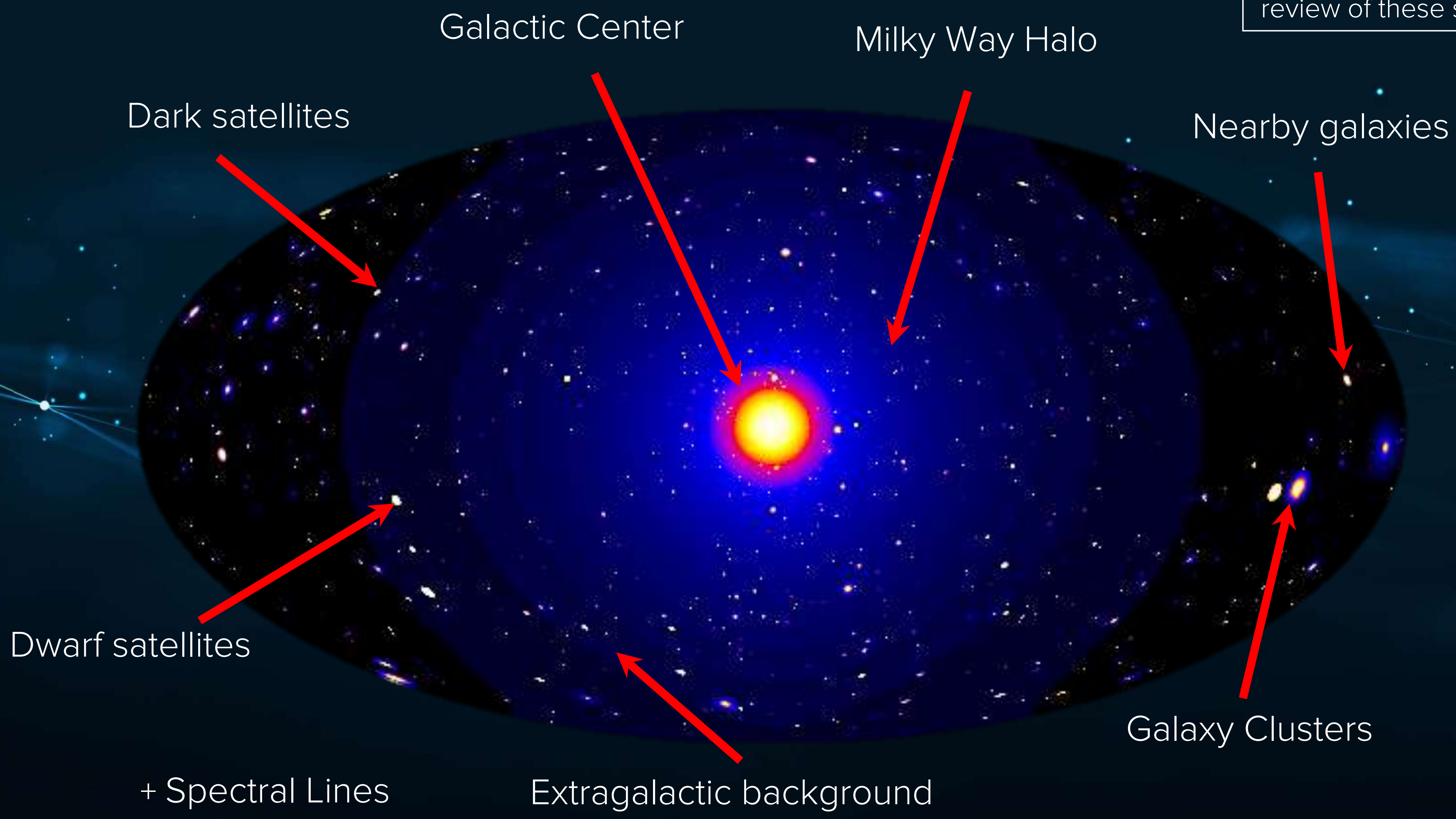




Is DM hidden in the gamma-ray sky? Have we already detected it?

DM predictions

See talk by **R. Leane** for a review of these searches



DM predictions

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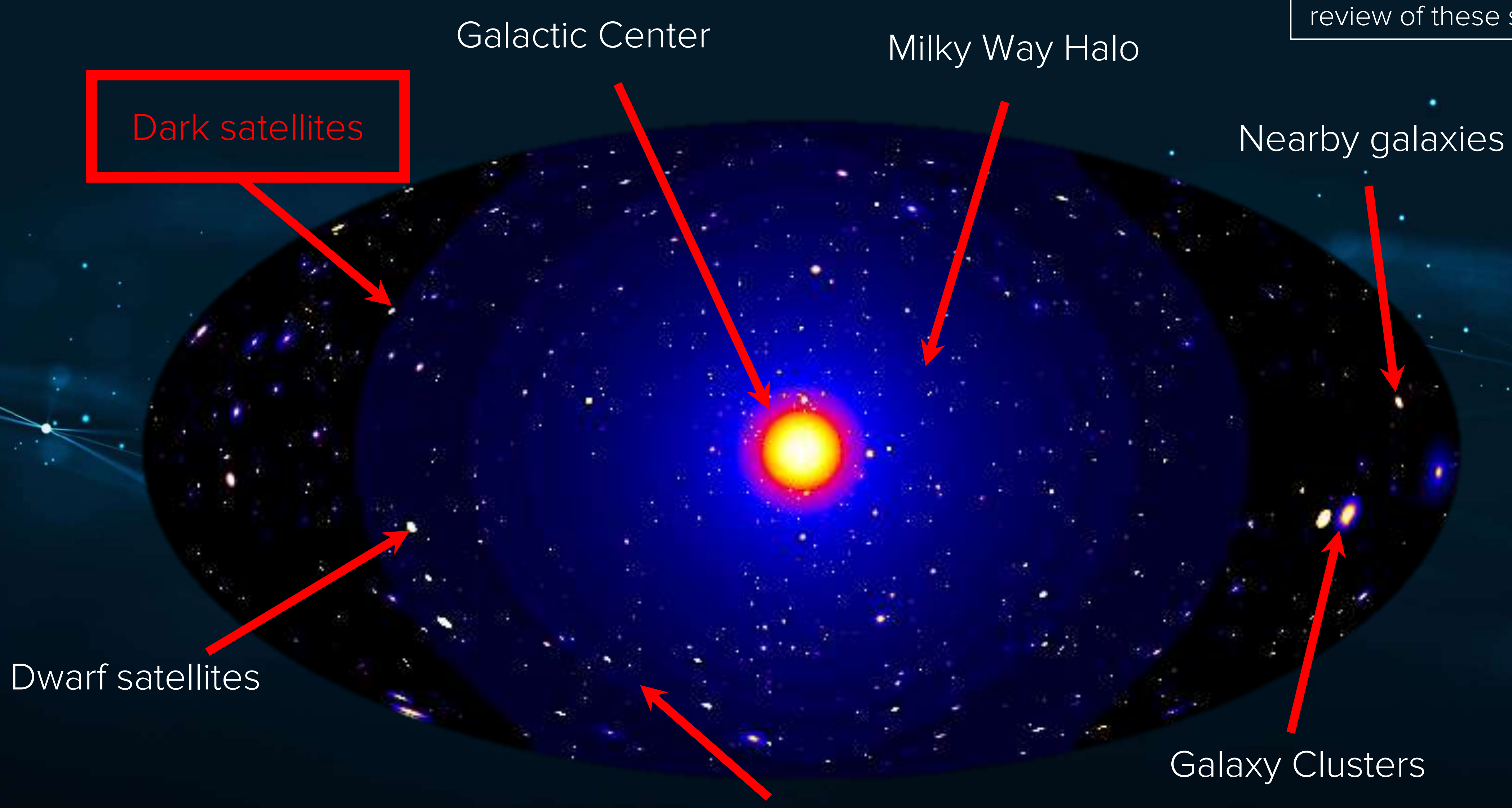

+ Spectral Lines

The WIMP DM annihilation cookbook

$$F(\chi\chi \rightarrow ??) = \frac{\langle\sigma v\rangle}{2m_\chi^2} \cdot J_{factor} \cdot N_\gamma$$

$$F(\chi\chi \rightarrow ??)$$

Gamma-ray data
(What do we see in the sky?)

$$J_{factor} = \int_{l.o.s} dr\, \rho_{DM}^2(r)$$

Astrophysical factor
(How much DM and how is it distributed?)

$$N_\gamma = \sum_i B_i \int_{E_{th}}^{E} dE \left(\frac{dN}{dE}\right)_i$$

Particle physics factor
(How does DM annihilate?)

The WIMP DM annihilation cookbook

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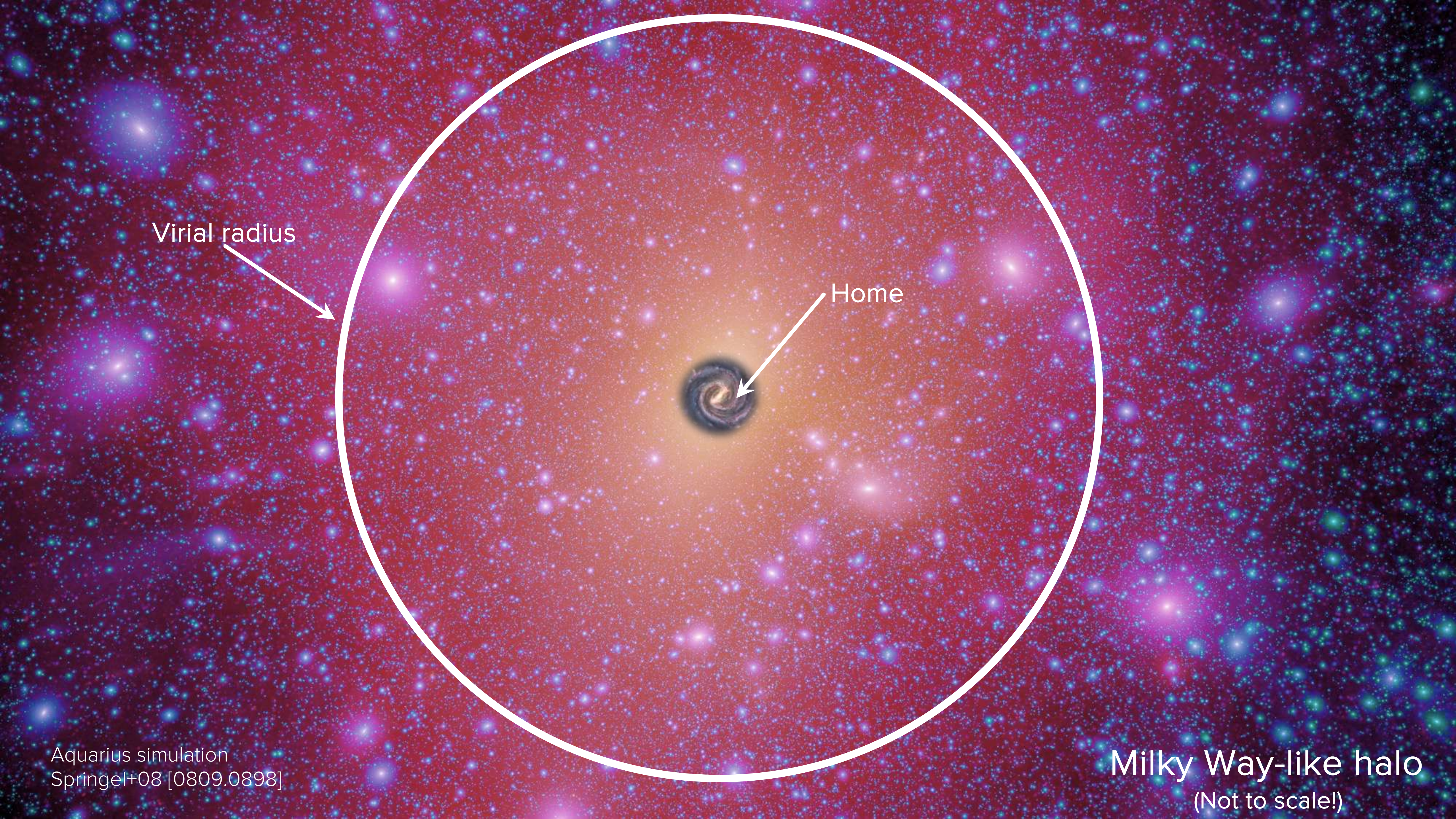
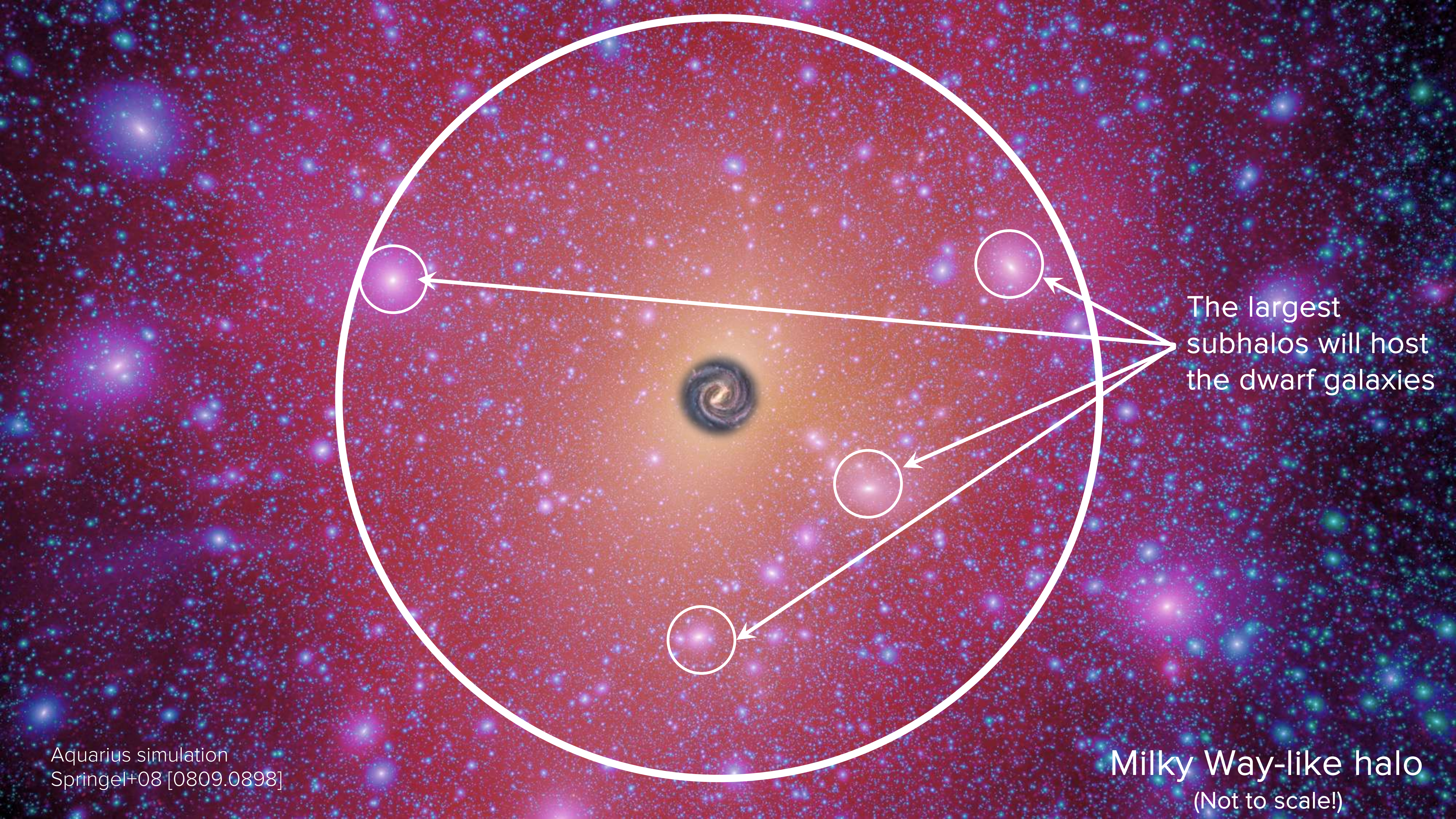
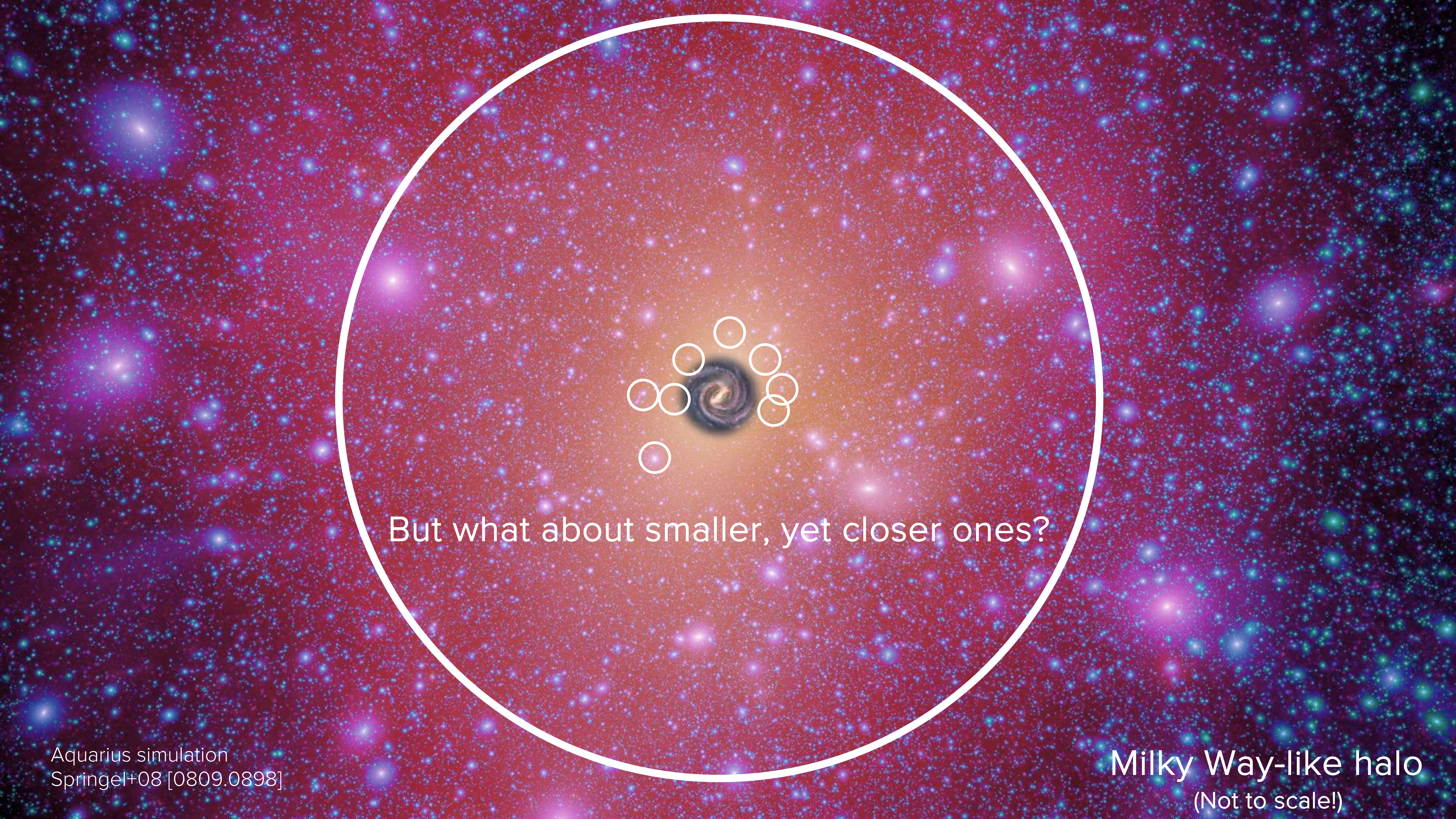

Virial radius
Home
Aquarius simulation
Springel+08 [0809.0898]
Milky Way-like halo
(Not to scale!)


The largest
subhalos will host
the dwarf galaxies
Aquarius simulation
Springel+08 [0809.0898]
Milky Way-like halo
(Not to scale!)


But what about smaller, yet closer ones?
Aquarius simulation
Springel+08 [0809.0898]
Milky Way-like halo
(Not to scale!)

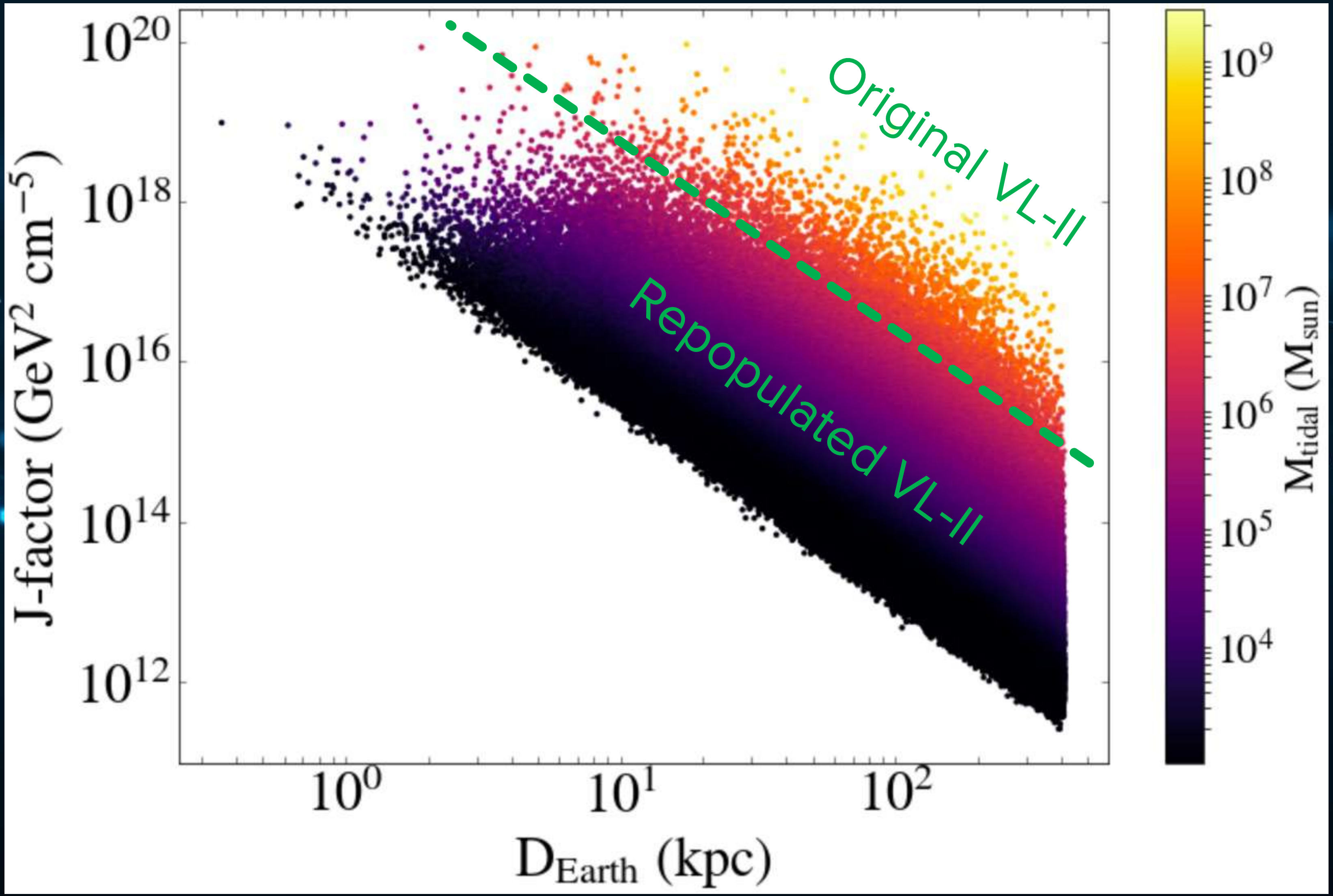
VL-II repopulation with low-mass subhalos

- Depending on the particle mass, subhalos are expected to have masses as low as $10^{-12} - 10^{-6}\ \mathrm{M_\odot}$
- But any simulation is incomplete due to numerical resolution

$$\frac{dn}{dM} \propto M^{-\alpha}. \quad \alpha = [1.9 - 2]$$

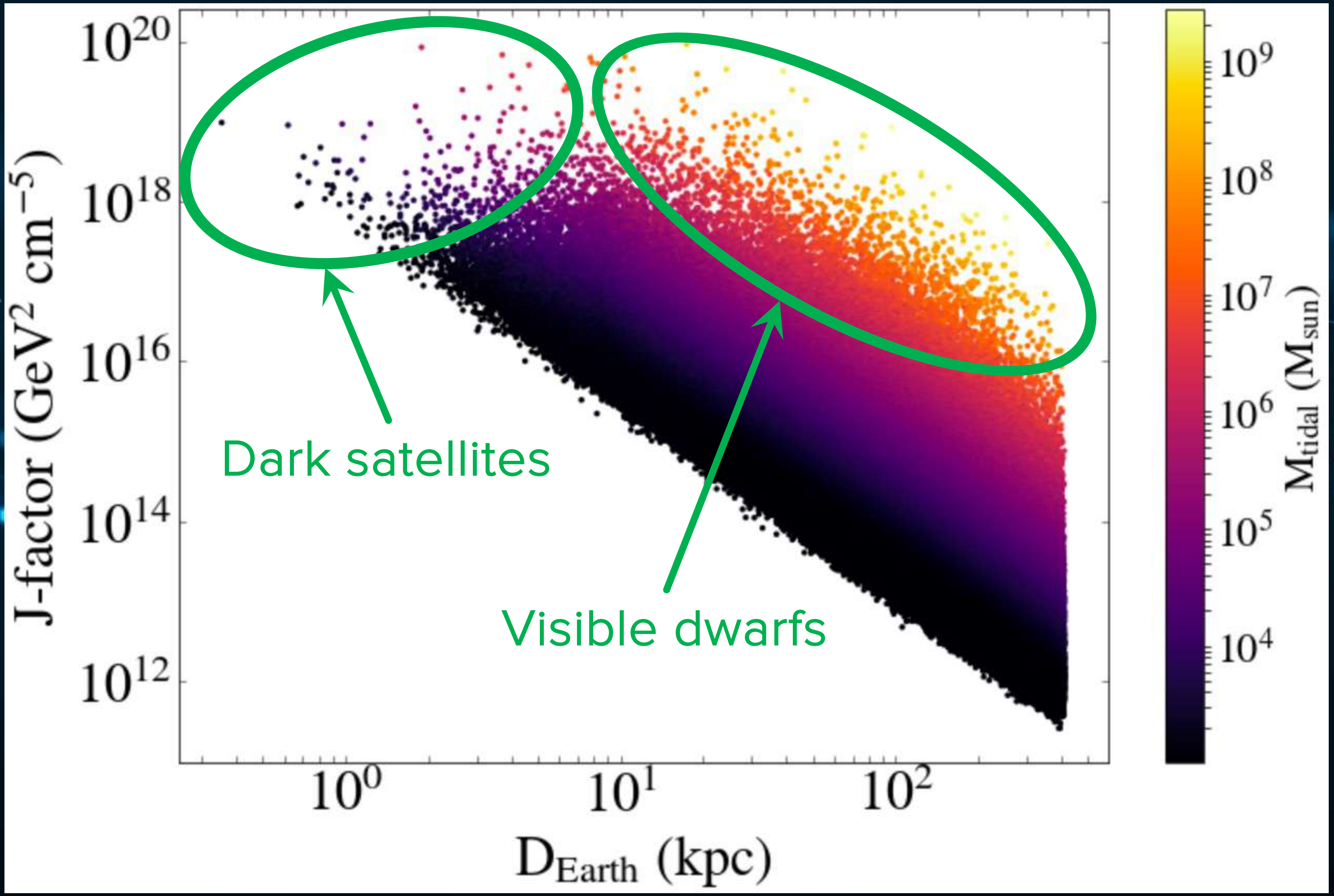
- In Via Lactea II (VL-II) simulation (Diemand+08), the resolution is $\sim 5 \cdot 10^6\ \mathrm{M_\odot}$ - are we losing subhalos with relevant J-factors?
- Characterizing the original VL-II and using LCDM recipes of structure formation, we generate mock realizations pushing down the mass resolution limit to $10^3\ \mathrm{M_\odot}$

VL-II repopulation with low-mass subhalos



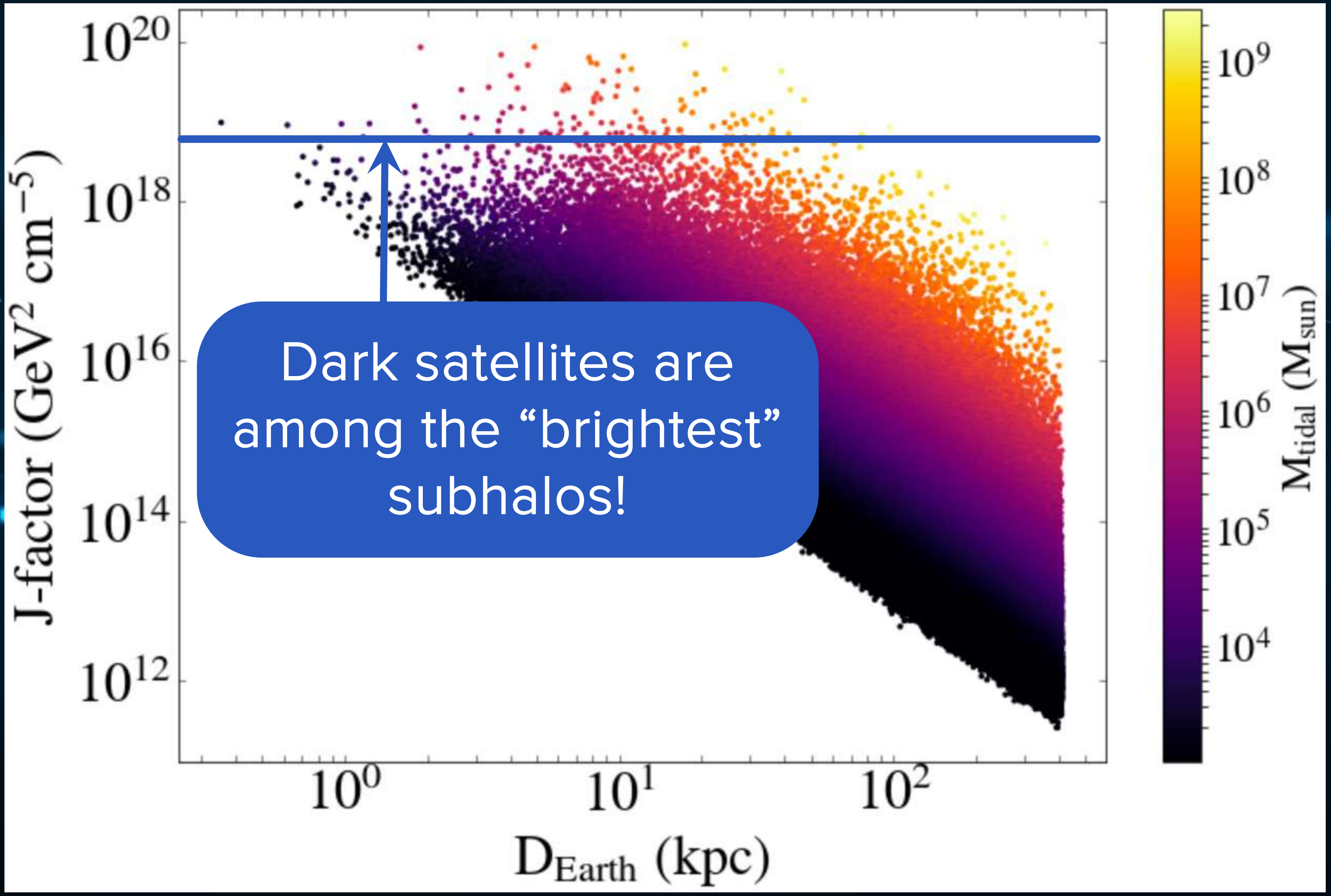
JCB+19 [1906.11896]

VL-II repopulation with low-mass subhalos



JCB+19 [1906.11896]

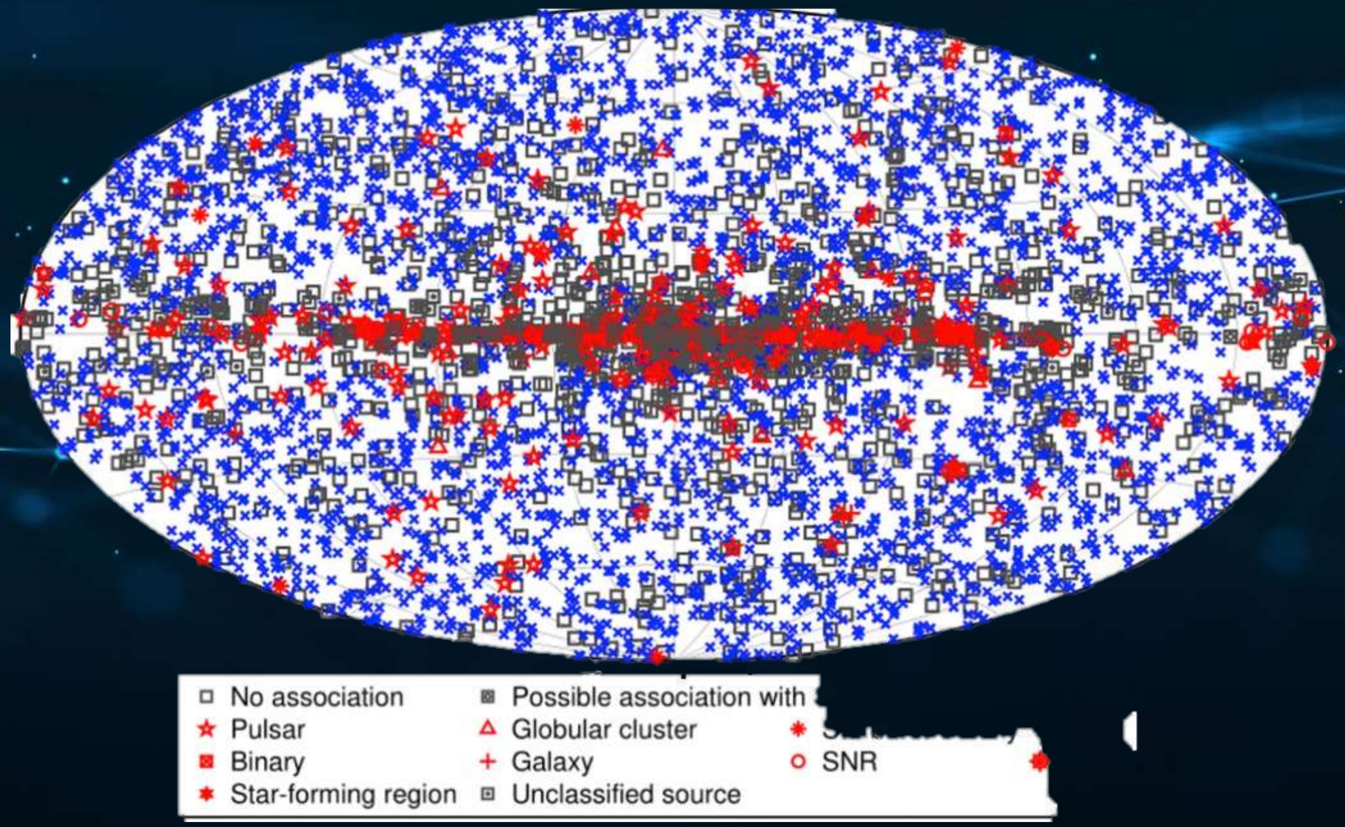
VL-II repopulation with low-mass subhalos



JCB+19 [1906.11896]

unIDs as DM targets

These low-mass subhalos would appear in the gamma-ray sky as <u>unidentified sources (unIDs)</u>



Ca. 1/3 of LAT sources (~1500) are unIDs – are some of them DM subhalos?

unIDs as DM targets

There are some ‘filters’ according to the expected DM emission from a subhalo

With them, we can reject unIDs as potential candidates

1. Source associations
2. Latitude
3. Flux variability
4. Machine learning identification
5. Multiwavelength emission

LAT catalogs filtering

	Original # of unIDs	unIDs compatible with DM
2FHL	48	4
3FHL	177	24
3FGL	1010	16

JCB+19 [1906.11896]

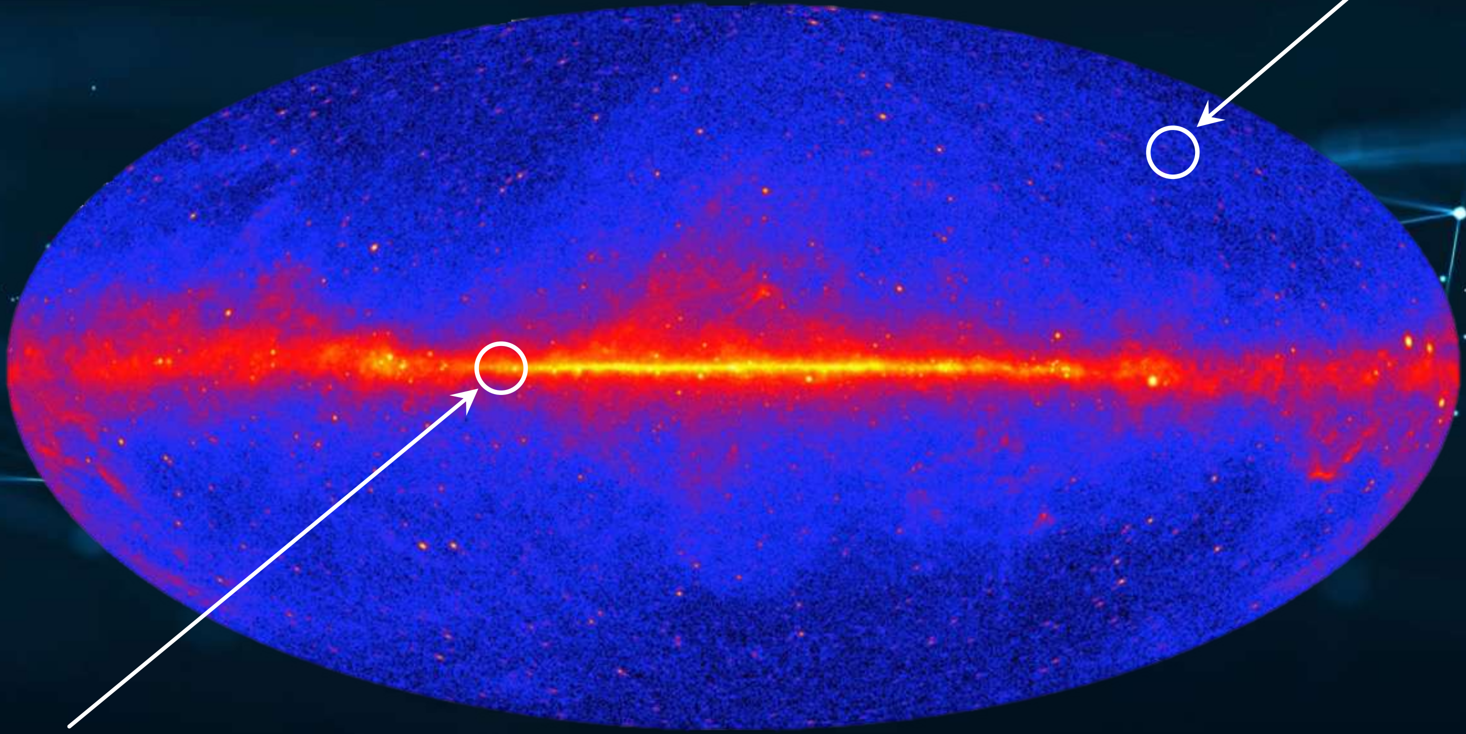
LAT sensitivity to DM subhalos

$$\langle \sigma v \rangle \propto \frac{m_\chi^2 \cdot F_{min}}{J_{factor} \cdot N_\gamma}$$

- Another key ingredient is the LAT sensitivity to DM subhalos, F_{min}
- This is the required flux to have a detection over the background
- Normally taken as the threshold flux of the catalog
- But, important dependance on WIMP mass, annihilation channel, source sky position and catalog setup

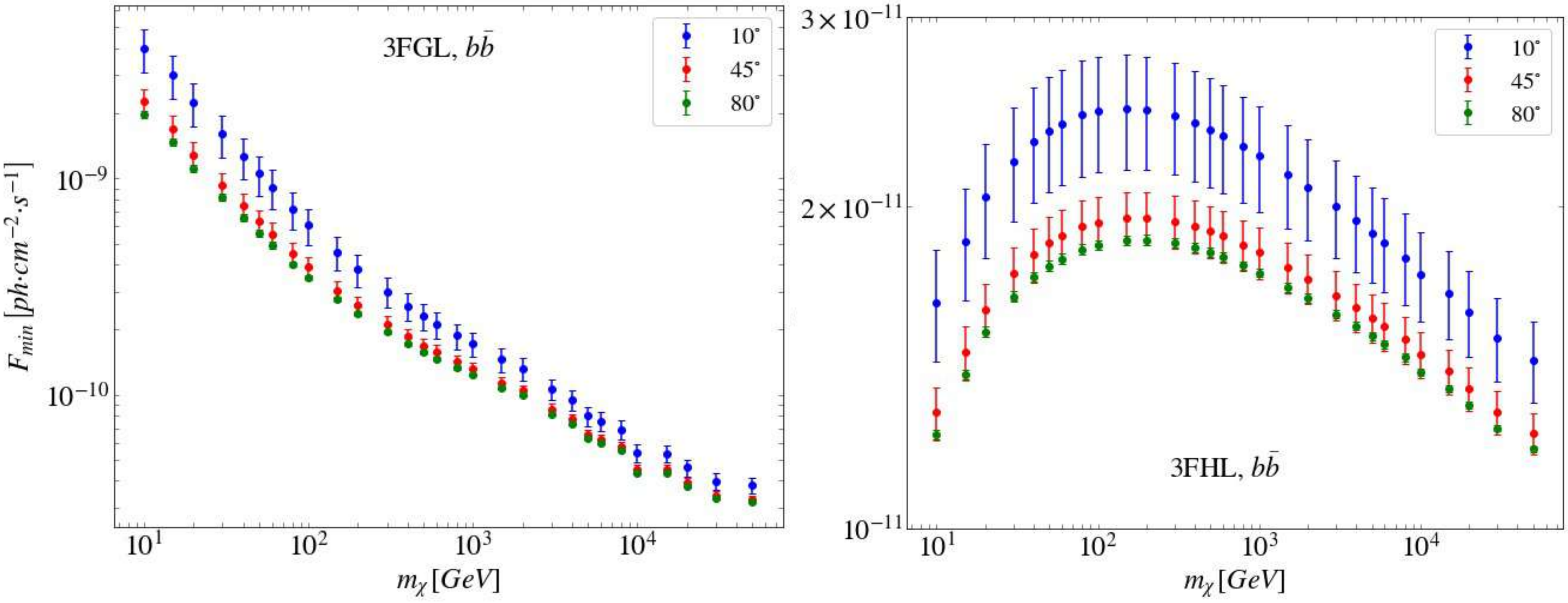
LAT sensitivity to DM subhalos

…than one here



A DM subhalo here will require
more flux to be detected…

LAT sensitivity to DM subhalos

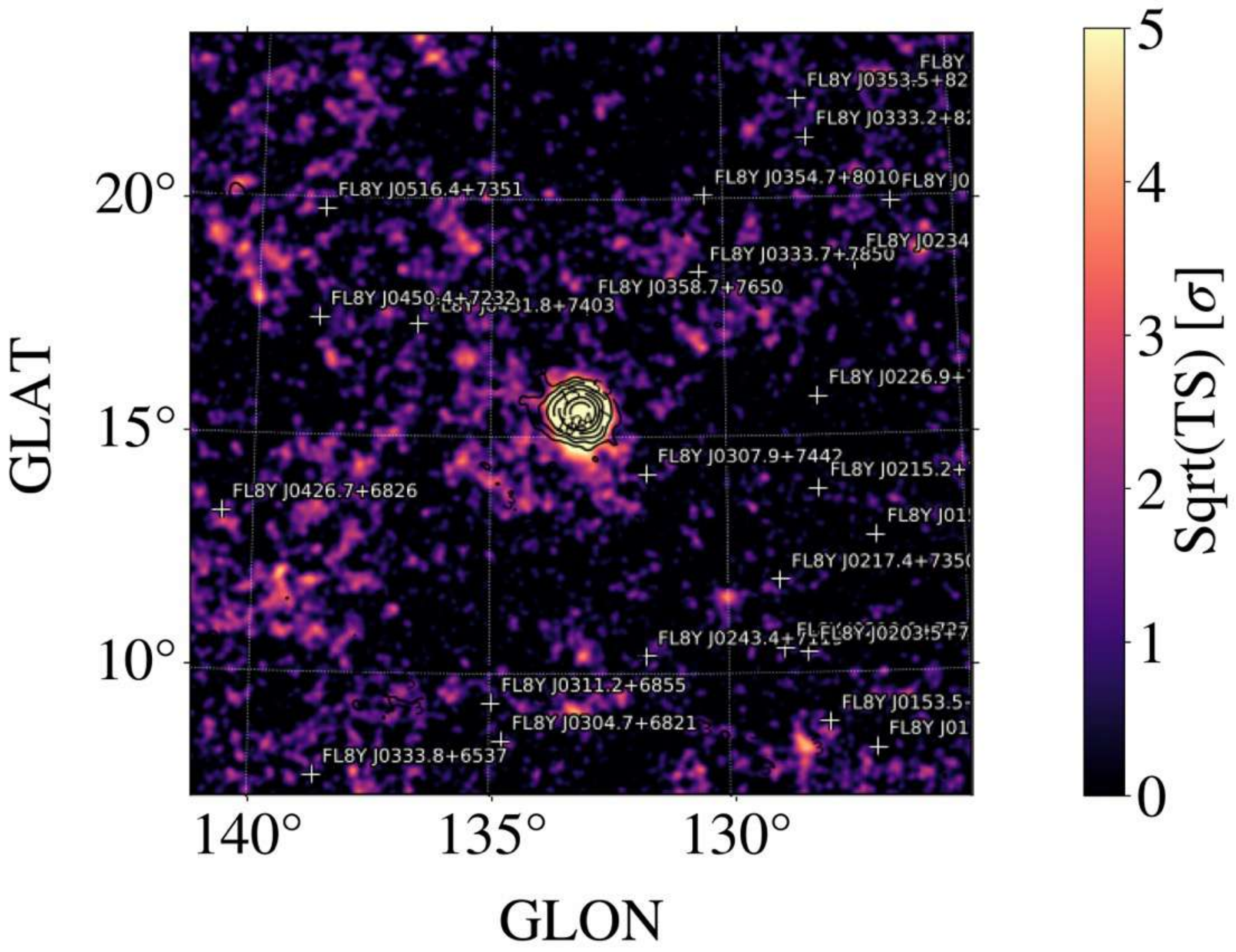


JCB+19 [1906.11896]

Spectral analysis

- For a shortlist of candidates, we perform a dedicated spectral analysis on them
- One of the main advantages is that we have improved statistics (10 years of LAT data), to be able to (dis)favour the DM hypothesis – in fact, some of the dim sources do not reach detection in 10 years and are therefore rejected
- We use *fermipy* for the analysis

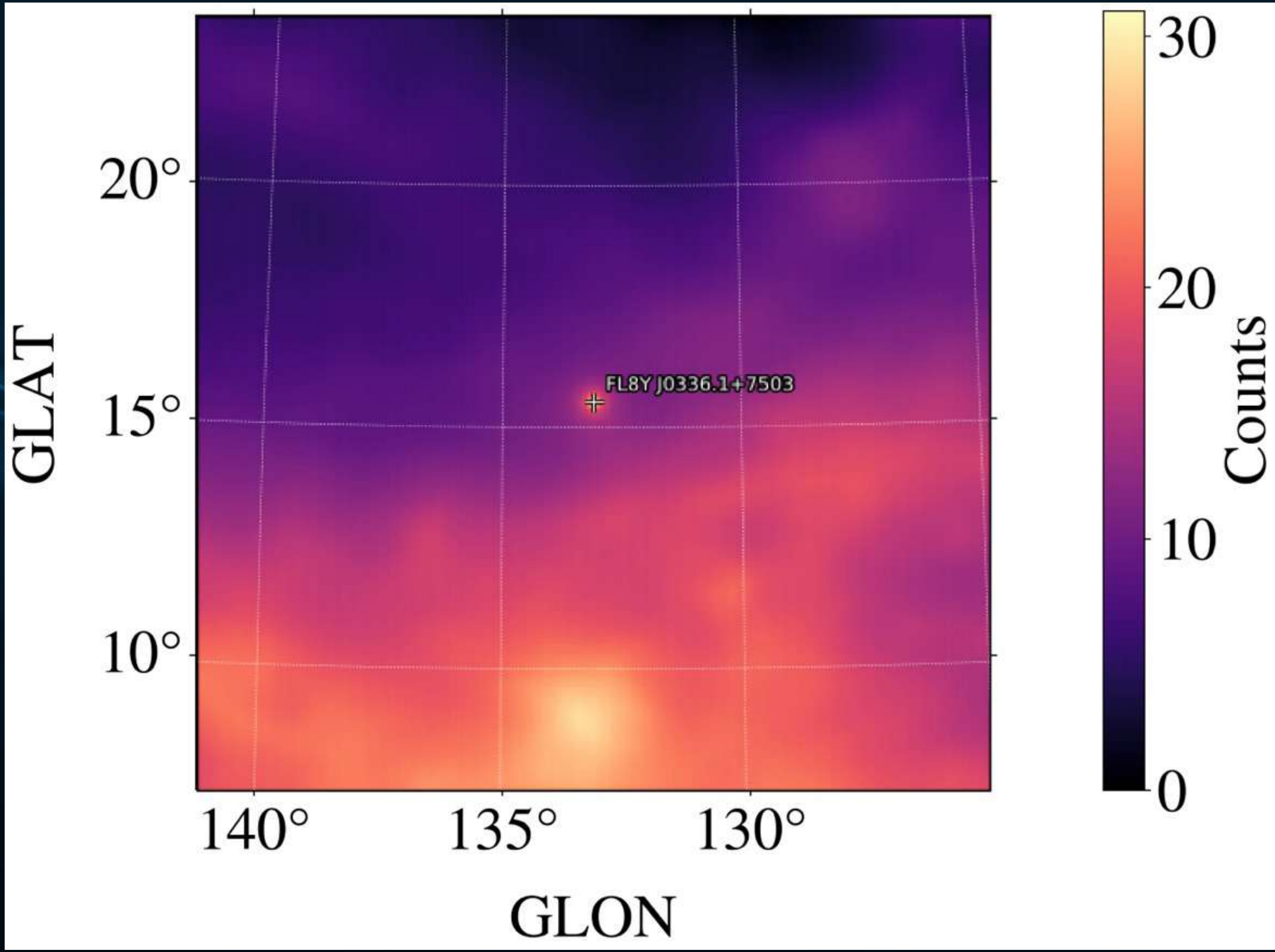
Spectral analysis



Point-source detection map

JCB+19 [1910.14429]

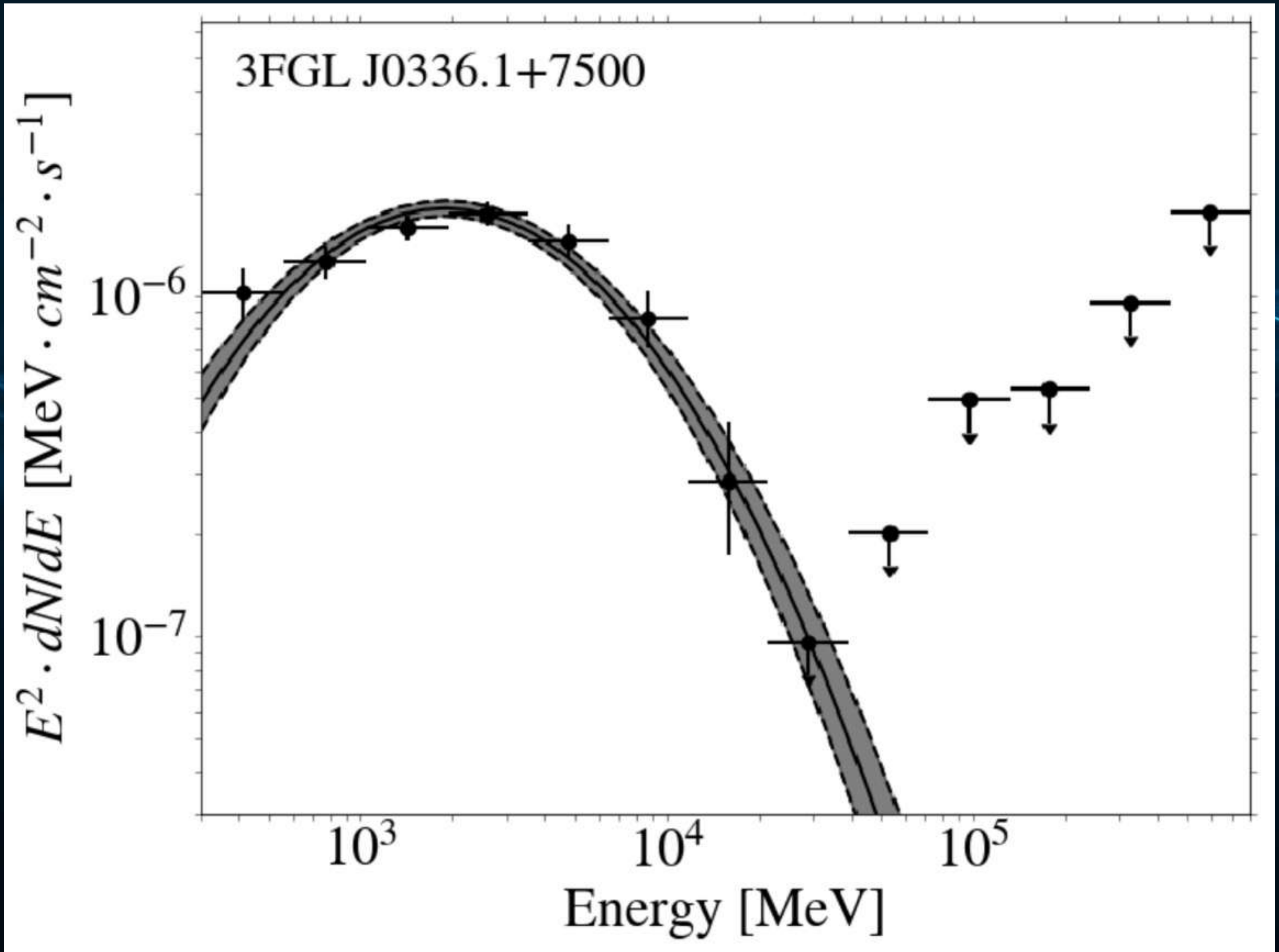
Spectral analysis



Model

JCB+19 [1910.14429]

Spectral analysis



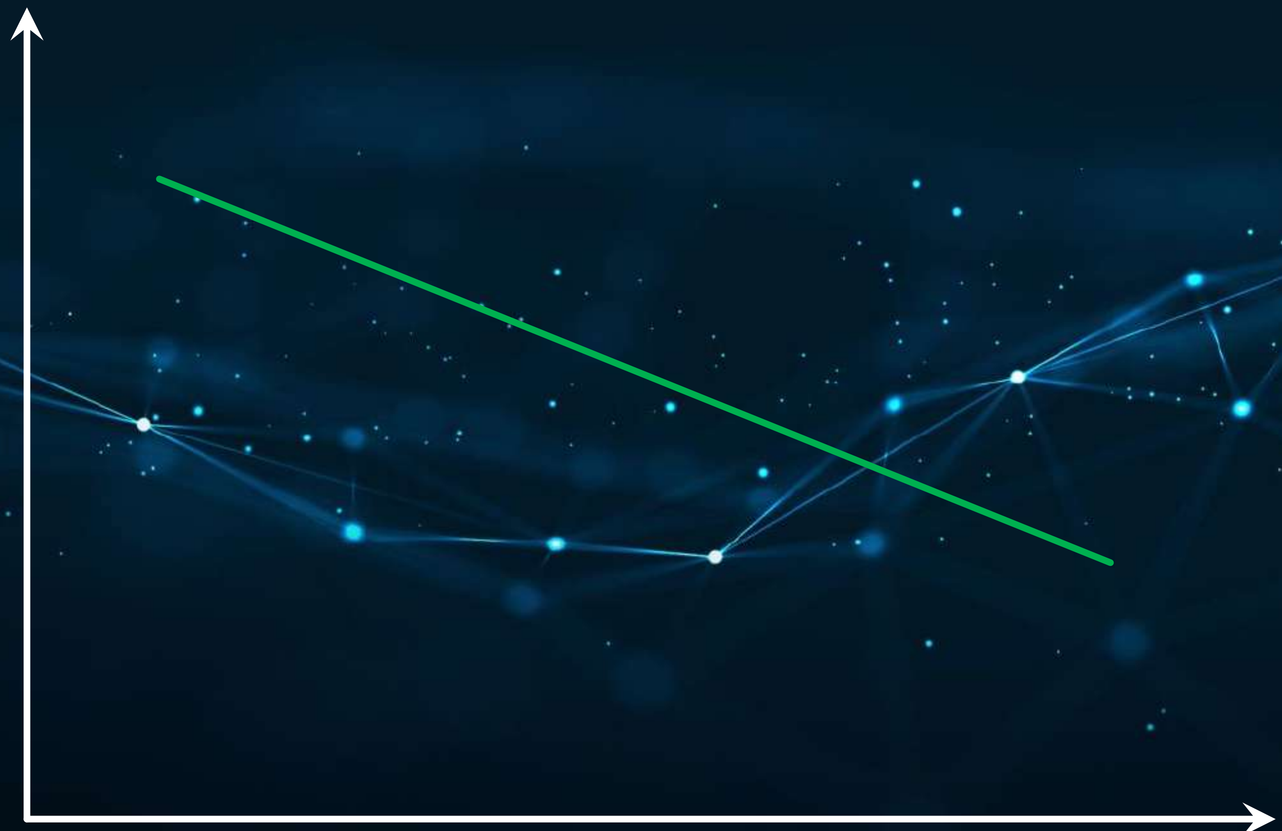
JCB+19 [1910.14429]

Spectral Energy Distribution (SED)

Spectral analysis

We work with three astrophysical parametrizations:

Spectral analysis



We work with three astrophysical parametrizations:

Power law

$$\frac{dN}{dE} = K\left(\frac{E}{E_0}\right)^{-\alpha}$$

Spectral analysis

We work with three astrophysical parametrizations:

Log-parabola

$$\frac{dN}{dE} = K \left(\frac{E}{E_0}\right)^{-\alpha - \beta \log(E/E_0)}$$

Spectral analysis

We work with three astrophysical parametrizations:

Super-Exponential cutoff power law

$$\frac{dN}{dE} = K\left(\frac{E}{E_0}\right)^{-\alpha} \exp\left(-\frac{E}{E_{cut}}\right)^{\beta}$$

Spectral analysis

Then, we compute the likelihood of each model and compare them to the best DM fit, for each channel, via the generalized likelihood ratio test (Akaike 1974)

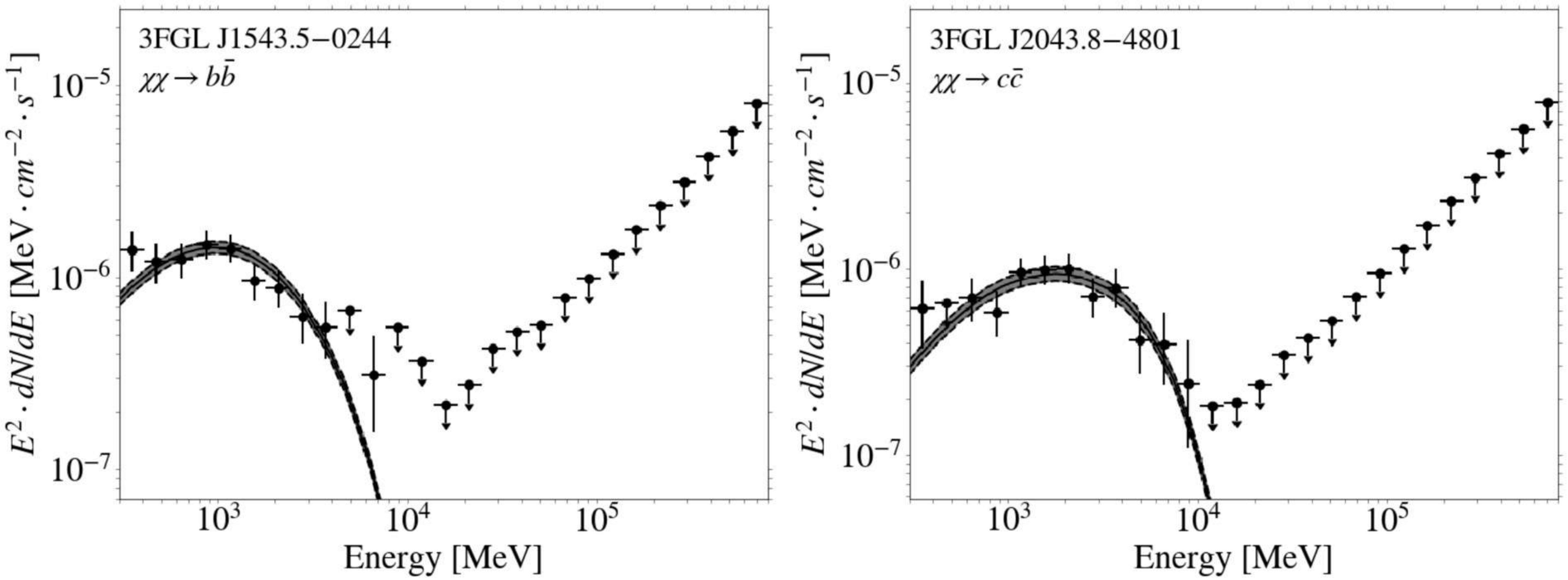
$$\Delta \mathrm{TS} = 2\left[\left(k_0 - k_\chi\right) + \log\left(\frac{\mathcal{L}_\chi}{\mathcal{L}_0}\right)\right] \begin{cases} \chi = \mathrm{DM} \\ 0 = \mathrm{Astro} \end{cases}$$

Difference in degrees of freedom of the models

“Traditional” LRT

We would require $\Delta \mathrm{TS} > 25$ to have a positive detection of DM

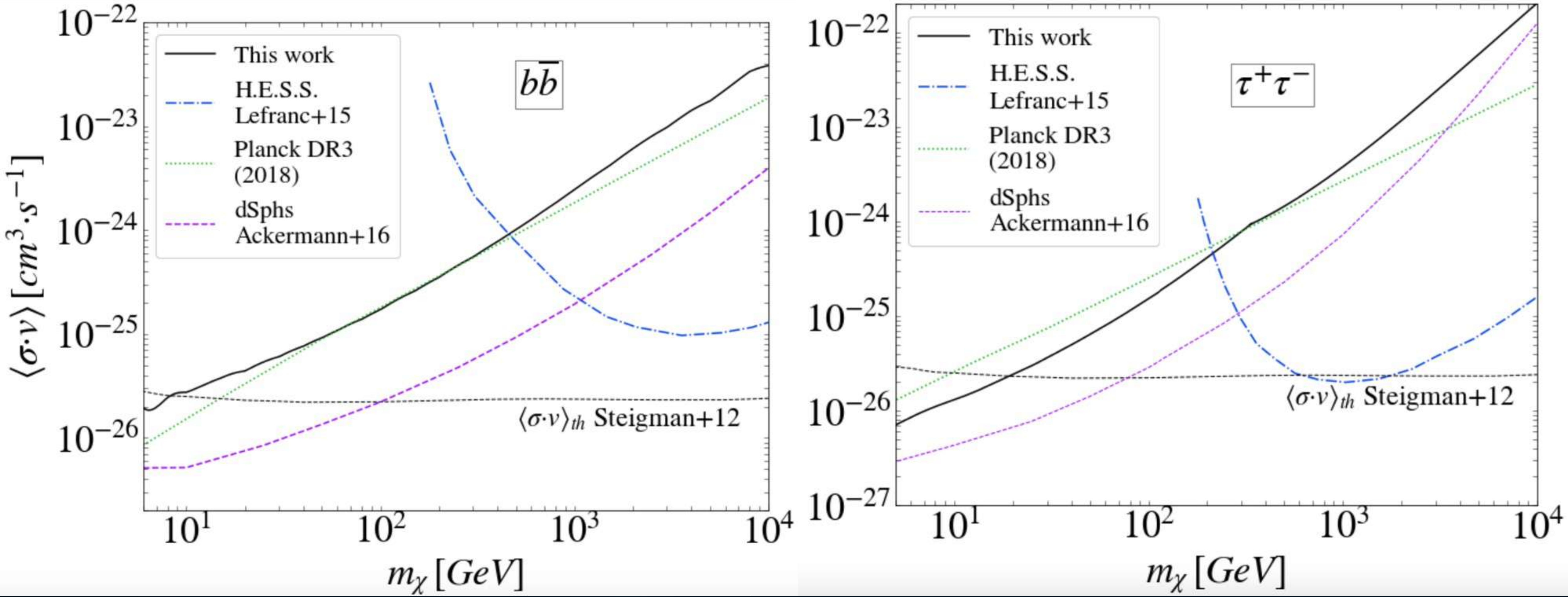
Spectral analysis



JCB+19 [1910.14429]

Two best candidates - $\Delta TS \sim 10$ (not strong enough!)

DM constraints



JCB+19 [1910.14429]

As we do not trust the previous candidates enough, we just set limits

The spectral analysis improves the constraints a factor ~ 4

Spatial analysis

Brightest DM subhalos are expected to be spatially extended

3.3 Prospects for Detecting Spatial Extension

Thus far our discussion has been restricted to the detection of dark matte[r] like gamma-ray sources. Of those subhalos detectable by Fermi, however, [...] and nearby may be discernibly spatially extended, potentially enabling one to distinguish a dark matter subhalo from a pulsar, blazar, or other gamma-ray point source. The unambigu- ous observation of a spatially extended gamma-ray source with no corresponding emission at other wavelengths would constitute a smoking gun for annihilating dark matter [28].

1610.07587

2 Why Spatial Extension would be a "Smoking Gun" for Annihilating Dark Matter

In the introduction of this paper, we asserted that a robust detection of an extended gamma-ray source without observable counterparts at other wavelengths would constitute a "smoking gun" for annihilating dark matter. We recognize, however, that this conclusion might strike some readers as controversial. In this section, we discuss this issue further, and argue that any spatially extended gamma-ray source must also produce easily observable emission at other wavelengths.

1602.07303

5 Spatial analysis of remaining DM candidates

5.1 Technical setup and data analysis results

Spatial extension has been studied by many authors as a possible "smoking gun" for DM annihilation (see e.g. [17, 18, 24, 49–51]). In this section we search for spatial extension, in

1910.14429

V. SPATIAL EXTENSION

Most astrophysical gamma-ray emitters (pulsars, blaz- ers, etc.) are effectively point sources, without any po- tentially observable spatial extension. A fraction of dark matter subhalos, on the other hand, could be detectably extended, especially those most nearby and large. In this section, we study the dark matter subhalo candidate sources identified in the previous section in an effort to determine whether they exhibit any evidence of spatial extension.

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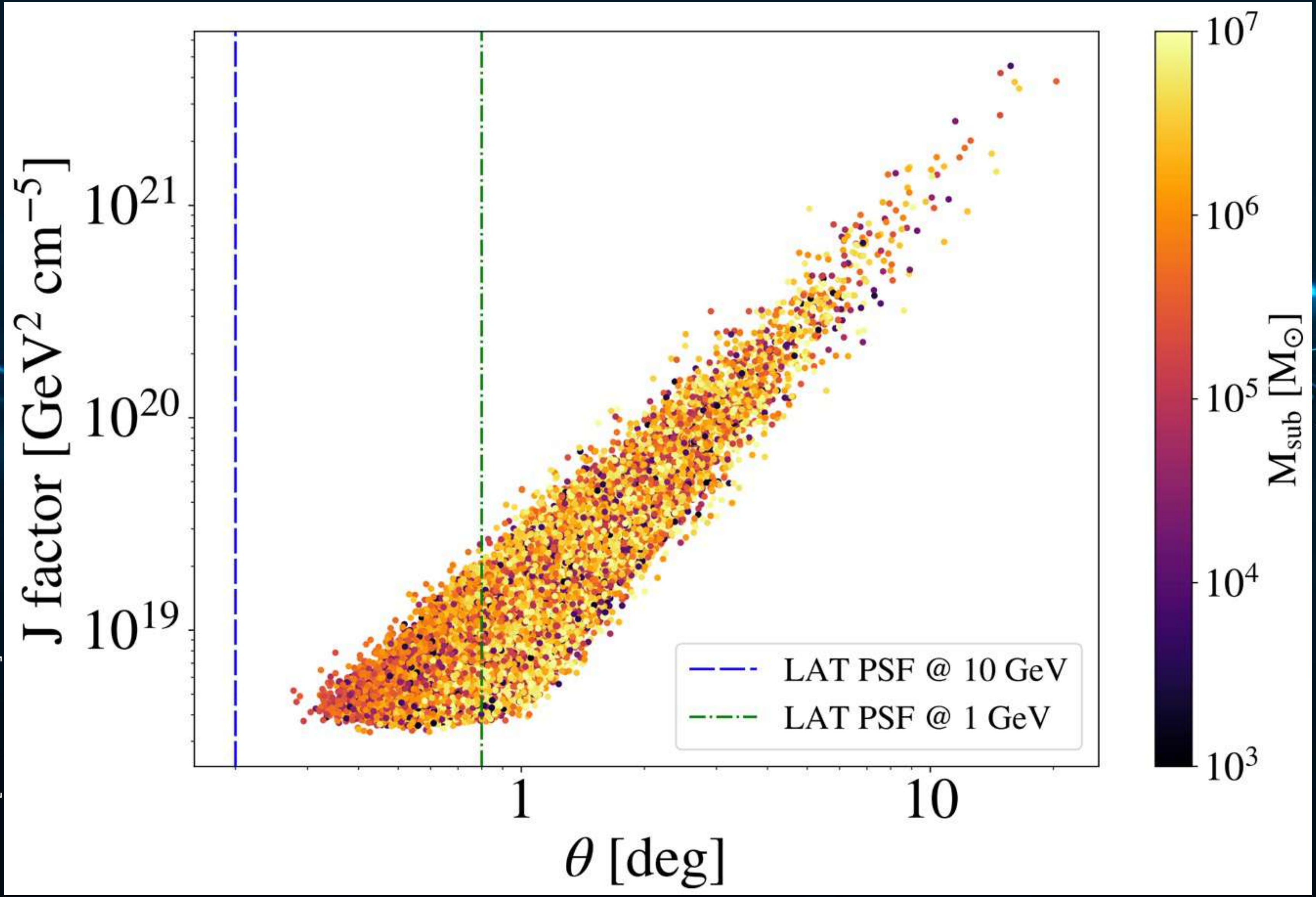
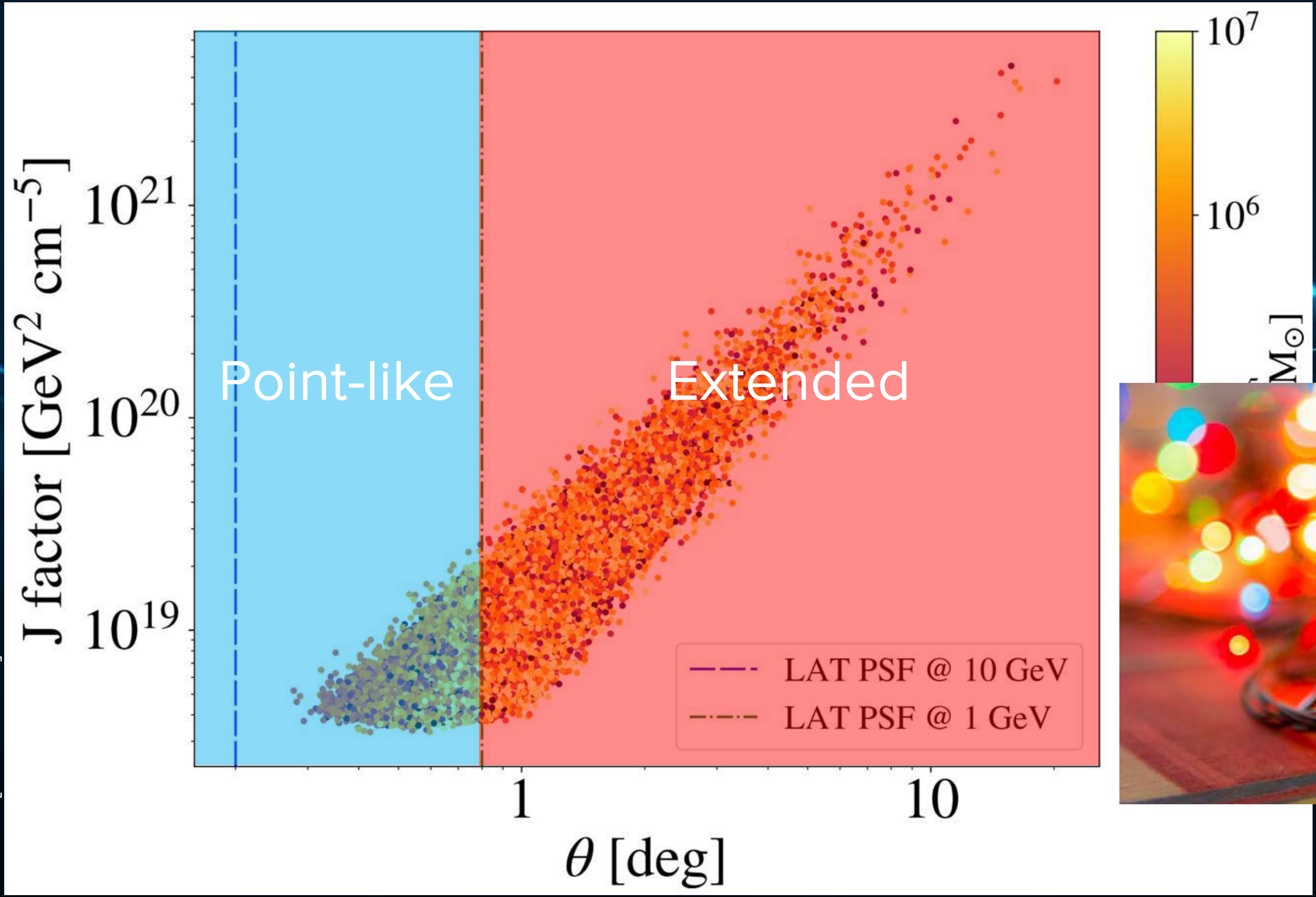
Spatial analysis



JCB+19 [1910.14429]

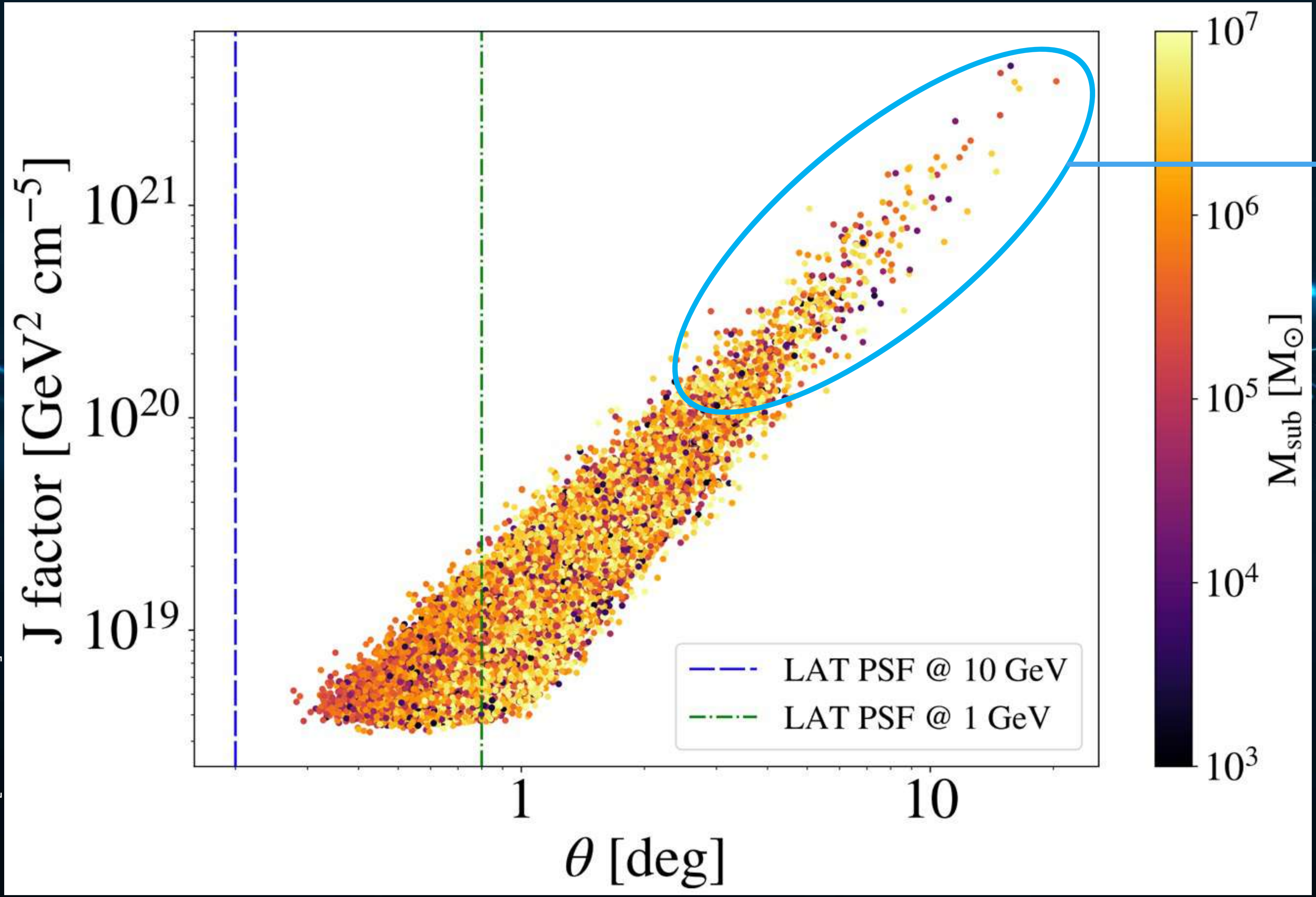
Spatial analysis



Due to the Point Spread Function (PSF), an extended source can be effectively seen as point-like

JCB+19 [1910.14429]

Spatial analysis



JCB+19 [1910.14429]

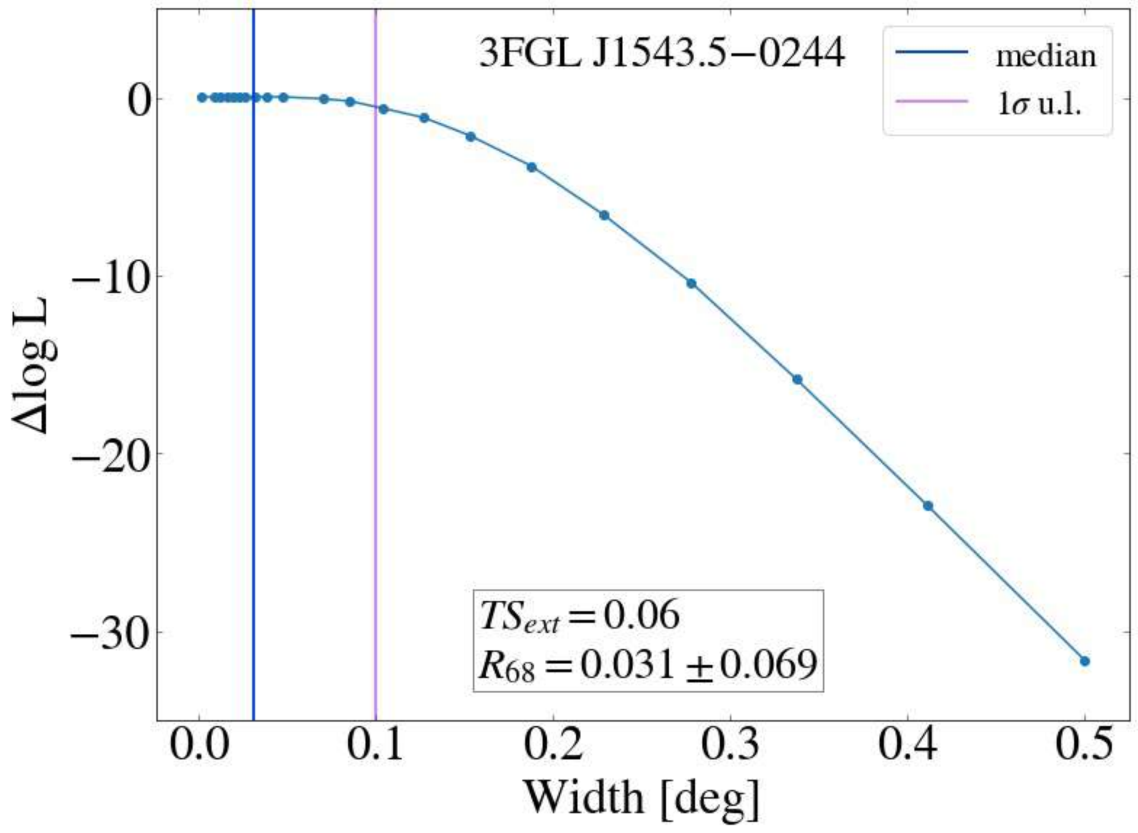
The brightest subhalos should have angular extensions of $\mathcal{O}(10°)$

Is any of our candidates extended?

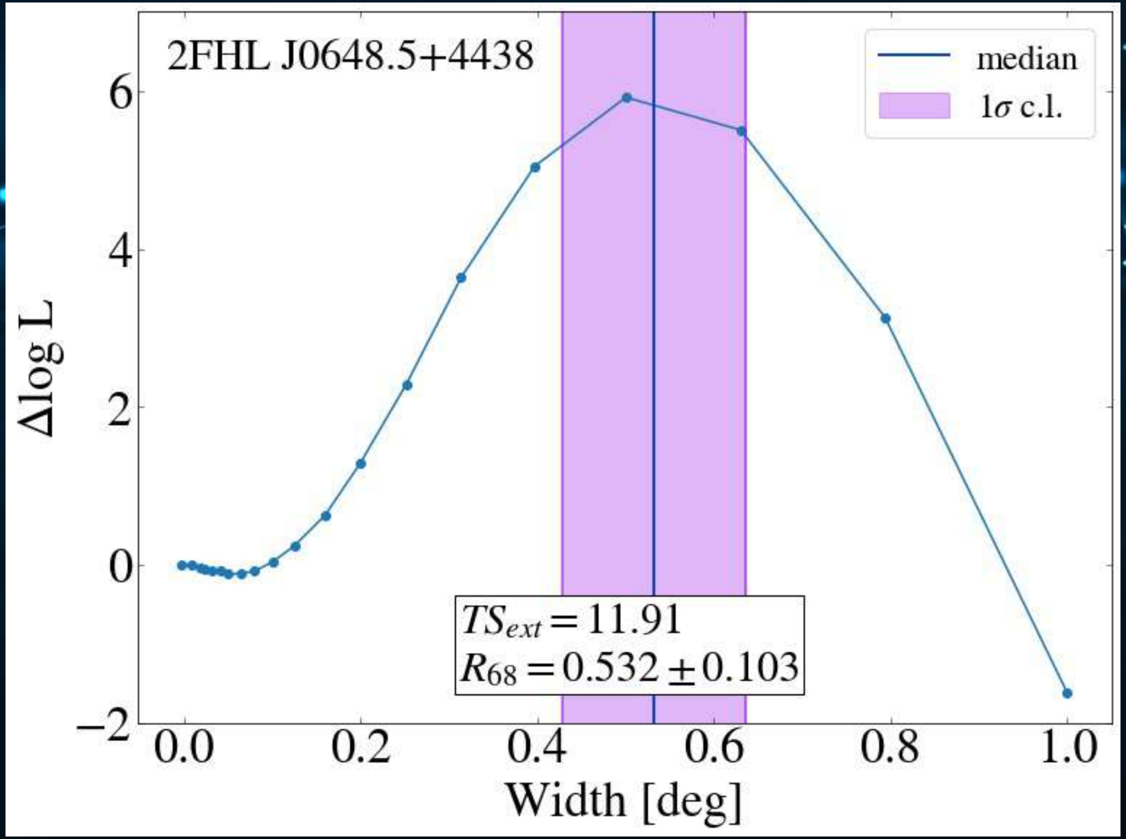
Spatial analysis

$$TS_{ext} = -2\log\left(\frac{\mathcal{L}_{ext}}{\mathcal{L}_{point}}\right)$$

JCB+19 [1910.14429]



Our best DM candidates – point like

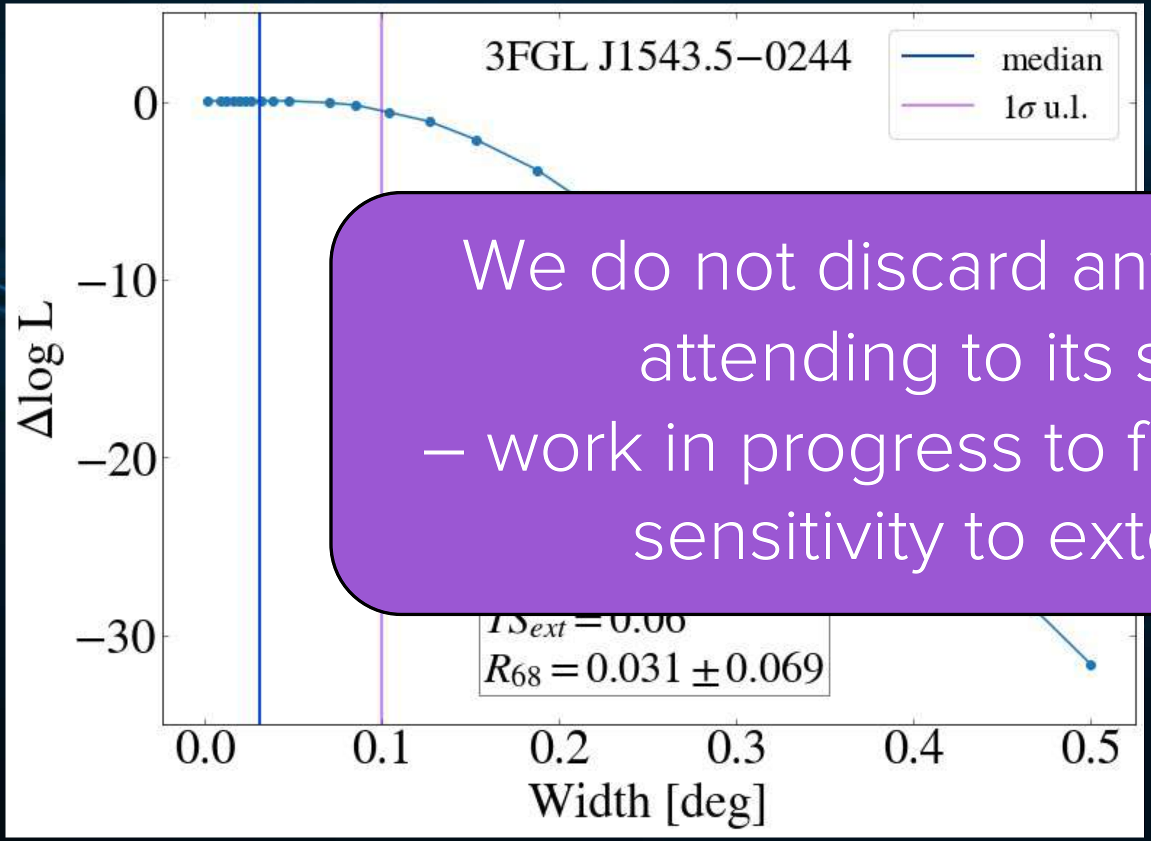


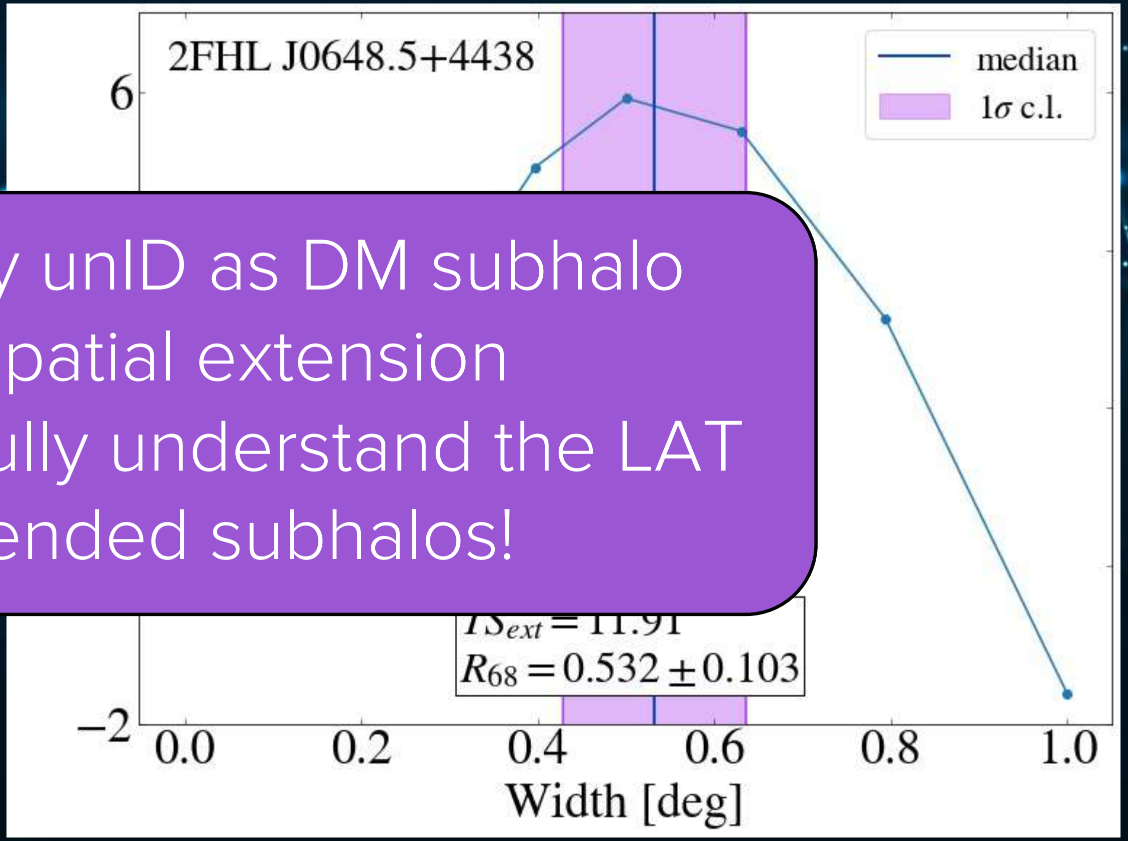
Extended unID – not fitted to DM

Spatial analysis

$$TS_{ext} = -2\log\left(\frac{\mathcal{L}_{ext}}{\mathcal{L}_{point}}\right)$$

JCB+19 [1910.14429]





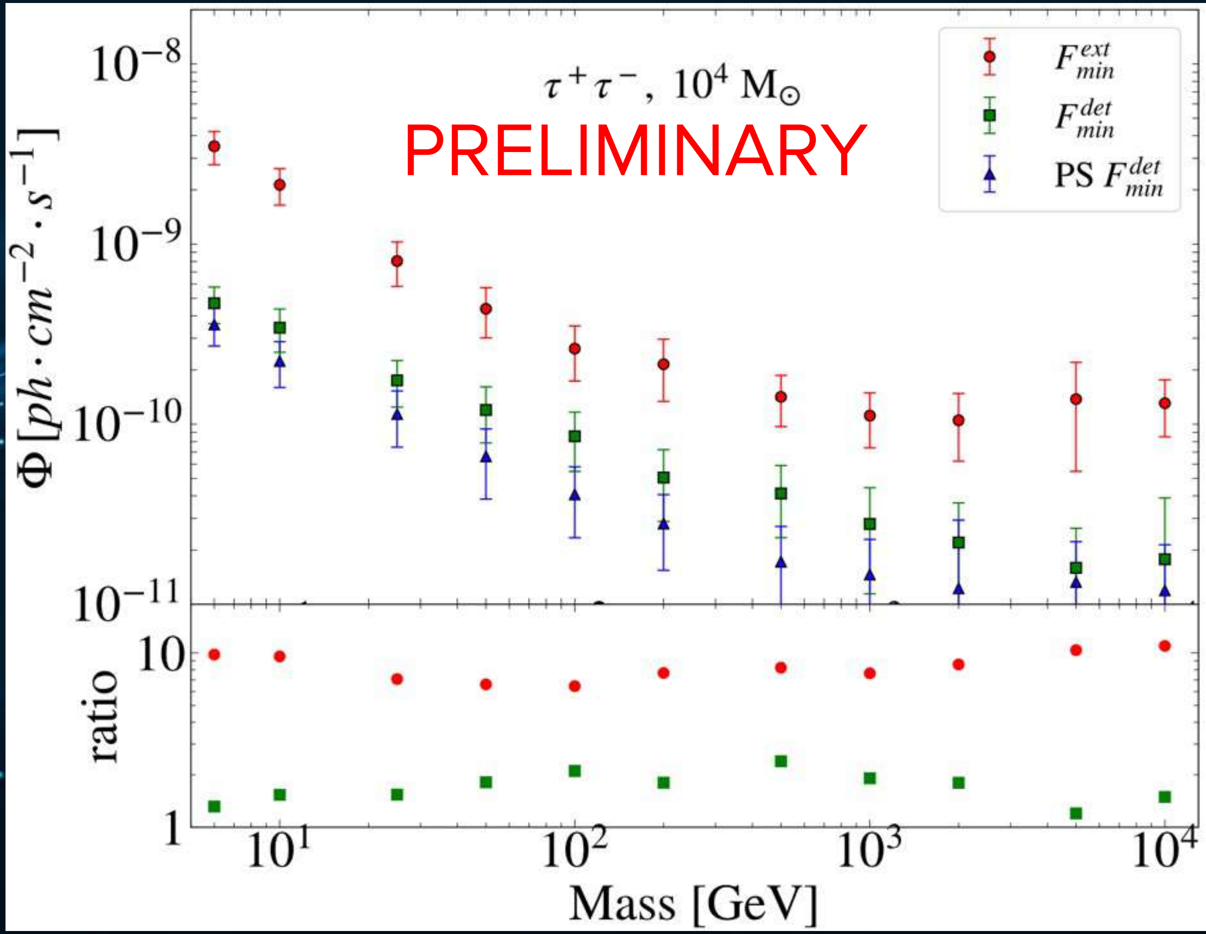
We do not discard any unID as DM subhalo attending to its spatial extension
– work in progress to fully understand the LAT sensitivity to extended subhalos!

Our best DM candidates – point like

Extended unID – not fitted to DM

Spatial analysis (preliminary results, JCB+21 in prep.)

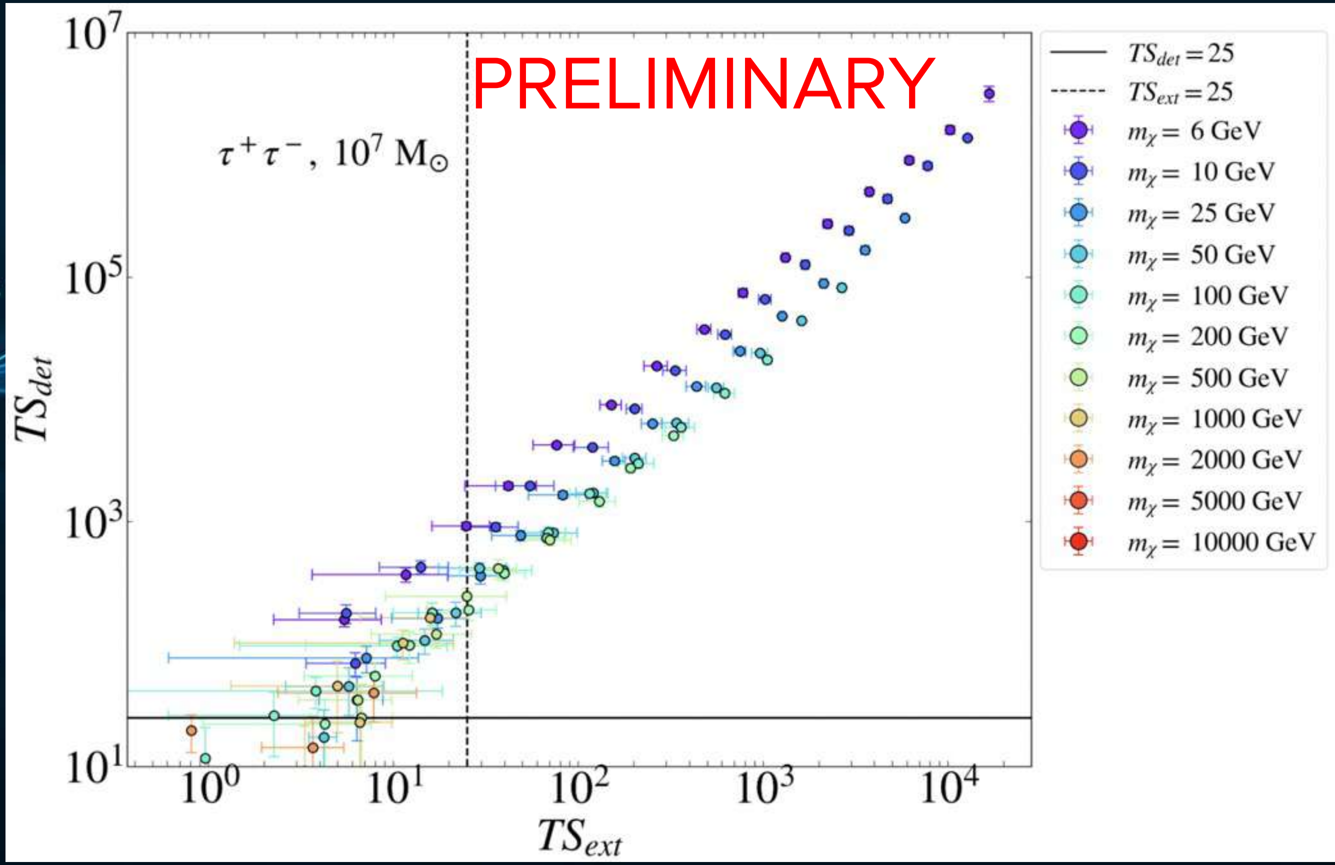
- It is unclear whether the LAT is able to see these bright subhalos as extended sources – a dedicated analysis is necessary
- By simulating subhalos with real gamma-ray data and CLUMPY spatial profiles, we can study how does the LAT sensitivity change
- The F_{min} to detect them is a factor ~2 larger , while we need a flux ~ 10 times larger unequivocally detect spatial extension $(TS_{ext} = 25)$



Spatial analysis (preliminary results, JCB+21 in prep.)

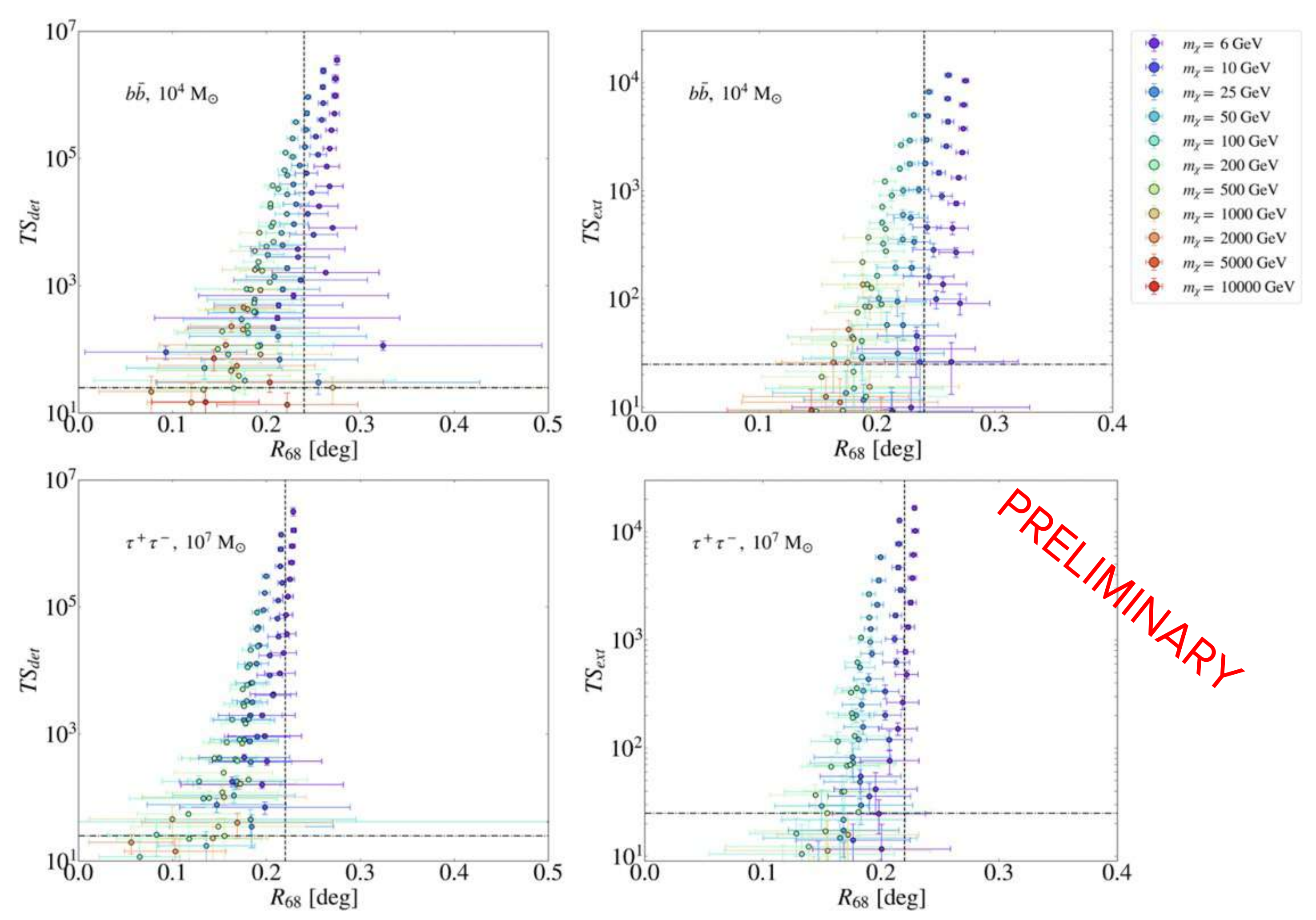
- We can also compute the relation between the extension and detection significances, which turns out to be remarkably linear

- Heavier WIMPs require large annihilation cross sections to be detected – above $\sim 200 - 500$ GeV, the LAT is very little sensitive to subhalo DM annihilation



Spatial analysis (preliminary results, JCB+21 in prep.)

- In most cases, light WIMPs are detected as extended, with a 68% containment angle between $0.1 - 0.3°$
- Above 500-1000 TeV only hints of extensión can be found for large J-factor/cross section values
- Eventually, it could be used as an additional 'filter' to refine the constraints



Summary and conclusions

- DM subhalos, appearing as unidentified gamma-ray sources (unIDs) are competitive and independent targets for indirect DM detection in a variety of gamma-ray telescopes

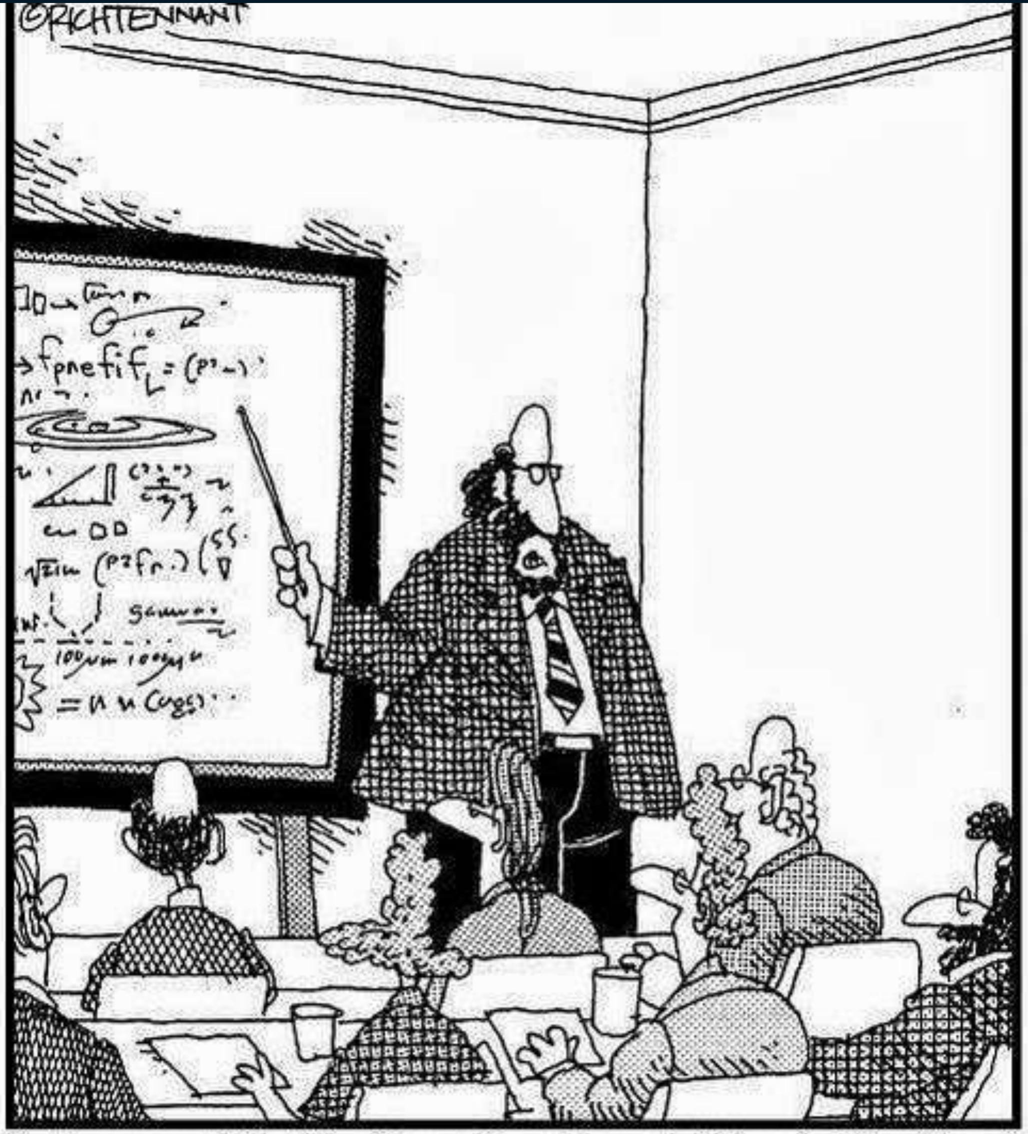
- We also need powerful N-body simulations to fully understand the number, distribution and brightness of DM subhalos

- Subhalo candidates can be identified among the poll of unIDs by applying a series of 'filters'

- Performing a full, dedicated spectral analysis on the remaining unIDs with the latest data can (dis)favour the DM hypothesis

- The achievable constraints, by comparing the N-body simulations predictions with the actual gamma-ray data, are comparable and complementary to the best in the field

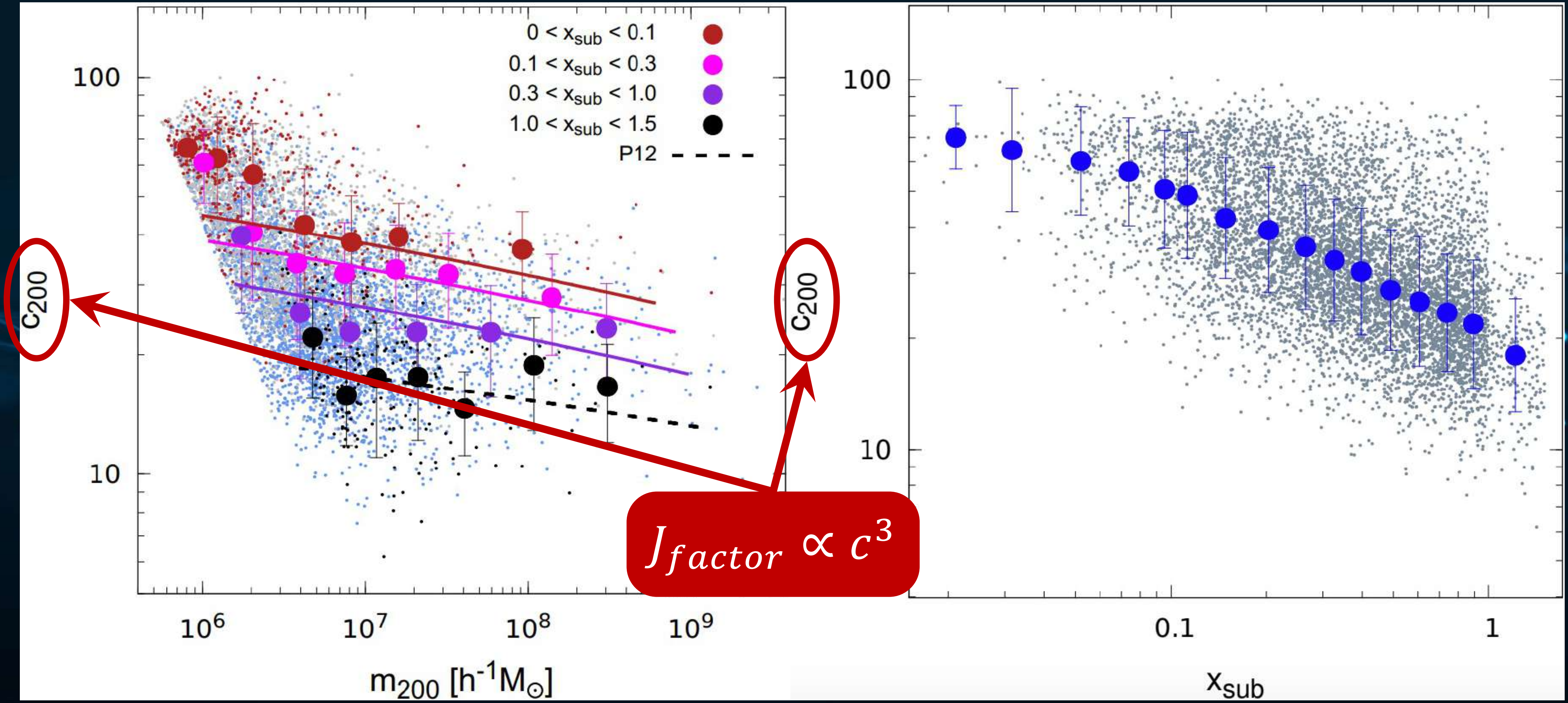
- Ongoing work on spatial extension of subhalo signals may point it to be a “smoking gun” for DM subhalo detection



"Along with 'Antimatter,' and 'Dark Matter,' we've recently discovered the existence of 'Doesn't Matter,' which appears to have no effect on the universe whatsoever."

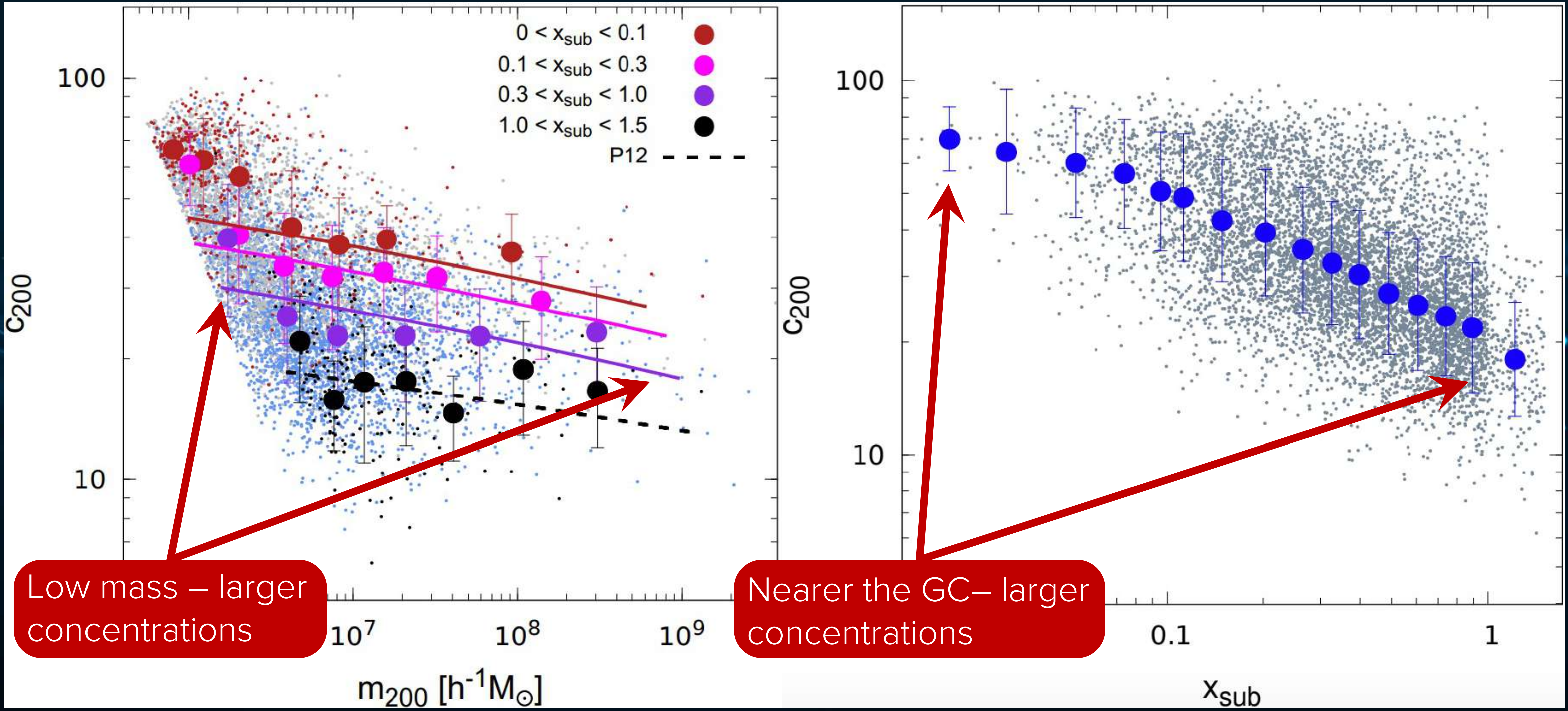
Thank you
for your time!

N-body cosmological simulations



Moliné+17 [1603.04057]

N-body cosmological simulations



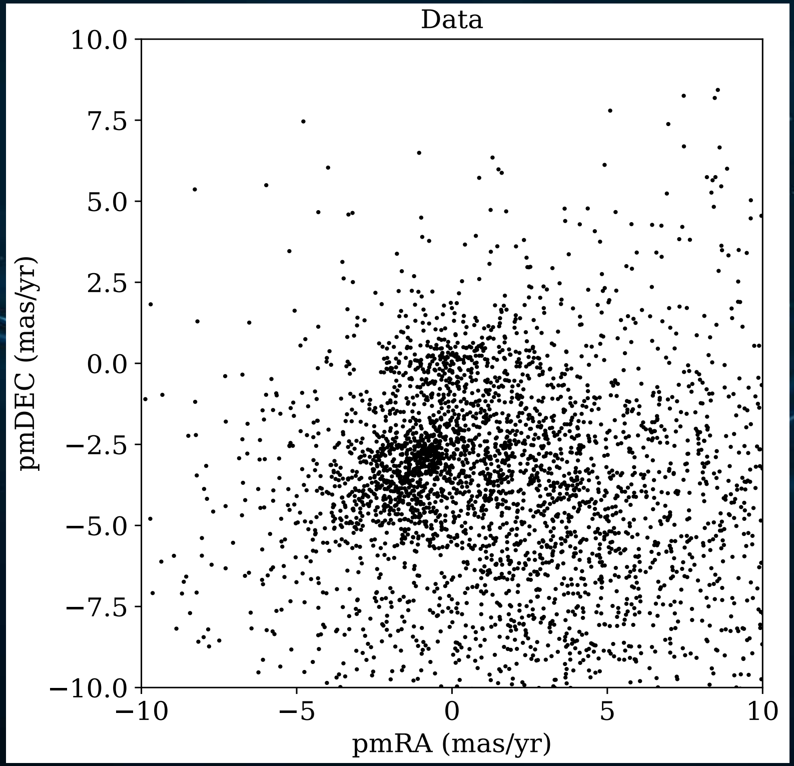
Moliné+17 [1603.04057]

Source name	DM channel(s)	ΔTS	m_χ (GeV)	Astro. models
3FGL J1543.5−0244	$b\bar{b}$	9.26	15.2 ± 1.3	LP, PLE
	Z^0Z^0	8.29	11.1 ± 0.9	
	$c\bar{c}$	6.27	11.8 ± 0.7	
3FGL J2043.8−4801	$c\bar{c}$	10.31	22.4 ± 1.7	PLE, LP
	Z^0Z^0	9.21	23.3 ± 5.7	
	$\tau^+\tau^-$	3.21	8.5 ± 0.4	
3FHL J0041.7−1608	$c\bar{c}$	1.87	666 ± 99	PL
3FHL J0343.5−6302	Z^0Z^0	3.89	112 ± 14	PL, LP
	$c\bar{c}$	0.59	67.1 ± 6.7	
3FHL J0620.9−5033	$\tau^+\tau^-$	0.63	56.7 ± 9.2	PL, PLE
3FHL J1441.3−1934	$\tau^+\tau^-$	4.92	48.1 ± 13.3	PLE, PL
	$\mu^+\mu^-$	4.91	29.6 ± 2.9	
	e^+e^-	3.89	29.6 ± 3.0	
	$b\bar{b}$	2.79	328 ± 45	
	$c\bar{c}$	2.68	197 ± 22	
	Z^0Z^0	2.12	299 ± 32	
3FHL J1716.1+2308	Z^0Z^0	3.19	207 ± 25	PLE, PL
	$c\bar{c}$	2.59	162 ± 47	

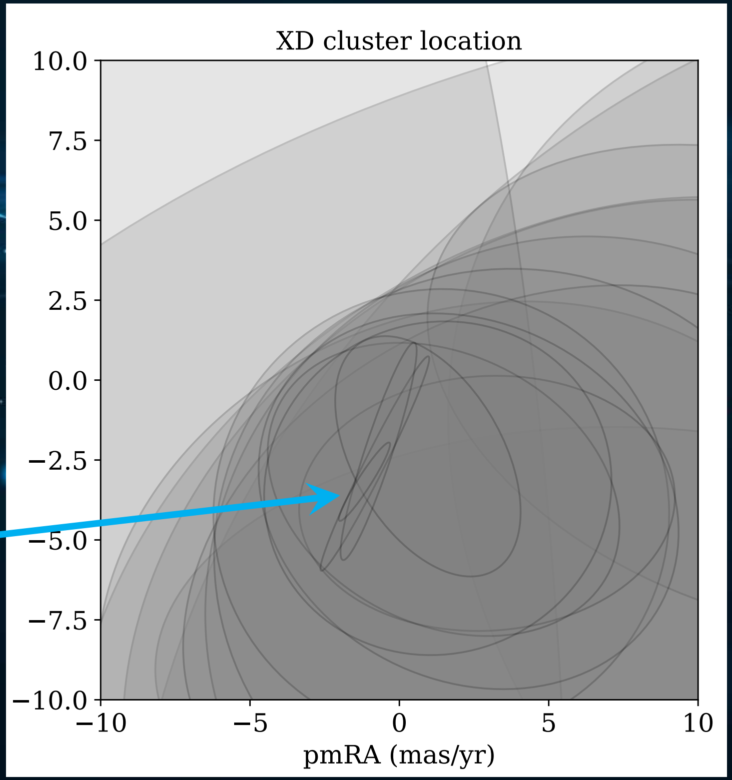
JCB+19 [1910.14429]

Searching for stellar streams with *Gaia*

If one of our unIDs, with a spectrum compatible with DM, is coincident with a stellar stream, if might be the remnant of a stripped dSph



Star overdensity, proper motion compatible with the Sagittarius stream



JCB+19 [1910.14429]

We only find one source (3FHL J0041.7-1608) coincident with the Sagittarius stream, yet we cannot univoquely associate them