UNASSOCIATED GAMMA-RAY SOURCES AS TARGETS FOR INDIRECT DARK MATTER DETECTION WITH FERMI-LAT

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SUSY2018

Barcelona, Spain

DM ANNIHILATION IN THE WIMP MODEL

$\chi\chi \rightarrow$  $\begin{cases} \tau^+\tau^- \\ b\bar{b} \\ W^+W^- \\ ?_1\,?_2 \end{cases} \rightarrow \cdots \rightarrow \gamma\gamma$

$$F(E > E_{th}) = J_{factor} * f_{pp}(E > E_{th})$$

Astrophysics (Density profile, distance…)

Particle Physics (channel, annihilation spectra…)

$$J_{factor} = \int_{\Delta\Omega} d\Omega \int_{l.o.s} \rho_{DM}^2[r(\lambda)]d\lambda$$

DM density profile

$$f_{pp} = \sum_f B_f \frac{1}{4\pi} \frac{dN_f}{dE_f} \frac{\langle\sigma v\rangle}{2m_\chi^2}$$

Branching ratio taken as 1

DM ANNIHILATION IN THE WIMP MODEL

$$\chi\chi \rightarrow \left\{ \begin{array}{c} \tau^+\tau^- \\ b\bar{b} \\ W^+W^- \\ ?_1\,?_2 \end{array} \right. \rightarrow \cdots \rightarrow \gamma\gamma$$

$$F(E > E_{th}) = J_{factor} * f_{pp}(E > E_{th})$$

Astrophysics (Density profile, distance…)

Particle Physics (channel, annihilation spectra…)

$$\langle\sigma v\rangle \propto \frac{m_\chi^2 \cdot F_{min}}{J_{factor} \cdot \int_{E_{th}}^{E} \left(\frac{dN}{dE}\right) dE} = \frac{m_\chi^2 \cdot F_{min}}{J_{factor} \cdot N_\gamma}$$

Instrument (F_{min})

Theory (N_γ)

Simulations (J_{factor})

We want to probe the lowest possible $\langle\sigma v\rangle$ values to have the highest sensitivity to a dark matter annihilation signal

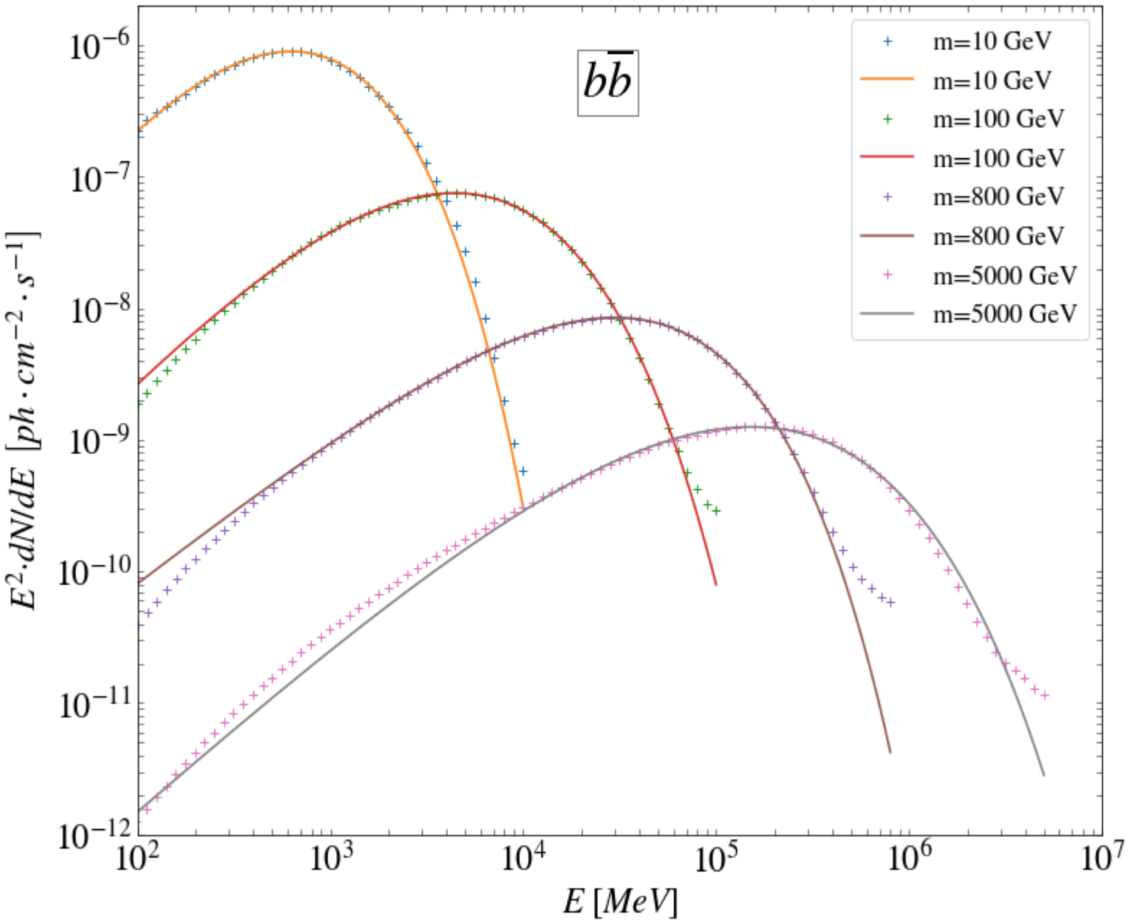
DARK MATTER (DM) SUBHALOS AS TARGETS

- ΛCDM cosmological model predicts lots of substructure → DM subhalos
- Subhalo with masses below $\sim 10^7 M_\odot$ do not retain gas (baryons) → no emission
- BUT, if they annihilate (WIMP model) → DM-induced gamma-ray emission
- *Fermi*-LAT (2008-) → We have gamma-ray source catalogs
- Lots of unidentified sources (unIDs) in catalogs → Some of them may be subhalos
- N-body cosmological simulations → What do we expect?
- We do not have an unequivocal signal of DM annihilation → **constraints on** $\langle \sigma v \rangle$, m_χ

FIRST INGREDIENT: DM INTEGRATED SPECTRA

- From Cirelli+16 PPPC4 (PYTHIA8), including electroweak corrections
- 'Usual' annihilation channels $(b\bar{b}, \tau^+\tau^-, W^+W^-, etc.)$
- Wimp masses from 5 GeV up to 100 TeV
- Parametric fit to Power Law with SuperExponential Cutoff:

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

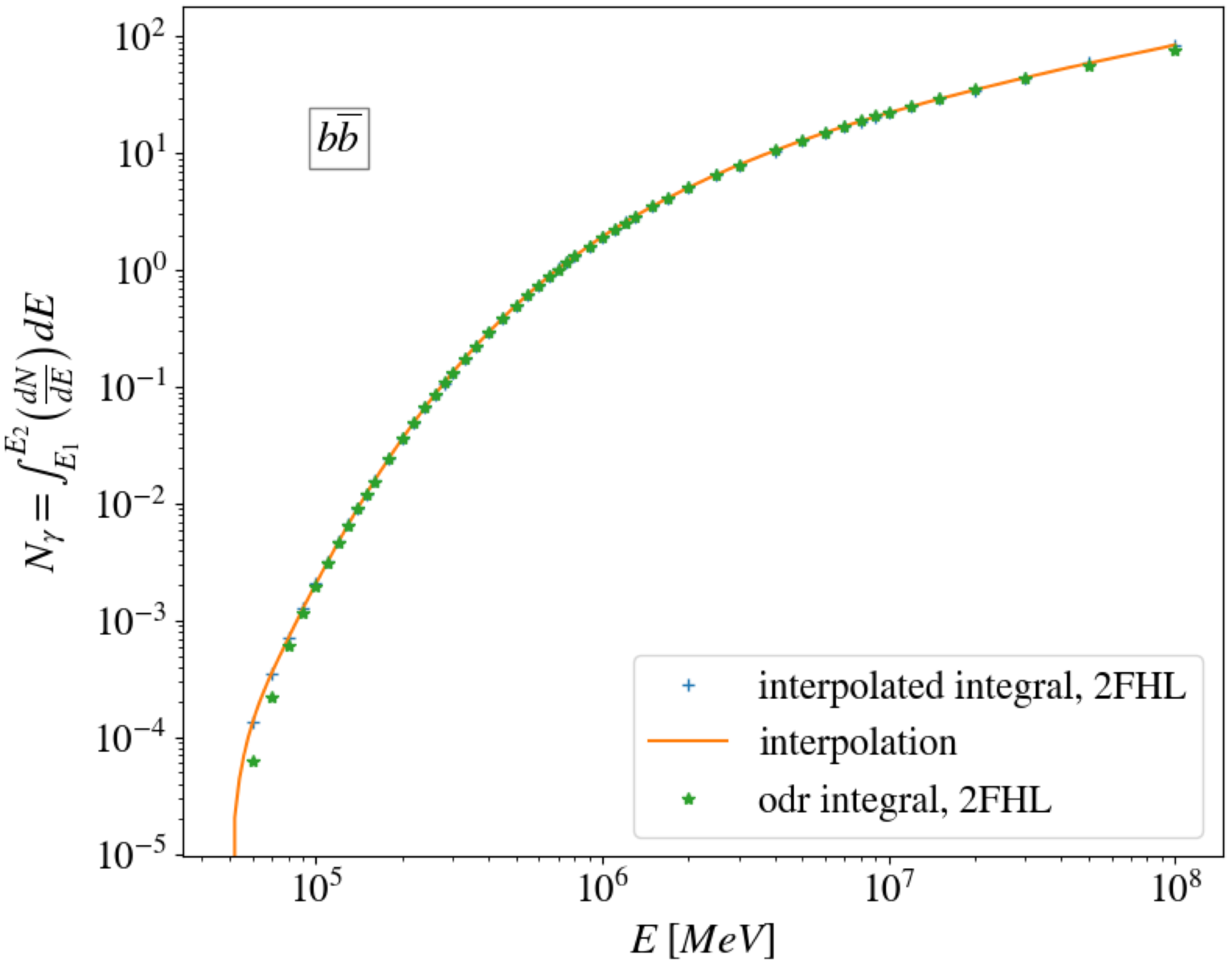


FIRST INGREDIENT: DM INTEGRATED SPECTRA

- We want the integrated spectra,

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

- Dependance on the Fermi-LAT catalog energy threshold



SECOND INGREDIENT: J-FACTOR

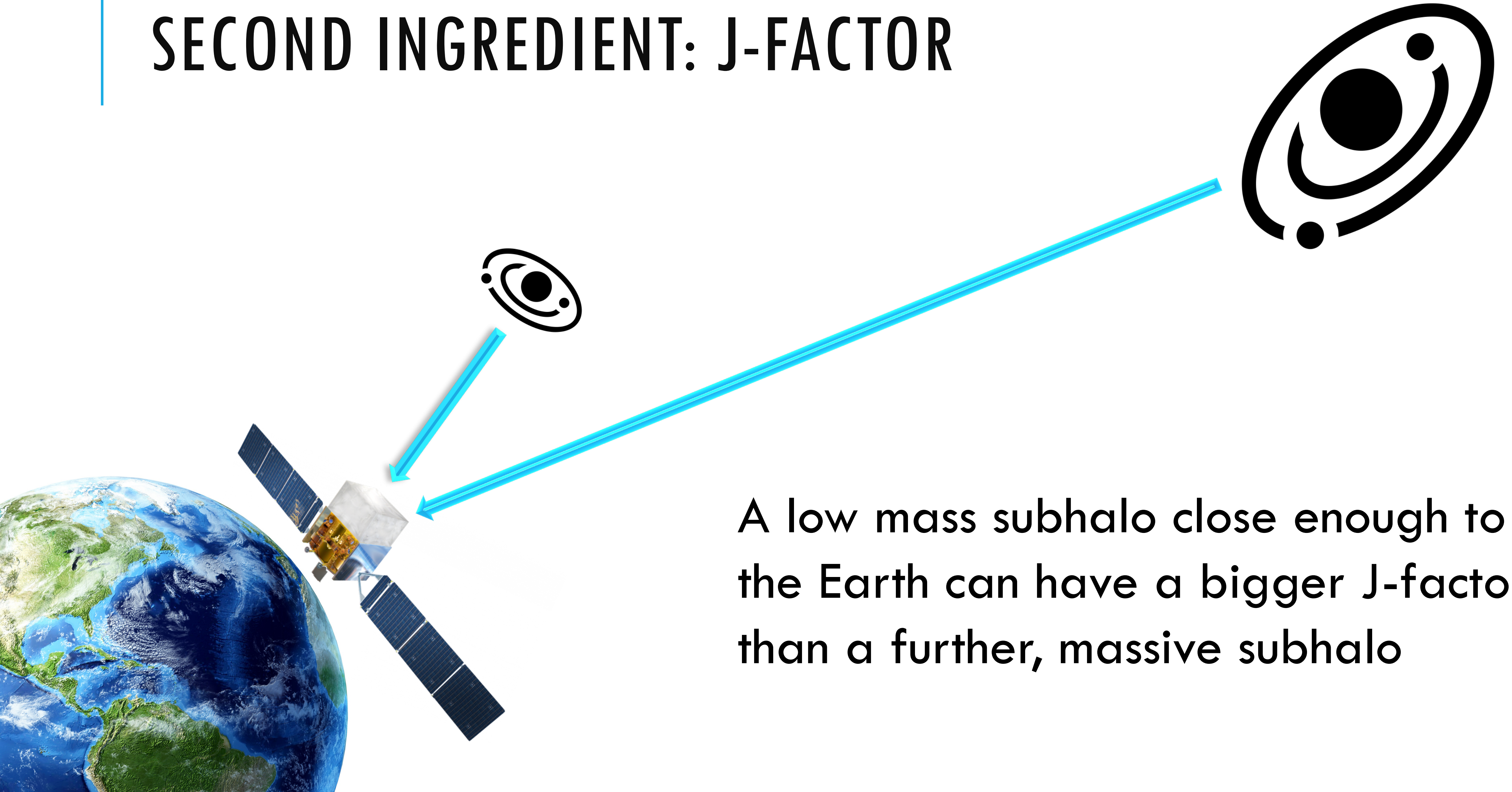
- We use Via Lactea II (VL-II) simulation (Diemand+08), DM only, Milky Way size, resolving subhalo masses down to $\sim 10^5 M_\odot$

- We use subhalo radial distributions and abundances as found by these simulations

- Internal subhalo properties are modeled as in Moliné+17

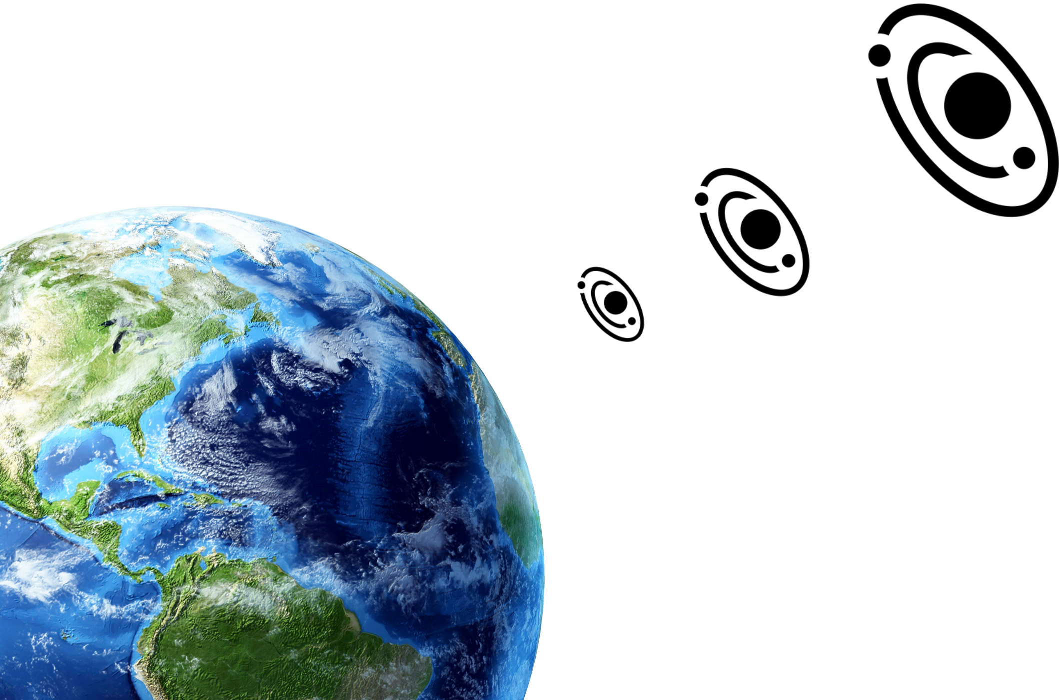
- Subhalos below the resolution limit can also yield large annihilation fluxes → important to include them

SECOND INGREDIENT: J-FACTOR



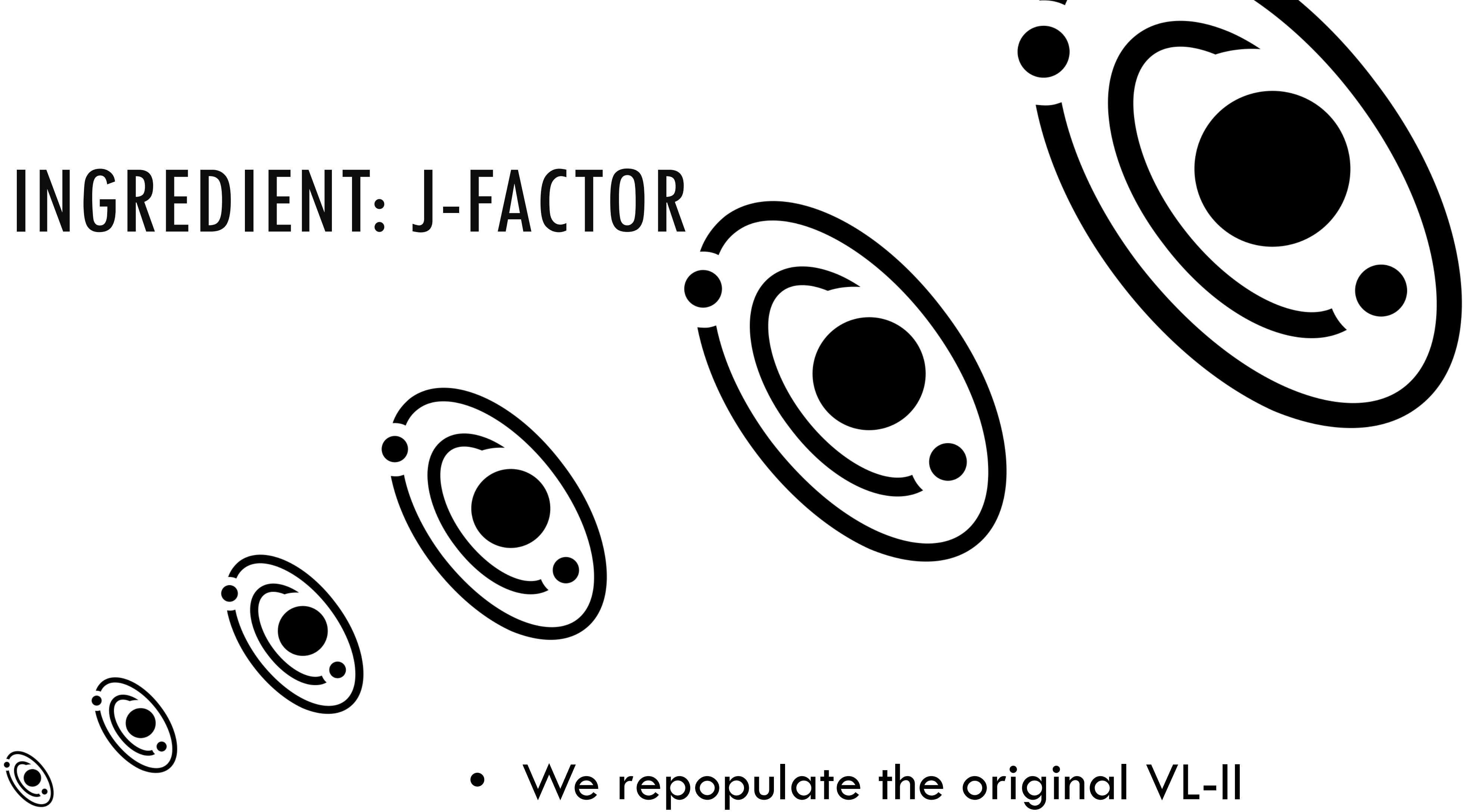
A low mass subhalo close enough to the Earth can have a bigger J-factor than a further, massive subhalo

SECOND INGREDIENT: J-FACTOR



- The less massive the subhalo, the nearer it must be to have a relevant flux
- Also, $J \propto c^3 \propto M^{-3}$ (c ≡concentration, bigger for lower masses)

SECOND INGREDIENT: J-FACTOR



- We repopulate the original VL-II simulation in a realistic yet computationally feasible way below its mass resolution limit.

GAMMA-RAY OBSERVATORIES

E. range: 20 MeV → 1 TeV
E. resolution: ~10% @ GeV
FoV: ≈ 2.4 sr
Angular res.: ~0.2º@10 GeV
Aeff ~ m^2

Fermi-LAT
[>2008]

E. range: 0.1 → 100 TeV
E. resolution: ~20% @ 10 TeV
FoV: ≈ 2 sr
Angular res.: ~0.2º@10 TeV
Aeff ~22,000 m^2

DESY/Milde Science Comm./Exozet

HAWC
[>2015]

MAGIC
[>2003]

HESS
[>2002]

VERITAS
[>2006]

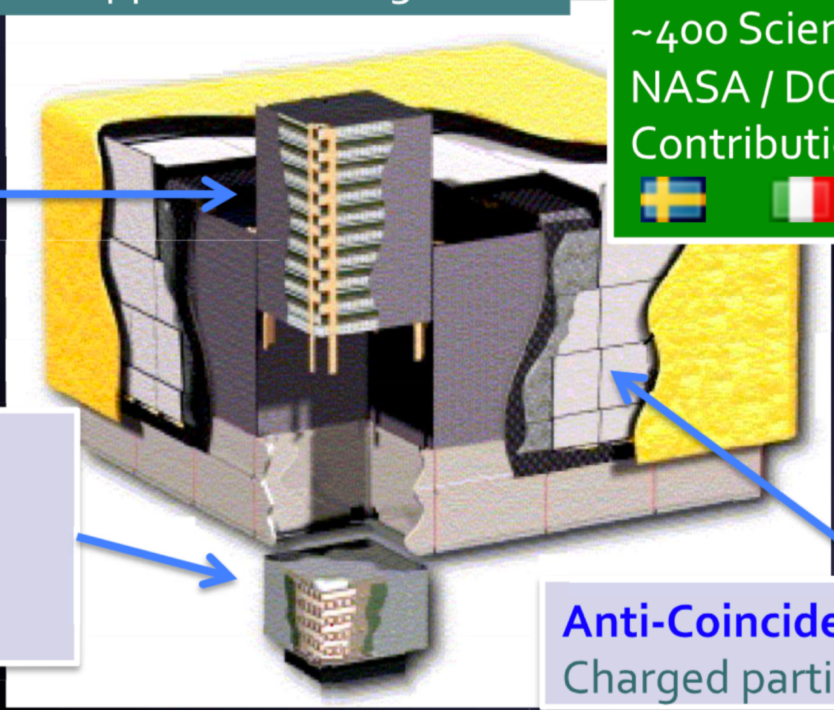
E. range: 50 GeV → 100 TeV
E. resolution: ~20%
FoV: ≈ 4 deg.
Angular res.: ≈ 0.1º
Aeff ~ 10^5 m^2

Slide adapted from Sánchez-Conde

The Fermi Large Area Telescope

LAUNCHED IN JUNE 2008
Mission approved through 2016

Fermi LAT Collaboration:
~400 Scientific Members,
NASA / DOE & International Contributions



[1.8 m x 1.8 m x 0.7 m]

Si-Strip Tracker:
convert $\gamma \rightarrow e^+e^-$
reconstruct γ direction
EM v. hadron separation

Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

Sky Survey:
2.5 sr field-of-view
whole sky every 3 hours

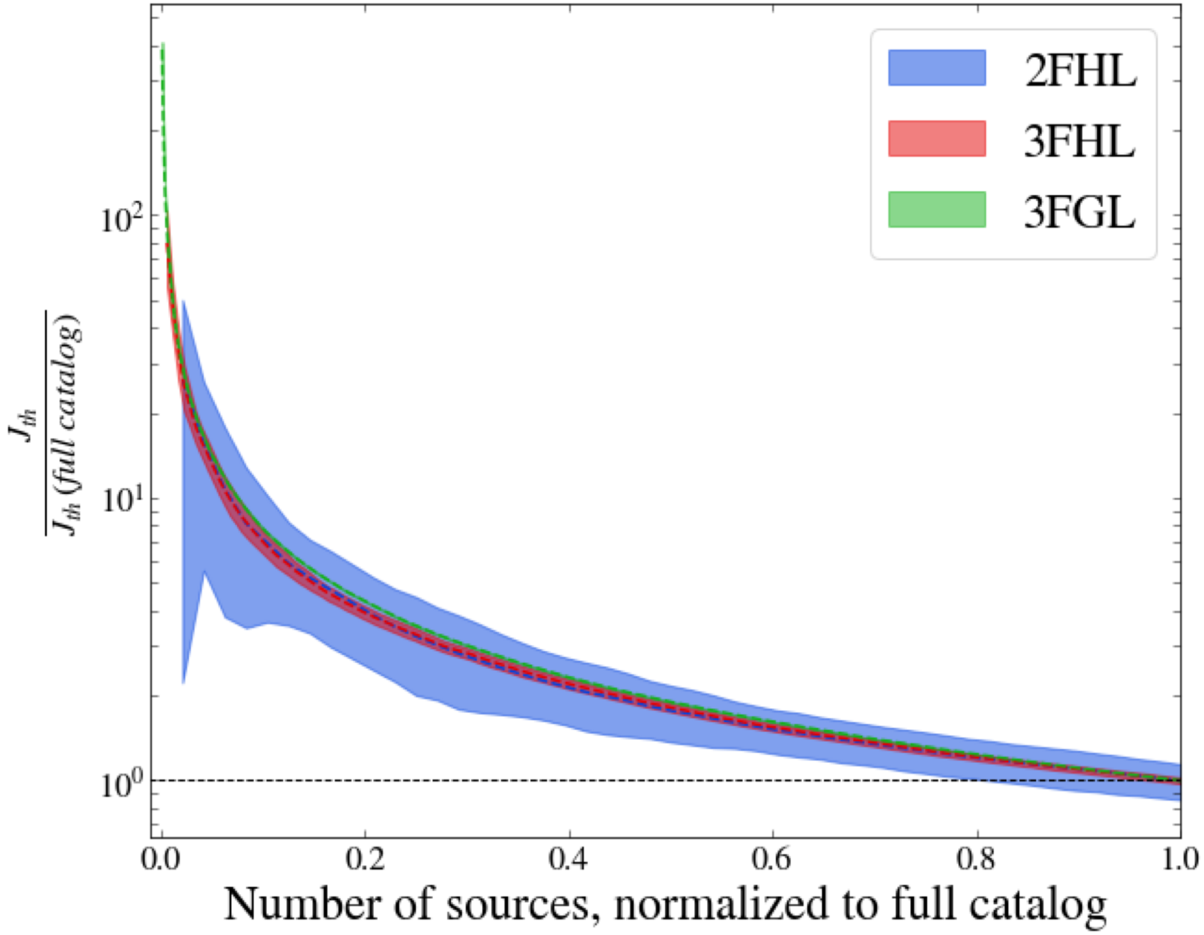
Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 HZ

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

FERMI-LAT UNASSOCIATED SOURCES (UNIDs)

	Obs. Time (yr)	Energy Range	Total	UnIDs
2FHL (1508.04449)	6.7	50 -2000 GeV	360	48
3FHL (1702.00664)	7	10 - 2000 GeV	1556	177
3FGL (1501.02003)	4	0.1 – 300 GeV	3033	1010

UNIDs "FILTERING"



- $\langle \sigma v \rangle \propto J^{-1}$ → less DM subhalo candidates among unIDs means better constraints
- Exponential rise in our constraining power below ~20% of sources in every catalog
- **20% = 202 sources in 3FGL, 10 in 2FHL and 35 in 3FHL**
- From these numbers down, every source we remove has a big impact

DM SUBHALO FILTERS

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

We adopt a **conservative** approach

DM SUBHALO FILTERS

1. Source associations
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3. Flux variability
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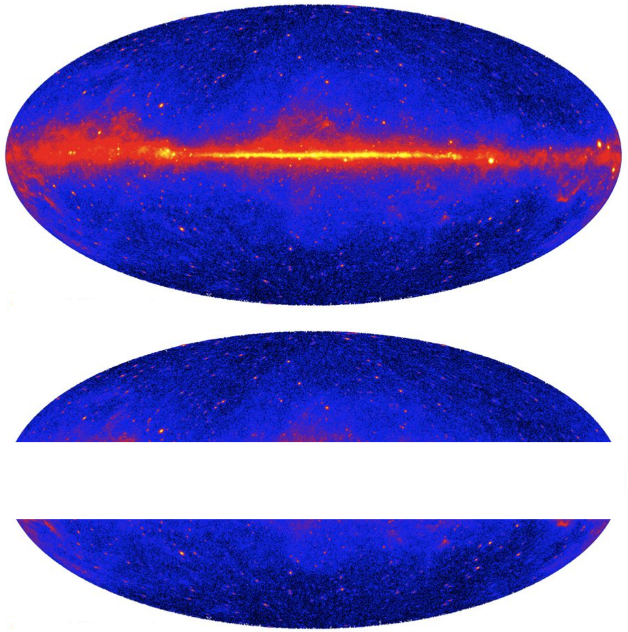
6. Complex regions

Improved observational campaigns provide new associations of unIDs (to known astrophysical objects), which are removed from our sample

DM SUBHALO FILTERS

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

The Galactic plane is a complex region with lots of astrophysical objects (e.g. pulsars) → cut out $|b| \leq 10°$



DM SUBHALO FILTERS

1. Source associations
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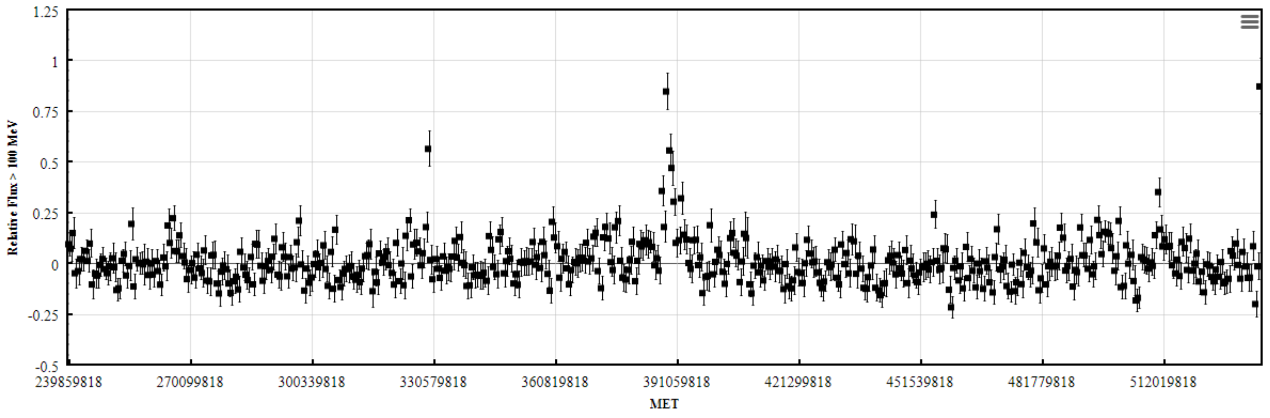
DM subhalos expected to have a steady flux → no variability (FAVA)



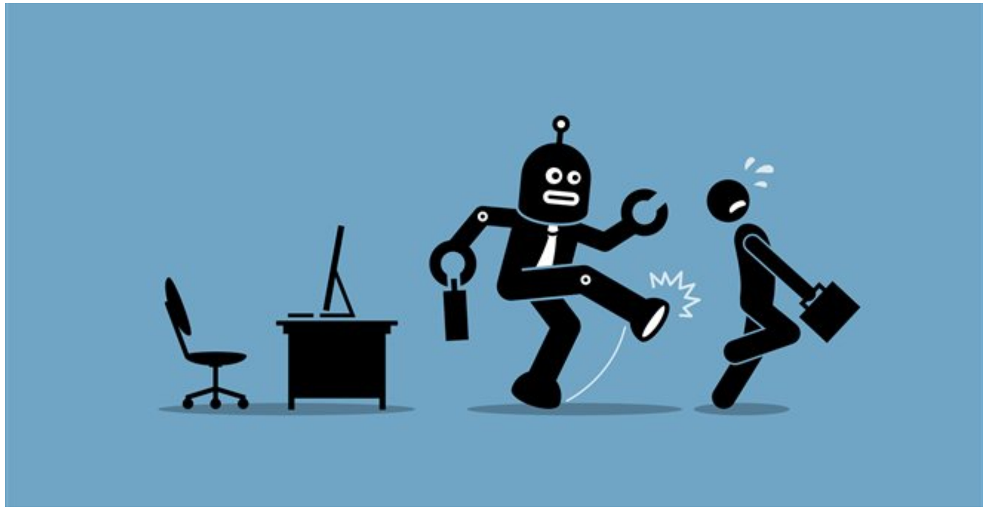
https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/

(1304.6082)

DM SUBHALO FILTERS

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

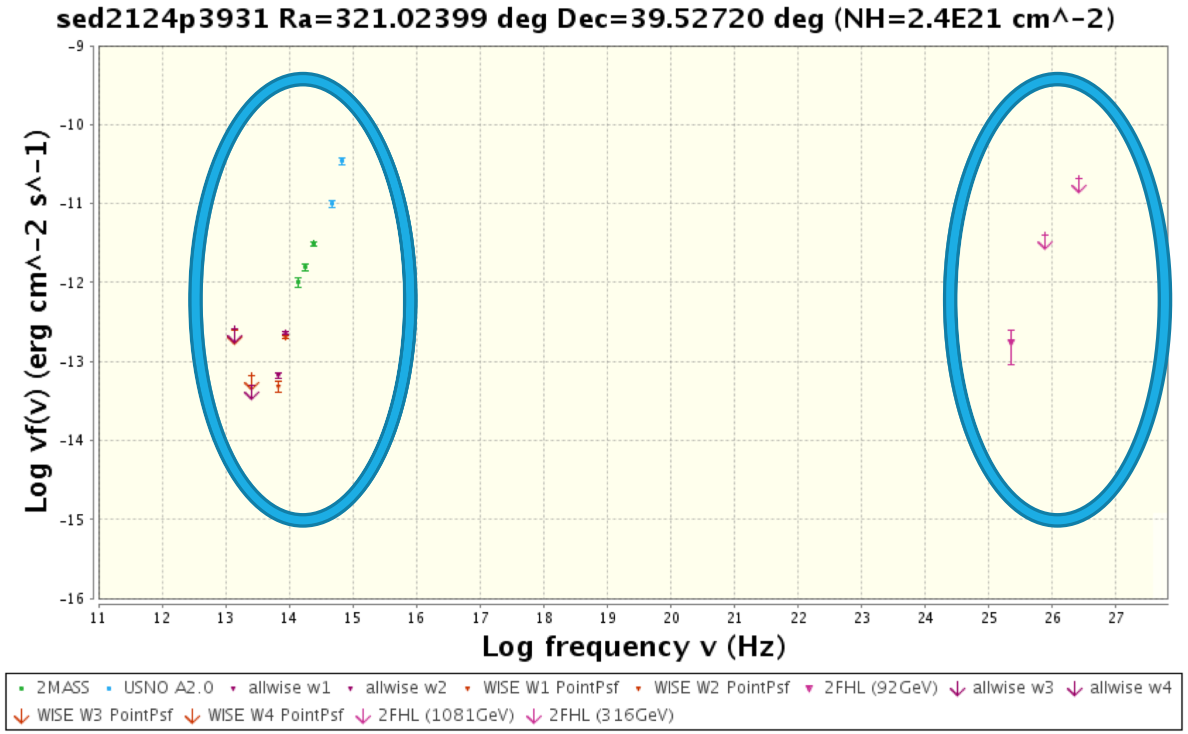
Trained with the associated objects, a machine learning can predict with great accuracy the type of source
Salvetti+17 (1705.09832), Lefaucheur+17 (1703.01822)



DM SUBHALO FILTERS

1. Source associations
2. Latitude
3. Flux variability
4. Machine learning
5. Multiwavelength emission
6. Complex regions

DM is not expected to emit in any other wavelength, so exhibiting emission in IR, optical, UV or X-ray is a cut

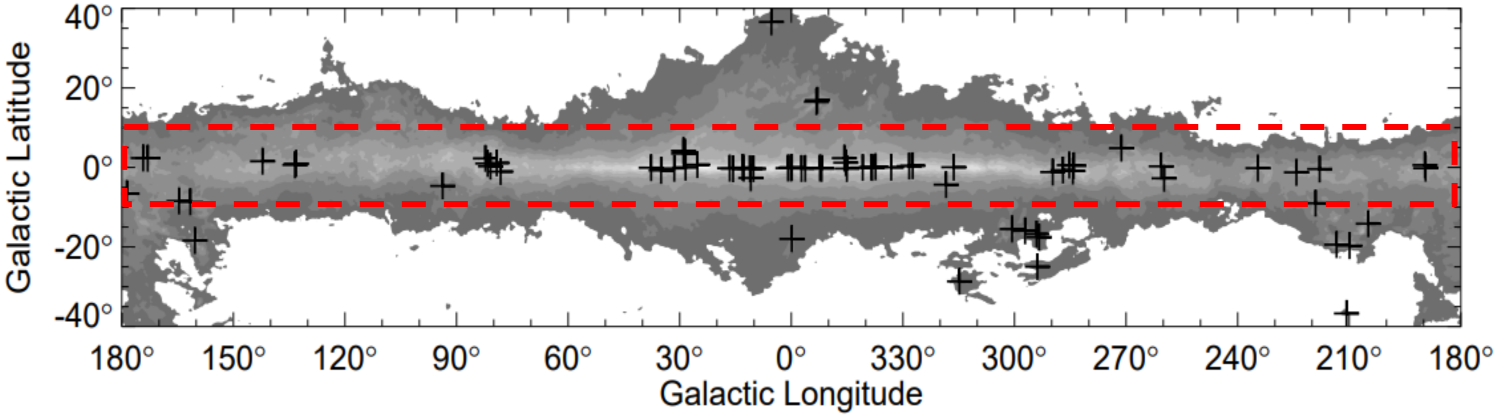


tools.asdc.asi.it

DM SUBHALO FILTERS

1. Source associations
2. Latitude
3. Flux variability
4. Machine learning
5. Multiwavelength
6. Complex regions

In Sec. 3.8 of 1501.02003 (3FGL paper) – Considered potential artifacts due to diffuse emission mismodeling



FAMOUS (EX-)CANDIDATES

- 3FGL J2212.5+0703 (Bertoni+16) – actually 2 sources
- 3FGL J1924.8-1034 (Xia+17) – classified as AGN by machine learning
- 3FGL J1119.9-2204 (Hooper+17) – seen with SWIFT in X-rays
- 3FGL J0318.1+0252 (Hooper+17) – seen with SWIFT in X-rays
- 3FGL J2212.5+0703 (Hooper+17) – FAVA correlation, seen with SWIFT

All 3FGL (low energy) sources

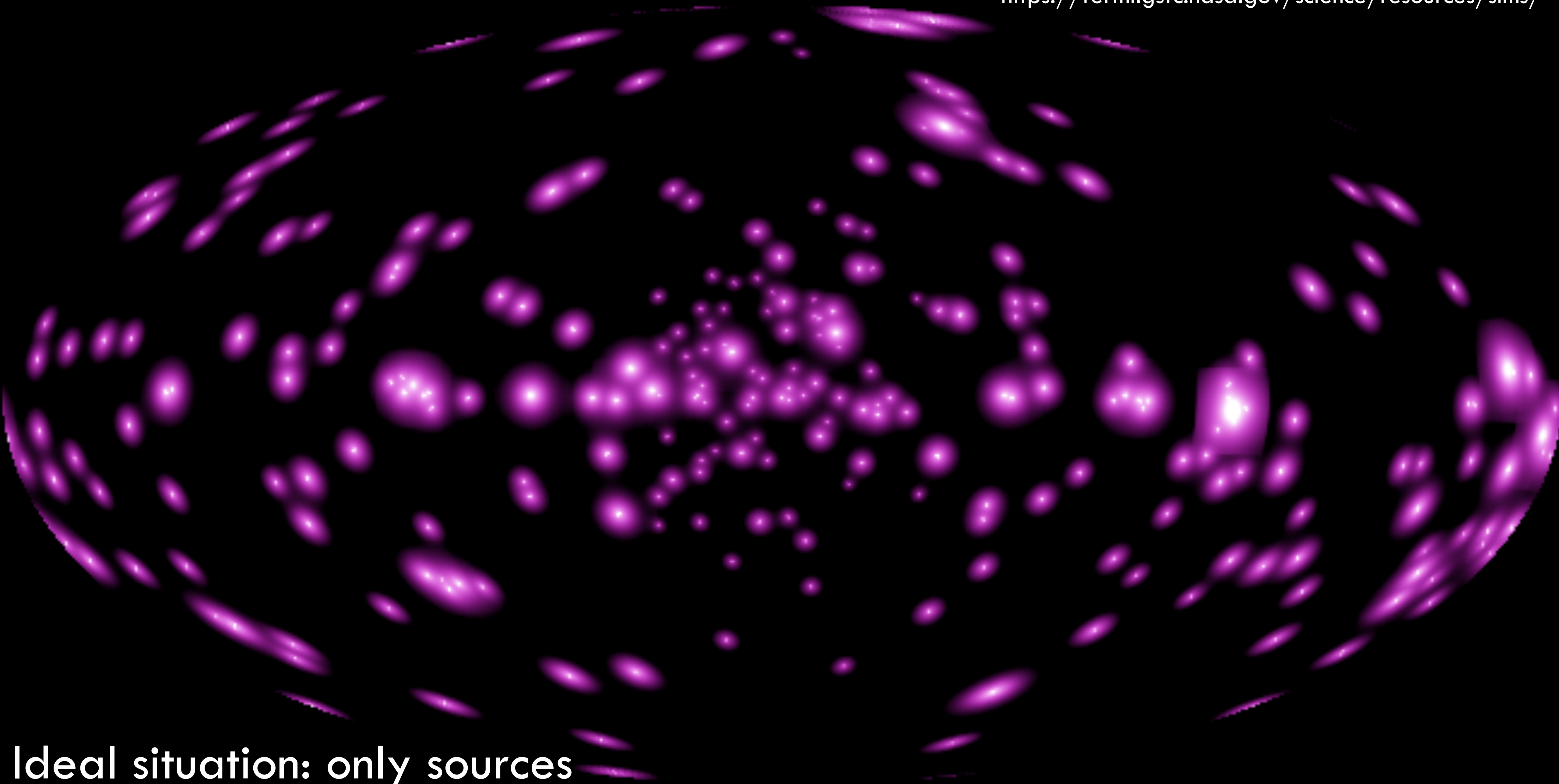
UNIDS FILTERING RESULTS

	Original	Result
2FHL	48	4
3FHL	177	24
3FGL	1010	16

THIRD INGREDIENT: LAT SENSITIVITY TO DM SUBHALOS

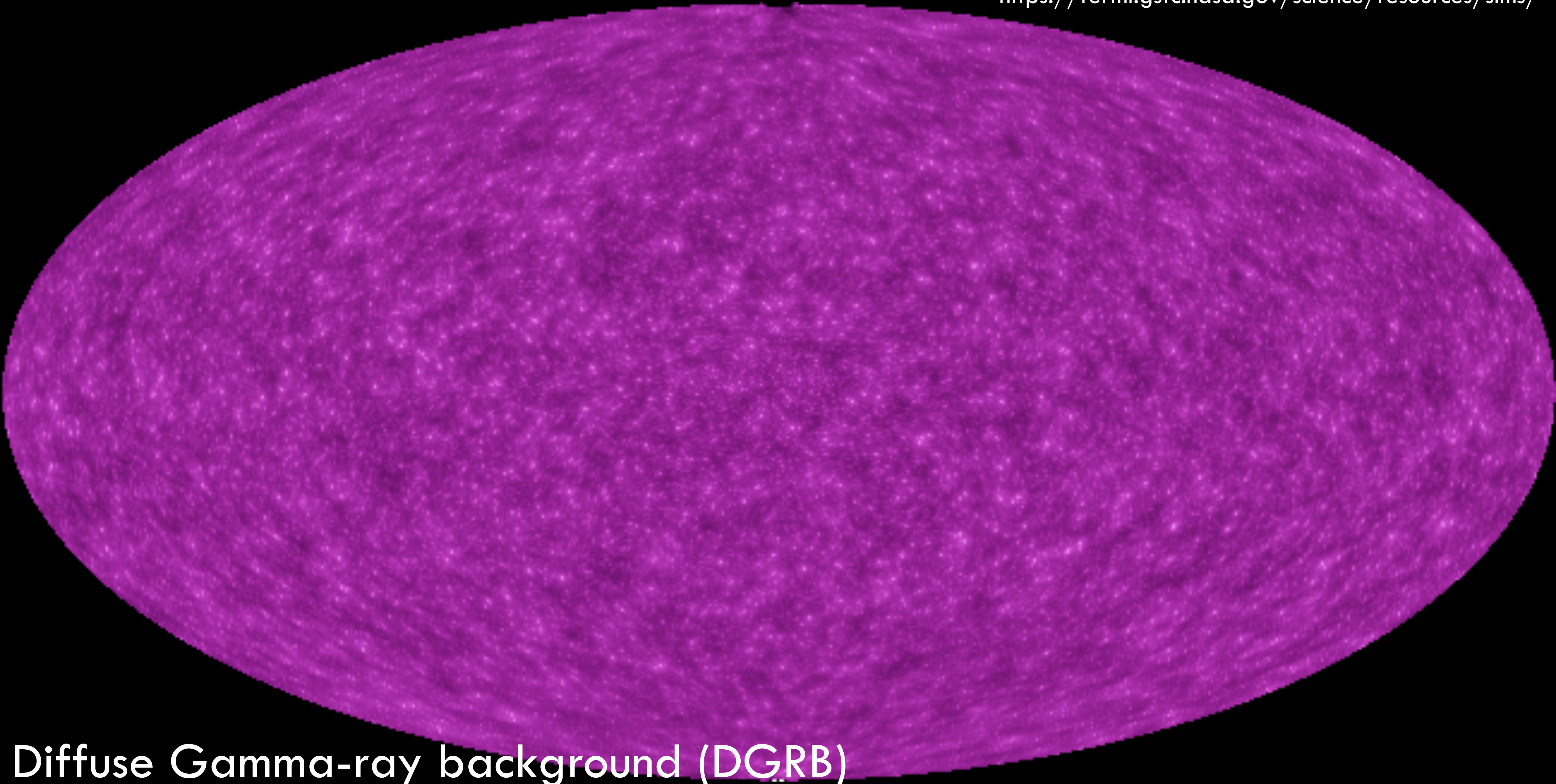
- Minimum flux to have a 5-sigma detection over background
- Normally taken as the threshold flux of the catalog
- BUT, important dependance on **annihilation channel**, **source sky position** and **catalog setup**

https://fermi.gsfc.nasa.gov/science/resources/sims/

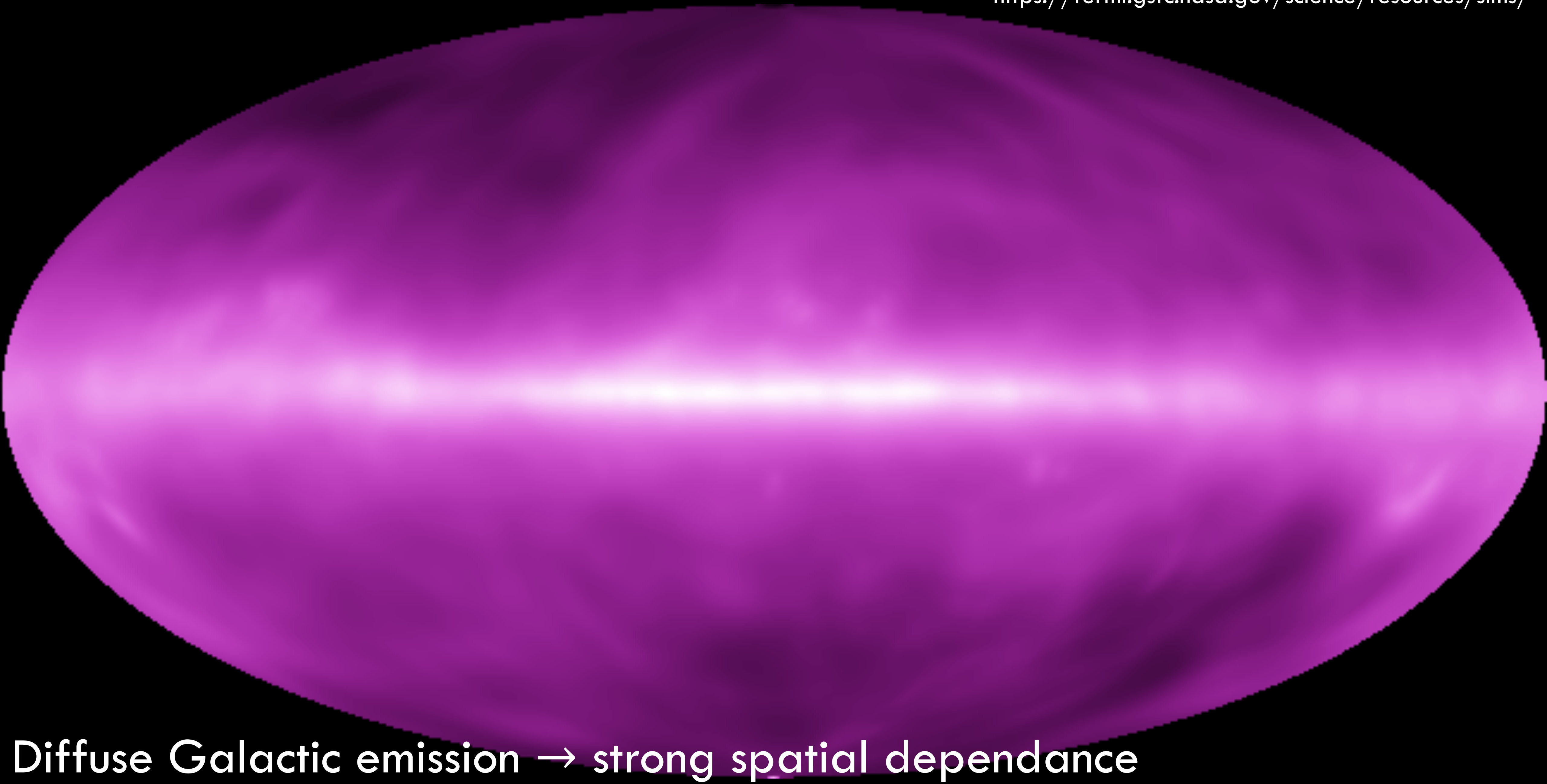


Ideal situation: only sources

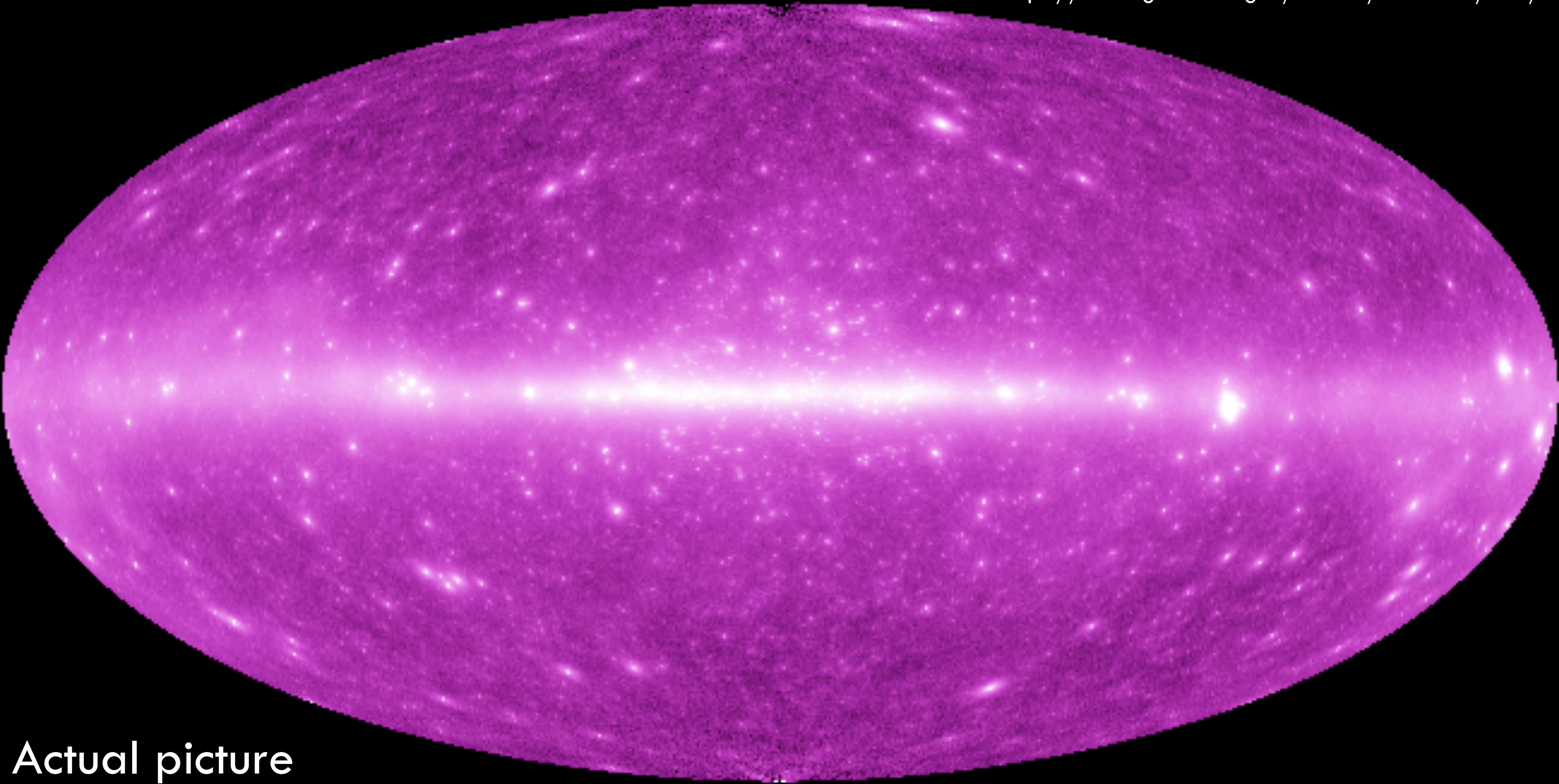
https://fermi.gsfc.nasa.gov/science/resources/sims/



Diffuse Gamma-ray background (DGRB)

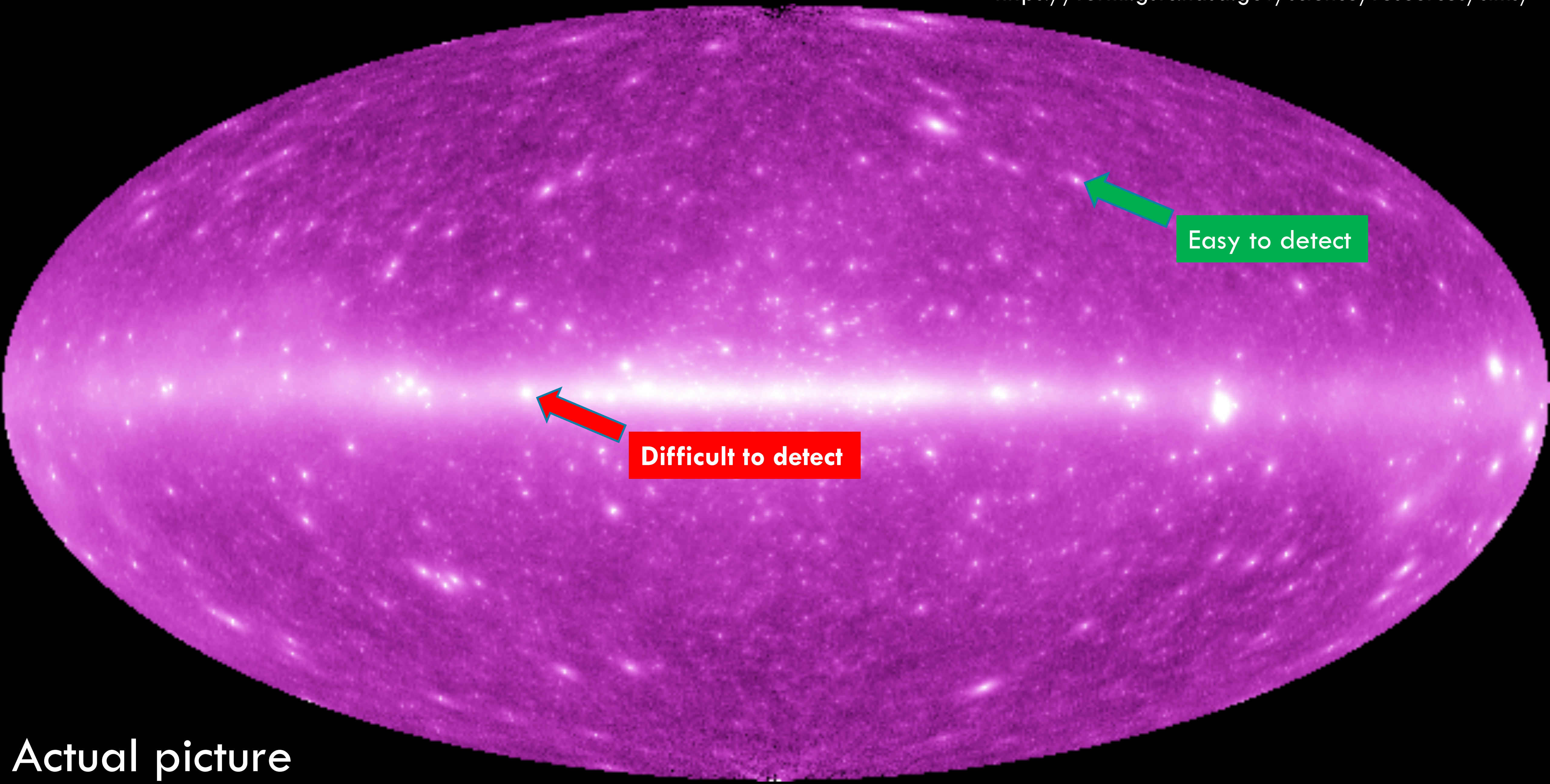

https://fermi.gsfc.nasa.gov/science/resources/sims/
Diffuse Galactic emission → strong spatial dependance

https://fermi.gsfc.nasa.gov/science/resources/sims/



Actual picture

https://fermi.gsfc.nasa.gov/science/resources/sims/



Actual picture

THIRD INGREDIENT: LAT SENSITIVITY TO DM SUBHALOS

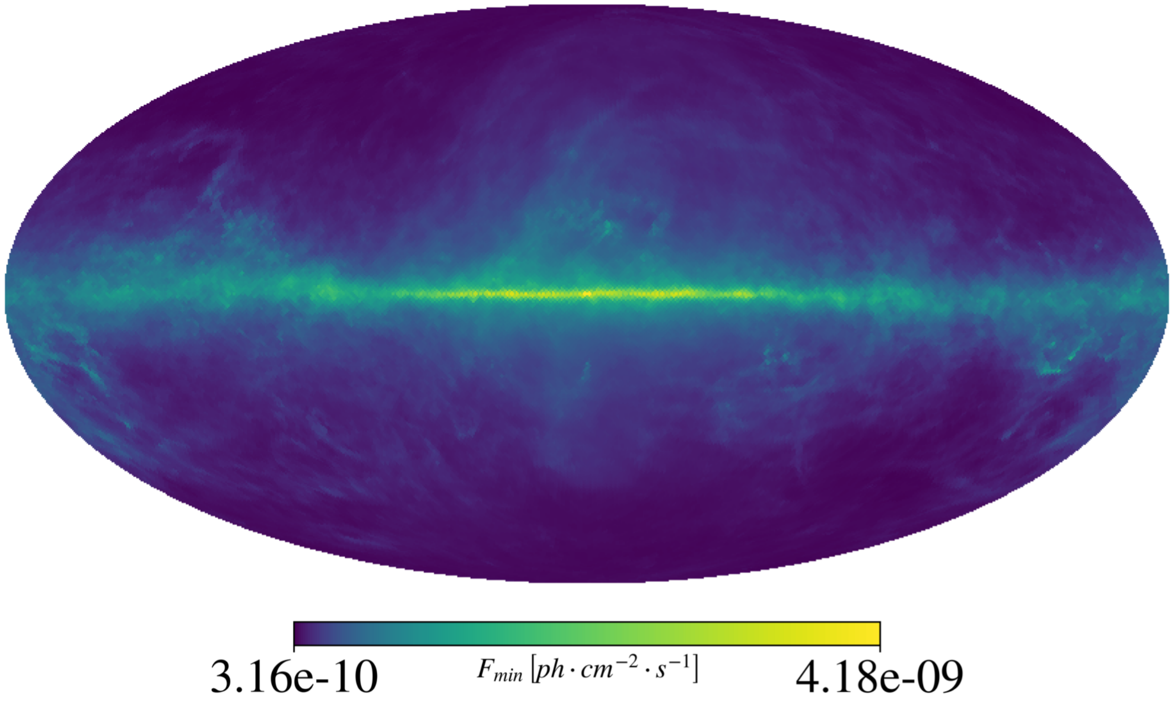
- We use the ***fermipy*** analysis software (1707.0955) to simulate sources mimicking the catalog setup (observation time, energy range, diffuse+isotropic templates…)

- A putative dark matter source is simulated for each position, catalog setup, annihilation channel and DM mass

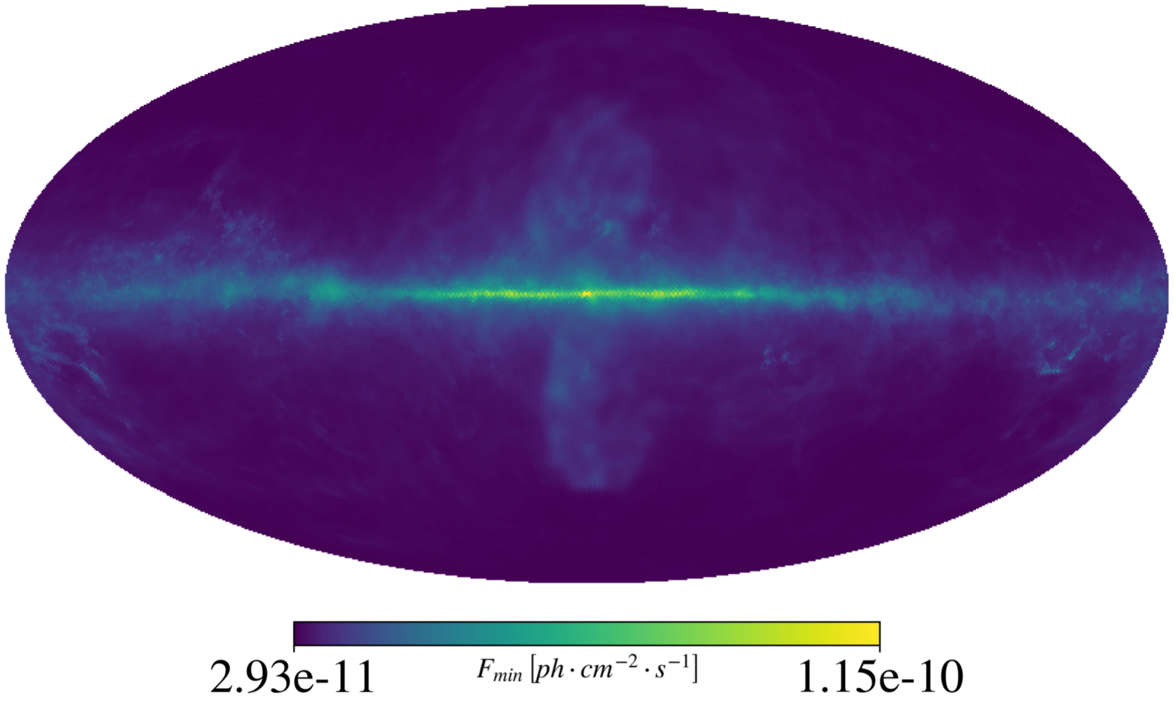
- All-sky maps with this information

COMPARISON BETWEEN DIFFERENT DM MASSES

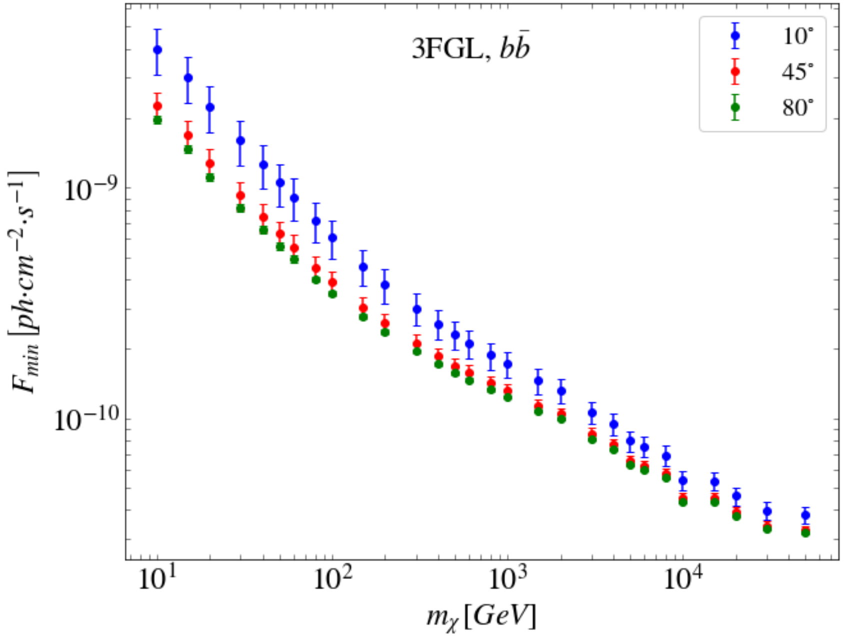
$m_{DM} = 10\ GeV$



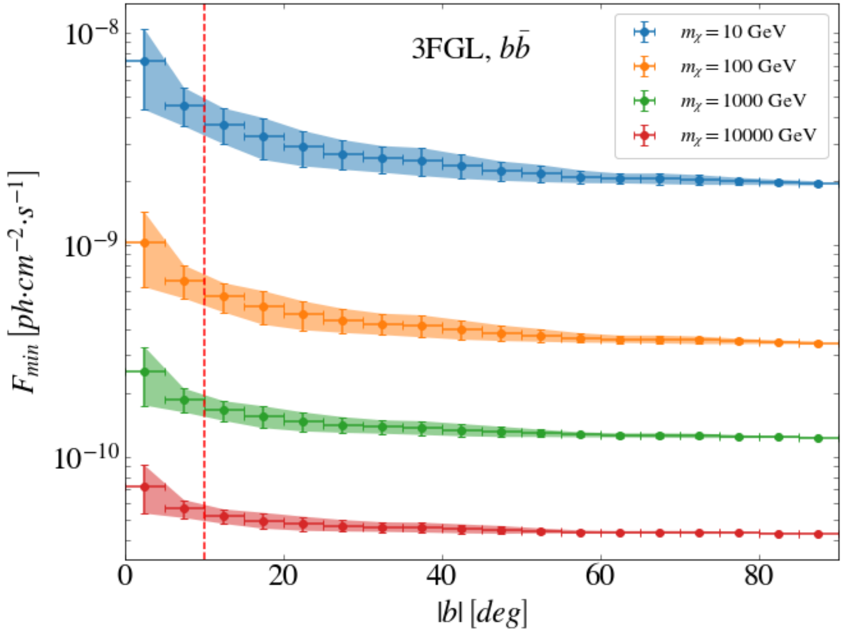
$m_{DM} = 1\ TeV$



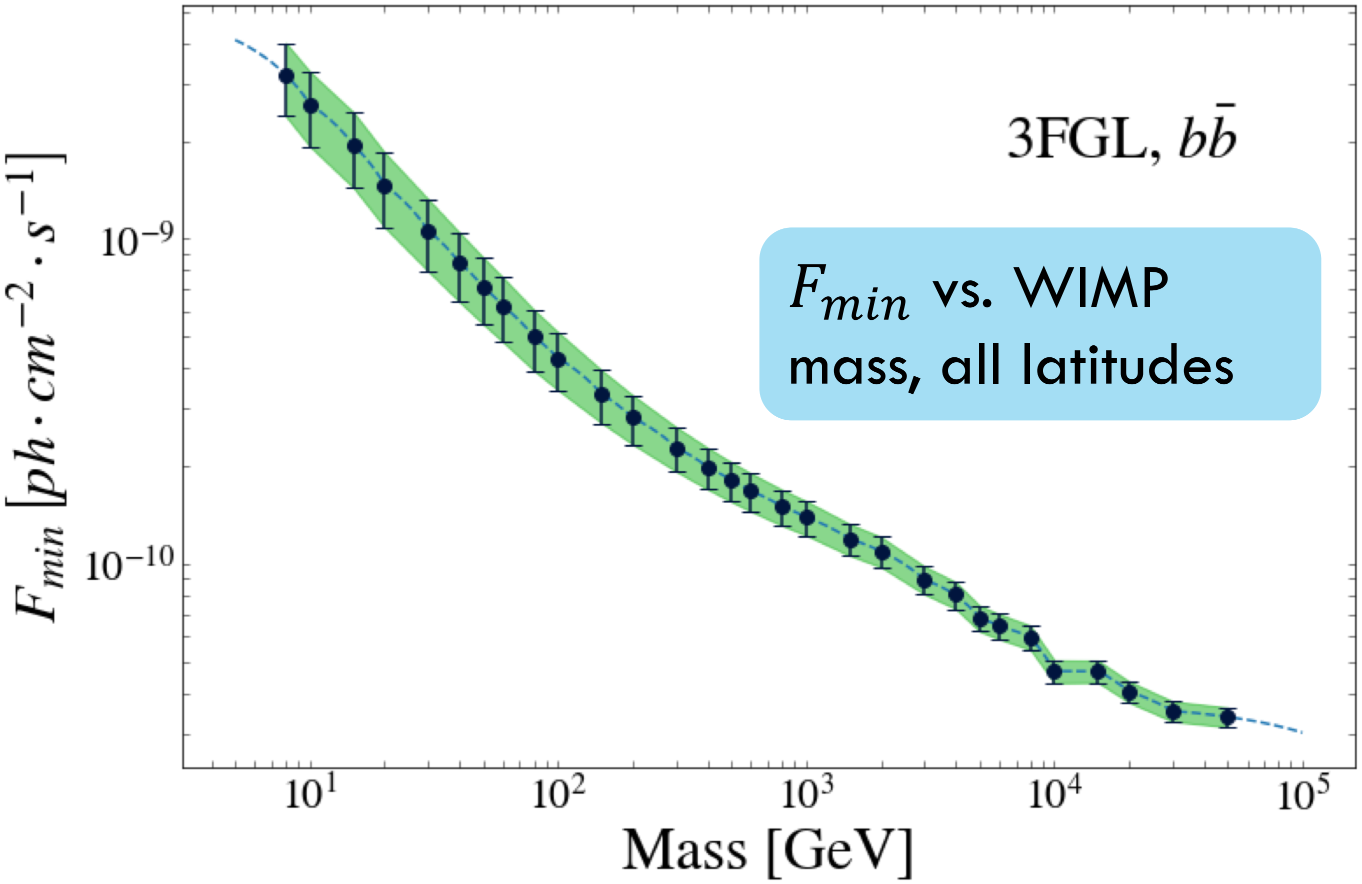
3FGL setup, $\tau^+\tau^-$ channel



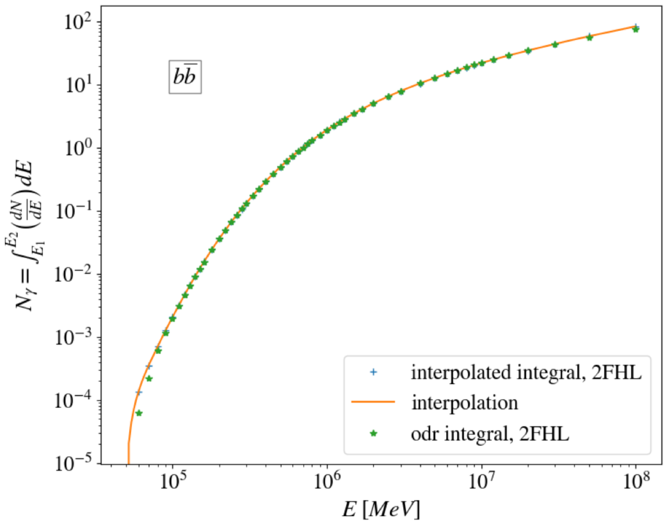
F_{min} vs. WIMP mass



F_{min} vs. Gal. latitude



F_{min} vs. WIMP mass, all latitudes



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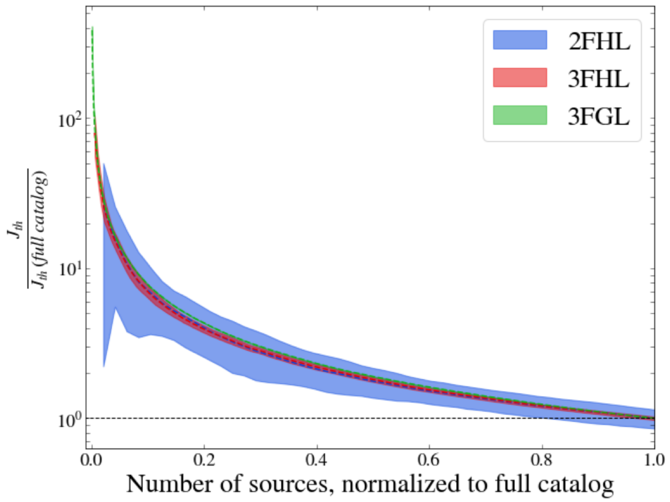

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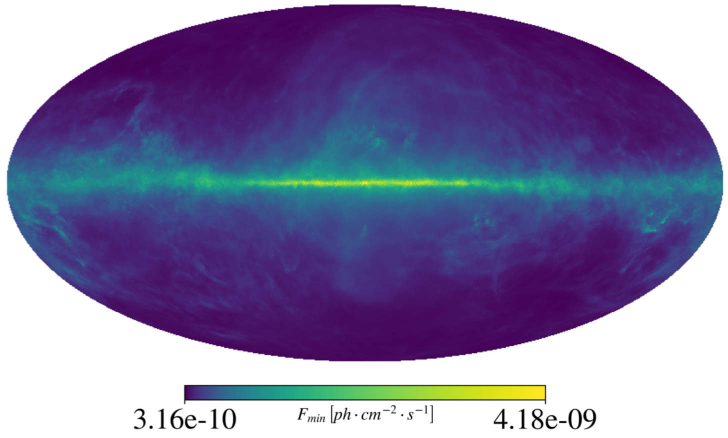

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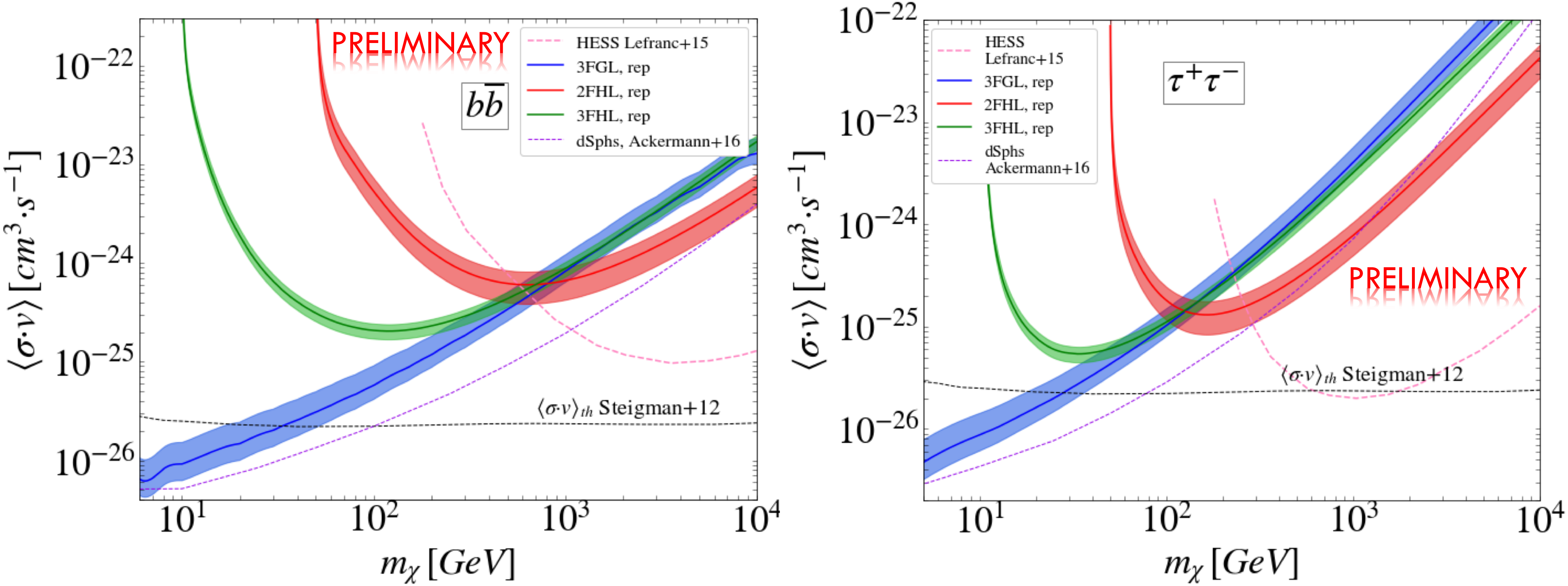
DM annihilation spectra

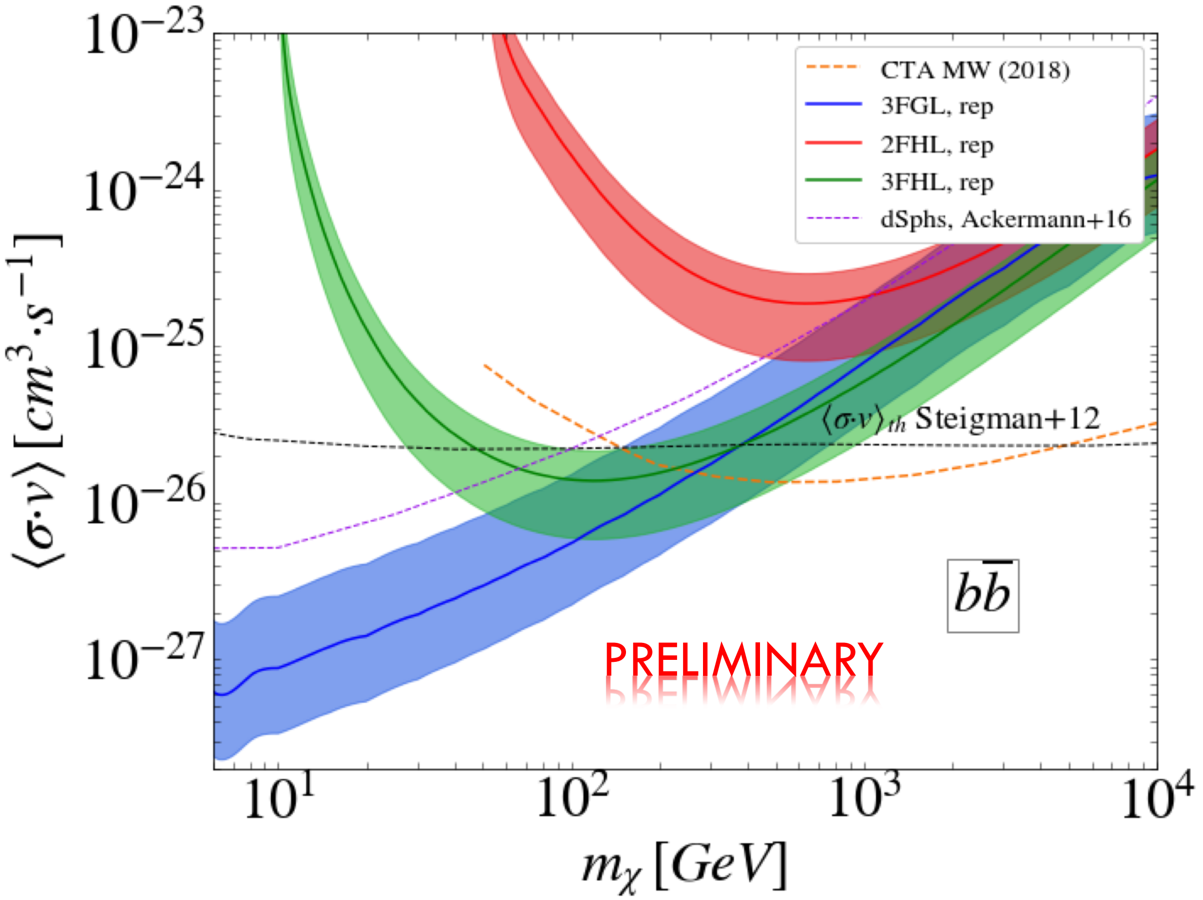
J-factor

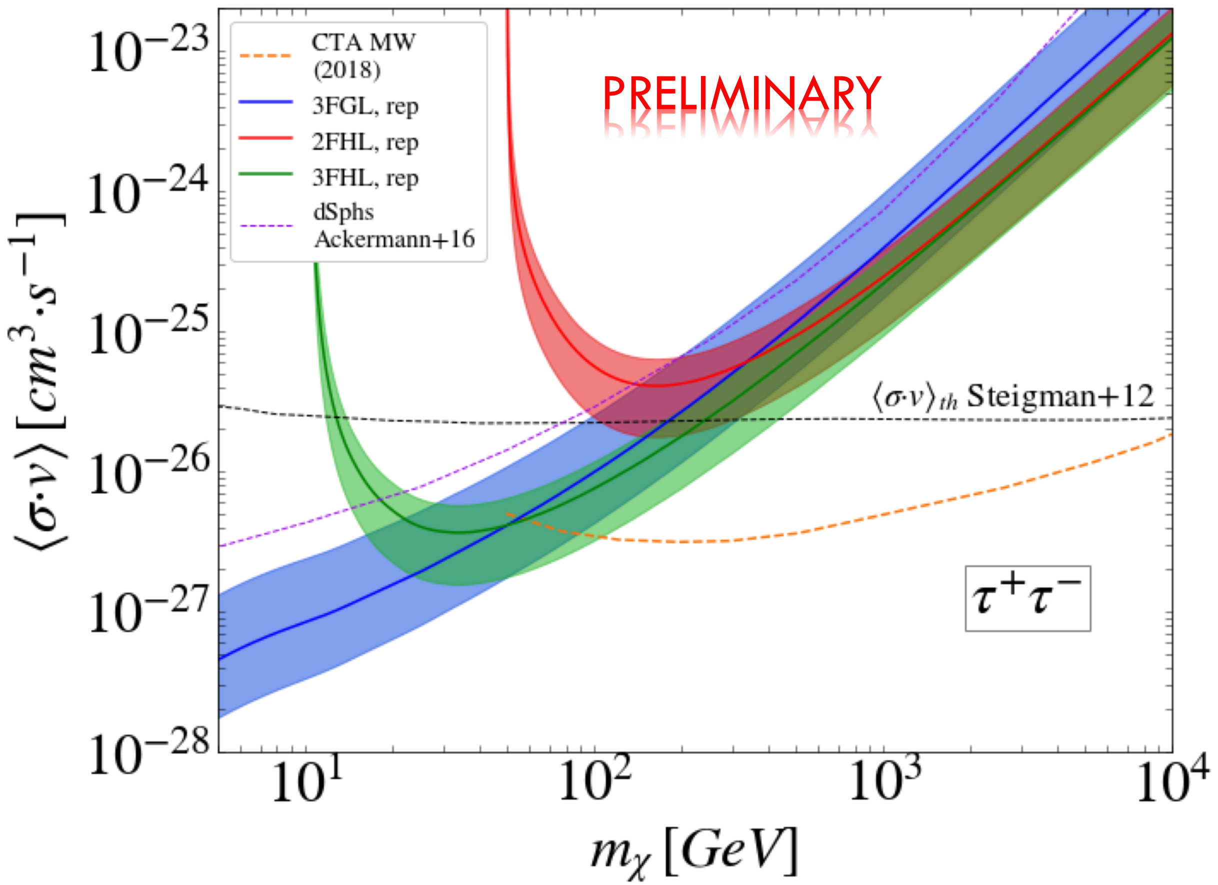
Minimum flux

DARK MATTER CONSTRAINTS



SENSITIVITY REACH OF THE METHOD





CONCLUSIONS & FUTURE

- The method proves to be complementary and competitive to other indirect searches

- Conservative yet realistic constraints

- The constraints can be improved via new associations, potentially ruling out thermal WIMPs up to ~400 GeV ($b\bar{b}$) and ~250 GeV ($\tau^+\tau^-$)

CONCLUSIONS & FUTURE

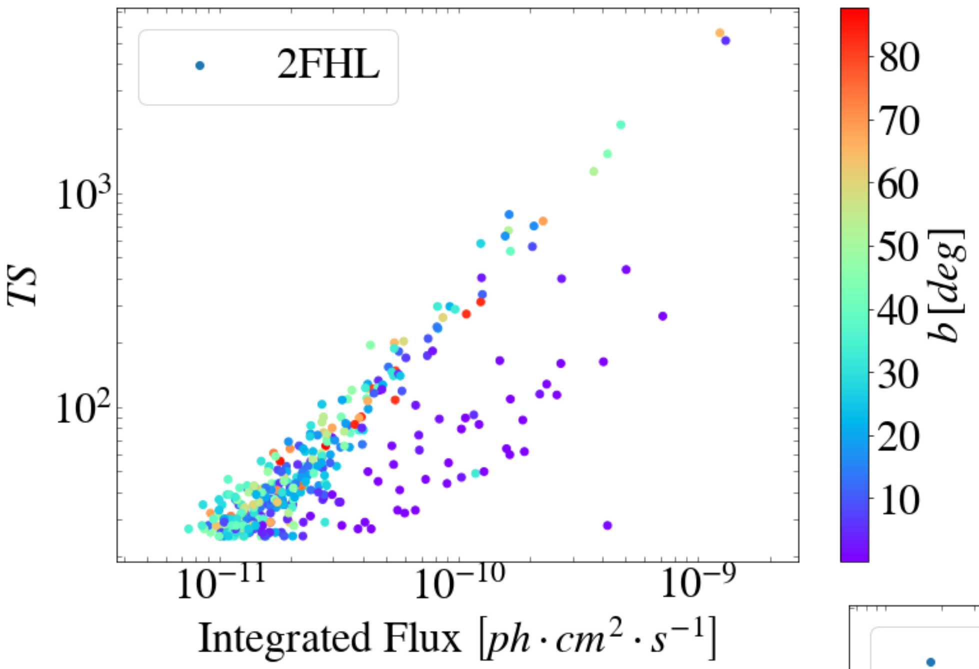
- The future 4FGL will be the deepest and most complete gamma-ray catalog, providing new analysis targets

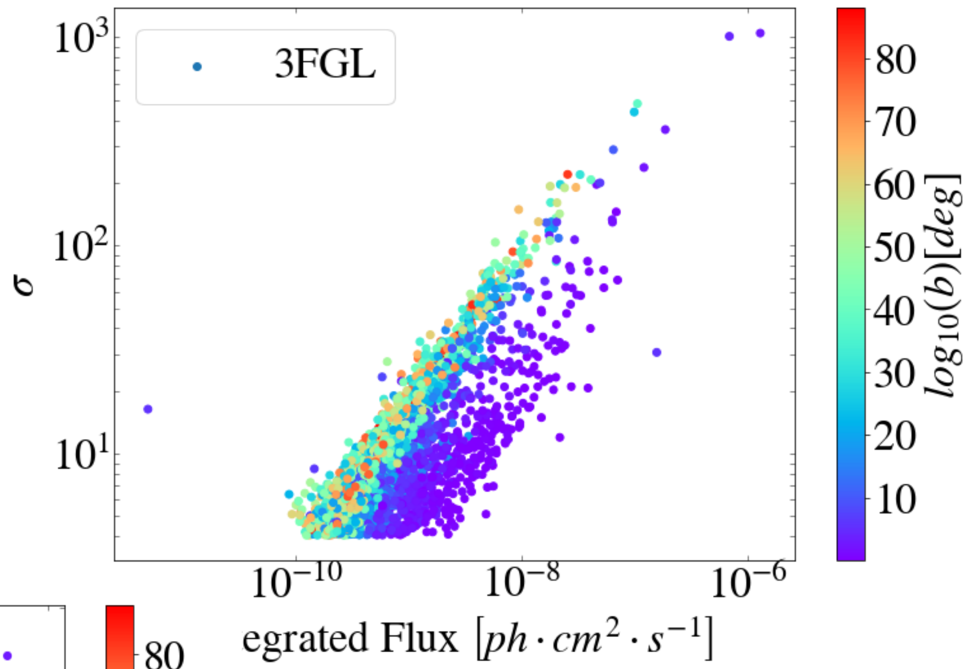
- This analysis was blind to spectral information and a **dedicated spectral and spatial analysis** is ongoing already to improve the limits further

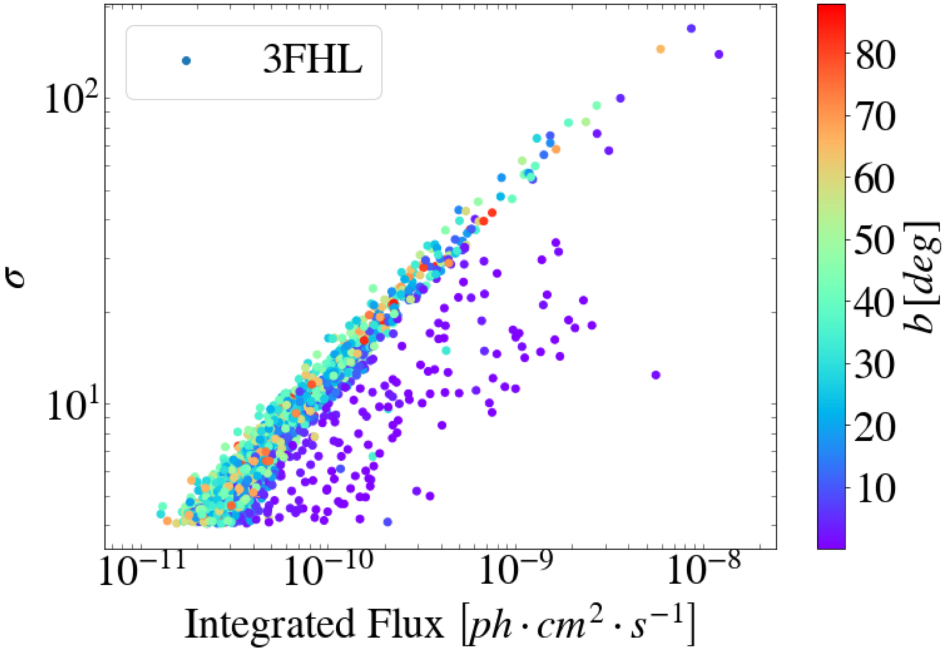
Thank you very much

BACKUP SLIDES

SIGNIFICANCE = FLUX?

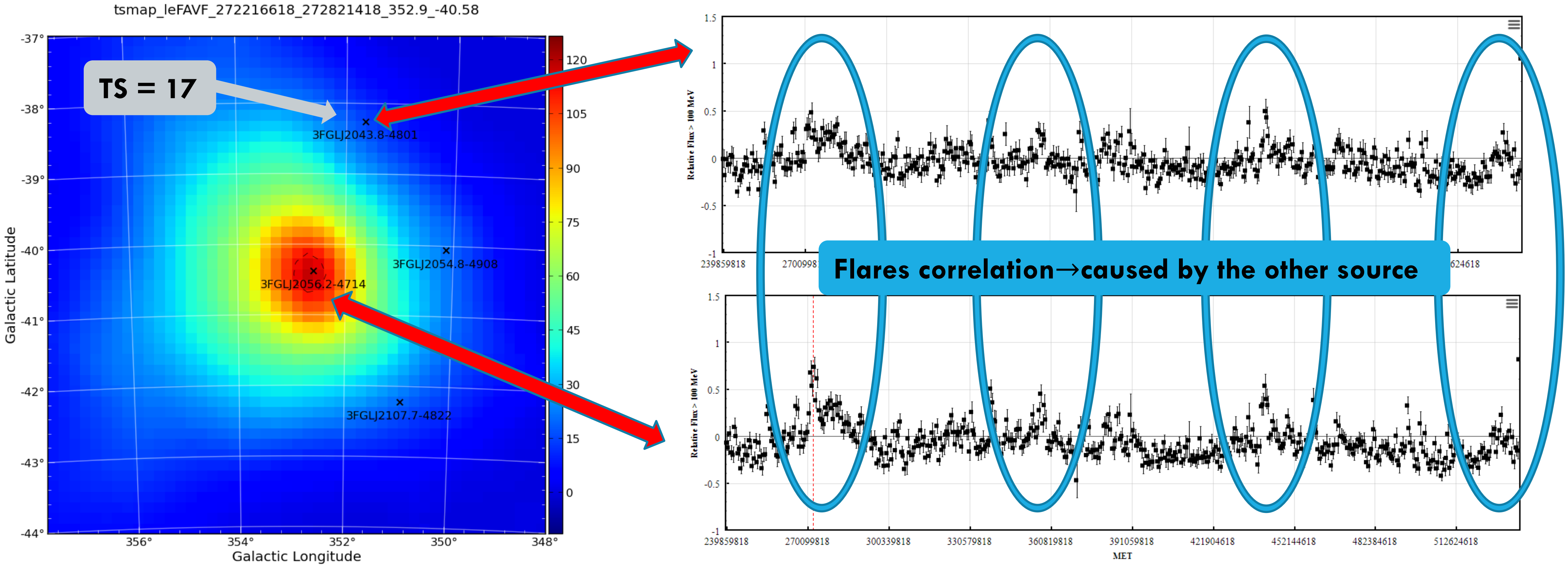






VARIABILITY

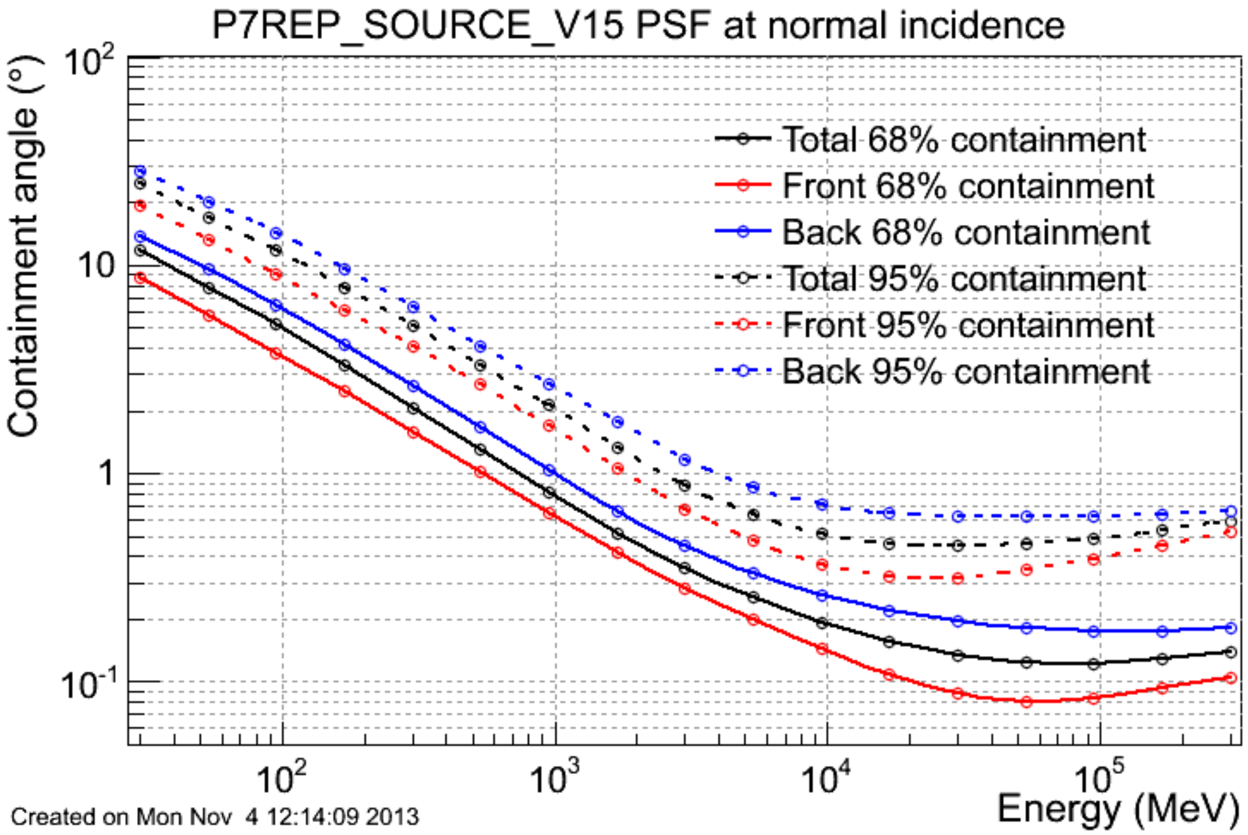
- We require at least a flare at 5σ, and not spatially or temporally coincident with a known flare (to avoid PSF "spill over")

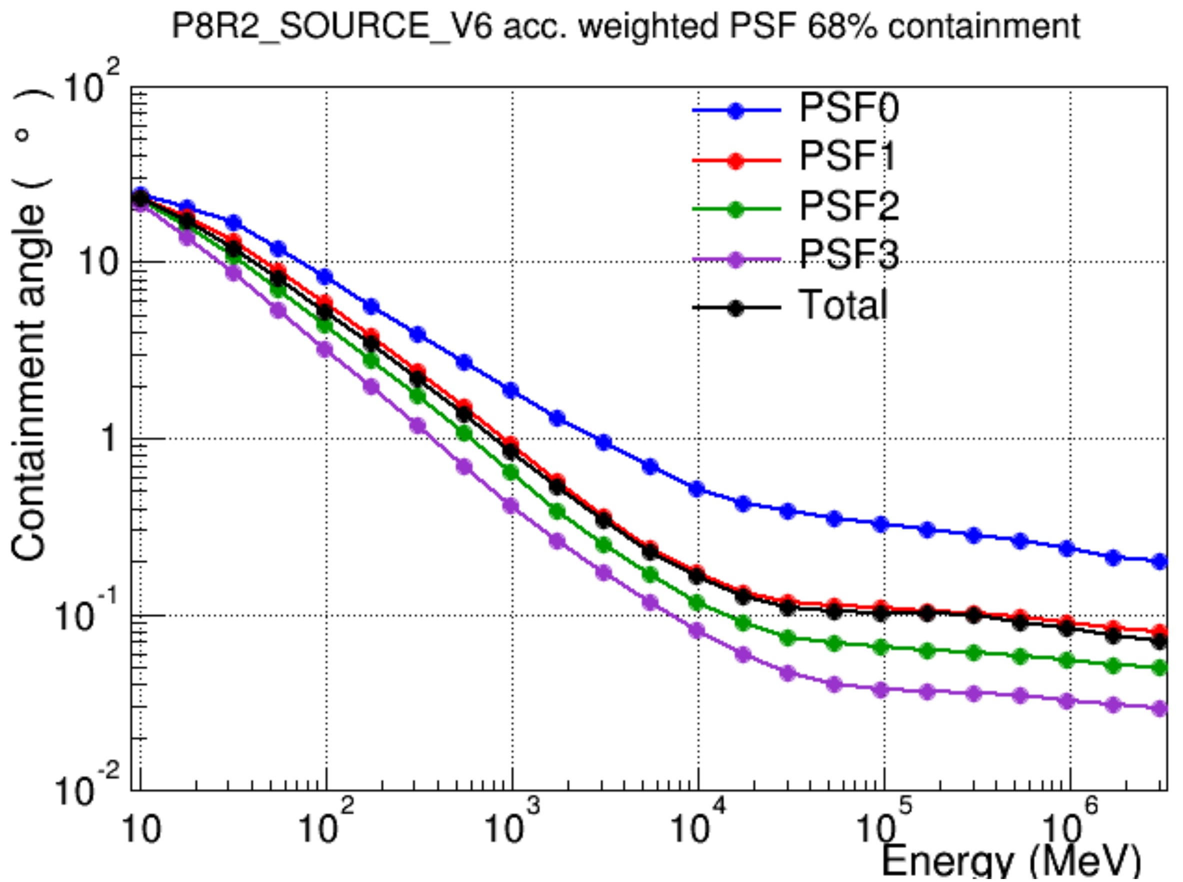


MULTIWAVELENGTH EMISSION

	ASDC	Stroh+13 www.swift.psu.edu /unassociated/	SWIFT (HEASARC)	Total
2FHL	4	0	2	6
3FHL	10	2	30	42
3FGL	7	16	207	230
	IR-Optic	X-Ray		

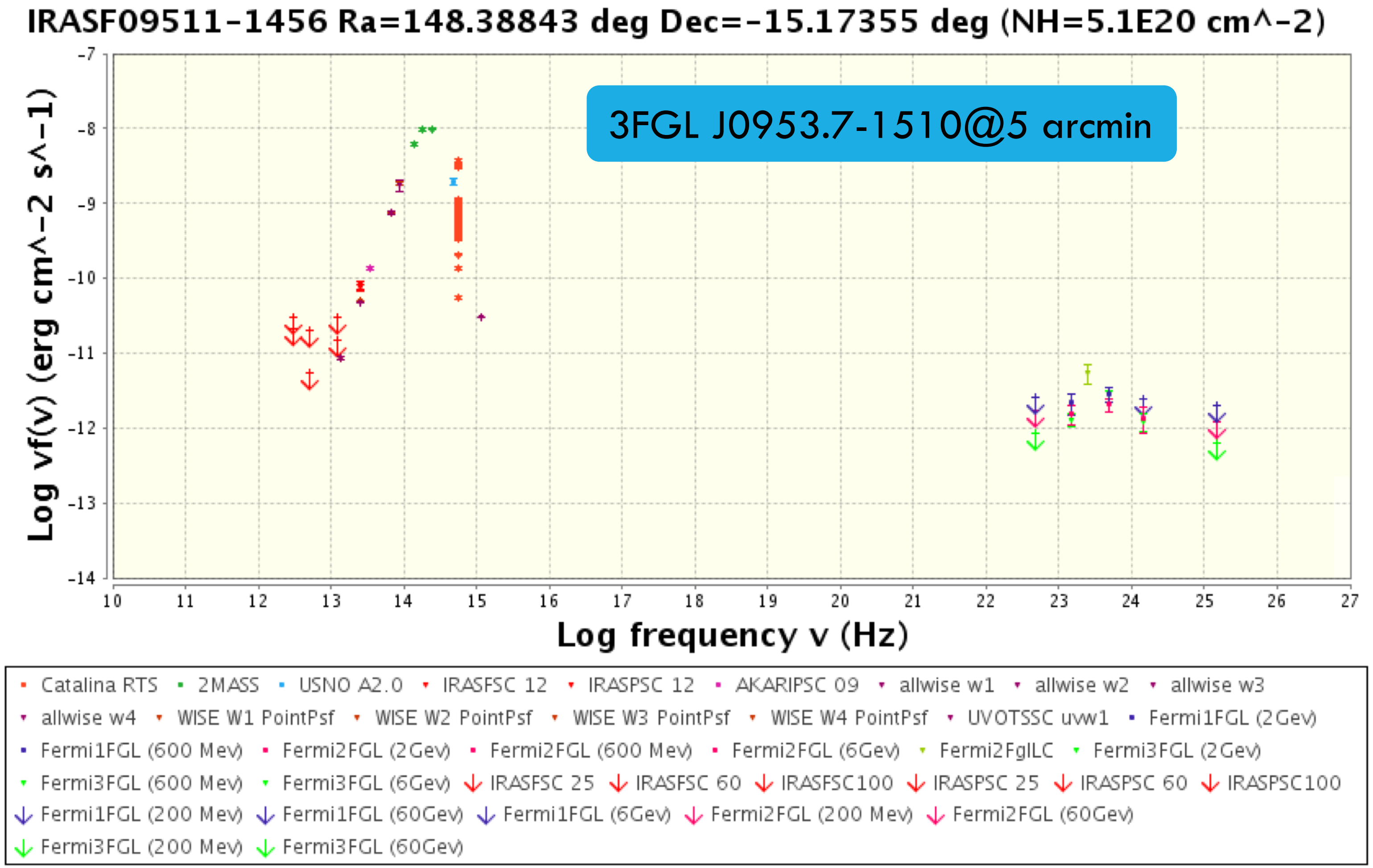
WHY NO OTHER SOURCE IN 5/10 ARCMIN?



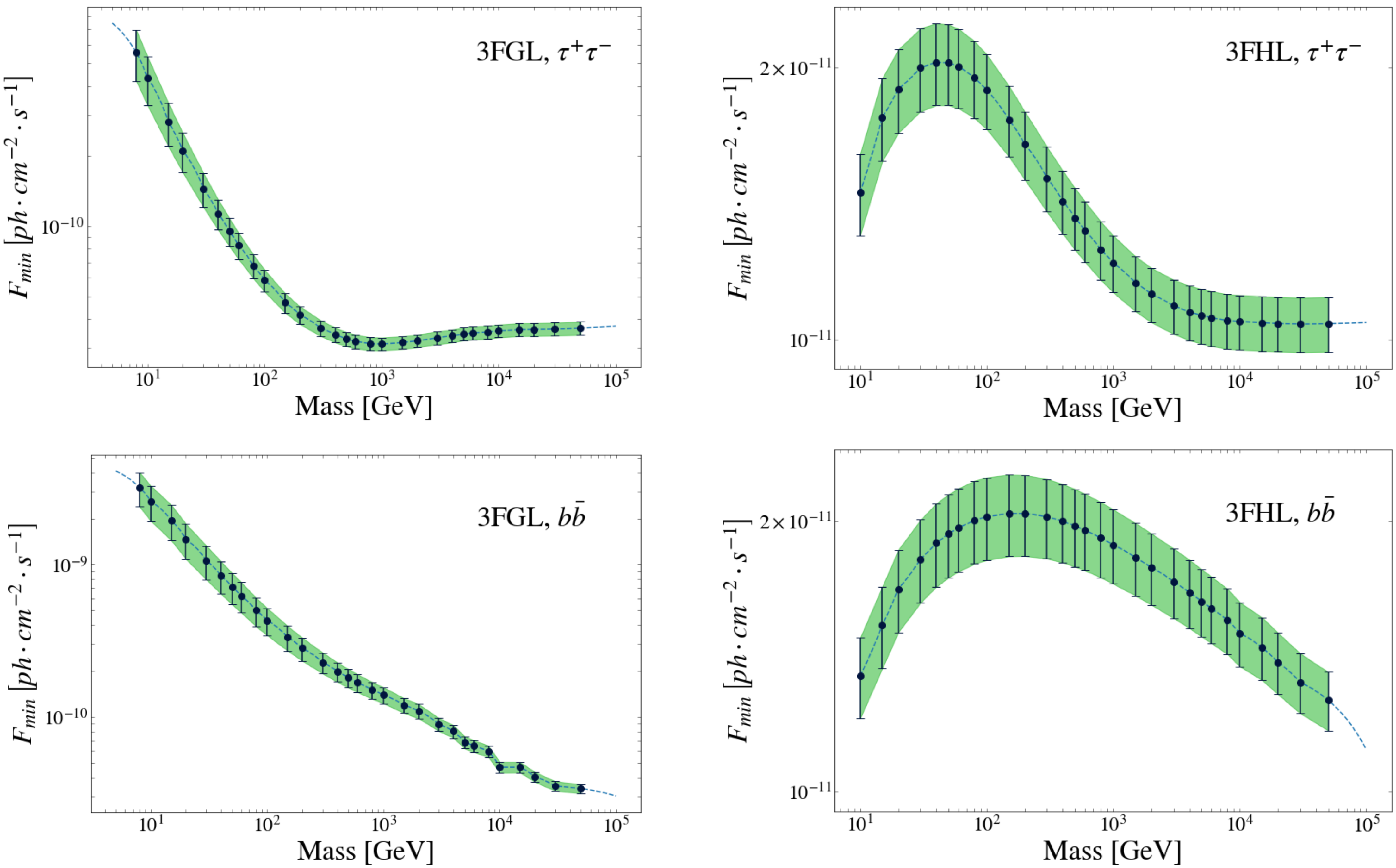


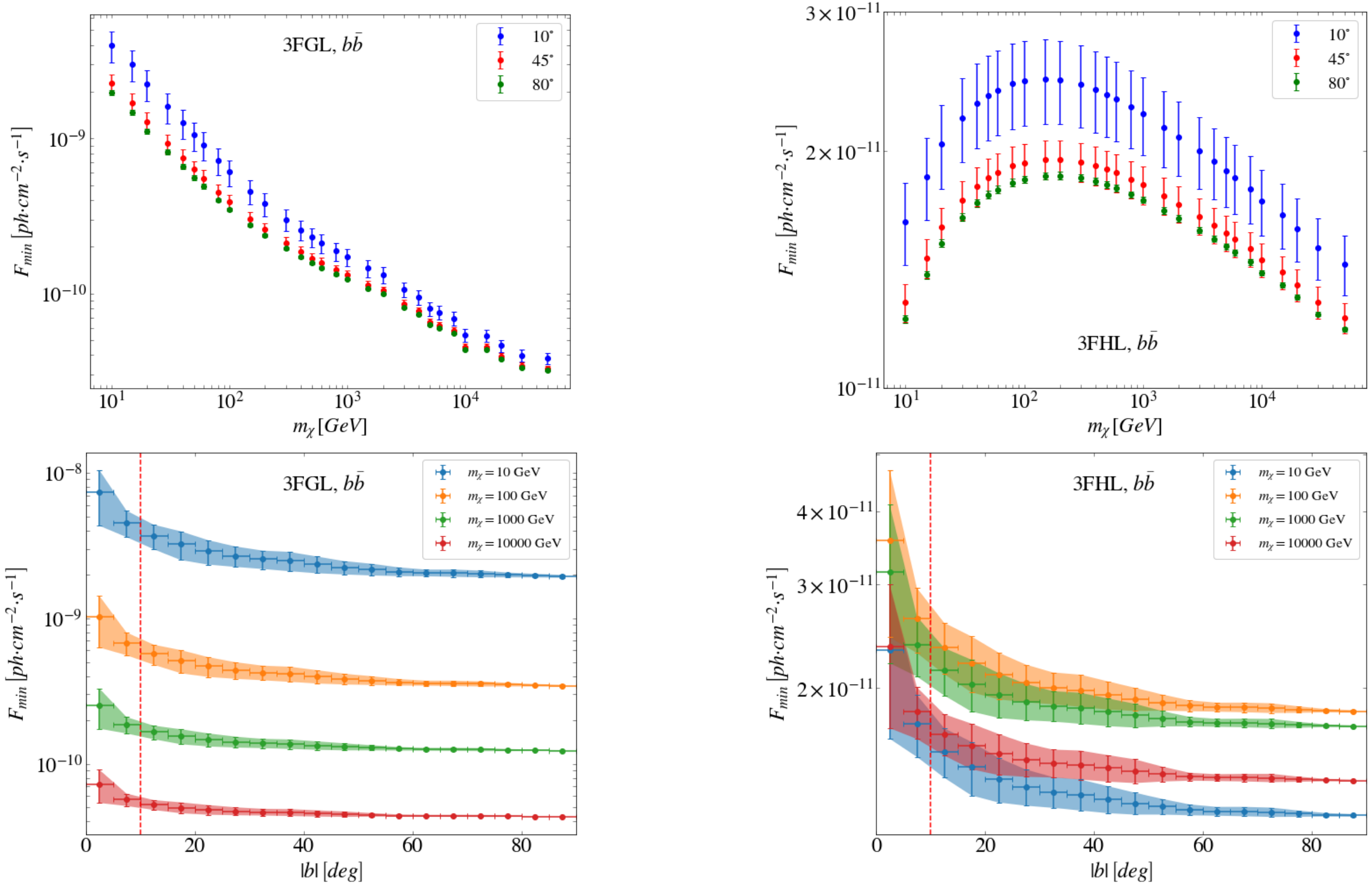
PSF “spill over”

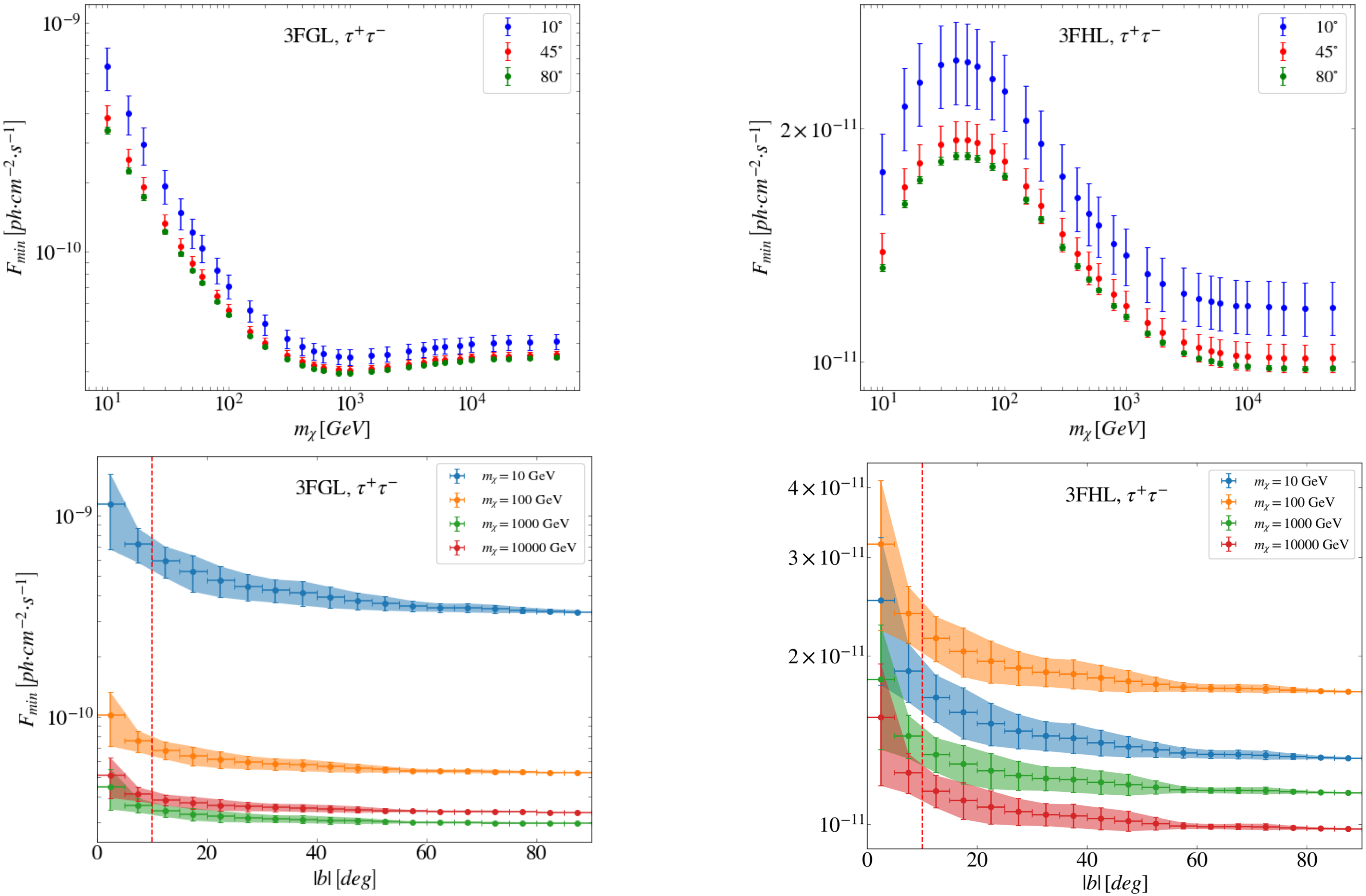
WHY NO OTHER SOURCE IN 5/10 ARCMIN?



- Data on the left refer to 2 sources at 2.3 and 2.6 arcmin
- Due to Fermi PSF, it is uncertain whether any of these sources correspond to the gamma source or to another thing
- To be sure, we require 5 or 10 arcmin (depending on the source positional uncertainty) to be completely empty of other sources
- Should we have any multiwavelength emission in there, we reject the unID from our “clean” list
- We discard **4 2FHL, 10 3FHL and 7 3FGL sources**

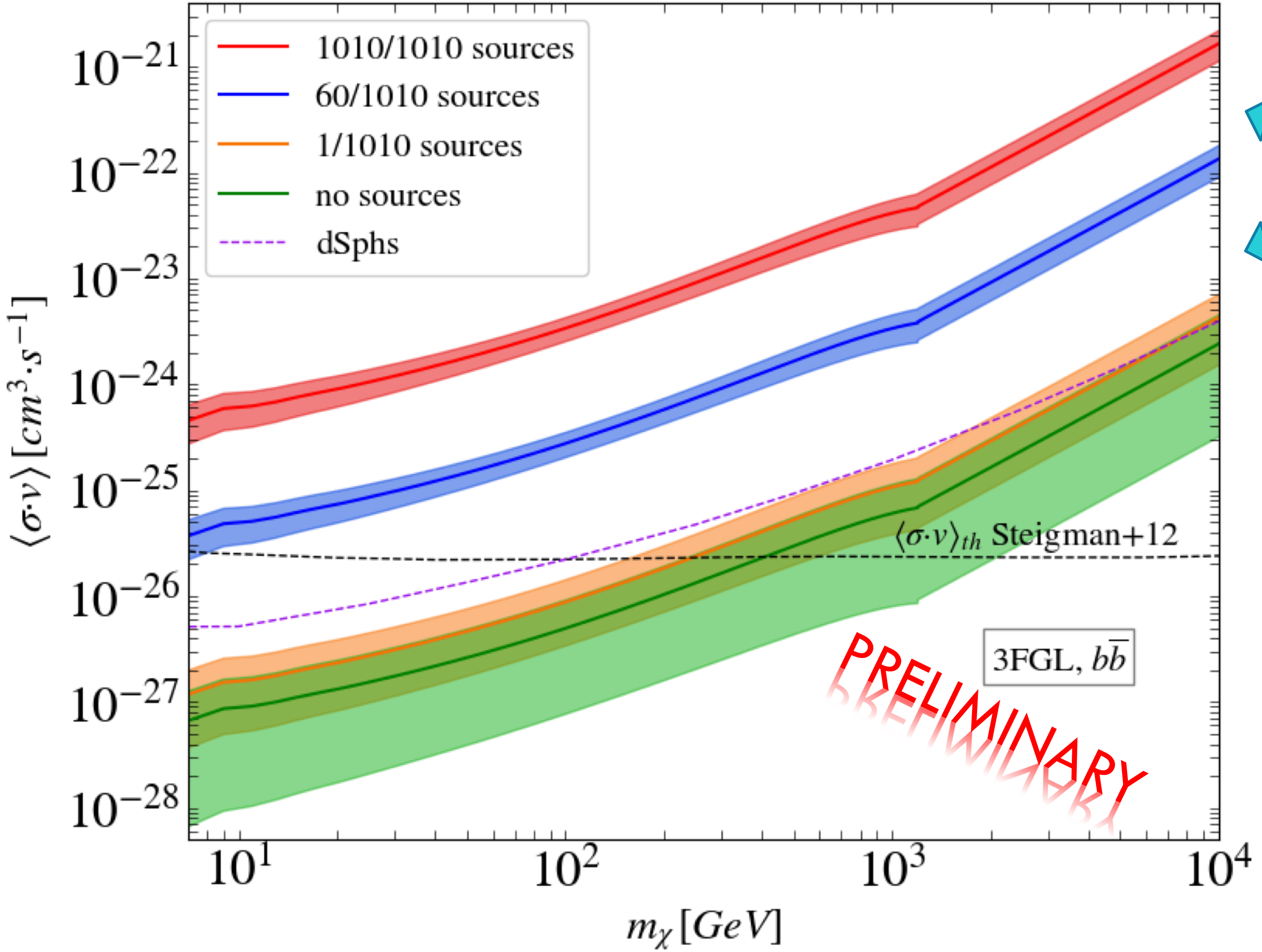

3FGL, $\tau^+\tau^-$
3FHL, $\tau^+\tau^-$
3FGL, $b\bar{b}$
3FHL, $b\bar{b}$
F_{min} $[ph \cdot cm^{-2} \cdot s^{-1}]$
Mass [GeV]
10^{-10}
10^{-9}
2×10^{-11}
10^{-11}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}


3FGL, $b\bar{b}$
10°
45°
80°
$F_{min}\,[ph \cdot cm^{-2} \cdot s^{-1}]$
$m_\chi\,[GeV]$
3FHL, $b\bar{b}$
$m_\chi = 10$ GeV
$m_\chi = 100$ GeV
$m_\chi = 1000$ GeV
$m_\chi = 10000$ GeV
$|b|\,[deg]$

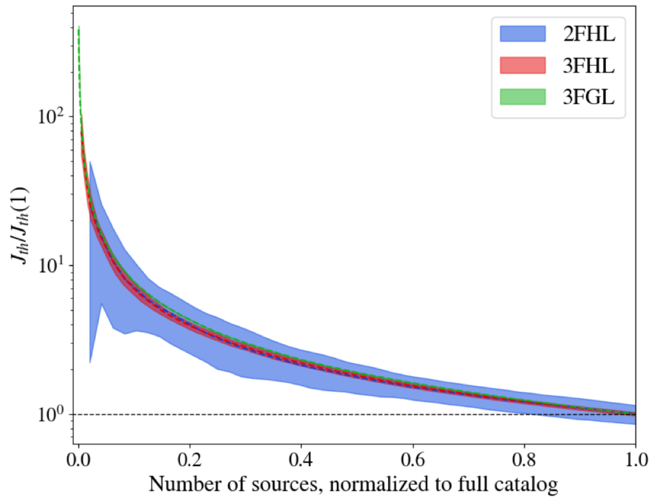


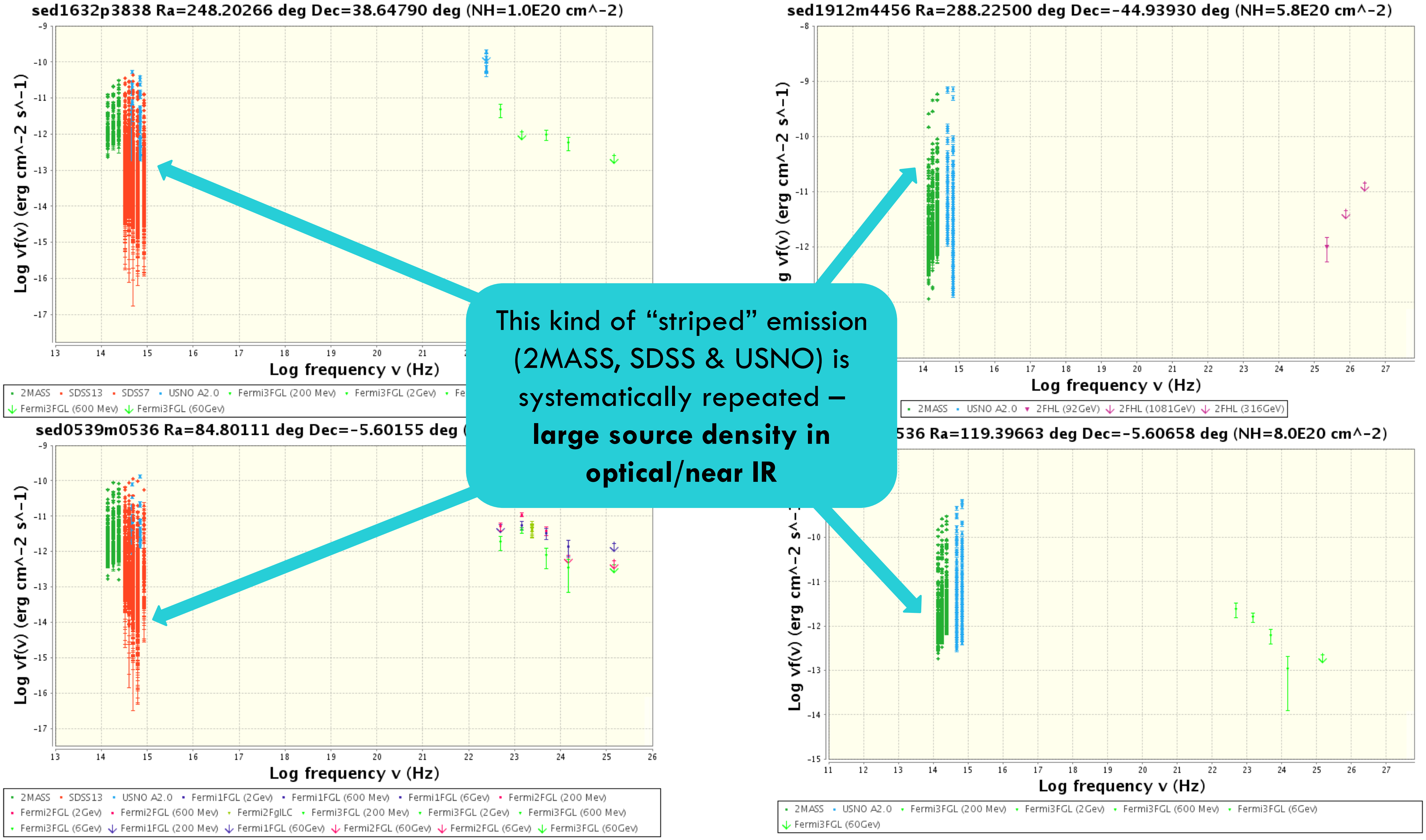
3FGL, $\tau^+\tau^-$
10°
45°
80°
$F_{min}\,[ph{\cdot}cm^{-2}{\cdot}s^{-1}]$
$m_\chi\,[GeV]$
3FHL, $\tau^+\tau^-$
$m_\chi = 10$ GeV
$m_\chi = 100$ GeV
$m_\chi = 1000$ GeV
$m_\chi = 10000$ GeV
$|b|\,[deg]$

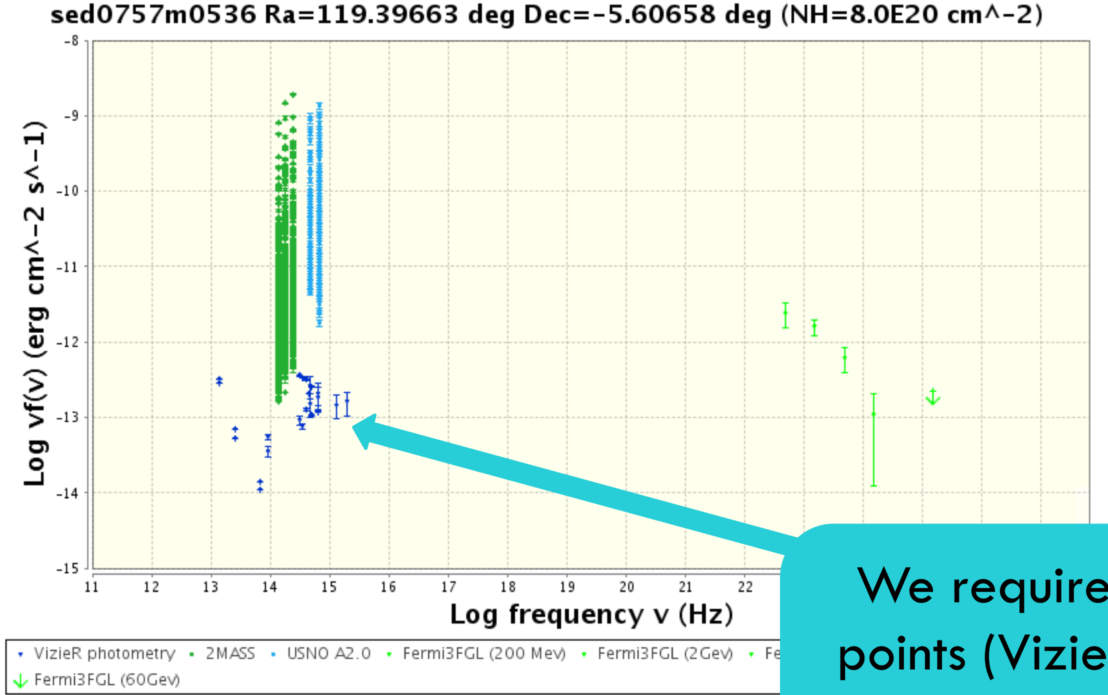
CONSTRAINTS DEPENDING ON THE NUMBER OF UNIDs

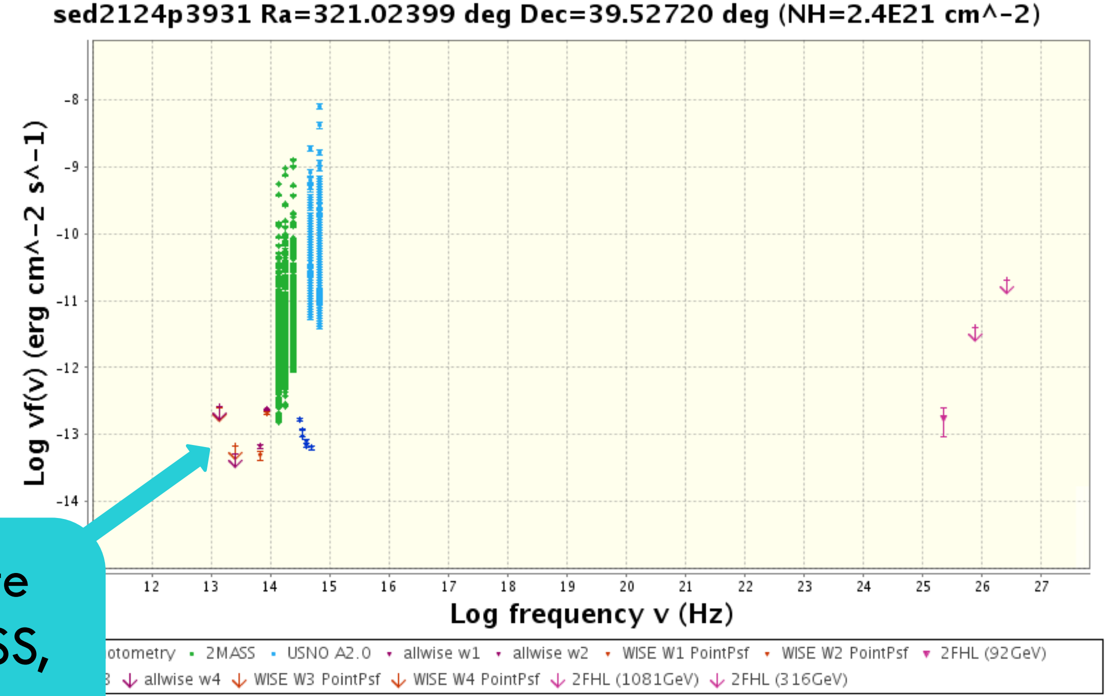


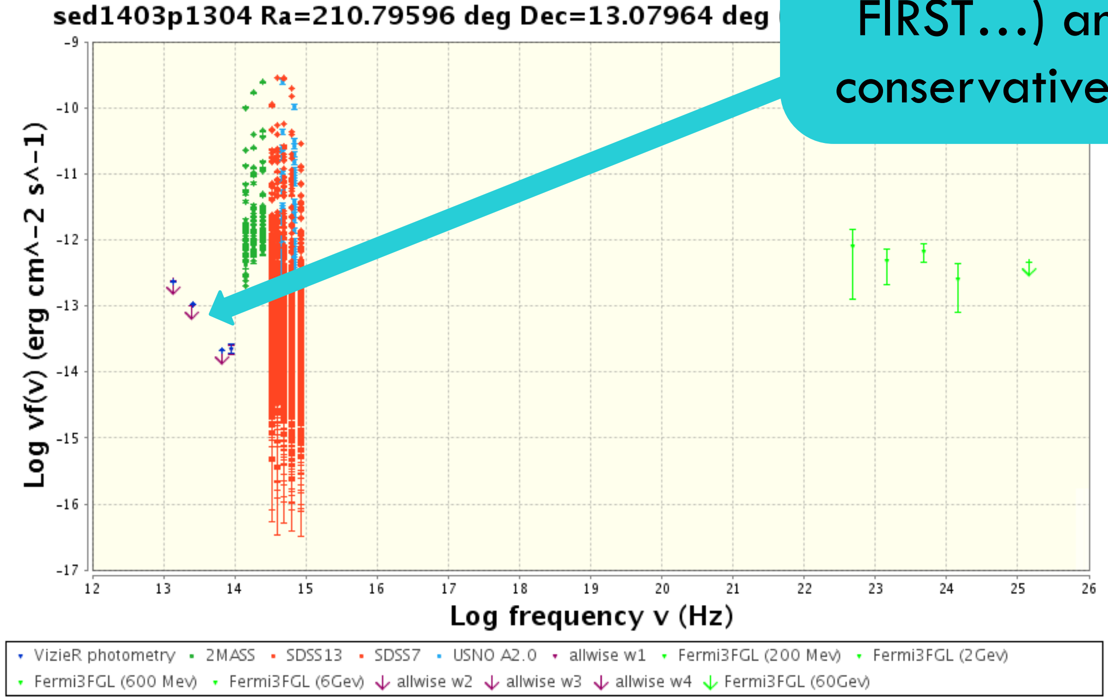
More improvement removing the last 60 sources than the first 950!

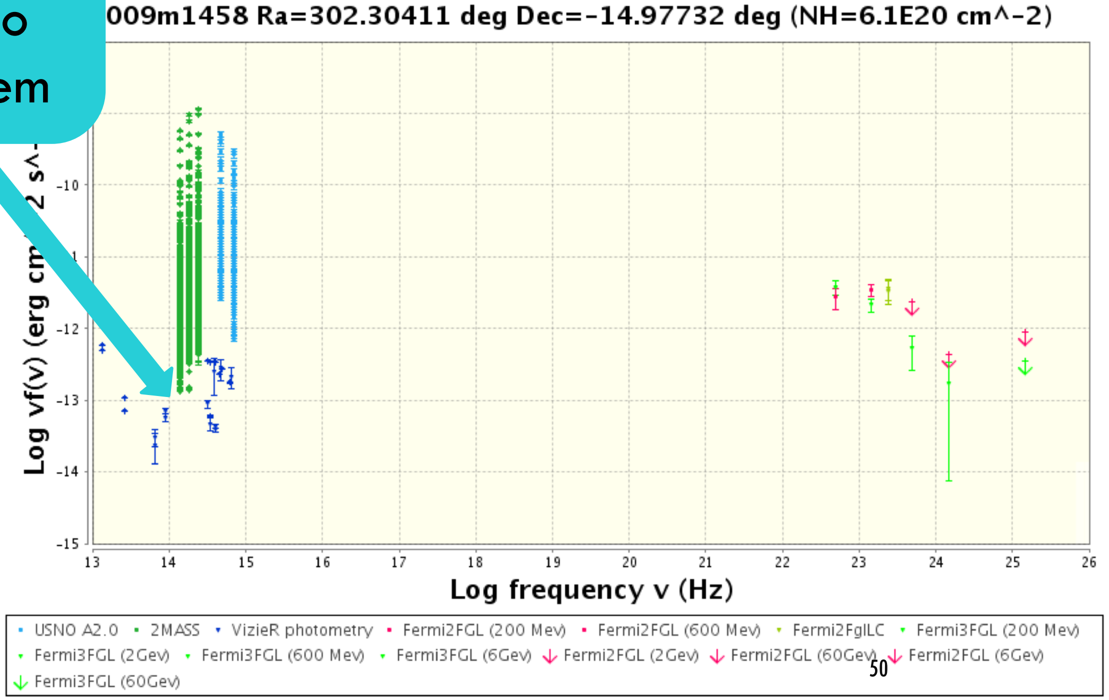



sed1632p3838 Ra=248.20266 deg Dec=38.64790 deg (NH=1.0E20 cm^-2)
Log vf(v) (erg cm^-2 s^-1)
Log frequency v (Hz)
2MASS SDSS13 SDSS7 USNO A2.0 Fermi3FGL (200 Mev) Fermi3FGL (2Gev) Fe
Fermi3FGL (600 Mev) Fermi3FGL (60Gev)
sed1912m4456 Ra=288.22500 deg Dec=-44.93930 deg (NH=5.8E20 cm^-2)
g vf(v) (erg cm^-2 s^-1)
Log frequency v (Hz)
2MASS USNO A2.0 2FHL (92GeV) 2FHL (1081GeV) 2FHL (316GeV)
sed0539m0536 Ra=84.80111 deg Dec=-5.60155 deg (
Log vf(v) (erg cm^-2 s^-1)
Log frequency v (Hz)
2MASS SDSS13 USNO A2.0 Fermi1FGL (2Gev) Fermi1FGL (600 Mev) Fermi1FGL (6Gev) Fermi2FGL (200 Mev)
Fermi2FGL (2Gev) Fermi2FGL (600 Mev) Fermi2FglLC Fermi3FGL (200 Mev) Fermi3FGL (2Gev) Fermi3FGL (600 Mev)
Fermi3FGL (6Gev) Fermi1FGL (200 Mev) Fermi1FGL (60Gev) Fermi2FGL (60Gev) Fermi2FGL (6Gev) Fermi3FGL (60Gev)
536 Ra=119.39663 deg Dec=-5.60658 deg (NH=8.0E20 cm^-2)
Log vf(v) (erg cm^-2 s^-1)
Log frequency v (Hz)
2MASS USNO A2.0 Fermi3FGL (200 Mev) Fermi3FGL (2Gev) Fermi3FGL (600 Mev) Fermi3FGL (6Gev)
Fermi3FGL (60Gev)
This kind of “striped” emission (2MASS, SDSS & USNO) is systematically repeated – large source density in optical/near IR









We require other discrete points (VizieR, WISE, NVSS, FIRST…) and other WL to conservatively discard them