Subhalo searches in gamma-ray astronomy

News from the Dark 7, Montpellier
16/06/2022

Francesca Calore (CNRS/LAPTh)

Galactic Subhalo searches in gamma-ray astronomy

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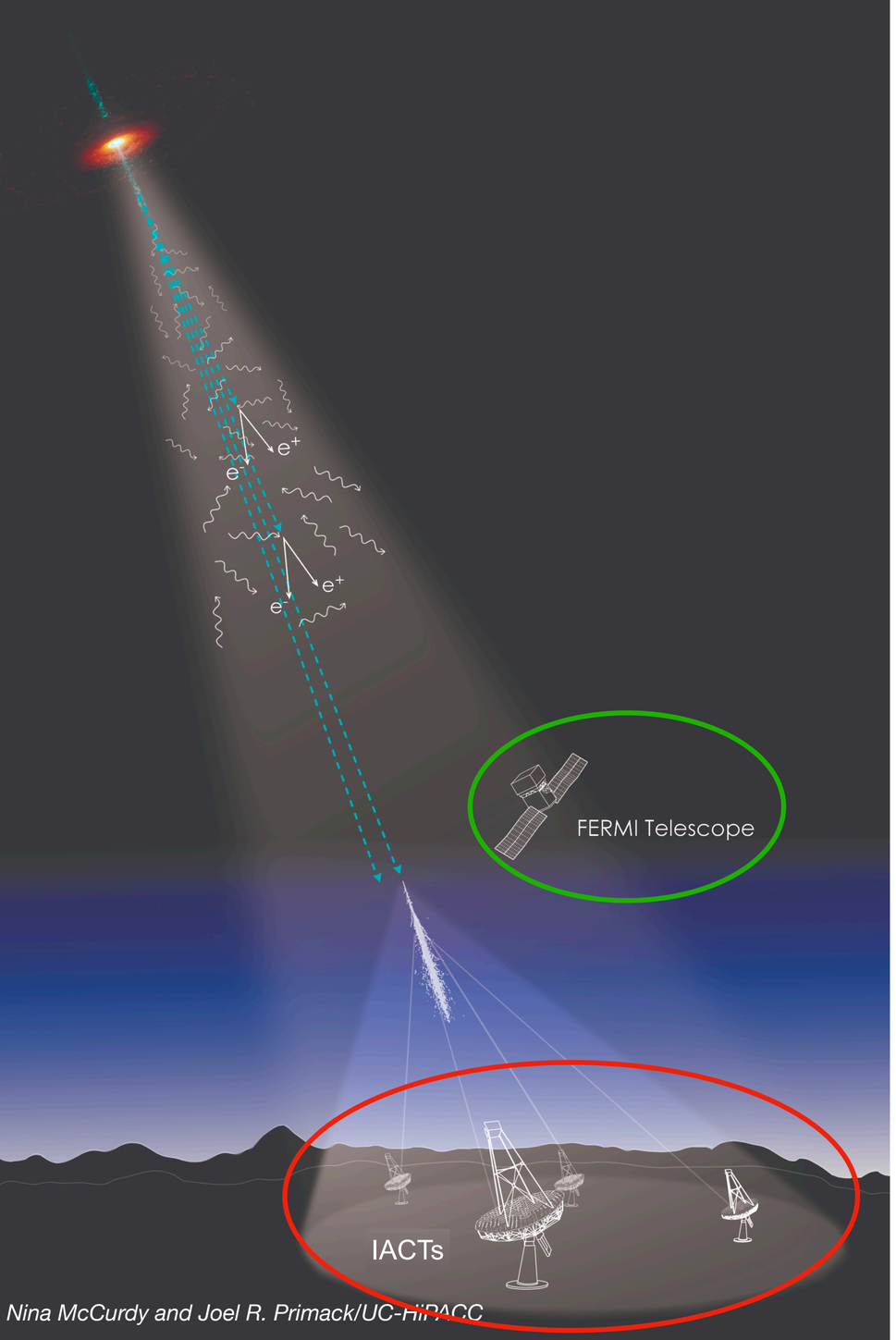
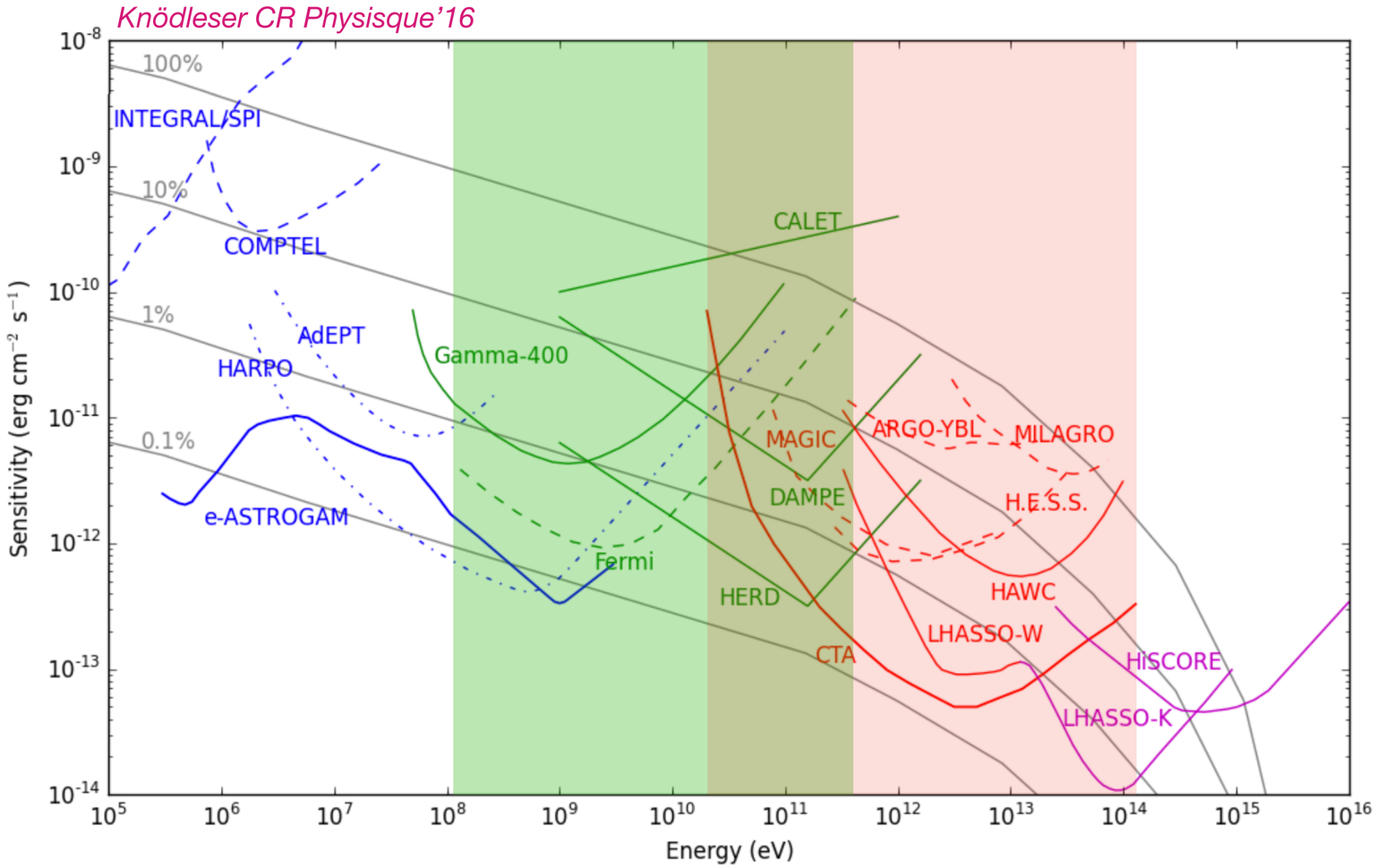
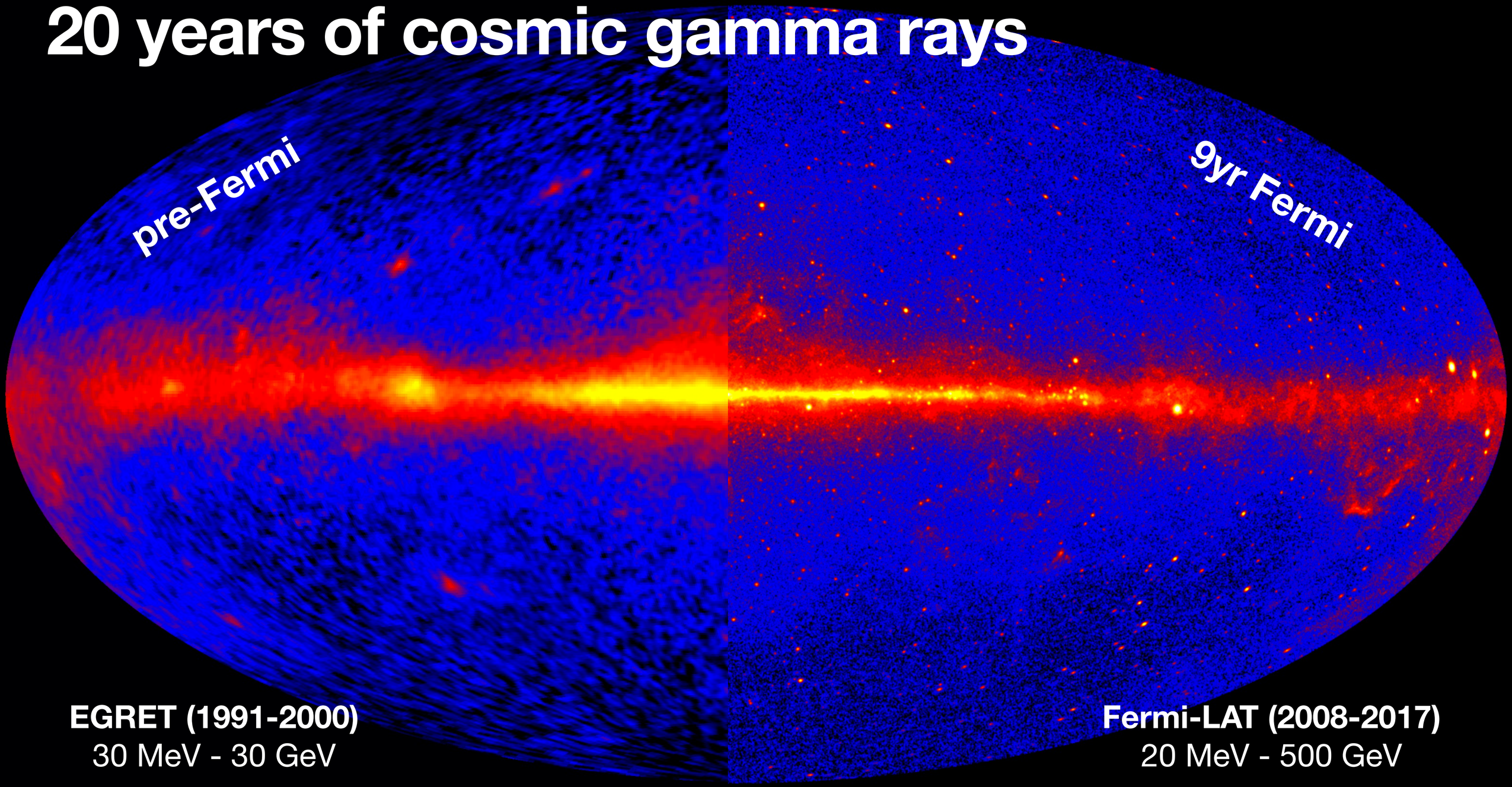
Gamma-ray astronomy





Differential 5σ point source sensitivities of present and future gamma-ray instruments

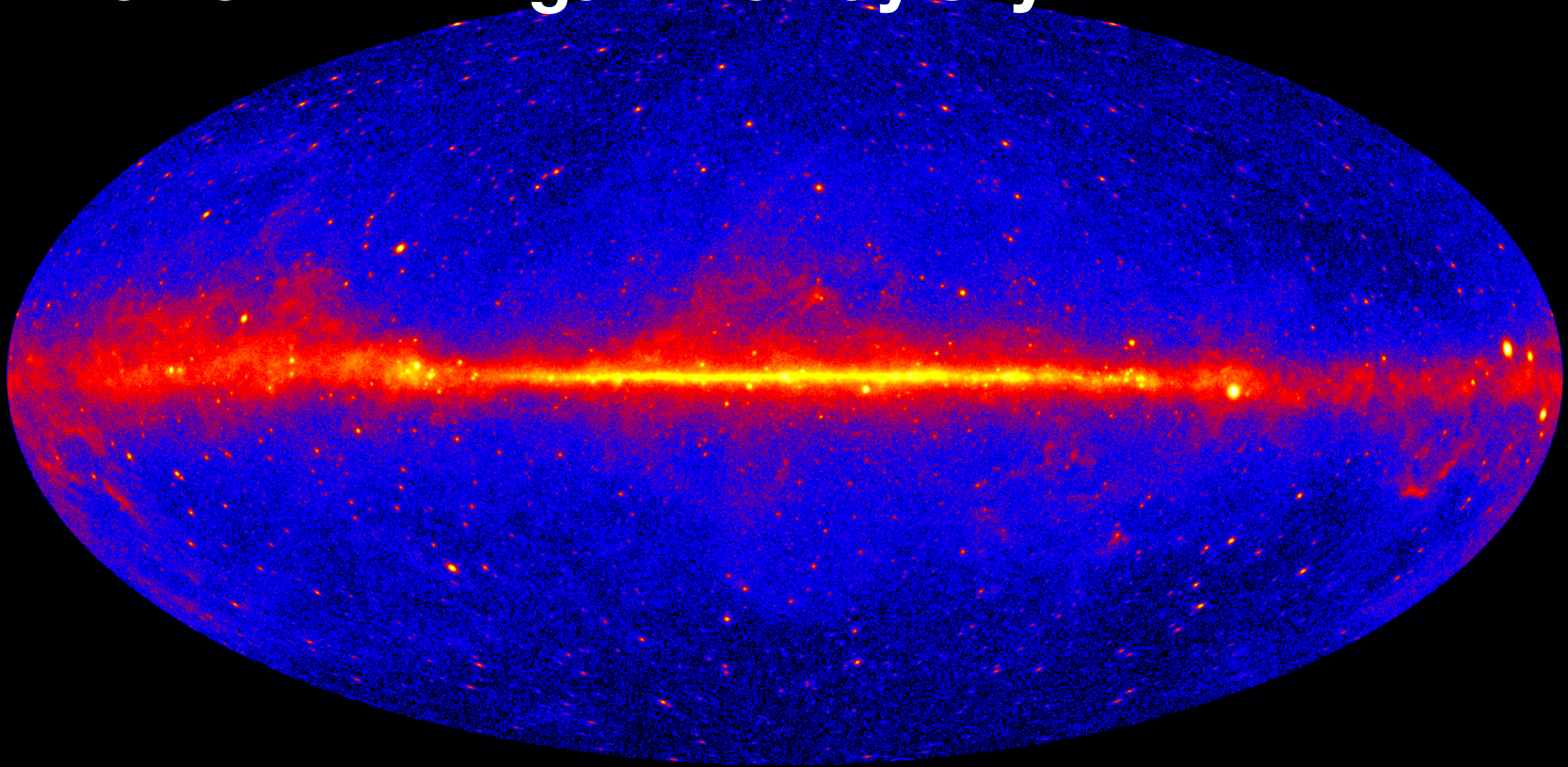
20 years of cosmic gamma rays



EGRET (1991-2000)
30 MeV - 30 GeV

Fermi-LAT (2008-2017)
20 MeV - 500 GeV

The Fermi-LAT gamma-ray sky



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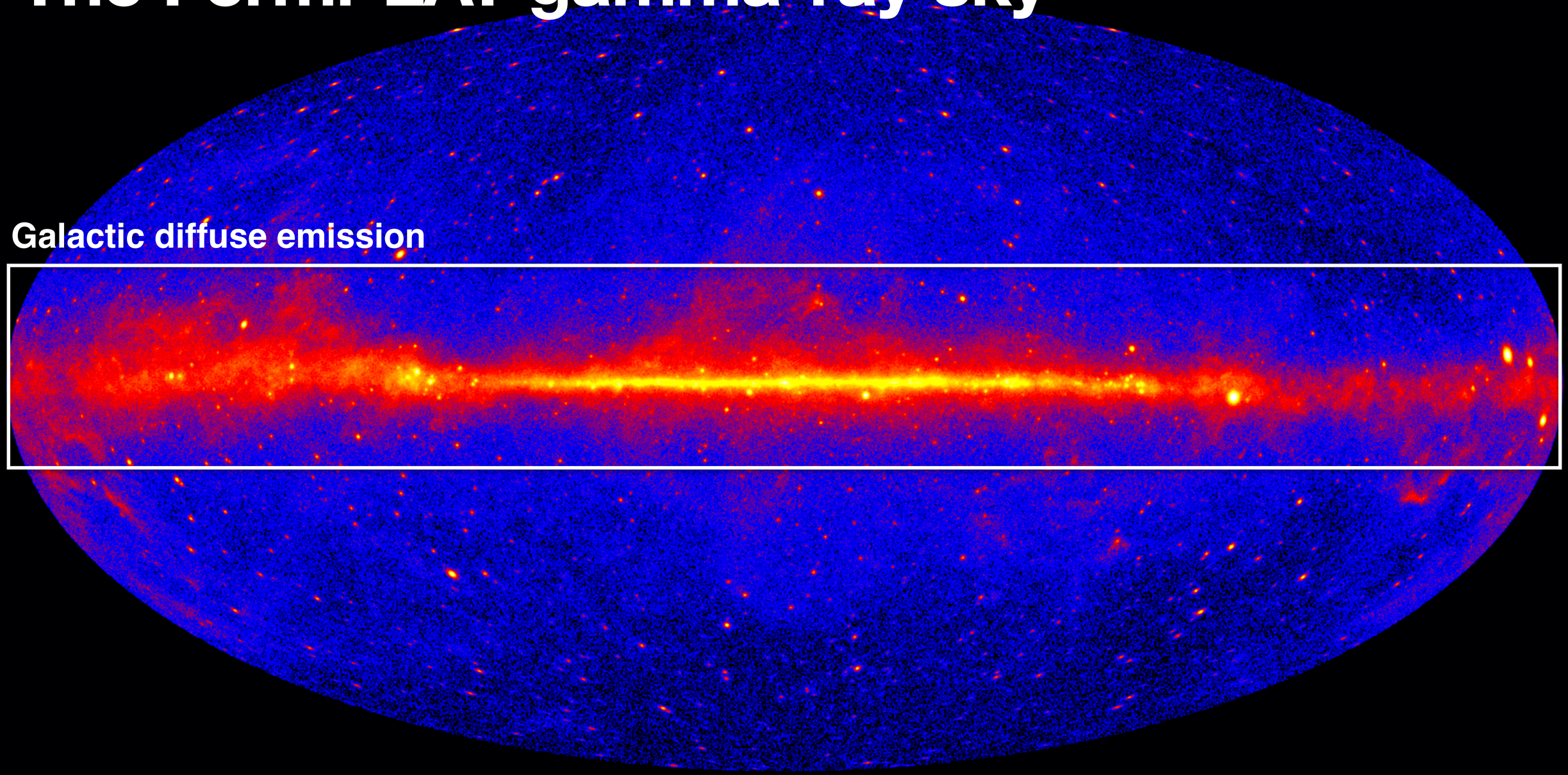
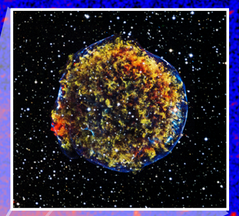


The Galactic diffuse emission

CR interactions with gas and radiation field

CR sources



Tycho's SNR (SN 1572)

Cassiopeia A

W51C

W44

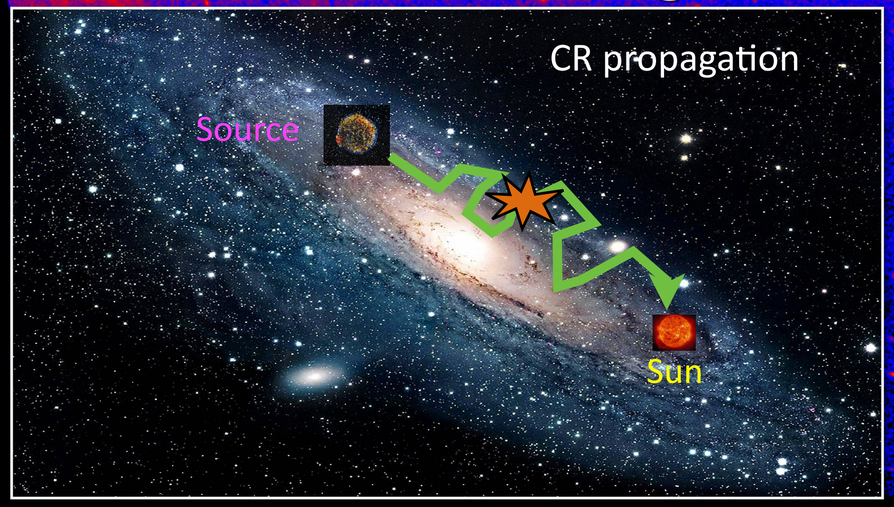
W49B

SNR G008.7−00.1

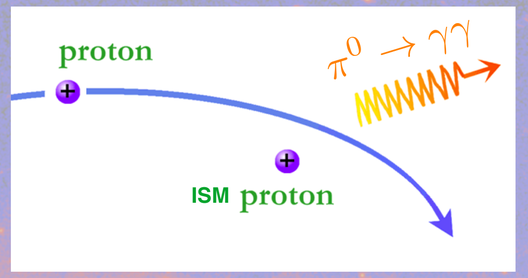
CTB 37A

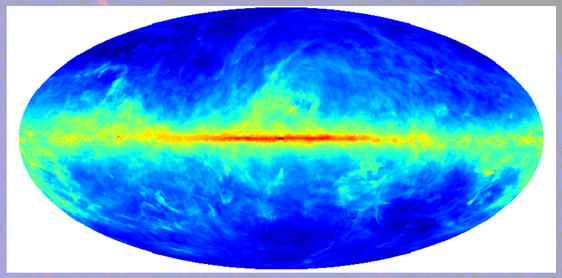
IC 443

CR propagation

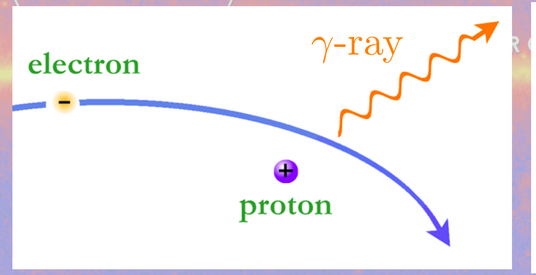


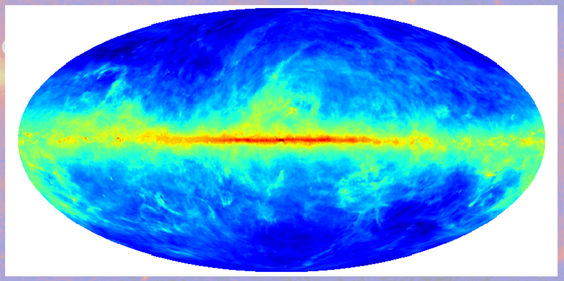
Pion decay



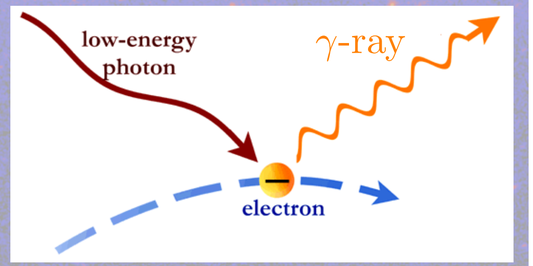


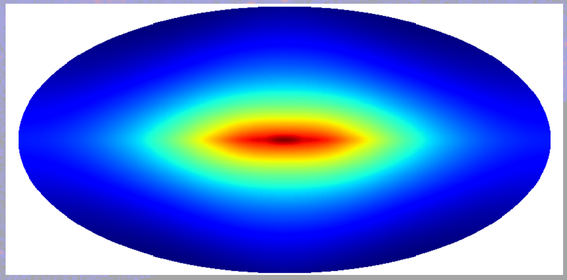
Bremsstrahlung



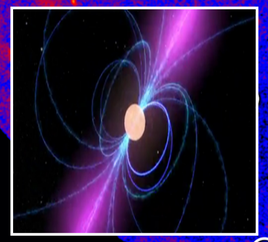


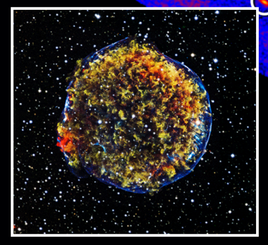
Inverse Compton





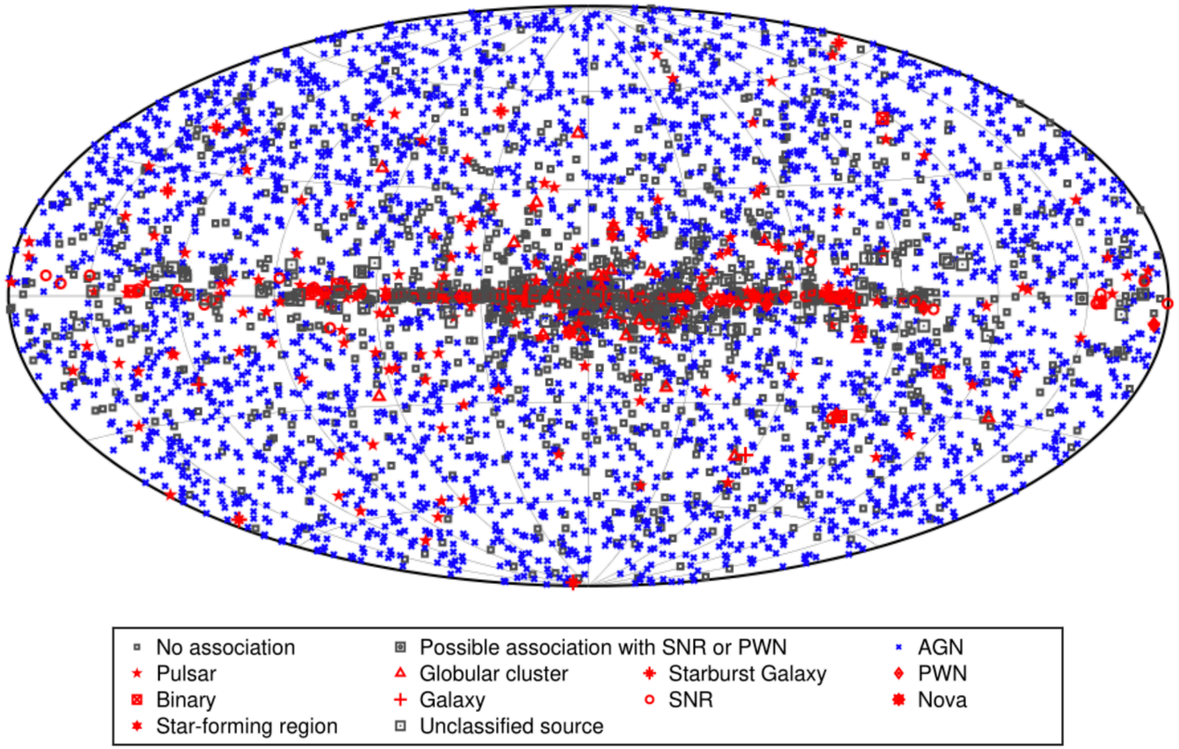
Fermi-LAT gamma-ray sources





Detected sources

Fermi-LAT gamma-ray sources

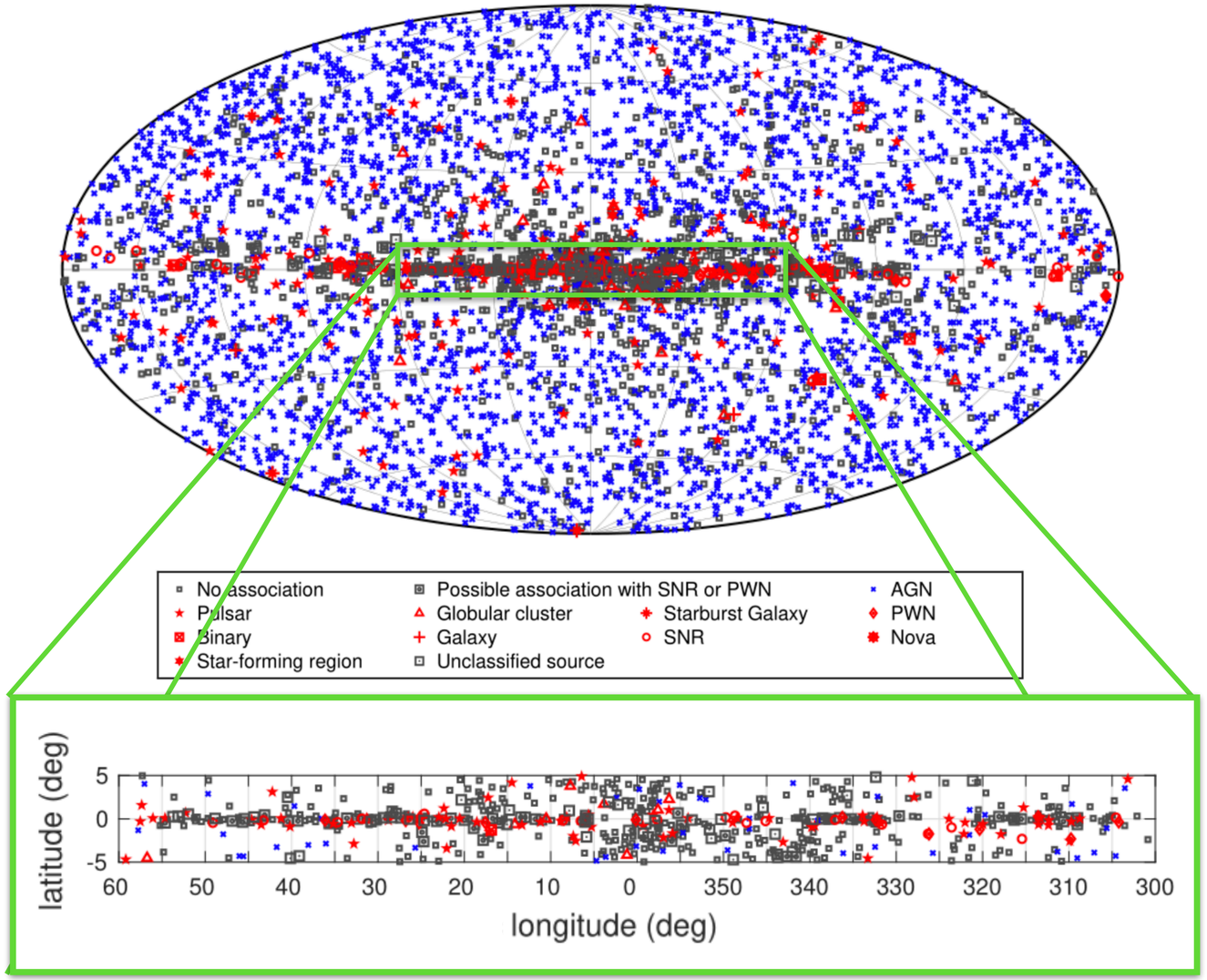


FERMI-LAT FOURTH SOURCE CATALOG (4FGL)

Fermi-LAT Collab. ApJS'20

- 8yr data-set
- **5064** sources above 4σ significance
- **3130** AGN; **239** pulsars

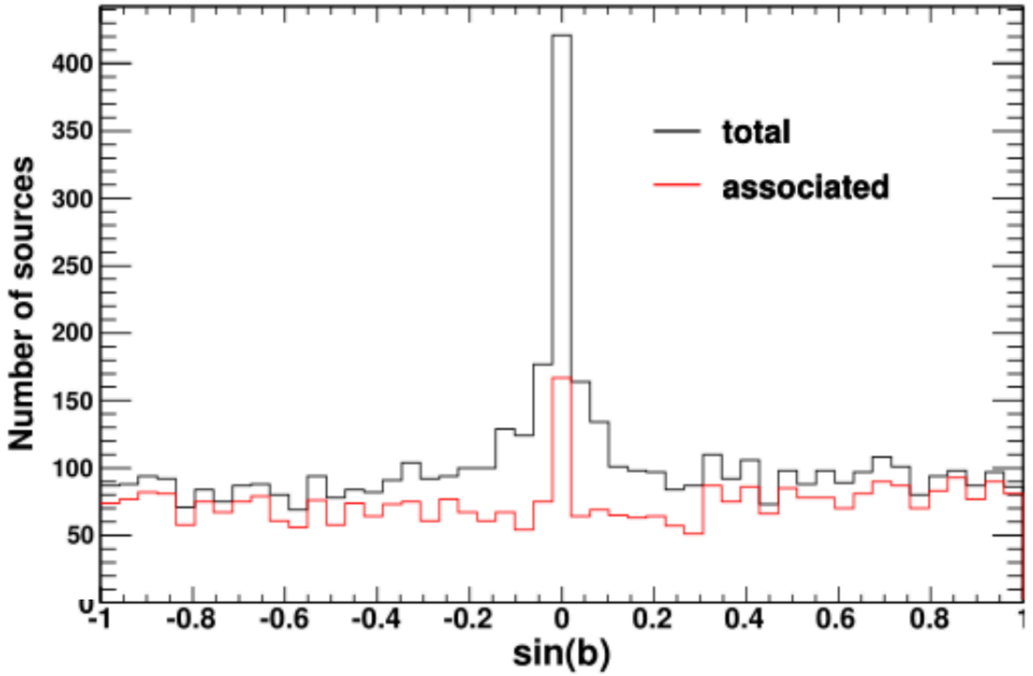
Fermi-LAT gamma-ray sources



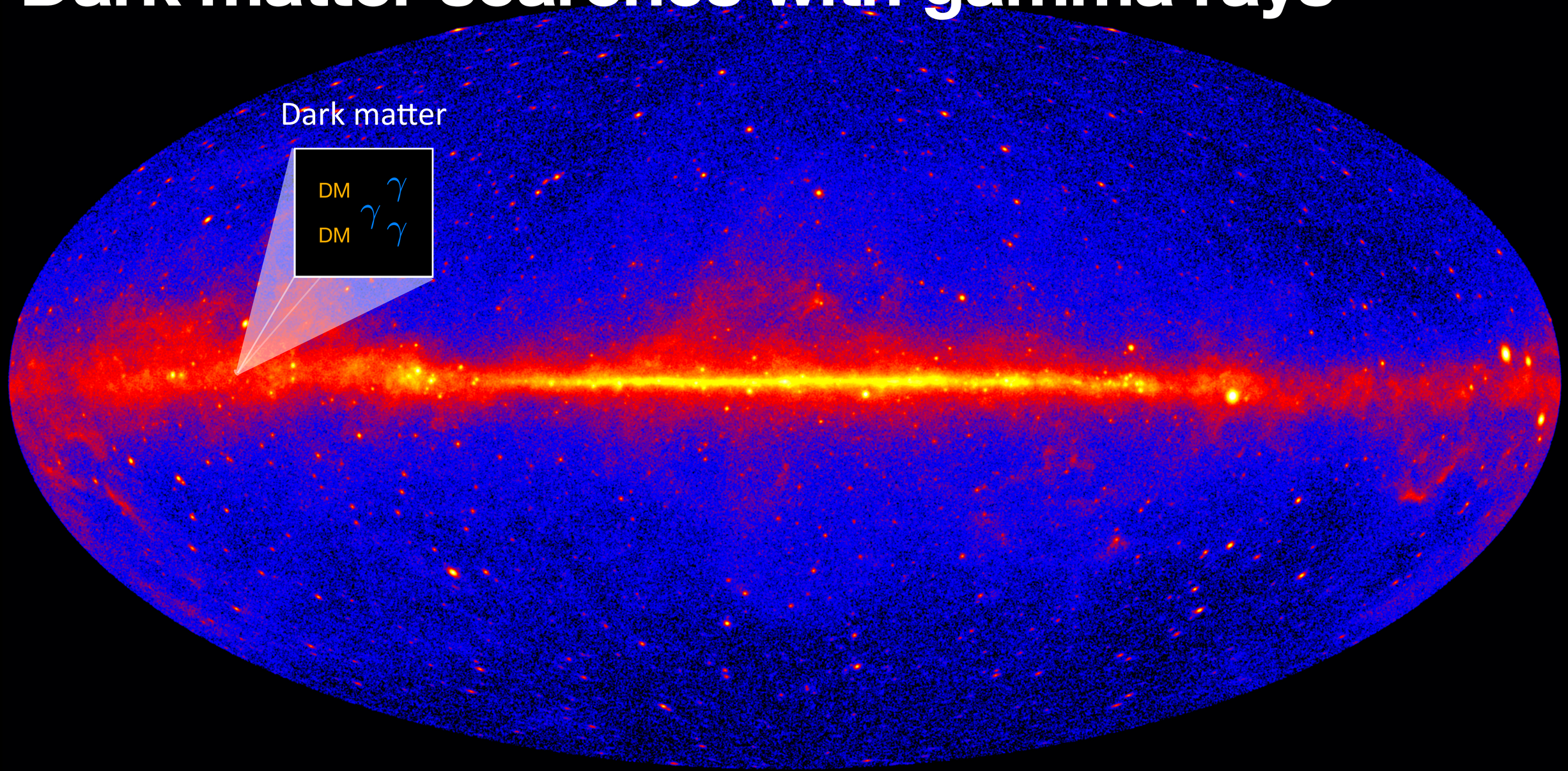
FERMI-LAT FOURTH SOURCE CATALOG (4FGL)

Fermi-LAT Collab. ApJS'20

- 8yr data-set
- **5064** sources above 4σ significance
- **3130** AGN; **239** pulsars
- **1336** sources w/o counterparts at other wavelengths

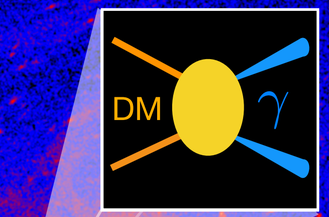


Dark matter searches with gamma rays



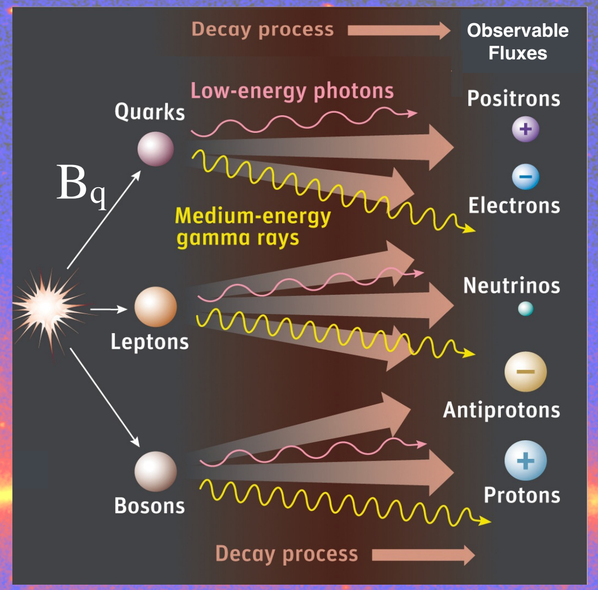
Dark matter searches with gamma rays

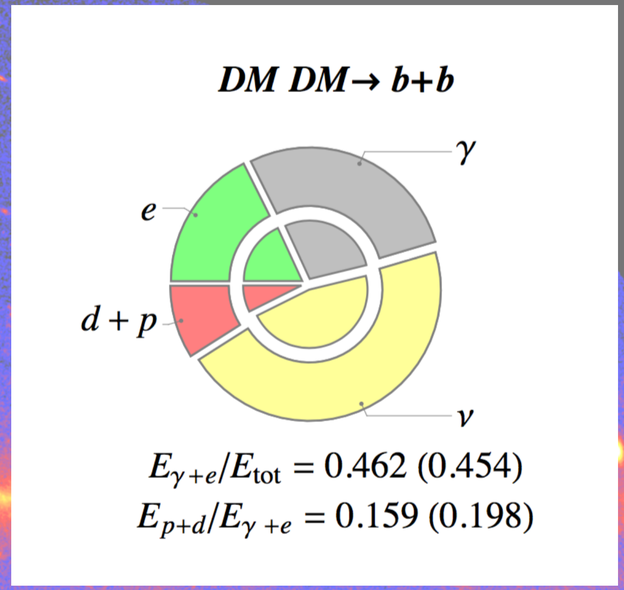
Dark matter*



*Weakly Interacting Massive Particles

DM annihilation/decay

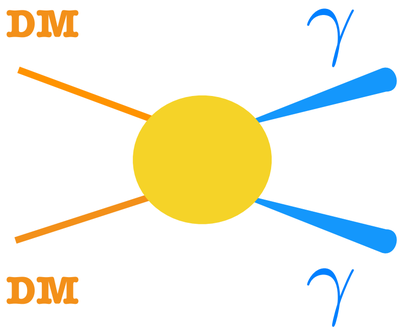




- Prompt emission from final state particles (bb, qq, WW etc.)
- 100% BR usually assumed to be model independent
- Secondary emission from leptonic final states
- **Spatial distribution**: smooth Galactic halos and sub-haloes

$$\Phi(E,\psi) = \frac{\sigma_{\rm A} v}{8\pi m_\chi^2}\frac{dN_\gamma}{dE}\int d\ell\,\rho\left[r(\ell,\psi)\right]^2$$

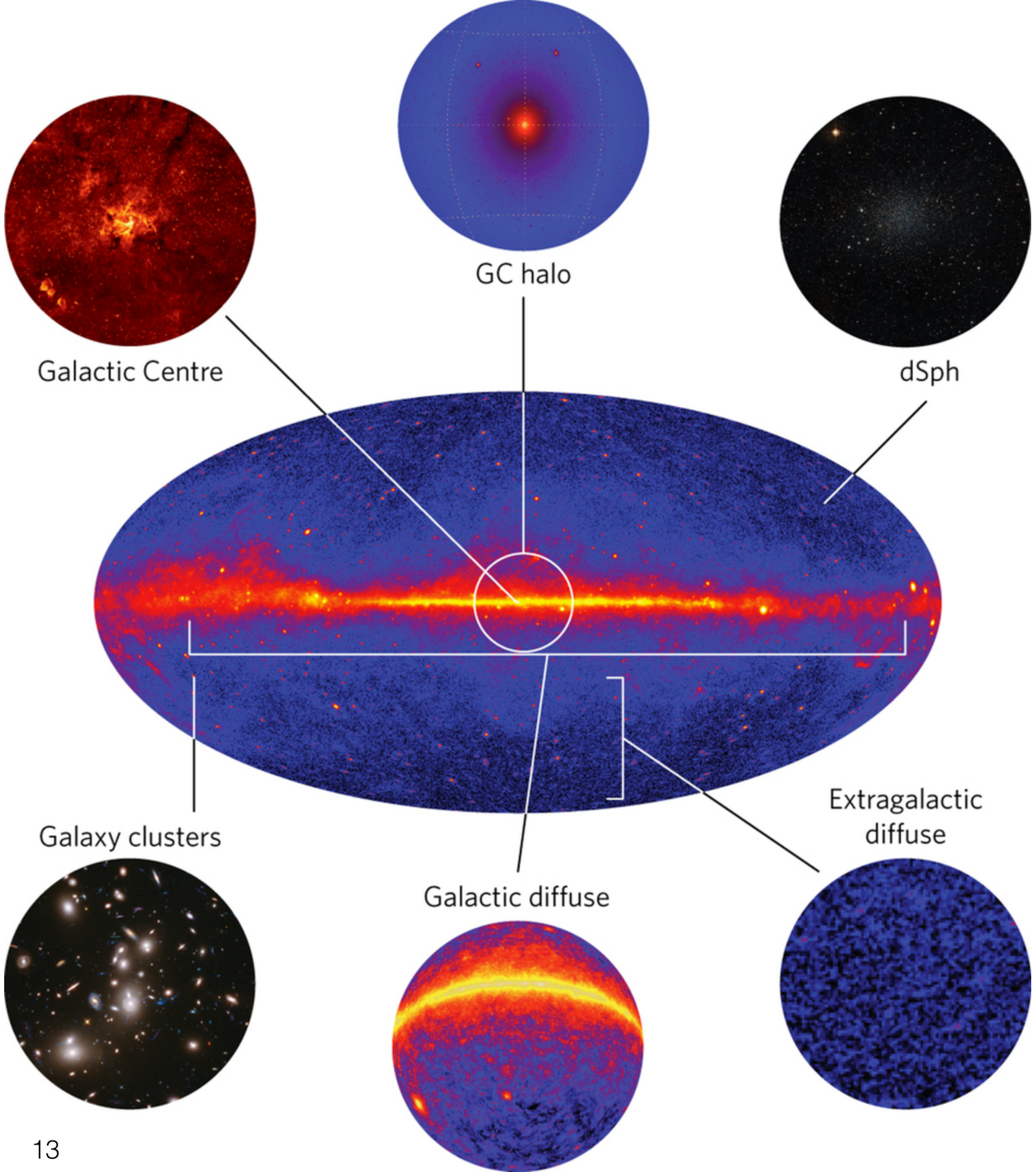
Targets for WIMP gamma-ray searches



$$\mathcal{J} \propto \int d\ell \, \rho \left[r(\ell, \psi) \right]^2$$

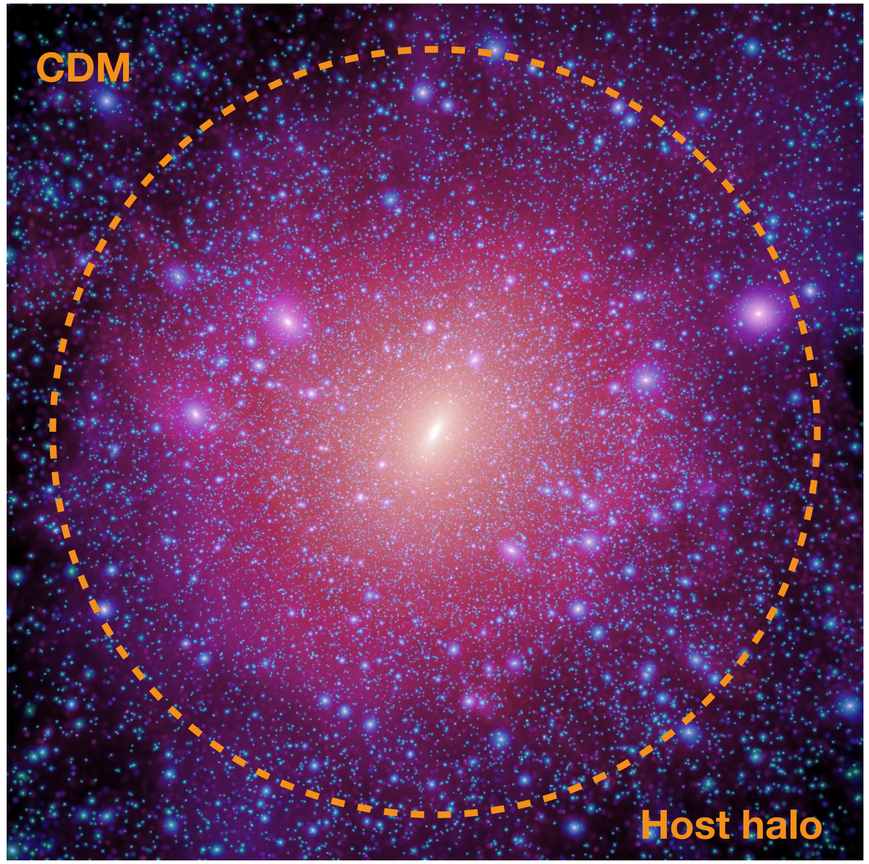
+ dedicated searches for gamma-ray lines
+ similar targets for radio searches (synchrotron)

Conrad & Reimer Nature Phys. 13 (2017)



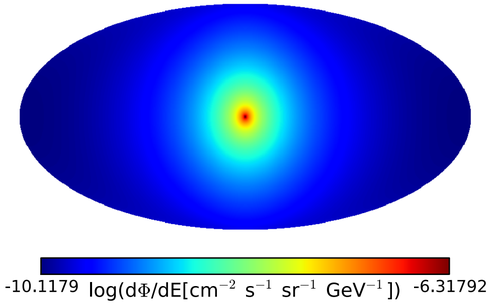
Dark matter signal morphology

Smooth halo and sub-structures

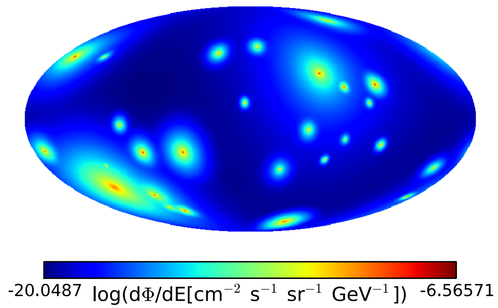


Springel+ MNRAS'08

Expected gamma-ray flux from self-annihilation



Main halo



Sub-haloes

Calore+ MNRAS'14

SPATIAL (ANGULAR) FEATURES

Specific searches leveraging on spatial signatures:
anisotropies/cross-correlation in gamma/cosmic rays;
"dark" subhaloes as unassociated sources

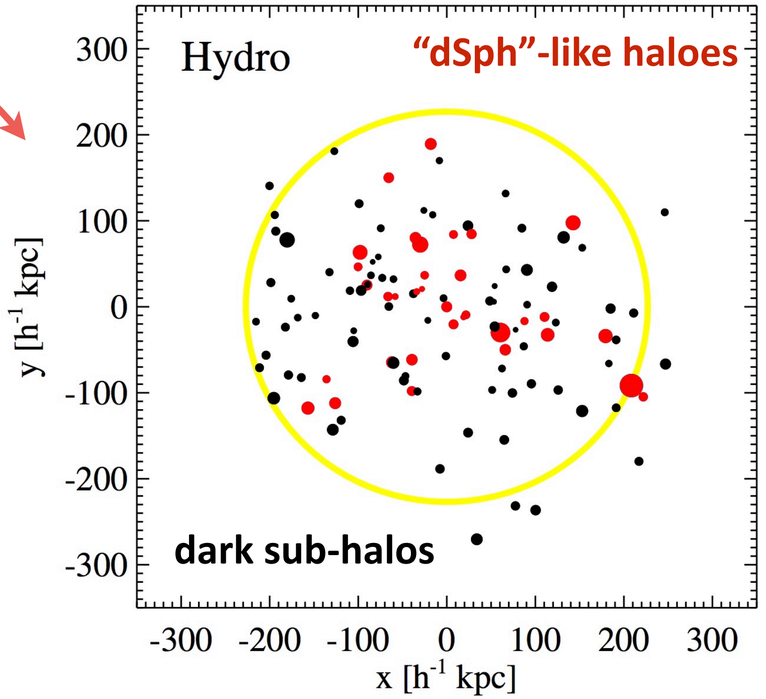
* In WIMP and non-thermal axion models

[See for example: *Ando, Phys.Rev.D80:023520,2009; Fornengo&Regis, Front. Physics 2:6, 2014*]

Dark and bright sub-haloes

Simulations of **galaxy formation** allow us to predict the distribution and size of haloes in cosmological volumes and their stellar content

Zhu+ MNRAS'16



[See also semi-analytical models: **Ando**'s and **Facchinetti**'s talks]

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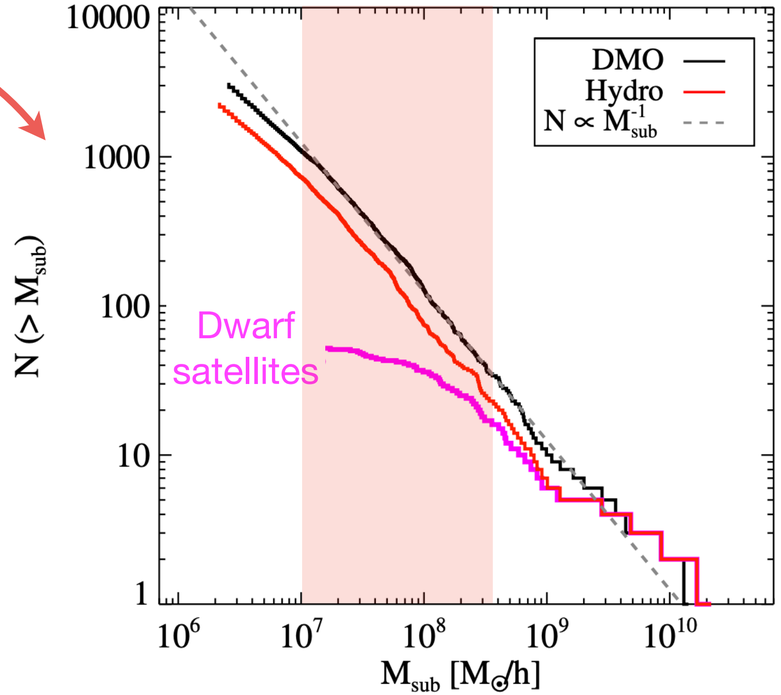

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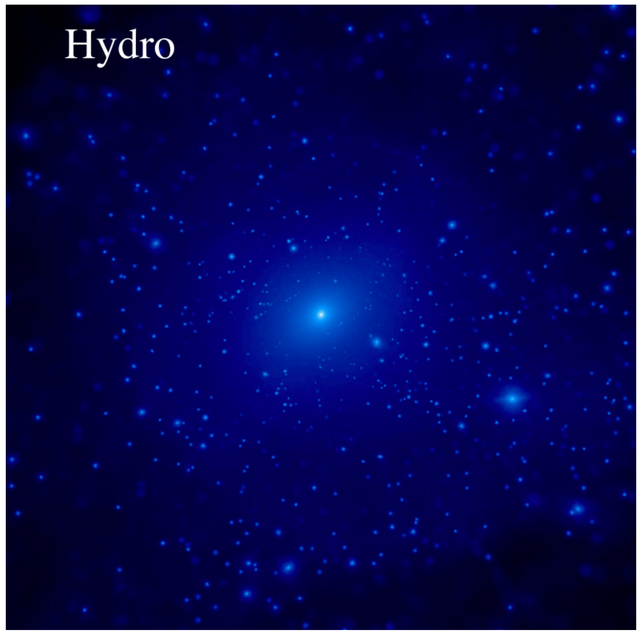
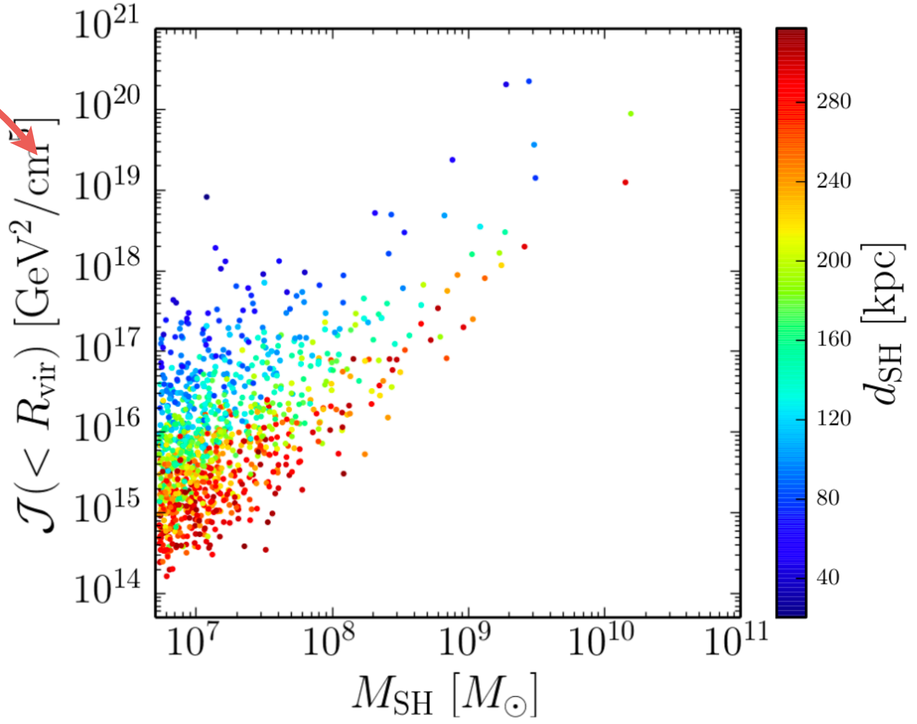


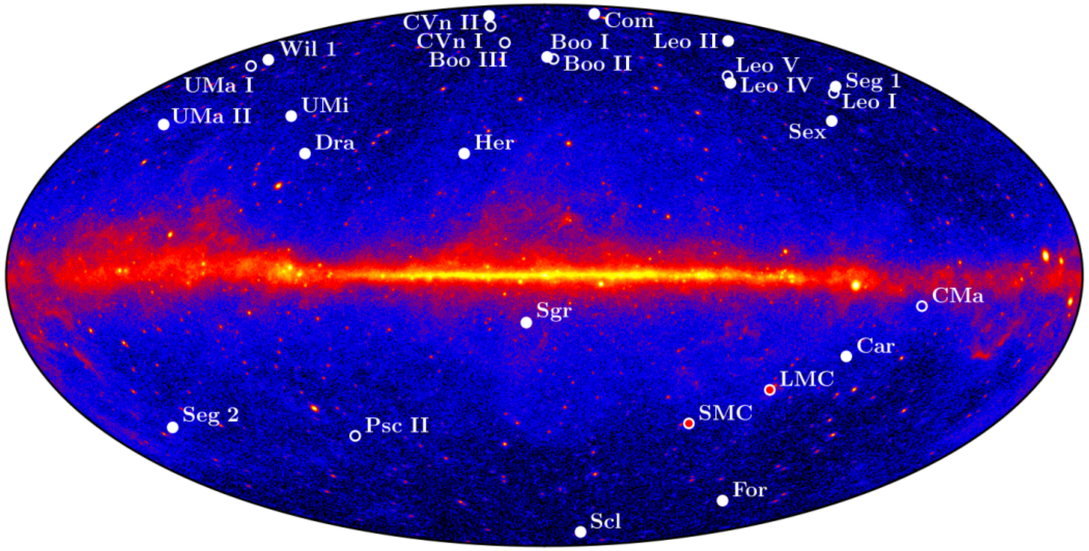
Zhu+ MNRAS'16



$$\mathcal{J} = 2\pi \int_{\theta_{\rm min}}^{\theta_{\rm max}} d\theta \sin(\theta) \int_{\rm l.o.s} \rho^2(r(l,\theta)) dl$$

[See also semi-analytical models: **Ando**'s and **Facchinetti**'s talks]

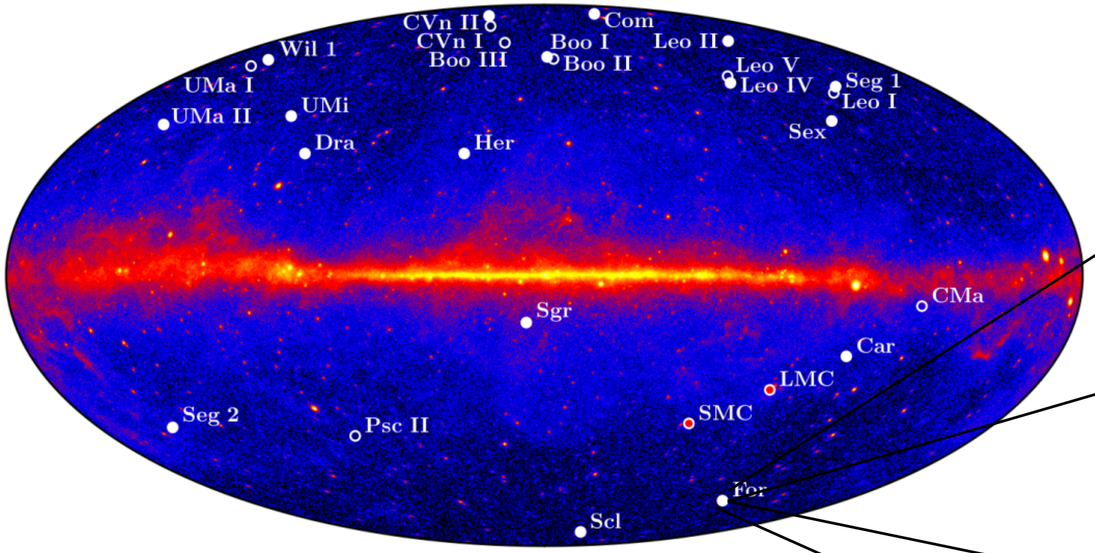
Dark matter search towards dwarf spheroidal galaxies



$$\mathcal{J} \propto \int d\ell \, \rho \left[r(\ell, \psi) \right]^2$$

Fermi-LAT Collaboration, PRL'11

Dark matter search towards dwarf spheroidal galaxies



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Fermi-LAT Collaboration, PRL'11

Credit: ESO/Fornax galaxy

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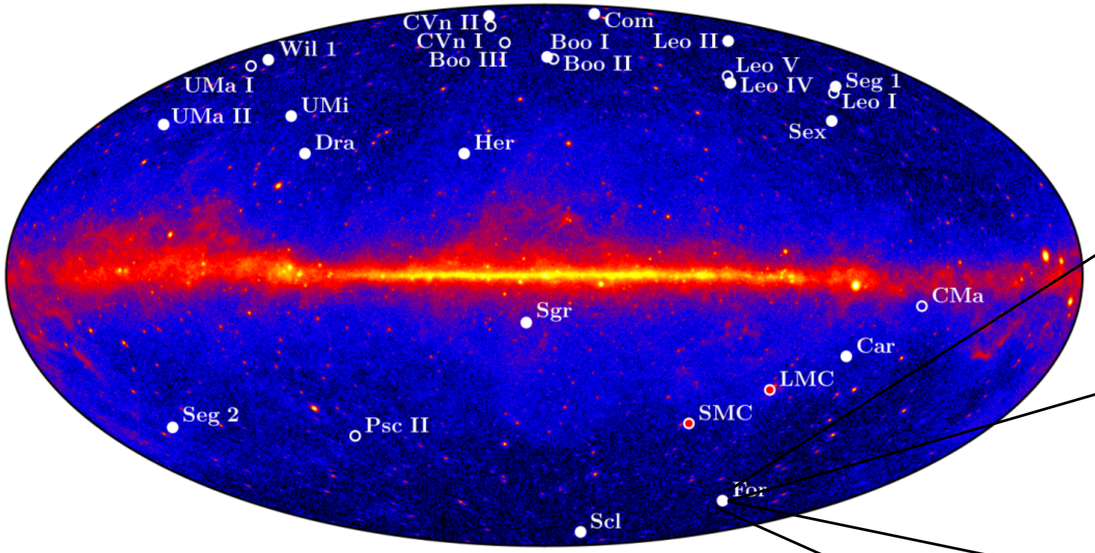

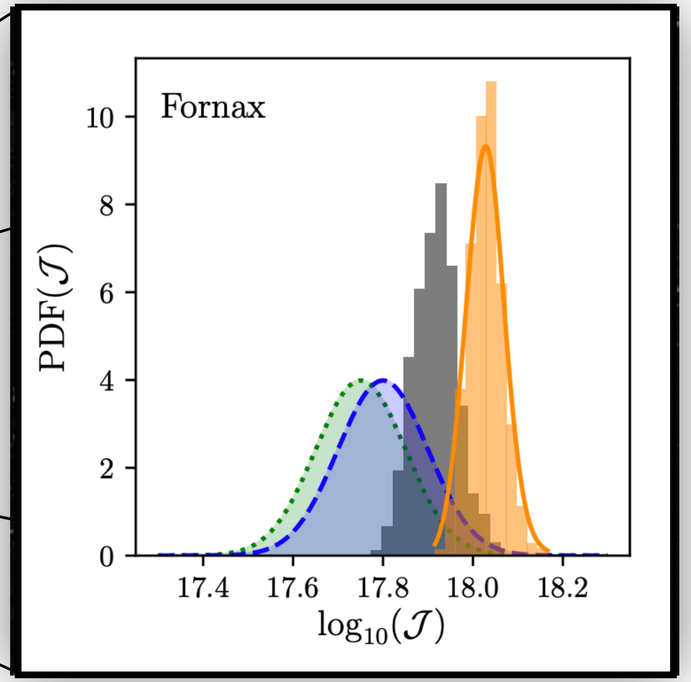

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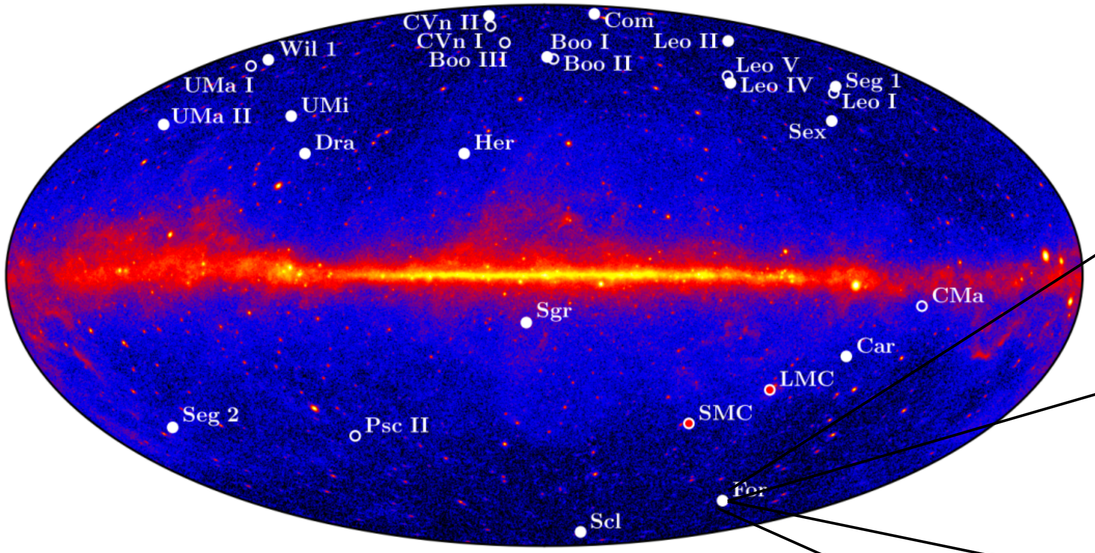
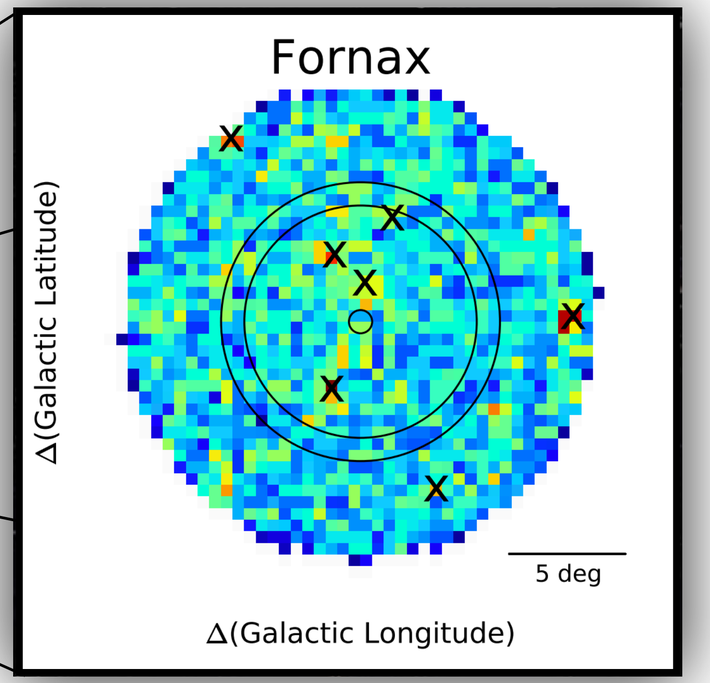
Fermi-LAT Collaboration, PRL'11

GRAVSPHERE
Alvarez, FC+ JCAP'20

Dark matter search towards dwarf spheroidal galaxies



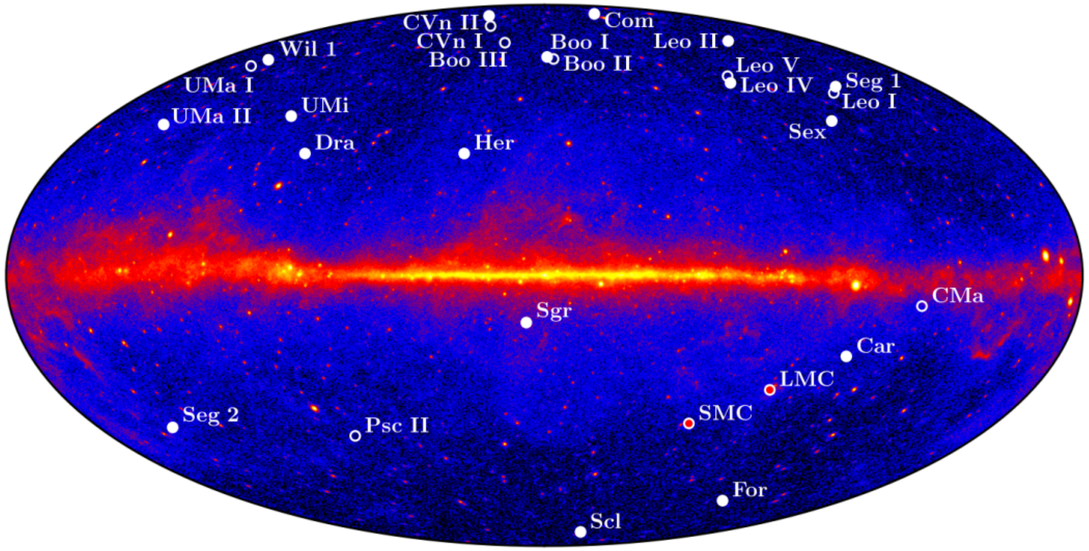


$$\mathcal{J} \propto \int d\ell \, \rho \left[r(\ell, \psi) \right]^2$$

Fermi-LAT Collaboration, PRL'11

Mazziotta+Astrop. Phys.'12

Limits from dwarf spheroidal galaxies

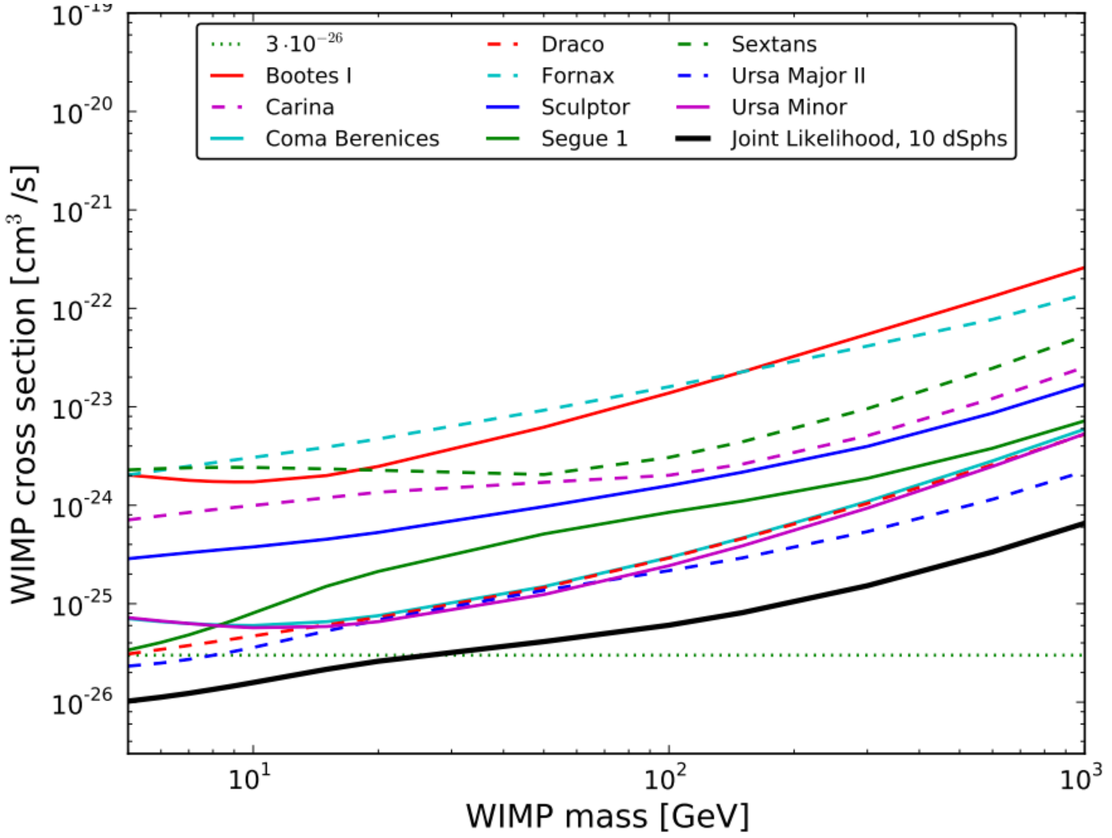


$$L(D|\mathbf{pw},\{\mathbf{p}\}_i) = \prod_i L_i^{\mathrm{LAT}}(D|\mathbf{pw},\mathbf{p}_i) \times \frac{1}{\ln(10)\, J_i \sqrt{2\pi}\sigma_i} e^{-\left[\log_{10}(J_i) - \overline{\log_{10}(J_i)}\right]^2 / 2\sigma_i^2}$$

Analysing dSphs as a group results in sensitivity competitive with other targets => **Stacking technique**.

Fermi-LAT Collaboration, PRL'11

$$\mathcal{J} \propto \int d\ell\, \rho\left[r(\ell,\psi)\right]^2$$



Limits from dwarf spheroidal galaxies

Current status

- Exclude thermal cross section below 100 GeV (16 dSphs stacking, 6 yr of data)

  Albert+ ApJ'17

- Syst unc J-factor determination for ultra-faint dSphs (tri-axiality, contamination, velocity anisotropy)

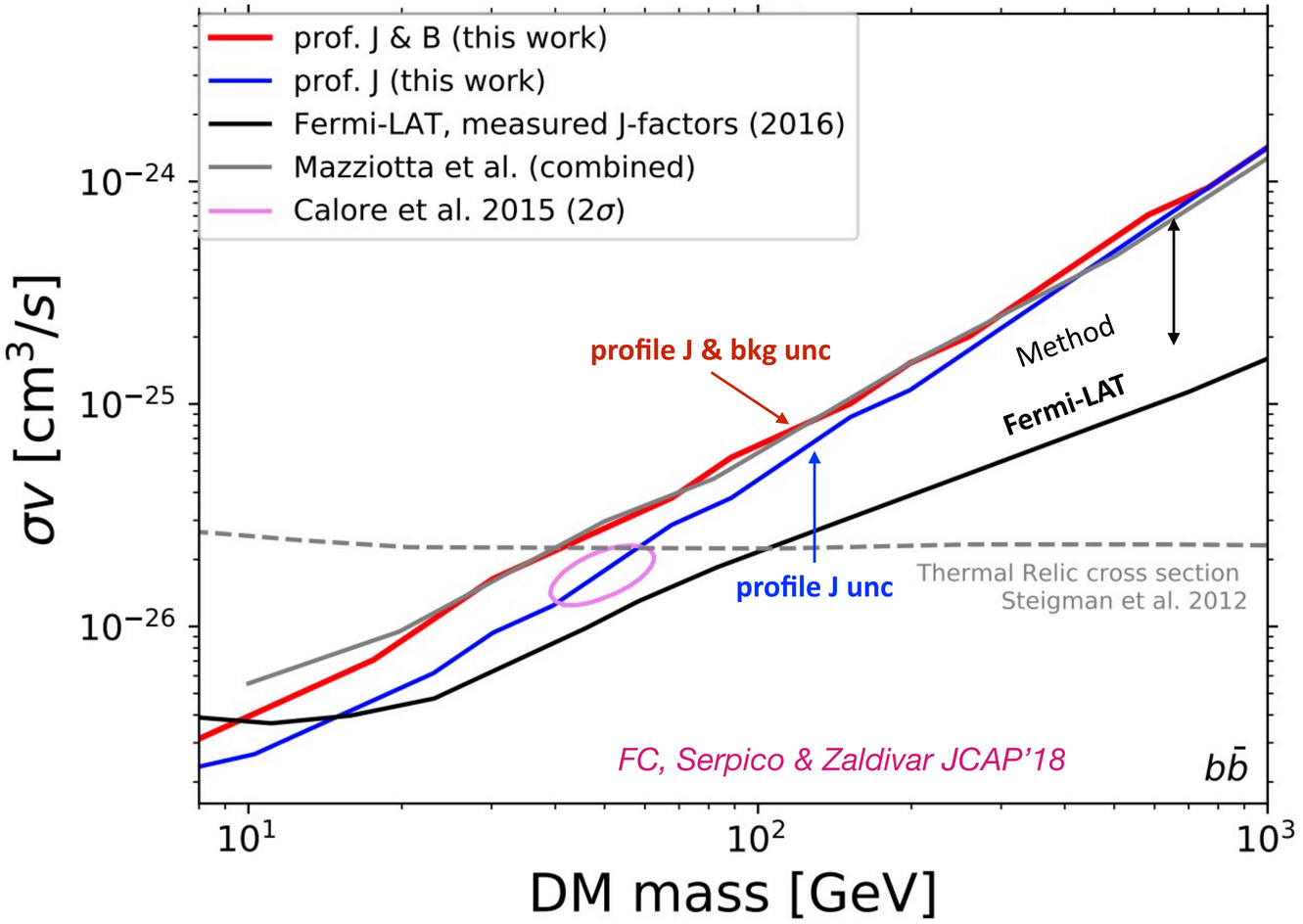
  Ullio&Valli JCAP'16; Hayashi+ MNRAS'16; Klop+ PRD'17; Ando+PRD'20

- Syst unc background mis-modelling are important (3x weaker limits)

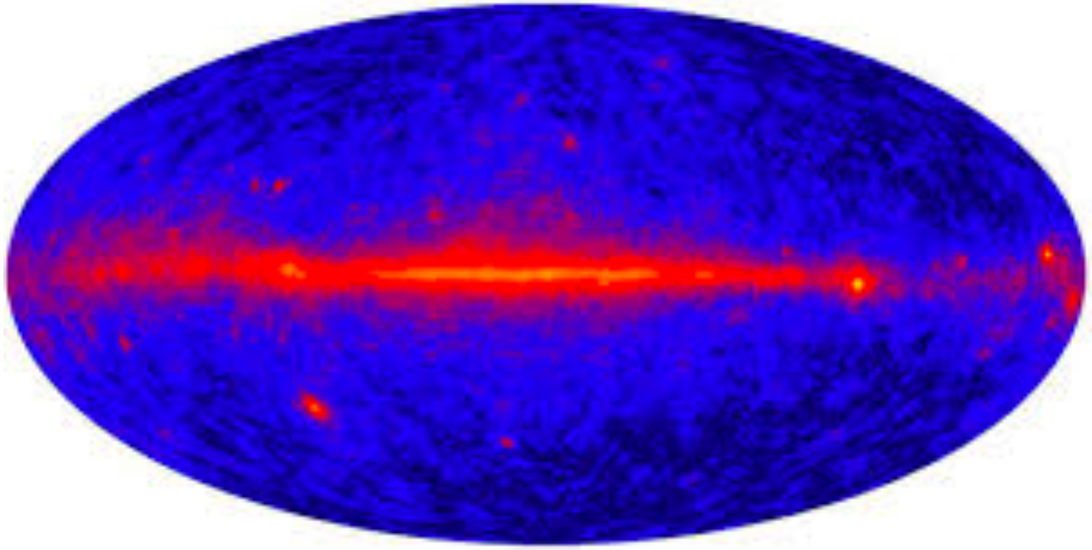
  FC, Serpico & Zaldivar JCAP'18; Alvarez, FC+ JCAP'20

- Improved sensitivity by combining data from ~20 targets taken by 5 instruments (Fermi-LAT, MAGIC, HESS, VERITAS, HAWC)

  Armand ICRC21



Dark matter search towards dark haloes



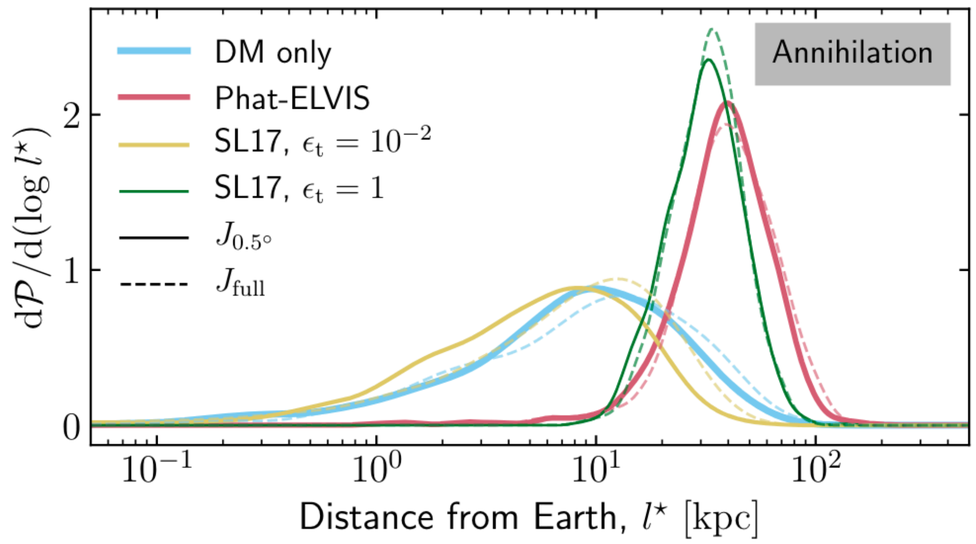
Where do we look for?

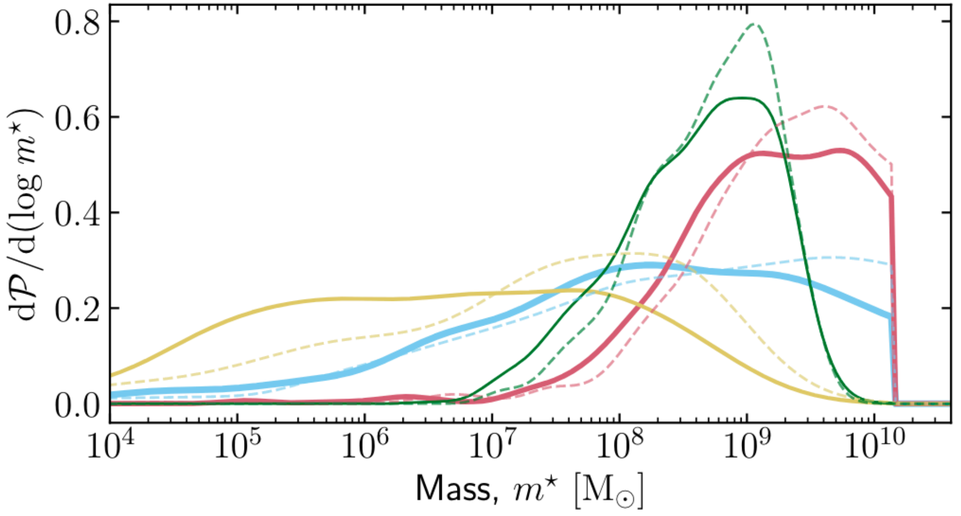
- Sub-halo position is unknown
- We can adopt a probabilist approach to identify most likely regions to host sub-haloes

Hütten+ Galaxies'19; Facchinetti+ 2007.10392

- Looking for individual objects is challenging

Hütten+ Galaxies'19





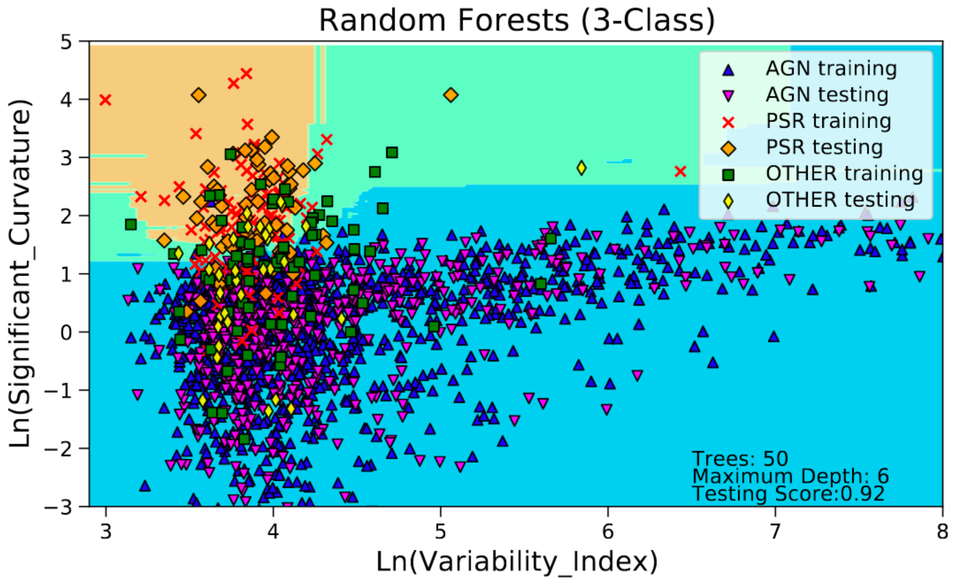
Dark matter sub-halo candidates

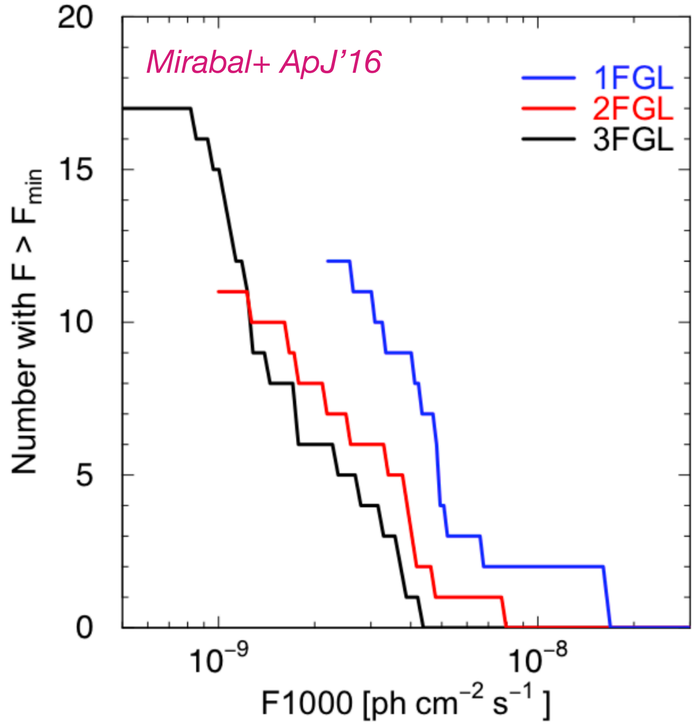
How many among Fermi-LAT point-like sources?

- **Classification** of Fermi-LAT gamma-ray sources based machine learning
- Supervised learning (Random Forest, XGBoost, BDT), Neural networks
- Discriminating variables mainly related spectral properties and variability
- Advanced spectral modelling for sub-halos

Coronado-Blazquez+ JCAP'19

Bhat&Malyshev A&A'22





Mirabal+ ApJ'16; Saz Parkinson+ ApJ'17; Salvetti+ MNRAS'17; Coronado-Blazquez+ JCAP'19a & JCAP'19b; Vibho&Assaf A&C' 22; Bhat&Malyshev A&A'22; Finke+MNRAS'21; Germani+ MNRAS'21

Do we have already detected dark sub-haloes **among** currently unassociated gamma-ray sources?

Bertoni+ JCAP'15; Schoonenberg+ JCAP'16; Hooper&Witte JCAP'17; FC+PRD'17; Coronado-Blazquez+ JCAP'19, Galaxies 20,etc

Limits from dark subhaloes searches

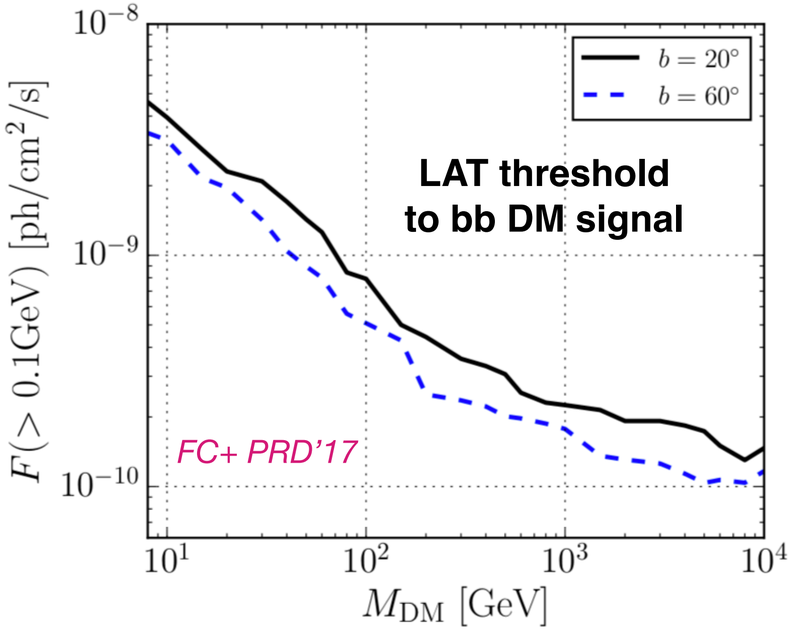
1. **Number of gamma-ray DM subhalo candidates from data**

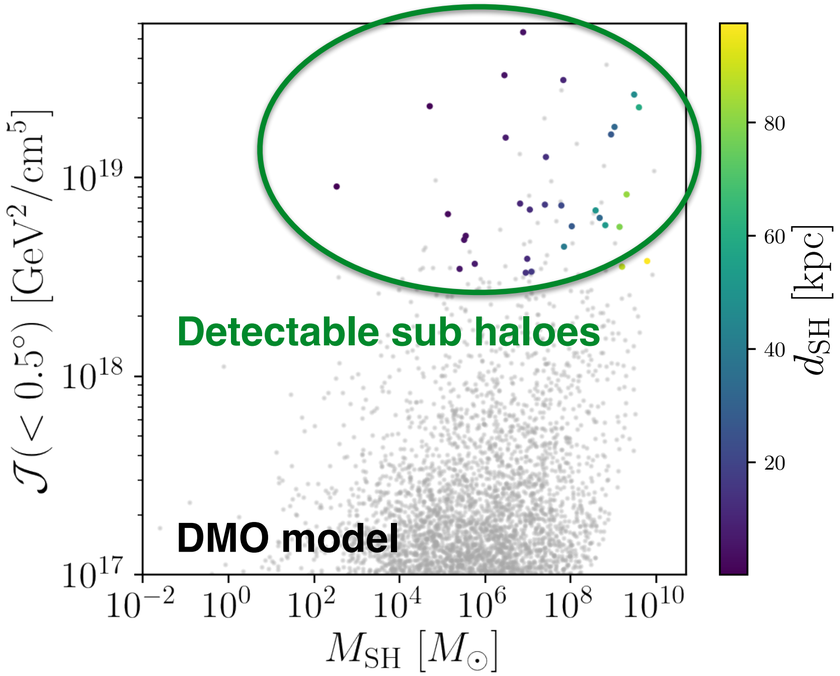
Mirabal+ ApJ'16; Saz Parkinson+ ApJ'17; Salvetti+ MNRAS'17; Coronado-Blazquez+ JCAP'19

2. **Number of detectable gamma-ray DM subhaloes from models**

- Use sub halo models to infer distribution and number of dark objects in the Galaxy
  — relevant effects of baryonic potential
- Convolve with realistic Fermi-LAT detection threshold to DM sub halo signals

Hütten+ Galaxies'19

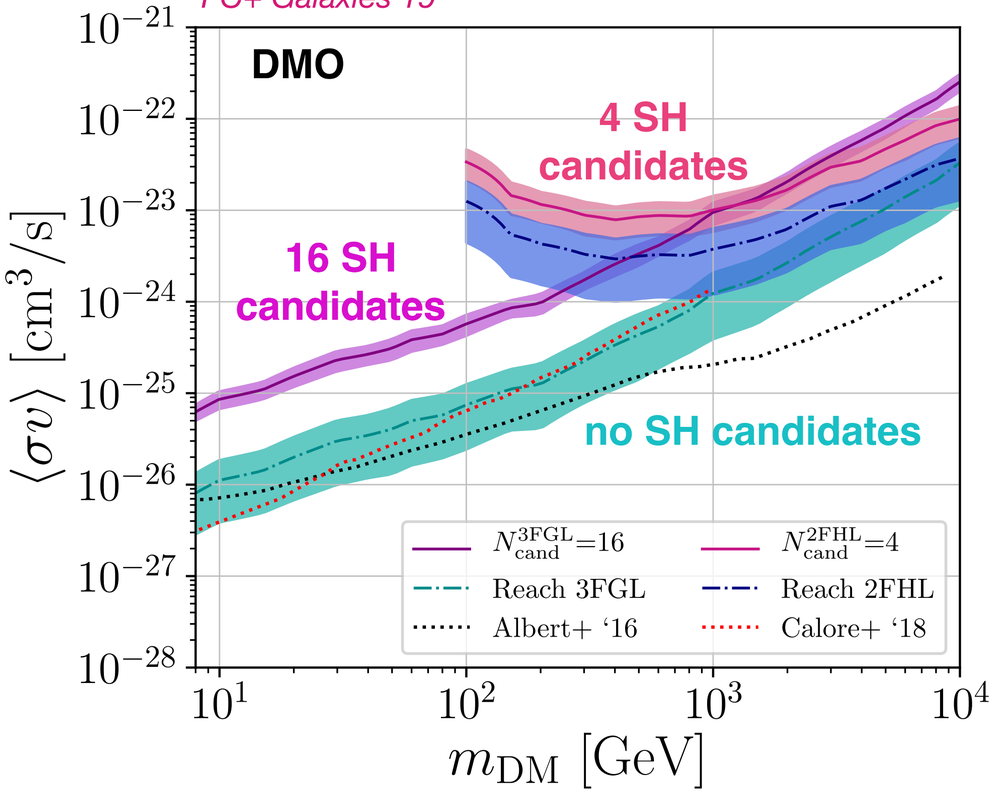




Limits from dark subhaloes searches

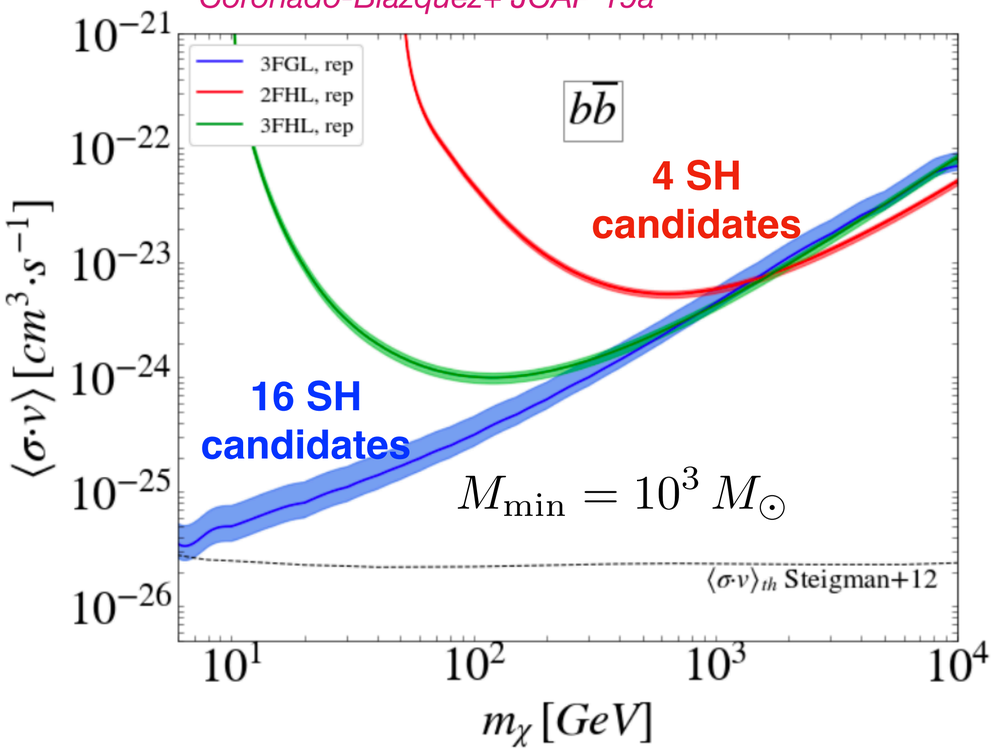
- To match (2) with (1), one has to tune the DM particle physics free-parameters
- Limits on DM annihilation cross-section depends on **sub halo modelling**

FC+ Galaxies'19



Based on Aquarius
Hütten+ Galaxies'19

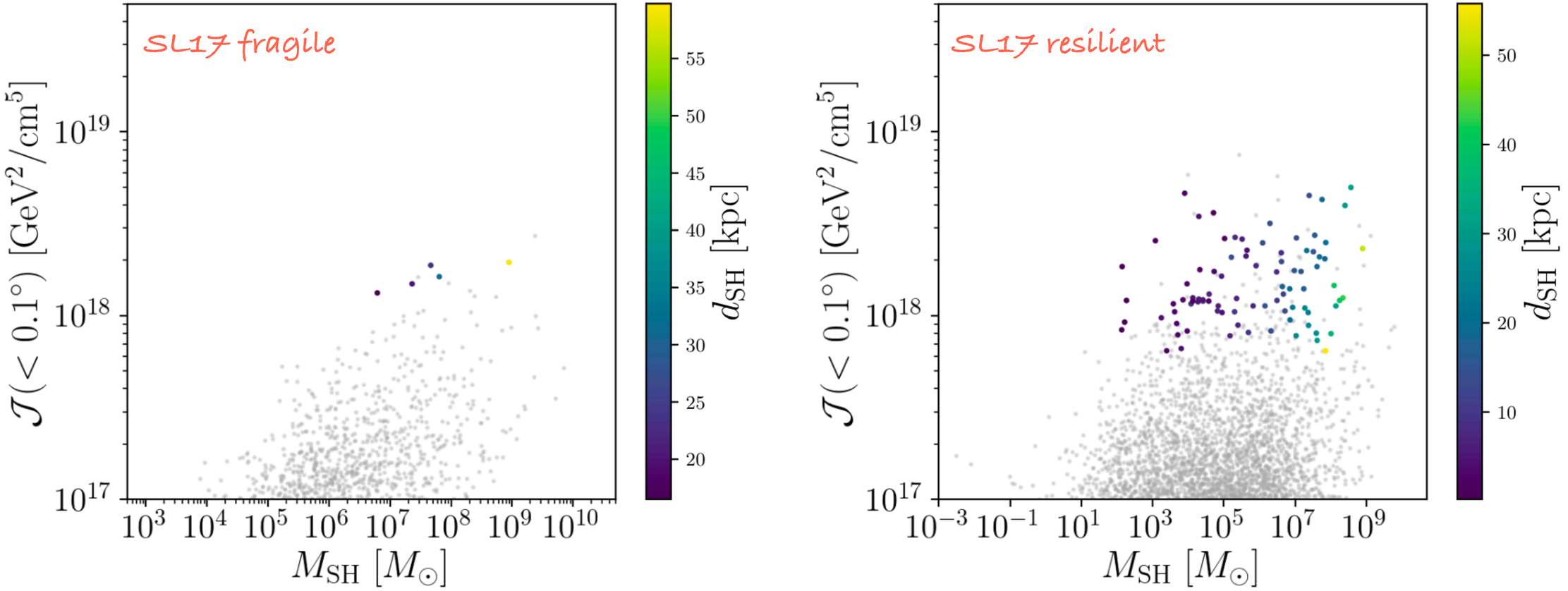
Coronado-Blazquez+ JCAP'19a



Via Lactea II N-body simulation
repopulated with low-mass halos

Limits from dark subhaloes searches

- To match (2) with (1), one has to tune the DM particle physics free-parameters
- Limits on DM annihilation cross-section depends on **sub halo modelling**



DM + Disk Potential: Semi-analytical model *Stref & Lavalle PRD'17* **Facchinetti's talk**

Limits from dark subhaloes searches

- To match (2) with (1), one has to tune the DM particle physics free-parameters
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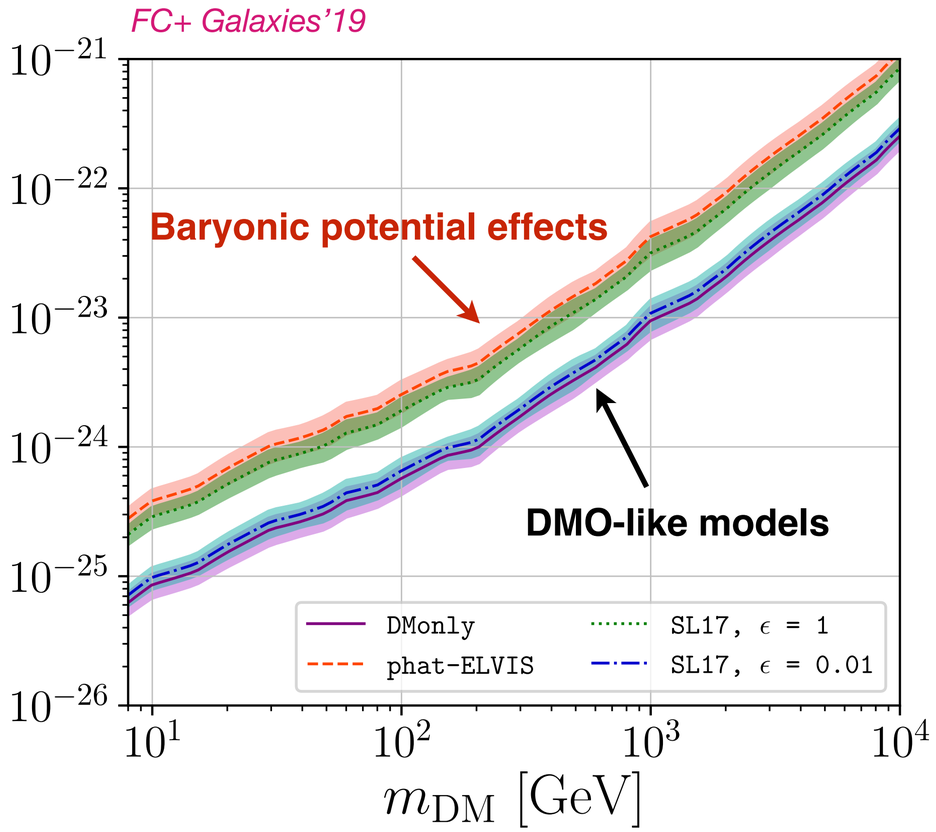
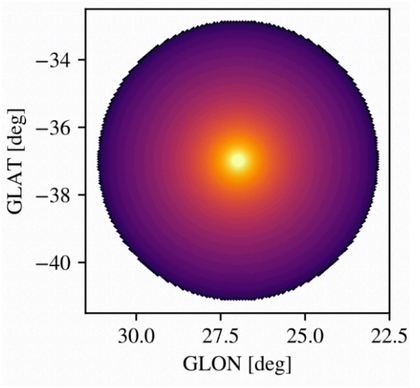


Future:

Follow-up observations crucial to reduce the number of subhalo candidates

See e.g. *Kaur+ ApJ' 19*

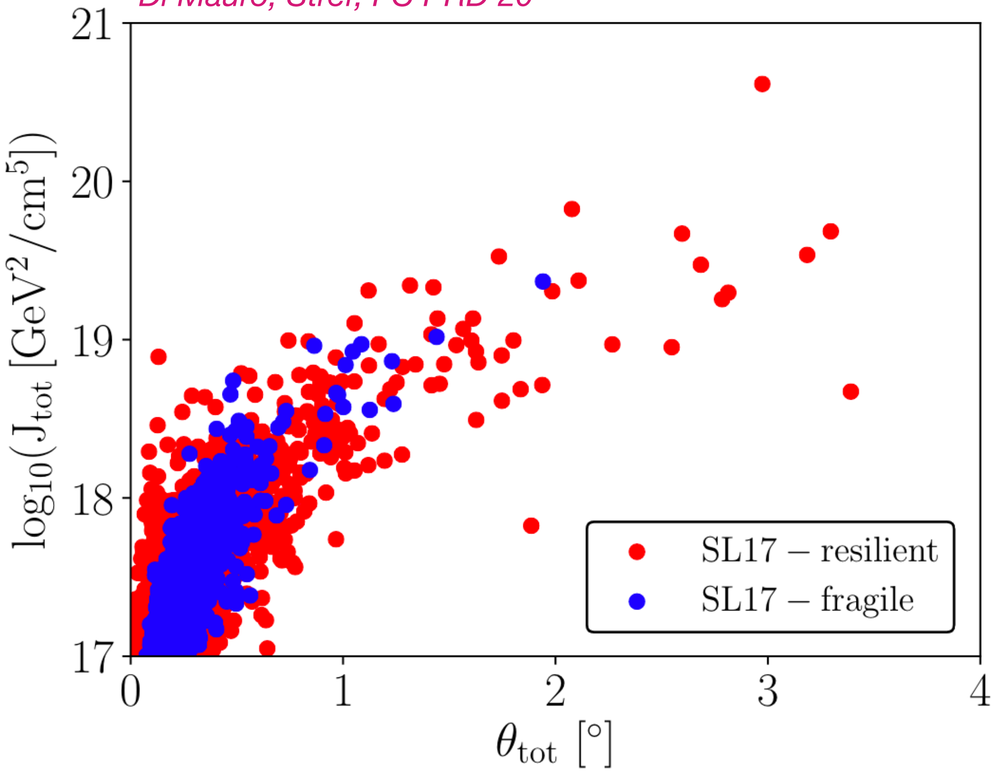
On the relevance of spatial extension

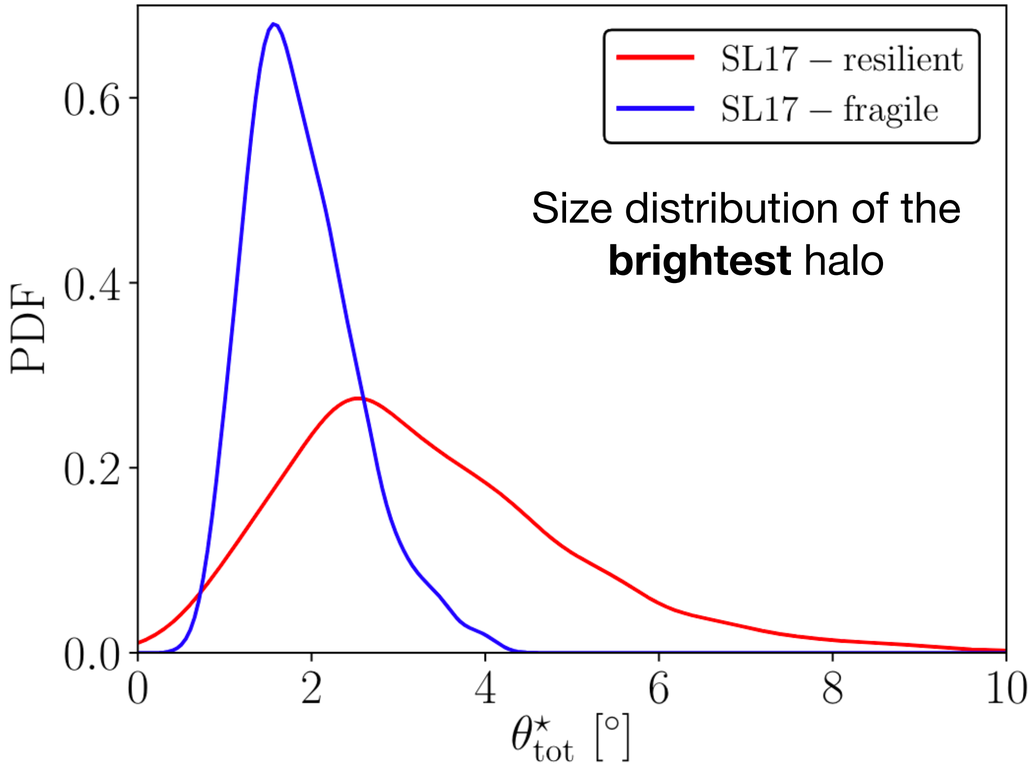


$$\theta_{\rm tot} = \arcsin(R_{\rm vir}/d)$$

Total angular size of an halo in the sky

Di Mauro, Stref, FC PRD'20





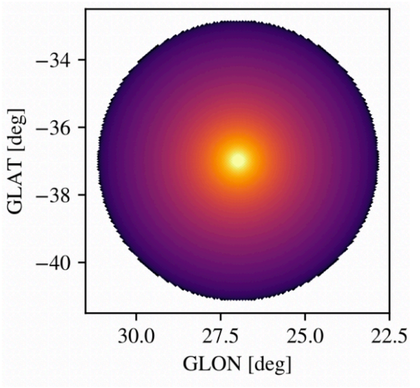
Brightest sub haloes expected to be significantly extended for the LAT vs point-like approximation

This holds true for:
- different DM profiles (NFW or Einasto)
- The 68% J-factor containment angle

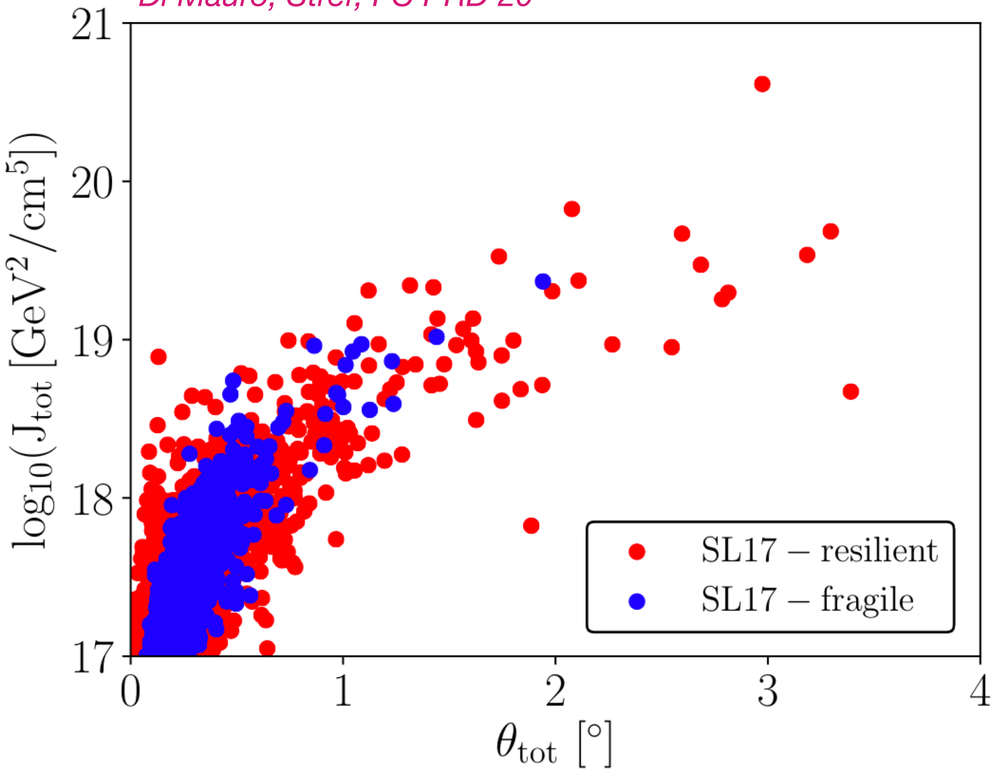
On the relevance of spatial extension

$$\theta_{\rm tot} = \arcsin(R_{\rm vir}/d)$$

Total angular size of an halo in the sky



Di Mauro, Stref, FC PRD'20



Brightest sub haloes expected to be significantly extended for the LAT
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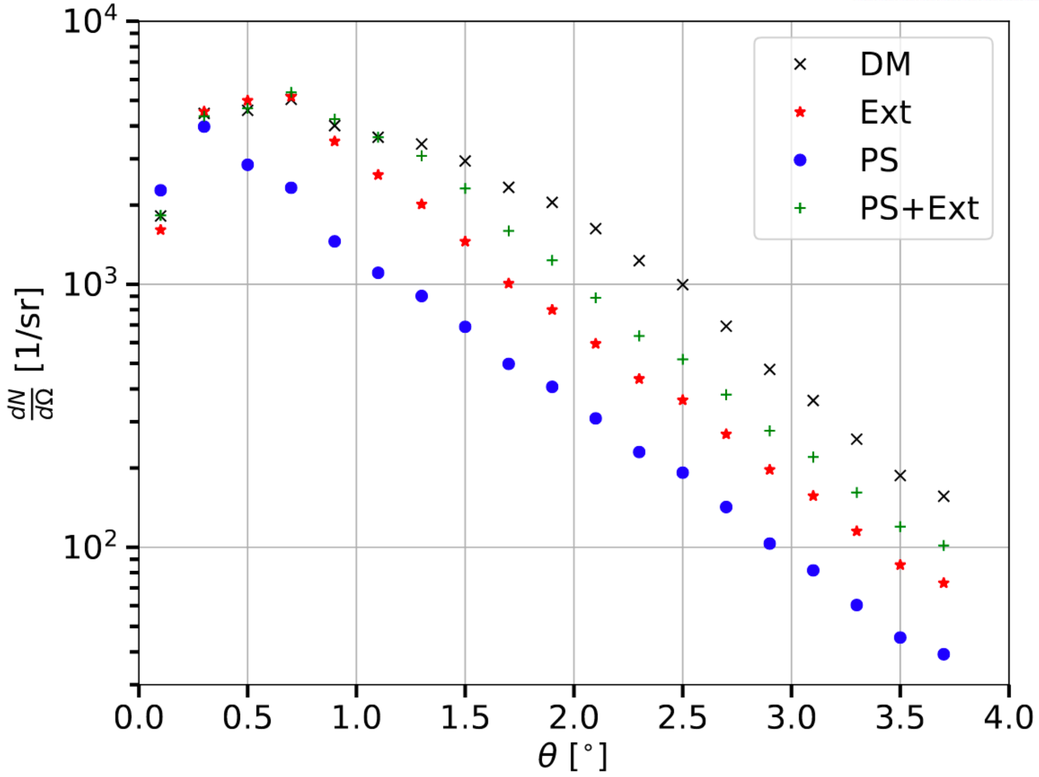
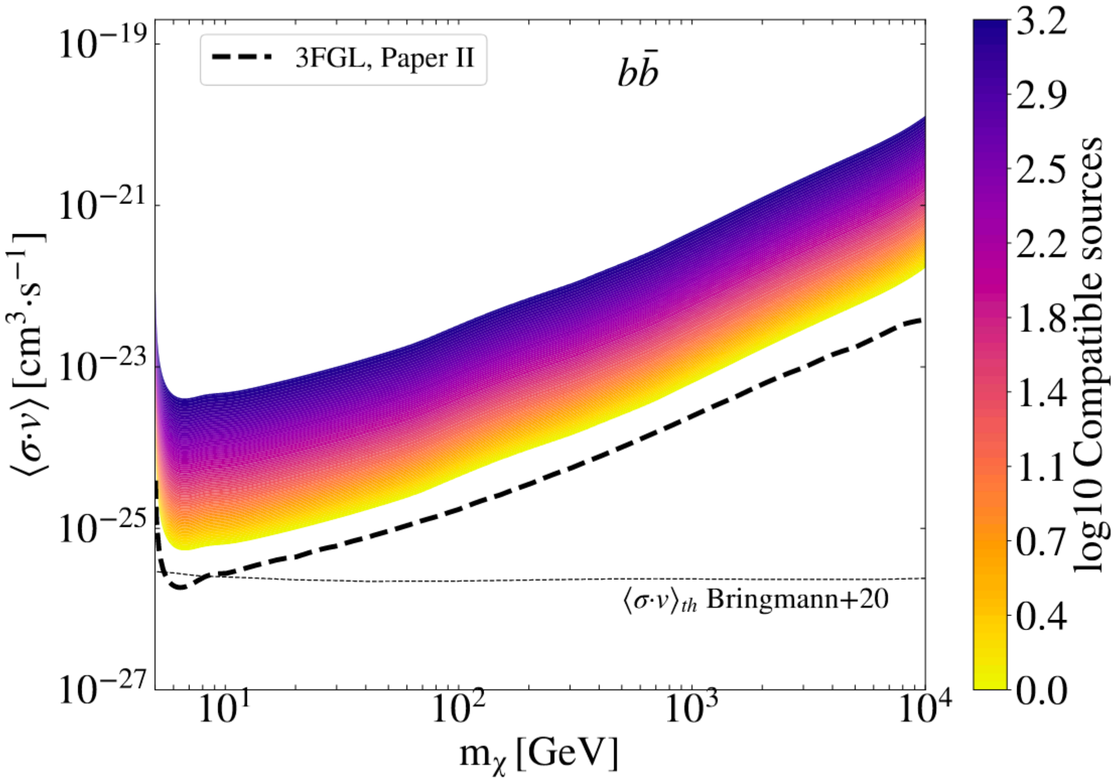


An extended profile better reproduces the surface brightness of the DM annihilation signal

On the relevance of spatial extension

Impact on sub-halo sensitivity?



Coronado-Blazquez+ PRD'22

Impact on limits from dSPhs?

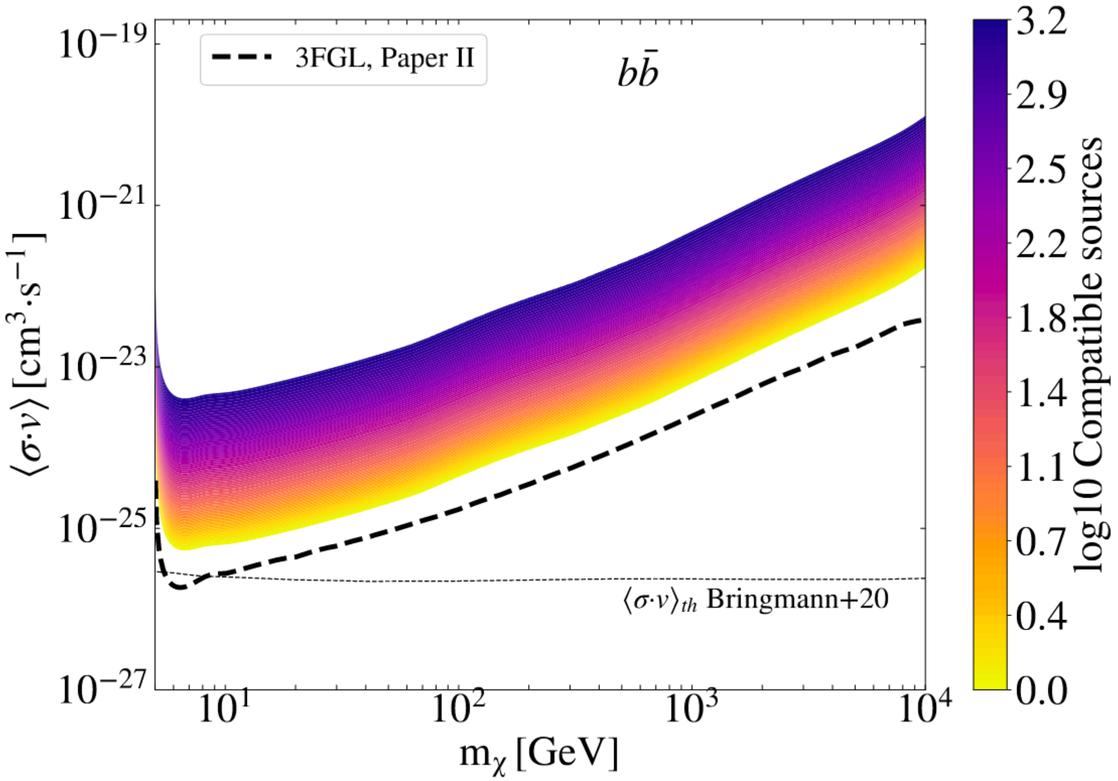
Di Mauro, Stref, FC In prep

Classical	PS $\log_{10}(J_{05})$ [GeV^2/cm^5]	Ext $\log_{10}(J_{\rm tot})$ [GeV^2/cm^5]	Ext θ_{68} [°]
Ursa Minor	18.31 ± 0.08	18.55 ± 0.05	0.59
Draco	18.64 ± 0.04	18.73 ± 0.03	0.35
Sculptor	18.39 ± 0.05	18.67 ± 0.09	0.65
Sextans	18.07 ± 0.08	18.15 ± 0.06	0.35
Leo I	17.50 ± 0.06	17.52 ± 0.06	0.12
Leo II	17.51 ± 0.05	17.51 ± 0.05	0.07
Carina	17.92 ± 0.07	18.01 ± 0.11	0.36
Fornax	17.76 ± 0.05	18.00 ± 0.07	0.59

- J-factor increases by a few %
- Significant extension (0.5 deg) for a few objects

On the relevance of spatial extension

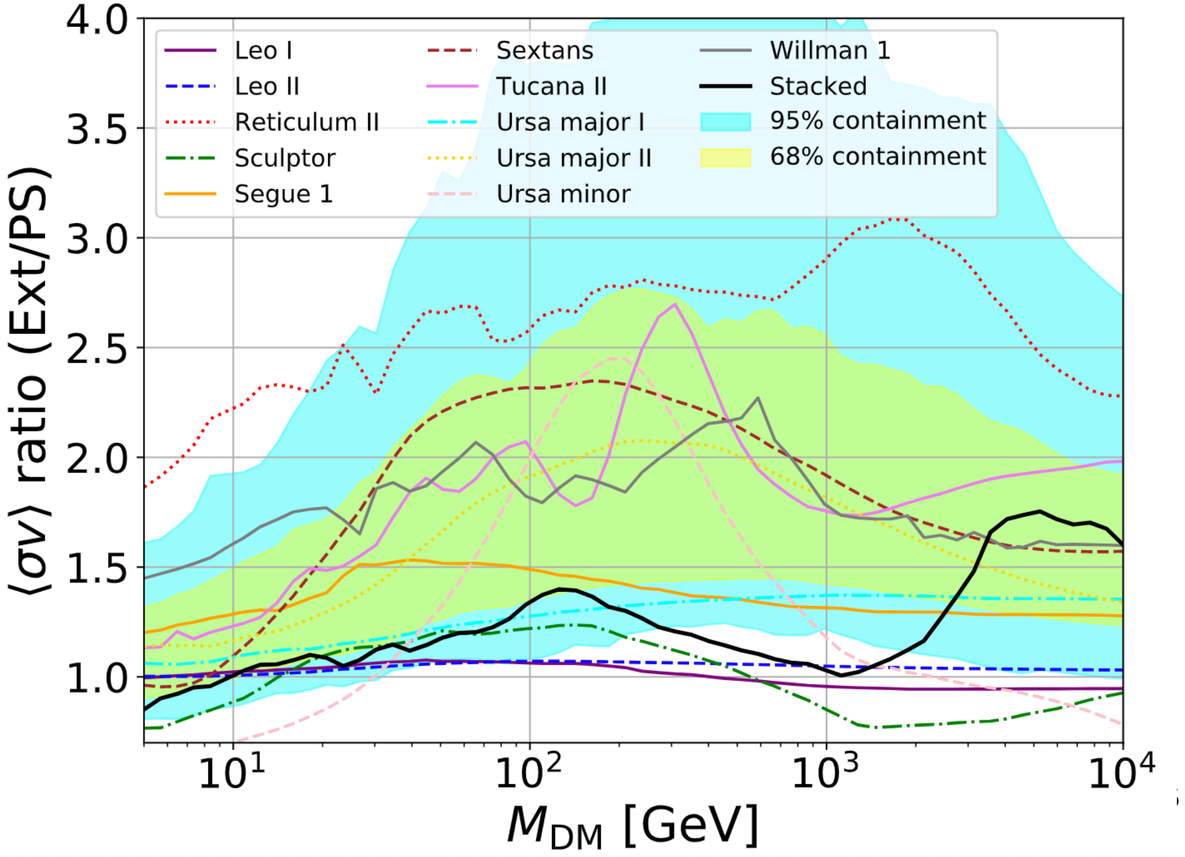
Impact on sub-halo sensitivity?



Coronado-Blazquez+ PRD'22

Impact on limits from dSPhs?

Di Mauro, Stref, FC In prep

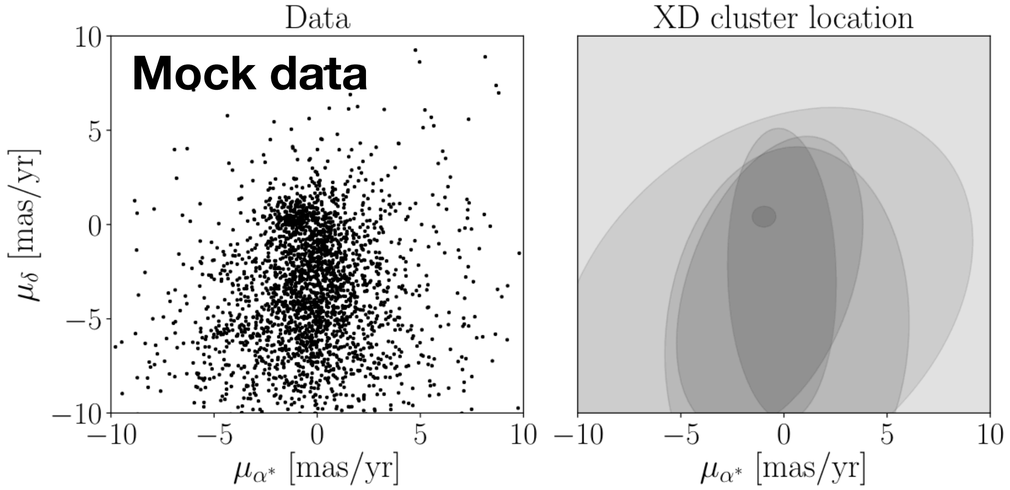


Joint effect of: J-factor normalisation and uncertainties, and size

Searches for faint optical counterparts

Look for *kinematical signature* of a stellar counterpart in the fields of DM sub-halo candidates with Gaia

Ciuca, FC+ MNRAS'18

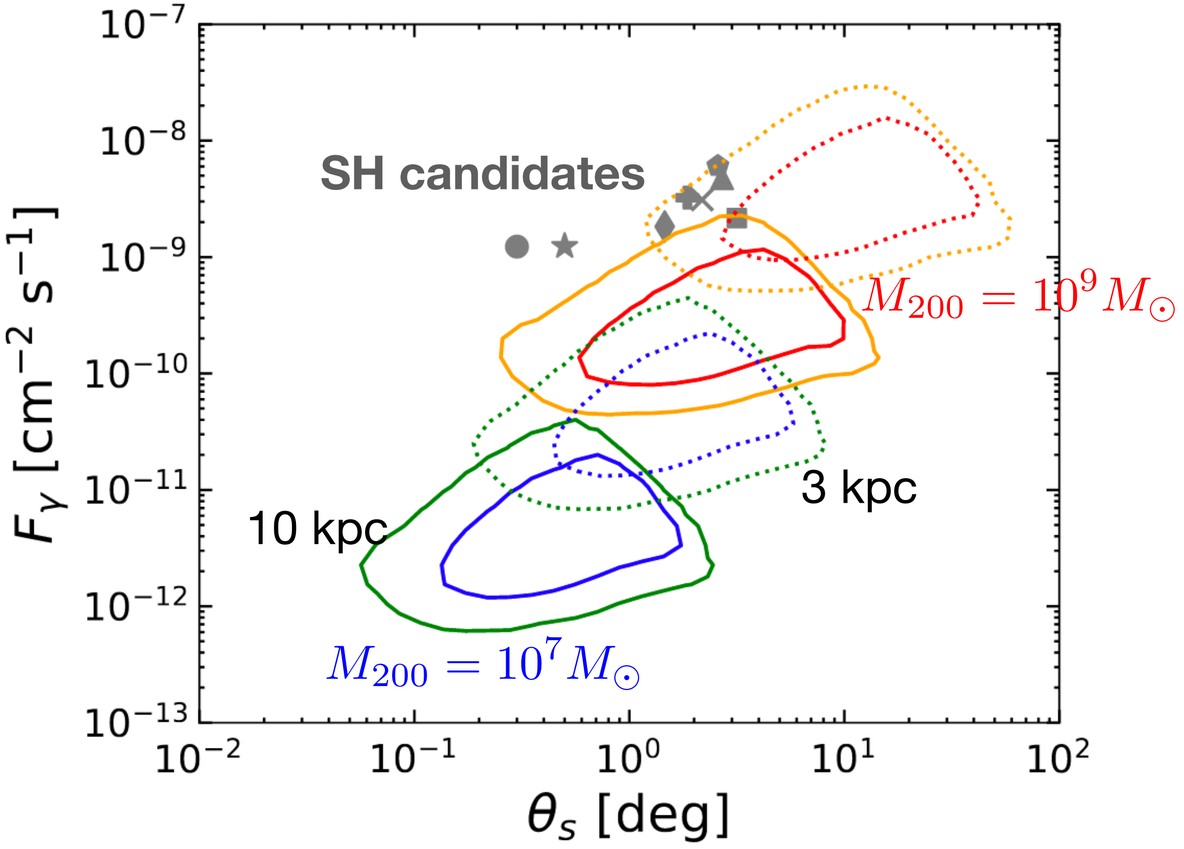


=> **No detection** within 20 kpc
=> conservative limit on the stellar mass of $M_* < 10^4 M_\odot$
=> pre-infall halo mass? $M_{200} < 10^9 M_\odot$
=> low-mass halo or tidally stripped high-mass one?

See also *Coronado-Blazquez+ JCAP'19b*

Effects of tidal mass loss in the MW

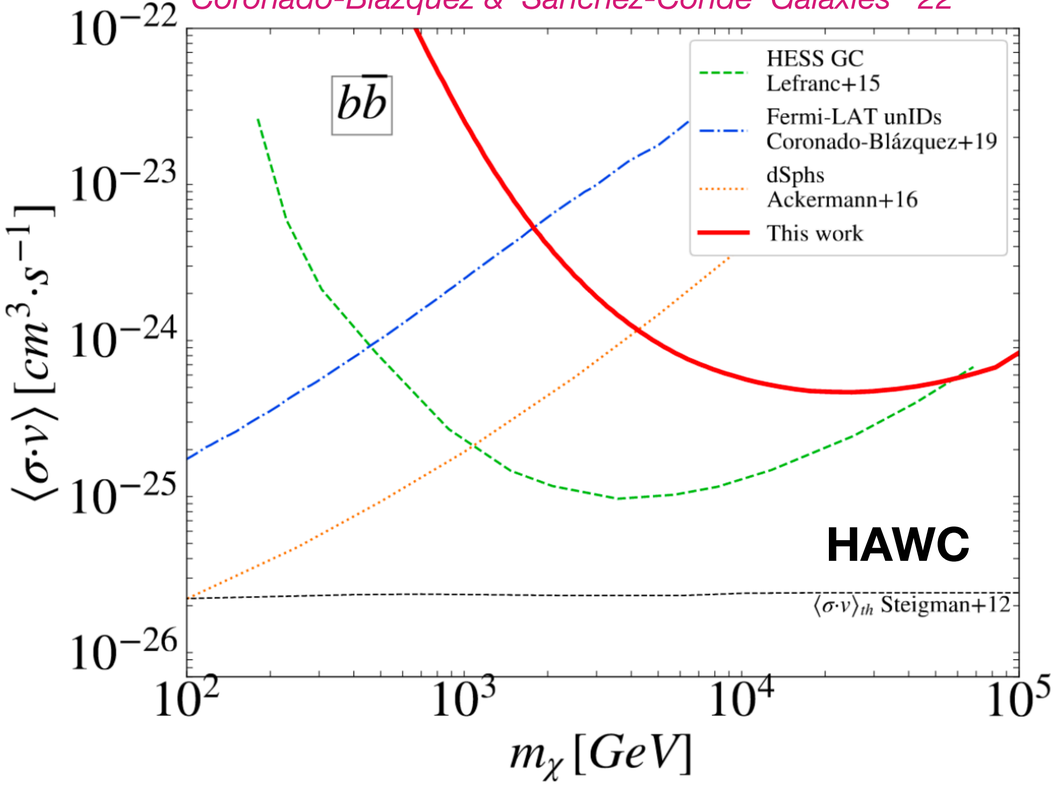
Ando's talk



- Cross-section already saturating current constraints
- Unlikely scenario of very massive, nearby halo

Searches for sub-haloes at TeV energies

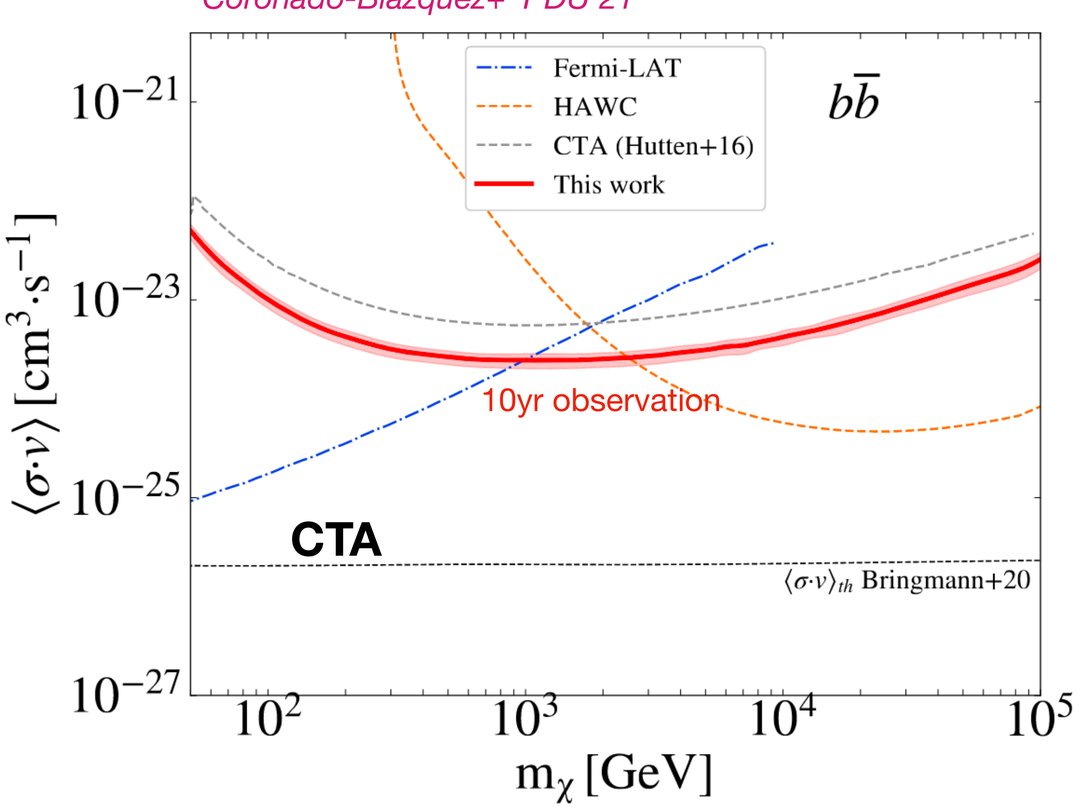
Coronado-Blazquez & Sanchez-Conde Galaxies ' 22



UnID sources in HAWC observations at high latitudes
One possible, extended, sub-halo candidate

Abdalla (HESS) ApJ'21; Makyshev+ 2109.01498

Coronado-Blazquez+ PDU'21

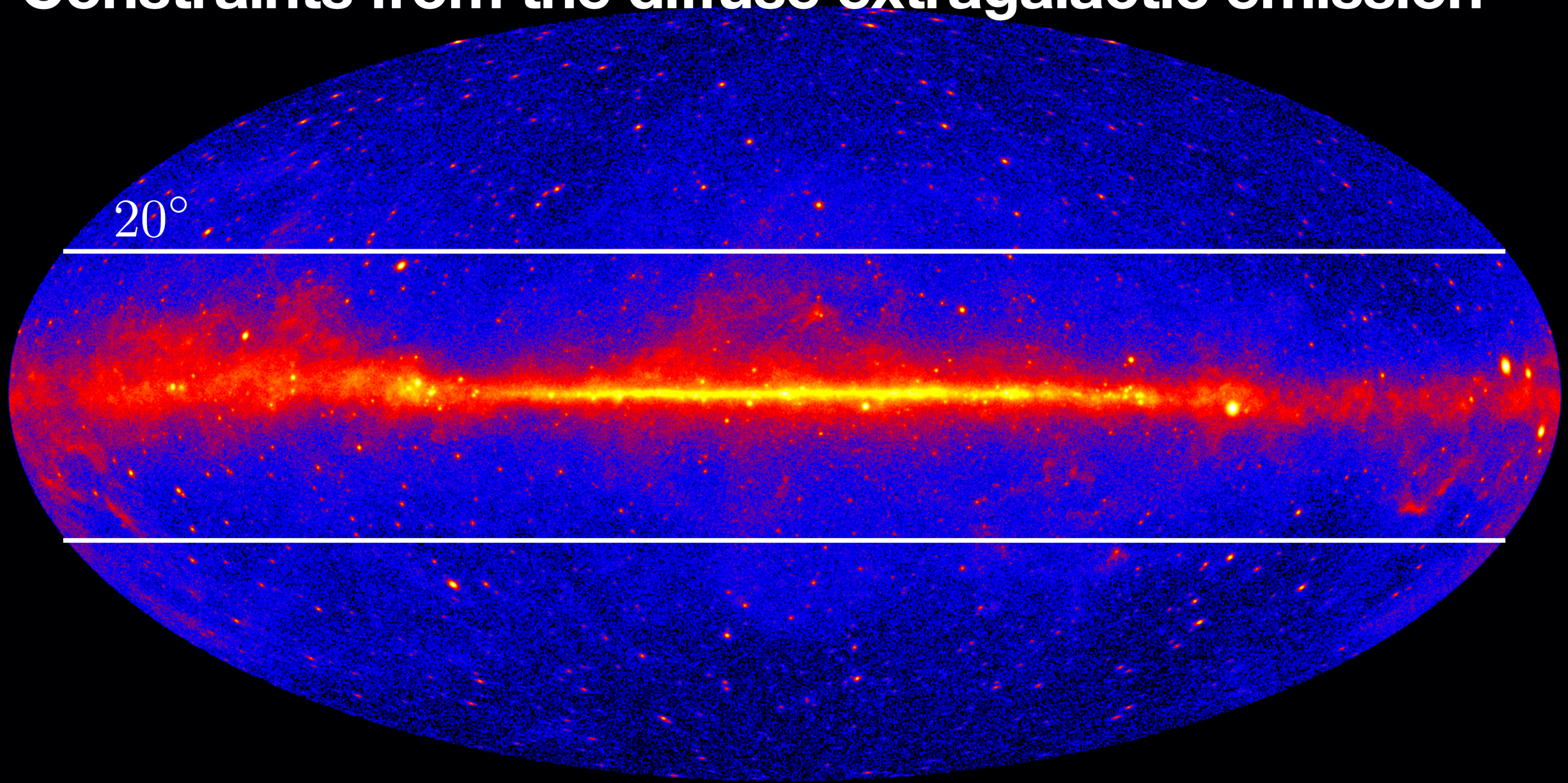


CTA detectability of **individual** sub haloes using the different planned pointing strategies

See also *Hütten+ JCAP'16*

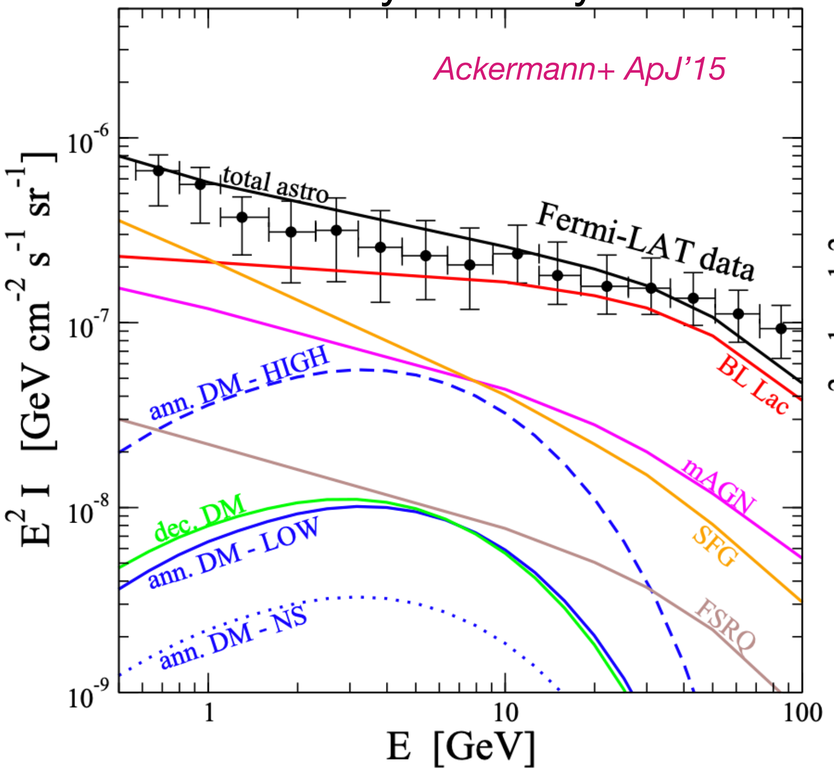
v-dependent effects are relevant at the TeV scale *Facchinetti+ 2203.16491, Lacroix+ 2203.16440*

Constraints from the diffuse extragalactic emission

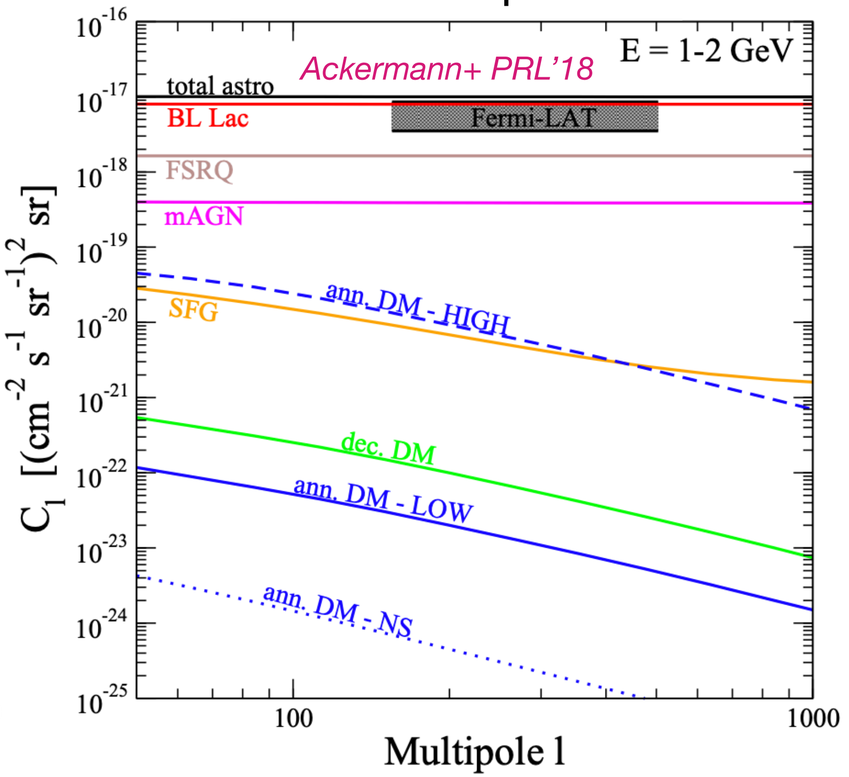


Constraints from the diffuse extragalactic background

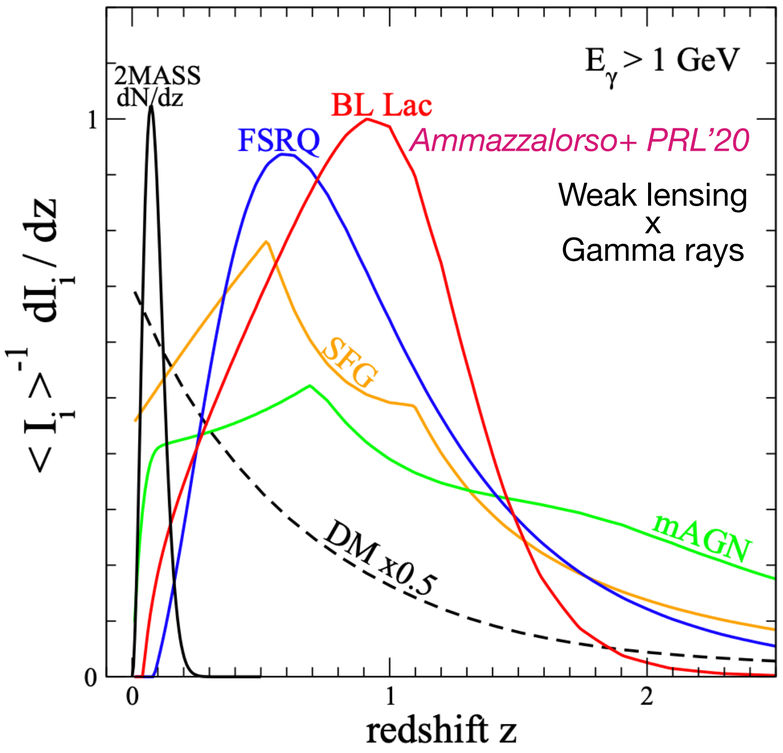
All-sky intensity



Anisotropies



X-correlation



Exploit spatial (redshift) features of DM signals to set constraints

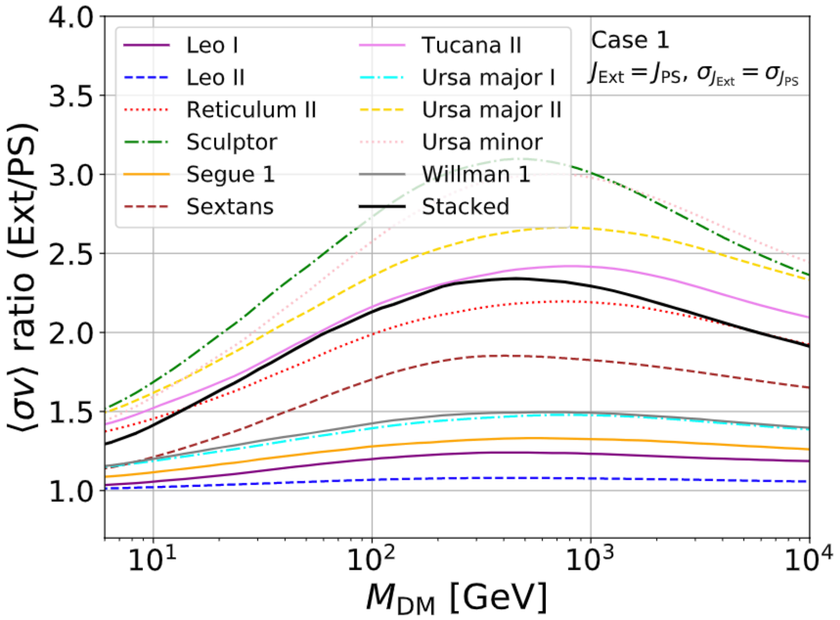
Bringmann+ PRD'14, Chang+ PRD'18, Siegal-Gaskins JCAP'08, FC+ MNRAS'14; Zechlin+ PRD'18; Regis+ PRL'15, Cuoco+ ApJS'15, Camera+ JCAP'15

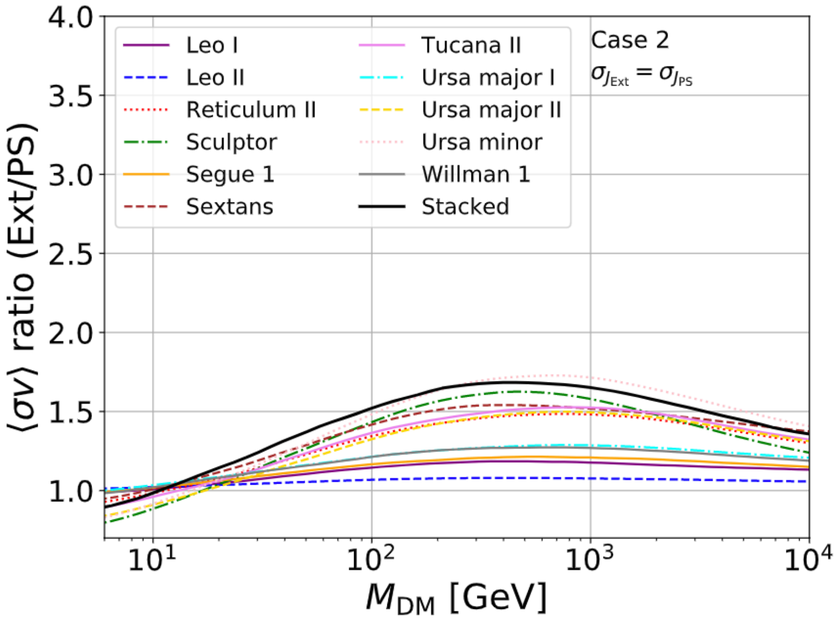
Conclusions & Outlook

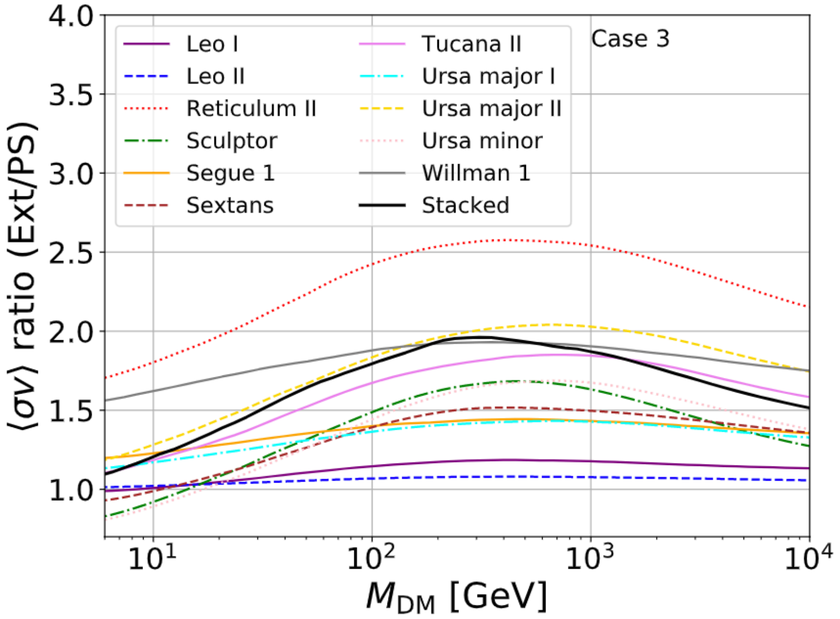
- ✓ **Gamma-ray particle astrophysics** has been flourishing in the last decade setting some of the strong constraint of dark matter particles at the weak scale
- ✓ **Sub-haloes** can be searches for among yet **unassociated gamma-ray sources**
- ✓ The search for sub-haloes is unavoidably affected by **large uncertainties** pertaining to the sub-halo model
- ✓ Nonetheless they offer a probably unique way to claim the **detection of a signal**
- ✓ **MM/MW follow-up searches** of unassociated gamma-ray sources are crucial to test the dark matter hypothesis

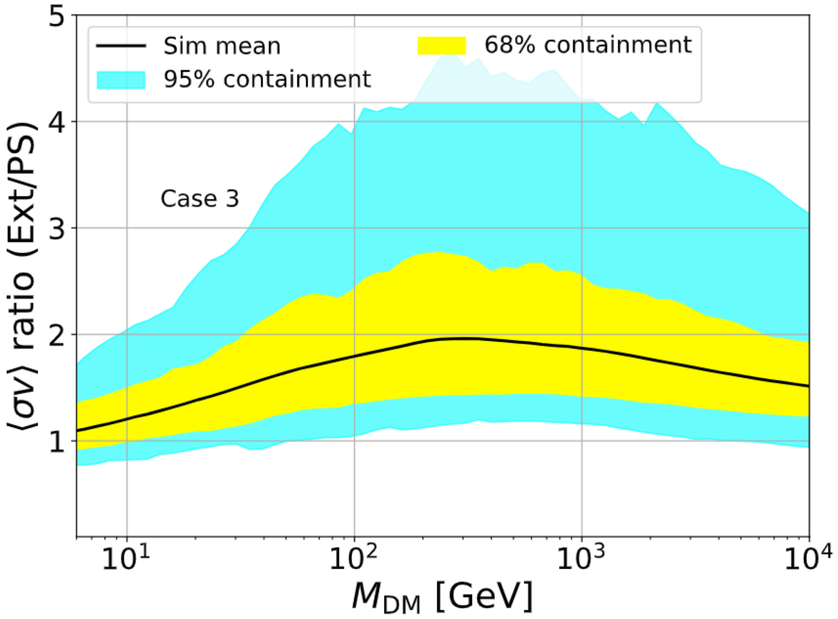
Thank you for the attention

On the relevance of spatial extension









Simulations results:

- Effect of extension
- Effect of J-factor normalisation
- Effect of J-factor uncertainty

Di Mauro, Stref, FC In prep