Astroparticle Physics

A syllabus for using astroparticle observations to delve deeper in our universe

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Particle Astrophysics

Plan of the lectures

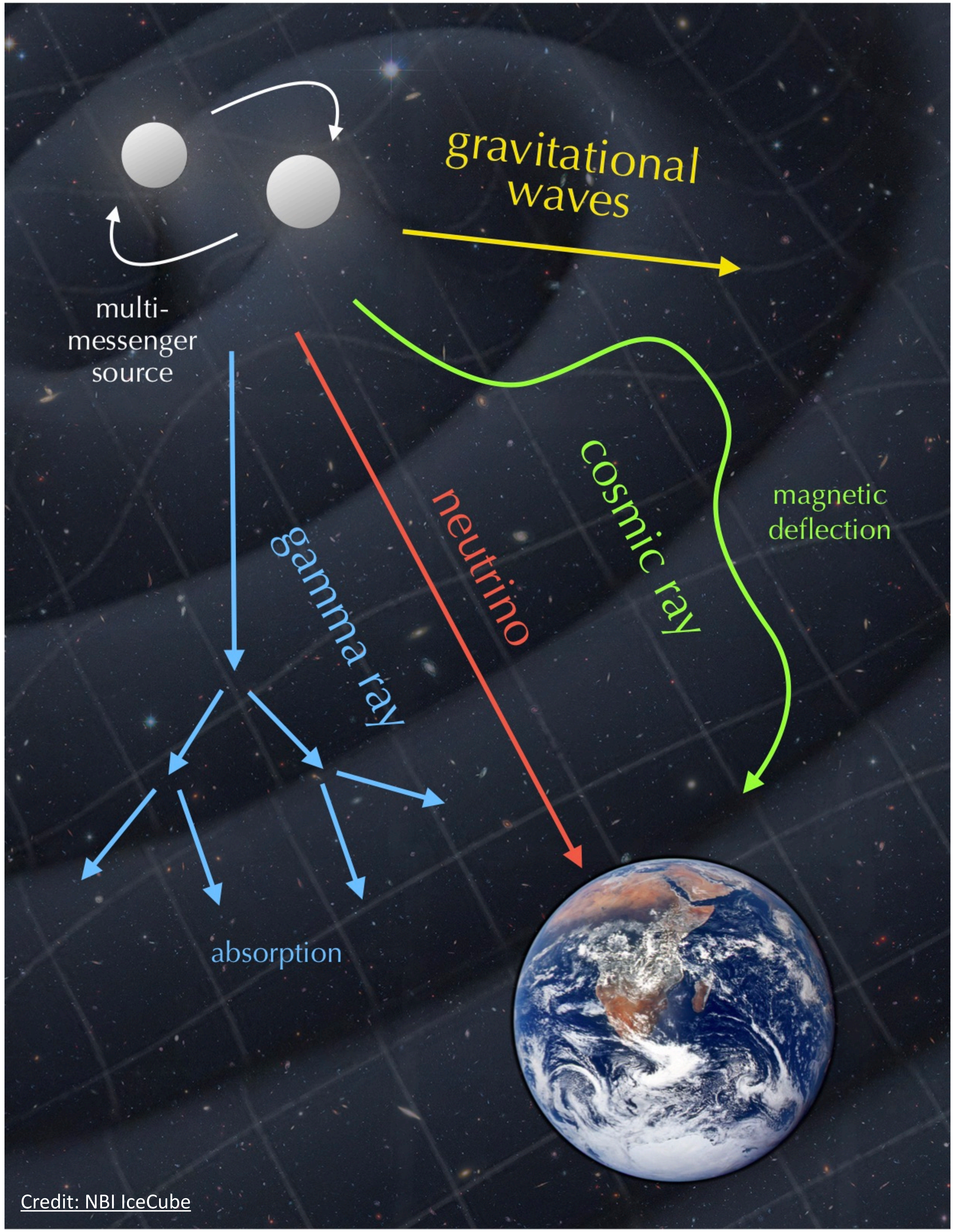
Yesterday

- Particles from the sky: Detection techniques and observations
- **Charged cosmic rays**: production and origin
- **Gamma rays** and **neutrinos**

Today

- The multi-messenger connection
- Probing exotic physics with astroparticle observations

Complemented by *Cosmology* (D. Alonso), *Dark Matter* (A. Green), *BSM Physics* (V. Sanz) and *Gravitational Waves* (C. Sopuerta) lectures



Searching for exotic phenomena with astroparticle

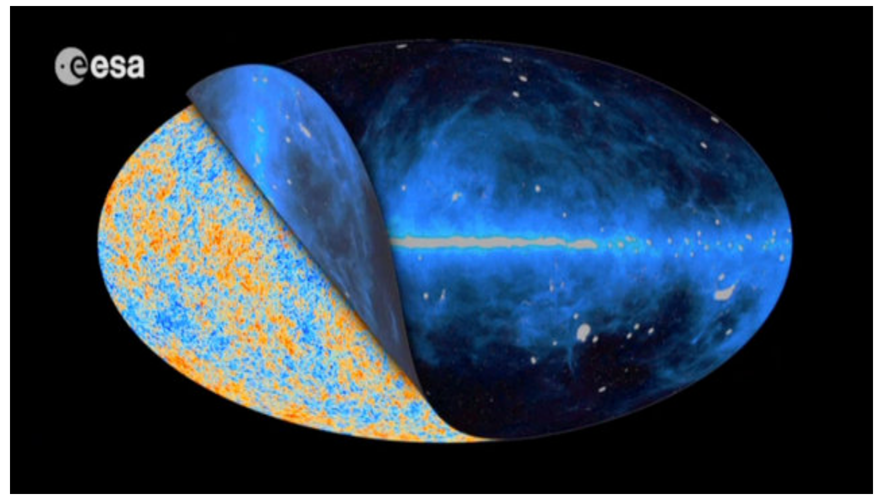
Why do we want to look for new physics?

1. Physics BSM is strongly motivated (Veronica Sanz lecture)
2. It already happened in the past to find some surprise in astro data which led to major discoveries
3. Anomalies in astroparticle observables do exist and BSM physics may be the answer
4. If there, you expect astrophysical signatures of BSM physics. If you don’t find them you can set constraints onto the relevant parameter space

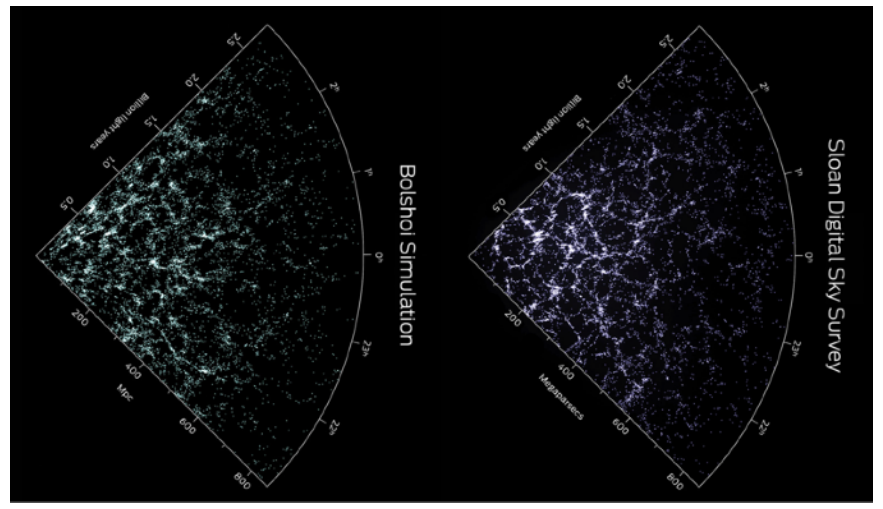
Dark matter in the sky

Dark matter gravitational evidence

Cosmic microwave background



Large Scale Structures



Galaxy clusters

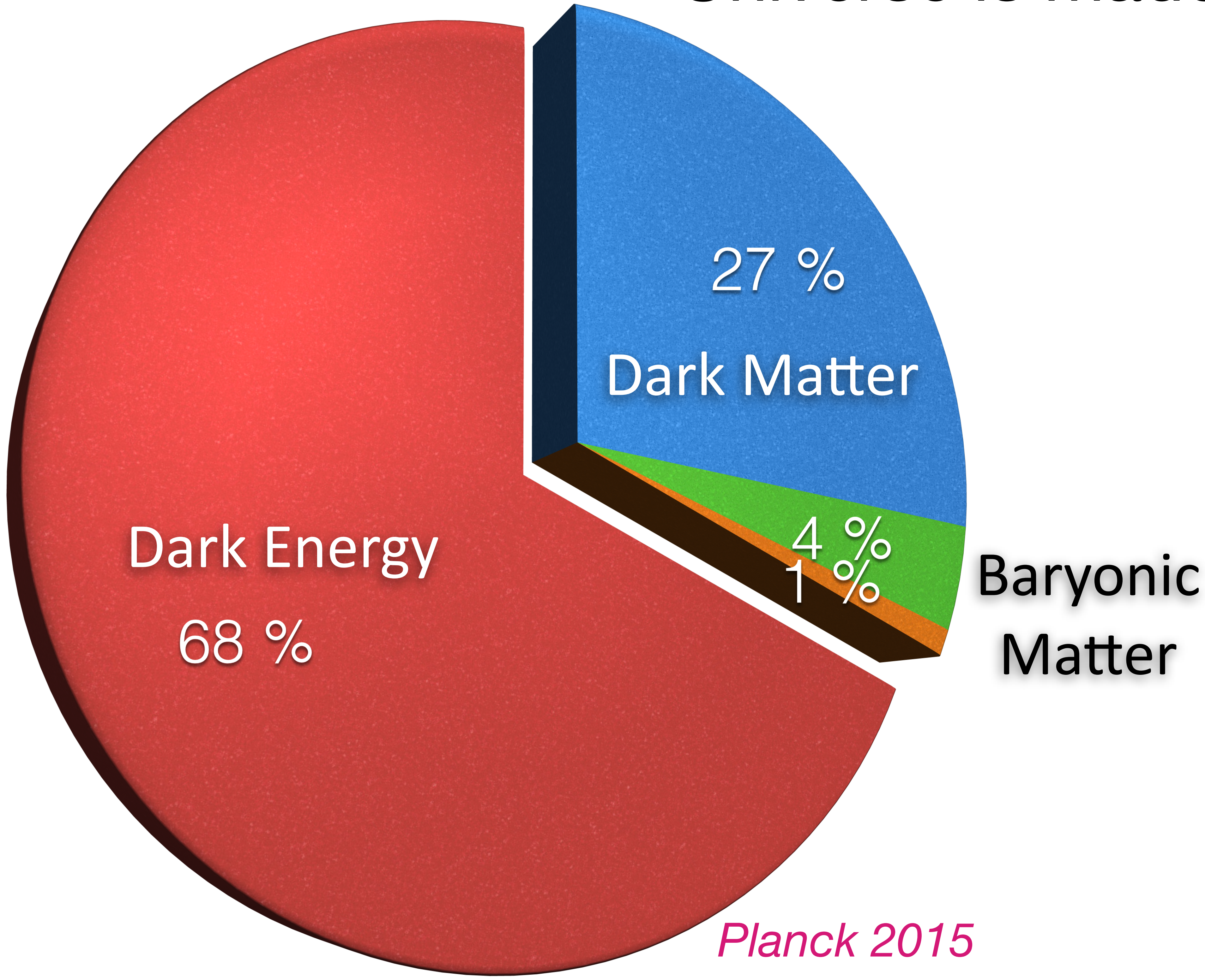
Galaxies

~Gpc

~Mpc

~kpc (10^{19} m)

We do not know what most of the Universe is made of!



We add one (or more?) extra-ingredient, which interacts only gravitationally

The dark matter landscape

Vast parameter space in mass and interaction strength

The dark matter landscape

$10^{-19}\,\mathrm{eV}$ $\mu\mathrm{eV}$ $0.1\,\mathrm{eV}$ keV MeV GeV $10^2\,\mathrm{TeV}$ $10^{-16}\,M_\odot$ $10\,M_\odot$ $10^3\,M_\odot$

Dark matter behaves “classically"

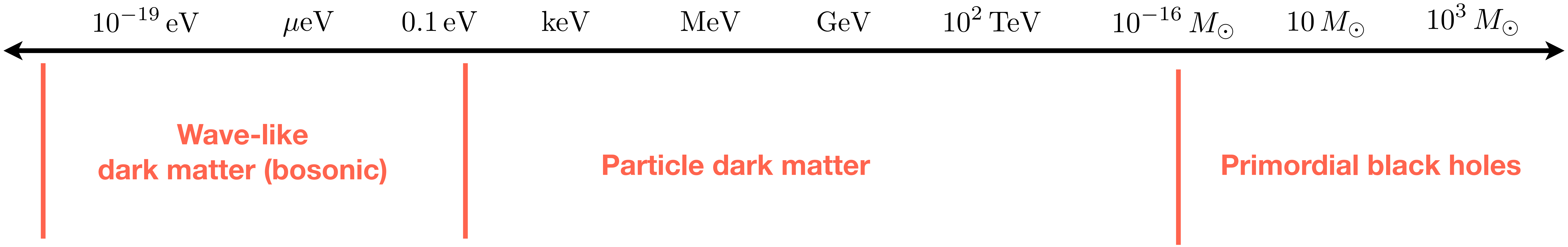
$$m \gtrsim 10^{-22}\,\mathrm{eV}$$

If bosonic, from confinement in dwarf galaxies

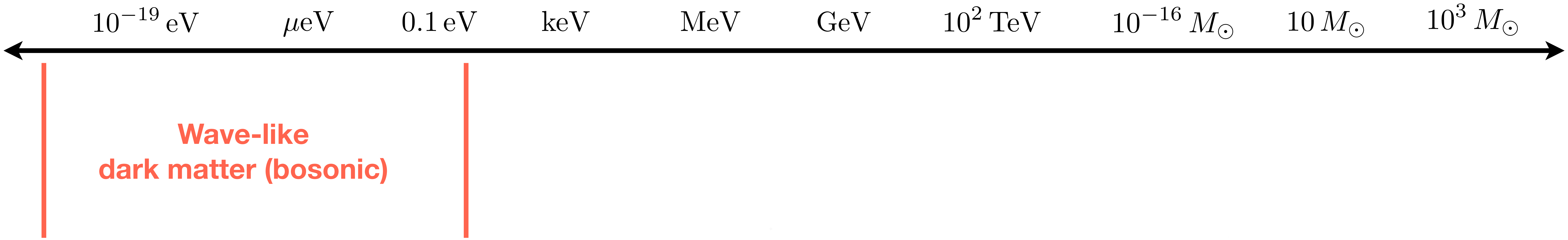
Dark matter “lighter” than halo mass

Vast parameter space in mass and interaction strength

The dark matter landscape



The dark matter landscape



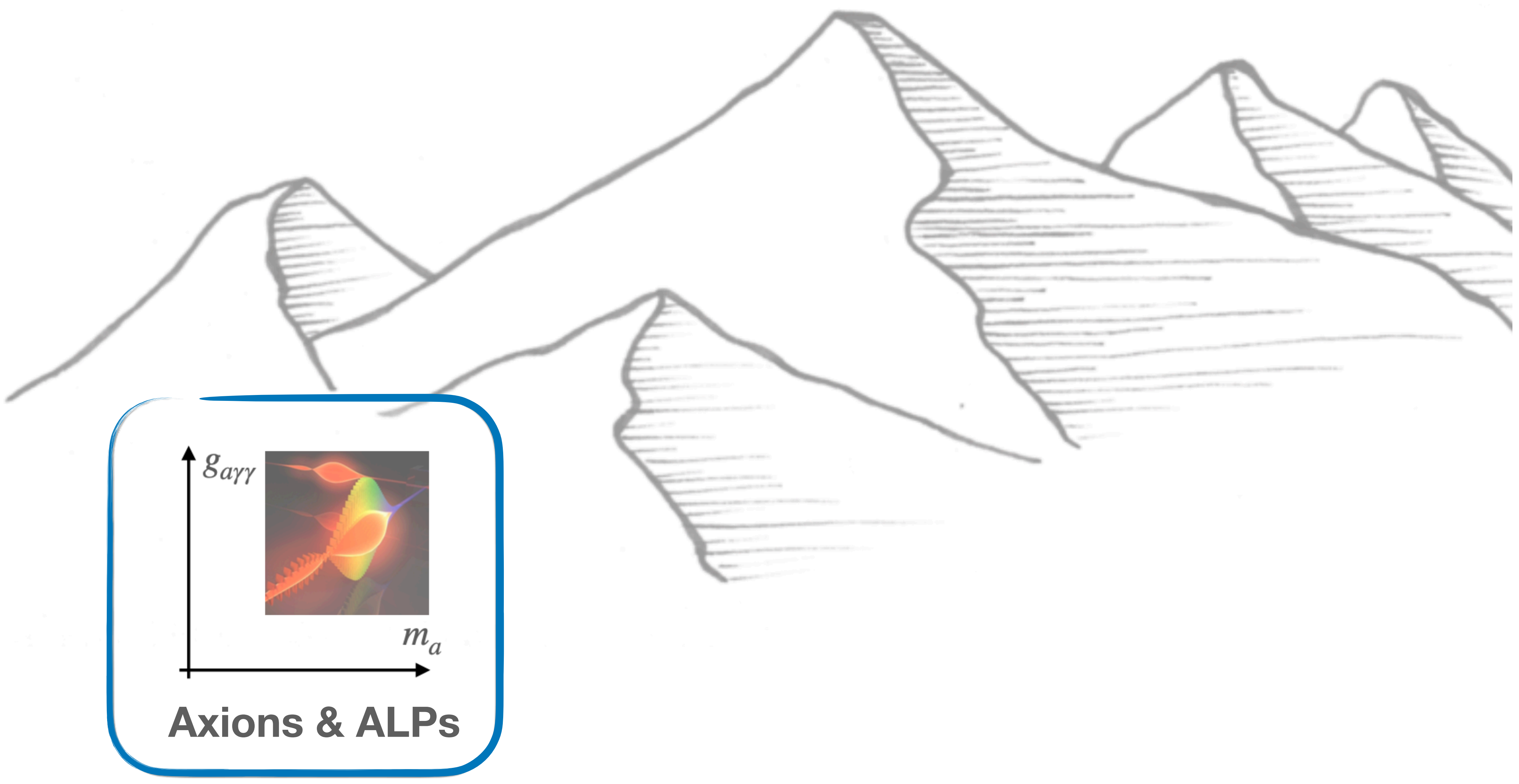
Axion-like particles

- Very light pseudo-scalar bosons predicted by multiple extensions of the Standard Model

  Chang+ PRD 2000; Turok PRL 1996; Arvanitaki+ PRD'10

- They represent weakly interacting slim (ultralight) particles (**WISPs**)
- They can be cold dark matter candidates for certain values of mass and coupling

  Preskill+ PLB 1983; Sikivie International Journal of Modern Physics '10



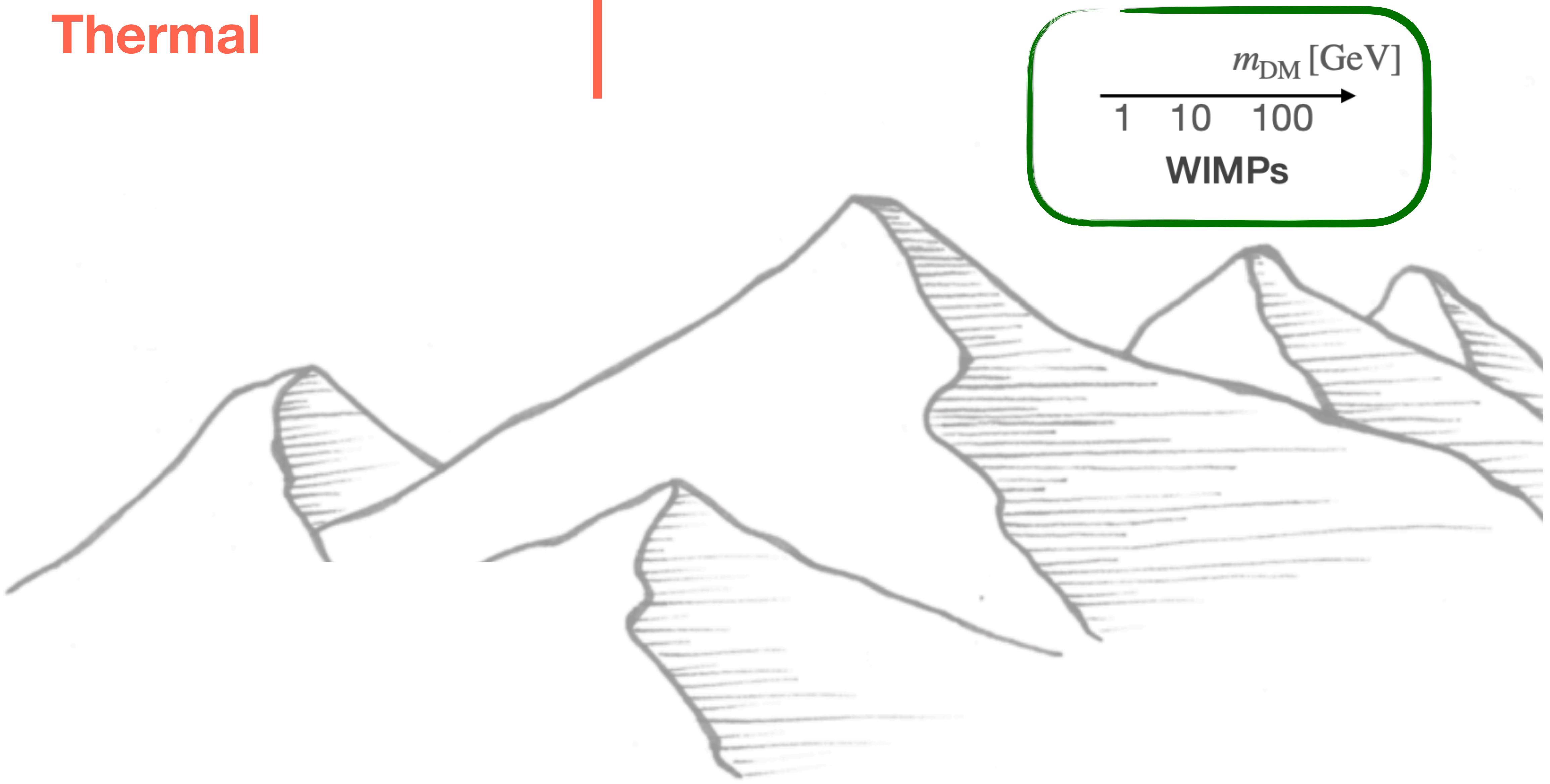
Credit: J. Alvey, EuCAPT Symposium 2021

The dark matter landscape

$10^{-19}\,\mathrm{eV}$ $\mu\mathrm{eV}$ $0.1\,\mathrm{eV}$ keV MeV GeV $10^2\,\mathrm{TeV}$ $10^{-16}\,M_\odot$ $10\,M_\odot$ $10^3\,M_\odot$

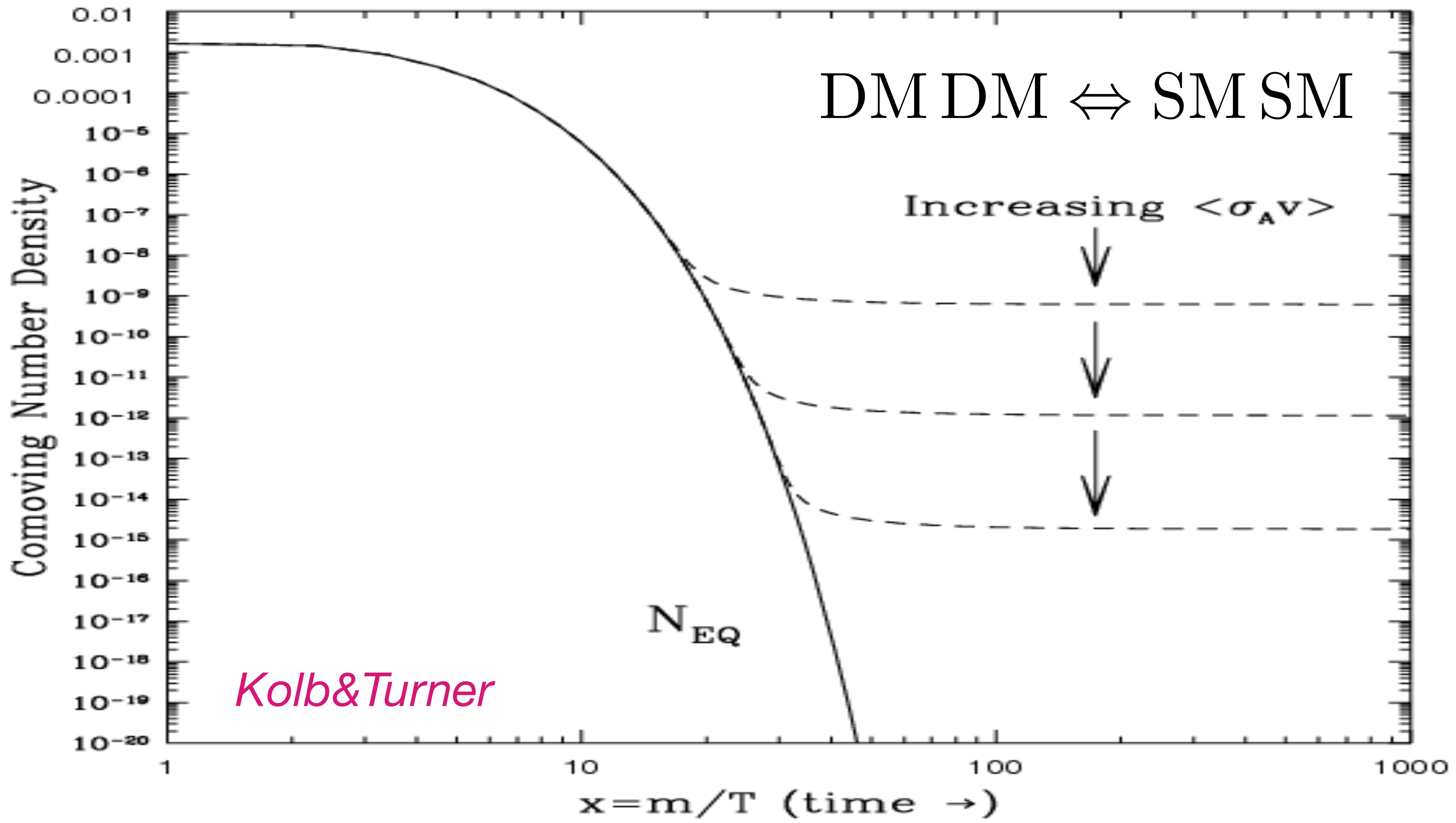
Particle dark matter

Thermal



Weakly interacting massive particles (WIMPs)

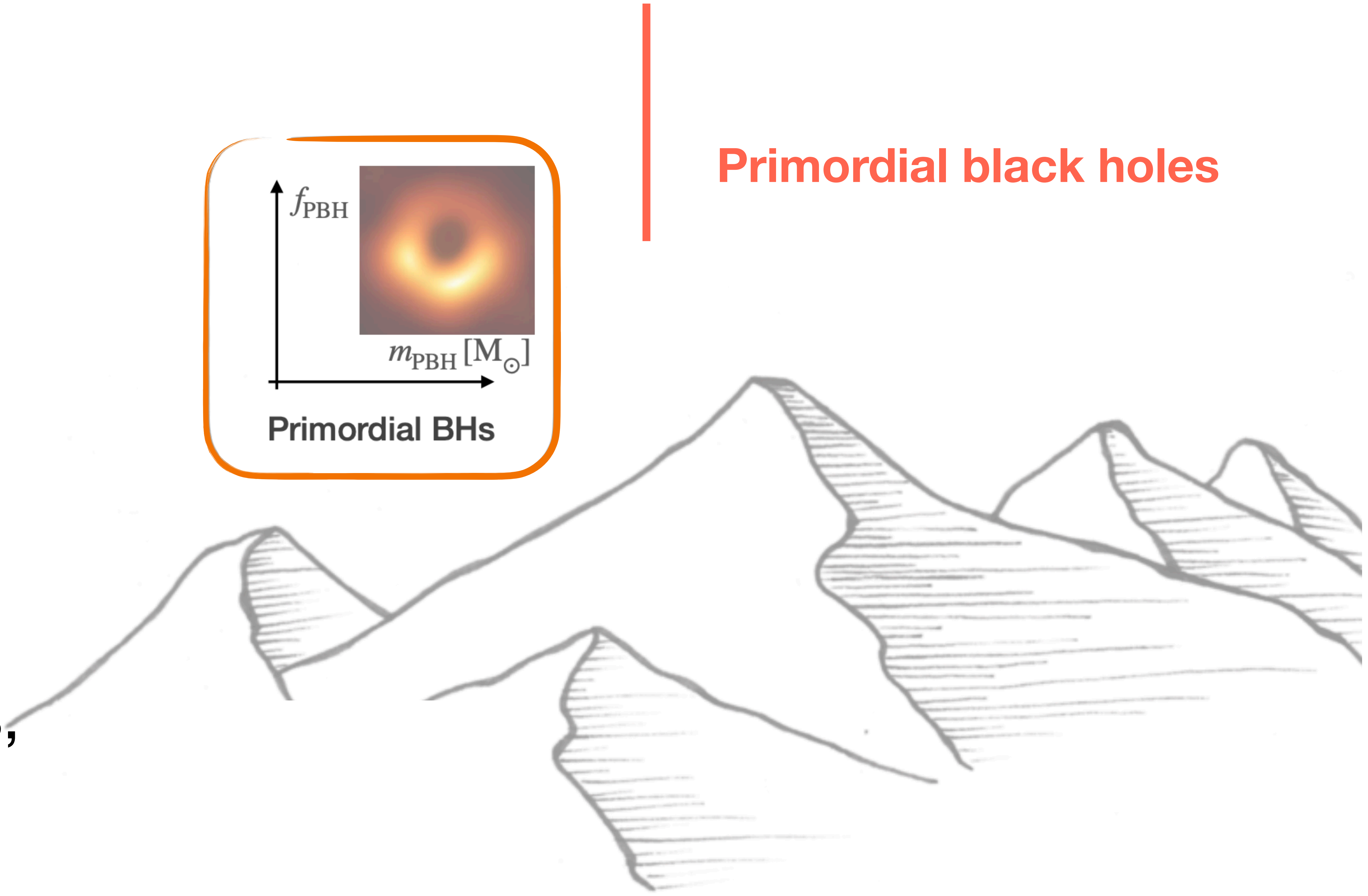
- Freeze-out production mechanism



$$\Omega_{\mathrm{DM}}h^2 \sim \frac{10^{-27}\mathrm{cm}^3/\mathrm{s}}{\langle\sigma(\mathrm{DM\,DM}\to\mathrm{SM\,SM})\mathrm{v}\rangle}$$

Credit: J. Alvey, EuCAPT Symposium 2021

The dark matter landscape



Primordial black holes (PBH)

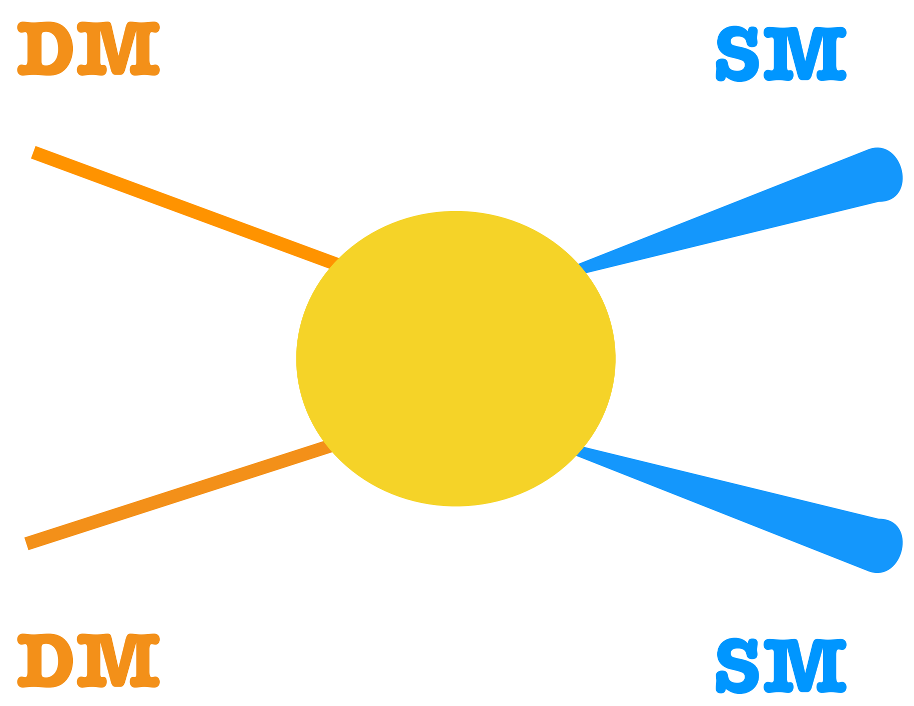
- Different possible production mechanism, e.g. primordial fluctuations
- Allowed fraction of PBH dark matter strongly constrained by CMB, dynamics of stellar clusters, X-ray and radio observations

Review & Refs in Carr+PRD'16, Green & Kavanagh J. Phys. G'21

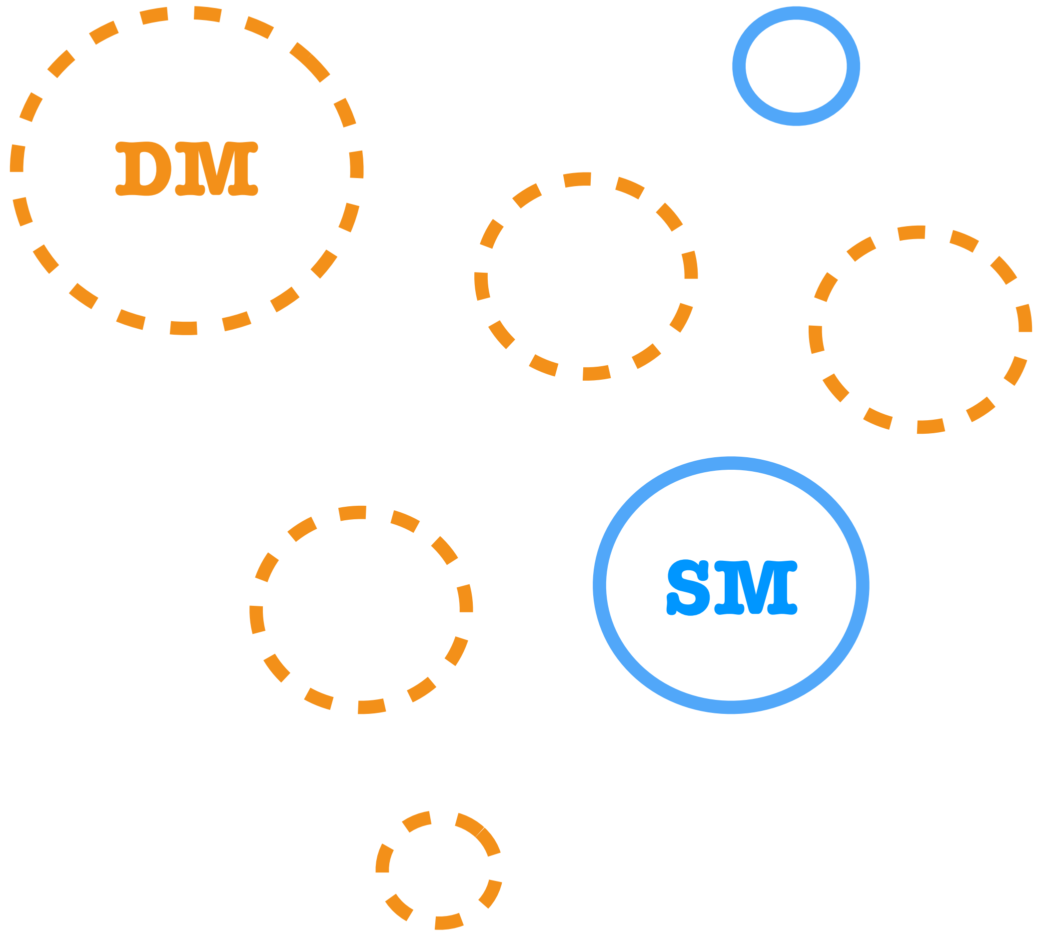
Credit: J. Alvey, EuCAPT Symposium 2021

Dark matter indirect detection

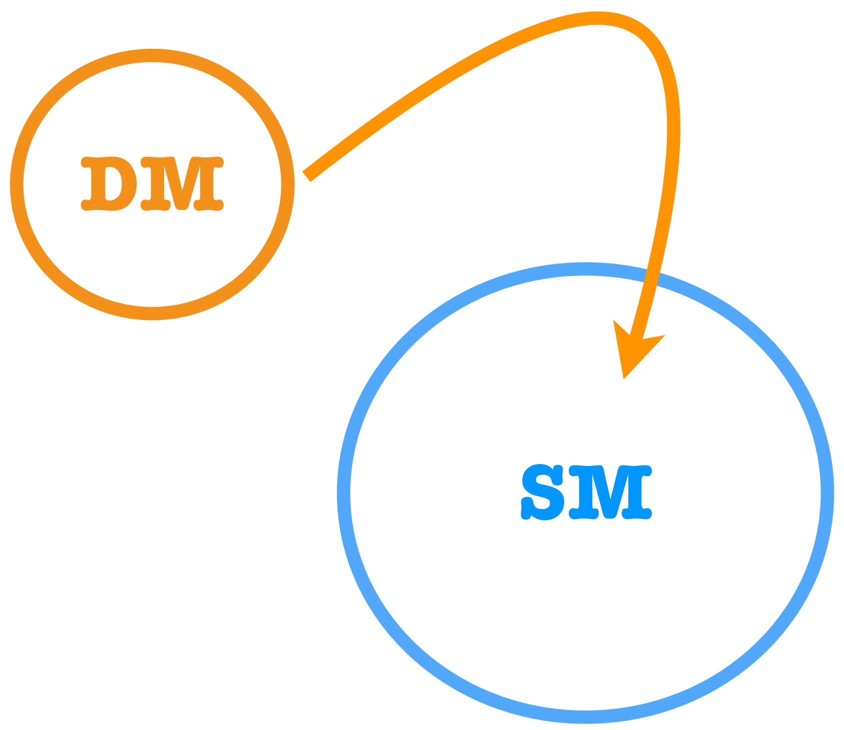
What dark matter does



Energy/particle injection



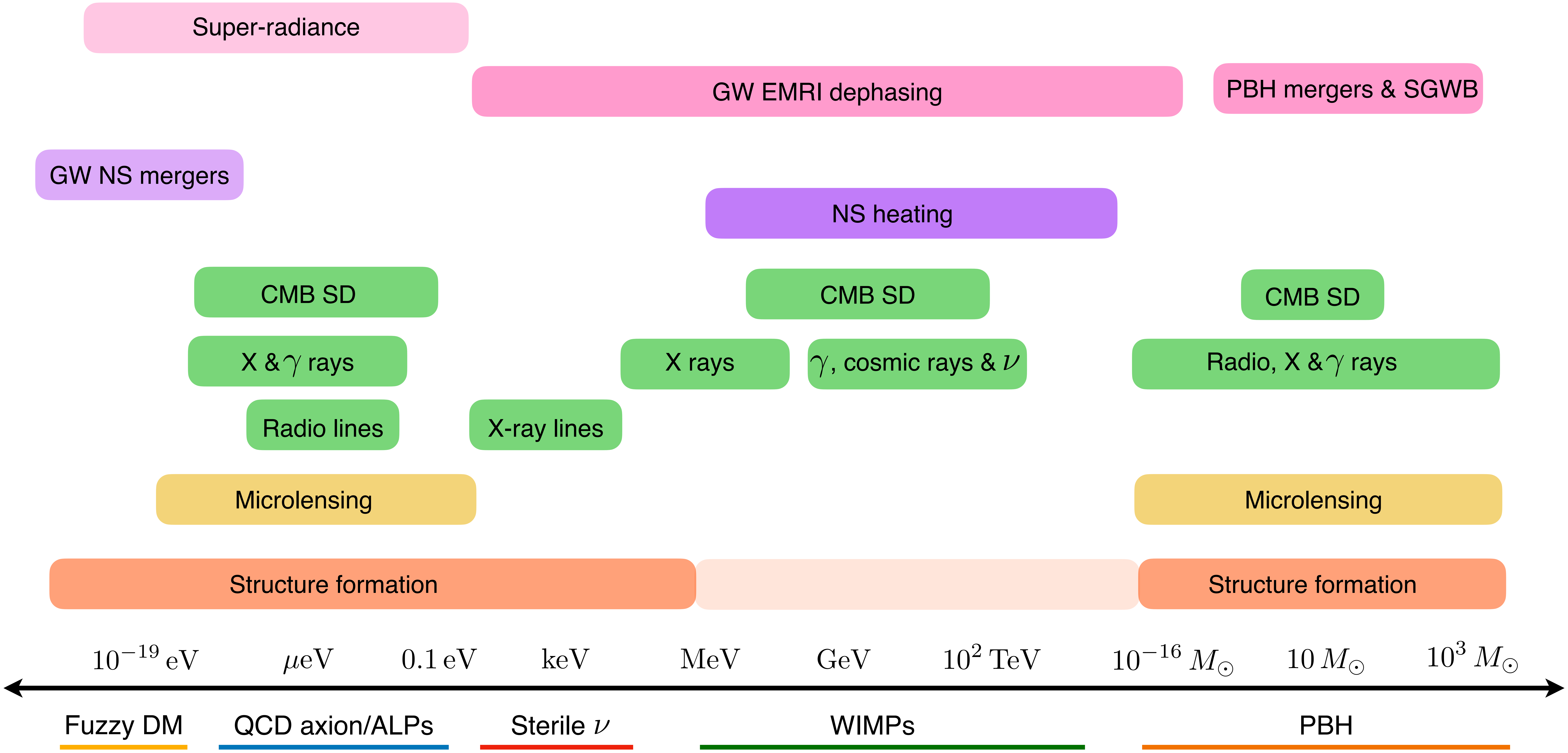
Gravitational interaction



Capture/scattering/accretion in/onto astrophysical objects

Astroparticle observables for dark matter

EuCAPT White Paper, arXiv:2110.10074



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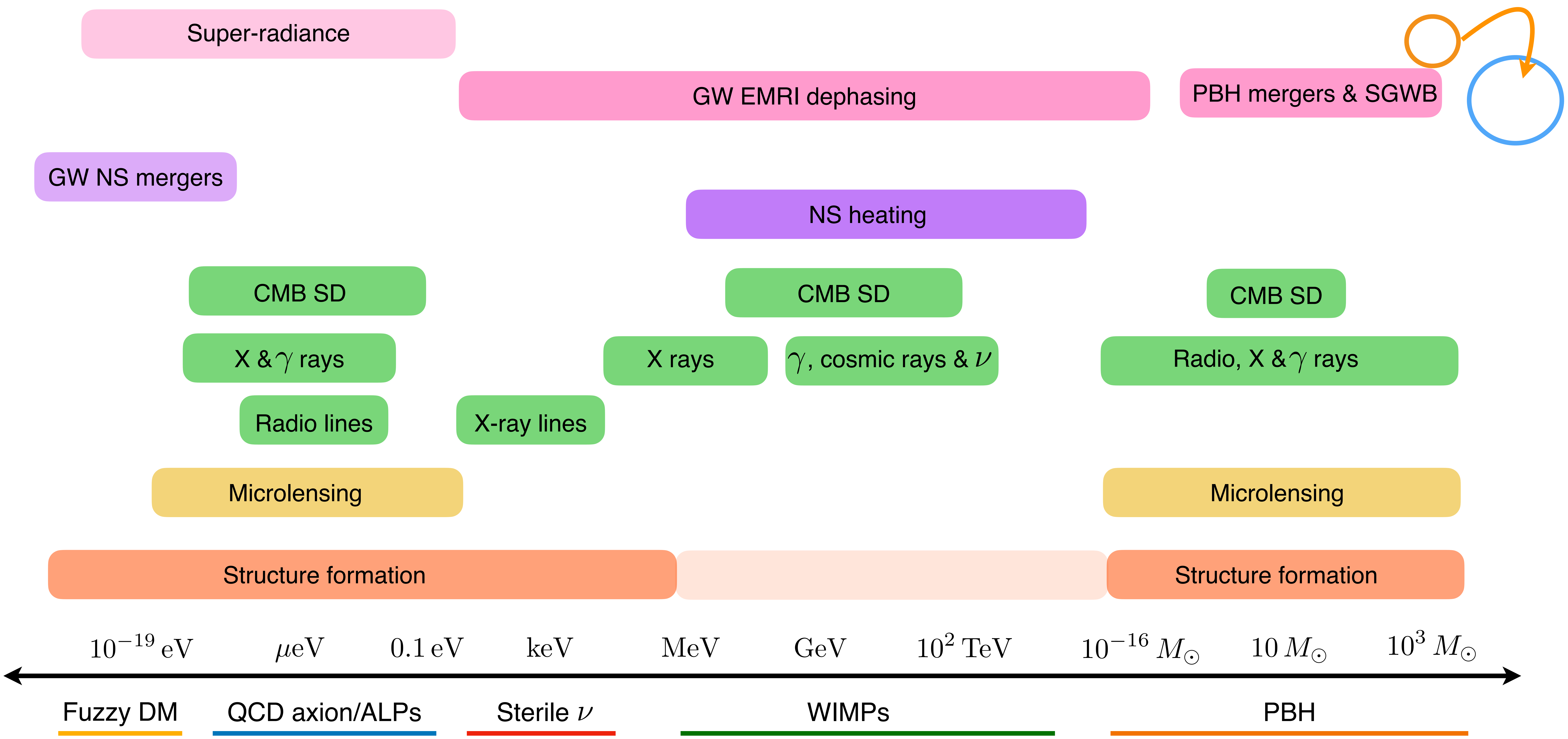

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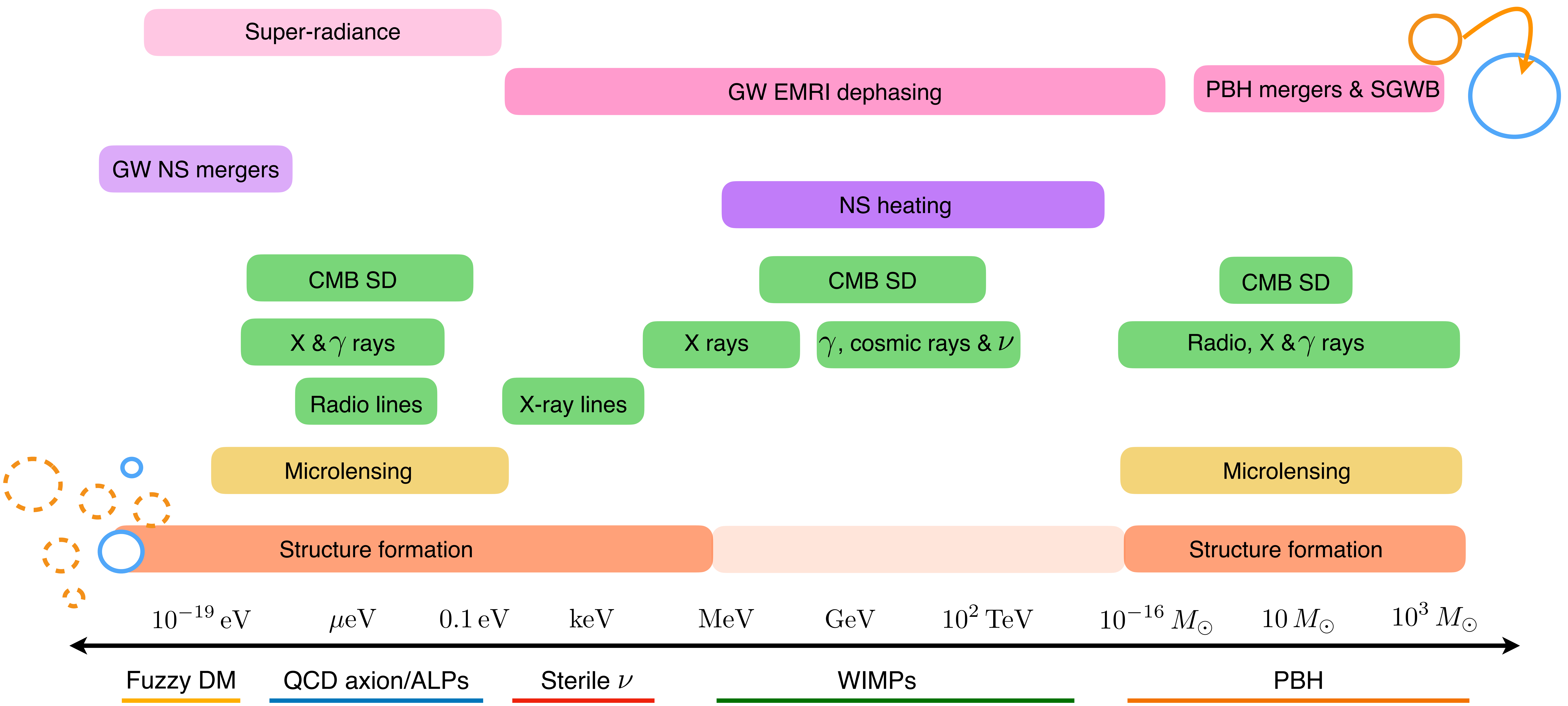

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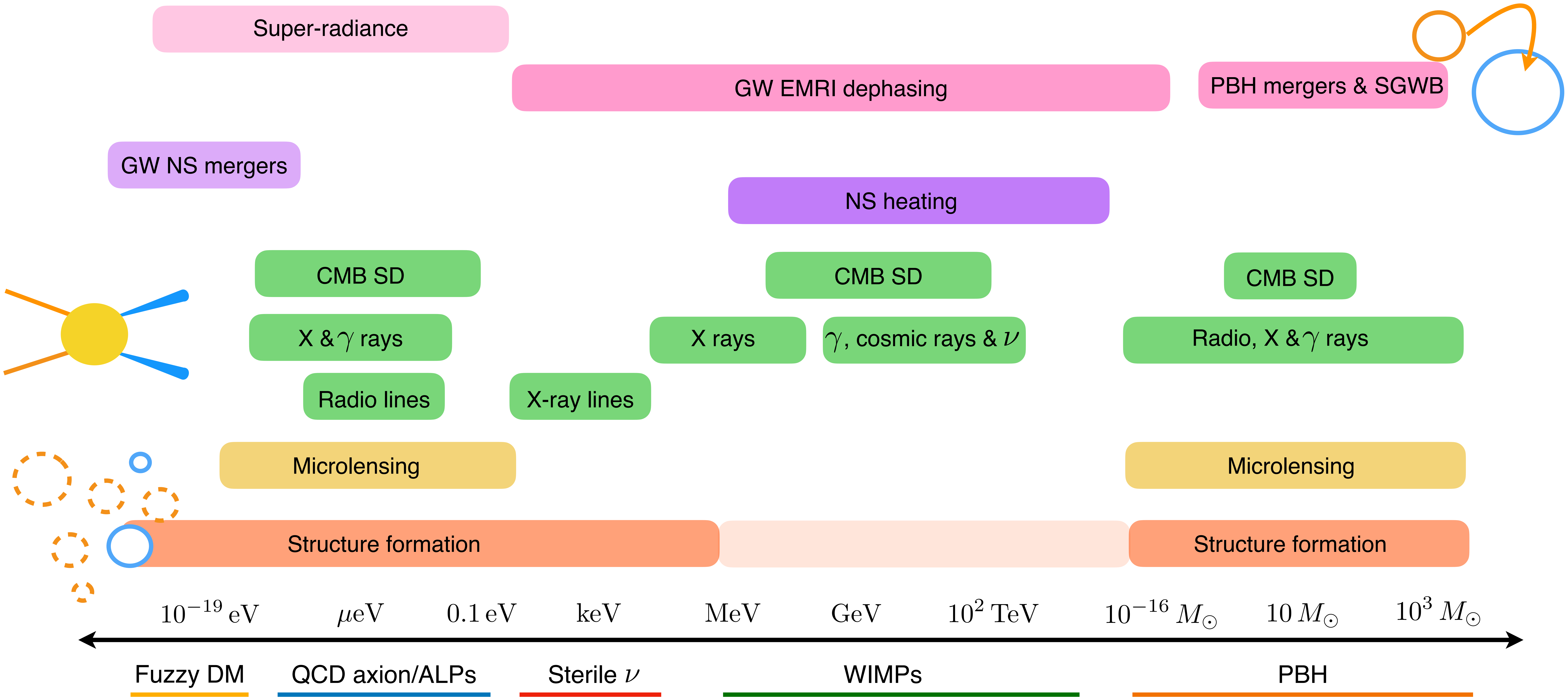
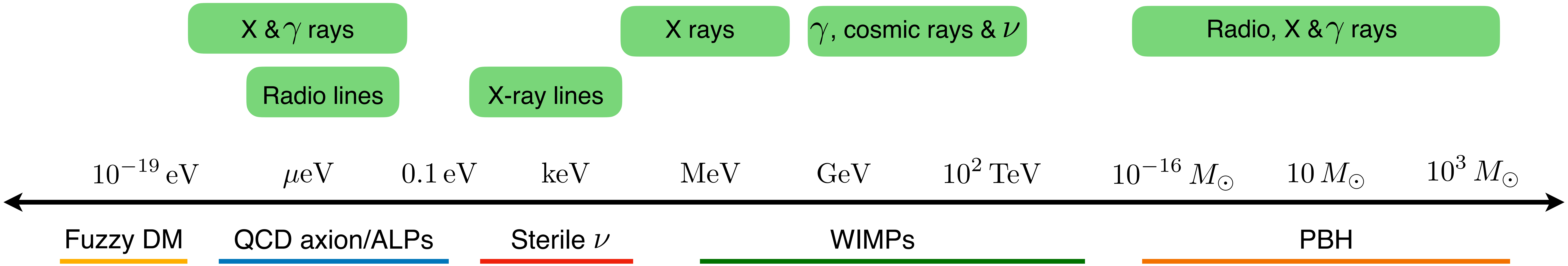


Travelling messengers

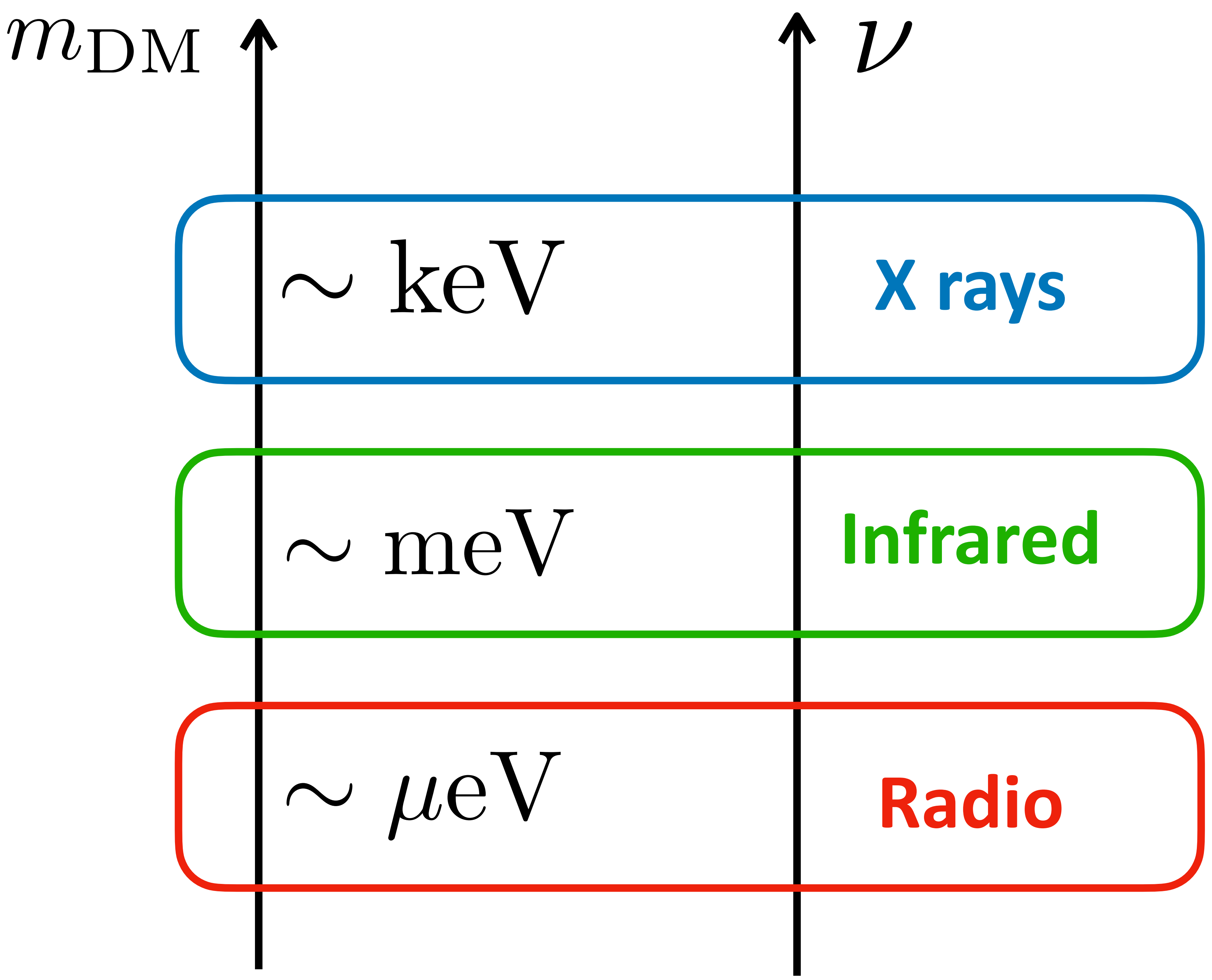


Radio and X-ray lines

$$m_{\rm DM} \lesssim {\rm MeV}$$

Narrow line signal @ energy scale of the DM mass

$$E_\gamma = \frac{m_{\rm DM}}{2}$$



Observational strategy:

- Minimal amount of model assumptions when performing the data analysis
- Narrow sensitivity to parameters space given data

Axions and ALPs radio lines

- Narrow lines from **spontaneous decay** in radio (MHz for μeV masses), IR (for meV to eV masses), and X rays (keV masses)

Irastorza & Redondo PPNP'19

- **Stimulated decay** can occur in the presence of non-relativistic ambient radiation (e.g. CMB)

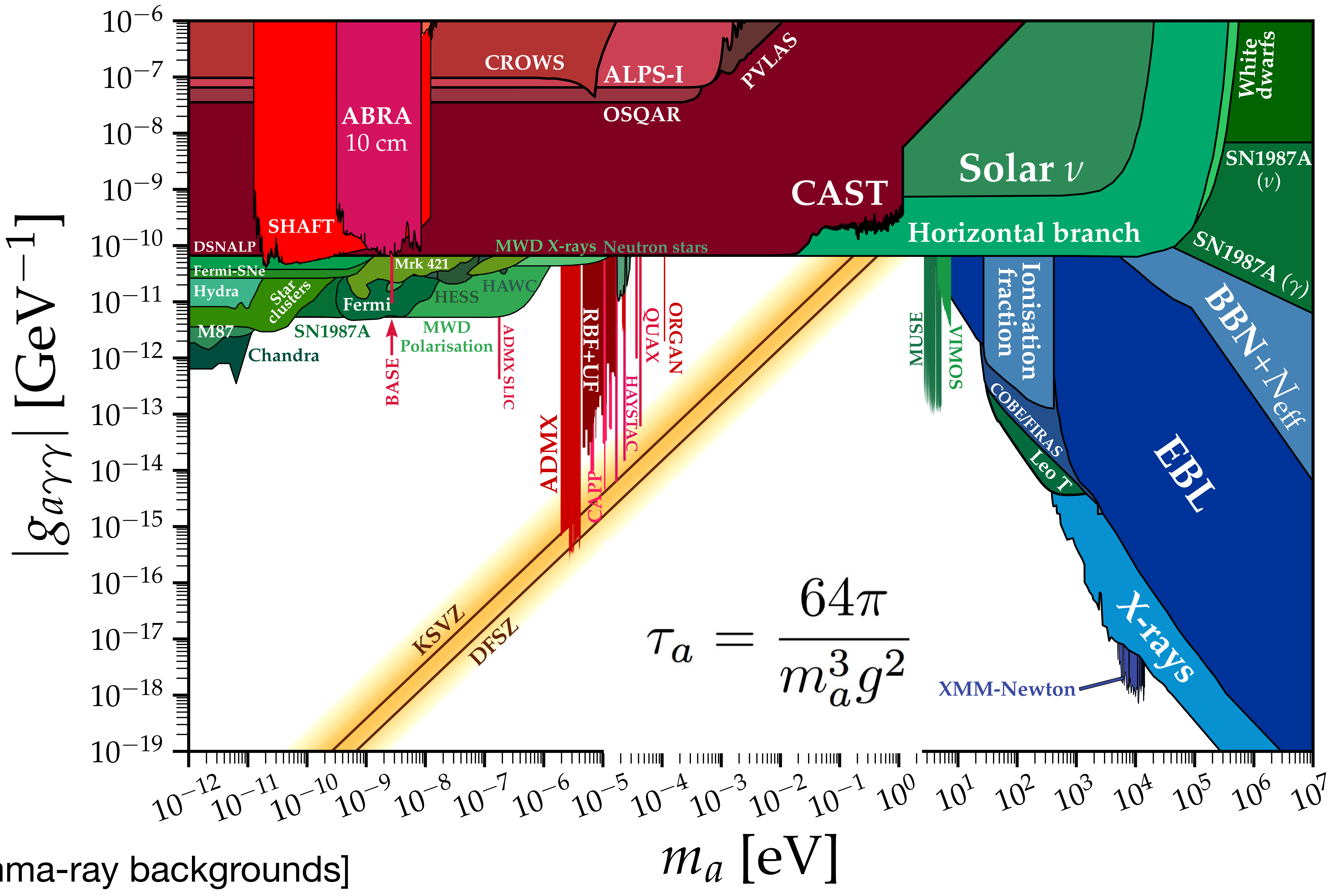
Caputo+ PRD'18; JCAP'19; Battye+ PRD'20

- Monochromatic radio emission (MHz - GHz) from **DM axion/ALP-photon conversion**:
  - *Resonant* conversion from highly magnetised neutron stars (NSs), or white dwarf stars

    Pshirkov JETP'09; Huang+2018; Hook+PRL'18

  - *Non-resonant* transitions in the Galactic center and/or of discrete astrophysical objects

    Kelley&Quinn ApJ'17; Sigl PRD'17

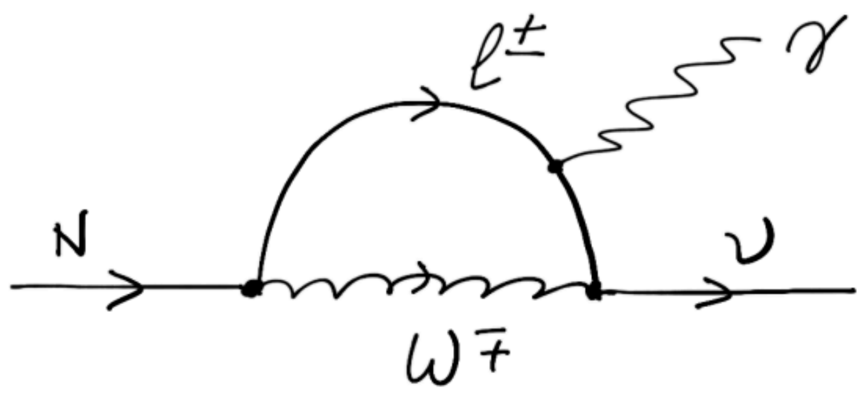


[Axion-photon conversion leads to **diffuse signals** to be looked for in cosmic X- and gamma-ray backgrounds]

https://github.com/cajohare/AxionLimits

Sterile neutrinos X-ray lines

- X-ray lines for **sterile neutrinos** in the keV to MeV mass range
- Loop mediated radiative decay



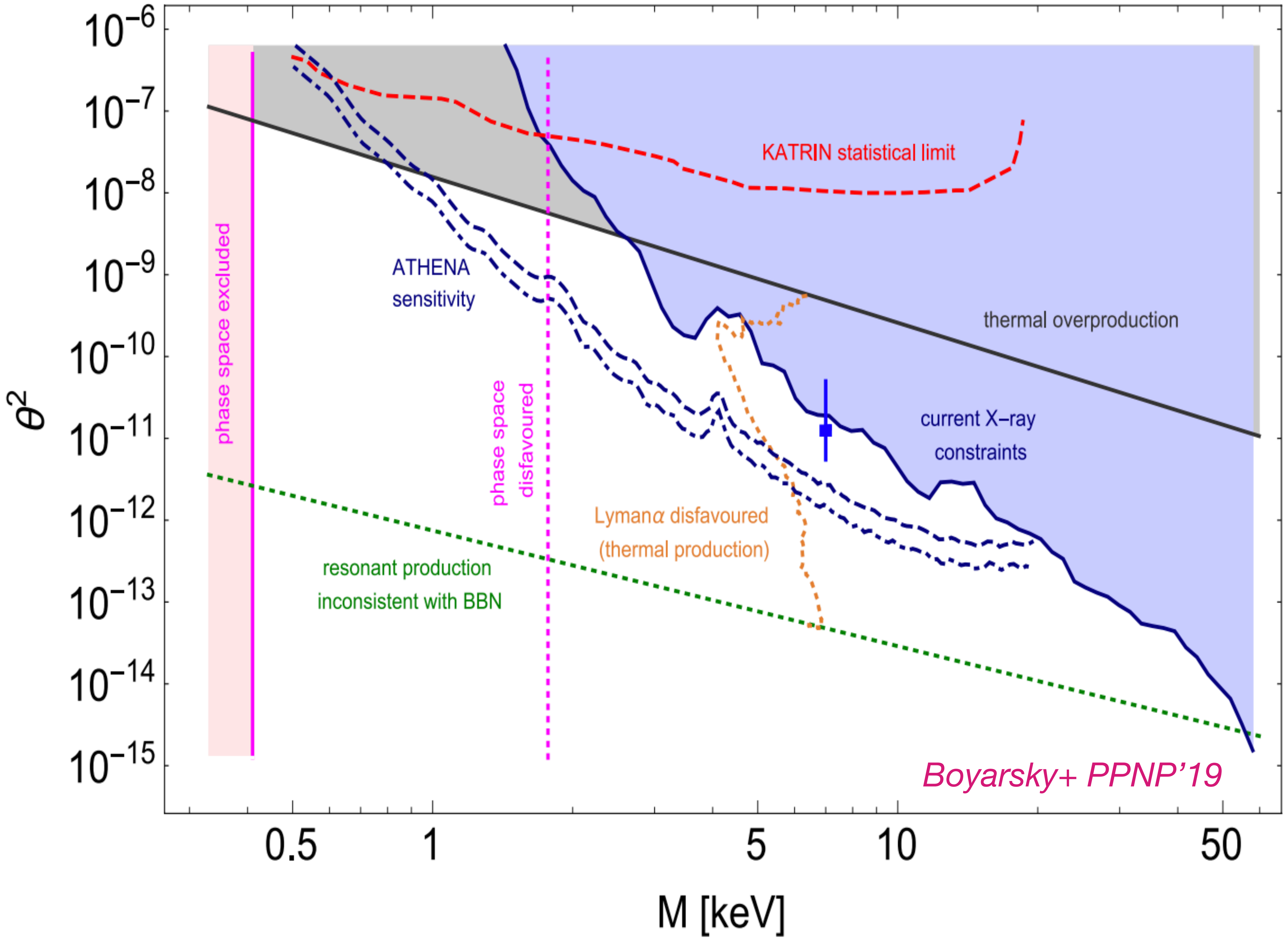
$$\Gamma_N \approx 10^{-29}\,\mathrm{s}^{-1}\left[\frac{\sin^2(2\theta)}{10^{-7}}\right]\left(\frac{\mathrm{M}}{1\mathrm{keV}}\right)^5$$

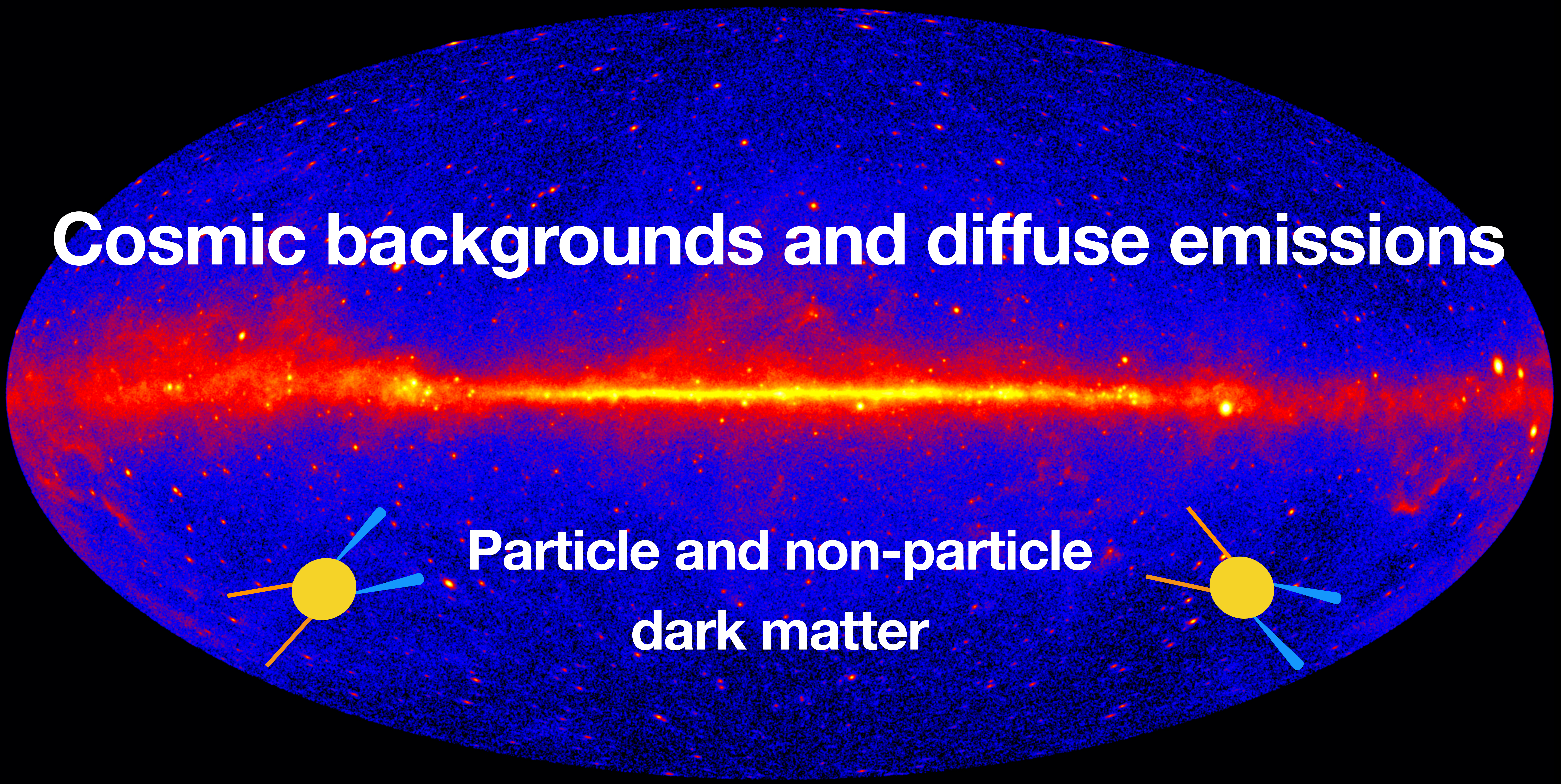
- Tentative **3.5 keV line** detection strongly constrained by null observation in XMM-Newton black-sky pointings

Dessert+ Science' 20

- Future progresses with eROSITA, XARM (ex-Hitomi), Linx, and Athena+

Boyarsky+ PPNP'19
Dekker+ PRD'21




Cosmic backgrounds and diffuse emissions
Particle and non-particle
dark matter

Particle dark matter emission*

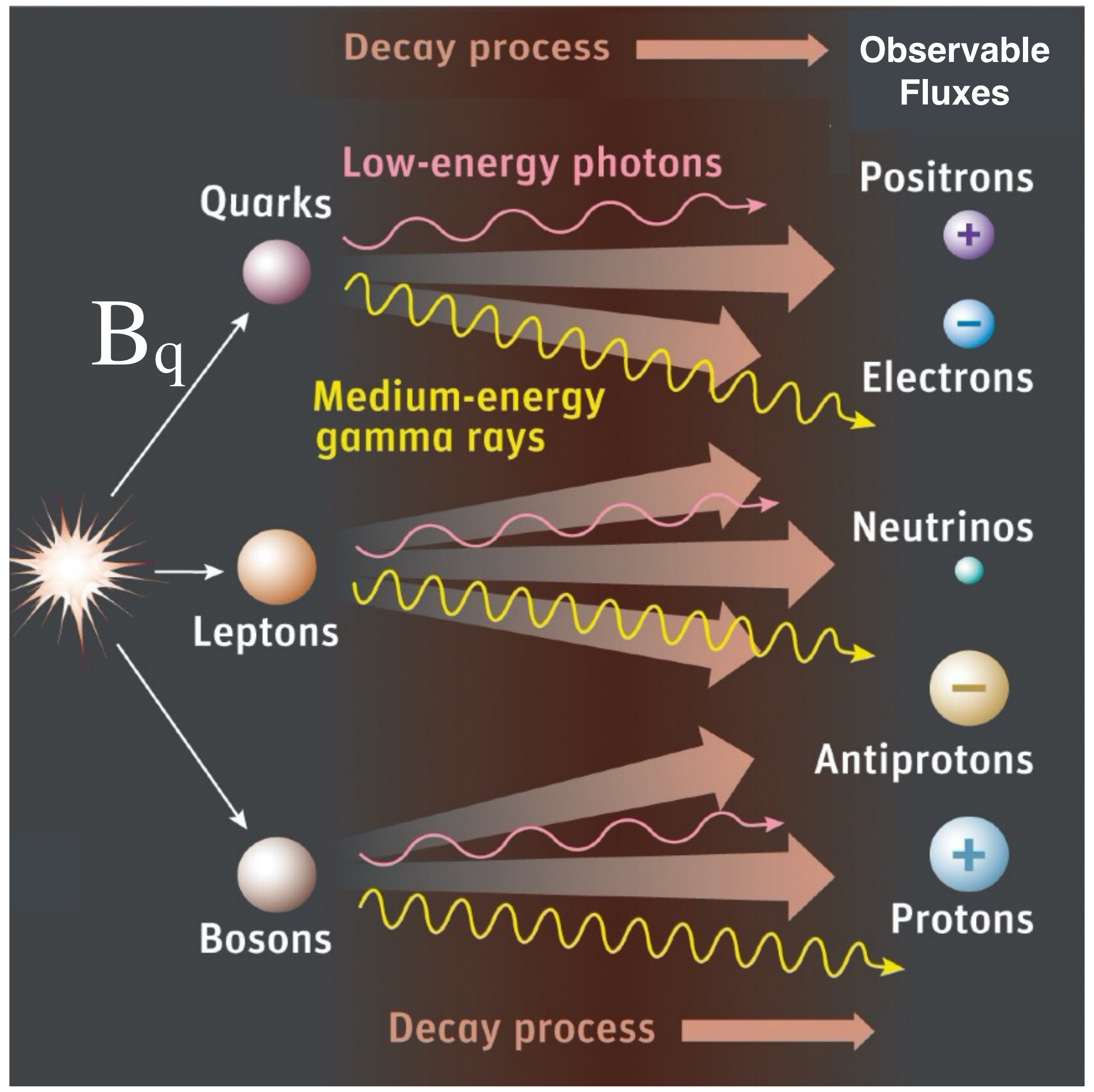
From radio to TeV gamma rays

$$E_{\rm CM} = N\, m_{\rm DM}\,, \qquad N = 1\ ({\rm decay}),\ 2\ ({\rm annih})$$

Centre of mass energy $\simeq$ Signal energy

$$m_{\rm DM} \gtrsim {\rm MeV}$$

DM annihilation/decay



[*Dark matter = Weakly interacting massive particles, **WIMPs**]

Particle dark matter emission

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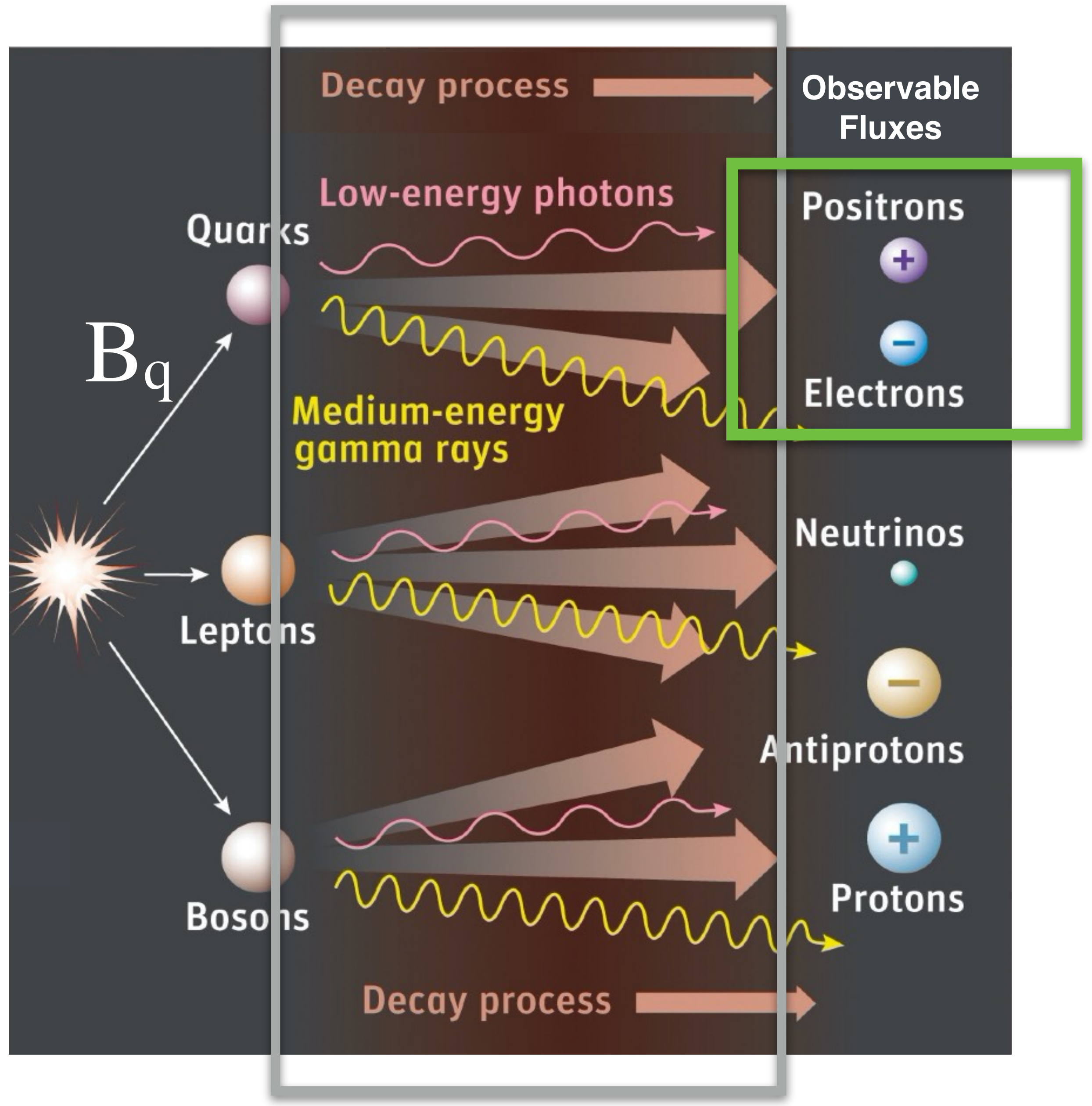

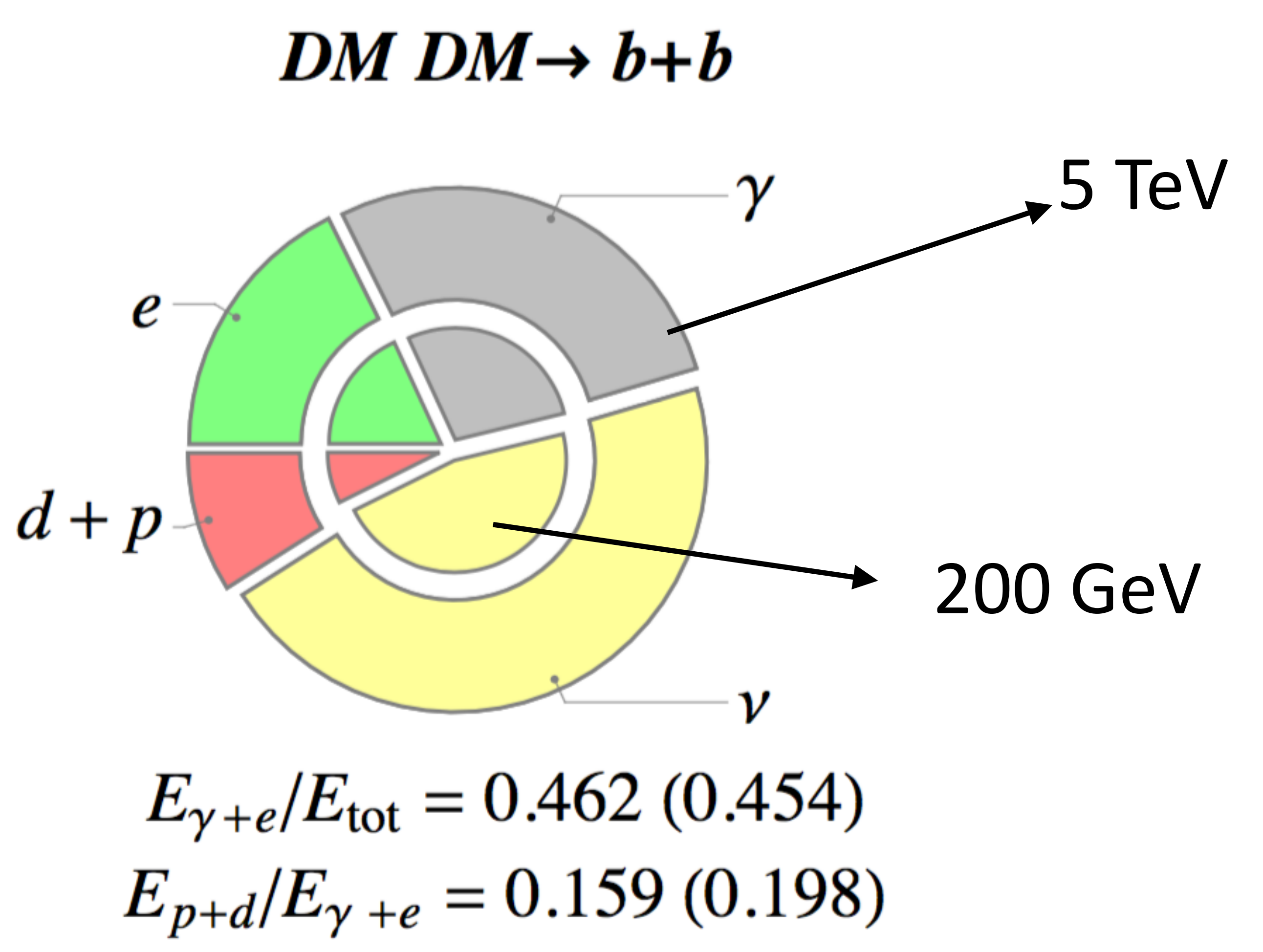

Prompt emission of observable particles *i*

$$\sum_f B_f \frac{dN_i^f}{dE}(E)$$

Particle dark matter emission

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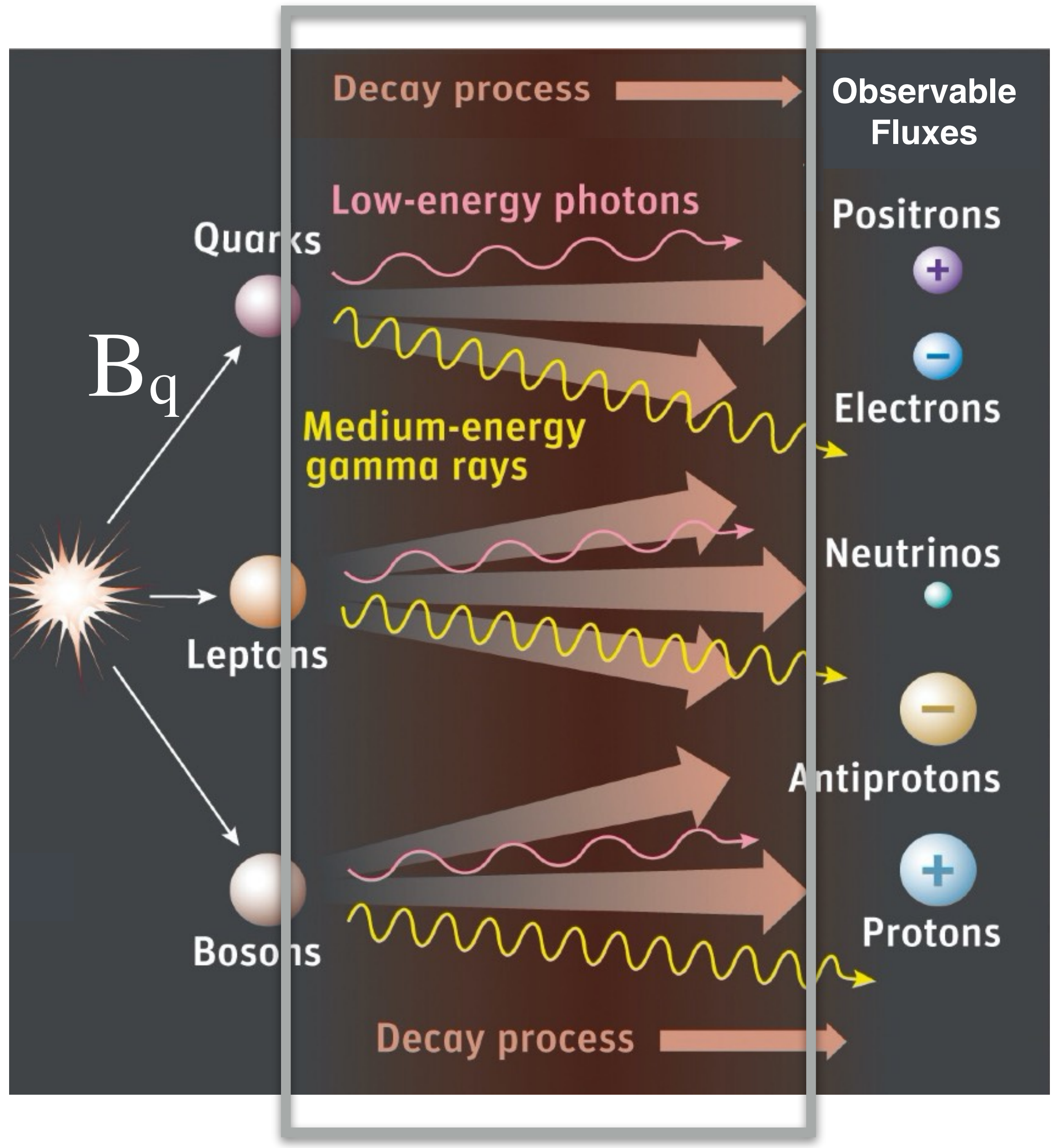
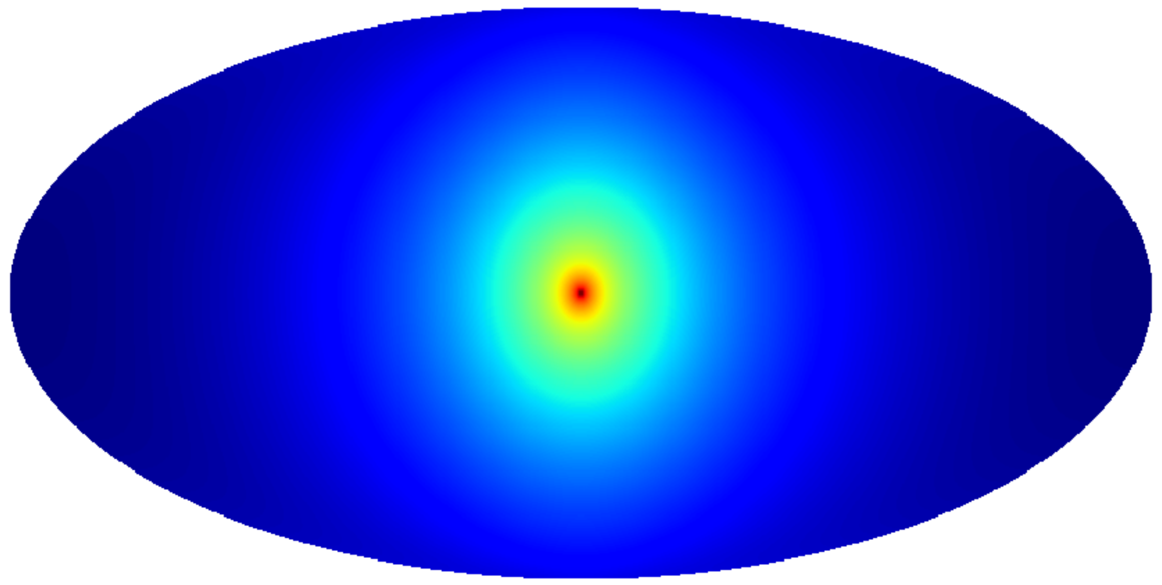
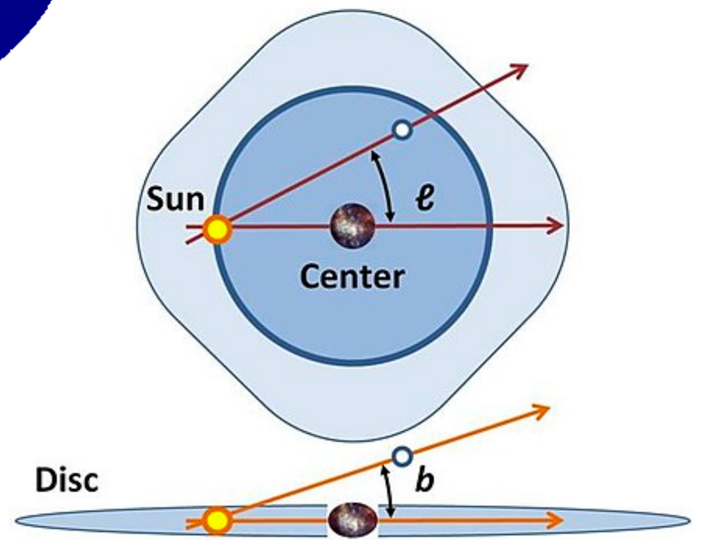


Example: Self-conjugated dark matter annihilation

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, s, \Delta\Omega) = \frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\sum_i B_i \frac{dN_\gamma^i}{dE_\gamma}\frac{1}{4\pi}\int_0^{\Delta\Omega} d\Omega \int_{\rm l.o.s} \rho_{\rm DM}^2(s)ds$$

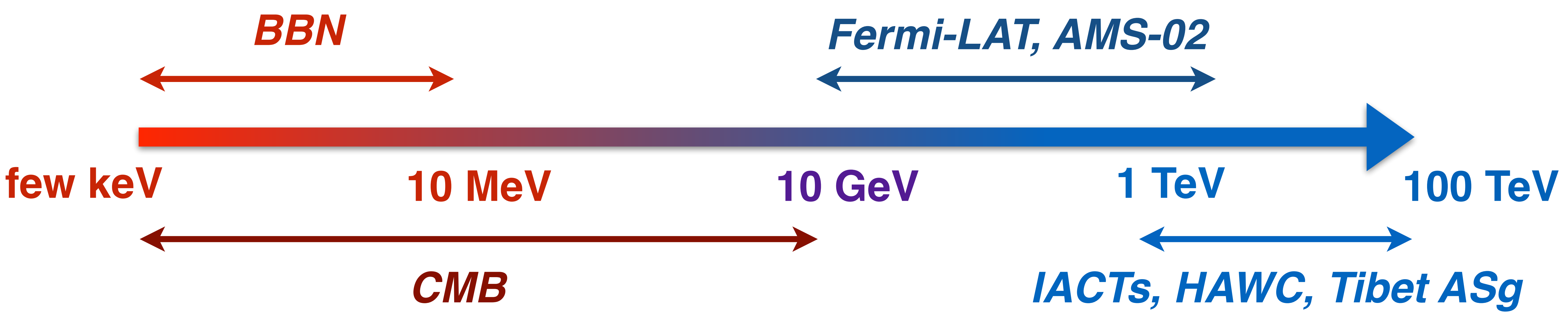
Differential **gamma-ray** flux



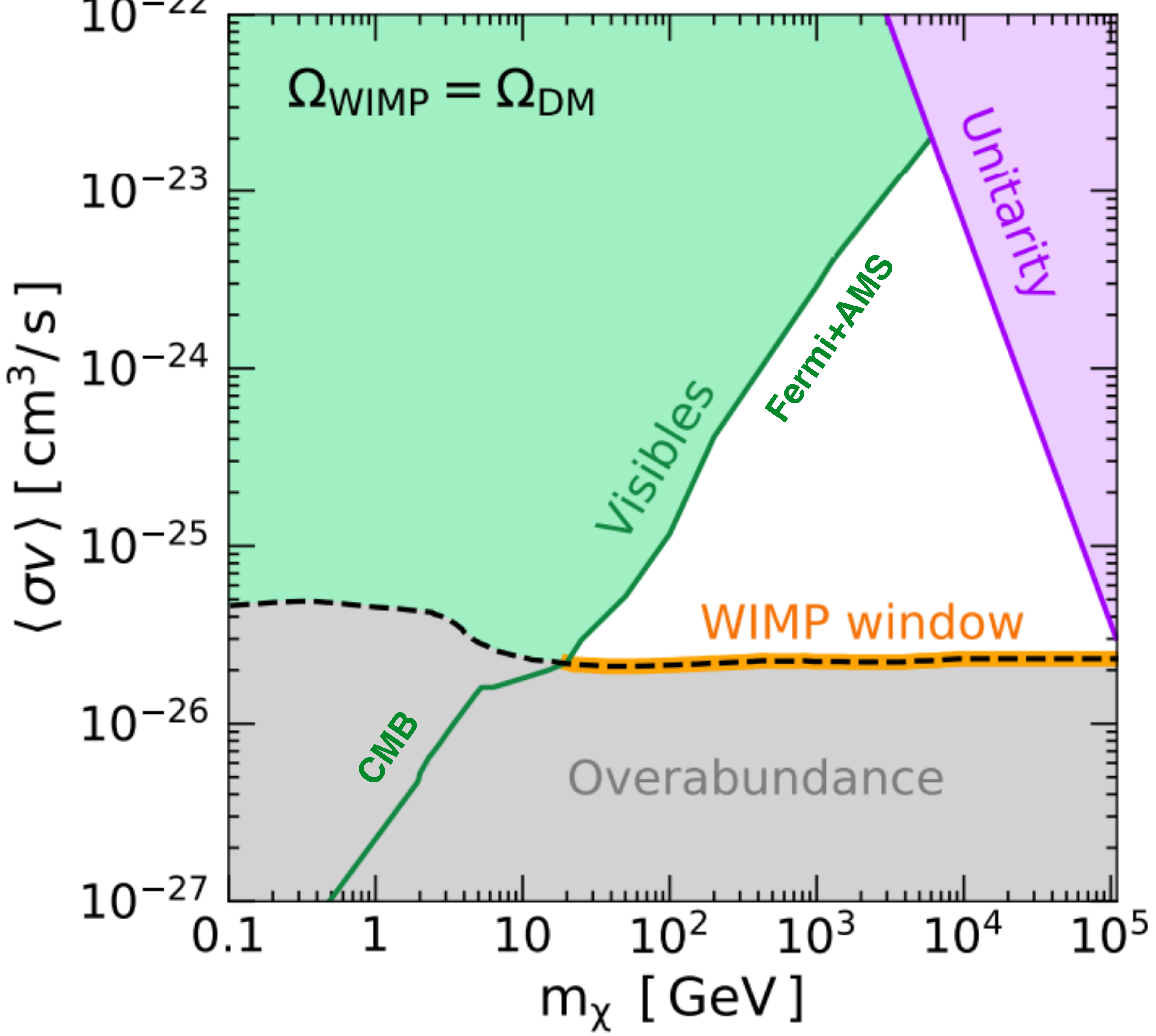


[Gamma-ray lines typically suppressed at loop level for generic WIMP models]

WIMP annihilation window



Leane+ PRD'18

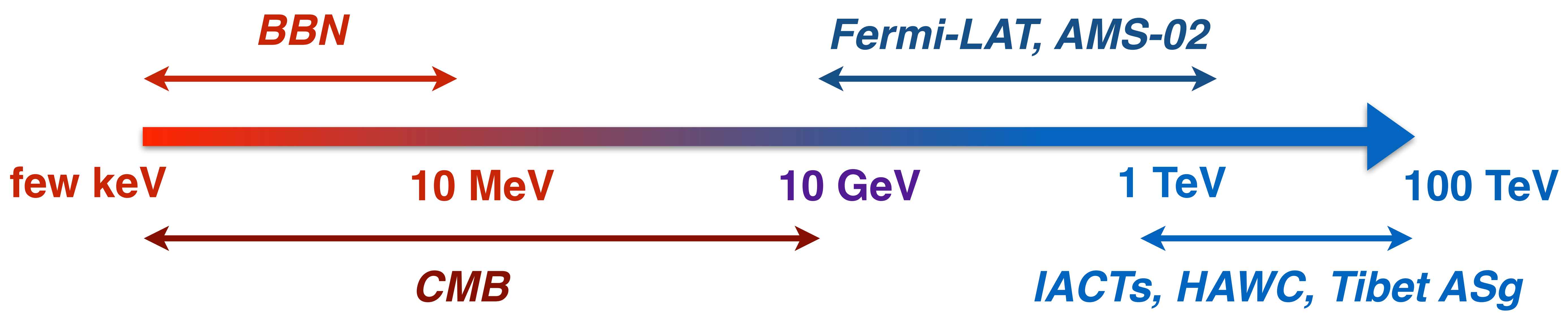


- **Total cross-section** sets **relic abundance**
- **Indirect detection** provides model-independent UL on annihilation **cross-section for a given final state**

→ Consistent and conservative interpretation of the data in the context of the generic thermal WIMP

[Low DM masses constrained by energy injection at early times and CMB observations *Slatyer & Wu, PRD'17*]

WIMP annihilation window



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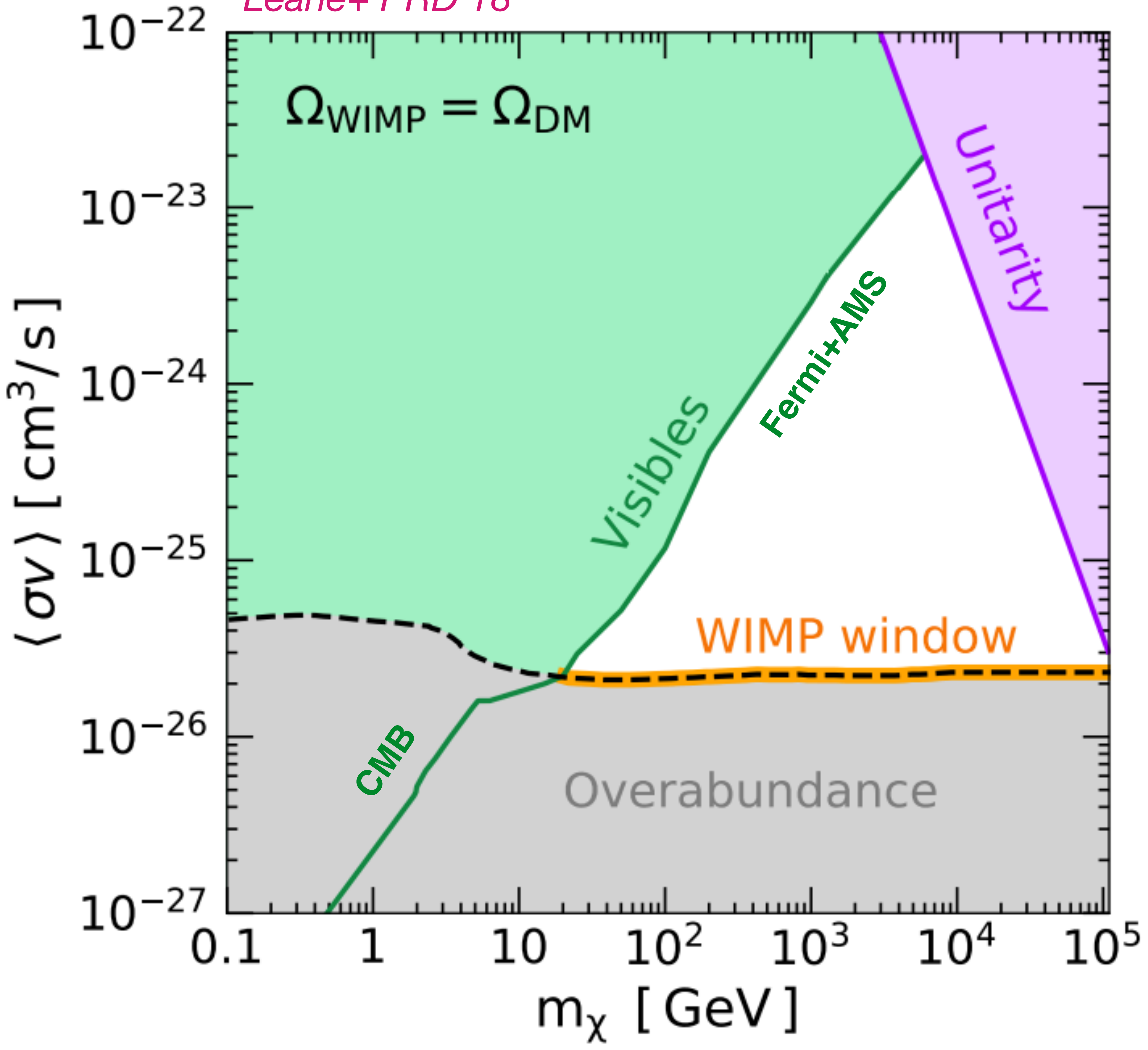

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- **Indirect detection** provides model-independent UL on annihilation **cross-section for a given final state**

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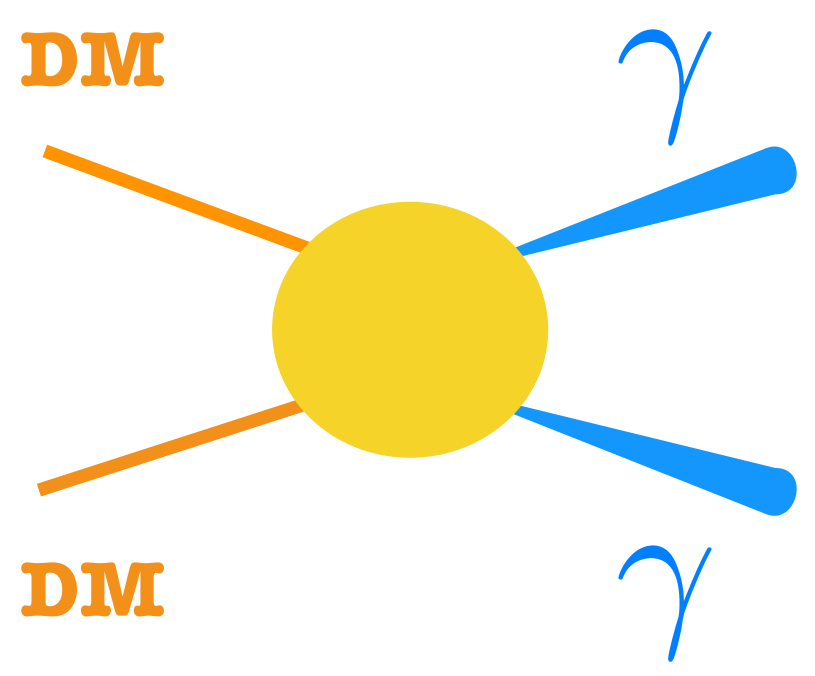
TAKE AWAY: Window of opportunity still open for thermal WIMP DM

[Low DM masses constrained by energy injection at early times and CMB observations *Slatyer & Wu, PRD'17*]

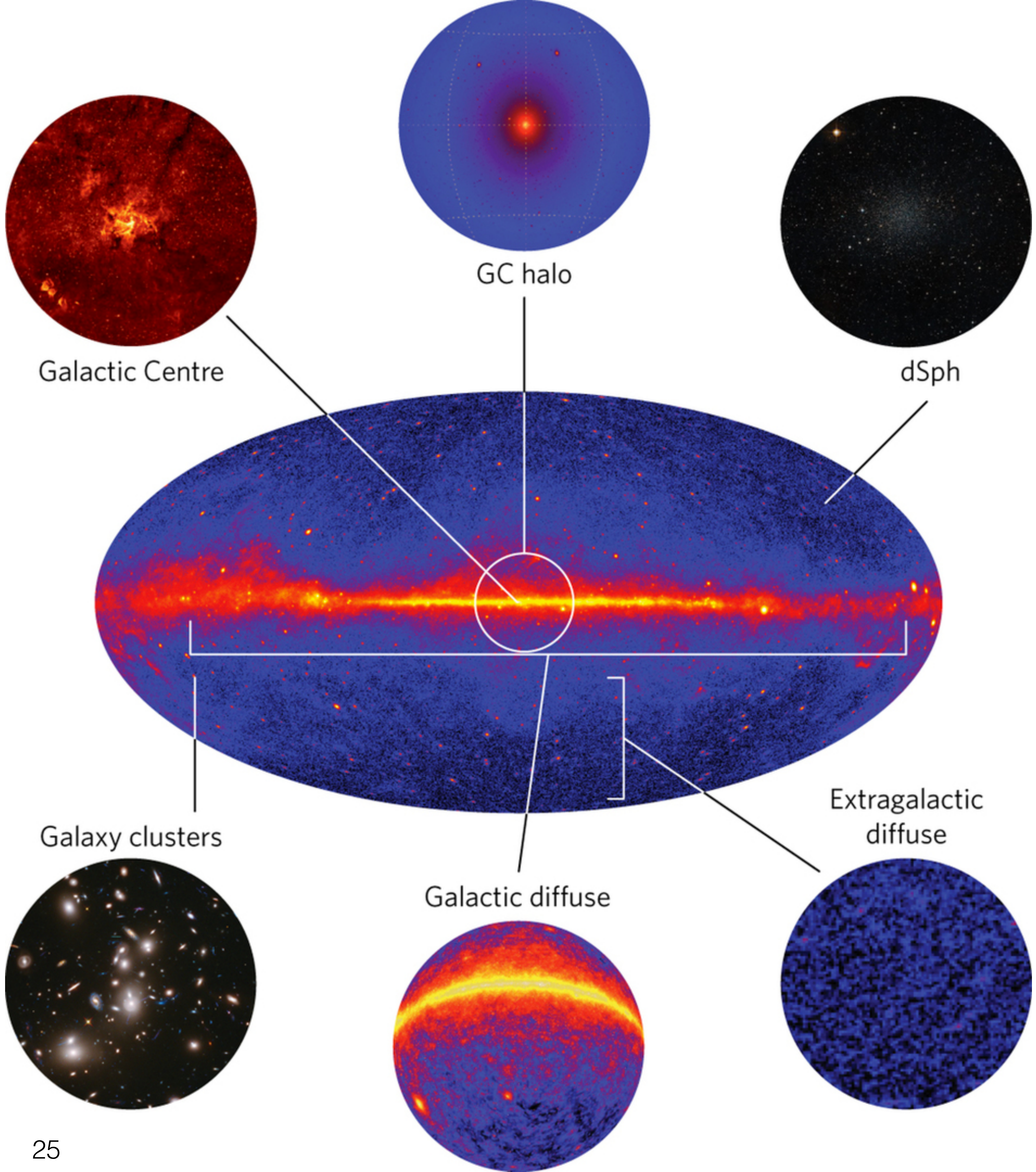
Targets for WIMP gamma-ray searches



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

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

Conrad & Reimer Nature Phys. 13 (2017)

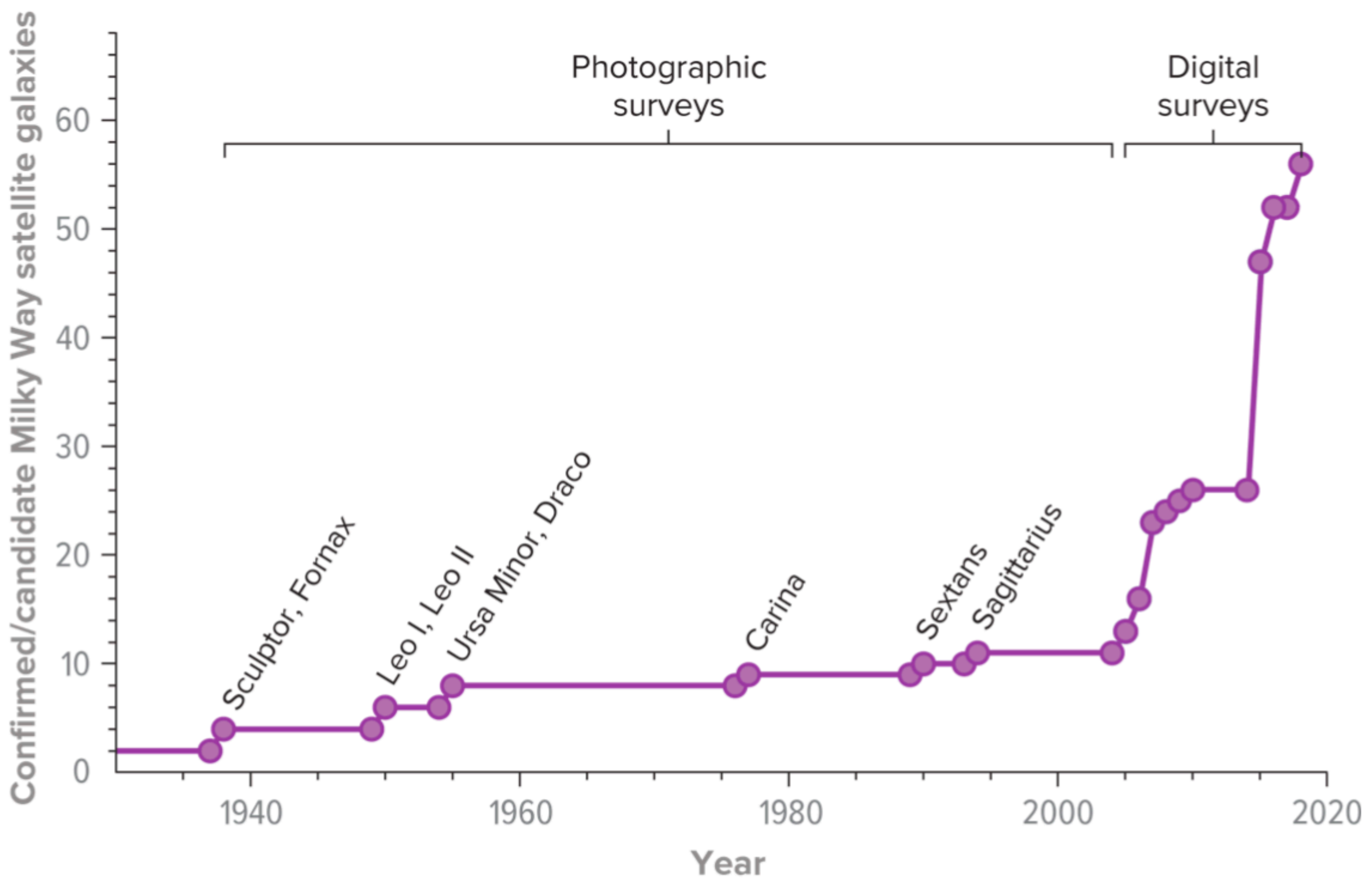


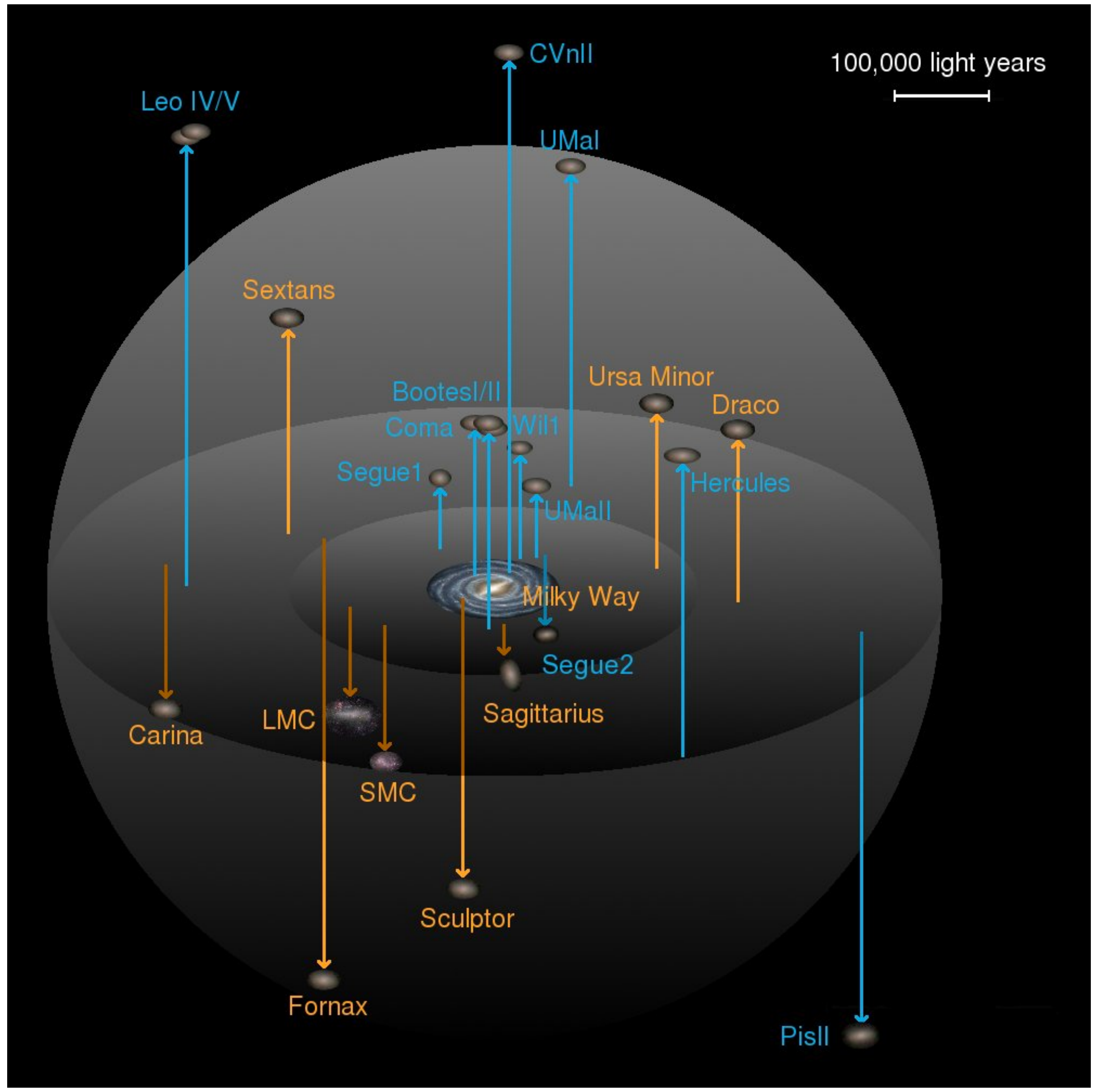
Dwarf spheroidal galaxies

Known satellites of the Milky Way at ~100 kpc from Earth

"Clean" target for DM searches, high mass-to-light ratio and little astrophysical emission

Winter+ ApJ'16

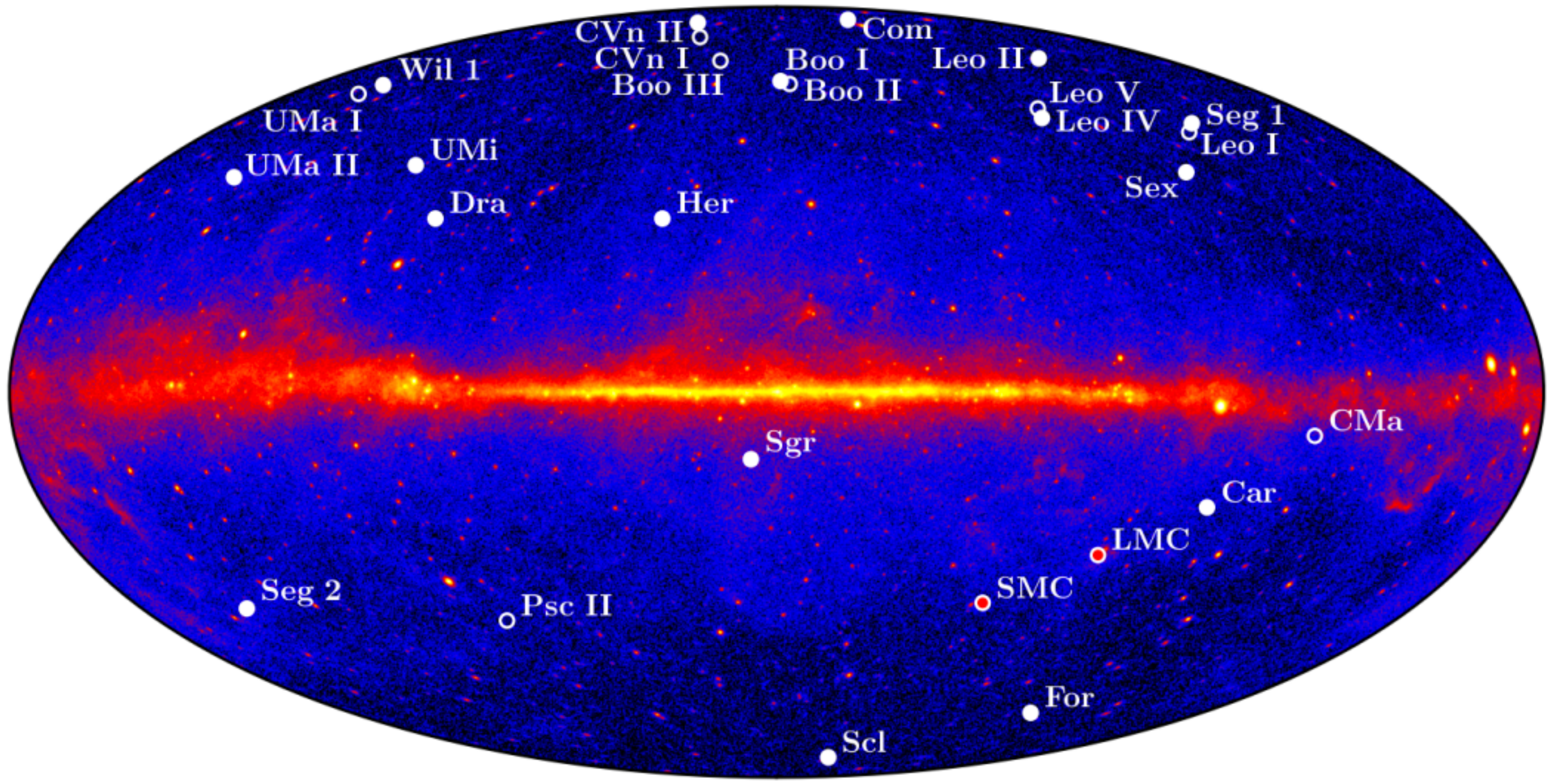




A growing Galactic crowd
> 50 satellites
(SDSS, PanSTARRS, DES)

Credit: J.D. Simon / AR Astronomy and Astrophysics

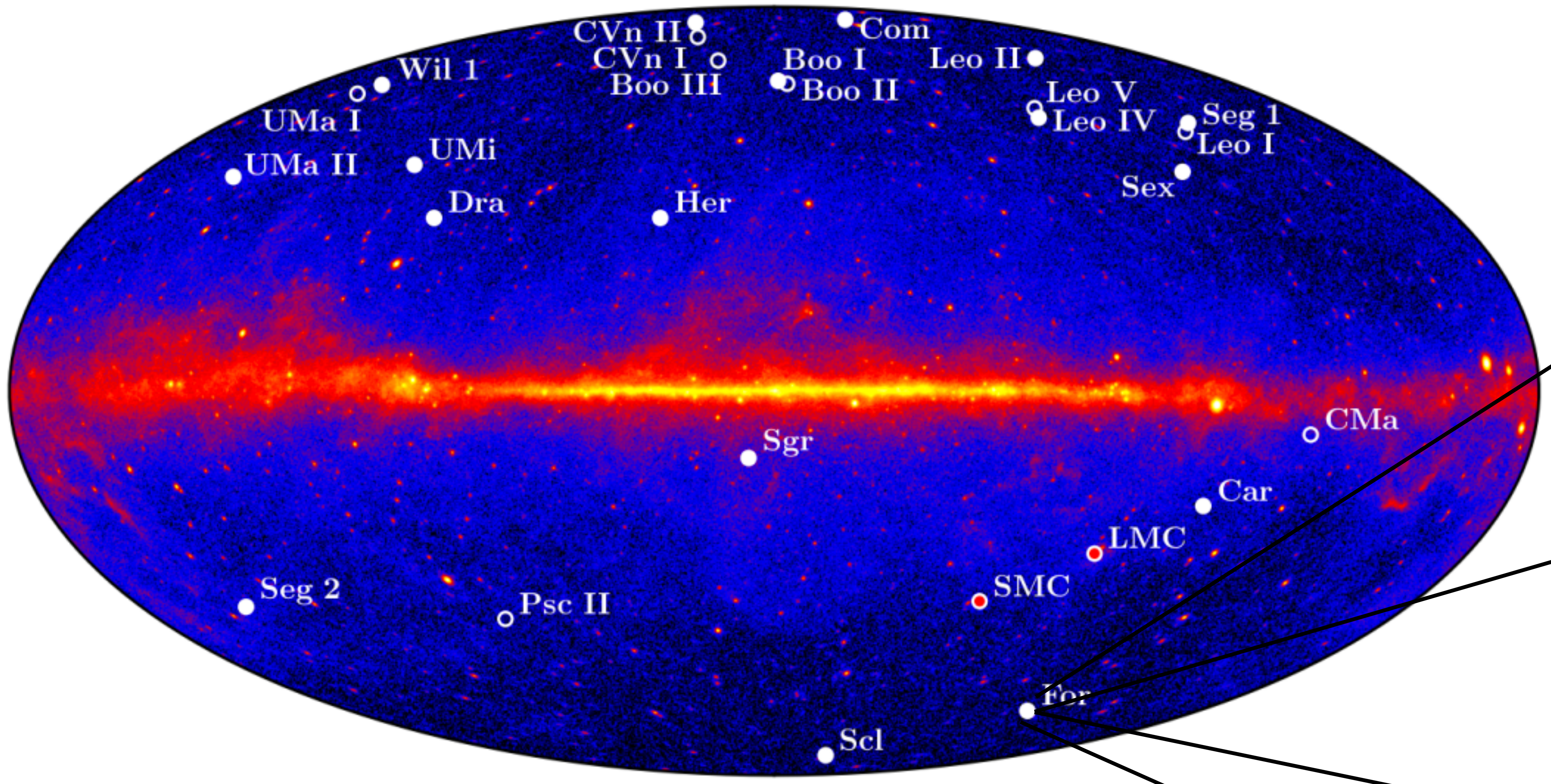
Limits from dwarf spheroidal galaxies



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

Fermi-LAT Collaboration, PRL'11

Limits from dwarf spheroidal galaxies



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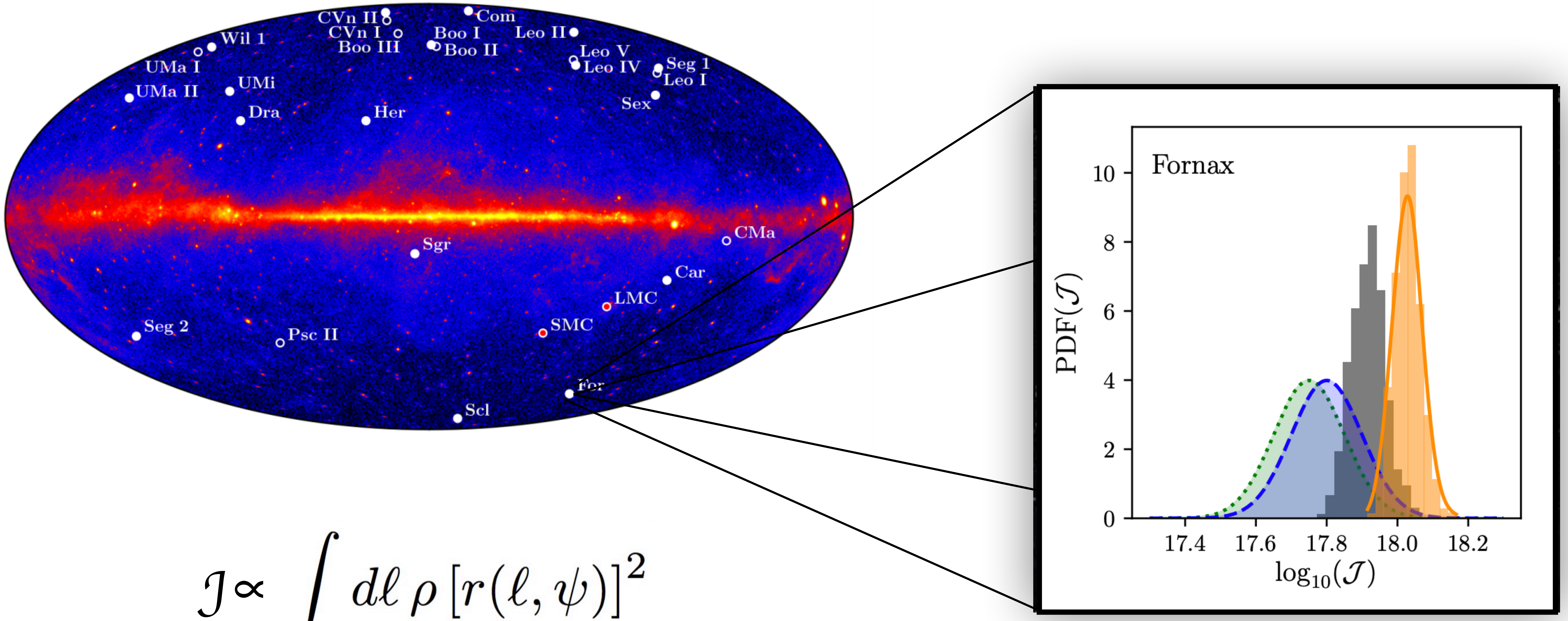
Fermi-LAT Collaboration, PRL'11

Credit: ESO/Fornax galaxy

Limits from dwarf spheroidal galaxies



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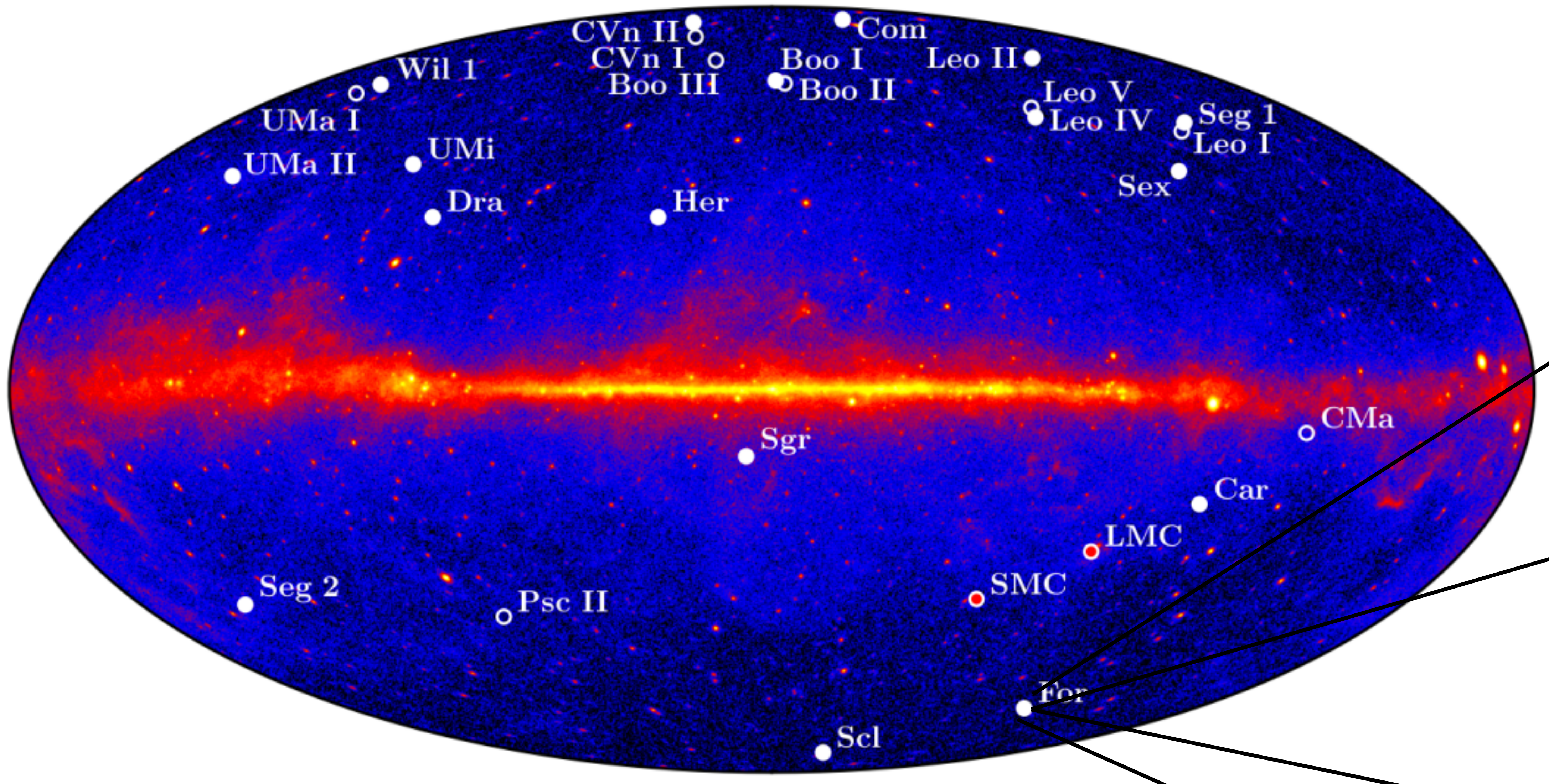
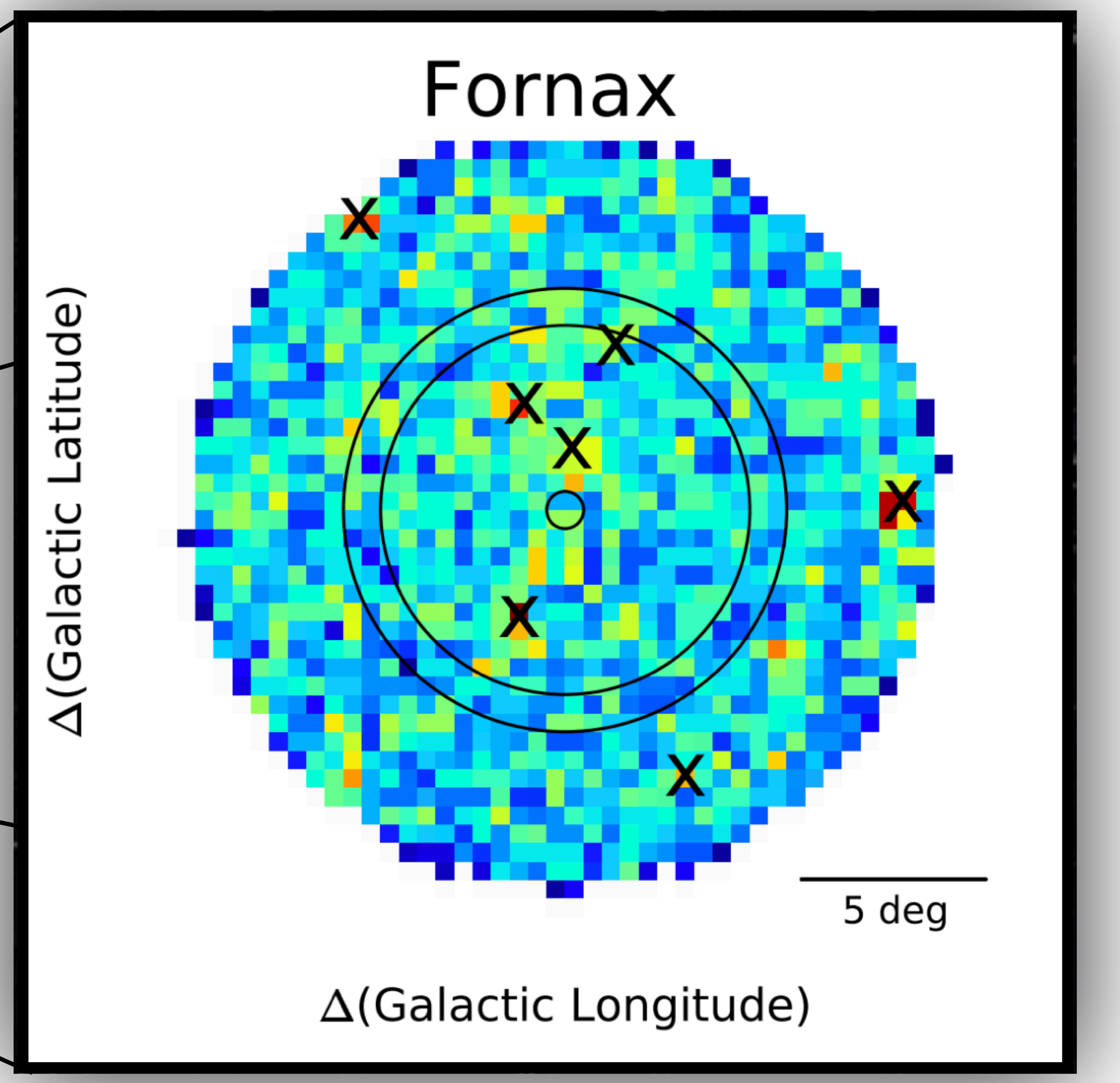
Fermi-LAT Collaboration, PRL'11

GRAVSPHERE
Alvarez, FC+ JCAP'20

Limits from dwarf spheroidal galaxies





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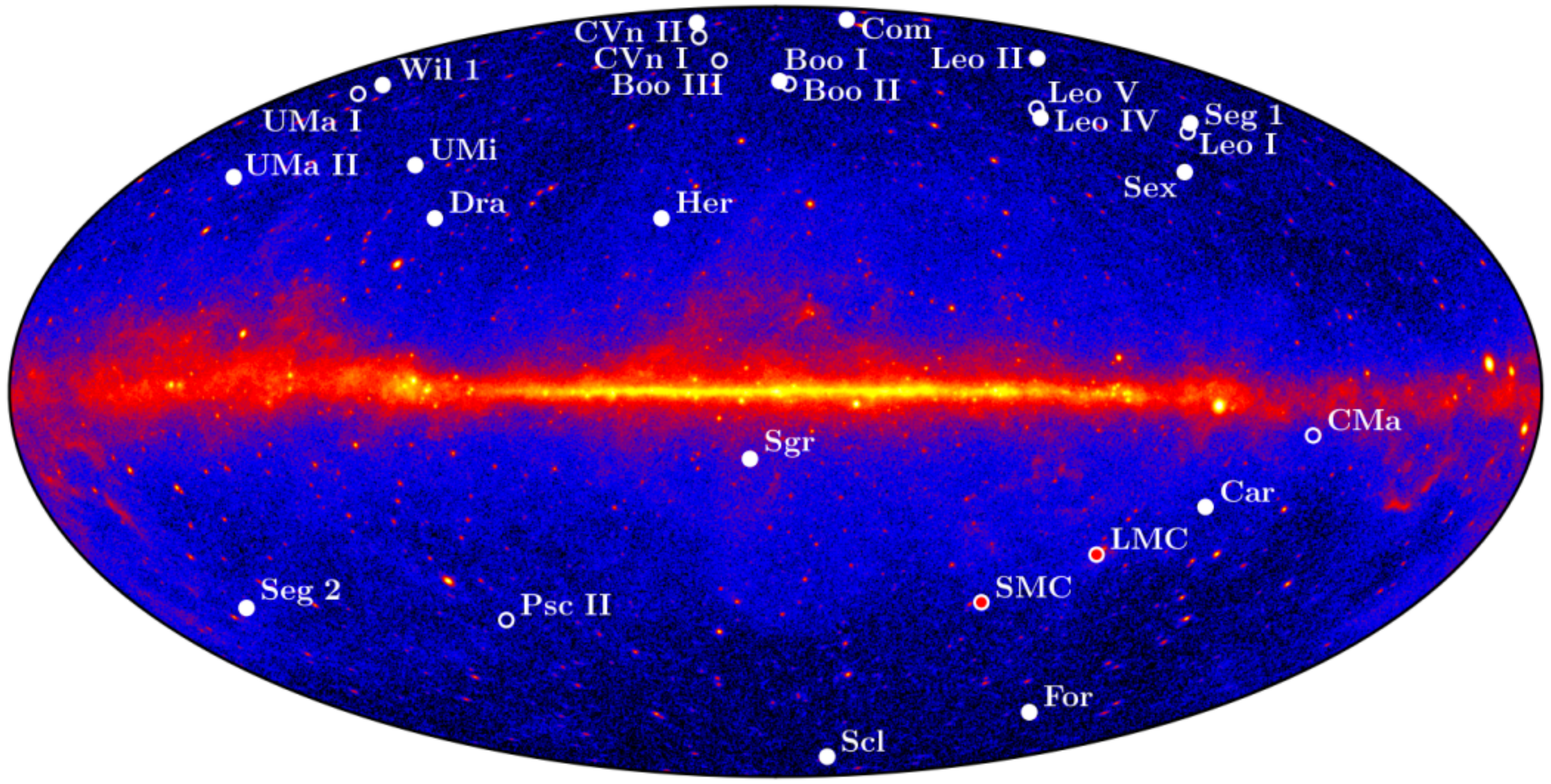
Fermi-LAT Collaboration, PRL'11

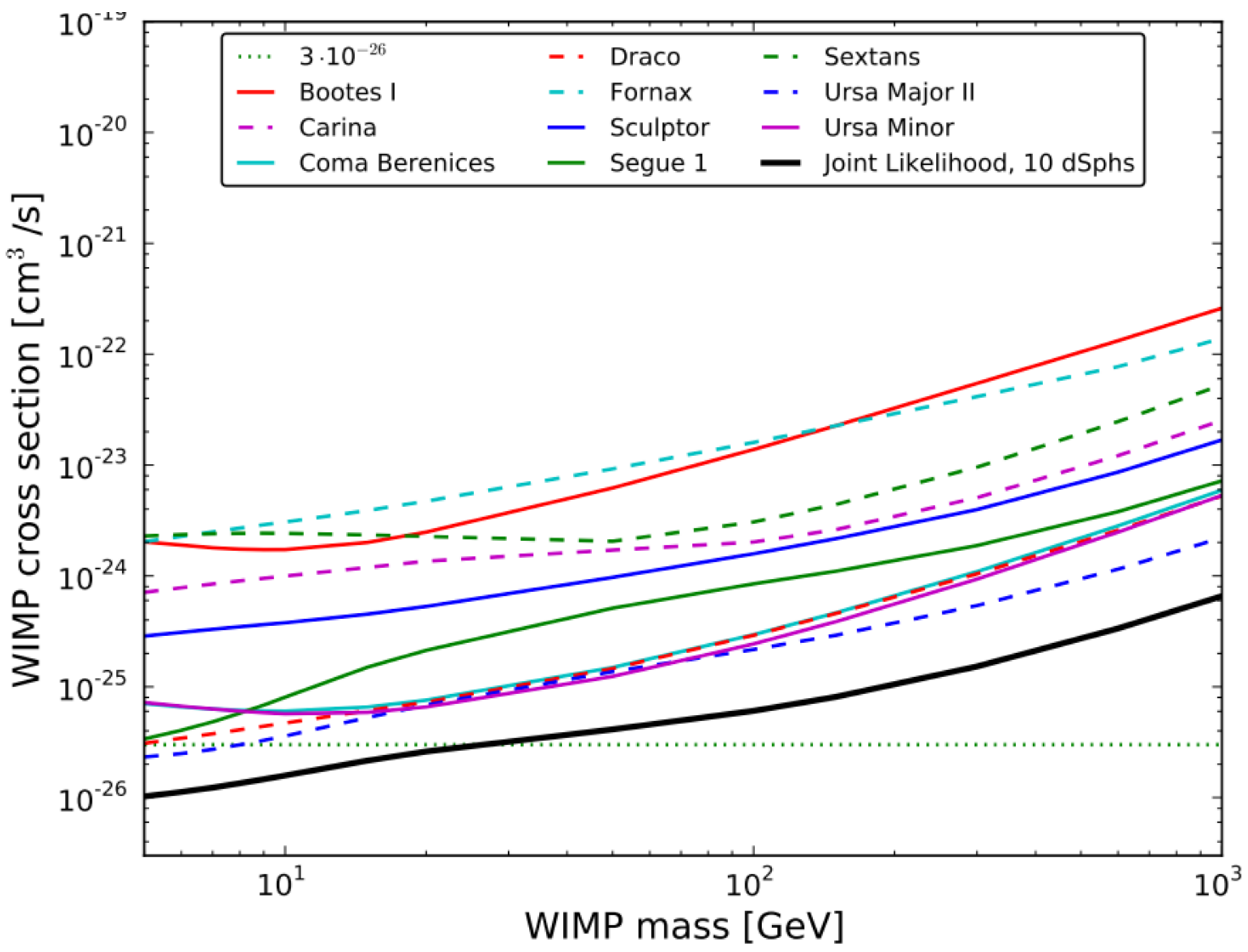
Mazziotta+Astrop. Phys.'12

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**

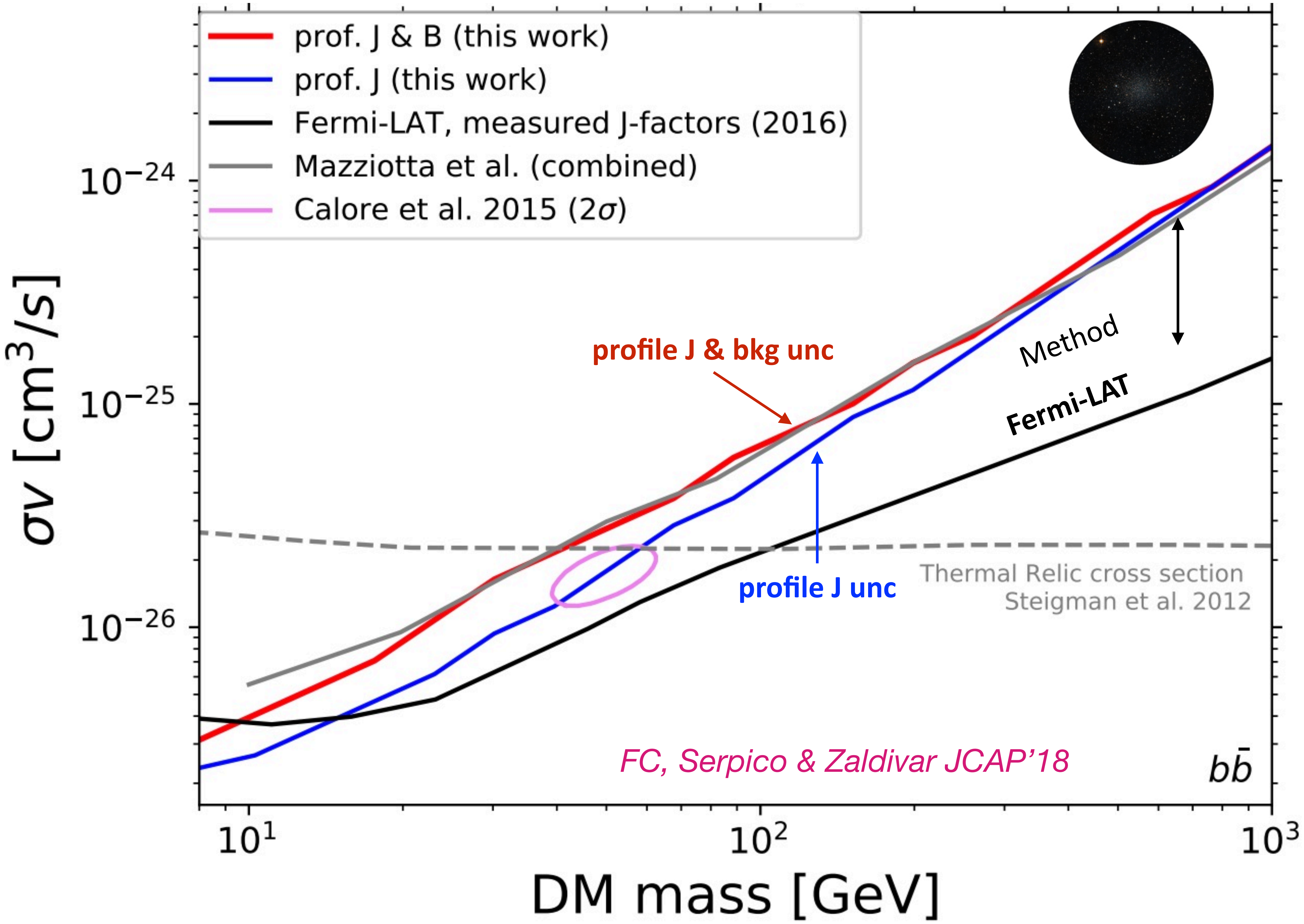
Fermi-LAT Collaboration, PRL'11

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

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



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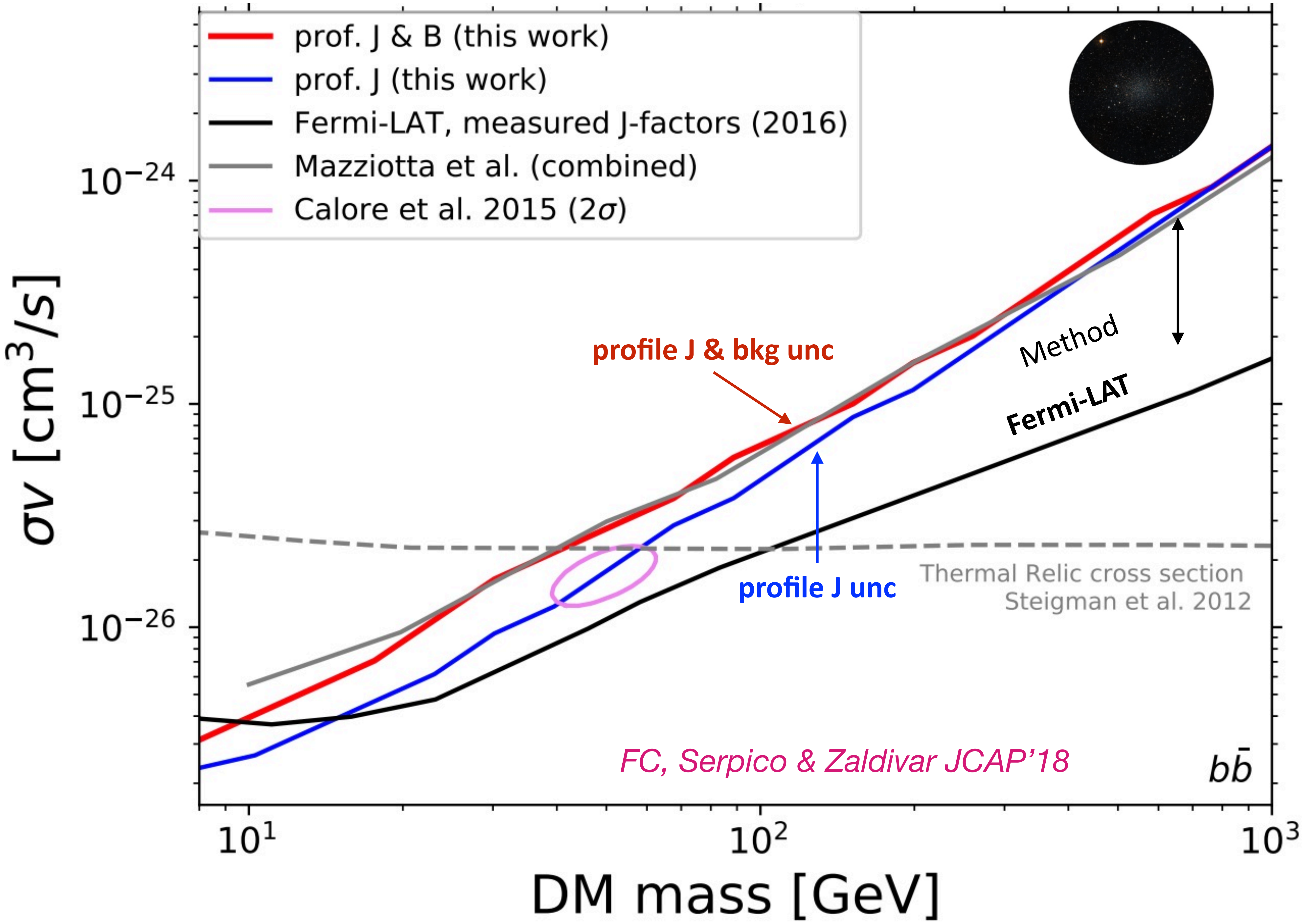


TAKE AWAY: Typically strong probes but keep in mind systematics

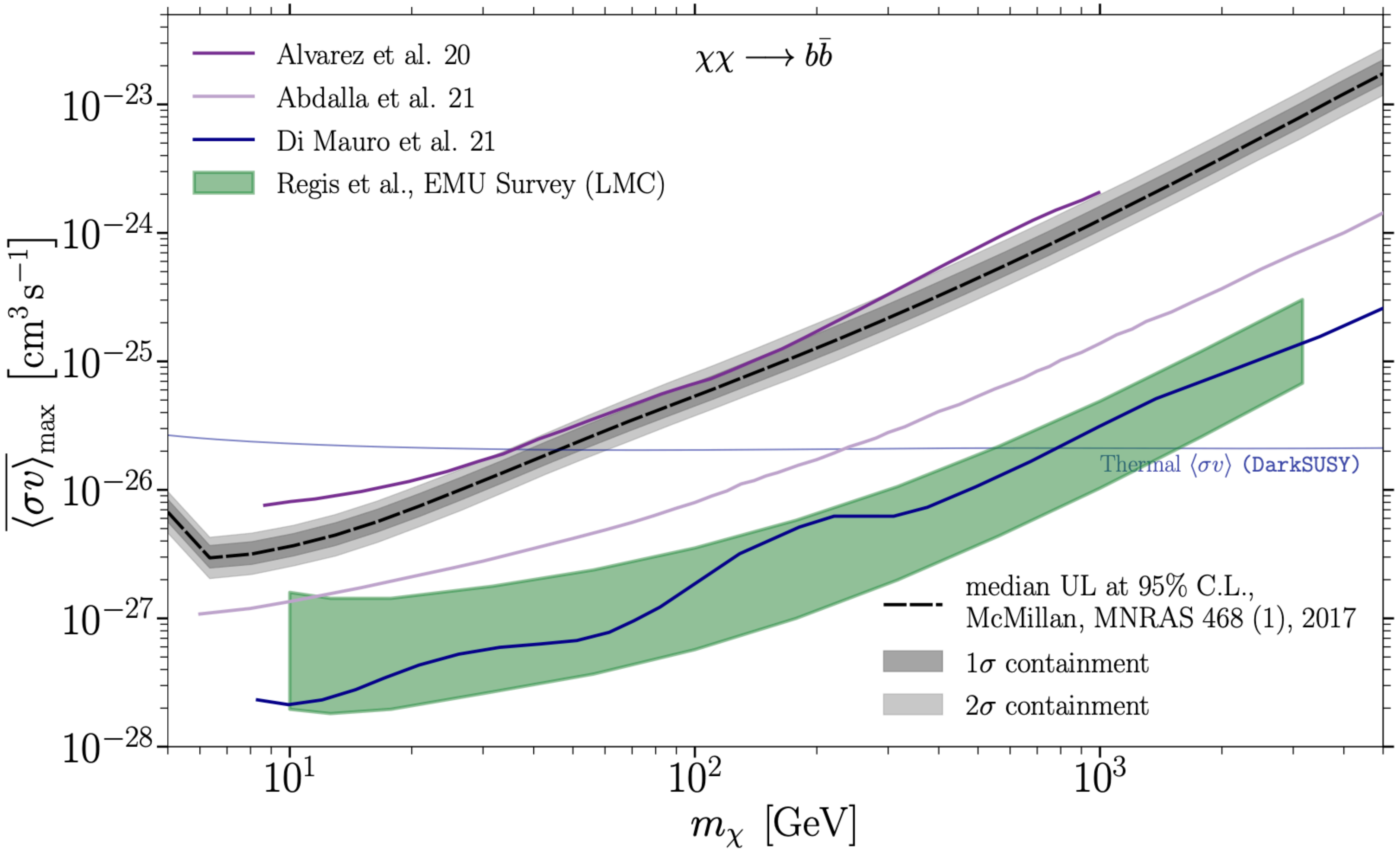
Limits on annihilating WIMPs

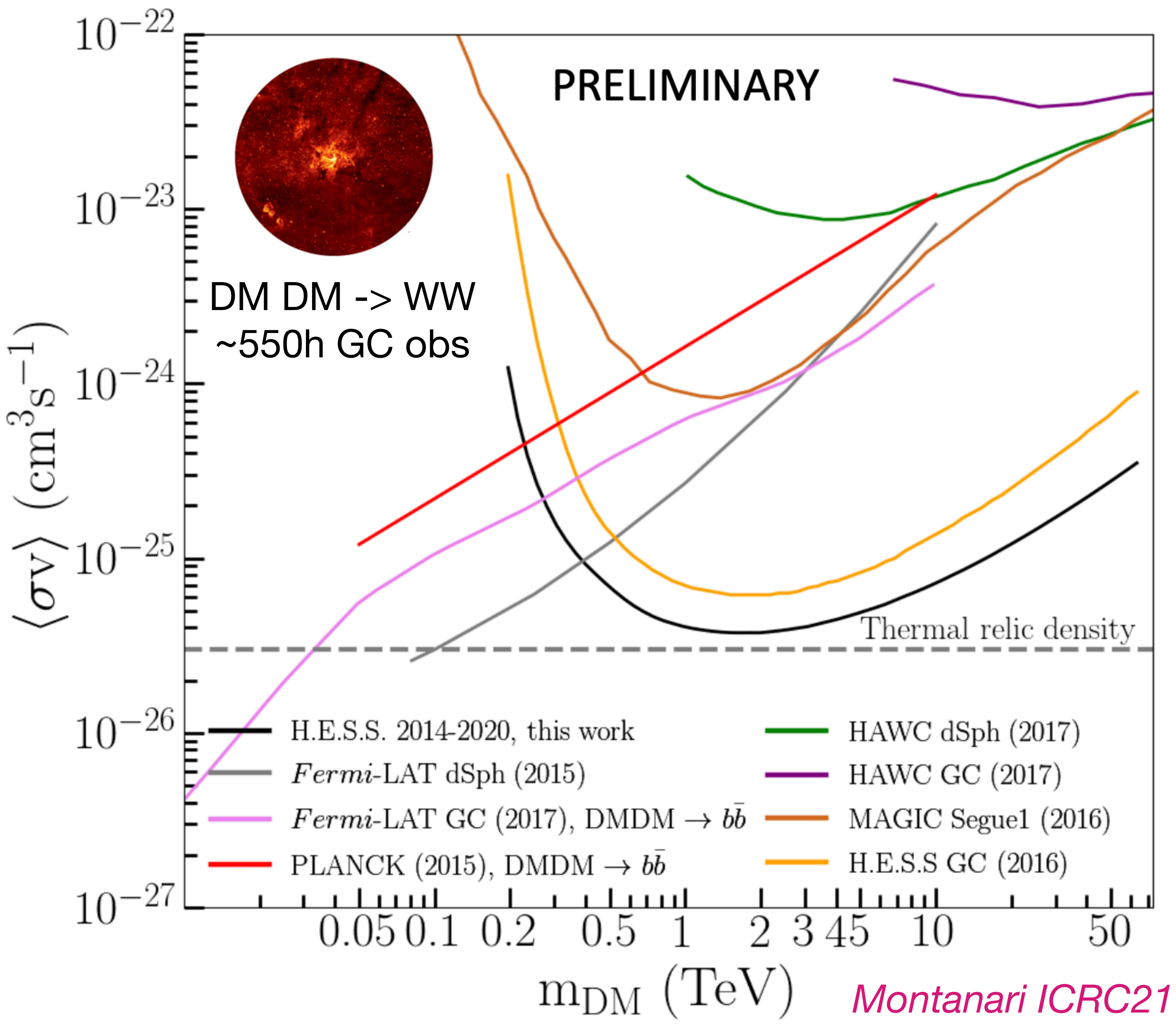
Summary of multi-targets and MW constraints

~ a few GeV — few TeV

0.2 TeV — 50 TeV

Eckner, FC+ 2208.03312





Montanari ICRC21

HAWC High Altitude Water Cherenkov Gamma-Ray Observatory

H.E.S.S.

MAGIC

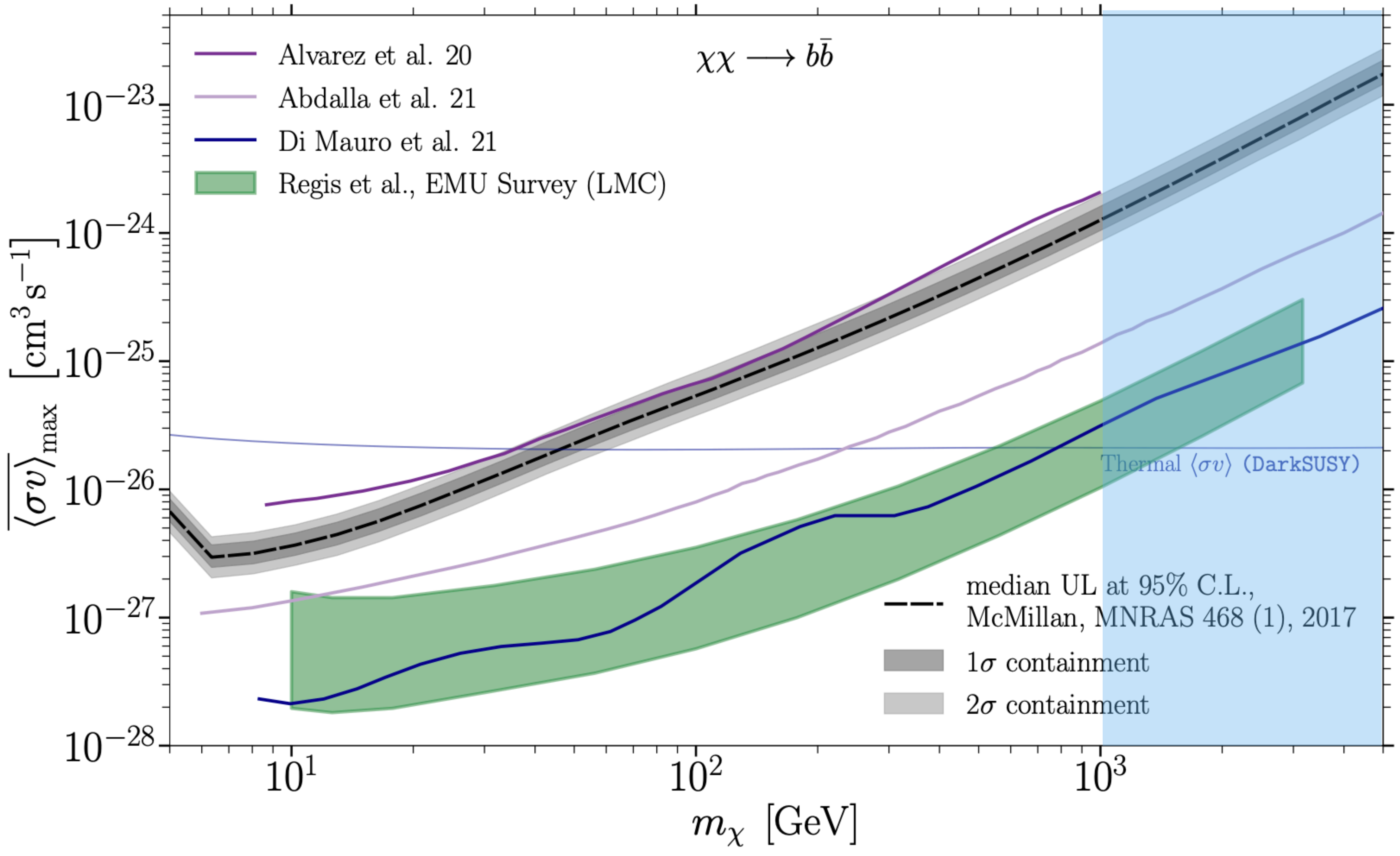
VERITAS

Prospects and opportunities

Extending the energy/mass scale

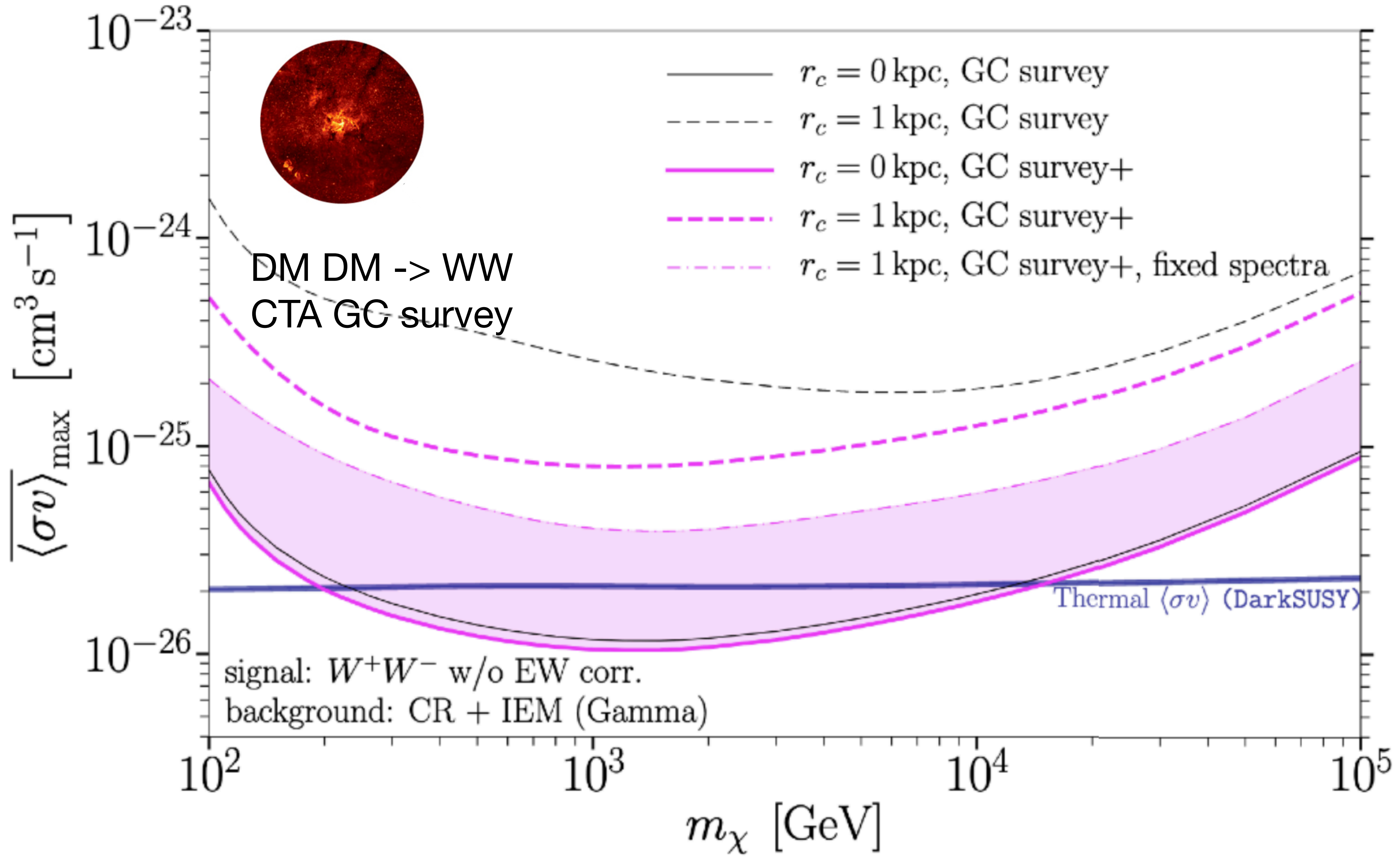
~ a few GeV — few TeV

Eckner, FC+ 2208.03312



TeV frontier

HAWC, CTA, SWGO

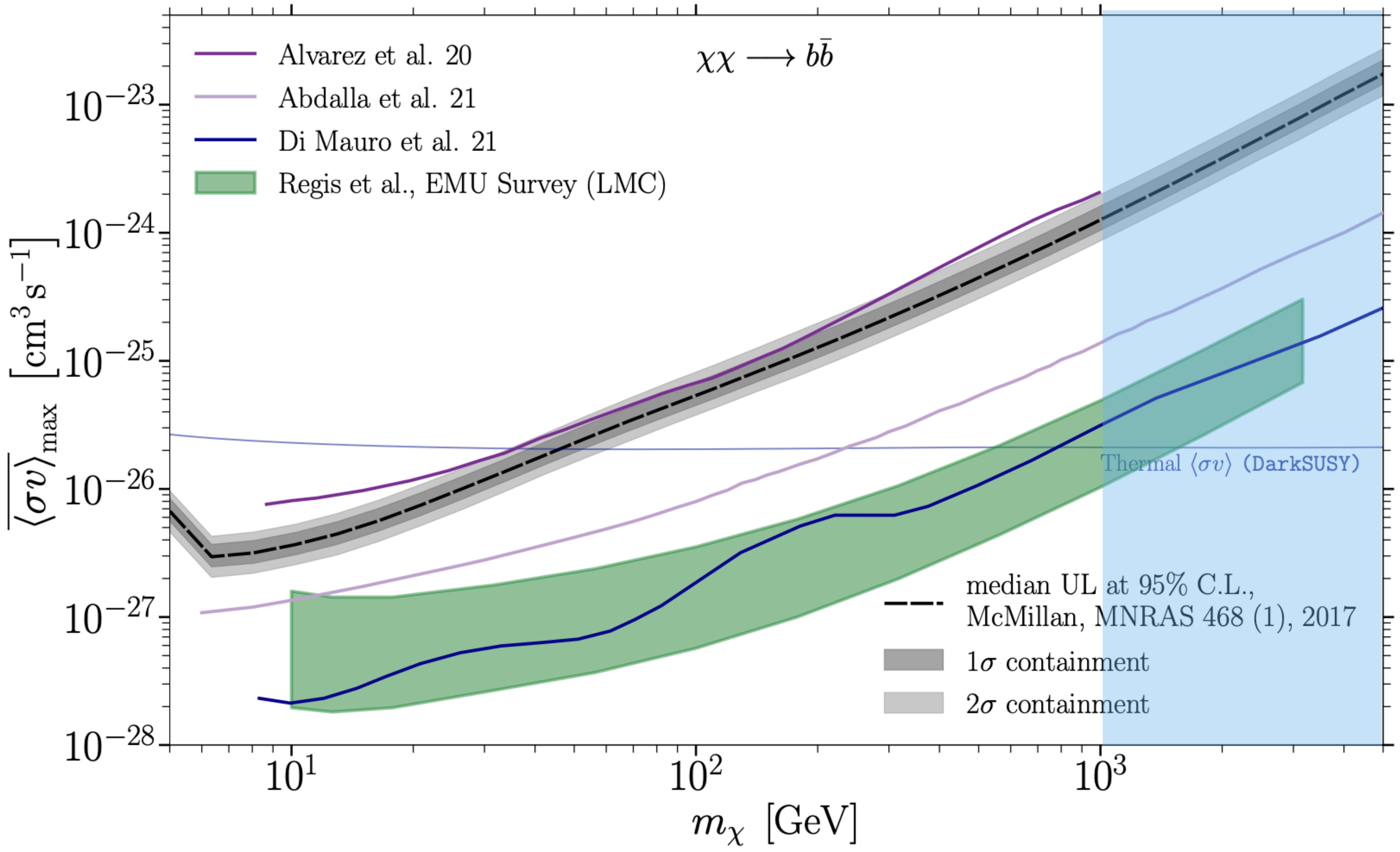


Prospects and opportunities

Extending the energy/mass scale

~ a few GeV — few TeV

Eckner, FC+ 2208.03312



Sub-PeV frontier

LHAASO,Tibet ASg

- Cannot be thermally produced (WIMpy) DM, since you hit the unitarity bound

  Griest & Kamiomkowski, PRD' 90

- Viable production mechanisms for PeV DM exist, e.g. inflation decay in low-scale reheating scenarios

  Harigaya+ 1402.2846

- The signal should come through decay and should appear in neutrino fluxes even before gamma rays

  Feldstein+ PRD'13; Esmaili & Serpico, JCAP'13; Chianese+ arXiv:2108.01678

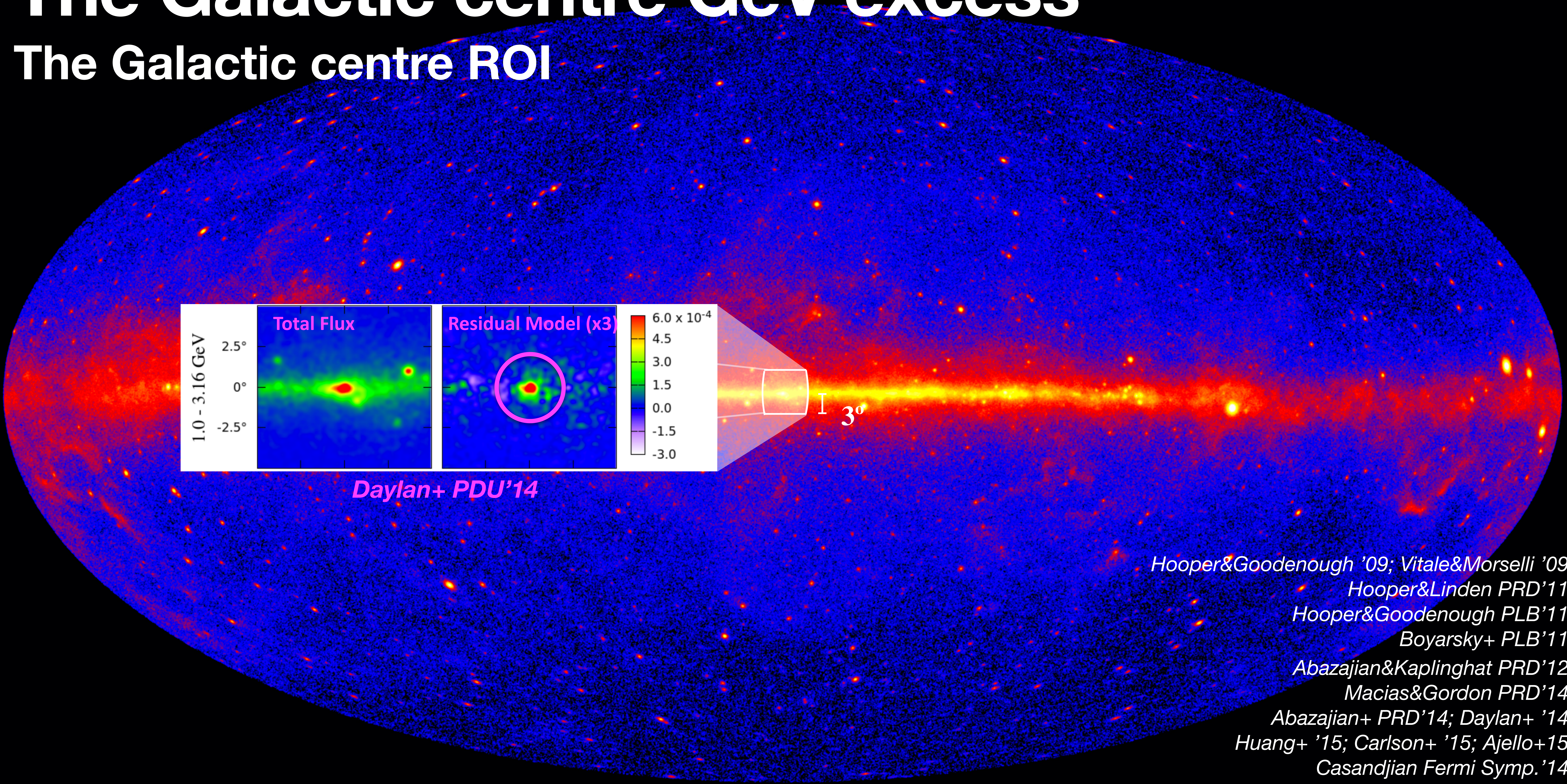
→ These data often provide *best bounds* to heavy DM lifetime

Esmaili & Serpico, PRD'21; *Chianese+ arXiv:2108.01678*

Anomalies and excess

The Galactic centre GeV excess

The Galactic centre ROI



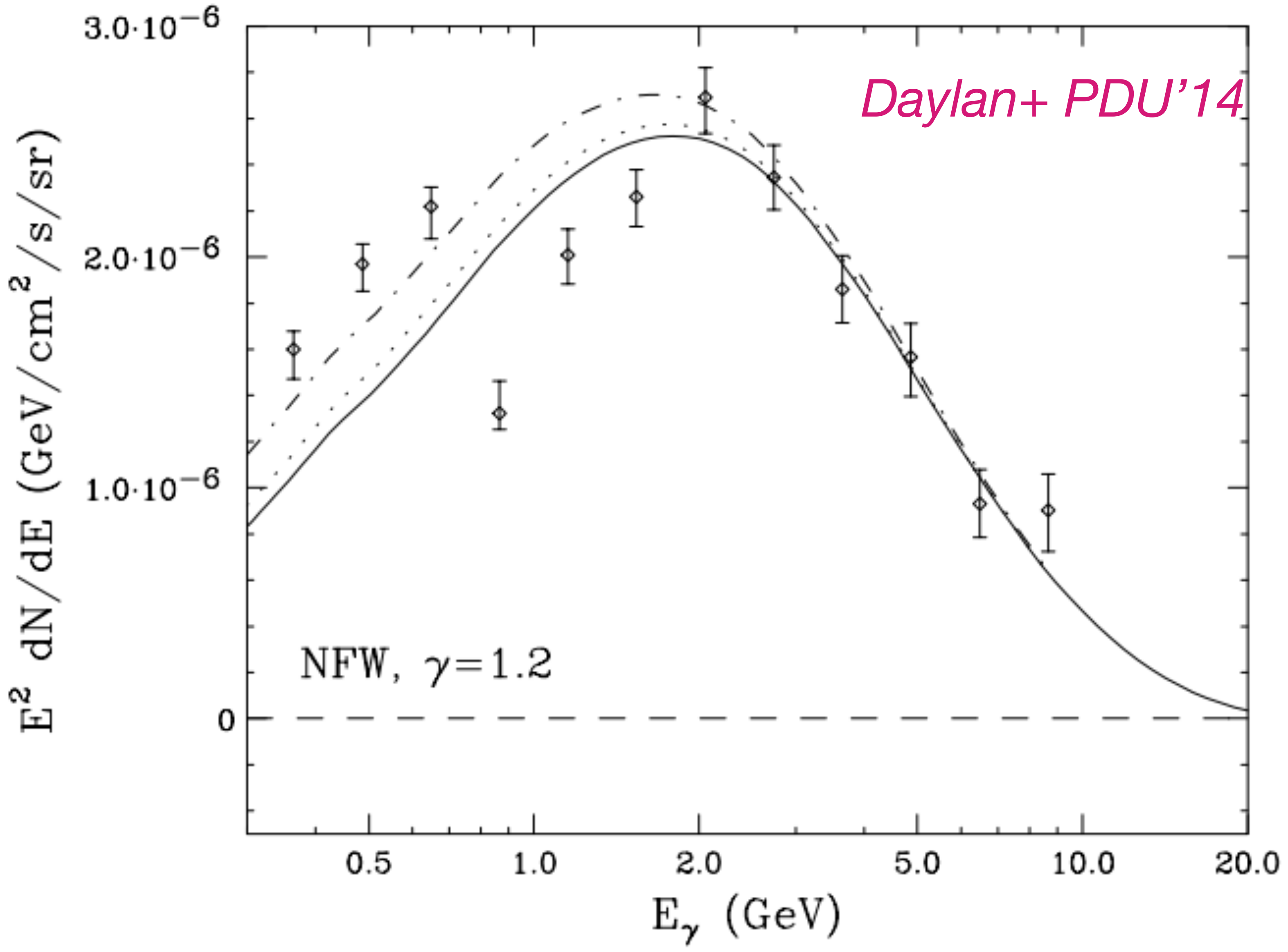
Hooper&Goodenough '09; Vitale&Morselli '09;
Hooper&Linden PRD'11;
Hooper&Goodenough PLB'11;
Boyarsky+ PLB'11;
Abazajian&Kaplinghat PRD'12;
Macias&Gordon PRD'14;
Abazajian+ PRD'14; Daylan+ '14;
Huang+ '15; Carlson+ '15; Ajello+15;
Casandjian Fermi Symp.'14;
de Boer+'16; Macias+'16; etc.

The GeV excess

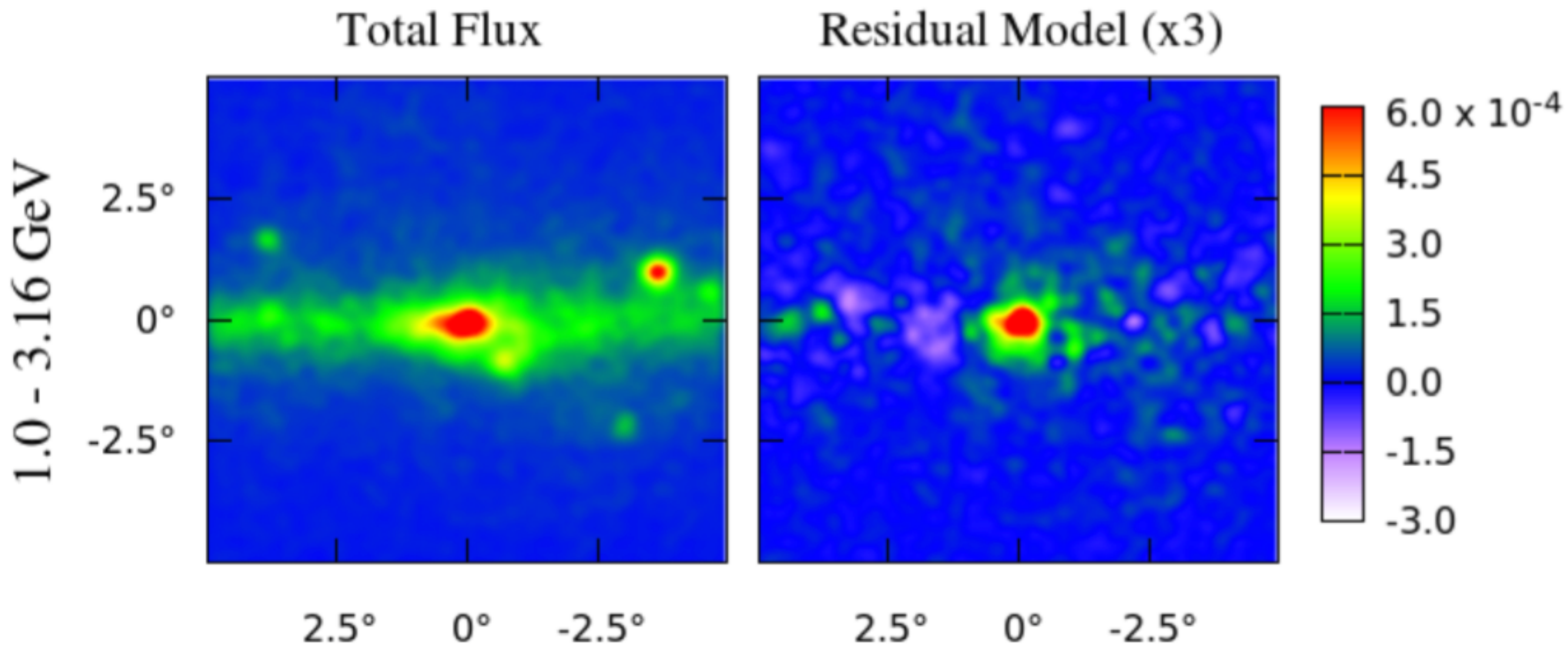
Galactic centre characterisation

$|\ell|, |b| \lesssim 2^\circ$

Spectrum



Morphology



- ✓ **Extended excess emission** above: model for diffuse emission, Sgr A* and other point sources
- ✓ The **spectrum** might strongly suffer from **background modelling**
- ✓ Compatible to be **spherically symmetric** about the Galactic centre
- ✓ Connection with HESS TeV GC ridge

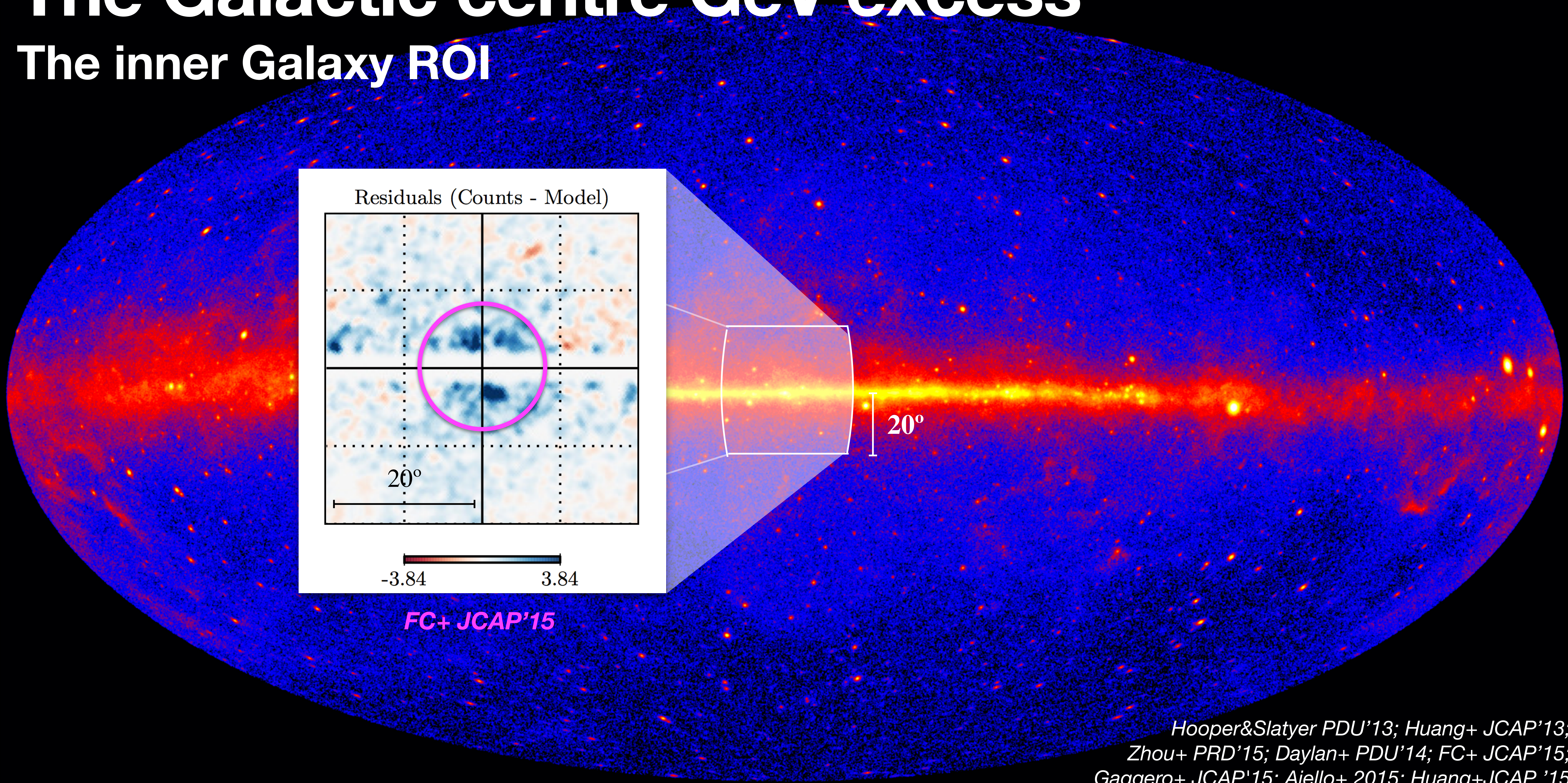
Abazjian+ PRD'14

$$\frac{dn}{dV} \sim r^{-\Gamma} \qquad \Gamma \sim 2.6$$

Macias&Gordon PRD'14; Macias+ MNRAS'15

The Galactic centre GeV excess

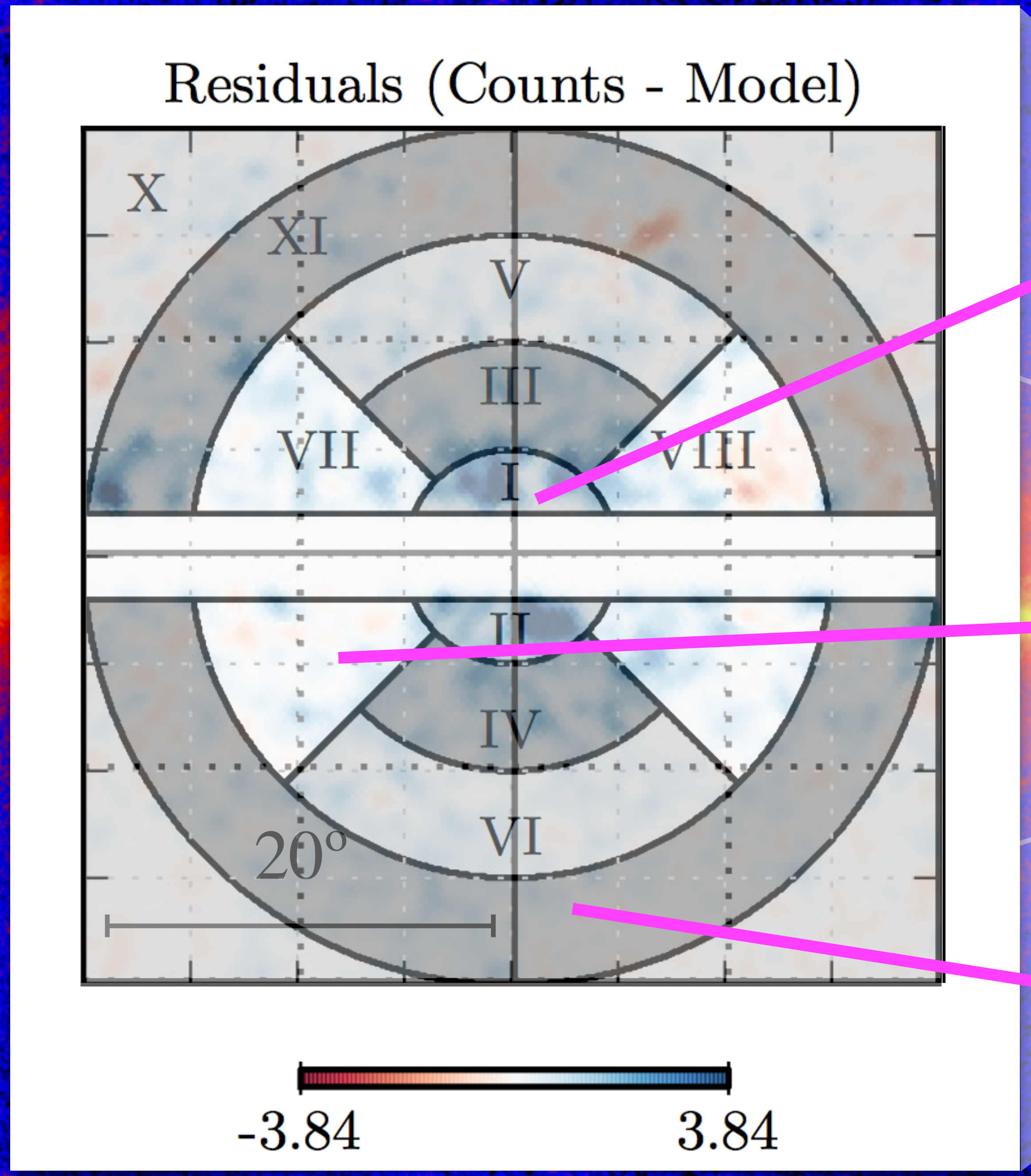
The inner Galaxy ROI



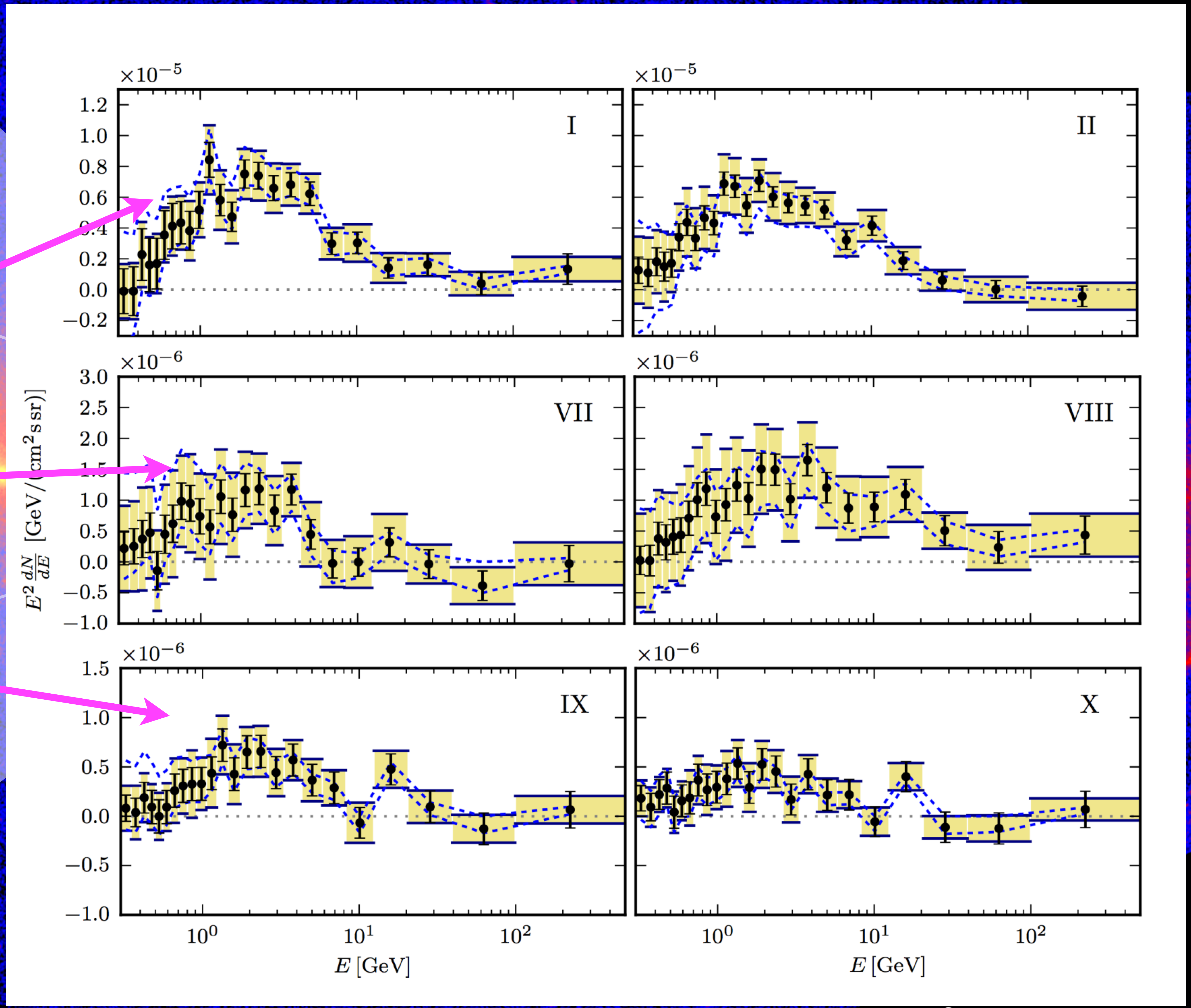
Hooper&Slatyer PDU'13; Huang+ JCAP'13; Zhou+ PRD'15; Daylan+ PDU'14; FC+ JCAP'15; Gaggero+ JCAP'15; Ajello+ 2015; Huang+JCAP '15 Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017; etc.

The Galactic centre GeV excess

The inner Galaxy ROI



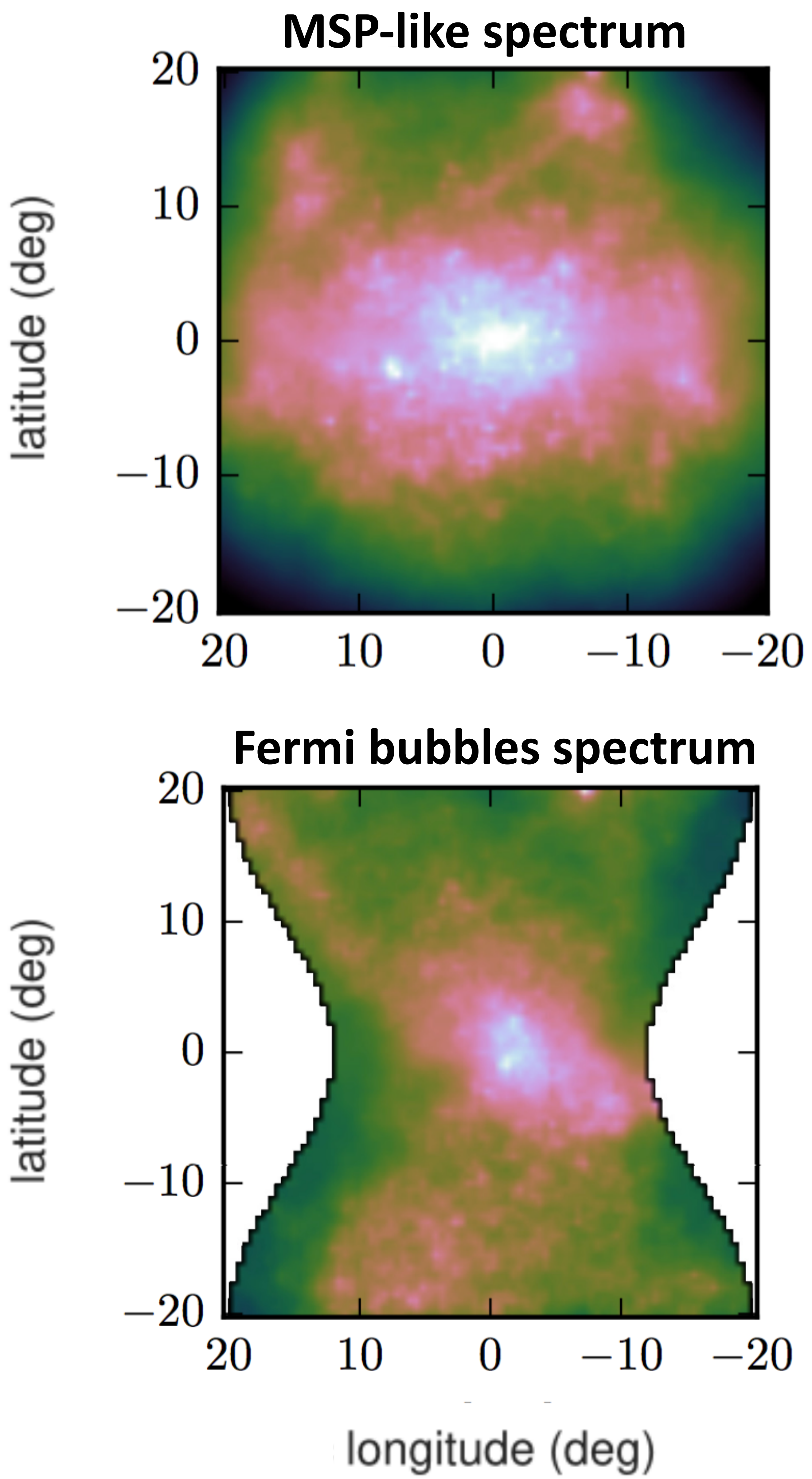
FC+ JCAP'15



1. Almost uniform spectrum peaked at ~2 GeV
2. Extended at least up to 10 degrees

Hooper&Slatyer PDU'13; Huang+ JCAP'13; Zhou+ PRD'15; Daylan+ PDU'14; FC+ JCAP'15; Gaggero+ JCAP'15; Ajello+ 2015; Huang+JCAP '15 Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017; etc.

The GeV excess emission



- Established evidence for an excess emission above **known** astrophysical backgrounds (diffuse emission + point-like sources)
- **Several independent techniques** find analogous results (template fitting, spectral decomposition, image reconstruction)

Hooper+ PDU'13; Huang+ JCAP'13; Daylan+ '14; FC+ JCAP'15; Ajello+ ApJ'15; Gaggero+ JCAP'15; etc

Selig+ A&A'14; Huang+ JCAP'16; de Boer+'16

Storm, Weniger & FC JCAP'17

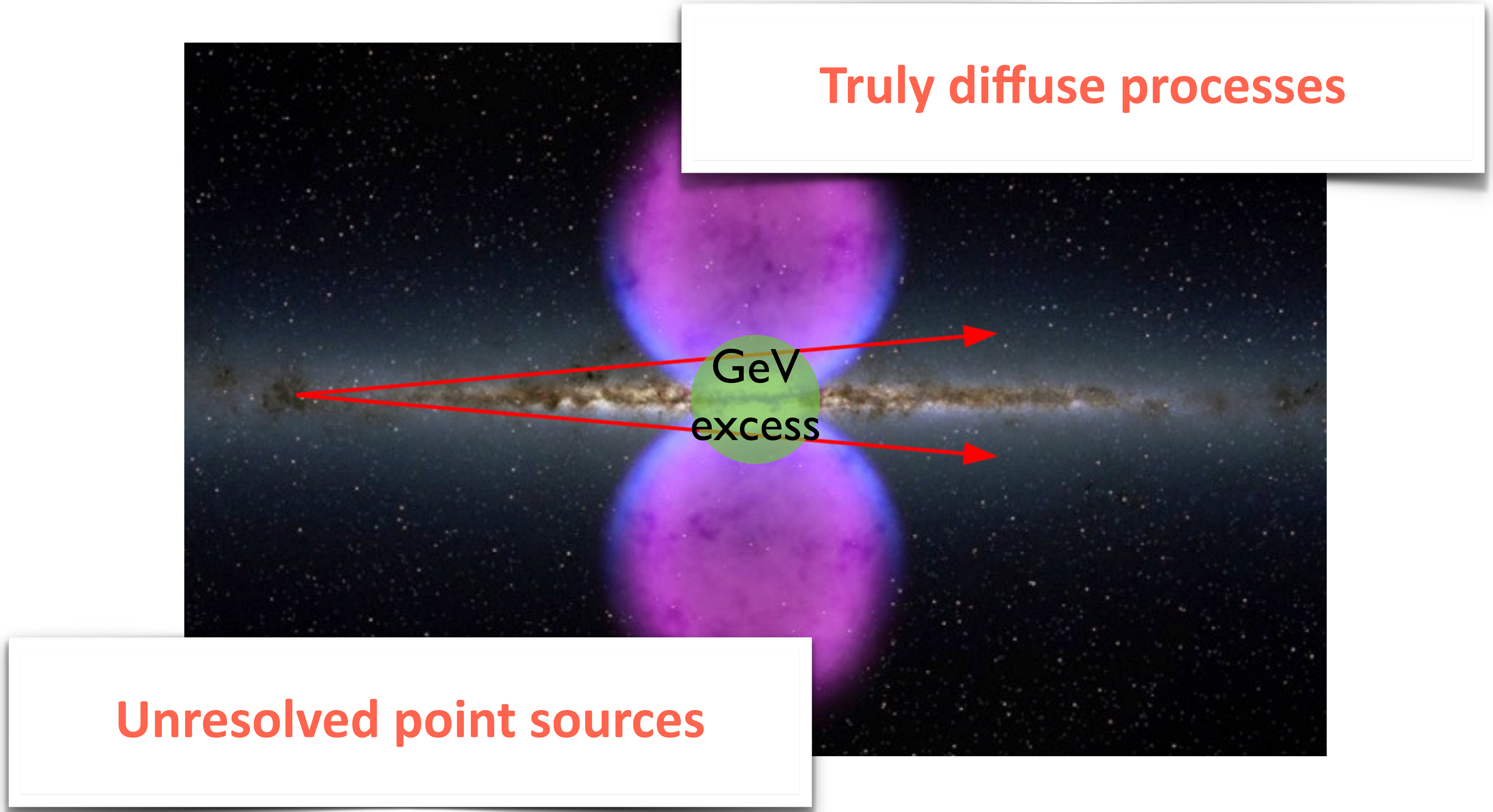
- **Template fitting - image reconstruction hybrid approach** (SKYFACT) has been proved very powerful in disentangling gamma-ray emission components

Storm, Weniger & FC JCAP'17

- **Residuals reduced significantly** when (realistic) nuisance parameters are included in the fit

What is the origin of the GeV excess?

Possible interpretations

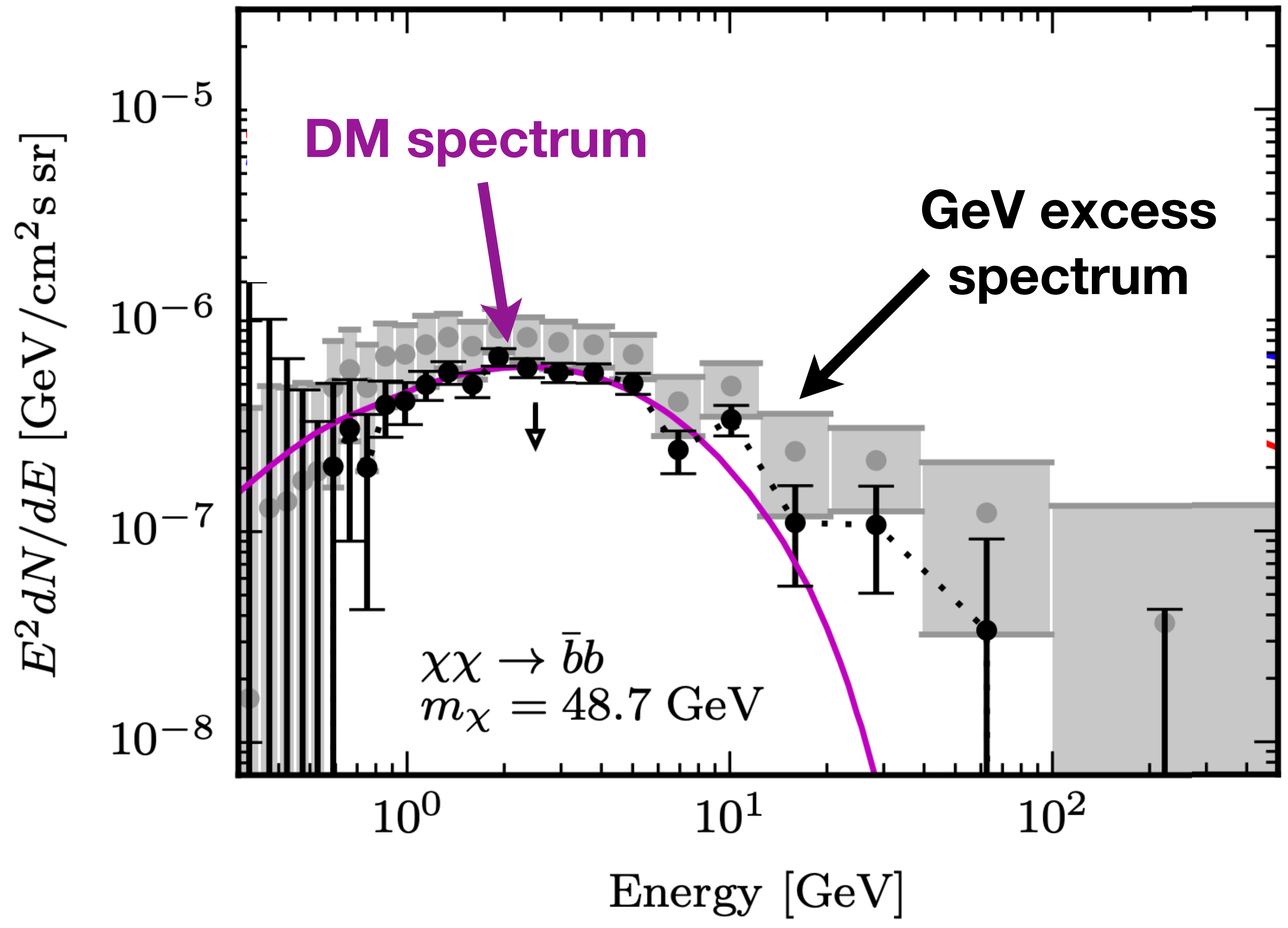


Constraints:
(a) Spectrum & Morphology of the excess? (b) Emission in other wavelengths?

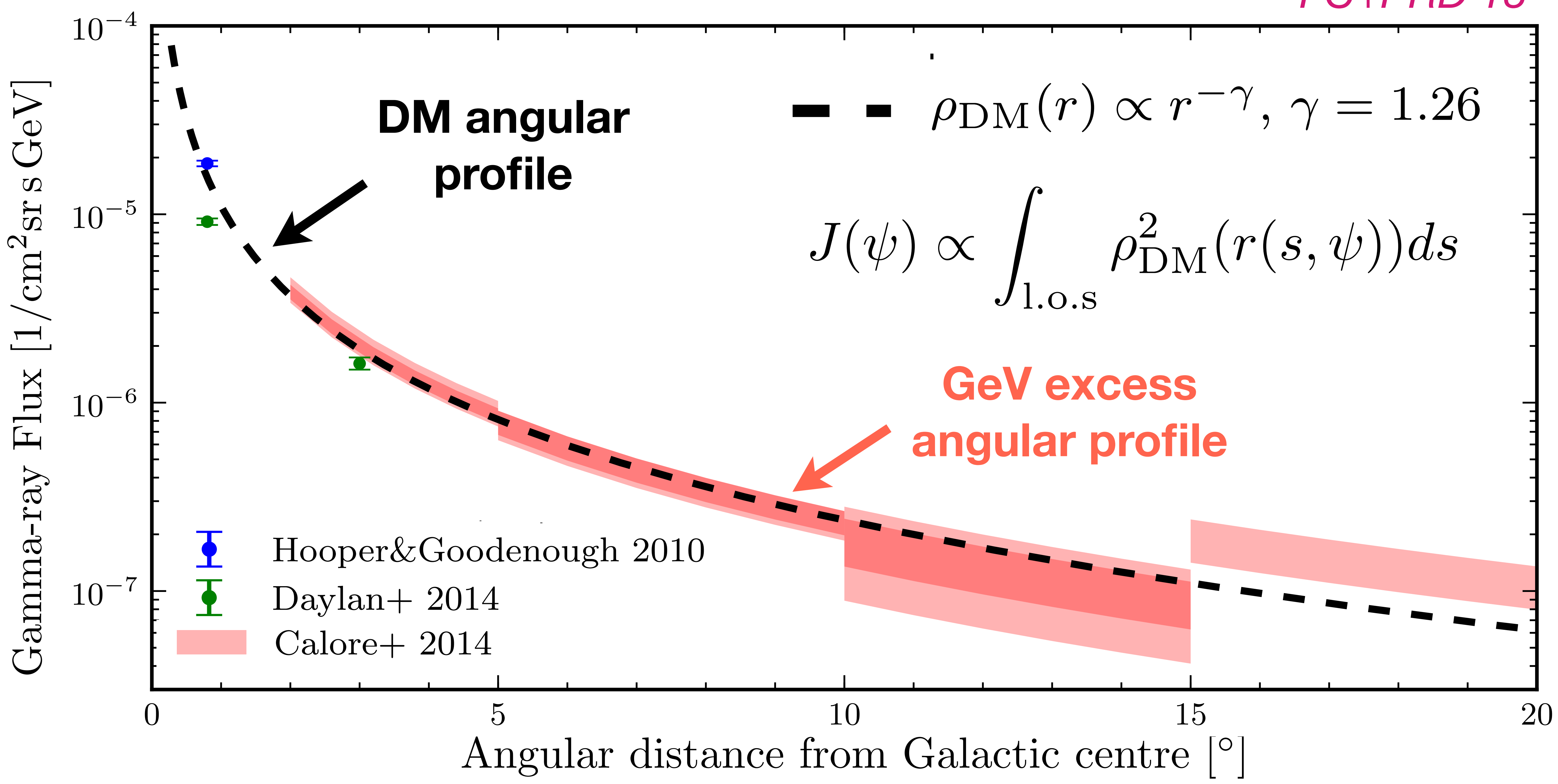
Diffuse processes I

Gamma rays from dark matter (DM) annihilation

- **Decay/Annihilation** of DM particles would lead to the production of **final gamma rays** with specific energy and spatial distribution



FC+PRD'15



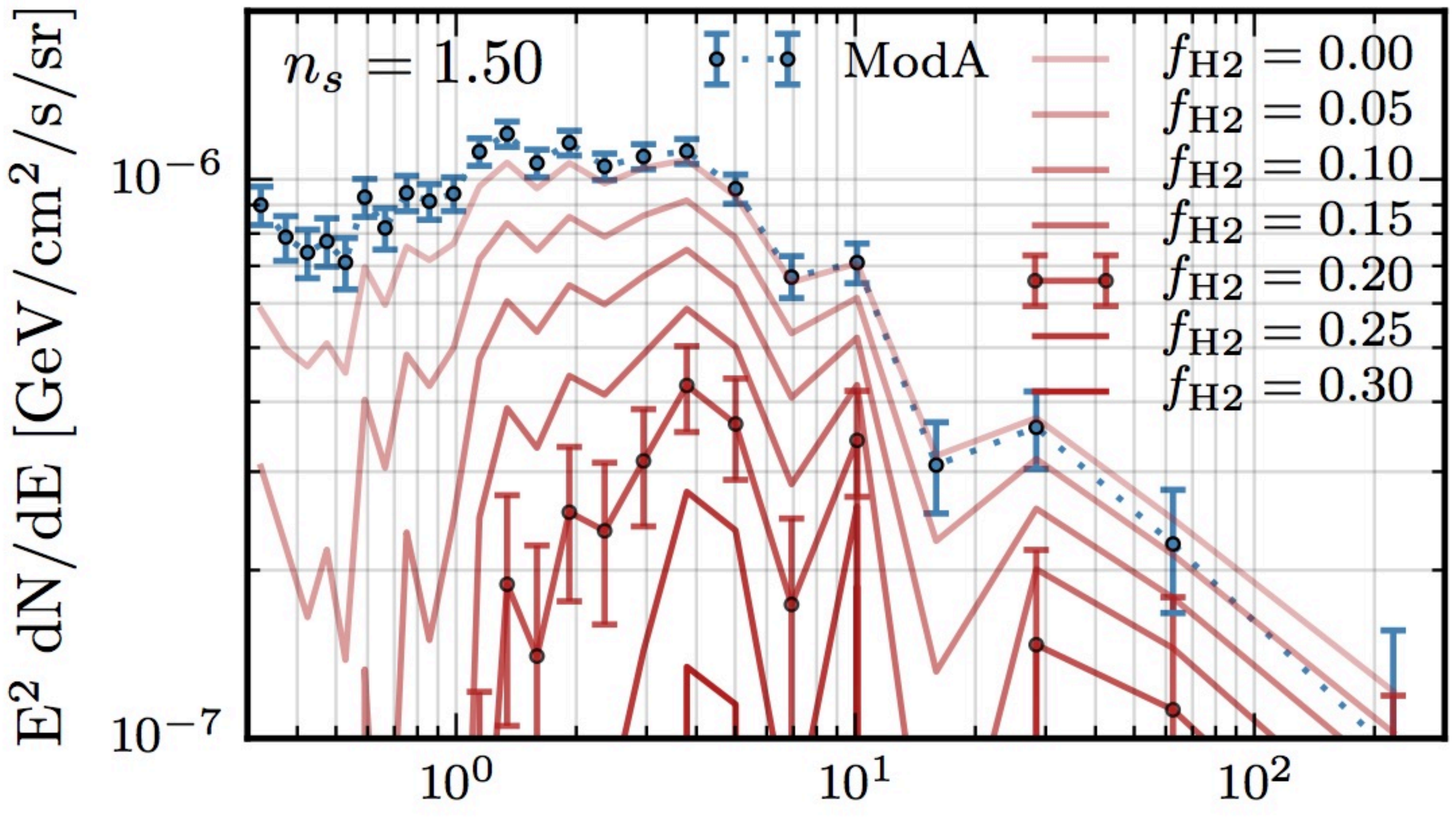
Agrawal+JCAP'15; Achterberg+JCAP'15; Bertone, FC+ JCAP'15; Liem, FC+ JCAP'16; O(>100) papers

Diffuse processes II

Cosmic rays in the GC

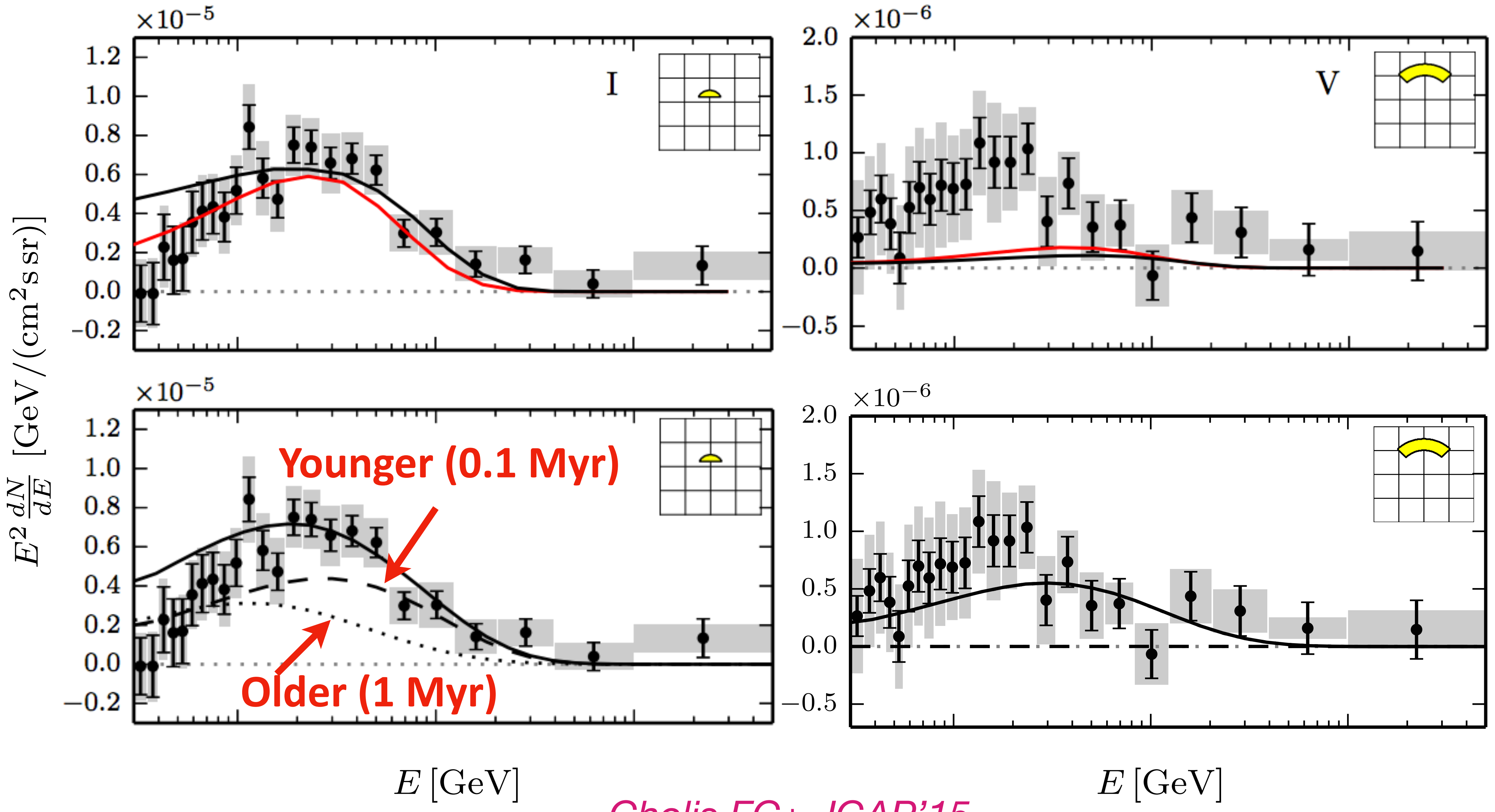
- **New population** of **cosmic rays** injected at the GC (electrons mostly)
- **Steady state** (from star formation in CMZ) and/or **time-dependent** (from outburst activity of the GC) source term

Gaggero+JCAP'15; Carlson+ PRD'16, PRL'16
Petrovic+ JCAP'14; Cholis,FC+ JCAP'15



Carlson+ PRD'16

Additional CR injection at the GC, accounting for enhanced SFR traced by H2 regions (5-10% of total SFR)

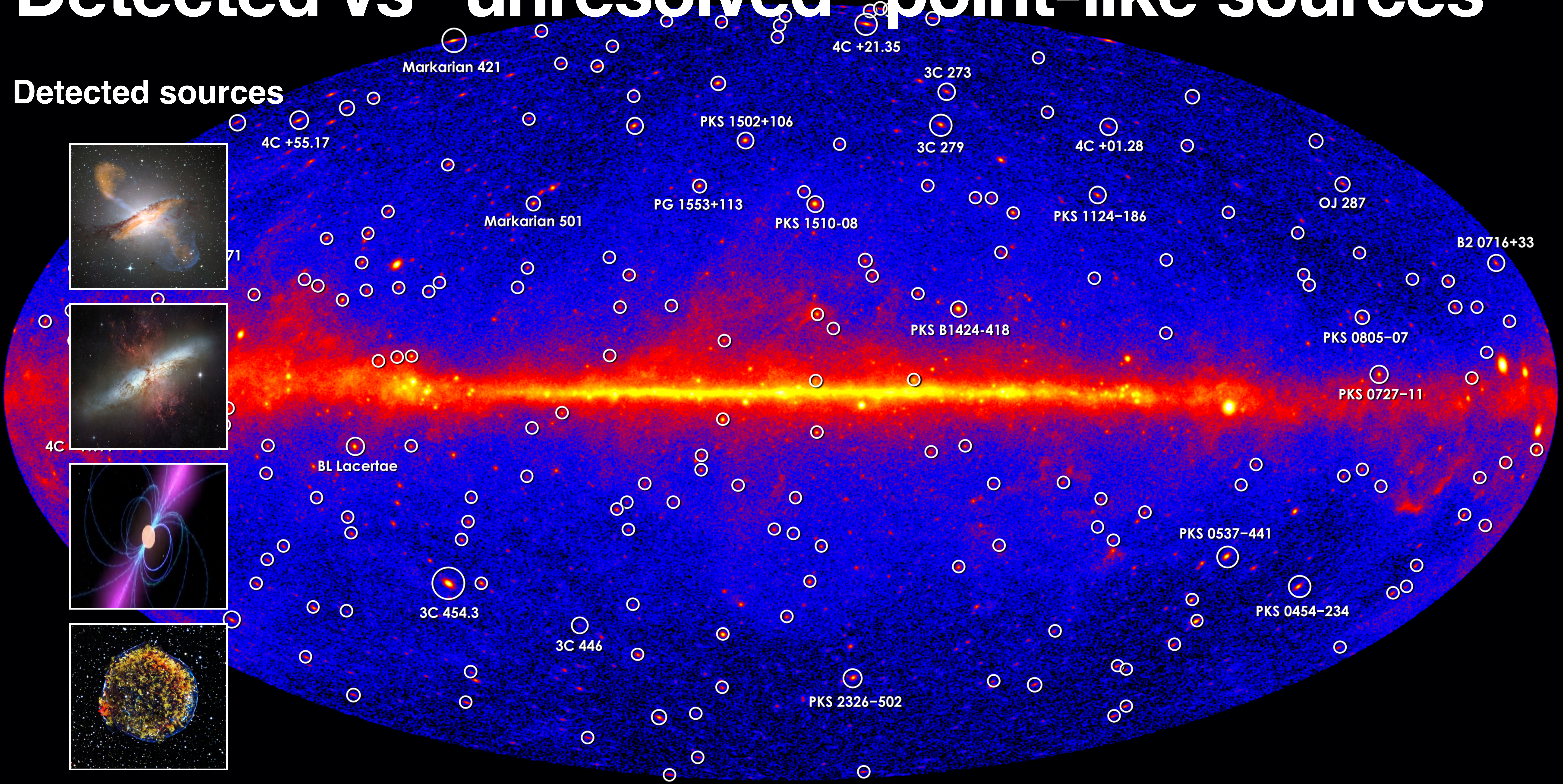


Cholis,FC+ JCAP'15

Time-dependent (burst) injection of leptons at the GC, and tuning of burst parameters (age, duration, injection spectrum, propagation parameters)

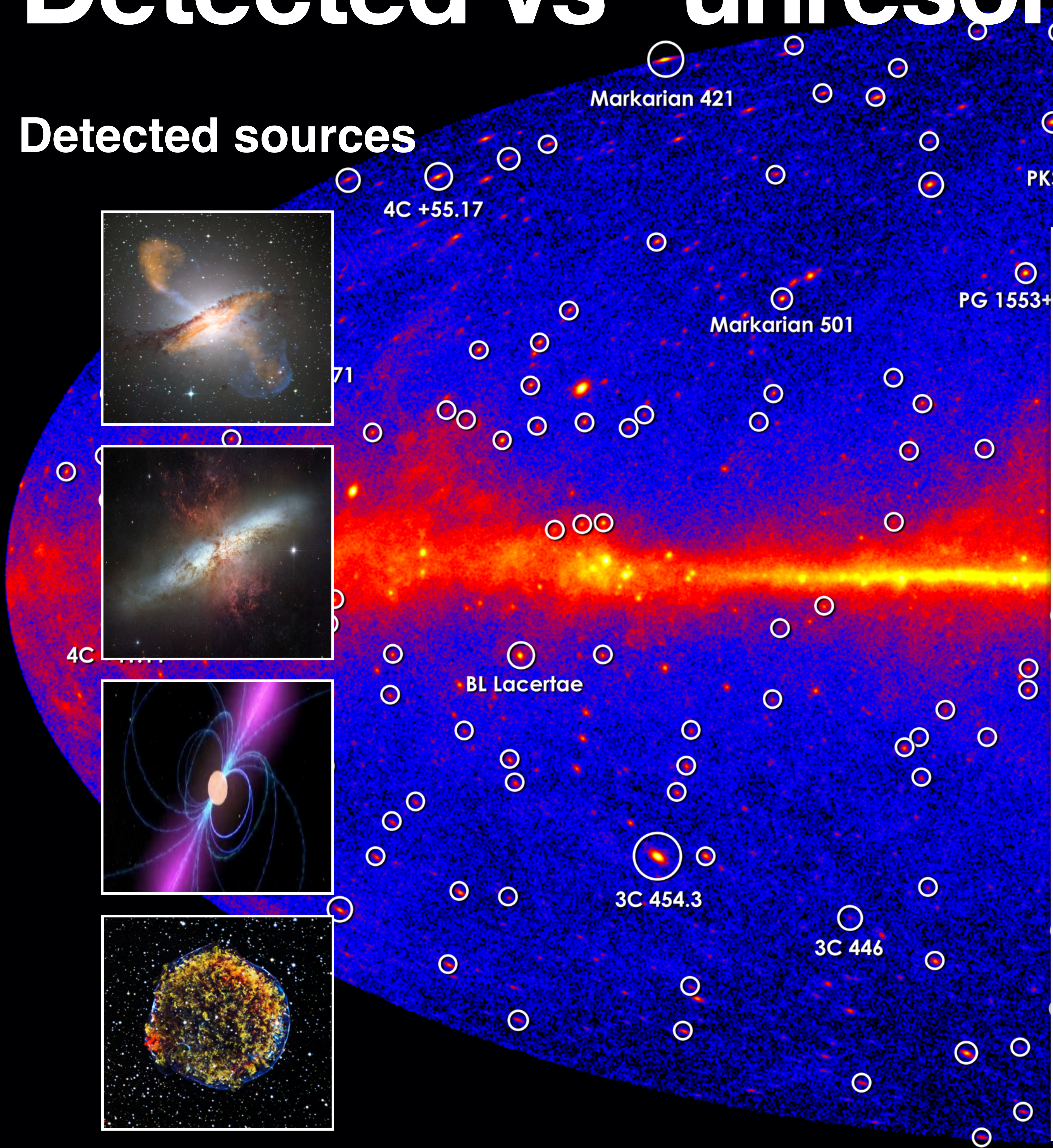
Detected vs “unresolved” point-like sources

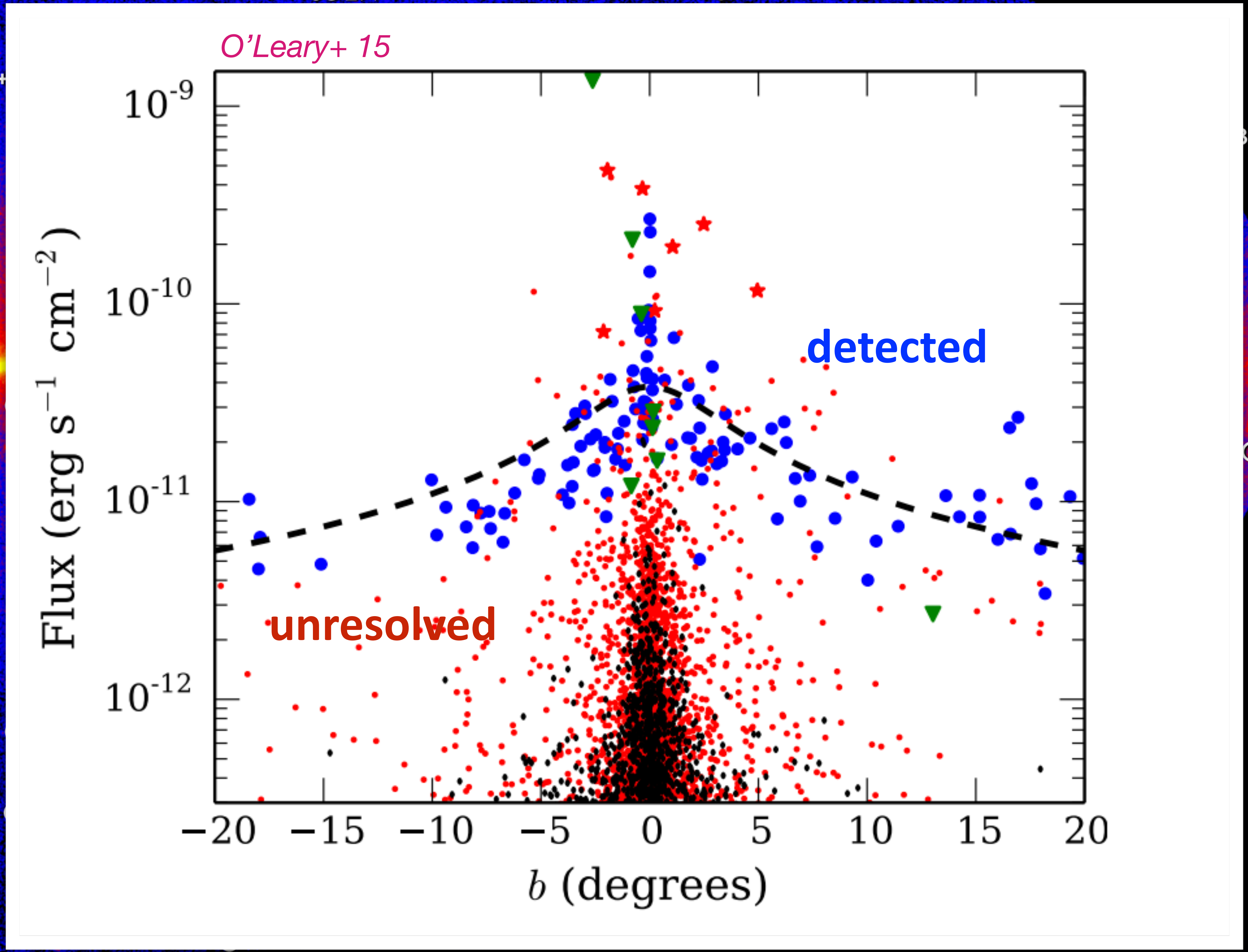
Detected sources



Detected vs “unresolved” point-like sources

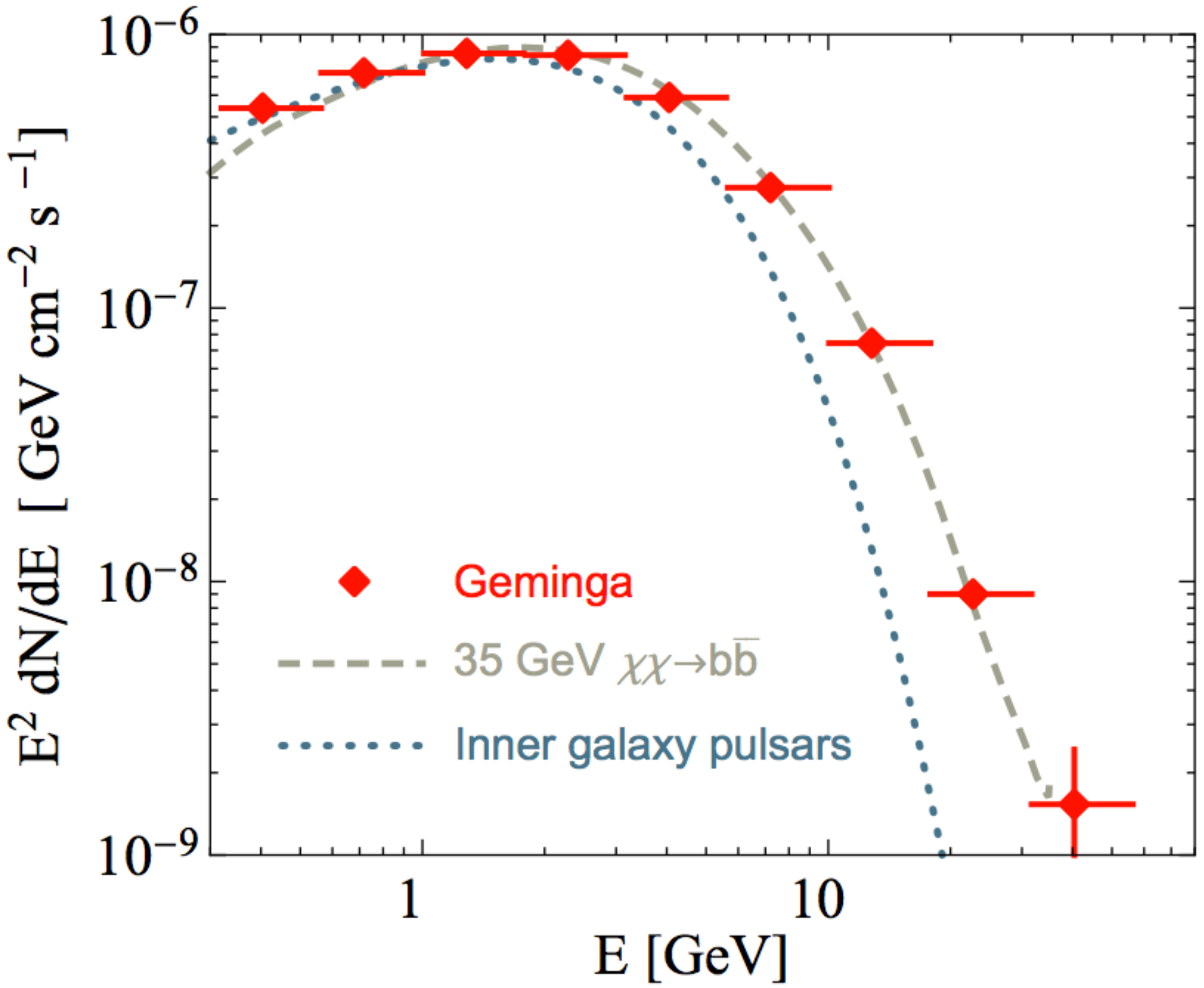
Detected sources





Unresolved sources: PSR and MSPs

Spectrum



- ✓ Excess spectrum compatible with observed **millisecond pulsars** (MSPs), and marginally **young pulsars**

Abazaijan&Kaplinghat'12

Morphology

$$\epsilon \propto r^{-\Gamma} e^{-r/R_{\rm cut}}$$

$$\Gamma = 2.5 \quad R_{\rm cut} = 3\,{\rm kpc}$$

- ✓ Proposed population of **MSPs in the bulge** (vs disc)

Hooper+PRD'14; Petrovic+ JCAP'15; Yuang+ MNRAS'14;

- ✓ **Young pulsars** from SF in the CMZ, but difficult to explain spatial extent and observed bright ones

O'Leary+ '15; Linden PRD'16

- ✓ **Bulge MSPs** from tidally disrupted globular clusters

Brandt&Kocsis ApJ'15; Abbate et al. 2017; Fragione et al. 2017; Arca-Sedda et al. 2017; Macias+JCAP'19

- ✓ Issues in luminosity function of observed MSP and LMXB-to-MSP ratio

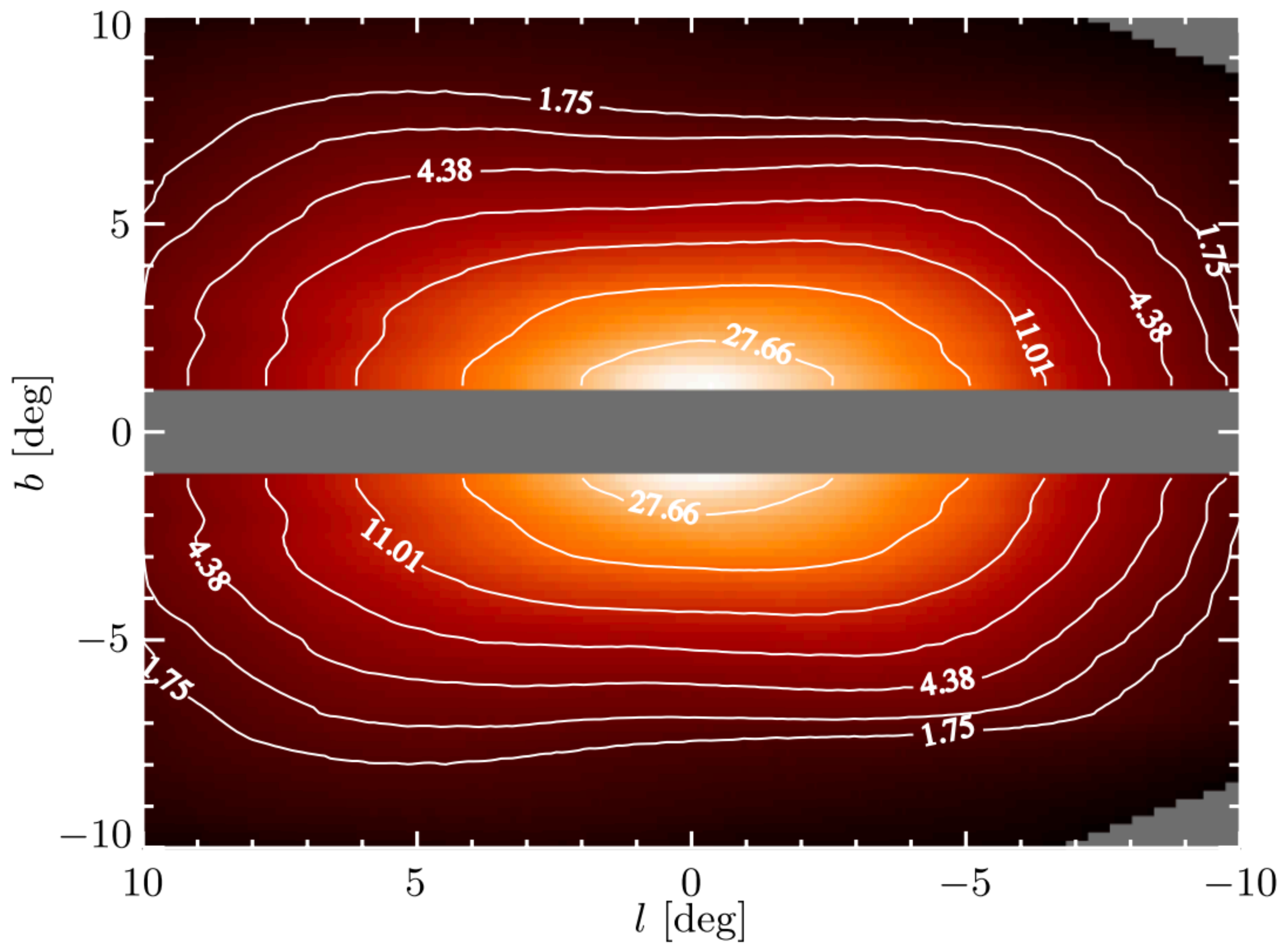
Cholis+'14; Hooper+'15; Hooper&Linden JCAP'16; Haggard+ JCAP'17; Ploeg+ JCAP'17

Going beyond dark matter templates

Stellar distribution in the bulge

Boxy bulge

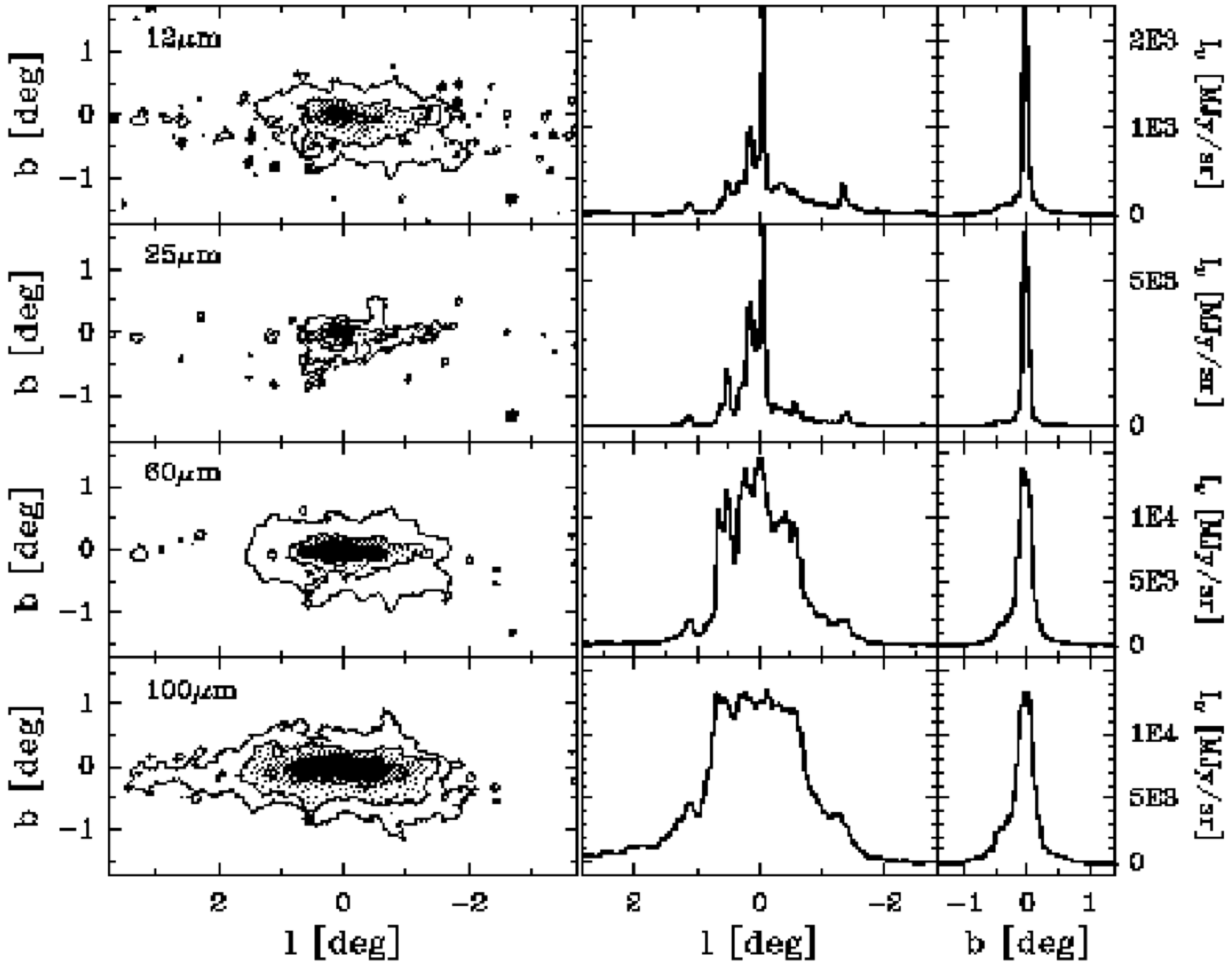
$0.9 \times 10^{10}\ M_\odot$



Wegg & Gerhard MNRAS'12

Nuclear bulge

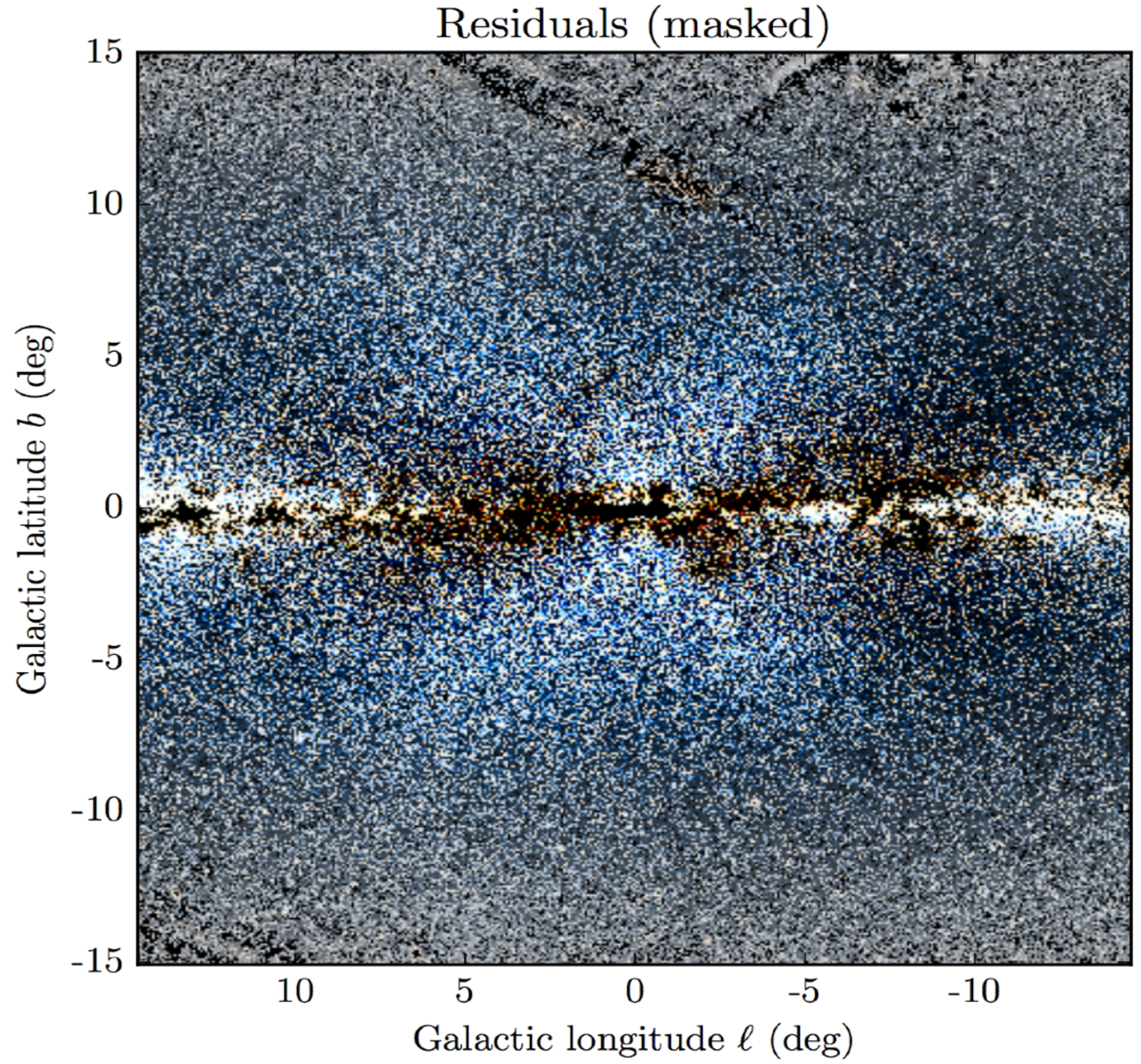
$1.4 \times 10^{9}\ M_\odot$



Launhardt+A&A'02

X-shaped bulge

~20% BB mass



Ness&Lang AJ'16

- **Red Clump stars** (near-IR) used to characterise the **three-dimensional density structure** of the BB
- Most recent non-parametrically deconvolved bulge model w/ VISTA Variables in the Via Lactea (VVV) data *Coleman+ MNRAS'20*
- X-shaped structure characteristic of boxy/peanut like morphology (extragalactic studies of barred galaxies and simulations)

Evidence for the stellar bulge GeV emission

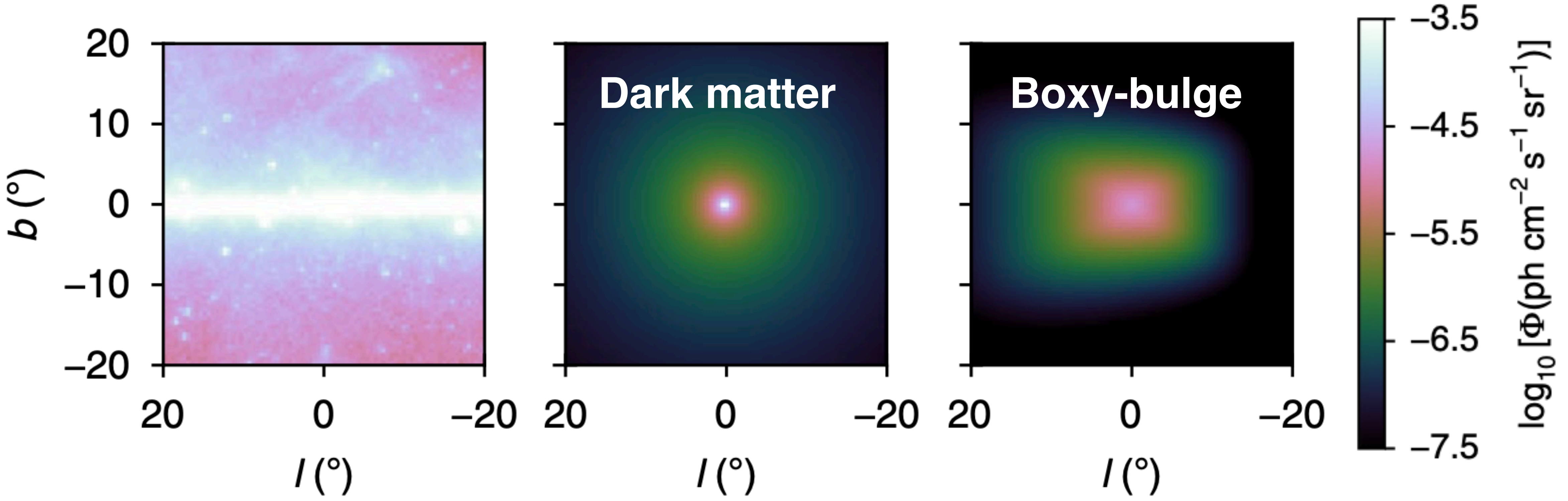
nature astronomy

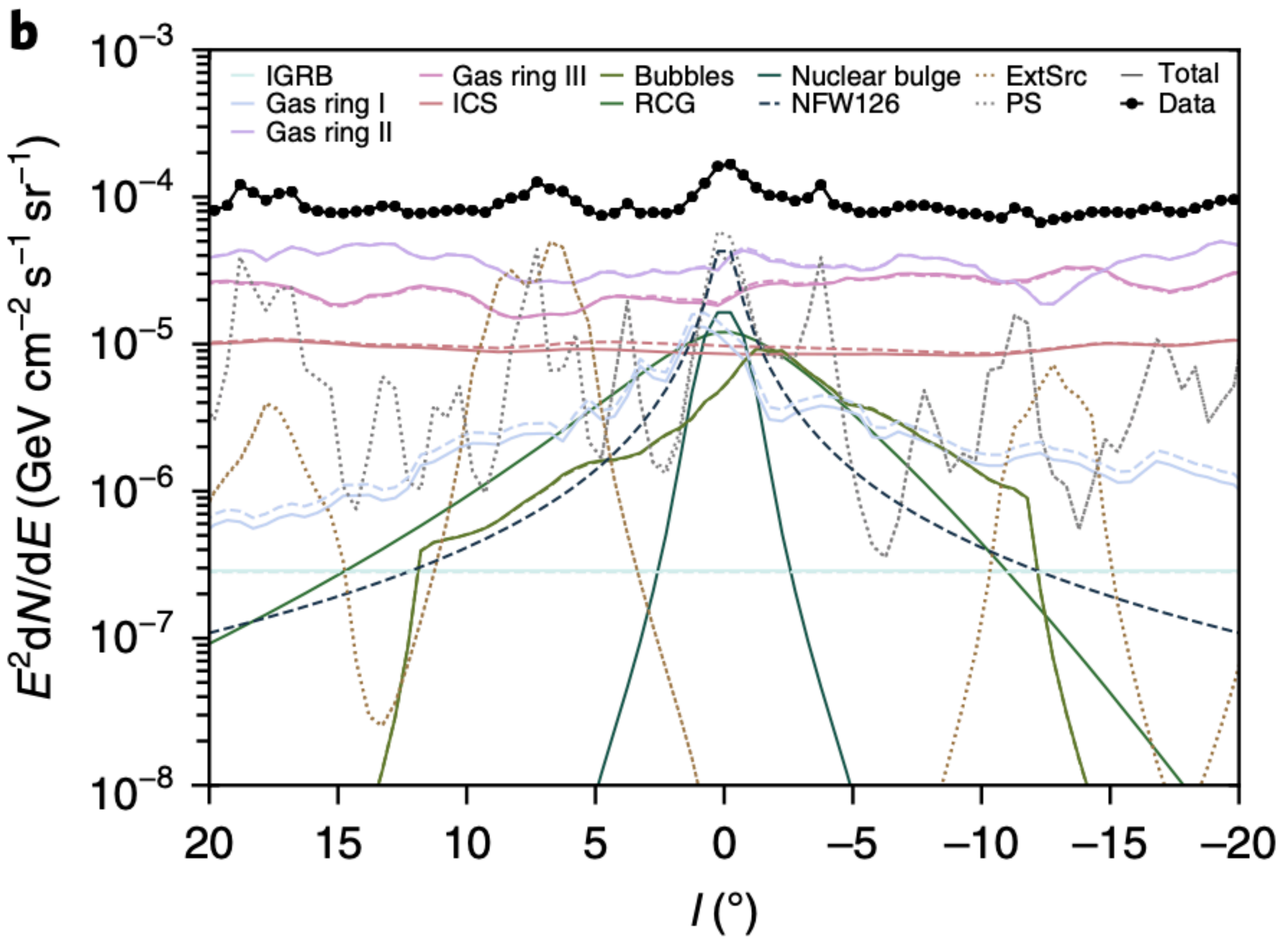
ARTICLES

https://doi.org/10.1038/s41550-018-0531-z

The Fermi-LAT GeV excess as a tracer of stellar mass in the Galactic bulge

Richard Bartels[1]*, Emma Storm[1], Christoph Weniger[1] and Francesca Calore[2]





- ✓ **Stellar bulge model**: **Boxy bulge** as traced by red-clump giants + **nuclear bulge**

  Cao+MNRAS'13; Launhardt+ A&A'02

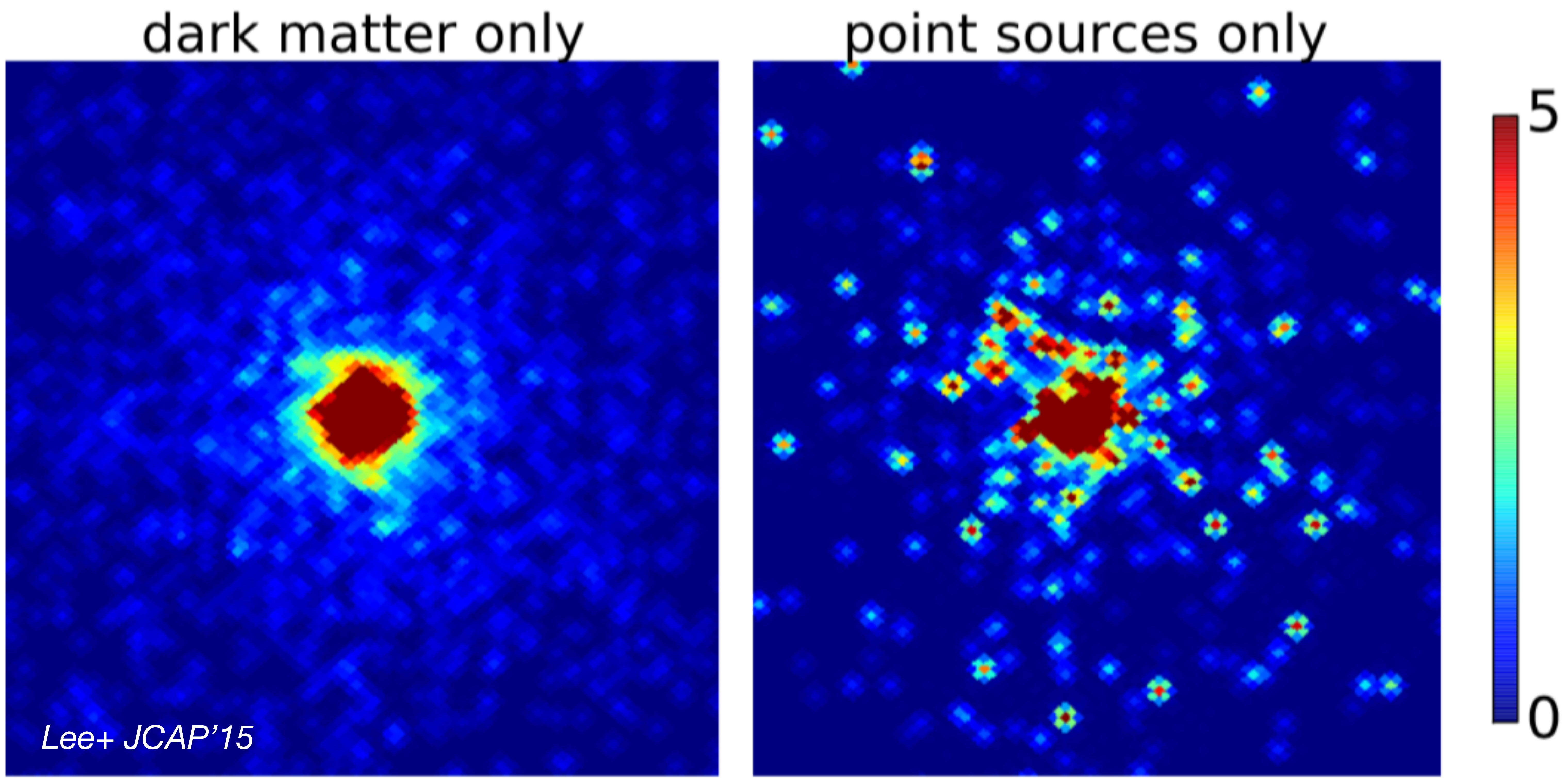
- ✓ Strong evidence for additional **stellar bulge model** (16σ); no evidence for additional **DM model** (< 3σ)

- ✓ Discriminating feature: Asymmetry at ~10 deg longitude => **Morphology** of the GCE **more oblate** than what found before

Macias+ Nature Astronomy'18; Macias+ JCAP'19

Statistics of photon counts

How to discriminate diffuse vs point-like emission

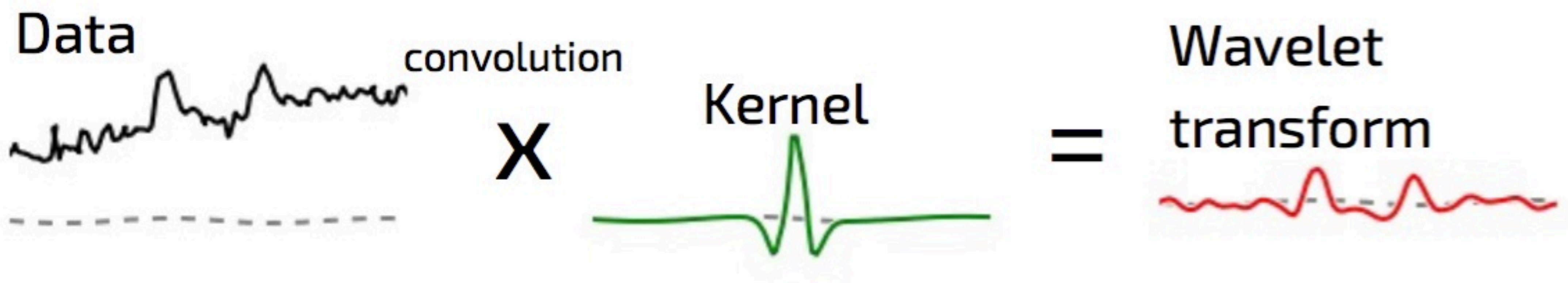


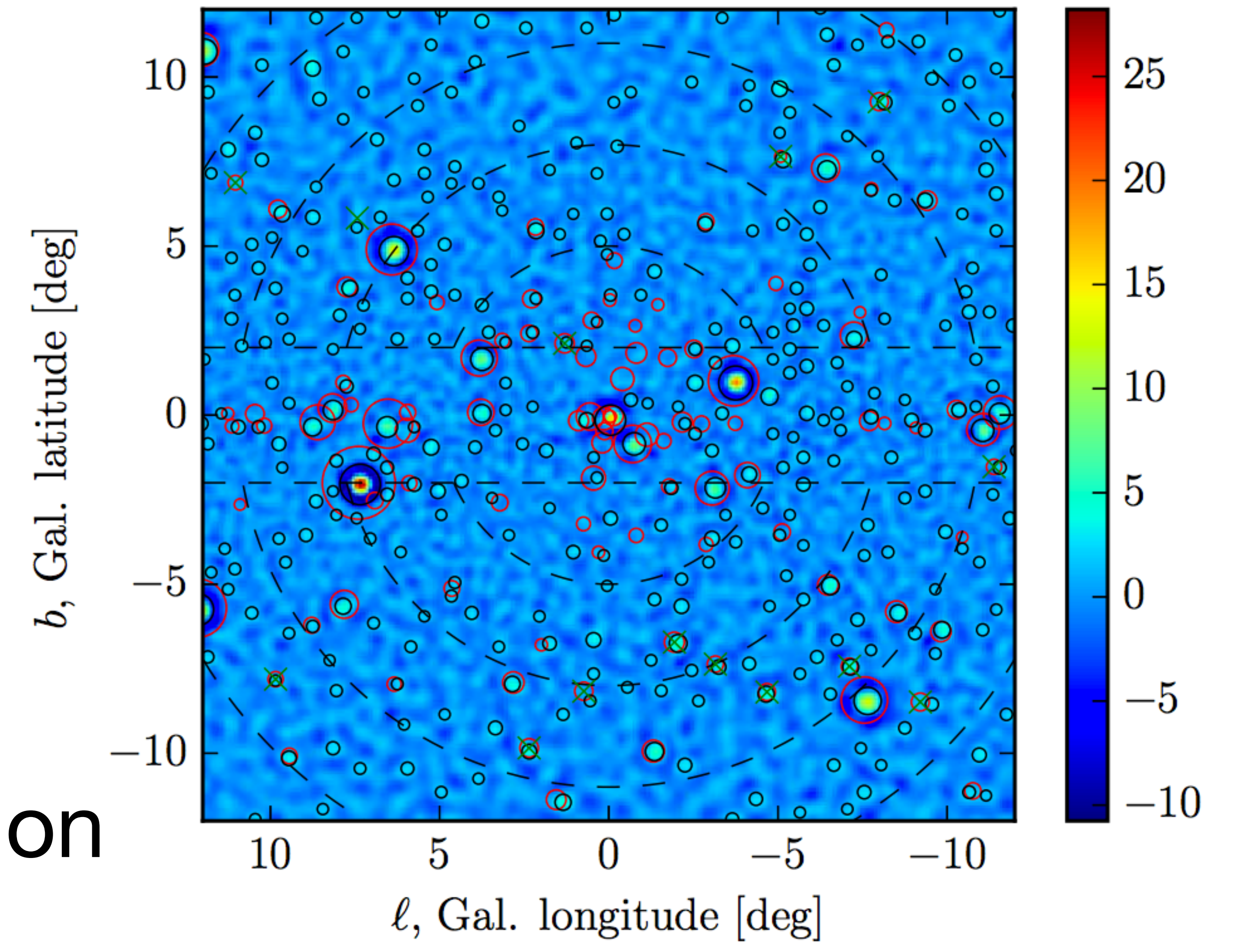
Differences in the **statistics of the photon counts** can be quantified and used for model comparison

Support for unresolved point sources (PS)

Local maxima of normalised wavelet transform

Bartels+ PRL'16

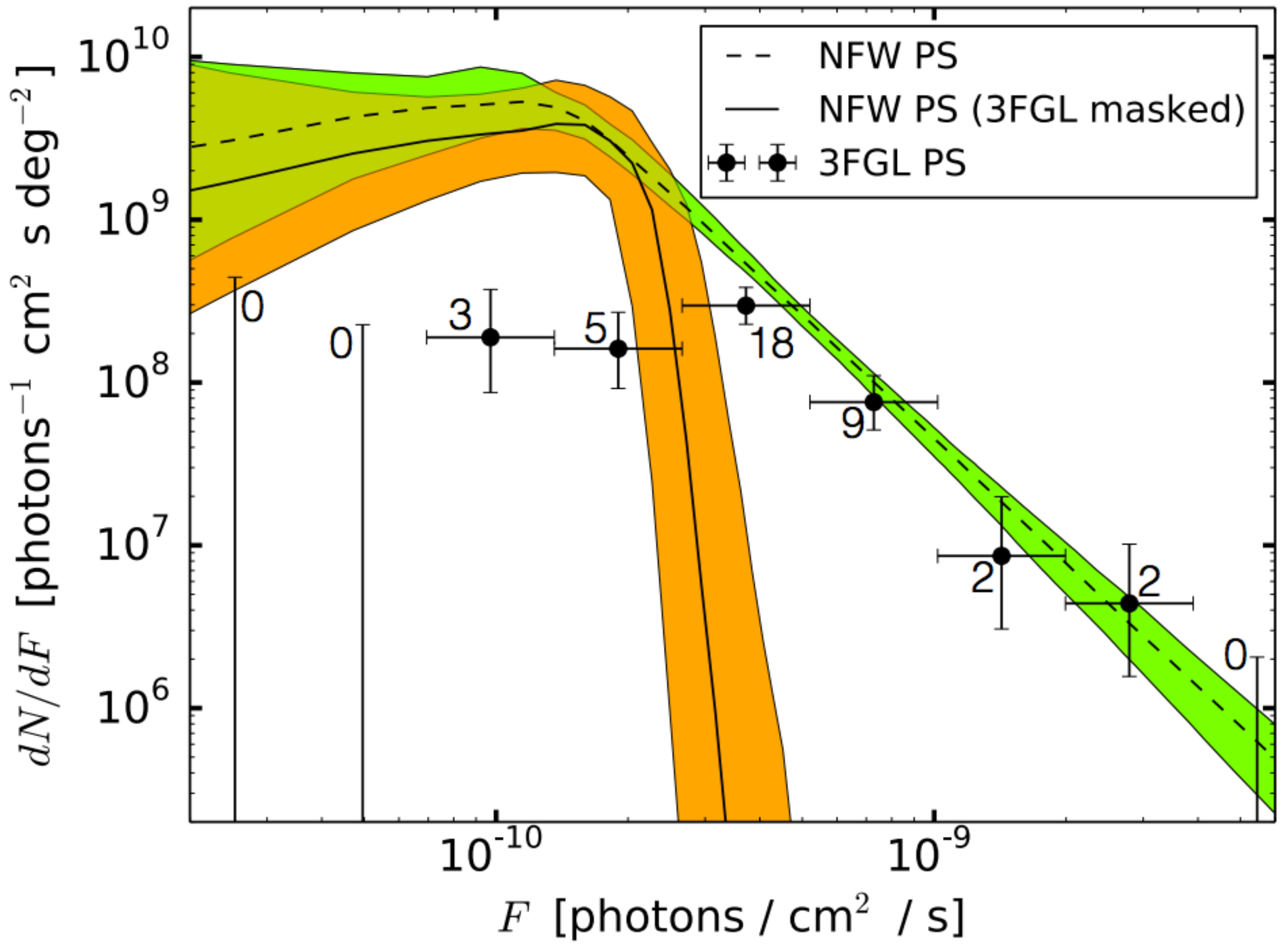


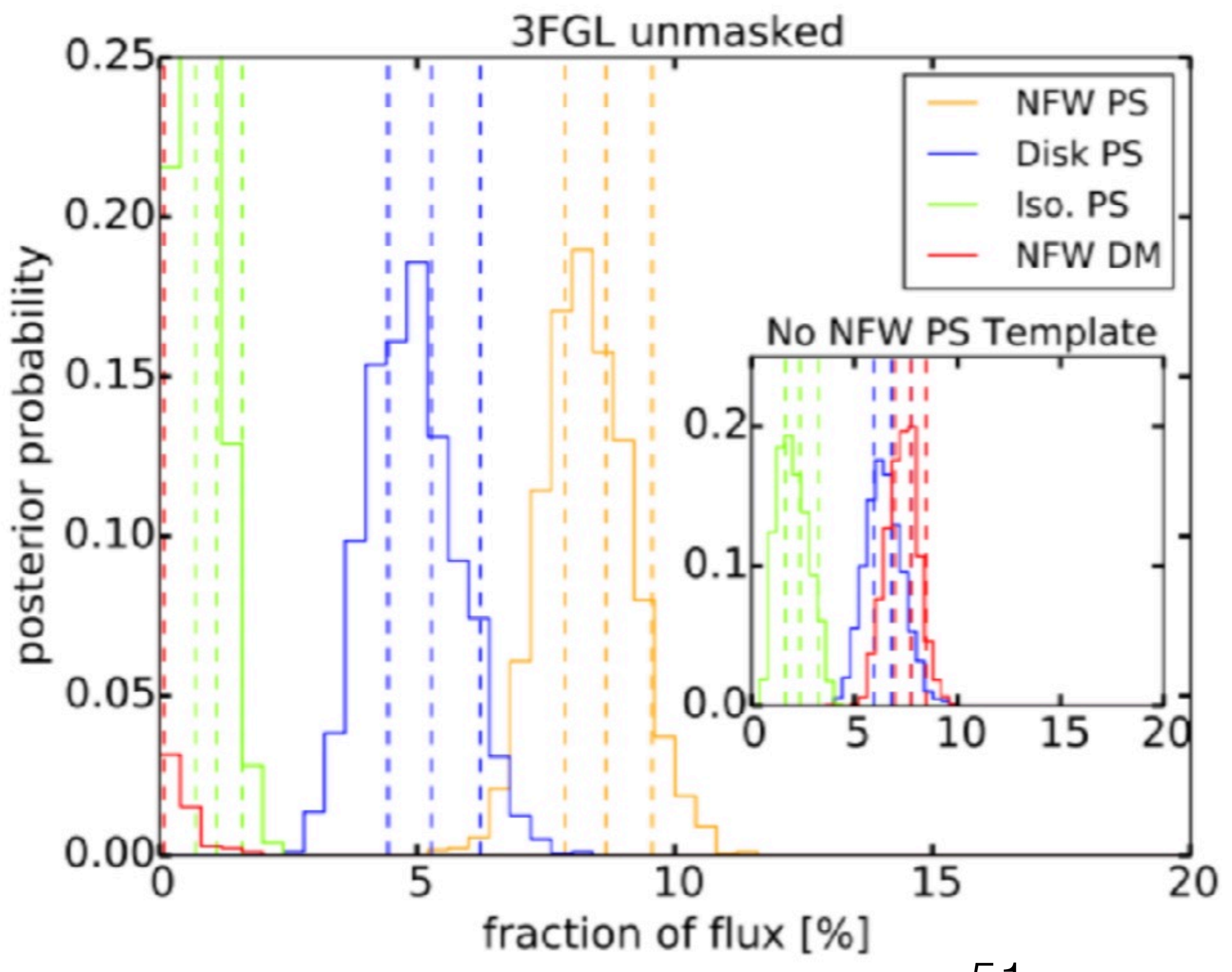


- Wavelet transform to look for **peaks** in data
- Enough peaks were found to explain the cumulative excess emission
- Evidence for unresolved PS population and constraints on luminosity function
- No modelling of diffuse emission required

Non-Poissonian template fitting

Lee+ PRL'16

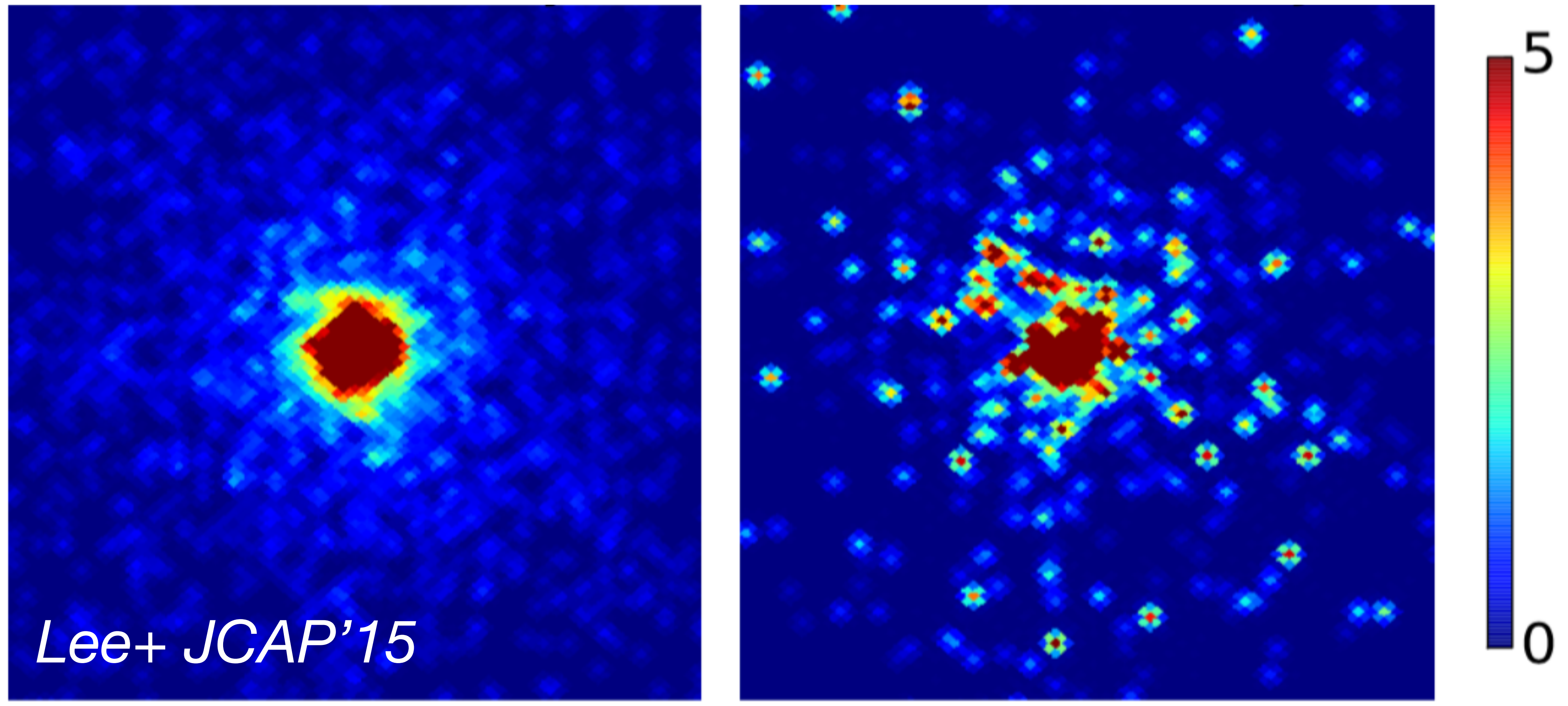




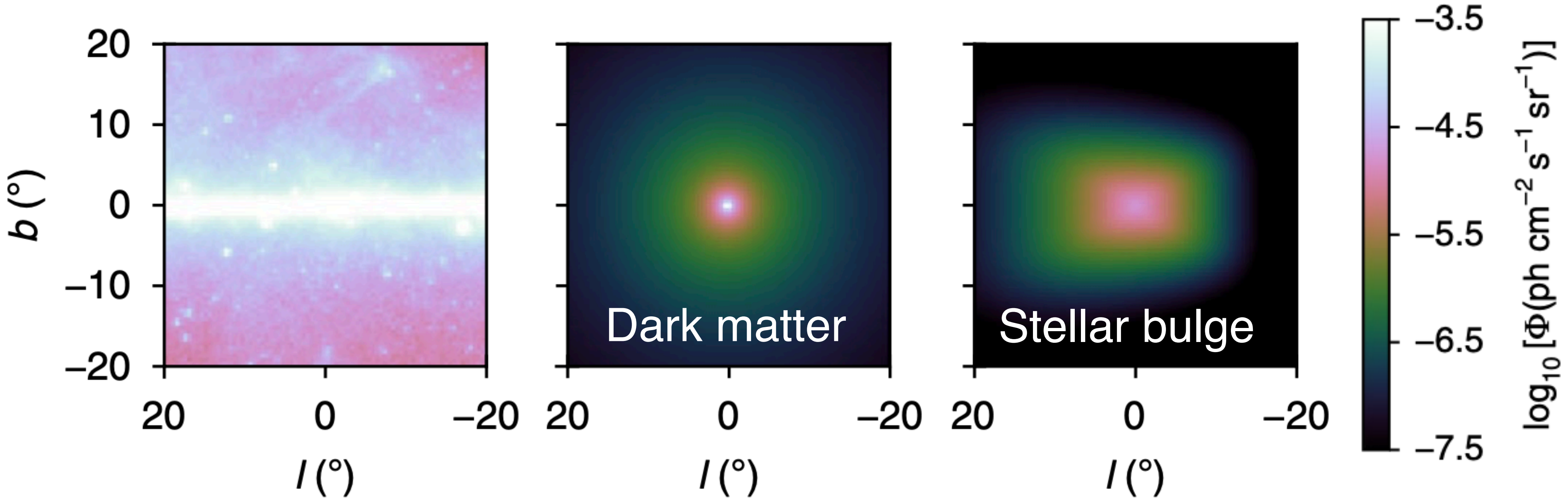
- Exploits difference in photon statistics: smooth signal (DM) vs larger variance across pixels (PS)
- PS fluctuations follow non-Poissonian statistics
- Sensitivity to spatial distribution and luminosity function of PS
- Required modelling of diffuse emission

The GeV excess nature

The gamma-ray perspective



Truly diffuse　　Unresolved sources



- Difference in **statistics of photon counts** can be quantified and used for model comparison

  Bartels+ PRL’16; Lee+PRL’16

- **Strong bias** from mis-modelling of foreground diffuse emission and controversial results

  Zhong+PRL’19; Leane&Slatyer PRL’20, PRD’20; Chang+ PRD’20, Buschmann+PRD’20

- Nonetheless: **evidence for unresolved point sources** is there with different, independent, methods

  Buschmann+PRD’20; FC+ 2102.12497; List+ 2107.09070

- **Stellar bulge morphology preferred over DM** also when modelling faint point sources

  FC+ PRL’ 21

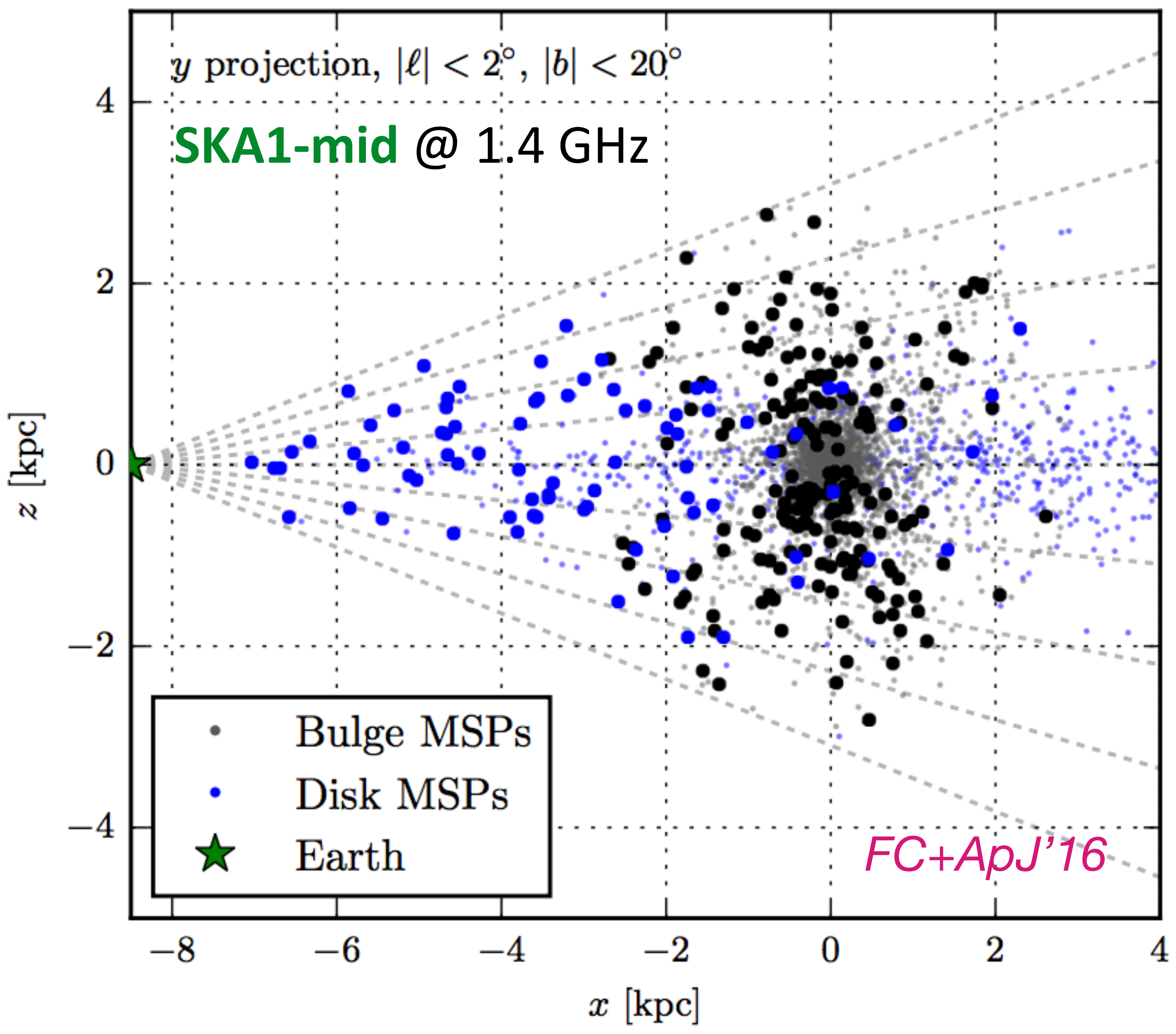
  Macias+ Nature Astronomy’18; Macias+ JCAP’19

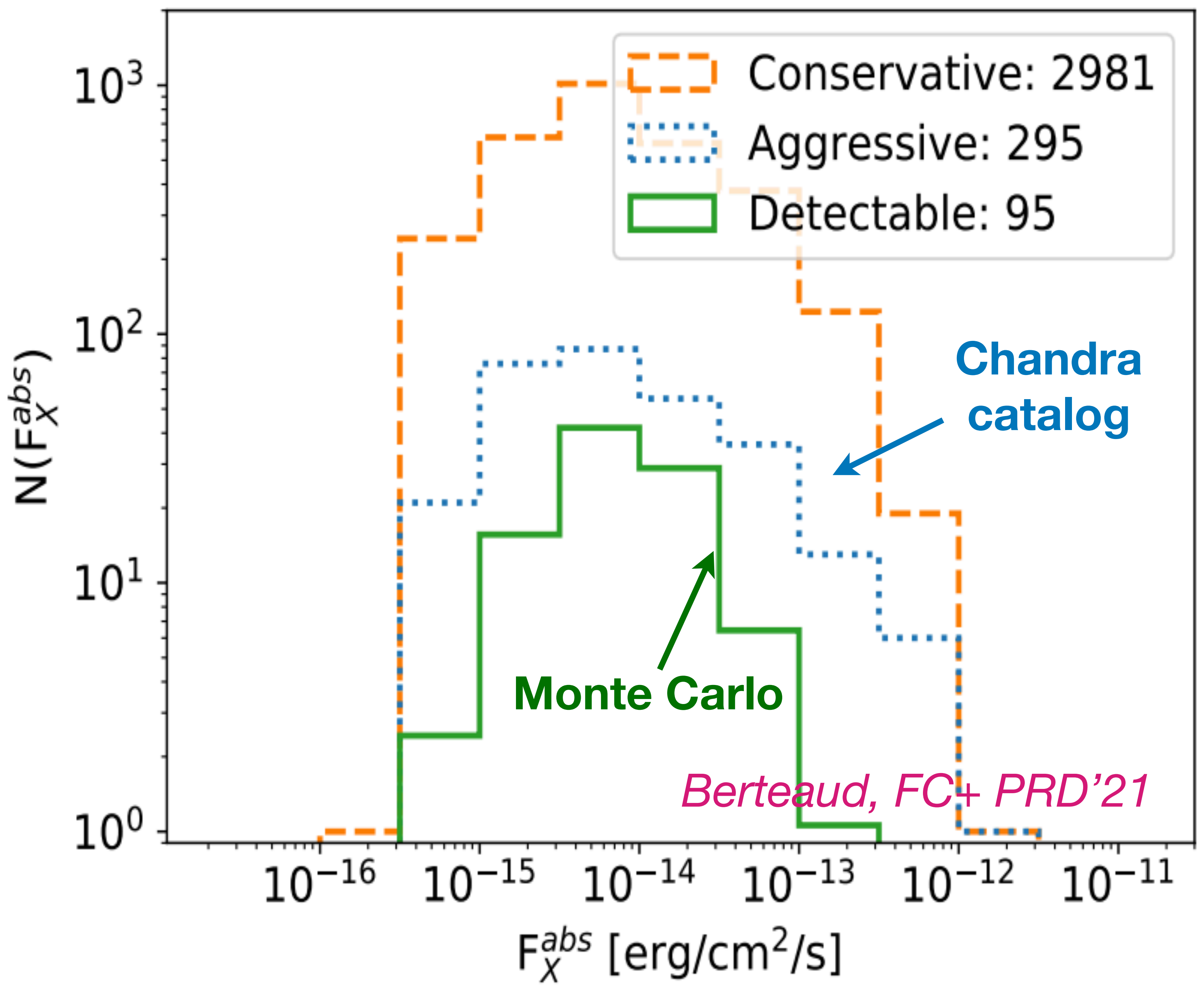
> An (at least) partial **stellar origin of the GeV excess** seems to be confirmed

Multi-messenger tests of the GeV excess

Complementary techniques and **multi-wavelength searches** to test the excess nature:

- Radio, X-ray, and (future) gravitational waves searches *FC+ApJ'16; FC+PRL'19; Berteaud, FC+ PRD'21*





- Very high-energy photons with CTA *Macias+ MNRAS'21*
- DM constraints from gamma rays (dwarf galaxies) and cosmic-ray antiprotons *Di Mauro & Winkler PRD'21*