Fundamental Physics with cosmic and gamma rays

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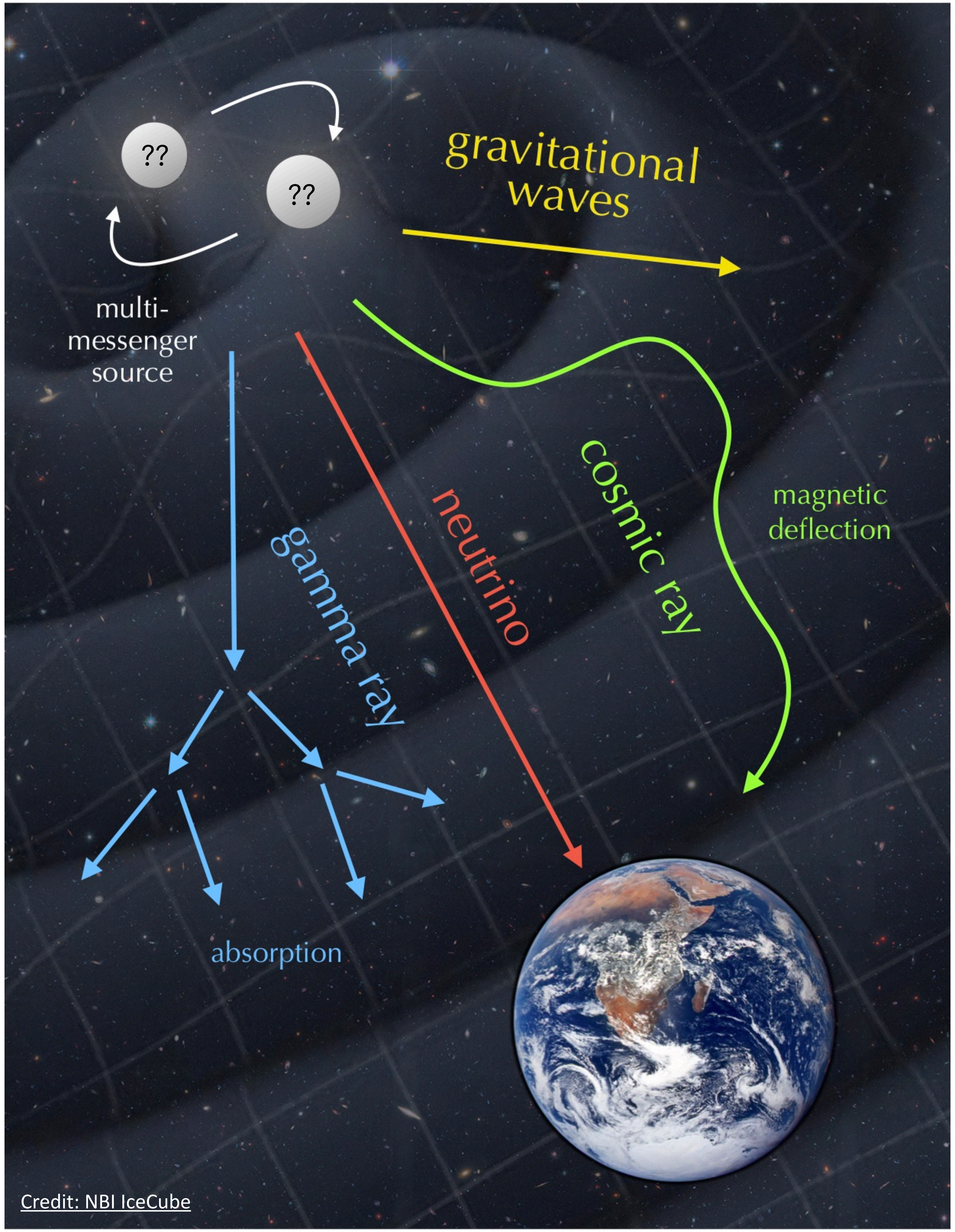
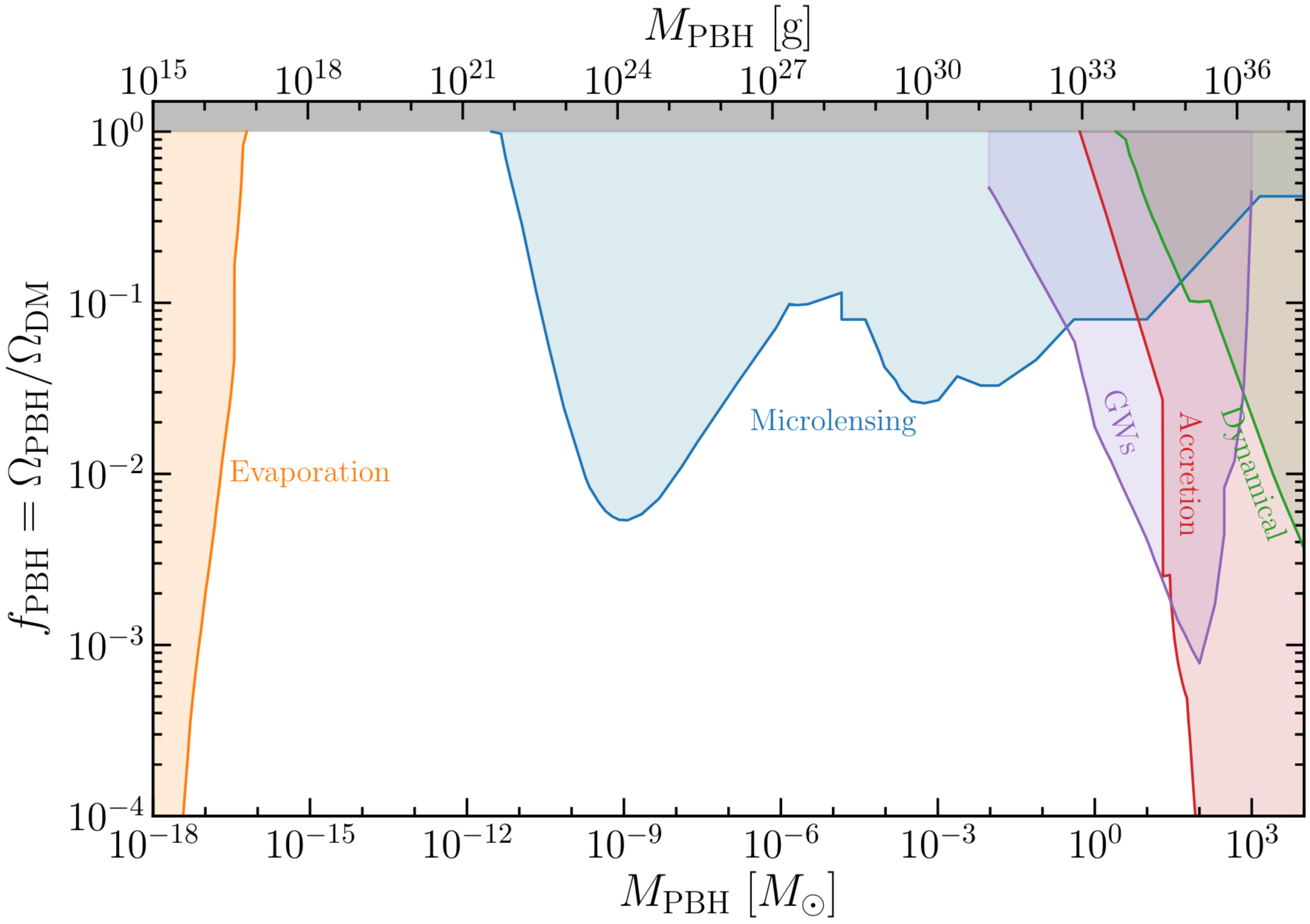
Plan of the lectures

- **Lecture 1**: Particles from the sky: **charged cosmic rays**, **gamma rays** and **neutrinos**
  - Detection techniques and observations
  - Production and origin
  - The multi-messenger connection
- **Lecture 2-3-4**: Probing **new physics** with astroparticle observations
  - Generalities of dark matter searches
  - **Particle** dark matter
  - **Primordial black holes**
  - Stellar/Astro **axion-like particles**
  - Anomalies and **excesses**



Primordial black holes

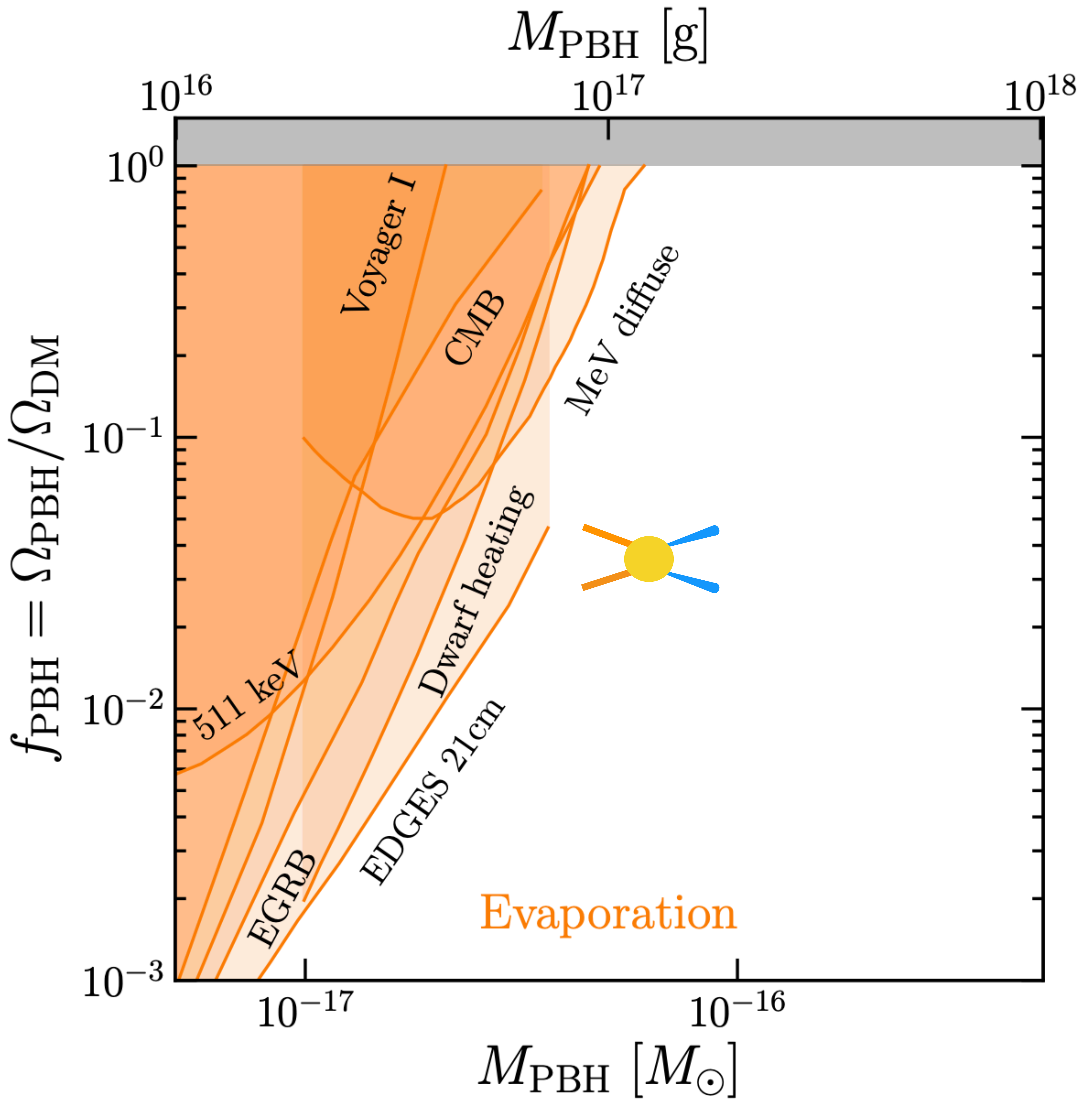
Limits on primordial black holes



Green & Kavanagh J. Phys. G'19

Limits on primordial black holes

Evaporation of PBH and cosmic backgrounds



Green & Kavanagh J. Phys. G'19

- PBH can emit **charged cosmic rays** and **photons** via Hawking radiation => Almost-black (grey) body emission

$$T_{\mathrm{PBH}} \simeq \frac{10^{13}\mathrm{g}}{M_{\mathrm{PBH}}}\,\mathrm{GeV}$$

Page & Hawking ApJ'76; Carr & MacGibbon Phys. Rep.'98

- Sufficient emission from $M_{\mathrm{PBH}} > 10^{14}$ g to set limits on their evaporation products today
- Photon contribution to the extragalactic gamma-ray and X-ray backgrounds

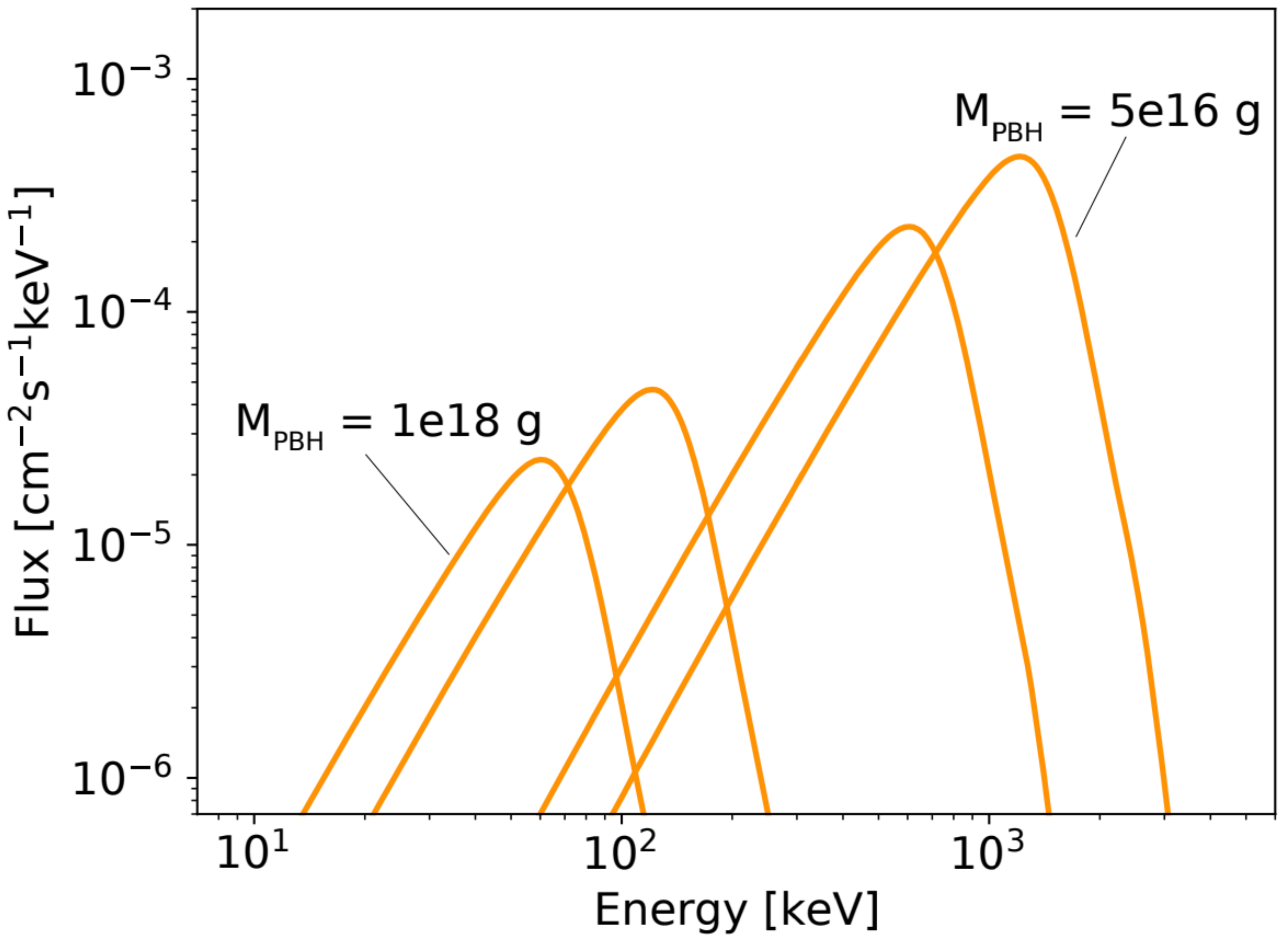
Carr+ PRD'10; Ballesteros+ PLB'20; Iguaz+ PRD'21

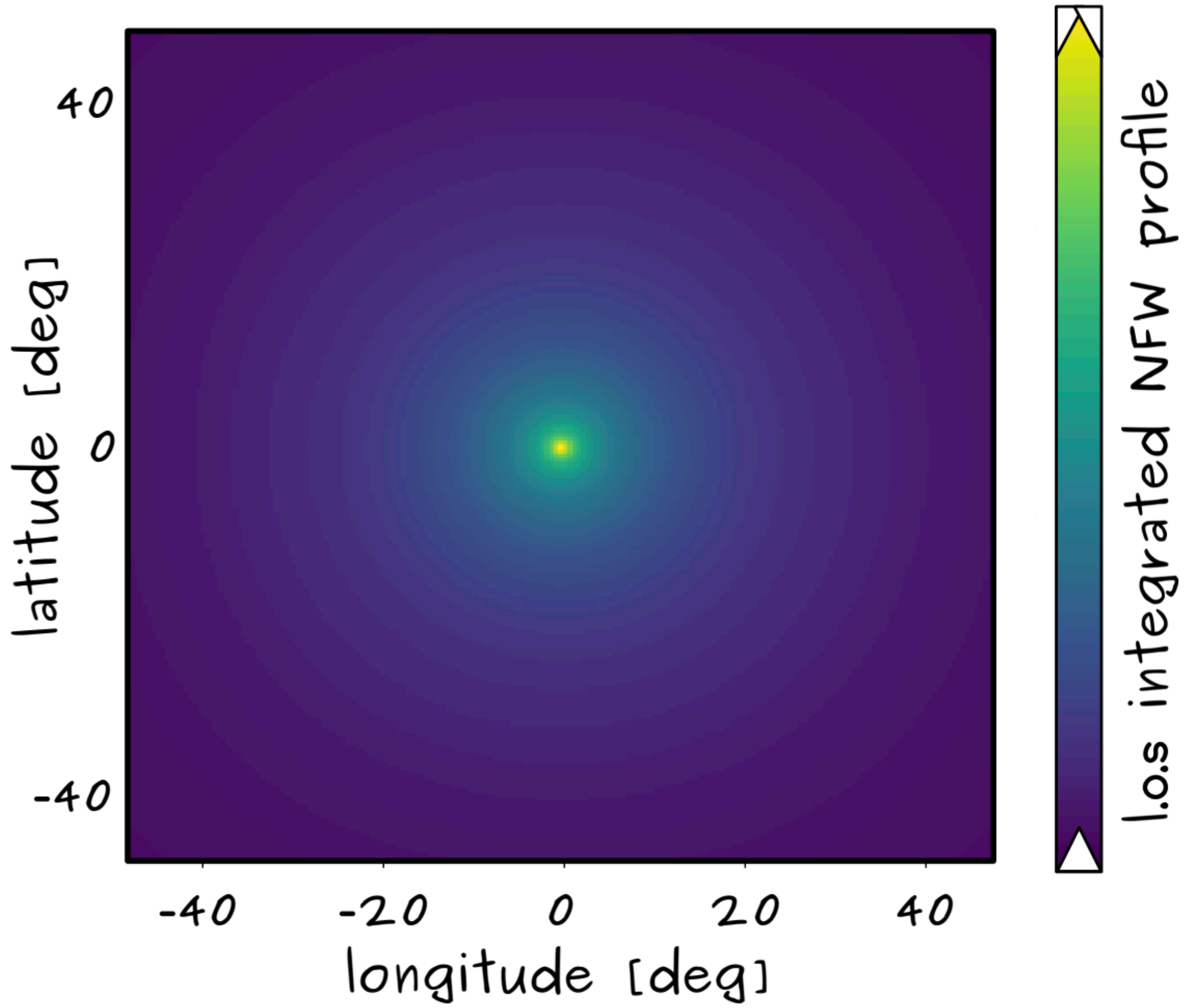
- Unconstrained mass range ~10^{17} — 10^{22} g, the so-called *asteroid mass gap* where f_{PBH} can be 1

Limits on primordial black holes

Evaporation of PBH and Galactic diffuse emission

$$\frac{d\Phi_\gamma}{dE}(l,b) = \frac{f_{\rm PBH}}{4\pi M_{\rm PBH}} \frac{d^2 N_\gamma}{dE dt} \int_{\rm l.o.s.} ds\, \rho(r(s,l,b))$$





Berteaud, FC+ PRD'22

MeV Galactic diffuse emission

Is there evidence for an additional PBH dark matter component?

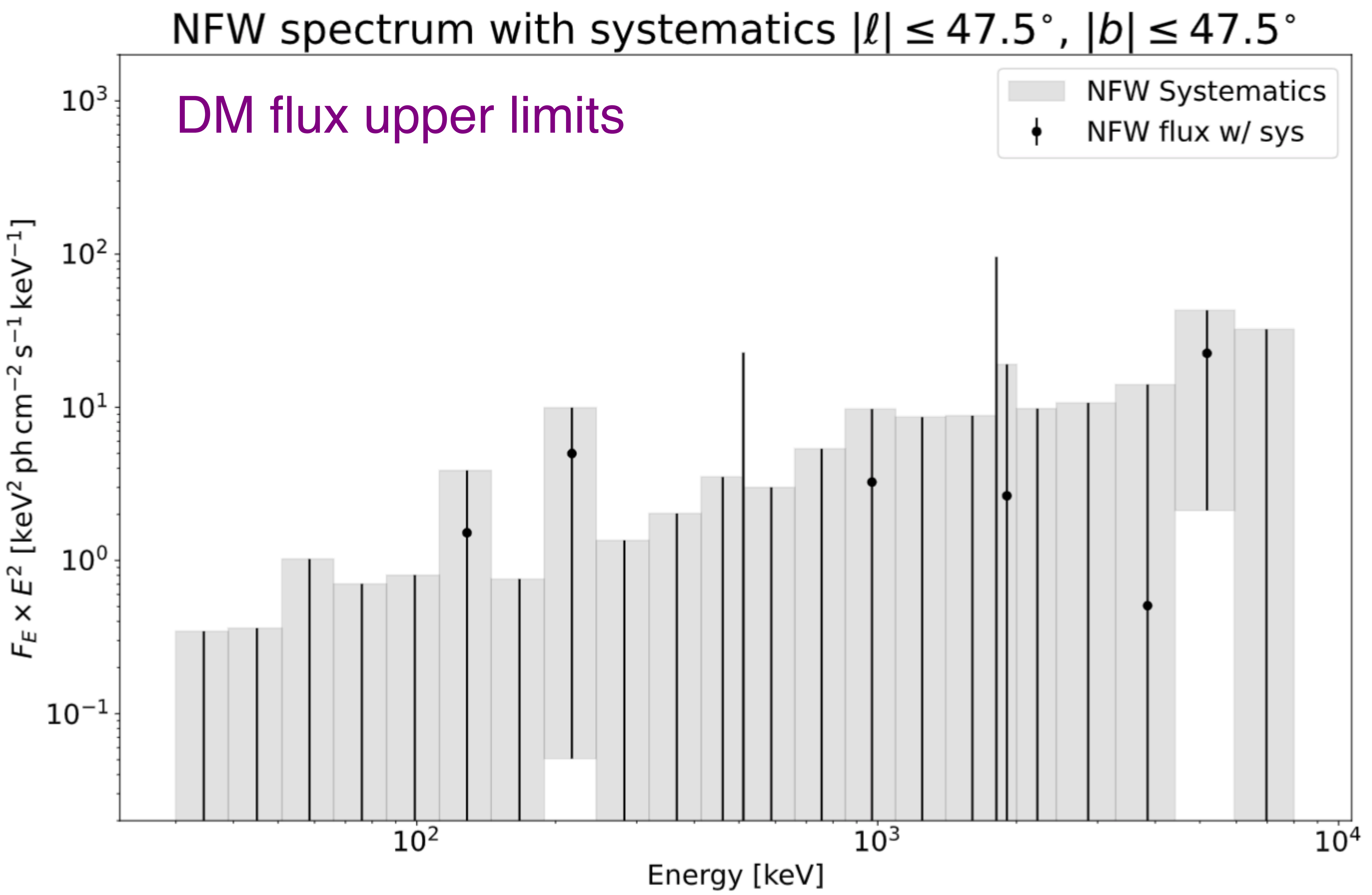
Modeled **spatial templates**

- **Inverse Compton scattering** of electrons off the interstellar radiation field $\mathrm{e}^{\pm}_{\mathrm{CR}} + \gamma \longrightarrow \mathrm{e}^{\pm} + \gamma_{\mathrm{MeV}}$
- Unresolved sources
- Nuclear lines
- Positronium annihilation line
- **PBH dark matter**

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E}(l,b) = \frac{f_{\mathrm{PBH}}}{4\pi M_{\mathrm{PBH}}} \frac{\mathrm{d}^2 N_\gamma}{\mathrm{d}E\mathrm{d}t} \int_{\mathrm{l.o.s.}} \mathrm{d}s\, \rho(r(s,l,b))$$

No signal detected

=> Upper limits on **PBH DM flux**



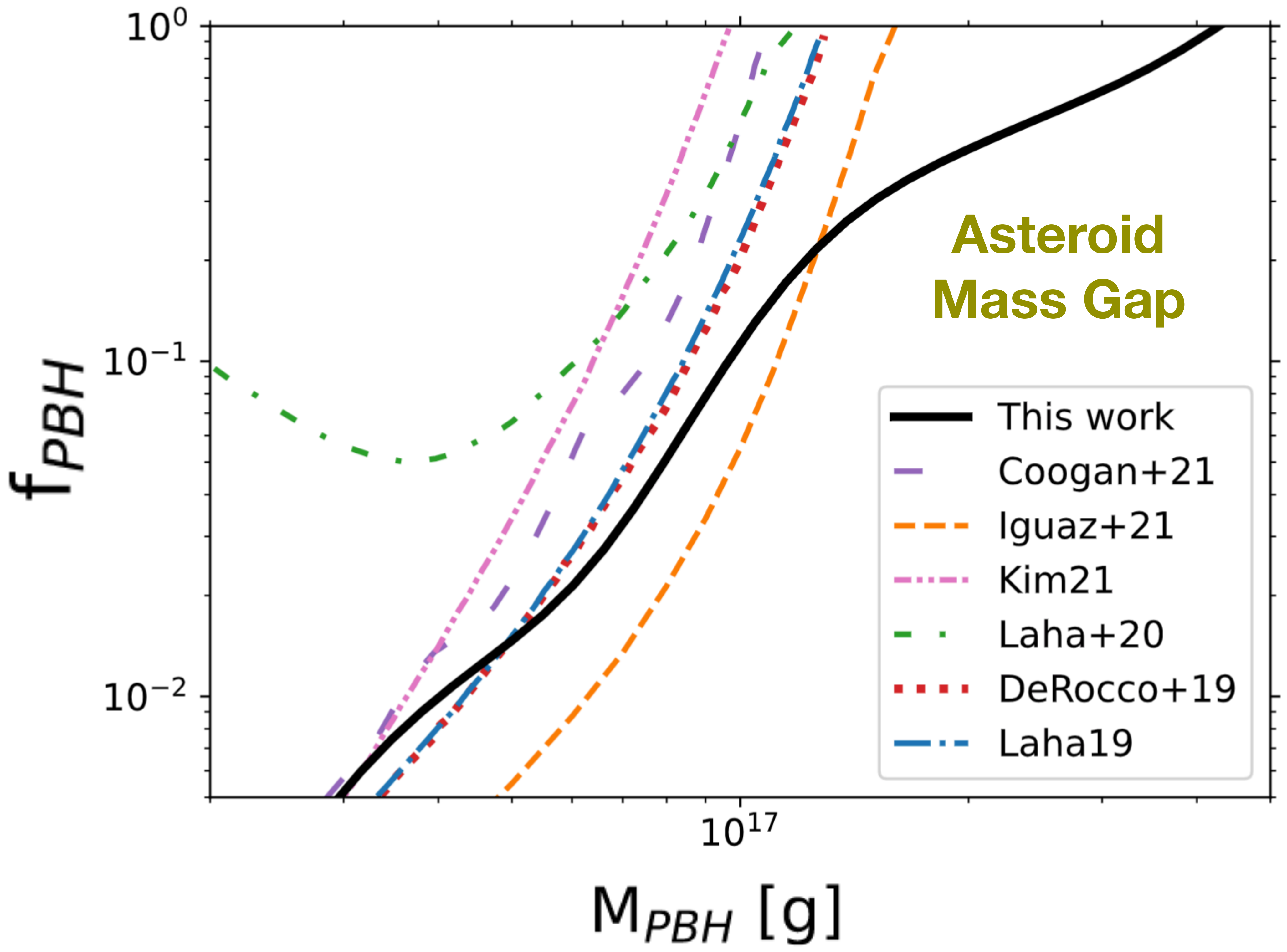
Limits on PBH dark matter

Spectral fit and constraints

Modeled **spectral components** — MCMC fit

- Inverse Compton: power law
- Unresolved sources: cutoff power law
- Nuclear lines: narrow gaussians
- Positronium annihilation: line + continuum
- **PBH dark matter**

$$\frac{\mathrm{d}\Phi_\gamma}{\mathrm{d}E}(l,b) = \frac{f_{\mathrm{PBH}}}{4\pi M_{\mathrm{PBH}}}\frac{\mathrm{d}^2N_\gamma}{\mathrm{d}E\mathrm{d}t}\int_{\mathrm{l.o.s.}}\mathrm{d}s\,\rho(r(s,l,b))$$



=> Upper limits on **PBH DM fractions**

[Same analysis applied for light decaying DM, *Dekker, FC+ arXiv:2209.06299*]

Stellar and Astro axions and axion-like particles

QCD axions and axion-like particles

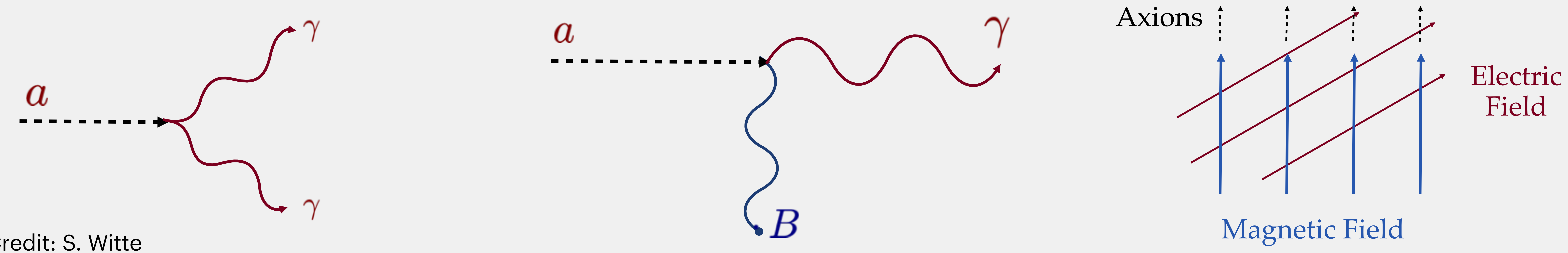
Axion Mass: $m_a \sim \frac{\Lambda^2_{QCD}}{f_a}$

Axion Couplings: $\mathcal{L} \supset \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}$ (Term for Strong CP Problem) $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$ (Electro-Mag) $\sum_f \frac{1}{f_a}\partial_\mu a\, \bar{f}\gamma^\mu\gamma_5 f$ (Fermions)

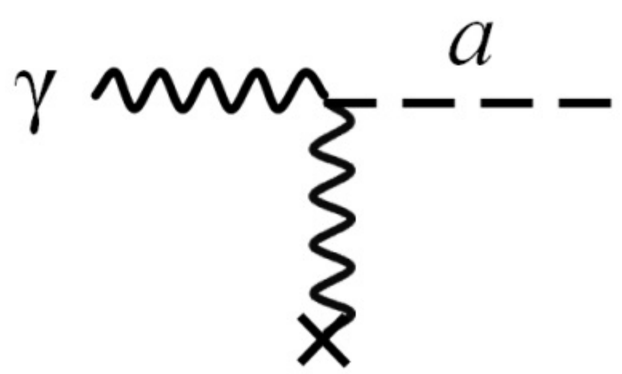
(Slight model dependence in couplings)

Axion Couplings: $\mathcal{L} \supset$ No Coupling $\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$ (Electro-Mag) $\cdots +$ other terms

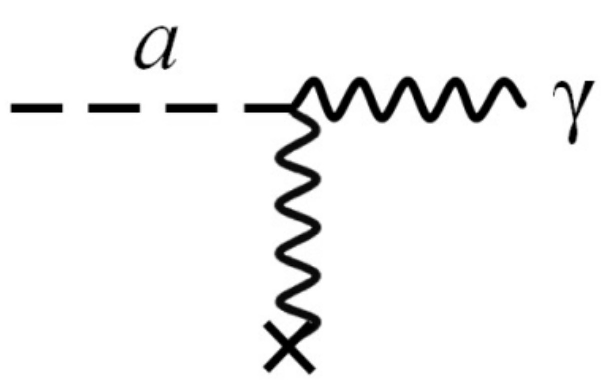
Low energy limit $a\vec{E} \cdot \vec{B}$



Credit: S. Witte



The ALP-photon mixing



For a **monochromatic photon-ALP beam** of energy E propagating along the x_3 axis in a cold plasma within a **homogeneous magnetic field B**:

$$\left(i\frac{\mathrm{d}}{\mathrm{d}x_3} + E + \mathcal{M}_0\right)\begin{pmatrix} A_1(x_3) \\ A_2(x_3) \\ a(x_3) \end{pmatrix} = 0$$

Schrödinger-like equation of motion

$$\mathcal{M}_0 = \begin{pmatrix} \Delta_\perp & 0 & 0 \\ 0 & \Delta_{||} & \Delta_{a\gamma} \\ 0 & \Delta_{a\gamma} & \Delta_a \end{pmatrix}$$

$$\Delta_\perp \equiv \Delta_{\rm pl} + \Delta_\perp^{\rm CM}$$

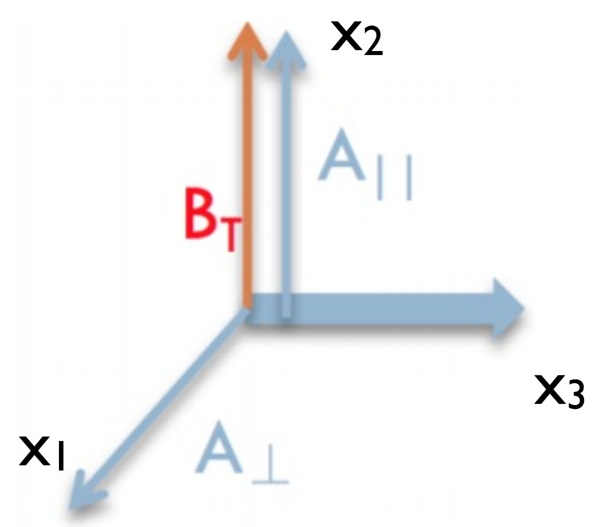
$$\Delta_{||} \equiv \Delta_{\rm pl} + \Delta_{||}^{\rm CM}$$

$$\Delta_{a\gamma} \simeq 7.6\times 10^{-2}\left(\frac{g_{a\gamma}}{5\times 10^{-11}\mathrm{GeV}^{-1}}\right)\left(\frac{B_T}{10^{-6}\,\mathrm{G}}\right)\mathrm{kpc}^{-1},$$

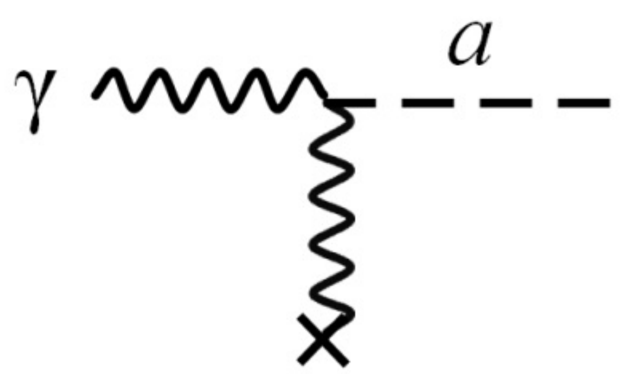
$$\Delta_a \simeq -7.8\times 10^{-3}\left(\frac{m_a}{10^{-8}\mathrm{eV}}\right)^2\left(\frac{E}{\mathrm{TeV}}\right)^{-1}\mathrm{kpc}^{-1},$$

$$\Delta_{\rm pl} \simeq -1.1\times 10^{-10}\left(\frac{E}{\mathrm{TeV}}\right)^{-1}\left(\frac{n_e}{10^{-3}\,\mathrm{cm}^{-3}}\right)\mathrm{kpc}^{-1},$$

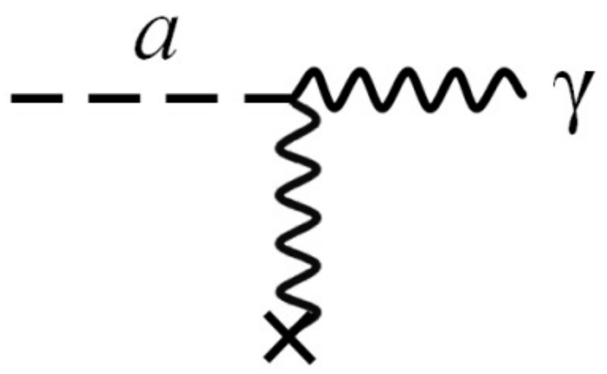
$$\Delta_{\rm QED} \simeq 4.1\times 10^{-6}\left(\frac{E}{\mathrm{TeV}}\right)\left(\frac{B_T}{10^{-6}\,\mathrm{G}}\right)^2\mathrm{kpc}^{-1}.$$



Raffelt & Stodolsky PRD'88; Horns+PRD'12; and others



The ALP-photon mixing



Considering the propagation of photons in a **single magnetic domain d** with a **coherent B-field**, the propagation equations reduce to a 2-dimensional problem:

$$P^{(0)}_{\gamma\to a} = \sin^2 2\theta \, \sin^2\left(\frac{\Delta_{\rm osc}\, d}{2}\right) = (\Delta_{a\gamma} d)^2 \frac{\sin^2(\Delta_{\rm osc} d/2)}{(\Delta_{\rm osc} d/2)^2}$$

Probability for purely polarised photon beam ($A_\parallel$) to oscillate into an ALP after distance d

$$\Delta_{\rm osc} \equiv \left[(\Delta_a - \Delta_{\rm pl})^2 + 4\Delta_{a\gamma}^2\right]^{1/2}$$

Oscillation wave number

$$E_c \equiv \frac{E|\Delta_a - \Delta_{\rm pl}|}{2\Delta_{a\gamma}}$$

Critical energy

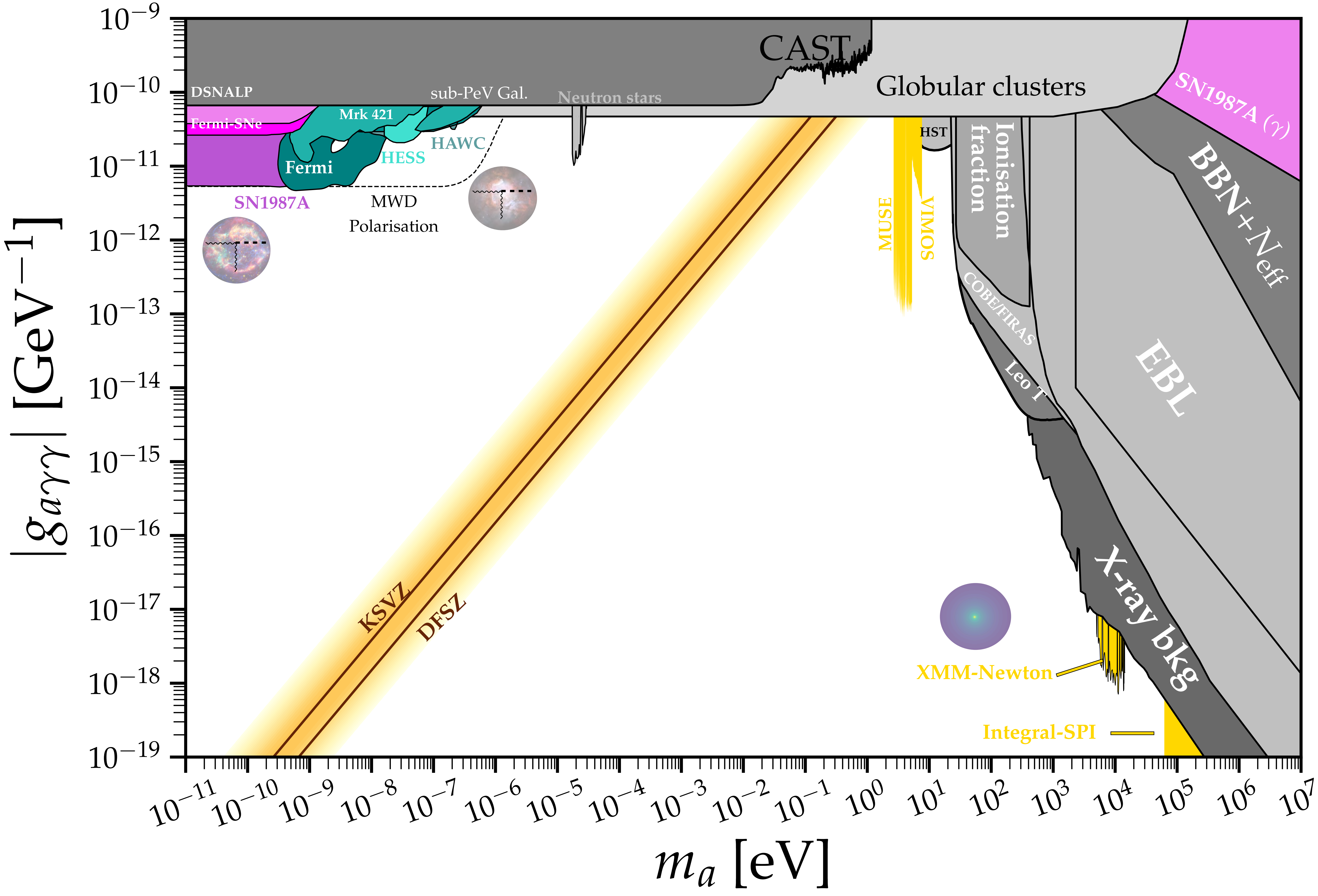
$$\Delta_{\rm osc} = 2\Delta_{a\gamma}\sqrt{1+\left(\frac{E_c}{E}\right)^2}$$

$E \gg E_c$ → $\Delta_{\rm osc} \simeq 2\Delta_{a\gamma}$ **Strong mixing regime**

$E \simeq E_c$ → **Oscillation regime**

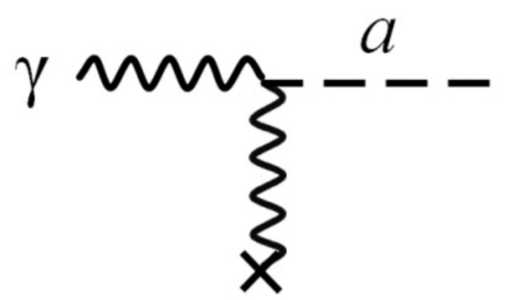
e.g. Mirizzi & Montanino JCAP'09

Constraints on ALP-photon mixing



https://github.com/cajohare/AxionLimits

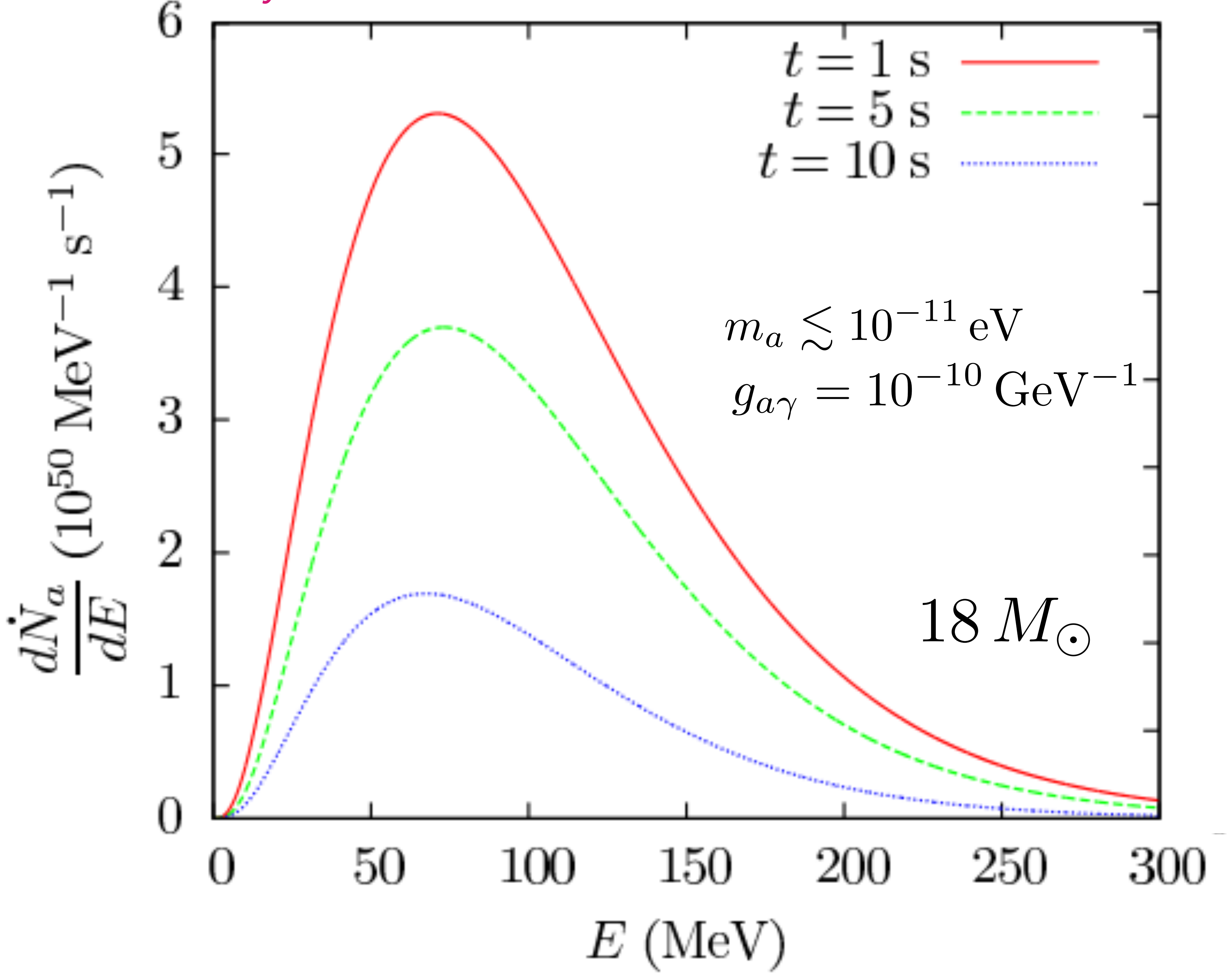
ALPs production in CC SNe



Production of ALPs in the SNe mainly by **Primakoff effect**

$$\gamma + Ze \to Ze + a$$

Payez+ JCAP'14



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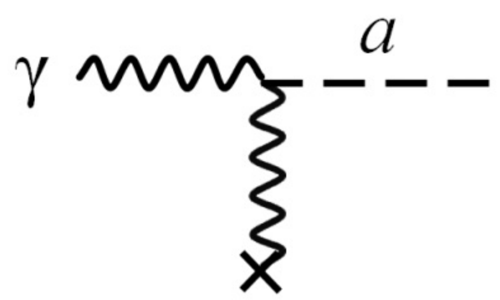

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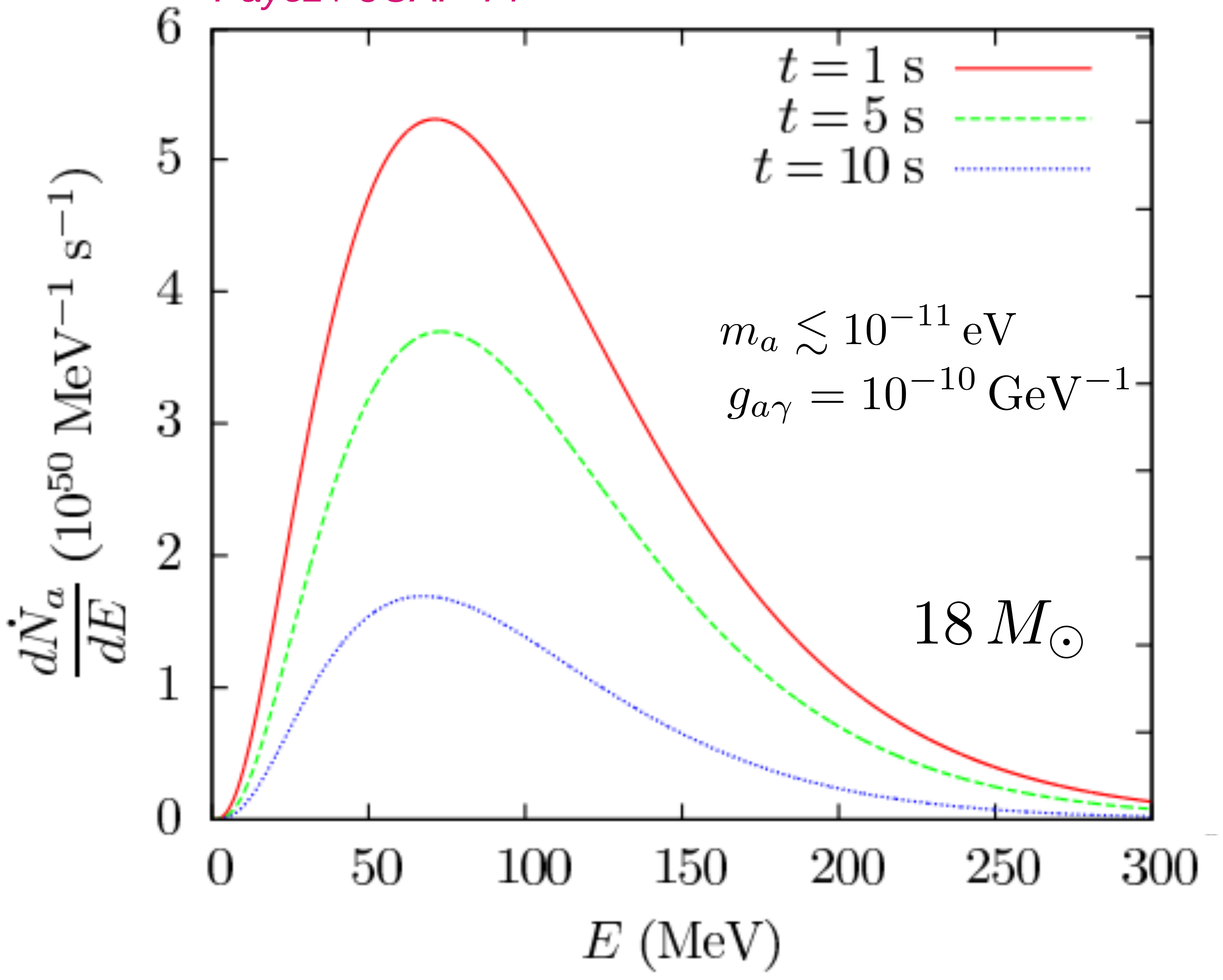
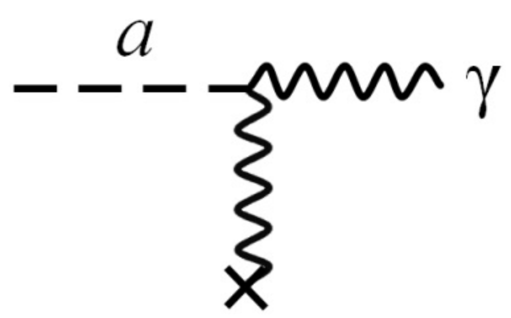


For Galactic SNe

$$\frac{d\Phi_a}{dE} = \frac{1}{4\pi d^2}\frac{d\dot{N}_a}{dE}$$

ALP-photon Galactic conversion



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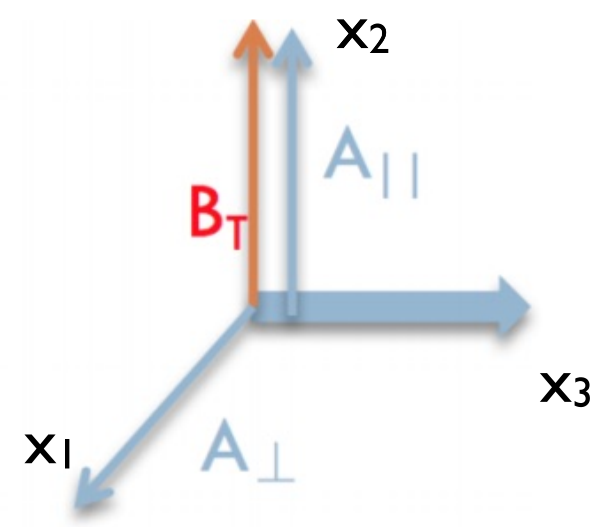
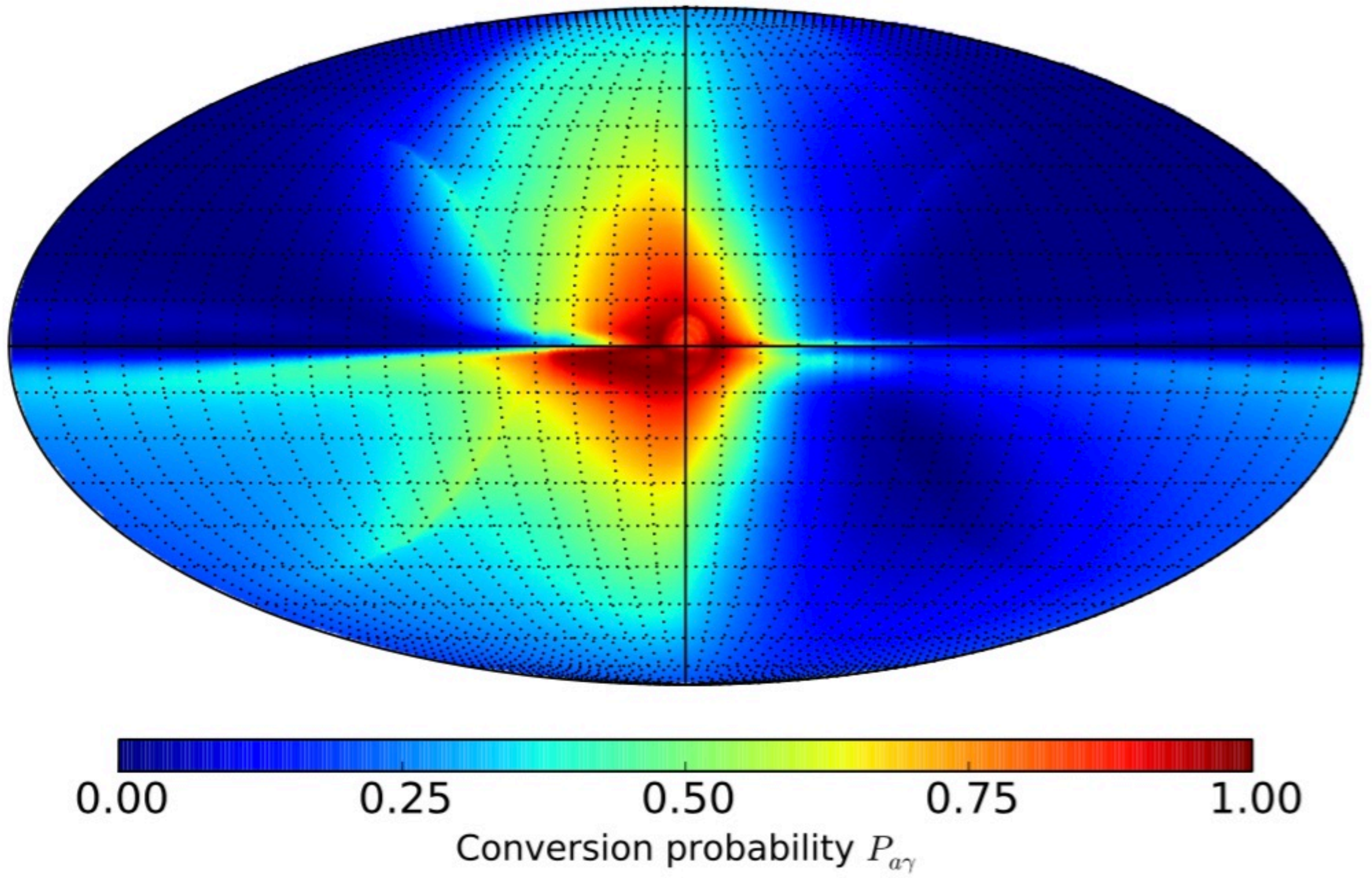


$$P_{a\to\gamma} = \left(\frac{g_{a\gamma}B_T}{2}\right)^2 d^2$$

$$\sim 0.015 \left(\frac{g_{a\gamma}}{10^{-11}\,\mathrm{GeV}}\right)^2 \left(\frac{B_T}{10^{-6}\,\mathrm{G}}\right) \left(\frac{d}{\mathrm{kpc}}\right)^2$$

Raffelt & Stodolsky PRD'88; Horns+PRD'12; and others

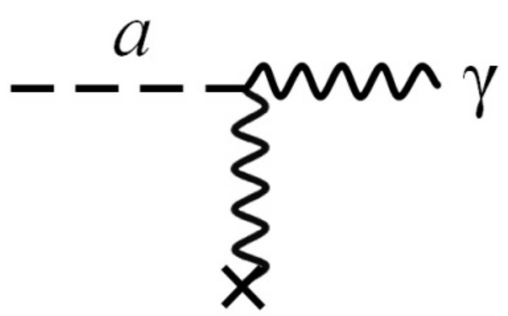


$g_{a\gamma} = 5 \times 10^{-11}\ \mathrm{GeV}^{-1}$
pure ALP beam
propagating through entire Milky Way
[Jansson & Farrar 2012 model]

ALP searches sensitive to the product $\mathbf{g_{a\gamma}\,B_T}$

Good knowledge of B-field is required!

ALPs gamma-ray flux from CC SNe



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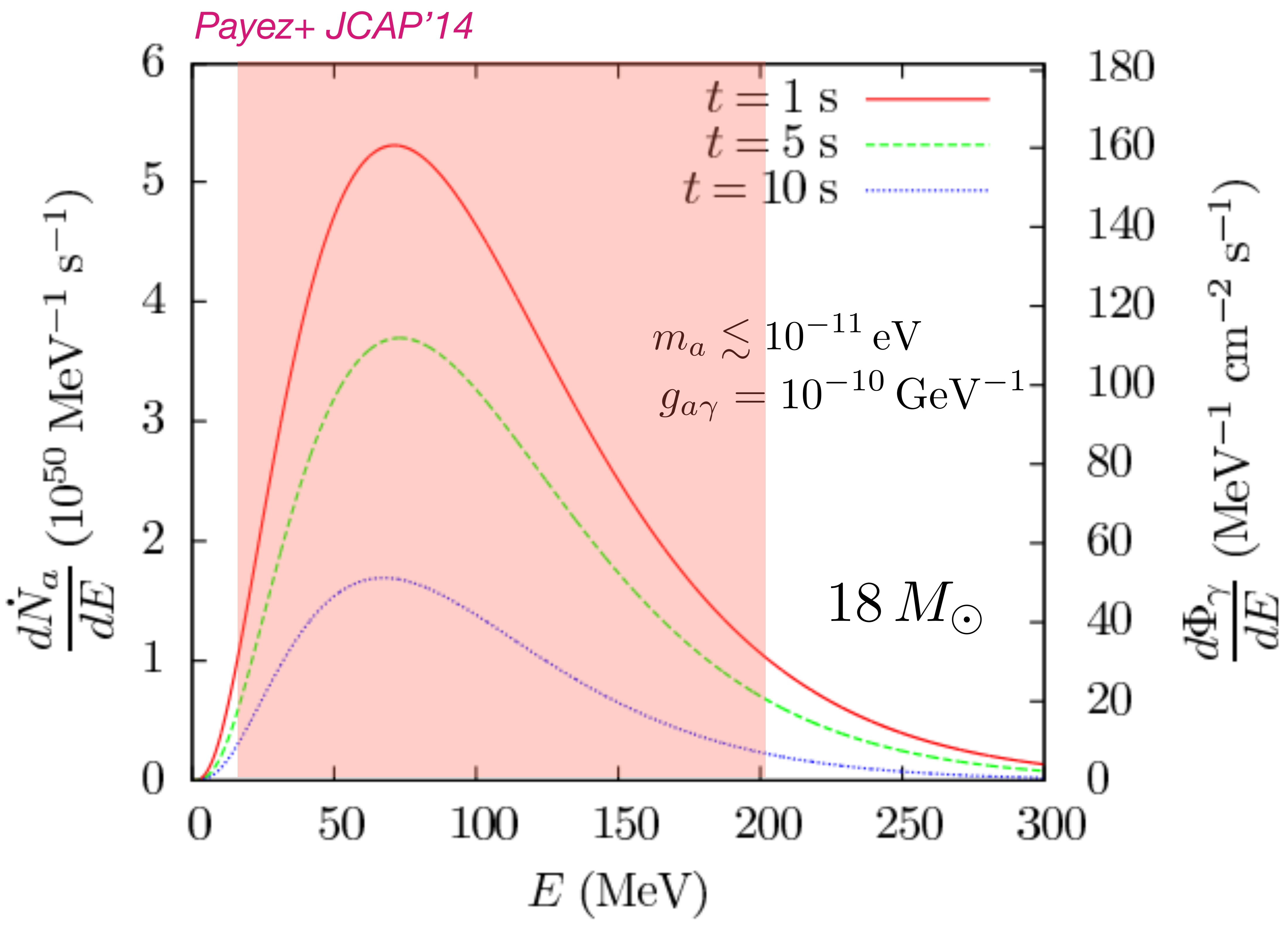


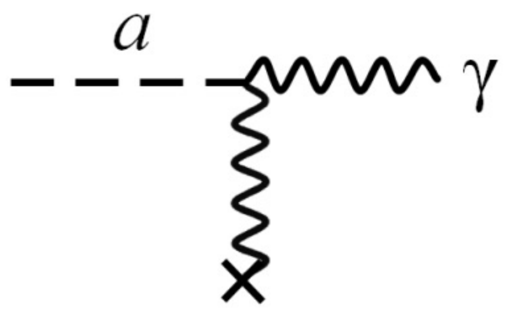
For Galactic SNe

$$\frac{d\Phi_a}{dE} = \frac{1}{4\pi d^2}\frac{d\dot{N}_a}{dE}$$

$$\frac{d\Phi_\gamma}{dE} = \frac{1}{4\pi d^2}\frac{d\dot{N}_a}{dE}P_{a\gamma}(E)$$

For massless ALPs, one-to-one correspondence between ALPs and photon energy

Gamma-ray bursts from CC SNe



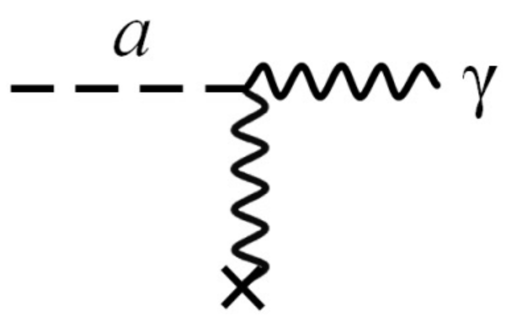
Production of ALPs in the SNe mainly by **Primakoff effect** $\gamma + Ze \rightarrow Ze + a$

ALPs produced in **O(10) sec bursts**, with an energy spectrum peaked at **60-80 MeV**

➡ Specific **time dependent** and **spectral** signatures

➡ Chance to see a Galactic SN depends on SN rate (~3/century) and field-of-view of telescope

Gamma-ray bursts from CC SNe



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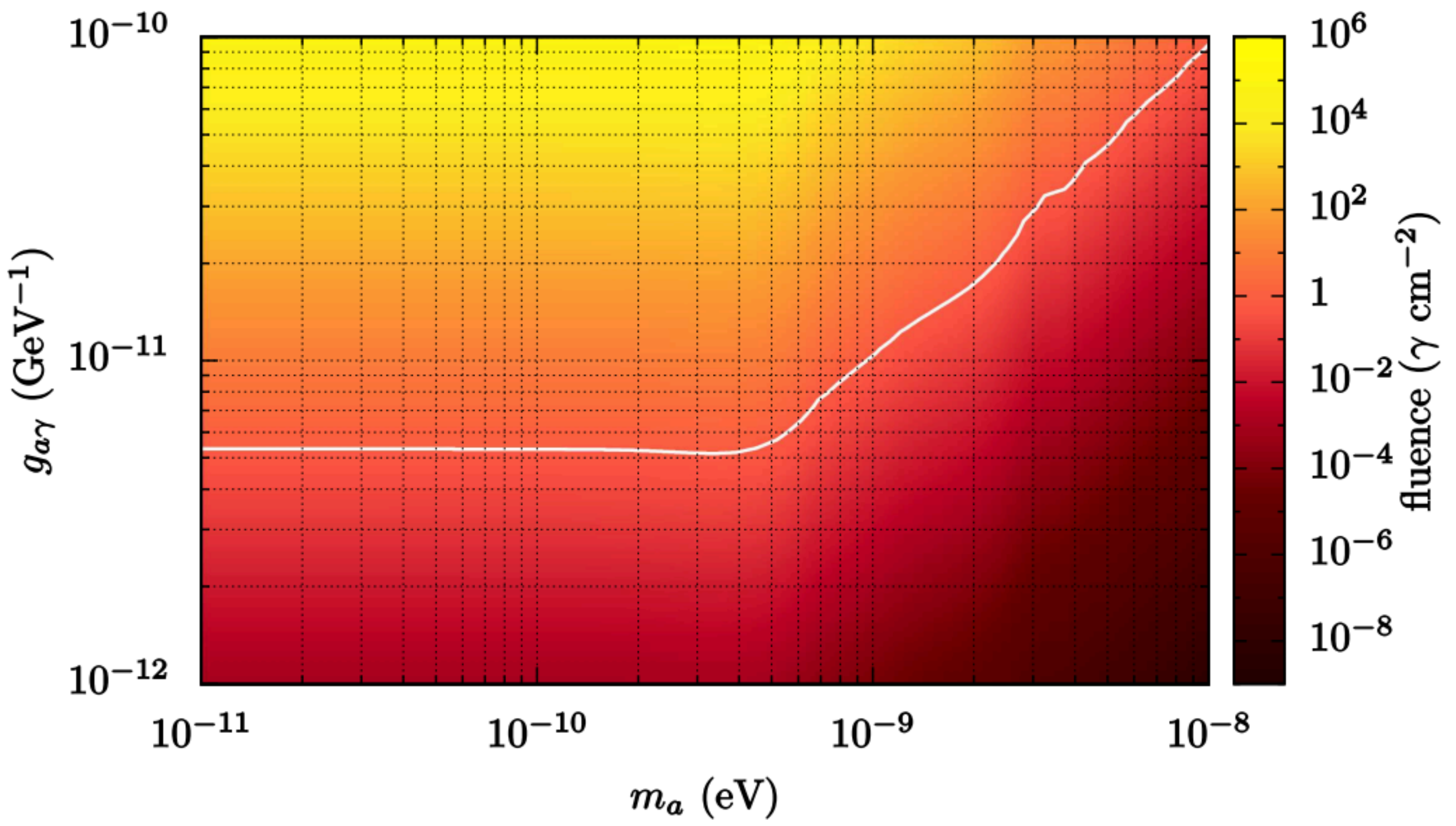
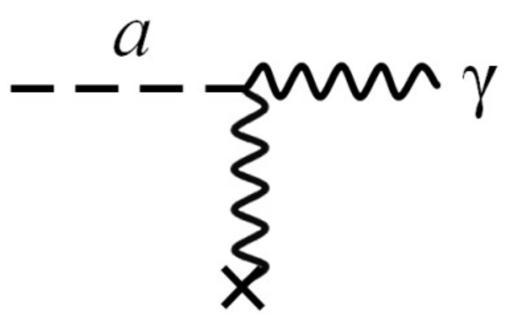
- **SN1987A**: Lack of gamma-ray burst in the Gamma-Ray Spectrometer (GRS) of the Solar Maximum Mission (SMM)

$$g_{a\gamma} \lesssim 5.3 \times 10^{-12}\ \text{GeV}^{-1}, \quad \text{for} \quad m_a \lesssim 4.4 \times 10^{-10}\ \text{eV}$$

Payez+ JCAP'14



Gamma-ray bursts from CC SNe



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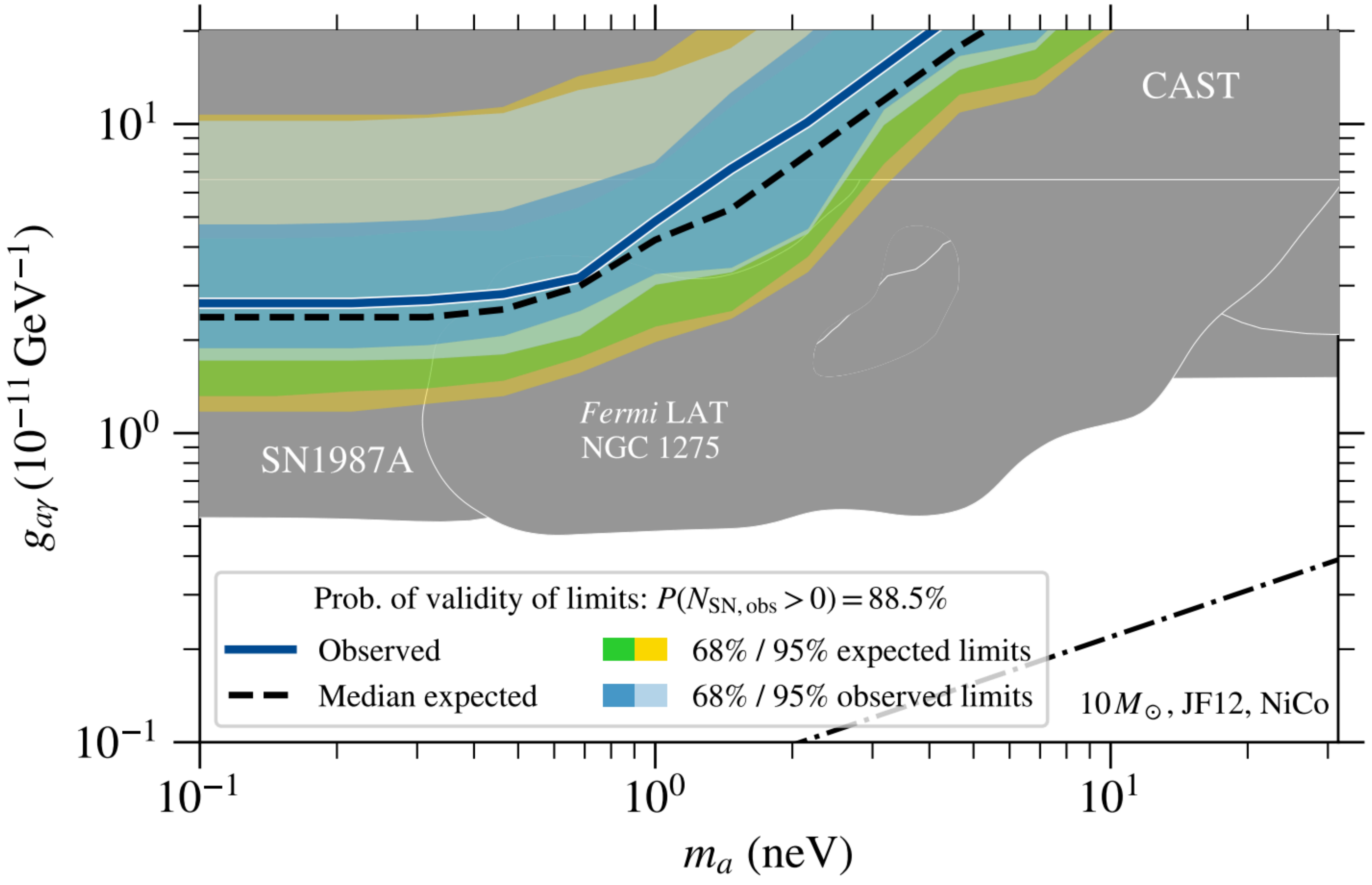
Payez+ JCAP'14

- **Extragalactic SNe**: Search for gamma-ray burst at the time and direction of 20 optically characterised SNe

Meyer & Petrushevska PRL'20

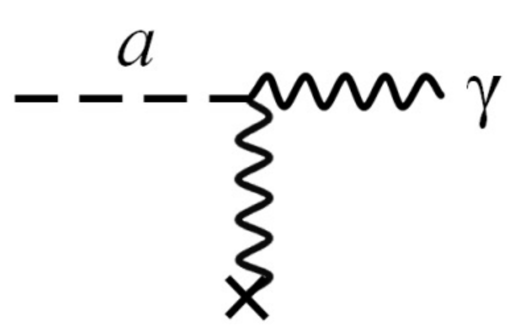
Crnogorcevic+ PRD'21



- The same **cumulative contribution** can be considered for **ALP production in SNe**

FC+ PRD'20, 2110.03679

Future gamma-ray bursts from CC SNe



Production of ALPs in the SNe mainly by **Primakoff effect** $\gamma + Ze \to Ze + a$

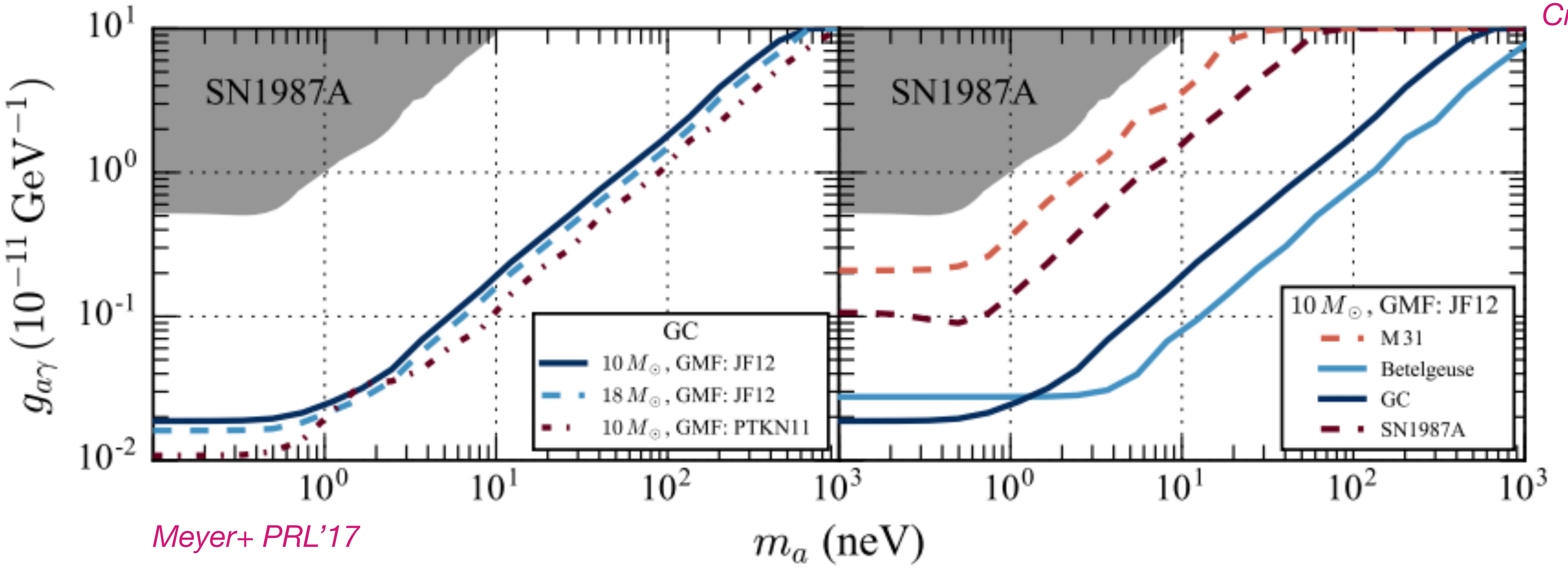
ALPs produced in **O(10) sec bursts**, with an energy spectrum peaked at **60-80 MeV**

➡ Specific **time dependent** and **spectral** signatures

➡ 3% chance to see a Galactic SN with the LAT over the next 7 years

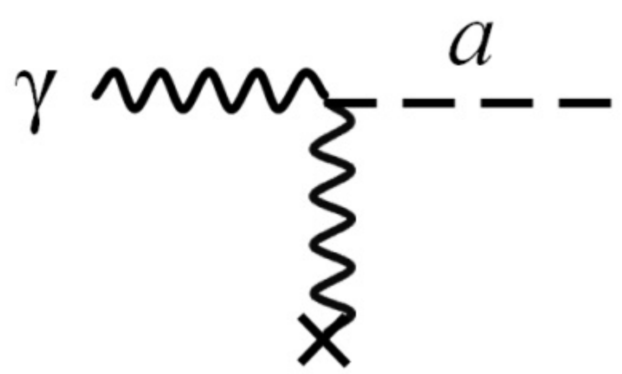
- **Future Fermi-LAT Galactic SN**: Projected constraints from observation of short gamma-ray burst from SN explosion with the LAT from time-dependent signal

Meyer+ PRL'17
Crnogorcevic+ PRD'21



Meyer+ PRL'17

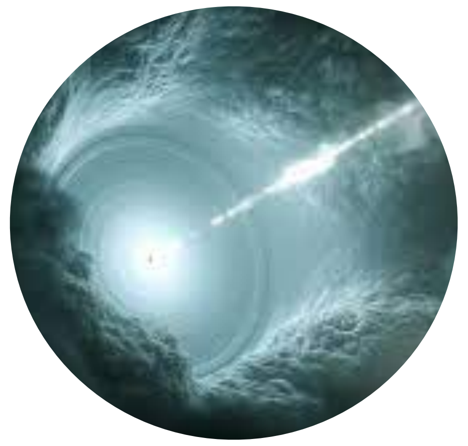
ALPs production in HE emitters



Photons in *source* B field

Extragalactic gamma-ray emitters

- AGNs jets
- Star-forming and star-burst galaxies
- Galaxy clusters



In-situ photon spectrum through hadronic (pp and pg) or leptonic interactions

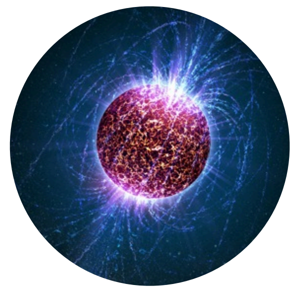
$$\left(\frac{dN_\gamma}{dE}\right)_{\rm P}$$

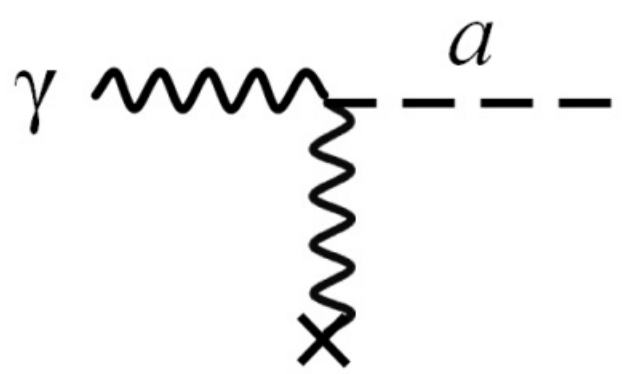
In-situ conversion into ALPs

* Interstellar medium
* Intergalactic radiation fields
* Magnetic field strength and coherence length

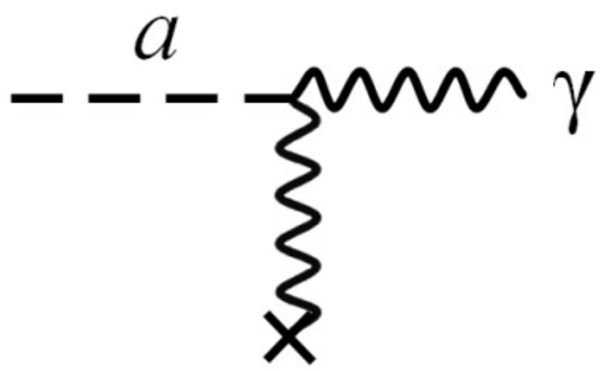
$$\left(\frac{dN_a}{dE}\right)_{\rm S} \propto P_{\rm S}(\gamma \to a) \times \left(\frac{dN_\gamma}{dE}\right)_{\rm P}$$

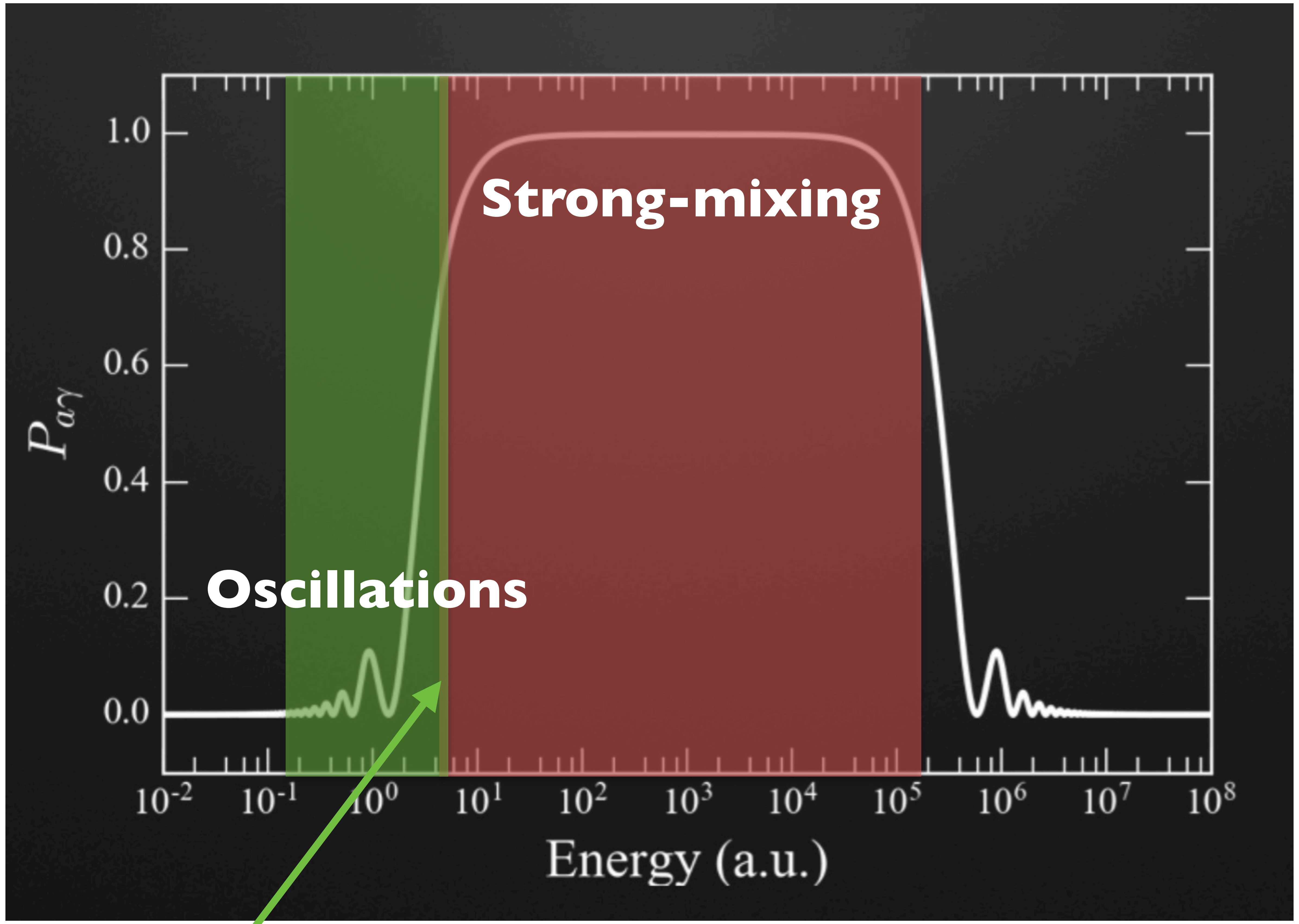
[Also photons from **Galactic objects** like pulsars and SNRs with conversion in Galactic magnetic field]





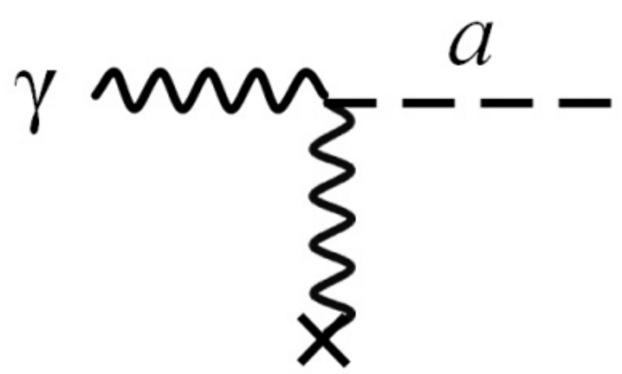
The ALP-photon mixing

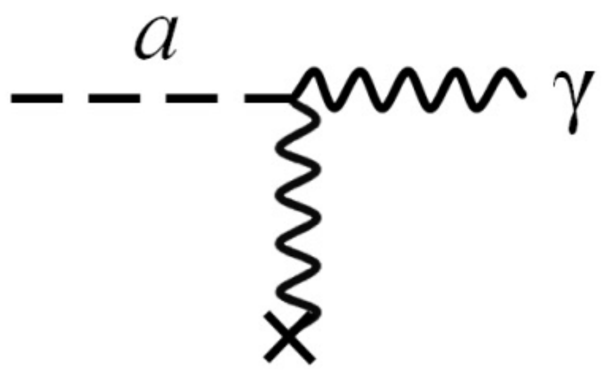


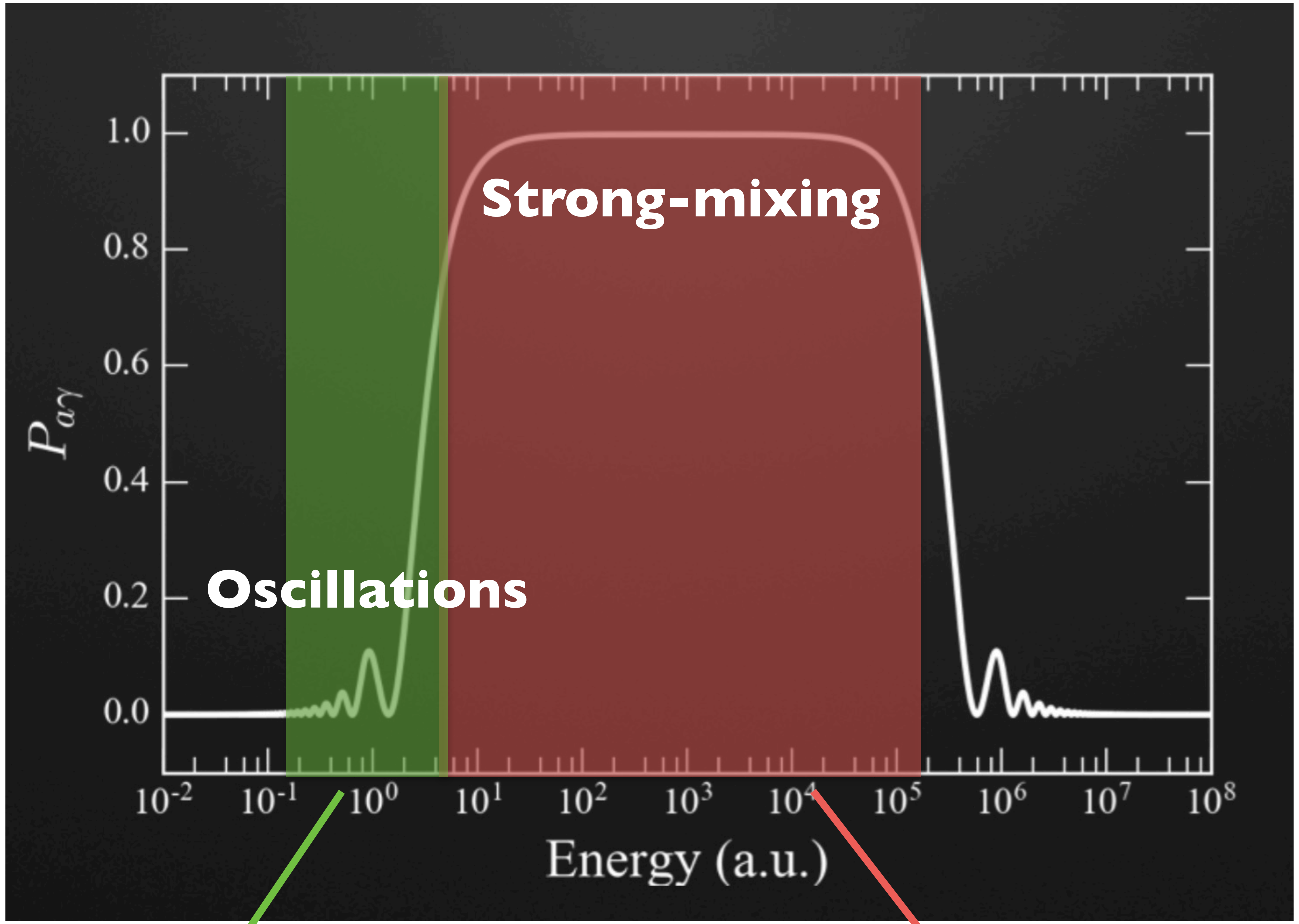


$$E_c \simeq 2.5\ \text{GeV}\,\frac{|m_a^2-\omega_{Pl}^2|}{1\,\text{neV}}\left(\frac{B_\perp}{\mu\text{G}}\right)^{-1}\left(\frac{g_{a\gamma\gamma}}{10^{-11}\ \text{GeV}^{-1}}\right)^{-1}$$

The ALP-photon mixing







I. Spectral irregularities at $\sim E_c$

II. ALPs do not get absorbed, enhancing the photon flux

Searches for spectral irregularities

$$E_\gamma \simeq E_c$$

$$E_c \simeq 2.5\ \mathrm{GeV} \frac{|m_a^2 - \omega_{Pl}^2|}{1\,\mathrm{neV}} \left(\frac{B_\perp}{\mu\mathrm{G}}\right)^{-1} \left(\frac{g_{a\gamma\gamma}}{10^{-11}\ \mathrm{GeV}^{-1}}\right)^{-1}$$

Galaxy cluster

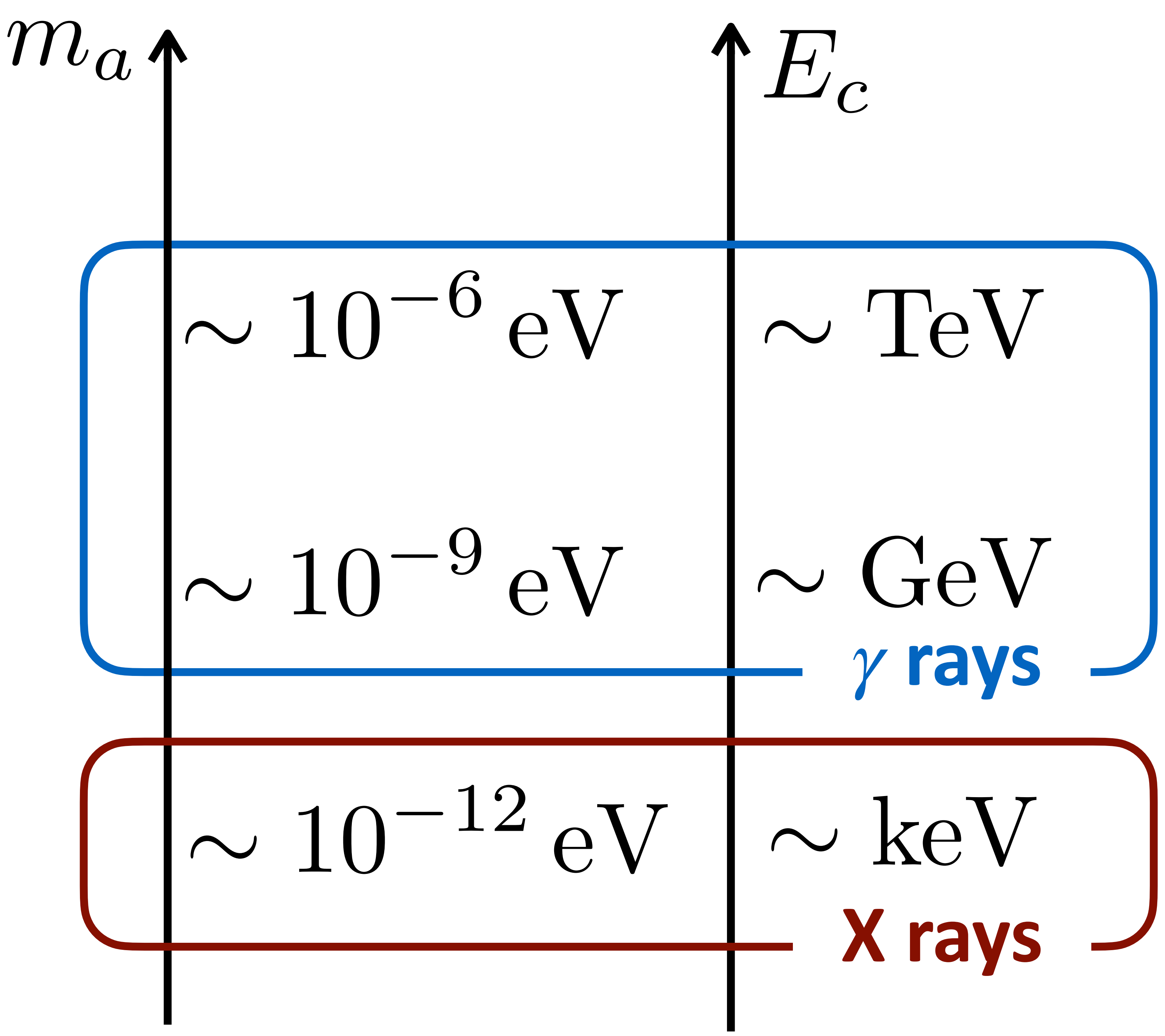
$n_e \sim 0.01\,\mathrm{cm}^{-3}$

$B_0 \sim 1 - 10\,\mu\mathrm{G}$

Milky Way

$n_e \sim 0.1\,\mathrm{cm}^{-3}$

$B \sim 1\,\mu\mathrm{G}$



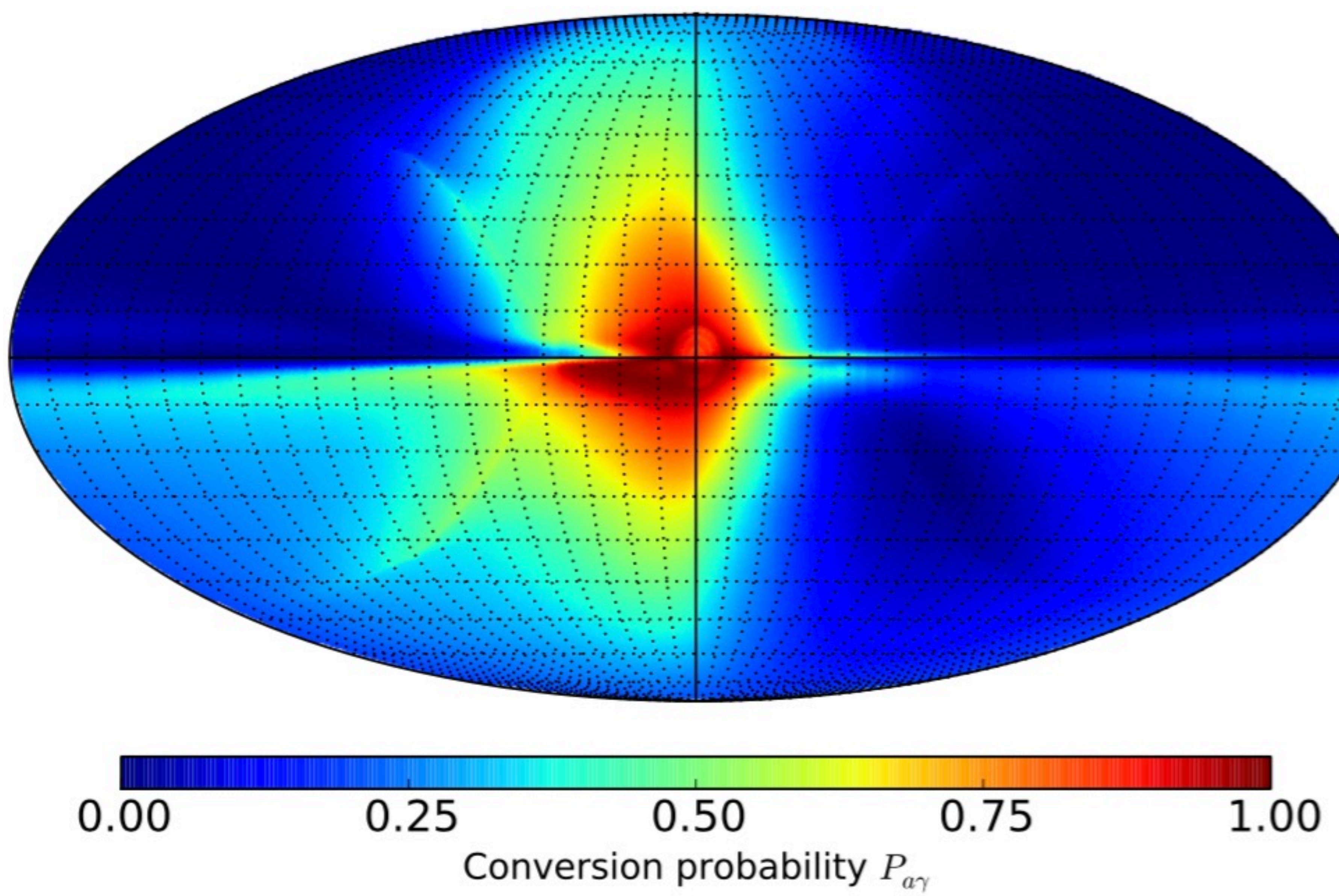
Wouters & Brun ApJ'13; Conlon+ JCAP'17

Searches for spectral irregularities

High-energy gamma rays

Some basic requirement:

- Very **bright gamma-ray sources** ⟶ High statistics for a good spectral determination
- Sources far enough and in the **direction of strong transversal B-fields**, e.g. behind or within a galaxy cluster
- Good knowledge of B-field! As ALP searches are sensitive to the product $\mathbf{g_{a\gamma} B_T}$, the constraint on $g_{a\gamma}$ is only as good as the knowledge of B_T.

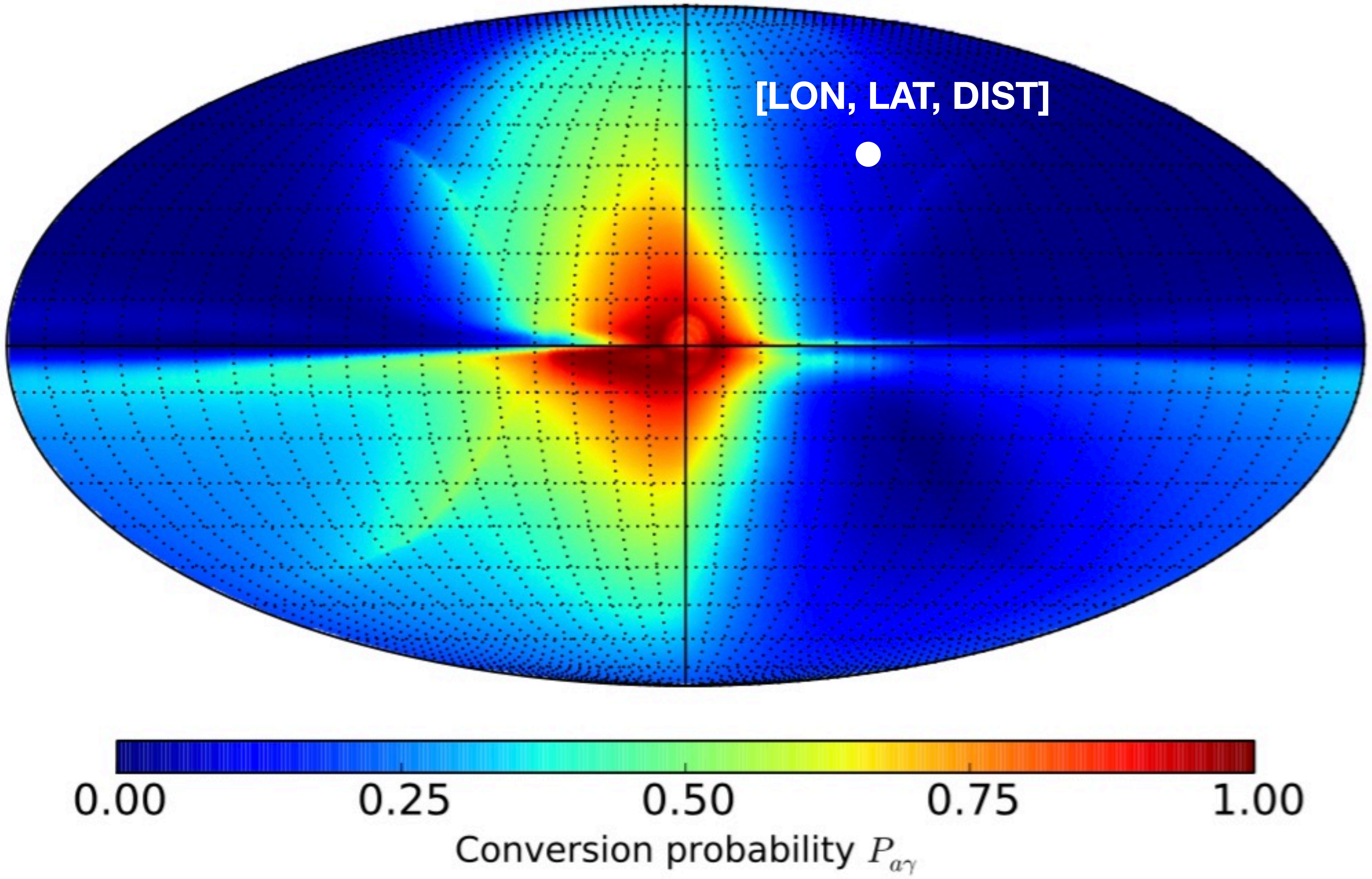


Conversion probability in Galactic B-field

$g_{a\gamma}$ = 5 x 10^{-11} GeV^{-1}
pure ALP beam
propagating through entire Milky Way
[Jansson & Farrar 2012 model]

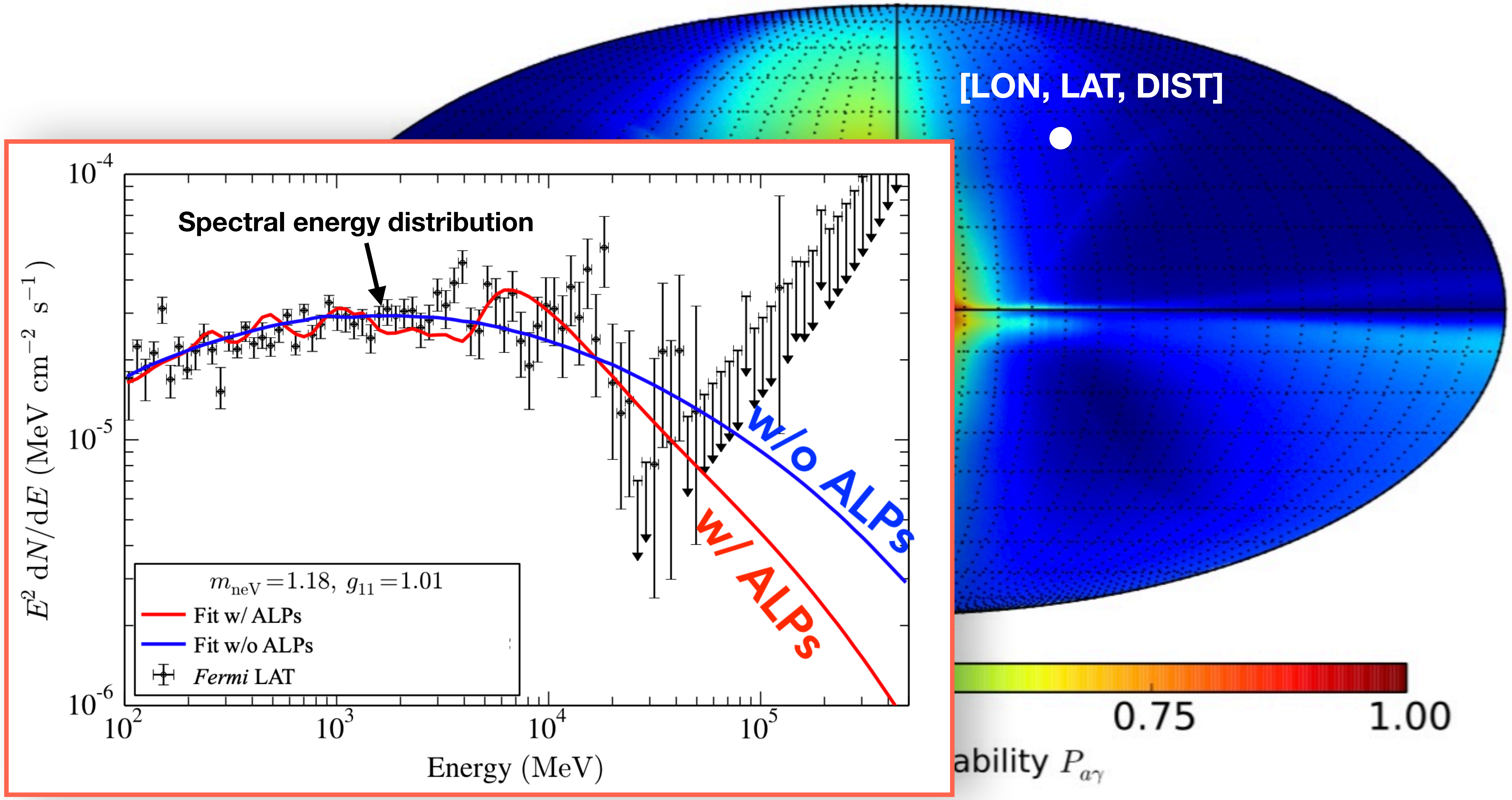
Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets



Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets

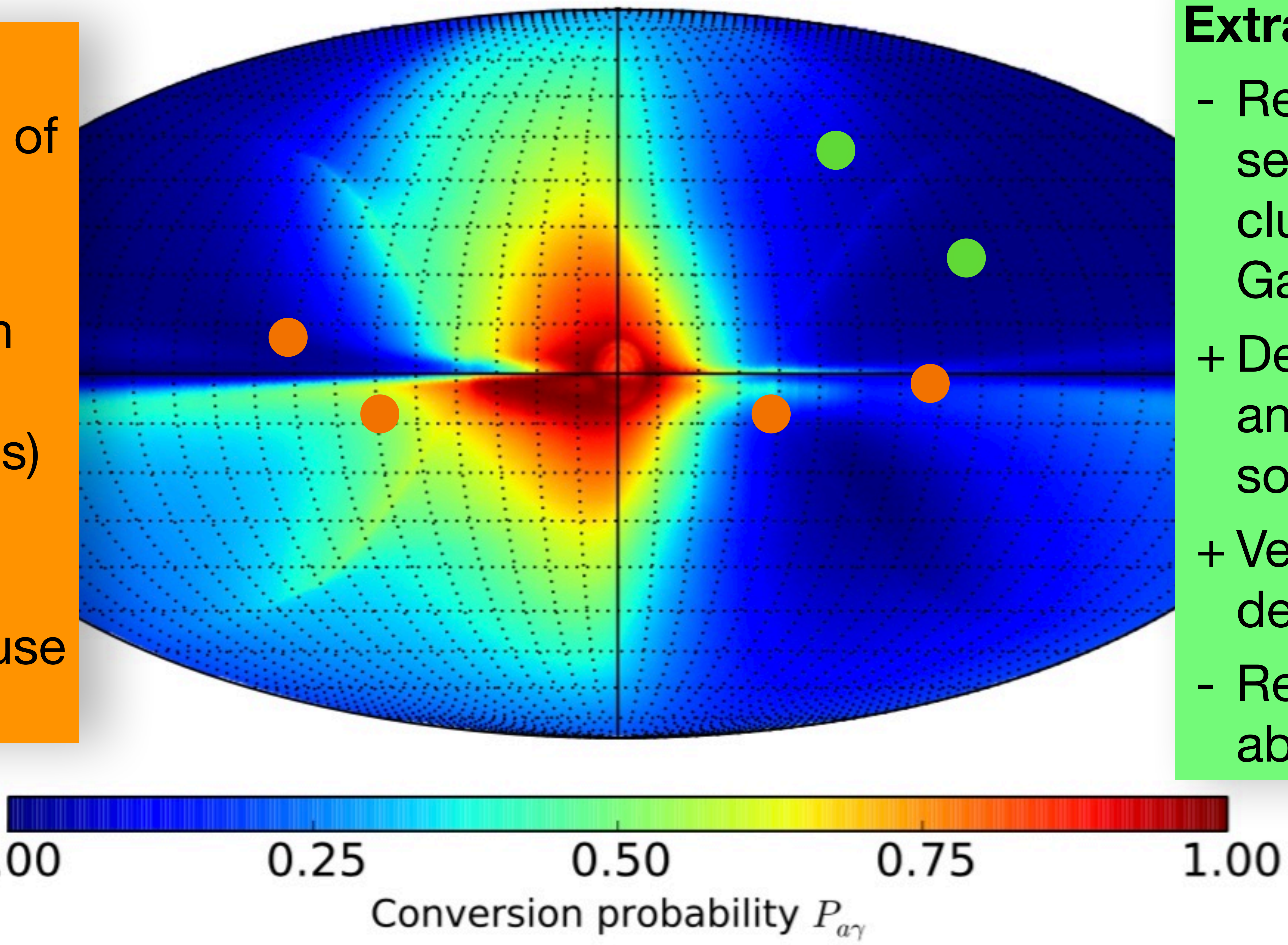


Searches for gamma-ray spectral irregularities

Galactic and extragalactic targets

Galactic targets:

+ Require only modelling of Galactic B field
- Strength of the conversion depends on position in the Galaxy (e.g. beyond spiral arms)
- Larger systematics on spectral determination due to gamma-ray diffuse emission foreground



Extragalactic targets:

- Require modelling of several B fields (intra-cluster, intergalactic, Galactic)
+ Depends only on latitude and longitude of the sources
+ Very accurate spectral determination
- Require modelling of EBL absorption

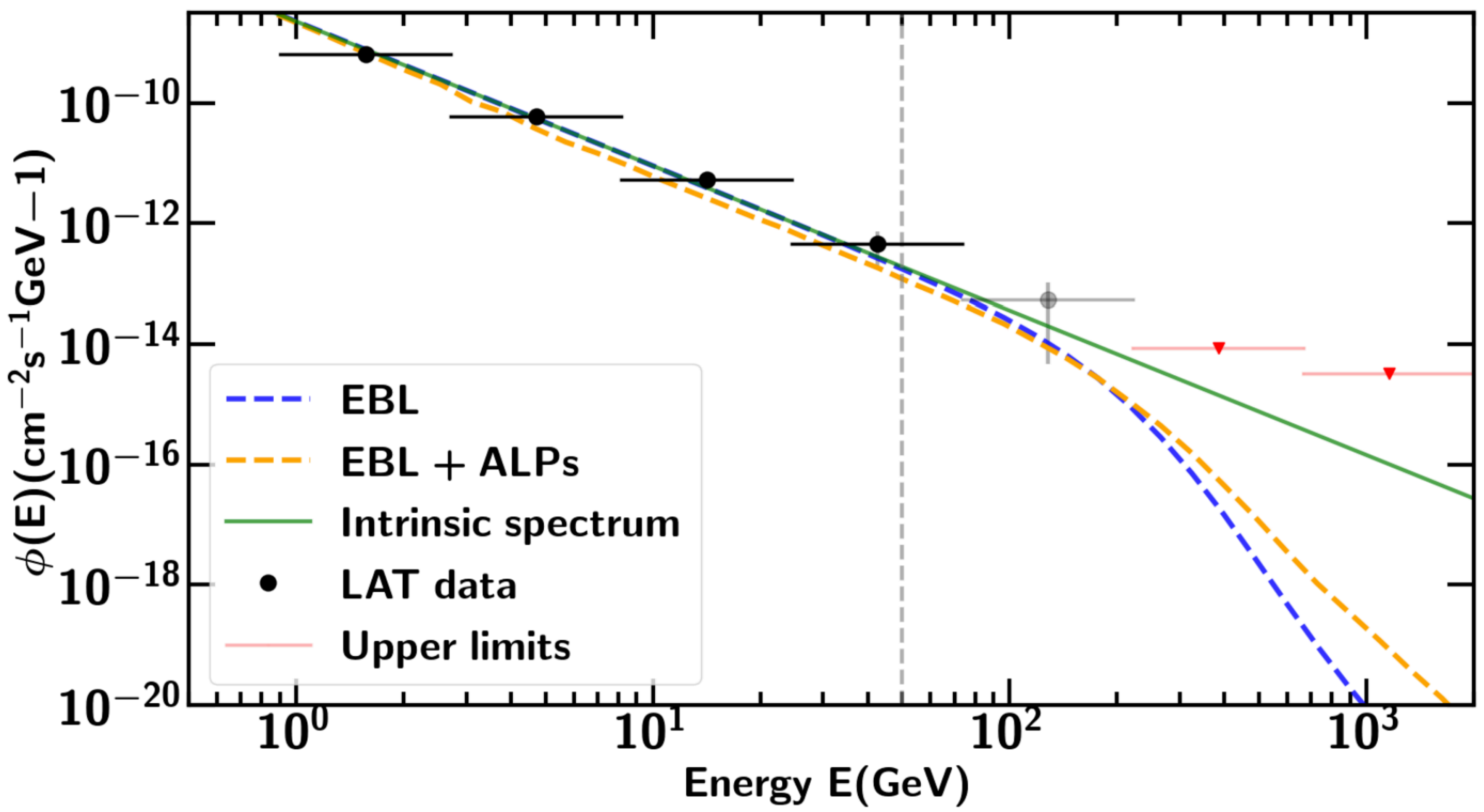
ALPs and the opacity of the Universe

- **VHE photons** from distant sources are **attenuated** by pair production onto the **Extragalactic Background Light (EBL)**

$$\phi_{obs}(E) = \phi_{int}(E) \cdot \exp\left[-\tau(E,z)\right] \qquad \tau = \frac{d}{n(E)\sigma(\gamma\gamma \rightarrow e^+e^-)}$$

- The flux of very distant sources and at very high energies should be exponentially suppressed
- In the past, indications of **anomalous cosmic transparency** from gamma-ray studies interpreted as possible signs of ALPs *De Angelis et al. (2009,2011,2015); Essey & Kusenko (2012); Horns & Meyer (2012); Rubtsov & Troitsky (2014); etc*
- Latest data **consistent with EBL expectations**

Biteau&Williams+ApJ'15; Dominguez&Ajello ApJL'15



➡ Search for ALPs-induced anomalous EBL absorption

Buehler+ 2004.09396

Constraints on ALP-photon mixing

High-energy gamma rays

Core-collapse SNe

- Searches for **single SNe** events or cumulative flux from **all past SNe**

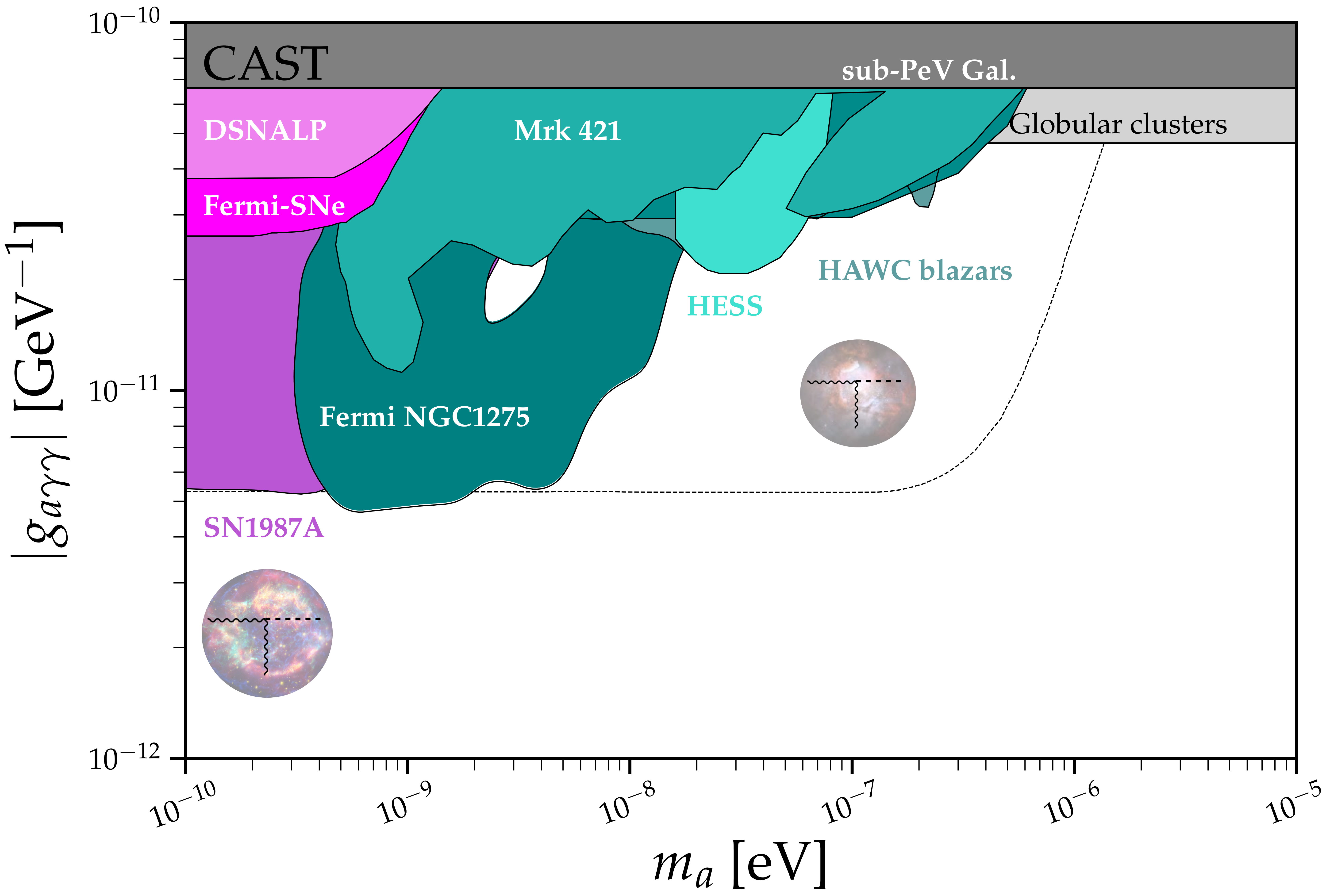
Payez+ JCAP'14; Meyer & Petrushevska PRL'20; Crnogorcevic+ PRD'21 FC+ PRD'20, Eckner, FC+PRD'22

- MeV to GeV cosmic backgrounds offer a unique window on this production mechanism

High-energy gamma-ray sources

- Search for **spectral distortion** of high-energy Galactic and extra-galactic sources from X- to gamma rays (e.g. NGC1275, Mrk421)
- Search for **photons appearance** from photon-ALPs *in source* conversion (HAWC blazars, sub-PeV Gal.)

Jacobsen+2203.04332; Eckner&FC PRD'22



https://github.com/cajohare/AxionLimits

Anomalies and excesses

The anti-proton excess

Low-energy excess in antiproton data?

Signal:

- Excess in AMS-02 cosmic-ray antiprotons @ 10 — 20 GeV *Cuoco+ PRL'17; Cui+ PRL'17; Cholis+ '17*
- Accounting for covariance of various systematics the significance drops < 2σ

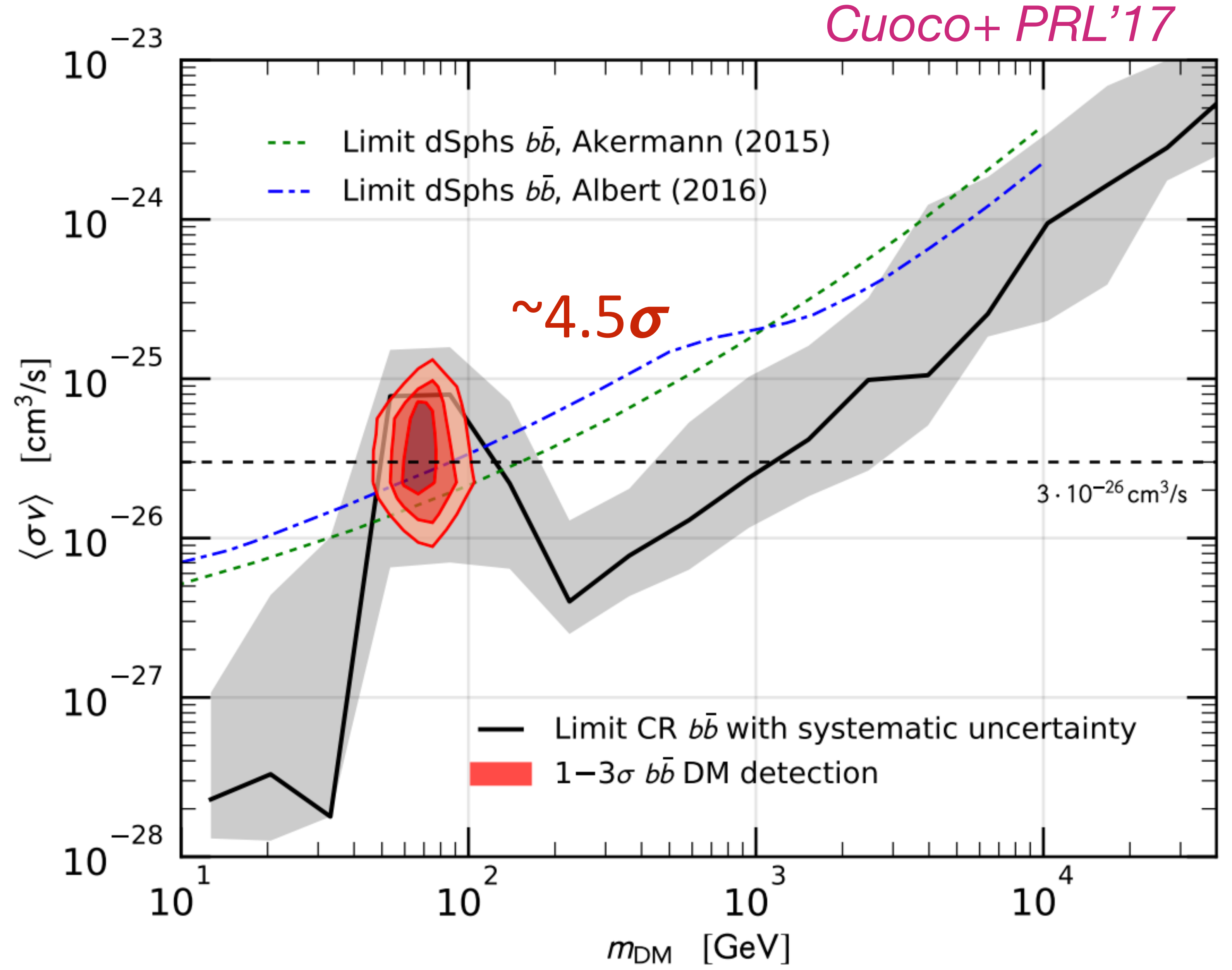
Reinert&Winkler JCAP'18; Boschini+ ApJ'17

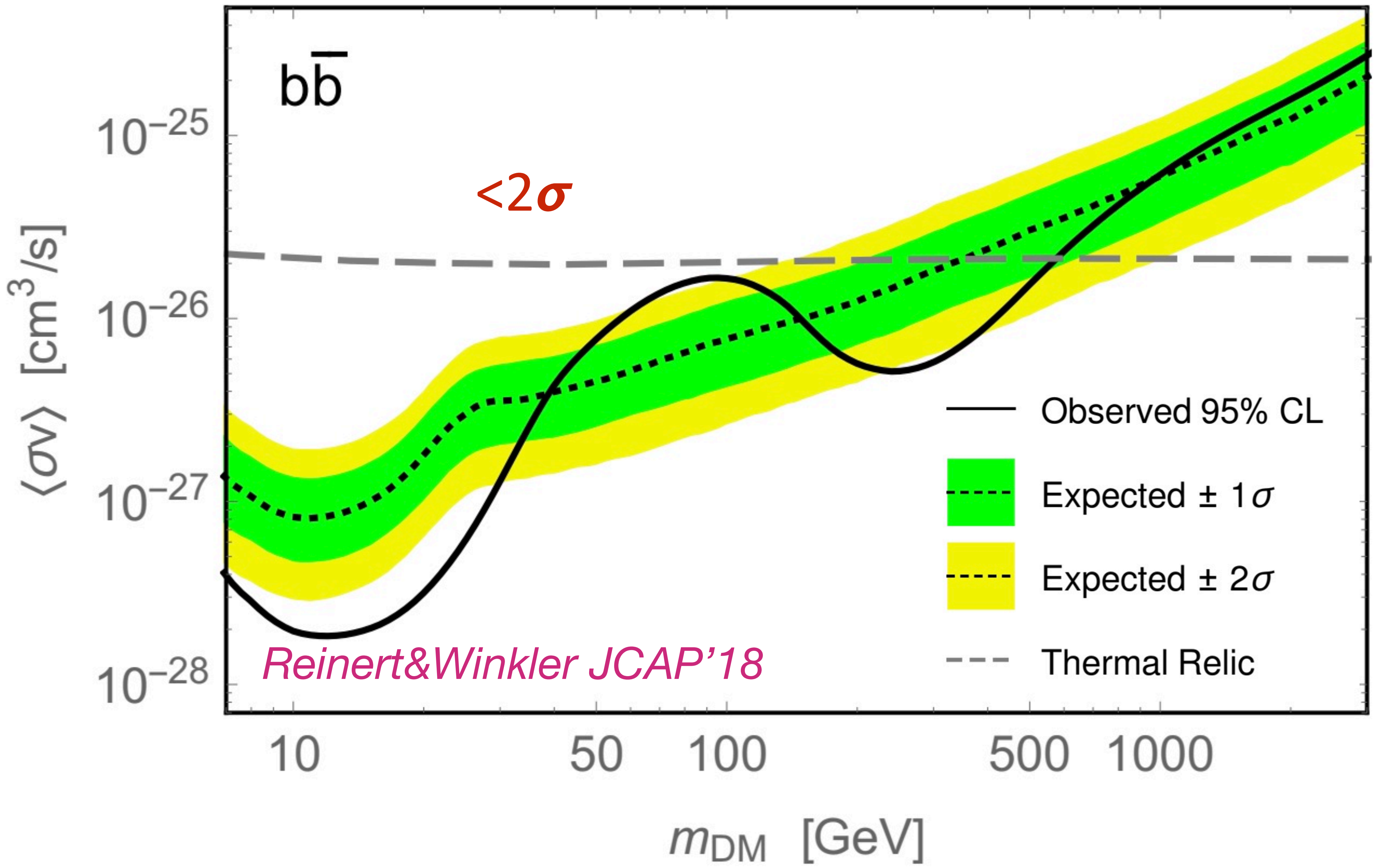
Interpretations:

- Dark matter annihilation with mass ~ 40 — 130 GeV (consistent with GeV excess) *Cuoco+ JCAP'17*
- However, simple propagation scenarios cannot explain *all* CR data
- Syst. uncertainties still large: pbar production cross section? Effects of solar modulation? Cosmic-ray propagation models?

➡Refined treatment of uncertainties is needed!

Cuoco+ PRL'17

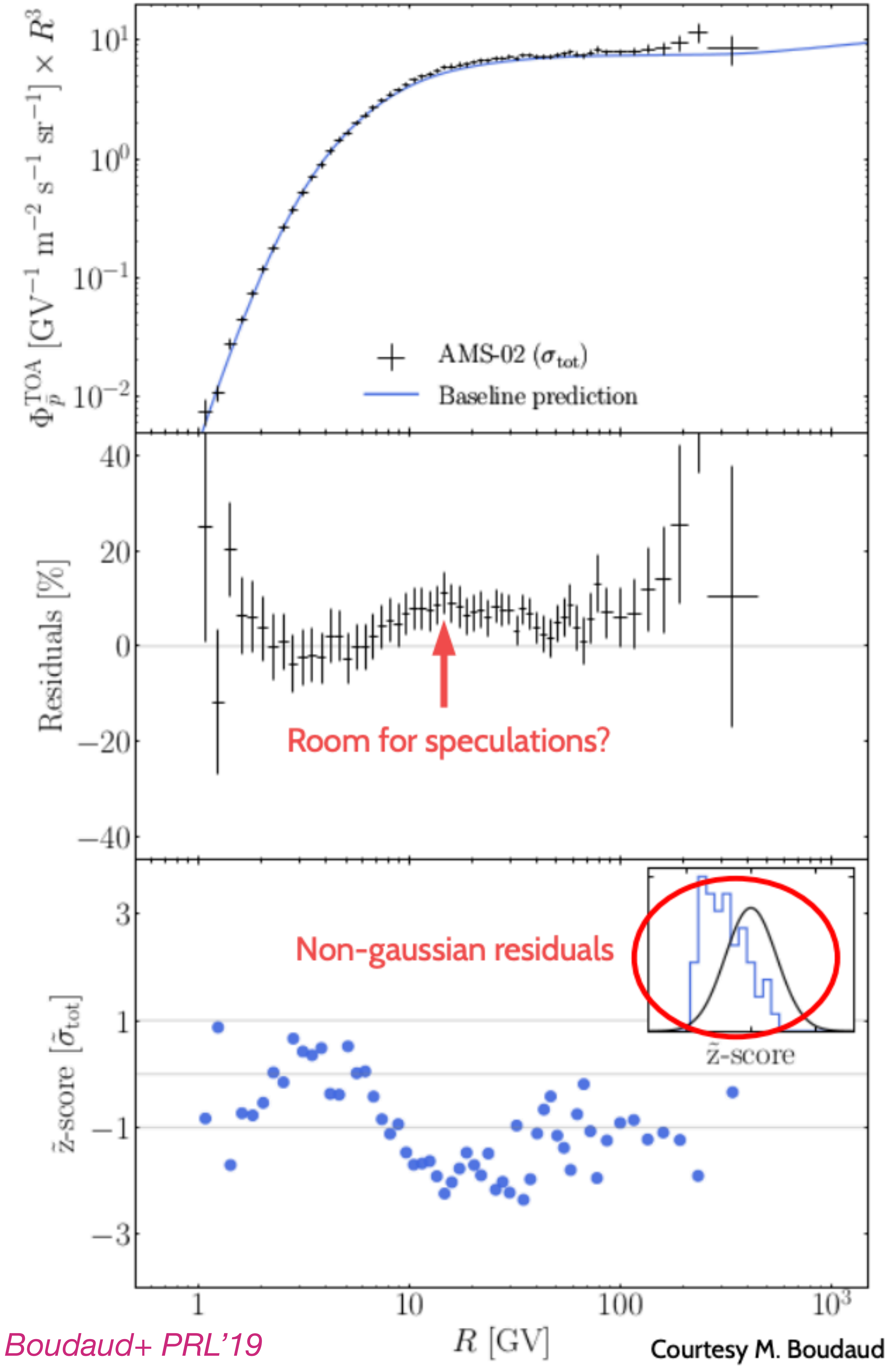




Antiproton uncertainties

Data: AMS02 antiproton from 2016
Model: semi-analytical
Comparison with data => discrepancy ~ few 10GV

New Physics?
Or sys uncertainties?



Boudaud+ PRL'19

Courtesy M. Boudaud

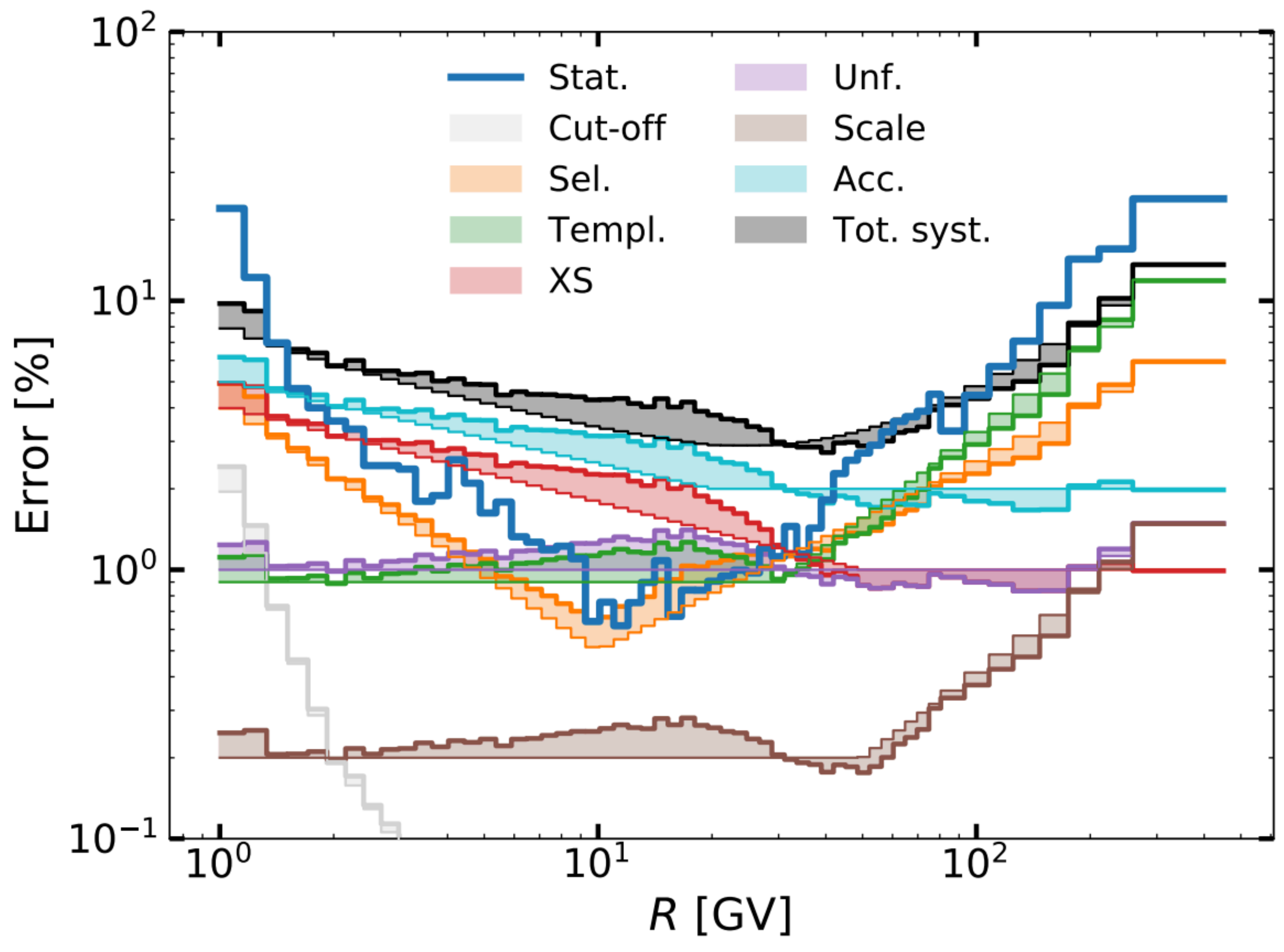
Antiproton uncertainties

Data: AMS02 antiproton from 2016
Model: semi-analytical
Comparison with data => discrepancy ~ few 10GV

New Physics?
Or sys uncertainties?

Errors on the **data**: Covariance matrix estimated from detector info
Errors on the **model**:

1. Pbar production cross-sections → Updated parameterisation and uncertainties
2. Transport → Updated transport models and uncertainties
3. Parents → Updated fit and contribution of high-Z elements



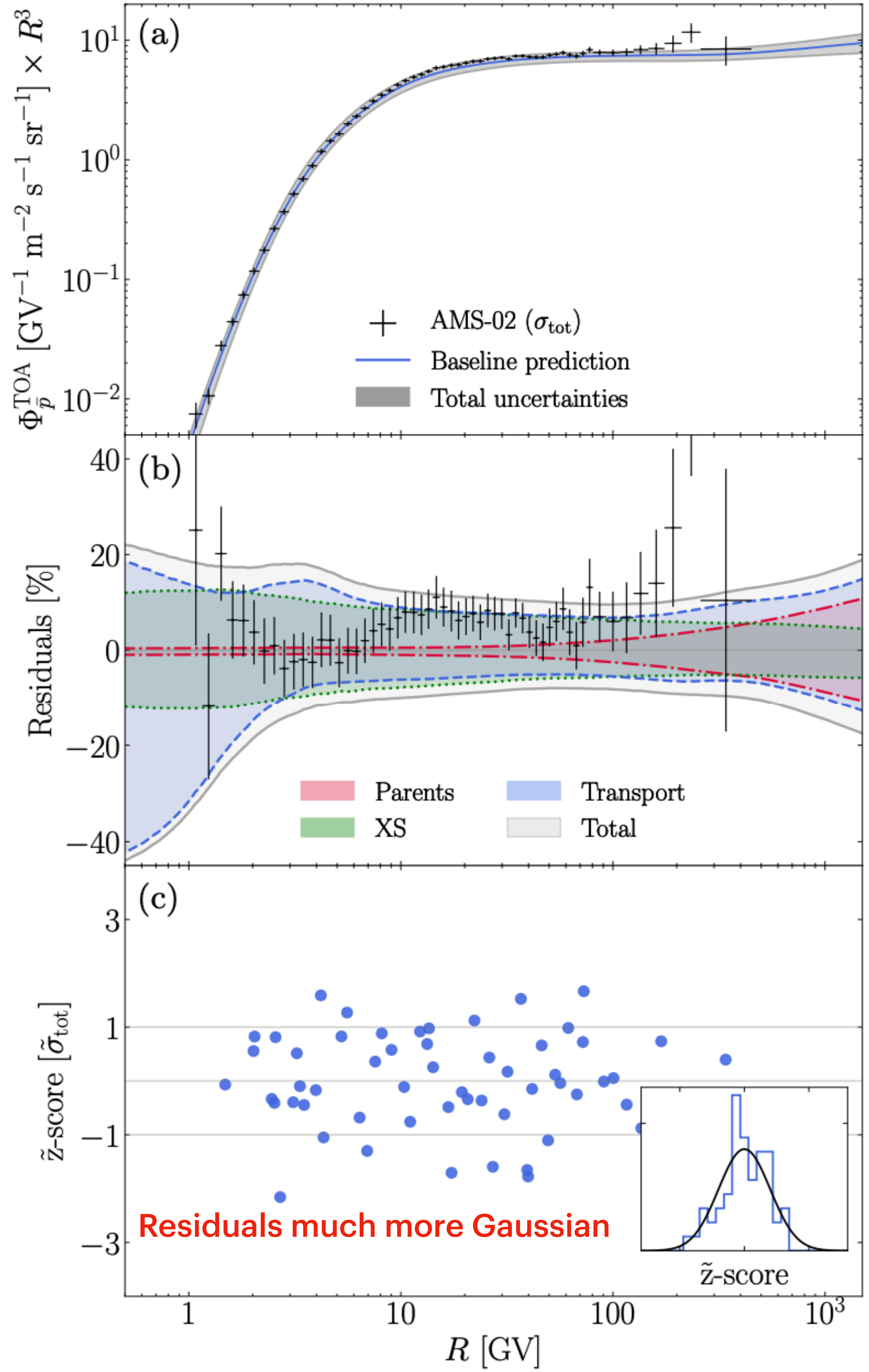
Antiproton uncertainties

Data: AMS02 antiproton from 2016
Model: semi-analytical
Comparison with data => discrepancy ~ few 10GV

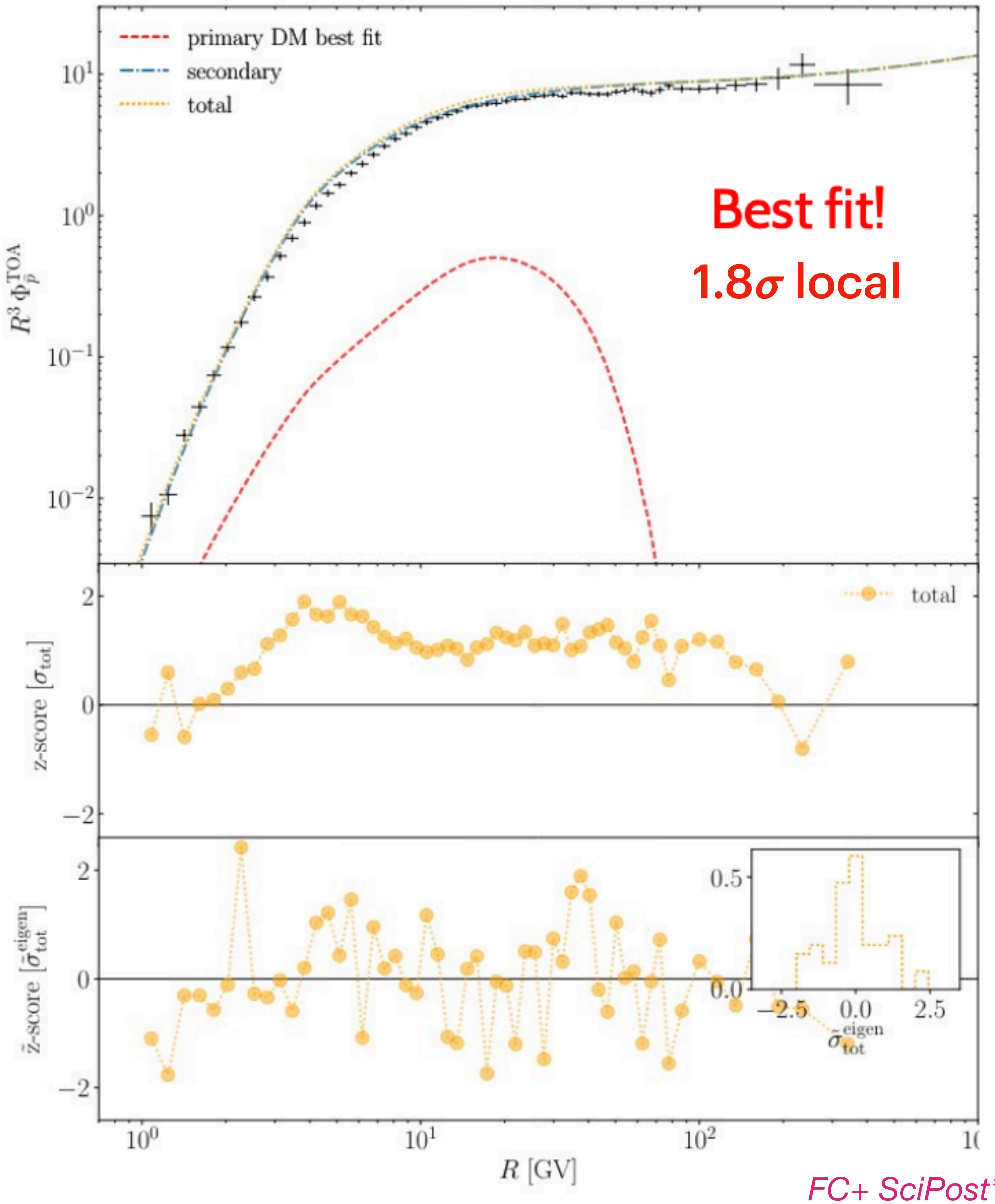
New Physics?
Or sys uncertainties?

AMS-02 antiprotons are consistent with a secondary astrophysical origin

$$\chi^2 = (\text{data}-\text{model})^T (\mathcal{C}^{\text{model}} + \mathcal{C}^{\text{data}})^{-1} (\text{data}-\text{model})$$



No room for dark matter



FC+ SciPost'22

Likelihood ratio:

$$LR(\mu_0) = -2\ln \frac{\sup_{\lambda\in\Lambda} \mathcal{L}(\lambda,\mu_0)}{\sup_{\{\lambda,\mu\}\in\Lambda\cup M} \mathcal{L}(\lambda,\mu)}$$

CR-specific parameters vs DM-specific ones

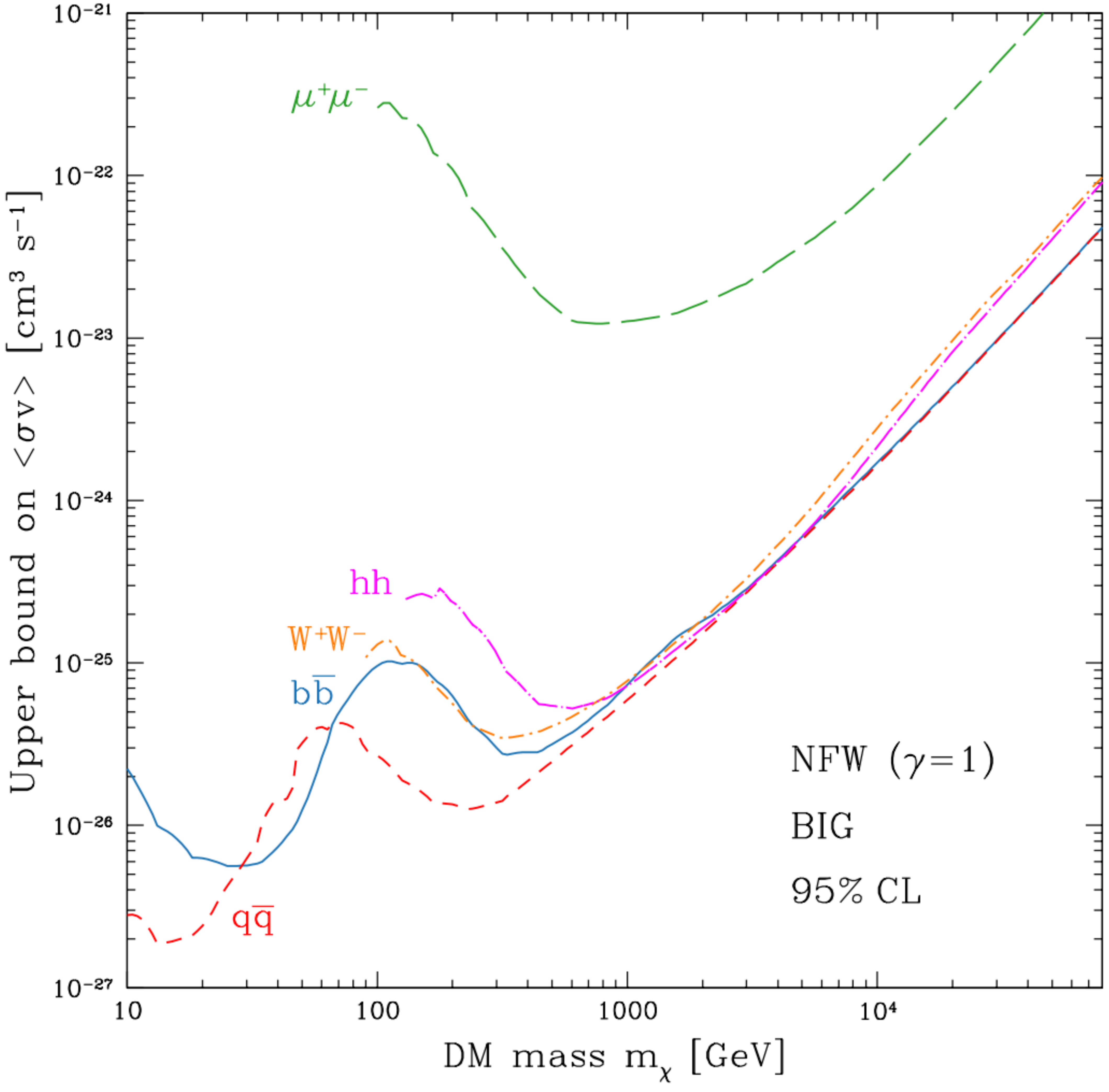
$$-2\ln\mathcal{L}(\lambda,\mu) \equiv \chi^2_{\rm LiBeB}(\lambda) + \chi^2_{\bar{p}}(\lambda,\mu)$$

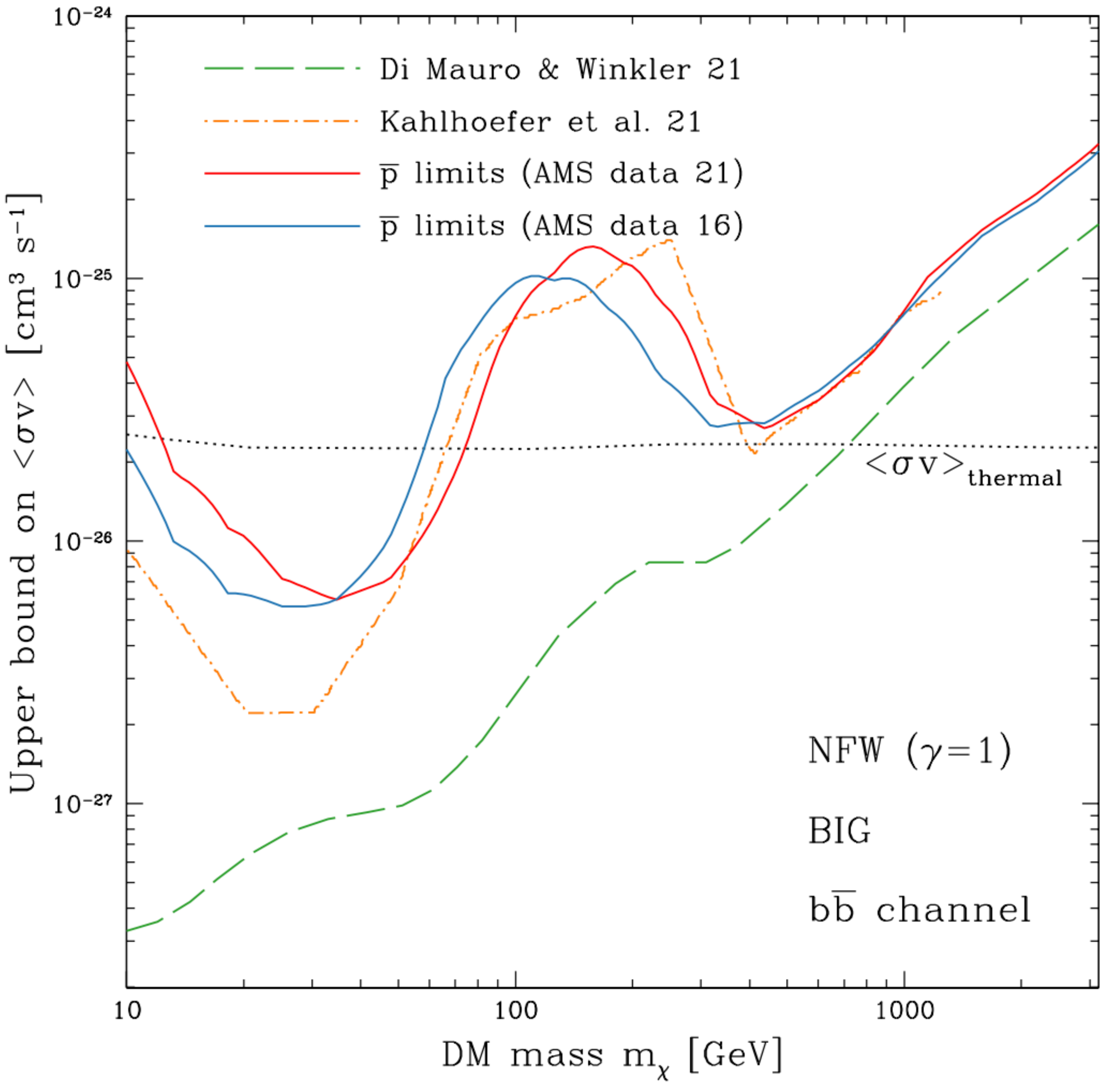
1. CR parameters derived from LiBeB, are good for anti-protons
2. DM does not alter best-fit for propagation parameters since subdominant
3. Uncertainty on primary antiproton flux dominated by the size of the diffusive halo, L

$$-2\ln\mathcal{L}(\lambda,\mu) \equiv -2\ln\mathcal{L}(L,\mu) = \left\{\frac{\log L - \log \hat{L}}{\sigma_{\log L}}\right\}^2 + x_i(\mathcal{C}^{-1})_{ij}x_j$$

Antiproton constraints on WIMPs

FC+ SciPost'22

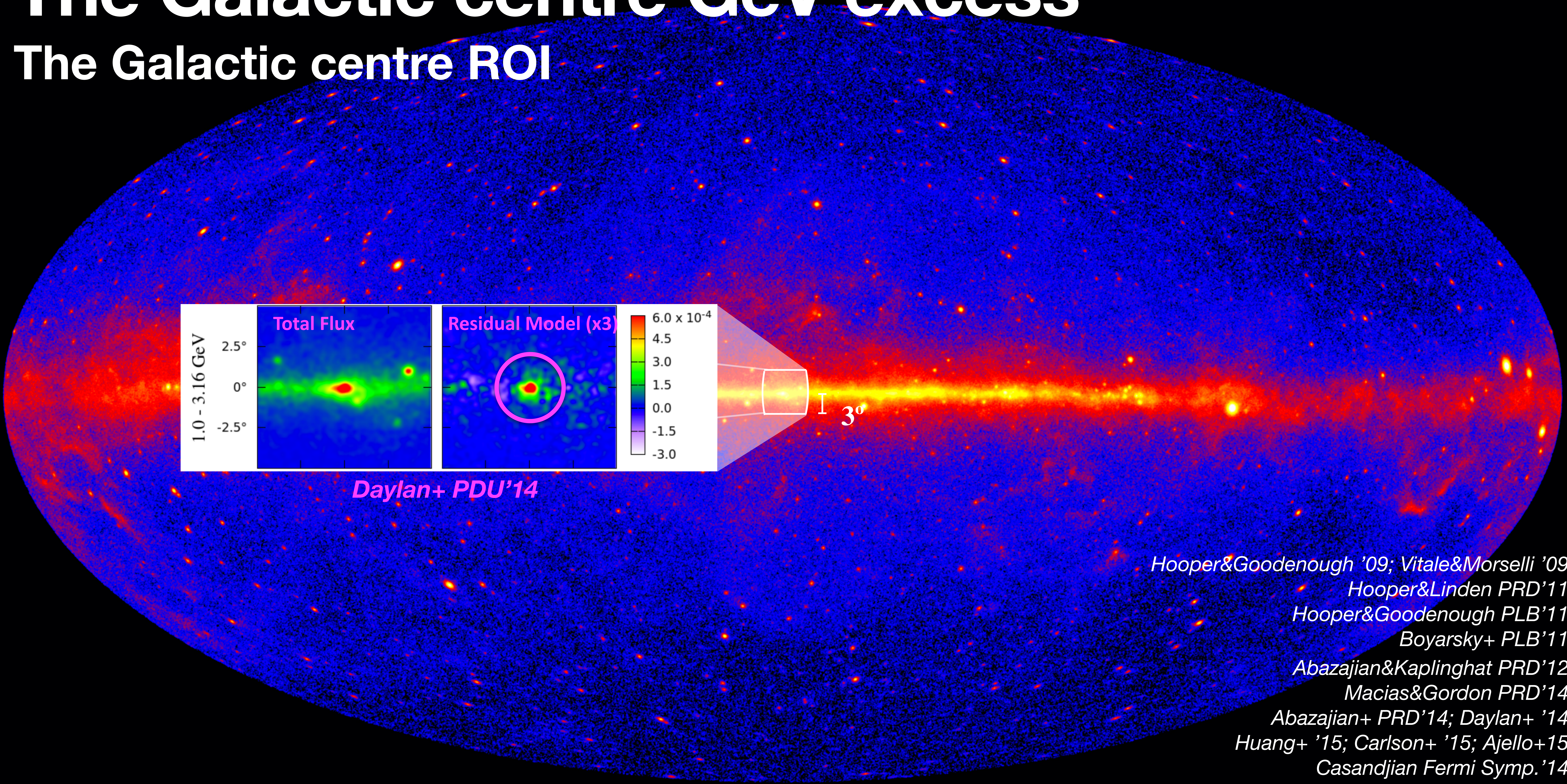




The Fermi-LAT GeV excess

The Galactic centre GeV excess

The Galactic centre ROI



Daylan+ PDU'14

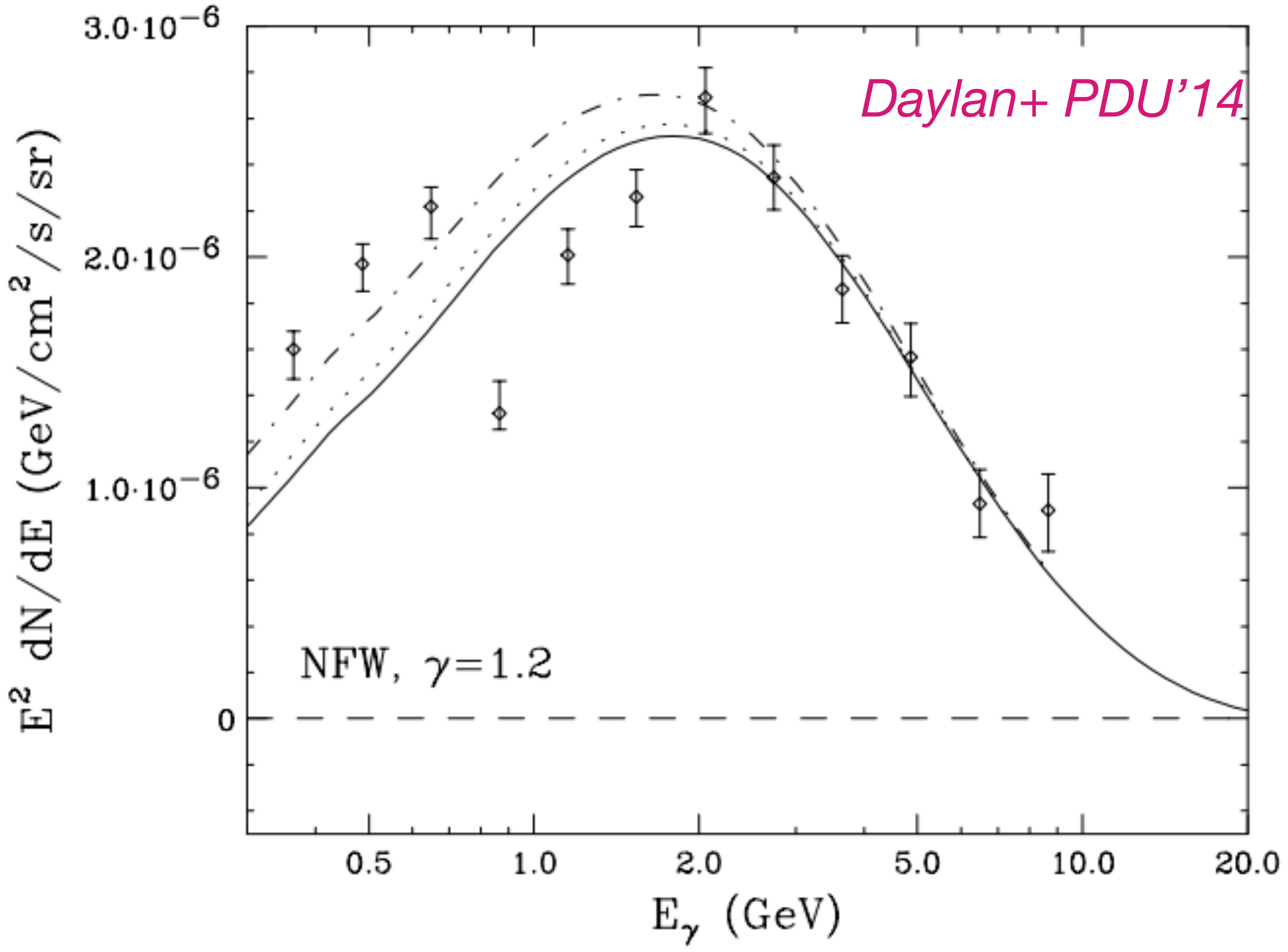
Hooper&Goodenough '09; Vitale&Morselli '09; Hooper&Linden PRD'11; Hooper&Goodenough PLB'11; Boyarsky+ PLB'11; Abazajian&Kaplinghat PRD'12; Macias&Gordon PRD'14; Abazajian+ PRD'14; Daylan+ '14; Huang+ '15; Carlson+ '15; Ajello+15; Casandjian Fermi Symp.'14; de Boer+'16; Macias+'16; etc.

The GeV excess

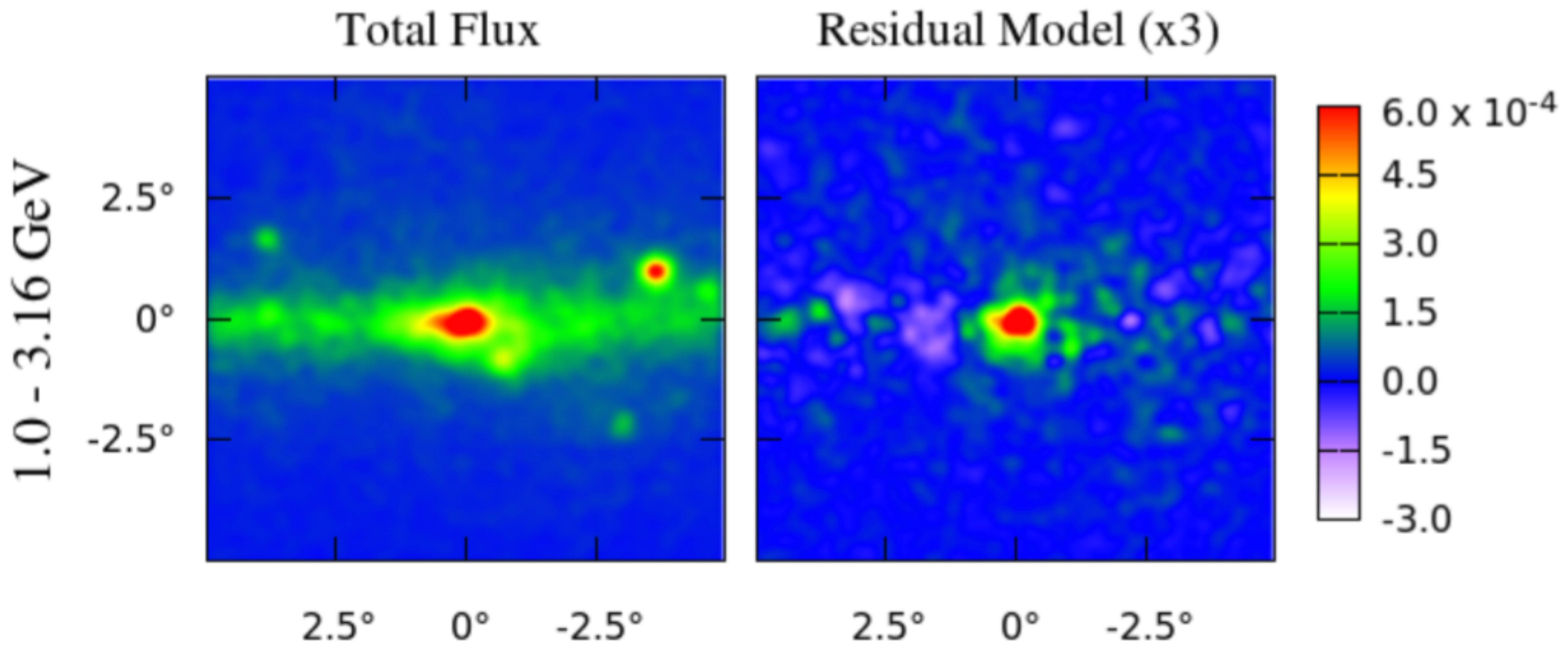
Galactic centre characterisation

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

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

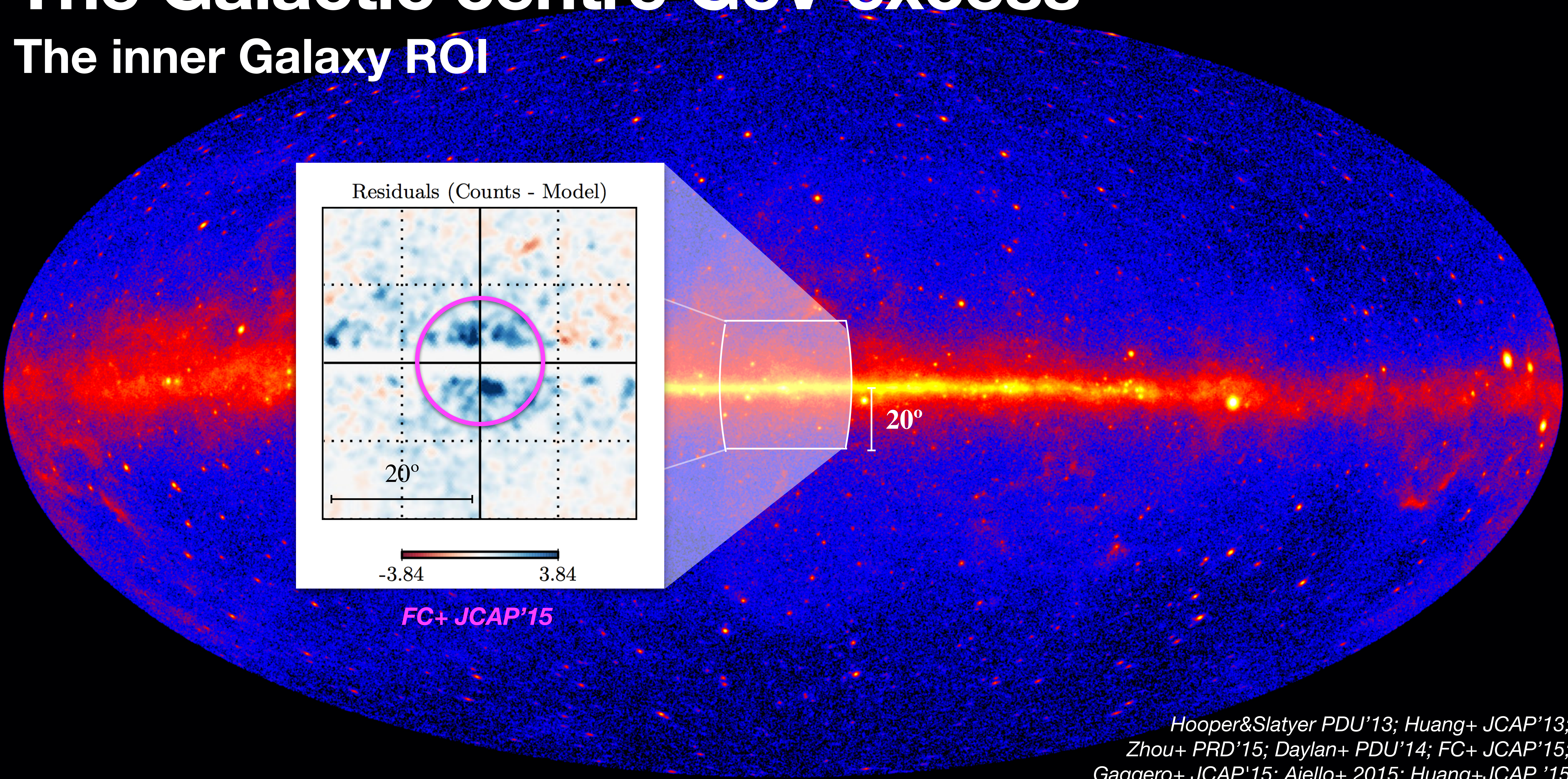
Abazjian+ PRD'14

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

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

The Galactic centre GeV excess

The inner Galaxy ROI

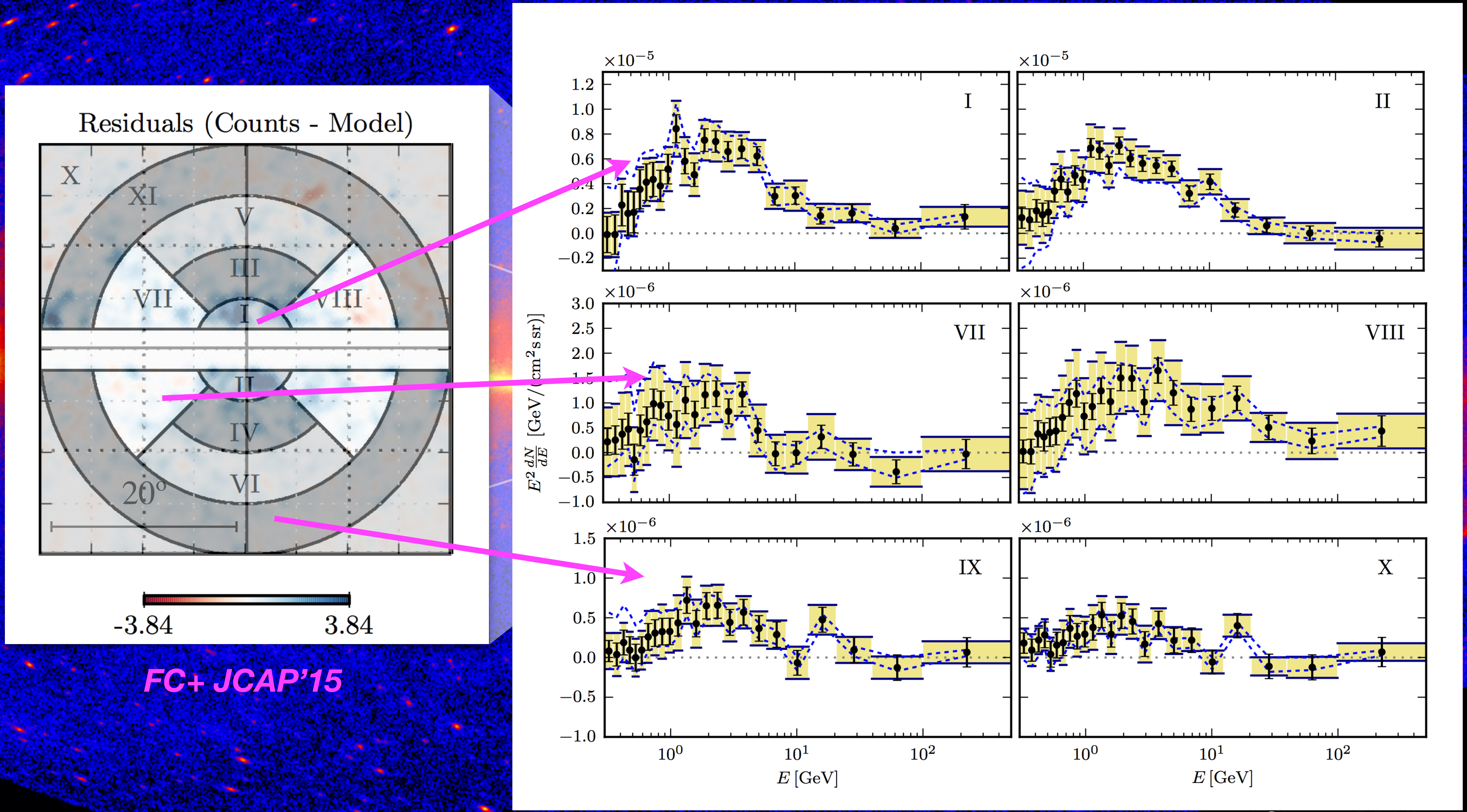


FC+ JCAP'15

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

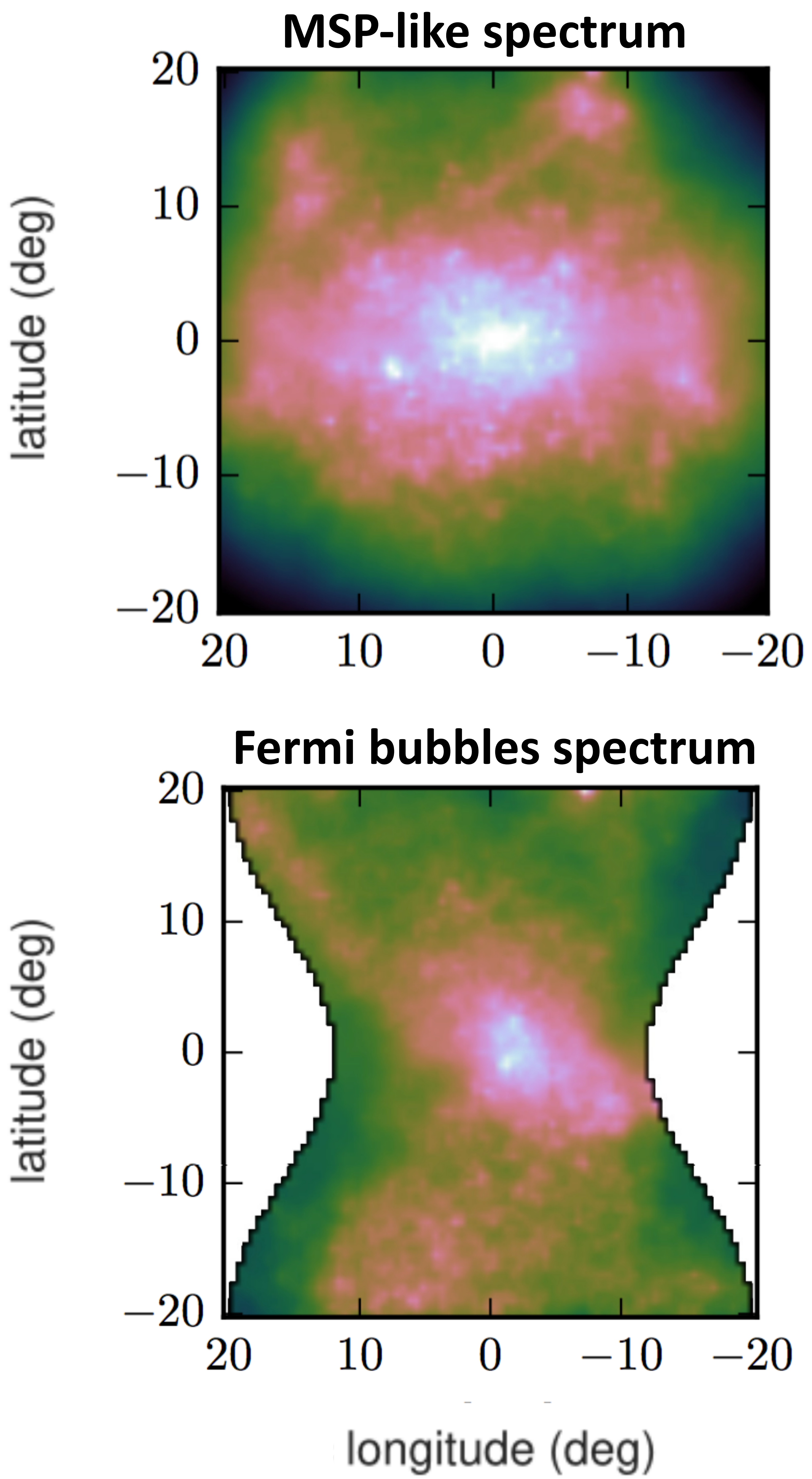


FC+ JCAP'15

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

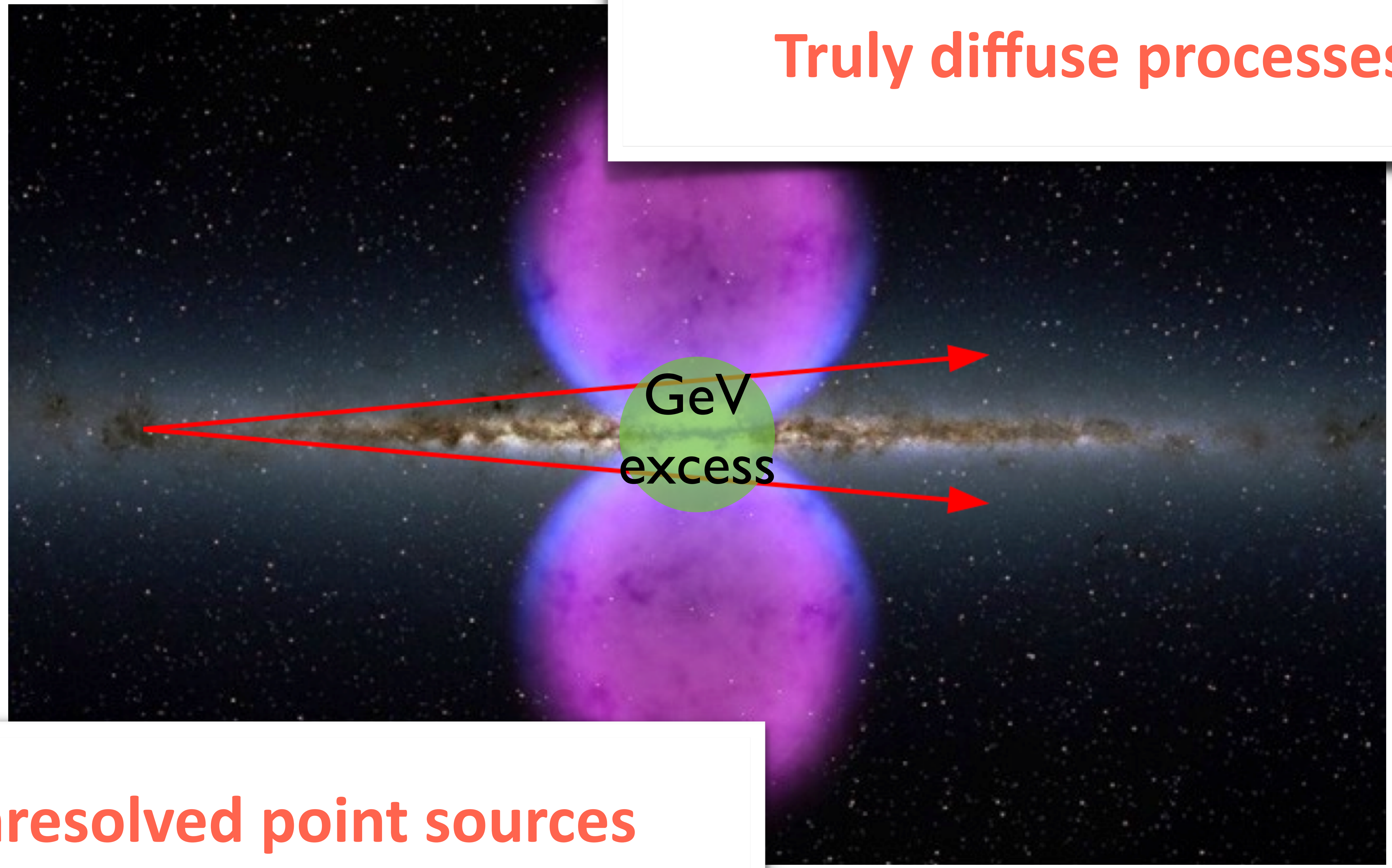
Storm, Weniger & FC JCAP'17

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

What is the origin of the GeV excess?

Possible interpretations

Truly diffuse processes



Unresolved point sources

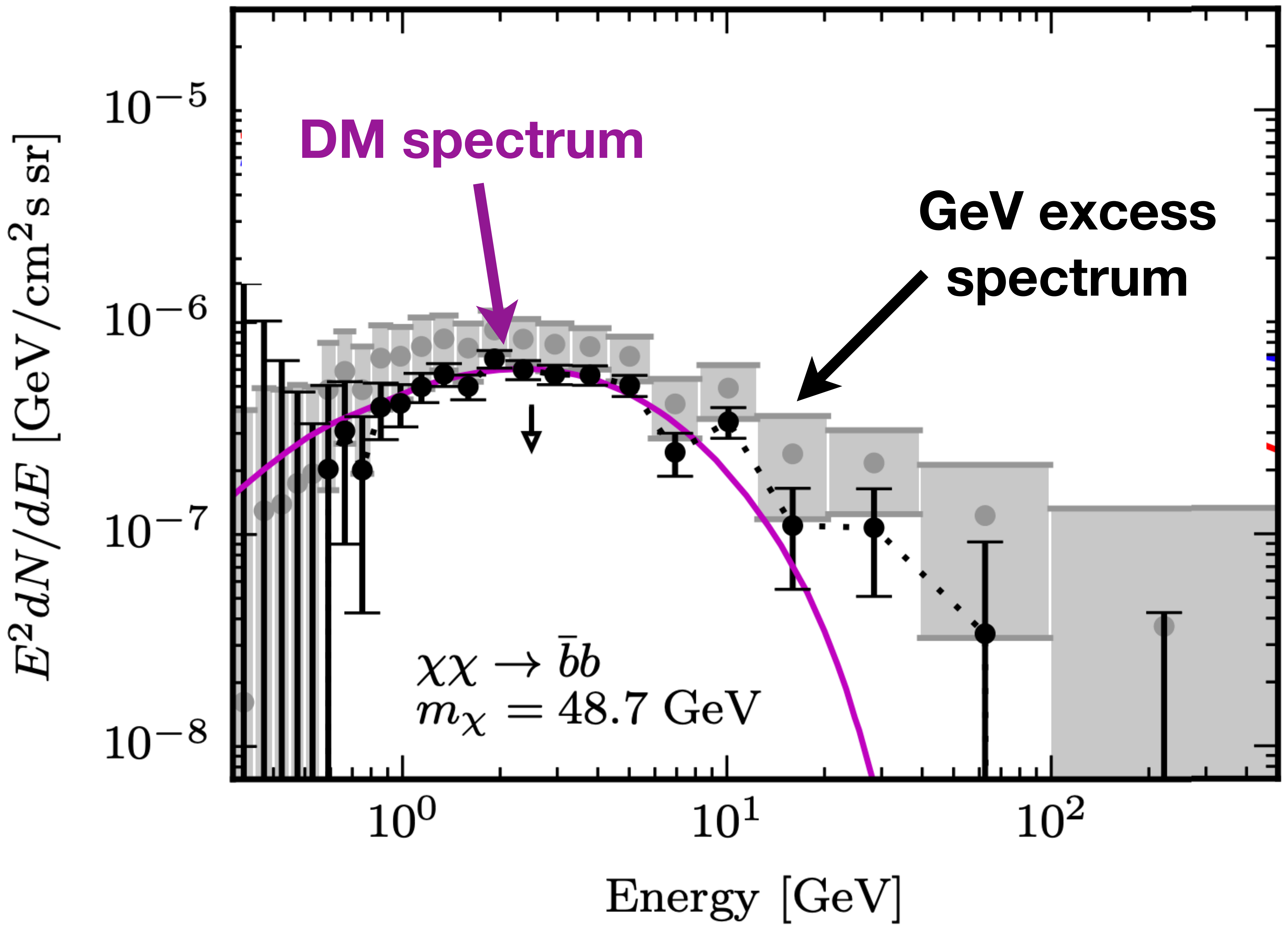
Constraints:

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

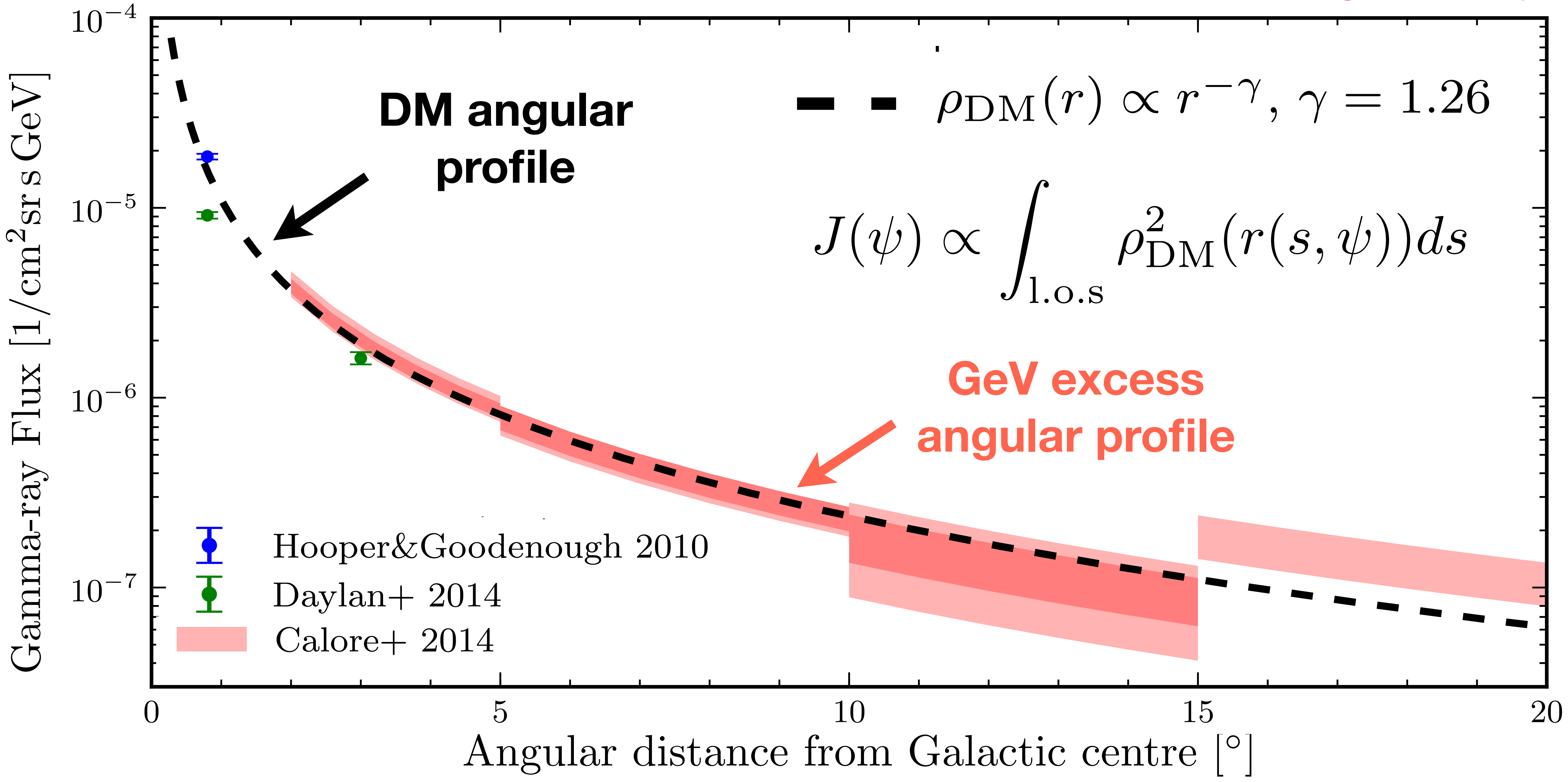
Diffuse processes I

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



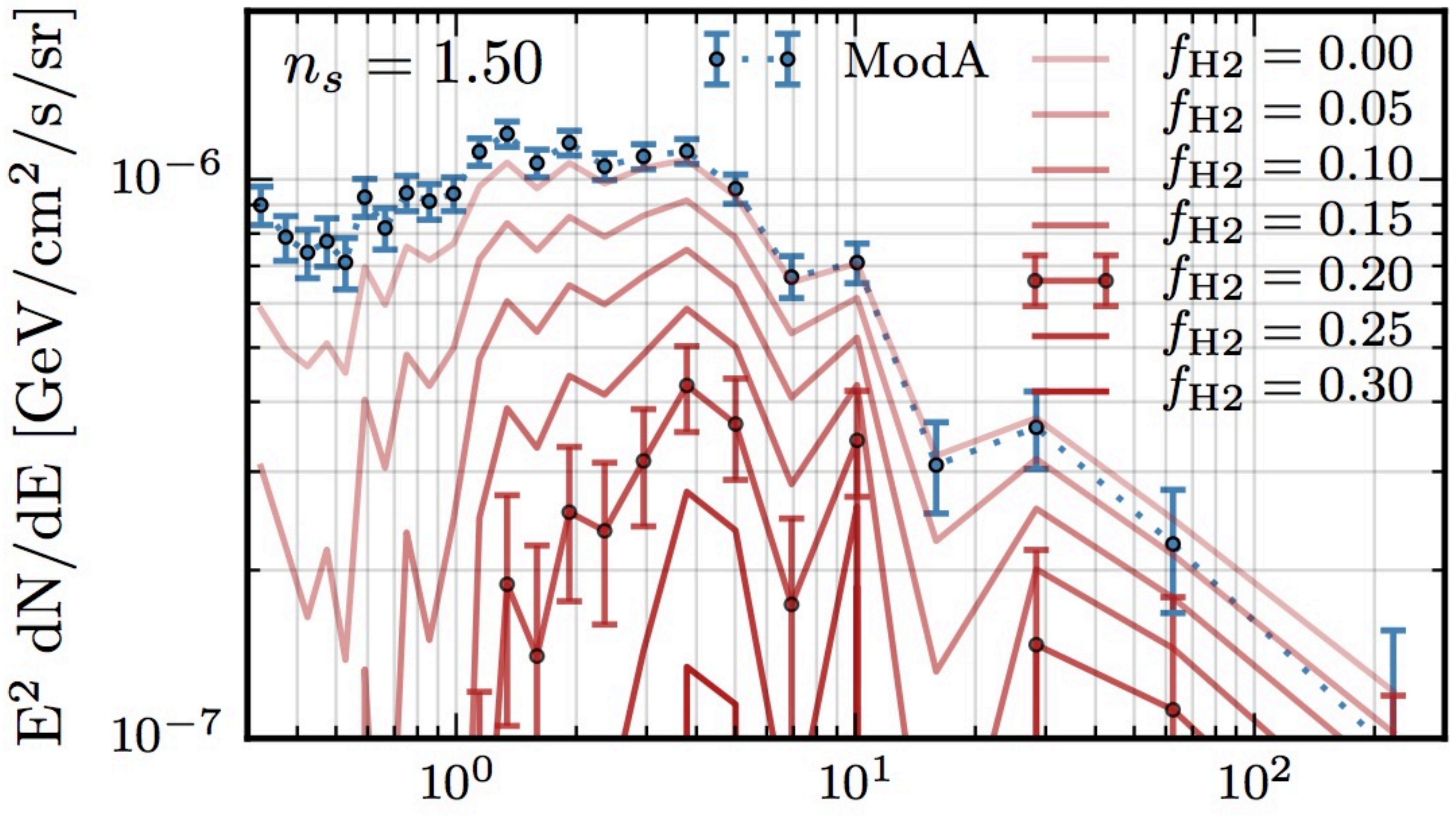
Agrawal+JCAP'15; Achterberg+JCAP'15; Bertone, FC+ JCAP'15; Liem, FC+ JCAP'16; O(>100) papers

Diffuse processes II

Cosmic rays in the GC

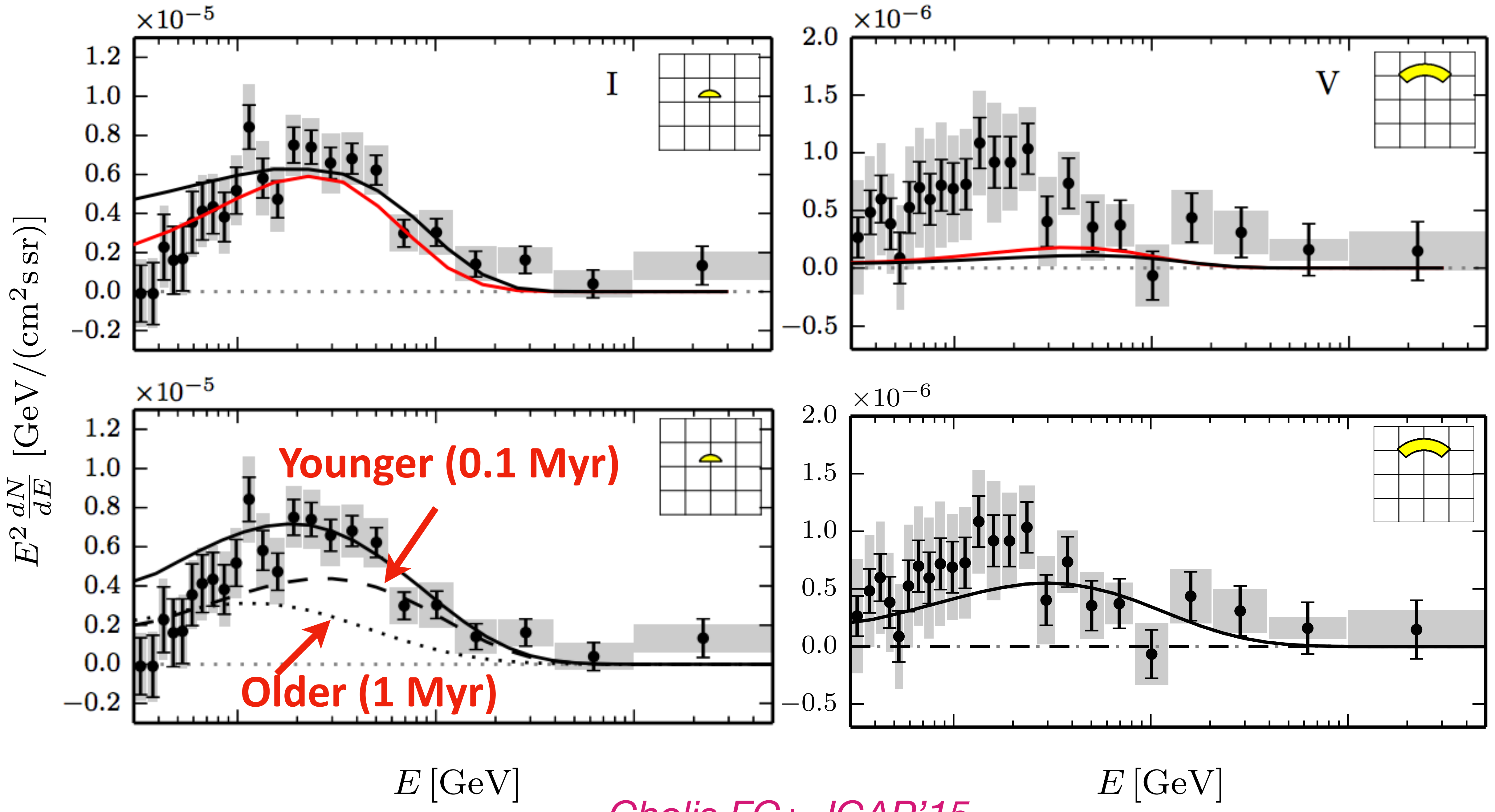
- **New population** of **cosmic rays** injected at the GC (electrons mostly)
- **Steady state** (from star formation in CMZ) and/or **time-dependent** (from outburst activity of the GC) source term

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)

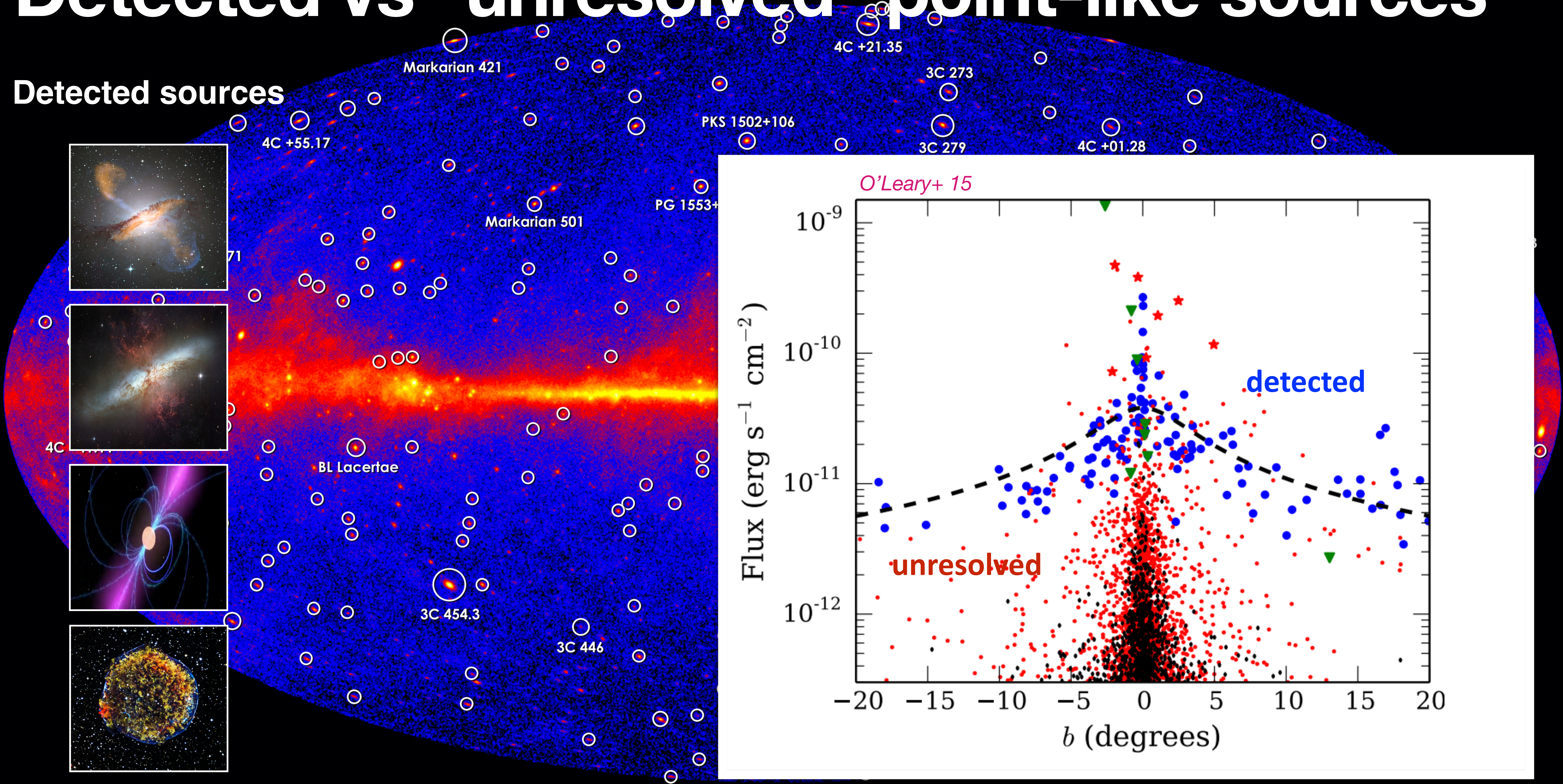


Cholis,FC+ JCAP'15

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

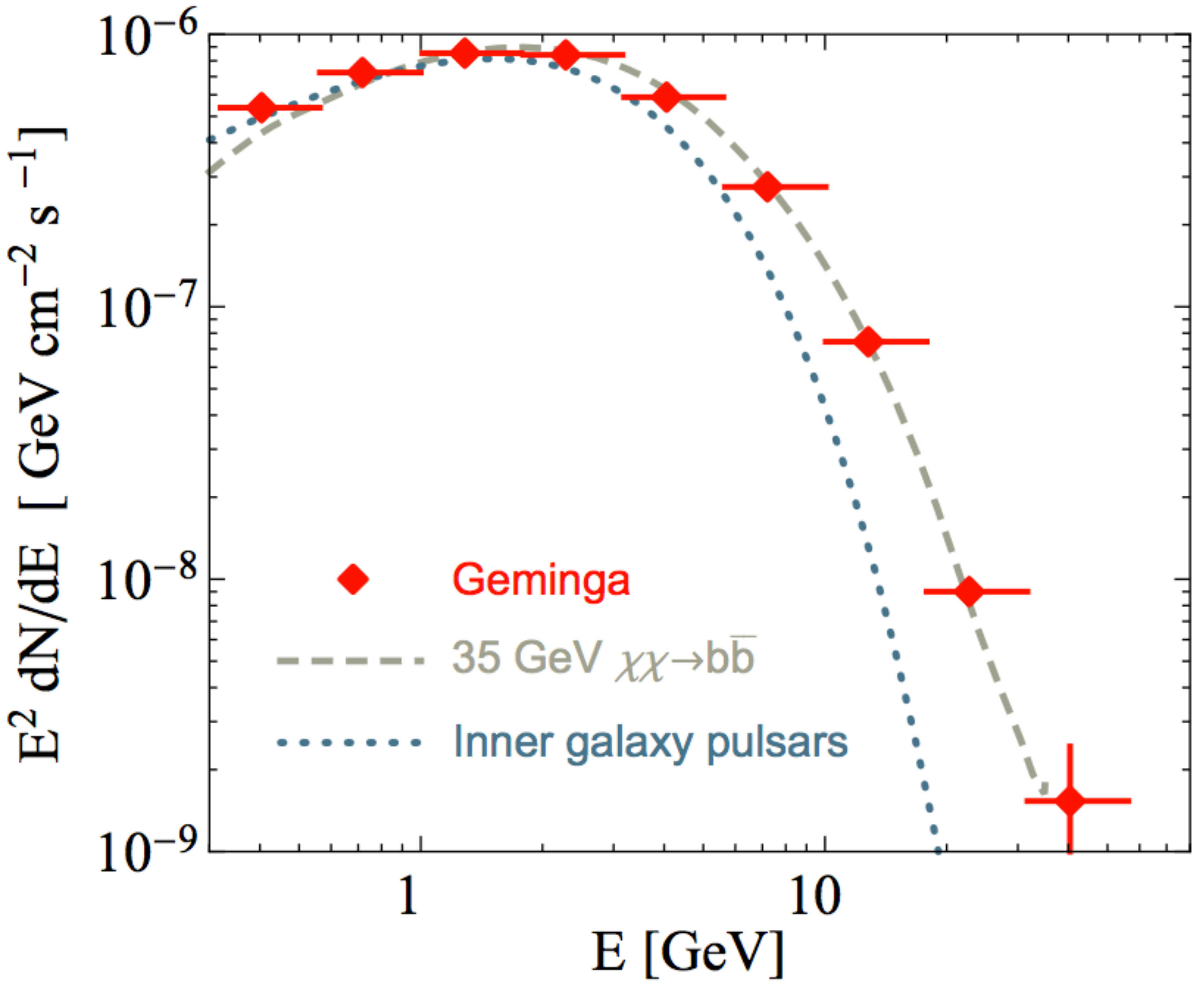
Detected vs "unresolved" point-like sources

Detected sources



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

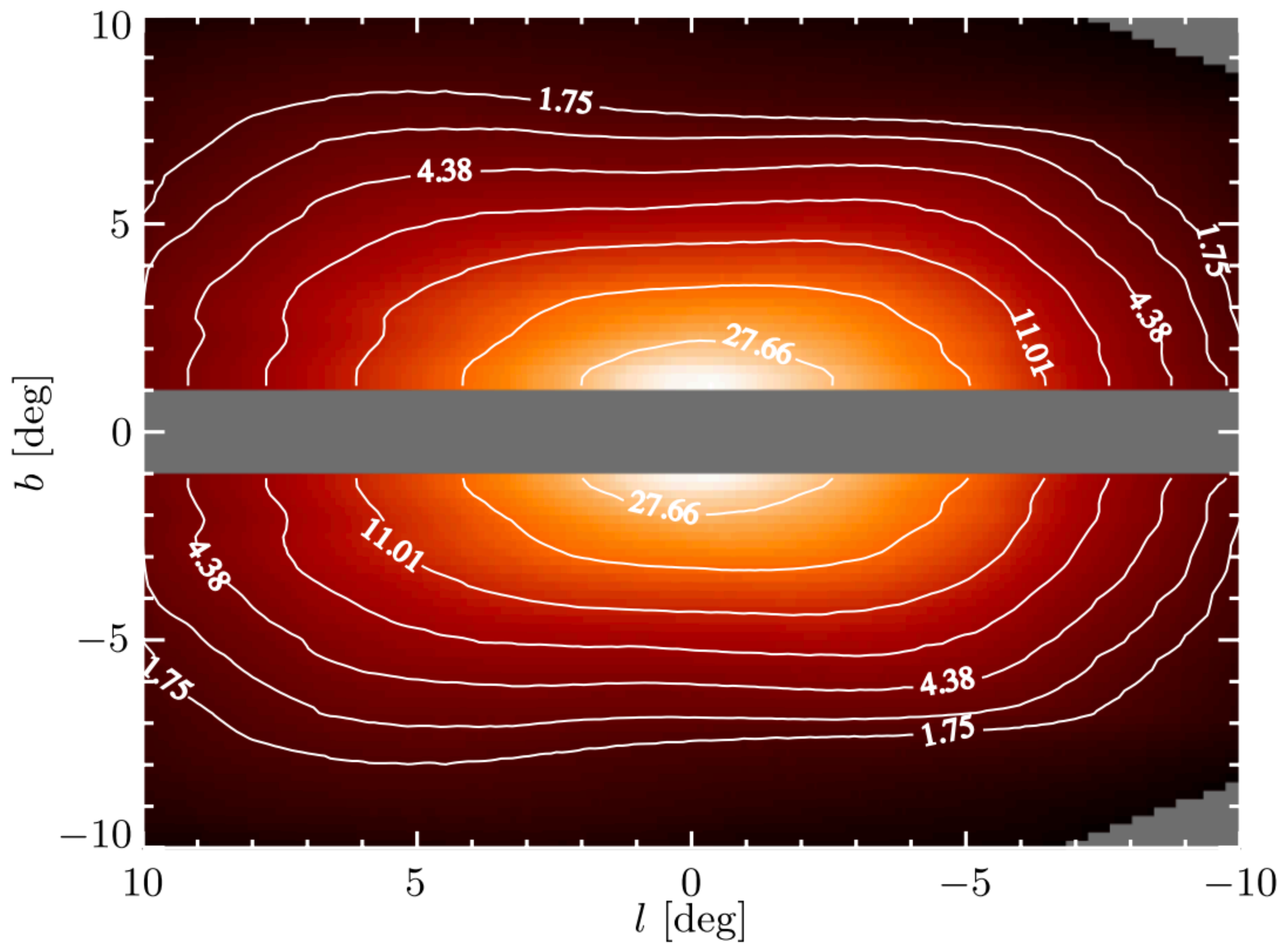
Cholis+'14; Hooper+'15; Hooper&Linden JCAP'16; Haggard+ JCAP'17; Ploeg+ JCAP'17

Going beyond dark matter templates

Stellar distribution in the bulge

Boxy bulge

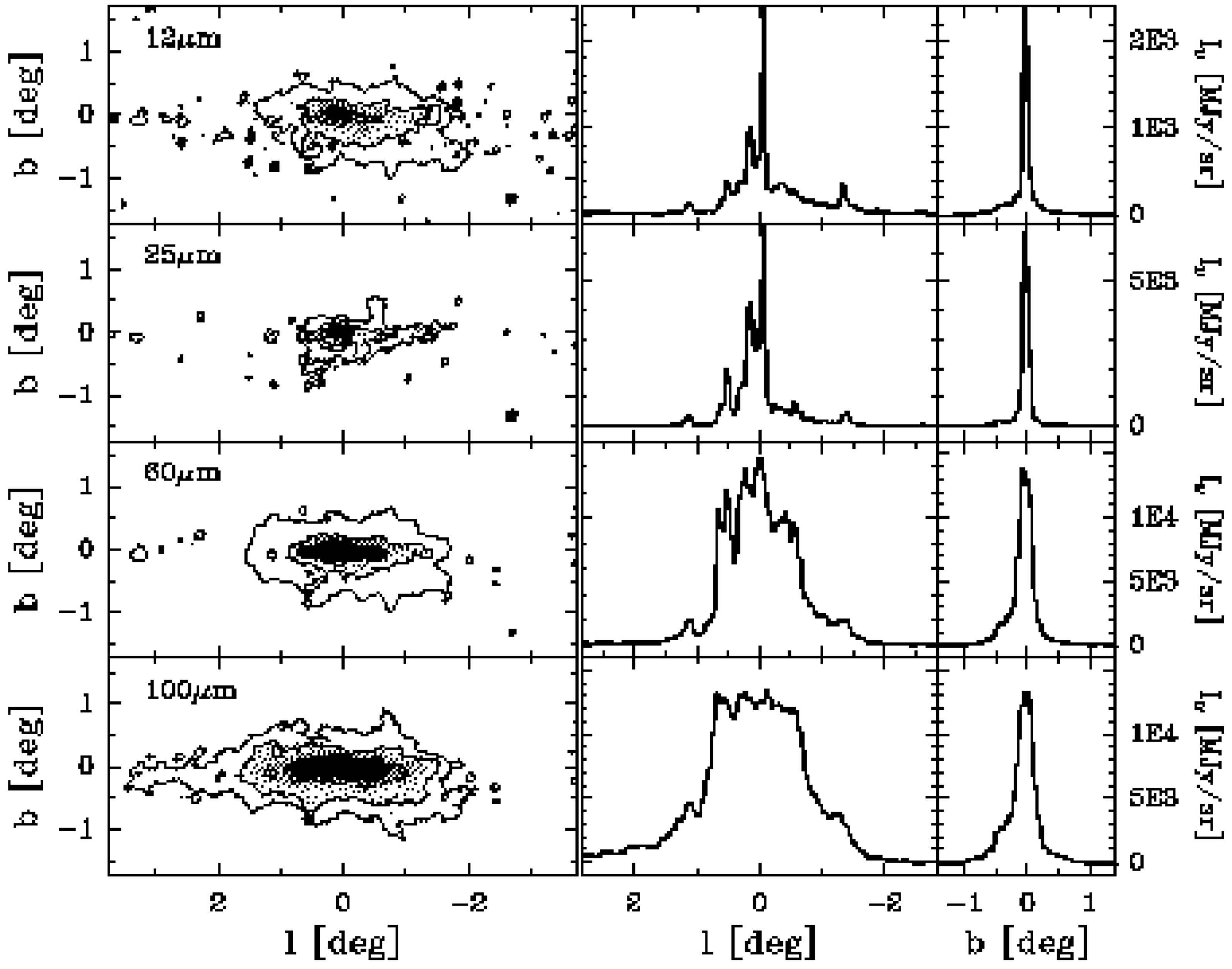
$0.9 \times 10^{10}\, M_\odot$



Wegg & Gerhard MNRAS'12

Nuclear bulge

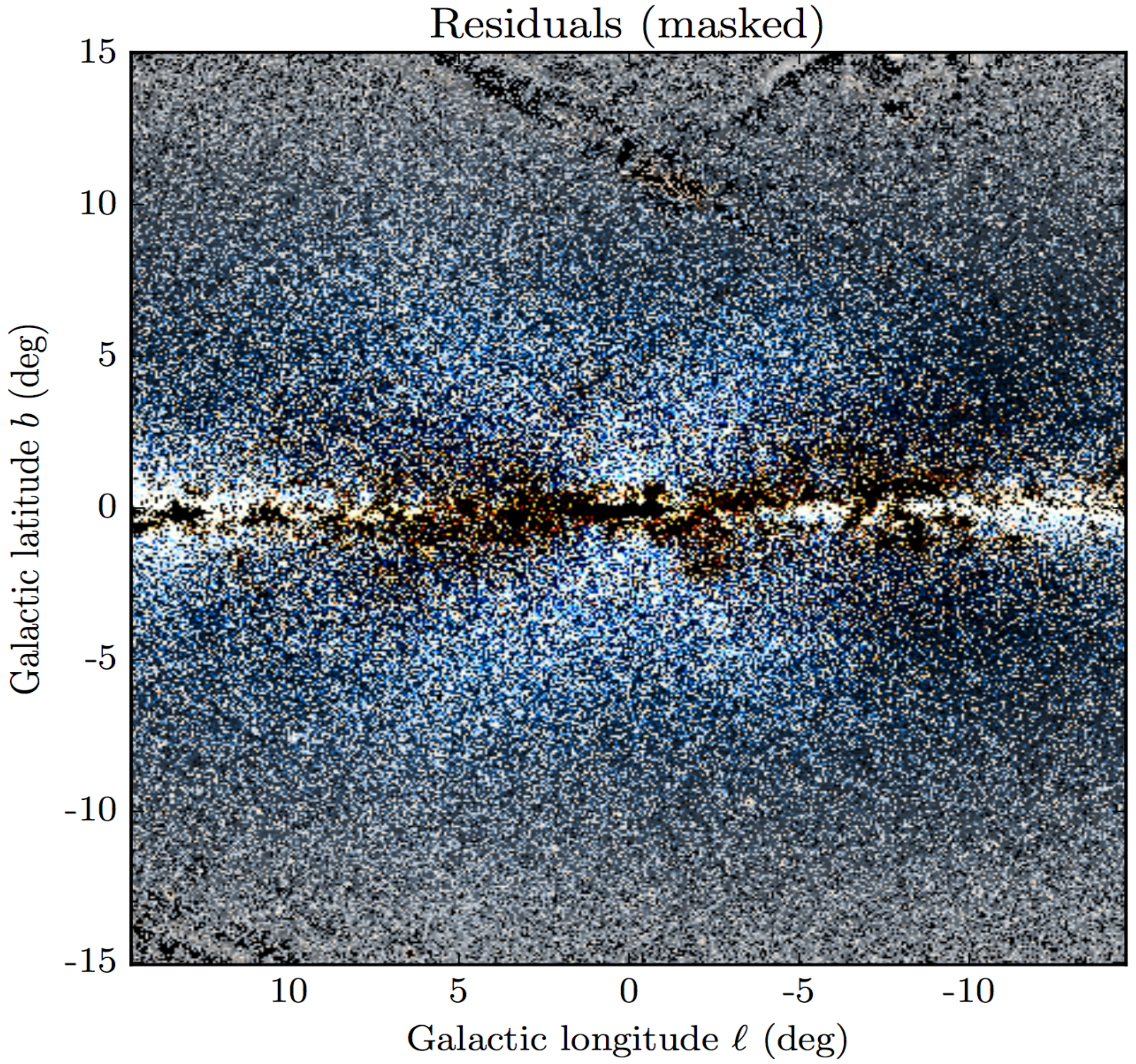
$1.4 \times 10^{9}\, M_\odot$



Launhardt+A&A'02

X-shaped bulge

~20% BB mass



Ness&Lang AJ'16

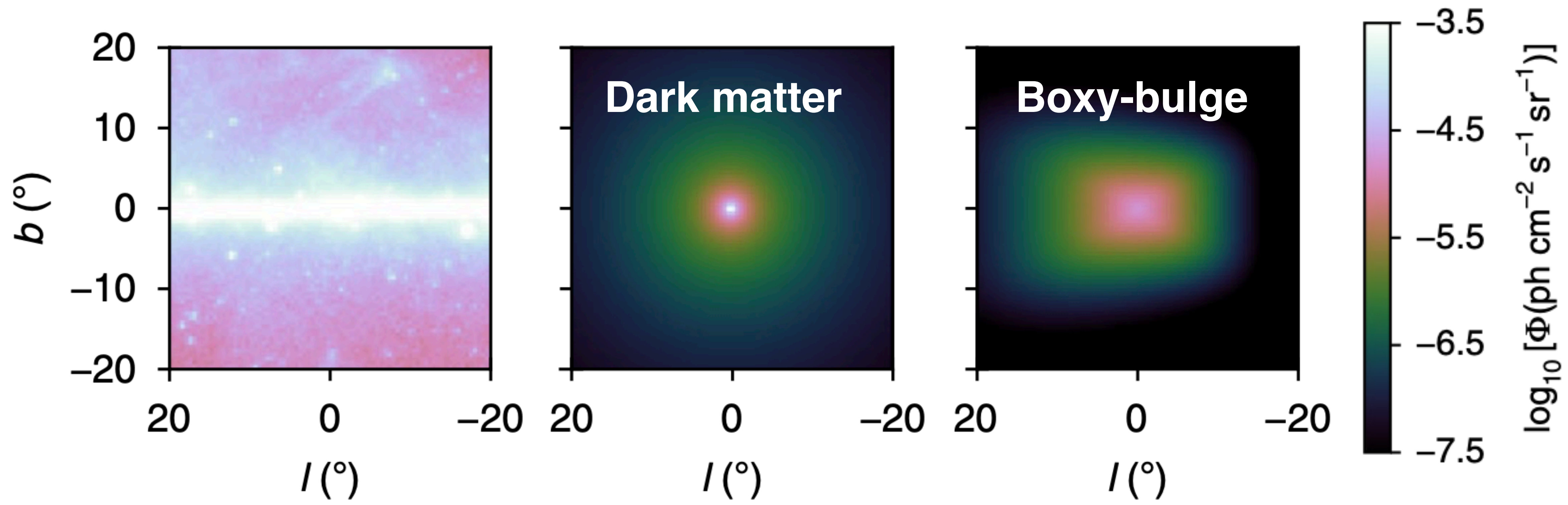
- **Red Clump stars** (near-IR) used to characterise the **three-dimensional density structure** of the BB
- Most recent non-parametrically deconvolved bulge model w/ VISTA Variables in the Via Lactea (VVV) data *Coleman+ MNRAS'20*
- X-shaped structure characteristic of boxy/peanut like morphology (extragalactic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

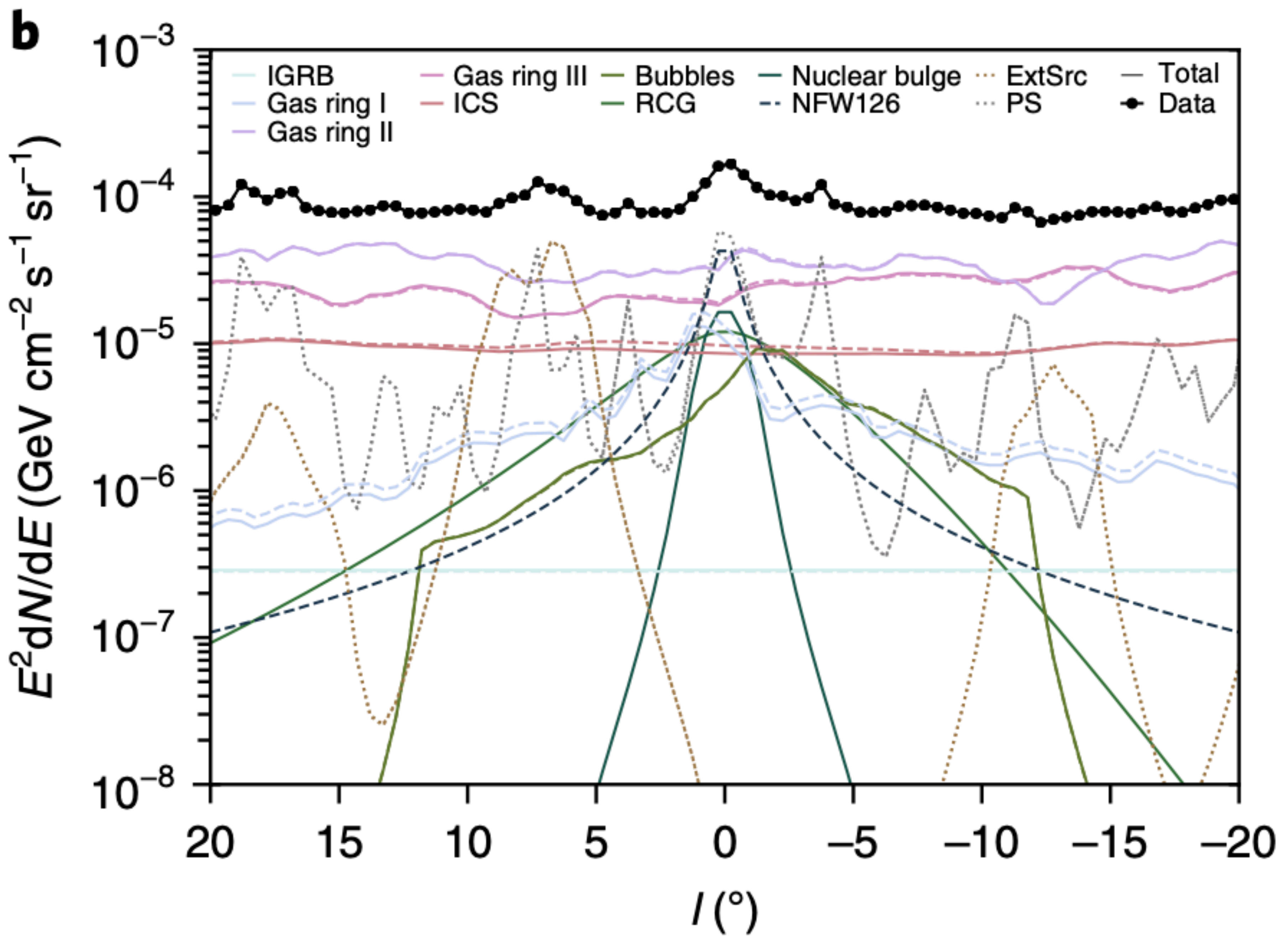
Evidence for the stellar bulge GeV emission

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**

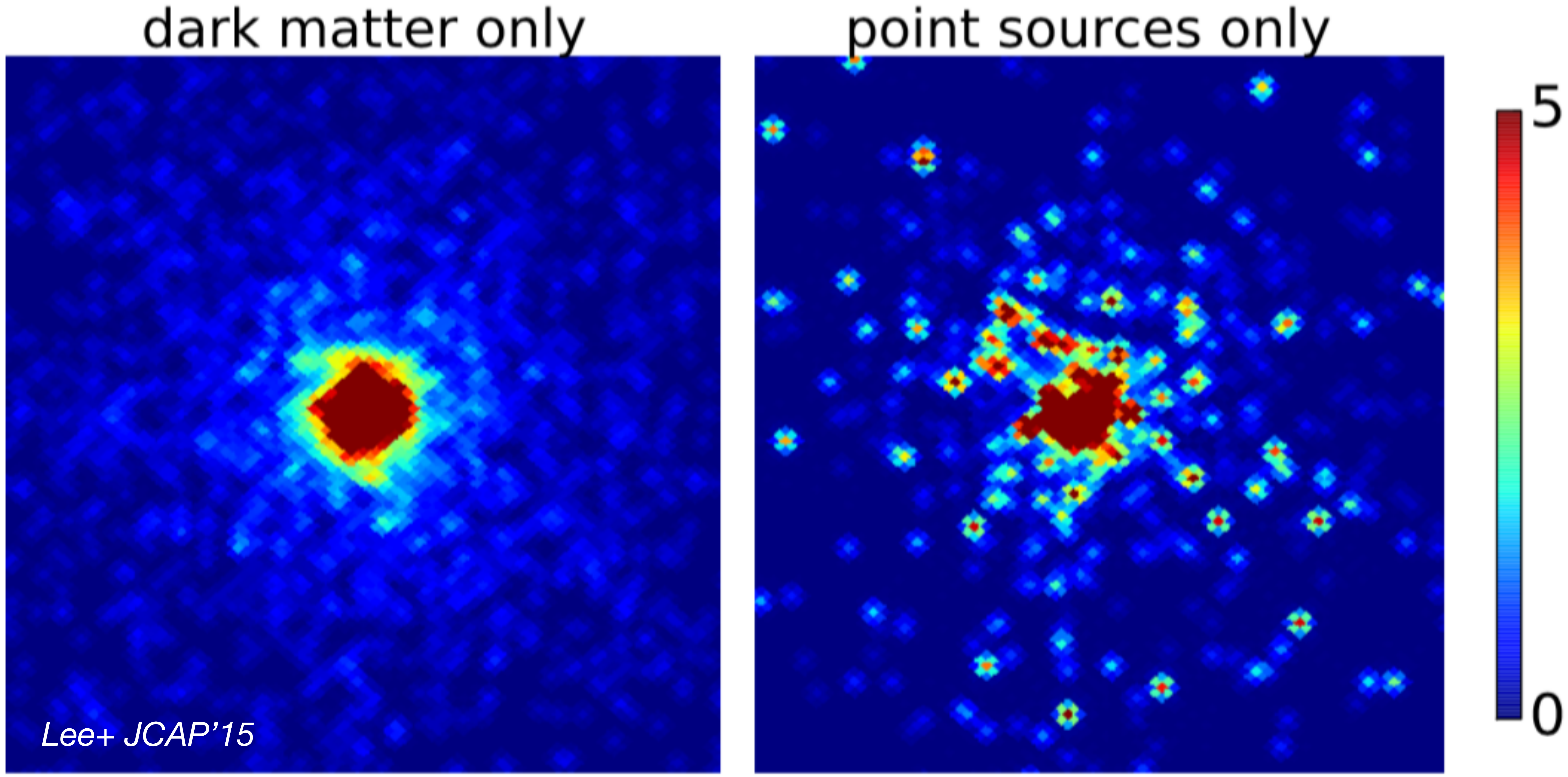
  Cao+MNRAS'13; Launhardt+ A&A'02

- ✓ 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

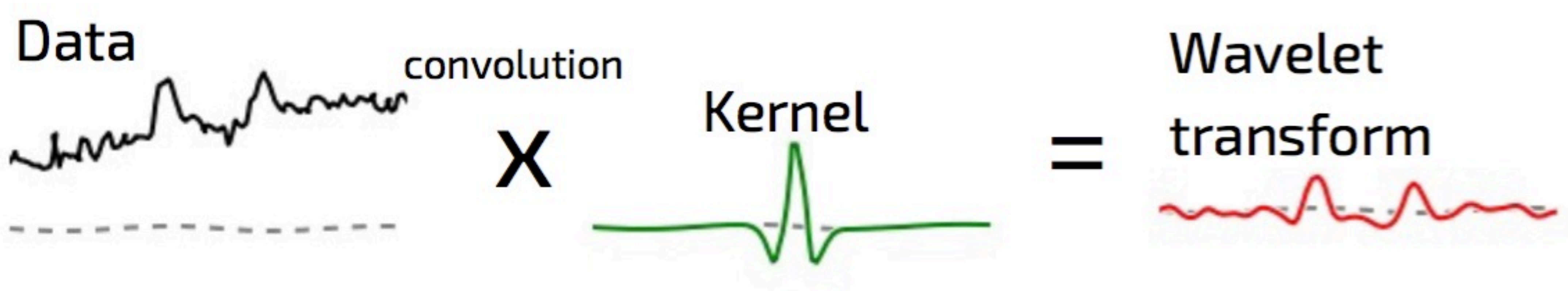


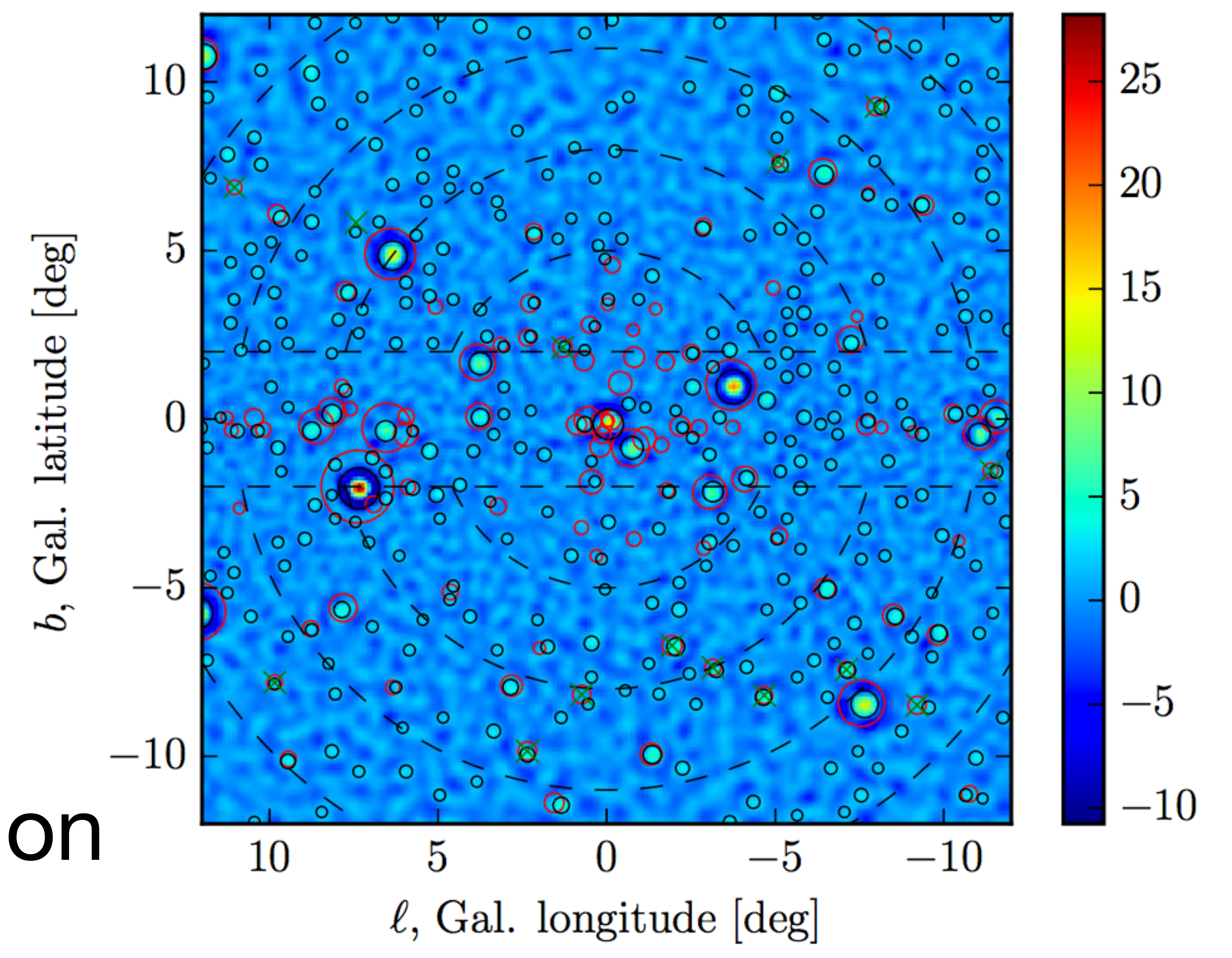
Differences in the **statistics of the photon counts** can be quantified and used for model comparison

Support for unresolved point sources (PS)

Local maxima of normalised wavelet transform

Bartels+ PRL'16

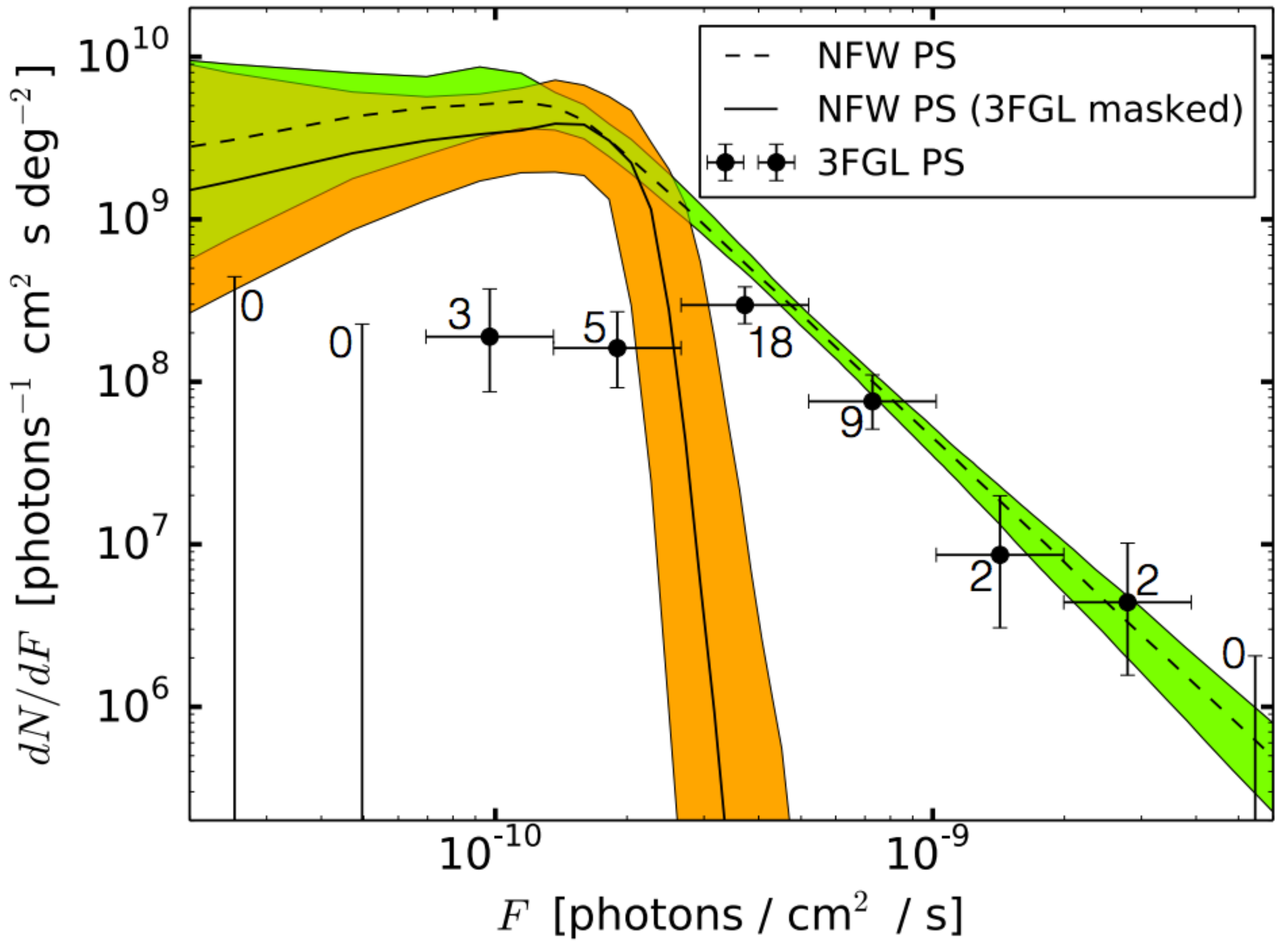


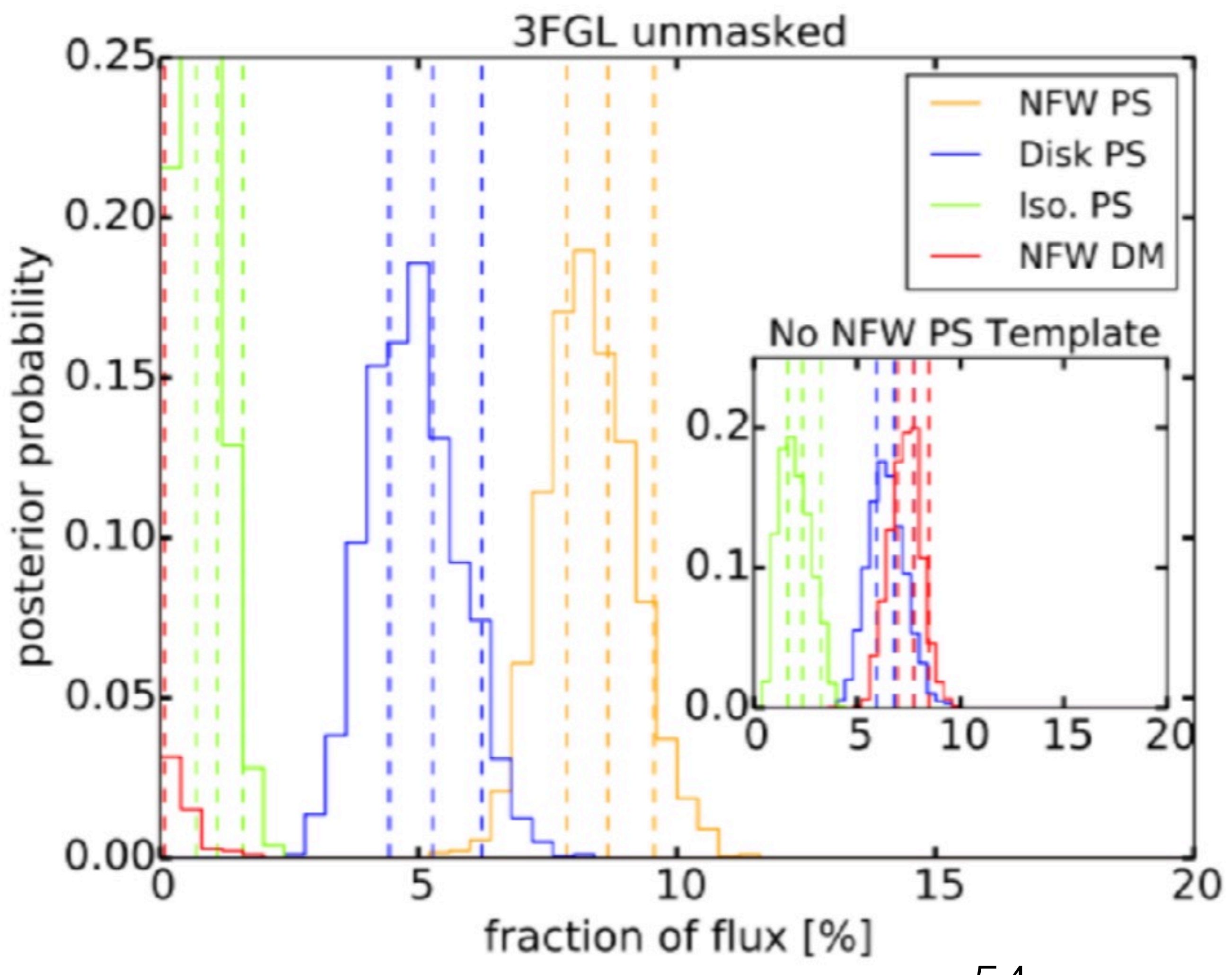


- Wavelet transform to look for **peaks** in data
- Enough peaks were found to explain the cumulative excess emission
- Evidence for unresolved PS population and constraints on luminosity function
- No modelling of diffuse emission required

Non-Poissonian template fitting

Lee+ PRL'16

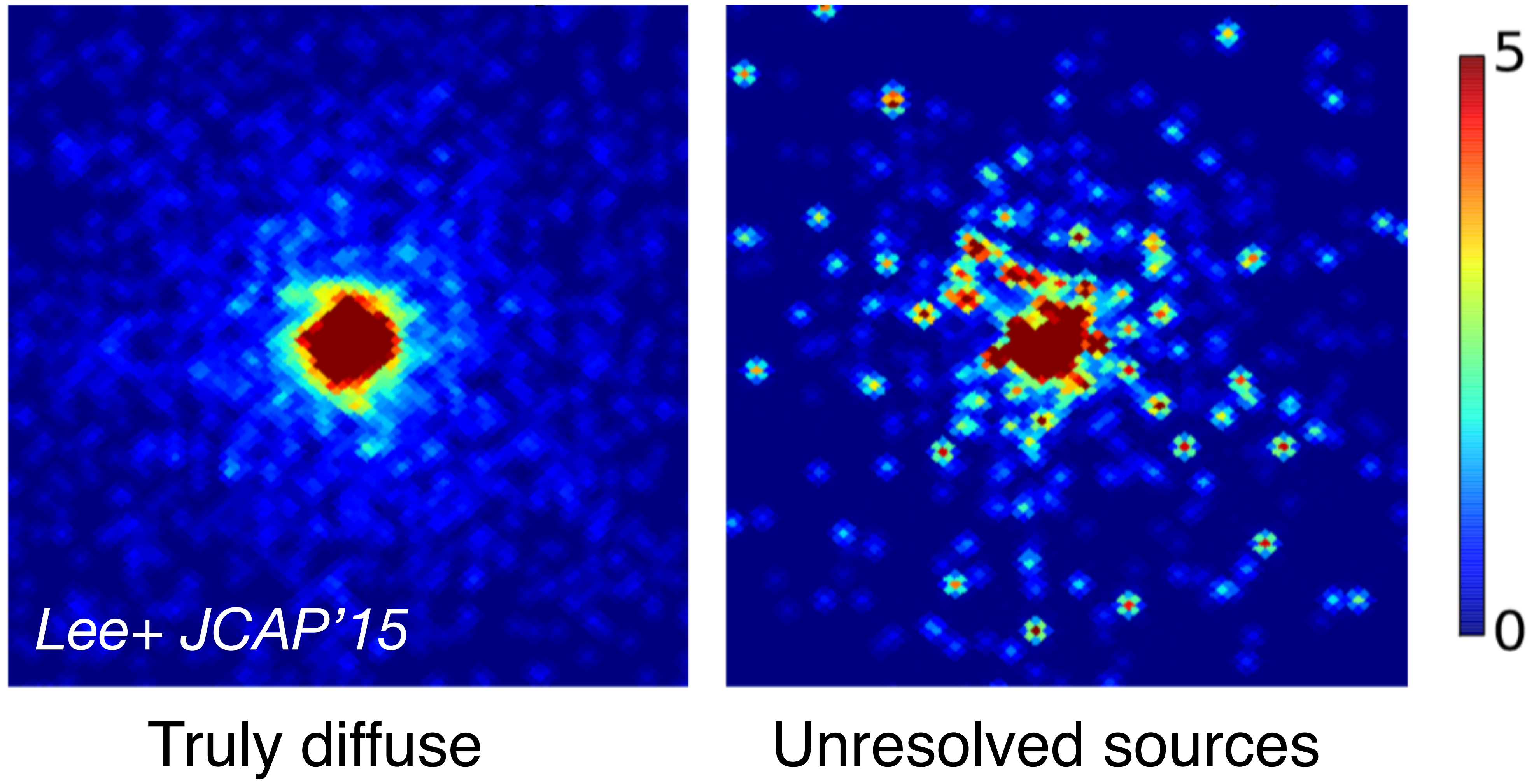


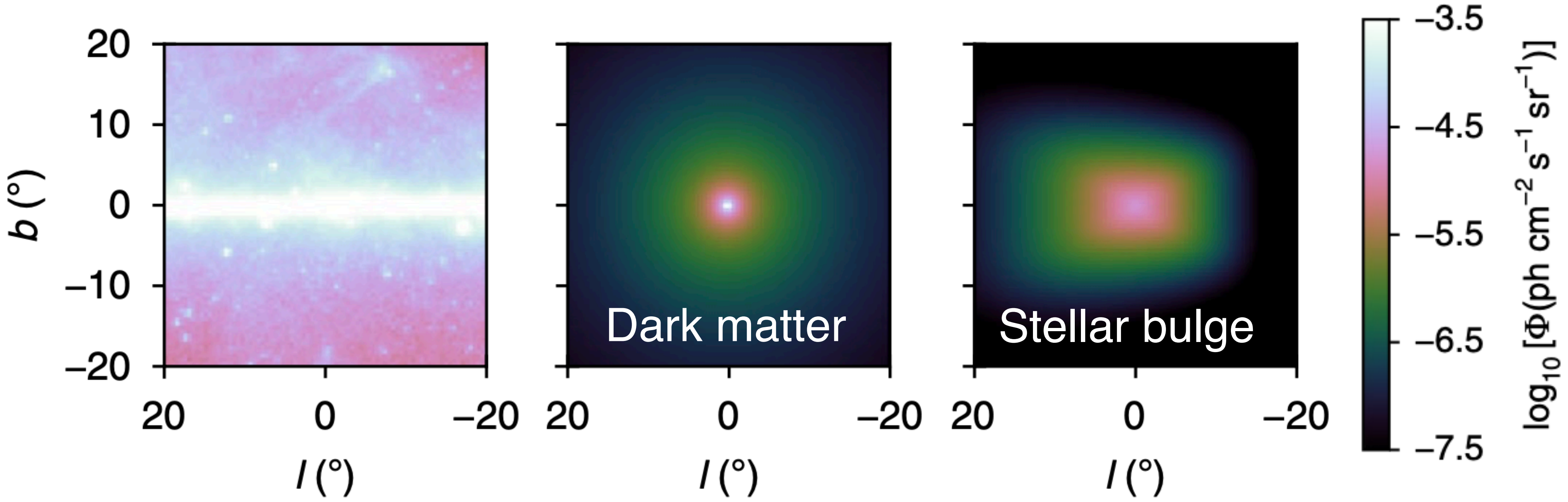


- Exploits difference in photon statistics: smooth signal (DM) vs larger variance across pixels (PS)
- PS fluctuations follow non-Poissonian statistics
- Sensitivity to spatial distribution and luminosity function of PS
- Required modelling of diffuse emission

The GeV excess nature

The gamma-ray perspective





- 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

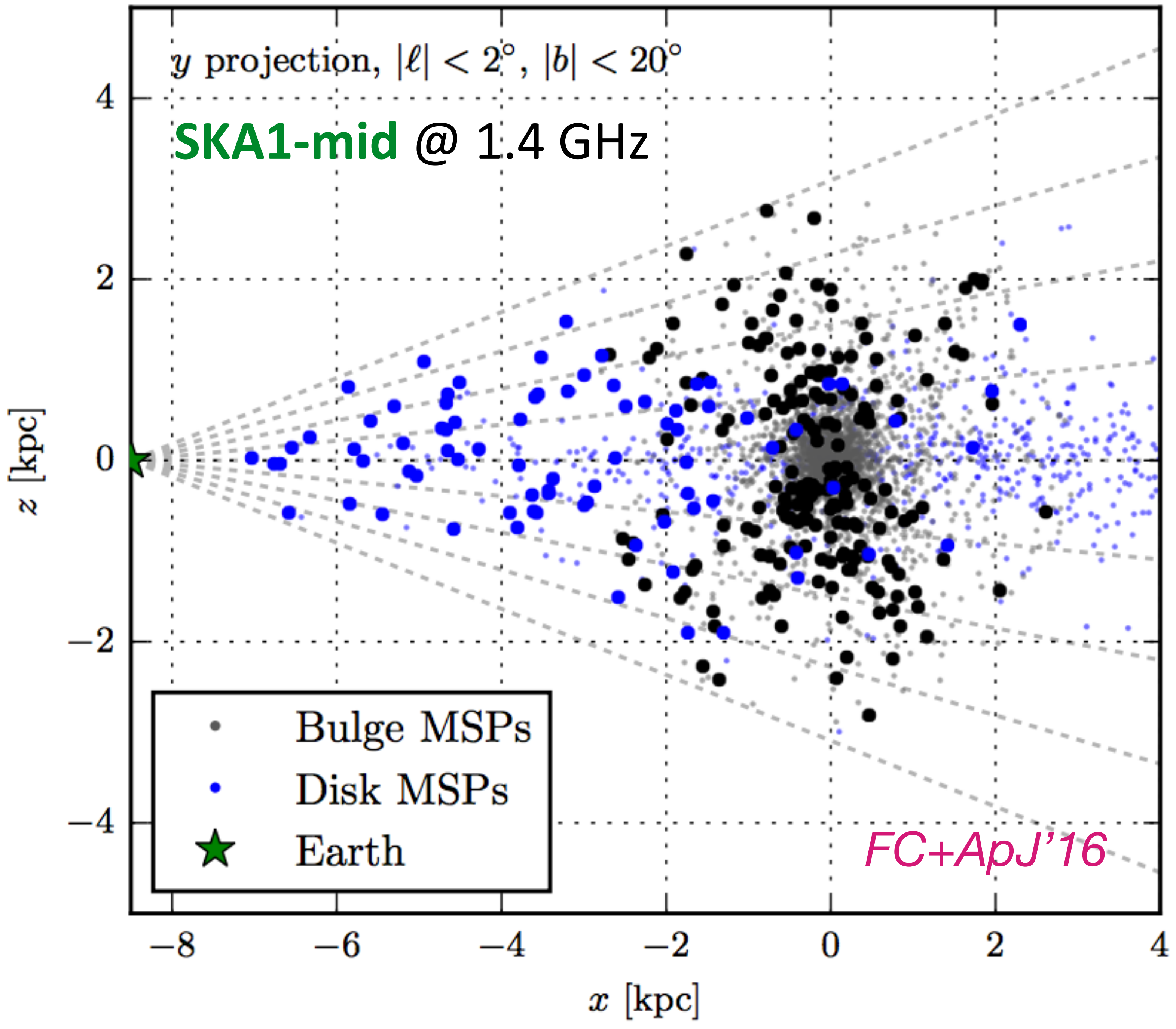
Macias+ Nature Astronomy'18; Macias+ JCAP'19

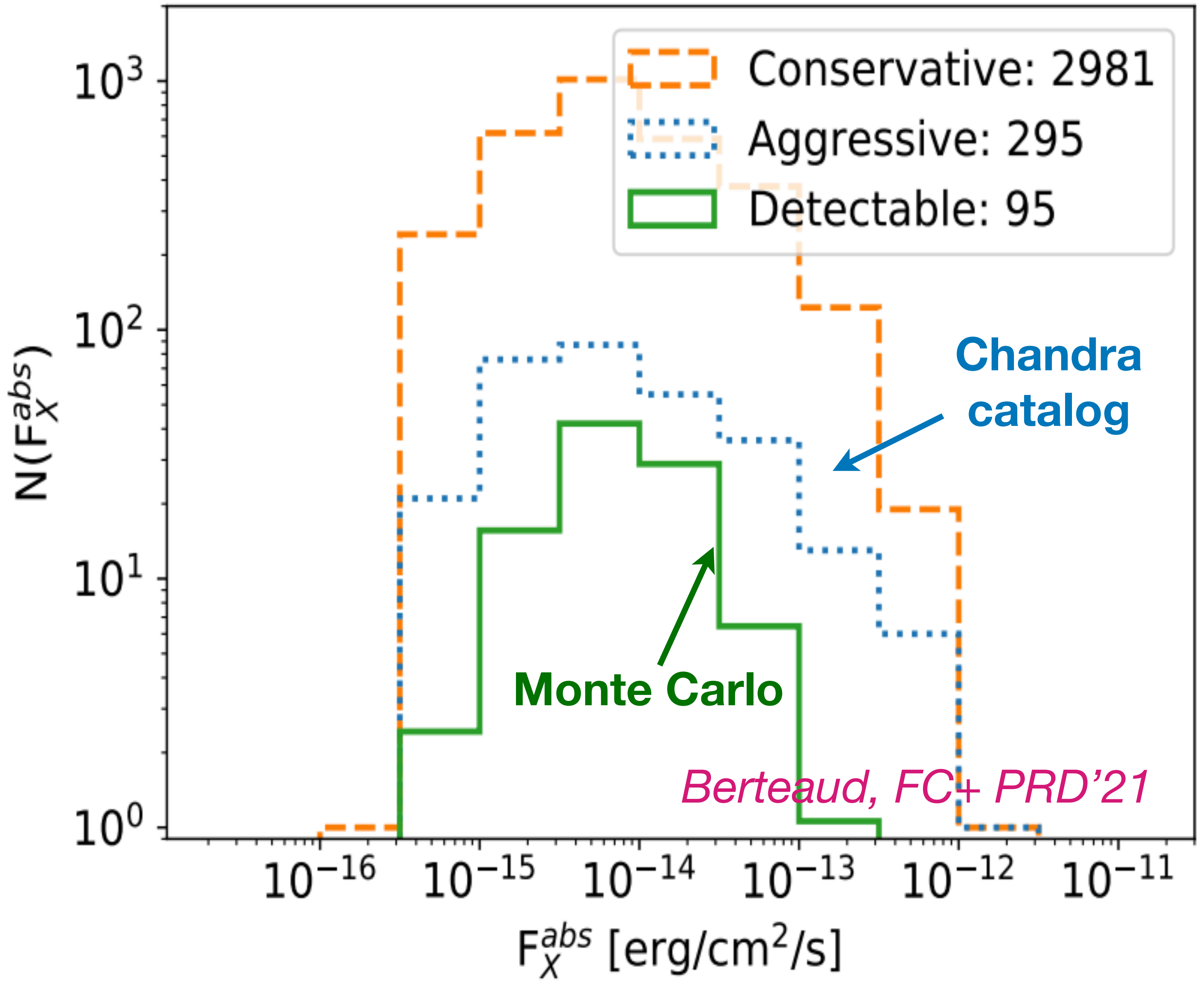
An (at least) partial **stellar origin of the GeV excess** seems to be confirmed

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*

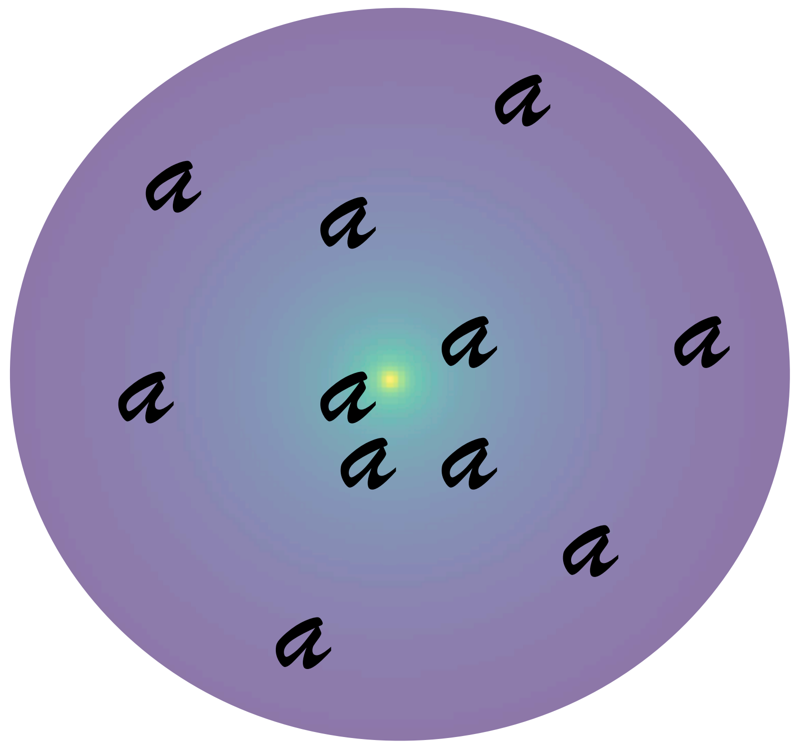


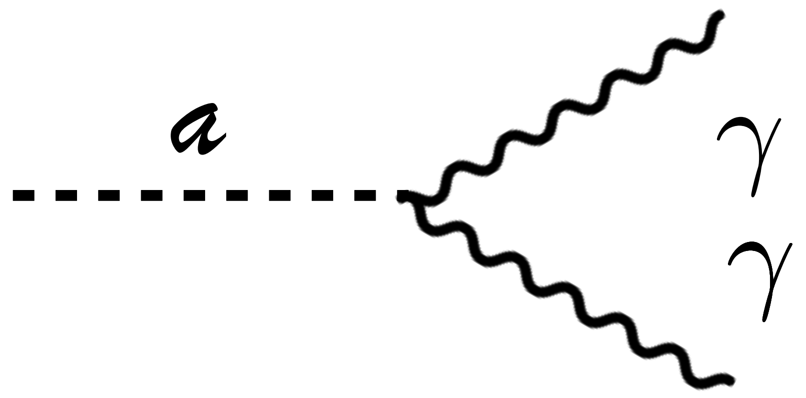


- Very high-energy photons with CTA *Macias+ MNRAS'21*
- DM constraints from gamma rays (dwarf galaxies) and cosmic-ray antiprotons *Di Mauro & Winkler PRD'21*

Bonus slides

Axions and ALPs dark matter





Spontaneous decay

$$\tau_a = \frac{64\pi}{m_a^3 g^2}$$

=> Rate not-negligible for heavy (> keV) ALPs, where conversion is suppressed

[Contribution from all galaxies in the universe: redshifted line and integral over star-formation history => contribution to **extragalactic backgrounds**]

Axions and ALPs dark matter

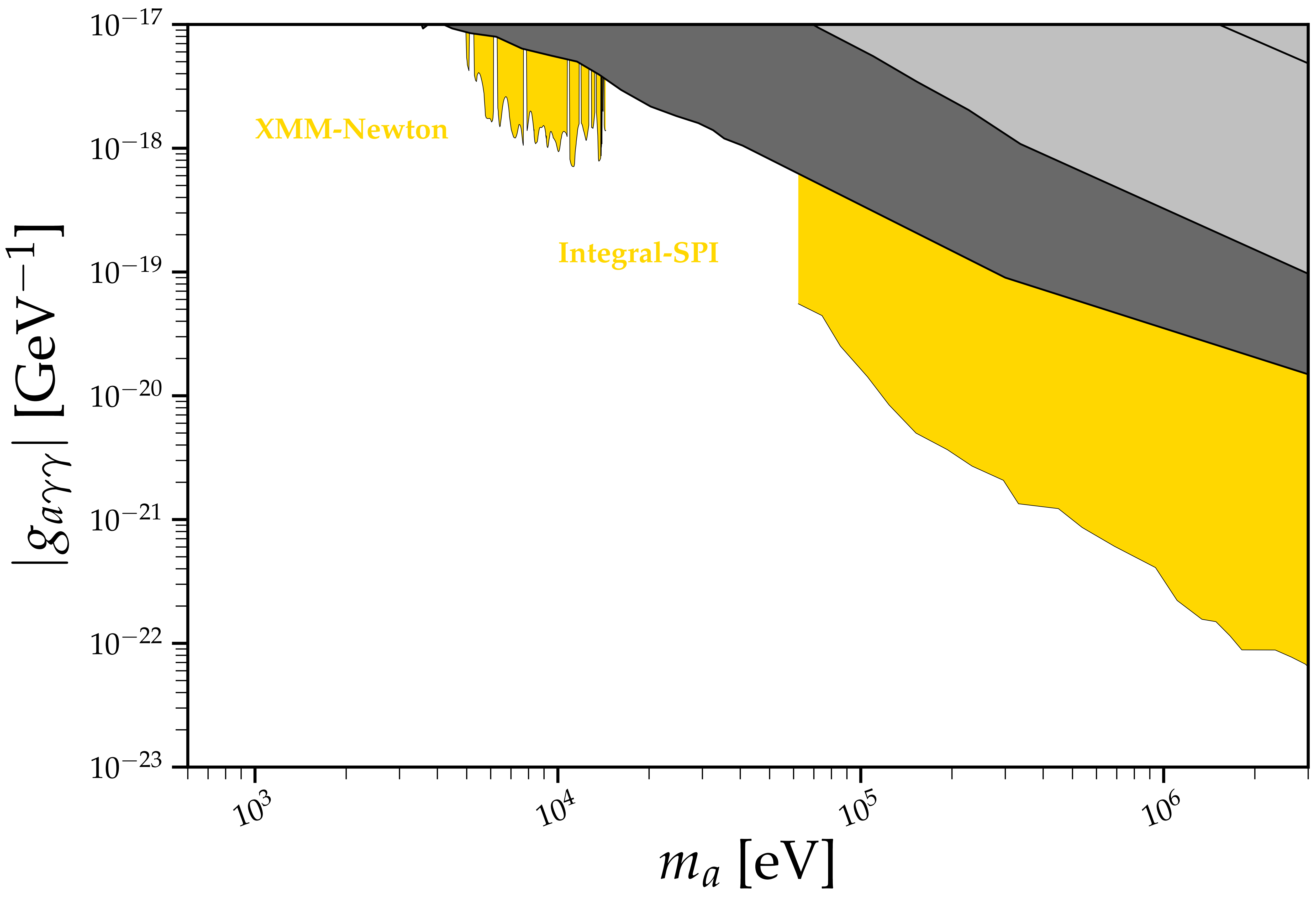
Heavy ALPs DM decay

- Search for narrow lines in X and gamma-ray data
- **XMM-Newton**: 5-16 keV, archival data => No evidence found for unassociated X-ray lines

Foster+ PRL'21

- **Integral-SPI**: new analysis of 16yr data with dedicated search for DM component in continuum Galactic emission

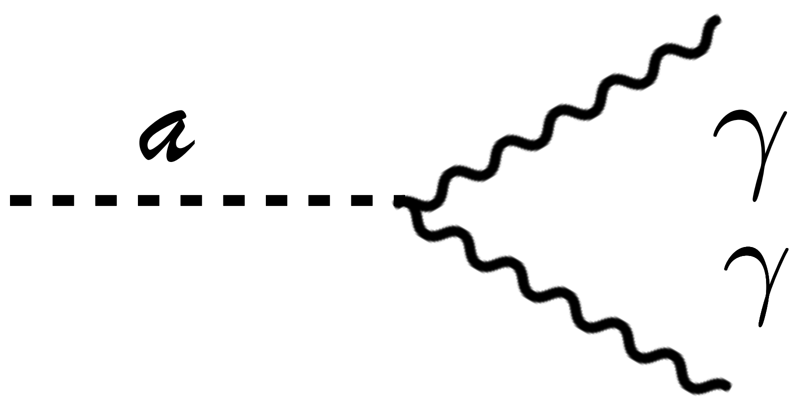
Berteaud, FC+PRD'22; FC+'22 arXiv:2209.06299



https://github.com/cajohare/AxionLimits

Axions and ALPs dark matter

Stimulated decay



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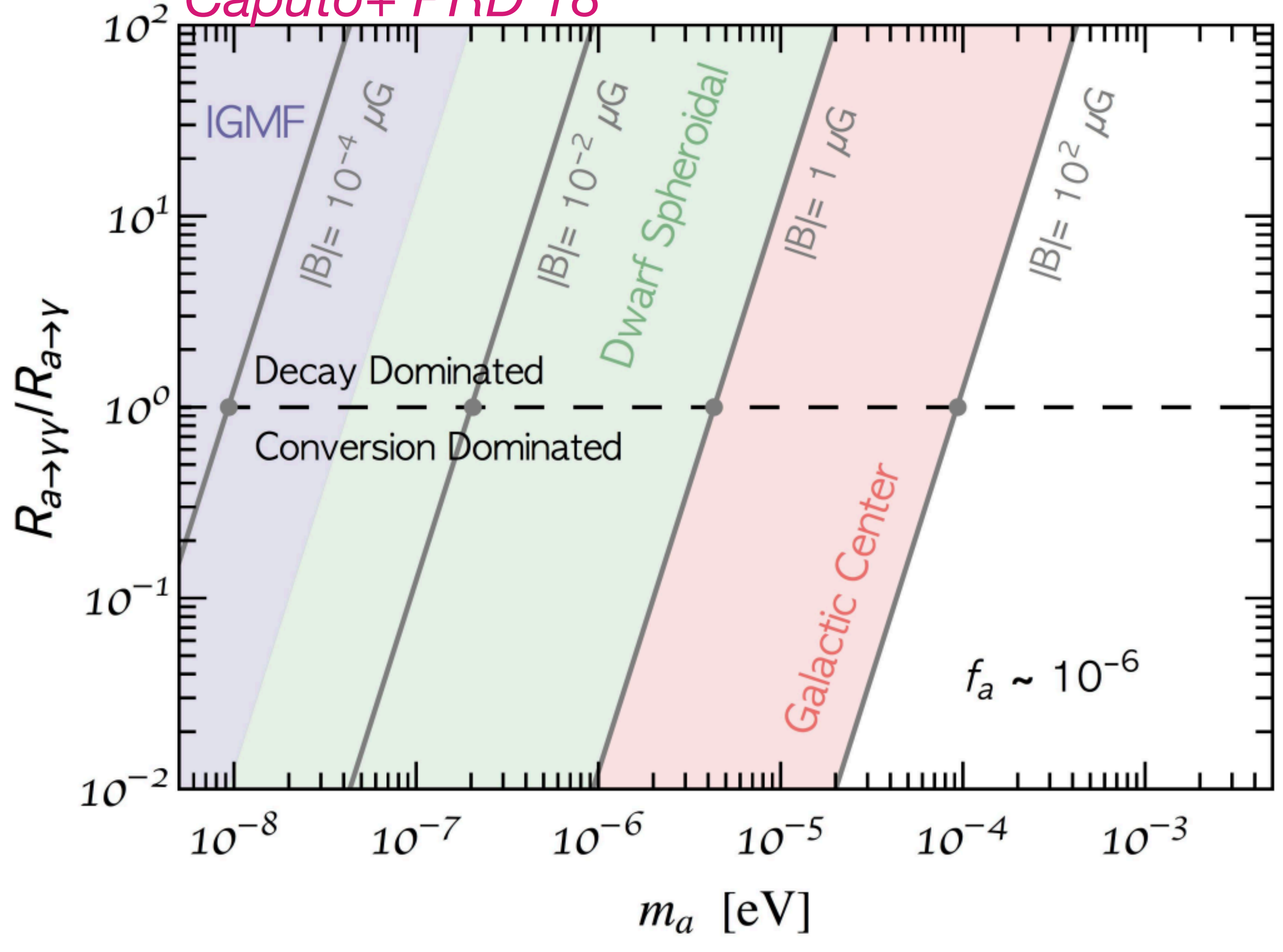
Spontaneous decay

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

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

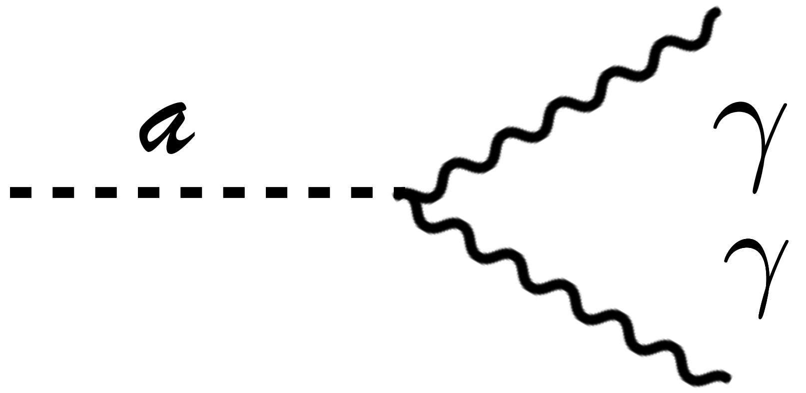
Caputo+ PRD'18



=> In large-scale astro environments with low B-field, stimulated decay dominate also for masses in the 10^{-6} eV mass range

Axions and ALPs dark matter

Stimulated decay



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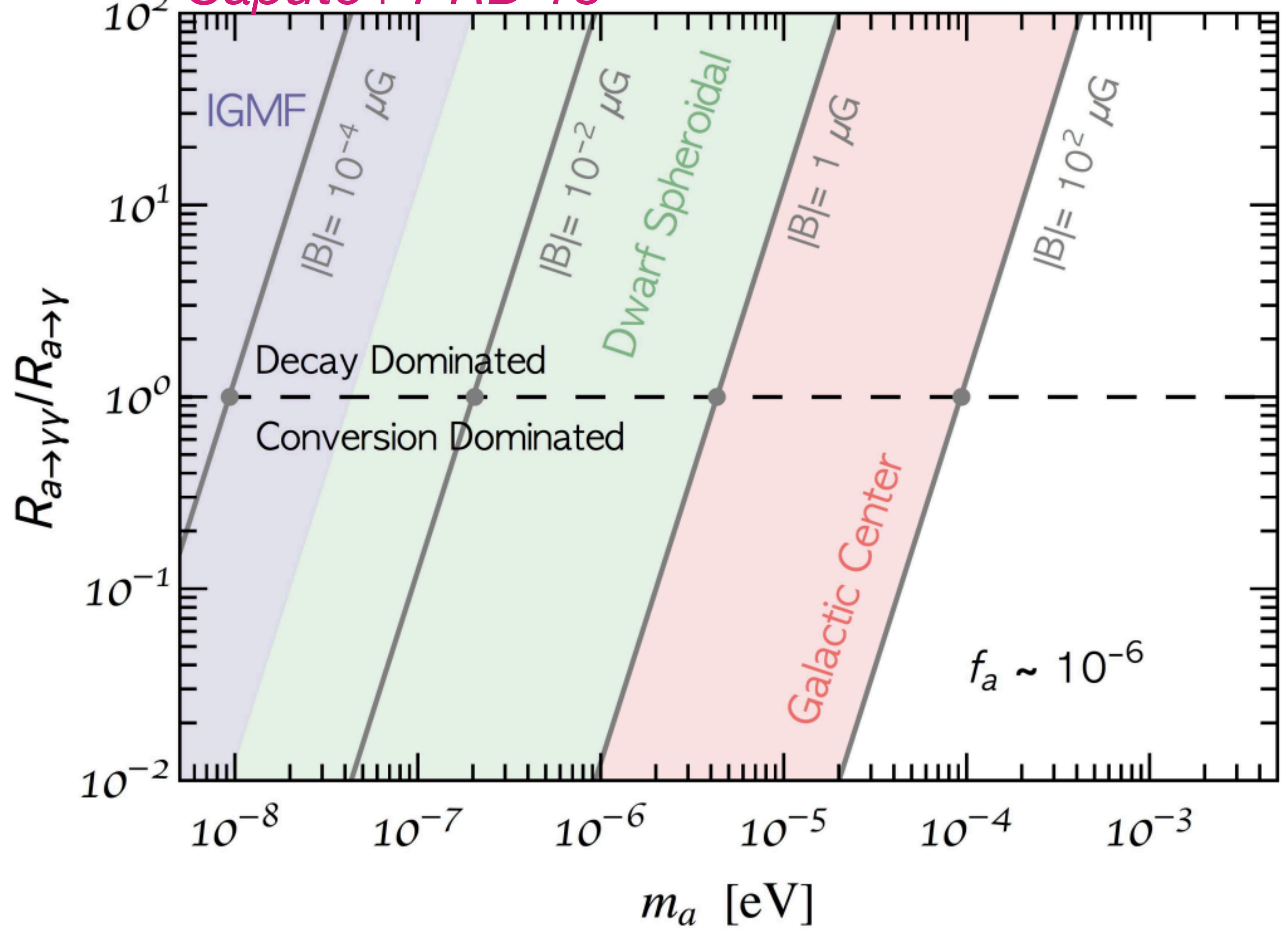
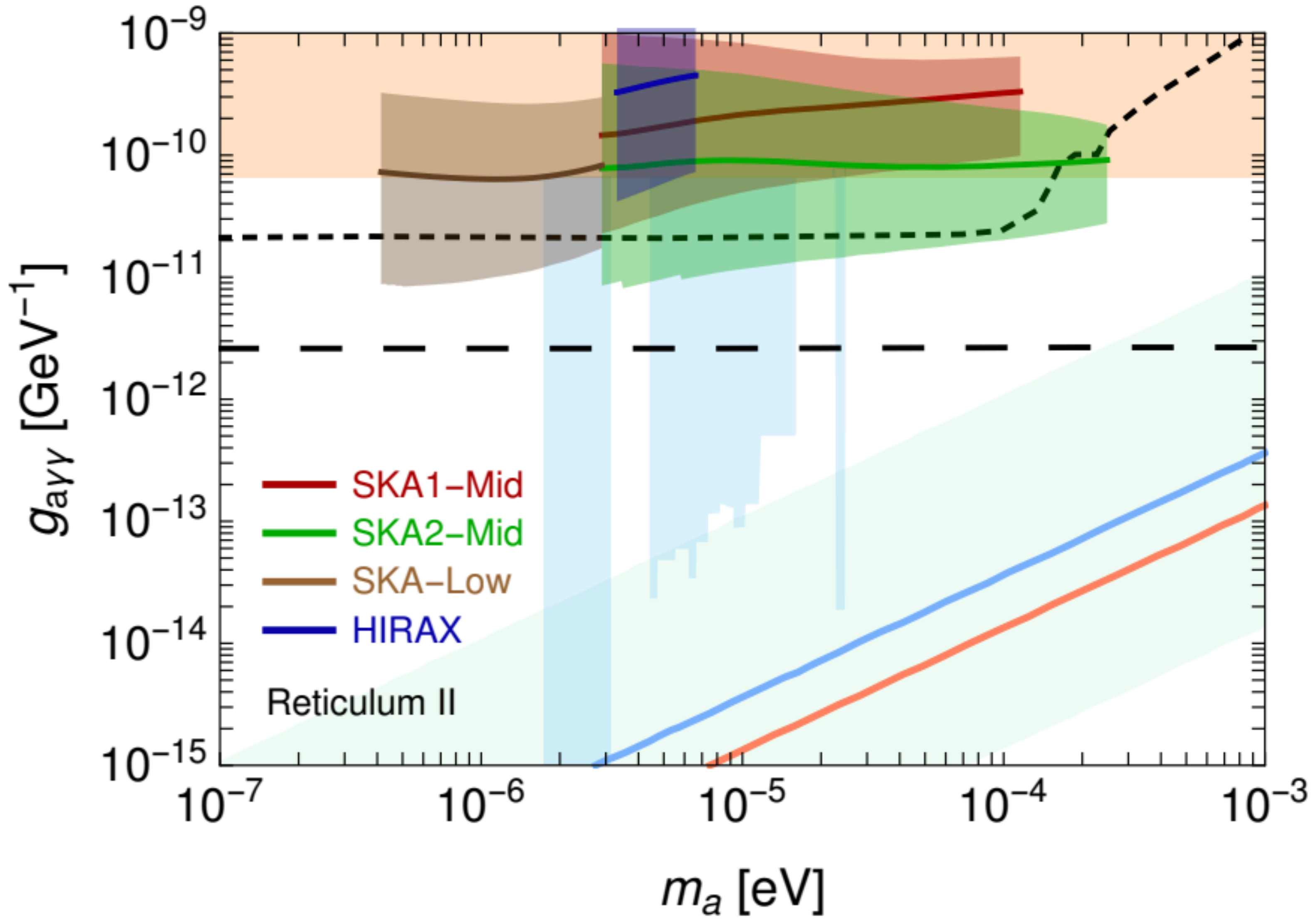
Caputo+ PRD'18

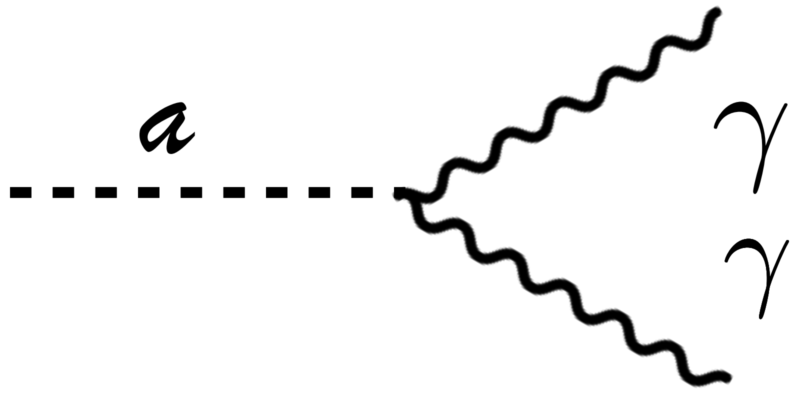




Caputo+JCAP'19

Axions and ALPs dark matter

Resonant conversion



Spontaneous decay

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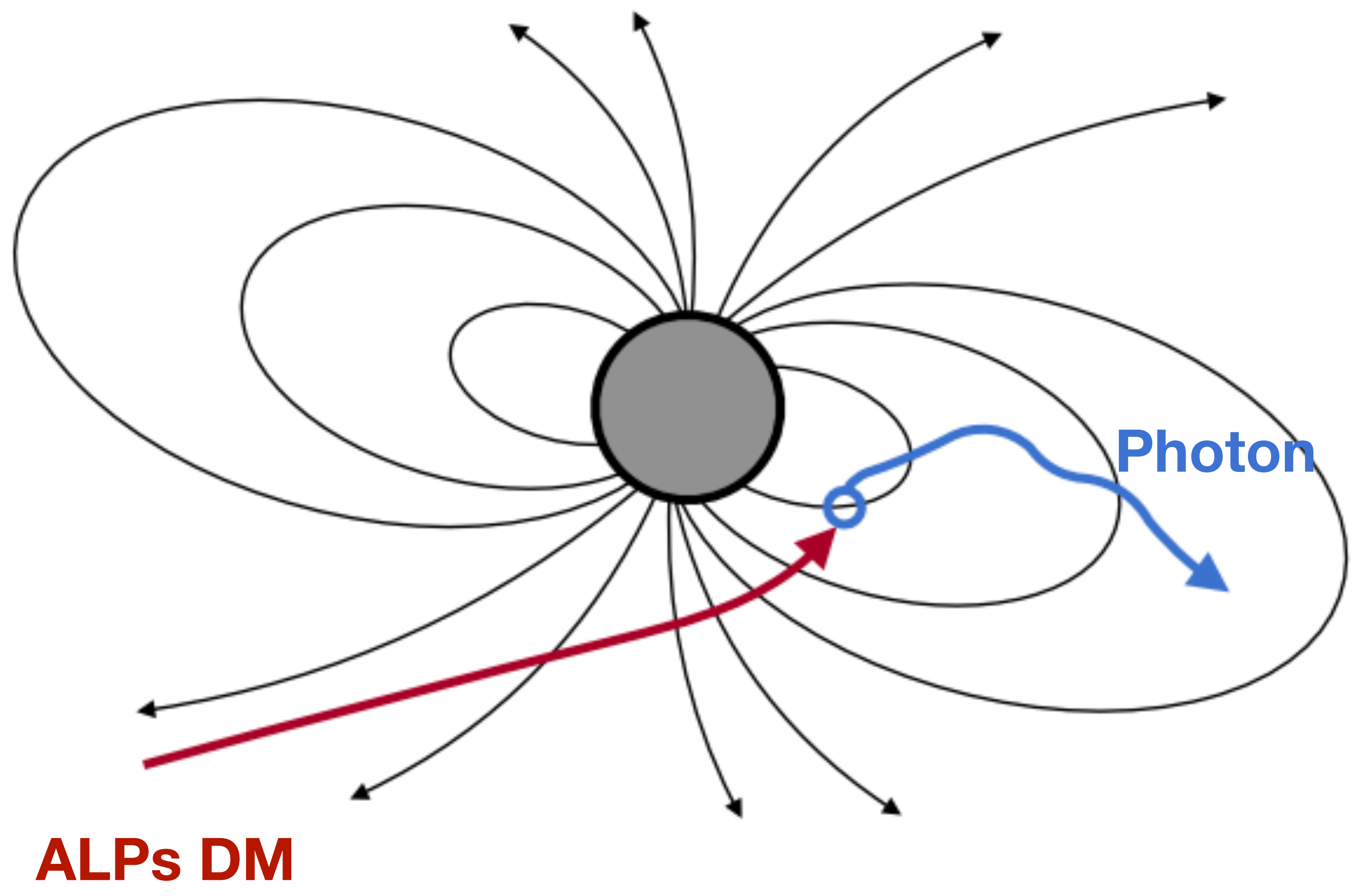
- Monochromatic radio emission (MHz - GHz) from **DM axion/ALP-photon conversion**:
  - *Resonant* conversion from highly magnetised neutron stars or white dwarf stars

    Pshirkov JETP'09; Huang+2018; Hook+PRL'18
  - *Non-resonant* transitions in the Galactic center and/or of discrete astrophysical objects

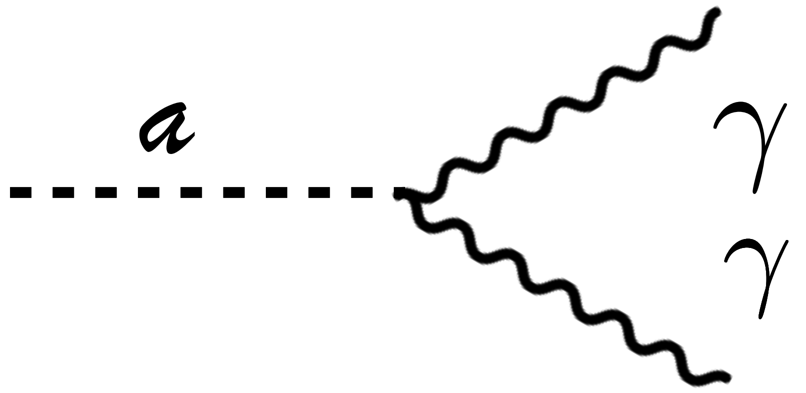
    Kelley&Quinn ApJ'17; Sigl PRD'17
  - Still large **limitations** in **model predictions**

    Leroy+ PRD'20; Witte+ PRD'21; Battye+ JHEP'21; Millar+JCAP'21



Axions and ALPs dark matter

Resonant conversion



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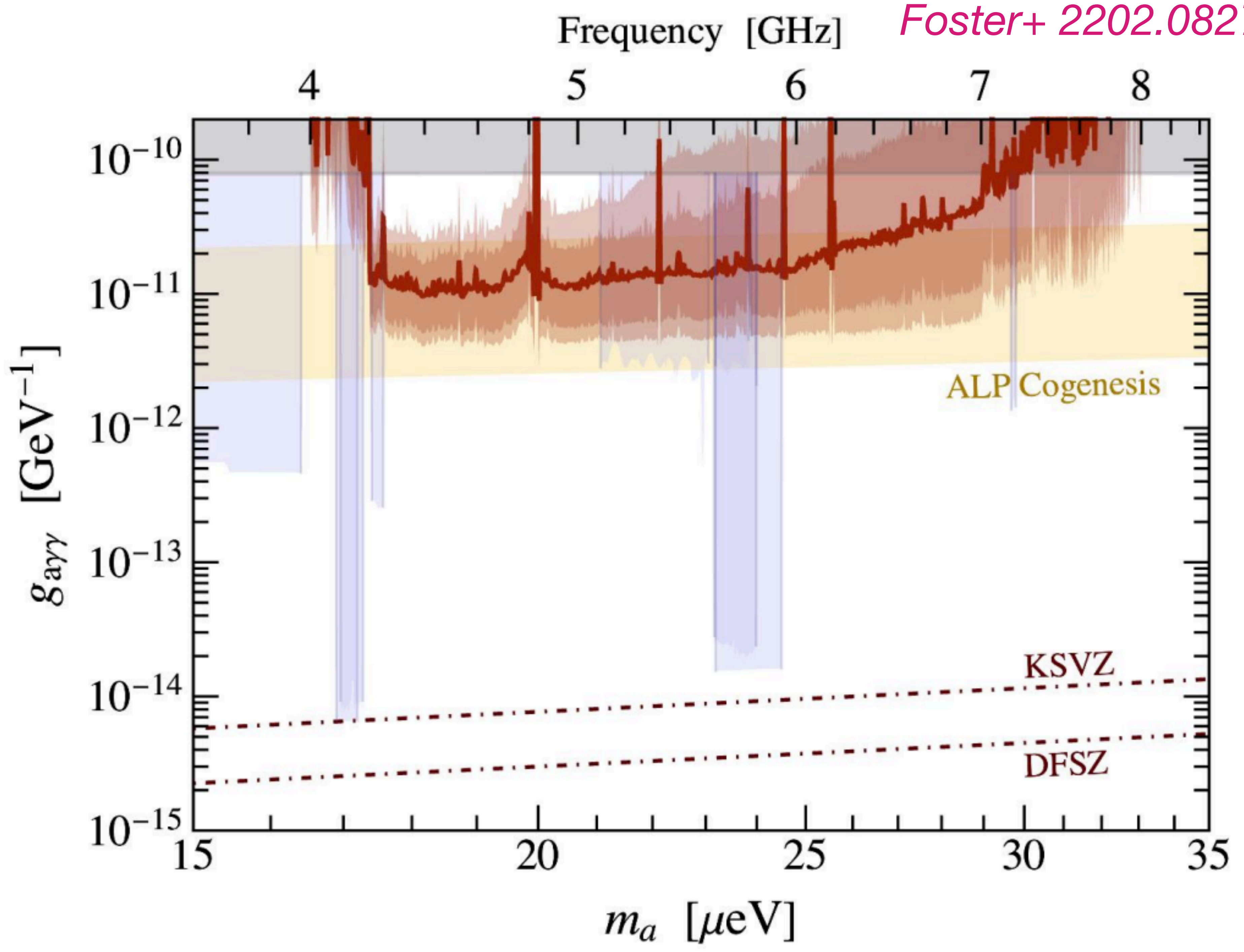
Foster+ 2202.08274



Particle DM: v-dependent x-section

$$\langle \sigma v \rangle = a + bv^2 + \mathcal{O}(v^4),\ v/c \sim 10^{-3}$$

Non-relativistic regime:
if present, **s-wave** is dominant

- S-wave can be suppressed (e.g. helicity suppression) or models may allow for v-dependent cross sections (long-range interactions for TeV scale dark matter)
- The connection between Early Universe and today annihilation is altered in a non-trivial way

$$\langle \sigma v \rangle \equiv S(v/c) \times \langle \sigma v \rangle_0$$

$$S(v/c) = (v/c)^n$$

- n=-1: **Sommerfeld**-enhanced annihilation in the Coulomb limit
- n=0: **s-wave** velocity-independent annihilation
- n=2: **p-wave** annihilation. This scenario is relevant if DM is a Majorana fermion, which annihilates to Standard Model fermion/antifermion pairs

Particle DM: v-dependent x-section

Gamma-ray flux

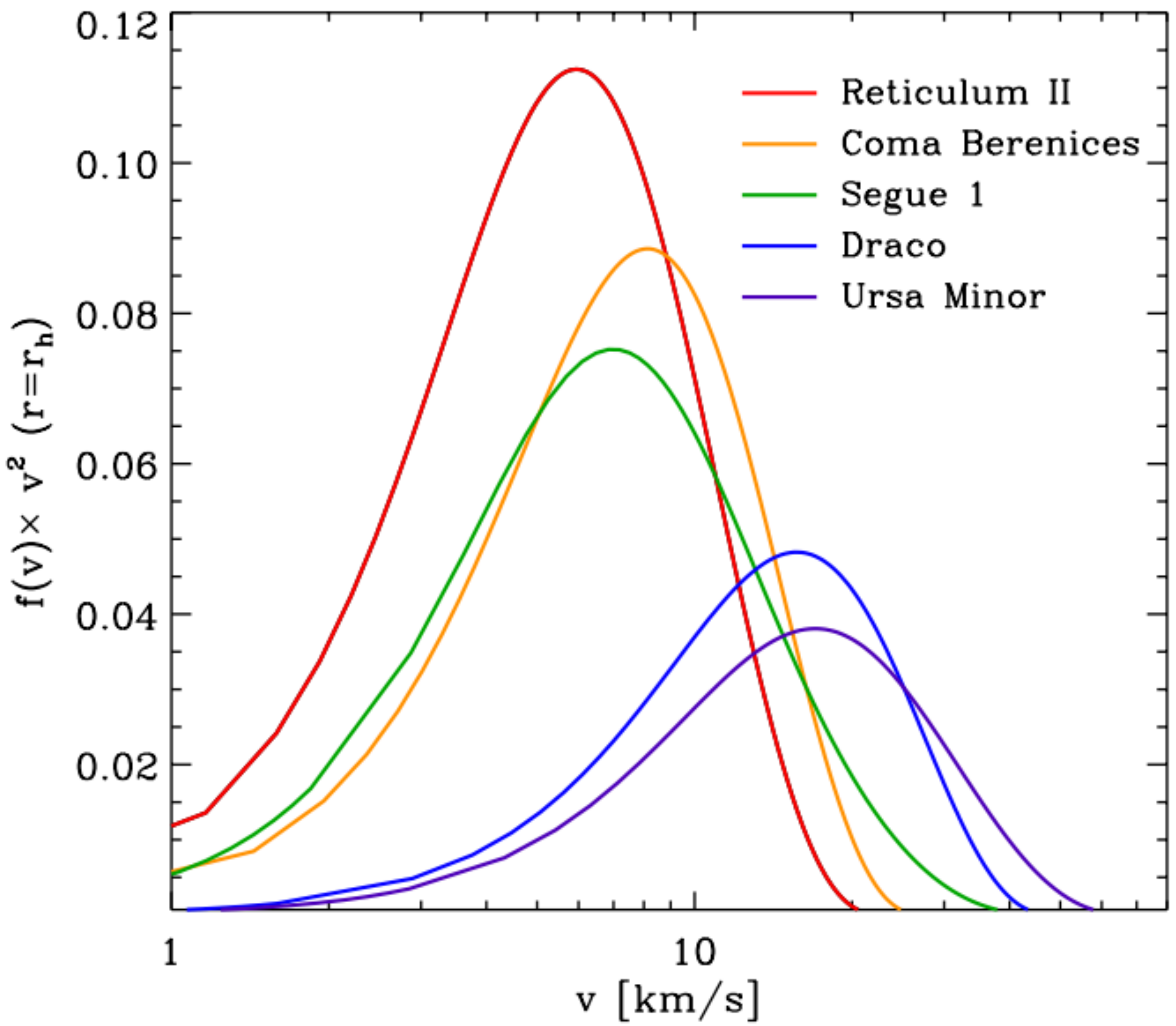
$$\langle \sigma v \rangle \equiv S(v/c) \times \langle \sigma v \rangle_0$$

$$\frac{d\Phi_\gamma}{dE_\gamma} = \frac{\langle \sigma v \rangle_0}{2m_{\rm DM}^2} \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \times \frac{1}{4\pi} \int_0^{\Delta\Omega} d\Omega \int_{\rm l.o.s} ds \int d^3 v_1 f(r(s,\Omega), \mathbf{v}_1) \int d^3 v_2 f(r(s,\Omega), \mathbf{v}_2) S(|\mathbf{v}_1 - \mathbf{v}_2|/c)$$

DM phase-space distribution

$$\rho(r) \equiv \int f(r, \mathbf{v}) d^3 v$$

$$f(\mathbf{v}) \equiv \int f(r, \mathbf{v}) dr$$



Boddy et al., Phys. Rev. D 95, 123008 (2017) [1702.00408]

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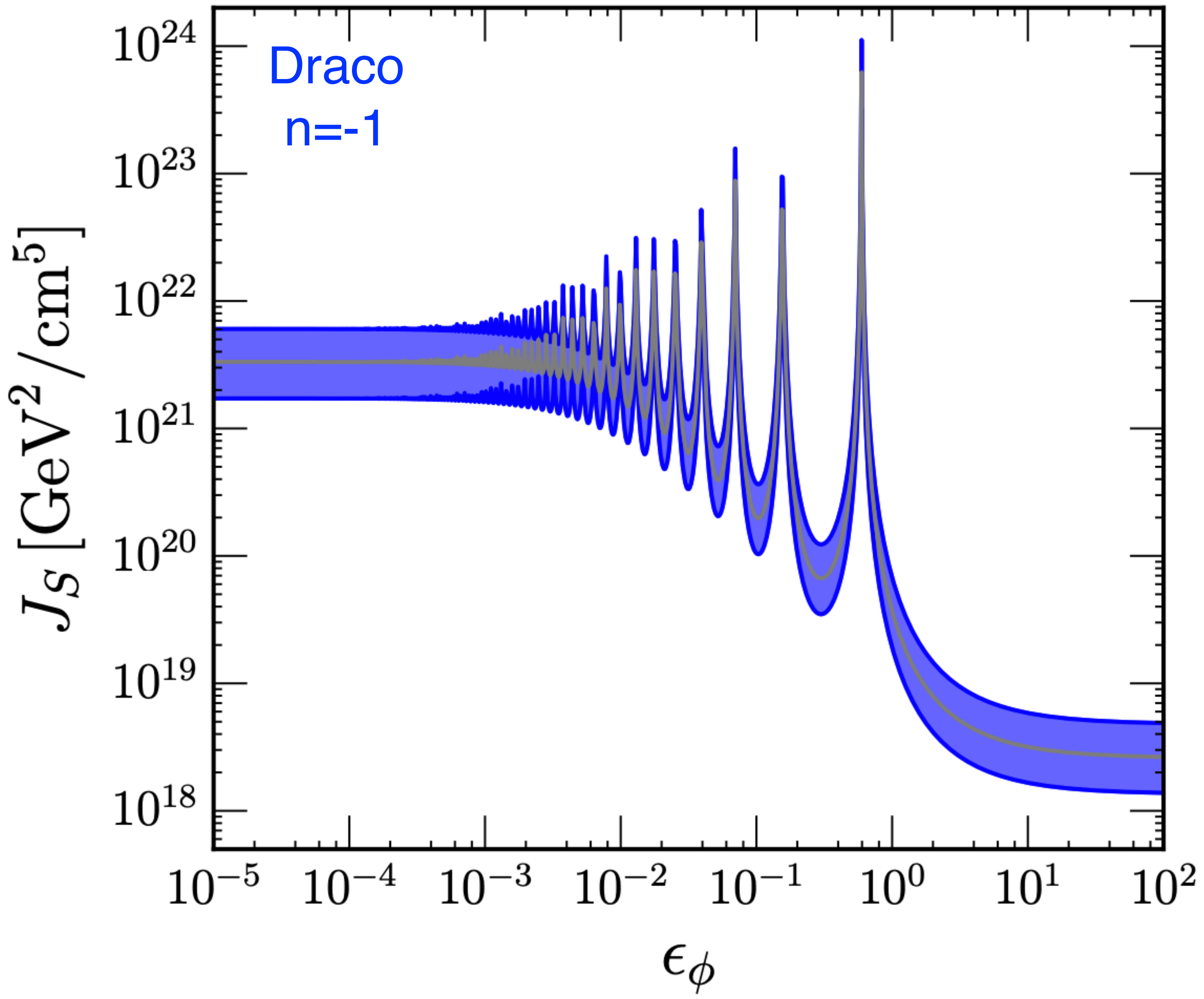
$$J_S(\Delta\Omega) \overset{\text{S=1}}{\rightarrow} J(\Delta\Omega) \int_0^{\Delta\Omega} d\Omega \int_{\rm l.o.s} \rho(r(s,\Omega)) \times \rho(r(s,\Omega))\, ds$$

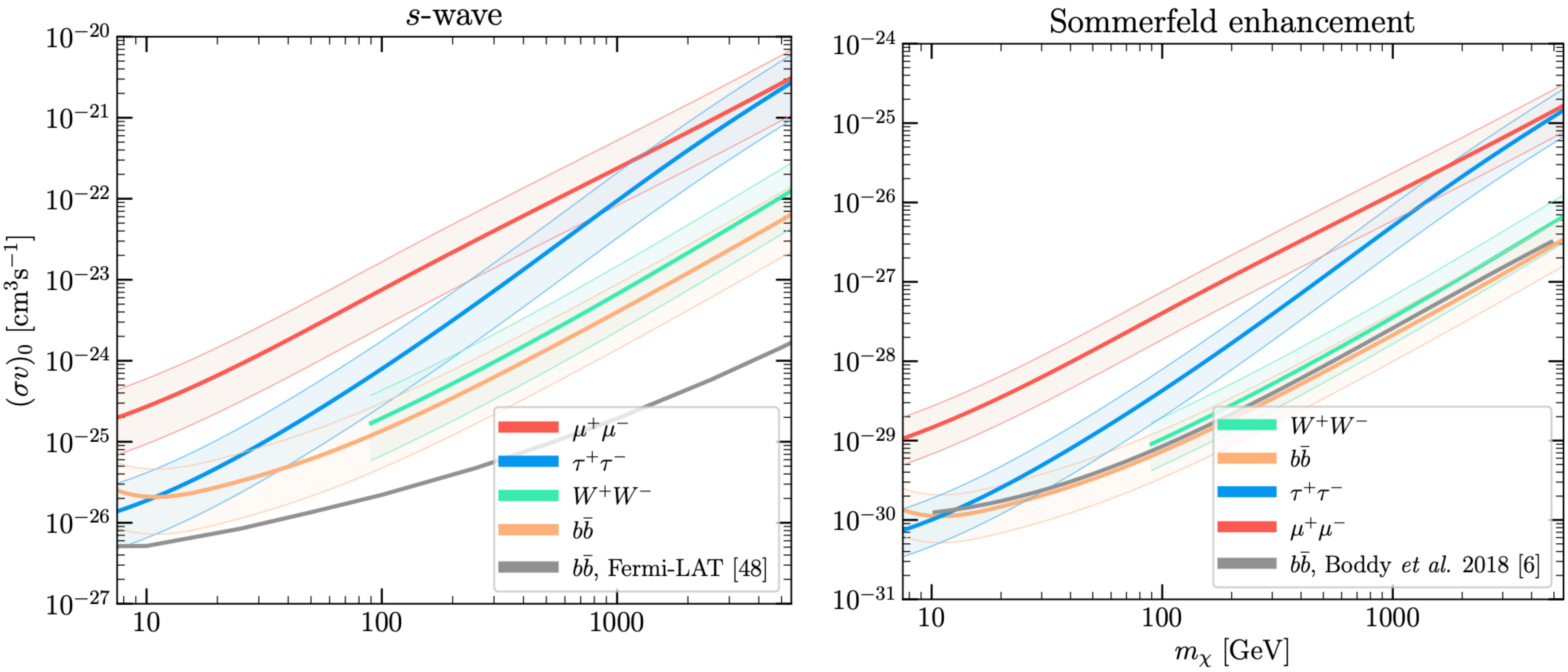


v-dependence of xsec can be translated in v-dependence of J-factors, allowing an easier **recasting** of limits under s-wave assumptions

Boddy et al., Phys. Rev. D 95, 123008 (2017) [1702.00408]
Boddy et al., Phys. Rev. D 102, 023029 (2020) [1909.13197]

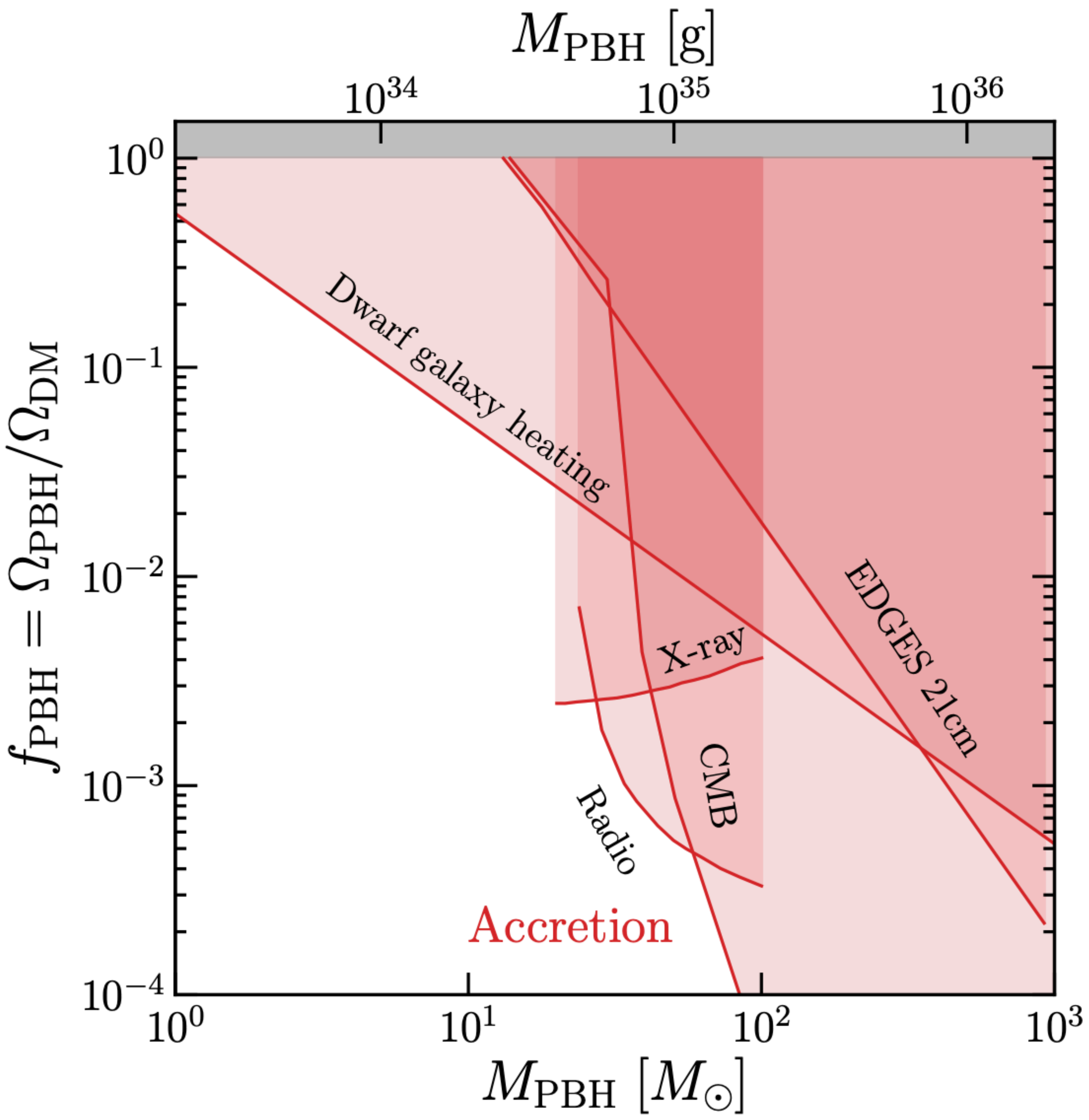
Particle DM: v-dependent x-section

Impact on DM limits



Boddy et al., Phys. Rev. D 102, 023029 (2020) [1909.13197]

Limits on accreting PBH



- **10-100 solar mass** PBH can accrete interstellar gas and produce observable **X-ray** and **radio emission** today

  Gaggero, FC+ PRL'17; Inoue & Kusenko JCAP'17; Lu+ ApJL'21

- Same mechanism can also modify the recombination history of the Universe => constraints set by anisotropies and spectrum of the **CMB**

  Carr MNRAS 1981; Ricotti+ ApJ'08; Poulin, FC+ PRD'17

- Significant **theoretical uncertainties**: e.g. accretion rate and the ionizing effects of the radiation; impact of more realistic/complex mass functions

  Manshanden+ JCAP'19

➡ **Future** radio facilities (**SKA**, **ngVLA**) have the potential to either set very strong constraints on PBH abundance or to detect a population of PBHs at the GC

Weltman+ PASA'20