ISAPP School 2021

Gamma rays to shed light on dark matter

WIMP gamma-ray searches

Francesca Calore (CNRS/LAPTh)
calore@lapth.cnrs.fr
30/07/2021

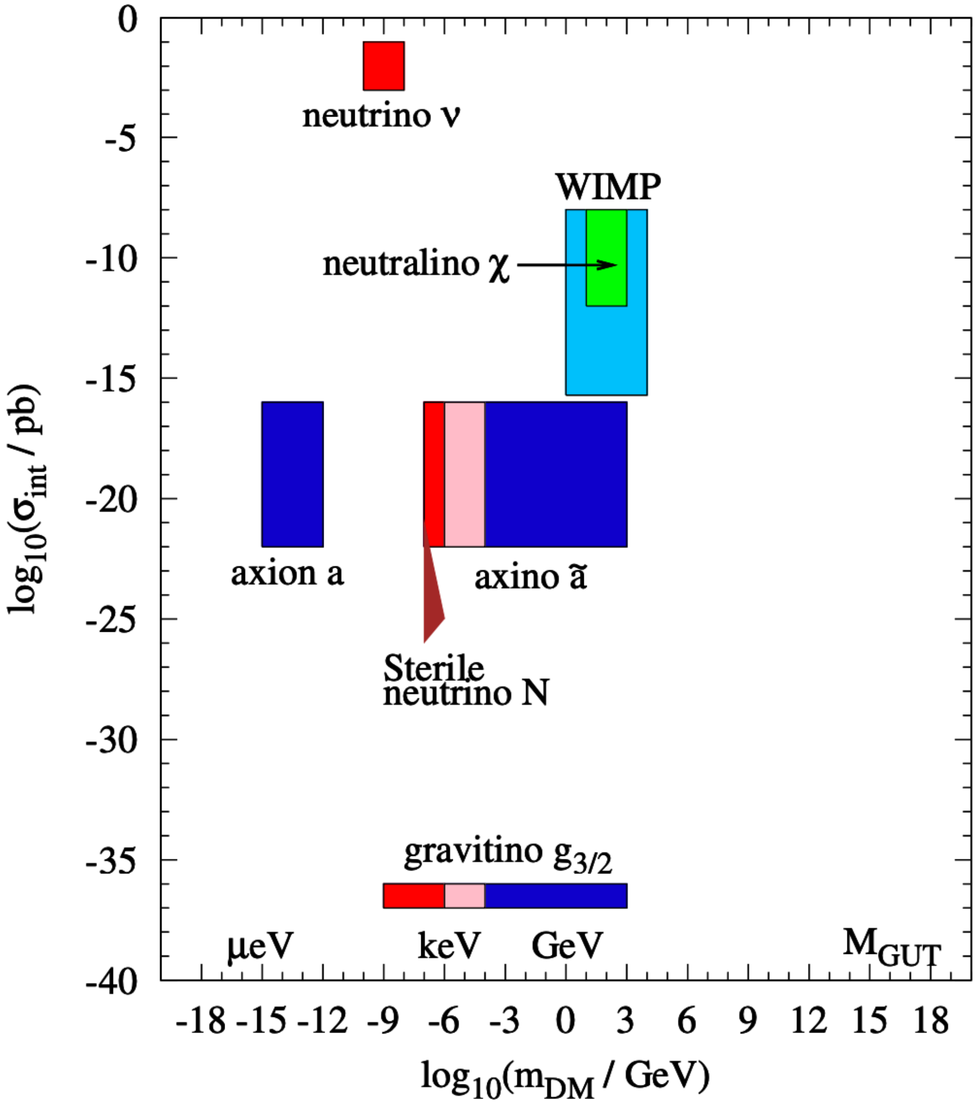
Outline

- WIMP models and Early Universe connection
- WIMP indirect detection: spectral features and spatial signatures
- Feature-based searches:
  1. Searches for WIMP with the diffuse gamma-ray background
  2. Searches for WIMP line-like signals
  3. Searches for WIMP towards dwarf spheroidal galaxies and dark sub haloes
- TeV WIMP and long-range interactions
  1. Sommerfeld enhancement
  2. Bound state formation
- V-dependent cross sections and J-factors
- Decaying WIMP
- Model-based searches

\+ Bonus slides

Weakly Interacting Massive Particles

DM candidates cover a vast parameter space (incomplete figure)



Roszkowski et al., Rept.Prog.Phys. 81 (2018) no.6 [1707.06277]

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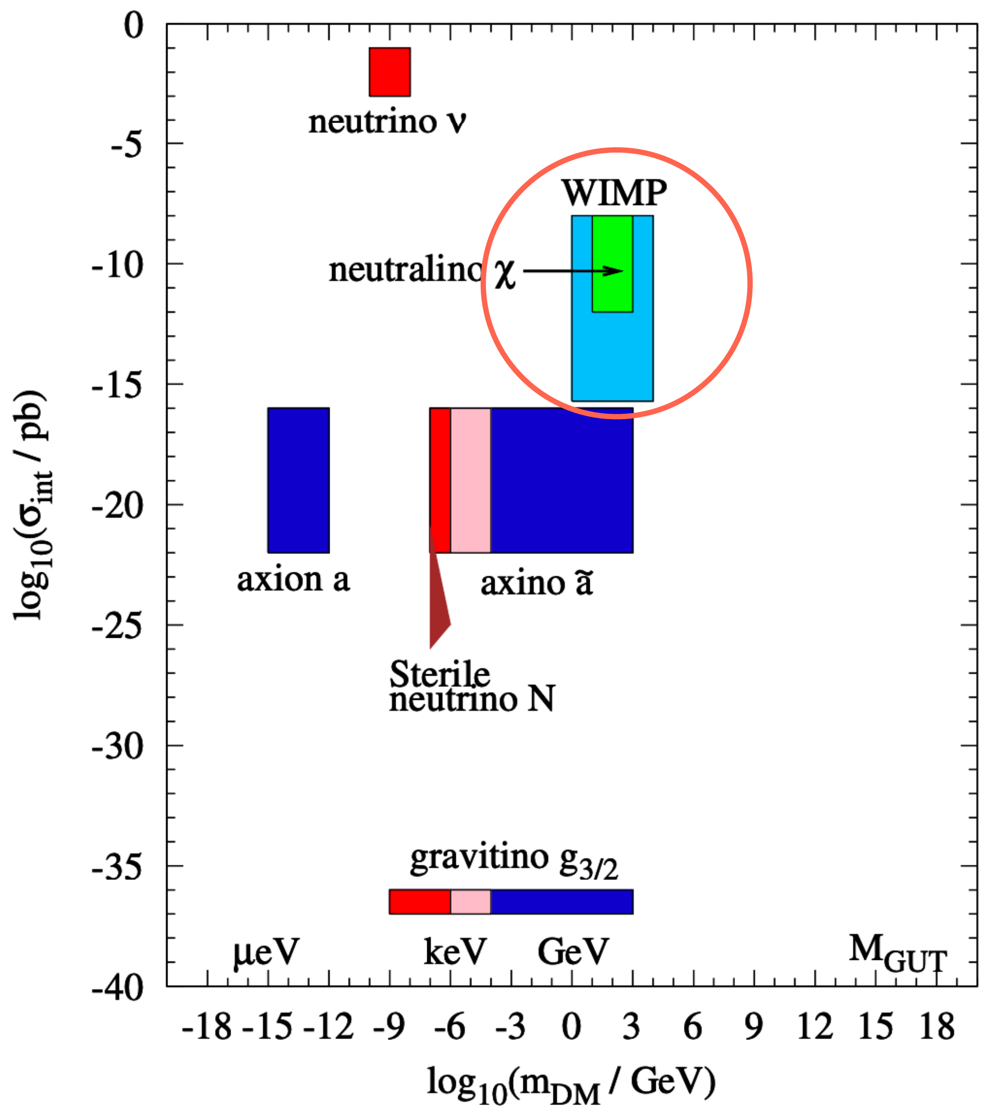

WIMP

- Particle with mass in the range from ~2 GeV (Lee-Weinberg bound) up to ~100 TeV (a rough unitarity bound)
- Interacting via the weak nuclear force or just having a (sub)weak but non negligible coupling to the Standard Model particles
- Typically thermally produced in the Early Universe (freeze out mechanism)

Roszkowski et al., Rept.Prog.Phys. 81 (2018) no.6 [1707.06277]

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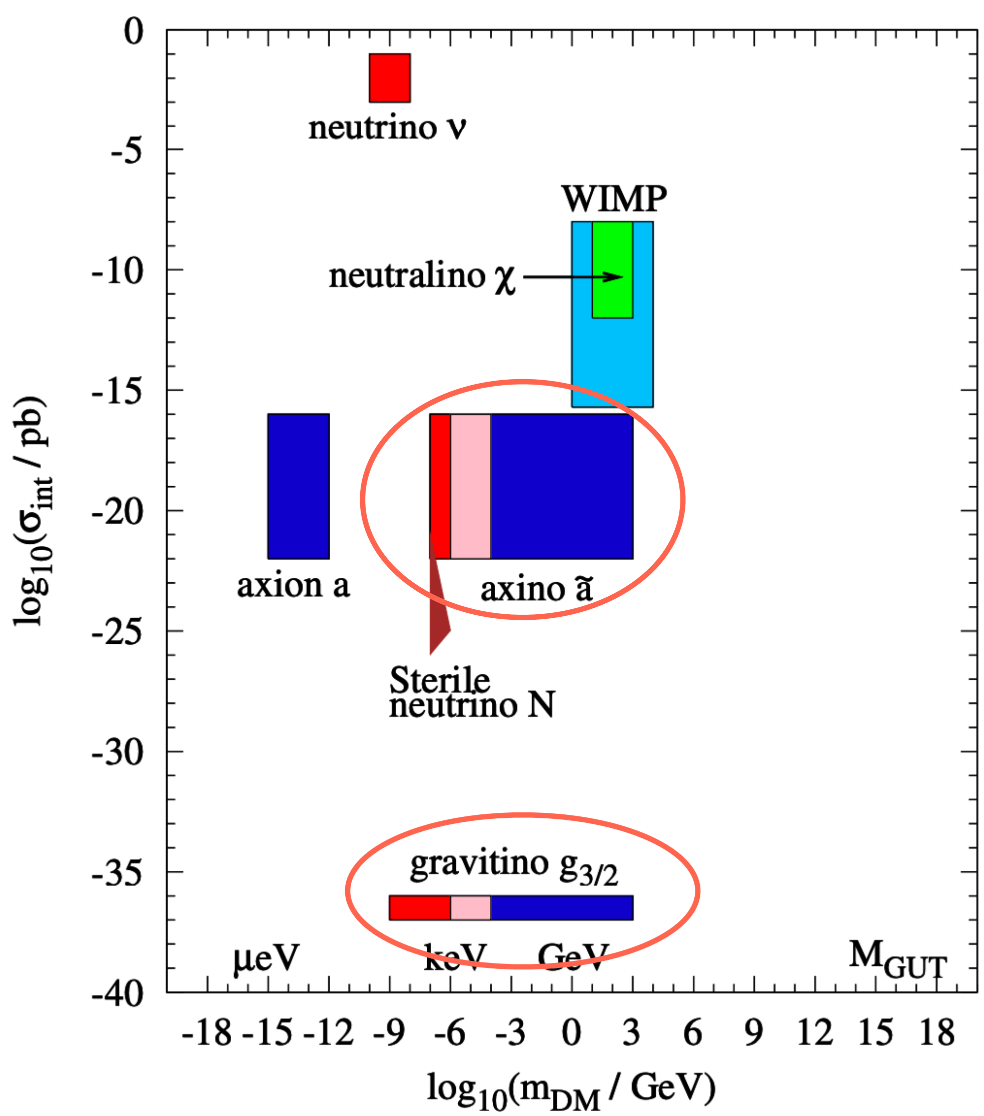


Super-WIMP (or EWIMP or FIMP)

- Weaker than weak (extremely weak) coupling with Standard Model particles
- Axino (SUSY partner of the axion) and gravitino (fermionic partner of graviton) in RPV models
- Examples of decaying WIMP
- Can be produced thermally or through freeze-in mechanism
- May be hot, warm or cold DM

Roszkowski et al., Rept.Prog.Phys. 81 (2018) no.6 [1707.06277]

WIMP models

Broad category of hypothetical candidates coming from specific theoretical scenarios

Lightest neutralino of low energy SUSY models

- Lightest mass state of a combination of the superpartners of the neutral gauge bosons and Higgs particles

J. R. Ellis et al., Nucl. Phys. B238 (1984)

Two Higgs Doublet Models (2HDM)

- Extend the Higgs sector by the addition of another doublet giving rise to additional charged and neutral Higgs bosons
- Simpler extension, inert doublet model (IDM), with additional Z_2 symmetry

G. C. Branco et al., Phys. Rept. 516 (2012) [arXiv:1106.0034]

Little Higgs Models

- Higgs fields are the Goldstone bosons of global symmetry broken at the cut off scale
- Heavy states are introduced to act as partners of the top quark and gauge bosons
- The DM candidate can come in the form of additional scalars or a heavy partner to the photon (vector DM)

M. Schmaltz and D. Tucker-Smith, Ann. Rev. Nucl. Part. Sci. 55 (2005) [hep-ph/0502182]

Models with compactified universal extra dimensions (UED)

- DM candidate from the tower of Kaluza-Klein (KK) states
- The lightest KK state is often a heavy copy of the hypercharge gauge boson

T. Appelquist et al., Phys. Rev. D64 (2001) [hep-ph/0012100]

Thermal decoupling (freeze-out)

Successful framework to explain Universe evolution (CMB, BBN)

$\Gamma \ll H(T)$ reaction in statistical (thermodynamic) equilibrium

$\Gamma(T_{\mathrm{f.o.}}) \sim H(T_{\mathrm{f.o.}})$ decoupling @ freeze-out T

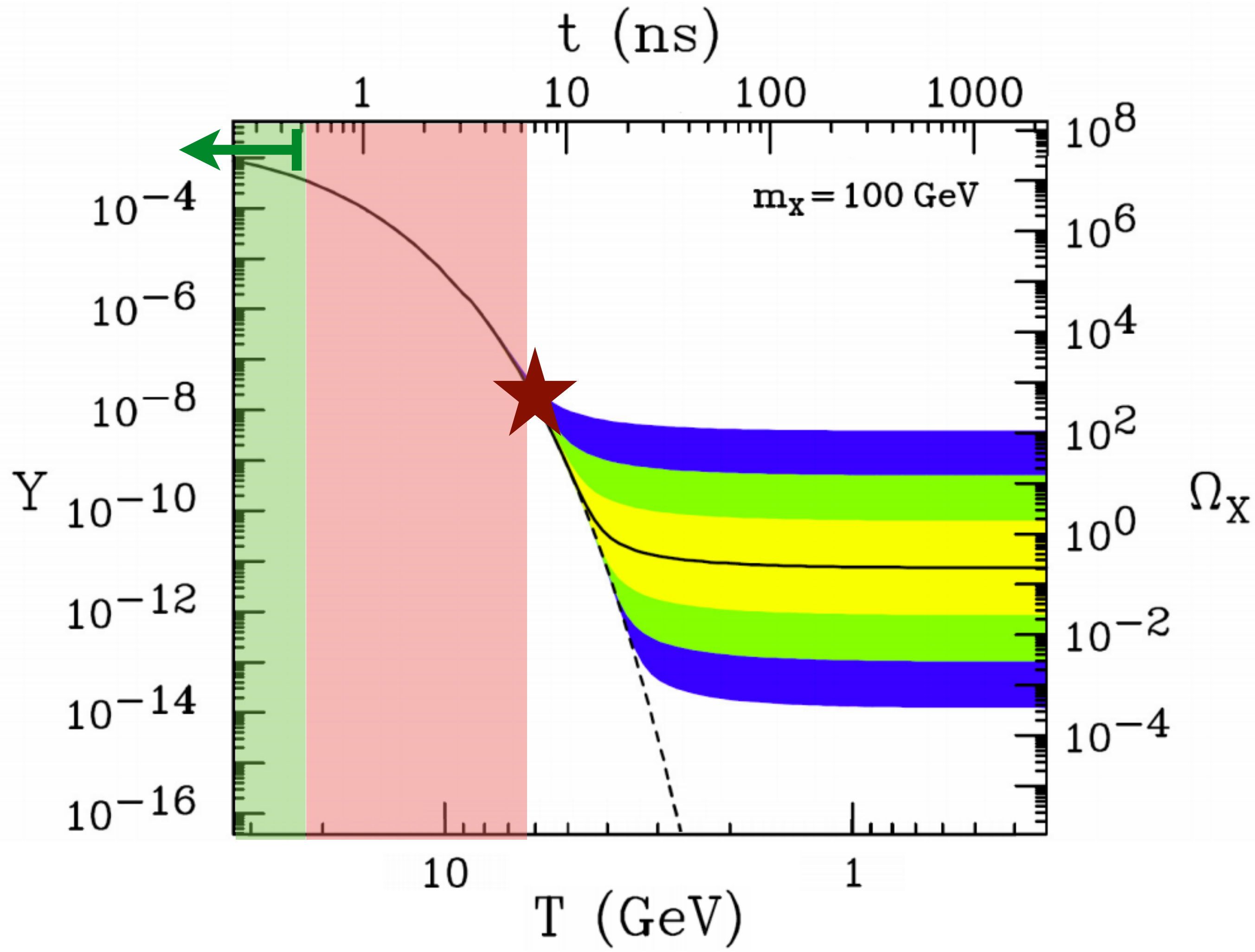
$$H^2(T) \equiv \frac{8\pi G_N}{3}\rho(T) \propto T^4$$

$$H(T) \propto T^2/M_P$$

energy density dominated by radiation

[Equilibrium : chemical — changing the number of particle per species — or kinetic — conserving number of particles]

Thermal decoupling (freeze-out)



$$Y_i \equiv \frac{n_i}{s} \sim n_i a^3$$ comoving number density

$$T \gg m_X \qquad Y_X^{\rm rel} \sim const$$

$$T \ll m_X \qquad Y_X^{\rm non-rel} \sim e^{-m_X/T}$$

★ $$Y_X(T_{\rm f.o.}) = Y_0$$

Cold relic history very sensitive to details of decoupling because of rapid variation of Y_i → Sensitivity to **new physics** through:

- Interaction rate, i.e. interaction type
- Number of relativistic d.o.f for the evolution of H(T)

[For textbook see *Kolb & Turner, "The Early Universe" (1988)*]

Thermal decoupling (freeze-out)

Formal derivation: phase space density evolution, collisional Boltzmann equations

$$L[f] = C[f]$$

$$\dot{n} = -3Hn + \frac{g}{(2\pi)^3} \int \frac{d^3p}{E} C[f]$$

Non-relativistic relic, in equilibrium through processes $X\bar{X} \leftrightarrow a\bar{a}$

$$\langle \sigma \cdot v_{\text{Møl}} \rangle = \frac{\int \sigma(s) \cdot v_{\text{Møl}} f_1(p_1) f_2(p_2) d^3p_1 d^3p_2}{\int f_1(p_1) f_2(p_2) d^3p_1 d^3p_2} \qquad v_{\text{Møl}} \equiv \frac{\sqrt{(p_1 \cdot p_2)^2 - m_1^2 m_2^2}}{E_1 E_2}$$

$$\dot{n}^{*} = -3Hn - \langle \sigma v_{\text{Møl}} \rangle (n^2 - n_{\text{eq}}^2)$$

*$n = n_X + n_{\bar{X}}$

Thermal decoupling (freeze-out)

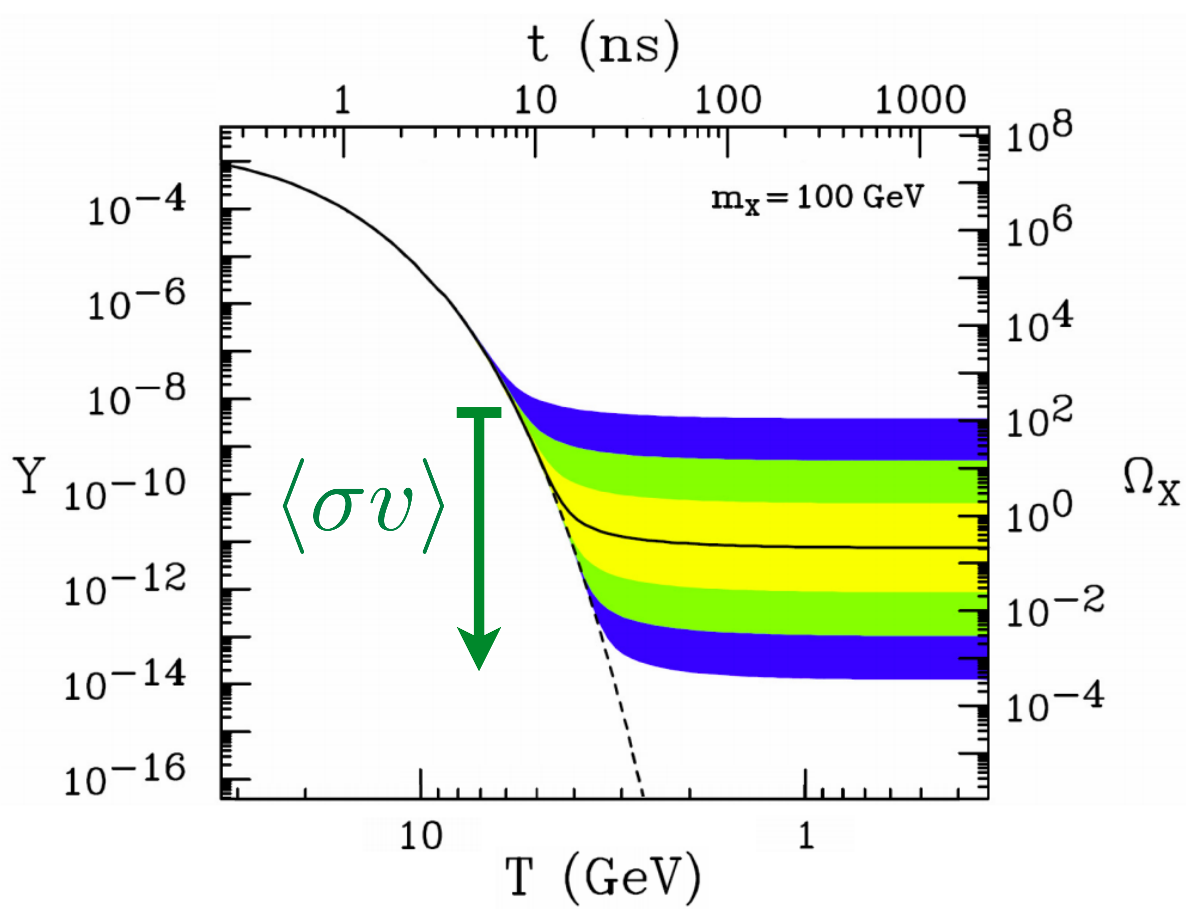
When does the freeze-out occur? [Non-relativistic relic]

$$\langle E \rangle \equiv \frac{\rho}{n} \overset{\text{NR}}{\sim} \frac{mn + \frac{3}{2}Tn}{n} = m(1 + \frac{3}{2}\frac{T}{m})$$

$$E^2 = p^2 + m^2 \qquad E \overset{\text{NR}}{\sim} m(1 + \frac{1}{2}\frac{p^2}{m^2}), \quad \frac{p^2}{m^2} \ll 1$$

$$\rightarrow \quad x \equiv \frac{m}{T} \overset{\text{NR}}{\gg} 3$$

Some estimates... [from solving Boltzmann equation]



$$Y(x \gg x_f) = Y_0 \simeq \mathcal{O}(1)\frac{1}{M_P M_X \langle \sigma v \rangle}*$$

$$x_f \simeq 20 - 30$$

$$\Omega_X h^2 \simeq \frac{0.1\,\text{pb}\cdot\text{c}}{\langle \sigma v \rangle}$$

WIMP Miracle

$*\langle \sigma v \rangle = \int_{x_f}^{\infty} \langle \sigma \cdot v_{\text{Møl}} \rangle x^{-2} dx$ In the NR limit: $T \sim \langle v^2 \rangle$ Expansion in power of x: $\langle \sigma \cdot v_{\text{Møl}} \rangle \sim a + b x_f^{-1}$

Thermal decoupling (freeze-out)

Three exceptions in the calculation of the relic abundance

1. Co-annihilation with other particles degenerate in mass (5% —10%); coupled Boltzmann equations
2. Dark matter mass slightly below mass threshold to open up a new channel
3. Annihilation close to a pole of the cross section, i.e. resonant annihilation

Griest & Seckel, Phys.Rev.D 43 (1991) 319
Edsjo & Gondolo, *Phys.Rev.D 56 (1997) 1879[hep-ph/9704361]*

How to…

MicrOMEGAs: a code for the calculation of Dark Matter Properties
including the **relic density**, direct and **indirect rates**
in a general supersymmetric model
and other models of New Physics

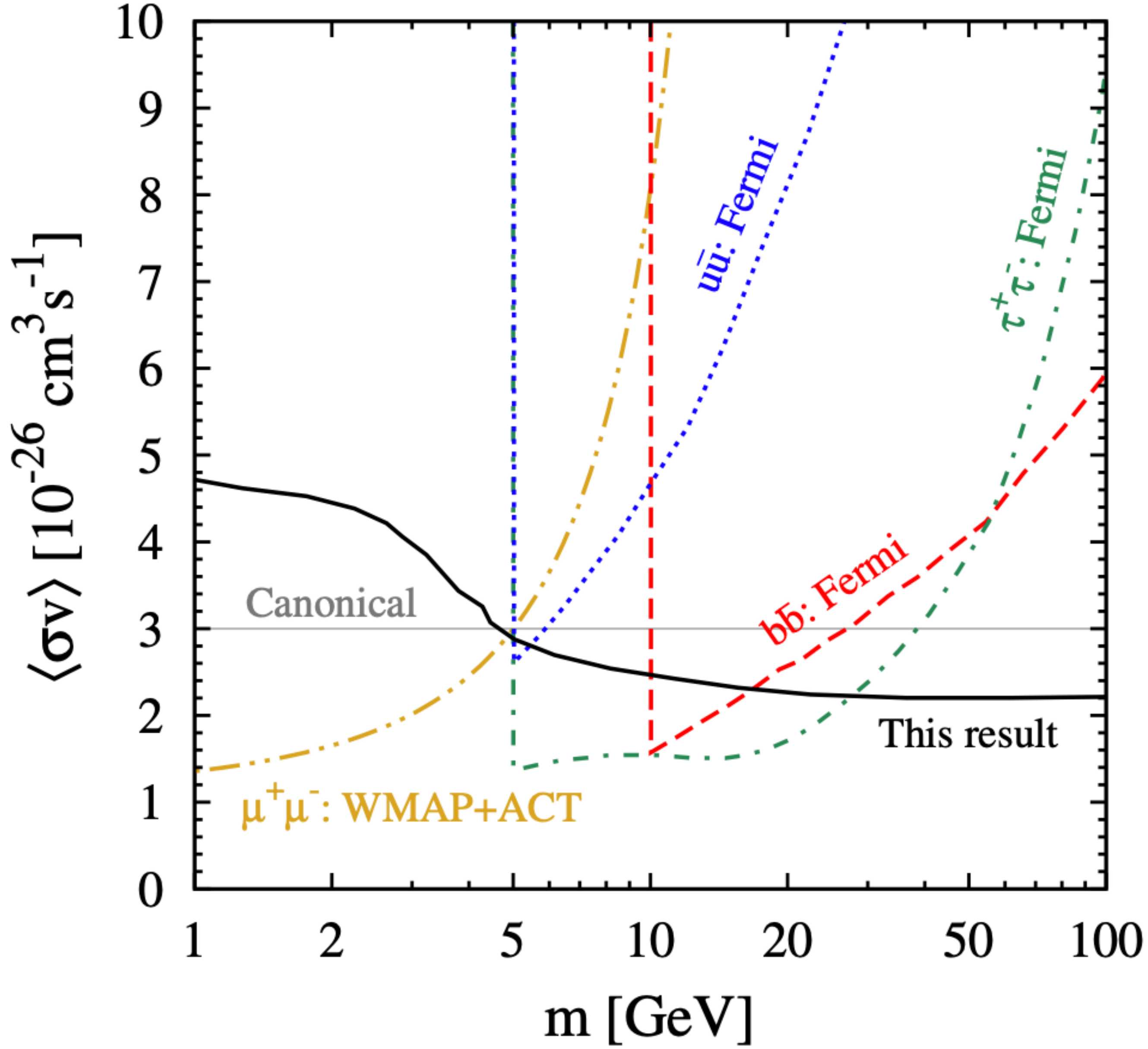
https://lapth.cnrs.fr/micromegas/

http://www.darksusy.org/

The "thermal cross-section"

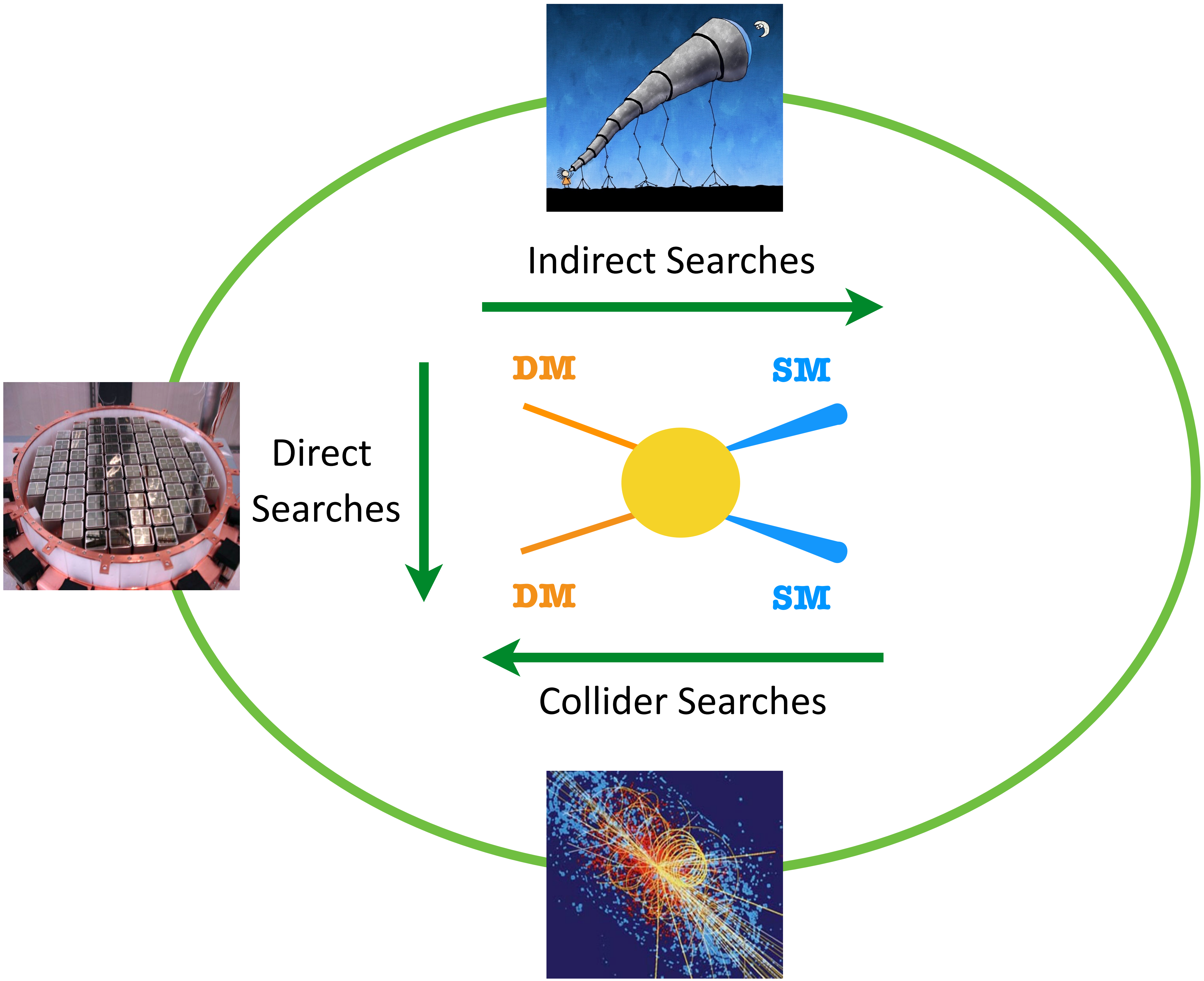
For vanilla like WIMP the right relic abundance is met for

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \text{cm}^3/\text{s}$$



Steigman et al., Phys.Rev. D86 (2012) [1204.3622]

WIMP detection strategies

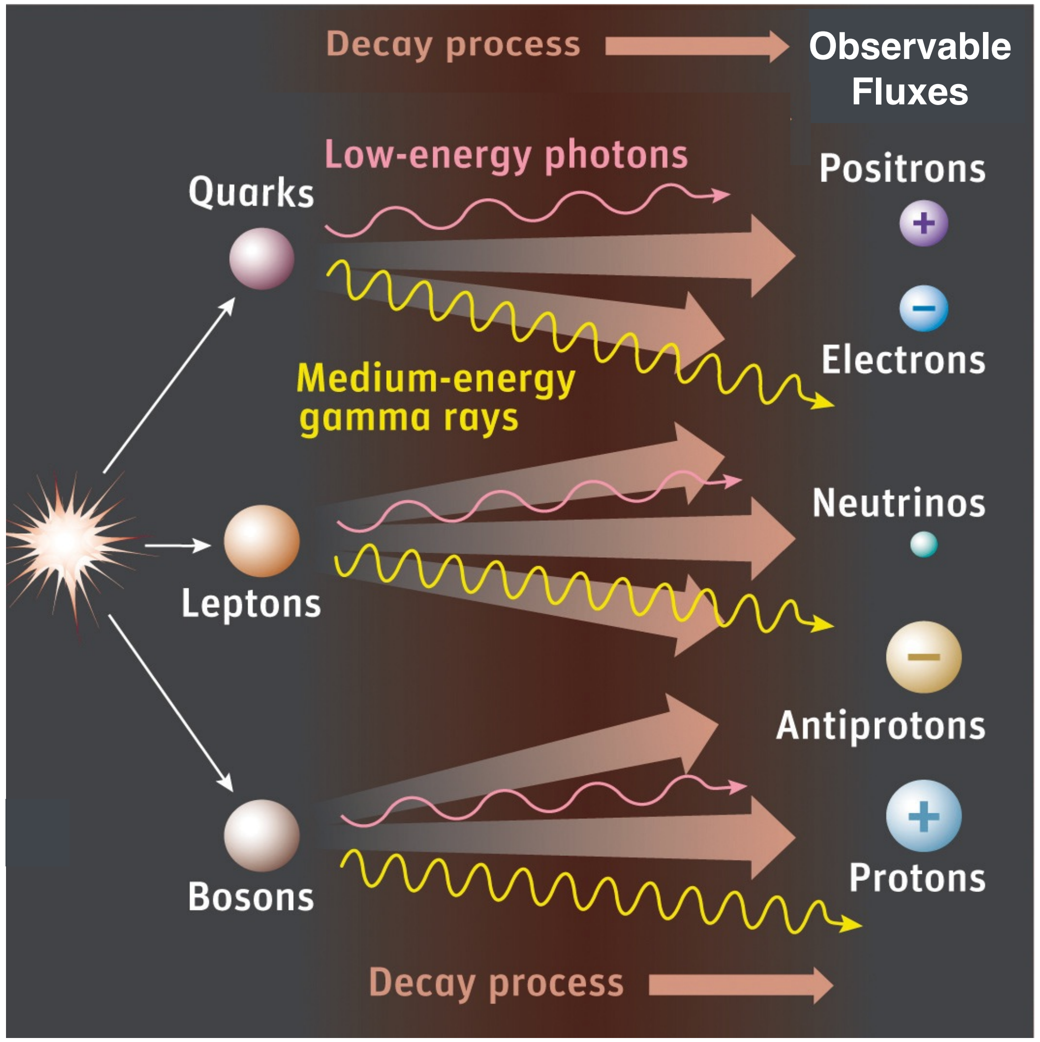


Indirect dark matter detection

Two key-assumptions:

1) **Dark matter exists** and is the main responsible for the gravitational potential inferred in galaxies, clusters and cosmo.
2) **Dark matter is non-gravitationally coupled** to standard matter.

DM annihilation/decay



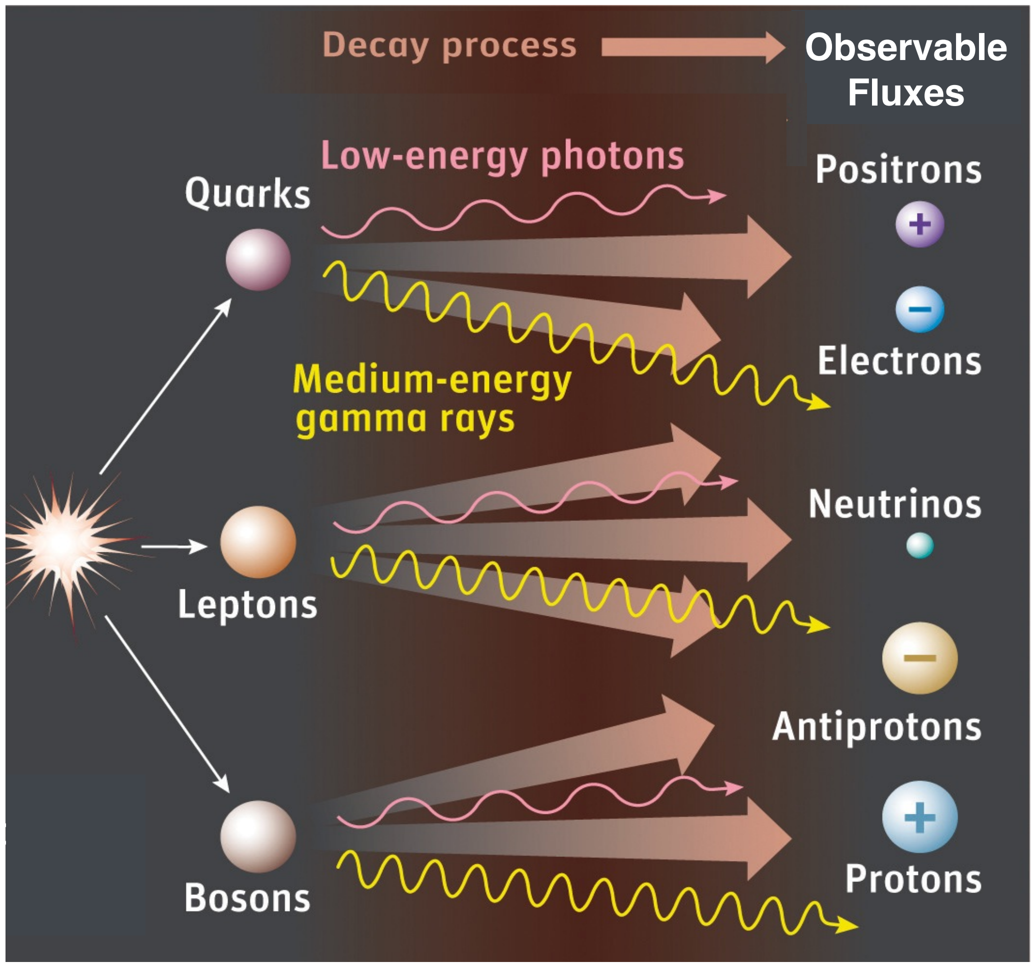
DM annihilation/decay leads to production of **observable fluxes** of stable particles.

Disclaimer:

1) Not necessarily signatures at the GeV-TeV-scale
2) DM at the electroweak scale is one among possible valuable solutions

Indirect dark matter detection

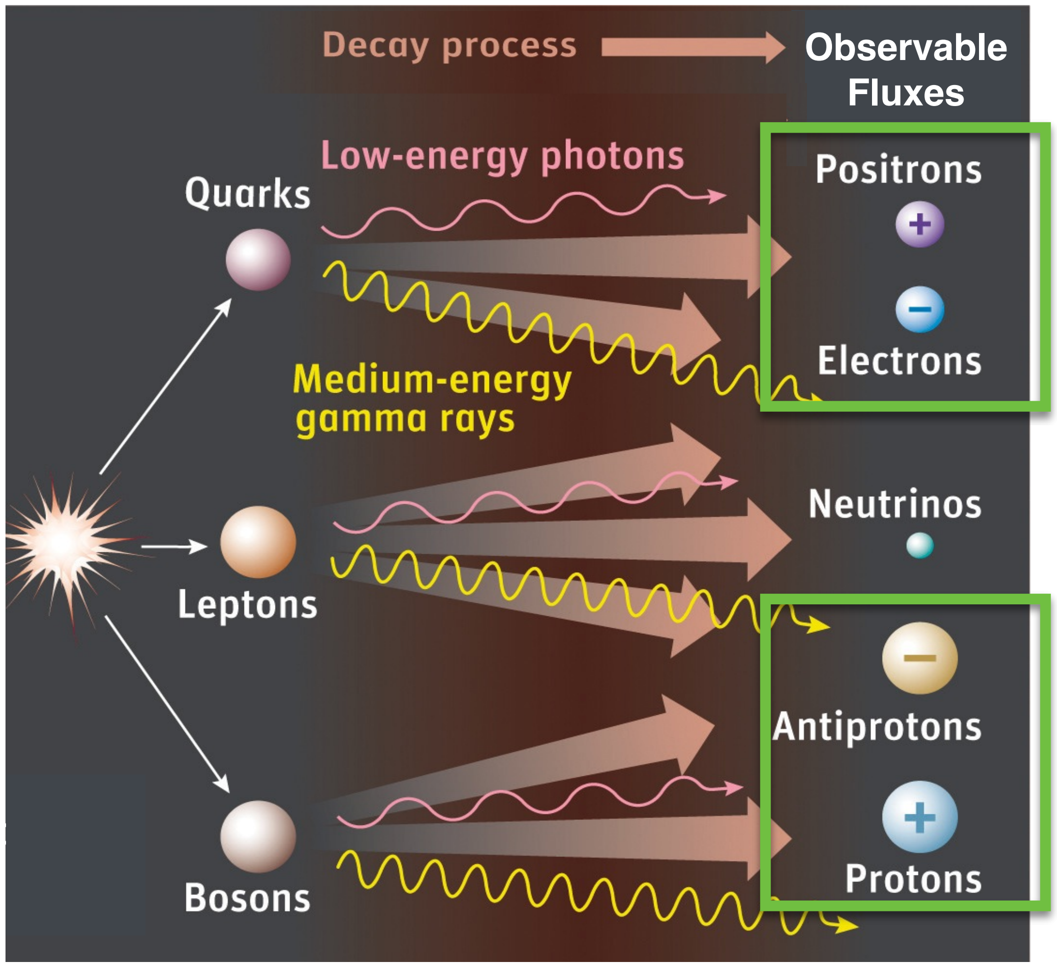
DM annihilation/decay

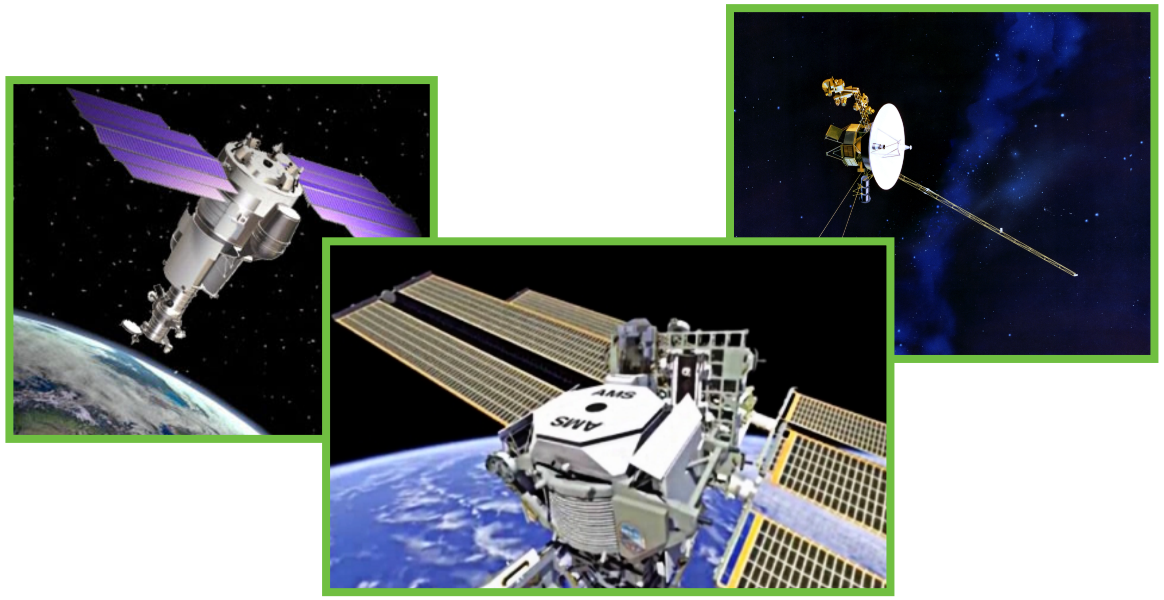


Indirect searches
for stable dark matter annihilation
(or decay) products.

Indirect dark matter detection

DM annihilation/decay





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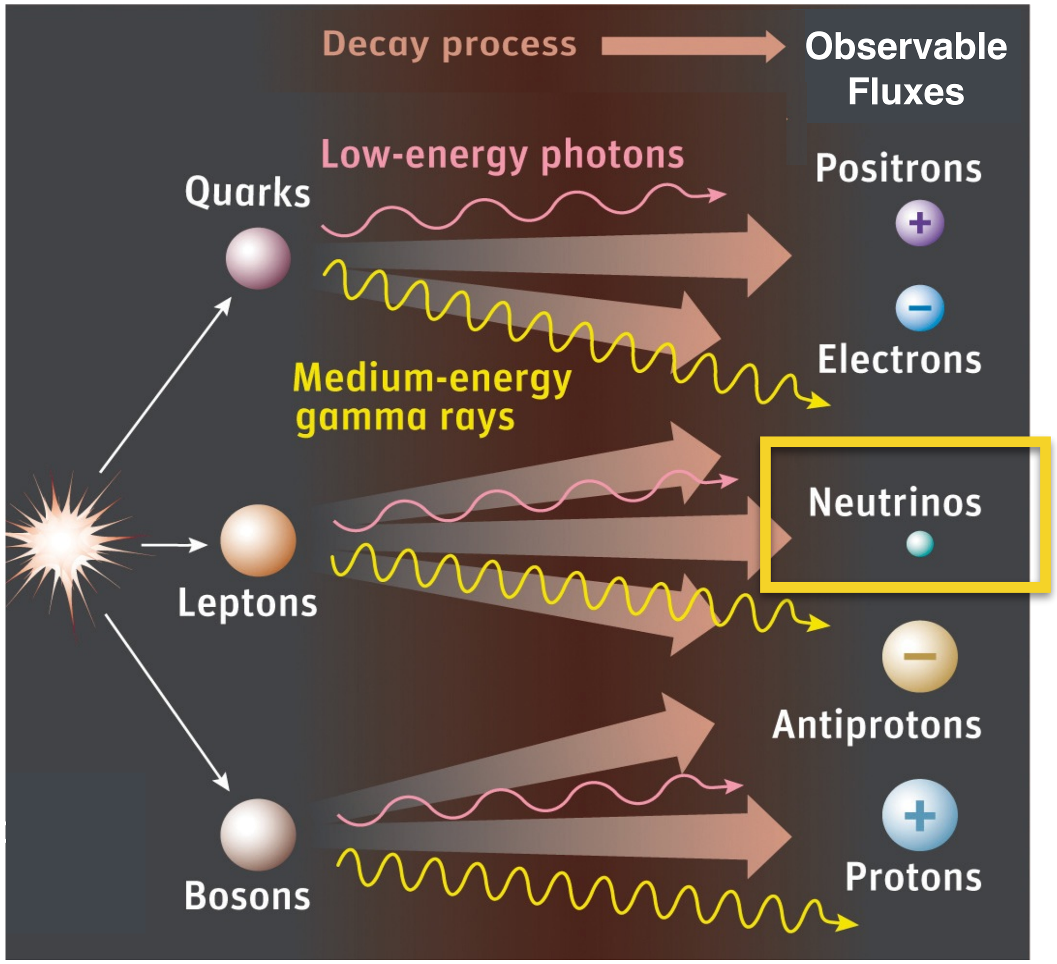

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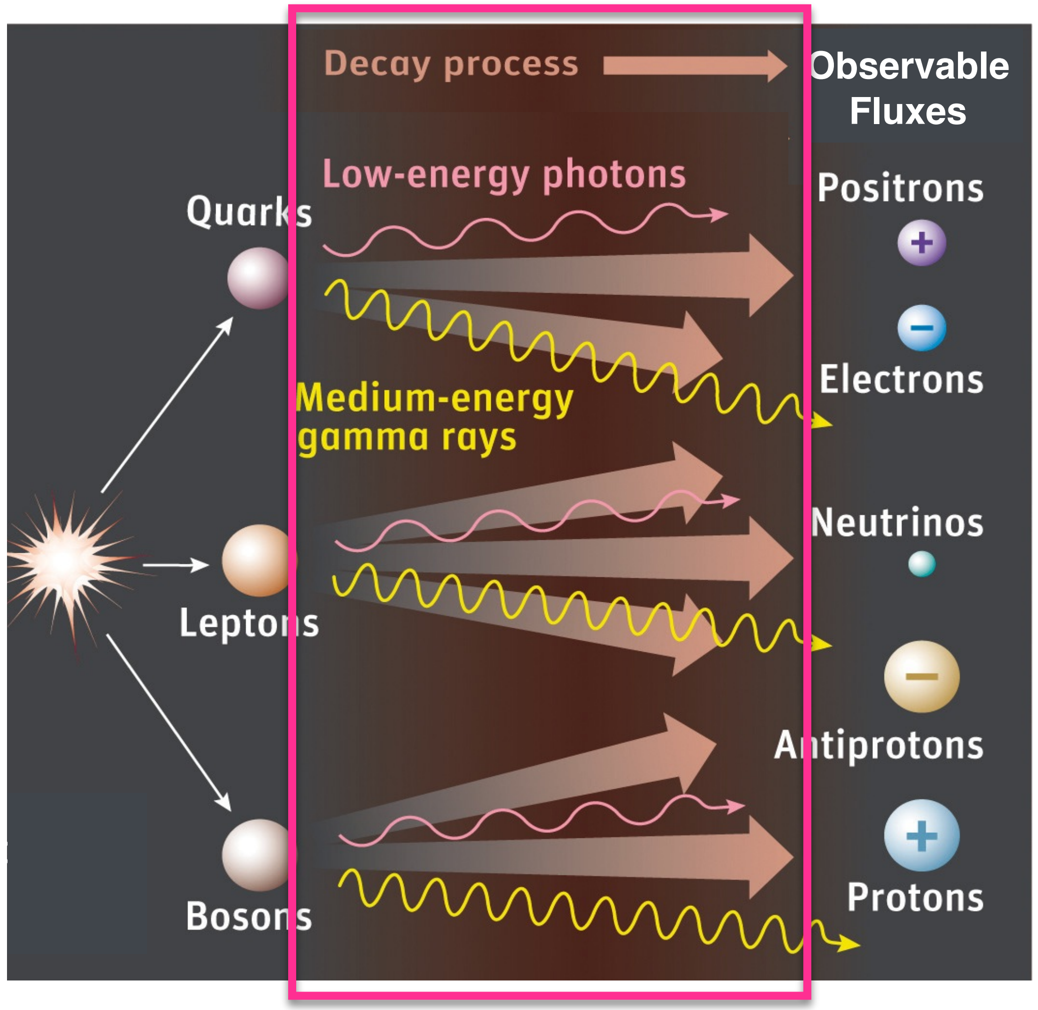

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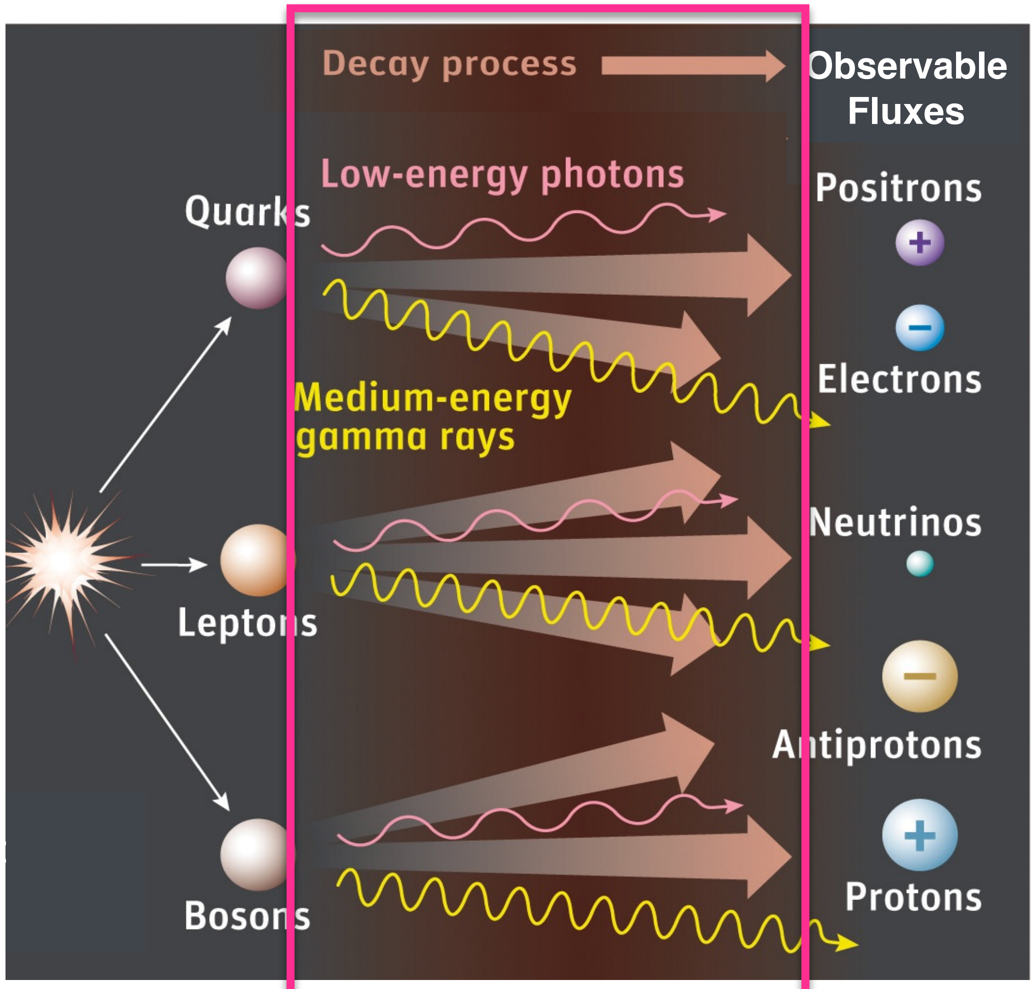
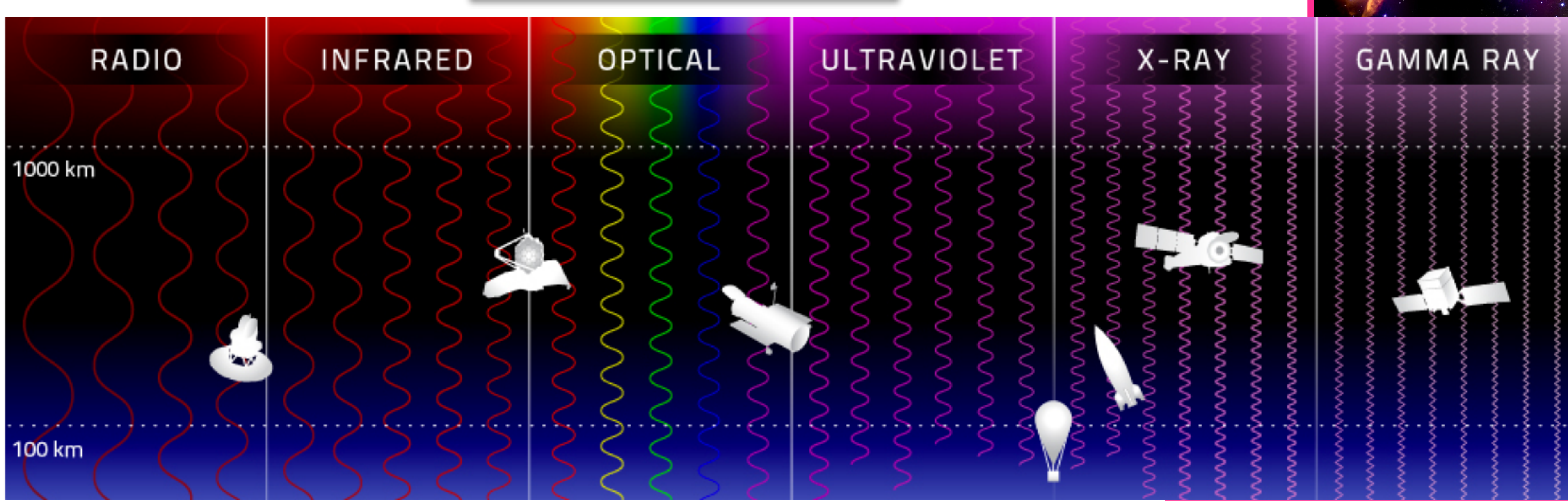
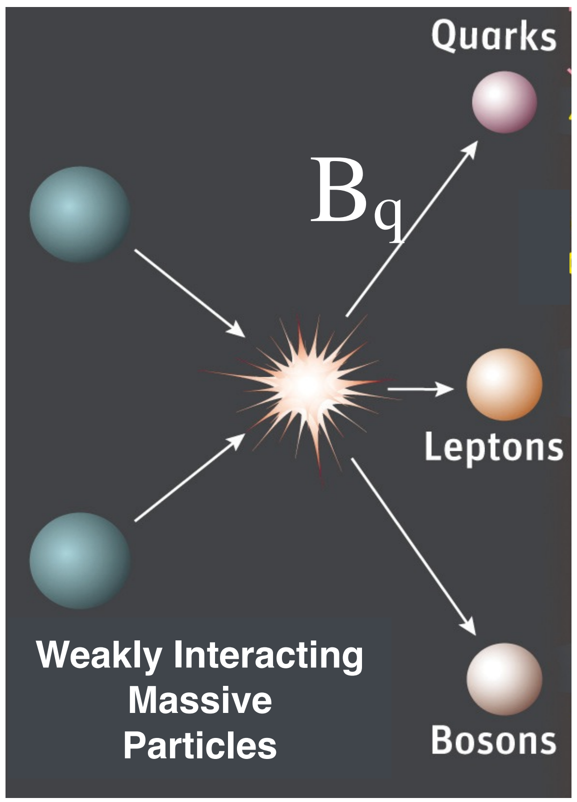


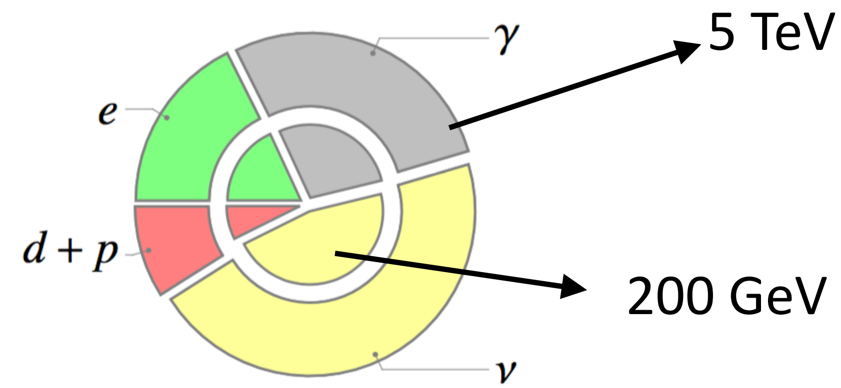


Energy distribution into final state particles



$\mathrm{DM\,DM} \rightarrow \mathrm{SM\,SM}$

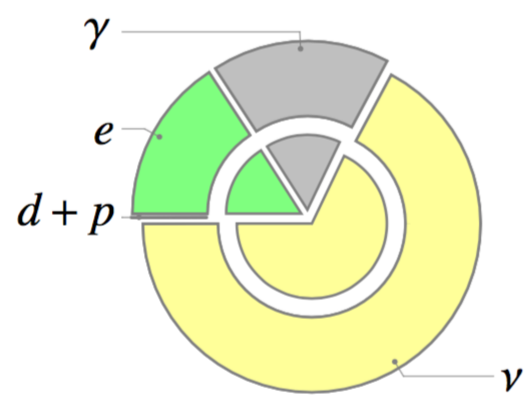
DM DM→ b+b



$E_{\gamma+e}/E_{\text{tot}} = 0.462\ (0.454)$

$E_{p+d}/E_{\gamma+e} = 0.159\ (0.198)$

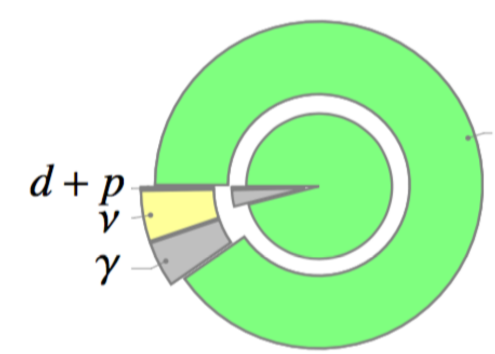
DM DM→ $\tau_R^- + \tau_R^+$



$E_{\gamma+e}/E_{\text{tot}} = 0.321\ (0.328)$

$E_{p+d}/E_{\gamma+e} = 0.000\ (0.001)$

DM DM→ $e_L^- + e_L^+$

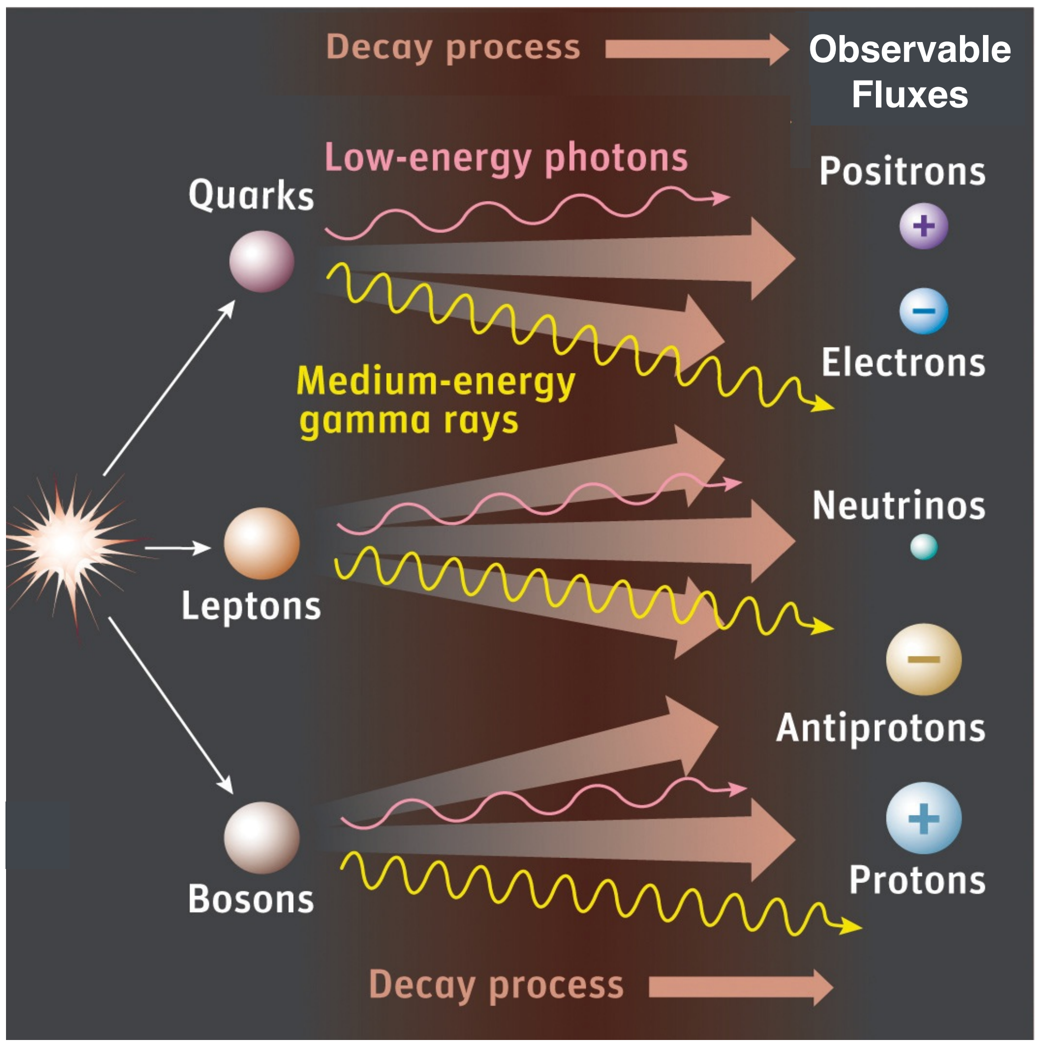


$E_{\gamma+e}/E_{\text{tot}} = 0.996\ (0.948)$

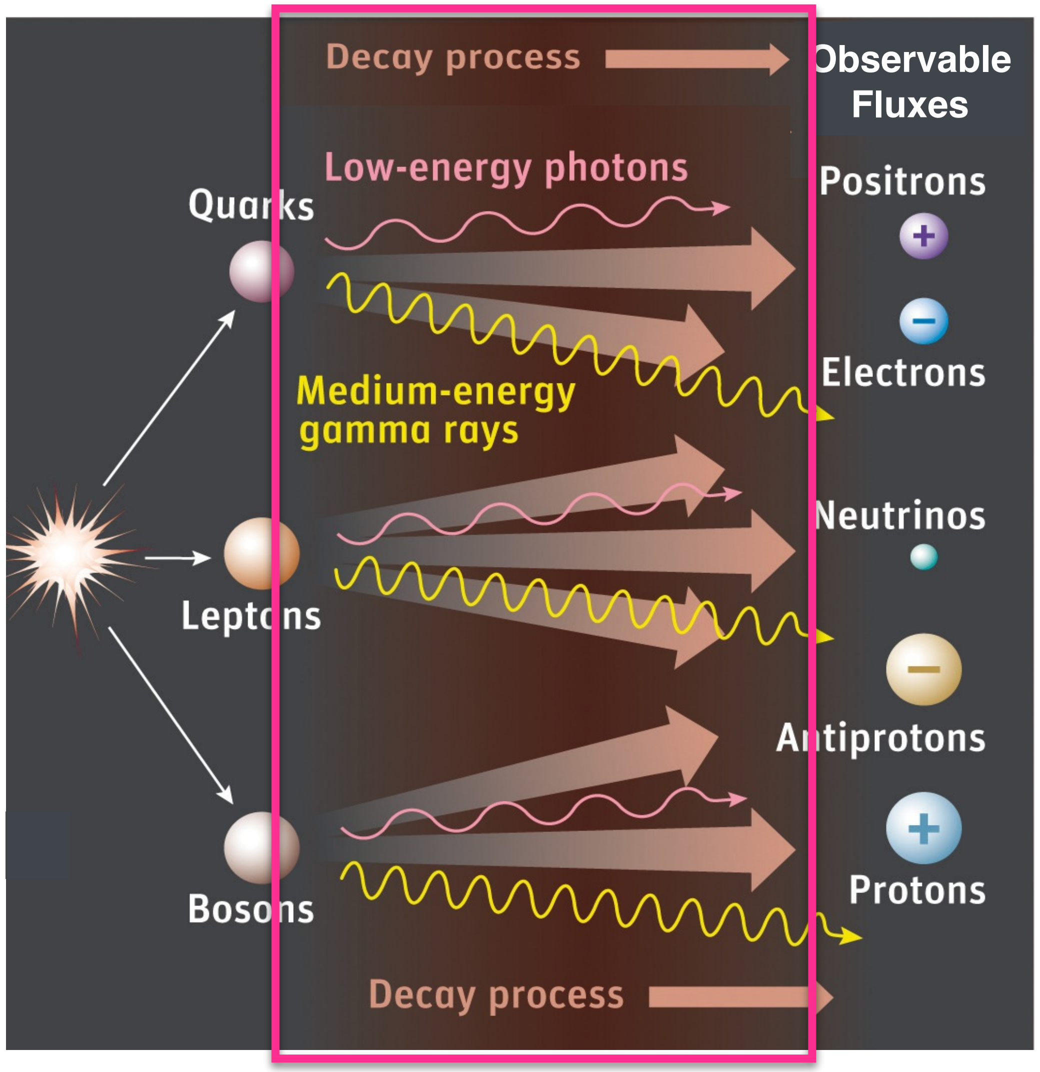
$E_{p+d}/E_{\gamma+e} = 0.000\ (0.002)$

- Energy fraction going into photons and electrons (±) with respect to the total.
- Energy fraction into hadronic final states with respect to photons and electrons.

Dark matter emitted radiation



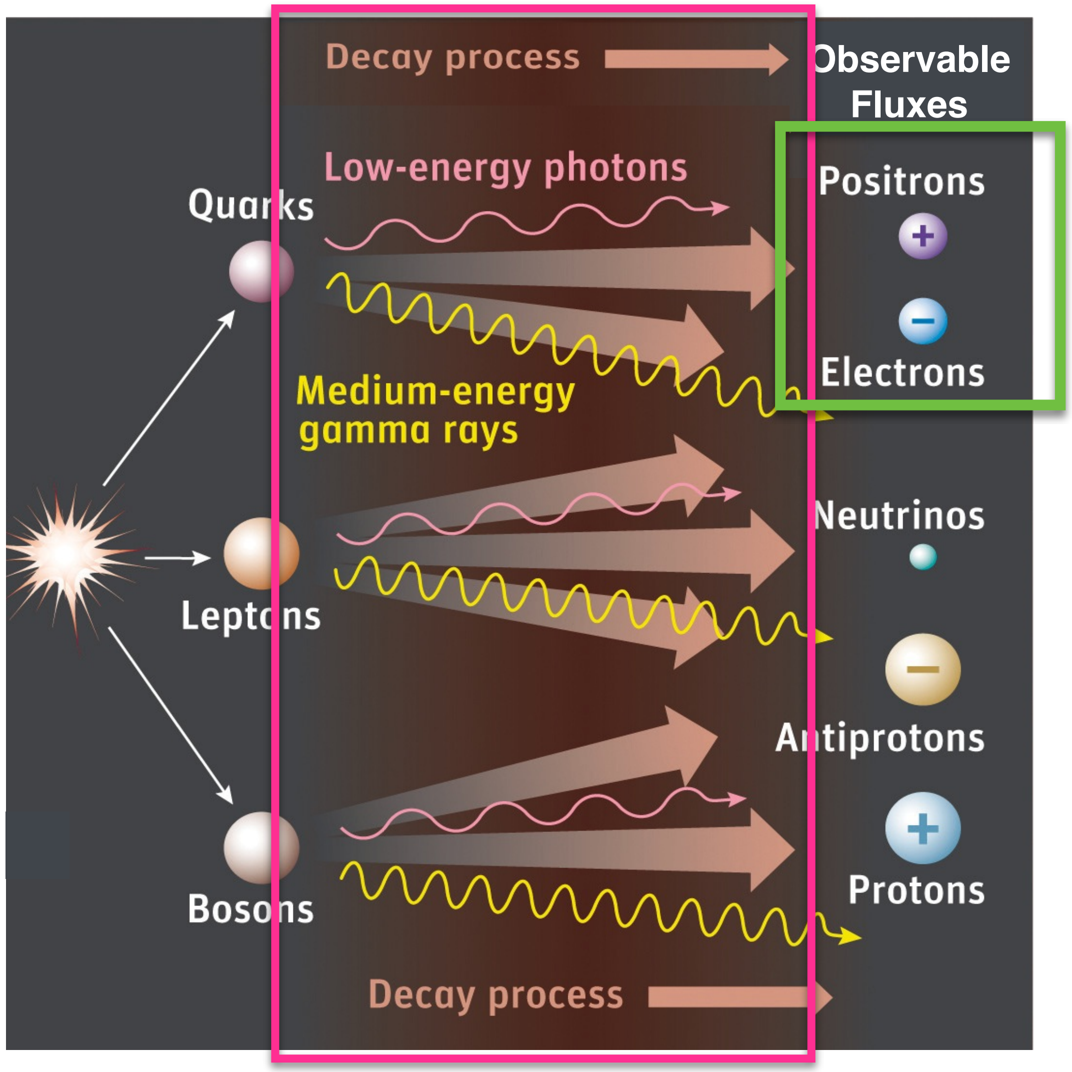
Dark matter emitted radiation



Prompt gamma-ray emission

- Production and decay of neutral pions
- Higher order radiative corrections
- Monochromatic line emission
- Other spectral features?

Dark matter emitted radiation



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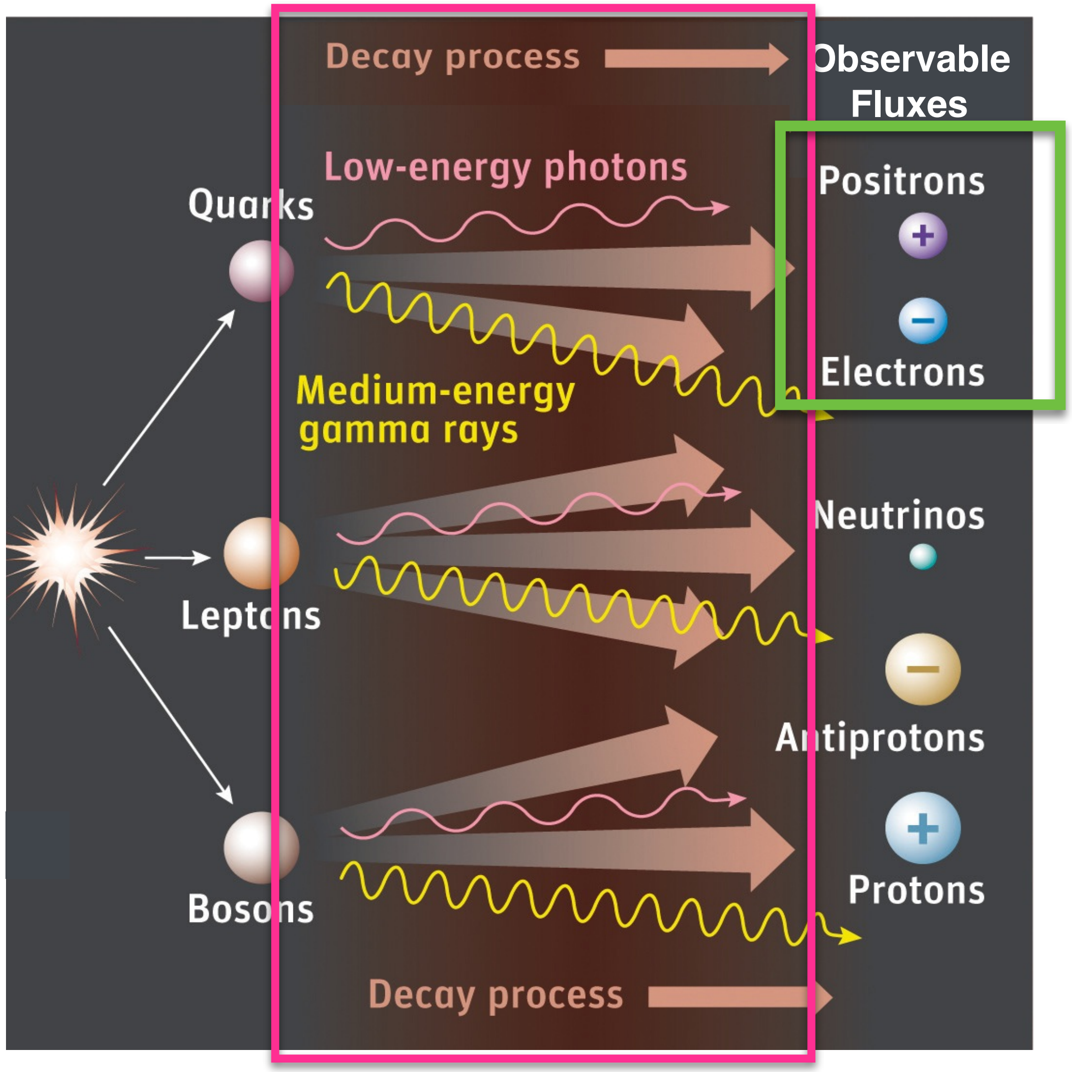
Radiative emission of electrons/positrons

- Inverse Compton scattering
- Synchrotron radiation
- Bremsstrahlung

Dark matter emitted radiation



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→ **Multiwavelength emission**

Dark matter source term

$$[\mathrm{GeV}^{-1}\mathrm{s}^{-1}]$$

Annihilation

$$Q_i^{\mathrm{ann}}(r,E) = \langle \sigma_{\mathrm{ann}} v \rangle \times N_{\mathrm{pairs}}(r) \times \sum_f B_f \frac{dN_i^f}{dE}(E)$$

$$N_{\mathrm{pairs}}(r) = s \times N(r) = s \times \frac{\rho^2(r)}{m^2} \qquad s = \left\{ \frac{1}{2}, \frac{1}{4} \right\}$$

Majorana (s = 1/2) Dirac (s = 1/4)

Decay

$$Q_i^{\mathrm{dec}}(r,E) = \Gamma_{\mathrm{dec}} \times N(r) \times \sum_f B_f \frac{dN_i^f}{dE}(E)$$

$$N(r) = \frac{\rho(r)}{m}$$

Gamma rays from radiative processes

$$Q_i^{\rm ann}(r,E) = \langle \sigma_{\rm ann} v \rangle \times N_{\rm pairs}(r) \times \sum_f B_f \frac{dN_i^f}{dE}(E)$$

Prompt emission

$$j_\gamma(E,r) = Q_\gamma(E,r)\, E$$

Gamma-ray emissivity

$$\phi_\gamma(E,\theta) = \frac{1}{E} \int_{l.o.s.} ds\, \frac{j_\gamma(E, r(s,\theta))}{4\,\pi}$$

Differential gamma-ray flux

Radiative emission

$$j_i(\nu, r) = 2 \int_{m_e}^{M_\chi} dE\, P_i(r, E, \nu)\, n_e(r, E)$$

$$S_i(\nu, \theta, \theta_d) = \int d\Omega' \exp\left(- \frac{\tan^2 \theta'}{2\, \tan^2 \theta_d} \right) \int_{l.o.s.} dI_i(\nu, s, \tilde{\theta})$$

Intensity

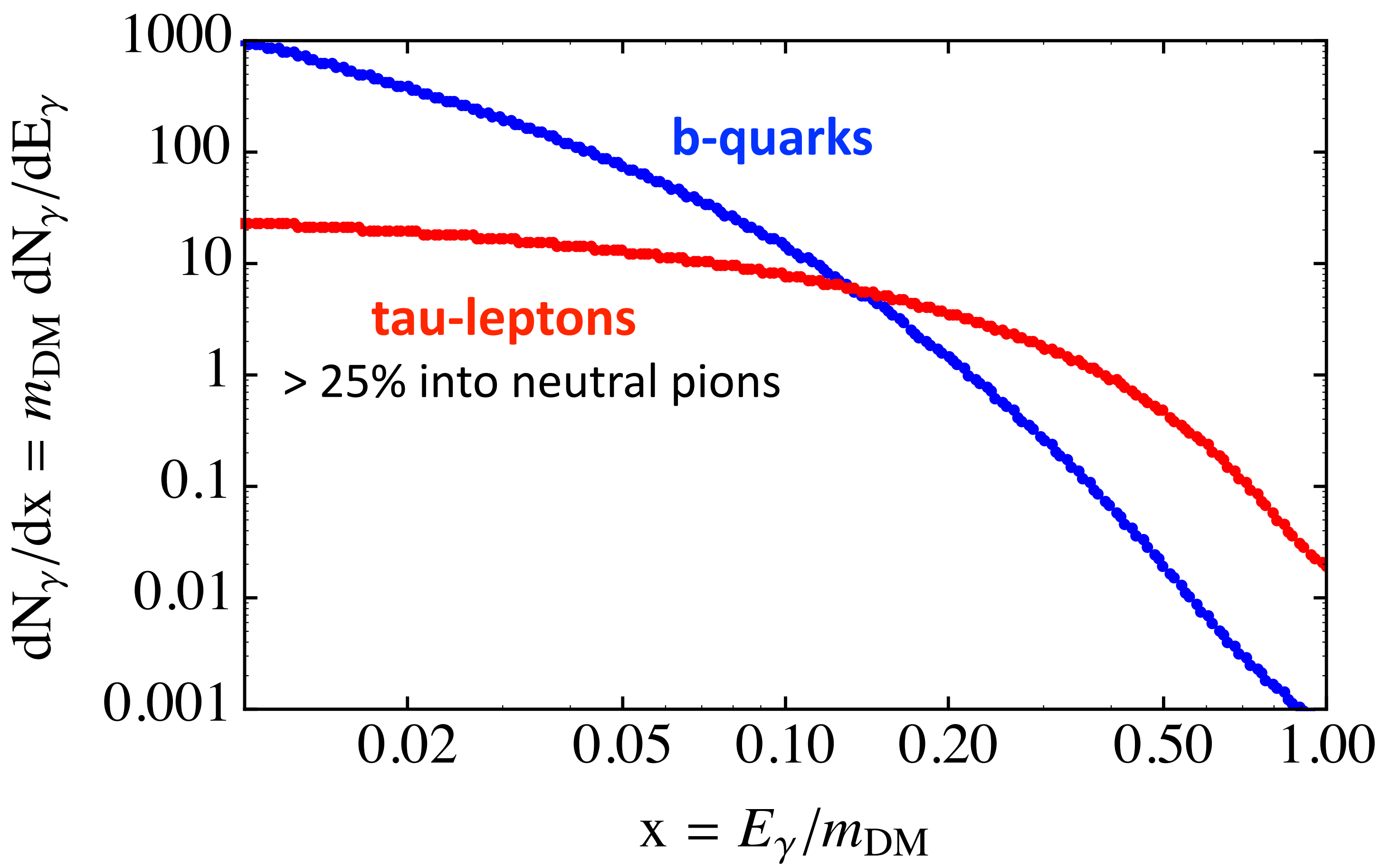
$$\frac{dI_i(\nu, s, \tilde{\theta})}{ds} = -\alpha(\nu, s, \tilde{\theta})\, I_i(\nu, s, \tilde{\theta}) + \frac{j_i(\nu, s, \tilde{\theta})}{4\pi}$$

Regis&Ullio, PRD'08

Spectra of prompt photons

$$Q_i^{\rm ann}(r,E) = \langle \sigma_{\rm ann} v \rangle \times N_{\rm pairs}(r) \times \boxed{\sum_f B_f \frac{dN_i^f}{dE}(E)}$$

100% Branching ratio (independent on PP model)



$$x \equiv \frac{E_X}{m_\chi}$$

$$\frac{dN_X}{dx} \equiv m_\chi \frac{dN_X}{dE}$$

Helicity suppression (Majorana DM)

Relevance of higher order corrections because of helicity suppression of two-body processes

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

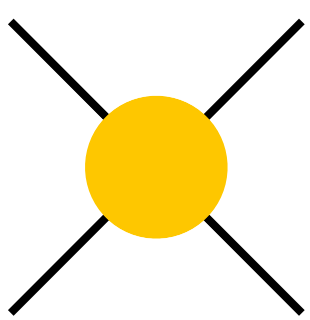
Non-relativistic regime: if present, s-wave is dominant

- The initial annihilating pair acts as a decaying pseudo-scalar particle, i.e.

$$J^P = 0^-$$

- Two-body annihilation into light fermion-antifermion pairs is helicity suppressed, i.e.

$$\langle \sigma v \rangle \propto m_f^2 / m_\chi^2$$



$\chi\chi \to f\bar{f}$

Yukawa and/or Isospin suppression

Bringmann,FC+ arXiv:1705.03466

… same as decay of charged pions

Helicity suppression

An example from SM physics: the decay of charged pions

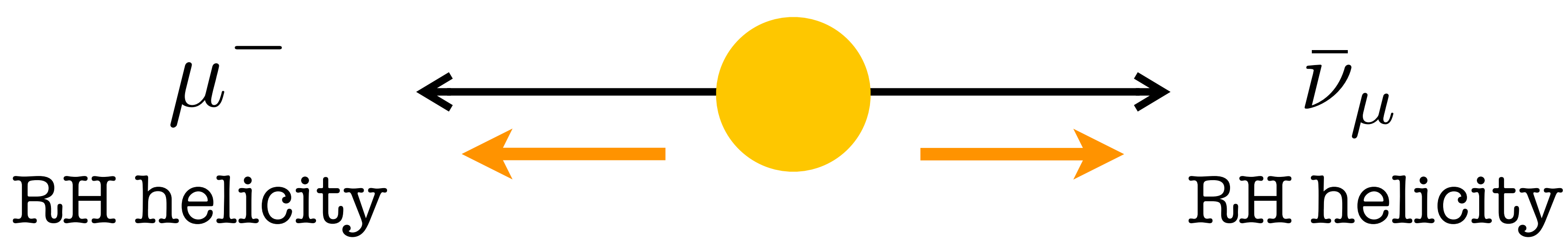
$$\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} \sim 10^{-4}$$

Helicity suppression

An example from SM physics: the decay of charged pions

$$\frac{\Gamma(\pi^- \to e^- \bar{\nu}_e)}{\Gamma(\pi^- \to \mu^- \bar{\nu}_\mu)} \sim 10^{-4}$$

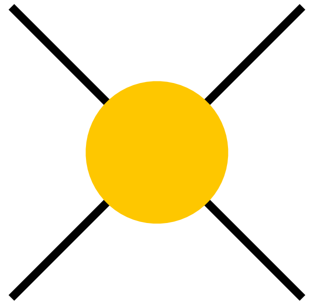
$$S_{\pi^-} = 0$$



Weak interactions couple only to
RH chiral anti-particles and LH chiral particles

$$\Gamma \propto m_f^2 / m_\pi^2$$

The relevance of radiative corrections



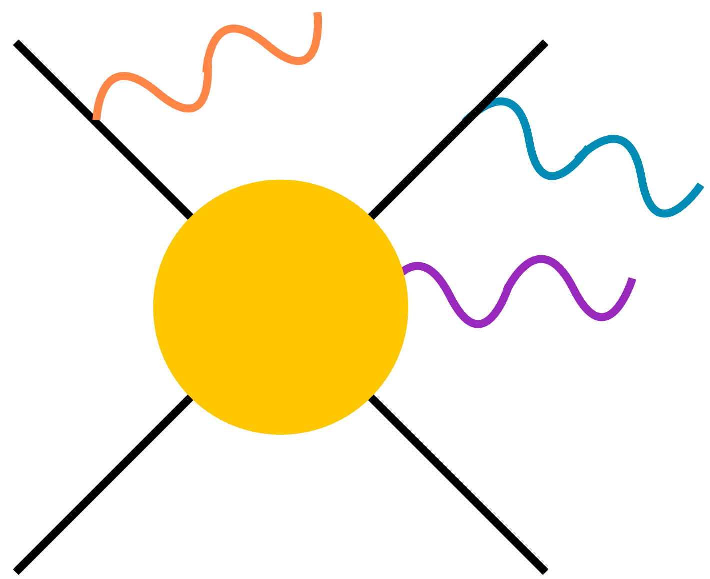
$$\chi\chi \to f\bar{f}$$

$$\langle\sigma v\rangle \propto m_f^2/m_\chi^2$$

The emission of an **additional boson in the final state** may overcome this suppression, **lifting of the helicity suppression**

$$\chi\chi \to f\bar{F}B$$

$$B = \gamma, Z, W^{\pm}, h, g$$



$$\langle\sigma v\rangle \propto \cancel{\frac{m_f^2}{m_\chi^2}}\,\frac{\alpha}{\pi}$$

$$\langle\sigma v\rangle_{3-\text{body}} \gg \langle\sigma v\rangle_{2-\text{body}}$$

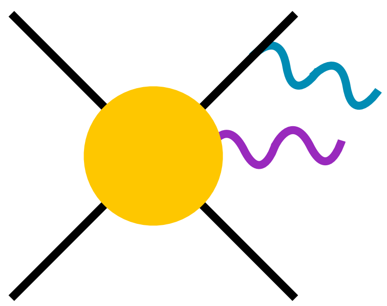
[Photon: *Bergström+ PLB'89; Flores+ PLB'89*

Z/W: *Bell+ PRD'11; Ciafaloni+ JCAP'10; Garny+ JCAP'11; Bringmann&FC, PRL'13*

Gluon: *Asano+ PLB'13; Garny+ JCAP'12*

Higgs: *Luo&You, JCAP'13; Kumar+ PLB'16; Bringmann,FC+ arXiv:1705.03466*]

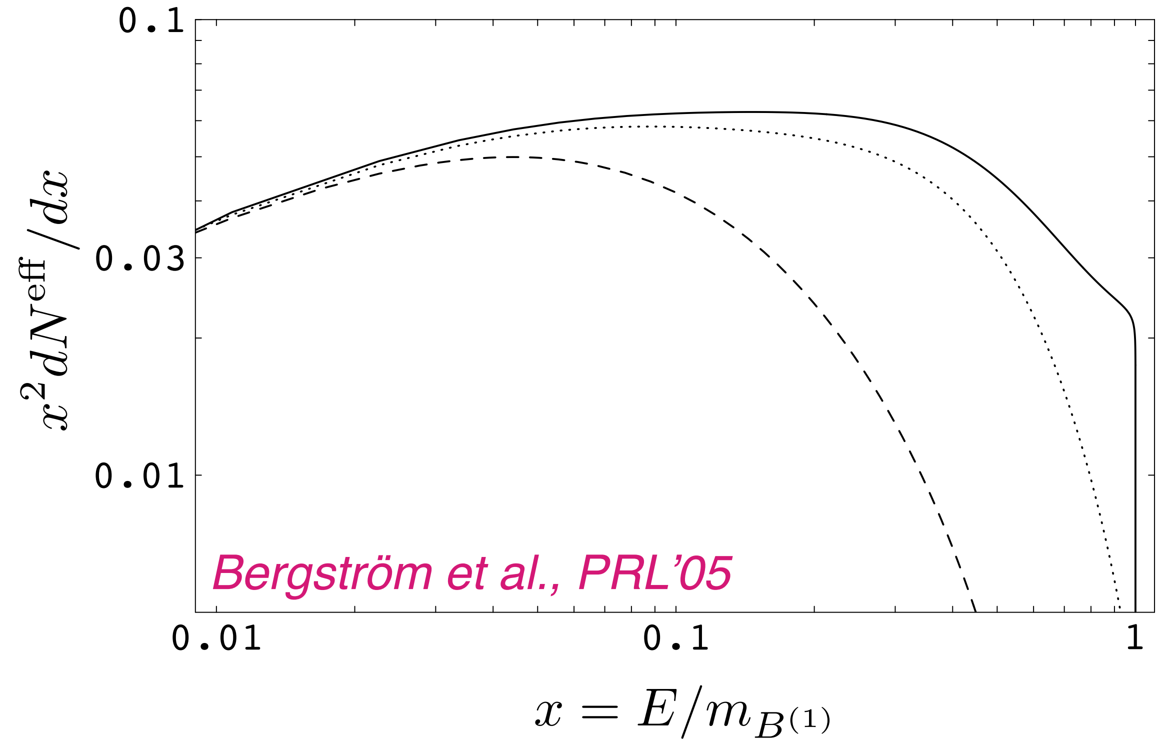
Electromagnetic corrections



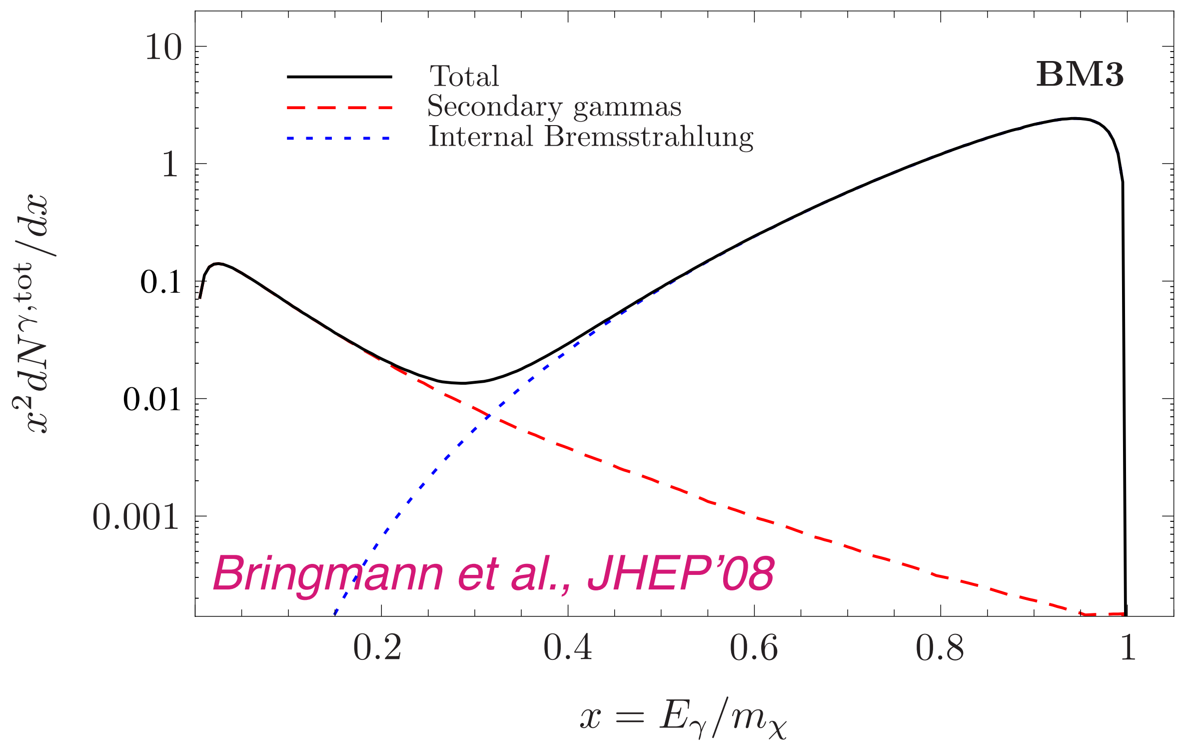
$\chi\chi \to f\bar{f}\gamma$

- **FSR**: logaritmich enhancement of soft collinear photons (fermion on-shell) => **model-independent** spectrum
  Birkedal et al., hep-ph/0507194
- **VIB**: lifiting of helicity suppression in t-channel diagrams => **model-dependent** spectrum
  Bergström et al., PRL'05; Bringmann et al., JHEP'08

Lightest Kaluza-Klein Particle



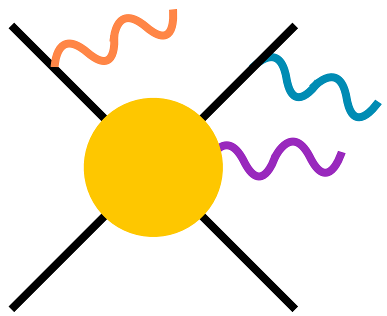
Neutralino in stau-coannihilation region



Sharp spectral features at the high-end of the photon energy distribution

[Emission of W, Z, higgses => multi-messenger signal, opens up new channels *Ciafaloni et al., JCAP'11; Cirelli et al., JCAP PPPC4DMID; Bringmann&Calore PRL'13; Kumar+ PLB'13; Bringmann,FC+ arXiv:1705.03466; etc*]

Electroweak and Higgs corrections



$$\chi\chi \to f\bar{F}B$$
$$B = Z, W^{\pm}, h$$
$$[A, H, H^{\pm}]$$

- Emission of W, Z, higgses => multi-messenger signal, opens up new channels

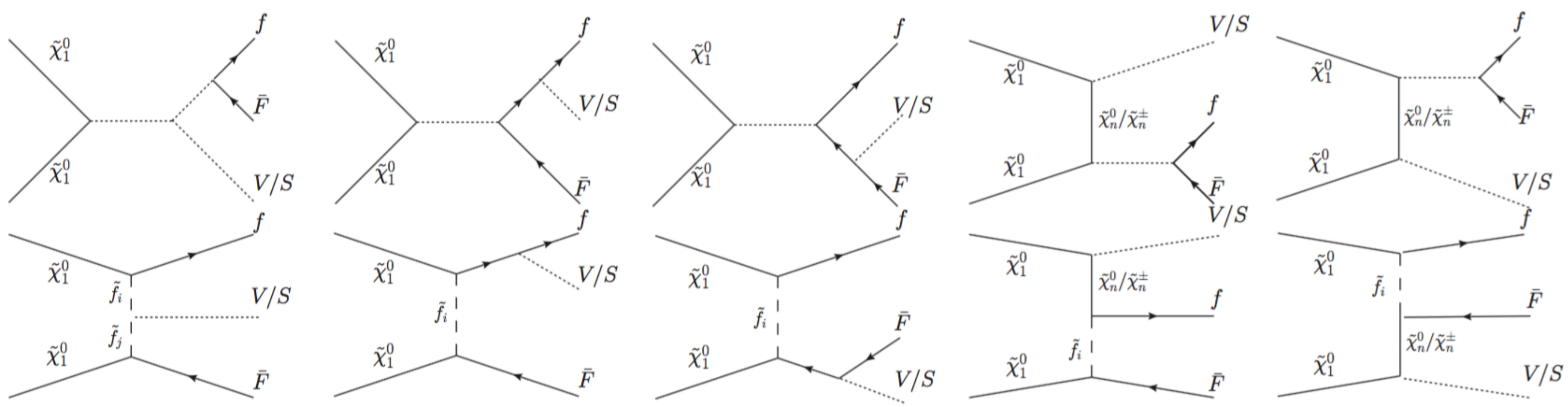
Kalchelriess et al., PRD'09

- **FSR**: soft collinear emission modelled by splitting functions => **model-independent** spectrum, sizeable changes at low enegies.

Ciafaloni et al., JCAP'11; Cirelli et al., JCAP'11; PPPC4DMID

- **VIB/ISR**: lifiting of helicity suppression => **model-dependent** spectrum

Ciafaloni+ JCAP'11/12; Bell+ PLB'11/PRD'11; Garny+ JCAP'11/12; Shudo&Nikei PRD'13; Bringmann&Calore PRL'13; Kumar+ PLB'13

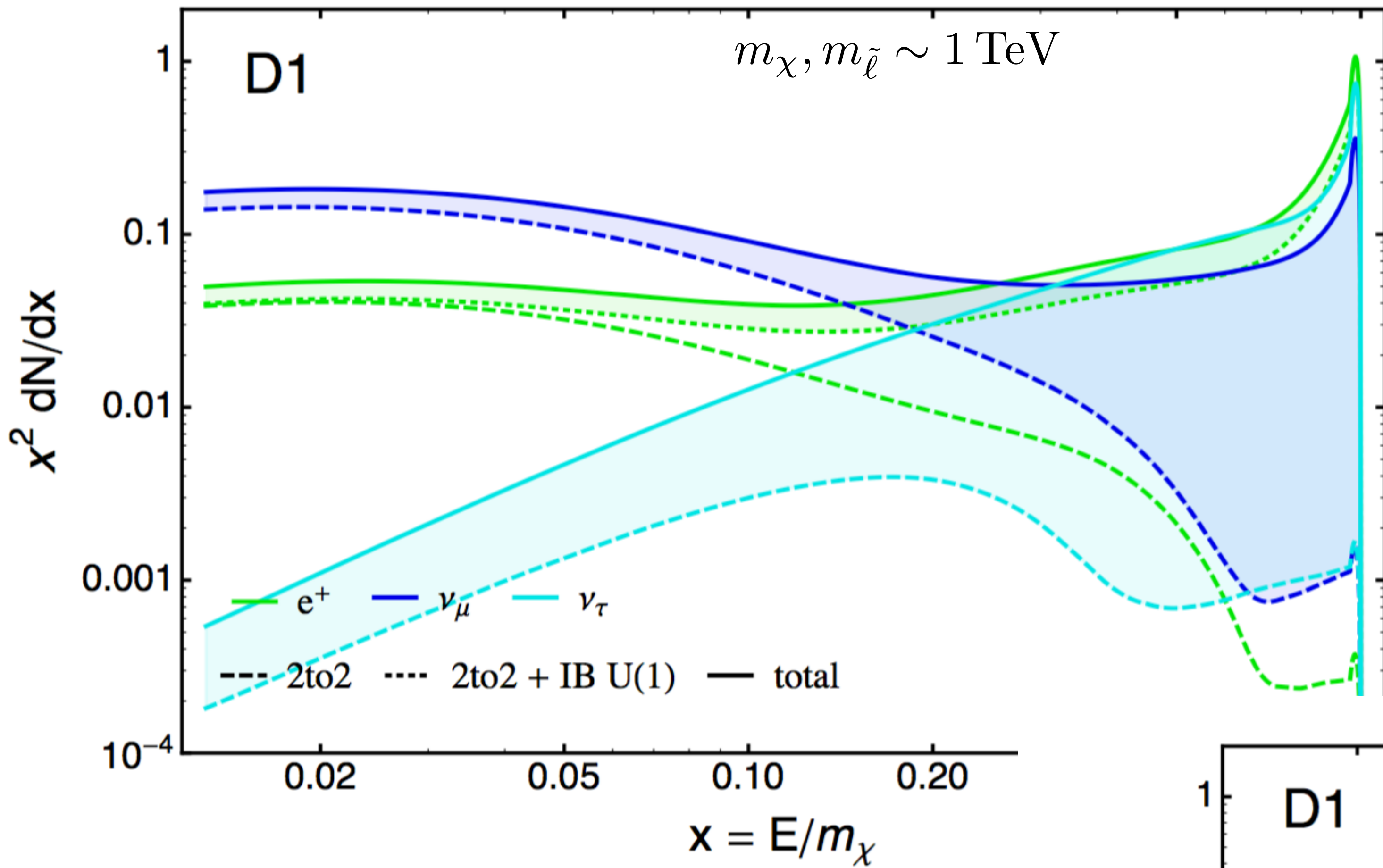


Bringmann&FC PRL'13
Bringmann,FC+ arXiv:1705.03466

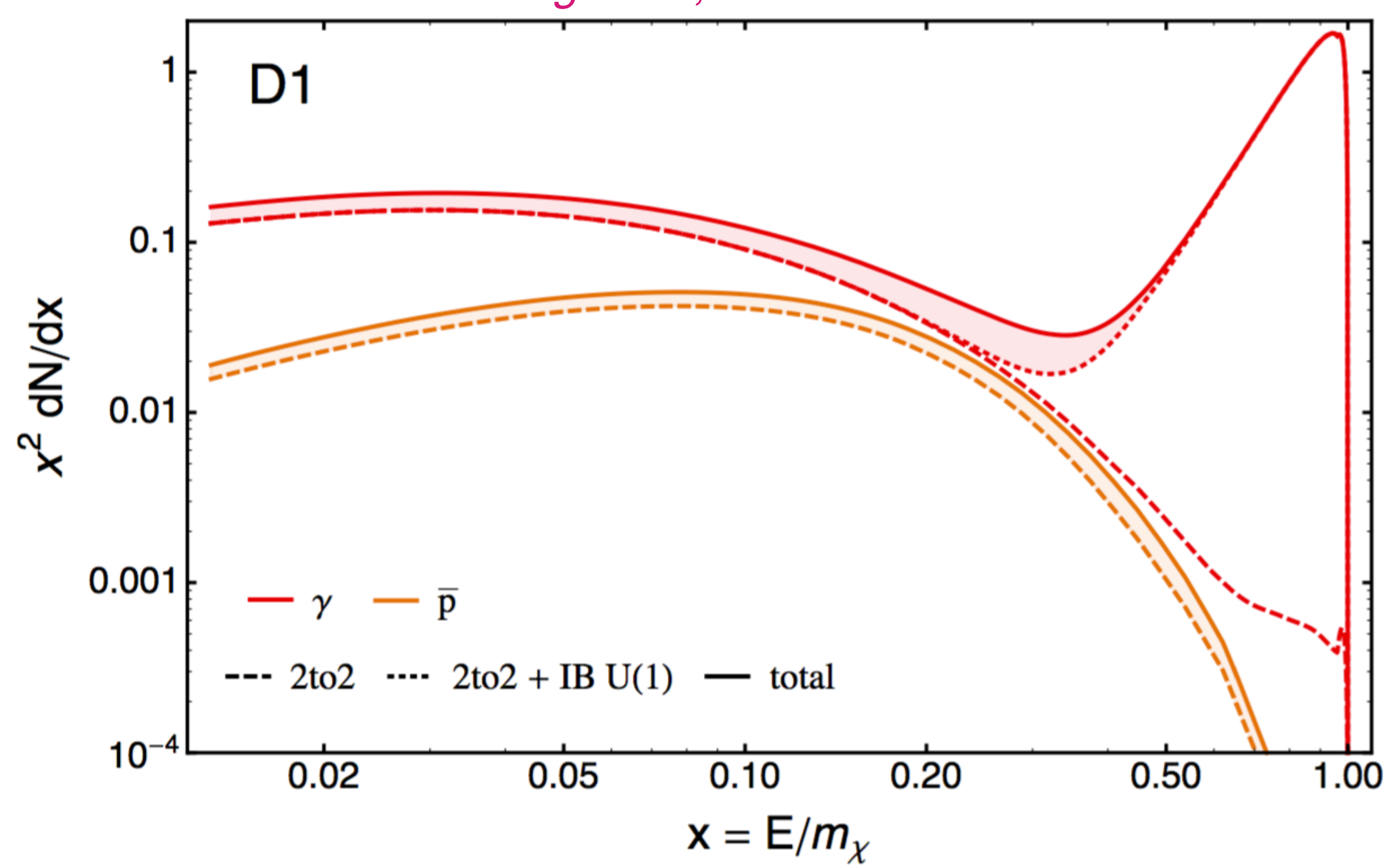
Full computation of Z, W and Higgses corrections for general Majorana dark matter and application to MSSM neutralinos

$$\chi\chi \to W^{+}\bar{F}f, Z\bar{f}f, H^{+}\bar{F}f, A\bar{f}f, H\bar{f}f, h\bar{f}f$$

Model-dependent spectral modifications



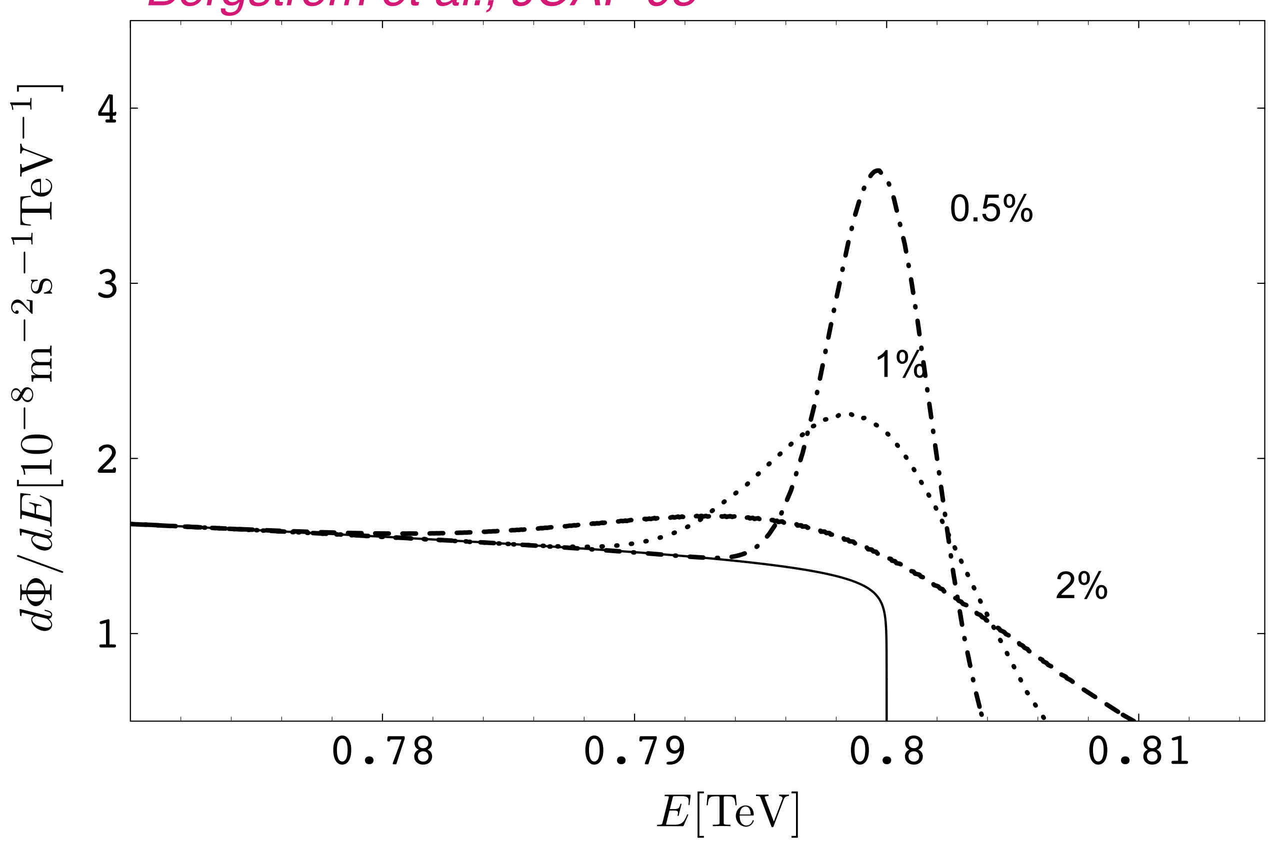
Bringmann,FC+ arXiv:1705.03466



Gamma-ray monochromatic lines

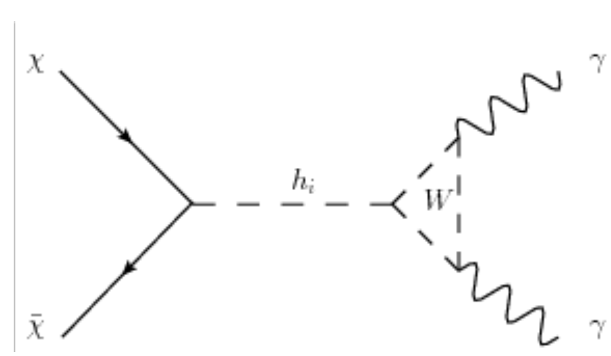
A **spectral feature** indicates an abrupt change of the gamma-ray flux as a function of energy, typically expected at the kinematic endpoint of the spectrum => **Smoking gun DM signature**

Bergström et al., JCAP'05



Gamma-ray line from loop suppressed direct annihilation into

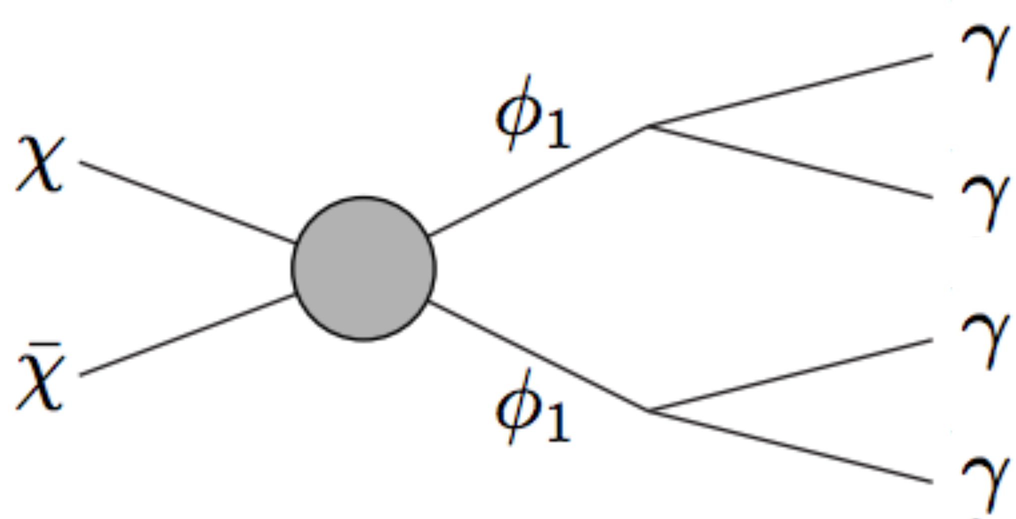
$$\gamma\gamma, Z\gamma, H\gamma \qquad E_\gamma = m_\chi\left(1 - \frac{m_P^2}{4m_\chi^2}\right)$$



NB: The direct DM-photon coupling is forbidden being DM a neutral particle (as neutrinos)

Box-shaped gamma-ray features

Mardon+ JCAP'09



Photons from cascade decays of light particle mediators.

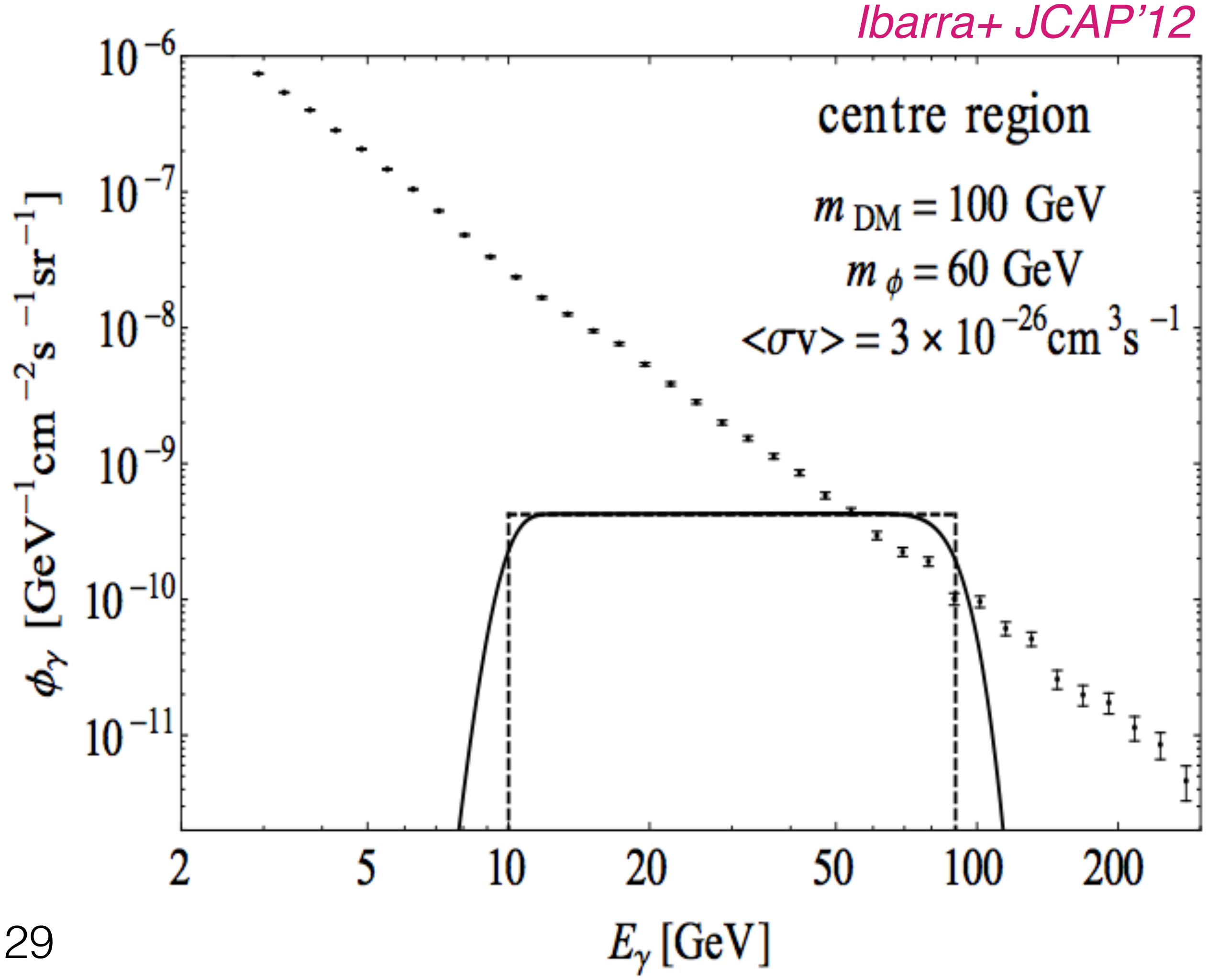
Isotropic photon emission

$$\frac{dN_\gamma}{dE_\gamma} = \frac{4}{\Delta E}\Theta(E - E_-)\Theta(E_+ - E)$$

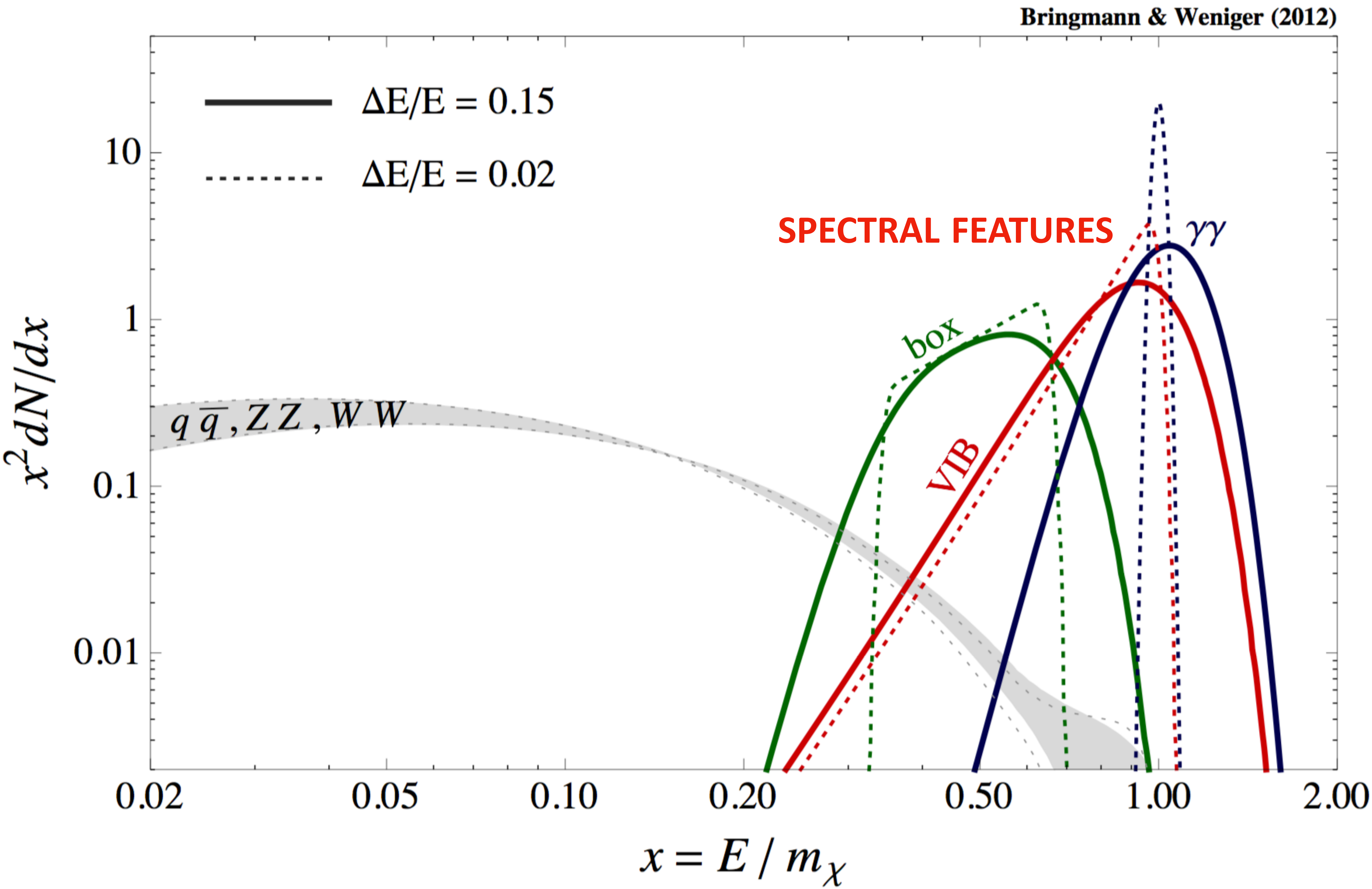
$$E_\pm = (m_{DM}/2)\left(1 \pm \sqrt{1 - m_\phi^2/m_{DM}^2}\right)$$

$$\Delta E = E_+ - E_- = \sqrt{m_{DM}^2 - m_\phi^2}$$

Ibarra+ JCAP'12



The prompt photon emission



How to…

Analytical fitting functions:

Fornengo, Pieri, Scopel, PRD 2004

Cembranos et al., PRD 2011

Numerical codes for computation of DM spectra:

DarkSUSY http://www.fysik.su.se/~edsjo/darksusy/

Gondolo+ JCAP'04

MicrOMEGAs https://lapth.cnrs.fr/micromegas/

Belanger+ JCAP'05

PPC 4 DM ID http://www.marcocirelli.net/PPPC4DMID.html

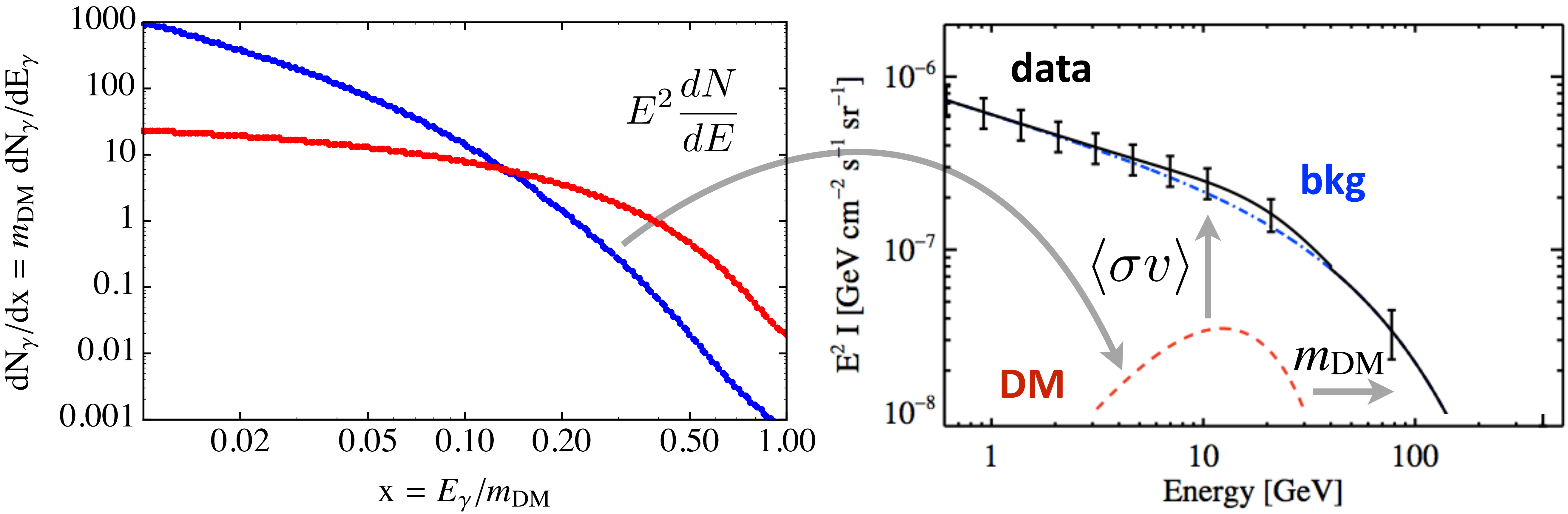
Cirelli+ JCAP 2012

For dependence on event Monte Carlo generators see, e.g.,

Cembranos+ JHEP'13

DM gamma-ray flux

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

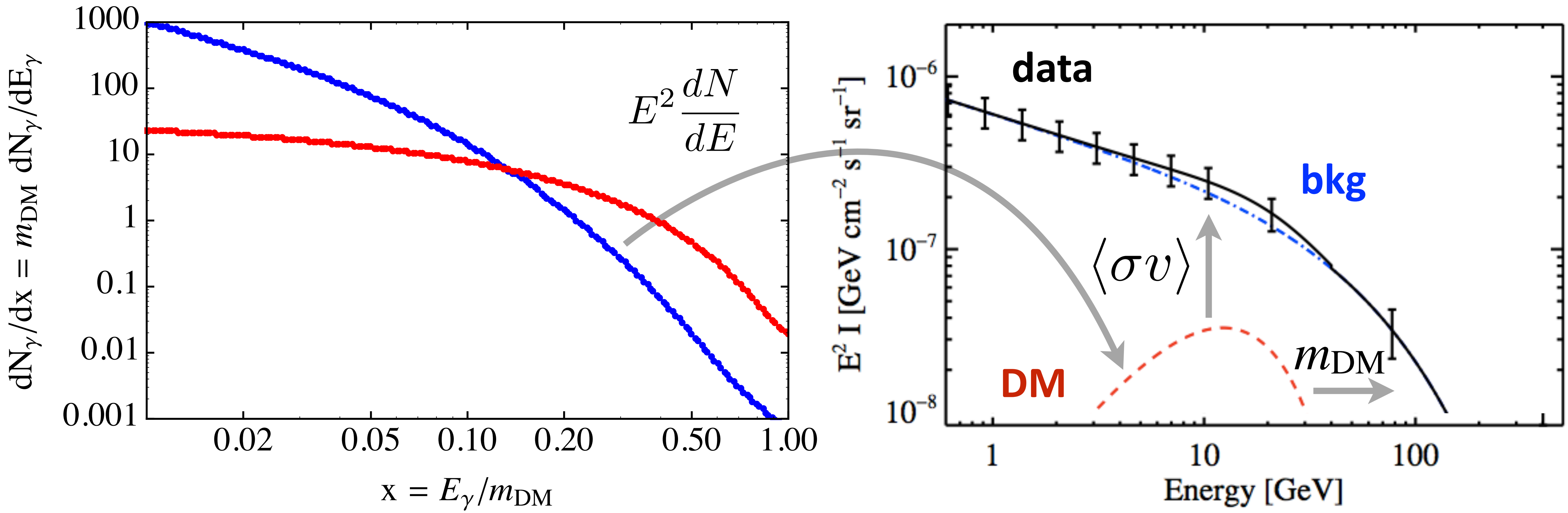


[Be careful! This equation holds in the s-wave approximation, i.e. of velocity dependent cross-section]

DM gamma-ray flux

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

Astrophysical J-factor



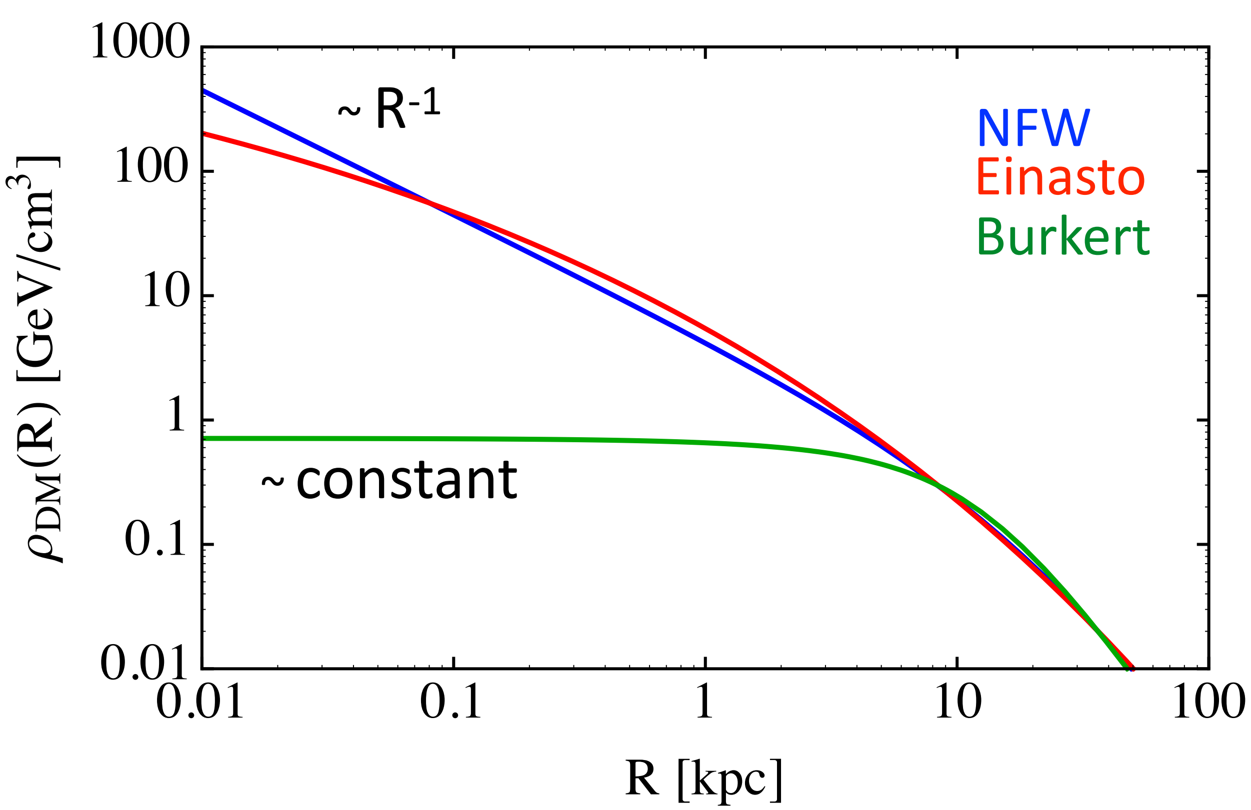
The overall intensity of the signal also crucially depends on the distribution of dark matter

The dark matter distribution

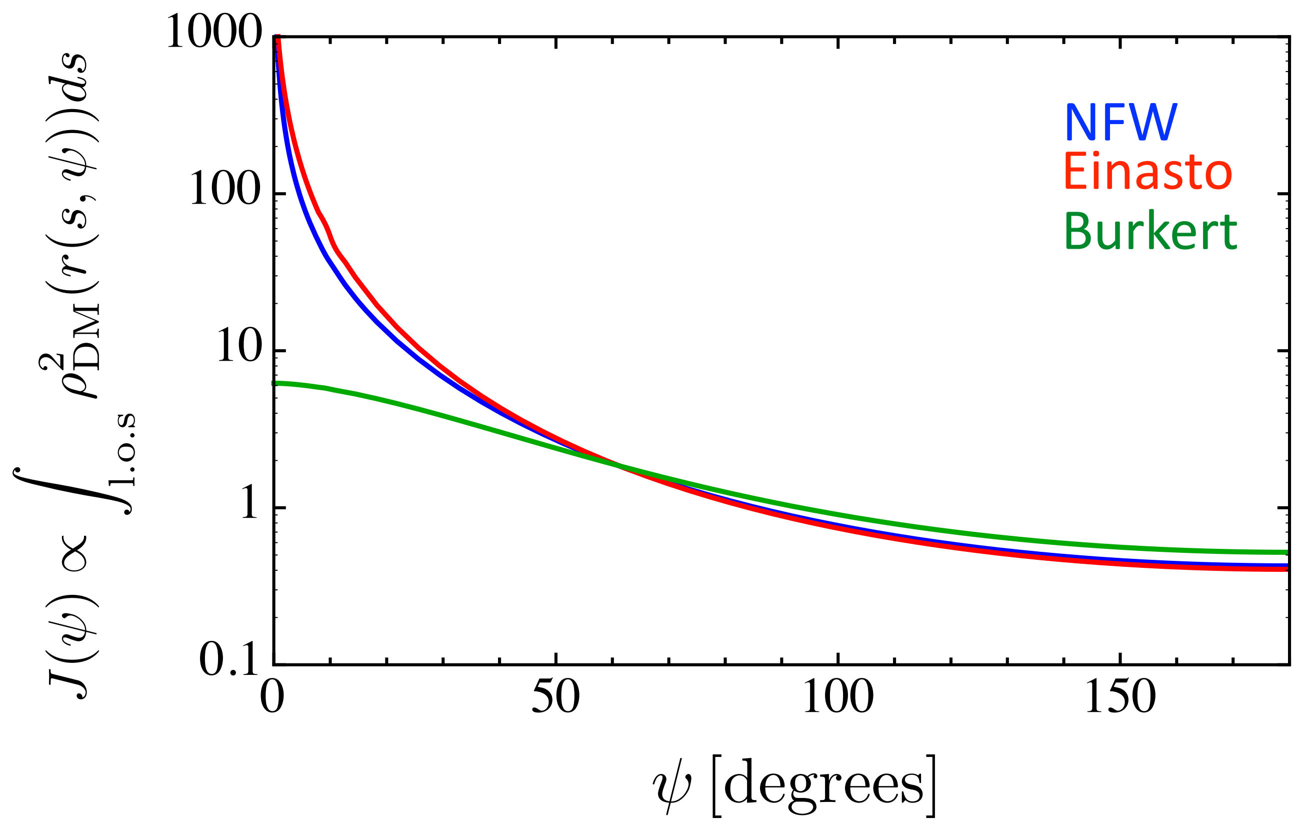
$$\int_0^{\Delta\Omega} d\Omega \int_{\mathrm{l.o.s}} \rho^2_{\mathrm{DM}}(s)ds$$

Astrophysical J-factor

Dark matter density profiles:

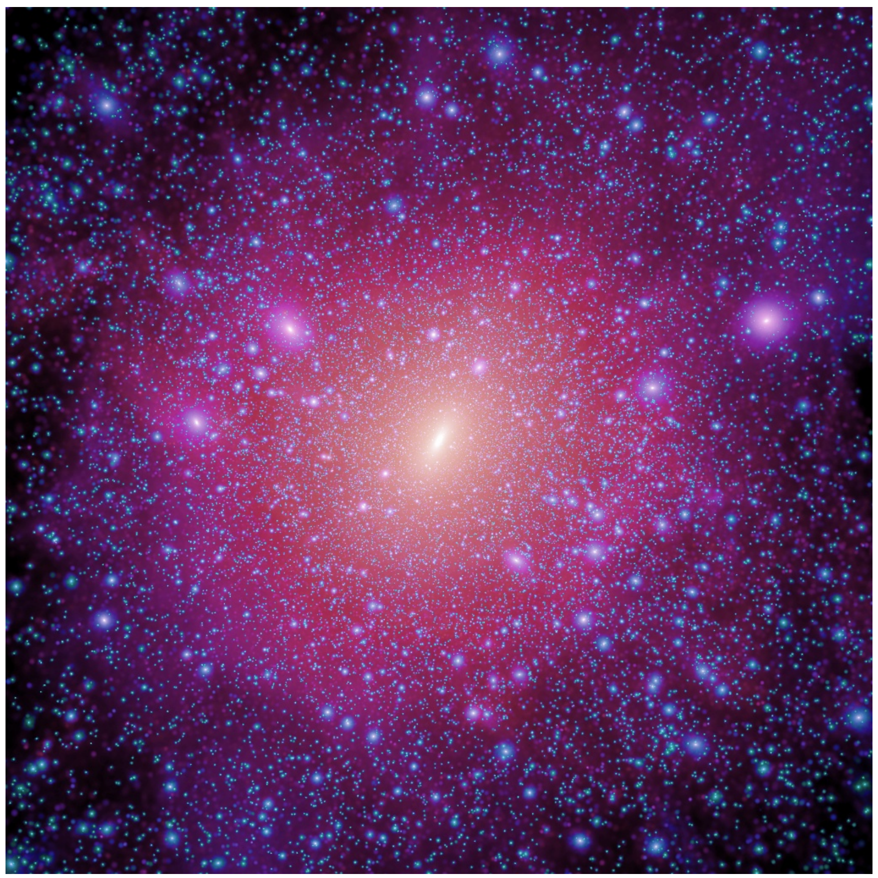


Spatial distribution of the signal:



The dark matter spatial distribution

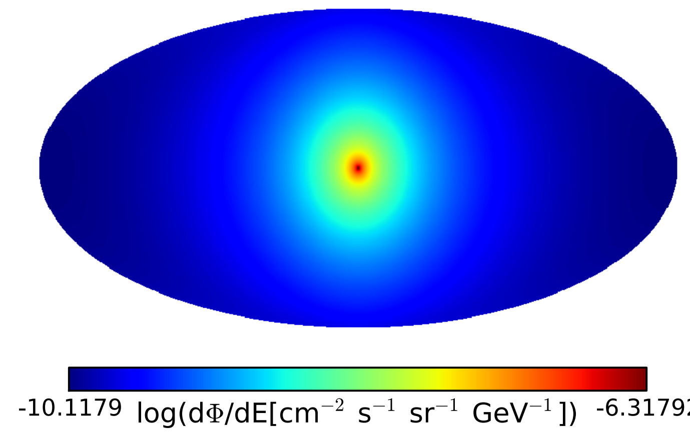
Aquarius DM N-body simulation



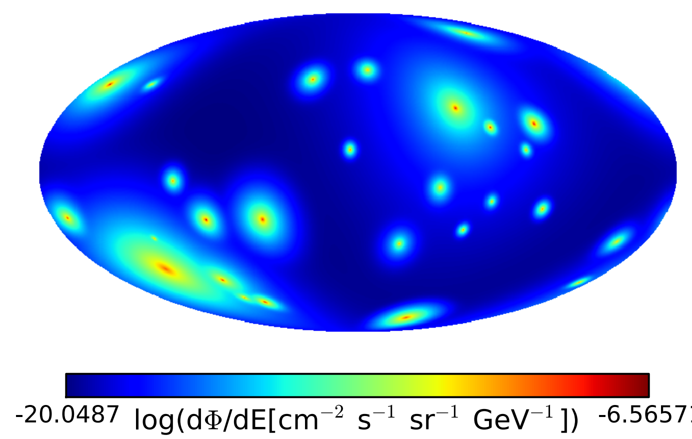
Springel+ MNRAS'08

Expected gamma-ray flux

Main halo



Sub-haloes



Calore+ MNRAS'14

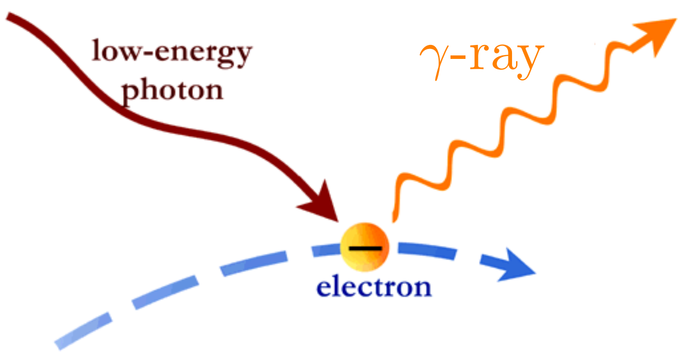
SPATIAL (ANGULAR) FEATURES

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

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

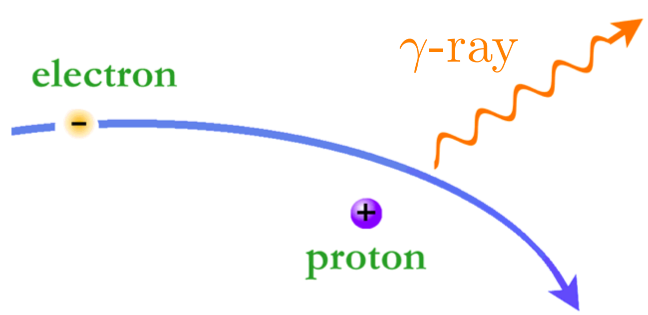
Radiative emission from leptons

$$\chi\chi \to \left\{ \begin{array}{r} ZZ,\, W^+W^-,\, \gamma\gamma \\ q\bar{q},\, l^+l^-,\, \nu\bar{\nu} \end{array} \right\} \xrightarrow[\text{decays}]{\text{hadronization}} \gamma,\, e^\pm,\, \mu^\pm,\, p/\bar{p},\, \pi^\pm,\, \nu/\bar{\nu},\, \ldots$$



Inverse Compton scattering

on CMB, star-light, infrared-light



Bremsstrahlung

onto gas of interstellar medium

Synchrotron radiation

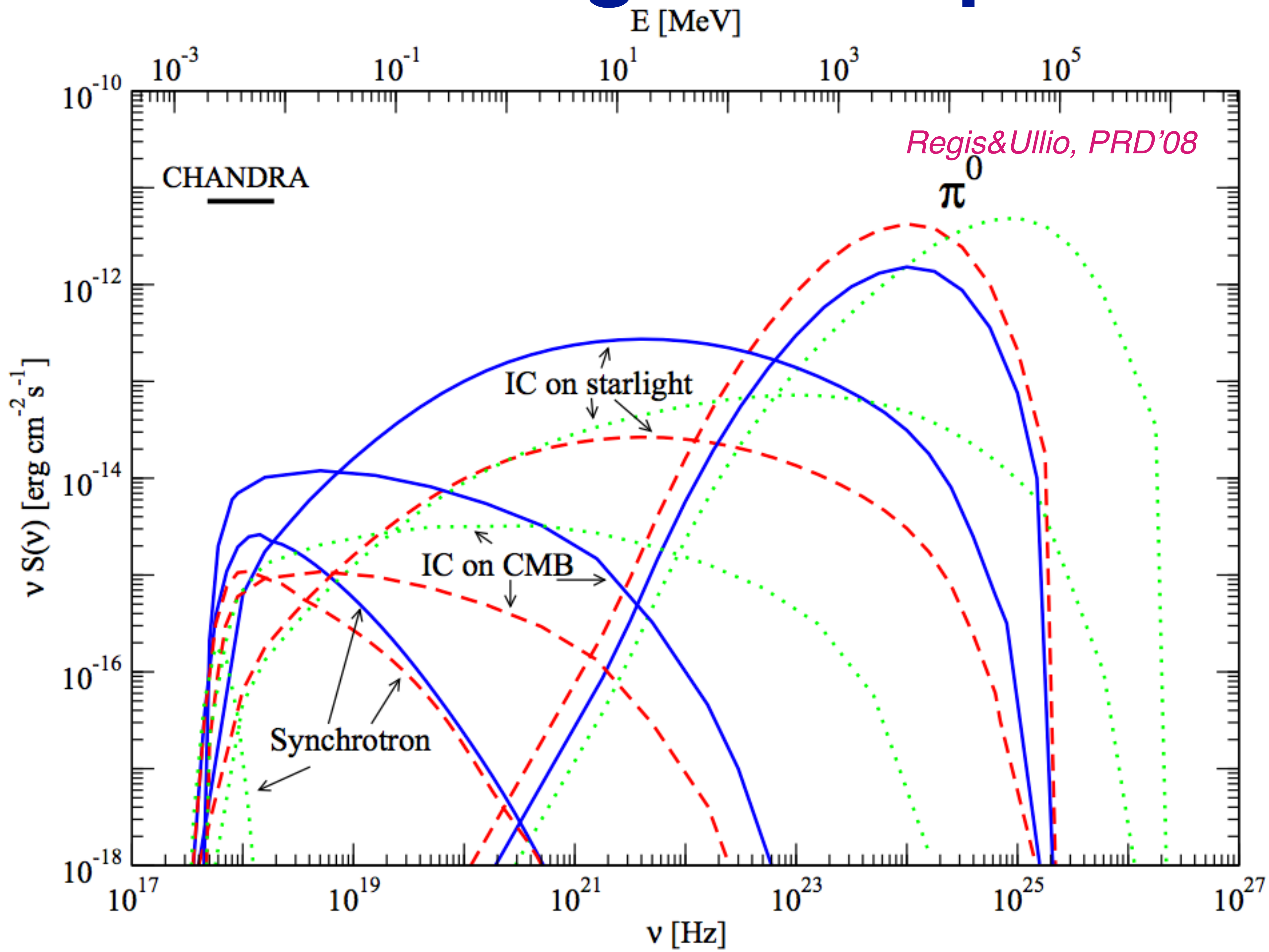
magnetic field $\mathcal{O}(\mu\text{Gauss})$

for $e^\pm$ of GeV-TeV

—> MHz-GHz radio signal

G. Rybicki and A.P. Lightman, 1979, 'Radiative Processes in Astrophysics', John Wiley & Sons Inc.
M. S. Longair, 2011, 'High Energy Astrophysics', Cambridge University Press.

Multi-wavelength DM spectrum



Multi-wavelength spectrum from radio to gamma-ray given by the **prompt** and **secondary** DM-induced emissions.

Feature-based searches

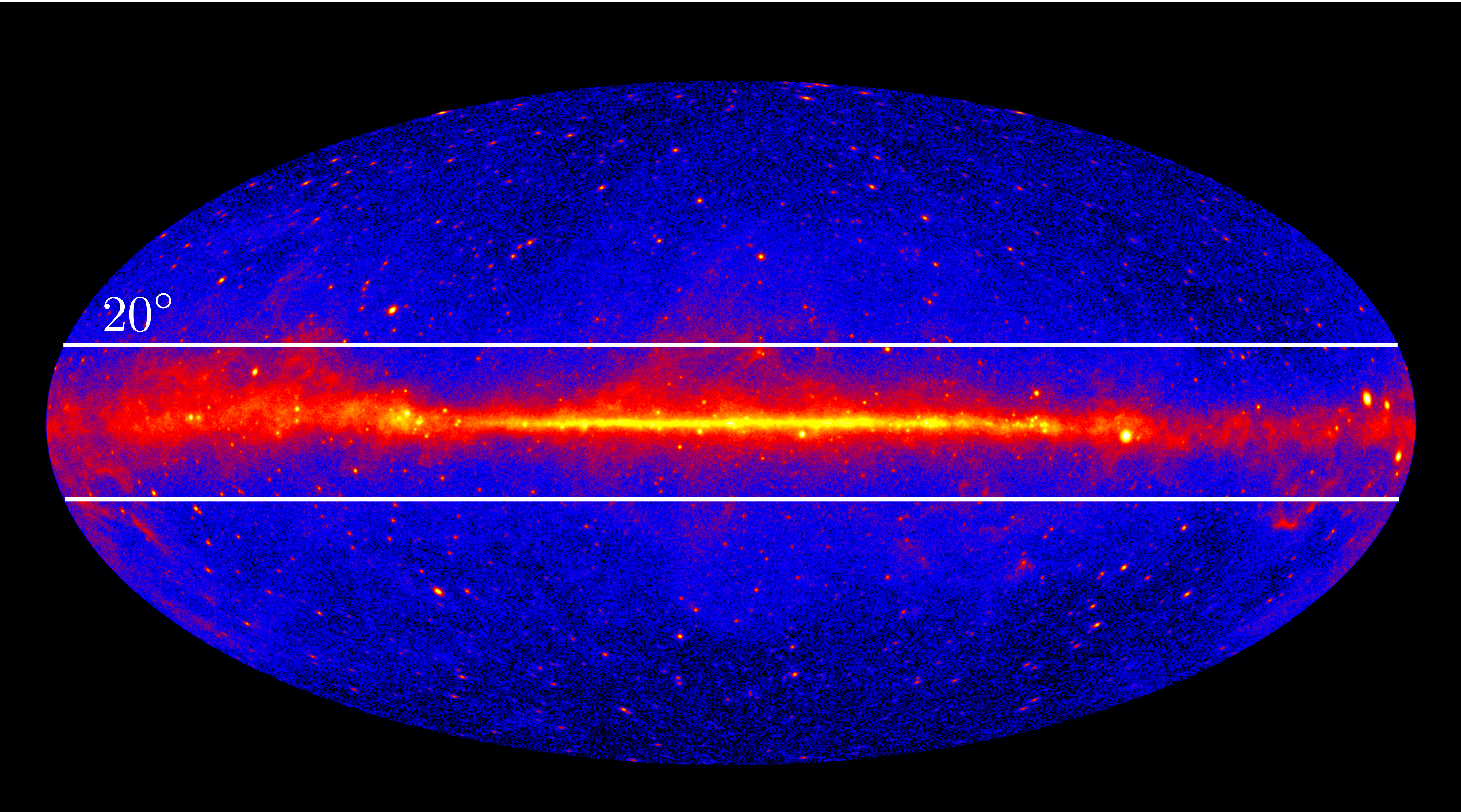
Different WIMP searches leverage on different WIMP (generic) features

- Generally, the signal looks like a smooth bump (from decay/hadronization products) from the main, smooth, Galactic halo => Importance of astrophysical background modelling
- Spectral features: look for sharp (or less sharp) features at the high-end of the energy spectrum
- Spatial (angular) features: look for specific DM-dominated targets and/or for angular correlations in the sky (anisotropies/cross-correlation)

1. Searches for DM in the isotropic diffuse gamma-ray background
2. Searches for DM gamma-ray lines
3. Searches for DM towards dwarf spheroidal galaxies and dark subhaloes

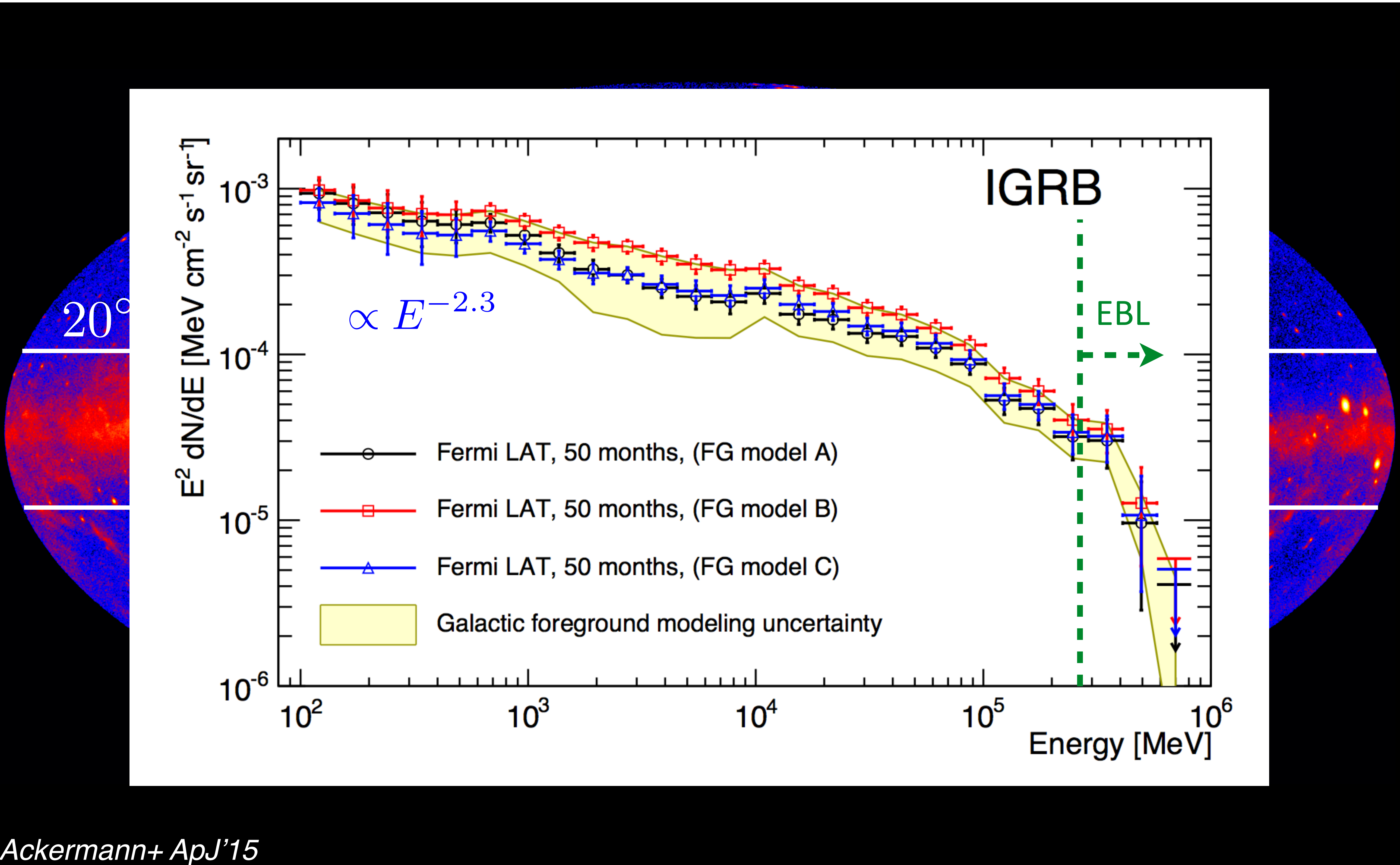
Searches at high latitudes: the IGRB

The high-latitude Fermi-LAT sky



Ackermann+ ApJ'15

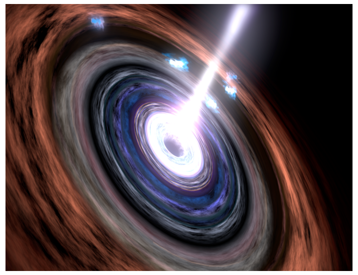
The high-latitude Fermi-LAT sky



Ackermann+ ApJ'15

The origin of the IGRB

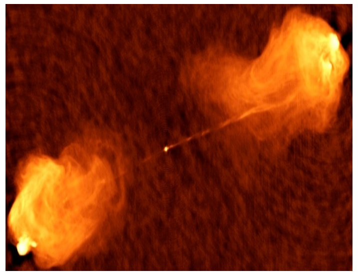
Unresolved Point Sources



Blazars

Most abundant and very bright sources; ca. 20%

Abdo+ ApJ'10; Ajello+ ApJ'12,'14,'15; Di Mauro+ ApJ'13



Mis-aligned active galaxies

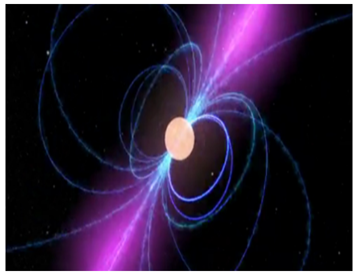
Less bright, few detected sources; ca. 25%

Inoue ApJ'11; Di Mauro, Calore+ ApJ'13

Star-forming galaxies

Large number density, a few detected objects; ca. 10% - 50%

Ackermann+ ApJ'14; Tamborra+ JCAP'14

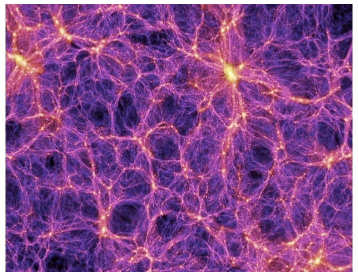


Galactic (Millisecond) Pulsars

Second most abundant population; < 1%

Faucher-Giguère+ JCAP'09; Gaskins+ MNRAS'11; Calore+ ApJ'14

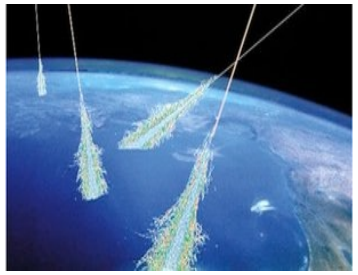
Diffuse Processes



Dark matter

Galactic and cosmological

e.g. Fornasa+ MNRAS'13



UHECRs

Cascade from interaction with CMB; ca. 1% - 50%

Kalashev+ PRD'09; Berezinsky+ PLB'10

Clusters of galaxies

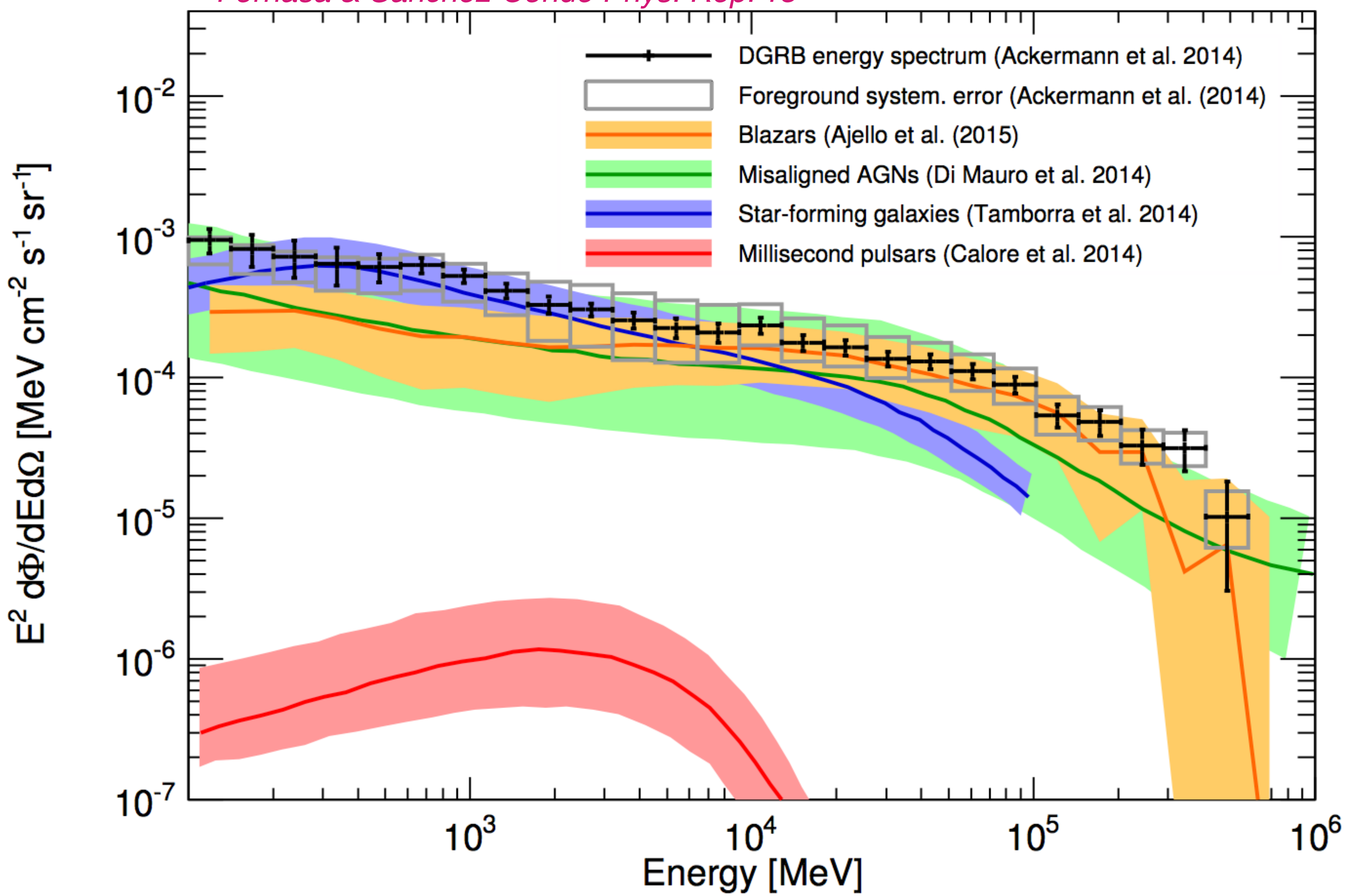
CR acceleration from shock waves, no gamma-ray emission, radio counterpart; < 1%

Keshet+ ApJ'03; Zandanel&Ando MNRAS'14; Zandanel+ A&A'15

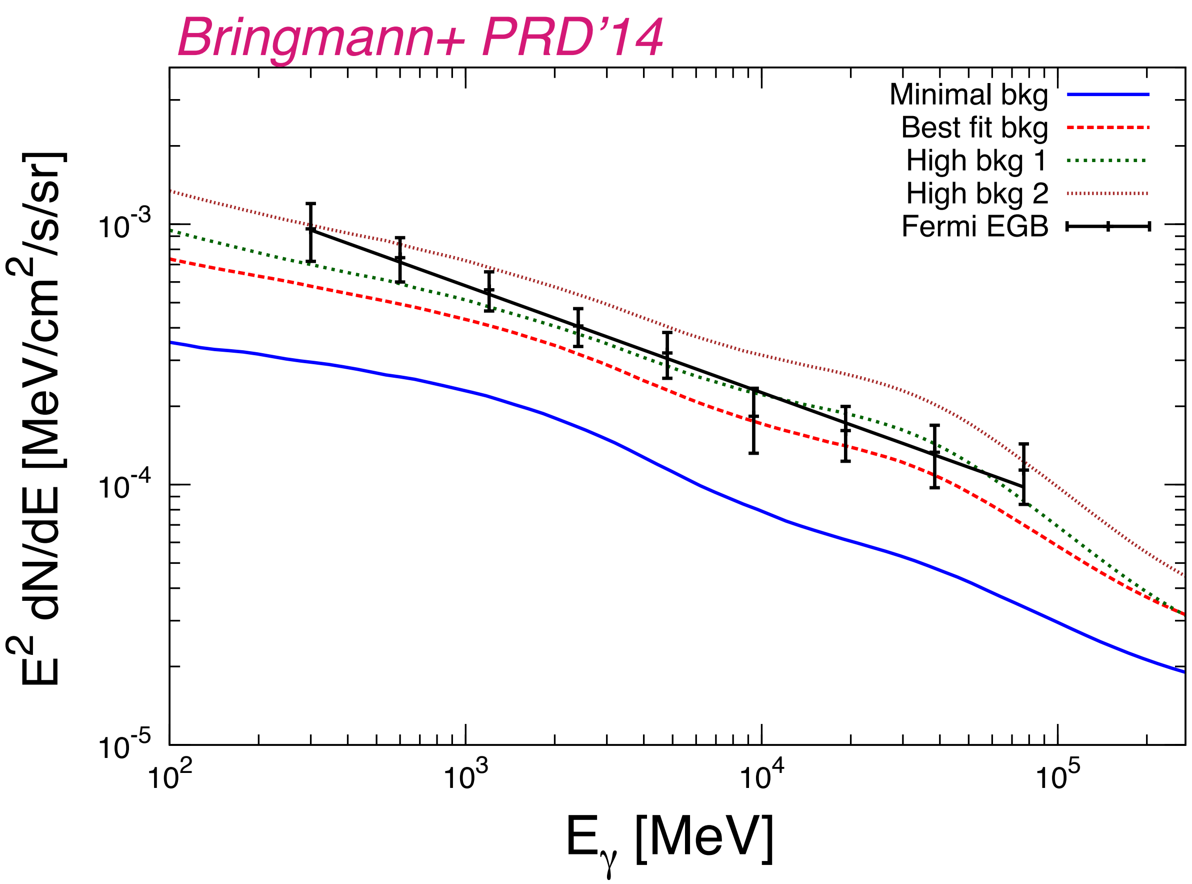
[...]

IGRB guaranteed astrophysical contributions

Fornasa & Sanchez-Conde Phys. Rep.'15



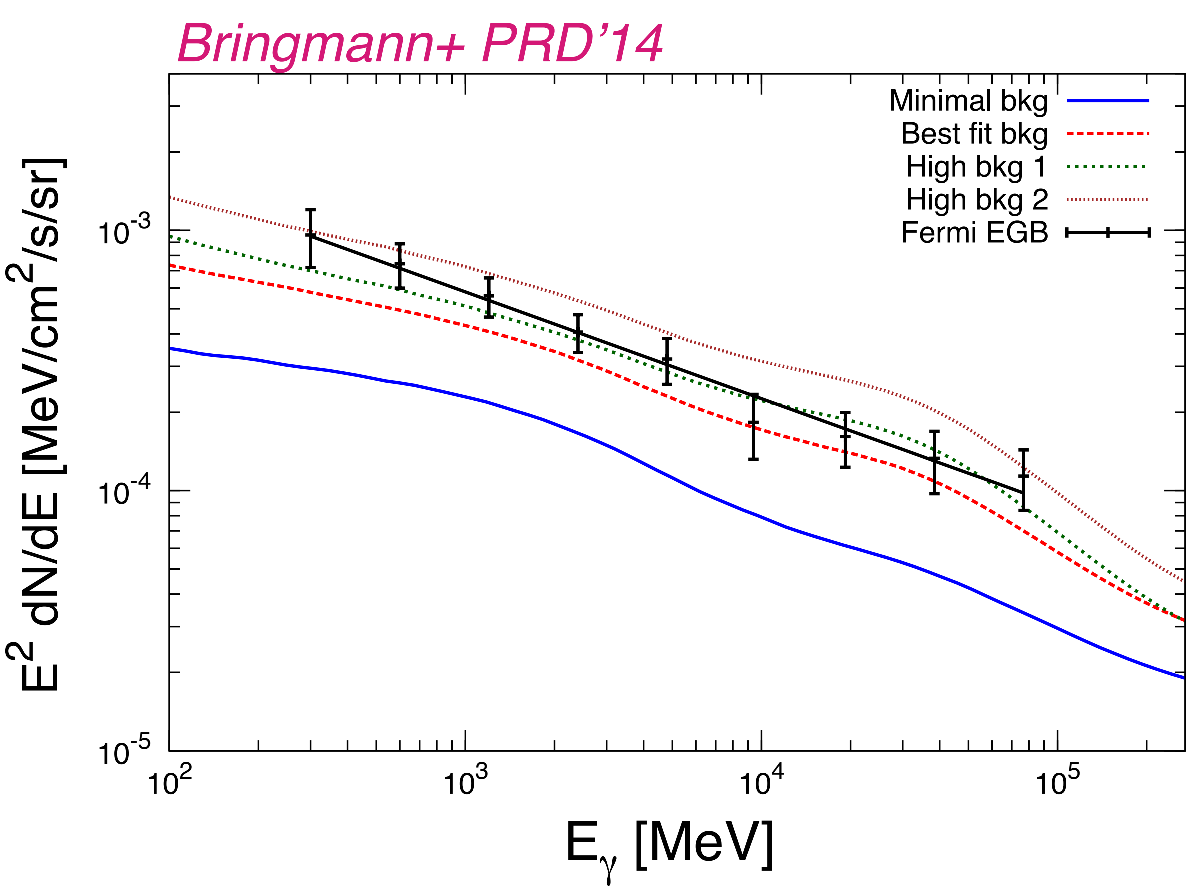
How much room is left for dark matter?

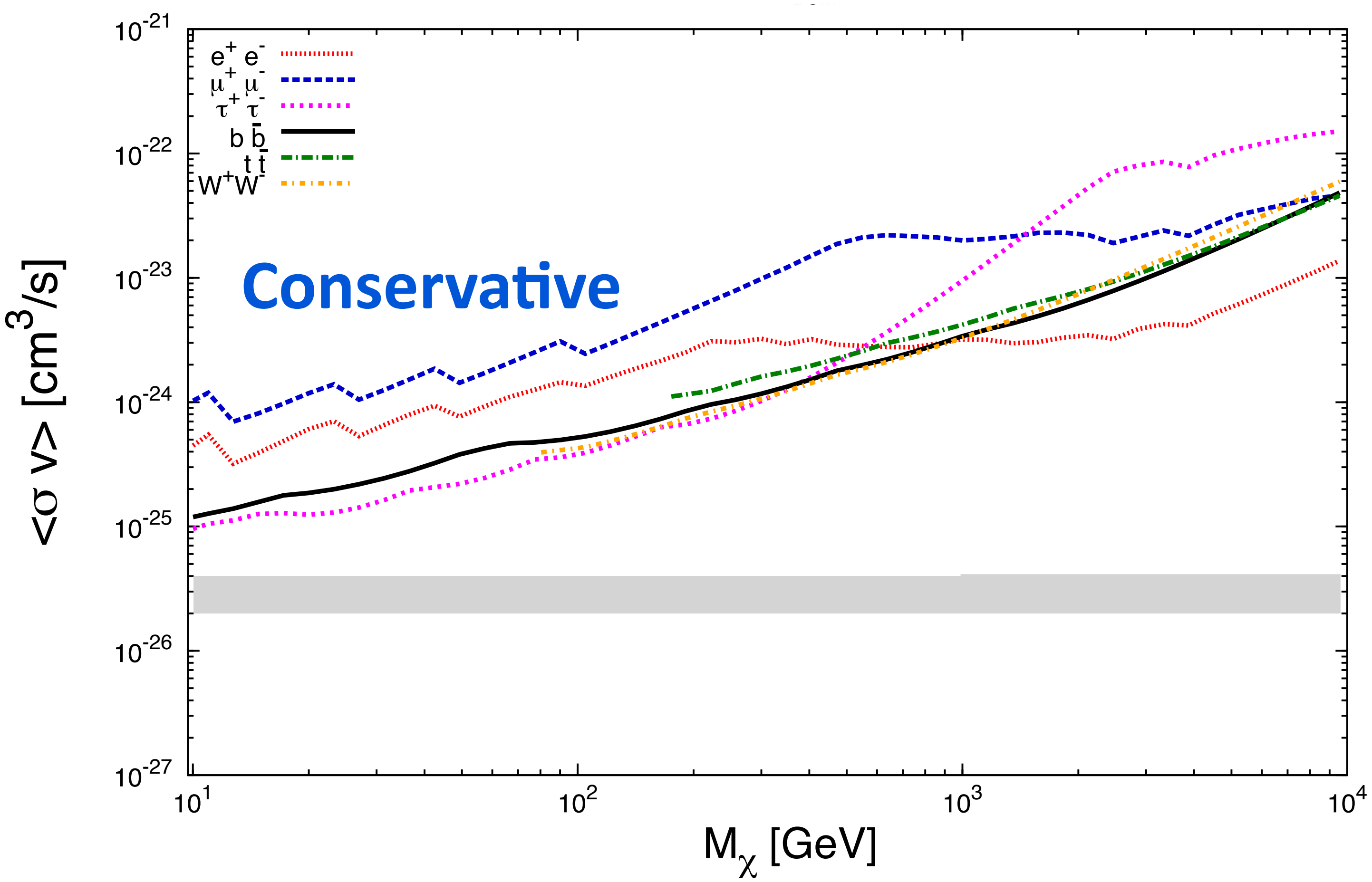


Conservative Scenario:
minimal blazars, millisecond psr, star-forming & MAGN

Optimistic (3s) Scenario:
best-fit blazars, millisecond psr, star-forming & 85% of max MAGN

How much room is left for dark matter?





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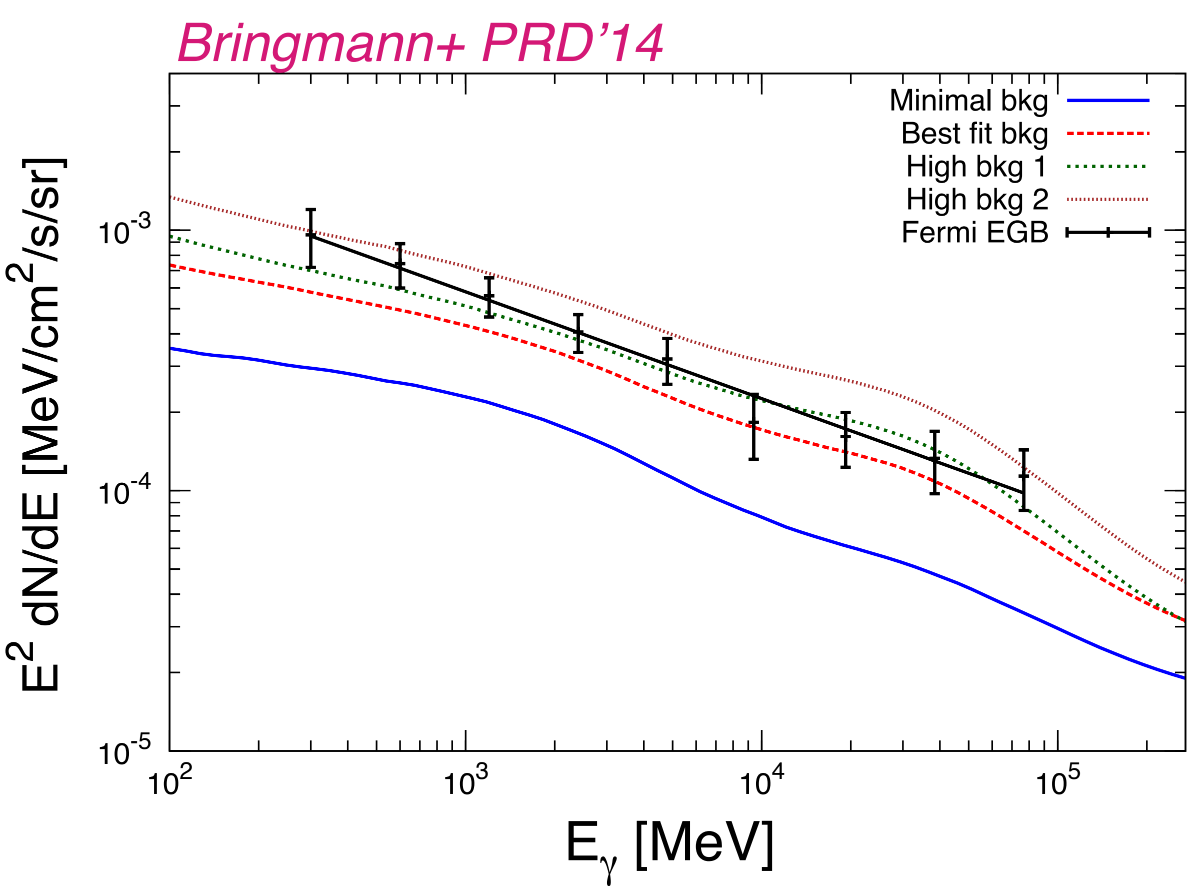
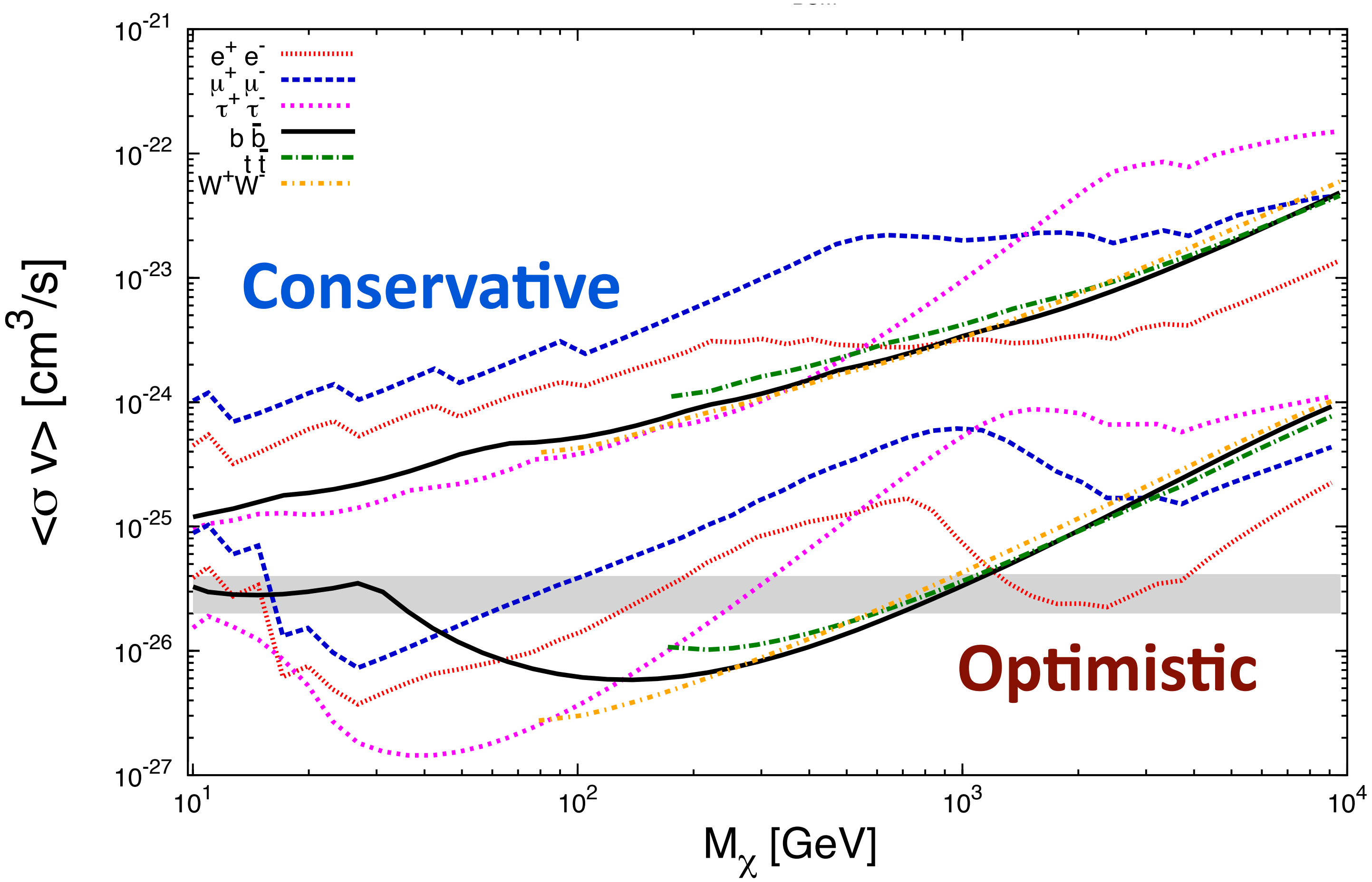
****Galactic Dark matter modelling**:
Burkert profile; prompt, ICS & synchrotron losses
no galactic DM sub-haloes

How much room is left for dark matter?





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****Galactic Dark matter modelling**:
Burkert profile; prompt, ICS & synchrotron losses
no galactic DM sub-haloes

Extragalactic DM contribution

Absorption of photons due to extragalactic bkg light

$$\frac{d\phi^{\rm DM}}{dE_0} = \frac{c\,\langle\sigma v\rangle(\Omega_{\rm DM}\rho_c)^2}{8\pi\, m_\chi^2}\int dz\,\frac{e^{-\tau(E_0,z)}(1+z)^3\zeta(z)}{H(z)}\frac{dN}{dE}\bigg|_{E=E_0(1+z)}$$

Ullio+ PRD'02

Hubble parameter

Flux multiplier, measure of the DM clustering at a given redshift

In real space: **Halo Model**

Cooray&Sheth Phys. Rep.'02

$$\zeta(z) = \frac{1}{\rho_c}\int_{M_{\rm min}} dM\,\frac{dn}{dM}\,M\,\frac{\Delta(z)}{3}\langle F(M,z)\rangle \qquad F(M,z)\equiv c_\Delta^3(M,z)\frac{\int_0^{c_\Delta} dx\,x^2\kappa^2(x)}{\left[\int_0^{c_\Delta} dx\,x^2\,\kappa(x)\right]^2}$$

In Fourier space: **Power Spectrum**

Serpico+MNRAS'12

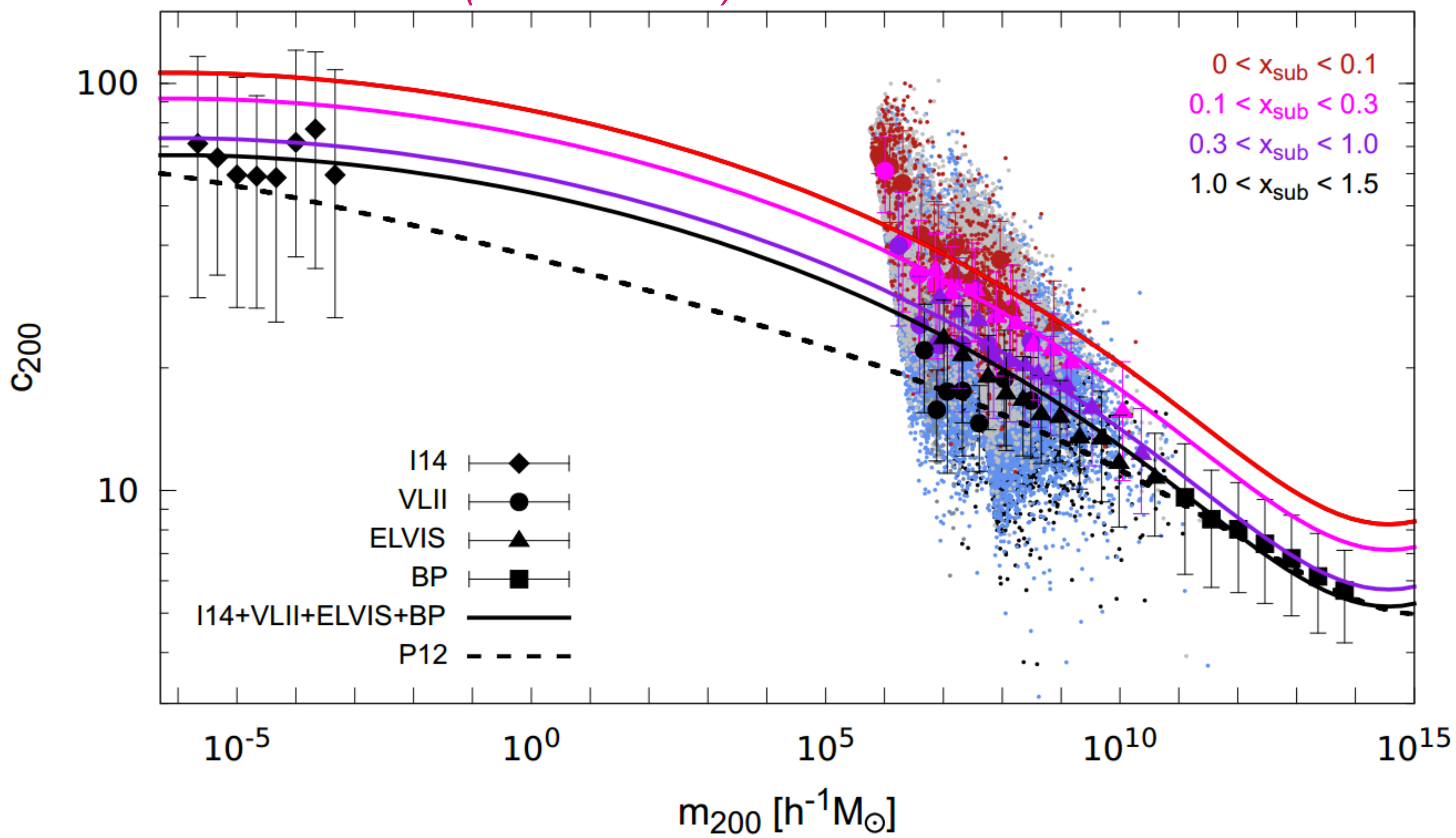
$$\zeta(z)\equiv\langle\delta^2(z)\rangle = \int^{k_{\rm max}}\frac{d\,k}{k}\frac{k^3 P_{NL}(k,z)}{2\pi^2}\equiv\int^{k_{\rm max}}\frac{d\,k}{k}\Delta_{NL}(k,z),$$

How to extrapolate down to the smallest scales?

Halo model

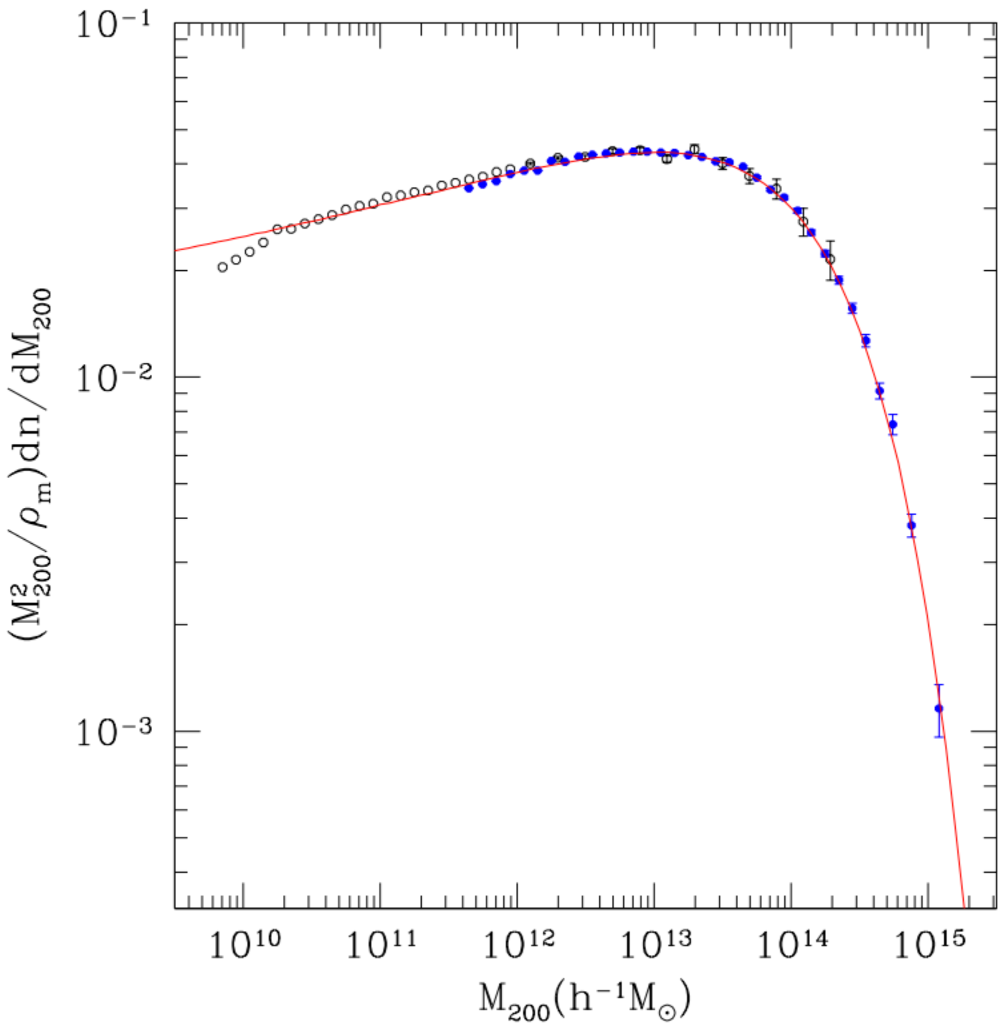
Concentration-mass relation

Moliné+ 2016 (1603.04057)

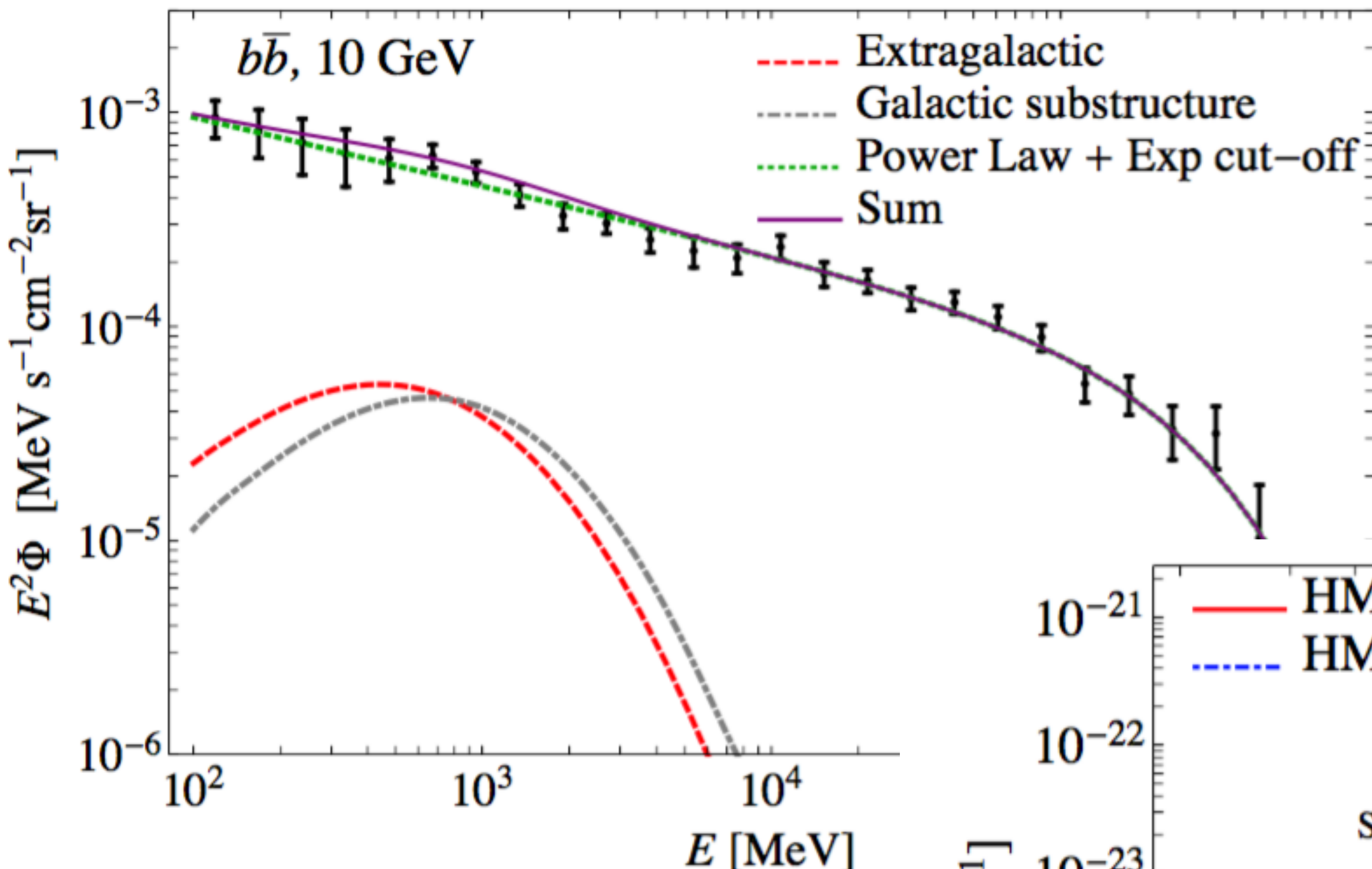


Halo-mass function

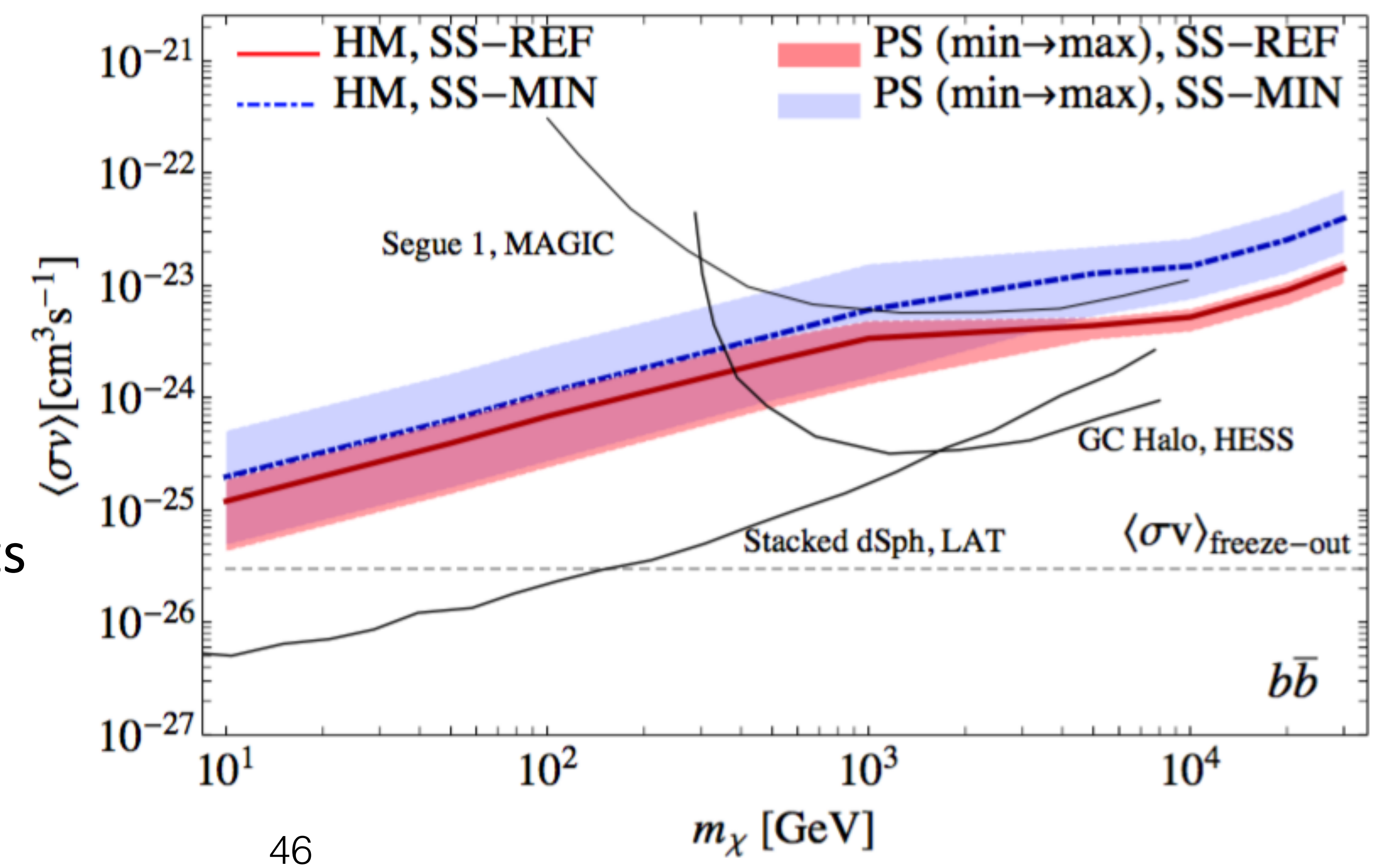
Prada+ MNRAS'11



Limits on DM annihilation



Gamma-ray spectrum: galactic and extragalactic contributions

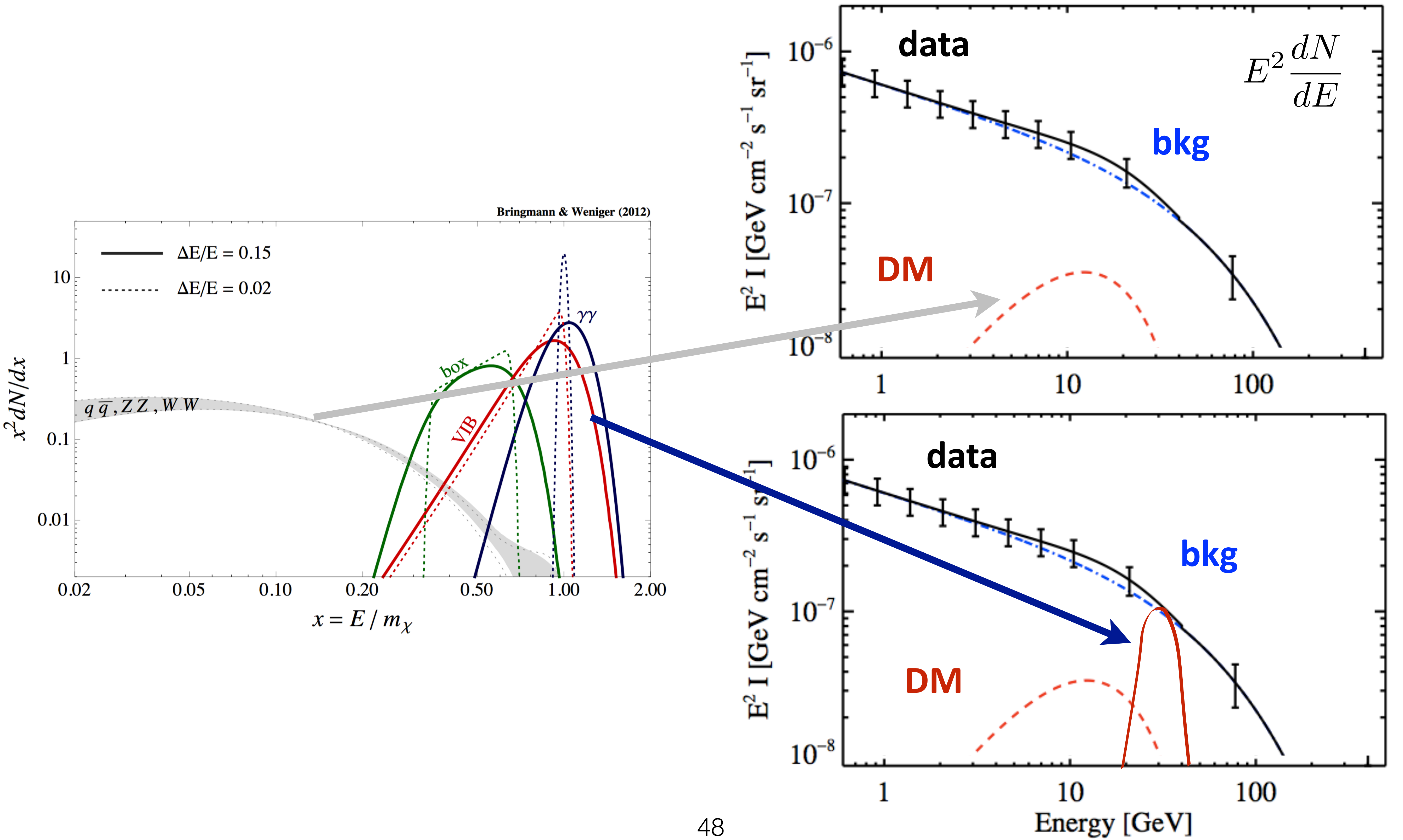


Upper limits:
Galactic subhalos
No modelling astro components

Fermi-LAT Collaboration JCAP'15

Searches for DM gamma-ray lines

The advantage of spectral features



Search for spectral features

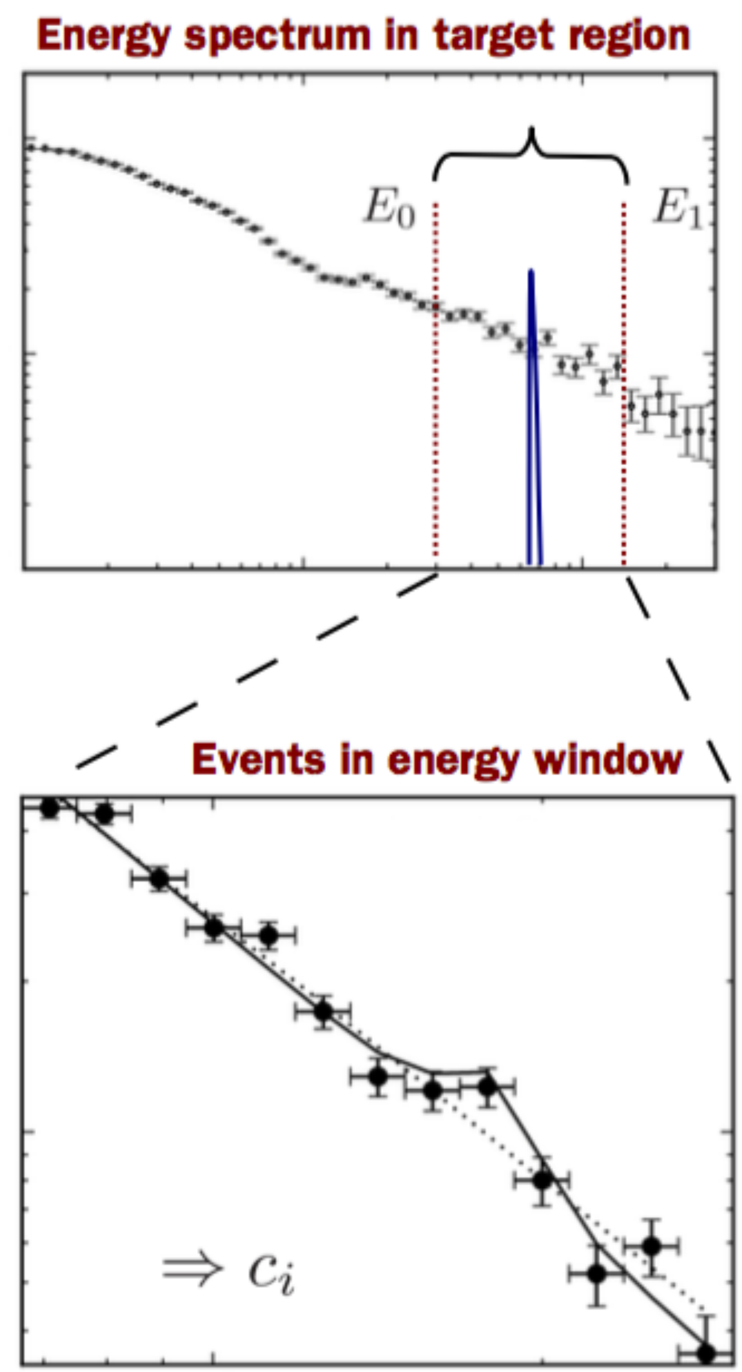
Searching dark matter spectral features over
a power-law background has been shown to be a powerful method to look for dark matter.
Only **3 free parameters**:

$$\frac{dJ}{dE} = \alpha \frac{dJ_{DM}}{dE} + \beta E^{-\gamma}$$

dark matter expected signal

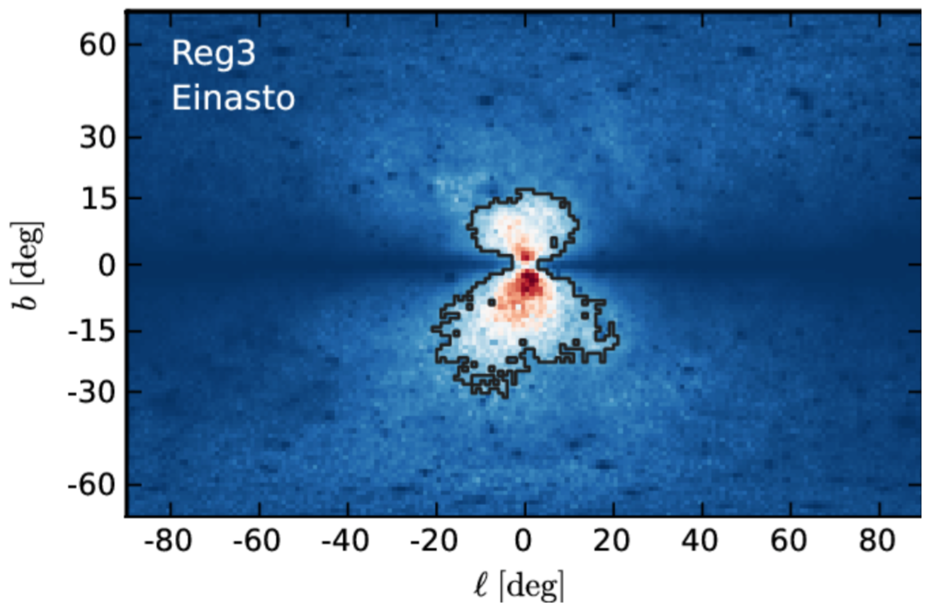
astrophysical modelled background

Bringmann+ PRD'11



Courtesy of C. Weniger

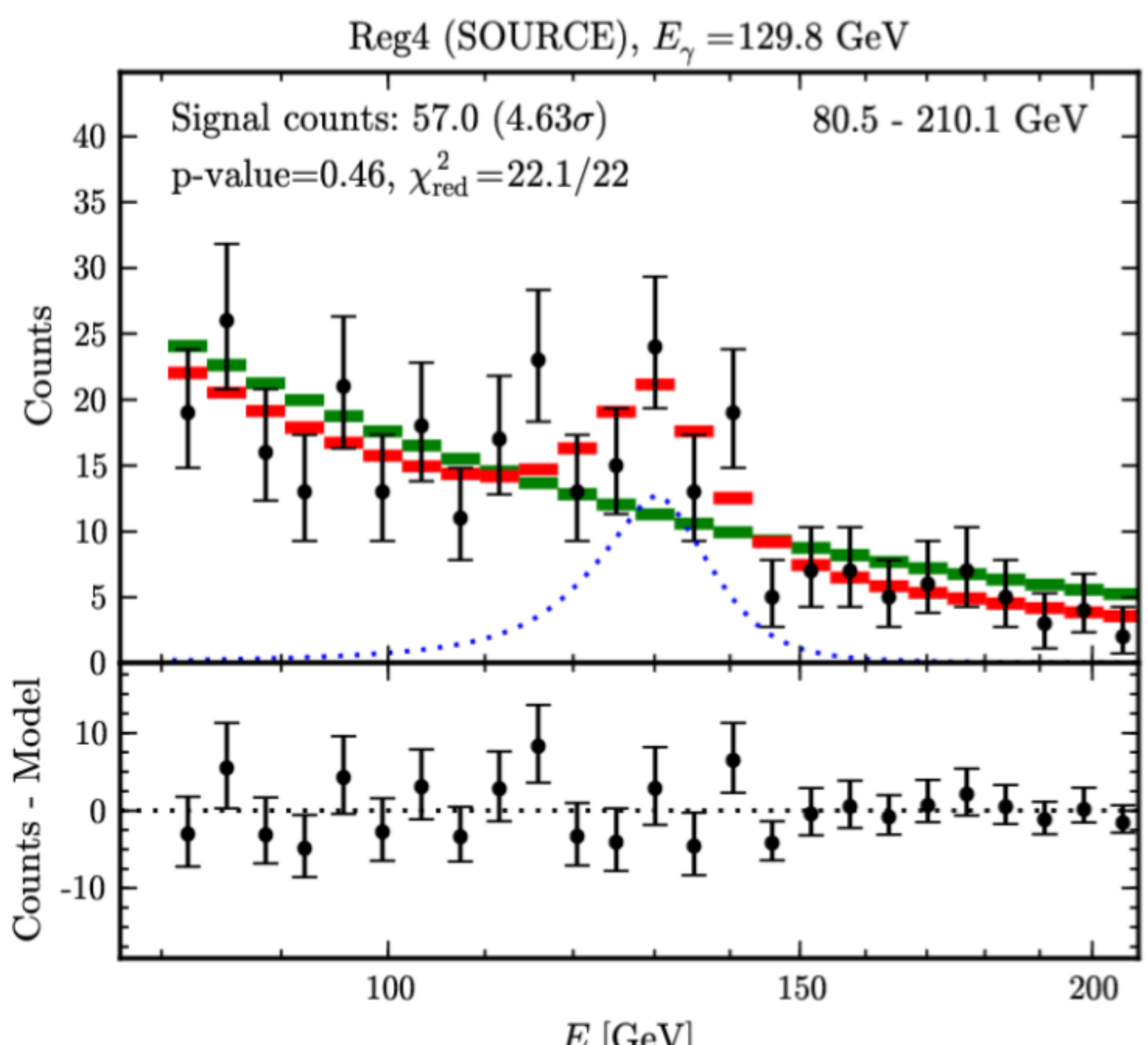
Gamma-ray line searches



Optimised region of interest about the Galactic center, depends on the DM profile.

$$\frac{N_S}{\sqrt{N_B}}$$

Signal/Noise ratio



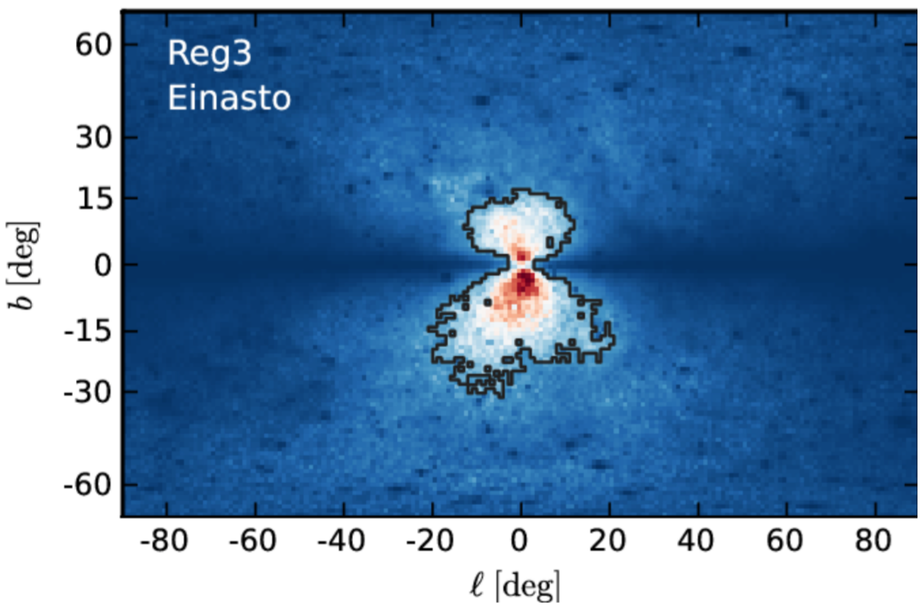
A gamma-ray line signal at 130 GeV?

Bringmann+ JCAP'12
Weniger JCAP'12

43 months of SOURCE data (P7V6)
Local significance: 4.6 sigma
Global significance: 3.2 sigma

Profumo&Linden, JCAP'12; Ibarra+ JCAP'12; Dudas+'12; Cline PRD'12; Choi&Seto PRD'12; Buckley&Hooper PRD'12; etc.…

Gamma-ray line searches



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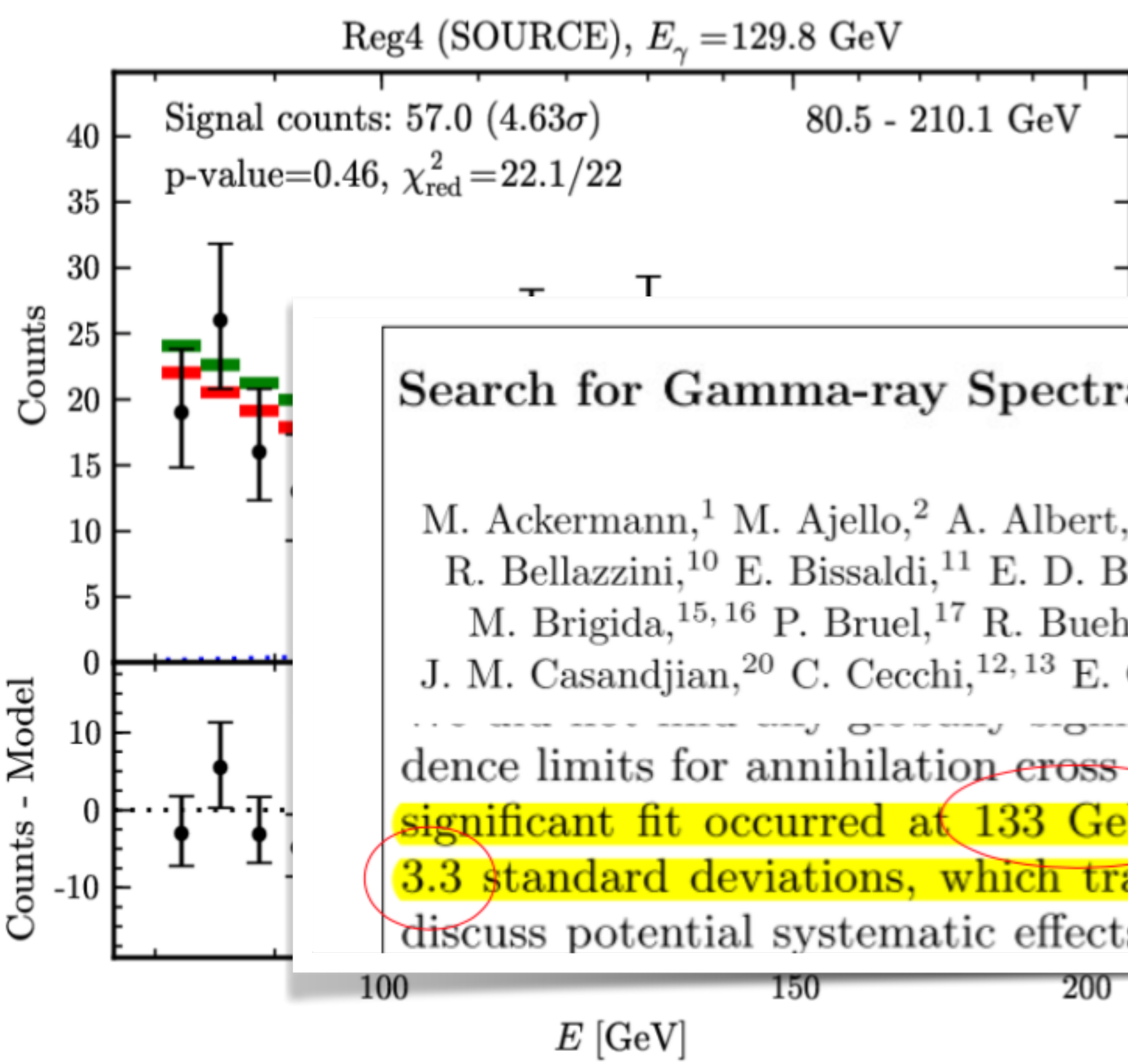

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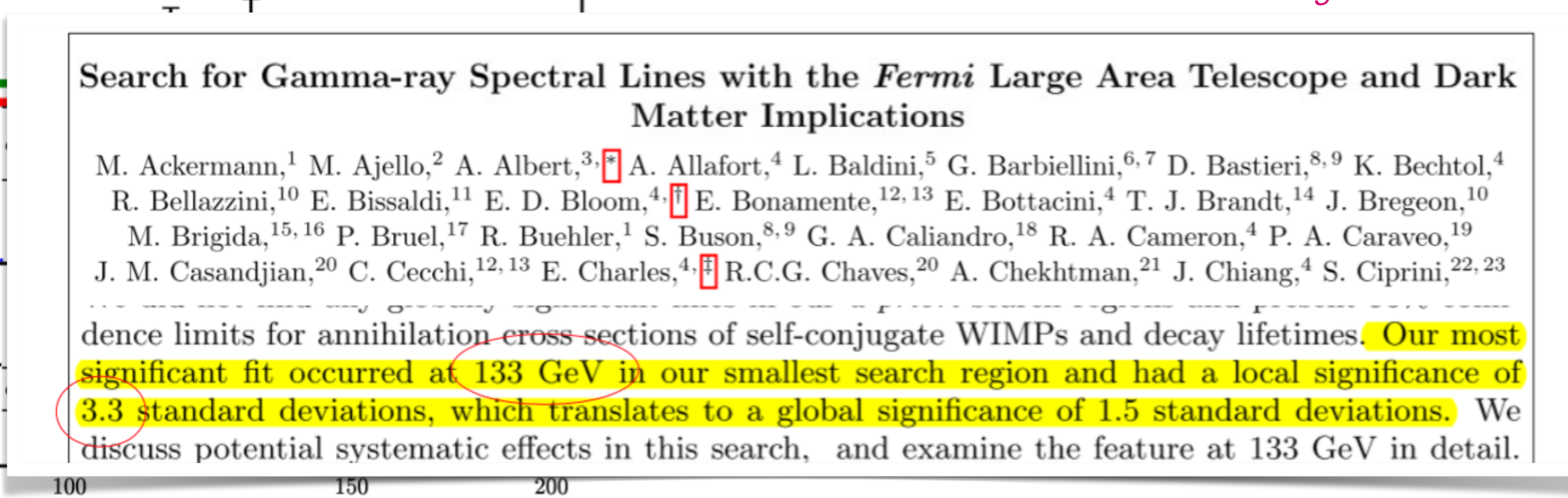
Bringmann+ JCAP'12
Weniger JCAP'12

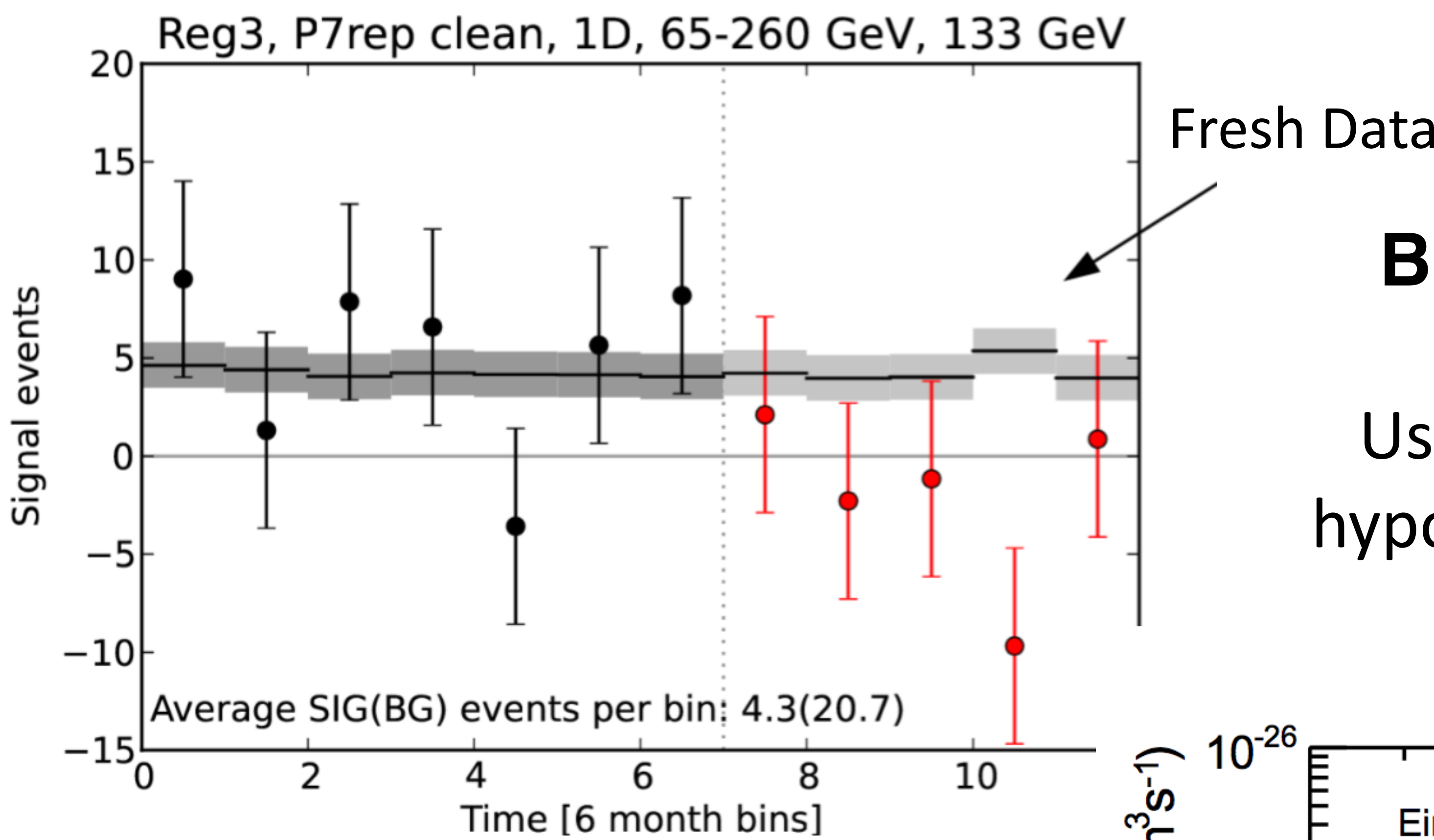


Search for Gamma-ray Spectral Lines with the *Fermi* Large Area Telescope and Dark Matter Implications

M. Ackermann,[1] M. Ajello,[2] A. Albert,[3,*] A. Allafort,[4] L. Baldini,[5] G. Barbiellini,[6,7] D. Bastieri,[8,9] K. Bechtol,[4] R. Bellazzini,[10] E. Bissaldi,[11] E. D. Bloom,[4,†] E. Bonamente,[12,13] E. Bottacini,[4] T. J. Brandt,[14] J. Bregeon,[10] M. Brigida,[15,16] P. Bruel,[17] R. Buehler,[1] S. Buson,[8,9] G. A. Caliandro,[18] R. A. Cameron,[4] P. A. Caraveo,[19] J. M. Casandjian,[20] C. Cecchi,[12,13] E. Charles,[4,‡] R.C.G. Chaves,[20] A. Chekhtman,[21] J. Chiang,[4] S. Ciprini,[22,23]

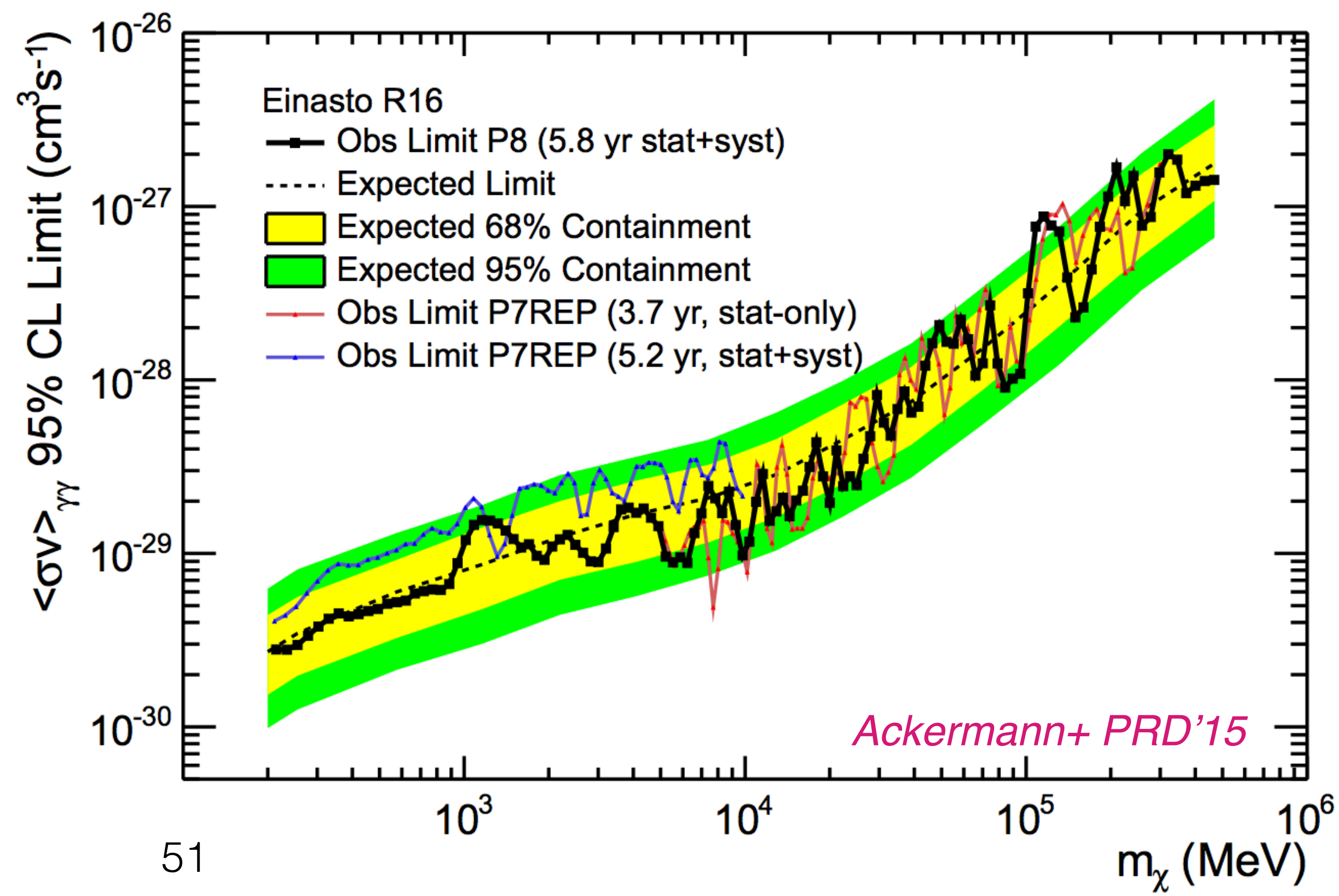
dence limits for annihilation cross sections of self-conjugate WIMPs and decay lifetimes. Our most significant fit occurred at 133 GeV in our smallest search region and had a local significance of 3.3 standard deviations, which translates to a global significance of 1.5 standard deviations. We discuss potential systematic effects in this search, and examine the feature at 133 GeV in detail.

Gamma-ray line searches



But no signal since Summer 2012!

Using Fermi LAT data alone, the signal hypothesis can be excluded at more than 3 sigma.

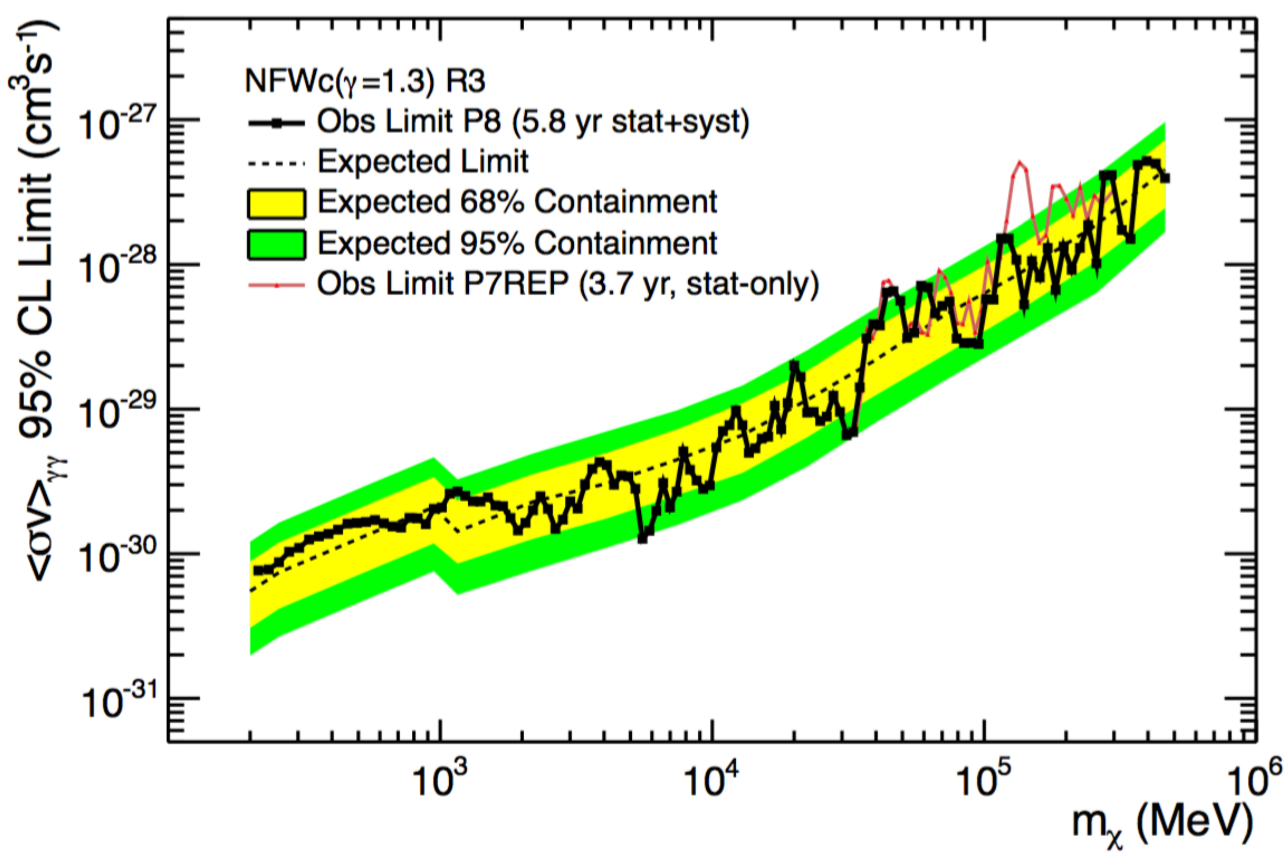


- PASS 8 event selection
- 200MeV - 500 GeV
- 5.8 years of data
- 5 optimised sky regions

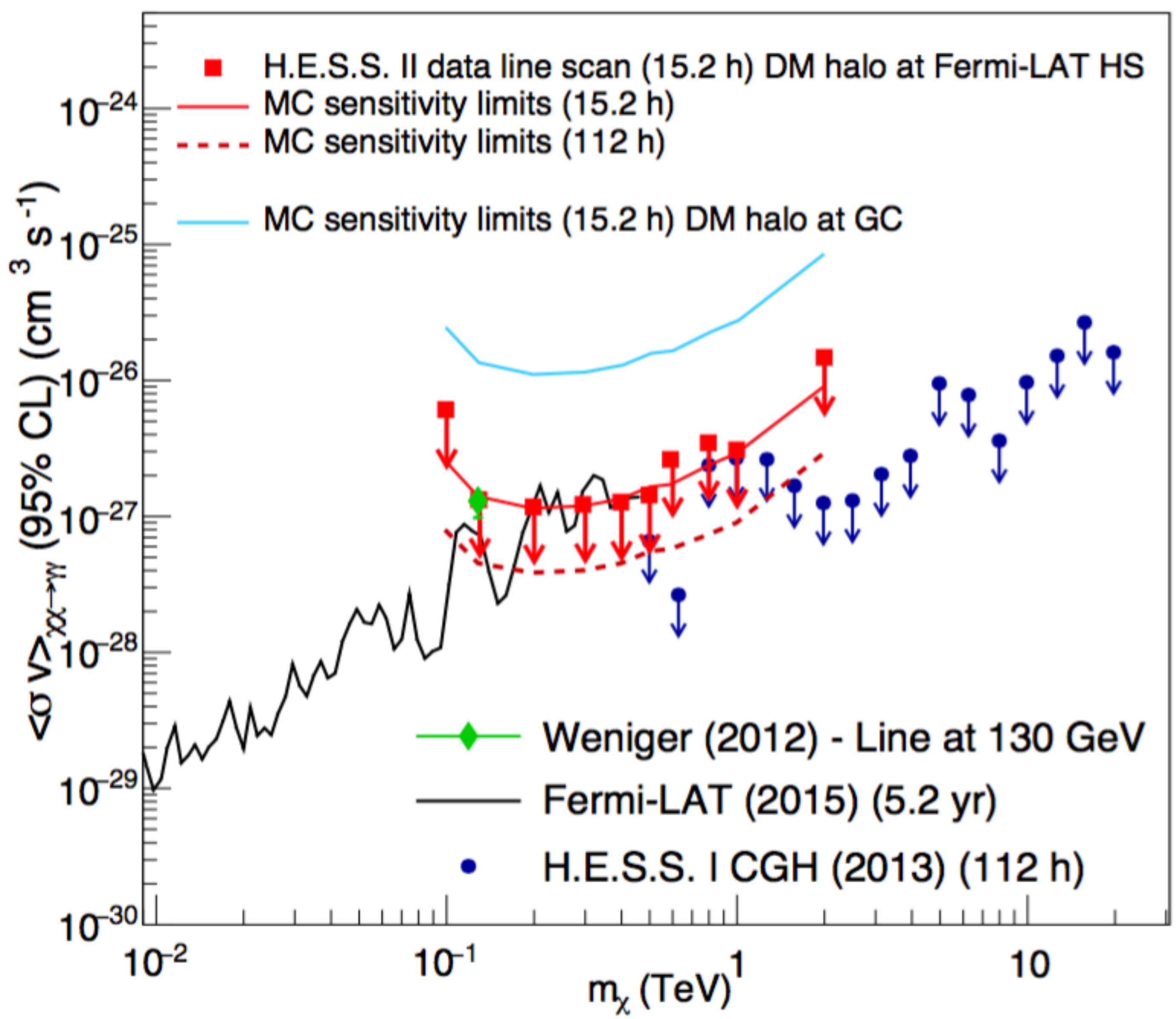
—> Local significance: 0.72 sigma
Consistent with statistical fluct.

Line-like searches at TeV energies

Ackermann+ PRD'15



Abdalla+ PRL'16



[Other targets? From line searches from dwarfs and combined analysis, see *Profumo+, Mon.Not.Roy.Astron.Soc. 461 (2016) no.4; Liang+, Phys.Rev. D94 (2016) no.10*]

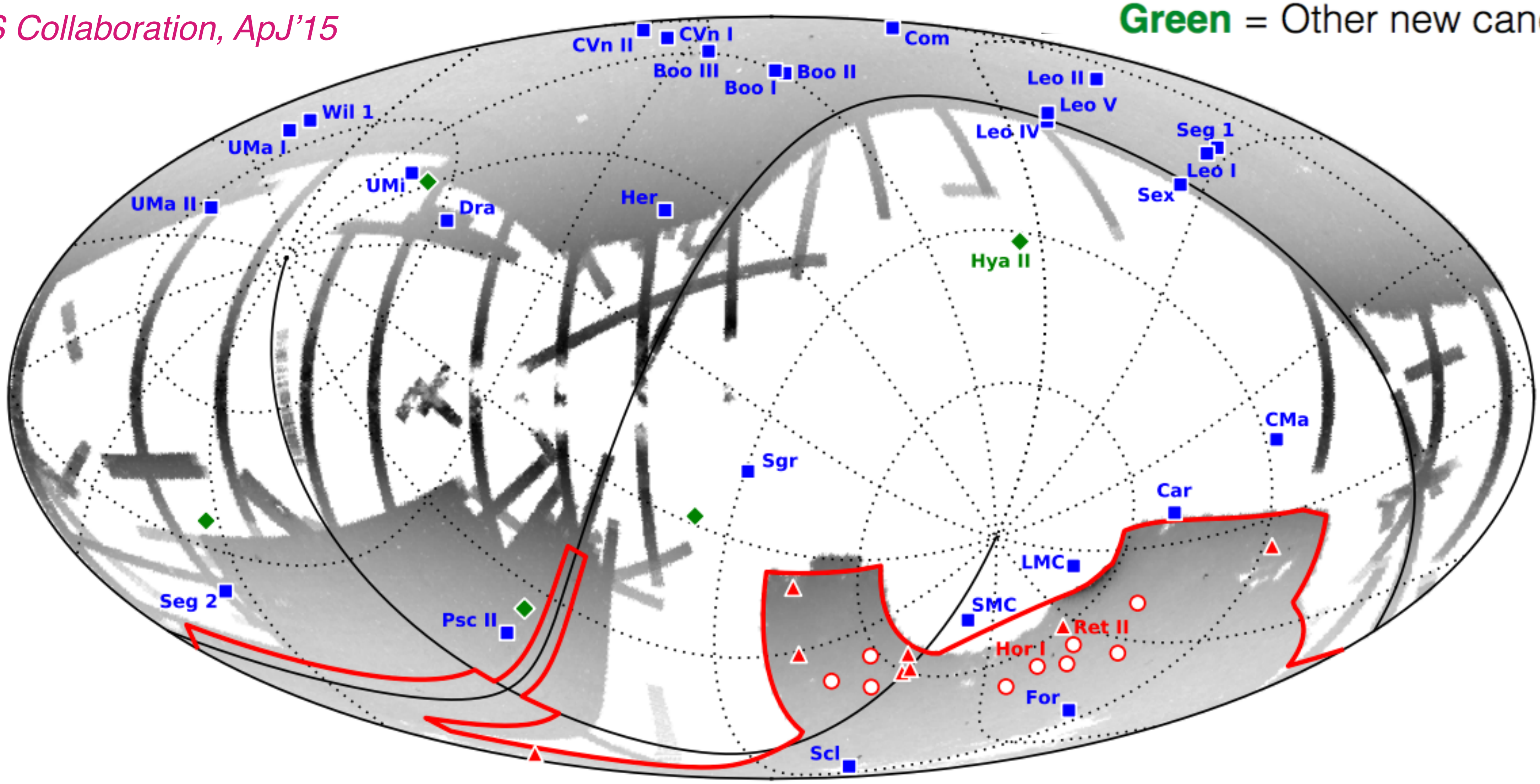
Searches towards dwarf spheroidal galaxies and dark sub haloes

Known dwarf spheroidal galaxies

Stellar density field from SDSS and DES

DES Collaboration, ApJ'15

Blue = Known prior to 2015
Red triangles = DES Y2Q1 candidates
Red circles = DES Y1A1 candidates
Green = Other new candidates

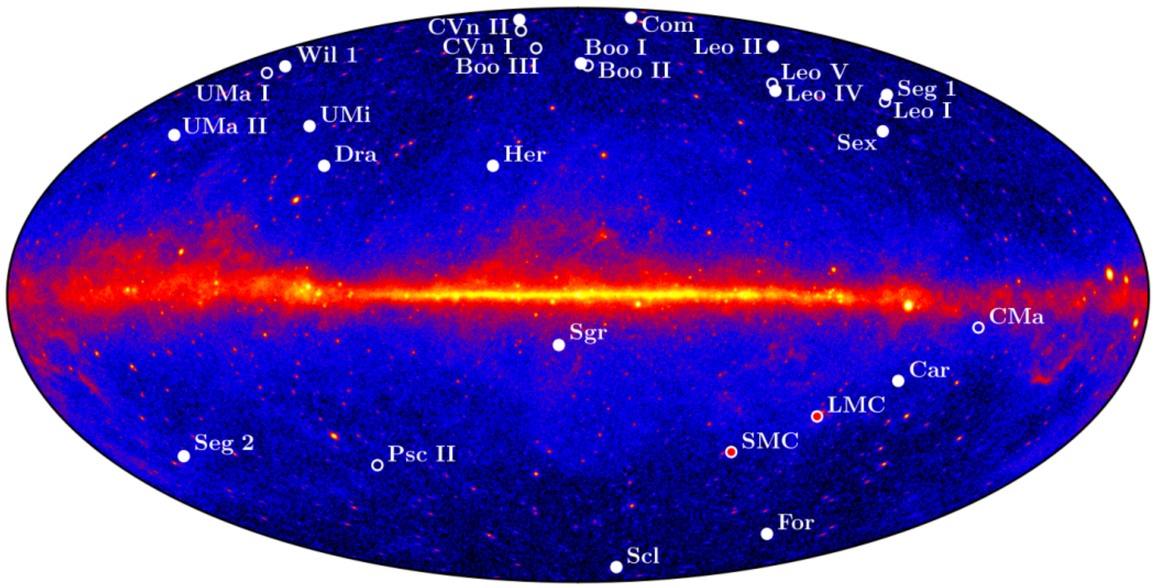


SDSS northern hemisphere, classical + ultra-faint dwarfs

DES southern hemisphere, 17 new dwarfs

Pan-STARRS, 3 new candidates

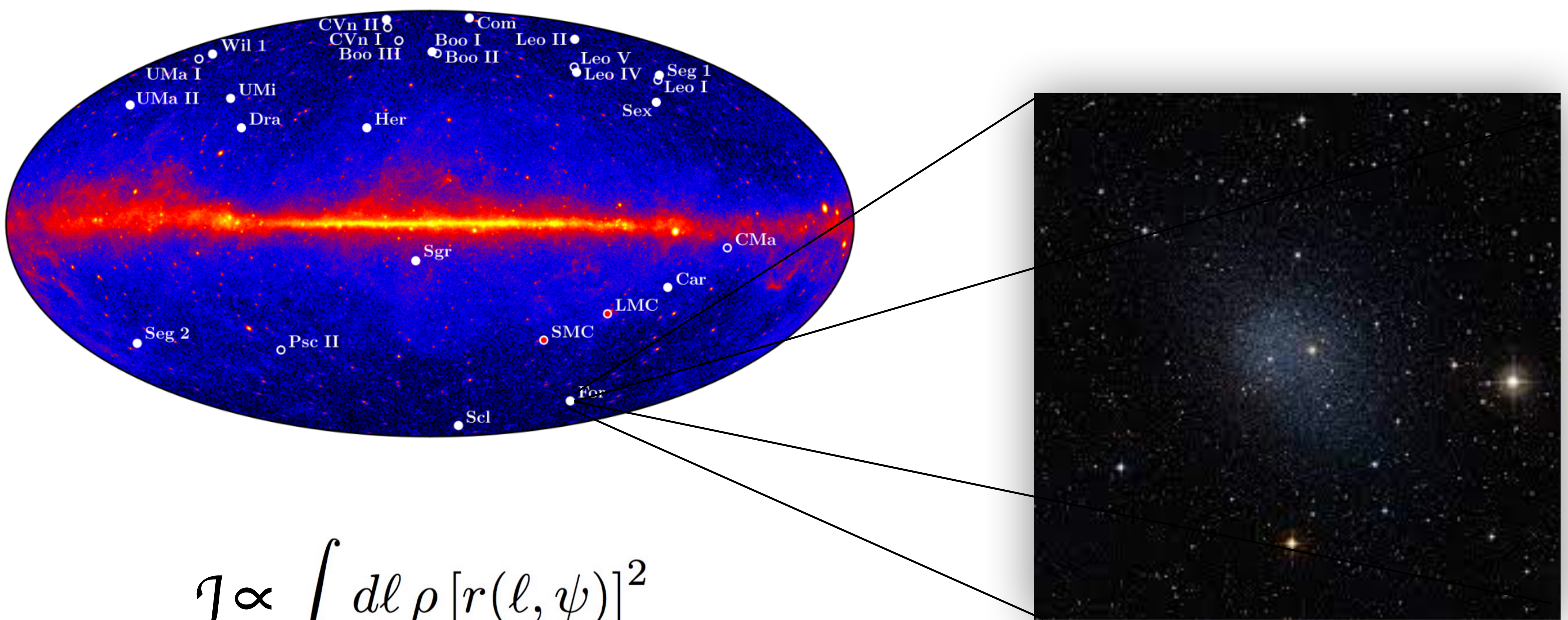
Limits from dwarf spheroidal galaxies



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

Fermi-LAT Collaboration, PRL'11

Limits from dwarf spheroidal galaxies

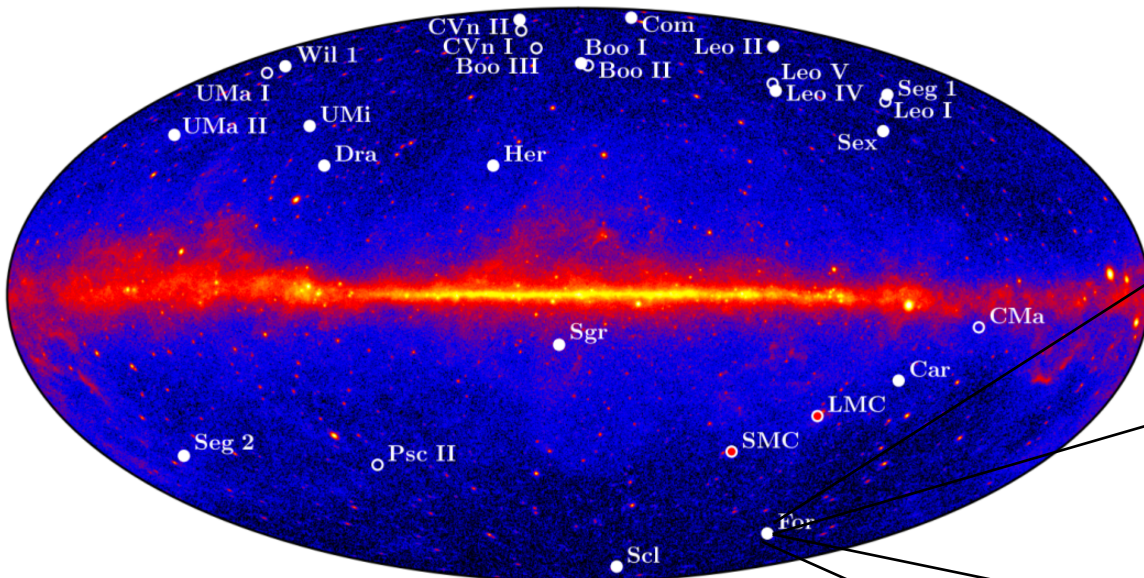


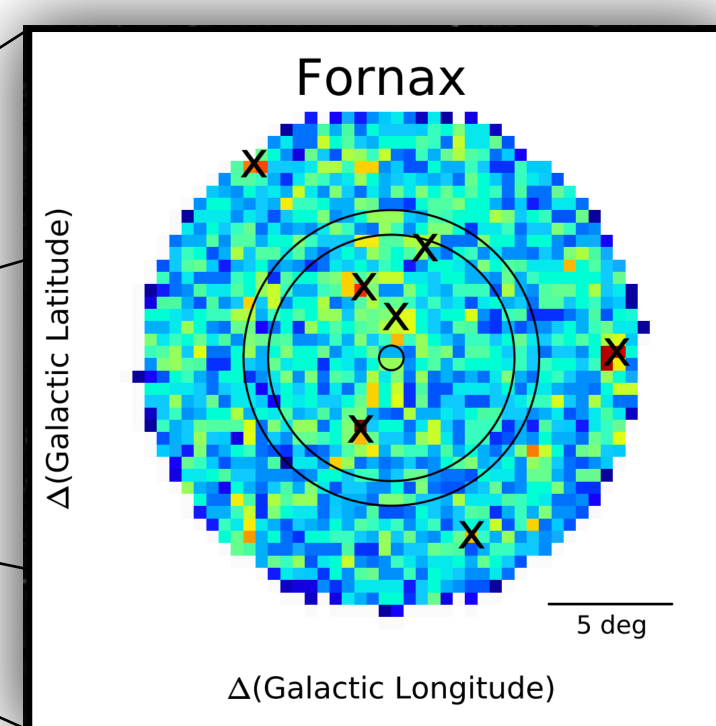
$$\mathcal{J} \propto \int d\ell \, \rho \left[r(\ell, \psi) \right]^2$$

Fermi-LAT Collaboration, PRL'11

Credit: ESO/Fornax galaxy

Limits from dwarf spheroidal galaxies



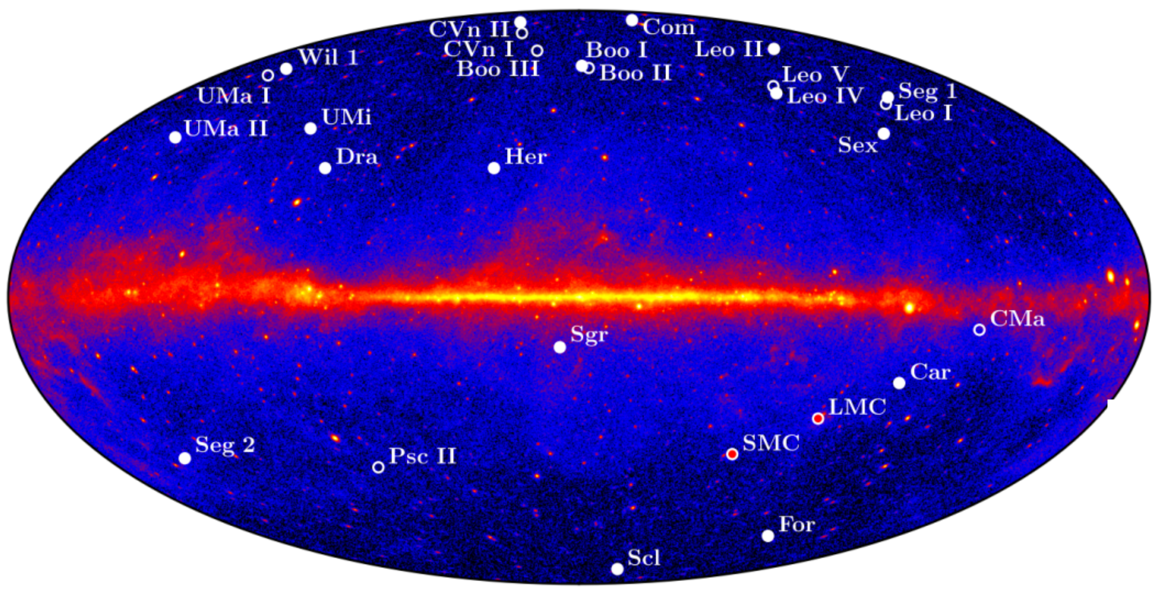


$$\mathcal{J} \propto \int d\ell \, \rho \left[r(\ell, \psi) \right]^2$$

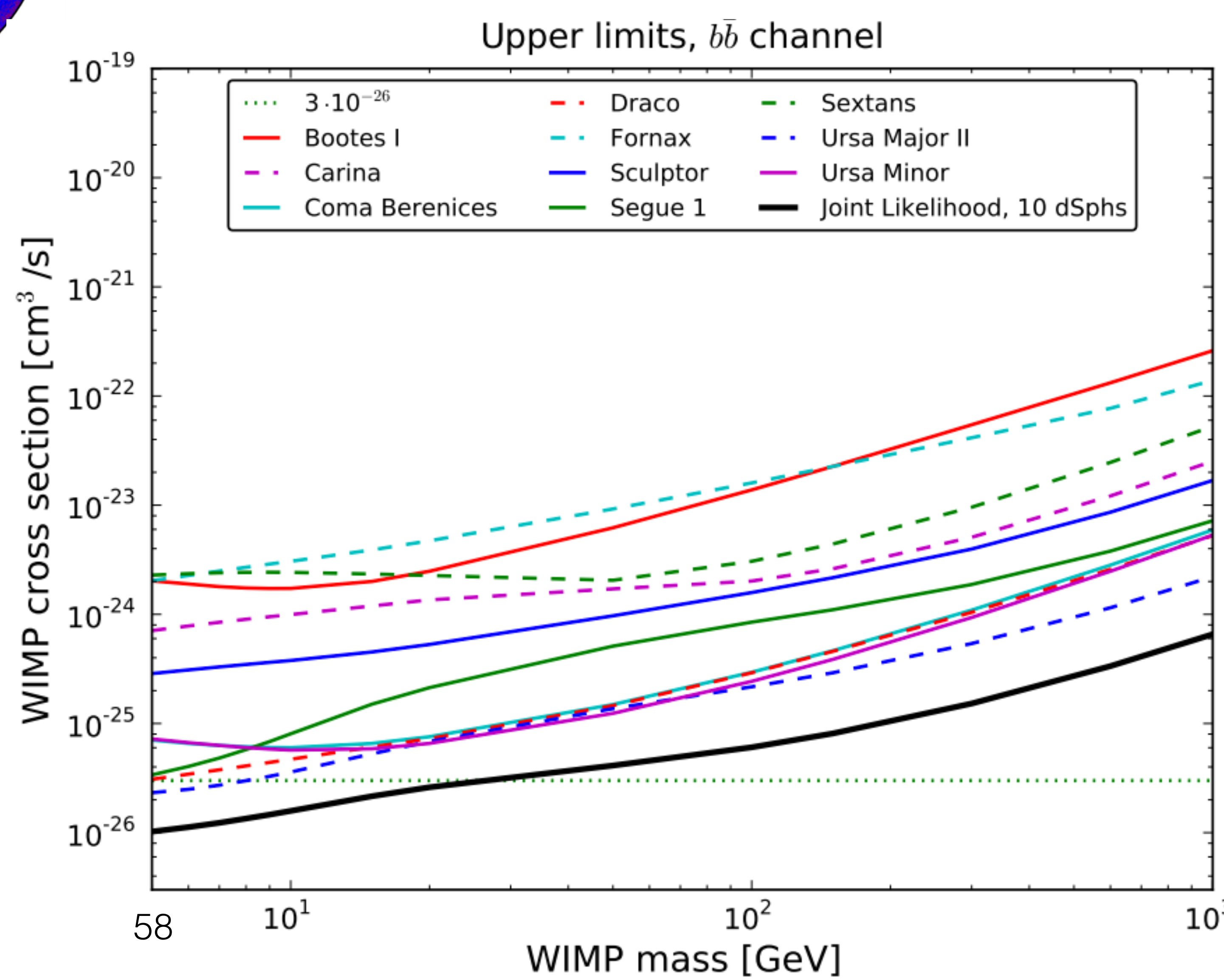
Mazziotta+Astrop. Phys.'12

Fermi-LAT Collaboration, PRL'11

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**.

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

Fermi-LAT Collaboration, PRL'11

Limits from dwarf spheroidal galaxies

Current status

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

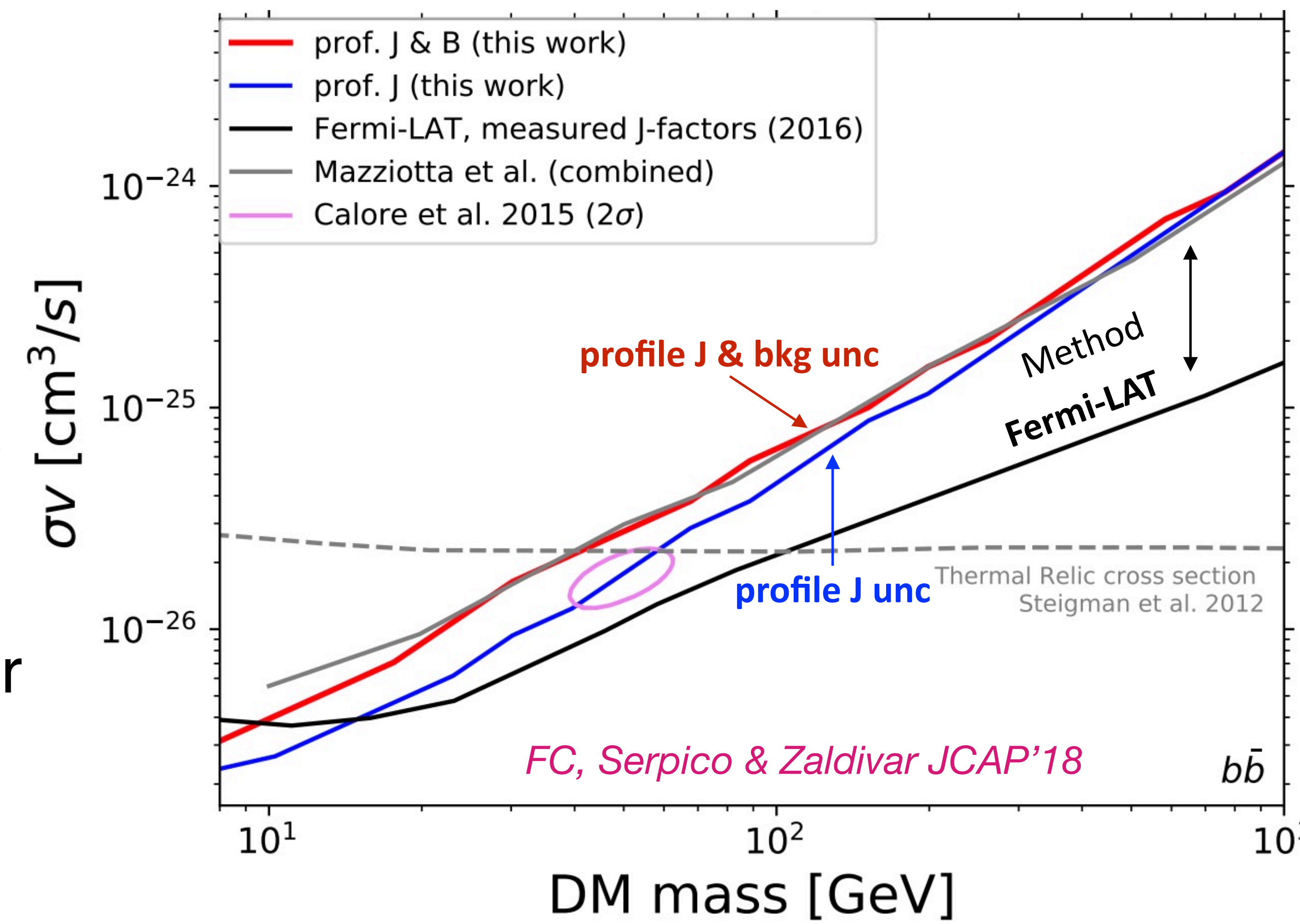
Albert+ ApJ'17

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

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

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

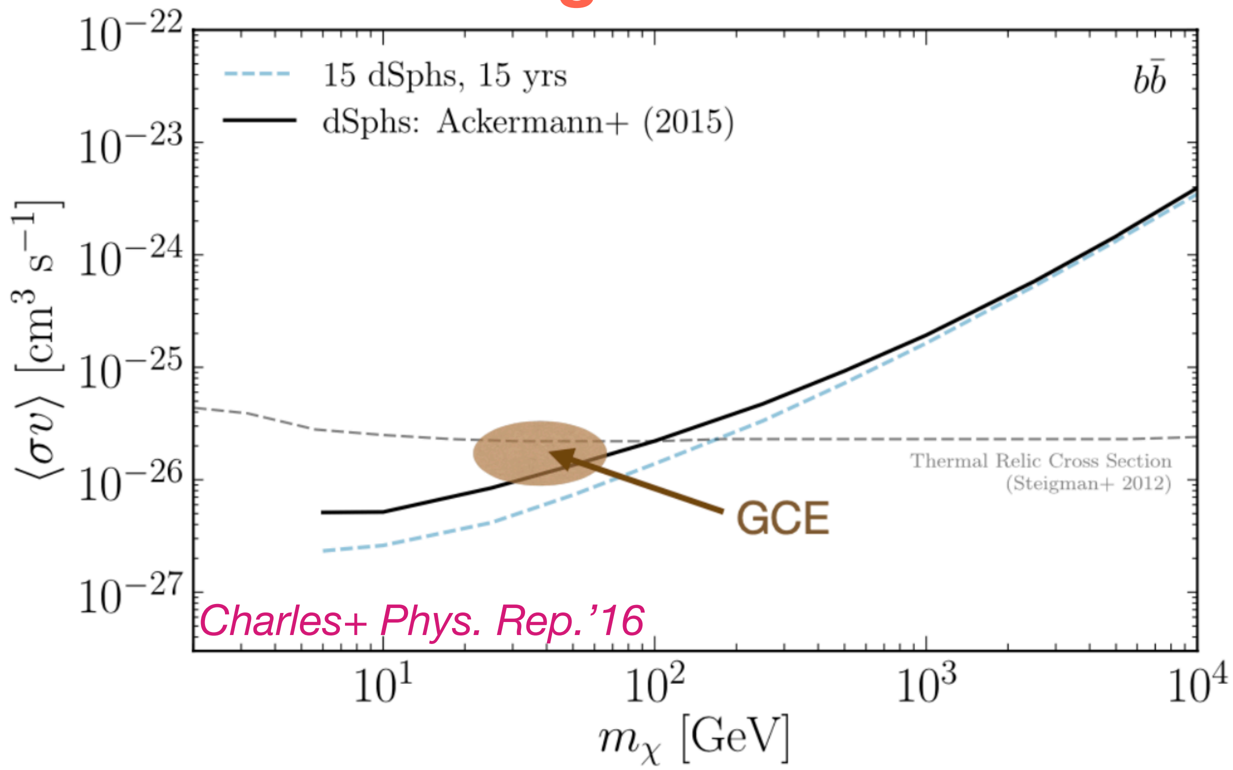
FC, Serpico & Zaldivar JCAP'18; Alvarez, FC+ JCAP'20



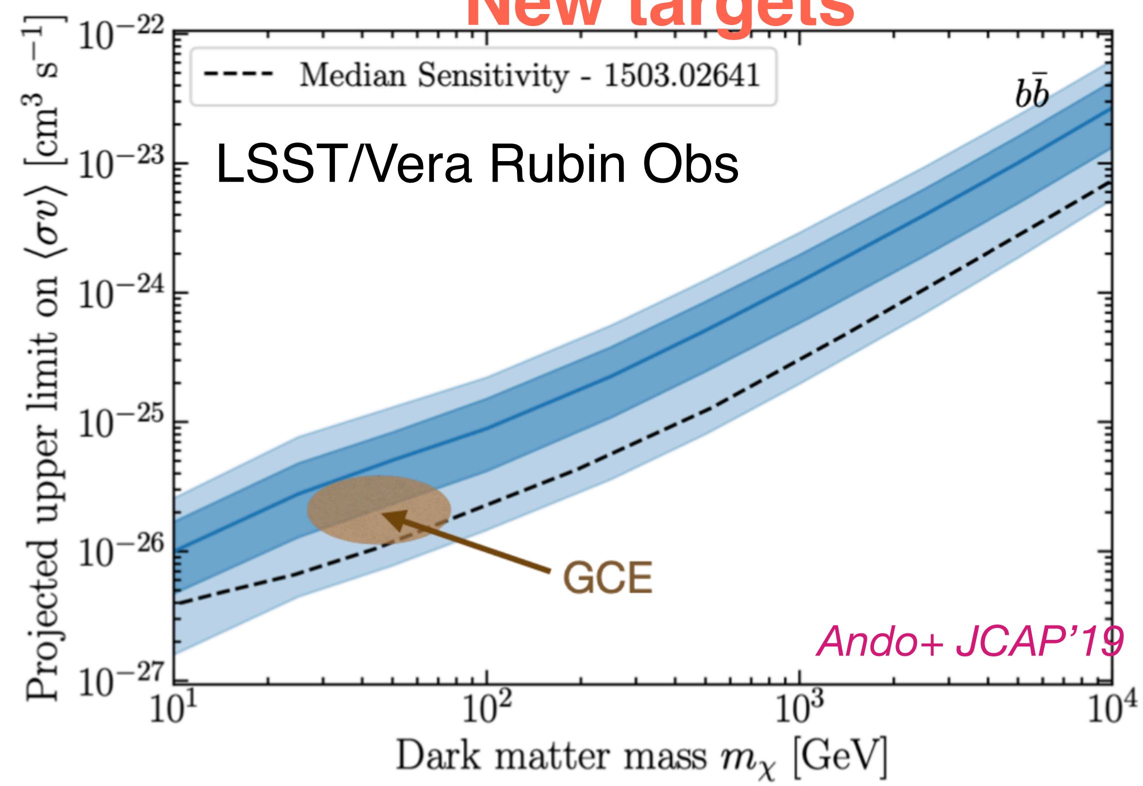
Limits from dwarf spheroidal galaxies

Future prospects

Longer observations



New targets



- New data from Fermi-LAT (improvement by a factor of 2-5)
- Expected hundreds of new dSphs with SDSS, Pan-Starrs, DES and LSST (> 2019)

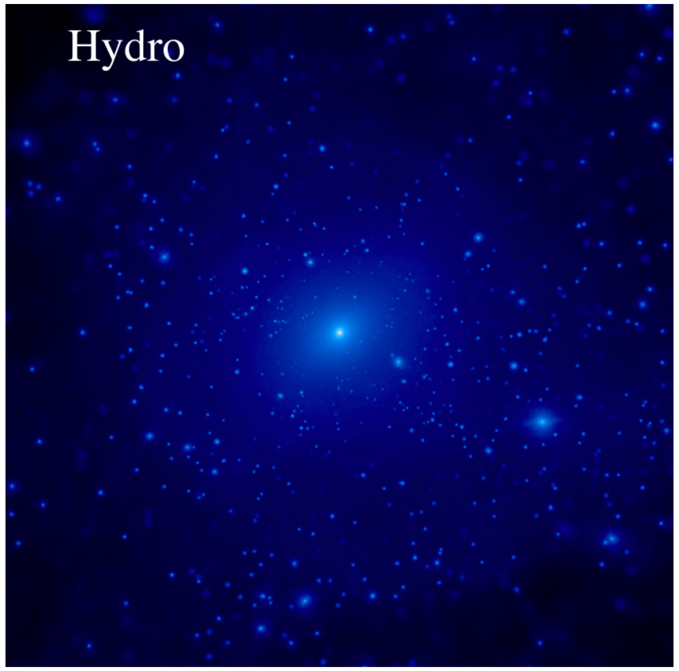
Hargis+ApJL'14

- Competitive bounds from future radio and X-ray telescopes

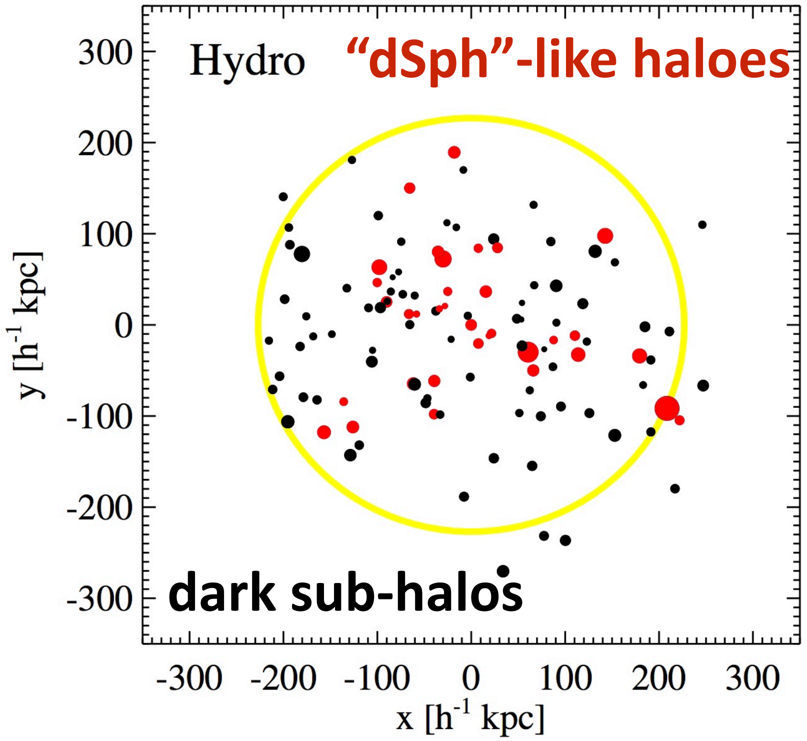
Regis+, JCAP'14; Jeltema&Profumo, MNRAS'12

Searches for dark 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



Do we have already detected dark subhaloes 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

Limits from dark sub haloes searches

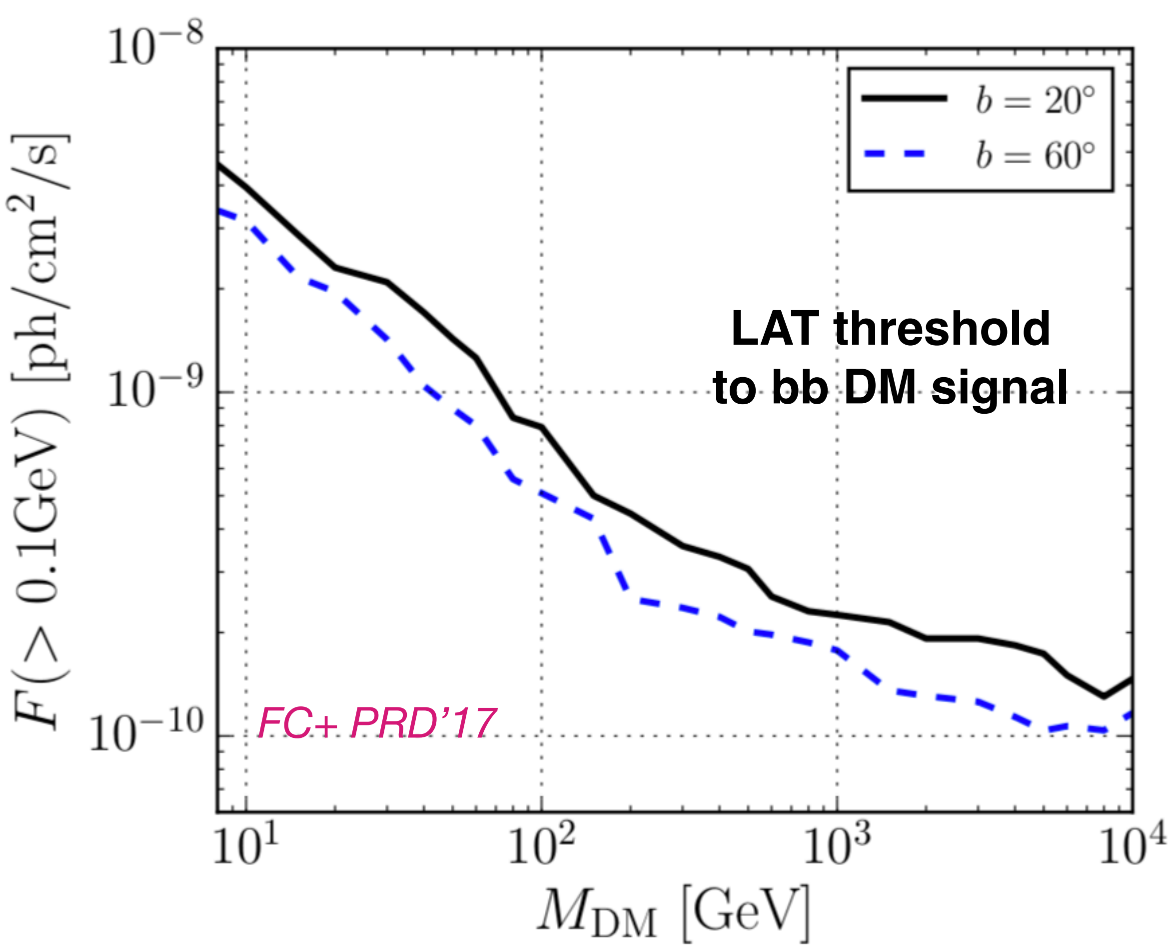
1. Number of gamma-ray DM subhalo candidates from data?

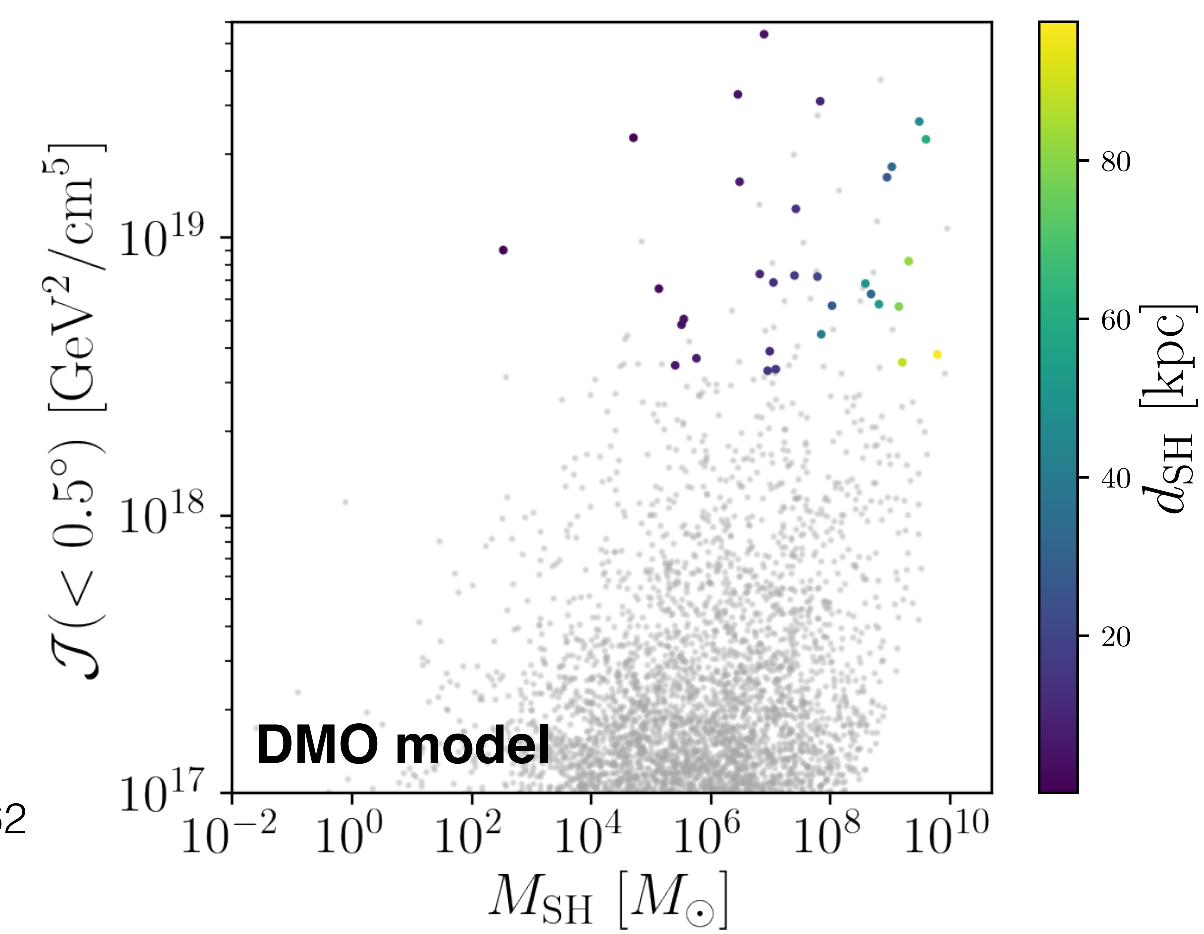
- Classification of Fermi-LAT gamma-ray sources based mainly on spectral properties

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 *Hütten+ Galaxies'19*
- Convolve with realistic Fermi-LAT detection threshold to DM sub halo signals





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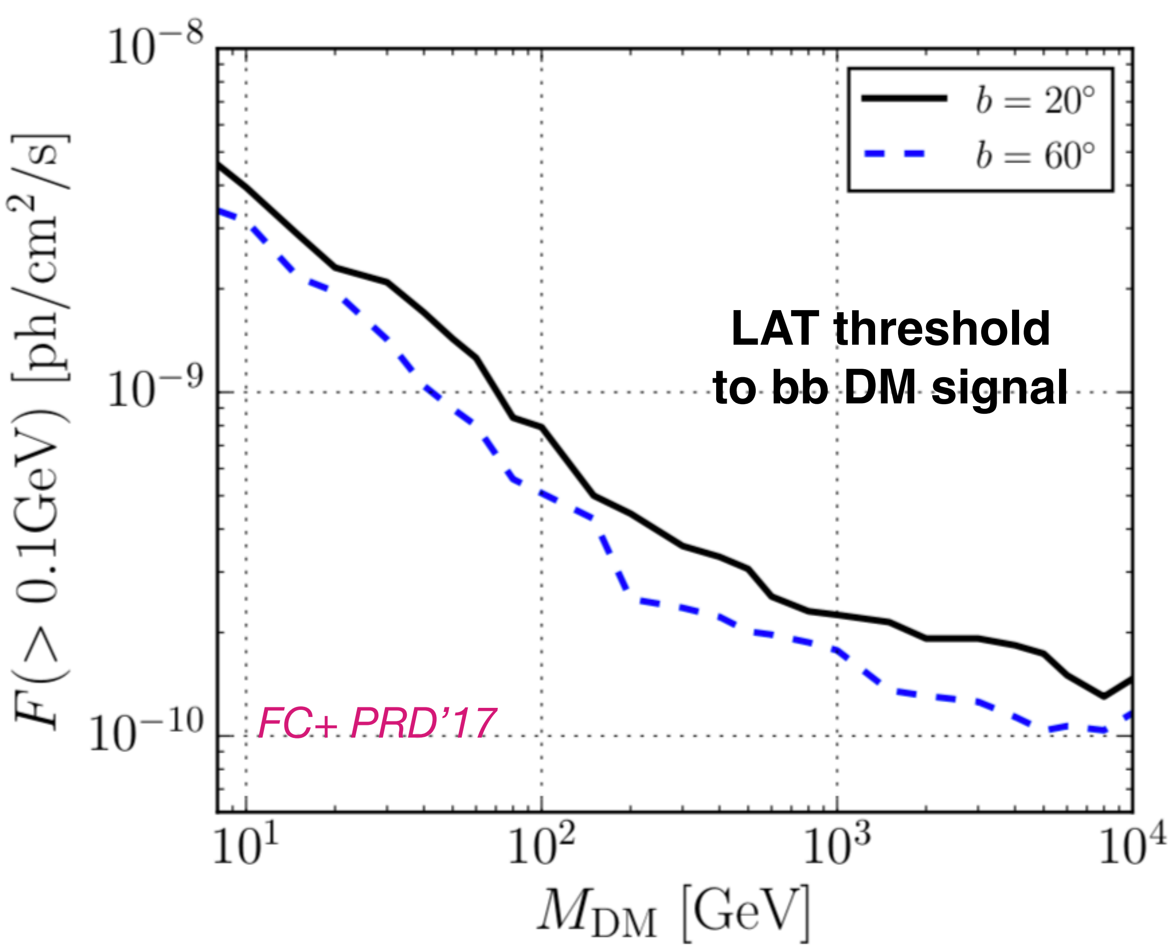
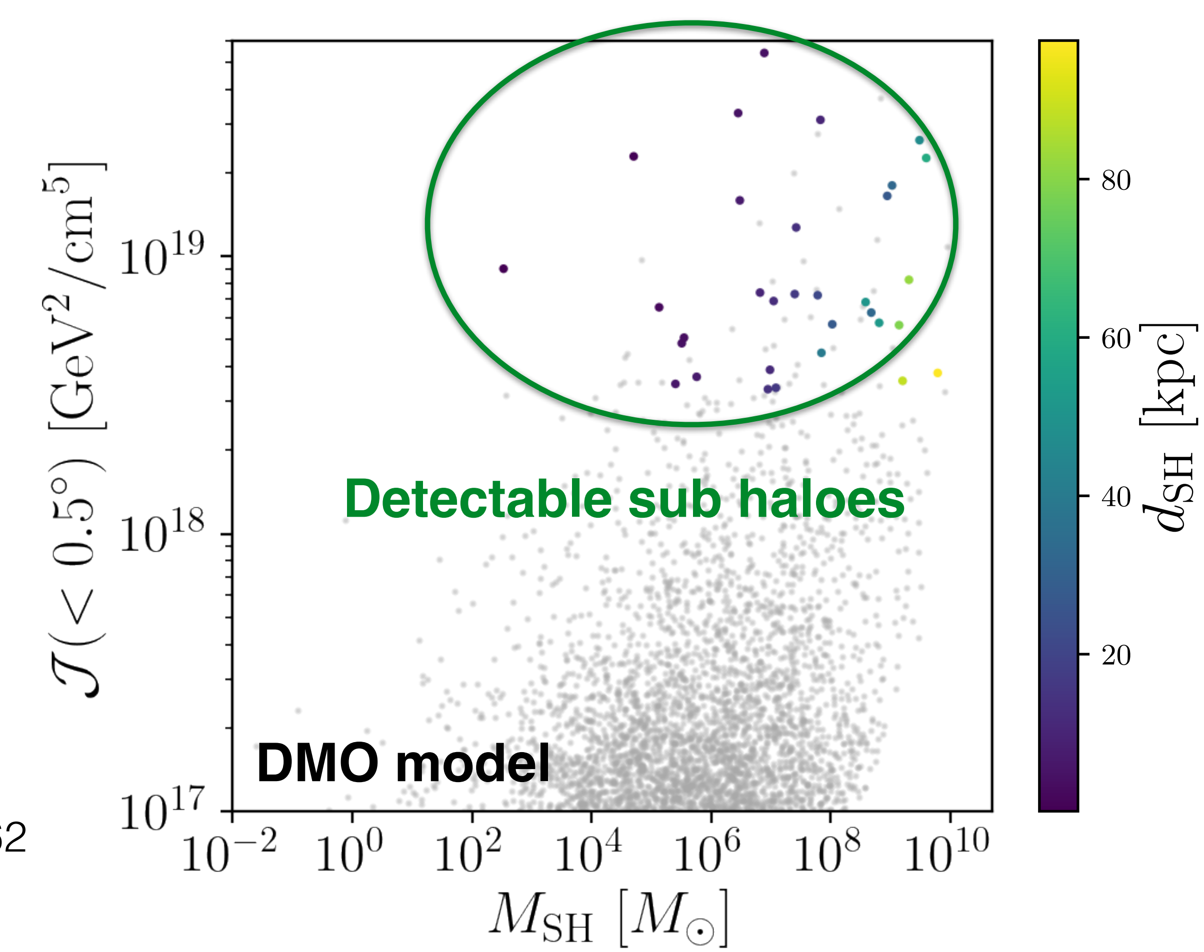
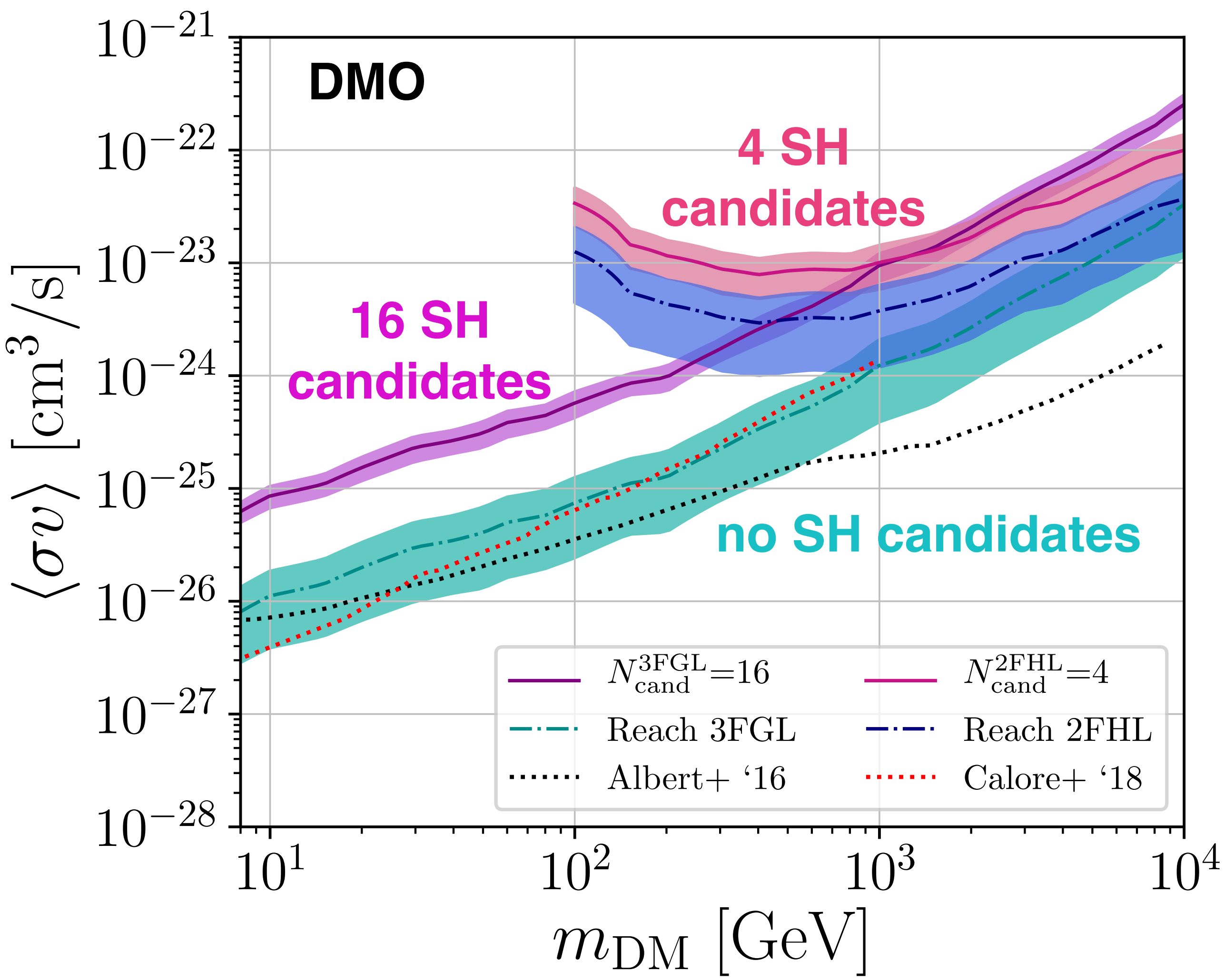


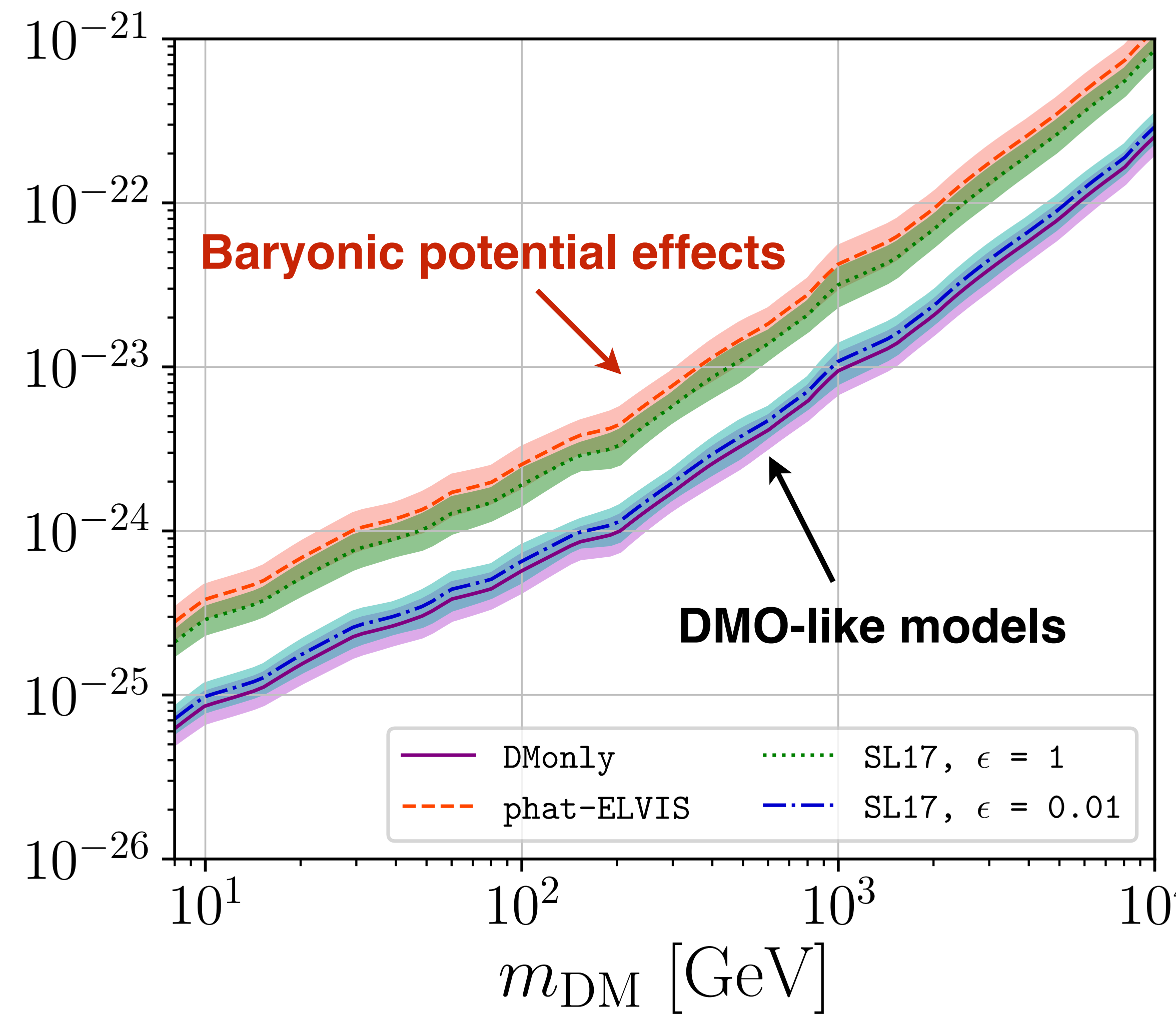


Limits from dark sub haloes searches

- 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 and sub halo spatial extension

Di Mauro, Stref, FC PRD'20

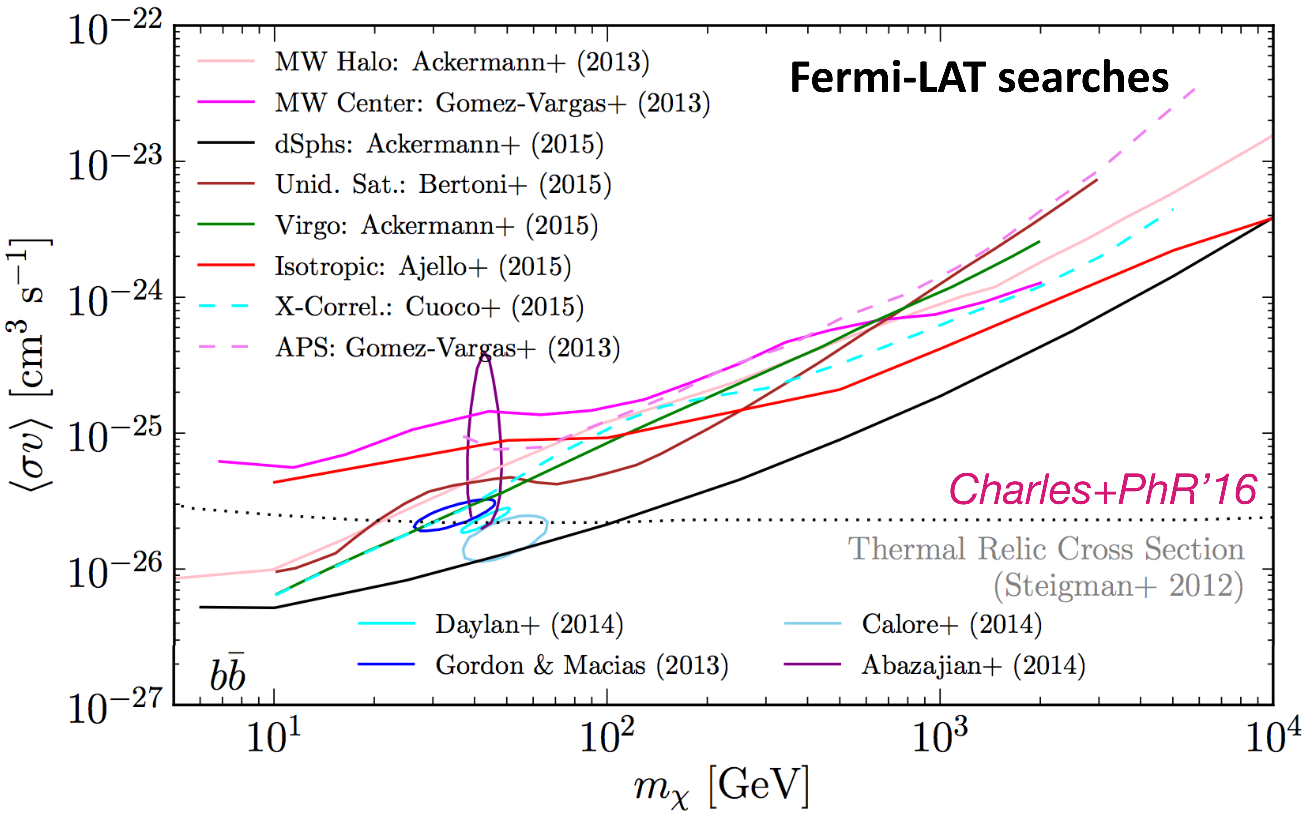


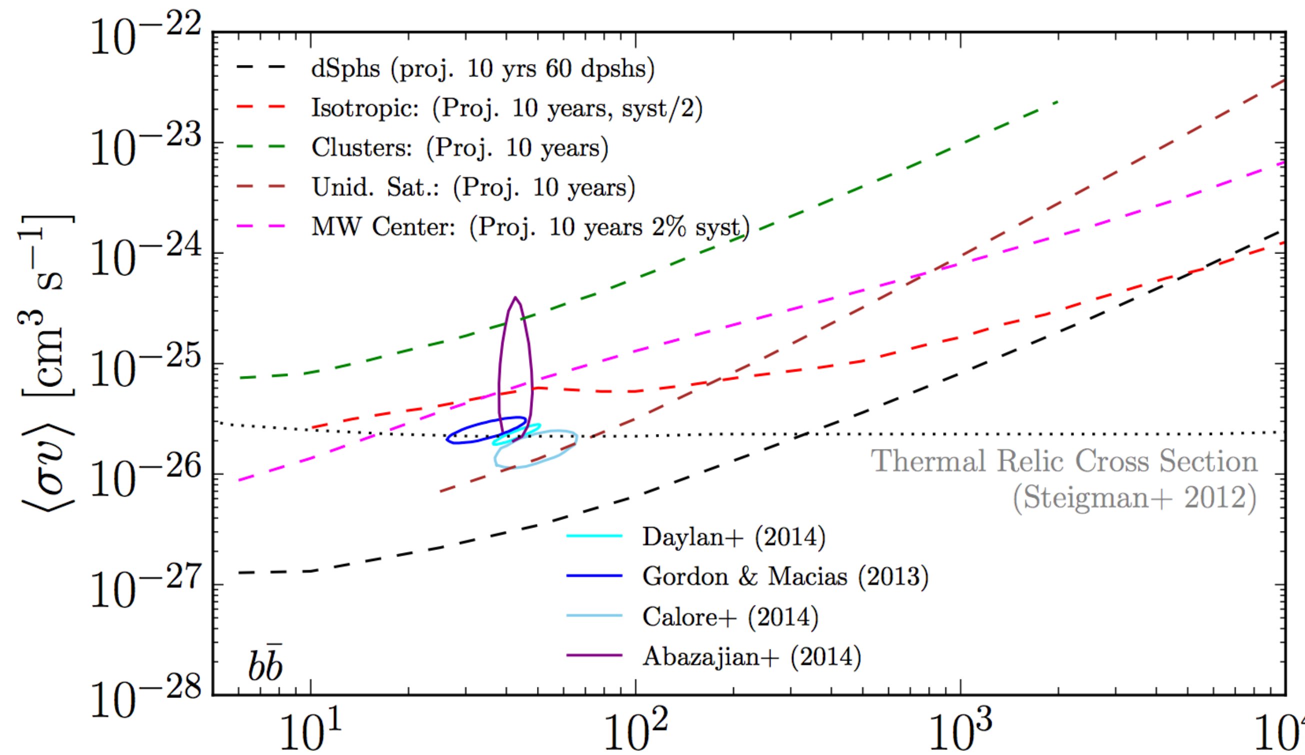


FC+ Galaxies'19

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

GeV photons: multi-target constraints

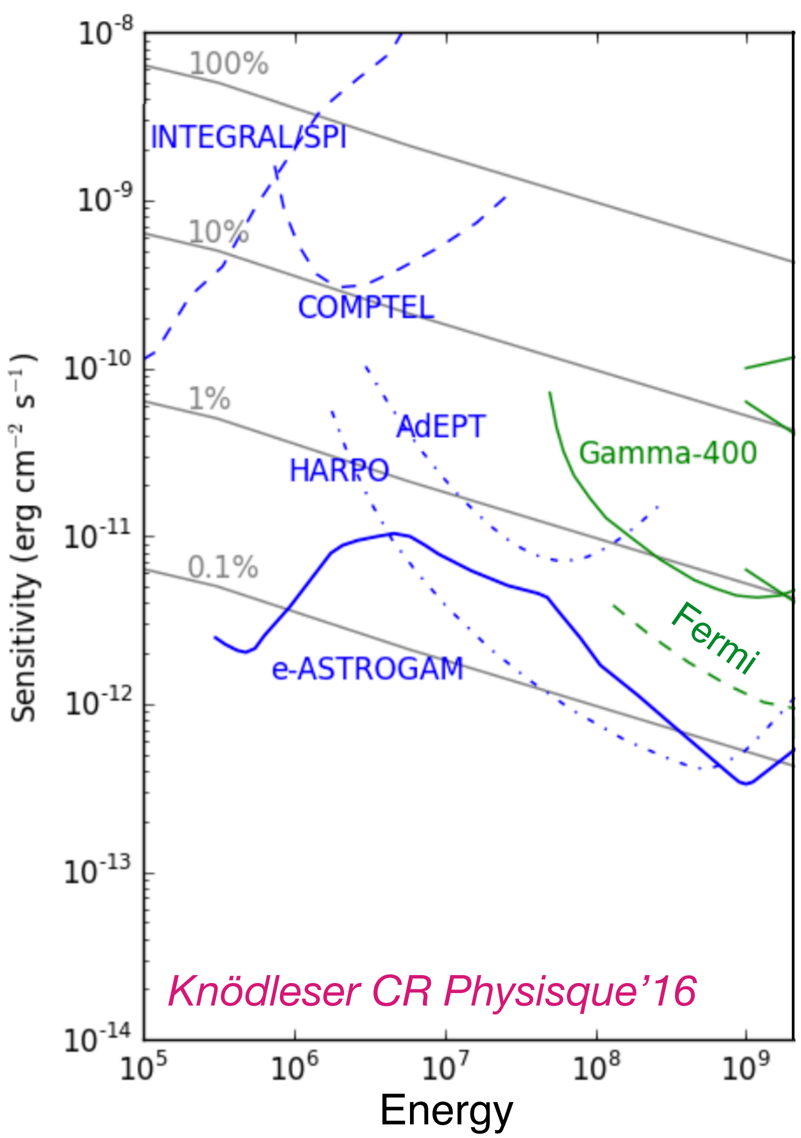


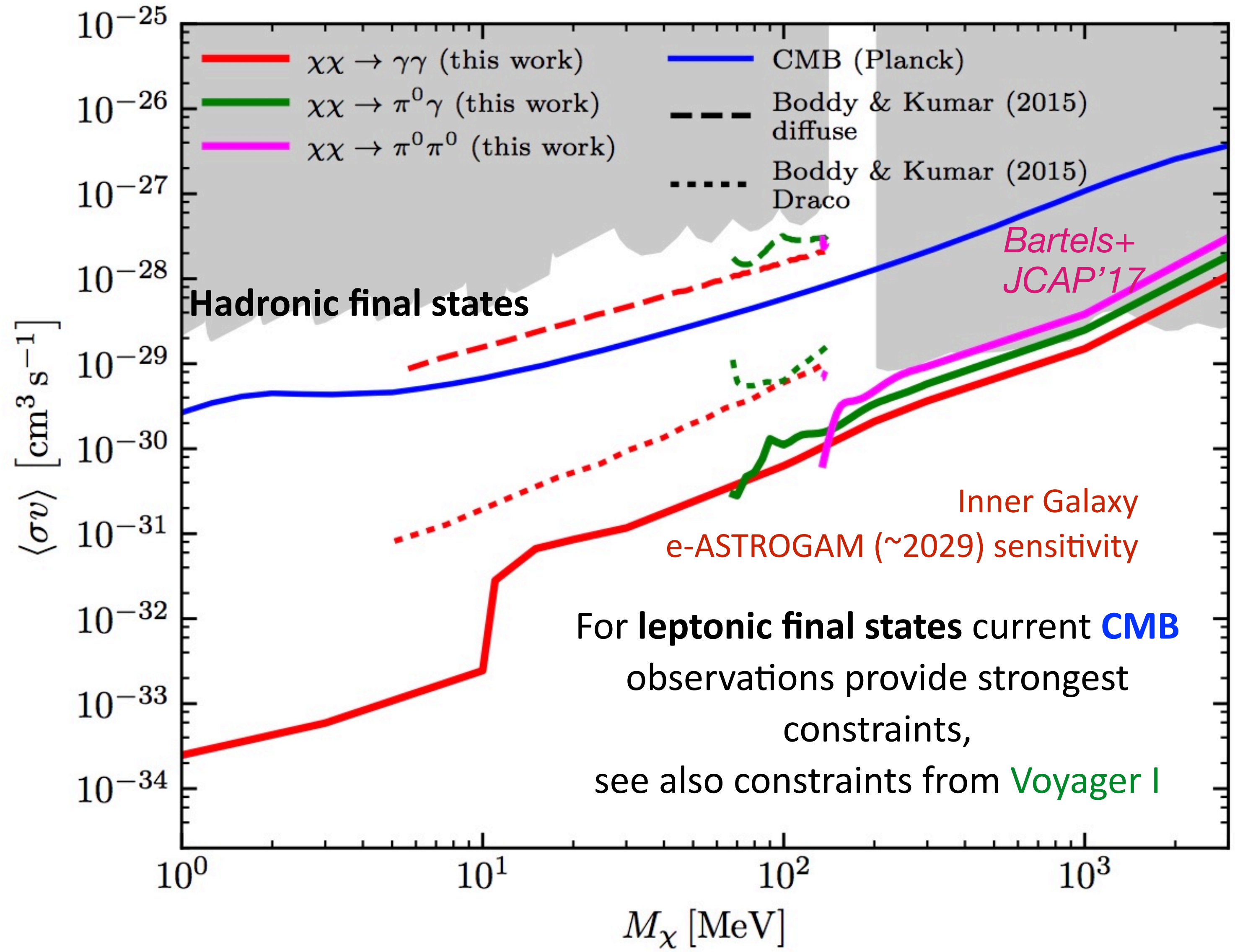


"MeV gap" Amego, e-ASTROGAM, GECCO, etc

HAWC, CTA

The sub-GeV sensitivity gap

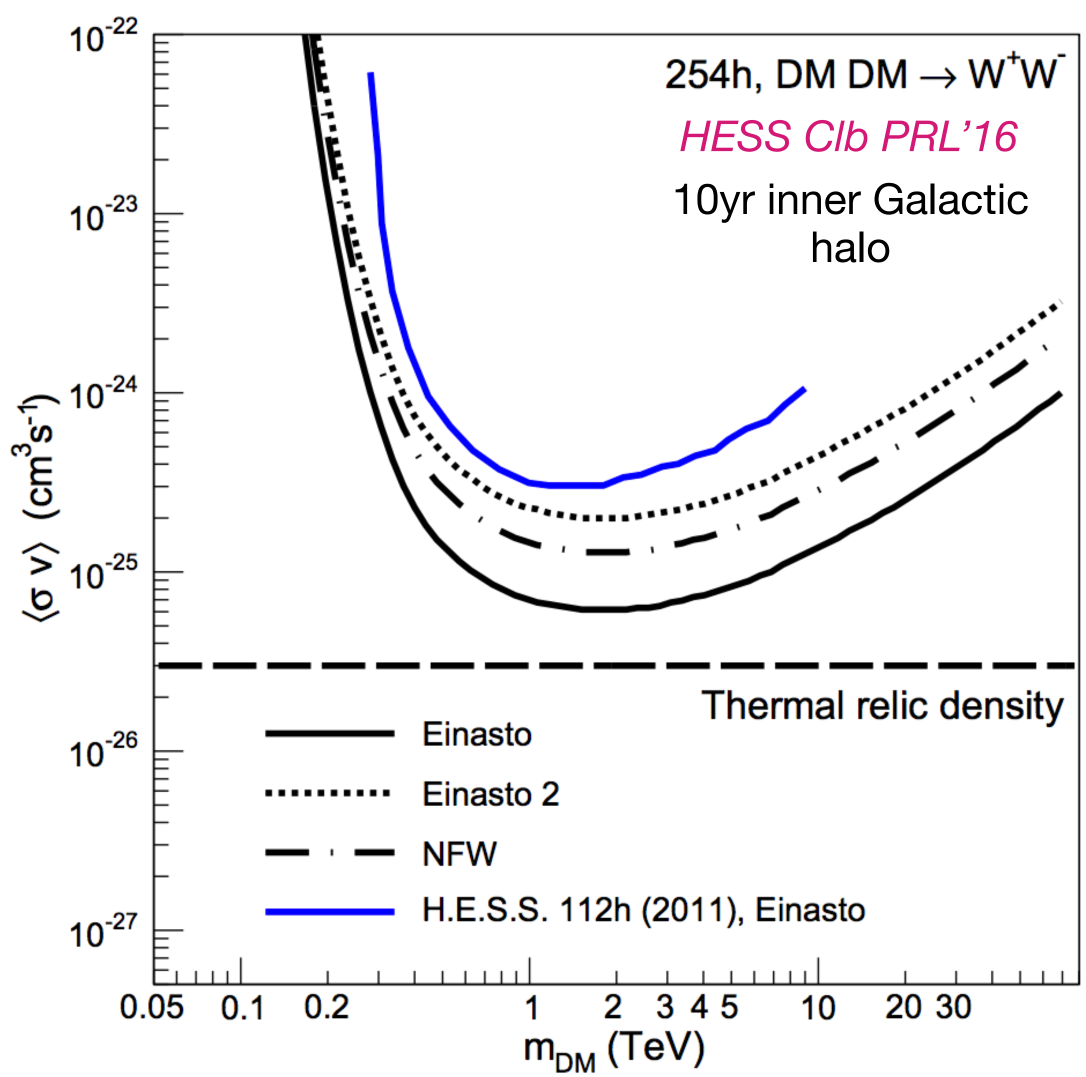


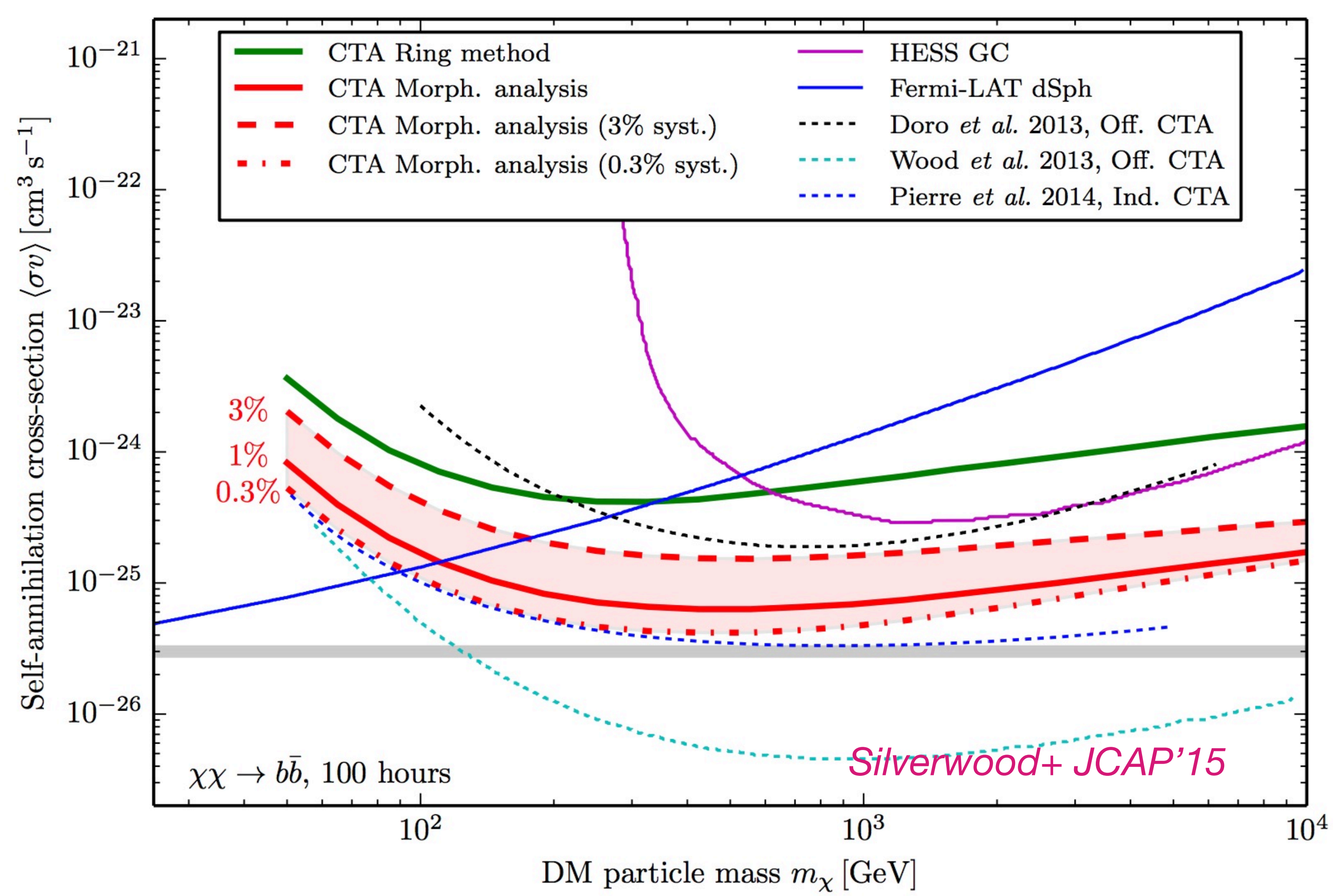


- Great potential in the unexplored MeV/sub-GeV range with new, high energy resolution instruments (e.g. **Amego**; **e-ASTROGAM**)
- Spectral features play an important role at sub-GeV energies *Boddy&Kumar PRD'15*
- Greatly improved DM limits prospects and discovery potential

Bringmann+PRD'17; Bartels+JCAP'17; Gonzalez-Morales+ PRD'17; De Angelis+'17

Very high-energy photons





Status

- Most constraining analysis at E>1TeV
- Other relevant targets: combined dSphs
- TeV scale thermal dark matter starts to be challenged *Baumgart+ 1808.08956; Rinchiuso+ PRD'18*

Future

- **HAWC** is already improving limits from dSphs (> 1 TeV) and Galactic centre (> 100 TeV) *Albert+ ApJ'18; Abeysekara+ JCAP'18*
- **CTA** (~2022) will improve HESS limits by factor up to 10 *Silverwood+ JCAP'15; Carr+ 2015; Lefranc+PRD'15*

Long-range forces

$$m_{\rm DM} \sim m_{W,Z} \sim 100\,{\rm GeV} \qquad\qquad m_{\rm med} \gtrsim m_{\rm DM}$$

Limit of contact-type interactions

$$m_{\rm DM} \gtrsim 100\,{\rm TeV} \gg {\rm m_{W,Z}}$$

Weak interactions manifest as long-range

=> emergence of non-perturbative effects (i.e described by instantaneous potentials) that can affect significantly the DM phenomenology

=> long-range force distorts the wave function of a pair of DM particles, and consequently affects all their interaction rates at low velocities

1. Sommerfeld enhancement — *Hisano et al., Phys.Rev. D71 (2005) 063528 [hep-ph/0412403]*
2. Bound state formation — *B. von Harling & K. Petraki, JCAP 1412, 033 (2014) [1407.7874]*

[This also occurs when DM communicates with the SM particles via non-SM mediators, light mediators]

Sommerfeld enhancement

Sommerfeld, 1931

- Calculated the scattering of a slowly moving electron-positron pair
- Coulomb force between the electron and positron becomes important and distorts the wave-functions of the incoming particles
- Higher probability of short range interactions enhances the cross section into two photons

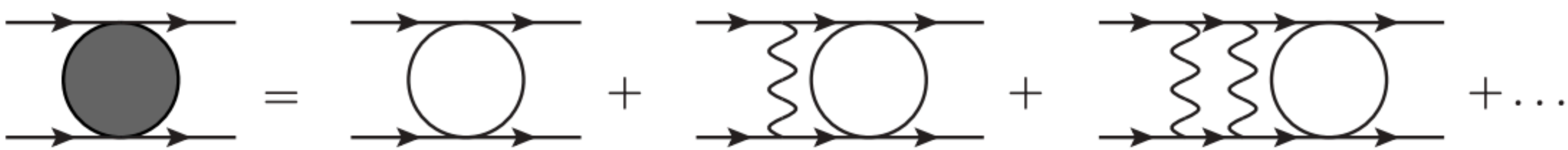


Figure 5.1: The white blob includes all short-range interactions, whereas the exchange of a mediator particle is a long-range effect. The grey blob includes all interactions with the Sommerfeld effect taken into account, which is obtained by performing a resummation over all possible ladder diagrams, where the mediator particles represent the rungs on the ladder.

L. G.van den Aarssen, PhD Thesis 2013

=> Finding the Sommerfeld enhancement factor boils down to solving the **Schrödinger equation** for the two-body wave-function of the annihilating particles, where potential V(r) actually consists of a potential and an annihilation part

Sommerfeld enhancement

$$-\frac{1}{2\mu}\nabla^2\psi_k = \left(\frac{k^2}{2\mu} - V(r)\right)\psi_k$$

Schrödinger equation

$$S(v) = |\psi_k(0)|^2$$

annihilation takes place at r = 0

$$\psi \to \exp^{ikz} + f(\theta)\frac{\exp^{ikr}}{r} \quad \text{for } r \to \infty$$

$$\sigma = S(v)\sigma_0$$

Factorization

Coulomb potential

$$S(v) = \frac{\pi/\varepsilon_v}{1 - e^{-\pi/\varepsilon_v}} \qquad \varepsilon_v \equiv v/\alpha.$$

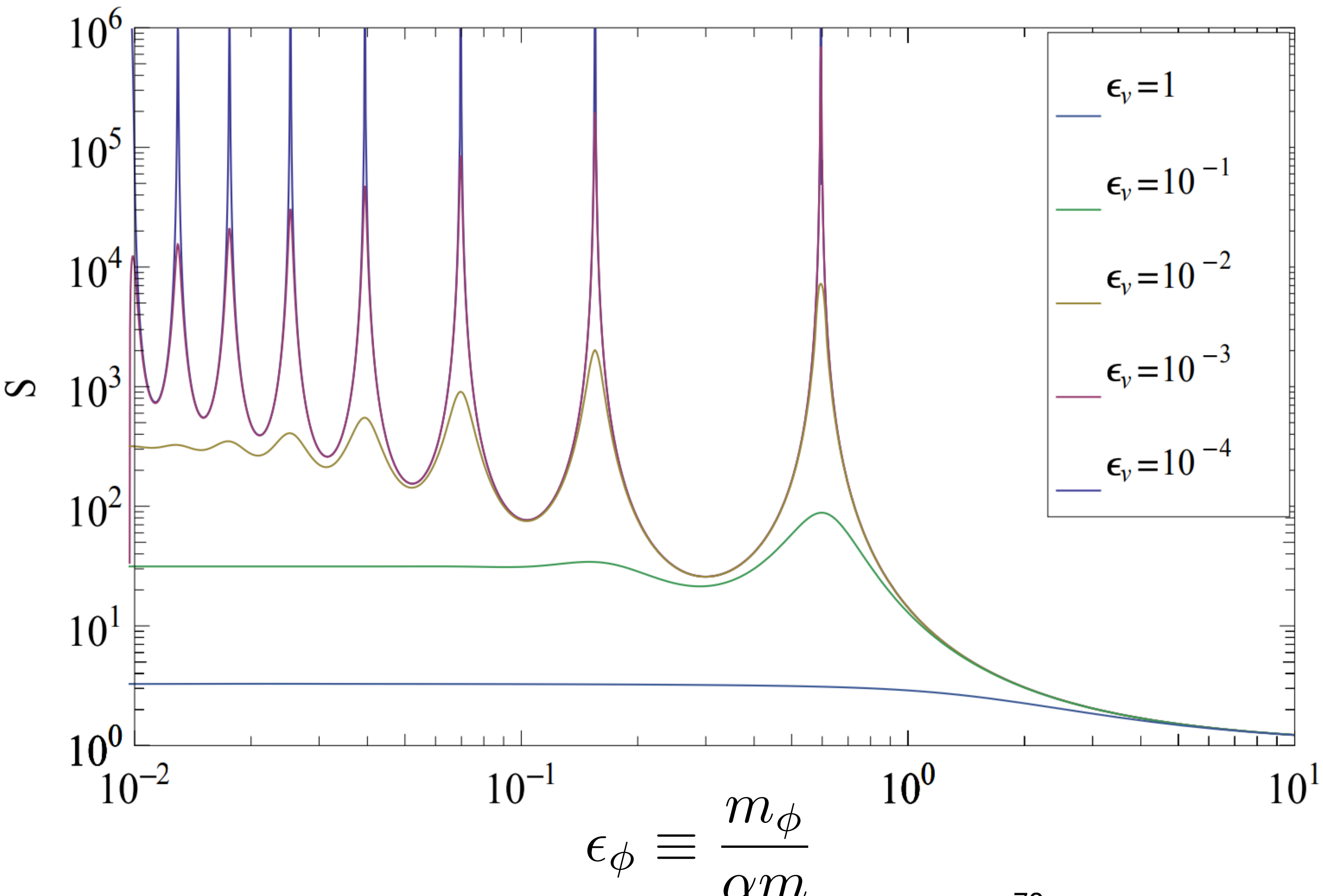
$$\sigma_{\rm ann} v \propto 1/v$$

Sommerfeld enhancement

Force carriers are usually massive => the repeated exchange of the mediator create an attractive Yukawa potential

$$V(r) = -\frac{\alpha}{r} e^{-m_\phi r} \quad m_\phi \ll m$$

No analytical solution exists



Hulthén potential

Analytical solution with resonances appearing at

$$m = n^2 \frac{\pi^2 m_\phi}{6\alpha}$$

$$\frac{m_\phi}{\alpha m} = \frac{\pi^2}{6} n^2$$

Bound state formation (BSF)

Unstable bound states

- Particle-antiparticle (positronium-like) bound states that can decay into radiation opens a new two-step DM annihilation channel
- Formation and decay of unstable bound states diminish the DM density in the early Universe *B. von Harling & K. Petraki JCAP 1412, 033 (2014) [1407.7874]*
- Bound state decay products enhance the high-energy radiative signals searched by telescopes (CMB and in galaxies today)

M. Cirelli et al., JCAP 1705(05), 036 (2017) [1612.07295]

Stable bound states

- Affect the galactic structure and the DM direct detection signatures

D. N. Spergel & P. J. Steinhardt, Phys.Rev.Lett. 84, 3760 (2000) [astro-ph/9909386]

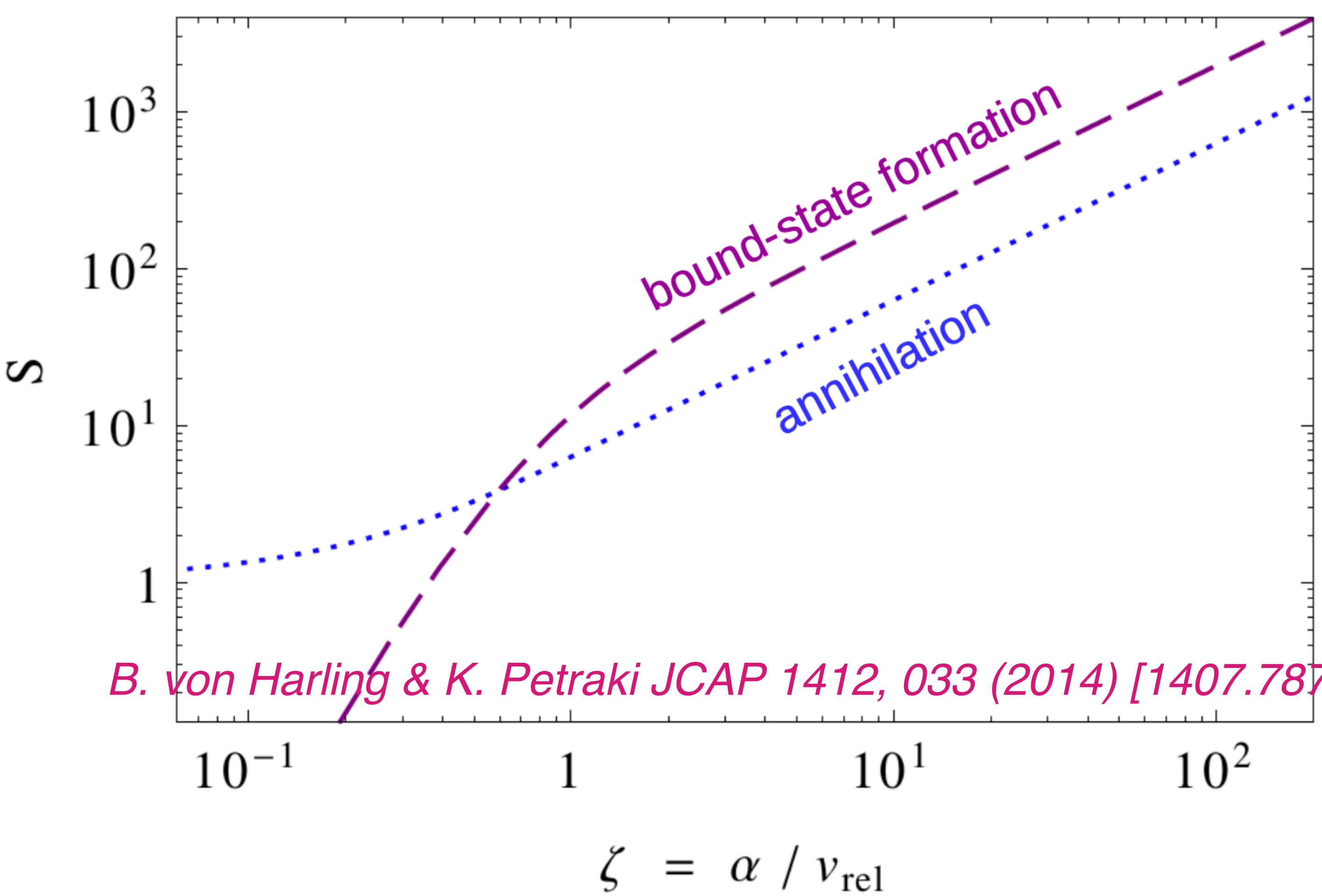
J. M. Cline et al., Phys.Rev. D85, 101302 (2012) [1201.4858]

[see systematic study in *Baldes, FC+, SciPost Phys. 9, 068 (2020) [2007.13787*]]

Bound state formation (BSF)

More generally

- DM capture into bound states, be they stable or unstable, invariably necessitates the **dissipation of energy**
- Detectable indirect signals from: (a) energy dissipated during BSF, and/or (b) transition between bound levels *L. Pearce & A. Kusenko, Phys. Rev. D87, 123531 (2013) [1303.7294]* *P. Asadi et al., JCAP 02, 005 (2017) [1610. 07617]*
- BSF cross sections in galactic environments may exceed the so-called canonical annihilation cross section (Sommerfeld enhanced)



B. von Harling & K. Petraki JCAP 1412, 033 (2014) [1407.7874]

- The formation of stable bound states in the early Universe changes the density of particles available to participate in the corresponding processes inside halos, and thus again affects the expected indirect signals => Need to **compute cosmology first**!

WIMPonium

P. Asadi et al., JCAP 02, 005 (2017) [1610. 07617]

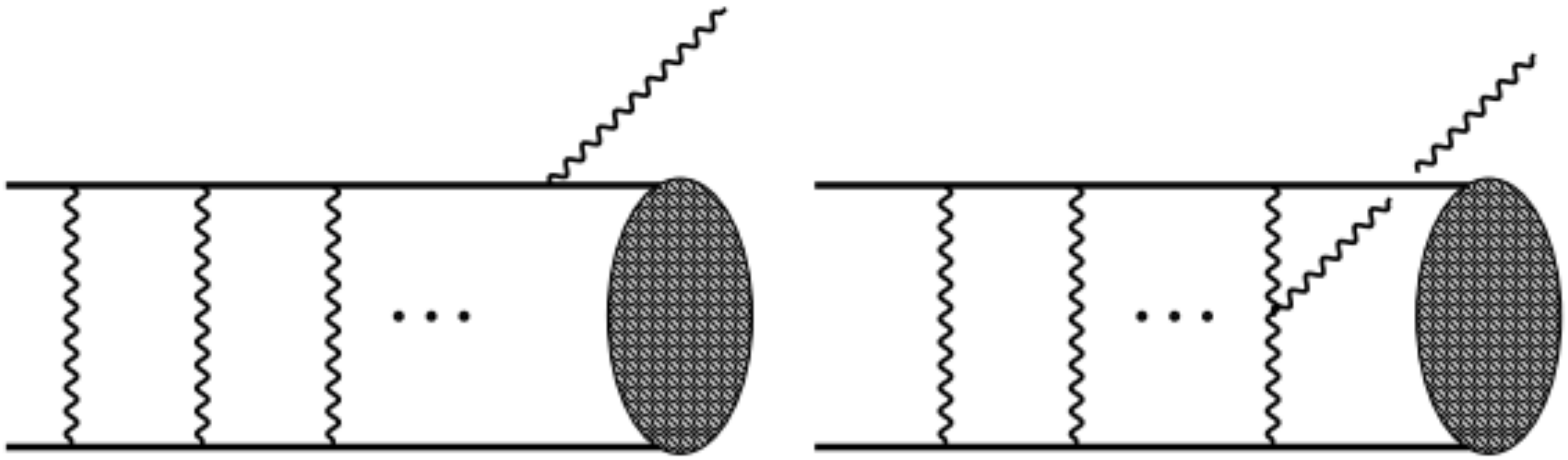


Figure 1. WIMPs exchange a ladder of weak gauge bosons, which gives rise to a non-local potential in the nonrelativistic limit. Finally, the dipole emission of a single photon can convert the initial, positive-energy scattering state to a negative-energy bound state, WIMPonium. (**Right:**) Since the potential contains charged force carriers, $W^{\pm}$, they can also emit radiation to capture into the bound state.

WIMPonium

P. Asadi et al., JCAP 02, 005 (2017) [1610. 07617]

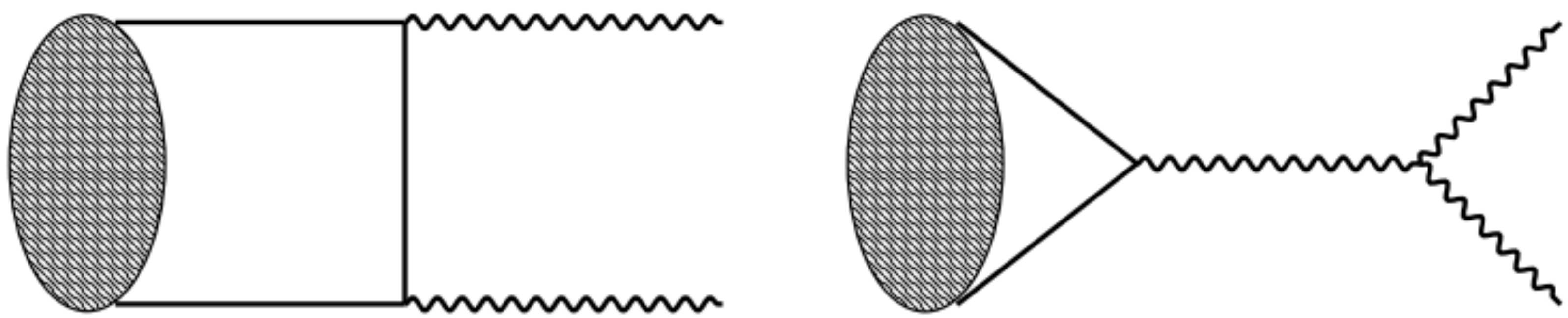


Figure 2. Since we consider WIMPonium constituents that are charged under the electroweak gauge group, its lifetime is set by weak-scale physics. Excited states typically transition to deeper bound states, but the deeper bound states will annihilate to SM particles. We note that if the WIMPonium is in a $^1S_0$ state, s-channel annihilation through a gauge boson is forbidden.

- The capture rate derived for the wino is **very small**, consistently well below the direct annihilation cross section
- Presence of **bound states will not directly enhance the annihilation rate** by a significant fraction
- This is the wino case! More relevant for models with **non-trivial dark sectors**

Velocity dependent cross-section

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

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

S-wave can be suppressed [example?] or models may allow for v-dependent cross sections [example?] => the connection between Early Universe and today annihilation is altered in a non-trivial way

Velocity dependent cross-section

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

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

- 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
- n=4: **d-wave** annihilation. This scenario is relevant if DM is instead a real scalar into Standard Model fermion/antifermion pairs

Gamma-ray flux for v-dependent xsec

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

$$\frac{d\Phi}{dE_\gamma} = \frac{\langle \sigma v \rangle_0}{2m_{\rm DM}^2} \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \times$$

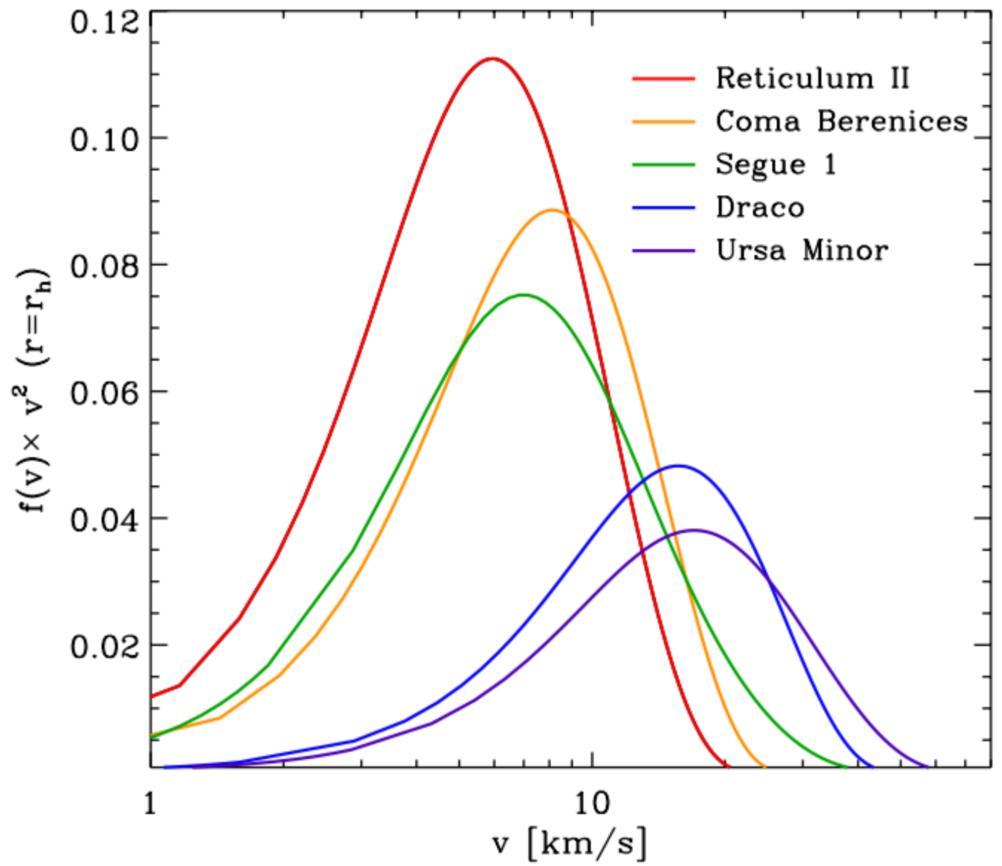
$$\frac{1}{4\pi} \int_0^{\Delta\Omega} d\Omega \int_{\rm l.o.s} ds \int d^3 v_1 f(r(s,\Omega), \mathbf{v}_1) \int d^3 v_2 f(r(s,\Omega), \mathbf{v}_2) S(|\mathbf{v}_1 - \mathbf{v}_2|/c)$$

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

DM phase-space distribution

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

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

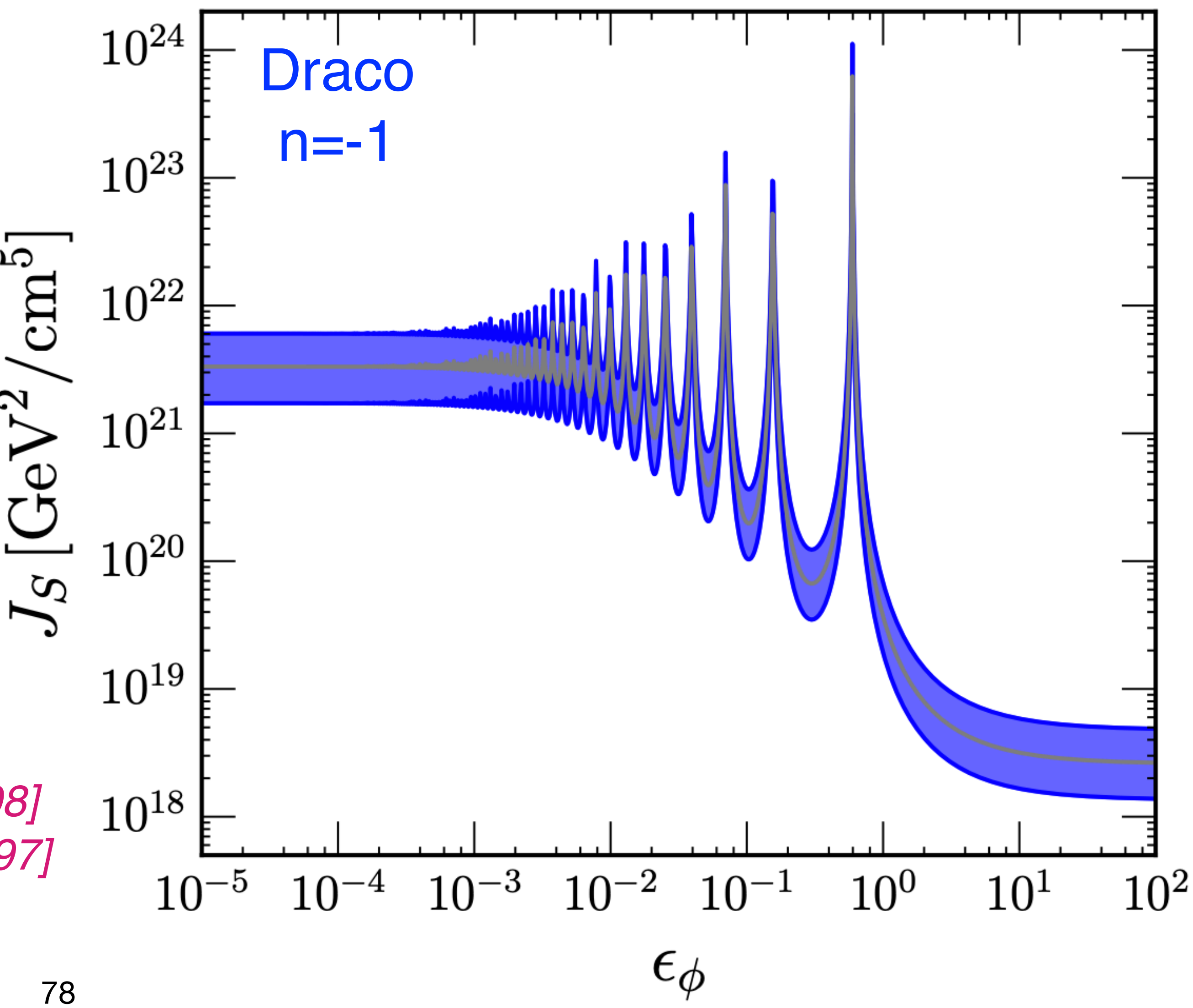


v-dependent J-factor

$$J_S(\Delta\Omega) = \int_0^{\Delta\Omega} d\Omega \int_{\rm l.o.s} ds \int d^3v_1 f(r(s,\Omega),\mathbf{v}_1) \int d^3v_2 f(r(s,\Omega),\mathbf{v}_2) S(|\mathbf{v}_1 - \mathbf{v}_2|/c)$$

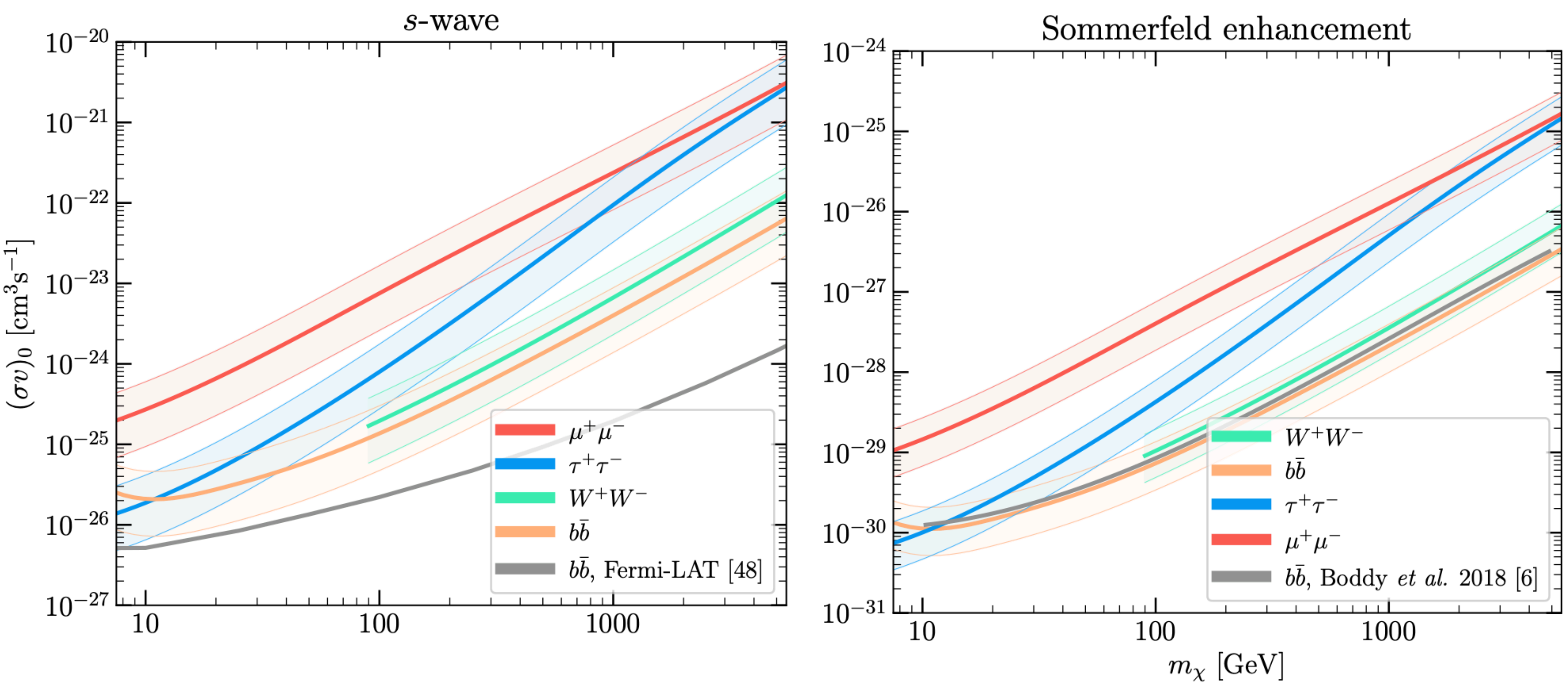
$$J_S(\Delta\Omega) \xrightarrow{S=1} J(\Delta\Omega) \int_0^{\Delta\Omega} d\Omega \int_{\rm l.o.s} \rho(r(s,\Omega)) \times \rho(r(s,\Omega))\, ds$$

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



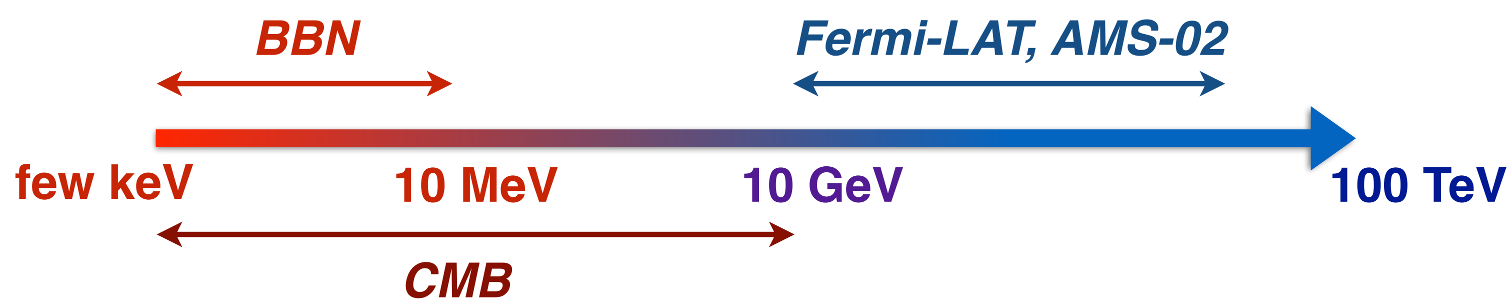
Boddy et al., Phys. Rev. D 95, 123008 (2017) [1702.00408]
Boddy et al., Phys. Rev. D 102, 023029 (2020) [1909.13197]

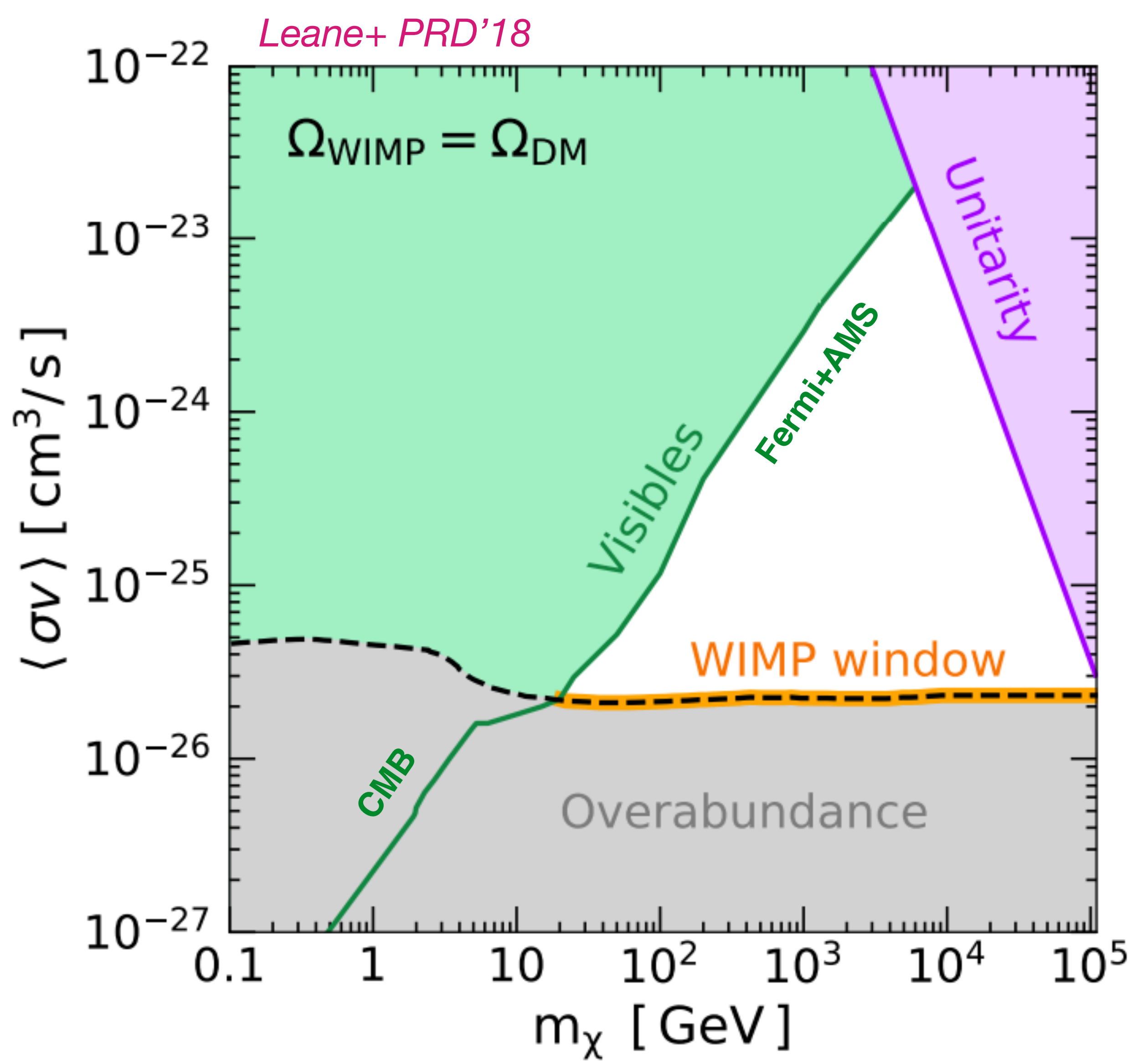
Impact on DM limits



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

The WIMP window





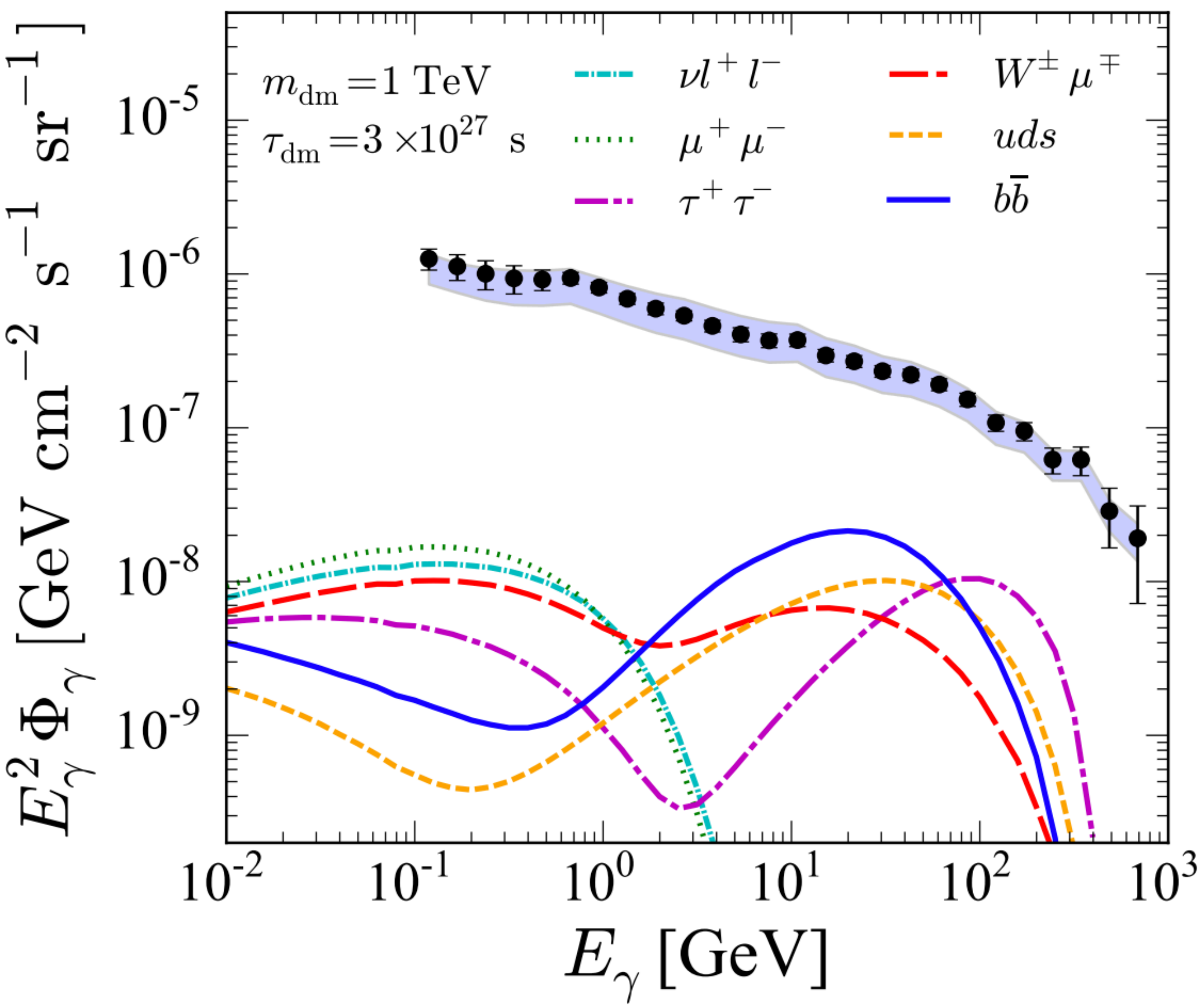
- **Total cross-section** sets **relic abundance**
- **Indirect detection** provides model-independent UL on annihilation **cross-section for a given final state**

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

Decaying WIMP

DM models: gravitino and axino in RPV models; or leptophilic models (positron fraction)

$$m_{\rm dm}\,,\ \tau_{\rm dm}\,,\ \frac{dN_I}{dE}\quad (I=\gamma,\, e^{\pm},\cdots)$$



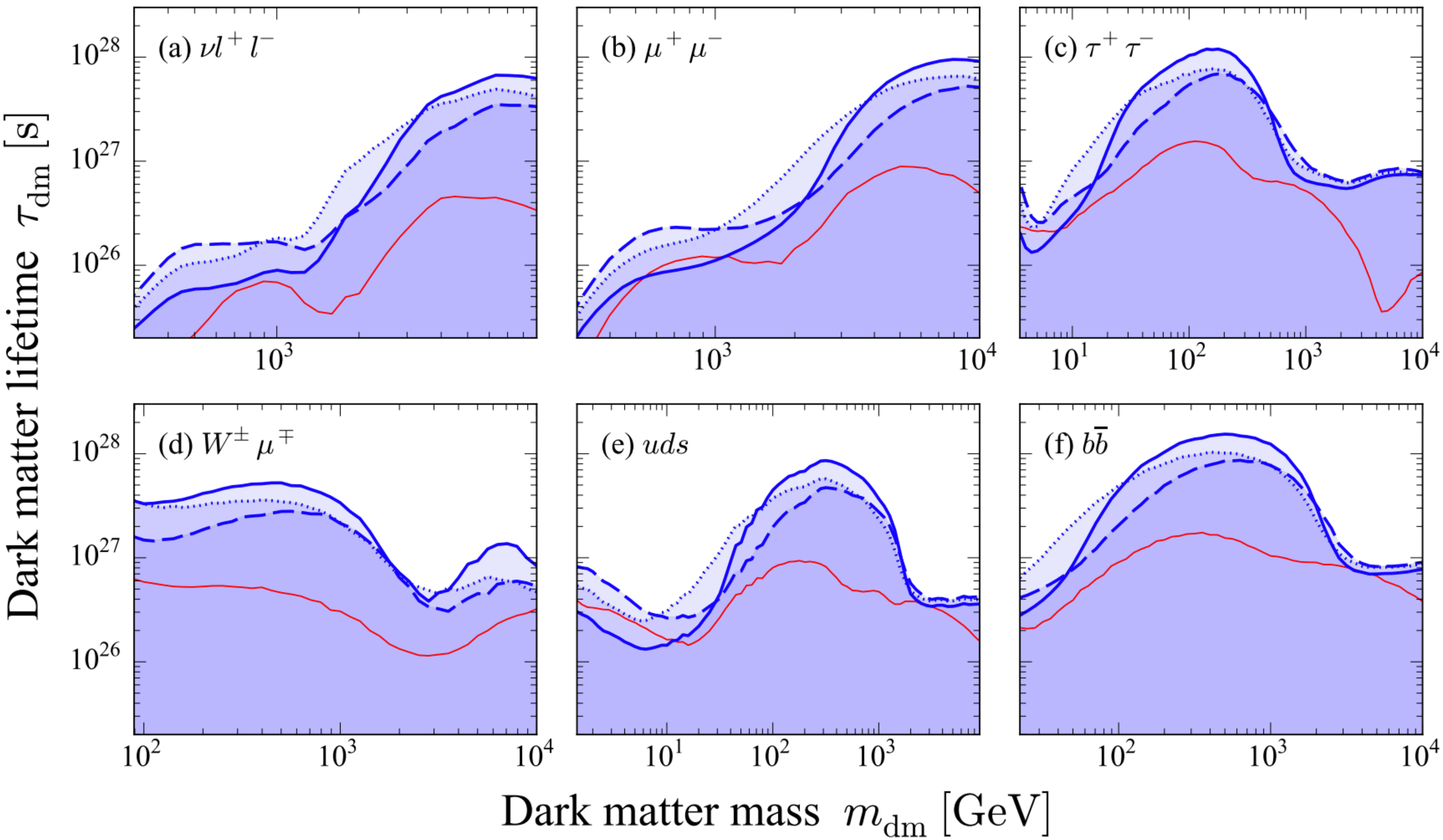
Extragalactic signal
Considering prompt and IC emission
Modelling astrophysical bkg EGRB

Ando & Ishiwata, JCAP 05 (2015) 024 [1502.02007]

[For a review see *Ibarra+ Int.J.Mod.Phys. A28 (2013) 1330040*]

Limits on decaying WIMP

Ando & Ishiwata, JCAP 05 (2015) 024 [1502.02007]

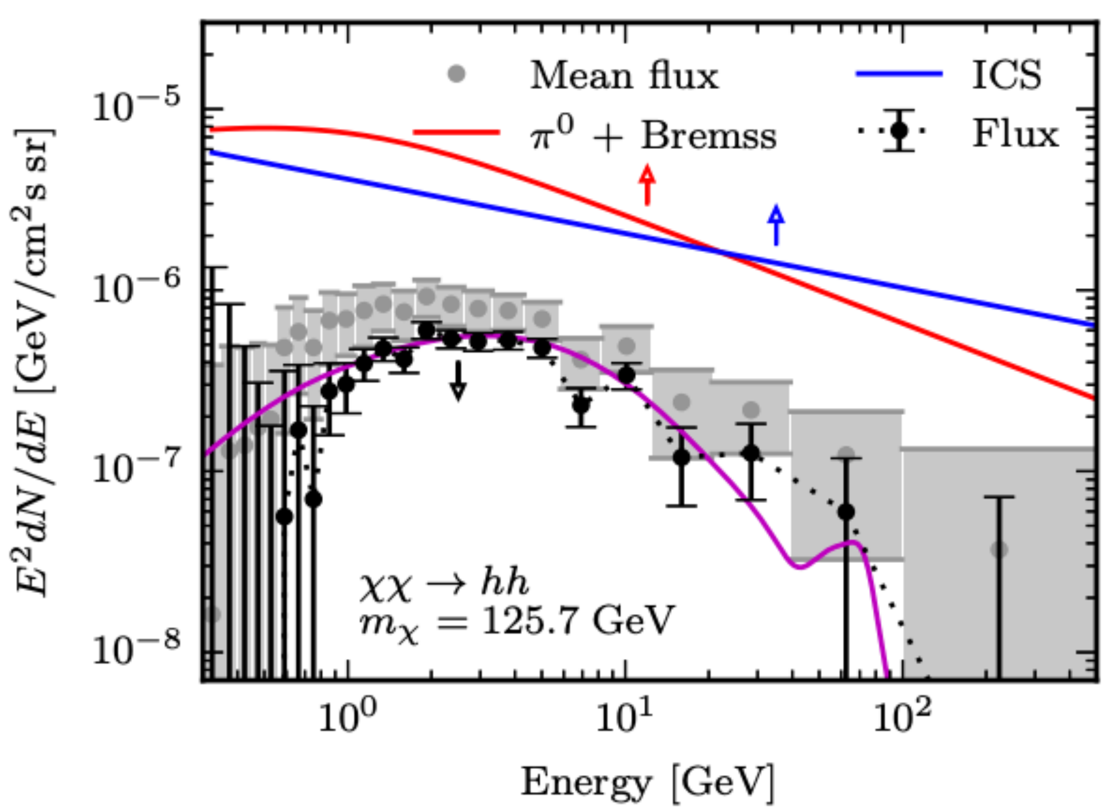


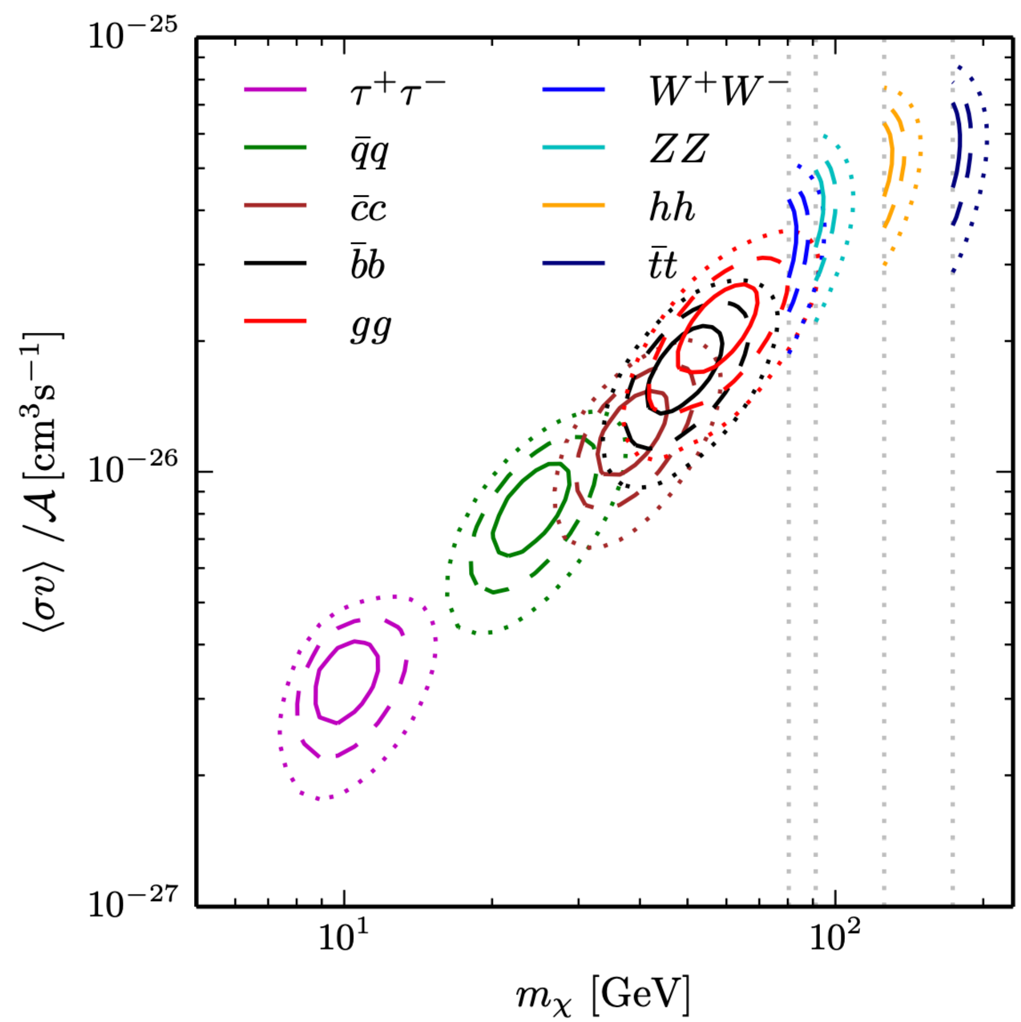
[Other prototypical decaying DM candidate: sterile neutrino, constrained from X-rays, see *Iakubovsky, Advances in Astronomy and Space Physics (2014); Hitomi Collab, ApJ, 837, L15 (2017)* and refs. therein]

Model- vs feature-based approach

- DM-specific features can be studied one at a time and allow to derive more general conclusions (as we have seen so far)
- Models are predictive => can link different observables (direct/indirect/collider) and break degeneracies

Difficult to distinguish among different DM scenarios based on ID results only
Example: **Fermi GeV excess**





Calore et al., Phys. Rev. D 91, 063003 (2015) [1411.4647]

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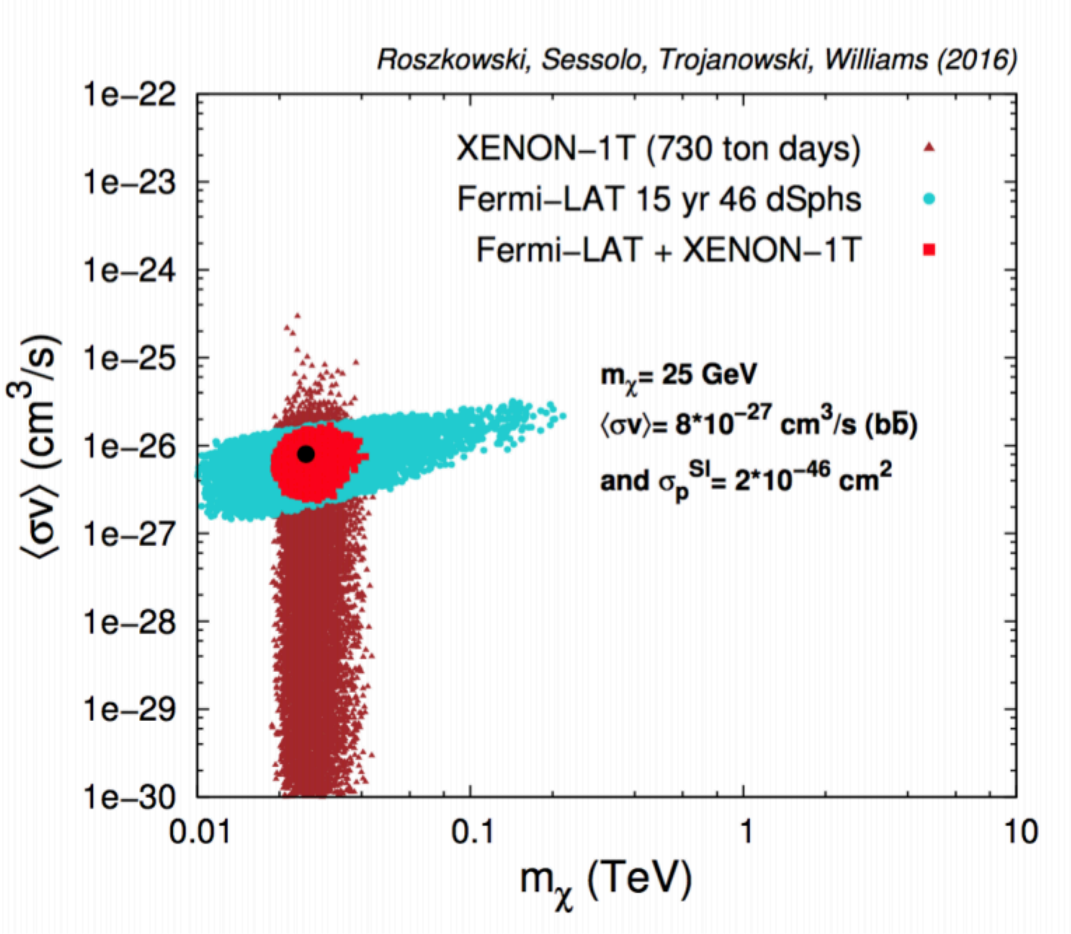
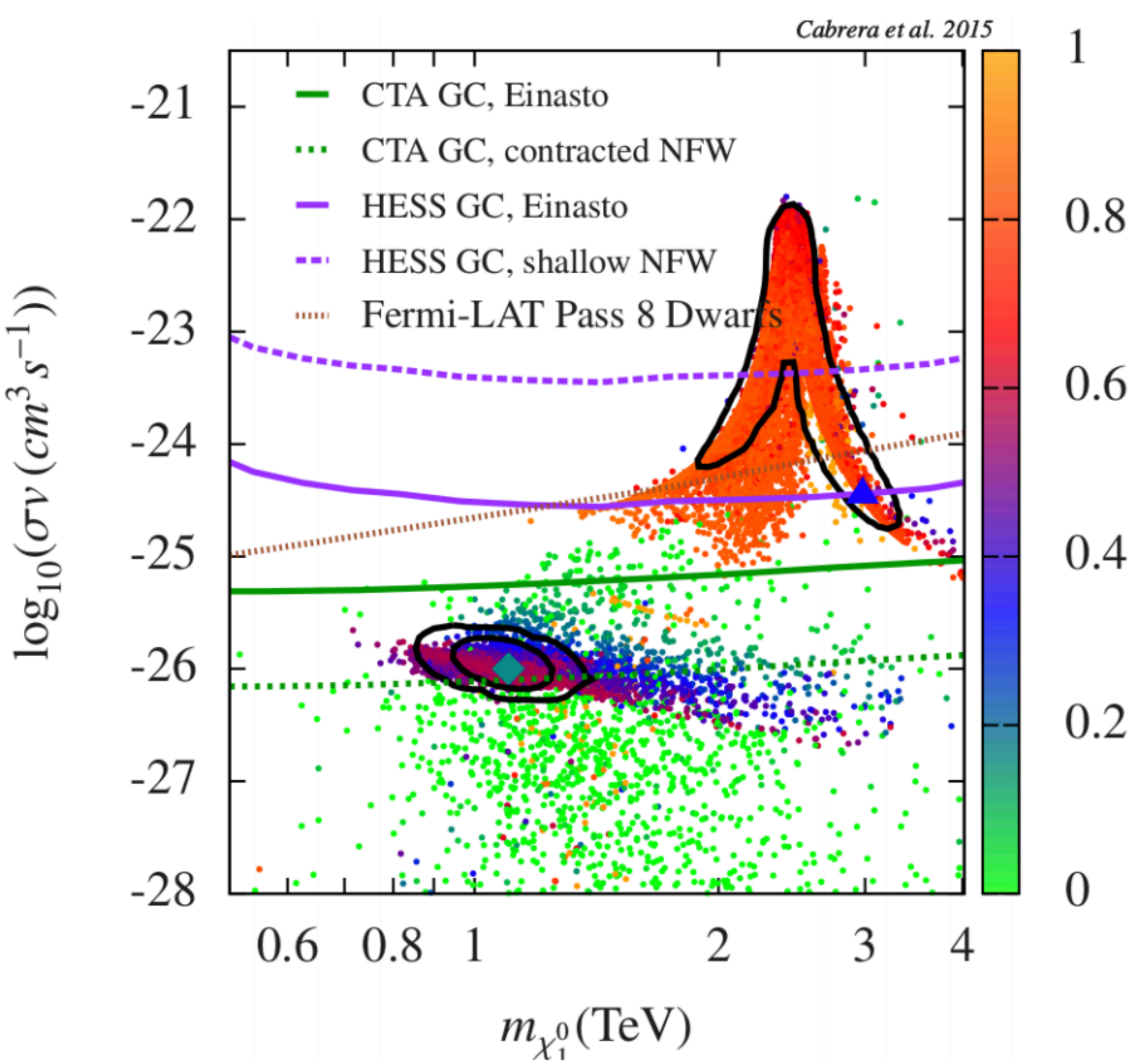
<u>How to break degeneracies?</u>



For a low DM mass a good reconstruction of m_χ in DD can help interpret the results of ID searches

pMSSM neutralino DM

- Most general parametrization of the MSSM, based only on assumptions of Minimal Flavor Violation, R-parity conservation, and a level of CP violation not exceeding that of the SM
- 19 parameters, all defined at the SUSY scale
- Relic abundance constraint be fairly easily satisfied in different parts of the parameter space for different neutralino WIMP compositions



- Global scans of the parameter space (relic abundance, DD, colliders)
- 2-3 TeV mass, wino-like neutralino
- CTA with ~ 500 h of observation of the Galactic Center will probe most of the pMSSM parameter space with DM mass in the TeV range (otherwise out of reach)

Cabrera et al., Phys. Rev. D 92, 035018 (2015) [1503.00599]