



Searches for Dark Matter with gamma rays

Next Frontiers in the Search for Dark Matter



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Laboratoire d'Annecy-le-Vieux de Physique Théorique



The dark matter landscape

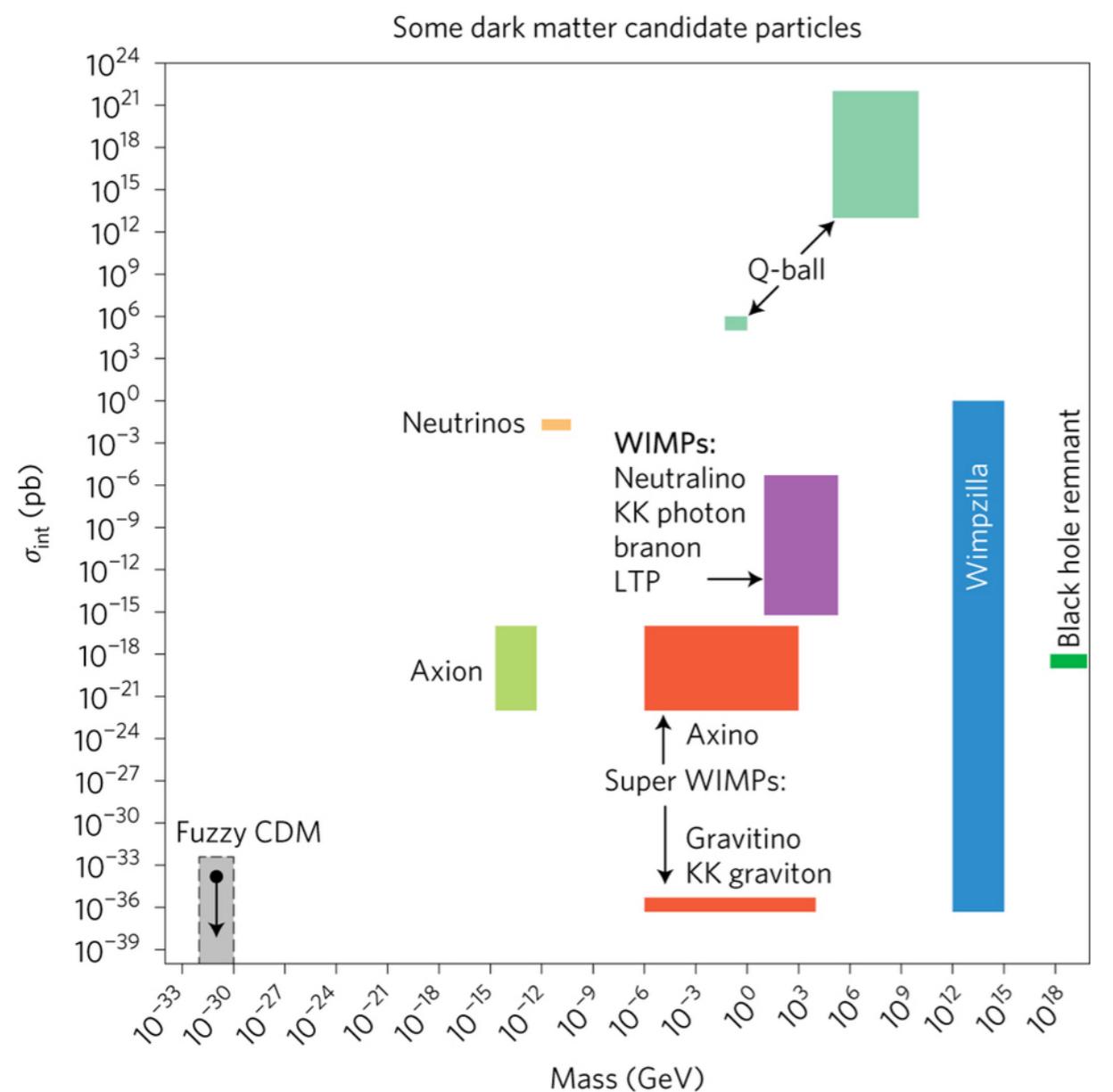
10^{-22} eV

10^{-2} eV

1 GeV 1 TeV

10^{19} GeV
 (10^{-5} g)

10^{57} GeV
 (10^{33} g)

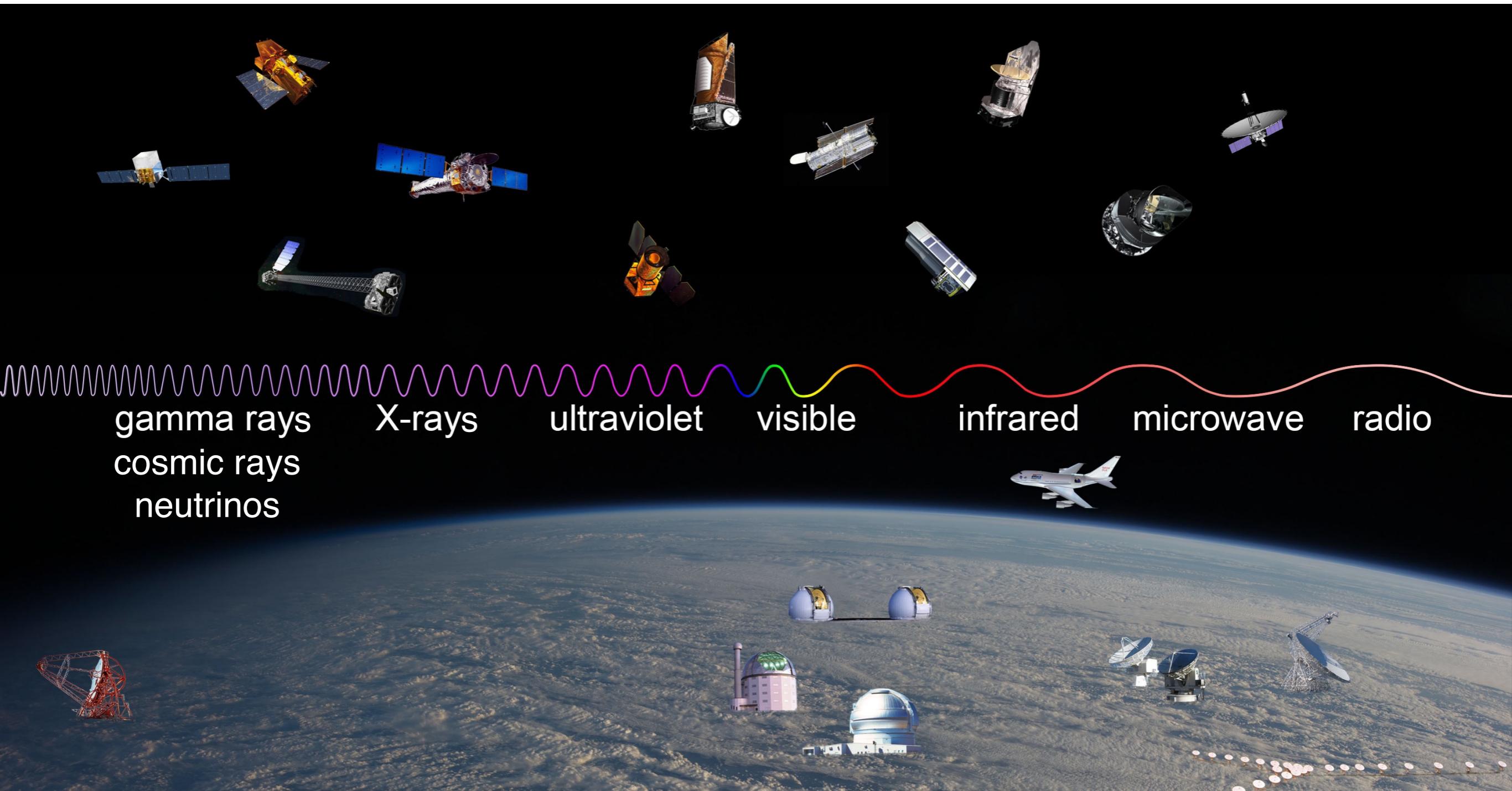


- Identification strategies are necessarily (more or less) model dependent
- The **theoretical prejudice in dark matter searches** is also set by what we can probe with available data
- You always need some sort of signature of your model!

Conrad & Reimer, Nature Physics 13 (2017) 224-231

The astronomical data landscape

Ground-based telescopes and spaceborne instruments dedicated to detection of electromagnetic radiation, cosmic rays and HE neutrinos



Indirect DM detection

How can we use astroparticle experiments to get insights into the DM nature?

General goal & method:

- * To identify (theoretically) some effects (a.k.a signatures) which yield information about the dark matter nature
- * To carry out data analysis to discover these effects on top of the (often dominating) astrophysical background(s)
- * When data are not available, to actually ask for observation time...

Guaranteed results:

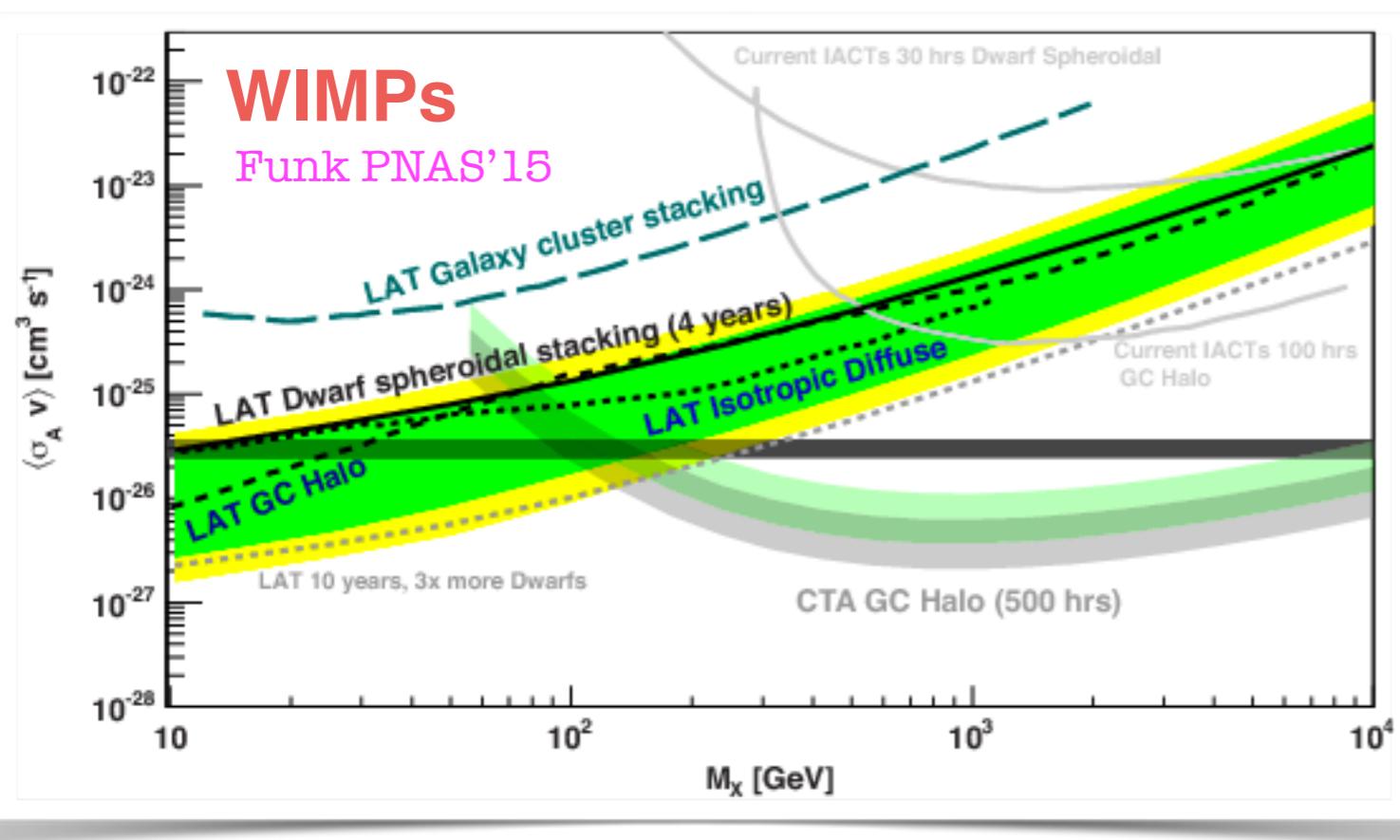
1. Constraints the dark matter nature
2. A better understanding of the astrophysical background

What DM models?

Any model which can affect the fluxes of observable charged particles and/or photons through **new production mechanisms or distortion effects**.

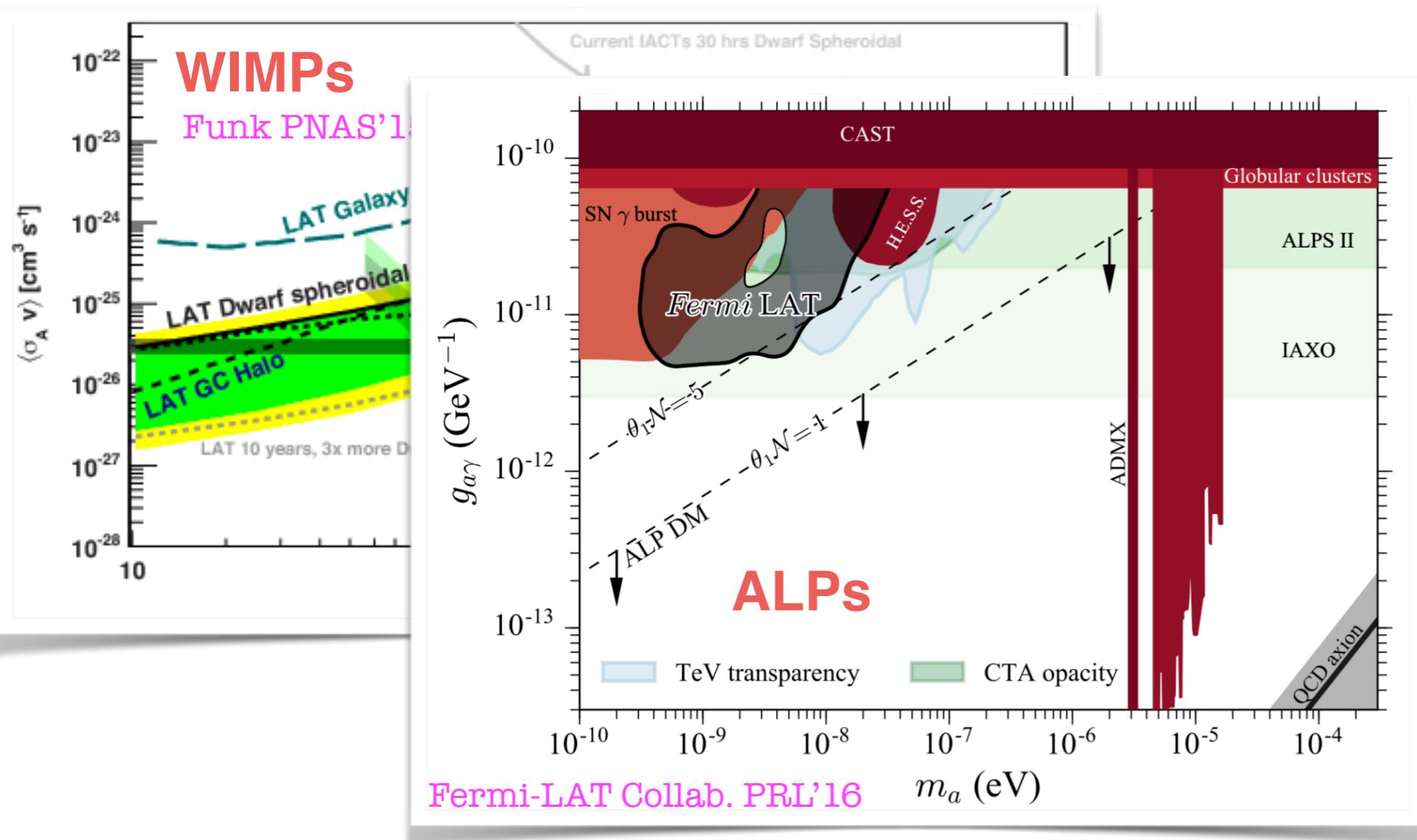
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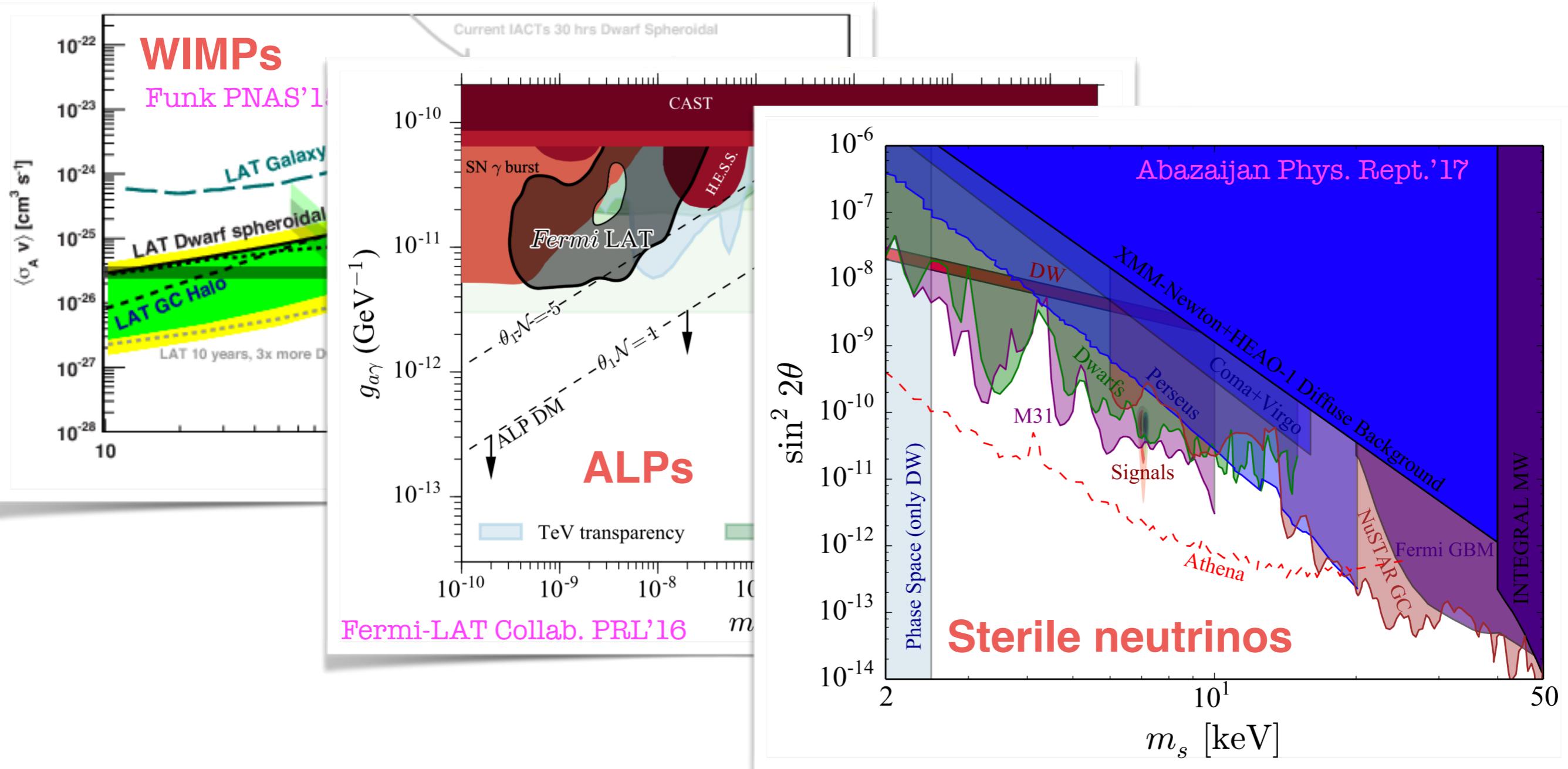
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Weakly Interacting Massive Particles (WIMP)

The dark matter landscape

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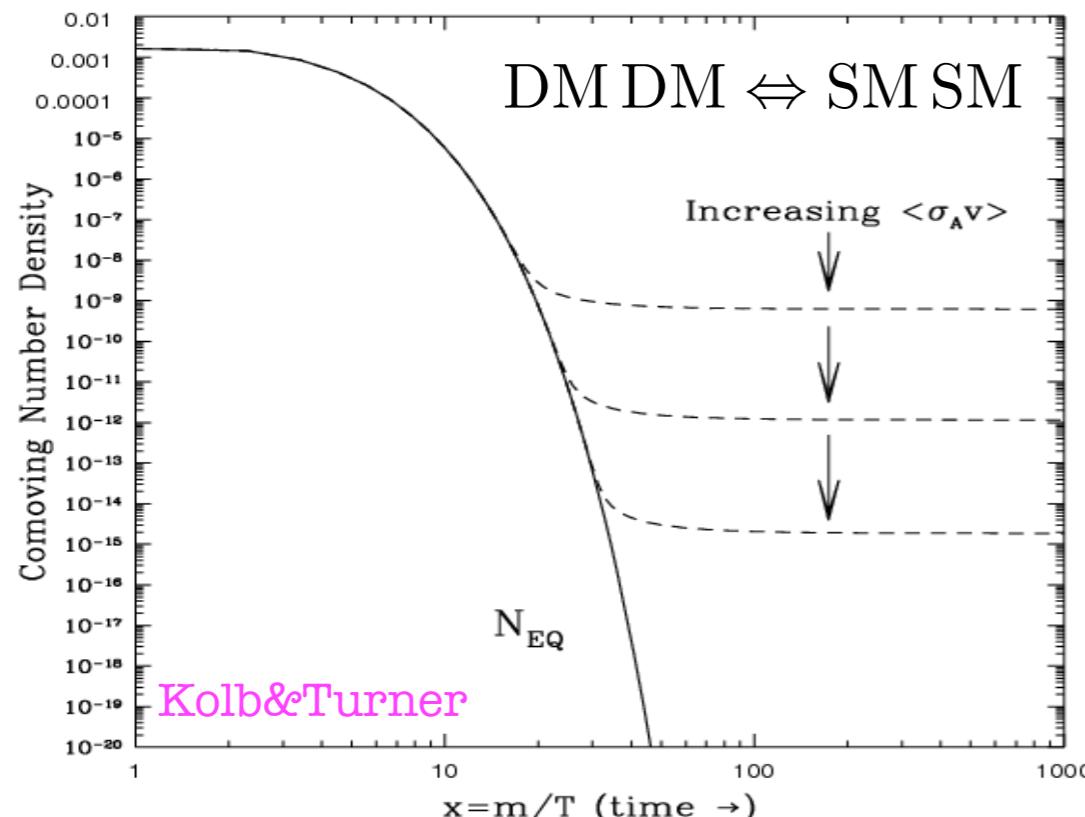
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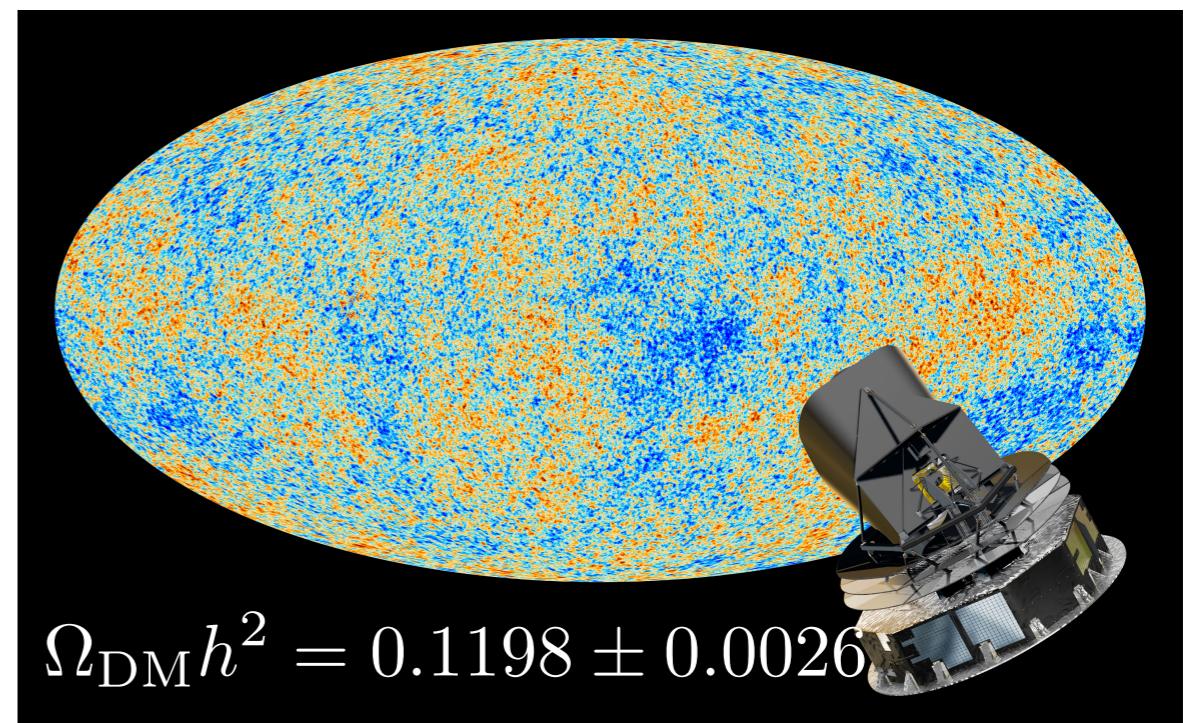
10^{19} GeV
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Freeze-out production mechanism



CMB temperature anisotropy

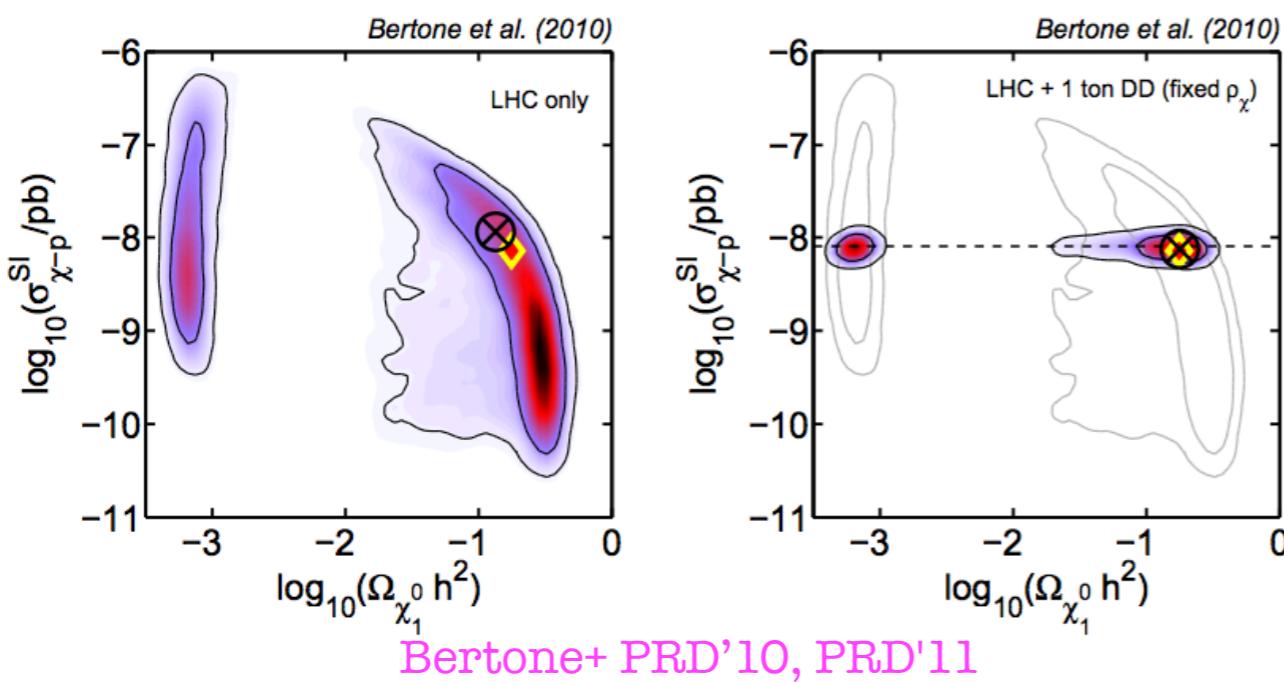
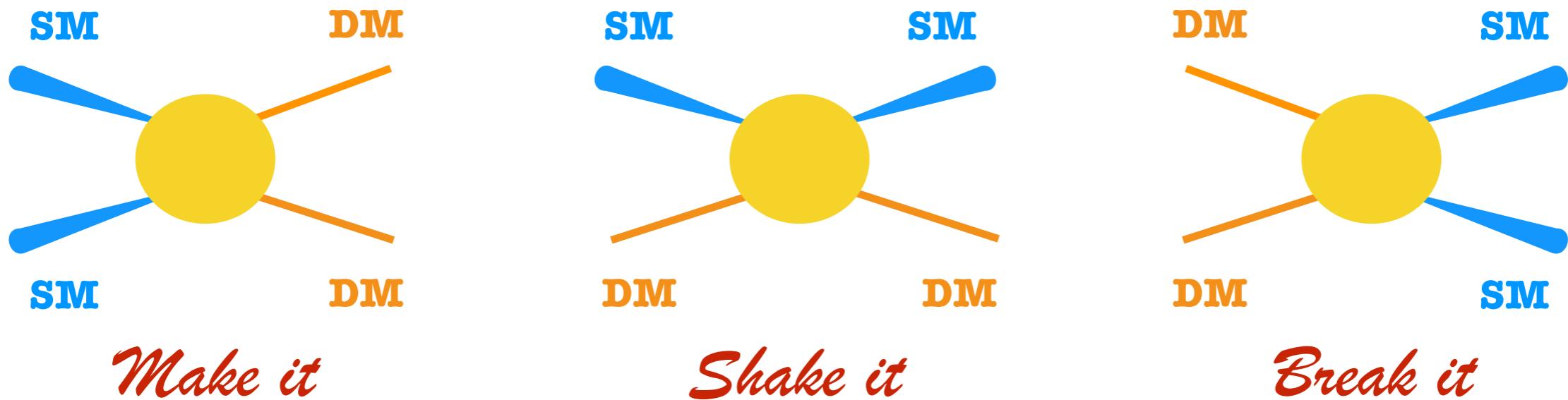


$$\Omega_{\text{DM}} h^2 \sim \frac{10^{-27} \text{ cm}^3/\text{s}}{\langle \sigma(\text{DM DM} \rightarrow \text{SM SM})v \rangle}$$

$$\langle \sigma(\text{DM DM} \rightarrow \text{SM SM})v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{s}$$

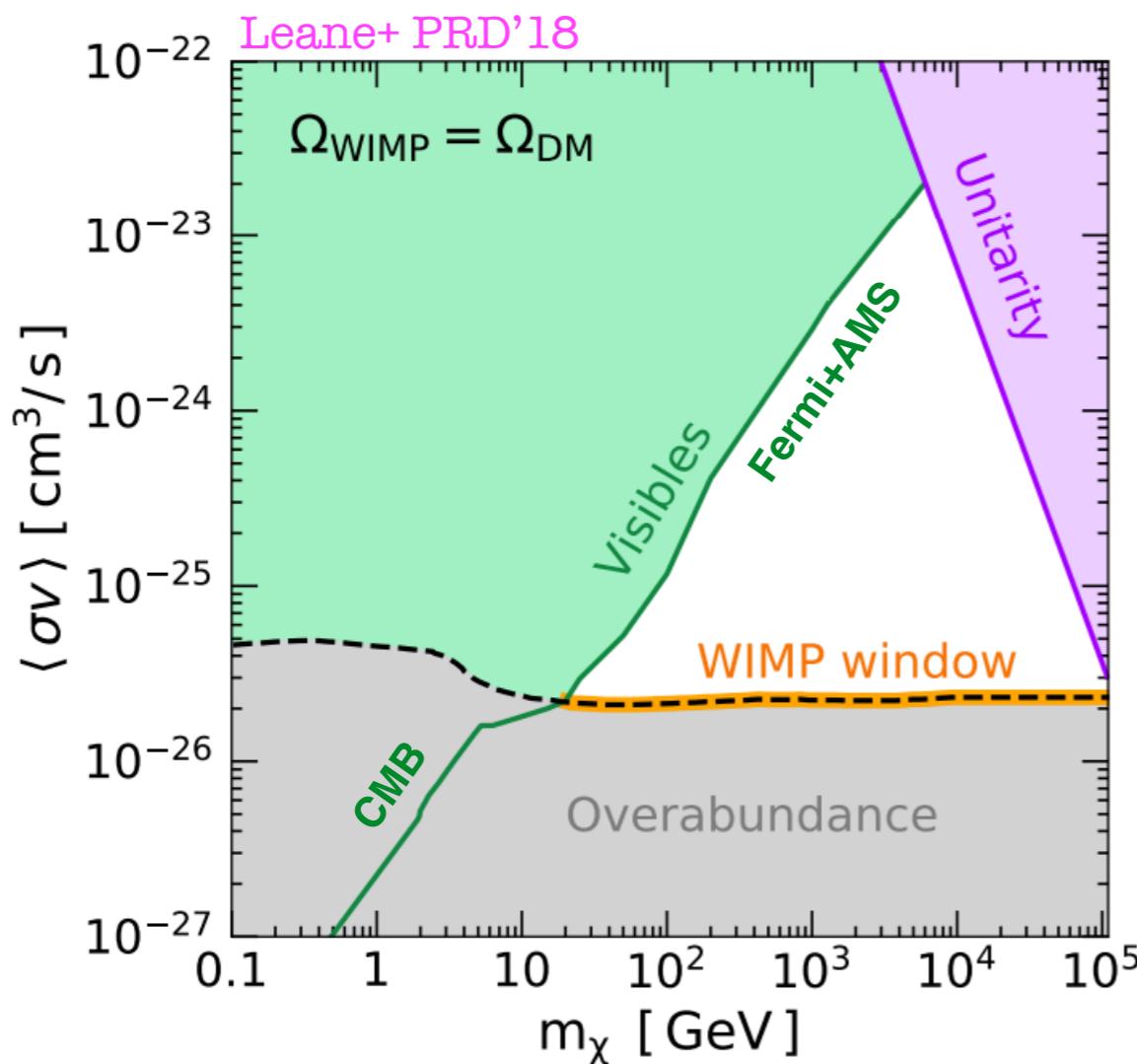
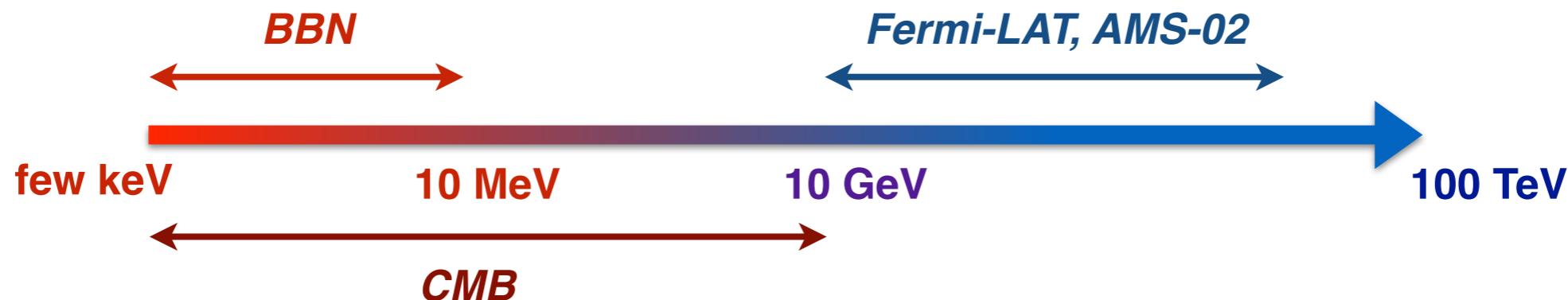
The WIMP search program

a.k.a. How to probe the WIMP model parameter space combining multiple observations



Complementarity among collider, DD and ID searches is required for the **identification of newly discovered particles as dark matter!**

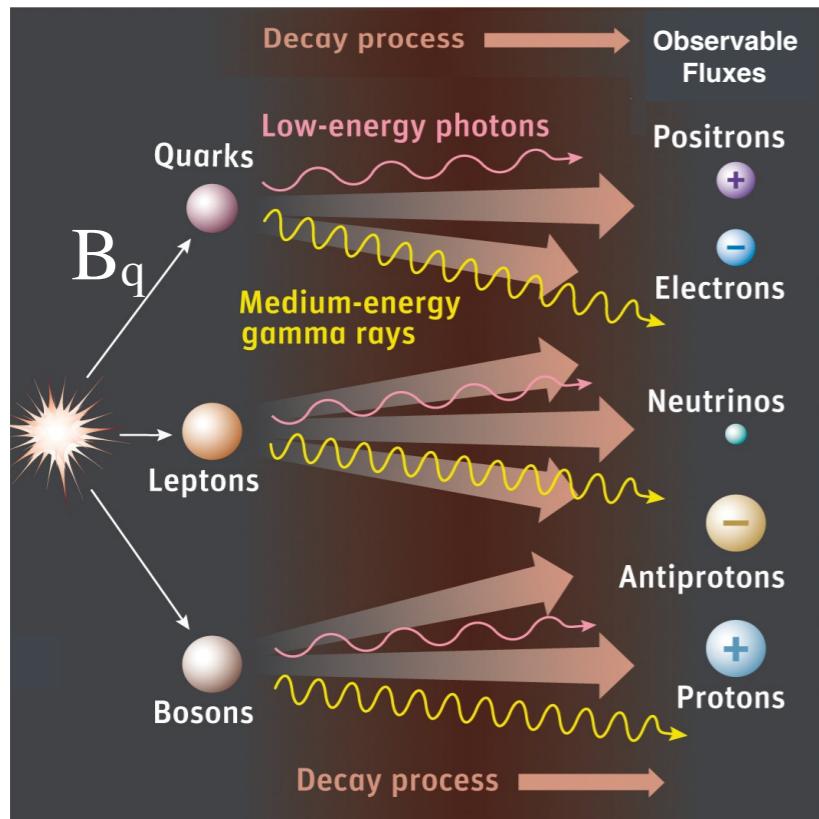
The WIMP window



- **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

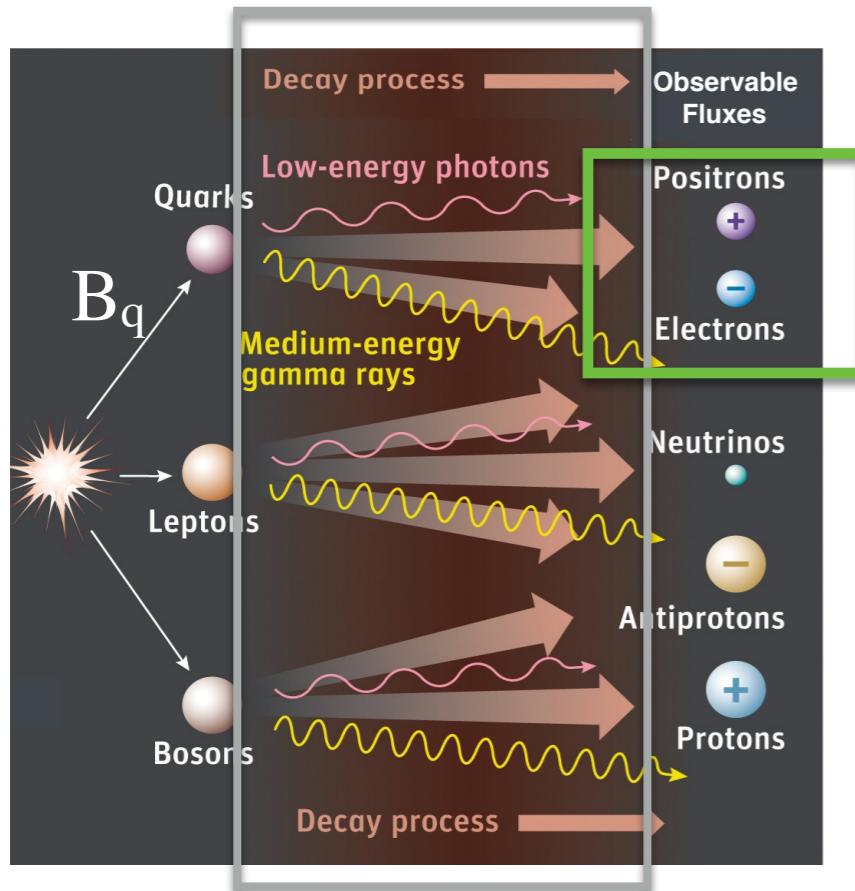
WIMP indirect detection

DM annihilation/decay

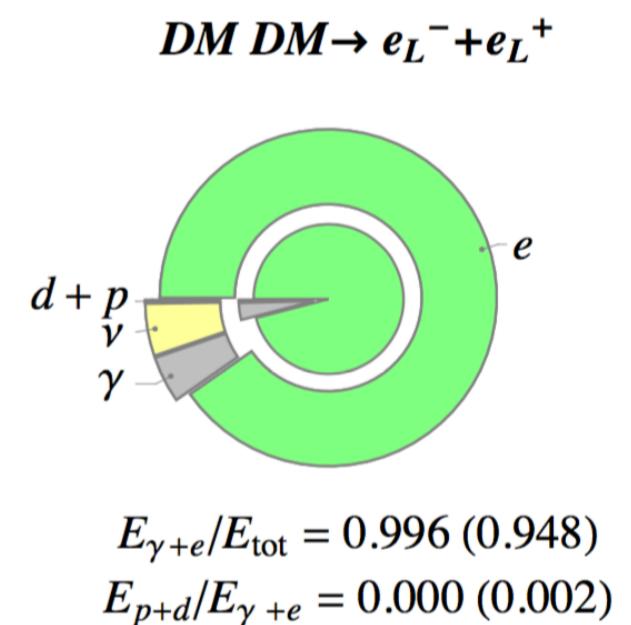
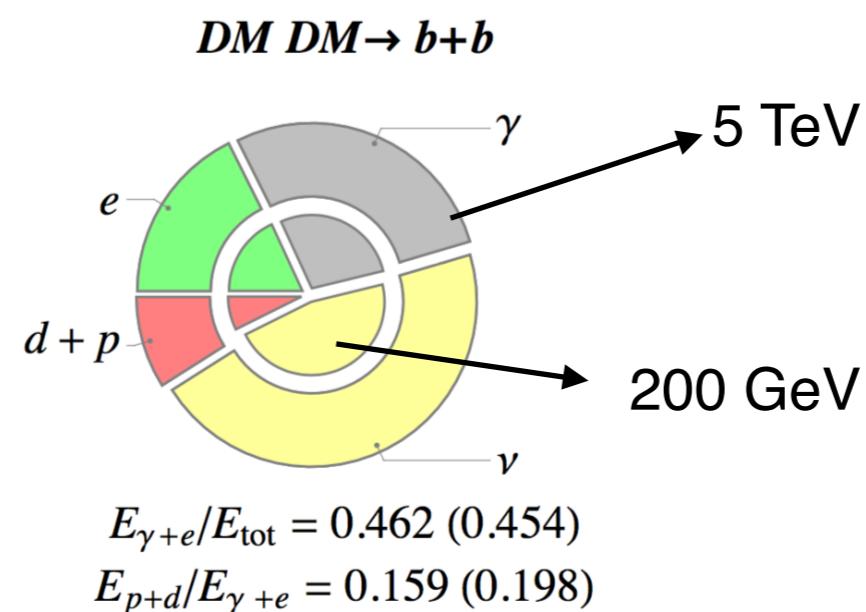


WIMP indirect detection

DM annihilation/decay



Energy distribution into final state particles



Cirelli+ JCAP'11

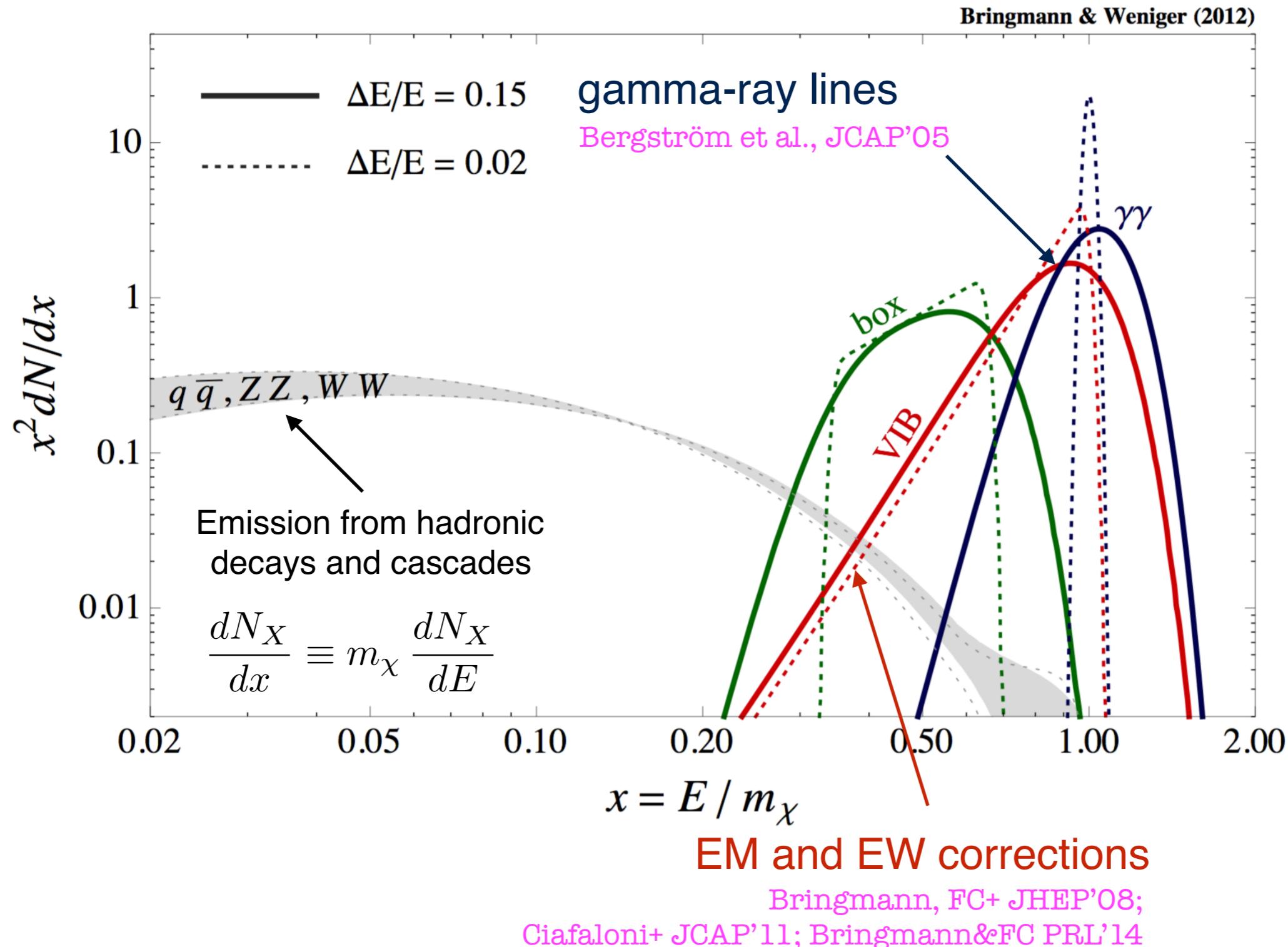
Prompt (or “secondary”) emission of final particles i

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

100% branching ratio is usually assumed, independent on PP model

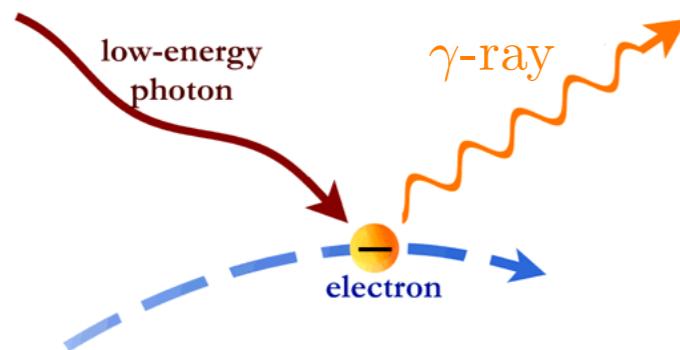
[Searches w/ cosmic rays: M. Cirelli; ID heavy dark matter: B. Shakya]

The prompt photon spectrum

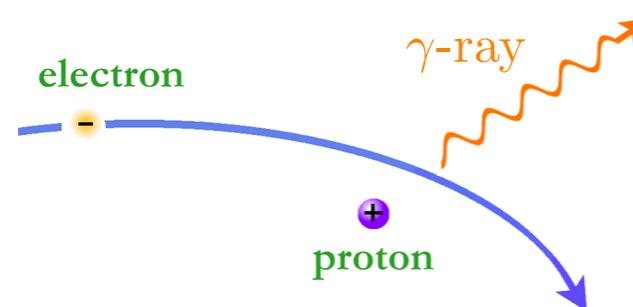


Radiative emission from leptons

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



Inverse Compton scattering
on CMB, star-light, infrared-light

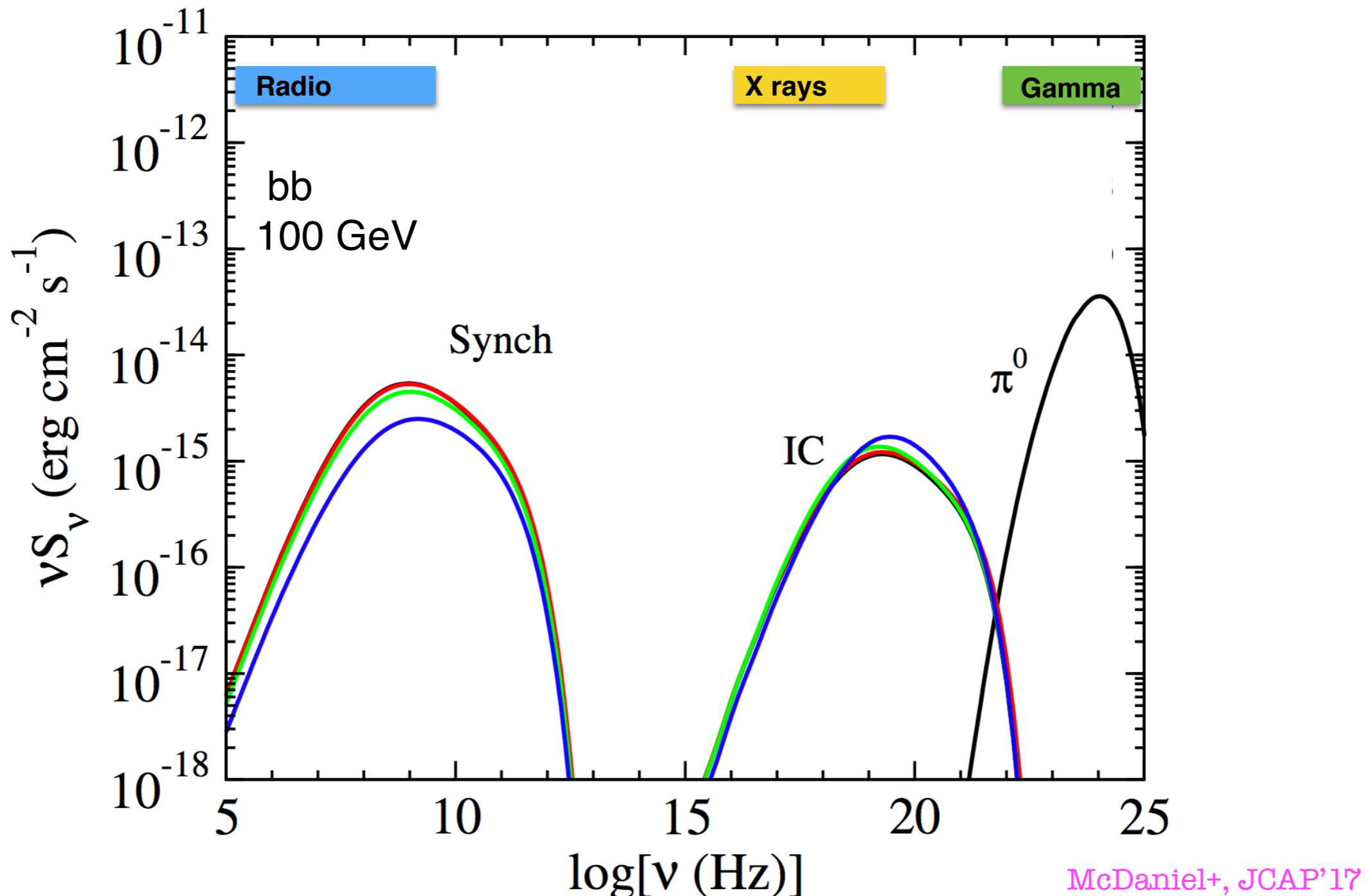


Bremsstrahlung
onto gas of interstellar medium



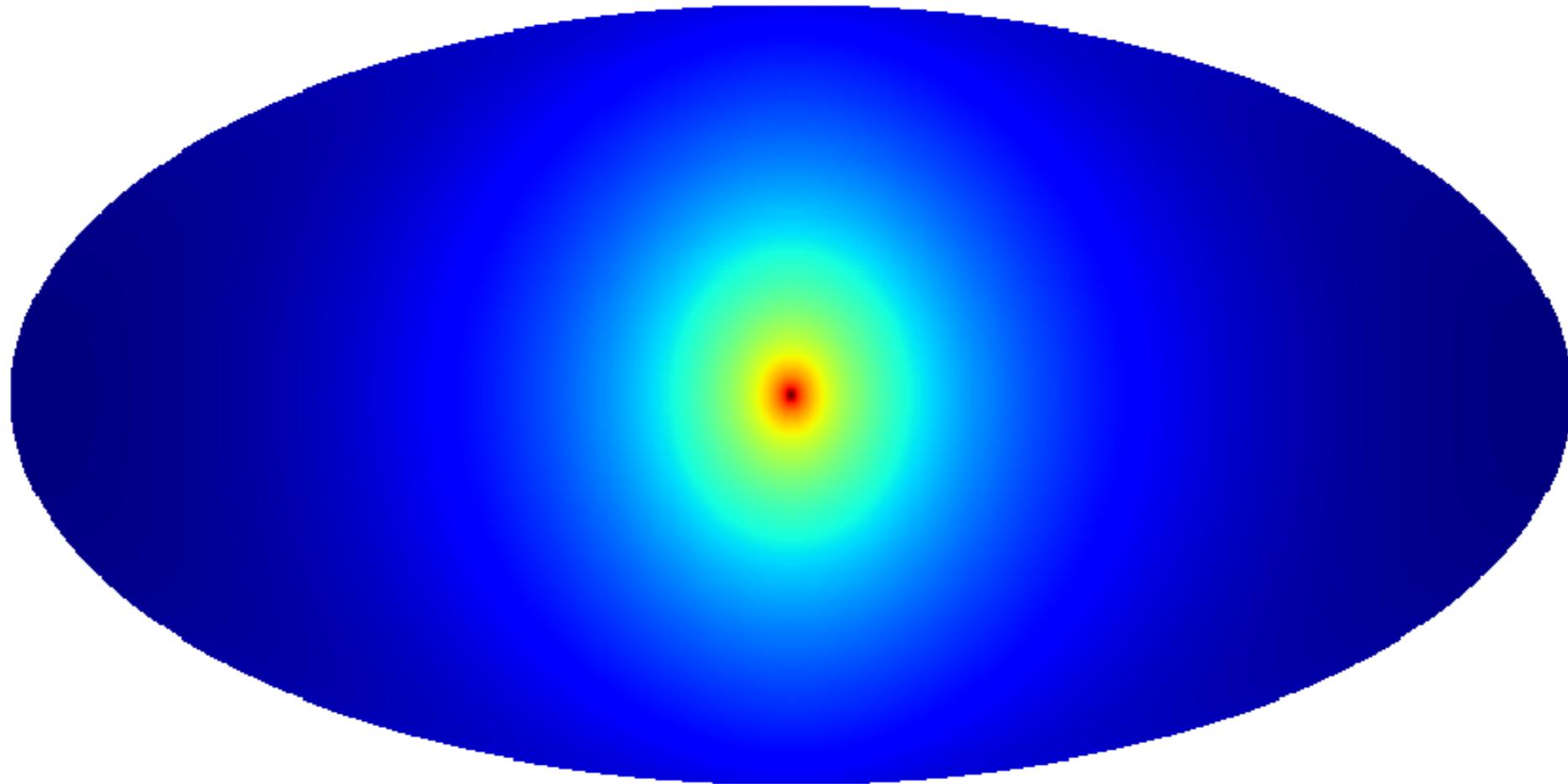
Synchrotron radiation
magnetic field $\mathcal{O}(\mu\text{Gauss})$
for e^\pm of GeV-TeV
=> MHz-GHz radio signal

Multi-wavelength DM spectrum



What are we looking for?

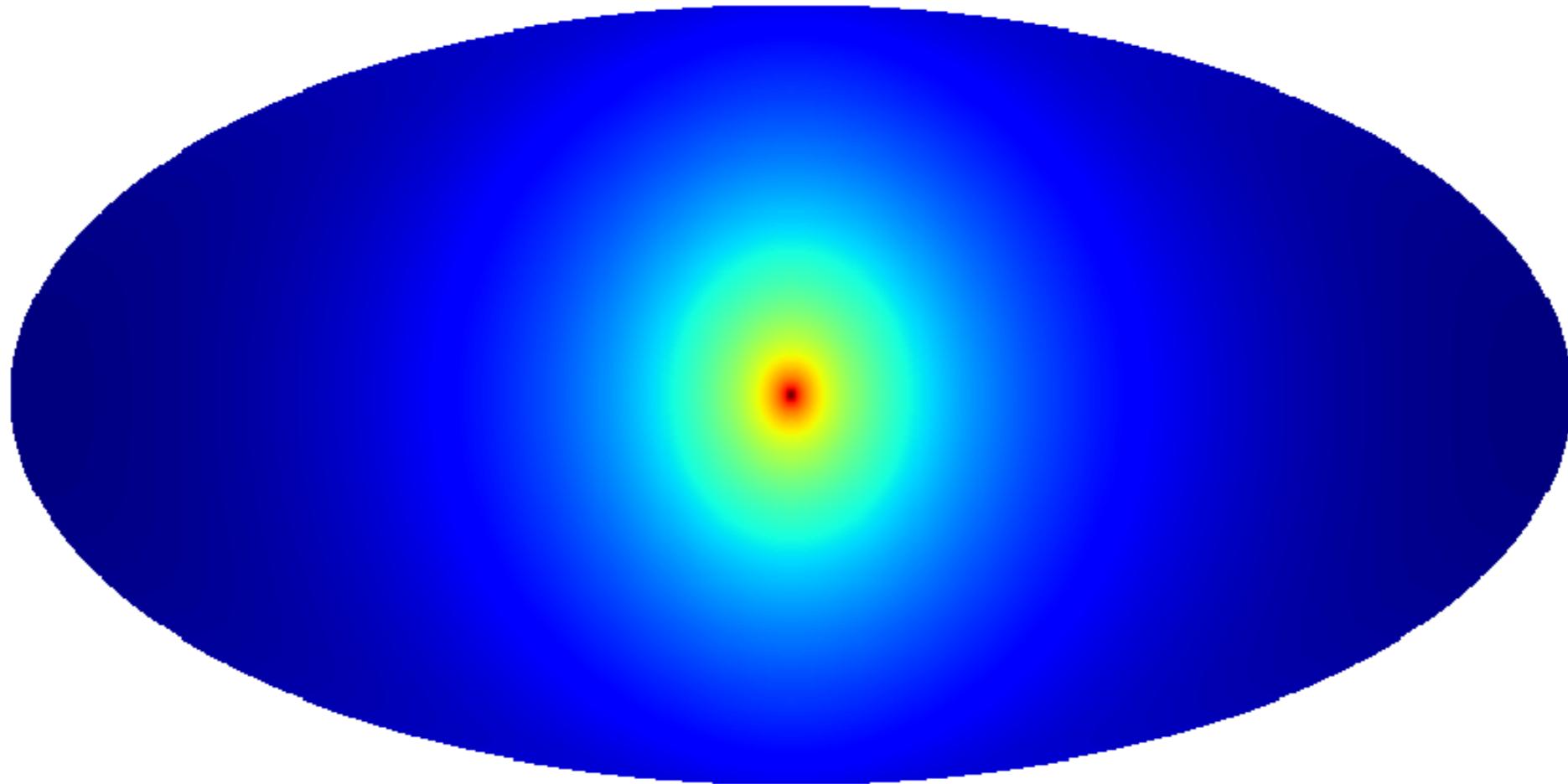
Expected gamma-ray (prompt) flux from dark matter annihilation in the smooth Galactic halo



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

What are we looking for?

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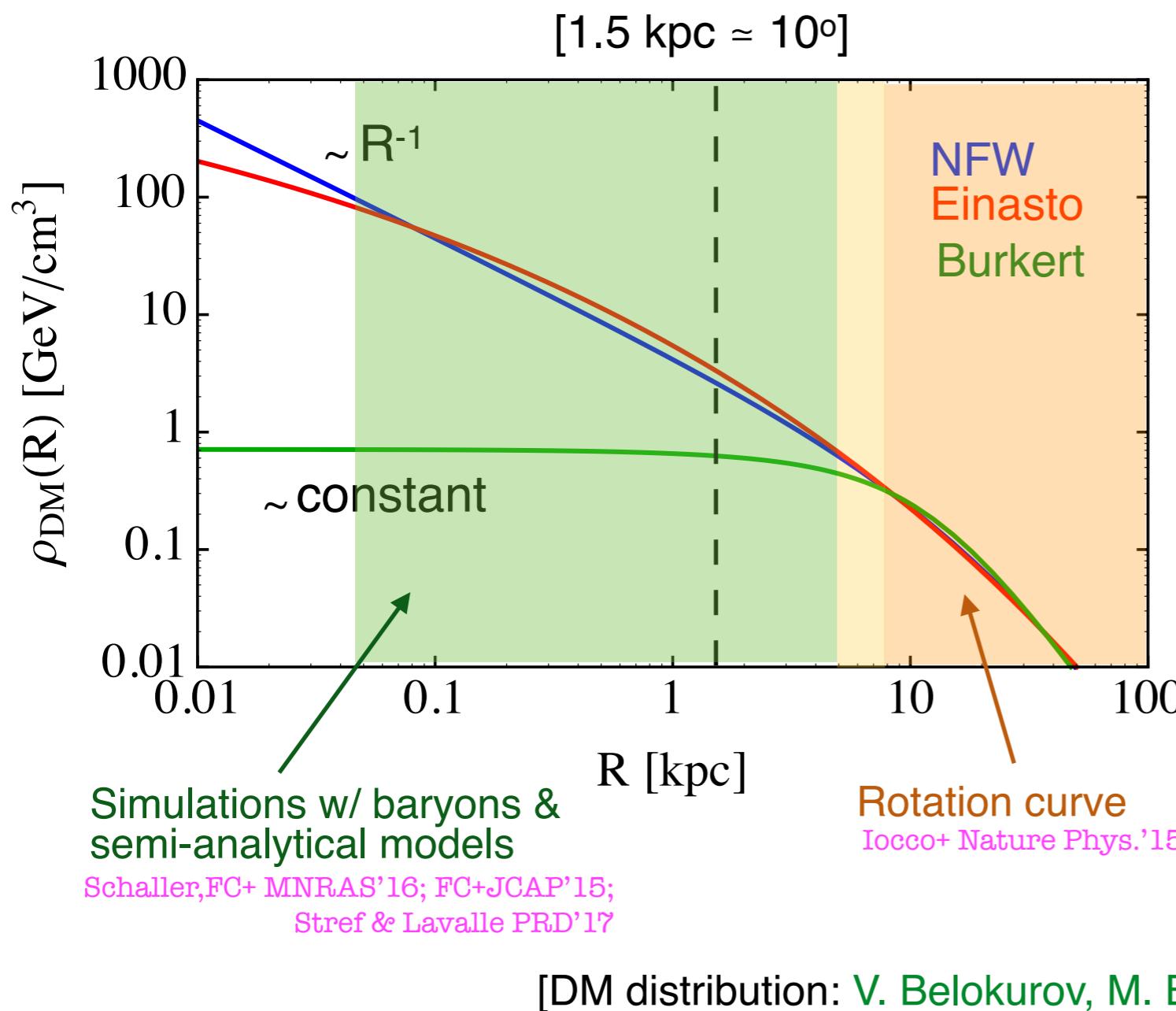


$$\Phi(E, \psi) = \frac{\sigma_A v}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \int d\ell \rho [r(\ell, \psi)]^2$$

Direct link with cosmology: if the annihilation cross section is not velocity dependent, bounds on σv today are directly connected to the DM relic density

Dark matter spatial distribution

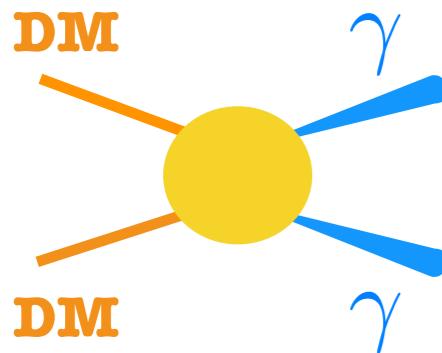
$$\Phi(E, \psi) = \frac{\sigma_A v}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \int d\ell \rho [r(\ell, \psi)]^2$$



- The distribution of DM in galaxies is affected by large uncertainties
- **Unavoidable modelling uncertainty** to account for when deriving constraints on DM models

Probing the WIMP window with high-energy gamma rays

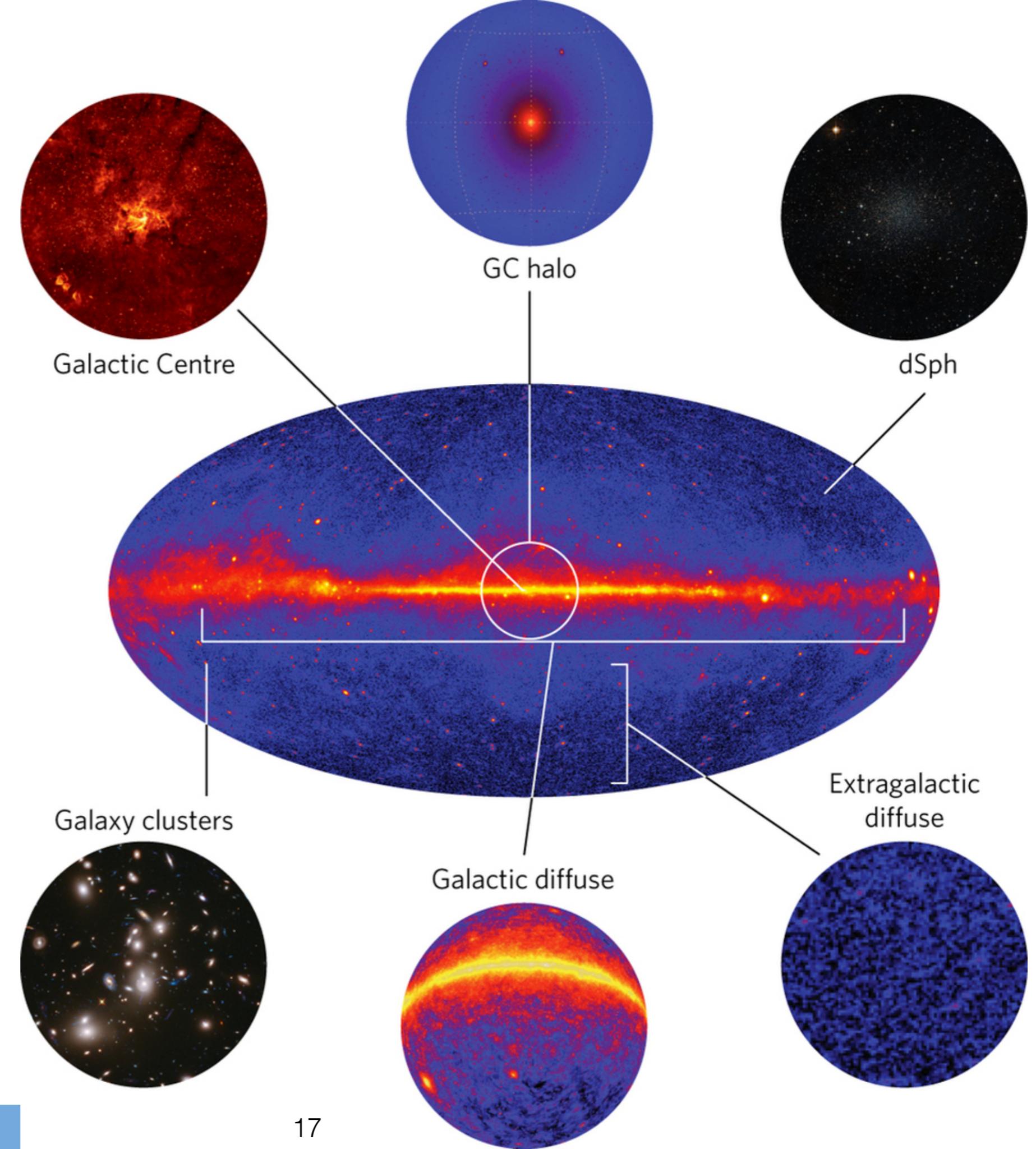
Targets for dark matter gamma-ray searches



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

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

Conrad & Reimer
Nature Phys. 13 (2017)

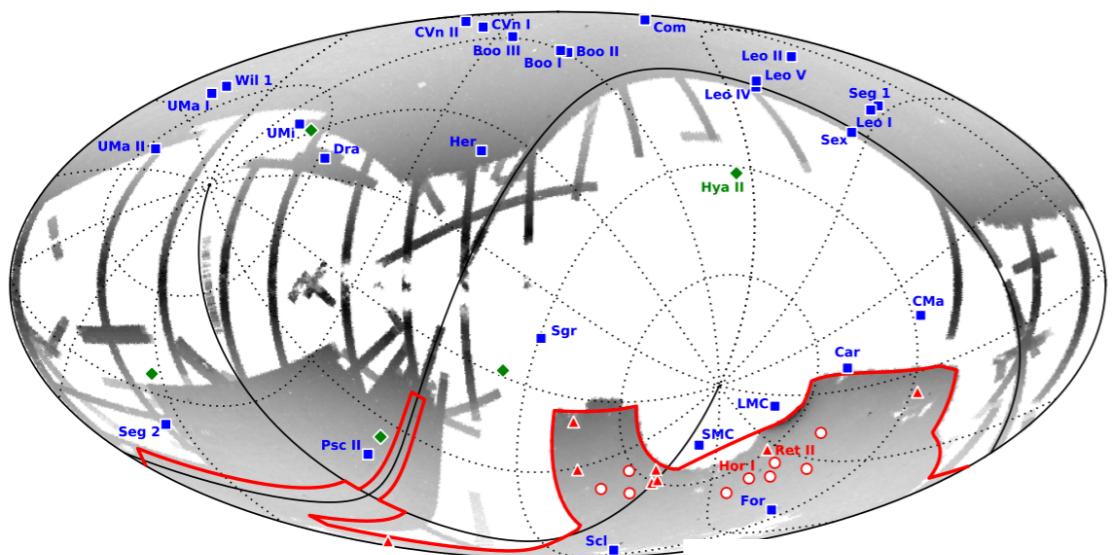
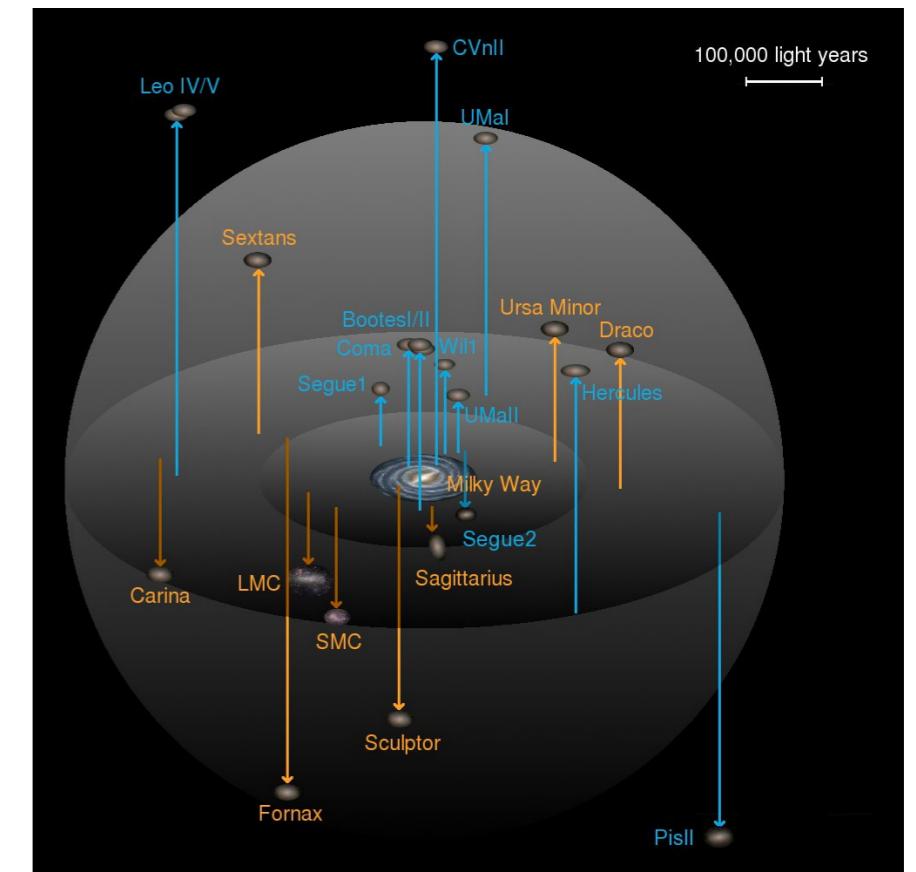


Dwarf spheroidal galaxies

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

“Clean” target for DM searches, high
mass-to-light ratio and no
astrophysical emission

Winter+ ApJ’16



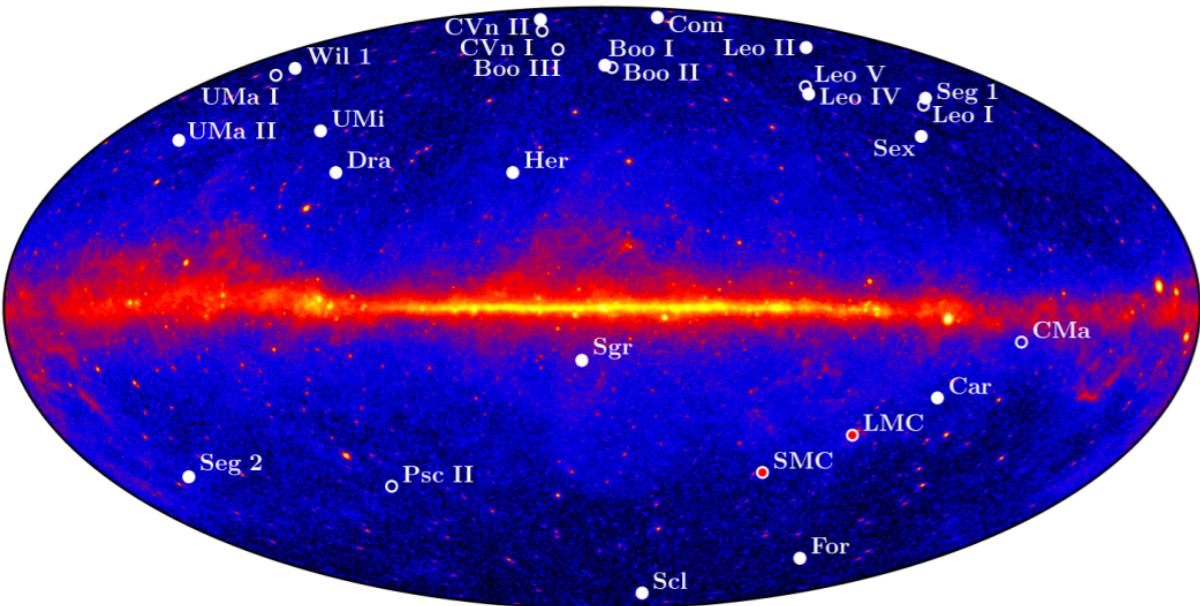
Blue = Known prior to 2015
Red triangles = DES Y2Q1 candidates
Red circles = DES Y1A1 candidates
Green = Other new candidates

[Isolate dSphs: M. Collins]

SDSS northern hemisphere,
classical + ultra-faint dSphs
DES southern hemisphere, 17 new
Pan-STARRS, 3 new candidates

DES Collaboration, ApJ’15

Stacking dSphs



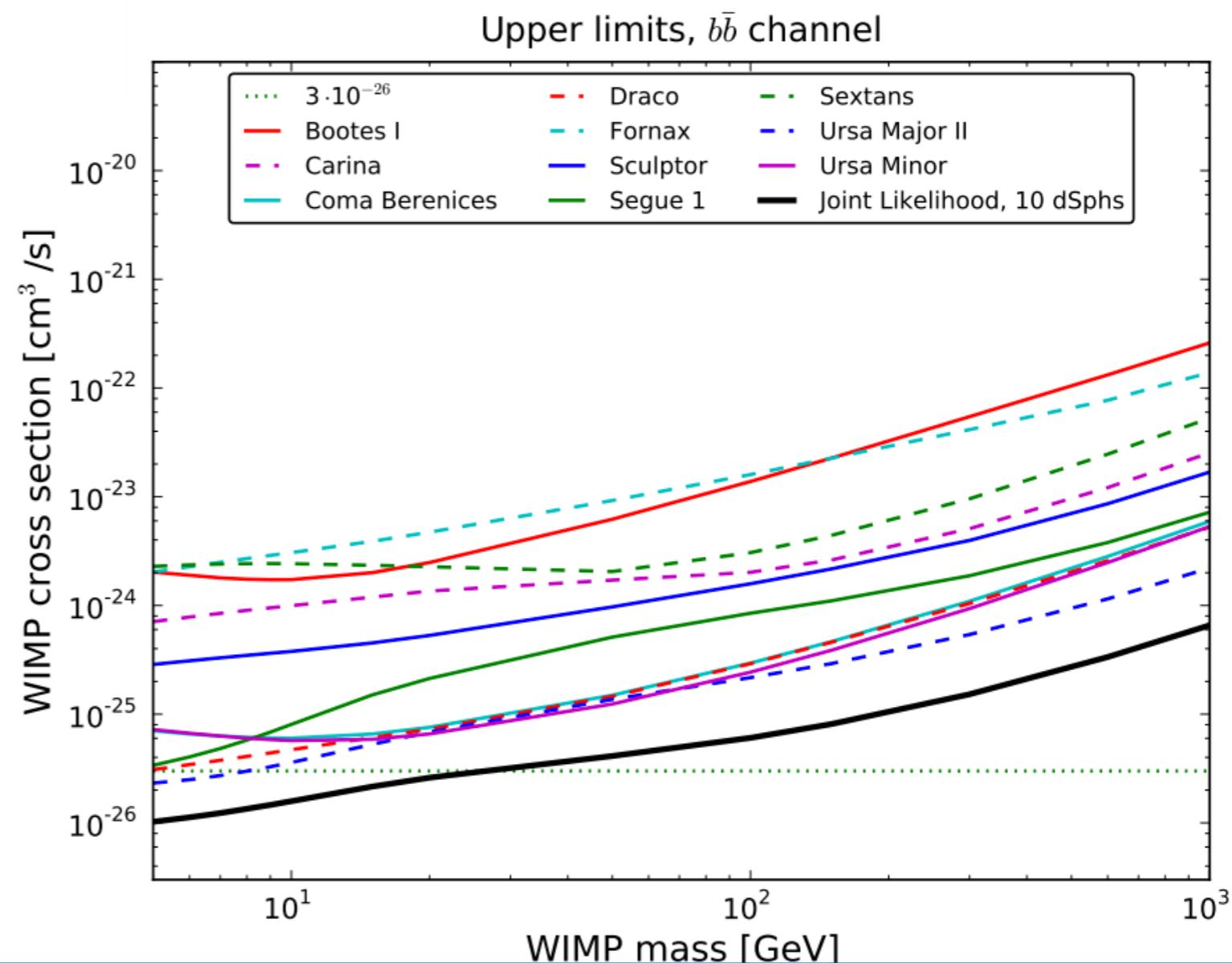
Analysing dSphs as a group results in sensitivity competitive with other targets => **Stacking technique.**

Fermi-LAT Collaboration, PRL'11

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

$$L(D|\mathbf{p}_W, \{\mathbf{p}\}_i) = \prod_i L_i^{\text{LAT}}(D|\mathbf{p}_W, \mathbf{p}_i)$$

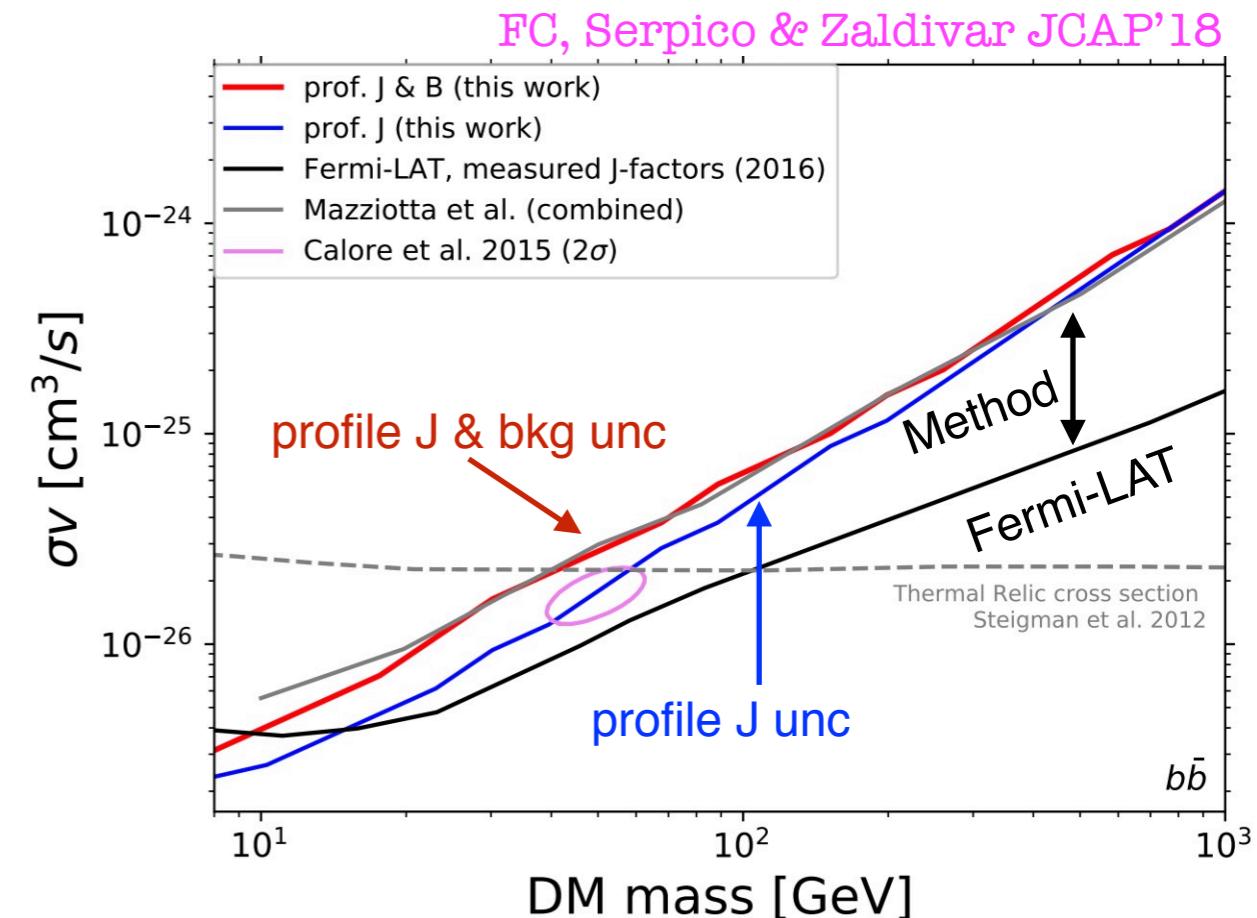
$$\times \frac{1}{\ln(10) J_i \sqrt{2\pi} \sigma_i} e^{-[\log_{10}(J_i) - \overline{\log_{10}(J_i)}]^2 / 2\sigma_i^2}$$



Dark matter limits from dSphs

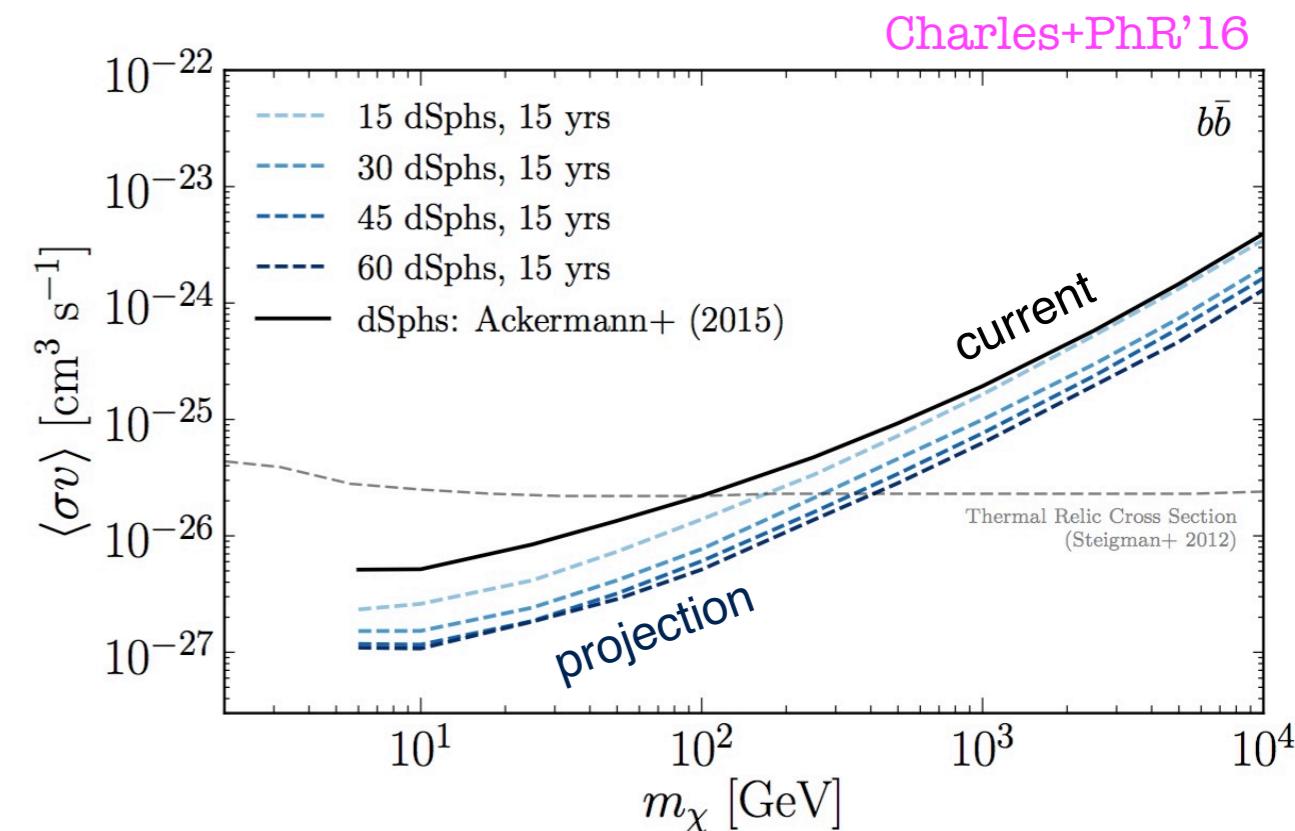
Status:

- 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



Future:

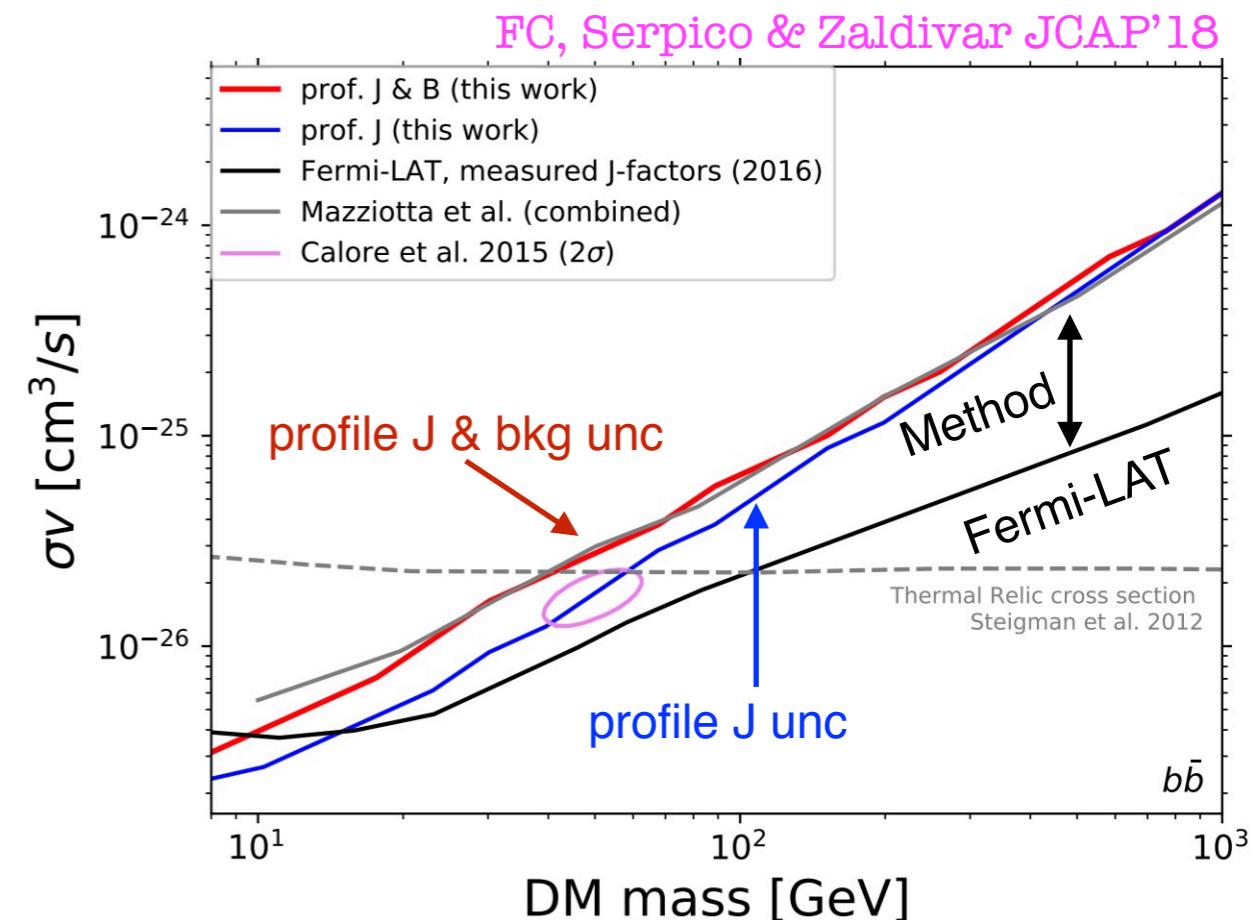
- New data from Fermi-LAT (improvement by a factor of 2-5)
- Expected hundreds of new dSphs with SDSS, Pan-Starrs, DES and LSST (> 2019) Hargis+ApJL'14
- Competitive bounds from future radio and X-ray telescopes Regis+, JCAP'14;
Jeltema&Profumo, MNRAS'12



Dark matter limits from dSphs

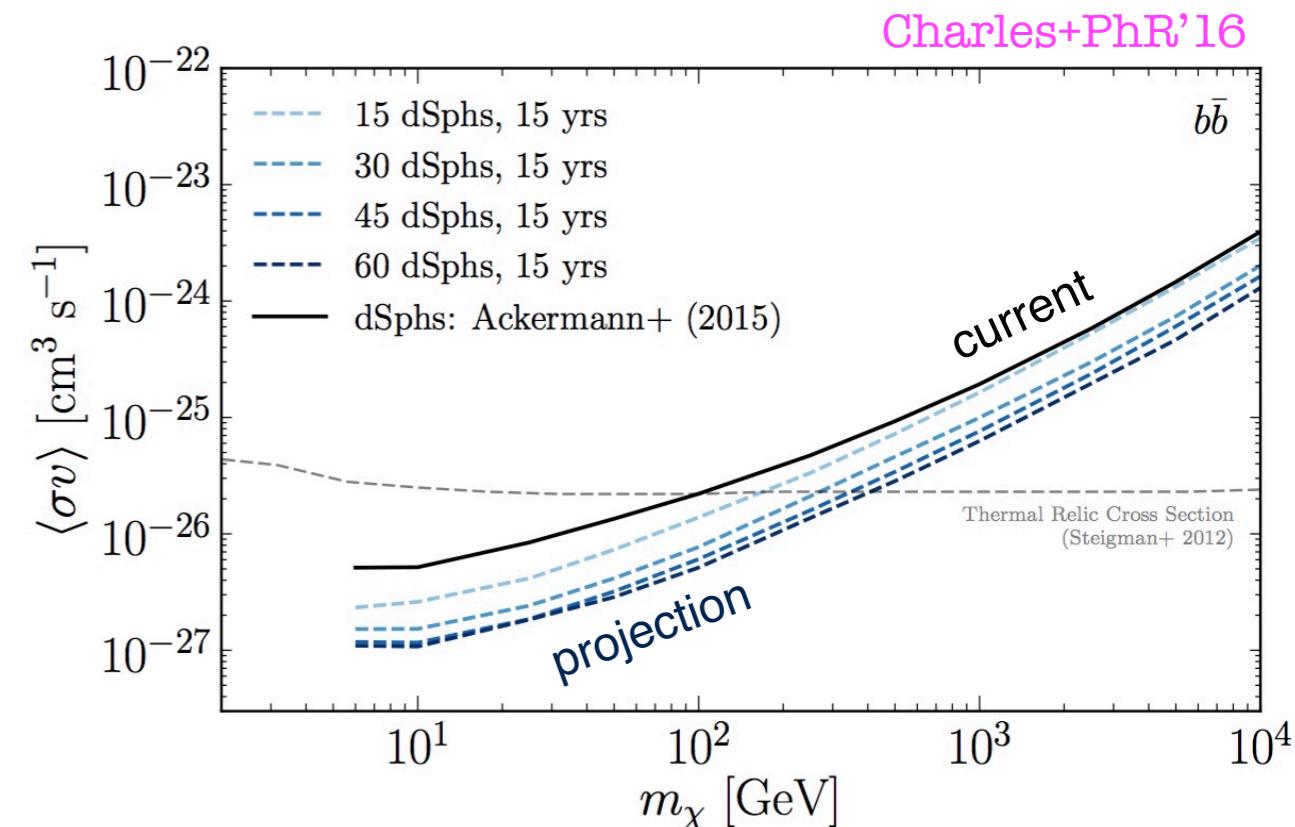
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A data-driven background estimation

Caveats of standard analysis:

- * Still affected by “accidental” background due to line of sight emissions (diffuse Galactic, extended Galactic sources, and both Gal. and extra-gal. point-like sources)
- * Use predefined background models (diffuse and isotropic) where only normalisation is fitted

However:

- * New spatially-dependent contributions (unresolved sources, alternative diffusion mechanisms) may provide unequal performances in different regions of the sky.
- * There is no guarantee that the bkg is consistently determined from one region to another.

Data-driven optimisation of the background pdf

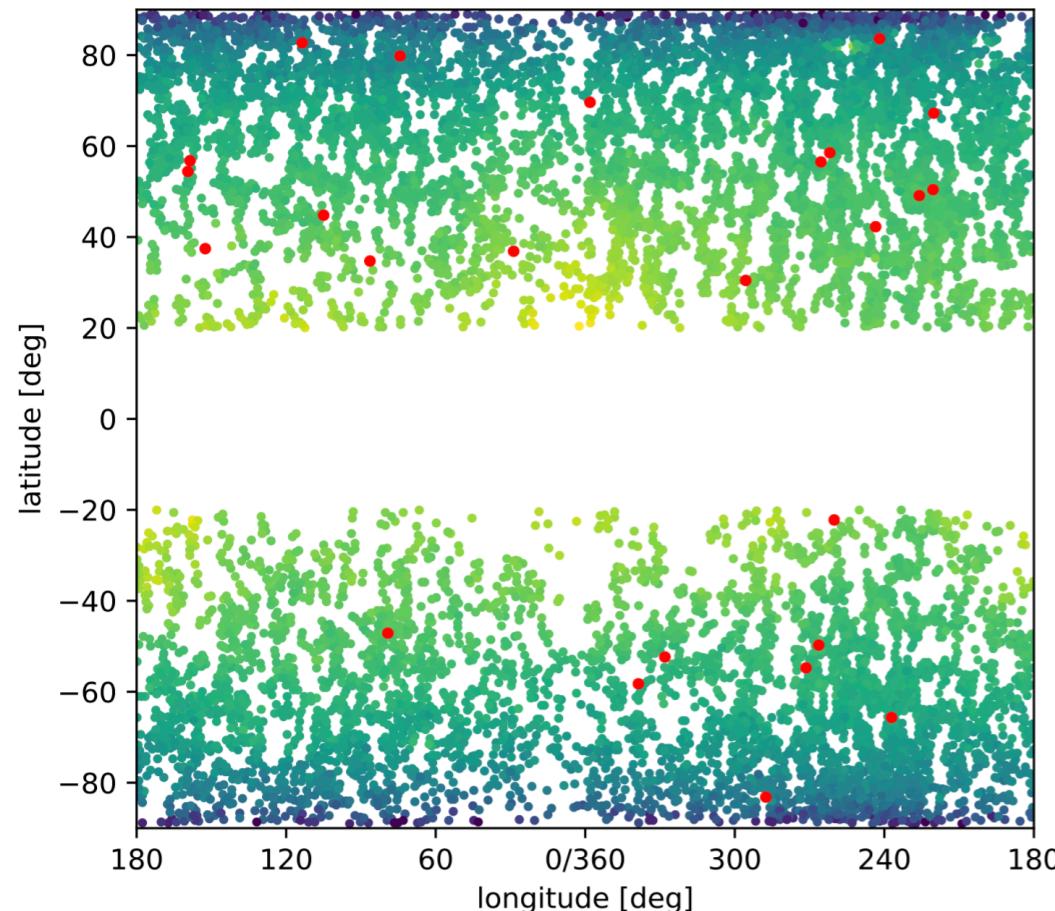
FC, Serpico & Zaldivar JCAP'18

- This approach, agnostic of the (astro)physical bkg, allows us to study the robustness of the dSph limits against simplistic (and too rigid) bkg assumptions.

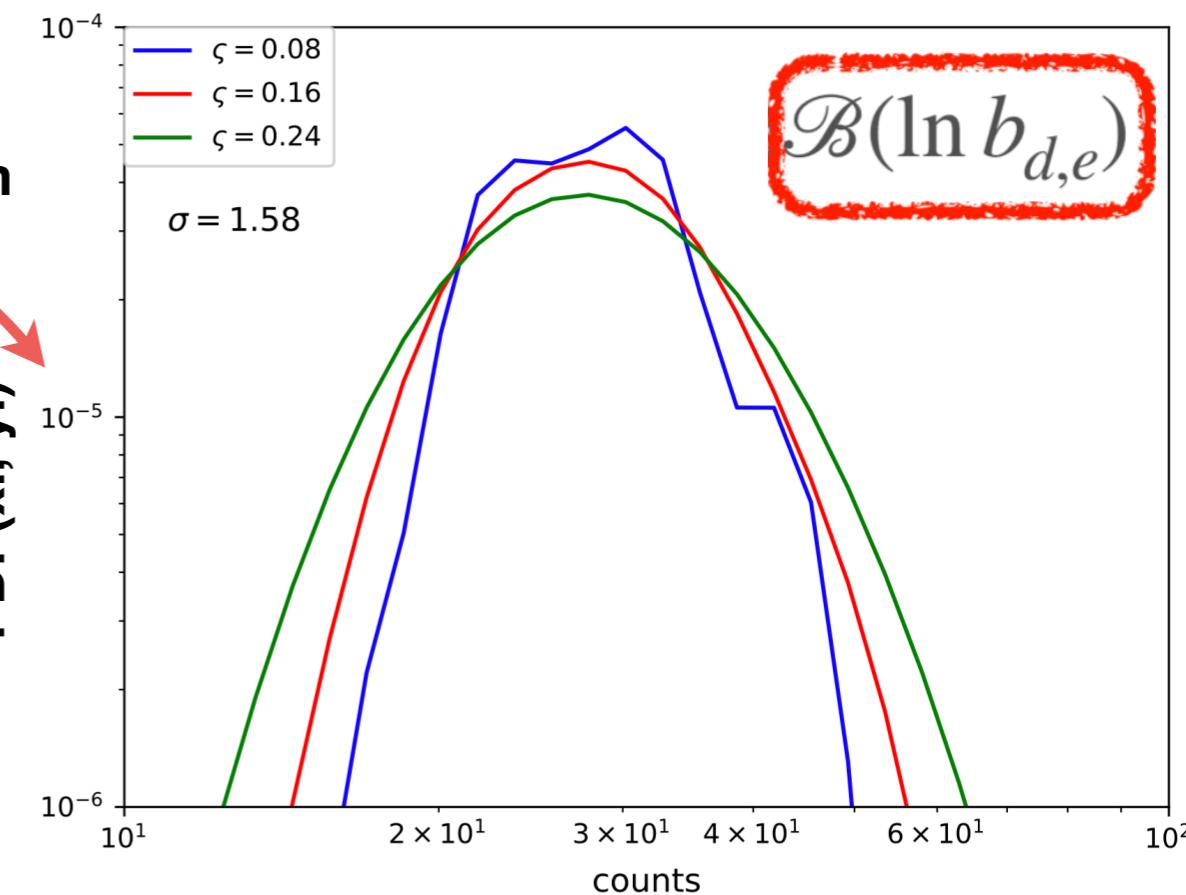
[Other data-driven methods: Geringer-Samet+ PRL'11, Mazziotta+ AP'12, Boddy+ PRD'18]

Relevance of bkg mismodelling: Linden 905.11992]

A data-driven background estimation



Kernel pdf optimisation



$$\mathcal{L}_{d,e}(\lambda_{d,e}, \log_{10} J_d, \ln b_{d,e}) = \frac{\lambda_{d,e}^{c_{d,e}} e^{-\lambda_{d,e}}}{c_{d,e}!} \mathcal{N}(\log_{10} J_d) \mathcal{B}(\ln b_{d,e})$$

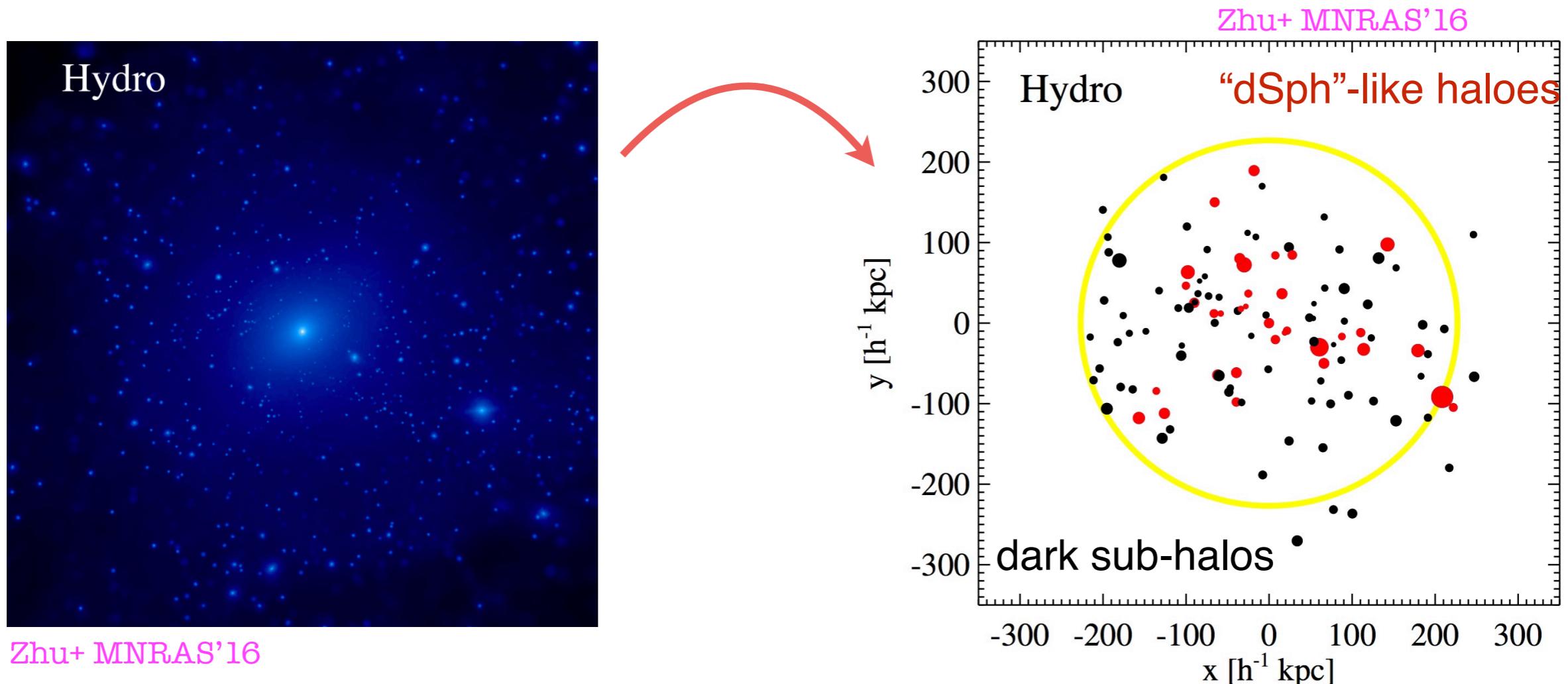
$$\lambda_{d,e} = \lambda_{d,e}(\langle \sigma v \rangle, m_{\text{DM}}, \log_{10} J_d, \ln b_{d,e}) = 10^{\log_{10} J_d} \langle \sigma v \rangle f_{d,e}(m_{\text{DM}}) + e^{\ln b_{d,e}}$$

Standard profile likelihood method extended to **profiling over bkg uncertainties**.

- Bounds on DM degrades by a factor 2-3
- Room remains for improvement [new analysis on-going w/ more realistic J-factor pdf, energy-dep. bkg pdf optimisation]

Searches for dark subhaloes

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



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

[But also: anisotropies/cross-correlation searches]

Dark matter limits from subhaloes

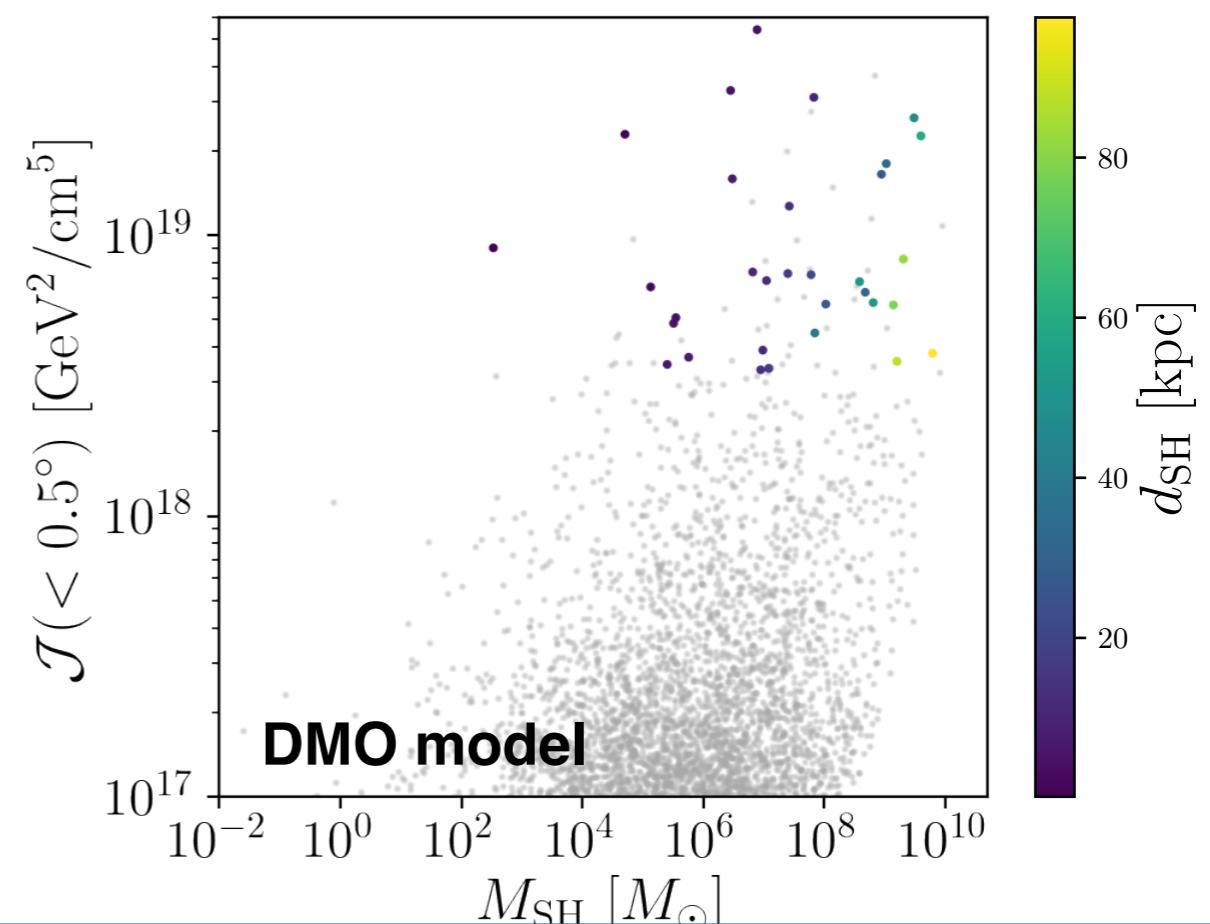
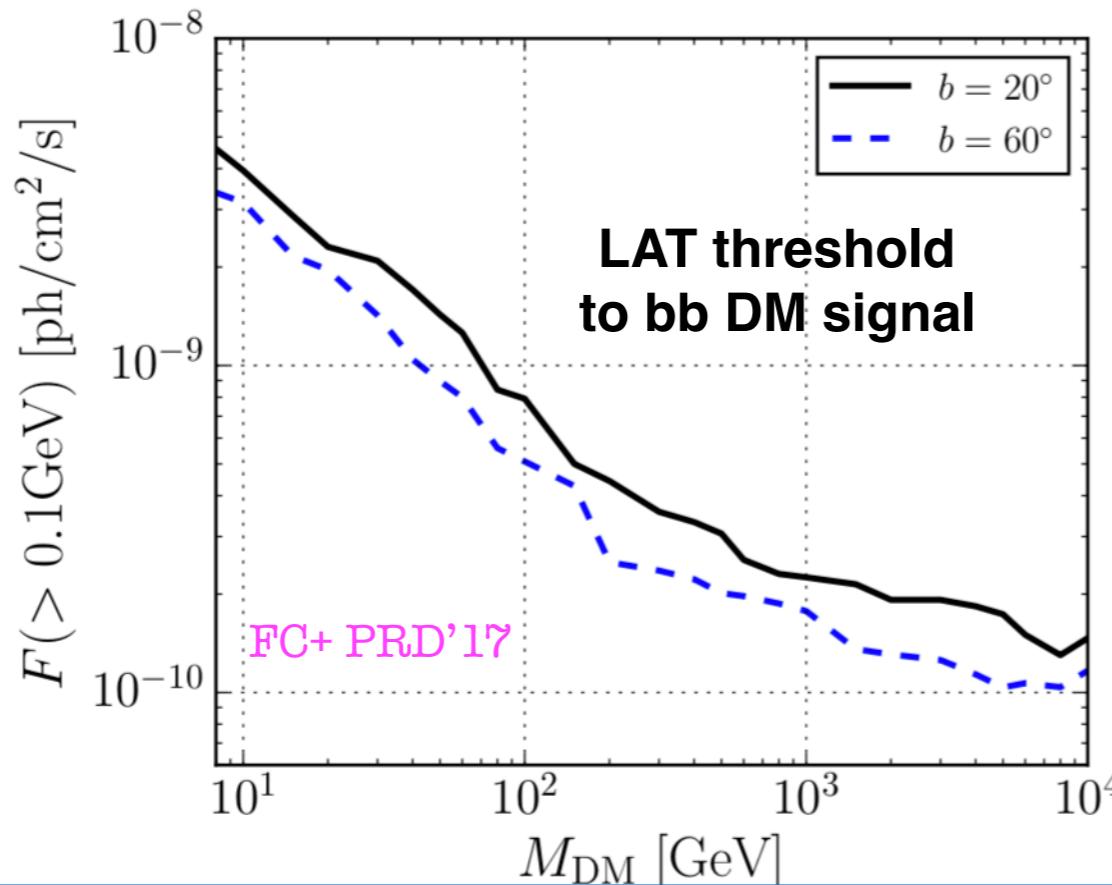
1. Number of gamma-ray DM subhalo candidates **from data?**

- 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



Dark matter limits from subhaloes

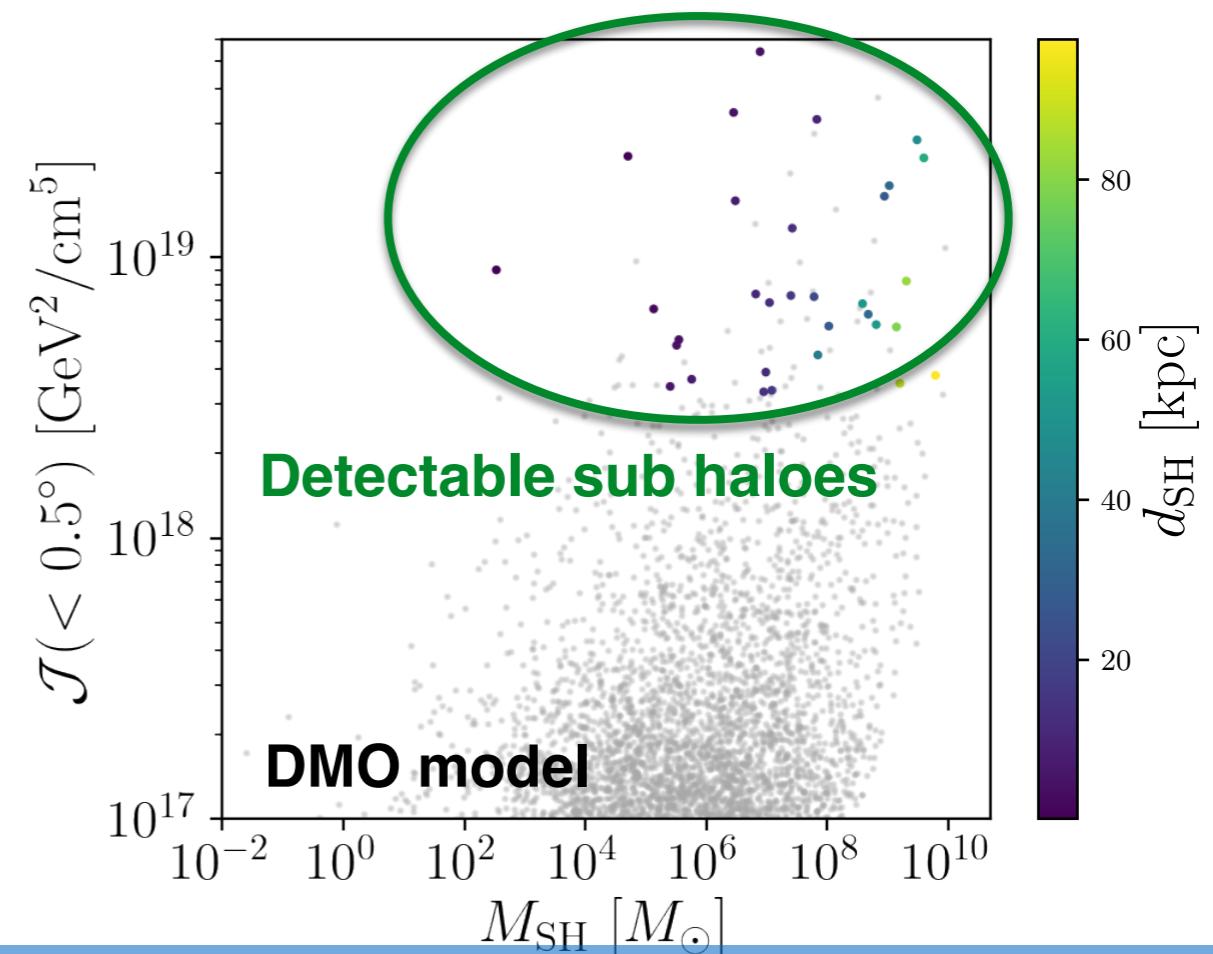
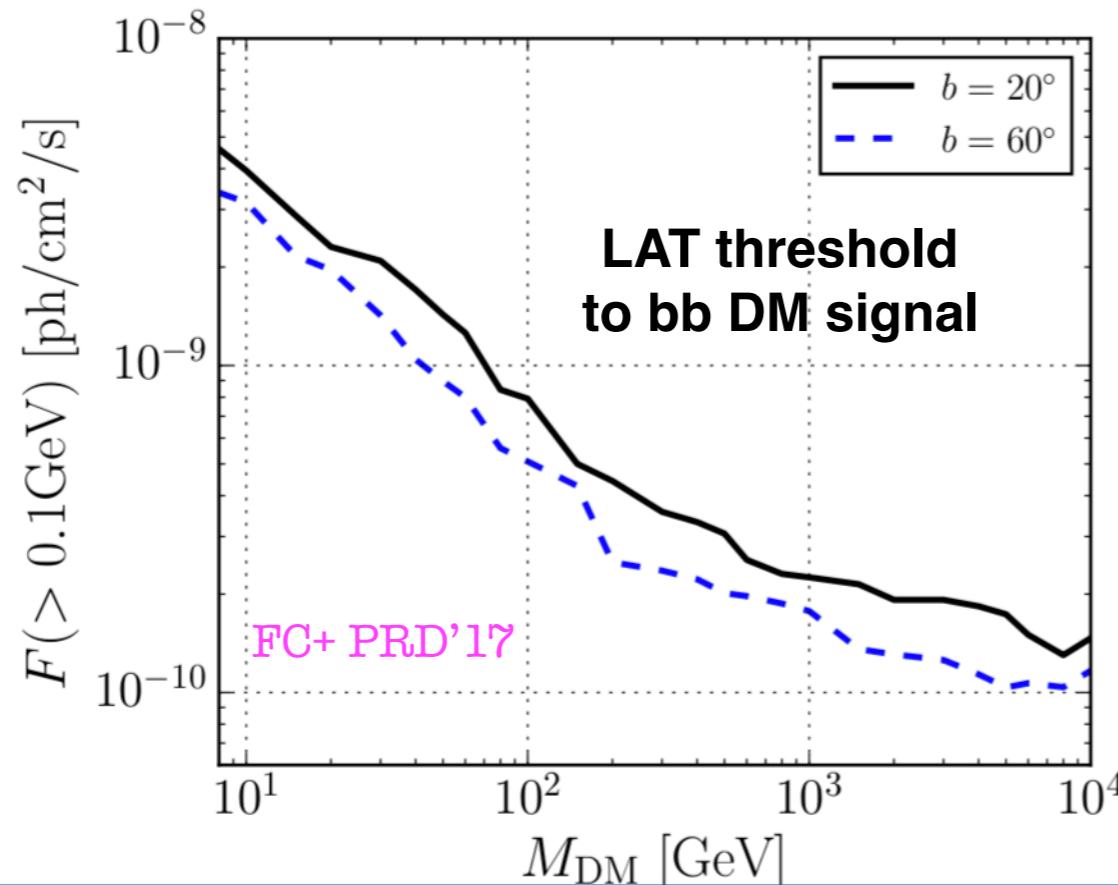
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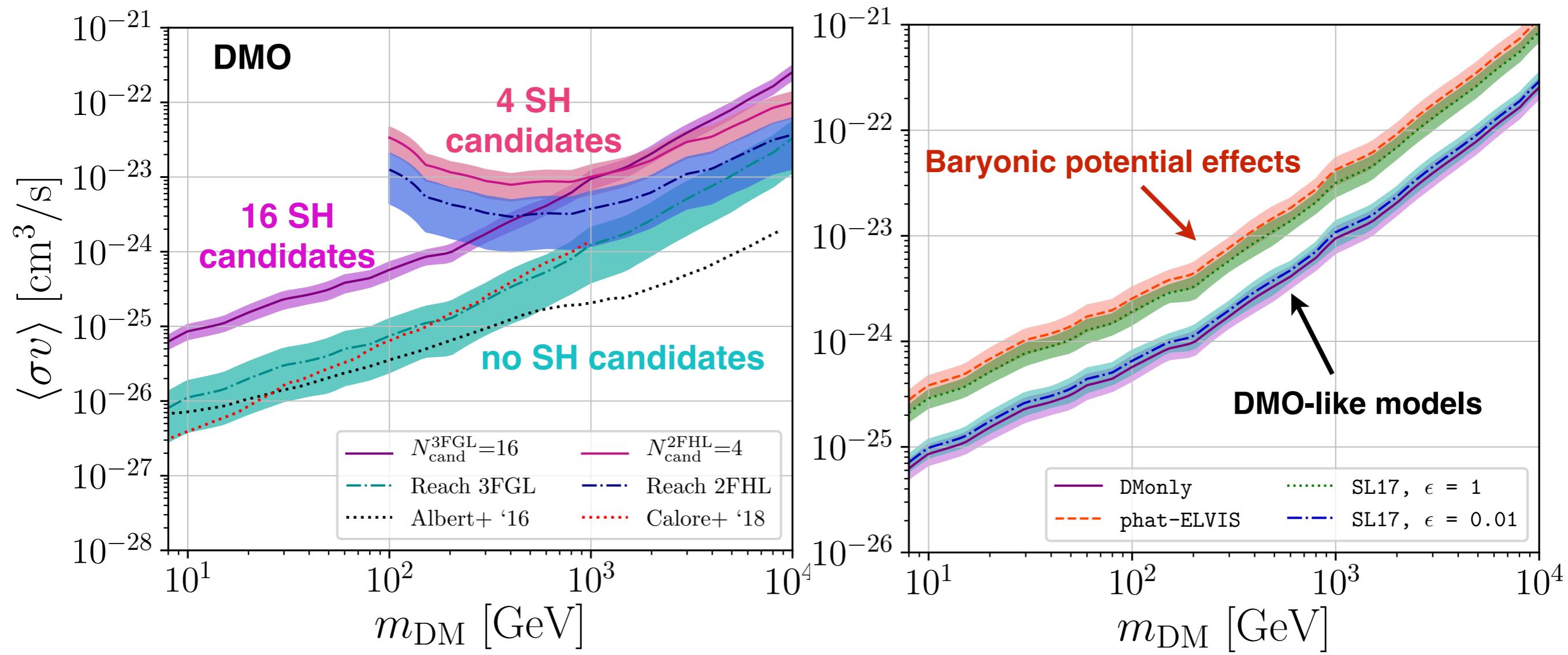
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Dark matter limits from subhaloes

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



FC+ Prepared for Galaxies'19

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

Beyond limits Hints for dark matter signals?

The Galactic centre GeV excess

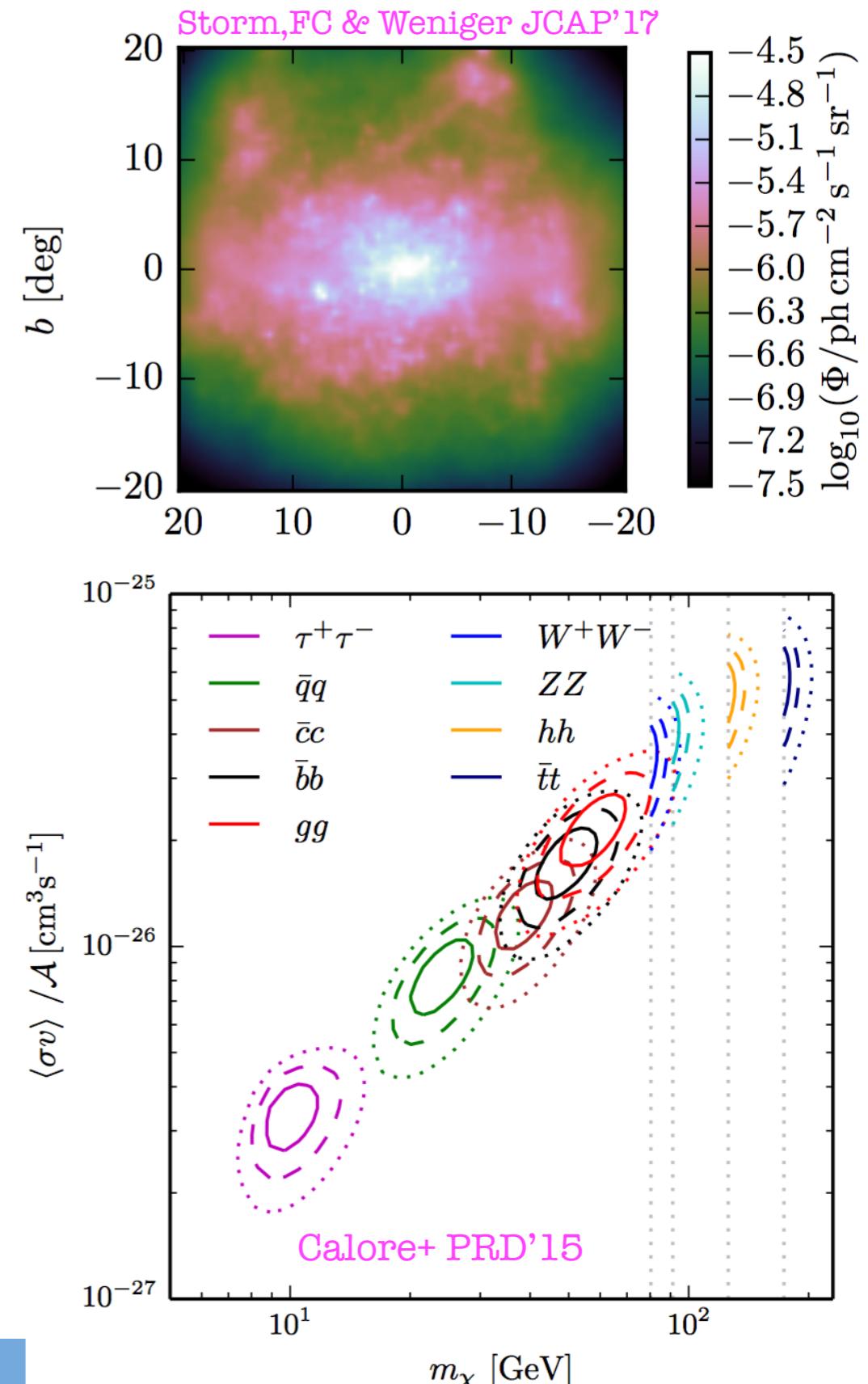
Signal:

- Well-established excess of Fermi-LAT GeV photons from the inner Galaxy**
- Peculiar spectrum peaked at a few GeV
- Extended emission up to ~ 10 degrees (~ 1.5 kpc), almost spherically symmetric (but not quite so)

Interpretations:

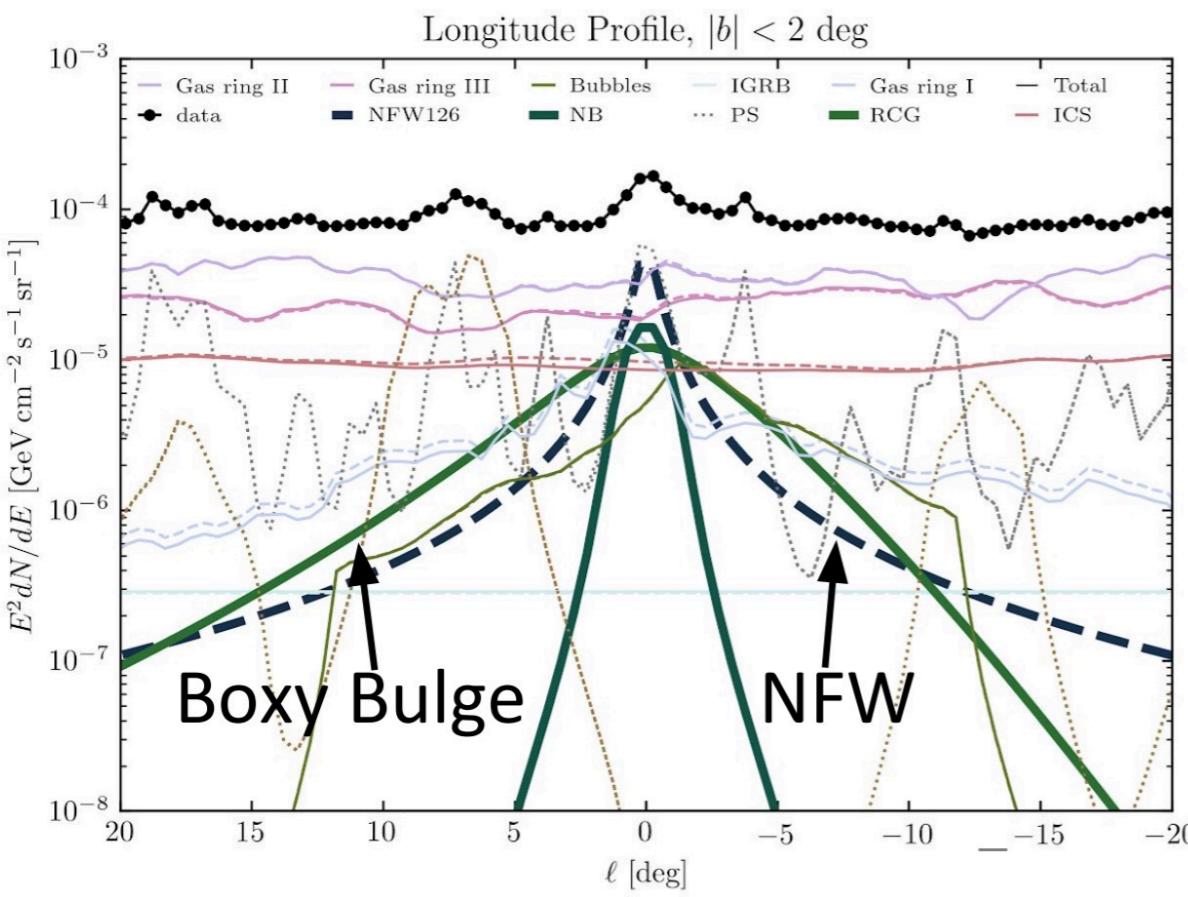
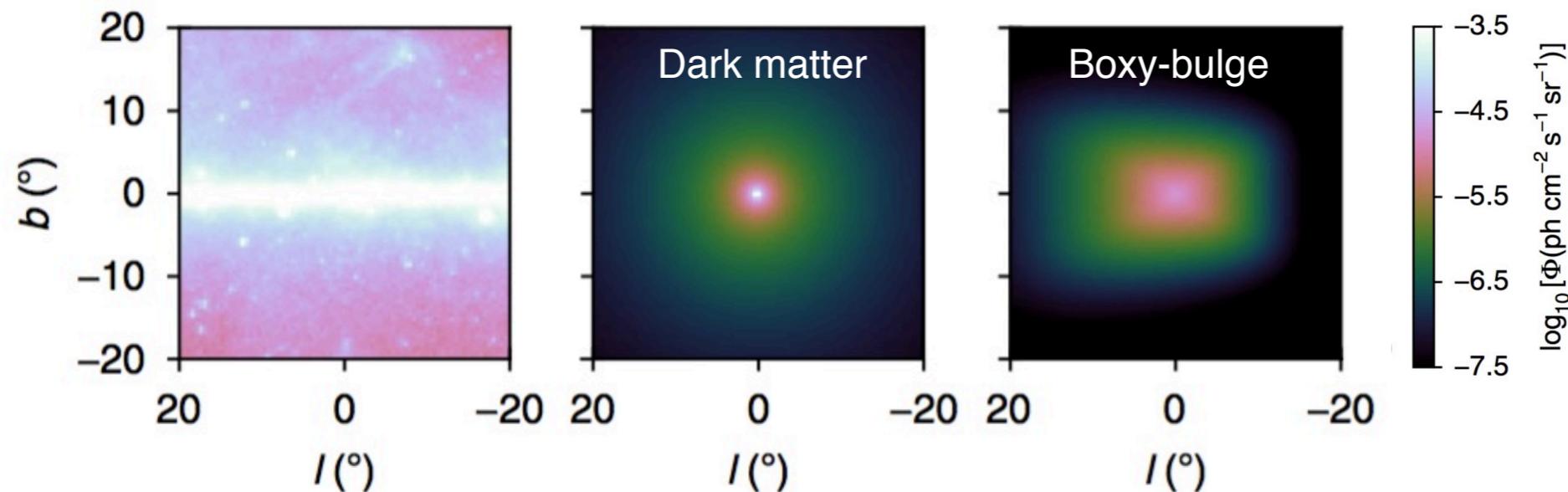
- Diffuse emission from electrons/positrons at the Galactic centre (enhanced SF or activity GC)
Gaggero+ JCAP'15; Carlson+PRD'15;
Petrovic+ JCAP'14; Cholis,FC+JCAP'15
- Sub-threshold millisecond pulsar-like point sources
Bartels+PRL'16; Lee+PRL'16; Ackermann+'17
- Dark matter annihilation: large freedom in channel/masses thanks to syst uncertainties
Calore+ PRD'15; Agrawal+JCAP'15

**Some Refs. since 2009: Hooper&Goodenough '09; Vitale&Morselli '09; Abazajian&Kaplinghat PRD'12; de Boer+'16; Macias+'16; Hooper&Slatyer PRD'13; Huang+ JCAP'13; Zhou+ PRD'15; Daylan+'14; Calore+ JCAP'15; Gaggero+ 2015; Ajello+ 2015; Huang+JCAP '15; Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017; Leane & Slatyer'19



Evidence for stellar bulge emission

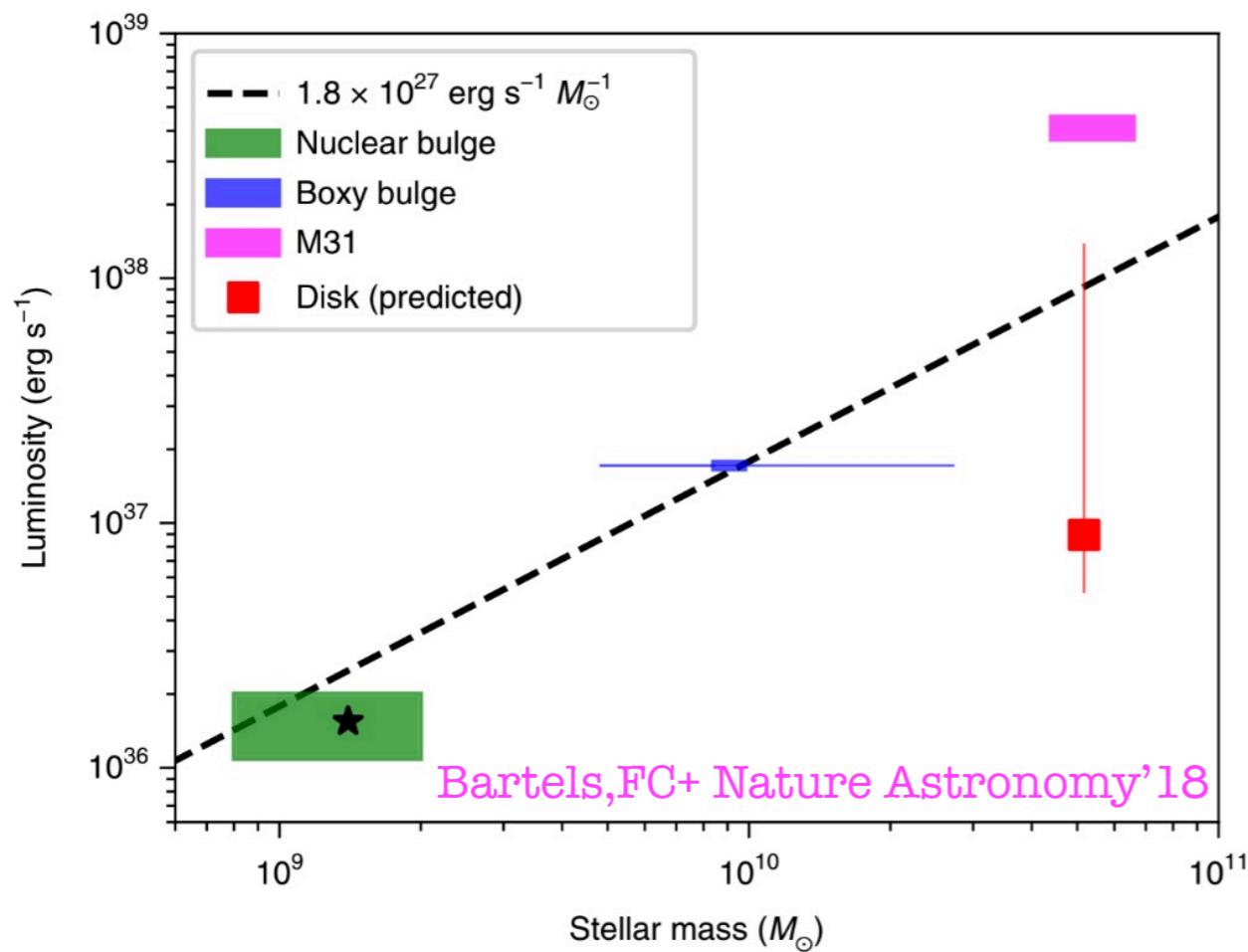
Bartels, FC+ Nature Astronomy'18



- ✓ **Stellar bulge model (boxy + nuclear bulge) is preferred over (spherically symmetric) DM models with high statistical significance (16σ)**
- ✓ **Morphology of the GCE is more oblate than what found before**
- ✓ Large enough ROI to discriminate foreground components (stable results)

[See also Macias+ Nature Astronomy'18]

Gamma-ray to stellar mass ratios



- ✓ **Gamma-ray luminosity shows correlation with stellar mass in the Galactic bulge**
- ✓ If from MSP: bulge and disk component consistent with each other
Bartels+ MNRAS'18; Eckner+ ApJ'18
- ✓ Debate: In-situ formation of MSP (+ dynamical formation) or from disrupted globular clusters
Fragione+ 1808.02497, MNRAS'18; Eckner+ ApJ'18

→ The dark matter origin of the excess becomes less and less likely

- Degeneracy with Fermi bubbles hard emission, i.e. high-energy tail?
Linden+ PRD'16; Horiuchi+ JCAP'16
- Contribution of molecular clouds in the CMZ?
Dogiel+ ApJ'18
- Connection with TeV diffuse emission from the GC?
Hooper&Linden PRD'18; Guepin+ JCAP'18; Song+ PRD'19
- Connection with 511 keV positron annihilation line?
Crocker+ Nature Astronomy'17; Bartels, FC+ MNRAS'18

Multi-messenger tests of the GeV excess

Testing a faint population of millisecond pulsars in the Galactic bulge

- ✓ **Current radio telescopes** are simply **not sensitive yet** to a pulsar population in the Galactic bulge
- ✓ **Future radio telescopes can discover** this population with a few hundreds hours of observations
- ✓ MeerKAT survey observations 2020 (?)

FC+ApJ'16

- ✓ Neutron stars high rotation velocities make any irregularity (ellipticity) in their shape a **quadrupolar source of gravitational waves**
- ✓ A **population of millisecond pulsars in the bulge** represents the **dominant contribution to the stochastic GW background** in the LIGO/Virgo sensitivity range
- ✓ Search on-going w/ Virgo SGWB group

FC+PRL'19

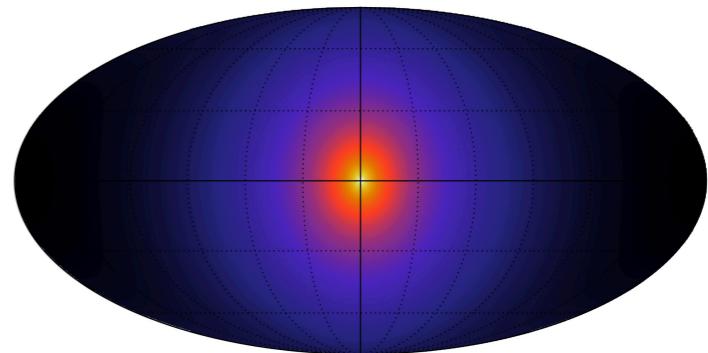
Conclusions

- ✓ Searches for dark matter with **astroparticle experiments successfully test different dark matter models** (not only WIMPs! [see ALPs and PBH searches])
- ✓ Nowadays from indirect detection we can get **strong constraints but assessing their robustness is crucial especially when cross-checking signal hints**
- ✓ The **origin of some longstanding excesses is still unclear** and the dark matter interpretation tantalised by astrophysical alternatives
- ✓ We need a **fully multi-messenger approach** to improve our understanding of these anomalous signals through a **continuous refinement of our astrophysical background models**
- ✓ Great experimental progress at multiple wavelengths (LOFAR, SKA, Athena, CTA, etc) will provide us **access to yet uncharted portions of the DM parameter space and new windows of opportunity for DM detection!**

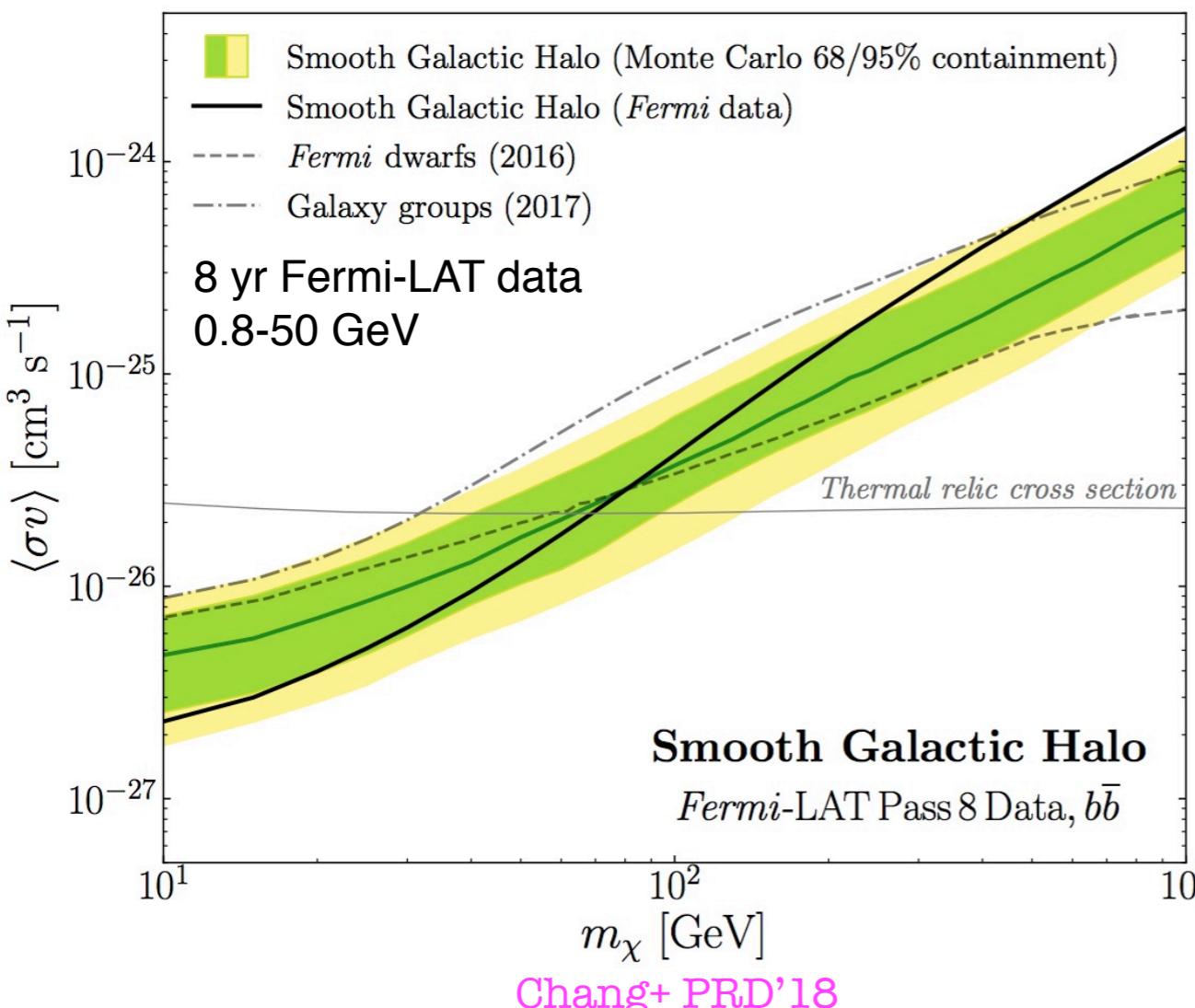
Backup slides

The high-latitude Milky Way halo

The high-latitude region provides robust constraints on annihilating dark matter into hadronic final states

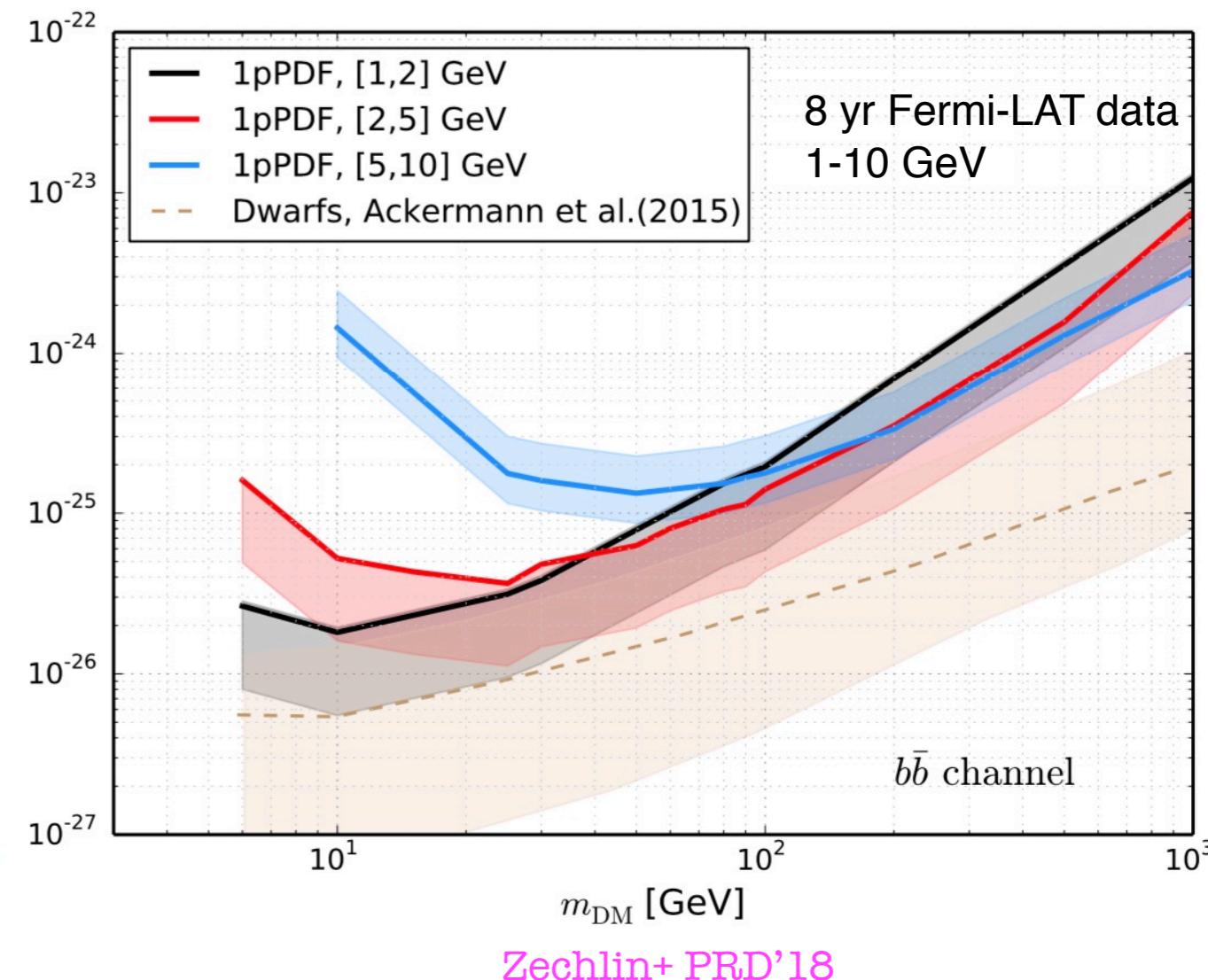


Template fitting



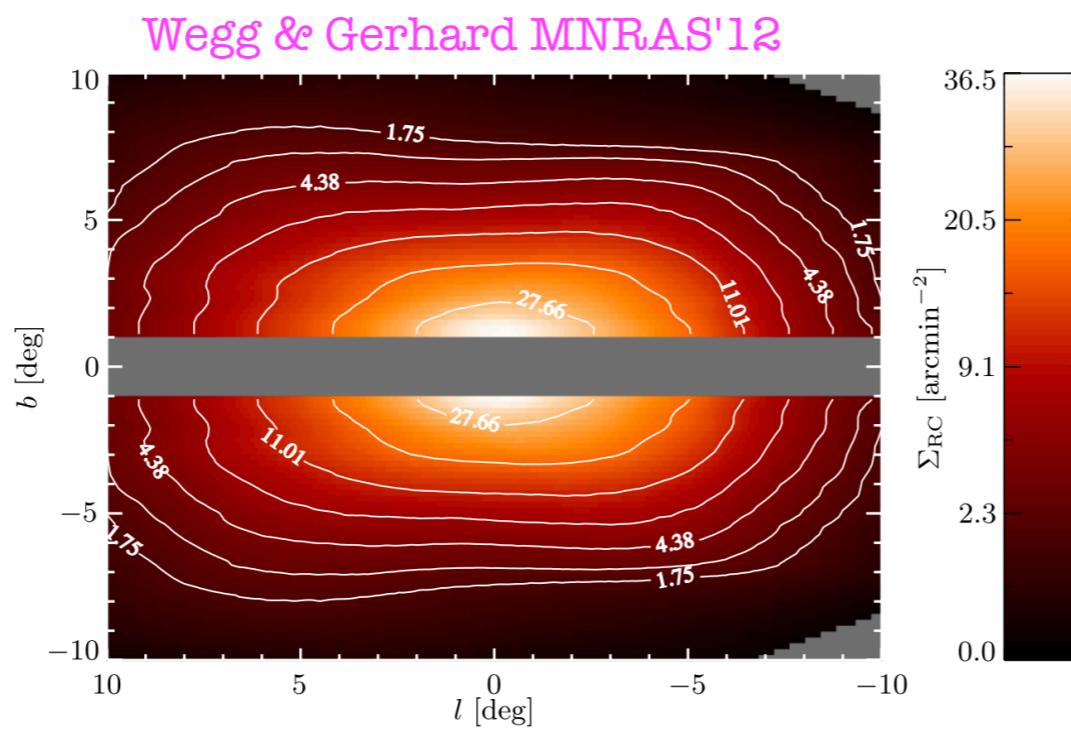
1-point Statistics

Malyshev+ApJ'11; Zechlin+ApJS'16, ApJL'16



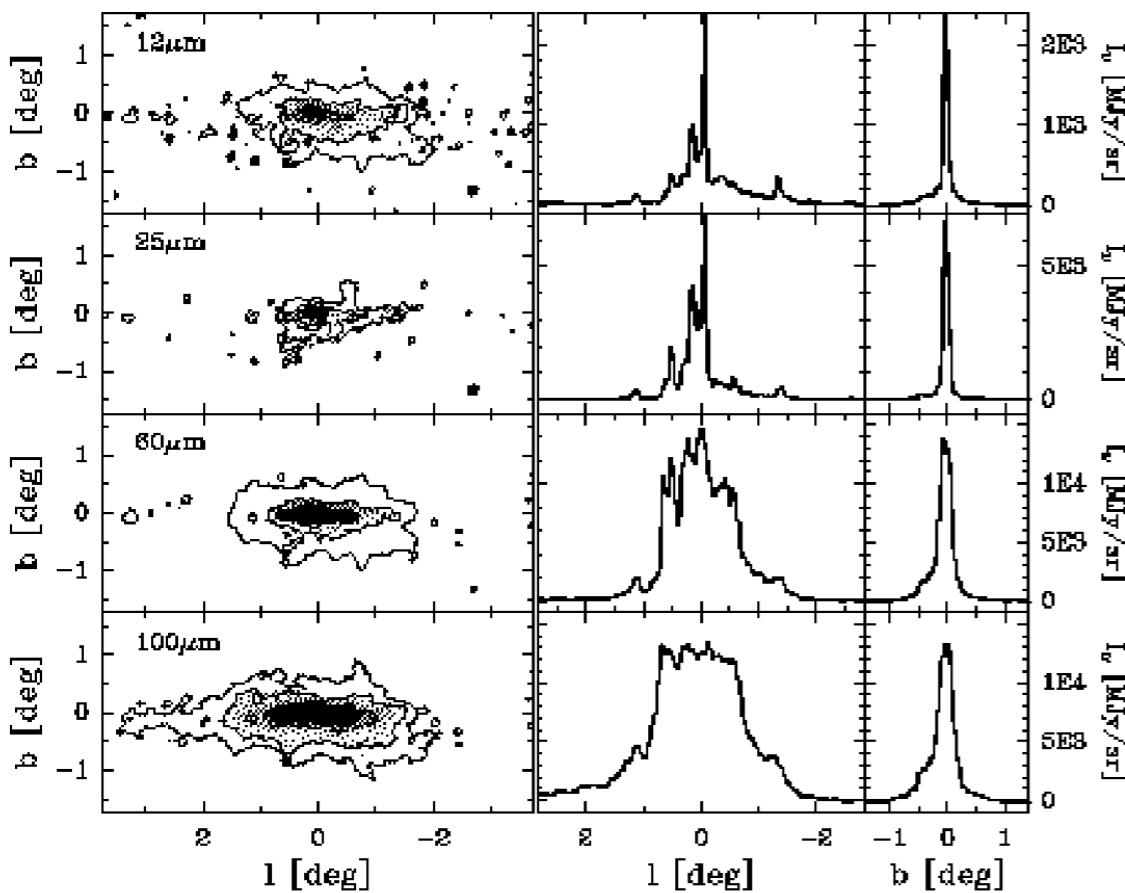
Stellar distribution in the bulge

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

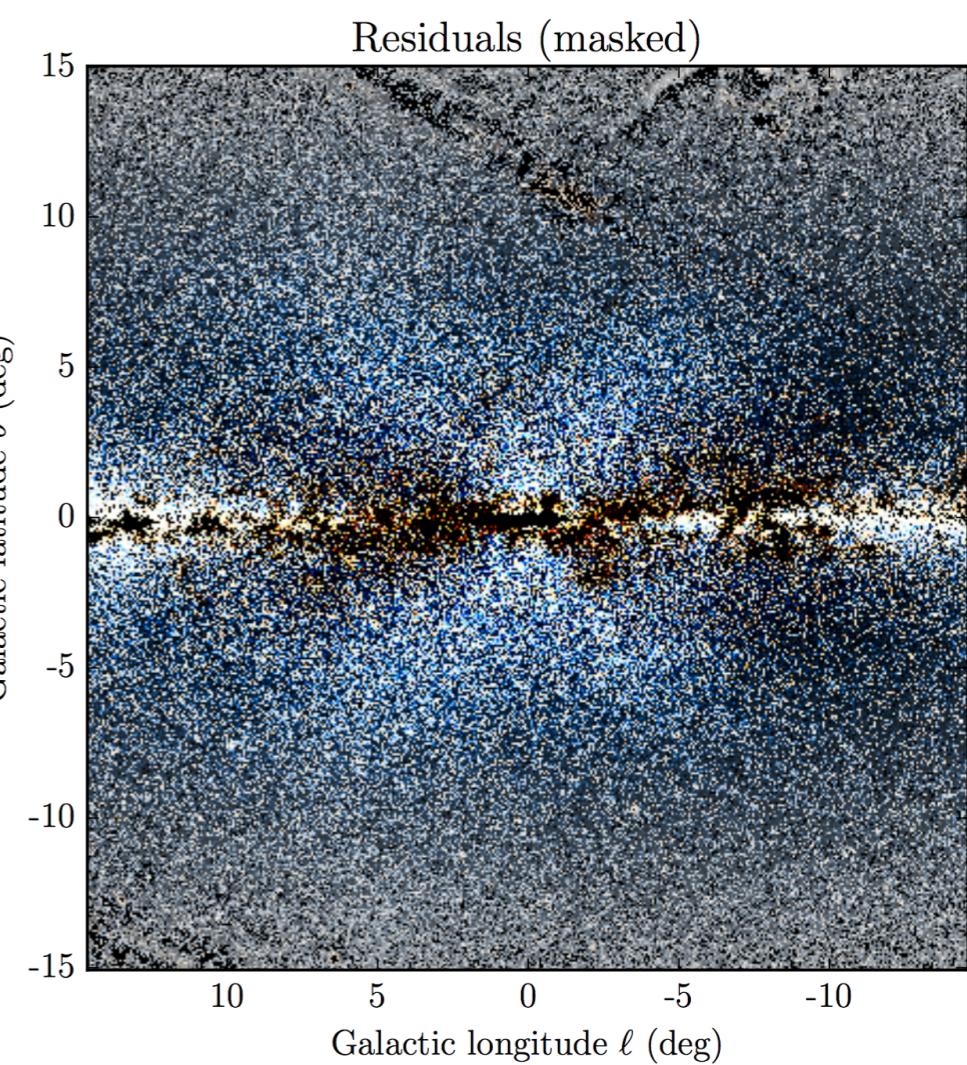


Nuclear bulge
Launhardt+A&A'02

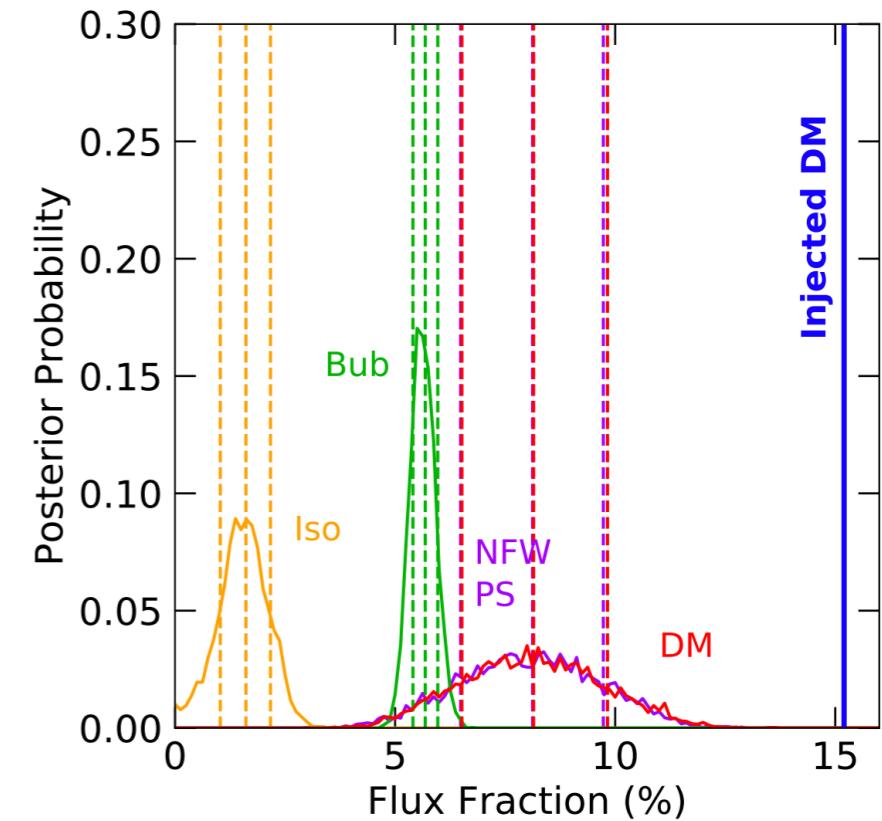
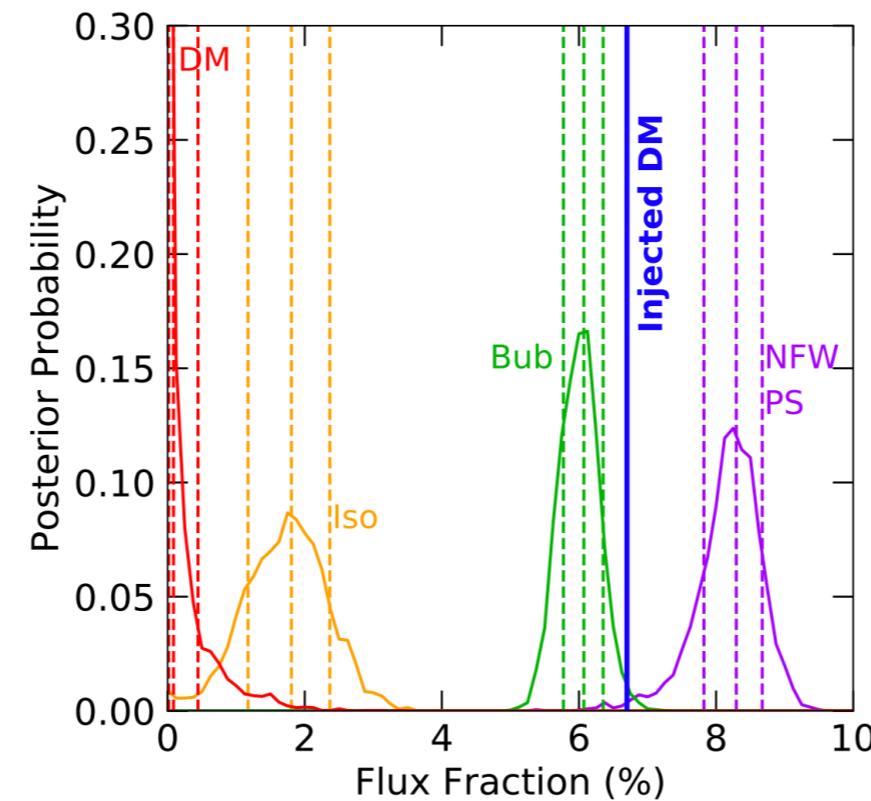
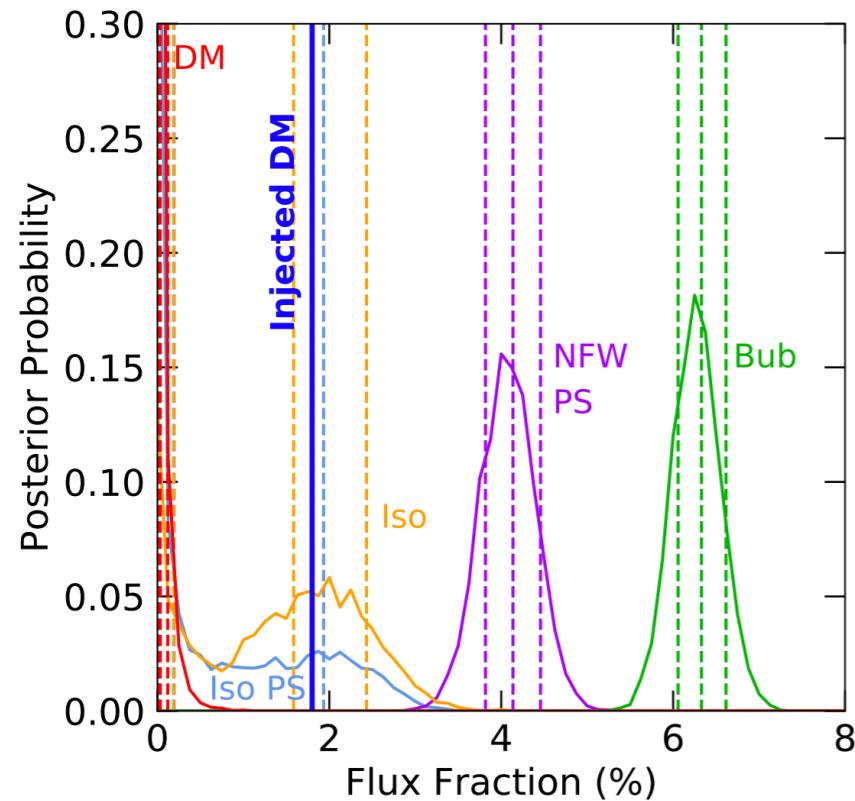
$1.4 \times 10^9 M_{\odot}$



X-shaped bulge
Ness&Lang AJ'16



NPTF and mis-modelling



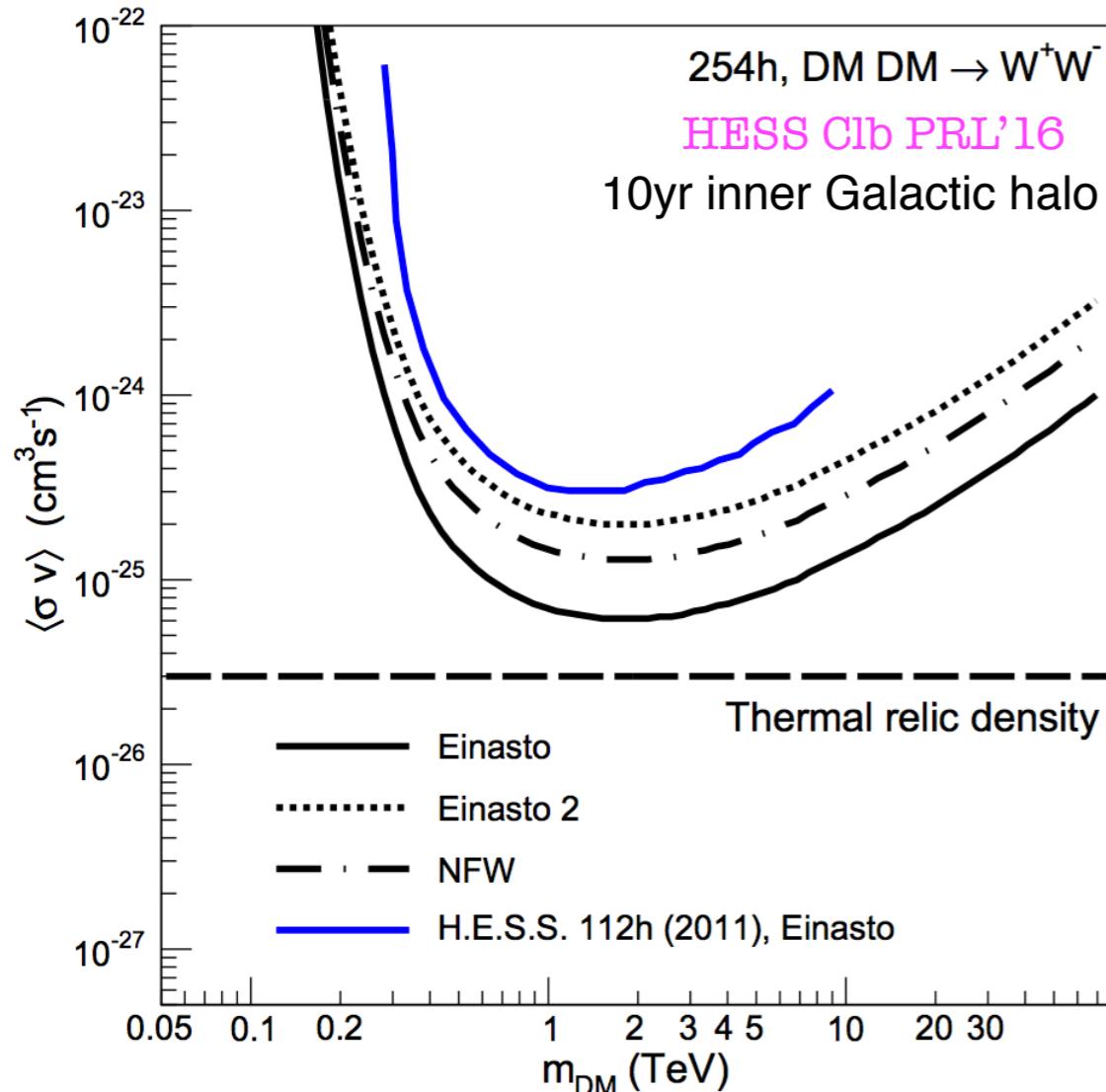
Leane & Slatyer 1904.08430

“Dark Matter Strikes Back at the Galactic Center”

[But see also Chang+ 1908.10874]

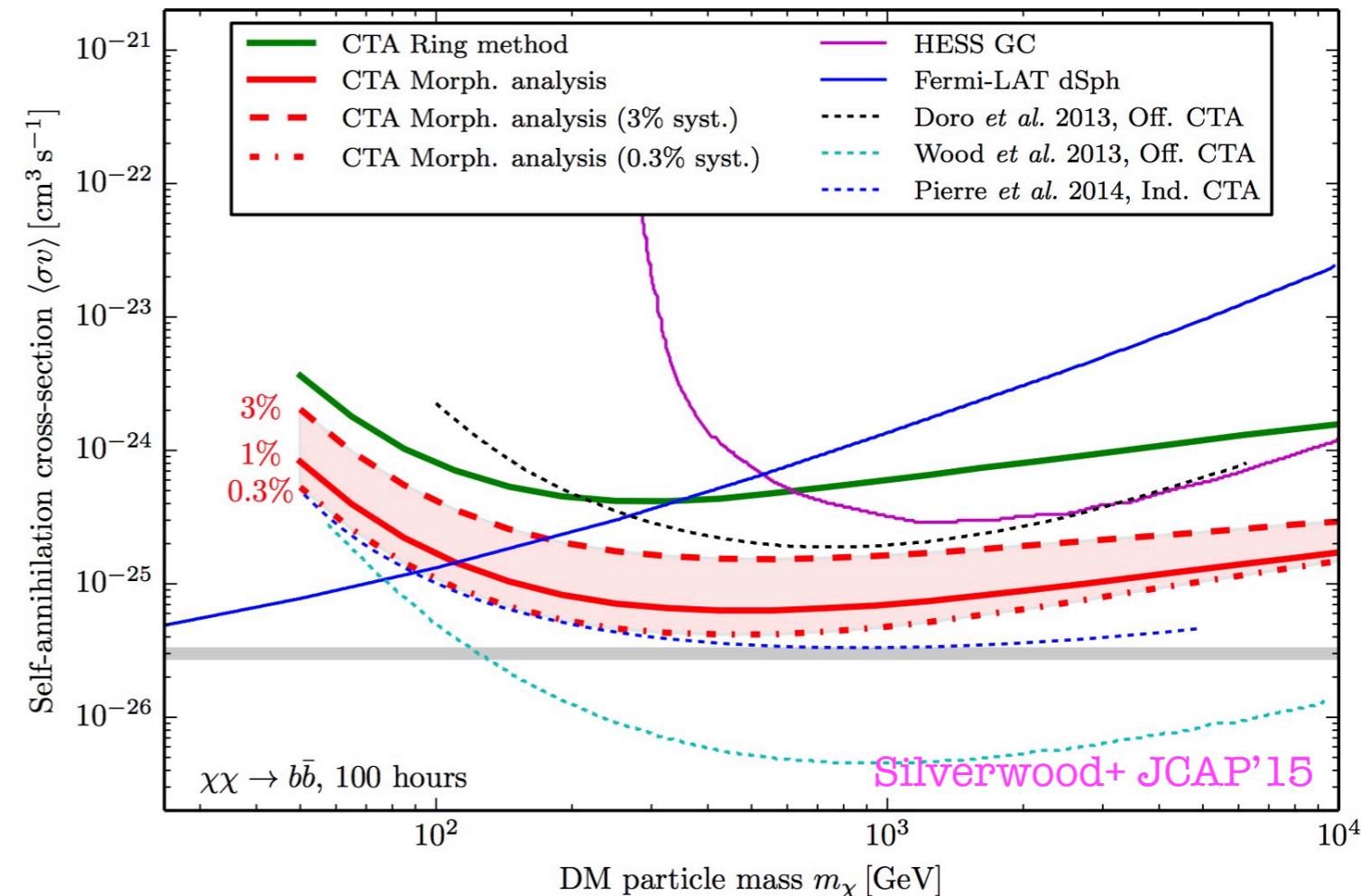
Very high-energy photons

Status



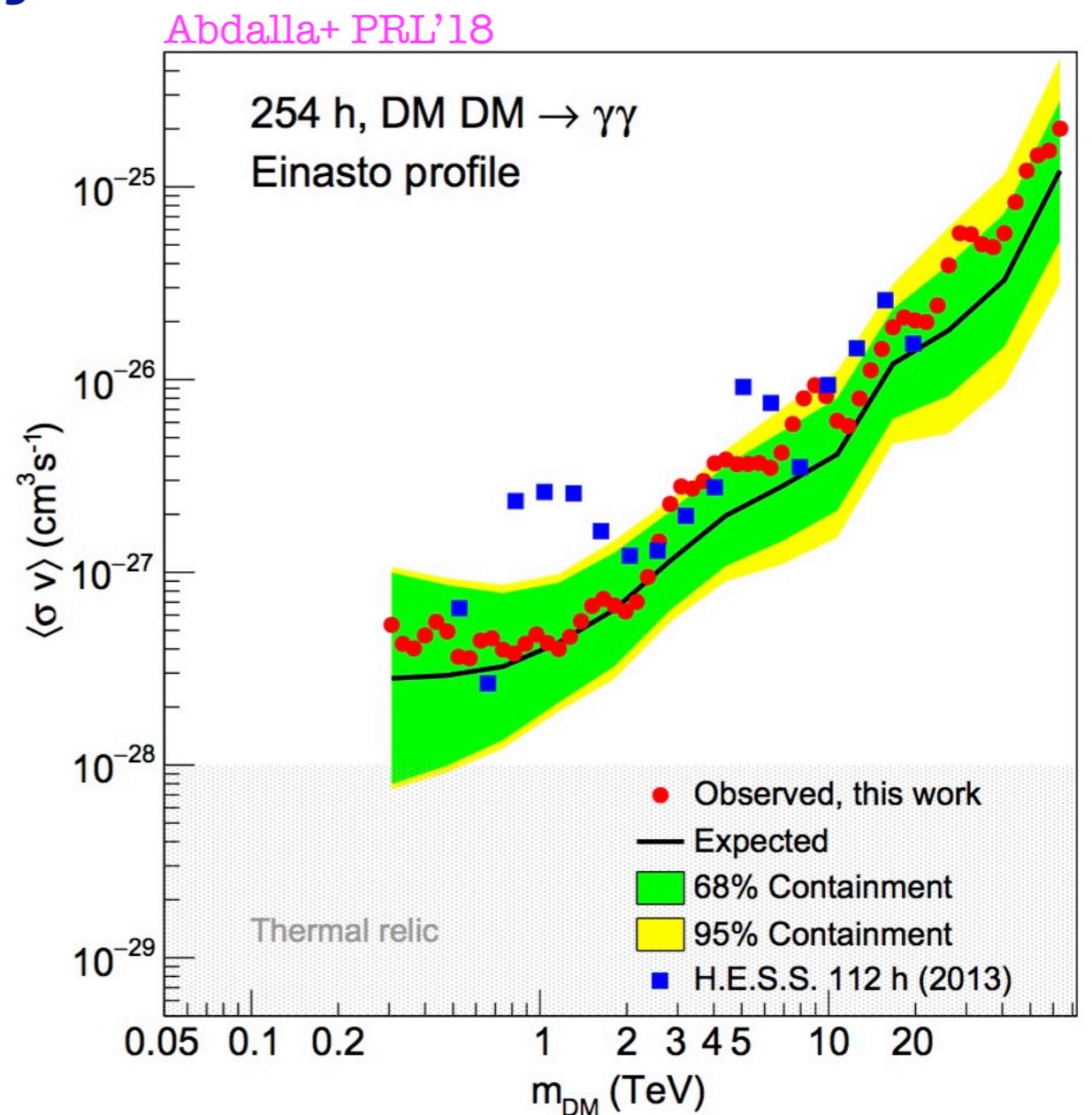
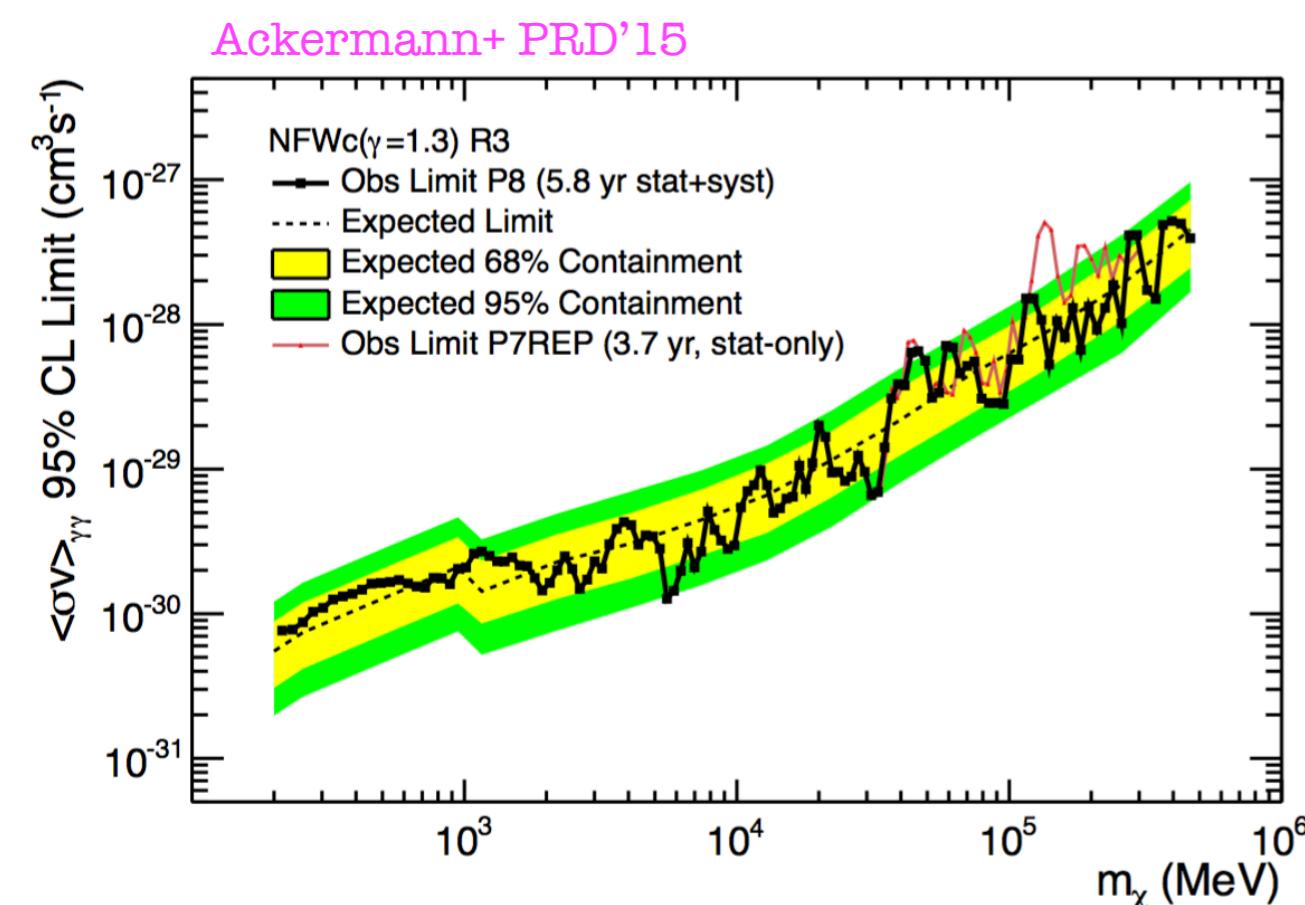
- Most constraining analysis at E>1TeV
 - Other relevant targets: combined dSphs
 - TeV scale thermal dark matter starts to be challenged
- Baumgart+ 1808.08956;
Rinchiuso+ PRD'18

Future

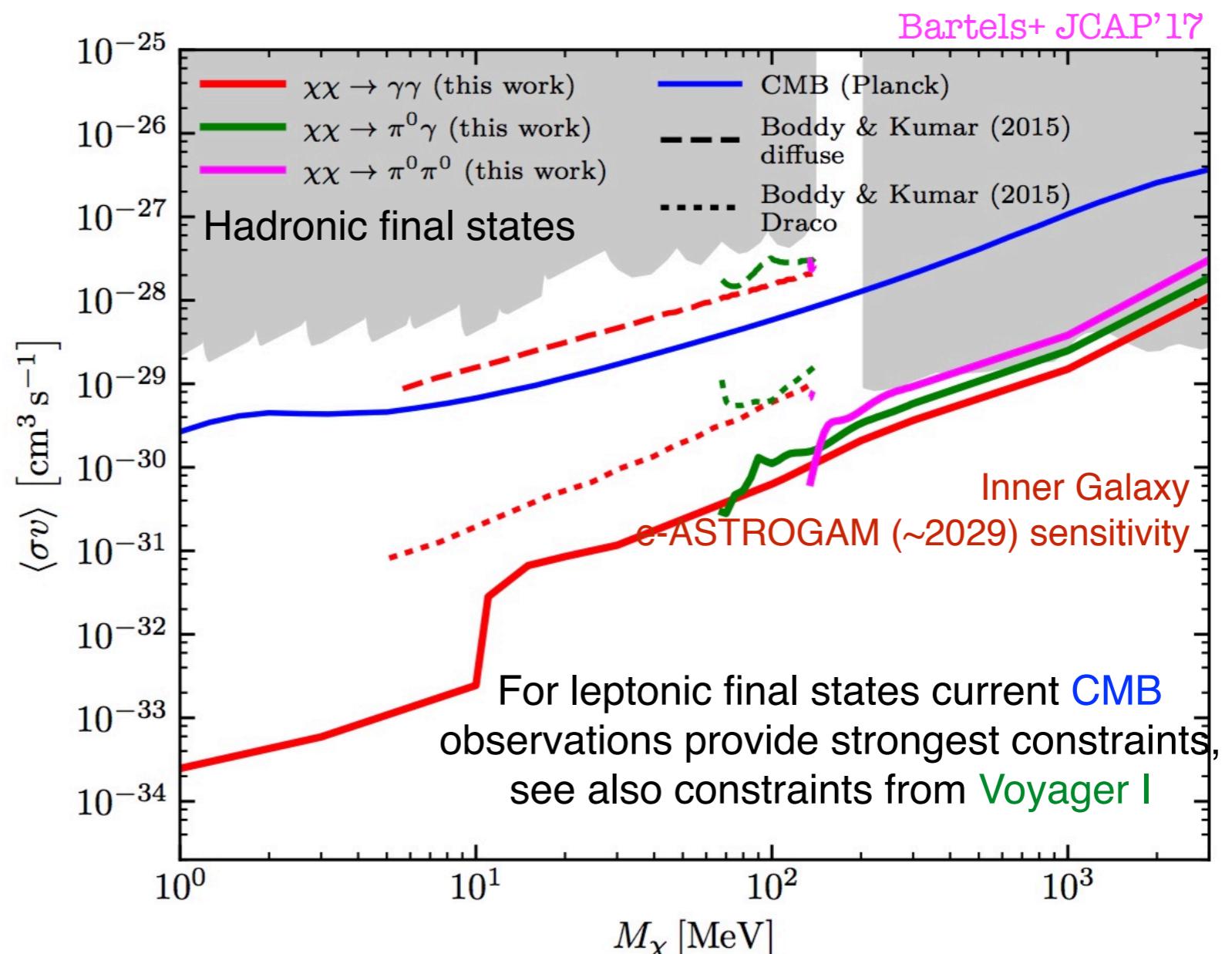
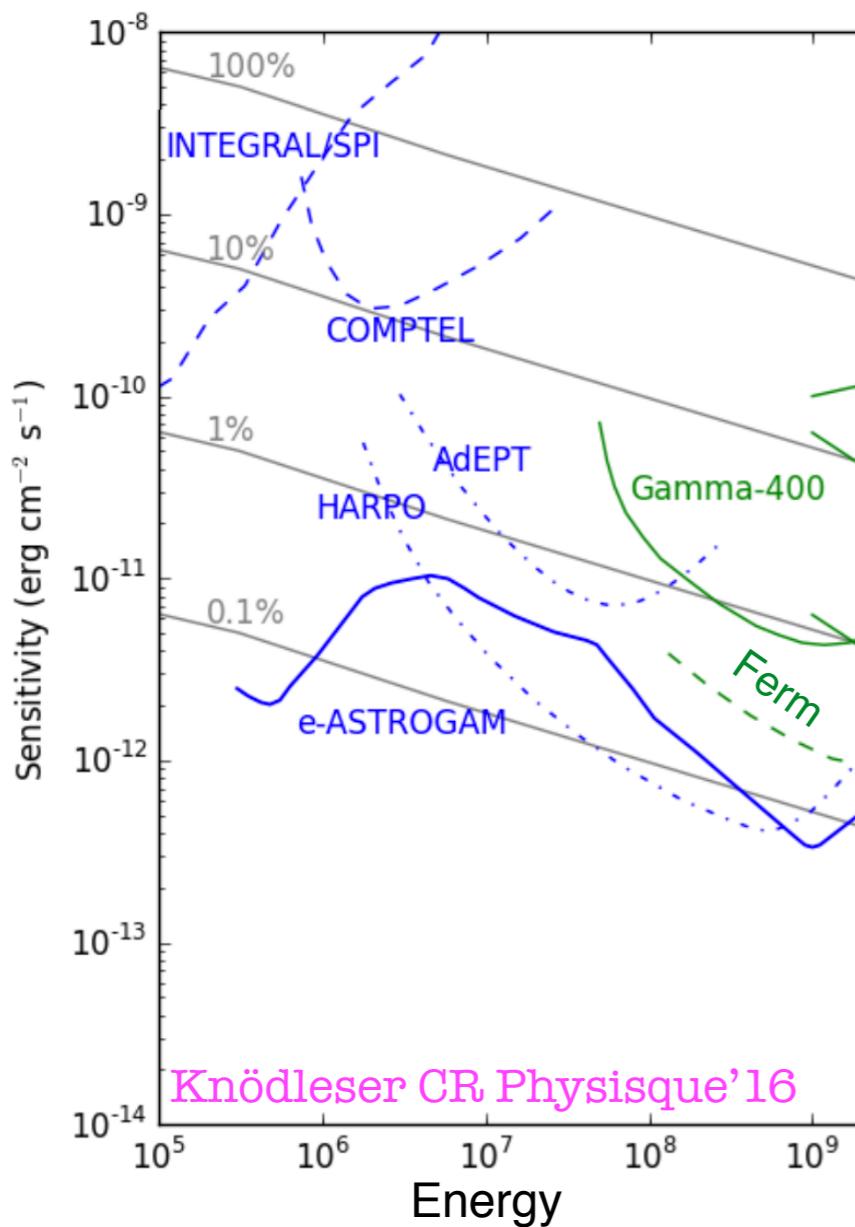


- HAWC is already improving limits from dSphs (> 1 TeV) and Galactic centre (> 100 TeV)
- Albert+ ApJ'18; Abeysekara+ JCAP'18
- CTA (~2022) will improve HESS limits by factor up to 10
- Silverwood+ JCAP'15;
Carr+ 2015; Lefranc+PRD'15

Status of line signal searches in gamma rays



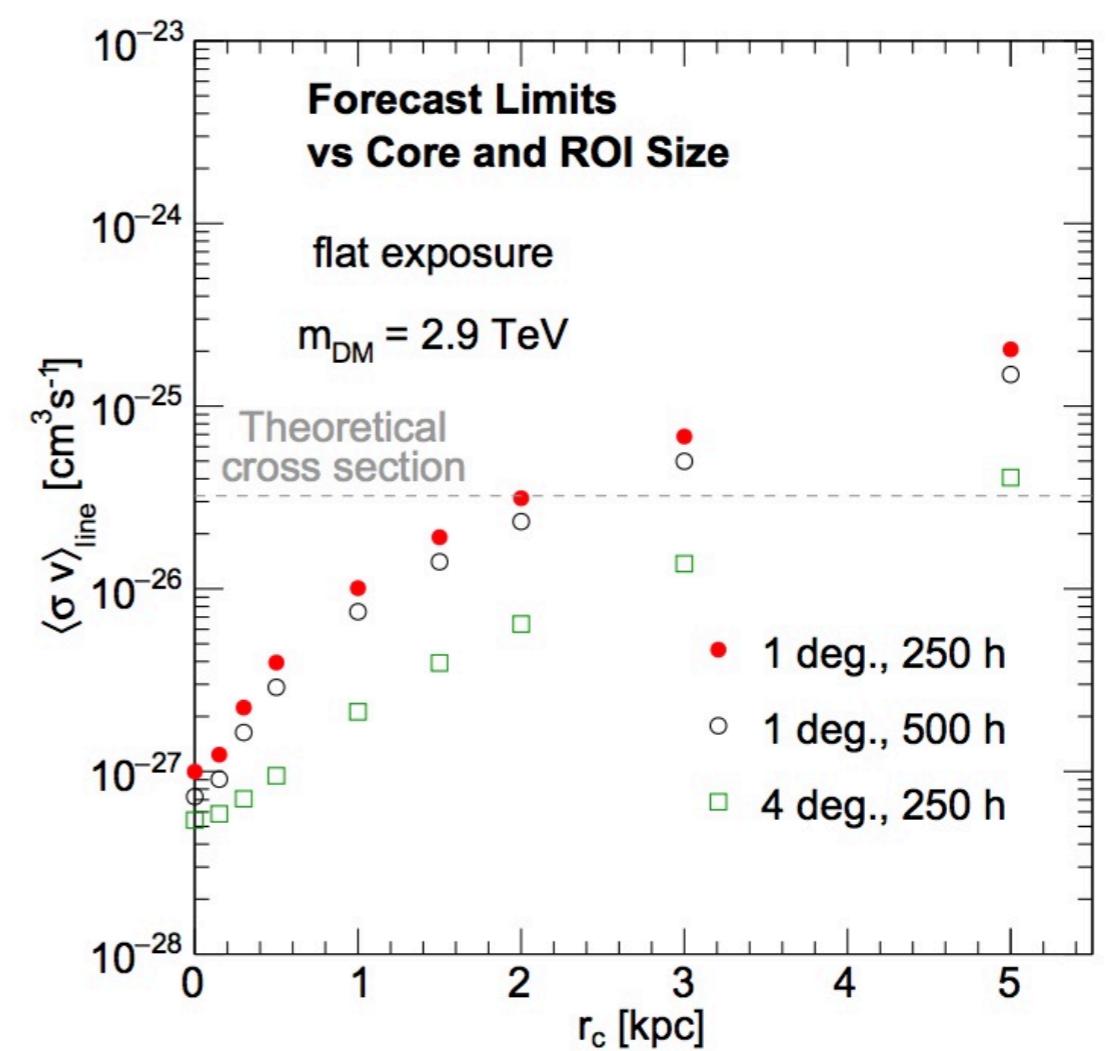
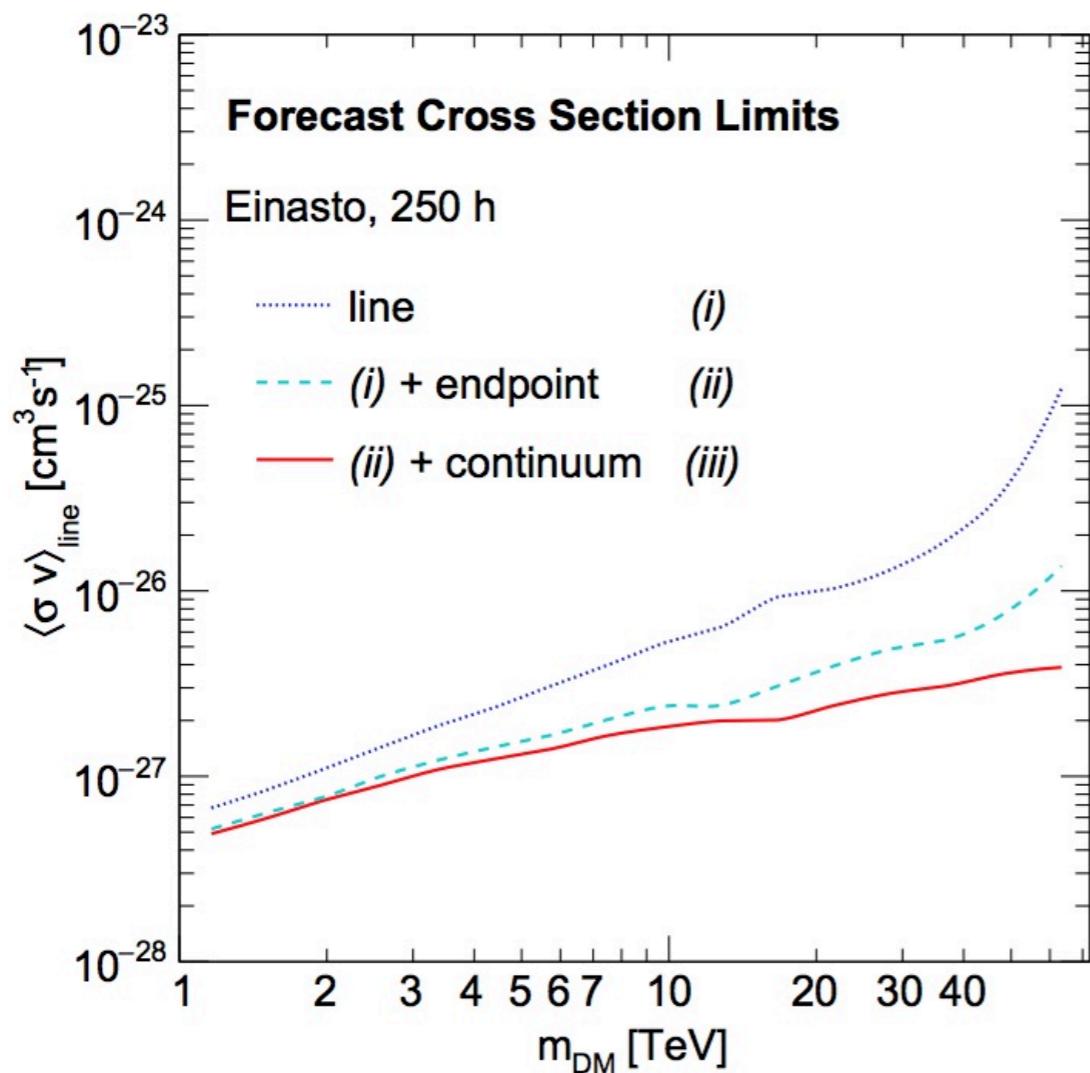
The sub-GeV sensitivity gap



- 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

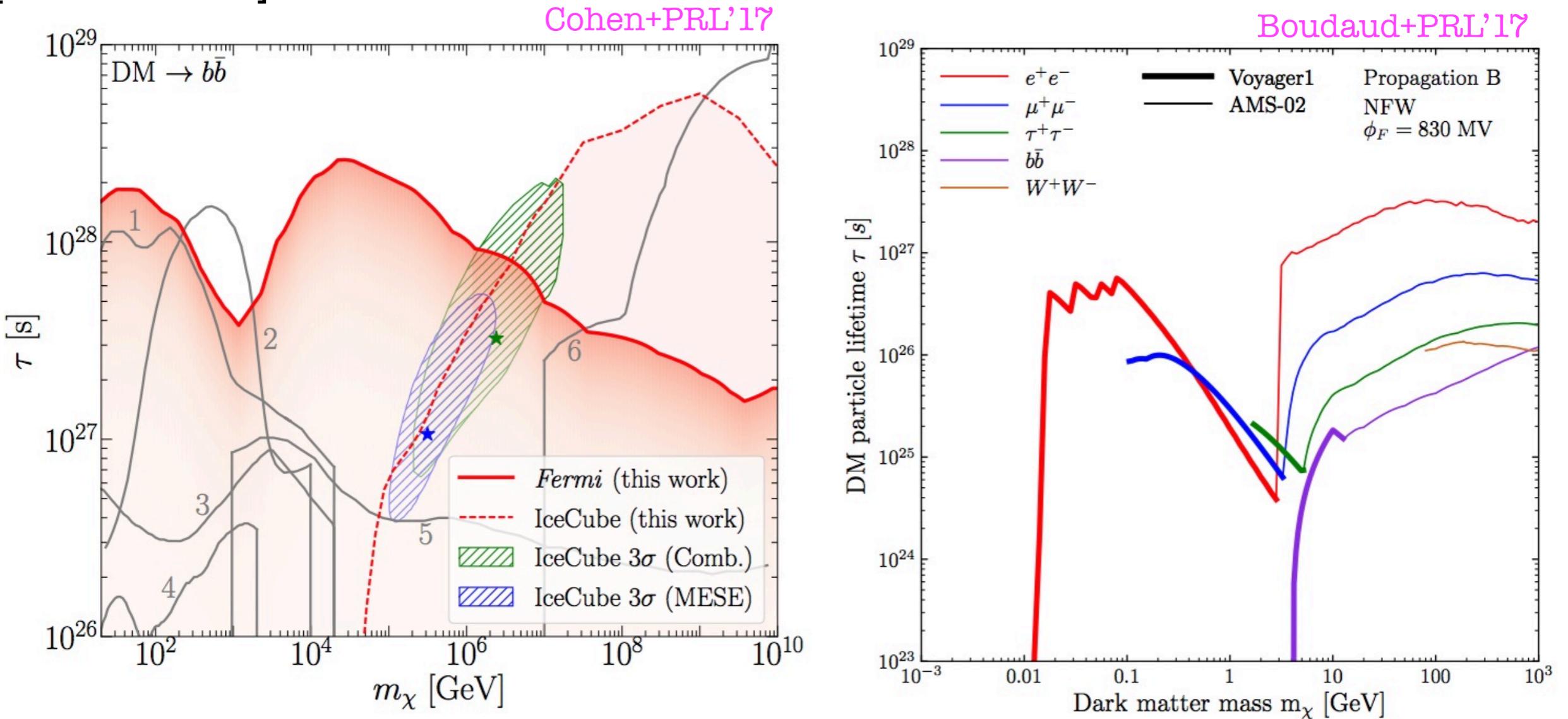
TeV-wino DM



Baumgart+ 1808.08956; Rinchiuso+ PRD'18

Status of decaying dark matter

- Light DM (10 MeV - GeV) constrained by: photon diffuse bkg [Essig+’13]; CMB [Slatyer&Wu’17]; Voyager [Boudaud+PRL’17]
- Heavy ($>$ GeV) DM constrained by: dSPhs, MW halo, extragalactic photons [Cohen+PRL’17]



Decay lifetimes below $\sim 10^{27-28}$ s ruled out for most final states and keV-EeV DM masses; for few-MeV DM decaying to e^+e^- , lifetimes can be as short as 10^{24-25} s