Journées Théorie

PNHE

1-2 Octobre 2018

Dark Matter Searches with Gamma Rays

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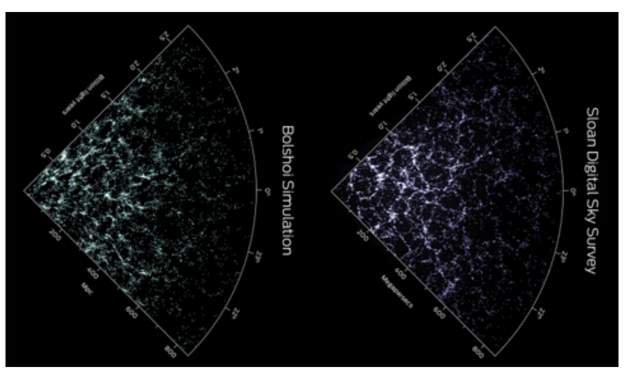
Illustration by Sandbox Studio, Chicago

Dark matter gravitational evidence

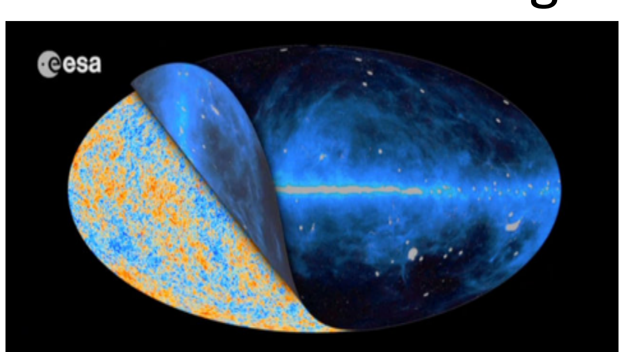
Rotation curves

Galaxy clusters

Large Scale structures



Cosmic microwave background

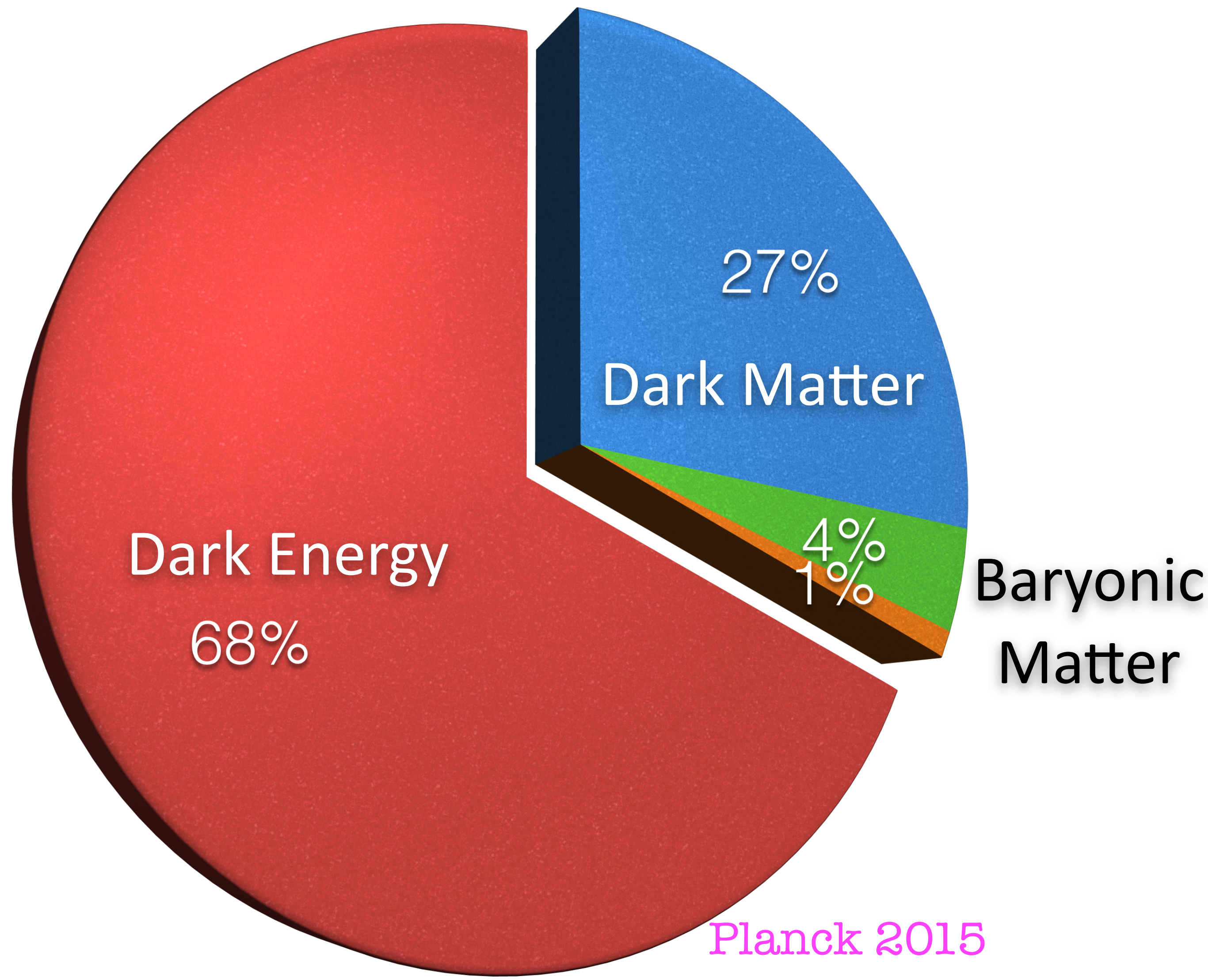


~kpc

~Mpc

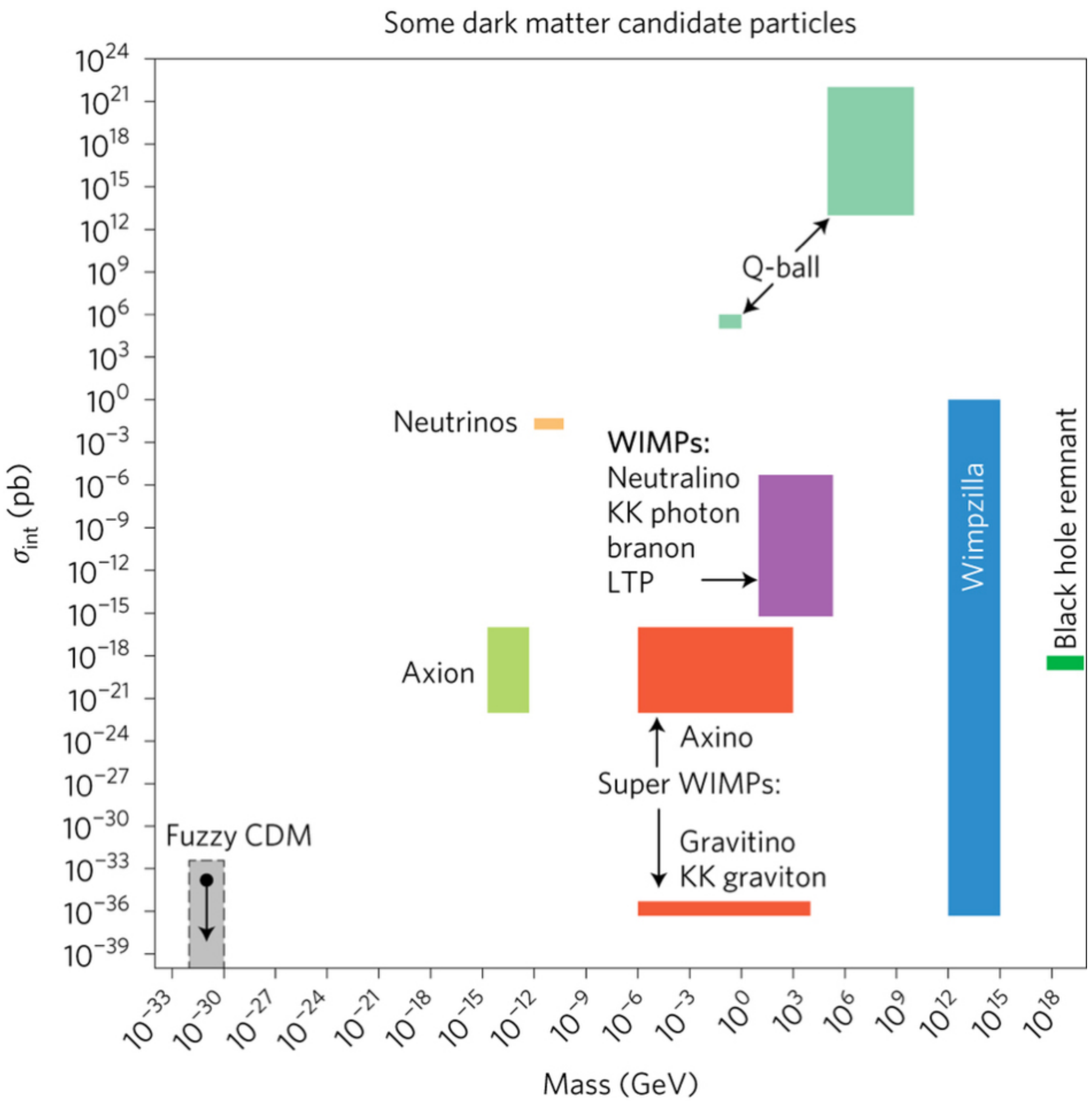
~Gpc

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



Dark matter constitutes about 85% of the matter content of the Universe.

The dark matter landscape

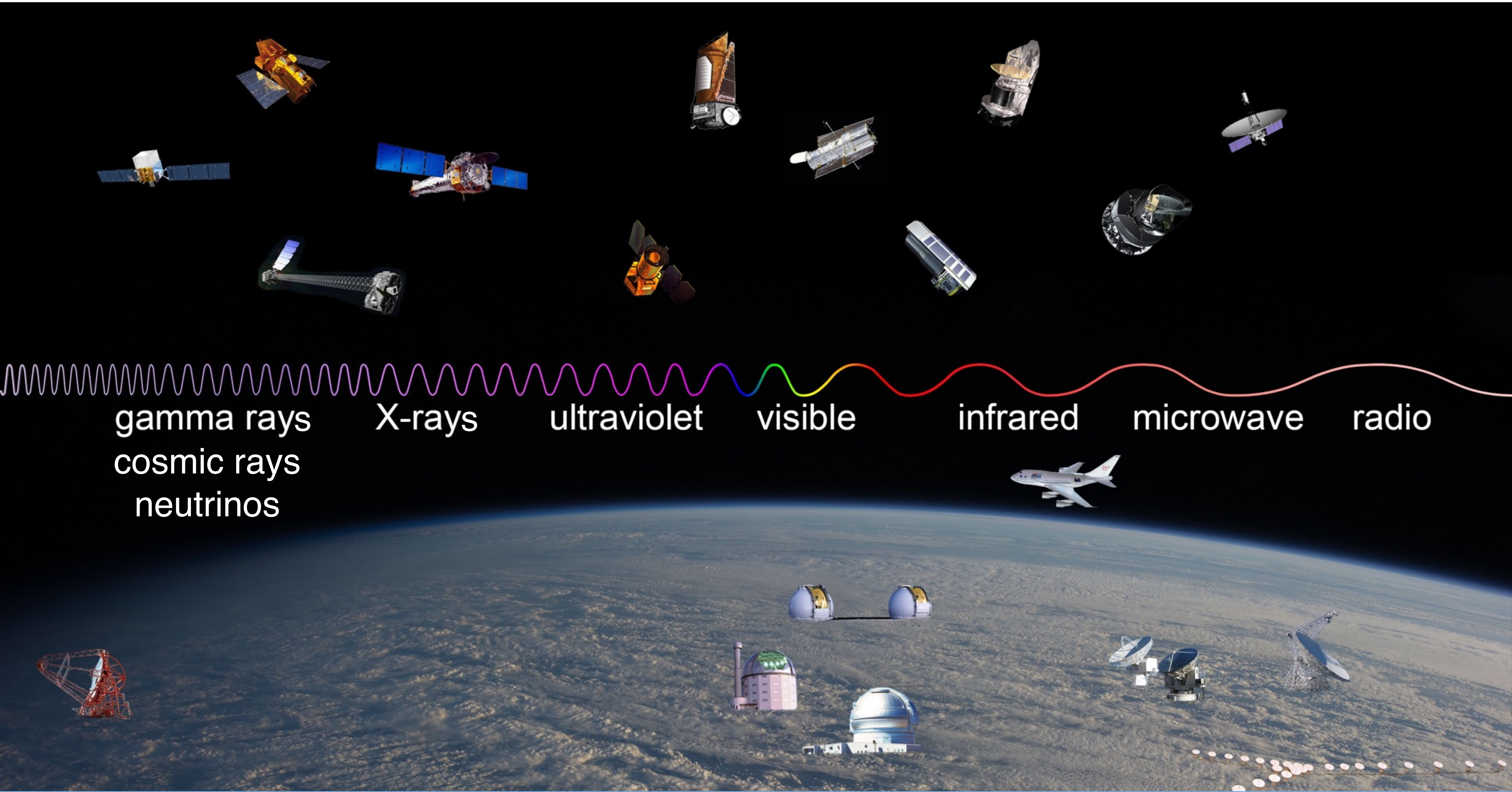


- Input from theory helps to better define the dark matter candidate of interest
- Identification strategies might be more or less model dependent
- The theoretical prejudice in dark matter searches is mostly set by what we can probe with available data

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



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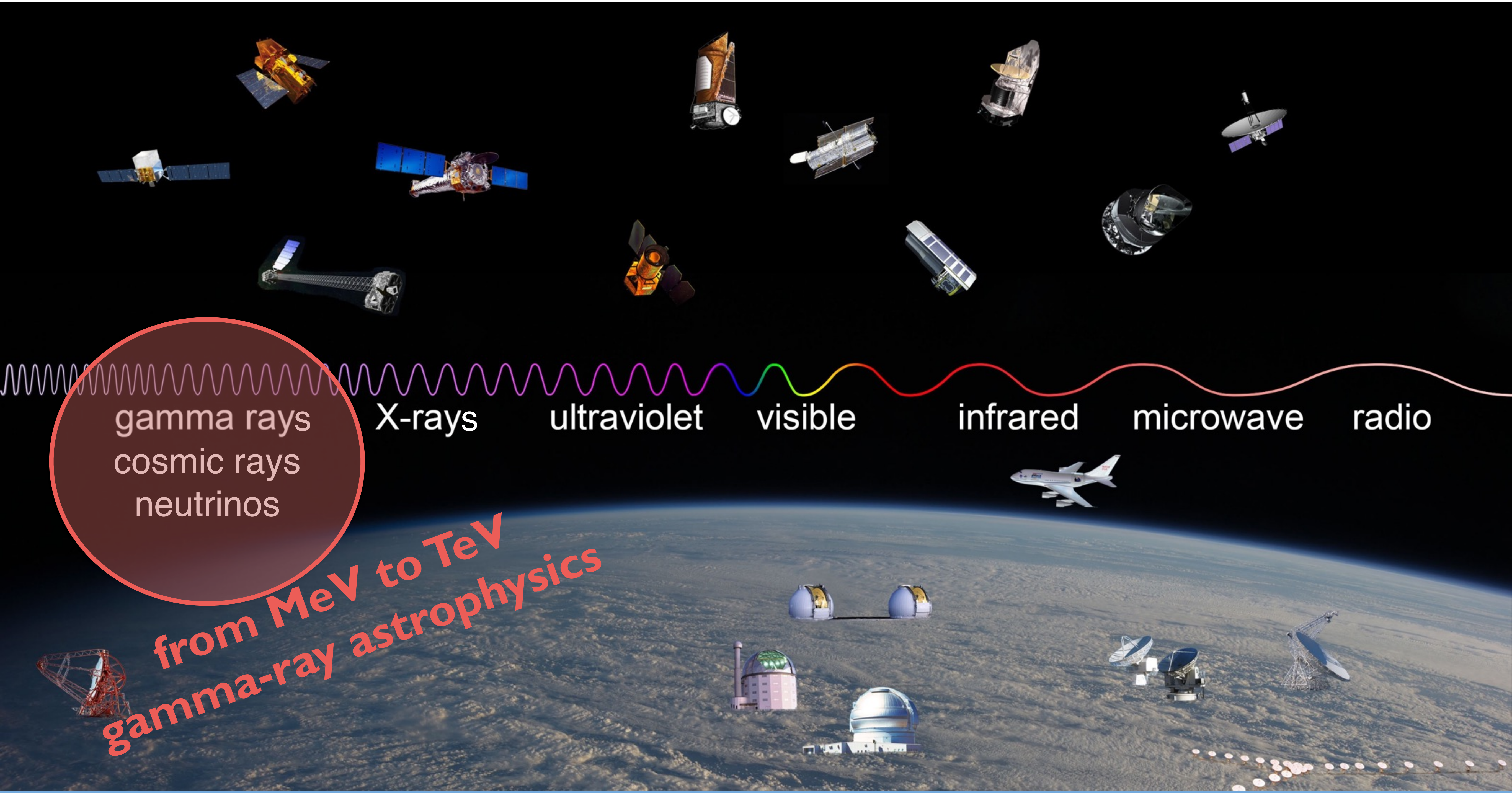
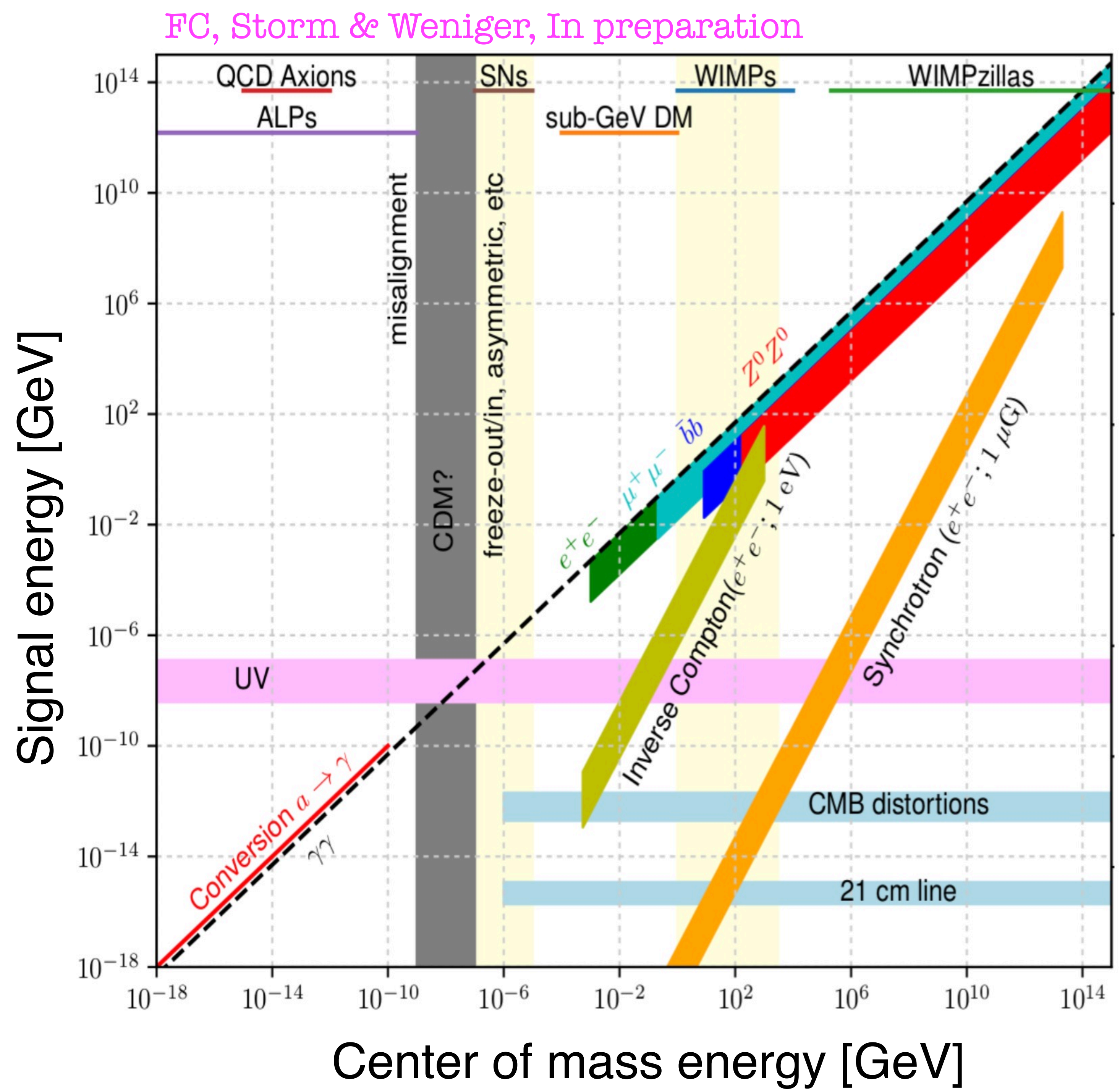


Dark matter candidates & Photon energy



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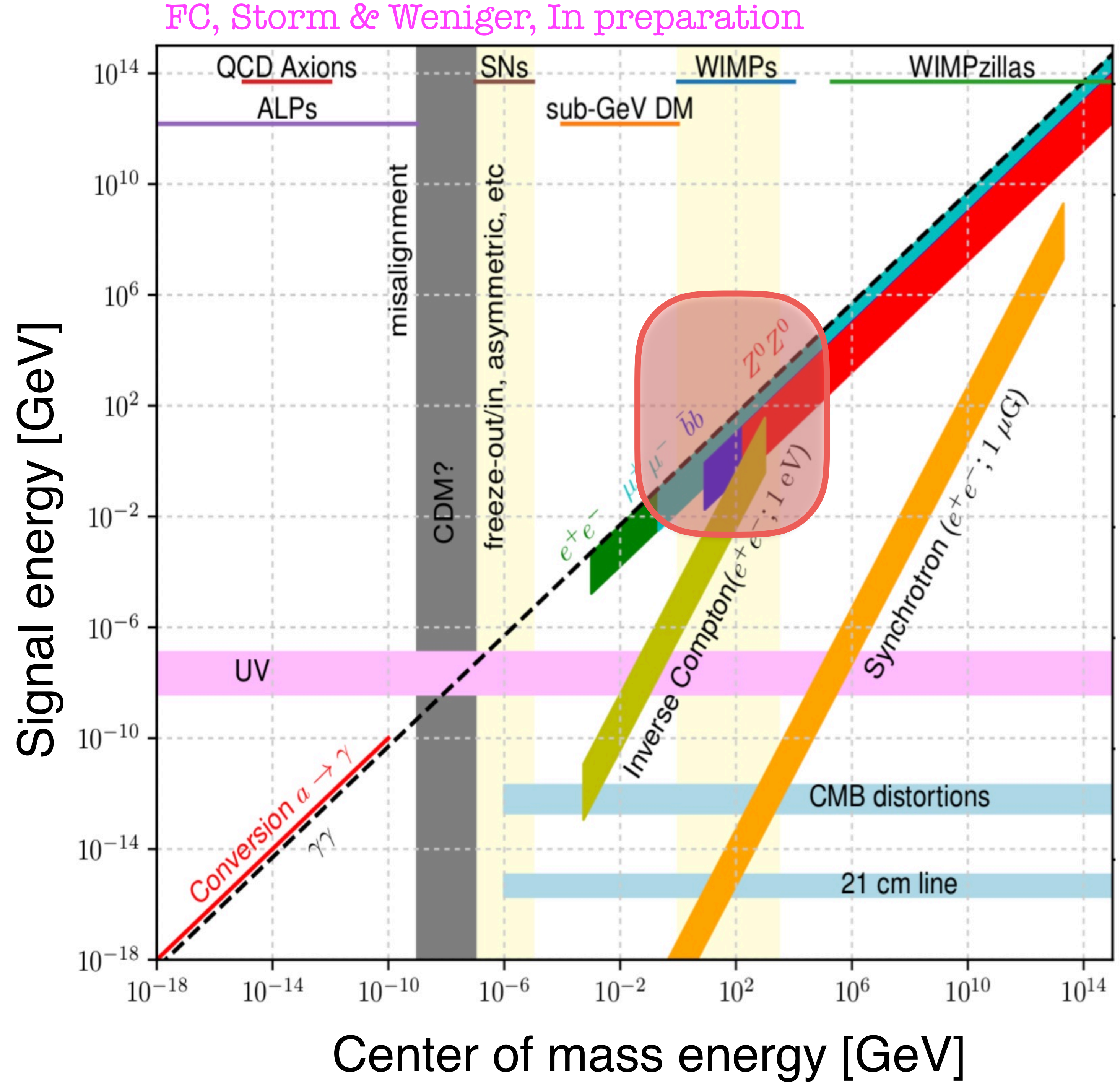
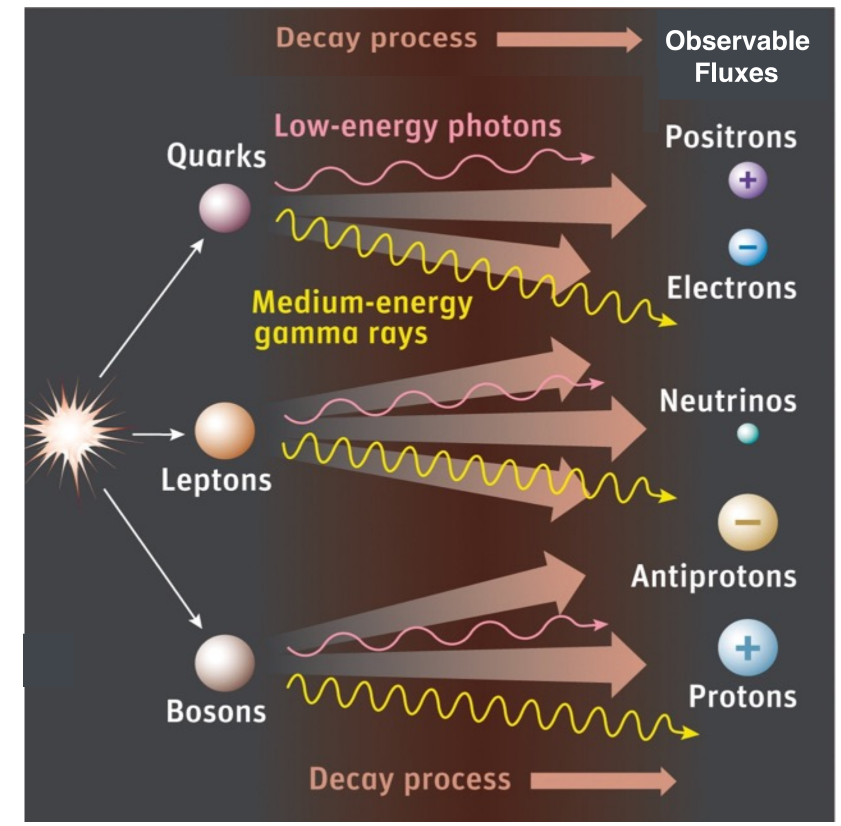


Focus on searches for
WIMP dark matter

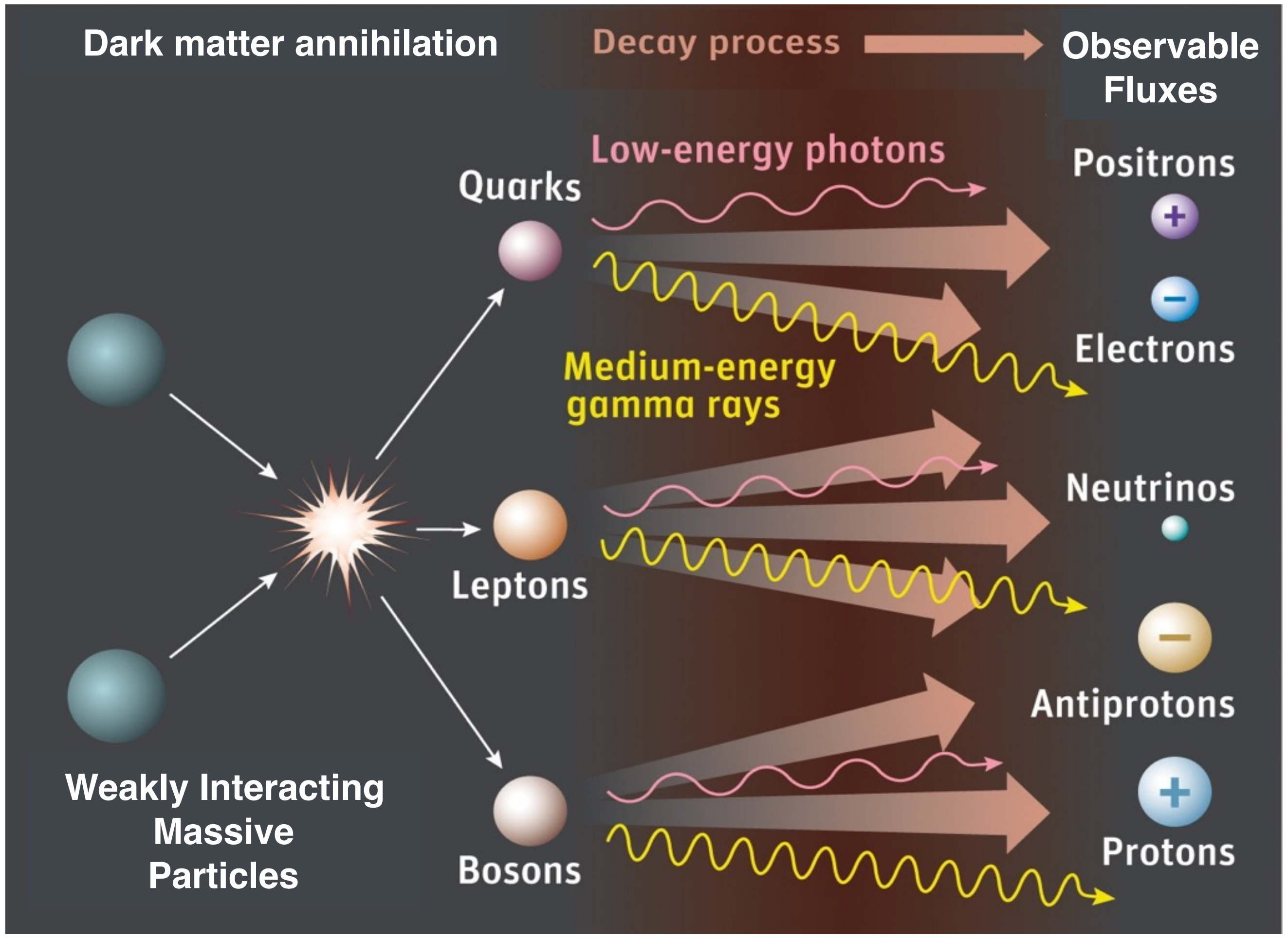
DM annihilation/decay



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

[Dark matter candidates and phenomenology: **P. D. Serpico**]

Indirect (WIMP) dark matter detection



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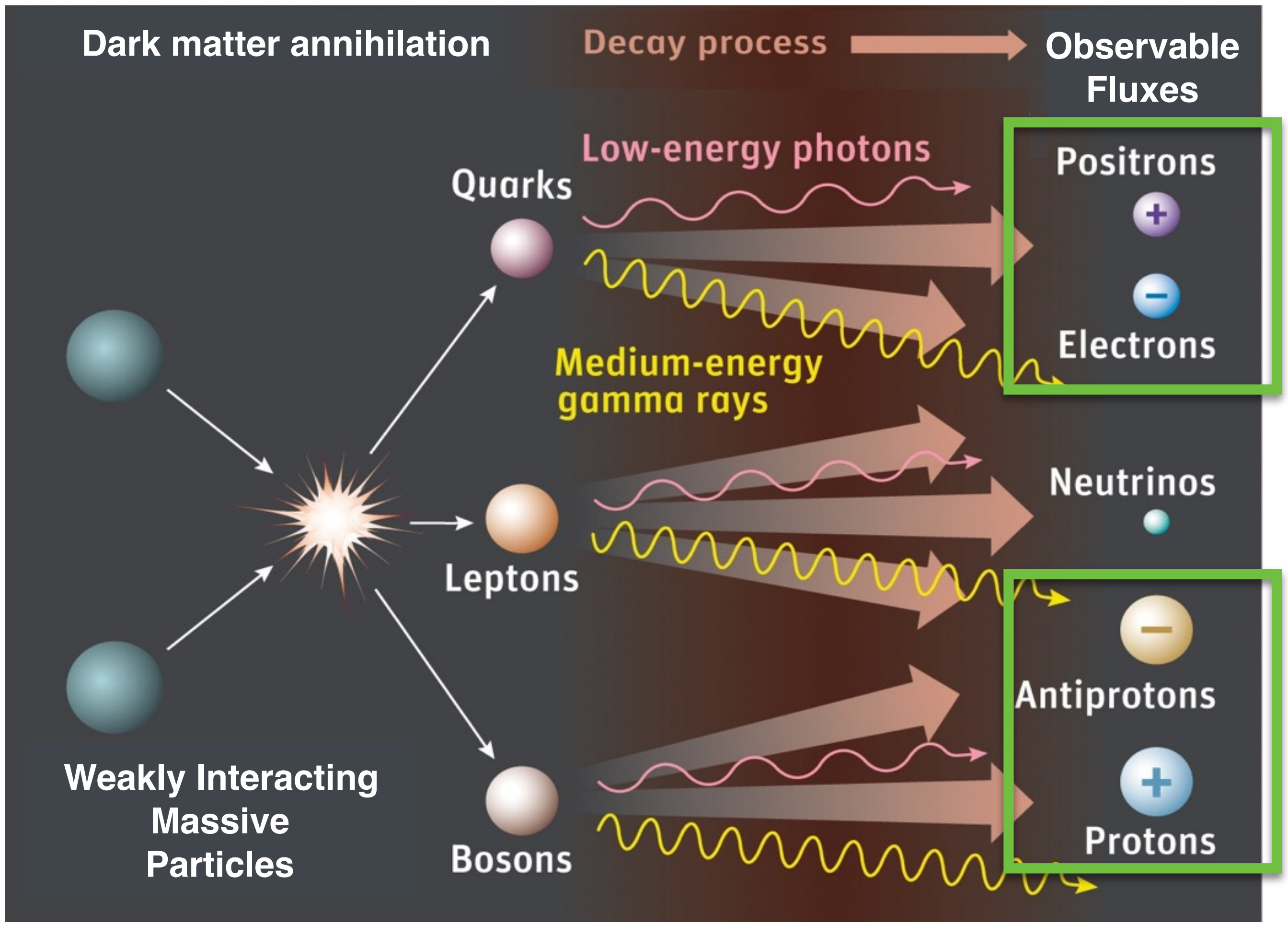

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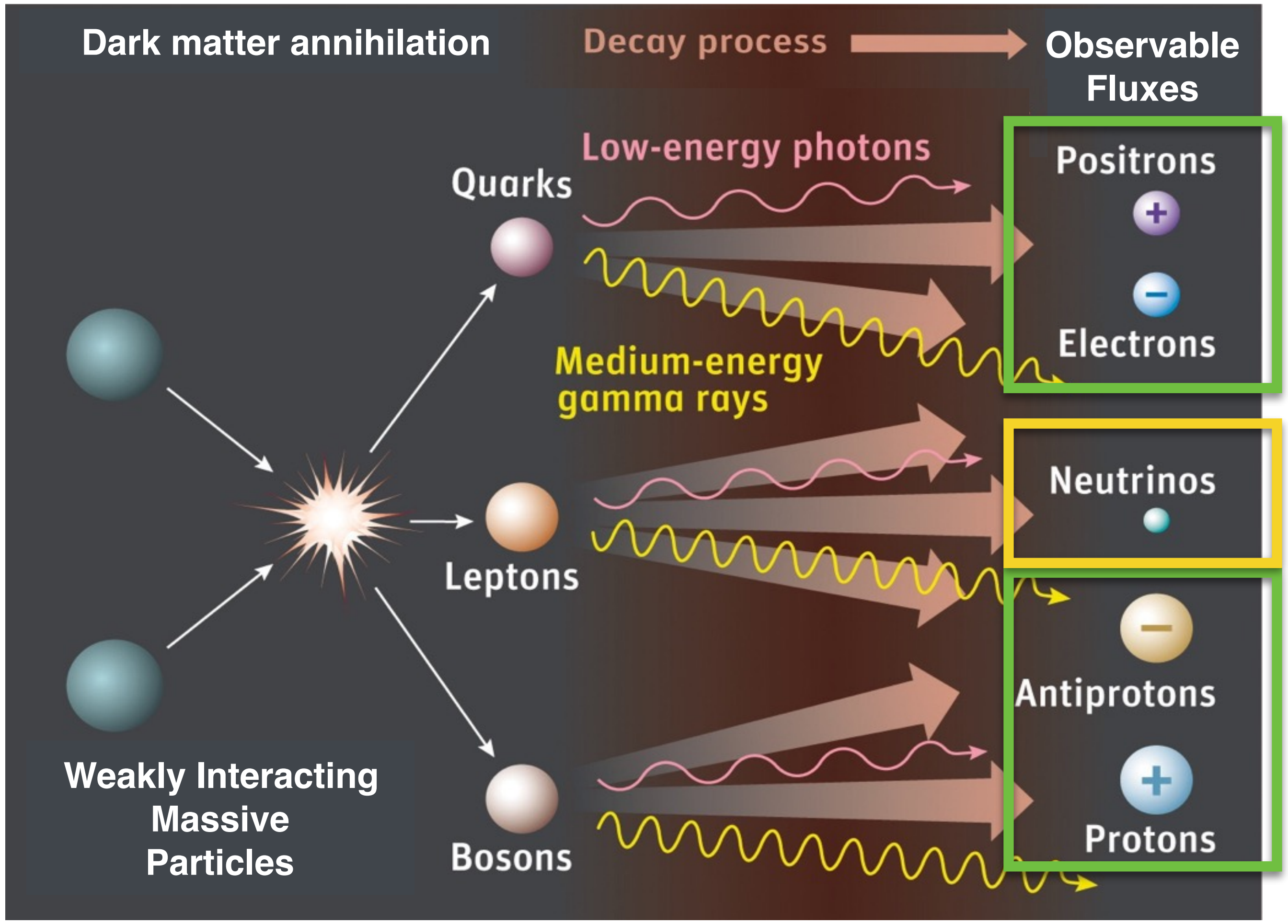

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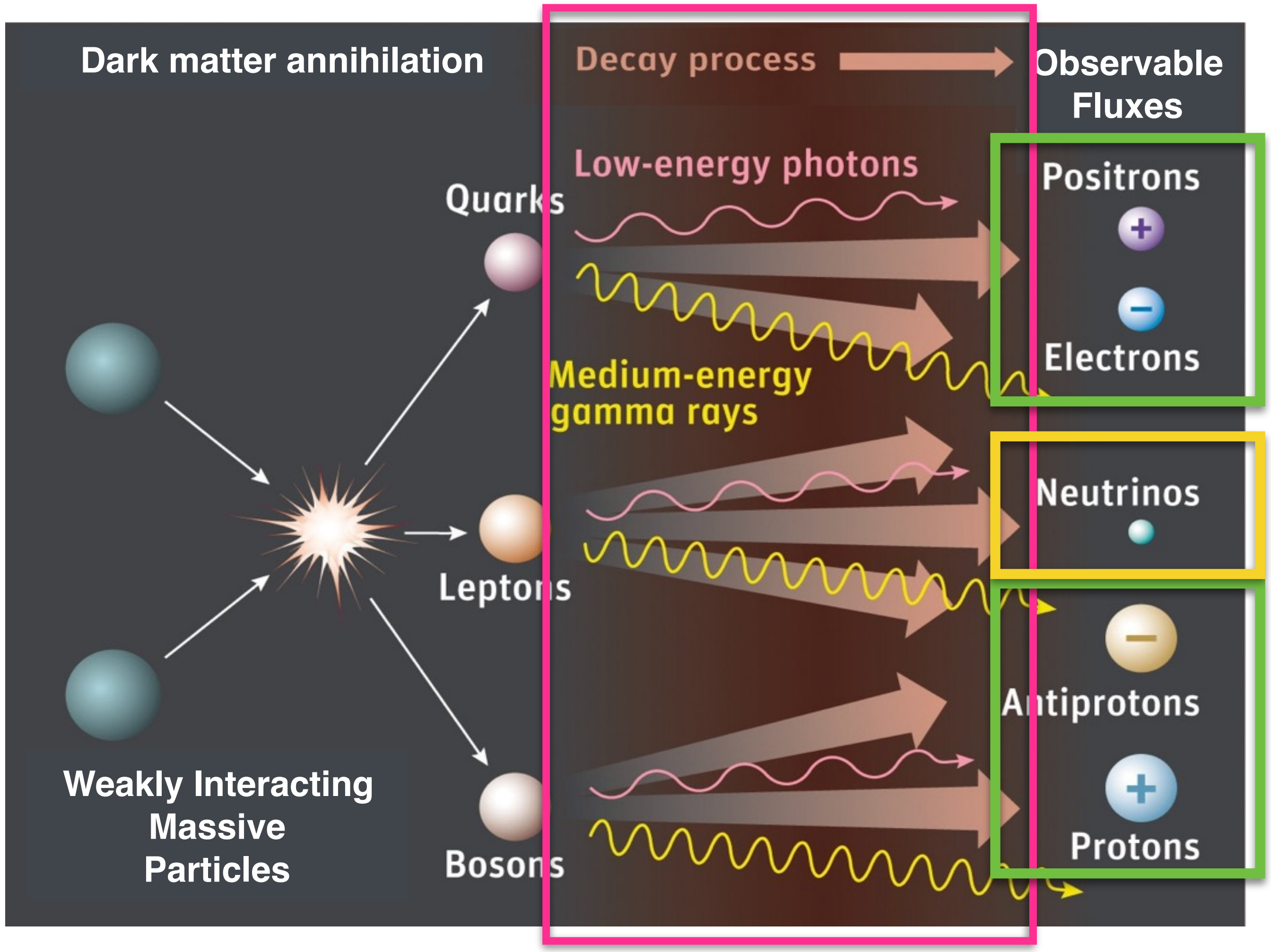

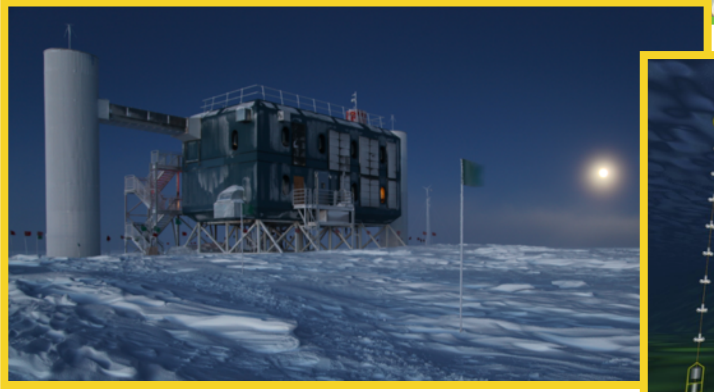

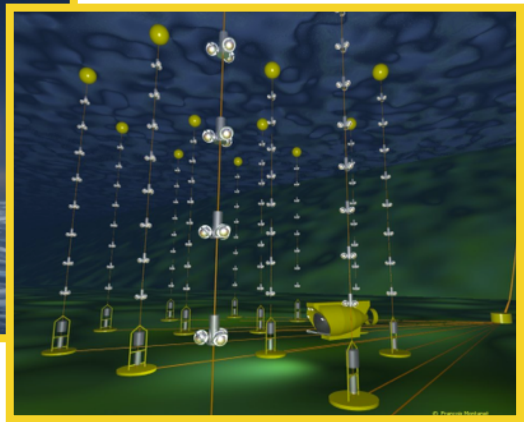

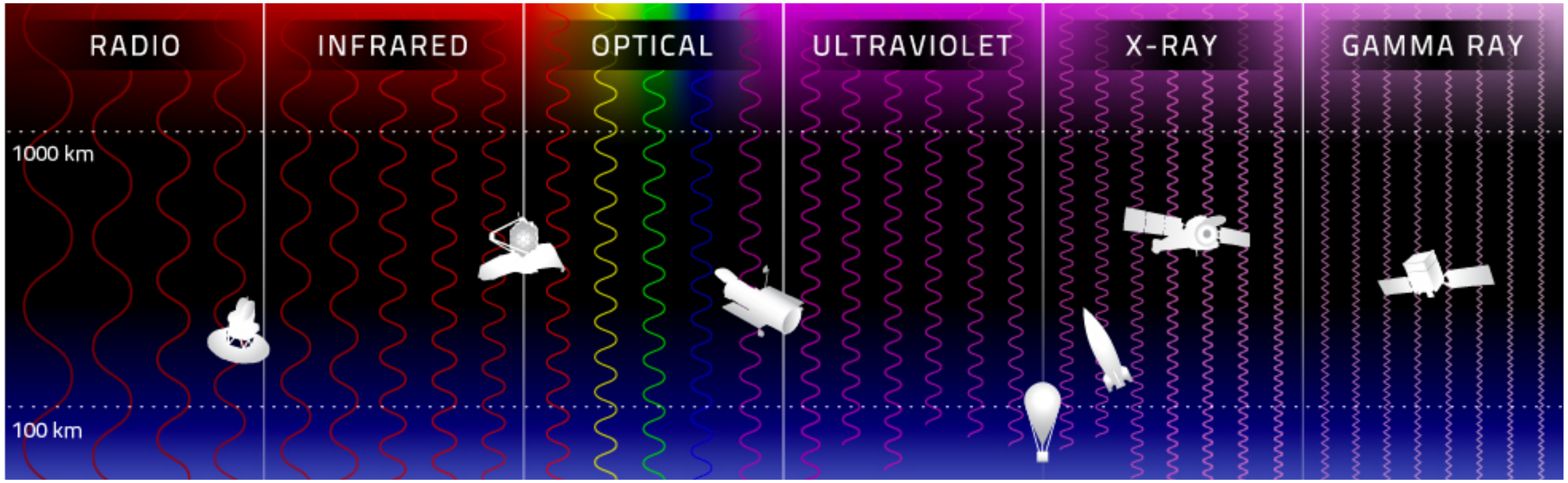

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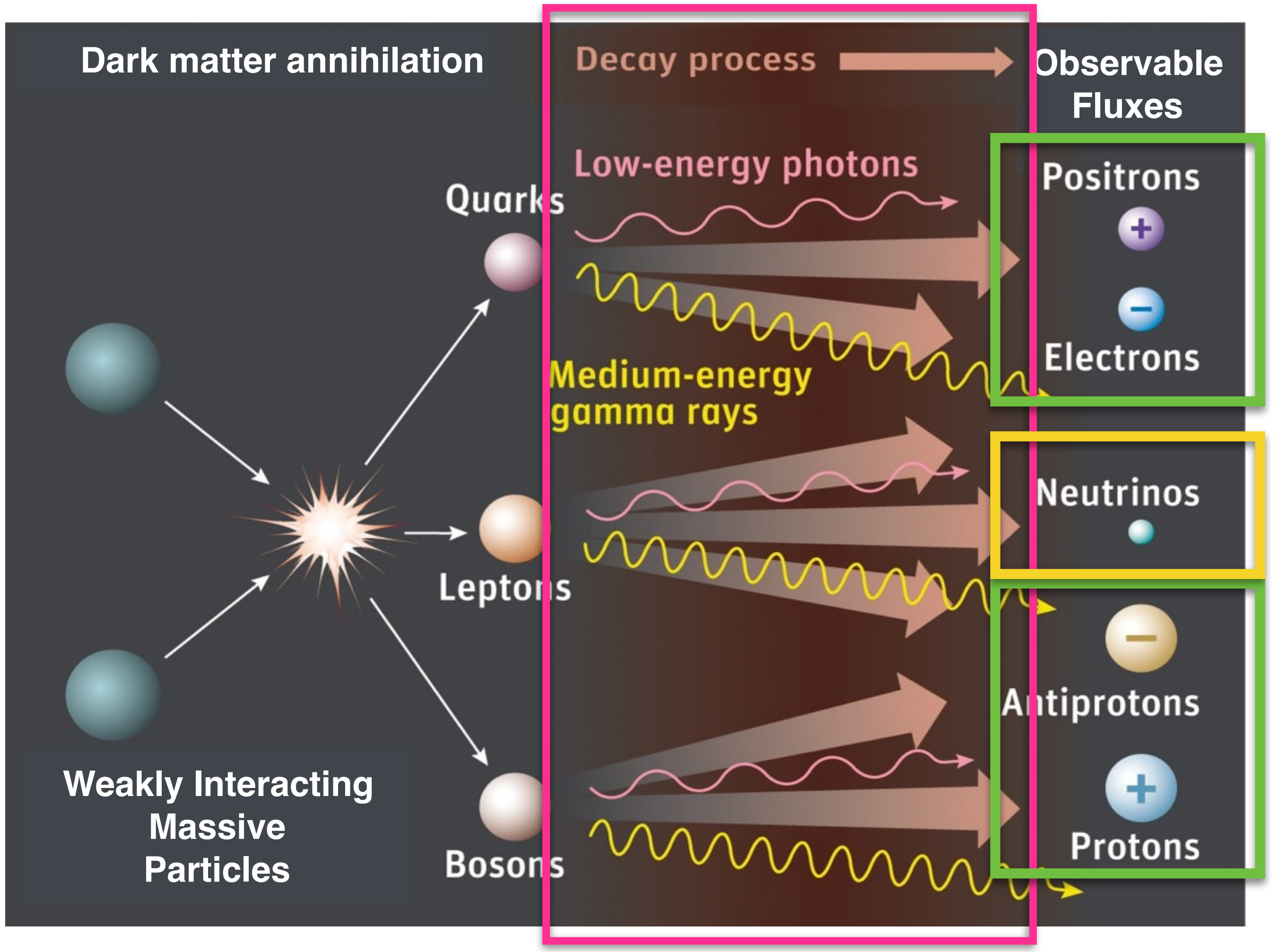

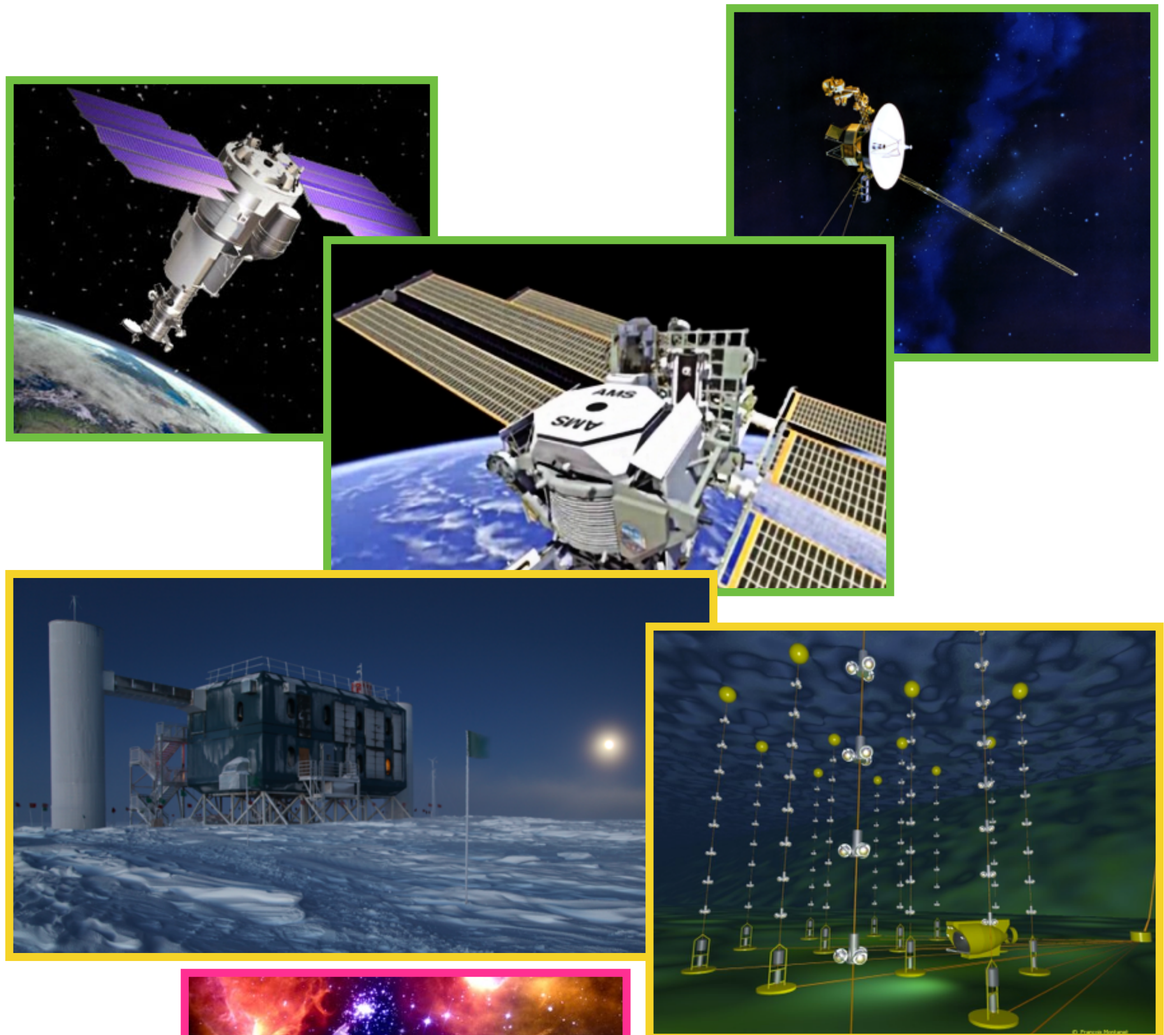

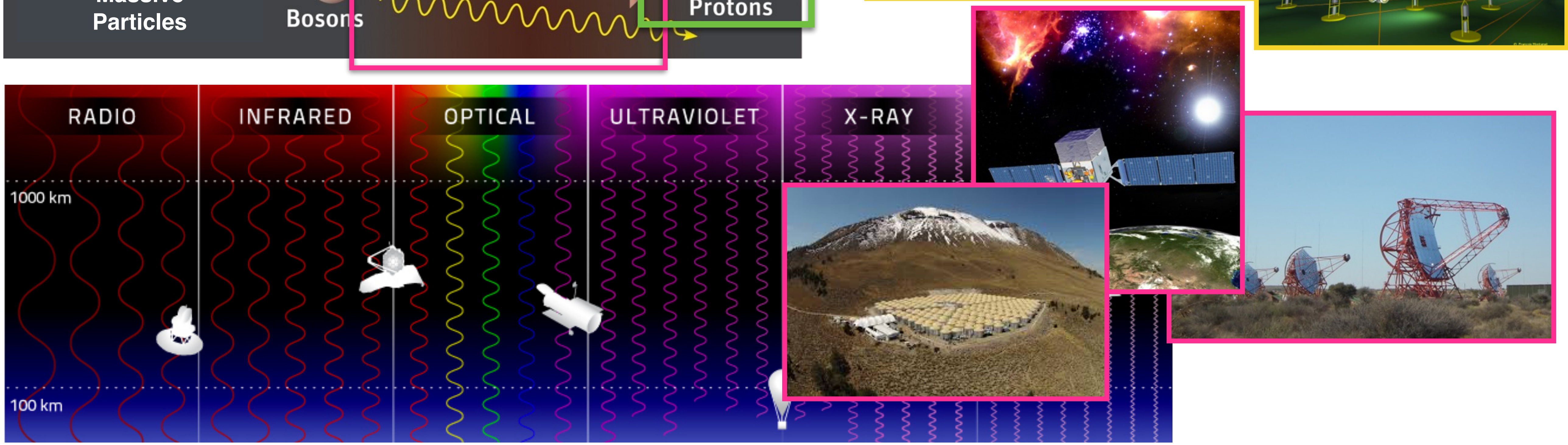

Dark matter signals prediction

DM annihilation source term

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

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

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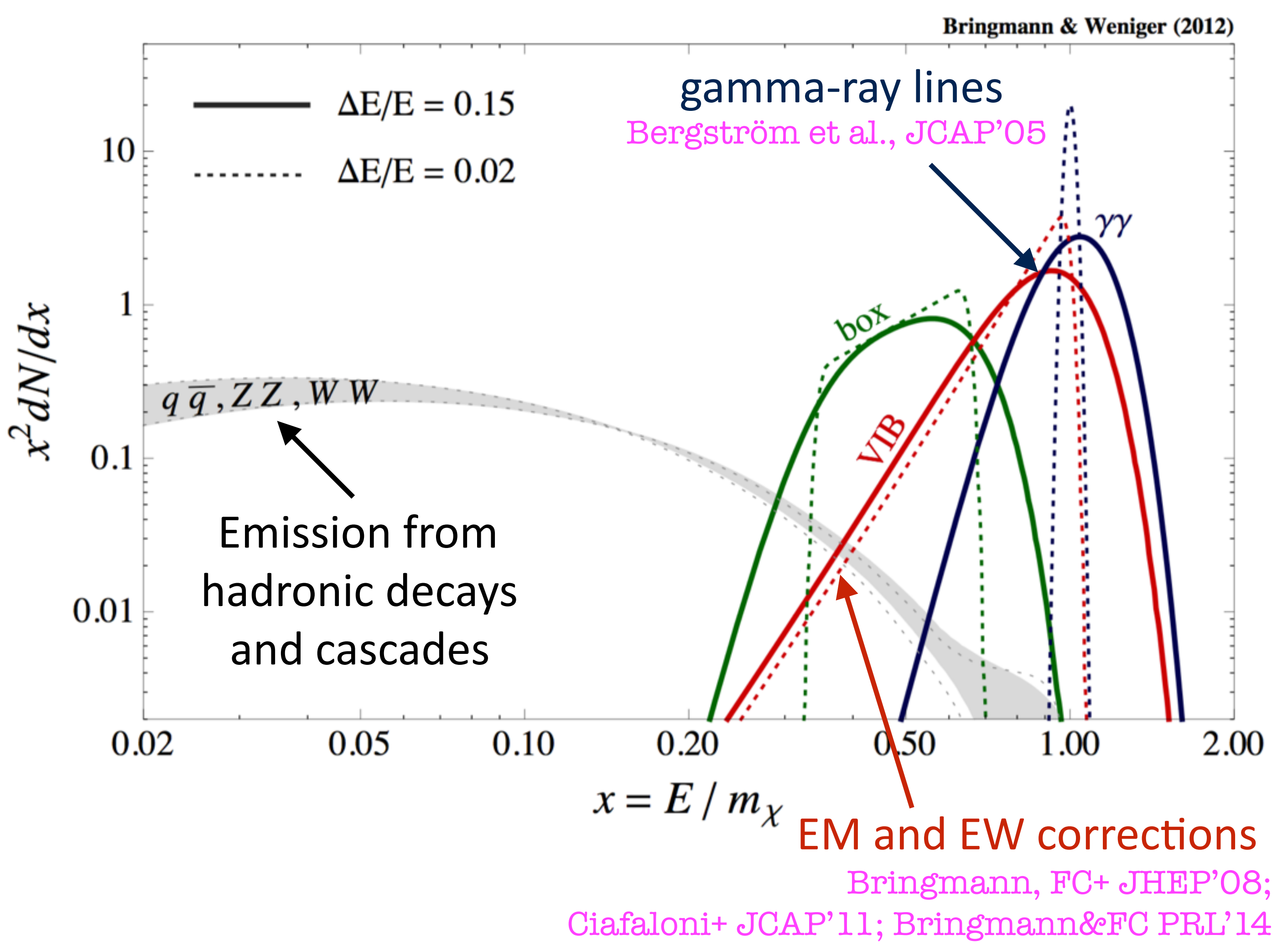
Key ingredients:

- **Spectral energy distribution** (spectral features, Sommerfeld enhancement for TeV scale DM, radiative emission for leptonic final states)



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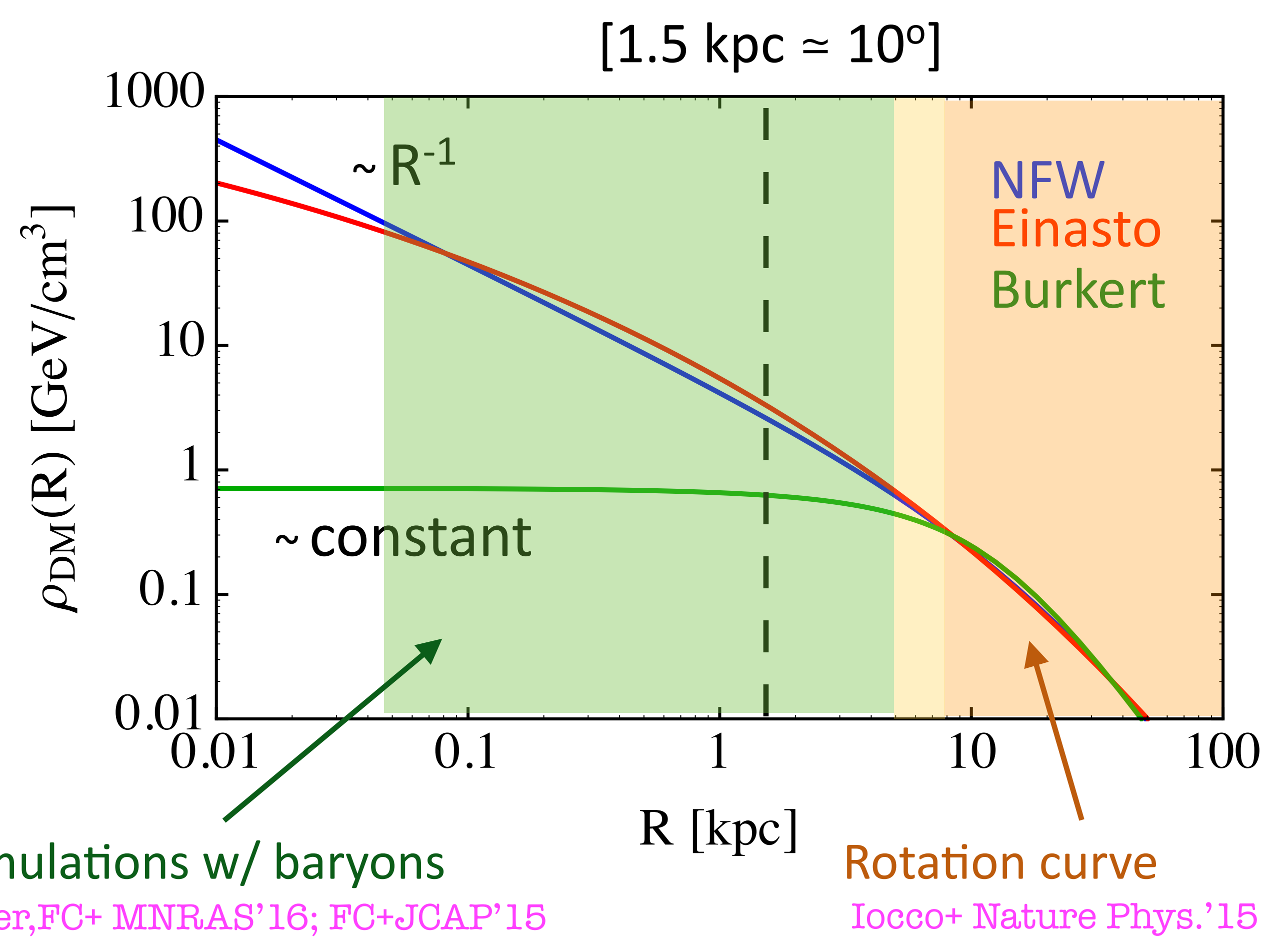
- **Spatial distribution** in astrophysical targets (asymmetric density profiles, substructures boost factor, local DM density)



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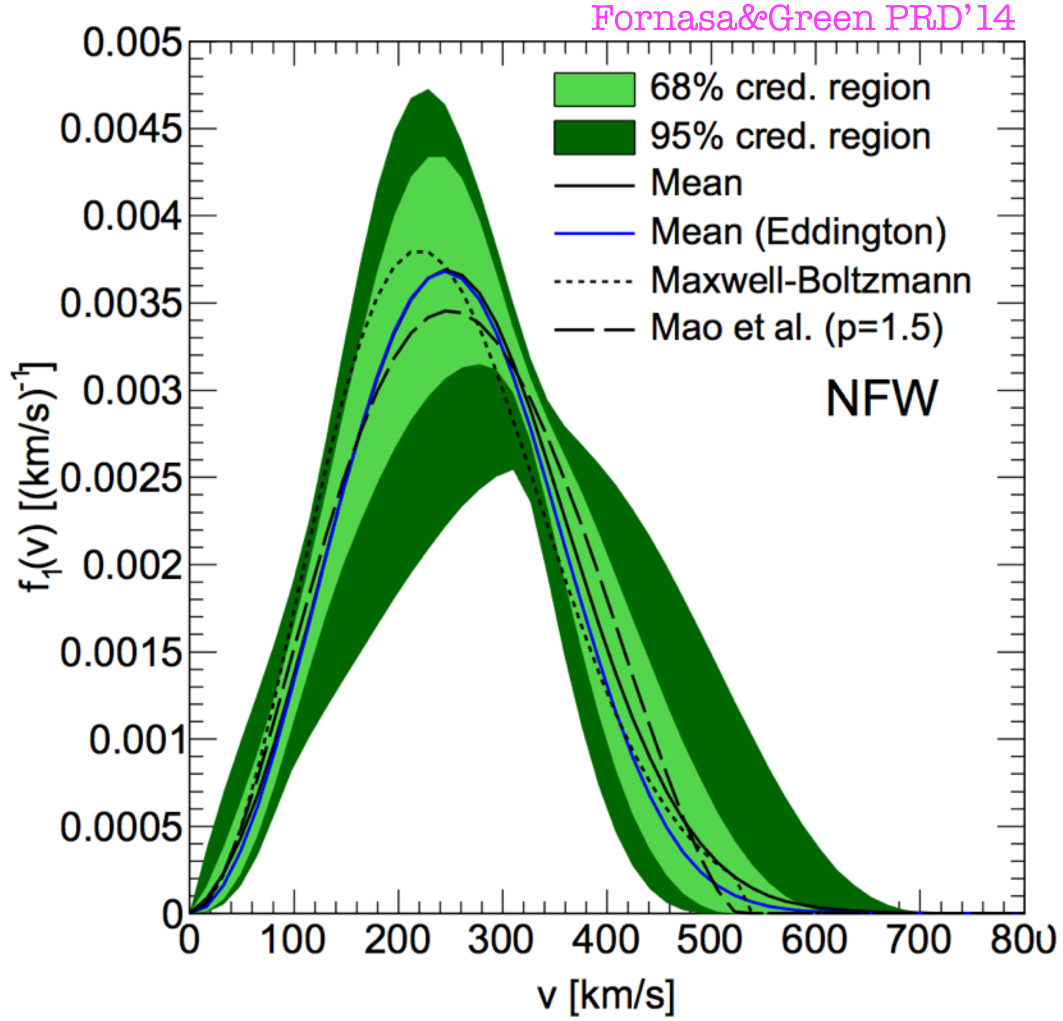
Key ingredients:

- **Spectral energy distribution** (spectral features, Sommerfeld enhancement for TeV scale DM, radiative emission for leptonic final states)
- **Spatial distribution** in astrophysical targets (asymmetric density profiles, substructures boost factor, local DM density)
- **Velocity distribution** in the Galaxy (velocity dependent cross section, direct detection)

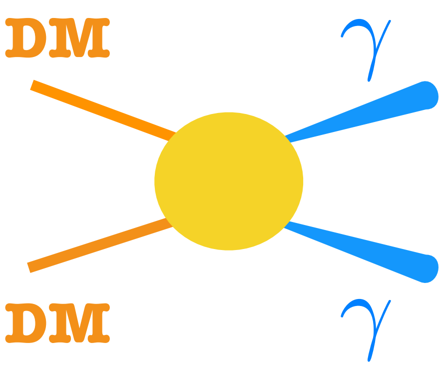
Fornasa&Green PRD'14



Kavanagh&O'Hare PRD'16; Bozorgnia, FC+ JCAP'16

Current limits on WIMPs: from GeV to TeV photons

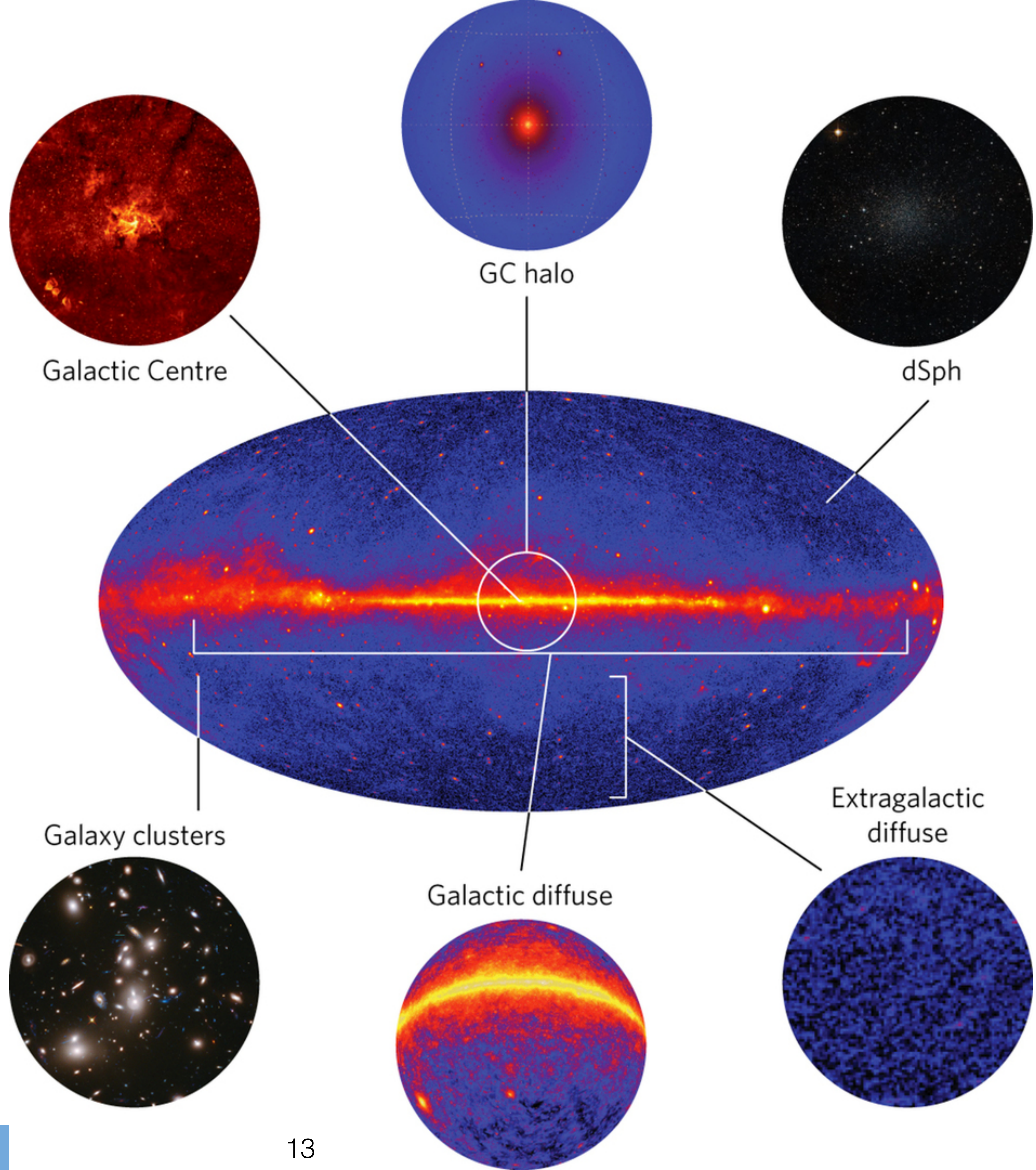
Targets for dark matter gamma-ray searches



$$\int_{\mathrm{l.o.s.}} ds\ \rho_{\mathrm{DM}}(\vec{r}[s,\Omega])^2$$

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

Conrad & Reimer
Nature Phys. 13 (2017)



Dwarf spheroidal galaxies

Target:

- **dSphs galaxies**: “clean” target for DM searches, high light-to-mass ratio and no astrophysical emission Winter+ ApJ’16

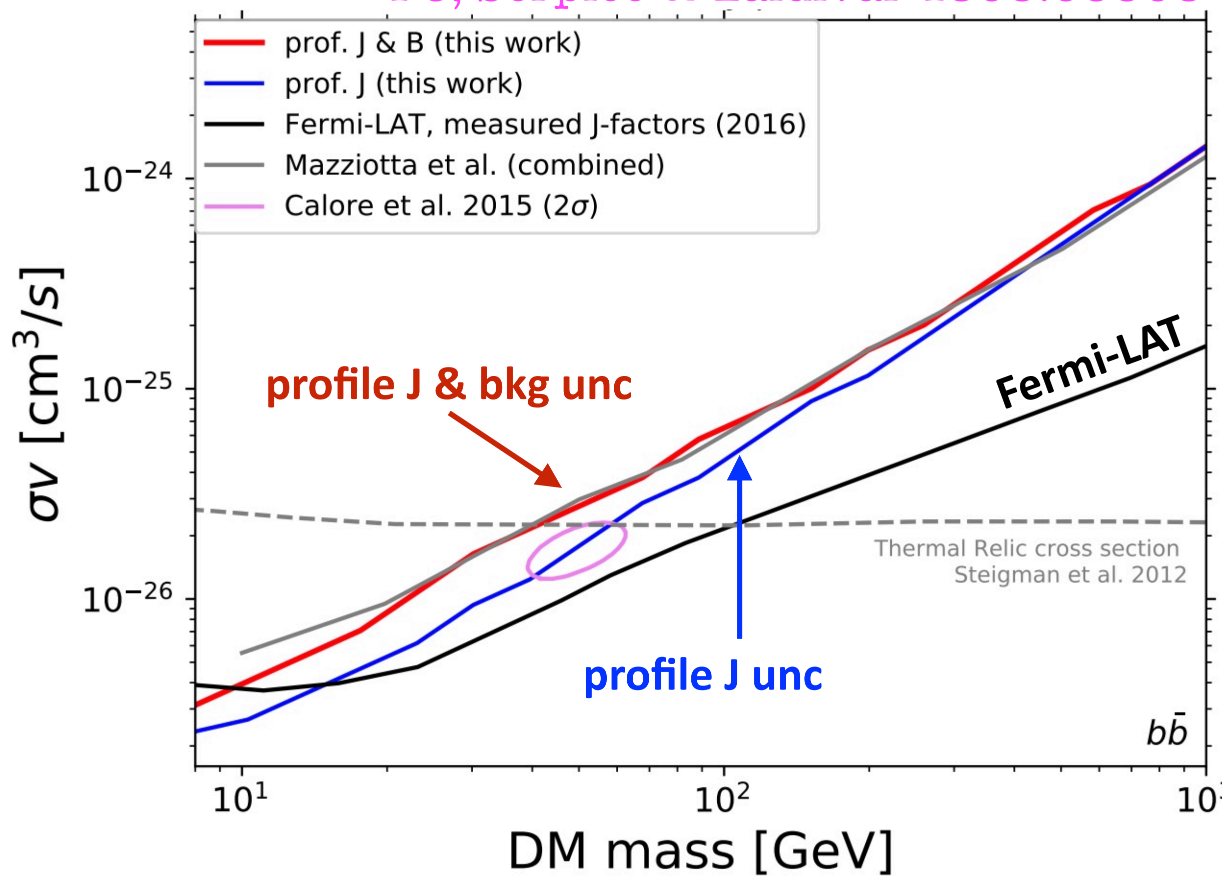
Status:

- 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 1803.05508

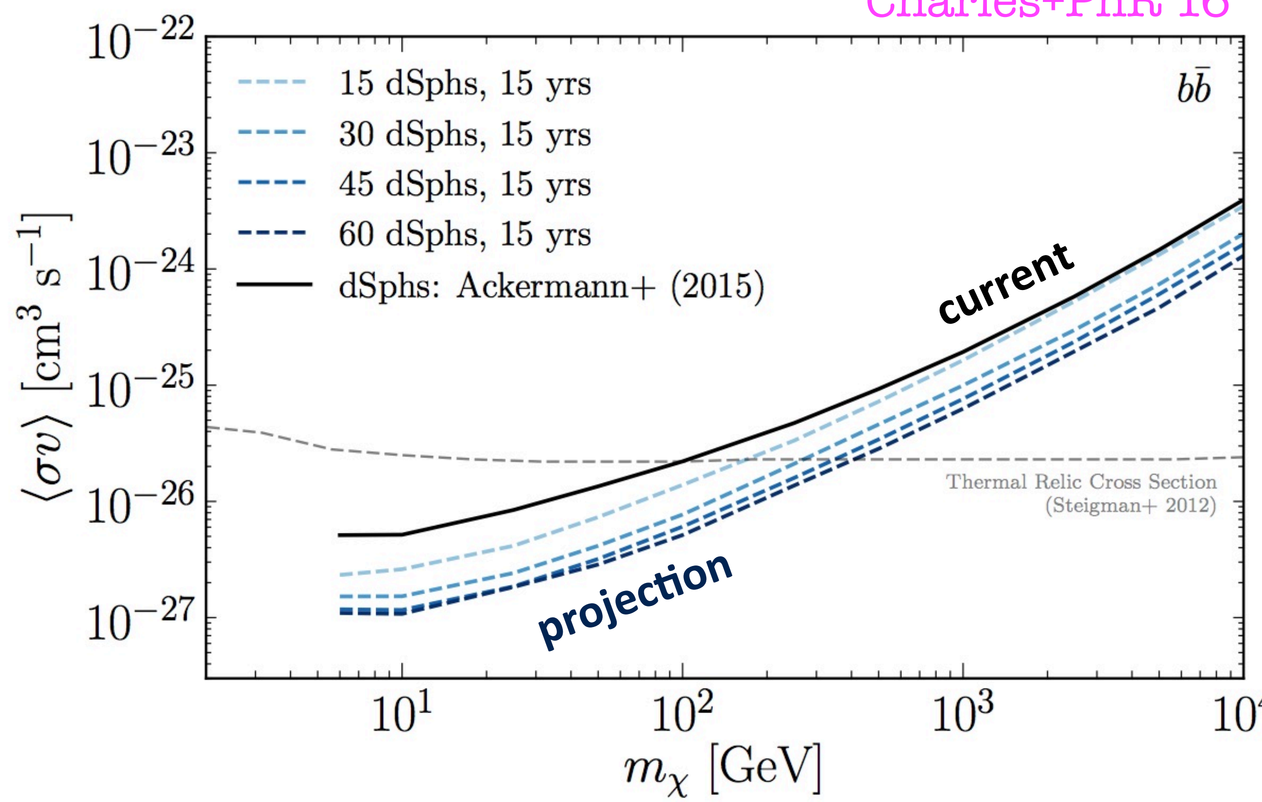
Future:

- New data from Fermi-LAT (improvement by a factor of 2-5) Charles+PhR’16
- Expected hundreds of new dSphs with SDSS, Pan-Starrs, DES and LSST (> 2019) Hargis+ApJL’14

FC, Serpico & Zaldivar 1803.05508



Charles+PhR’16



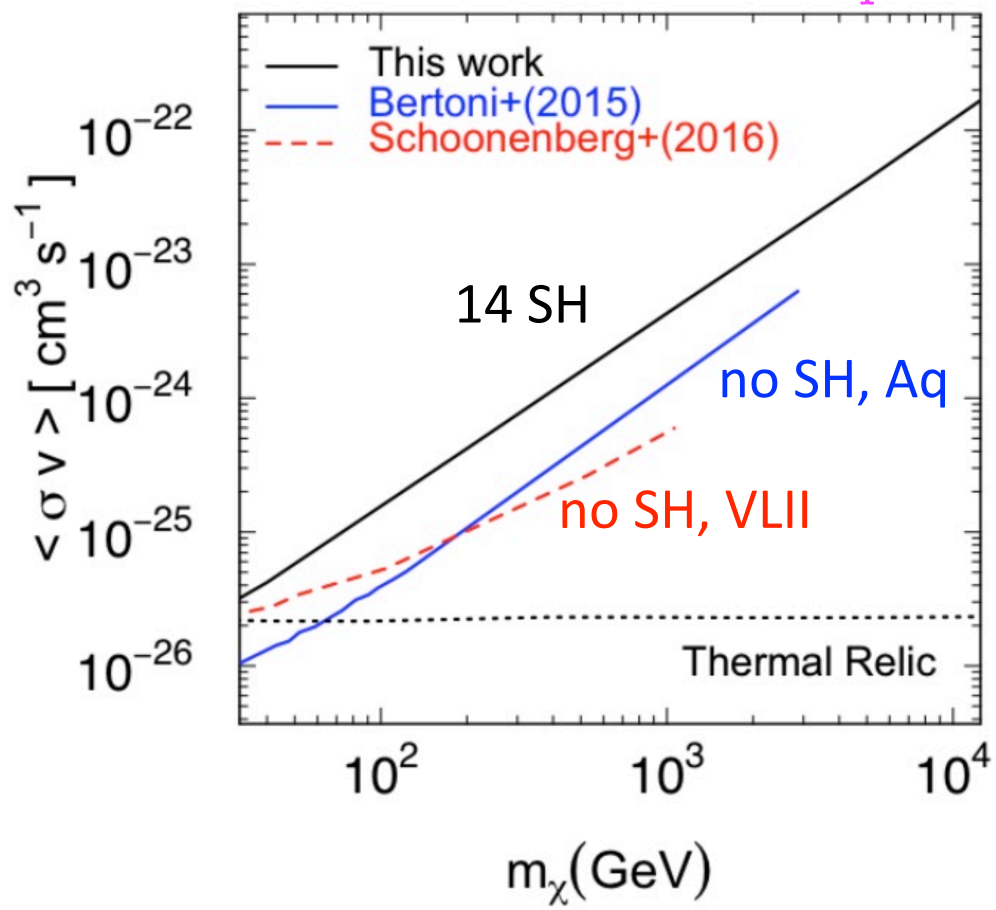
Dark matter subhaloes

Do we have already detected DM subhaloes among unassociated Fermi-LAT sources?

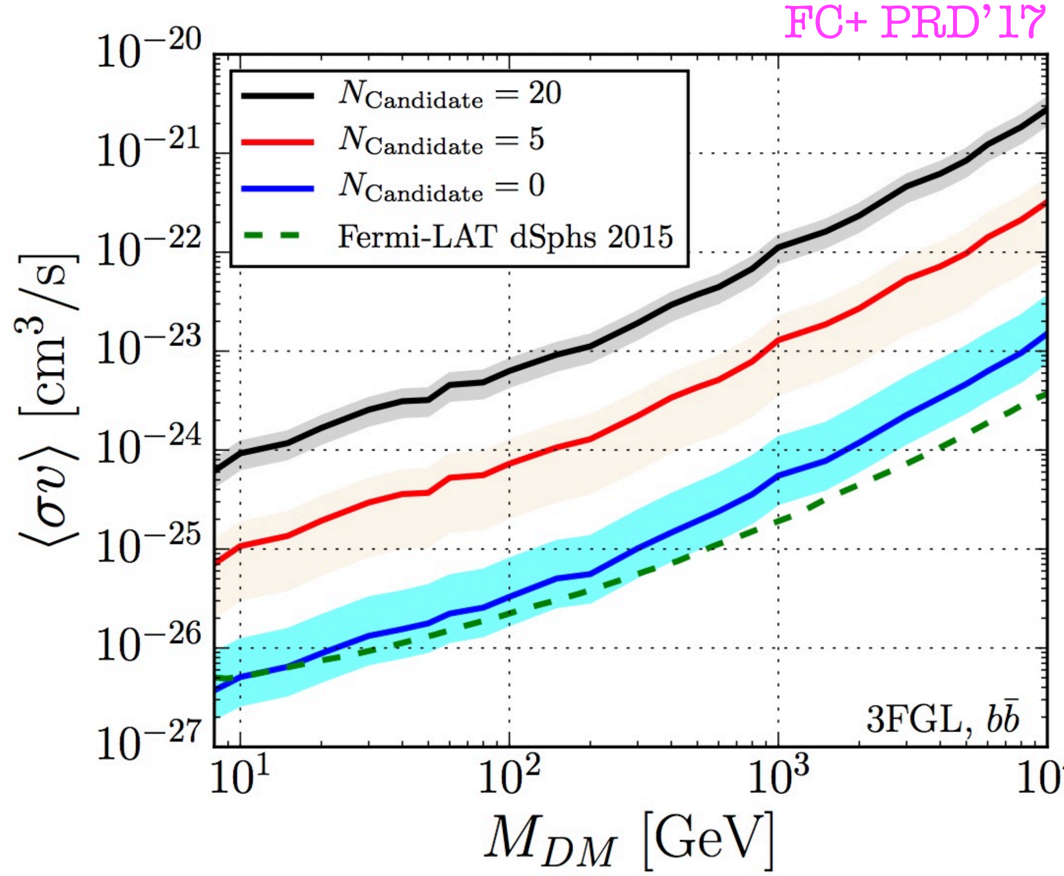
Bertoni+ JCAP'15; Mirabal+ ApJ'16; Schoonenberg+ JCAP'16; Hooper&Witte JCAP'17; FC+ PRD'17

- DM subhaloes (**dark satellites**) searches: strong gravitational lensing (Vegetti+ Nature'12), star stream gaps (Carlberg ApJ'12) + gamma rays
- The realistic estimation of the LAT sensitivity to the DM subhalo population from hydrodynamic simulations is crucial (th. unc) FC+ PRD'17
- Machine learning algorithms are excellent tools to identify SH candidates Mirabal+ ApJ'16; Saz Parkinson+ ApJ'17; Salvetti+ MNRAS'17
- CTA sensitivity in the extragalactic survey comparable to CTA dSPhs sensitivity Hütten+ JCAP'16
- Search for nearby dSPhs towards 8 Fermi-LAT (unIDs & extended) sources with **GAIA DR2** ⟶ Reject that they owe to DM annihilation Ciucă, FC+ MNRAS'18

Mirabal+ ApJ'16

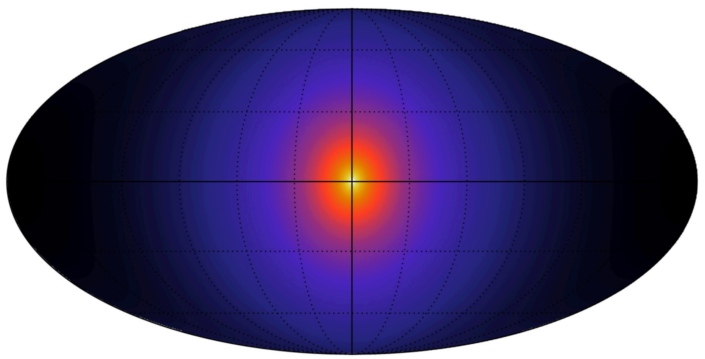


FC+ PRD'17

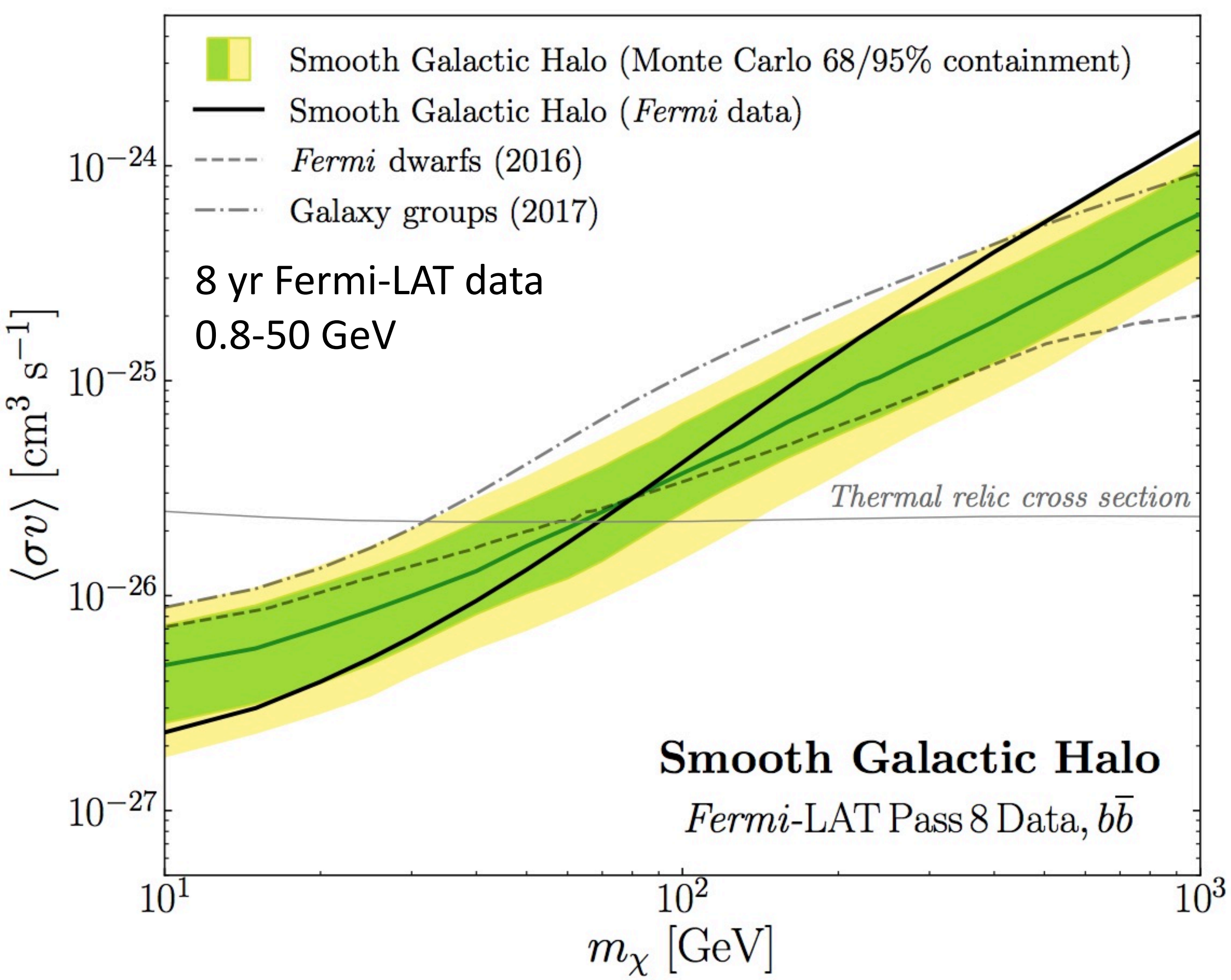


The high-latitude Milky Way halo

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



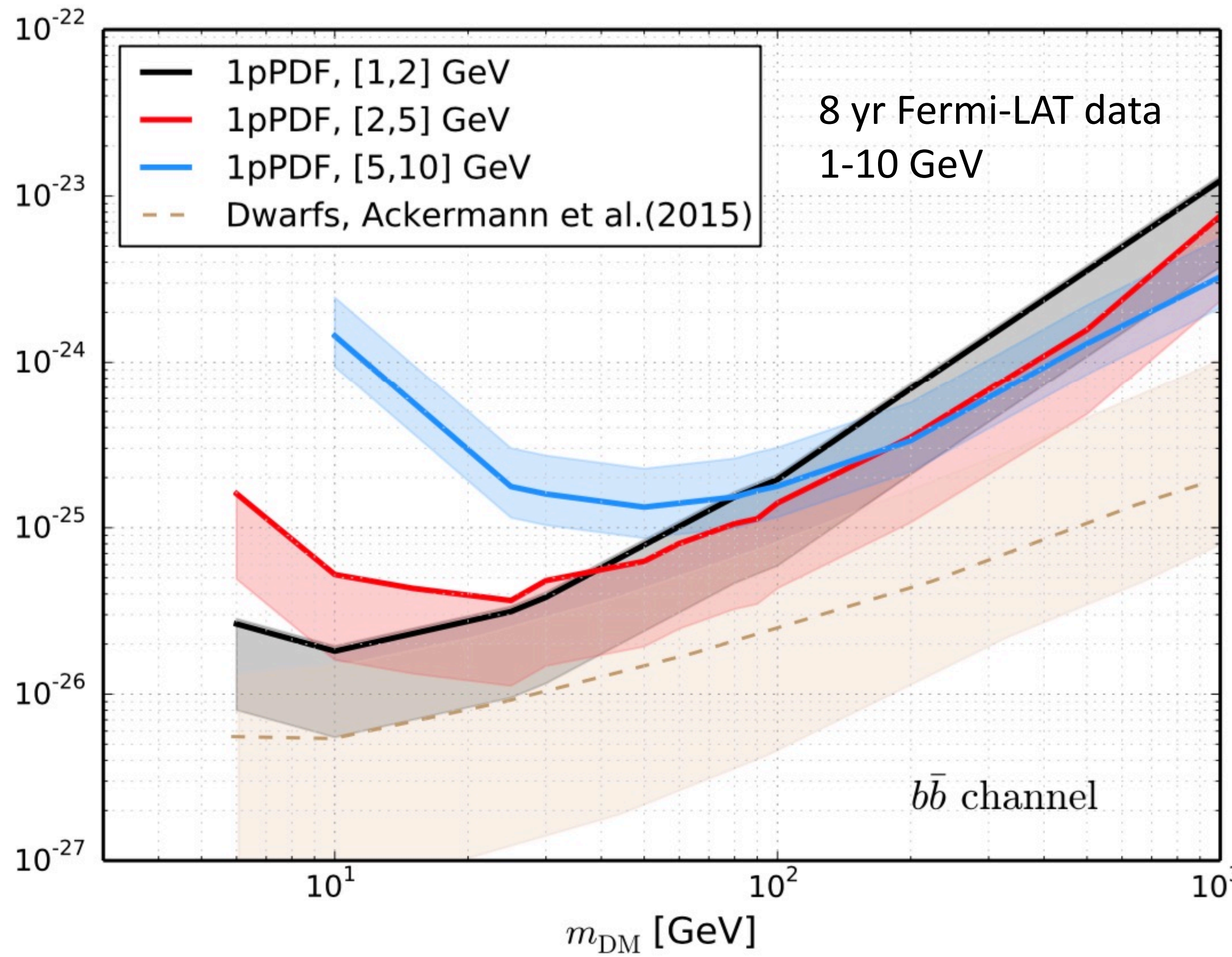
Template fitting



Chang+1804.04132

1-point Statistics

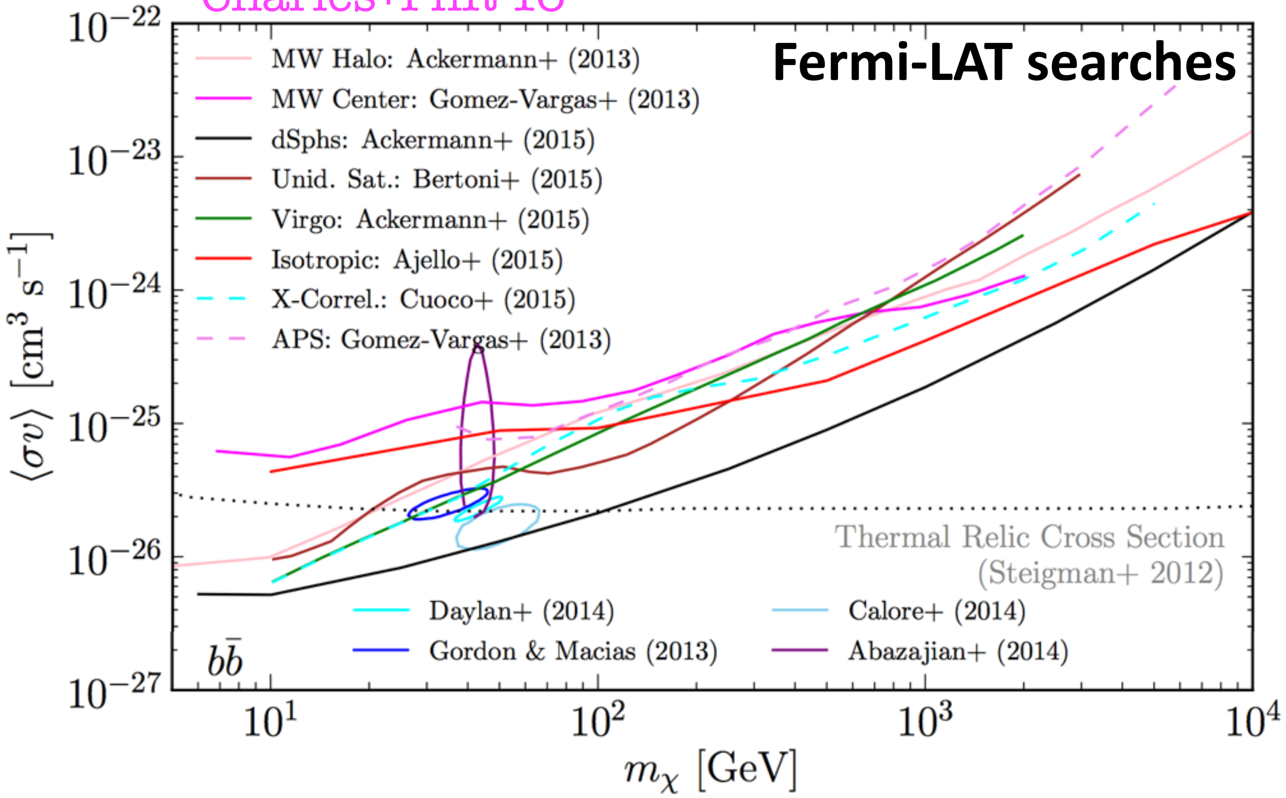
Malyshev+ApJ'11; Zechlin+ApJS'16, ApJL'16

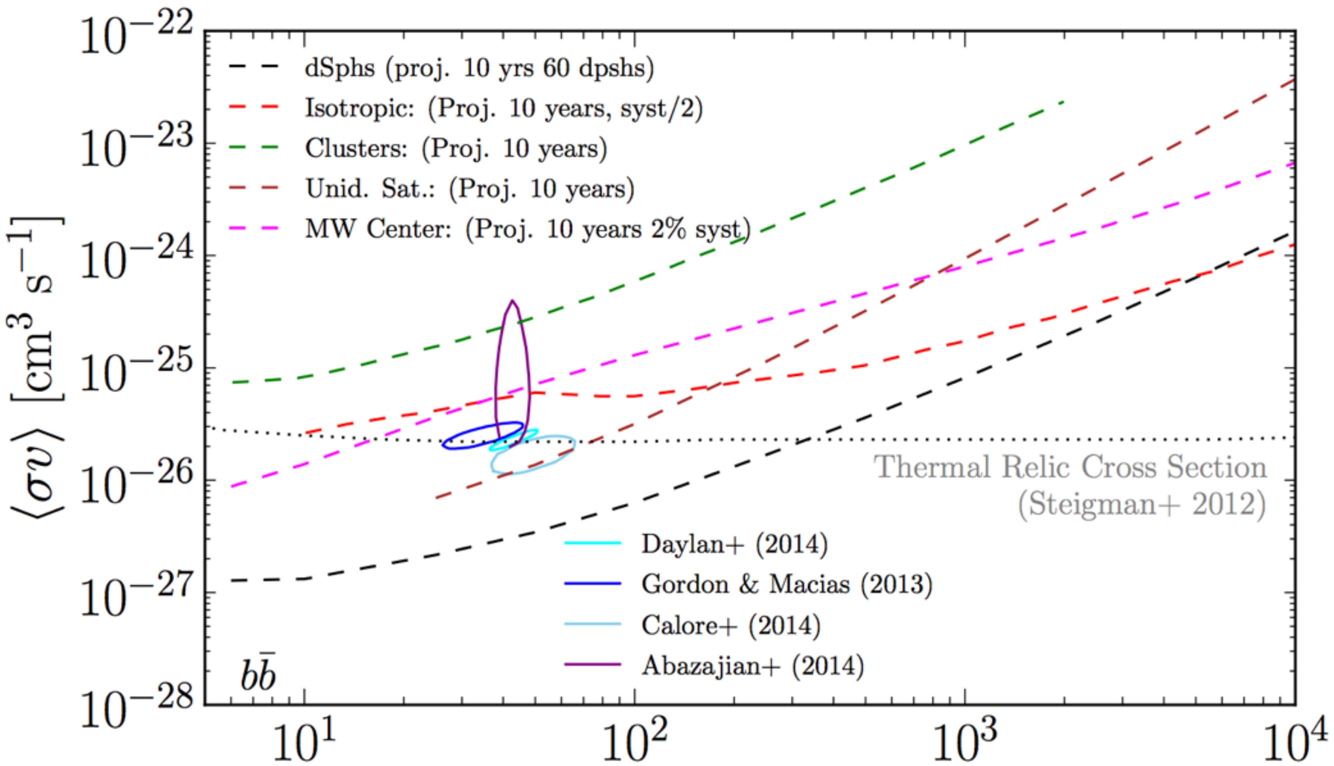


Zechlin+1710.01506

GeV photons: Multi-target constraints

Charles+PhR'16





Status

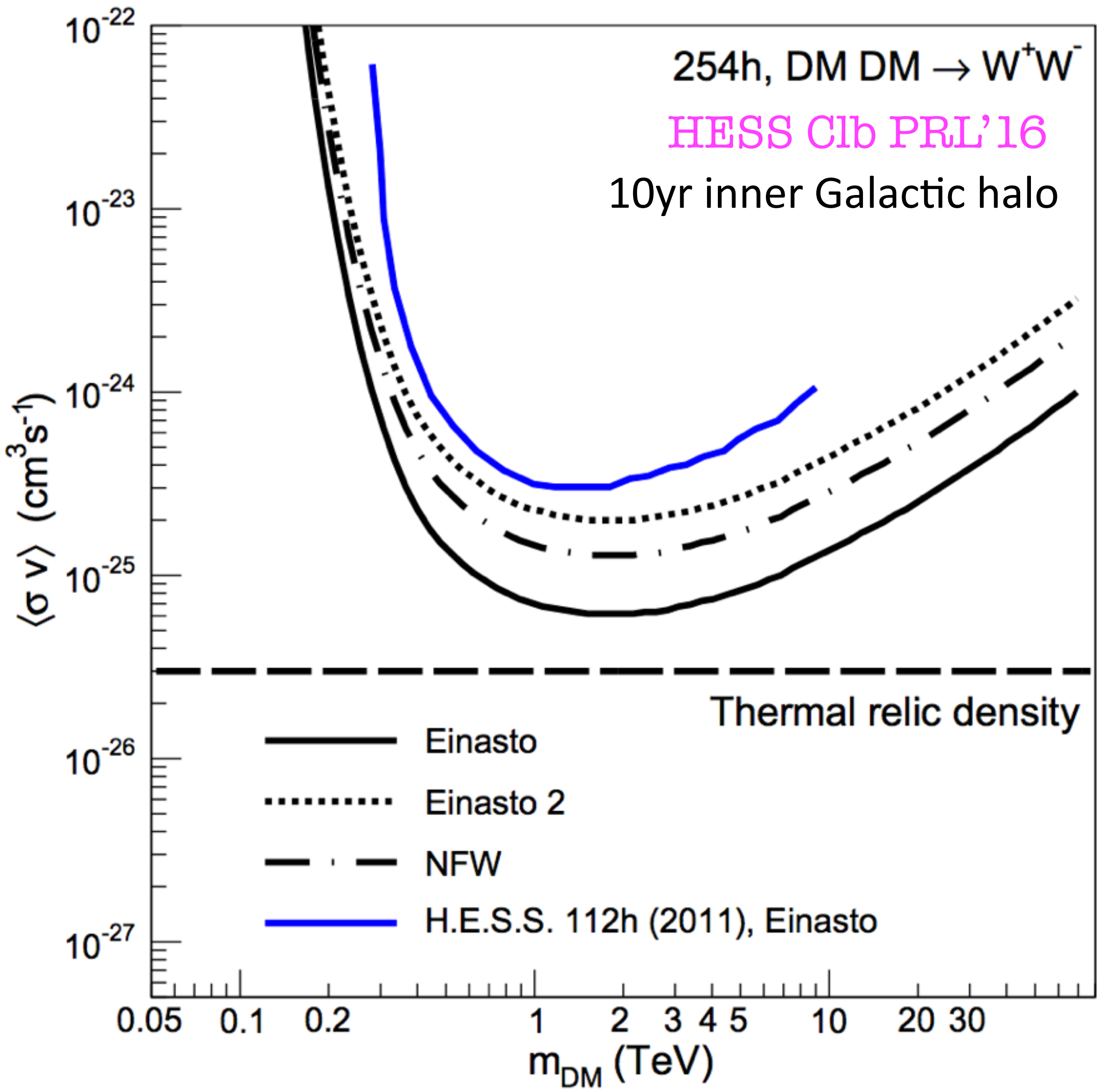
- Comparison with current limits from other Galactic and extragalactic targets
- Mild tension with GeV excess, but astro unc on dSphs bkg and Galactic DM profile are important
  Calore+ 1803.05508
  Benito,FC+ JCAP'16; Keeley+ PRD'18
- Powerful limits from galaxy group catalogs
  Lisanti+ PRD'18, PRL'18

Future

- **Fermi-LAT** limits improvement depends on target (syst., bkg or signal limited)
- Future **radio telescopes**: great improvement in sensitivities [e.g. Storm+ApJ'17]

Very high-energy photons

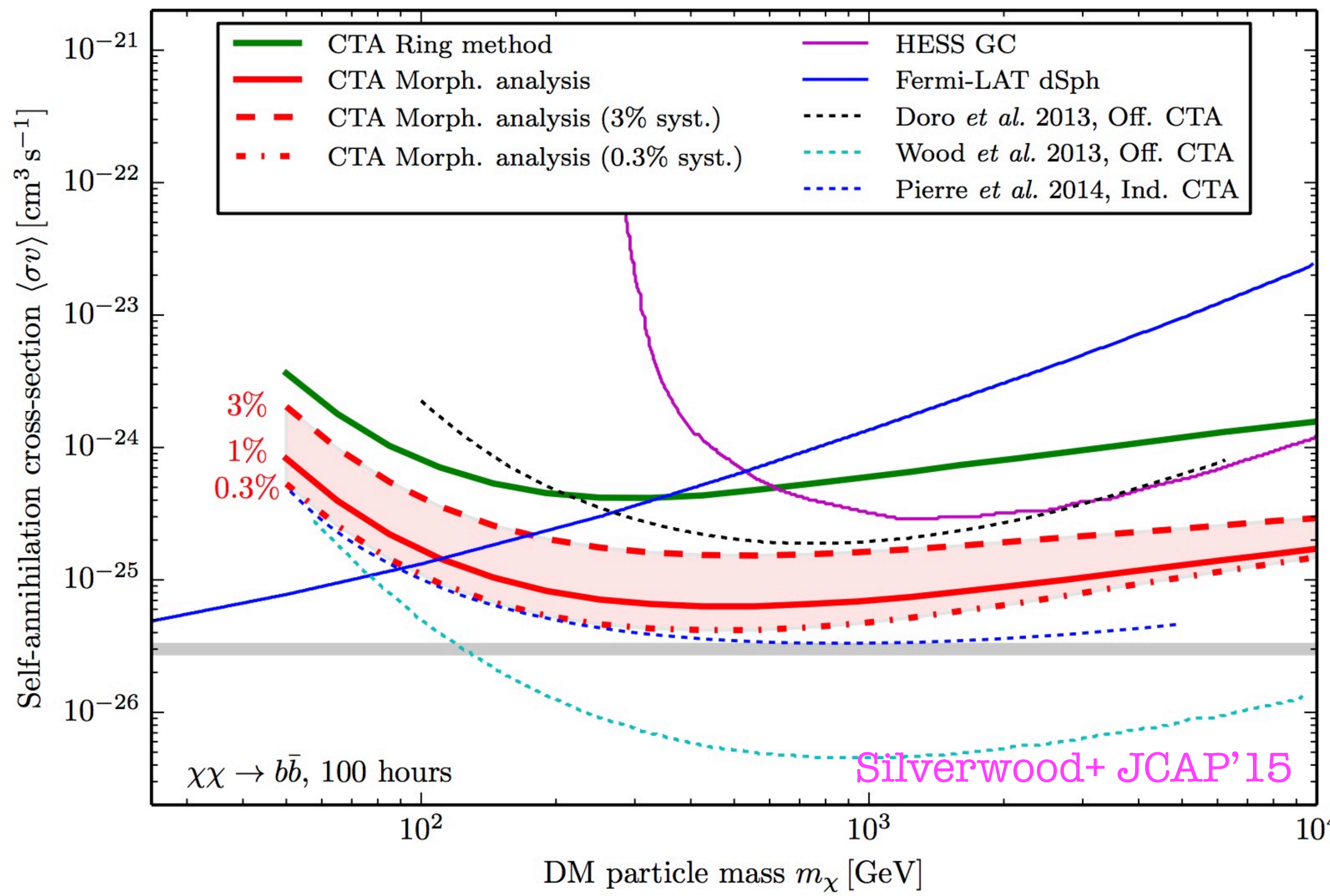
Status



- Most constraining analysis at E>1TeV
- Other relevant targets: combined dSphs
- TeV scale thermal dark matter starts to be challenged

Baumgart+ 1808.08956; Rinchiuso+ 1808.04338

Future

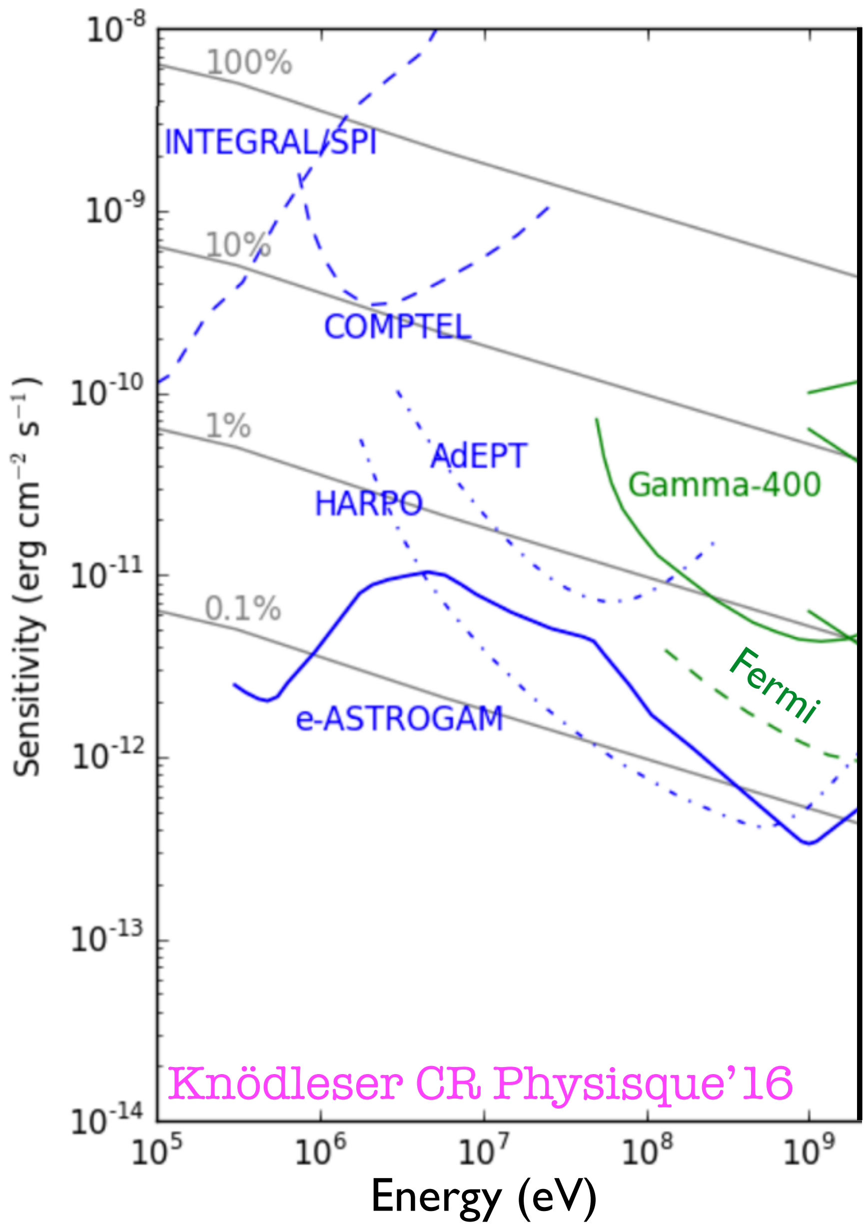


- **HAWC** is already improving limits from dSphs (> 1 TeV) and Galactic centre (> 100 TeV)

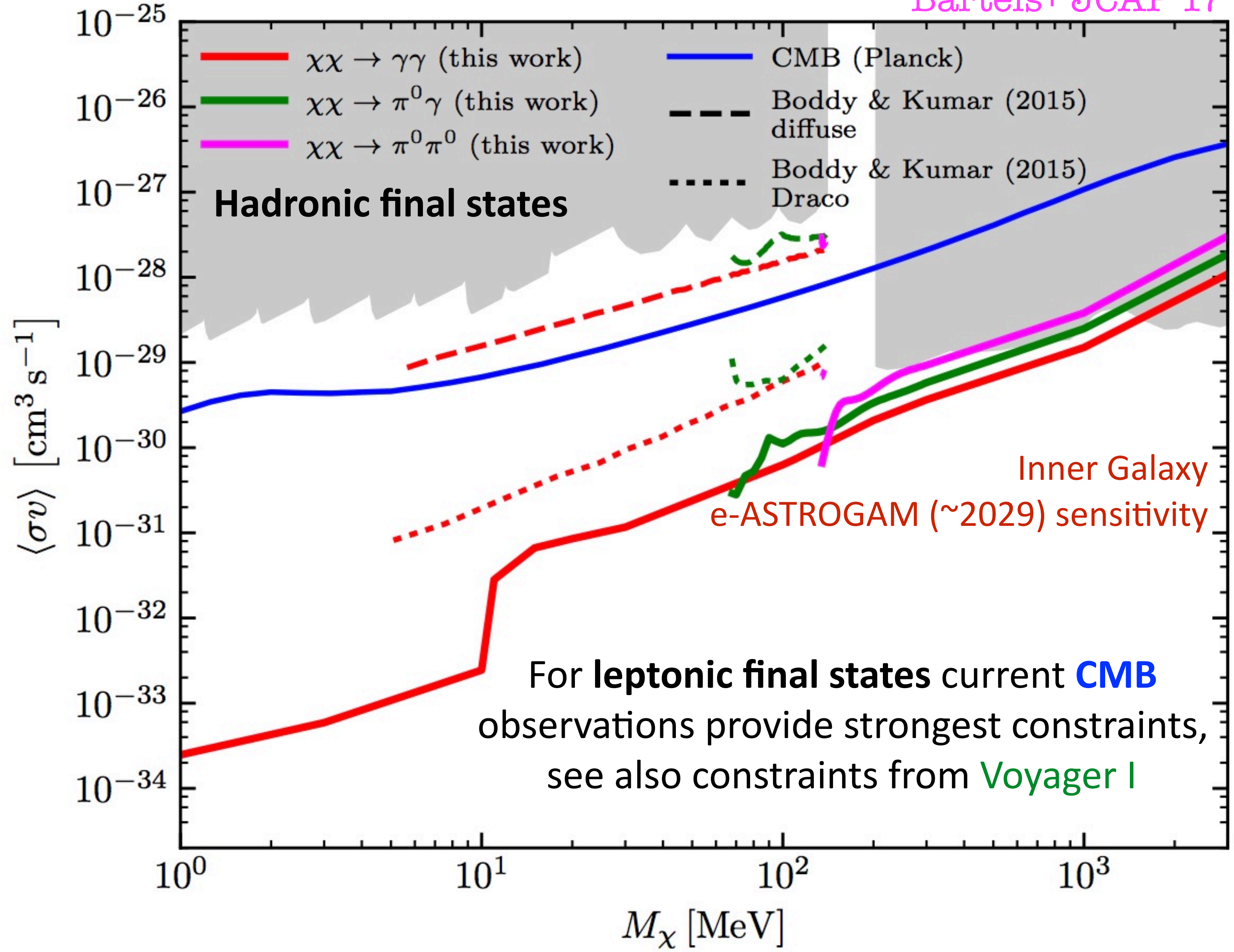
  Albert+ ApJ'18; Abeysekara+ JCAP'18
- **CTA** (~2022) will improve HESS limits by factor up to 10

  Silverwood+ JCAP'15; Carr+ 2015; Lefranc+PRD'15

The sub-GeV sensitivity gap



Bartels+ JCAP'17



- 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

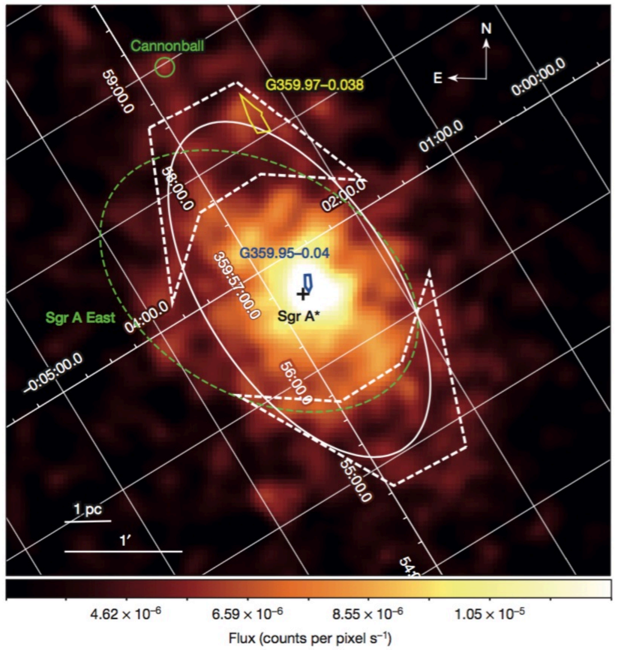
Beyond limits …
… Hints for dark matter signals?

Beyond limits …
… Hints for dark matter signals?

aka: What anomalies in the gamma-ray sky?

Some gamma-ray anomalies in the GC region

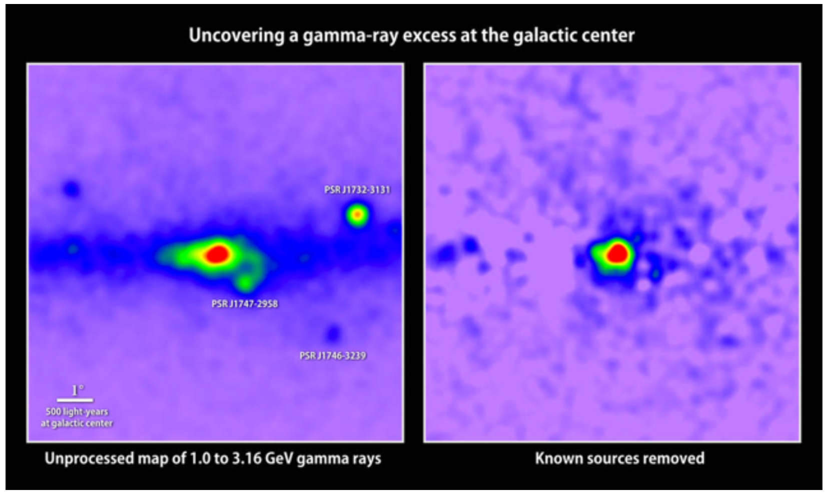
Perez+Nature'15

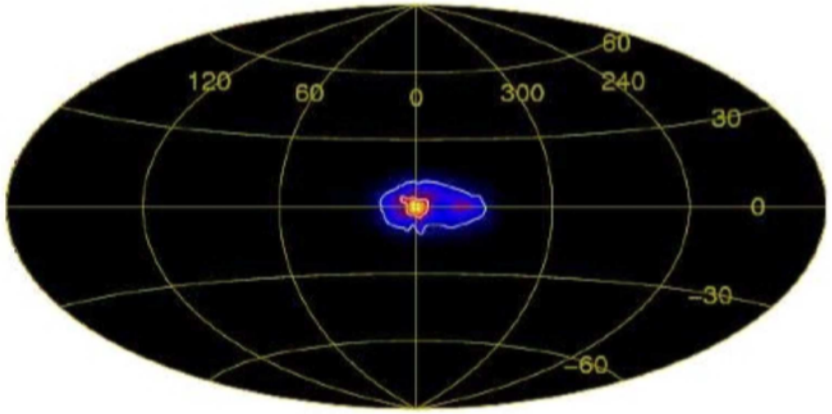


X-ray @ 20-40 keV
NuSTAR
hard diffuse excess emission

Gamma-ray @ few GeV
Fermi-LAT
Fermi GeV excess

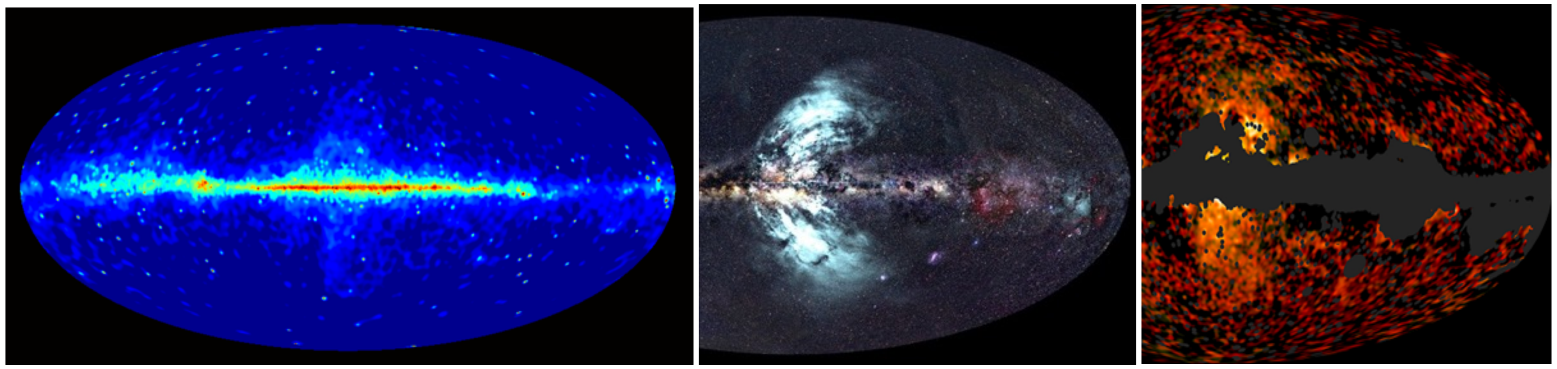
Daylan+PRD'16





Gamma-ray @ 511 keV
INTEGRAL/SPI
Positron annihilation line
Purcell+'93,'97; Knödlseder+'03,'05

Su+'10; Fermi-LAT Collab'14; Carretti+'13; Planck Collab.'13



Gamma-ray @ hundreds GeV
Fermi-LAT
Fermi bubbles, and their **radio/ microwave** conterparts

Excesses extended far beyond central CMZ and nuclear bulge

The Galactic centre GeV excess

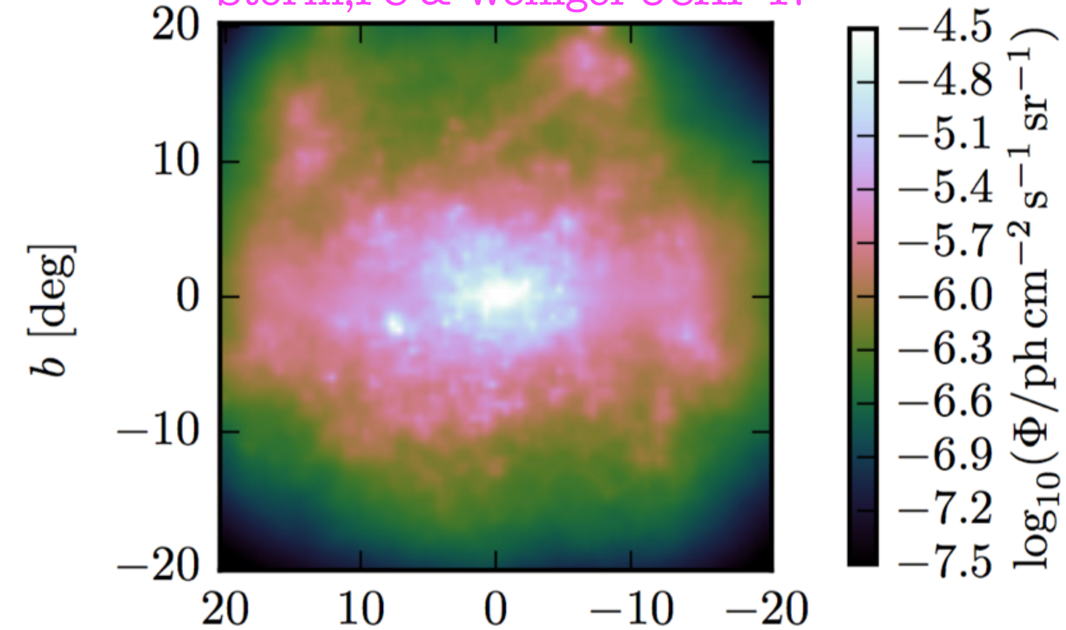
Signal:

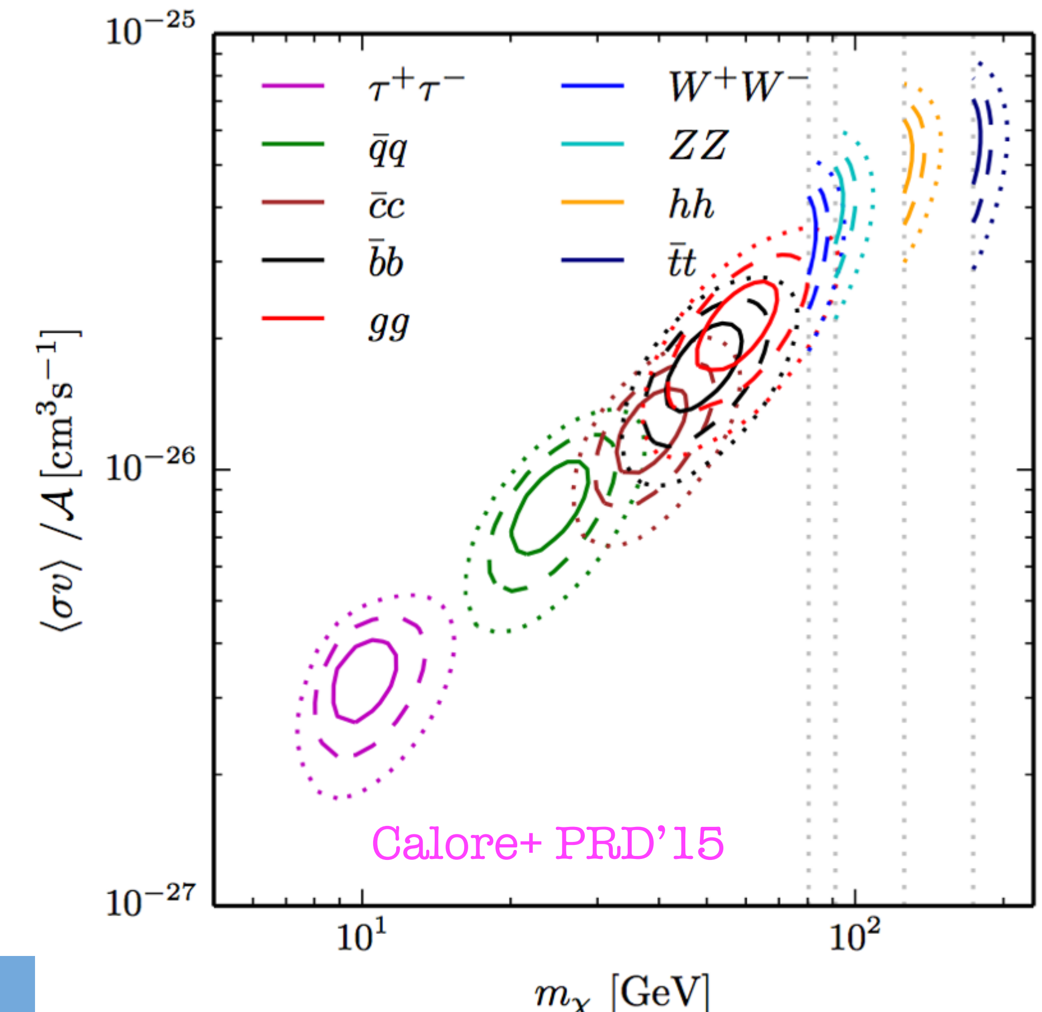
- Well-established excess of Fermi-LAT GeV photons from the inner Galaxy**
- Peculiar spectrum peaked at a few GeV
- Extended emission up to ~10 degrees (~1.5 kpc), almost spherically symmetric (but not quite so)

Interpretations:

- Diffuse emission from electrons/positrons at the Galactic centre (ehnanced 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

Storm,FC & Weniger JCAP'17

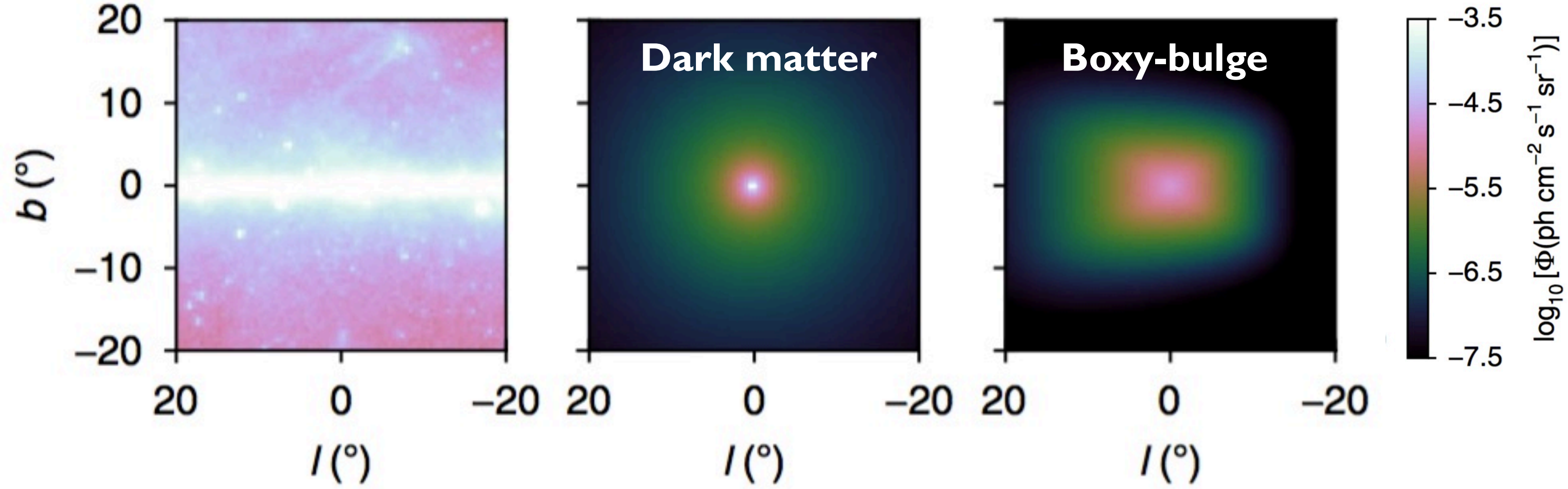


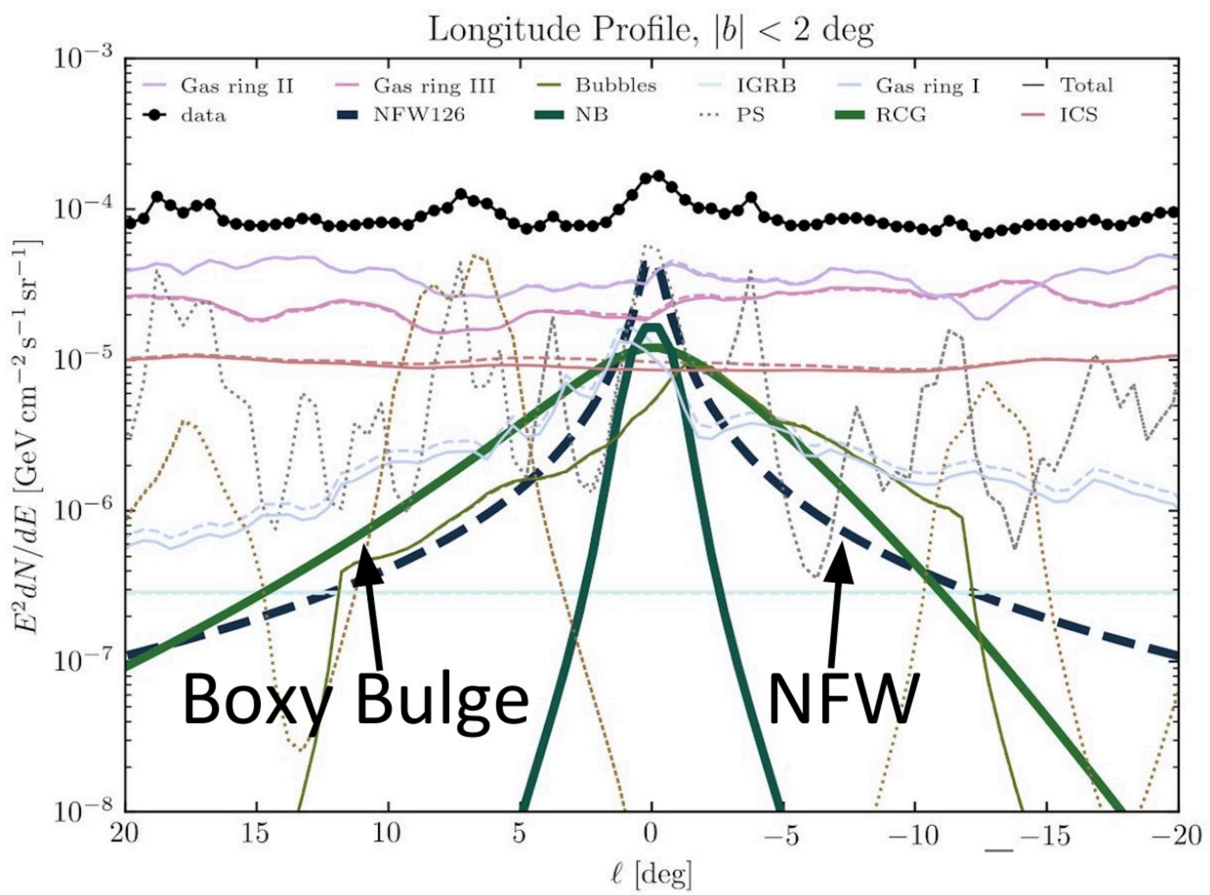


**Some Refs. since 2009: Hooper&Goodenough '09; Vitale&Morselli '09; Abazajian&Kaplinghat PRD'12; de Boer+'16; Macias+'16; Hooper&Slatyer PDU'13; Huang+ JCAP'13; Zhou+ PRD'15; Daylan+ '14; Calore+ JCAP'15; Gaggero+ 2015; Ajello+ 2015; Huang+JCAP '15; Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017

Evidence for stellar bulge emission

Bartels,FC+ Nature Astronomy'18



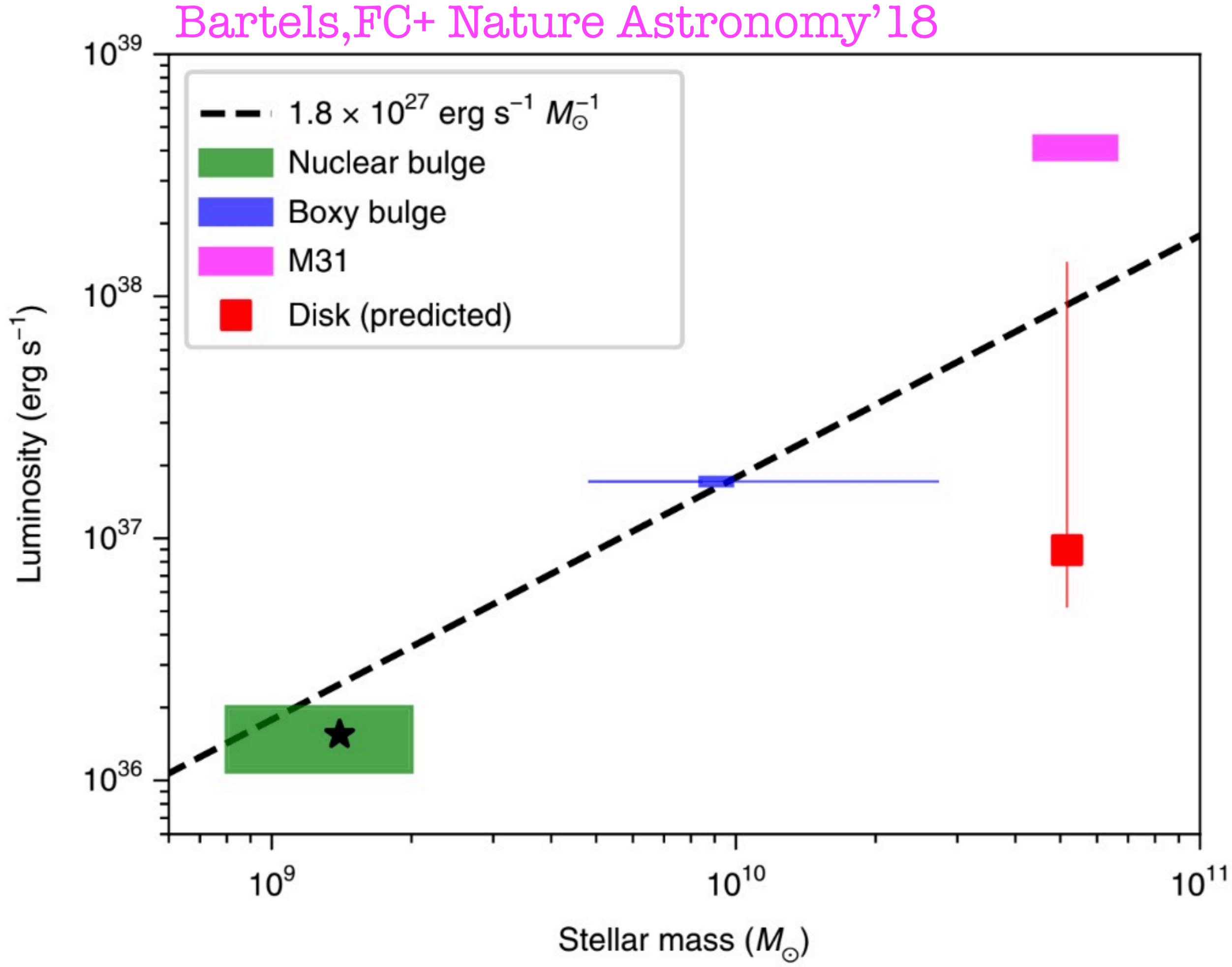


- ✓ **Stellar bulge model** (boxy + nuclear bulge) is **preferred** over (spherically symmetric) DM models with high statistical significance (16σ)
- ✓ **Morphology** of the GCE is **more oblate** than what found before
- ✓ Large enough ROI to discriminate foreground components (stable results)

[See also Macias+ Nature Astronomy'18]

Gamma-ray to stellar mass ratios

Bartels,FC+ Nature Astronomy'18



- ✓ **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
- Connection with TeV diffuse emission from the GC?
  Hooper&Linden PRD'18; Guepin+ JCAP'18
- Connection with 511 keV positron annihilation line?
  Crocker+ Nature Astronomy'17; Bartels,FC+ MNRAS'18

Galactic binaries: 511 keV line and GC excess

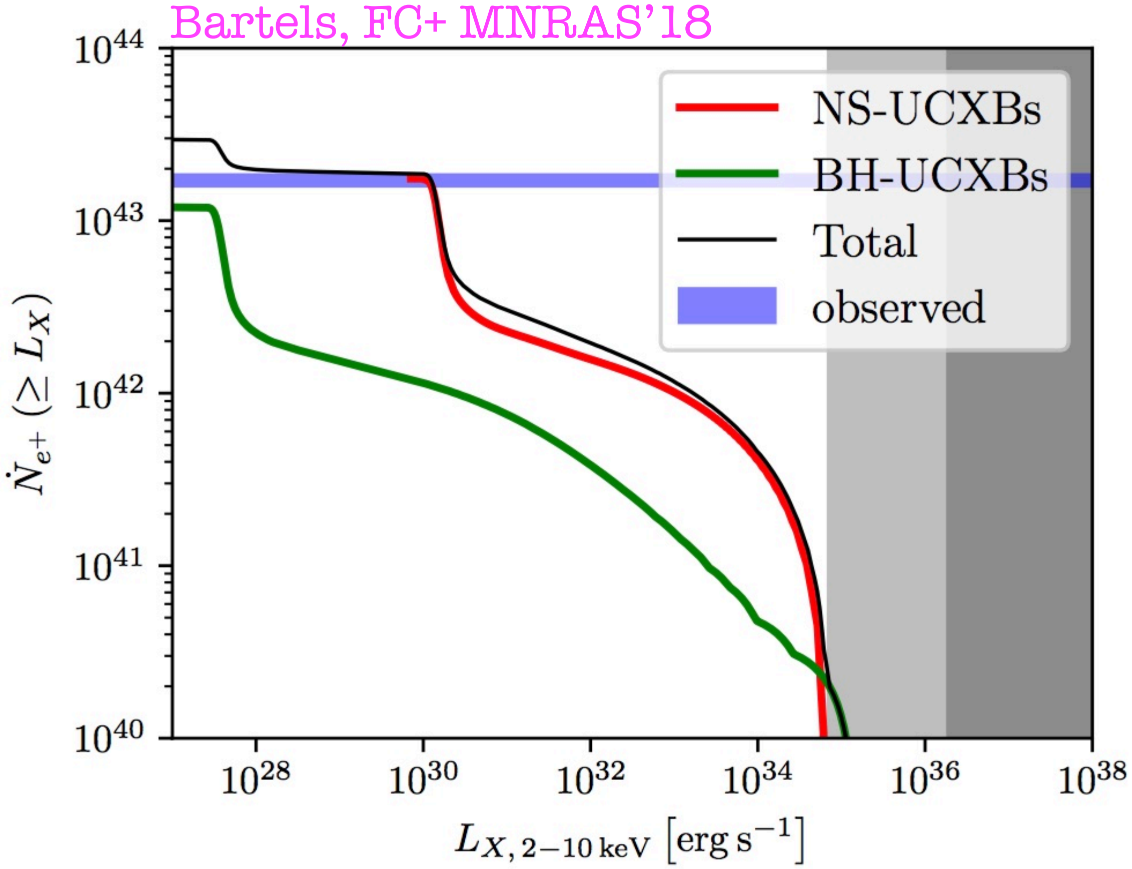
Bartels, FC+ MNRAS'18

Scenario:

- Population synthesis of ultra-compact X-ray binaries predicts about **2×10^5 NS-UCXB in the bulge**, which leads also to **~10^5 MSPs** van Haaften+ A&A'13,'15
- NS-UCXB progenitors of "recycled" MSPs that explain the GeV excess
- NS(BH)-UCXB in hard state with low accretion rates are jet dominated Deller+ ApJ'15; Fender+MNRAS'03
- Positron from cold, mildly relativistic, leptonic jets

Guessoum+ A&A'06; Bandyopadhyay+ MNRAS'09; Siegert+ A&A'16

Bartels, FC+ MNRAS'18

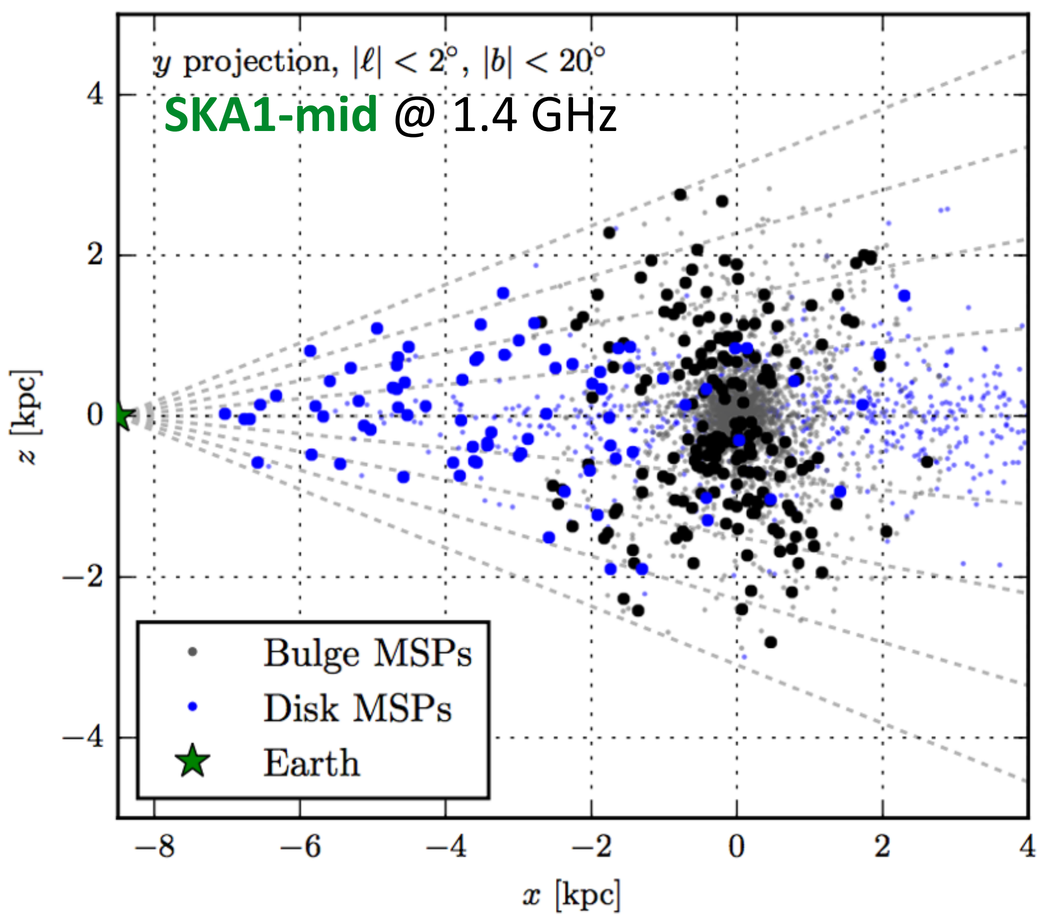


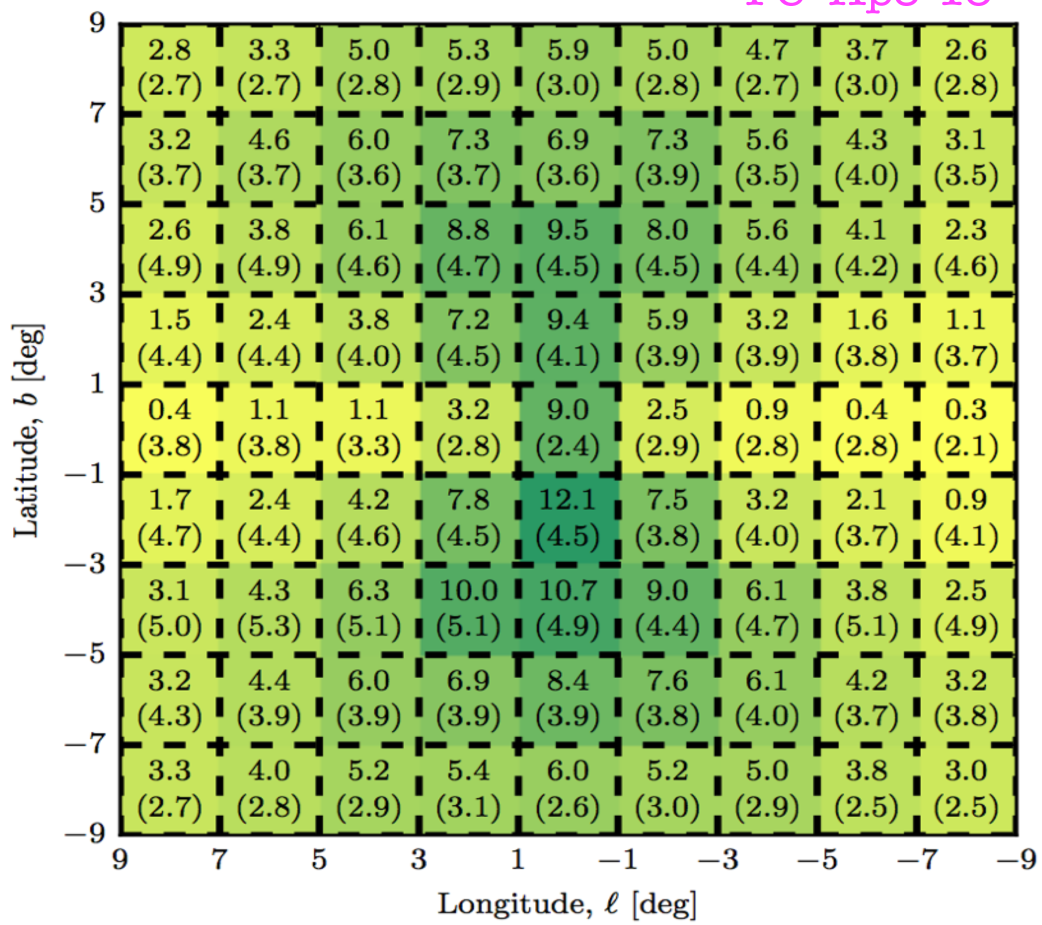
Future: How to test this scenario?

- ✓ 511 keV SPI signal: including bulge template in a model-fitting analysis of the 511 keV line?
- ✓ 511 keV IBIS signal: wavelet-based approach to look for dim point-sources?
- ✓ 511 keV line emission from Milky Way globular clusters —> good sensitivity prospects

Discovering radio MSPs in the inner Galaxy

FC+ApJ'16





Bulge population is just below sensitivity of Parkes HTRU mid-latitude survey.

- GBT targeted searches ~100h: ~3 bulge MSPs
- MeerKAT (and SKA) mid-lat survey ~300h: ~30 bulge MSPs

➡ With future dedicated observations we can **discover this MSP bulge population**.
➡ We need observation time (Fermi GI Proposals, TRAPUM project, etc.)

Conclusions

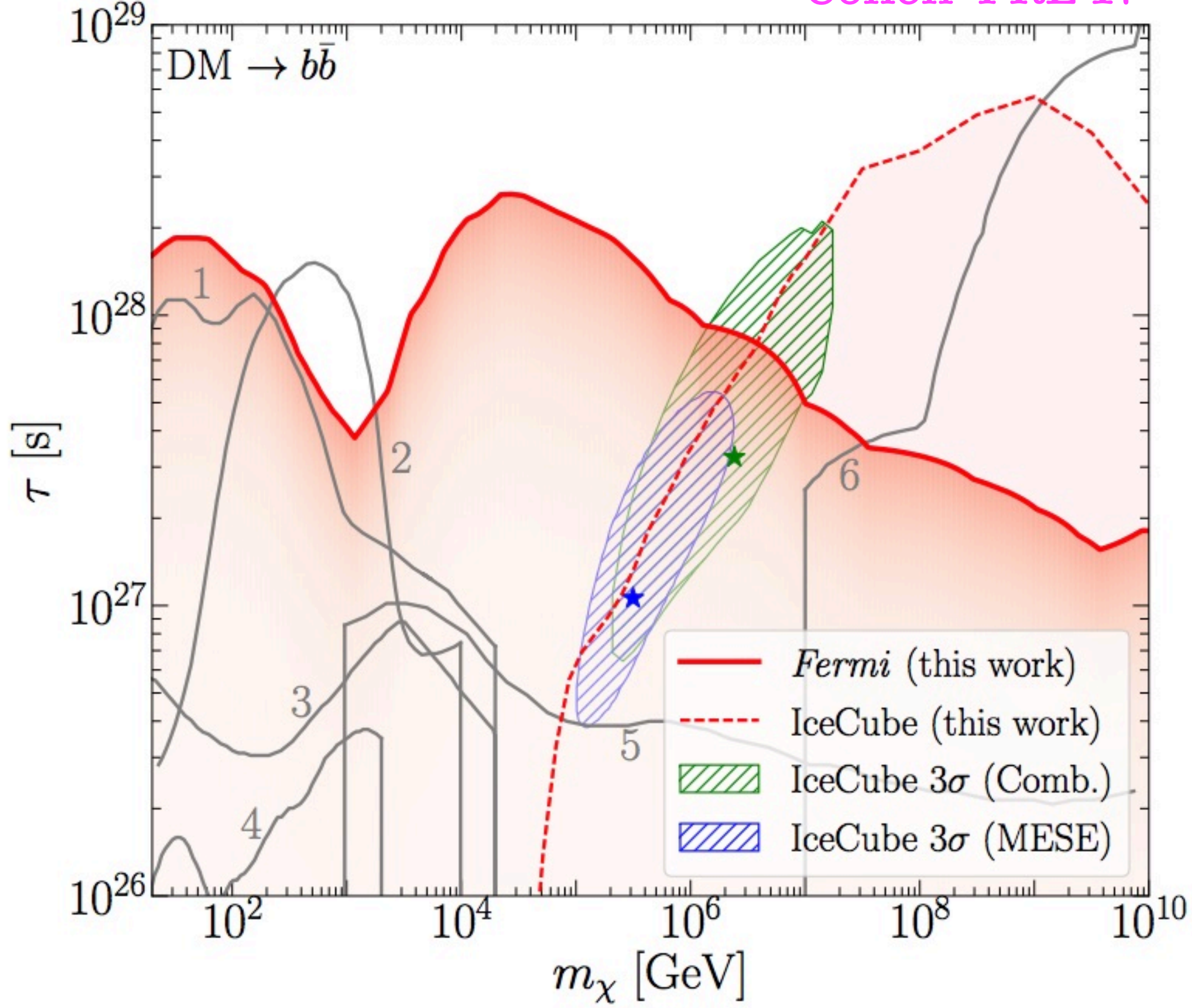
- ✓ Nowadays we can get strong constraints on particle dark matter (not only WIMPs) from indirect detection in the 10 GeV - 1 TeV mass range, but the parameter space to explore is still large
- ✓ Looking for dark matter has often led to the discovery of exciting anomalies which call into question our standard frameworks for point-source and diffuse high-energy emission
- ✓ The origin of the Galactic centre excess is still unclear, however future experimental developement (from radio to gamma rays) will further improve our understanding of this anamalous signal
- ✓ Great experimental progress at multiple wavelengths (LOFAR, SKA, Athena, CTA, etc) will open up new windows for dark matter discovery

Backup slides

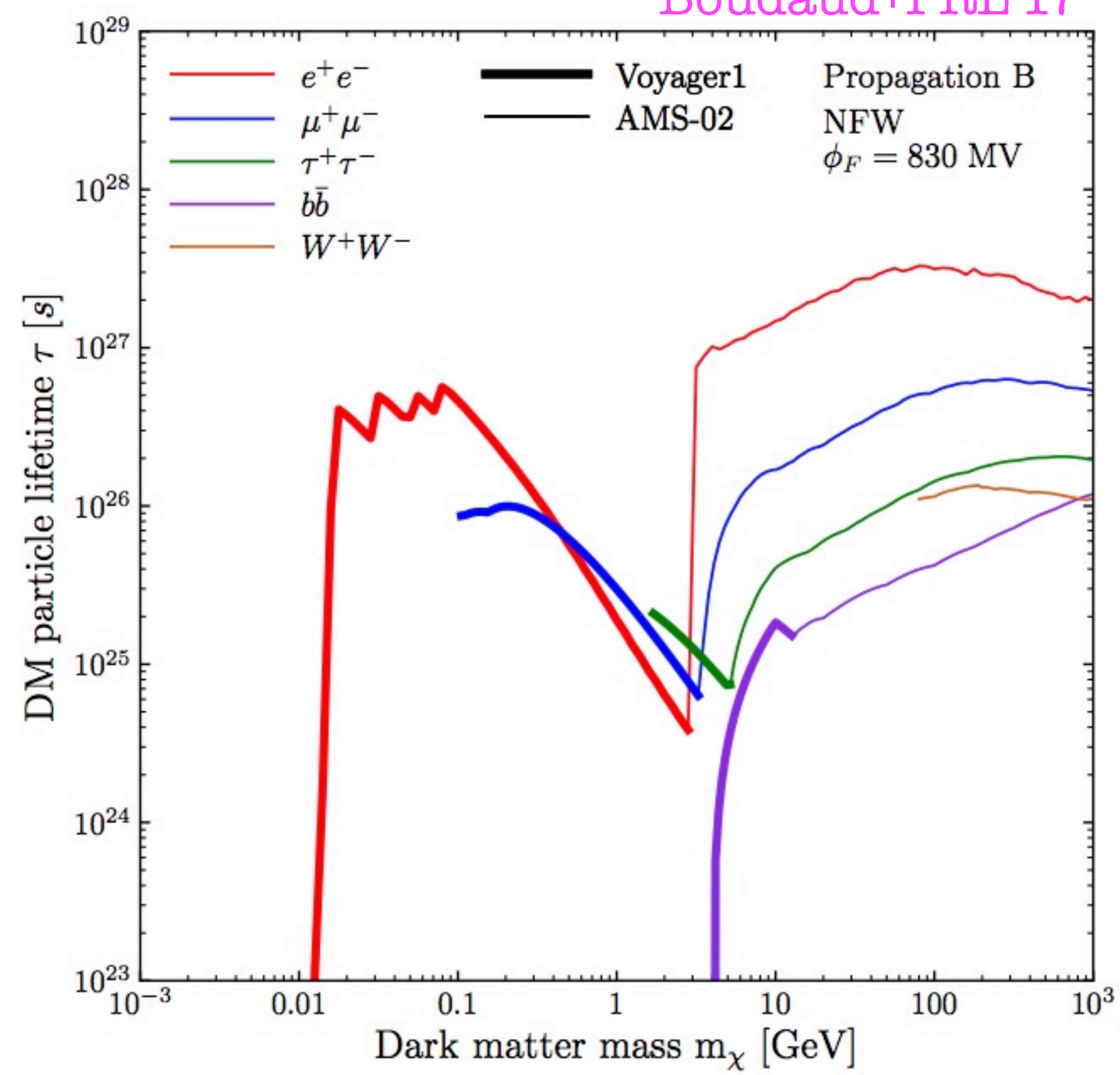
Status of decaying dark matter

- 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]

Cohen+PRL'17



Boudaud+PRL'17

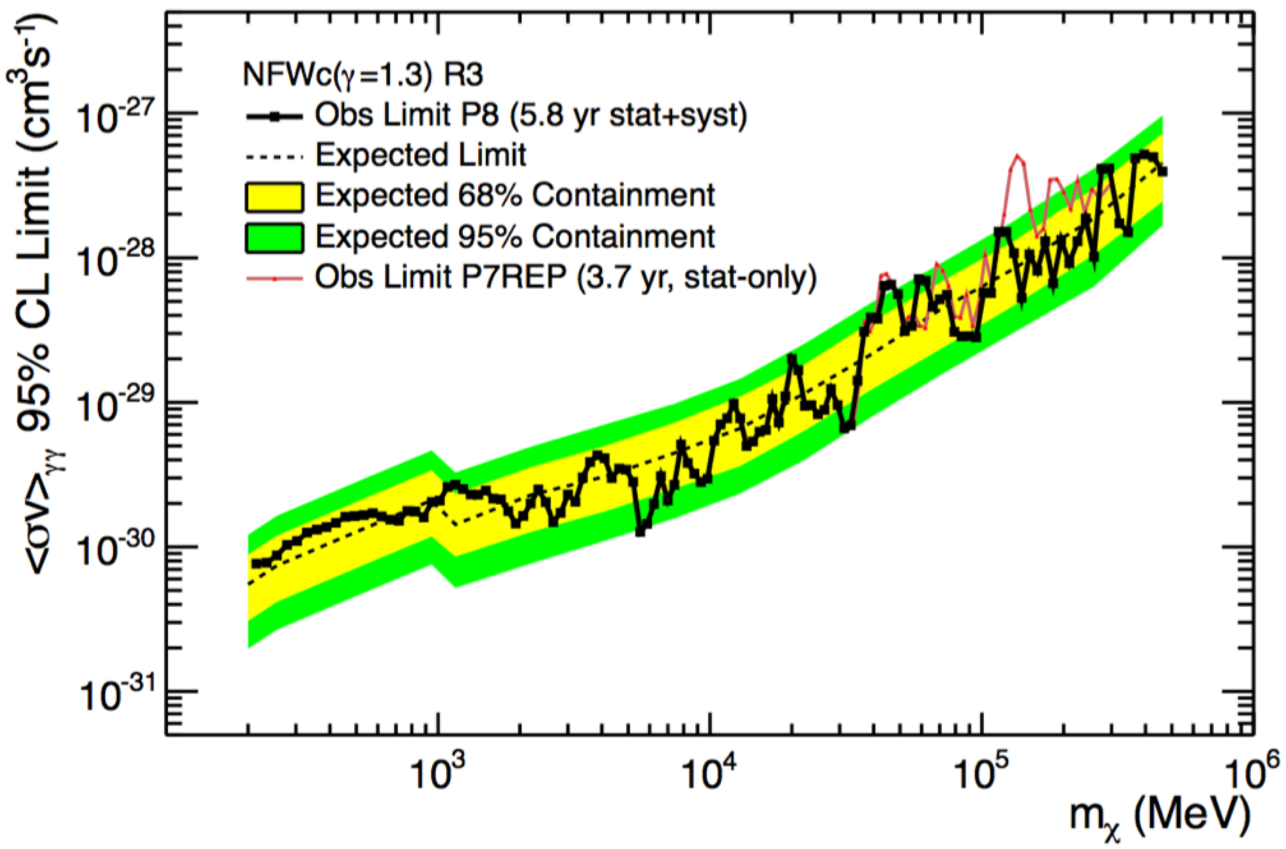


Decay lifetimes below ~$10^{27\text{-}28}$ s ruled out for most final states and keV-EeV DM masses;

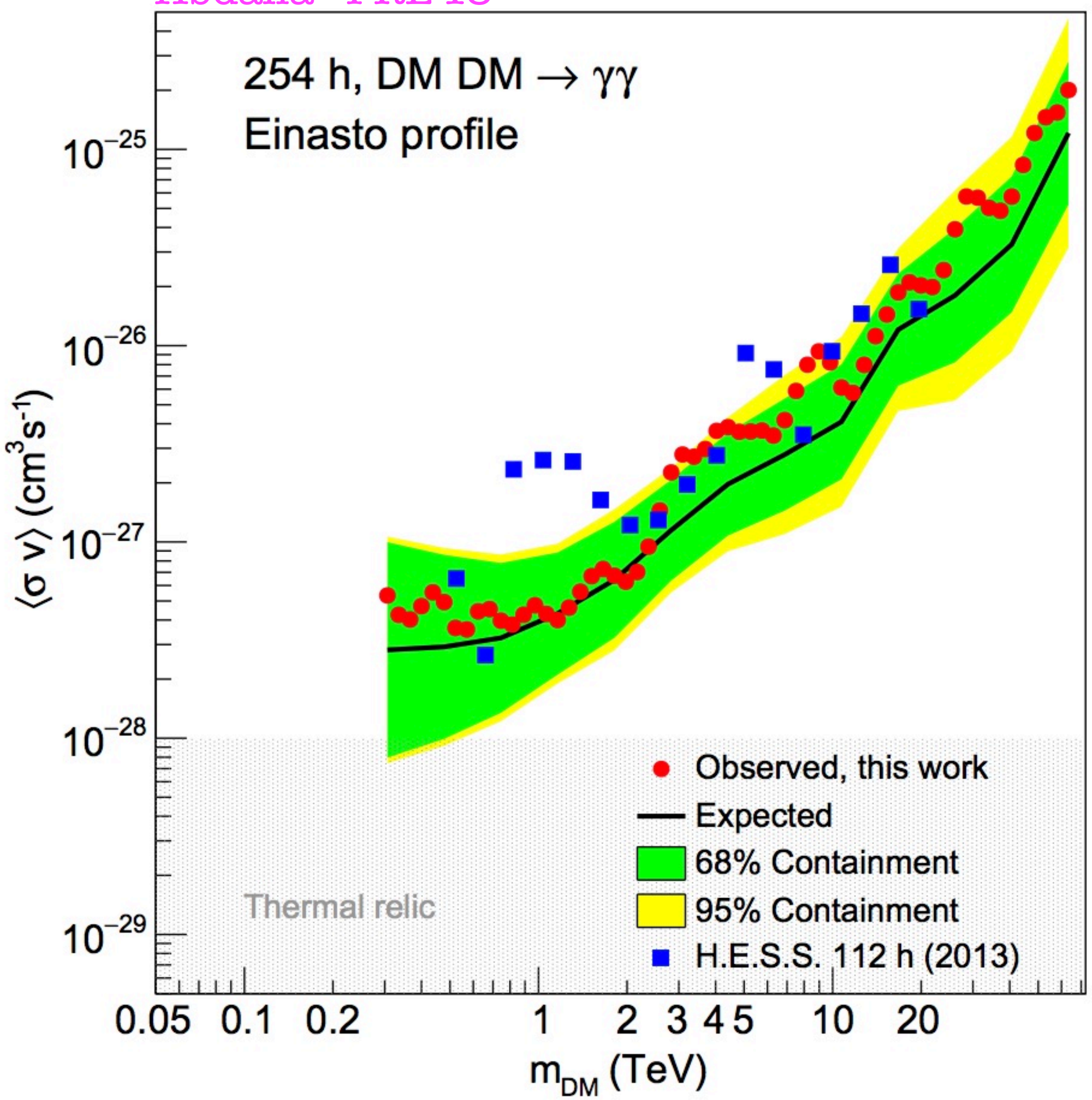
for few-MeV DM decaying to e+e-, lifetimes can be as short as $10^{24\text{-}25}$ s

Status of line signal searches in gamma rays

Ackermann+ PRD'15



Abdalla+ PRL'18



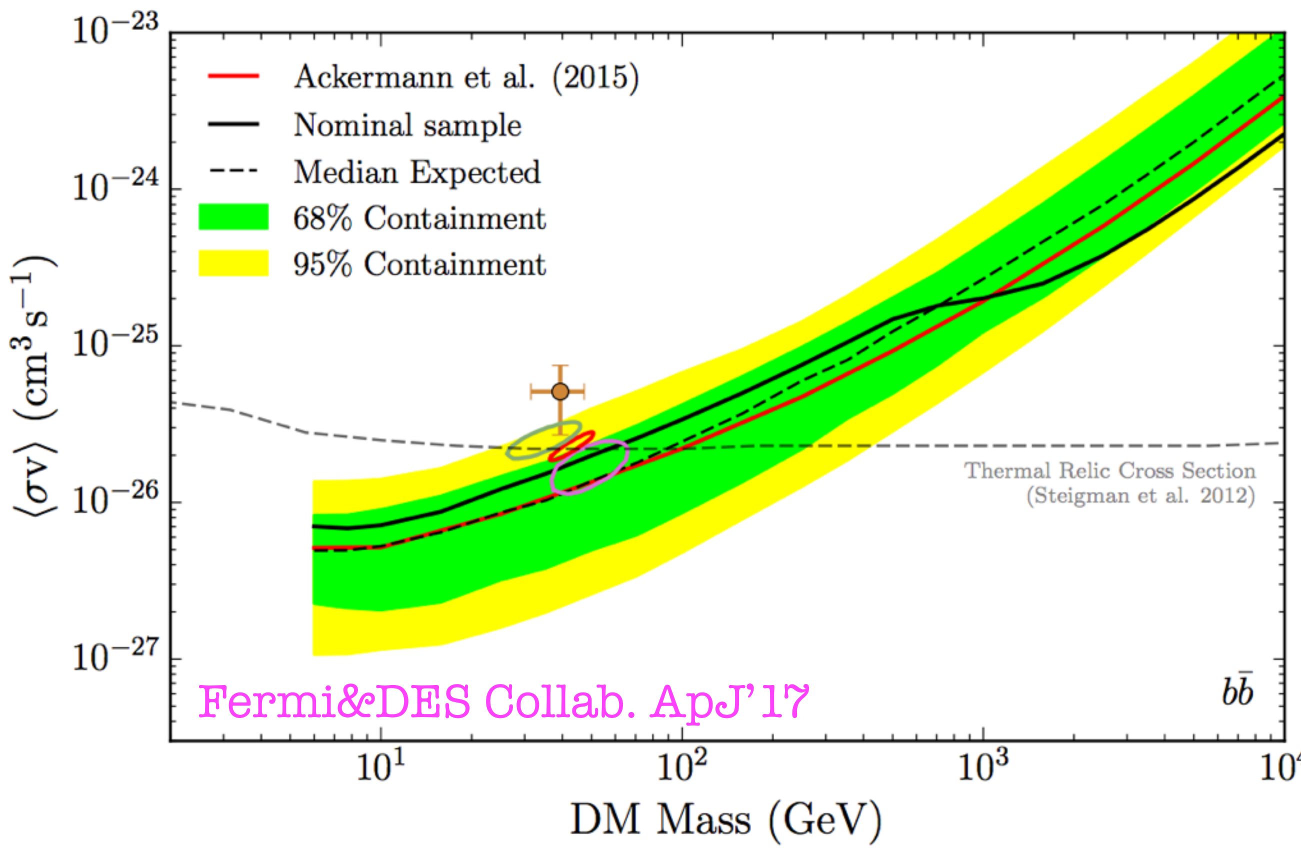
Weak excesses in dwarf spheroidal galaxies

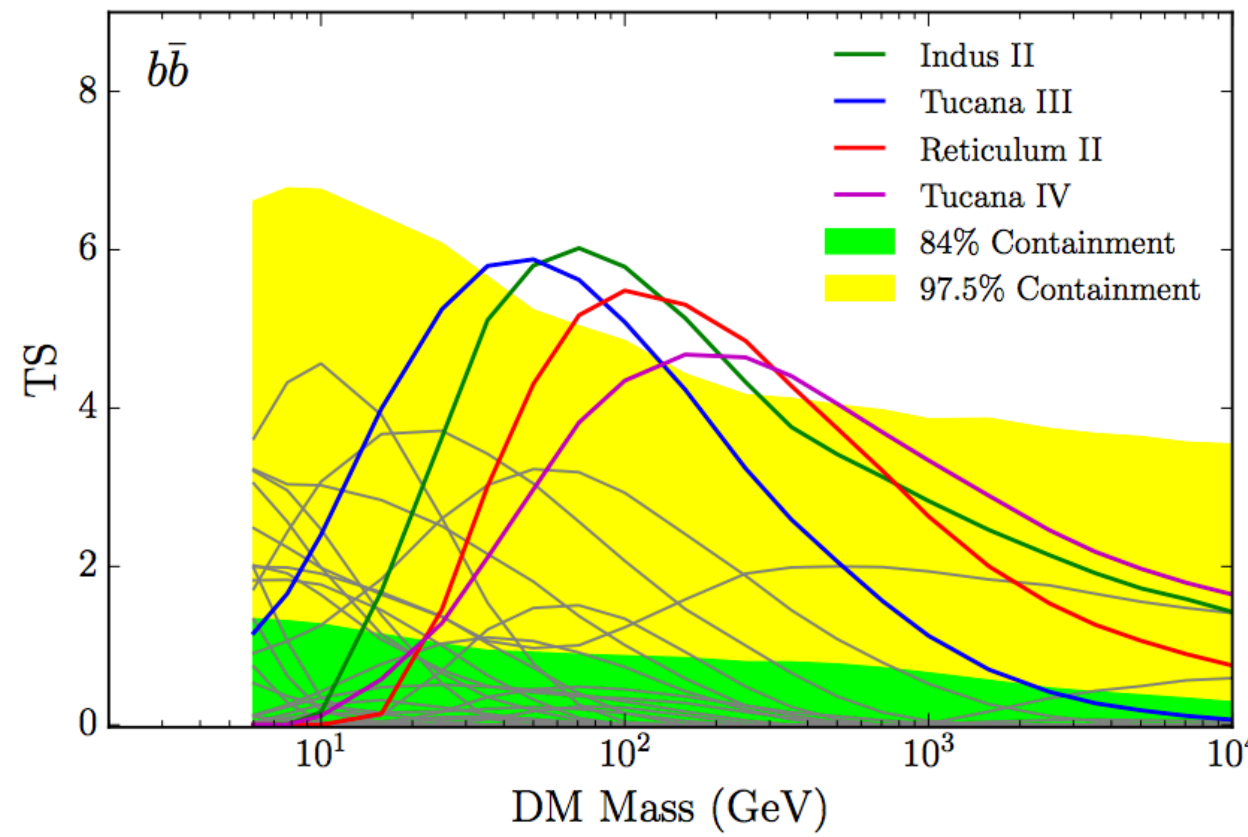
Signal:
- < 3σ excesses in dSphs galaxies
- Fermi-LAT + DES targets (Indus II, Reticulum II and Tucana III)

Interpretations:
- Dark matter annihilation with mass ~ 40 — 100 GeV
- Syst. uncertainties on J-factor determination for ultra-faint dSphs

Future:
- New data from Fermi-LAT (improvement by a factor of 3-4)
- New large optical surveys and spectroscopic data (LSST, Maunakea Spectroscopic Explorer)
- Radio searches with ATCA/SKA

Regis+ JCAP'17





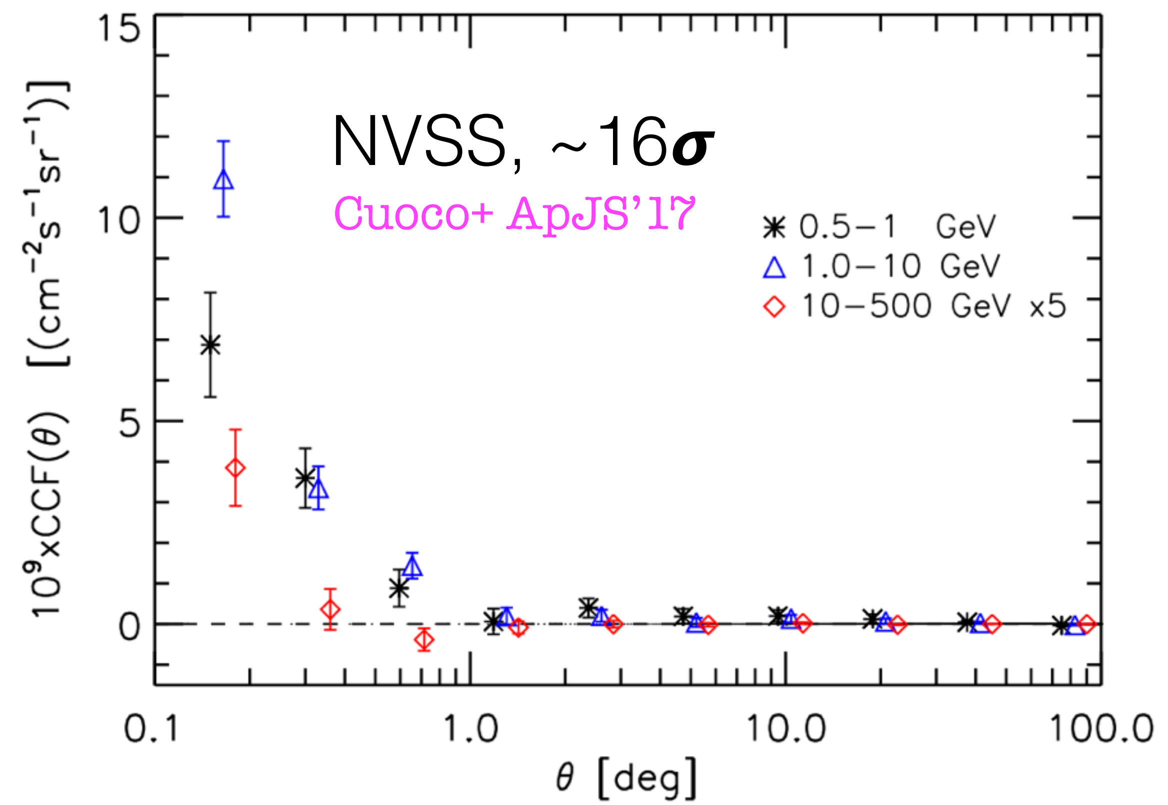
X-correlation: Fermi-LAT & Galaxy catalogs

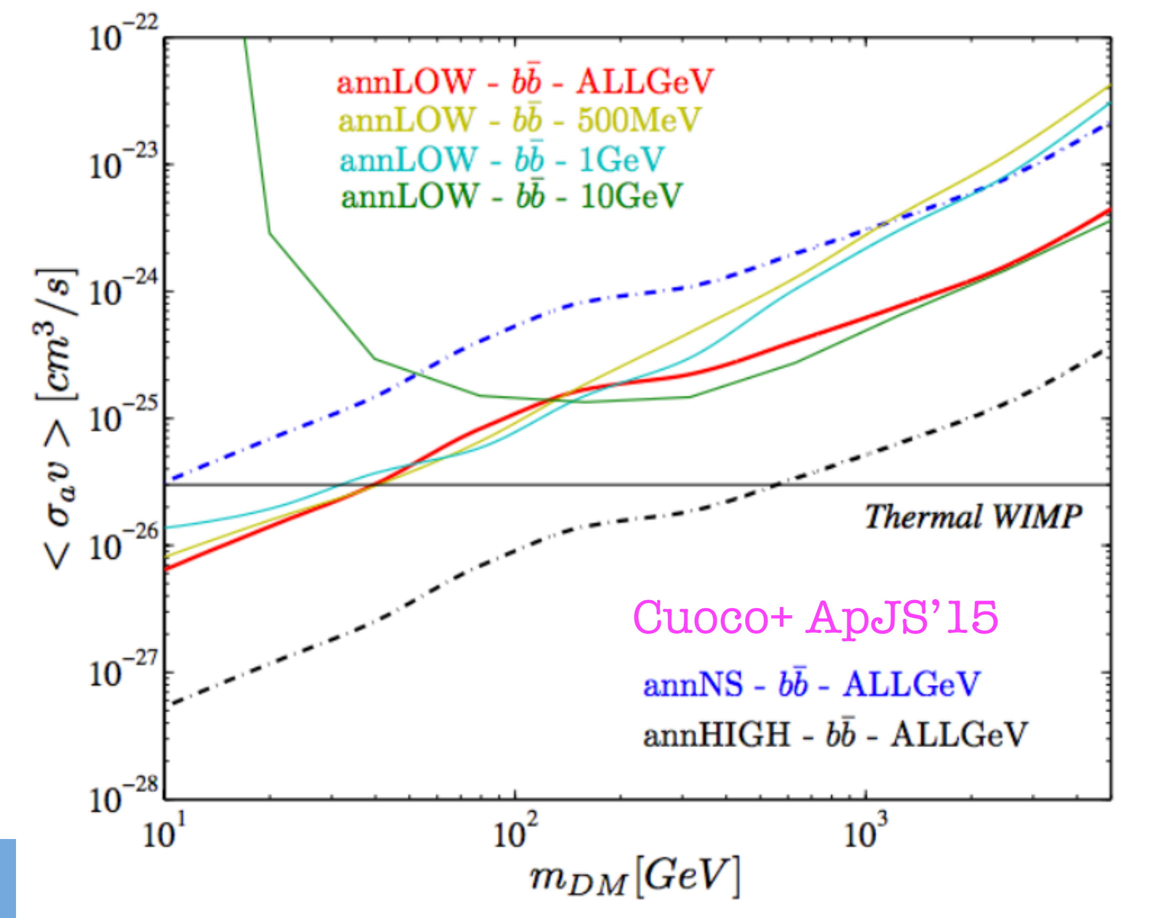
Signal:
- Detection (> 10σ, NVSS) of cross-correlation signal between extragalactic gamma-ray background and galaxy catalogs Cuoco+ ApJS'17
- Fermi-LAT x Galaxy catalogs (NVSS, 2MASS, SDSS-DR12, WISExSuperCOSMOS, 2MPZ, WIxSC)

Interpretations:
- Degeneracy between DM interpretation and AGN hosted in big halos (groups or clusters)
- Tomographic approach account for the full redshift distribution of source populations: DM and astro peak at different z Regis+ PRL'15

Future:
- X-correlation with other catalogs, weak lensing and cosmic shear
- Low-z tomography => highest sensitivity to DM

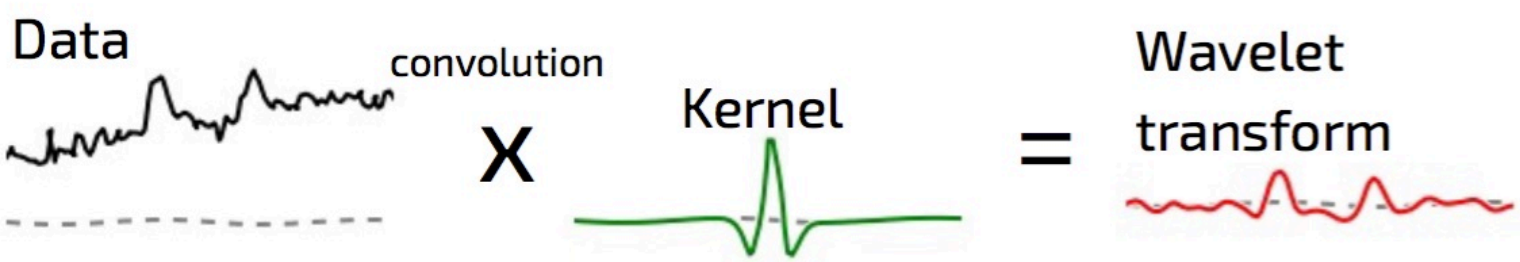
[Detection in X-corr gamma rays with cluster catalogs Branchini+ ApJS'17; no detection with weak lensing data Troester+ MNRAS'17; detection with CMB lensing Fornengo+ ApJ'15]



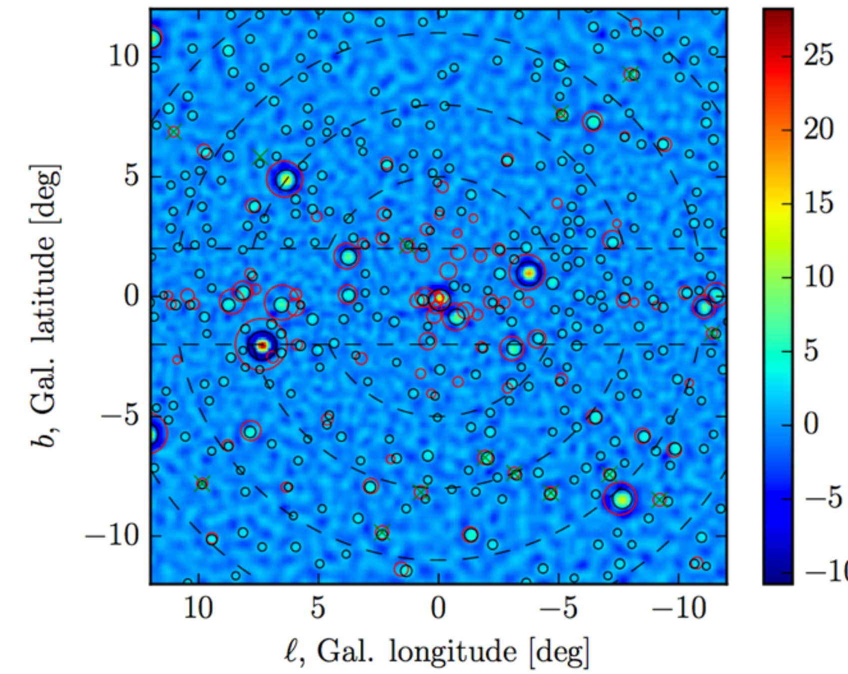


Support for unresolved point sources

Local maxima of normalised wavelet transform



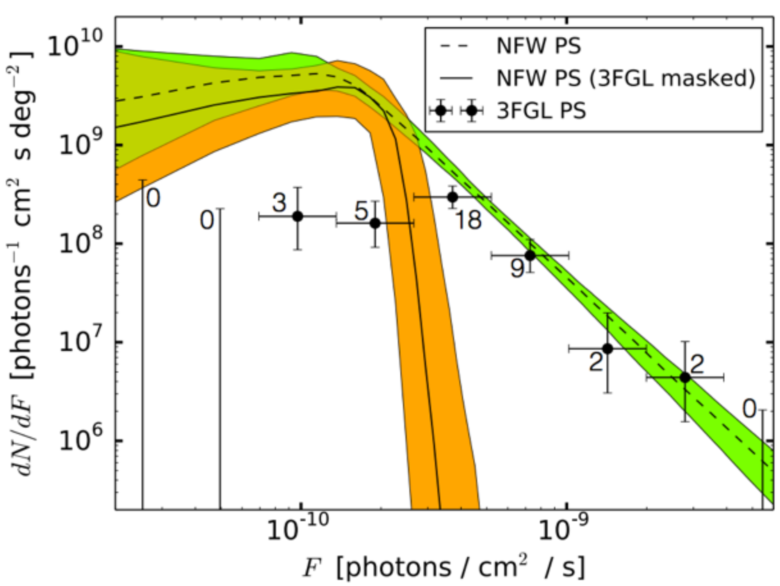
Bartels+ PRL'16

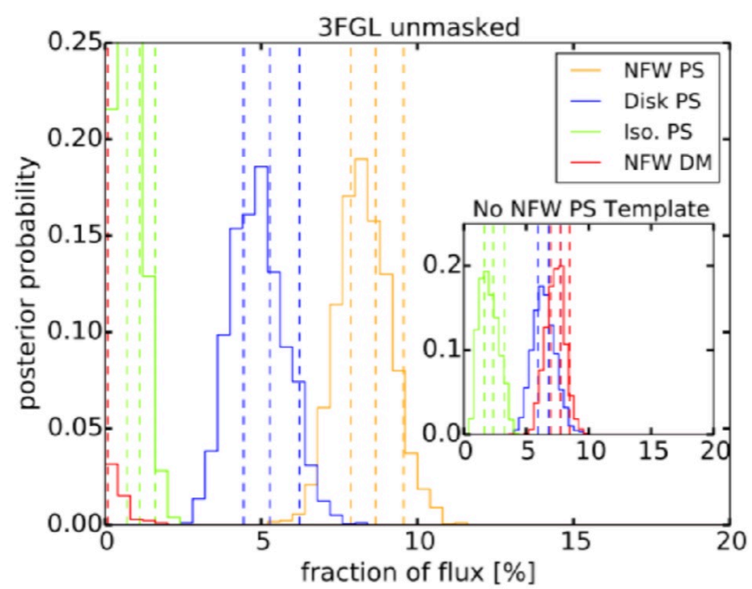


- No background modelling
- Evidence for MSP-like population in the bulge
- Constraints on luminosity function

Non-Poissonian template fitting

Lee+ PRL'16





- The statistics of PS is non-Poissonian
- PS NPT NFW distribution absorbs the most of the excess
- A priori, it suffers more form contamination of background modelling

Caveat: Do we model the small scale gas correctly?