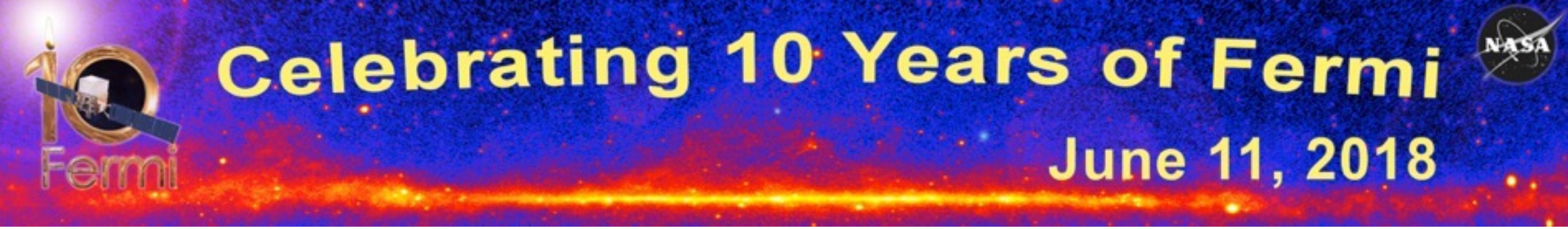


8th International Fermi Symposium

18th October 2018, Baltimore

Ten years of dark matter searches with the Fermi-LAT

Francesca Calore

Laboratoire d'Annecy-le-Vieux
de Physique Théorique

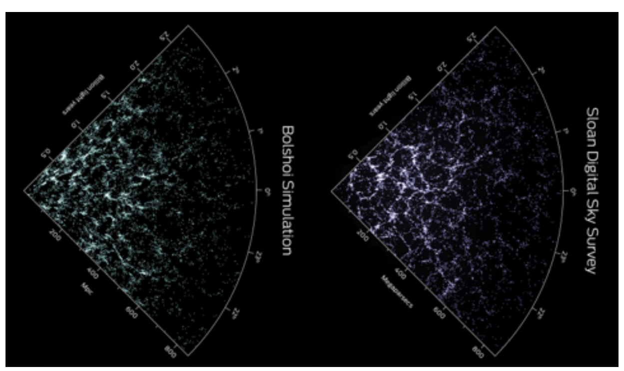
Illustration by Sandbox Studio, Chicago

Dark matter gravitational evidence

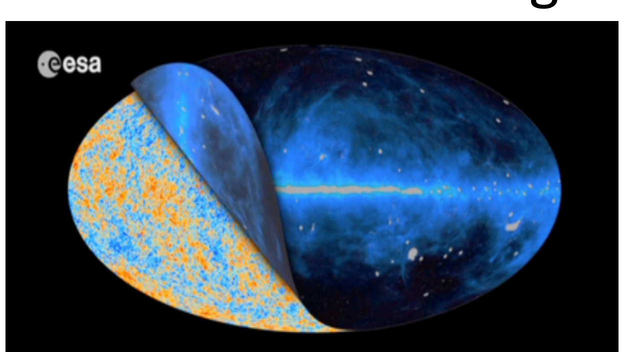
Rotation curves

Galaxy clusters

Large Scale structures



Cosmic microwave background

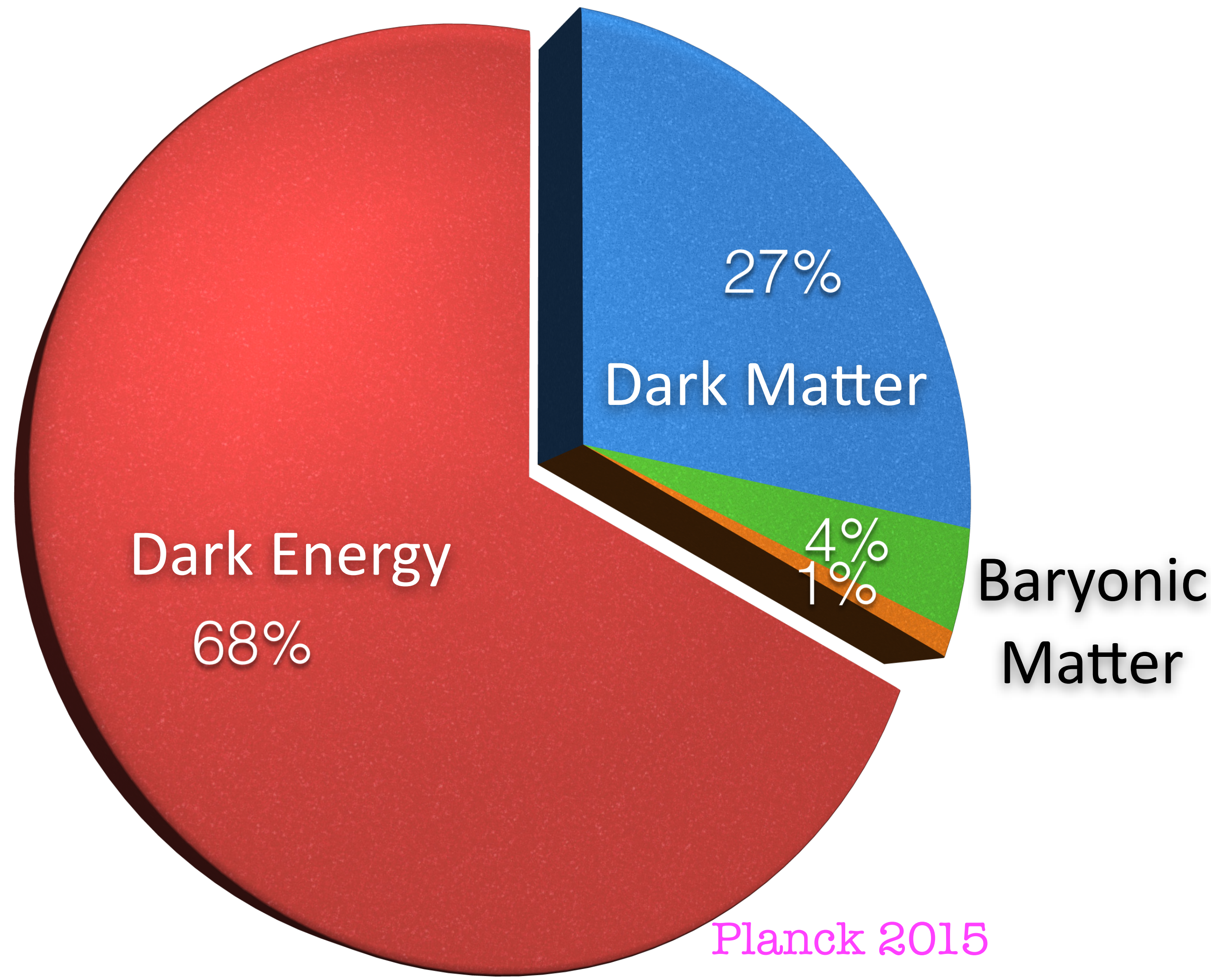


~kpc

~Mpc

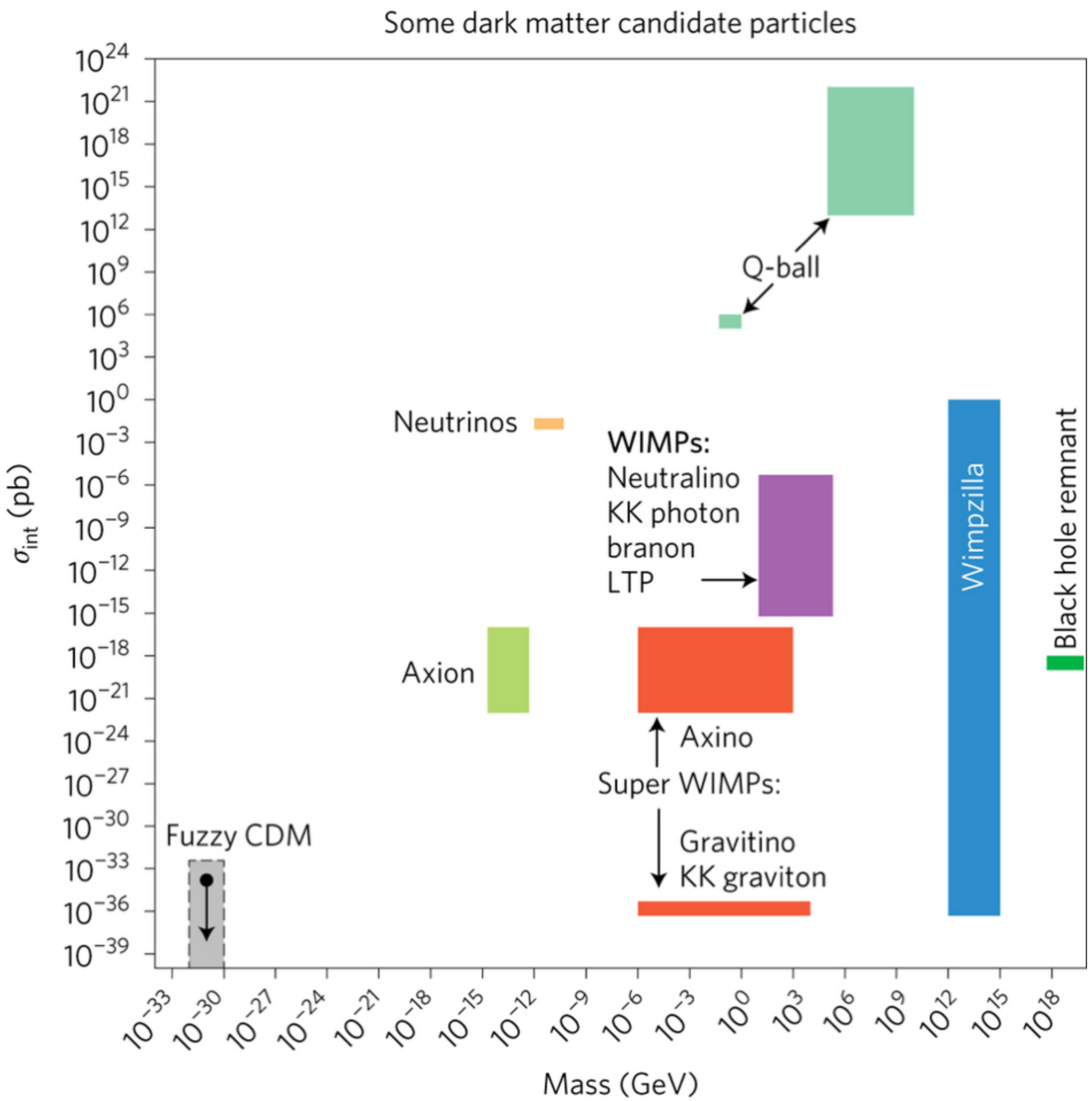
~Gpc

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



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

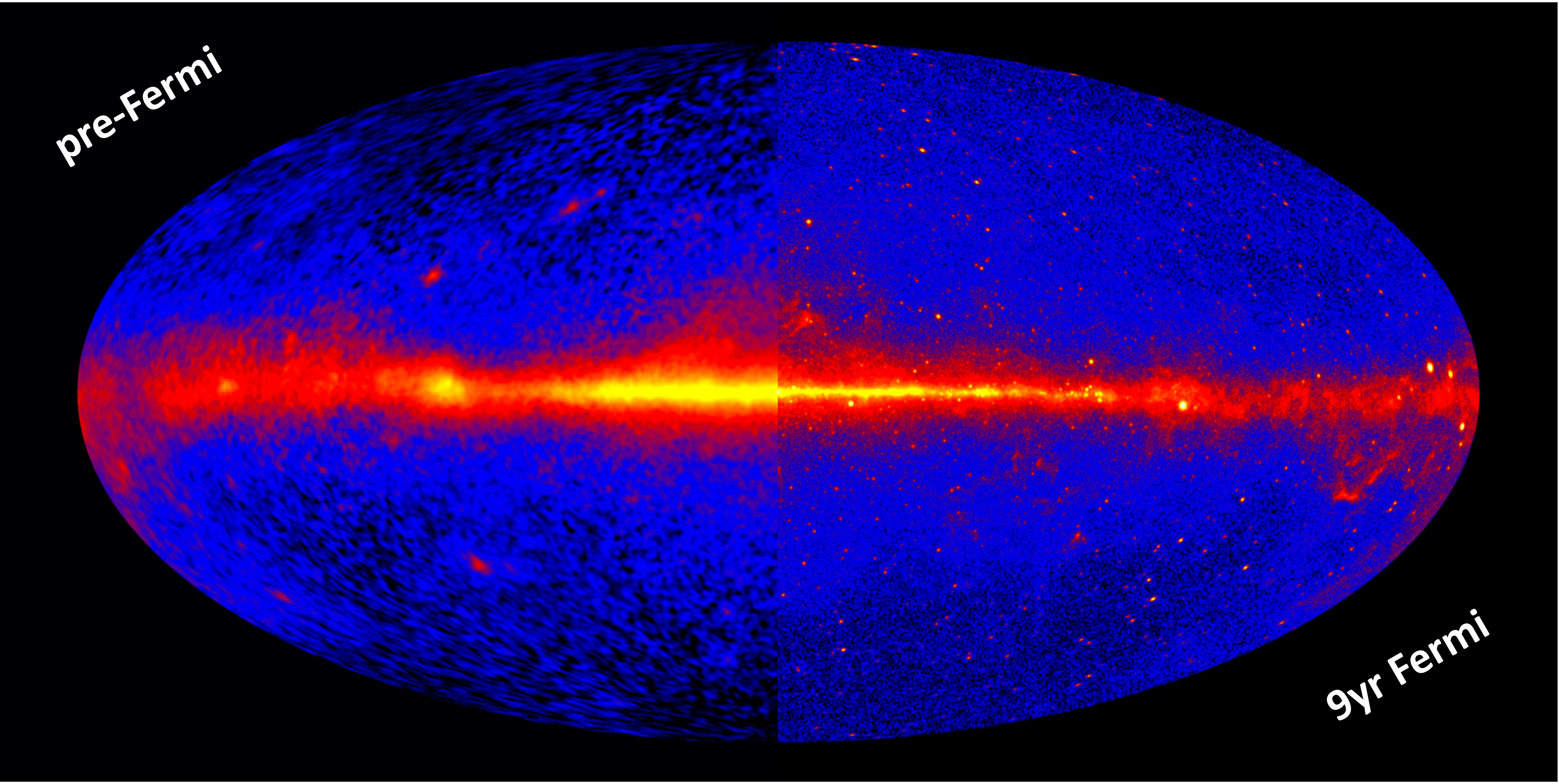
The dark matter landscape



- 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

20 years of high-energy gamma rays

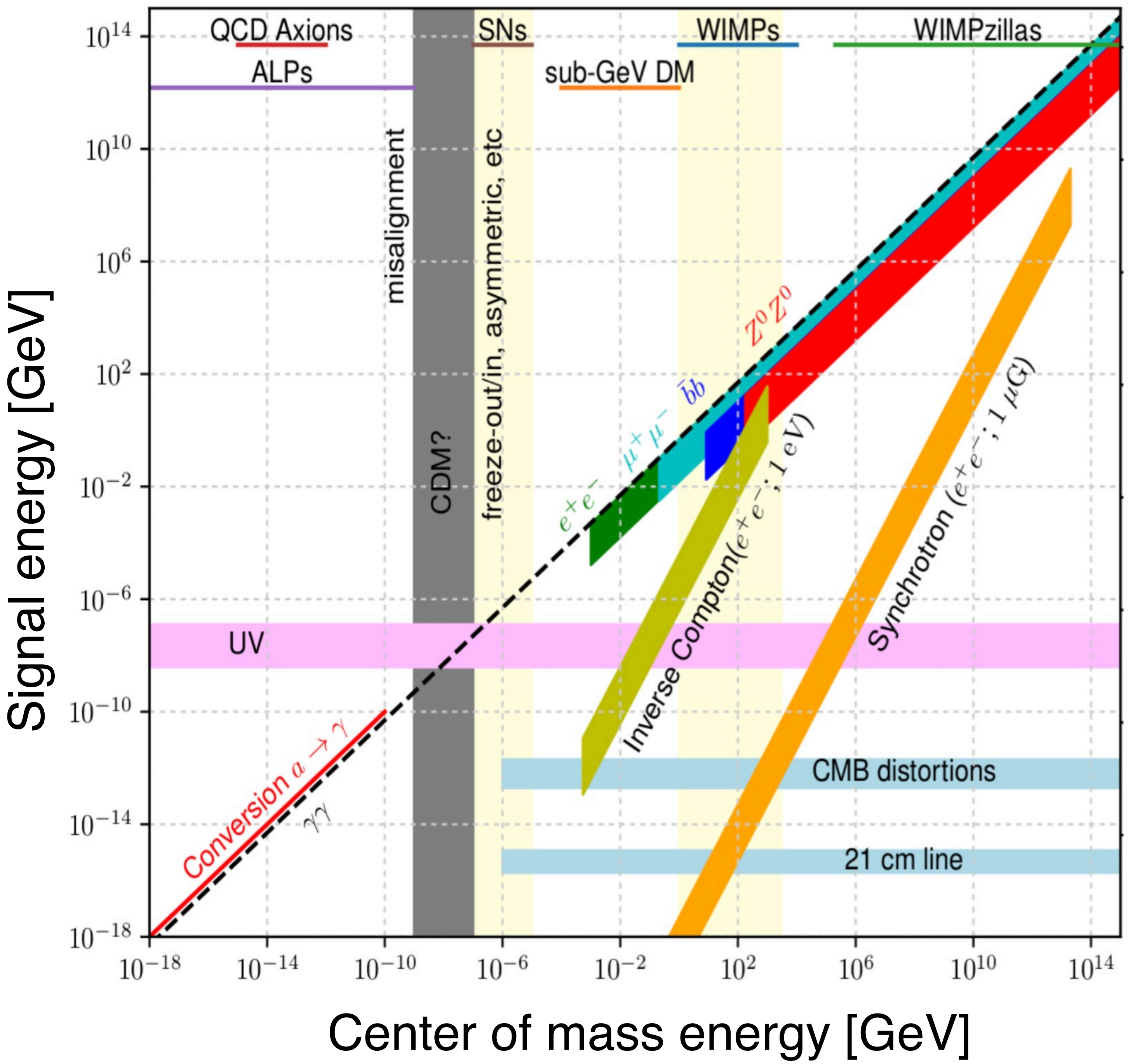


EGRET (1991-2000)
30 MeV - 30 GeV

Fermi-LAT (2008-2017)
20 MeV - 500 GeV

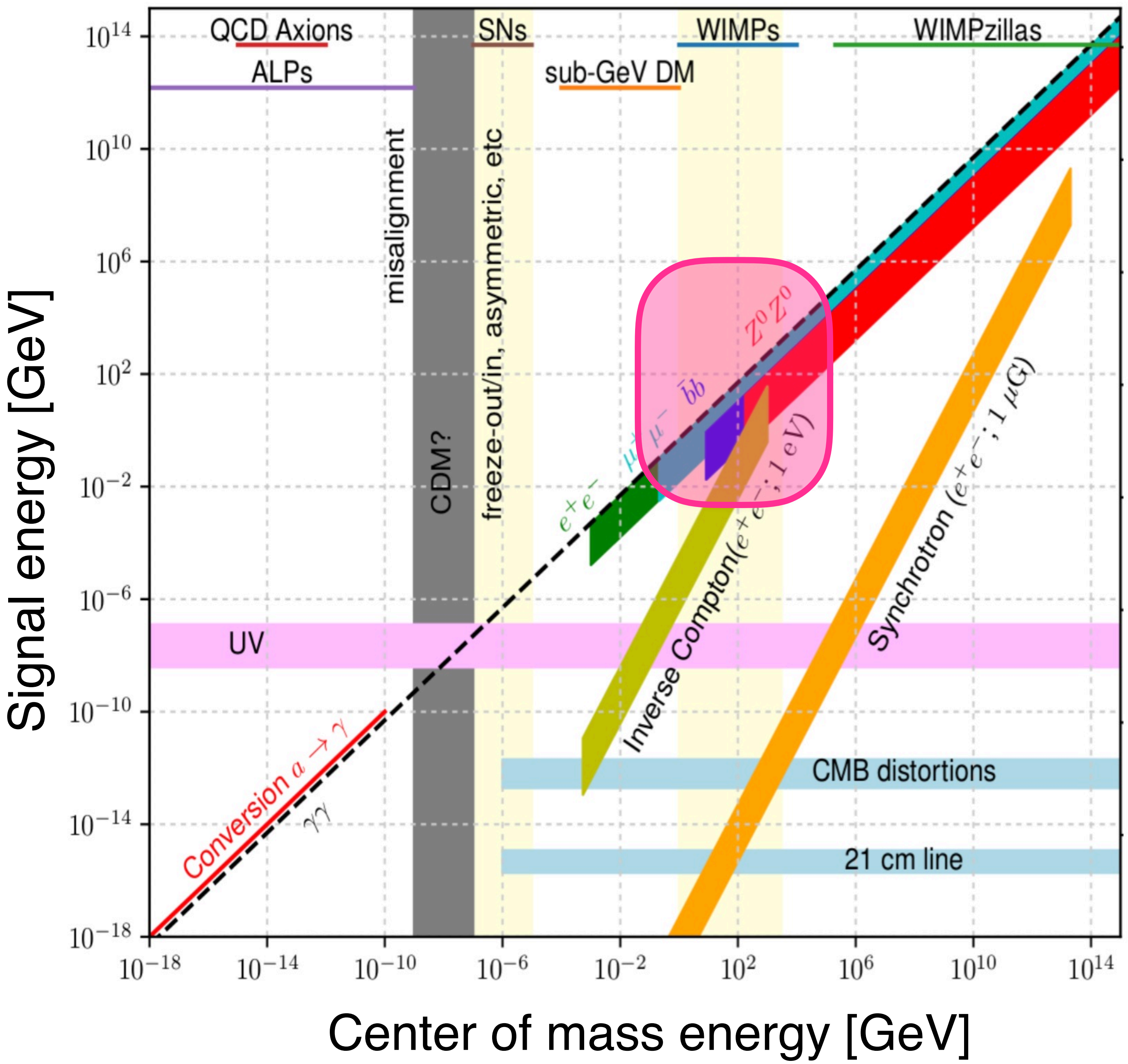
Dark matter candidates & Photon energy

FC, Storm & Weniger, In preparation



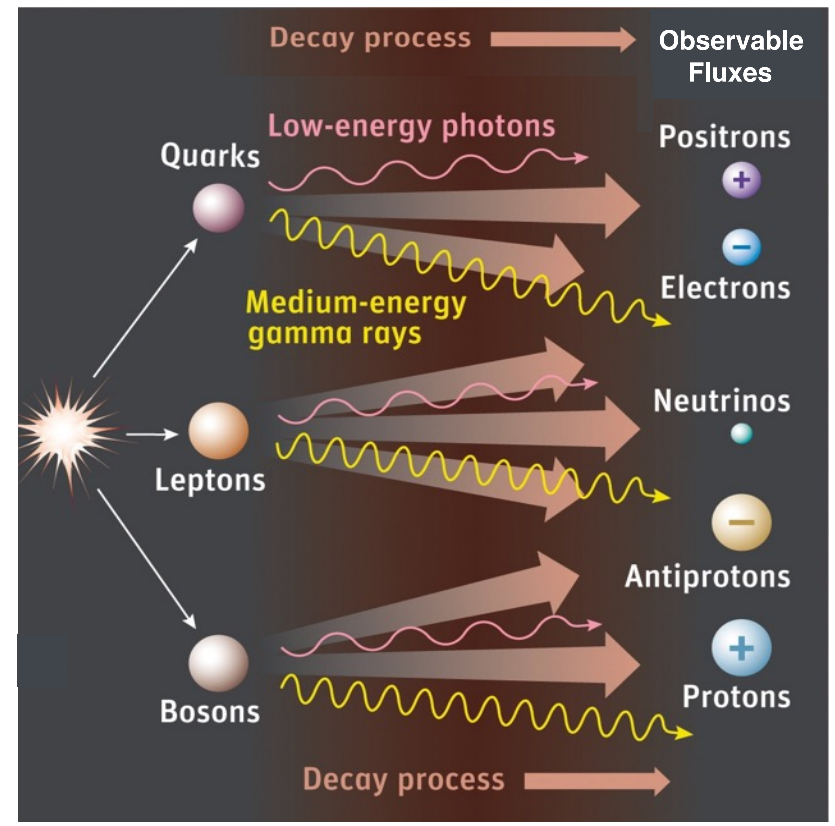
Dark matter candidates & Photon energy

FC, Storm & Weniger, In preparation



Focus on searches for
WIMP dark matter

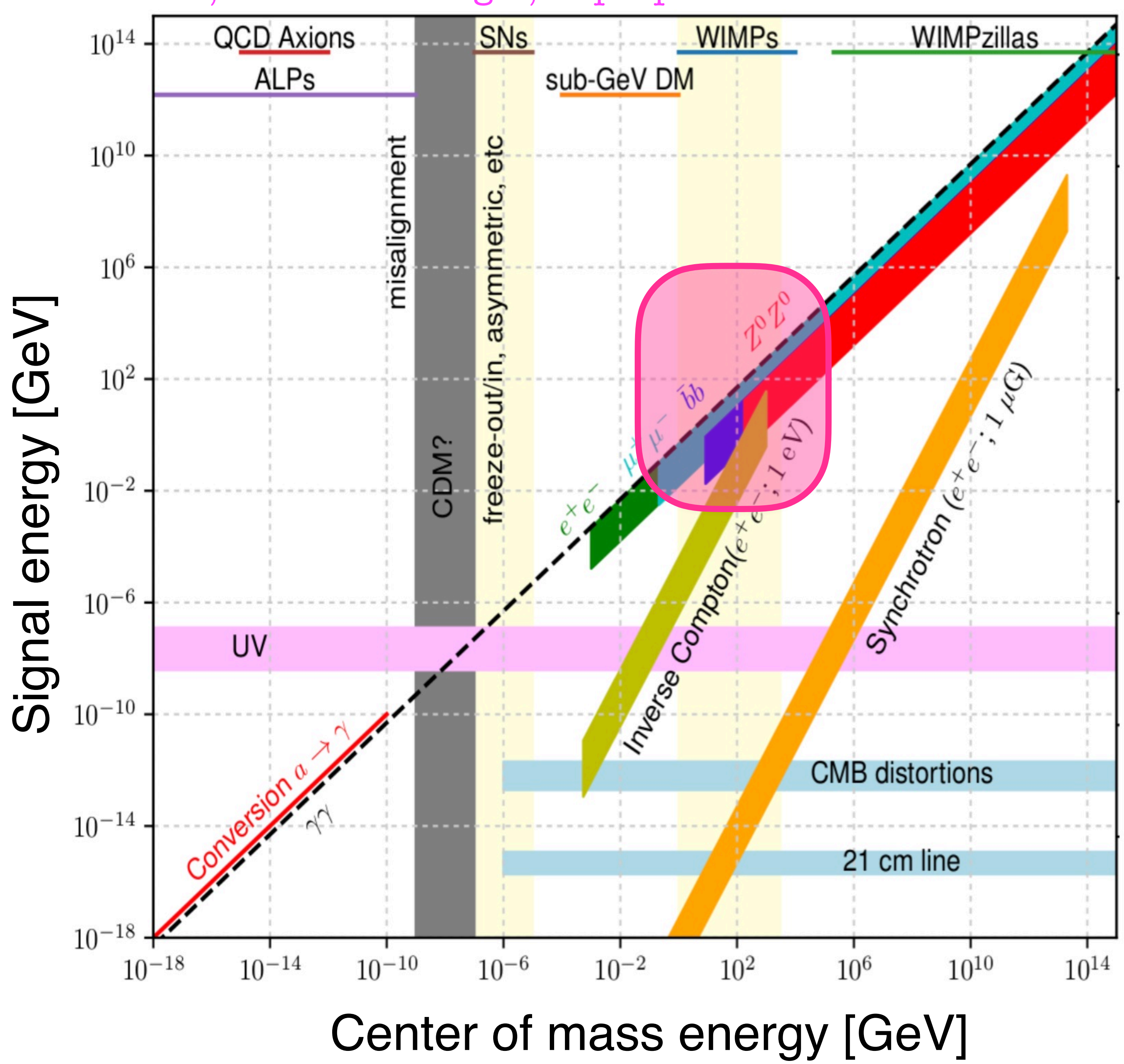
DM annihilation/decay



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

Dark matter candidates & Photon energy

FC, Storm & Weniger, In preparation



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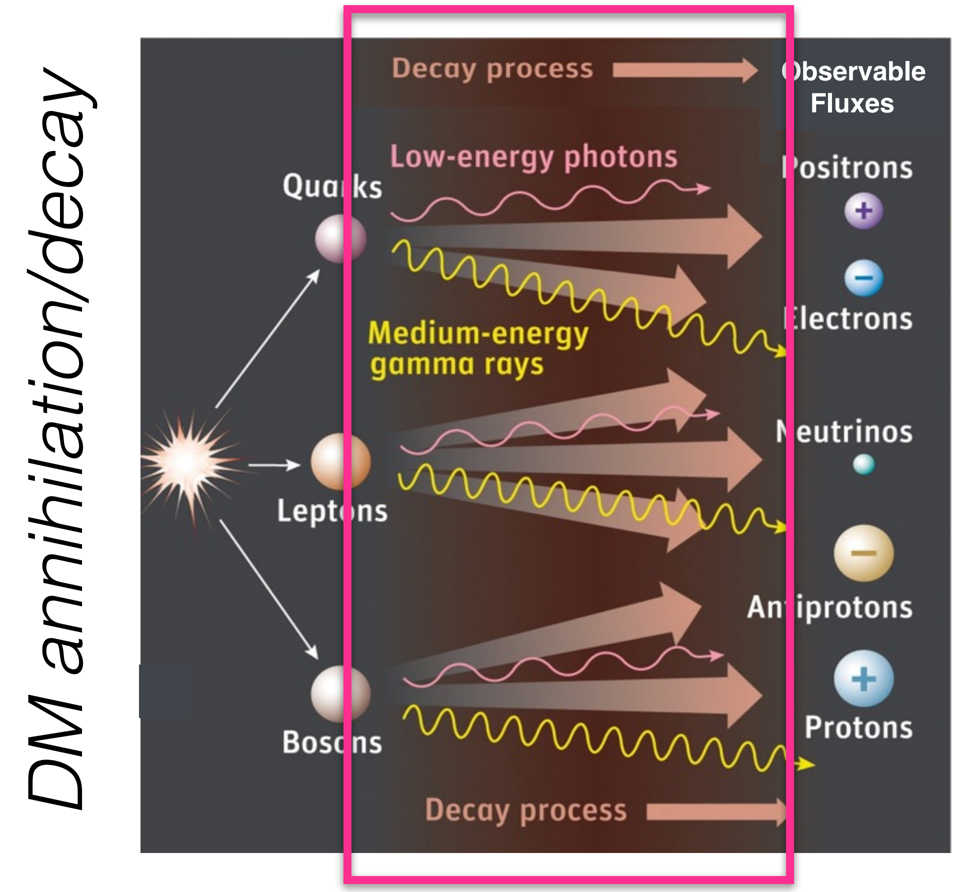
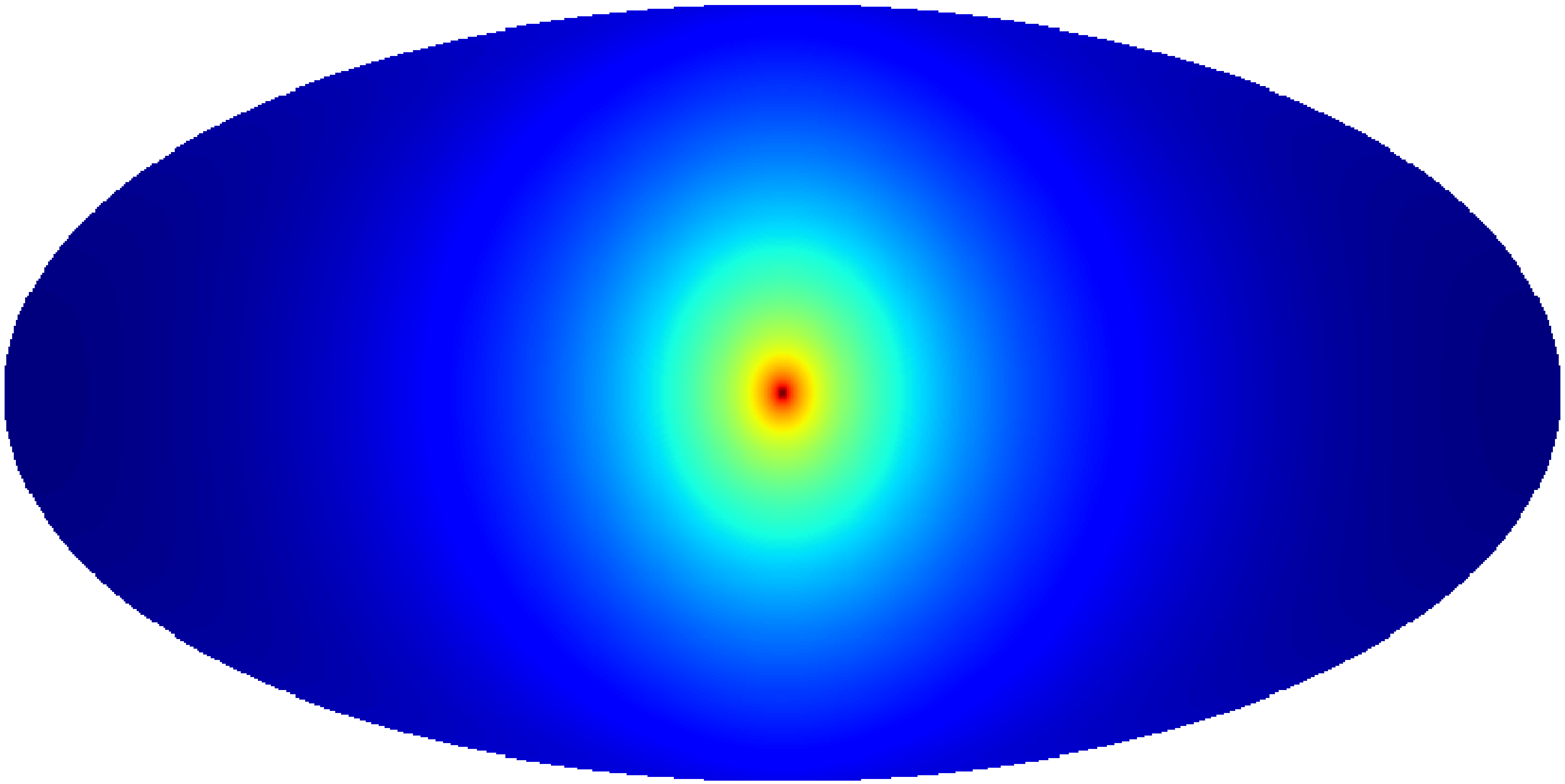


What are we looking for?

Expected gamma-ray flux from **dark matter annihilation** in the smooth Galactic halo

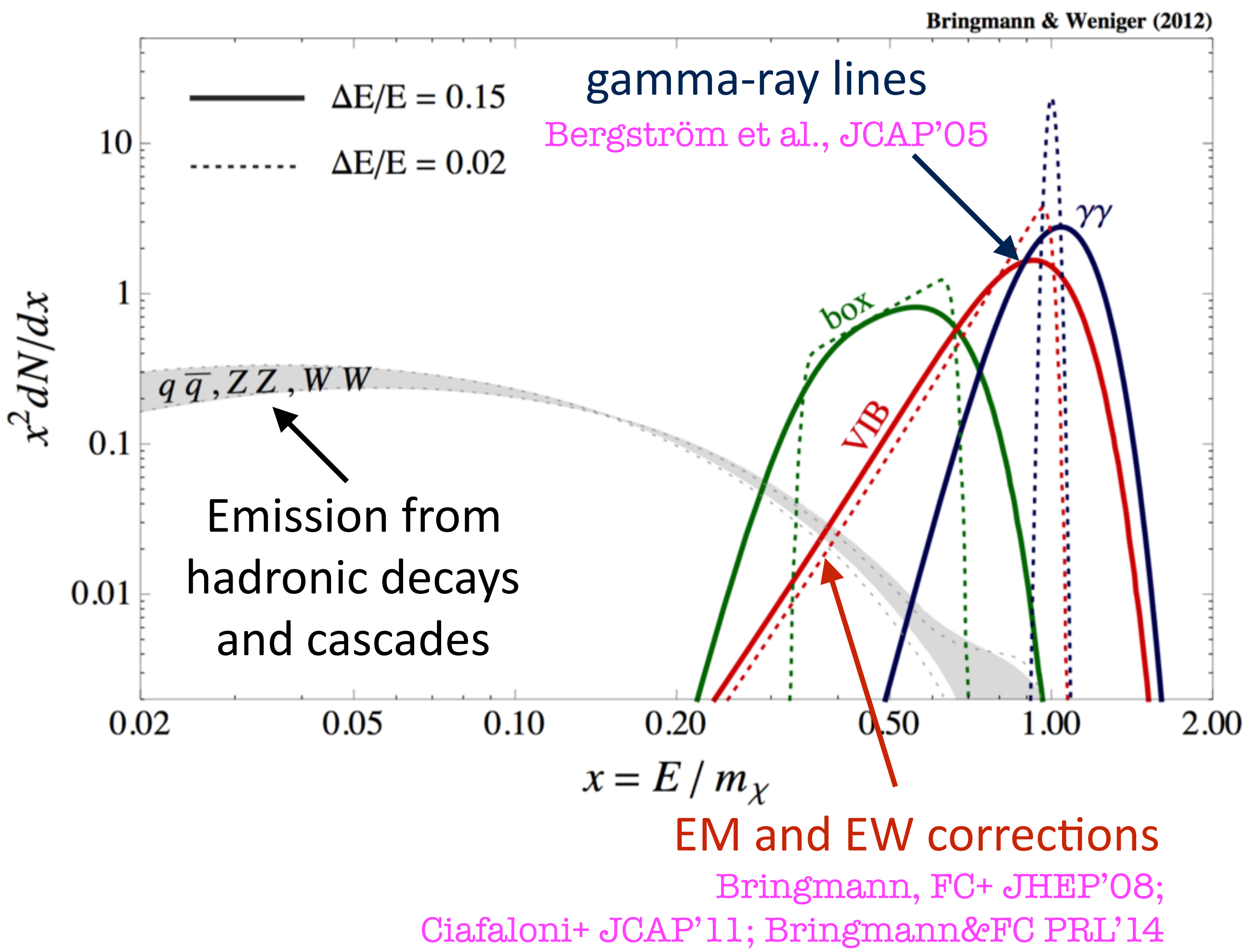


$$\Phi(E,\psi) = \frac{\sigma_{\rm A} v}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \int d\ell \, \rho \left[r(\ell,\psi) \right]^2$$

Dark matter signal predictions

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

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



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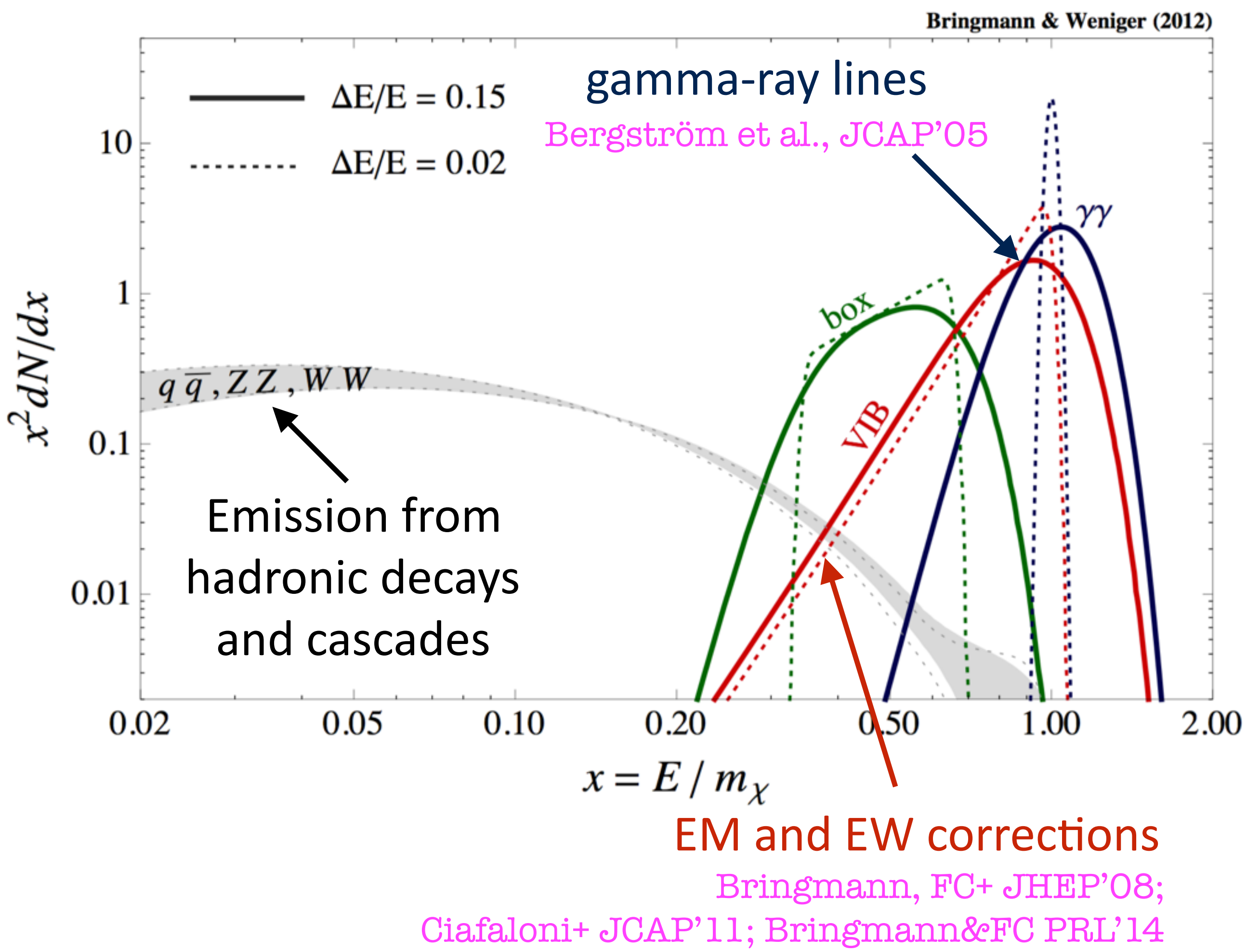
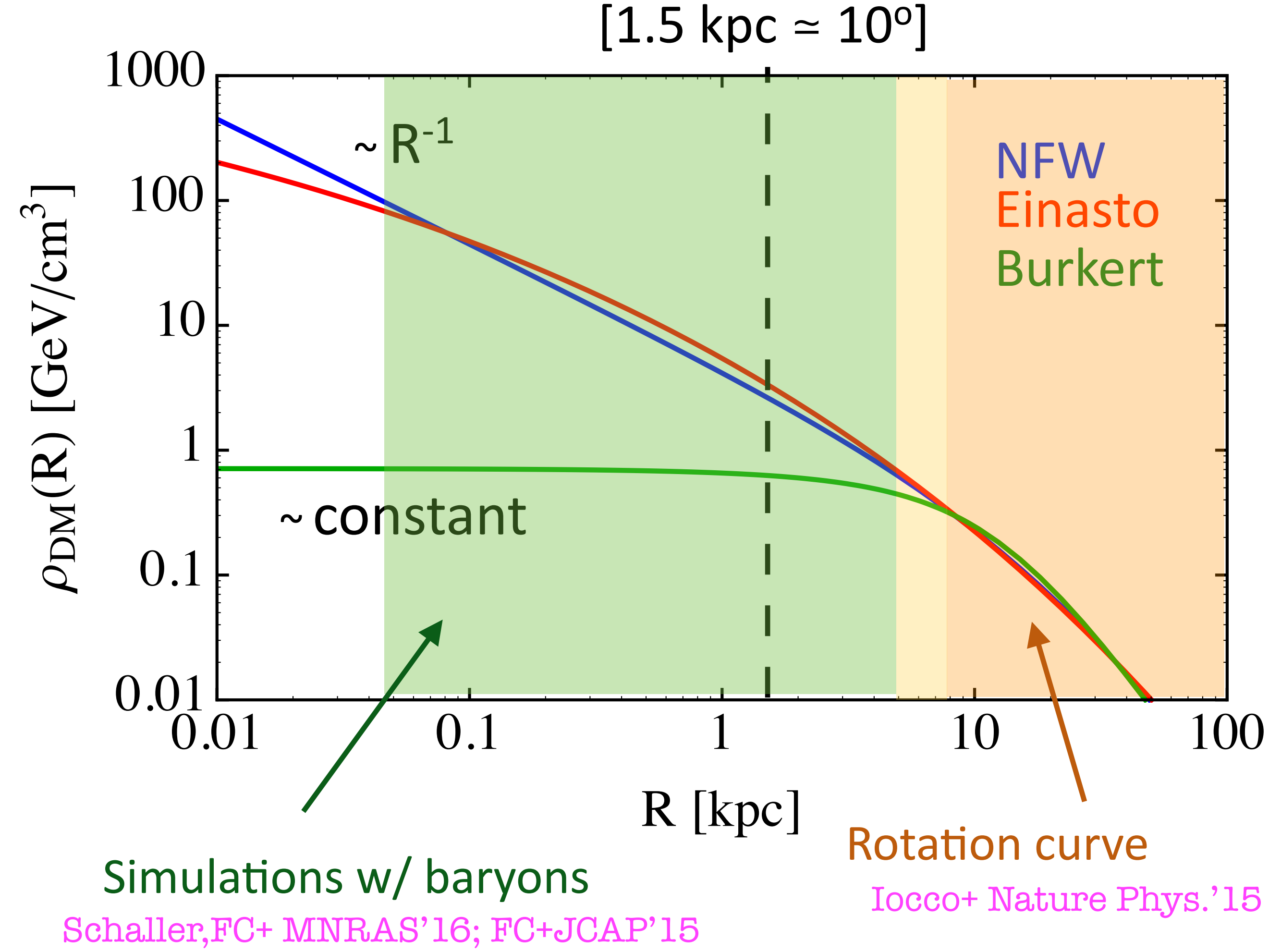
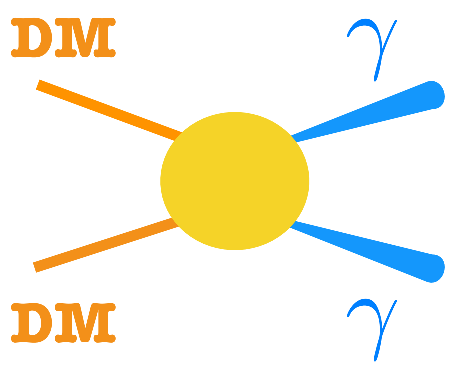


Spatial distribution in astrophysical targets (asymmetric density profiles, substructures boost factor, local DM density)



Dark matter searches with the Fermi-LAT: Current limits on WIMPs

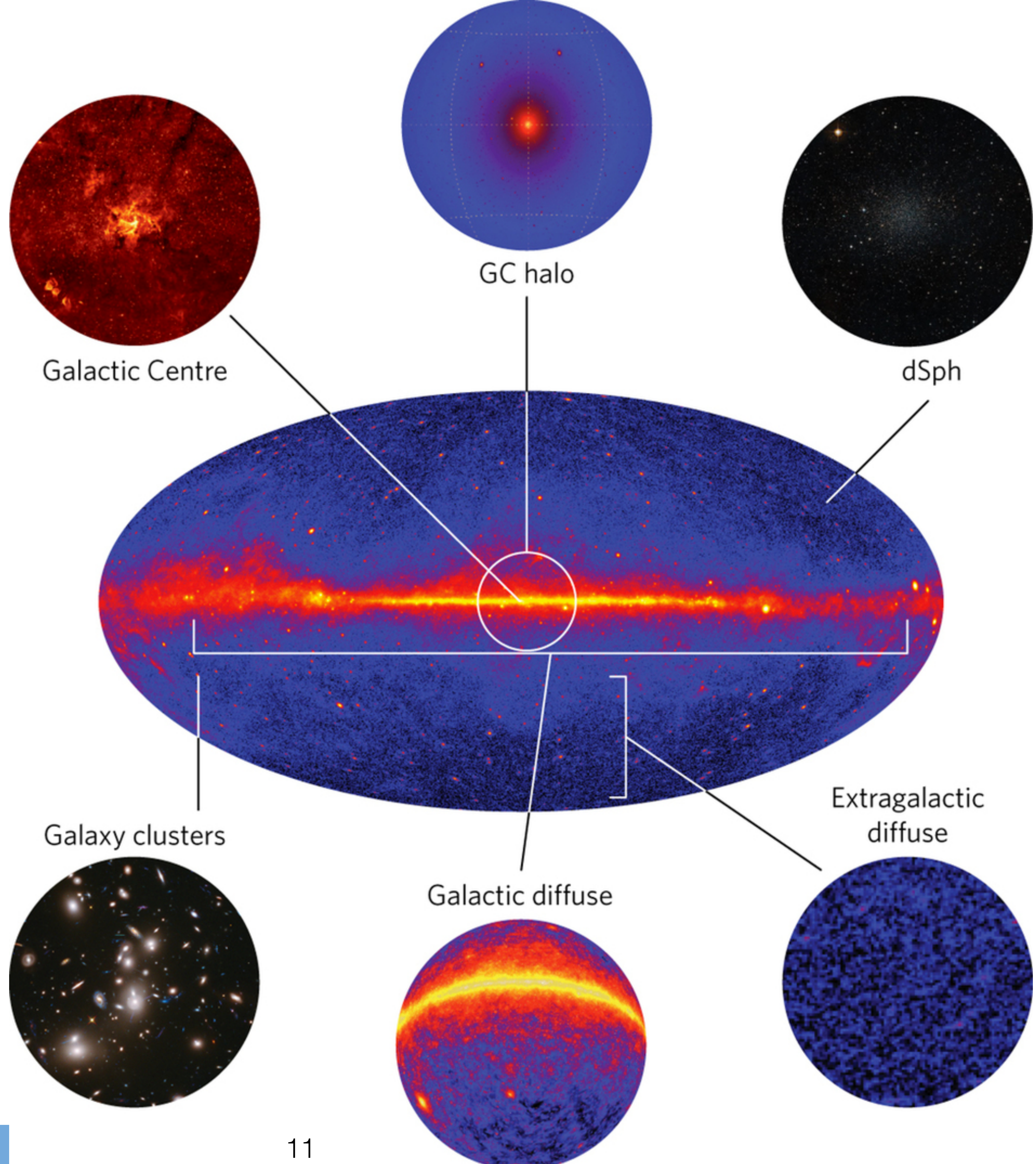
Targets for dark matter gamma-ray searches



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

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

Conrad & Reimer
Nature Phys. 13 (2017)



Dwarf spheroidal galaxies

Target:

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

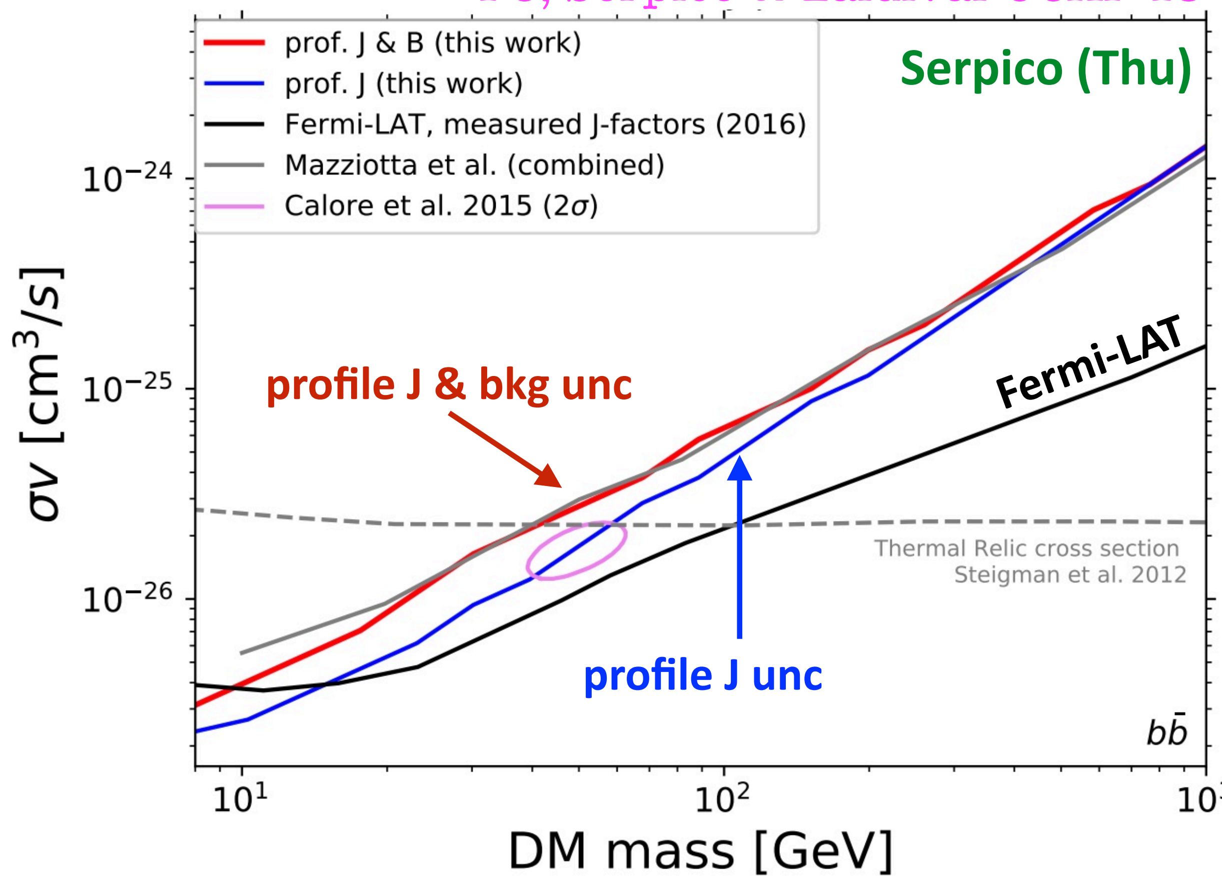
Status:

- 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

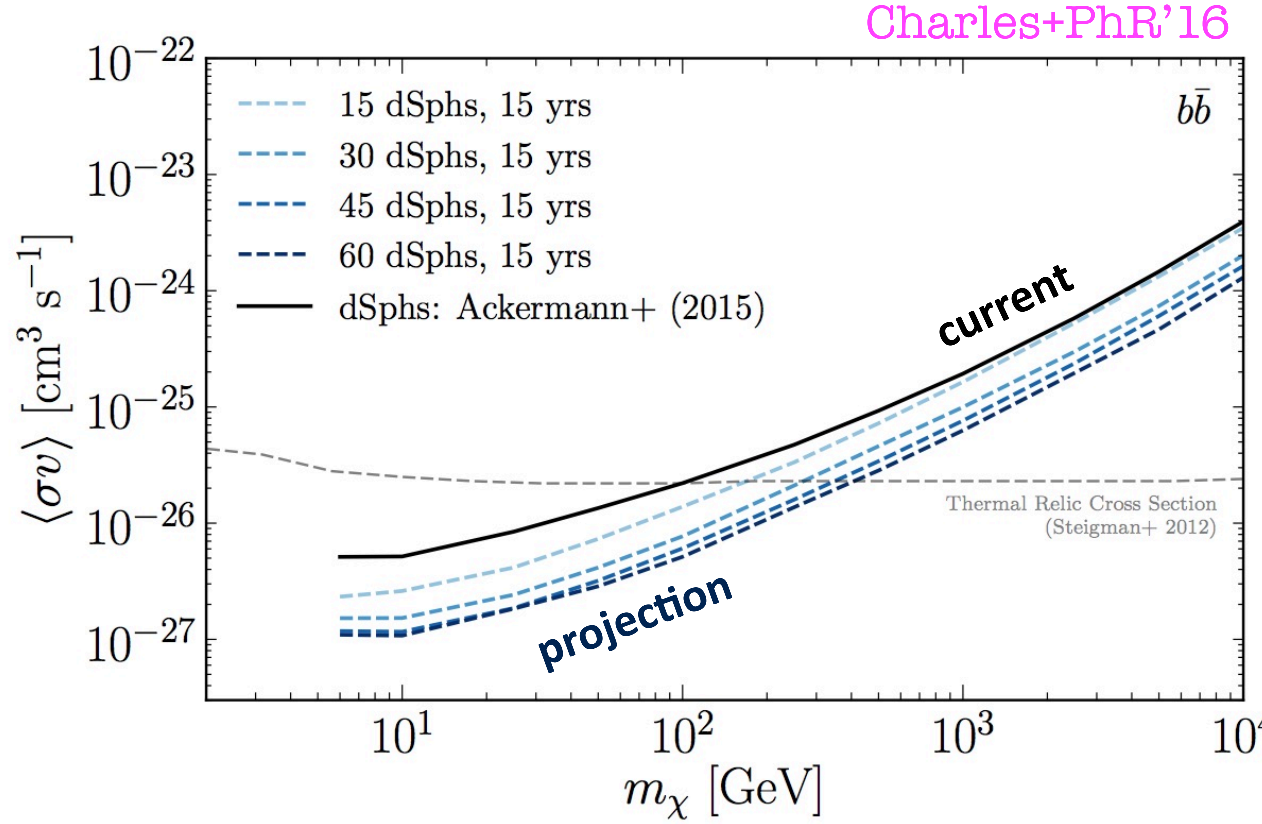
Future:

- 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 JCAP'18



Charles+PhR'16



Dark matter subhaloes

Target:

- DM subhaloes (**dark satellites**) searches: strong gravitational lensing (Vegetti+ Nature'12), star stream gaps (Carlberg ApJ'12)
- Gamma rays: look for subhalo candidates in Fermi-LAT **unassociated sources**

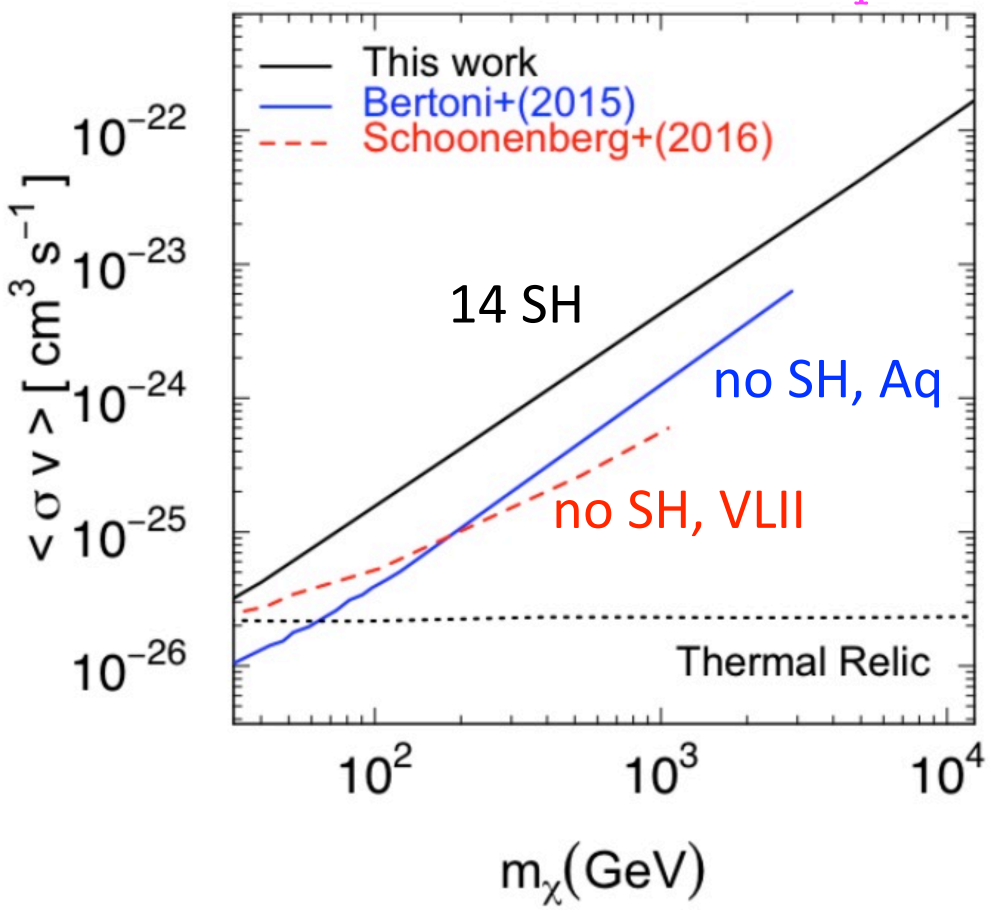
Status:

- Machine learning algorithms are excellent tools to identify SH candidates Mirabal+ ApJ'16; Saz Parkinson+ ApJ'17; Salvetti+ MNRAS'17
- The realistic estimation of the LAT sensitivity to the DM subhalo population from hydrodynamic simulations is crucial (th. unc) FC+ PRD'17

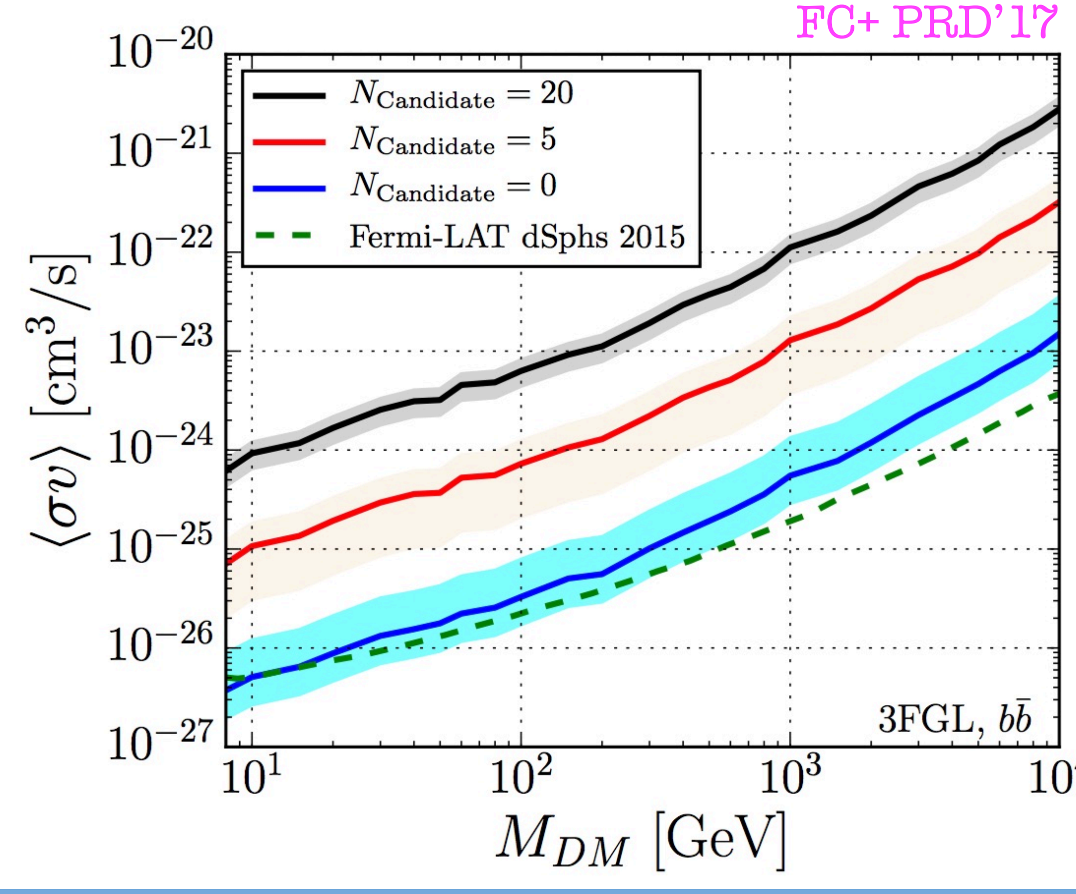
Future:

- CTA sensitivity in the extragalactic survey comparable to CTA dSPhs sensitivity Hütten+ JCAP'16
- **Follow-up observations** of point sources crucial to reduce the number of SH candidates; e.g. search for nearby dSPhs towards Fermi-LAT (unIDs & extended) sources with **GAIA DR2** Ciucă, FC+ MNRAS'18

Mirabal+ ApJ'16

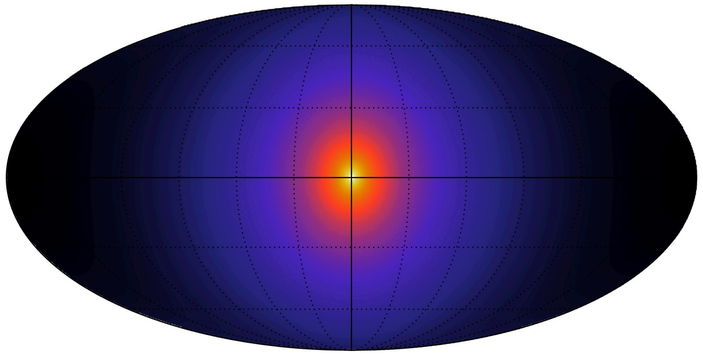


FC+ PRD'17

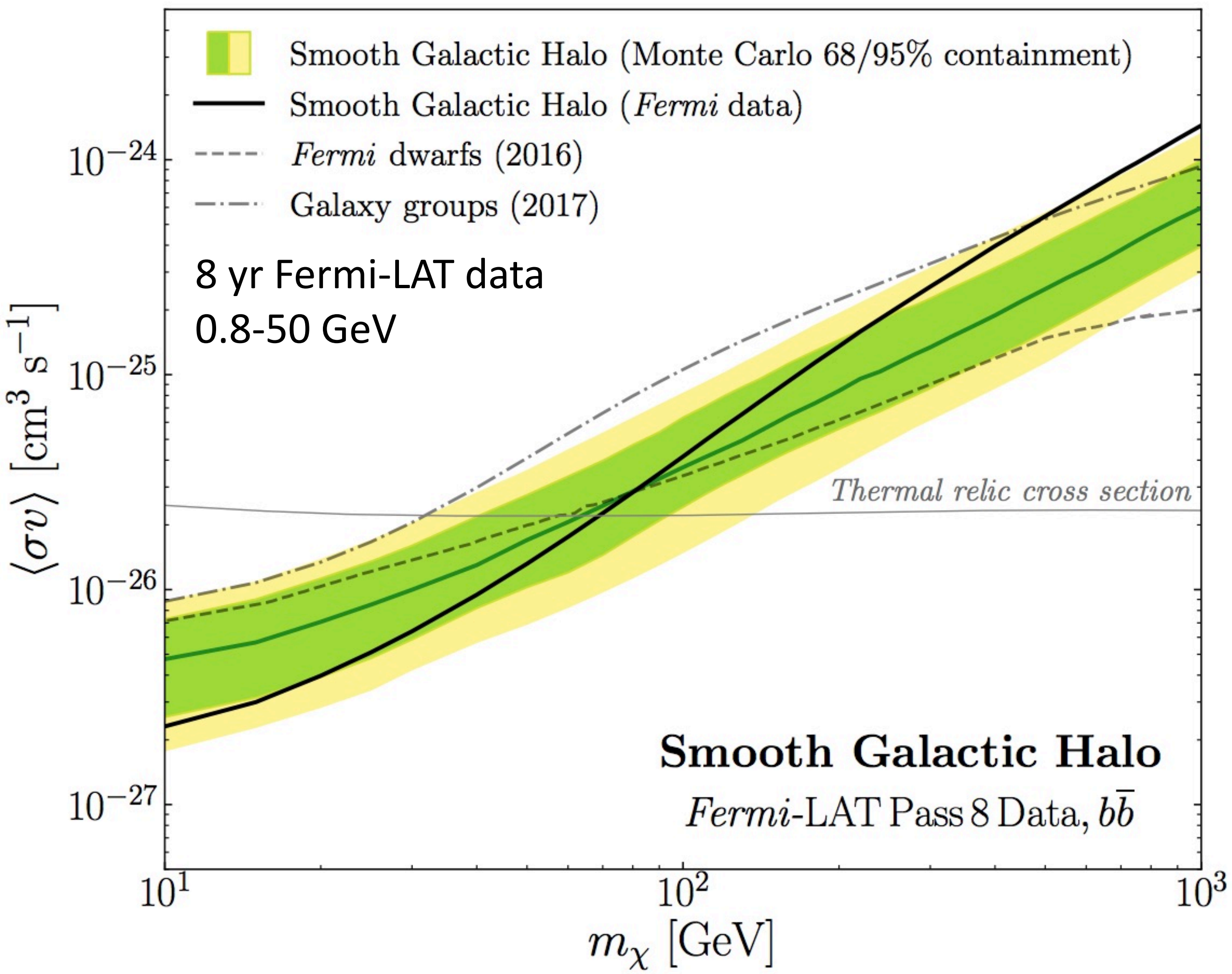


The high-latitude Milky Way halo

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



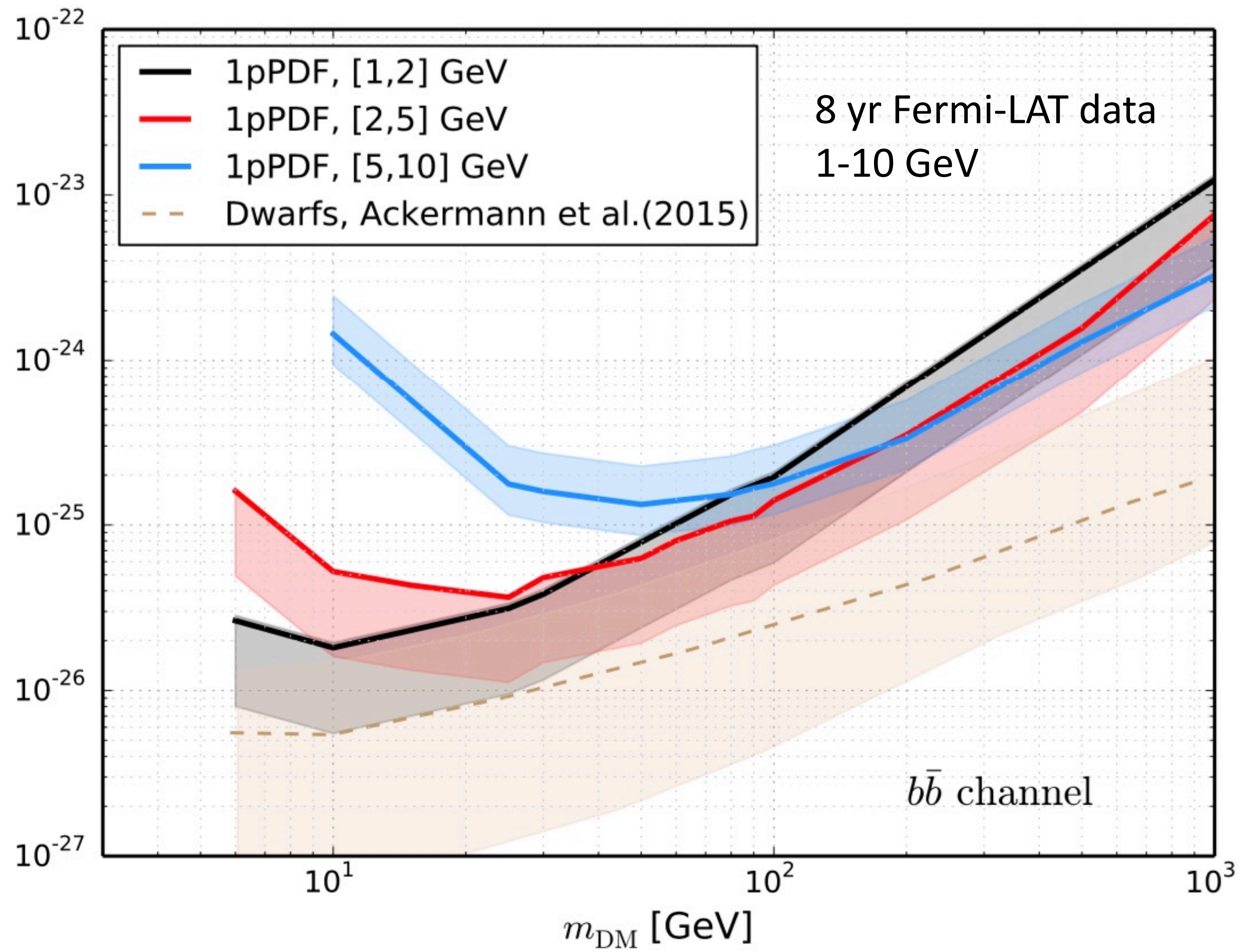
Template fitting



Chang+1804.04132

1-point Statistics

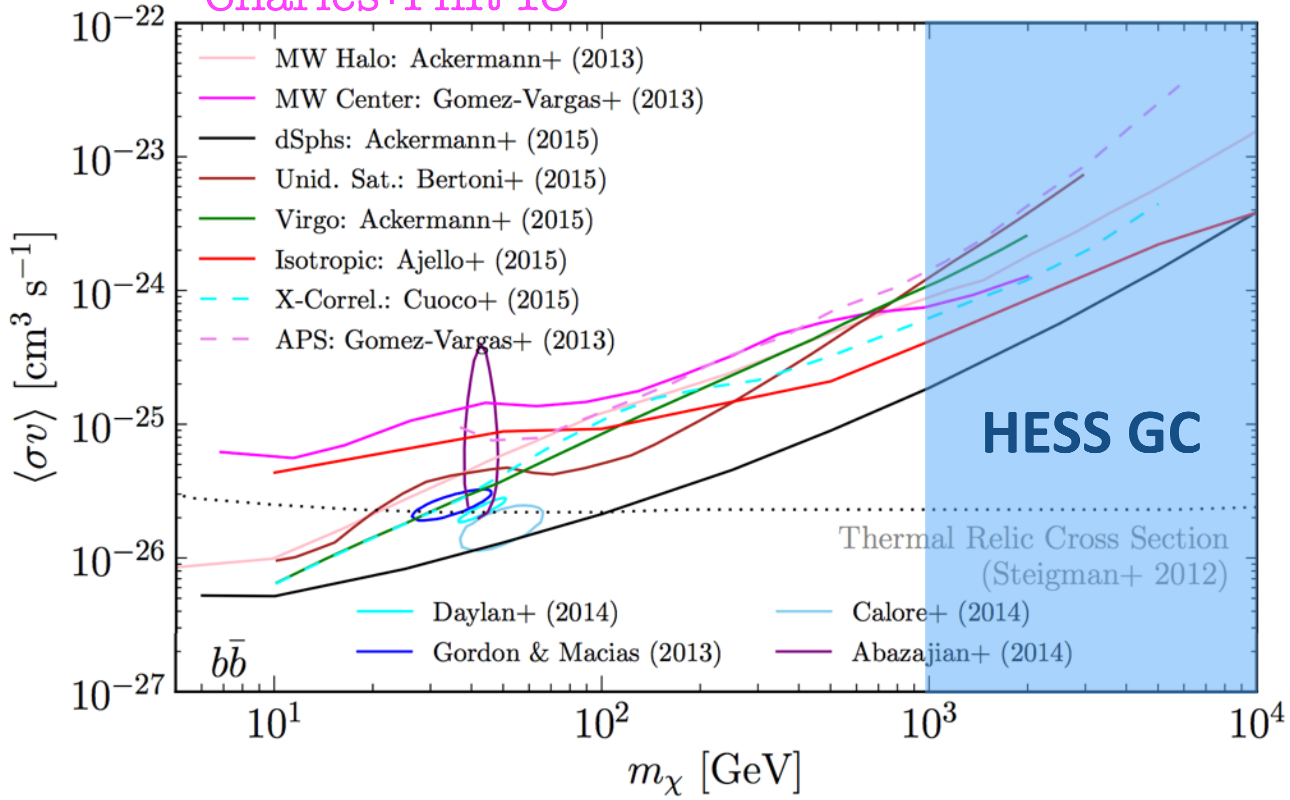
Malyshev+ApJ'11; Zechlin+ApJS'16, ApJL'16

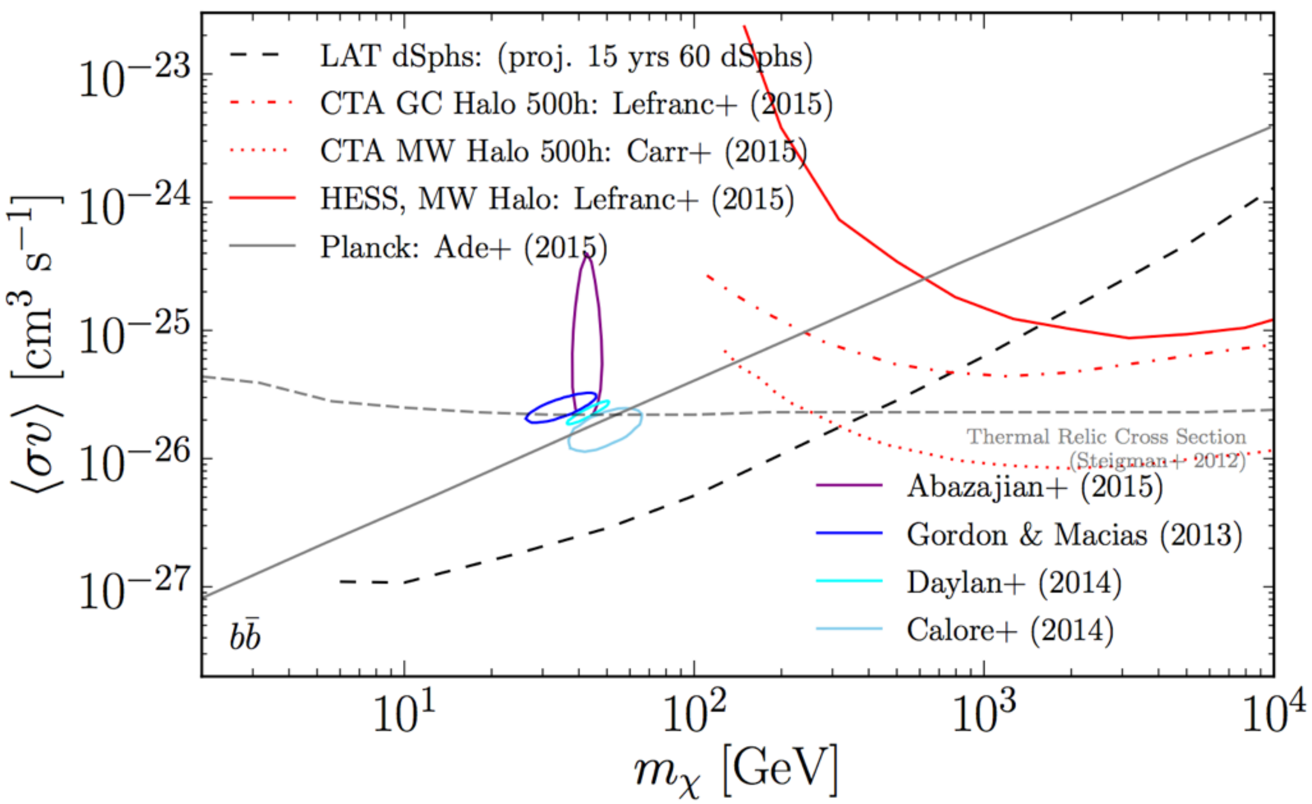


Zechlin+1710.01506

Multi-target constraints

Charles+PhR'16





Status

- Current limits from other Galactic and extragalactic targets
- Powerful limits from galaxy group catalogs

Lisanti+ PRD'18, PRL'18

[Combined targets: see talk by **Di Mauro (Thu)**]

Future

- **Fermi-LAT** limits improvement depends on target (syst., bkg or signal limited)
- **HAWC** will improve limits from observations of dwarfs and Galactic centre; **CTA** will improve **HESS** limits by factor up to 10.

Silverwood+ JCAP'15; Doro+ AP'13; Carr+ 2015; Lefranc+ PRD'15

- Great potential in the unexplored MeV/sub-GeV range (e.g. **Amego**; **e-ASTROGAM**)

Bringmann+PRD'17; Bartels+2017

[CTA: see talk by **Zaharijas (Thu)**]

Beyond limits …
… Hints for dark matter signals?

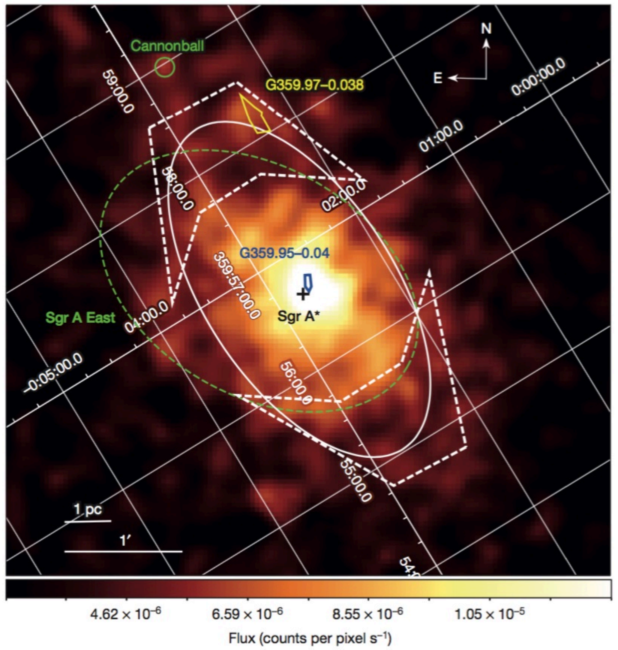
Beyond limits …

… Hints for dark matter signals?

aka: What anomalies in the gamma-ray sky?

Some gamma-ray anomalies in the GC region

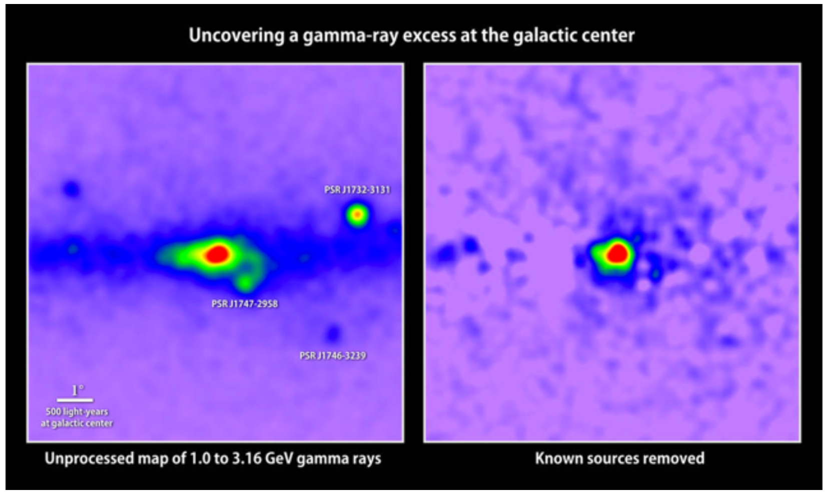
Perez+Nature'15

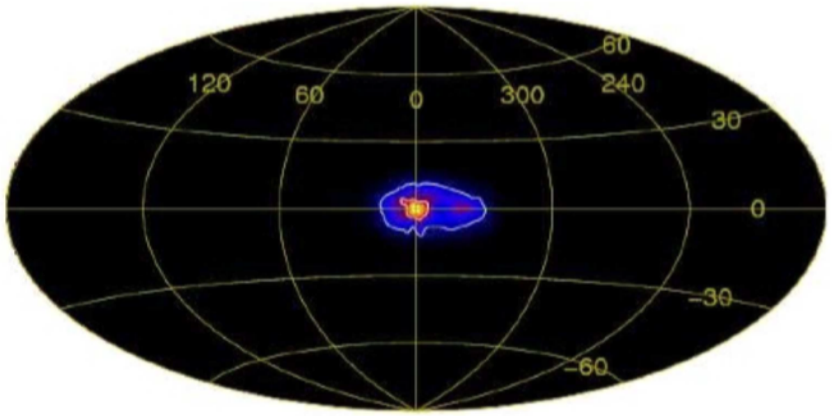


X-ray @ 20-40 keV
NuSTAR
hard diffuse excess emission

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

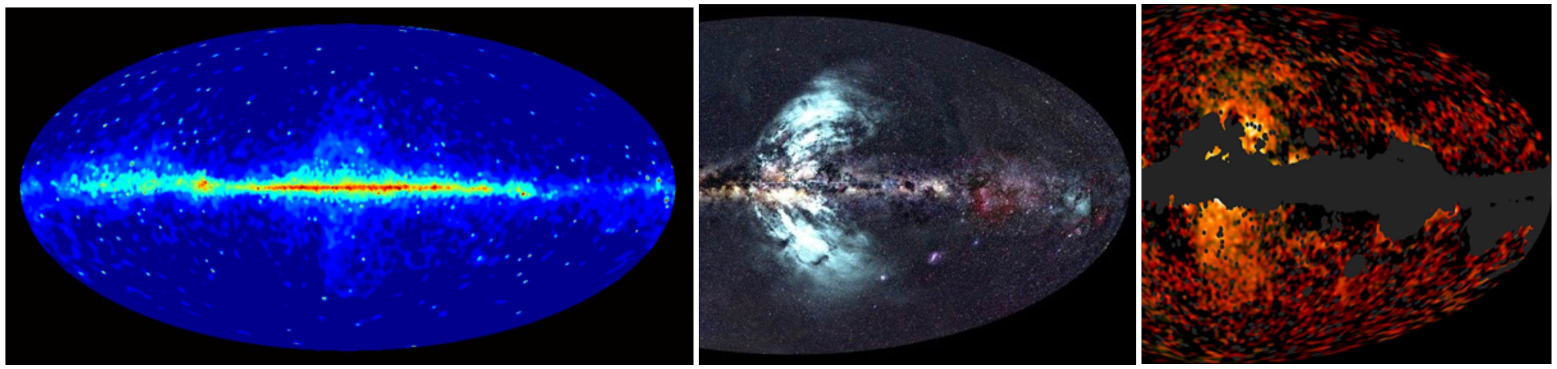
Daylan+PRD'16





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



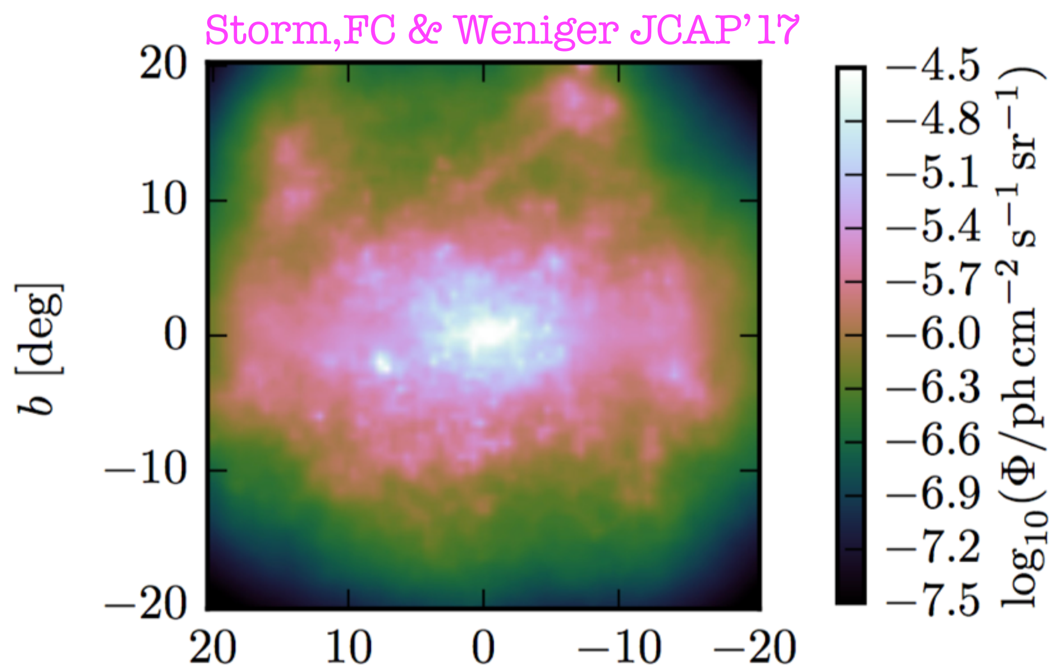
Gamma-ray @ hundreds GeV
Fermi-LAT
Fermi bubbles, and their **radio/ microwave** conterparts

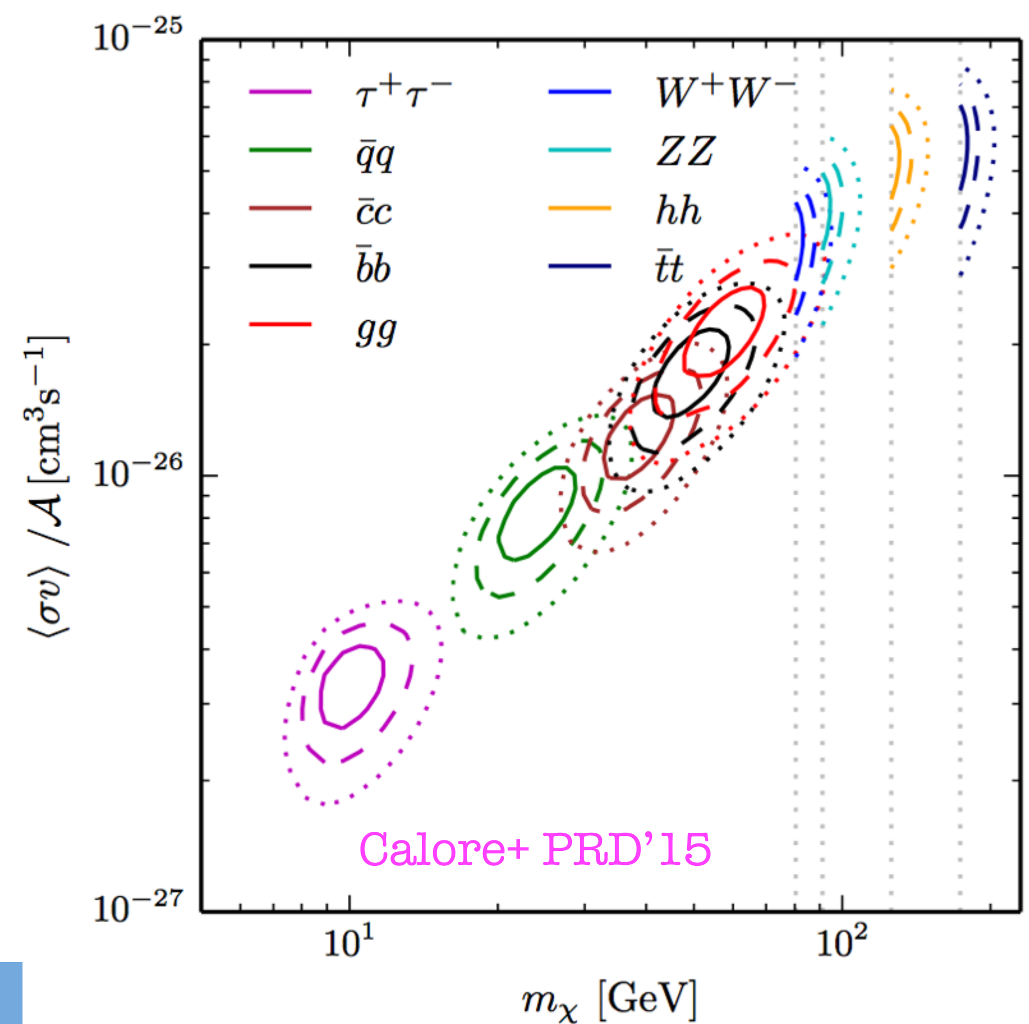
Excesses extended far well beyond central CMZ and nuclear bulge

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

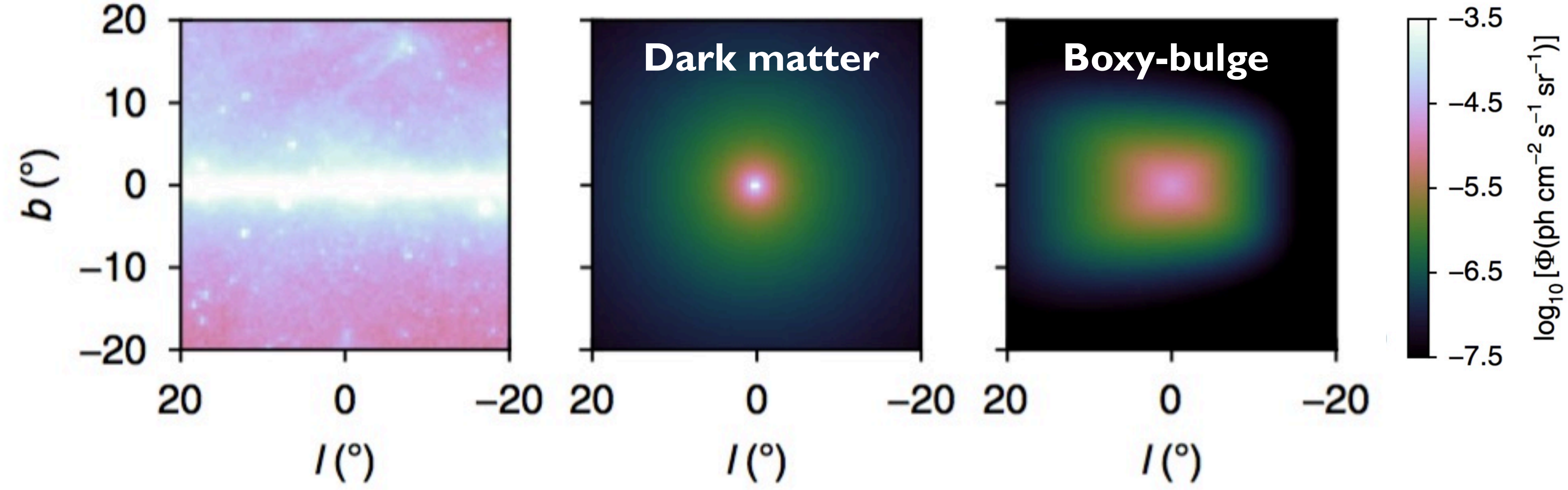


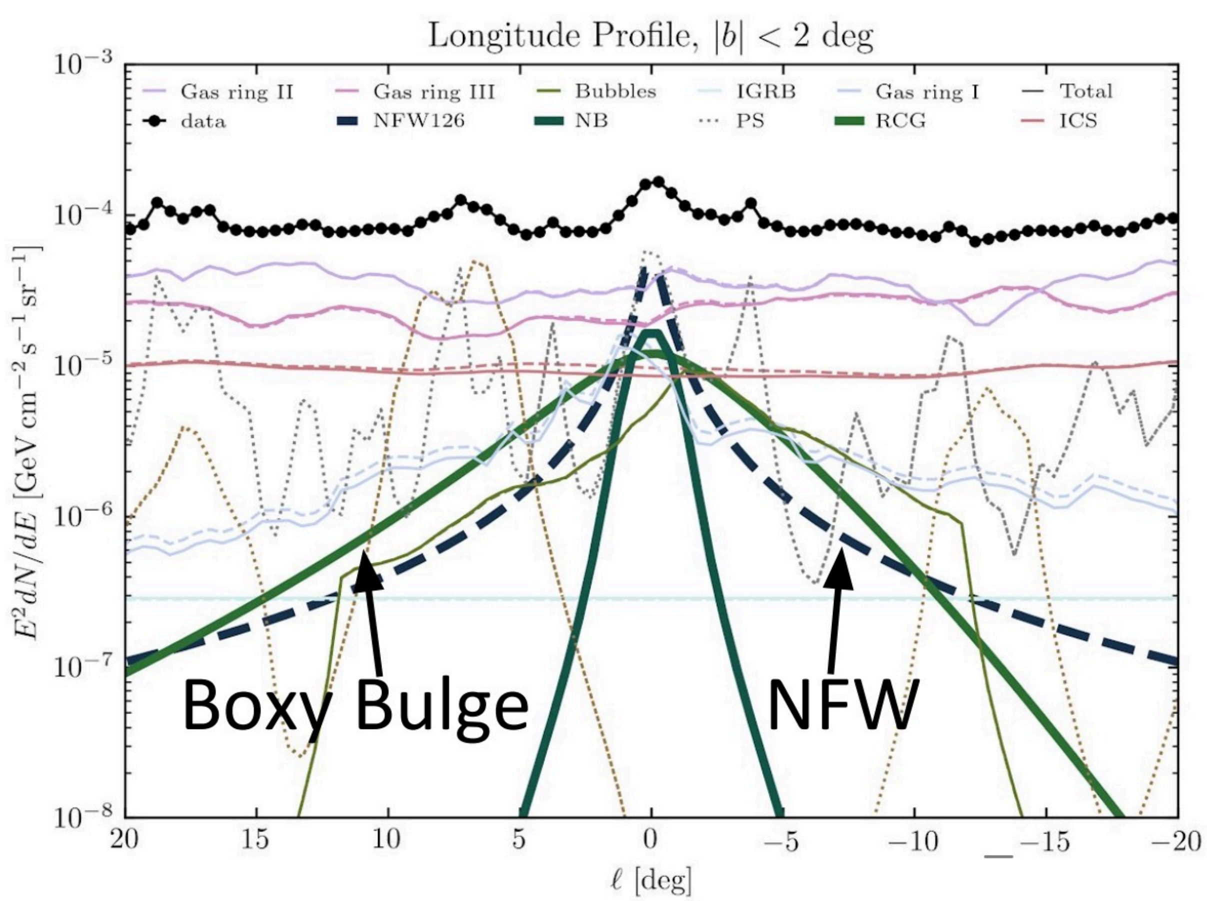


**Some Refs. since 2009: Hooper&Goodenough '09; Vitale&Morselli '09; Abazajian&Kaplinghat PRD'12; de Boer+'16; Macias+'16; Hooper&Slatyer PDU'13; Huang+ JCAP'13; Zhou+ PRD'15; Daylan+ '14; Calore+ JCAP'15; Gaggero+ 2015; Ajello+ 2015; Huang+JCAP '15; Linden+PRD'16; Horiuchi+'16; Ackermann+ApJ'17; Ackermann+2017

Evidence for stellar bulge emission

Bartels,FC+ Nature Astronomy'18



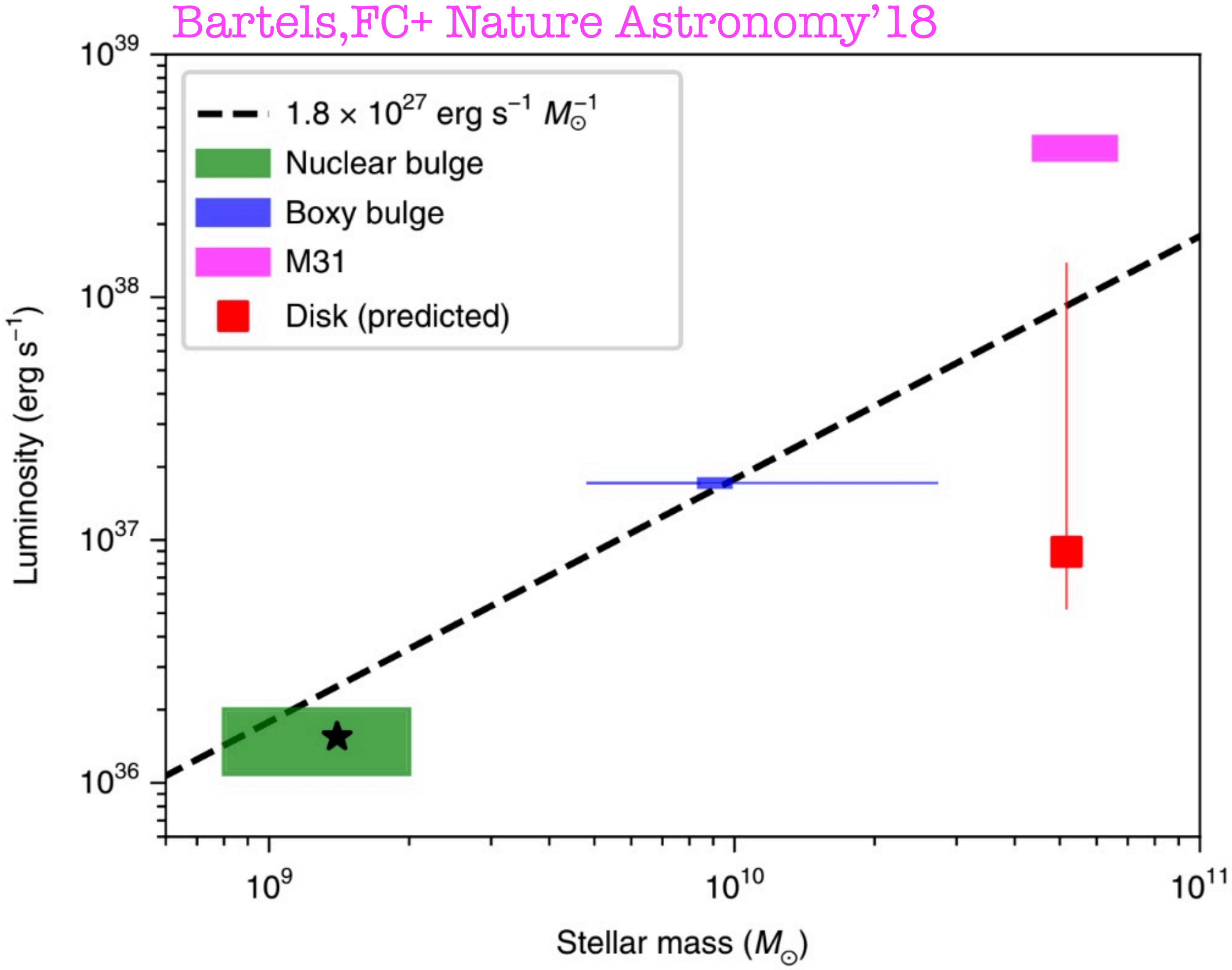


- ✓ **Stellar bulge model** (boxy + nuclear bulge) is **preferred** over (spherically symmetric) DM models with high statistical significance (16σ)
- ✓ **Morphology** of the GCE is **more oblate** than what found before
- ✓ Large enough ROI to discriminate foreground components (stable results)

[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

[M31: see talk by **Hou (Thu)**]

→ 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?

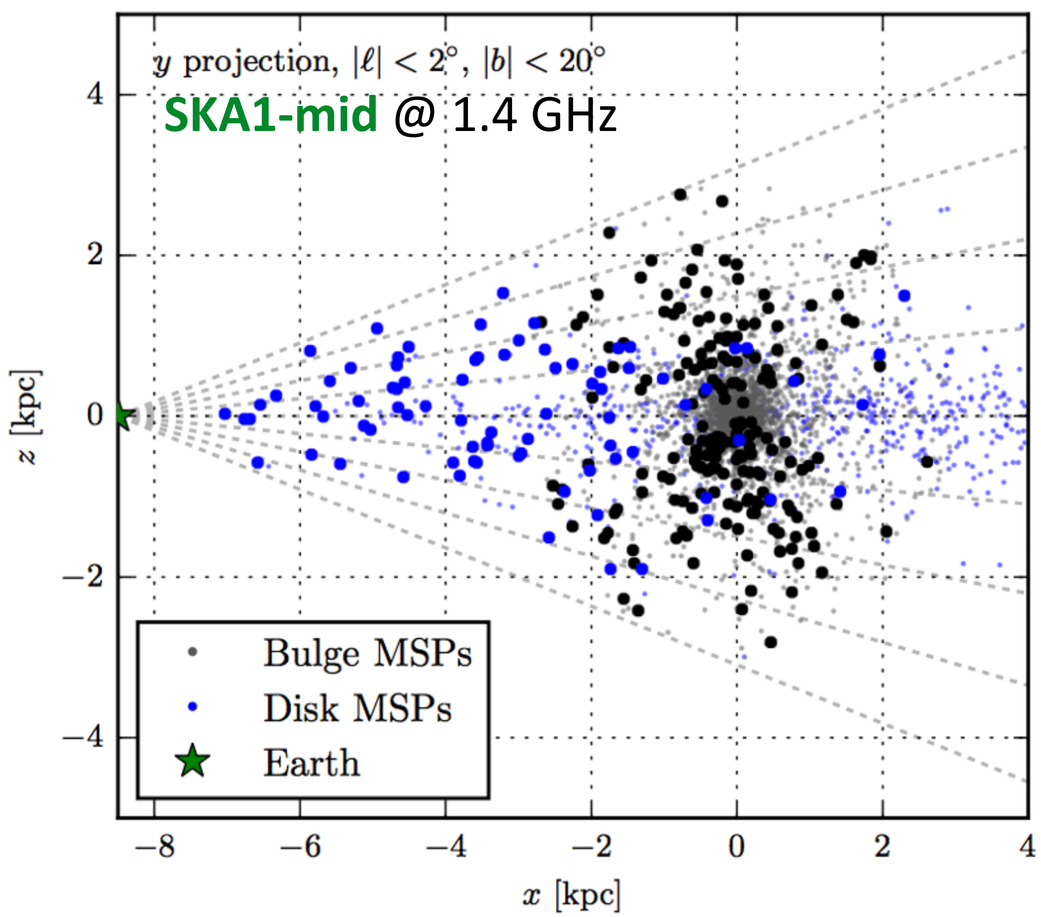
  Dogiel+ 1810.05821
- Connection with TeV diffuse emission from the GC?

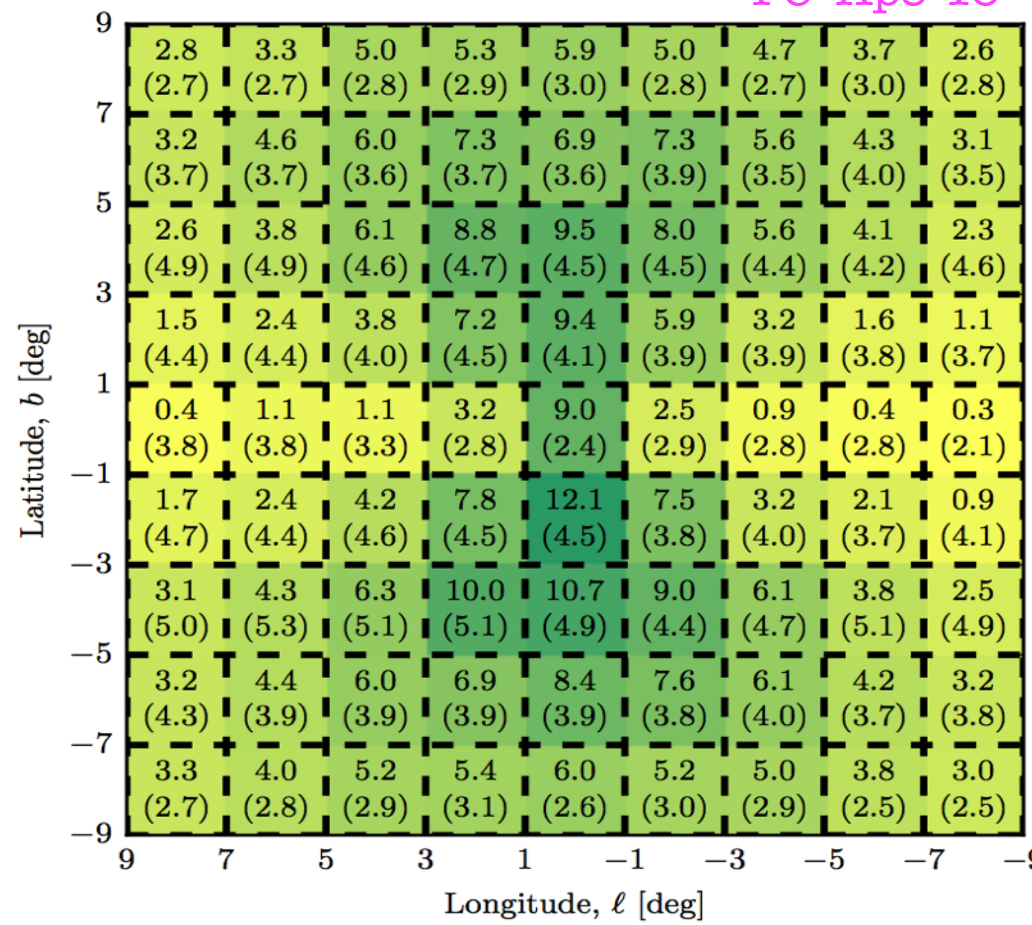
  Hooper&Linden PRD'18; Guepin+ JCAP'18
- Connection with 511 keV positron annihilation line?

  Crocker+ Nature Astronomy'17; Bartels,FC+ MNRAS'18

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

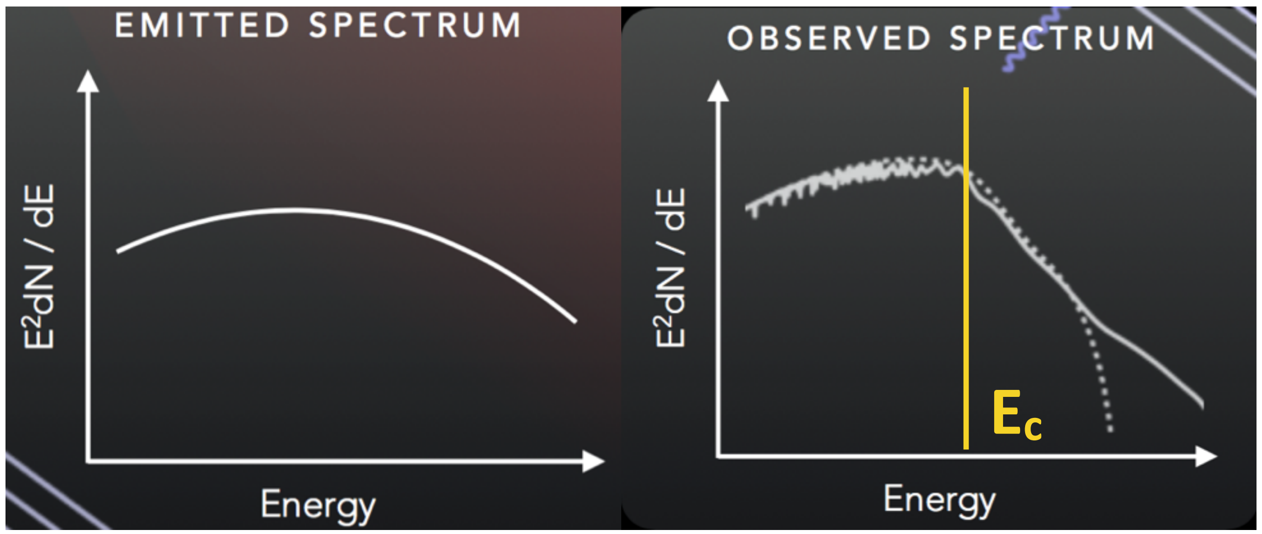
➡ With future dedicated observations we can **discover this MSP bulge population**.
➡ We need observation time (Fermi GI Proposals, TRAPUM MeerKAT lecagy, etc.)

[Talks by **Ray (Tue), Kerr (Wed), Sanpa-arsa (Wed)**]

Beyond WIMPs with the Fermi-LAT

ALPs: gamma-ray spectral distorsions

Photon-ALPs oscillation in external and Galactic magnetic fields, due to mixing between ALPs and photon polarization along field direction



Credit: M. Meyer

1) Reduced absorption (EBL)
2) Oscillations below critical energy

Csaki et al. 2003; De Angelis et al. 2007,2011; Mirizzi et al. 2007; Hooper & Serpico, 2007; Abramowski et al. 2013; Wouters & Brun 2013; M.Meyer et al. 2013, 2014

[Talk by **Prescod-Weinstein (Thu)**]

ALPs: gamma-ray spectral distorsions

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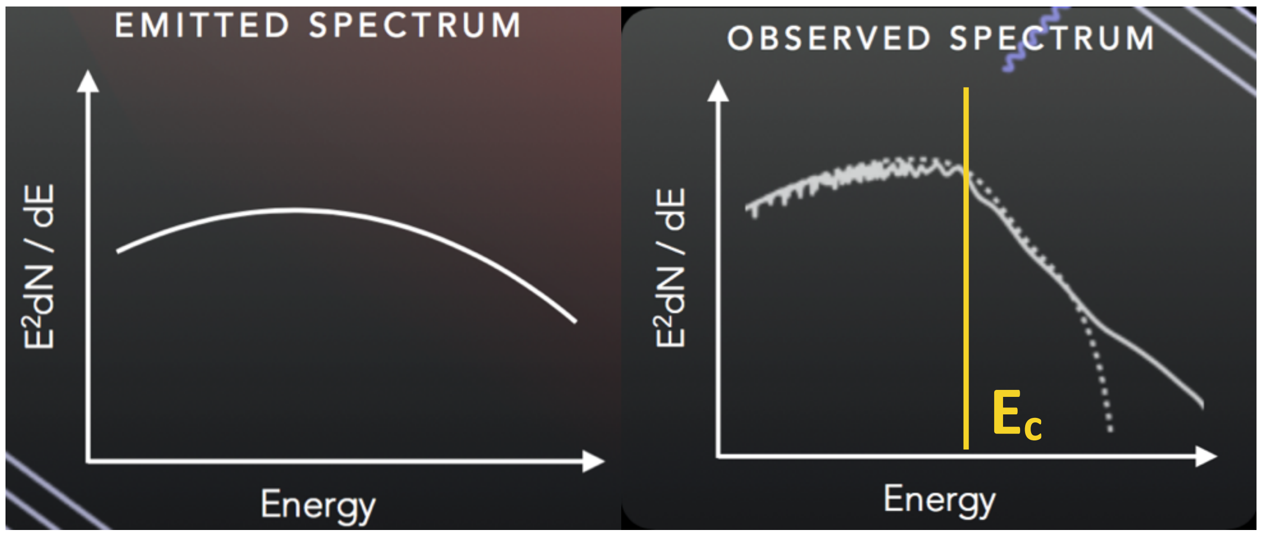

Credit: M. Meyer

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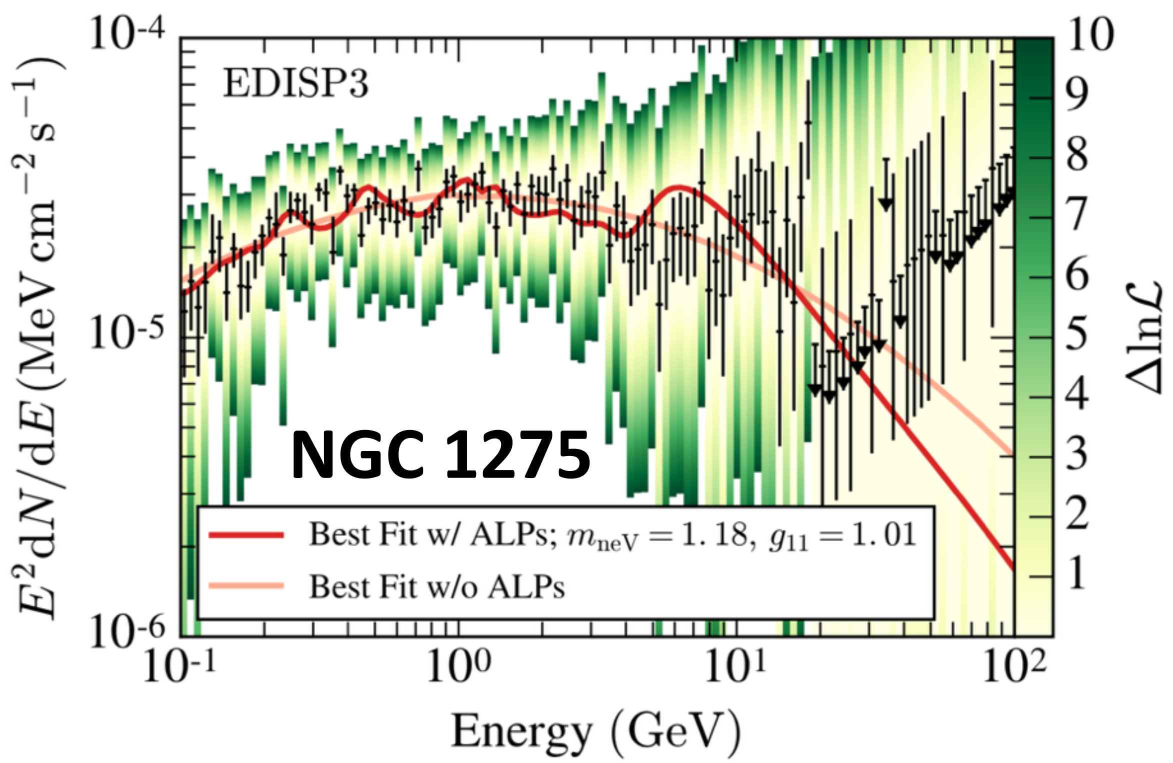
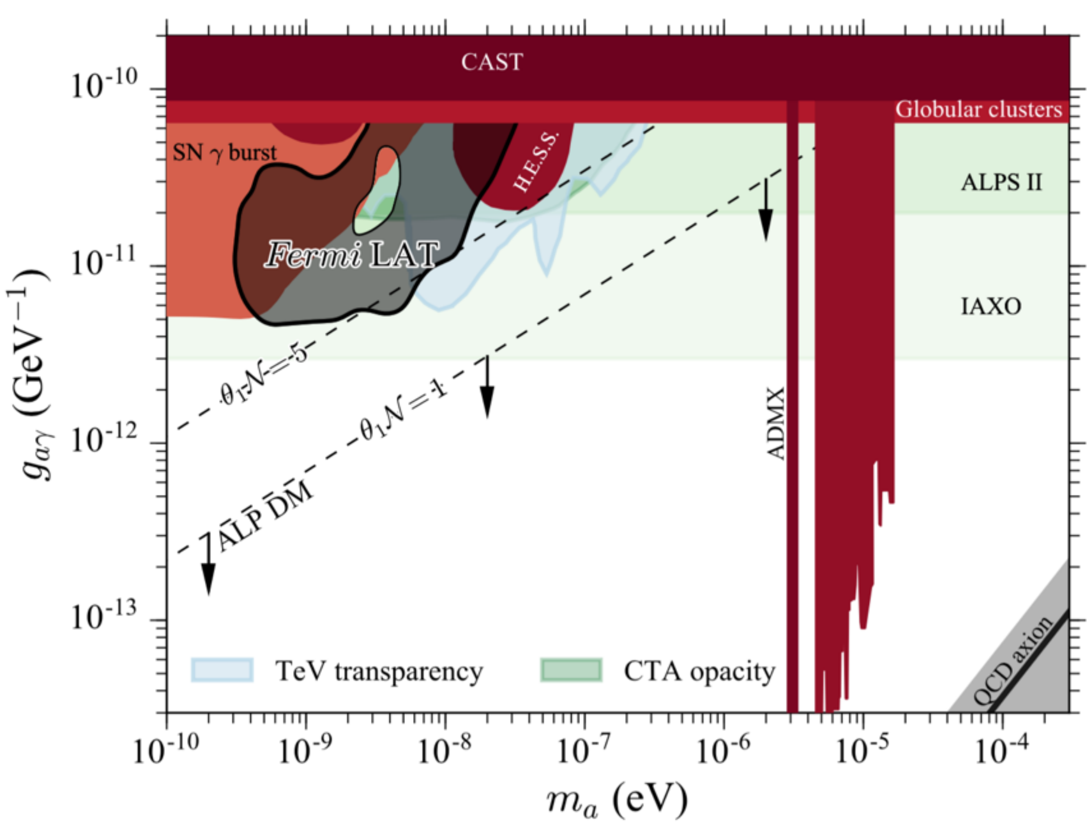


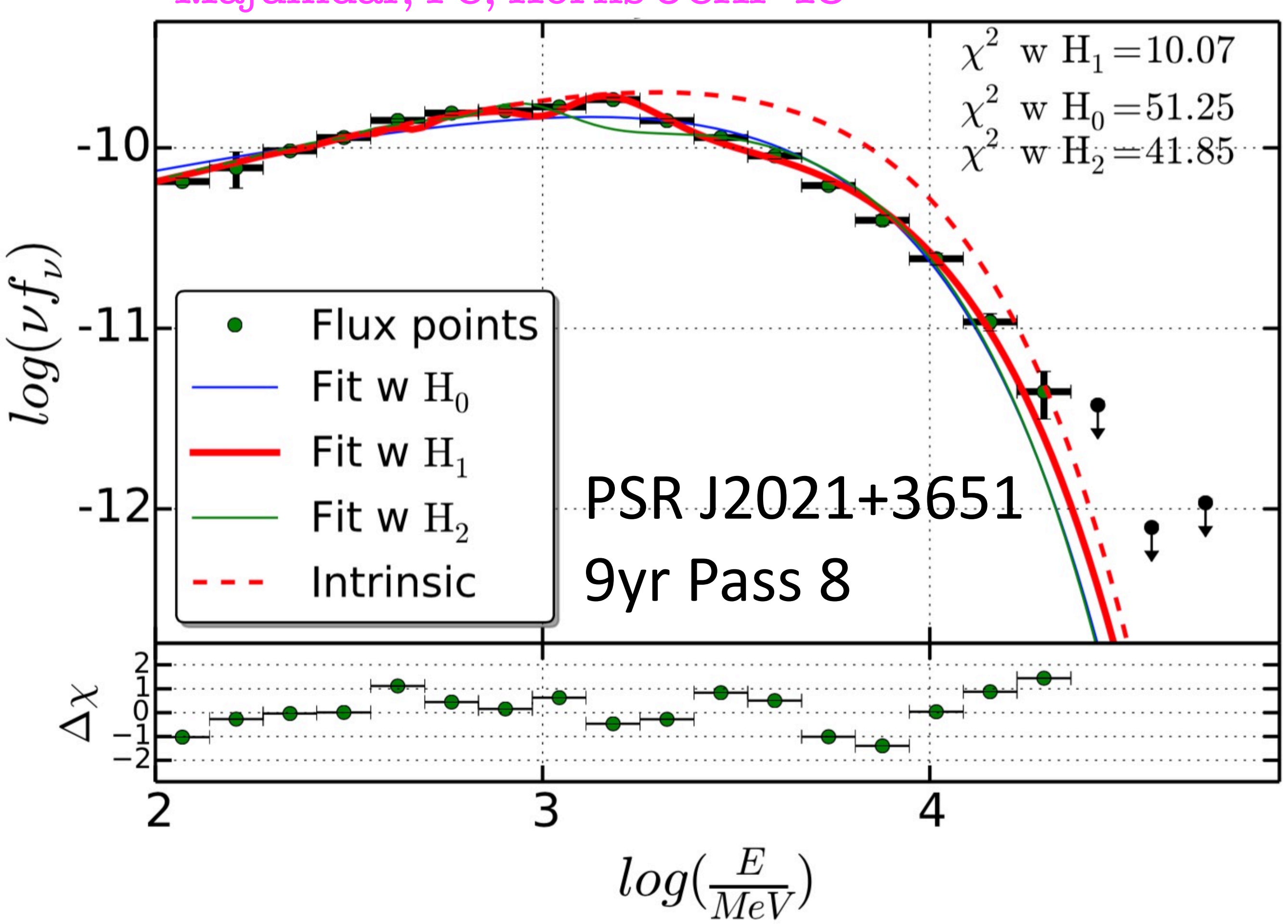


Fermi-LAT Collab. PRL'16; Malyshev+1805.04388

ALPs in Galactic sources

- At **Galactic scales** oscillations can be relevant at **GeV energies**
- Search for oscillation features in the disappearance channel from 6 bright Galactic pulsars
- Oscillations features enhanced for sources at large distance and in the l.o.s. with high transversal B-field (conversion in large-scale regular B-field component)

Majumdar, FC, Horns JCAP'18



✓ Significant fit improvement w/ ALPs: **4.6σ** significance for the combined fit

✓ 20%-40% spectral variation vs ~3% exper. syst. uncertainty (from Vela as control sample)

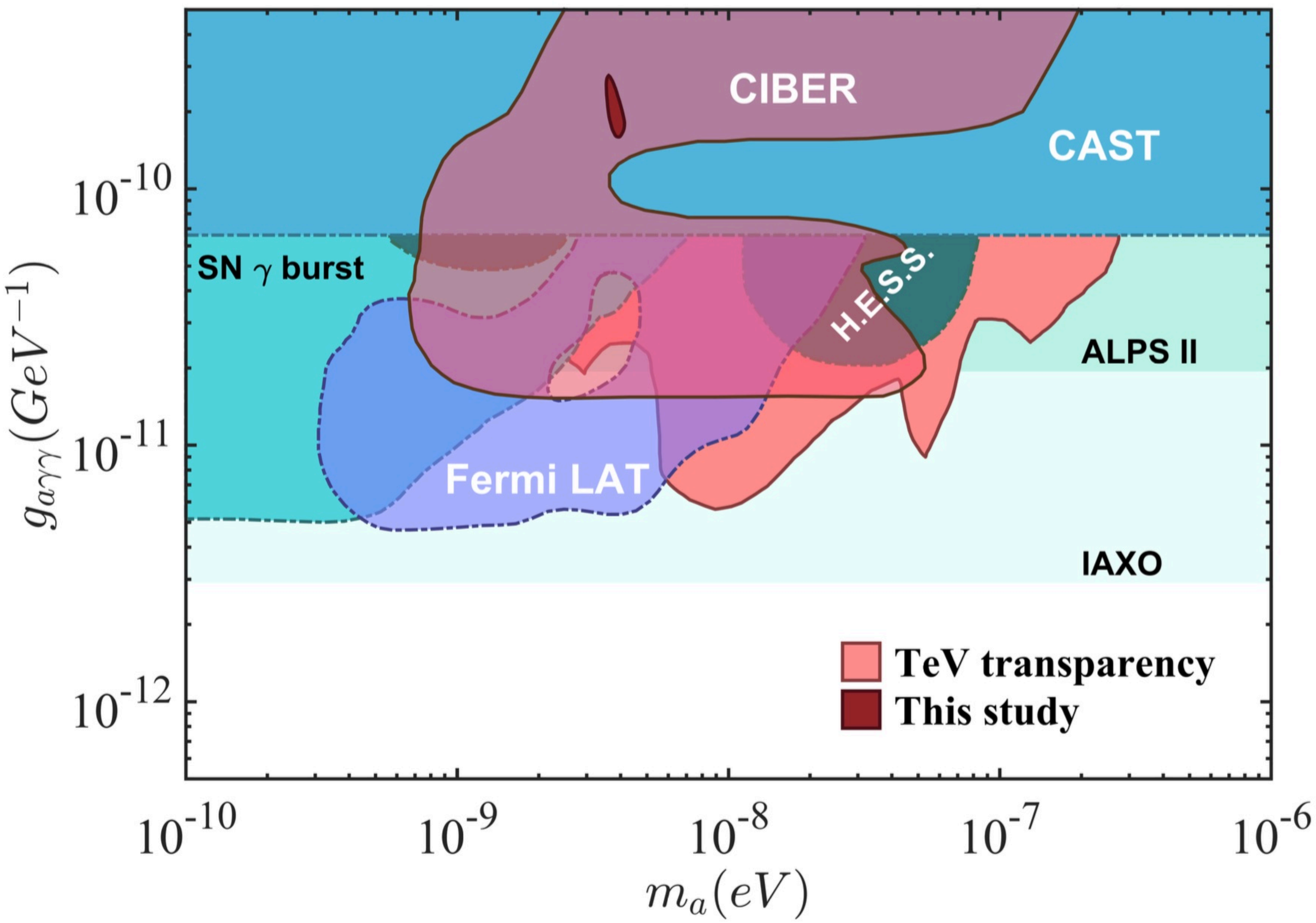
✓ Although, differences in mass and coupling for individual l.o.s. are not fully consistent

✓ Consistent results from SNR IC433

Xia+PRD'18

[See also talk by **Lloyd (Thu)**]

ALPs-photon coupling constraints



- Excluded by CAST limits and SN1987A CAST Collab+Nature Phys'17; Payez+JCAP'14
- Excluded by latest limits from NCG1275 Malyshev+1805.04388
- Consistent with TeV trasparency lower-limit and CIBER contours Meyer+PRD'13; Kohri & Kodama PRD'17

How to relieve the tension?

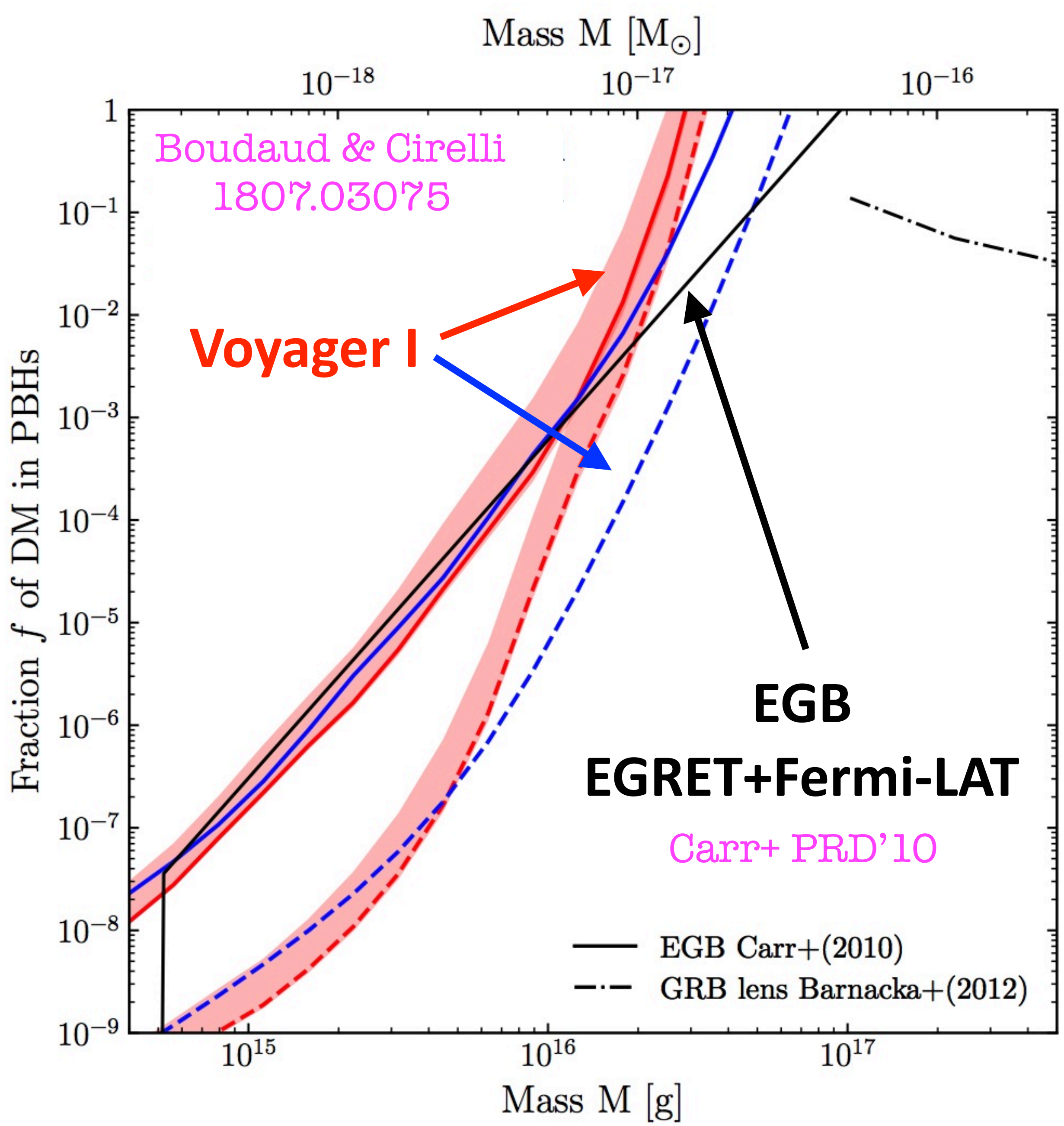
✓ **Plasma/environment effects** can alleviate the tension with SN1987A/CAST limits Jaekel+PRD'07

✓ **Axion mediated dark-photon** mixing can also explain oscillations and the re-casted limits do not exclude the best-fit region Choi+1806.09508

Primordial black holes

- Extragalactic diffuse gamma-ray background can be used to constrain PBH which are evaporating at the present epoch (10^{14} - 10^{17} g)
- Spectrum of emitted particles is centered at MeV - a few GeV energies

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



✓ Extragalactic diffuse background limits on the mean cosmological number density

✓ Galactic diffuse background constrains PBH clustered in the Galactic halo (EGRET)

Lehoucq+ A&A'09

✓ Looking for moving Fermi-LAT sources with hard gamma-ray spectra (evaporation phase) probes the local PBH density

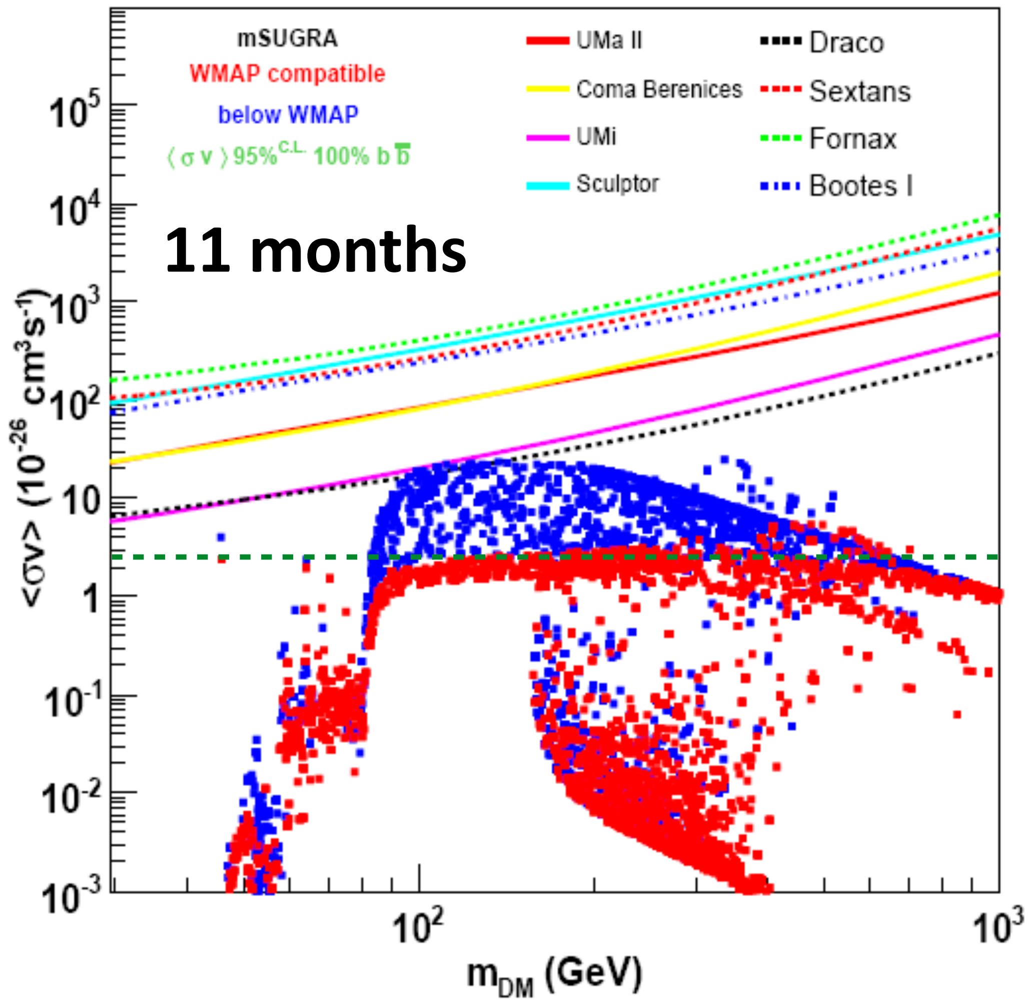
Fermi-LAT Clb ApJ'18

✓ Strongest constraints from Voyager I data

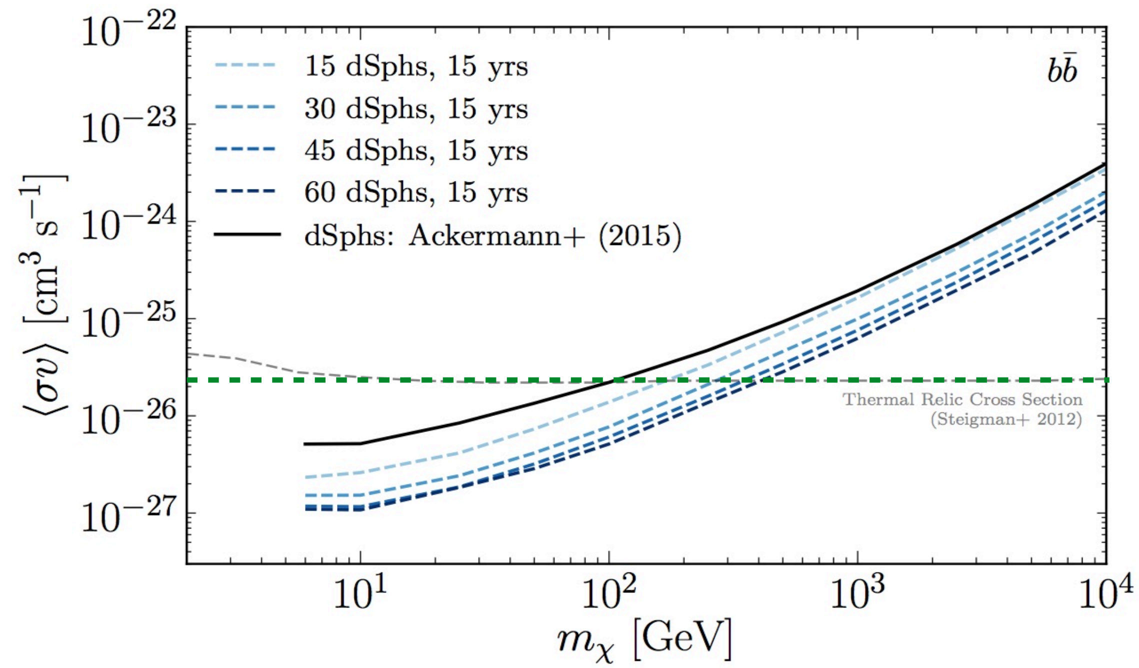
Boudaud & Cirelli 1807.03075

Conclusions & Outlook

Abdo+ ApJ'10



6 years



- ✓ The Fermi-LAT has truly made a **major leap forward in probing WIMP dark matter**, tantalising the termal cross-section for few GeV - 100 GeV masses
- ✓ Fermi-LAT data can be succesfully used to constrain non-WIMP dark matter models, e.g. ALPs, PBH

Conclusions & Outlook

- ✓ Current searches can be improved by exploiting the **complementarity with other wavelengths/messengers**, e.g. antiproton constraints; radio, X-rays and optical follow up of unassociated/faint sources; identification of more dSPhs galaxies with optical surveys

- ✓ **Synergy with future gamma-ray instruments** from sub-GeV to TeV energies will be crucial in reducing the contamination from astrophysical sources/ foregrounds

- ✓ **Exciting anomalies** do persist **in the gamma-ray sky** calling into question our standard frameworks for point-source and diffuse high-energy emission.

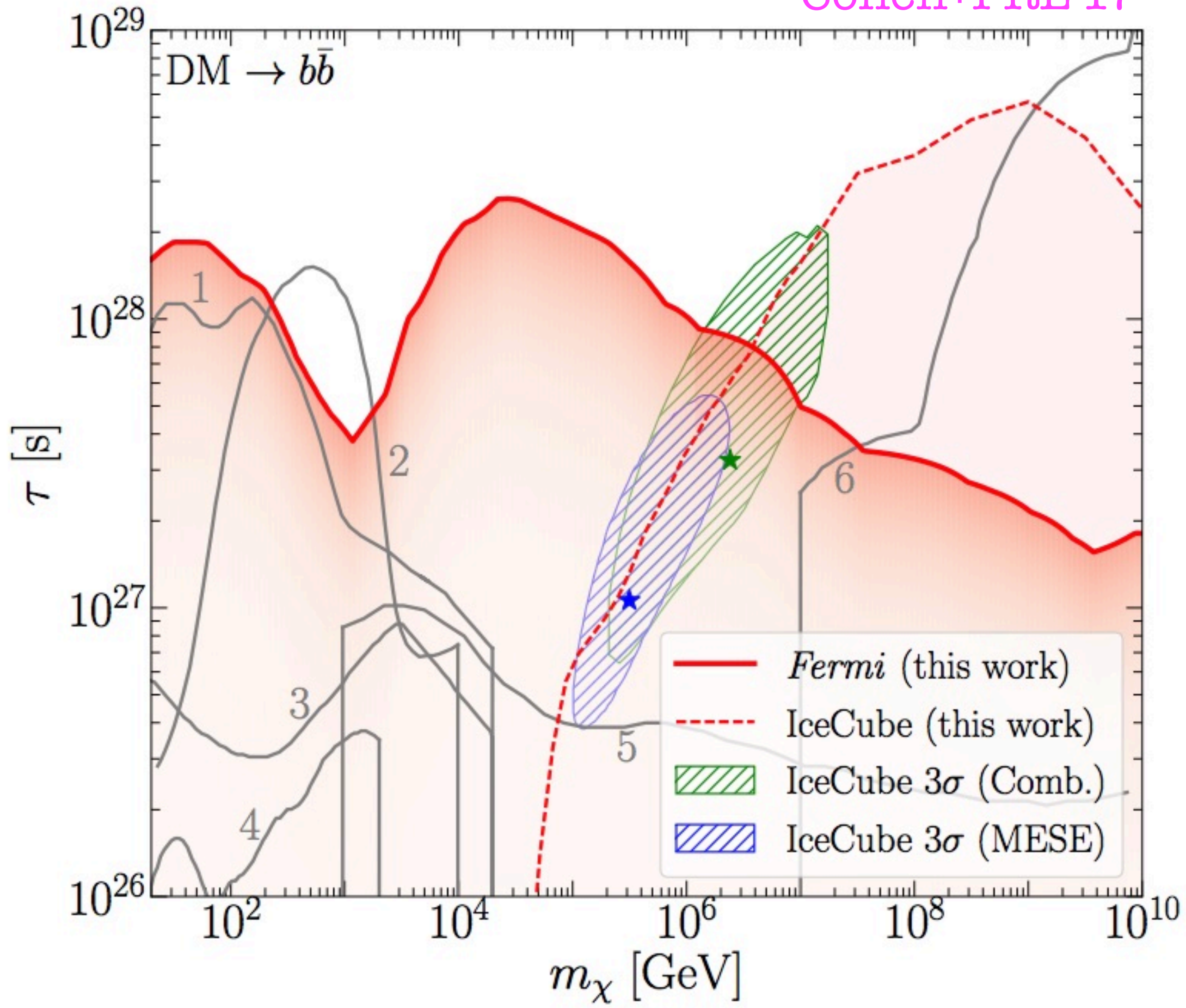
- ✓ **Fermi-LAT** can play a **leading role for dark matter searches** in the coming years if we exploit its great data e.g. to (a) reduce further theoretical model systematics; (b) improve the characterisation (and identification) of point sources

Backup slides

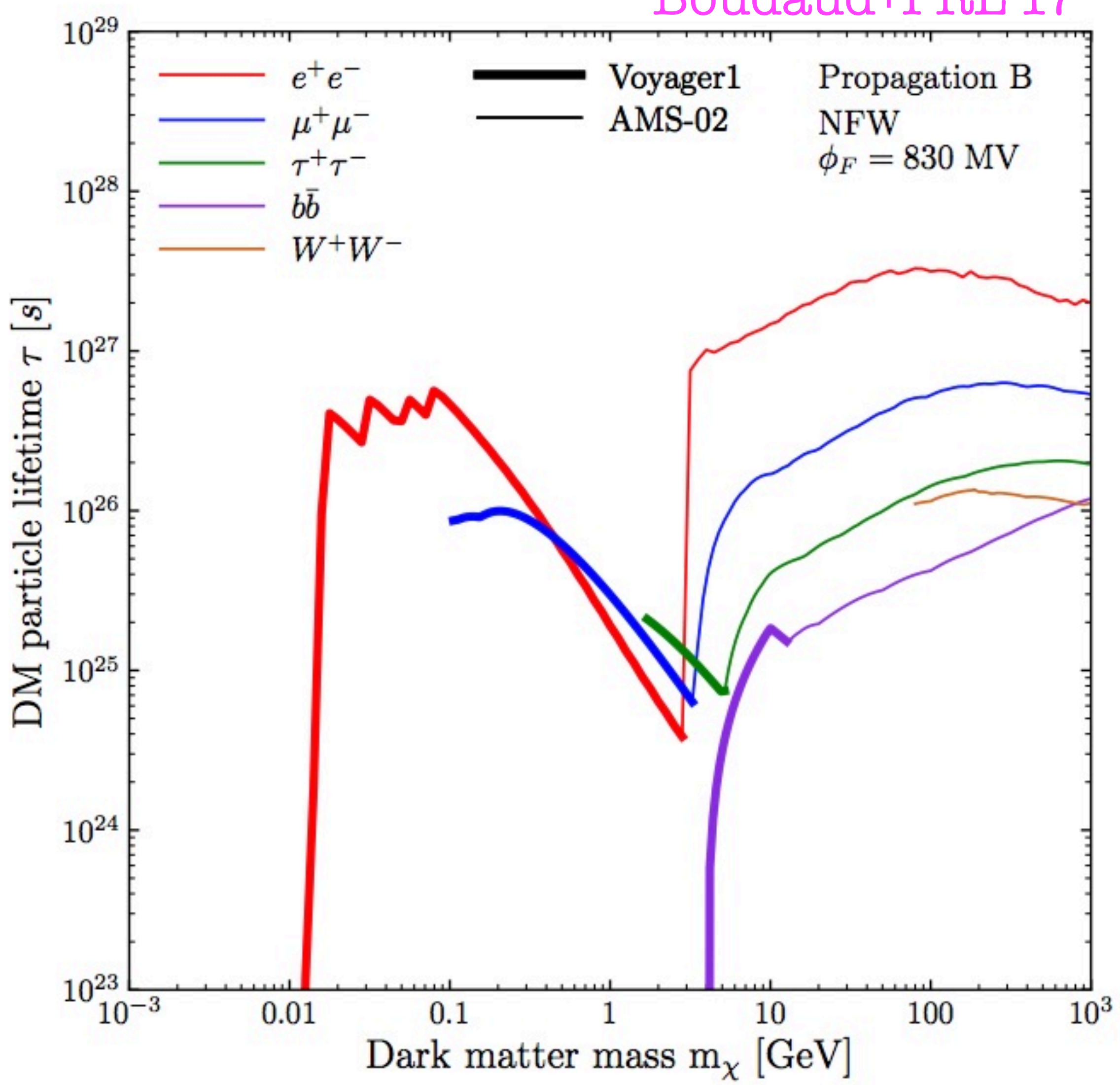
Status of decaying dark matter

- 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

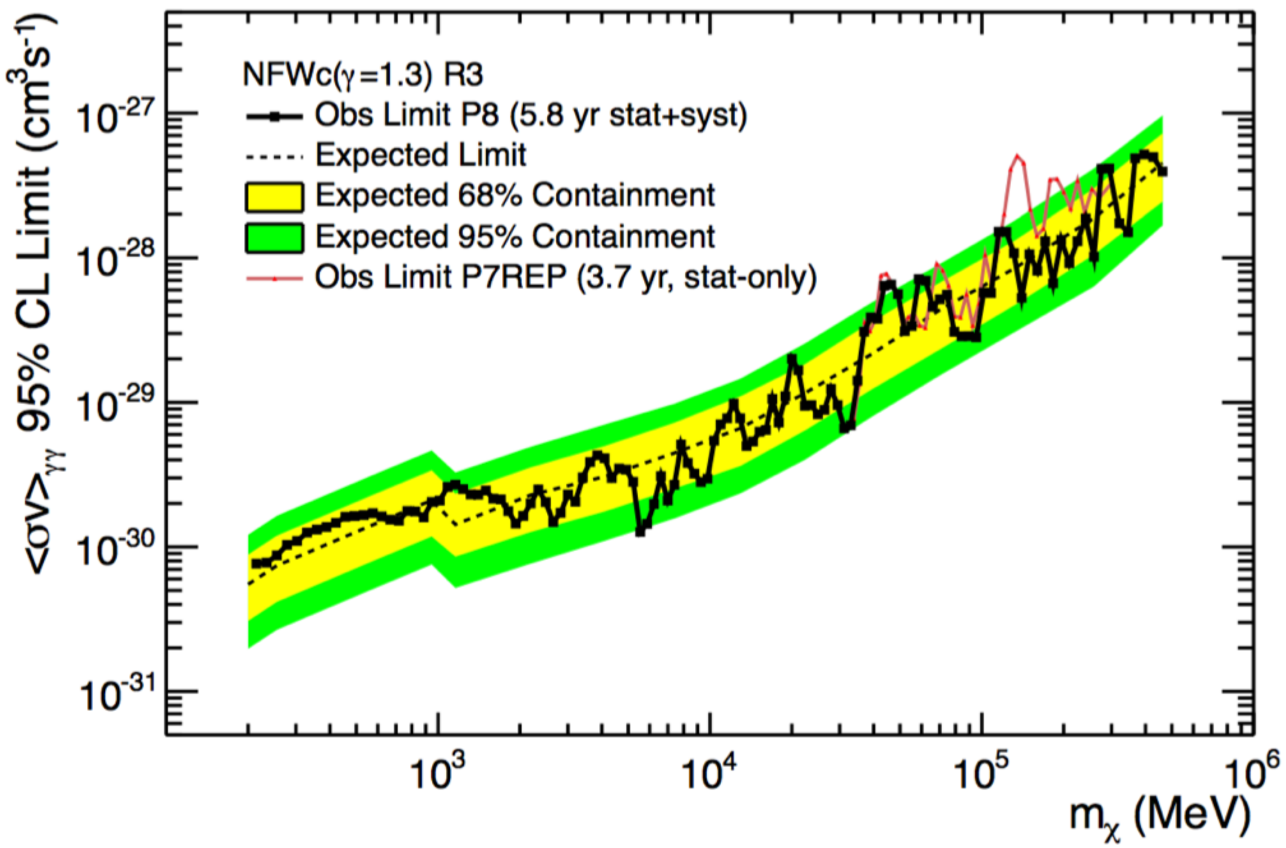


Decay lifetimes below ~10^{27-28} s ruled out for most final states and keV-EeV DM masses;

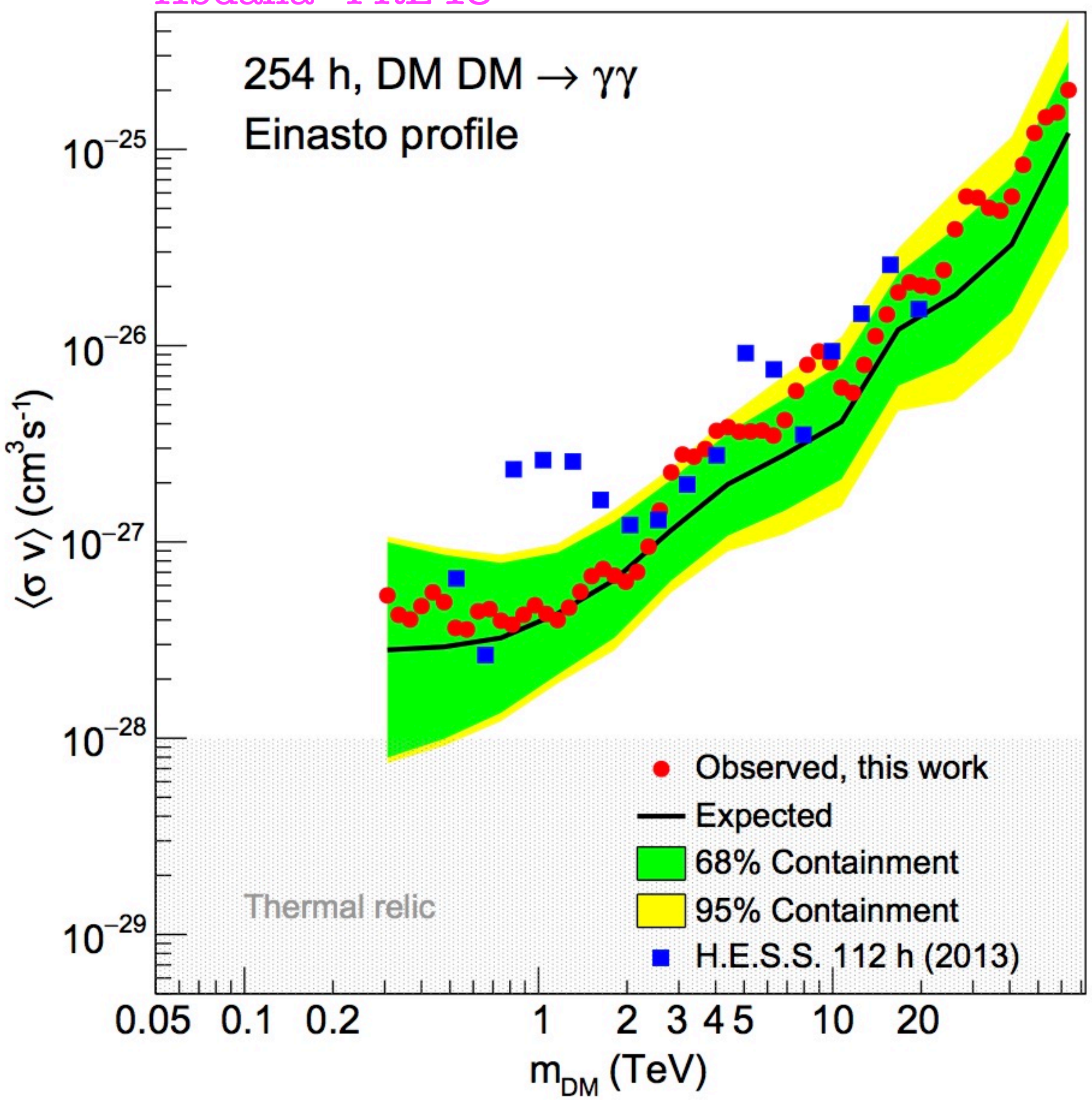
for few-MeV DM decaying to e+e-, lifetimes can be as short as 10^{24-25} s

Status of line signal searches in gamma rays

Ackermann+ PRD'15

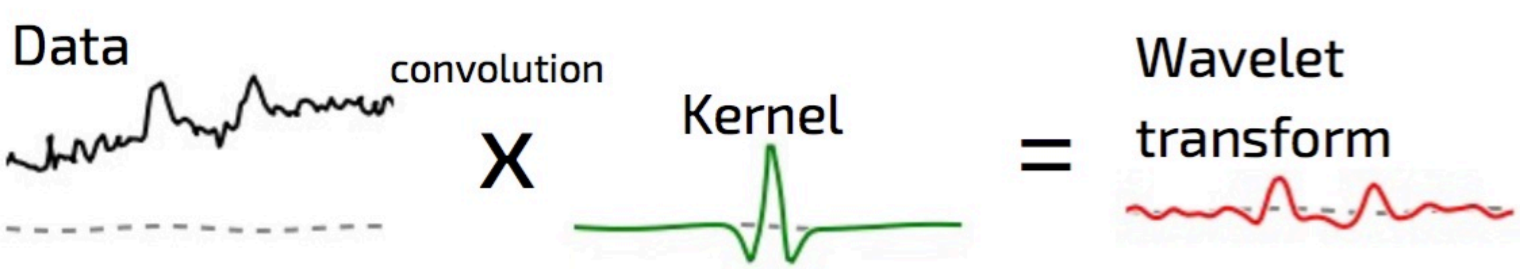


Abdalla+ PRL'18

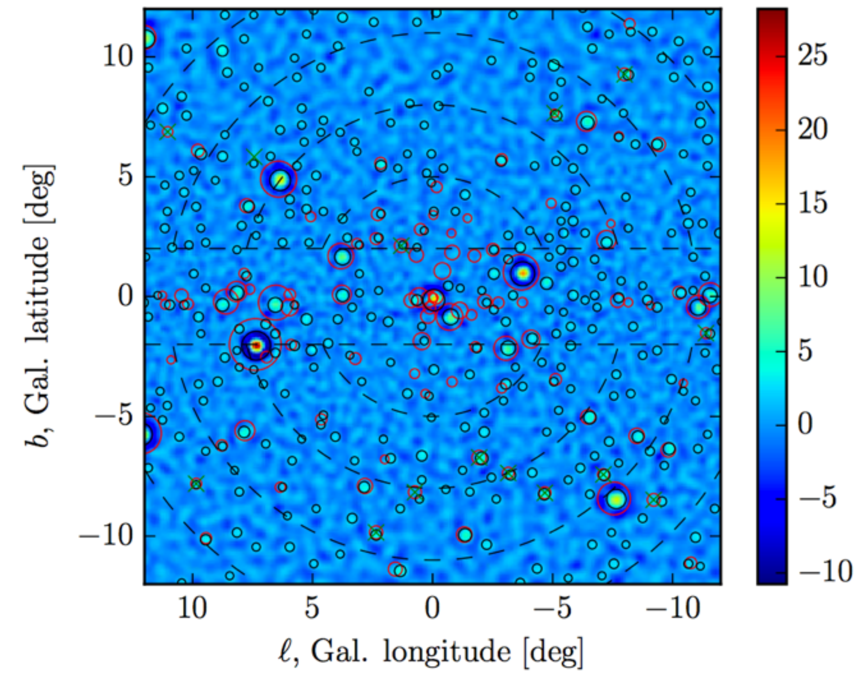


Support for unresolved point sources

Local maxima of normalised wavelet transform



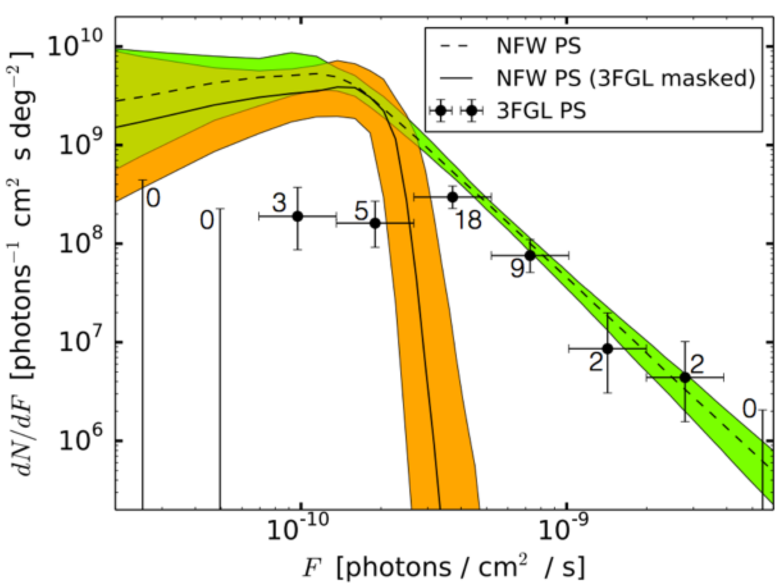
Bartels+ PRL'16

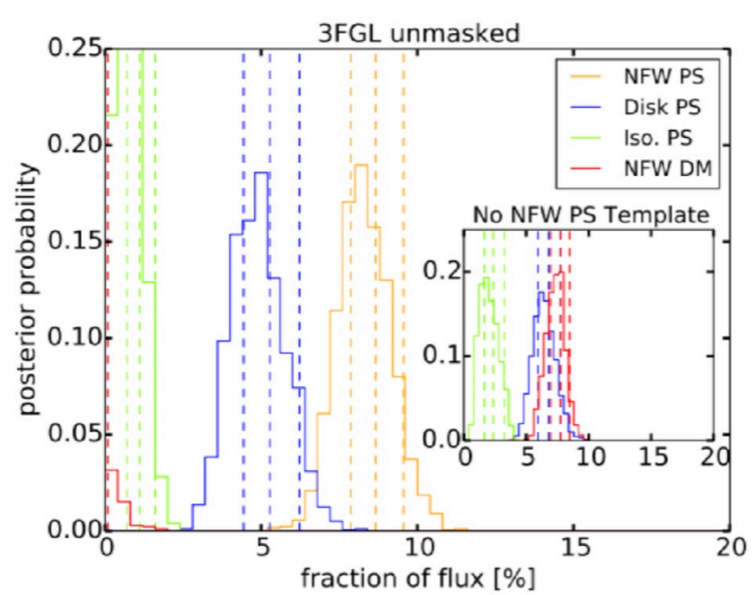


- No background modelling
- Evidence for MSP-like population in the bulge
- Constraints on luminosity function

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

<u>Caveat</u>: Do we model the small scale gas correctly?