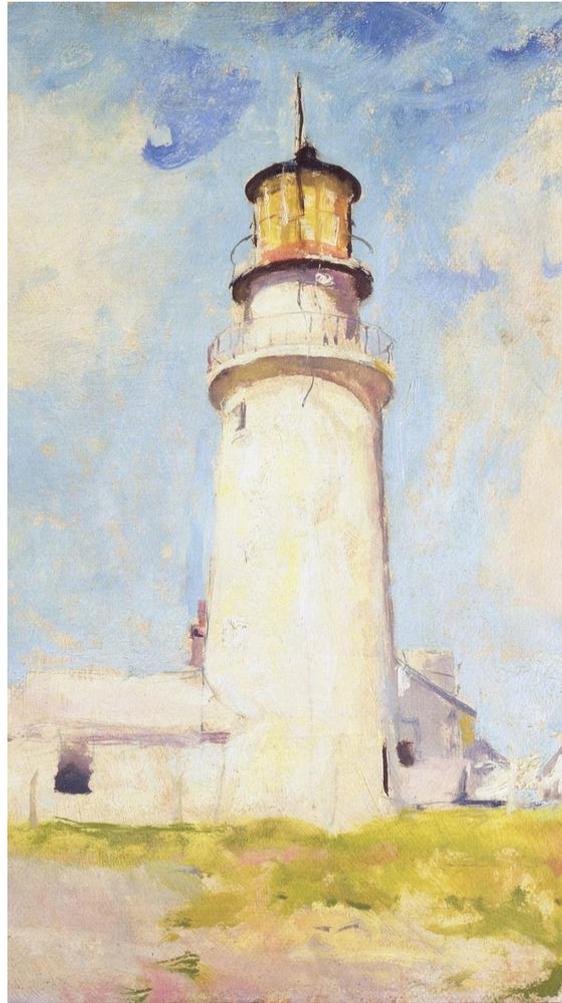
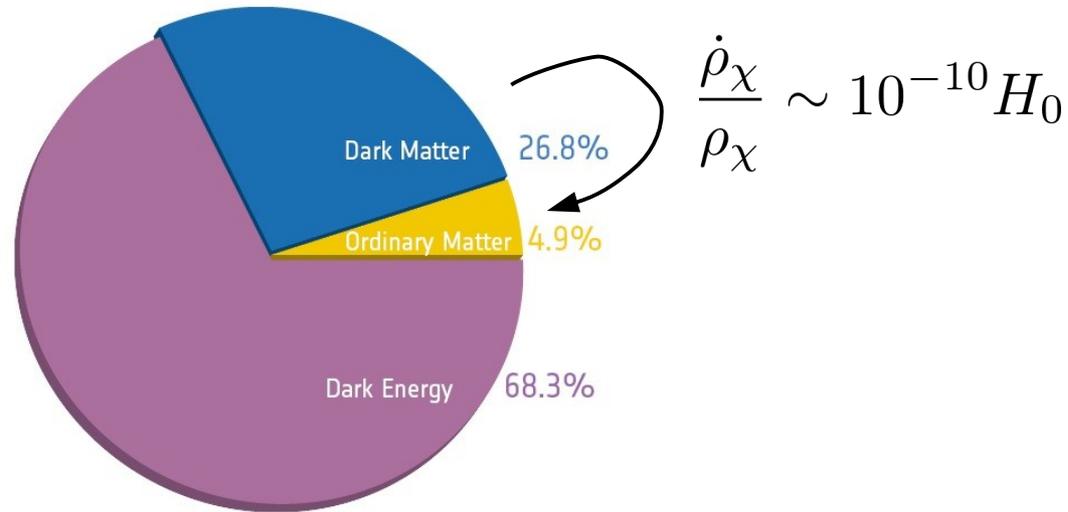


Dark matter – Indirect searches



Is dark matter really dark?

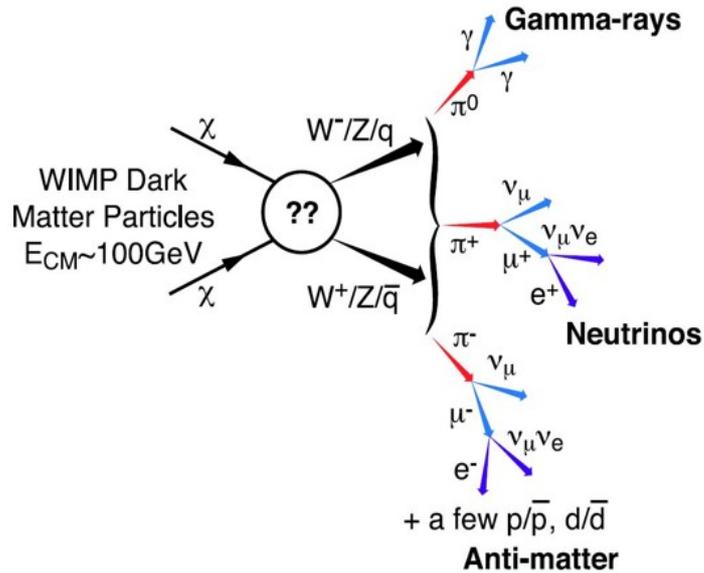


- Many DM models predict energy transfer from the dark into the visible sector
- Very roughly speaking, even a tiny (1 : billion – trillion) energy transfer from the dark into the visible sector, over the course of billions of years, would be visible in astronomical observations
- This is the target of indirect searches for dark matter

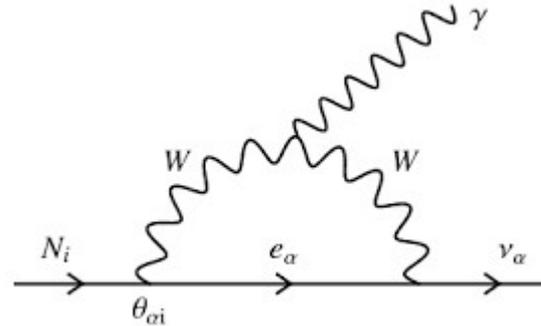
$$H_0^{-1} \sim 10^{18} \text{ s}$$

Energy transfer mechanisms

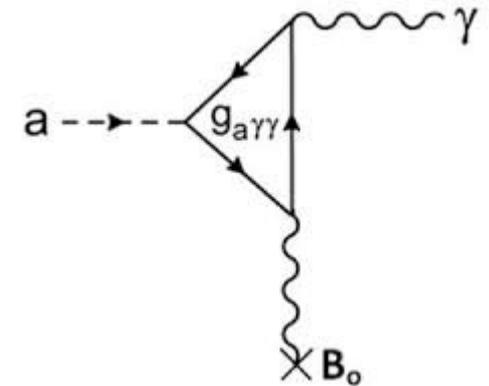
1) Self-annihilation (e.g. WIMPs)



2) Decay (e.g. sterile neutrinos)



3) Conversion (e.g. axions)



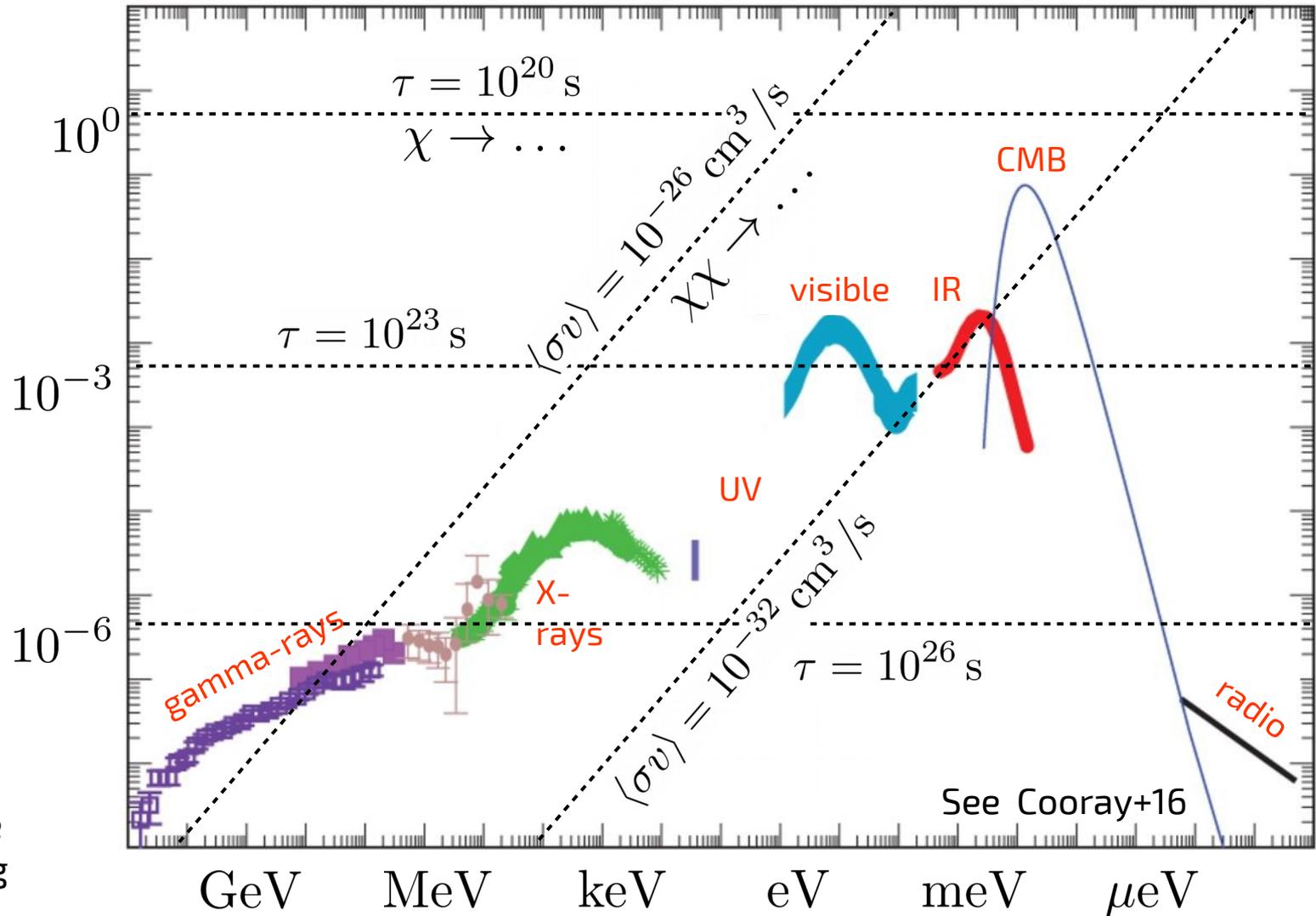
Average energy densities in Universe

Dark matter energy density >> Radiation energy density

$$\rho_{\text{dm}} \sim 1.3 \times 10^3 \frac{\text{eV}}{\text{cm}^3}$$

$$\rho_{\text{rad}} \sim 1 \frac{\text{eV}}{\text{cm}^3}$$

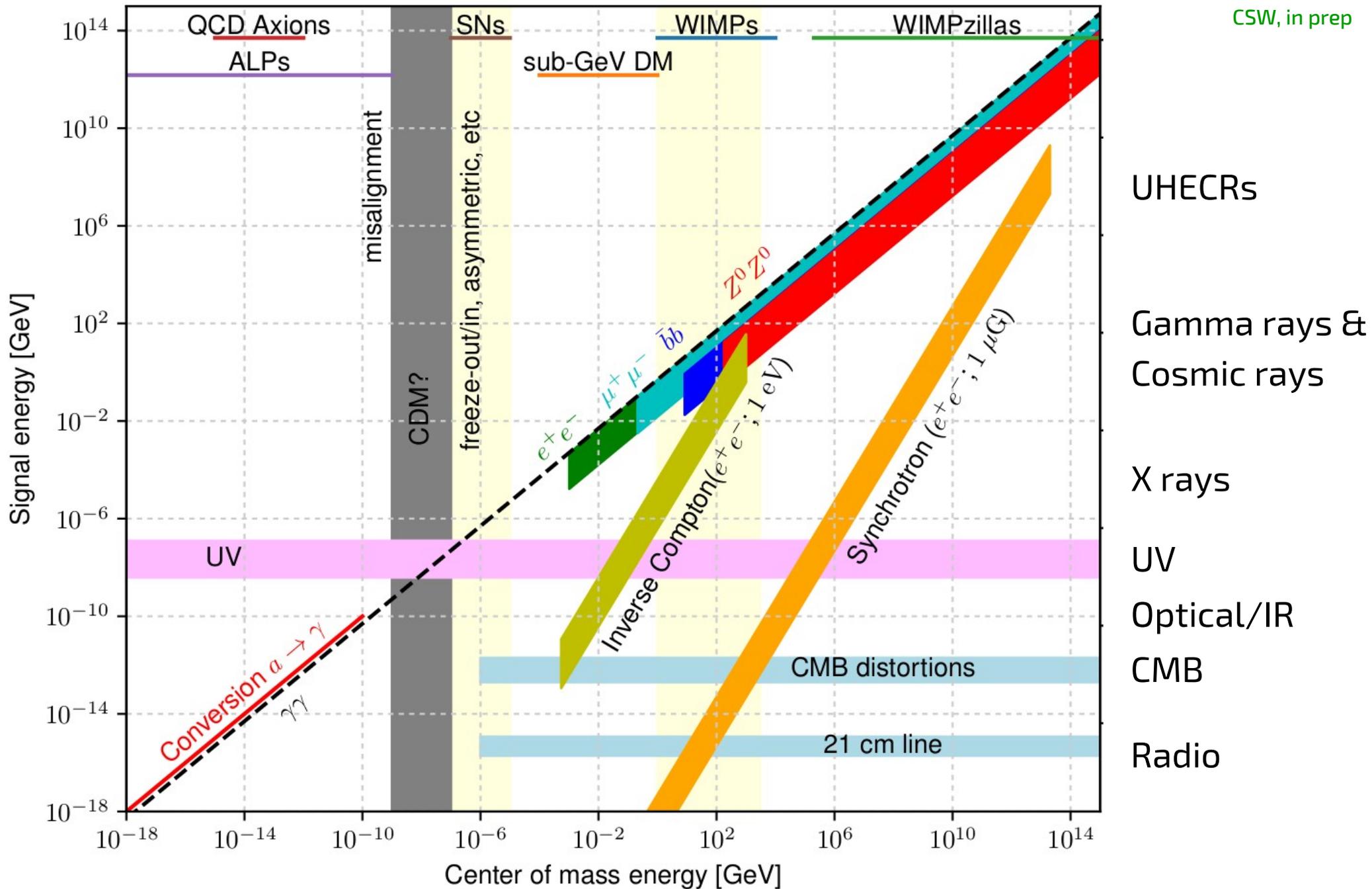
$$\frac{d\rho}{d \log E} \left[\frac{\text{eV}}{\text{cm}^3} \right]$$



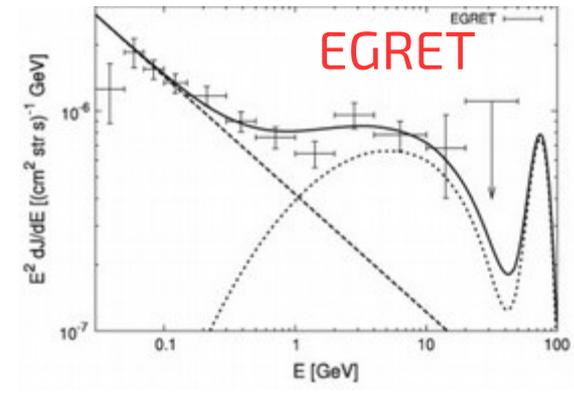
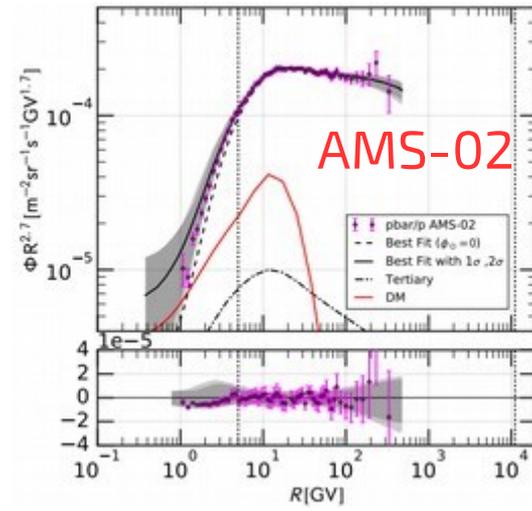
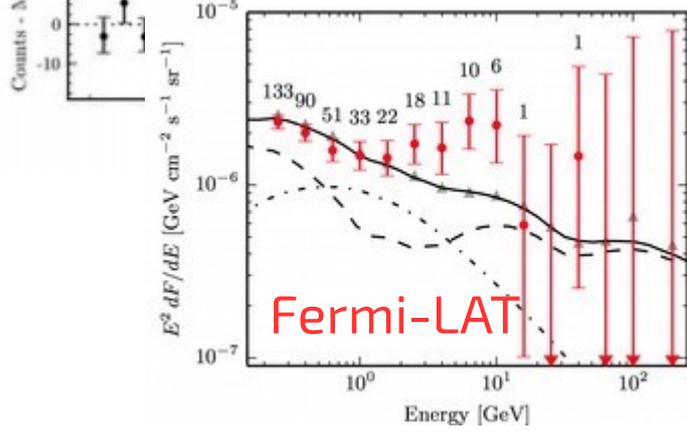
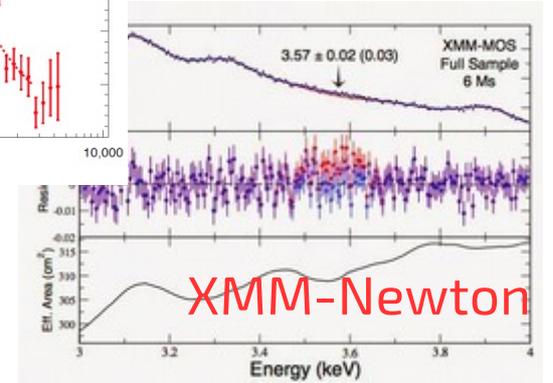
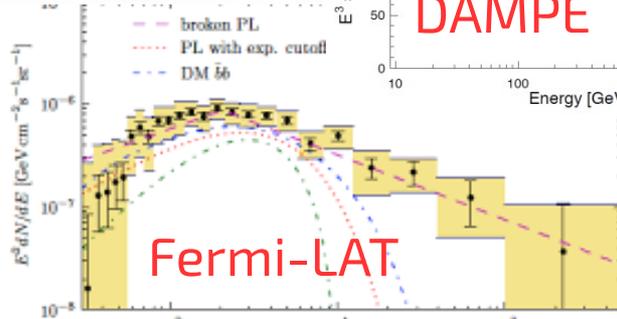
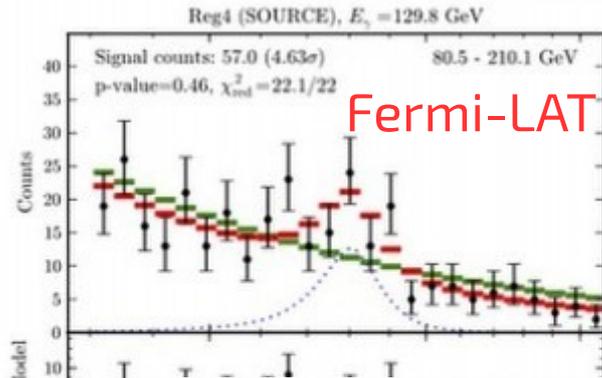
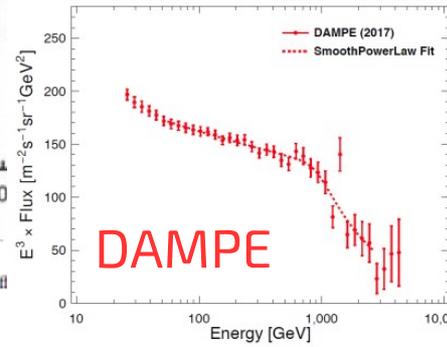
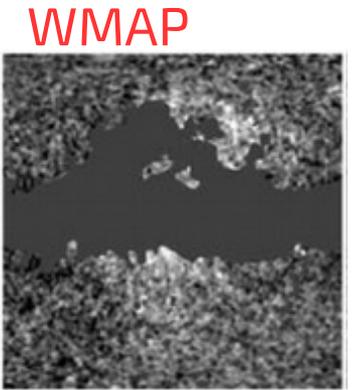
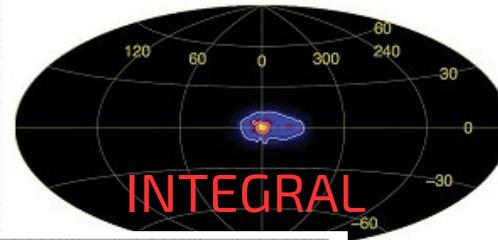
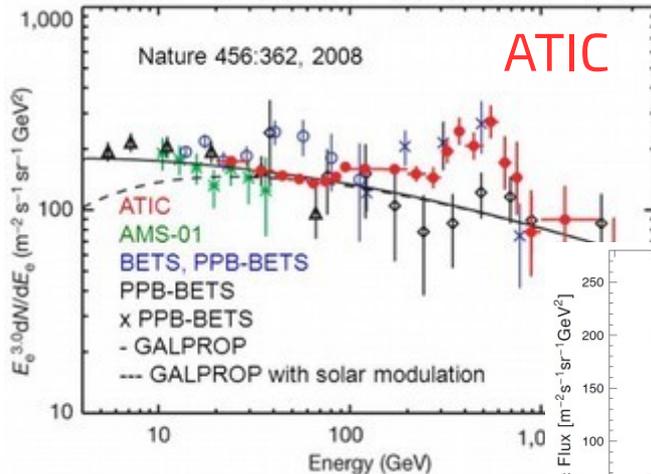
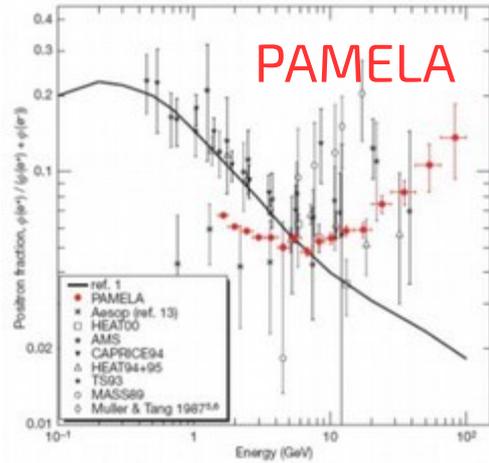
Rough estimate:

Assume that all DM rest mass energy is emitted in photons around the corresponding frequency (within one dex), since beginning of the Universe.

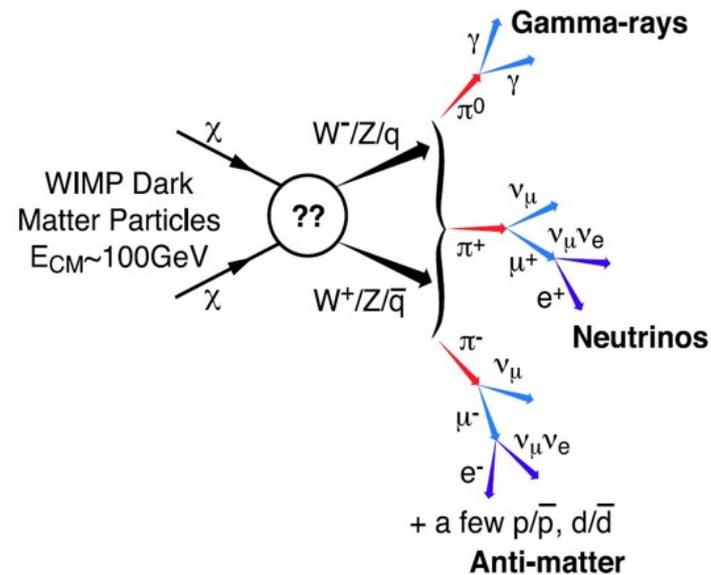
Relevant radiation mechanisms



Lots of signal candidates over the years



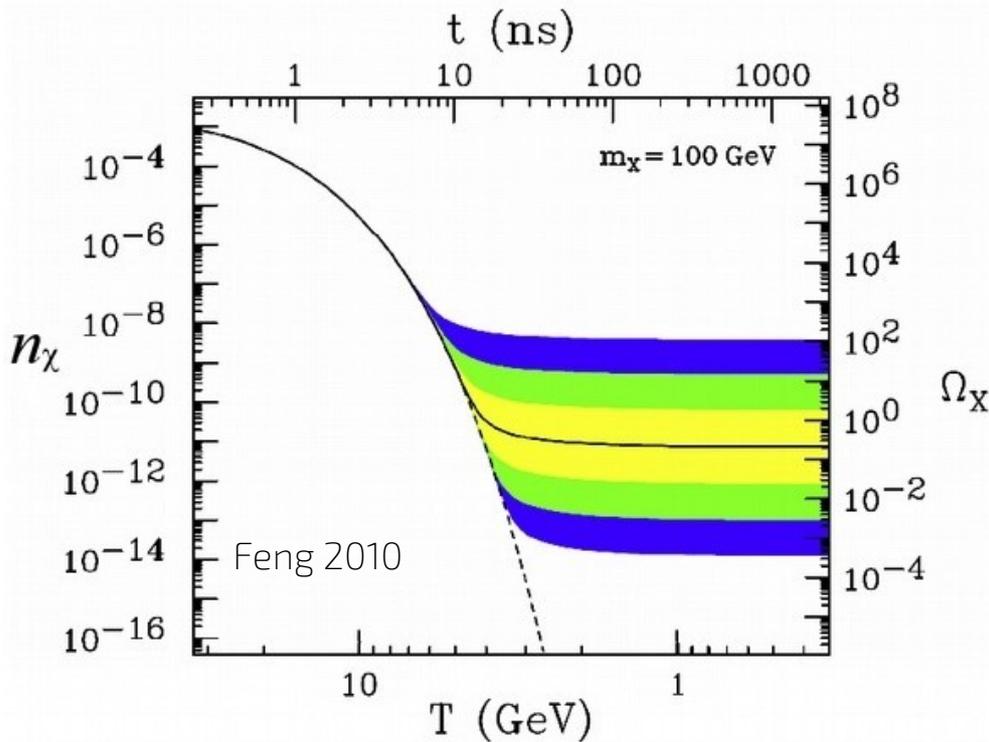
1) Dark matter self-annihilation



The annihilation cross section

s-wave annihilation ($\sigma v \approx \text{const}$)

→ Direct link between relic density and velocity weighted cross section today



$$\frac{\Omega_\chi h^2}{0.1} \approx \frac{3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle}$$

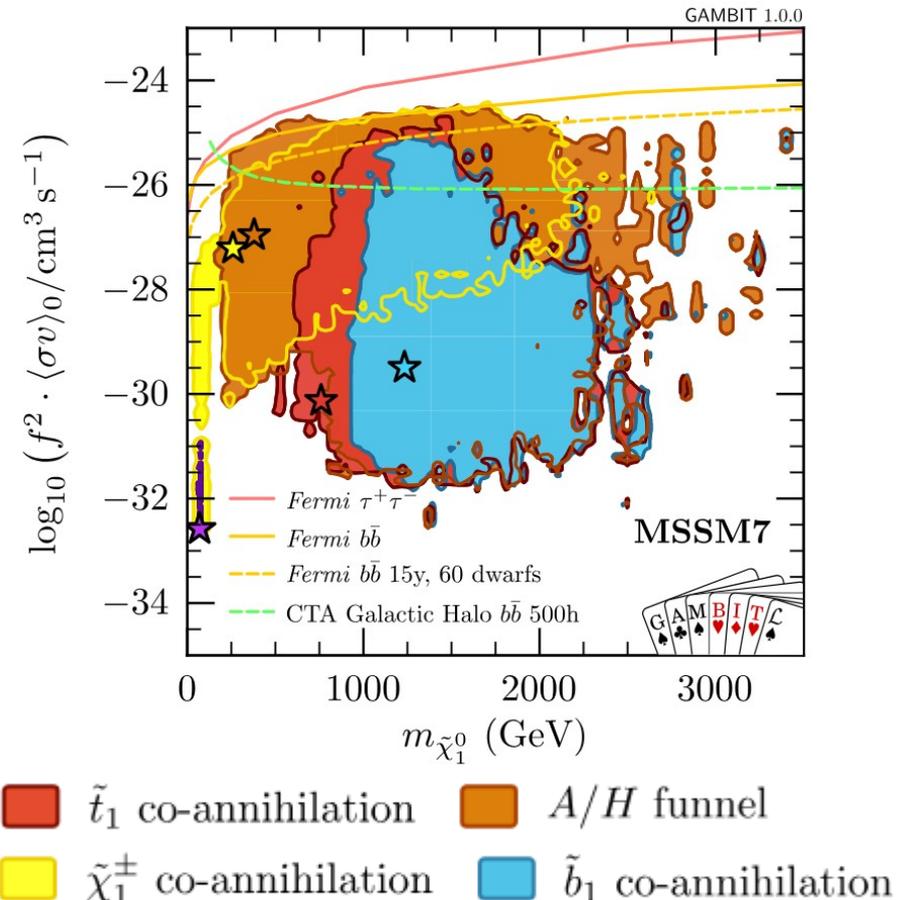
s-wave: $\langle \sigma v \rangle_{T \sim \text{GeV}} = (\sigma v)_{v=0}$

in general

$$\langle \sigma v \rangle_{T \sim \text{GeV}} \neq (\sigma v)_{v=0}$$

Example MSSM7

(rescaled by DM fraction)



- \tilde{t}_1 co-annihilation
- A/H funnel
- $\tilde{\chi}_1^\pm$ co-annihilation
- \tilde{b}_1 co-annihilation

DM annihilation/decay and cosmic rays

DM self-annihilation into gamma rays

Gunn+ 1978; Stecker 1978, ...

Proposal to search for anti-protons from MSSM neutralinos

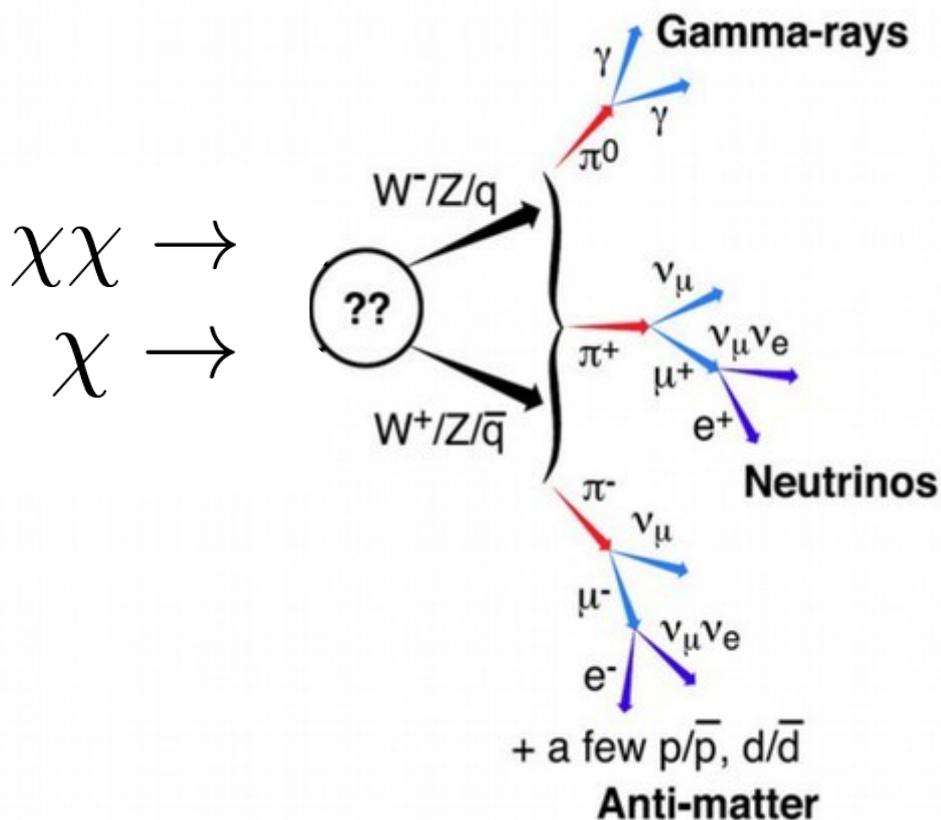
Silk & Srednicki 1984; ...

Searching for neutrinos from the Sun

Silk, Olive & Srednicki 1985; Press & Spergel 1985; ...

Searches for gamma-ray lines

Bergström & Snellmann 1988; Rudaz 1989; ...



Decay

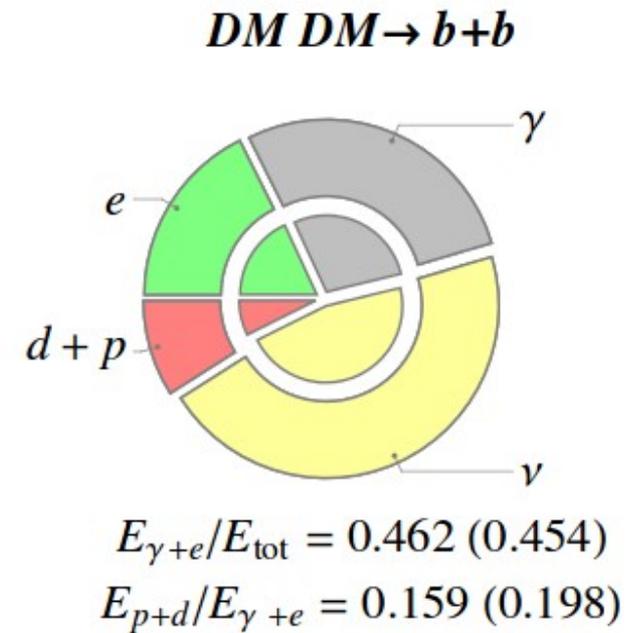
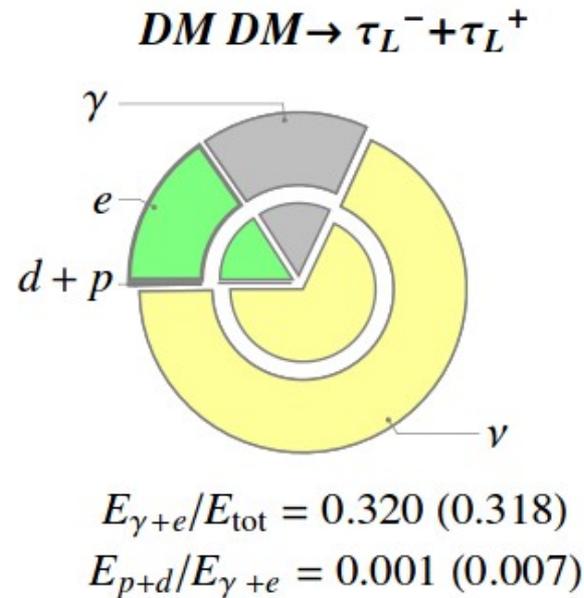
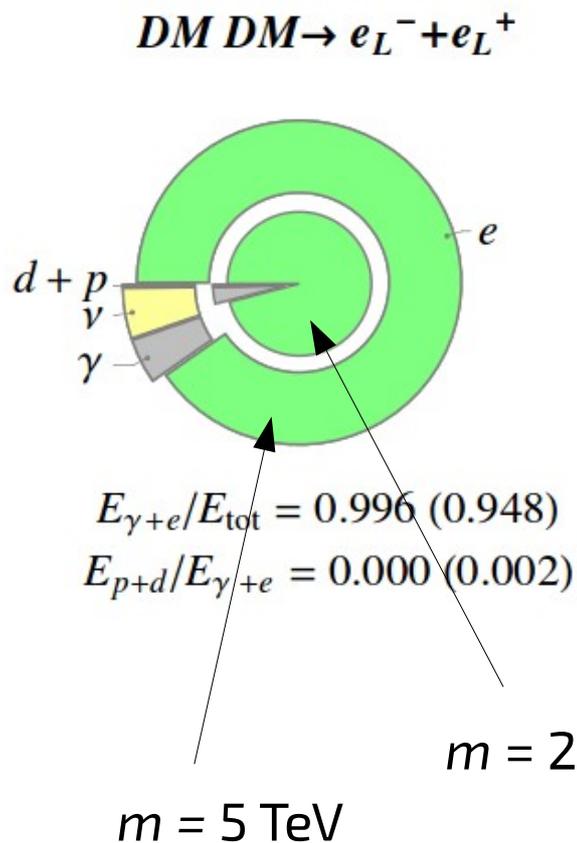
Very model dependent (sterile neutrinos, R-parity violating gravitino DM, axions, ...)

Distribution of rest DM mass energy

How much energy is dumped into photons, neutrinos, electrons, protons and deuterons depends on the **annihilation channel**.

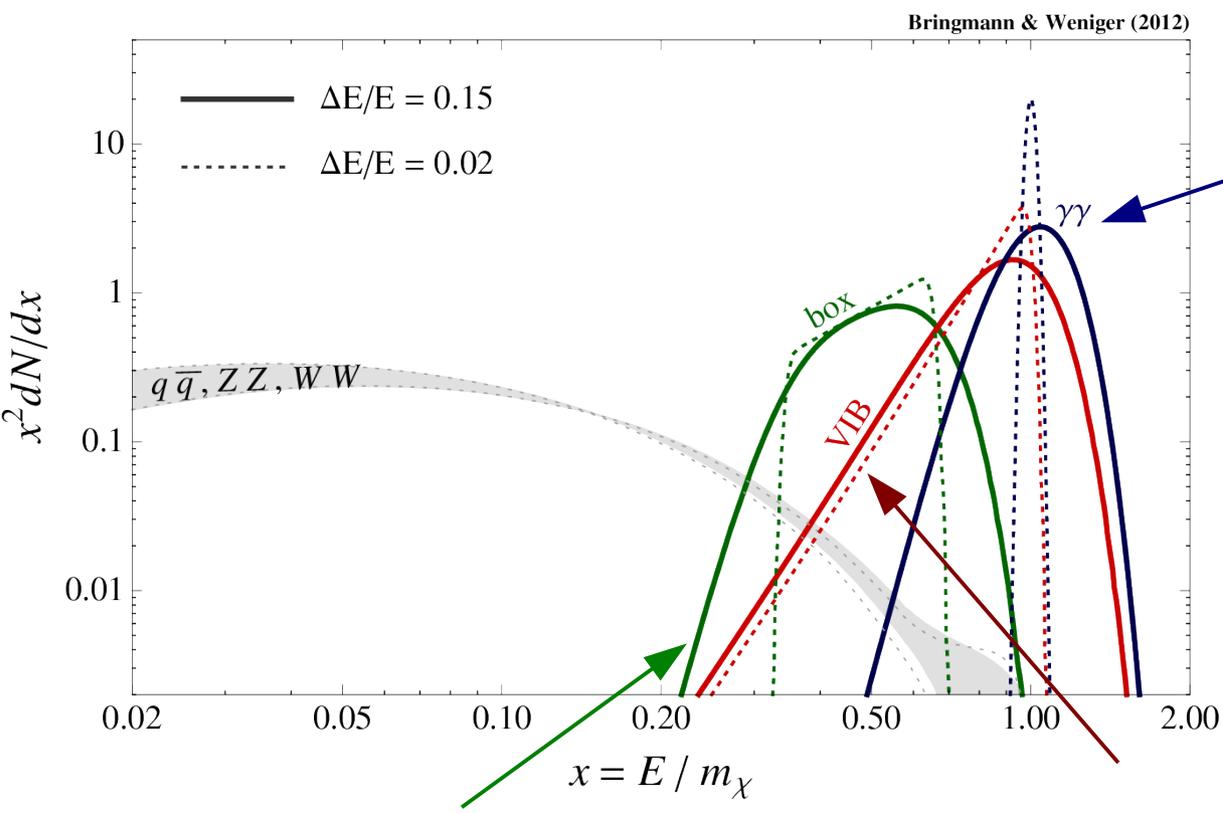
Leptonic channels

Hadronic channel



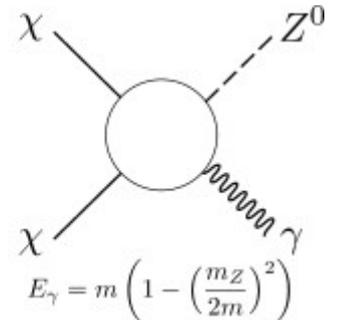
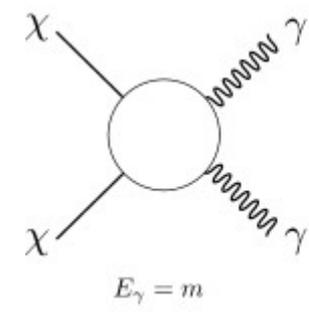
Cirelli et al. (2010) "PPPC4DMID"

Gamma-ray spectral features



Gamma-ray lines

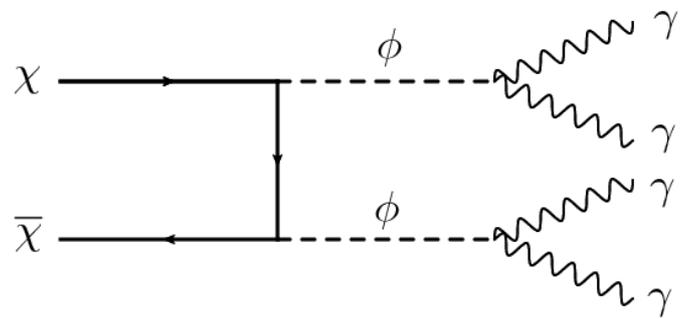
$$\chi\chi \rightarrow \gamma\gamma, \gamma Z^0$$



[Bergström & Snellman (1988)]

Cascade decays

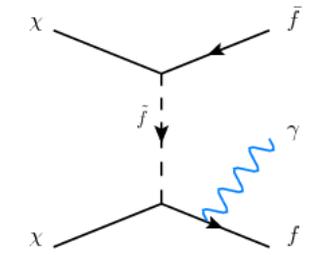
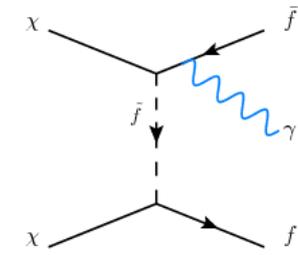
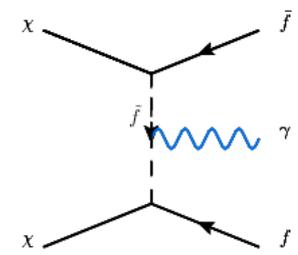
$$\chi\chi \rightarrow \phi\phi \rightarrow \gamma\gamma\gamma\gamma$$



[e.g. Ibarra et al. 2012]

Internal Bremsstrahlung (IB)

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

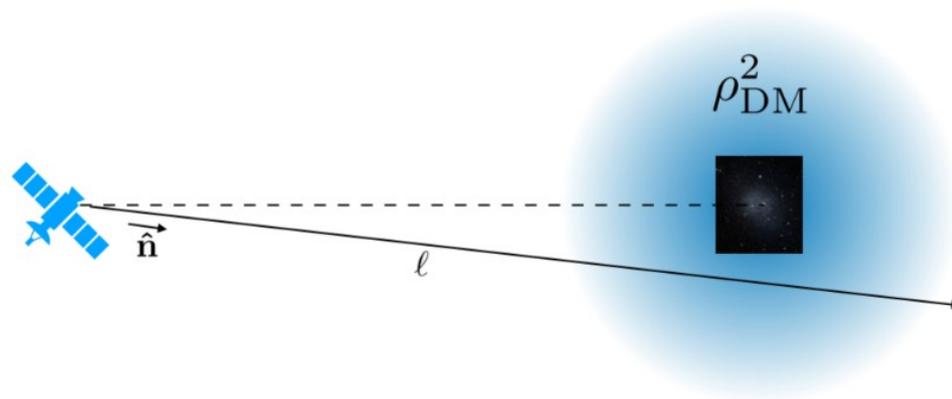


[e.g. Bringmann, Bergström & Edsjö (2008)]

Differential intensity of DM signal photons

Differential signal intensity

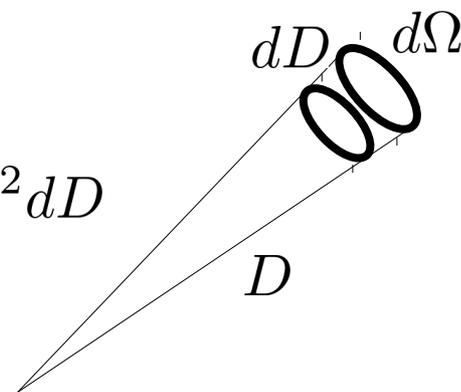
$$\frac{d^2 F}{d\Omega dE} = \frac{1}{2} \frac{(\sigma v_{\text{rel}})_0}{m_\chi^2} \frac{dN_\gamma}{dE} \times \frac{1}{4\pi} \int_{\text{l.o.s.}} dD \rho_{\text{DM}}(\vec{r}[D, \Omega])^2$$



Differential flux from a region ΔV at distance D .

$$\frac{dF}{dE} = \frac{1}{4\pi D^2} \int_{\Delta V} dV \frac{dN_\gamma}{dV dt dE}$$

$$dV \rightarrow d\Omega D^2 dD$$



Volume emissivity
(see above)

$$\frac{dN_\gamma}{dV dt dE} = \alpha \frac{dN_\gamma}{dE} (\sigma v_{\text{rel}})_0 n_\chi^2$$

Spatial characteristics

Signal is approx. proportional to column square density of DM:

$$\propto \int_{\text{l.o.s.}} ds \rho_{\text{DM}}^2$$

Extended or diffuse:

(for observations with gamma rays)

Galactic DM halo

- good S/N
- difficult backgrounds
- angular information

Extragalactic

- nearly isotropic
- only visible close to Galactic poles
- angular information
- Galaxy clusters?

review on N-body simulations: Kuhlen,
Vogelsberger & Angulo (2012)

Point-like:

(for observations with gamma rays)

Galactic center (~8.5 kpc)

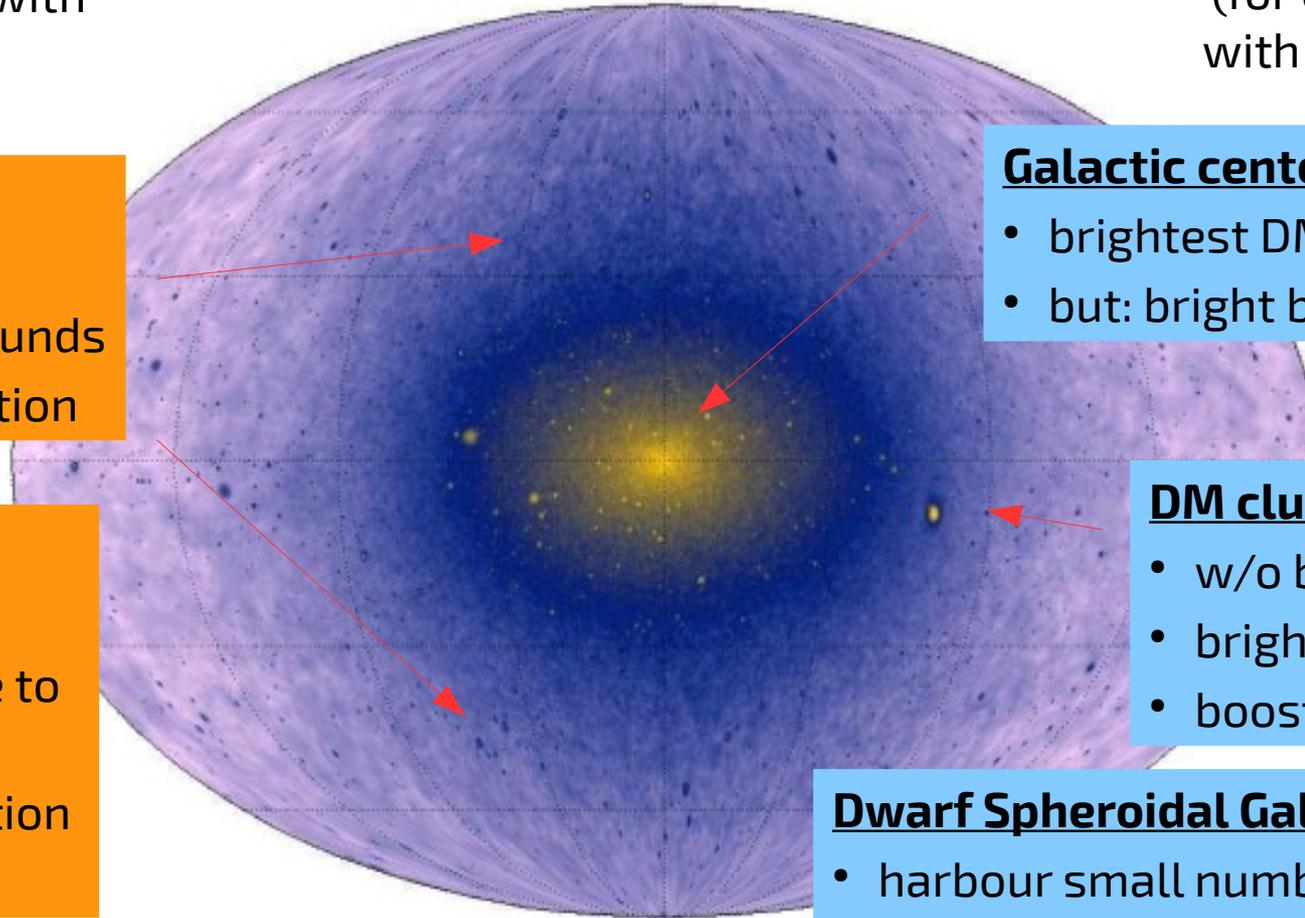
- brightest DM source in sky
- but: bright backgrounds

DM clumps

- w/o baryons
- bright enough?
- boost overall signal

Dwarf Spheroidal Galaxies

- harbour small number of stars
- otherwise dark (no gamma-ray emission)



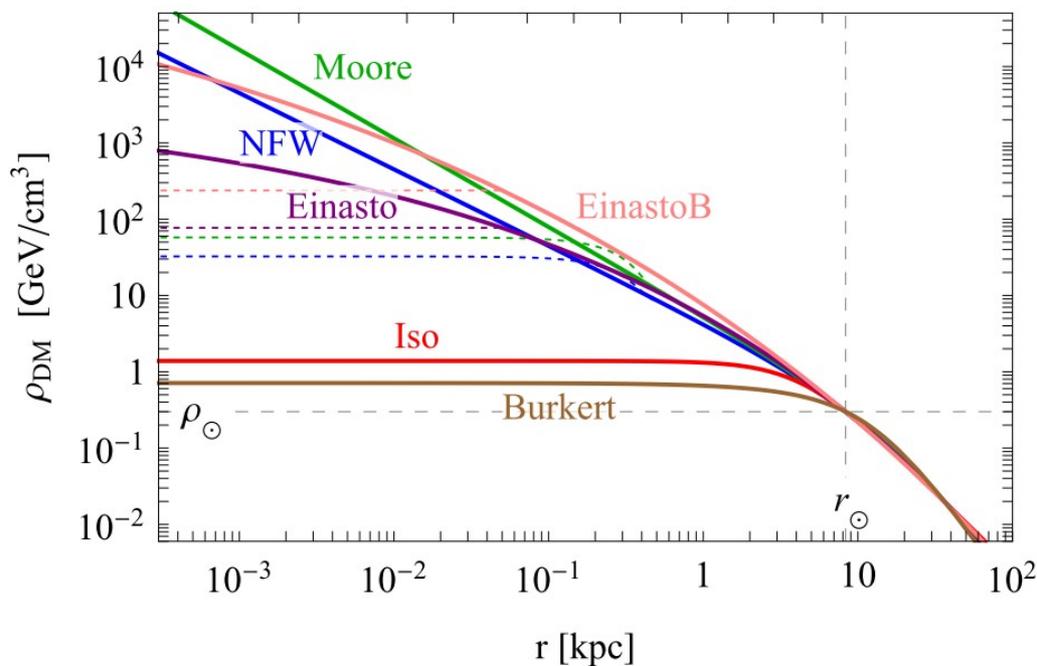
Dark matter profile

The DM distribution very close (<1kpc) to the Galactic center is observationally only poorly constrained.

Viable DM density

profiles: Angle from the GC [degrees]

10'' 30'' 1' 5' 10' 30' 1° 2° 5° 10° 20° 45°

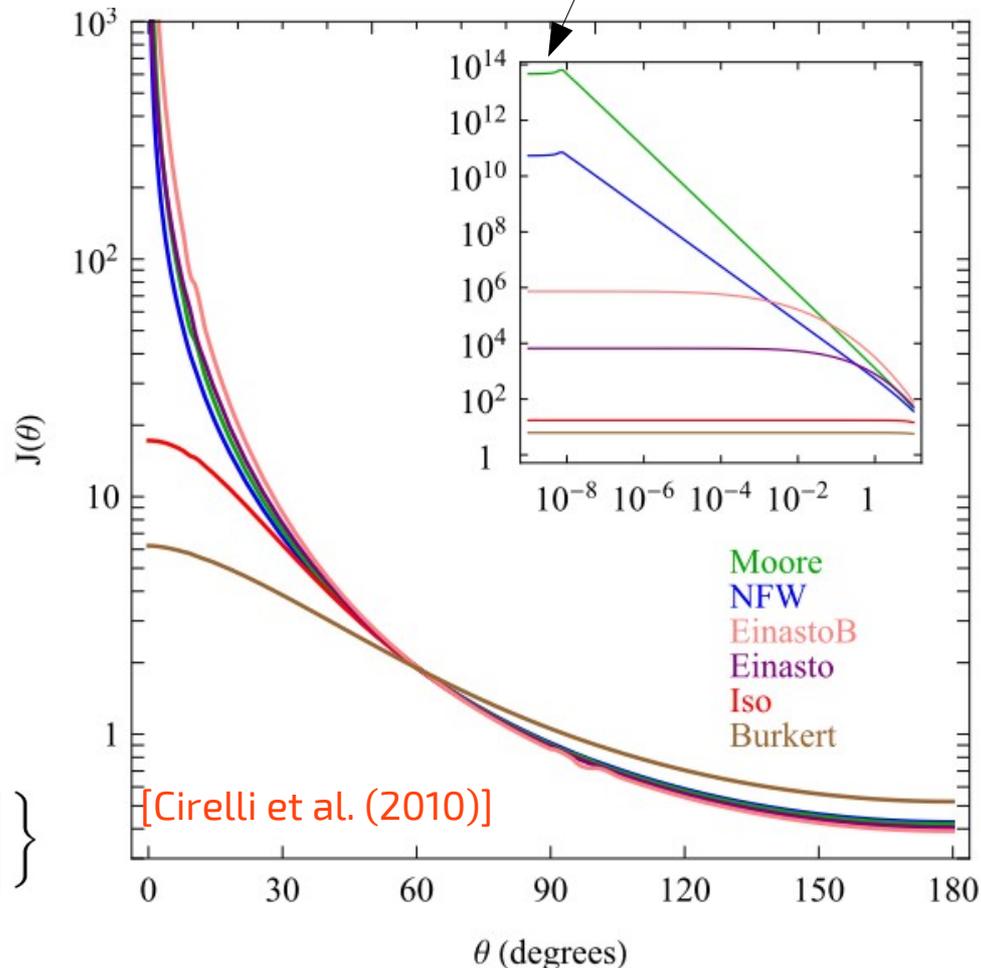


$$\text{NFW: } \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r} \left(1 + \frac{r}{r_s}\right)^{-2}$$

$$\text{Einasto: } \rho_{\text{Ein}}(r) = \rho_s \exp \left\{ -\frac{2}{\alpha} \left[\left(\frac{r}{r_s}\right)^\alpha - 1 \right] \right\}$$

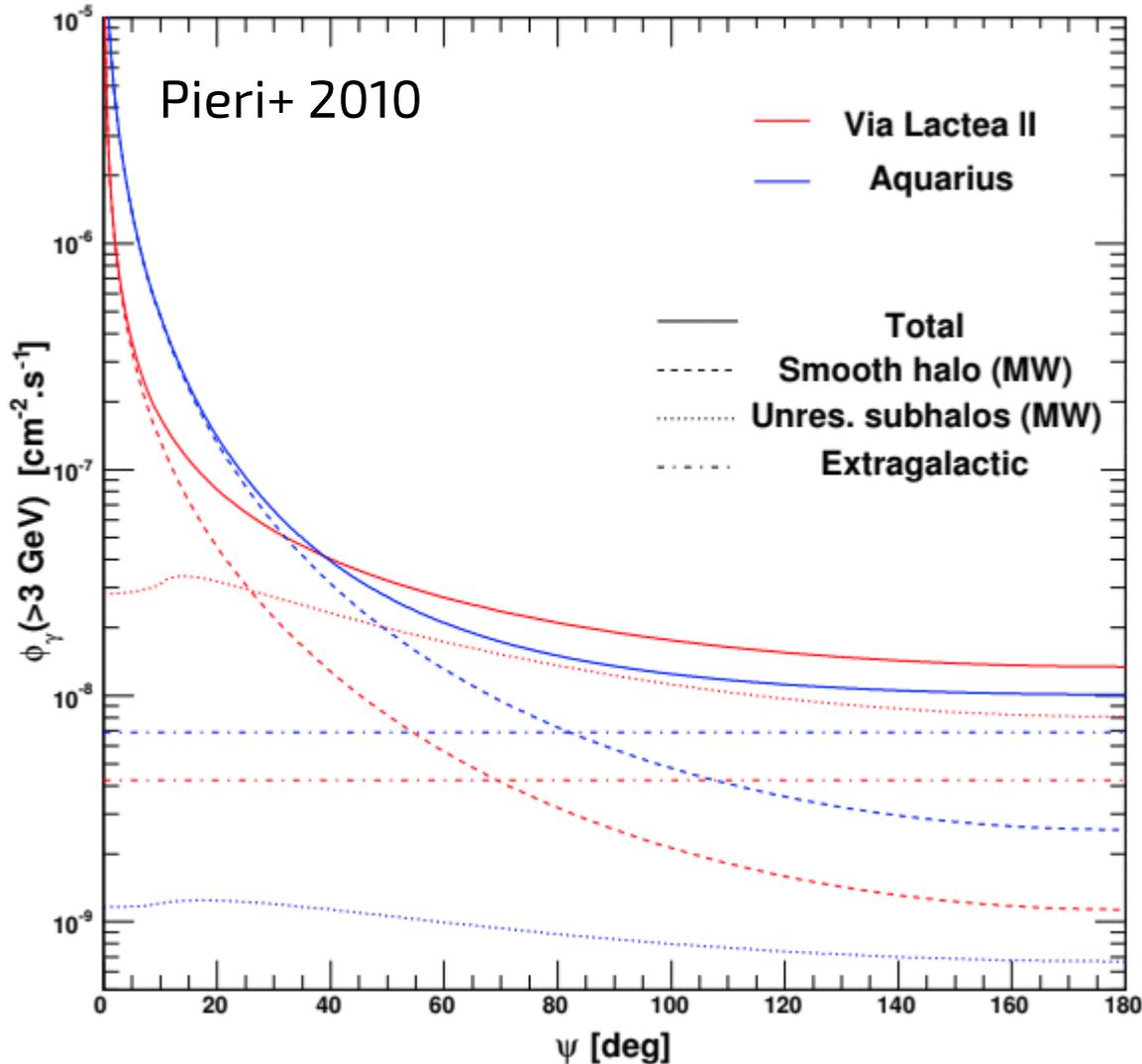
$$\text{Isothermal: } \rho_{\text{Iso}}(r) = \frac{\rho_s}{1 + (r/r_s)^2}$$

Signal morphology:



[Cirelli et al. (2010)]

Dark matter substructure boosts



$$\langle \rho^2 \rangle_V = B_F \langle \rho \rangle_V^2$$

Relevance of substructure

- Effective contribution depends critically on concentration-mass relation
- Tidal forces diminish substructure in inner Galaxy
- Usually not sizeable in the inner Galaxy or in dwarf spheroidals
- Largest for massive Galaxy clusters

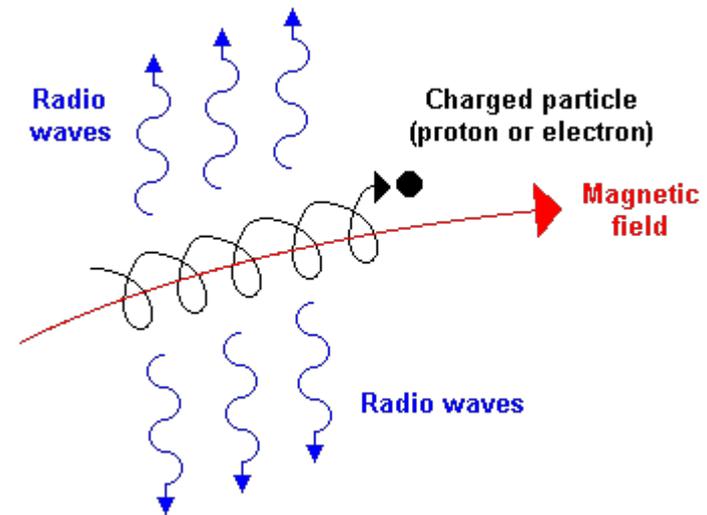
Some recent work: Moline+ 1603.04057, Okoli+ 1711.05271

(Secondary photons)

Various mechanisms can generate photon signals from high energetic electrons and positrons.

Synchrotron emission

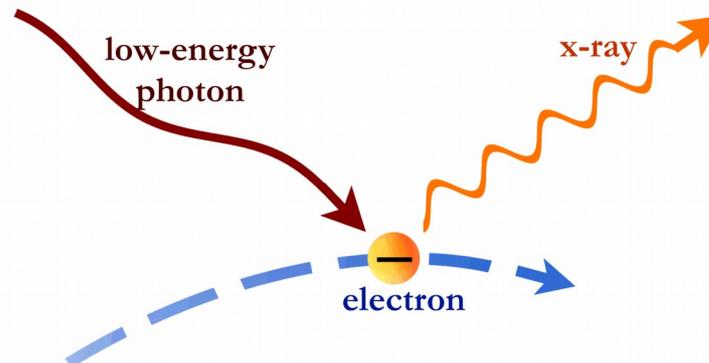
Radio emission of electrons propagating the Galactic magnetic field



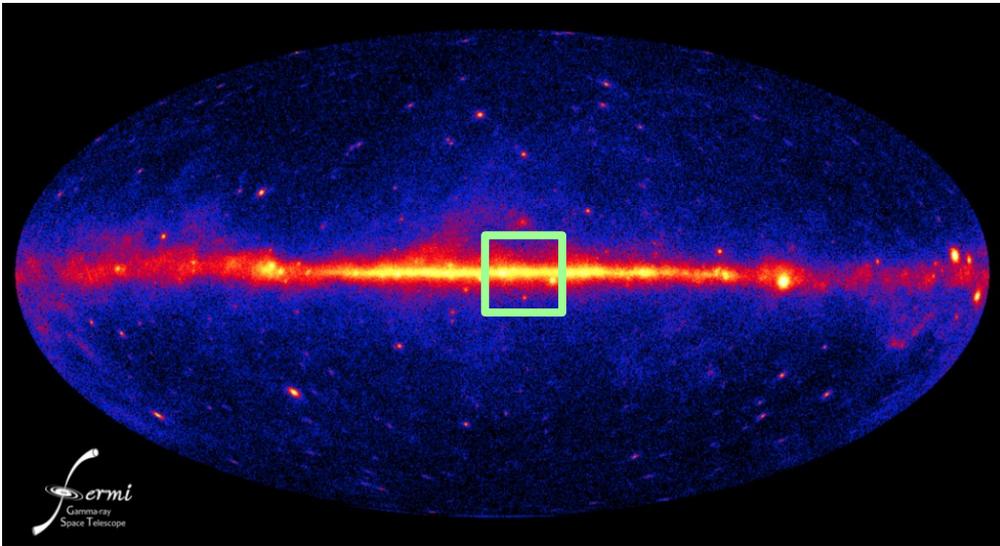
nrumiano

Inverse Compton emission

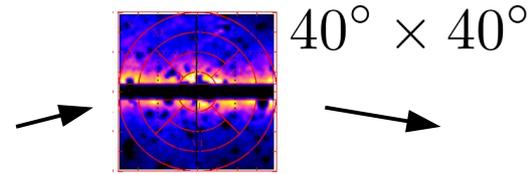
Up-scattering of the interstellar radiation field (starlight, dust emission, CMB) to GeV energies



Fermi LAT - Galactic center GeV excess



Different groups, different ROIs



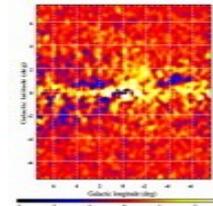
Calore+14

$7^\circ \times 7^\circ$

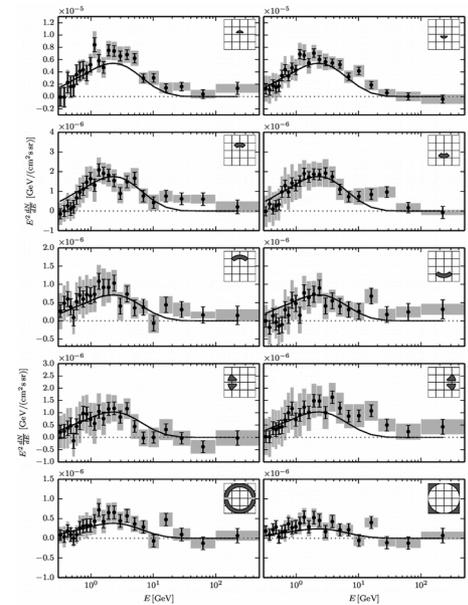


Daylan+ 14
(GC analysis)

$14^\circ \times 14^\circ$



Ajello+15

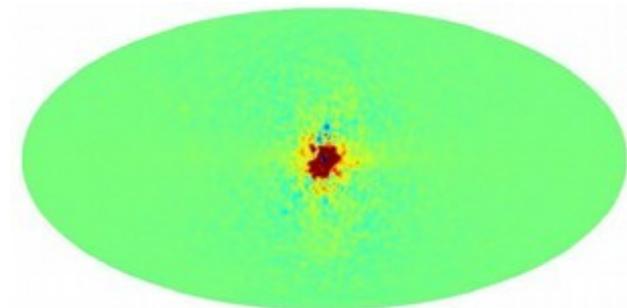


The Fermi GeV bulge emission

- Initial claims by Goodenough&Hooper (2009) [see also Vitale&Morselli (2009)]
- Controversial discussion in the community for six years
- In 2015, existence of “GeV excess” finally got the blessing from the Fermi LAT collaboration
- **Is it a DM signal?**

... Hooper & Linden 11; Boyarsky+ 11; Abazajian & Kalpinhat 12; Hooper & Slatyer 13; Gorden & Macias 13; Macias & Gorden 13; Huang+ 13; Abazajian+ 14; Daylan+ 14; Zhou+ 14; Calore+ 14; Huang+15; Cholis+ 15; Bartels+ 15; Lee+ 15, ...)

Information field theory:

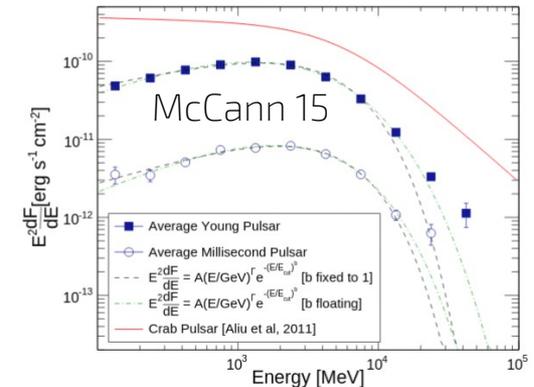


Huang+ 15

Fermi LAT GeV excess - Status

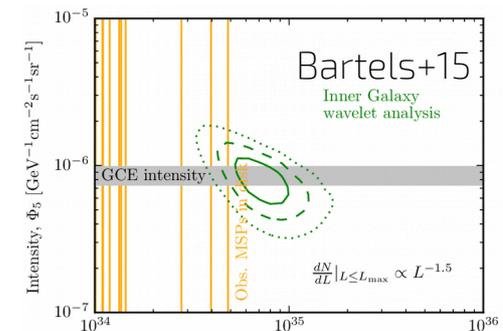
Situation

- Thousands of (hypothetical) millisecond pulsars in the Galactic bulge could potentially cause the emission (spectrum works) Abazajian 2010
- Production plausibly related to disruption of globular clusters Brandt & Kocsis 2015



Photon clustering

- Point source origin of emission suggests clustering of photons, supported by wavelet fluctuation analysis
- Non-Poissonian template fit results recently retracted (but not relevant for wavelet analysis) Lee+15, see also Leane+19

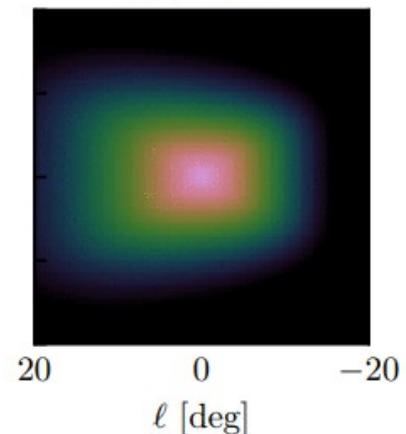


Spatial distribution

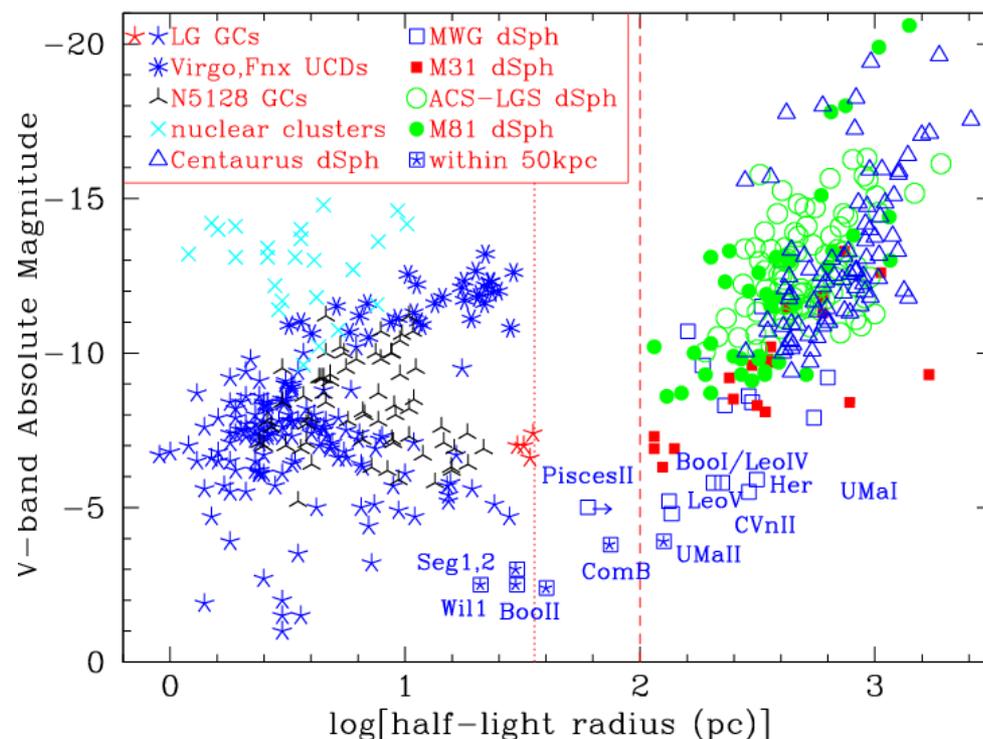
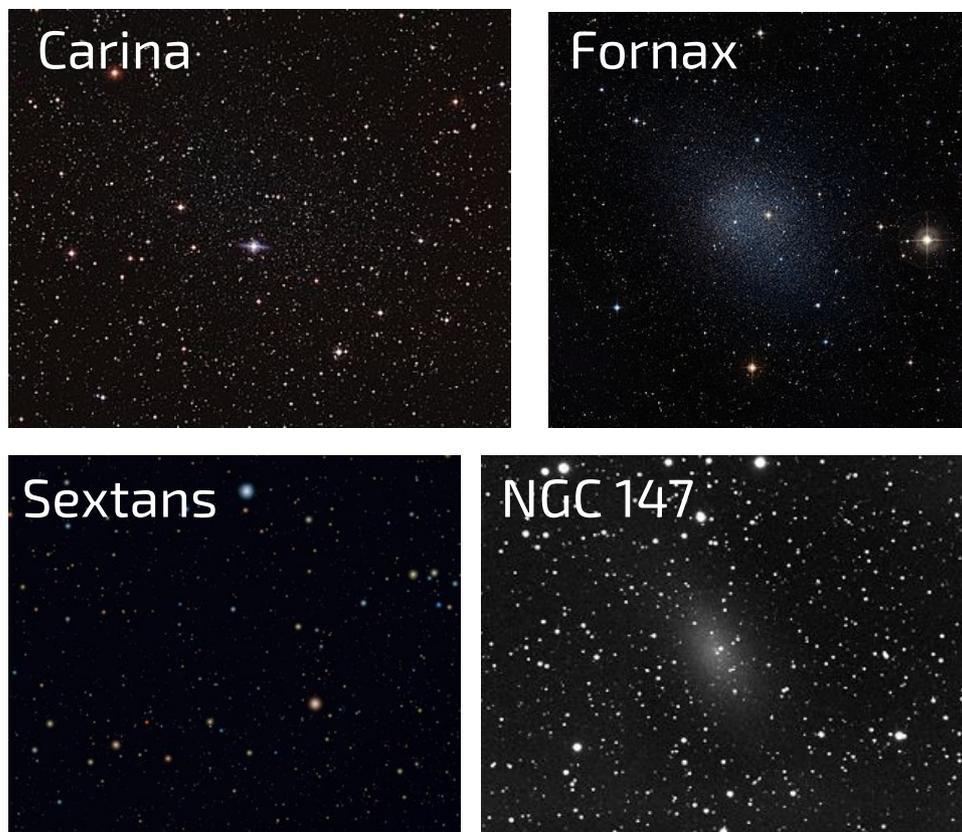
- Excess emission appears to trace stellar mass in Galactic bulge rather than a spherical (DM) profile → Suggests astrophysical origin Bartels+18

But: Situation remains unclear, difficult to make definitive statements with photon data alone → Radio searches (MeerKAT should find ~10 bulge MSPs within 100 h in a dedicated survey, maybe 2019/2020?) Calore+15

(c) RCG



Searches in dwarf spheroidal galaxies

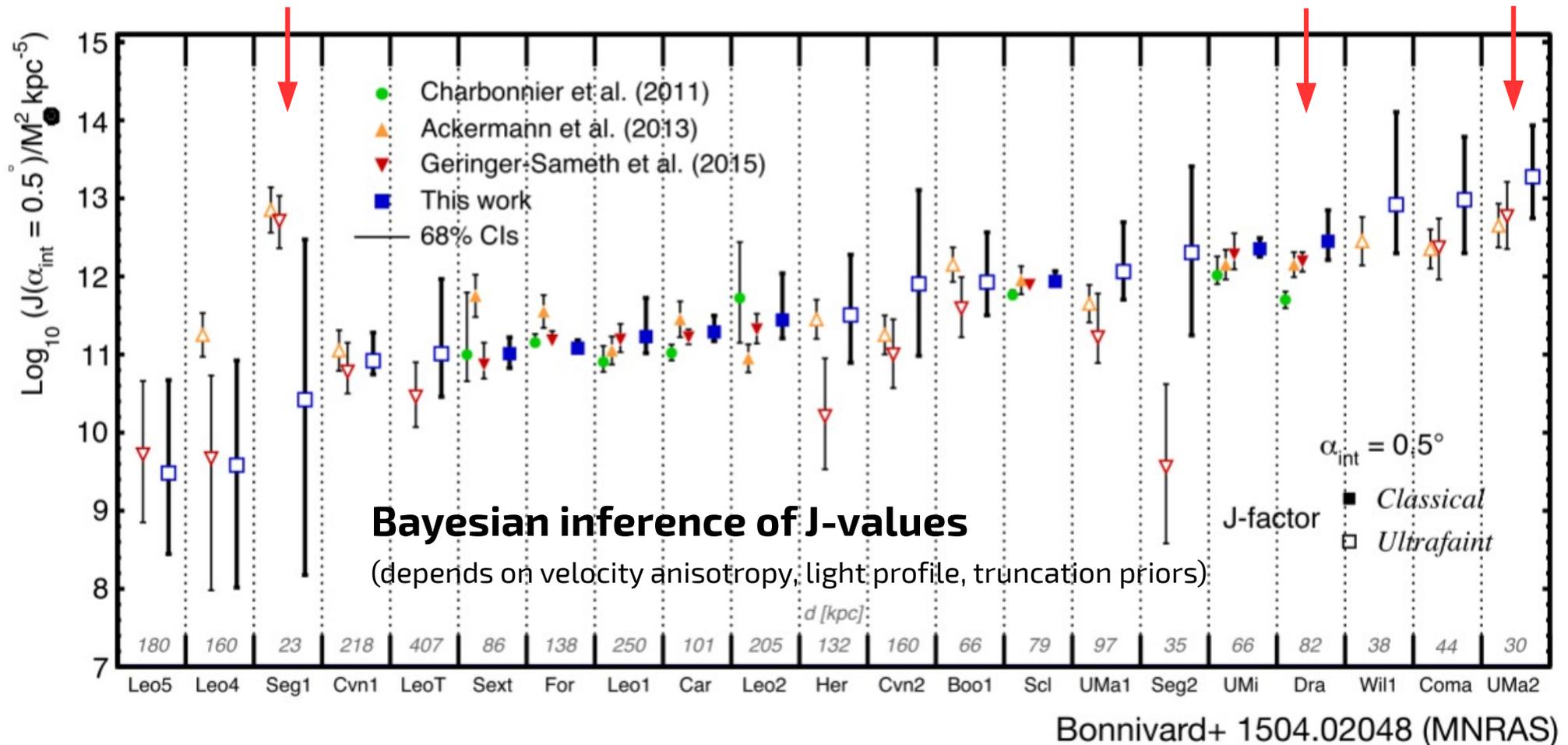


Credit: Wyse+ 2010

Dwarf spheroidal galaxies

- 9 classical dwarfs
- >25 ultra-faint dwarfs around found in recent surveys (SDSS, DES)
- dSphs have very large M/L ratios → Completely DM dominated
- Astrophysically inactive → no gamma-ray emission expected
- → Perfect target for DM annihilation signal searches

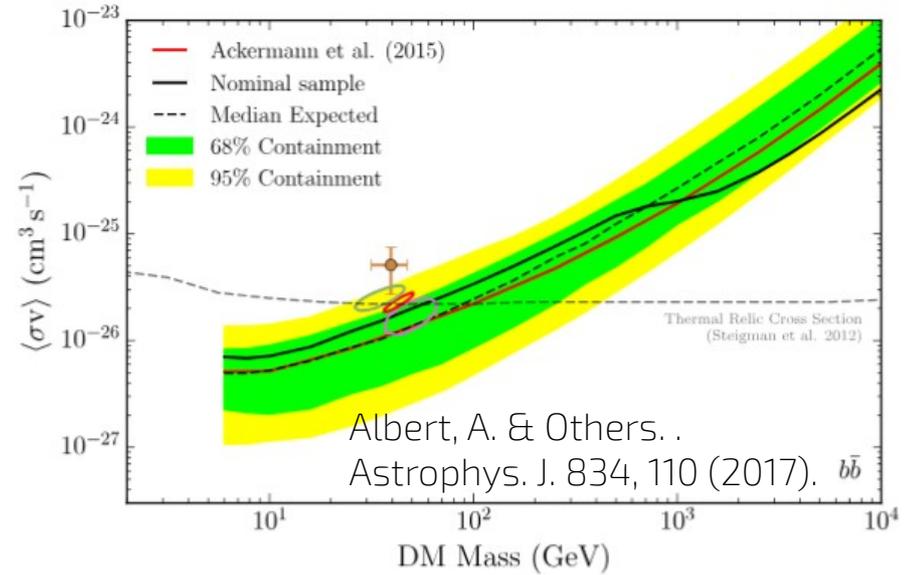
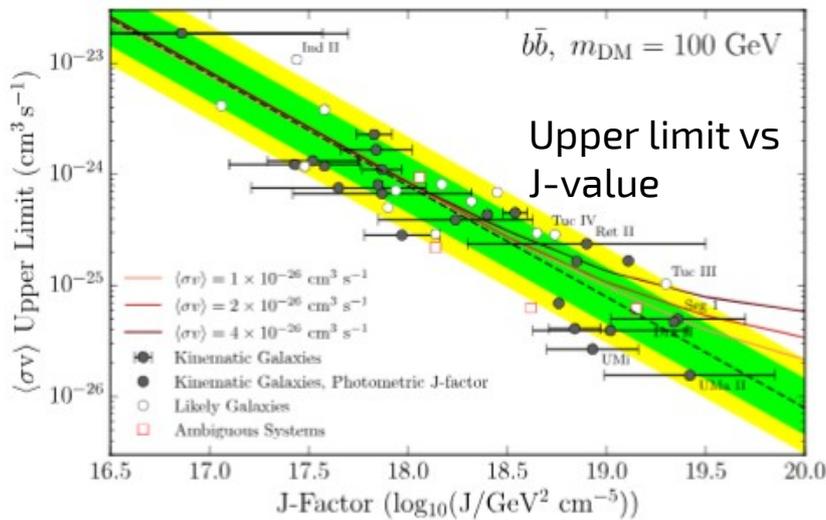
“J-values” in the literature



Situation

- Still quite some discussion about J-values in the literature (e.g. Bonnivard+ '15, Geringer-Sameth+ '15, Charbonnier+ '11, Walker+ '11)
- Impact of tri-axiality somewhere around factor 2 (Bonnivard+ '15, Hayashi+ '16)
- Non-parametric approach can reduce J-values by up to factor 4 (Ullio & Valli 2015)
- Still, thanks to combination of sources, limits are arguably the most robust

Fermi LAT - Dwarf Spheroidal Galaxies

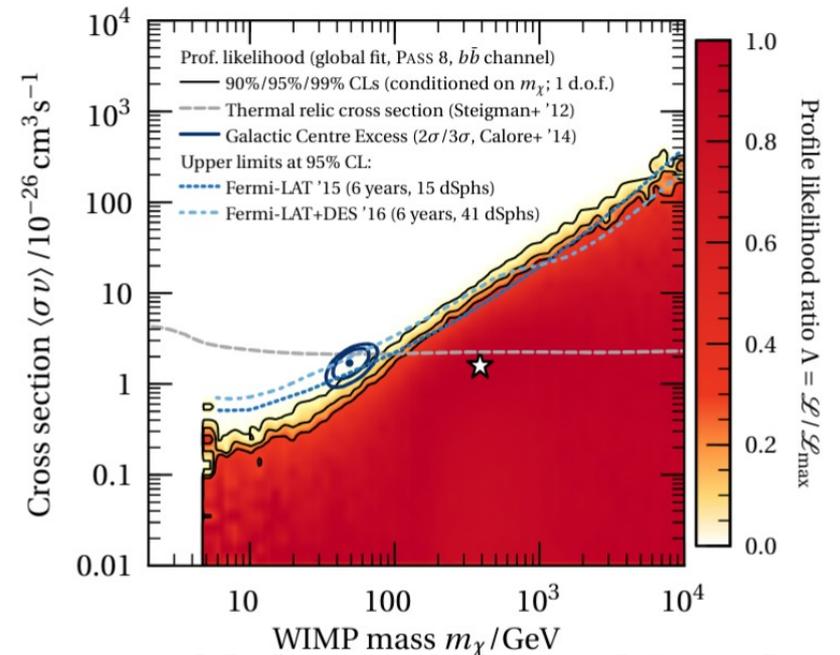


Latest Fermi coll. limits from 39 dSphs, only for half of them the J-value is kinematically determined
 → GeV excess OK (thanks to excesses in 4 dSphs)

Recent analysis of 27 dSphs with J-value, using Bayesian and Frequentist methods, long tail J-value priors → GeV excesses in tension [Hoof+ 2018]

Ongoing J-values discussion

- Ongoing discussion about “J-values” in the literature [e.g. Bonnivard+ '15, Geringer-Sameth+ '15, Charbonnier+ '11, Walker+ '11]
- Impact of tri-axiality somewhere around factor 2 [Bonnivard+ '15, Hayashi+ '16]
- Non-parametric approach can reduce J-values by up to factor four [Ullio & Valli 2015]

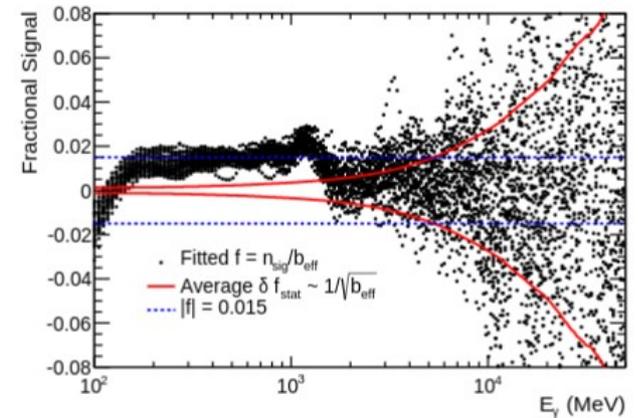


Hoof, S., Geringer-Sameth, A. & Trotta, R. arXiv [astro-ph.CO] (2018).

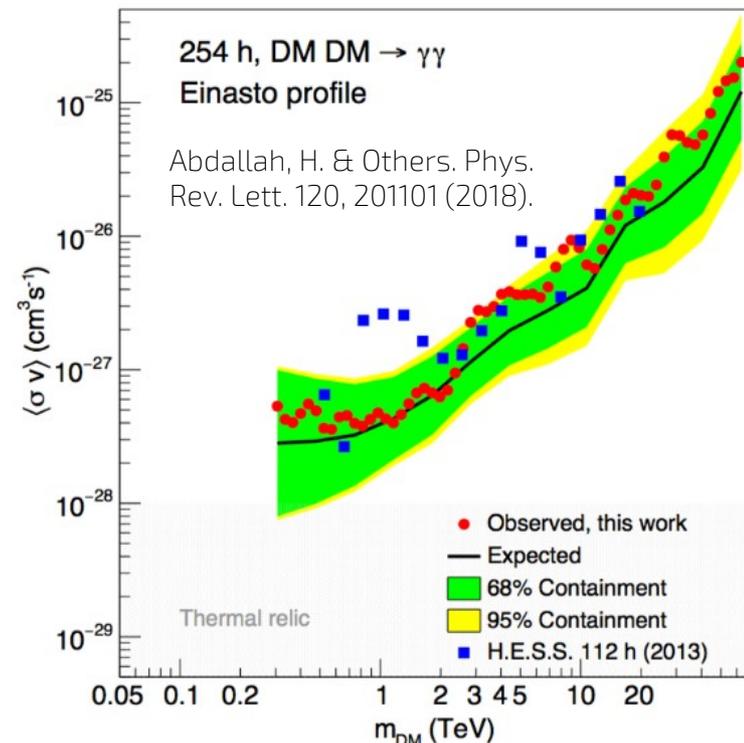
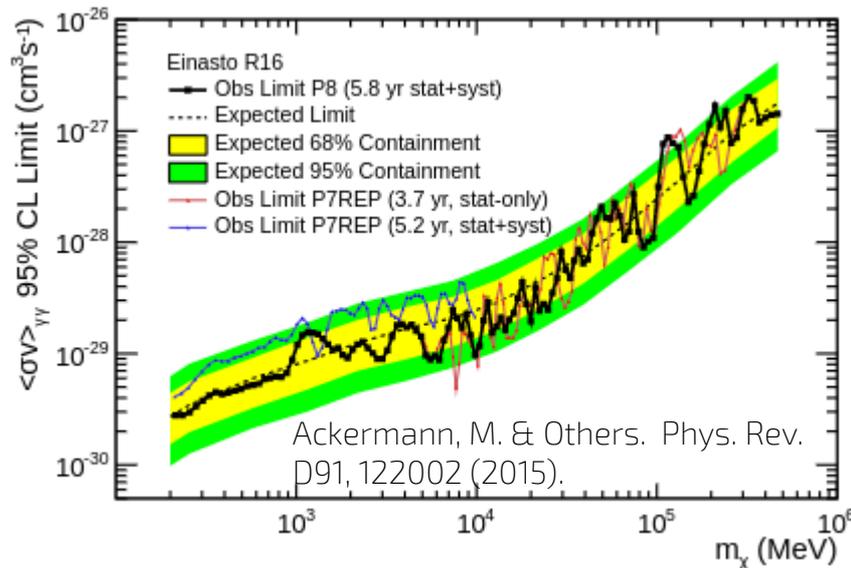
Line constraints in general

$$\chi\chi \rightarrow \gamma\gamma$$

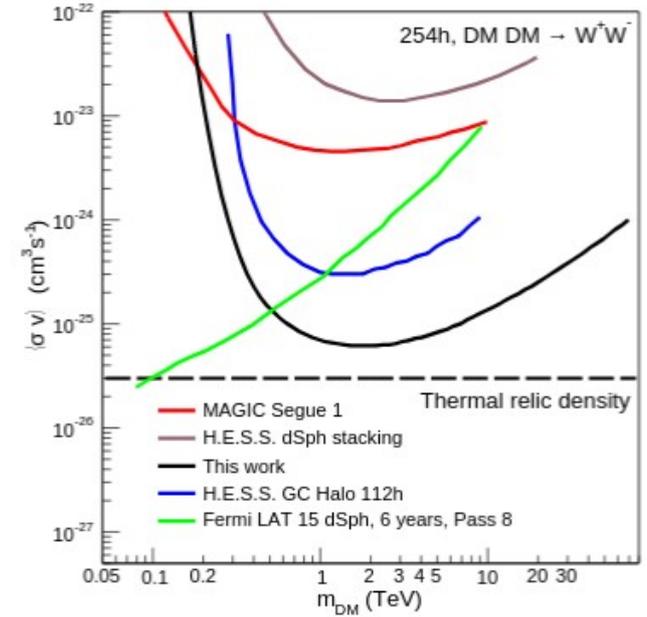
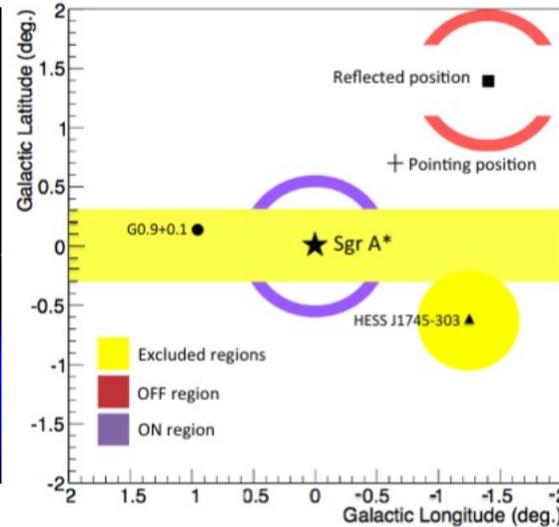
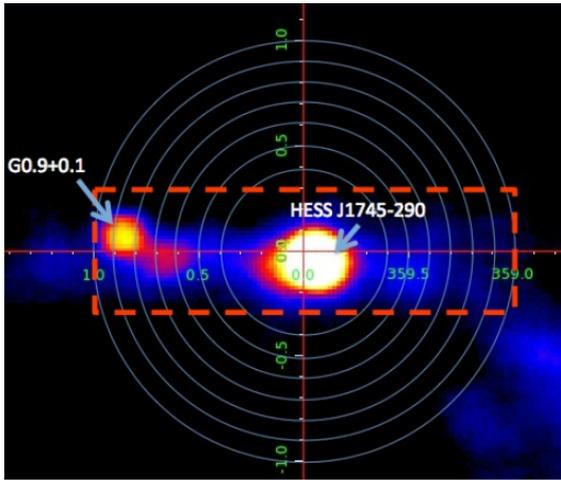
- Gamma ray lines, virtual internal Bremsstrahlung, etc, would provide clear discoveries against astro bkgs
- Observational constraints are usually strongest from the Galactic center (highest statistics, ~no bkg confusion)
- Branching ratios small as well → Only in exceptional cases the leading constraint



Systematics dominated below 3 GeV



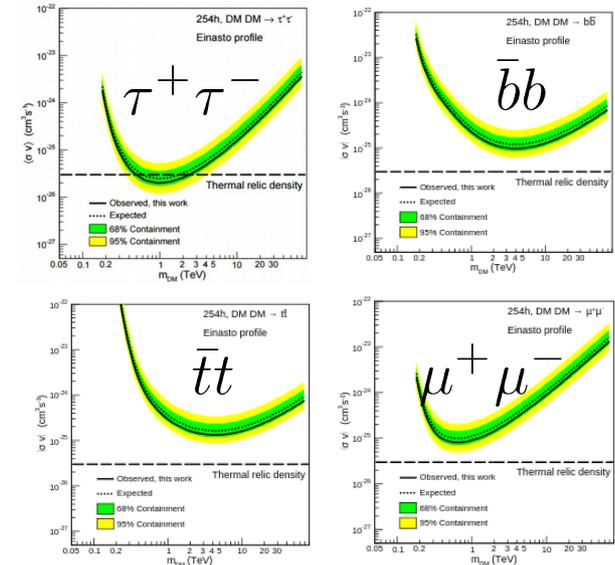
H.E.S.S. - Galactic center



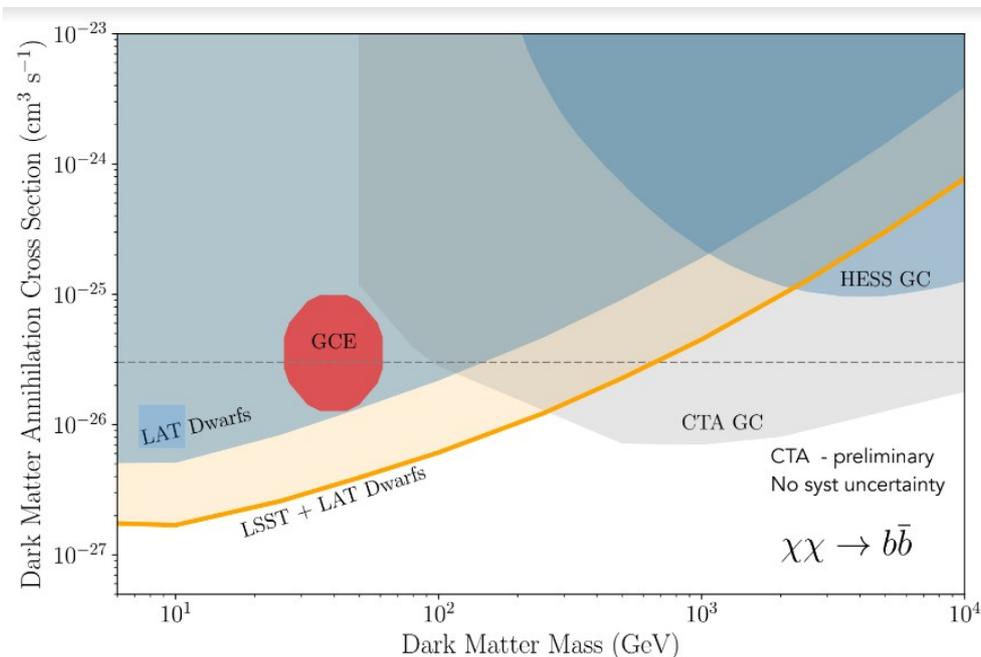
Abdallah, H. et al. Phys. Rev. Lett. 117, 111301 (2016).

DM searches with Cherenkov telescopes

- Large CR backgrounds imply that brightest targets are best \rightarrow GC
- Strongest limits from HESS GC halo observations, recent updates use improved stat. method (HESS 2016)
- Relevant limits at ultra-high-energy gamma rays ($m > 100$ TeV) come from IceCube [e.g., Murase & Beacom 2012]
- Constraints practically disappear for cored profiles

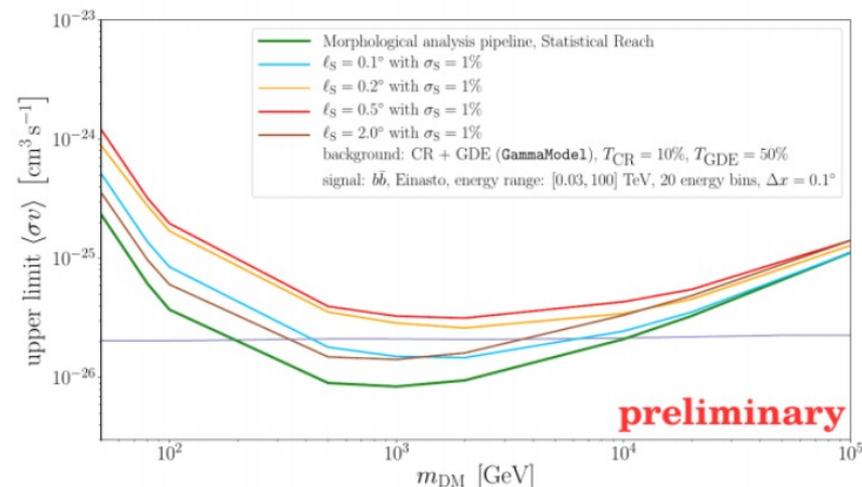


Outlook GeV - TeV energies



From Drlica-Wagner, A. & Others. arXiv [astro-ph.CO] (2019).

See also Carr, J. & Others. PoS ICRC2015, 1203 (2016).



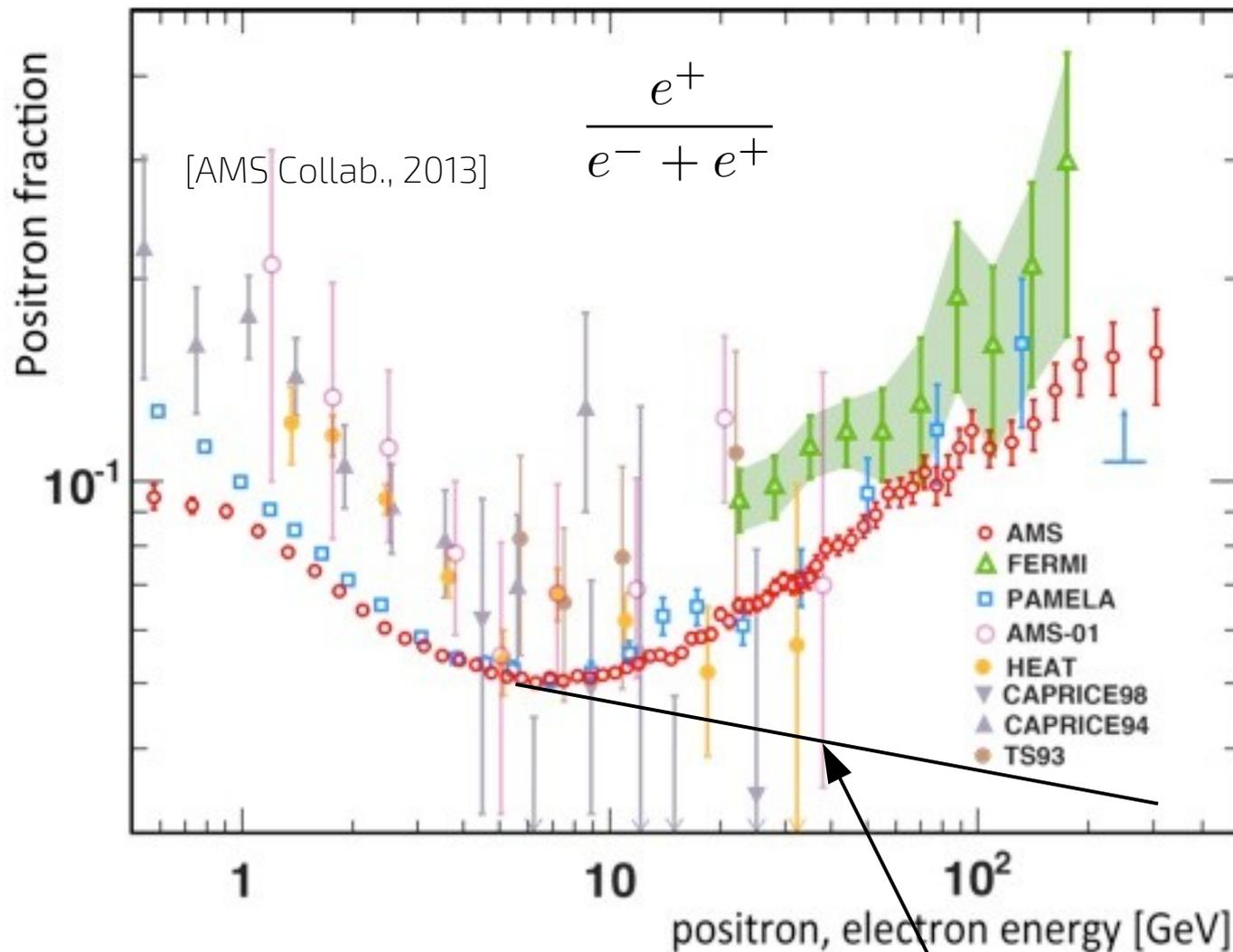
- Obtaining subthermal constraints is challenging, requires understanding bkg's at ~1% level

Silverwood, H., CW, Scott, P. & Bertone, G. JCAP 1503, 055 (2015); Balázs, C. et al. 2017; Pierre, M., Siegal-Gaskins, J. M. & Scott, P. 2014

General high energy prospects:

- Above $m \sim 100$ TeV, HAWC will improve limits from observations of dSph & GC (Abeysekara+ 2014; Proper+ 2015)
- LHAASO (~ 2022) will dominate above $m \sim 100$ TeV in the long run (e.g. Knödlseder 2016)
- CTA (~ 2025) will improve HESS limits by factor up to 10 (Silverwood+ 2015, Doro+ 2013, Carr+ 2015, Lefranc+ 2015)

PAMELA positron excess



Standard cosmic-ray propagation scenarios predict a decrease

Pulsars or DM are possible explanations

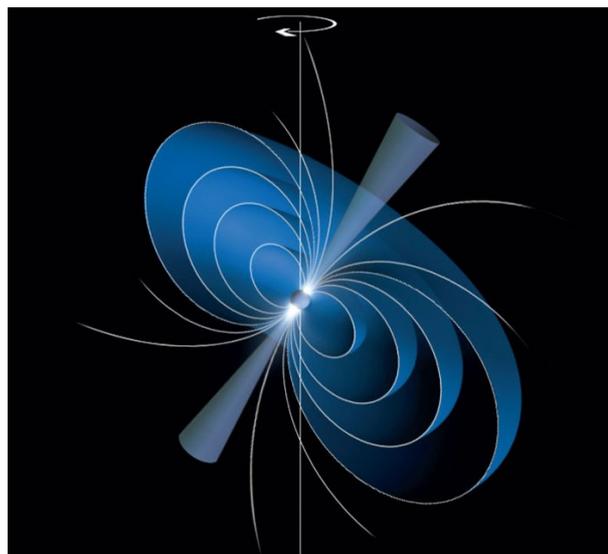
Dark matter annihilation or decay into leptonic final states, e.g.

$$\chi\chi \rightarrow \mu^+ \mu^-, \tau^+ \tau^-$$

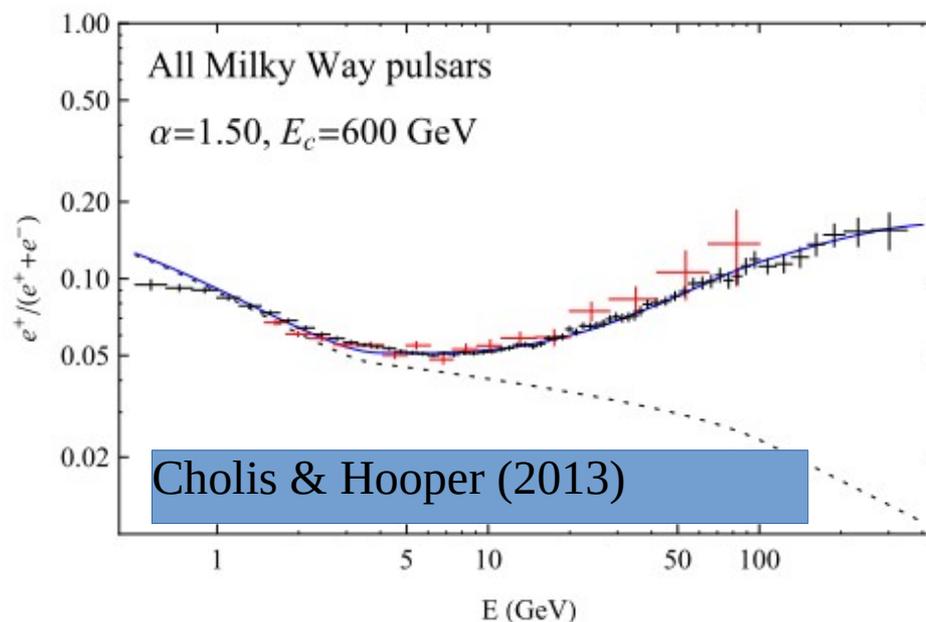
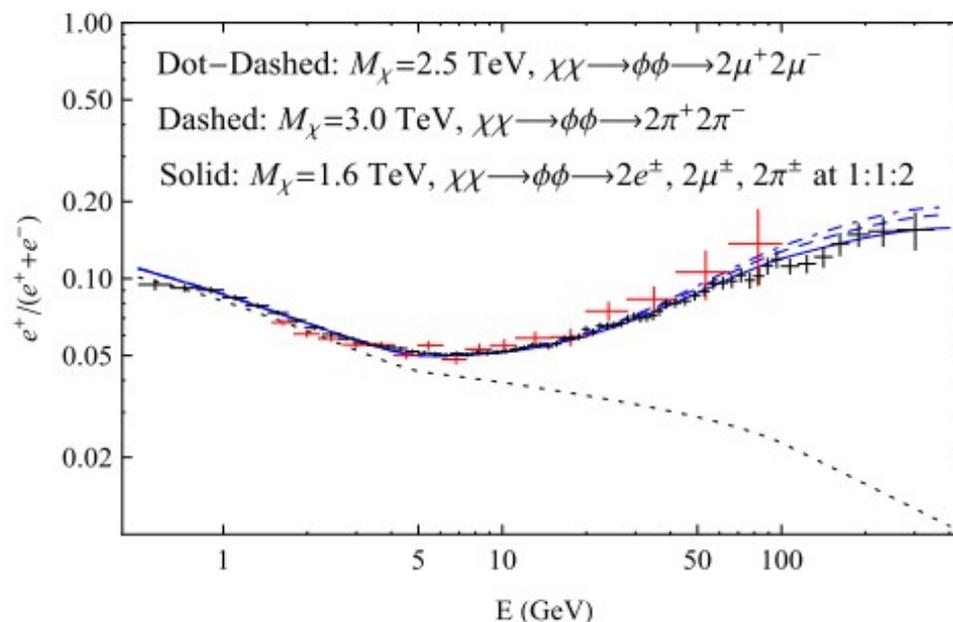
This is already strongly constrained by the non-observation of corresponding gamma-ray, anti-proton etc. signatures.

Papucci & Strumia 2010; Cirelli+ 2010; Ibarra+ 2010...

Pair production in pulsar magnetosphere



e.g. Profumo 2008



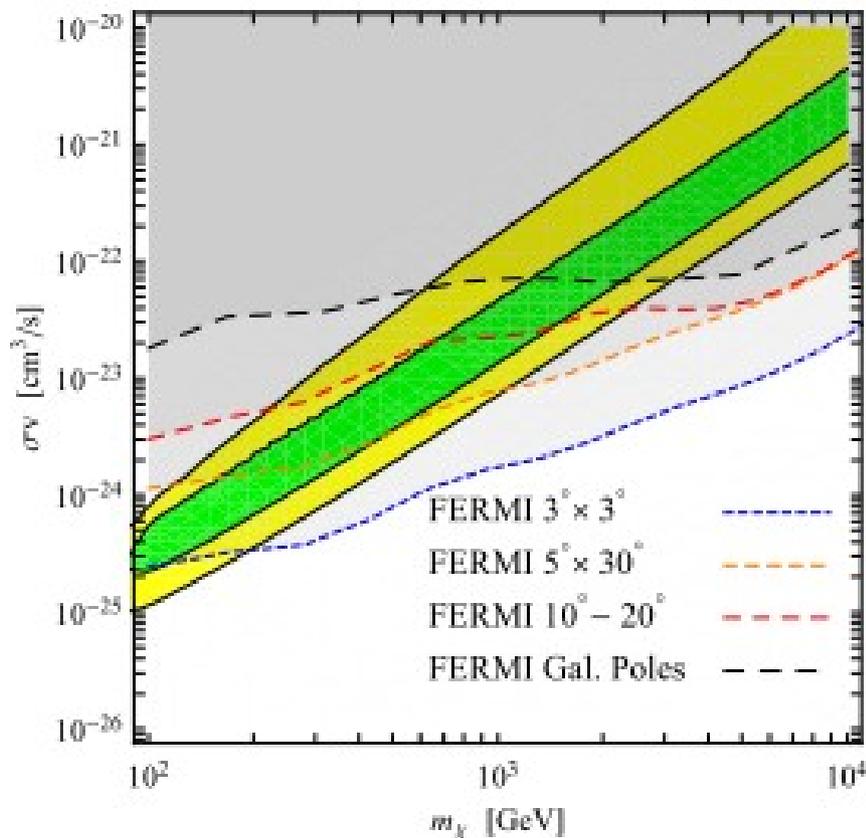
Tension with other indirect searches

Annihilation into leptons produces always an Inverse Compton Emission component, that is not seen in gamma rays

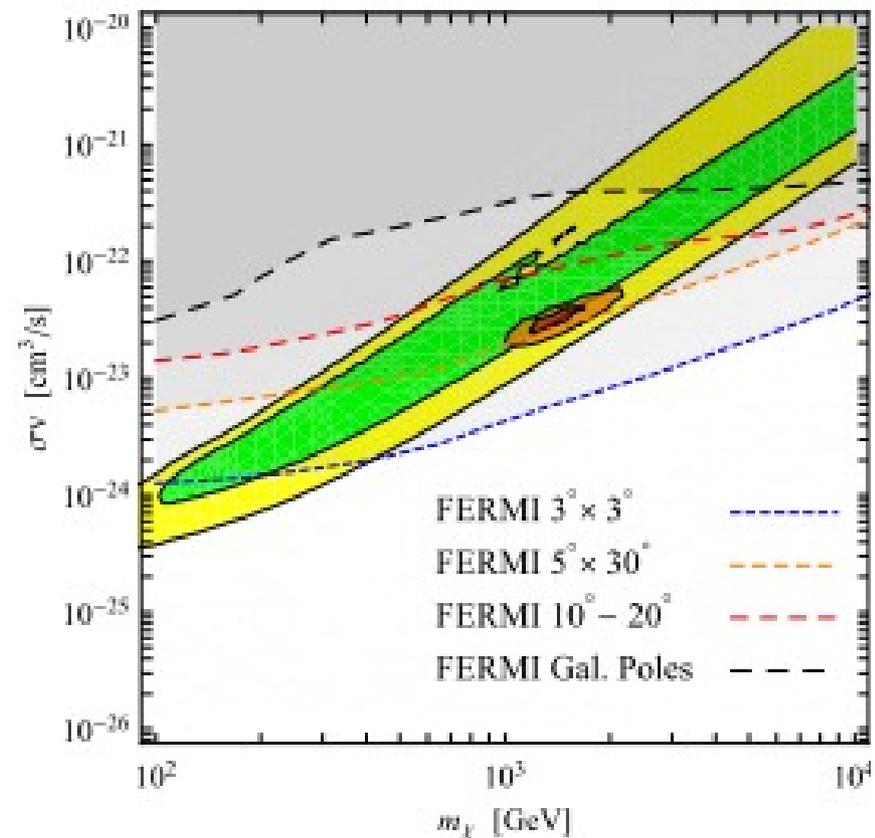
[Cirelli, Panci & Serpico (2009)]

(fits to PAMELA data)

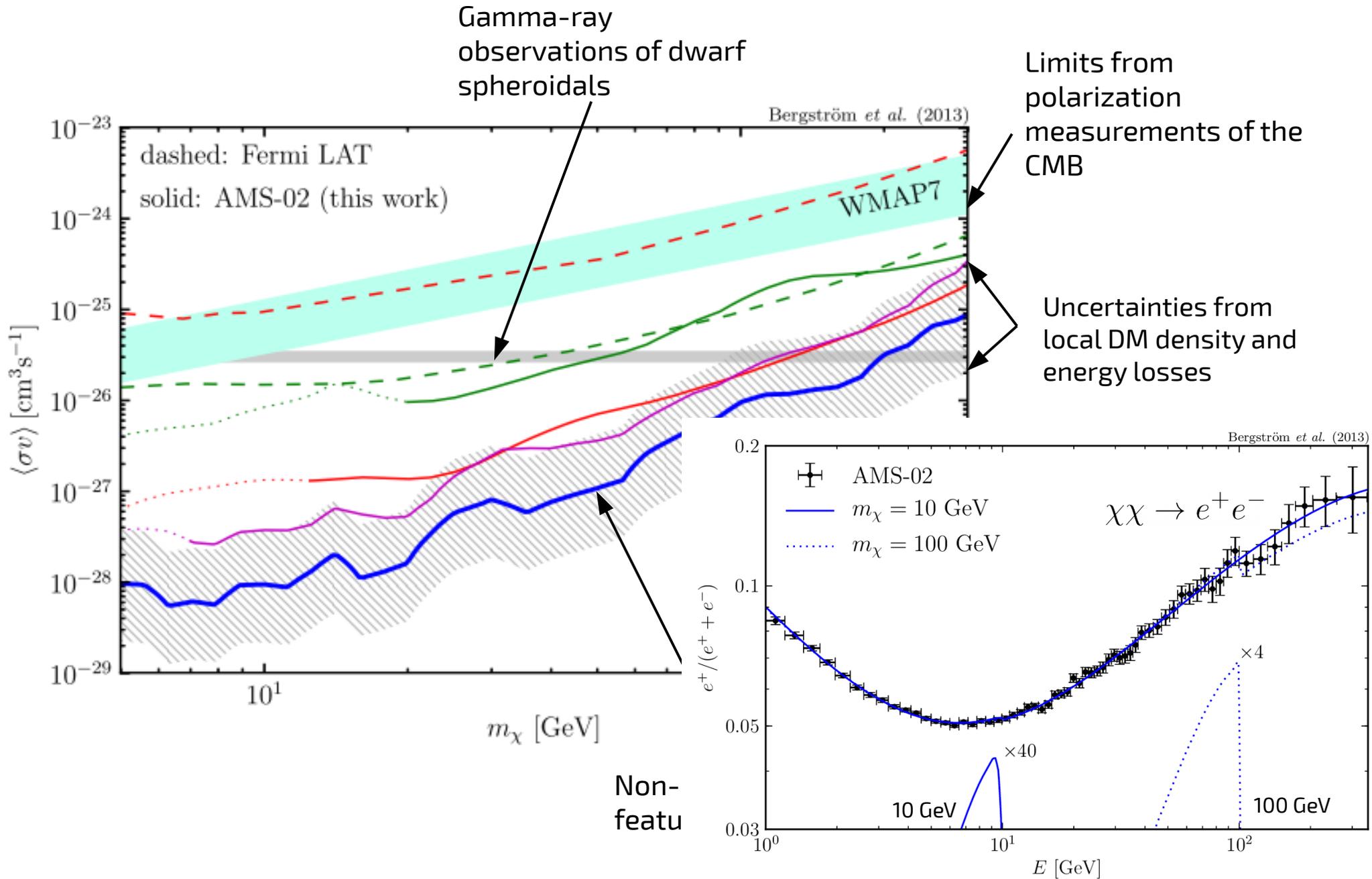
DM DM $\rightarrow ee$, NFW profile



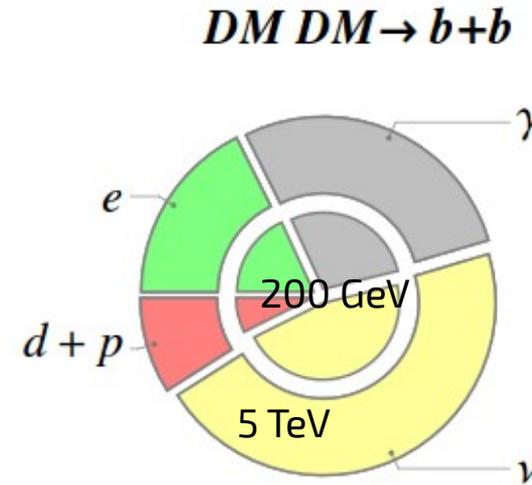
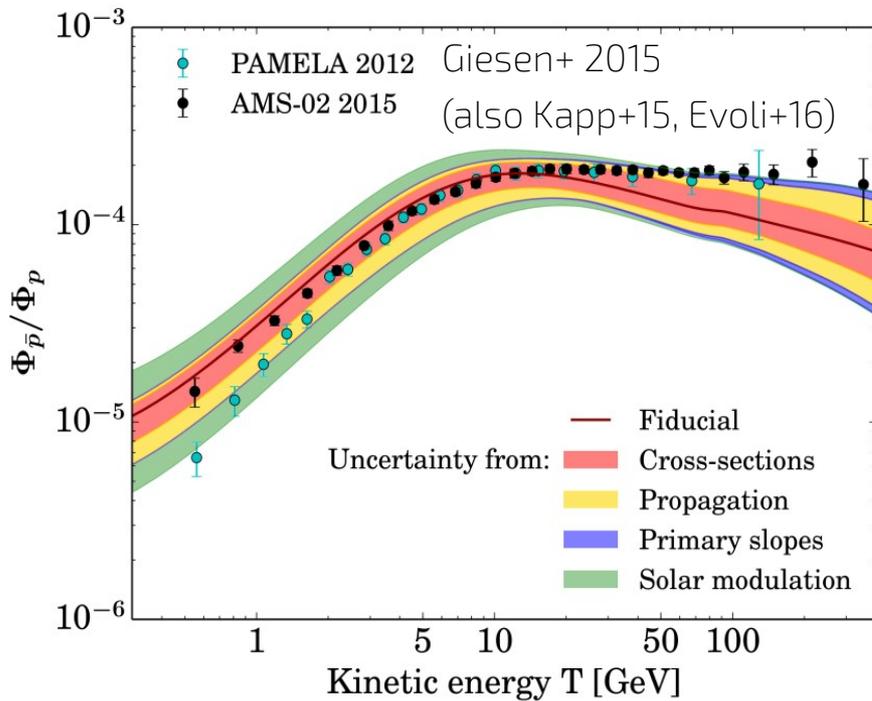
DM DM $\rightarrow \mu\mu$, NFW profile



Leptons



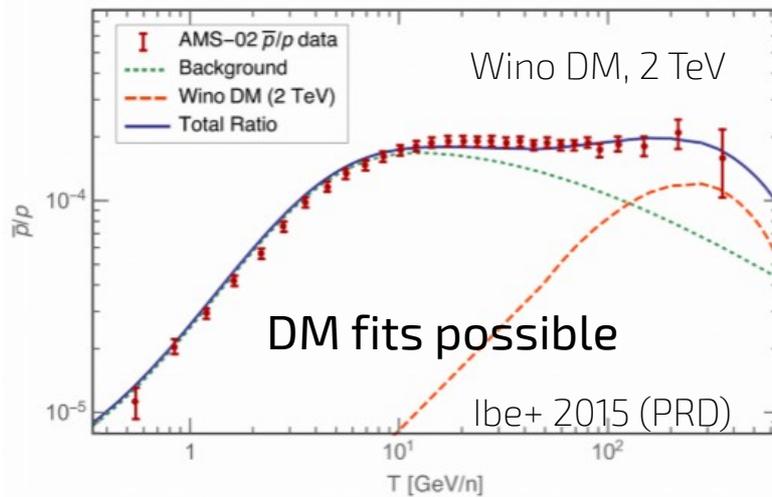
DM searches with anti-protons



Cirelli et al. (2010) "PPPC4DMID"

Anti proton constraints

- Background of secondary anti-protons can be predicted within factor of a few
- AMS-02 measurements marginally consistent with secondary background (Giesen+ 15; Evoli+ 15)
- Hard to exclude astro explanation for excesses above secondaries (e.g. nearby SNR; e.g. Kachelriess+ '15, non-universal diffusion, etc)

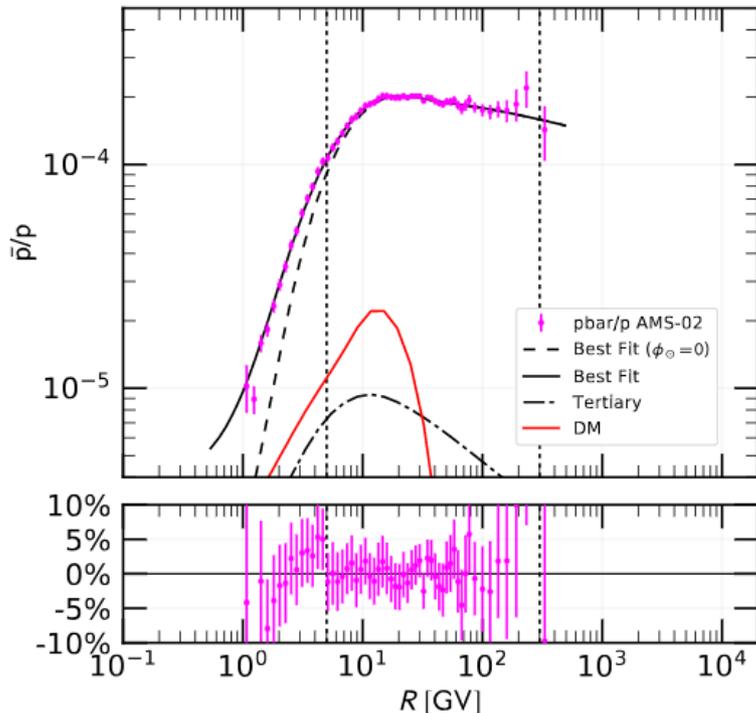


See also: Winkler+ 17; Carlson+14; Cirelli+14; Jin+15; Ibe+15; Hamaguchi+15; Lin+15; Kohri+15; Balazs&Li15; Doetinchem+15; Fornengo+13

Anti-proton ~ 15 GV excess?

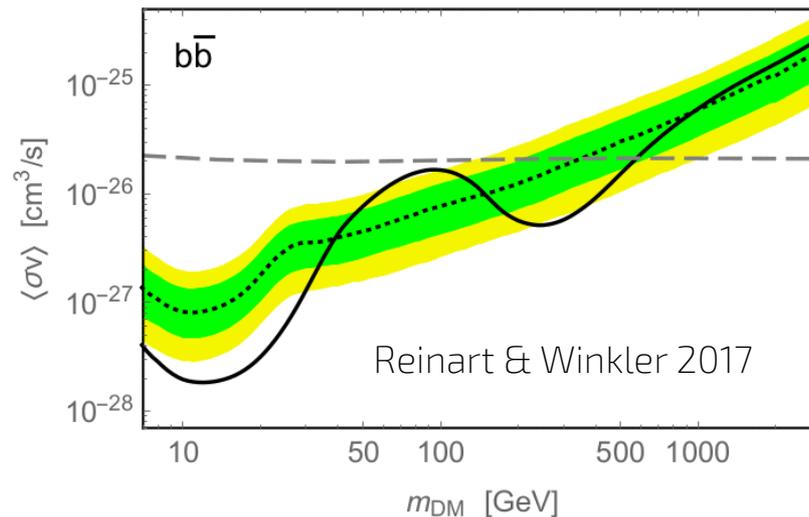
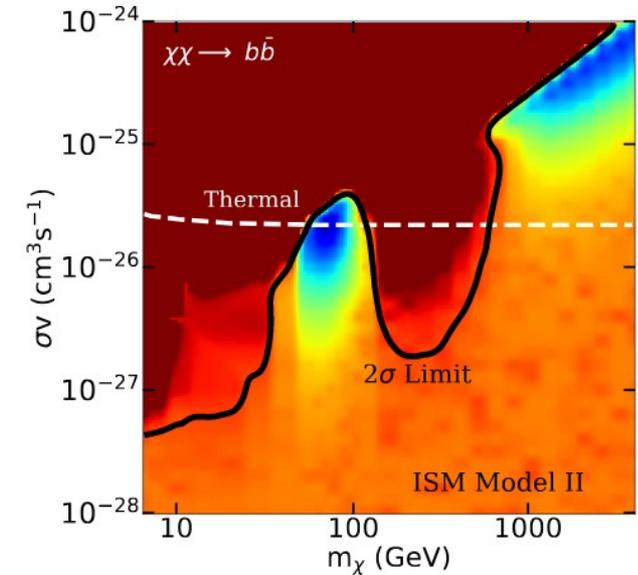
Cuoco+ 2019

- First identified in Cuoco+ 2017, with ~ 4 sigma significance
- After new systematic checks, still at few sigma level
- Marginalizing over pbar production cross section reduces significance
- Correlated instrumental systematics are important, of same order as excess, but correlation structure is now publically available



Cholis+ 2019

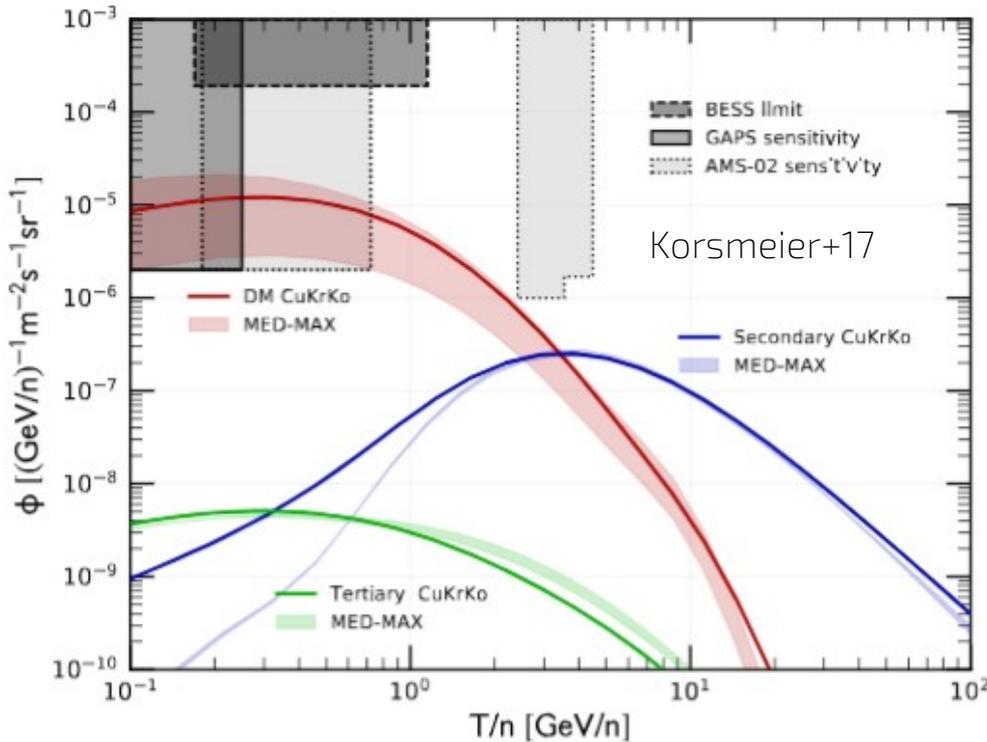
- Check time-/charge-dependent diffusion
- Confirm excess with even higher significance (though no marginalization over all parameters)



Outlook - GAPS

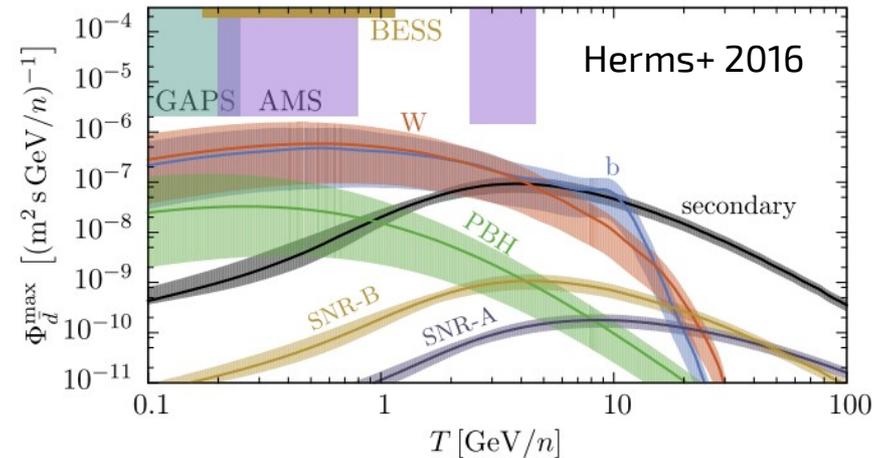
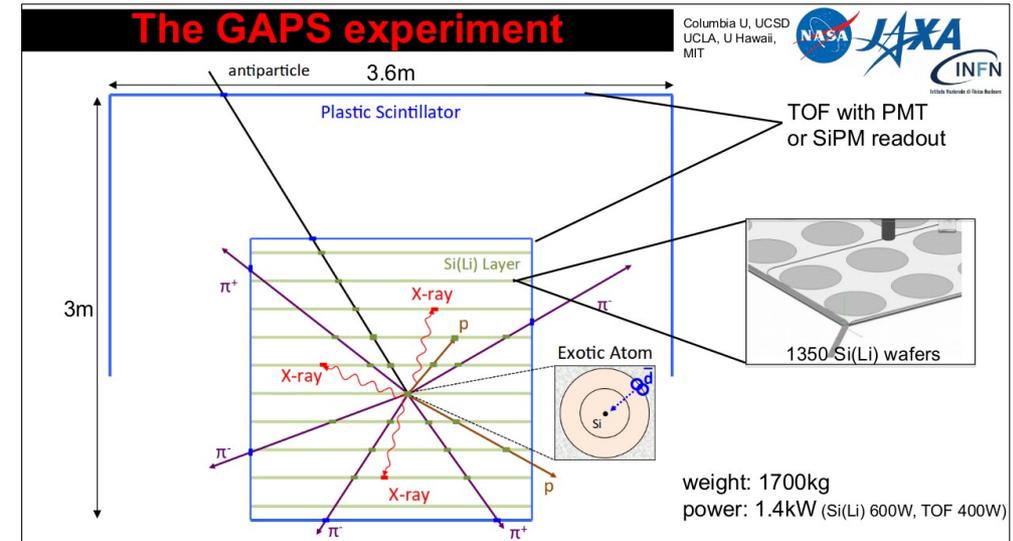
Searches for **anti-deuterons** with exotic atom formation

Supported by USA, Italy, Japan. First flight planned for ~2021.



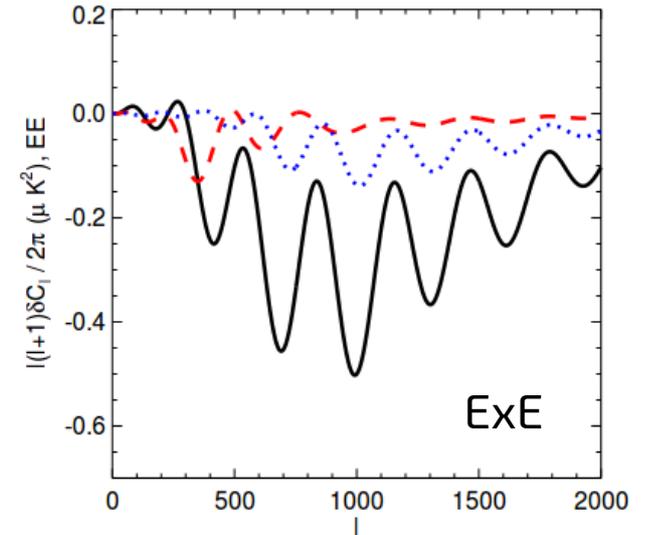
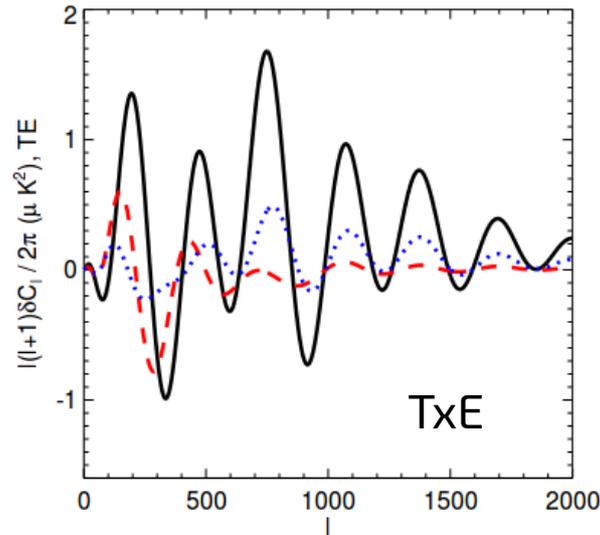
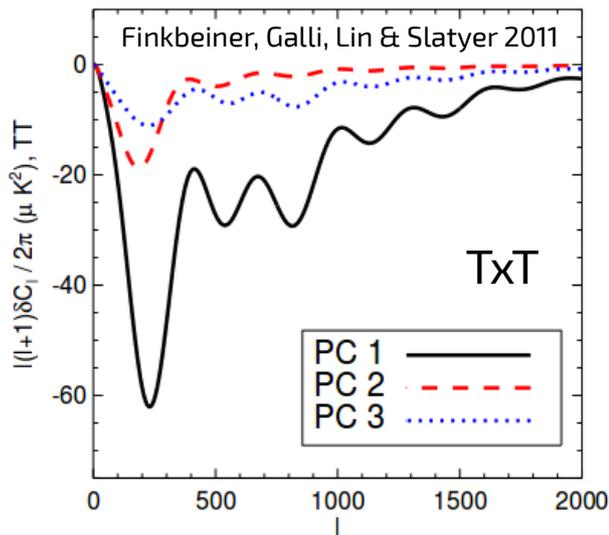
See also Aramaki+ 2016

Credit: P. von Doetinchem



Sever constraints on the range of detectable models comes from AMS-02 anti-protons.

DM annihilation and the CMB

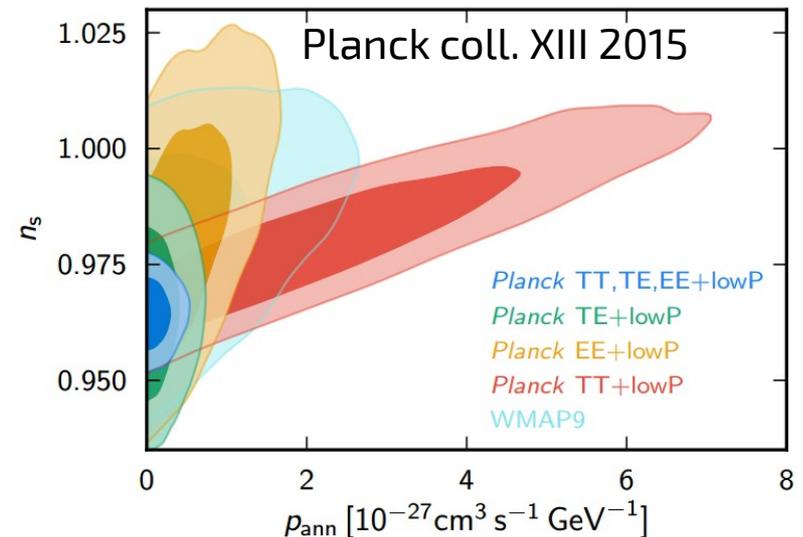


Bounds on annihilating DM

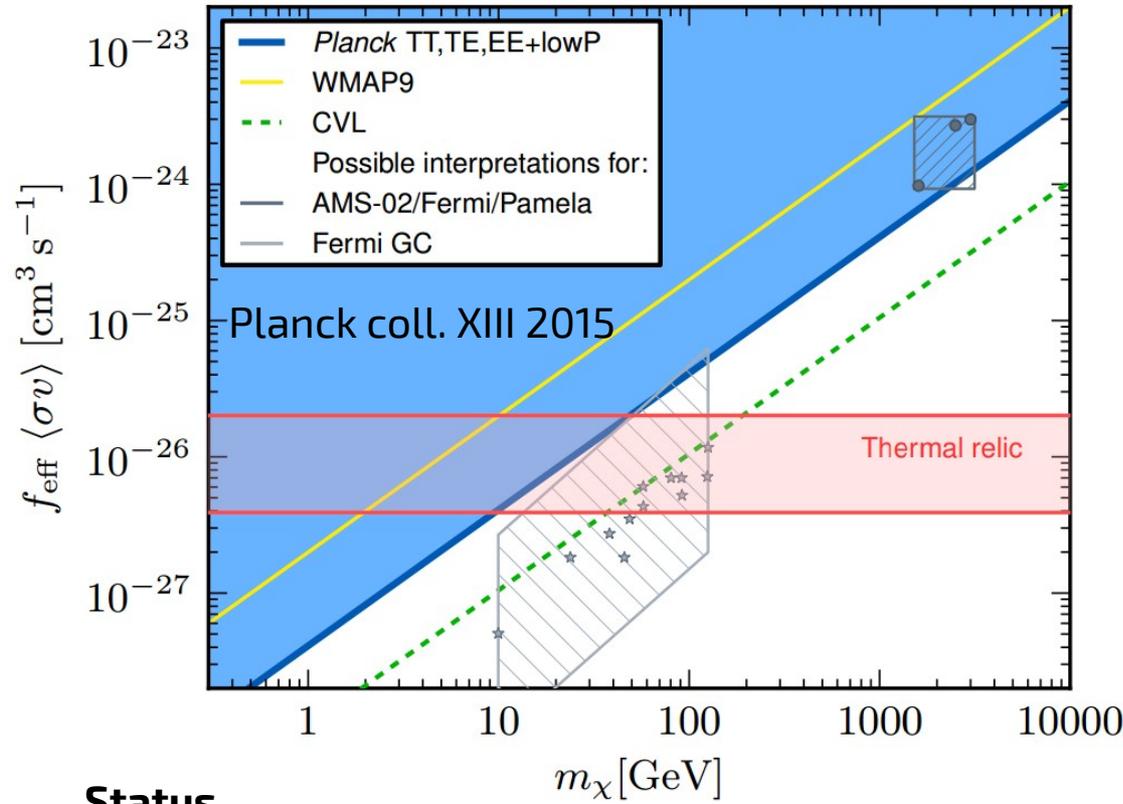
- Energy injection

$$p_{\text{ann}}(z) \equiv f(z) \frac{\langle \sigma v \rangle}{m_\chi}$$

- Energy injection at $z \sim 500 - 1000$ increases free electron fraction
 - broadening of surface of last scattering
 - less fluctuations at small scales
- Insensitive to details of non-linear structure formation



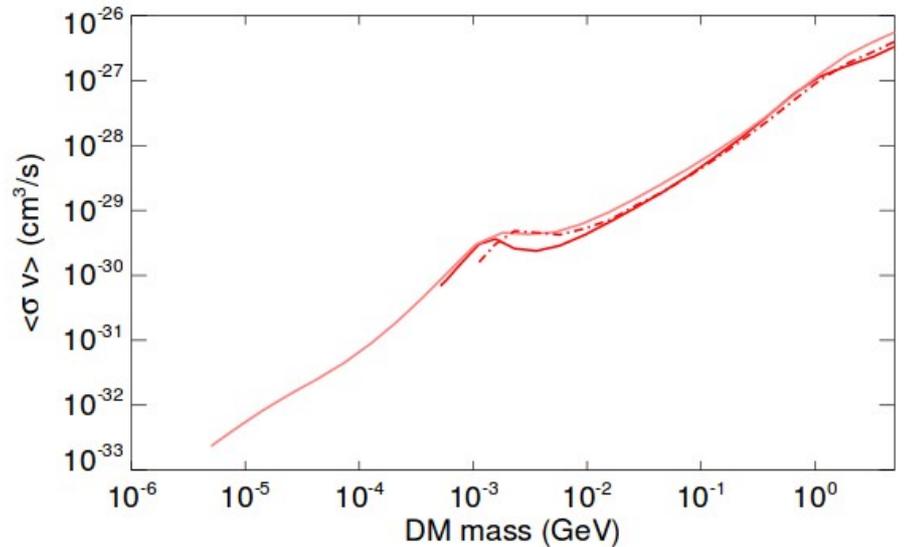
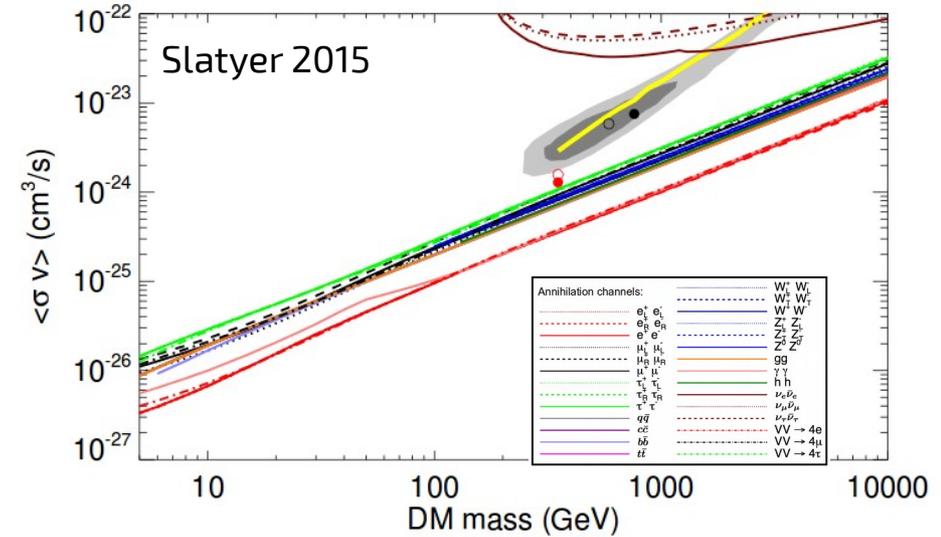
Bounds on DM from Planck observations



Status

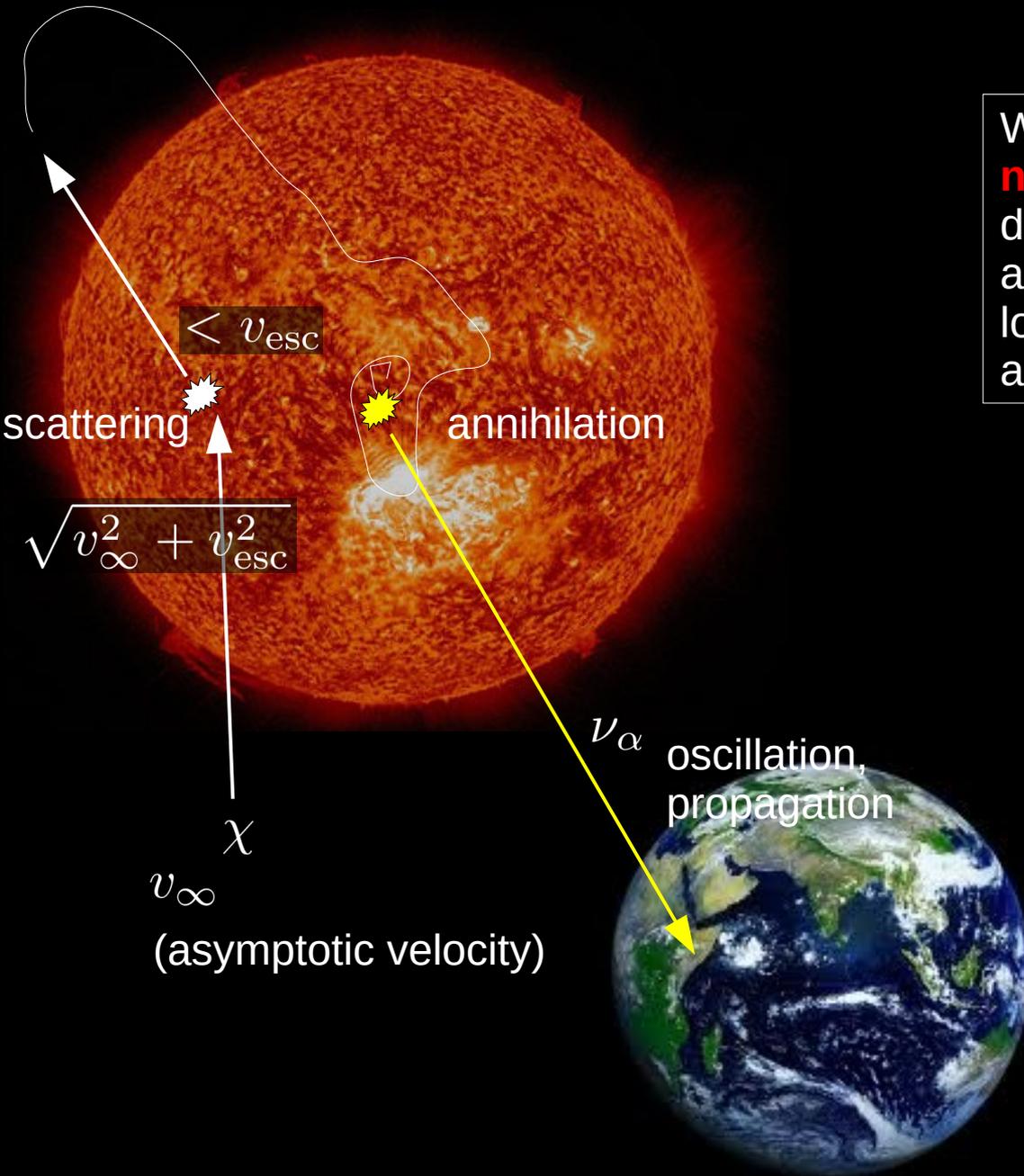
- Bounds depend on effective energy deposition (f_{eff}), otherwise very robust
- Exclude s-wave annihilation below $m \sim 10$ GeV unless annihilation into neutrinos dominates

$$\langle\sigma v\rangle \lesssim (1 - 4) \times 10^{-27} \left(\frac{m_\chi}{1 \text{ GeV}}\right) \text{cm}^3 \text{s}^{-1}$$



see also Ali-Haimoud+15; Liu+16; Chluba+16; Cline&Scott 13; Galli+13; Madhavacheril+13

The Sun as DM collection vessel



WIMPs occasionally **scatter on atomic nuclei inside the Sun**. If their velocity drops below the escape velocity, they are trapped in an orbit around the Sun, lose more energy and finally accumulate at the Sun's center.

$$\dot{N} = C - C_A N^2$$

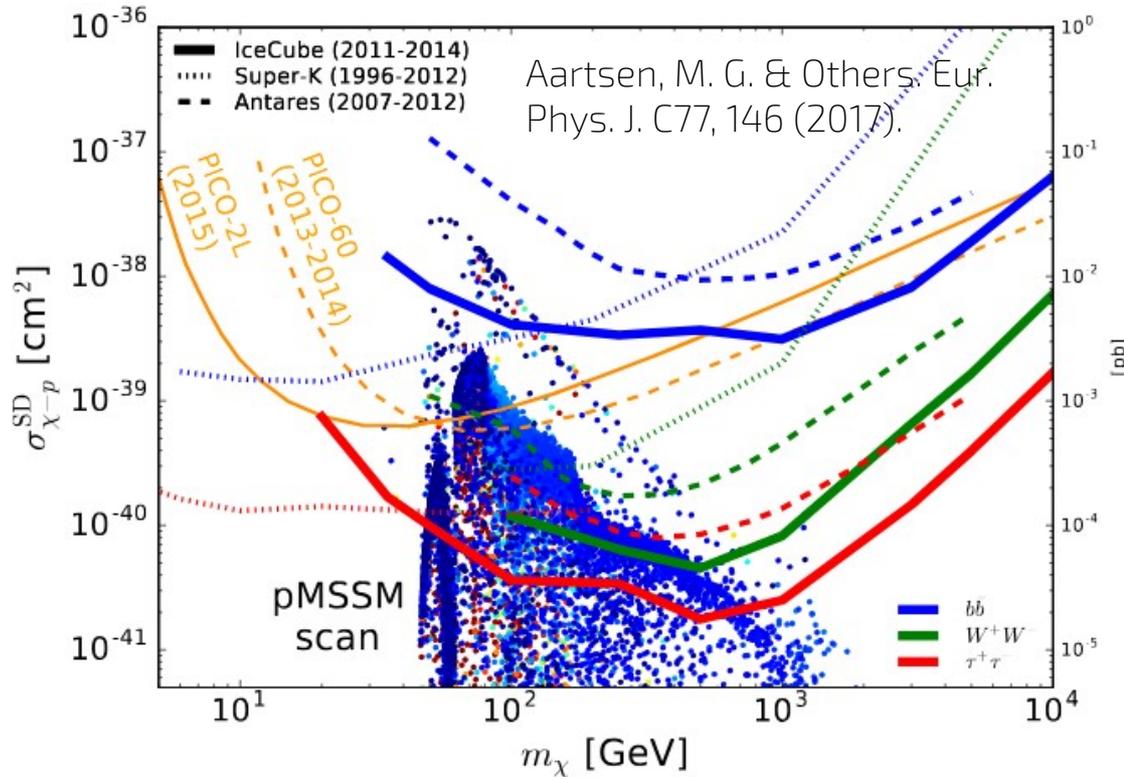
\dot{N} : Number of WIMPs
 C : Capture rate $C \propto \sigma \rho_\chi$
 C_A : Annihilation rate
 N : Number of WIMPs

In equilibrium, the annihilation rate is fully determined by the capture rate:

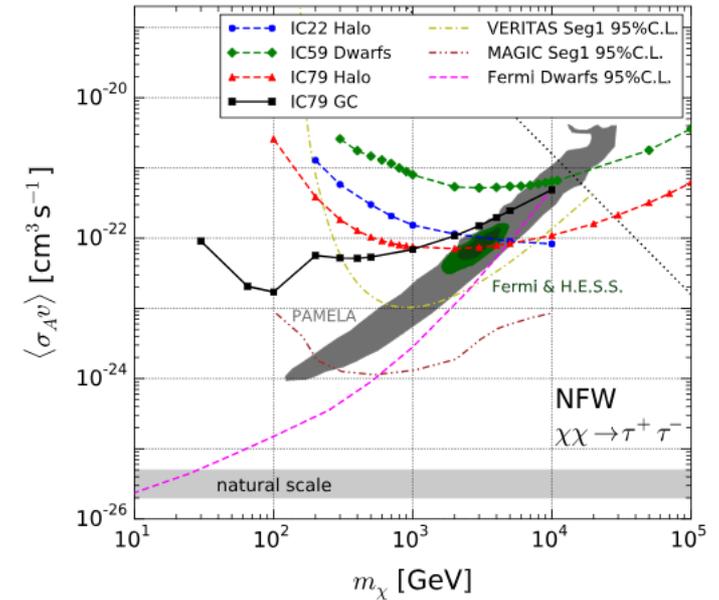
$$\Rightarrow \Gamma_A = \frac{C_A}{2} N_{\text{eq}}^2 = \frac{C}{2}$$

CR neutrinos from the Sun

DM annihilation of WIMPs **captured in the Sun**
 → Flux depends on WIMP-proton scattering
 (in equilibrium)



DM annihilation in MW

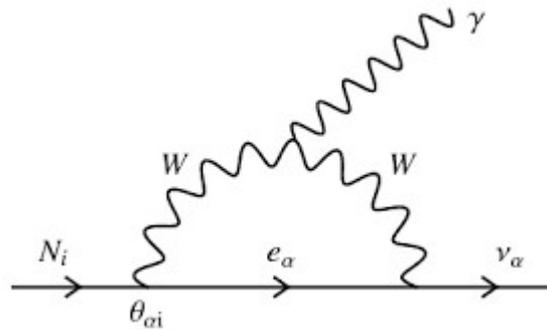


Aartsen, M. G. & Others. Eur. Phys. J. C75, 492 (2015).

Situation

- Most stringent bounds on spin-dependent scattering cross-section in the 10 GeV to multiple TeV range come from neutrino telescopes (IceCube, Super-K)
- However, searches for signal from GC not very competitive since neutrinos usually accompanied by photons etc

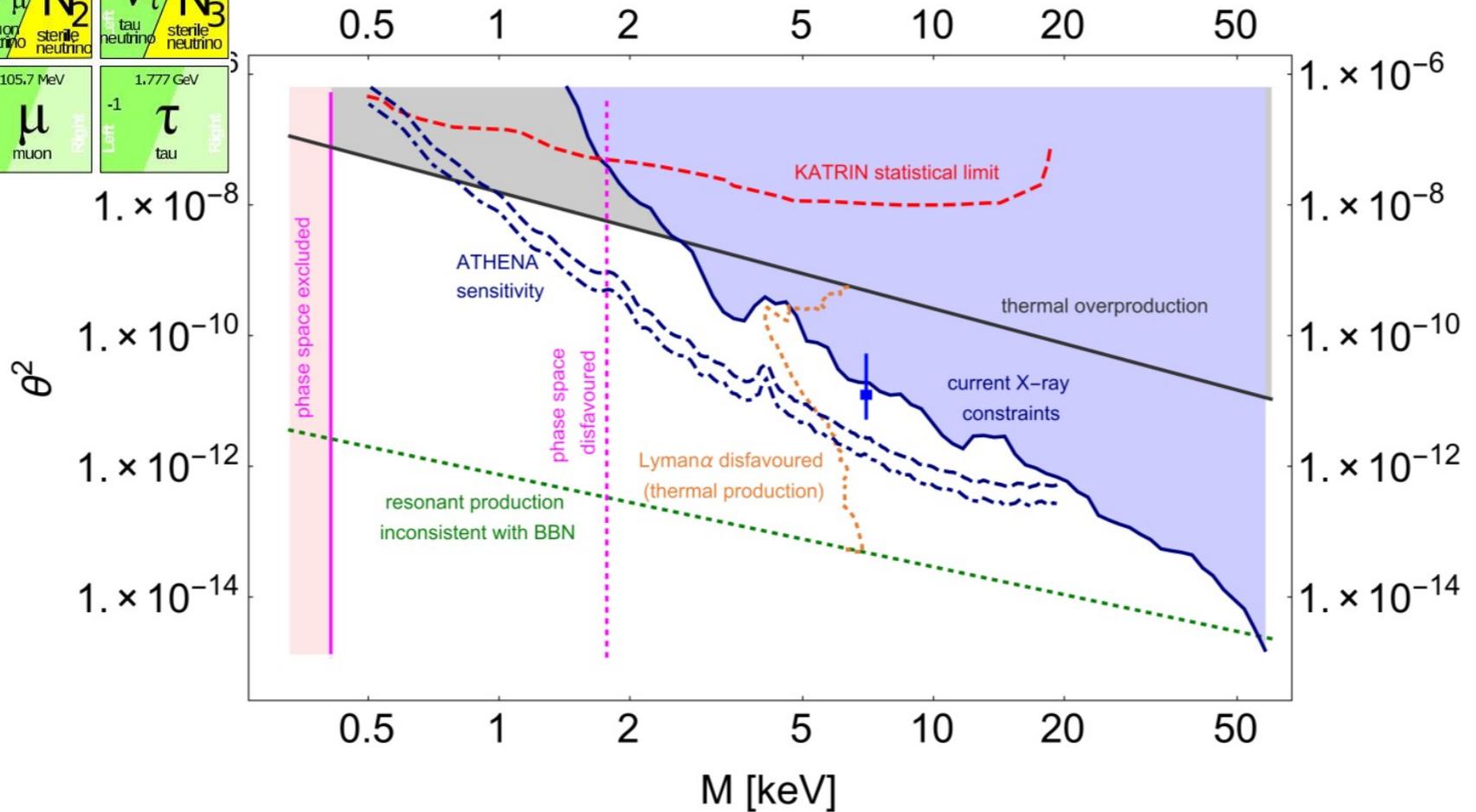
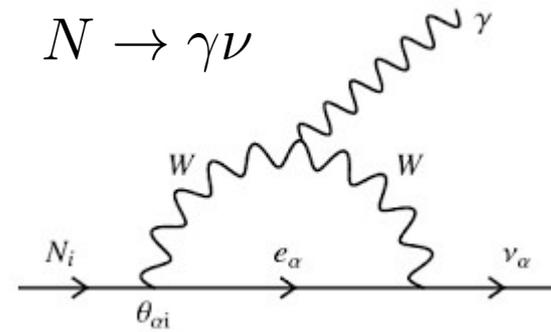
2) Dark matter decay



Sterile neutrino DM searches

nuMSM

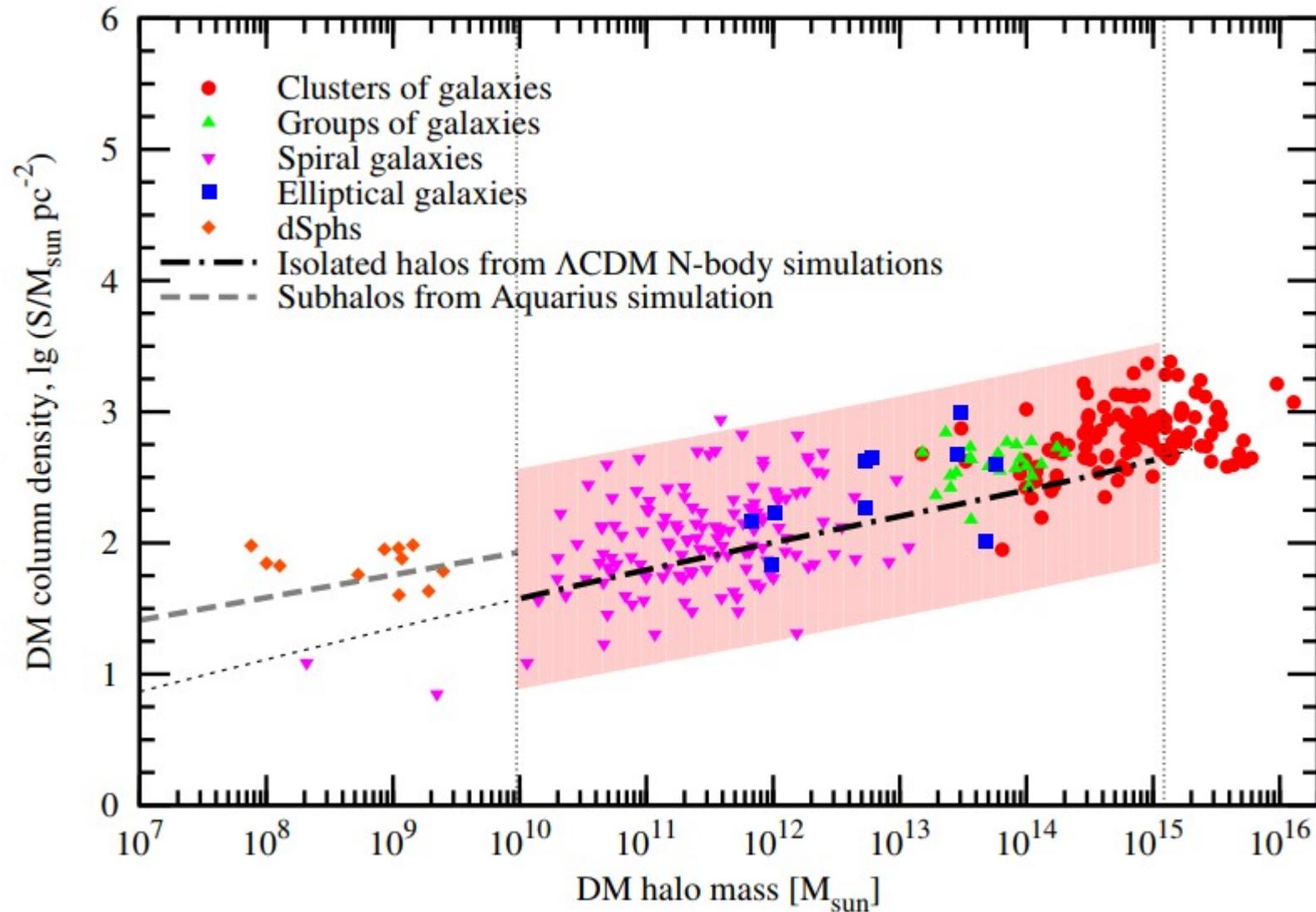
mass →	2.4 MeV	1.27 GeV	171.2 GeV
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
name →	u up	c charm	t top
	Left Right	Left Right	Left Right
Quarks			
mass →	4.8 MeV	104 MeV	4.2 GeV
charge →	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
name →	d down	s strange	b bottom
	Left Right	Left Right	Left Right
Leptons			
mass →	<0.0001 eV ~10 keV	~0.01 eV ~GeV	~0.04 eV ~GeV
charge →	0	0	0
name →	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino
	Left Right	Left Right	Left Right
Leptons			
mass →	0.511 MeV	105.7 MeV	1.777 GeV
charge →	-1	-1	-1
name →	e electron	μ muon	τ tau
	Left Right	Left Right	Left Right



Credit: Ruchaysky

Comparable DM column density

Boyarisky+ 09

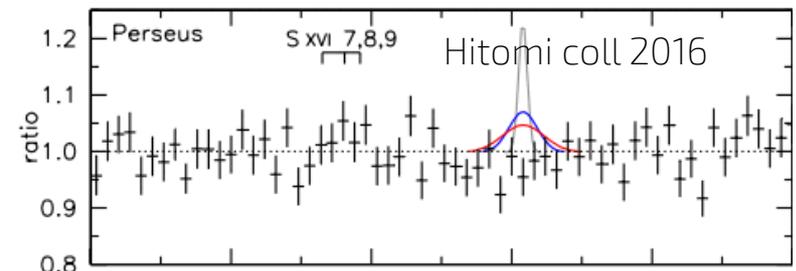
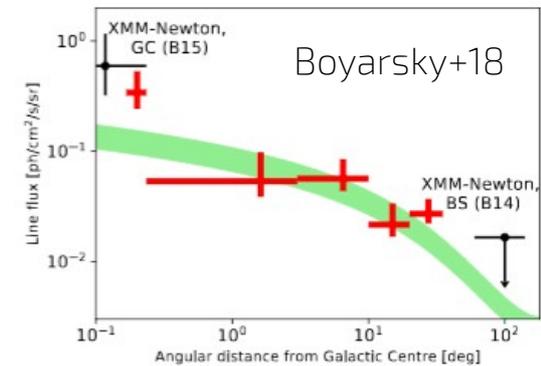
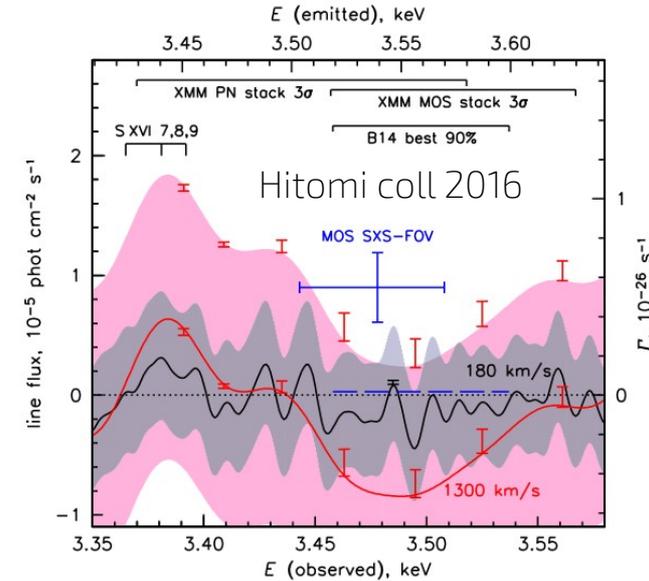
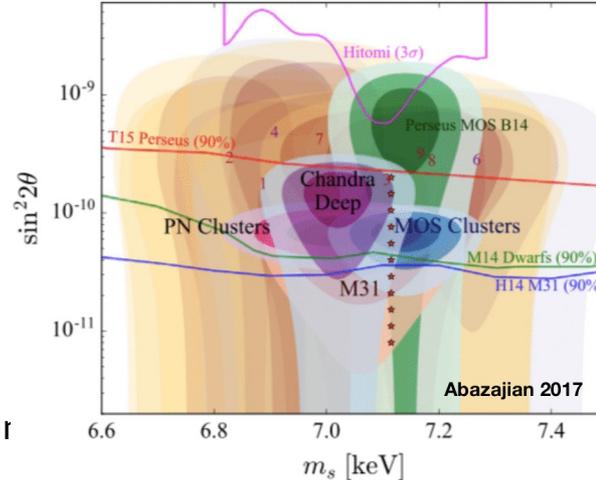


The central column density of halos with very different sizes is comparable, making a large range of objects good targets for decaying DM searches.

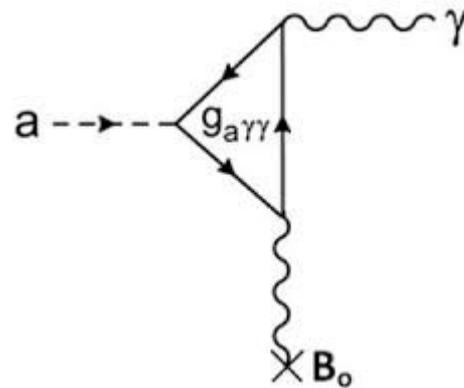
The “3.5 keV feature”

Situation

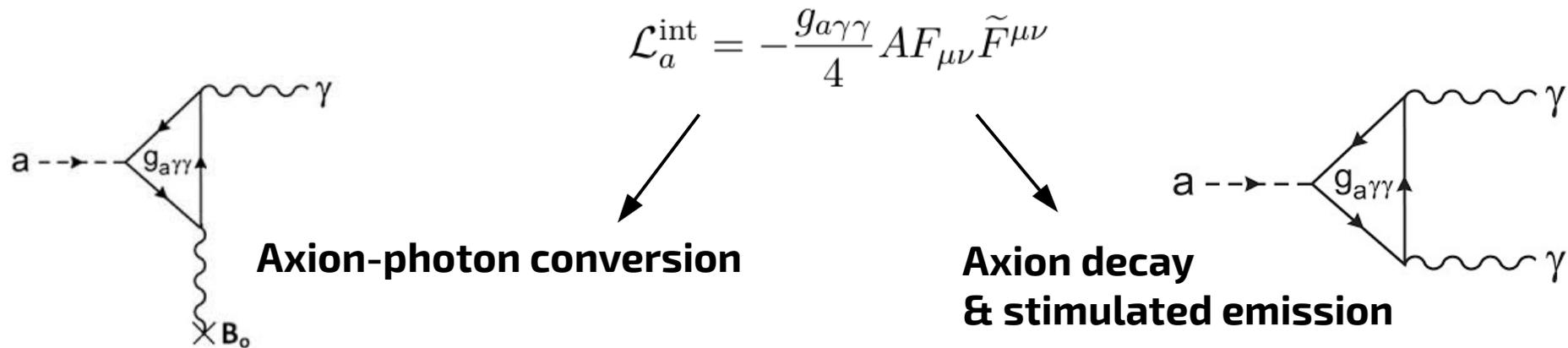
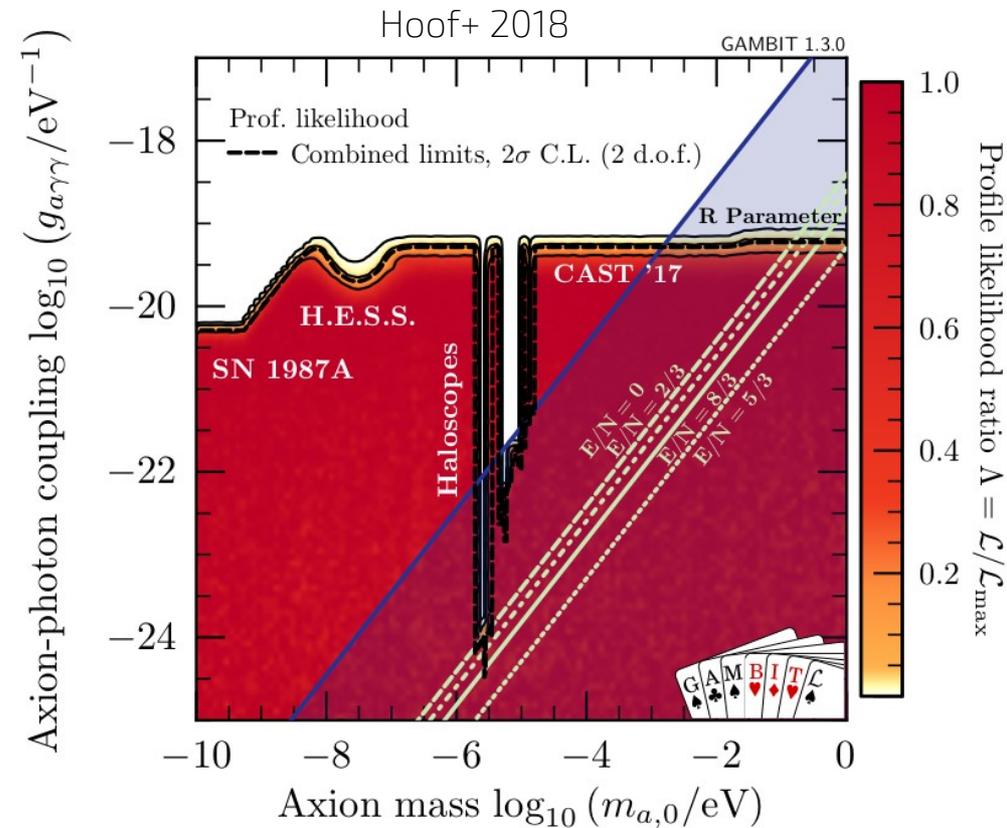
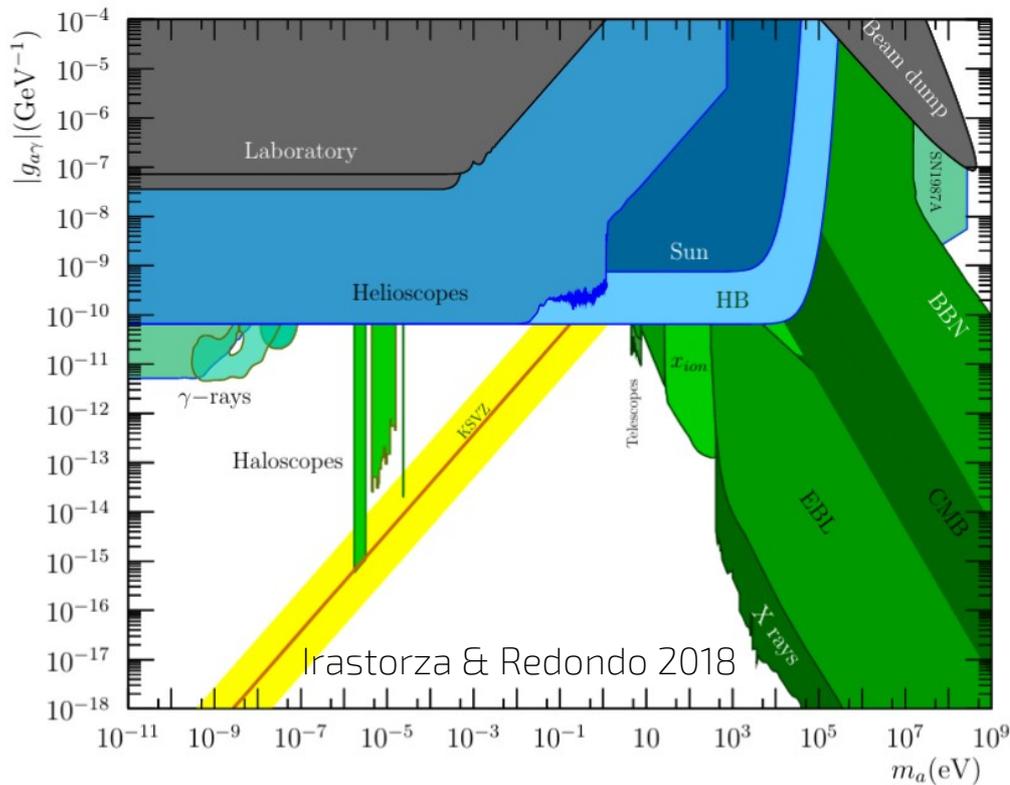
- Found in 4 different detectors
XMM-MOS/PN, Chandra, Suzaku, NuStar
[Boyarsky+14, Bulbul+14, ...]
- Found / hinted for in multiple targets
Milky Way & Andromeda, Perseus cluster, Draco dSph, stacked clusters, COSMOS & Chandra deep fields
- However: Results are somewhat analysis- and target dependent, need to get bkg's right etc
Non-detections in some deep field analysis, nearby galaxies
[Anderson+15, Dessert+18, Boyarsky+18]
- Hitomi observations disfavour Potassium line interpretation (or other narrow lines)
Still possible: Sulphur ion charge exchange?
[Gu+15&17, Shah+16]



3) Dark matter conversion

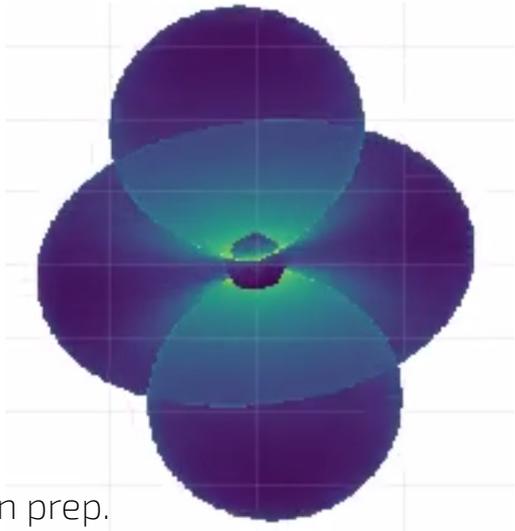


Axion Dark Matter - Status



Radio searches for axions - Sensitivity

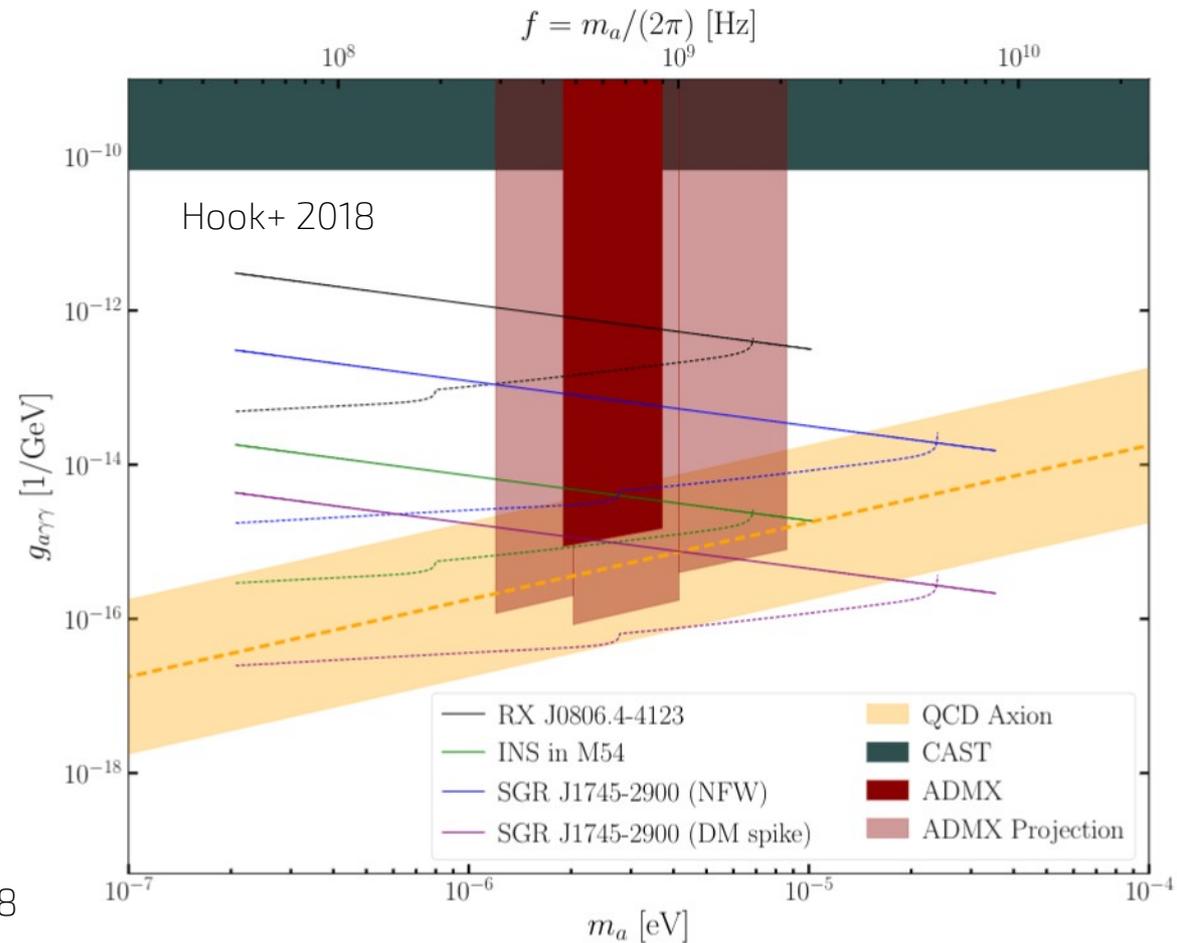
Ray-tracing simulation of DM axion-photon conversion signal from neutron stars



Leroy+, in prep.

See also Pshirkov 2009; Kelley & Quinn, 2017; Safdi+18

- Searches have clear discovery potential for QCD axions, but constraints will depend on our understanding of neutron star magnetospheres.
- Other targets: Dwarf spheroidals, white dwarfs (X-ray)
Safdi+19; Caputo+18



Some ongoing searches (all this year)

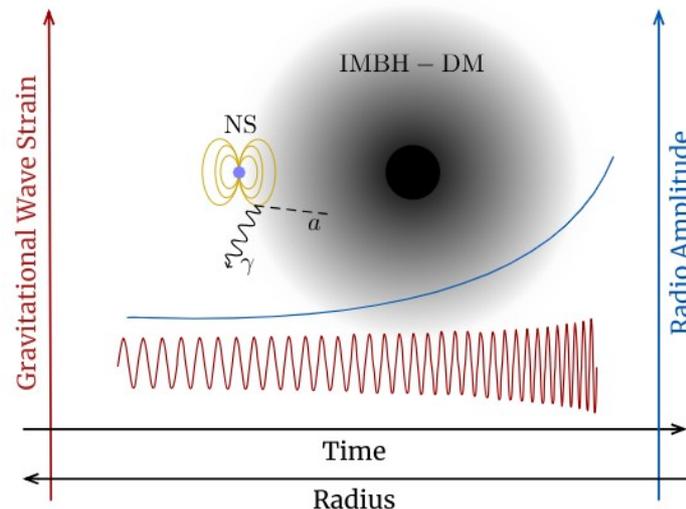
- Effelsberg telescope
- Greenbank telescope
- Murchison Widefield array
- Sardinia radio telescope

Probing axion DM with GWs & radio?

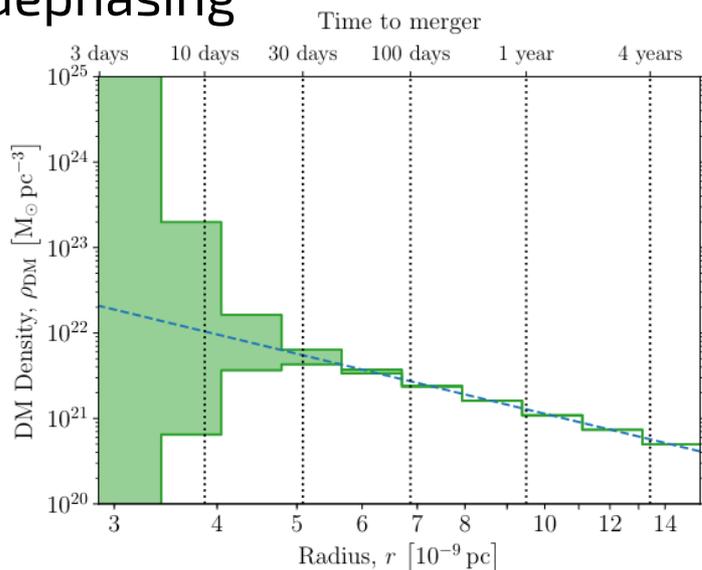
Grav. Wave (LISA) & radio observation

- De-phasing of GW signal
→ Measurement of DM spike profile
- Radio observations
→ Probing axion-photon conversion

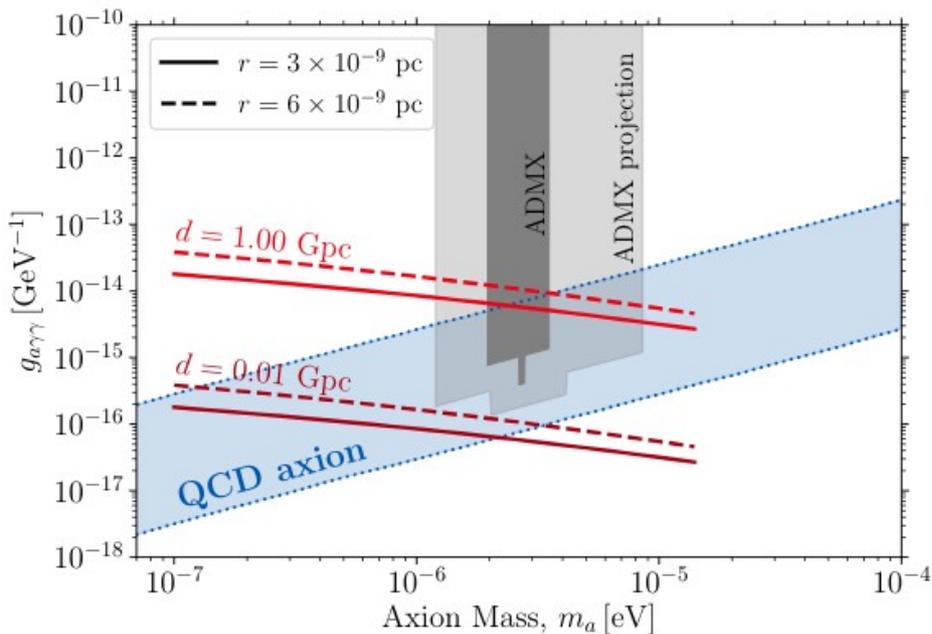
Edwards+ 19



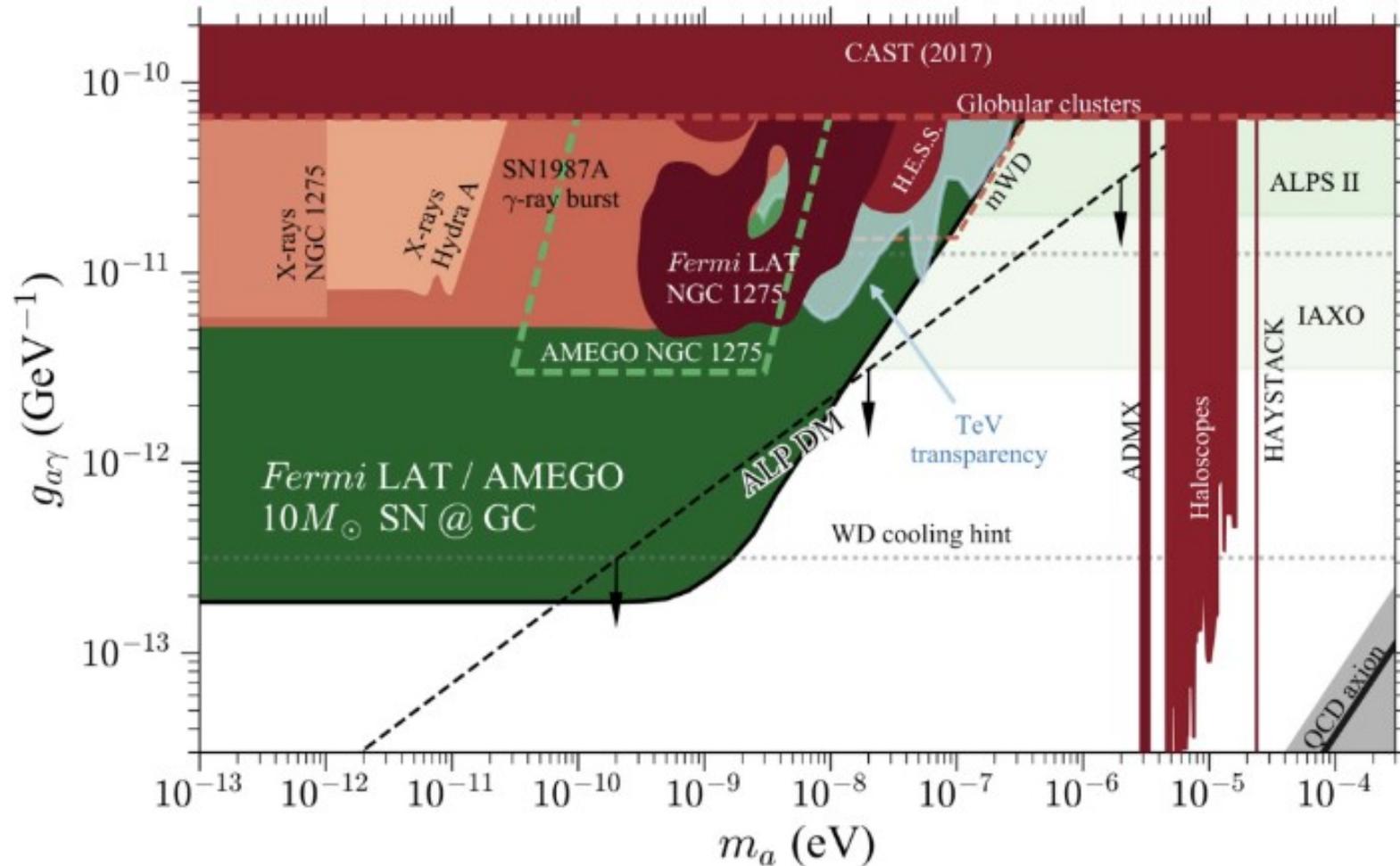
DM profile reconstruction uncertainties from dephasing



Reach SKA (100h)

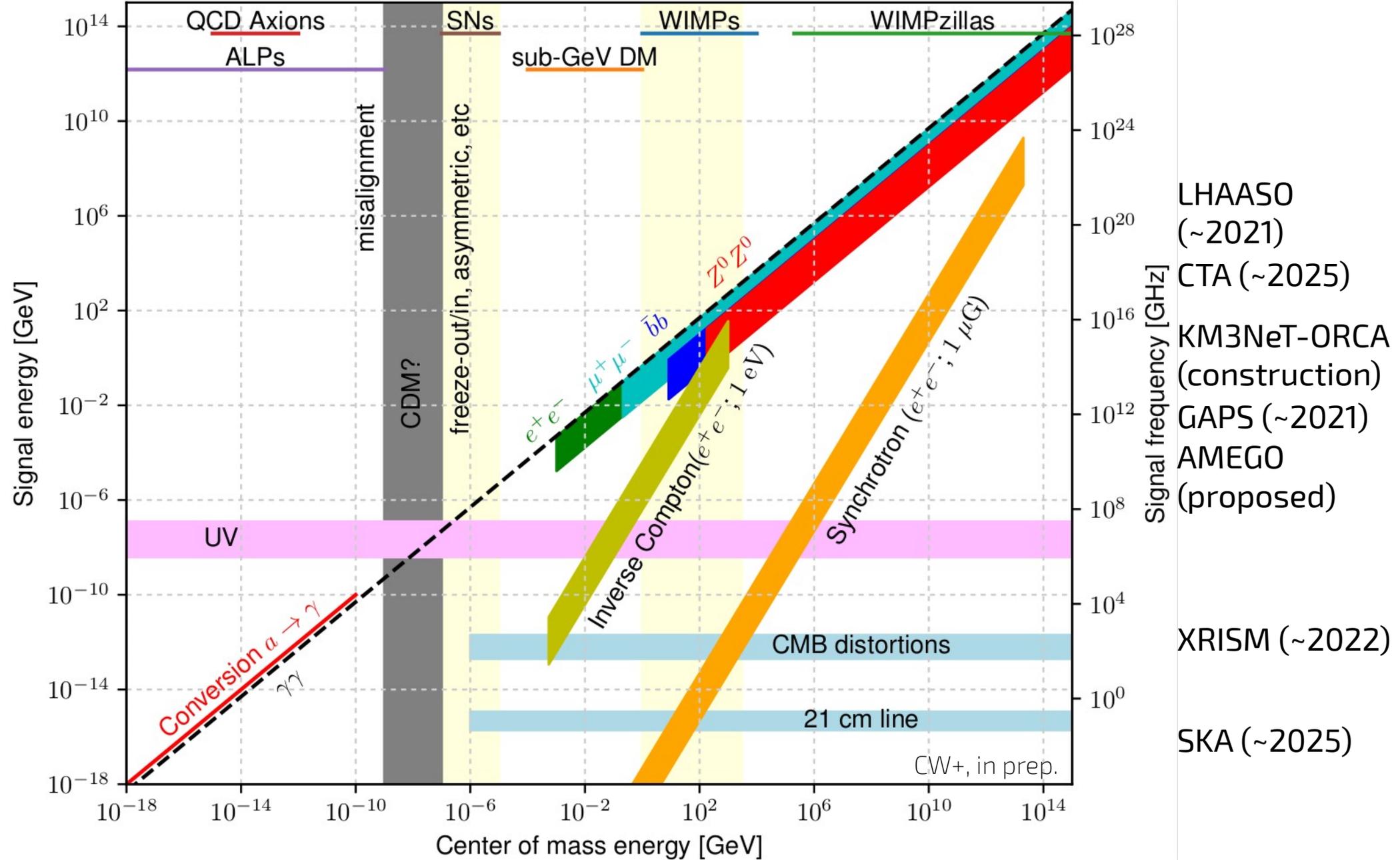


Oscillation signatures



The existence of axions (if DM or not) would affect propagation of GeV and TeV gamma-ray through intergalactic magnetic fields \rightarrow Constraints from H.E.S.S., Fermi-LAT, etc

Outlook across frequencies



Anomalies

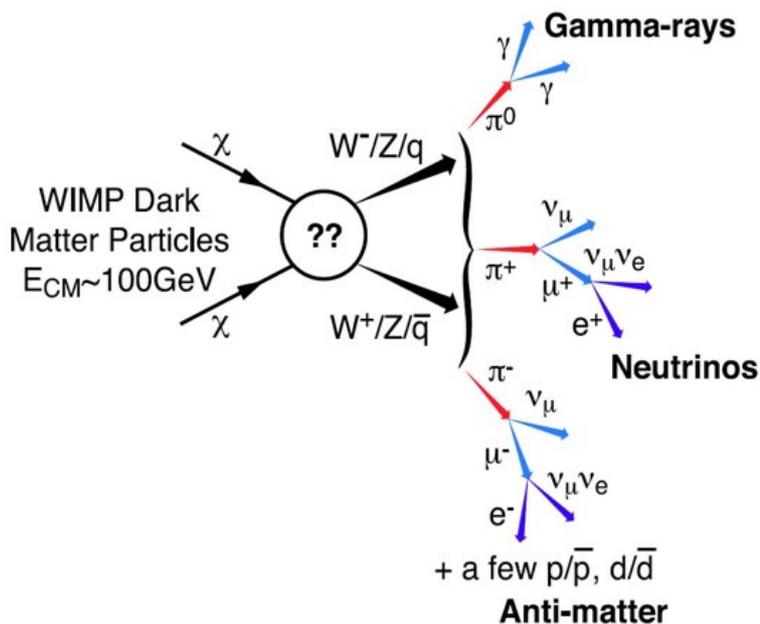
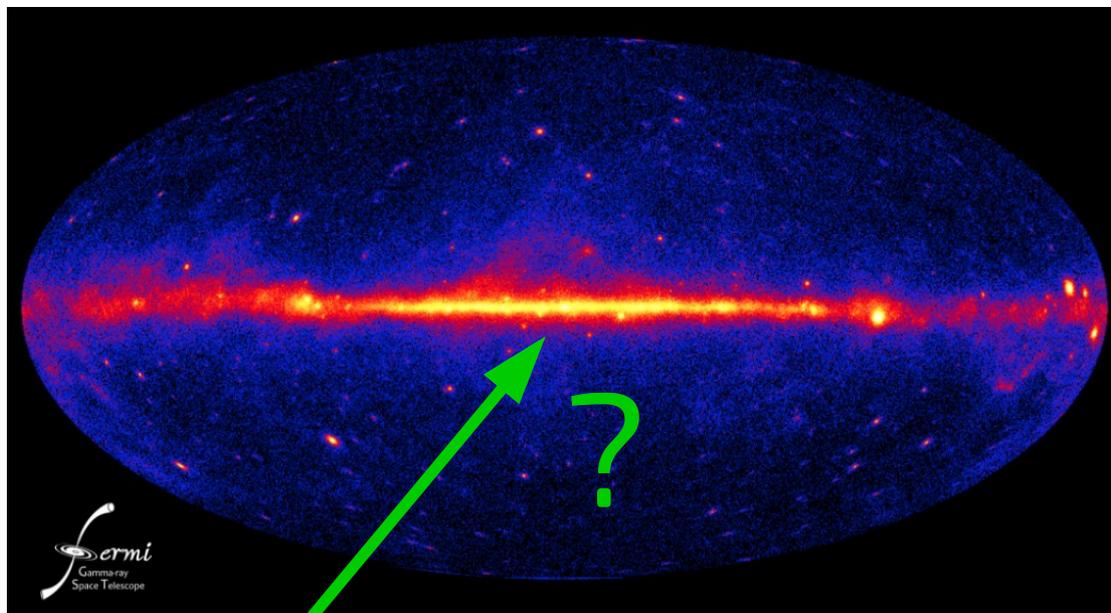


- 1) Fermi GeV excess
- 2) Anti-proton excess
- 3) 3.5 keV line

1) Fermi GeV excess

“Fermi GeV excess”

Five years of
Fermi LAT
data
> 1 GeV



The Fermi GeV bulge emission

- Initial claims by Goodenough&Hooper (2009) [see also Vitale&Morselli (2009)]
- Controversial discussion in the community for six years
- In 2015, existence of “GeV excess” finally got the blessing of the Fermi LAT collaboration
- **Is it a DM signal?**

... Hooper & Linden 11; Boyarsky+ 11; Abazajian & Kalpinghat 12; Hooper & Slatyer 13; Gorden & Macias 13; Macias & Gorden 13; Huang+ 13; Abazajian+ 14; Daylan+ 14; Zhou+ 14; Calore+ 14; Huang+15; Cholis+ 15; Bartels+ 15; Lee+ 15, ...)

Literature

Papers that looked at data

- Goodenough & Hooper, arXiv:0910.2998
- Vitale & Morselli, 2009
- Hooper & Goodenough, Phys. Lett. B697 (2011) 412
- Hooper & Linden, Phys. Rev. D84 (2011) 123005
- Boyarsky, Malyshev & Ruchayskiy, Phys. Lett. B705 (2011) 165
- Abazajian & Kaplinghat, PRD 86 (2012) 083511
- Hooper & Slatyer, Phys. Dark Univ. 2 (2013) 118
- Gordon & Macias, Phys. Rev. D88 (2013) 083521
- Macias & Gordon, PRD 89 (2014) 063515
- Abazajian, Canac, Horiuchi, Kaplinghat, Phys. Rev. D90 (2014) 023526
- Cholis, Evoli, Calore, Linden, Weniger, Hooper, JCAP 1512 (2015) 12
- Calore, Cholis & Weniger, JCAP 1503 (2015) 038
- Zhou, Liang, Huang, Li, Fan, Chang, Phys. Rev. D91 (2015) 123010
- Gaggero, Taoso, Urbano, Valli & Ullio, JCAP 1512 (2015) 056
- Daylan, Finkbeiner, Hooper, Linden, Portillo et al., Physics of Dark Universe 12 (2016) 1
- De Boer, Gebauer, Neumann, Biermann, arXiv:1610.08926 (ICRC 2016 proceedings)
- Huang, Ensslin & Selig, JCAP 1604 (2016) 030
- Carlson, Linden, Profumo, Phys. Rev. D94 (2016) 063504
- Bartels, Krishnamurthy, Weniger, Phys. Rev. Lett. 116 (2016) 5
- Macis, Gordon, Crocker, Coleman, Paterson, arXiv:1611.06644
- Lee, Lisanti, Safdi, Slatyer, Xue, Phys. Rev. Lett. 116 (2016) 5
- Ajello et al. 2016, Astrophys. J. 819, 44
- Ackermann et al., 2017, Astrophys. J. 840, 43
- Ajello et al., 2017, arXiv:1705.00009 (+ a few that I must have missed)

Excess is likely DM

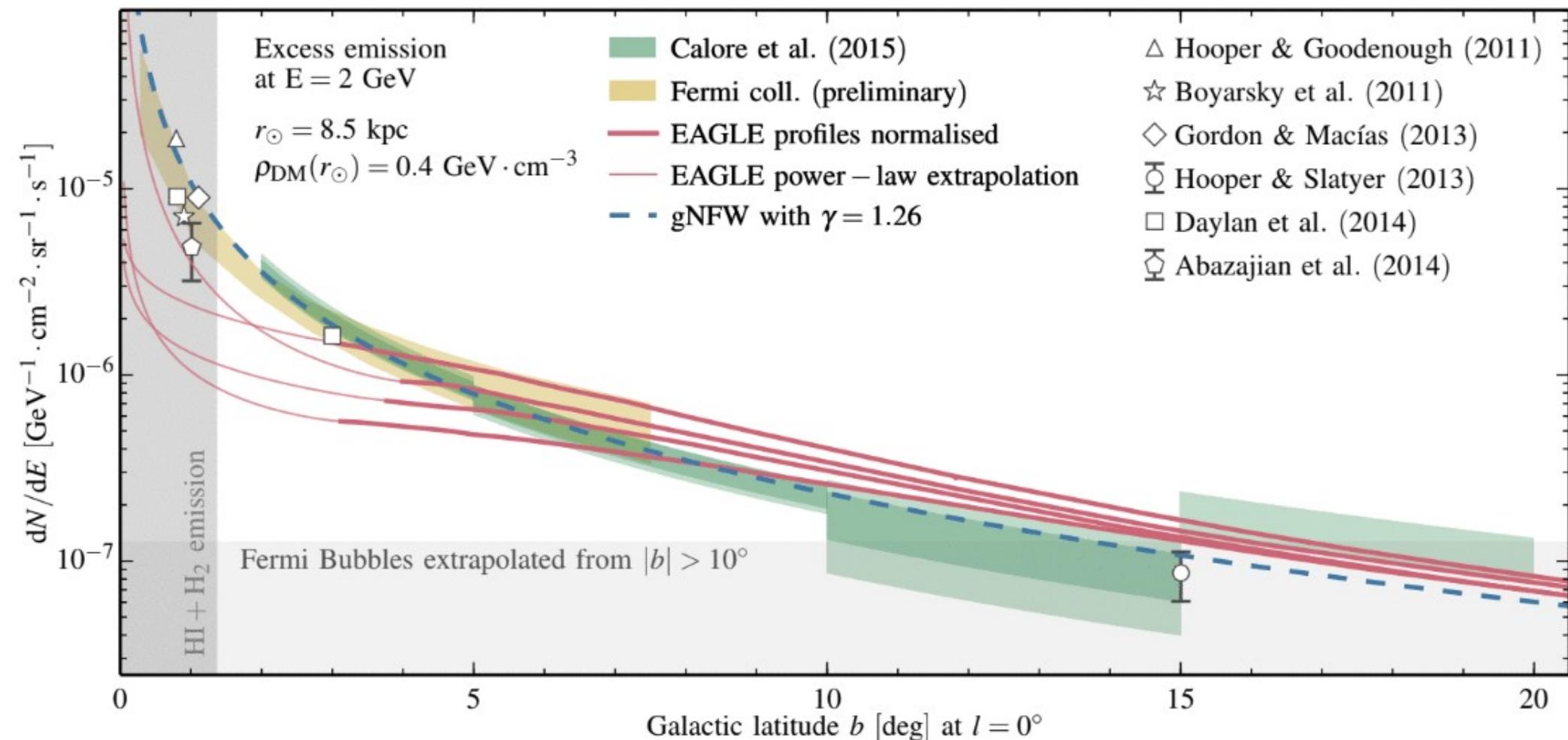
Excess is there

Excess is likely not DM

Excess is not there

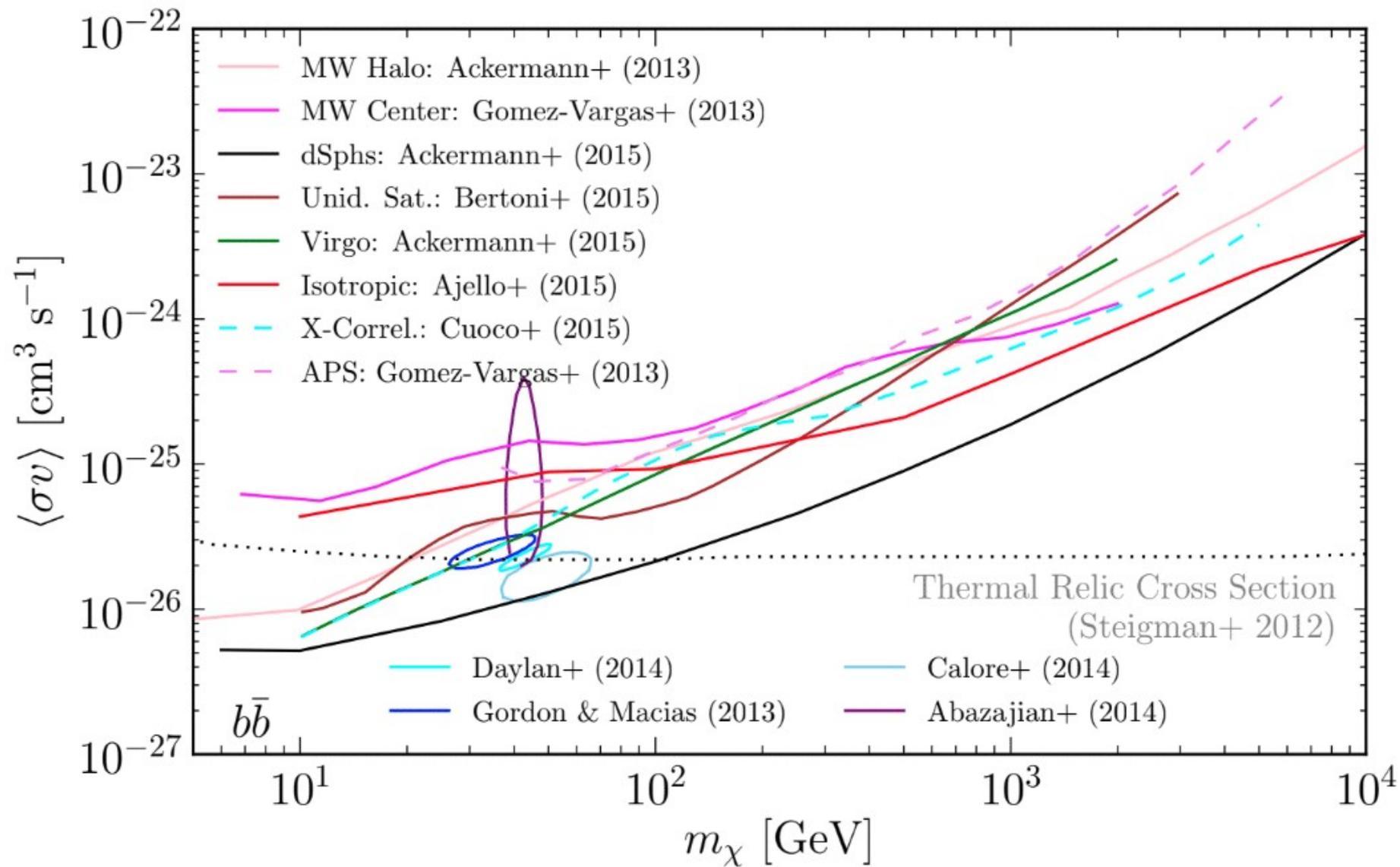
+ hundreds of DM theory papers

Emission profile



Calore+15, Charles+16

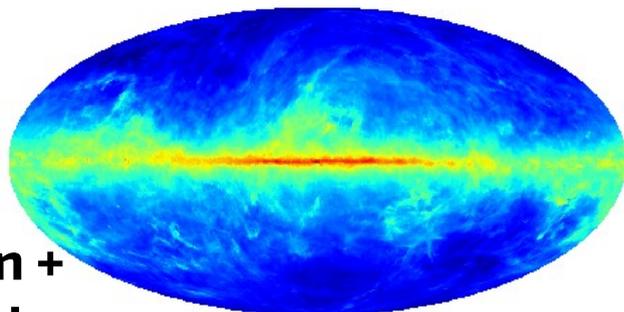
Comparison with dwarfs



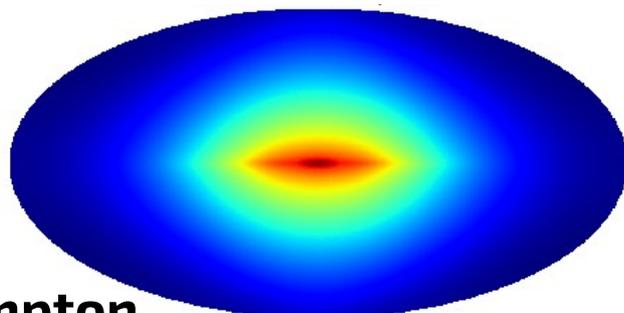
Charles+ 2016

Template regression

Neutral pion +
Bremsstrahlung

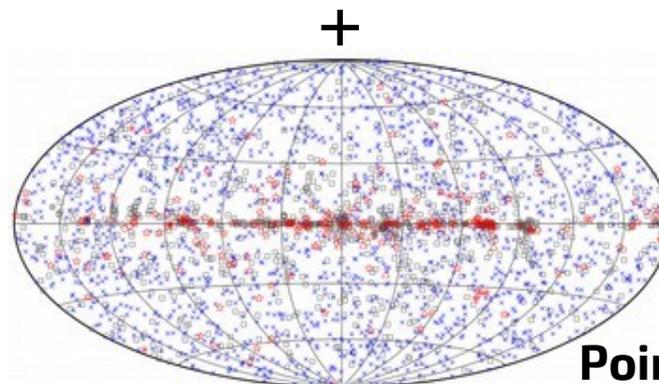
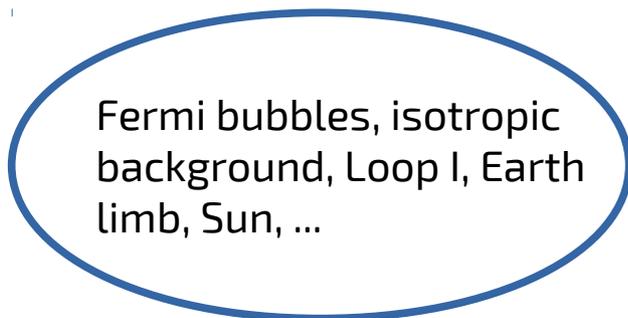


+



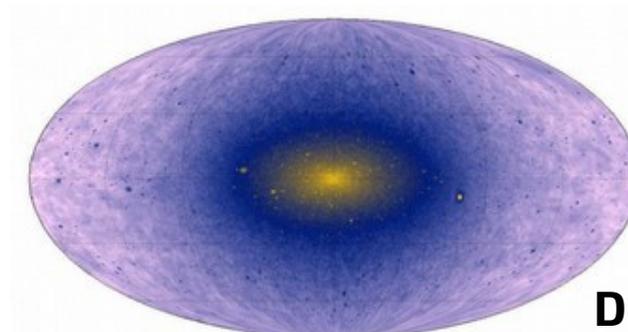
Inverse Compton

+



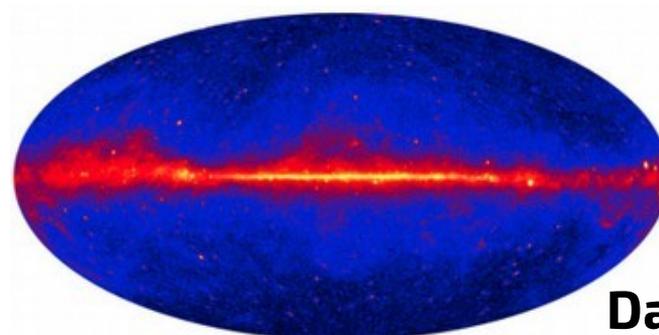
Point sources

+



DM signal

=



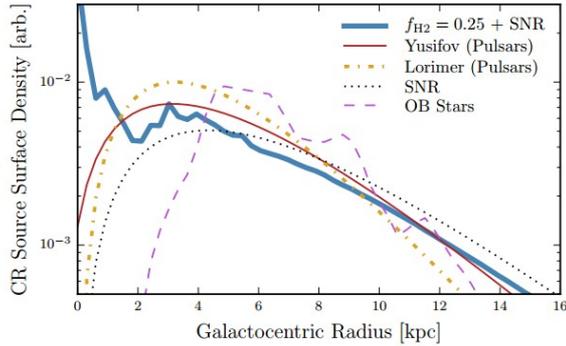
Data

Free parameters: $N_{\text{params}} = N_{\text{ebins}} \times N_{\text{comp}}$

How to get the templates

1) Inject primary CR at sources

Carlson+ 2015



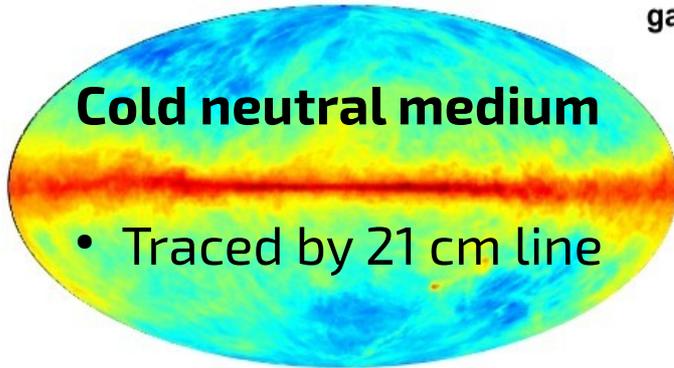
2) Propagate them with the code of your choice



DRAGON

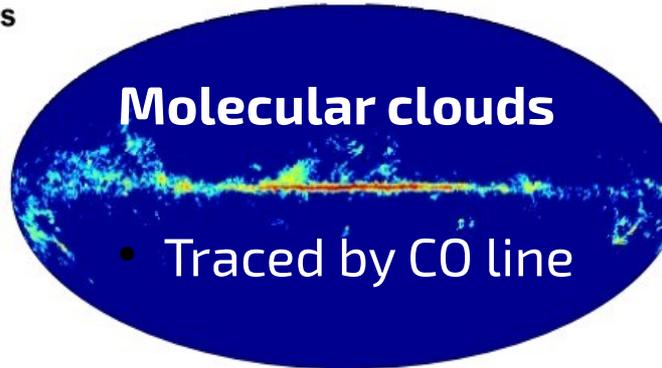
3) Interaction with gas & ISRF

HI (LAB) Kalberla '05

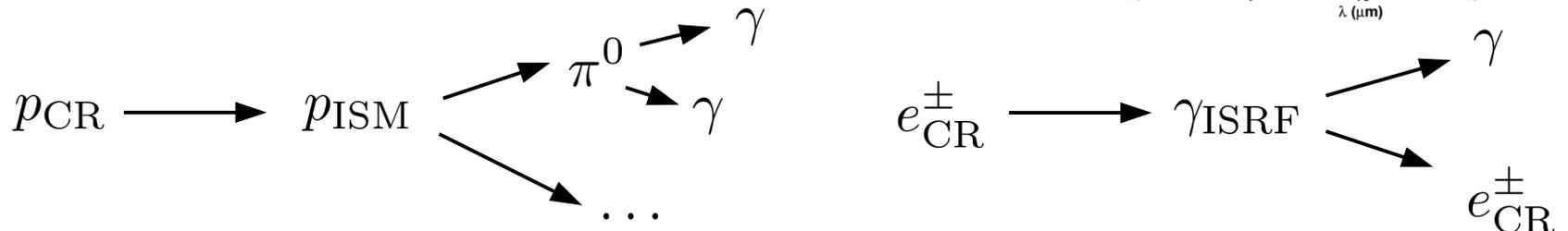
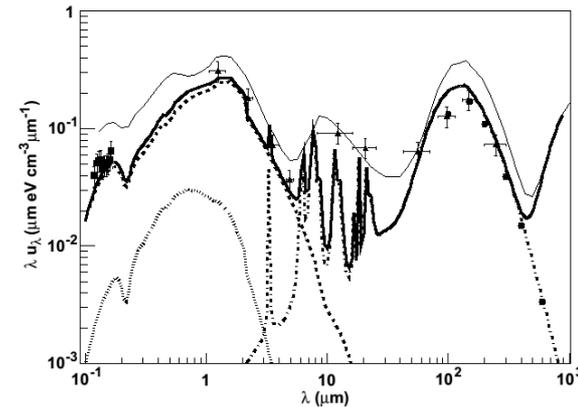


HII <<
gas

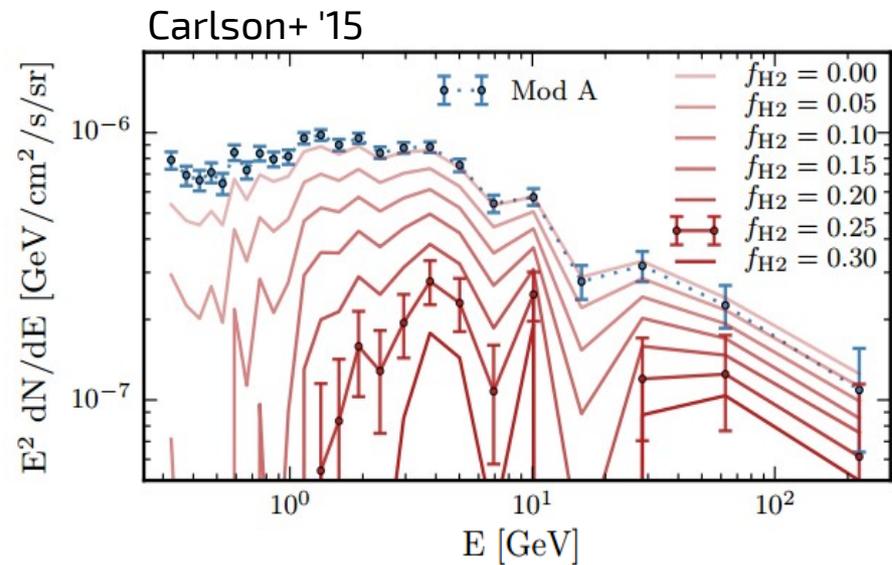
CO (Cfa) Dame '01



Strong+ 2000; Porter & Strong 2005;
Moskalenko+ 2006; Porter+ 2008

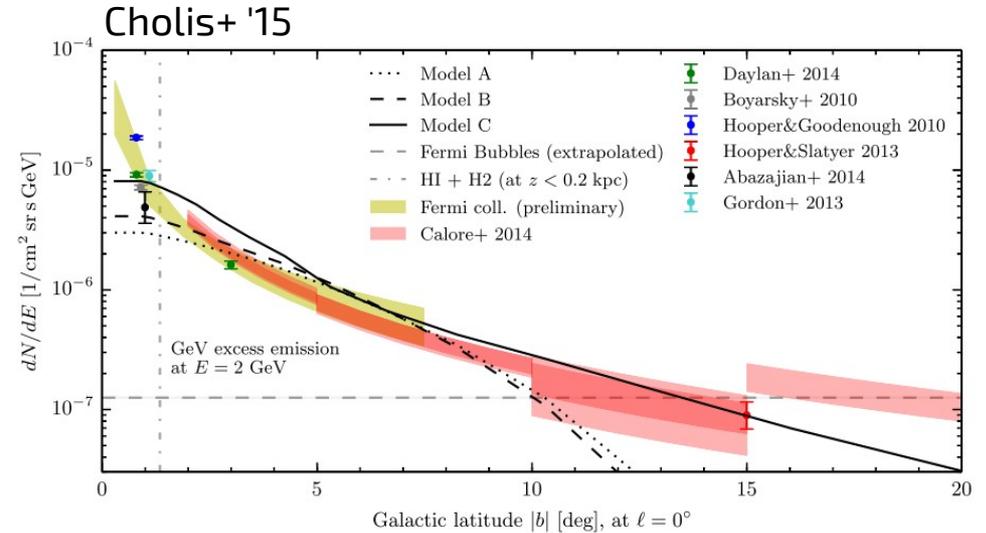


Possible contributions to bulge emission



Expected contributions

- Star formation (Gaggero+ '15, Carlson+ '15)
 - GeV excess: $1e37$ erg/s
 - 1 SN ($1e51$ erg) per 100 yr, 10% in GC, 10% into CR, 1% into leptons
 - few $1e37$ erg/s → enough to power GeV excess
- Bubble-related emission (very hard to model)
- Young pulsars (can be reasonably modeled, O'Leary+ '15)
- Millisecond pulsars* (spectrum expected to bump at GeV energies, but not clear how many, how distributed, etc; Abazajian 11; Brand & Kocsis 15)



Speculative contributions

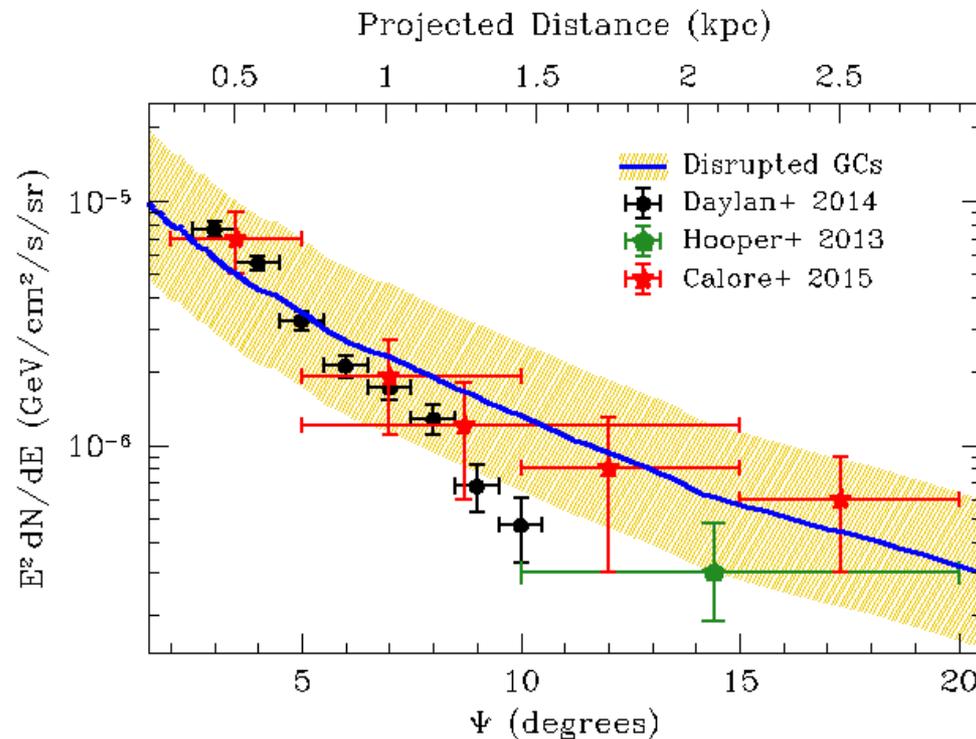
- Dark matter annihilation* (spectrum not exactly known but can bump at \sim GeV energies, not clear how strong signal, what shape)
- Past activity of central black hole (cooling effects might in principle explain the observed peaked spectrum; e.g. Cholis+15; Petrovic+13)

*predict extended quasi-diffuse uniform spectrum

Millisecond pulsars for the GeV excess

Why?

- Fermi GeV bulge emission could be due to combined flux from thousands of bulge MSPs [Abazajian '11; Petrovic+ '13; Brand & Kocsis '15]
- Required number density and spherical distribution possibly created from disrupted globular clusters

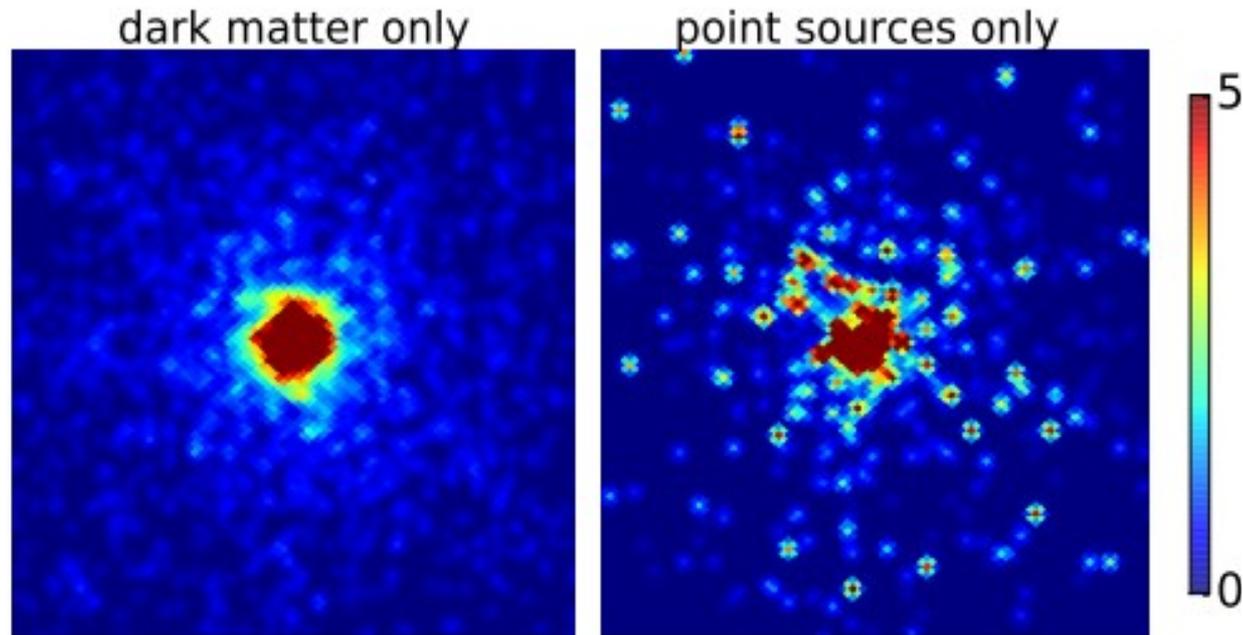


Brandt & Kocsis '15

For a list of possible caveats (e.g. pulsar aging) see e.g. Hooper+'13, Cholis+'14, Linden & Hooper '16

An observational challenge

A signal composed of point sources would appear more “speckled” than a purely diffuse signal (like from DM annihilation)

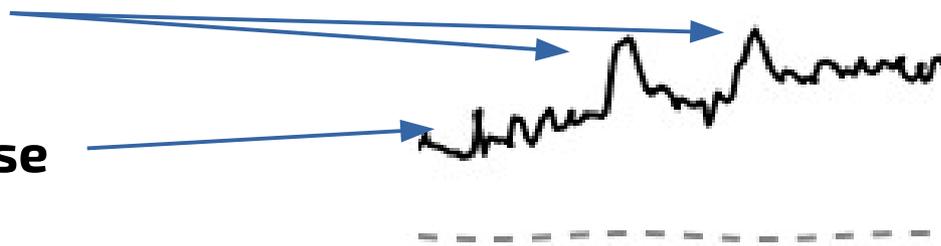


(Credit: Lee+ 2014)

Find **peaks**

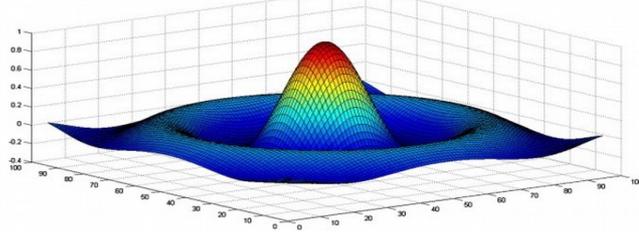
on top of

Poisson noise



Wavelet transform to filter out point sources

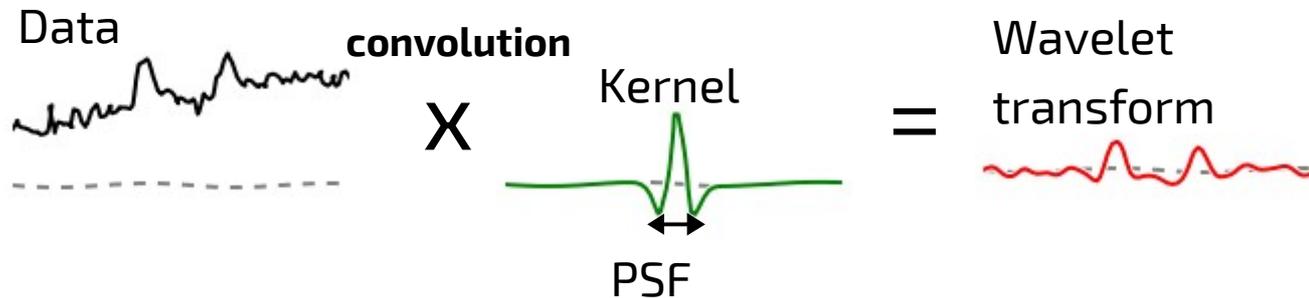
Mexican hat wavelet



Credit:
<https://www.researchgate.net>



Our work: Wavelet fluctuation analysis (Bartels+15 PRL)

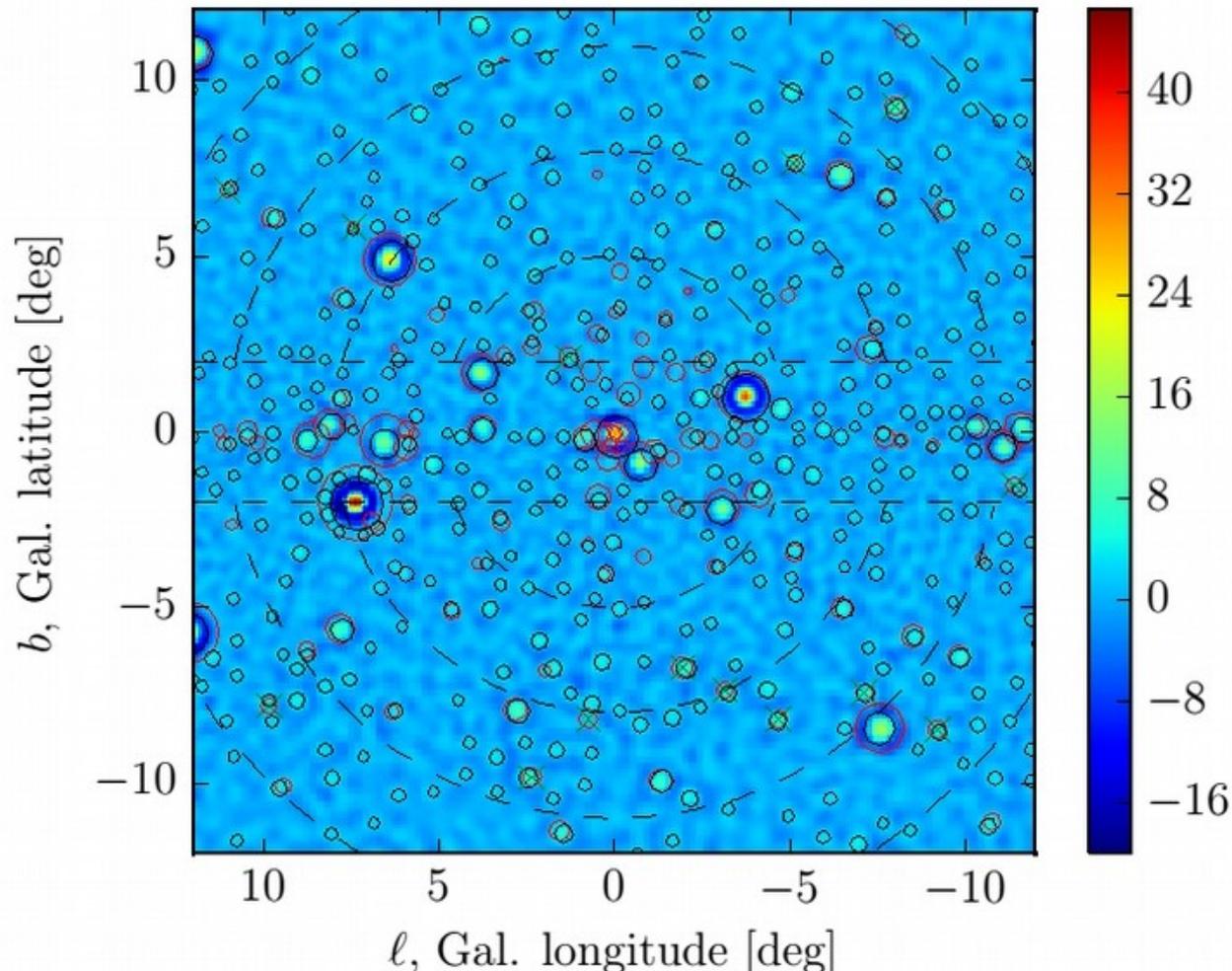


Wavelet approach is robust and simple

- No background modeling required for wavelet analysis (separation of scales!!!)
- Build-in source localization
- Extremely fast (allowed careful Monte Carlo tests of the results)

See also Lee+15 for an analysis using non-Poissonian noise

Wavelet transform of inner Galaxy data



MSP model used in Monte Carlo

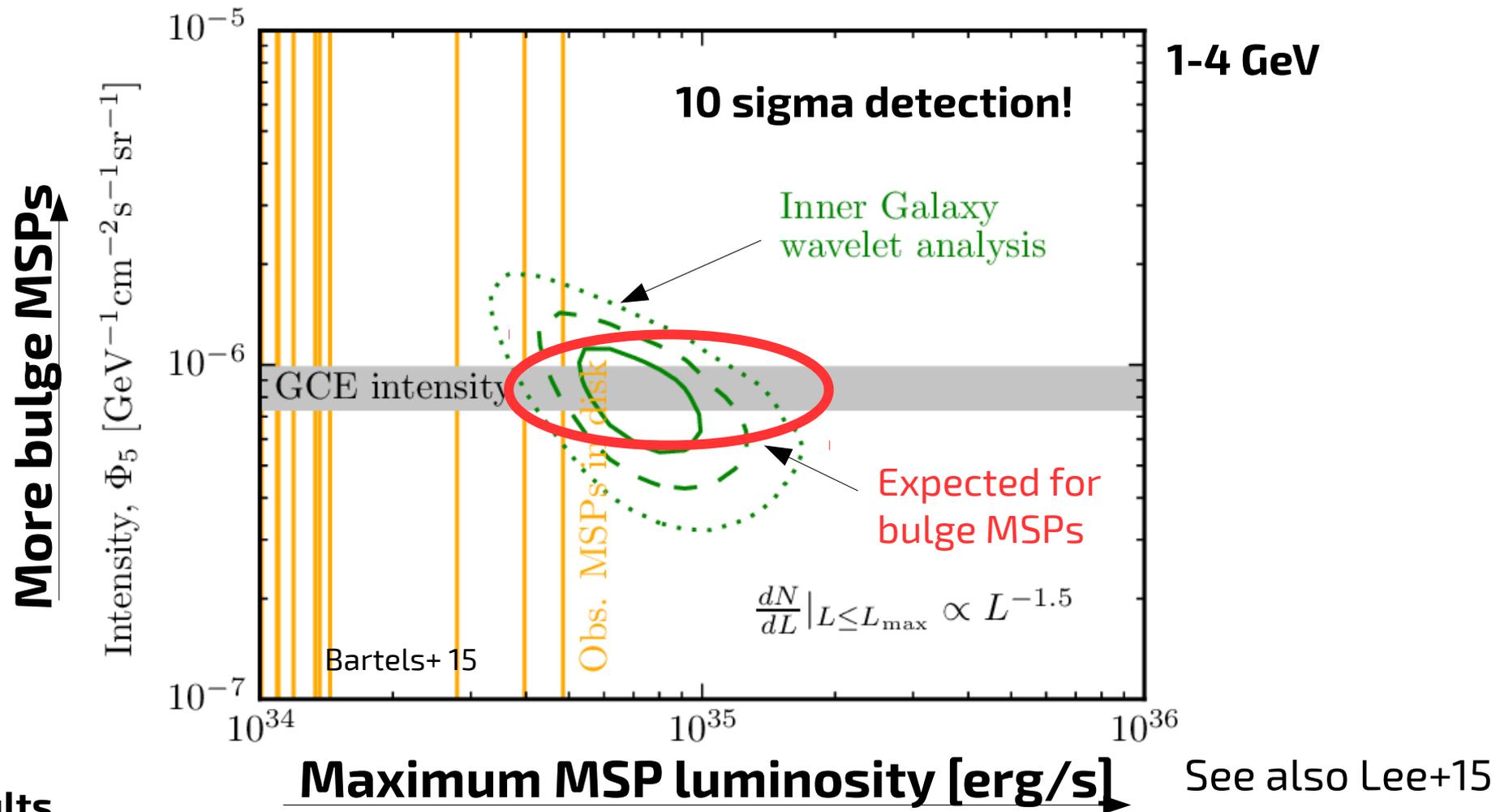
$$\frac{dN_{\text{MSP}}}{dV dL} \propto \frac{\mathcal{N}}{r^{2.5}} \frac{\theta(L_{\text{max}} - L)}{L^{1.5}}$$

Free parameters

- Total number of sources N
- Cutoff luminosity L_{max}

- 1) Count peaks in different sky regions and bin them according to significance
- 2) Run MCs for different bulge population configurations
- 3) Compare using a Poisson likelihood
- 4) Study all kinds of systematics (foreground sources, gas fluctuations etc)

Strong support for MSP hypothesis



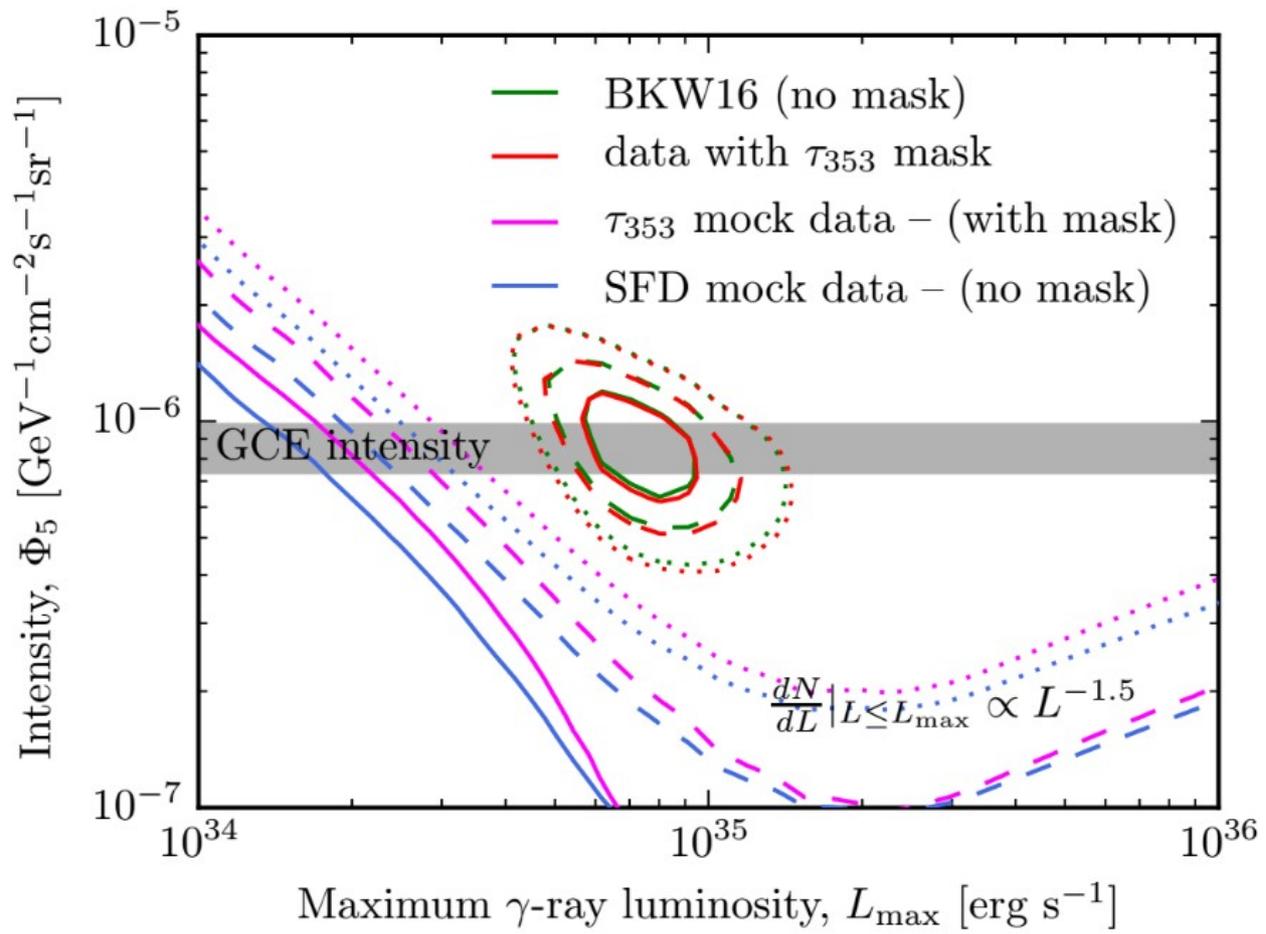
Results

- For a luminosity function index around 1.5, a MSP population with the best-fit normalization would reproduce 100% of the excess emission
- The best-fit cutoff luminosity is compatible with gamma-ray emission from detected nearby MSPs (beware of large uncertainties due to uncertainties in the distance measure, Petrovic+ 2014, Brandt & Kocsis 2015)

Gas fluctuations etc unlikely to cause signal

Small scale feature in gas

- Even assuming that *all* diffuse emission comes from gas, we predict a non-detection (Schlegel+97 with ~0.1 deg resolution; Planck optical depth map)



The ugly truth

NONE of the diffuse emission models gives an acceptable fit to the data

1. Even the best models are excluded by many hundred sigmas

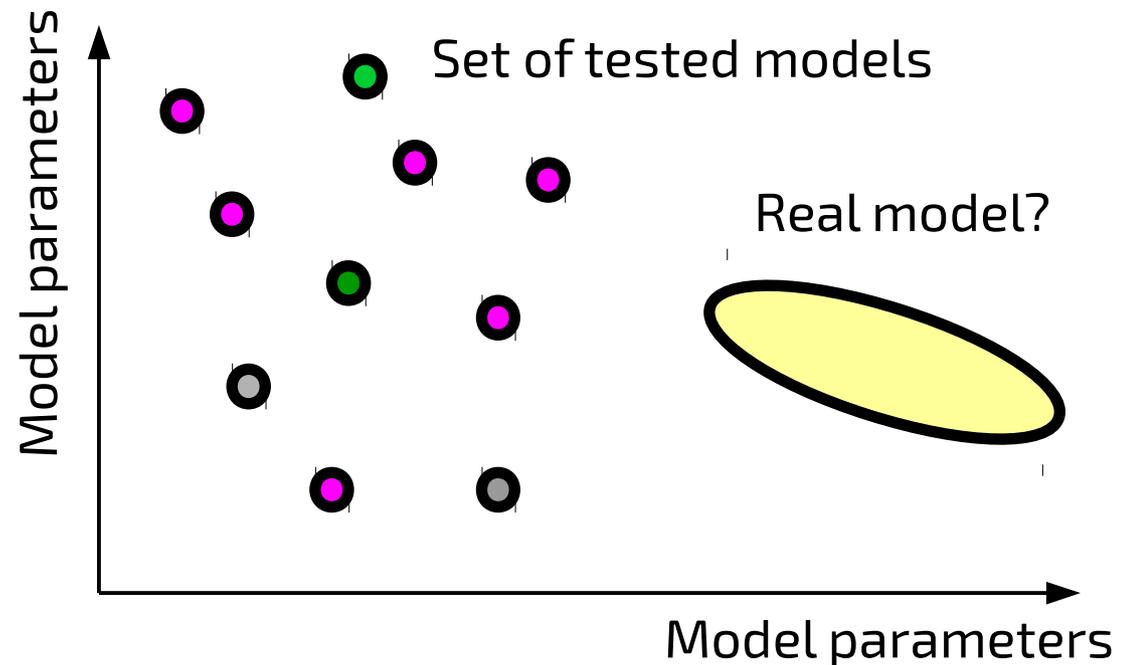
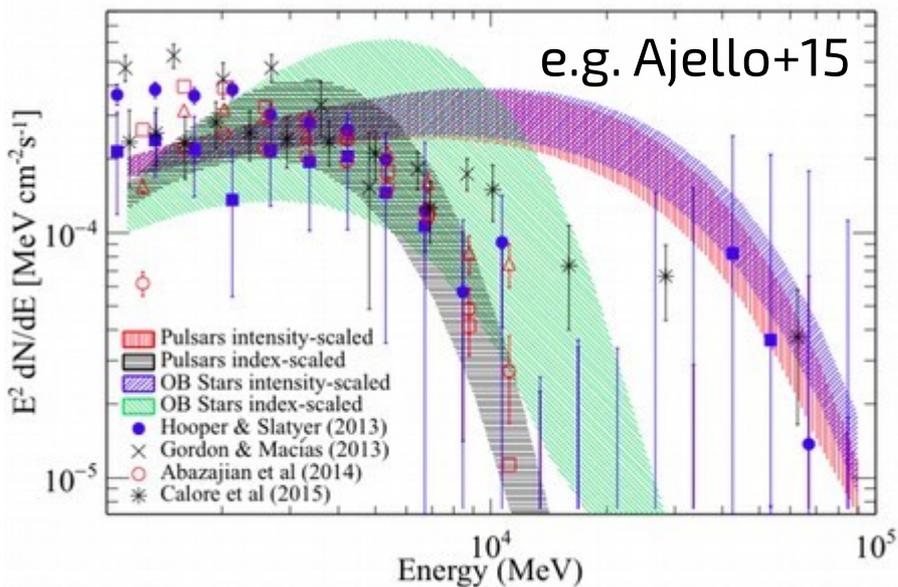
Goodness-of-fit tests typically return **p-value** $< 10^{-300}$

2. Many excess along the Galactic disk

Some of the excesses have same size as Galactic center excess (Calore+15)

3. “Bracketing uncertainties” by looking at many wrong models does not give the right answer

But everybody is doing it.



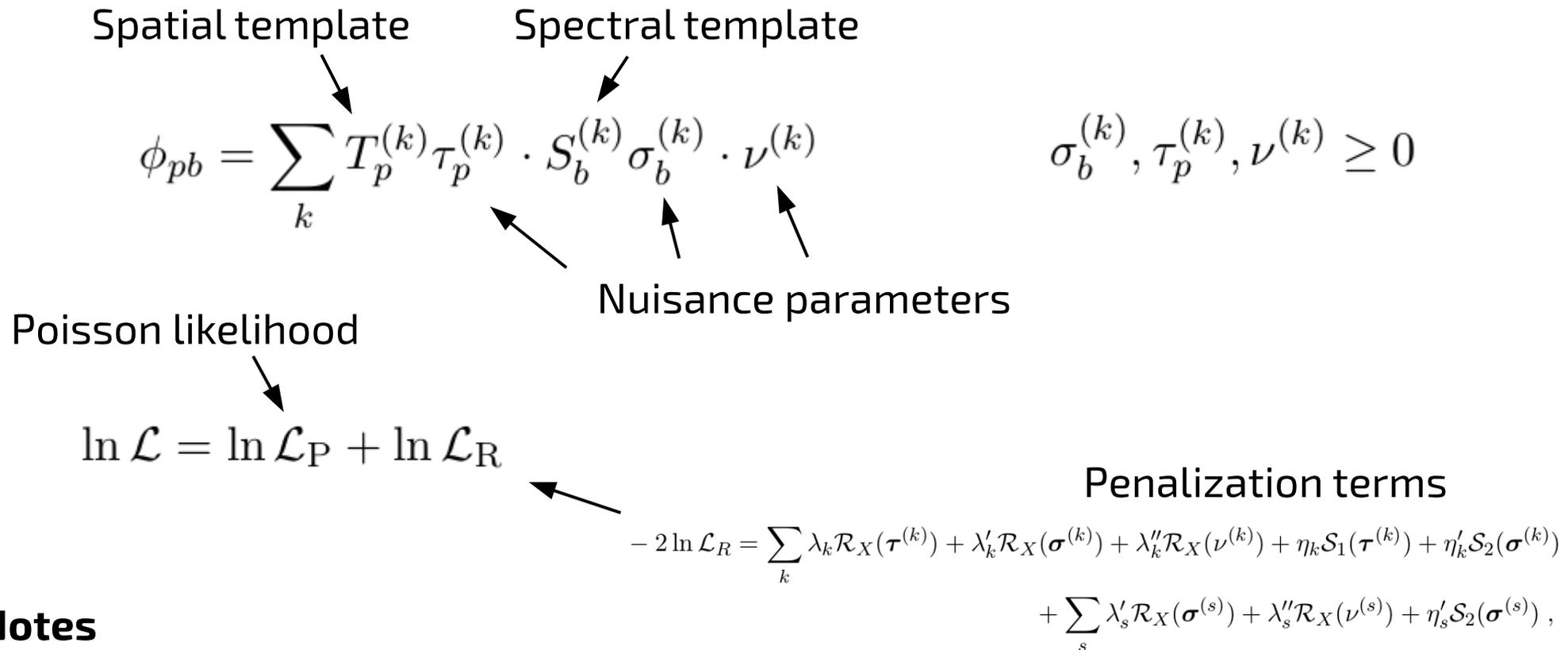
We need better models and/or massively enlarge the parameter space.

Accounting for systematics with SkyFACT

SkyFACT (Sky Factorization with Adaptive Constrained Templates)

- Based on penalized likelihood estimation
- Hybrid between template fitting & image reconstruction

Storm, CW, Calore, 2017



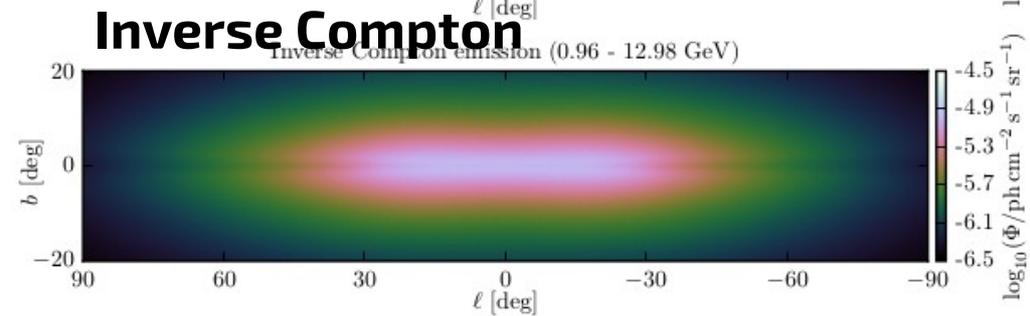
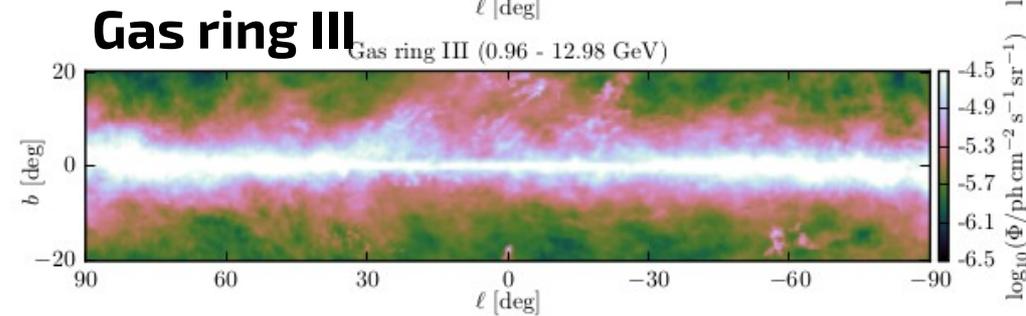
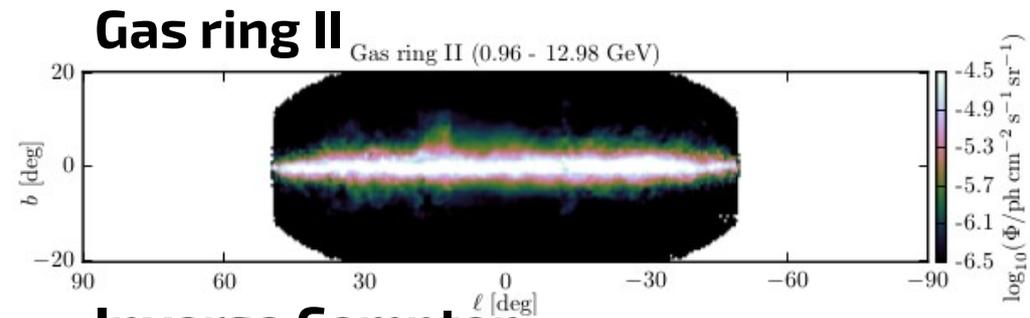
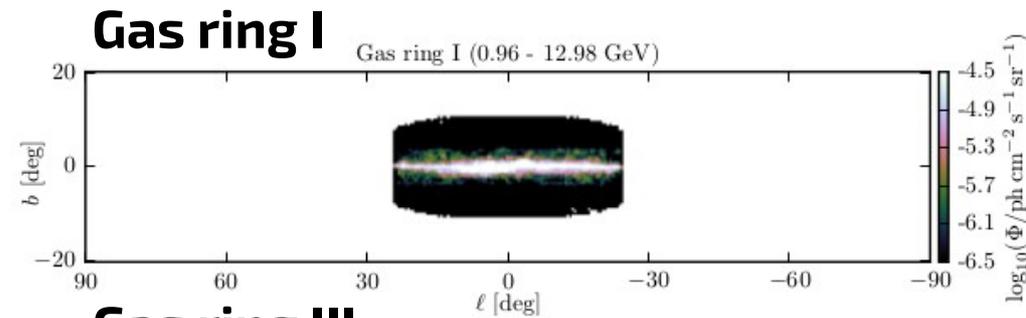
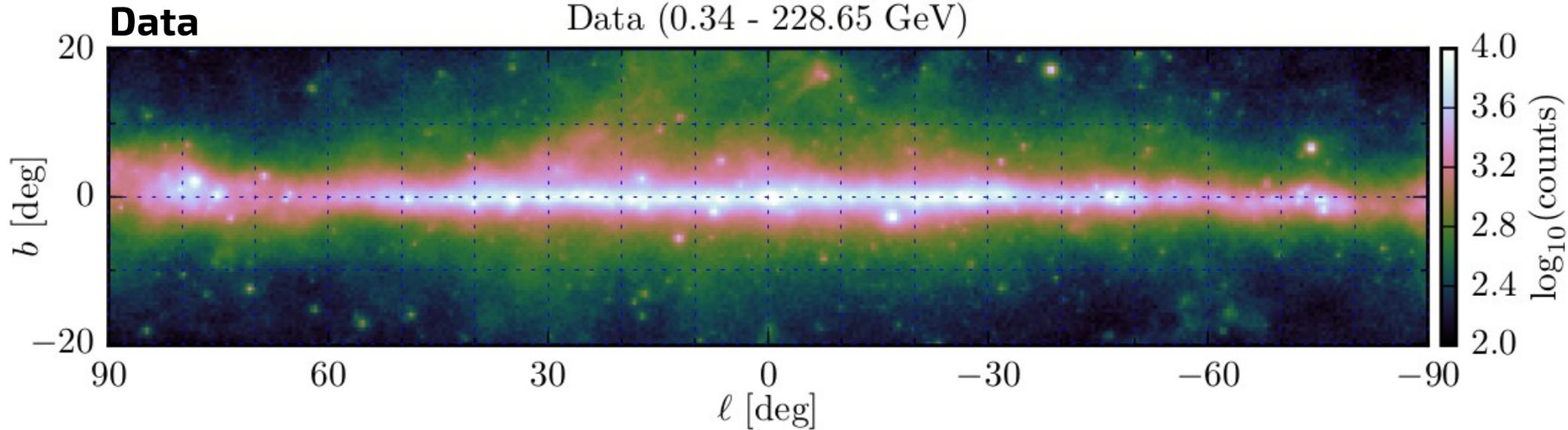
Notes

- Typically $>10^5$ parameters
- Problem typically convex \rightarrow only one minimum

We adopt a maximum-entropy prior

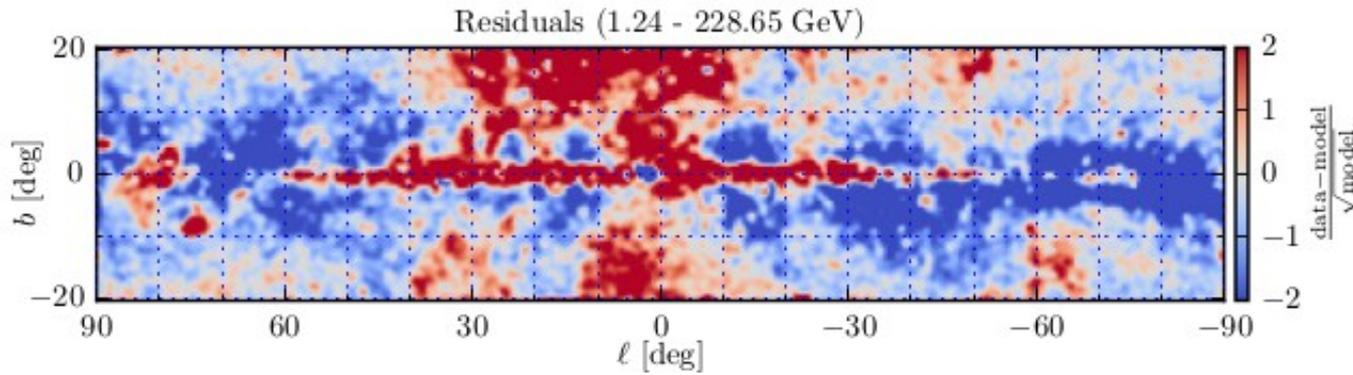
$$\lambda \mathcal{R}_{MEM}(\mathbf{x}) = 2\lambda \sum_i 1 - x_i + x_i \ln x_i$$

Data and templates

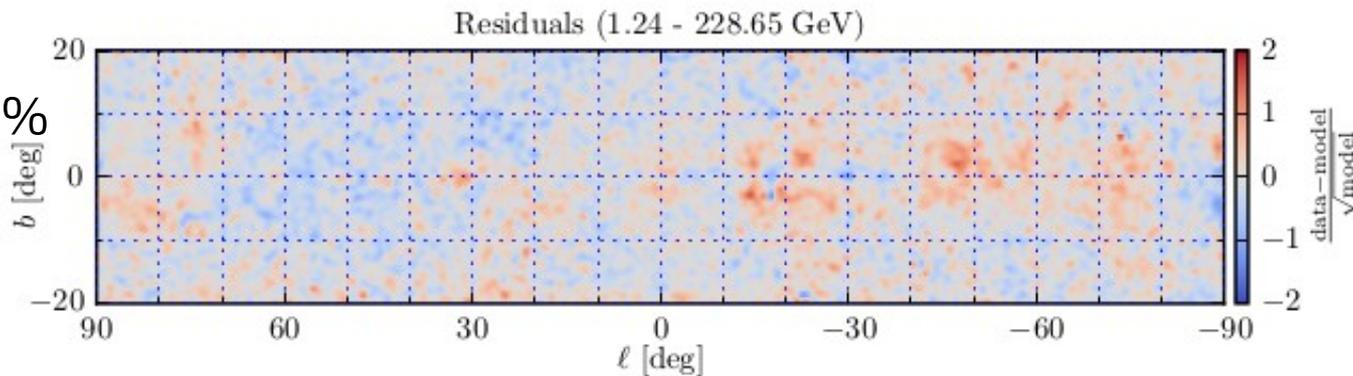


Residuals ~ 2 GeV

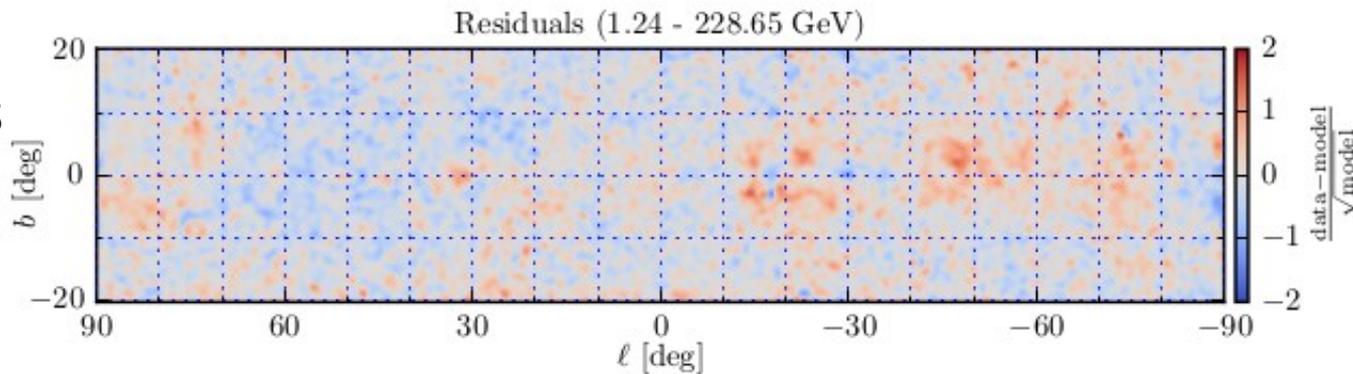
Regular
template
fit



Templates
with 10%-30%
uncertainty

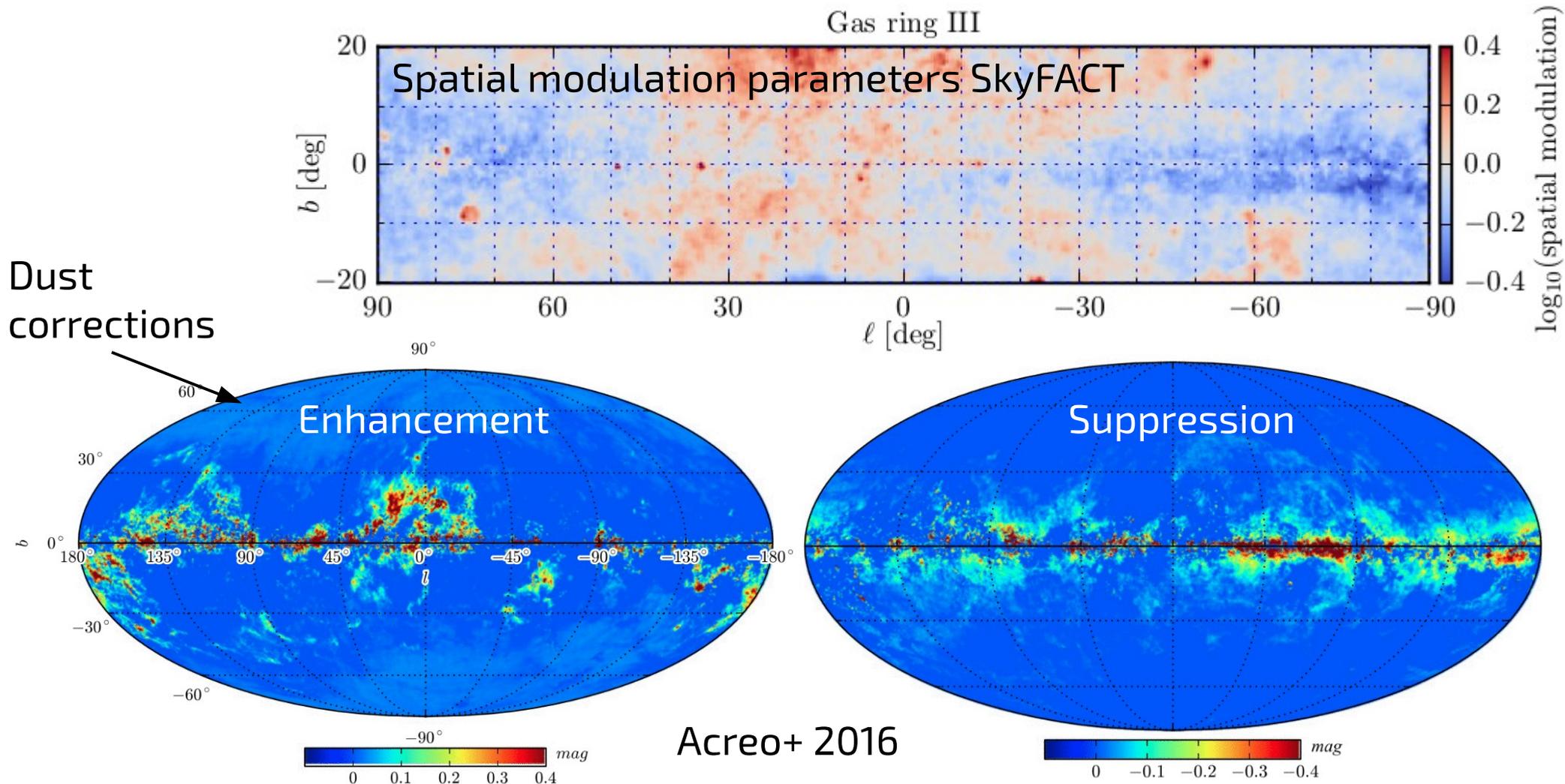


+ GeV excess



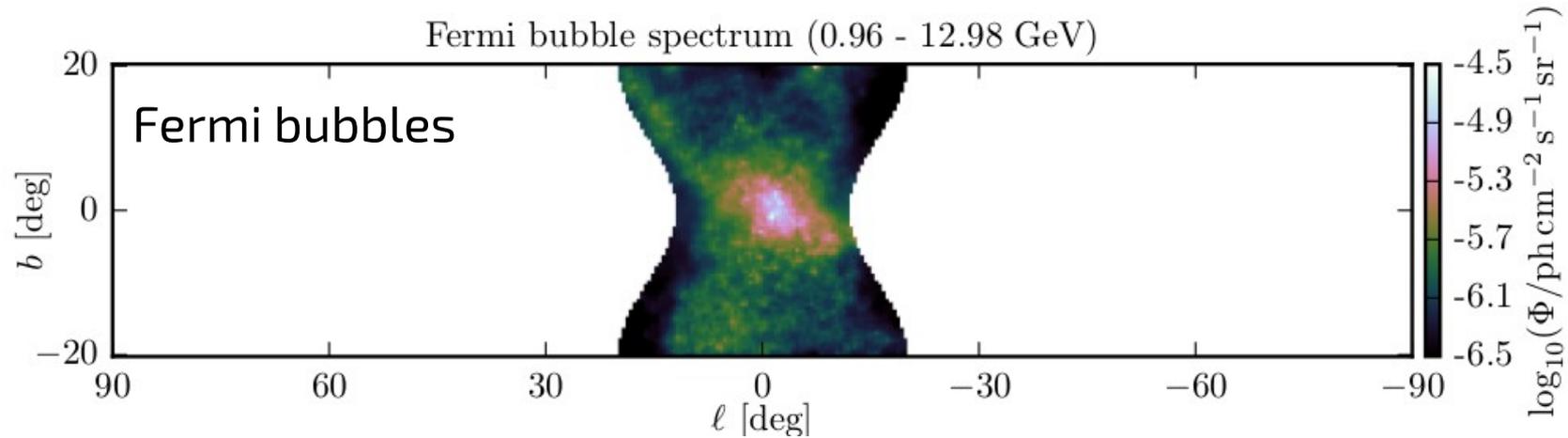
Dark gas corrections

- Fraction of gas neither emits CO (molecular gas) nor 21 cm line (atomic gas)
→ Not included in gas maps
- Correction factors are usually derived by considering dust reddening maps (assuming that dust is well mixed with ISM)



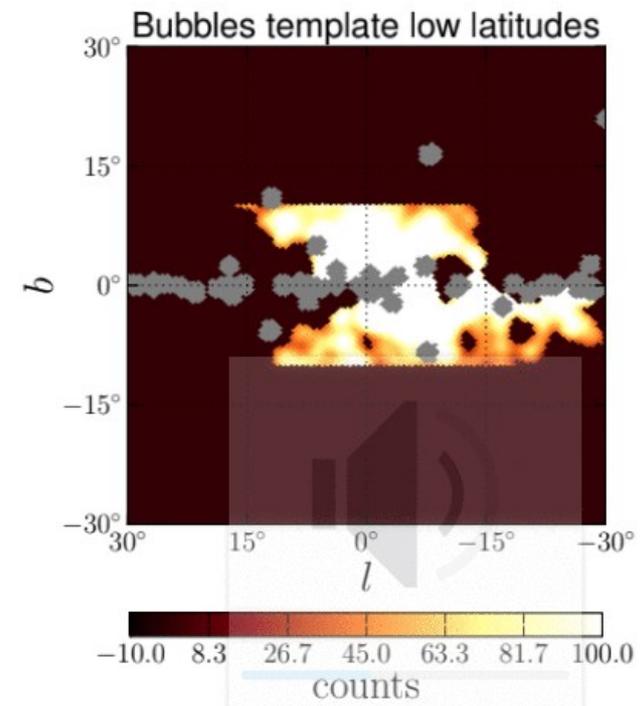
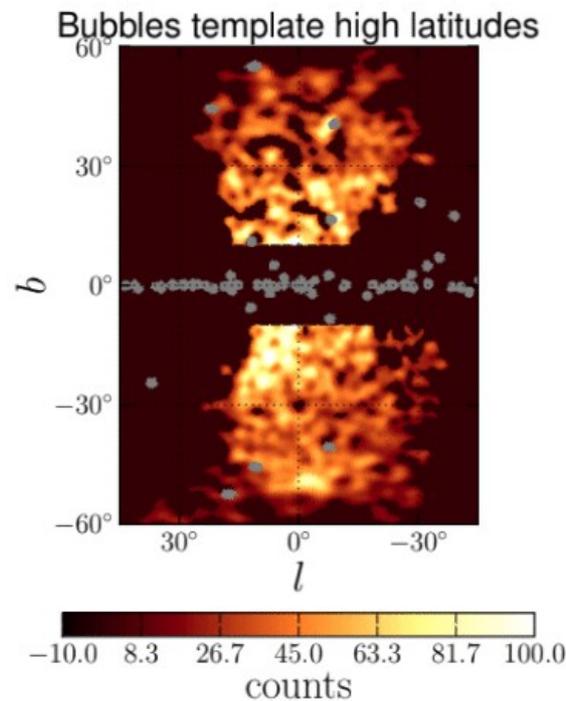
Low-latitude Fermi bubbles

Modulation parameters

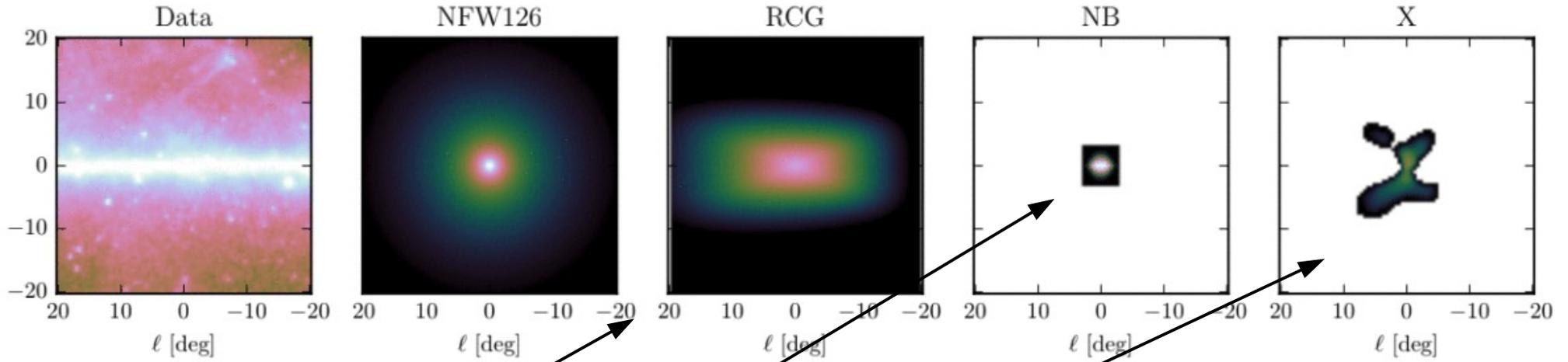


Ackermann+ 17

- Low-latitude part of Fermi bubbles is not well studied
- However, a MSP component + bubble component (hard spectrum) decomposition is possible
- Suggests strongly enhanced HE emission in the inner few degrees
- ICS from star formation?
- However, statistically not very significant, hard to study



Using stellar mass distribution as templates

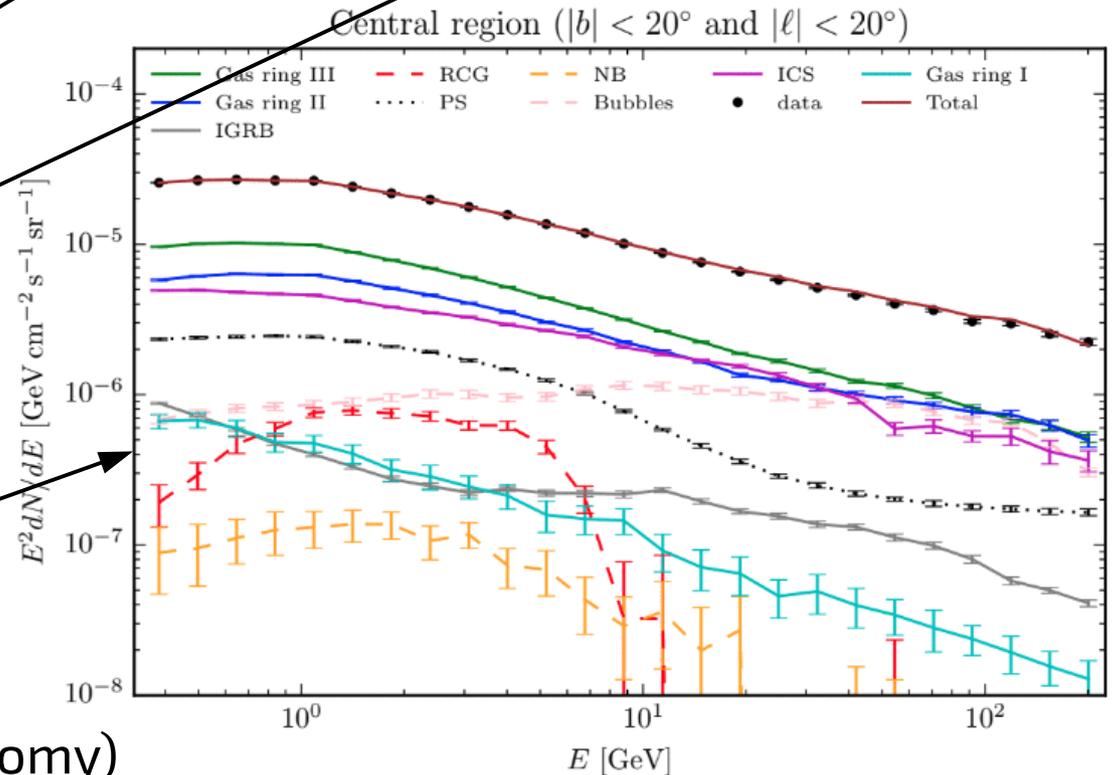


Red-clump giants

Nuclear bulge

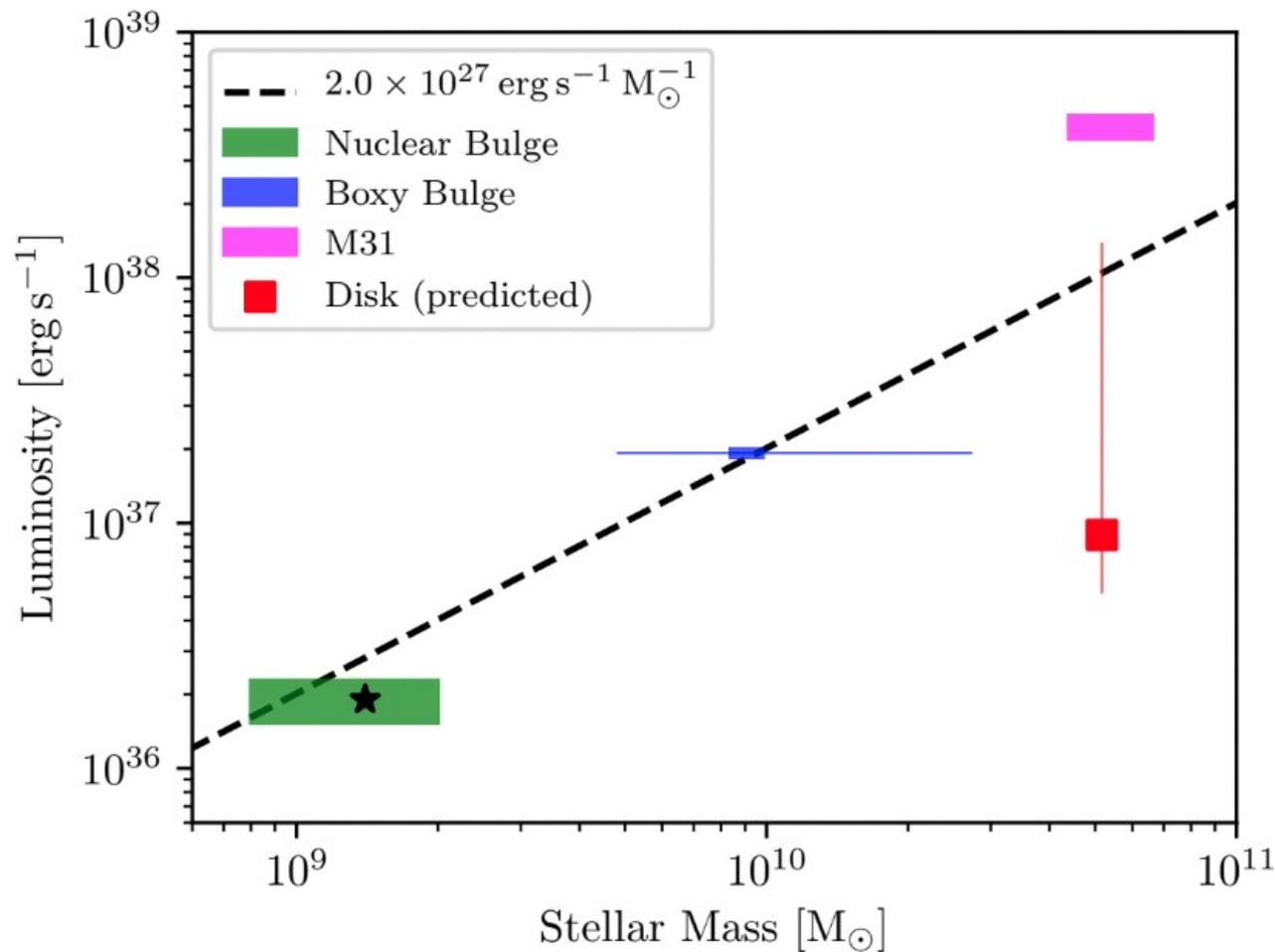
WISE template (X-shape)

Best-fit spectra



Bartels+ 1711.04778 (Nature Astronomy)

Emission scales with stellar mass



- This supports the idea that the GeV excess is of stellar origin, i.e. generated by objects that are distributed like the majority of bulge stars
- Association with boxy bulge might disfavour production via disrupted globular clusters, but needs further study

Previous searches & current situation

Radio searches:

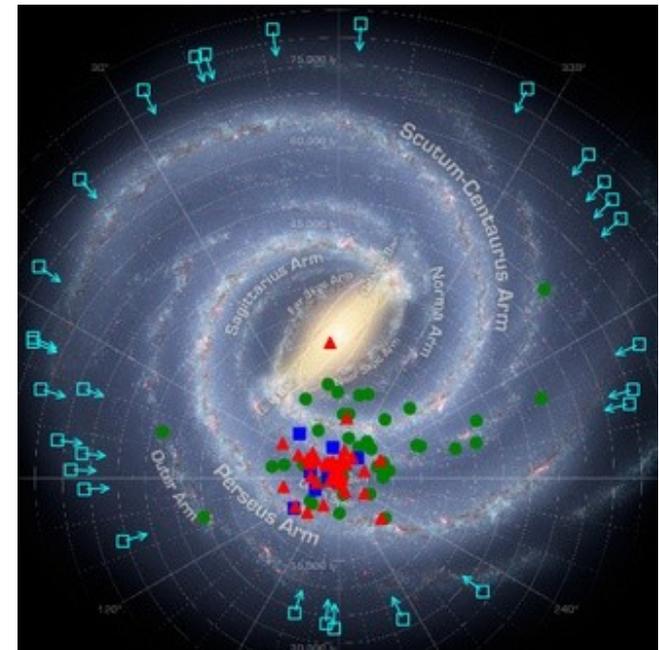
- Observations since 1980s (mostly Parkes, Arecibo), since 2002 GBT
- Today*: ~370 MSPs (~240 field, ~130 in globular clusters) [e.g., Stovall+13]
 - From surveys (e.g. Parkes HTRU)
 - From deep observations of globular clusters
 - *From radio follow-ups of Fermi LAT sources (~70 MSPs) [Ray+12]*
- MPS searches *at* the Galactic center are very hard [Marcquart & Kanekar 15]

*As of Jan 2016

Gamma-ray searches:

- Discovery of numerous gamma-ray MSPs came as surprise, but now well established (Abdo+10)
- MSPs usually appear as unassociated sources in Fermi LAT data (spectral curvature, non-variable)
- Follow-up searches required to (1) discover associated radio pulsation and (2) fold ephemerides back into gamma rays
- At least one MSP found by blind search for gamma-ray pulsation alone

For a review see Grenier & Harding 15



[Abdo+ 2013, 2nd Fermi Pulsar catalog]

Modeling MSP bulge population

Density of radio-bright MSPs

- We use six **globular clusters** observed in gamma rays (Ter 5, 47 Tuc, M 28, NGC 6440, NGC 6752, M 5) to estimate expected radio emission of bulge population

$$\frac{L_{\gamma}^{\text{stacked}}}{N_{\text{rb}}^{\text{stacked}}} = (1.0 \pm 0.3) \times 10^{34} \text{ erg s}^{-1}$$

- Fully takes into account beaming effects
- Radio-bright (here): $L_{1400} > 10 \mu\text{Jy}$
- $L_{\gamma}^{\text{bulge}} = (2.7 \pm 0.2) \times 10^{37} \text{ erg s}^{-1} \longrightarrow N_{\text{rb}}^{\text{bulge}} = (2.7 \pm 0.9) \times 10^3$
- Luminosity function from Bagchi+11

Spatial distribution

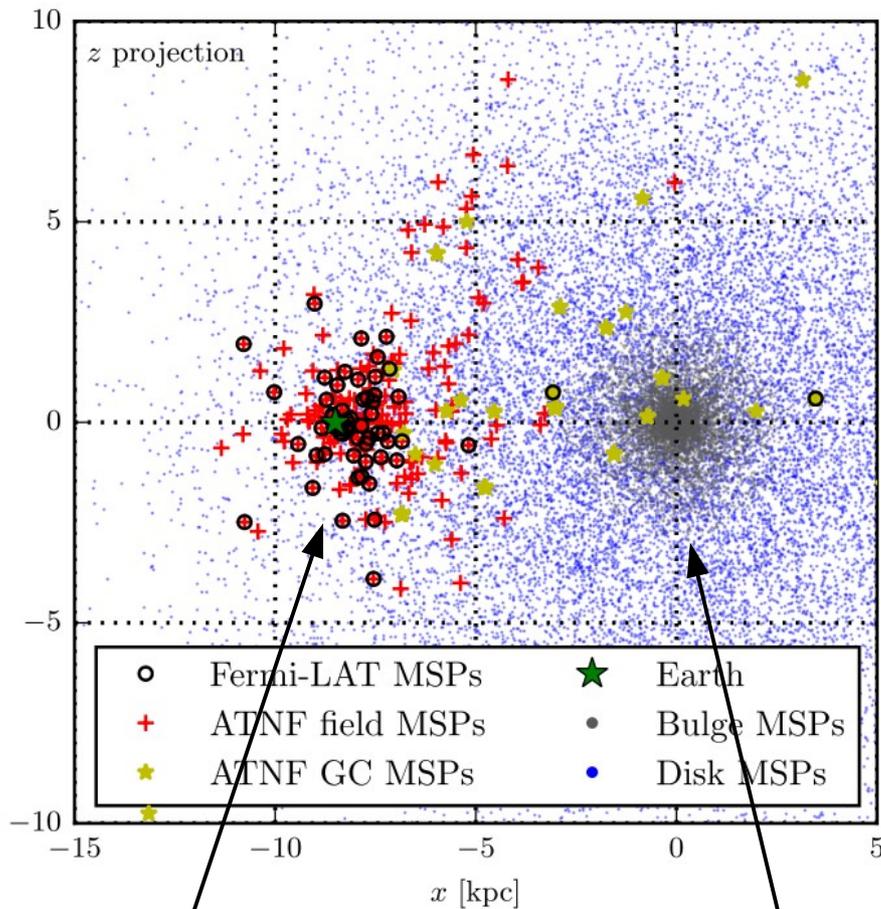
- Assumed to follow observations of GeV bulge emission as seen by Fermi
- Volume emissivity follows inverse radial power law

$$\frac{dS}{dV} \sim r^{-2.5}$$

Expected radio emission of bulge MSPs

Modeled pulsars in x-y plane

- Predict enhancement of MSP density by several orders of magnitude in the Galactic bulge w.r.t disk

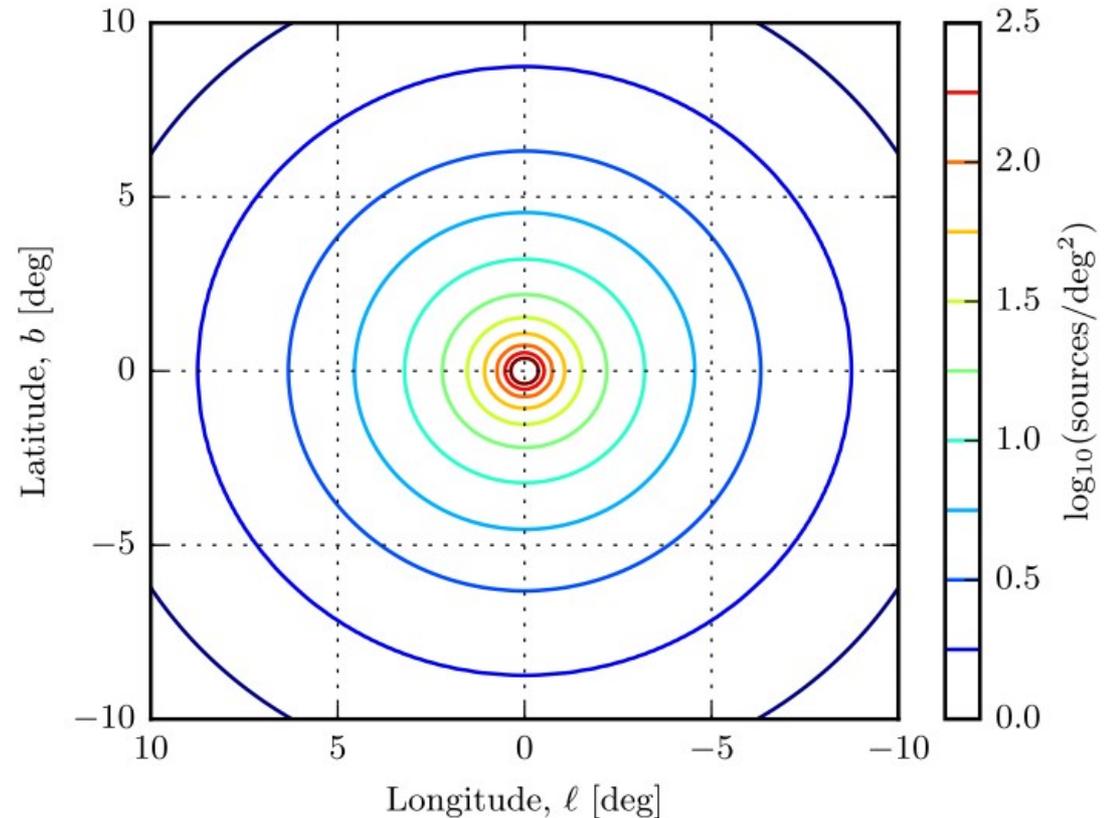


Earth

Bulge

Surface density of radio-bright bulge MSPs

- Varies from $\sim 100 \text{ deg}^{-2}$ to $\sim 1 \text{ deg}^{-2}$, depending on the distance from the GC.



Sensitivity calculations

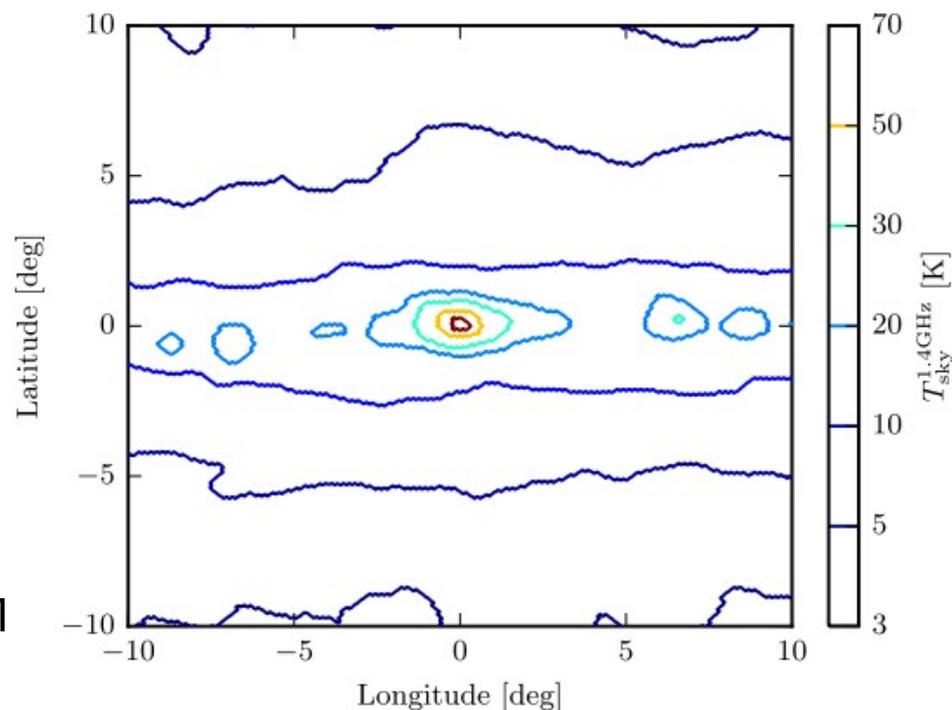
Radio-meter equation for pulsar searches

$$S_{\nu, \text{rms}} = \frac{T_{\text{sys}}}{G \sqrt{t_{\text{obs}} \Delta\nu n_p}} \left(\frac{W_{\text{obs}}}{P - W_{\text{obs}}} \right)^{1/2}$$

- We require 10 sigma signal for “detection”

Observational challenges

- Varying sky-temperature ($\sim 5\text{-}50$ K @ 1.4GHz; extrapolated from Haslam 408 MHz map)
- Intrinsic pulse width ($\sim 10\%$) smeared out by various effects
 - Temporal smearing due to scattering on the ionized ISM
 - Dispersive smearing across individual frequency channels, data sampling, DM step size in search
- Uncertainties in the DM (here taken from NE2001 model)
- About $\frac{3}{4}$ of field MSPs are found in binary systems \rightarrow Orbital motion has significant impact on blind searches



Planned radio searches for bulge MSPs

Radio detection prospects (Calore+ '15)

(Bulge population is just below sensitivity of Parkes HTRU mid-lat survey)

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

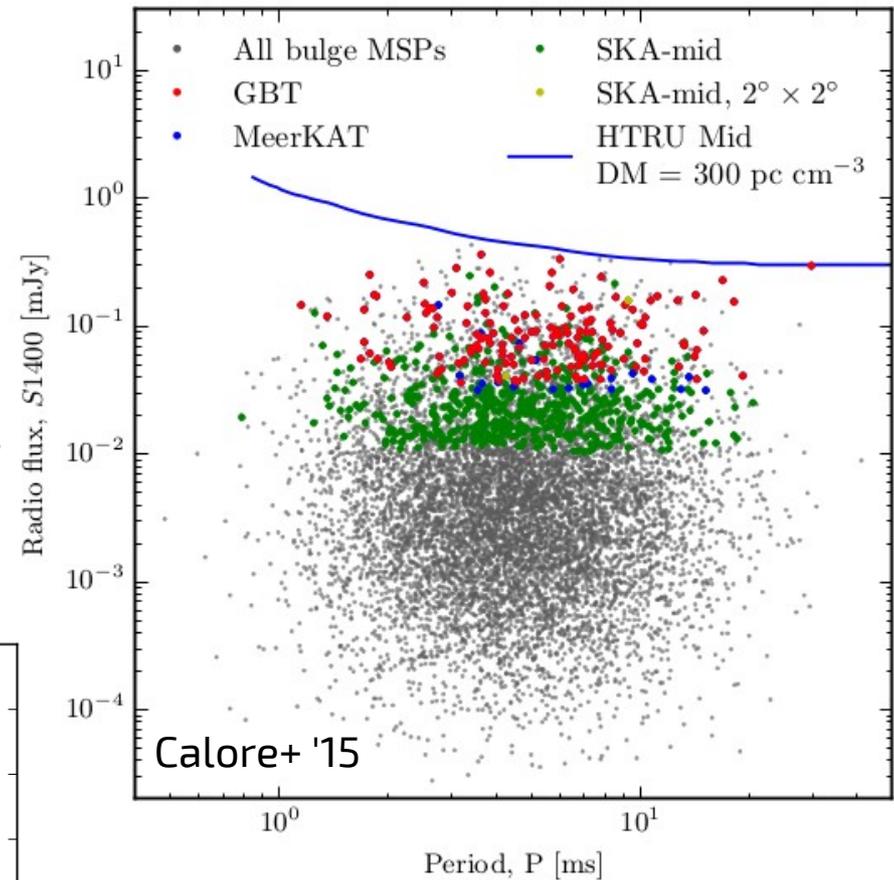
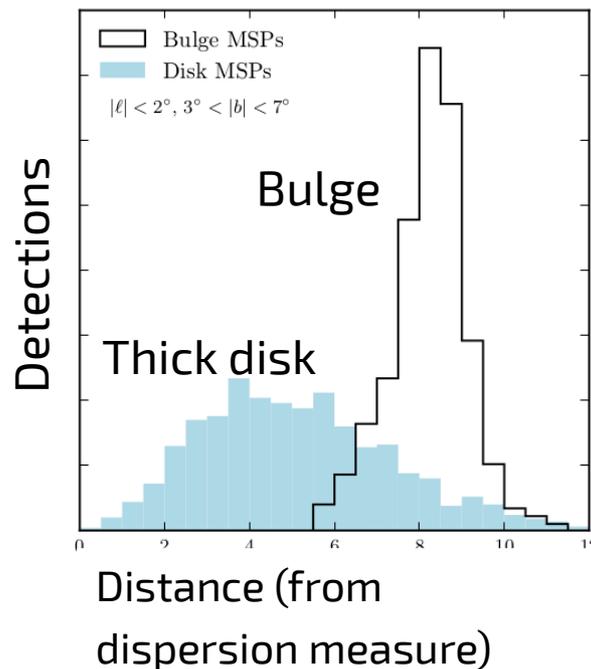
Our plans for the near future

- We teamed up with MeerKAT TRAPUM → plans for dedicated survey in ~2020?

$18^\circ \times 18^\circ$

2.8	3.3	5.0	5.3	5.9	5.0	4.7	3.7	2.6
(2.7)	(2.7)	(2.8)	(2.9)	(3.0)	(2.8)	(2.7)	(3.0)	(2.8)
3.2	4.6	6.0	7.3	6.9	7.3	5.6	4.3	3.1
(3.7)	(3.7)	(3.6)	(3.7)	(3.6)	(3.9)	(3.5)	(4.0)	(3.5)
2.6	3.8	6.1	8.8	9.5	8.0	5.6	4.1	2.3
(4.9)	(4.9)	(4.6)	(4.7)	(4.5)	(4.5)	(4.4)	(4.2)	(4.6)
1.5	2.4	3.8	7.2	9.4	5.9	3.2	1.6	1.1
(4.4)	(4.4)	(4.0)	(4.5)	(4.1)	(3.9)	(3.9)	(3.8)	(3.7)
0.4	1.1	1.1	3.2	9.0	2.5	0.9	0.4	0.3
(3.8)	(3.8)	(3.3)	(2.8)	(2.4)	(2.9)	(2.8)	(2.8)	(2.1)
1.7	2.4	4.2	7.8	12.1	7.5	3.2	2.1	0.9
(4.7)	(4.4)	(4.6)	(4.5)	(4.5)	(3.8)	(4.0)	(3.7)	(4.1)
3.1	4.3	6.3	10.0	10.7	9.0	6.1	3.8	2.5
(5.0)	(5.3)	(5.1)	(5.1)	(4.9)	(4.4)	(4.7)	(5.1)	(4.9)
3.2	4.4	6.0	6.9	8.4	7.6	6.1	4.2	3.2
(4.3)	(3.9)	(3.9)	(3.9)	(3.9)	(3.8)	(4.0)	(3.7)	(3.8)
3.3	4.0	5.2	5.4	6.0	5.2	5.0	3.8	3.0
(2.7)	(2.8)	(2.9)	(3.1)	(2.6)	(3.0)	(2.9)	(2.5)	(2.5)

(SKA)



End

Thank you!