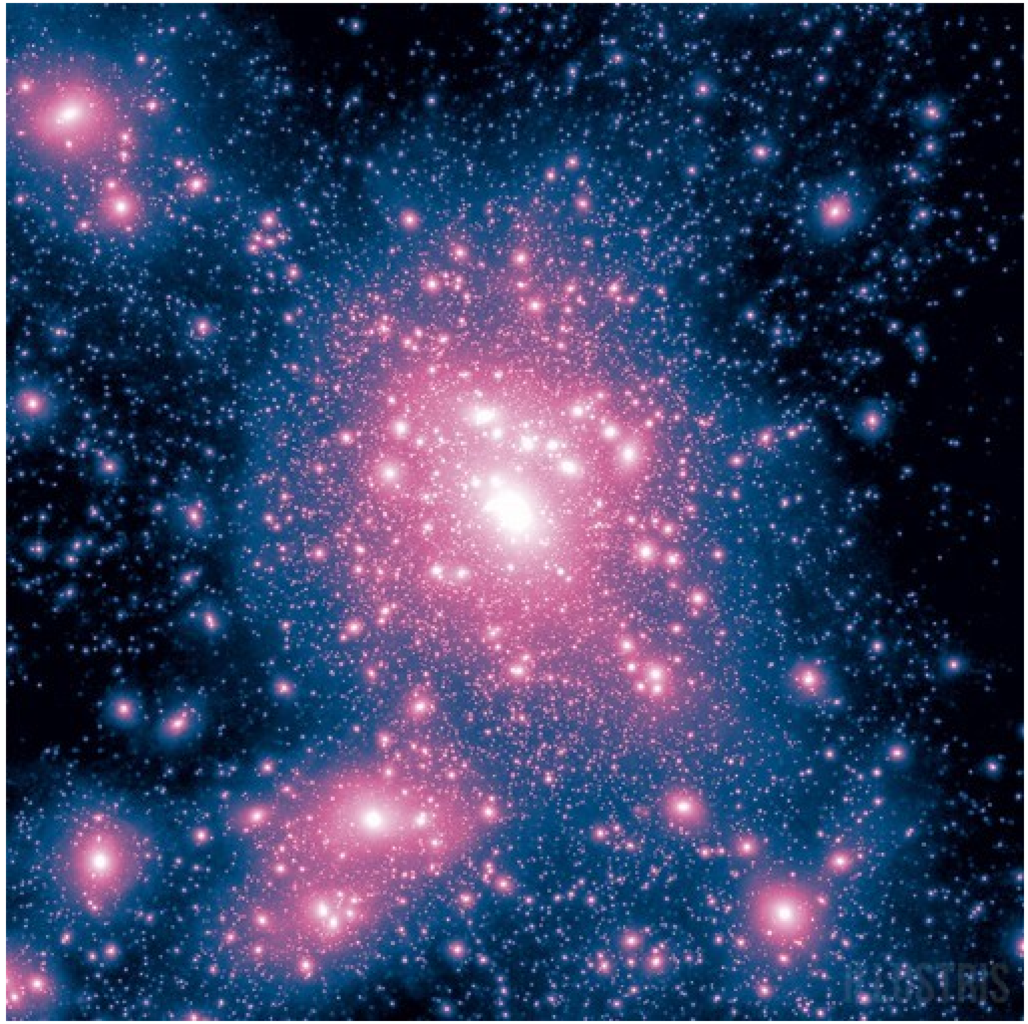
# Indirect dark matter searches



ATI PhD school, UCLA
20th Feb 2018

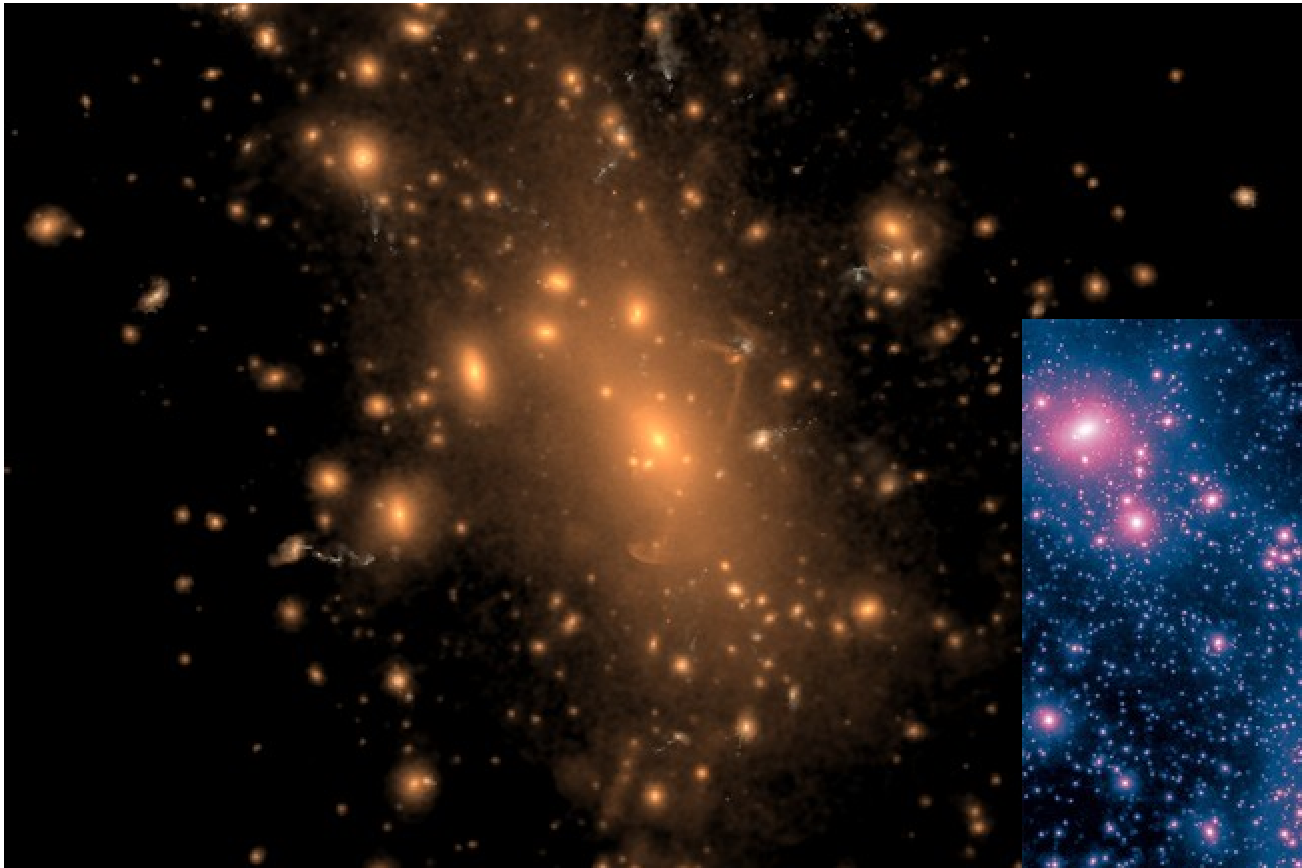
**Christoph Weniger**
University of Amsterdam

# Overview

- General idea and mechanisms
- Overview of most relevant constraints
  - Dwarfs, CMB, Air Cherenkov Telescopes
- Anomalies and hints in the data
  - AMS-02 anti-protons
  - Fermi GeV excess
  - 3.5 keV X-ray line (?)
- Some new statistical techniques (?)
- Outlook

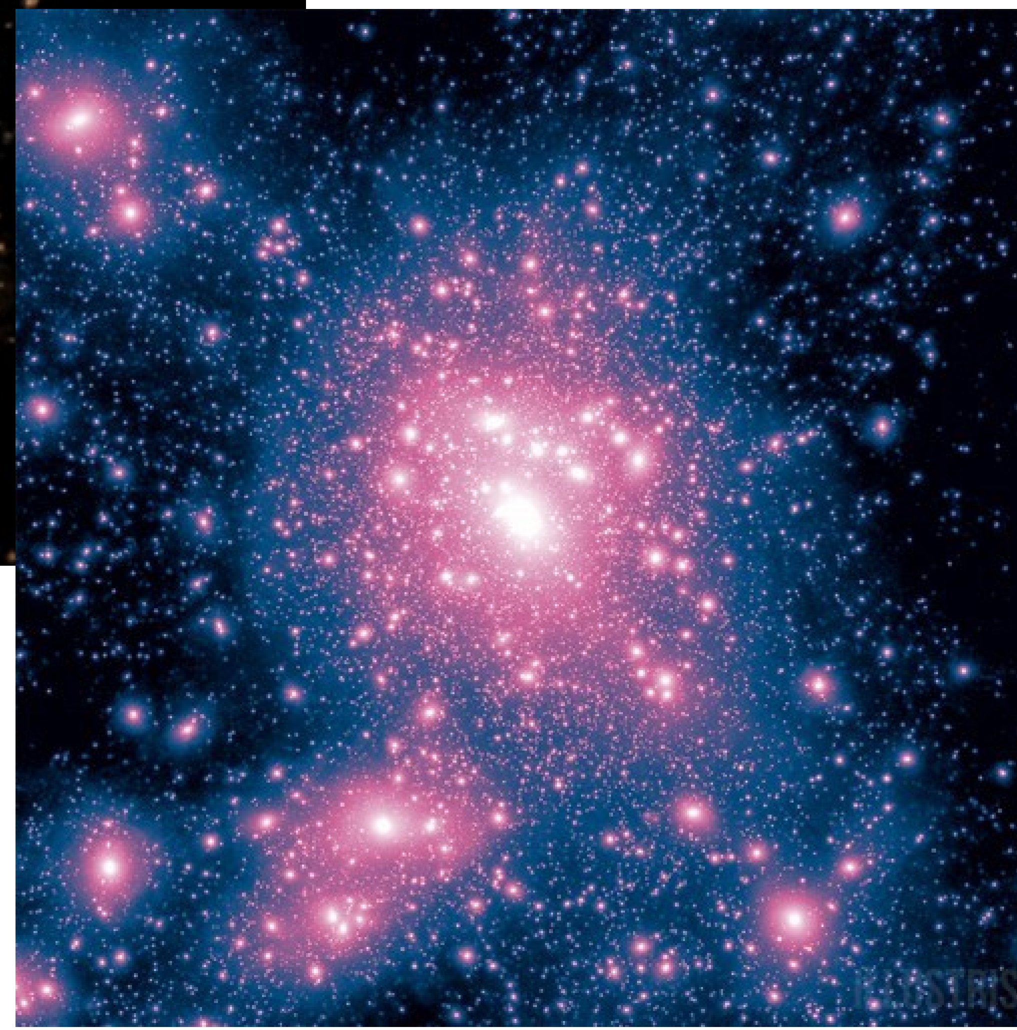
# General idea and mechanisms

# Is dark matter dark?



Stellar light distribution

DM annihilation radiation



**Illustris simulation, most massive z=0 cluster**

http://www.illustris-project.org/media/

# Dark matter annihilation/decay and cosmic rays

**DM self-annihilation into gamma rays**

Gunn+ 1978; Stecker 1978, ...

**Proposal to search for anti-protons from MSSM neutralinos**

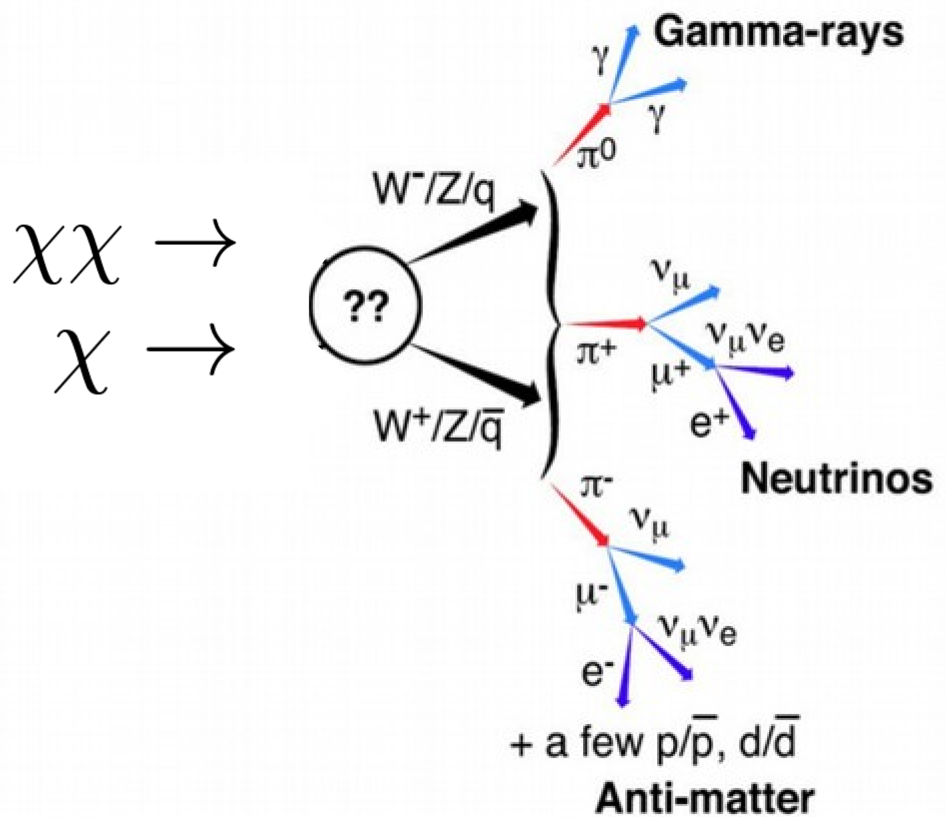
Silk & Srednicki 1984; ...

**Searching for neutrinos from the Sun**

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

**Searches for gamma-ray lines**

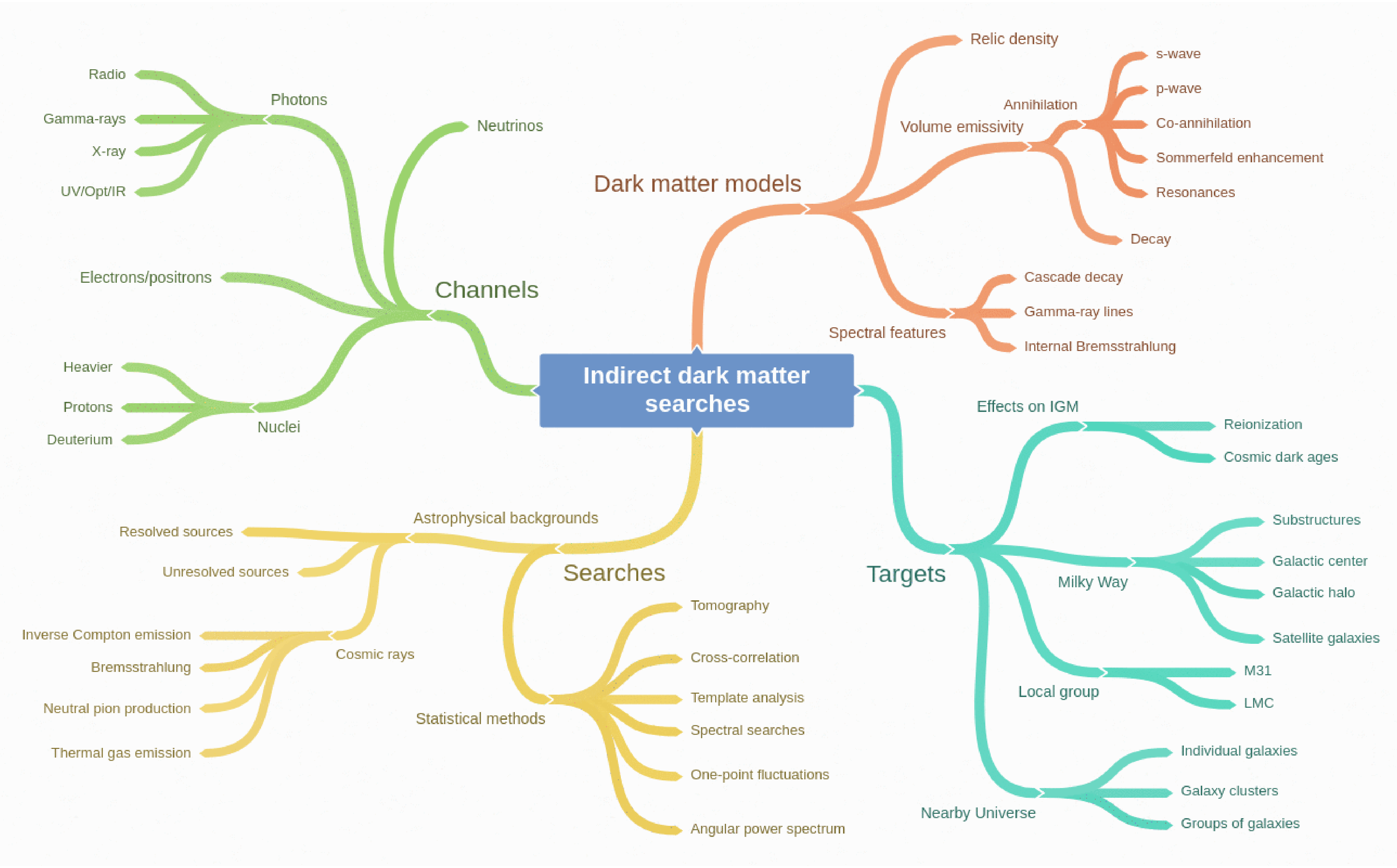
Bergström & Snellmann 1988; Rudaz 1989; ...




**Decay**

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

# Overview


Indirect dark matter searches
Channels
Photons
Radio
Gamma-rays
X-ray
UV/Opt/IR
Neutrinos
Electrons/positrons
Nuclei
Heavier
Protons
Deuterium
Dark matter models
Relic density
Volume emissivity
Annihilation
s-wave
p-wave
Co-annihilation
Sommerfeld enhancement
Resonances
Decay
Spectral features
Cascade decay
Gamma-ray lines
Internal Bremsstrahlung
Searches
Astrophysical backgrounds
Resolved sources
Unresolved sources
Cosmic rays
Inverse Compton emission
Bremsstrahlung
Neutral pion production
Thermal gas emission
Statistical methods
Tomography
Cross-correlation
Template analysis
Spectral searches
One-point fluctuations
Angular power spectrum
Targets
Effects on IGM
Reionization
Cosmic dark ages
Milky Way
Substructures
Galactic center
Galactic halo
Satellite galaxies
Local group
M31
LMC
Nearby Universe
Individual galaxies
Galaxy clusters
Groups of galaxies

# Source terms

## Differential source terms

$$\frac{d\mathcal{S}_i}{dE} \equiv \frac{d^5 N}{dt dV dE}$$

## Dark matter decay

$$\phi_{\rm dm} \to \gamma\gamma, \bar{f}f, \ldots$$

$$\psi_{\rm dm} \to \gamma\nu, Z^0\nu, \ldots$$

$$\frac{d\mathcal{S}_i}{dE} = \frac{\Gamma_{\rm dm}}{m_{\rm dm}}\frac{dN_i}{dE}\rho_{\rm dm}$$

Stable standard model particles

$$i = \gamma, e^{\pm}, \nu_i, p^{\pm}, N^{\pm}$$

## Dark matter annihilation

$$\phi_{\rm dm}\phi_{\rm dm} \to \gamma\gamma, \bar{f}f, \ldots$$

$$\psi_{\rm dm}\psi_{\rm dm} \to \gamma\gamma, \bar{f}f, \ldots$$

$$\frac{d\mathcal{S}_i}{dE} = \alpha(\sigma v_{\rm rel})_{v\to 0}\frac{dN_i}{dE}\frac{\rho^2_{\rm dm}}{m^2_{\rm dm}}$$

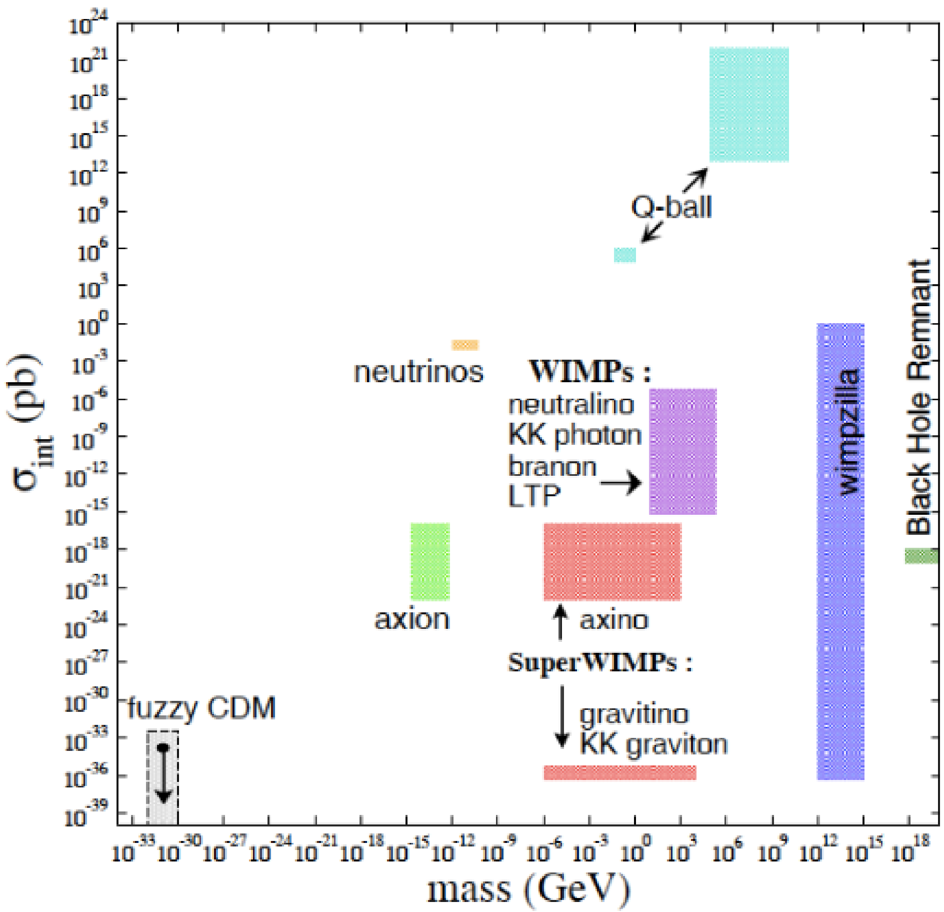
$\alpha = \frac{1}{2}$ Majorana, real scalar

$\alpha = \frac{1}{4}$ Dirac, compex scalar

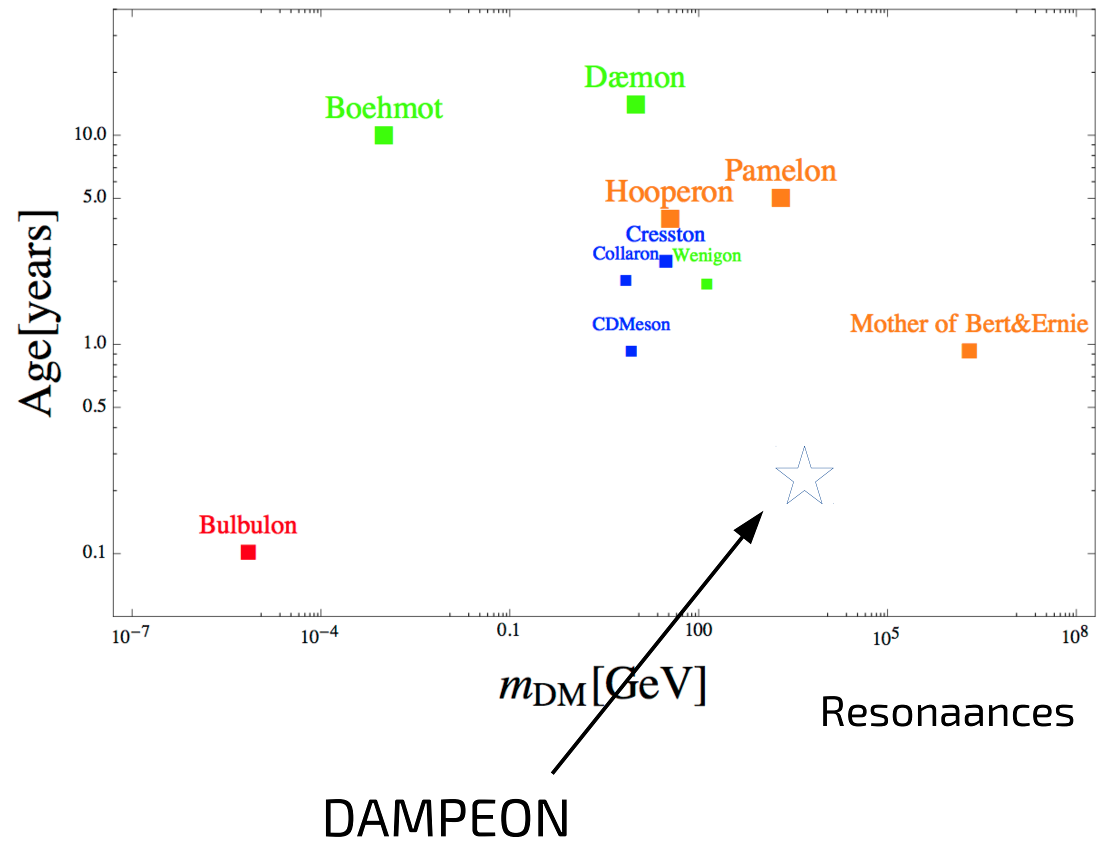
# Candidates for particle dark matter

**Mass-scales and interactions are suggested by**

- Theoretical arguments → Various incarnations of **WIMPs, Sterile neutrinos, Axions, …**
- Hints in the data → **positron excess, 511 keV line, Fermi GeV excess, PeV neutrinos, …**




E-K Park 2007




Resonaances

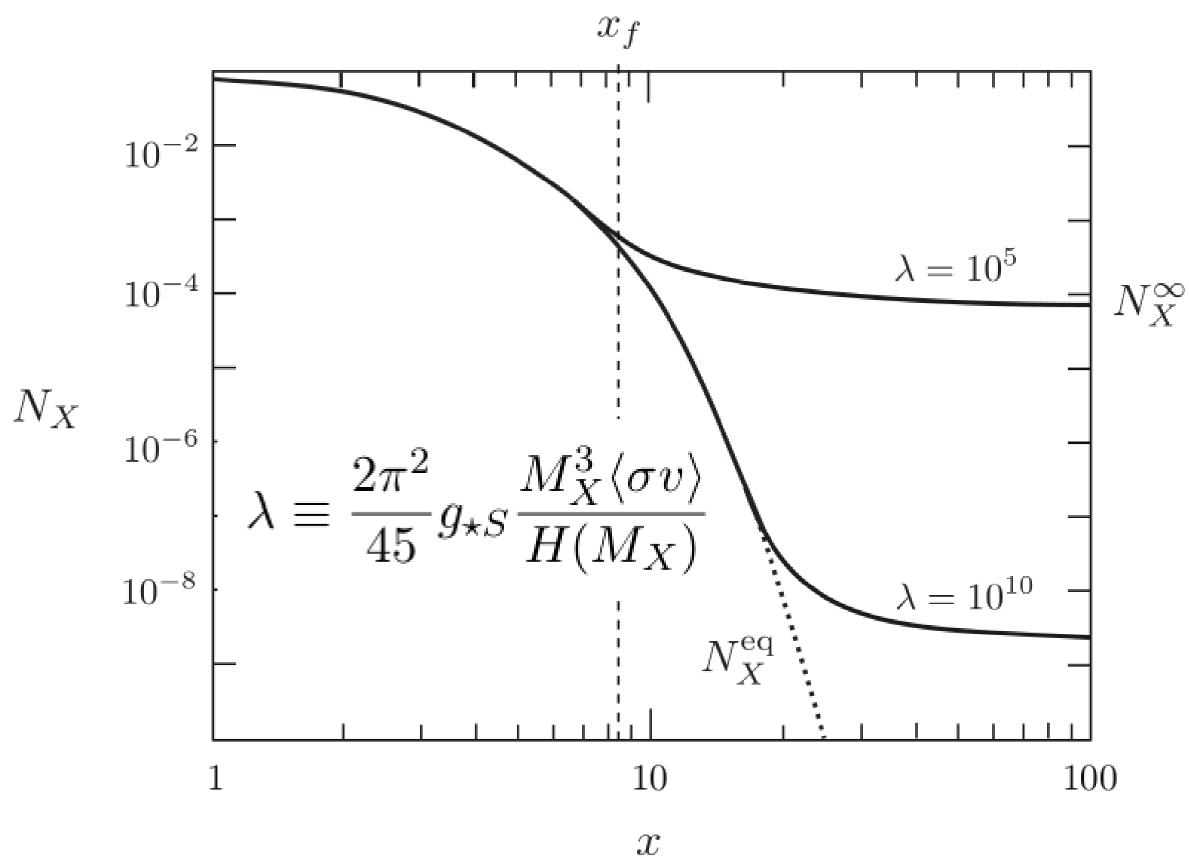
# Dark matter freeze-out

**Boltzmann equation** for particles in comoving volume

$$\frac{dN_X}{dt} = -s\langle\sigma v\rangle\left[N_X^2 - (N_X^{\rm eq})^2\right]$$

$$N_X \equiv n_X/s \qquad x \equiv \frac{M_X}{T}$$

$$X + \bar{X} \leftrightarrow \ell + \bar{\ell}$$




**Relic density today**

$$\Omega_X = \frac{\rho_{X,0}}{\rho_{\rm crit,0}} = \frac{M_X N_X^\infty s_0}{\rho_{\rm crit,0}}$$

**"WIMP miracle"**

$$\Omega_X h^2 \sim 0.1 \frac{3\times 10^{-26}{\rm cm}^3{\rm s}^{-1}}{\langle\sigma v\rangle} \sim \frac{10^{-3} G_F}{\langle\sigma v\rangle}$$

# Origins of velocity dependence

Origin for velocity depends of velocity-weighted annihilation cross-section.

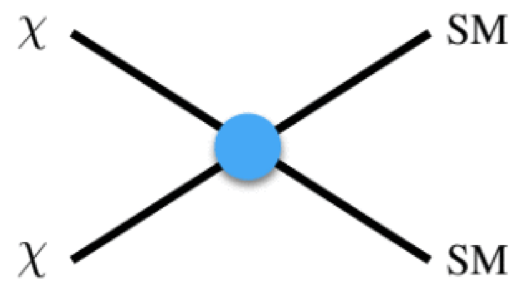
**Hard process**

Non-relativistic expansion:

$$\sigma v = a + bv^2 + \dots$$

*a* dominates: s-wave

*b* dominates: p-wave $(e.g., \;\; \chi_1^0 \chi_1^0 \to \bar{f} f)$

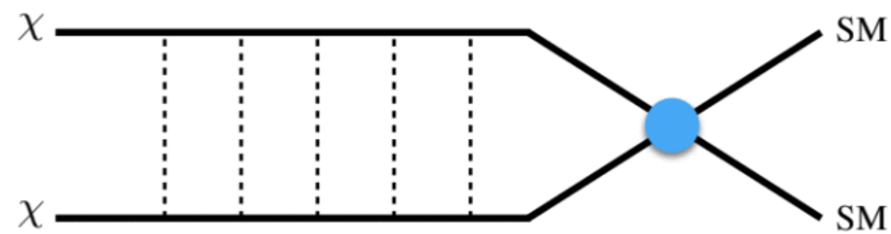


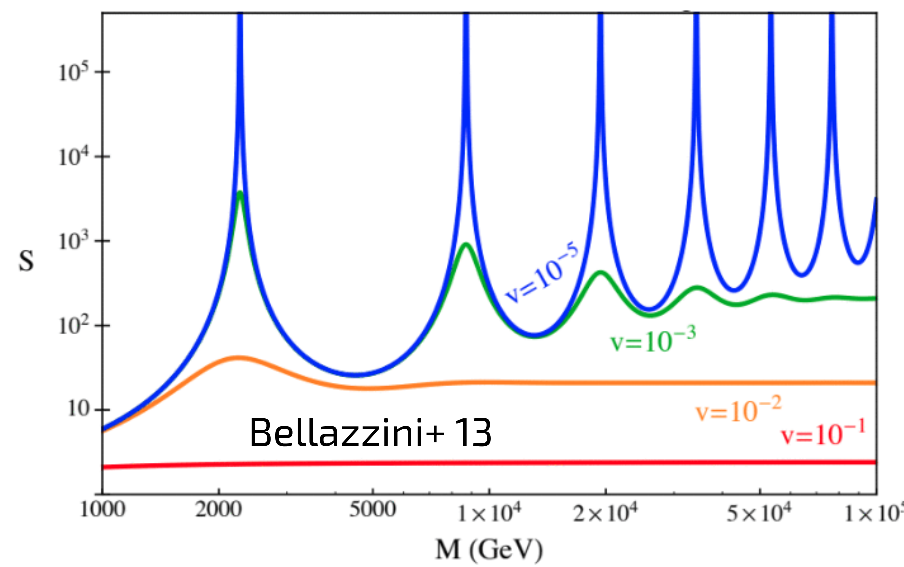

**Sommerfeld enhancement**

Attractive force between initial states

→ Change in wave function at origin

$$S = \frac{|\psi(0)|^2}{|\psi_0(0)|^2}$$



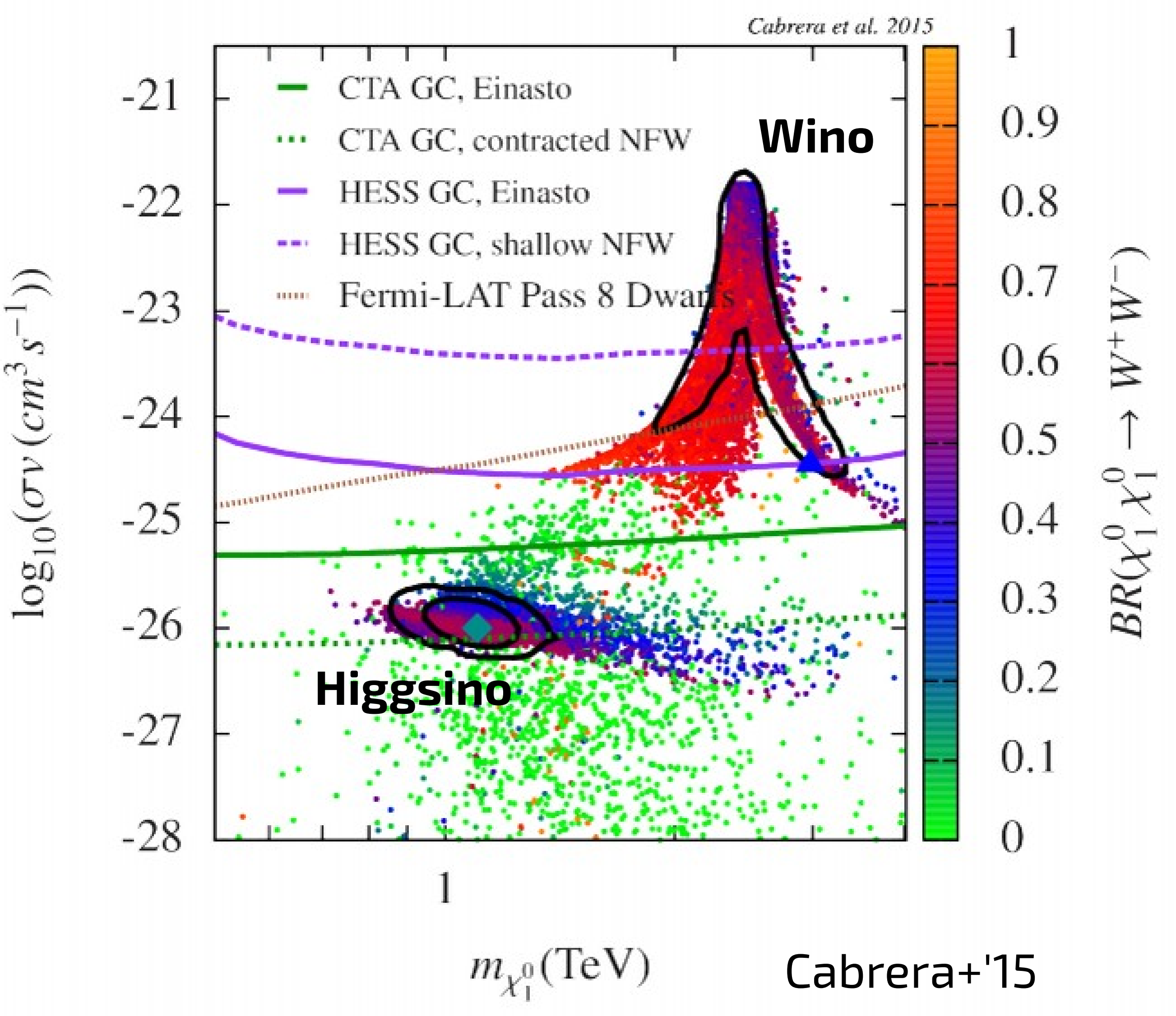




**And: resonances**, **co-annihilation, …**

For more details see, e.g., Lisanti 1603.03797

# Wino dark matter

Example: Lightest neutralino in MSSM-9



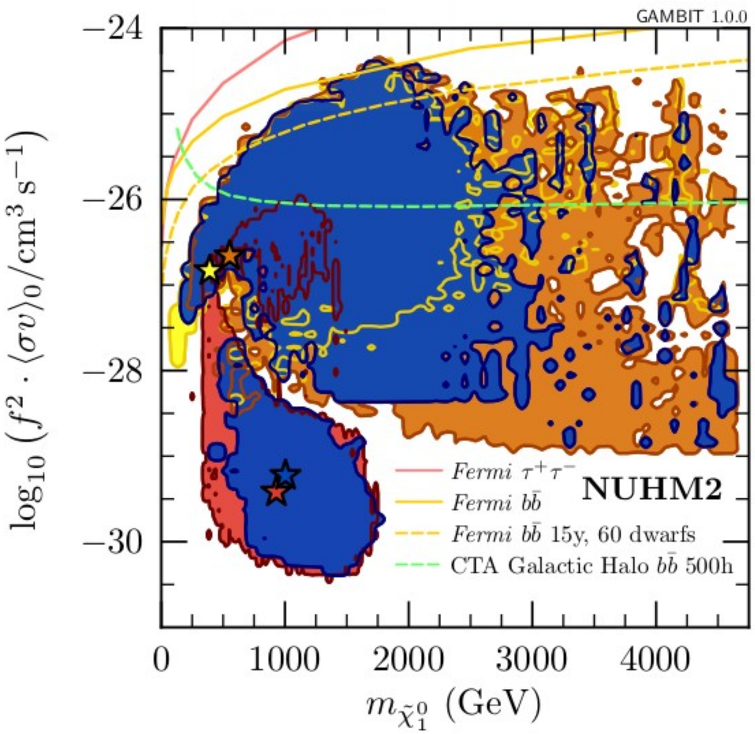

Cabrera+'15

# NUHM2 (Non-universal Higgs mass MSSM)

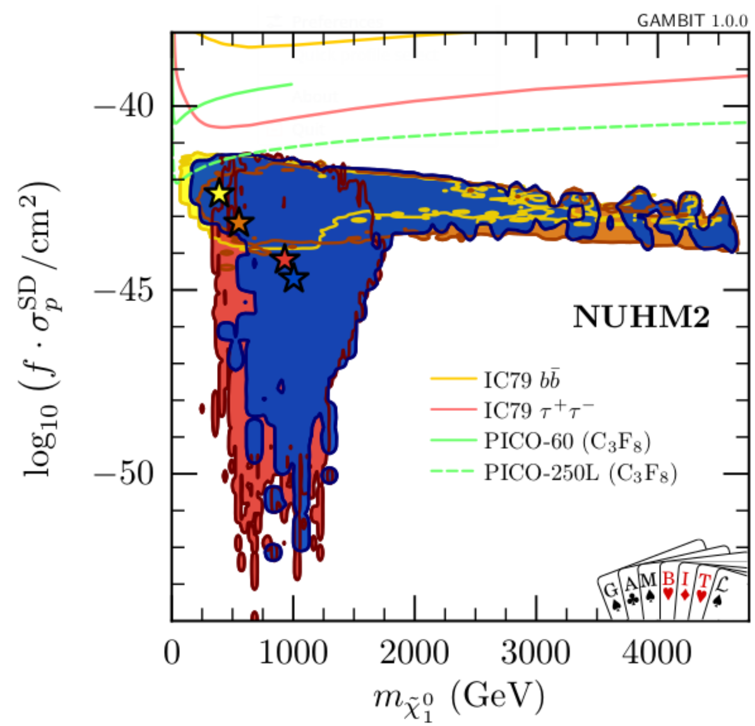
GAMBIT, 1705.07935

**Parameters:** $m_0, m_{1/2}, A_0, \tan(\beta), \mathrm{sgn}(\mu), m_{H_u}, m_{H_d}$ $\Omega_{\chi_1^0} \lesssim \Omega_{\mathrm{dm}}$

**Annihilation cross-section**



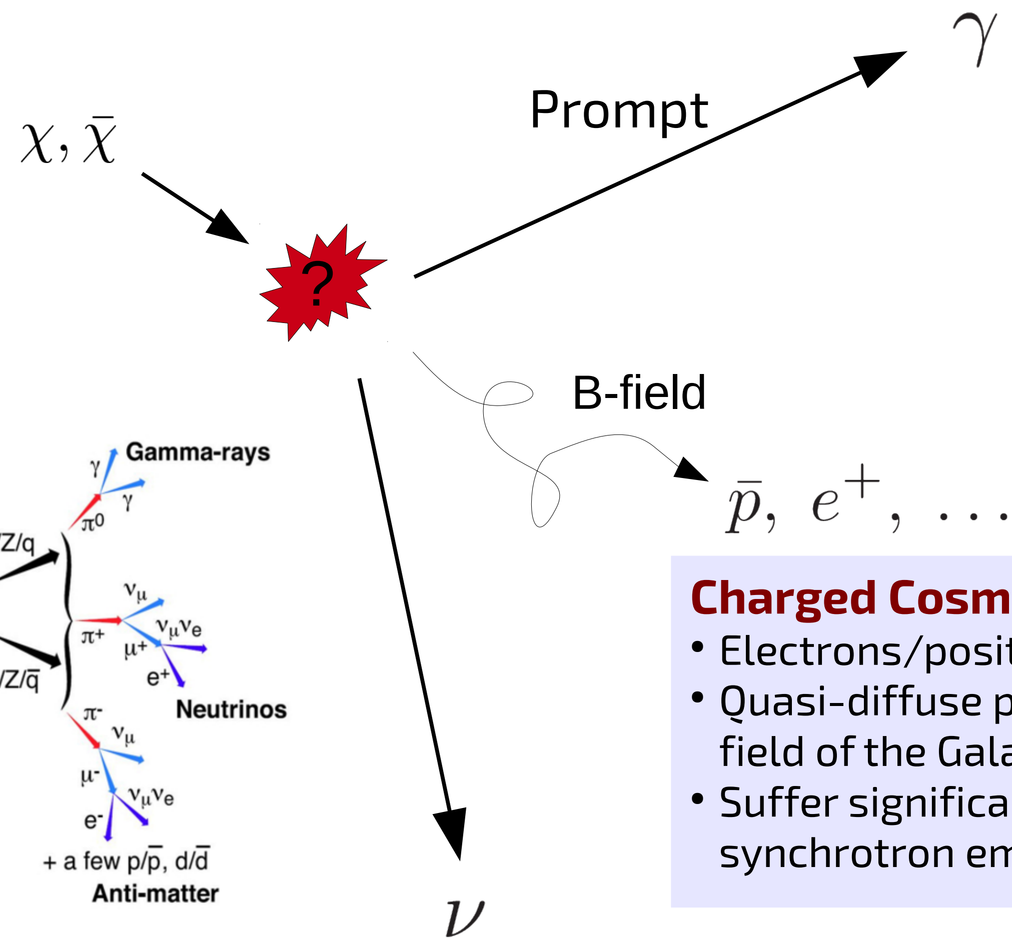

**Spin-dependent scatter**

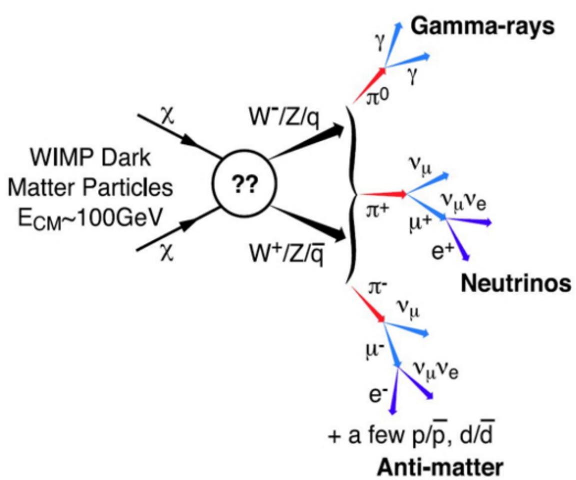



$\tilde{t}_1$ co-annihilation | $A/H$ funnel | $\tilde{\chi}_1^\pm$ co-annihilation | $\tilde{\tau}_1$ co-annihilation

- Again, super-thermal cross-sections get significant contributions from A-full regime
- Other annihilation processes also relevant, rich phenomenology
- **We did not yet include radiative corrections, Sommerfeld enhancement etc**

# The annihilation channels




**Gamma rays**
- Propagation on geodesics
- Absorption or energy losses small at ~GeV energies
- Point towards their sources

**Charged Cosmic rays**
- Electrons/positrons, nuclei
- Quasi-diffuse propagation in turbulent magnetic field of the Galaxy
- Suffer significant energy losses, mostly synchrotron emission, inverse Compton losses

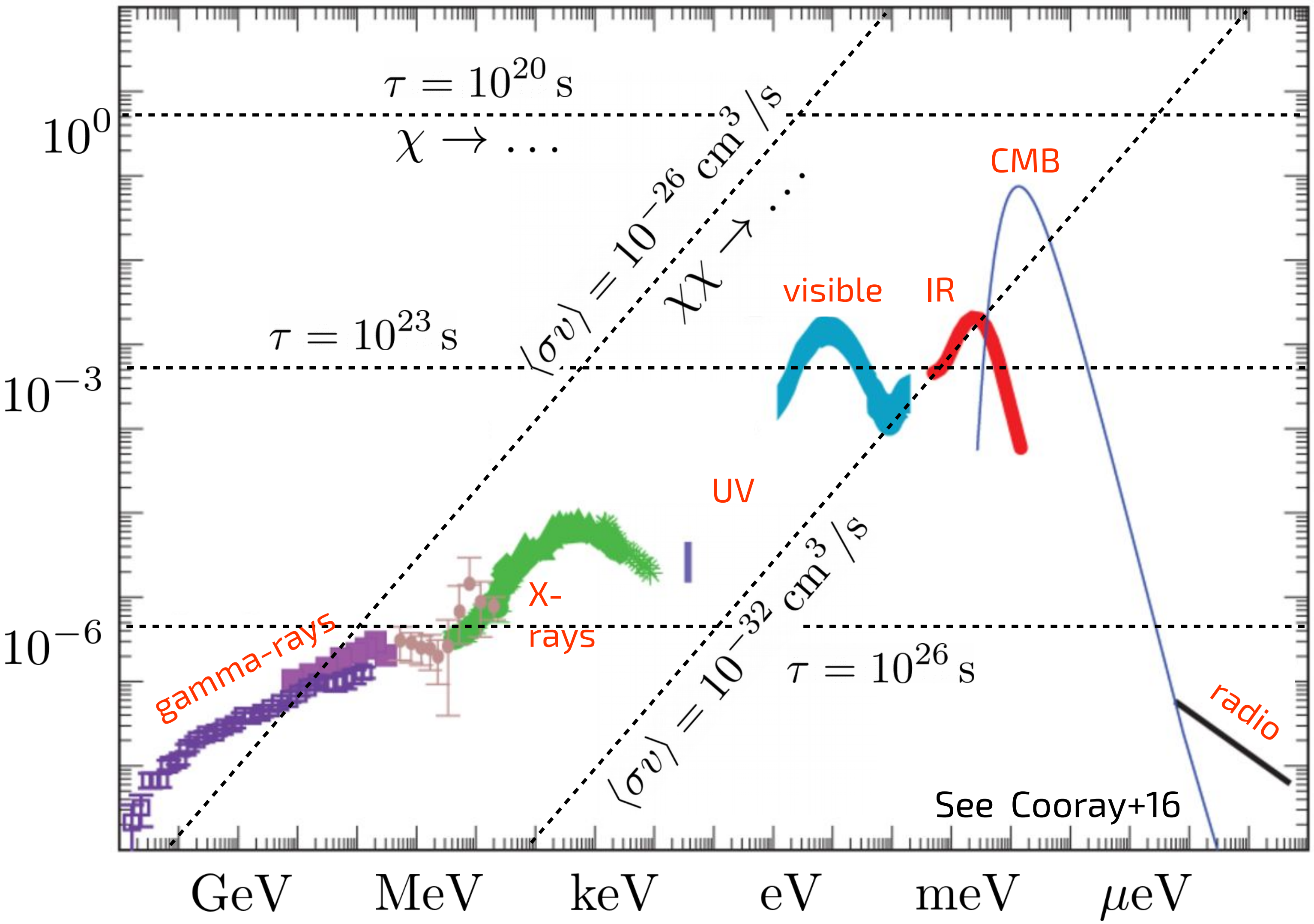
**Neutrinos**
- Geodesics
- Very hard to measure
- Can escape from the core of dense stellar objects

# Average energy densities in today's Universe

**Dark matter energy density >> Radiation energy density**

$$\rho_{\rm dm} \sim 1.3 \times 10^3 \frac{\rm eV}{\rm cm^3} \qquad \rho_{\rm rad} \sim 1 \frac{\rm eV}{\rm cm^3}$$

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




**Rough estimate:**

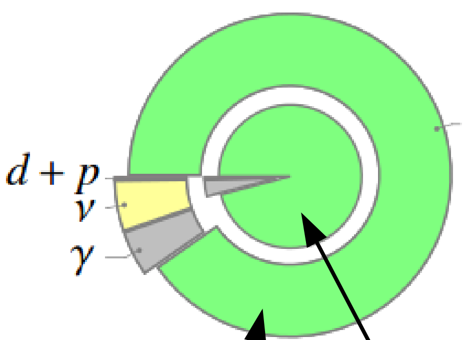
Assume that all DM rest mass energy is emitted in photons around the corresponding frequency (witin one dex), since beginning of the Universe.

# 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

$DM\,DM \rightarrow e_L^- + e_L^+$

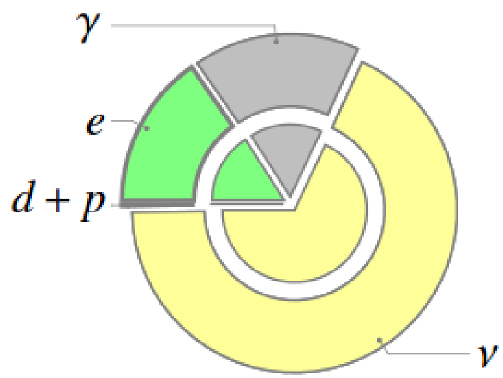



$$E_{\gamma+e}/E_{tot} = 0.996\ (0.948)$$
$$E_{p+d}/E_{\gamma+e} = 0.000\ (0.002)$$

$m$ = 200 GeV

$m$ = 5 TeV

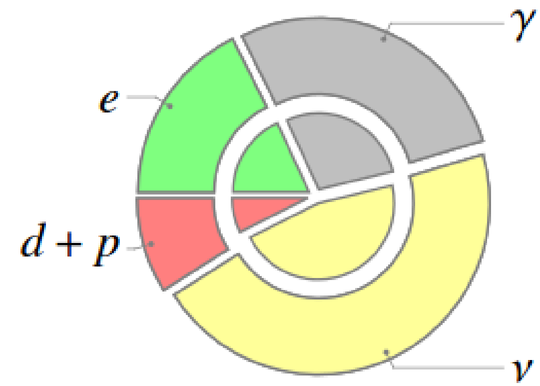
$DM\,DM \rightarrow \tau_L^- + \tau_L^+$




$$E_{\gamma+e}/E_{tot} = 0.320\ (0.318)$$
$$E_{p+d}/E_{\gamma+e} = 0.001\ (0.007)$$

## Hadronic channel

$DM\,DM \rightarrow b + b$

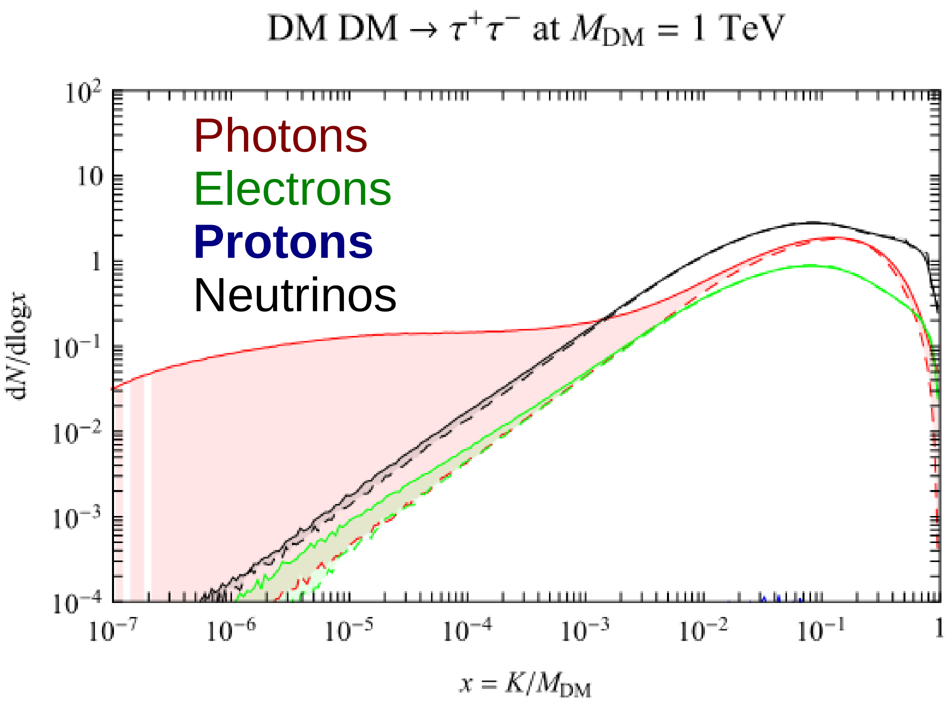



$$E_{\gamma+e}/E_{tot} = 0.462\ (0.454)$$
$$E_{p+d}/E_{\gamma+e} = 0.159\ (0.198)$$

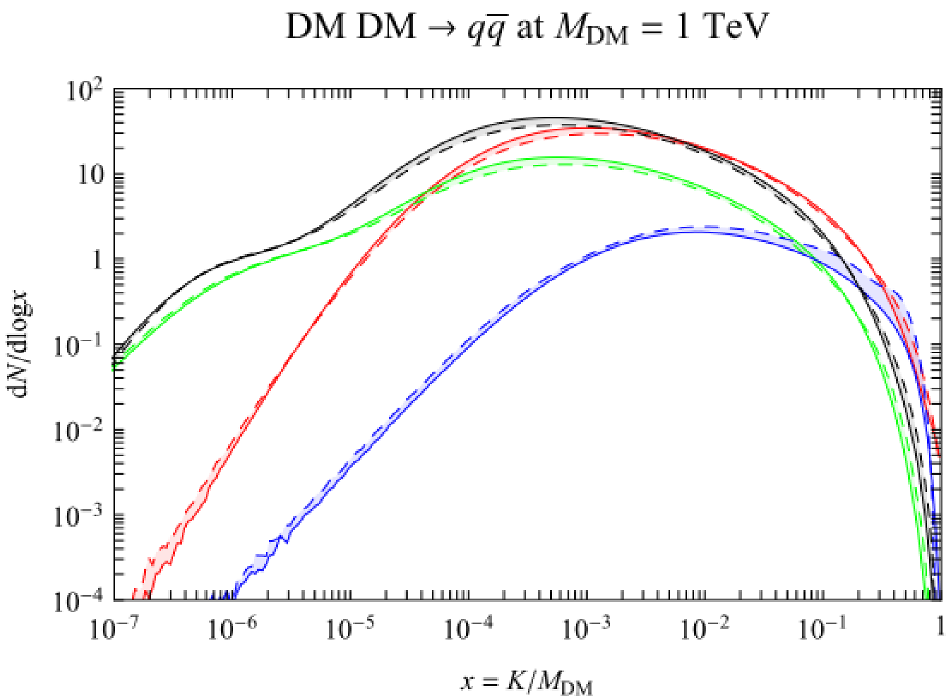
Cirelli et al. (2010) “PPPC4DMID”

# Final state energy spectra

**Annihilation into tau leptons**

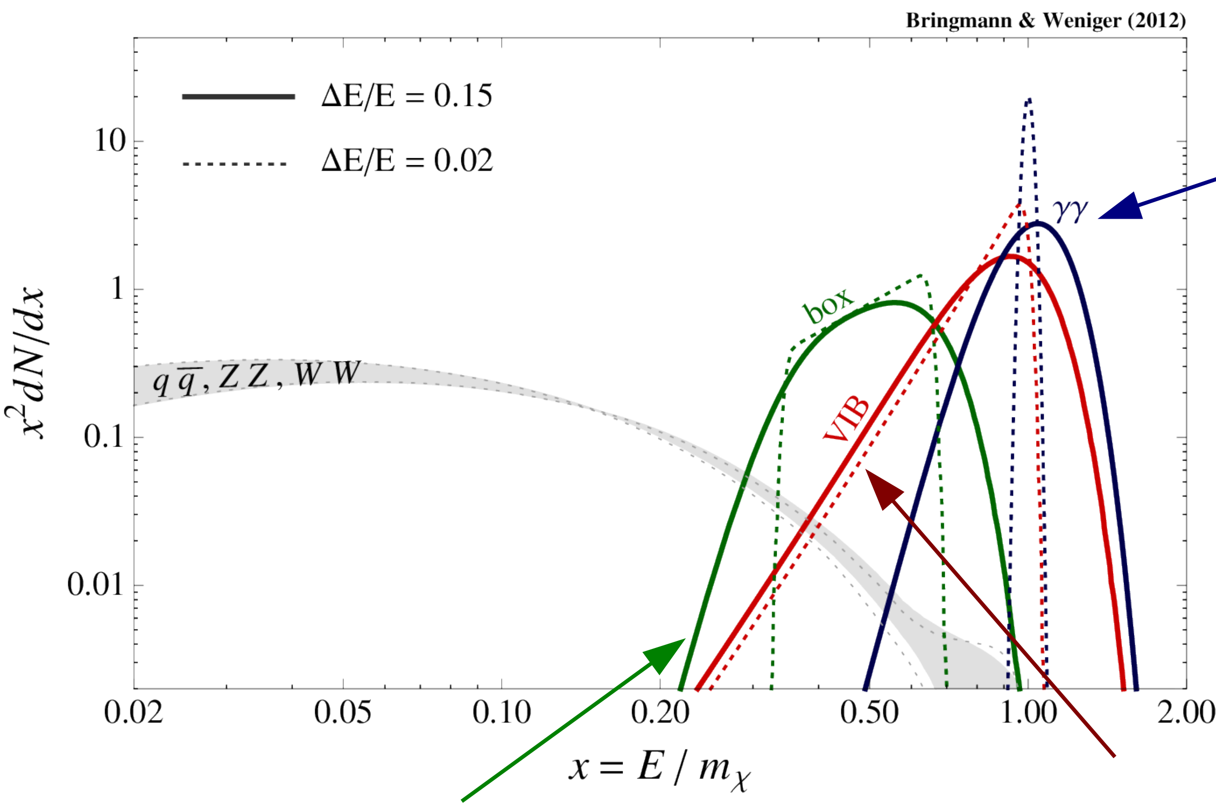



**Annihilation into quarks**



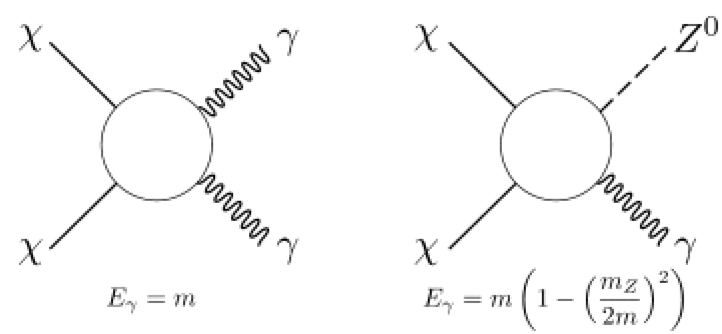

Cirelli et al. (2010)

# Gamma-ray spectral features




**Gamma-ray lines**

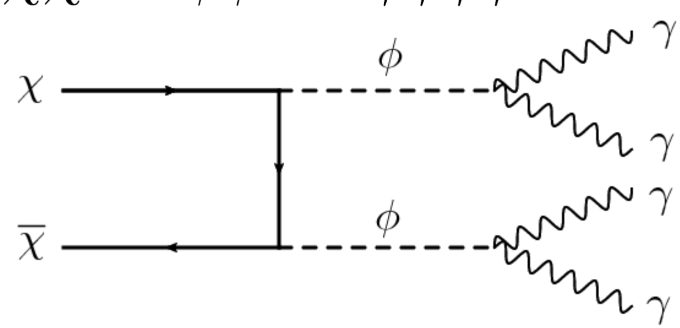
$$\chi\chi \to \gamma\gamma, \gamma Z^0$$




[Bergström & Snellman (1988)]

**Cascade decays**

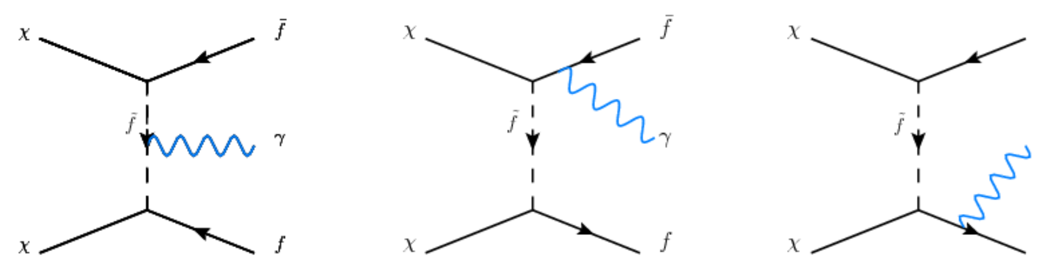
$$\chi\chi \to \phi\phi \to \gamma\gamma\gamma\gamma$$



[e.g. Ibarra et al. 2012]

**Internal Bremsstrahlung (IB)**

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

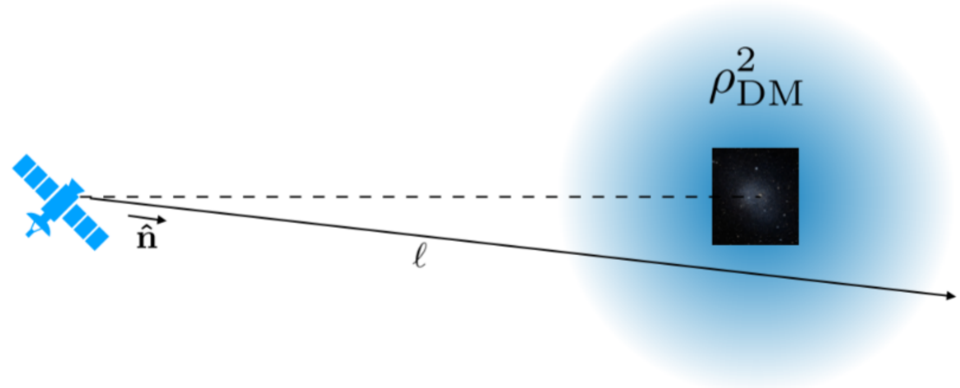


[e.g. Bringmann, Bergström & Edsjö (2008)]

# Differential intensity of DM signal photons

**Differential signal intensity**

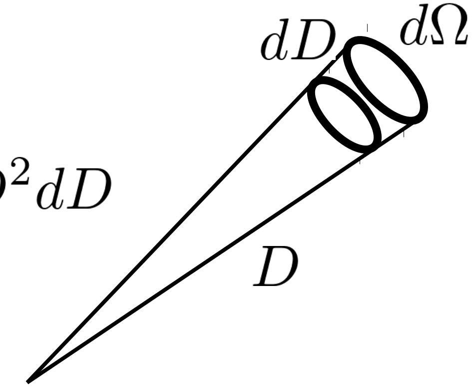
$$\frac{d^2F}{d\Omega dE} = \frac{1}{2}\frac{(\sigma v_{\rm rel})_0}{m_\chi^2}\frac{dN_\gamma}{dE} \times \frac{1}{4\pi}\int_{\rm l.o.s.} dD\ \rho_{\rm DM}(\vec{r}[D,\Omega])^2$$




**Differential flux** from a region $\Delta V$ at distance *D.*

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

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



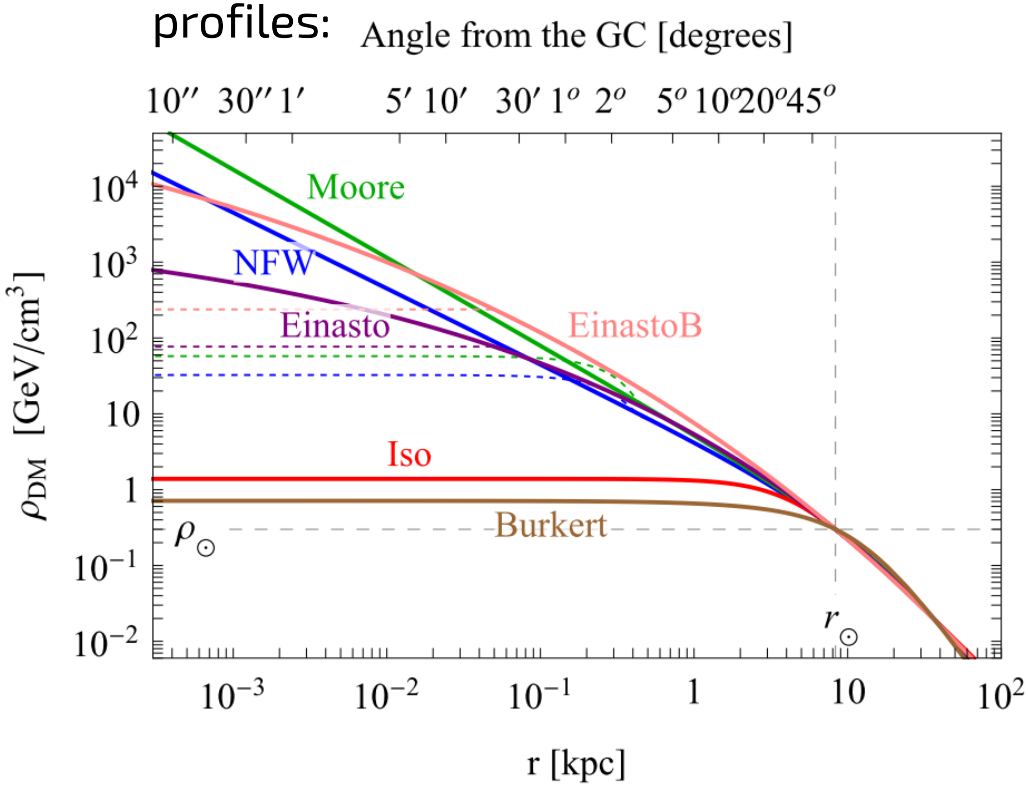

Volume emissivity (see above)

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

# Dark matter profile

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

Viable DM density profiles:



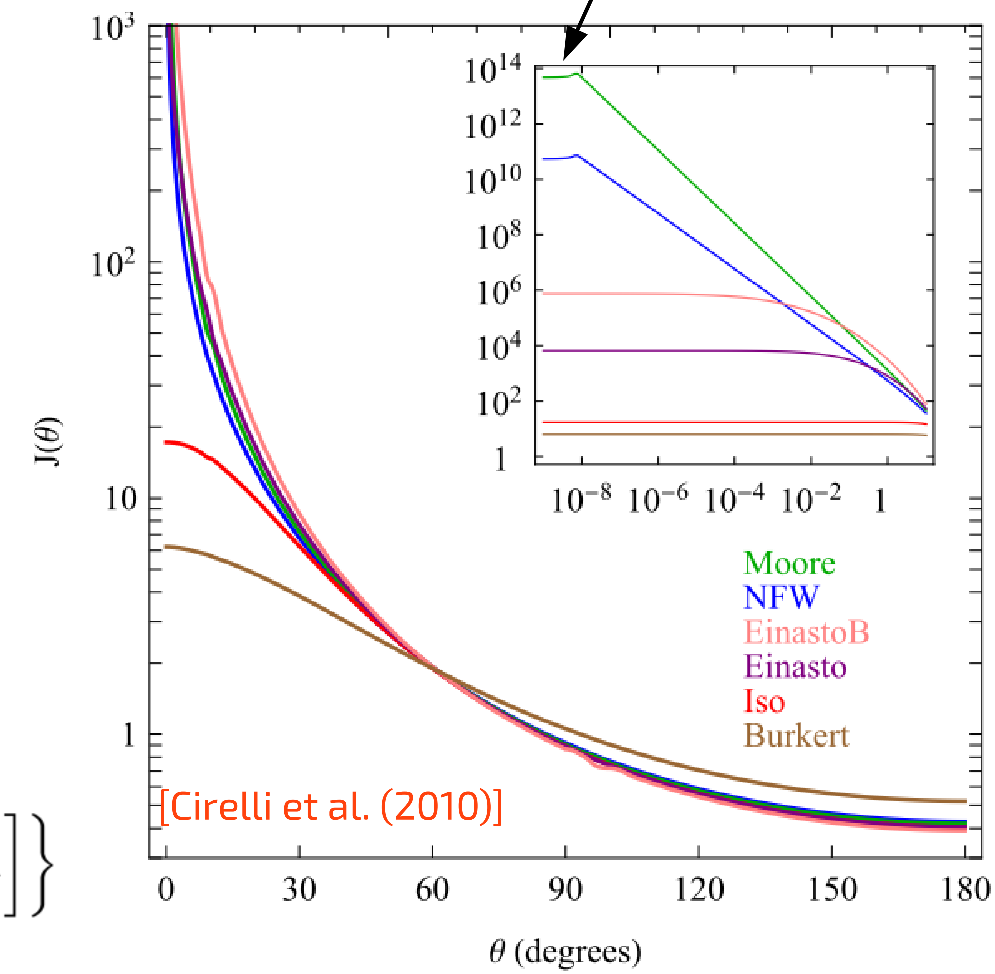

$$\text{NFW}: \quad \rho_{\text{NFW}}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

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

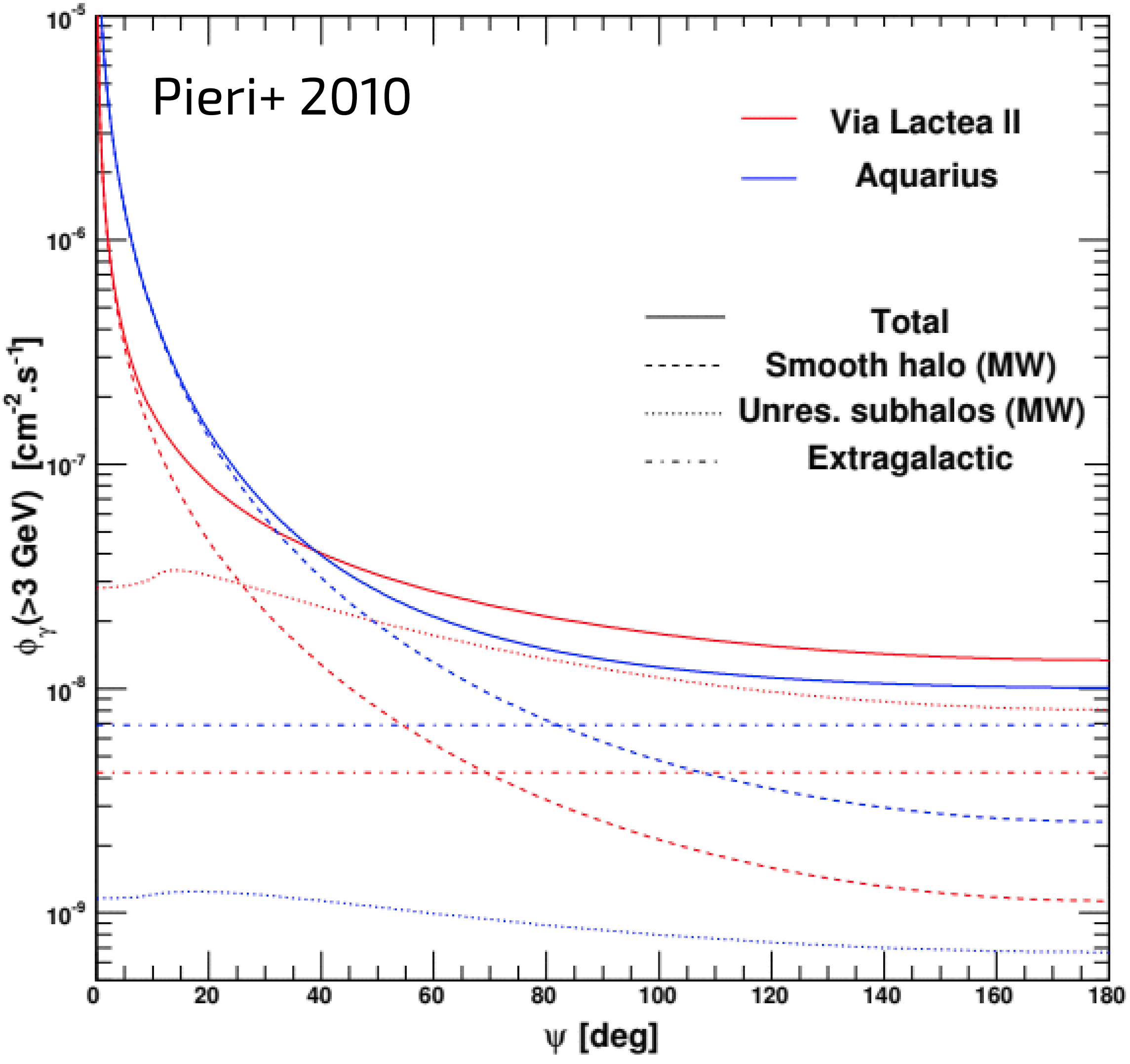
$$\text{Isothermal}: \quad \rho_{\text{Iso}}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

Cutoff from self-annihilation

Signal morphology:



# 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 subtructure 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

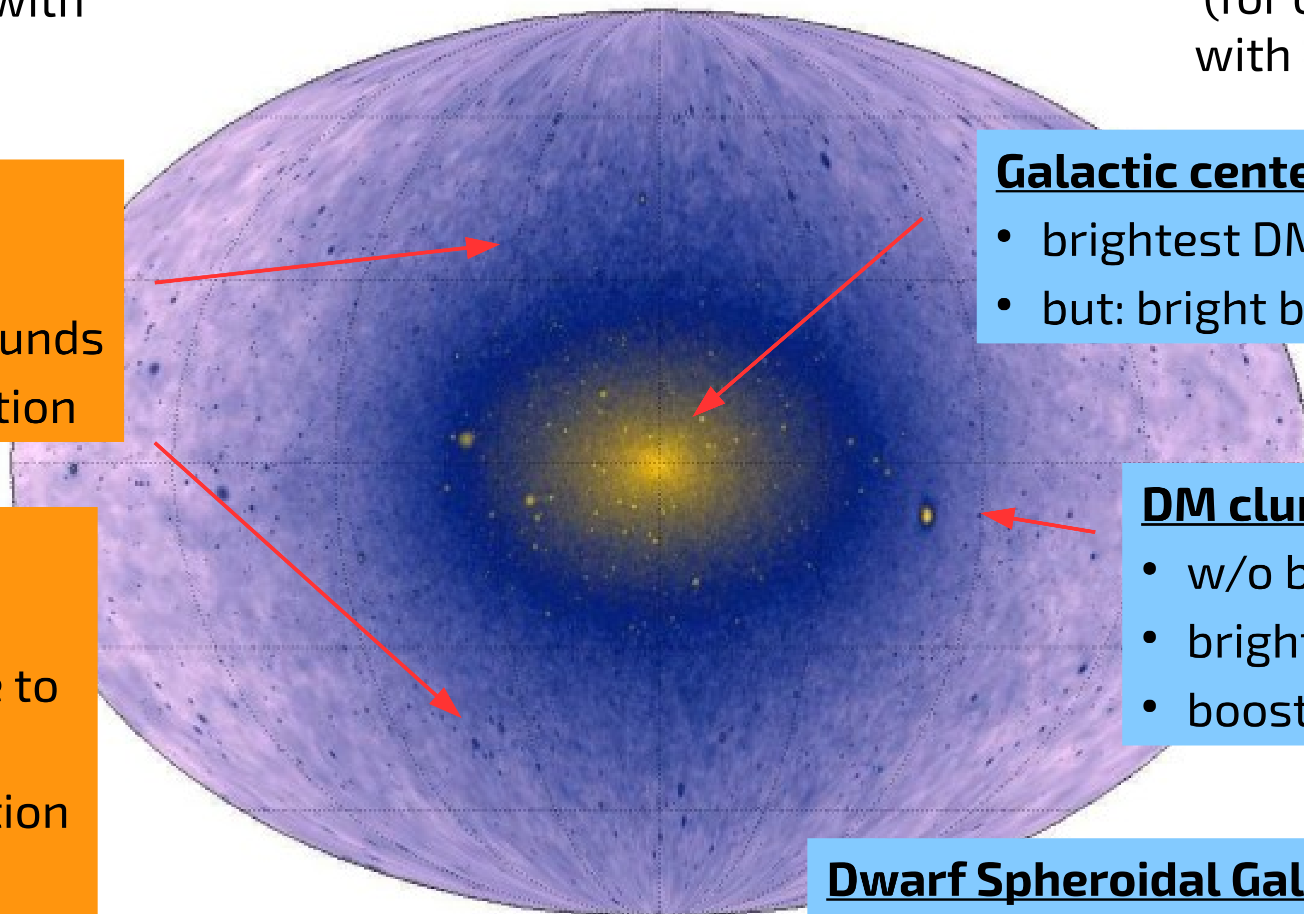
# Spatial characteristics

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

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

**Extended or diffuse:**
(for observations with gamma rays)

**Point-like:**
(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?

**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)

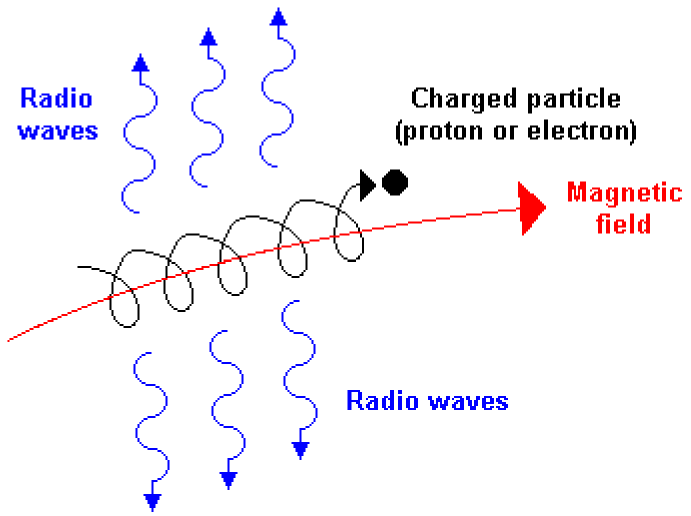
review on N-body simulations: Kuhlen, Vogelsberger & Angulo (2012)

# Secondary photons

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

**Synchrotron emission**

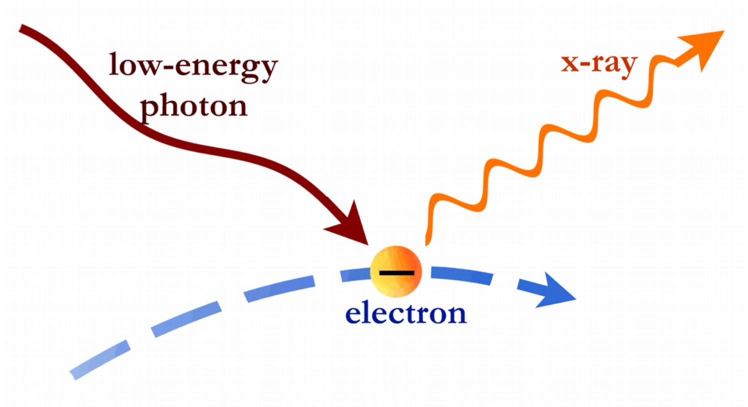
Radio emission of electrons propagating the Galactic magnetic field




nrumiano

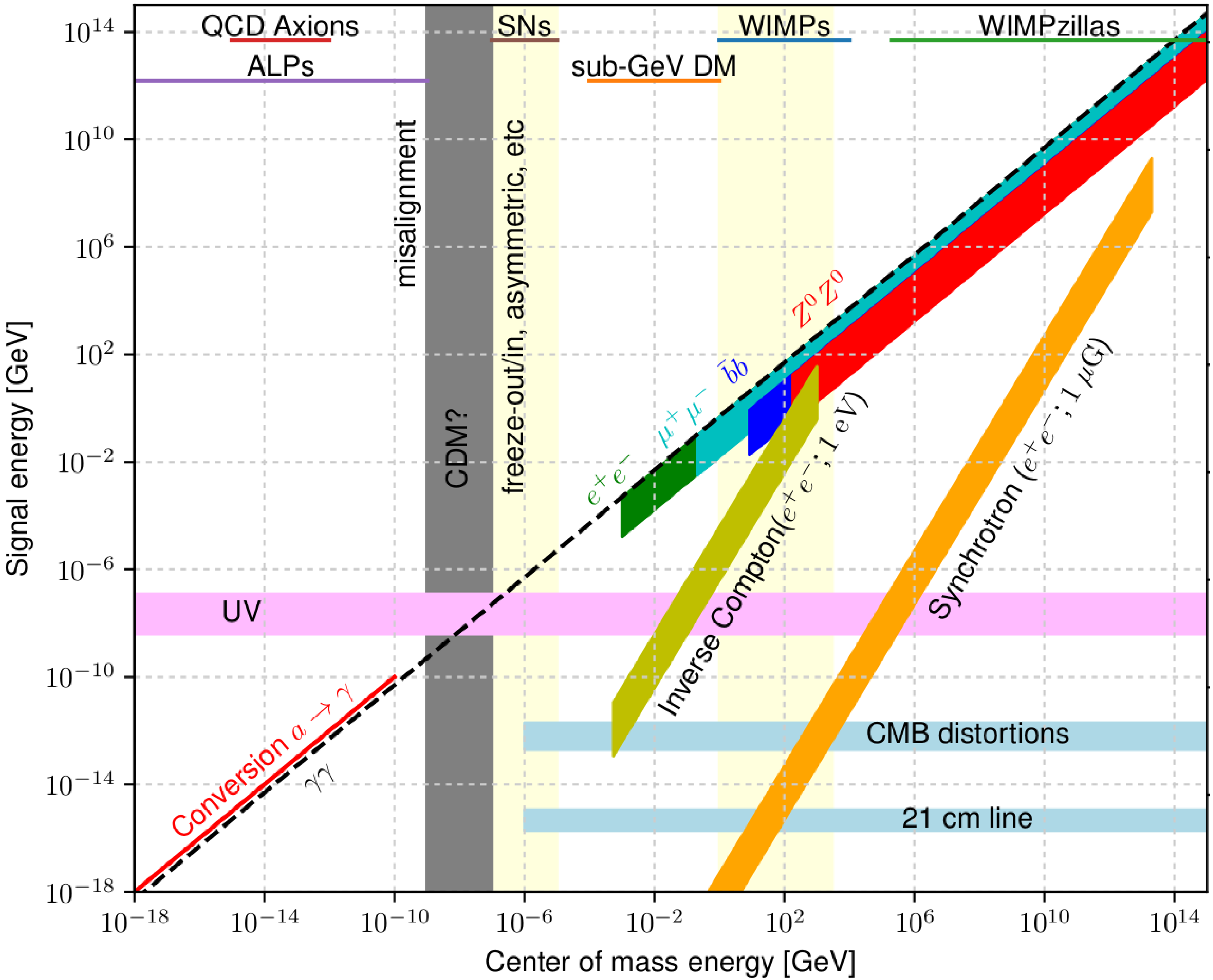
**Inverse Compton emission**

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



# Relevant radiation mechanisms

CSW, in prep




UHECRs

Gamma rays & Cosmic rays

X rays

UV

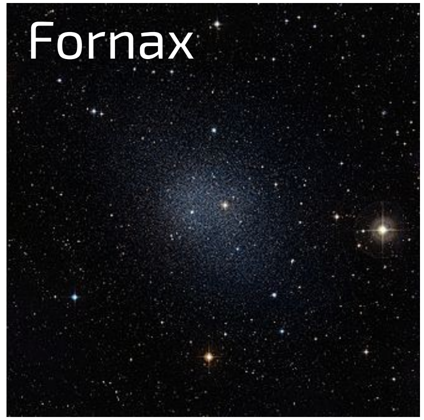
Optical/IR

CMB

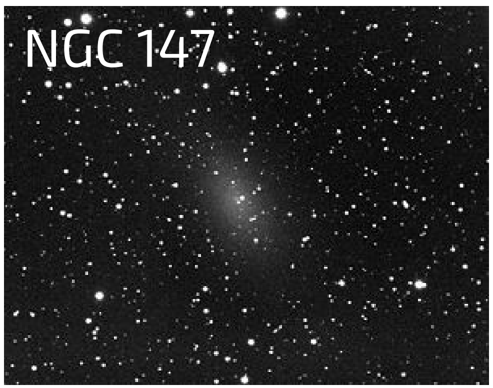
Radio

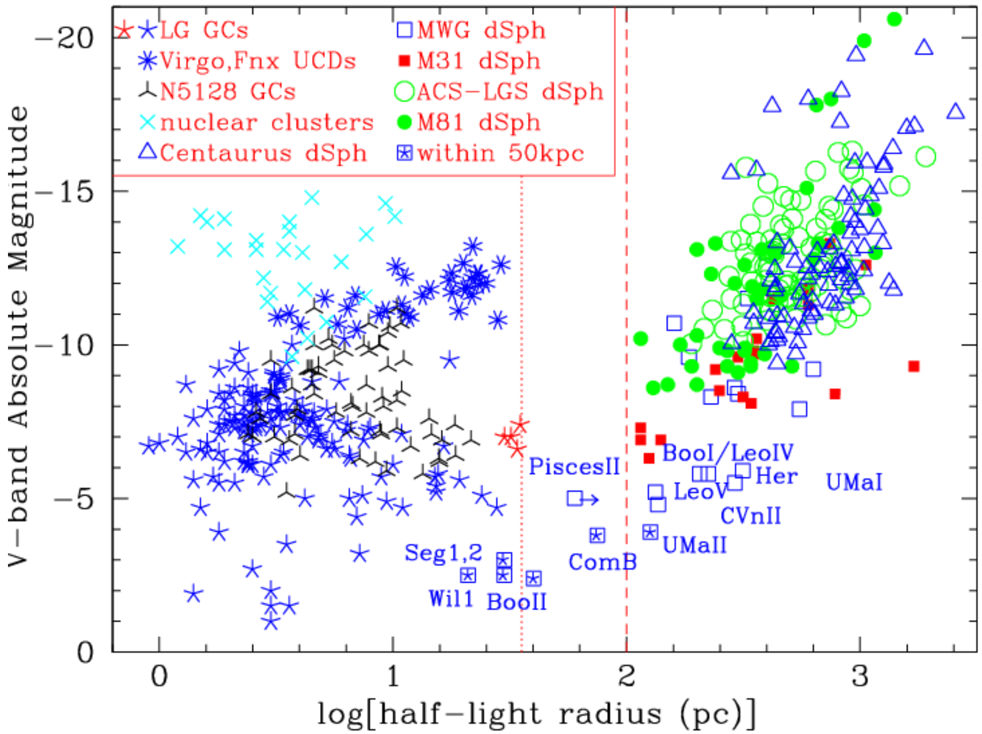
# The most common constraints on WIMP DM

# Searches in dwarf spheroidal galaxies





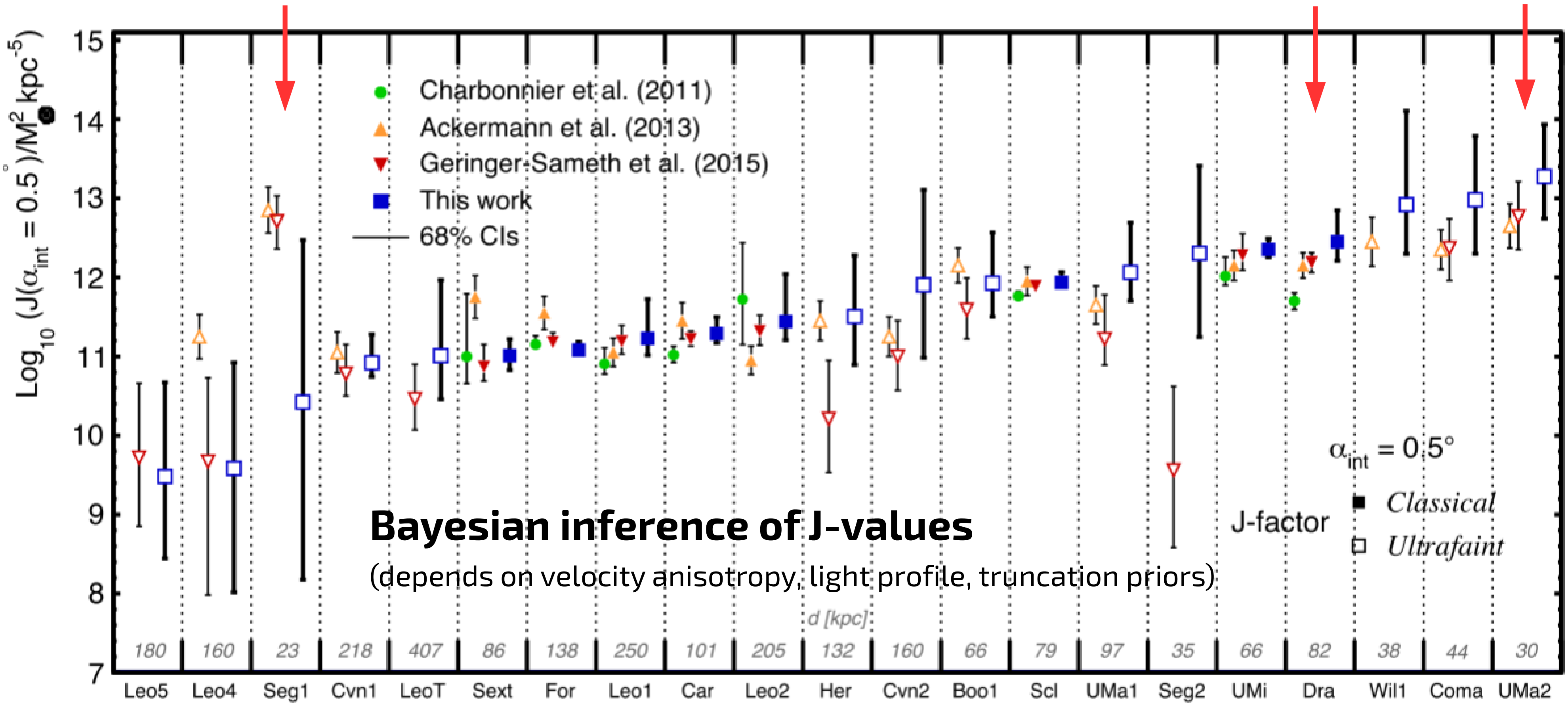




Credit: Wyse+ 2010

**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



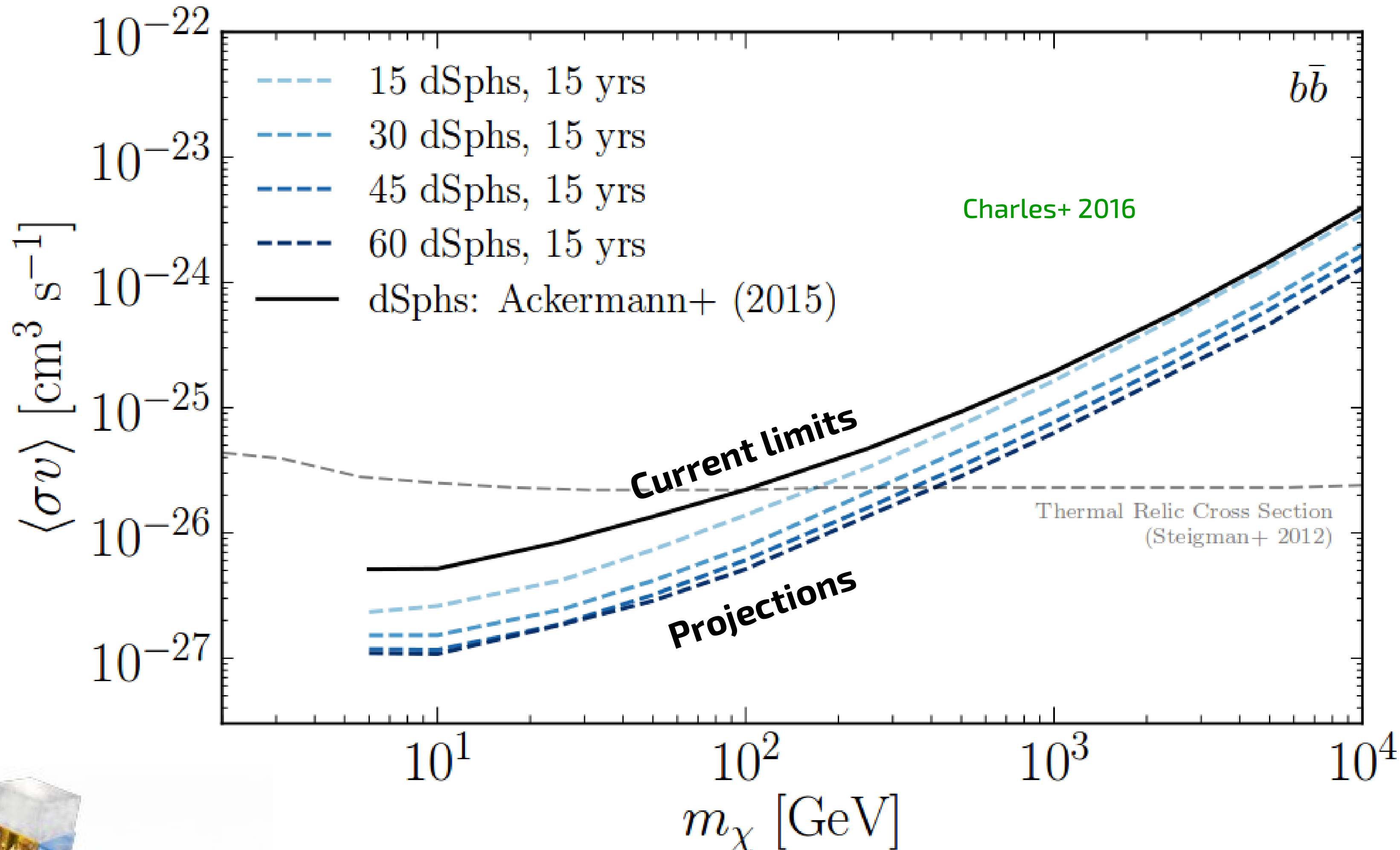

Bonnivard+ 1504.02048 (MNRAS)

**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

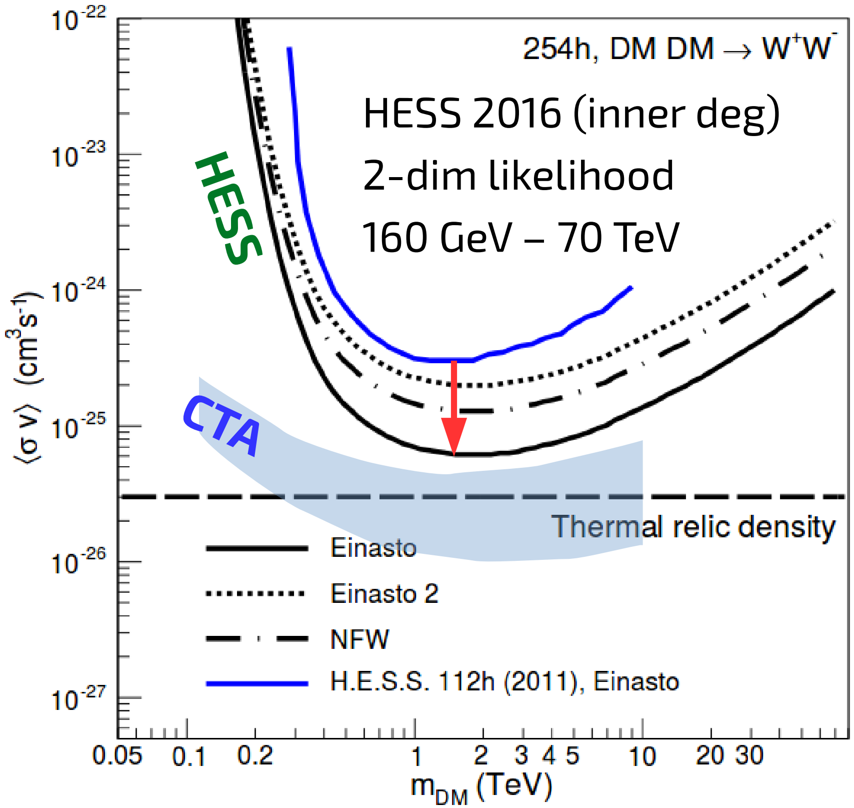
# Fermi LAT limits from dwarf spheroidal galaxies

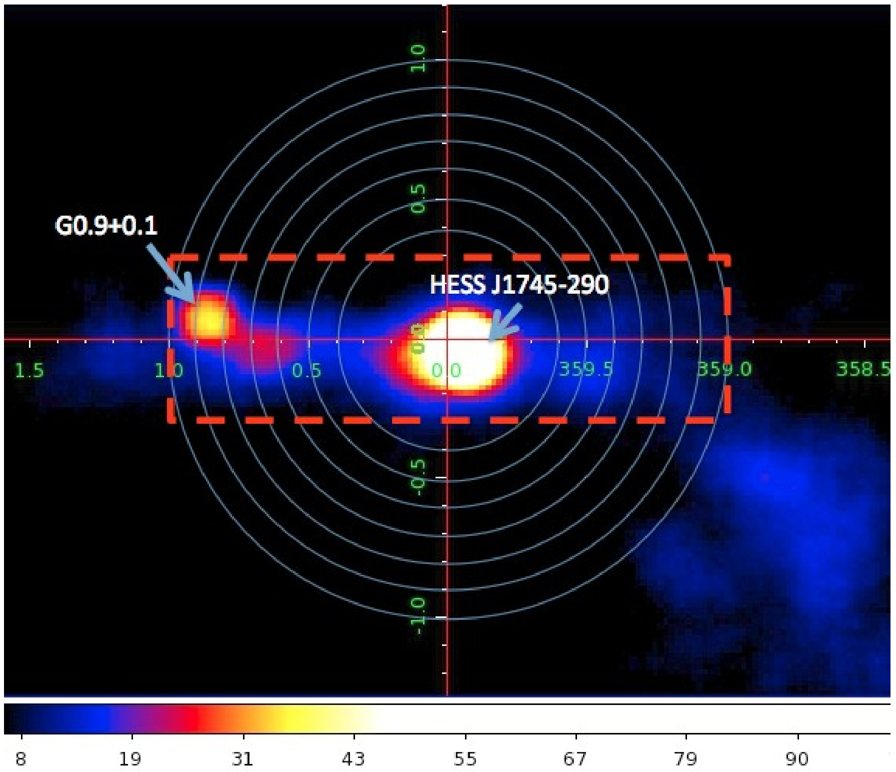
Combined likelihood limits using data from the Fermi Large LAT, ~0.5 – 300 GeV

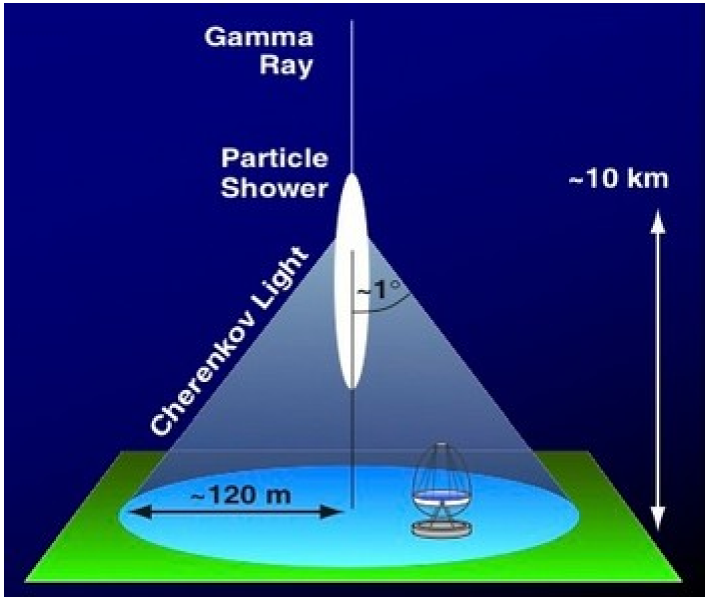



$$\mathcal{L}(\sigma v) = \prod_{i=\mathrm{dwarfs}} \mathcal{L}_i(\sigma v)$$

# At higher energies: Air Cherenkov Telecopes



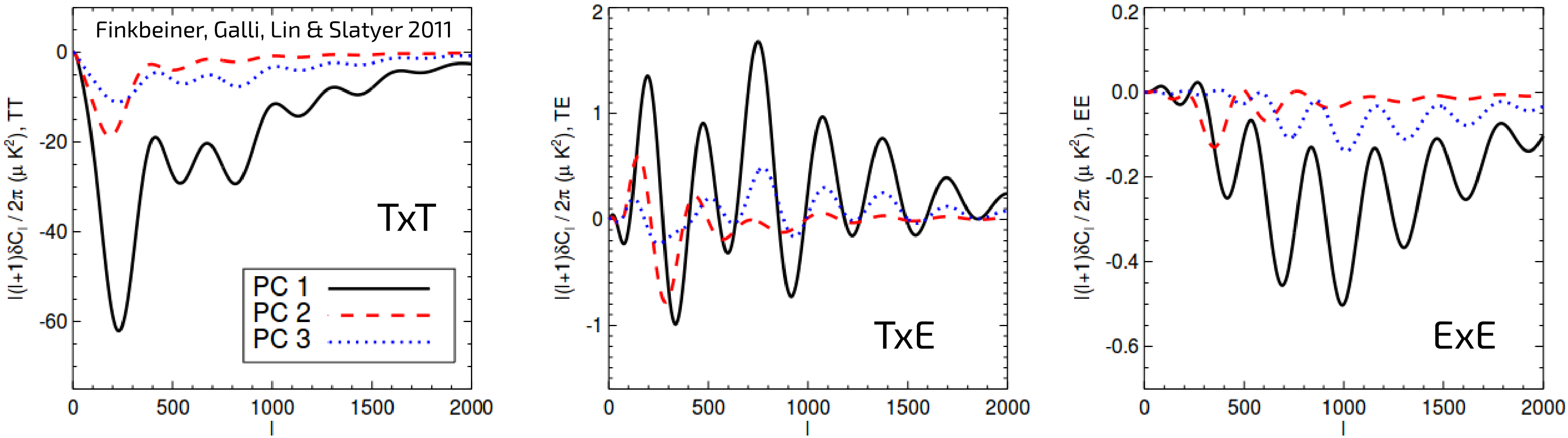




**DM searches with Cherenkov telescopes**

- Large CR backgrounds imply that brightest targets are best → Go for the 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 (Murase & Beacom 2012)

# At lower energies: CMB

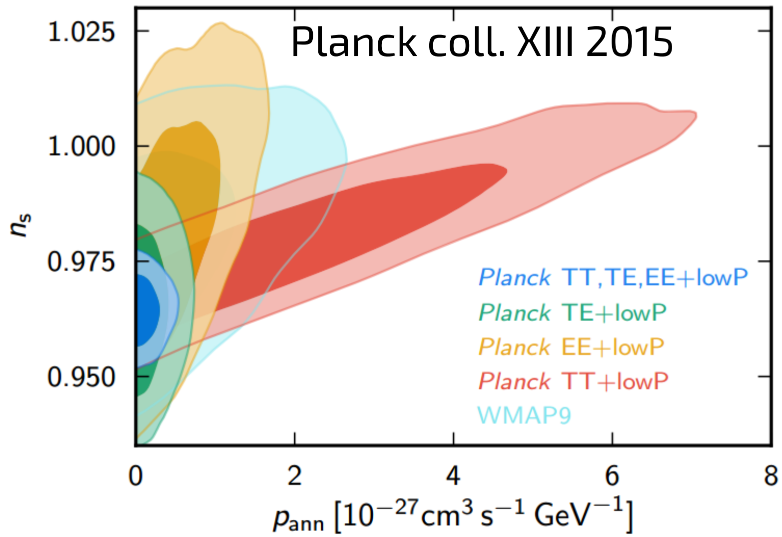



**Bounds on annihilating DM**

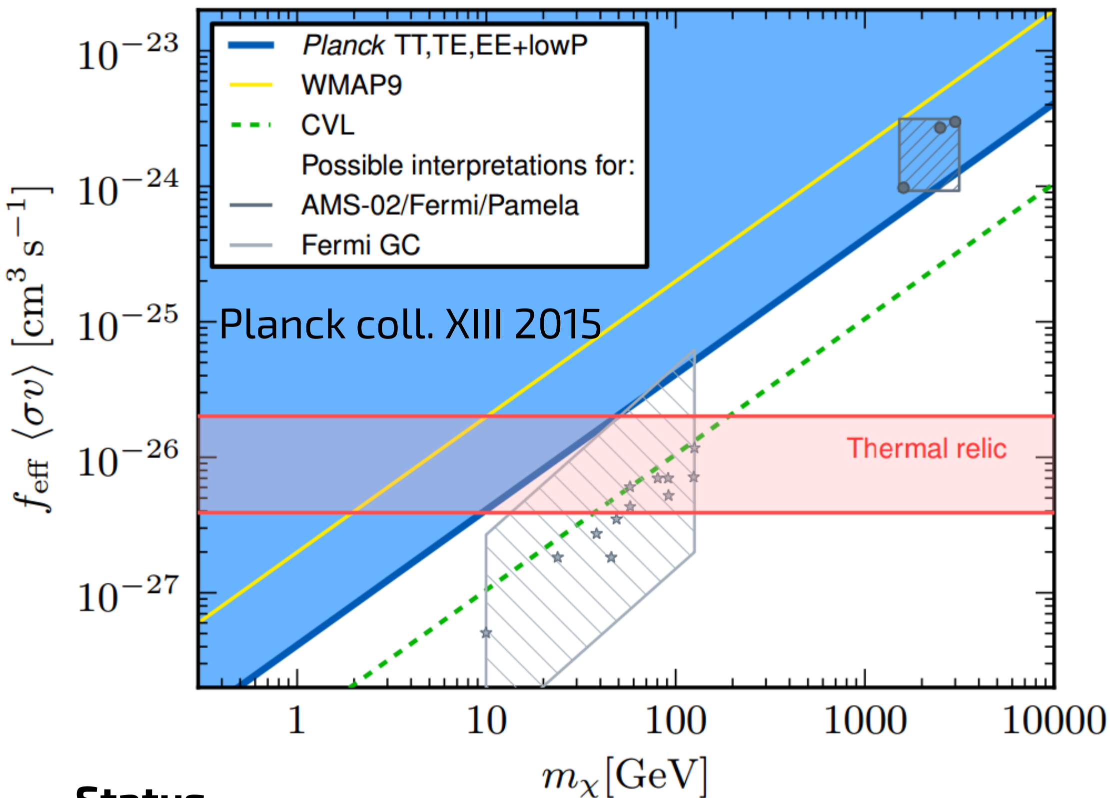
- Energy injection

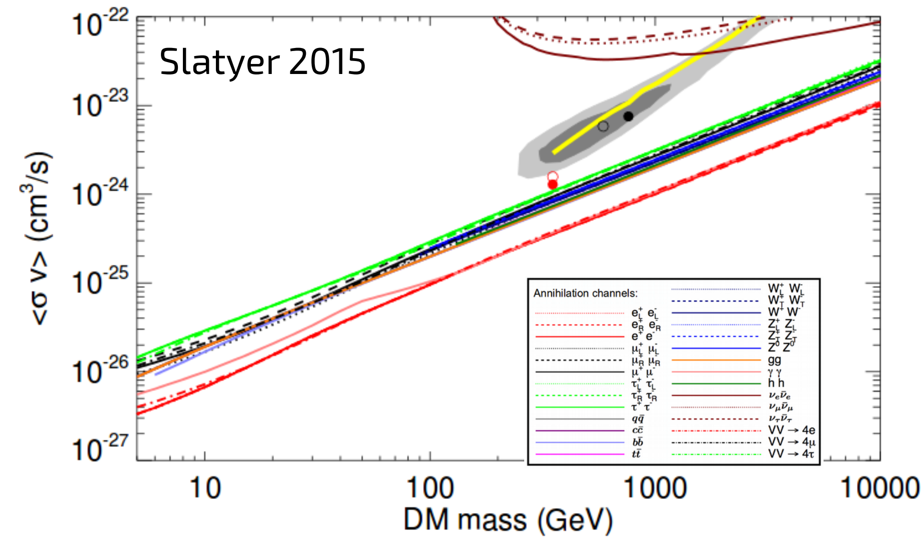
$$p_{\rm ann}(z) \equiv f(z)\frac{\langle\sigma v\rangle}{m_\chi}$$

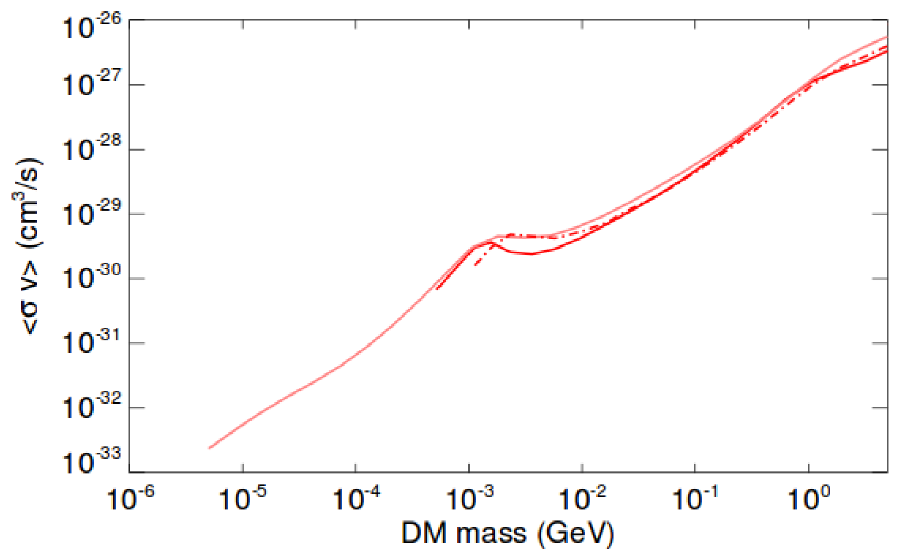
- Energy injection at z~500 – 1000 increases free electron fraction
  - → broadening of surface of last scattering
  - → less fluctuations at small scales
- Insensitive to details of non-linear structure formation



# Bounds on DM from Planck observations




**Status**

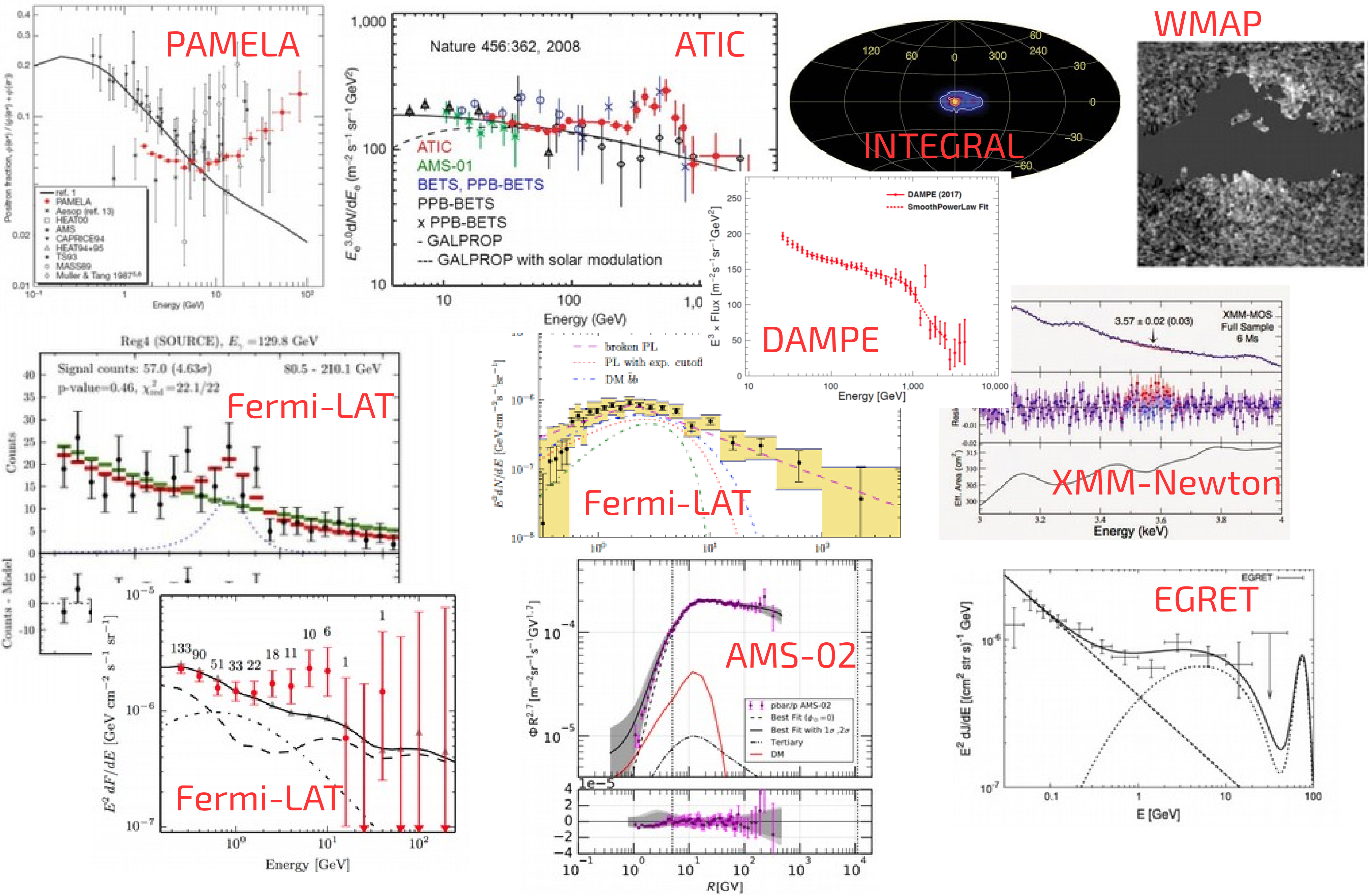
- Bounds depend on effective energy deposition ($f_{\rm eff}$), otherwise *very* robust
- Exclude s-wave annihilation below m~10 GeV unless annihilation into neutrinos dominates

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

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

# Anomalies

# Some signal claims of recent years



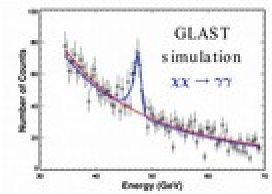
# Different searches, different challenges

**Number of 'control regions'**

dwarf spheroidals

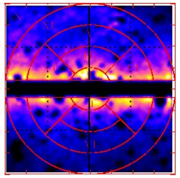
dark matter subhalos

gamma-ray lines, etc




HARD

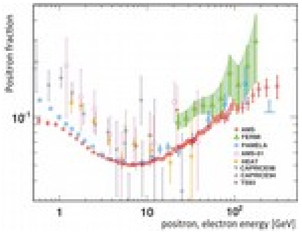
extragalactic background



Galactic bulge/center

galactic neutrinos

anti-proton cosmic rays




positron cosmic rays

anti-deuteron cosmic rays

solar HE neutrinos

**Background modeling complexity**

# Why bothering with indirect searches?

- **We have no choice**
  DM might be easiest to detect via indirect searches (sterile neutrino DM, Wino DM, …). Would be foolish to not try it as good as we can.

- **Robust detections *are* possible**
  Searches are not as clean as lab experiment, we can just observe and model what we see. However, we have the entire Universe available to test any given signal hypotheses. Not too bad.

- **Only approach that probes > 30 order of magnitude in DM mass**
  Dark matter particles over a huge range of masses can leave their non-gravitational imprints in the sky (from radio to UHECRs).

- **Instruments come “for free”**
  Telescopes are seldomly build with the primary goal of detecting particle dark matter. But they usually cover new sensitivity ground. Would be foolish to not exploit them.

# Anomalies

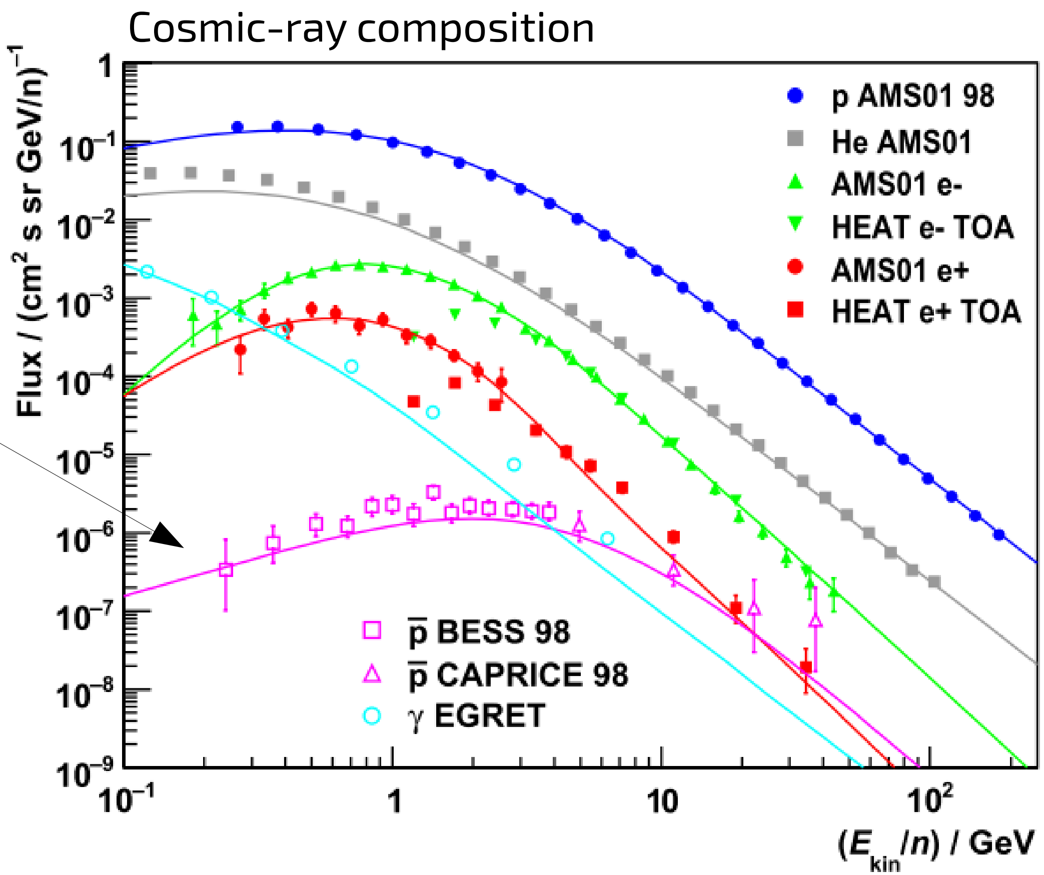
## Anti-protons

# Why anti-protons?

1) Low backgrounds

Observed: One **antiproton** per 10000 **protons**

Remember: WIMP DM annihilates equally into matter and antimatter.

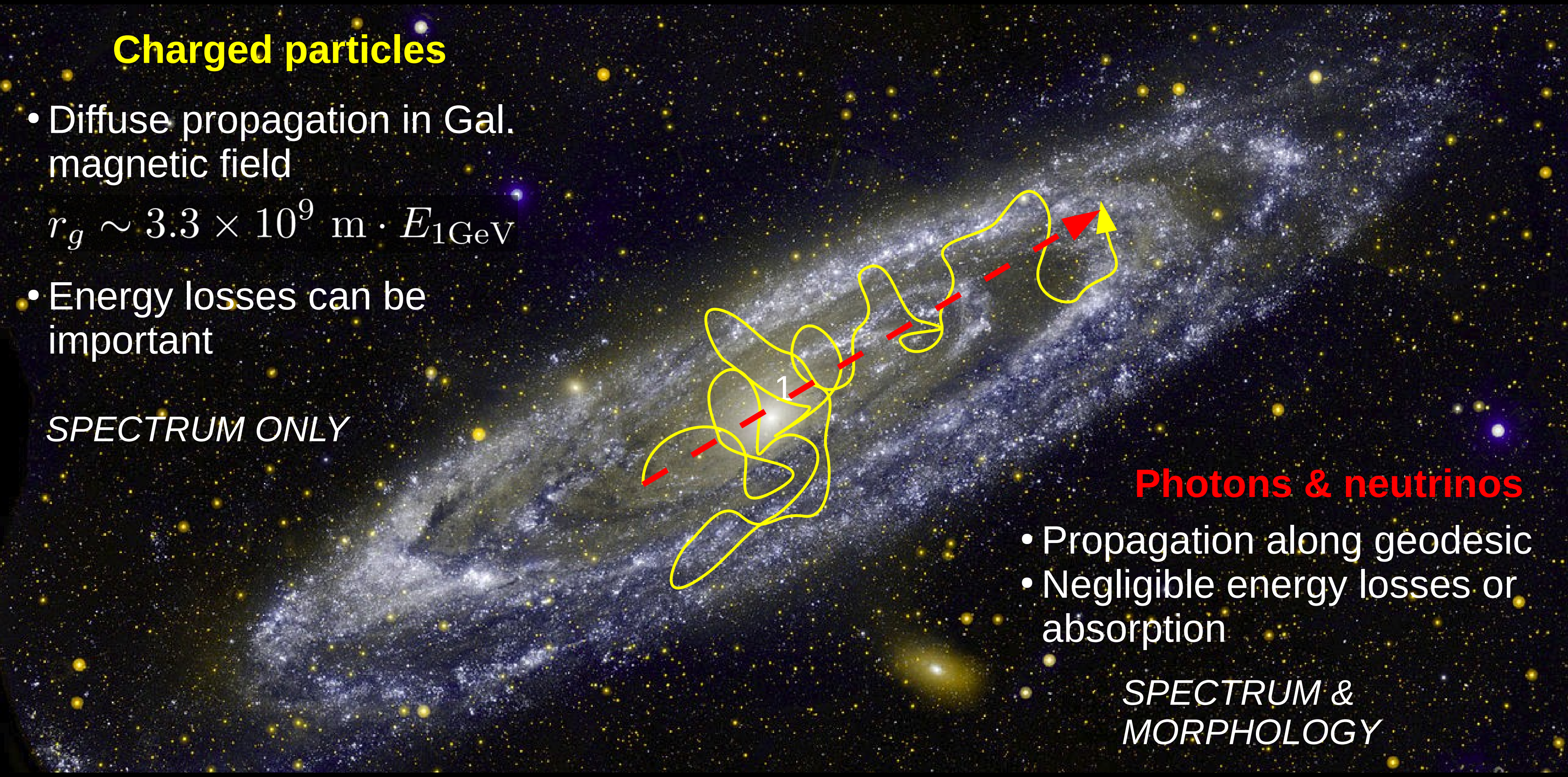



2) Backgrounds extremely* well understood

Early papers: Buffington+ 1981; Silk & Srednicki 1984; Stecker+ 1985; Eliis+ 1988; Stecker & Tylka 1989; Bergström+ 1999; Maurin+ 2001; Donato+ 2004; …

*up to a factor of two

# Propagation of messengers from DM



**Charged particles**

- Diffuse propagation in Gal. magnetic field

$$r_g \sim 3.3 \times 10^9 \ \mathrm{m} \cdot E_{1\mathrm{GeV}}$$

- Energy losses can be important

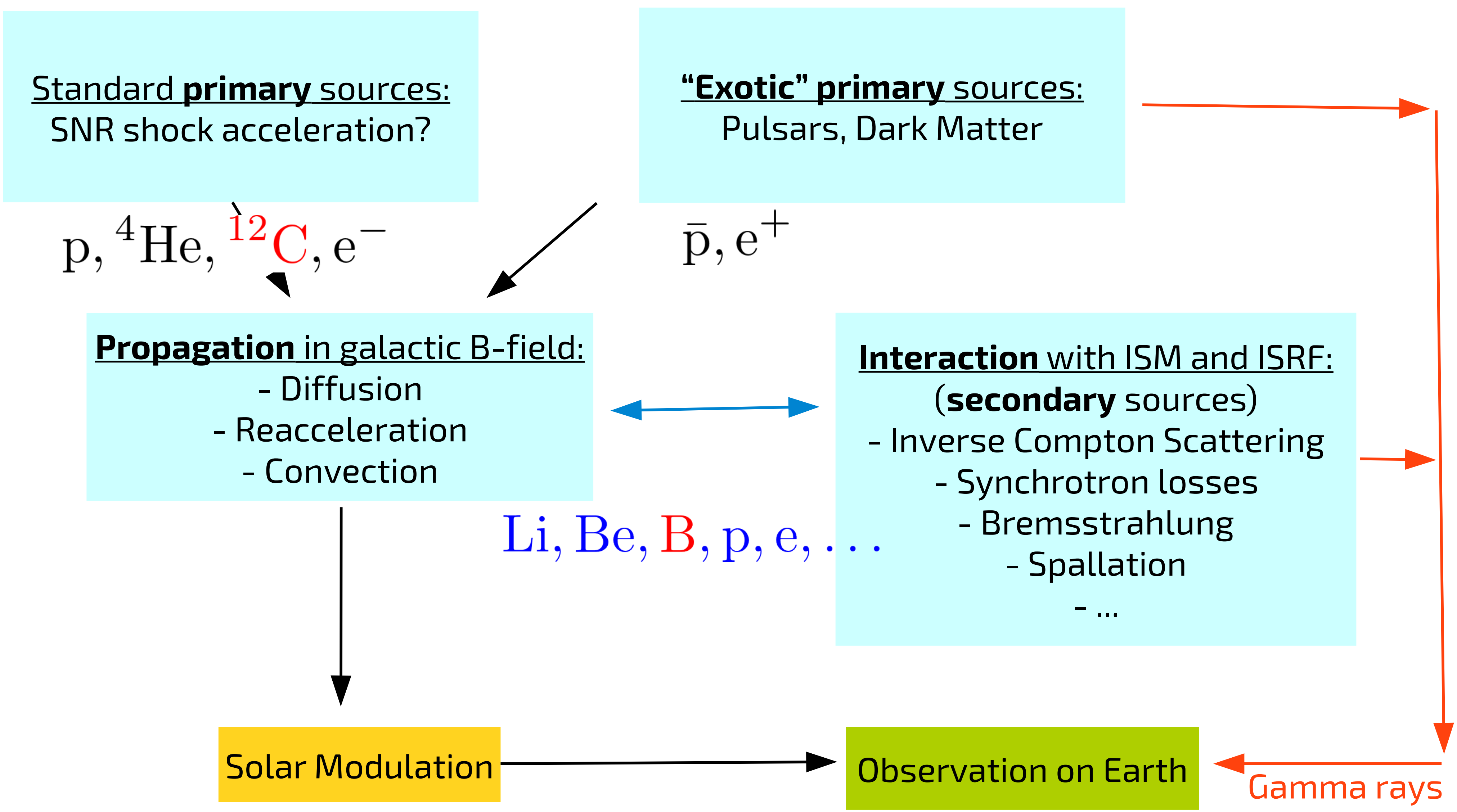
*SPECTRUM ONLY*

**Photons & neutrinos**

- Propagation along geodesic
- Negligible energy losses or absorption

*SPECTRUM & MORPHOLOGY*

# Overview of relevant processes



# Propagation universality in rigidity

Kinematics can be described in terms of particle rigidity (momentum per charge):

$$\mathscr{R} = \mathbf{p}\,c/Z\,e$$

EoM in electromagnetic field is then:

$$\frac{1}{c}\frac{d\mathscr{R}}{dt} = \mathbf{E}(\mathbf{r},t) + \frac{\mathscr{R}\times\mathbf{B}(\mathbf{r},t)}{\sqrt{|\mathscr{R}|^2+\mathscr{R}_0^2}}$$

Velocity:

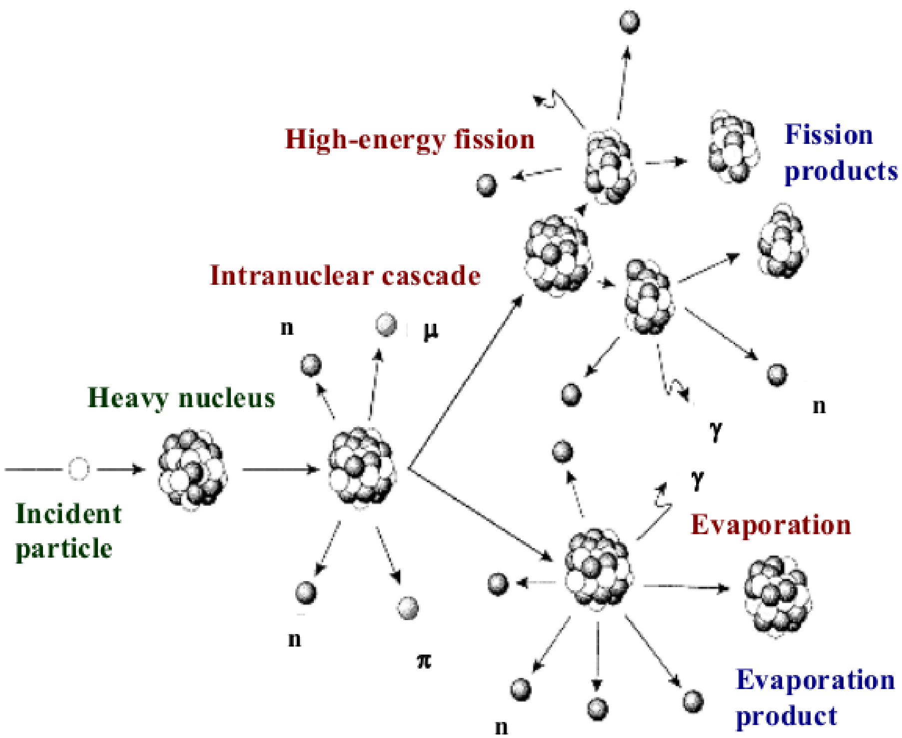
$$\frac{1}{c}\frac{d\mathbf{r}}{dt} = \frac{\mathscr{R}}{\sqrt{|\mathscr{R}|^2+\mathscr{R}_0^2}}$$

$$\mathscr{R}_0 = \frac{A\,m_p\,c^2}{Z\,e}$$

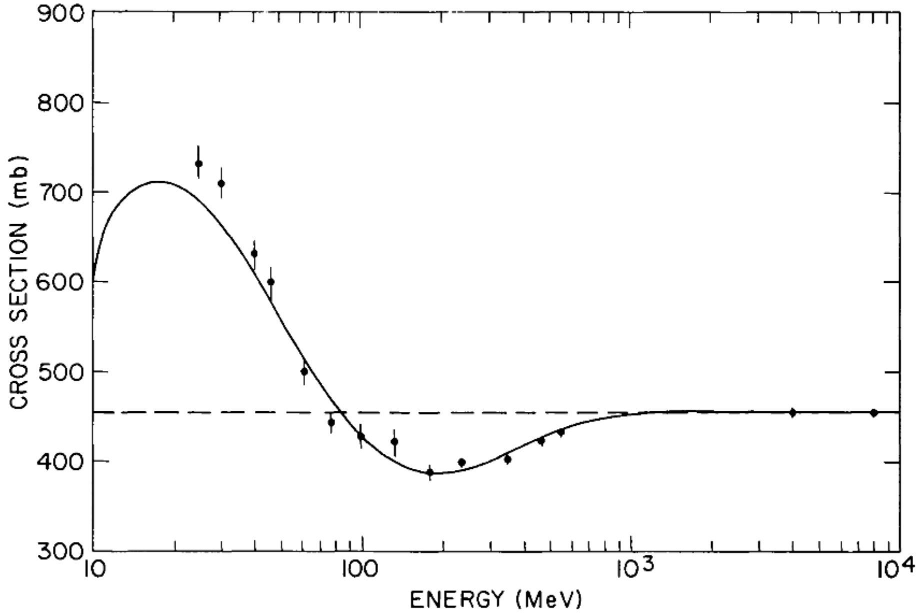
In the relativistic limit, the EoM becomes independent of $R_0$, and hence on the particle species.

See e.g. Serpico+'15, 1509.04233

# Spallation




Letaw+ 1983




**Rough geometric scaling:**

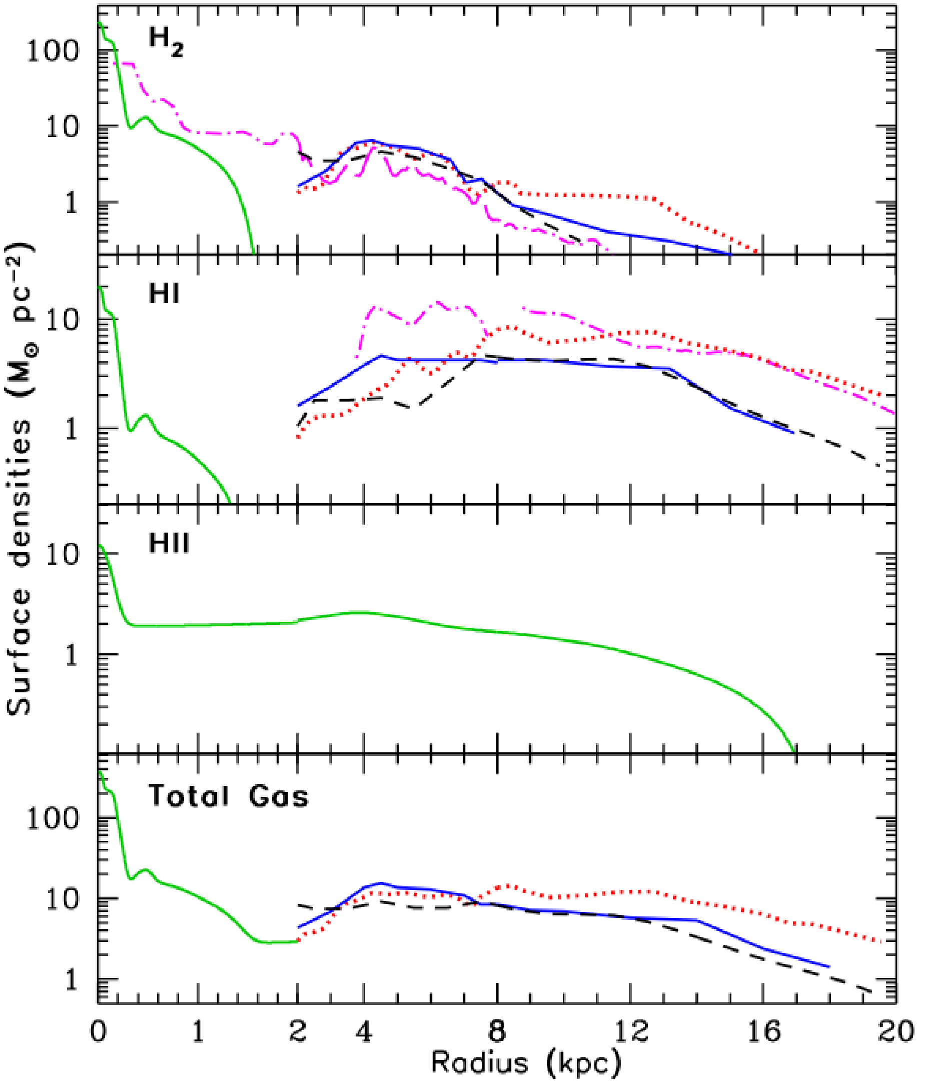
$$\sigma_r^p \approx \sigma_r^{\bar{p}} \approx 40 \text{ mb}$$
$$\sigma_r(A) \approx 250 \text{ mb } (A/12)^{2/3}$$

Johannesson+ 2016

Most secondaries originate from spallation reactions, which to a good approximation preserve the energy per nucleon, $E/A \sim R/2$.

See e.g. Serpico+'15, 1509.04233

# Surface density of Milky Way




$$10\,\mathrm{M_\odot\,pc^{-2}} \simeq 2\;10^{-4}\,\mathrm{g\,cm^{-2}}$$

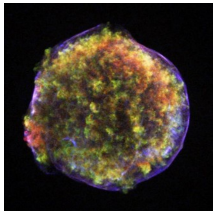
Probability for p-p interaction per "disk-crossing": P(p-p) ~ $10^{-3}$

→ Many disk-crossings required / propagation within dense regions

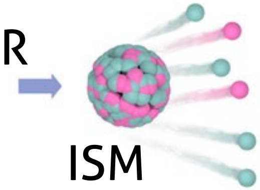
→ Interaction time scales of the order >$10^5$ yr

# Why grammage matters

Two sources for cosmic rays

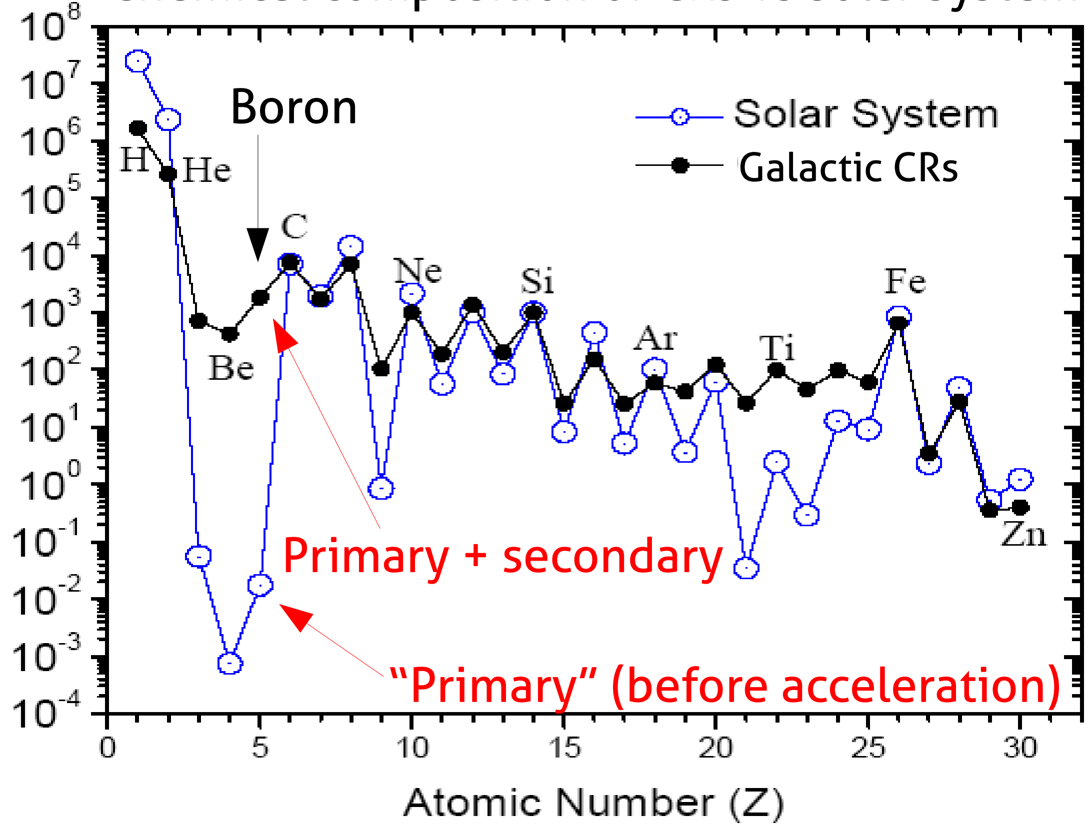


**Primary cosmic rays** from supernova remnants (likely)

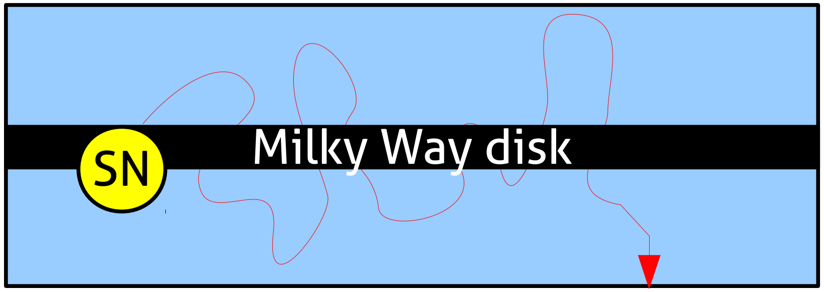



**Secondary cosmic rays** from spallation etc

Chemical composition of CRs vs solar system




Diffusion in a box




**Total grammage** (column density along propagation path)

$$G_{\text{total}} = n_{\text{crossings}} G_{\text{disk}} \sim \mathcal{O}(10\ \text{g cm}^{-2})$$

Secondary Boron: $n_B \sim n_C \sigma(C \to B) \cdot G_{\text{total}} \Rightarrow G_{\text{total}}$

Secondary antiprotons: $n_{\bar{p}} \sim n_p \sigma(p \to \bar{p}) \cdot G_{\text{total}} \Rightarrow n_{\bar{p}}$

# Leaky box & spectral indices

**Diffuse propagation:**

$$\frac{dN}{dt} = \dot{Q} - \frac{N}{\tau_p}$$

Diffusion distance

$$\langle x \rangle \simeq \sqrt{6D\tau} \sim L$$

*L*: Extend of diffusion region

Implied escape time

$$\tau_p \sim \frac{L^2}{6D}$$

**Spectrum of primaries:**

$$\dot{Q} \propto \mathcal{R}^{-\gamma}$$

Source spectrum

$$D \propto D_0 \mathcal{R}^{\delta}$$

Diffusion parameter

$$N_{\rm prim} \propto \frac{L^2}{D_0} \mathcal{R}^{-\gamma-\delta}$$

Steady state solution

**Spectrum of secondaries:**

$$\dot{Q}_{\rm sec} \propto N_{\rm prim}/L$$

$$N_{\rm sec} \propto \frac{L^3}{D_0^2} \mathcal{R}^{-\gamma-2\delta}$$

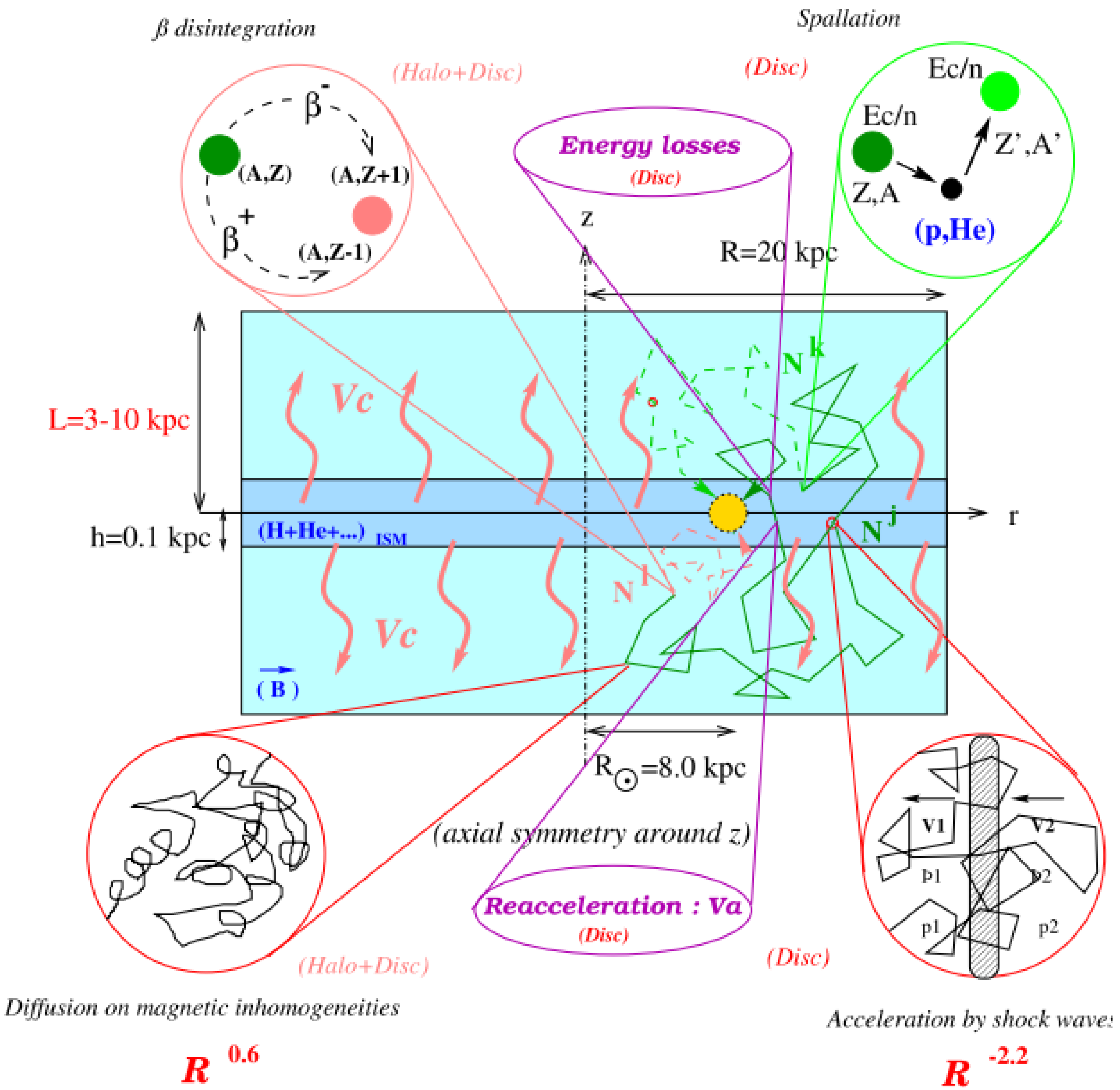
$$\frac{N_{\rm sec}}{N_{\rm prim}} \propto \frac{L}{D_0} \mathcal{R}^{-\delta}$$

**Conclusions**

- Secondary-to-primary ratios probe diffusion parameter slope
- There is a degeneracy between normalization of diffusion parameter and diffusion zone size.

# CR propagation illustrated

[excellent review: Lavalle & Salati (2012)]




**Most relevant assumption:**

- Cylindrical symmetry
- Homogeneous diffusion coefficient

**Most relevant parameters:**

- Diffusion zone height, L
- Diffusion constant, D

# Cosmic ray transport equation

D: **Diffusion** constant
$v_c$: **convection** velocity

**Reacceleration**

$$\frac{\partial N_i}{\partial t} - \boldsymbol{\nabla} \cdot (D\,\boldsymbol{\nabla} - \boldsymbol{v}_c)\, N_i + \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\boldsymbol{\nabla} \cdot \boldsymbol{v}_c\right) N_i - \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{N_i}{p^2} =$$

$$= Q_i(p, r, z) + \sum_{j>i} c\beta n_{\rm gas}(r, z)\sigma_{ji} N_j - c\beta n_{\rm gas}\sigma_i^{\rm in}(E_k) N_i\ ,$$

**Source** term

ISM **interaction**

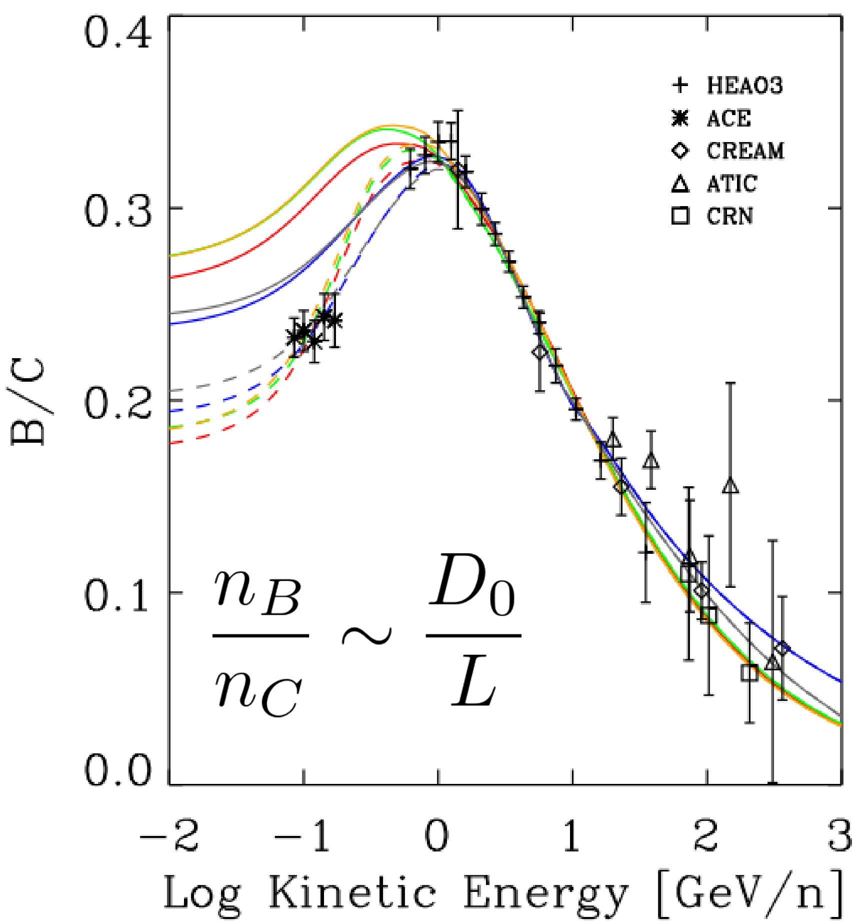
$$D(E) = D_0 \beta (\mathcal{R}/1\mathrm{GV})^{\delta}$$

[see Evoli et al. (2012), and refs therein; Strong, Moskalenko and Ptuskin (2007)]]

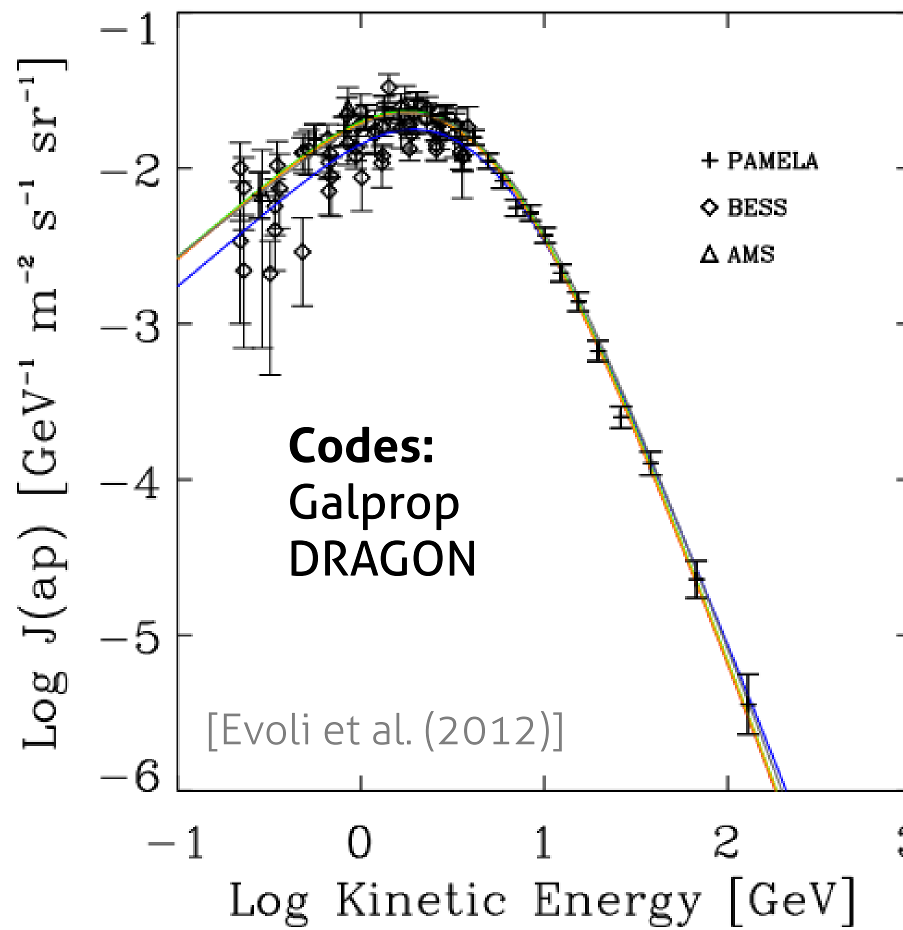
# Fit to B/C, predictions for anti-protons

Viable parameters for the propagation model: (fit to B/C and p data)

| Model | $z_t$(kpc) | $\delta$ | $D_0(10^{28}\text{cm}^2/\text{s})$ | $\eta$ | $v_A$(km/s) | $\gamma$ | $dv_c/dz$(km/s/kpc) | $\chi^2_{B/C}$ | $\chi^2_p$ | $\Phi$ (GV) | $\chi^2_{\bar{p}}$ | Color in Fig.s |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $KRA$ | 4 | 0.50 | 2.64 | −0.39 | 14.2 | 2.35 | 0 | 0.6 | 0.47 | 0.67 | 0.59 | Red |
| $KOL$ | 4 | 0.33 | 4.46 | 1. | 36. | 1.78/2.45 | 0 | 0.4 | 0.3 | 0.36 | 1.84 | Blue |
| $THN$ | 0.5 | 0.50 | 0.31 | −0.27 | 11.6 | 2.35 | 0 | 0.7 | 0.46 | 0.70 | 0.73 | Green |
| $THK$ | 10 | 0.50 | 4.75 | −0.15 | 14.1 | 2.35 | 0 | 0.7 | 0.55 | 0.69 | 0.62 | Orange |
| $CON$ | 4 | 0.6 | 0.97 | 1. | 38.1 | 1.62/2.35 | 50 | 0.4 | 0.53 | 0.21 | 1.32 | Gray |



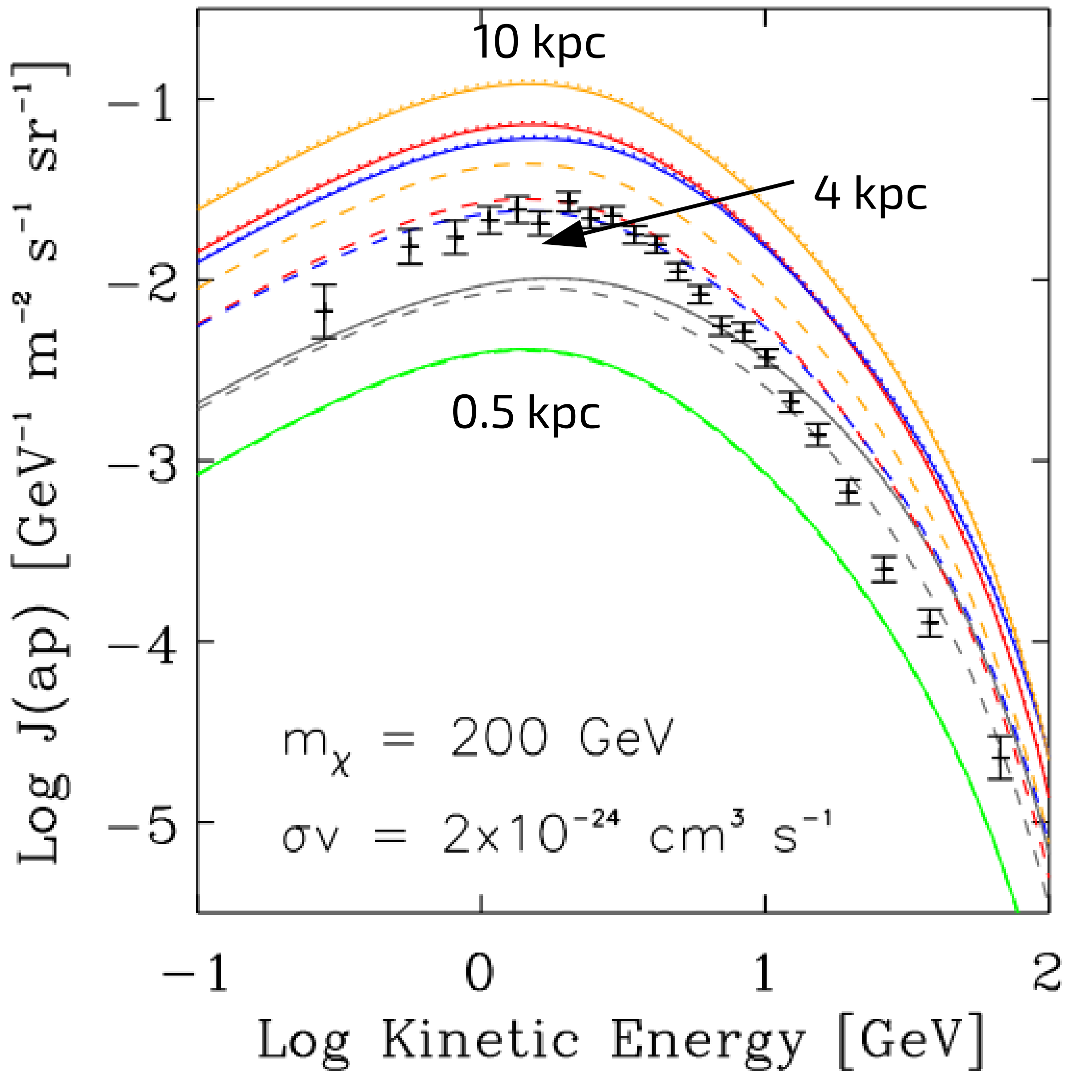

$$\frac{n_B}{n_C} \sim \frac{D_0}{L}$$




**Codes:**
Galprop
DRAGON

[Evoli et al. (2012)]

# Predictions for anti-proton DM signal



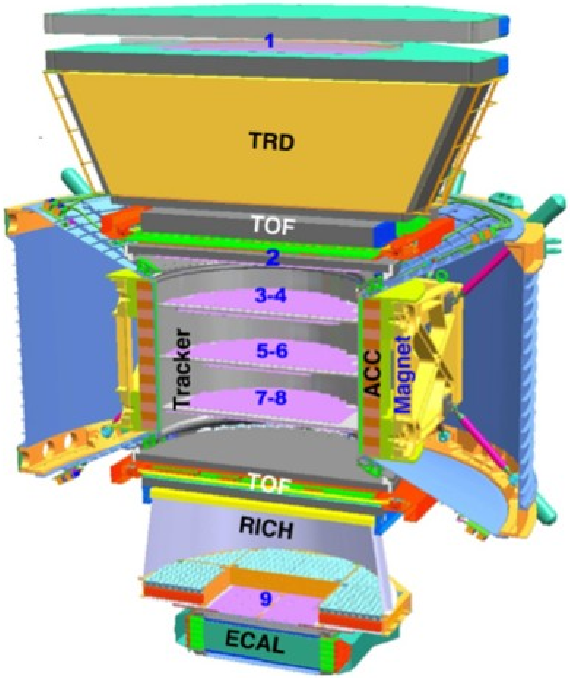

Leaky box prediction

$$\sim L^2$$

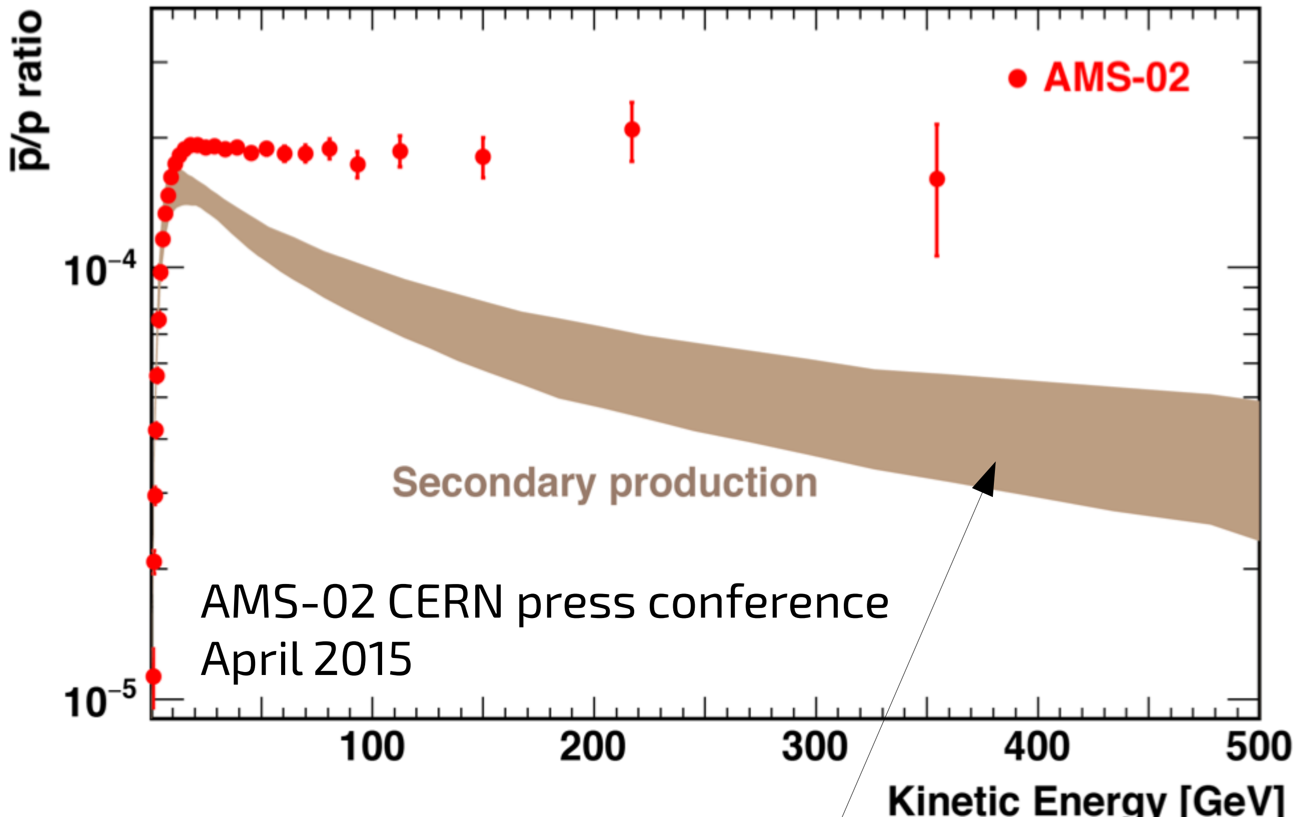
[Evoli et al. (2012)]

Signal flux normalization depends primarily on diffusion zone height.

# Anti-protons from AMS-02




AMS-02
Taking data since 2011



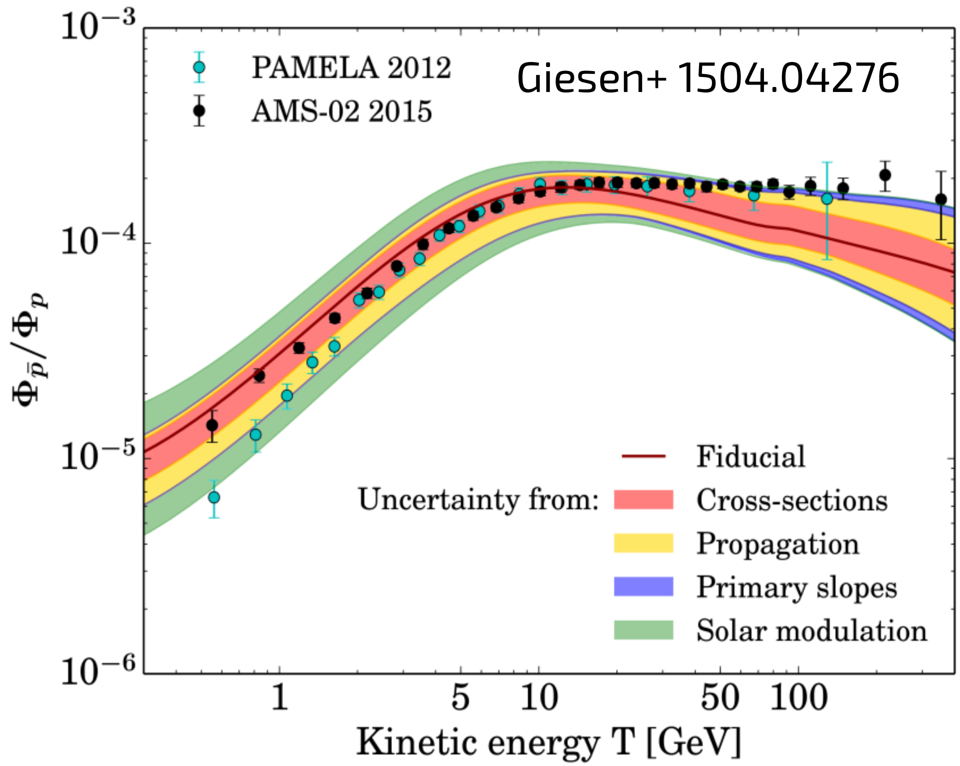

AMS-02 CERN press conference
April 2015

Samuel Ting

**Preliminary anti-proton to proton ratio**

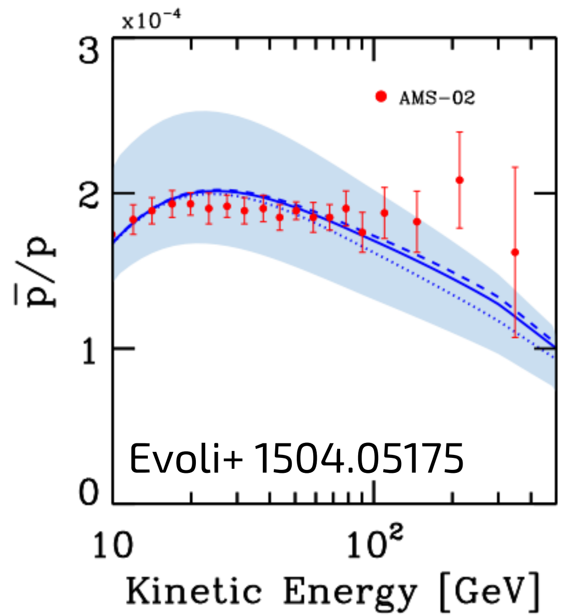
- Up to 350 GeV – Syst. + stat. error bars?
- Compatible with previous results by PAMELA, though with significantly smaller error bars at high energies
- Shown as excess above the expectations from secondary production (ICRC 2015: "**Theoretical prediction based on pre-AMS knowledge of cosmic ray propagation**")

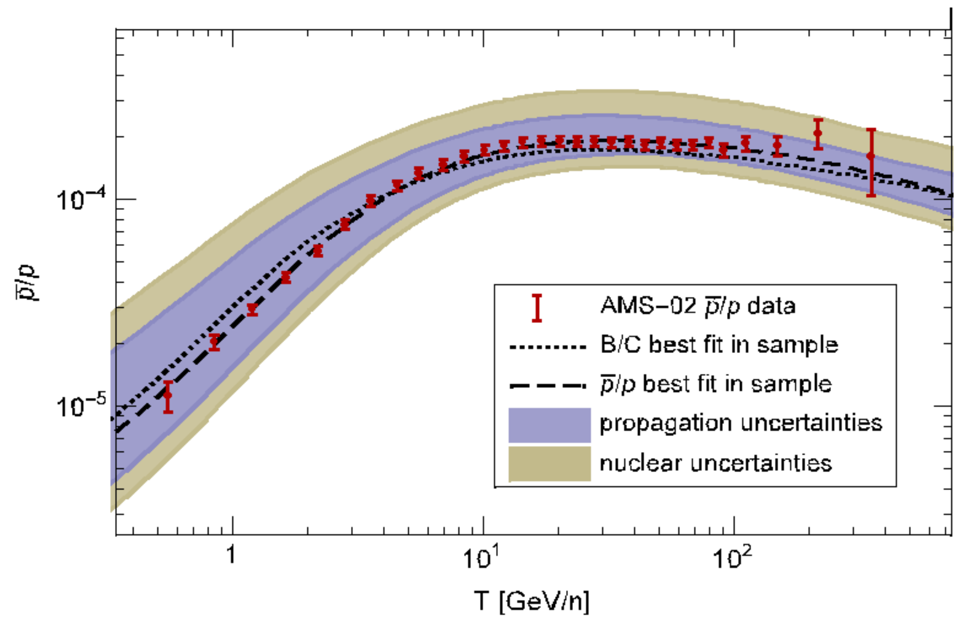
# No clear excess above secondary backgrounds



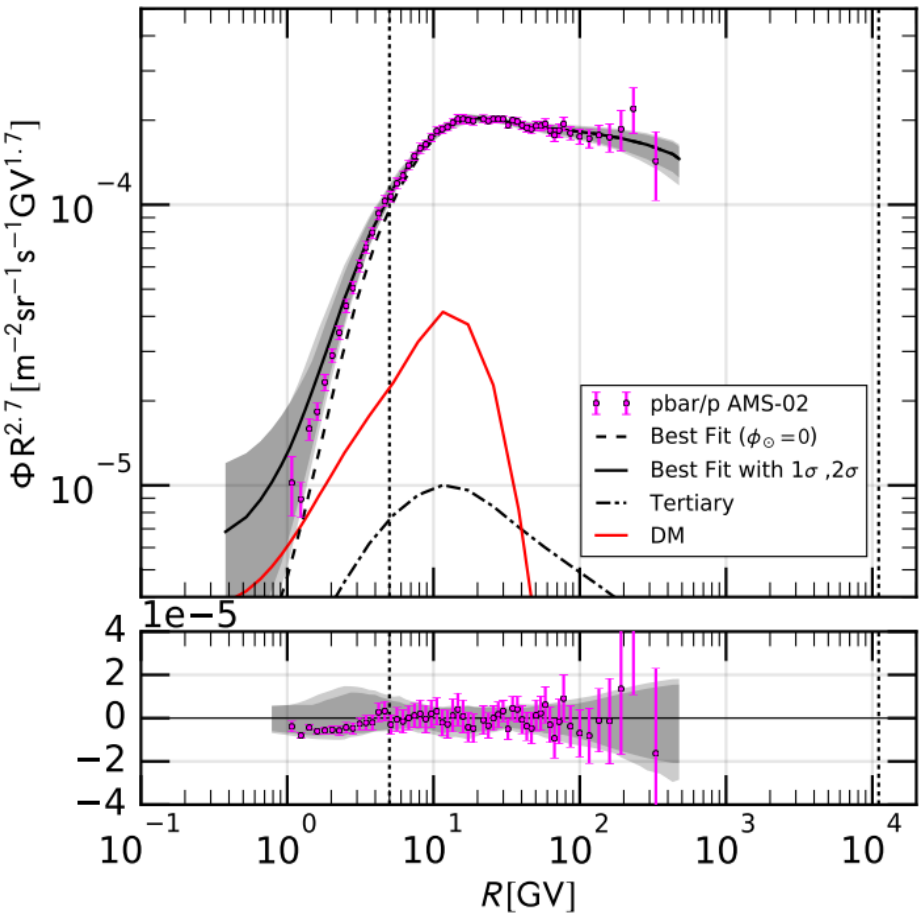

**Relevant uncertainties for CR BG**
- pbar production cross-section
- spectrum of CR primaries
- CR propagation
- solar modulation (below ~10 GeV)

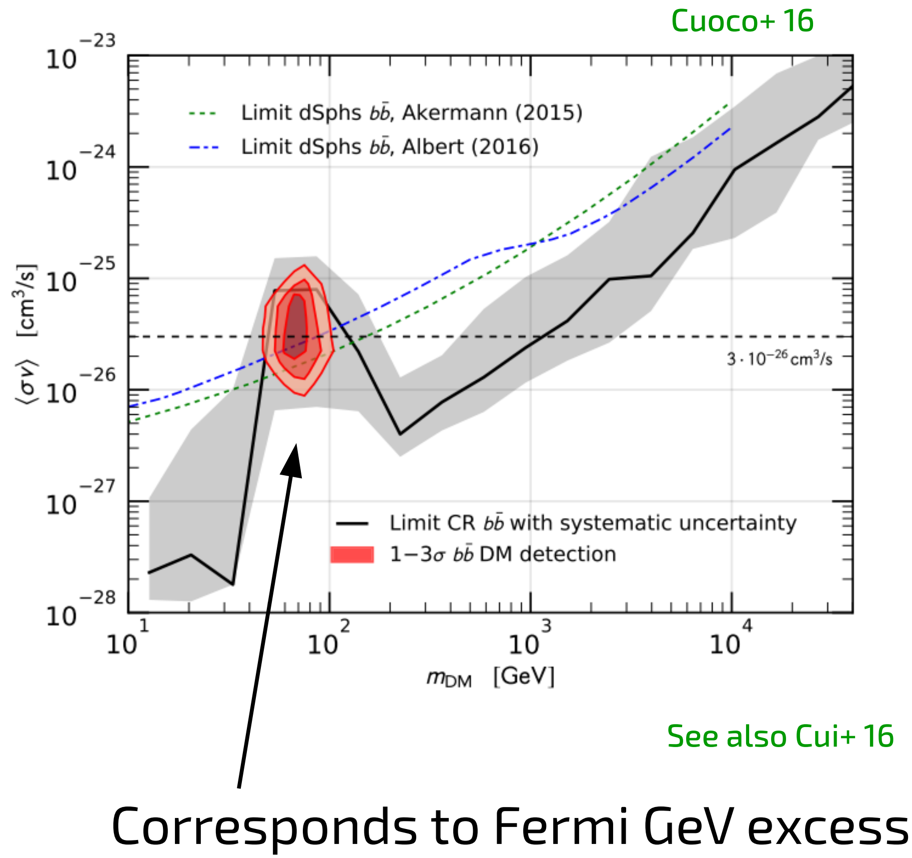
**Situation**
- **No excess** observed above astrophysical background, when all uncertainties are taken into account
  → Only upper limits



# Anti-proton limits and signal hints

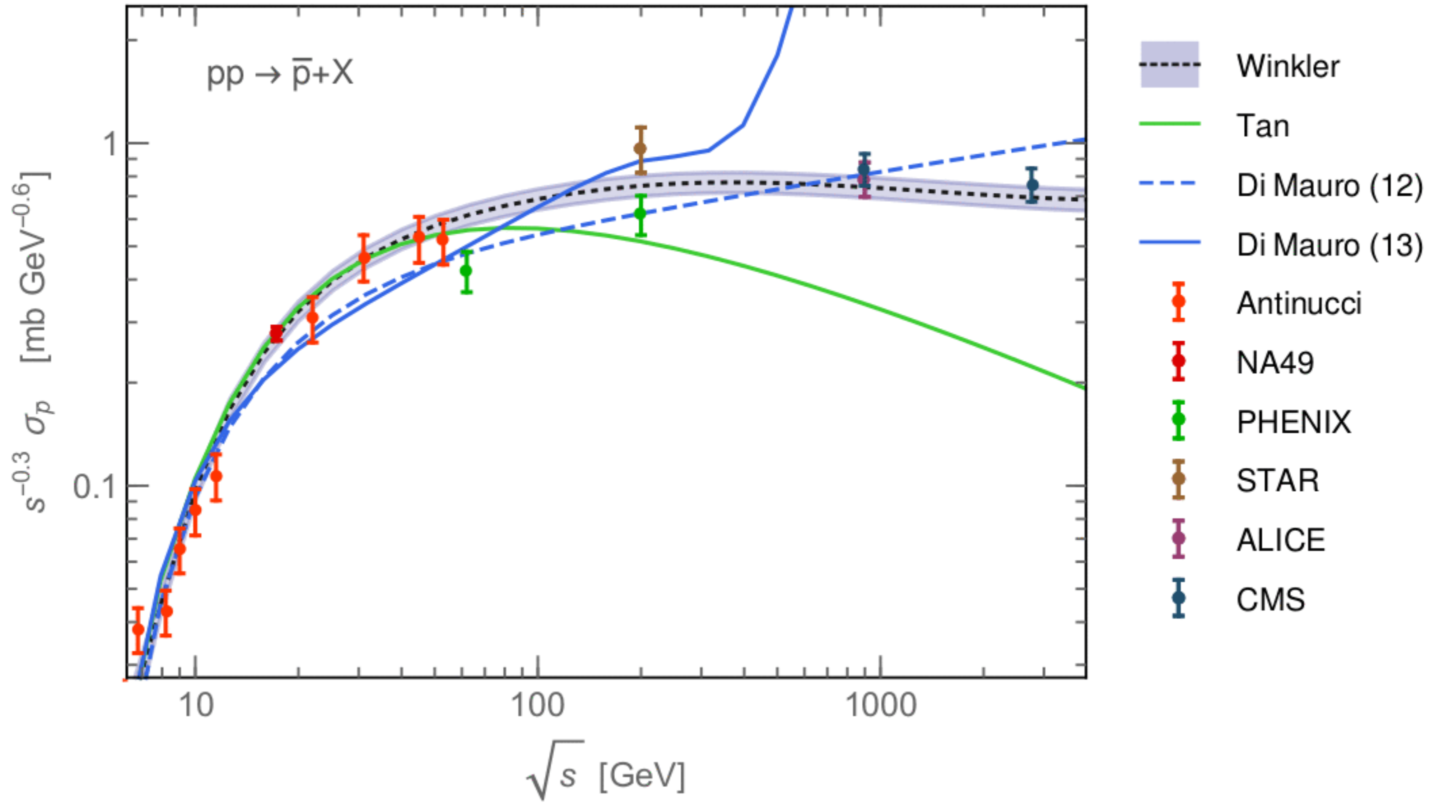



Simple propagation scenarios are insufficient to explain *all* CR data (and DM does not help)
→ Extraction of reliable limits or signal becomes a huge challenge

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

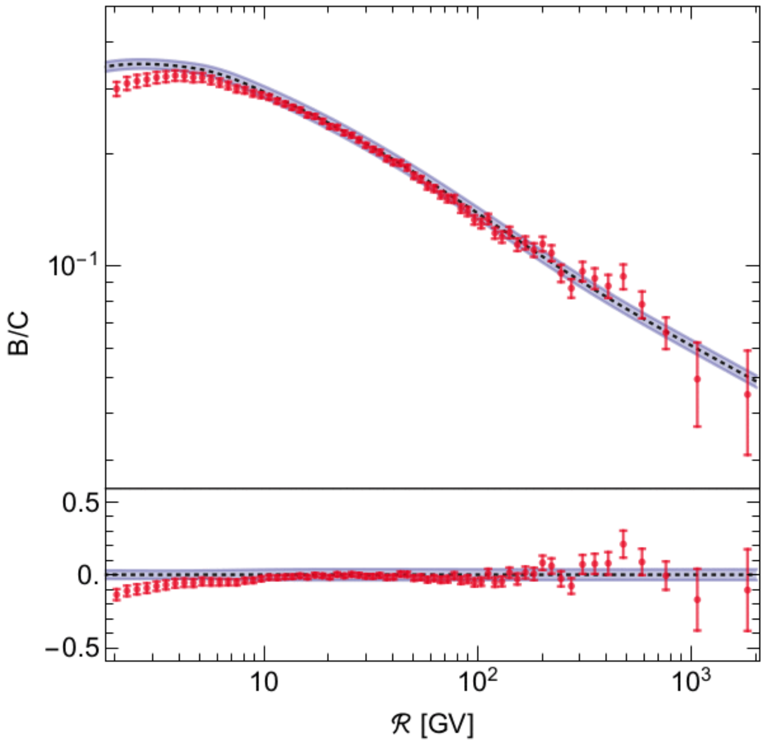
# Reanalysis of cross-sections

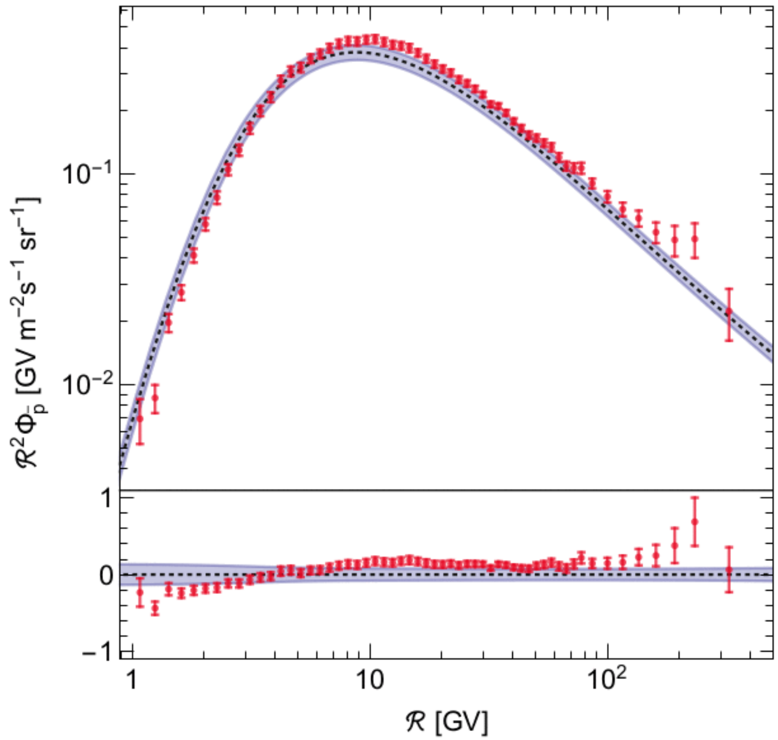



**Reinart & Winkler 2017**

- Refitting nuclear spallation data for Boron production from Carbon, Oxygen, Nitrogen, …
- Charge-dependent solar modulation
- Refitting primary cosmic ray measurements (including obseved hardening at high energies)
- Positron flux to provide lower limit on diffusion zone height
- Full incorporation of covariance matrix

# Best-fit B/C and antiproton spectrum

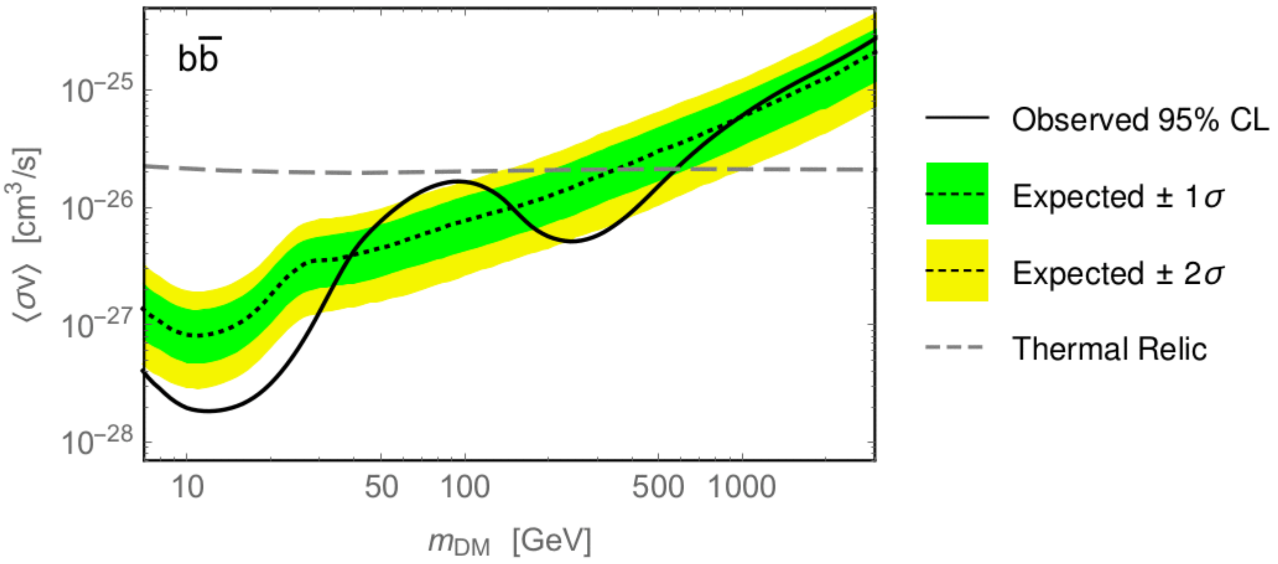



- Combined fit to B/C and pbar data provides statistically good fit without extra components
- Significance of additional DM signal is down below 2 sigma

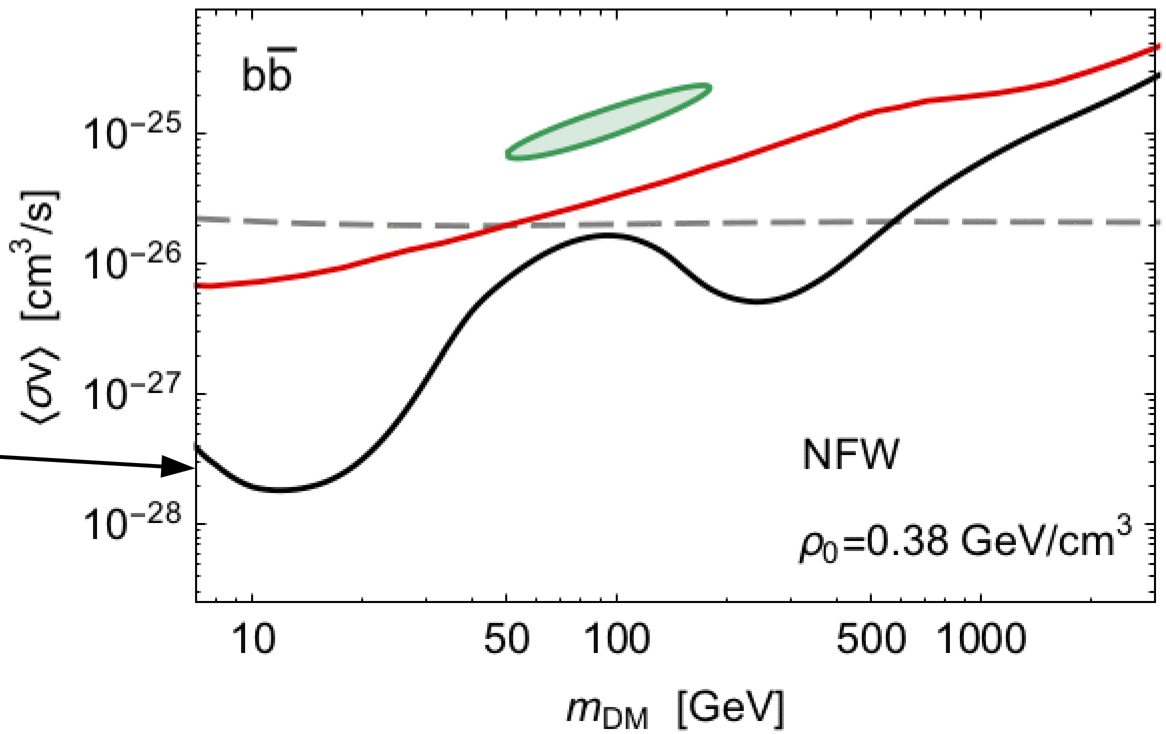
| Best Fit | B/C (w/o break) | B/C (w/ break) | $\bar{\text{p}}$ (w/ break) | B/C + $\bar{\text{p}}$ (w/ break) |
|---|---|---|---|---|
| $K_0$ $[\frac{\text{kpc}^2}{\text{Gyr}}]$ | $39.6 \cdot L_{4.1}$ | $34.3 \cdot L_{4.1}$ | $39.5 \cdot L_{4.1}$ | $32.5 \cdot L_{4.1}$ |
| $\delta$ | 0.479 | 0.507 | 0.446 | 0.506 |
| $V_a$ $[\frac{\text{km}}{\text{s}}]$ | 0 | 0 | $59.7 \cdot \sqrt{L_{4.1}}$ | $15.6 \cdot \sqrt{L_{4.1}}$ |
| $V_c$ $[\frac{\text{km}}{\text{s}}]$ | 0 | 1.3 | 0 | 0 |
| $\Delta\delta$ | no break | 0.157 | 0.157 | 0.157 |
| $\mathcal{R}_b$ [GV] | | 275 | 275 | 275 |
| $s$ | | 0.074 | 0.074 | 0.074 |
| $\phi_0$ [GV] | 0.72 | 0.72 | 0.72 | 0.72 |
| $\phi_1$ [GV] | | | 0.66 | 0.84 |
| $\chi^2_{\text{B/C}}$ (67 bins) | 64.2 | 48.0 | | 55.1 |
| $\chi^2_{\bar{p}}$ (57 bins) | | | 21.3 | 47.9 |
| $\chi^2_{\text{AMS/PAM}}$ (17 bins) | | | 10.9 | 12.6 |

# Method can be used to obtain strong DM upper




- Limits easily beat dSph limits over entire energy range.
- However, it is somewhat disconcerning that limits are stronger than sensitivity

  → More work needed to make this completely convincing.



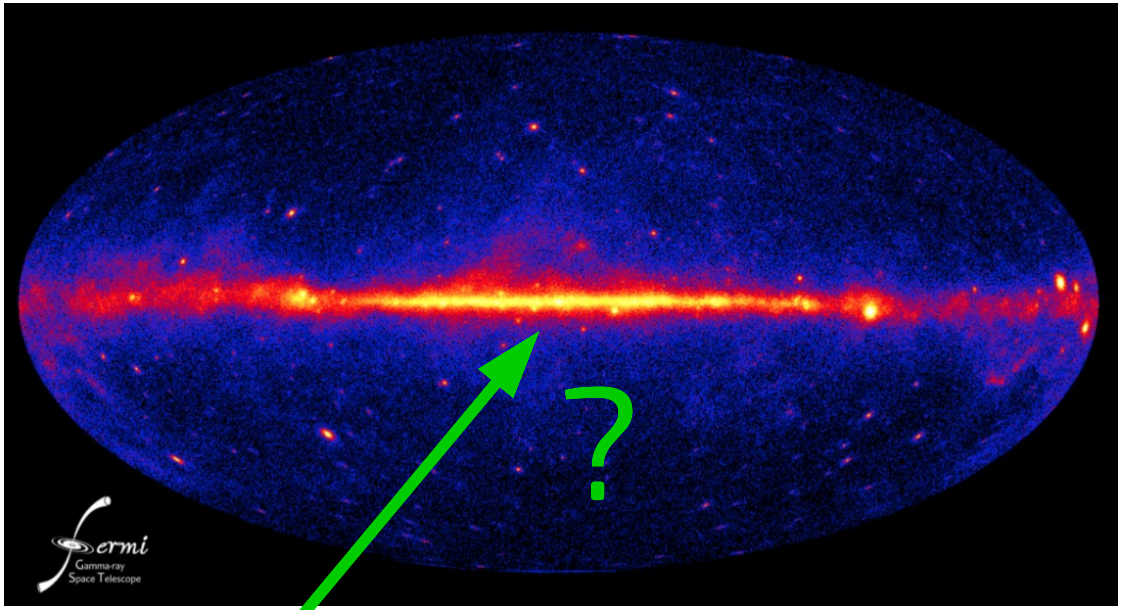
# Anomalies

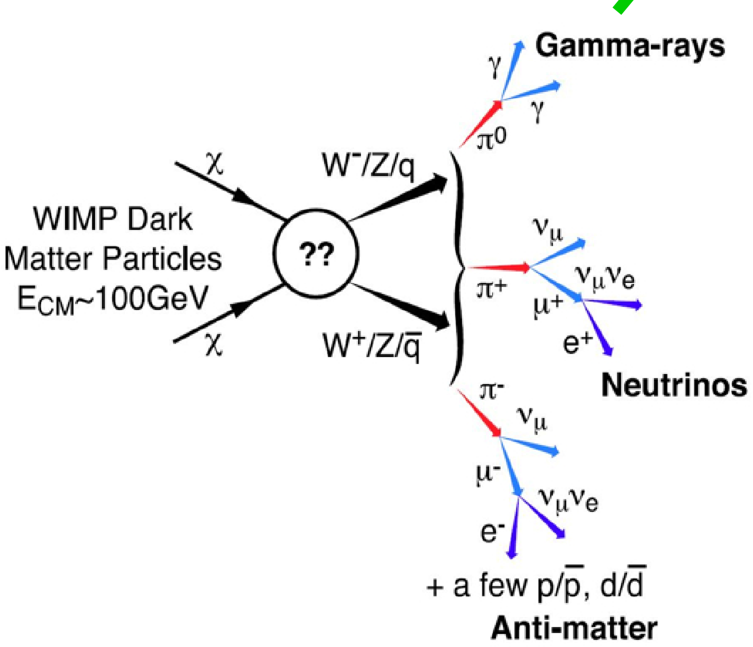
## Fermi GeV excess

# "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 overview

**Papers that looked at data**

- Goodenough & Hooper, arXiv:0910.2998
- Vitale & Morselli, 2009
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(+ a few that I must have missed)

**Excess is likely DM**

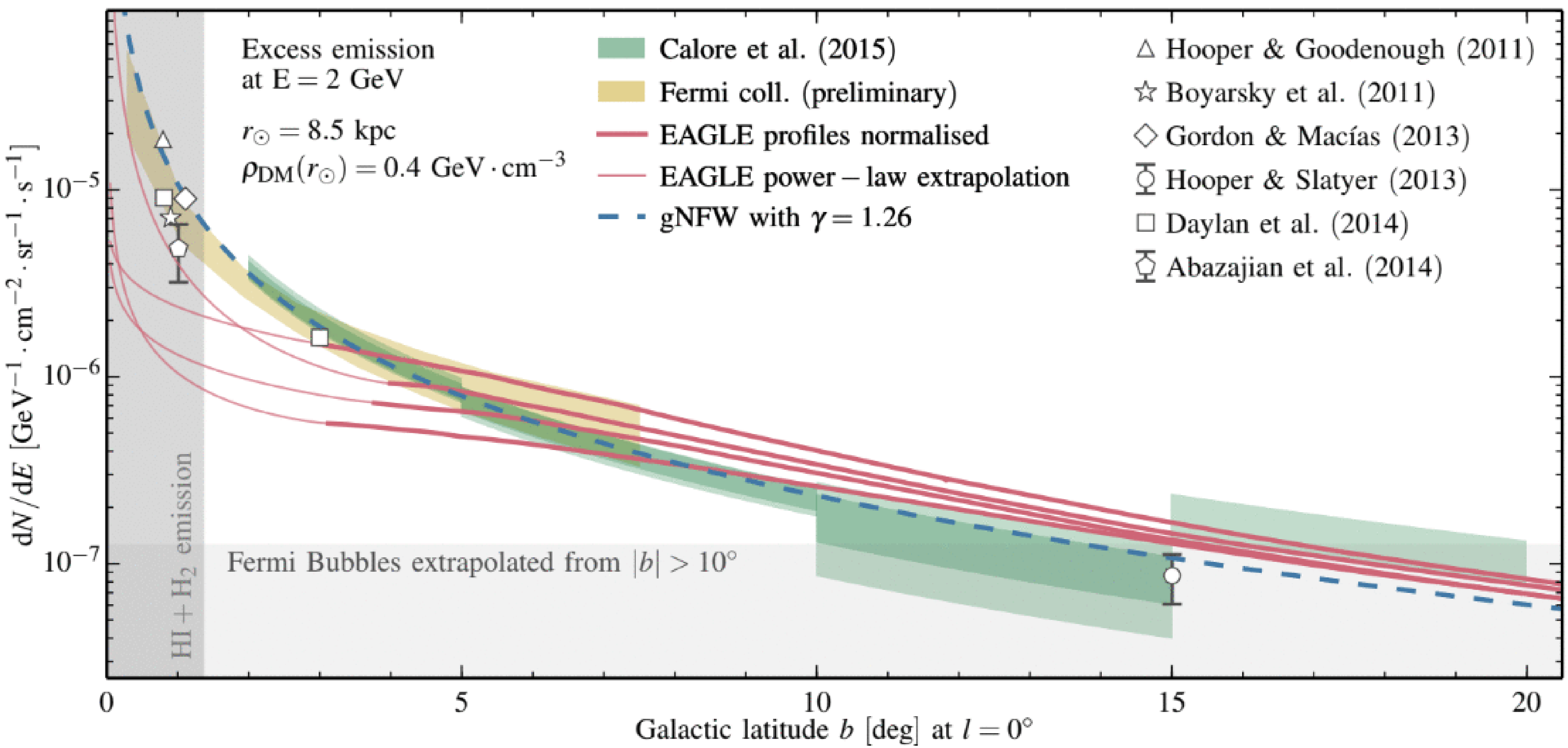
**Excess is there**

**Excess is likely not DM**

**Excess is not there**

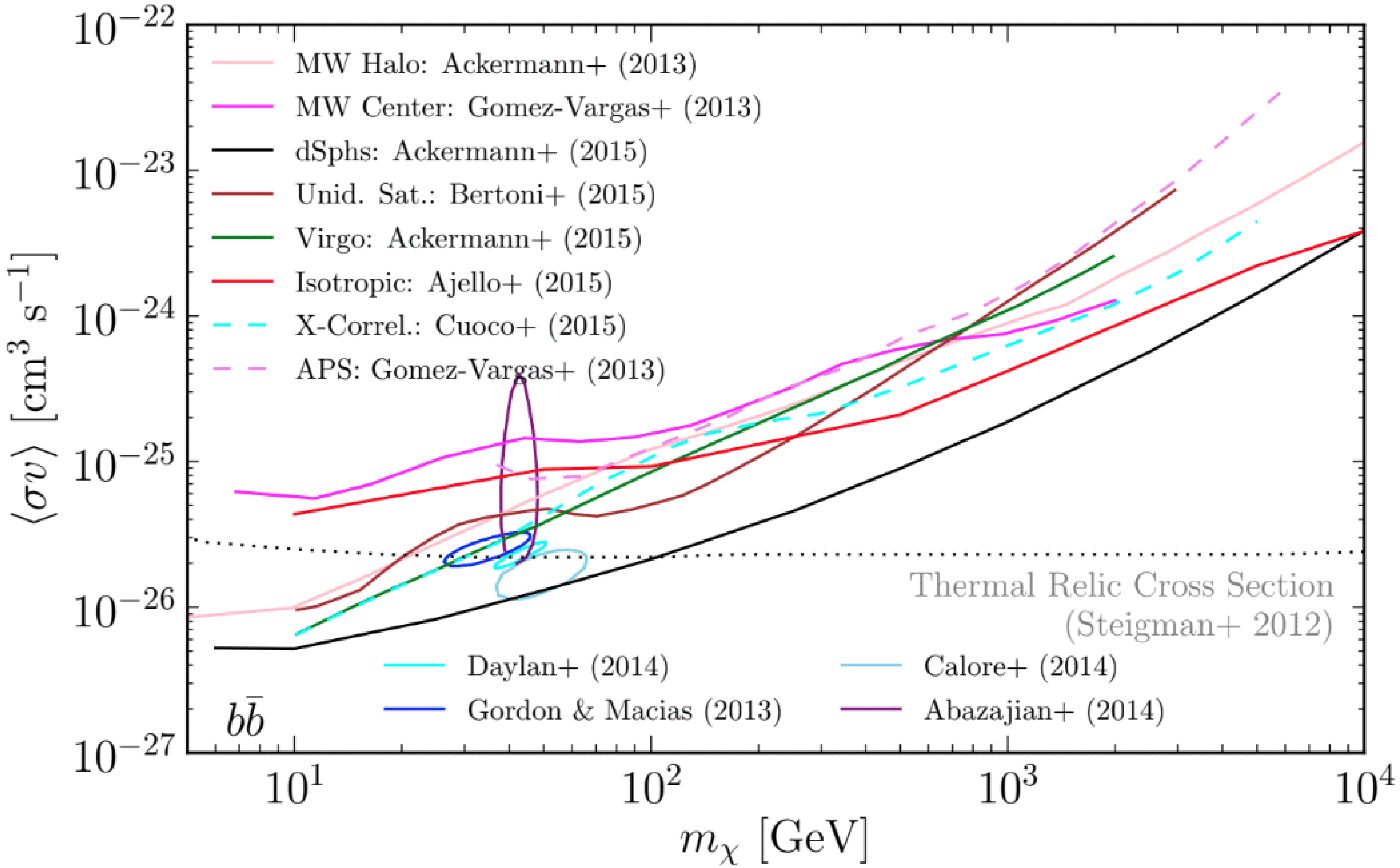
**+ hundreds of DM theory papers**

# Emission profile



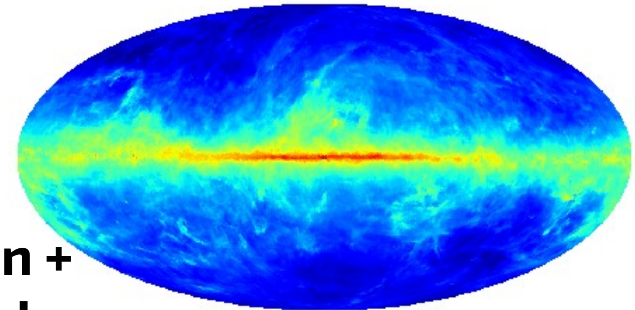

Calore+15, Charles+16

# Comparison with dwarfs



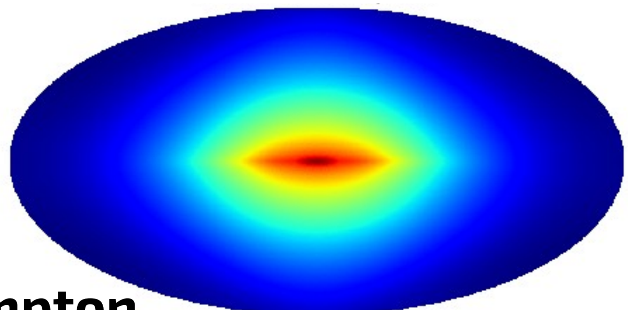

Charles+ 2016

# Most analyses are based on template regression



**Neutral pion + Bremsstrahlung**

+

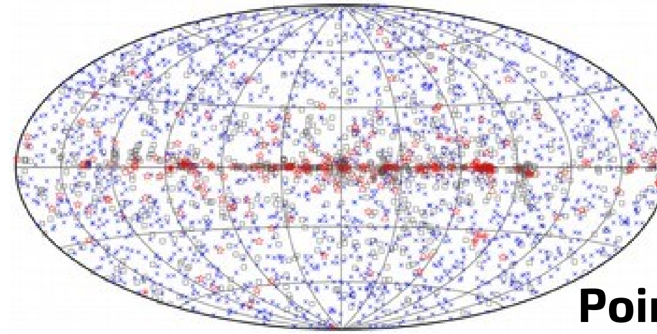


**Inverse Compton**

+

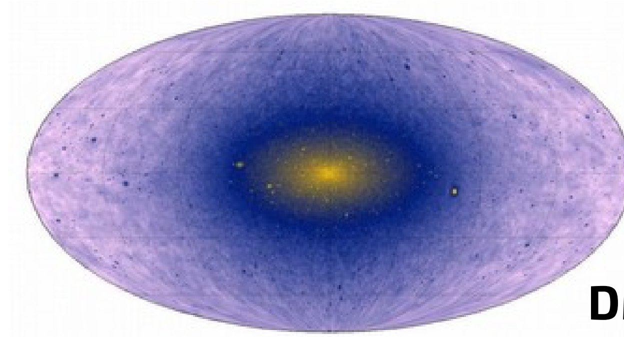
Fermi bubbles, isotropic background, Loop I, Earth limb, Sun, ...

+



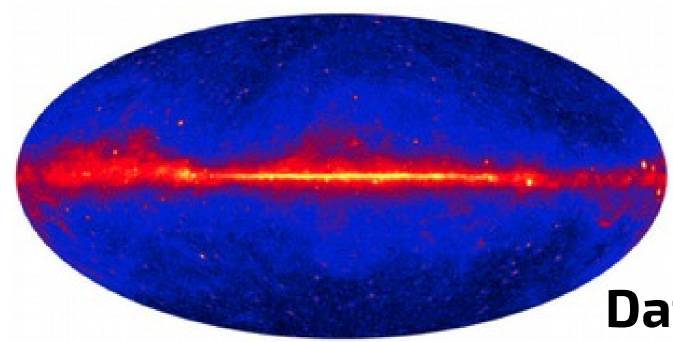
**Point sources**

+



**DM signal**

=



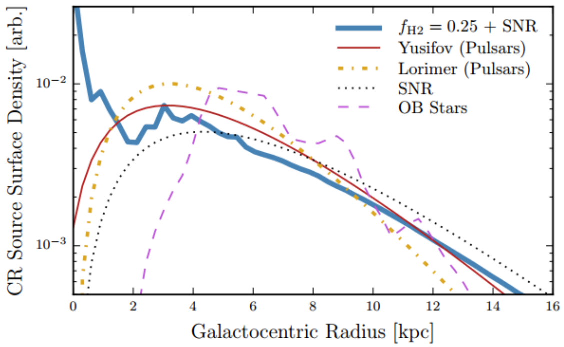
**Data**

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

GALPROP

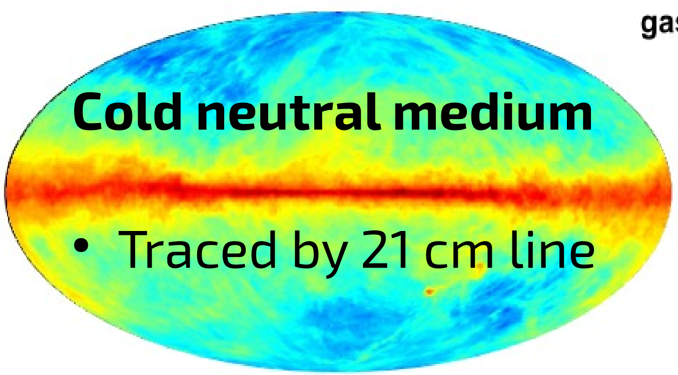
DRAGON

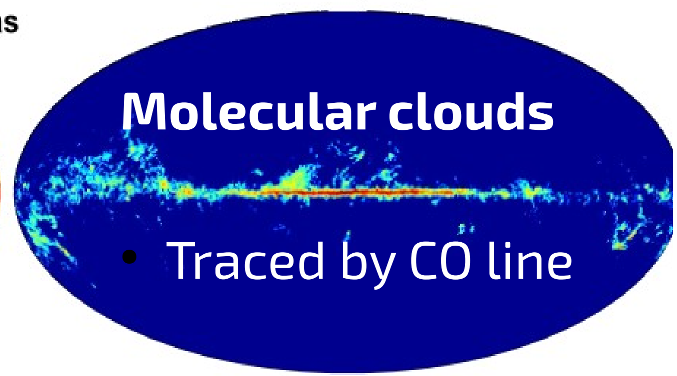
## 3) Interaction with gas & ISRF

HI (LAB) Kalberla '05

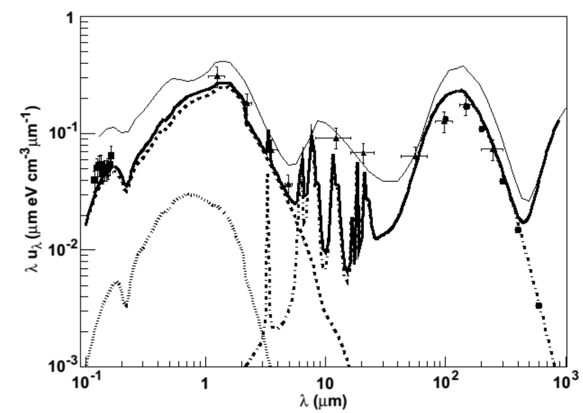
HII << gas

CO (CfA) Dame '01




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

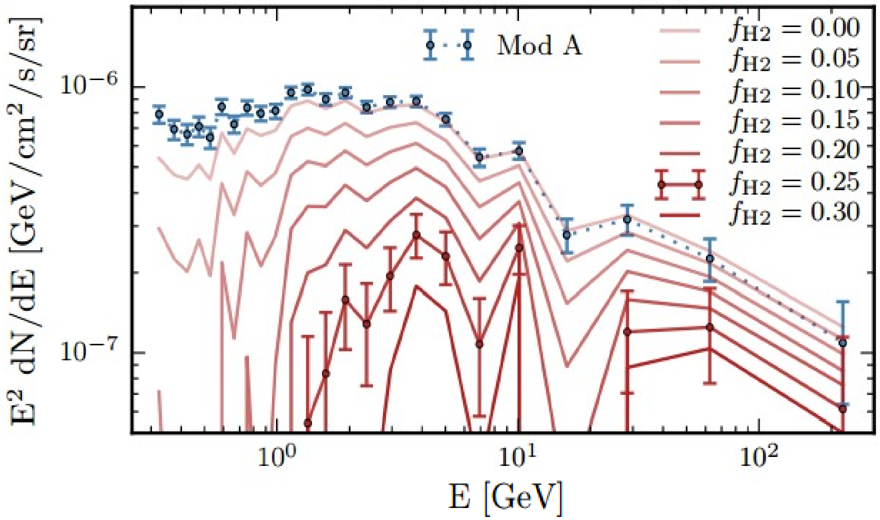



$$p_{\rm CR} \longrightarrow p_{\rm ISM} \to \pi^0 \to \gamma\,\gamma, \quad p_{\rm ISM} \to \dots$$

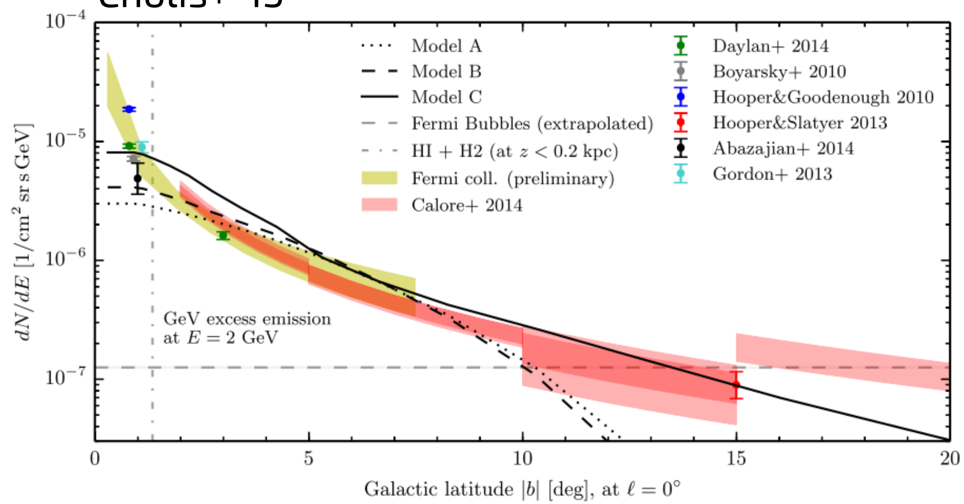
$$e^{\pm}_{\rm CR} \longrightarrow \gamma_{\rm ISRF} \to \gamma, \quad \gamma_{\rm ISRF} \to e^{\pm}_{\rm CR}$$

# Possible contributions to bulge emission

Carlson+ '15




Cholis+ '15




## 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

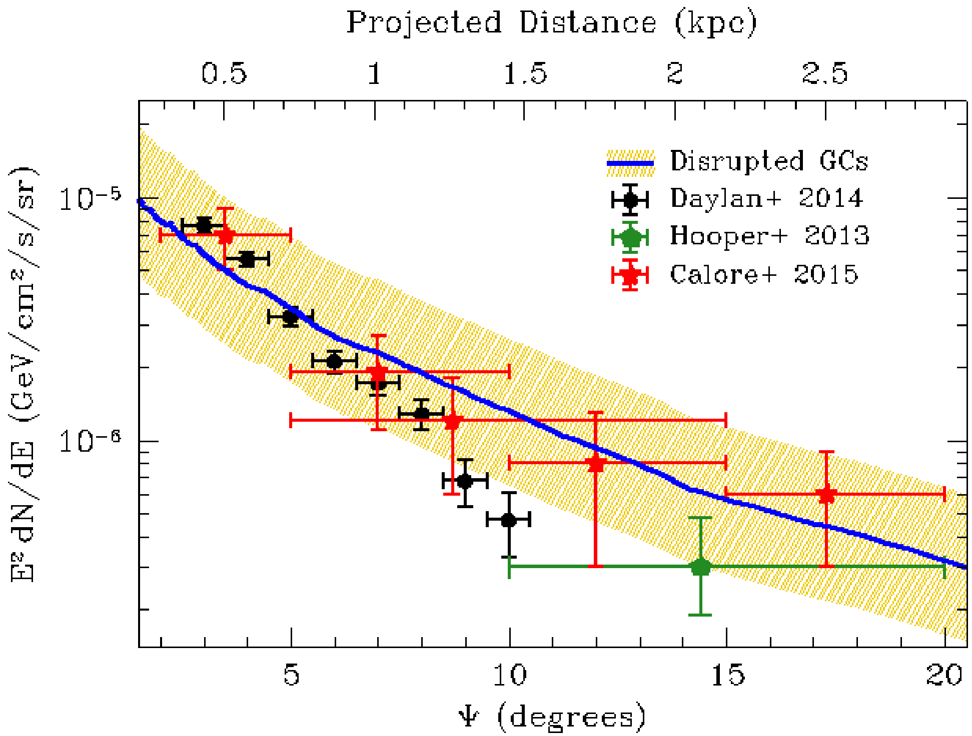
- Dark matter annihilation* (spectrum not exactly known but can bump at ~GeV energies, not clear how strong signal, what shape)
- Past activity of central black hole (cooling effects might in principle explain the observed peaked spectrum; e.g. Cholis+15; Petrovic+13)

*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

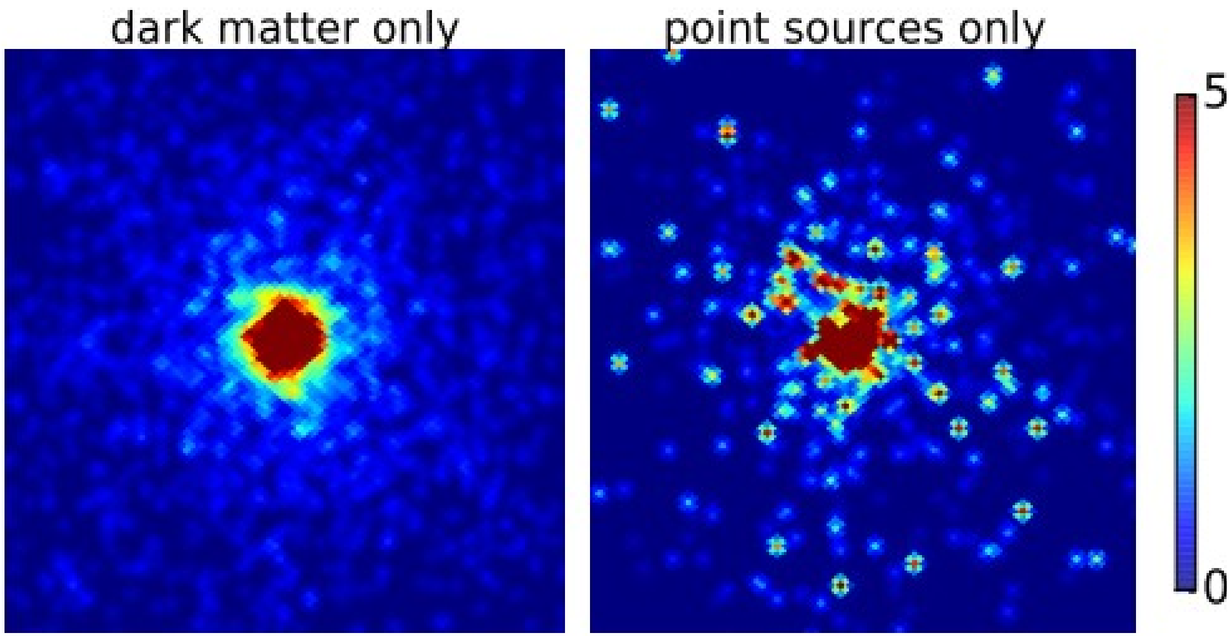



Brandt & Kocsis '15

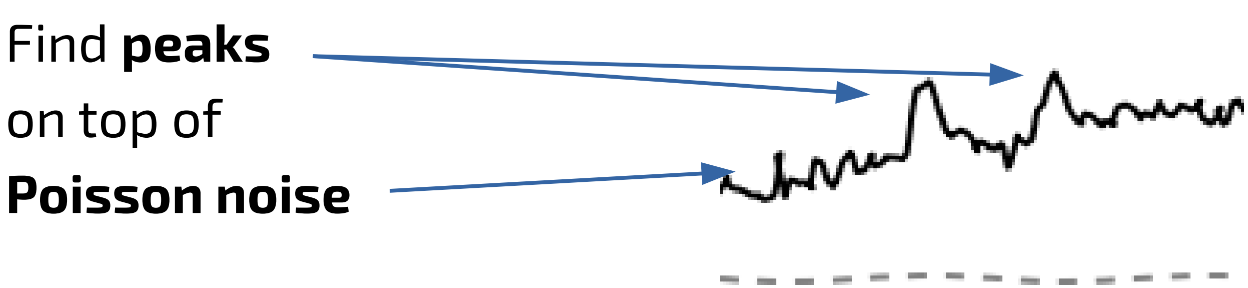
For a list of possible caveats (e.g. pulsar aging) see e.g. Hooper+'13, Cholis+'14, Linden & Hooper '16

# An observational challenge

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

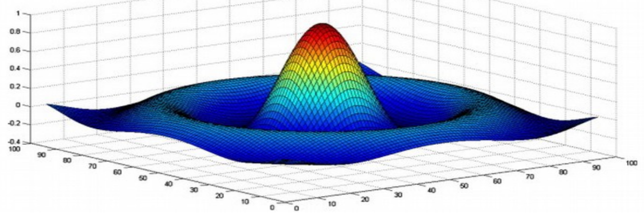



(Credit: Lee+ 2014)



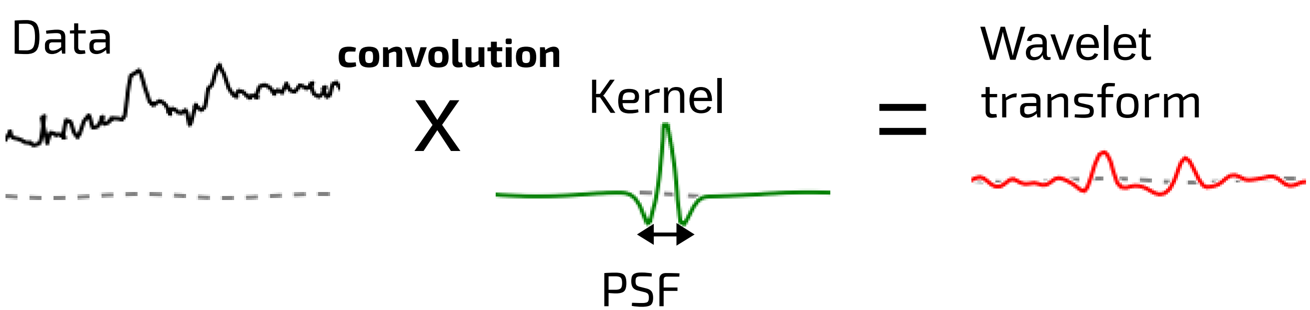
# Wavelet transform to filter out point sources

**Mexican hat wavelet**



Credit:
https://www.researchgate.net


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

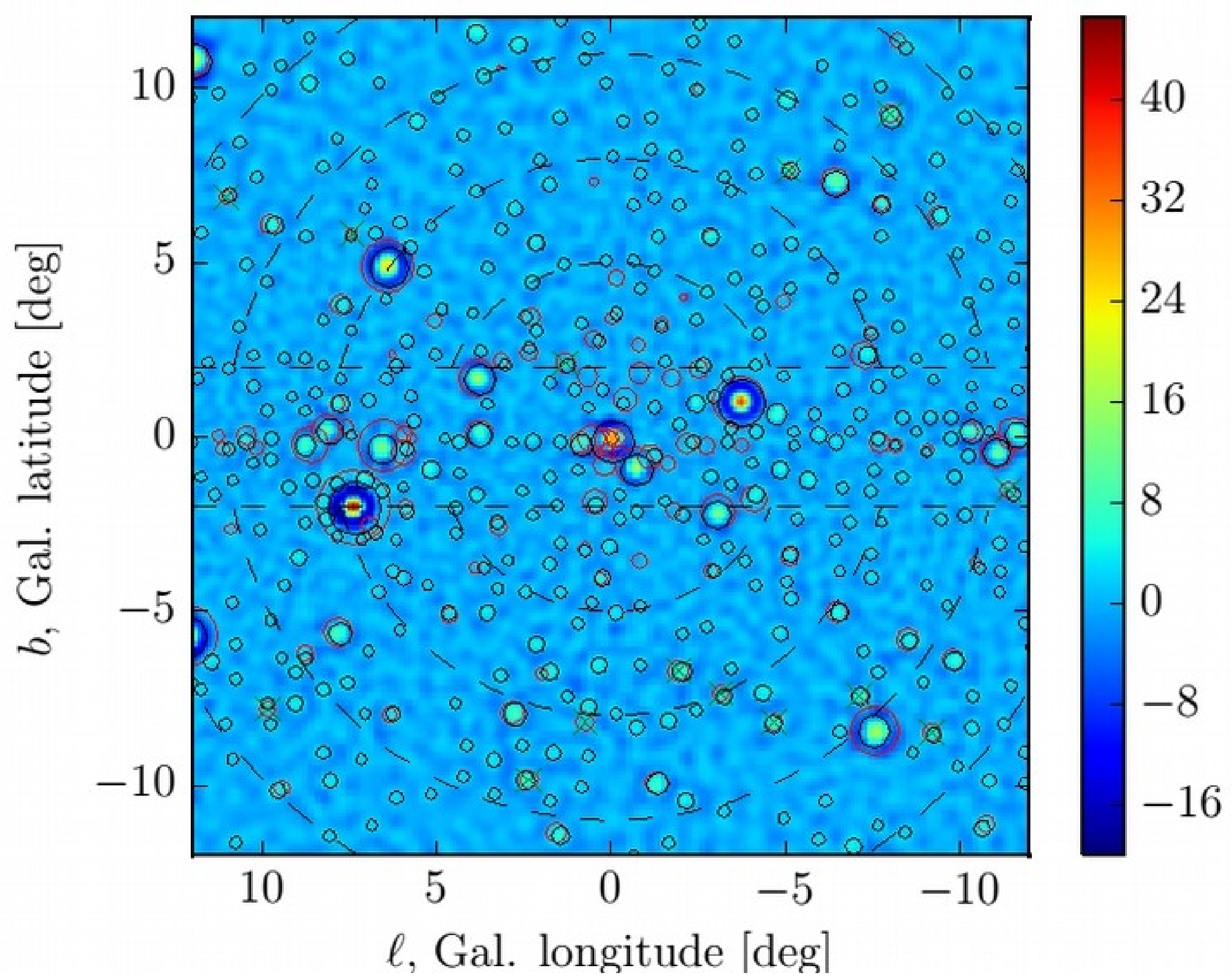



**Wavelet approach is robust and simple**

- 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**

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

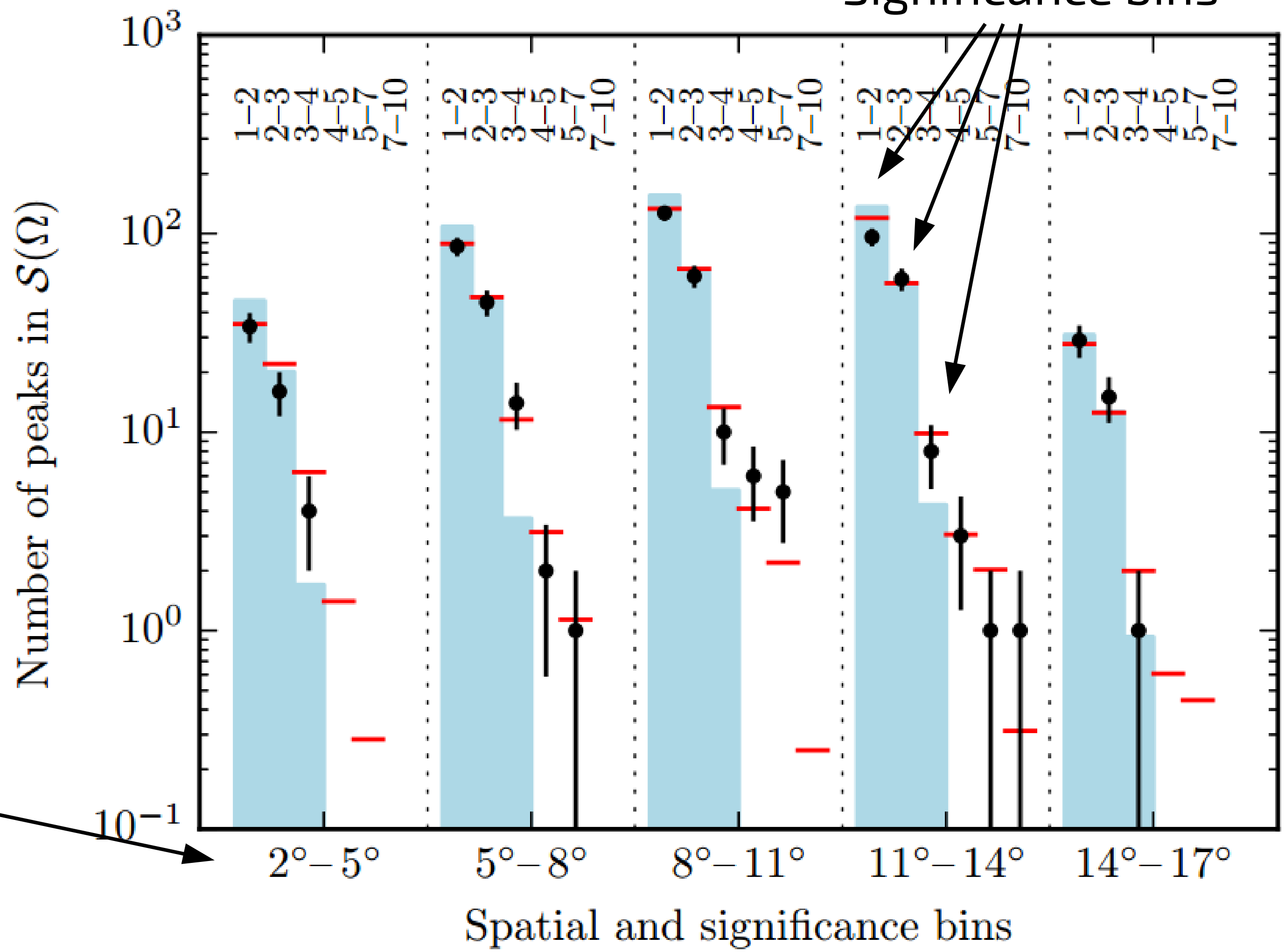
Free parameters

- 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)

# Histogram of wavelet transform peaks

Significance bins




Radial bins

**We find**

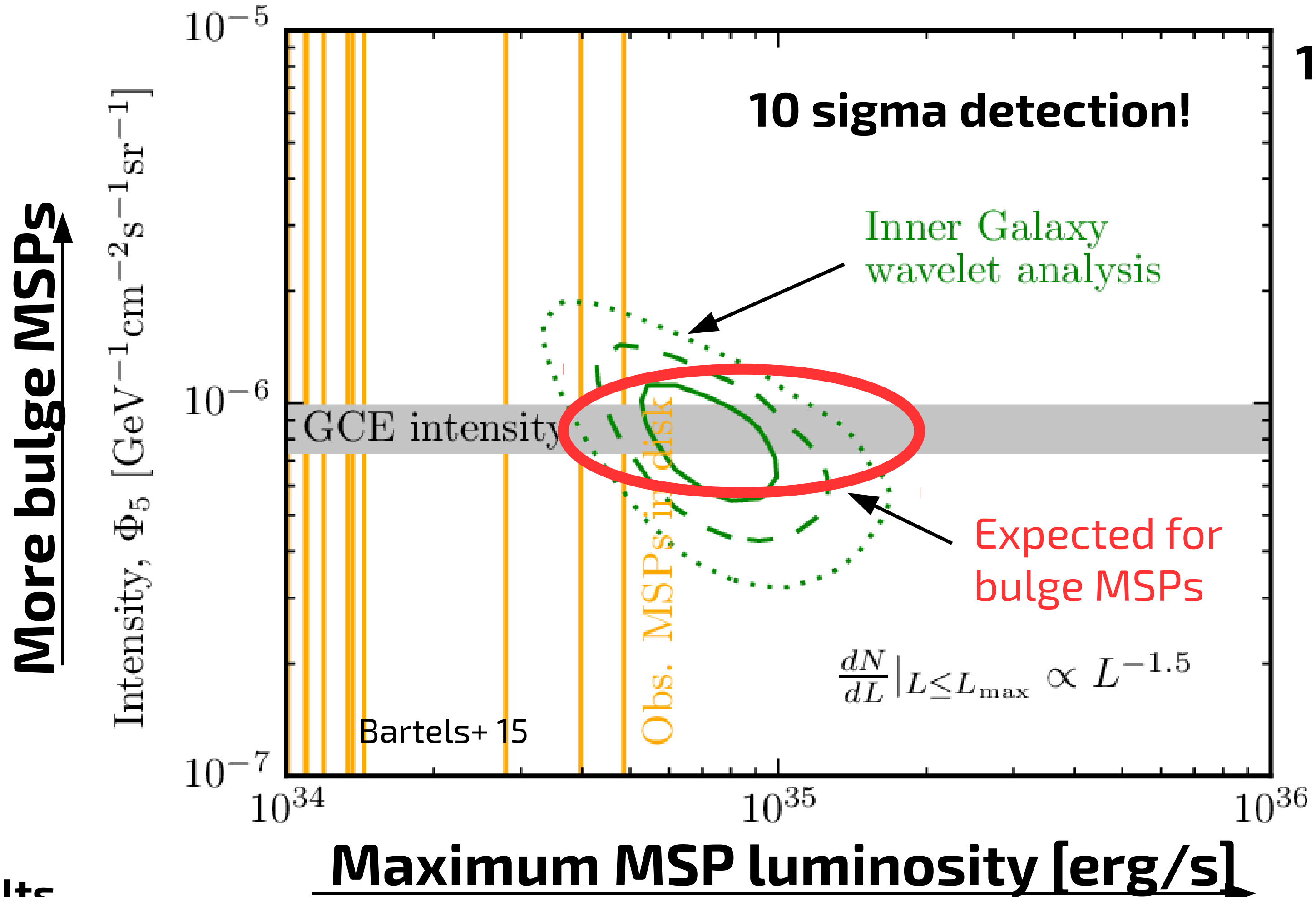
- Suppression at <2 sigma
- Excesses at >3 sigma

Blue bars: Null hypothesis (diffuse only emission)

Black: Measured data

Red: best fitmodel with PSC population in bulge

# Strong support for MSP hypothesis




See also Lee+15

**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)

# Relevant gamma-ray source classes

**Extragalactic sources**

- Unlikely (at >5sigma leve) that extragalactic source density is peaked sufficiently towards inner Galaxy

**Supernova remnants and PWN**

- Very rare at |b|>2 deg
- Not peaked towards inner Galaxy (usually more closeby)
- Usually detected at other frequencies first

**Young pulsars and MSPs**

- Peak in selected energy range (by design)
- Detected (radio) pulsars do not peak towards the inner galaxy

**Globular clusters**

- Emission will be approximately the combined emission of many pulsars

**Unassociated sources**

- At higher latitudes, large fraction is expected to be young and millisecond pulsars

We expect that wavelet signal is dominated by whatever source class (except EG) is responsible for the majority of the unassociated sources in the inner galaxy. Spherical distribution more plausible for MSPs than for young pulsars

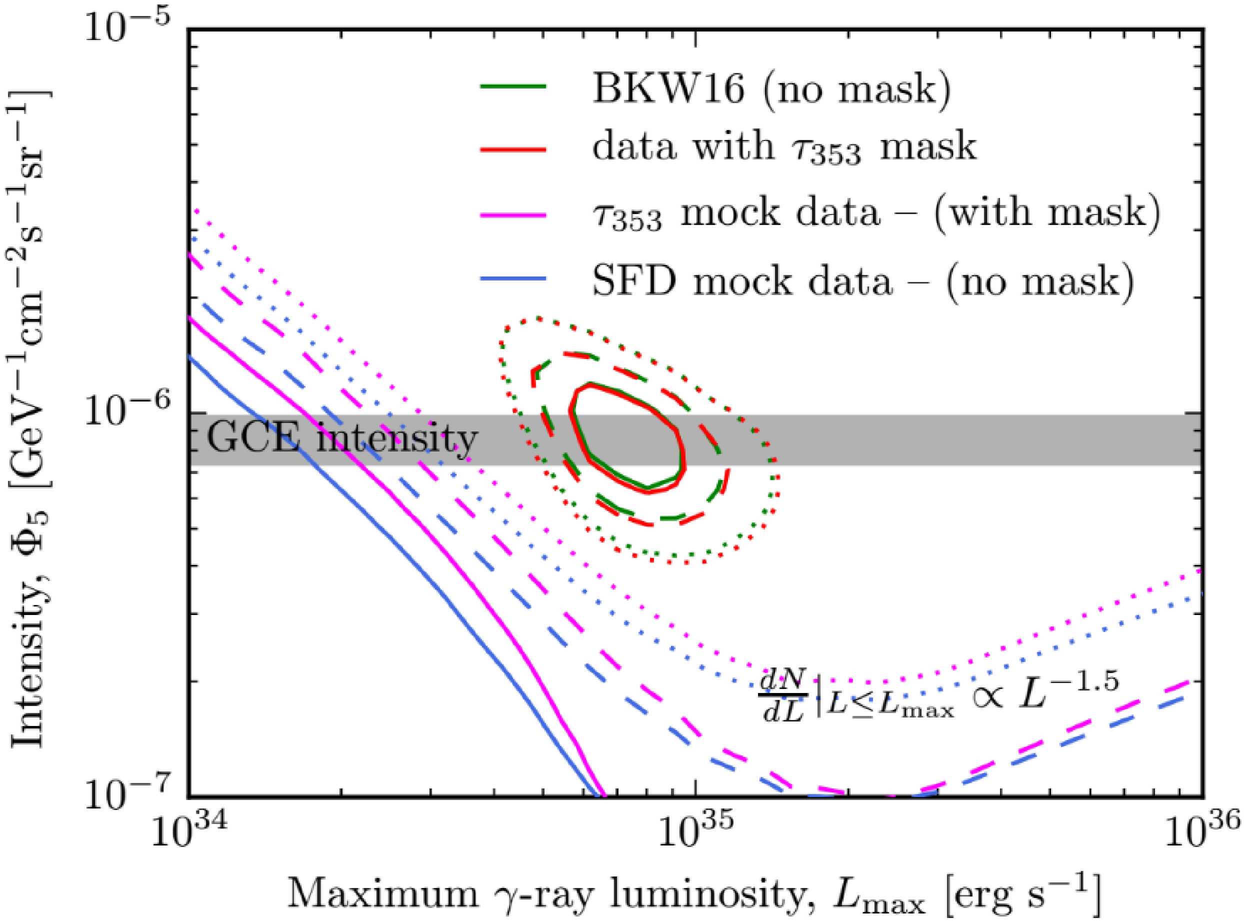
→ MSPs the (by far?) most likely interpretation

# 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)

Check out extensive appendix of Bartels+16 for more details.



# Yes, but…

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

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

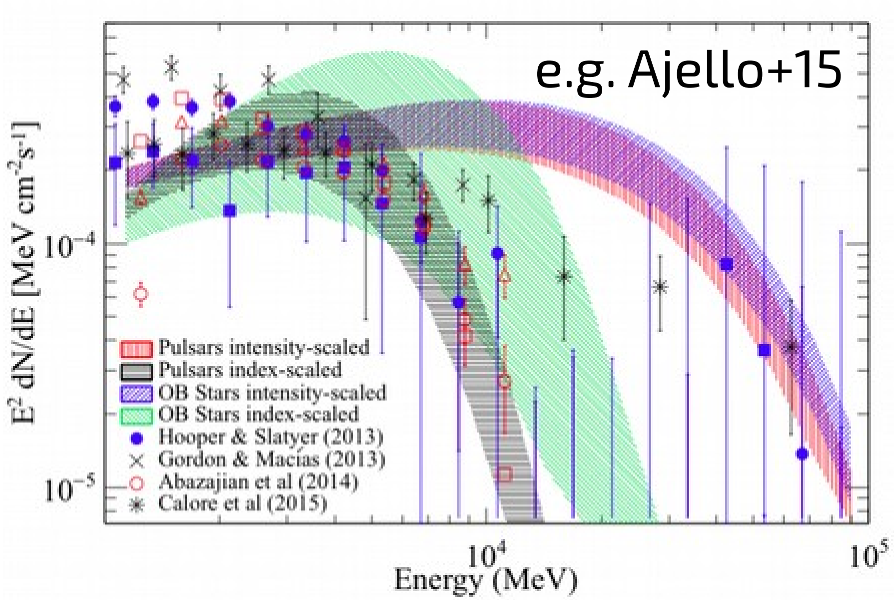
Goodness-of-fit tests typically return **p-value < $10^{-300}$**

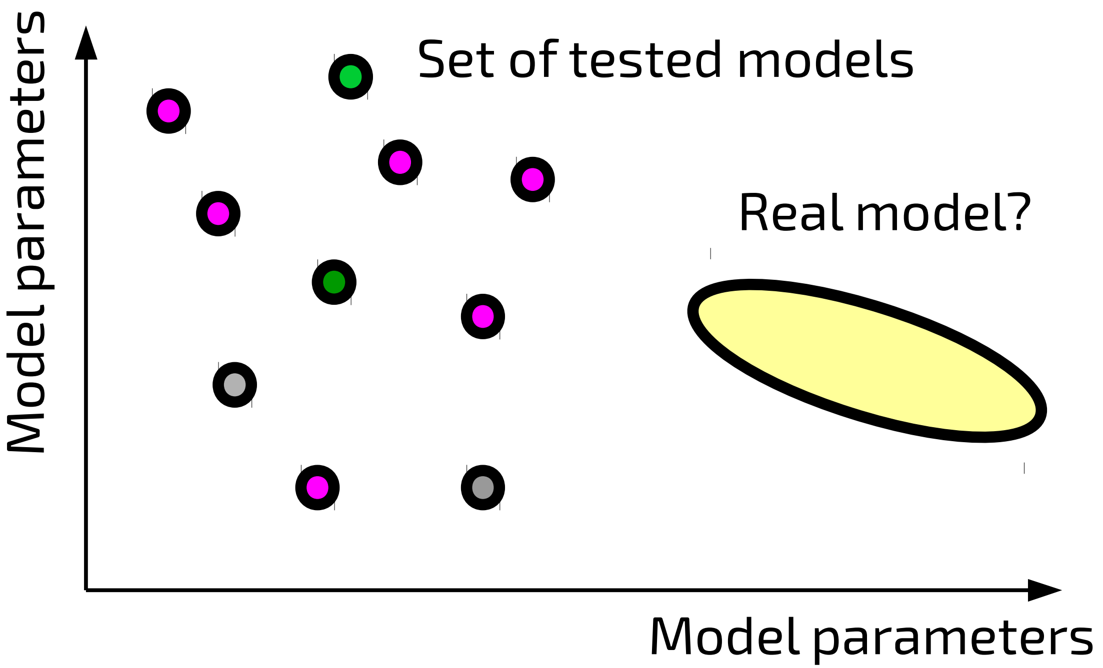
**2. Many excess along the Galactic disk**

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** (**S**ky **F**actorization with **A**daptive **C**onstrained **T**emplates)

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

Storm, CW, Calore, 2017

Spatial template — Spectral template

$$\phi_{pb} = \sum_k T_p^{(k)} \tau_p^{(k)} \cdot S_b^{(k)} \sigma_b^{(k)} \cdot \nu^{(k)}$$

$$\sigma_b^{(k)}, \tau_p^{(k)}, \nu^{(k)} \geq 0$$

Nuisance parameters

Poisson likelihood

$$\ln \mathcal{L} = \ln \mathcal{L}_{\mathrm{P}} + \ln \mathcal{L}_{\mathrm{R}}$$

Penalization terms

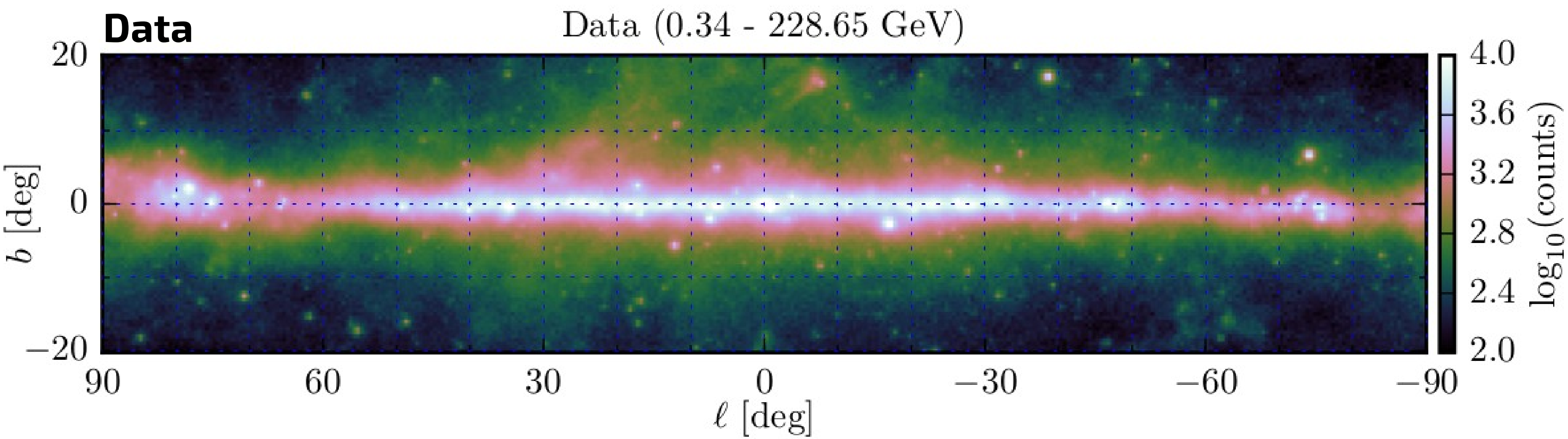
$$-2\ln \mathcal{L}_R = \sum_k \lambda_k \mathcal{R}_X(\boldsymbol{\tau}^{(k)}) + \lambda'_k \mathcal{R}_X(\boldsymbol{\sigma}^{(k)}) + \lambda''_k \mathcal{R}_X(\nu^{(k)}) + \eta_k \mathcal{S}_1(\boldsymbol{\tau}^{(k)}) + \eta'_k \mathcal{S}_2(\boldsymbol{\sigma}^{(k)})$$
$$+ \sum_s \lambda'_s \mathcal{R}_X(\boldsymbol{\sigma}^{(s)}) + \lambda''_s \mathcal{R}_X(\nu^{(s)}) + \eta'_s \mathcal{S}_2(\boldsymbol{\sigma}^{(s)}) \; ,$$

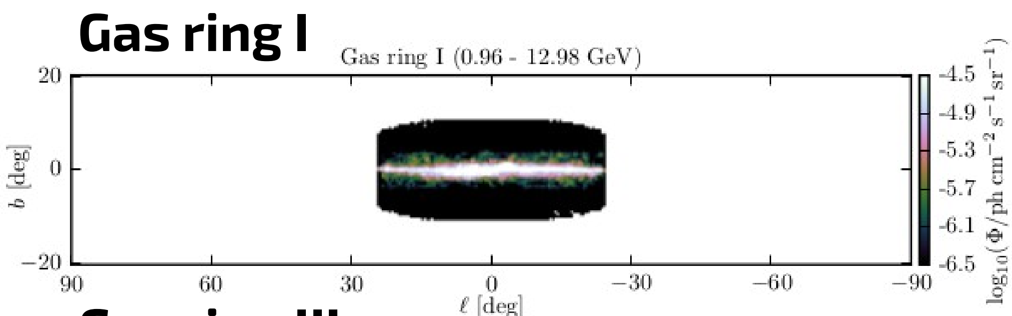
**Notes**

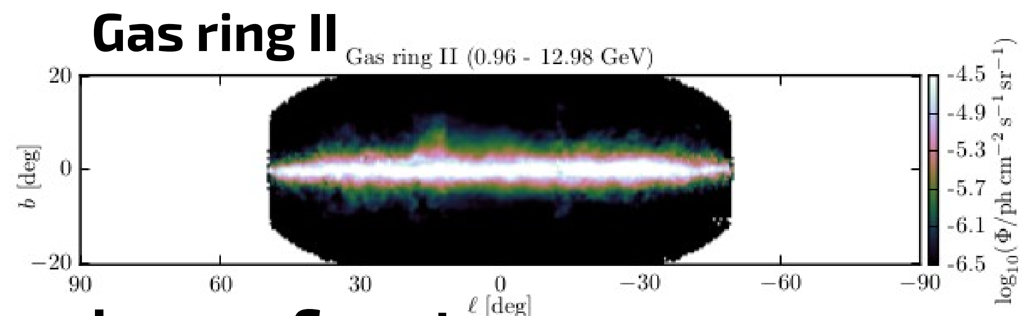
- Typically >10^5 parameters
- Problem typically convex → only one minimum

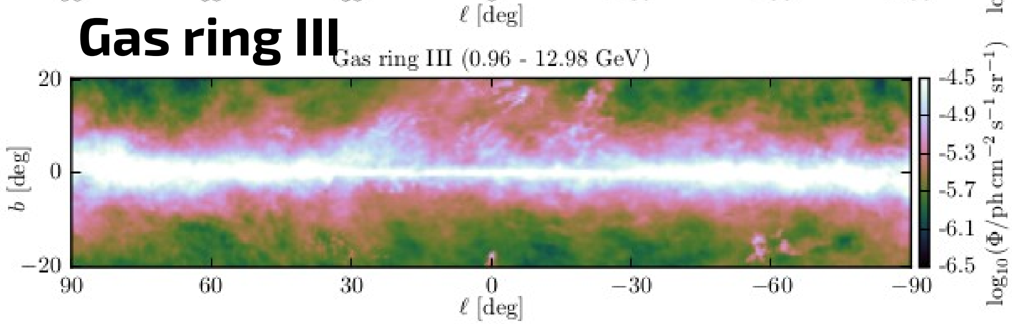
We adopt a maximum-entropy prior

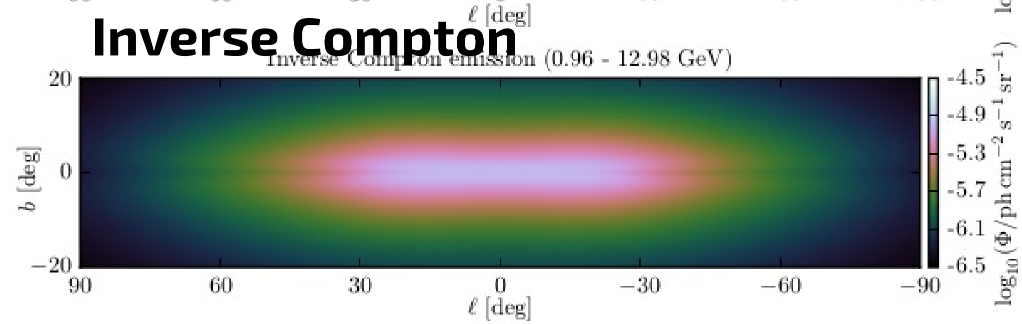
$$\lambda \mathcal{R}_{MEM}(\boldsymbol{x}) = 2\lambda \sum_i 1 - x_i + x_i \ln x_i$$


Data
Data (0.34 - 228.65 GeV)
b [deg]
ℓ [deg]
log10(counts)
4.0
3.6
3.2
2.8
2.4
2.0
20
0
−20
90
60
30
0
−30
−60
−90


Gas ring I
Gas ring I (0.96 - 12.98 GeV)
b [deg]
ℓ [deg]
log10(Φ/ph cm−2 s−1 sr−1)

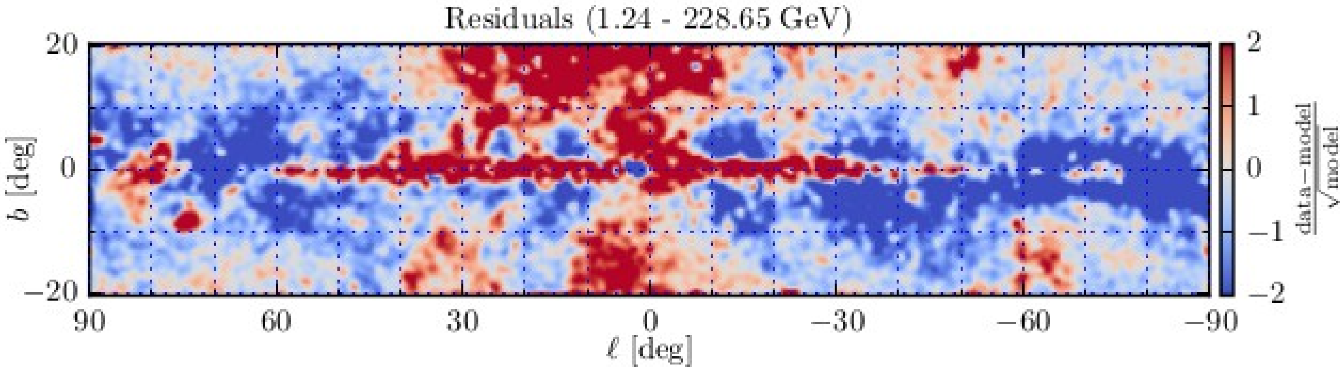

Gas ring II
Gas ring II (0.96 - 12.98 GeV)
b [deg]
ℓ [deg]
log10(Φ/ph cm−2 s−1 sr−1)


Gas ring III
Gas ring III (0.96 - 12.98 GeV)
b [deg]
ℓ [deg]
log10(Φ/ph cm−2 s−1 sr−1)

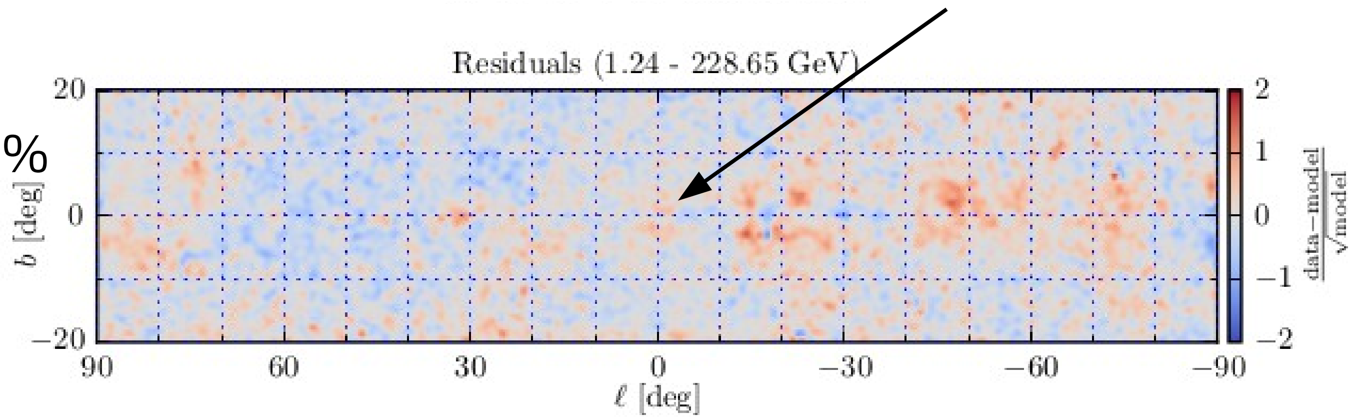

Inverse Compton
Inverse Compton emission (0.96 - 12.98 GeV)
b [deg]
ℓ [deg]
log10(Φ/ph cm−2 s−1 sr−1)

# Residuals ~2 GeV

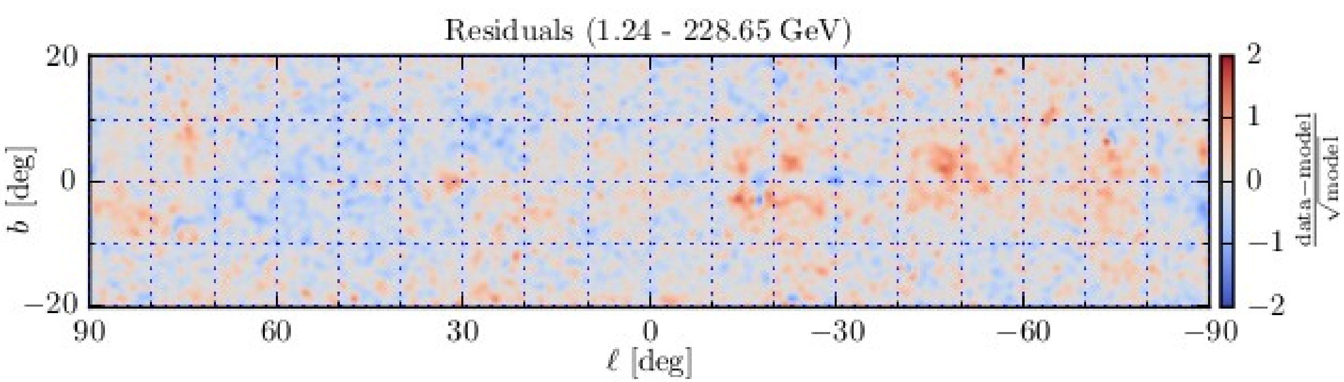
Regular template fit




Templates with 10%-30% uncertainty

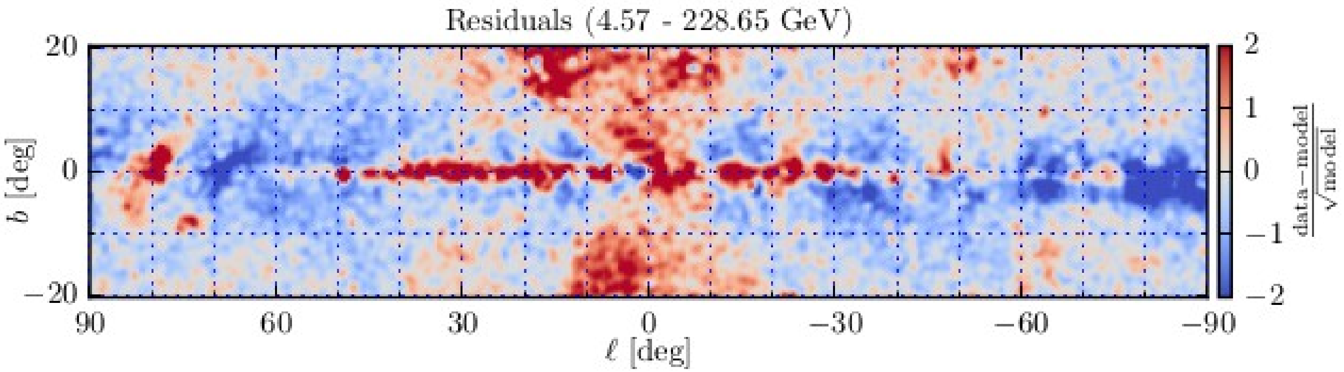



+ GeV excess

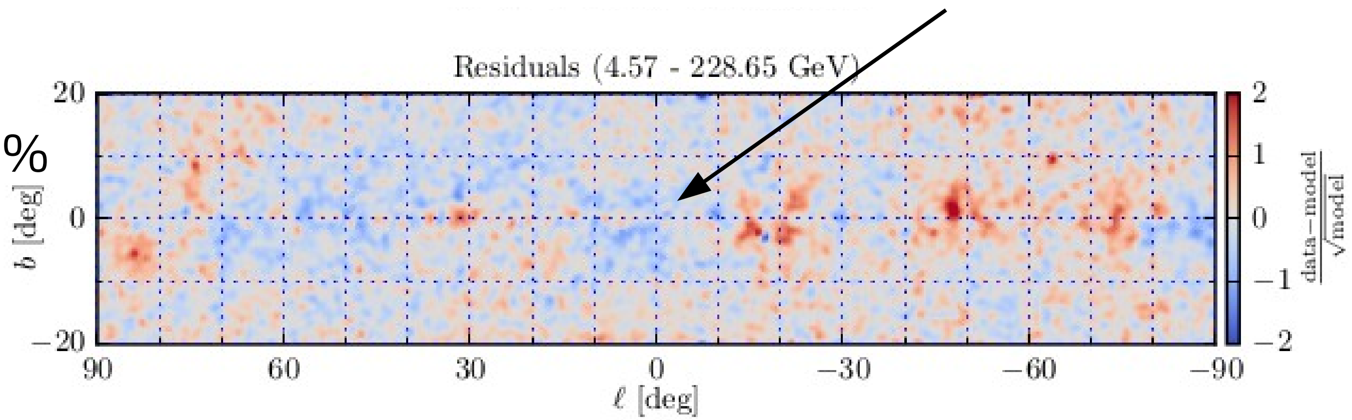


# Residuals ~ 6 GeV

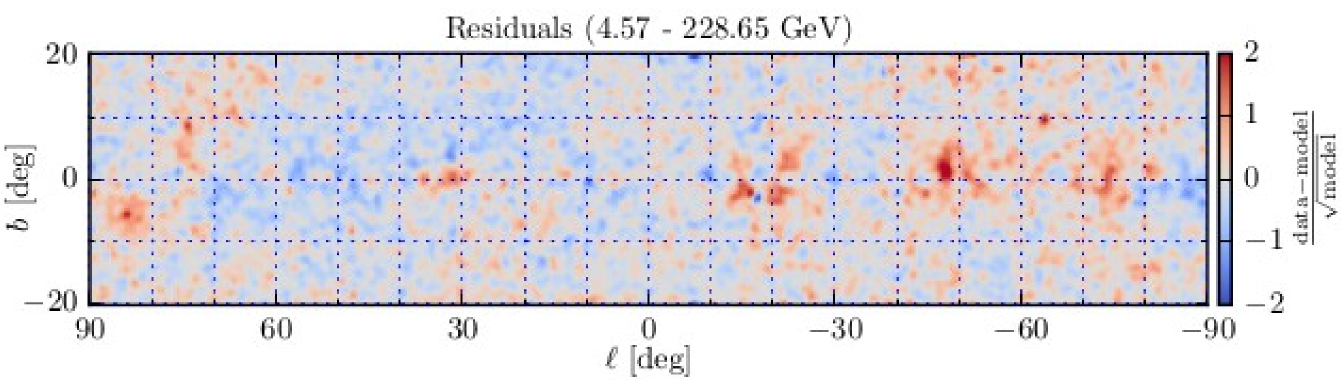
Regular template fit




Templates with 10%-30% uncertainty

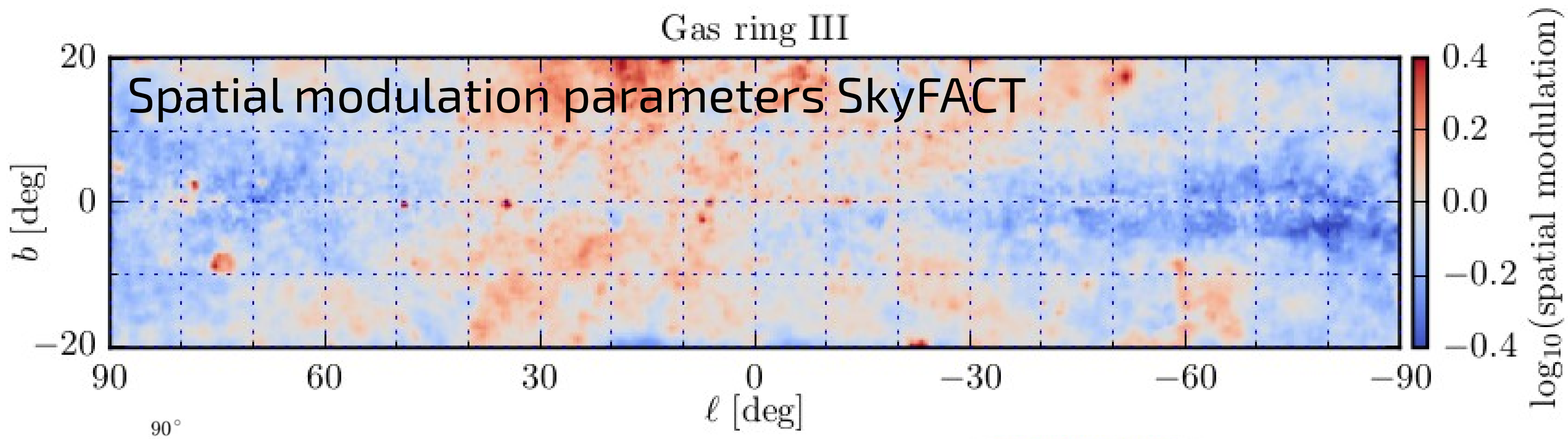



+ GeV excess

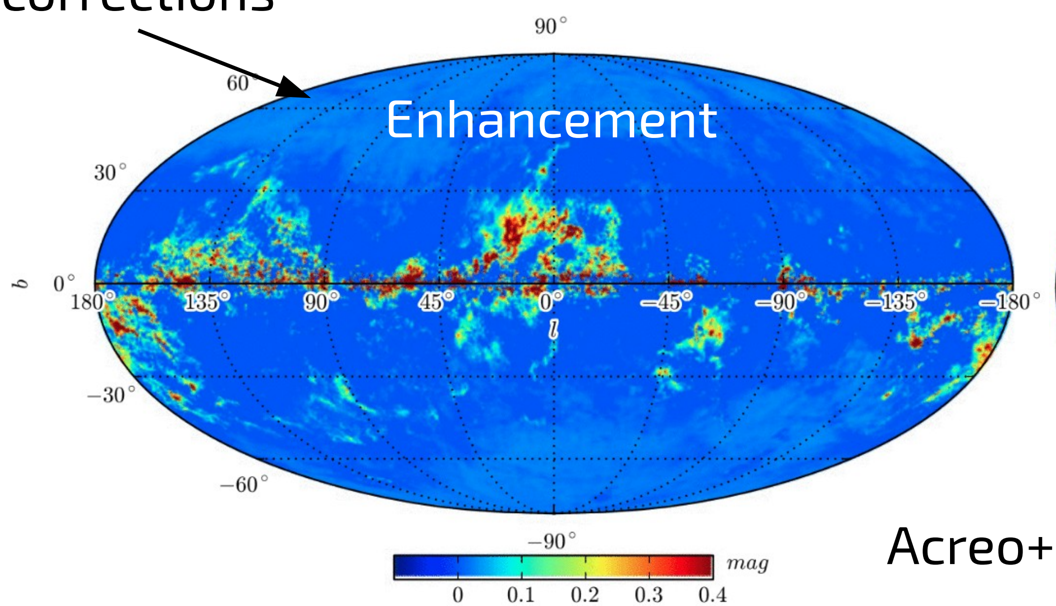


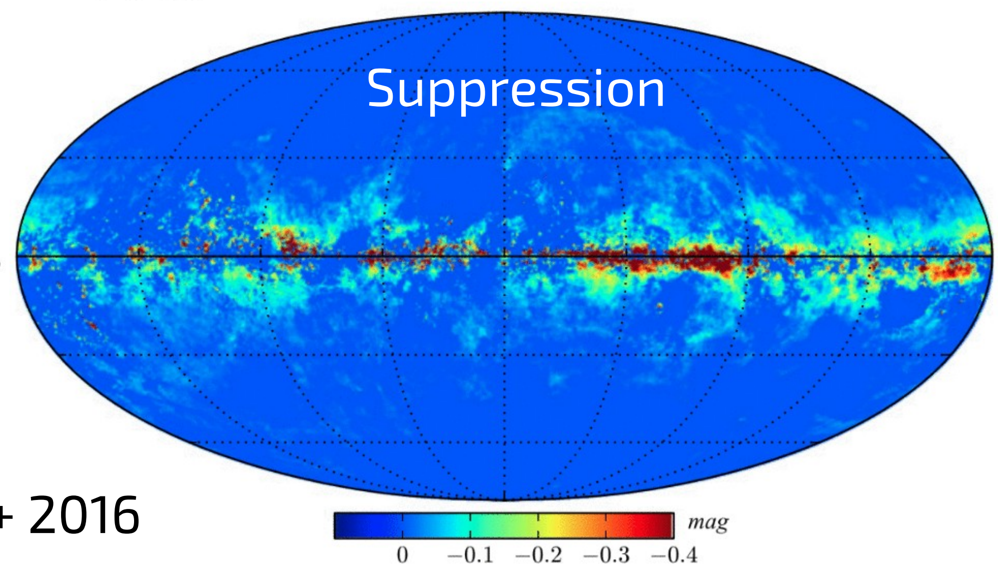
# Dark gas corrections

- 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)




Dust corrections

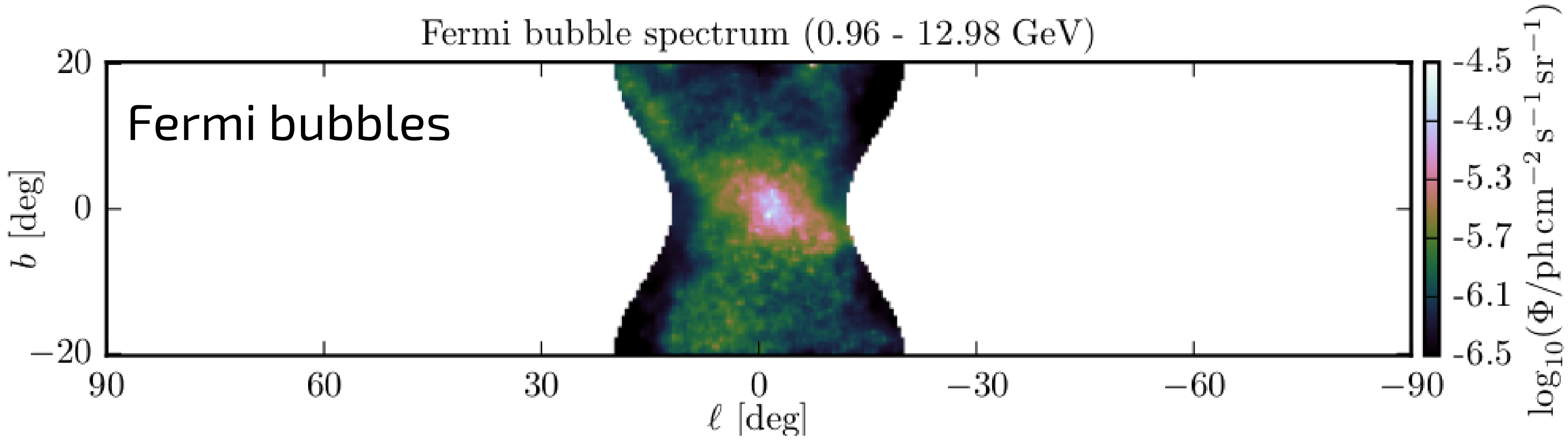



Acreo+ 2016

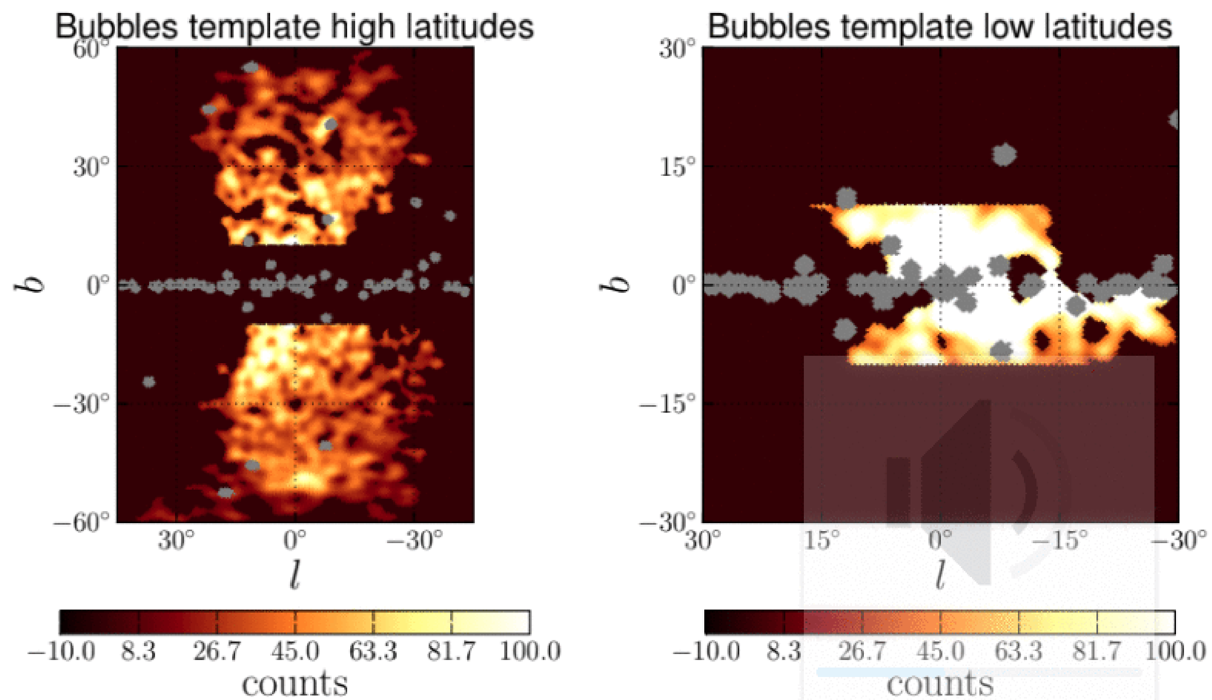
# Low-latitude Fermi bubbles

Modulation parameters

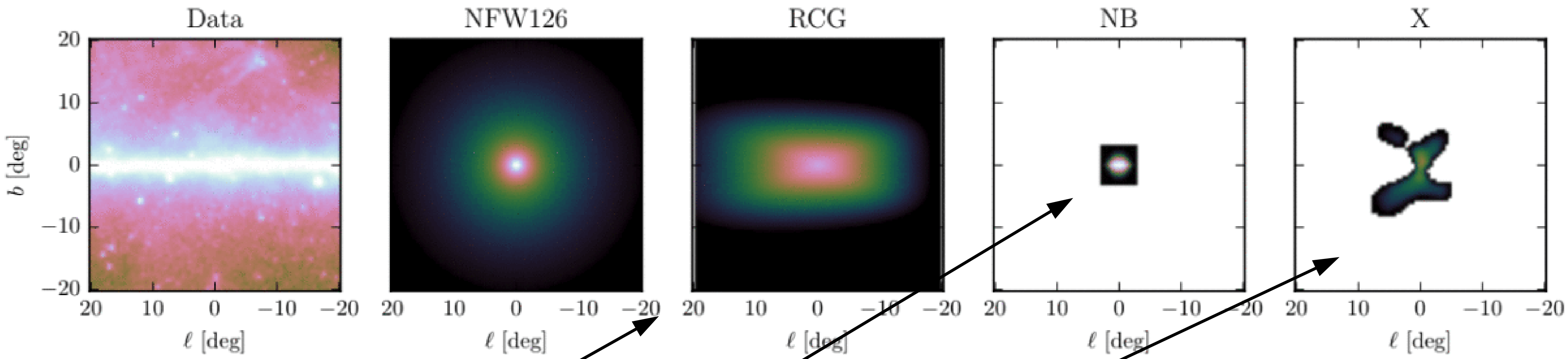



Ackermann+ 17

- 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

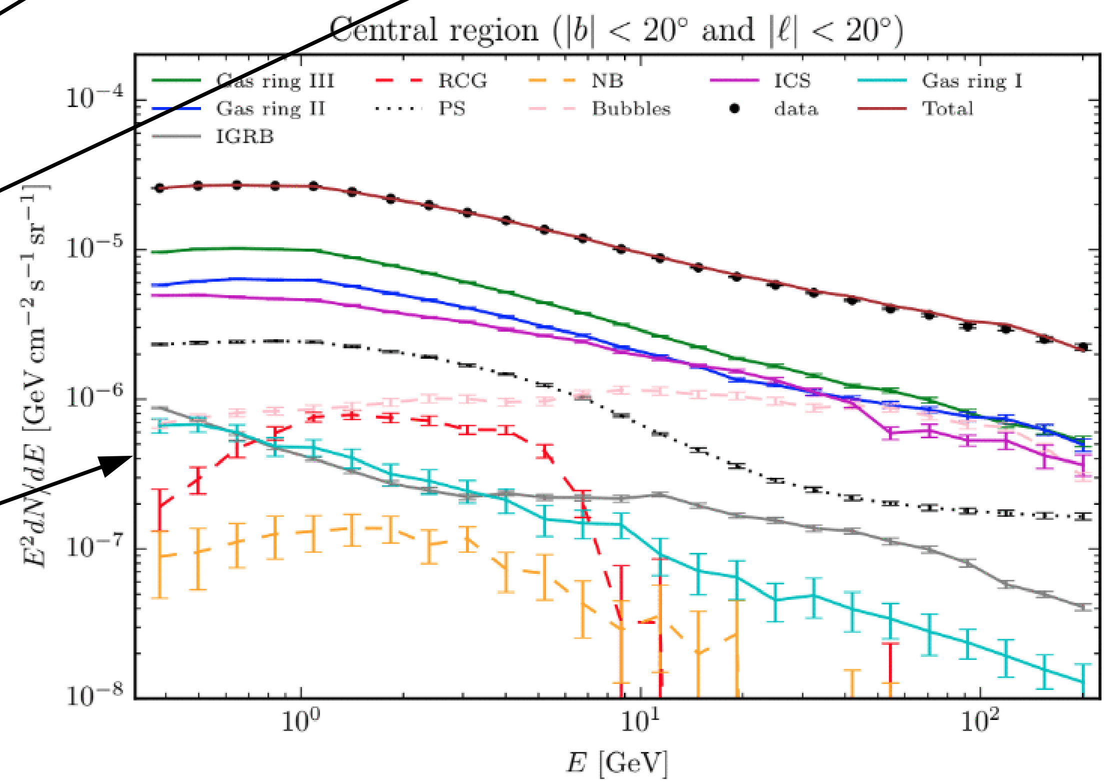



Red-clump giants

Nuclear bulge

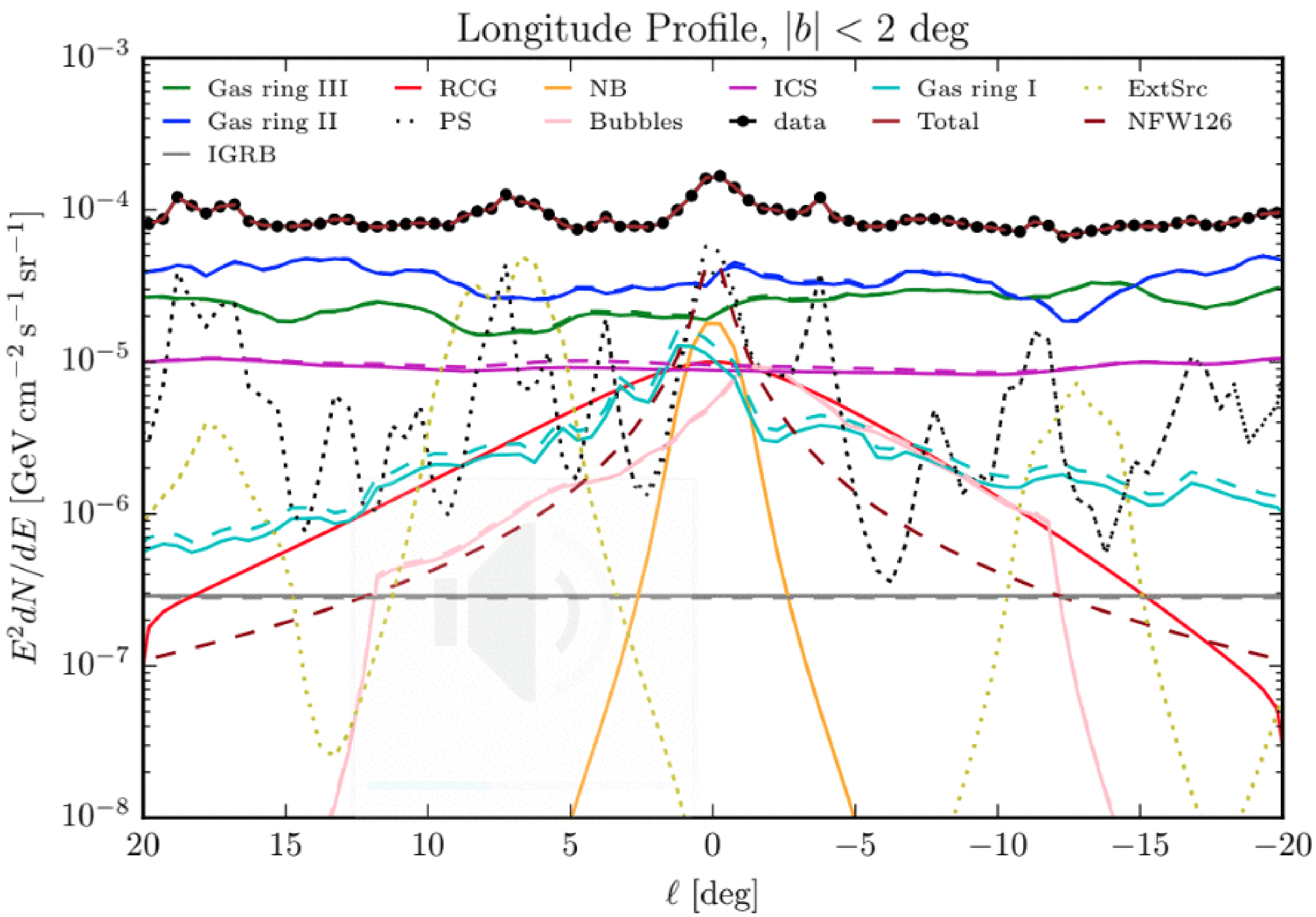
WISE template (X-shape)

Best-fit spectra



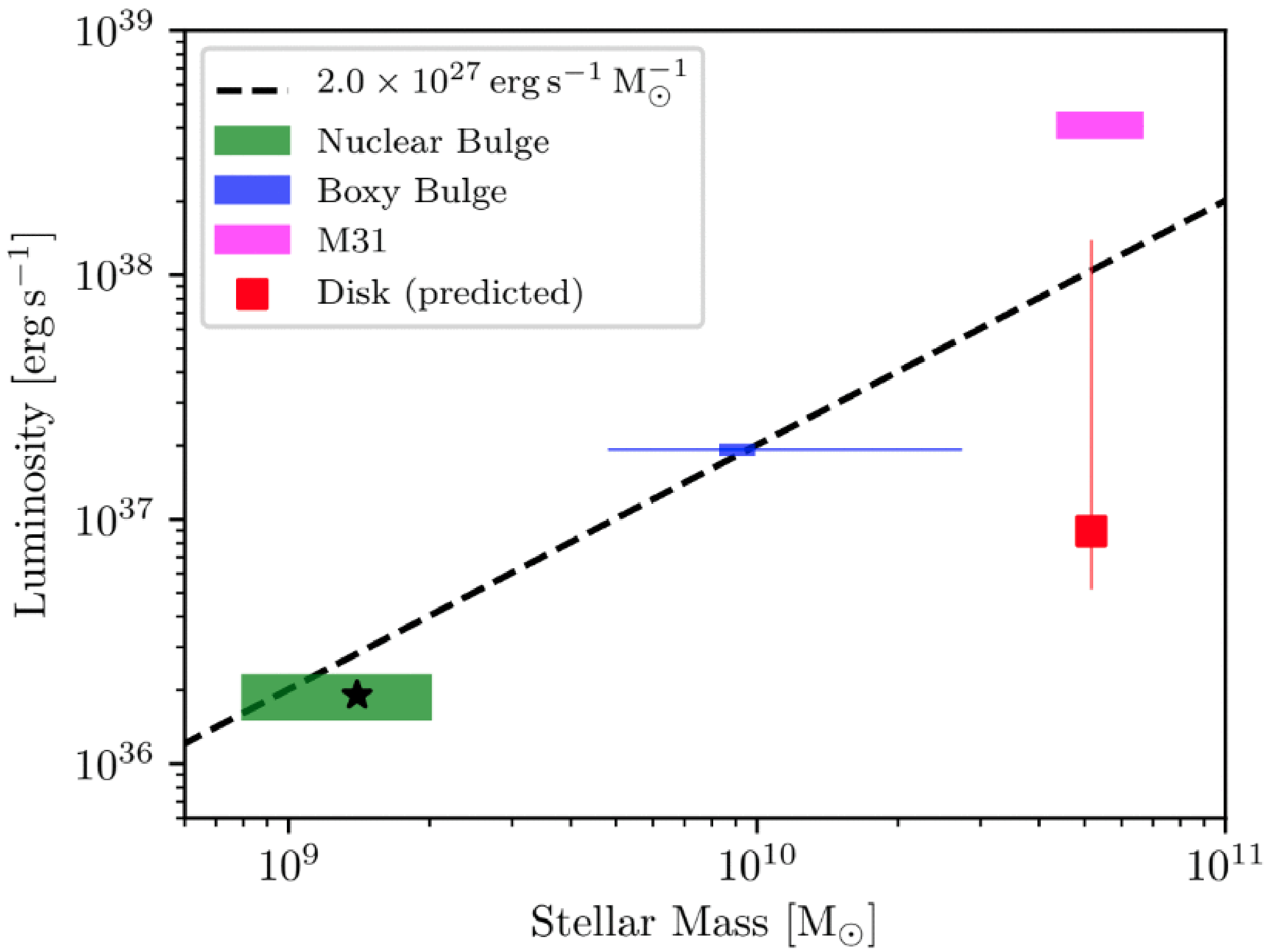

Bartels+ 1711.04778

# Longitude profile




- Bubble component is clearly displaced from center
- Shape quite different from contracted NFW, but hard to determine within disk

# 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

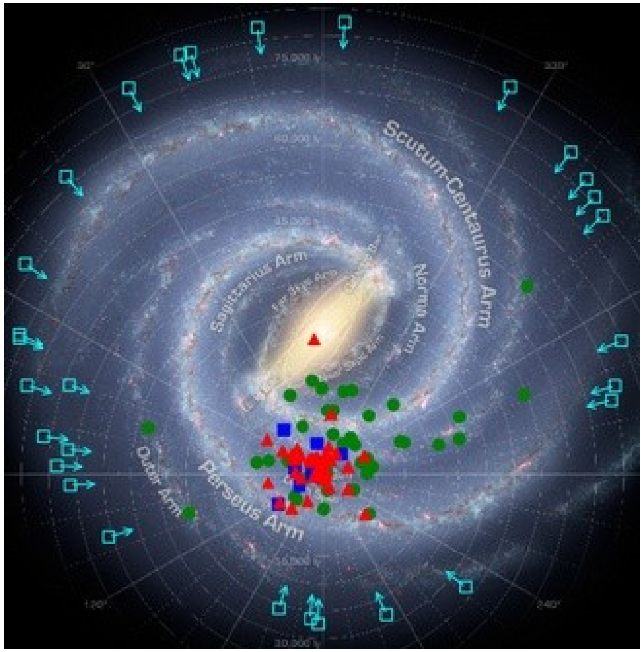
**Radio searches:**

- 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 unassociatd 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




[Abdo+ 2013, 2nd Fermi Pulsar catalog]

For a review see Grenier & Harding 15

# 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

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

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

**Spatial distribution**

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

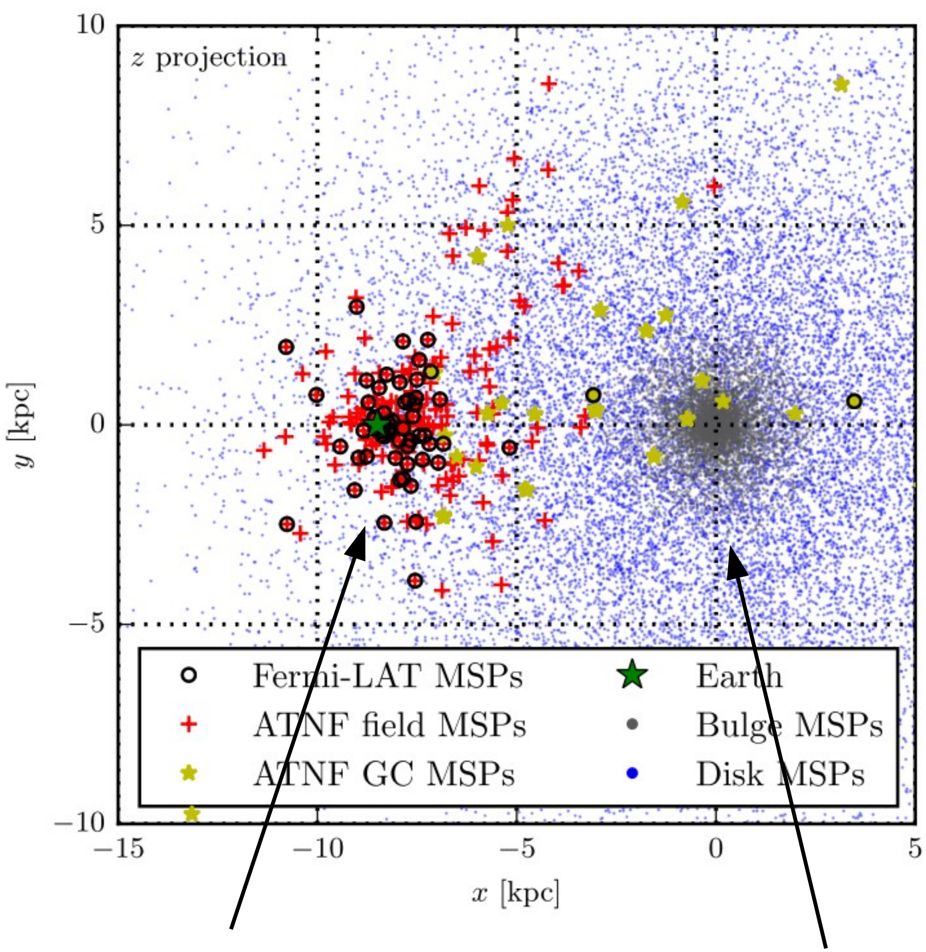
$$\frac{dS}{dV} \sim r^{-2.5}$$

**Calore, Di Mauro, Donato, Hessels, CW 2016**

# Modeling the radio properties 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

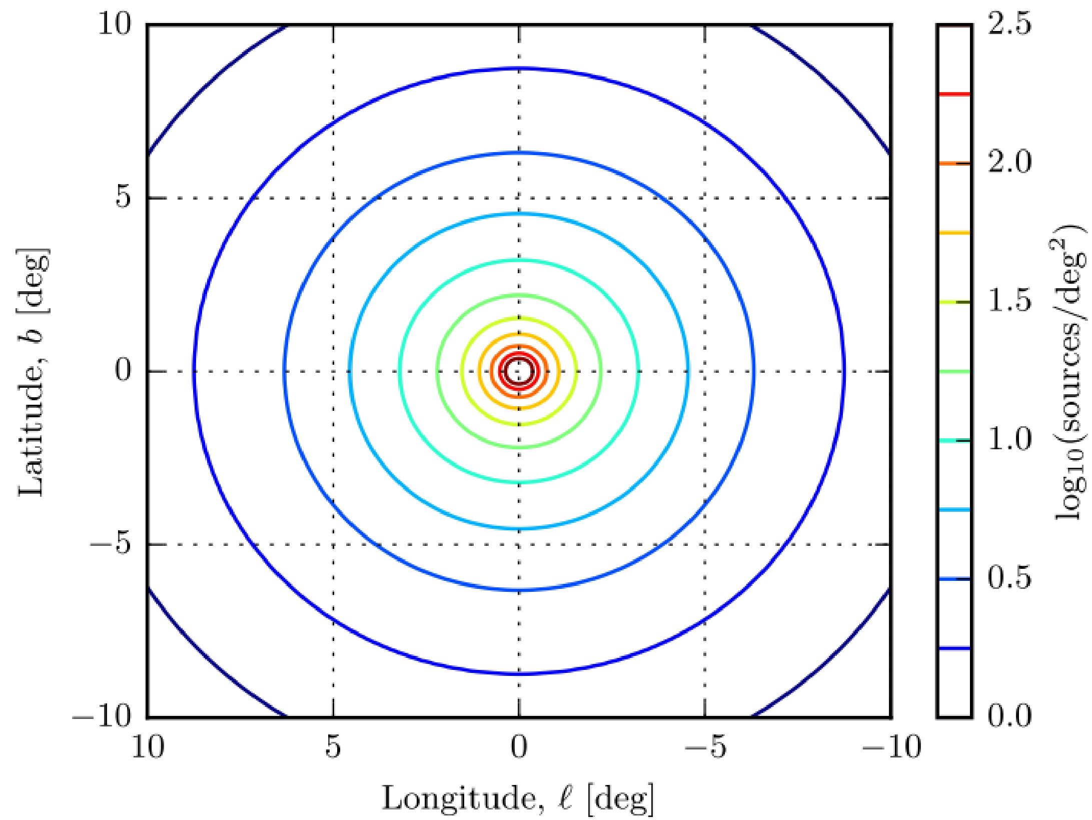



Earth

Bulge

### Surface density of radio-bright bulge MSPs

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



# Sensitivity calculations

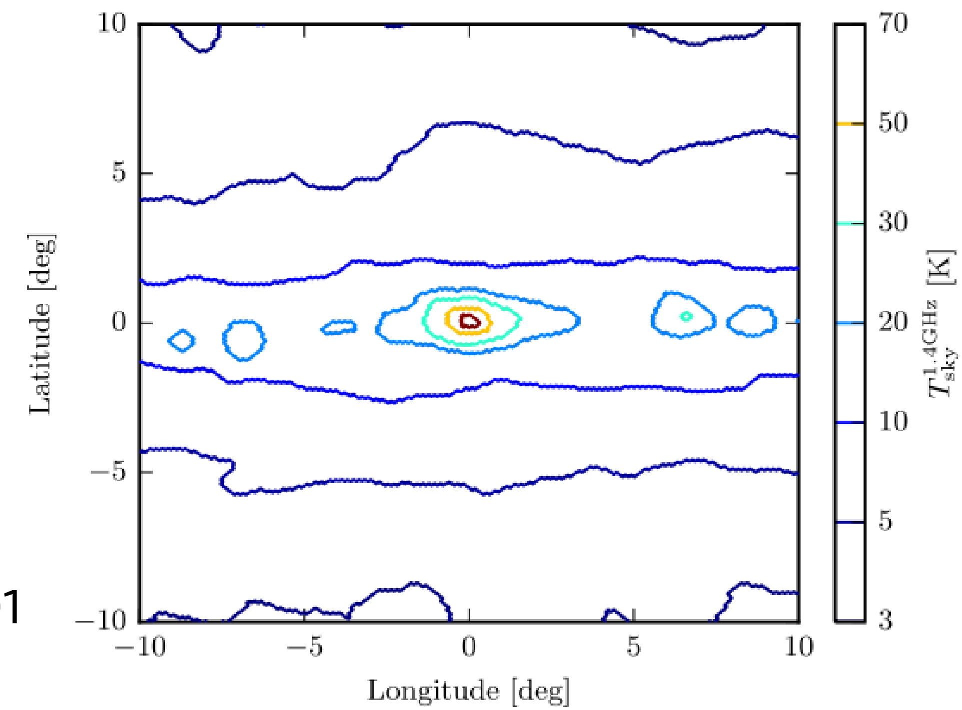
**Radio-meter equation for pulsar searches**

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

- We require 10 sigma signal for "detection"

**Observational challenges**

- Varying sky-temperature (~5-50 K @ 1.4GHz; extrapolated from Haslam 408 MHz map)
- Intrinsic pulse width (~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 ¾ of field MSPs are found in binary systems → Orbital motion has significant impact on blind searches



# Planned radio searches for bulge MSPs

**Radio detection prospects** (Calore+ '15)

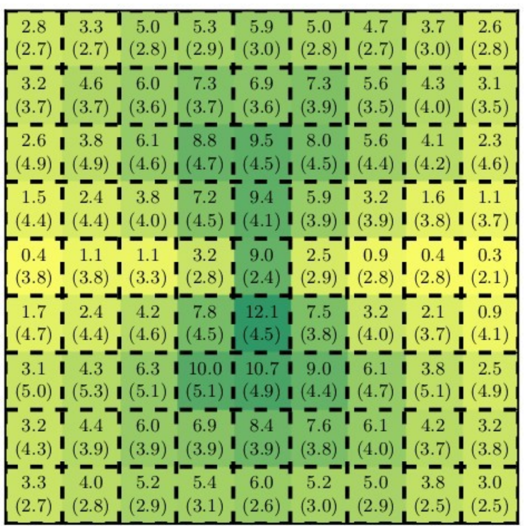
(Bulge population is just below sensitivity of Parkes HTRU mid-lat survey)

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

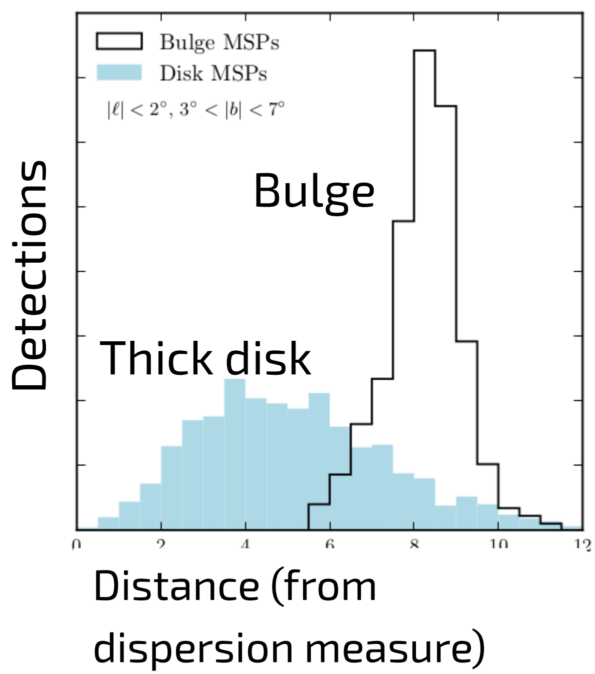
**Our plans for the near future**

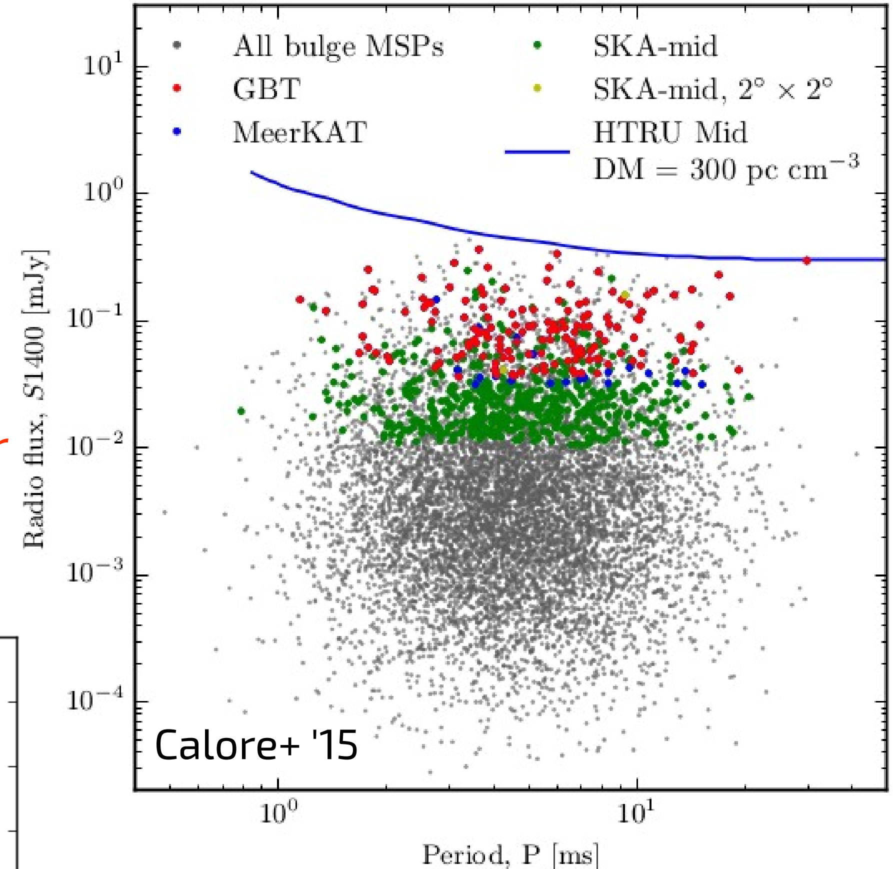
- We teamed up with MeerKAT TRAPUM → plans for dedicated survey in ~2019!

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




(SKA)



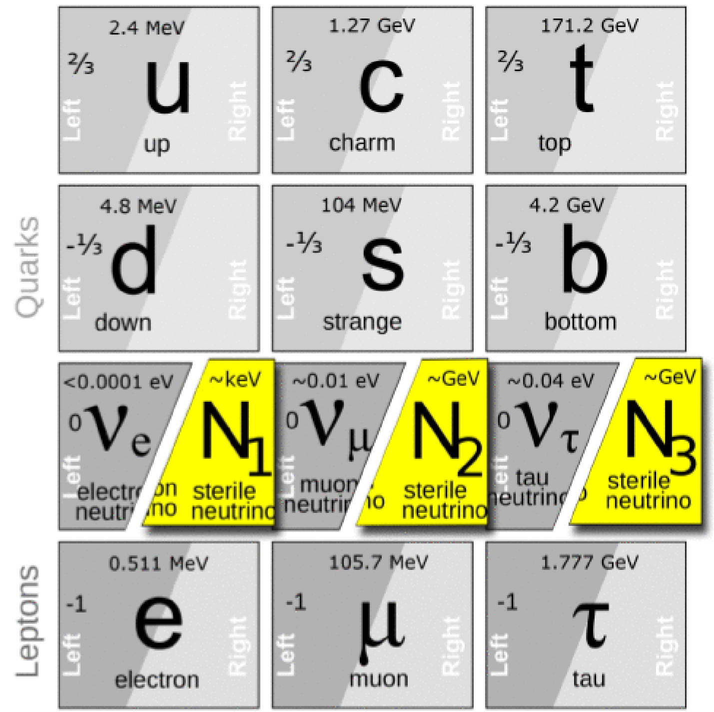



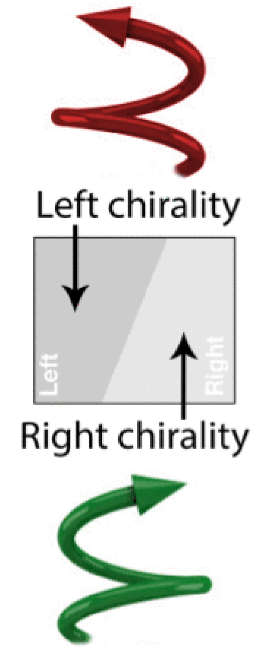

# Anomalies

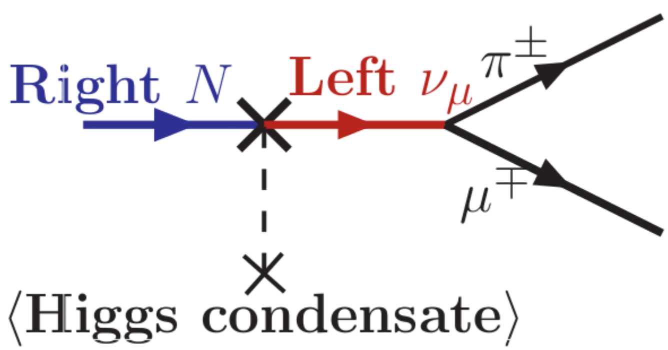
## X-ray line

# Sterile neutirnos

- Right-handed neutrino is **neutral** – no electromagnetic interactions
- Right-handed neutrino is a **lepton** – no strong interactions
- Weak interactions are different for left- and right-particles – right-handed neutrino is **sterile**

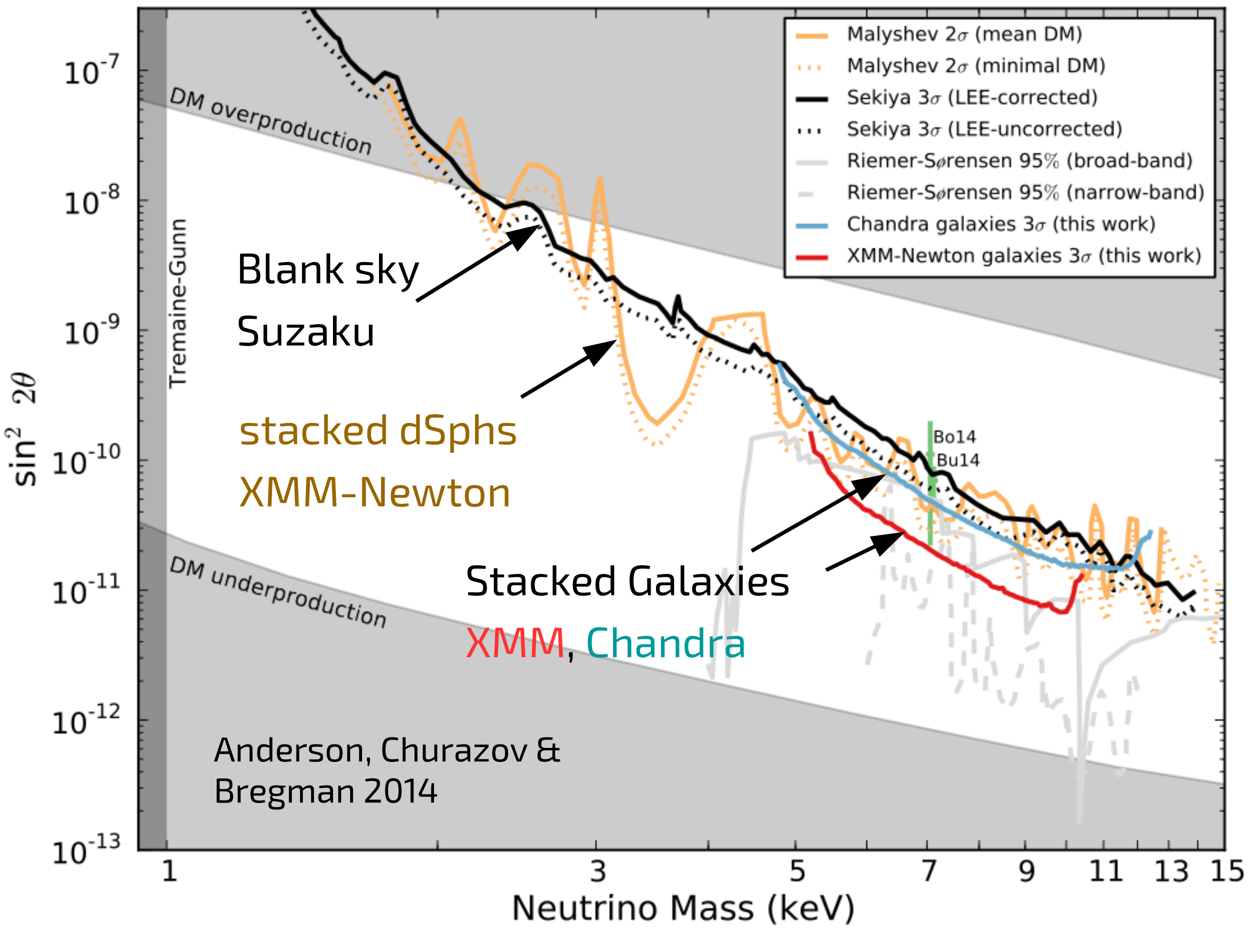


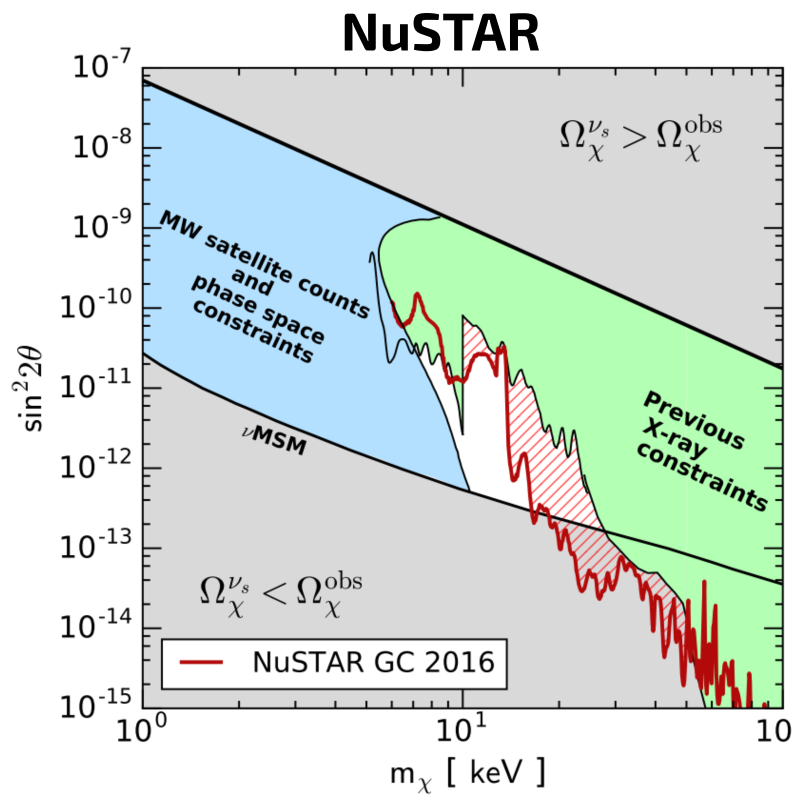




Slide credit: Oleg Ruchaisky

# Sterile neutrino Dark Matter

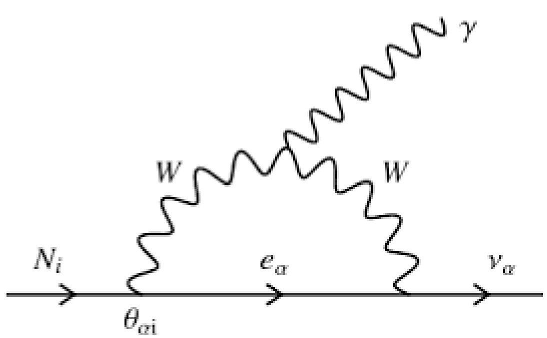



Perez+ 17 (PRD)

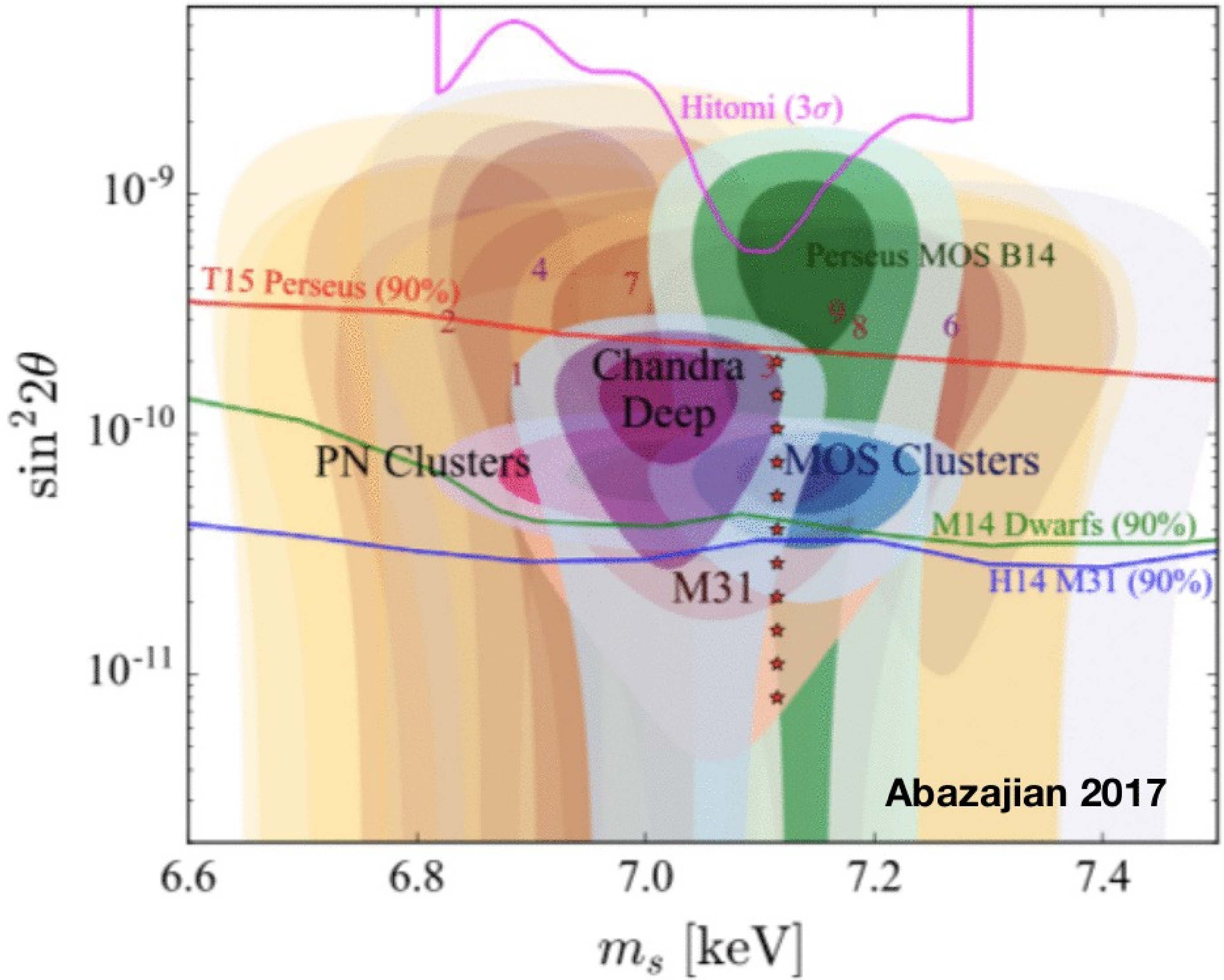
**Sterile neutrino dark matter**

- Upper limit from non-resonant production
- Lower limit from resonant production
- Left limit from phase space arguments (Tremaine & Gunn 1978; e.g. Hannestad 2006)
- Upper-right limits from X-ray line searches



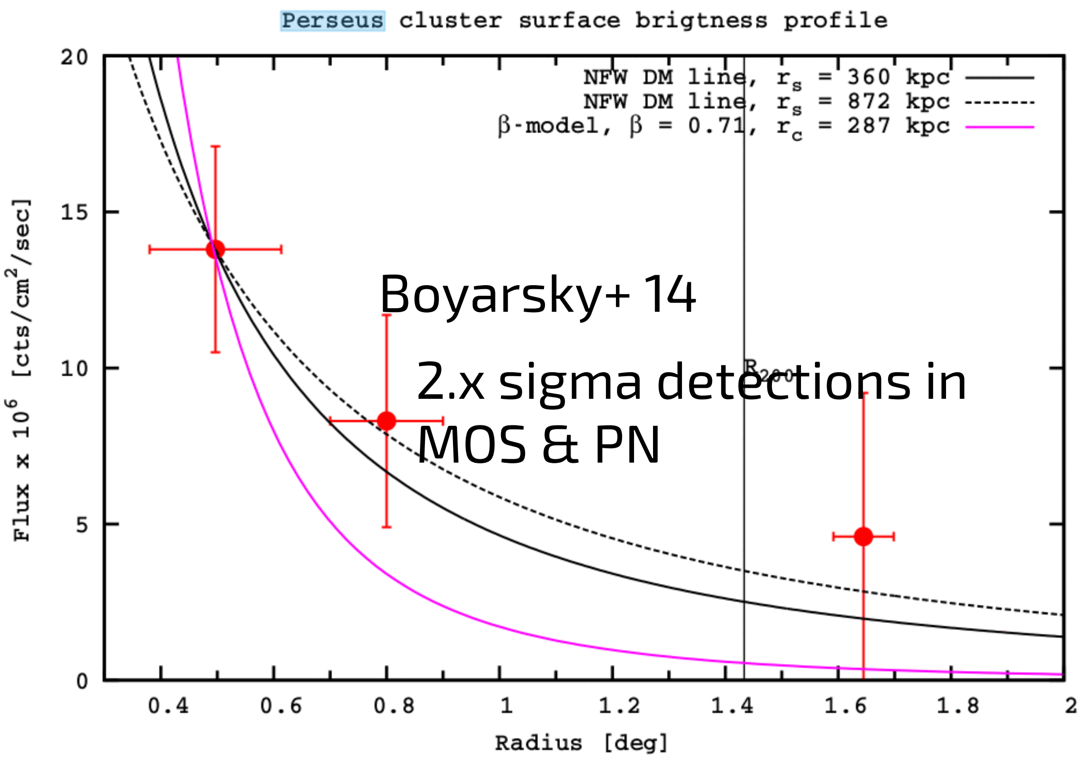
# The 3.5 keV line

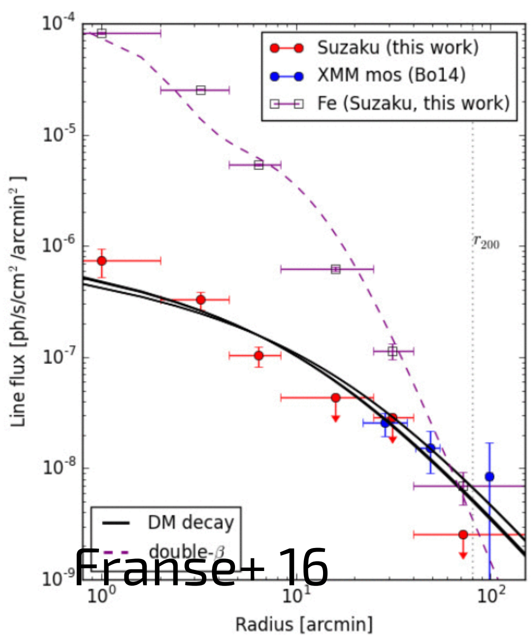
Compared to 130 GeV line, fluxes of 3.5 keV excesses look reasonably constistent with vanilla DM expectations.



**Overview**

- Nearby, z~0.0176, cool core cluster with AGN at center
- Observed by: Chandra (1.5 Ms on NGC1275), XMM-Newton (0.5/0.2 Ms), Suzaku
- Analyses: Boyarsky+ 14, Bulbul+ 14, Carlson+, Urban+, Franse+ 16, Tamura+



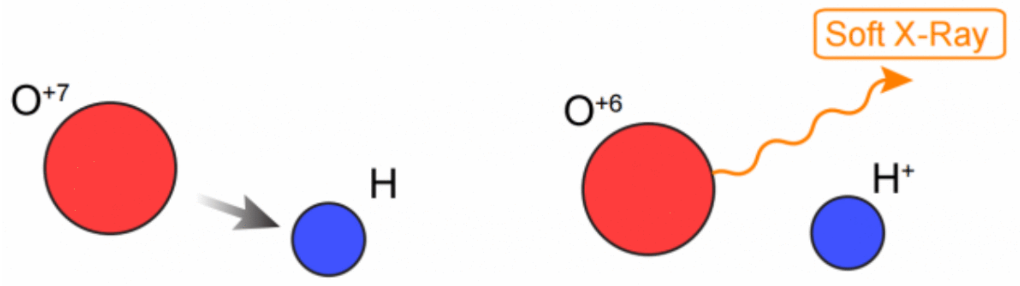




Bulbul+ 14:

| | | |
|---|---|---|
| Perseus center (XMM, MOS) | $\Delta\chi^2 = 12.8$ | $3.1\sigma$ for 2 d.o.f. |
| Perseus center (Chandra, ACIS-S) | $\Delta\chi^2 = 11.8$ | $3.0\sigma$ for 2 d.o.f. |
| Perseus center (Chandra, ACIS-I) | $\Delta\chi^2 = 6.2$ | $2.5\sigma$ for 1 d.o.f. |

# The possible role of charge exchange emission

**Charge exchange interaction**




**Relevant everywhere were ionized gas meets neutral medium**

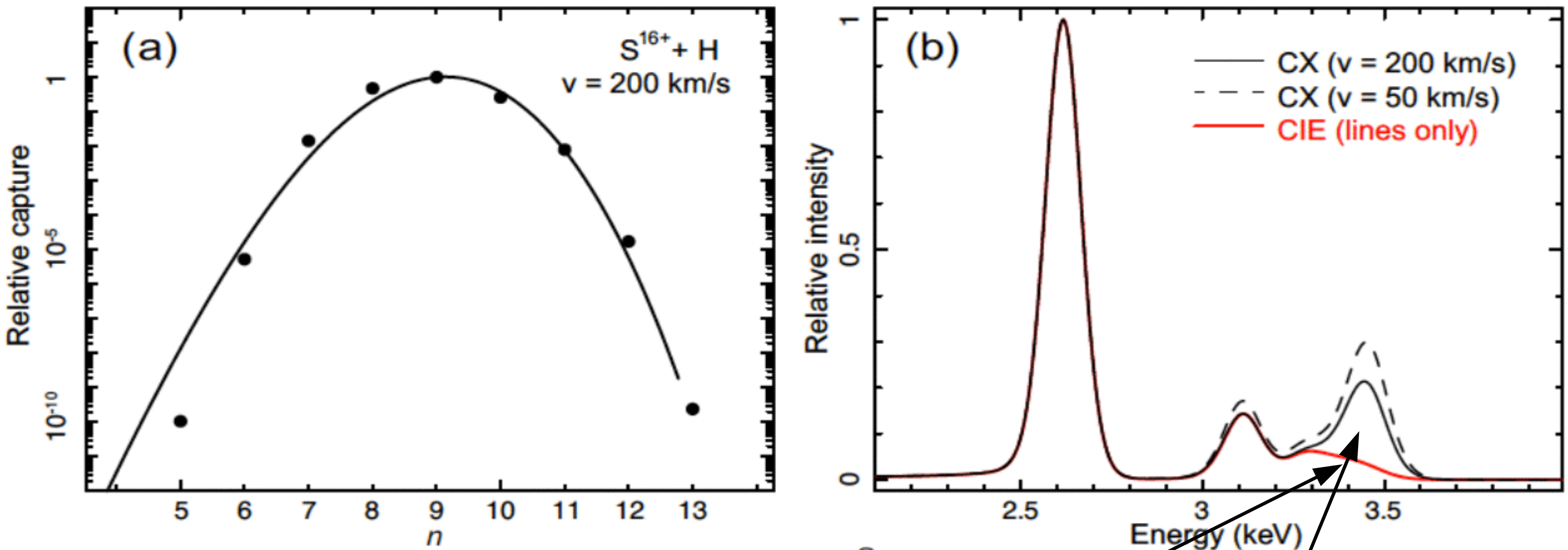
- Earth magnetosphere
- Anywhere in the heliosphere
- Effects apparent in uncleaned ROSAT data, proportional to solar activitiy
- Standard QM, line positions known, rates sometimes expensive to calculate

Image credit: Jelle Kaastra

# Fully ionized sulfur + Hydrogen

**Set-up**

- At v~200 km/s, most interactions end up in Rydberg level n=9.
- Produces line around **3.45 keV**
- Neutral gas penetrating ionized plasma can give rise to line emission



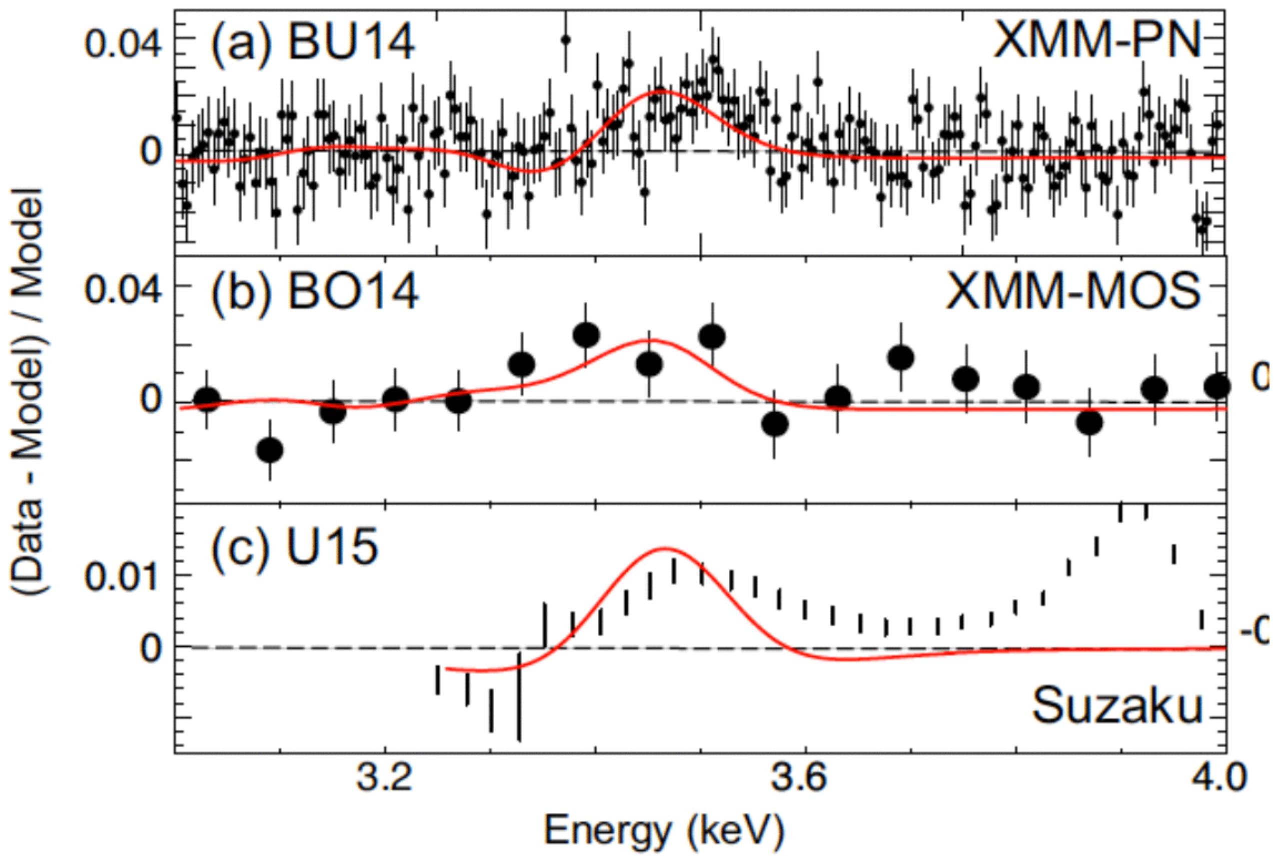

Collisional ionization equilibrium

Charge exchange spectrum

- Line enhancement w.r.t. CIE if high *n* are excited in collisions

Gu et al., 2015

# Could account for Perseus observations



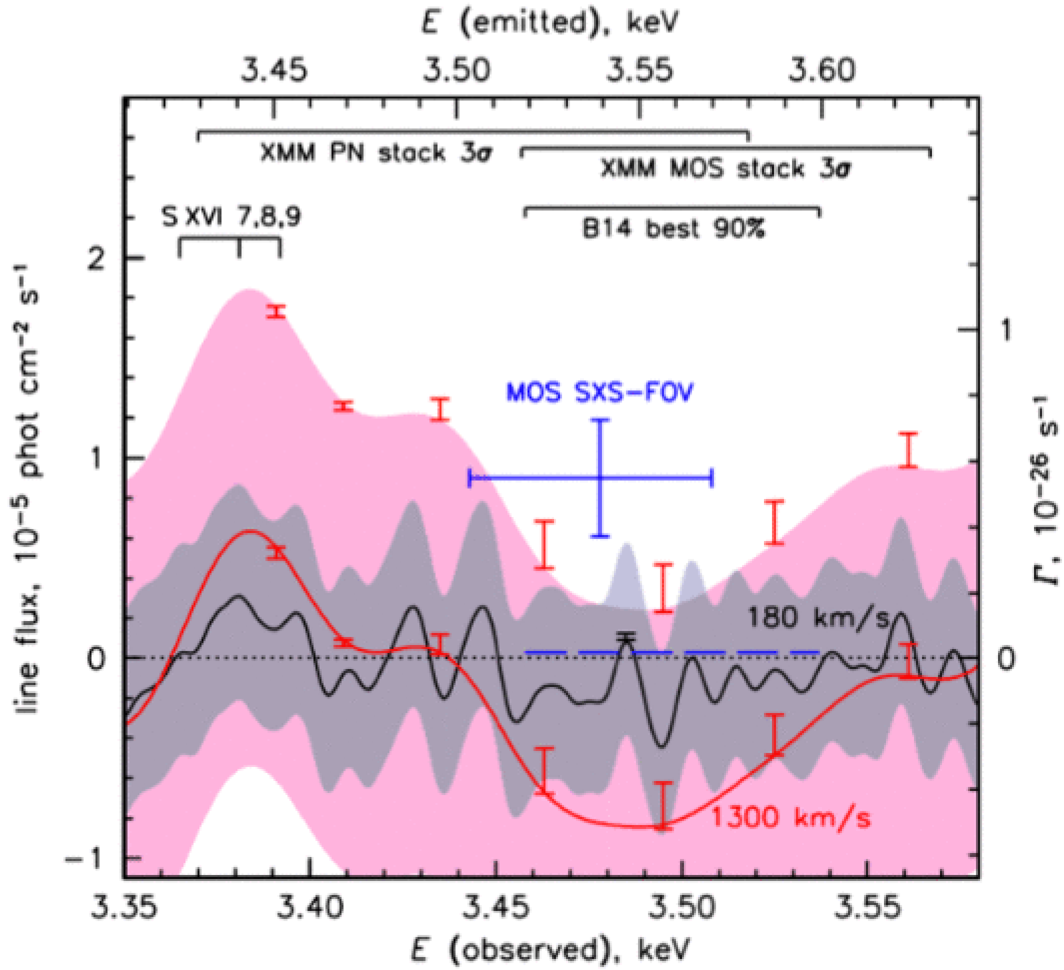

S XVI charge exchange line can account for part of the 3.5 keV, provided contributions from neutral and ionized material are sufficient.

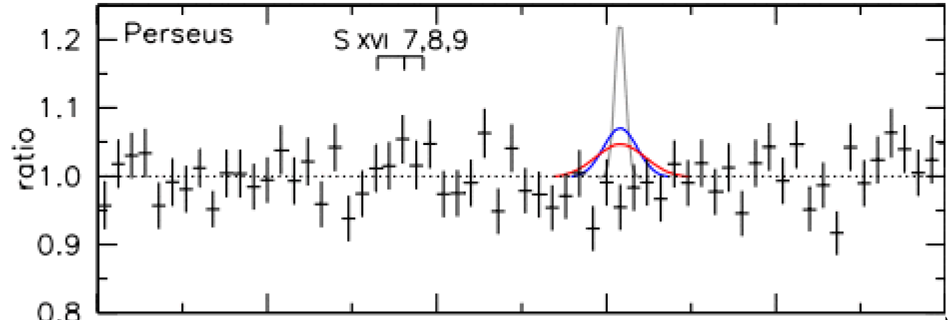
Gu et al., 2015

# Hitomi observations of Perseus

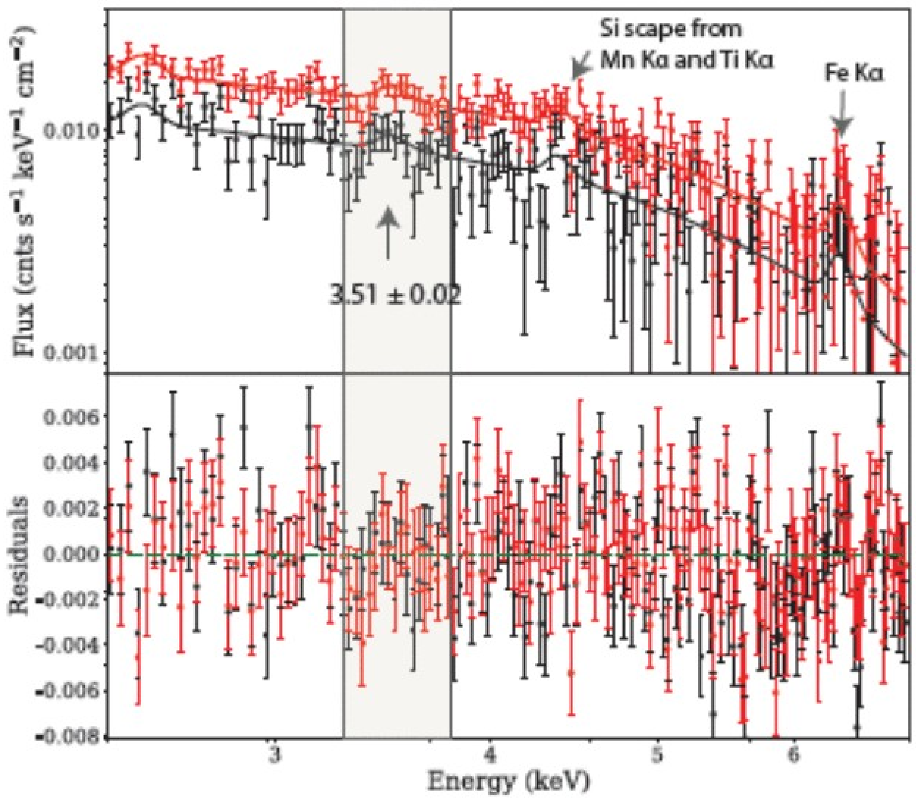
**Hitomi 2016 legacy**

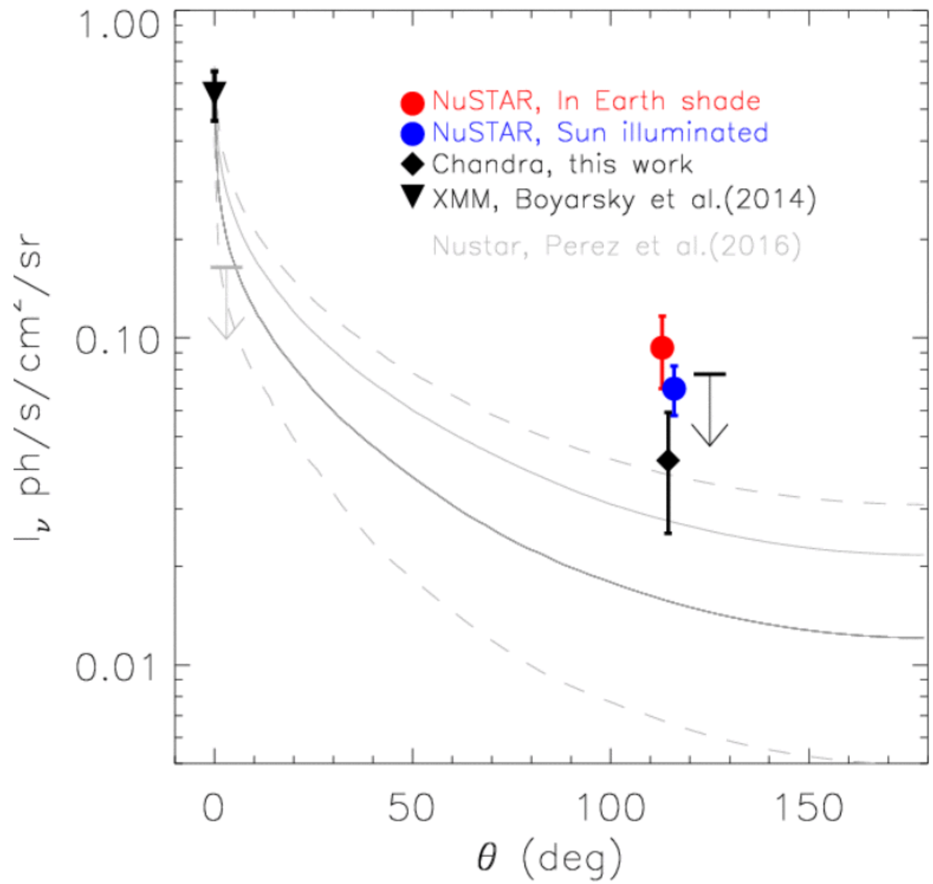
- First-light observations of Perseus cluster
- Bulbul "all cluster" signal not bright enough
- But XMM MOS observations of Perseus were brighter, could be excluded at >99% CL
- Hints for S XVI line complex – charge exchange?
- DM line would be Doppler broadened, harder to detect



# Chandra deep-field observations



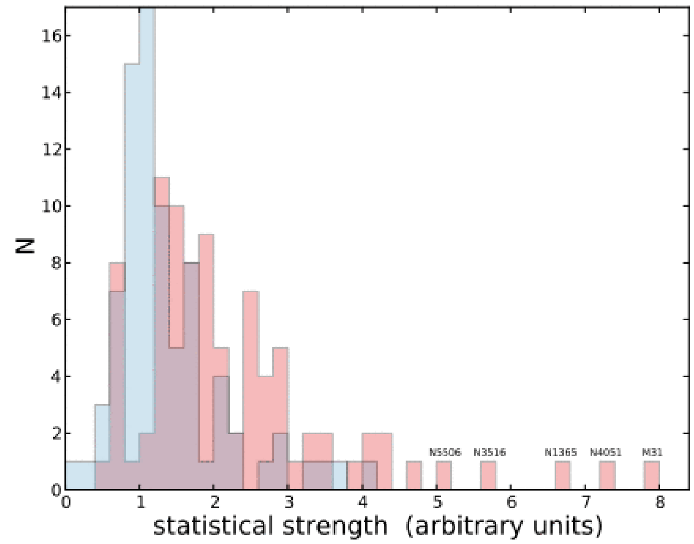

**Cappelluti+ 2017**

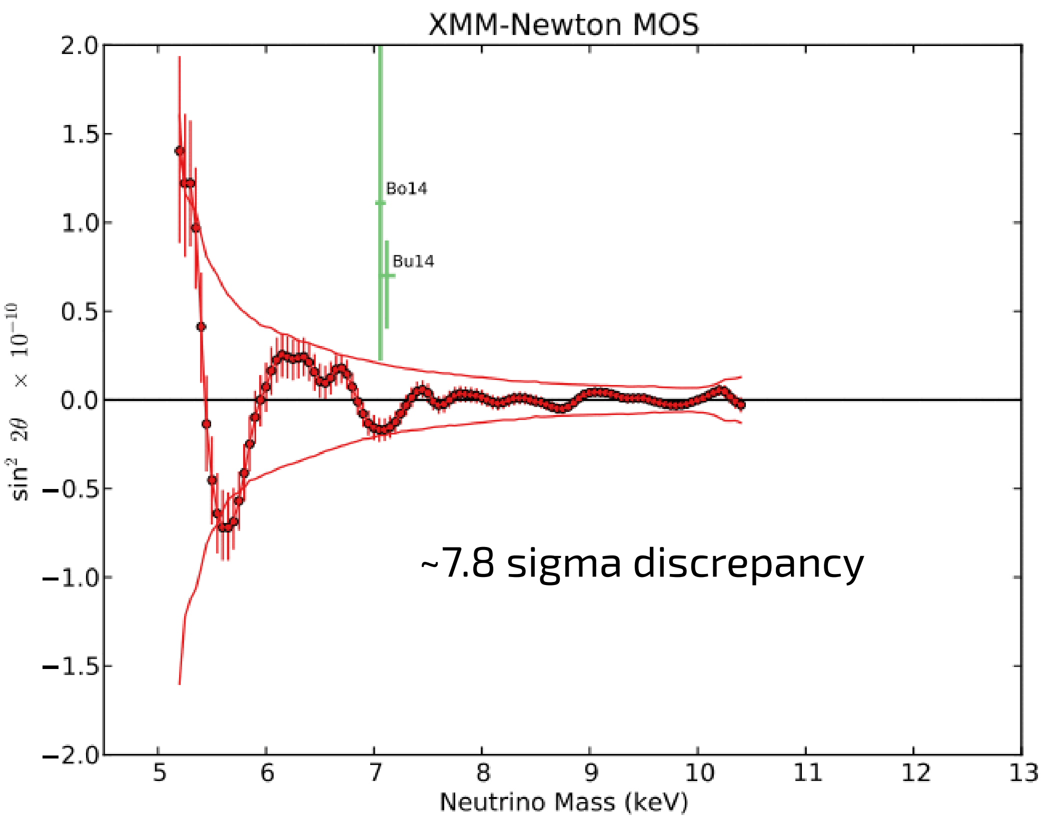
- Target ROIs are ~110 deg away from Galactic center
- Bayesian analysis reveals ~3 sigma detection
- 3.51 +- 0.02 keV, compatible with expectations from MW halo
- However, S/B is about 2%

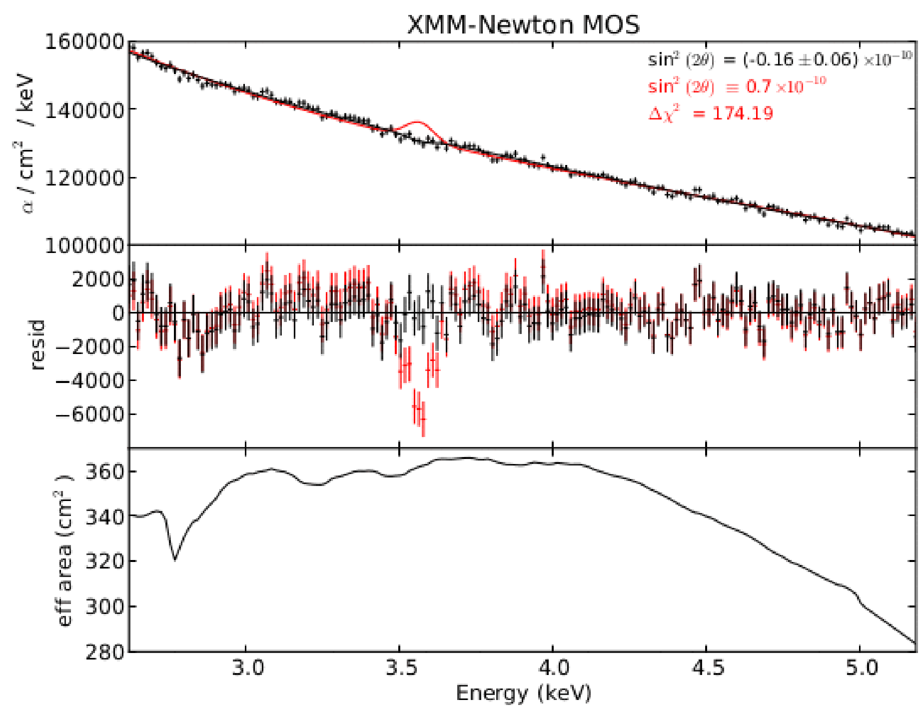
# Stacking analysis of nearby galaxies

**Anderson+ 14**

- 81 Chandra and 89 XMM-Newton galaxies
- Centers masked, reweighting technique for S/N per pixel
- Bkg modeling using splines, huge variations, but extending over somewhat larger energies than line
- Method could be confirmed with spline fit of “OFF region”
- Limits are often discarded because of unconventional background treatment. However, not clear what should be wrong.



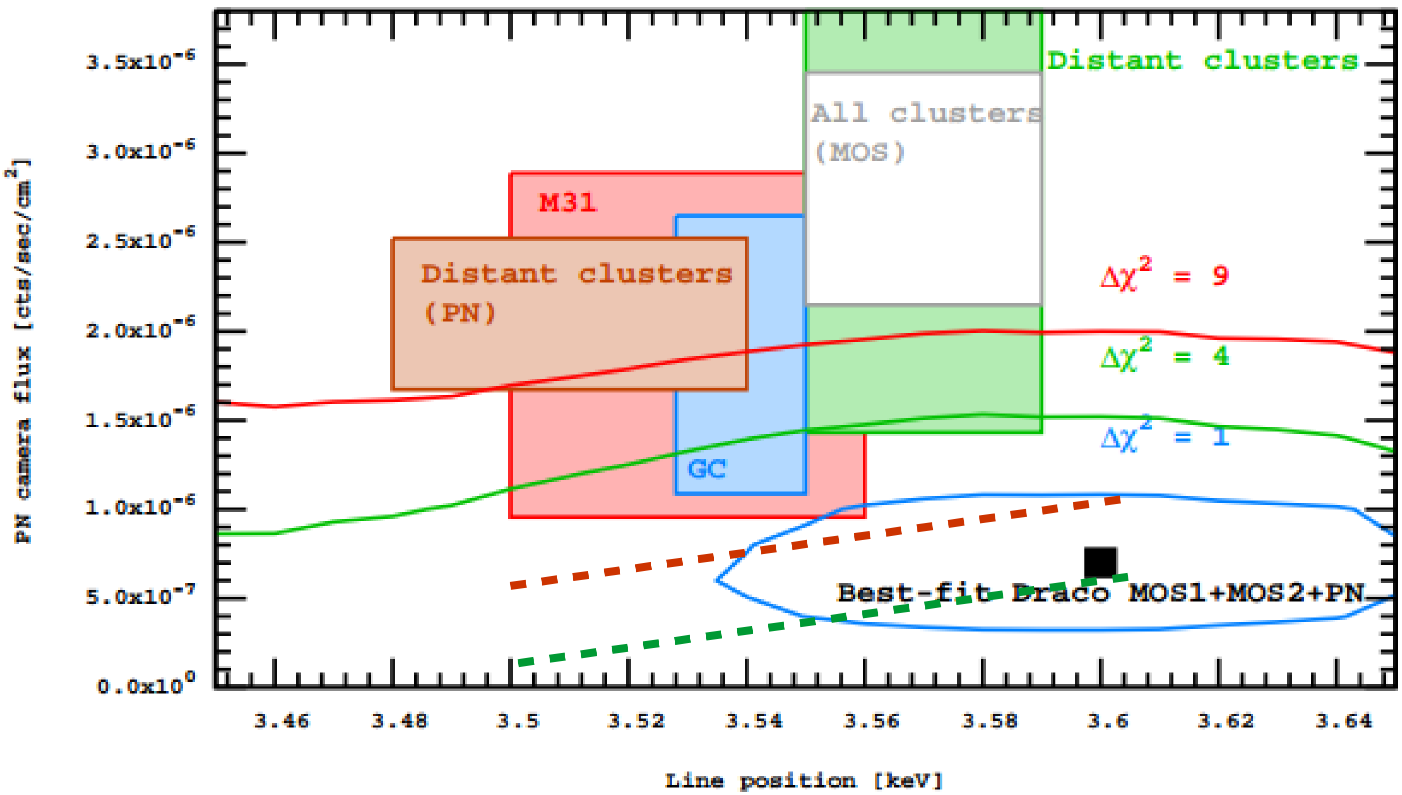



# Draco observations with XMM-Newton

**Draco campaign with XMM-Newton**

- 1.5 Ms observation time in 2015
- Jeltema & Profumo '15: Claim they can exclude Bulbul line @ 99% CL. But analysis technique is somewhat problematic (rather simple BG model, problematic statistics)
- Boyarsky+ '15: Weak hint for line from MOS, lower than expected
  → sterile neutrino interpretation disfavored

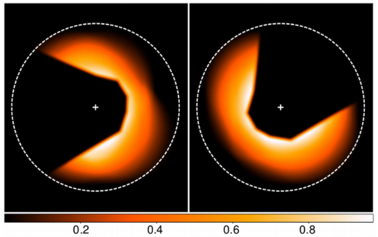


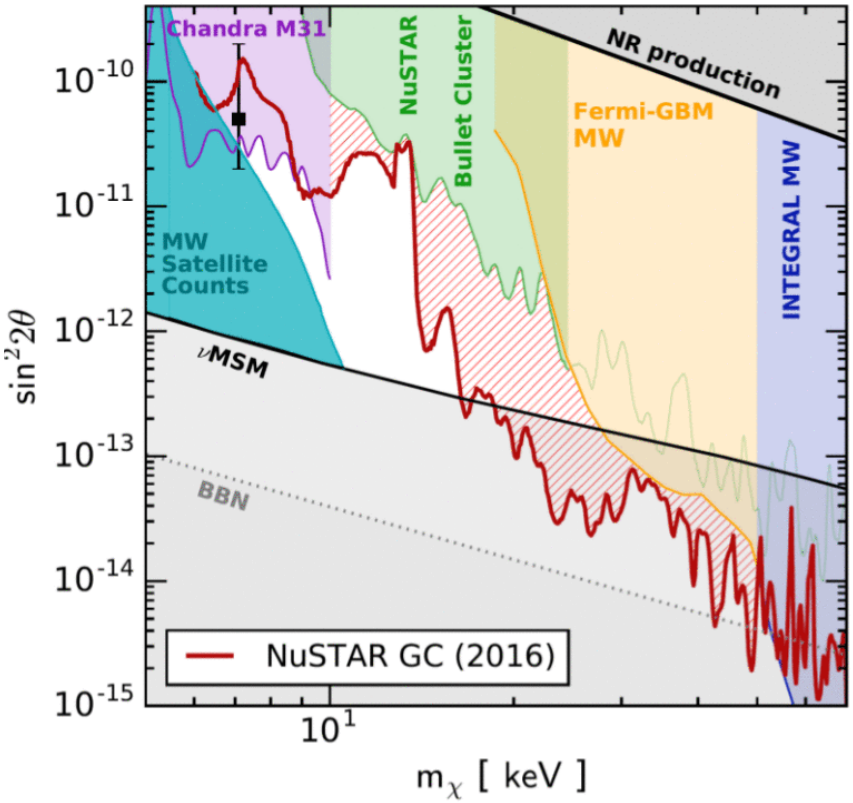
# Galactic center observations with NuSTAR

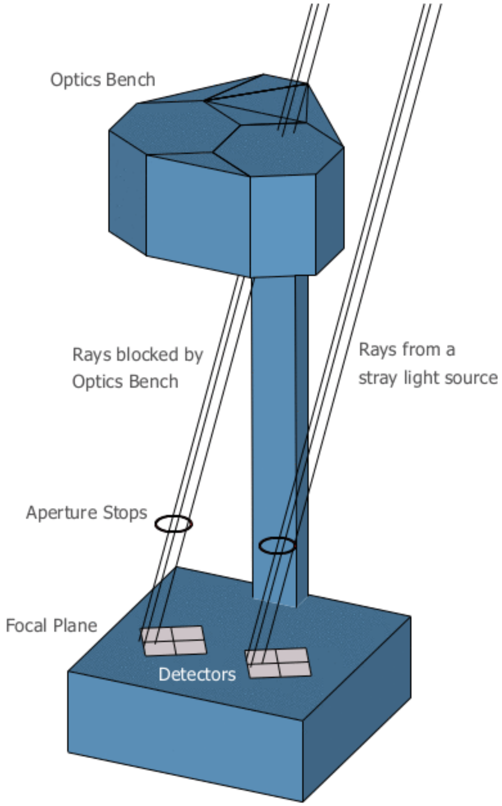
**Situation**

Perez et al., 2017

- Energy range of NuSTAR: 3-79 keV
- 6 GC observations (inner few deg), ~0.5 Ms combining both detectors



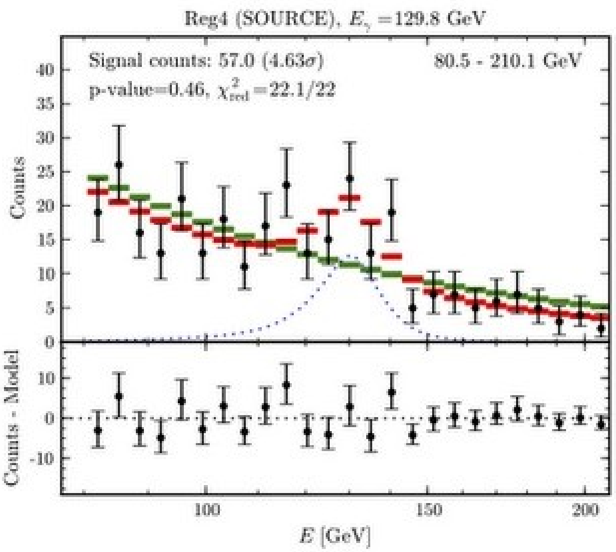




But: Highly significant *unidentified* 3.51 keV line is part of background model

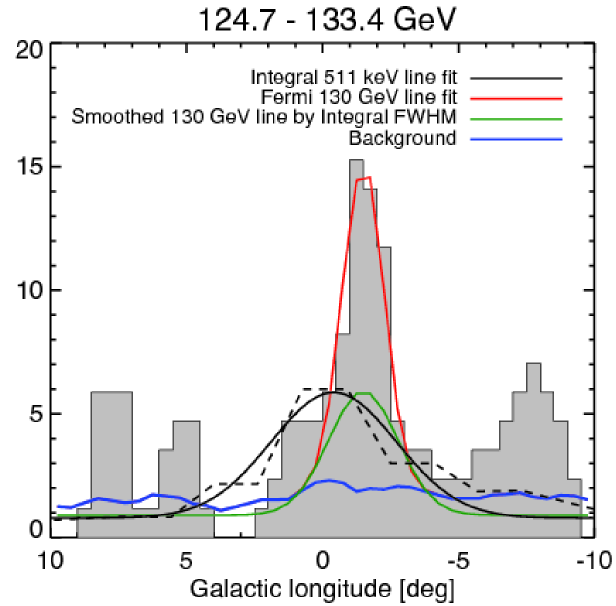
→ Will be investigated futher by instrument team

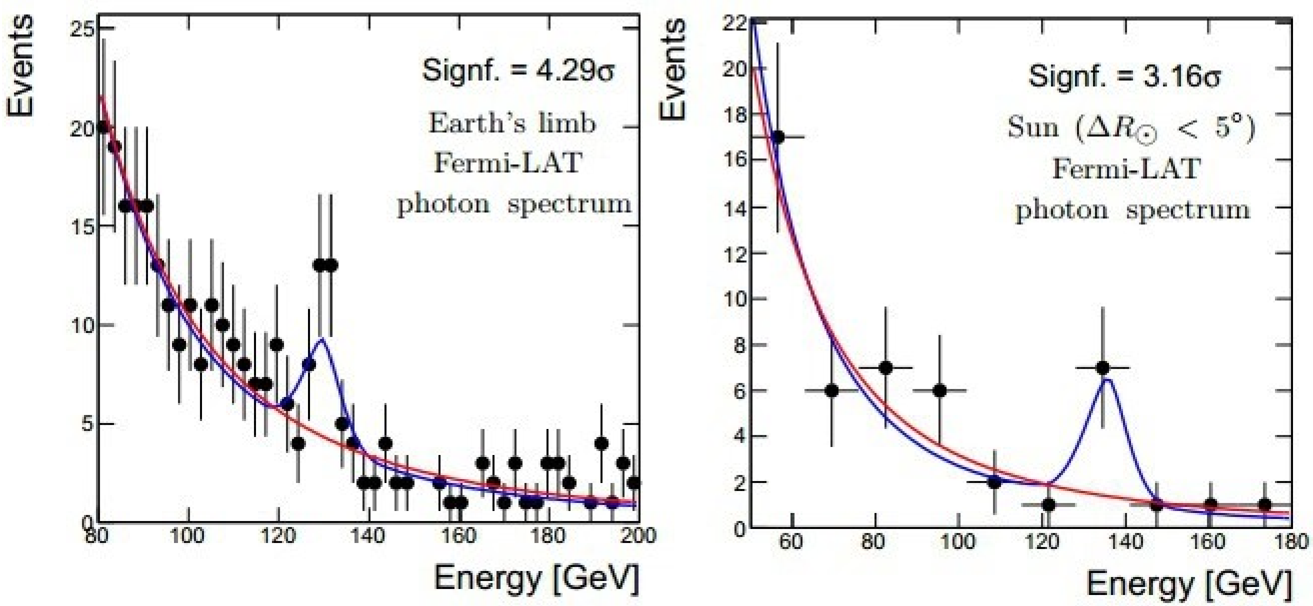
# Not the first of its kind: 511 keV, 130 GeV, 1.4 TeV

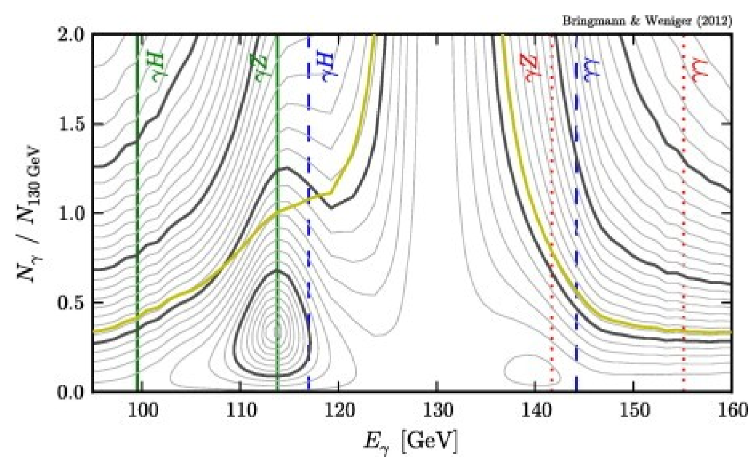



**130 GeV line in**

- GC & inner galaxy
- Stacked gal. Clusters
- Unassociated Fermi sources
- The Sun (5 deg radius)
- Earth limb (control region)
- Always ~3-5 sigma
- Disappeared with more data




Even two lines!

→ Line could not be reproduced with more data after ~2013. Statistical fluke (+instr. ?)

In comparison, 3.5 keV line aged quite well. Situation remains unclear.

# Ways forward

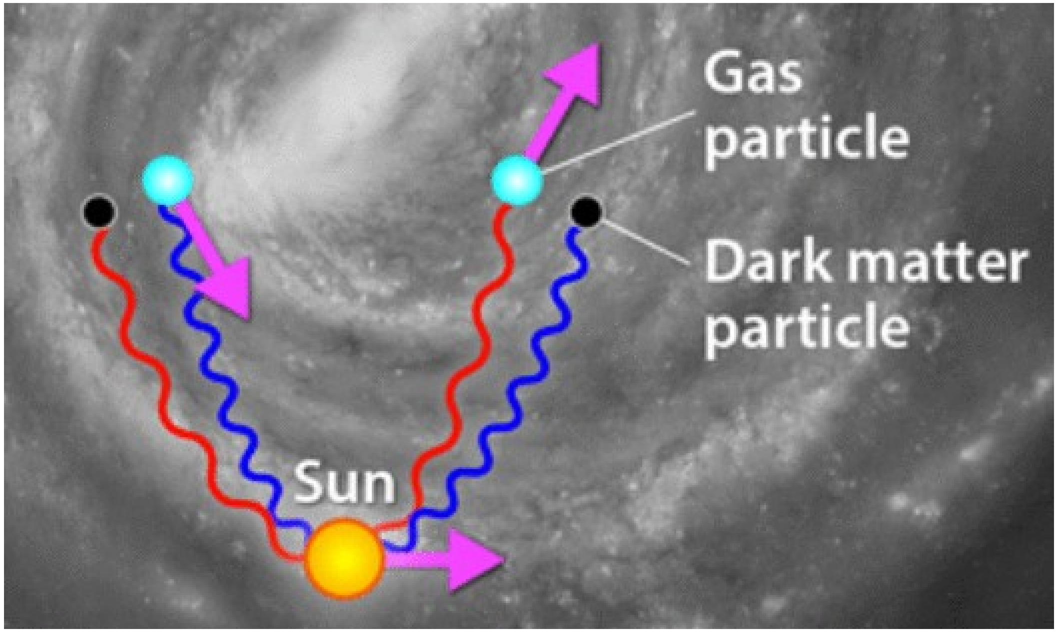
**Plans for the upcoming years**

- Micro-X – Sounding rocket with micro-calorimeter, 2019?
- XARM (Hitomi-II), 2021?
- Athena, 2029?
- E-ROSITA, full-sky coverage (half Russian, half German)
- Archived: Mapping DM with MW halo Chandra data
- Archived: Reanalysis of stacked galaxies?

# Velocity spectroscopy

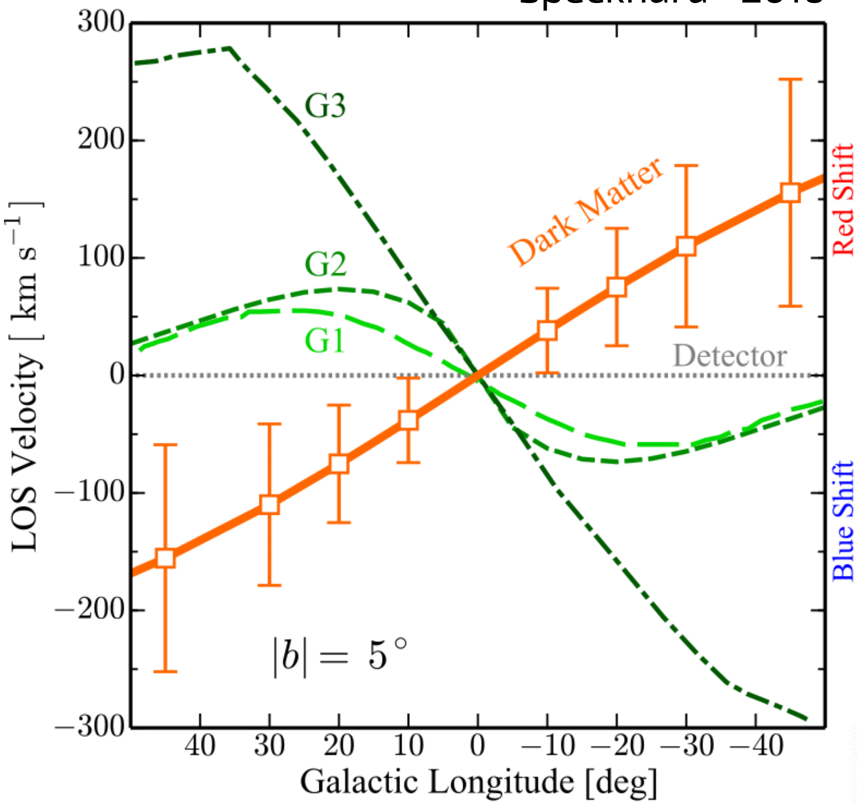
**Future missios with micro calorimeter (Micro-X, XARM)**

- 1e-3 resolution → Typical MW velocities (~100 km/s) become important
- Gas emission redshifted in +lon
- DM emission blue shifted in +lon
- 2 Ms Hitomi/XARM observation → 5 sigma detection



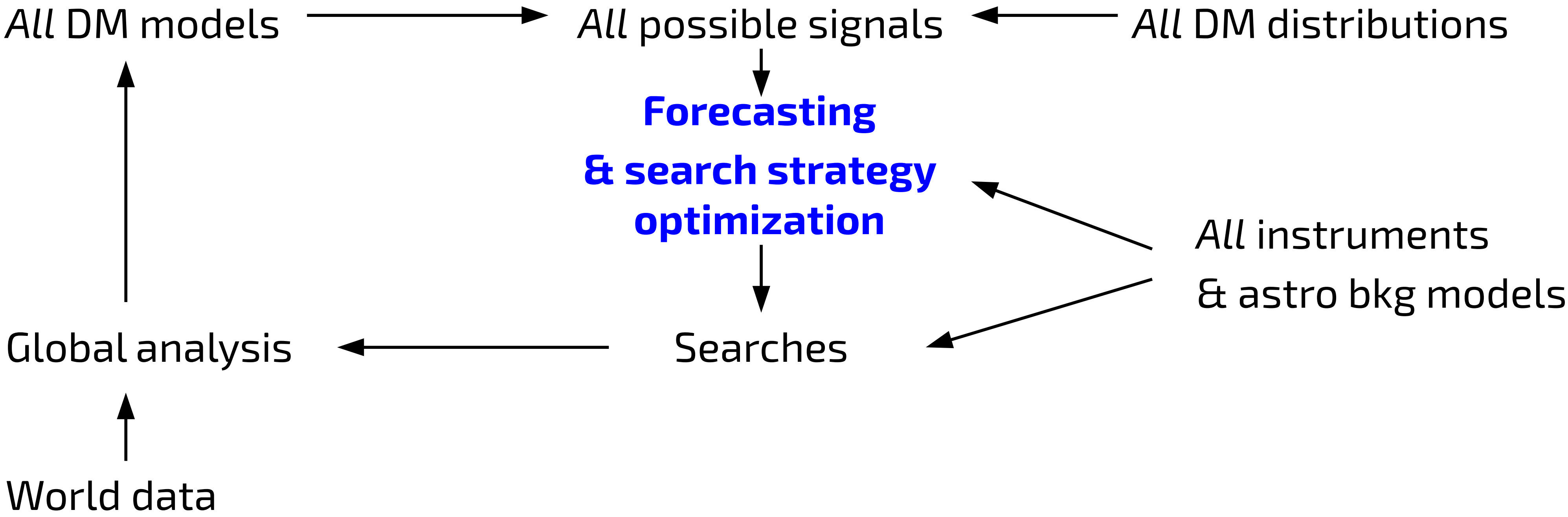

Credit: Kenny Ng

Speckhard+ 2016



# Information flux

# The forecasting bottle beck




**Problem**:

- How to identify minimum set of necessary searches to cover *all* possible DM models?
- How to make forecasting easy and informative?

**Solution**:

- Fisher forecasting on the rocks

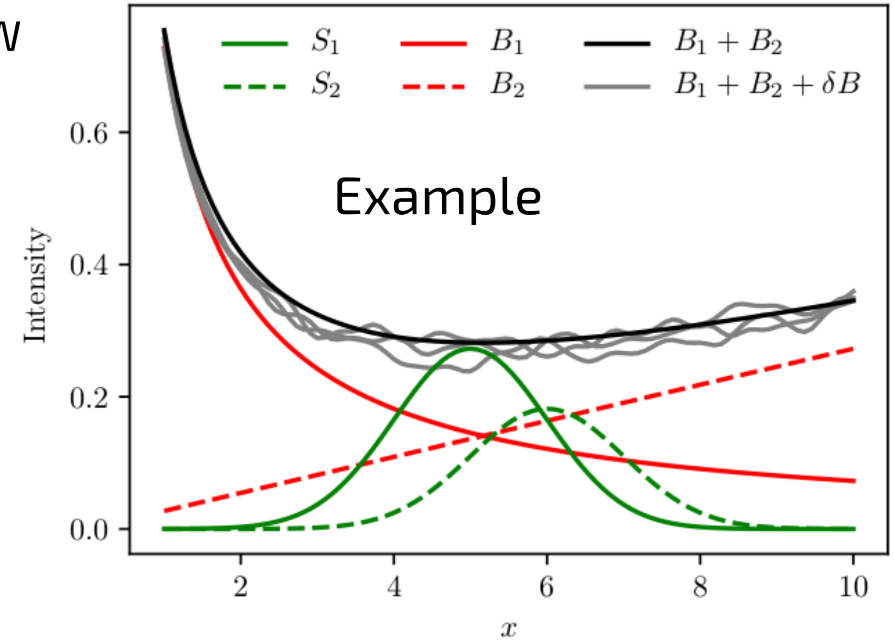
# S/N + systematics = Information flux

**Poisson model with background uncertainties**

(uncertainties described by Gaussian random field)

Edwards & CW 1704.05458

$$\mu_i(\boldsymbol{\theta}) = (S_i(\boldsymbol{\theta}) + B_i + \delta B_i) \cdot E_i$$




**Fisher information**

(accounts for background uncertainties)

$$\mathcal{I} \sim \frac{1}{\sigma^2}$$

**Information flux**

(derivative w.r.t. exposure per bin)

$$\mathcal{F}_i \equiv \frac{\partial \mathcal{I}}{\partial E_i}$$

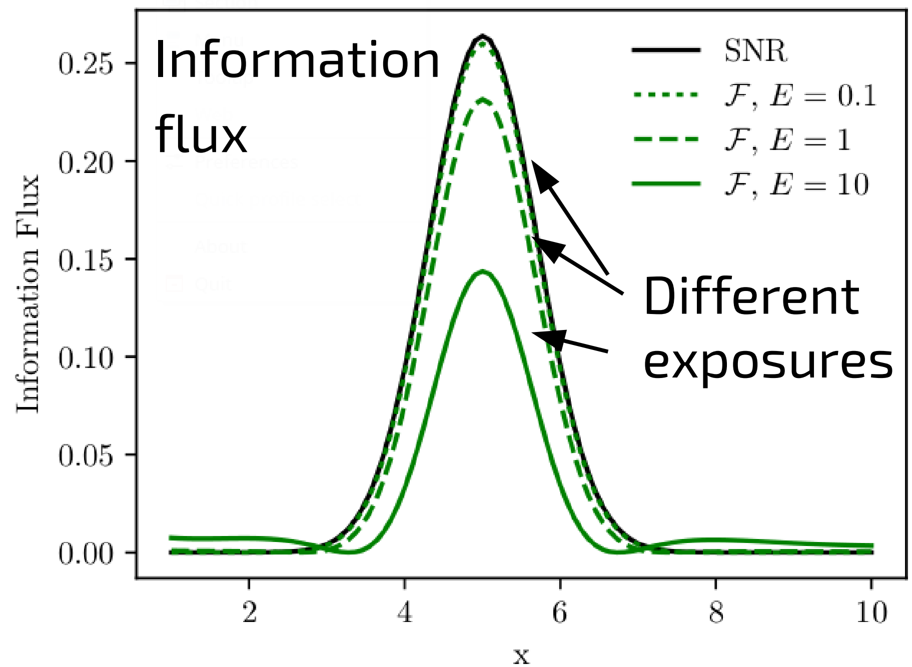
Stats. only

$$\mathcal{F}_i = \frac{S_i^2}{B_i}$$

(common **signal-to-noise** ratio)

In general

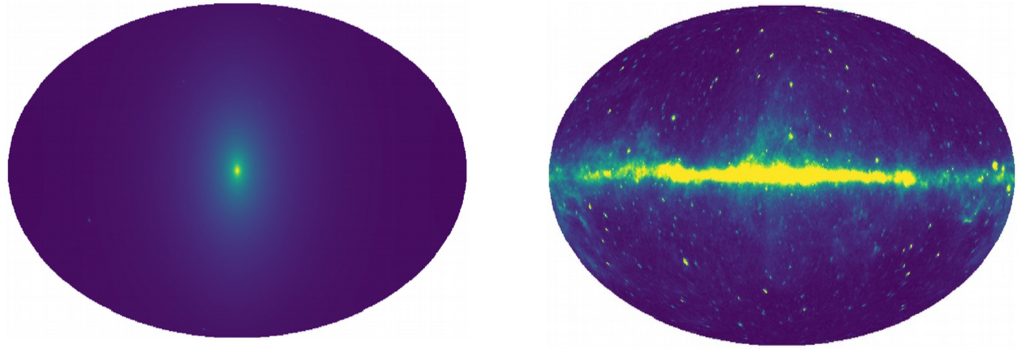
$$\mathcal{F}_i = \mathcal{F}_i(\mathbf{S}, \mathbf{B}, K)$$



# Dark information flux – DM annihilation

A toy example: Galactic halo vs nearby galaxies

**DM signal** **Background**



Galactic halo dominates

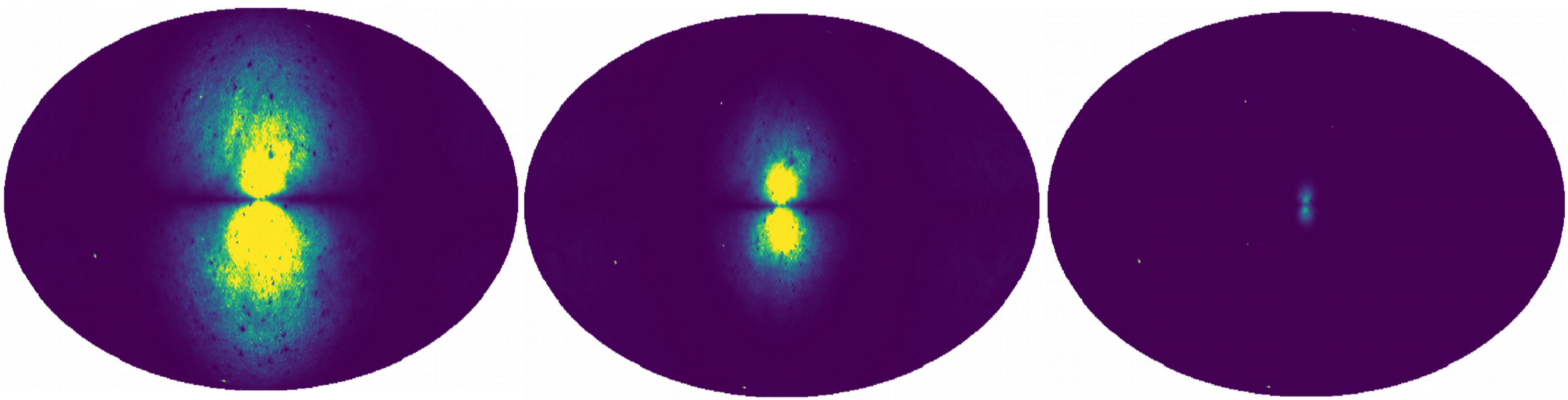
Here: 10% with ~10 deg correlation length

**Can be used to calculate**

- projected upper limits
- discovery thresholds
- reconstruction contours
- in the Poissonian regime
- no Monte Carlos

M31 as relevant as GC

Statistics only | 1/100 x Fermi LAT exposure | Fermi LAT exposure

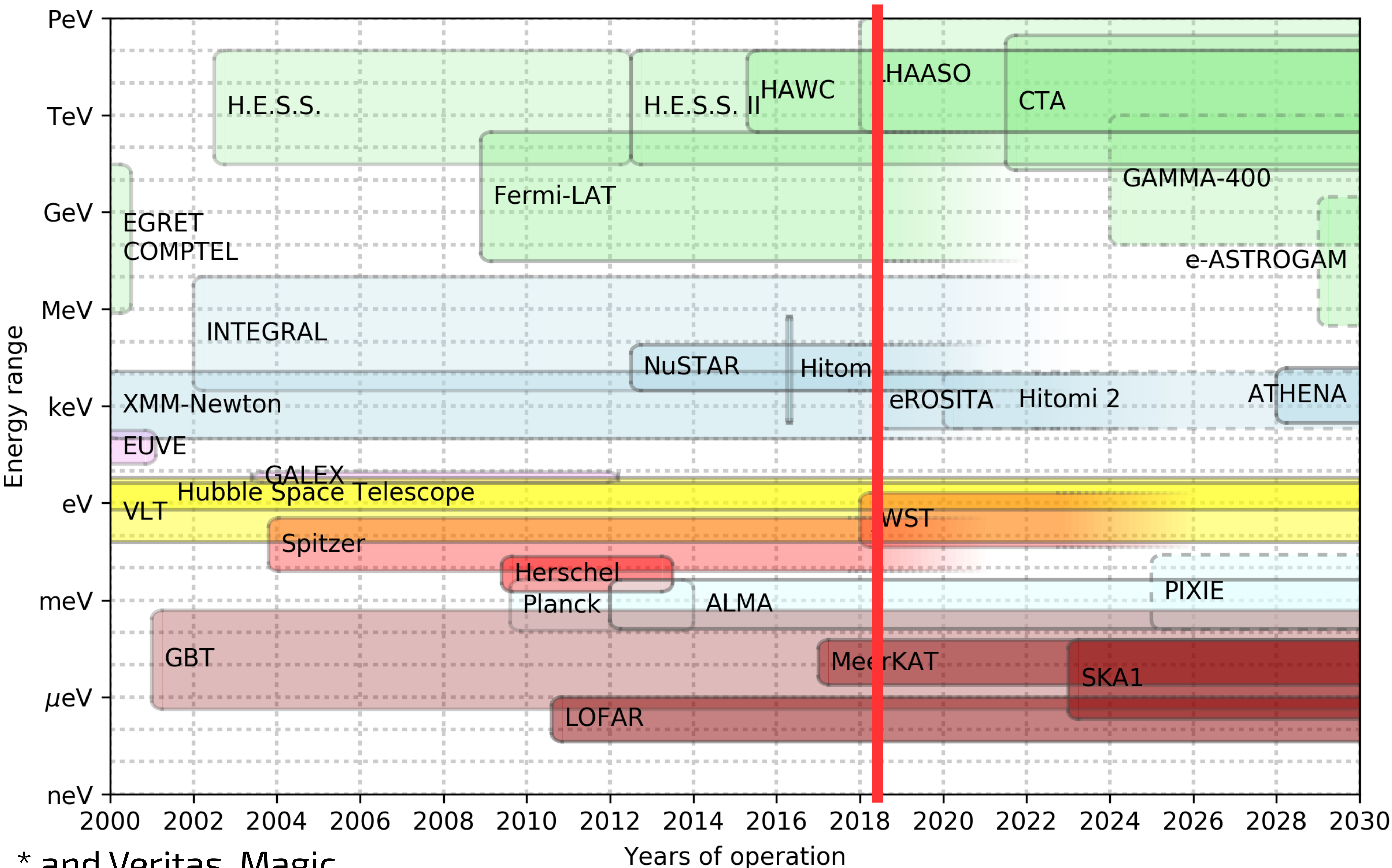


Edwards & Weniger, 1712.05401

http://www.github.com/cweniger/swordfish

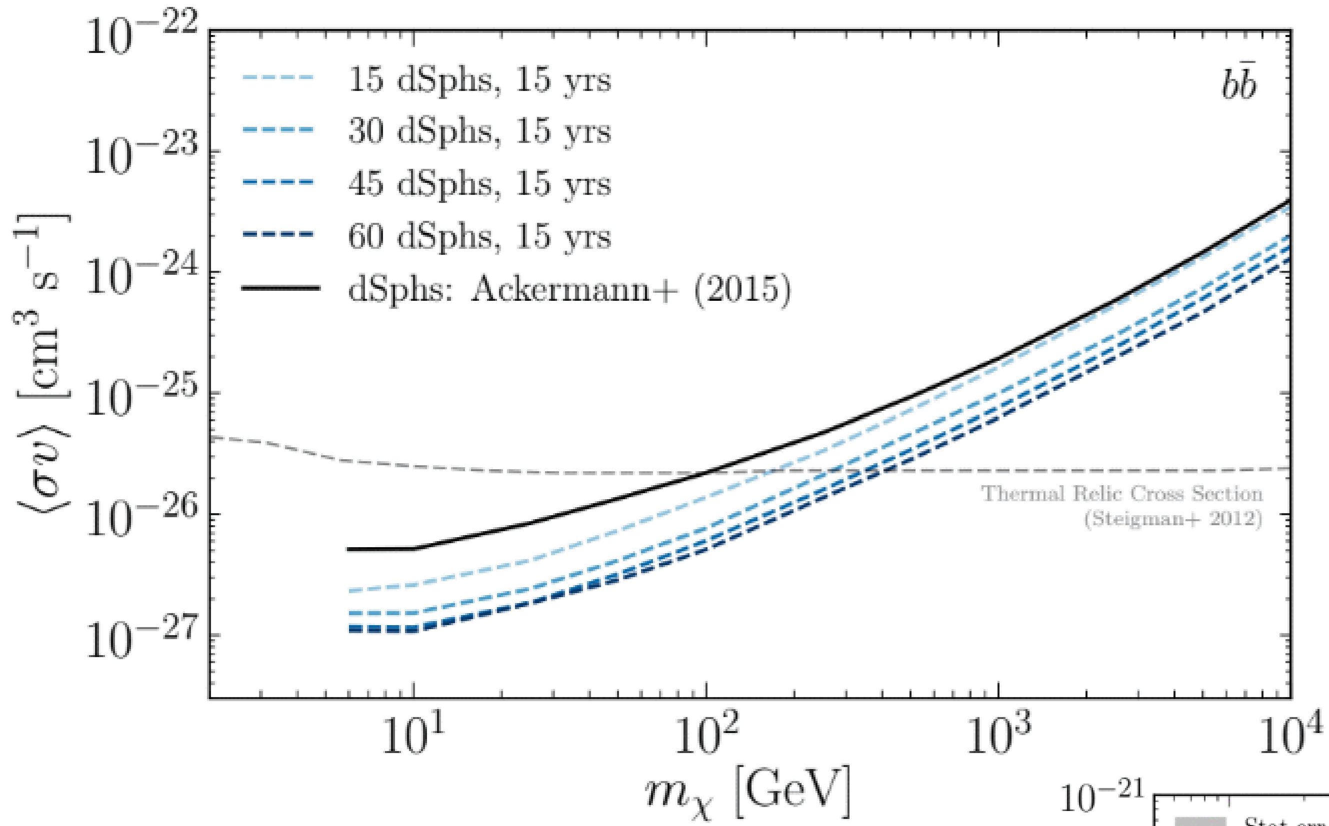
# Outlook

# Instrumental panorama – Photons*

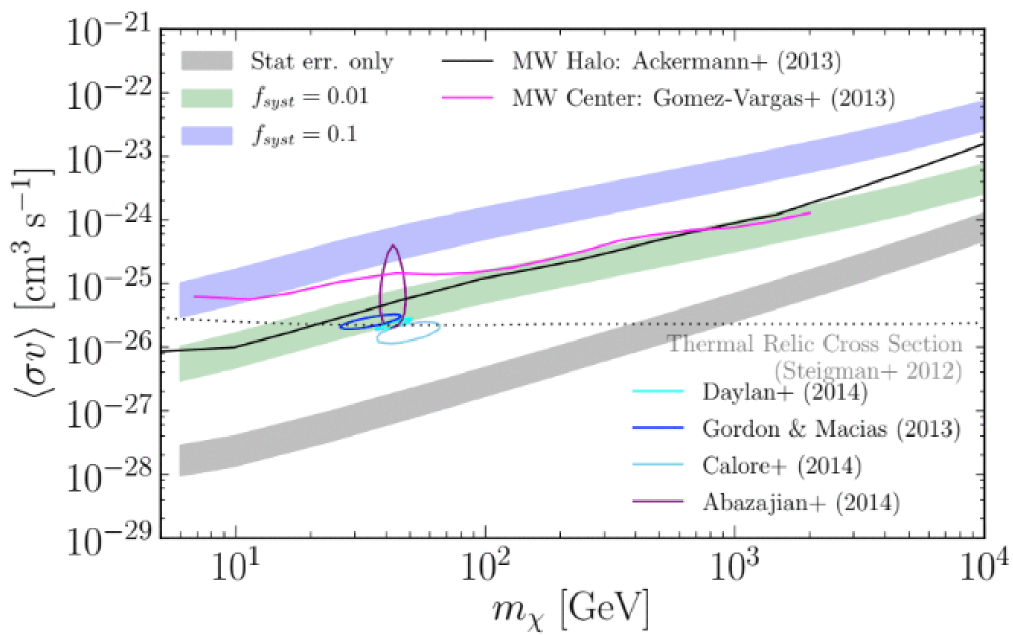



* and Veritas, Magic, …

# Future for WIMPs



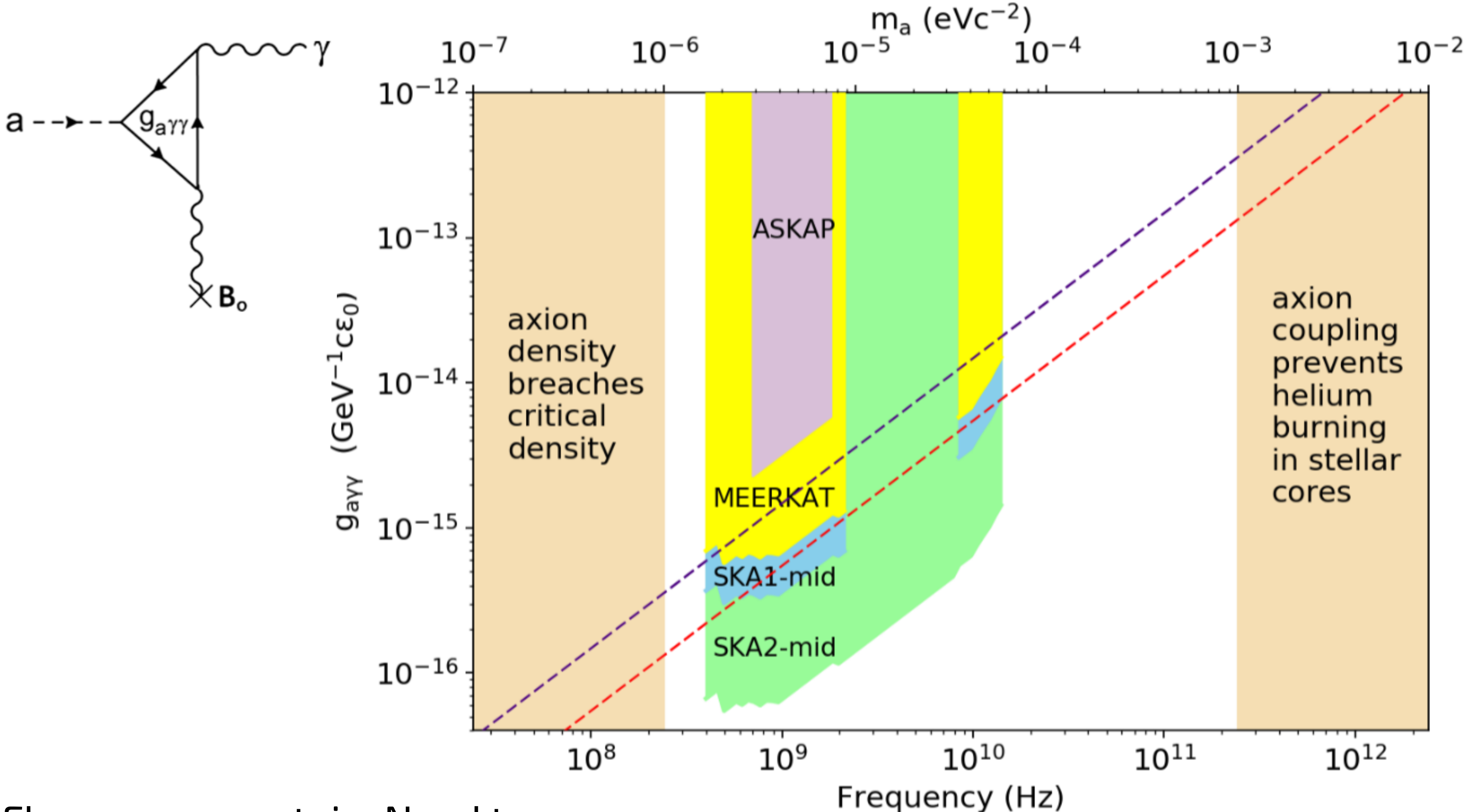

Charles+ 2016




**Future Fermi LAT**

- Dwarf limits strengthen by x5 ?
- MW halo has huge potential, but hard to access

# Radio searches for axion DM

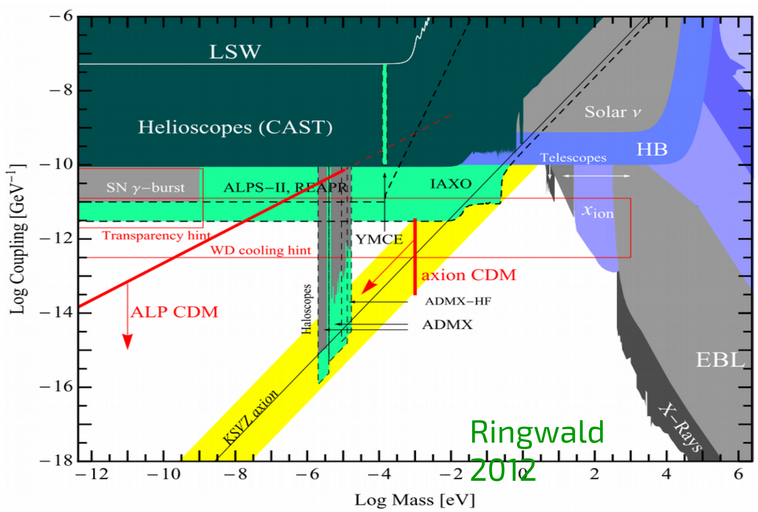


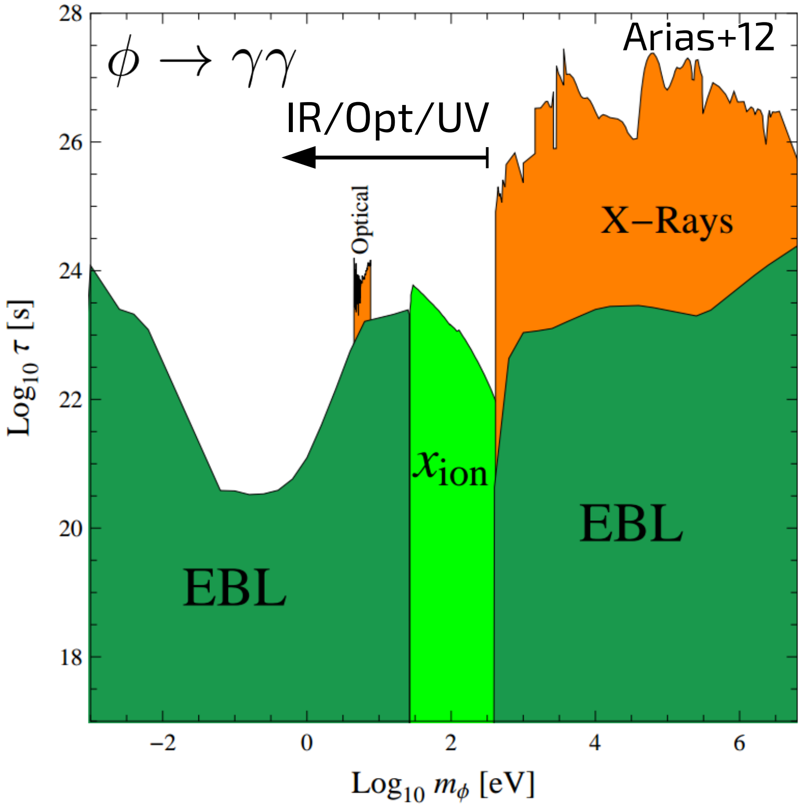

Kelley & Quinn 2017

Flux **very** uncertain: Need to know variation of Galactic B-field at meter scale…

$$\Gamma \propto |B(k = m_a)|^2$$

# DM searches at IR/Optical/UV frequencies



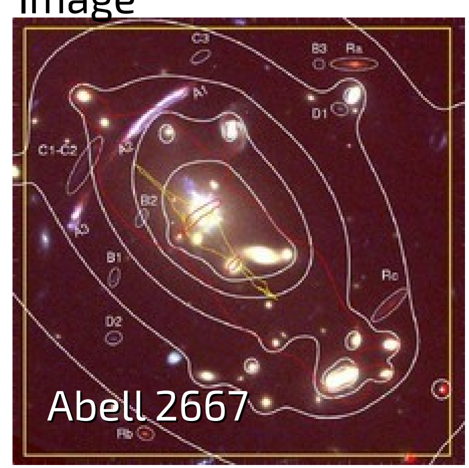

**The eV gap ($10^{-3}$ – $10^{2}$ eV)**

- Decay of axion-like particle DM could in principle give signals in that range
- Weak broad-band constraints come from extragalactic background light (EBL)
- Dedicated search for decaying DM signals in Abell 2667 only at optical frequencies (Grin+ '06)

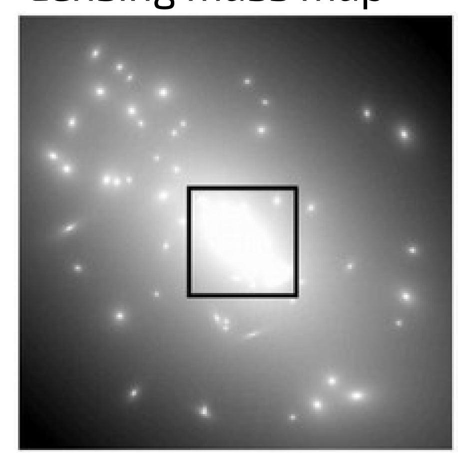
**Future**

- DM theory challenge: any other DM signals predicted/possible in this frequency range?
- Dedicated analyses of archived data in this range might improve existing limits significantly

Image



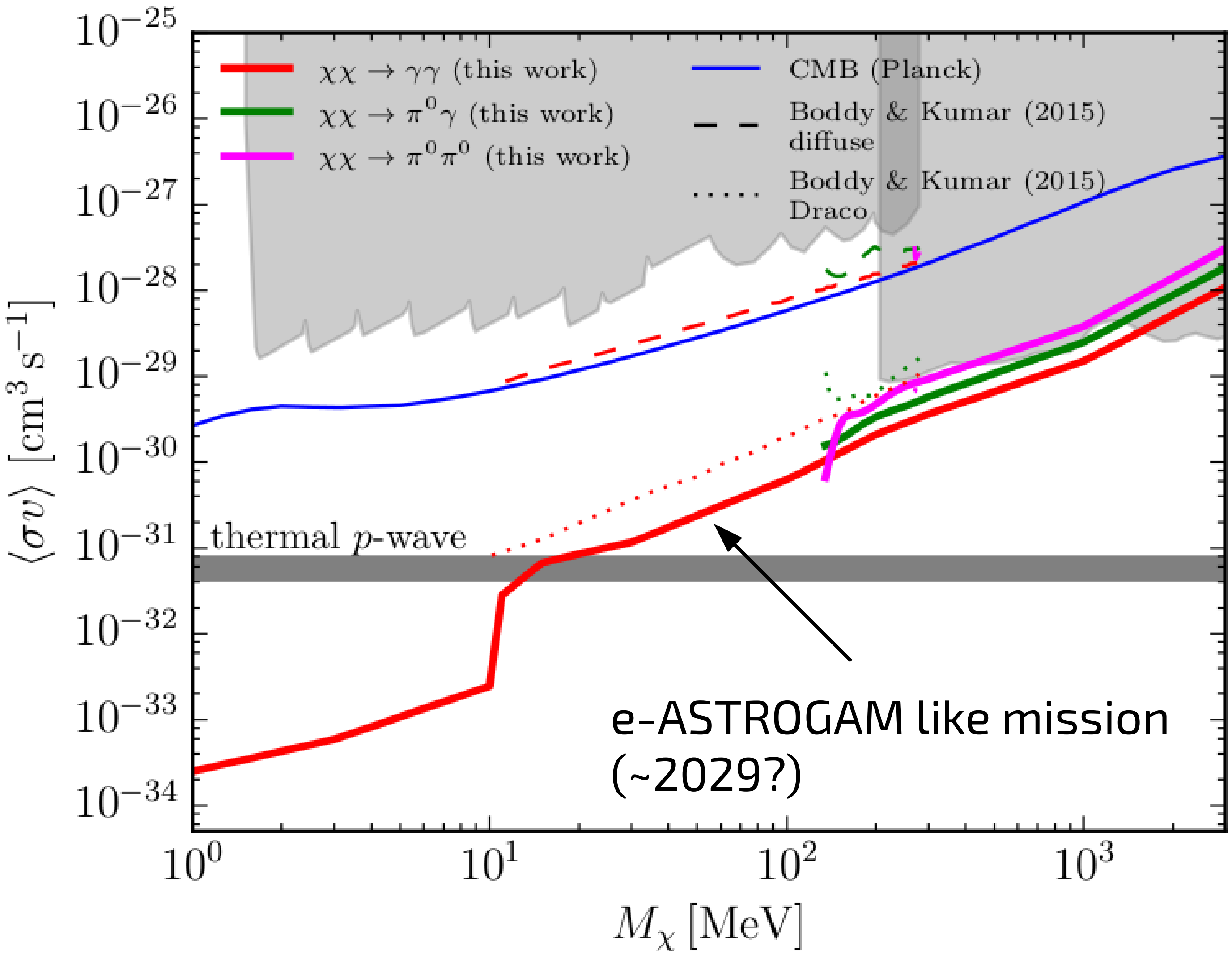

Lensing mass map



Grin+06

# The "MeV gap"

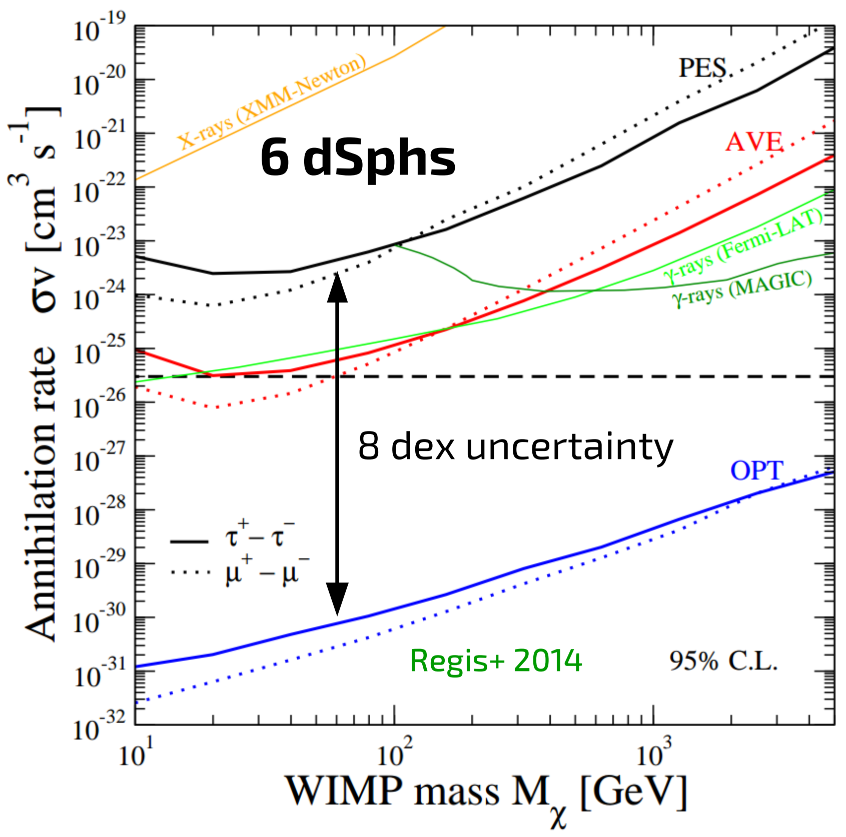
Searches for DM with a future dedicated ~MeV mission could improve existing limits by many orders of magnitude.

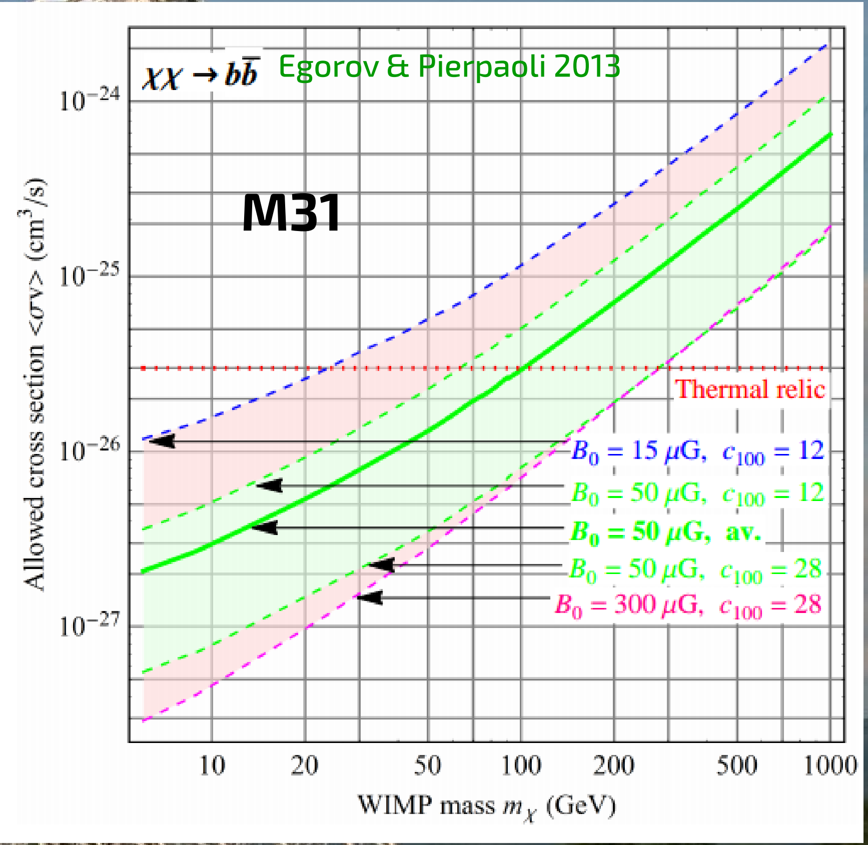



Bartels+ 17 (PRD)

# Radio searches for synchrotron emission from DM

$e^{\pm}$ from DM annihilation/decay + B-field → Synchrotron radiation

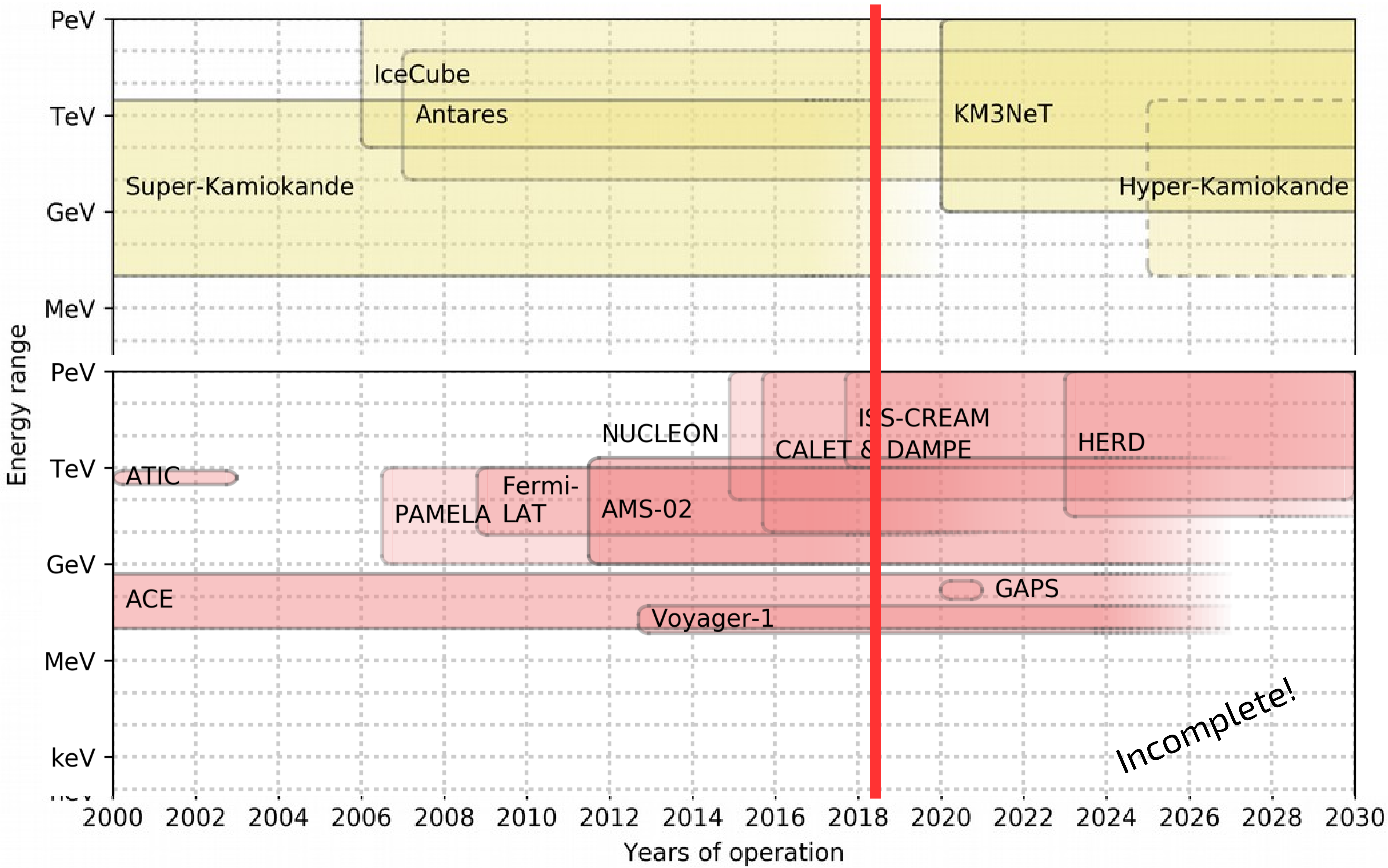



**Radio searches for dark matter**

- Dark matter annihilation/decay into leptons gives rise to synchrotron emission
- Signal strength depends on magnetic fields → additional, often large, uncertainty for signal flux
- Current limits from dSph and M31 (e.g. ATCA , VLSS, WENSS, NVSS, GB6) are potentially comparable to Fermi dwarf limits, but (much) less robust

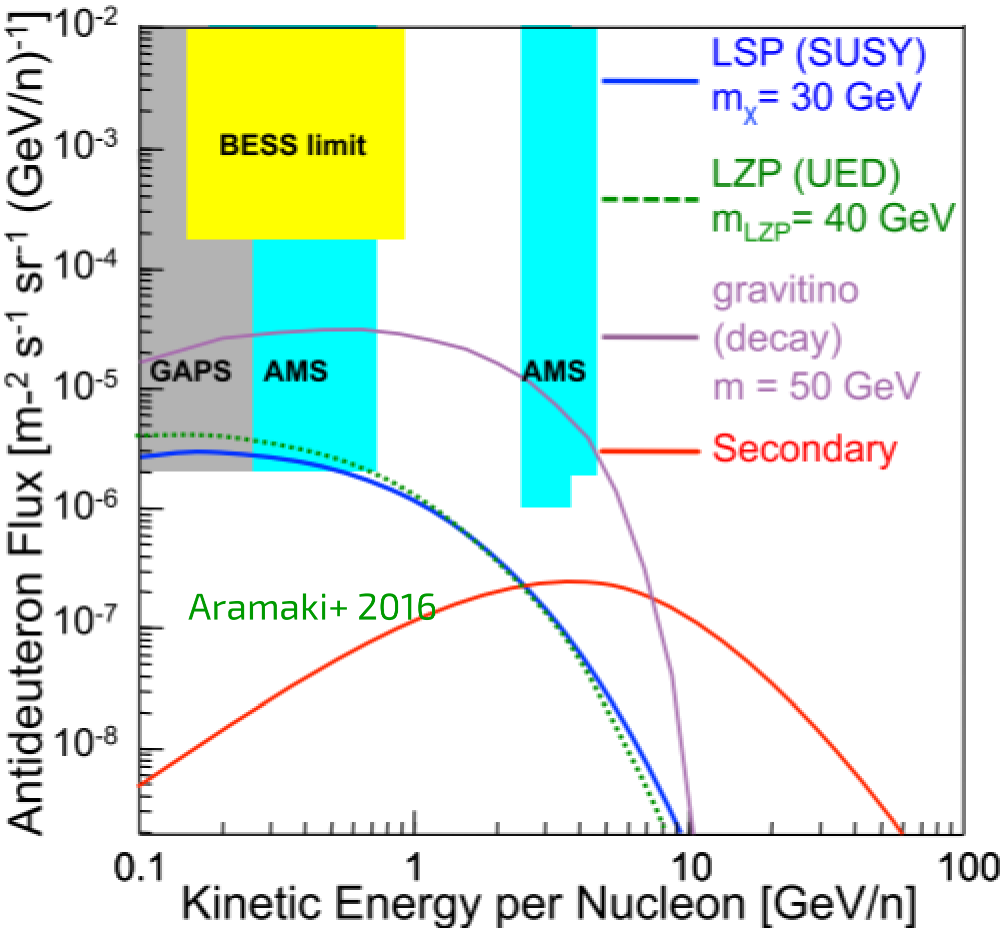
# Instr. panorama – Neutrinos & Cosmic Rays



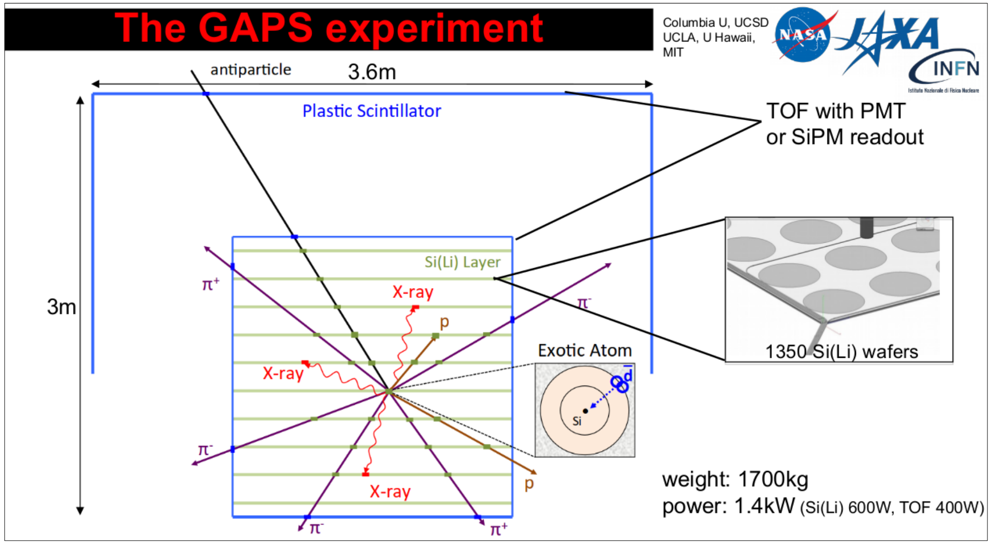
# General AntiParticle Spectrometer (GAPS)

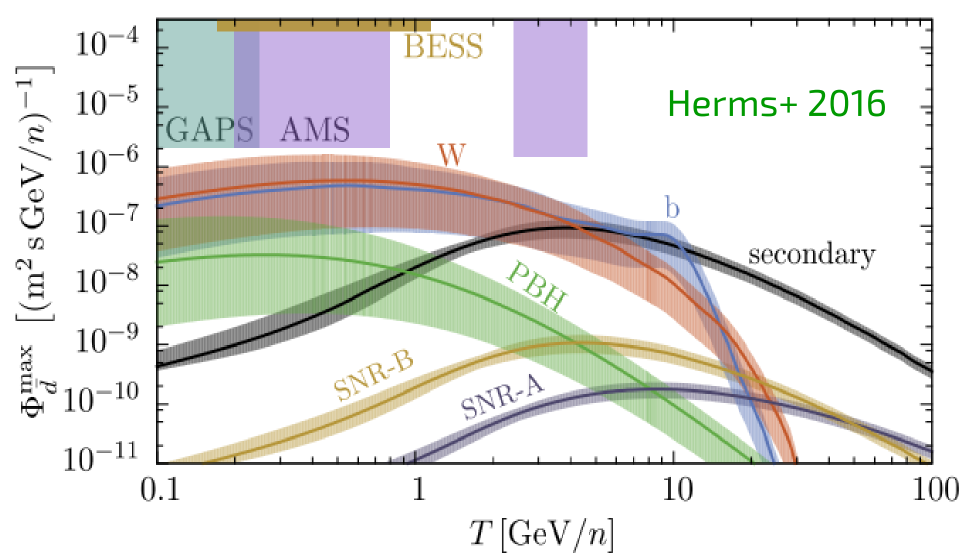
Funded by NASA & JAXA. First flight planned for ~2020.

→ Searches for **anti-deuterons**

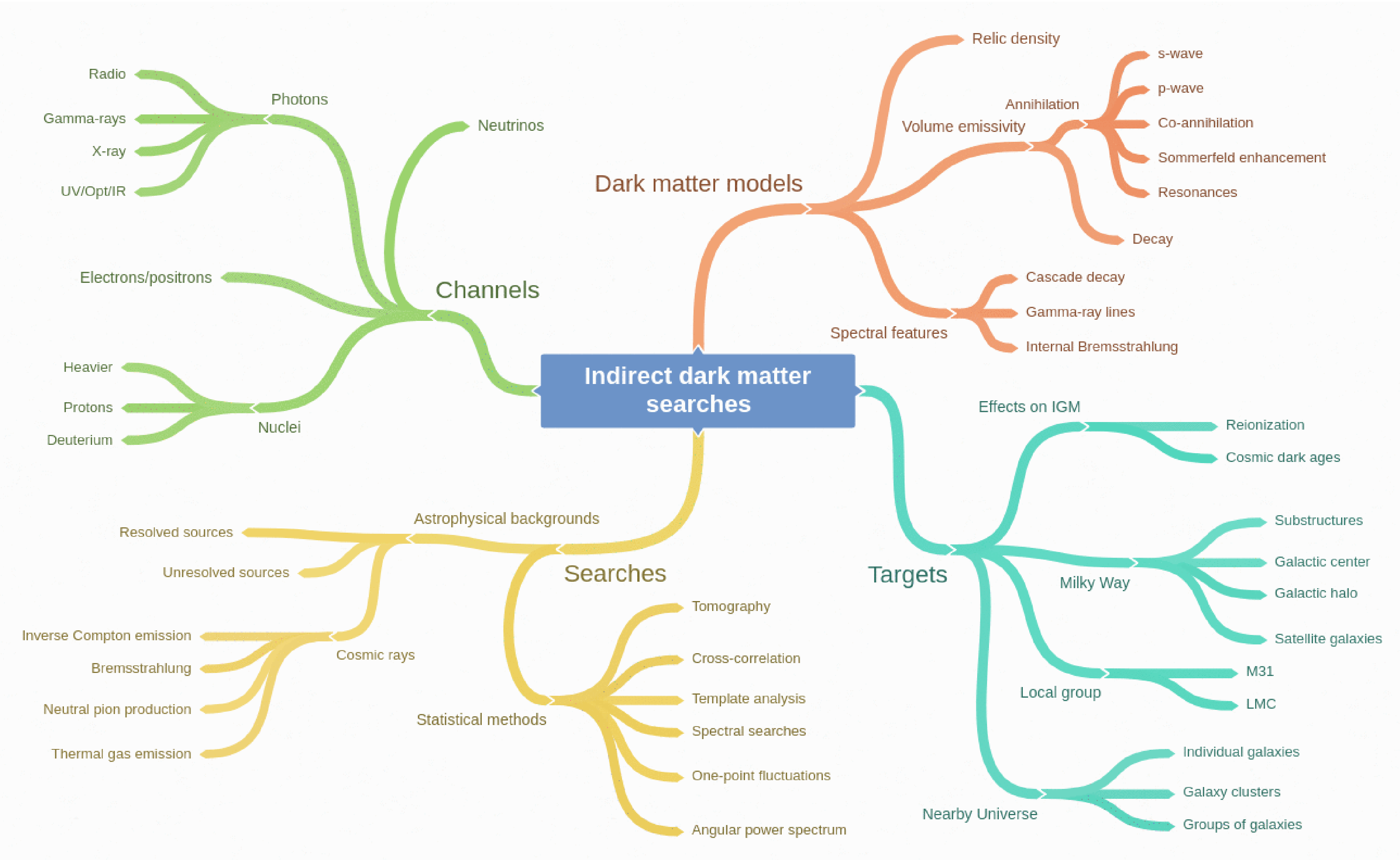



Credit: P. von Doetinchem



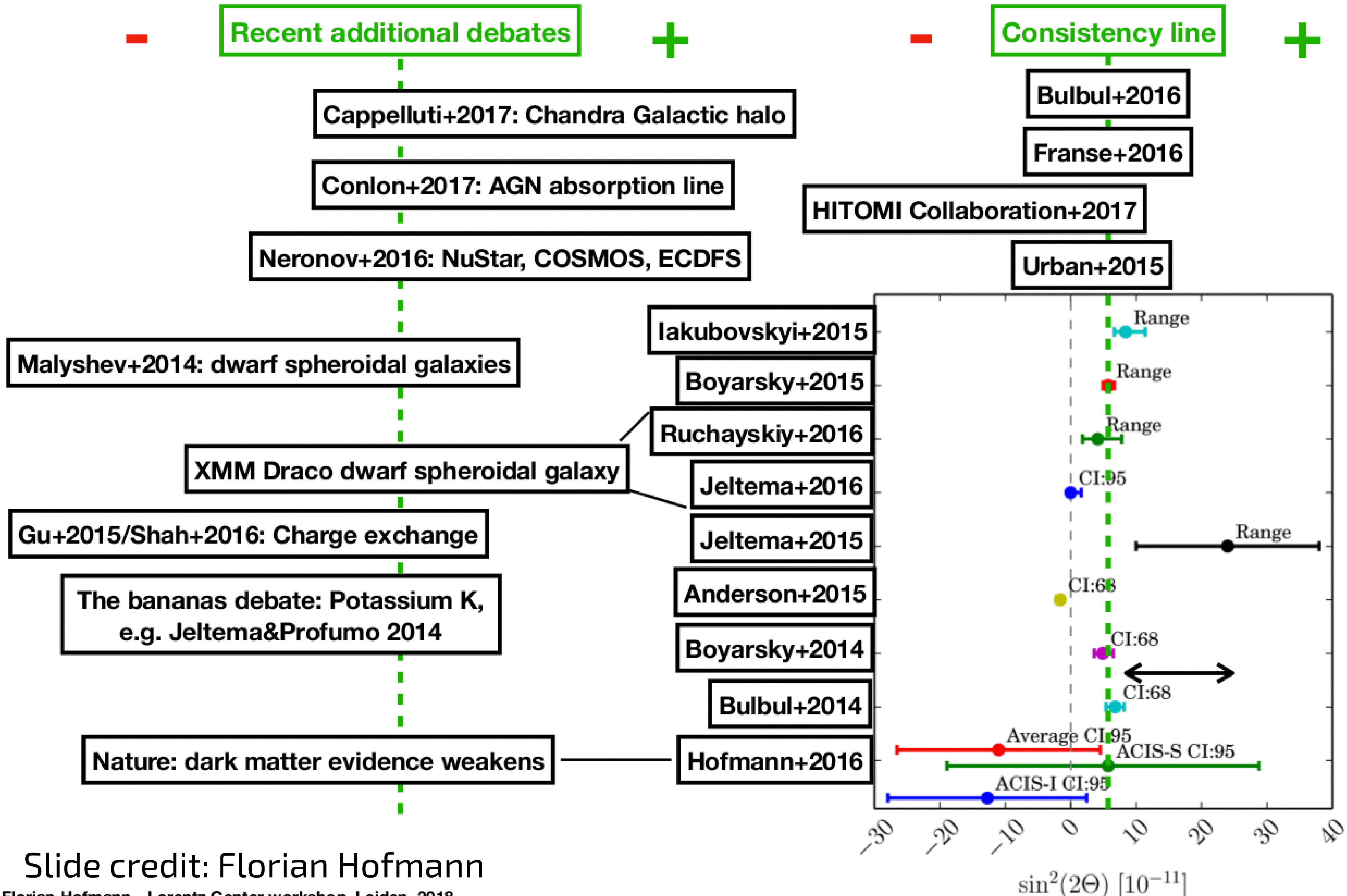
# Conclusions




Thank you!

# Backup slides

# Overview



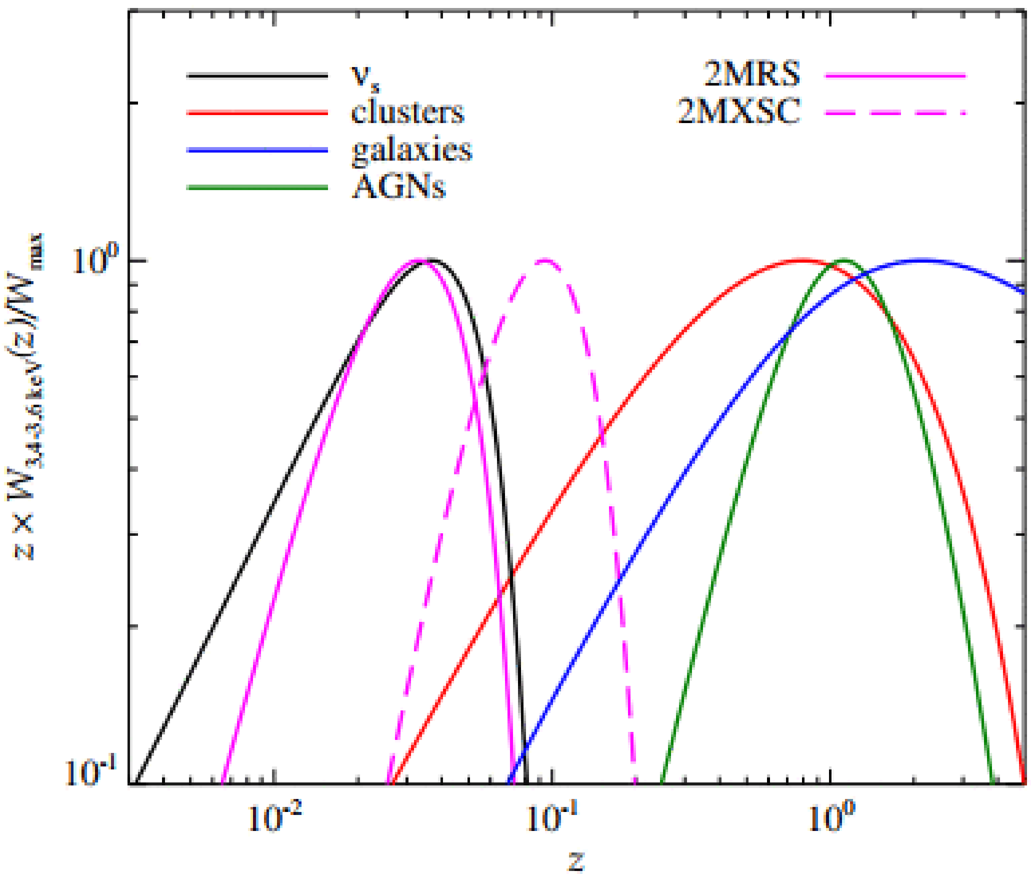

Slide credit: Florian Hofmann

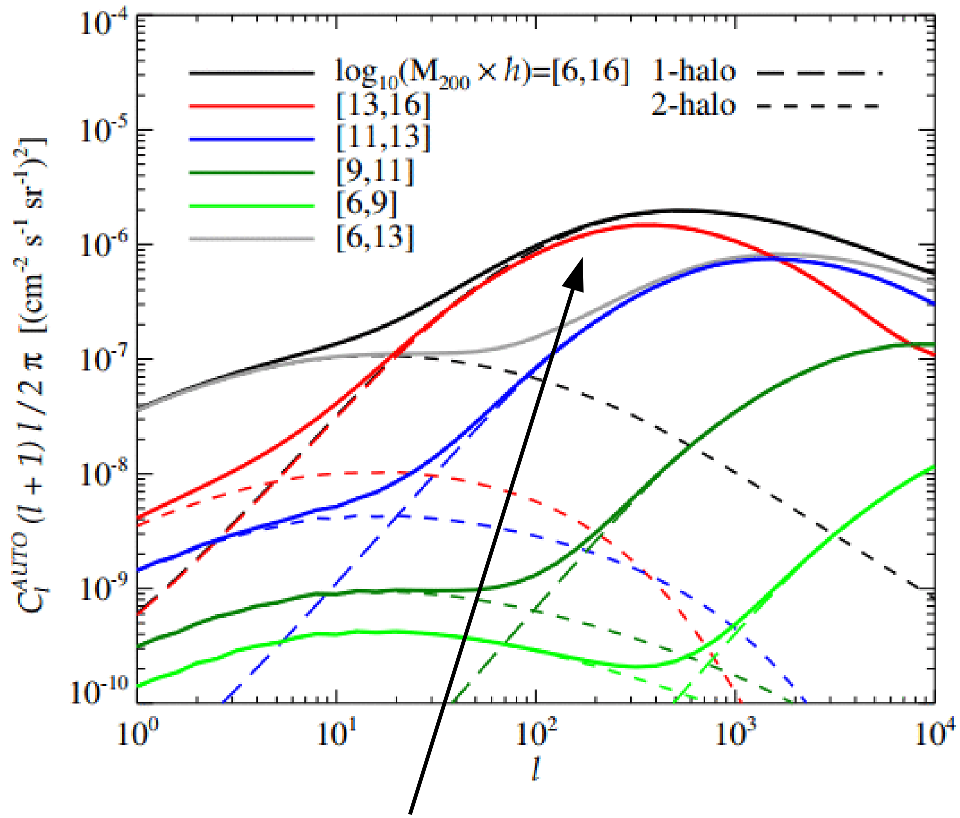
# e-ROSITA

1 deg^2 FOV, similar eres. XMM, 4 yr scan mode, 60 eV resolution @ 3.5 keV (?)

Aeff is half of XMM @ 3.5 keV

Pointed observations after 4yrs?

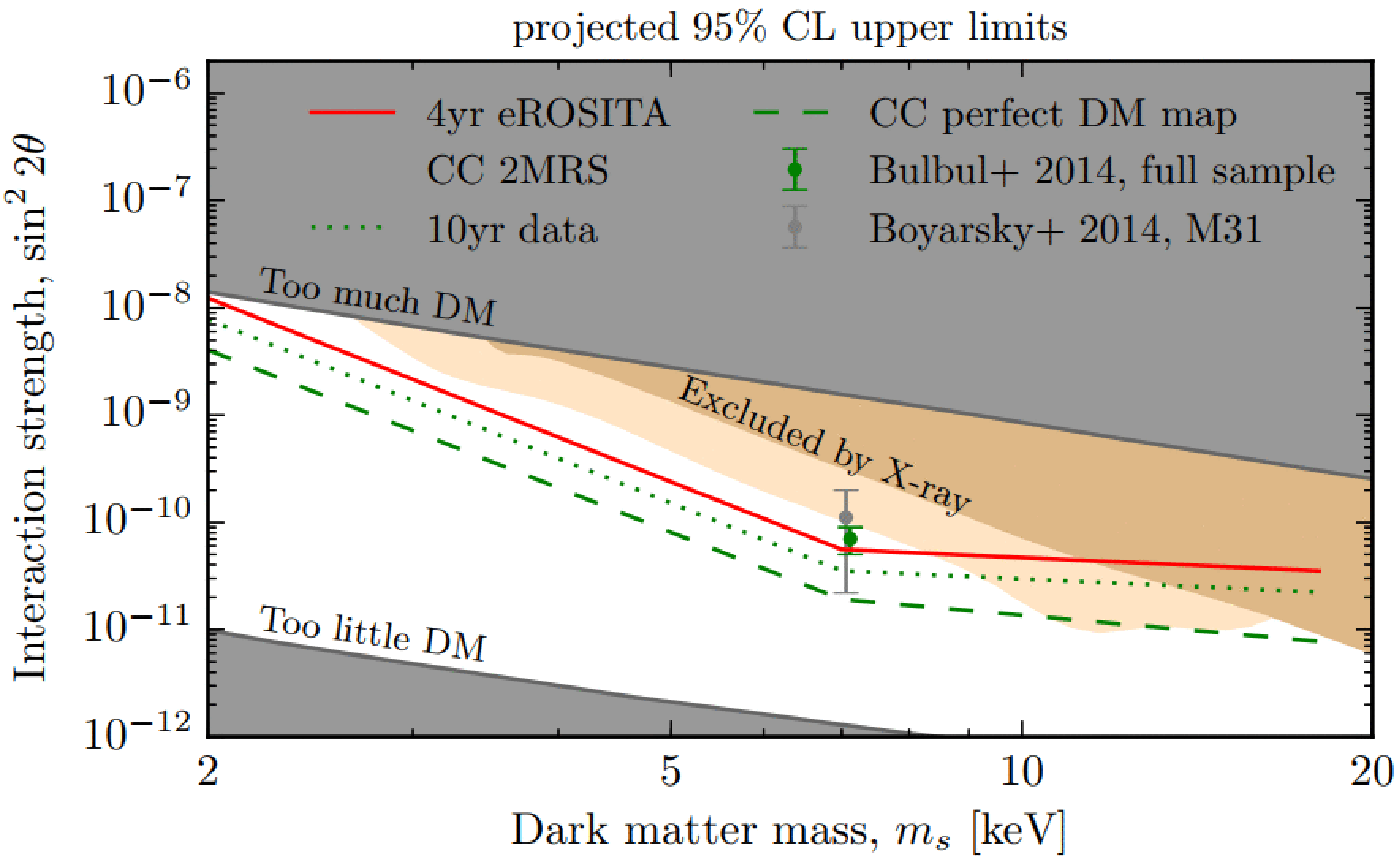



Most integrated S/N at large angular scales, most massive objects

Zandanel, Ando, CW, 2015

# e-ROSITA



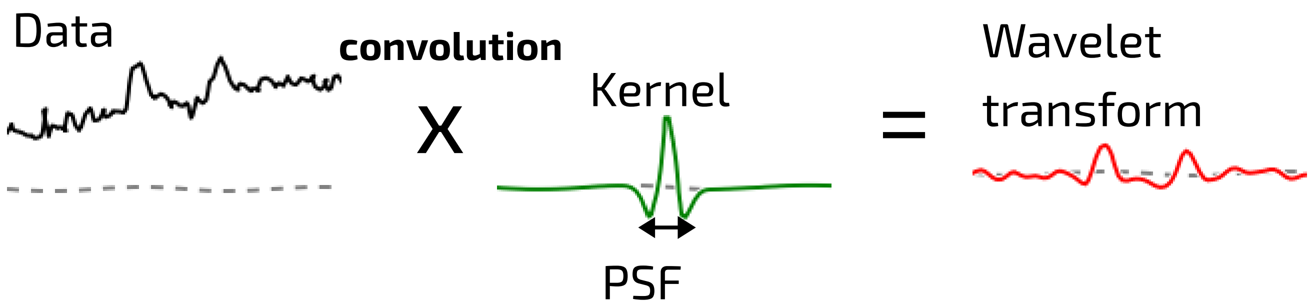

Note: We average over 200 eV bins around line → true sensitivity could be higher by factor of few

Zandanel, Ando, CW, 2015

# Formalism: Why signal-to-noise?

Problems with plain wavelet transforms:

- **Peaks in the wavelet transform** correspond usually point source (if they are bright enough).




- The wavelet transform is a measure of the source flux
- Problematic aspects
  - Steep gradients in astrophysical backgrounds → Sources with same flux are detectable far from the disk but not close to the disk
  - Even worse: 1,2,3,…-sigma fluctuations will correspond to different flux levels in different regions of sky →
    **Null hypothesis (no PSCs, only diffuse background) has very complicated characteristics in wavelet space**

- ***Idea: Look at signal-to-noise instead of fluxes!***

# Formalism: Signal-to-noise ratio

One can show that the variance of the wavelet transform

$$\mathcal{F}_{\mathcal{W}}[\mathcal{C}](\mathbf{\Omega}) = \int d\mathbf{\Omega}'\, \mathcal{W}(\mathbf{\Omega} - \mathbf{\Omega}')\, \mathcal{C}(\mathbf{\Omega}')$$

is given by

$$\mathrm{Var}(\mathcal{F}_{\mathcal{W}}[\mathcal{C}](\mathbf{\Omega})) = \langle \mathcal{F}_{\mathcal{W}^2}[\mathcal{C}](\mathbf{\Omega}) \rangle$$

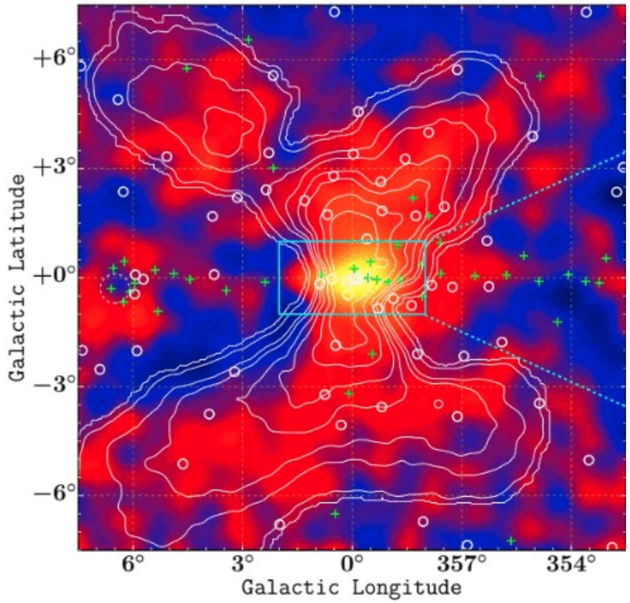
The signal-to-noise of the wavelet transform is then just given by:

$$\mathcal{S}(\mathbf{\Omega}) = \frac{\mathcal{F}_{\mathcal{W}}[\mathcal{C}](\mathbf{\Omega})}{\sqrt{\mathcal{F}_{\mathcal{W}^2}[\mathcal{C}](\mathbf{\Omega})}}$$

On approximately isotropic fluxes, with variations at length scales much larger than the wavelet transform kernel, *S* behaves (approximately) like a smoothed Gaussian random field with variance one →

Simple behavior in absence of point sources!

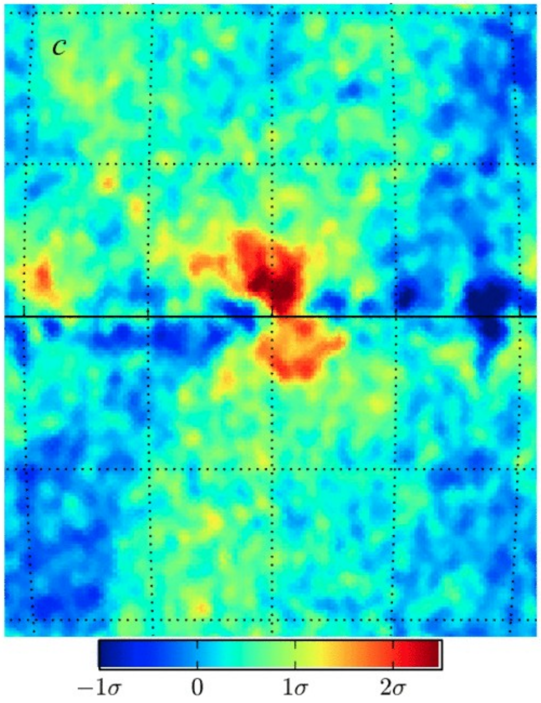
# X-shaped excess?




Macias+ 16, WISE template vs excess emission

**Morphology of the Fermi GeV excess**

- Some studies (e.g. Macias+ 16) found that the GeV excess emission can be better described by an "X-shaped" bulge
- X-shapes are seen in other galaxies, related to boxy bulge
- X-shapes can be generated as projection of stable circular & oscillating (z direction) orbits
- However, we found no indication for an X-shaped excess (next slides)




Acero+ 16 residuals