Indirect Searches for Dark Matter
Overview and recent developments

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GRAPPA
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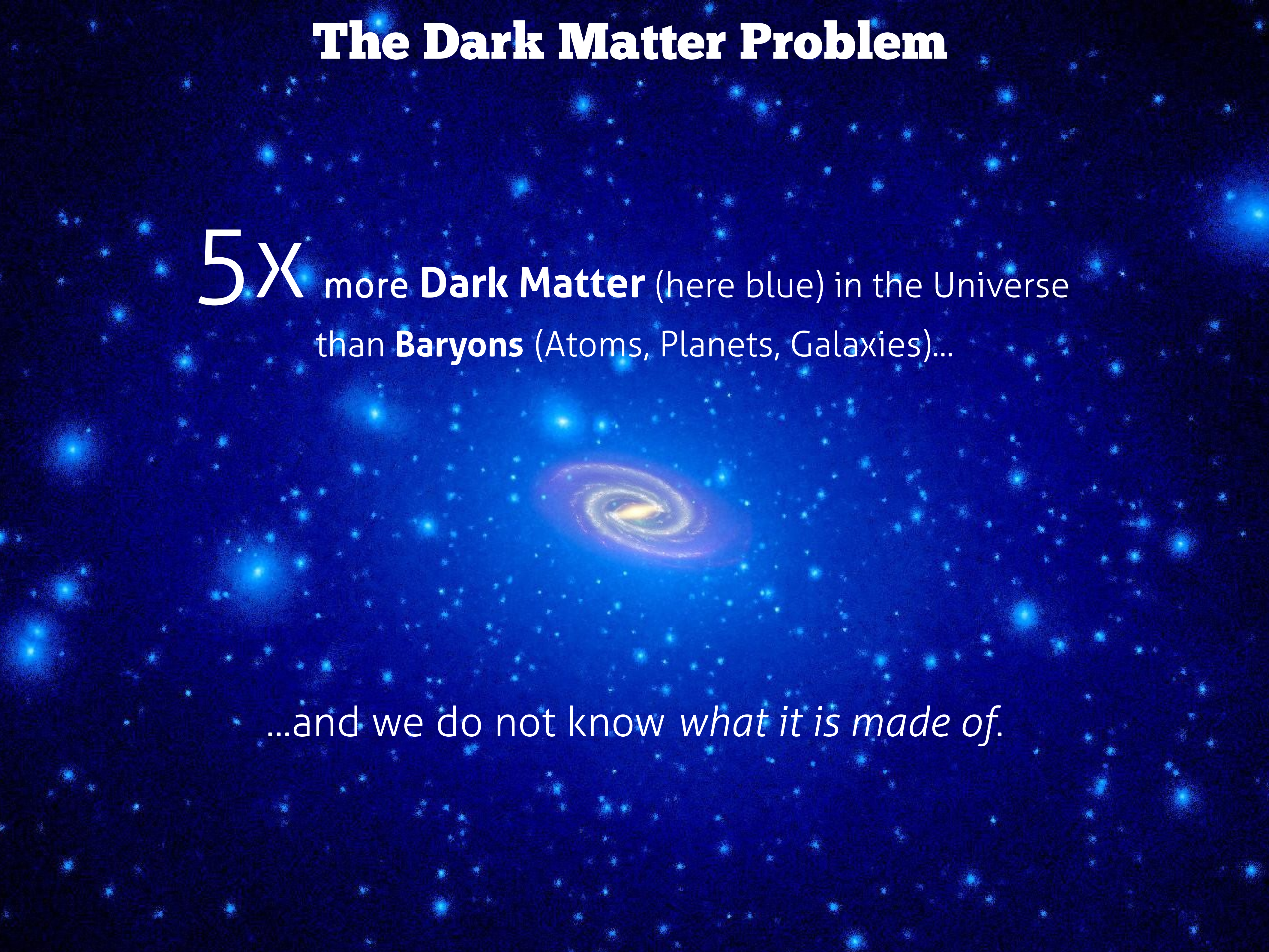
NWO

The Dark Matter Problem



5X more **Dark Matter** (here blue) in the Universe than **Baryons** (Atoms, Planets, Galaxies)...

...and we do not know *what it is made of*.

Overview

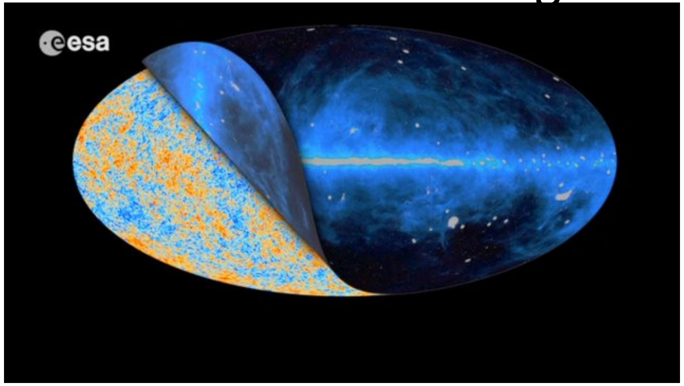
- **Introduction**: What to search for?
- Generalities about **Indirect searches**
- **Multi-messengers**
  - Gamma-ray lines
  - Antiprotons
  - Positrons
  - Neutrinos
  - Gamma-ray continuum
- Future prospects & **Conclusions**

==> In case of questions, interrupt me at any time! <==

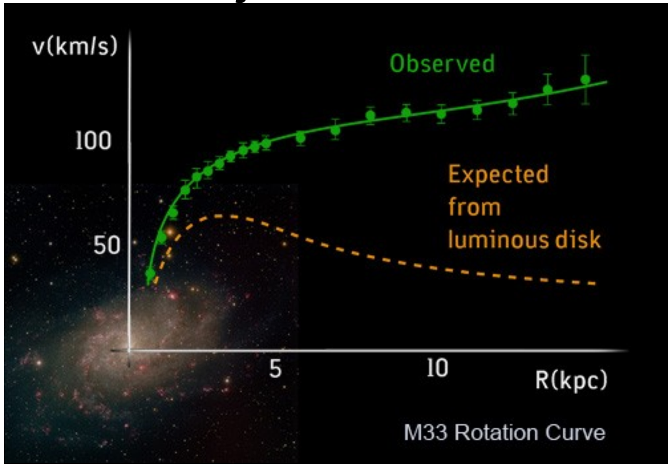
Evidence for dark matter is omnipresent

Evidence for the existence of **non-baryonic** dark matter in the Universe comes from gravitational observations at different length scales (from sub-galactic to cosmological scales).

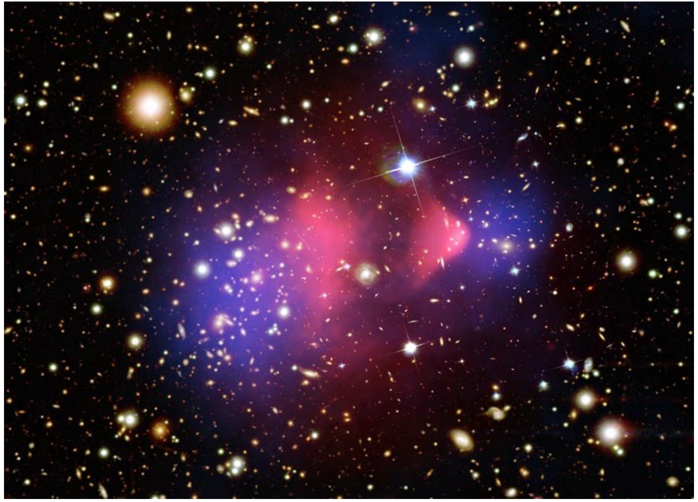
Cosmic microwave background



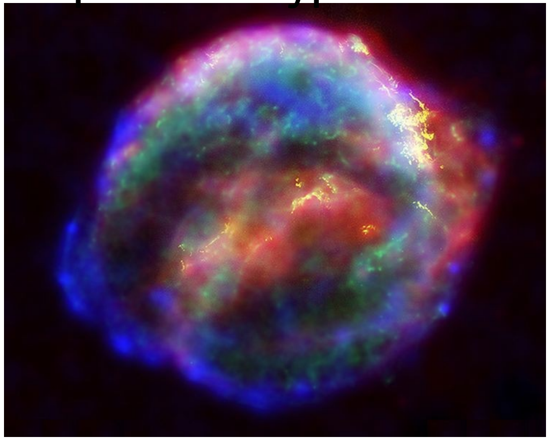
Galaxy rotation curves

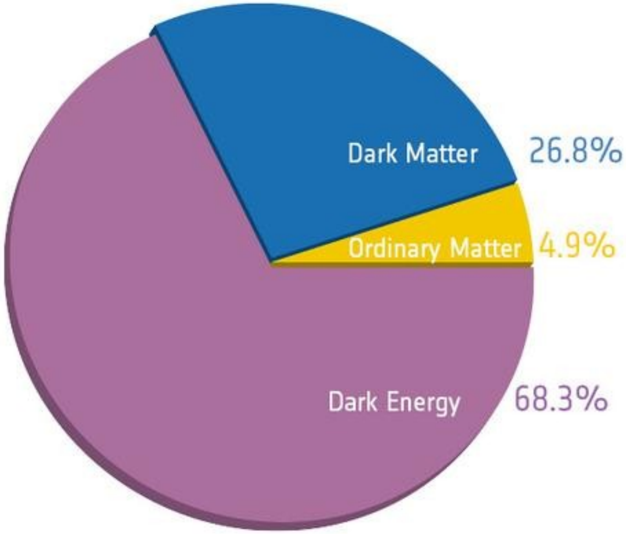


Galaxy clusters

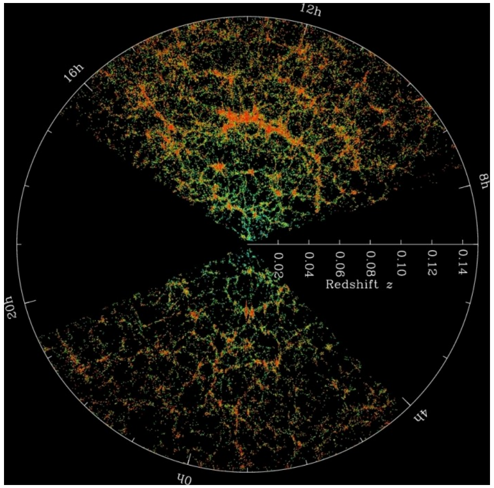


Supernova Type 1A



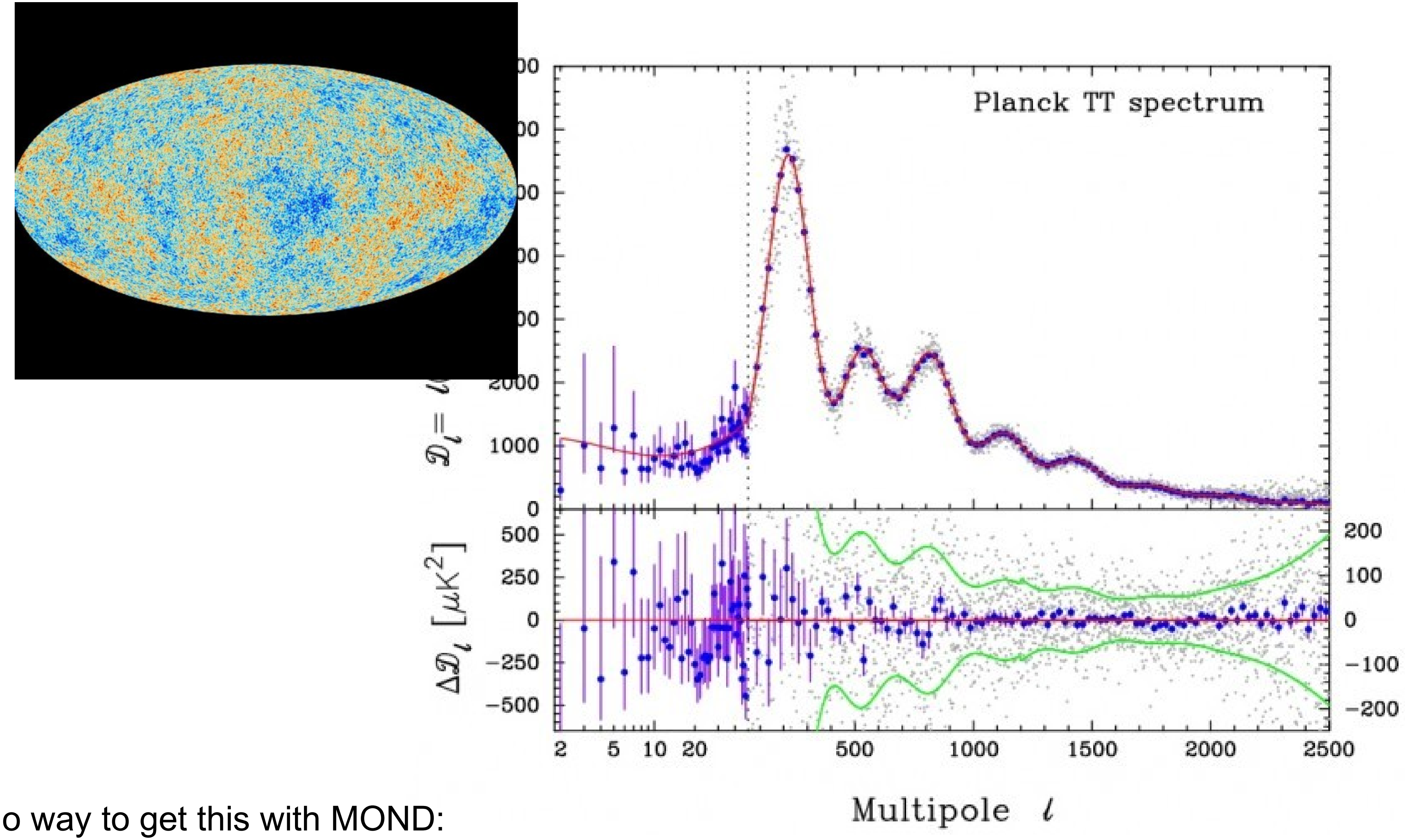


Large scale structures



85% of all matter in the Universe is dark and non-baryonic.

Why a particle and not modified gravity?

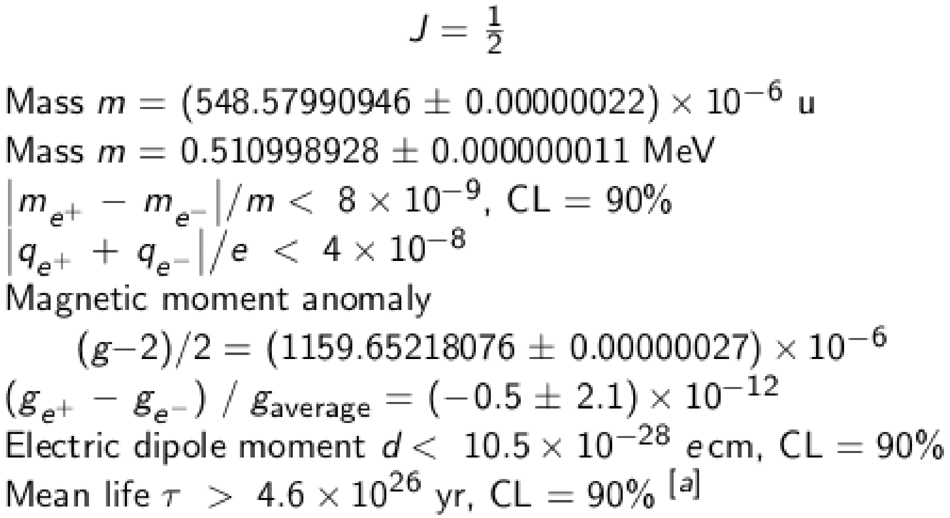


No way to get this with MOND:

$$\mu\left(\frac{a}{a_0}\right) = \frac{GM}{r^2}$$

A particle physicist's wishlist

What we know about the electron:



$J = \frac{1}{2}$

Mass $m = (548.57990946 \pm 0.00000022) \times 10^{-6}$ u

Mass $m = 0.510998928 \pm 0.000000011$ MeV

$\left|m_{e^+} - m_{e^-}\right|/m < 8 \times 10^{-9}$, CL = 90%

$\left|q_{e^+} + q_{e^-}\right|/e < 4 \times 10^{-8}$

Magnetic moment anomaly

$(g{-}2)/2 = (1159.65218076 \pm 0.00000027) \times 10^{-6}$

$(g_{e^+} - g_{e^-}) \,/\, g_{\text{average}} = (-0.5 \pm 2.1) \times 10^{-12}$

Electric dipole moment $d < 10.5 \times 10^{-28}$ $e$cm, CL = 90%

Mean life $\tau > 4.6 \times 10^{26}$ yr, CL = 90% [a]

In case of dark matter:

- Spin?
- Mass?
- Lifetime?
- Self conjugate?
- Dipole moment?
- Decay modes?
- Couplings?
- Charges?

What we actually know

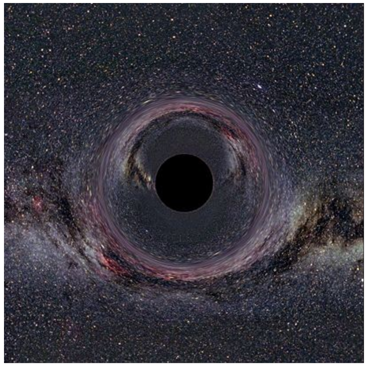
About 80 years after the first discovery of dark matter, we can now bracket its particle mass to **within 70-80 orders of magnitude.**

Uncertainty principle

Hu+ 2000

$$10^{-22}\mathrm{eV} \lesssim m_{\mathrm{DM}} \lesssim 10^{50}\mathrm{GeV}$$

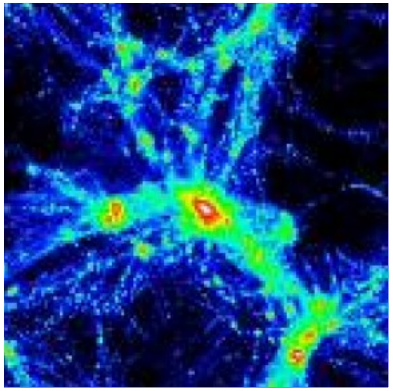
MACHO searches (massive compact halo objects)



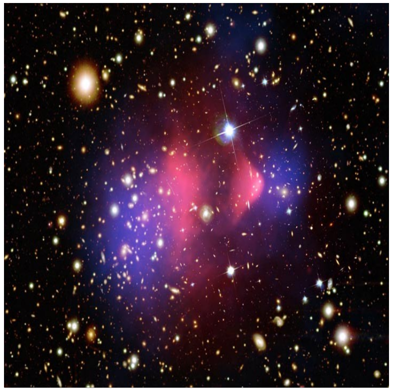
Tisserand+ 2007

We have searched hard, but only found various upper limits so far.

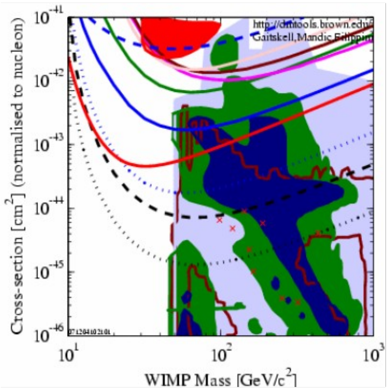
cold:
negligible velocity dispersion



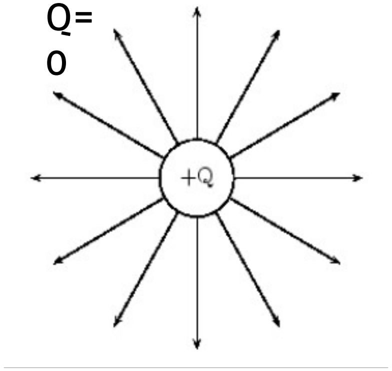
collisionless:
negligible self-interaction

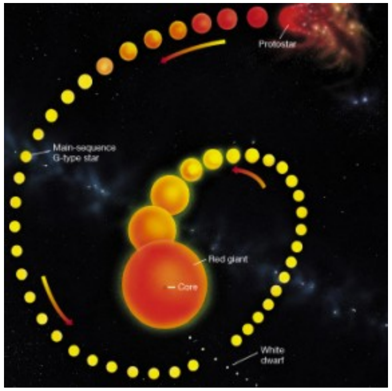


weakly coupled:
negligible interaction with the rest of the world



Q= 0

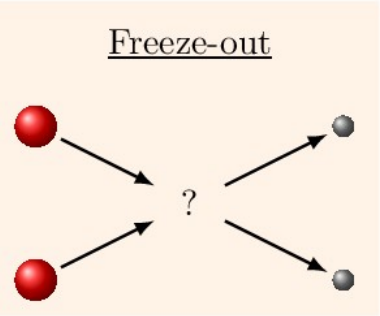


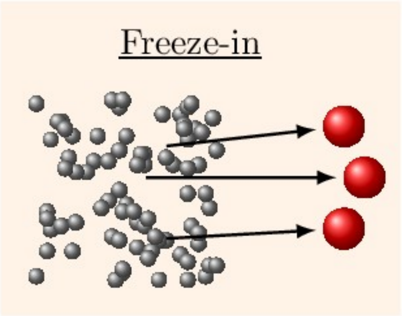


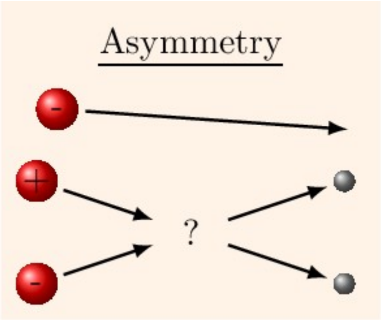
The two corner stones of all DM speculation

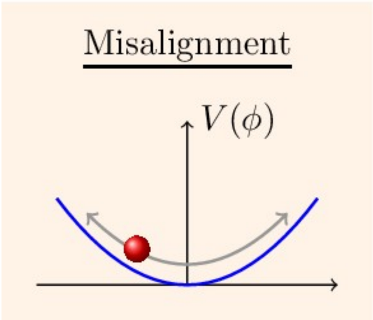
DM must have been “produced” in the early Universe
→ **DM couples to Standard Model**

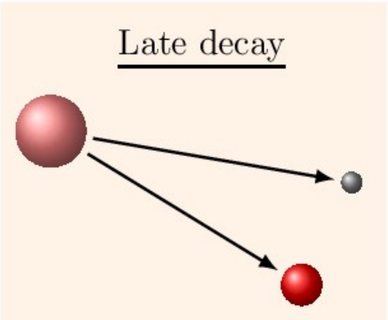
Many ideas for production mechanisms:
Freeze-out, freeze-in, via decay of heavier particles, misalignment mechanism, primordial asymmetry









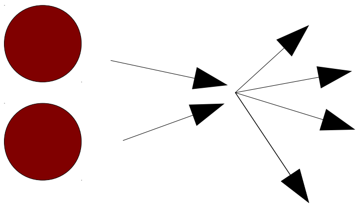


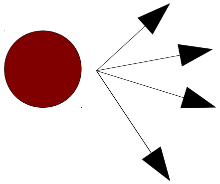
$$\rho_{\mathrm{DM}} \sim 0.3\,\mathrm{GeV\,cm^{-3}} \sim \mathrm{Brick}/(10\mathrm{km})^3$$

DM is still around today
→ **DM is (meta-)stable**

Protected by (Z_2?) symmetry in Lagrangian. This symmetry might be slightly broken.

Many possibilities: DM could be its own antiparticle and be able to **self-annihilate**, DM could be unstable and **decay on cosmological time-scales**.





$$\tau_{\mathrm{DM}} \gg \tau_{\mathrm{Universe}}$$

Most popular models/paradigms for DM

Axions [e.g. Ringwald (2012)]

Pseudo Goldstone boson of broken Peccei-Quinn symmetry
Why: Solves strong CP problem
Props: Super light (<<1 eV), super weakly interacting, super cold

Sterile Neutrinos [e.g. Boyarsky, Ruchayskiy, Shaposhnikov, 2009]

Minimal extension of standard model with right-handed neutrinos
Why: Explains baryon asymmetry & neutrino masses
Props: keV masses, very weakly interacting, non-thermal production

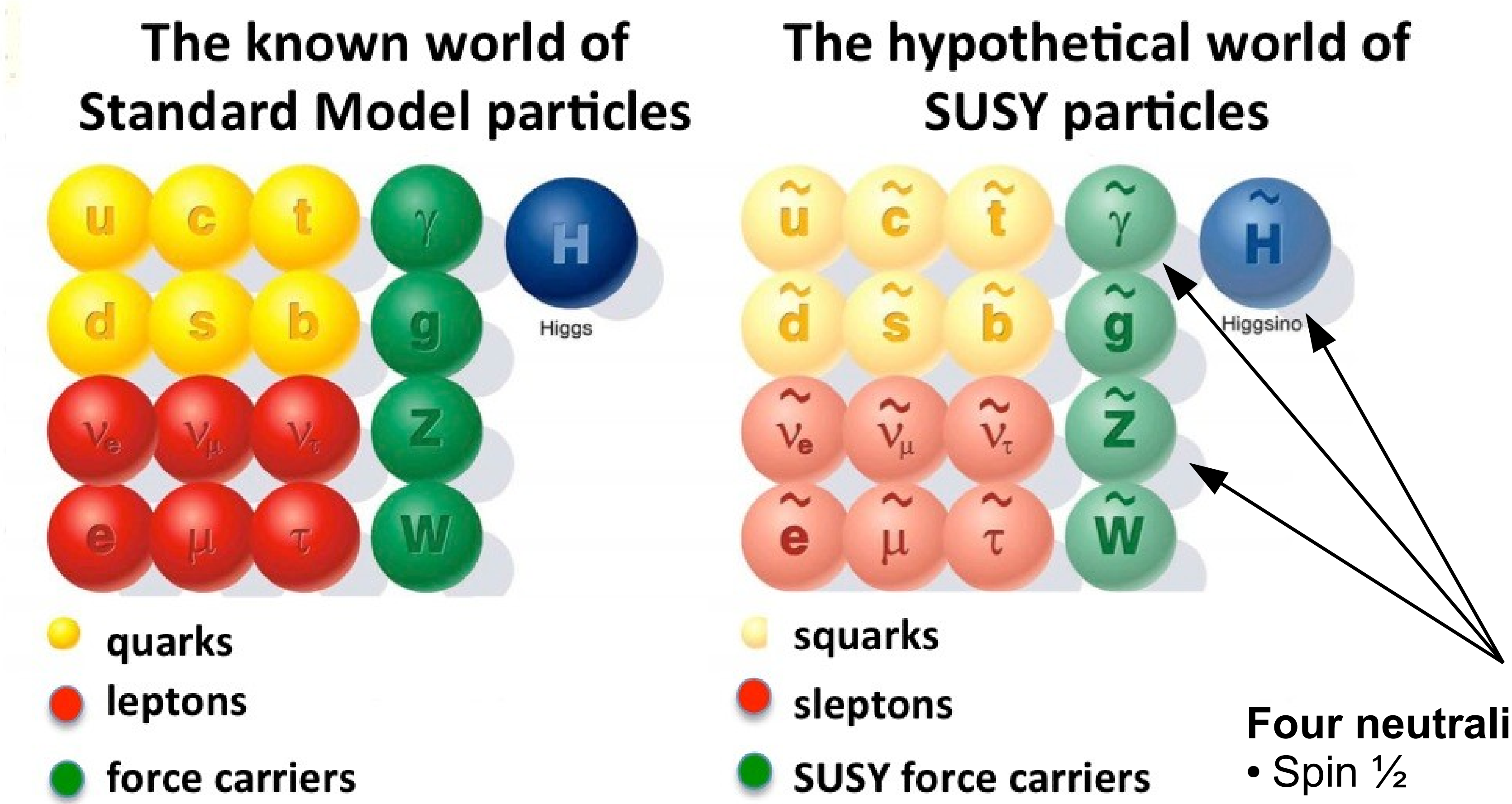
Weakly interacting massive particles (WIMPs)

Generic neutral particle with masses and coupling at electroweak scale
Why: Can solve gauge hierarchy problem
Props: The currently leading hypothesis for what dark matter is made of

[e.g. Jungman et al., (1995); Bertone, Hooper, Silk (2005)]

And SuperWIMPs, WIMPzillas, asymmetric DM, FIMPs, ...

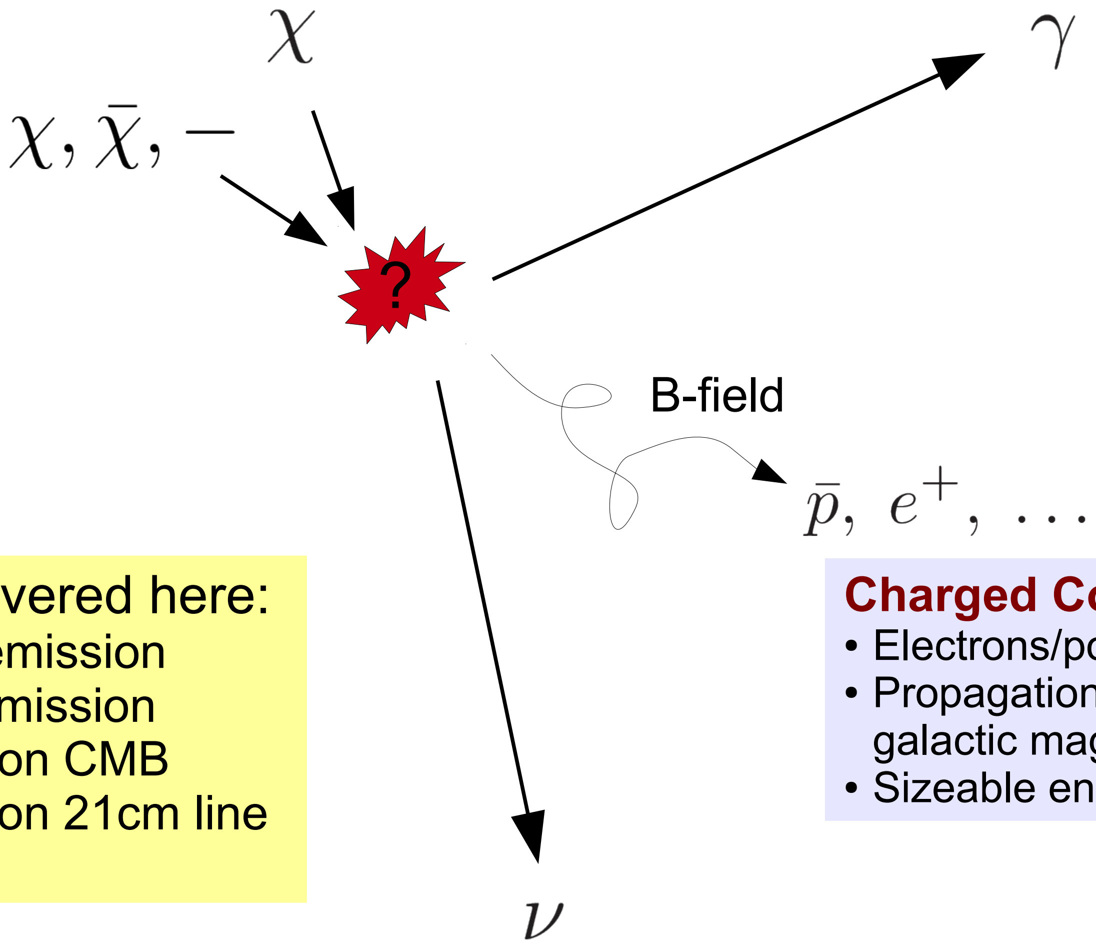
The Minimal Supersymmetric Standard Model



Four neutralinos:
- Spin ½
- Neutral
- Lightest one is stable (Lightest supersymmetric particle, **LSP**)

General idea of indirect detection

(Self-)annihilation or
decay of DM particles



Gamma rays
- Extremely simple propagation (geodesics)
- Absorption or energy losses negligible
- Point towards their sources

Charged Cosmic rays
- Electrons/positrons, nuclei
- Propagation distorted by galactic magnetic fields
- Sizeable energy losses

Neutrinos
- Simple propagation
- But: <u>very</u> hard to measure

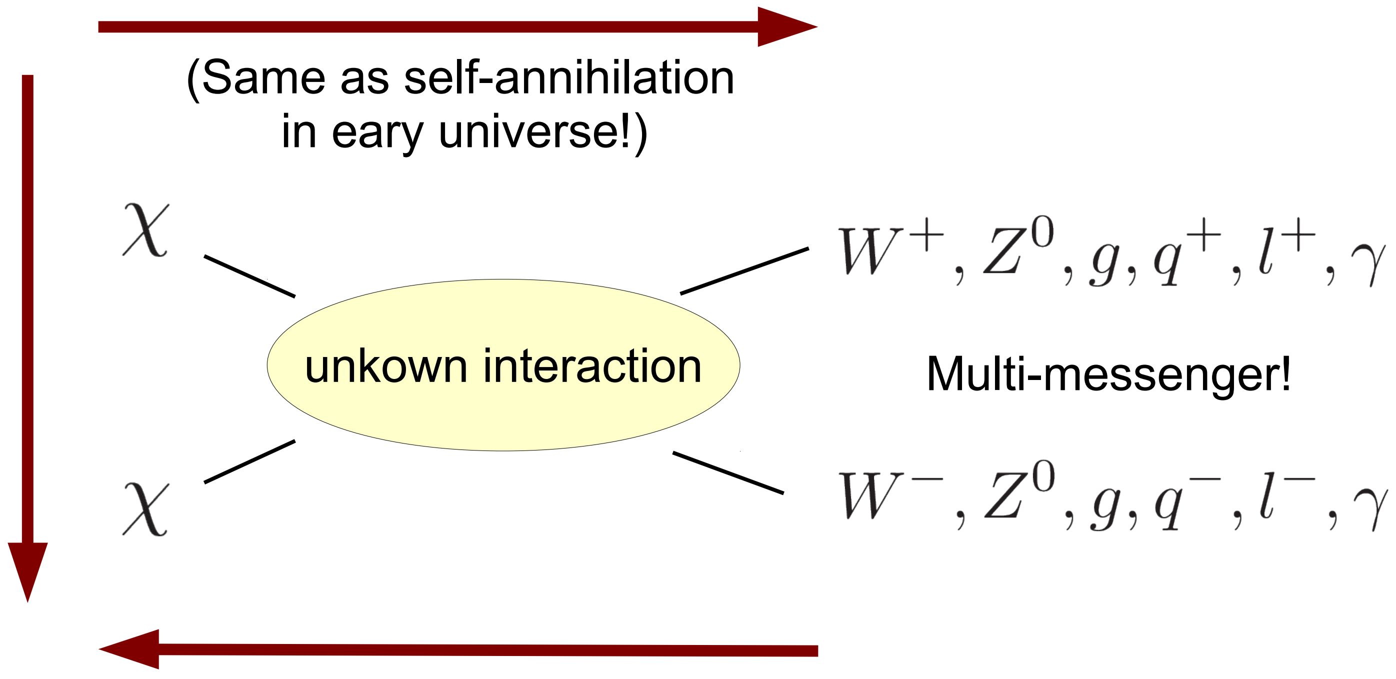
Not covered here:
Radio emission
X-ray emission
Impact on CMB
Impact on 21cm line
...

The three-folded search for WIMP DM

WIMPs appear in beyond-SM models, and they can be DM. How do we find them?

The interaction between SM particles and dark matter can be read in different ways:

III) Indirect searches:
WIMPs self-annihilate
→ energy injection everywhere



(Same as self-annihilation in eary universe!)

χ

χ

unkown interaction

$W^+, Z^0, g, q^+, l^+, \gamma$

Multi-messenger!

$W^-, Z^0, g, q^-, l^-, \gamma$

II) Direct searches:
WIMPs scatter
→ search for recoil
on atomic nuclei

I) Collider searches:
WIMP production
→ searches at particle colliders

Each of these three approaches is a research field on its own!

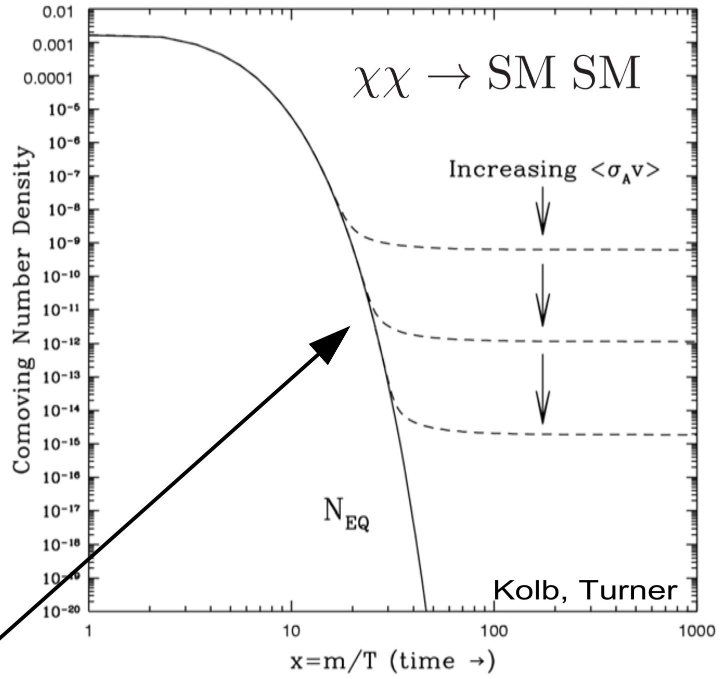
WIMP Relic density calculation

Number density is governed by Boltzmann equation:

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[n^2 - n_{\rm eq}^2 \right]$$

Interaction rate: $\Gamma \equiv \langle \sigma v \rangle n$

Hubble rate: $H \sim \frac{T^2}{M_{\rm pl}}$



Kolb, Turner

$$\langle \sigma v_{\rm M\o l} \rangle = \frac{\int \sigma v_{\rm M\o l}\, dn_1^{\rm eq}\, dn_2^{\rm eq}}{\int dn_1^{\rm eq}\, dn_2^{\rm eq}}$$

$$\int dn = \int f(E,t) \frac{g\, d^3p}{(2\pi)^3}$$

$\Gamma \gg H$

$\chi\chi \leftrightarrow \bar{f} f$

DM in equilibrium with thermal SM bath

$\Gamma \sim H$

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

Interactions freeze out

$\Gamma \ll H$

$\chi\chi \not\rightarrow \bar{f} f$

Interactions decoupled

Full calculation: annihilations freeze out at

$$T \sim m_\chi / 20$$

[see e.g. Gondolo, Gelmini (1990)]

WIMP relic density:

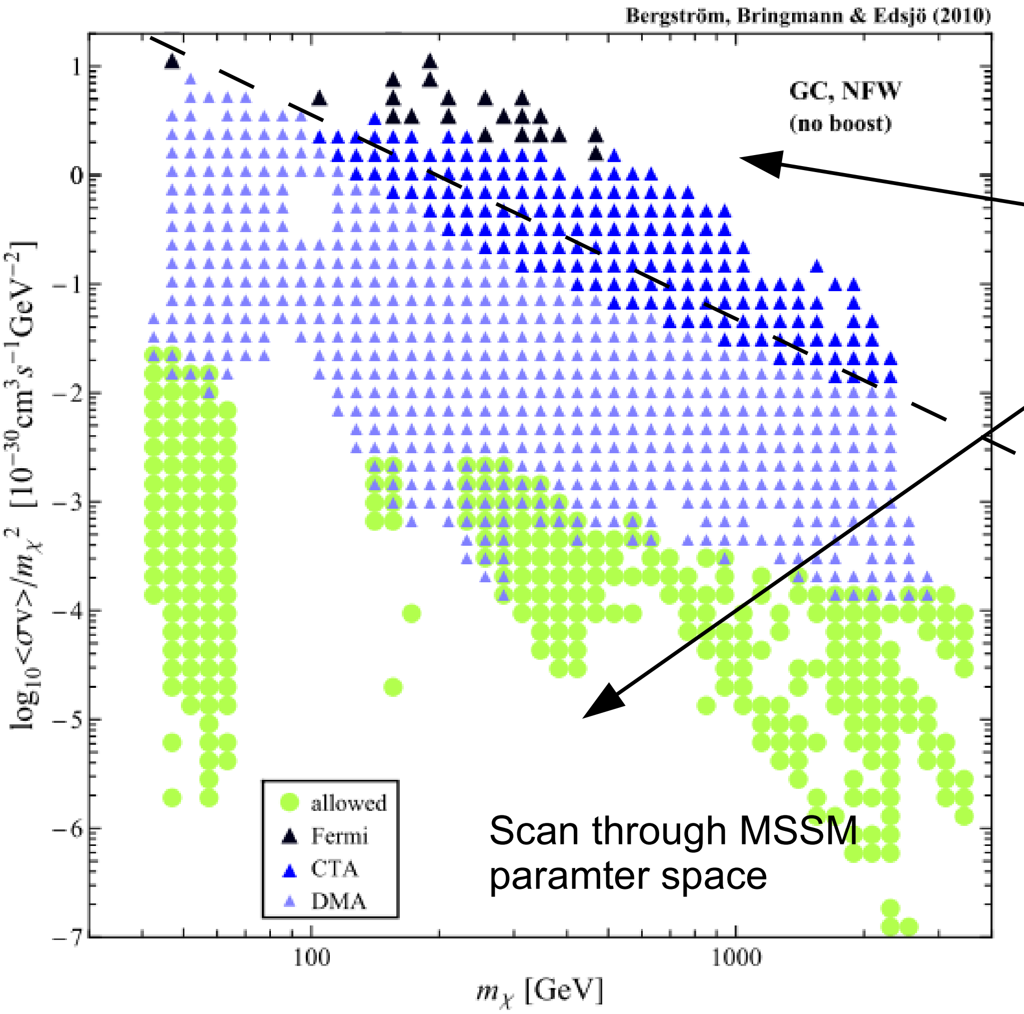
$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27} {\rm cm}^3 {\rm s}^{-1}}{\langle \sigma v \rangle} \simeq 0.1$$

Annihilation cross-section

Remember: Annihilation cross-section in early Universe fixed by observed relic density.

$$\langle \sigma v \rangle_{\rm tot} \sim 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

In general, the velocity-averaged annihilation cross-section is a function of the velocity distribution. However, sometimes the velocity dependence is negligible.



Scan through MSSM paramter space

"Thermal value" only a rough estimate for what is expected today:
>8 orders of magnitude uncertainty!!

Reasons:

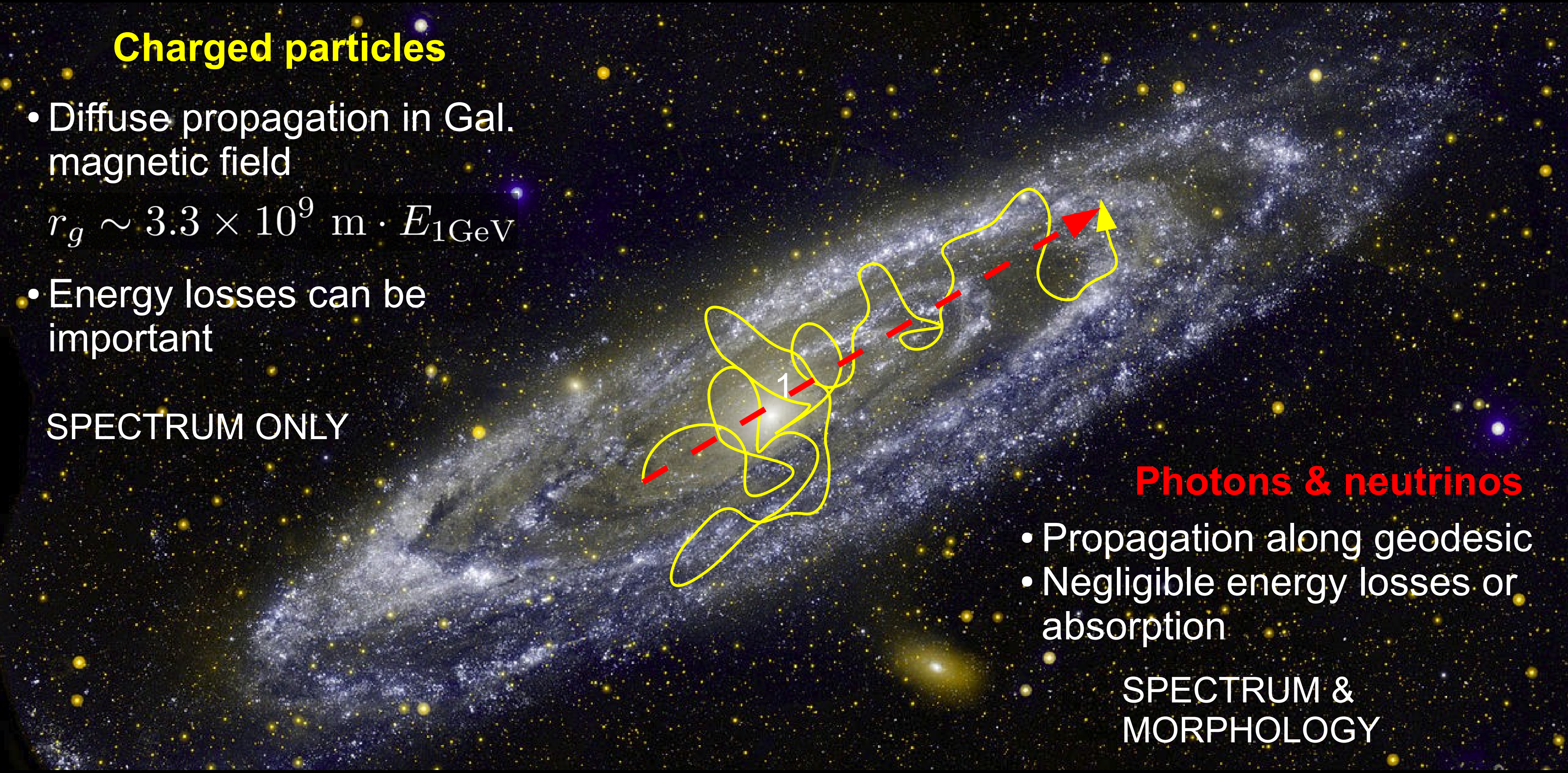
- Cross-section velocity (temperature) dependent
- Resonances close to DM mass
- Coannihilation with other non-SM particles (not present today)

[Bergström, Bringmann & Edsjö (2010)]

Indirect searches

Propagation of messengers from DM

Source term: $$\frac{d^3N_X}{dV\,dt\,dE} = \frac{\langle\sigma v\rangle \boxed{\rho^2_{\rm DM}}}{2m^2_{\rm DM}} \boxed{\frac{dN_X}{dE}}$$



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

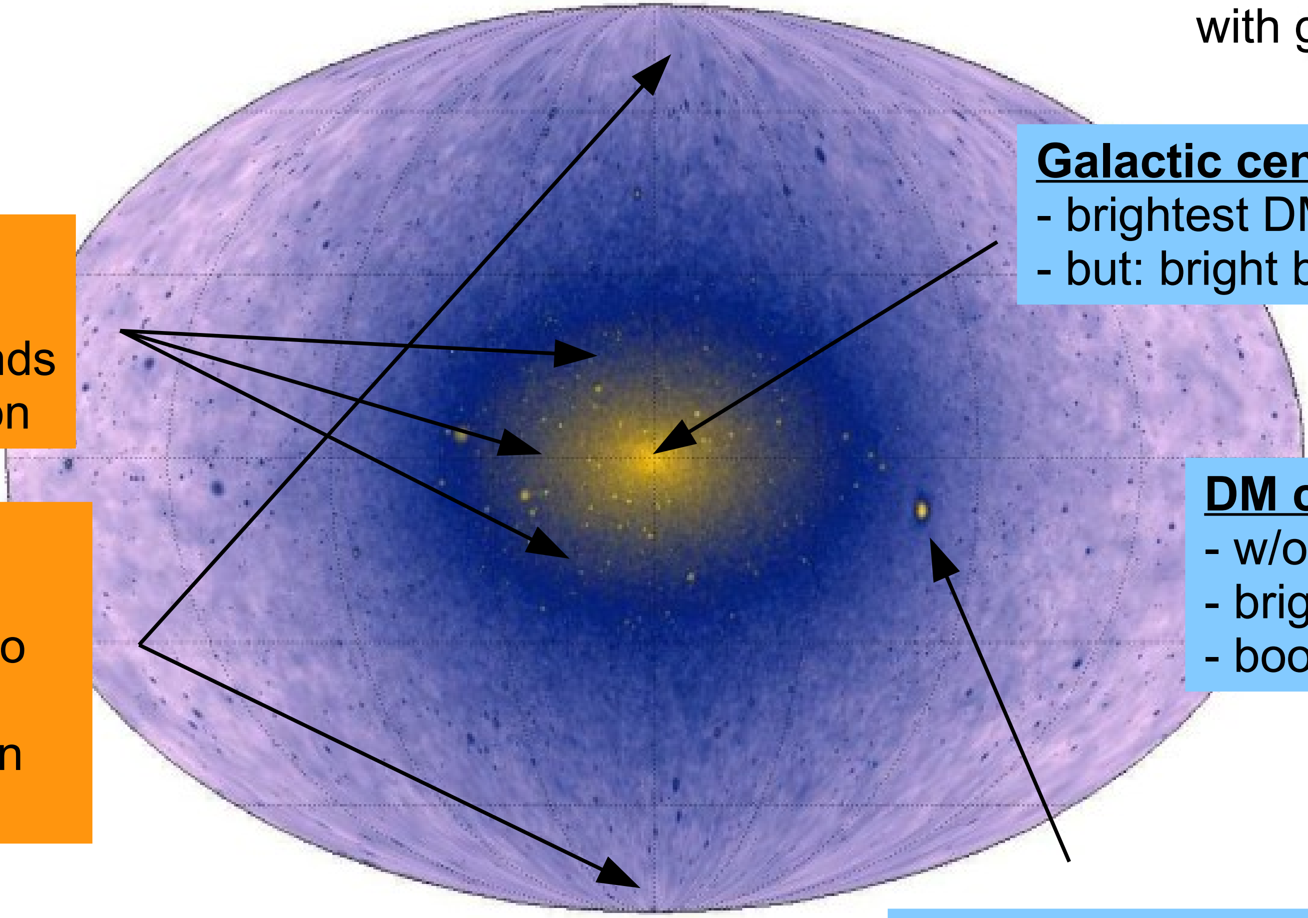
Potential targets for searches with photons

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

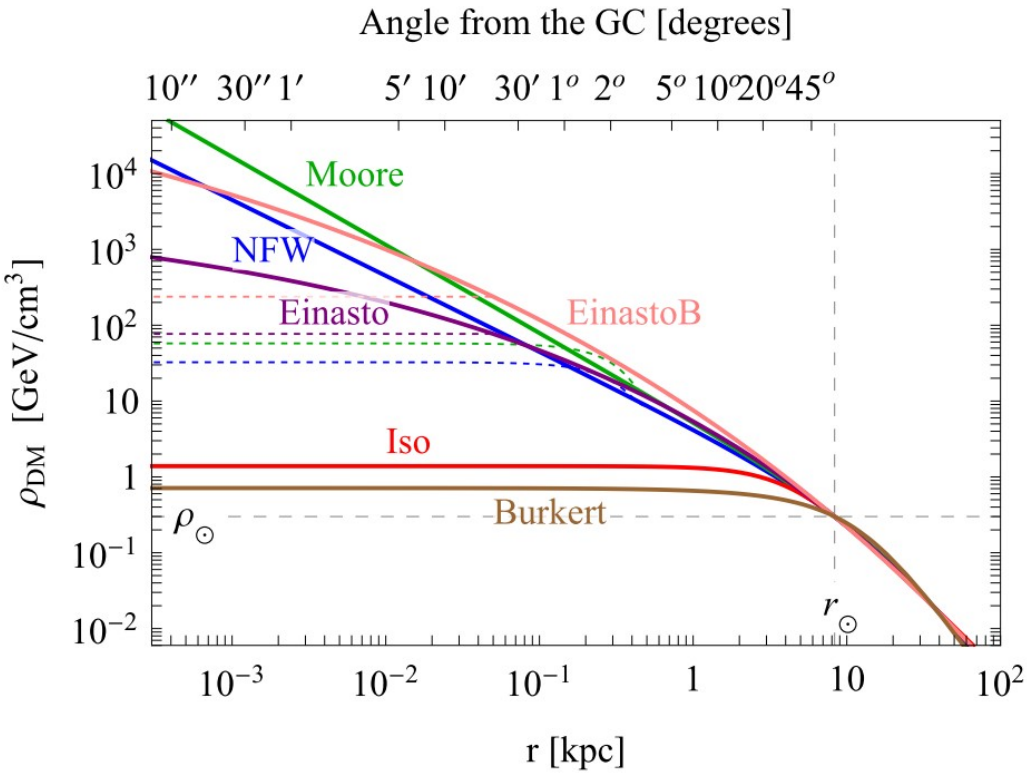
Dwarf Spheroidal Galaxies
- harbour small number of stars
- otherwise dark (no gamma-ray emission)

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

Analytical Dark matter density profiles

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

Viable DM density profiles:



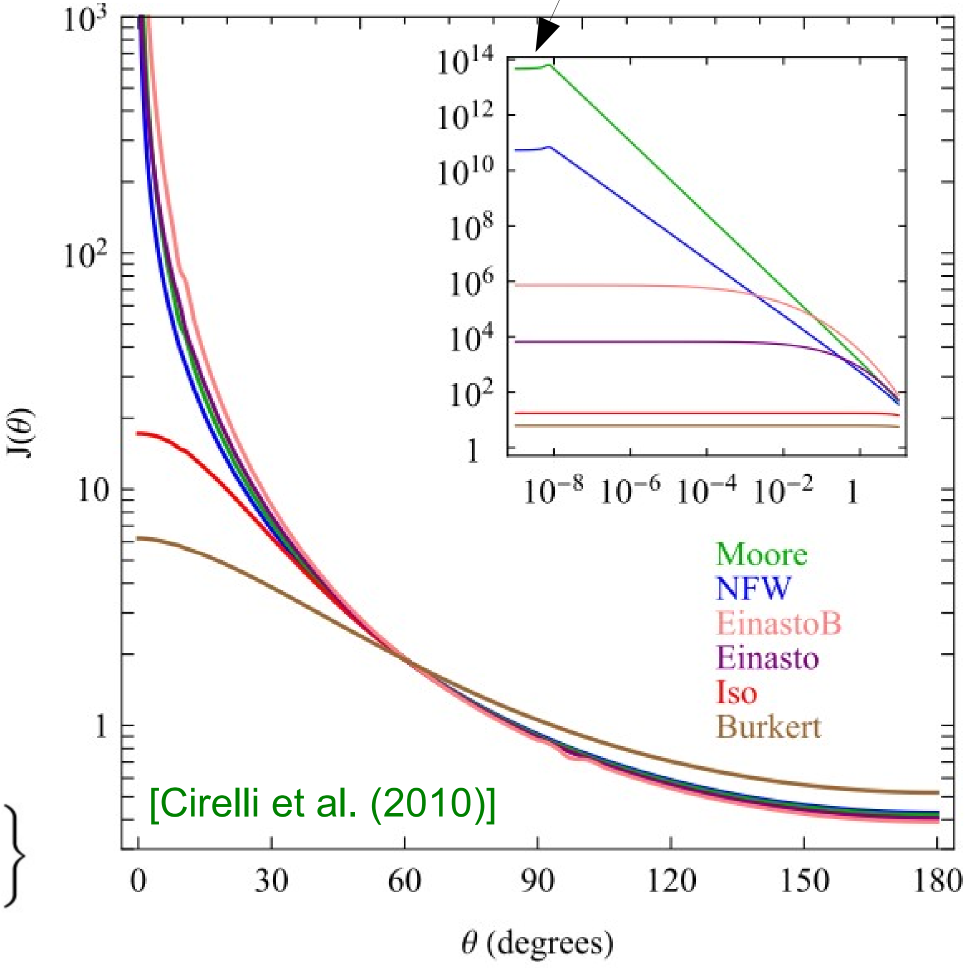
$$\text{NFW}: \quad \rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1+\frac{r}{r_s}\right)^{-2}$$

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

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

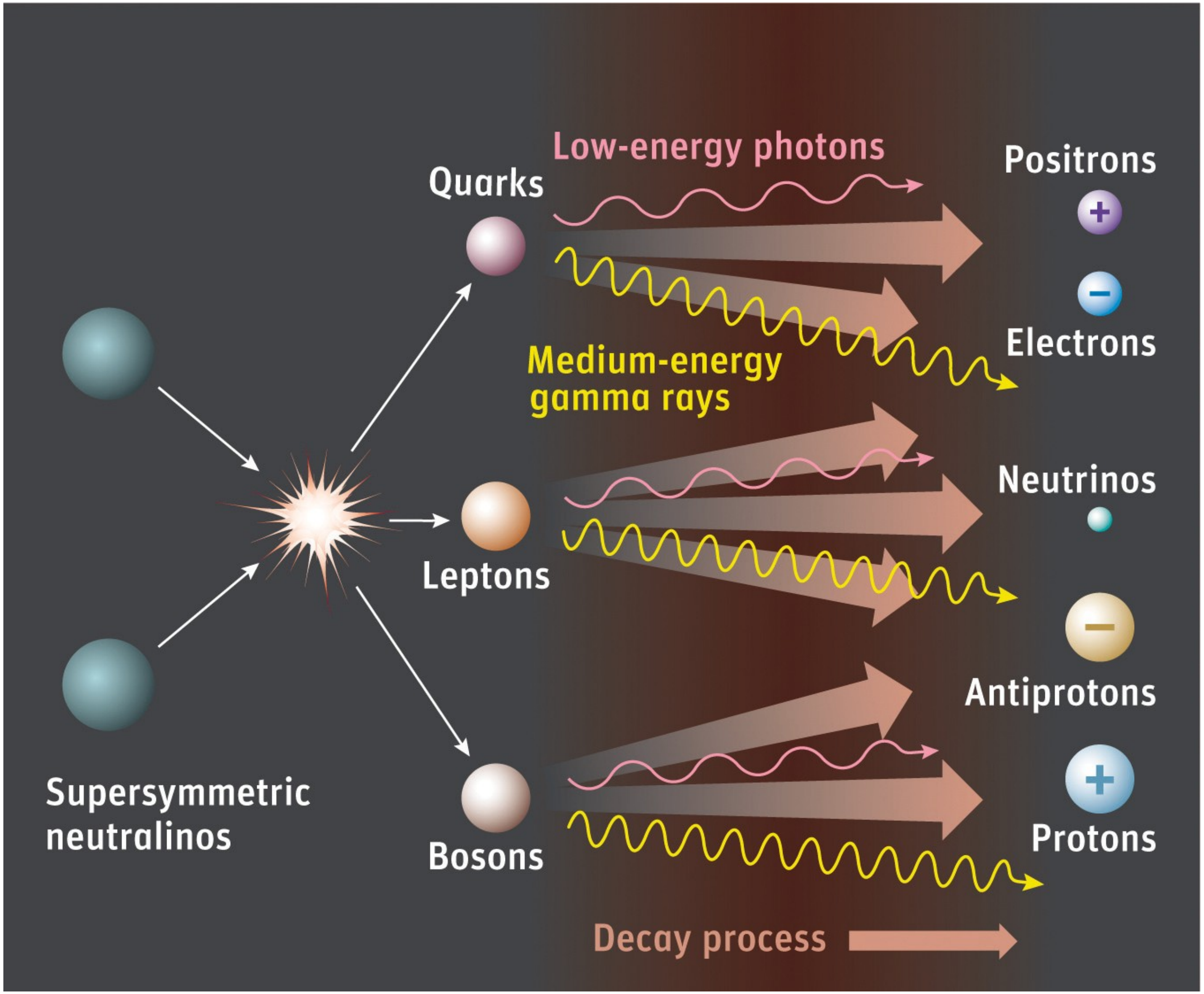
Signal morphology:

Cutoff from self-annihilation



[Cirelli et al. (2010)]

WIMP annihilation cartoon



All relevant information is encoded in the species-dependent energy spectrum.

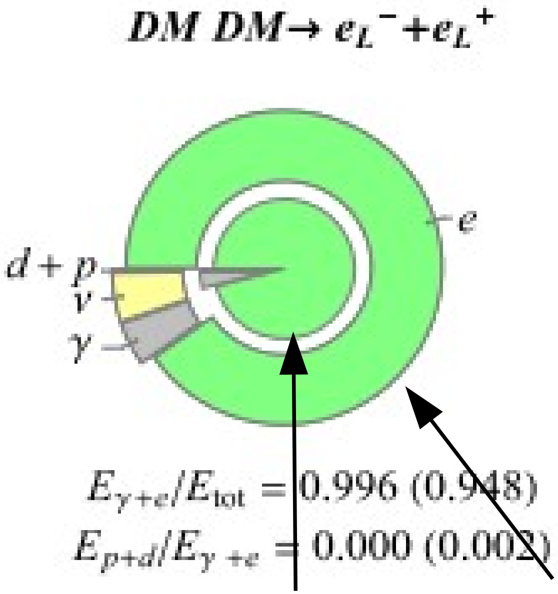
$$\frac{dN_X}{dE}$$

$$X = e^+, \bar{p}, \gamma, \nu, \ldots$$

Channeling of rest-mass energy of DM

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

Leptonic channels

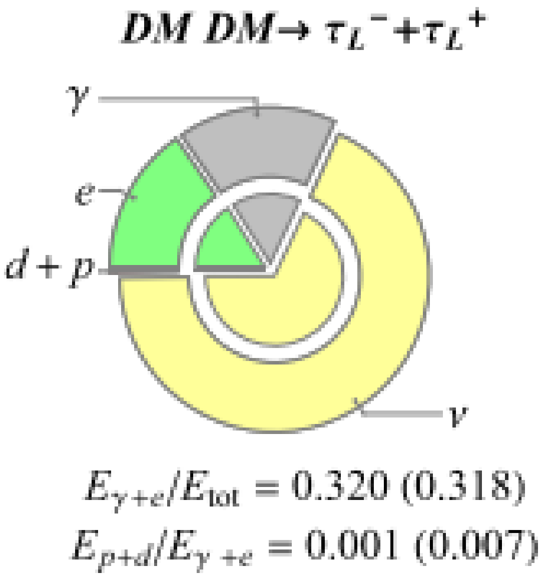


$E_{\gamma+e}/E_{\rm tot} = 0.996\ (0.948)$

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

Few 100 GeV

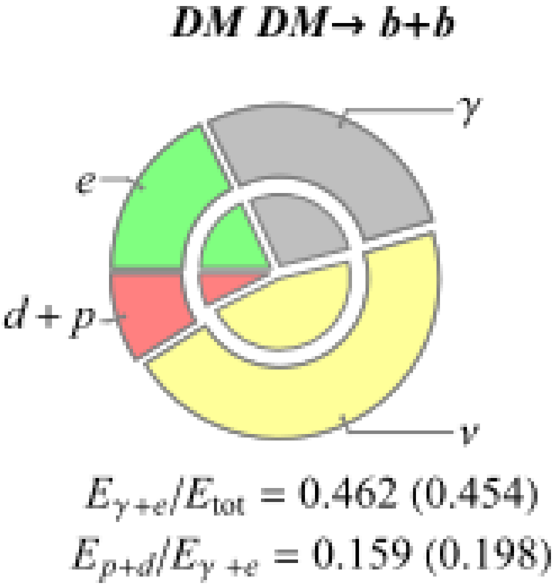
Few TeV



$E_{\gamma+e}/E_{\rm tot} = 0.320\ (0.318)$

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

Hadronic channel



$E_{\gamma+e}/E_{\rm tot} = 0.462\ (0.454)$

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

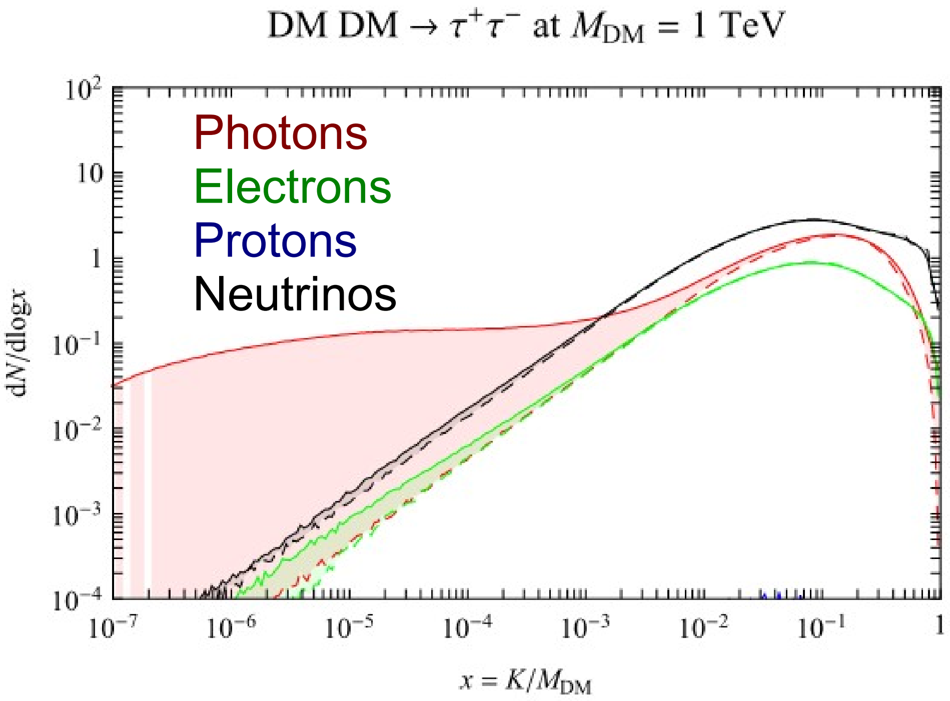
Fractional energy dumped into final states X

$$f_X = \int_0^{m_{\rm DM}} dE \, \frac{E}{2m_{\rm DM}} \frac{dN_X}{dE}$$

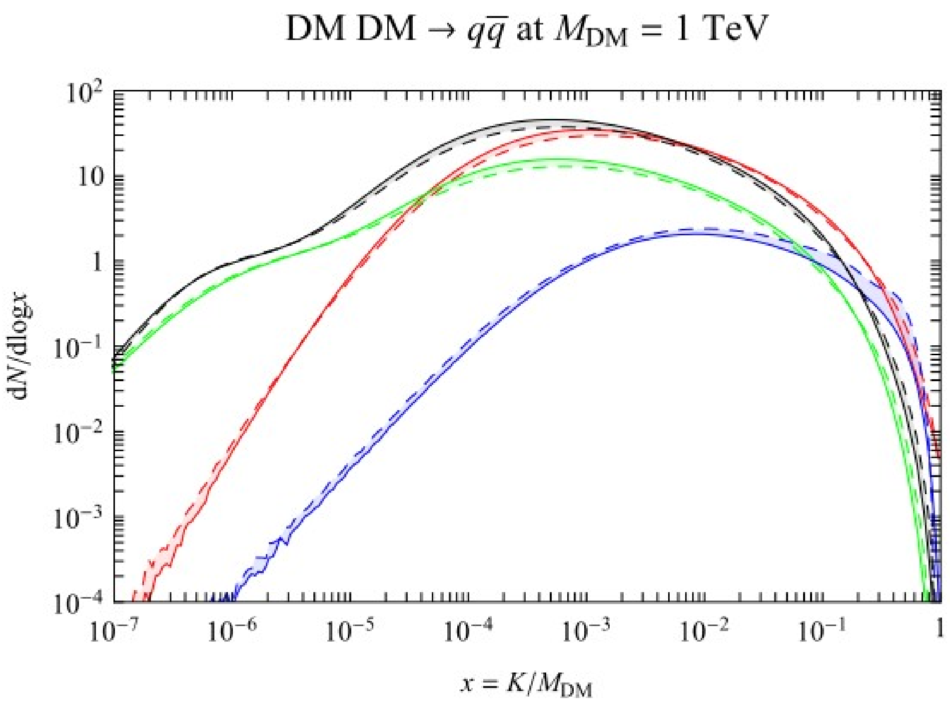
[very useful: Cirelli et al. (2010) “PPPC4DMID”]

Energy spectra of different species

Annihilation into tau leptons



Annihilation into quarks



- Muons/electrons + neutrinos

$$\tau^- \to e^- \bar{\nu}_e \nu_\tau$$
$$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$$

- Pions + Tau neutrino

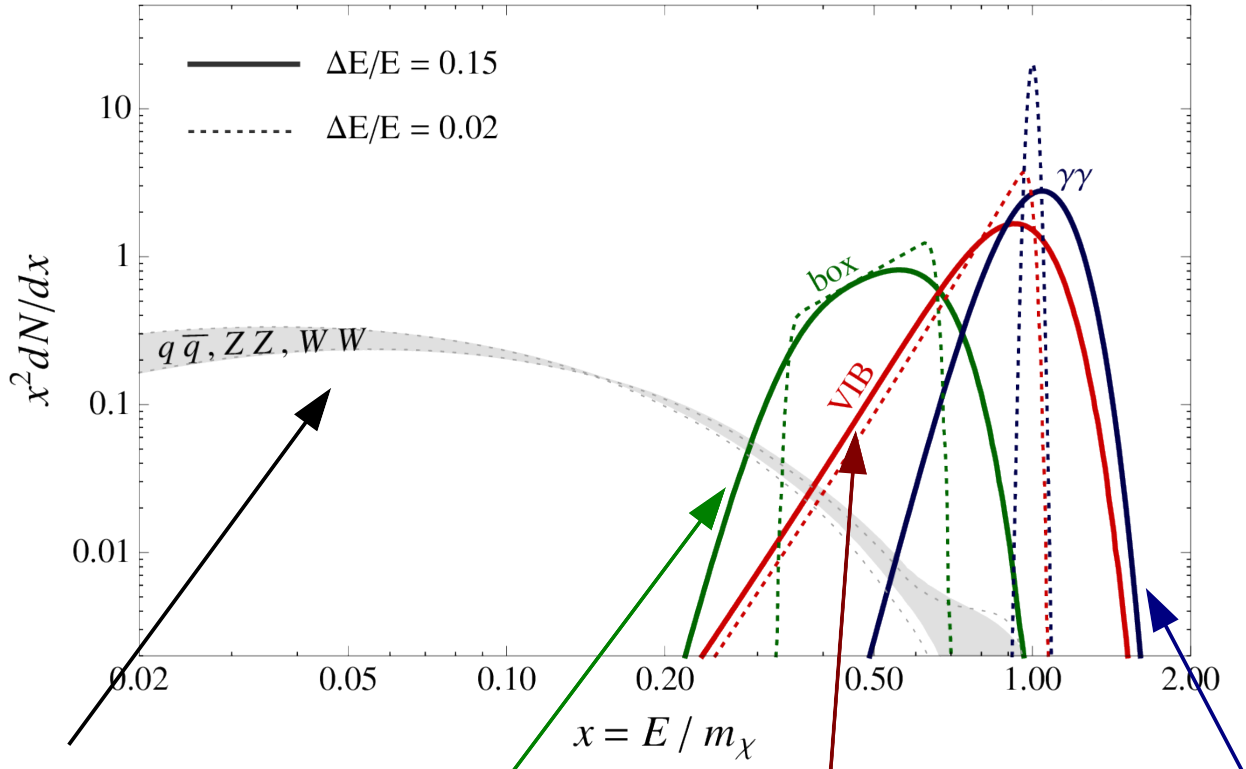
$$\tau^- \to (\pi^0)^n (\pi^+ \pi^-)^m \pi^- \nu_\tau$$

- Cascade processes produces pions

$$\pi^0 \to \gamma\gamma$$

[Cirelli et al. (2010)]

Extra features in case of photons



Bringmann & Weniger (2012)

Continuum emission aka secondary photons

(from hadronic channels, as discussed above)

Cascade decays

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

Internal Bremsstrahlung (IB)

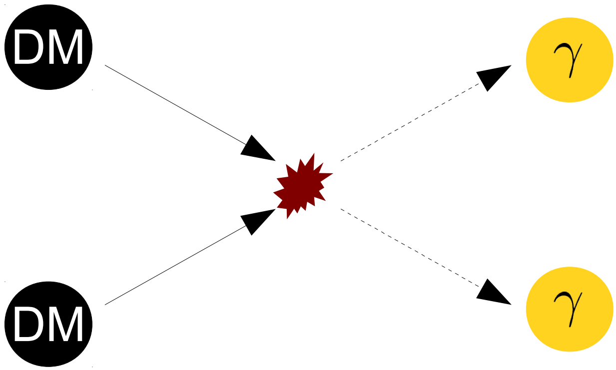
$$\chi\chi \rightarrow \bar{f}f\gamma$$

Gamma-ray lines

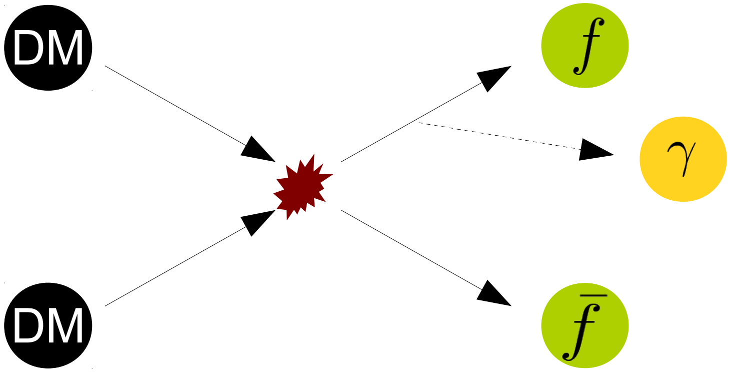
$$\chi\chi \rightarrow \gamma\gamma$$

DM annihilation processes

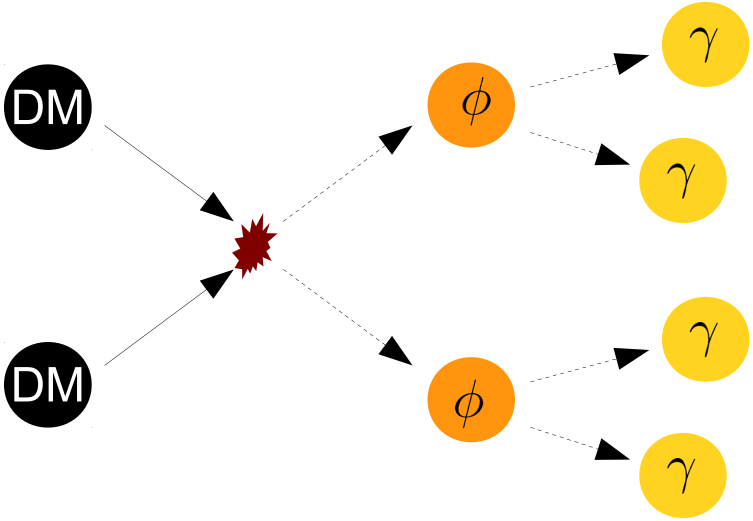
Gamma-ray lines:
Two-body annihilation into photons



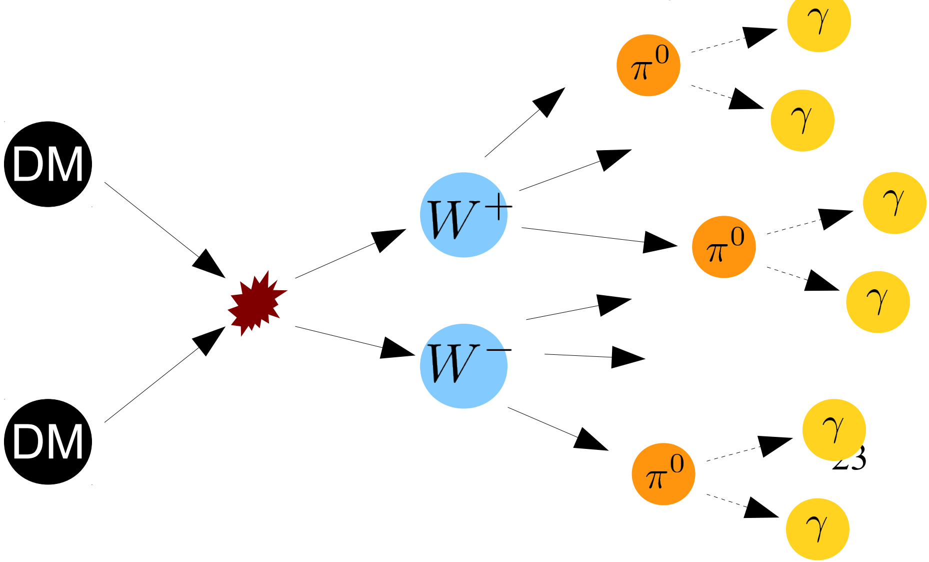
Bremsstrahlung:
Photon production in “hard process”



Box-shaped spectra:
Photons from cascade decay



Continuum emission:
Photons from neutral pion decay

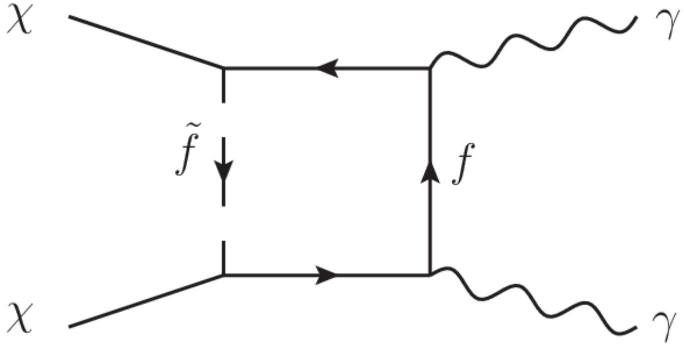


Gamma-ray lines

- produced in two-body annihilation

  $\chi\chi \to \gamma\gamma,\ \gamma Z,\ \gamma h$
- simple energy spectrum

$$\frac{dN}{dE} \propto \delta(E - E_\gamma) \qquad E_\gamma = m_\chi \left(1 - \frac{m_P^2}{4m_\chi^2}\right)$$



[started with Bergström & Snellman (1988)]

Generic branching ratios are discouraging small:

$$\mathrm{BR}(\chi\chi \to \gamma\gamma) \sim \alpha_{\mathrm{em}}^2 \sim 10^{-4}$$

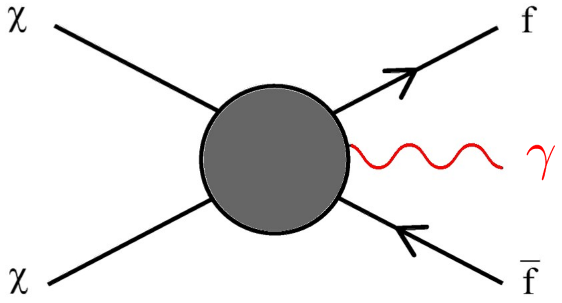
This would be impossible to detect.

BUT: For neutral spin ½ particles, only two-body **decay** mode is: $\chi \to \gamma\nu$

Internal Bremsstrahlung

Charged final states give rise to **internal bremsstrahlung (IB)**

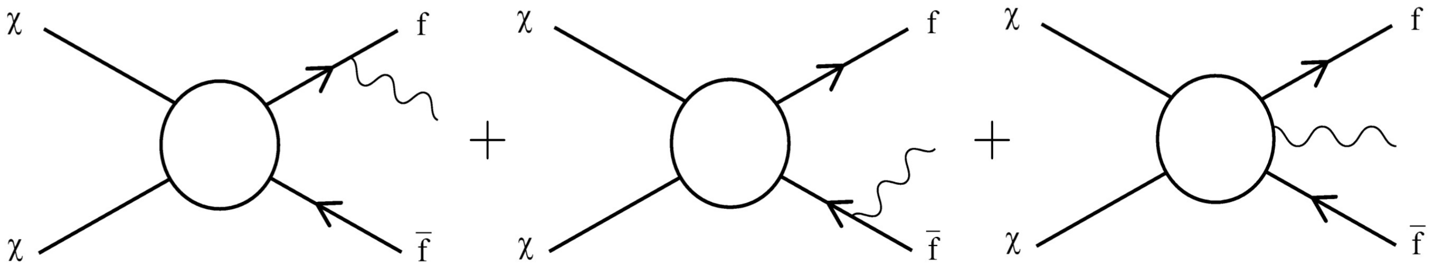
$$\chi\chi \to f\bar{f} \quad \overset{\mathcal{O}(\alpha)}{\Longrightarrow}$$



(here: χ is a Majorana fermion)

Splits up into two contributions:

=



"Final State Radiation"

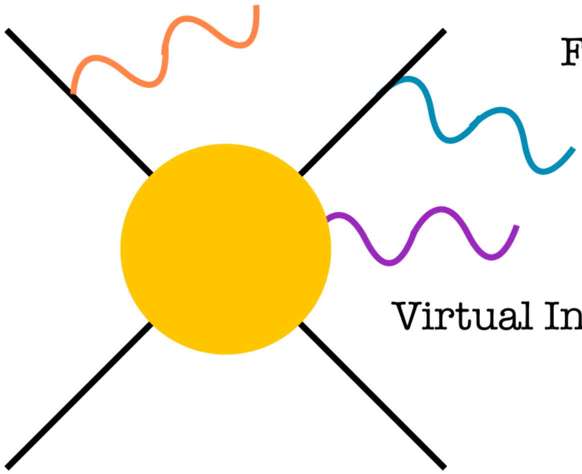
"Virtual Internal Bremsstrahlung"

1^{st} order in $(m_f/m_\chi)^2$

0^{th} order in $(m_f/m_\chi)^2$

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

Electroweak corrections



Initial State Radiation
(ISR)

Final State Radiation
(FSR)

Virtual Internal Bremsstrahlung
(VIB)

$$\chi\chi \to f\bar{F}V$$

$$V = \gamma, Z, W^{\pm}, g$$

- Emission of W, Z ⟶ multi-messenger signal.
- Enhancement mechanisms:
  - FSR: logarithmic enhancement from soft and collinear bosons.
  - VIB & ISR: lifting of helicity suppression.
- More stable particles in the low-energy tail of the energy spectrum.

Courtesy F. Calore

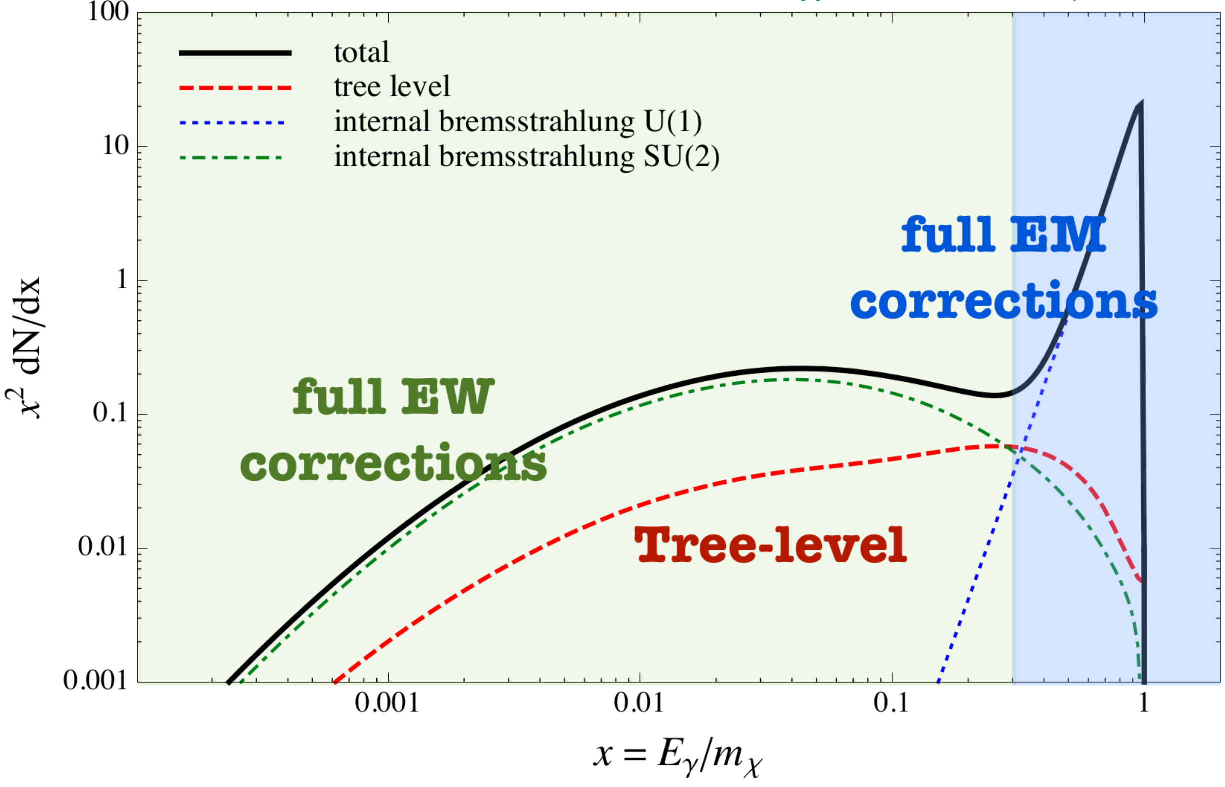
Electroweak corrections

- Current discussion:
  - Specific models corresponding to some MSSM neutralino limit (*i.e.* bino, wino, higgsino).

    Kachelrieß et al., PRD'09, Bell et al., PRD'11, Garny et al., JCAP'11, '12
  - Rather model-independent approaches (*e.g.* effective field theory operaters).

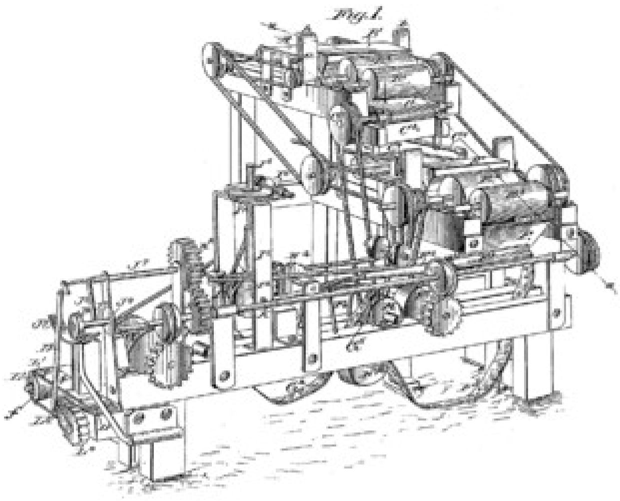
    Ciafaloni et al., JCAP'11, '12
  - First fully general calculation of EW corrections for neutralino DM annihilation in the framework of the MSSM.

Bringmann&Calore, PRL'14



Courtesy F. Calore

The DM indirect search machinery



Some piece of new data.

Excess is observed above the expected background.

Particle theorists build many models ("signal building") to explain excess in terms of DM annihilation or decay.

Theoretical models make additional predictions.

In conflict with obs.

More baroque DM models.

(most typical outcome)

Observed

Corroborating evidence for DM.

Strong evidence for DM.

(haven't been here so far)

Can it be fully explained by astrophysics?

Probably not

Excellent.

Maybe yes

Damn. (still interesting for astronomy friends)

Rest of the lecture:

1) Gamma-ray lines

2) Anti-protons

3) Positrons

4) Neutrinos

5) Gamma-ray continuum

1) Gamma-ray lines

The smoking gun.

Current gamma-ray experiments

GeV to TeV energy range

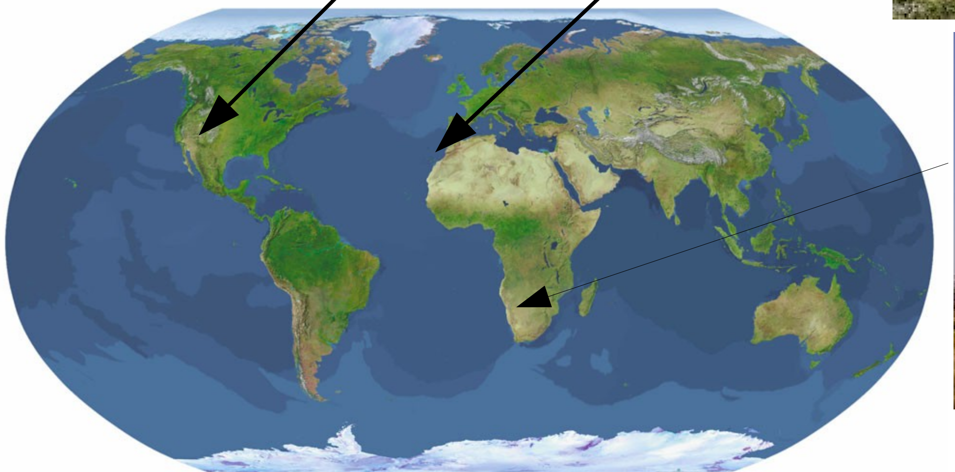
Space based:
(Pair conversion detector)

Fermi LAT
since 2008

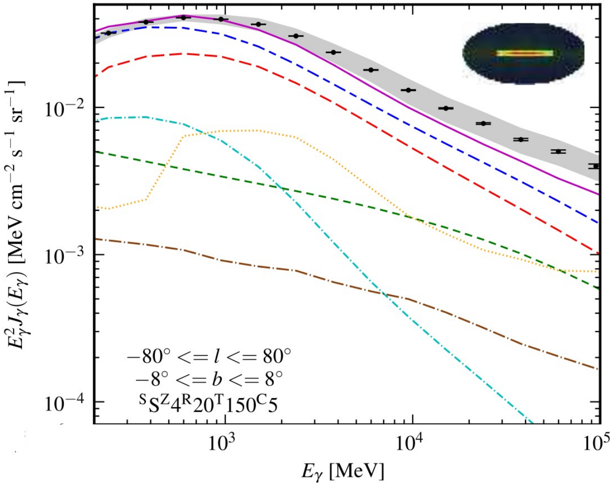
A_{eff}~1m^2
T~<10yr
20 MeV – 300 GeV

Ground based:
(Atmospheric Cherenkov Telescopes)

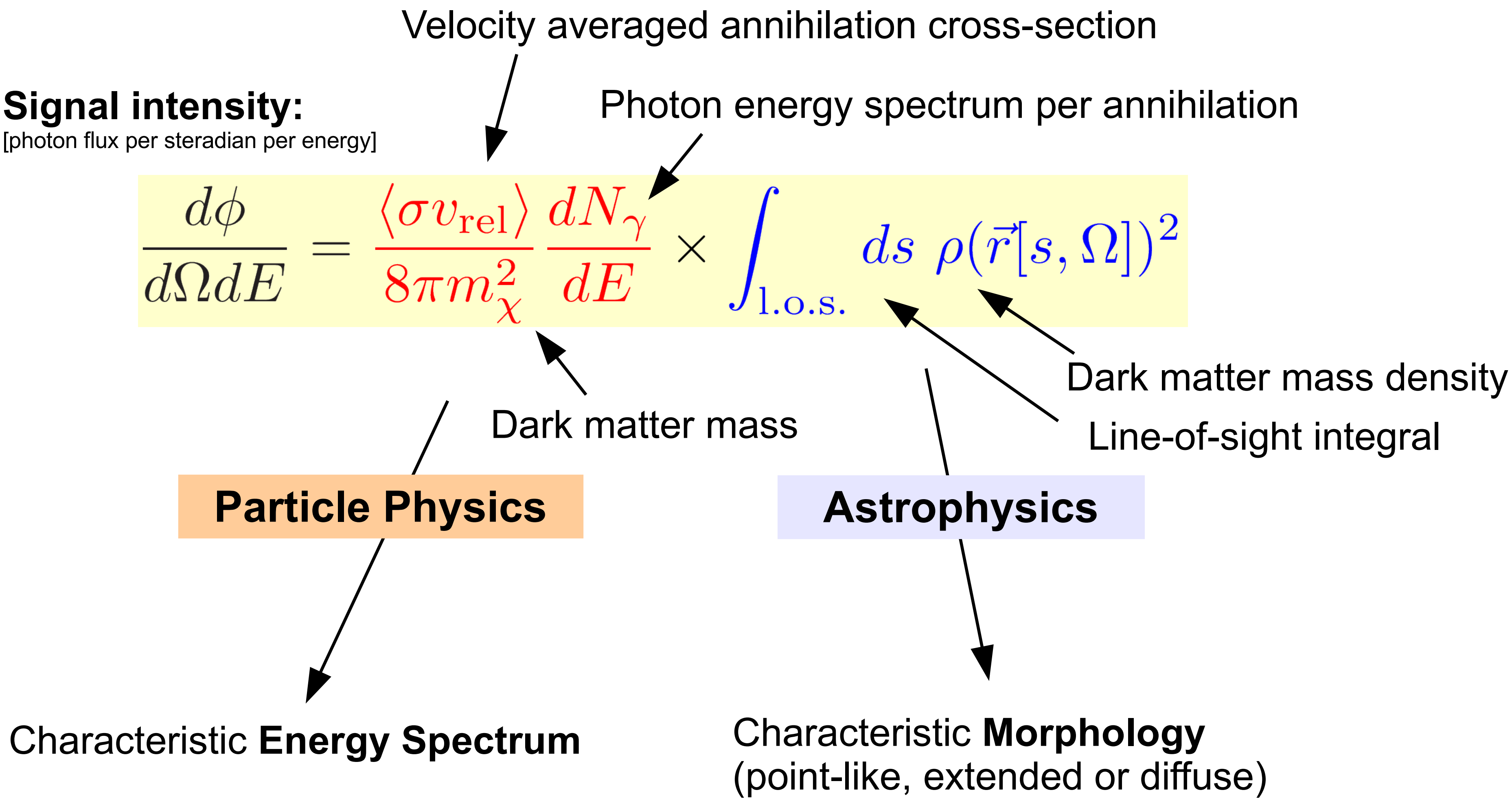
A_{eff}~1km^2
T~<100h
>10 GeV



Fluxes are falling rapidly with increasing energy
High energy measurements require huge collection areas



The gamma-ray signal flux



Signal intensity:
[photon flux per steradian per energy]

Velocity averaged annihilation cross-section

Photon energy spectrum per annihilation

$$\frac{d\phi}{d\Omega dE} = \frac{\langle \sigma v_{\rm rel} \rangle}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} ds \; \rho(\vec{r}[s,\Omega])^2$$

Dark matter mass

Dark matter mass density

Line-of-sight integral

Particle Physics

Astrophysics

Characteristic **Energy Spectrum**

Characteristic **Morphology**
(point-like, extended or diffuse)

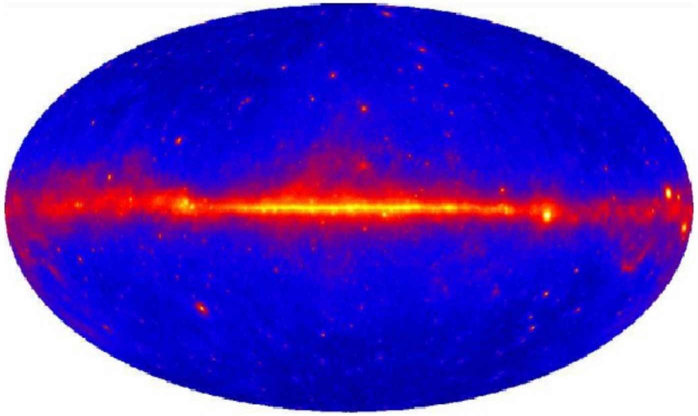
In case of gamma-ray lines:

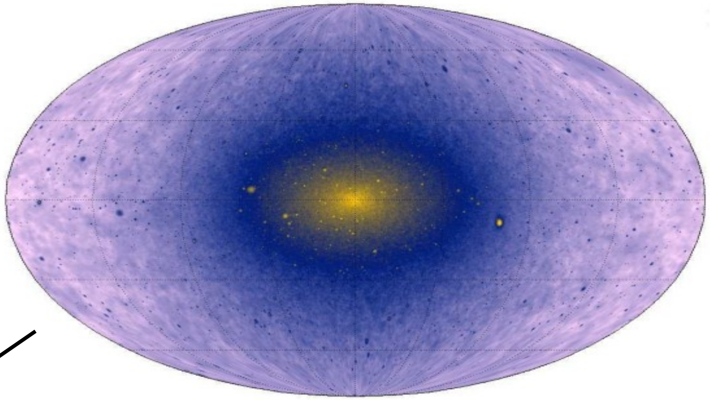
$$\frac{dN_\gamma}{dE} = 2\,\delta(E - m_{\rm dm})$$

It is convenient to define a “J-value”:

$$J_{\Delta\Omega} \equiv \int_{\Delta\Omega} d\Omega \int_{\rm l.o.s.} ds \rho(r[s,\vec{\Omega}])^2$$

Regions of interest for line searches



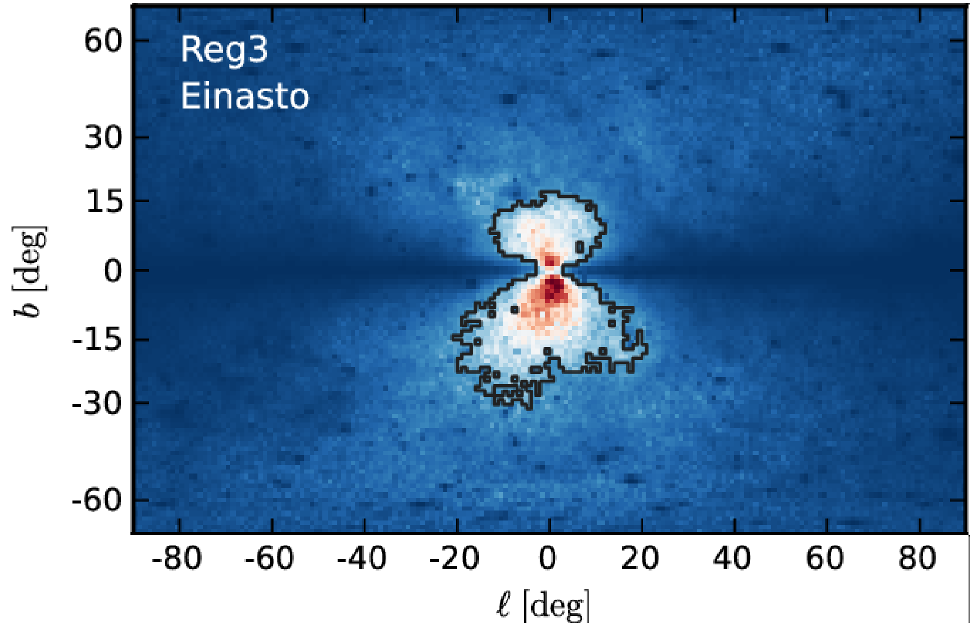


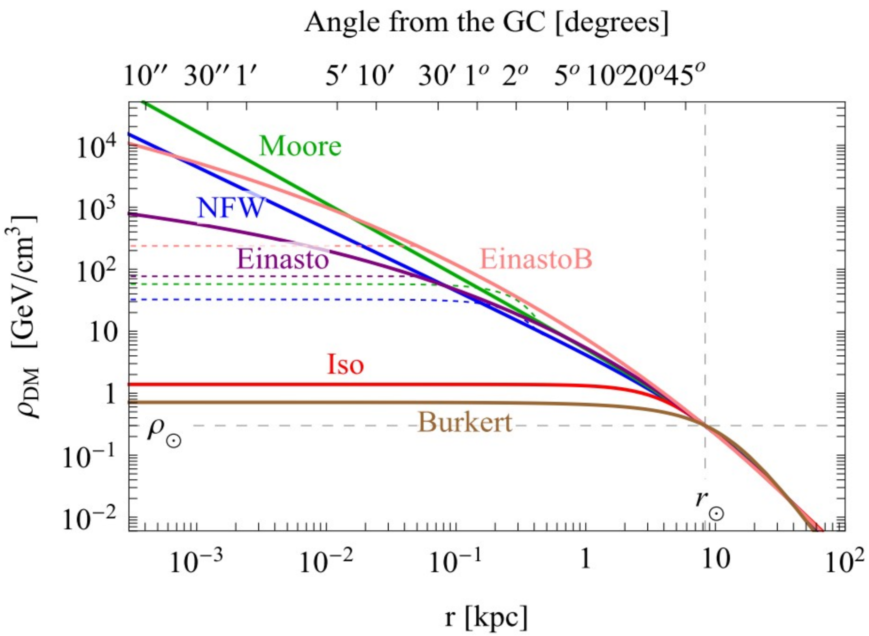
Signal

DM profile

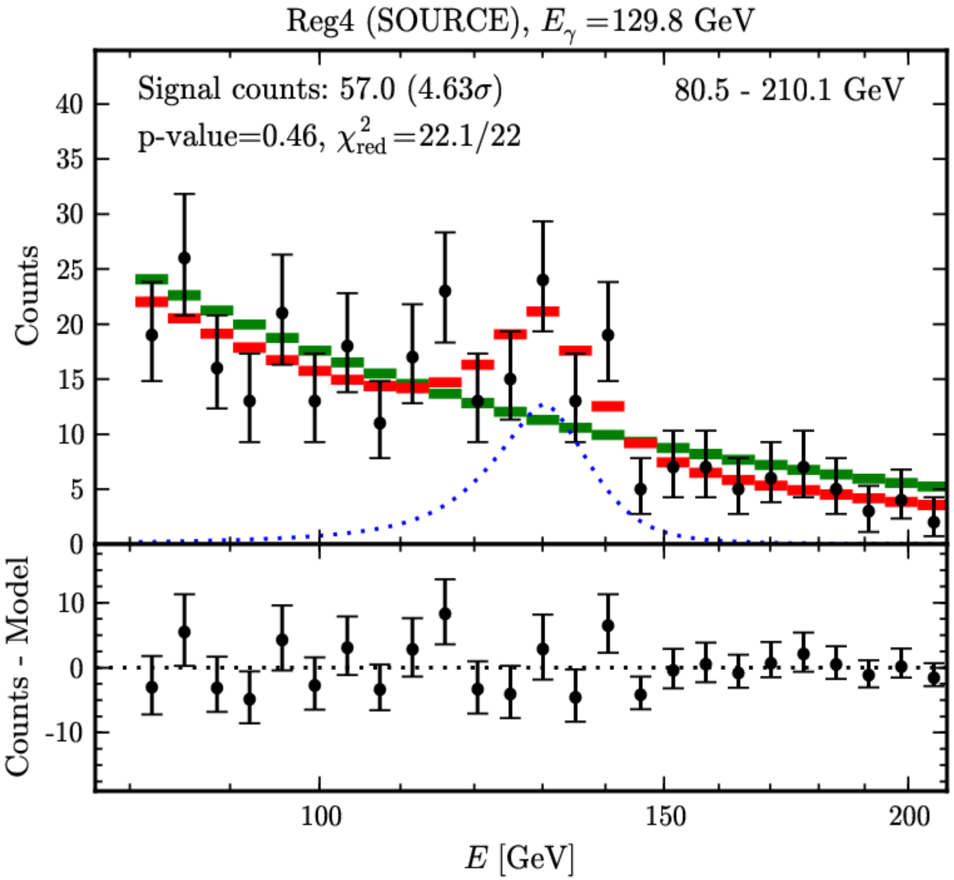
Background

Region with optimal signal/noise: $\frac{N_S}{\sqrt{N_B}}$





Early 2012: A gamma-ray line signal at 130 GeV?



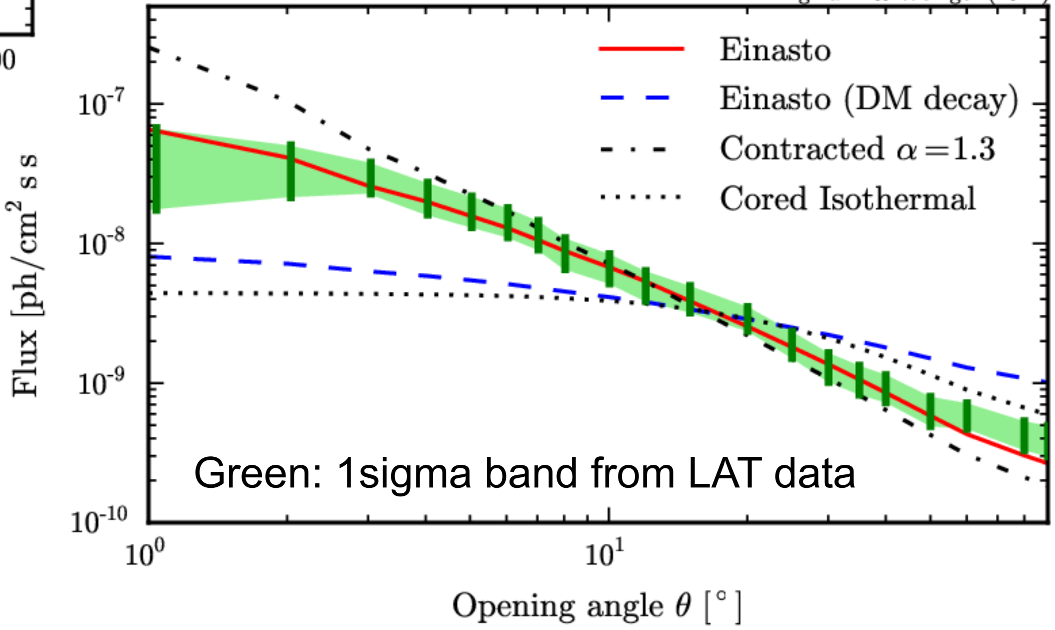
[Bringmann *et al.*; CW; 2012]

<u>Using:</u>
43 months of SOURCE class events (P7V6)

we found a line-like excess at 130 GeV with local significance of 4.6 sigma
(→ global significance 3.2 sigma)

Morphology largely compatible with Einasto/NFW profile:

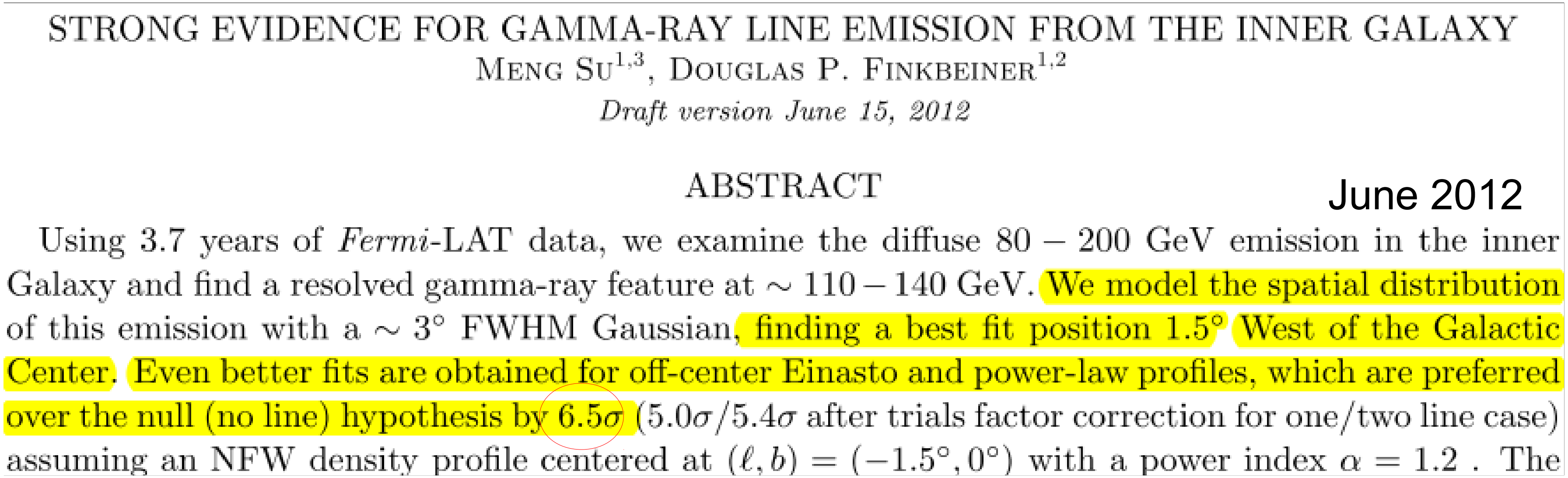
Bringmann & Weniger (2012)



Green: 1sigma band from LAT data

Many follow up studies

Many more great papers: Profumo, Linden, JCAP 1207 (2012) 011; Ibarra, Gehler, Pato, JCAP 1207 (2012) 043; Dudas et al., arXiv:1205.1520; Cline, PRD86 (2012) 015016; Choi, Seto, PRD86 (2012) 043515; Kyae, Park, arXiv:1205.4151; Lee, Park, Park, arXiv:1205.4675; Boyarsky, Malyshev, Ruchayskiy, arXiv:1205.4700; Rajaraman, Tait, Whiteson, arXiv:1205.4723; Acharya et al., arXiv:1205.5789; Buckley, Hooper, PRD86 (2012) 043524; Geringer-Samet, Koushiappas, PRD86 (2012) 021302; Li, Yuan, PLB715 (2012) 35; Chu et al., arXiv:1206.2279; Das, Ellwanger, Mitropoulos, JCAP 1208 (2012) 003; Kang et al., arXiv:1206.2863; Weiner, Yavin, arXiv:1206.2910...



STRONG EVIDENCE FOR GAMMA-RAY LINE EMISSION FROM THE INNER GALAXY

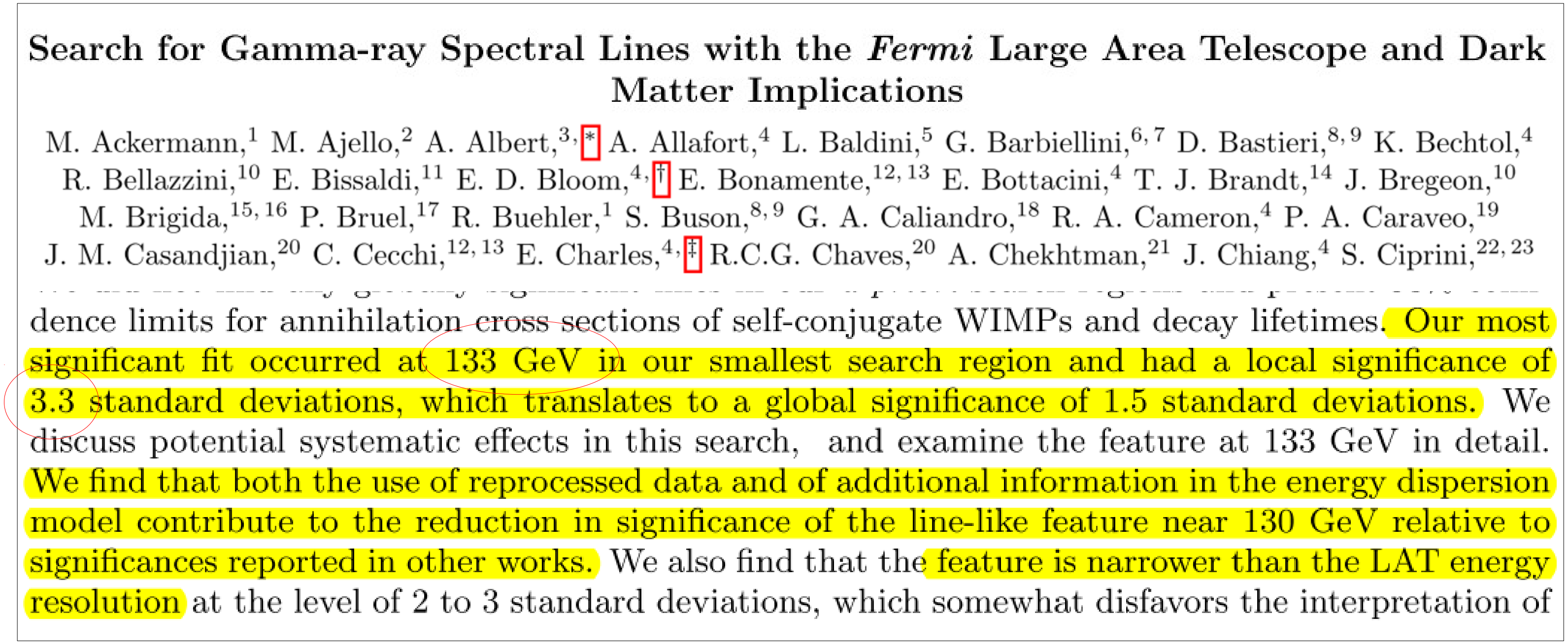
Meng Su[1,3], Douglas P. Finkbeiner[1,2]

Draft version June 15, 2012

ABSTRACT

June 2012

Using 3.7 years of *Fermi*-LAT data, we examine the diffuse 80 – 200 GeV emission in the inner Galaxy and find a resolved gamma-ray feature at ∼ 110 – 140 GeV. We model the spatial distribution of this emission with a ∼ 3° FWHM Gaussian, finding a best fit position 1.5° West of the Galactic Center. Even better fits are obtained for off-center Einasto and power-law profiles, which are preferred over the null (no line) hypothesis by 6.5σ ($5.0\sigma/5.4\sigma$ after trials factor correction for one/two line case) assuming an NFW density profile centered at $(\ell, b) = (-1.5°, 0°)$ with a power index $\alpha = 1.2$. The

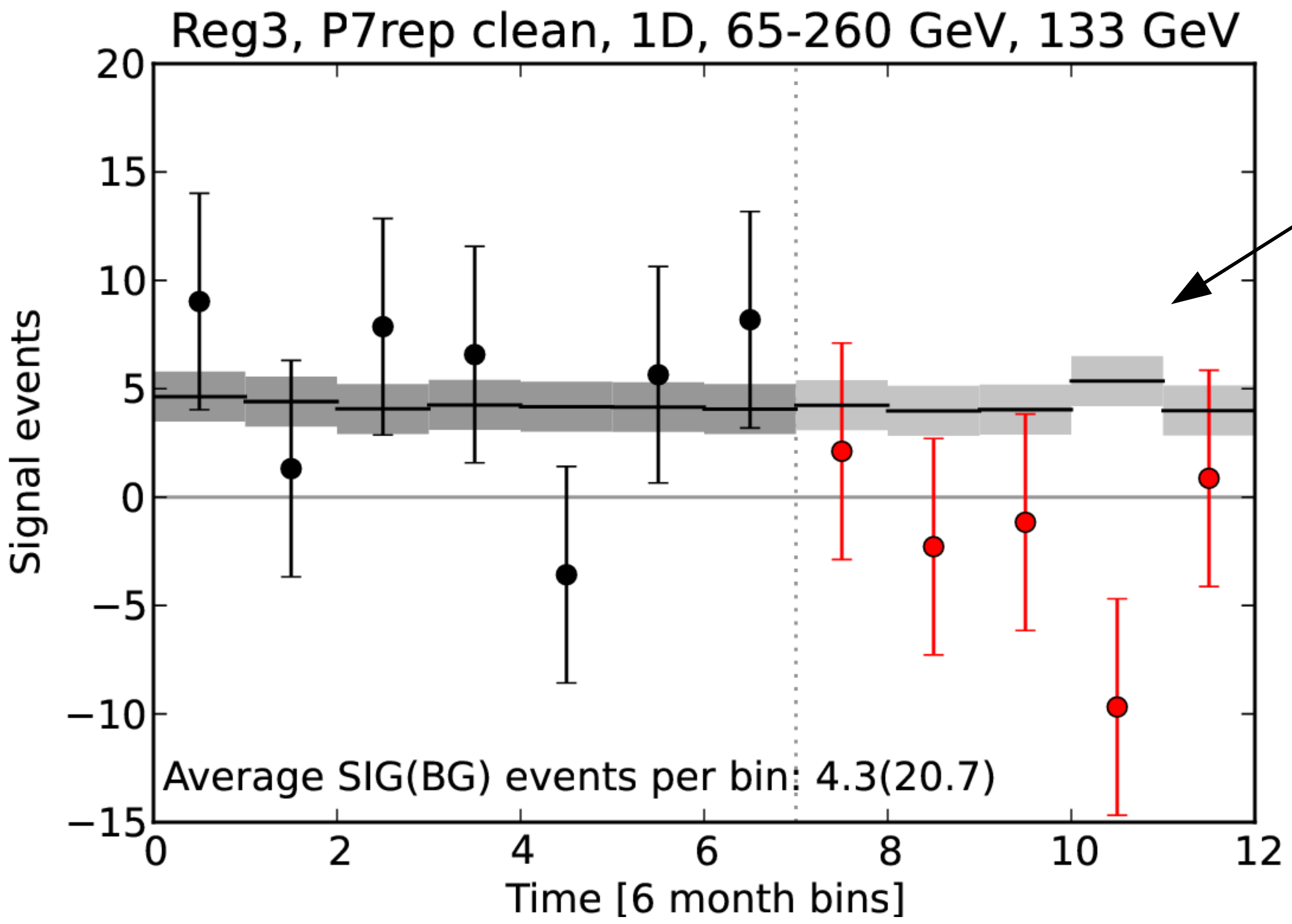


Search for Gamma-ray Spectral Lines with the *Fermi* Large Area Telescope and Dark Matter Implications

M. Ackermann,[1] M. Ajello,[2] A. Albert,[3,*] A. Allafort,[4] L. Baldini,[5] G. Barbiellini,[6,7] D. Bastieri,[8,9] K. Bechtol,[4] R. Bellazzini,[10] E. Bissaldi,[11] E. D. Bloom,[4,†] E. Bonamente,[12,13] E. Bottacini,[4] T. J. Brandt,[14] J. Bregeon,[10] M. Brigida,[15,16] P. Bruel,[17] R. Buehler,[1] S. Buson,[8,9] G. A. Caliandro,[18] R. A. Cameron,[4] P. A. Caraveo,[19] J. M. Casandjian,[20] C. Cecchi,[12,13] E. Charles,[4,‡] R.C.G. Chaves,[20] A. Chekhtman,[21] J. Chiang,[4] S. Ciprini,[22,23]

dence limits for annihilation cross sections of self-conjugate WIMPs and decay lifetimes. Our most significant fit occurred at 133 GeV in our smallest search region and had a local significance of 3.3 standard deviations, which translates to a global significance of 1.5 standard deviations. We discuss potential systematic effects in this search, and examine the feature at 133 GeV in detail. We find that both the use of reprocessed data and of additional information in the energy dispersion model contribute to the reduction in significance of the line-like feature near 130 GeV relative to significances reported in other works. We also find that the feature is narrower than the LAT energy resolution at the level of 2 to 3 standard deviations, which somewhat disfavors the interpretation of

But: <u>No</u> signal photons since Summer 2012



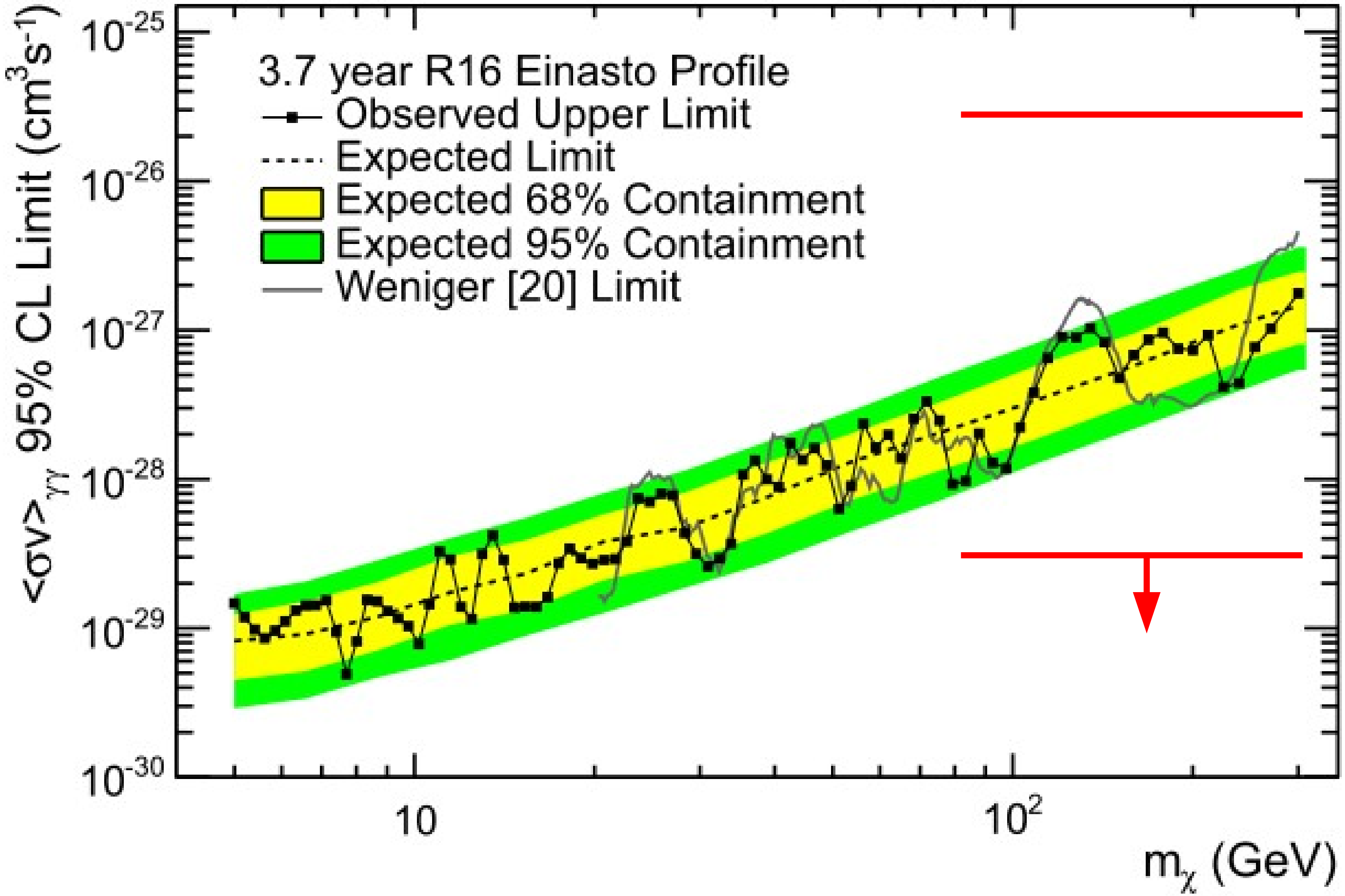
Fresh data

P-value (assuming P7rep best-fit; 21.5±11.2 expected, -9.0 observed):

$$p \lesssim 0.001$$

Using Fermi LAT data alone, the signal hypothesis can be excluded at more than 3 sigma.

Upper limits & loop-suppression



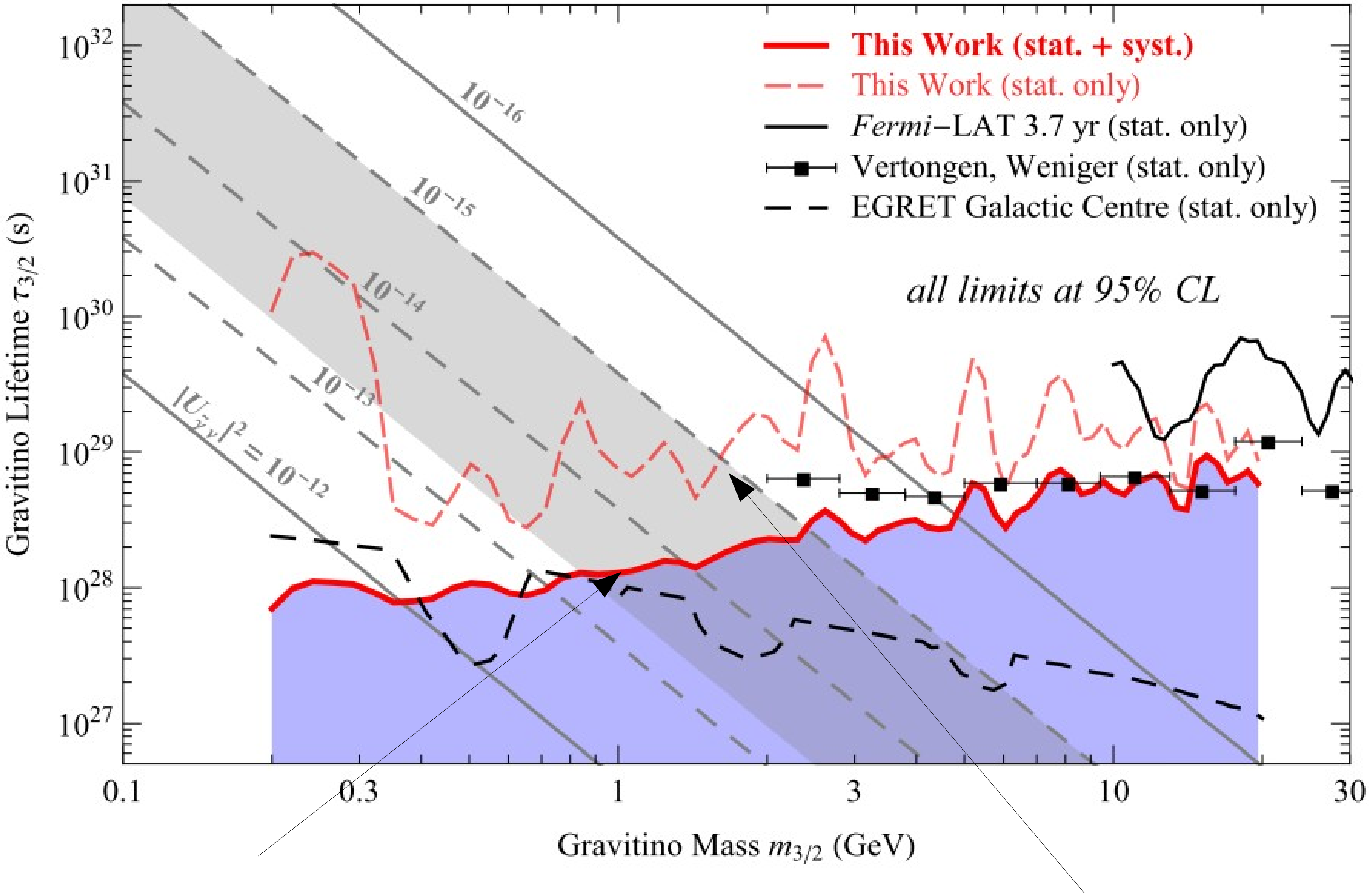
“Thermal cross-section”

Typical branching into gamma lines

- Limits are nominally extremely strong
- But: expected branching ratio is very small in most cases

Searches at lower DM mass

Albert et al., 2014

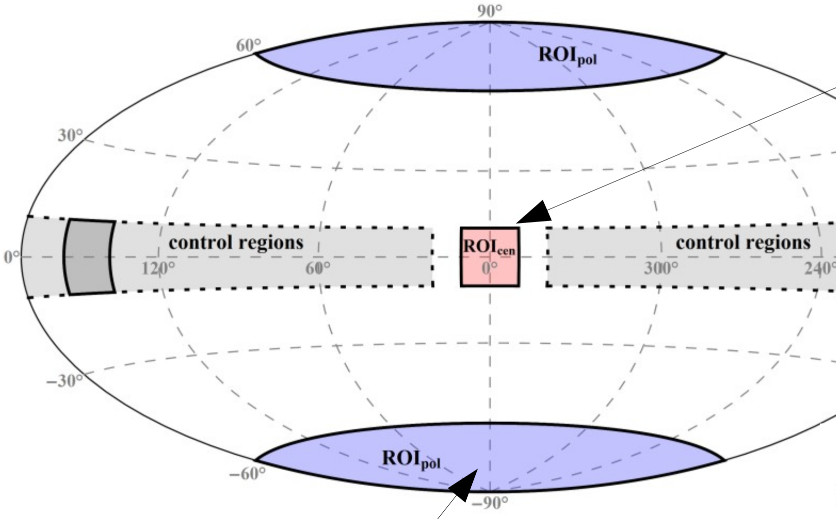


Our result when main systematics are taken into account.

Purely statistical

- First study that consistently takes into account systematics
- We slightly improve over previous limits from EGRET

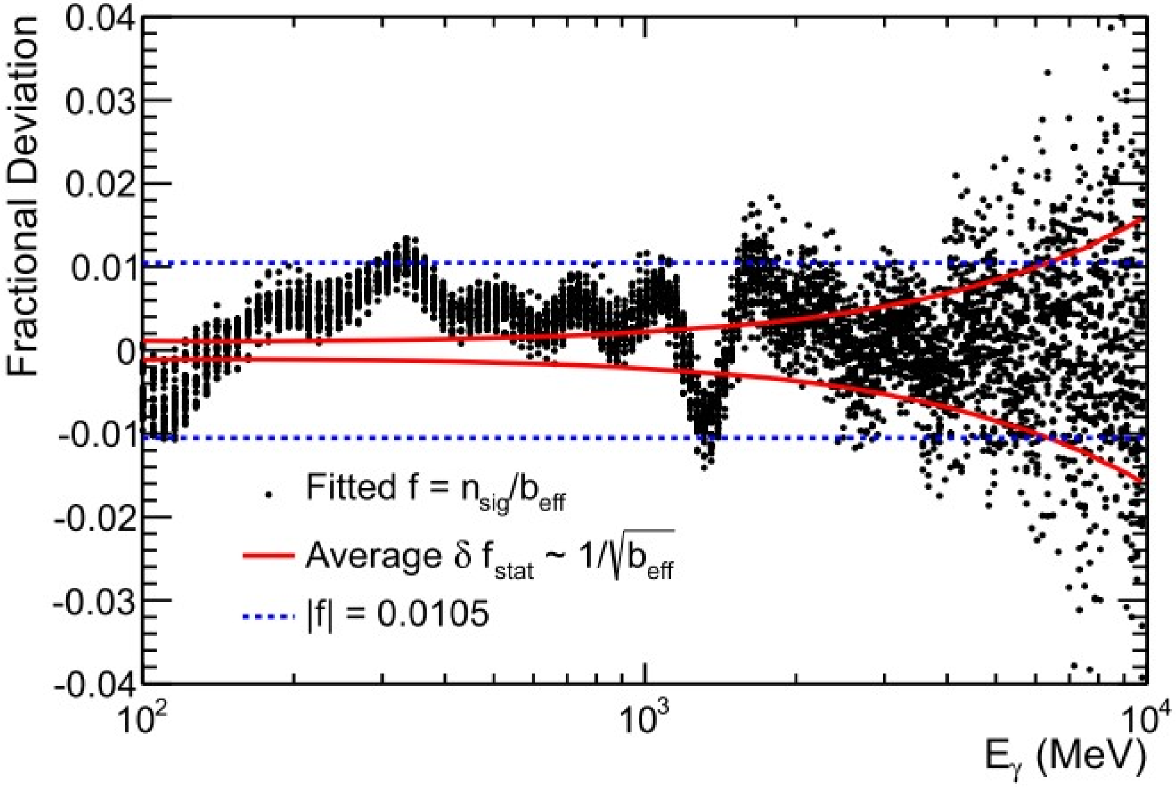
Systematics at low energies



ROI for DM annihilation.

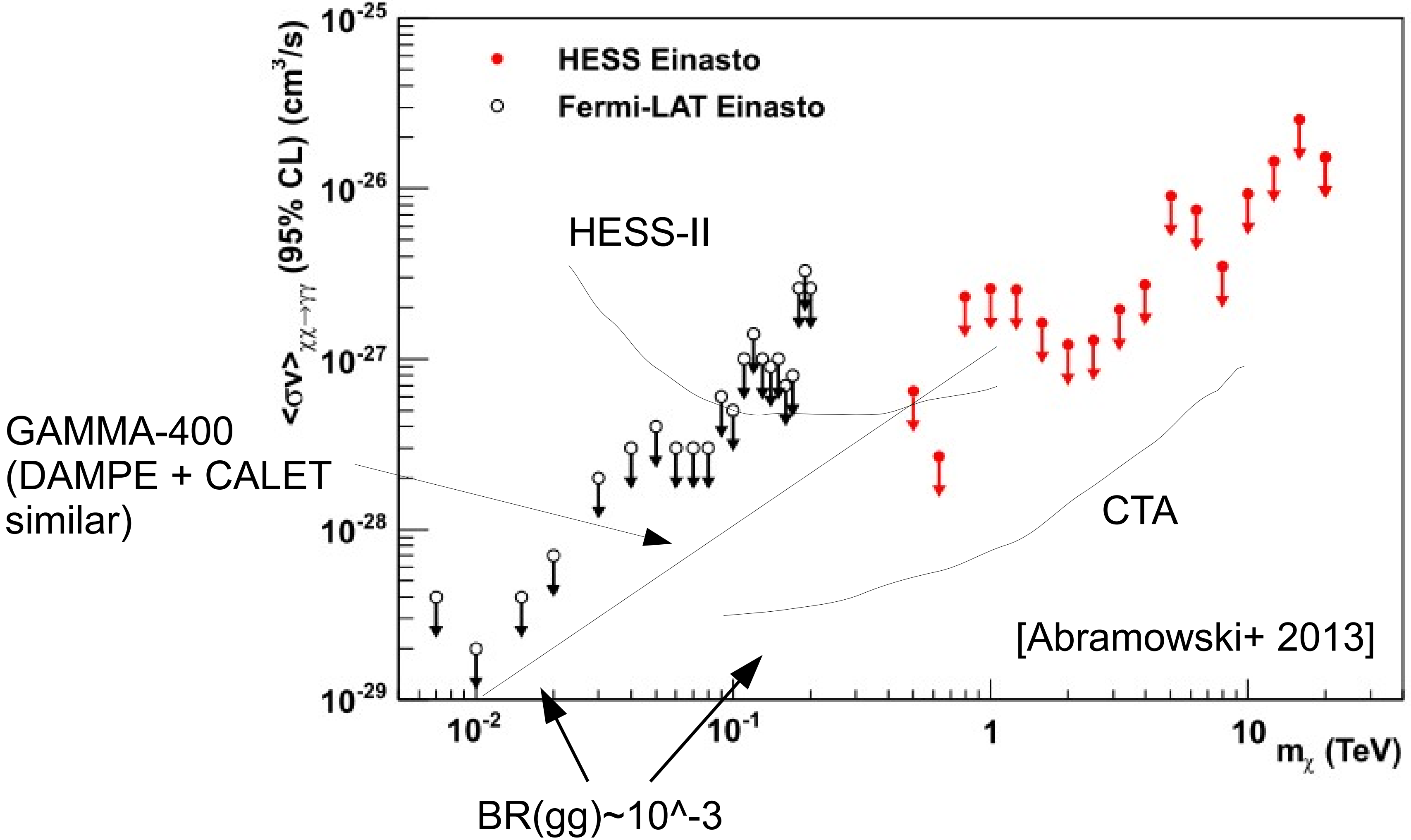
Galactic disk can be used as control region.

ROI for DM decay.



$$\mathcal{L}(\alpha, \Gamma, n_{\rm sig}, n_{\rm syst}) = P_{\mathcal{F}}(n_{\rm syst}, b_{\rm eff}) \prod_i P(c_i | \mu_i(\alpha, \Gamma, n_{\rm sig} + n_{\rm syst}))$$

Future prospects



HESS-II

GAMMA-400
(DAMPE + CALET
similar)

CTA

[Abramowski+ 2013]

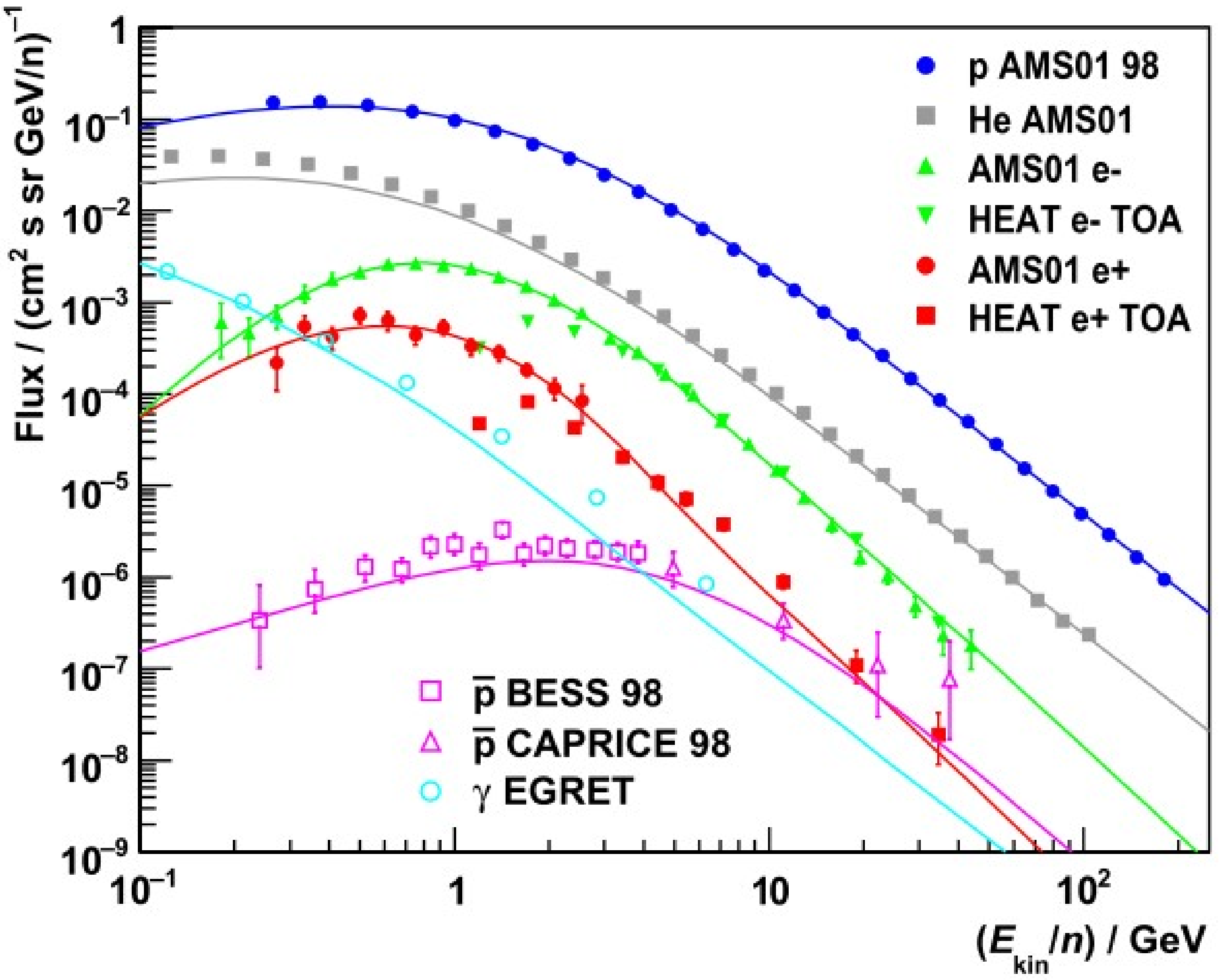
BR(gg)~10^-3

CTA: G. Pedaletti, Talk in Trieste Sep 2013
GAMMA-400 & HESS-II: Bergström+ 2012
DAMPE (and CALET) similar to GAMMA-400

2) Anti-protons

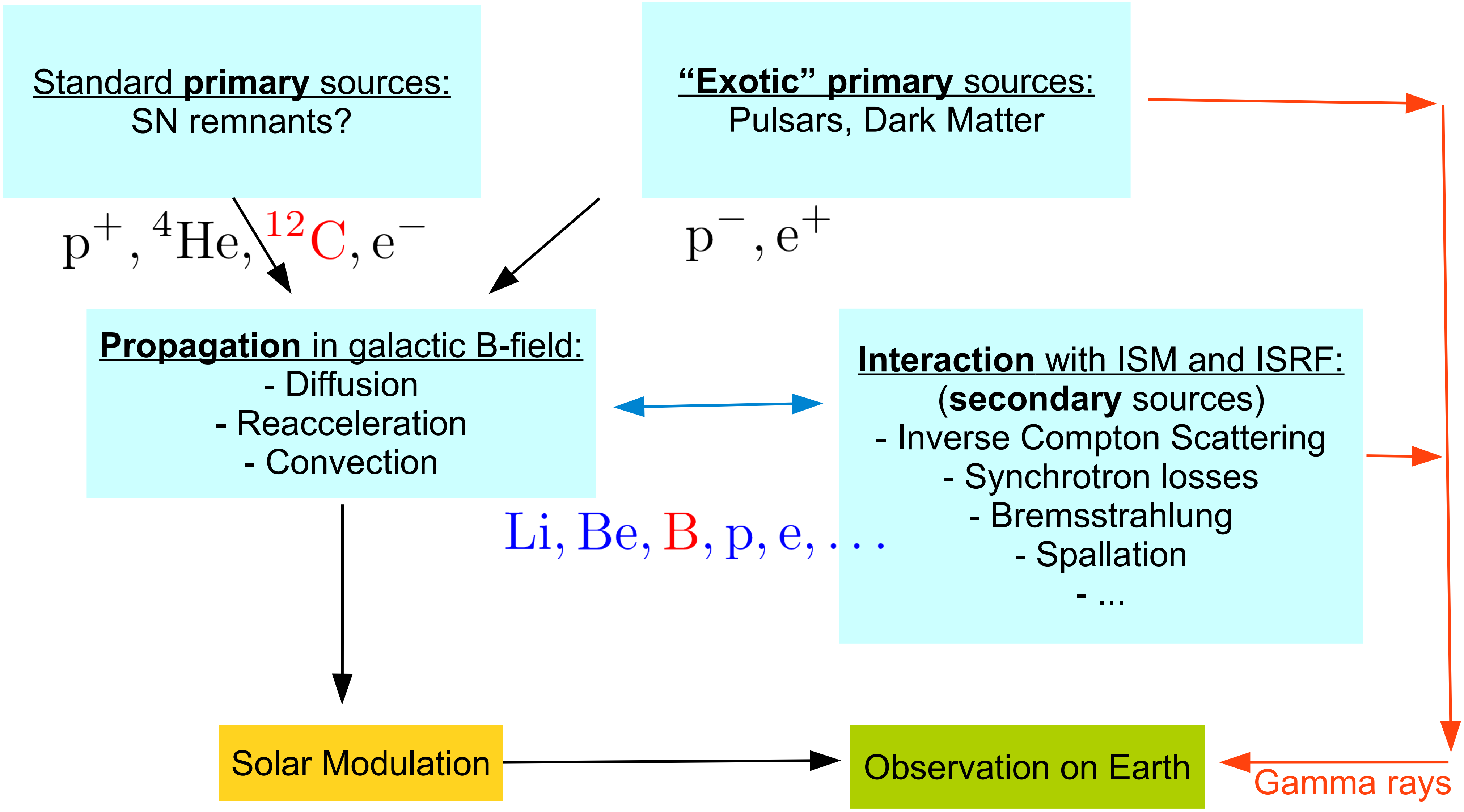
The trustworthy.

Charged cosmic rays and gamma rays



DM annihilation produces equal amounts of matter and anti-matter
→ Look at anti-matter CRs to enhance contrast

Procession of Galactic cosmic rays



Standard **primary** sources:
SN remnants?

$p^+, {}^4\mathrm{He}, {}^{12}\mathrm{C}, e^-$

"**Exotic**" **primary** sources:
Pulsars, Dark Matter

p^-, e^+

Propagation in galactic B-field:
- Diffusion
- Reacceleration
- Convection

Interaction with ISM and ISRF:
(**secondary** sources)
- Inverse Compton Scattering
- Synchrotron losses
- Bremsstrahlung
- Spallation
- ...

$\mathrm{Li}, \mathrm{Be}, \mathrm{B}, p, e, \ldots$

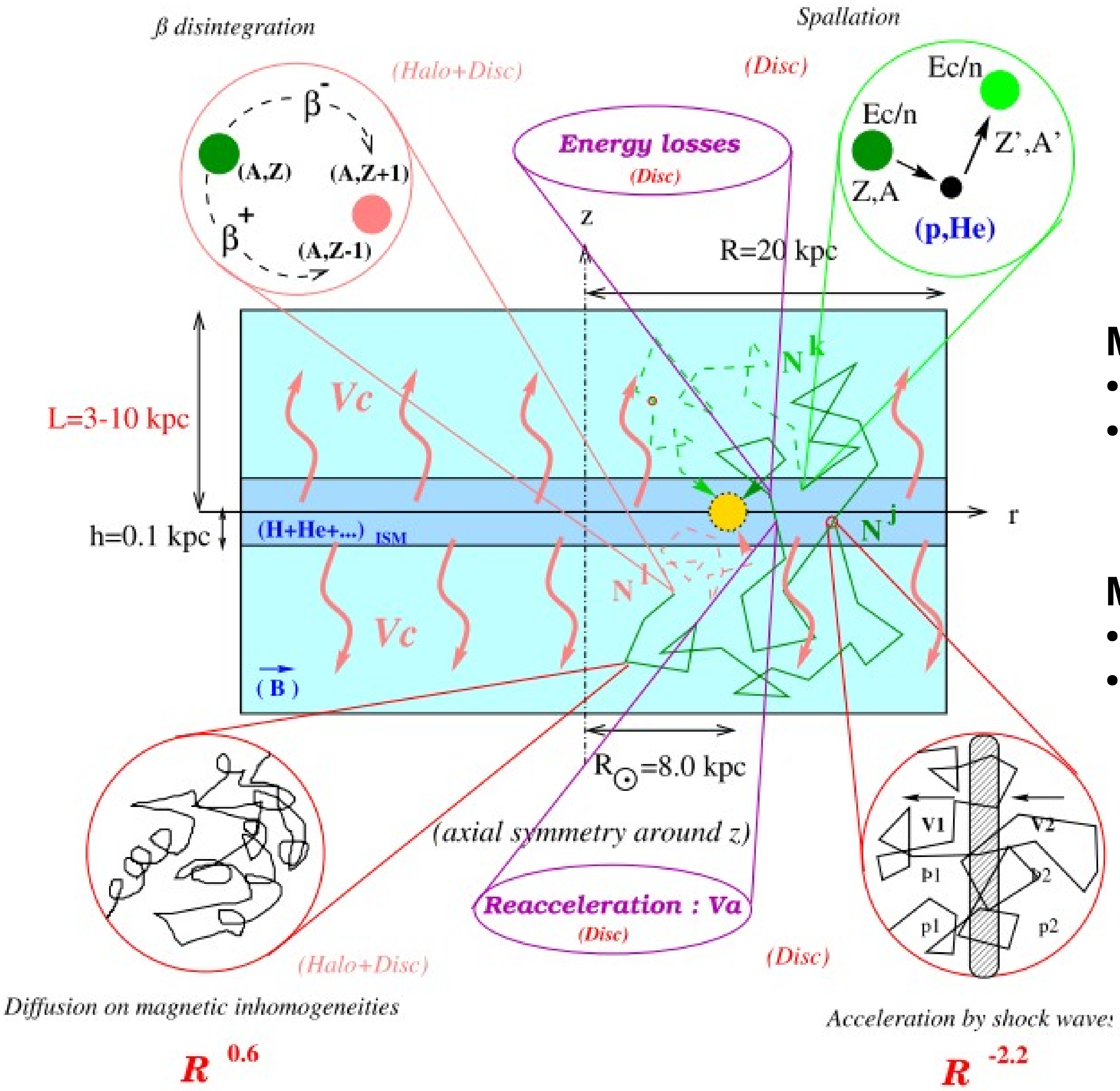
Solar Modulation

Observation on Earth

Gamma rays

The Galaxy seen by a cosmic-ray physicist

[excellent review: Lavalle & Salati (2012)]



Most relevant assumption:
- Cylindrical symmetry
- Homogeneous diffusion coefficient

Most relevant parameters:
- Diffusion zone height, L
- Diffusion constant, D

Transport equation of cosmic rays

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

Reacceleration

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

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

Source term

ISM **interaction**

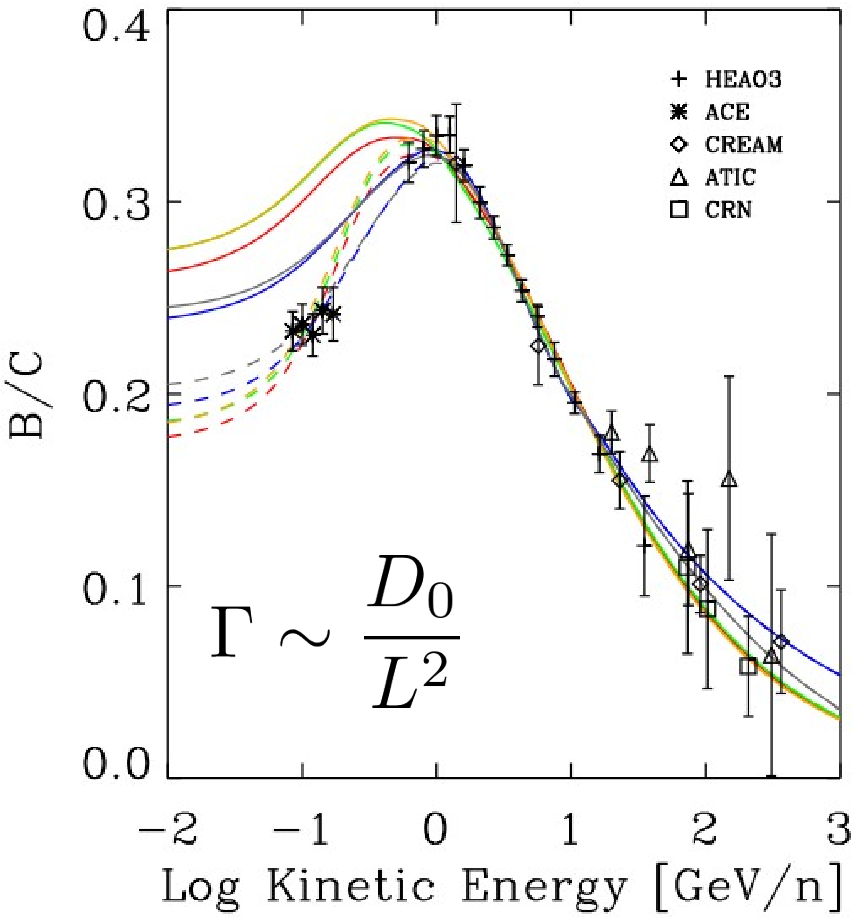
$$D(E) = D_0 \beta (\mathcal{R}/1\mathrm{GV})^{\delta}$$

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

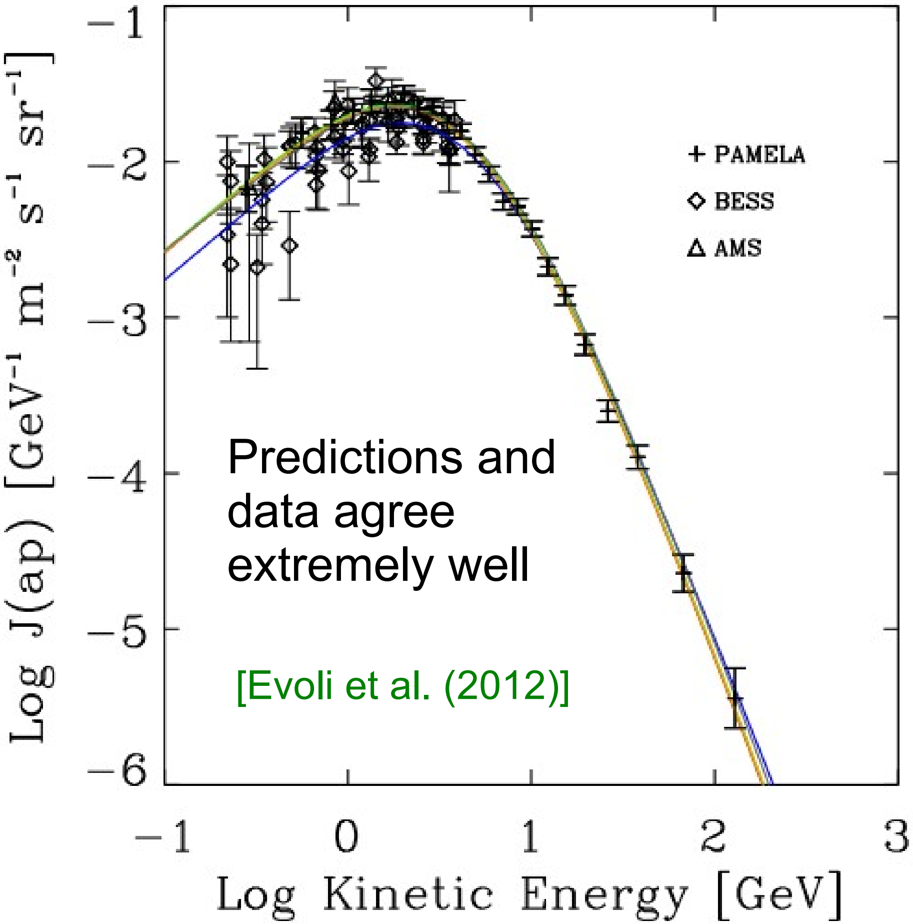
Propagation parameters

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

Model	z_t(kpc)	δ	$D_0(10^{28}\mathrm{cm}^2/\mathrm{s})$	η	v_A(km/s)	γ	dv_c/dz(km/s/kpc)	$\chi^2_{B/C}$	χ^2_p	Φ (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



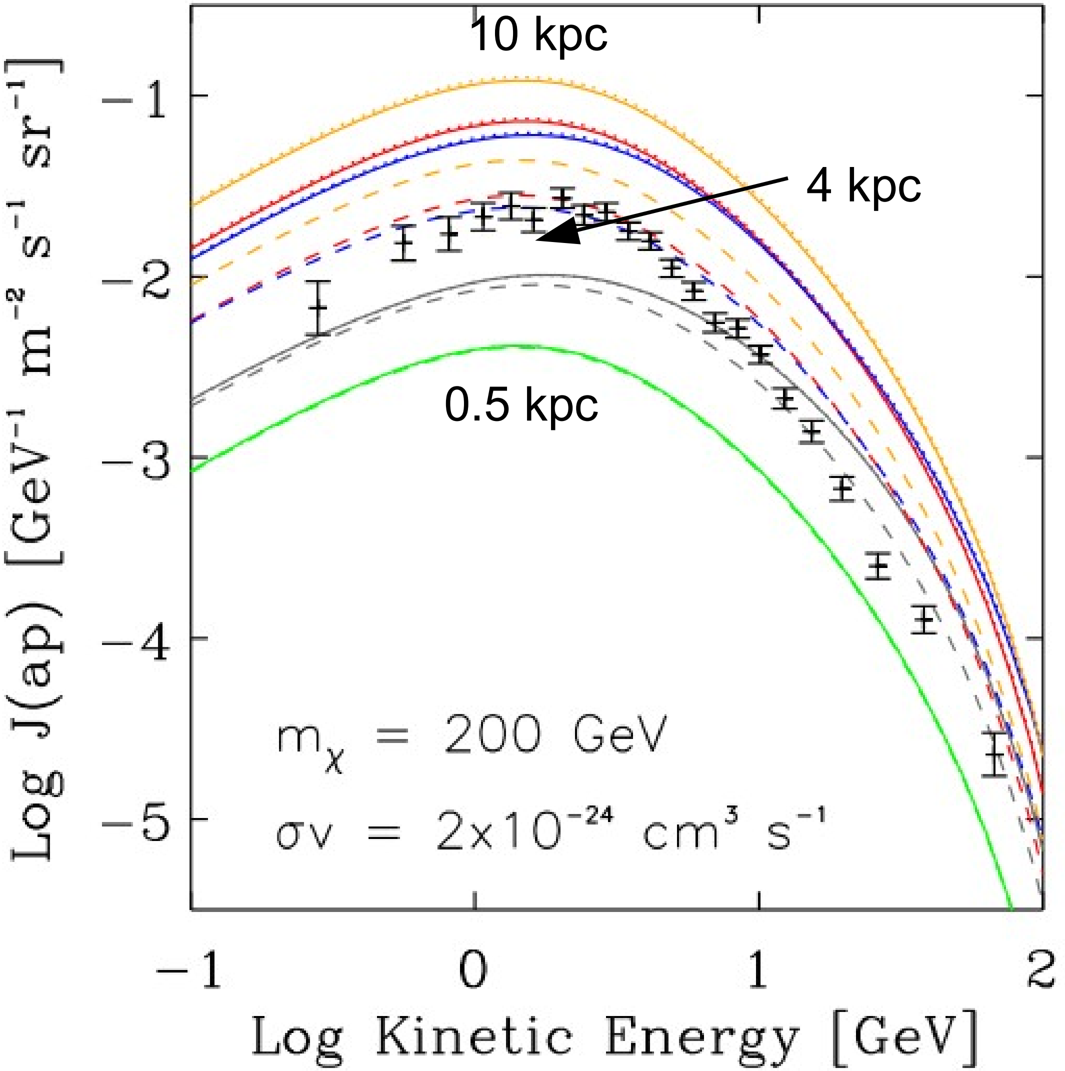
$$\Gamma \sim \frac{D_0}{L^2}$$



Predictions and data agree extremely well

[Evoli et al. (2012)]

Predictions for anti-proton DM signal

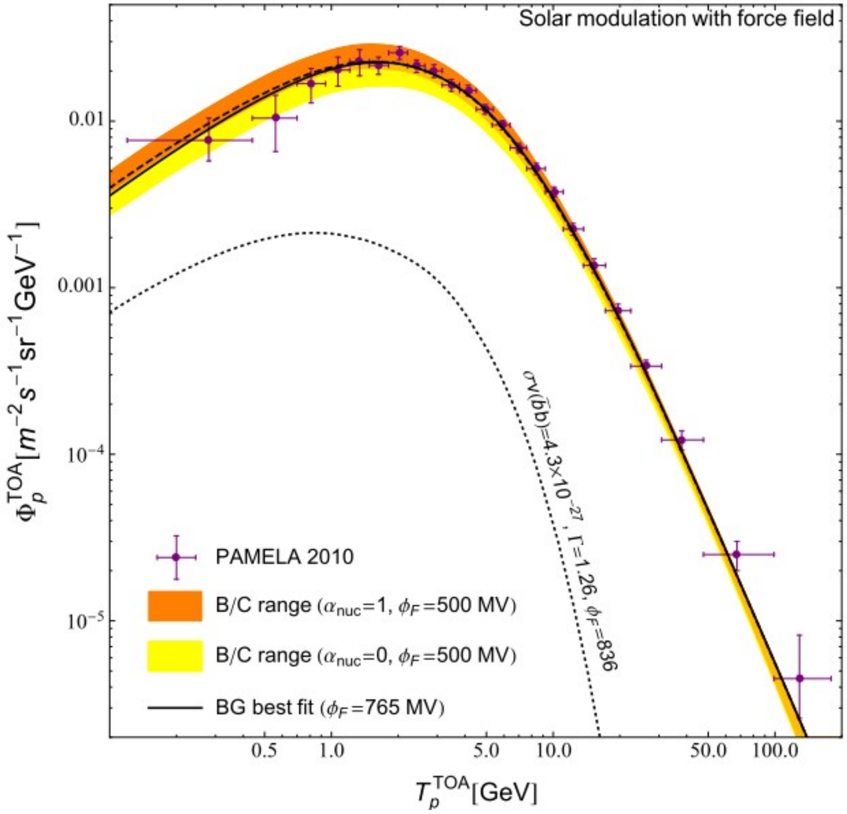


$\sim L$

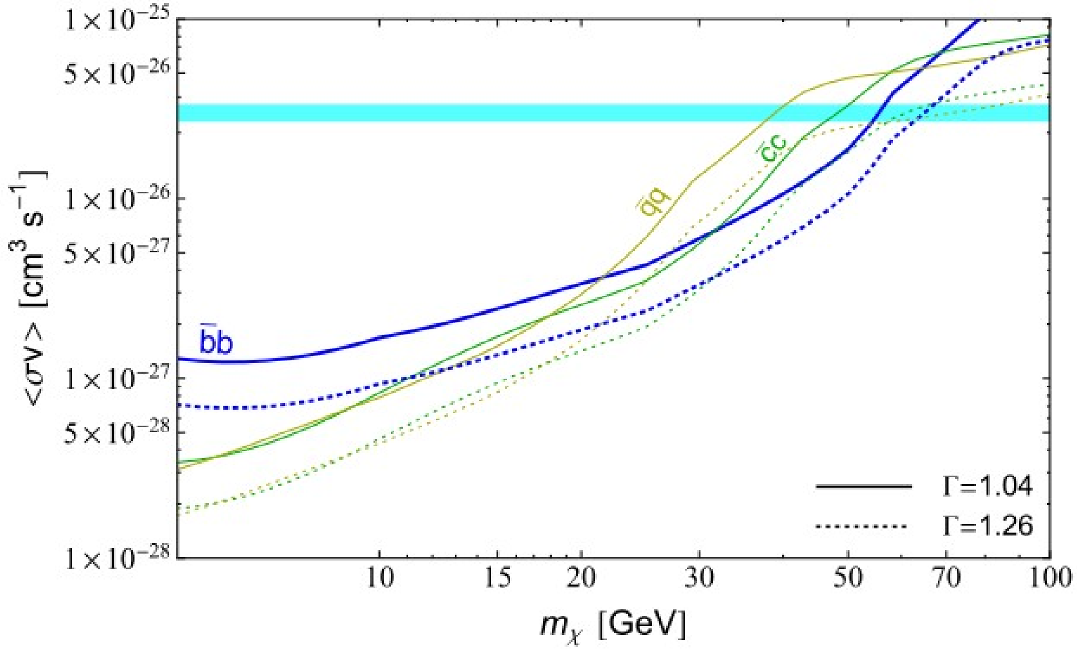
Signal flux normalization depends primarily on diffusion zone height.

[Evoli et al. (2012)]

Current upper limits from PAMELA data



Uncertainties in the predicted antiproton flux are much less than a factor of two. This allows efficient background “subtraction”/fits to the data.

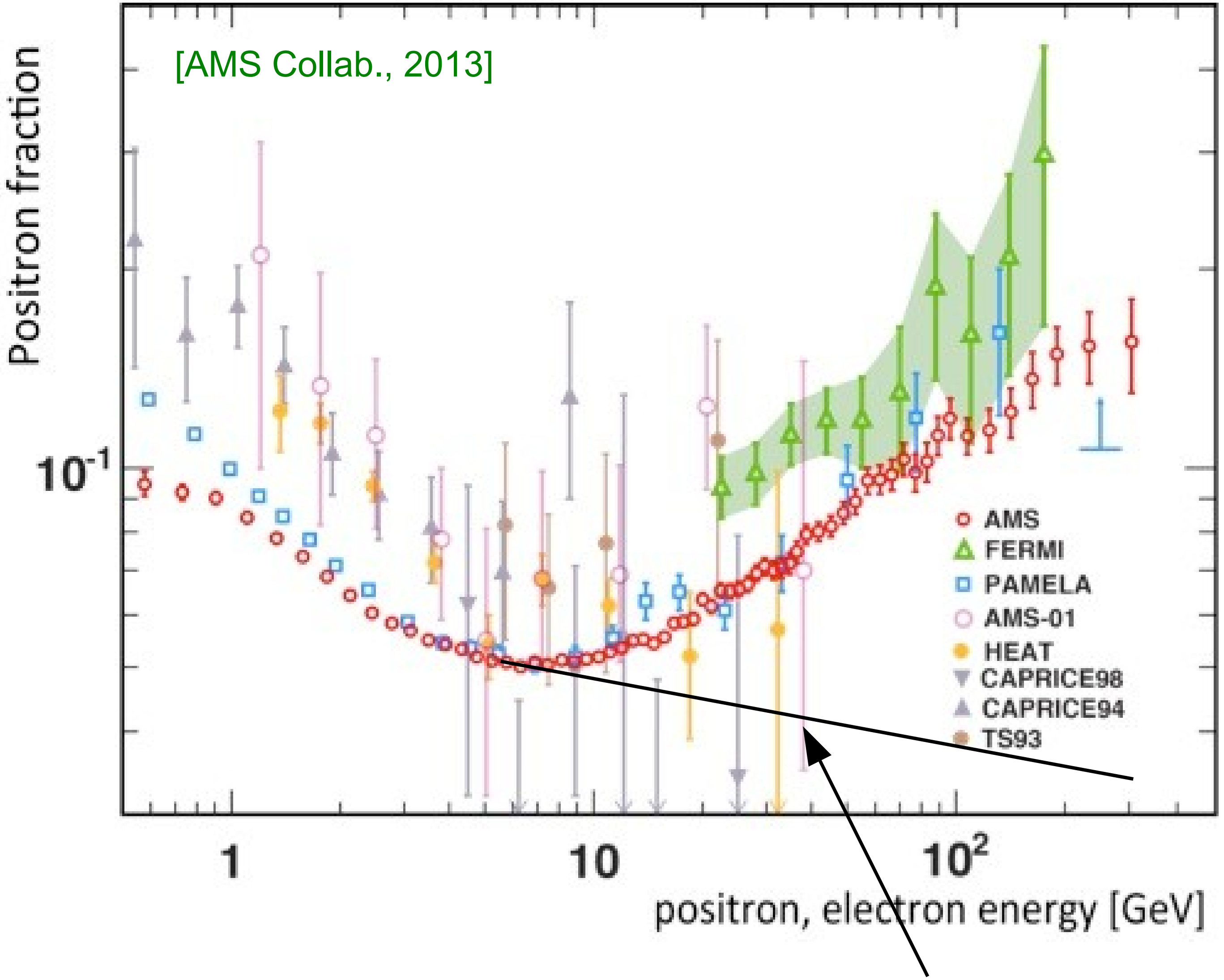


Exclusion of thermal cross-section below a few ten GeV.

3) Positrons

The exotic.

A rise in the positron fraction is observed



[AMS Collab., 2013]

Standard cosmic-ray propagation scenarios predict a decrease

Why is a decrease expected?

Primary electrons are accelerated together with protons
→ spectral index at injection $\alpha \sim 2.2 \pm 0.1$

After propagation: $\Phi_{e^-} \propto \epsilon^{-\alpha - 0.5 - \delta/2}$ $D(E) = D_0 \beta (\mathcal{R}/1\mathrm{GV})^{\delta}$

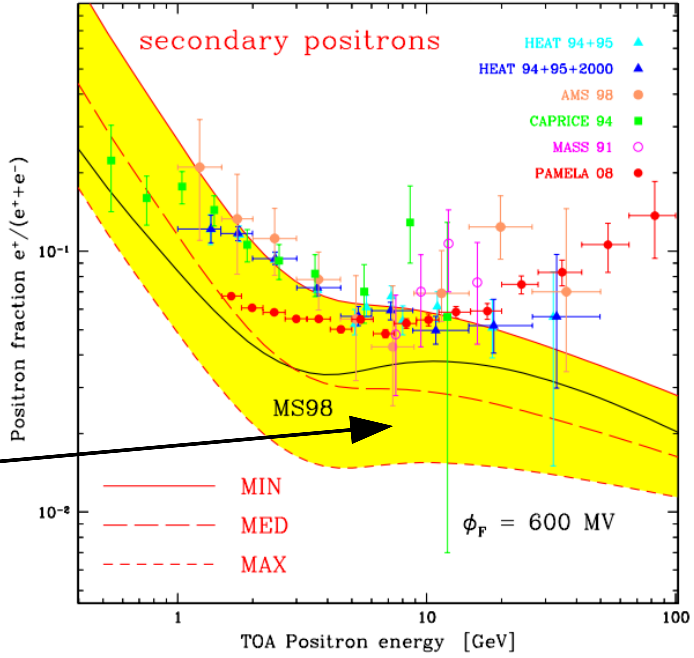
Secondary positrons (and electrons) are produced via CR proton – ISM interaction:

$$
\begin{aligned}
\mathrm{p} + \mathrm{H} &\longrightarrow \mathrm{X} + \pi^{\pm} \\
\pi^{\pm} &\longrightarrow \nu_{\mu} + \mu^{\pm} \\
\mu^{\pm} &\longrightarrow \nu_{\mu} + \nu_{e} + e^{\pm}
\end{aligned}
$$

→ spectral index at injection softer $\alpha \sim 2.7$

Decrease around $E^{-0.5}$
expected in positron fraction,
for all propagation models.

J. Lavalle & P. Salati (2012) based on A&A 501 821 (2009)



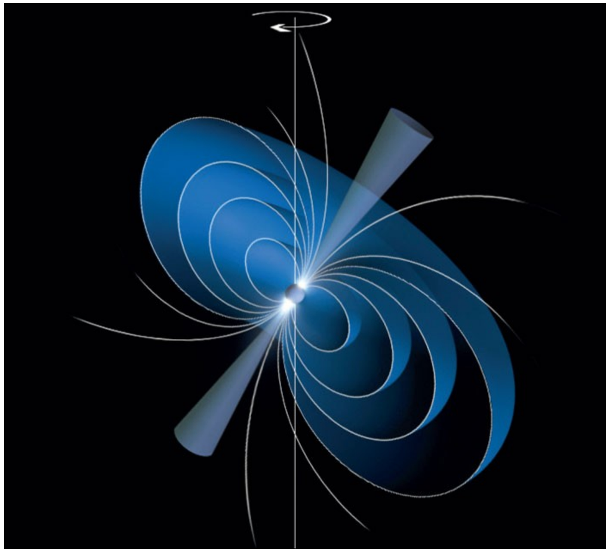
Pulsars or DM are possible explanations

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

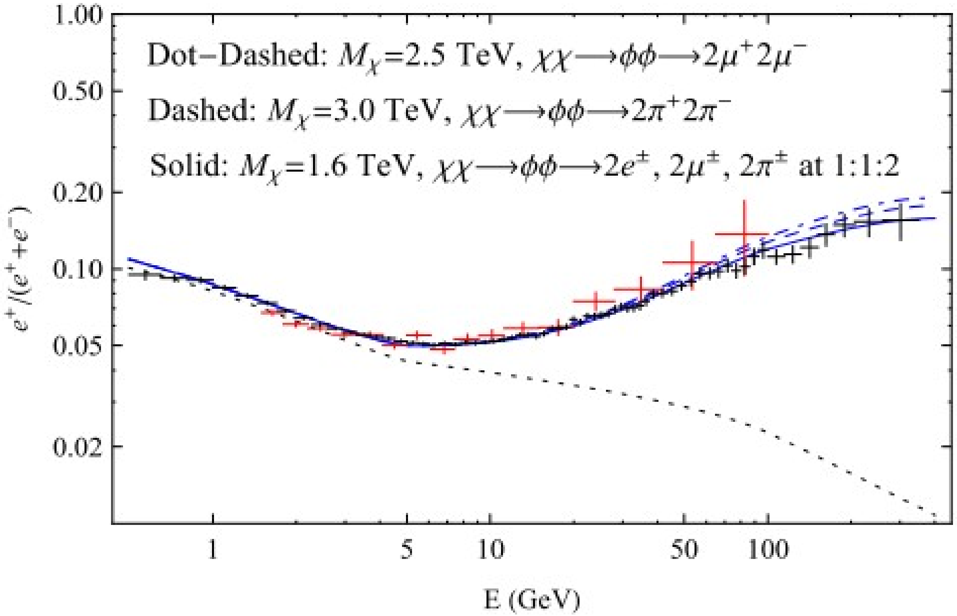
$$\chi\chi \rightarrow \mu^+\mu^-, \tau^+\tau^-$$

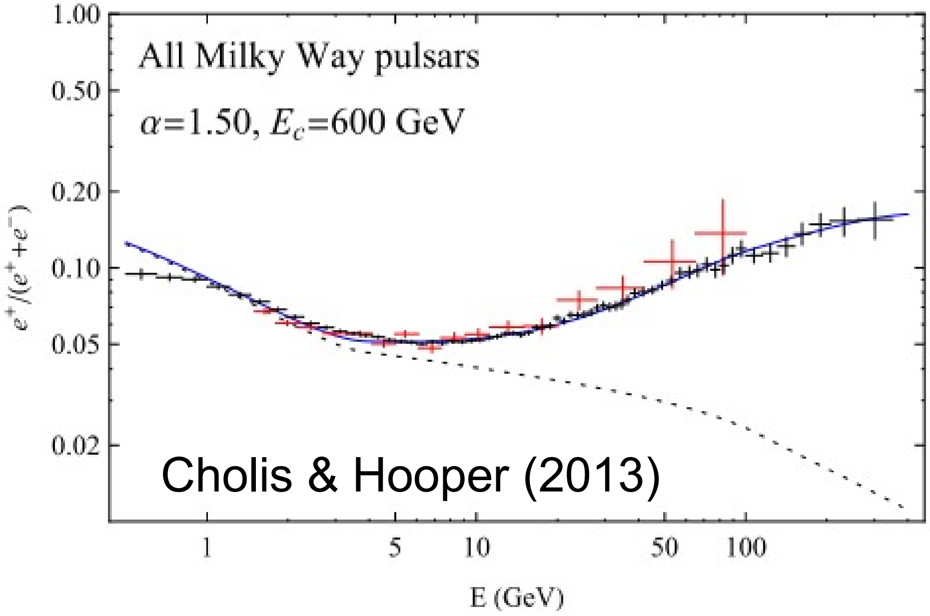
This is already strongly constrained by the non-observation of corresponding gamma-ray, anti-proton etc. signatures.
Papucci & Strumia 2010; Cirelli+ 2010; Ibarra+ 2010…

Pair production in pulsar magnetosphere



e.g. Profumo 2008





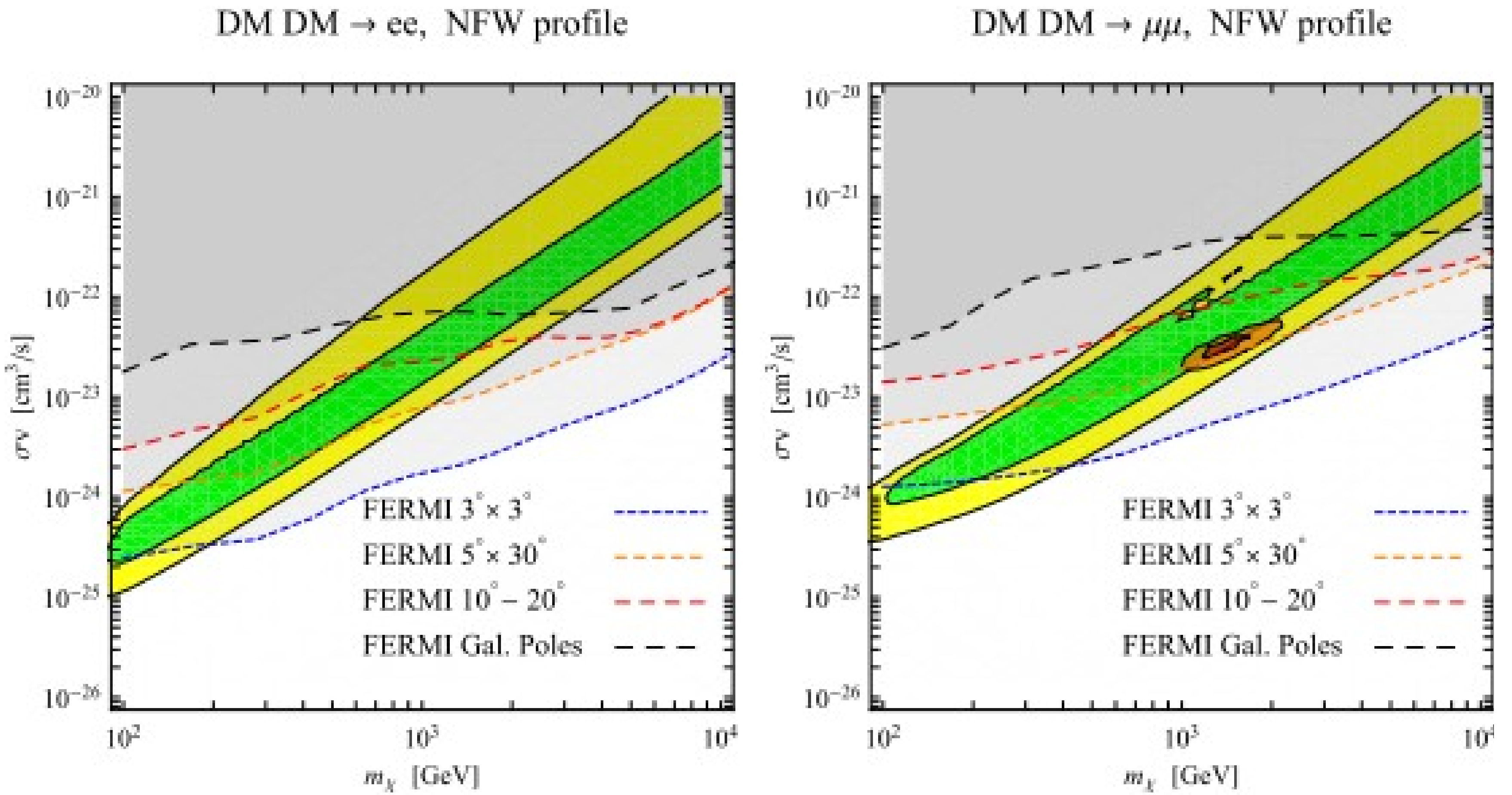
Cholis & Hooper (2013)

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)



Here: remain agnostic about origin of rise and search for <u>light</u> DM particles.

The signal spectrum

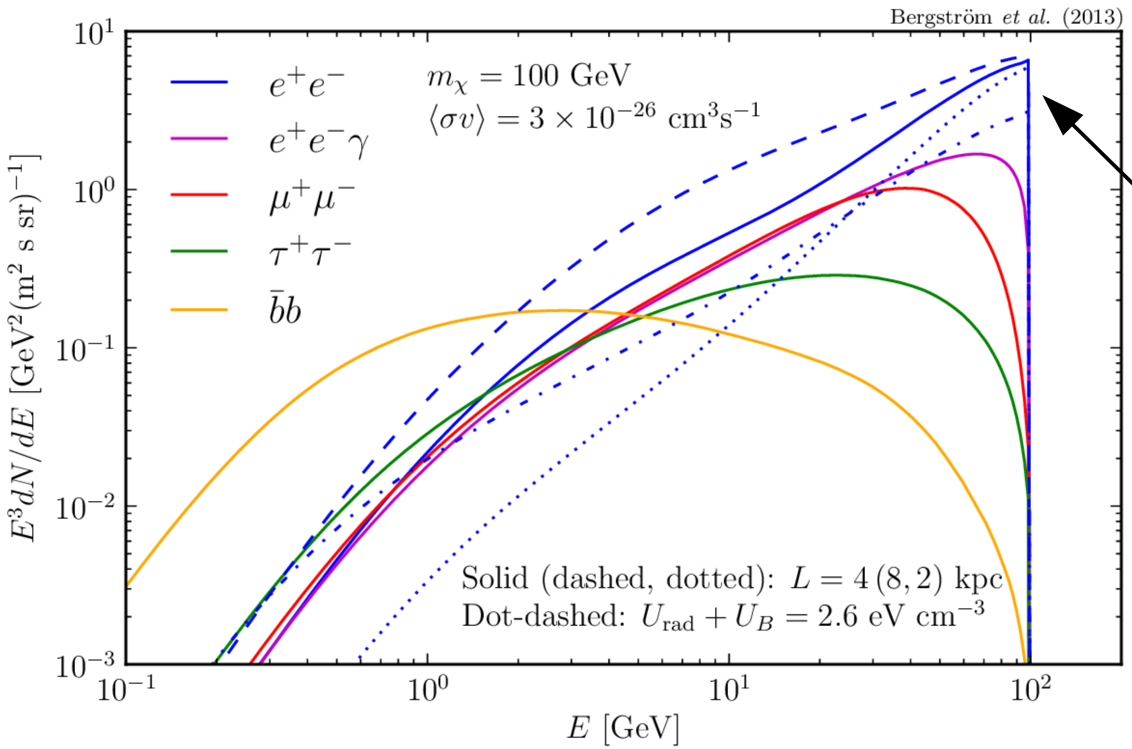
$$\frac{\partial f}{\partial t} - \nabla\left(\mathcal{K}(E,\vec{x})\nabla f\right) - \frac{\partial}{\partial E}\left(b(E,\vec{x})f\right) = Q(E,\vec{x})$$

Synchrotron radiation (B-field)
Inverse Compton Scattering

$$b_{\rm ICS}(E_e) = \frac{4}{3}\sigma_{\rm T}\gamma_e^2 \underbrace{\int_0^\infty d\epsilon\ \epsilon f_{\rm CMB}(\epsilon)}_{\equiv\rho_{\rm CMB}} \quad \text{and} \quad b_{\rm syn}(E_e) = \frac{4}{3}\sigma_{\rm T}\gamma_e^2\frac{B^2}{2}$$

Propagated spectra for different final states:

Electron spectrum becomes step-function



$$\frac{dN}{dE}_{\rm peak} \propto \frac{1}{b}$$

Perform spectral analysis

Phenomenological **background model** (works & is simple)

$$f = \frac{\Phi_{e+}}{\Phi_{e-} + \Phi_{e+}}$$

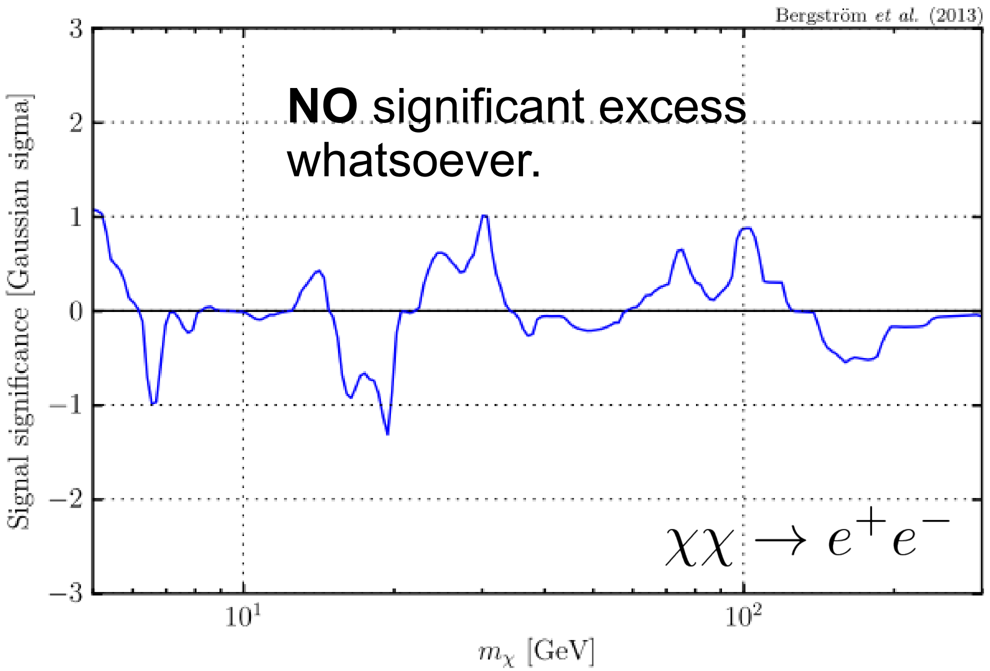
$$\Phi_{e^+} = C_{e^+} E^{-\gamma_{e^+}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

$$\Phi_{e^-} = C_{e^-} E^{-\gamma_{e^-}} + C_s E^{-\gamma_s} e^{-E/E_s}$$

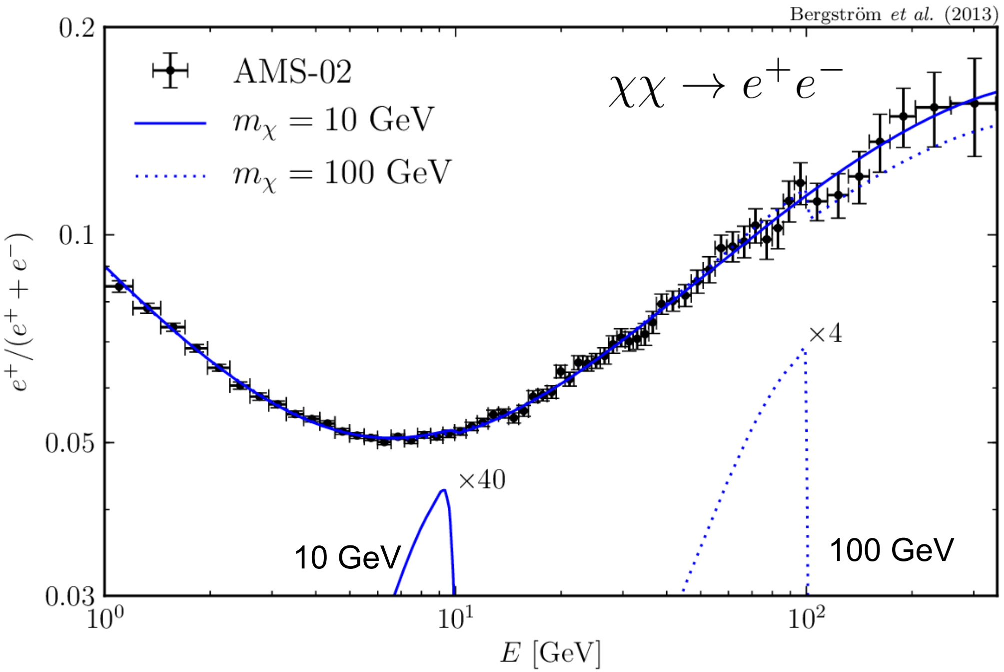
[Aguilar *et al.*, 2013]

Agnostic approach: allow **any** primary e+/e- source

Fit to the data:
- free parameters: signal normalization, γ_{e^-}, γ_s, C_s, C_{e^-} and E_s .
- systematic and statistical errors are added in quadrature
- energy dispersion is neglected



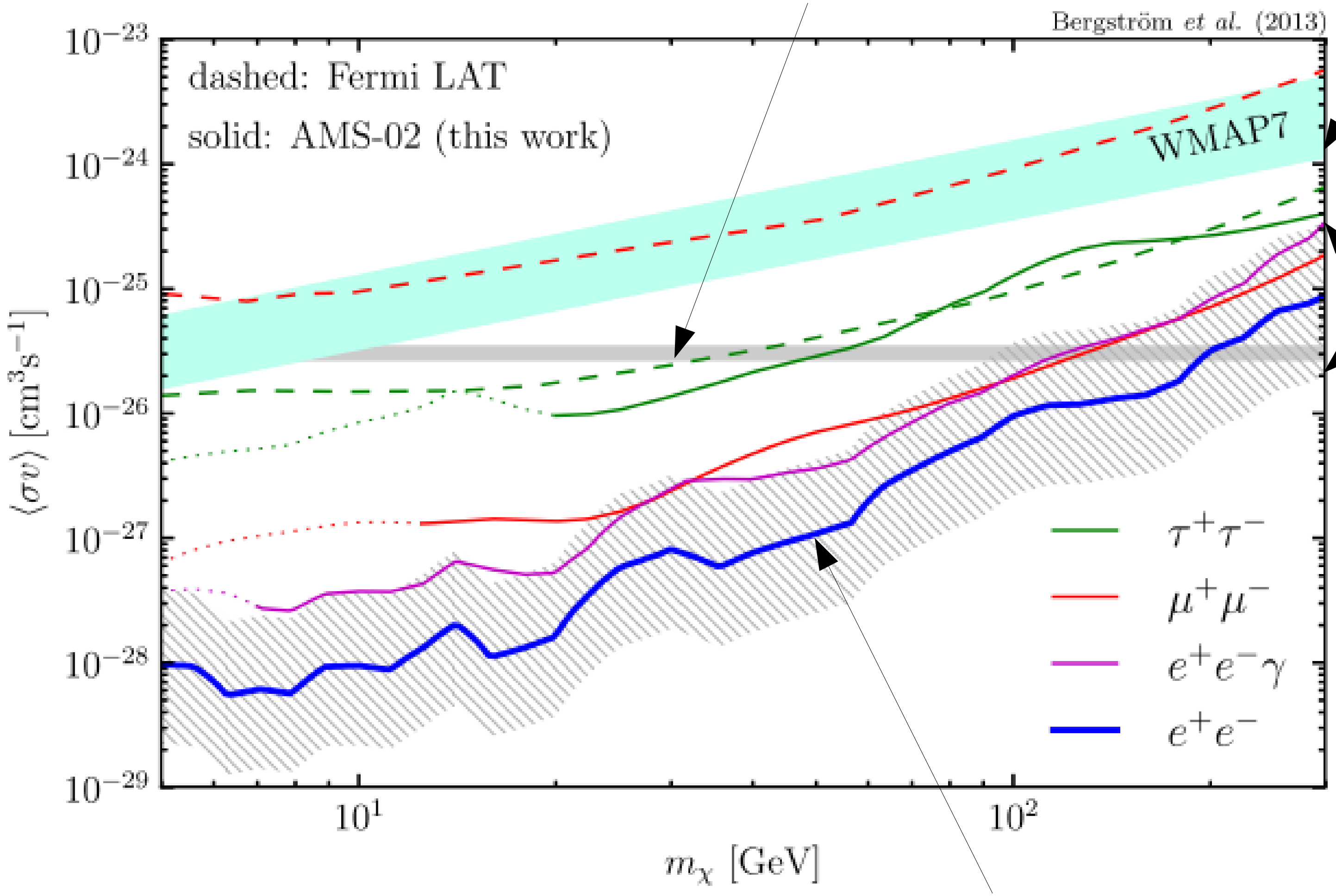
NO significant excess whatsoever.



Sensitive probe for leptonic DM annihilation!

Gamma-ray observations
of dwarf spheroidals

Limits from polarization
measurements of the
CMB



Uncertainties from
local DM density and
energy losses

Non-observations of spectral
features in positron fraction

Why this is not just terribly wrong

Effect of solar modulation

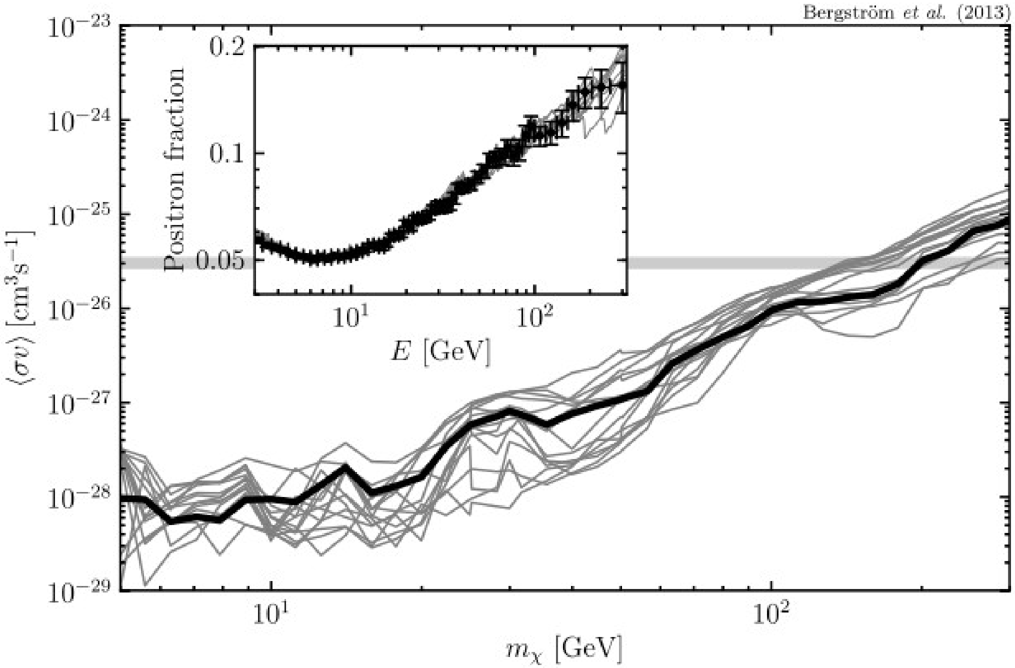
- Force-field approximation: affects fluxes down to 5 GeV by less then 20 – 40%.

Physical background models

- still have to fit data → no big change expected
- we find O(3) variations for different physical background models (that fit the positron fraction slightly worse than the simple model above)

DM signal could hide between pulsar bumps

- We simulated multi-pulsar backgrounds
  - taking pulsar distances, P & Pdot from ATNF catalog (w/o MSPs, <4kpc)
  - random variation of fraction that goes into e+/e- pairs (~O(5%))



<u>Outlook</u>: marginalize over background realizations + propagation models → make limits as robust as Fermi LAT dwarf spheroidal limits

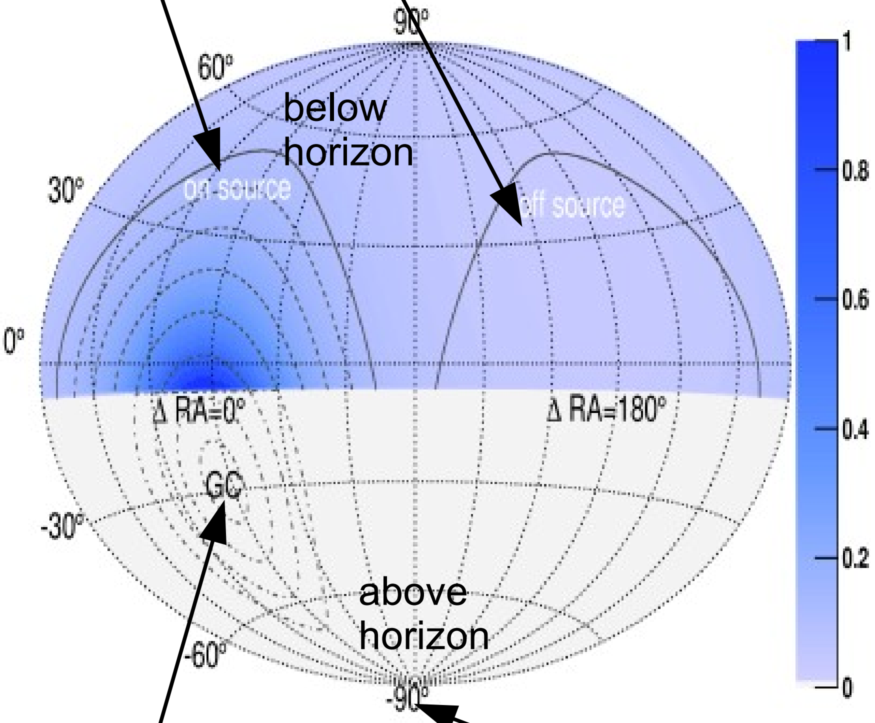
4) Neutrinos

The invisible.

DM limits from the Galactic halo

Signal region

Background region



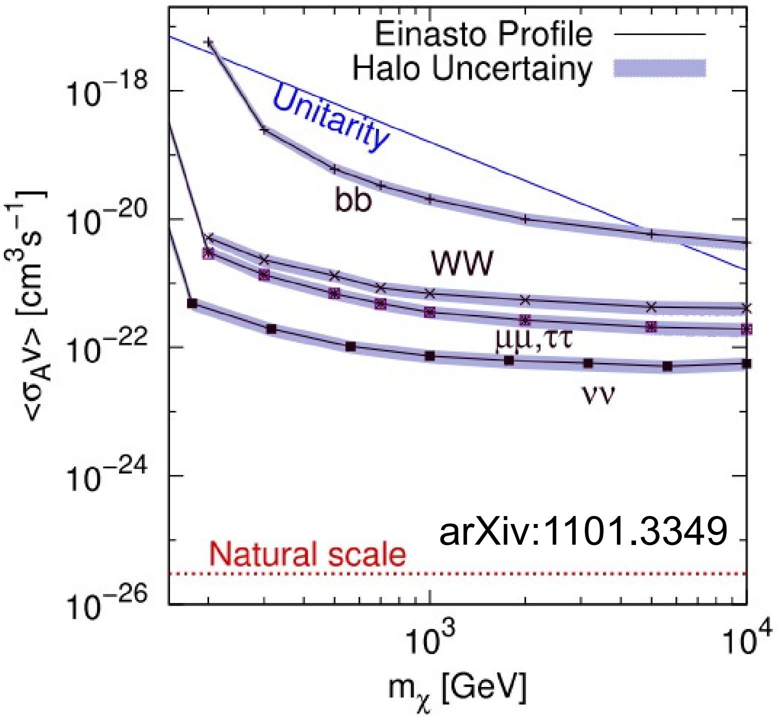
below horizon

above horizon

IceCube

Galactic center is on south hemisphere → above horizon for IceCube

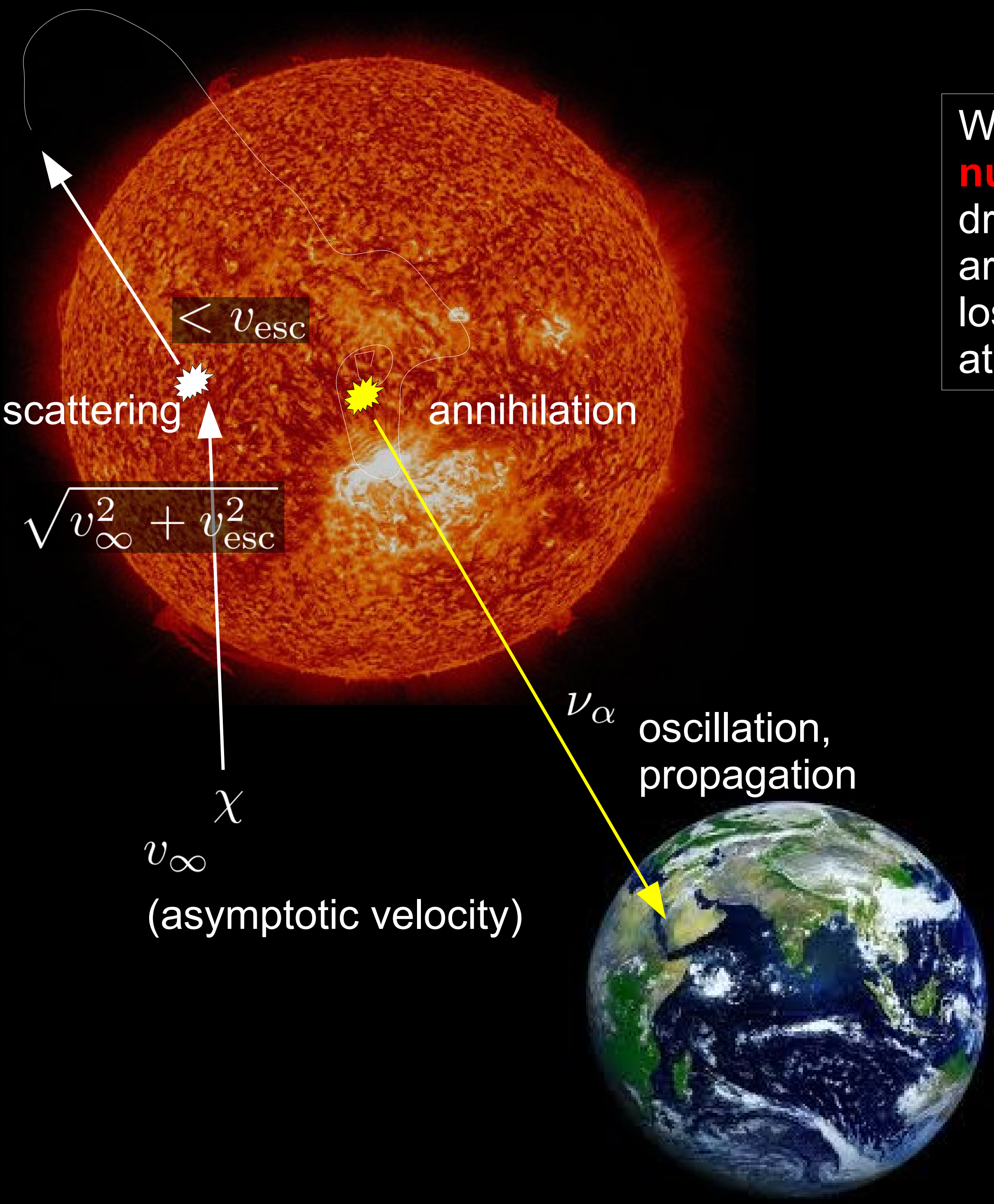
Comparison of fluxes in signal- and background-regions gives upper limits on DM signal from regions close to the Galactic center:



arXiv:1101.3349

Gamma-ray limits are way stronger...

A better target: The Sun!



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

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

Capture rate $C \propto \sigma \rho_\chi$

Annihilation rate

Number of WIMPs

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

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

Dark Matter limits from Sun observations

317 days of data from IceCube

Channels considered in analysis:

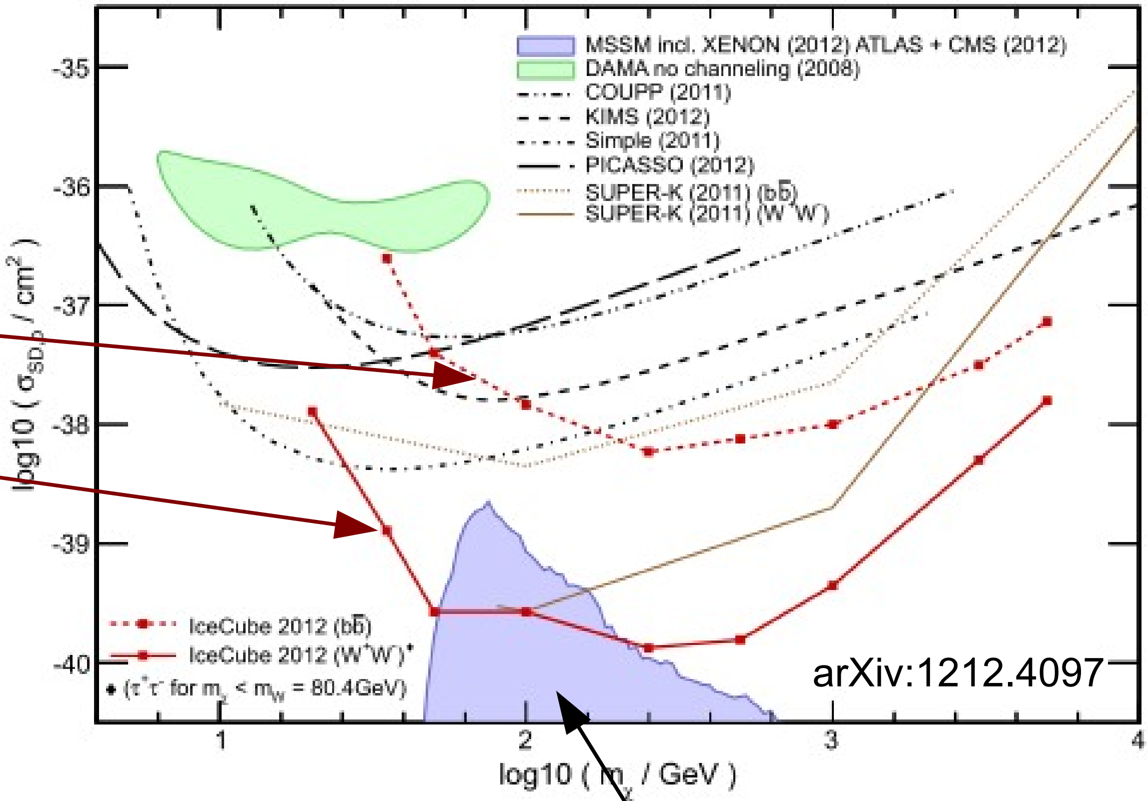
soft neutrinos from:

$\chi\chi \to \bar{b}b$

hard neutrinos from:

$\chi\chi \to W^+W^-$

Limits from Sun observations compared with limits from direct search experiments



arXiv:1212.4097

Cross-sections expected in the MSSM

In the case of spin-dependent interaction between dark matter and nucleons, neutrino observations of the Sun give the most stringent limits.

5) Gamma-ray continuum

The beast.

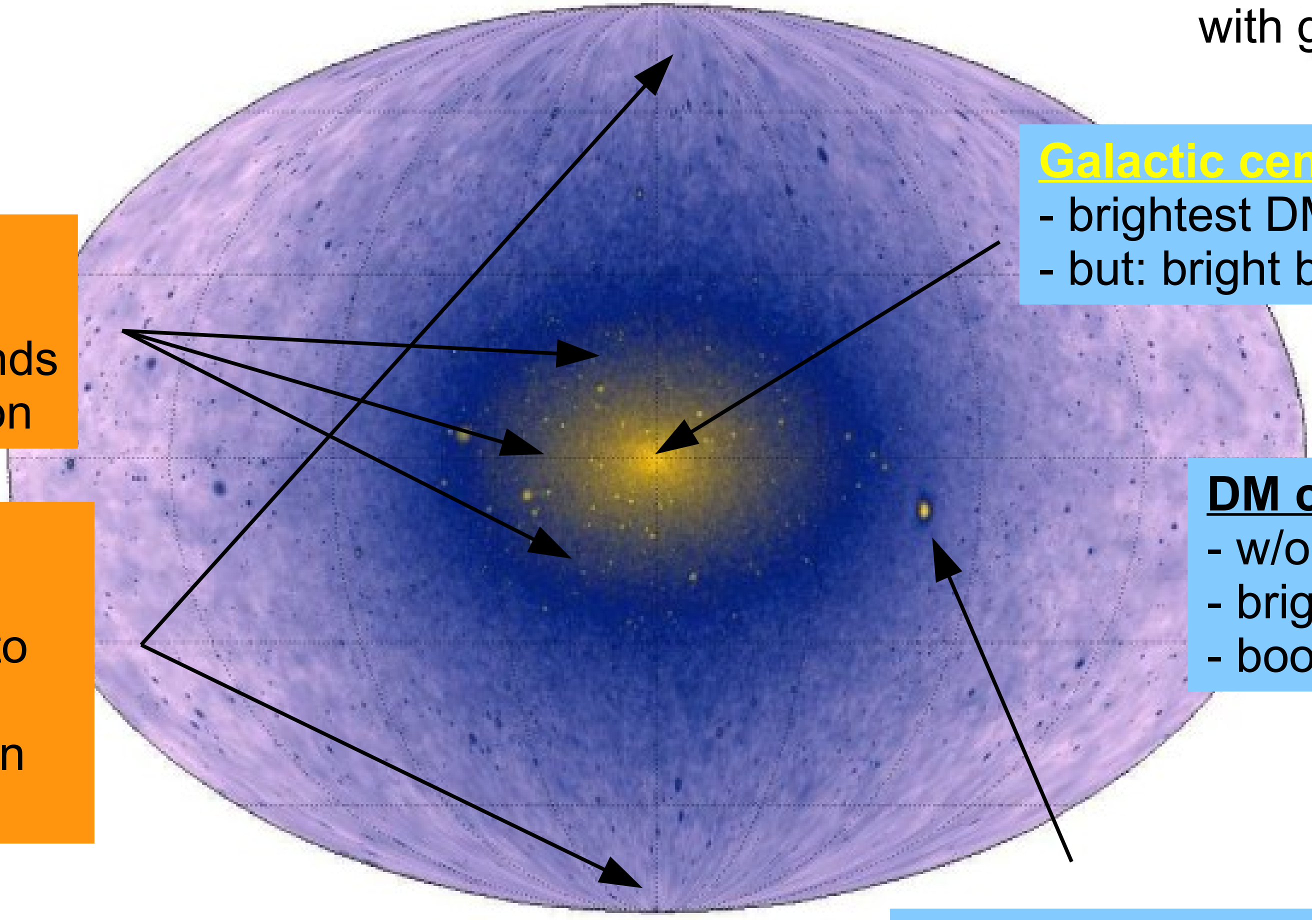
Potential targets for searches with photons

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)]

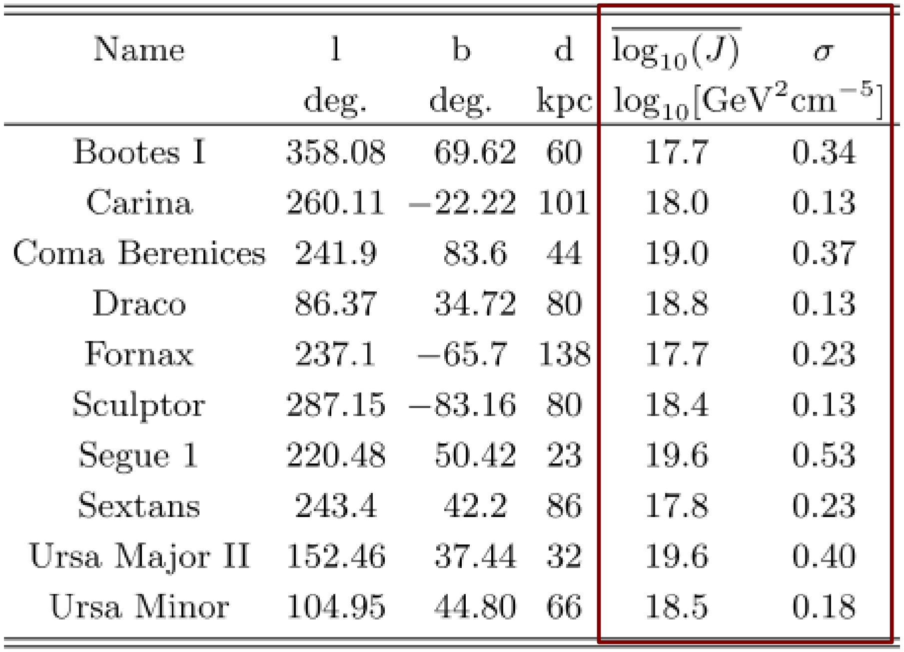
Searches in dwarfs spheroidal galaxies

Dwarf spheroidal galaxies are a class of small satellite Galaxies of the Milky Way

- dark matter content can be derived from stellar kinematics
- close: < 100 kpc from Galactic center
- known distance

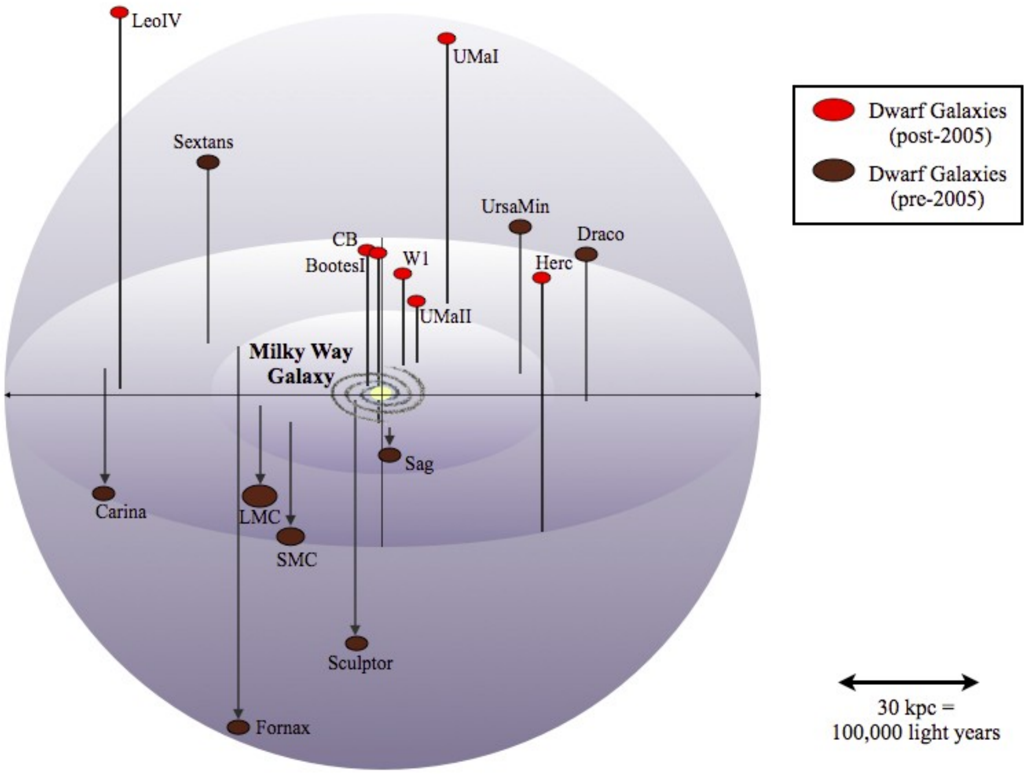
- **much** lower and simpler foregrounds than at the Galactic center

$$\phi_{\mathrm{BG}}(> 10\ \mathrm{GeV}) \sim 10^{-11}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$



Name	l	b	d	$\overline{\log_{10}(J)}$	σ
	deg.	deg.	kpc	$\log_{10}[\mathrm{GeV}^2\mathrm{cm}^{-5}]$	
Bootes I	358.08	69.62	60	17.7	0.34
Carina	260.11	−22.22	101	18.0	0.13
Coma Berenices	241.9	83.6	44	19.0	0.37
Draco	86.37	34.72	80	18.8	0.13
Fornax	237.1	−65.7	138	17.7	0.23
Sculptor	287.15	−83.16	80	18.4	0.13
Segue 1	220.48	50.42	23	19.6	0.53
Sextans	243.4	42.2	86	17.8	0.23
Ursa Major II	152.46	37.44	32	19.6	0.40
Ursa Minor	104.95	44.80	66	18.5	0.18

[arXiv:1108.3546]



Compare to Galactic center:

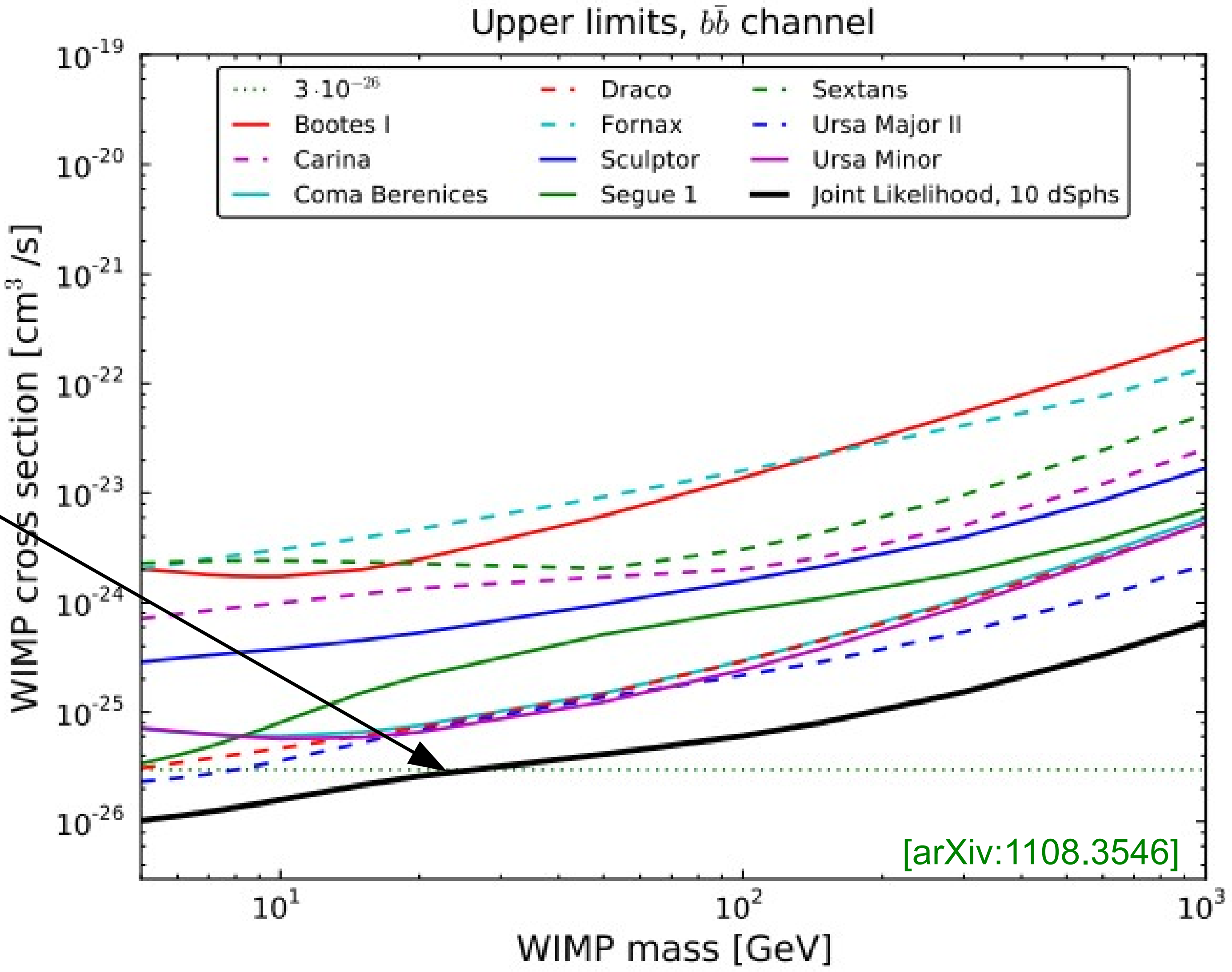
$$J_{\Delta\Omega} = 4 \times 10^{19} \ldots 1 \times 10^{22}\mathrm{GeV}^2\ \mathrm{cm}^{-5}$$

→ the GC is orders of magnitude brighter

2011: Searches in dwarfs spheroidal galaxies

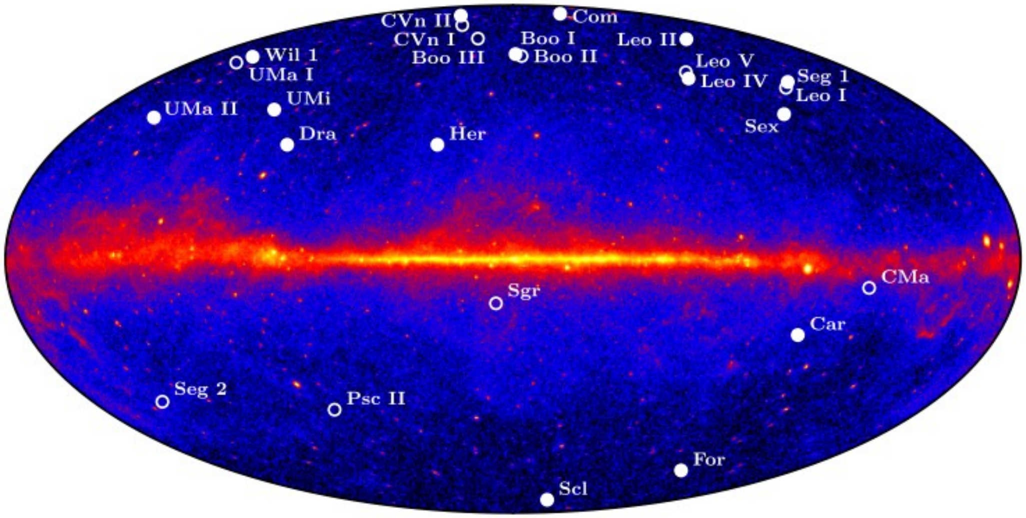
A search for gamma rays from dwarf spheroidals gives only upper limits. Combination of dwarfs, reach the thermal cross-section below DM masses of 30 GeV.

Stacking of dwarfs:
(combined profile likelihood analysis of dwarf spheroidals)



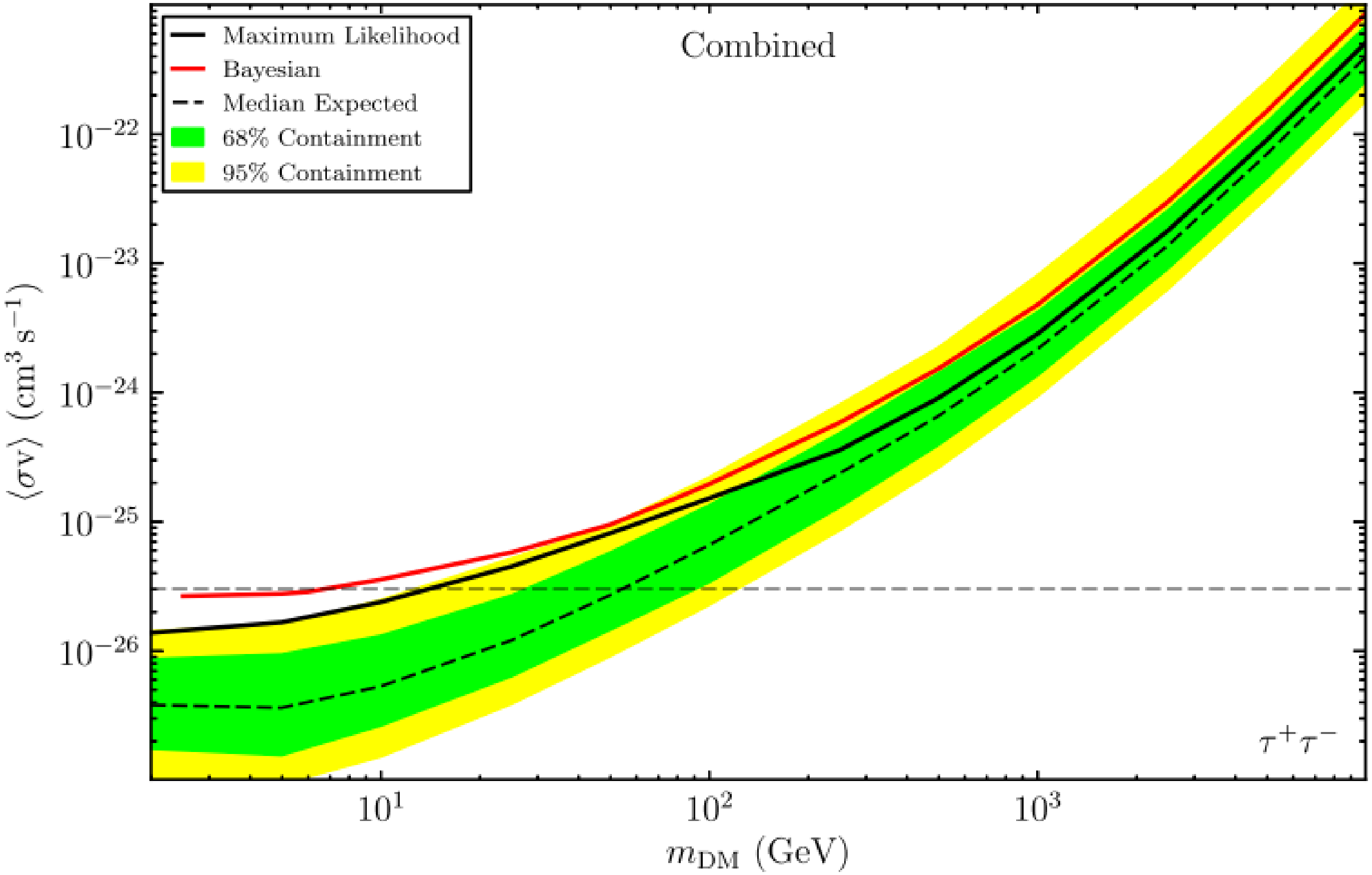
[arXiv:1108.3546]

2013: New dwarf limits got weaker



Combined analysis of 15 dwarfs gives limits that are somewhat weaker than expected.

Ackermann+ 2013



“Excess” characteristics:
Largest deviation for

$$\chi\chi \to \bar{b}b$$

$$m_{\mathrm{dm}} = 10 - 25\,\mathrm{GeV}$$

with local significance 2.3σ

$$TS = 8.7$$

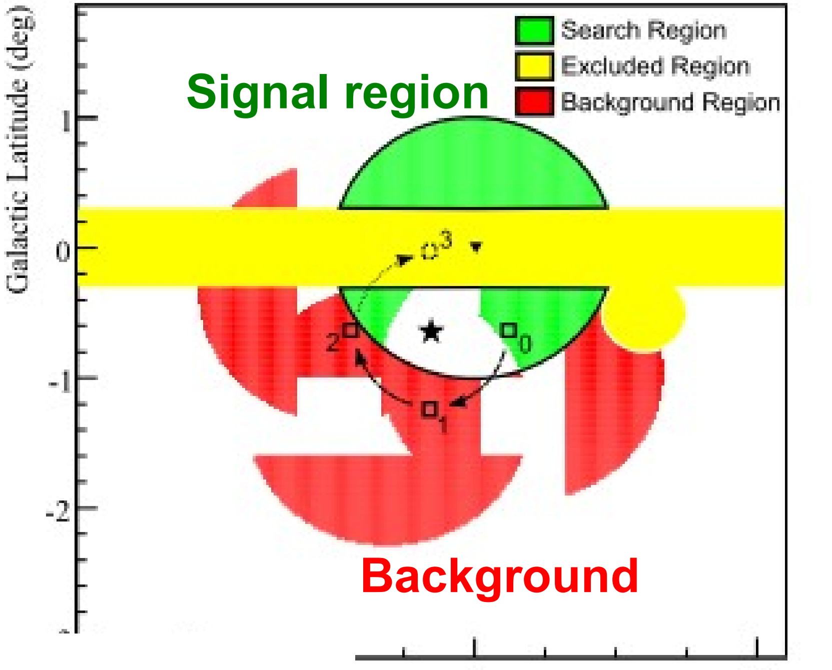
$$TS = -2\ln\frac{\mathcal{L}_{\mathrm{null}}}{\mathcal{L}}$$

H.E.S.S. observations of Galactic center

For Atmospheric Cherenkov Telescopes, the backgrounds are completely dominated by unrejected electron and proton Crs
→ Isotropic backgrounds!

Limits on a WIMP annihilation signal
Flux from search region (green) compared to flux from background region (red).
→ the fluxes are consistent
→ upper limits on DM signal.

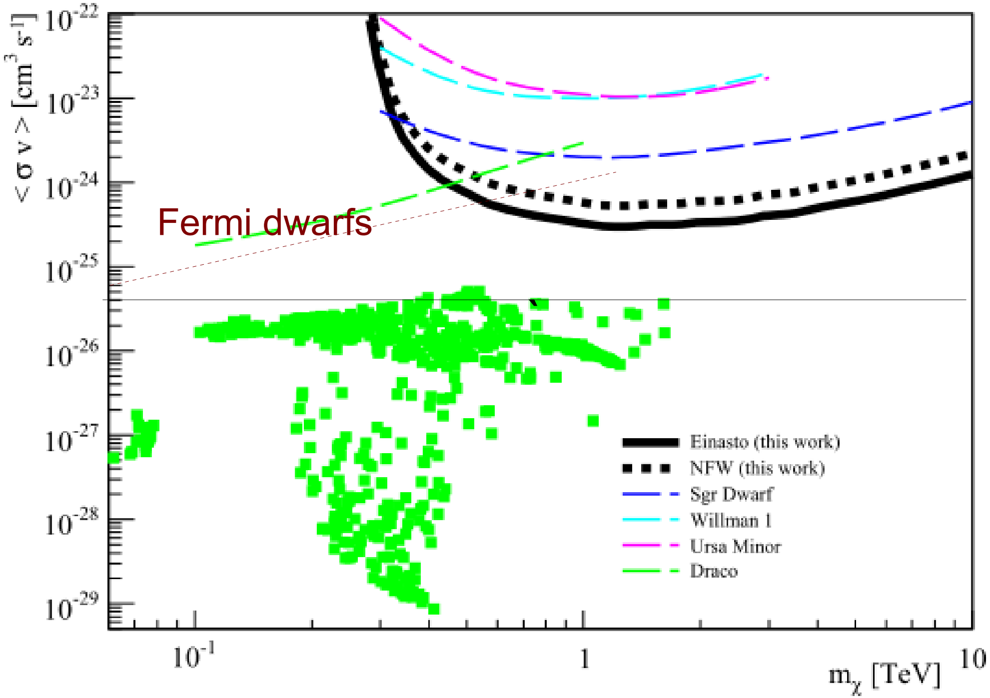
arXiv:1103.3266



Signal region

Background

Abramowski et al. 2011

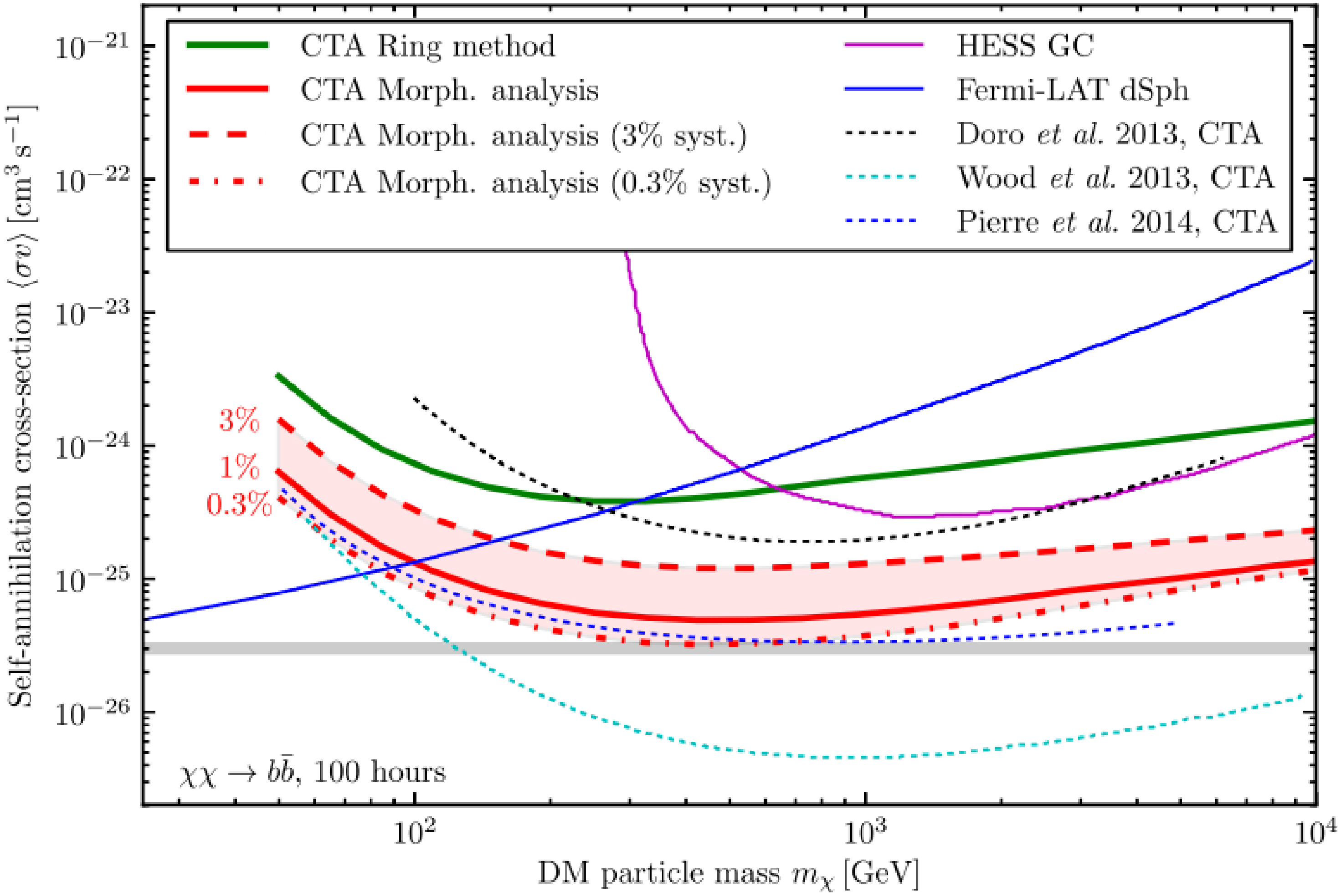


Fermi dwarfs

Thermal cross-section

CTA prospects

Silverwood+ 2014

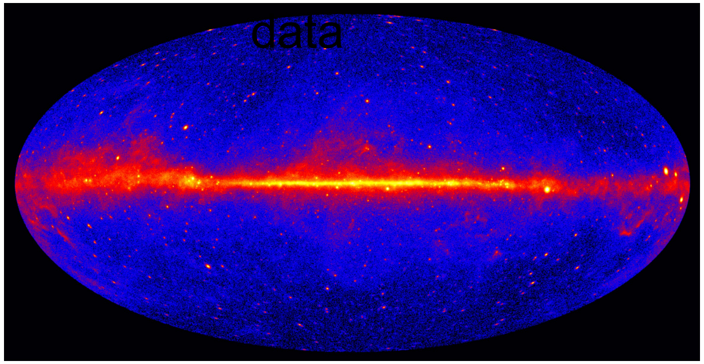


Realistic prospects for CTA:

- Sensitivity is mainly limited by instrumental systematics (non-uniform variations in the acceptance)
- Thermal cross-section should be reachable if systematics are under control at sub-percent level.

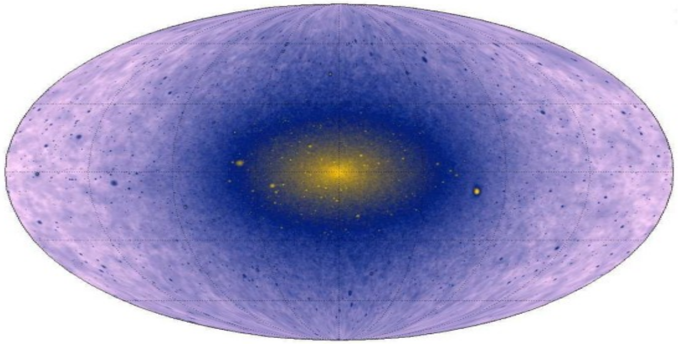
The Galactic halo Foreground subtraction

Fermi LAT data

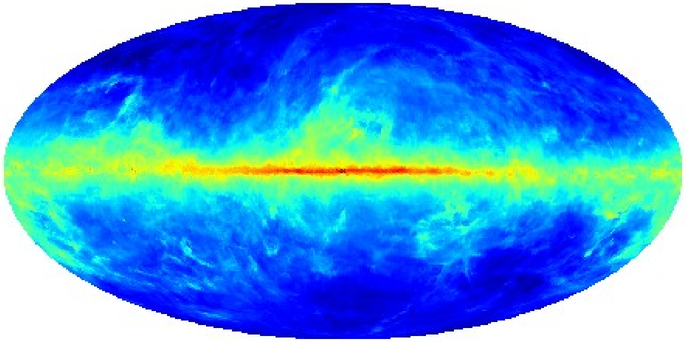


Subtract
- Diffuse foregrounds
- Point sources

Residual: Dark matter?

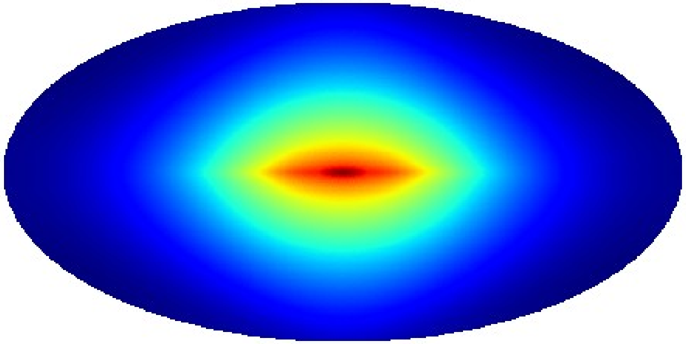


Pion decay



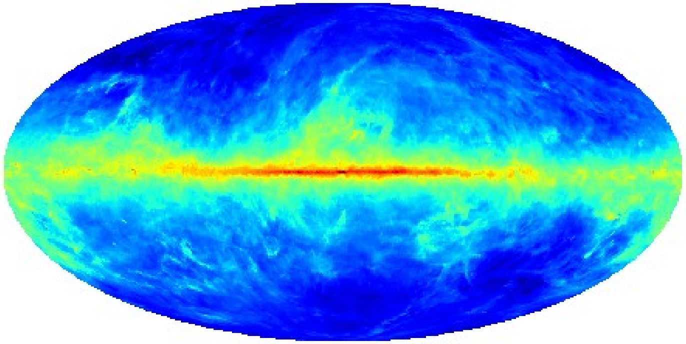
Traces
ISM*CR
protons

Inverse Compton



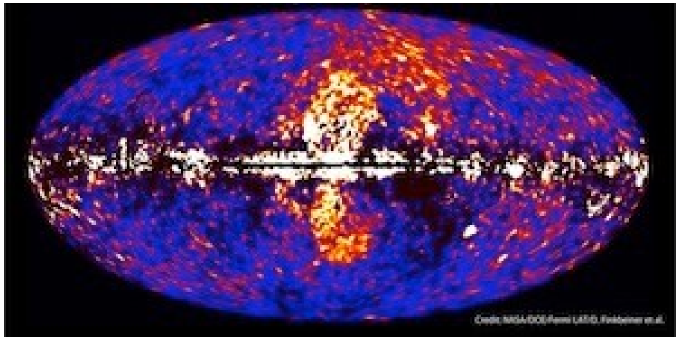
Traces
ISRF*CR
electrons

Bremsstrahlung



Traces
ISM*CR
electrons

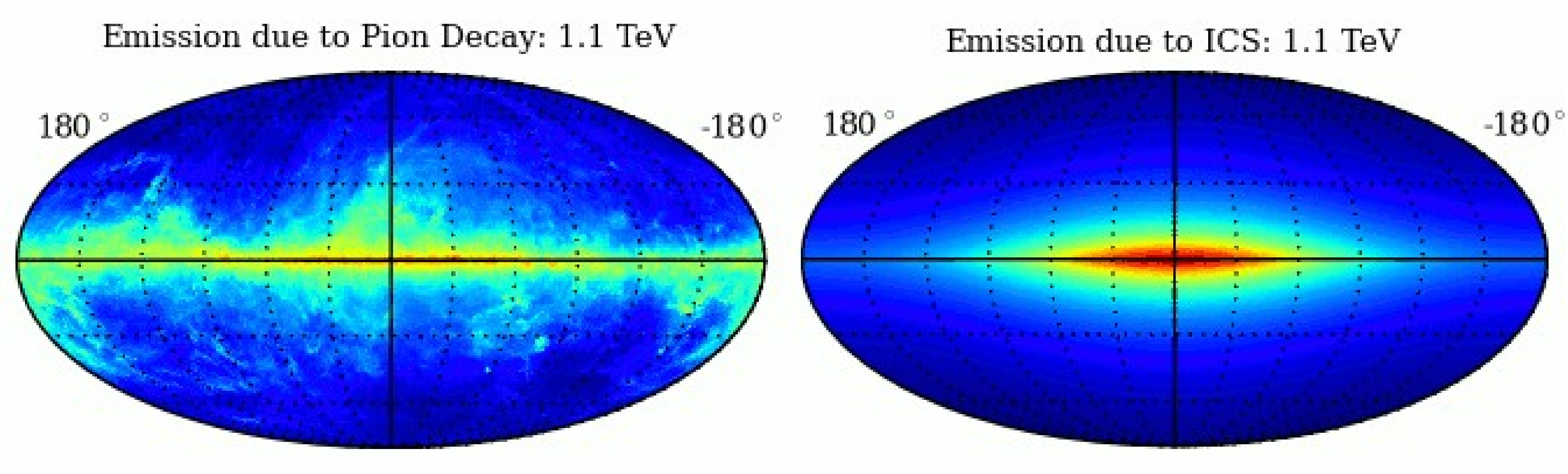
Fermi bubbles



Effective
template
Cause uncertain

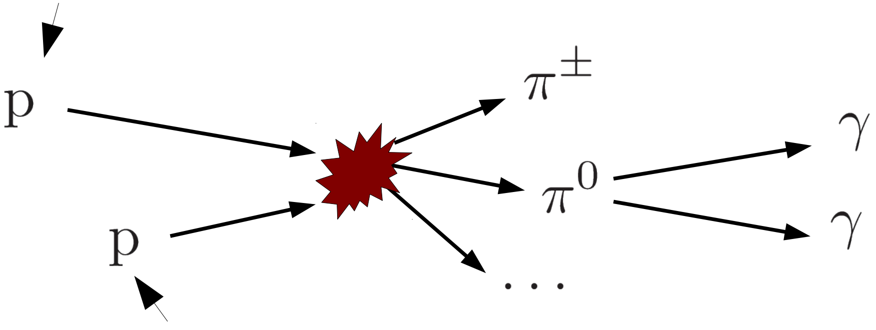
Diffuse Galactic backgrounds

The diffuse gamma-ray emission from our Galaxy is produced by interaction of high energetic charged particles (electrons, protons, …) with the interstellar medium (mostly Hydrogen and Helium) and interstellar radiation field (Cosmic Microwave background, starlight, dust radiation)



Proton-proton collisions & subsequent pion-decay:

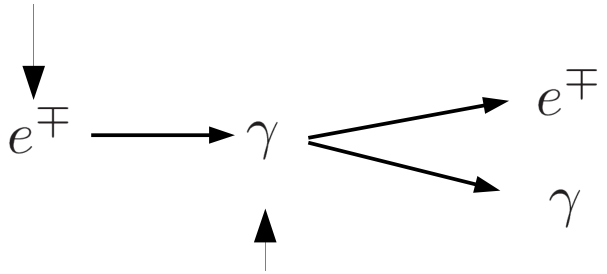
high energy proton



proton at rest

Inverse Compton scattering:

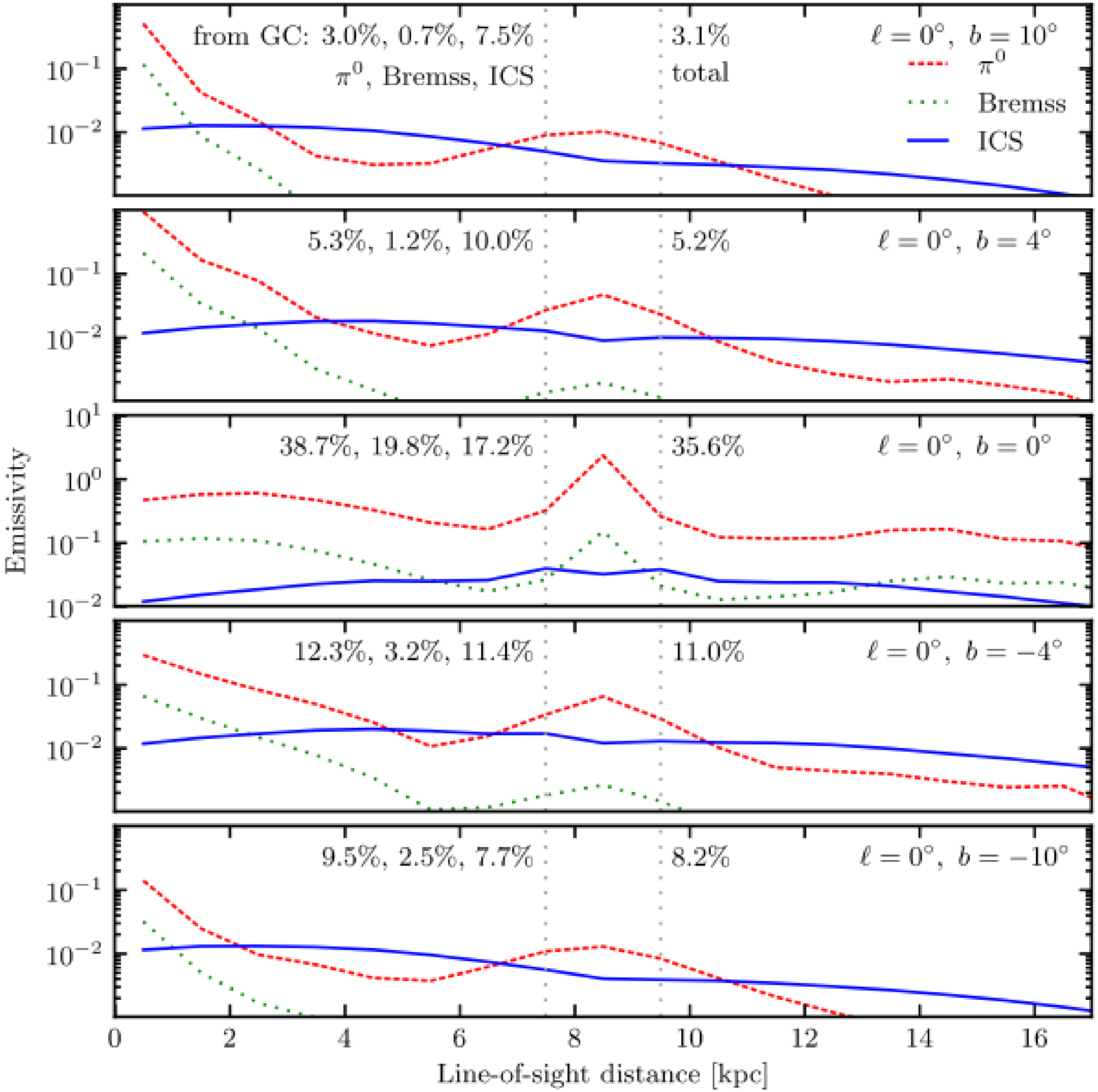
high energy electron



low energy photon
- cosmic microwave background
- starlight

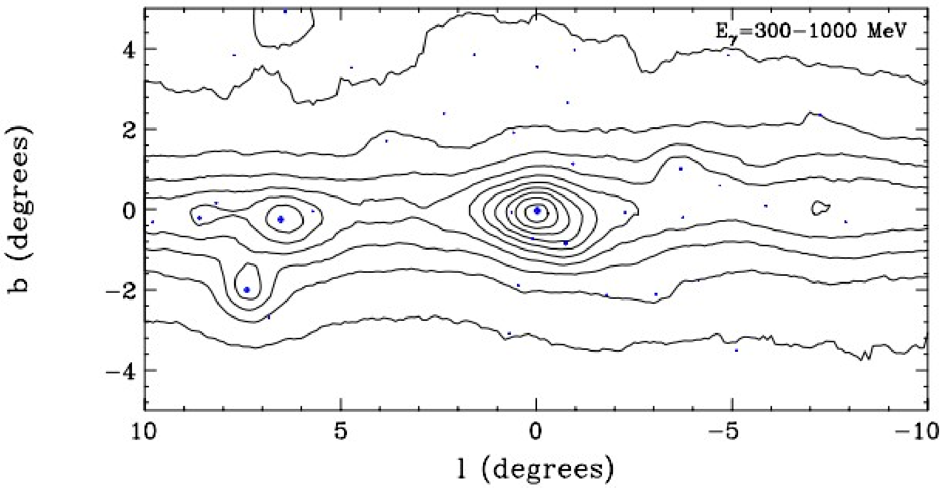
[review: Strong, Moskalenko & Ptuskin (2007)]

At high latitudes, most emission is local!



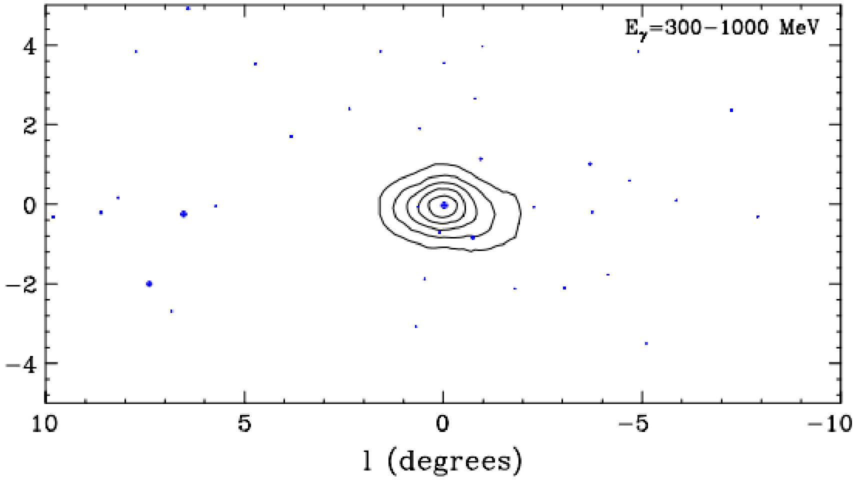
A “GeV Excess” at the Galactic center?

Claims for an extended emission of gamma-rays at the Galactic center



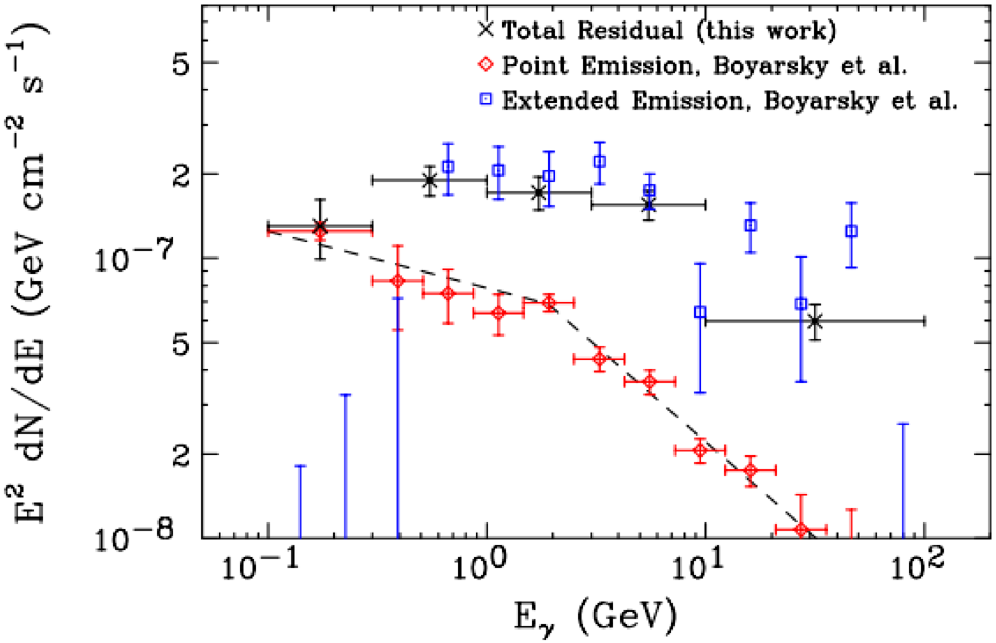
- point sources – “diffuse emission”

=



Hooper & Linden 2011

Extracted spectrum:

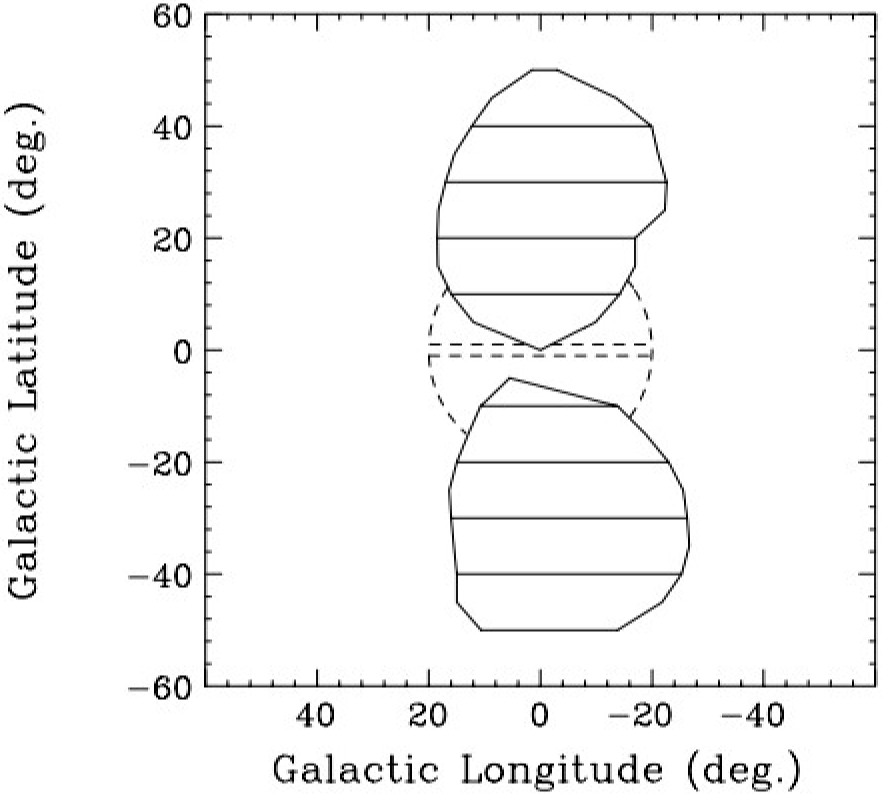


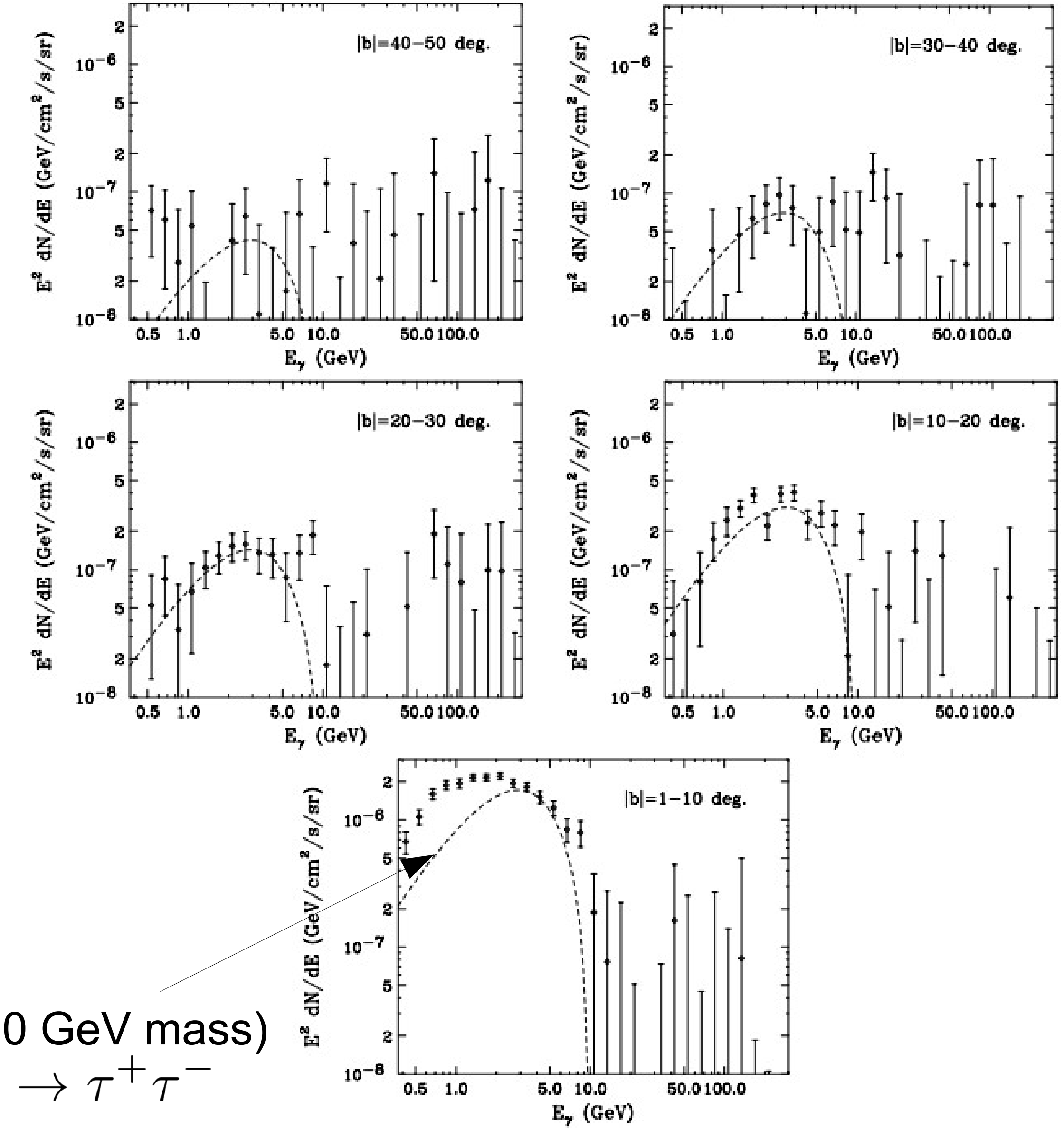
Dark matter interpretation:
- annihilation into e.g. tau+ tau-
- ~10 GeV DM mass
- contracted NFW profile

see also Abazajian & Kaplinghat 2012, Gordon & Macias 2013, Daylan+ 2014

A GeV Excess in the “inner Galaxy”?

Claims for the emission being extended up to high latitudes:





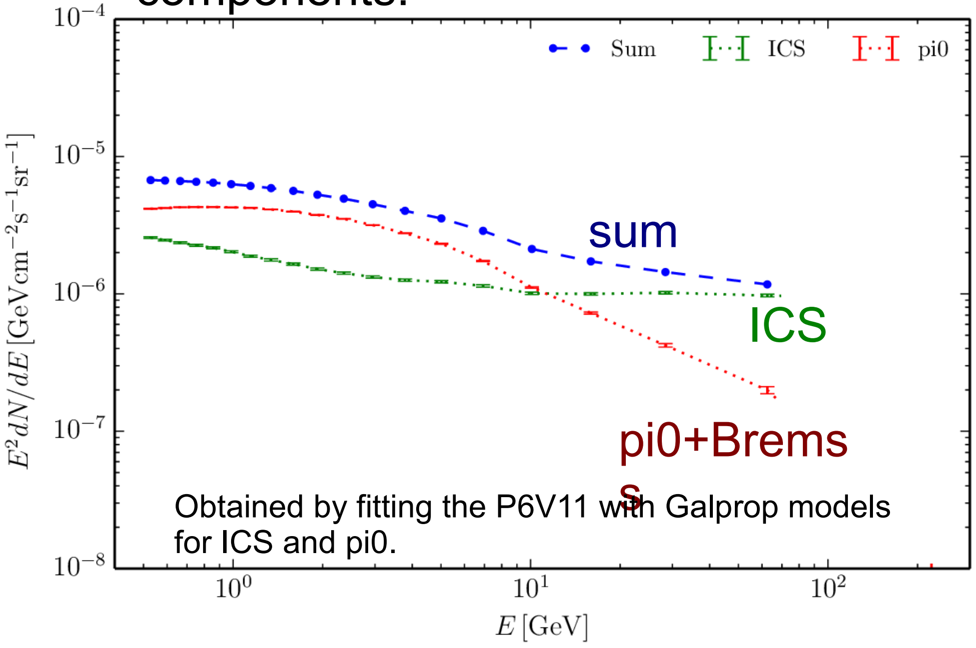
Hooper & Slatyer 2013

DM fit (10 GeV mass)

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

The omnipresent “P6V11” diffuse emission model

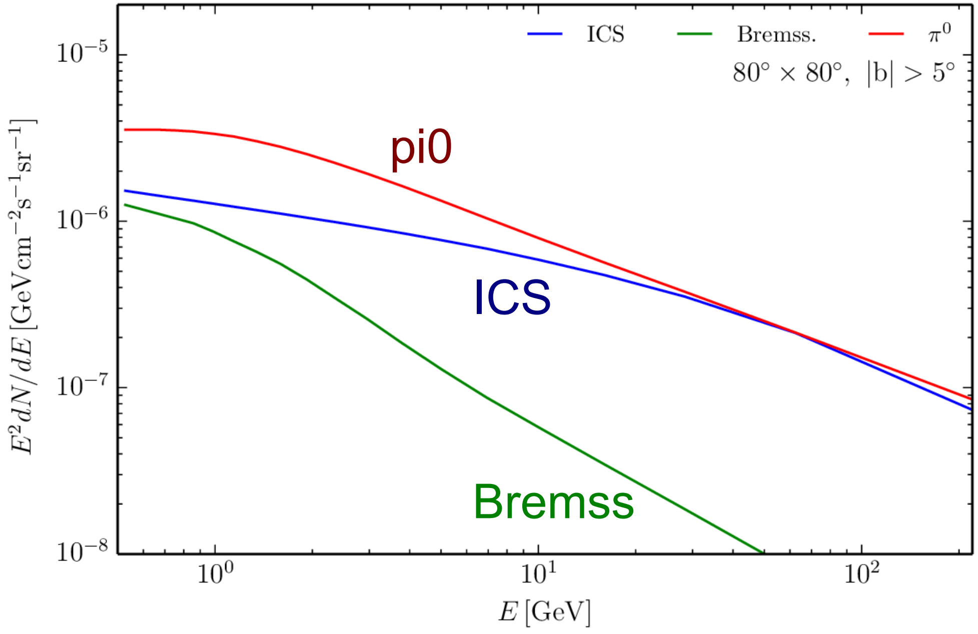
Decomposition of P6V11 in Inverse Compton and pi0+Bremss. components:



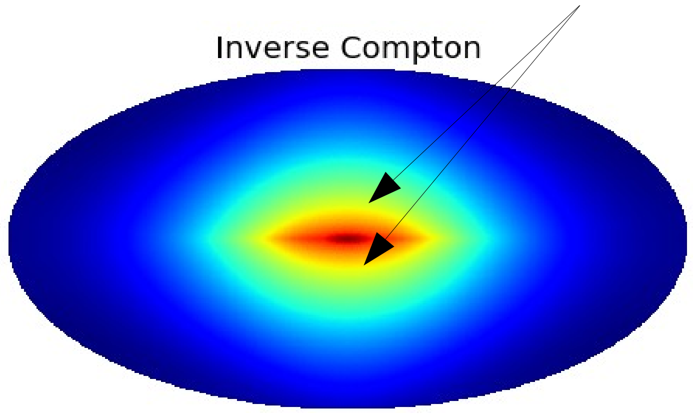
Obtained by fitting the P6V11 with Galprop models for ICS and pi0.

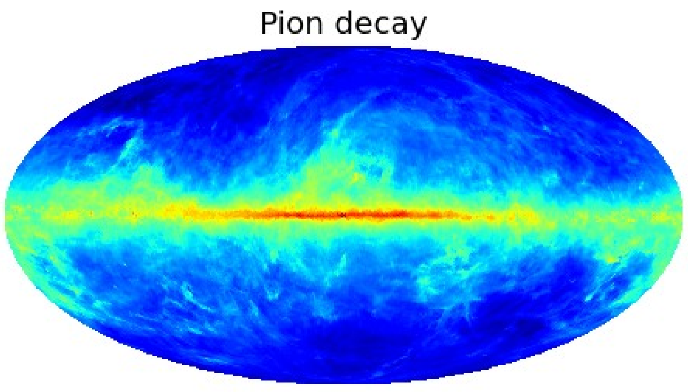
Flux from typical semi-realistic model:

[Ackermann *et al.*, 2012, 1202.4039]



ICS component **very hard** at >10 GeV energies → oversubtraction of BGs possible.





Key questions and features of our analysis

F. Calore, I. Cholis and CW, arXiv:1409.0042
“Background model systematics for the Fermi GeV excess”

Central questions:

- What is the **energy spectrum** of the excess?
- **How far** does the excess extend to high latitudes?
- Is the energy spectrum the **same everywhere**?
- Is the excess **spherically symmetric**?

Technical aspects of the fits

- Small **region of interest**, “inner Galaxy”:

$$2^\circ \leq |b| \leq 20^\circ \quad \text{and} \quad |\ell| \leq 20^\circ$$

- Masking of all <u>detected</u> **point sources** from the Fermi source catalog
- A large number of different and extreme models for the **Galactic diffuse emission** (GDE) → “systematic model uncertainties”
- Analysis of residuals in **large number of test regions** → “empirical model uncertainties”
- Analysis of morphological properties my dividing the ROI in ten segments

Likelihood function:

$$-2\ln\mathcal{L} = 2\sum_{i,j} w_{i,j}(\mu_{i,j} - k_{i,j}\ln\mu_{i,j}) + \chi^2_{\text{ext}}$$

PSC mask

Model components

External constraints

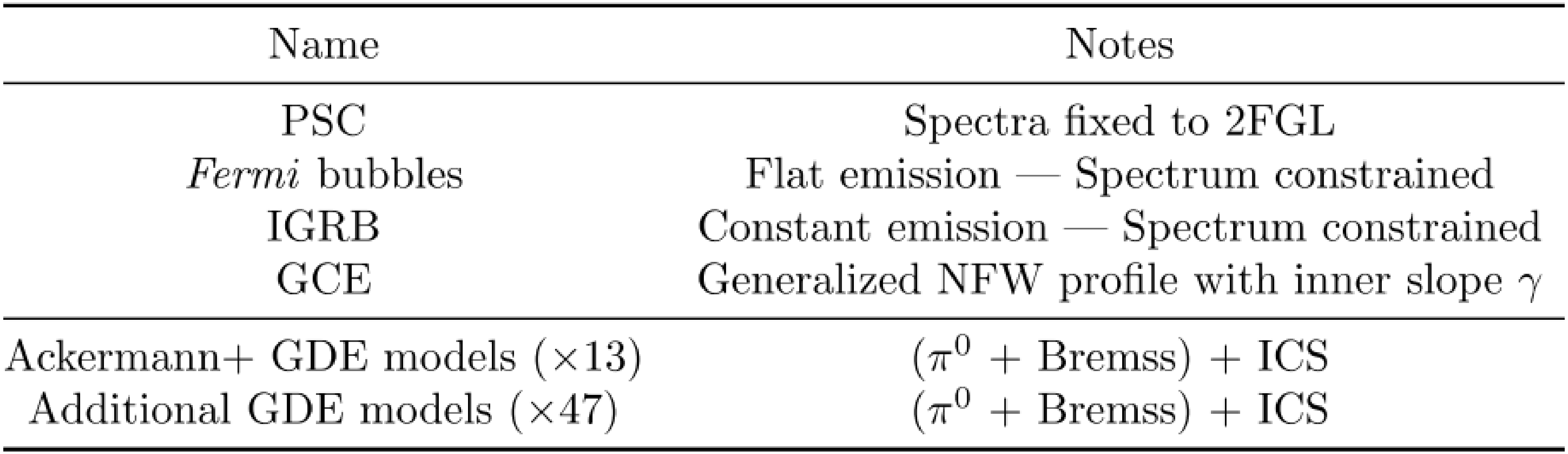
$$w_{i,j} = \frac{1}{\left(\frac{\mu^{\text{PSC}}_{i,j}}{f_{\text{PSC}}\ \mu^{BG}_{i,j}}\right)^{\alpha_{\text{PSC}}} + 1}$$

$$\mu_{i,j} = \sum_k \theta_{i,k}\mu^{(k)}_{i,j}$$

$$\chi^2_{\text{ext}} = \sum_{i,k}\left(\frac{\phi_{i,k} - \bar{\phi}_{i,k}}{\Delta\phi_{i,k}}\right)^2$$

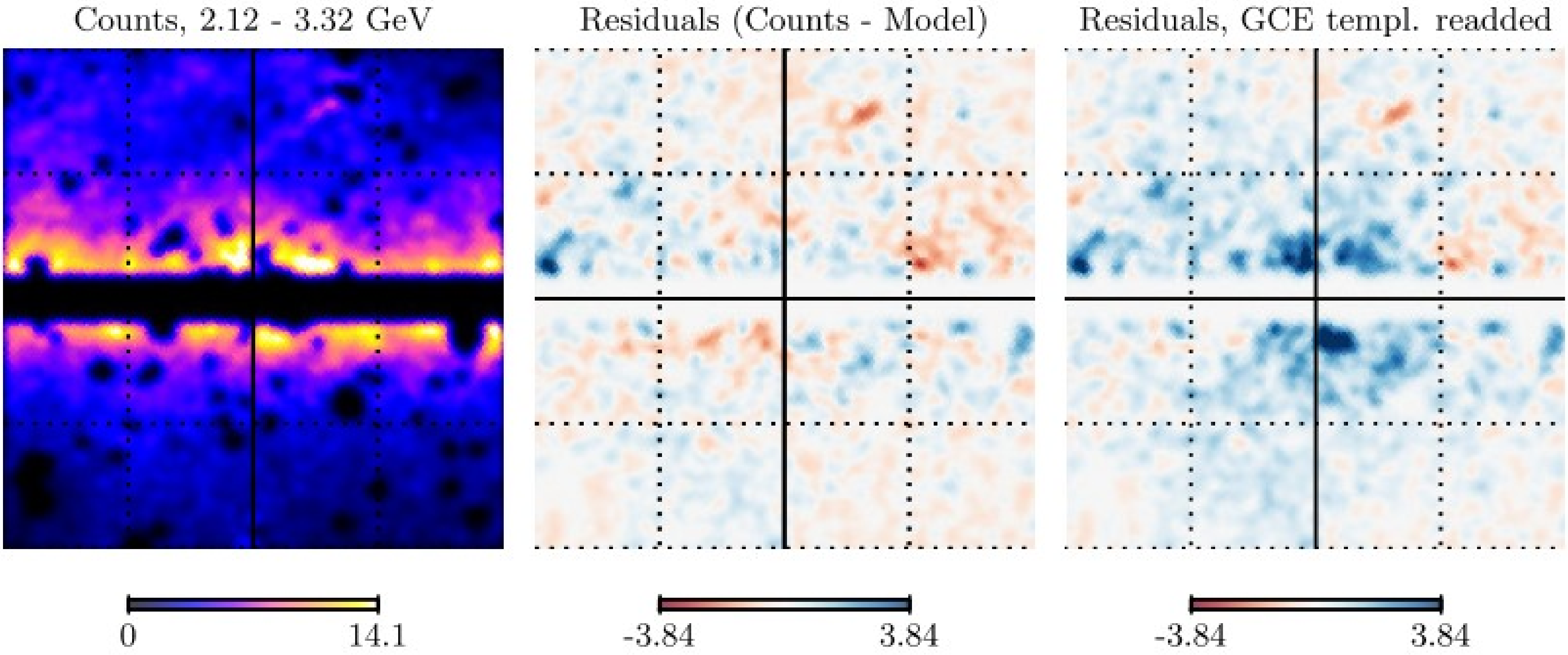
#fit parameters = #energy-bins x #components

Components



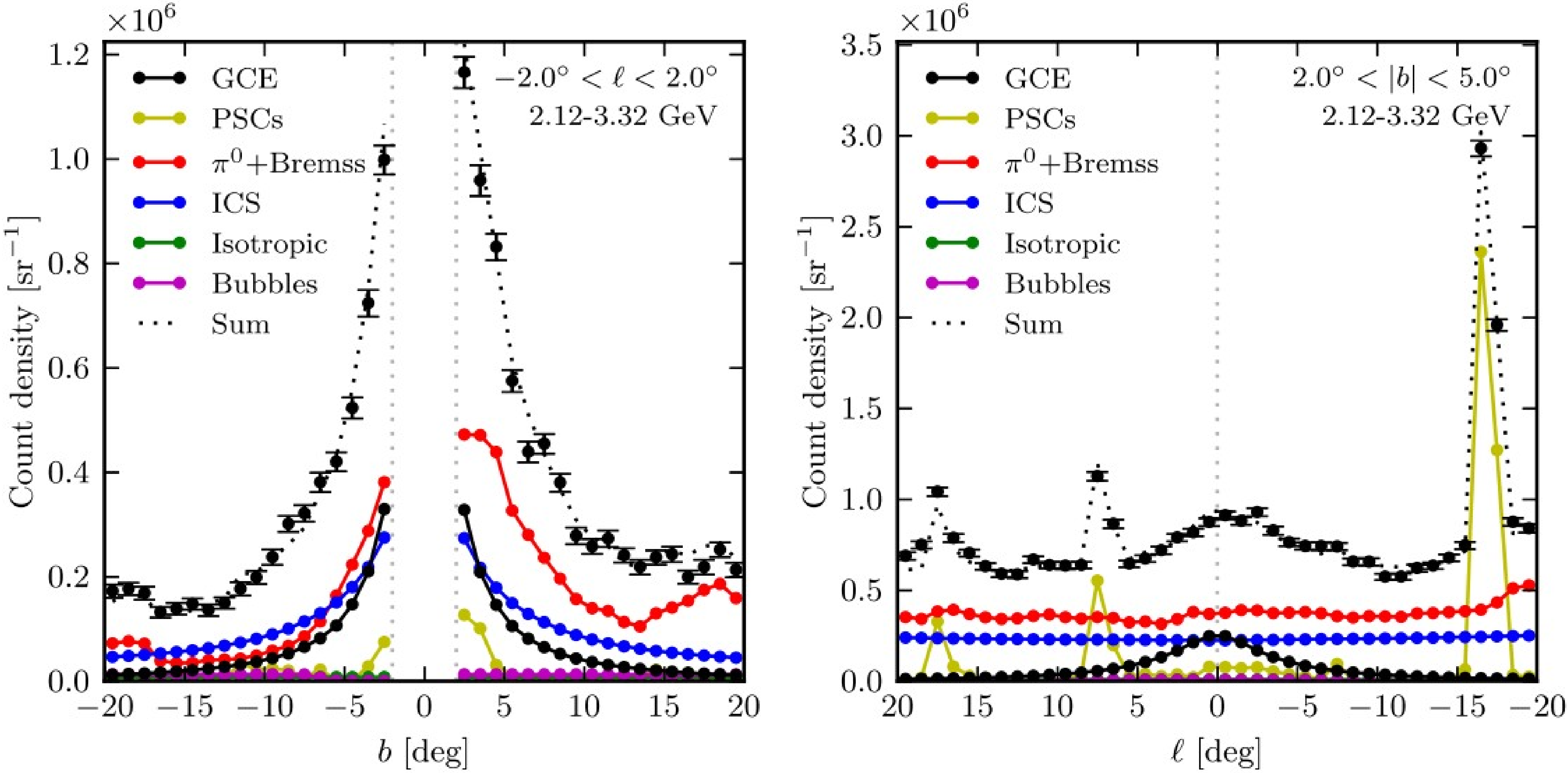
Name	Notes
PSC	Spectra fixed to 2FGL
Fermi bubbles	Flat emission — Spectrum constrained
IGRB	Constant emission — Spectrum constrained
GCE	Generalized NFW profile with inner slope γ
Ackermann+ GDE models (×13)	$(\pi^0$ + Bremss) + ICS
Additional GDE models (×47)	$(\pi^0$ + Bremss) + ICS

Typical residuals for one FG model

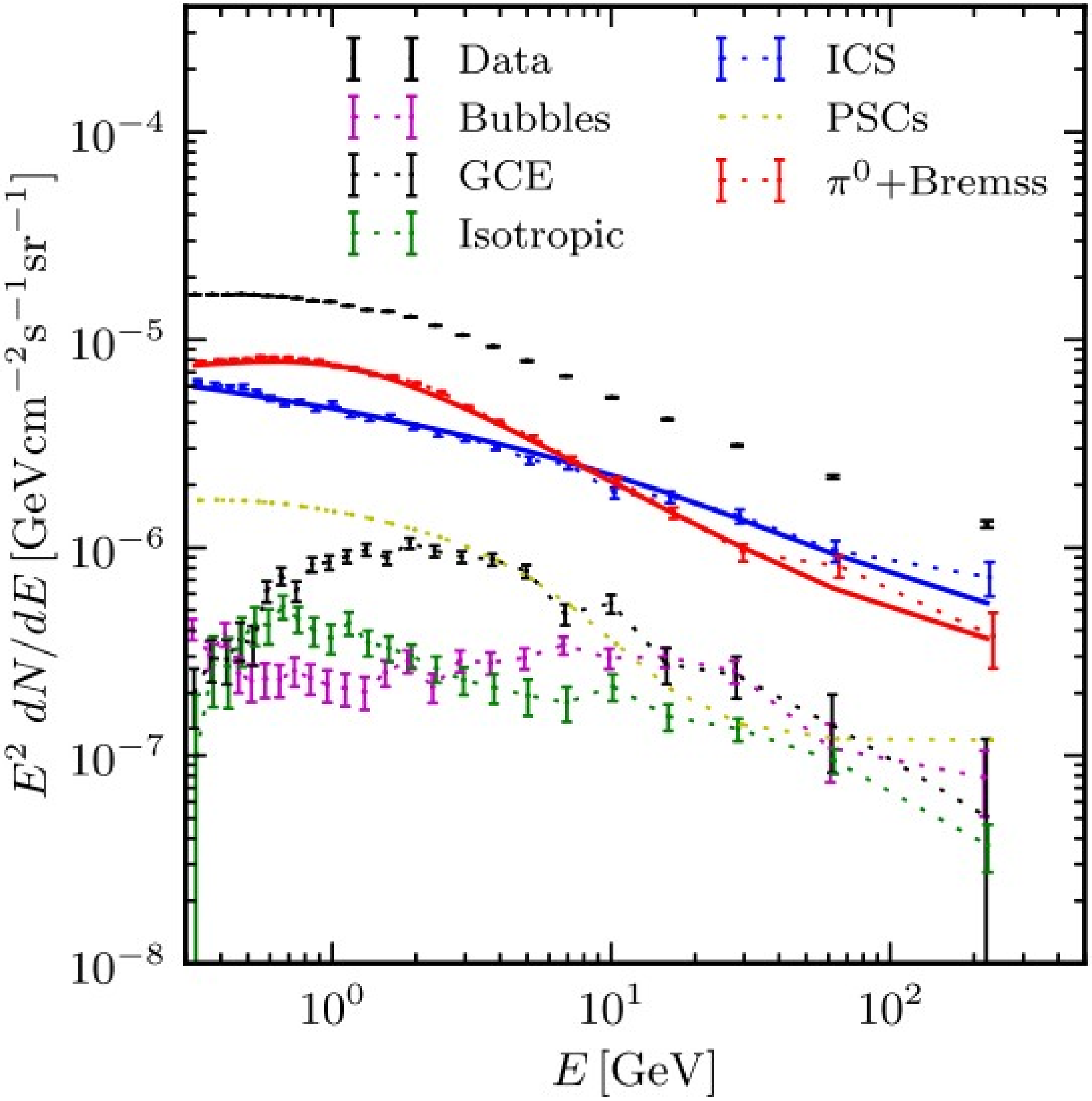


- Point source mask clearly visible
- Residuals at the level of <20% are observed
- Readding the DM template clearly shows an extended excess around the GC

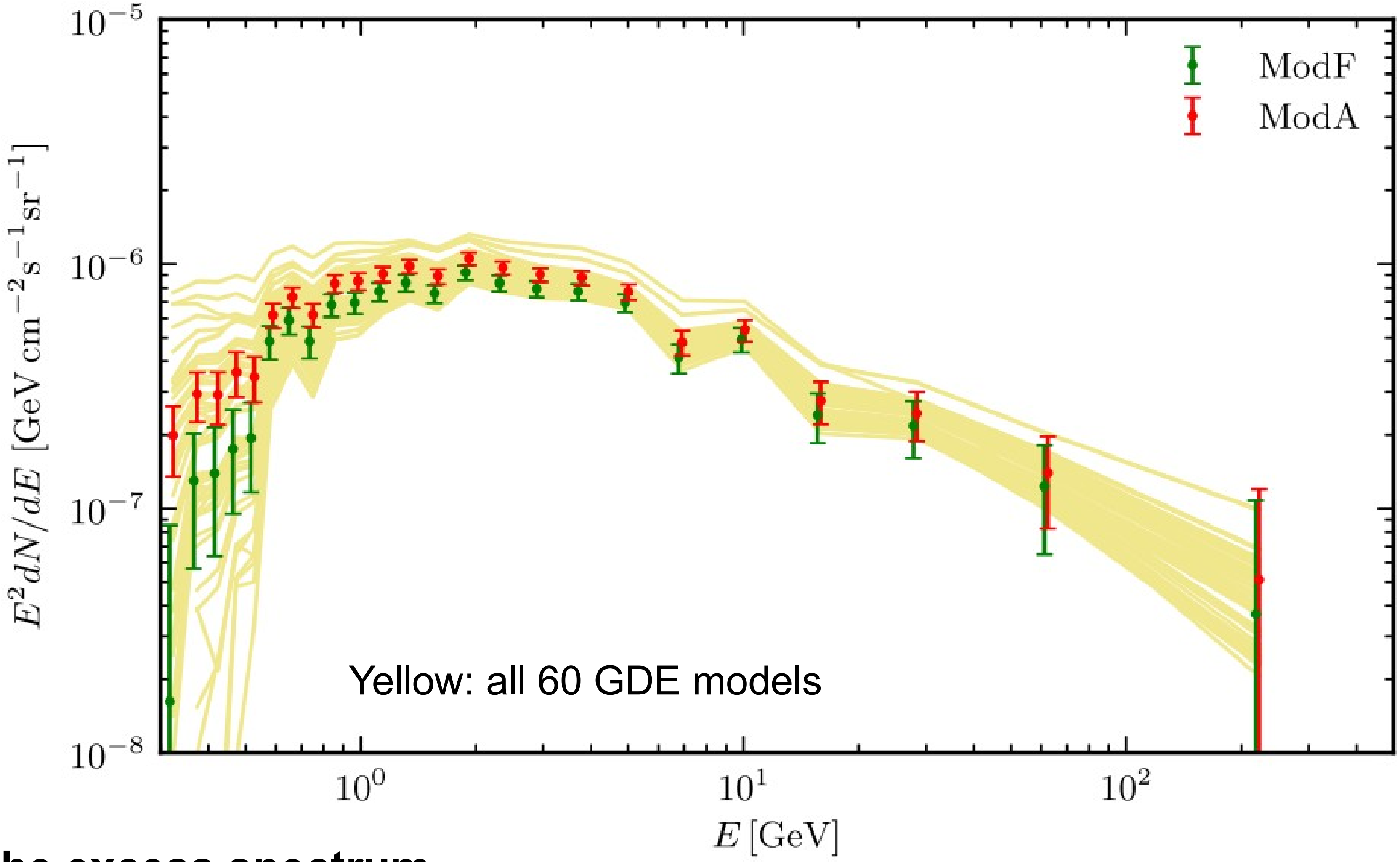
Typical residuals and morphological fits



Spectra


Data
Bubbles
GCE
Isotropic
ICS
PSCs
π^0+Bremss
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^0
10^1
10^2
$E^2\ dN/dE\,[\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}]$
$E\,[\mathrm{GeV}]$

Component spectra



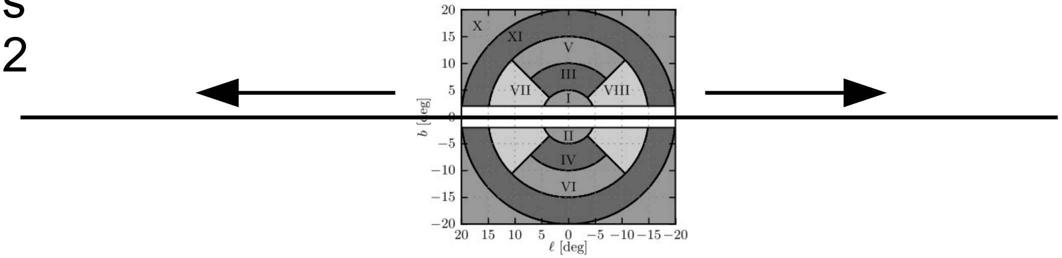
Yellow: all 60 GDE models

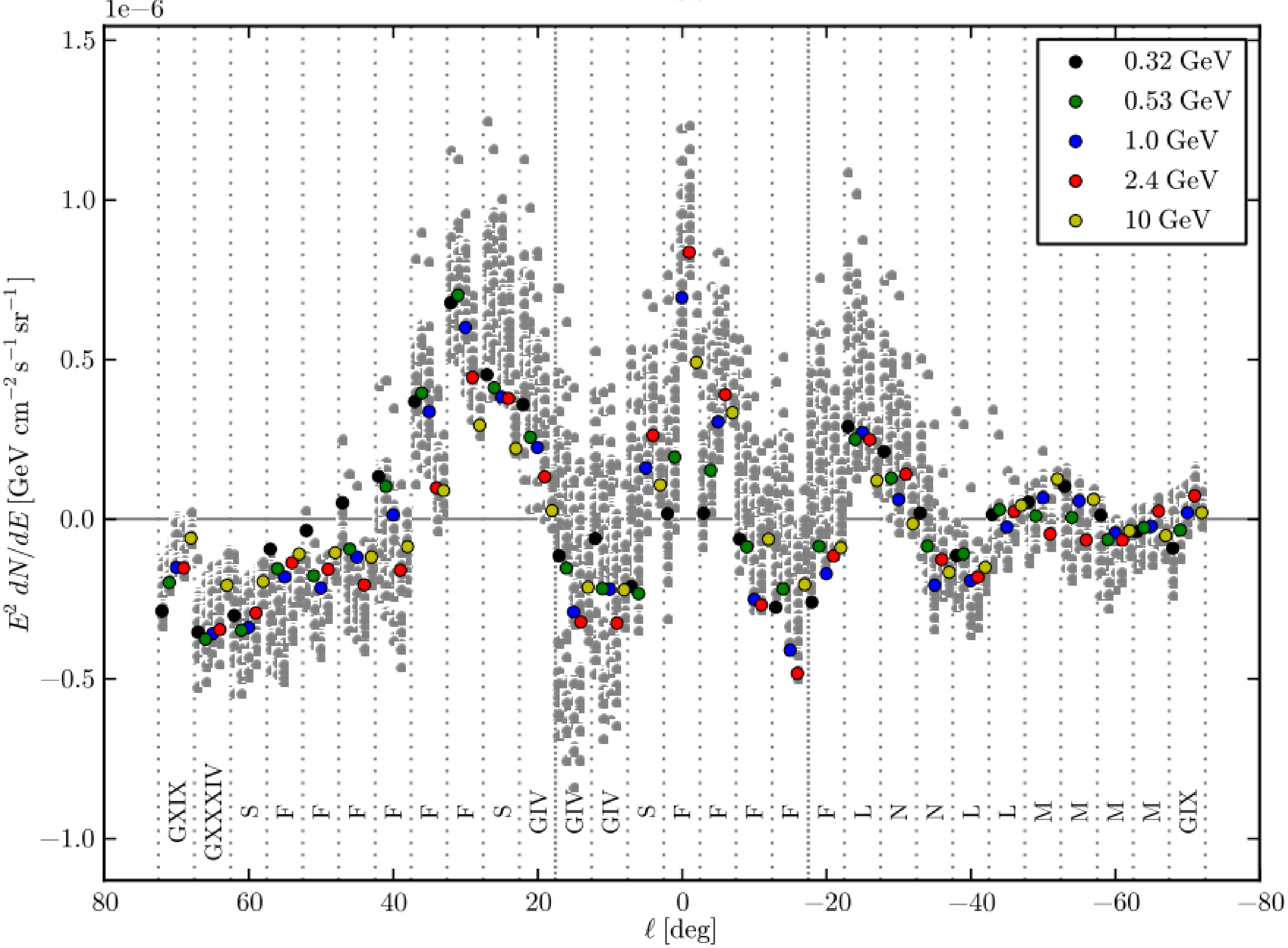
The excess spectrum

- Shows a peak at 1—3 GeV
- Follows a power-law above
- Is steeply rising below
- Does not vary dramatically (by a factor 2 – 3) with the diffusion model

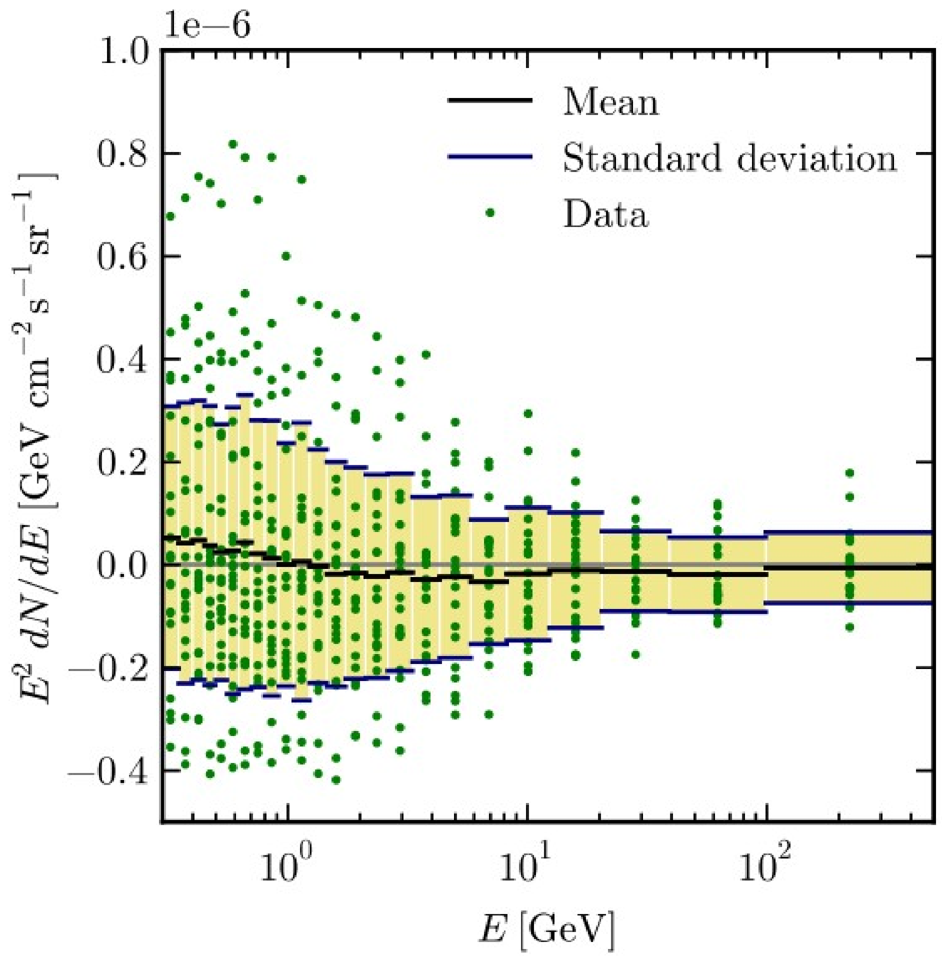
Empirical model systematics

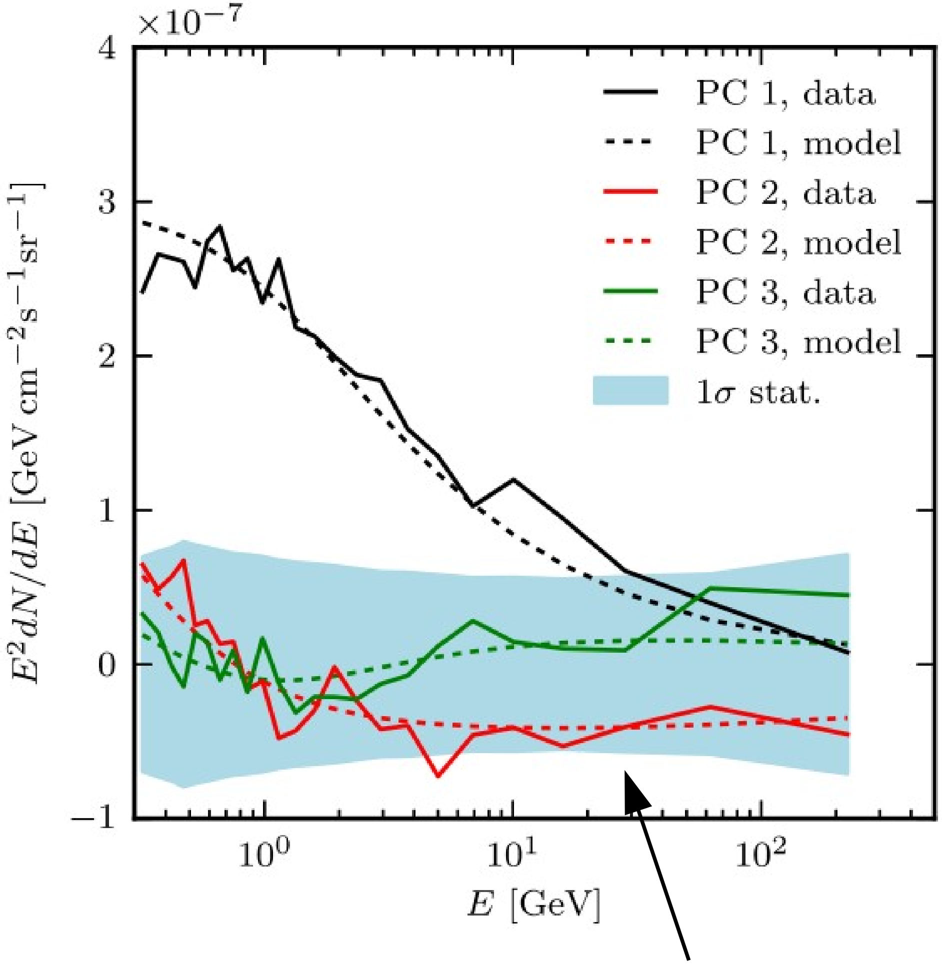
Check for residuals along the disk in 22 test regions:





Scan along disk





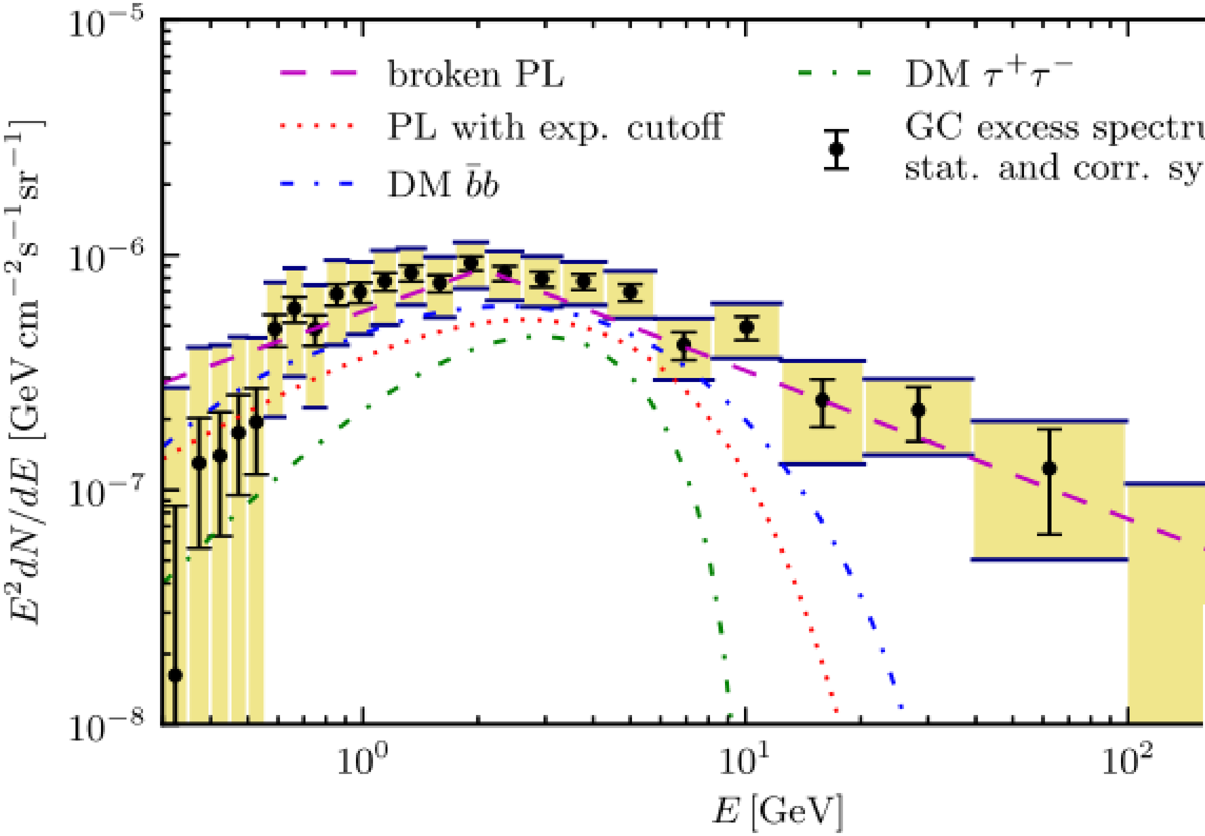
Fluctuations define an empirical **covariance matrix:**

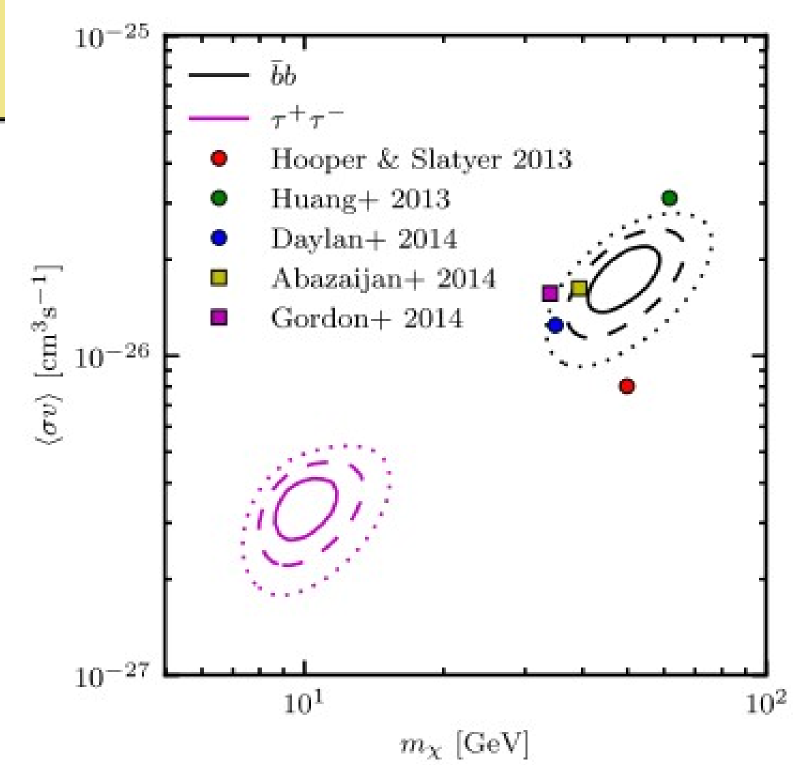
$$\Sigma_{ij,\mathrm{mod}} = \left\langle \frac{dN}{dE_i}\frac{dN}{dE_j} \right\rangle - \left\langle \frac{dN}{dE_i} \right\rangle \left\langle \frac{dN}{dE_j} \right\rangle$$

First three **principal components** of the covariance matrix.

This can be understood in terms of small variations in the ICS and pi0 backgrounds.

Fits



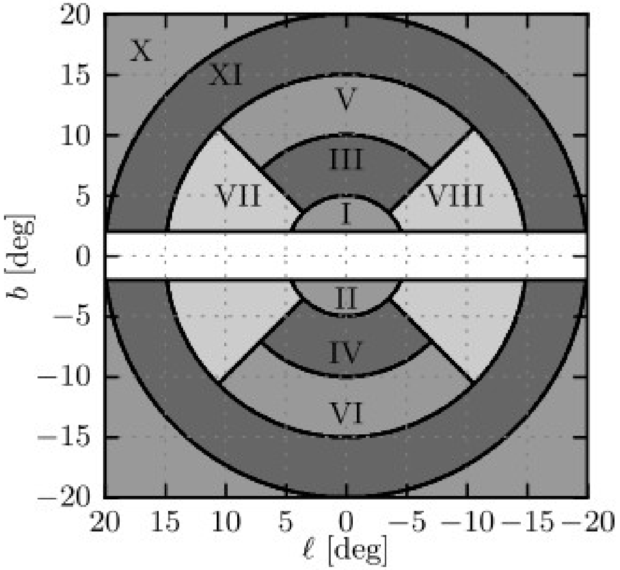


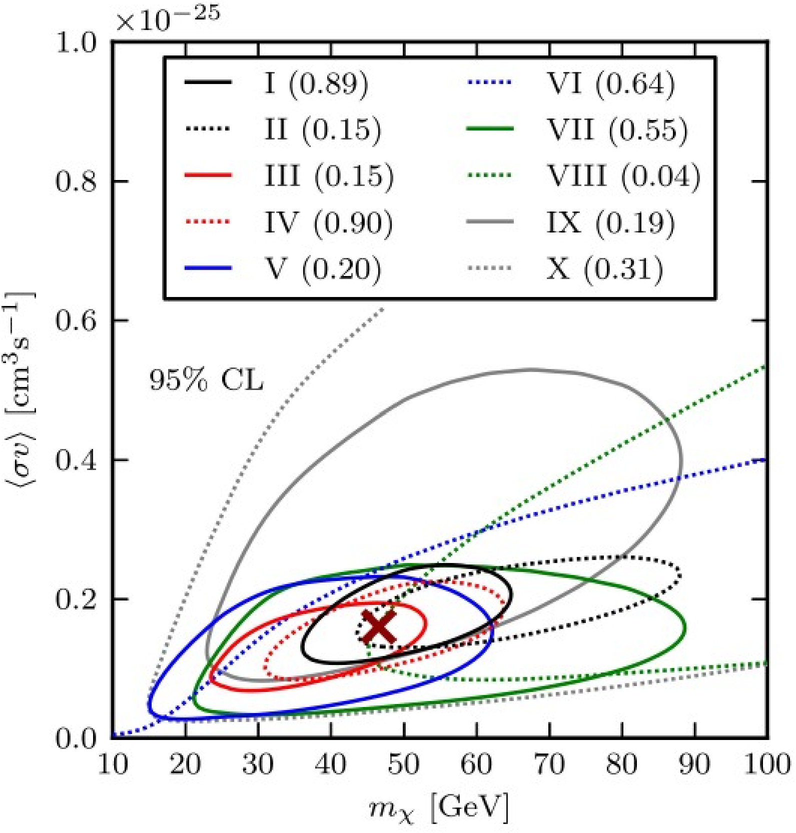
Spectral fits

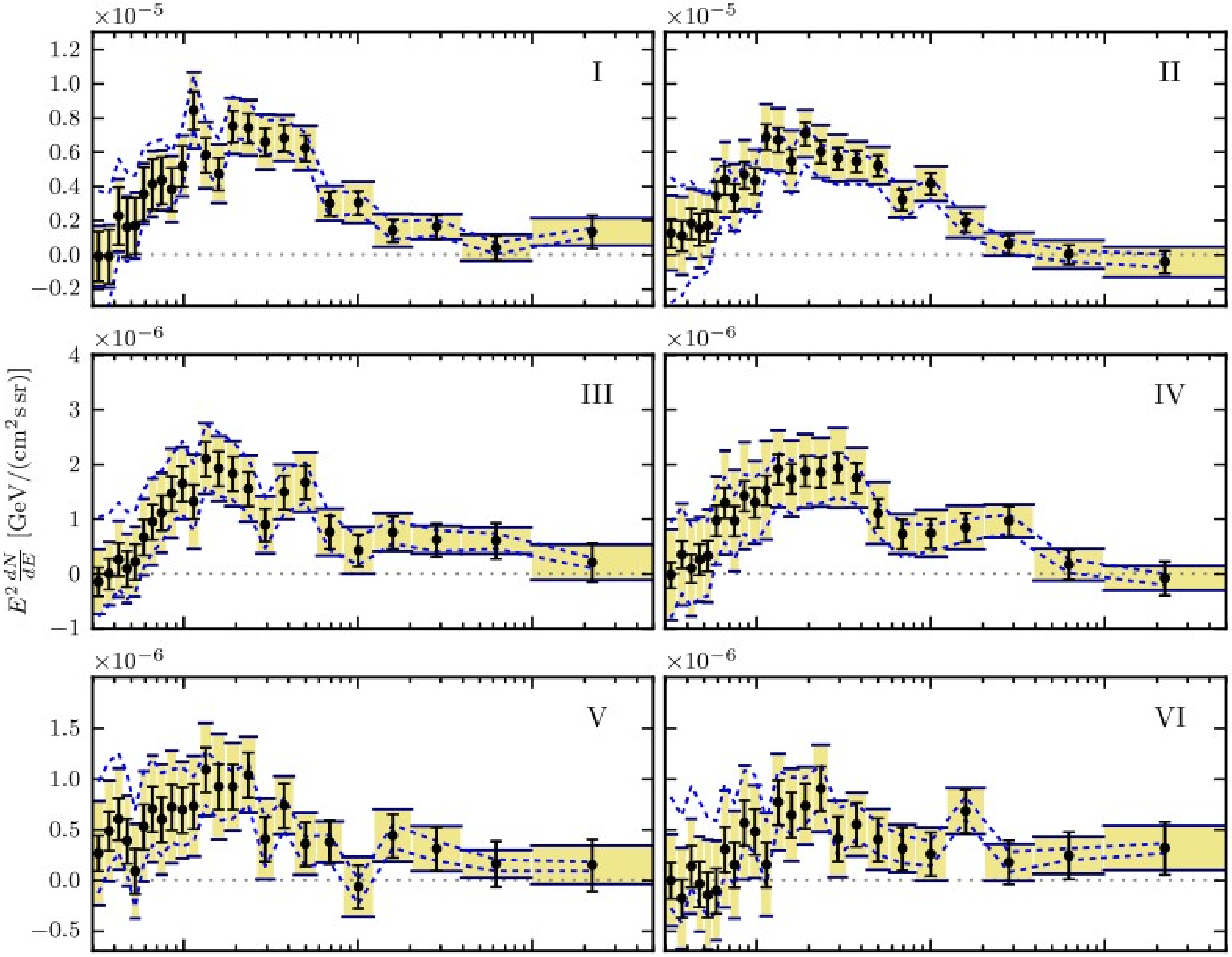
- Best fit given by simple broken power-law
- BUT: good fits can be also obtained with DM annihilation spectra

$$\chi^2 = \sum_{ij} \left(\frac{d\bar{N}}{dE_i}(\boldsymbol{\theta}) - \frac{dN}{dE_i} \right) \Sigma_{ij}^{-1} \left(\frac{d\bar{N}}{dE_j}(\boldsymbol{\theta}) - \frac{dN}{dE_j} \right)$$

Multi-region







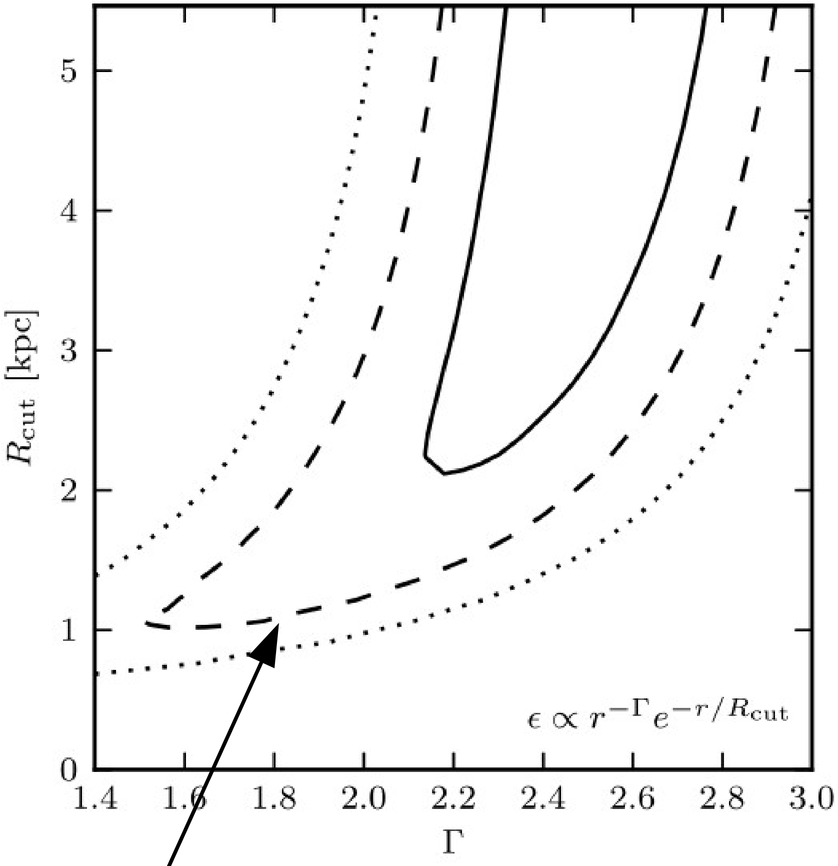
Morphology

- Excess is compatible with being spherical and having a uniform spectrum at 2 sigma
- Lower limit on extension is about 10 deg

Lower limit on the extension

To explore the **extension of the excess to high latitudes**, we consider the volume emissivity profile

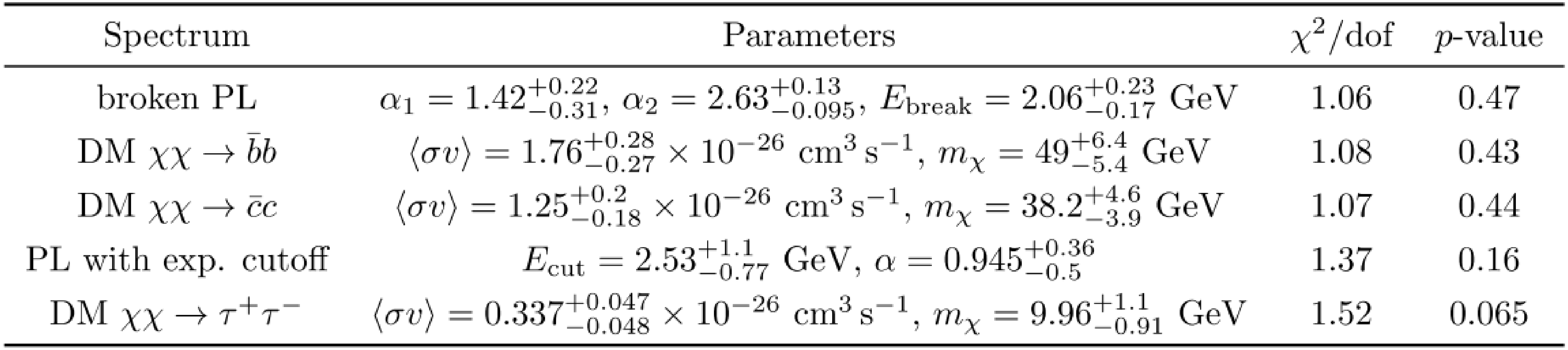
$$q \propto r^{-\Gamma} e^{-r/R_{\rm cut}}$$



We find a lower limit on the extension of at least 1 kpc (corresponding to more than 10 degrees).

$$\psi > 10.0^\circ \quad 95\%\mathrm{CL}$$

GCE conclusions



Spectrum	Parameters	χ^2/dof	p-value
broken PL	$\alpha_1 = 1.42^{+0.22}_{-0.31}$, $\alpha_2 = 2.63^{+0.13}_{-0.095}$, $E_{\mathrm{break}} = 2.06^{+0.23}_{-0.17}$ GeV	1.06	0.47
DM $\chi\chi \to \bar{b}b$	$\langle \sigma v \rangle = 1.76^{+0.28}_{-0.27} \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}$, $m_\chi = 49^{+6.4}_{-5.4}$ GeV	1.08	0.43
DM $\chi\chi \to \bar{c}c$	$\langle \sigma v \rangle = 1.25^{+0.2}_{-0.18} \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}$, $m_\chi = 38.2^{+4.6}_{-3.9}$ GeV	1.07	0.44
PL with exp. cutoff	$E_{\mathrm{cut}} = 2.53^{+1.1}_{-0.77}$ GeV, $\alpha = 0.945^{+0.36}_{-0.5}$	1.37	0.16
DM $\chi\chi \to \tau^+\tau^-$	$\langle \sigma v \rangle = 0.337^{+0.047}_{-0.048} \times 10^{-26}\ \mathrm{cm}^3\,\mathrm{s}^{-1}$, $m_\chi = 9.96^{+1.1}_{-0.91}$ GeV	1.52	0.065

Summary

- Given the large uncertainties in the background flux, it is not possible to discriminate reliably between a simple broken-PL and a more peaked DM-inspired spectra
- Excess can be well fitted with DM inspired spectra (hadronic or leptonic annihilation channels). The fact that the excess is consistent with being spherically symmetric and having a uniform spectrum is suggestive.
- The most relevant alternative are a class of unresolved point sources, possibly a population of bulge MSPs with unusual properties.

Conclusions

- Indirect searches for DM are a powerful probe to test DM annihilation and decay, not only WIMPs
- A successful identification of DM would require the observation of several signals → multi-messenger
- Several signal candidates exist, but no coherent picture emerged yet
- The most promising signal right now is the GCE

Stay tuned!