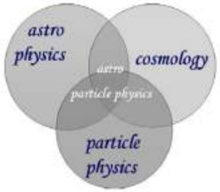
ASTROPARTICLE PHYSICS

Hilary 2021



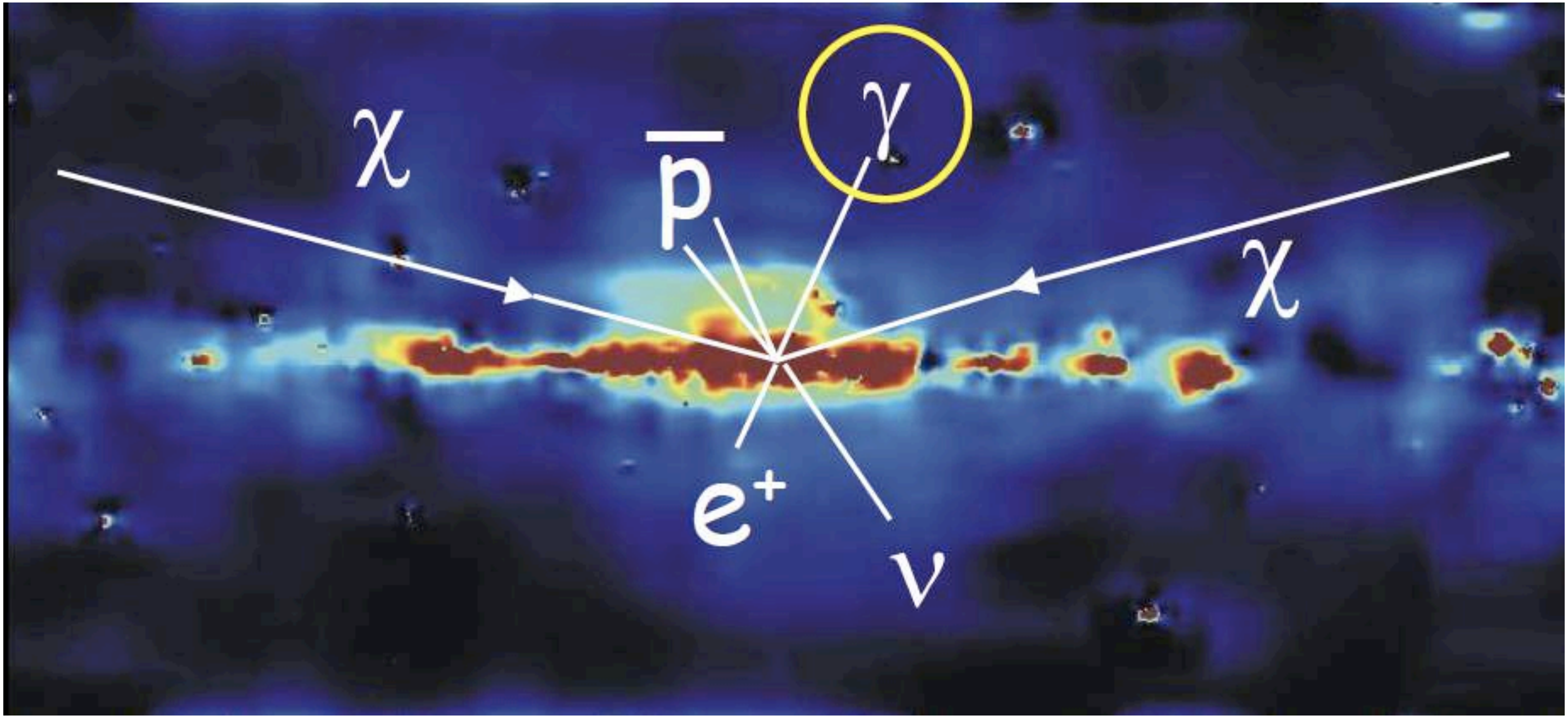
Oxford Physics

Oxford Master Course in Mathematical and Theoretical Physics

- The universe observed
- Relativistic world models
- Reconstructing the thermal history
- Big bang nucleosynthesis
- Dark matter: astrophysical observations
- Dark matter: relic particles
- Dark matter: direct detection
- Dark matter: indirect detection
- Cosmic rays in the Galaxy
- Antimatter in cosmic rays
- Ultrahigh energy cosmic rays
- High energy cosmic neutrinos
- The early universe: constraints on new physics
- The early universe: baryo/leptogenesis
- The early universe: inflation & the primordial density perturbation
- Cosmic microwave background & large-scale structure

 http://www-thphys.physics.ox.ac.uk/user/SubirSarkar/astropartphys.html

Many techniques for indirect detection ... and many claims!



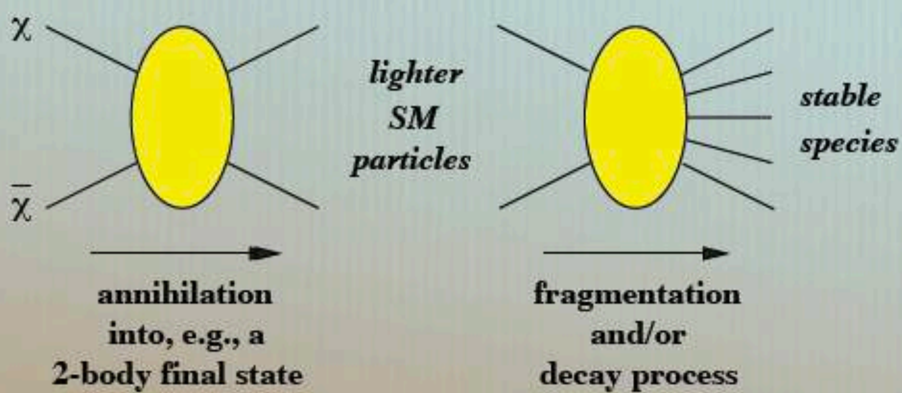
The 'WMAP/Planck haze' (radio), 'PAMELA excess' (e^+), 130 GeV line (gamma) have all been ascribed to dark matter annihilations … however there are many uncertainties!

Nevertheless these offer probes of dark matter elsewhere in the Galaxy, so usefully complement terrestrial direct detection experiments

Indirect detection of WIMP dark matter

A chance of detection stems from the WIMP paradigm itself:

Pair annihilations of WIMPs in DM halos (i.e. at T≅0)



Focus on: antiprotons, positrons, antideuterons, gamma-rays, (neutrinos)

- $(\sigma v)_{T\simeq 0} \overset{?}{\sim} \langle \sigma v \rangle_{T=T_f}$
- final state branching ratios
- $N_{\chi-\mathrm{pairs}} \propto [\rho_\chi(r)]^2 \simeq [\rho_{\mathrm{DM}}(r)]^2$

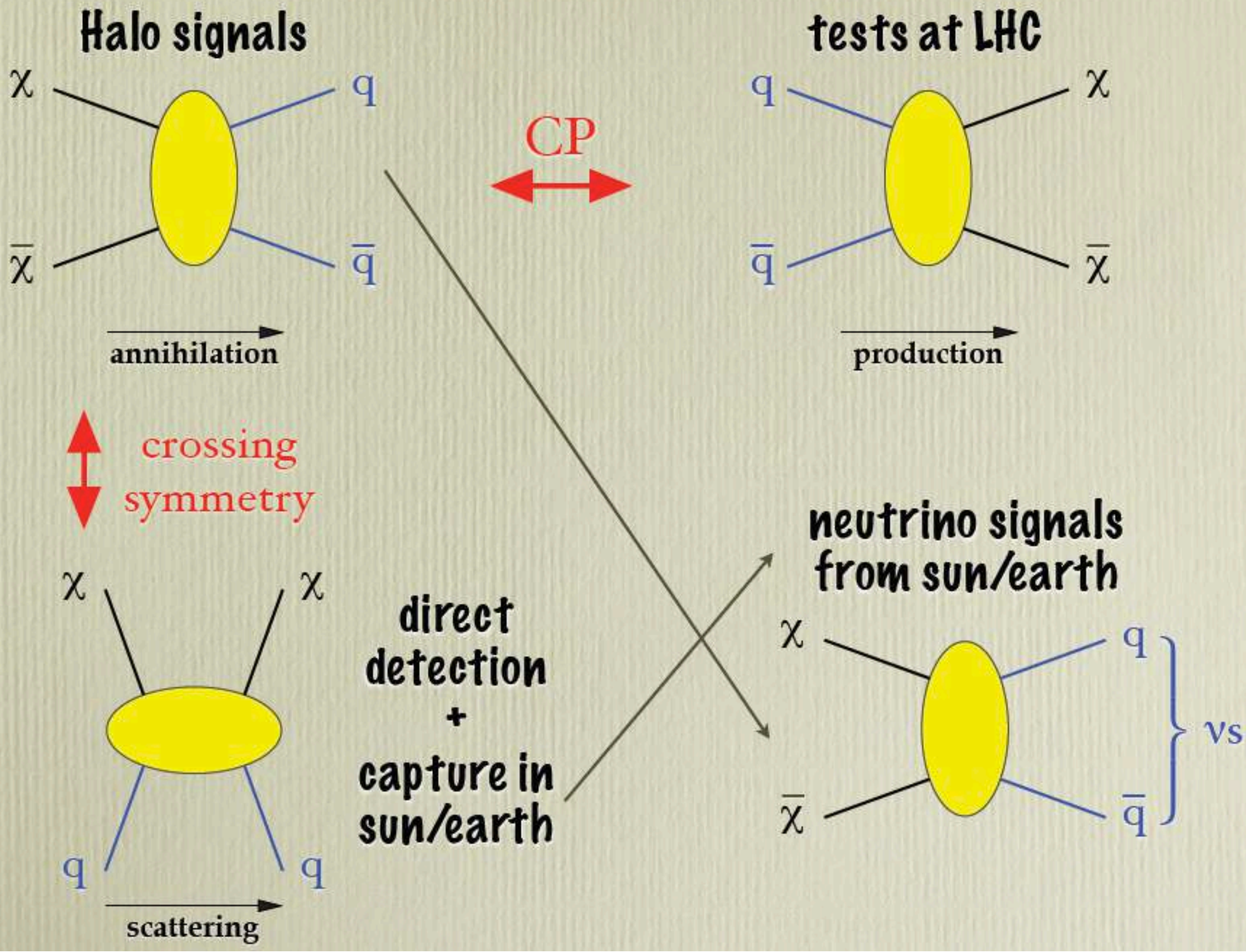
} WIMP DM source function

Dynamical observations (?)/ N-body simulations (?)

NB: WIMPs bound to our Galaxy are moving at only $\sim 10^{-3}$c (*cf*. ~0.1c at freeze-out)

Courtesety: Pierro Ullio

WIMP coupling to ordinary matter



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Indirect detection of WIMP dark matter

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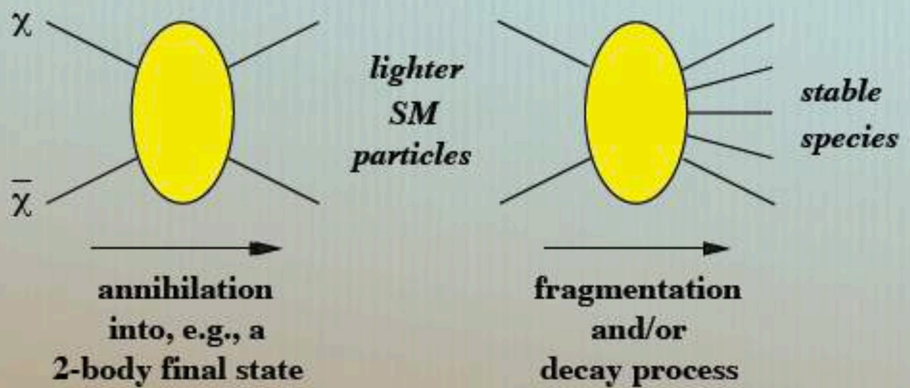


Focus on:
antiprotons,
positrons,
antideuterons,
gamma-rays,
(neutrinos)

Courtesety: Pierro Ullio

Search for the species with low or well understood backgrounds from other known astrophysical sources.

For "standard" annihilation rates, final states and DM density profiles, the ratio signal over background is the largest for antiprotons (antideuterons), can be sizable for gamma-rays, is fairly small for positrons and very small for neutrinos.

The induced gamma-ray flux can be factorized:

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\theta,\phi) = \frac{1}{4\pi}\boxed{\frac{\langle\sigma v\rangle_{T_0}}{2\,M_\chi^2}\sum_f \frac{dN_\gamma^f}{dE_\gamma}B_f}\cdot\boxed{\int_{\Delta\Omega(\theta,\phi)} d\Omega' \int_{l.o.s.} dl\;\rho_\chi^2(l)}$$

Particle Physics — DM distribution

Targets which have been proposed:

- The Galactic center (largest DM density in the Galaxy)
- The diffuse emission from the full DM Galactic halo
- Dwarf spheroidal satellites of the Milky Way
- Single (nearby?) DM substructures without luminous counterpart
- Galaxy clusters
- The diffuse extragalactic radiation

Courtesety: Pierro Ullio

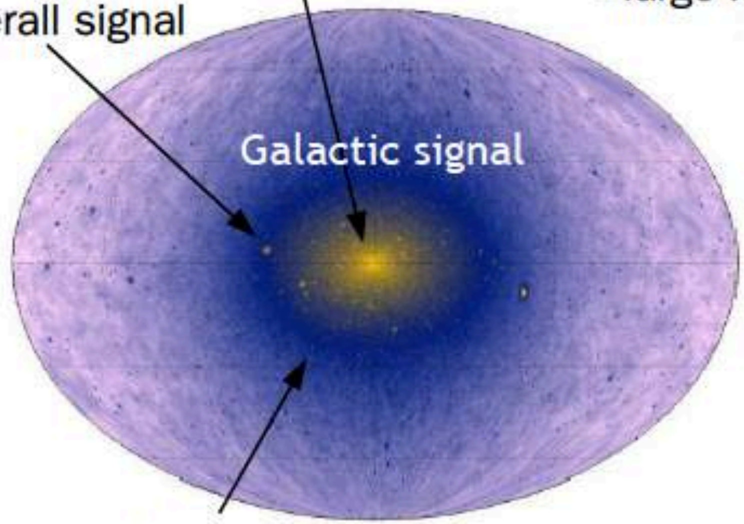
Uncertainties arise from the ill-known density profile of the dark matter distribution and from multiple possibilities for the annihilation channels, as well as astrophysical backgrounds

Easiest to search for γ-rays from dark matter annihilation ...

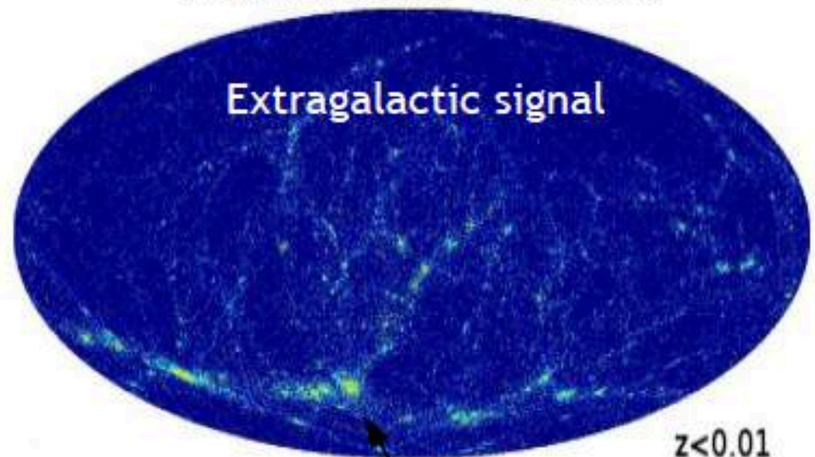
Galactic center
- brightest DM source in sky
- but: bright backgrounds

Dwarf Spheroidal Galaxies
- dark in gamma-ray
- large mass-to-light ratio

DM clumps
- bright enough?
- boost overall signal



Isotropic Gamma-Ray Background
- sensitive to evolution of DM halos
- background challenging to model
- angular power spectrum

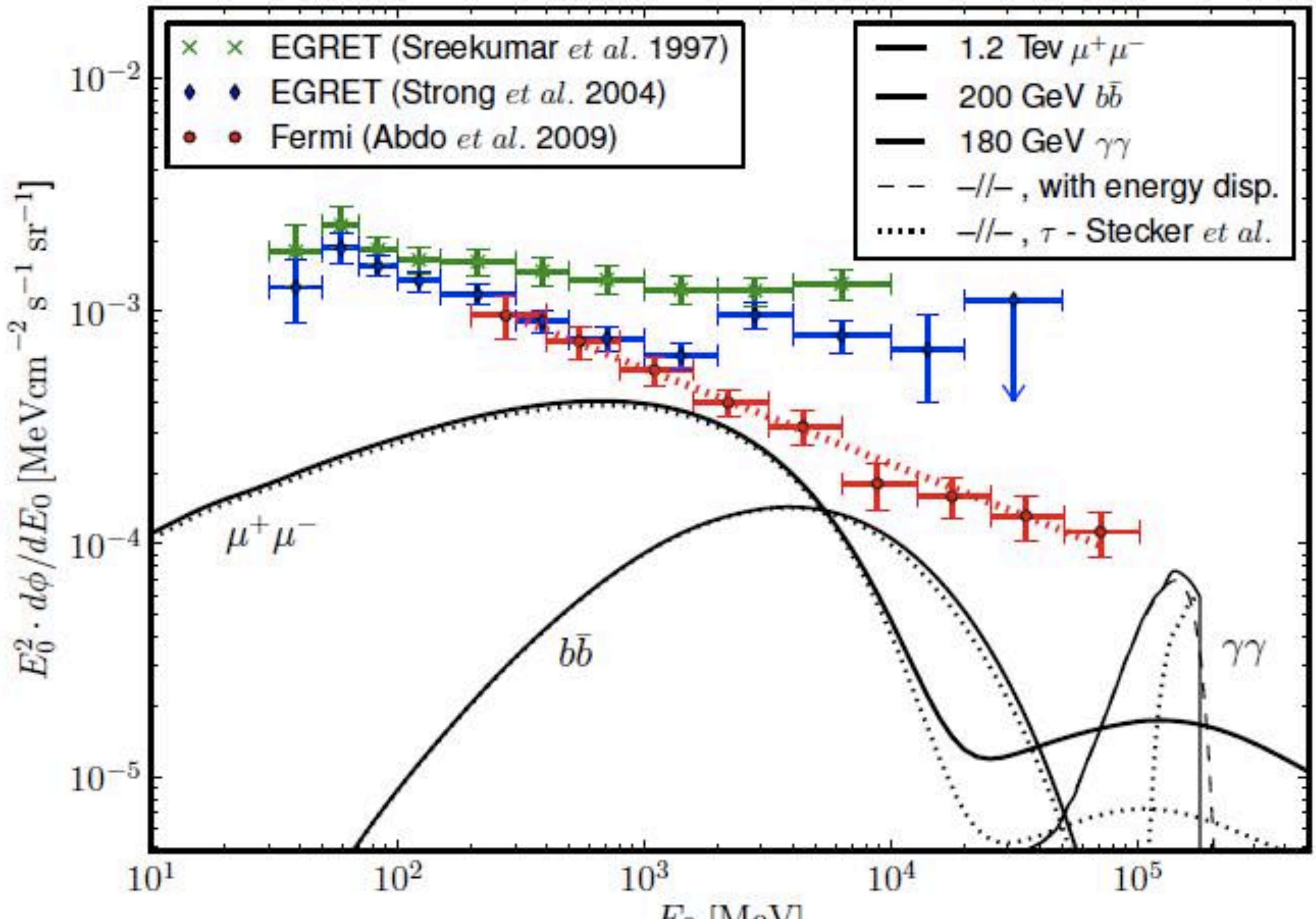


Galactic DM halo
- good S/N
- difficult backgrounds
- angular information

Galaxy clusters
- large substructure boost?
- backgrounds?

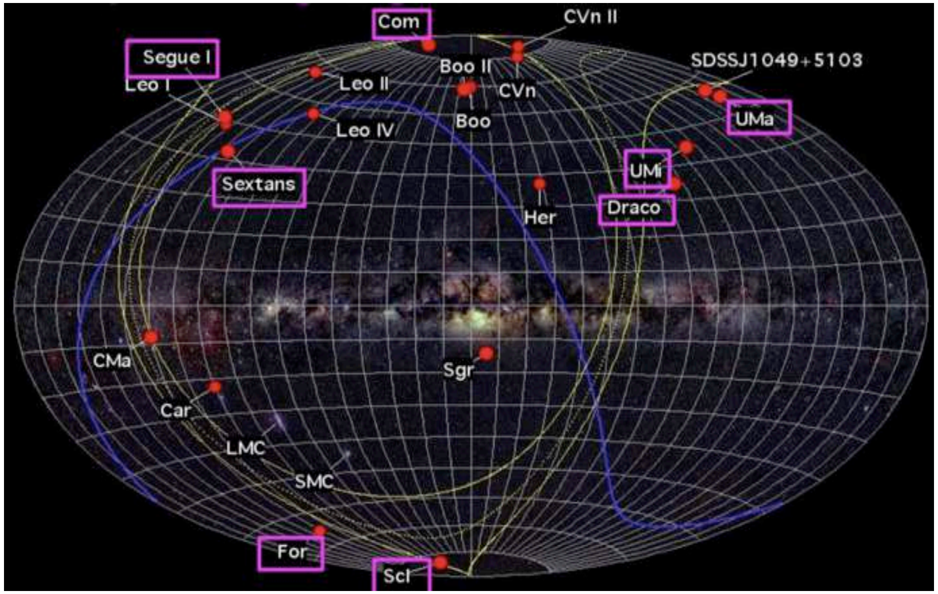
Dwarf spheroidals and the Galactic center/halo give the strongest constraints right now.

The summed DM signal expected from other galaxies is *below* the diffuse γ-ray background

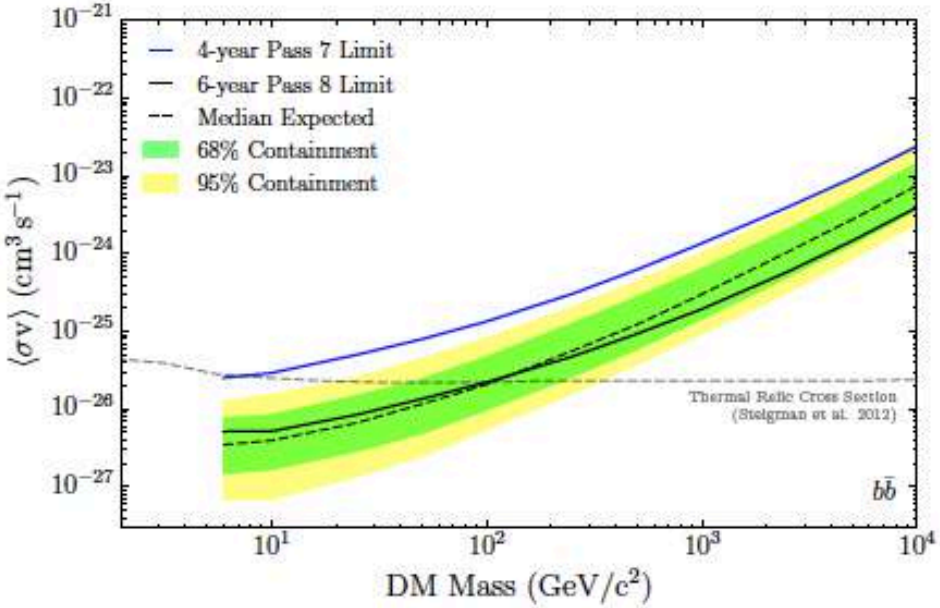


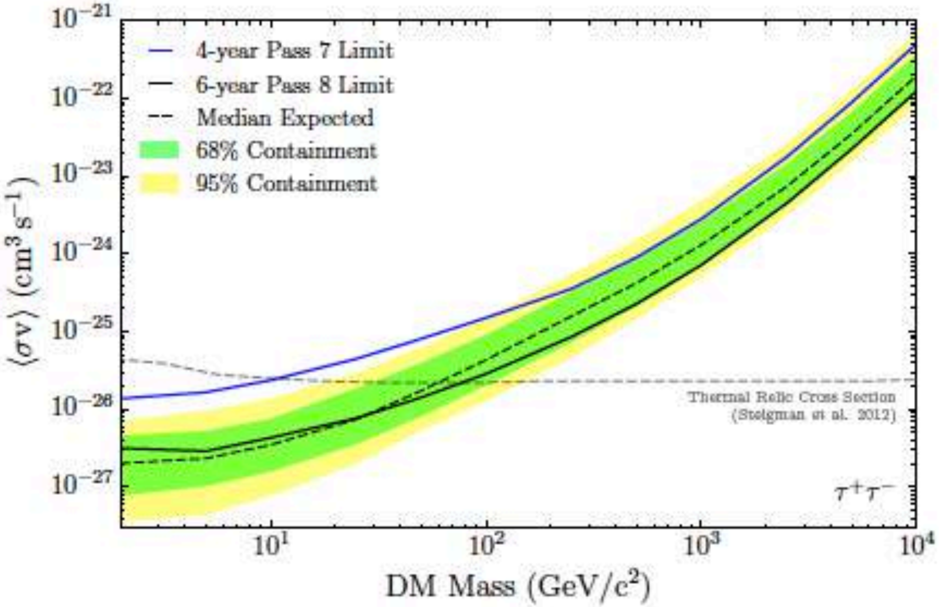
Fermi collaboration, JCAP **04**:014,2010

Particularly stringent limits have been set by *Fermi* observations of dwarf spheroidal galaxies (satellites of the Milky Way) which are highly dark matter dominated … until 2004, only 11 dSphs were known, however more have been identified in SDSS and, recently, DES data



Fermi collab. Phys. Rev.Lett.**115**:231301,2015



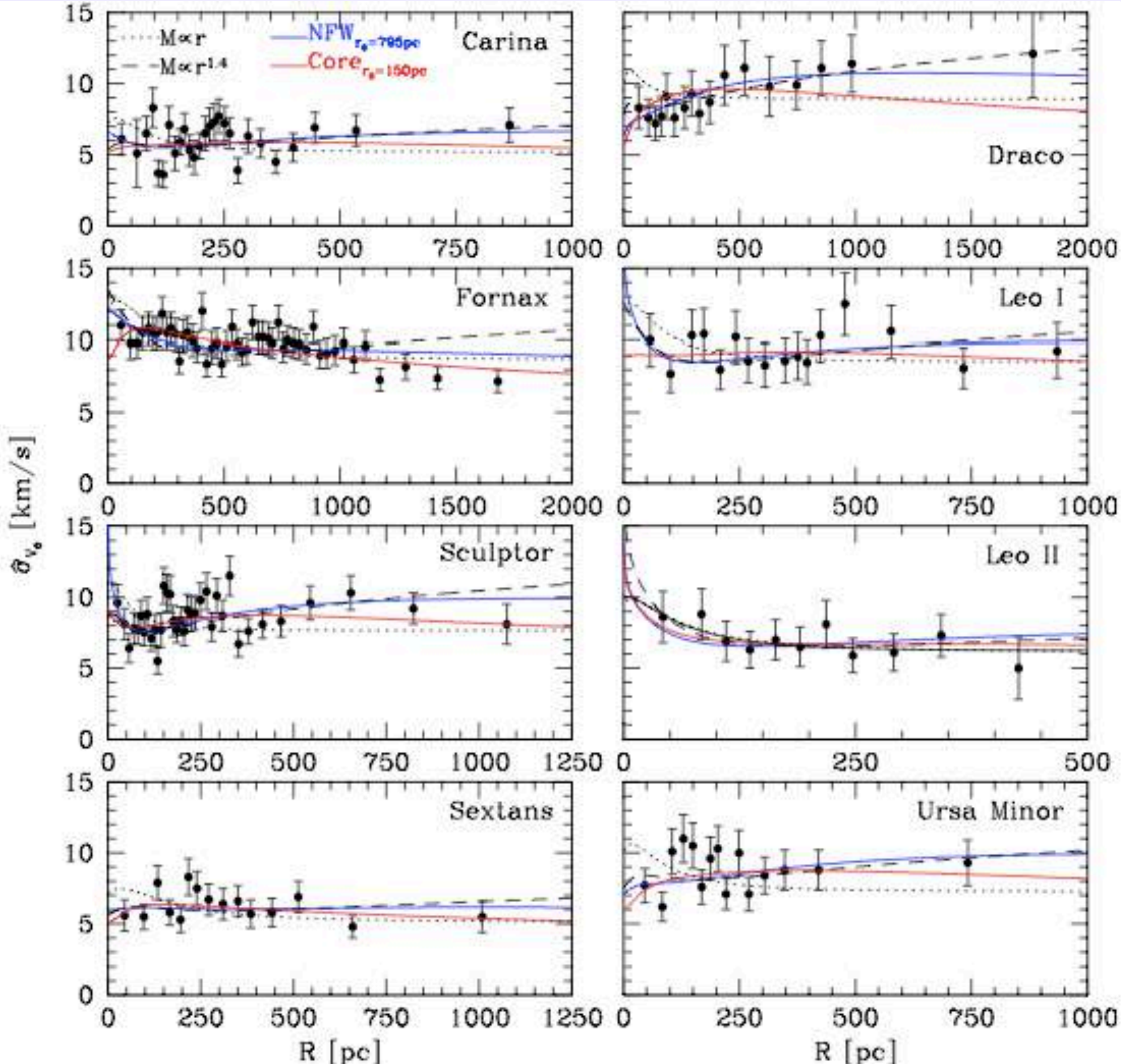


This appears to rule out thermal WIMPs as dark matter up to the weak scale

Sensitivity to the annihilation signal from dSphs is however rather dependent on how the dark matter distribution is modelled: cored halos reduce the signal by a factor of ~100 compared to e.g. a cuspy NFW profile (Evans *et al*, PRD **69**:123501,2004)

Although current kinematic stellar data is generally not good enough to determine the density profile from the rotation curves (Walker et al 2009), it has been shown that at least two dSphs – Fornax and Sculptor – have a cored rather than cuspy profile (Walker & Peñarrubia, ApJ 742:20,2011)

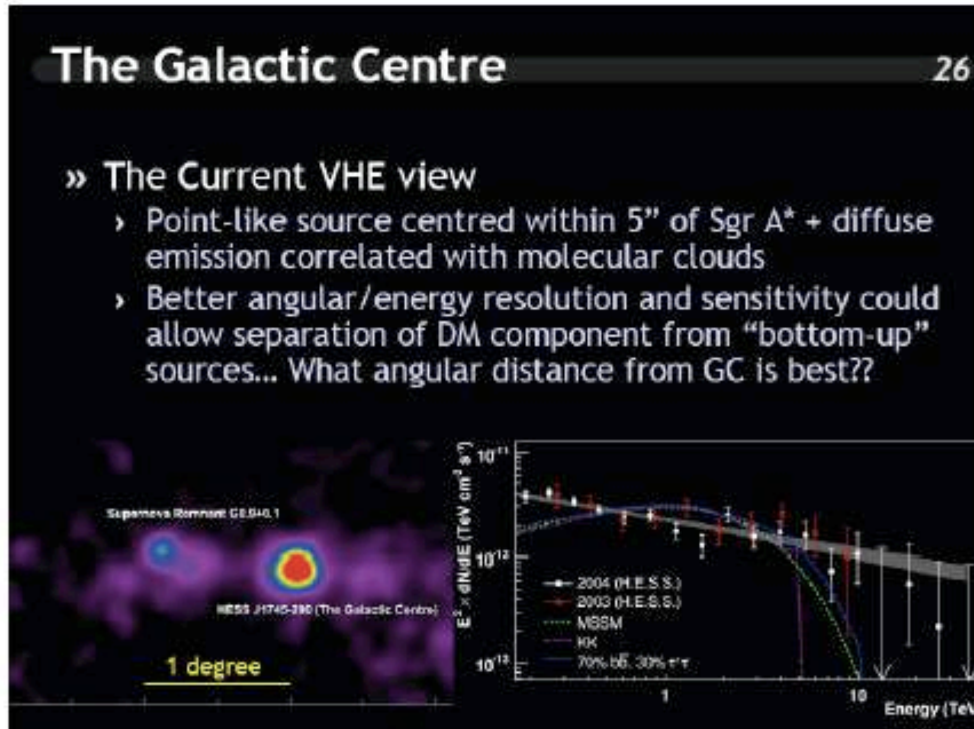
… challenge for CDM?



Galactic centre

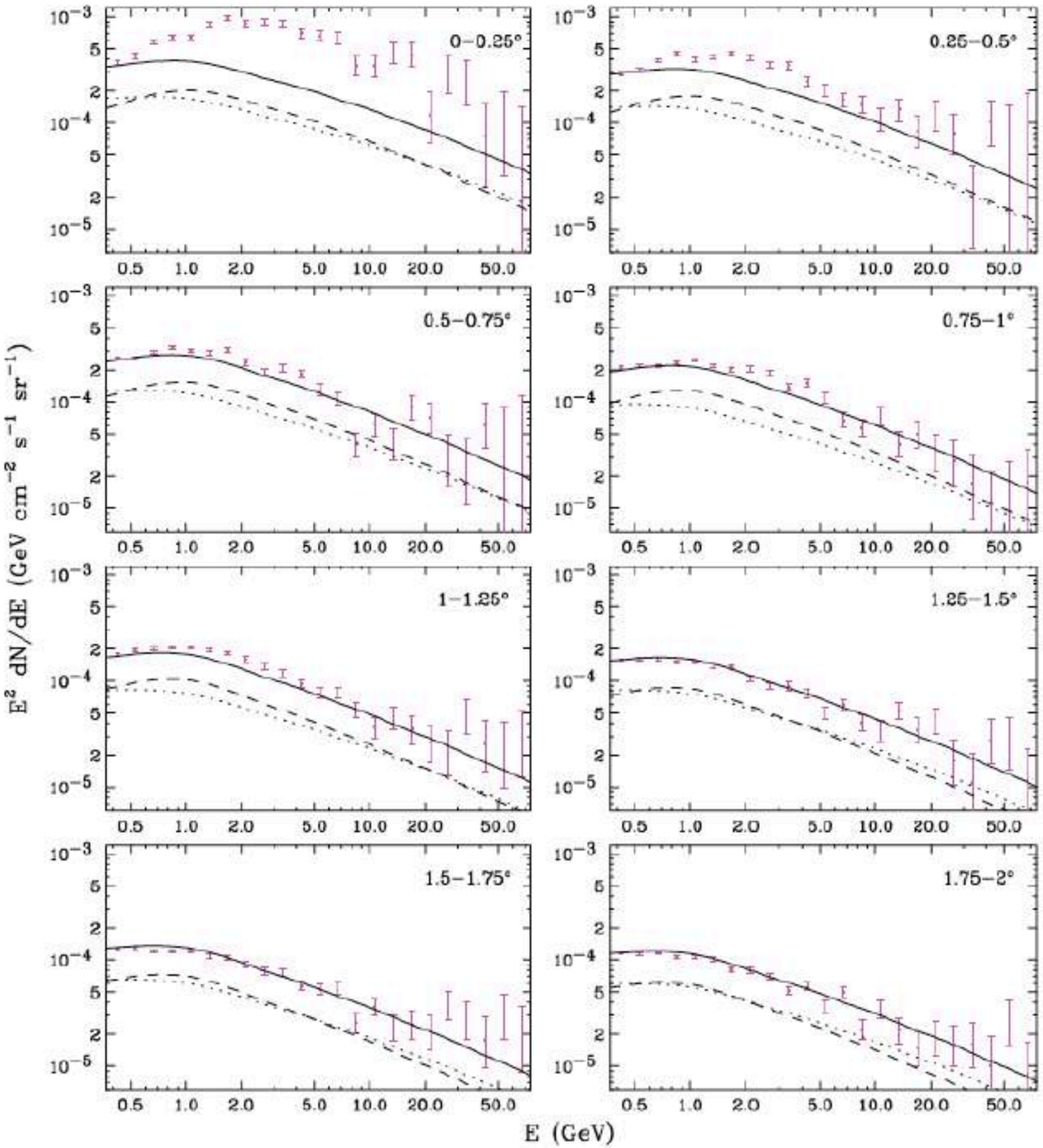
Dark matter density expected to be large at Galactic centre, but how large is very uncertain: relevant scales far smaller than those resolved by simulations and baryonic physics (and the central massive black hole) will modify the DM distribution.

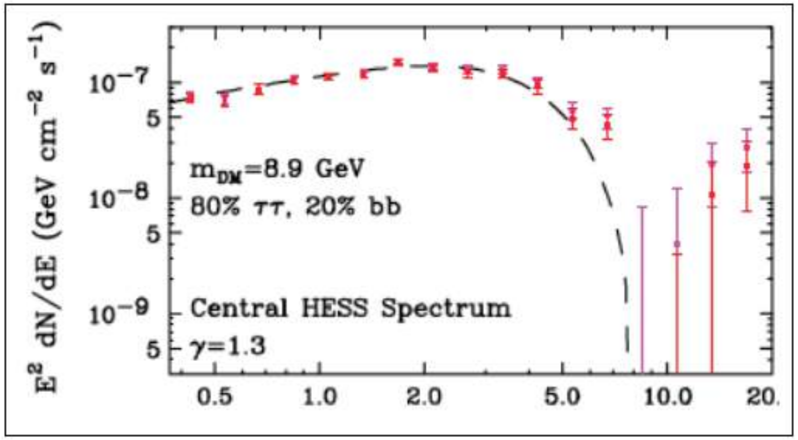
Current observational situation:



<u>Solution:</u> look close to, but away from, GC (where DM density will still be fairly large) and look at energy spectrum **and** angular variation.

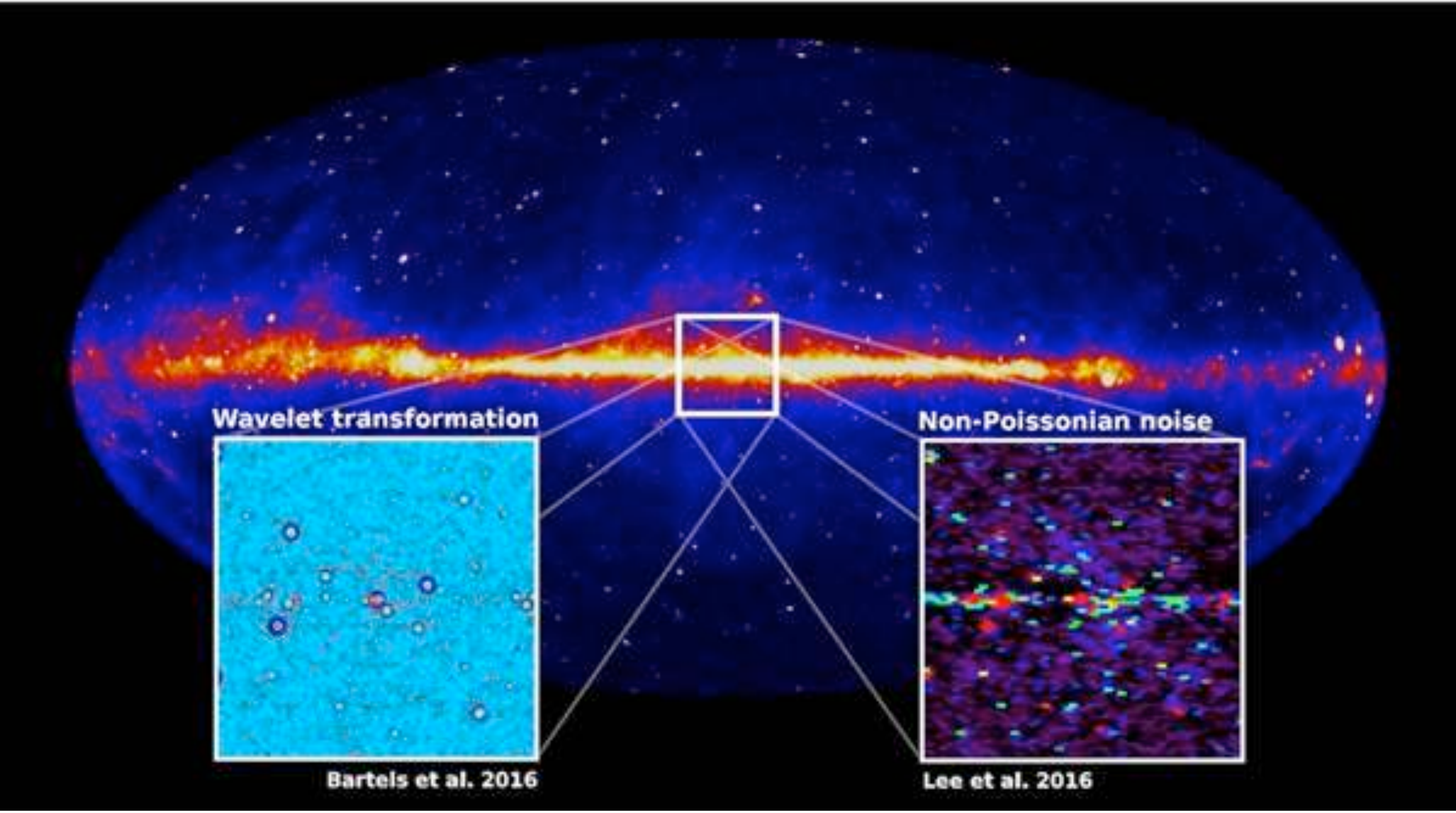
The Galactic Centre is a more promising site for the DM annihilation signal (notwithstanding the astrophysical backgrounds) … it has been claimed that Fermi has seen the signal of 7-10 GeV DM (Hooper & Goodenough, PLB **697**:412 2011)





By fitting the observed γ-ray emission to a disk+bulge model (π^0 + IC emission) they isolate a excess signal in the innermost region (~175 pc) – which has a hard spectrum consistent with dark matter annihilation

… however more likely to be emission by pulsars



Gamma ray map of the Milky Way galaxy, from the Fermi Space Telescope. Two independent statistical analyses show that the distribution of photons is clumpy rather than smooth, indicating that the excess gamma rays from the center of our galaxy are unlikely to be caused by dark matter annihilation (Bartels *et al*, PRL 116:051102,2016; Lee *et al*, PRL 116:051103,2016)

But Leanne & Slatyer, PRL 125:121105,2020 say this may be artefact of north-south asymmetry

Substructures

Numerical simulations contain far more substructure than observed in Milky Way (even taking into account, and extrapolating, new potential dwarfs discovered by SDSS).

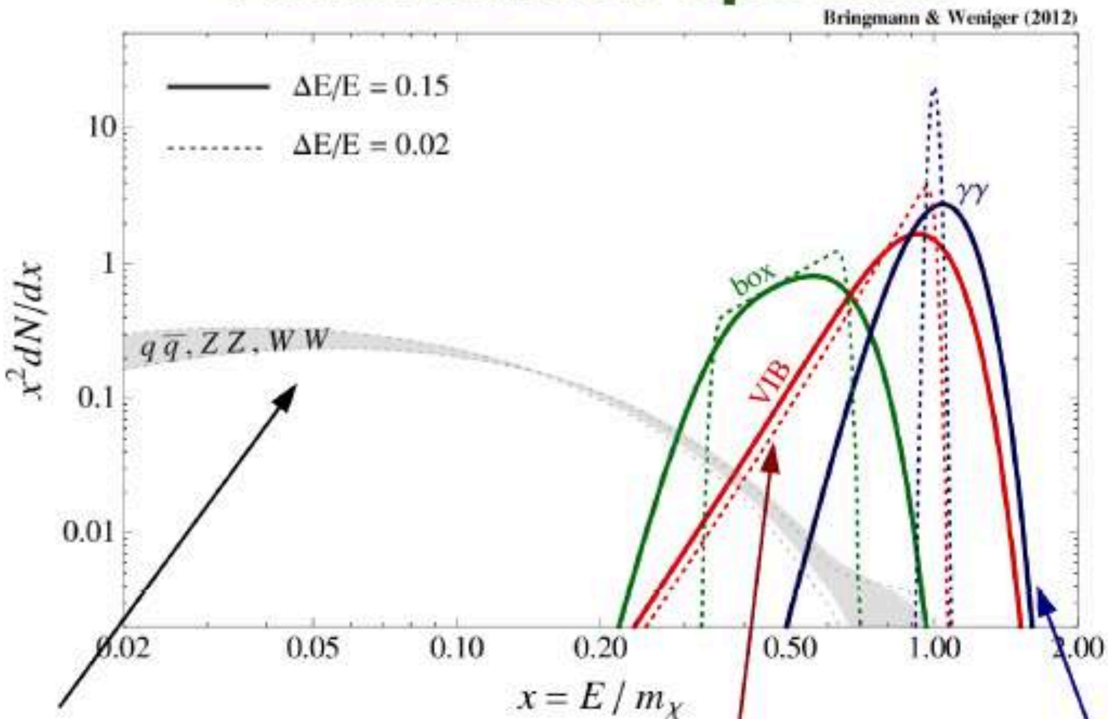
Milky Way halo could contain 'non-luminous' substructures with high gamma-ray fluxes (potentially discoverable by large FOV survey).

Other possibilities

Diffuse emission, galaxy clusters, DM spikes around Intermediate Mass Black holes, ...

However it is always necessary to optimise between having a stronger signal but also a concomitant astrophysical background - also the strategy is quite different for a satellite γ-ray detector having a wide FoV and a ground-based Atmospheric Cherenkov Telescope with a small FoV … and for searches for line emission versus continuum emission

Annihilation spectra



Continuum emission/ secondary photons

- often largest component
- featureless spectrum
- difficult to distinguish from astrophysical background

$$\chi\chi \to \bar{q}q \to \pi^0 \ldots$$
$$\pi^0 \to \gamma\gamma$$

Internal Bremsstrahlung (IB)

- radiative correction to processes with charged final states
- Generically suppressed by O(α)

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

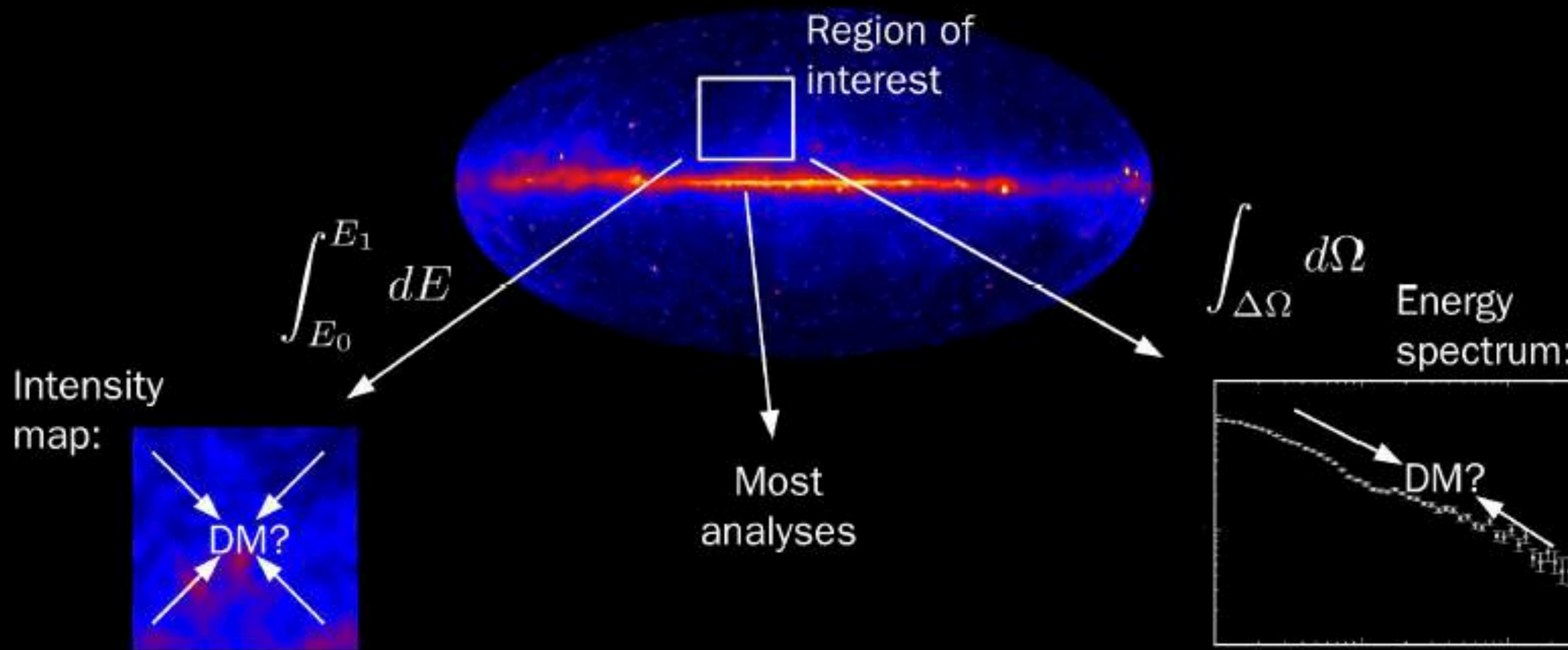
Gamma-ray lines

- from two-body annihilation into photons
- forbidden at tree-leve, generically suppressed by O(α²)

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

(smoking gun)

Signal/Background Discrimination



<u>Spatial</u> BG extrapolation
Targets:
- Dwarf Galaxies
- Galaxy Clusters
- Angular power spectrum
- EGBG …

→ works for <u>all</u> signal spectra

<u>Spectral</u> BG extrapolation
Targets:
- Gamma-ray lines
- Internal Bremsstrahlung

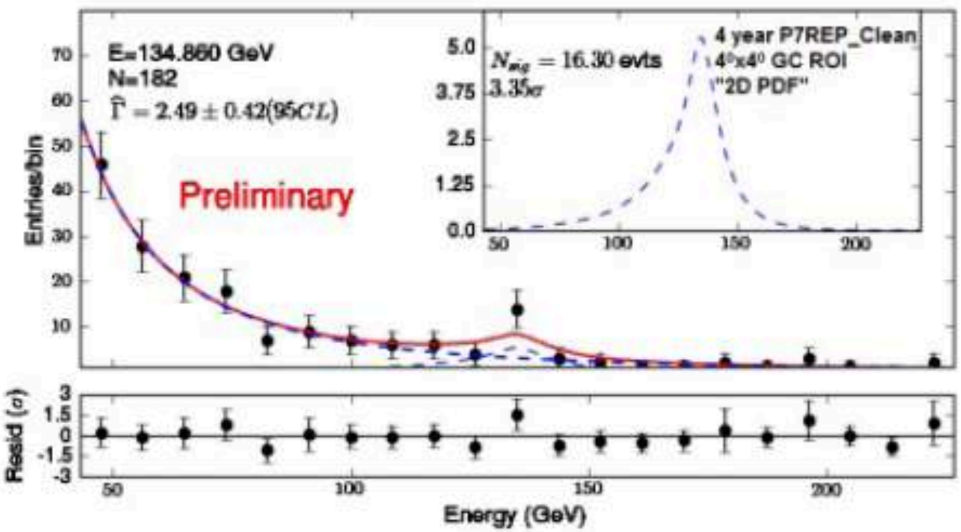
→ works in <u>all</u> sky regions

Courtesey: Christoph Weniger

[Slides from A. Albert; Fermi Symposium 2012]

Line-like Feature near 135 GeV

- **Our blind search does not find globally significant feature near 135 GeV**
  - Reprocessing shifts feature from 130 GeV to 135 GeV
  - Most significant fit was in R0, 2.23σ local (<0.5σ global)
- **Much interest after detection of line-like feature localized in the galactic center at 130 GeV**
  - See C. Weniger JCAP 1208 (2012) 007 arXiv:1204.2797
- 4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data
  - Look in 4°x4° GC ROI
  - Use 1D PDF (no use of P_E)
- 3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI
  - Use 1D PDF (no use of P_E)
- **3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data**
  - Look in 4°x4° GC ROI
  - Use 2D PDF
    - P_E in data → feature is slightly narrower than expected
  - <2σ global



Note: Fit in 4°x4° GC ROI
Not one of our a priori ROIs

The *PAMELA* 'anomaly'

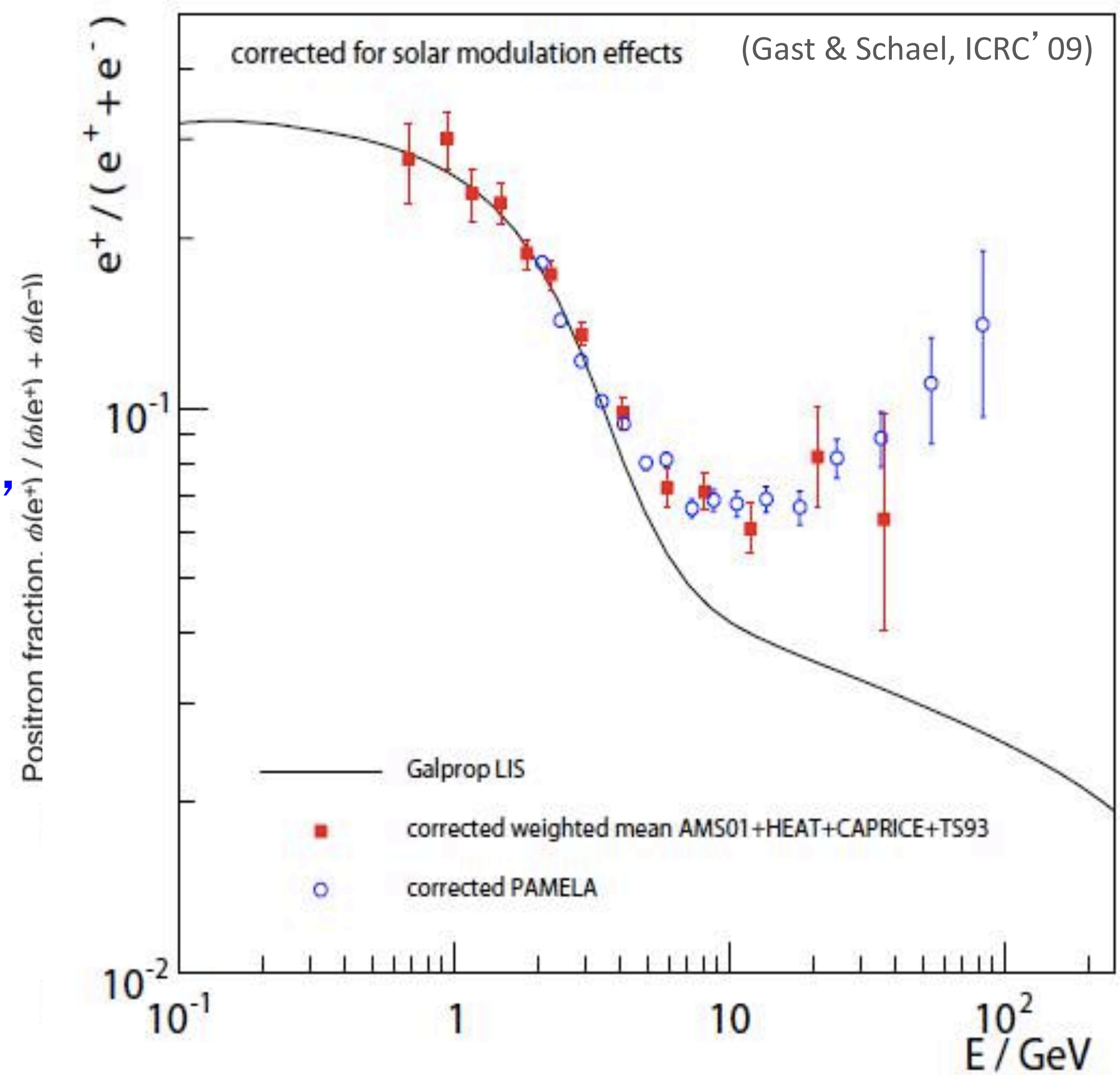
PAMELA has measured the positron fraction:

$$\frac{\phi_{e+}}{\phi_{e+} + \phi_{e-}}$$

Anomaly $\Rightarrow$ excess above 'astrophysicalbackground'

Source of anomaly:

- Dark matter?
- Pulsars?
- Supernova remnants?



Adriani et al, Nature **458**:607,2009

Dark matter has been invoked to explain the 'PAMELA anomaly'.

an 'excess' of e^+ in cosmic rays over the expected production of secondaries during propagation

DM annihilation

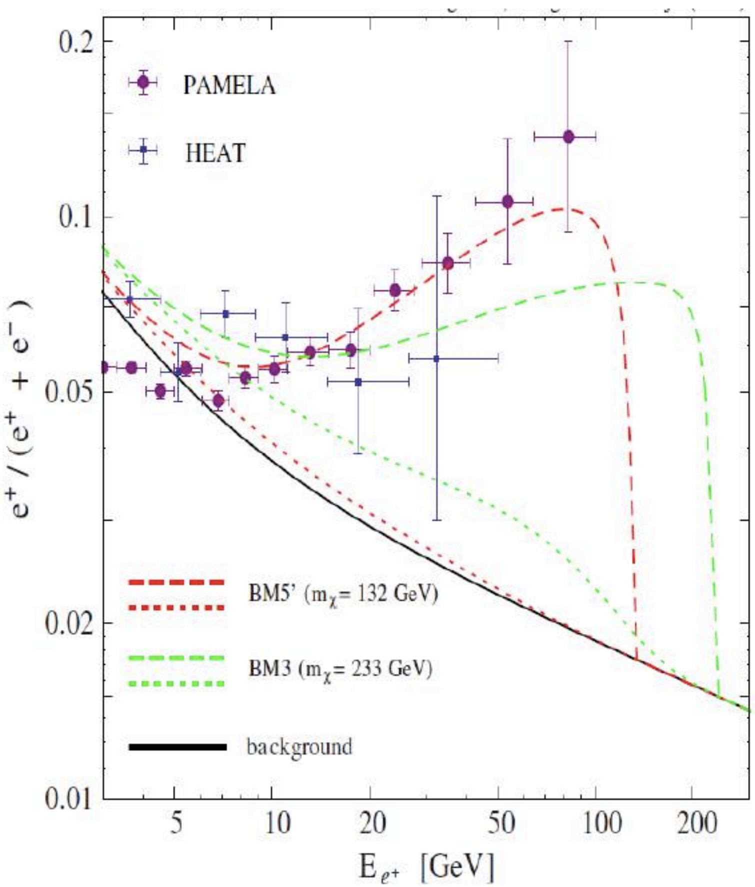
Rate $\propto n^2_{\mathrm{DM}}$

(e.g. few hundred GeV neutralino LSP or Kaluza-Klein state)

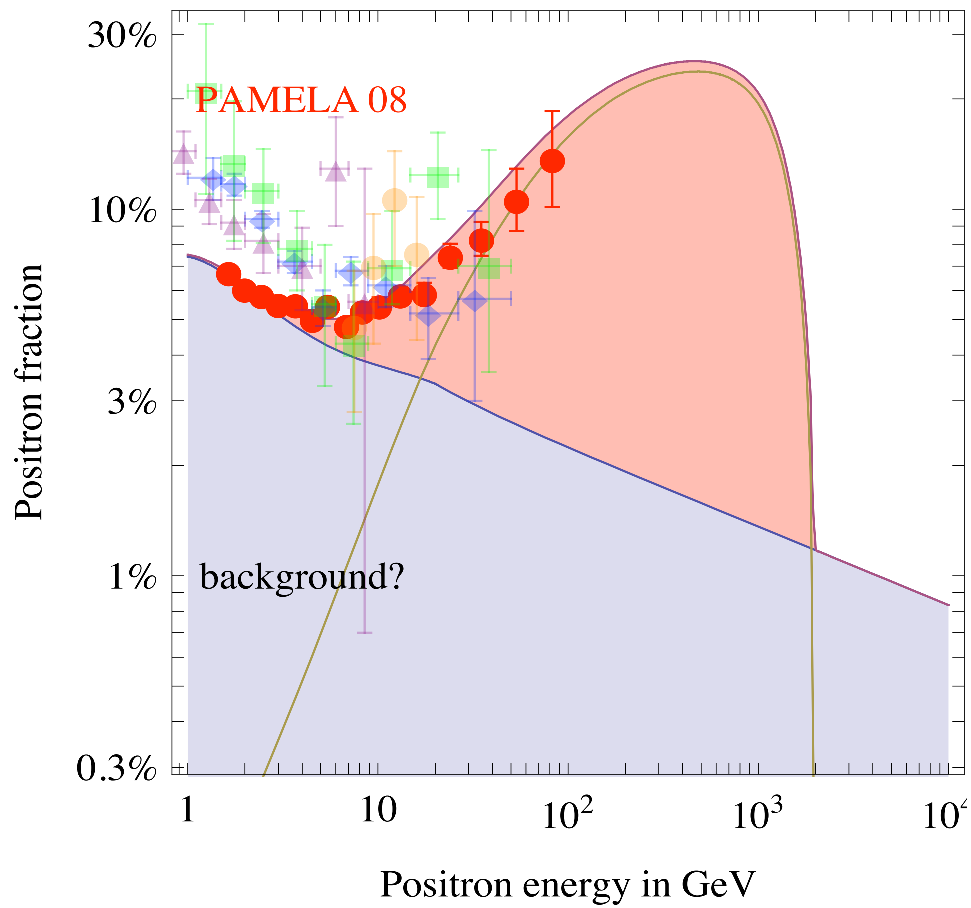
DM decay

Rate $\propto n_{\mathrm{DM}}/\tau_{\mathrm{DM}}$

(lifetime ~10^9 x age of universe e.g. dim-6 operator suppressed by M_{GUT} for a TeV mass techni-baryon)



Bergström, Bringmann, Edjsö, PR D78:127850,2008

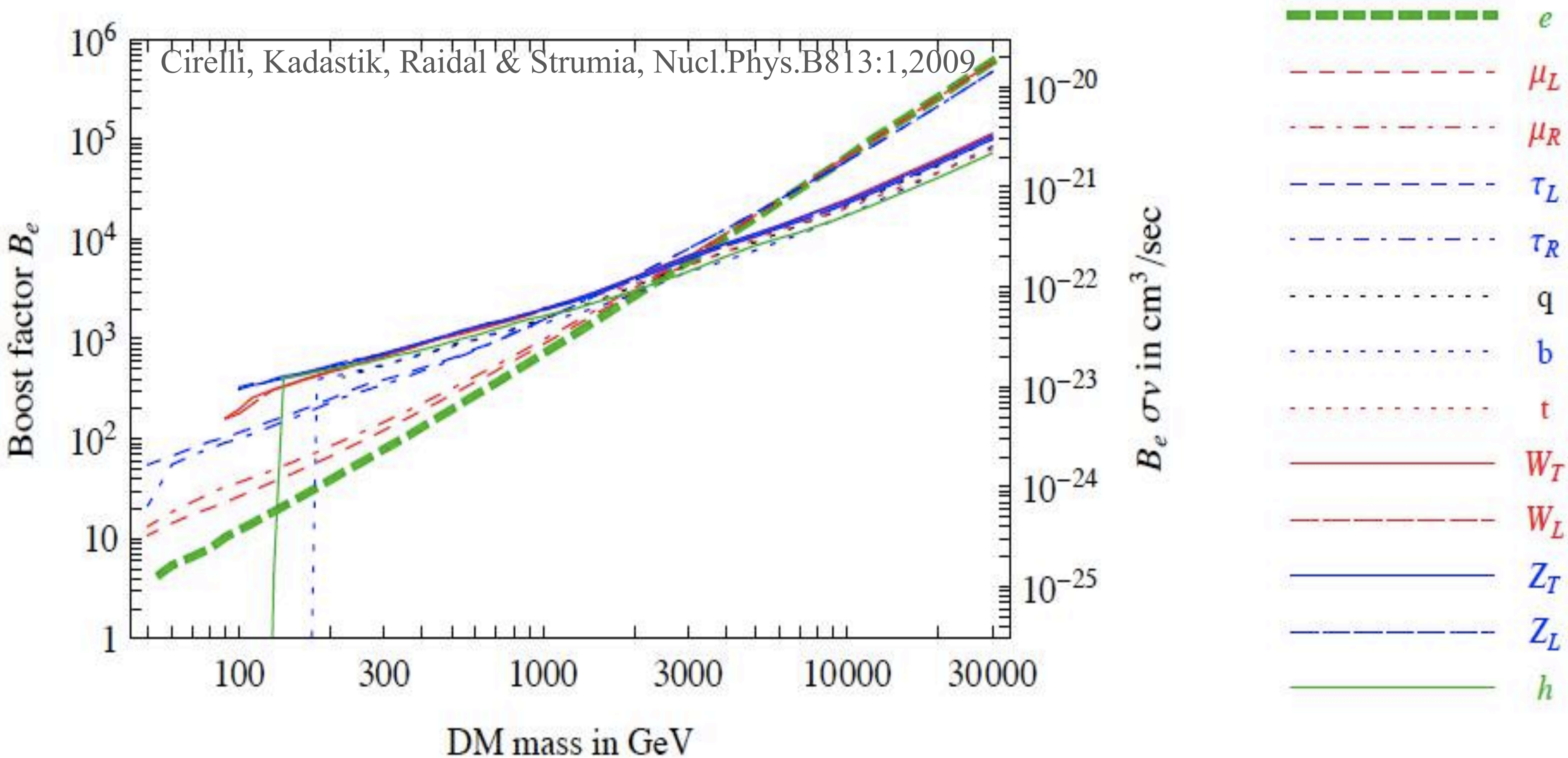


Nardi, Sannino, Strumia, JCAP **01**:043,2009

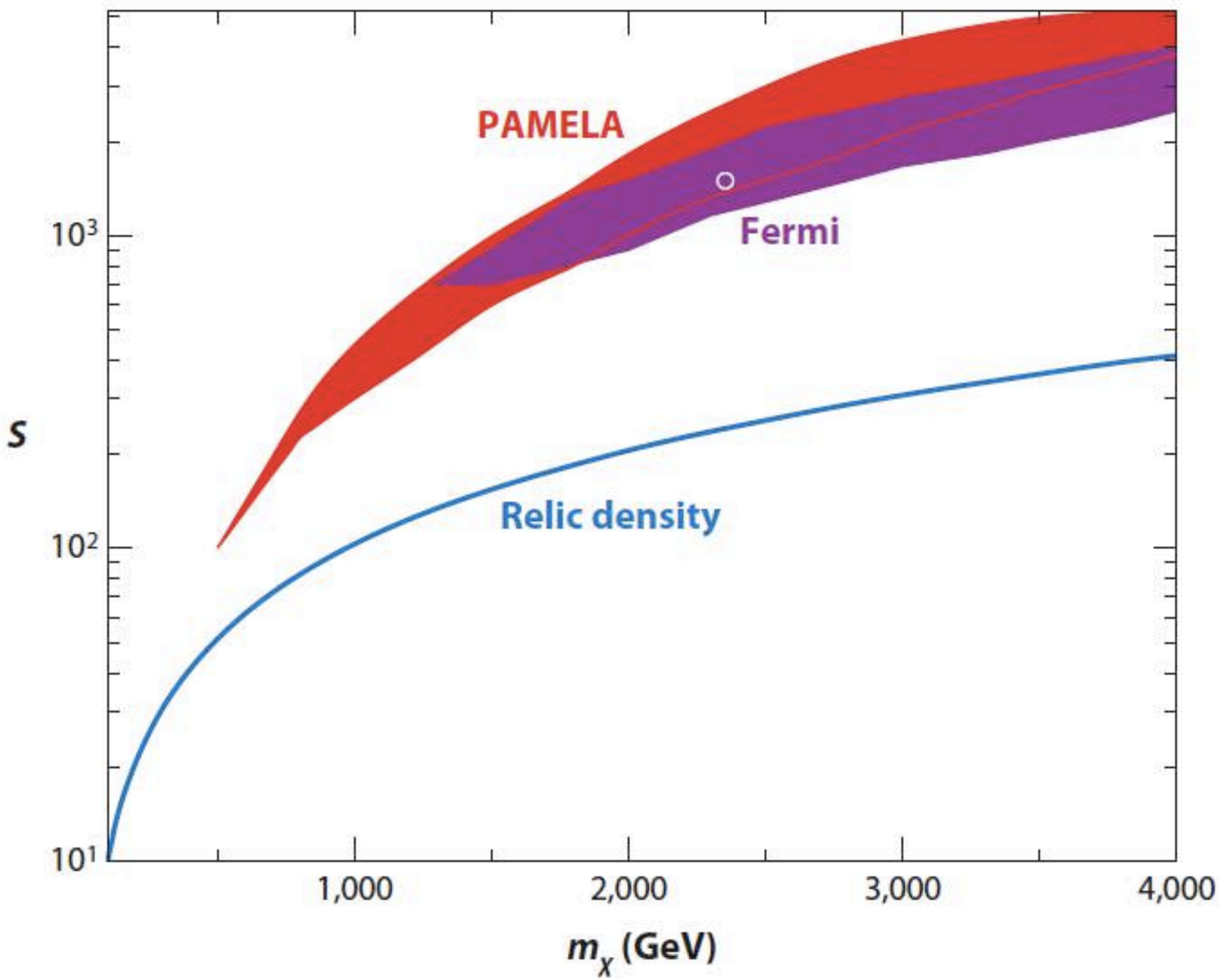
But DM annihilation requires huge 'boost factor' to match flux

➔ Such a large annihilation #-section would imply negligible relic abundance unless an inverse velocity dependence is invoked e.g. 'Somerfeld enhancement' (this requires hypothetical light gauge bosons to provide new long range force)

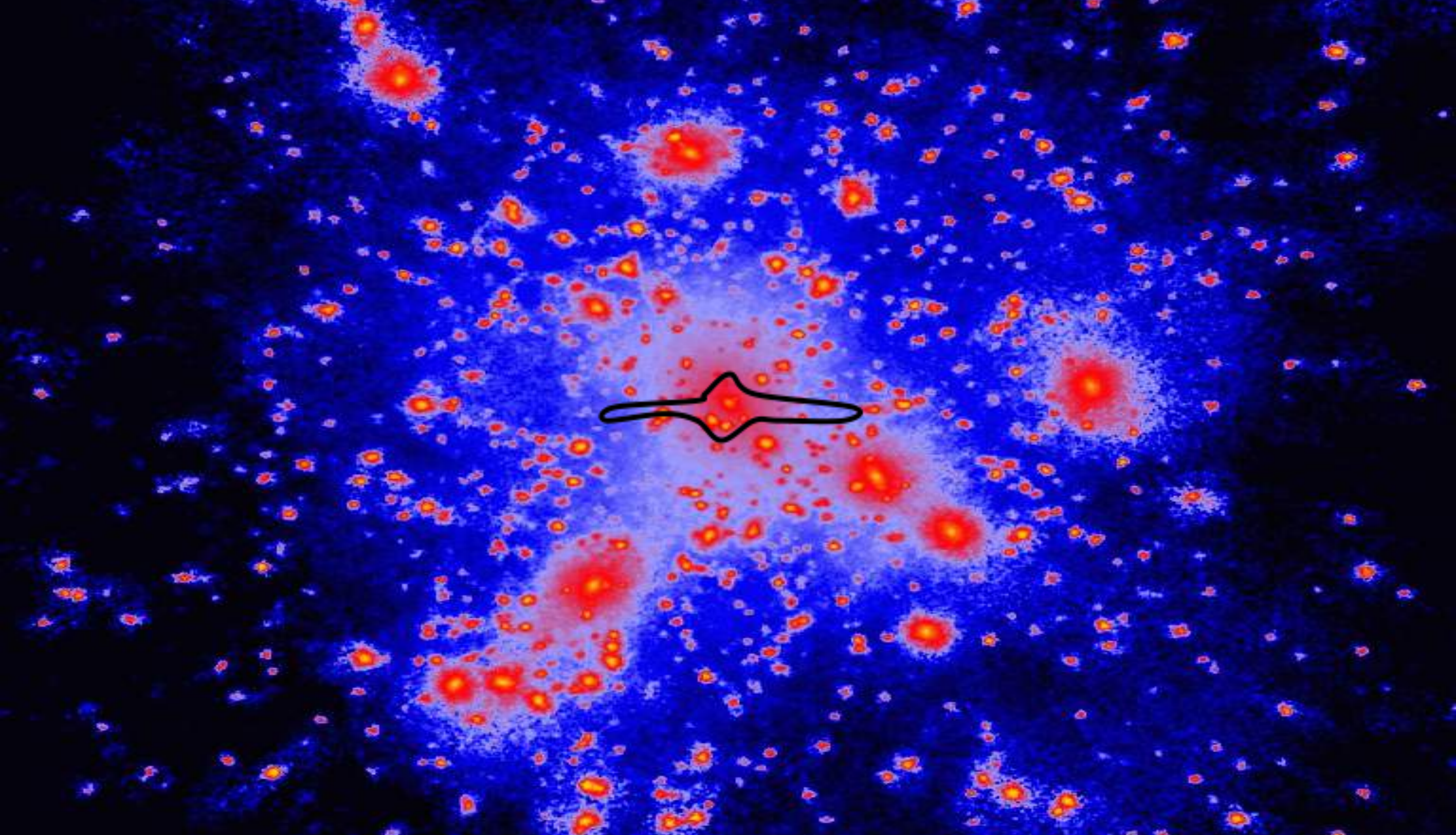
Arkani-Hamed *et al*, PR D**79**:015014,2009



The 'boost factor' required to match the PAMELA/FERMI data is much higher than the factor of ~few enhancement expected due to clumping of dark matter in the Galaxy (Lavalle *et al*, A&A **479**:427,2008)



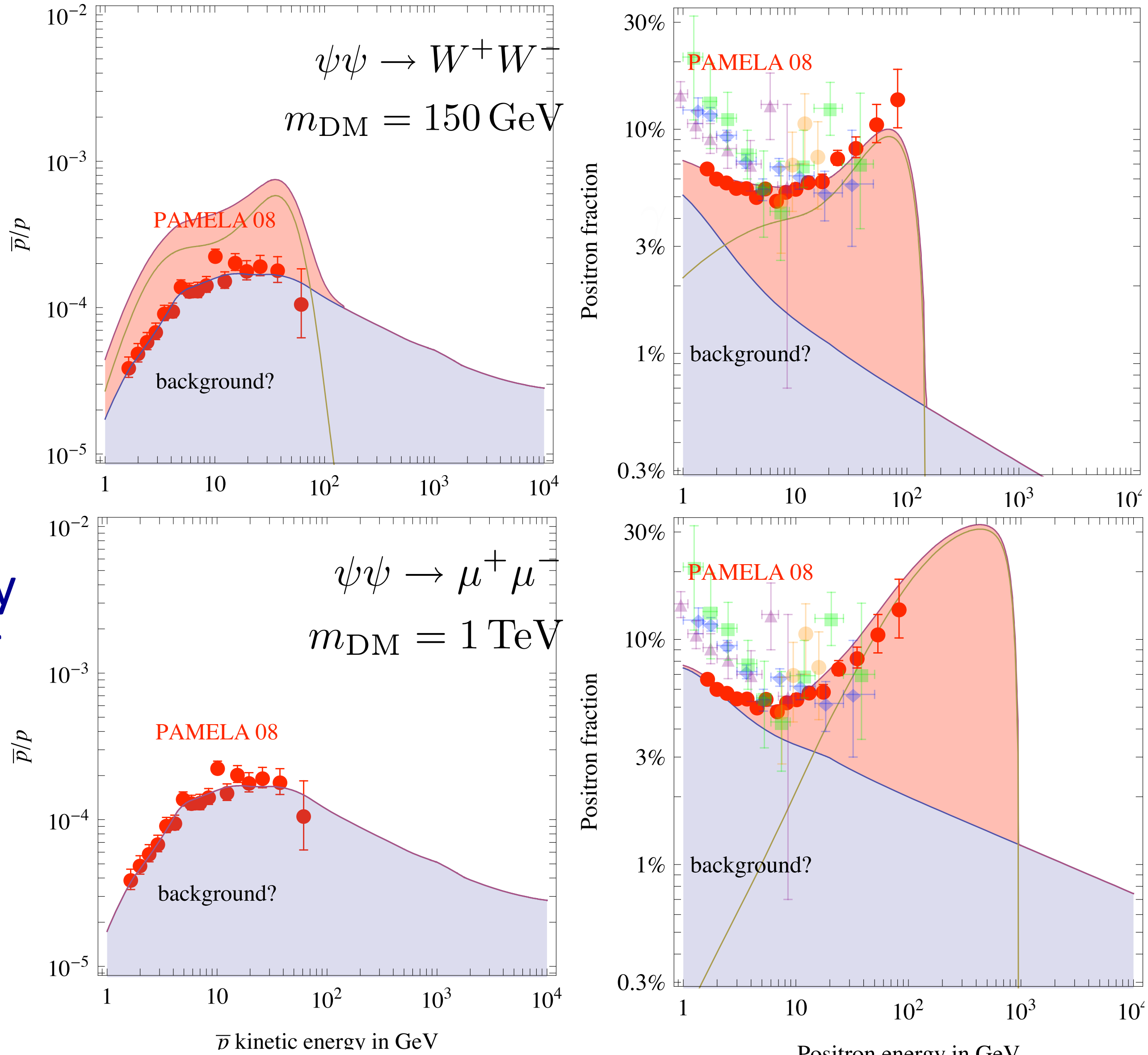
Numerical simulations of structure formation through gravitational instability in cold dark matter show that the Milky Way formed from the merger of smaller structures (+ tidal stripping, baryonic infall, disk formation *etc*) over several billion years …



So the distribution of dark matter *is* clumpy, however the ‘boost factor’ due to this is estimated to be no more than a factor of ~2-10 (Lavalle *et al*, A&A 479:427,2008)

But the observed antiproton flux is ~*consistent* with the background expectation (from standard cosmic ray propagation in the Galaxy)

This is a serious constraint on all dark matter models of the PAMELA anomaly



Can fit with DM decay or annihilation only if DM particles are 'leptophilic'

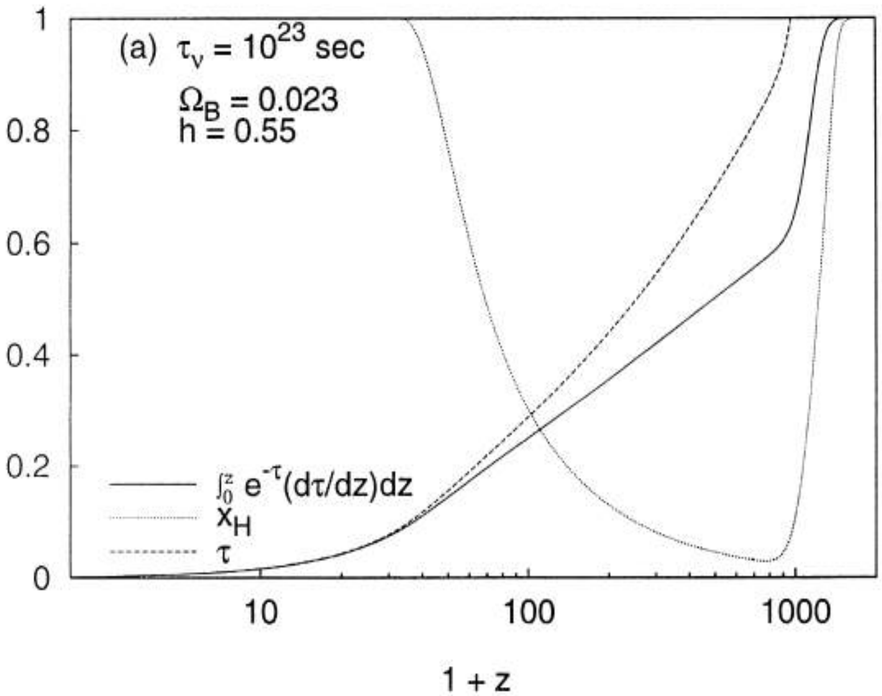
- very contrived … nevertheless many models proposed

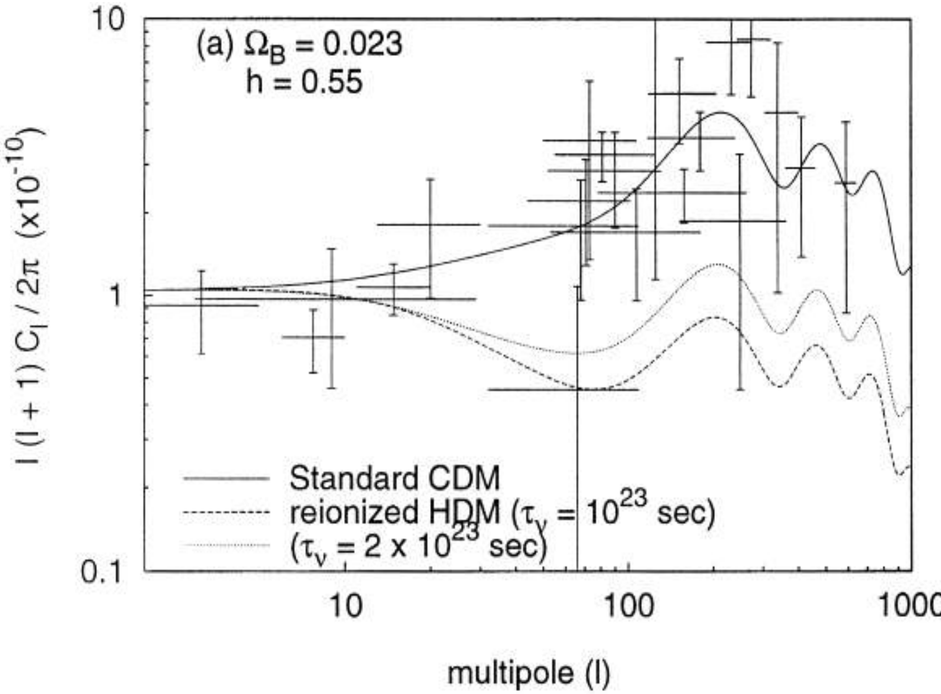
Cirelli *et al*, Nucl.Phys.B**813**:1,2009

DM annihilation/decay energy release would increase the ionisation fraction of the intergalactic medium and broaden the 'last scattering surface' of the CMB

This would result in damping of the 'acoustic' peaks in the power spectrum of CMB fluctuations – as was noted originally for a model of decaying dark matter

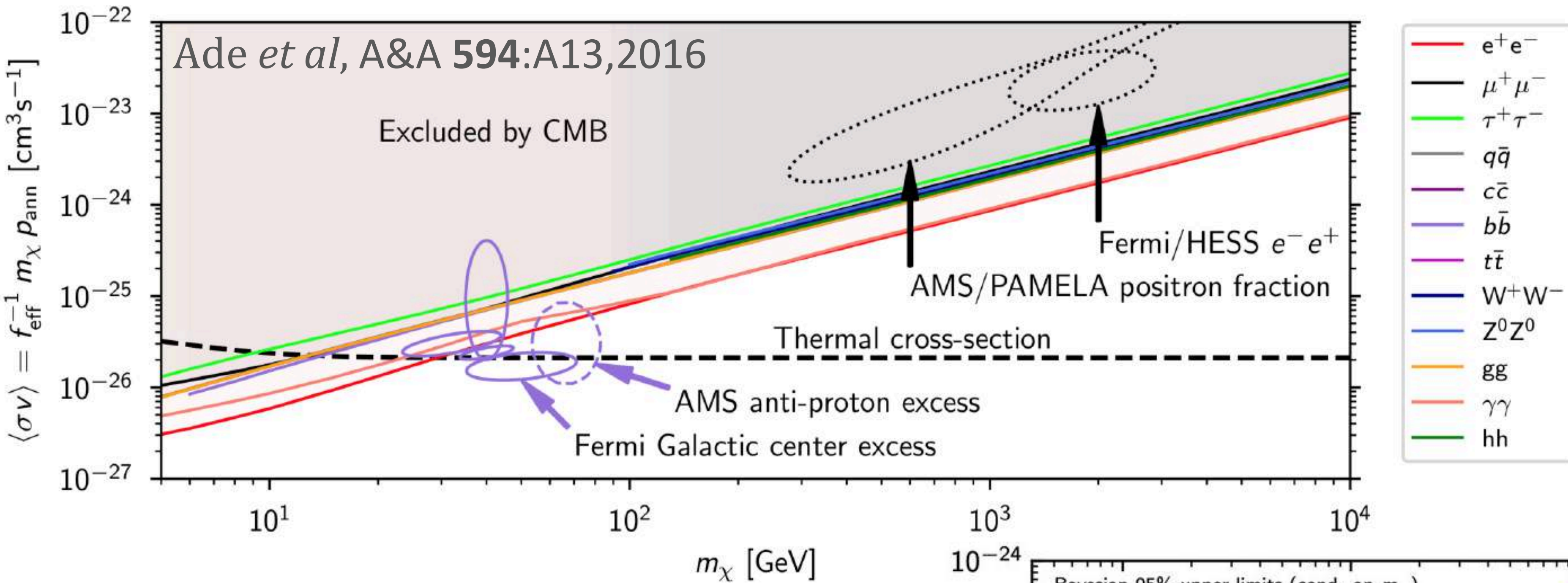
Adams *et al*, MNRAS **301**:210,1998



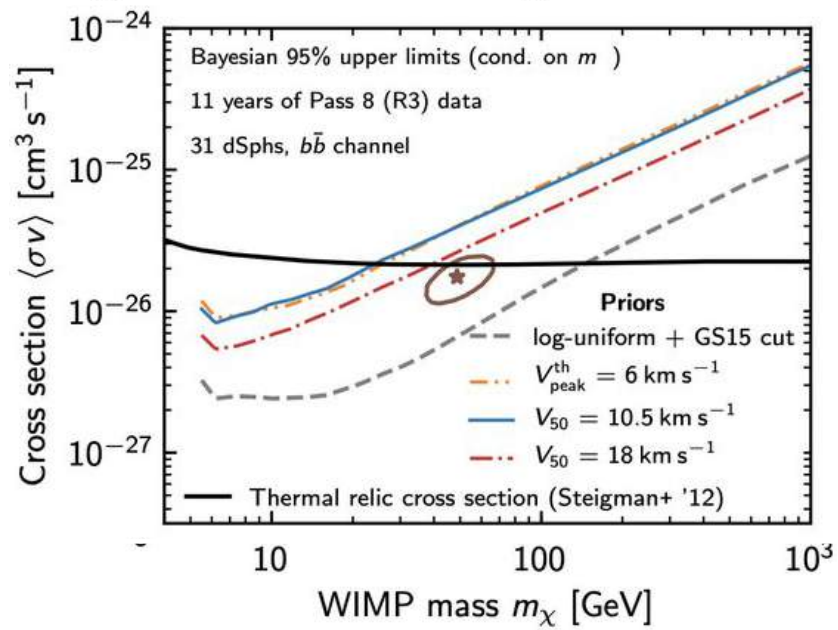


The results are easily generalised to *any* source of ionising photons (E >13.6 eV) e.g. generated in the annihilation of dark matter particles (and resulting radiation cascade) … the constraint is tightened further by including polarisation data (Padmanabhan, Finkbeiner, astro-ph/0503486)

Now that the CMB power spectrum is known to O(%) accuracy, *Planck* sets a strong limit on this, *disfavouring* DM interpretations of the PAMELA/AMS-02 anomaly

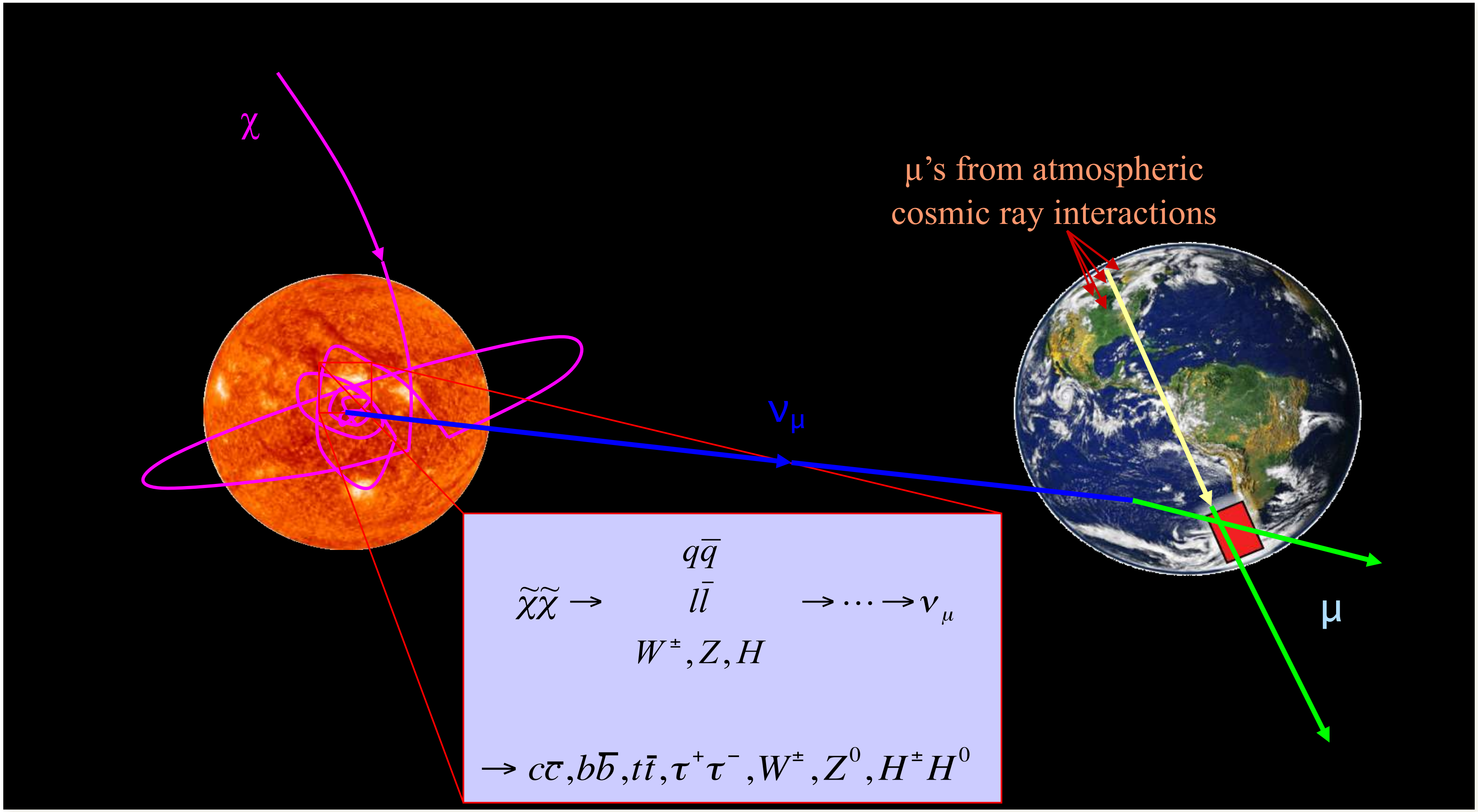


However this does not rule out a DM interpretation of the Fermi Galactic Centre 'excess' … which *may* be compatible with the upper limits from dSphs, taking due account of systematic uncertainties (Ando *et al*, arXiv:2002.11956)



Search for high energy neutrinos from WIMP annihilations in the Sun

(Silk, Olive & Srednicki, PRL **55:**257,1985)



- More sensitive to spin-dependent interactions (Sun mainly hydrogen)
- More sensitive to low WIMP velocities (easier to capture)
- May sample regions with higher DM density (as Sun orbits the Galaxy)

The WIMP number density inside the Sun/Earth obeys the equation:

$$\frac{dN}{dt} = \underbrace{C_c}_{\text{capture}} - \underbrace{C_a}_{\text{annihilation}} N^2$$

which gives the WIMP annihilation rate:

$$\Gamma_a \equiv \frac{1}{2} C_a N^2 = \frac{1}{2} C_c \tanh^2(t/\tau)$$

with: $t = t_\odot \simeq 4.5 \cdot 10^9$ years & $\tau \equiv 1/\sqrt{C_c C_a}$.

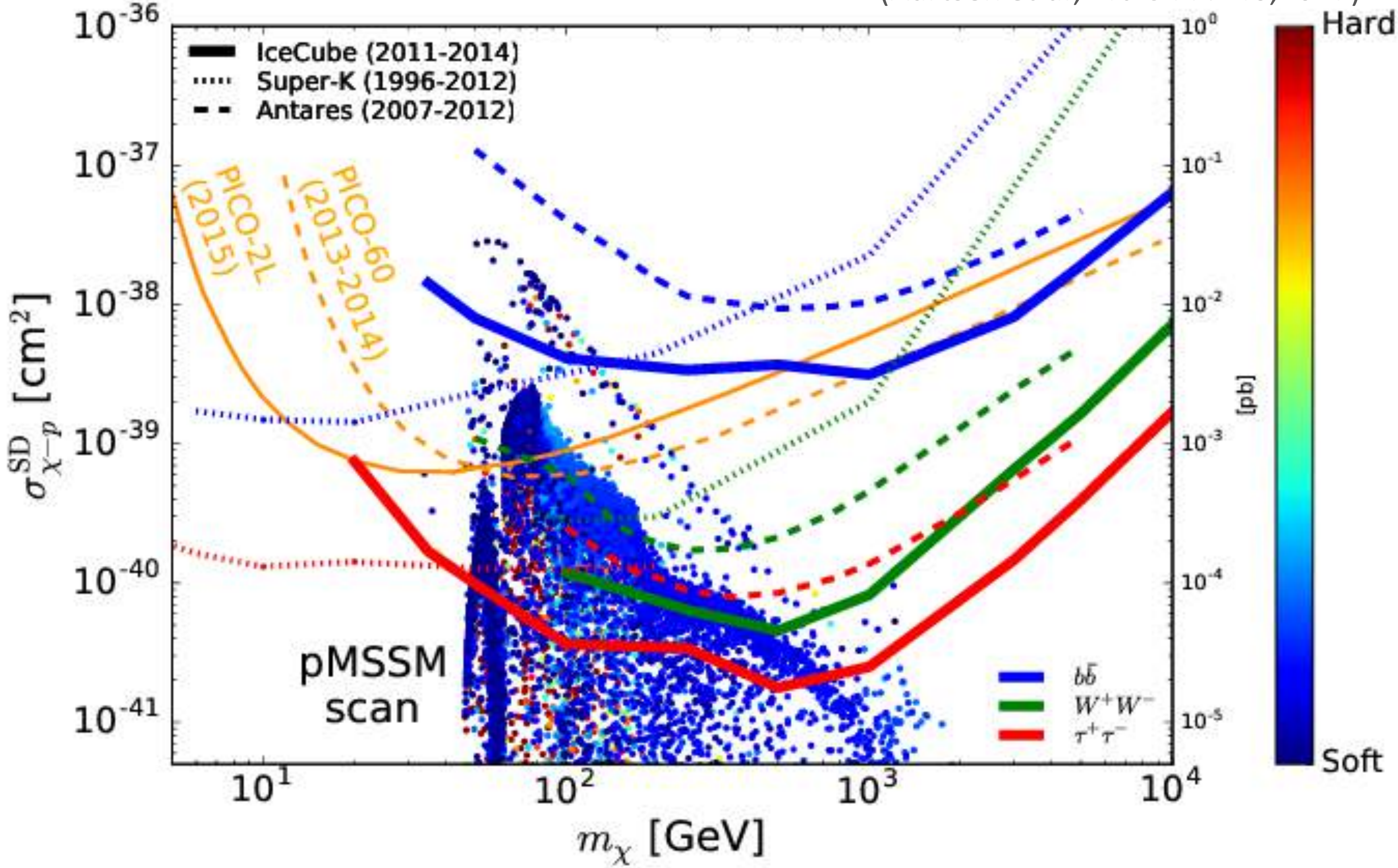
For $\tau \ll t_\odot$ capture and annihilation have reached equilibrium:

$$\Gamma_a = \frac{1}{2} C_c \longrightarrow \Phi_\mu \begin{cases} \propto \sigma^{SD}_{\chi\, p} & \text{Sun} \\ \propto \sigma^{SI}_{\chi\, p,n} & \text{Earth} \end{cases}$$

(??? - rarely in equilibrium)

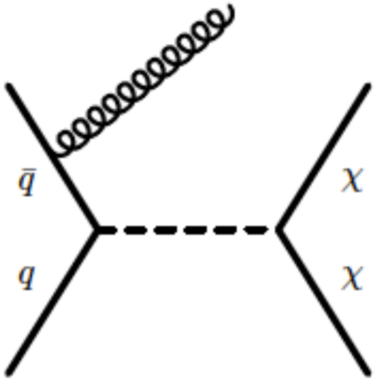
IceCube/DeepCore is especially sensitive to the spin-dependent cross-section

(Aartsen *et al*, EPJ C 77:146,2017)

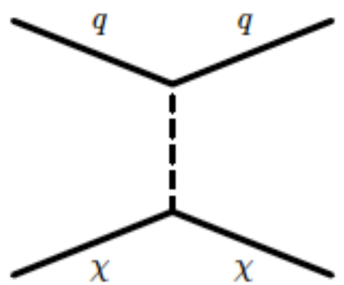


No excess events are seen towards the Sun, thus placing a restrictive limit

‘Monojet’ events at colliders directly measure the dark matter couplings that enter in direct detection (Goodman *et al* 2010, Bai *et al* 2011, Fox *et al* 2011)



So parametrise all possible dark matter interactions as effective operators, then calculate the expected signal (typically ~10 times smaller than the SM background) and use existing data to set bounds

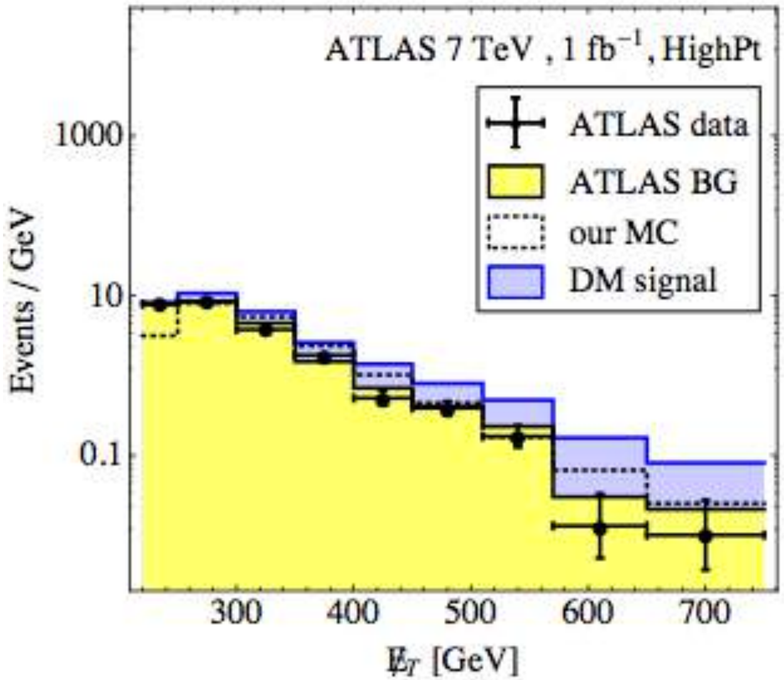


$$\frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q} q)\, (\bar{\chi}\chi) \ ,$$ SI, scalar exchange

$$\frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}\gamma_\mu q)\, (\bar{\chi}\gamma^\mu \chi) \ ,$$ SI, vector exchange

$$\frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}\gamma_\mu \gamma_5 q)\, (\bar{\chi}\gamma^\mu \gamma_5 \chi) \ ,$$ SD, axial-vector exchange

$$\frac{i\, g_\chi\, g_q}{q^2 - M^2} (\bar{q}\gamma_5 q)\, (\bar{\chi}\gamma_5 \chi) \ ,$$ SD and mom. dep., psuedo-scalar exchange



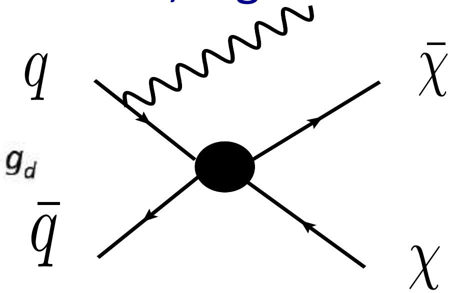
‘Monojet’ events at colliders directly measure the coupling of dark matter to SM, e.g.

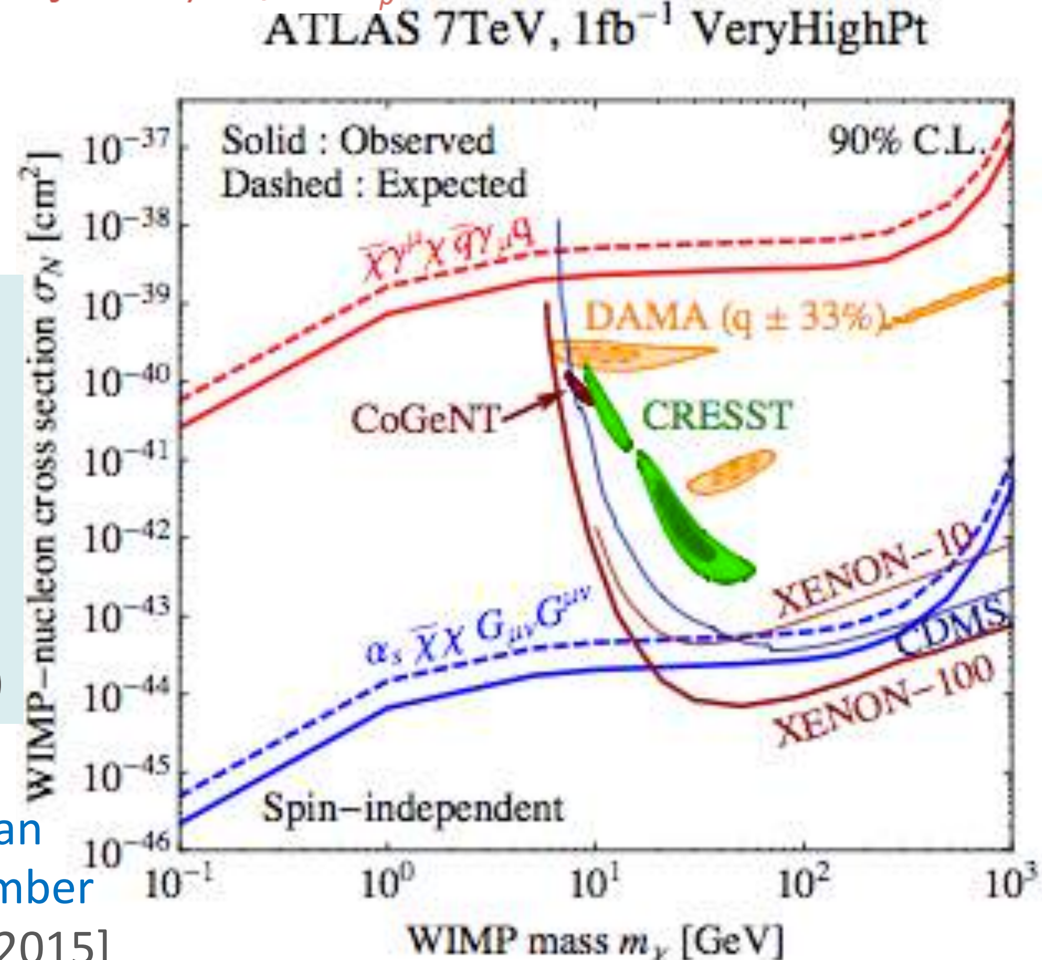
$$\mathcal{L}_\chi^{\rm eff} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$

→ $\sigma_p^{\rm SI} = \frac{f^2\mu_{\chi n}^2}{\pi\Lambda^4}$, where $f = 3$ for $g_u = g_d$

$\Lambda = m_R/\sqrt{g_q g_\chi}$

→ $\sigma\,(j + \text{MET}) \sim 1/\Lambda^4 \sim \sigma_p$



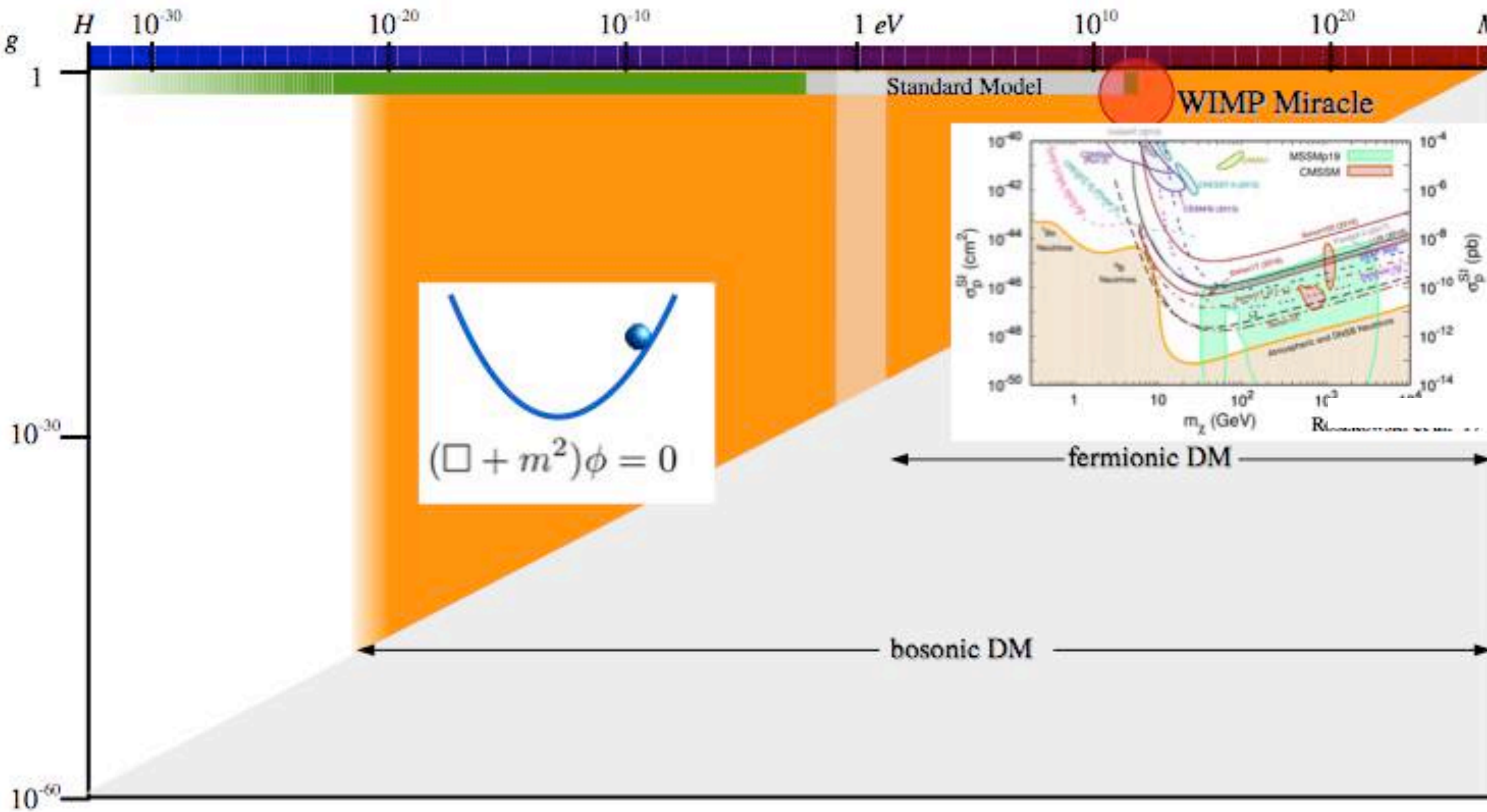


However these bounds require the scale Λ of the effective operator to exceed ~0.7 TeV, while perturbative unitarity requires $g_q, g_\chi < \sqrt{4\pi}$ i.e. $m_R < 2$ TeV … so for higher energy collisions *cannot* rely on effective operator description

(Fox *et al*, PRD86:015010,2012)

The current strategy is to test ‘simplified models’ defined by an effective Lagrangian describing the interactions of a small number of new particles [Phys.Dark Univ. 9-10:8,2015]

We have barely begun to scratch at the *many* possibilities for the nature of the (particle) Dark matter



(Courtesey: G. Villadoro)

However significant advances *have* been made in searches for WIMPs and QCD axions … and now the race is on to probe other candidates as well (ALPs, 'dark photons', etc)