Dark Matter Searches with Anti-Matter

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darkattack2012

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Science & Technology Facilities Council

UNIVERSITY OF OXFORD

Why anti-particles?

- If DM annihilates (or decays) into charged particles we might observe them
- Most galactic cosmic rays (GCRs) are particles: p, N, e^-
- *S/B* better anti-particle channels

What we know about GCRs...

Three fundamental observations:

1. Particles, that are under-abundant in the solar system, are produced as secondaries by spallation.

2. The local interstellar spectrum is a power law in rigidity; secondary spectra are softer than primary ones.

3. The arrival directions of GCRs are distributed isotropically.

Isotropy

- charged particles interact resonantly with magnetic inhomogeneities

➞ pitch-angle scattering

$$\nu = \left\langle \frac{\Delta\theta^2}{\Delta t} \right\rangle = \frac{\pi}{4} \left(\frac{\delta B^2(k)/8\pi}{B^2/8\pi} \right) \Omega \qquad \text{with} \qquad k \approx \frac{\Omega}{v \cos\theta}$$

- isotropises distribution function

$$f(\vec{r}, \vec{p}, t) \to f_0(\vec{r}, |\vec{p}|, t)$$

- leads to (rigidity-dependent) spatial diffusion

$$\frac{\partial f}{\partial t} + \left(\vec{u} \cdot \vec{\nabla} \right) f - \vec{\nabla} \cdot \left(D_{\|} \vec{\nabla} f \right) = \frac{1}{3} \left(\vec{\nabla} \cdot \vec{u} \right) p \frac{\partial f}{\partial p} \,,$$

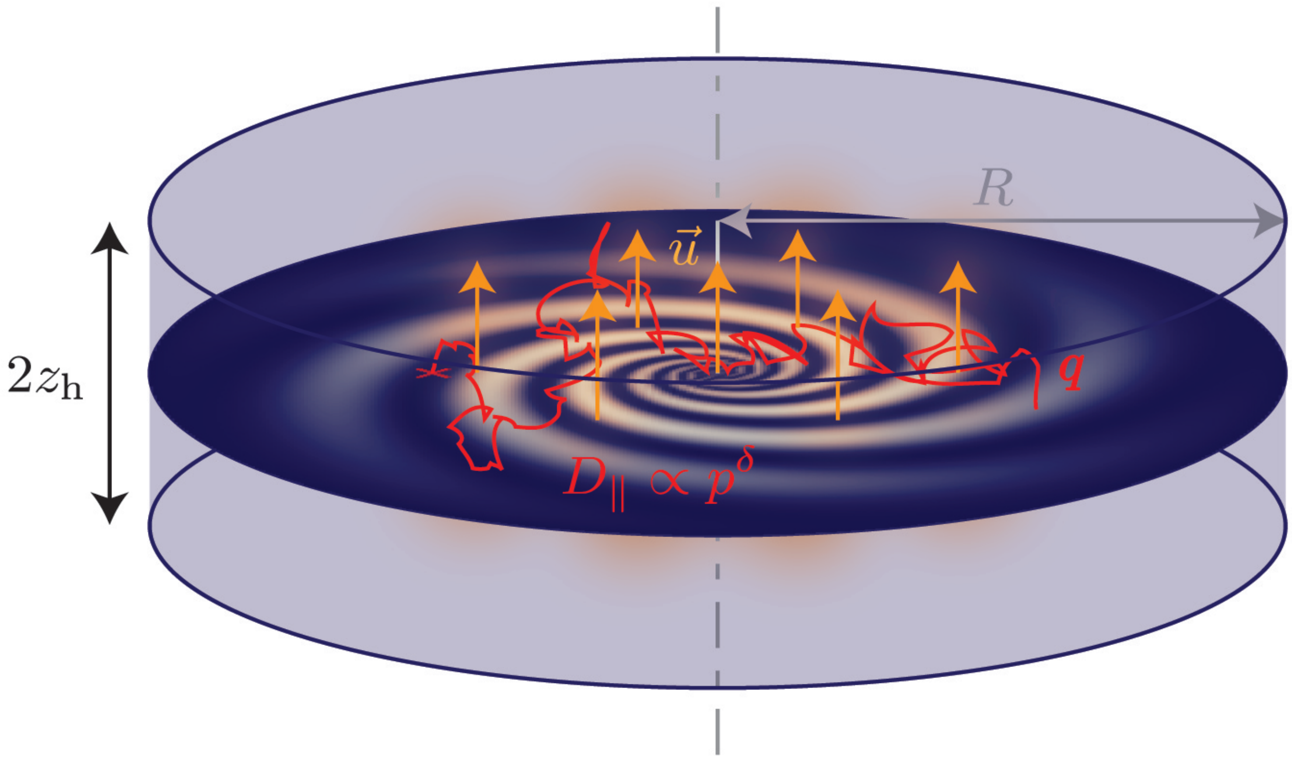
with

$$D_{\|} \simeq \frac{v^2}{3\nu} \propto \left(\frac{\delta B^2(k)/8\pi}{B^2/8\pi} \right)^{-1} \frac{1}{\Omega} \propto \mathcal{R}^{\delta} \quad \text{for} \quad \frac{\partial B^2(k)}{\partial k} \propto k^{\delta-2}$$

Propagation Setup

$$\frac{\partial n_i}{\partial t} - \vec{\nabla} \cdot \left(D_{xx} \cdot \vec{\nabla} n_i - \vec{u}\, n_i \right) - \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} n_i - \frac{\partial}{\partial p} \left(\frac{\mathrm{d}p}{\mathrm{d}t} n_i - \frac{p}{3} \left(\vec{\nabla} \cdot \vec{u} \right) n_i \right)$$

$$= q + \sum_{i<j} \left(c\, \beta\, n_{\mathrm{gas}}\, \sigma_{j \to i} + \gamma\, \tau_{j \to i}^{-1} \right) n_j - \left(c\, \beta\, n_{\mathrm{gas}}\, \sigma_i + \gamma\, \tau_i^{-1} \right) n_i \,,$$



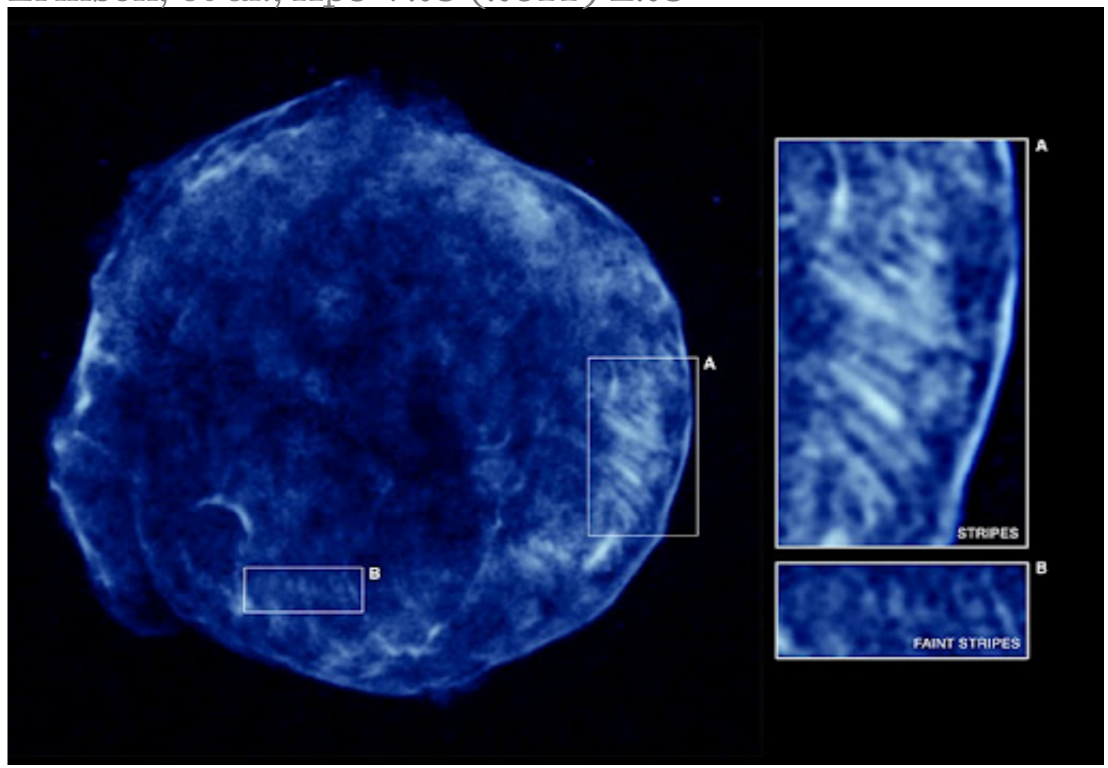
GCR sources

supernova remnants as candidate sources of GCRs:

- energetics
- theory: $\mathcal{R}^{-\Gamma}$
- evidence for high-energy electrons
  Koyama *et al.*, Nature 378 (1995) 255

Also sources of hadronic cosmic rays?

Eriksen, *et al.*, ApJ 728 (2011) L28+



Secondary-to-primary ratios

- secondaries not from sources but from spallation in ISM, e.g.

$$\mathrm{C} + \mathrm{p}_{\mathrm{ISM}} \text{ or } \mathrm{He}_{\mathrm{ISM}} \to \mathrm{B} + X$$

- primary produced with spectrum:

$$\mathrm{C} \propto \mathcal{R}^{-\Gamma}$$

- diffusion rigidity dependent:

$$D_{\|} \propto \mathcal{R}^{\delta}$$

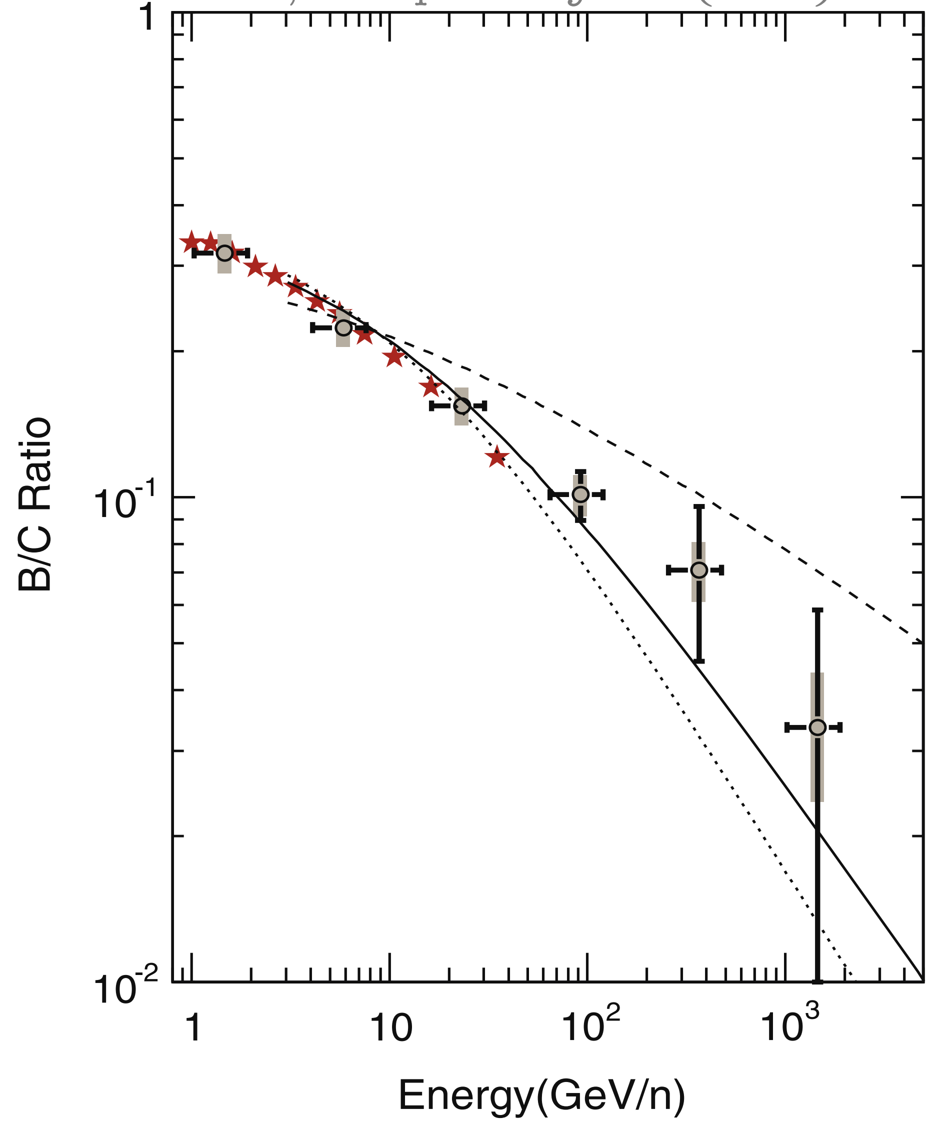
- propagated spectra:

$$\mathrm{C} \propto \mathcal{R}^{-\Gamma-\delta}$$

$$\mathrm{B} \propto \mathcal{R}^{-\Gamma-2\delta}$$

$$\mathrm{B/C} \propto \mathcal{R}^{-\delta}$$

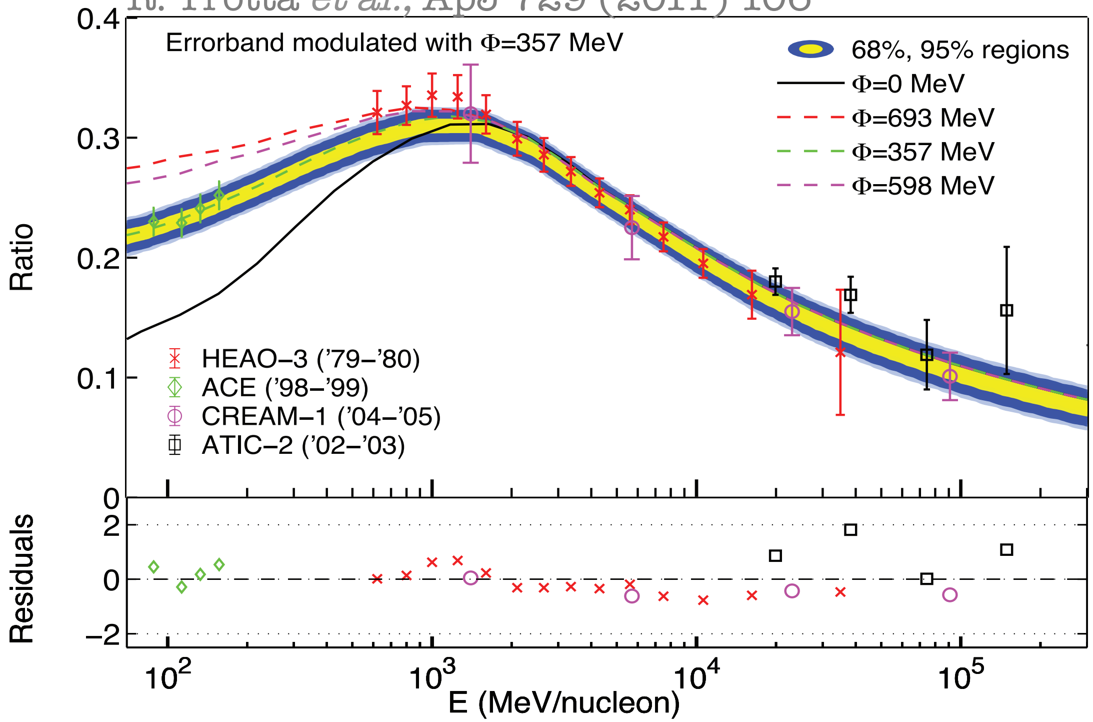
H. S. Ahn *et al.*, Astropart. Phys. 30 (2008) 133

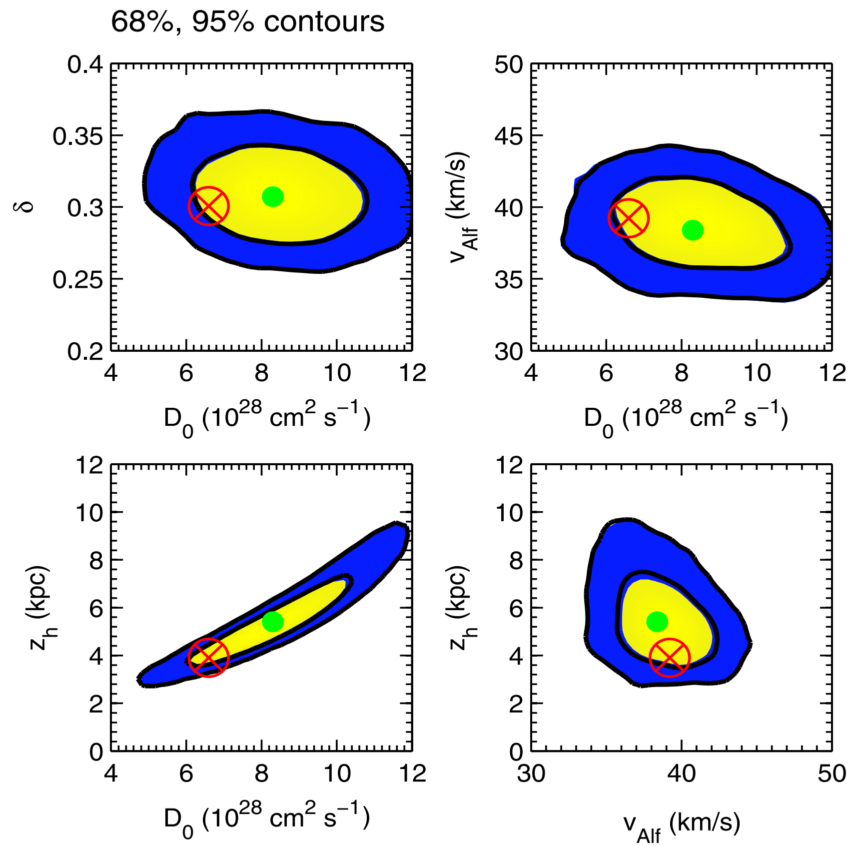


Parameter studies

transport equation can be solved (semi-)analytically (USINE)
or fully numerically (GALPROP, DRAGON)

R. Trotta *et al.*, ApJ 729 (2011) 106





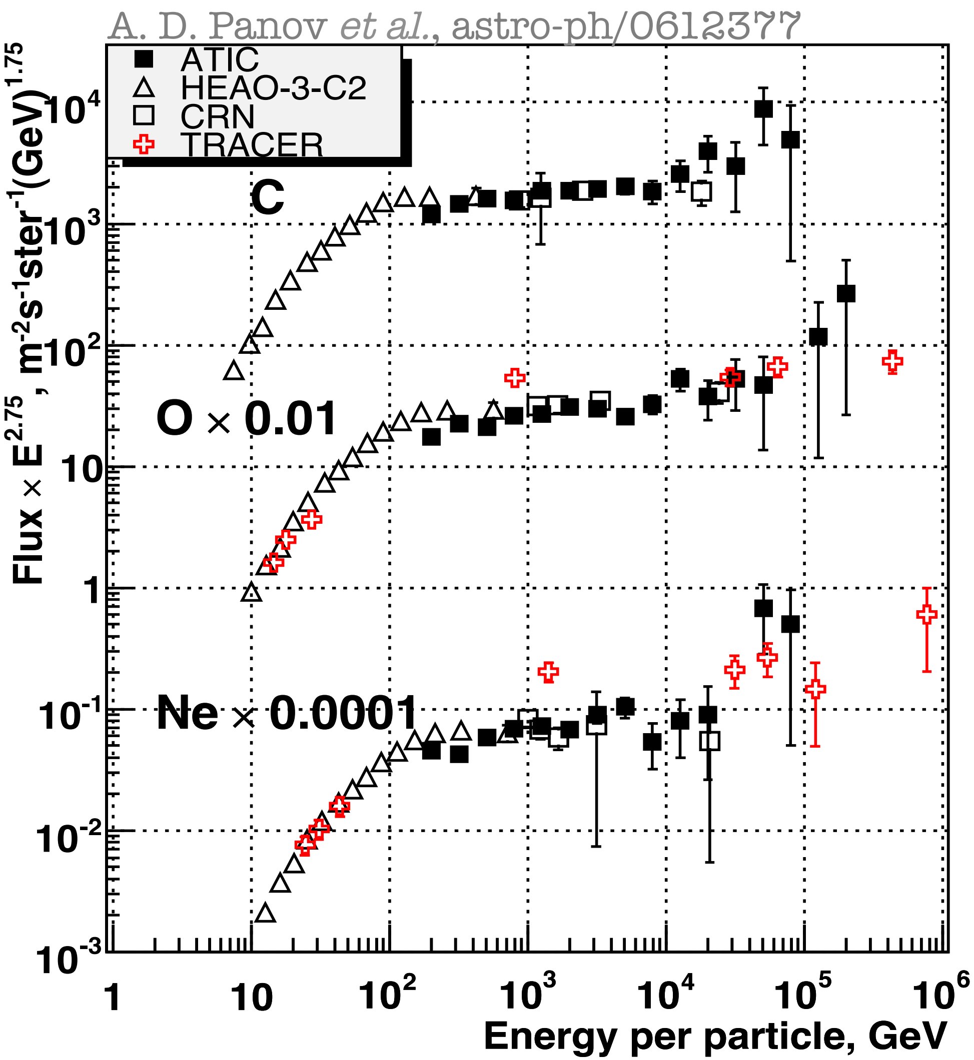
However, secondary-to-primary ratios depend on $D_{||}/z_h$ → degeneracy

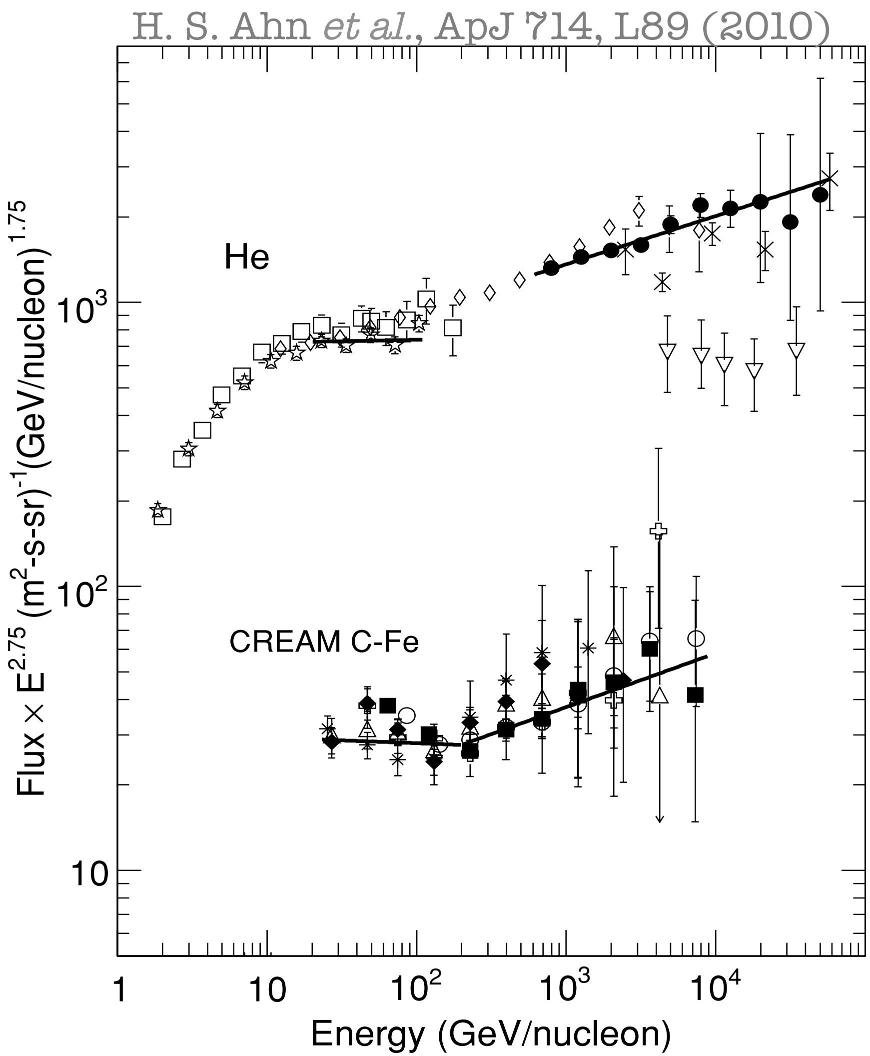
→ need separate measurement of $D_{||}$ to break degeneracy

Parameters

- diffusion coefficient $D_{\|}$;
  - spectral index: $\delta = 0.3 \ldots 0.9$
  - normalisation $D_0 \approx 8 \times 10^{28}\,\mathrm{cm}^2\mathrm{s}^{-1} \approx 0.3\,\mathrm{kpc}^2\,\mathrm{Myr}^{-1}$
- halo height $z_\mathrm{h} = 3 \ldots 10\,\mathrm{kpc}$
- convection velocity $u = 0 \ldots 20\,\mathrm{km\,s}^{-1}$
- reacceleration velocity $v_\mathrm{A} = 0 \ldots 50\,\mathrm{km\,s}^{-1}$
- solar modulation
  - force-field approximation: $\Phi = \mathrm{a\ few\ hundred\ MeV}$
  - importance up to TeV energies?!
  - charge-sign dependence?

Discrepant hardening





Discrepant hardening

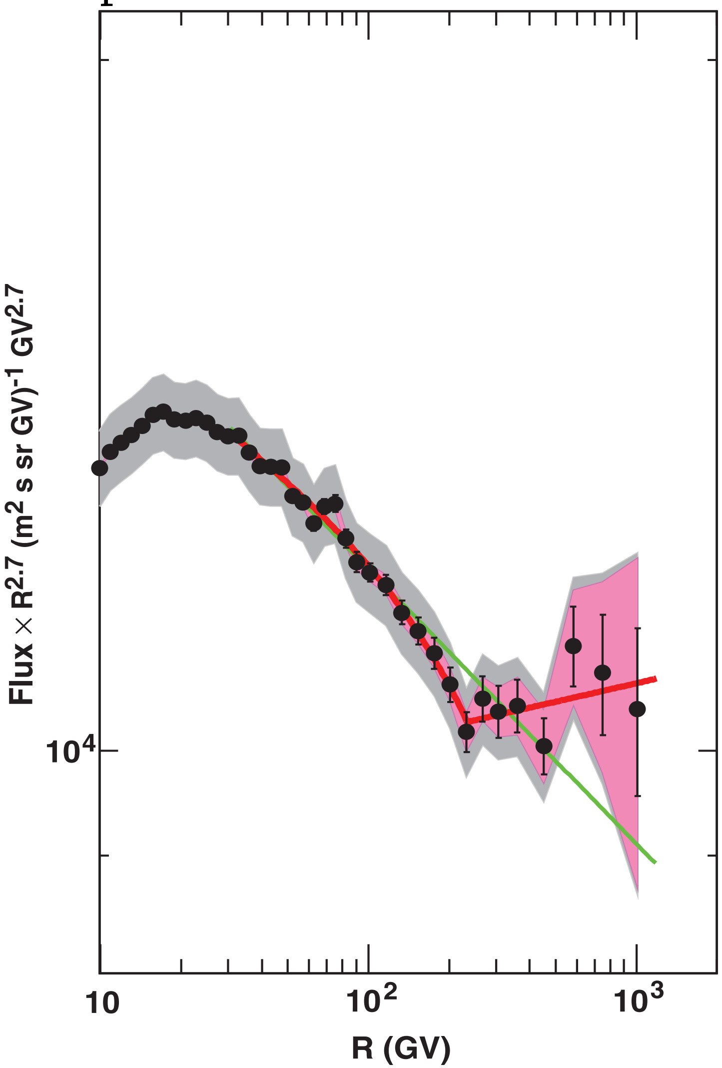
spectral break also observed with high significance ($\gtrsim$ 95% C.L.) in

protons
(@ 230 GeV,
2.85 ➞ 2.67)

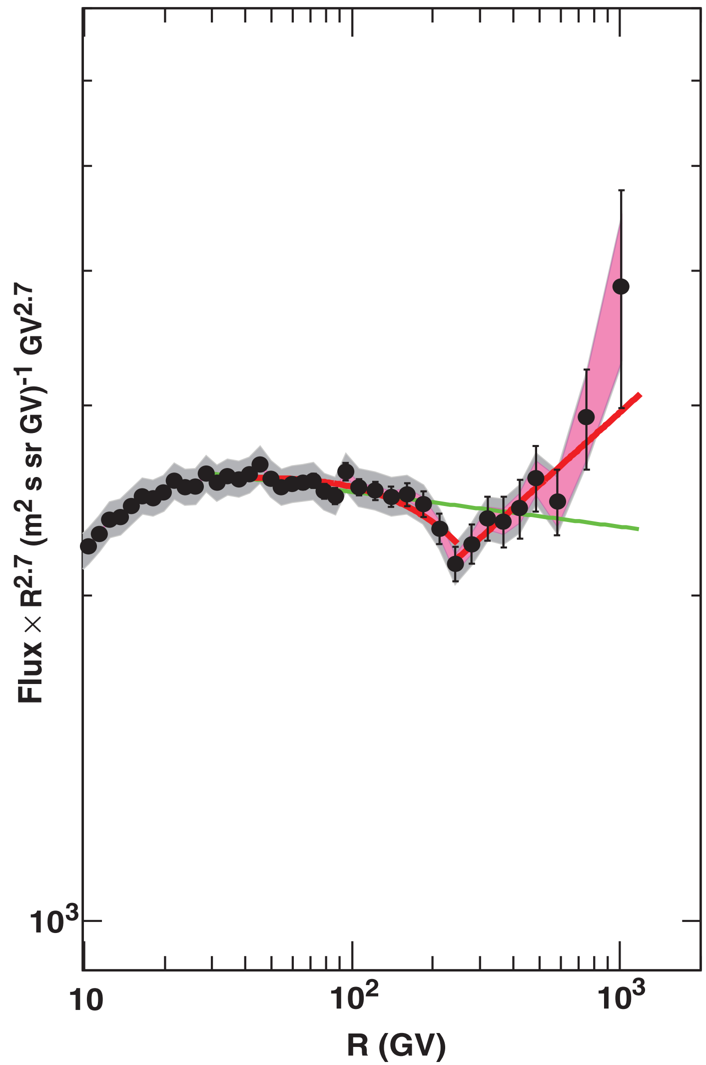
and Helium
(@ 240 GeV,
2.77 ➞ 2.48)

O. Adriani *et al.* Science 332, 69 (2011)

protons

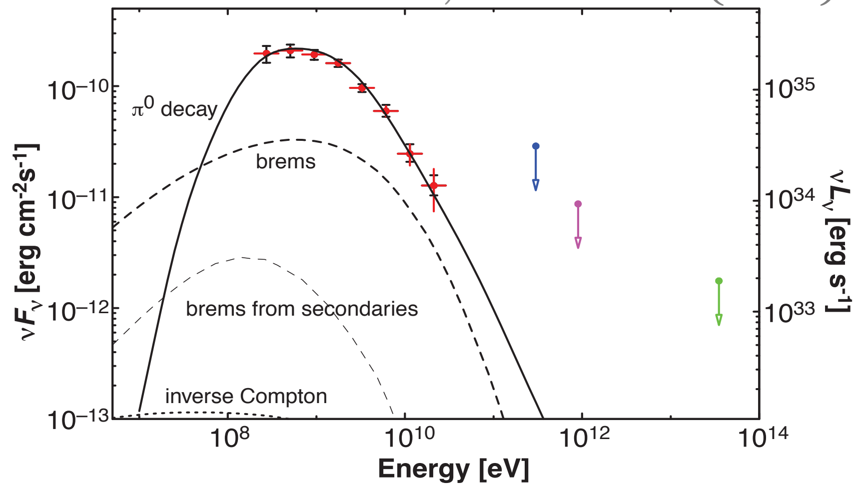


Helium

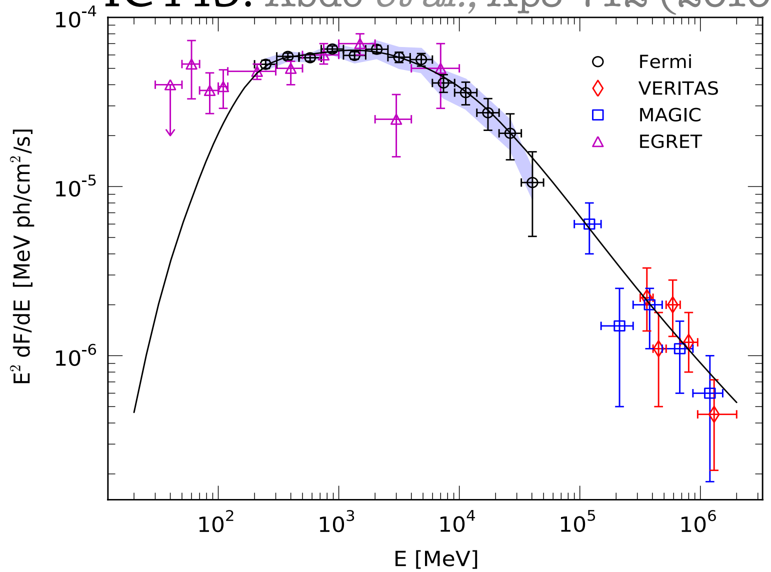


Breaks in source spectra

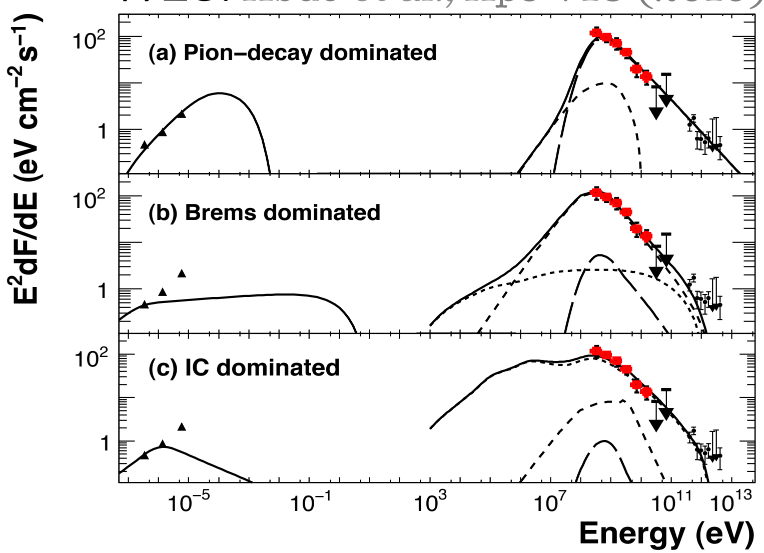
W44: Abdo *et al.*, Science 327 (2010) 1103



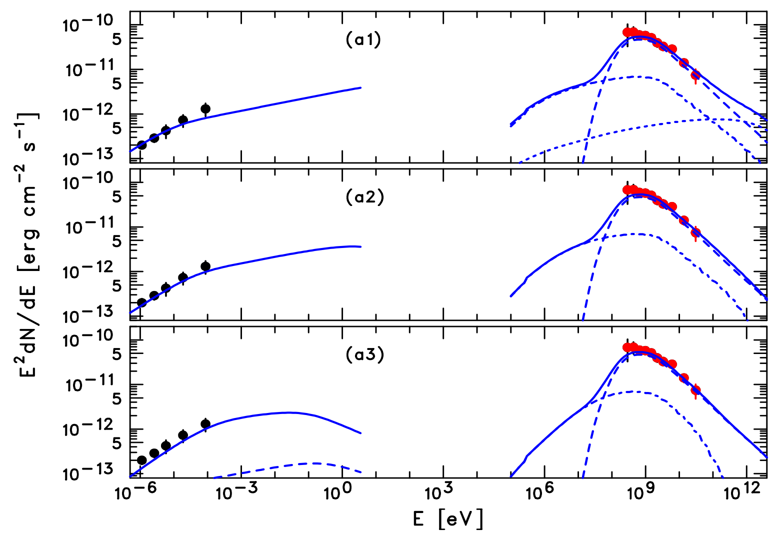
IC443: Abdo *et al.*, ApJ 712 (2010) 459



W28: Abdo *et al.*, ApJ 718 (2010) 348

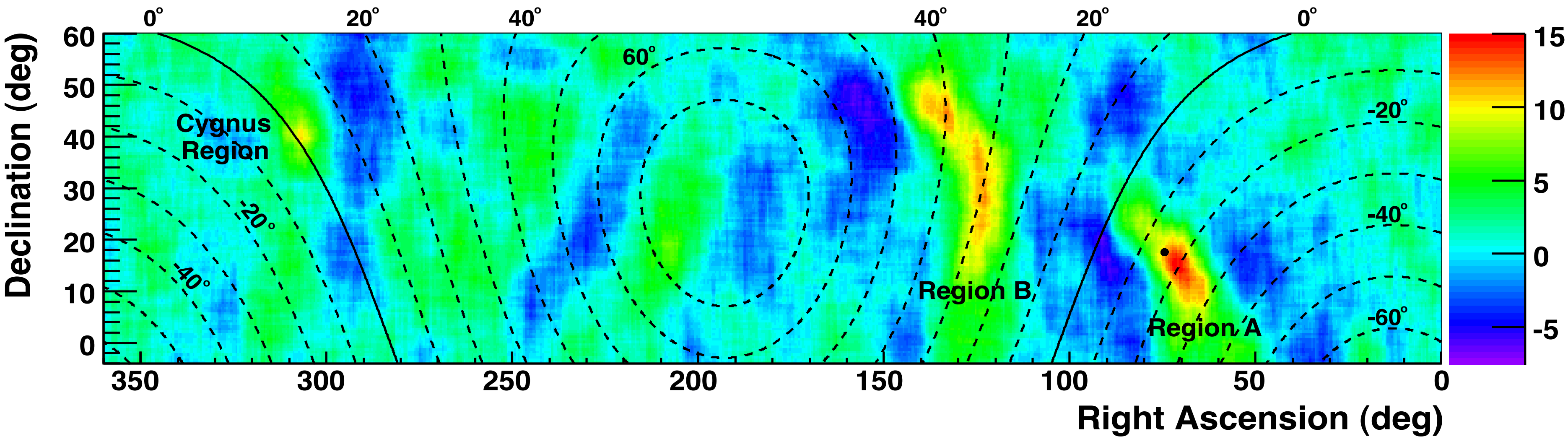


W49B: Abdo *et al.*, ApJ 722 (2010) 1303

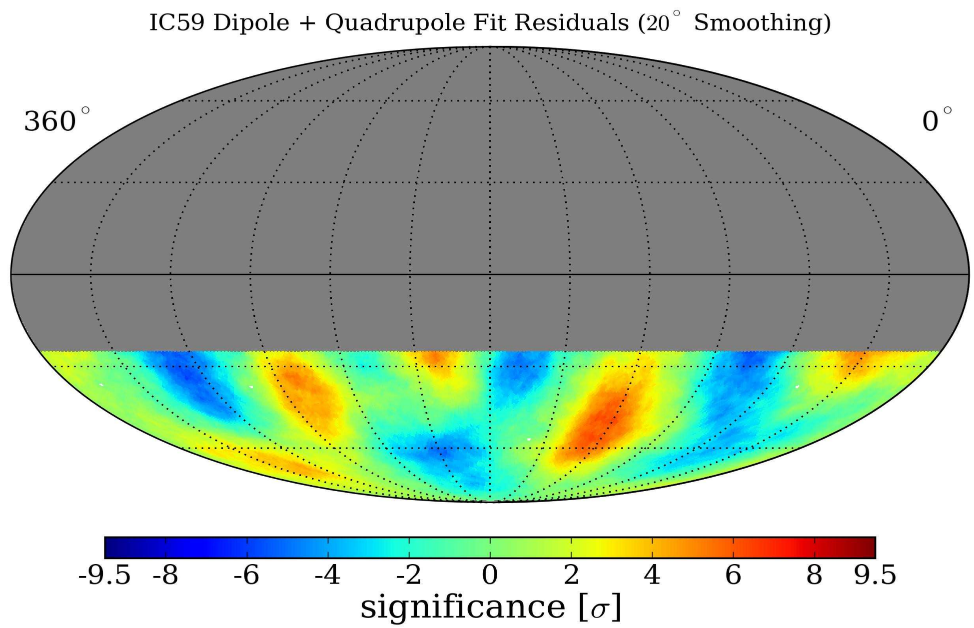


Anisotropies

Abdo *et al.*, PRL 101 (2008) 221101



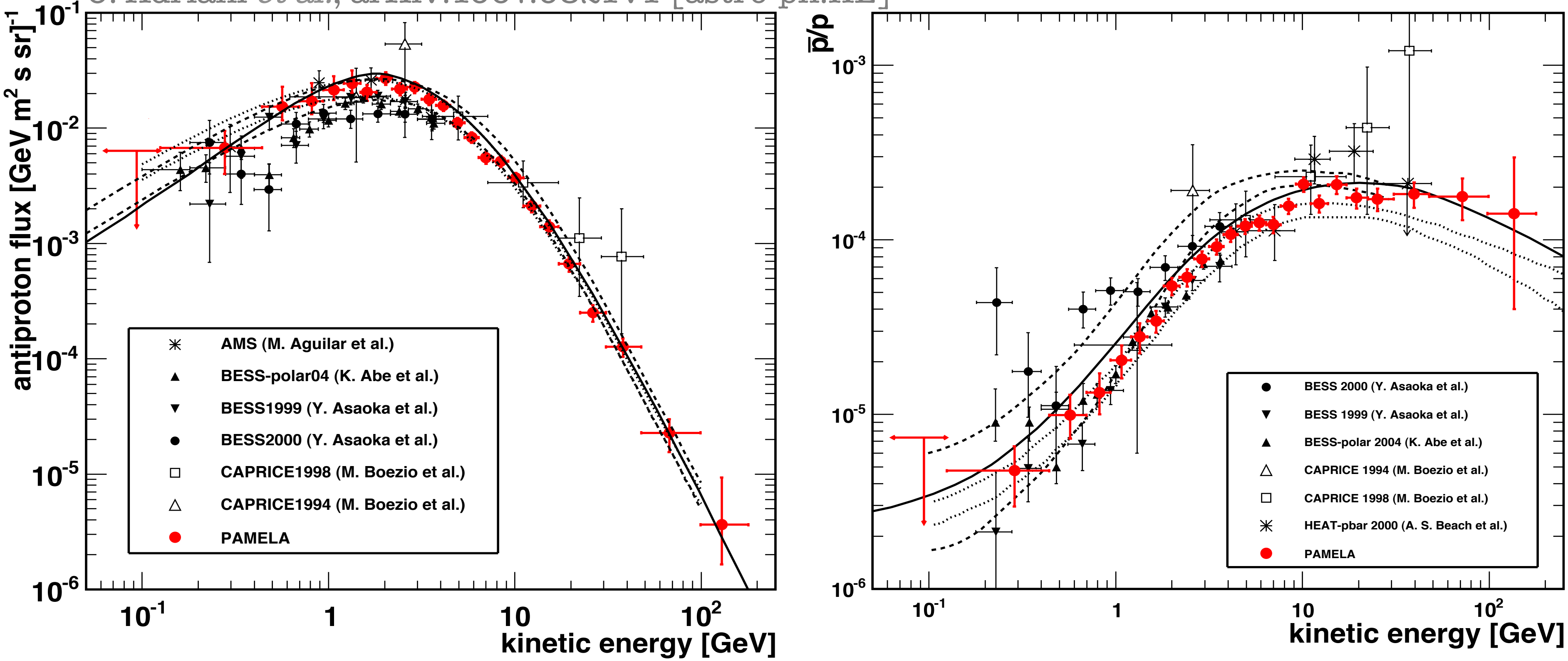
- for $D_{||} \propto \mathcal{R}^{\delta}$, (dipole-)anisotropy should also increase $\propto \mathcal{R}^{\delta}$; however, observationally much smaller
- even more puzzling, at tens of TeV several experiments have observed anisotropies at the level of 10^{-4} on scales down to 5°



Anti-protons

- idea: background for $\bar{p}/p$ similar to other secondary-to-primary ratios
- current data can be fit well in usual propagation setup
- potentially quite robust constraints on DM annihilation cross section

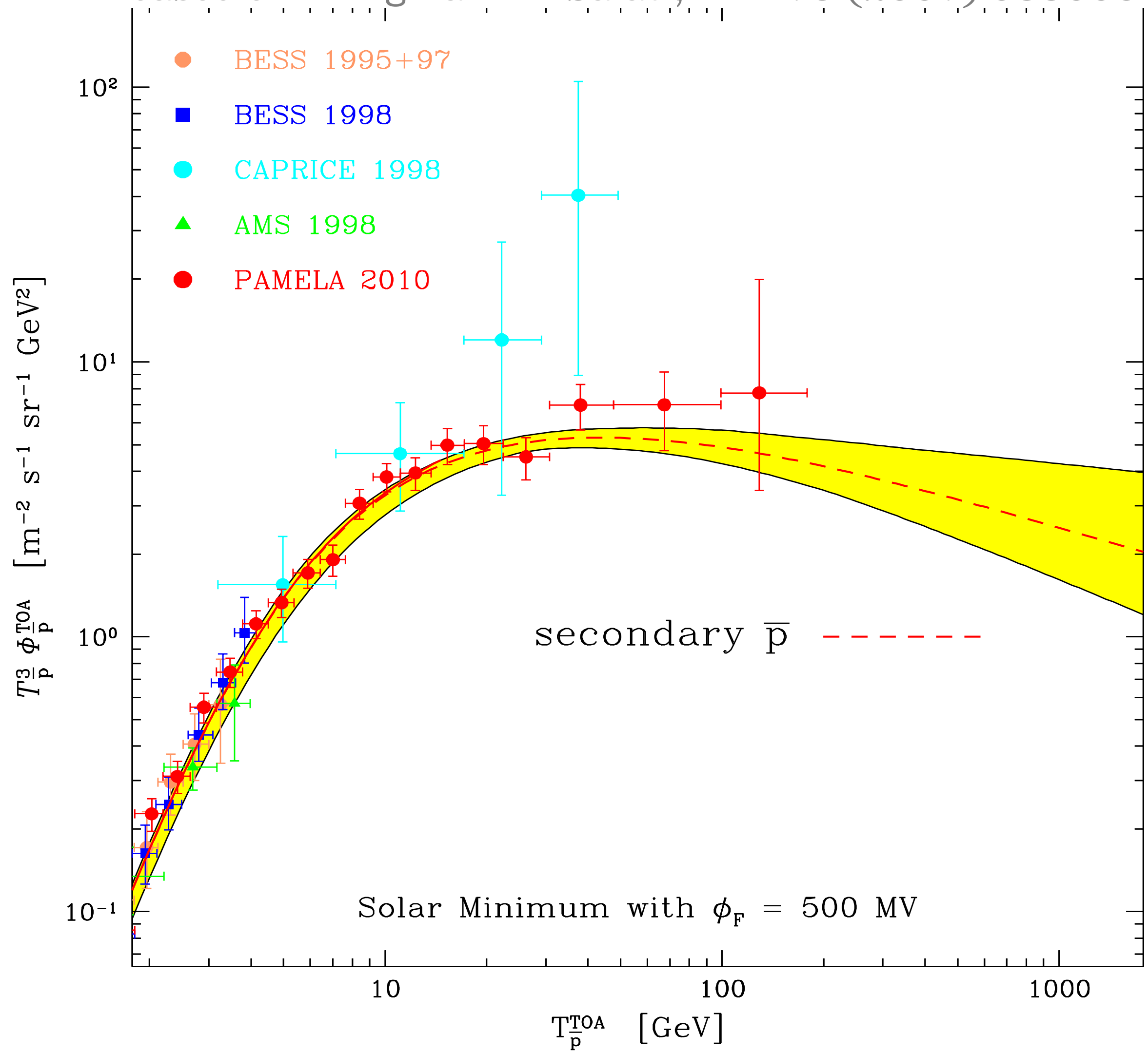
O. Adriani *et al.*, arXiv:1007.0821v1 [astro-ph.HE]



Background uncertainties

- enveloppe from **O**(1000) models that reproduce B/C
- uncertainties
  - ~30% up to 100 GeV
  - up to a factor 3 at 1 TeV

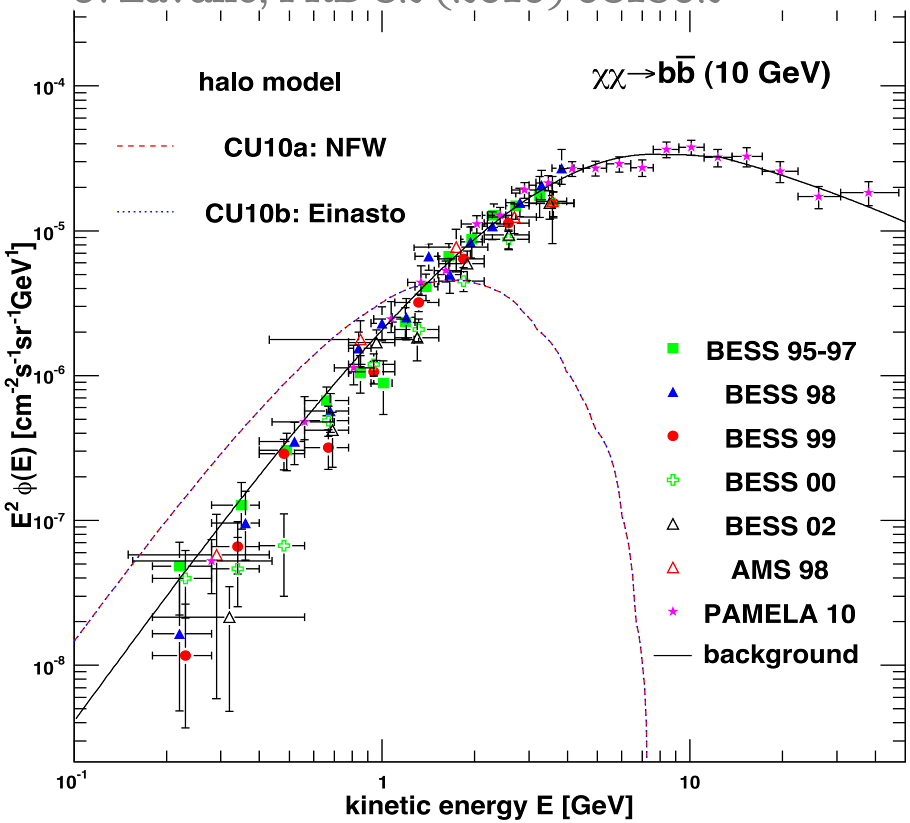
based on Bringmann & Salati, PRD 75 (2007) 083006

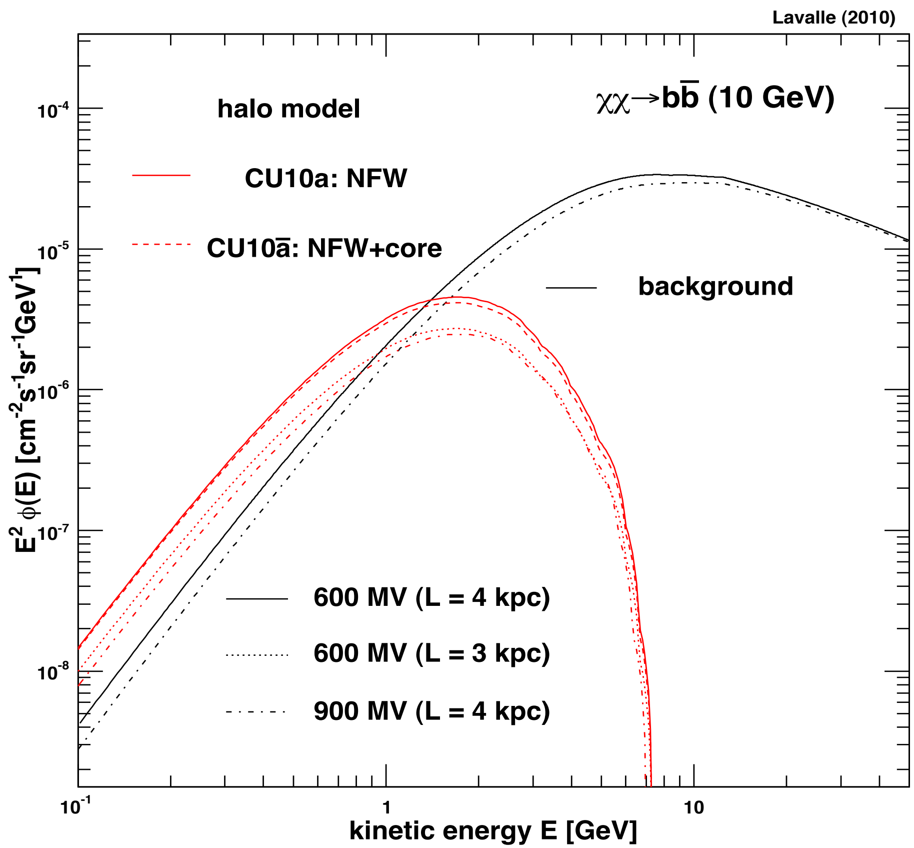


Example 1

- annihilation into $b\bar{b}$ with thermal cross section $\langle \sigma v \rangle = 3 \times 10^{-26}\,\mathrm{cm^3\,s^{-1}}$ is ruled out for light DM

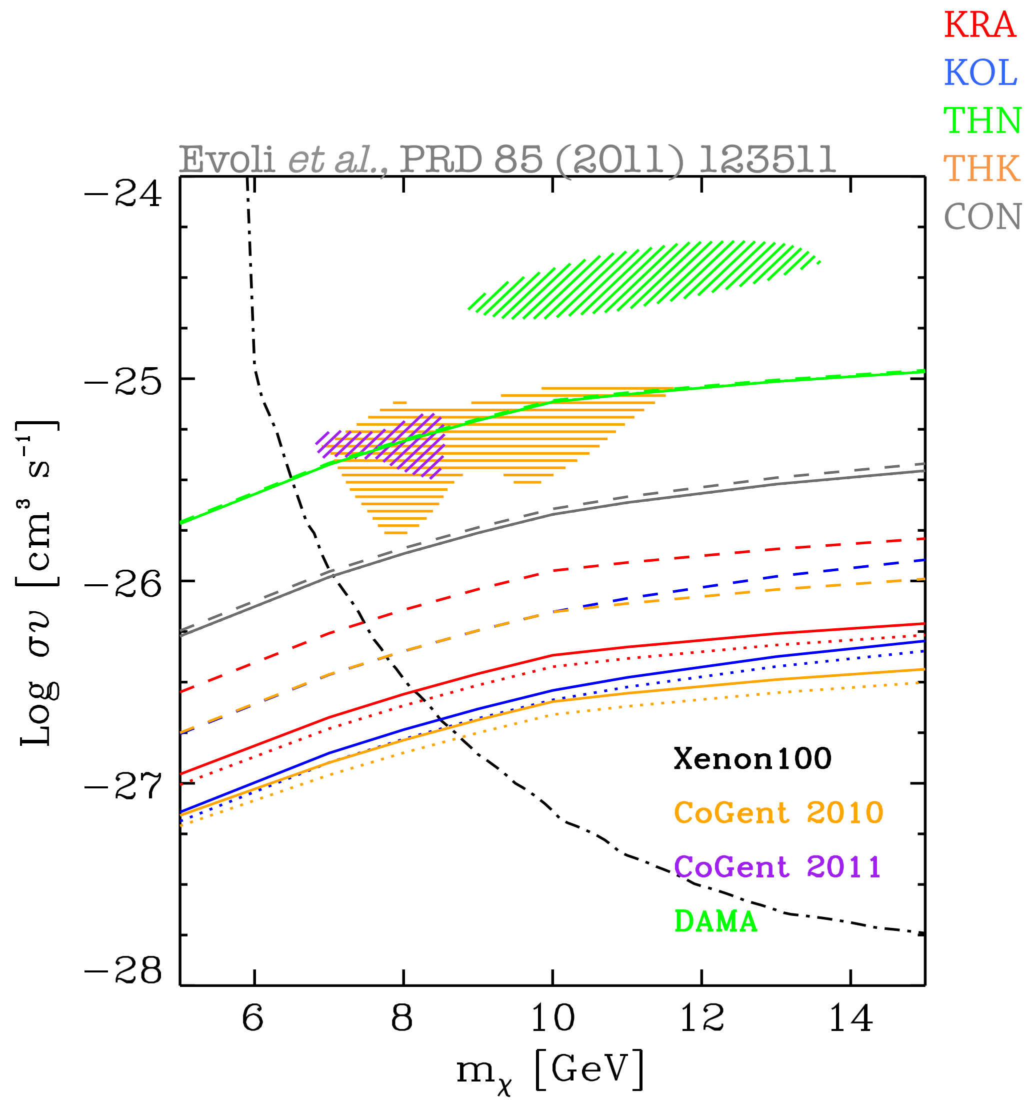
J. Lavalle, PRD 82 (2010) 081302





Example 1

- light DM to explain/check DAMA, CoGent
- assume DM is scalar and has scalar contact interactions with quarks
- if couplings proportional to Yukawa couplings ➞ thermal annihilation cross-sections

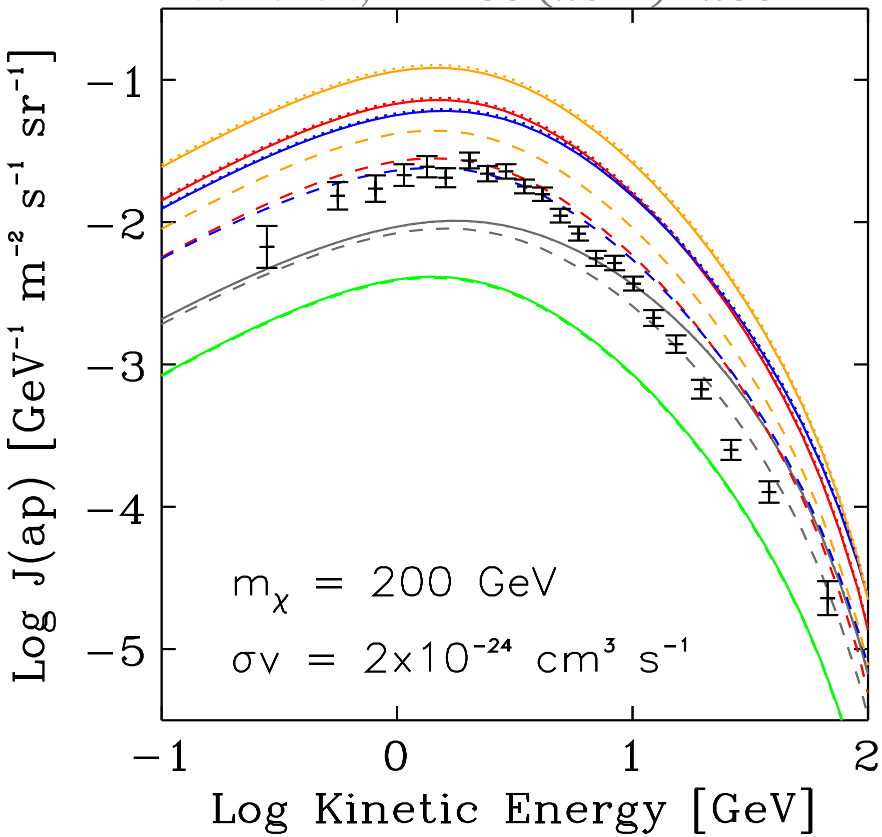


Example 2

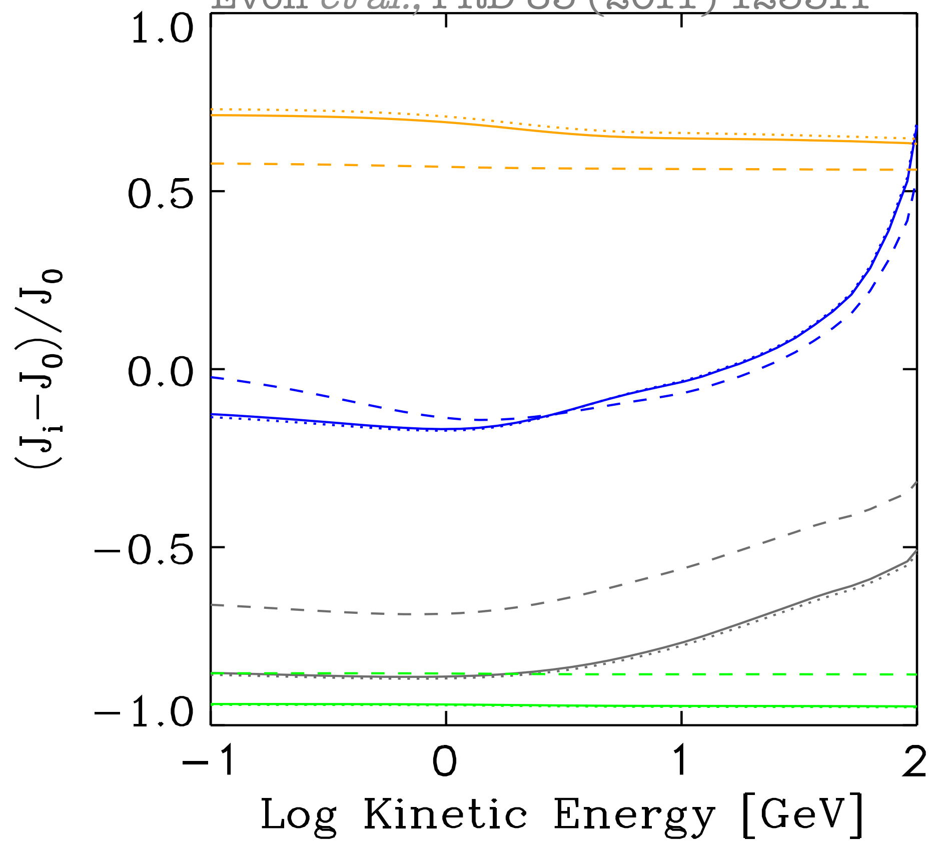
- pure wino LSP
- decays predominantly $\tilde{W}^0\tilde{W}^0 \longrightarrow W^+W^-$
- for 100 GeV masses either underabundant or non-thermal production

KRA
KOL
THN
THK
CON

Evoli *et al.*, PRD 85 (2011) 123511



Evoli *et al.*, PRD 85 (2011) 123511



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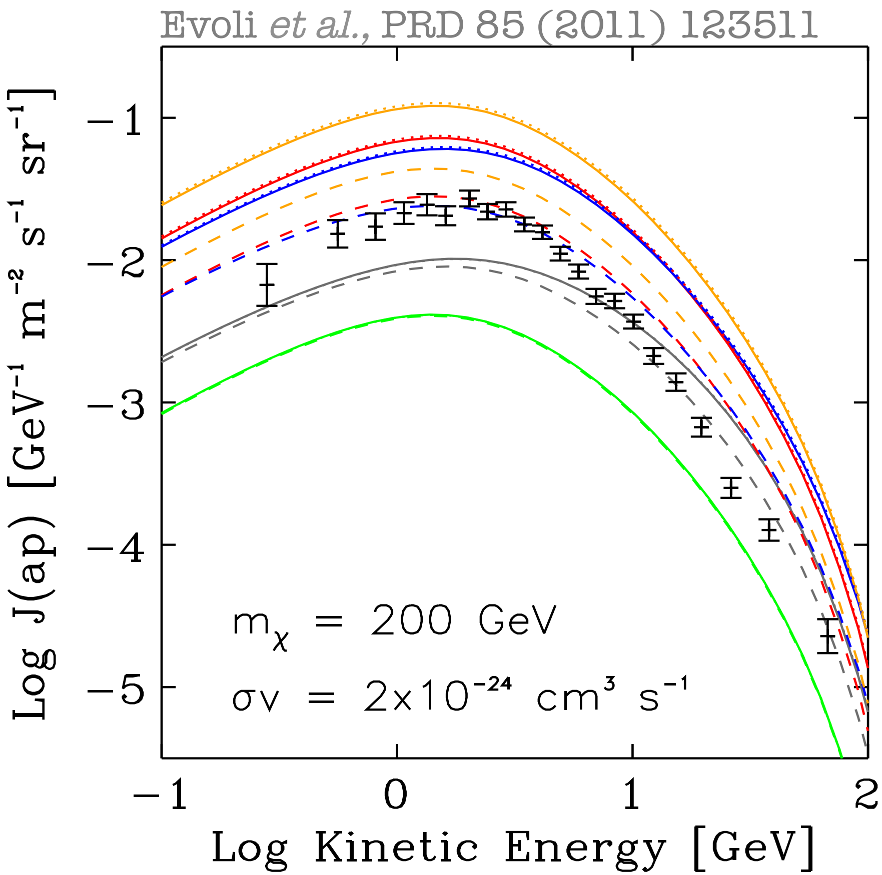
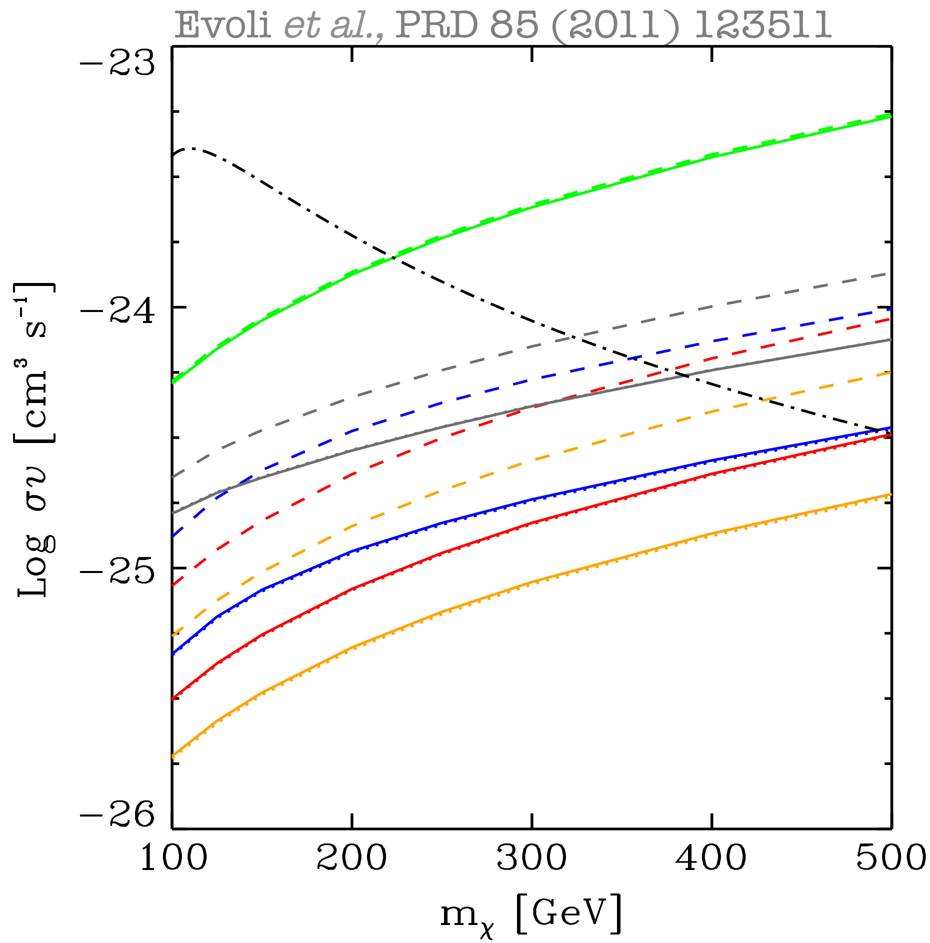
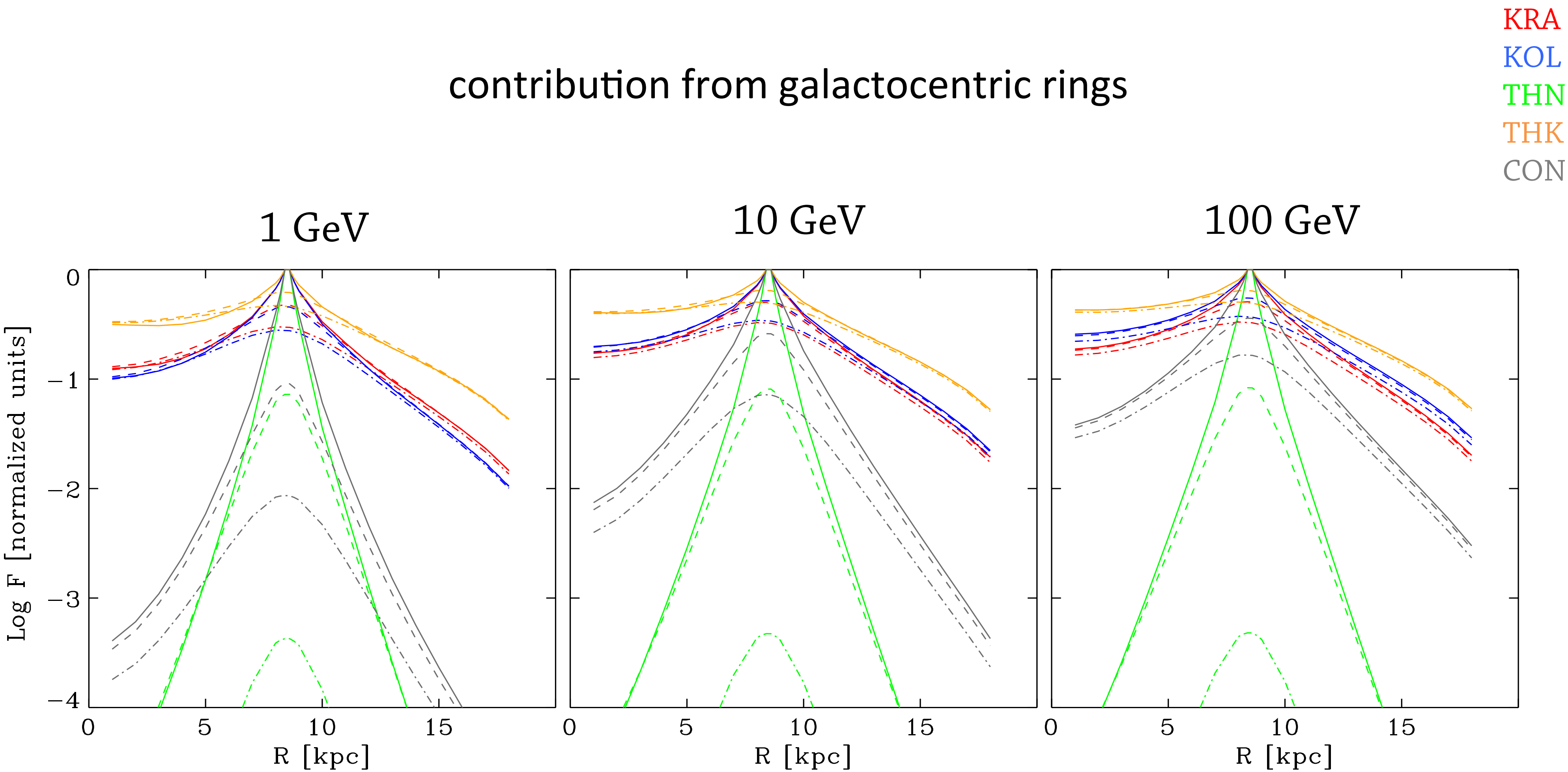




Where do p̄ come from?

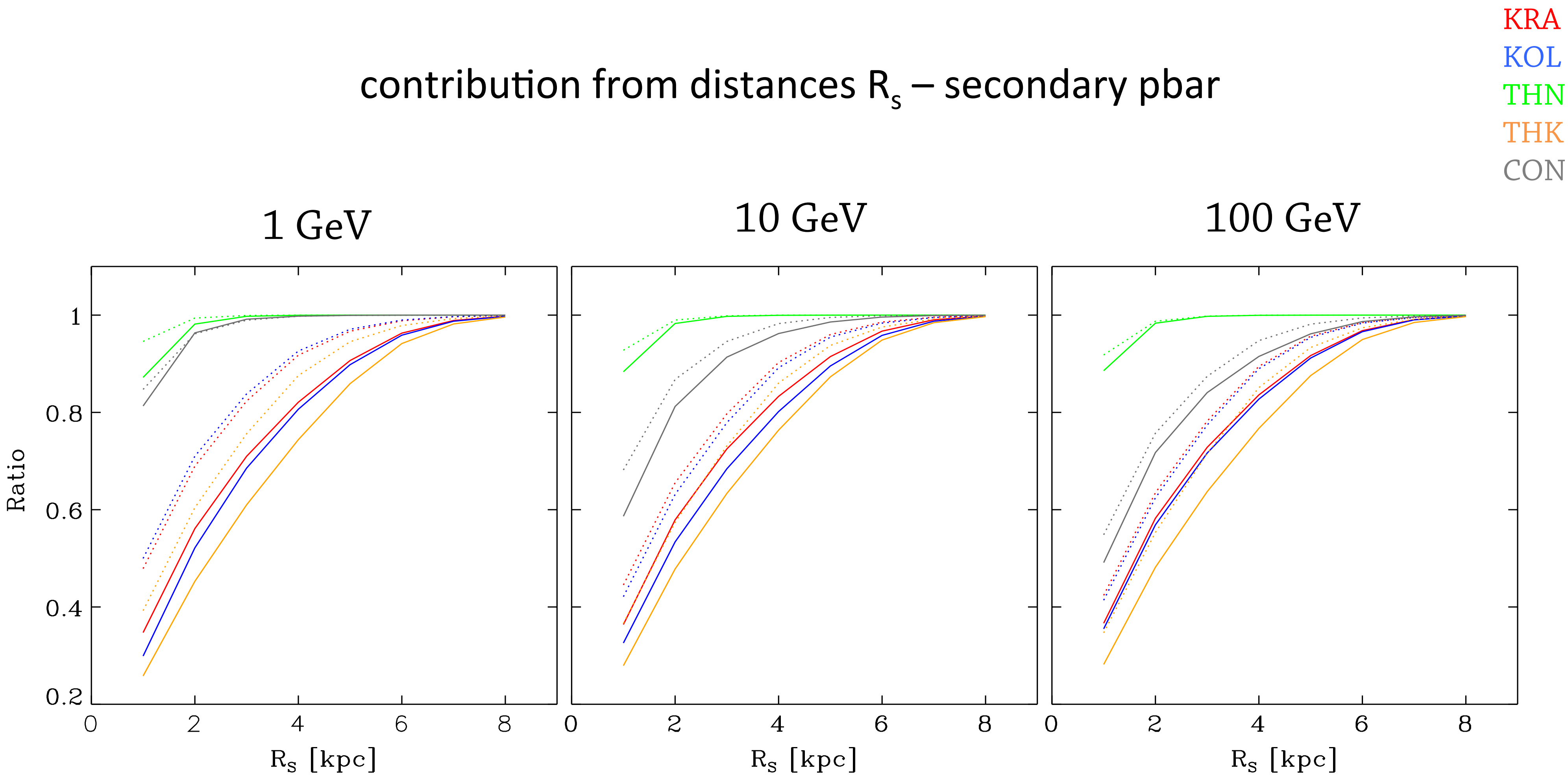
contribution from galactocentric rings



Evoli *et al.*, PRD 85 (2011) 123511

Where do $\bar{p}$ come from?

contribution from distances R_s – secondary pbar

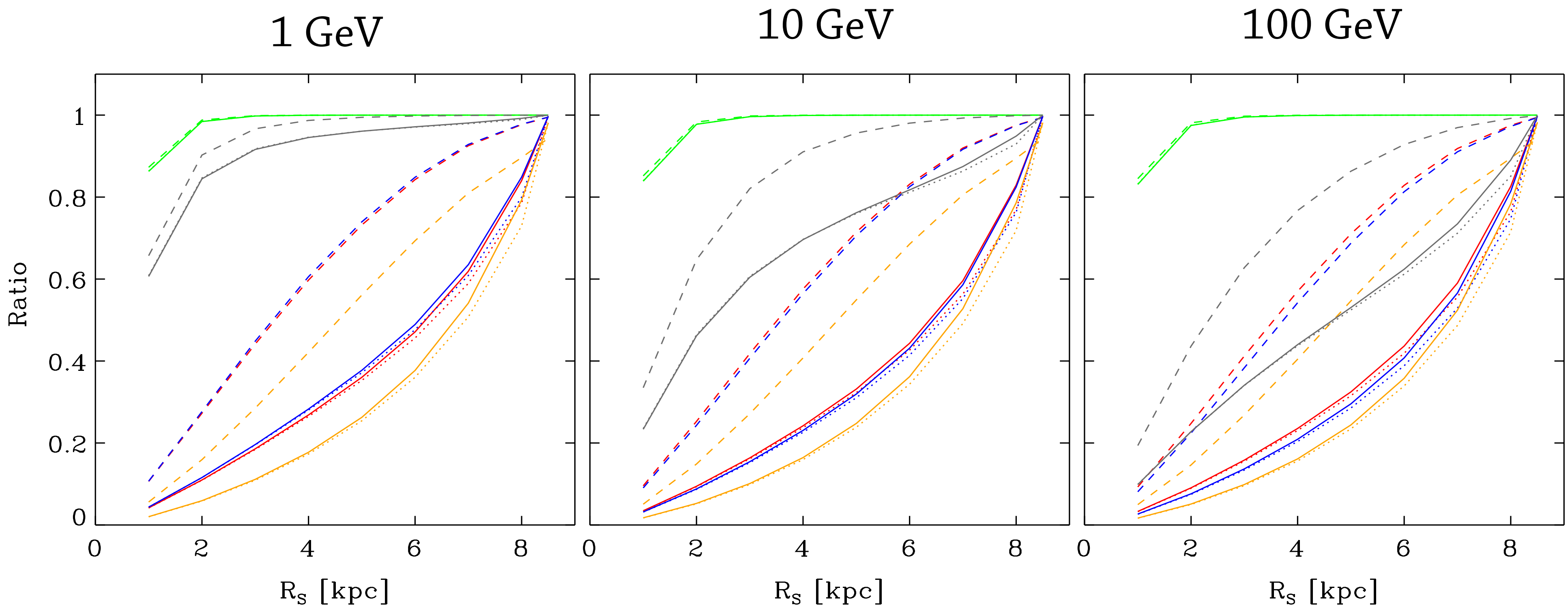


Evoli *et al.*, PRD 85 (2011) 123511

Where do $\bar{p}$ come from?

KRA
KOL
THN
THK
CON

contribution from distances R_s – DM induced pbar



Evoli *et al.*, PRD 85 (2011) 123511

Example 3

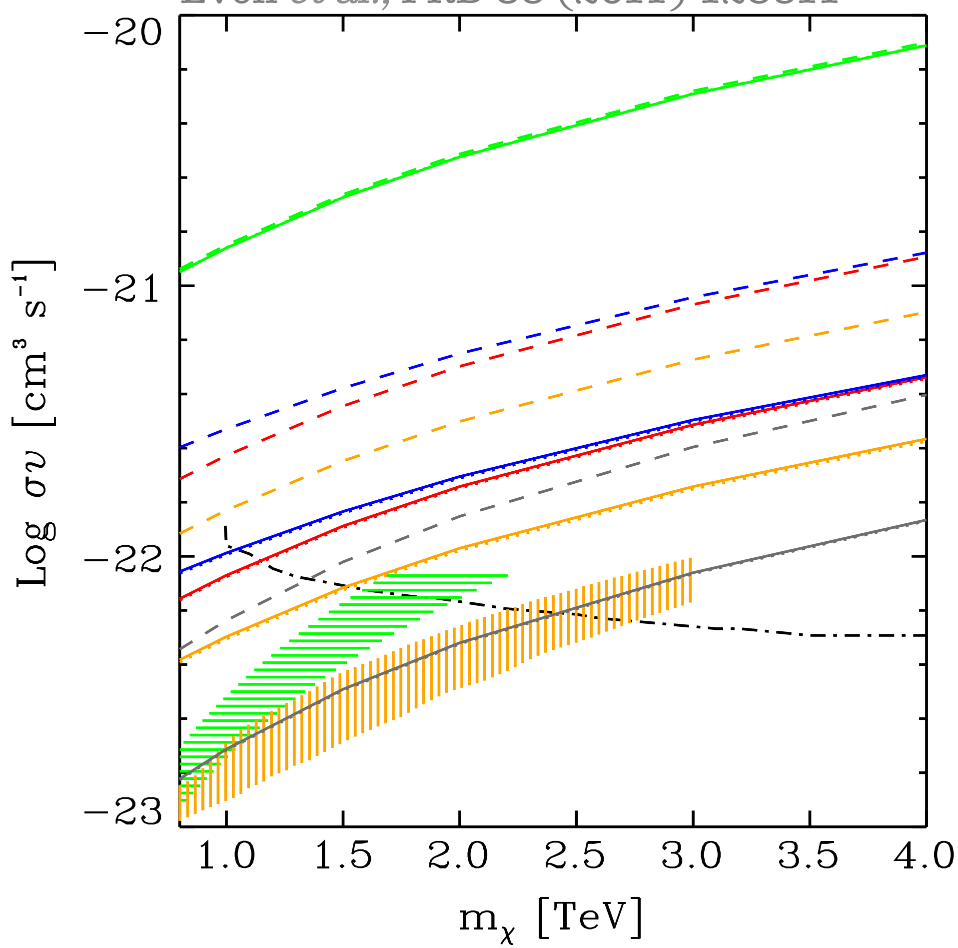
$b\bar{b}$ channel

		extreme propagation		DM halo profiles: NFW, Moore, cored isothermal			varying primary p & He	
	ref	1	2	3	4	5	6	7
100	3	28	2	4	4	6	2	2
200	6	60	3	8	6	11	3	4
300	9	90	4	13	10	18	5	5
400	10	130	4	15	11	22	7	6
500	11	150	4	16	12	23	9	6
600	12	170	4	18	13	26	10	7
700	13	190	5	20	15	29	11	8
800	15	220	6	23	17	33	12	9
900	17	240	6	26	19	38	14	10
1000	19	270	7	29	21	42	16	11

Boehm *et al.*, JCAP 06 (2010) 013

$\mu\mu$ channel

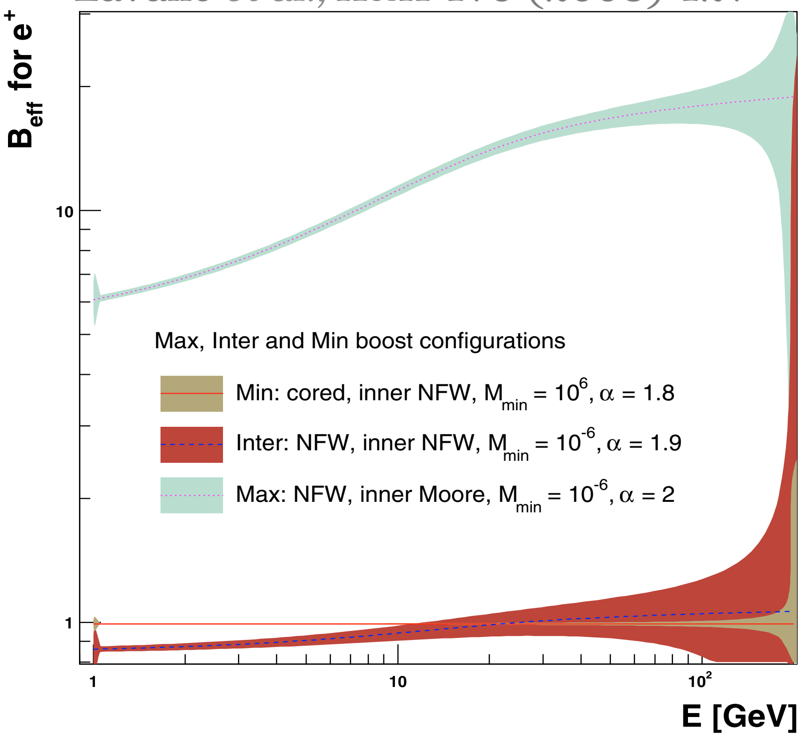
Evoli *et al.*, PRD 85 (2011) 123511

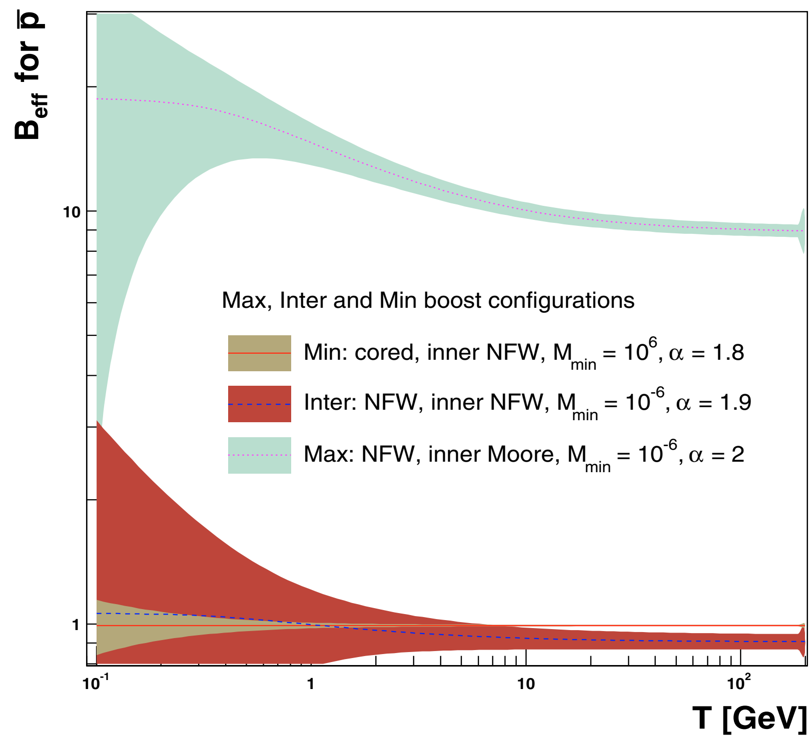


Caveats

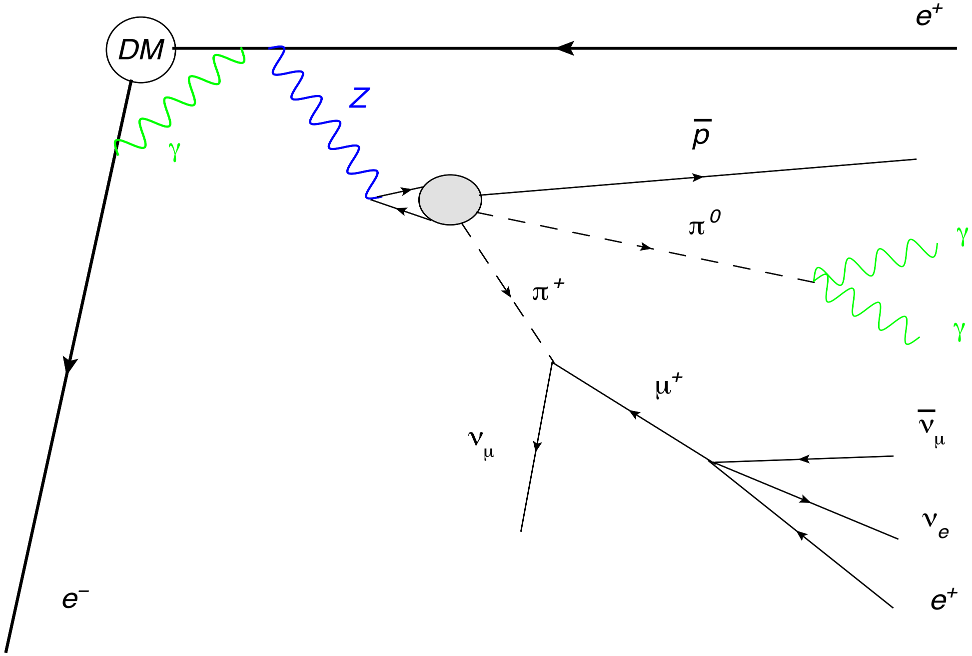
- non-standard diffusion models, e.g. z-dependent diffusion coefficient
  Perelstein & Shakya, PRD 83 (2011) 123508; Evoli *et al.*, PRD 85 (2011) 123511
- break in primary spectra: local source ➞ error in secondary prediction up to 30% at 1 TeV Donato & Serpico, PRD 83 (2010) 023014
- nearby clumps/subhalos:

Lavalle *et al.*, A&A 479 (2008) 427





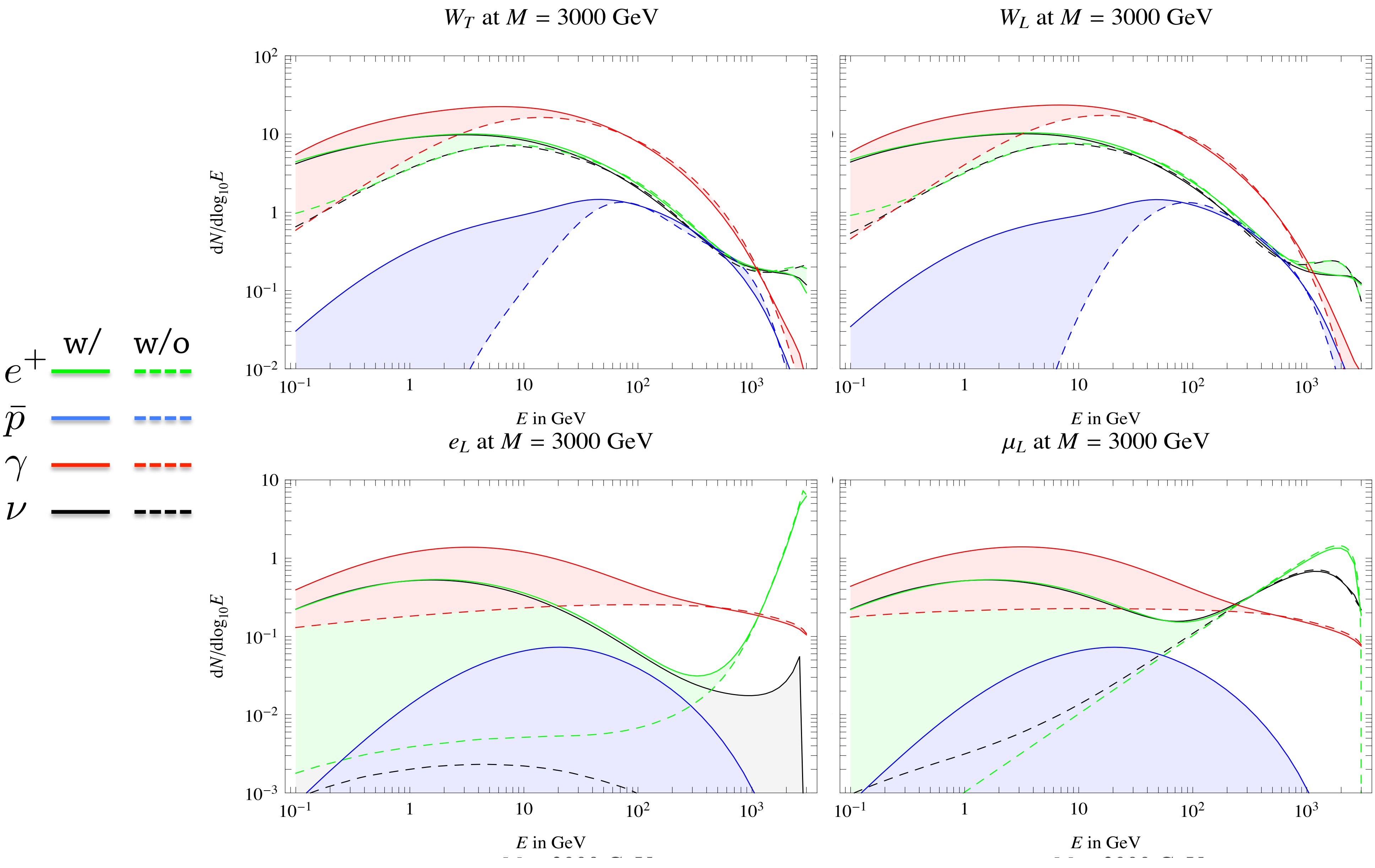
Electroweak corrections



Ciafaloni *et al.*, JCAP 03 (2011) 019

- naively might expect electroweak corrections to be negligible: $\alpha_2 \ln M^2/M_W^2$ or $\alpha_2 \ln^2 M^2/M_W^2$
- for 100 GeV typically of $\mathcal{O}(0.1)\ \%$, even at a few TeV only $\mathcal{O}(30)\ \%$
- but:
  - evade helicity suppression
    see e.g. Bell, Dent, Jacques, Weiler
  - prevents leptophilic or hadrophobic models
  - changes spectral shape

Electroweak corrections

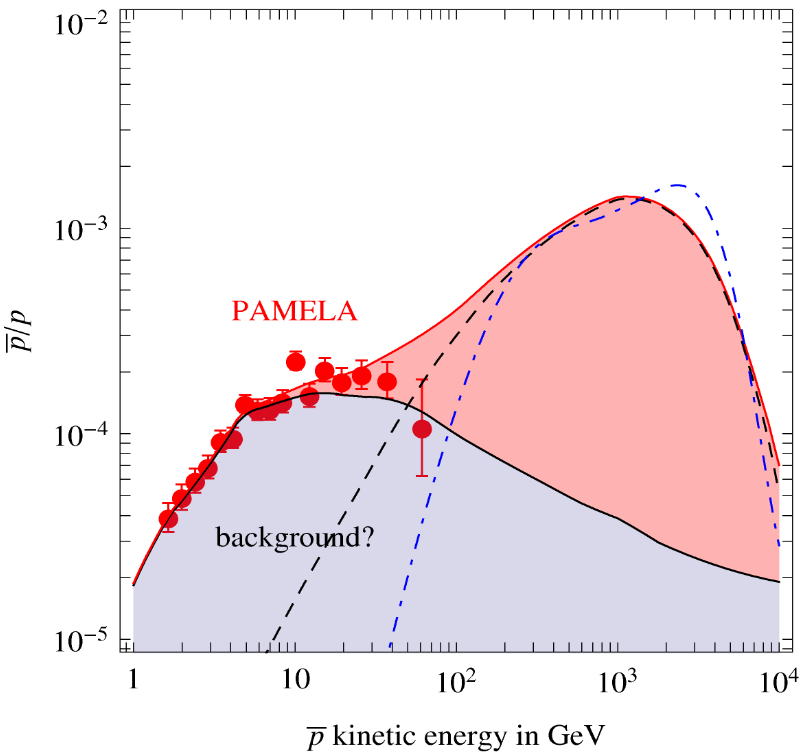


Ciafaloni *et al.*, JCAP 03 (2011) 019

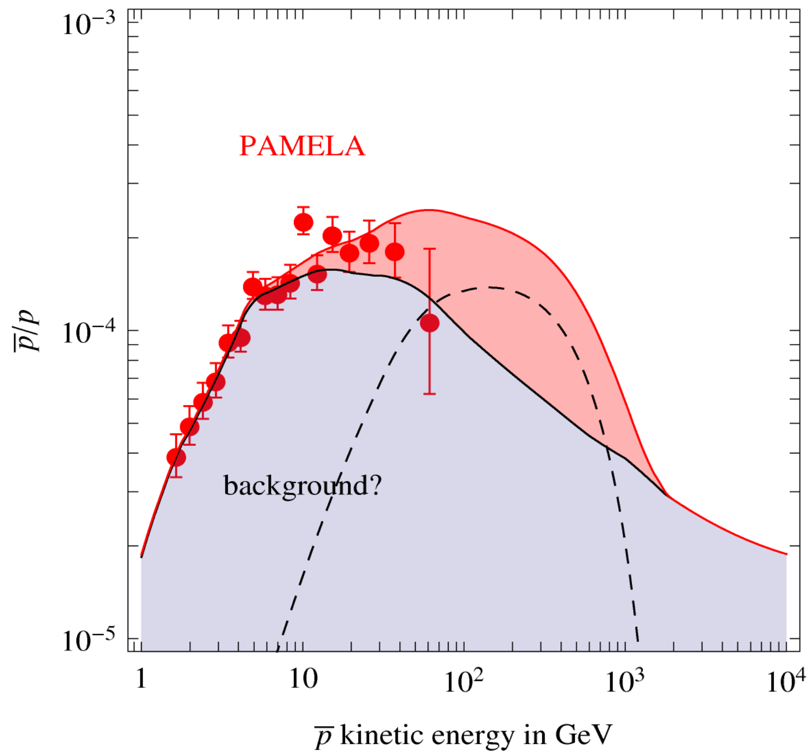
Electroweak corrections

Ciafaloni *et al.*, JCAP 03 (2011) 019

$\chi\chi \longrightarrow W_T^+ W_T^-$ with M = 10 TeV

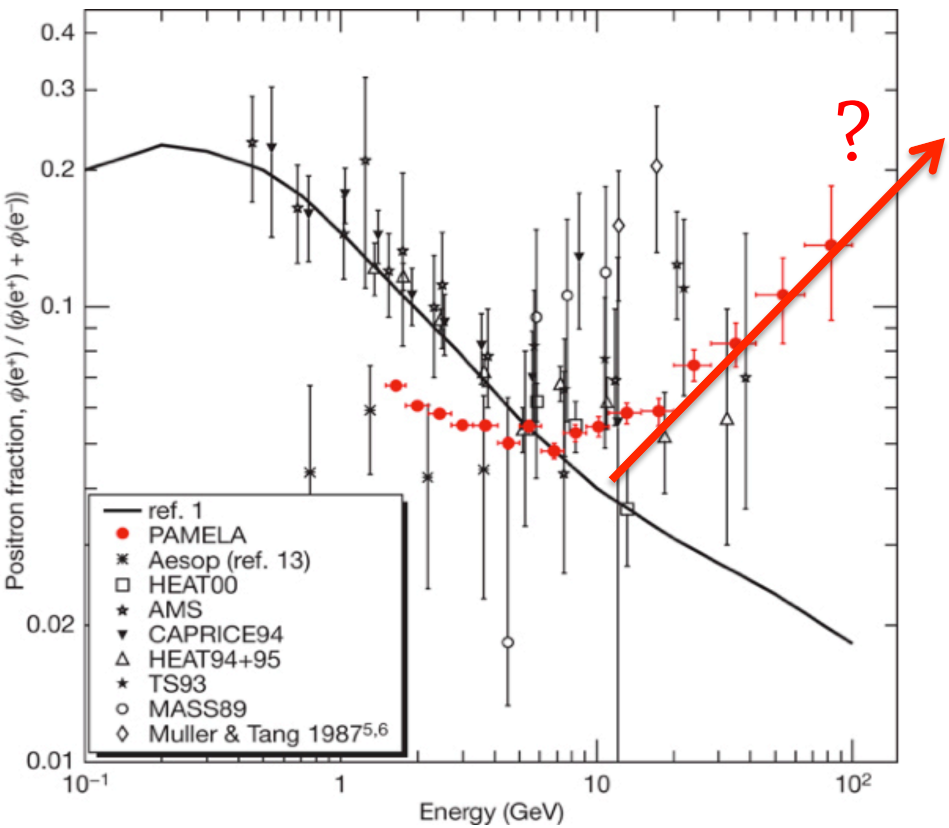


$\chi\chi \longrightarrow \mu_L^+ \mu_L^-$ with M = 2 TeV

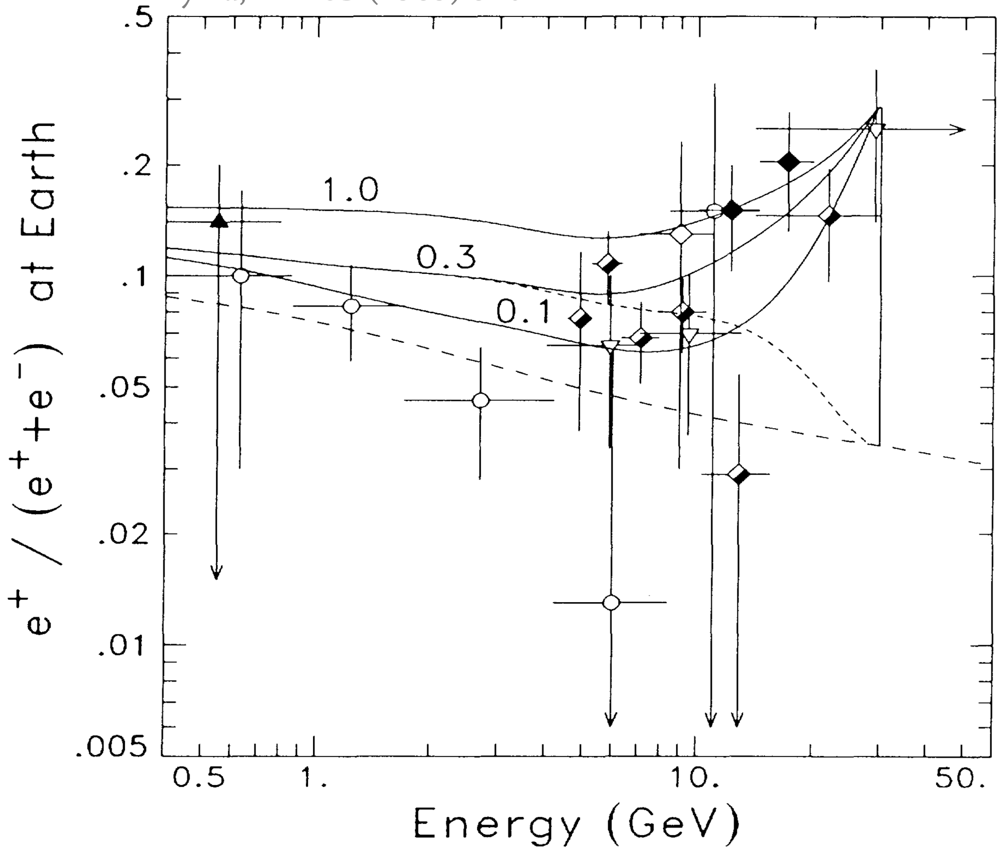


Autumn 2008

Adriani *et al.* *Nature* **458**, 607-609 (2009)



Tylka, PRL **63** (1989) 840



Results

Which DM can fit the data?

M.Pospelov and A.Ritz, 0810.1502: Secluded DM - A.Nelson and C.Spitzer, 0810.5167: Slightly Non-Minimal DM - Y.Nomura and J.Thaler, 0810.5397: DM through the Axion Portal - R.Harnik and G.Kribs, 0810.5557: Dirac DM - D.Feldman, Z.Liu, P.Nath, 0810.5762: Hidden Sector - T.Hambye, 0811.0172: Hidden Vector - Yin, Yuan, Liu, Zhang, Bi, Zhu, 0811.0176: Leptonically decaying DM - K.Ishiwata, S.Matsumoto, T.Moroi, 0811.0250: Superparticle DM - Y.Bai and Z.Han, 0811.0387: sUED DM - P.Fox, E.Poppitz, 0811.0399: Leptophilic DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.0477: Hidden-Gauge-Boson DM - K.Hamaguchi, E.Nakamura, S.Shirai, T.T.Yanagida, 0811.0737: Decaying DM in Composite Messenger - E.Ponton, L.Randall, 0811.1029: Singlet DM - A.Ibarra, D.Tran, 0811.1555: Decaying DM - S.Baek, P.Ko, 0811.1646: U(1) Lmu-Ltau DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.3357: Decaying Hidden-Gauge-Boson DM - I.Cholis, G.Dobler, D.Finkbeiner, L.Goodenough, N.Weiner, 0811.3641: 700+ GeV WIMP - E.Nardi, F.Sannino, A.Strumia, 0811.4153: Decaying DM in TechniColor - K.Zurek, 0811.4429: Multicomponent DM - M.Ibe, H.Murayama, T.T.Yanagida, 0812.0072: Breit-Wigner enhancement of DM annihilation - E.Chun, J.-C.Park, 0812.0308: sub-GeV hidden U(1) in GMSB - M.Lattanzi, J.Silk, 0812.0360: Sommerfeld enhancement in cold substructures - M.Pospelov, M.Trott, 0812.0432: super-WIMPs decays DM - Zhang, Bi, Liu, Liu, Yin, Yuan, Zhu, 0812.0522: Discrimination with SR and IC - Liu, Yin, Zhu, 0812.0964: DMnu from GC - M.Pohl, 0812.1174: electrons from DM - J.Hisano, M.Kawasaki, K.Kohri, K.Nakayama, 0812.0219: DMnu from GC - A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075: Decaying DM in GUTs - R.Allahverdi, B.Dutta, K.Richardson-McDaniel, Y.Santoso, 0812.2196: SuSy B-L DM- S.Hamaguchi, K.Shirai, T.T.Yanagida, 0812.2374: Hidden-Fermion DM decays - D.Hooper, A.Stebbins, K.Zurek, 0812.3202: Nearby DM clump - C.Delaunay, P.Fox, G.Perez, 0812.3331: DMnu from Earth - Park, Shu, 0901.0720: Split-UED DM - .Gogoladze, R.Khalid, Q.Shafi, H.Yuksel, 0901.0923: cMSSM DM with additions - Q.H.Cao, E.Ma, G.Shaughnessy, 0901.1334: Dark Matter: the leptonic connection - E.Nezri, M.Tytgat, G.Vertongen, 0901.2556: Inert Doublet DM - C.-H.Chen, C.-Q.Geng, D.Zhuridov, 0901.2681: Fermionic decaying DM - J.Mardon, Y.Nomura, D.Stolarski, J.Thaler, 0901.2926: Cascade annihilations (light non-abelian new bosons) - P.Meade, M.Papucci, T.Volansky, 0901.2925: DM sees the light - D.Phalen, A.Pierce, N.Weiner, 0901.3165: New Heavy Lepton - T.Banks, J.-F.Fortin, 0901.3578: Pyrma baryons - Goh, Hall, Kumar, 0902.0814: Leptonic Higgs - K.Bae, J.-H. Huh, J.Kim, B.Kyae, R.Viollier, 0812.3511: electrophilic axion from flipped-SU(5) with extra spontaneously broken symmetries and a two component DM with Z_2 parity - ...

Galactic Propagation of $e^{\pm}$

Transport equation

$$\frac{\mathrm{d}N(\vec{r},t)}{\mathrm{d}t} = \nabla\big(D\nabla N(\vec{r},t)\big) - \underbrace{\frac{\partial}{\partial E}\big(b(E)N(\vec{r},t)\big)}_{\text{energy losses}} + Q(\vec{r},t)$$

- Inverse Compton Scattering on CMB, IR, UV/opt.
- Synchrotron Radiation on galactic magnetic fields

$$b(E) = \frac{\mathrm{d}E}{\mathrm{d}t} = \frac{32\pi c}{9}\left(\frac{e^2}{mc^2}\right)^2 \frac{c}{(mc)^2}\left(w_{\mathrm{ph}} + \frac{H^2}{8\pi}\right)E^2 = \beta E^2$$

Falling Positron Fraction

energy loss time

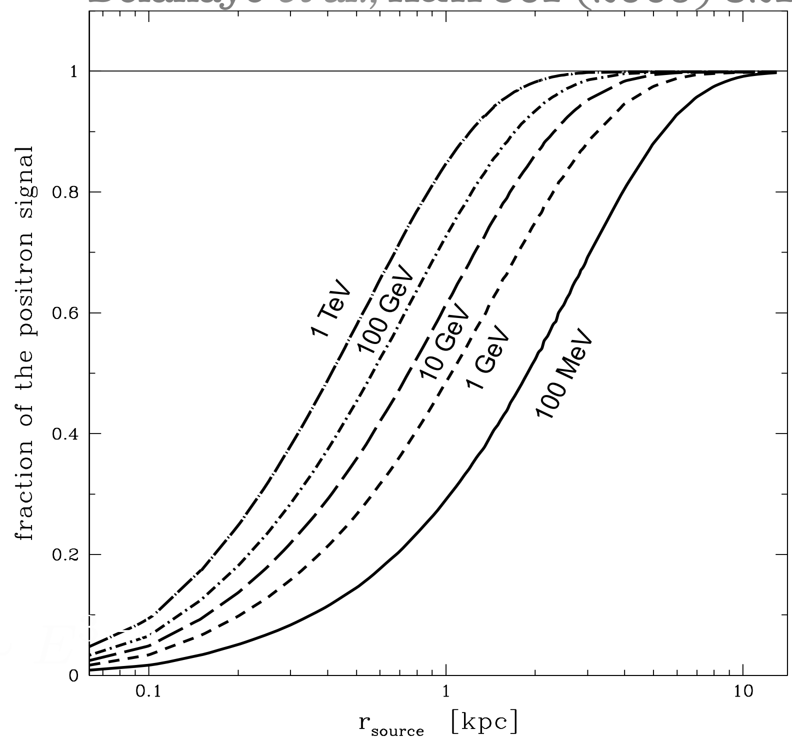
$$\tau_{b(t)}(E) = E \Big/ \frac{\mathrm{d}E}{\mathrm{d}t} = (\beta E)^{-1}$$

$$\Rightarrow N(E) \sim \tau_{b(t)}(E) Q(E) \sim E^{-1} Q(E)$$

average path length $\lambda \approx \sqrt{2Dt}$

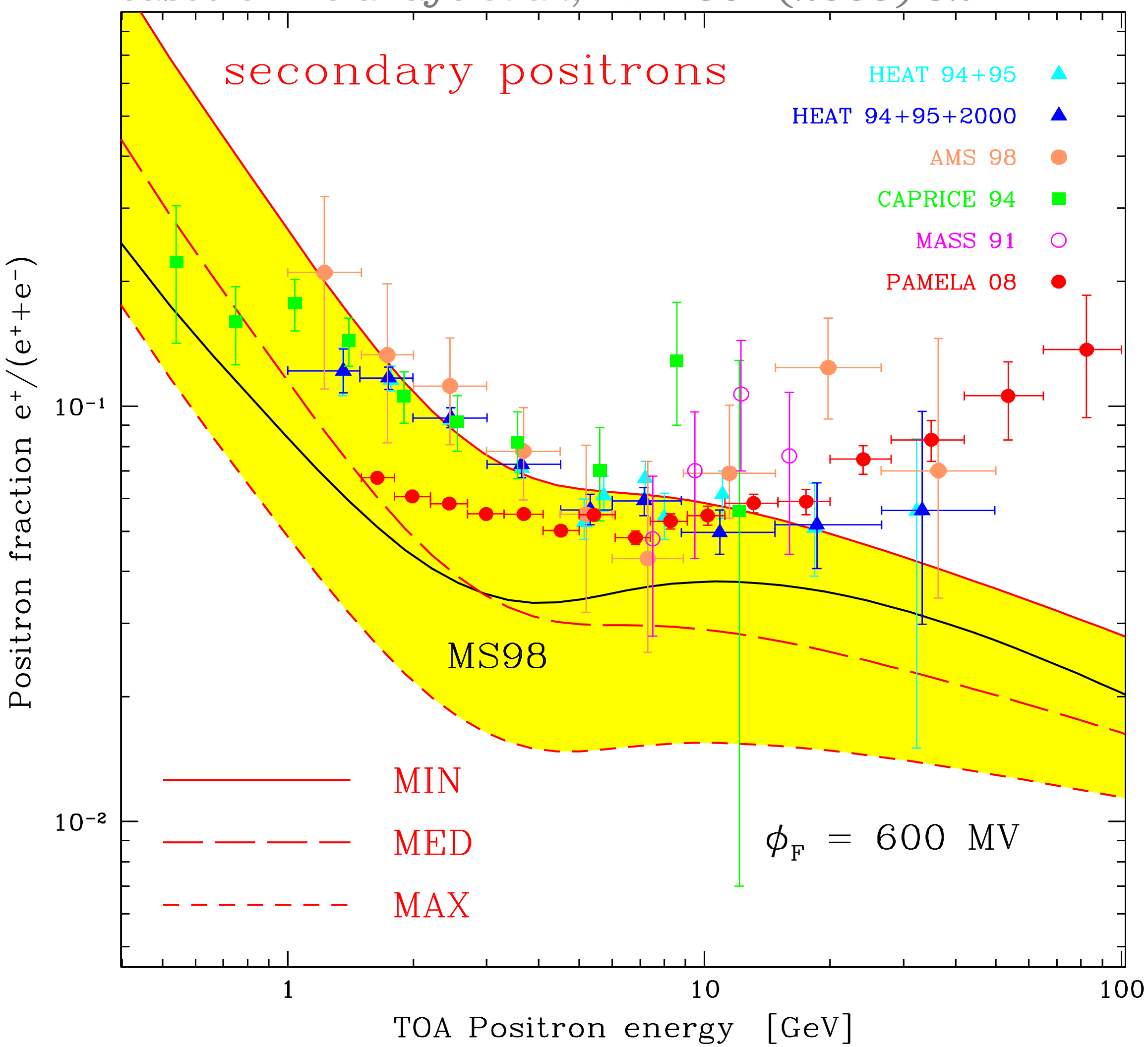
$$\lambda(E, E_0) = \sqrt{\int_0^{\tau_{b(t)}} D(E')\mathrm{d}\tau'} = \sqrt{\int_{E_0}^{E} \frac{D(E')\mathrm{d}E'}{b(E')}}$$

Delahaye *et al.*, A&A 501 (2009) 821



Background uncertainties

based on Delahaye *et al.*, A&A 501 (2009) 821

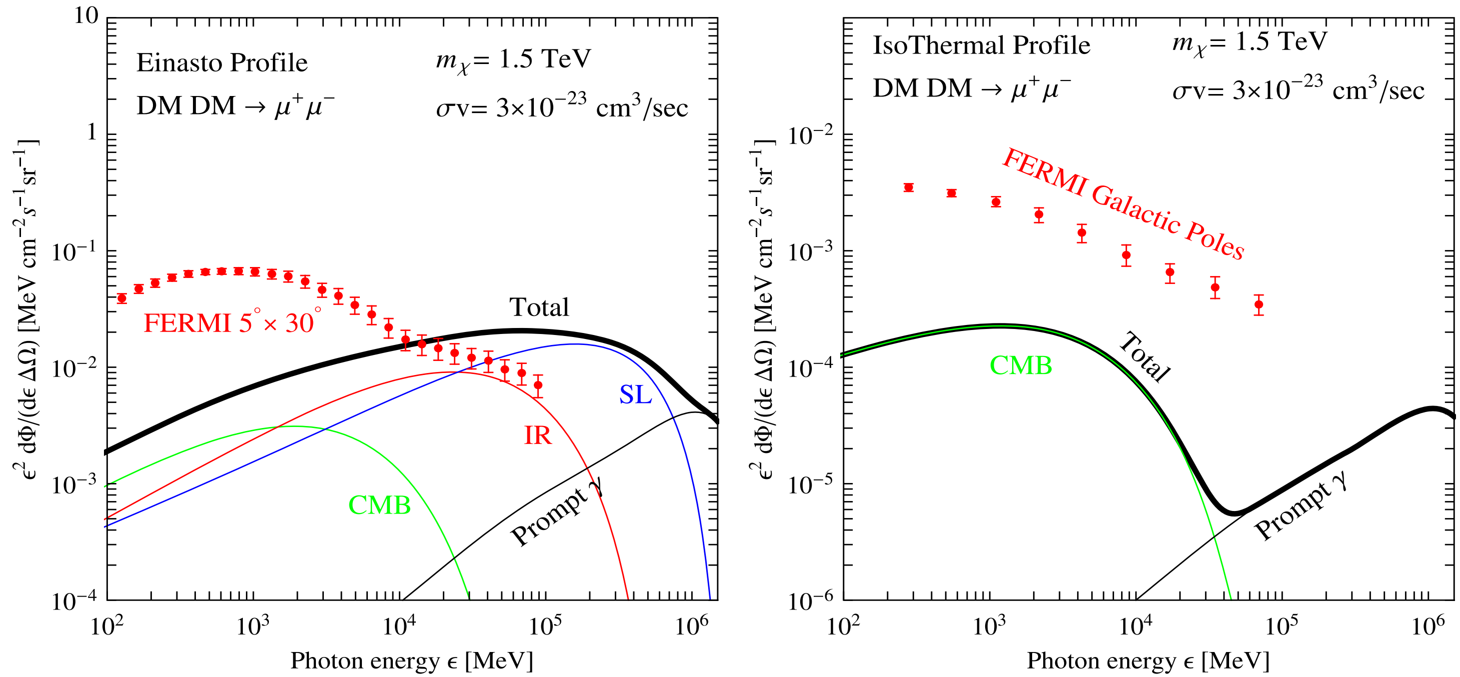


- enveloppe from ***O***(1000) models that reproduce B/C
- uncertainties due to
  - propagation model
  - primary fluxes
  - nuclear cross-sections
- however, still *decreasing* with energy where it should be *increasing*

Not subtracting backgrounds

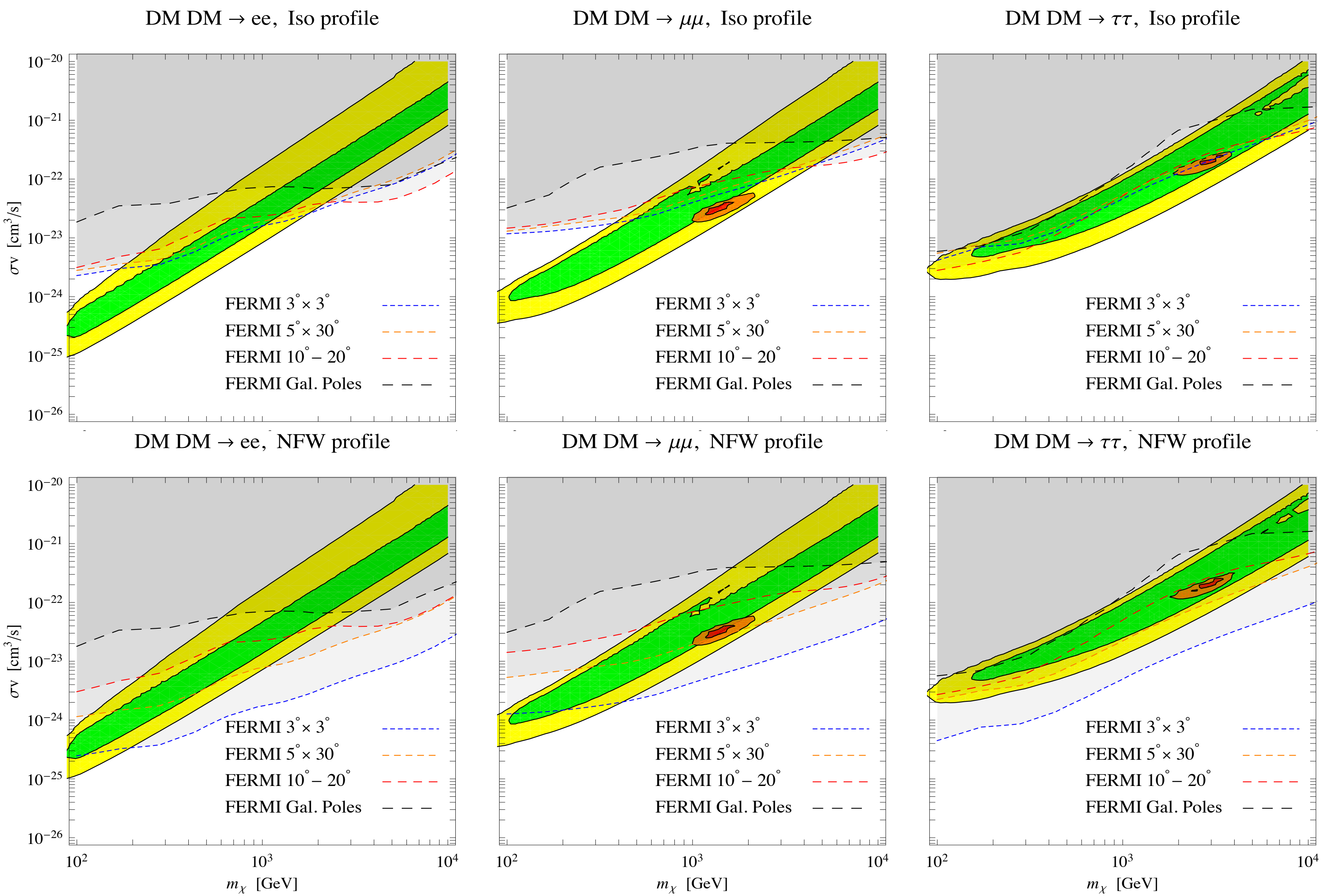
Cirelli, Panci & Serpico, *Nucl. Phys.* **B 840** (2010) 284

- derive bound by requiring that DM signal alone is not exceeding observed γ -rays
- no backgrounds considered — very conservative!



Not subtracting backgrounds

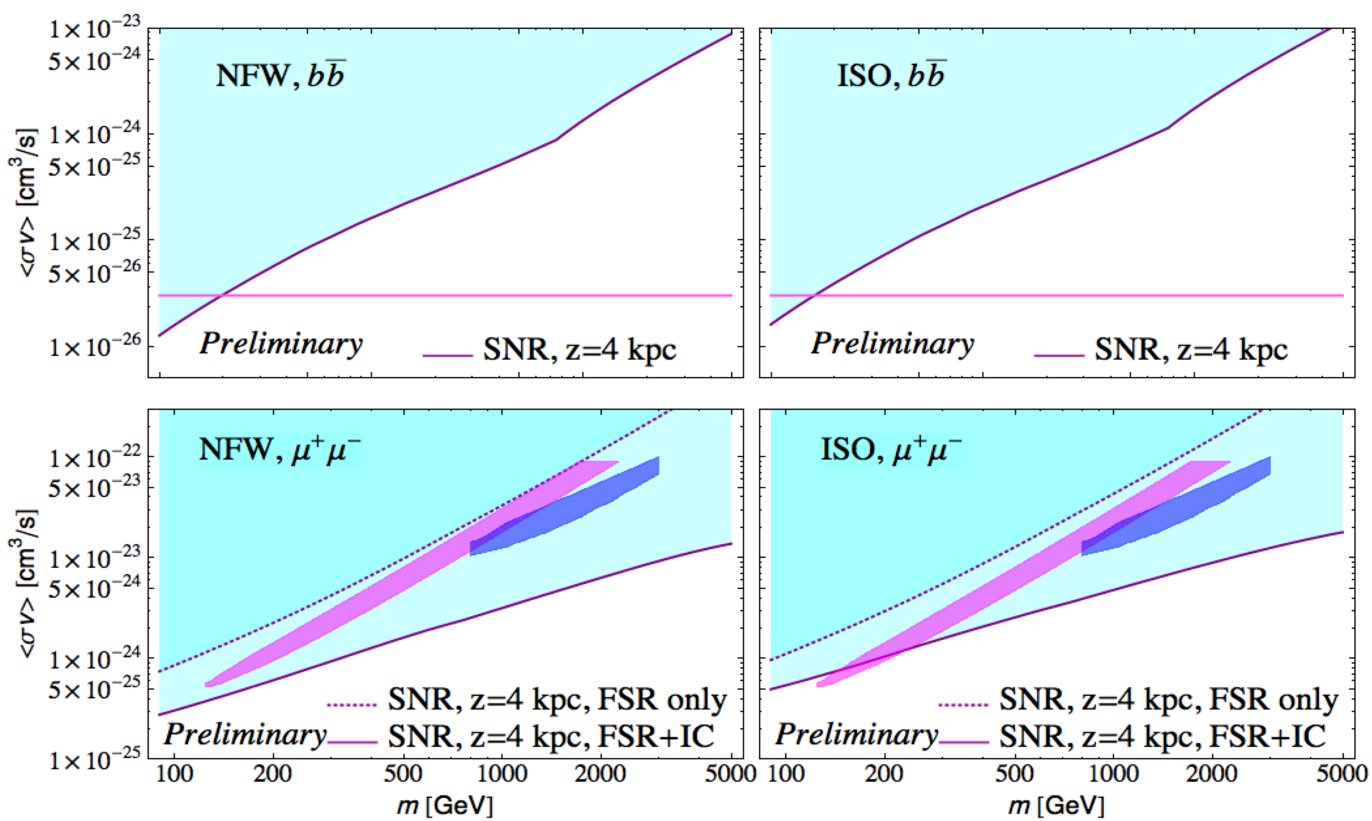
Cirelli, Panci & Serpico, *Nucl. Phys.* **B 840** (2010) 284



Subtracting backgrounds

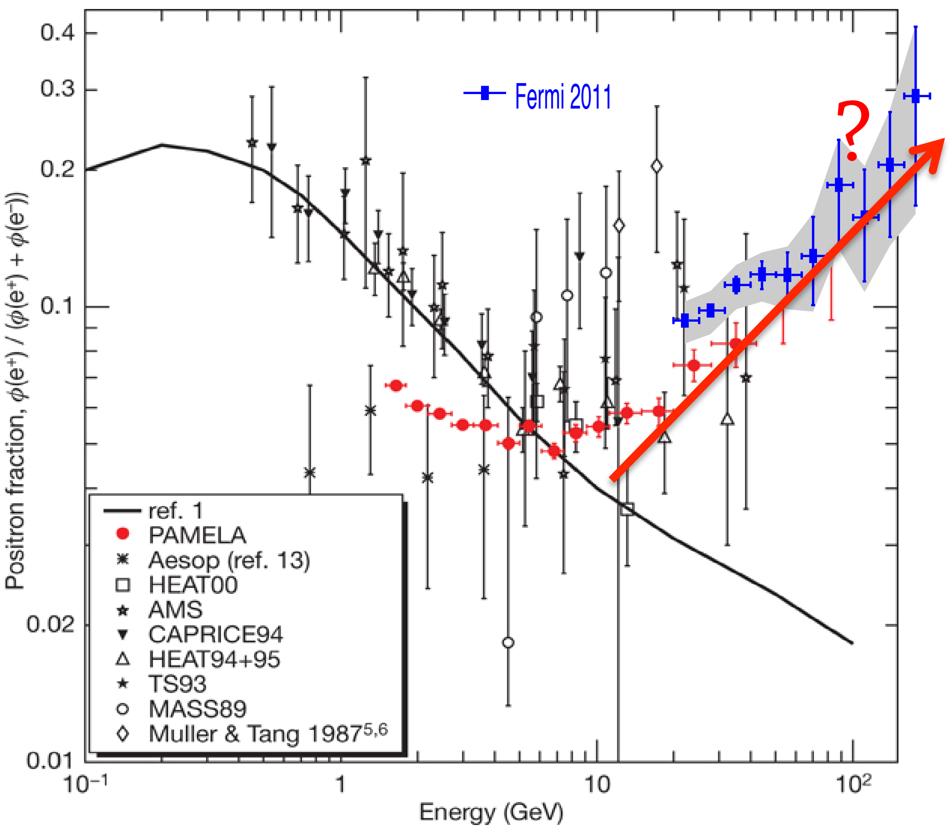
Zaharijas, *et al.*, IDM 2010

- model backgrounds with GALPROP and perform joined likelyhood analysis
- problem: fit always favours presence of DM component
- limit defined as 3σ above fitted DM component
- choose model parameters that give the weakest limit

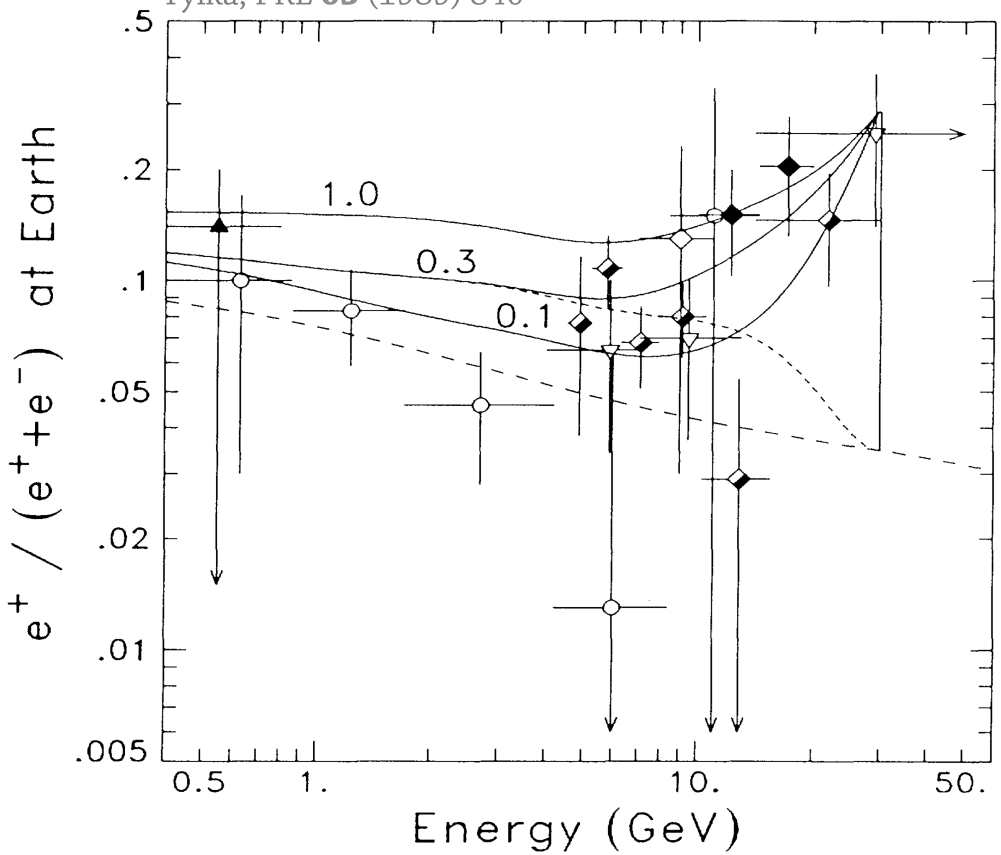


Confirmation by Fermi-LAT

Adriani *et al.* *Nature* **458**, 607-609 (2009)



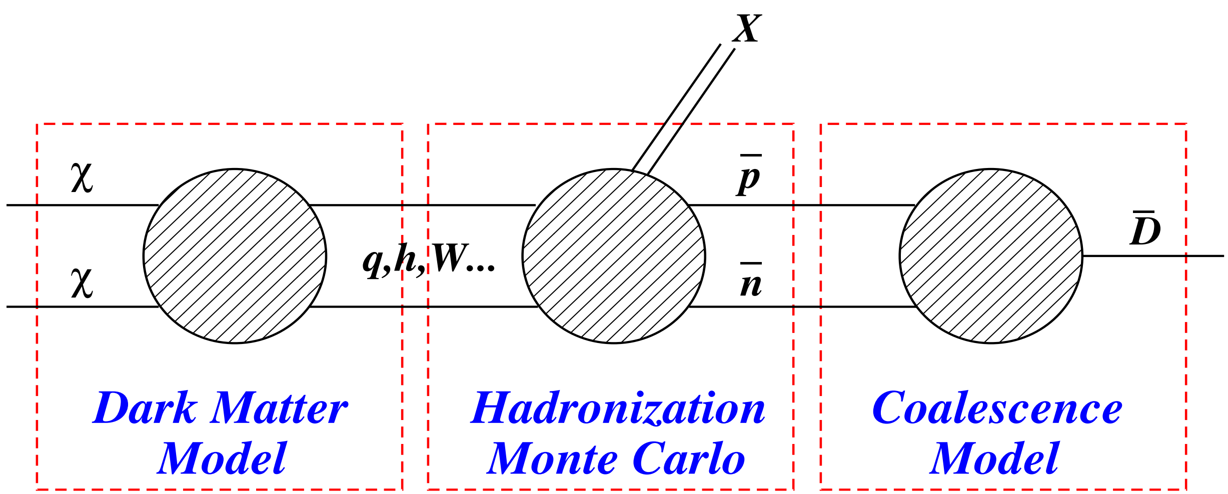
Tylka, PRL **63** (1989) 840



Anti-deuterons

Donato, Fornengo, Salati, PRD 62 (2000) 043003

- never observed in CRs
- background expected to be small
- coalescence: need $\bar{p}$ and $\bar{n}$ to be aligned in momentum space and their relative momentum close to the deuteron binding energy



Baer & Profumo JCAP 12 (2005) 008

Astro vs DM

Donato, Fornengo, Salati, PRD 62 (2000) 043003

spallation of p or He

- CoM boosted w/r to galactic frame
- expected to peak at few GeV/n

- tertiary $\bar{p}$ from inelastic reactions or production by spallation of $\bar{p}$ could affect the spectrum

DM annihilation

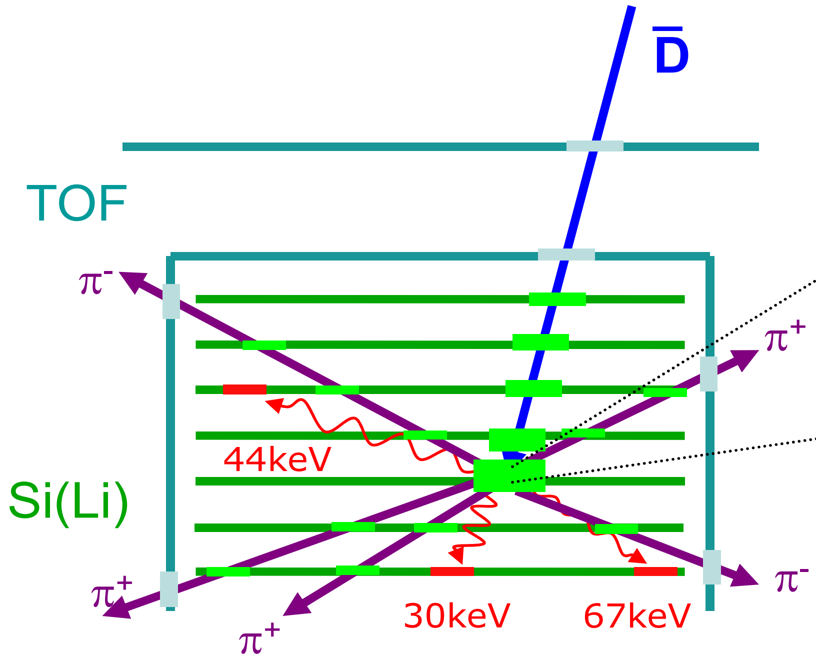
- DM at rest → $\bar{p}$ and $\bar{n}$ distributed isotropically
- peaks at lower energy

- correlation of $\bar{p}$ and $\bar{n}$ in jets from DM annihilation can increase signal

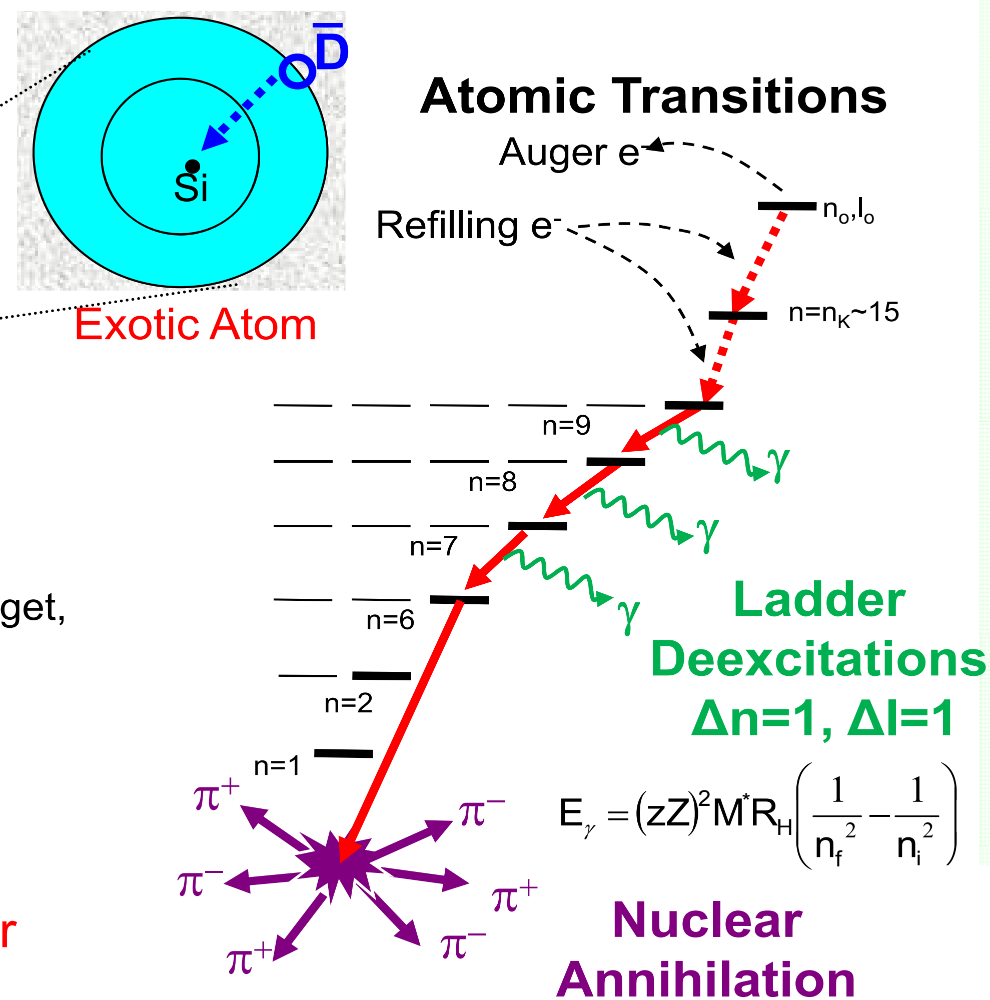
slide from R. Ong
TeVPA 2011

GAPS Detection Technique

- Conventional method of magnetic mass spectrometer is not optimal for GAPS. (Very large magnets with thin detector materials are needed for a deep survey).



Mori *et al.*, ApJ 566 (2002) 604

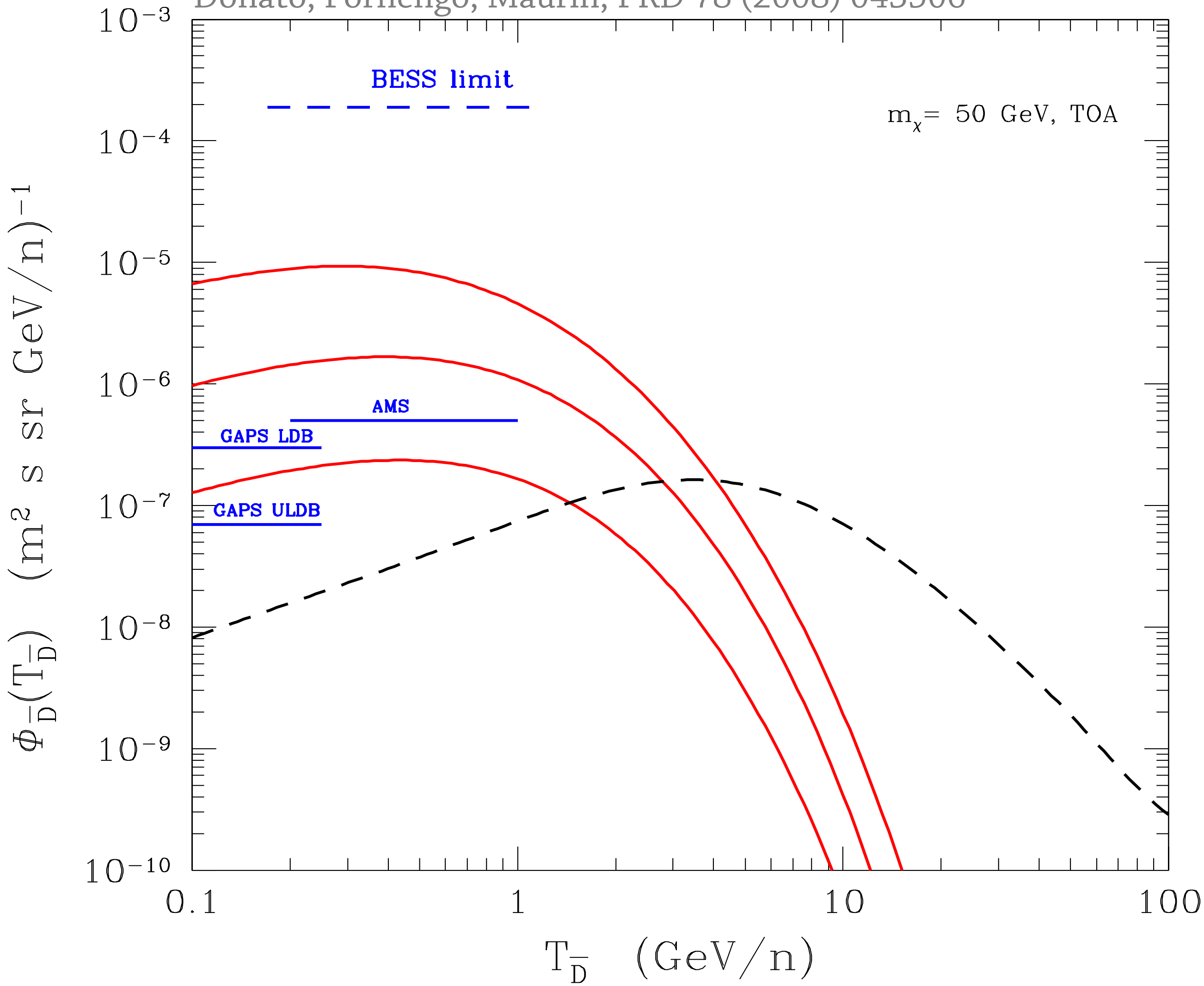


1. Once $\bar{D}$ is slowed down and stopped in the target,
2. an excited exotic atom is formed,
3. which deexcites with emitting X-rays,
4. and annihilates with producing a pion shower.

- Detection principle was verified and high X-ray yield was shown in accelerator tests (KEK antiproton beam, ’04 - ’05).

Astro vs DM

Donato, Fornengo, Maurin, PRD 78 (2008) 043506



Conclusion

- indirect searches (in particular in $\bar{p}$) can give additional constraints on some models
- indirect searches in antiparticles suffer from uncertainties in GCR diffusion models
- need data from upcoming experiments to improve our understanding of these models