Astroparticle Physics Review: Dark matter and related topics

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Outline

******* Disclaimer: anything related to 750 GeV things would* really *be fortuitous *******

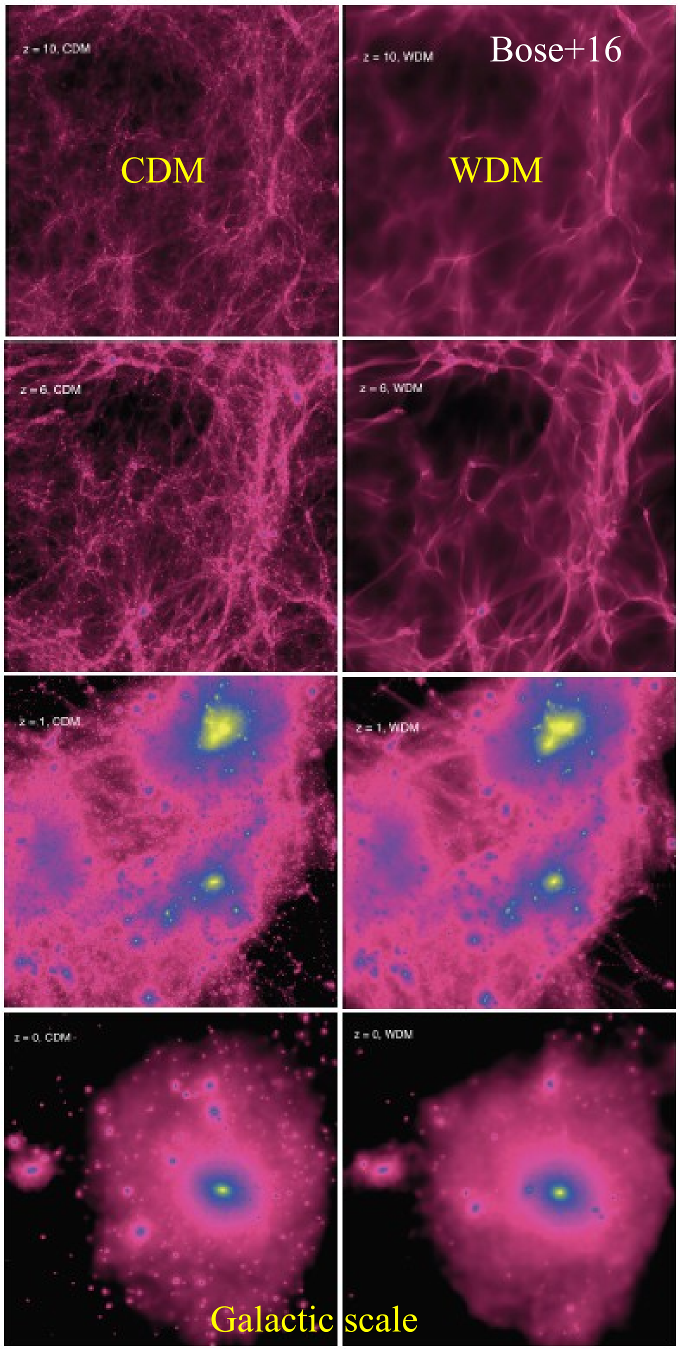
*** The (Cold) Dark Matter ((C)DM) paradigm: successes and issues**

*** Direct dark matter searches: a status**

*** Indirect dark matter searches (mostly within the Milky Way)**
  *** antimatter cosmic rays**
  *** gamma-rays**

*** Perspectives**

Dark matter: successes and issues



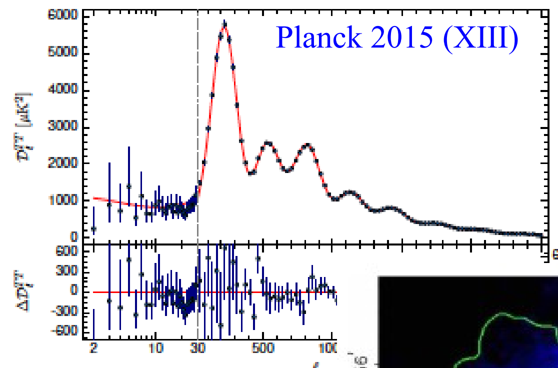
<u>So far, only gravitational evidence for DM</u>
(cosmological structures+CMB)

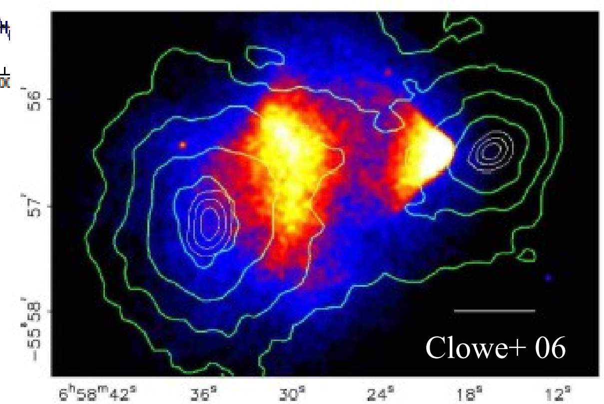
<u>CDM successes:</u>

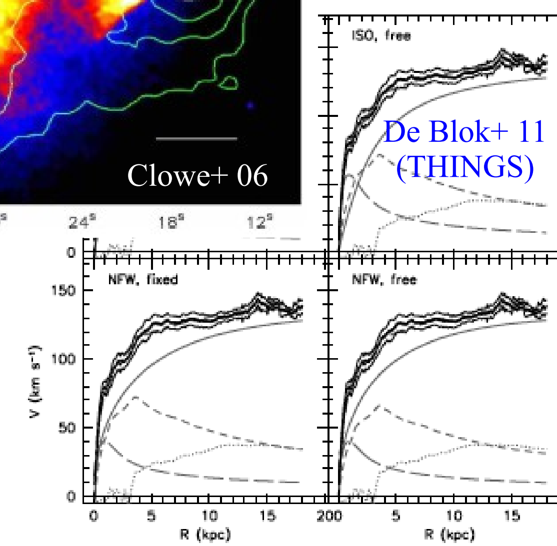
- CMB peaks
- Successful structure formation (from CMB perturbations)

=> CDM seeds galaxies, galaxies embedded in DM halos

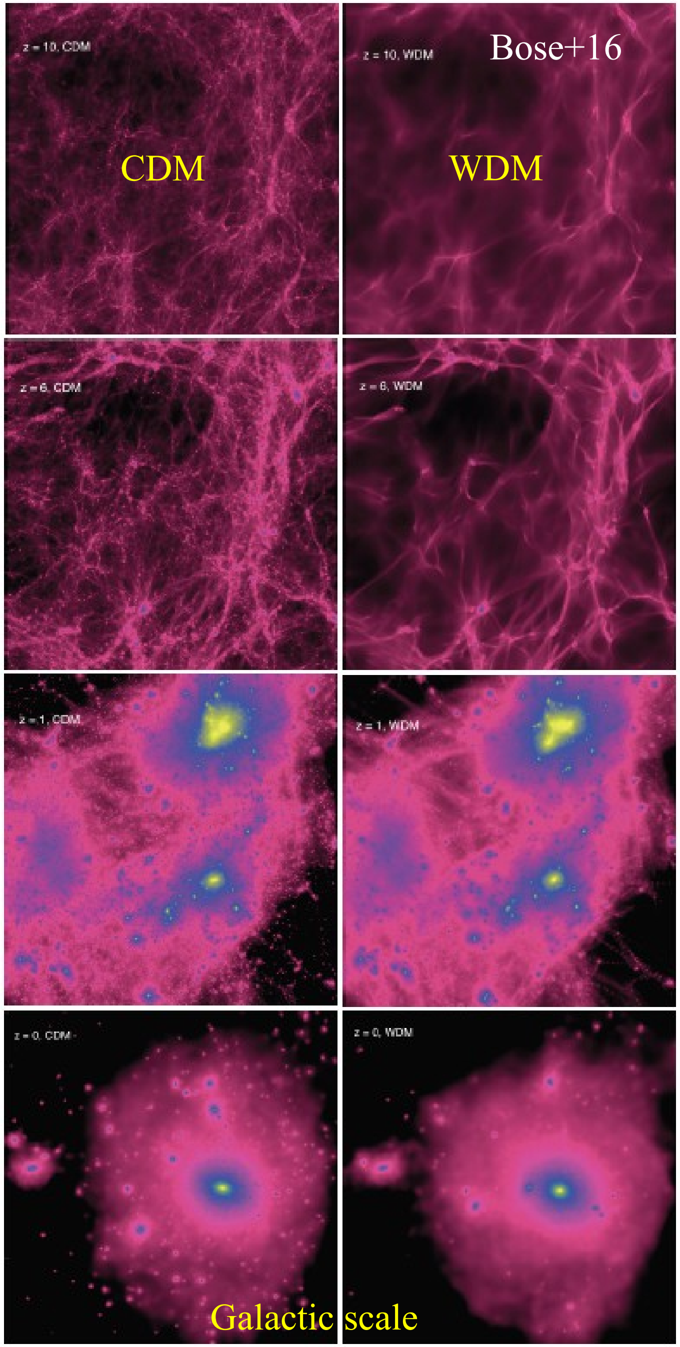
- Lensing in clusters + rotation curves of galaxies
- Also consistent with Tully-Fisher relation (baryonic physics)







Dark matter: successes and issues



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<u>How cold?</u>

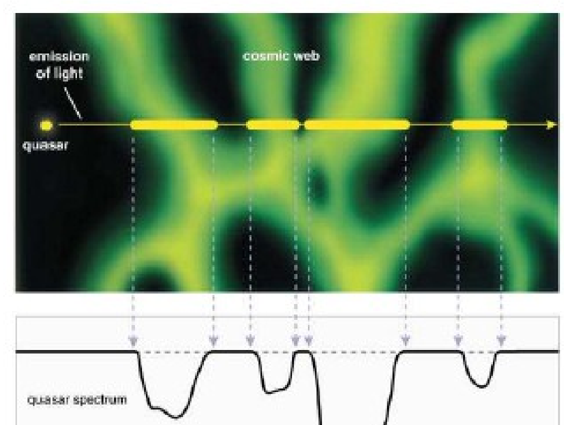
<u>Cold enough to form Dwarf Galaxies:</u>

* Tremaine & Gunn 79, Boyarsky+ 06: **m > 1 keV**

<u>Cold enough to be consistent with Lyman-alpha forest</u>

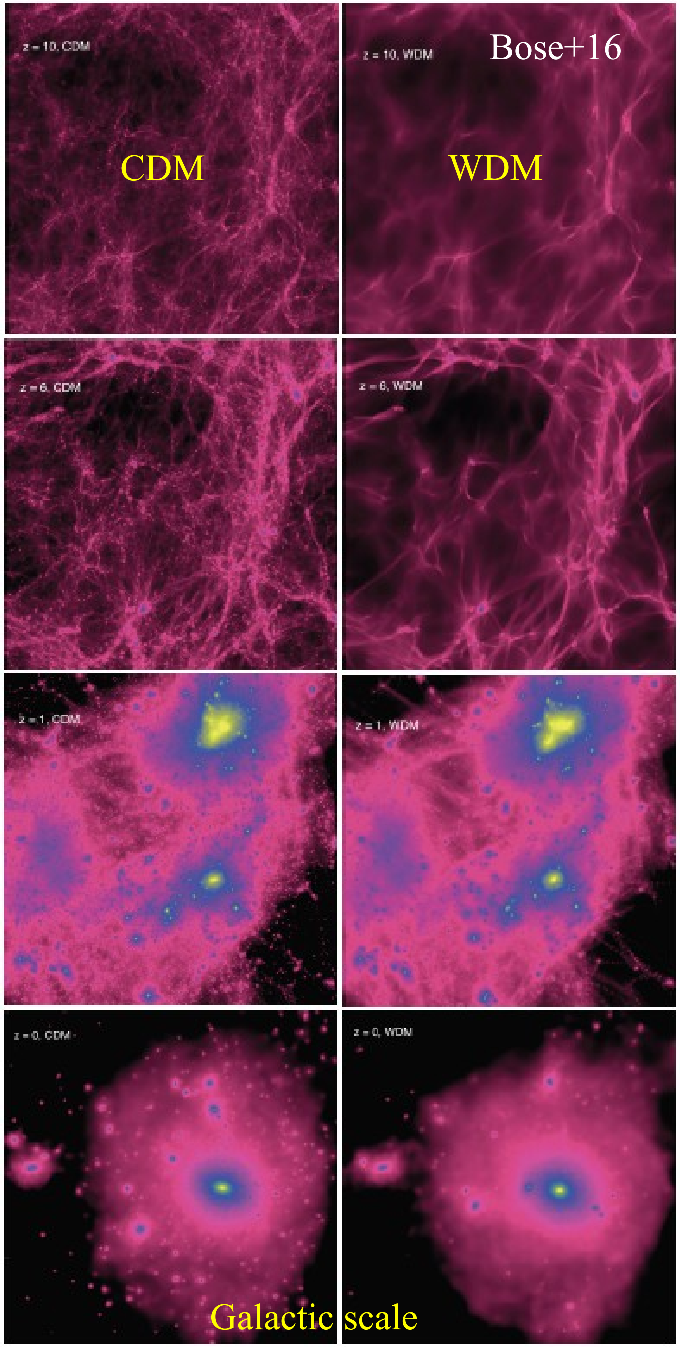
* Boyarsky+ 08 => **m > 5 keV** (thermal)

=> WDM and/or CDM allowed, but then WDM is almost CDM.



Courtesy O. Ruchayskiy

Dark matter: successes and issues



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NOT DEVOID OF ISSUES:

*** NOT DISCOVERED YET**

*** SMALL SCALE ISSUES:**

1) The core-cusp pb

Some galaxies better fitted with DM cores than with predicted cusps (e.g. NFW profile).

2) The too-big-to-fail pb (=missing satellite pb)

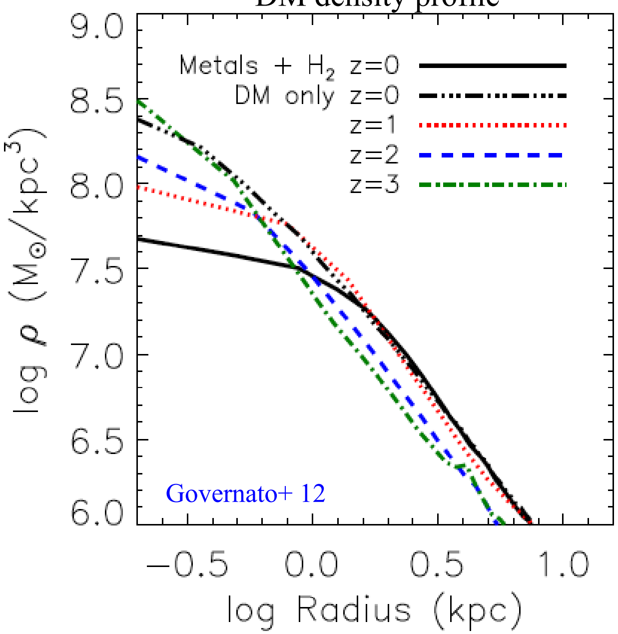
CDM predicts more satellite galaxies than observed.

CDM: solutions to small scale issues?

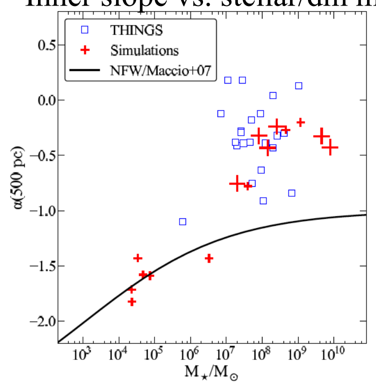
e.g. Governato+ 12:
CDM + more realistic physics for baryons => cusps are flattened
(From star formation: **feedback** from winds + SN **feedback**)

e.g. Maccio+ 12: WDM Catch 22 problem
To prevent cusp: m < 0.1 keV
=> cannot form dwarf galaxies + excluded
***** Forming DsphG => m > 1 keV**

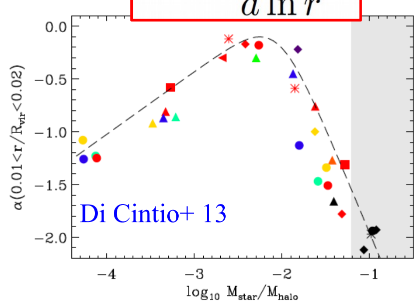
DM density profile



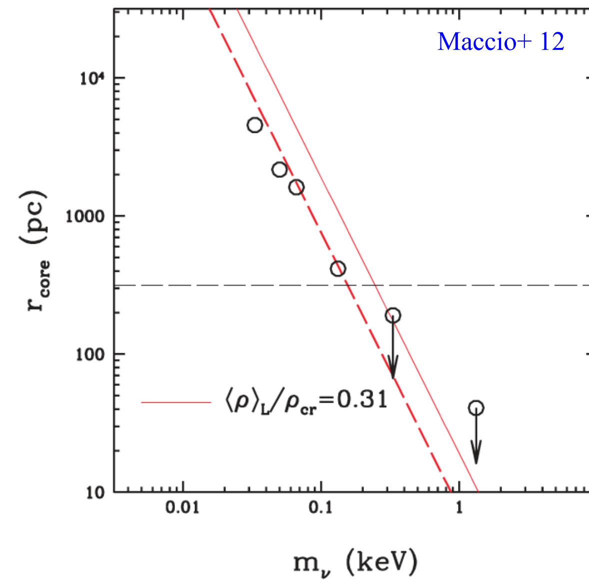
Inner slope vs. stellar/dm mass



$$\alpha \equiv \frac{d\ln\rho(r)}{d\ln r}$$



Core DM radius vs. thermal mass



Solutions to core-cusp problem:
* **NB: WDM alone does not solve the issue**

* CDM/WDM: **baryonic effects**
→ must be there, but to what extent?
* Other classes of DM: **self-interacting DM (SIDM)**

Solutions to missing satellite problem:
(↔ **too-big-to-fail** pb)

* CDM: **baryonic effects**
* **WDM**
* **SIDM**

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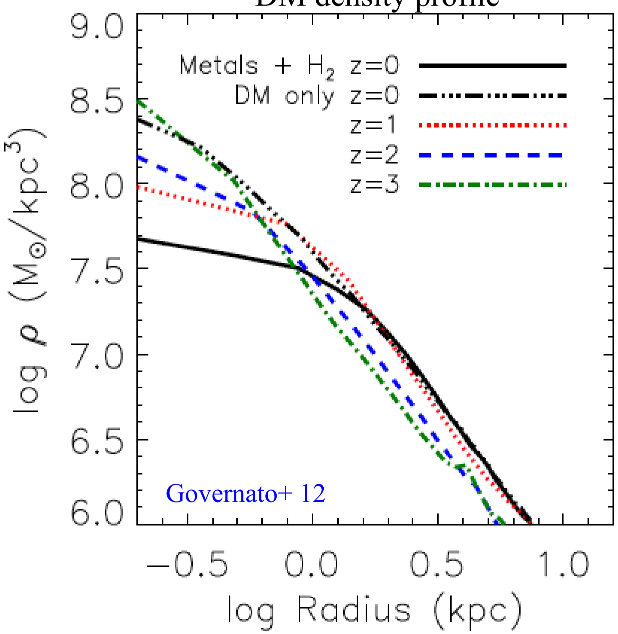

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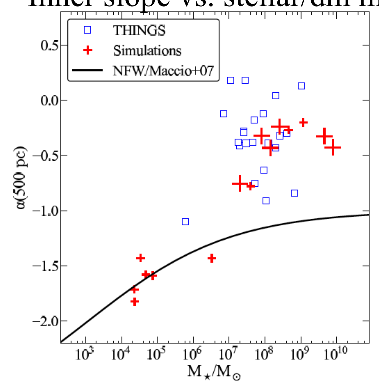

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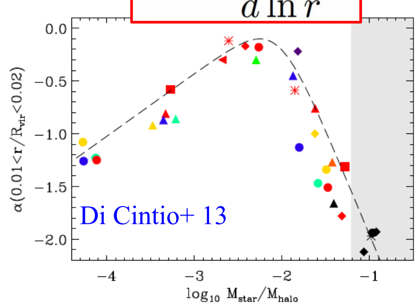

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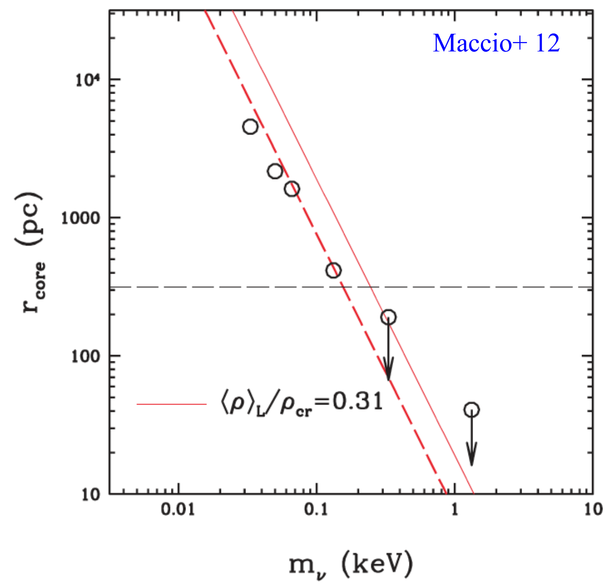

Still debated!!!

NB: Baryon physics must be present anyway

<u>Solutions to core-cusp problem:</u>
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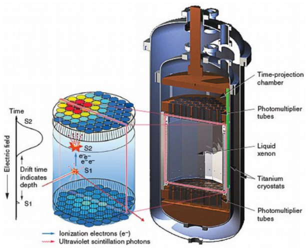
(↔ **too-big-to-fail** pb)

* CDM: **baryonic effects**
* **WDM**
* **SIDM**

Astro/particle complementarity

Direct detection rate – WIMP-matter scattering

$$\frac{d\Gamma_{\chi-\mathrm{N}}}{dE_r}(E_r,t) = \frac{\sigma_{\chi-\mathrm{N}}\, F^2(E_r)}{2\,\mu_r^2}\,\frac{\rho_\odot}{m_\chi}\int_{v>v_{\min}} d^3\vec{v}\,\frac{f(\vec{v},t)}{v}$$



Scattering

(→ kinetic decoupling in early universe)

WIMP → WIMP

SM → SM

$$\Gamma_{\mathrm{scat}} = \langle \sigma_{\mathrm{scat}}\, v\rangle\, n_{\mathrm{plasma}}$$

Annihilation vs. scattering

=> constraints from cosmological abundance

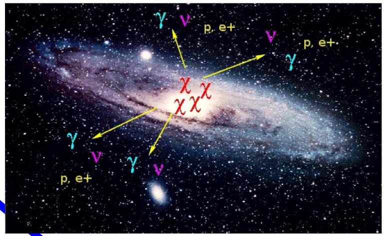
+ minimal scale for DM structures (subhalos)

Dark matter profile + phase space

(+ cosmic-ray transport)

=> constrained by Milky Way-mass model

(full gravitational potential DM + baryons)



Annihilation

(→ chemical decoupling in early universe)

WIMP → SM

$\overline{\mathrm{WIMP}}$ → $\overline{\mathrm{SM}}$

$$\Gamma_{\mathrm{ann}} = \langle \sigma_{\mathrm{ann}}\, v\rangle\, n_\chi$$

Indirect detection rate (e.g. gamma rays)

– WIMP annihilation

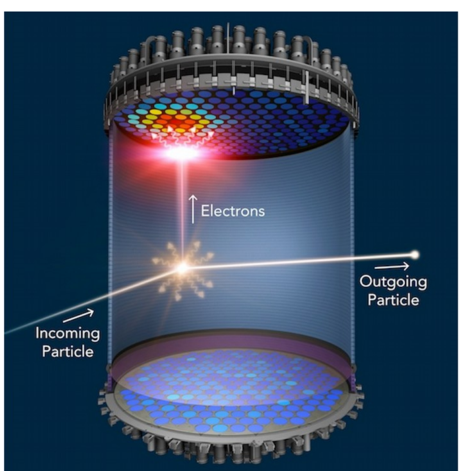
$$\frac{d\phi_\gamma^{\mathrm{ann.}}}{dE} = \frac{\delta\,\langle\sigma v\rangle}{4\,\pi}\,\frac{dN_\gamma}{dE}\int_{\mathrm{res.}} d\Omega \int_{\mathrm{l.o.s}} dl\,\left[\frac{\rho(r)}{m_\chi}\right]^2$$

Direct DM searches: recent results

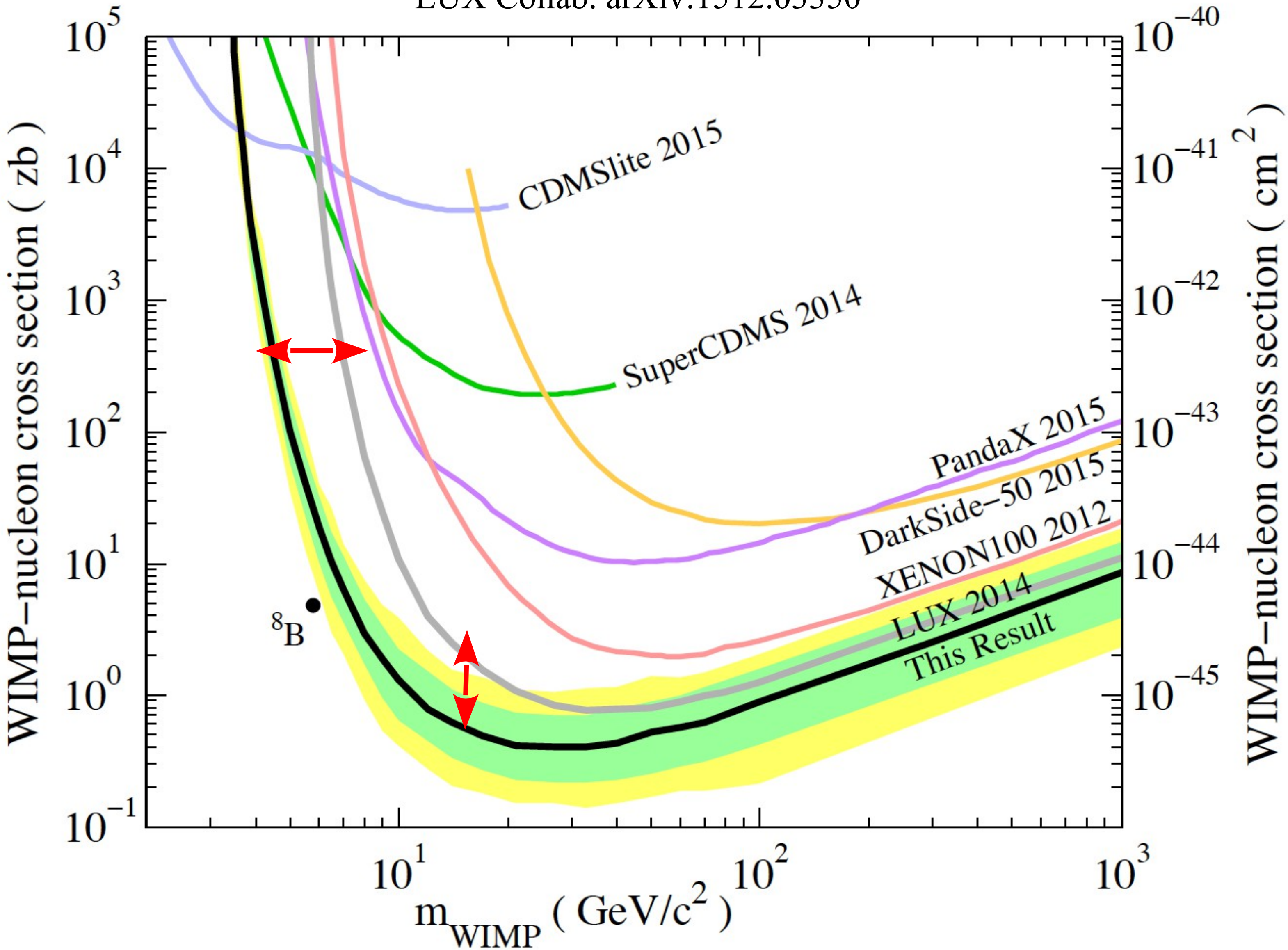
Latest LUX results:
(same data as 2014, improved analysis)

* Dual-phase xenon (S1,S2)
* 1.4x10^4 kg.day
* improved calibration
* improved efficiency
* increased fiducial volume
* threshold 3 → 1.1 keV!

=> the sub-zepto-barn era!



LUX Collab. arXiv:1512.03350



Direct DM searches: recent results

Latest CRESST results:
(same data as 2012, improved analysis)

* Ca(20)W(74)O(8)
* 52 kg.day
* threshold 0.6 → 0.3 keV!

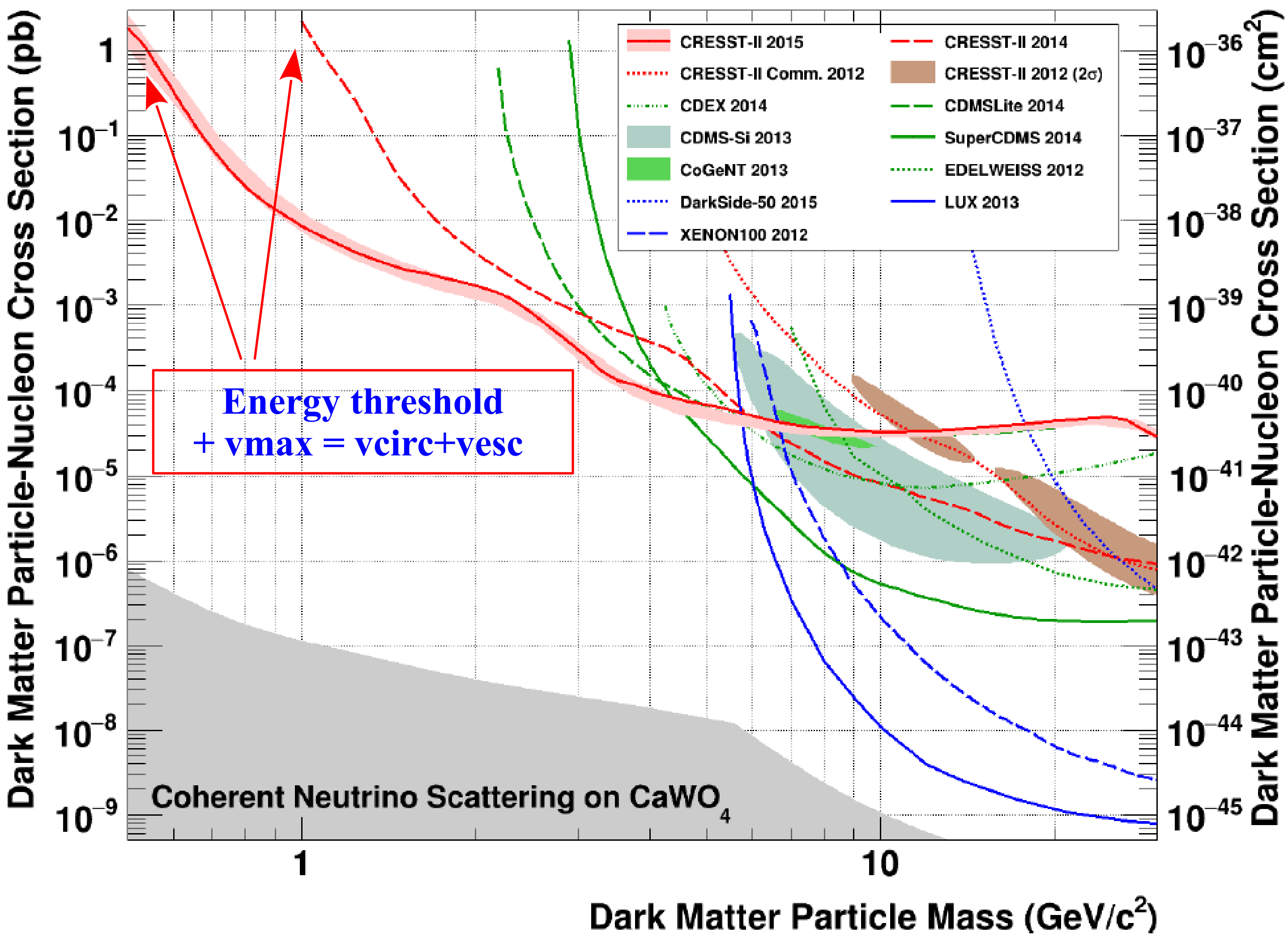
=> the sub-GeV era!

Limits assume "standard halo model" (**SHM**):

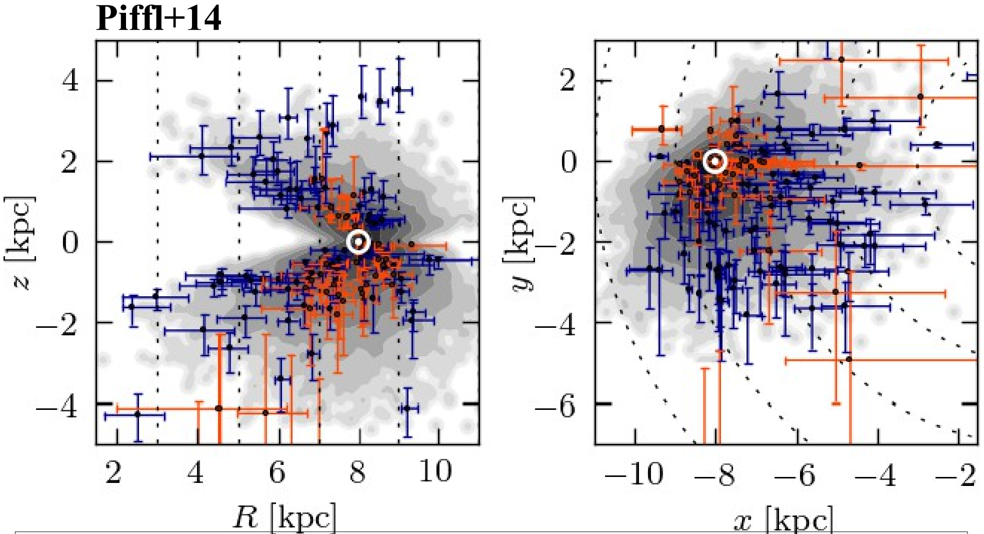
* local DM of 0.3 GeV/cm3
* v_{sun} = 220 km/s
* v_{esc} = 544 km/s
* truncated Maxwellian f(v)

→ indicative limits
(to be taken with care)

CRESST-II Collab. arXiv:1509.01515

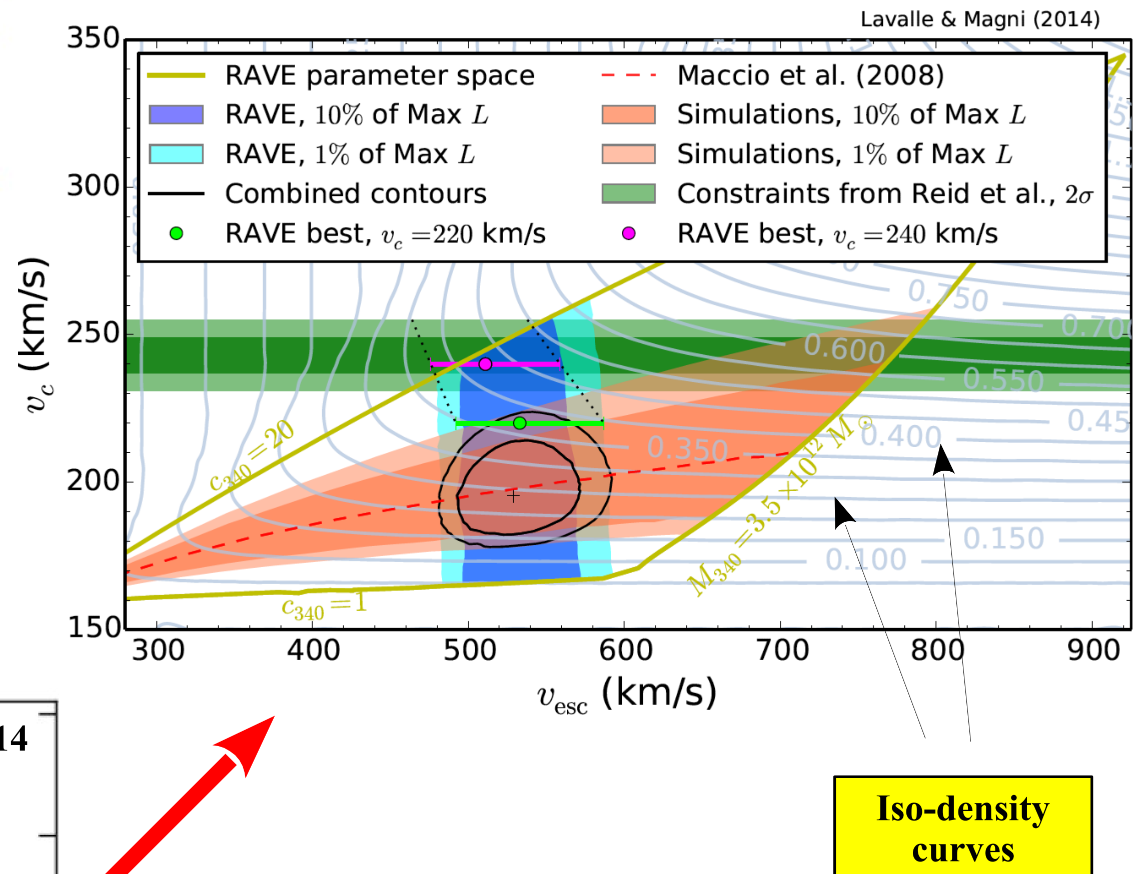


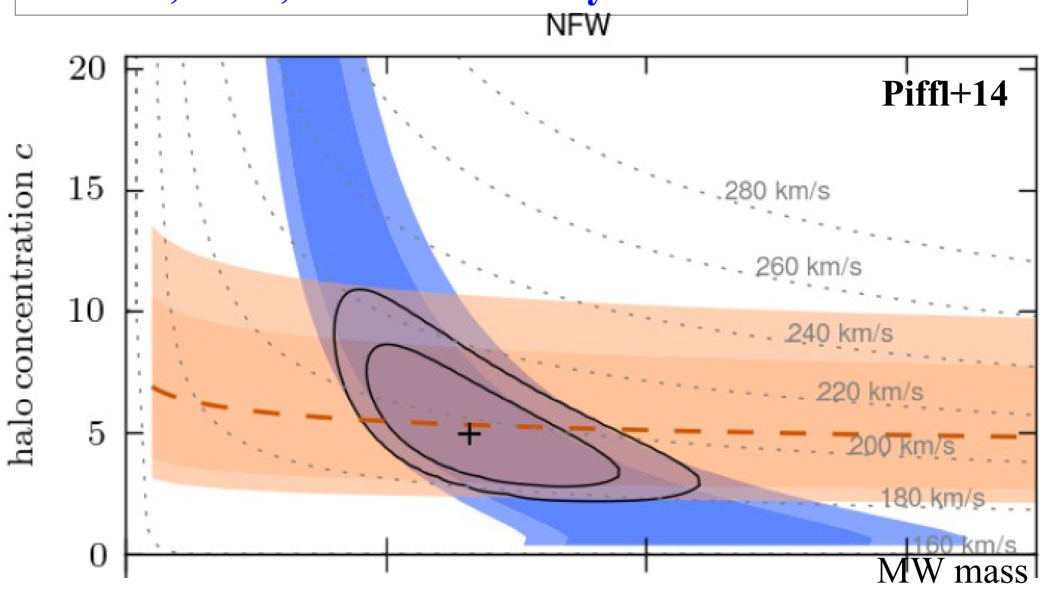
Beware astrophysical assumptions!



Quoted **escape speeds are from RAVE** survey (Smith+07, Piffl+14)
* v-tail of non-corotating stars (not in the disk)
* Galactic mass model assumed to “relocate” at solar position

=> vesc, vcirc, local DM density correlated!!!





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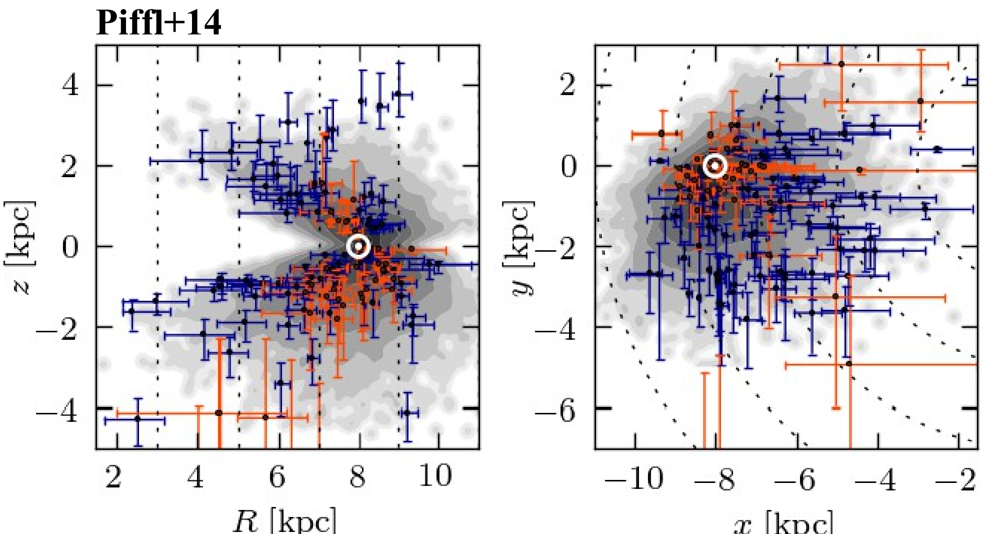

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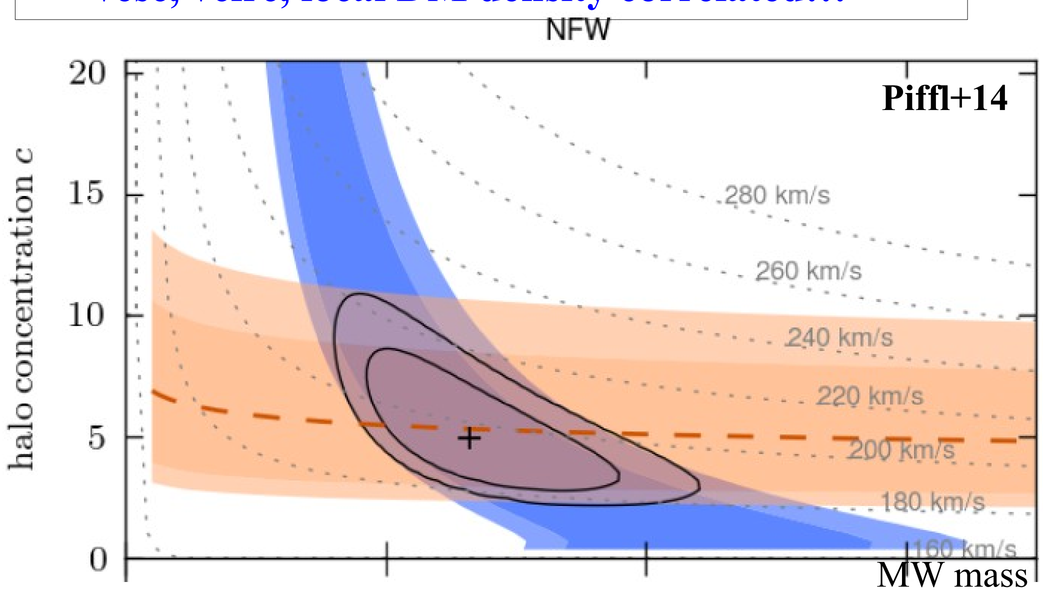
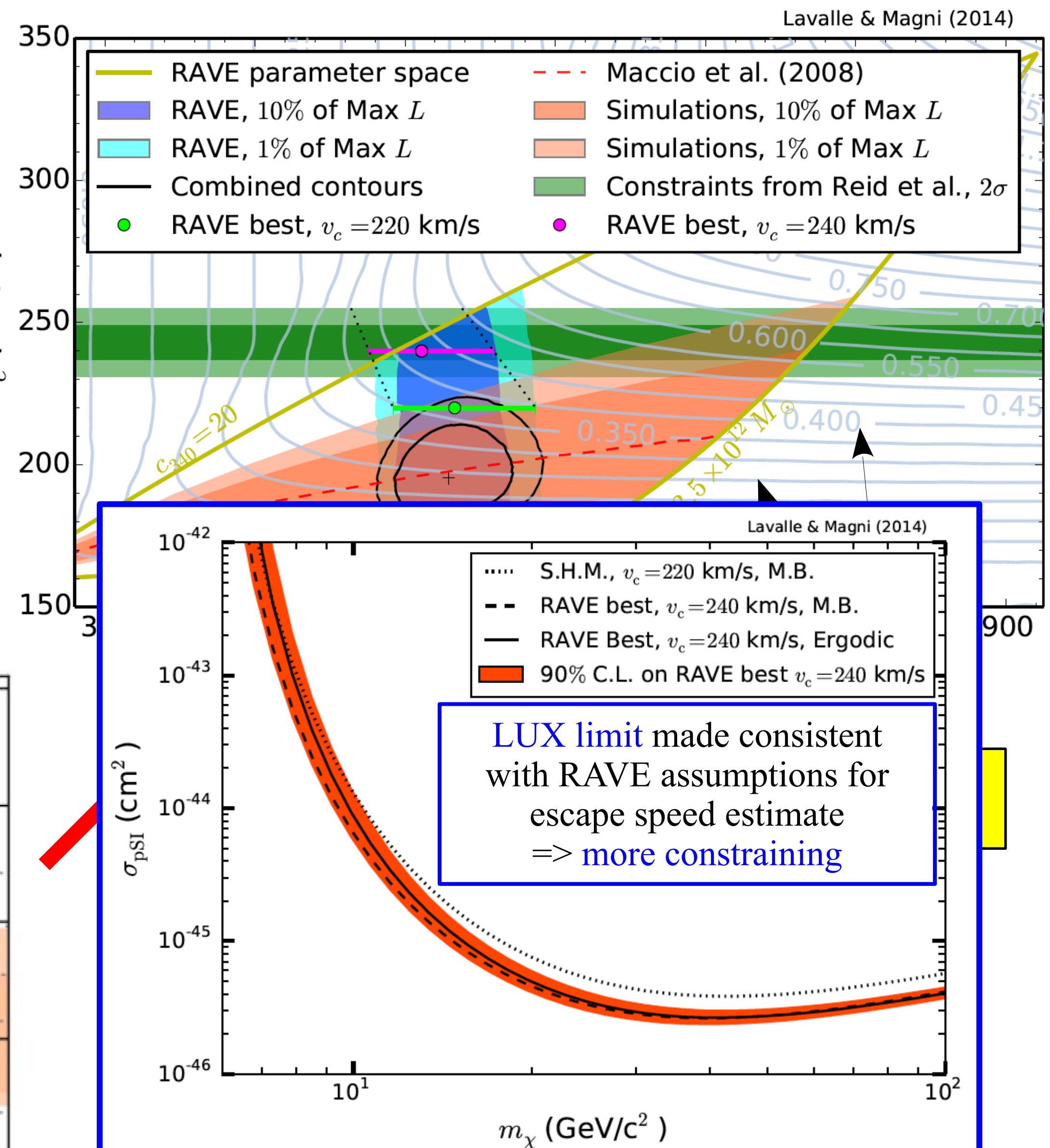




Integrating astrophysics out?

Fox+11, Frandsen+12, Gondolo+12, Herrero-Garcia+12, etc.

* Event rate (for all DD experiments) proportional to

$$\boxed{\tilde{\eta}(v_{\min}) = \sigma_p(\rho/m)\eta(v_{\min})}$$

which contains all the astrophysics

* For a given DM particle mass, one can trade the recoil energy for the min speed

$$v_{\min} = \sqrt{\frac{m_{A,Z}E}{2\mu_{A,Z}^2}}$$

$$dE = (4\mu_{A,Z}^2/m_{A,Z})v_{\min}\,dv_{\min}$$

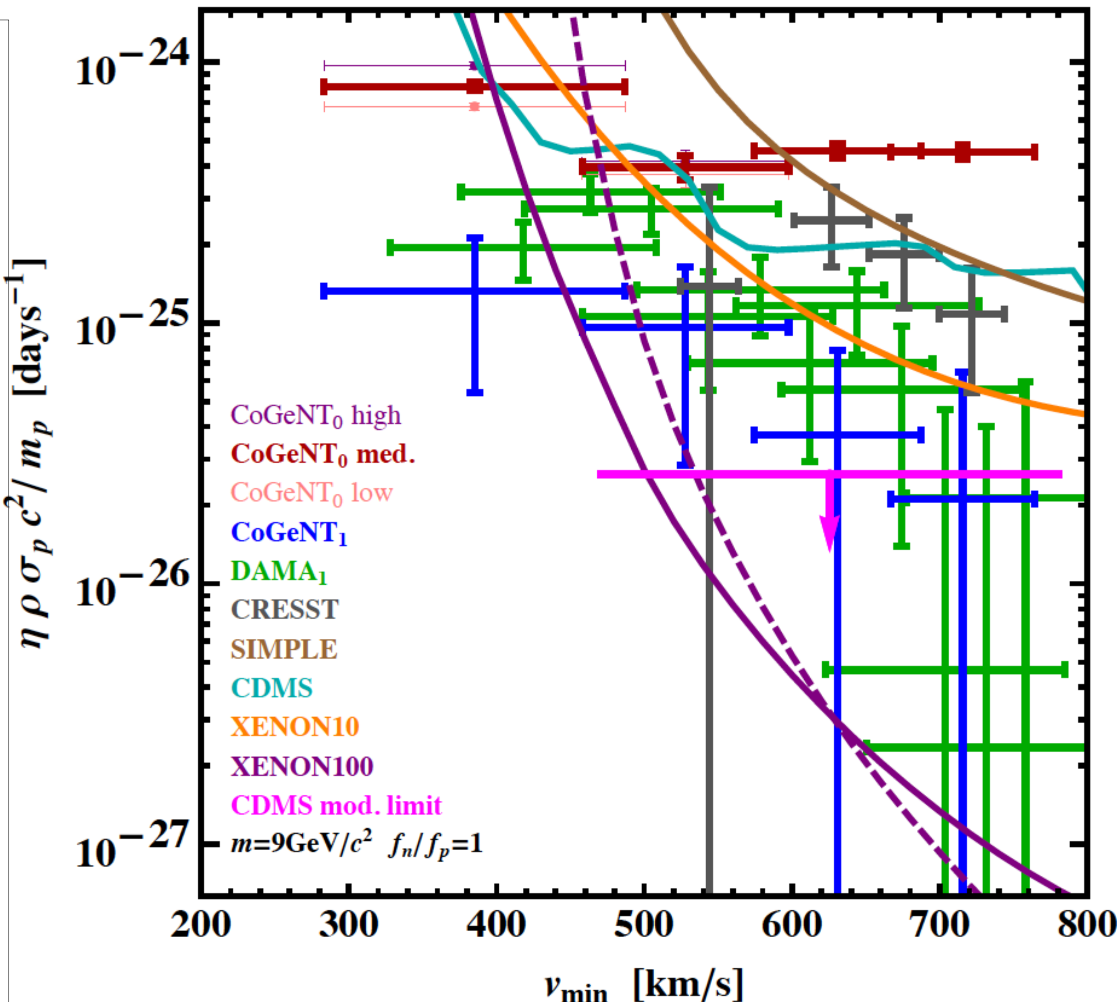
* The event rate in a bin can be recast as

$$R_{[E_1',E_2']} = \int_0^\infty dv_{\min}\,\mathcal{R}^{SI}_{[E_1',E_2']}(v_{\min})\,\tilde{\eta}(v_{\min})$$

=> For a given target nucleus, one can match an energy bin to a bin in min speed:

$$\boxed{[E_1', E_2']} \longrightarrow \boxed{[v_{\min,1}, v_{\min,2}]}$$

Gondolo+12



Check positive signals against limits for a given WIMP mass.

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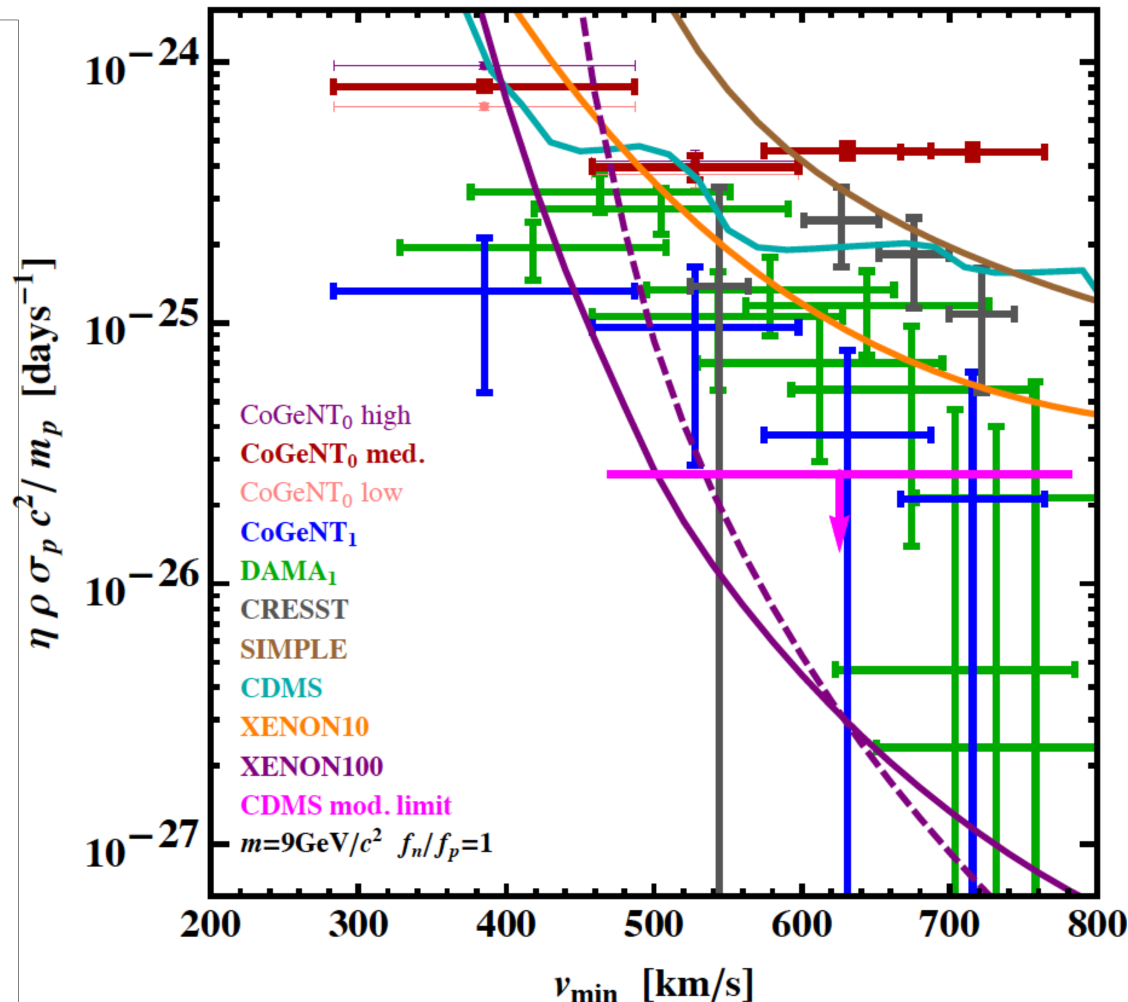


Check positive signals against limits for a given WIMP mass.
BUT ONLY FOR A GIVEN WIMP MASS

Integrating astrophysics out?

Ferrer, Ibarra, Wild – arXiv:150603386
*** Based on complementarity between DD and neutrino telescopes (WIMP capture in the Sun)
=> **Annihilating WIMPs only!!!**

* Expand f(v) over infinite set of DM streams

$$\boxed{f(\vec{v}) = \int_{|\vec{v}_0|\leq v_{\max}} \mathrm{d}^3 v_0 \, \delta^{(3)}(\vec{v}-\vec{v}_0) f(\vec{v}_0)}$$

$$R = \int_{|\vec{v}_0|\leq v_{\max}} \mathrm{d}^3 v_0 \, f(\vec{v}_0) \, R_{\vec{v}_0}$$

$$C = \int_{|\vec{v}_0|\leq v_{\max}} \mathrm{d}^3 v_0 \, f(\vec{v}_0) \, C_{\vec{v}_0}$$

* Each stream rate is bounded by experimental limit => max cross section (as a function of m) for each stream:

$$\sigma^{\mathrm{DD}}_{\max}(v_0)$$

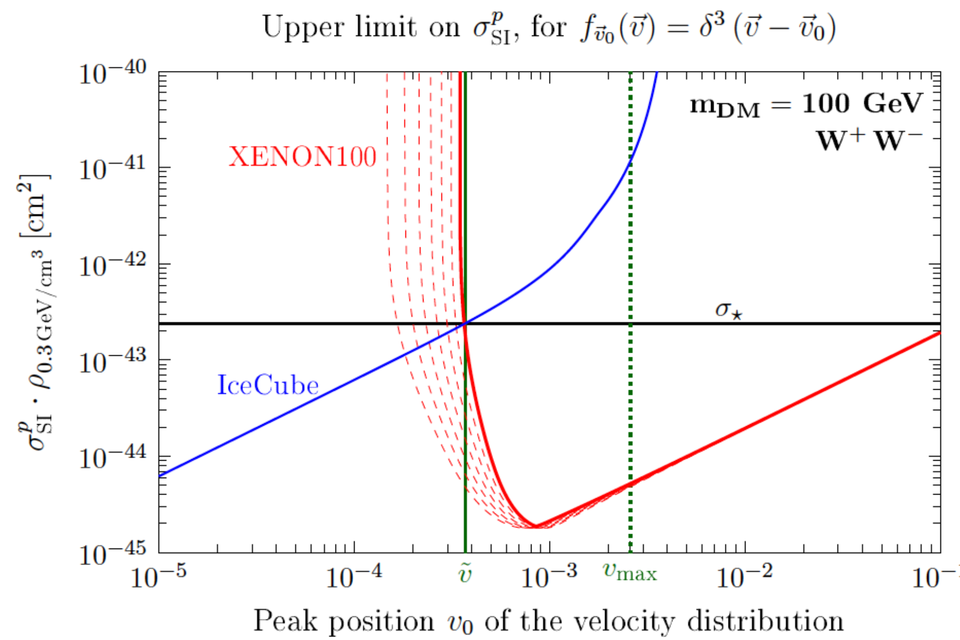
$$R_{\vec{v}_0}(\sigma) \geq R_{\max} \text{ for } \sigma \geq \sigma^{\mathrm{DD}}_{\max}(v_0)$$

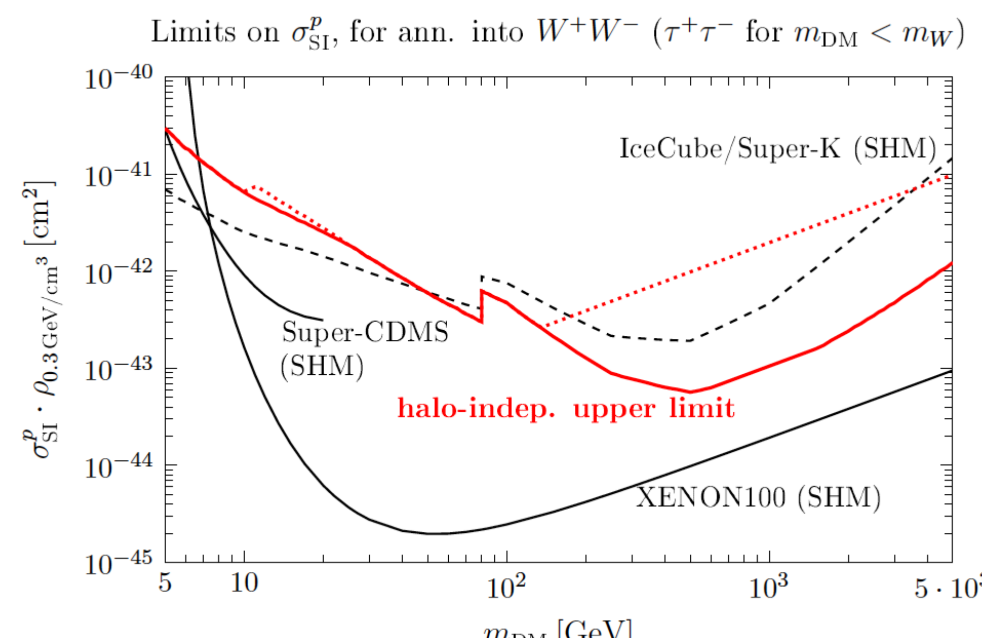
* After some algebra

$$\sigma \leq \left[\int_{|\vec{v}_0|\leq v_{\max}} \mathrm{d}^3 v_0 \frac{f(\vec{v}_0)}{\sigma^{\mathrm{DD}}_{\max}(v_0)}\right]^{-1}$$

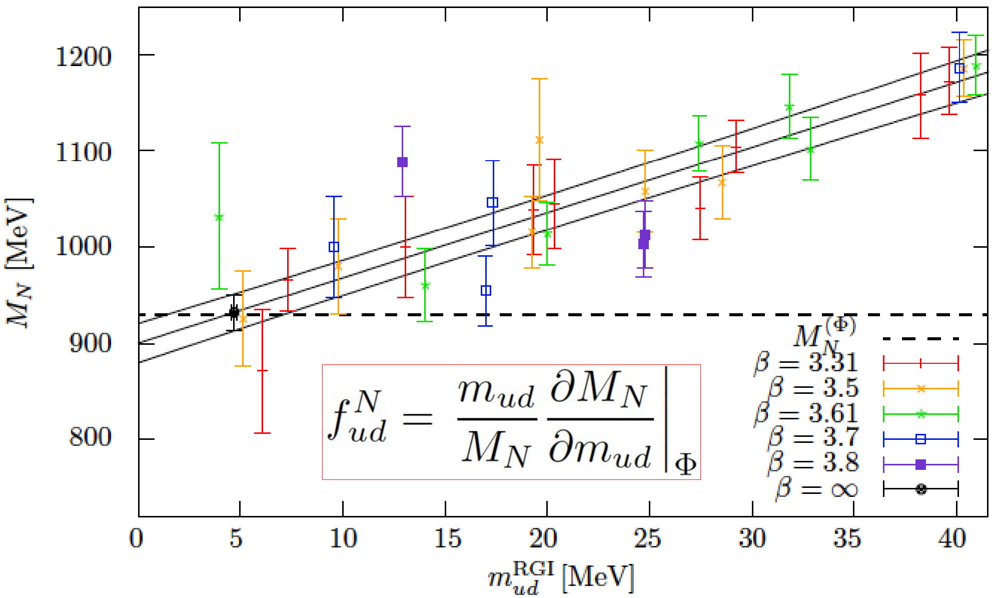
$$\boxed{\sigma \leq 2\sigma_*}$$

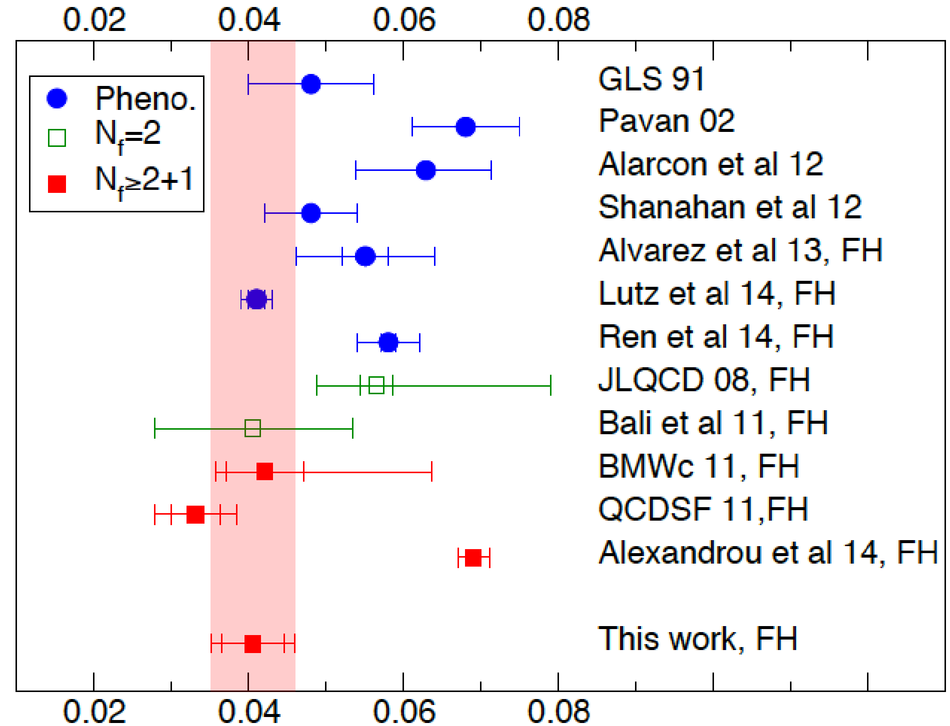
** Still depends on local DM density



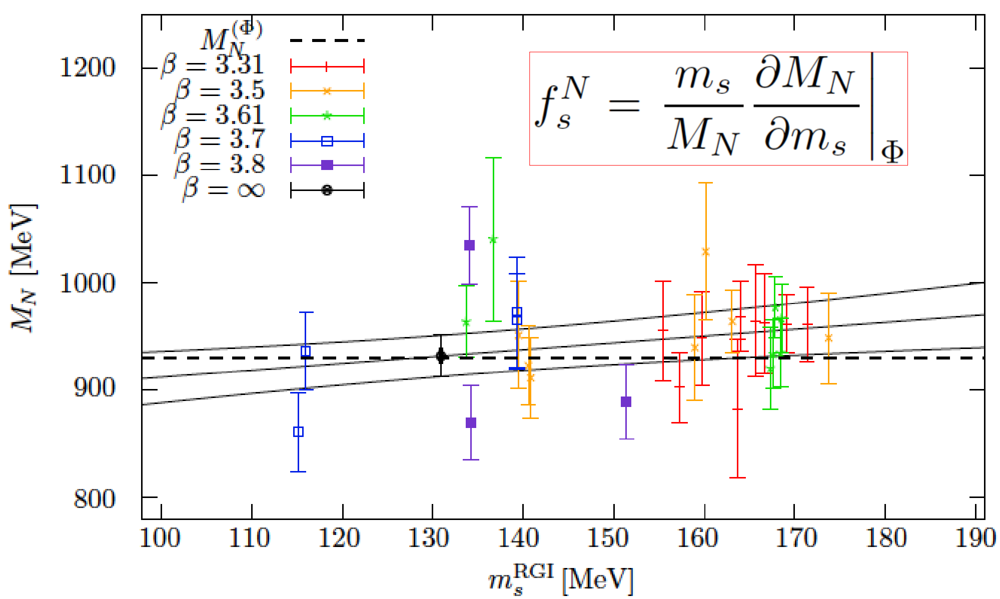


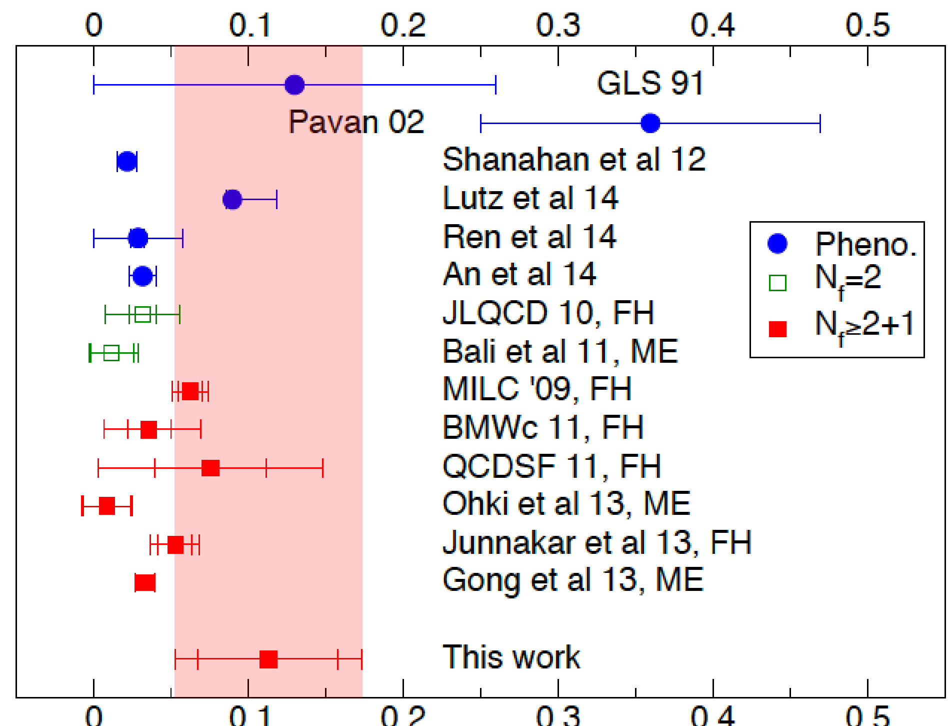
Direct detection on the Lattice: sigma term



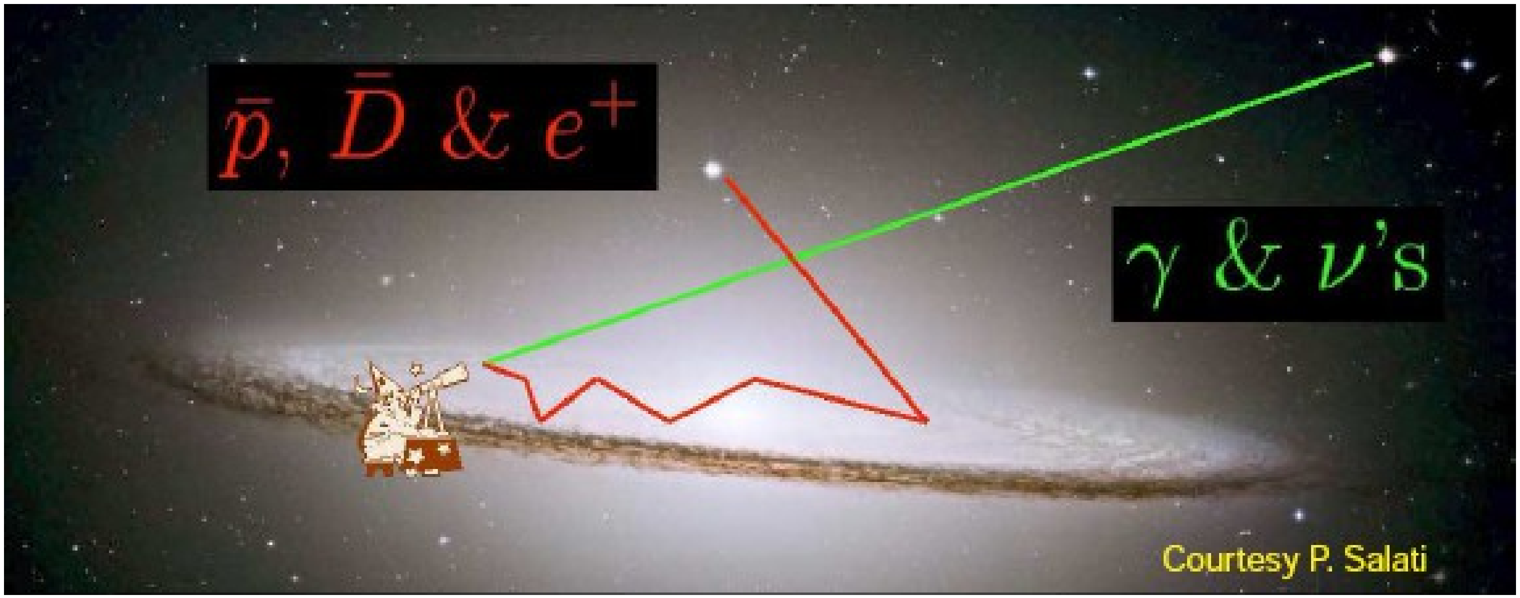


BMW collaboration arXiv:1510.08013
(incl. L. Lellouch & C. Torrero, CPT-Marseille)

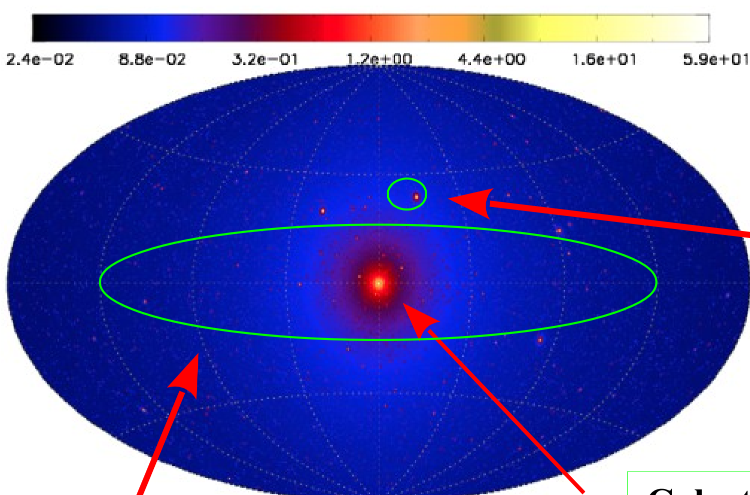




Up to the skies!



Pieri, JL+ 11

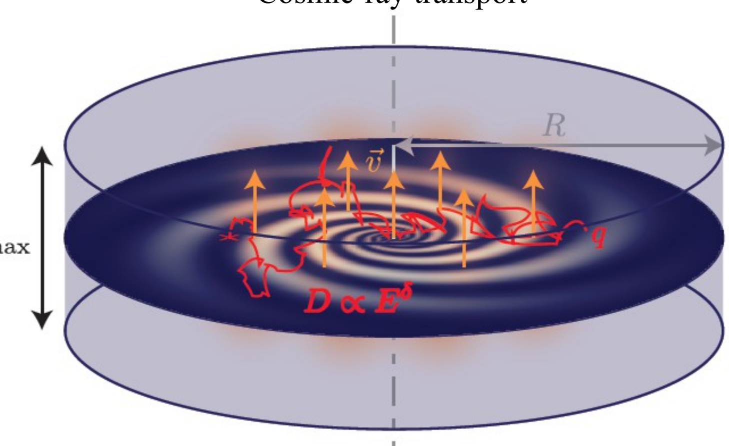


Big DM subhalos
* known **Dwarf Spheroidal Galaxies** (~20) – no other HE astrophysical processes expected there.

Galactic Center
* Closest/Largest expected annihilation rate
* **Large theoretical uncertainties (background not controlled)**

Diffuse gamma-ray emission
=> check spectral/spatial properties wrt background

Cosmic-ray transport



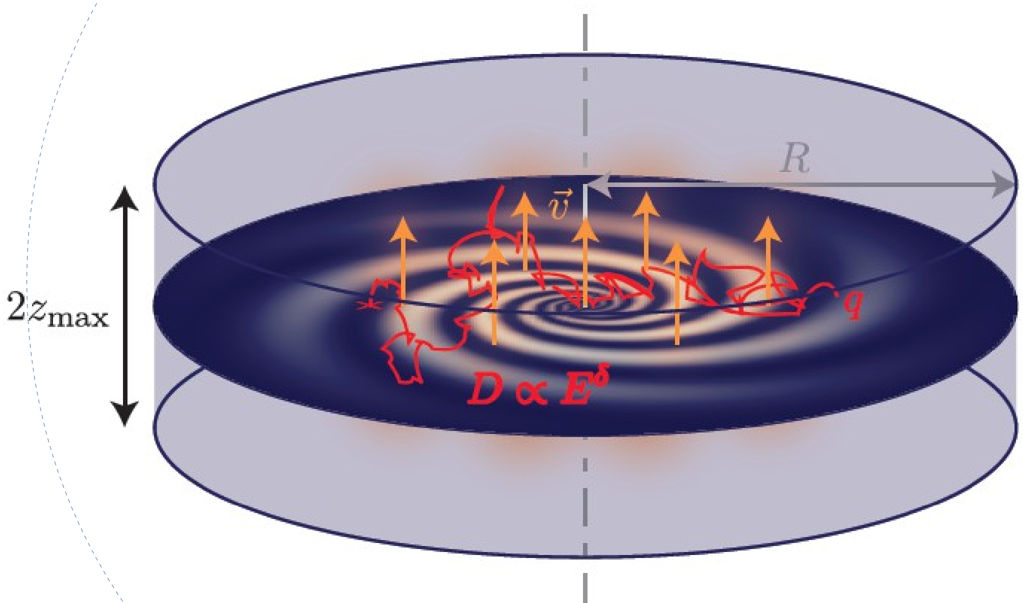
Mertsch PhD thesis 10

DM through (antimatter) cosmic rays

All over the **dark halo** (~200 kpc):
→ DM annihilation/decay + CMB

$$\bar{\chi}\,\chi \longrightarrow \text{matter} + \text{antimatter} + \gamma\text{s} + \nu\text{s}$$

In the **magnetic halo** ~ flat cylinder (width~5kpc):
→ diffusion of all charged cosmic rays (CRs)



Mertsch PhD thesis 10

$$\underbrace{\partial_t \mathcal{N}}_{\text{evolution}} = \underbrace{\mathcal{Q}(\vec{x}, E, t)}_{\text{source}} + \vec{\nabla}\underbrace{\left\{\left(K_{xx}(E)\vec{\nabla} - \vec{V}_c\right)\mathcal{N}\right\}}_{\text{spatial current } \vec{\mathcal{J}}_{xx}} - \partial_p \underbrace{\left\{\left(\dot{p} - \frac{p}{3}\vec{\nabla}\cdot\vec{V}_c - p^2 K_{pp}(E)\partial_p \frac{1}{p^2}\right)\mathcal{N}\right\}}_{\text{momentum current } \mathcal{J}_{pp}} - \underbrace{\frac{\tau_s + \tau_r}{\tau_s\,\tau_r}\mathcal{N}}_{\text{spallation, decay}}$$

In the **Galactic disk** (width ~ 200 pc):
* Astrophysical sources of I$^{\text{ary}}$ CRs: SNRs, PWNe, etc.
* Interstellar medium ISM (gas+dust)
* Production of **II$^{\text{ary}}$ CRs** from nuclear processes CR nuclei+ISM= **bckgd**!

DM through (antimatter) cosmic rays

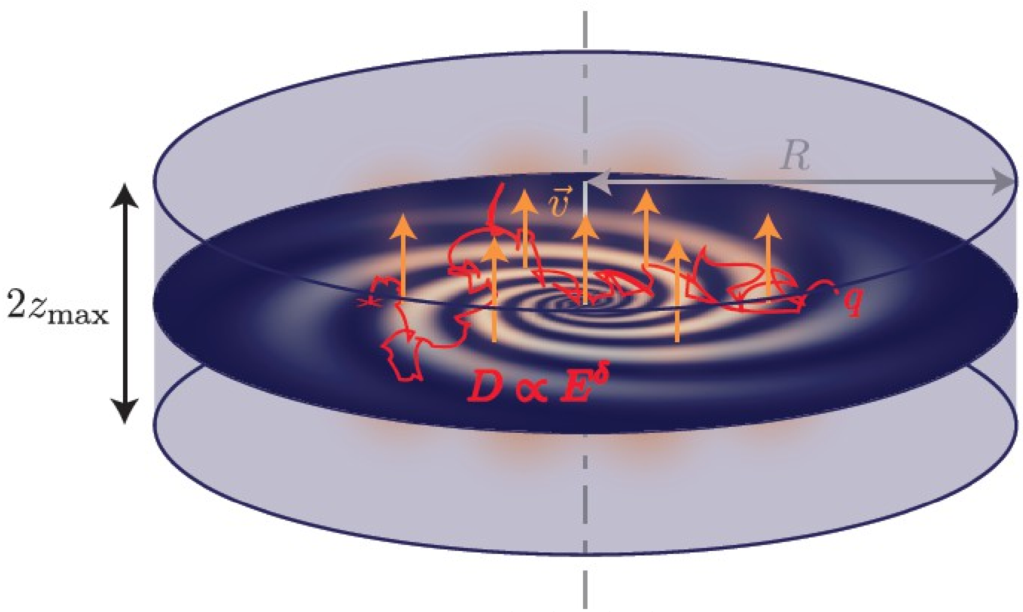
$$p + H \longrightarrow \bar{p}/\bar{n} + X$$

$$\mathcal{Q}_{\rm sec}(T,\vec{x}) = 4\pi \sum_{\substack{i={\rm CRs}\\ j={\rm ISM}}} \int dT_i \, \frac{d\phi_i(T_i,\vec{x})}{dT_i} \, \frac{d\sigma_{ij\to{\rm sec}}(T_i \to T)}{dT} \, n_j(\vec{x})$$

Secondary Production

Primaries:
WIMP annihilation
+ astrophysical sources

$$\underbrace{\partial_t \mathcal{N}}_{\text{evolution}} = \underbrace{\mathcal{Q}(\vec{x},E,t)}_{\text{source}} + \underbrace{\vec{\nabla}\left\{\left(K_{xx}(E)\vec{\nabla} - \vec{V}_c\right)\mathcal{N}\right\}}_{\text{spatial current } \vec{\mathcal{J}}_{xx}} - \underbrace{\partial_p\left\{\left(\dot{p} - \frac{p}{3}\vec{\nabla}\cdot\vec{V}_c - p^2 K_{pp}(E)\partial_p \frac{1}{p^2}\right)\mathcal{N}\right\}}_{\text{momentum current } \mathcal{J}_{pp}} - \underbrace{\frac{\tau_s + \tau_r}{\tau_s \tau_r}\mathcal{N}}_{\text{spallation, decay}}$$



Mertsch PhD thesis 10

$$\bar{p} + H \longrightarrow X$$

$$1/\tau_s(T,\vec{x}) = v_{\bar{p}} \, \sigma_{\bar{p}}(T) \, n_{\rm ISM}(\vec{x})$$

Destruction

DM through (antimatter) cosmic rays

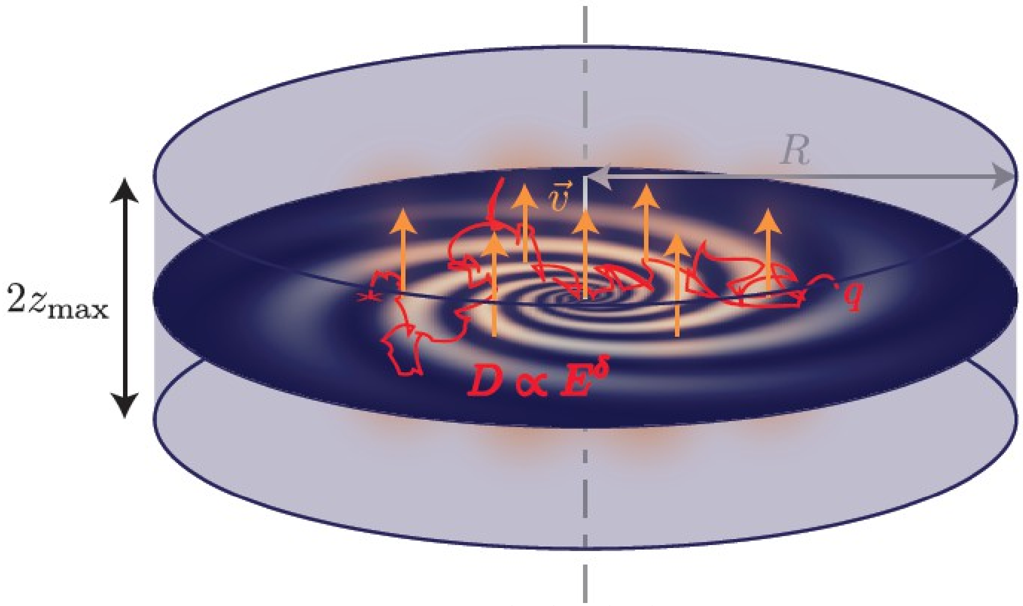
$$p + H \longrightarrow \bar{p}/\bar{n} + X$$

$$\mathcal{Q}_{\rm sec}(T,\vec{x}) = 4\pi \sum_{\substack{i={\rm CRs}\\ j={\rm ISM}}} \int dT_i \, \frac{d\phi_i(T_i,\vec{x})}{dT_i} \, \frac{d\sigma_{ij\to{\rm sec}}(T_i\to T)}{dT} \, n_j(\vec{x})$$

Secondary Production

Primaries:
WIMP annihilation
+ astrophysical sources

$$\underbrace{\partial_t \mathcal{N}}_{\rm evolution} = \underbrace{\mathcal{Q}(\vec{x},E,t)}_{\rm source} + \vec{\nabla}\underbrace{\left\{\left(K_{xx}(E)\vec{\nabla} - \vec{V}_c\right)\mathcal{N}\right\}}_{\text{spatial current } \vec{\mathcal{J}}_{xx}} - \partial_p \underbrace{\left\{\left(\dot{p} - \frac{p}{3}\vec{\nabla}\cdot\vec{V}_c - p^2 K_{pp}(E)\partial_p \frac{1}{p^2}\right)\mathcal{N}\right\}}_{\text{momentum current } \mathcal{J}_{pp}} - \underbrace{\frac{\tau_s + \tau_r}{\tau_s \tau_r}\mathcal{N}}_{\text{spallation, decay}}$$



Mertsch PhD thesis 10

$$\bar{p} + H \longrightarrow X$$

$$1/\tau_s(T,\vec{x}) = v_{\bar{p}} \, \sigma_{\bar{p}}(T) \, n_{\rm ISM}(\vec{x})$$

Destruction

NB: II[ary] antiprotons have exactly the same propagation history as the other II[ary] nuclei (e.g. the boron B) – except for tertiaries.

=> pbar/p carries same information as B/C, if pbar and B produced the same way.

Transport parameters

*** Assume pure spatial diffusion, homogeneous diff. Coeff. K(E)

→ Local **primary** cosmic-ray diff. Density:
NB: source term **Q not very well known**

$$\boxed{\mathcal{N}_A(E) \propto \frac{\mathcal{Q}_A(E)}{K(E)}}$$

→ Local **secondary** cosmic rays:
NB: source term **Q = primaries x interstellar gas**

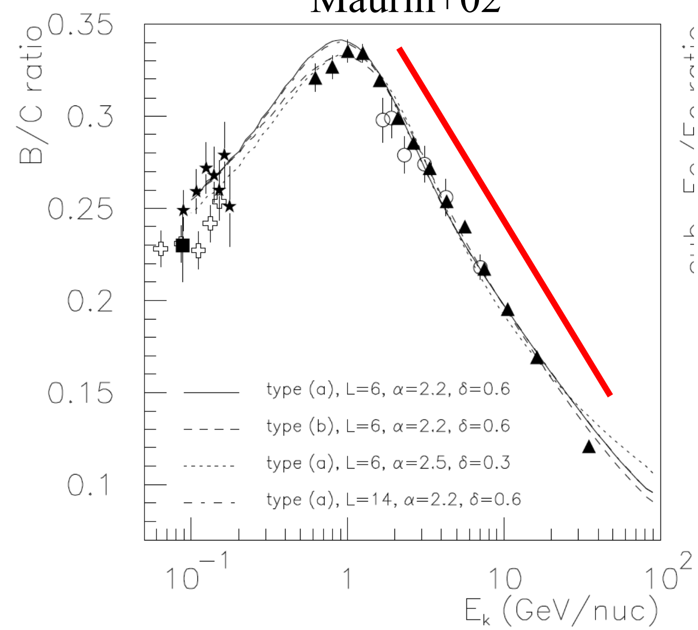
$$\boxed{\mathcal{N}_B(E) \propto \frac{\mathcal{Q}_B(E)}{K(E)} \approx \frac{\sigma_{AB}\, v\, n_{\rm ism}\, \mathcal{N}_A(E)}{K(E)}}$$

→ Ratio independent of source of primaries!

$$\boxed{\frac{\mathcal{N}_B(E)}{\mathcal{N}_A(E)} \propto \frac{1}{K(E)}}$$

(Slightly more complicated in practice
→ more parameters + degeneracies)

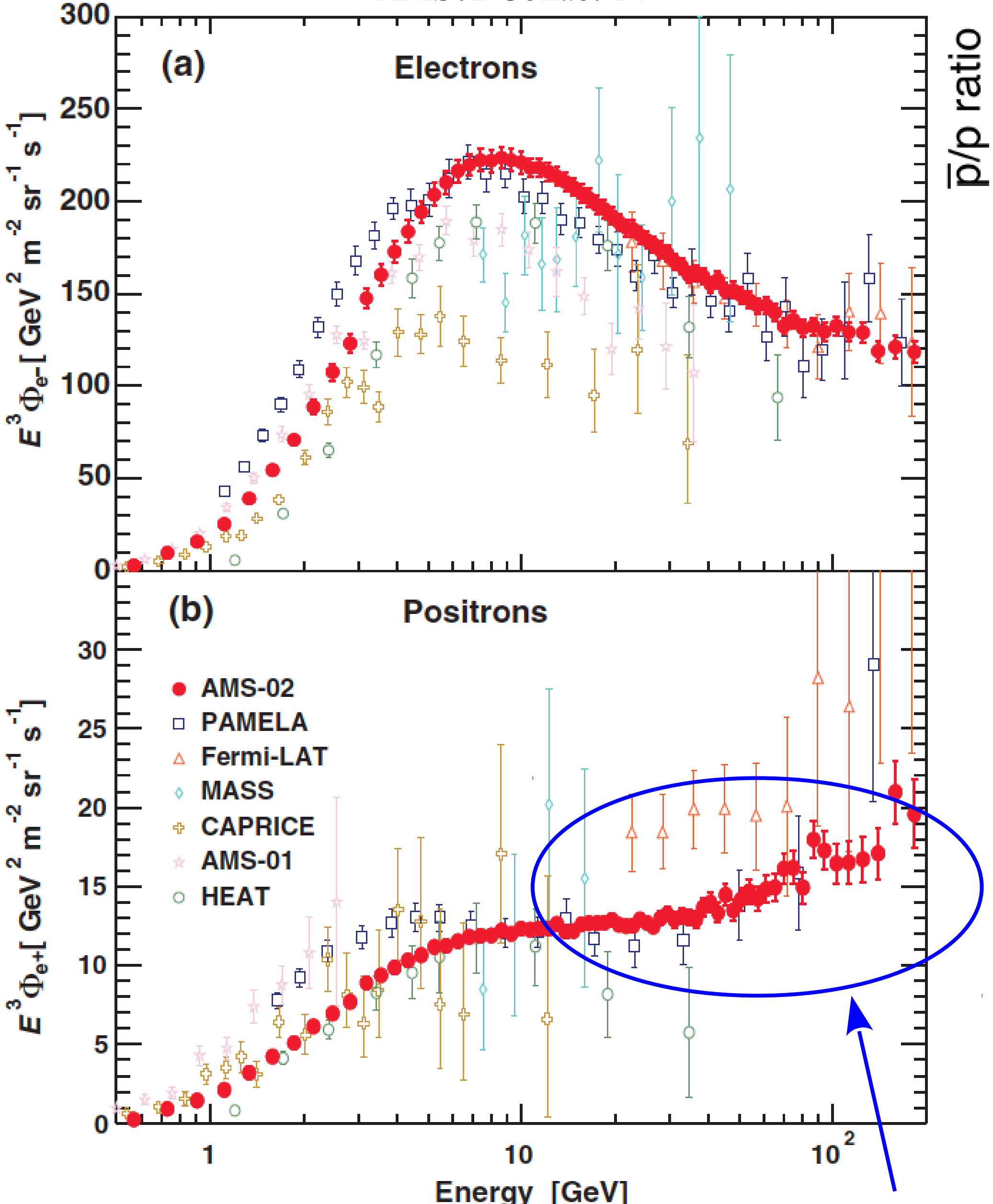
Maurin+02



Boron-to-carbon ratio

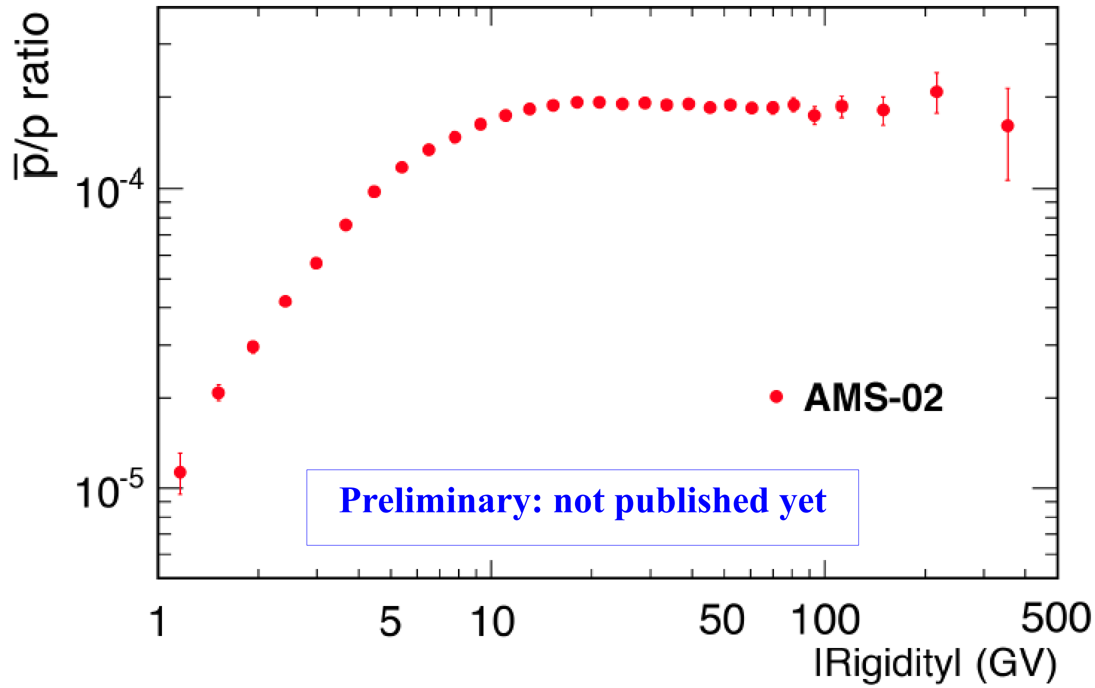
Cosmic-ray data

AMS02 Collab. 14



Astrophysical sources:
Local pulsars and/or SNRs accelerating secondary e+

AMS02 Collab. 15 (AMS-days@CERN)



The AMS-02 breakthrough:
→ **Precision era** (compared to # of points + errors of PAMELA)
→ **Confirm rising positron fraction** (first observed by PAMELA)
→ **unprecedented energies > 500 GeV**

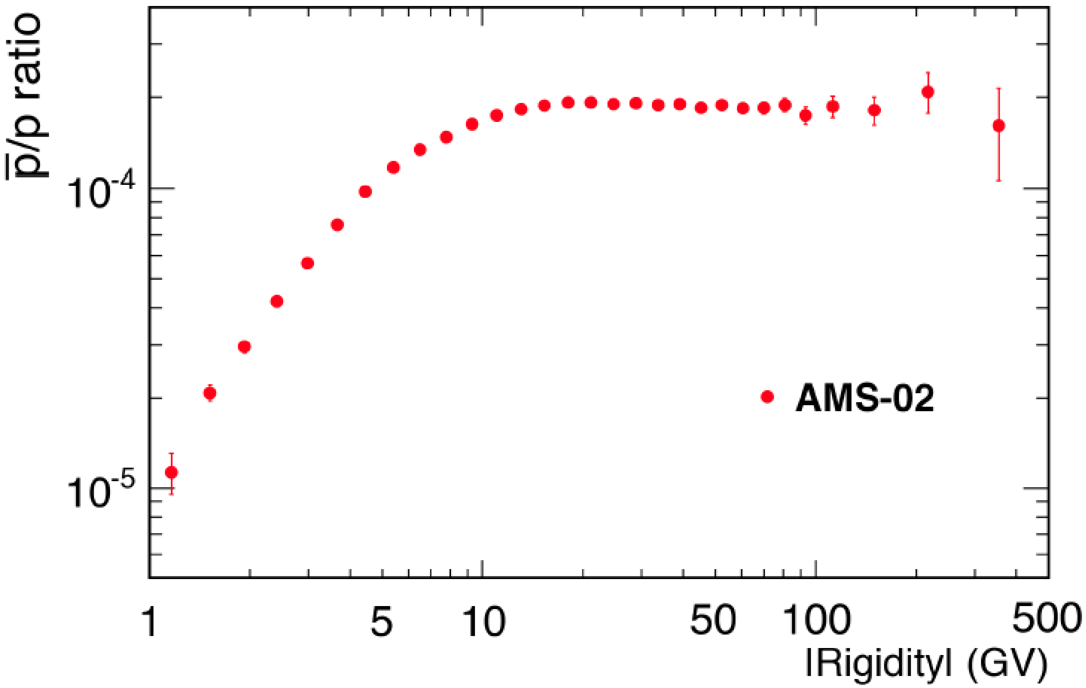
=> Improvements in theoretical CR physics expected
=> Dark matter signals/constraints?

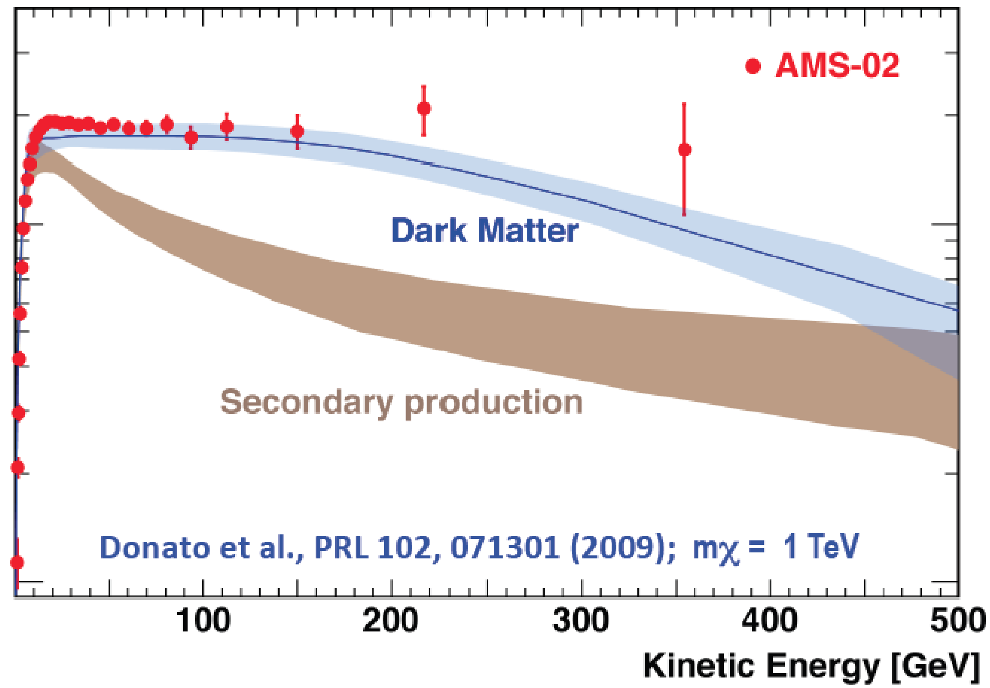
The Cosmic-Ray Saga

Standard astrophysical phenomena can explain these data

Don't underestimate the power of the dark sector

Antiprotons by AMS-02

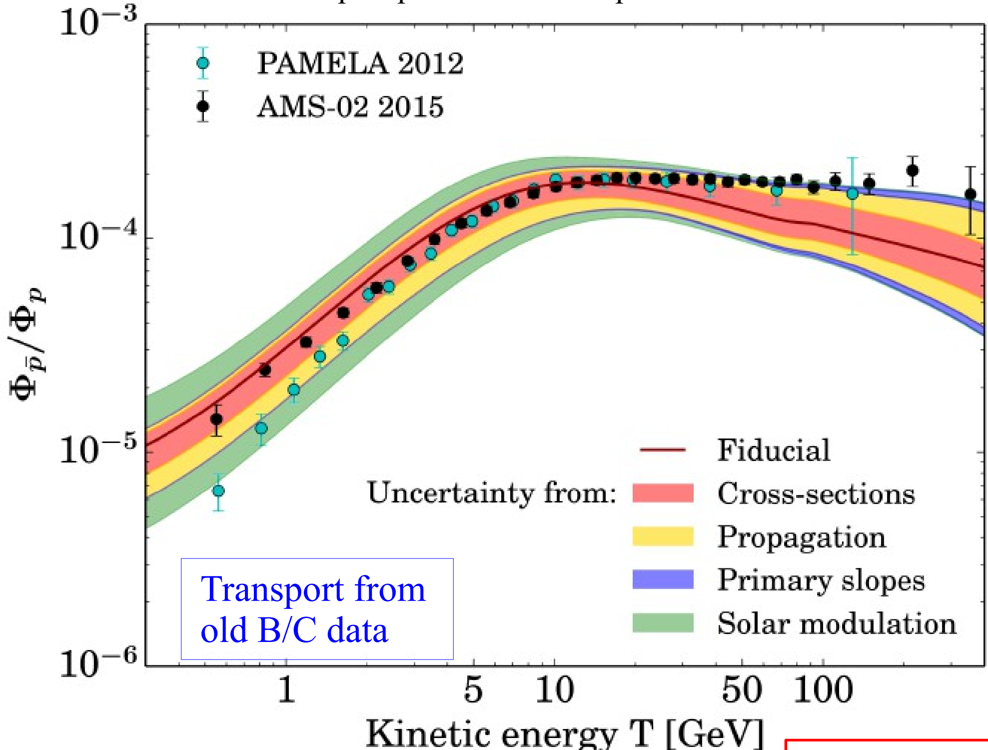




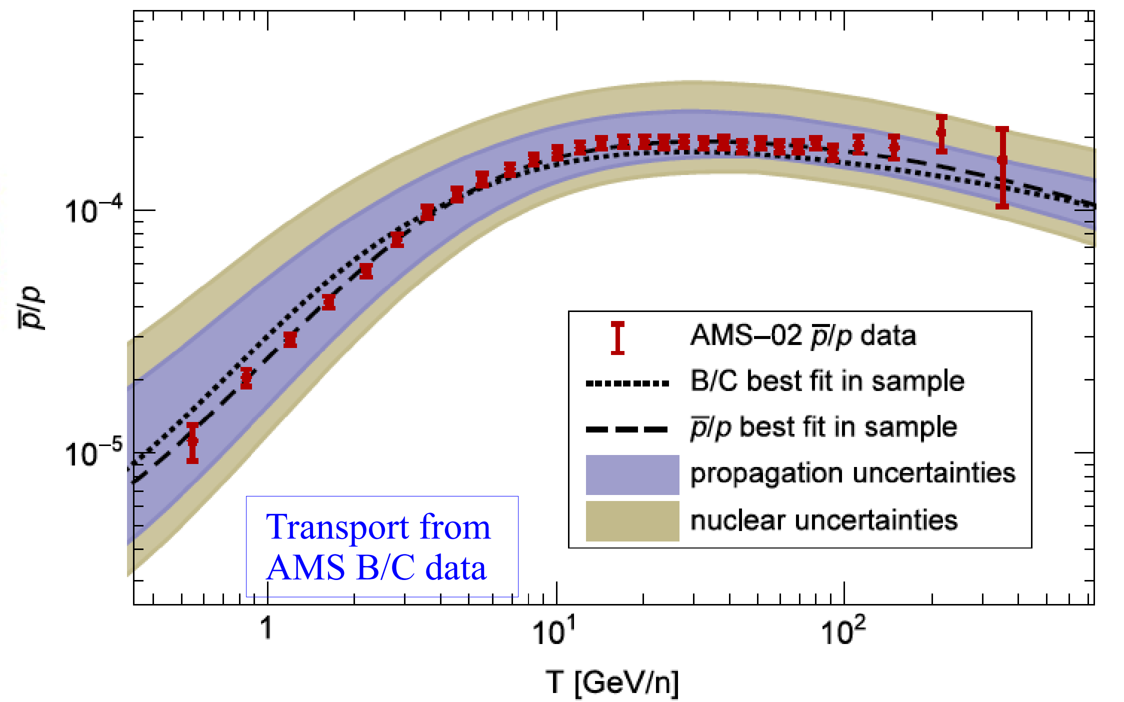
AMS-02: Kounine @ AMS days, CERN, 04/2015

Predictions for secondaries?

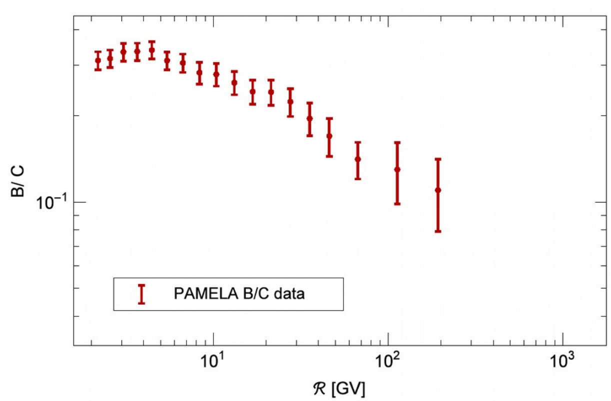
Giesen, Boudaud+15 (USINE)
Transport parameters from pre-AMS02 B/C data

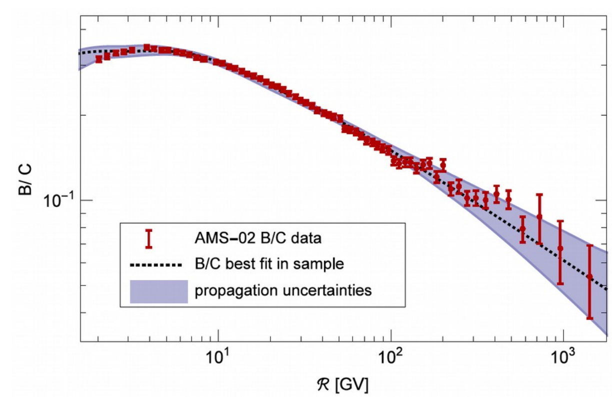


Kappl, Reinert & Winkler 15
Transport parameters from prelim. B/C AMS-02



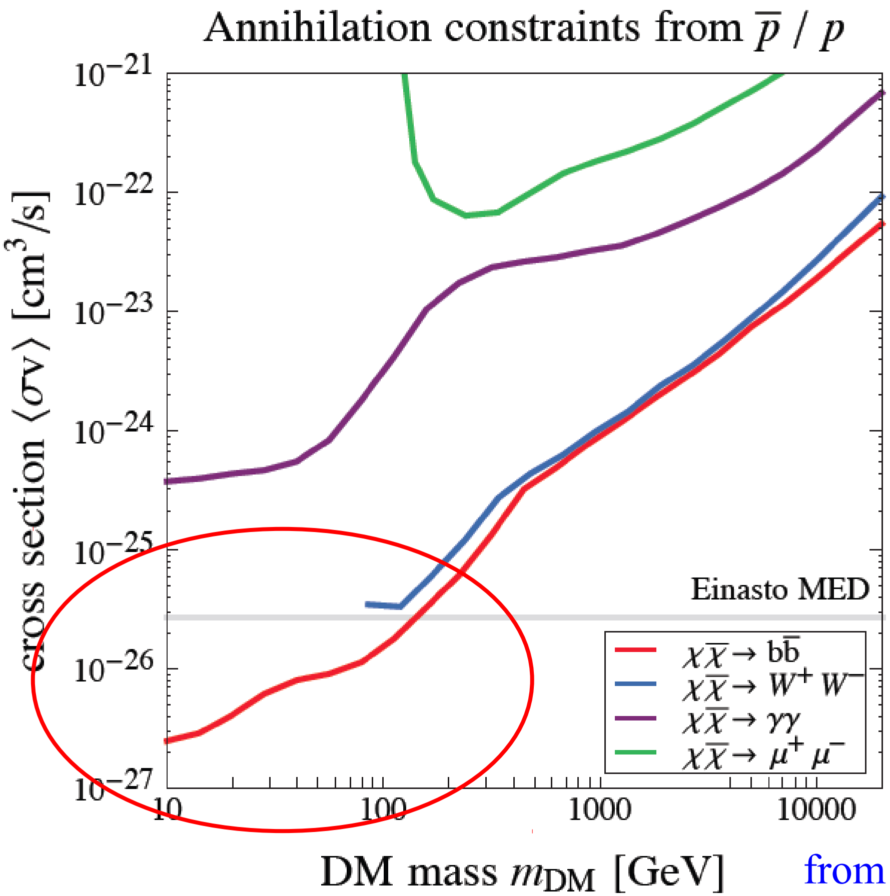
Consistent with secondary antiprotons

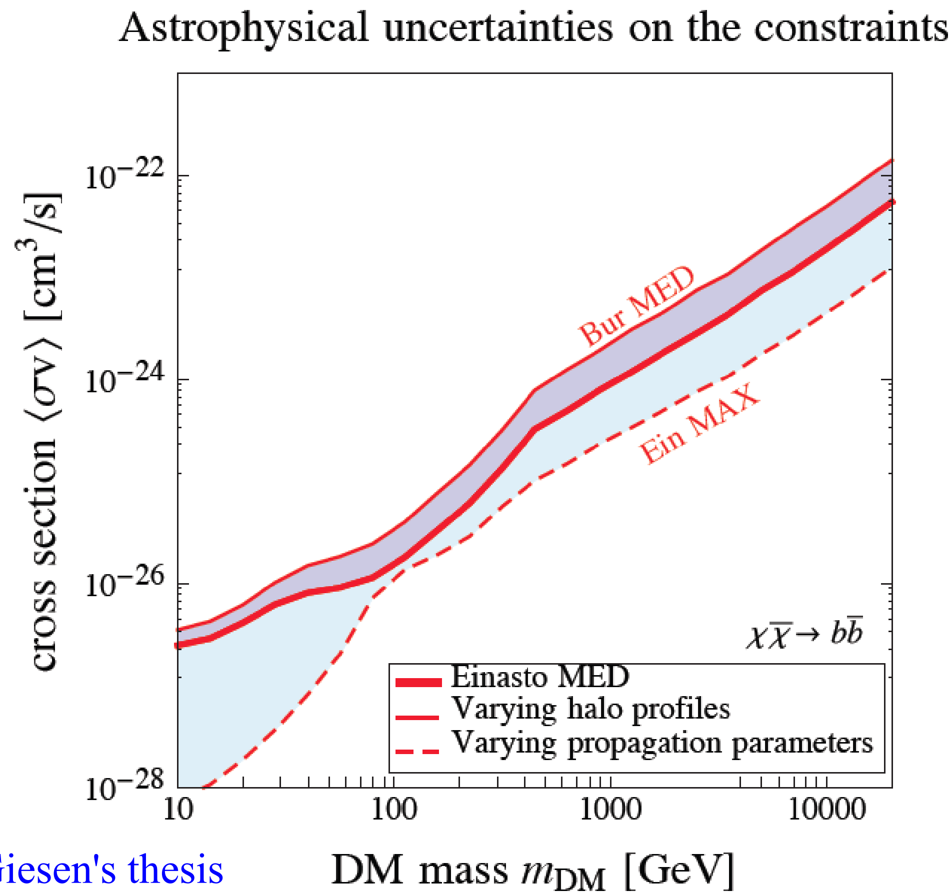




Antiproton constraints on WIMPs

M. Boudaud, G. Giesen+15

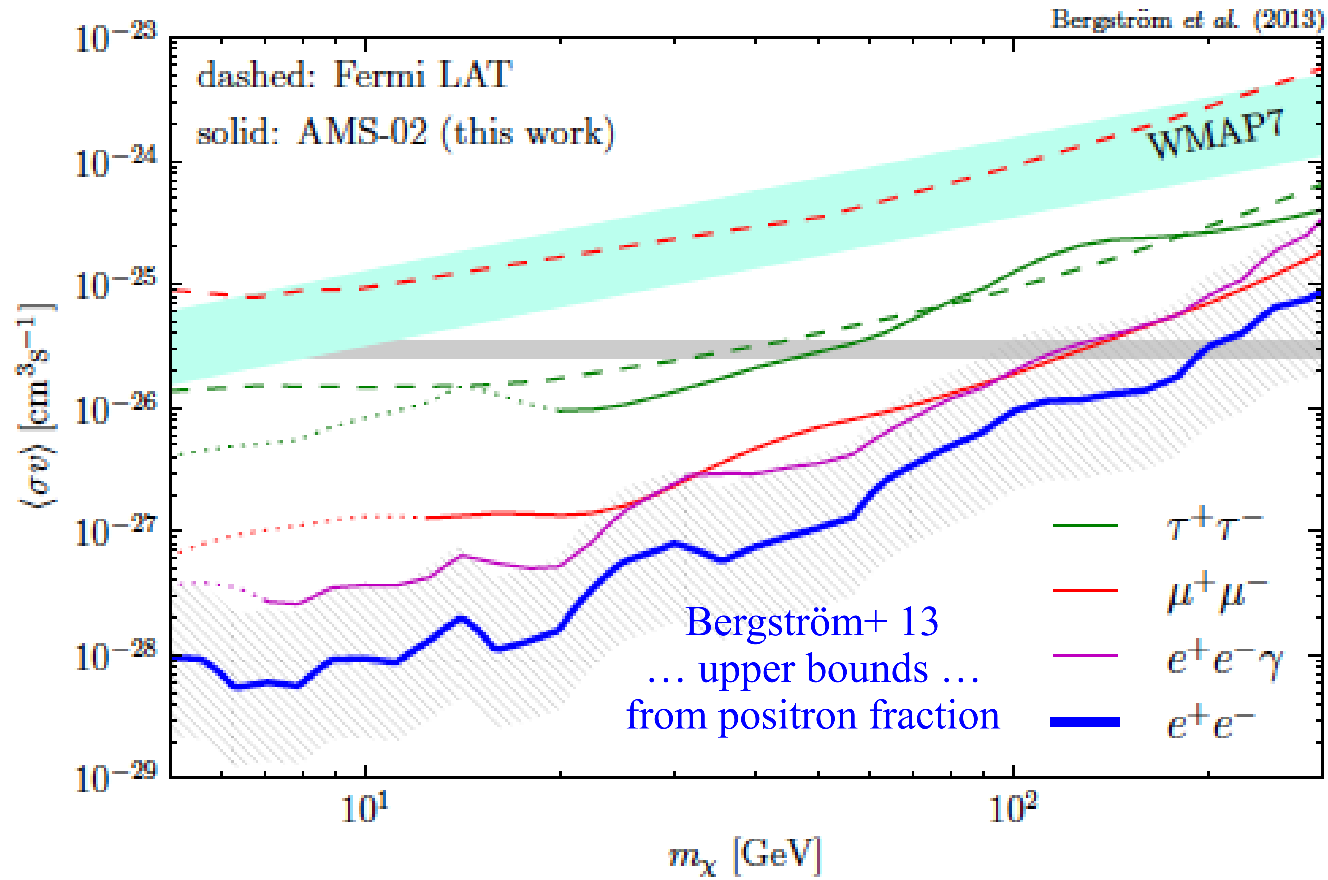




from G. Giesen's thesis

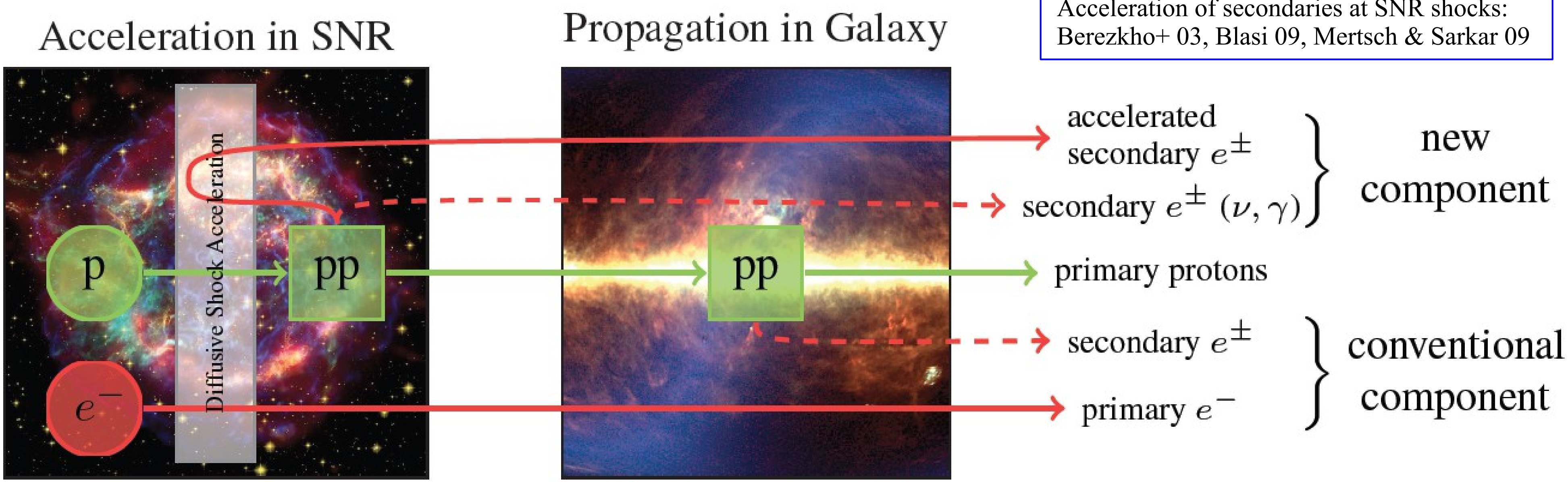
No much room left to play with CR transport parameters:
→ diffusion halo size > 3 kpc (see A. Putze)
+ moderate effect of halo shape

Positron constraints on WIMPs

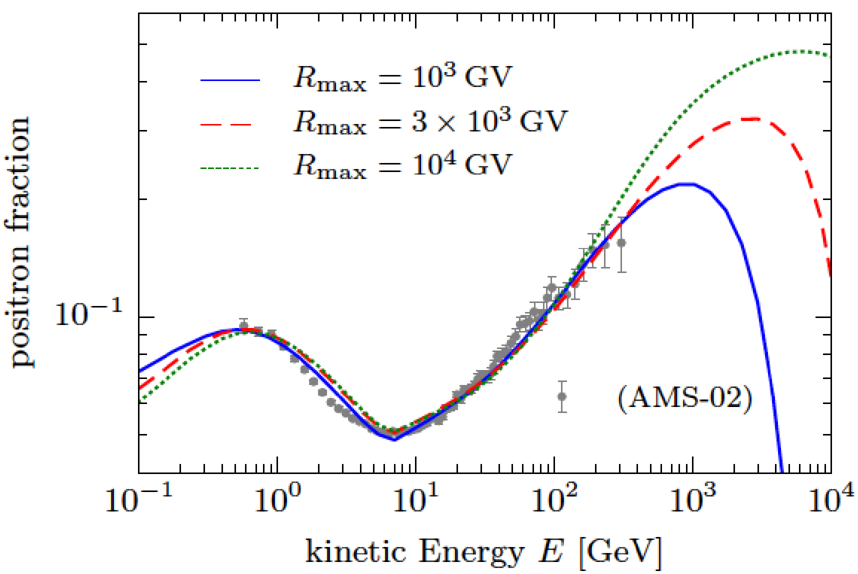


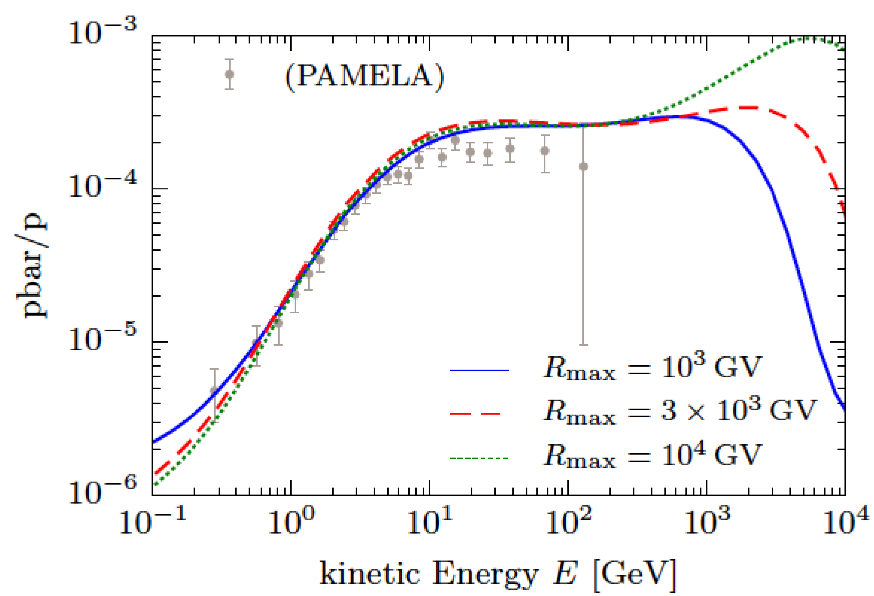
Astrophysical primaries?

Acceleration of secondaries at SNR shocks:
Berezkho+ 03, Blasi 09, Mertsch & Sarkar 09



Alhers+ 09





Mertsch & Sarkar 14

Astrophysical primaries?

Acceleration of secondaries at SNR shocks:
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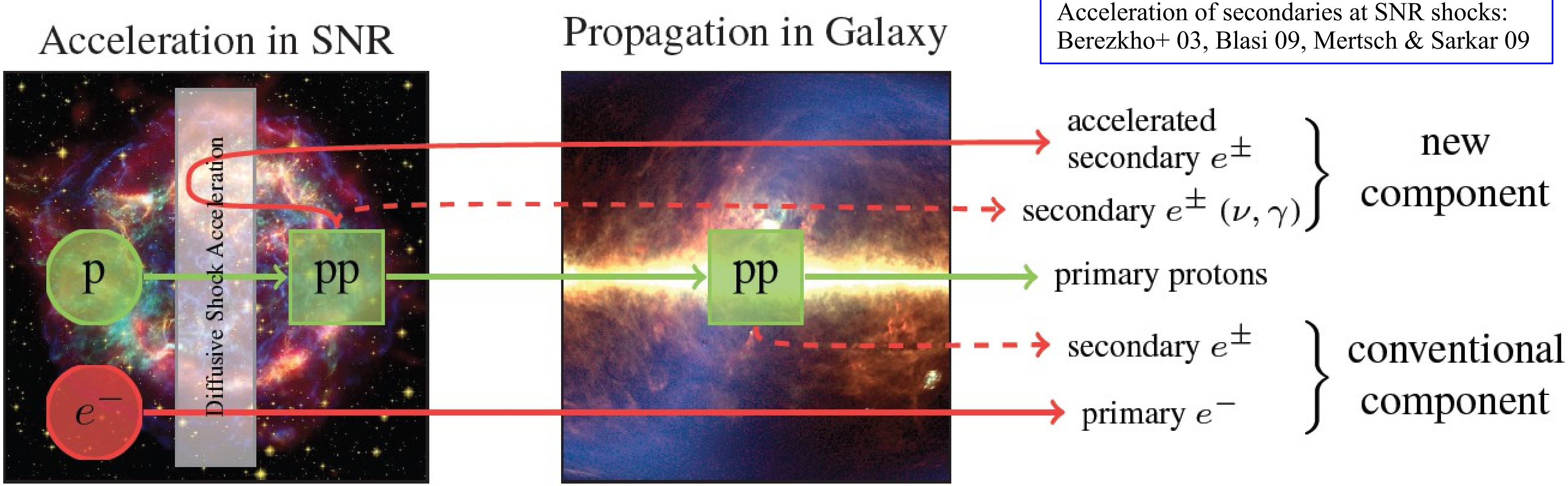
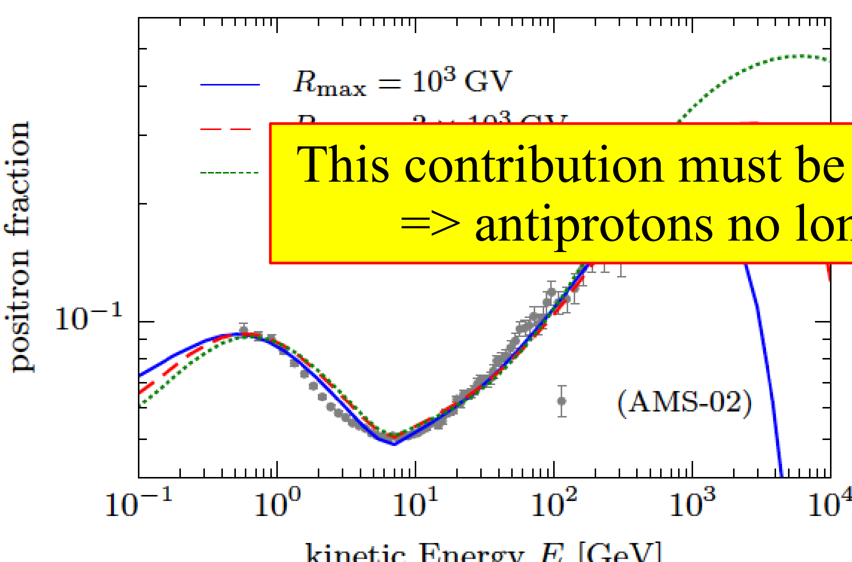
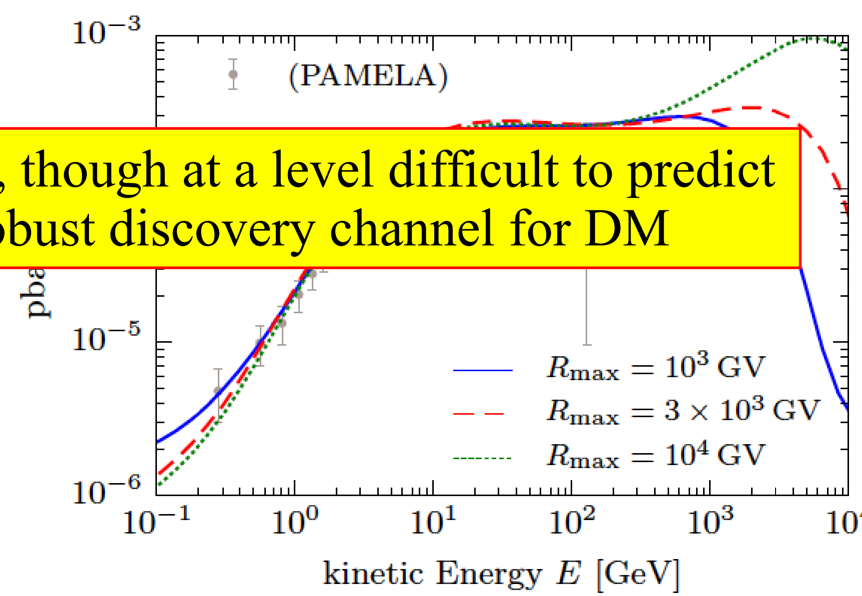


Alhers+ 09



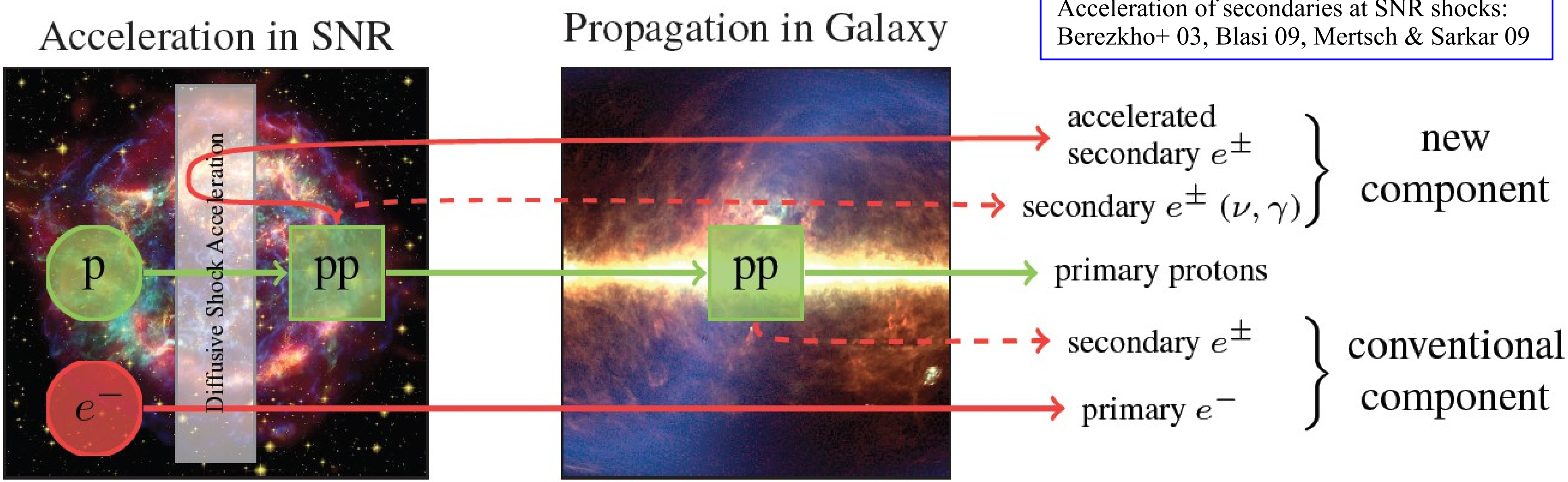


This contribution must be present, though at a level difficult to predict
=> antiprotons no longer a robust discovery channel for DM

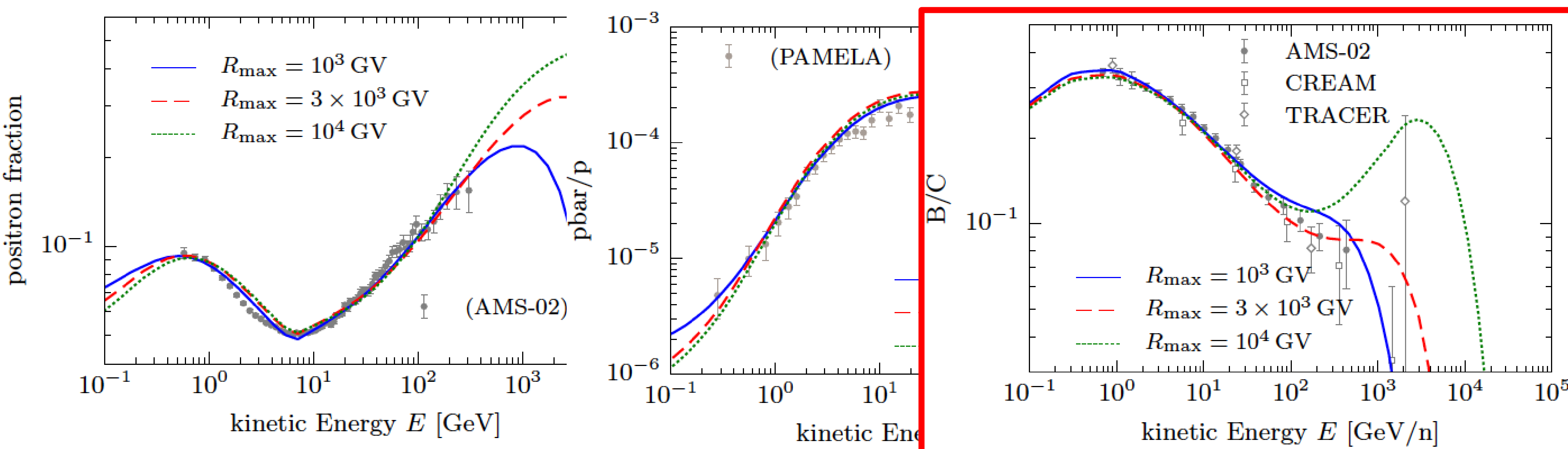
Mertsch & Sarkar 14

Astrophysical primaries?

Acceleration of secondaries at SNR shocks:
Berezkho+ 03, Blasi 09, Mertsch & Sarkar 09



Alhers+ 09



Mertsch & Sarkar 14

Other cosmic-ray anomalies?

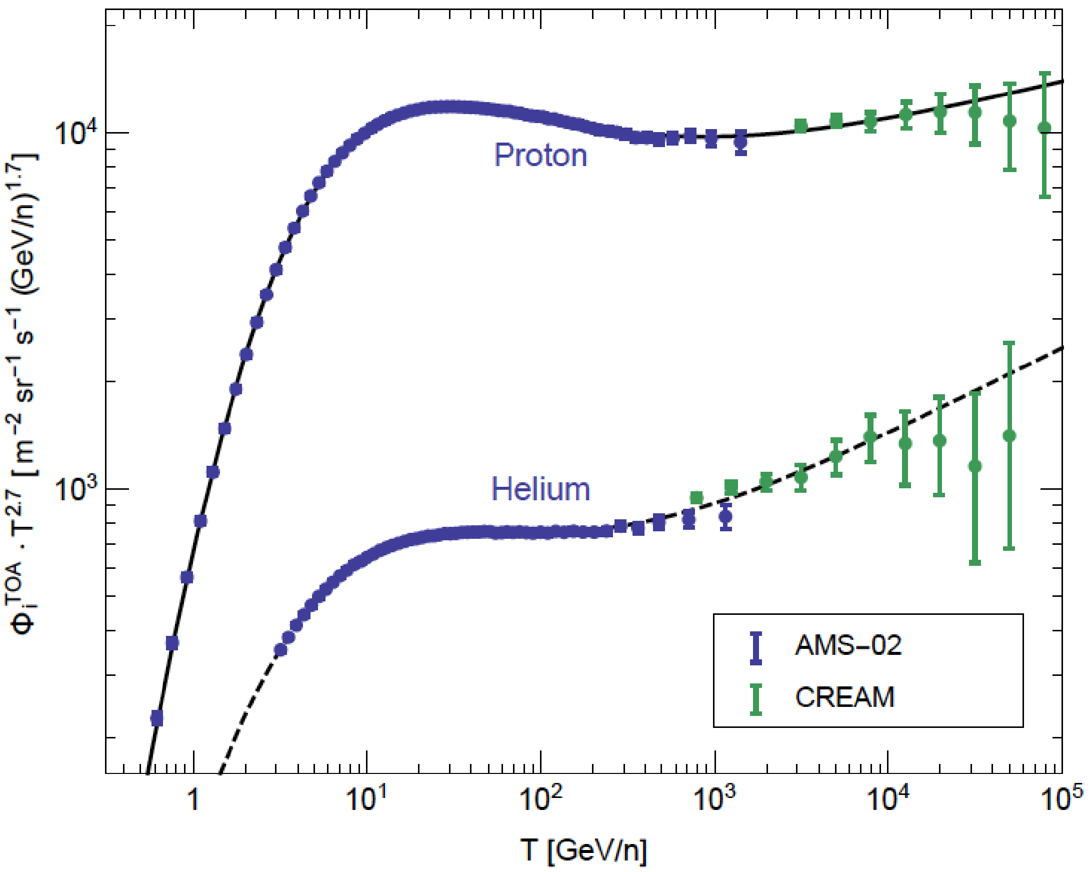
See e.g. P. Serpico, ICRC-2015
+ Y. Genolini

* **Spectral hardening** of primary CR spectra

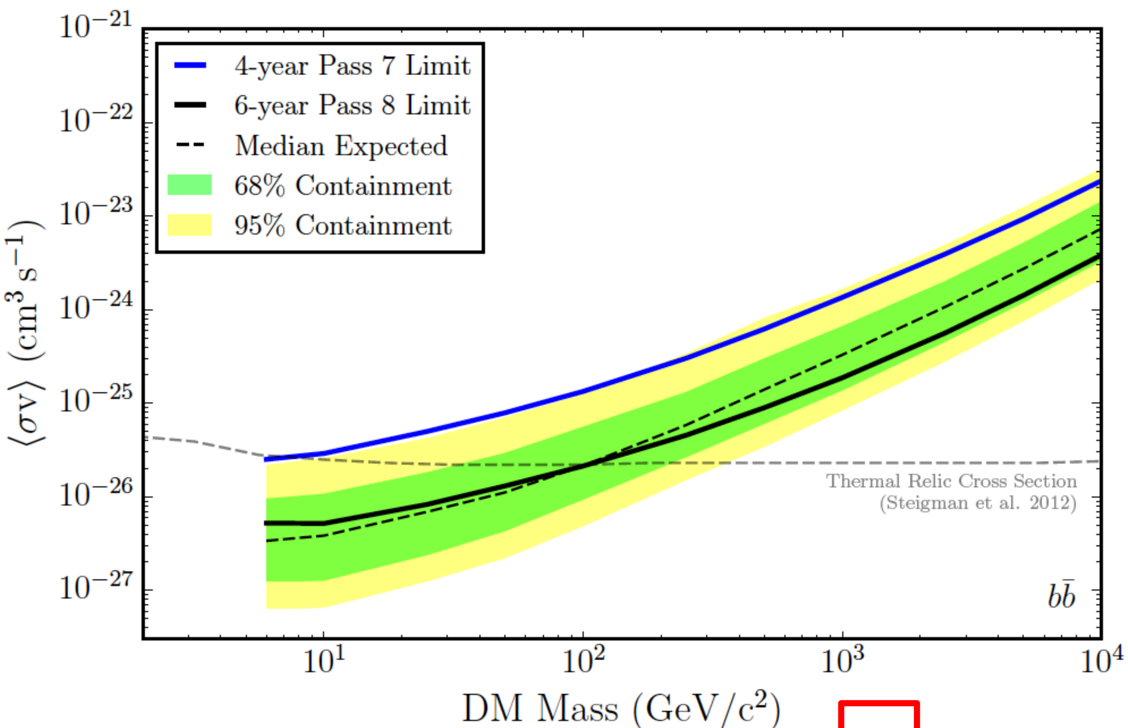
* **ratio p/He**

=> source-related (spatial distrib., acceleration)?
=> transport related?
=> under investigation

=> no DM in there ;-)

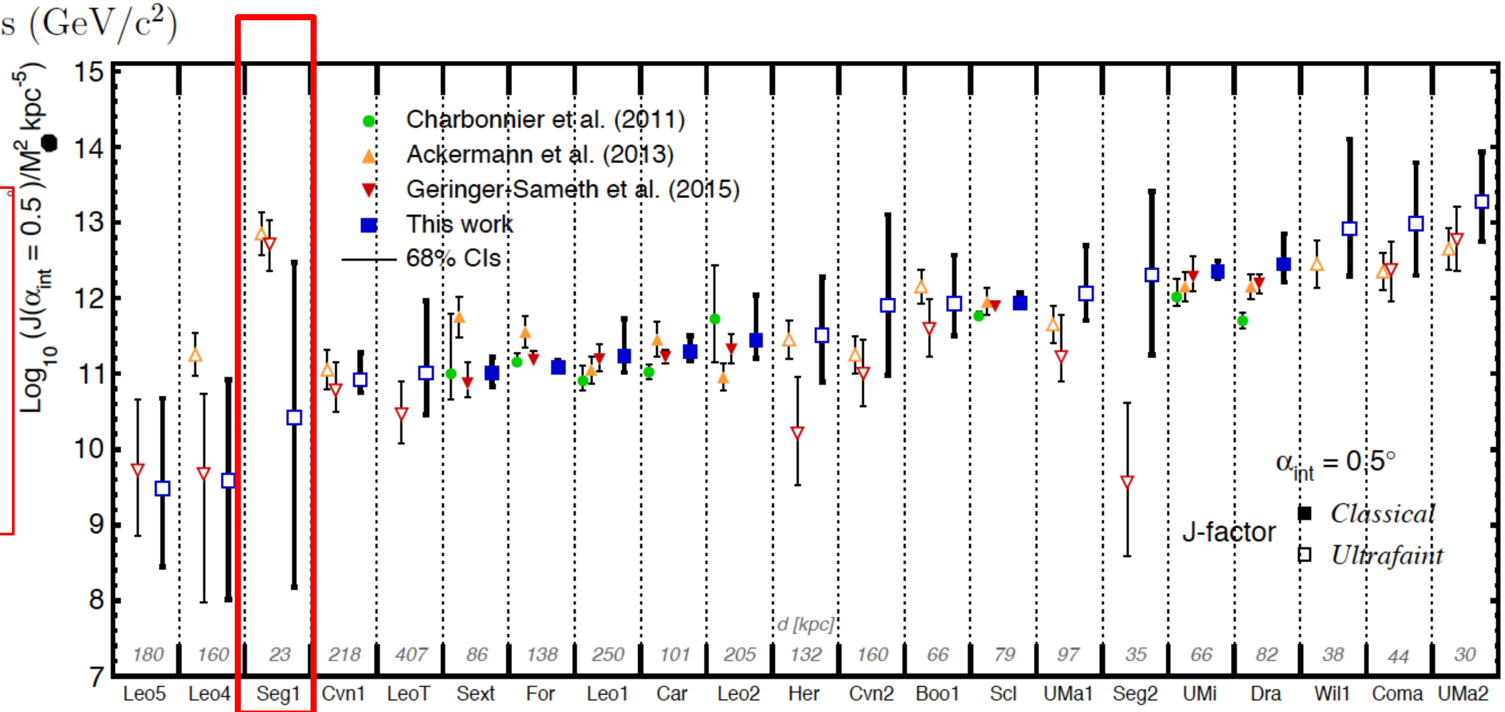


Satellite dwarf galaxies in gamma rays



Fermi Collab. 15:
* 15 satellite DSphG – stacked
* 6 yrs of data, PASS8 reconstruction
=> improved limit
=> start probing 100 GeV mass range!
=> DSphG population not complete
(more with DES, LSST, etc.)

Bonnivard+15
→ Individual J-factors+errors:
* Careful Jeans analysis from velocity dispersion measures
* Systematics from mock data
=> Segue I overestimated
=> Fermi limit likely affected



Conclusions and perspectives

*** Galactic DM distribution + phase space**
→ Gaia (dynamical constraints)
→ cosmological simulations

*** Direct and indirect detections in the ballpark**
→ direct also relevant to non-annihilating DM (+ couplings to e)
→ WIMP scenario under assault
→ TeV ID with CTA

*** Golden signals/targets:**
→ gamma-ray lines, signal from dwarf galaxies, neutrinos from the Sun

*** Cosmic rays:**
→ precision era
→ powerful constraints on DM
→ systematic unc. have decreased (small diff. halo excluded)
→ interesting astrophysics still to understand

*** Astrophysics matters**

*** Astrophysics matters**

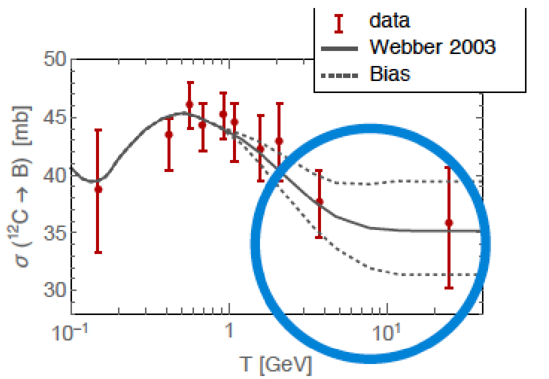
*** Astrophysics matters**

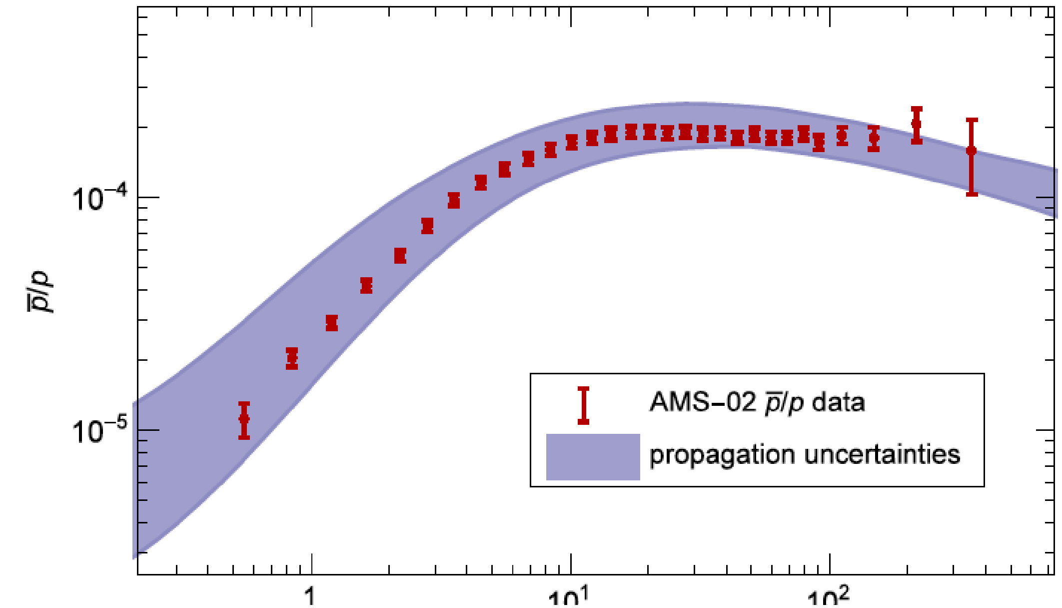
Complementary talks by:
* Y. Genolini, A. Putze (CRs)
* S. Galli, V. Poulin, A. Goudelis, A. Bharucha (cosmo)
* K. Petraki (bound states)
* K. Mawatari (DM@LHC)
* M. Pierre, J. Da Silva, G. Arcadi, B. Zaldivar, etc.

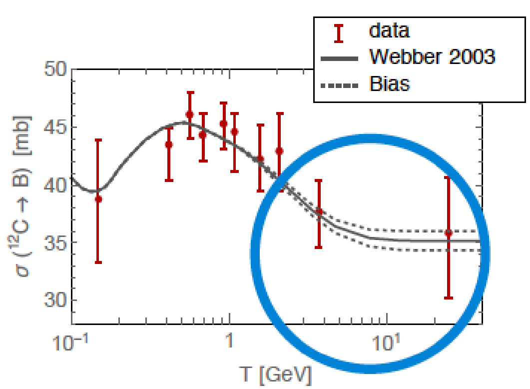
BACKUP

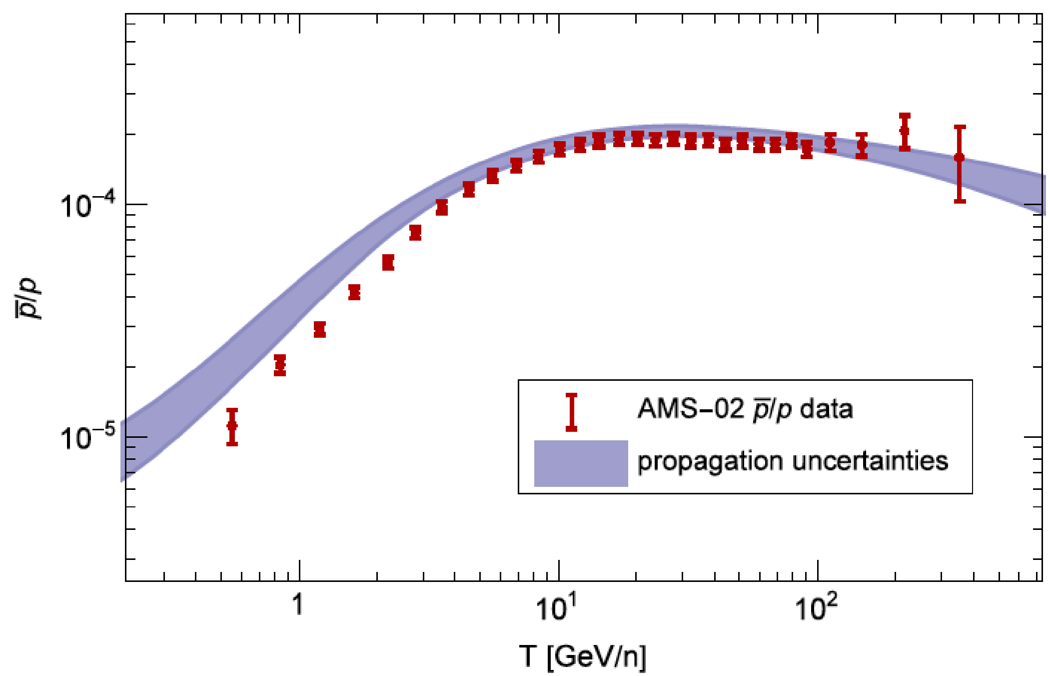
Nuclear Uncertainties

Courtesy Rolf Kappl

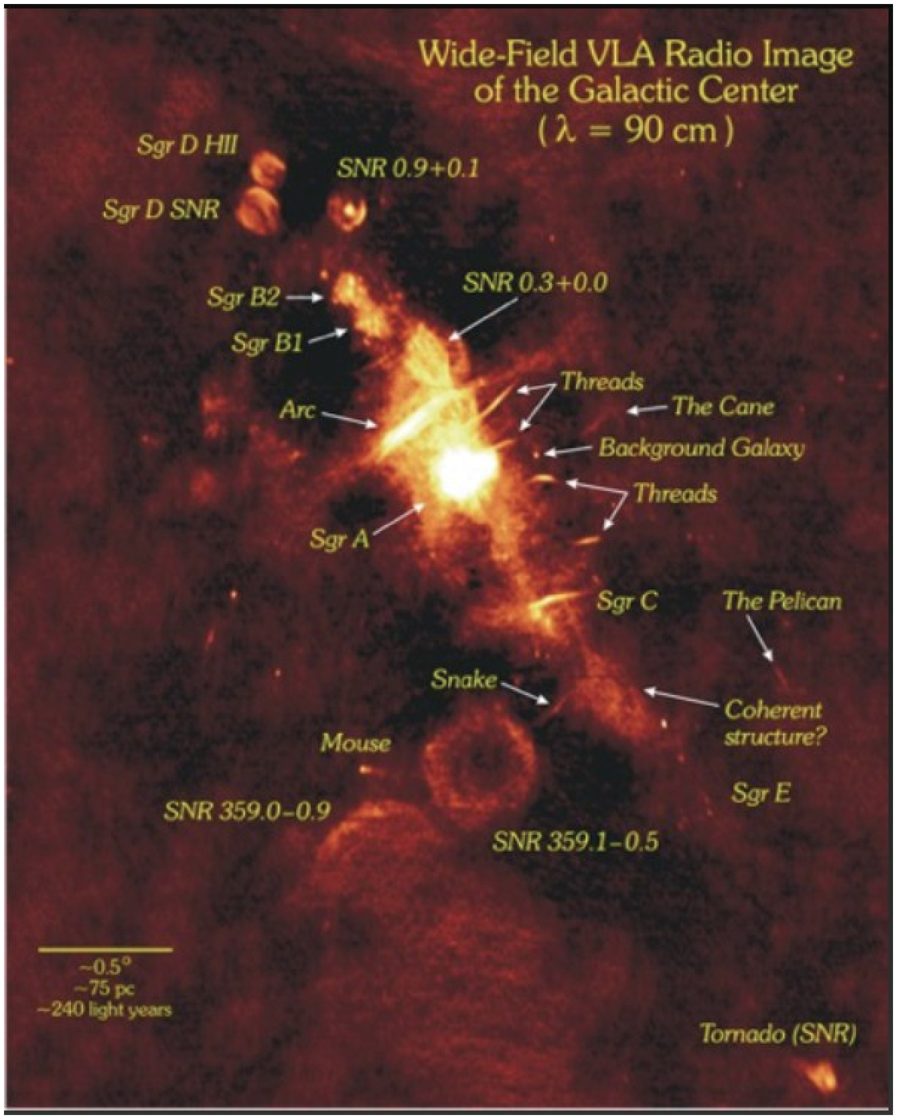








Galactic Center anomaly?



GC = very complicated region
→ star formation, molecular clouds, etc.

Is background under control? NO
→ Excess wrt what?

→ CR modeling too limited (steady state)
→ source distribution unknown (MSPs + other CR sources)
→ gas distribution very partially known

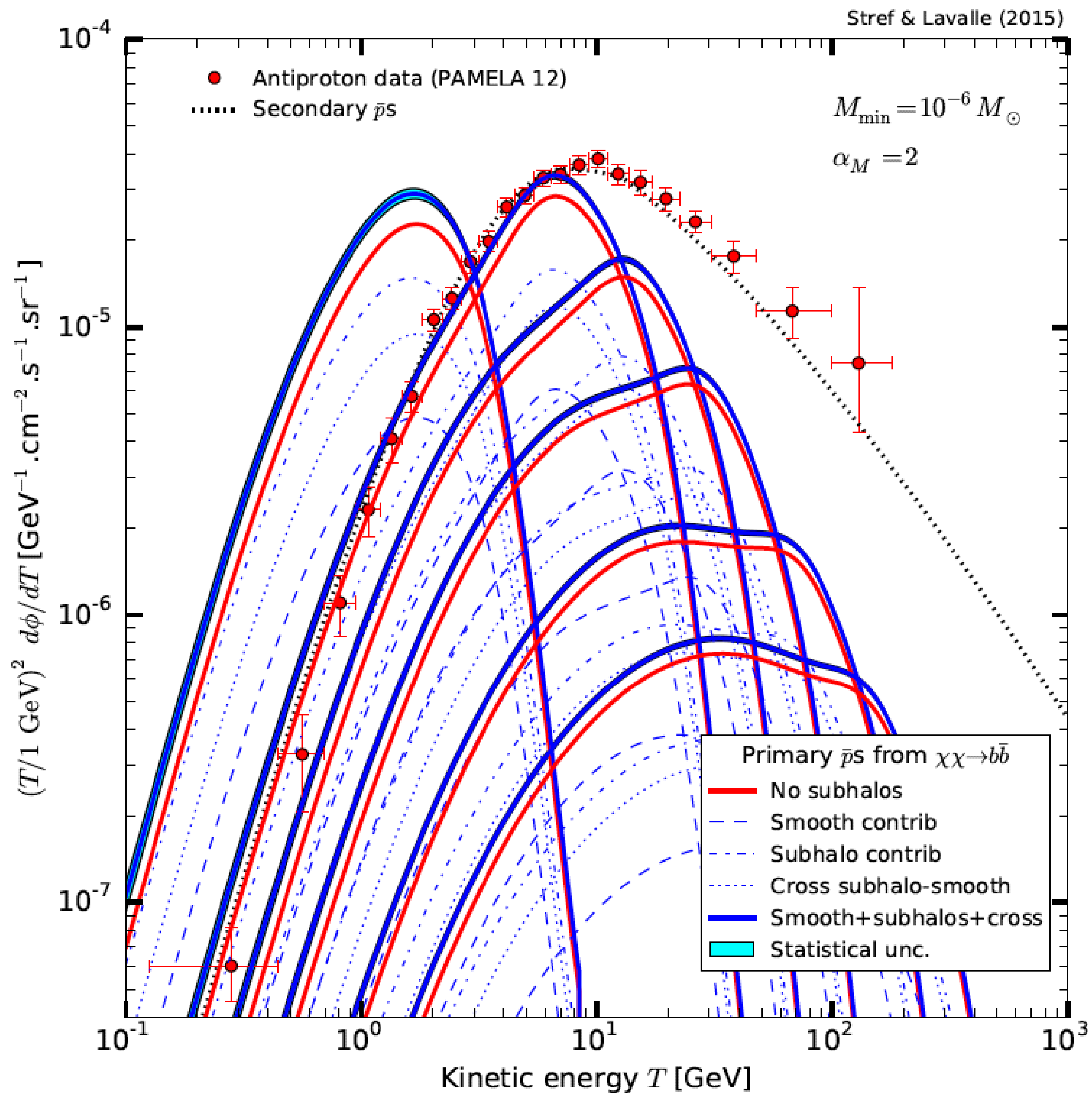
It should not come as a surprise that standard astrophysics plays a significant role there.

e.g. Carlson & Profumo 15: H2 + sources tracking H2
+ Carlson, Linden+, e.g. 1510.04698

Appears that we may have been premature in arguing that cosmic-ray emission can't spectrally reproduce the excess.

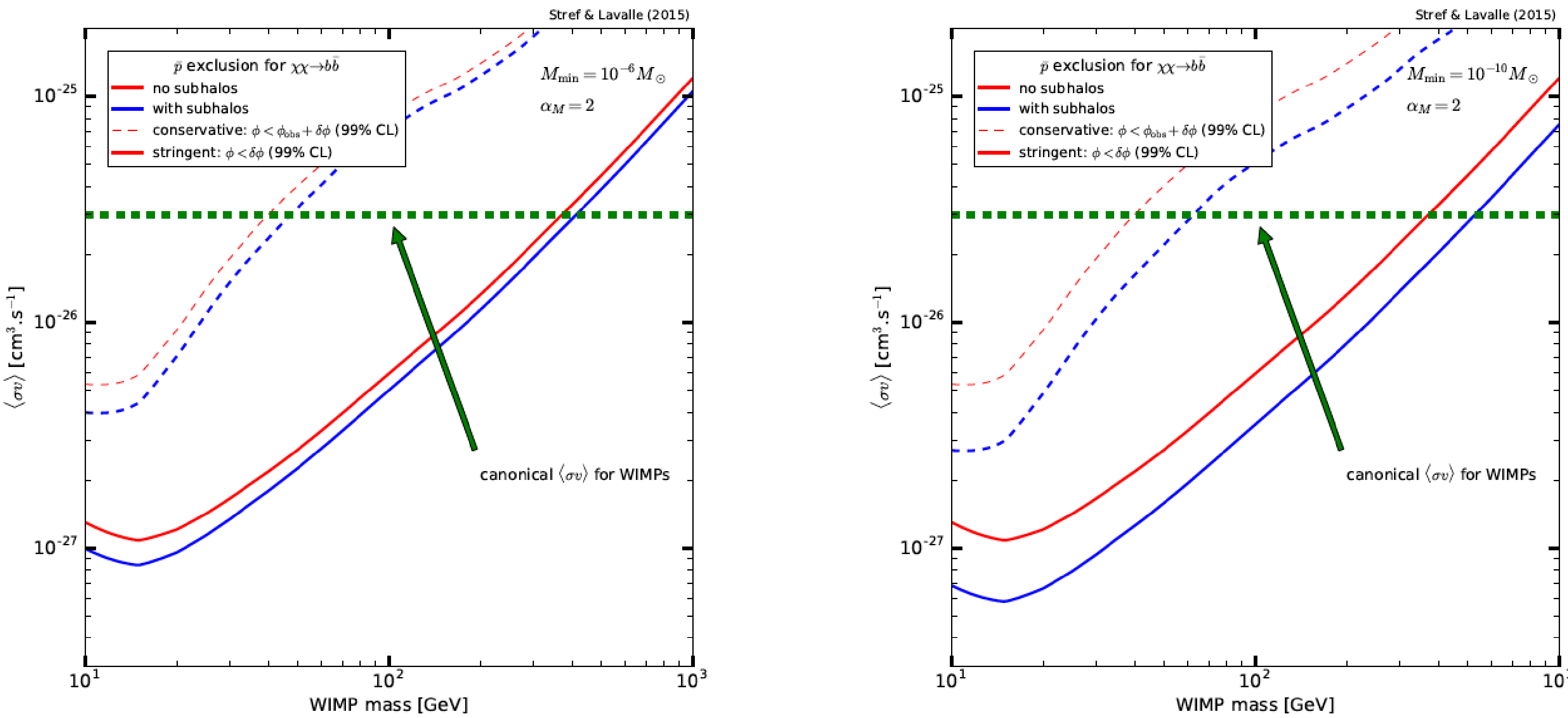
Tim Linden @ Gamma rays and dark matter (Austria), 12/2015

Antiproton flux from DM subhalos



Stref & JL, in prep.

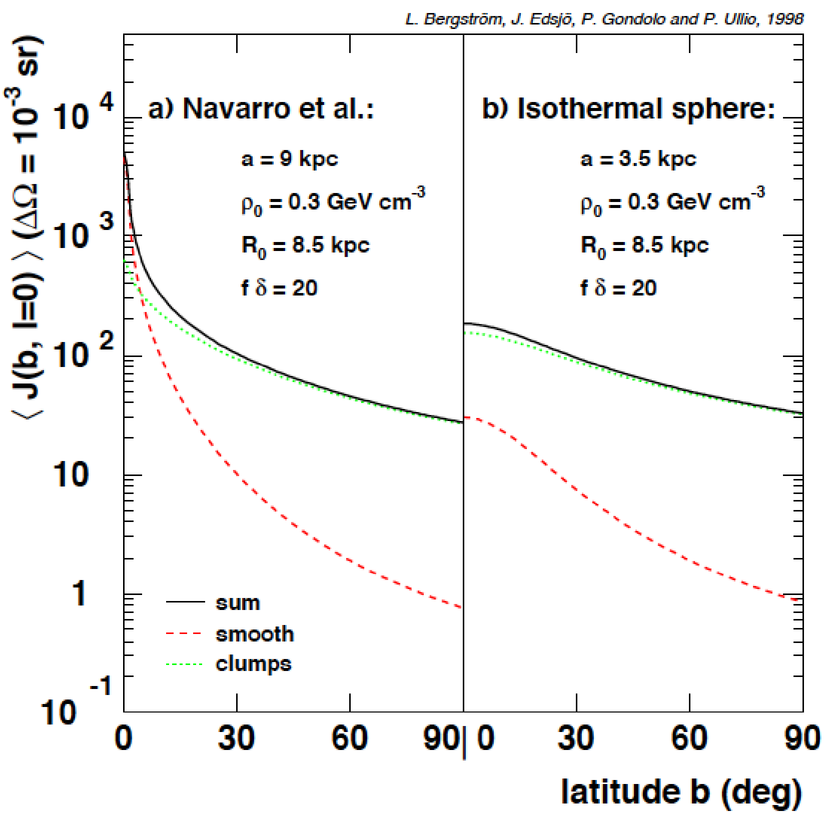
Constraints on s-wave annihilating WIMPs

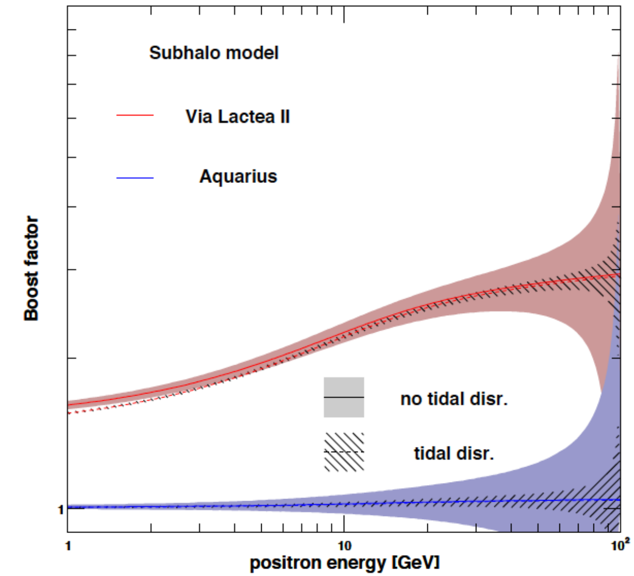


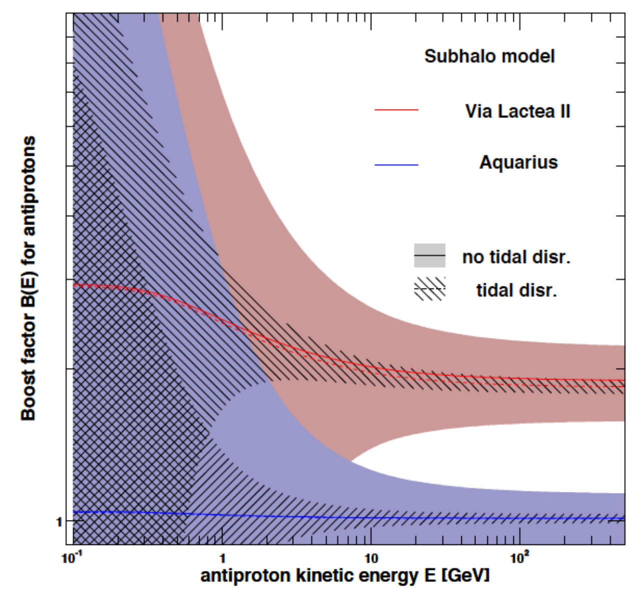
Stref & JL, in prep.

Impact on indirect DM searches

Bergström+98
Angular dependence of gamma-ray boost



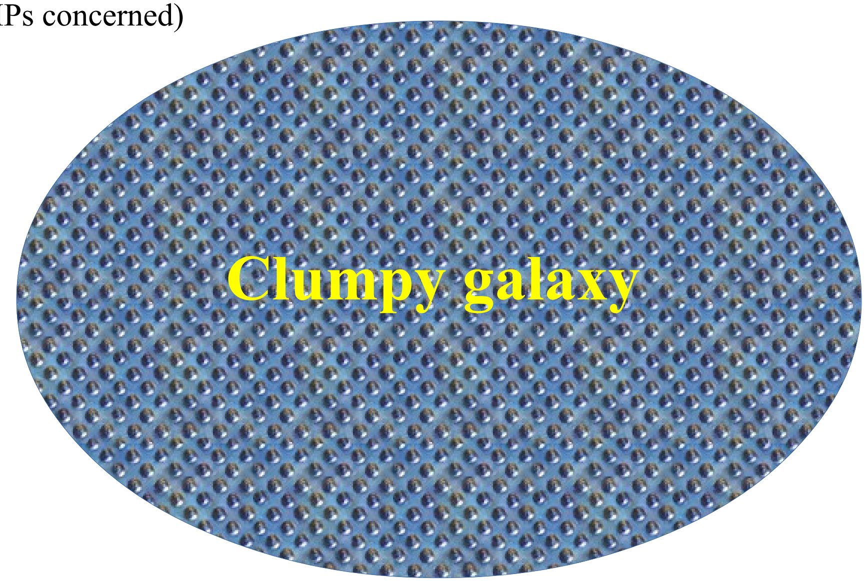




JL+07,08, Pieri,JL+11
Energy dependence of CR boost

Impact on indirect DM searches

(Only s-wave annihilating WIMPs concerned)

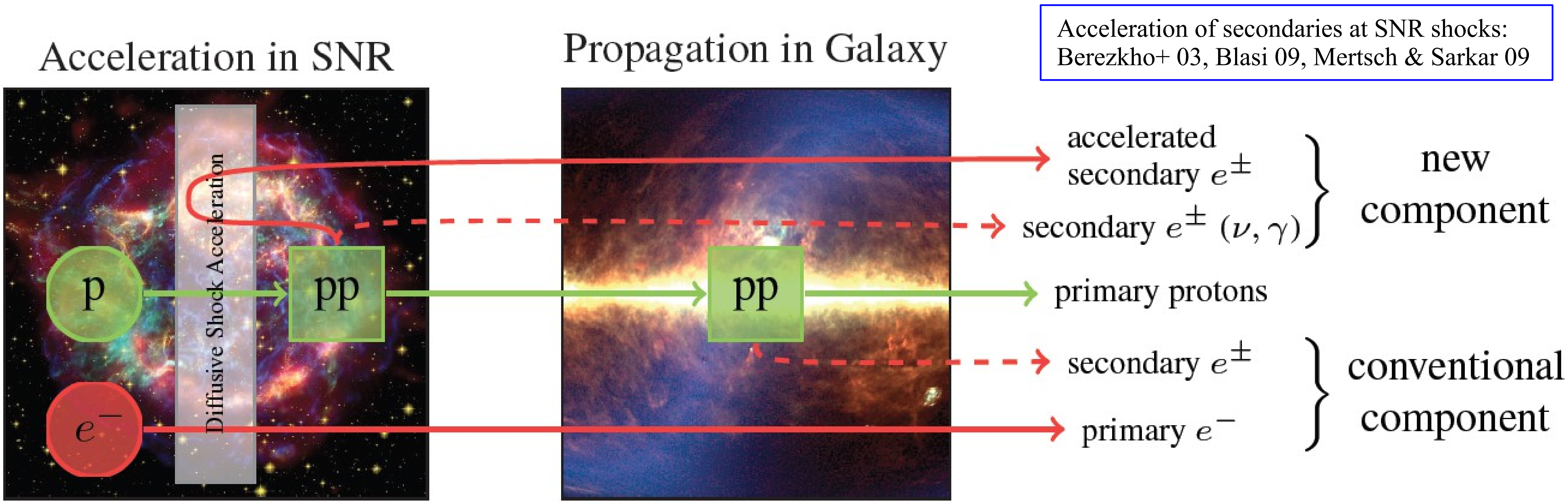


$$\mathcal{B} = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \geq 1$$

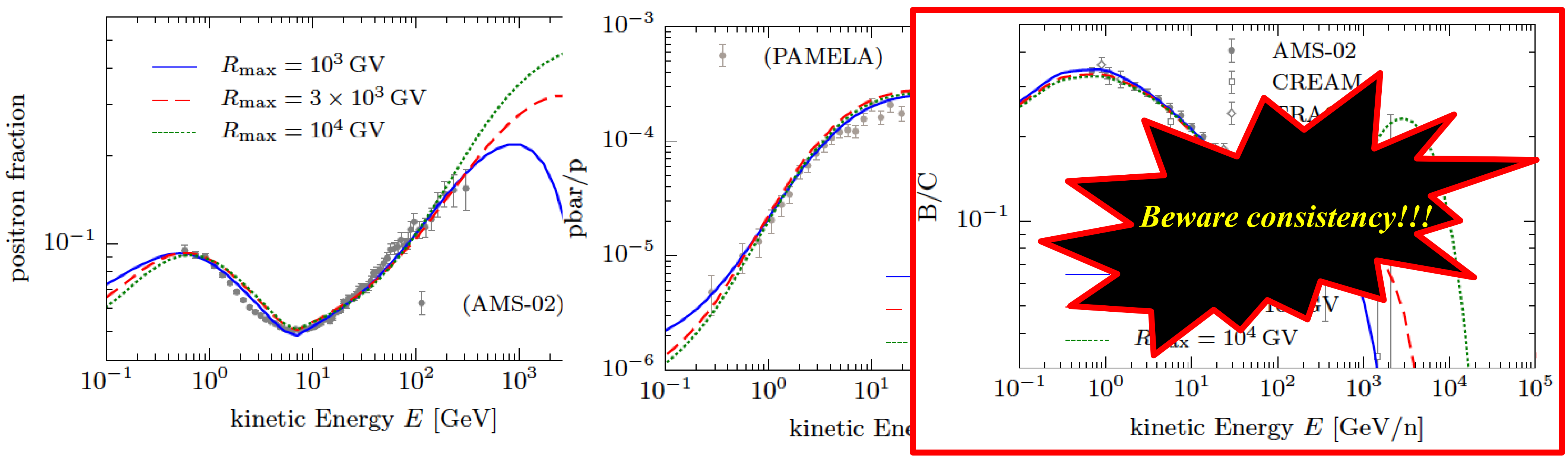
First noticed by Silk & Stebbins 93

The volume over which the average is performed depends on the cosmic messenger!

Primaries?



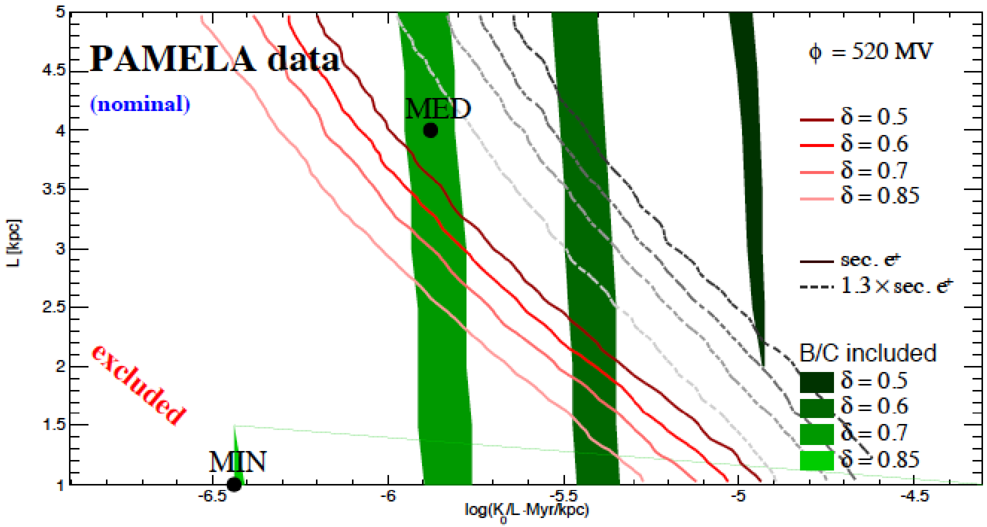
Alhers+ 09



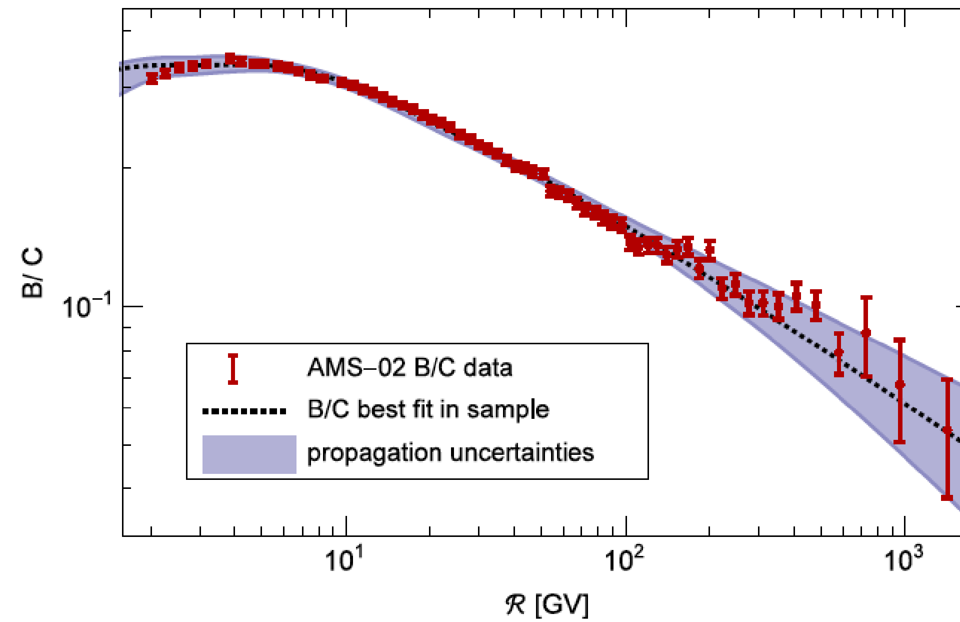
Mertsch & Sarkar 14

From WIMPs to subhalos

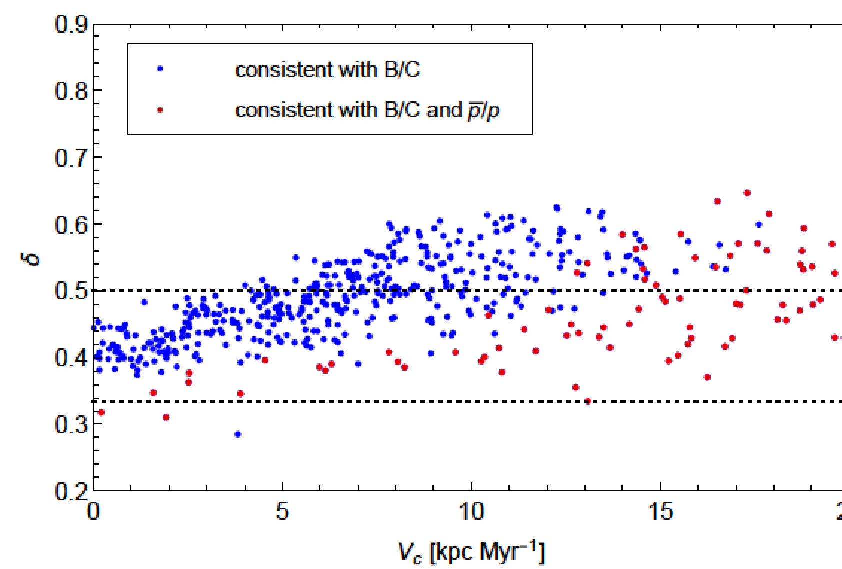
JL, Maurin, Putze 14
Positron constraints on diffusion models



Kappl+15
B/C from AMS-02 prelim. data

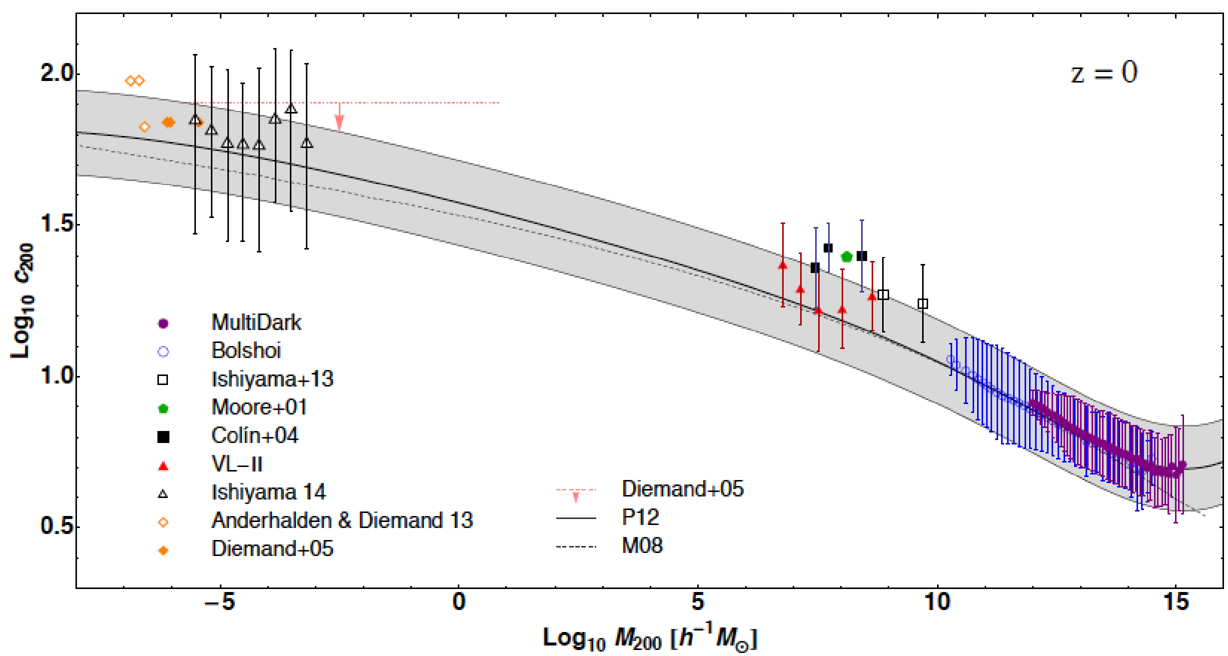


δ	K_0 (kpc^2 Myr^{-1})	L (kpc)	V_c (km s^{-1})	V_a (km s^{-1})
0.408	0.0967	13.7	0.2	31.9



Subhalo concentration

Sanchez-Conde & Prada 13
Compilation of cosmo simulation results



Subhalo flux and variance

Define subhalo flux pdf

$$\langle \phi_{\rm sub} \rangle = \int d\phi \, \phi \, \frac{d\mathcal{P}_\phi(\phi)}{d\phi}$$

Flux pdf completely set by:

$$\frac{d\mathcal{P}_\phi(\phi)}{d\phi} \propto \underbrace{\frac{d\mathcal{P}_V(\vec{x})}{dV}}_{\text{spatial distrib.}} \times \underbrace{\frac{d\mathcal{P}_M(M,\vec{x})}{dM}}_{\text{mass distrib.}} \times \underbrace{\frac{d\mathcal{P}_c(c,M,\vec{x})}{dc}}_{\text{concentration distrib.}}$$

Then average subhalo flux entirely defined (as variance is)

$$\begin{aligned} \langle \phi_{\rm sub} \rangle &= \mathcal{S} \int d^3\vec{x}_s \, \tilde{\mathcal{G}}(\vec{x}_{\rm obs} \leftarrow \vec{x}_s) \, \frac{d\mathcal{P}_V(\vec{x}_s)}{dV} \int dM \, \frac{d\mathcal{P}_M(M,\vec{x}_s)}{dM} \int dc \, \frac{d\mathcal{P}_c(c,M,\vec{x})}{dc} \, \xi(\vec{x}_s, M, c) \\ &= \mathcal{S} \times \langle \tilde{\mathcal{G}} \, \langle \xi \rangle_{c,M} \rangle_V \approx \mathcal{S} \times \langle \tilde{\mathcal{G}} \rangle_V \times \langle \xi \rangle_{c,M} \end{aligned}$$

On the same vein, define statistical variance

$$\sigma_\phi^2 = \langle \phi_{\rm sub}^2 \rangle - \langle \phi_{\rm sub} \rangle^2$$

Testing the mass index

Blanchet & JL 12
Gamma-ray constraints on mass index