Portoroz - 17 Apr 2013

Correlations among Dark Matter Signals

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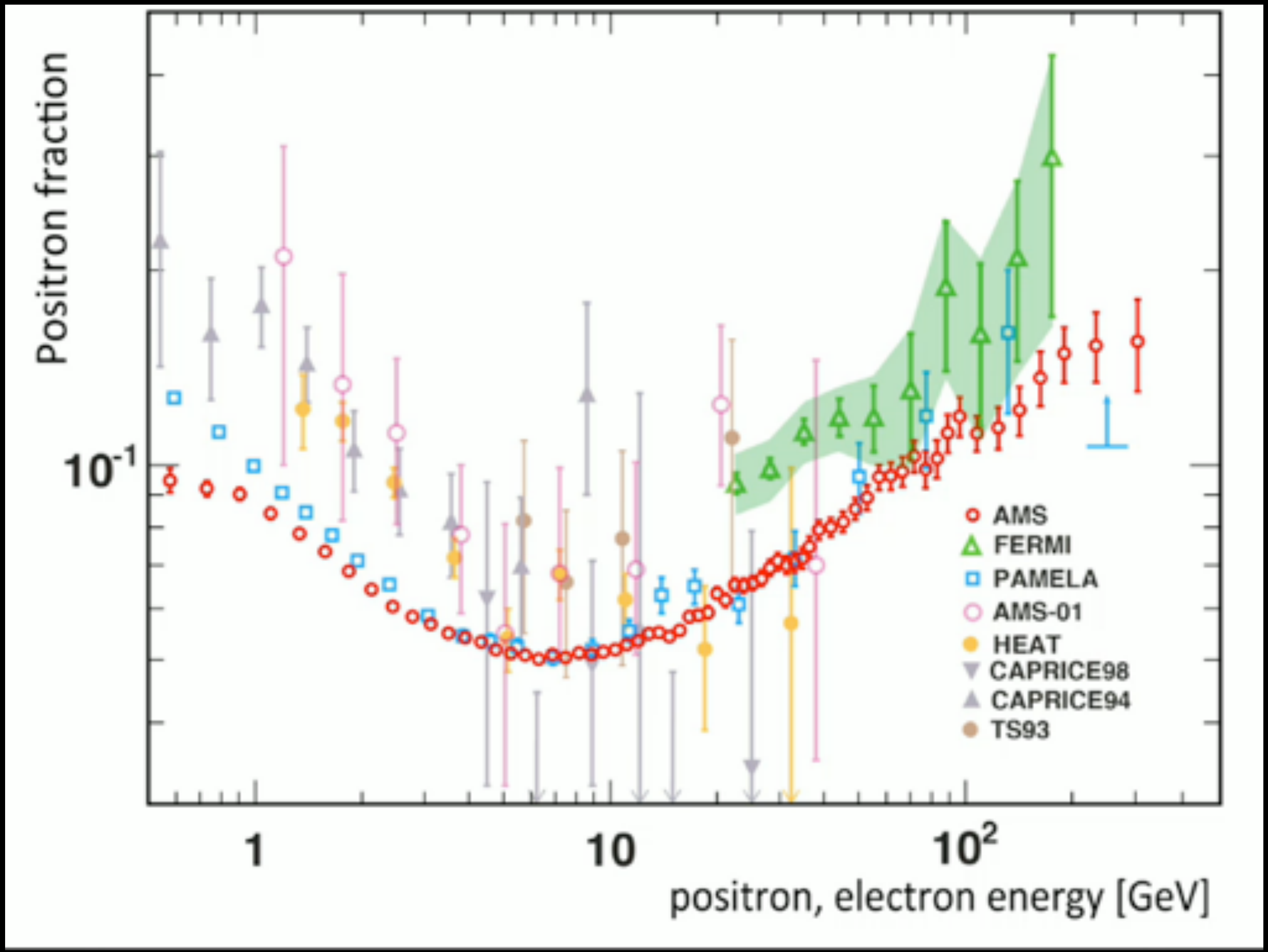
Based on: DS, Riotto, Xue - arXiv:1304.1336

- **AMS-02** has recently released data of positron fraction up to energies of ~350 GeV.

- Excess over “known” bkg, confirming previous **PAMELA** and **Fermi-LAT** measurements.



Recent News

where can positrons come from?

→ Dark Matter annihilations/decay

→ local astrophysical sources (e.g. **pulsars**)

- the Dark Matter explanation of the excess is already strongly constrained by other measurements (e.g. gamma-rays)
- so the astrophysical explanations look very likely

where can positrons come from?

Dark Matter annihilations/decay

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- the Dark Matter explanation of the excess is already strongly constrained by other measurements (e.g. gamma-rays)
- so the astrophysical explanations look very likely
- I want to insist on the DM interpretation and see how far we can get

- quick recap of indirect DM searches and electroweak corrections
- interpretation of new AMS-02 results
- correlations and predictions

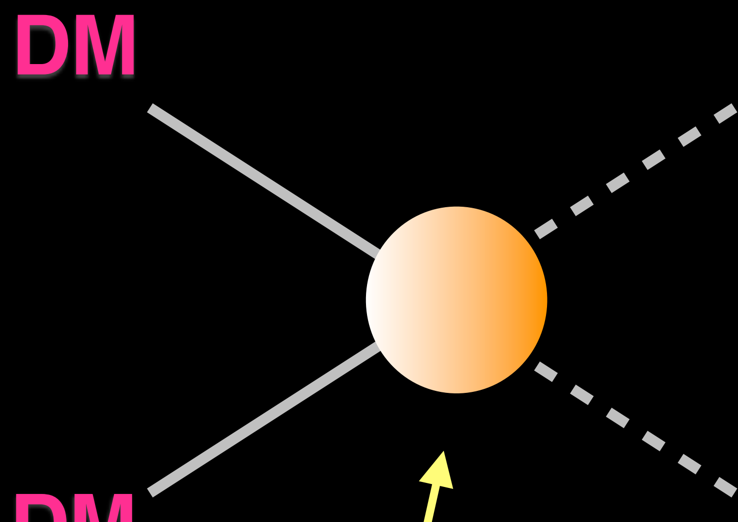
Indirect Detection

$e^+, \bar{p}$ AMS-02, Pamela, Fermi, HESS

γ ATIC, Fermi

ν IceCube, Antares, Km3Net

$\bar{d}$ GAPS, AMS-02



$\ell^-, \bar{q}, W^-, Z, \gamma, \ldots$

primary channels

$\ell^+, q, W^+, Z, \gamma, \ldots$

SM evolution

$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$

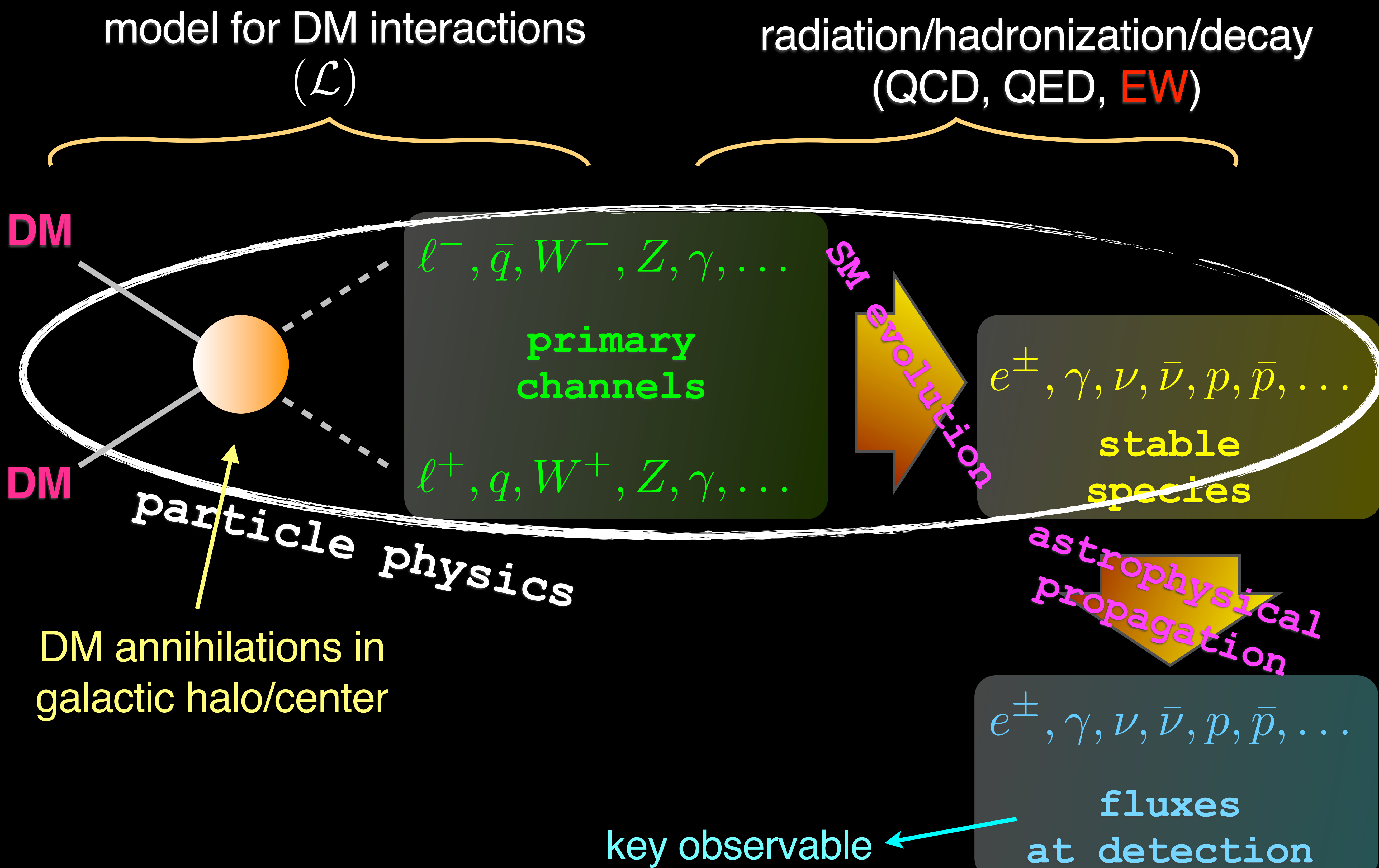
stable species

astrophysical propagation

$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$

fluxes at detection

DM annihilations in galactic halo/center


model for DM interactions
$(\mathcal{L})$
radiation/hadronization/decay
(QCD, QED, EW)
DM
DM
$\ell^-, \bar{q}, W^-, Z, \gamma, \ldots$
primary channels
$\ell^+, q, W^+, Z, \gamma, \ldots$
SM evolution
$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$
stable species
particle physics
astrophysical propagation
DM annihilations in galactic halo/center
$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$
fluxes at detection
key observable

Fluxes of cosmic rays received at Earth: $d\Phi_i/dE \equiv \beta_i n_i/(4\pi)$

where the number density $n_i(r, z, p)$ is the solution of the transport eq.:

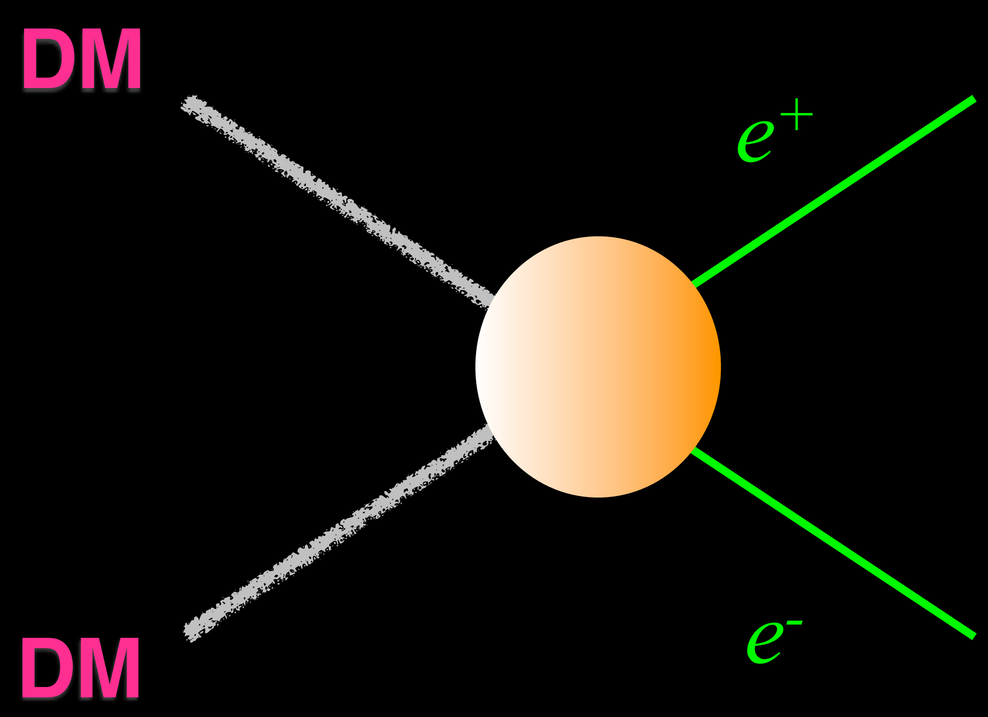
$$\frac{\partial n_i}{\partial t} = \boxed{\underbrace{Q(r,z,p)}_{\text{source}}} + \nabla \cdot \left(\underbrace{D \nabla n_i}_{\text{diffusion}} - \underbrace{\mathbf{V}_c n_i}_{\text{convection}} \right) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} n_i$$

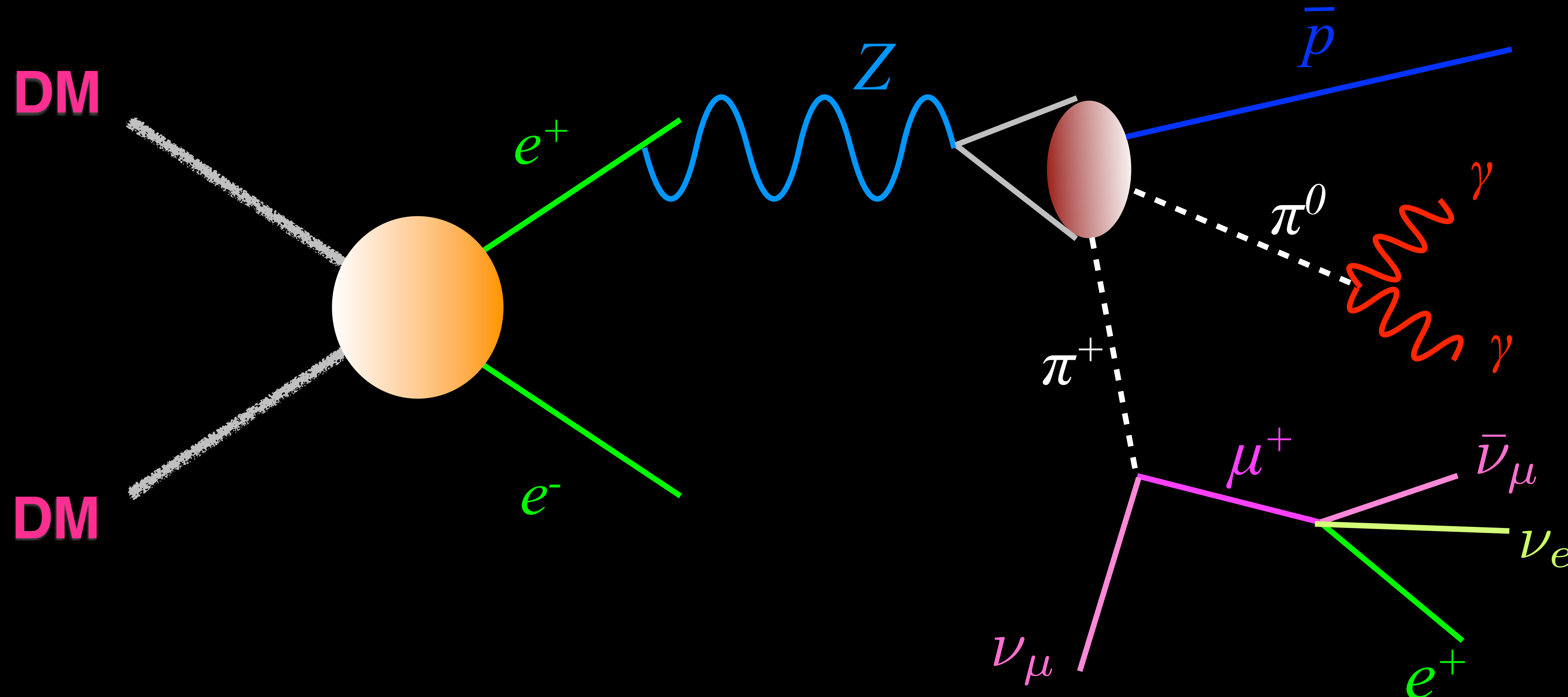
$$- \frac{\partial}{\partial p} \left[\dot{p} n_i - \frac{p}{3} \left(\nabla \cdot \mathbf{V}_c \right) n_i \right] - \underbrace{\frac{1}{\tau_{sp}} n_i}_{\text{spallation}} - \underbrace{\frac{1}{\tau_f} n_i}_{\text{fragmentation}}$$

$$Q(r, z, E) \propto \underbrace{\left[\rho_{\rm DM}(r,z)\right]^2}_{\text{halo profile}} \langle \sigma_{\rm ann} v \rangle \underbrace{\frac{dN_i}{dE}}_{\substack{\text{energy spectrum} \\ \text{of stable particle } i}}$$

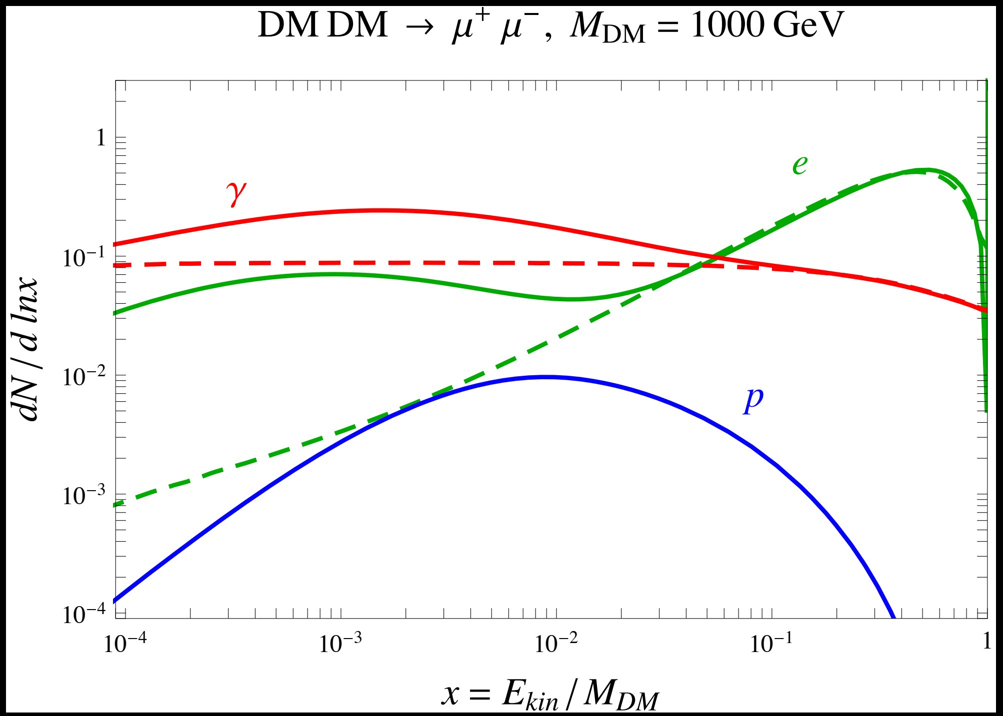
Astrophysics enters into:
- propagation parameters;
- DM halo profile.

Particle Physics enters into:
- energy spectrum dN_i/dE
- cross section $\langle \sigma_{\rm ann} v \rangle$


DM
DM
e^+
e^-

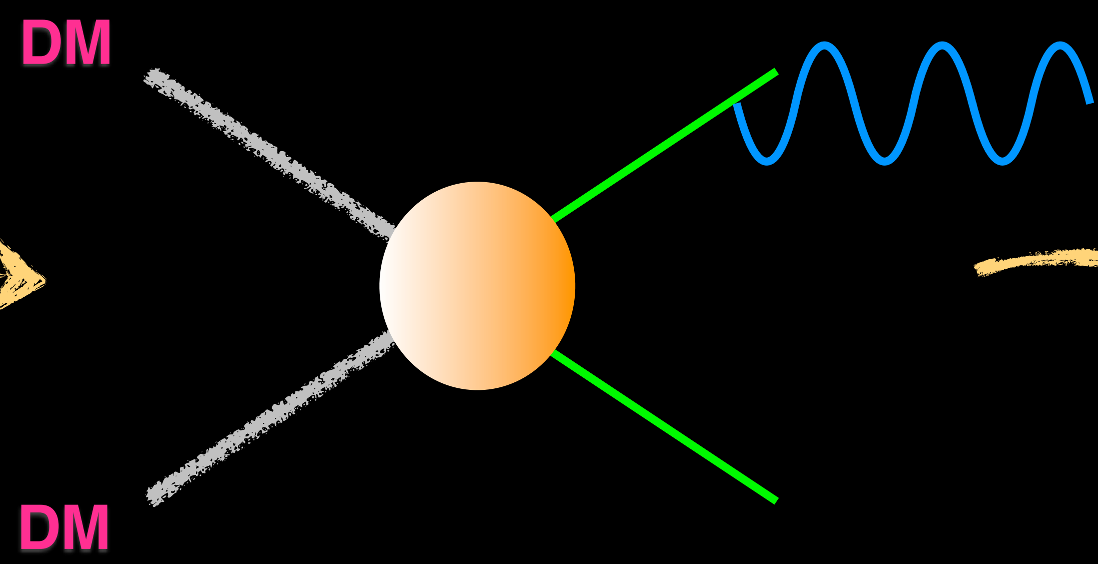


- The final state of DM annihilations can radiate γ,Z,W.
- It is a SM effect, affecting the final fluxes importantly.
- EW interactions connect all SM particles
  → all species will be present in the final state



assume DM
interpretation

fit



EW corrections

signal

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

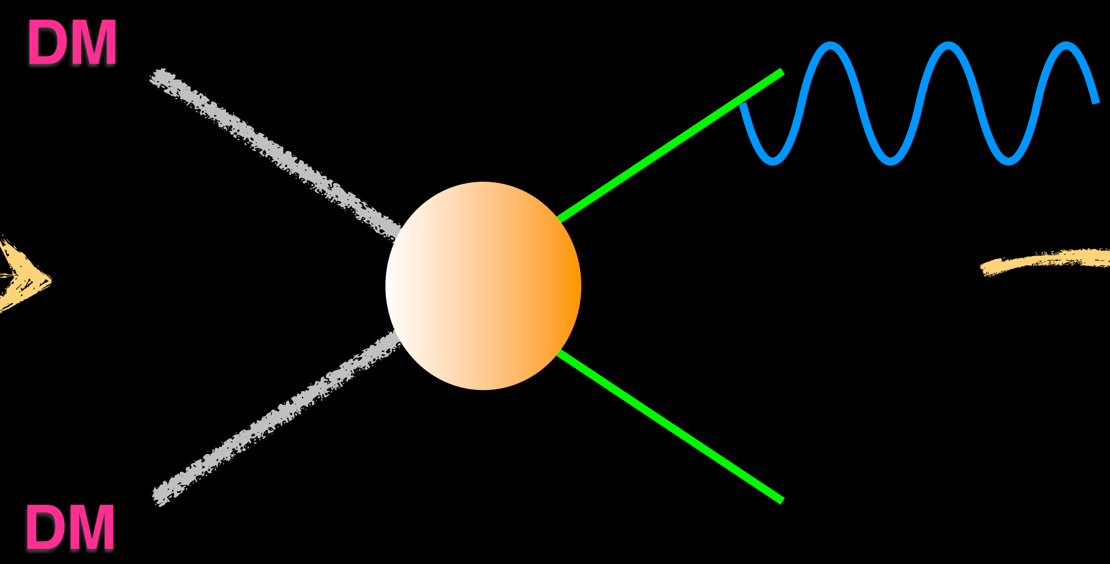
predictions

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

Correlations among DM signals

assume DM interpretation

fit



EW corrections

signal

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

predictions

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

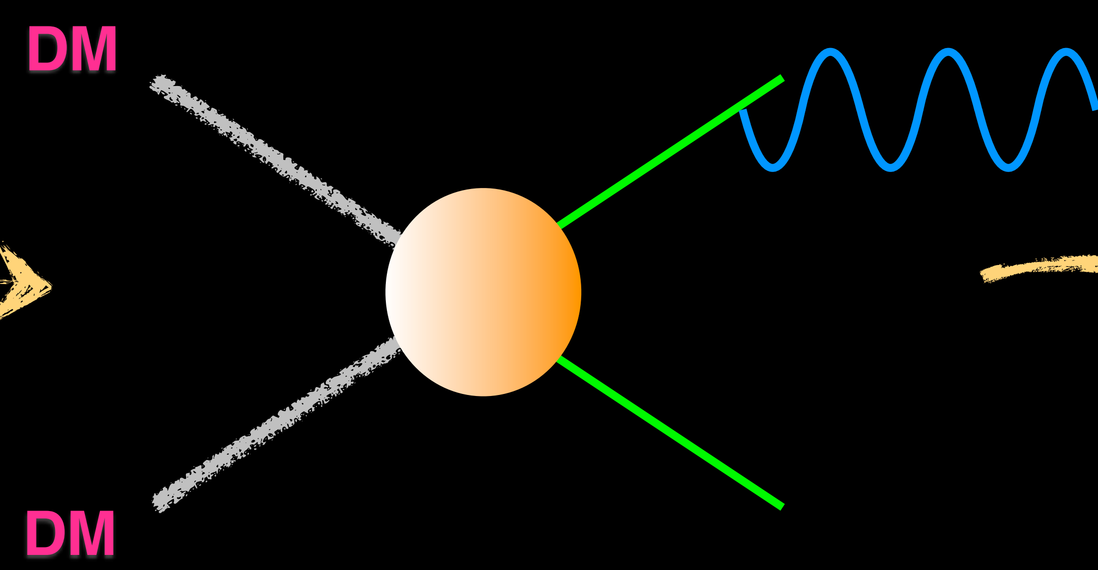
correlated fluxes

test with current/future data

verify/reject initial hypothesis

assume DM interpretation

fit



EW corrections

signal

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

predictions

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

correlated fluxes

✓ robust
✓ timely

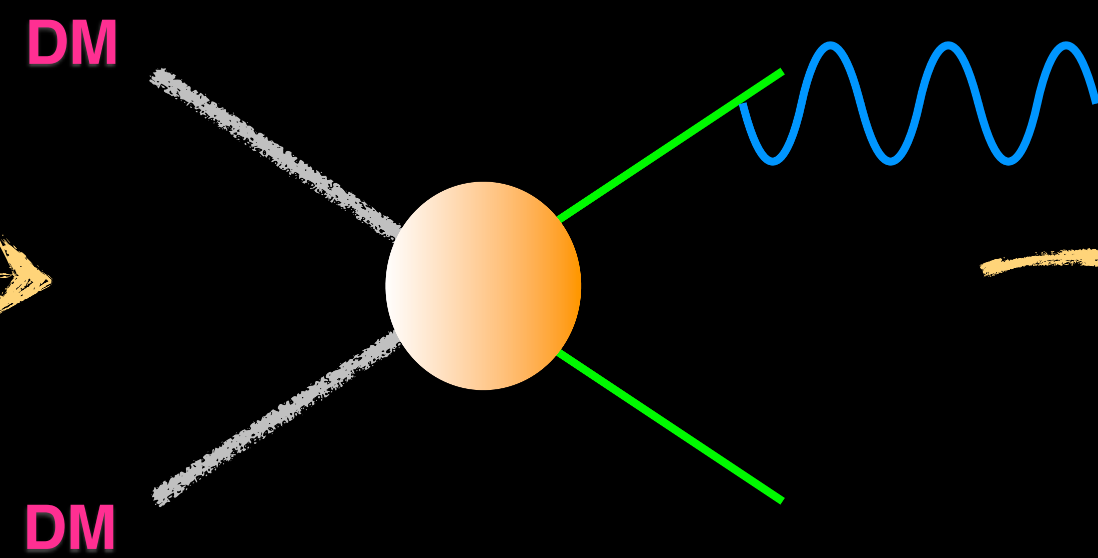
test with current/future data

verify/reject initial hypothesis

Correlations among DM signals

assume DM interpretation

fit



EW corrections

signal

$\boxed{e^+}$

predictions

$\boxed{\bar{p}}$

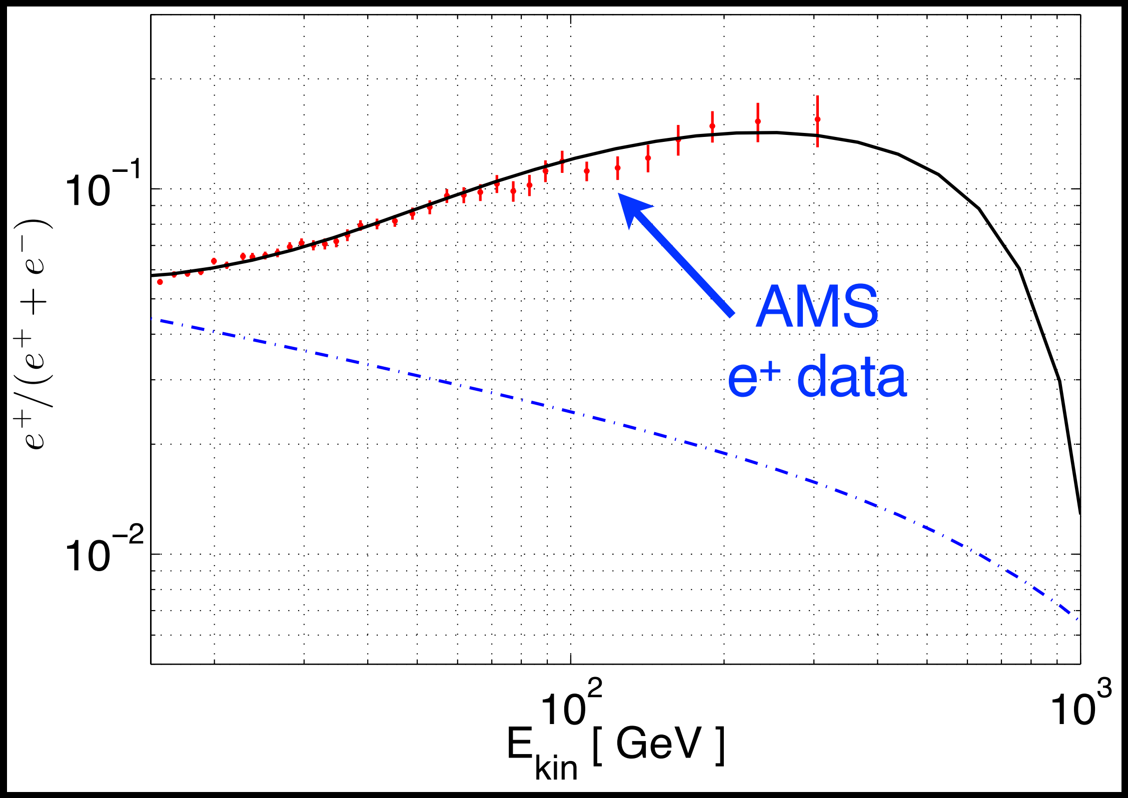
correlated fluxes

test with current/future AMS data

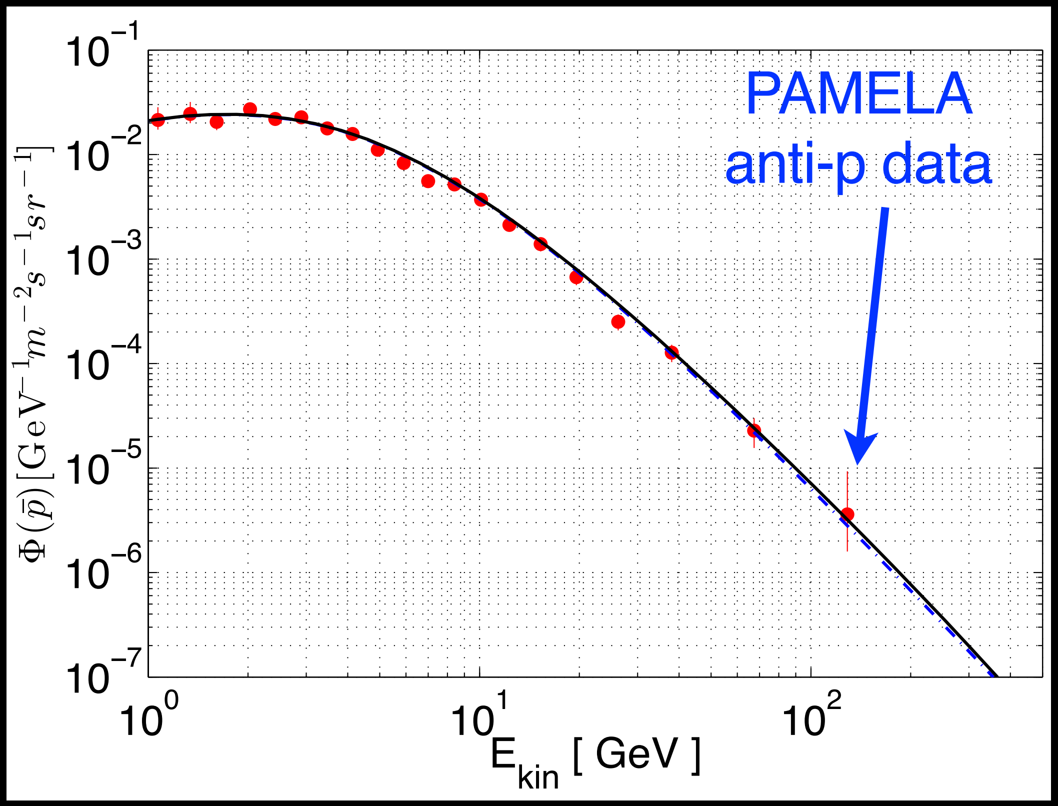
verify/reject initial hypothesis

possible interpretation as DM,
without upsetting the anti-p flux

positron fraction



anti-protons



$$\mathrm{DM\,DM} \to \tau^+\tau^-$$

$$M_{\mathrm{DM}} = 1\,\mathrm{TeV}$$

$$\langle \sigma_{\mathrm{ann}} v \rangle = 2.5 \times 10^{-23}\,\mathrm{cm^3 s^{-1}}$$

- before claiming any signal, bkg should be under control

- e^+ and anti-p fluxes (both **signal** & **background)** closely related: propagation from source to detection within the same environment

- cosmic-ray propagation is a very complex phenomenon, affected by several uncertainties

- crucial to use **consistently** the same propagation setup for all particle species involved in the analysis.

Method 1

Signal: propagate with "MED" propagation model
Bkg: reference one with floating normalizations and slopes

$$\Phi_i^{\rm bkg}(E, A_i, p_i) = A_i\, E^{p_i}\, [\Phi_i^{\rm bkg}(E)]_{\rm reference} \qquad\qquad (i = e^+, e^-, \bar{p})$$

then marginalize over A, p parameters.

✘ fluxes of different species are treated as uncorrelated;
✓ deal with astrophys. uncert. in a simple and conservative way.

Method 2

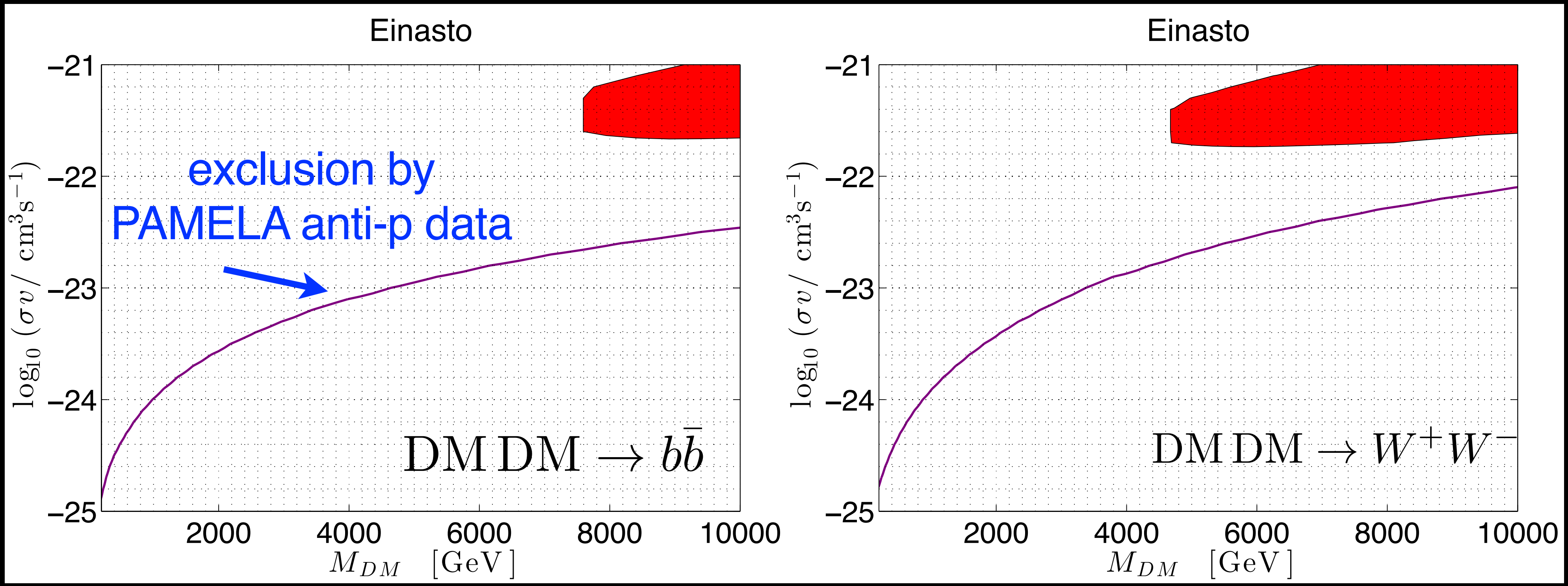
Propagate signal and bkg with our own propagation model, which provides a good fit to several data-sets (electron+positron, anti-p, Boron-to-Carbon ratio).

✘ not generic;
✓ consistent propagation of all species, for both signal and bkg.

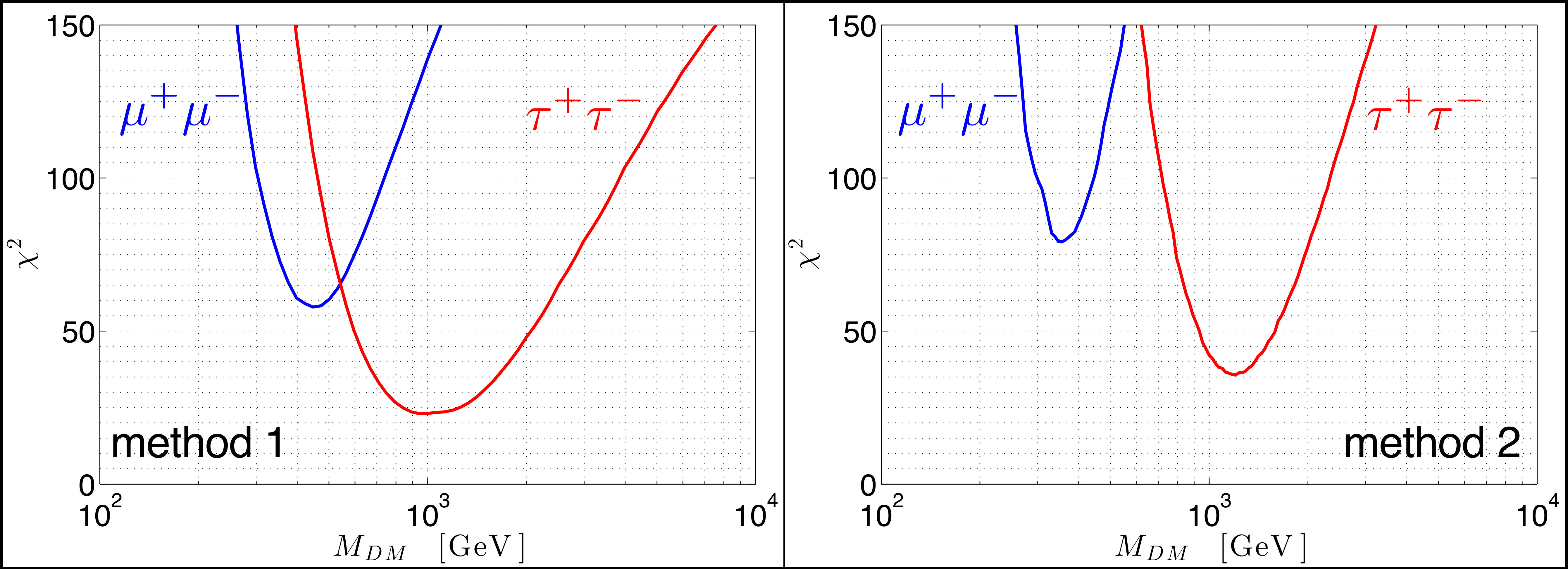
annihilation channels? $\mathrm{DM}\,\mathrm{DM} \to q\bar{q}, \ell^+\ell^-, W^+W^-, ZZ, hh, \ldots$

ALL channels produce hadrons (due to EW corrections), can easily upset anti-p data

Ex.



only **leptonic** annihilation channels are still allowed



- use only data with E>15 GeV (not affected by solar modulation)
- number of dof: 36-6=30 (method 1), 36-2=34 (method 2)
- e^+e^- gives even higher χ^2

$\chi^2_{\min}/\mathrm{dof}$

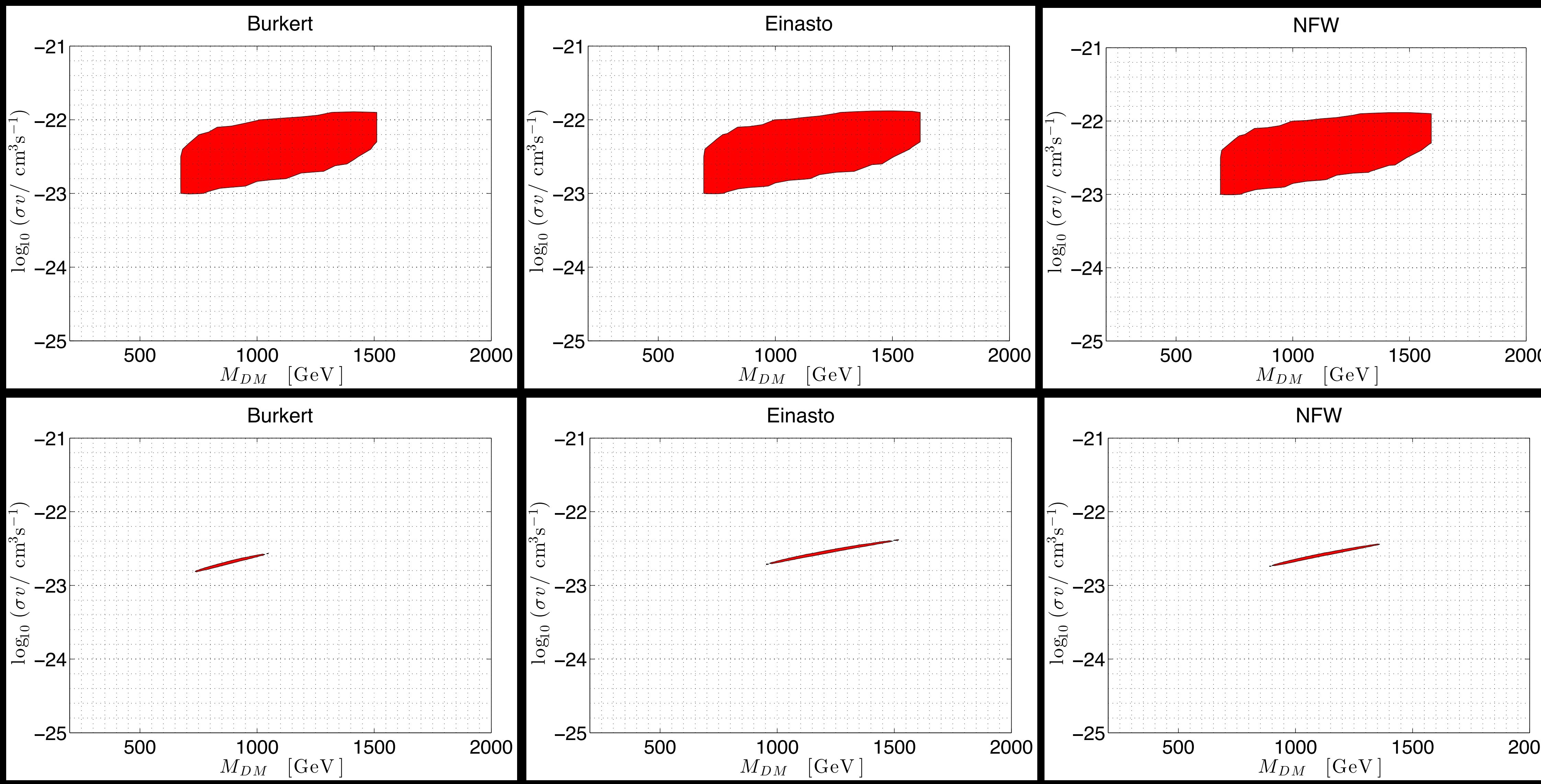
	$\mu^+\mu^-$	$\tau^+\tau^-$
method 1	1.9	0.7
method 2	2.4	1.0

only good fit to AMS-02: DM of ~ 1 TeV annihilating into taus

3σ best-fit contours for $\mathrm{DM\ DM} \to \tau^+\tau^-$

Method 1

Method 2

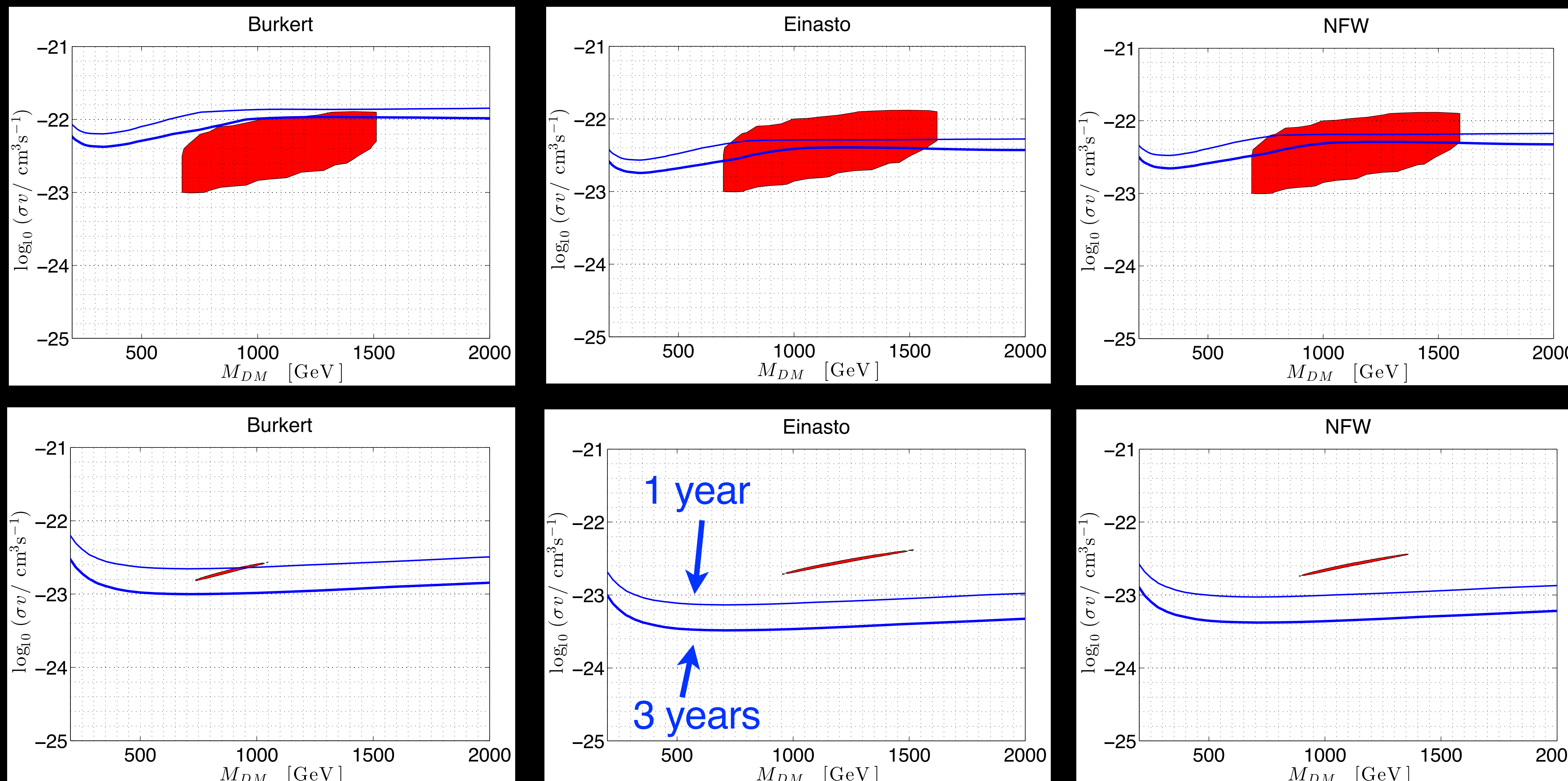


method 2 is more constrained → smaller contours

- we simulated projected (mock) data for anti-p, consistent with understanding of detector features from outside the collaboration

Method 1

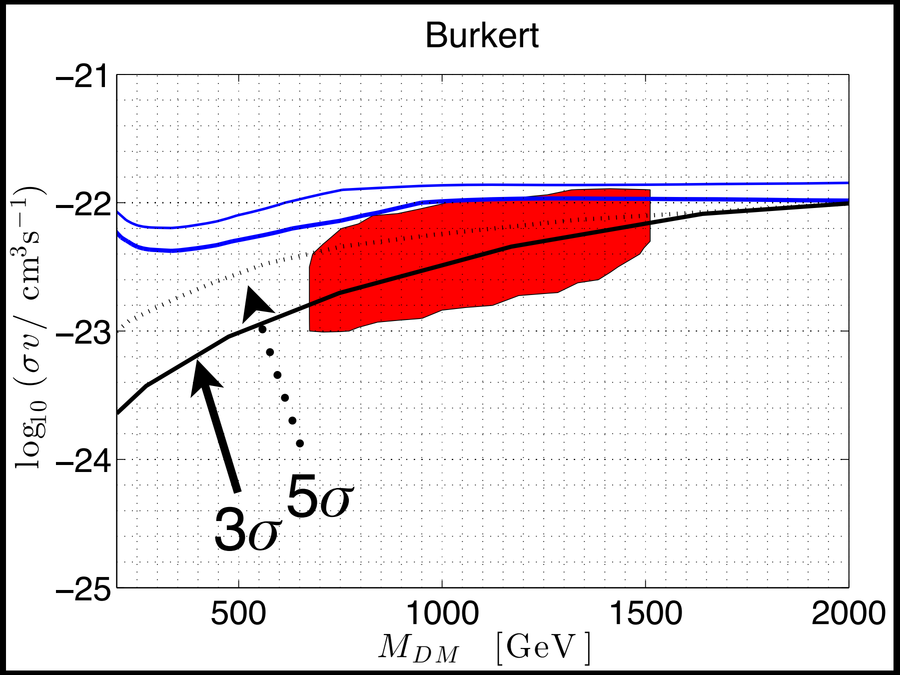
Method 2



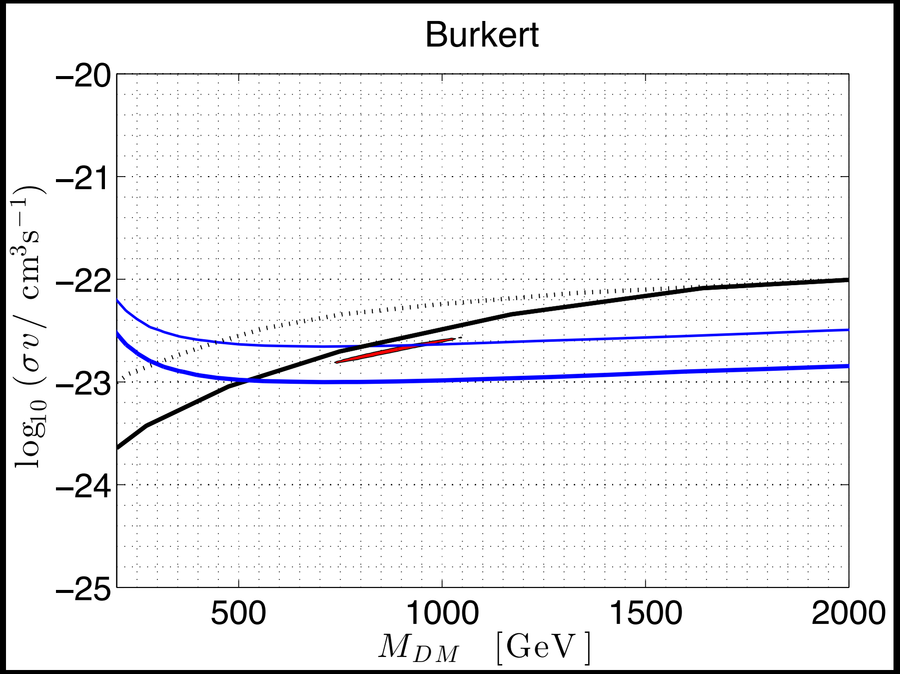
- 3 years of AMS-02 anti-p data would be enough to rule out *almost* competely the DM interpretation of the positron rise taking into account Fermi-LAT diffuse gamma-ray constraints

[Fermi-LAT Coll.- 1205.6474]

Method 1



Method 2



best-fit regions for other halo profiles are mostly excluded tension with $e^+ + e^-$ Fermi-LAT data, showing no drop up to ~1 TeV

[Cirelli et al. - 0809.2409v2]

need somewhat exotic annihilation channels ($\mathrm{DM\ DM} \to \phi\phi \to 2\mu^+ 2\mu^-$), perhaps with a break in the injection spectrum of primary electrons

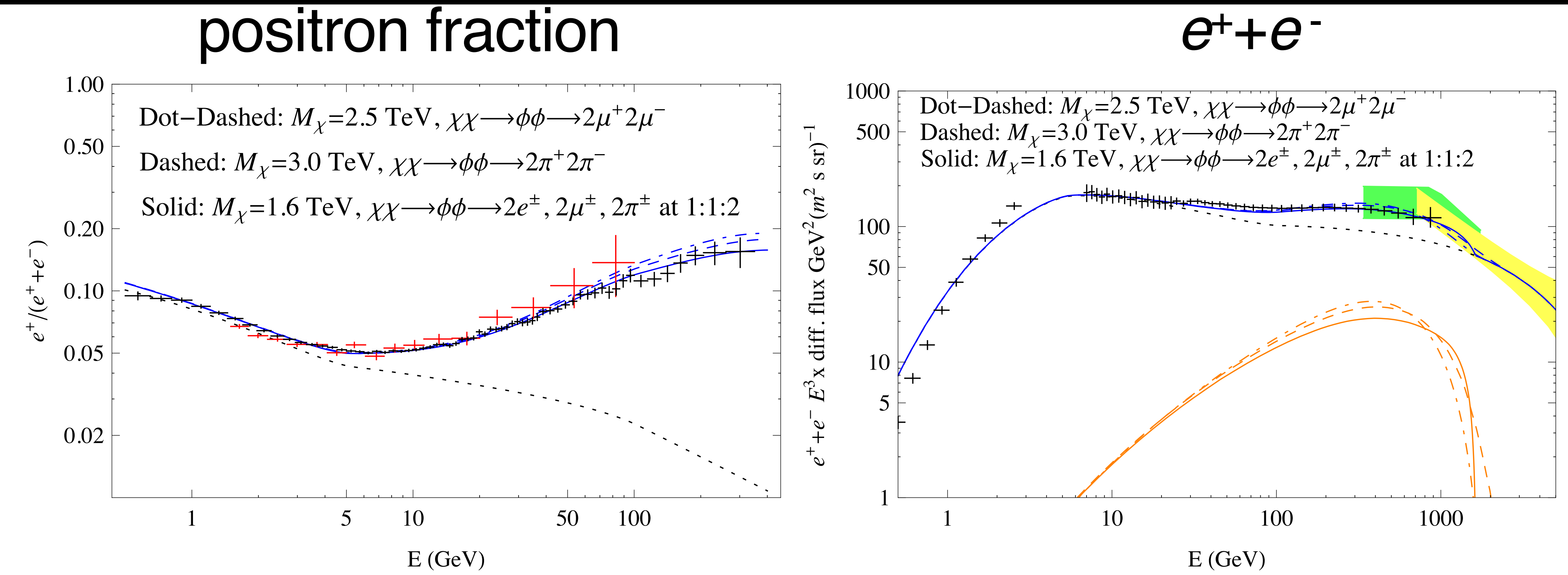


FIG. 6: The same as in Figs. 1, 2, 4 and 5 but for a diffusion zone half-width of $L = 8$ kpc, and for broken power-law spectrum of electrons injected from cosmic ray sources ($dN_{e^-}/dE_{e^-} \propto E_e^{-2.65}$ below 100 GeV and $dN_{e^-}/dE_{e^-} \propto E_e^{-2.3}$ above 100 GeV). The cross sections are the same as given in the caption of Fig. 5. With this cosmic ray background, the dark matter models shown can simultaneously accommodate the measurements of the cosmic ray positron fraction and the overall leptonic spectrum.

[Cholis, Hooper - 1304.1840]

Conclusions

* Complementarity: robust conclusions on the nature of DM should come from correlations of different signatures among different expts. (crucial role played by EW corrections)

* Interpretation of AMS-02 recent results on positron fraction:

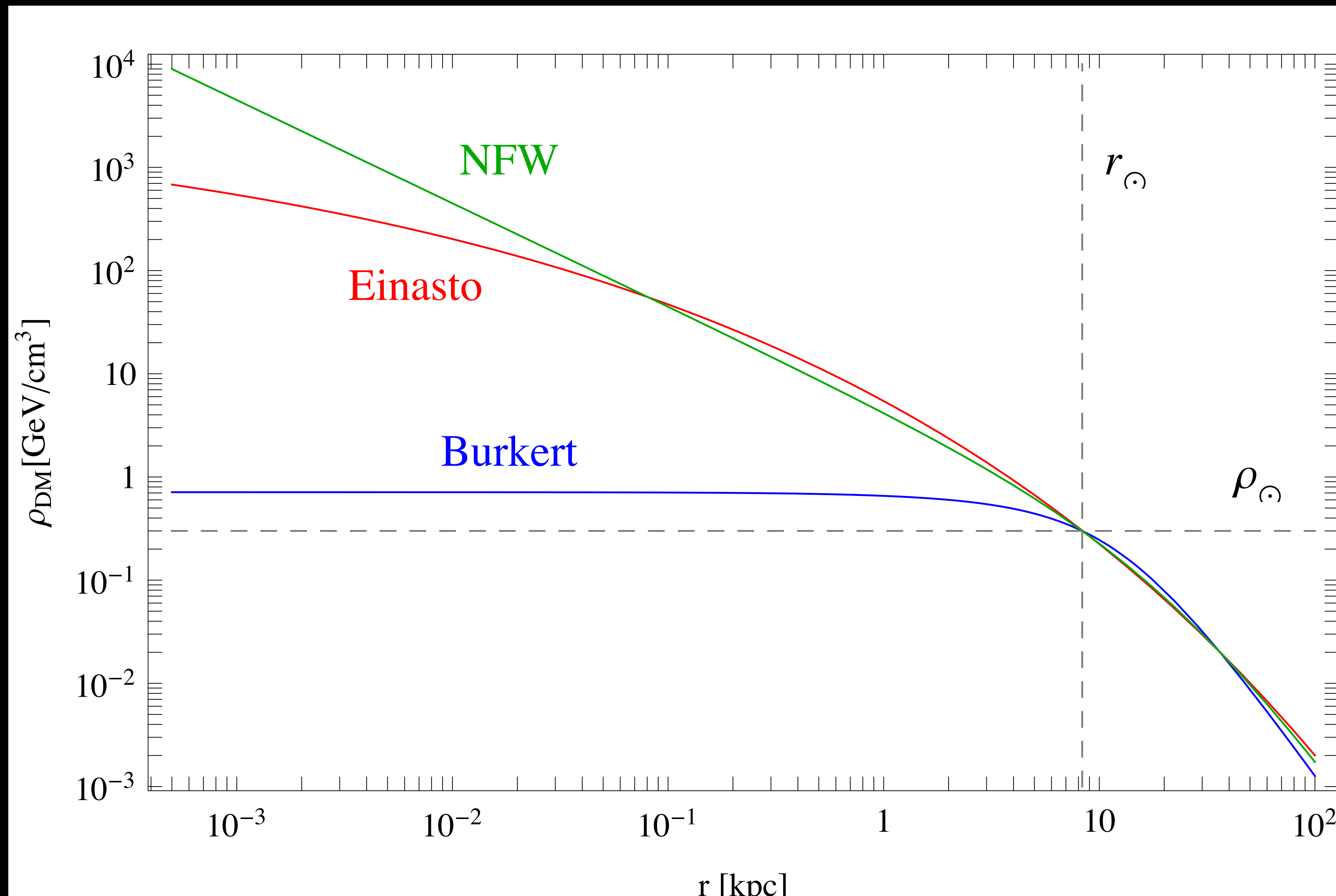
  * if data are interpreted as a signal of DM, the χ^2 favours: M_{DM} ~1 TeV, $\mathrm{DM\ DM} \to \tau^+\tau^-$
  * assuming no signal in future anti-p data
    → exclude almost completely the DM origin of the e^+ excess

we are on the verge of ruling out, once for all, the DM origin of the positron excess

* What's next?
  * break degeneracy with pulsars, using EW corrections;
  * explore more correlations (neutrinos, gamma-rays etc.)
  * wait for next AMS-02 data releases...

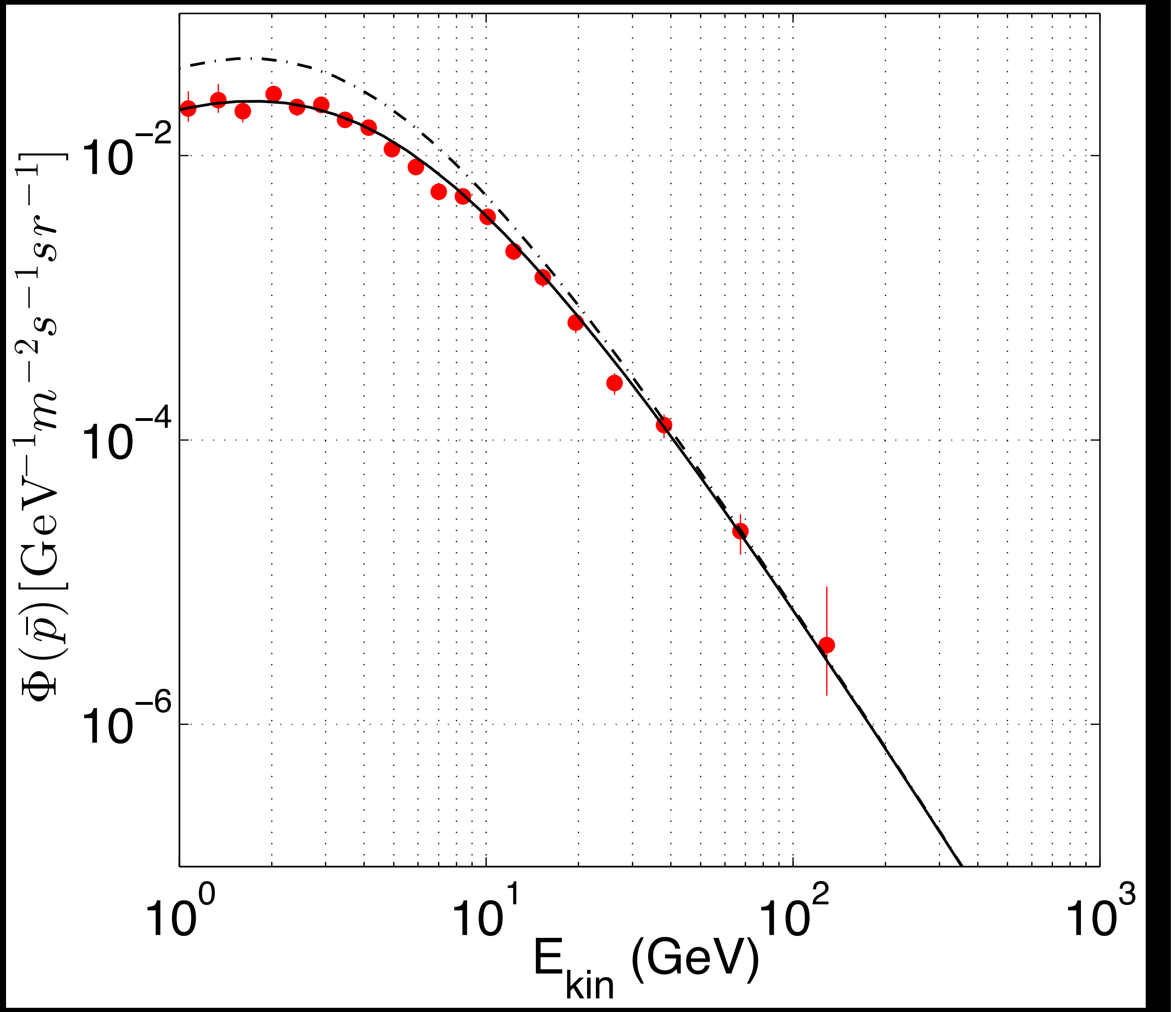
BACK-UP SLIDES

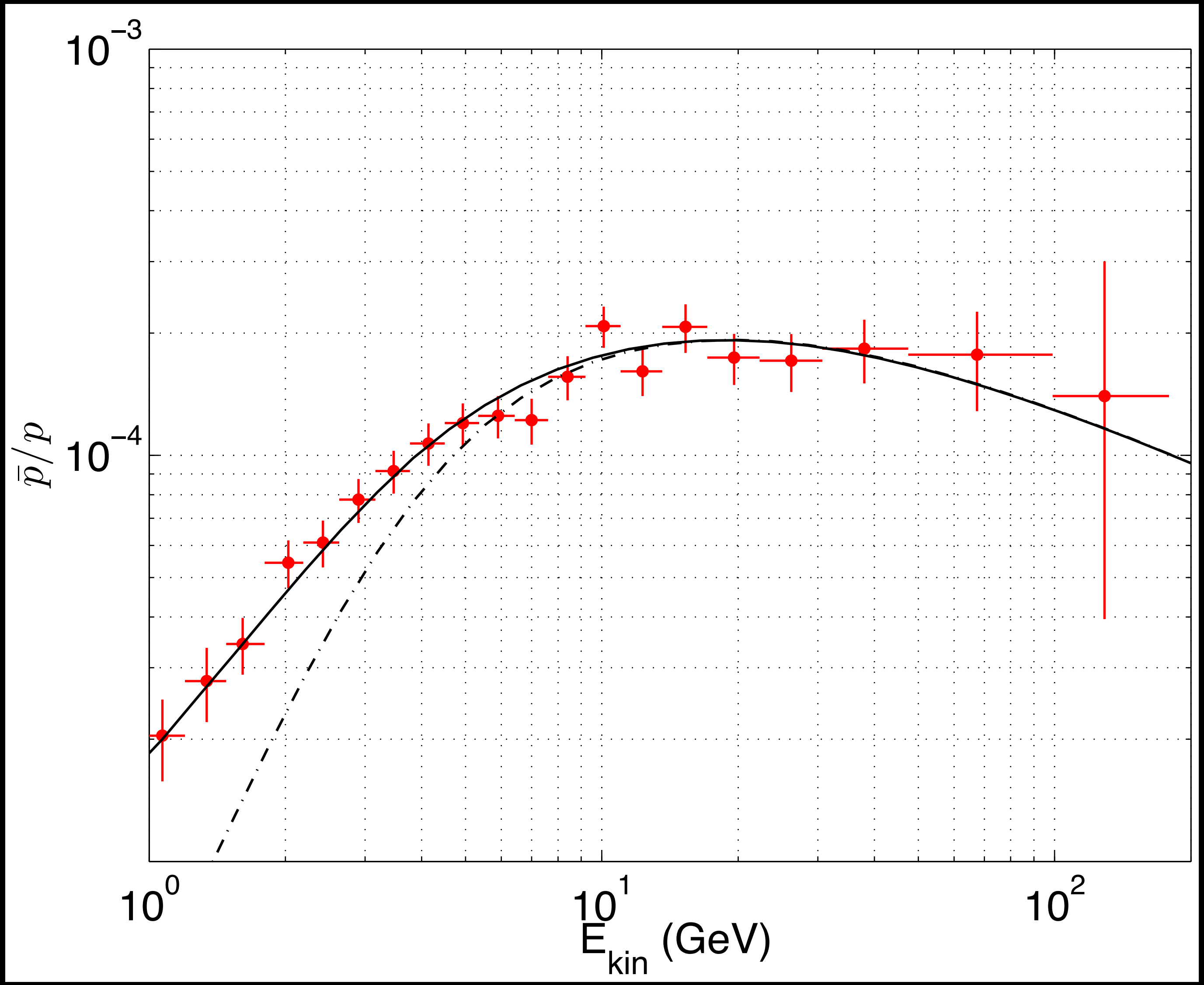
Halo Profiles



$$\rho(r) = \begin{cases} \rho_s \left[(1+r/r_s)(1+(r/r_s)^2)\right]^{-1}, & r_s = 12.67 \text{ kpc}, \quad \rho_s = 0.712 \text{ GeV/cm}^3, \quad \text{(Burkert)} \\ \rho_s \exp\left[-\frac{2}{0.17}\left[(r/r_s)^{0.17} - 1\right]\right], & r_s = 28.44 \text{ kpc}, \quad \rho_s = 0.033 \text{ GeV/cm}^3, \quad \text{(Einasto)} \\ \rho_s (r_s/r)\,(1+r/r_s)^{-2}, & r_s = 24.42 \text{ kpc}, \quad \rho_s = 0.184 \text{ GeV/cm}^3, \quad \text{(NFW)} \end{cases}$$

Fits of our reference propagation model to anti-p PAMELA data





solid/dashed = with/without correcting for solar modulation

EW corrections to DM annihilations are important in 3 cases:

1. when the low-energy regions of the spectra, which are largely populated by the decay products of the emitted gauge bosons, are the ones contributing the most to the observed fluxes;

2. when some species are absent without EW corrections (e.g. antiprotons from $\chi\chi \to \ell^+\ell^-$);
[Ciafaloni, Comelli, Riotto, Sala, Strumia, Urbano, 1009.0224]

3. when σ(2 →3), with soft gauge boson emission, is comparable or even dominant with respect to σ(2 →2):

   - DM Majorana fermion/real scalar and SM singlet;
   [Ciafaloni, Cirelli, Comelli, DS, Riotto, Urbano - 1104.2996]
   [DS, Monin, Thamm, Urbano - 1301.1486]

   - DM Majorana fermion/real scalar in an *$SU(2)_L$*-multiplet.
   [Ciafaloni, Cirelli, Comelli, DS, Riotto, Urbano - 1107.4453]
   [Ciafaloni, Comelli, DS, Riotto, Urbano - 1202.0692]