Higgs and BSM Physics at the LHC
ICTP, Trieste - 25 June 2013

Dark Matter: update and news

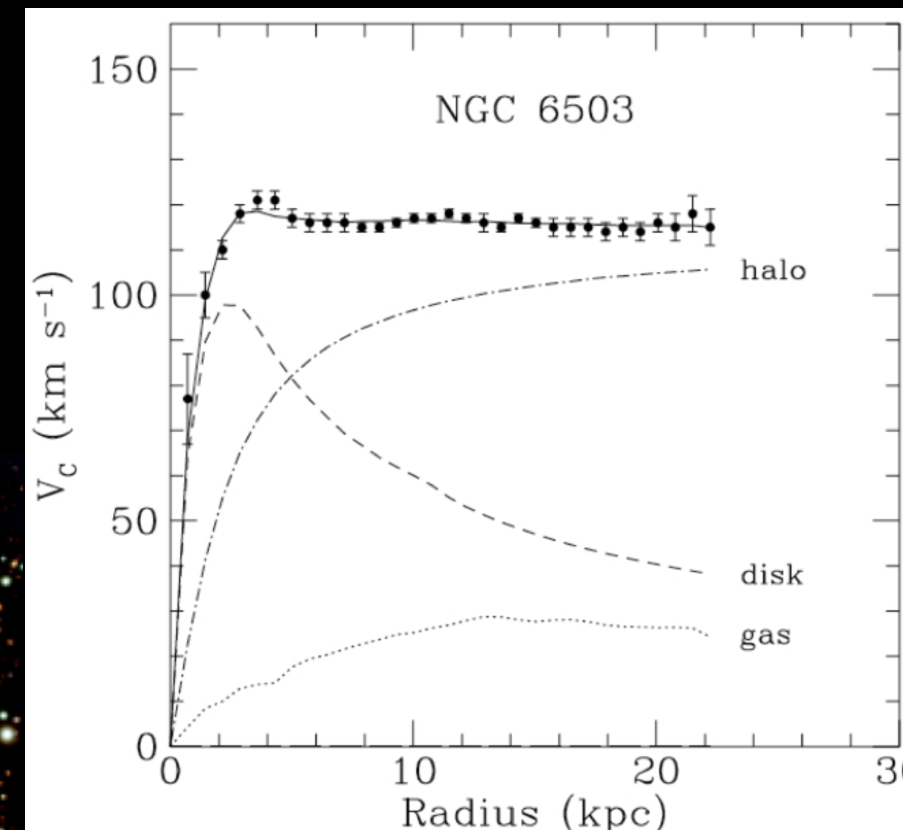
Andrea De Simone

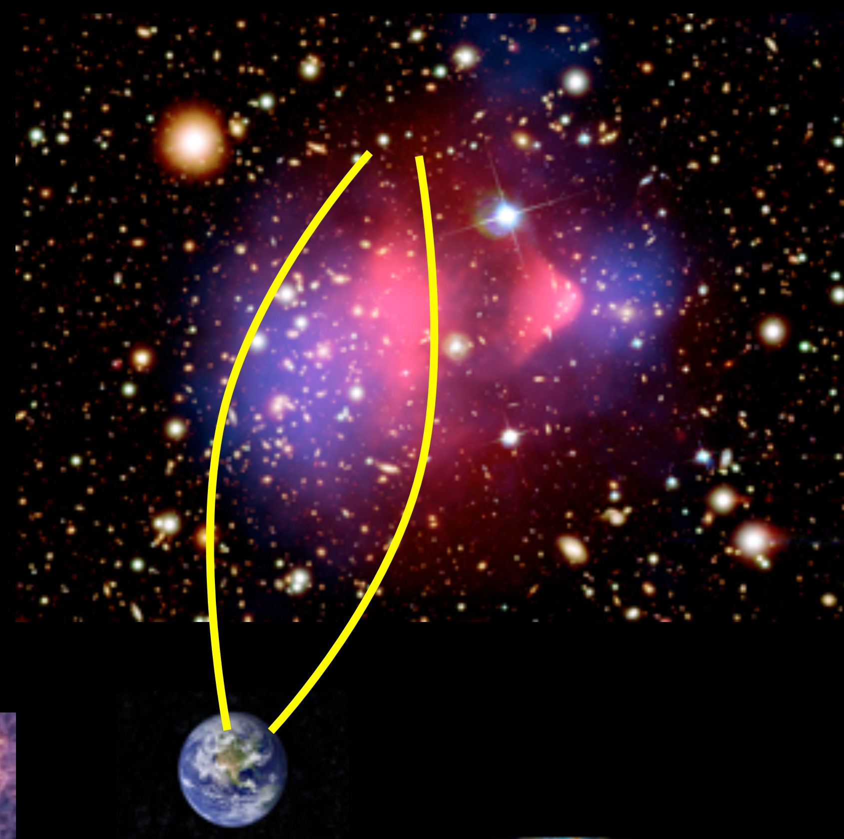
Based on:
DS, Riotto, Xue - JCAP 05(2013)003 [1304.1336]
Busoni, DS, Morgante, Riotto - to appear

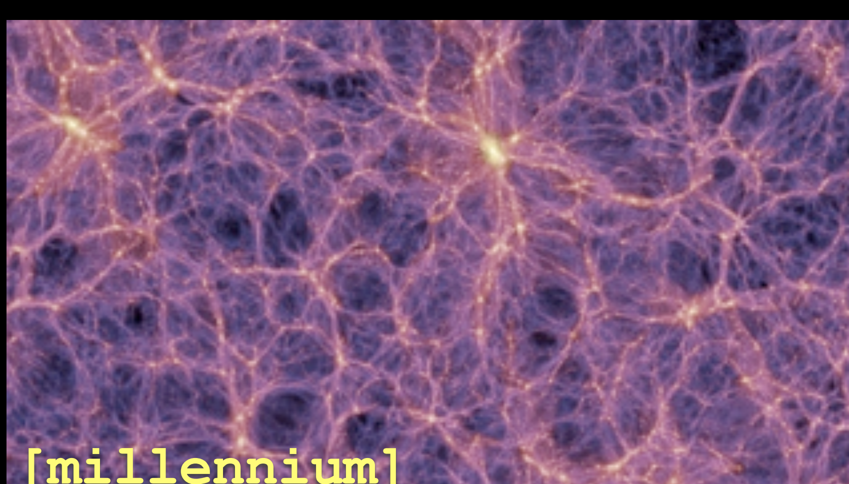
- Status of Dark Matter Searches
- Indirect Searches:
  New AMS-02 Data, Interpretation and Predictions
- Collider Searches:
  Validity of EFT approach

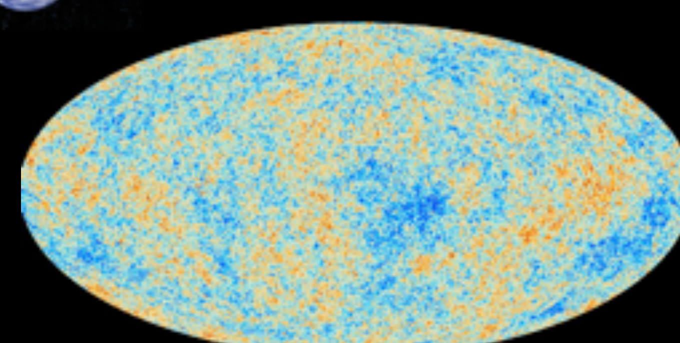
Evidences for DM

- rotation curves of galaxies
- gravitational lensing
- CMB+LSS

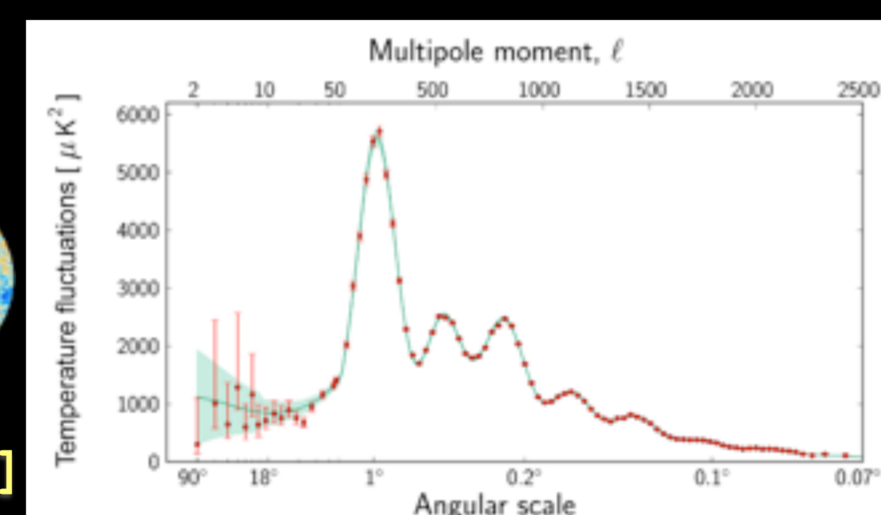








[Planck]



(an incomplete list)

WIMP	**non-WIMP**
neutralino	axion
minimal DM	gravitino
heavy neutrino	axino
inert Higgs doublet	sterile neutrino
LKP	techni-baryon,
LTP	Q-balls
...	...

(an incomplete list)

WIMP	non-WIMP
neutralino	axion
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LKP	techni-baryon,
LTP	Q-balls
...	...

After LHC run-I,
are we still confident of weak-scale DM?

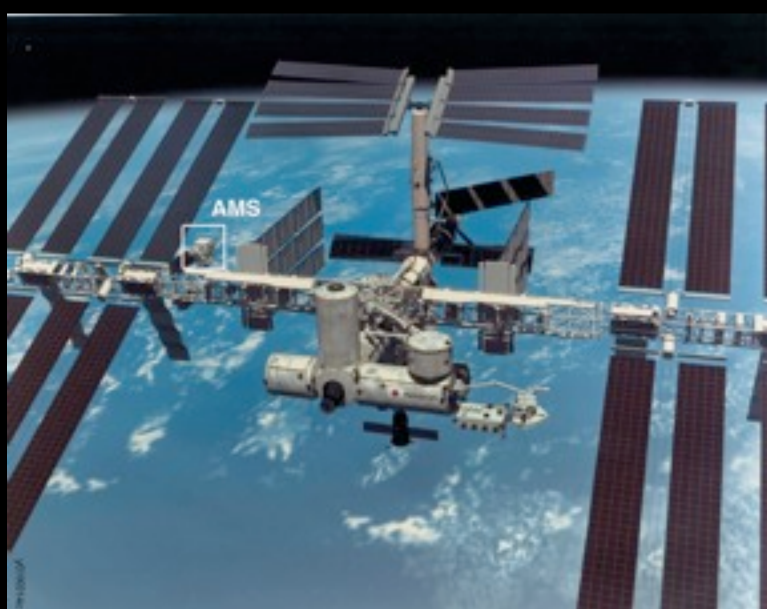
COLLIDER

$$p\,p \to \mathrm{DM} + X$$

LHC

INDIRECT DETECTION

$$\mathrm{DM}\;\;\mathrm{DM} \to e^+e^-\,,\ldots$$



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

γ **ATIC, Fermi**

ν **IceCube, Antares, Km3Net**

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

DIRECT DETECTION

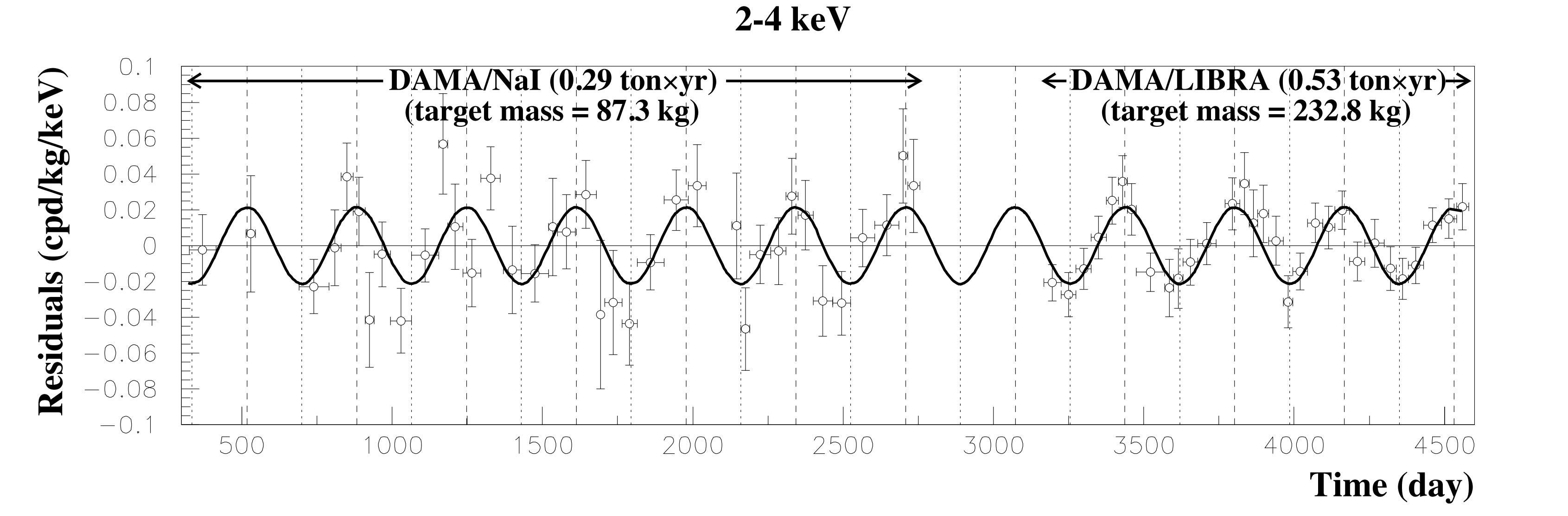
$$\mathrm{DM}\;\;\mathrm{Nucleus} \to \mathrm{DM}\;\;\mathrm{Nucleus}$$

Xenon, CDMS, CRESST, CoGeNT, Edelweiss...

- positive hints/signals

DAMA/Libra (NaI)

8σ observation of annual modulation



[DAMA Coll - 0804.2741]

CoGeNT (Ge)

2.7σ annual modulation

[CoGeNT Coll - 1106.0650]

CRESST ($CaWO_4$)

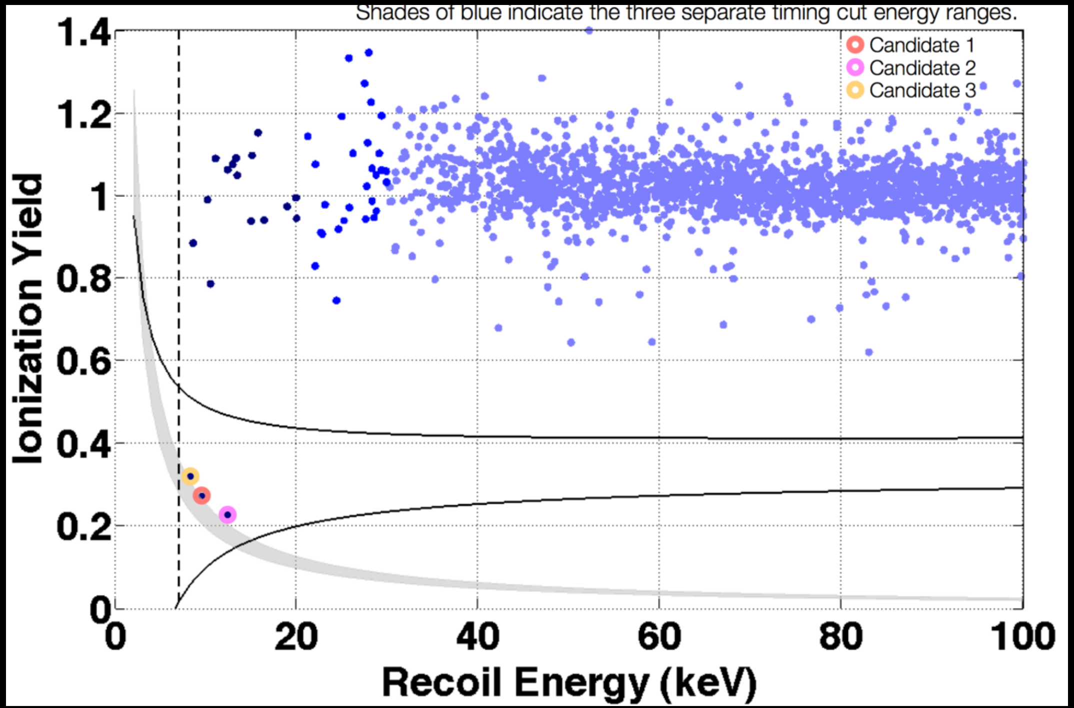
67 events, ~4σ

[CRESST - 1109.0702]

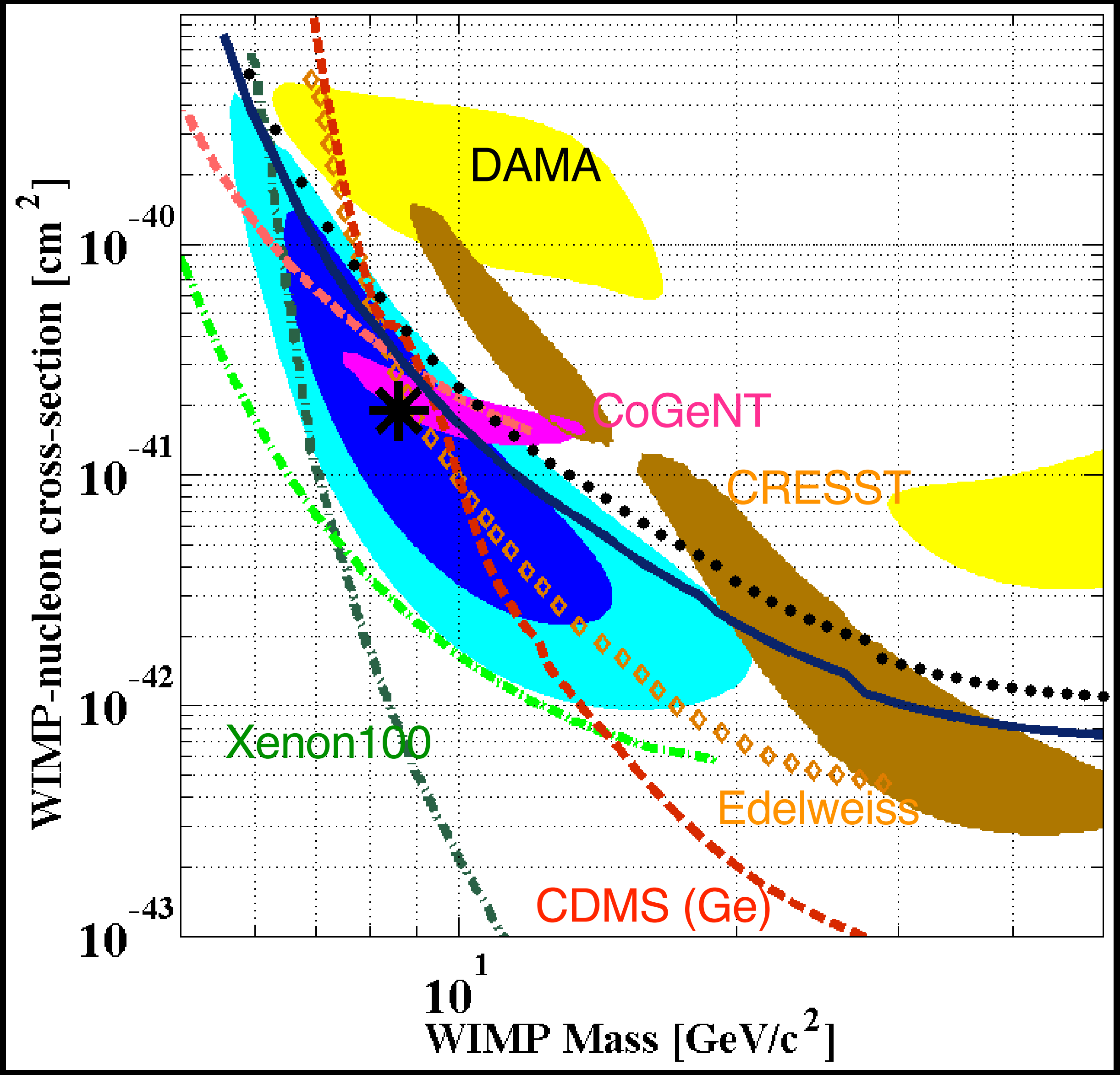
CDMS (Si)

3 events, <3σ

[CDMS - 1304.4279]

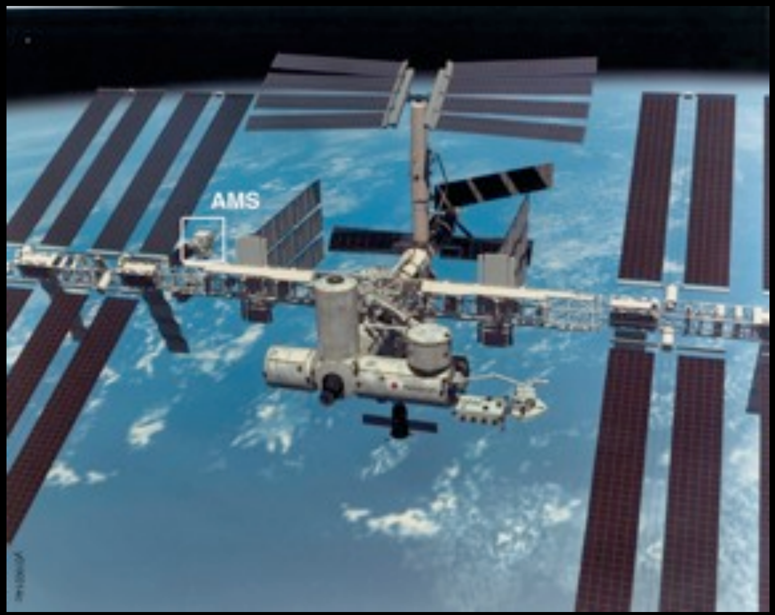


- null experiments: Xenon, CDMS (Ge), Edelweiss...



[CDMS - 1304.4279]

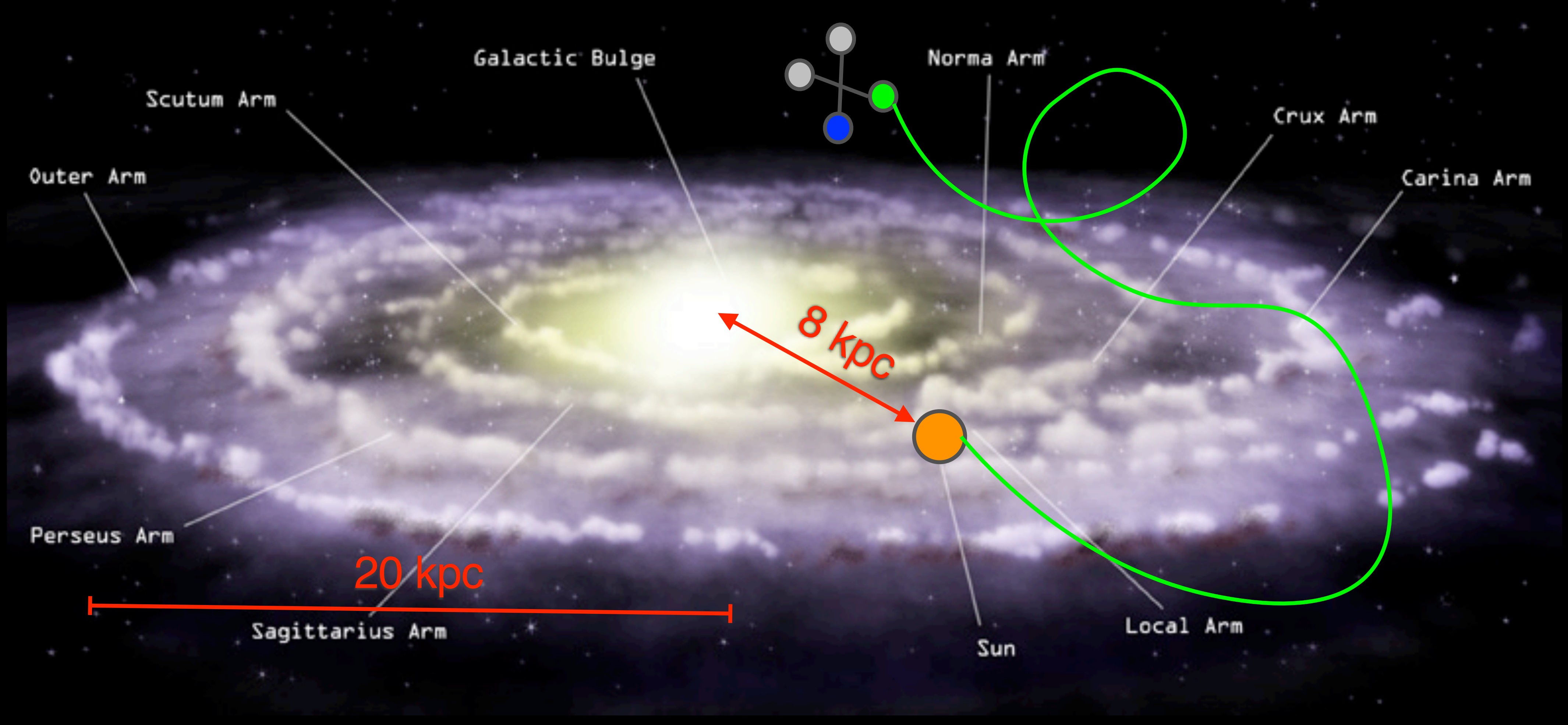
- puzzling situation: maybe it is telling us something about the WIMP-nuclei interactions or the structure of the DM halo

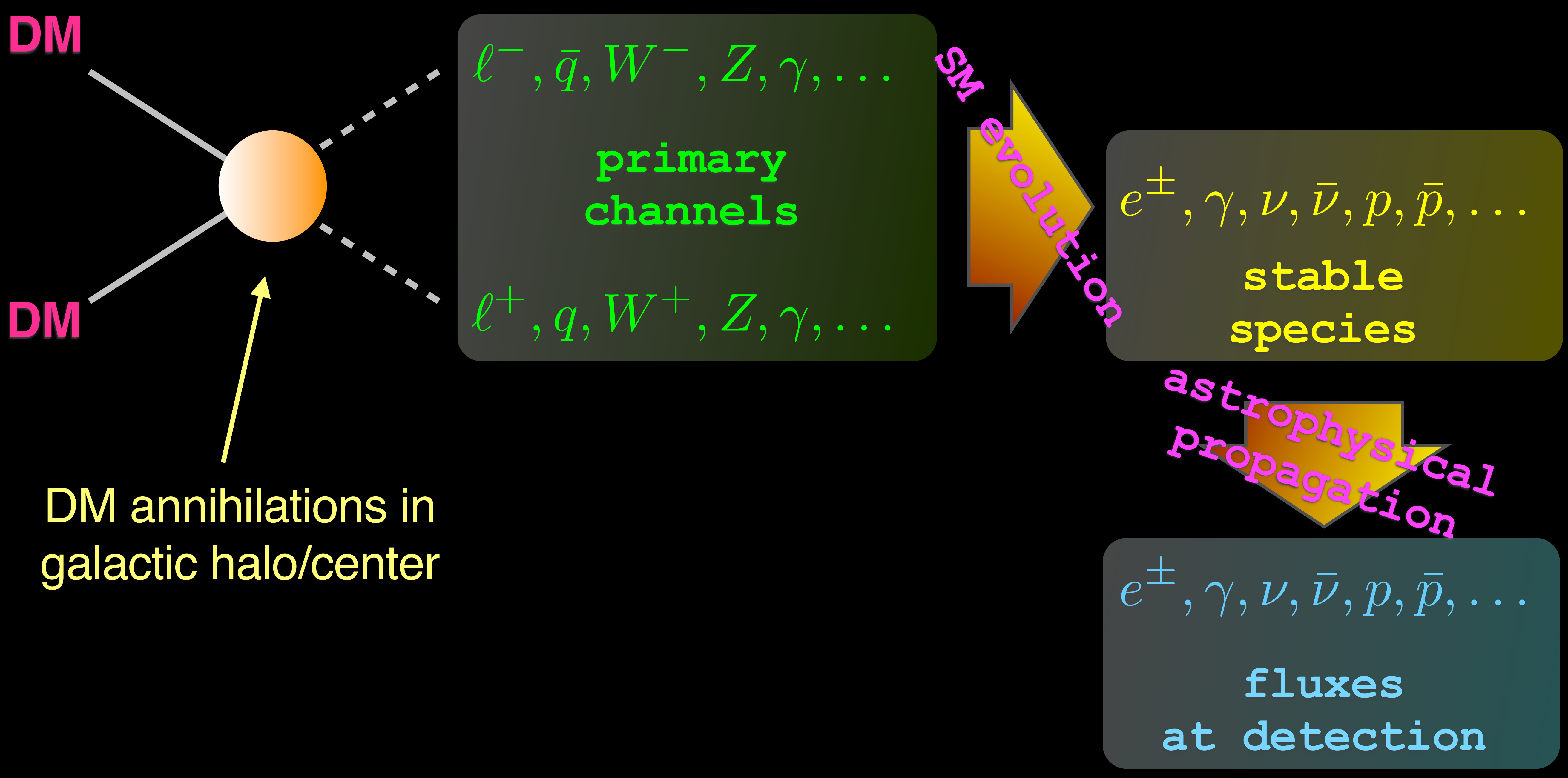


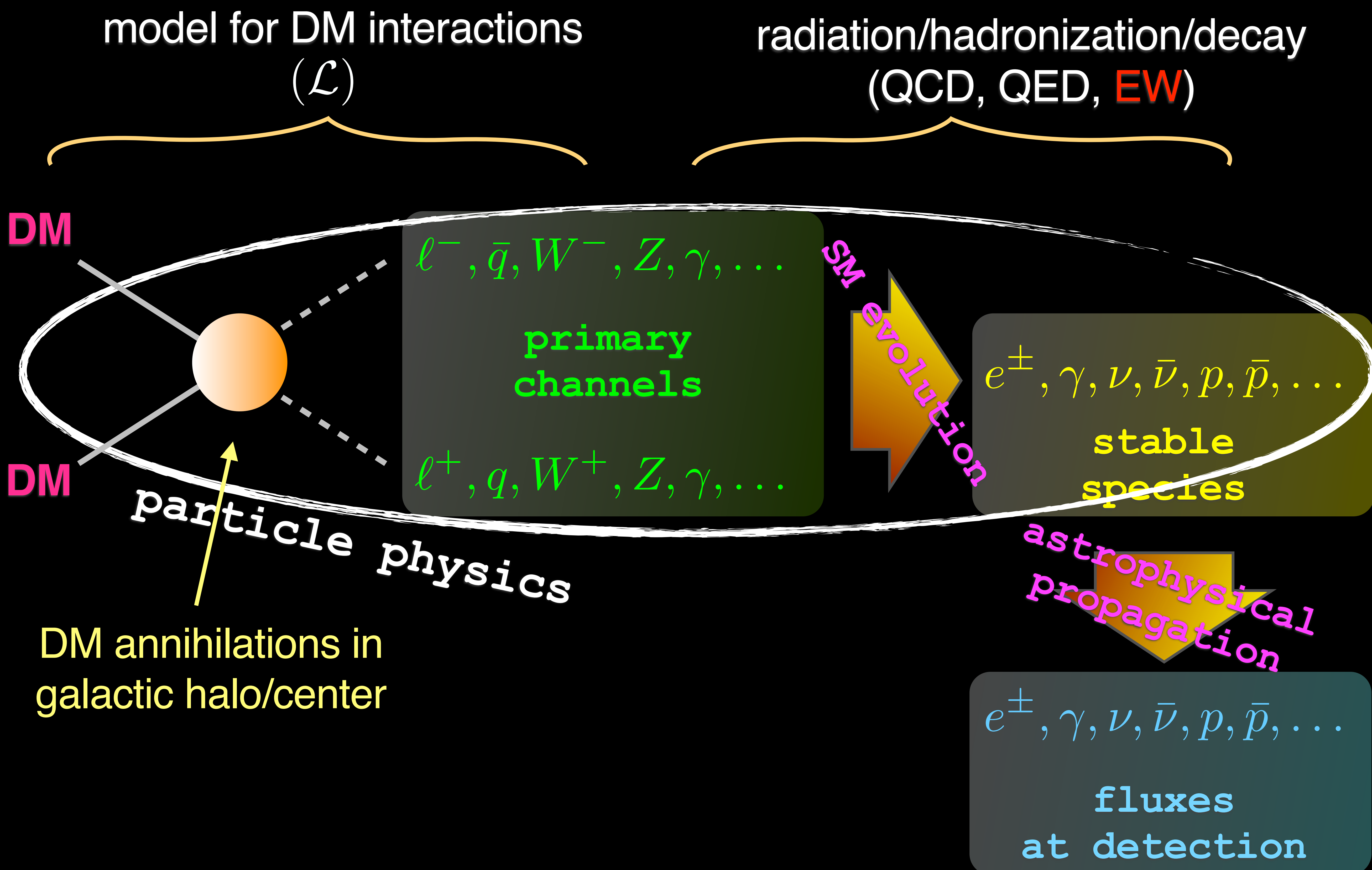
Part I

Indirect Searches

<u>Key observable:</u> fluxes of stable particles $(\gamma, \nu, \bar{p}, e^{+})$ from DM annihilations/decay in galactic halo or center

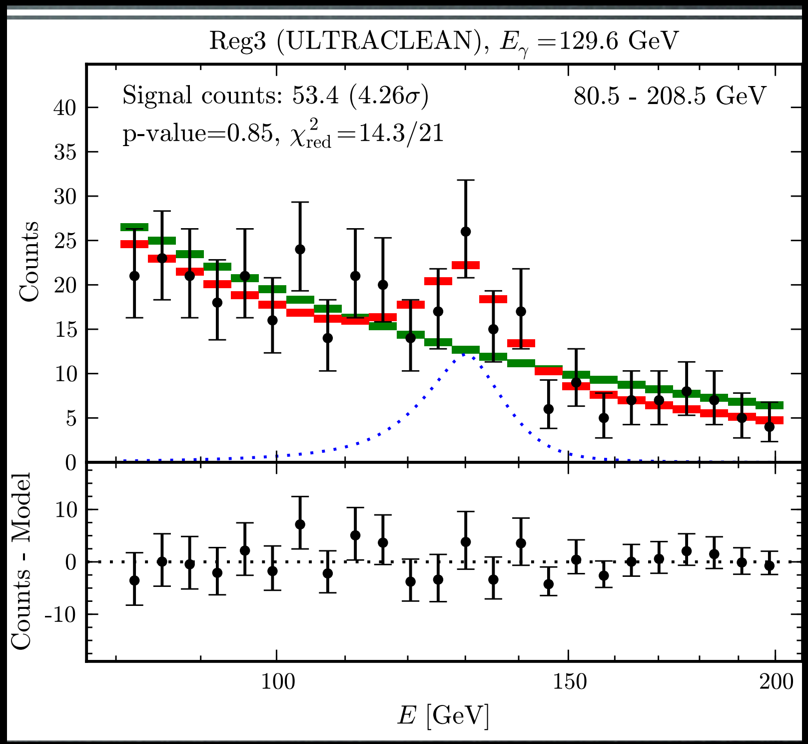



DM
DM
$\ell^-, \bar{q}, W^-, Z, \gamma, \ldots$
primary channels
$\ell^+, q, W^+, Z, \gamma, \ldots$
SM evolution
$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$
stable species
astrophysical propagation
$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$
fluxes at detection
DM annihilations in galactic halo/center

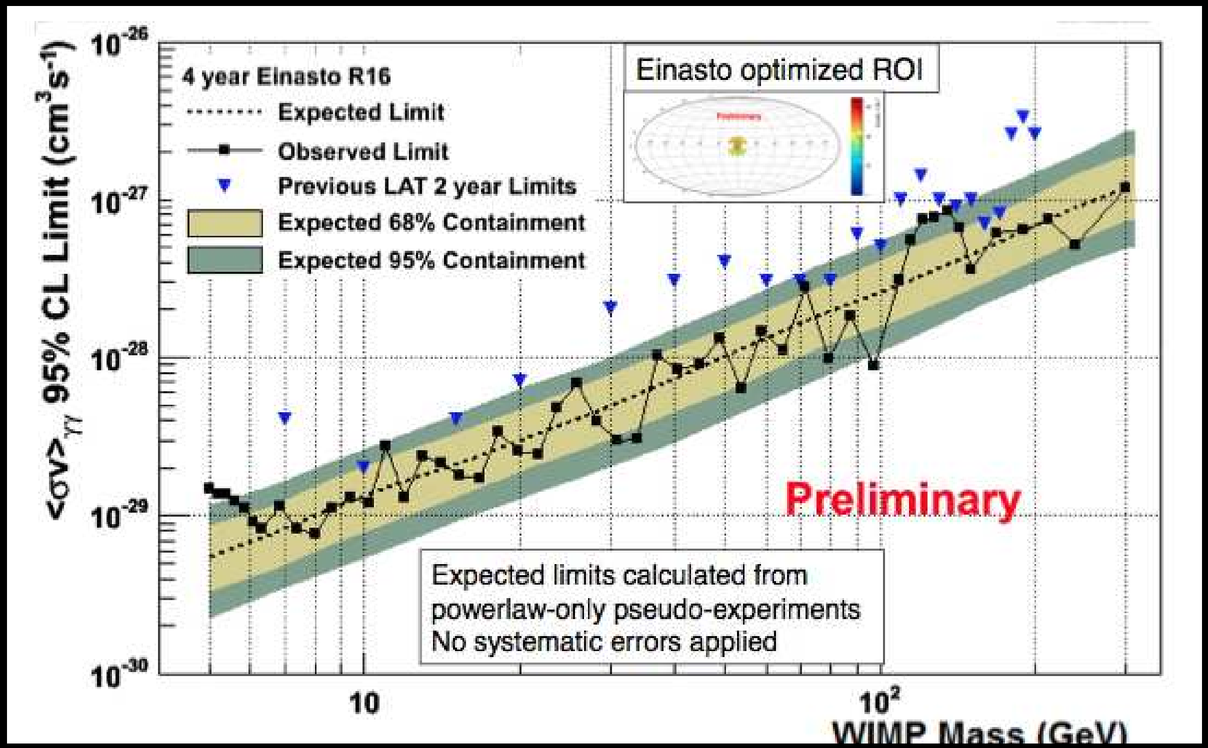

model for DM interactions
$(\mathcal{L})$
radiation/hadronization/decay
(QCD, QED, EW)
DM
DM
$\ell^-, \bar{q}, W^-, Z, \gamma, \ldots$
primary channels
$\ell^+, q, W^+, Z, \gamma, \ldots$
SM evolution
$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \ldots$
stable species
particle physics
astrophysical propagation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

- "Anomaly" in gamma rays (Fermi "135 GeV line")

4-year data



[Weniger, 1204.2797]



[Fermi Coll, 1305.7173]

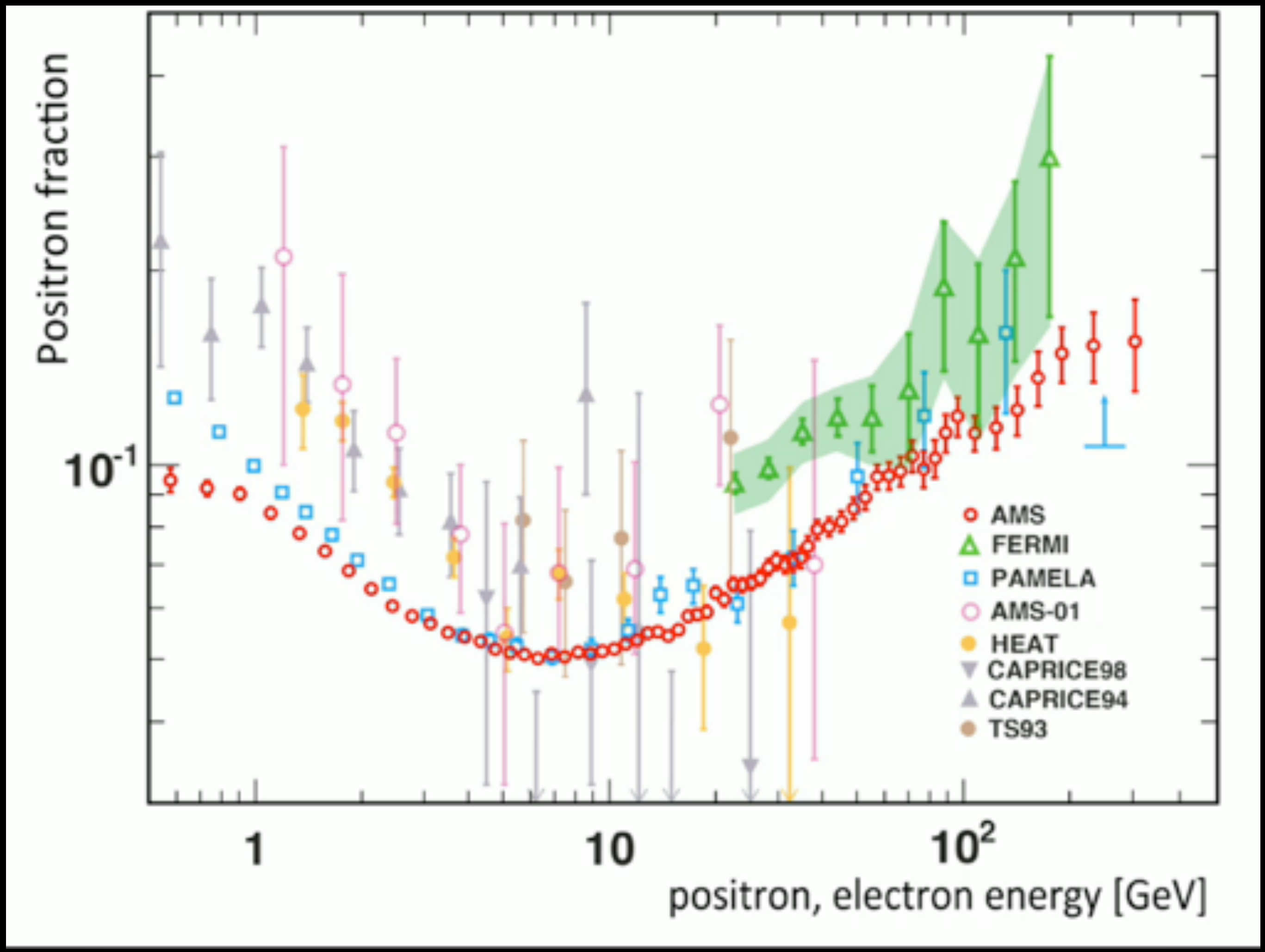
< 2σ global

systematics under scrutiny

- "Anomaly" in charged cosmic rays (positron fraction $e^+/(e^+ + e^-)$)

- **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.

$e^+/(e^+ + e^-)$



[AMS-02 Coll - PRL 110, 141102 (2013)]

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

Positron Fraction "anomaly"

where can positrons come from?

→ Dark Matter annihilations/decay

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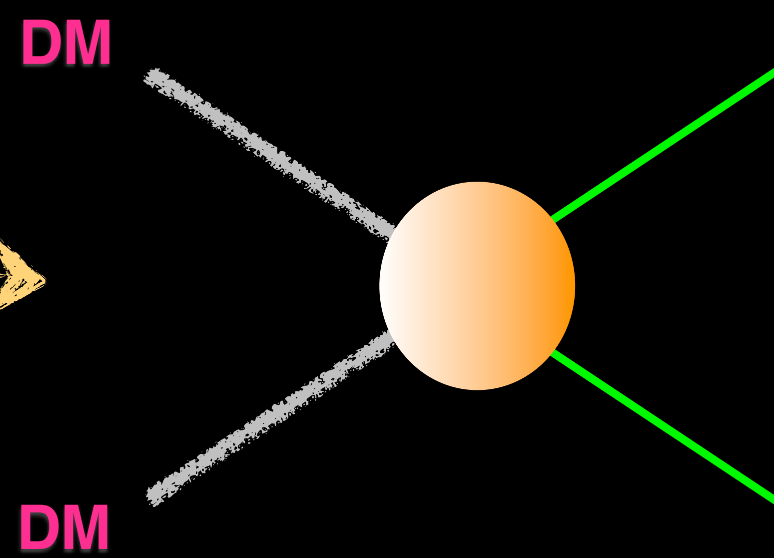
- the Dark Matter explanation of the excess is already strongly constrained by other measurements (e.g. gamma-rays)
- so the astrophysical explanations look very likely
- I want to insist on the DM interpretation and see how far we can get

assume DM interpretation

fit

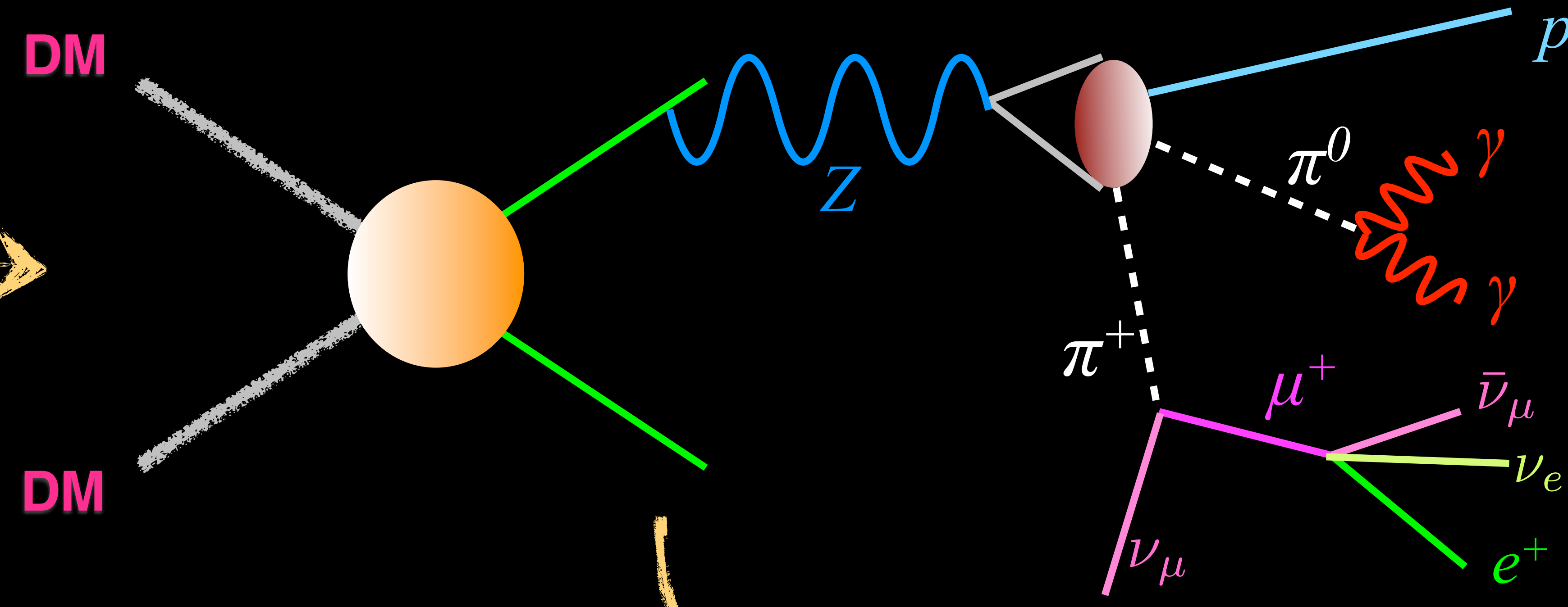


signal

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

assume DM interpretation

fit



signal

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

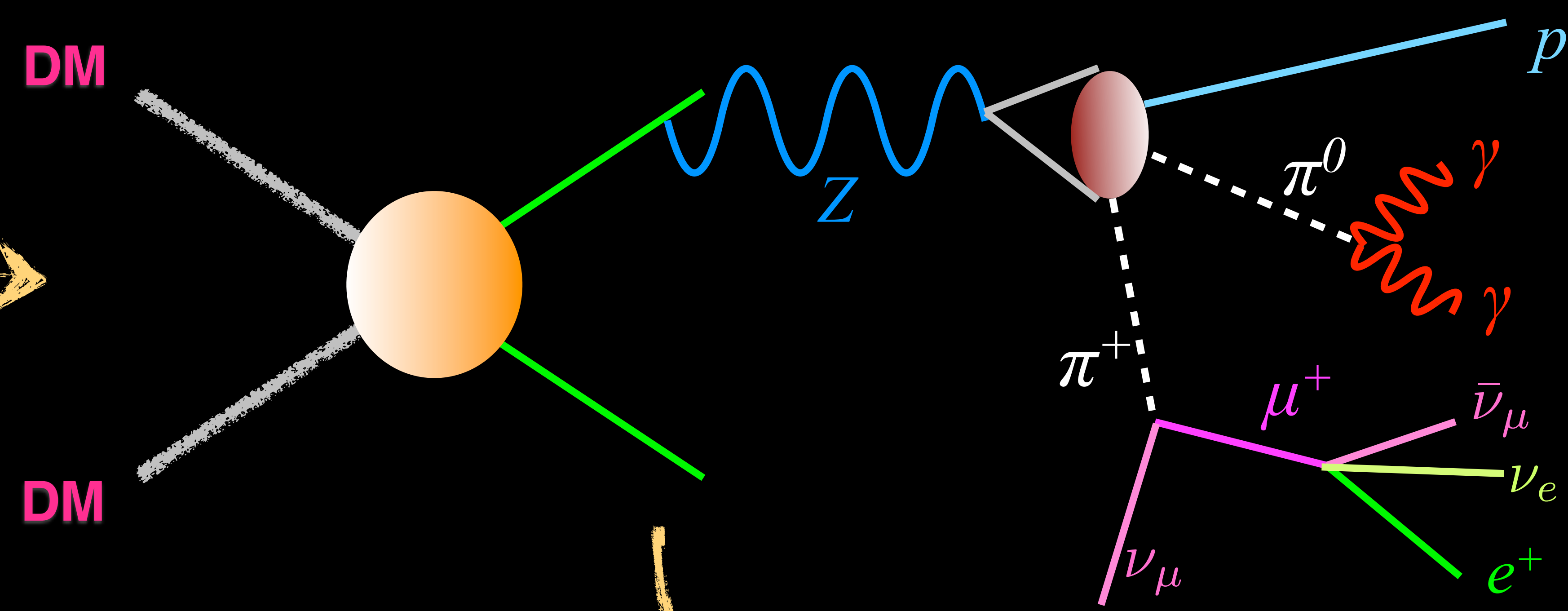
EW corrections

predictions

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

assume DM interpretation

fit



signal

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

EW corrections

predictions

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

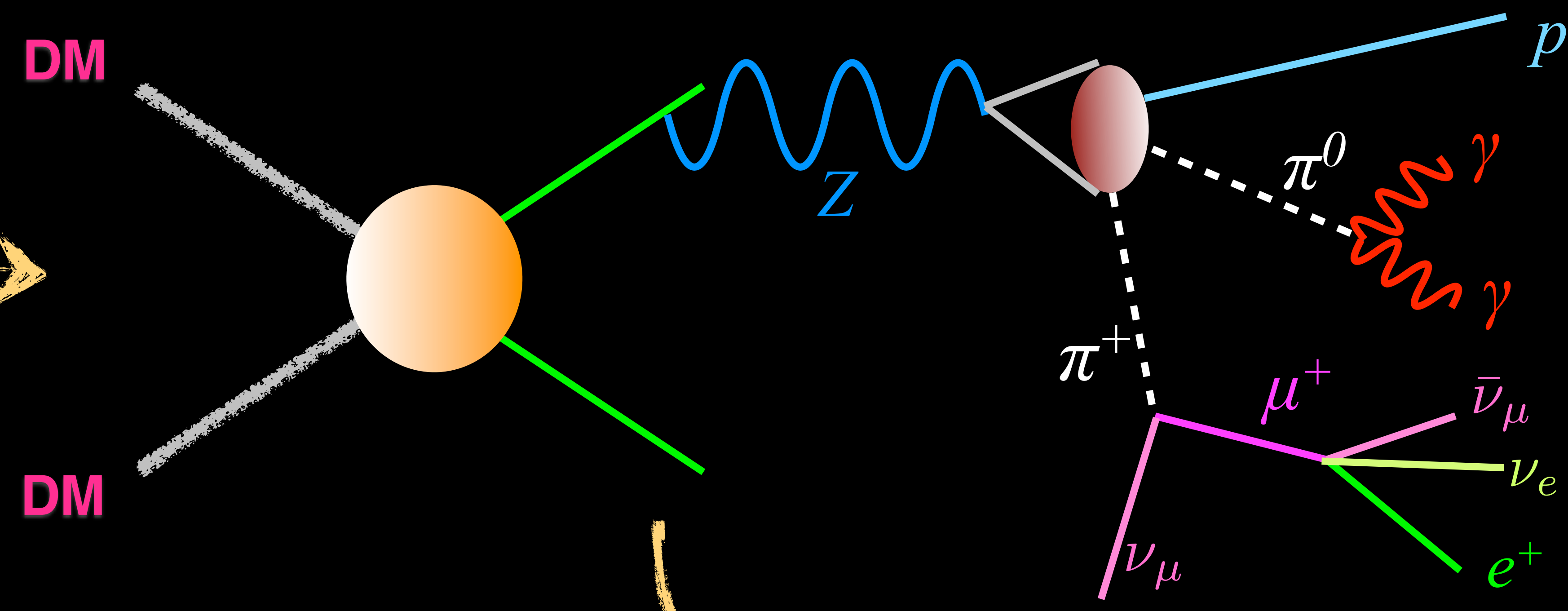
correlated fluxes

test with current/future data

verify/reject initial hypothesis

assume DM interpretation

fit



signal

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

EW corrections

predictions

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

correlated fluxes

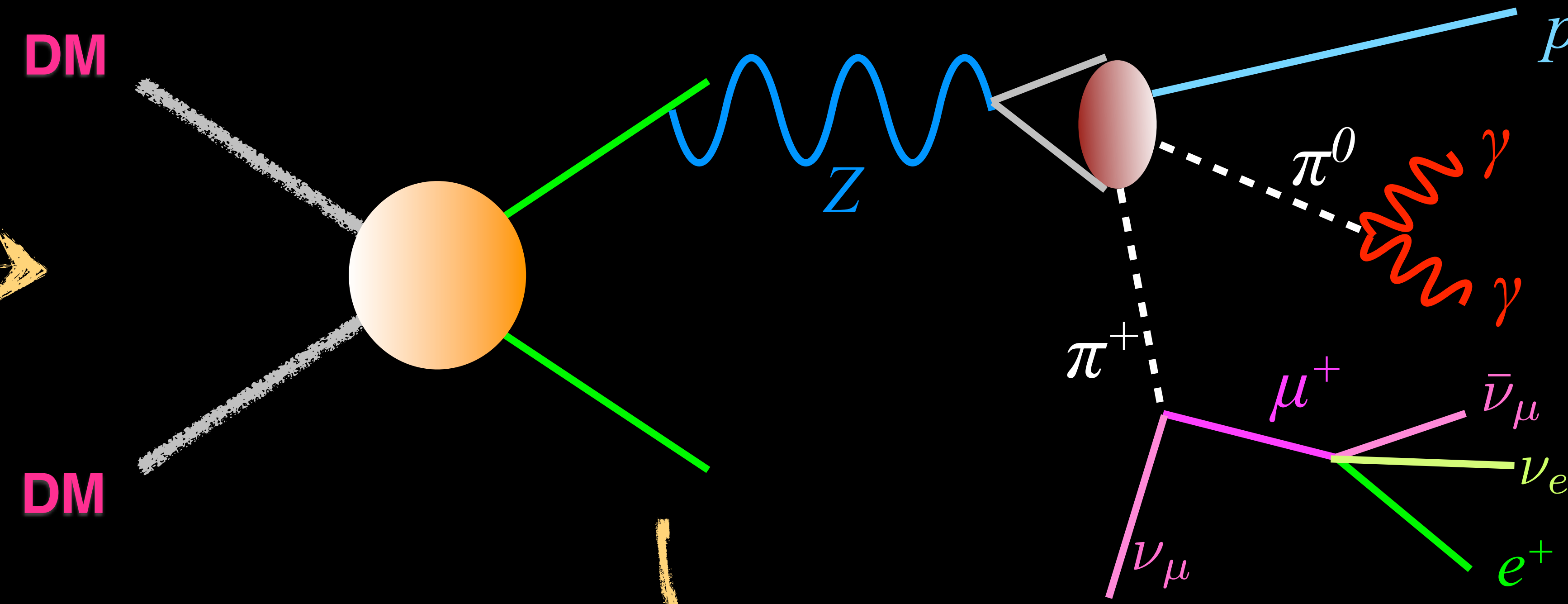
✓ robust
✓ timely

test with current/future data

verify/reject initial hypothesis

assume DM interpretation

fit



signal e^+

EW corrections

predictions $\bar{p}$

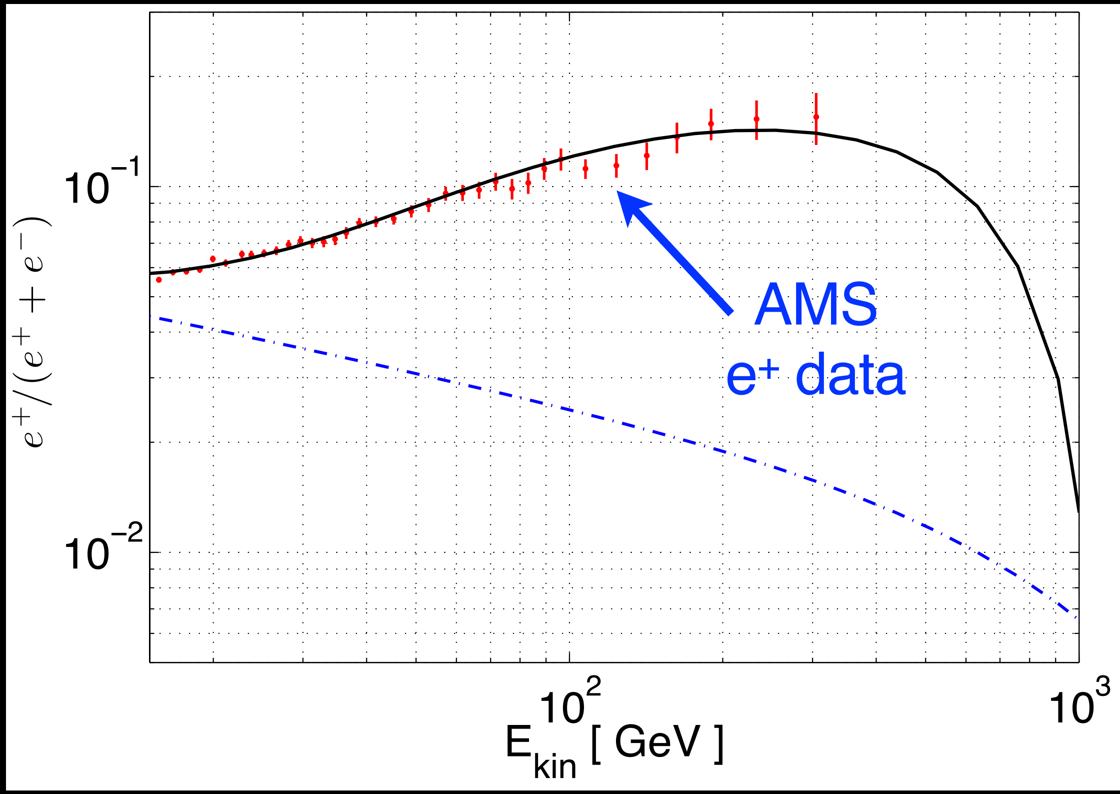
correlated fluxes

test with current/future AMS data

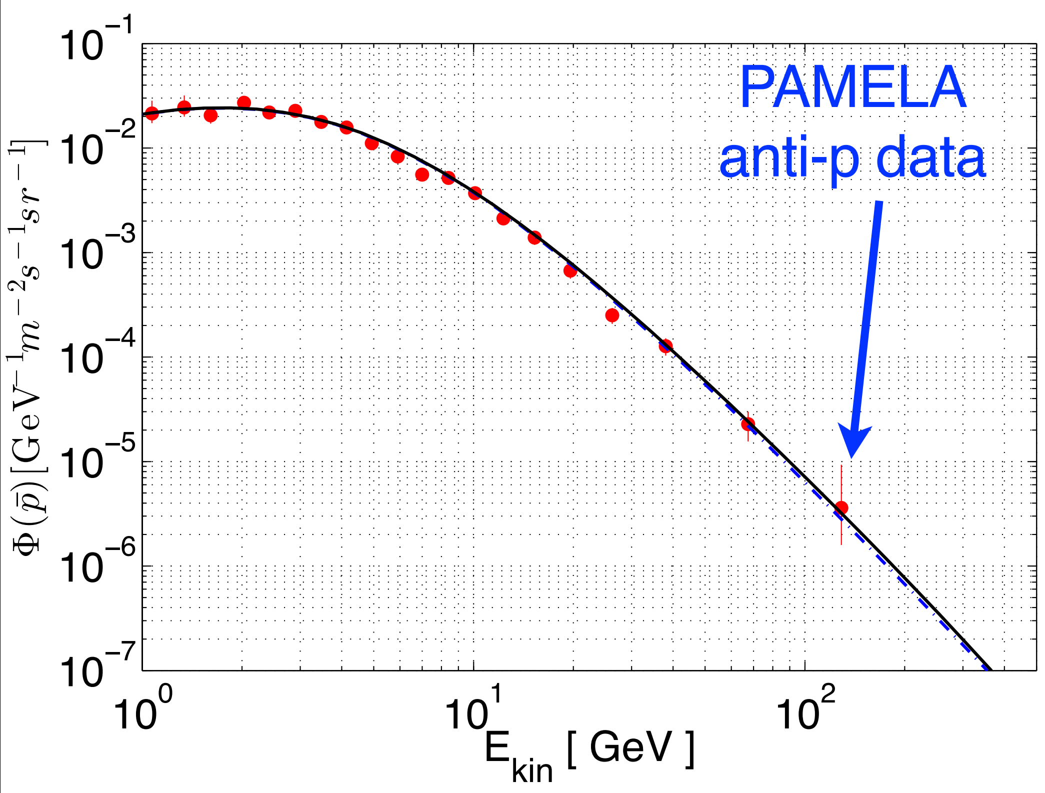
verify/reject initial hypothesis

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

positron fraction



anti-protons



[DS, Riotto, Xue - 1304.1336]

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

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

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

- cosmic-ray propagation is a very complex phenomenon, affected by several uncertainties
- 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
- crucial to use **consistently** the same propagation setup for all particle species involved in the analysis.

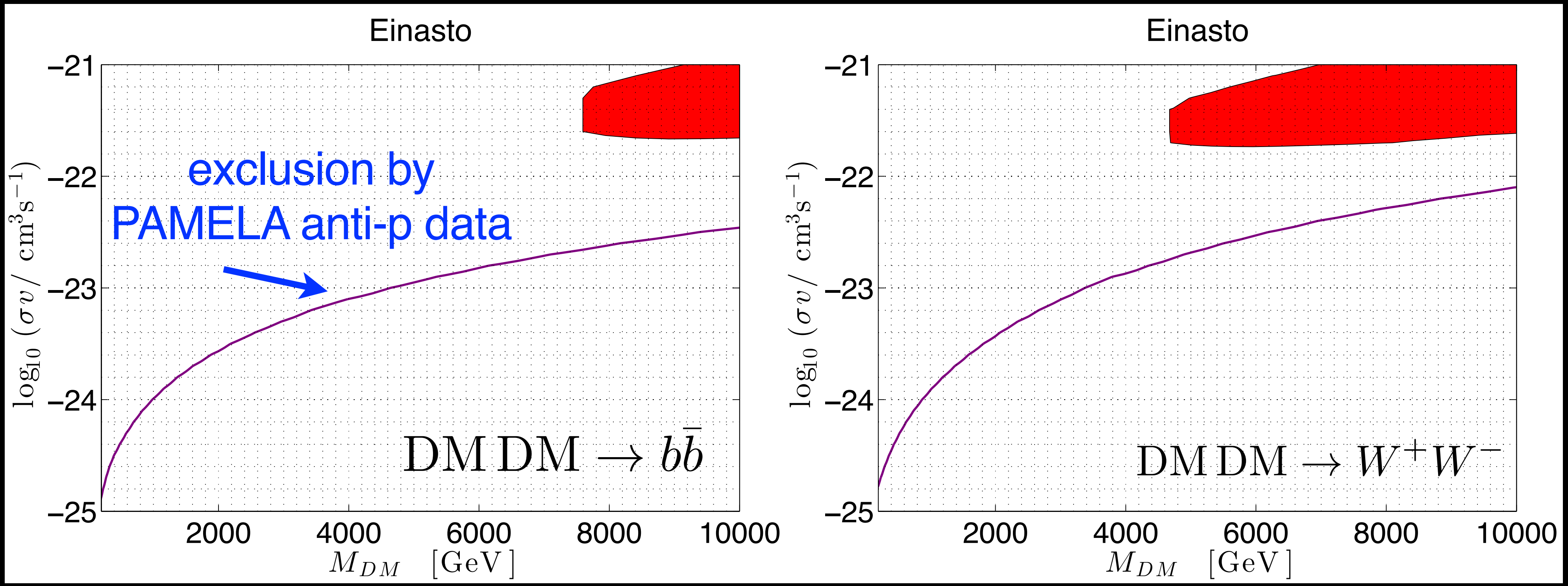
Model-independent analysis of AMS-02 data

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

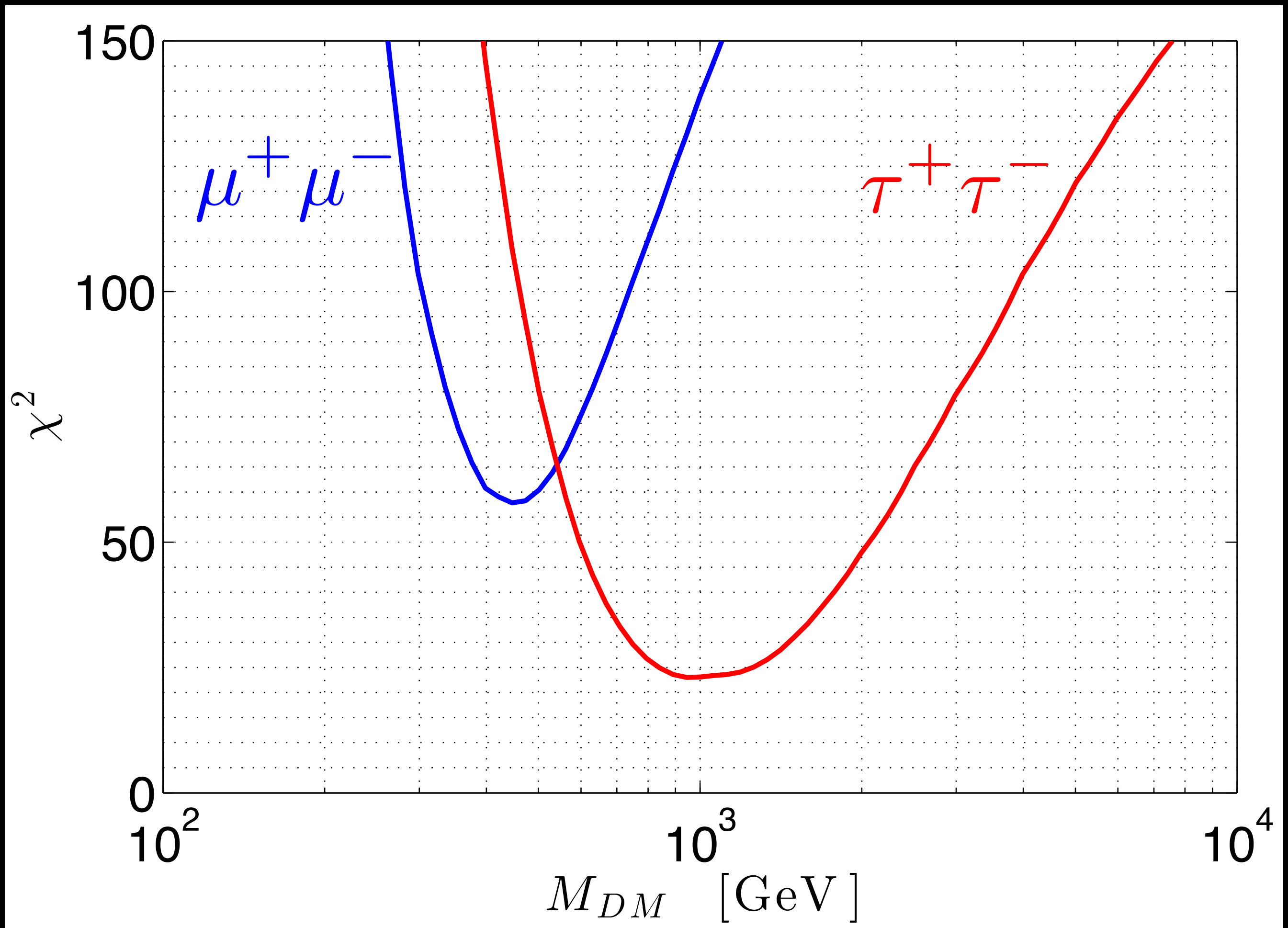
ALL channels produce hadrons (due to EW corrections)

⟶ can easily upset anti-p data

Ex.



only **leptonic** annihilation channels are still allowed

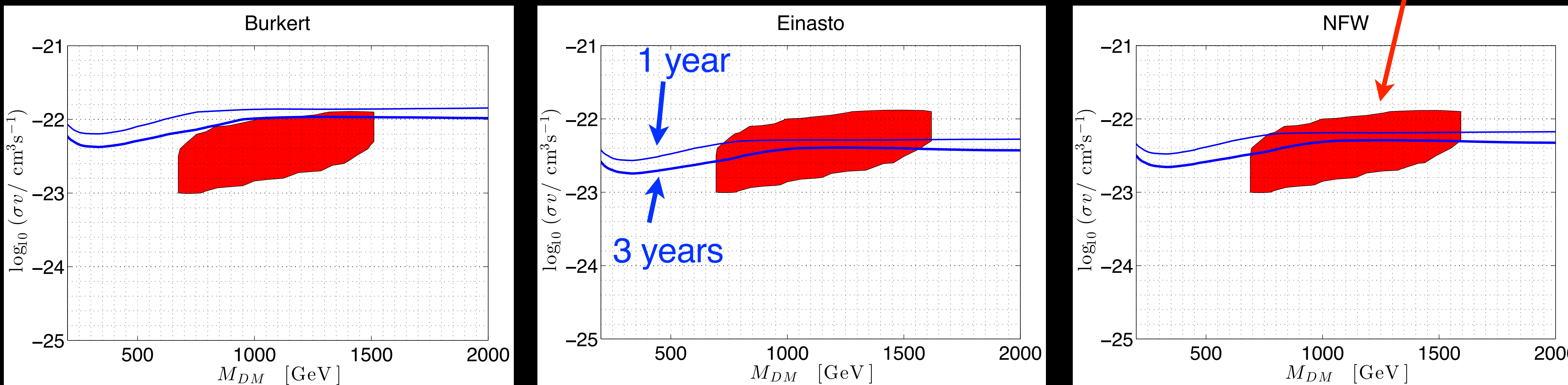


- use only data with E>15 GeV (not affected by solar modulation)
- number of dof: 36-6=30
- e^+e^- gives even higher χ^2

	$\mu^+\mu^-$	$\tau^+\tau^-$
$\chi^2_{\rm min}/{\rm dof}$	1.9	0.7

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

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

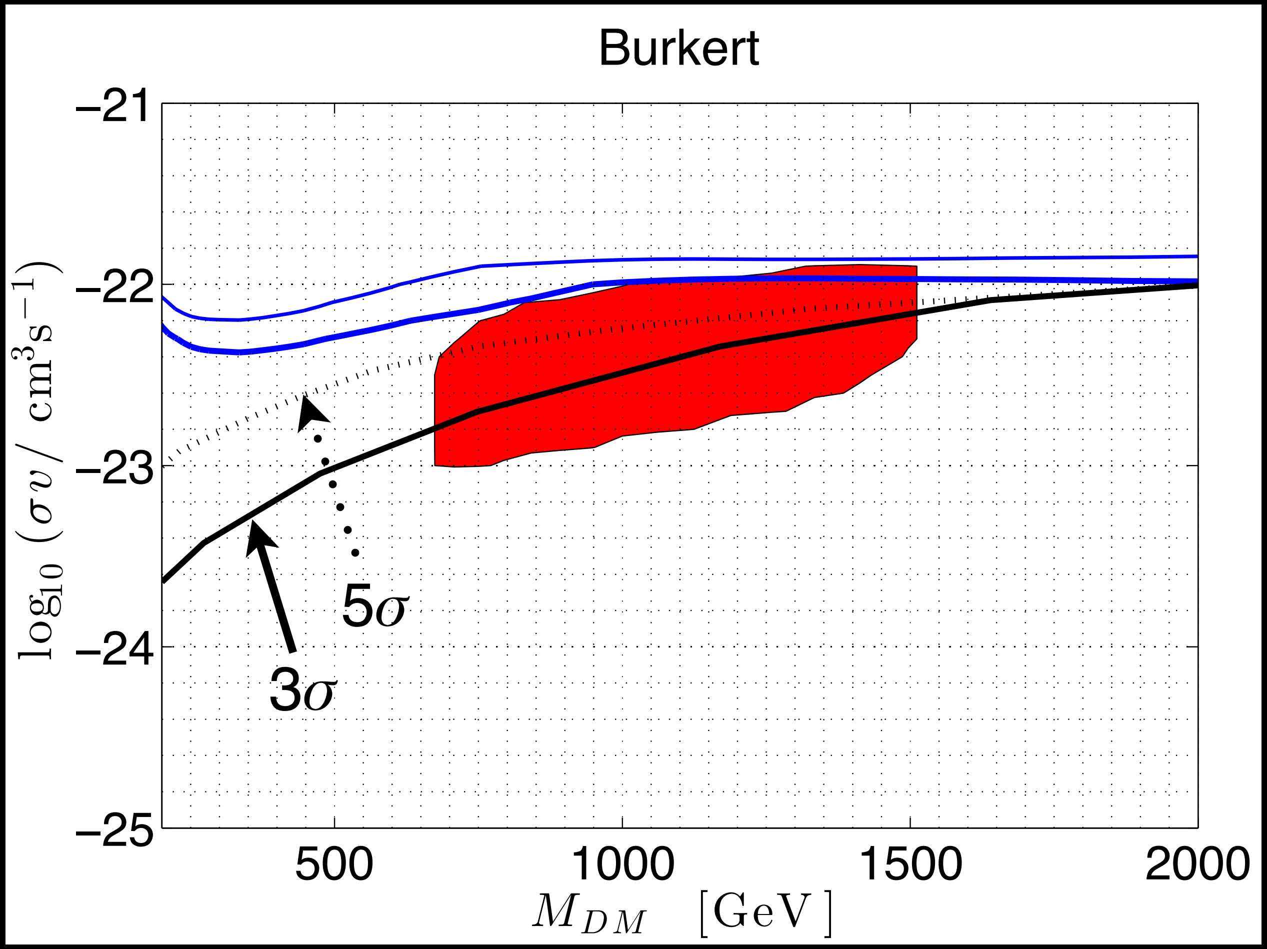


- we simulated projected (mock) data for anti-p, consistent with understanding of detector features from outside the collaboration

- 3 years of AMS-02 anti-p data would be enough to rule out ***almost*** competely the DM interpretation of the positron rise

Fermi-LAT diffuse gamma-ray constraints

[Fermi-LAT Coll.- 1205.6474]



best-fit regions for other halo profiles are mostly excluded

Constraints from other Data-sets

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

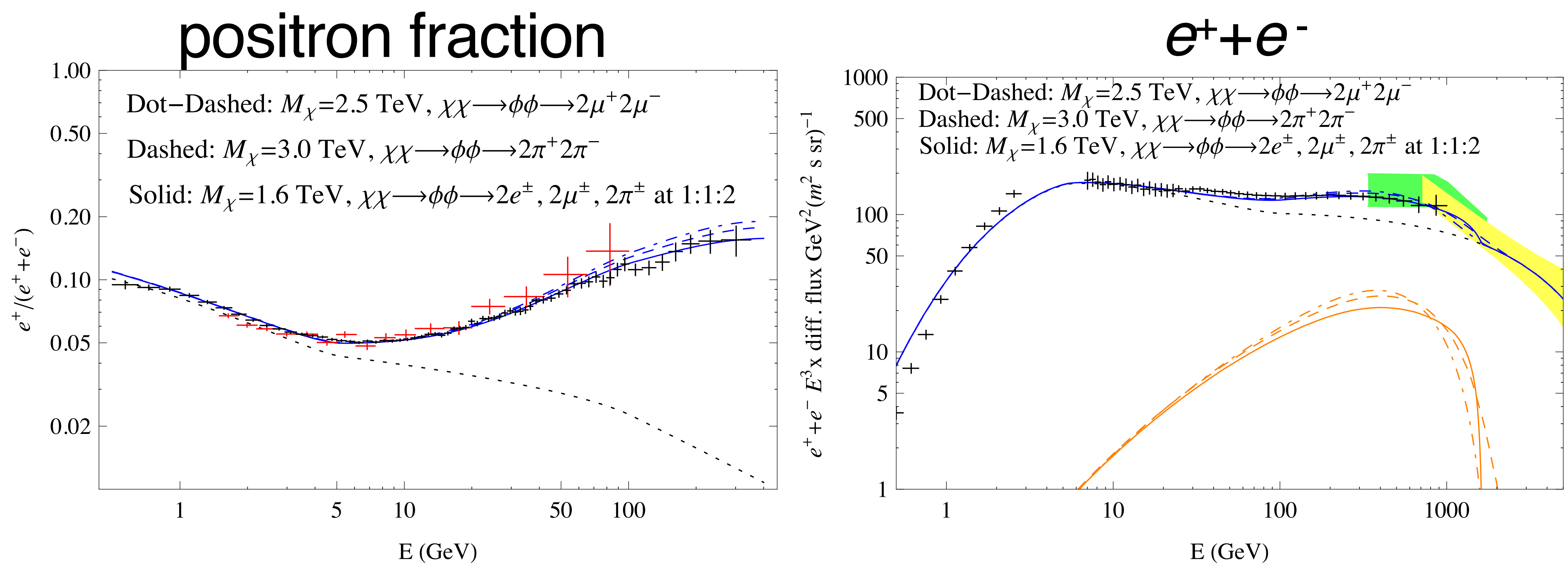


FIG. 6: The same as in Figs. 1, 2, 4 and 5 but for a diffusion zone half-width of $L = 8$ kpc, and for broken power-law spectrum of electrons injected from cosmic ray sources ($dN_{e^-}/dE_{e^-} \propto E_e^{-2.65}$ below 100 GeV and $dN_{e^-}/dE_{e^-} \propto E_e^{-2.3}$ above 100 GeV). The cross sections 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]

Wait for AMS release of $e^+ + e^-$...

- Interpretation of AMS-02 recent results

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

- If excluded, much less interest in e^+ as a channel for DM searches (huge astro bkg)

- Wait for more data (AMS, Fermi-LAT...) to clarify the situation

- **Complementarity**:
robust conclusions on the nature of DM should come from correlations of different signatures among different expts.

Part II

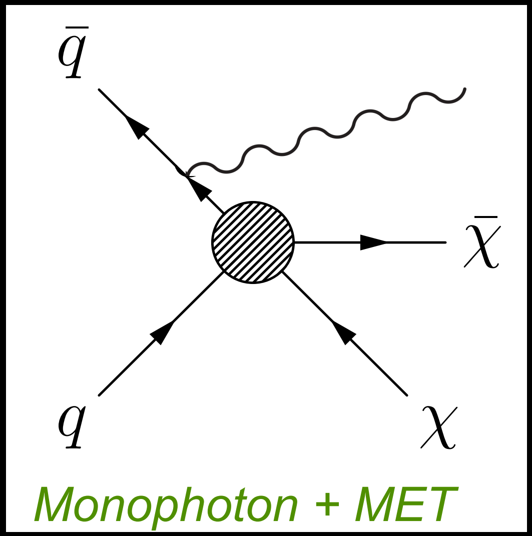
Collider Searches

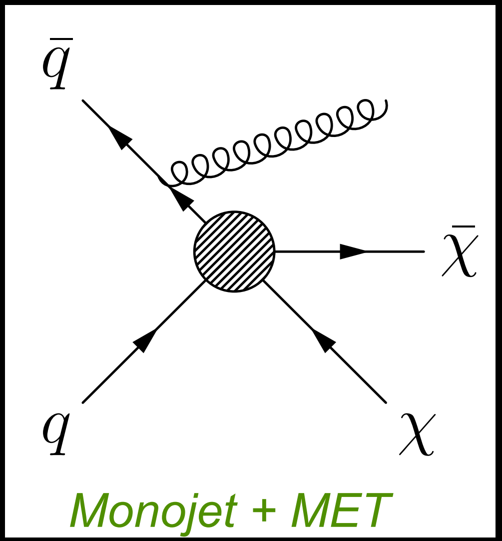
(in LHC we trust...)

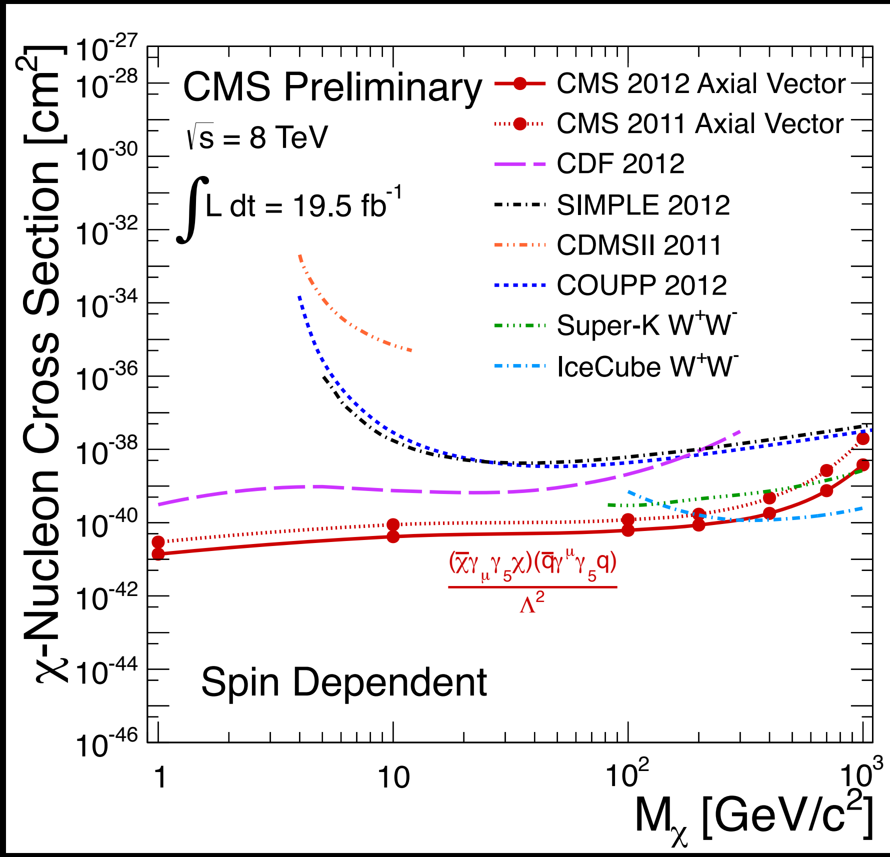
Some trivial considerations:

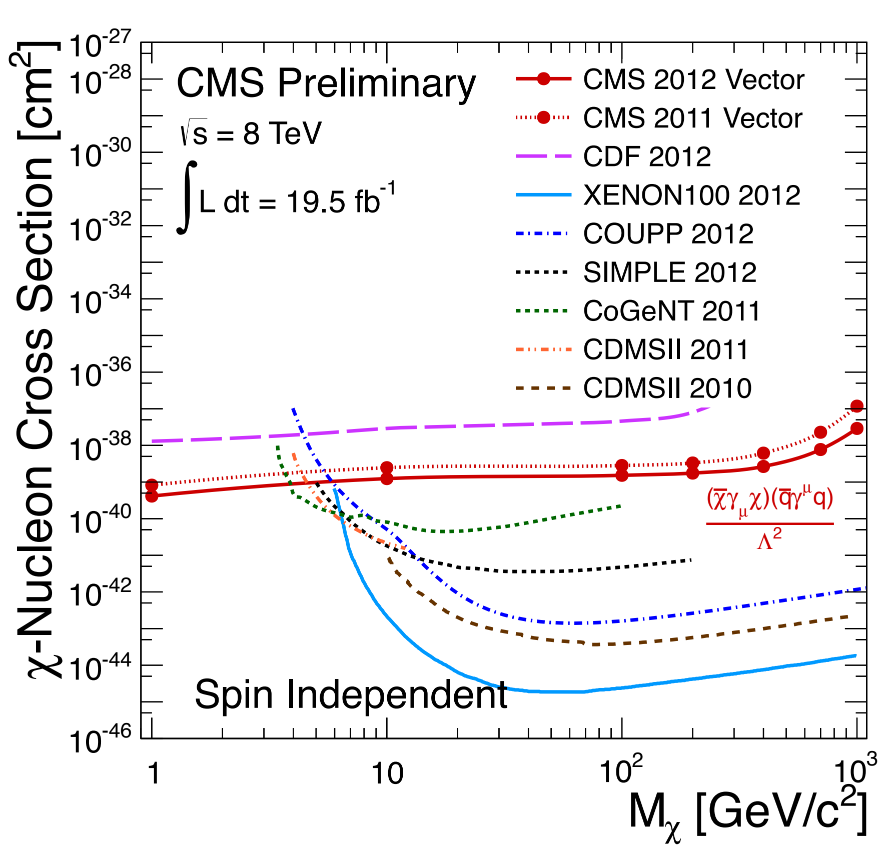
- DM in a collider is like a neutrino (missing ET)
- if stabilized by a Z_2 symmetry ⟶ DM produced in pairs
- Difficult search, unless correlating MET with other handles (ISR jets/photons, displaced vertices...)
- Need new ideas

- ✓ constrain DM-quarks interactions and translate into limits on DM-nucleon cross-section
- ✓ complementary/ competitive with direct detection
- ✓ no astrophysical uncertainties



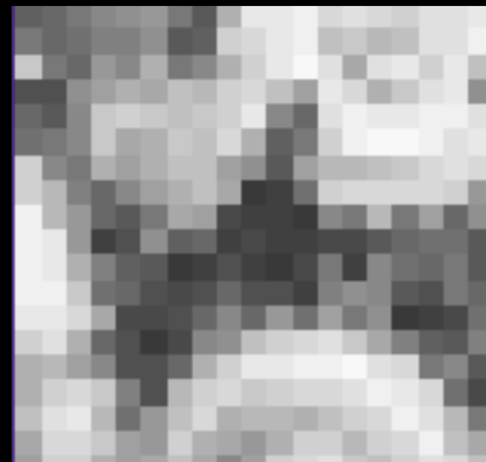






[CMS PAS EXO-12-048]

effective low-energy description



M_Z — (Λ~1 TeV) — **New States** — (say, 10 TeV) — E

EFT OK

Integrate out the UV physics connecting DM-SM and describe interactions with eff. ops.:

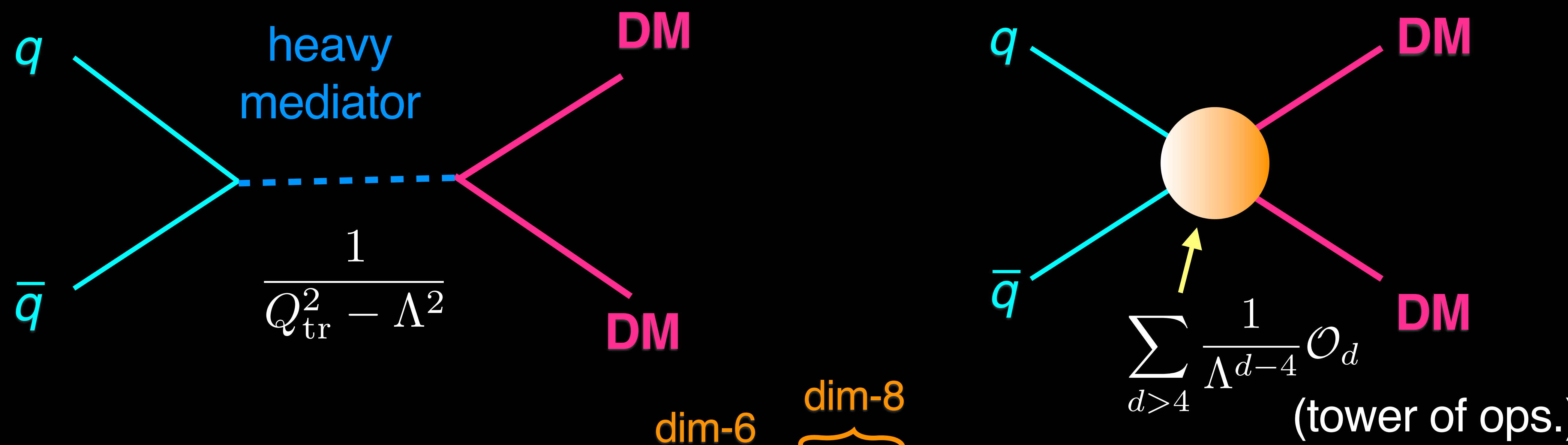
$$\frac{1}{\Lambda^2}(\bar{\chi}\Gamma^A\chi)(\bar{q}\Gamma_A q)$$

LHC can access regions beyond the validity of the eff. description

 = 

→ need to use EFT <u>carefully</u> and <u>consistently</u>

- the momentum transfer in the relevant process must be $Q_{\rm tr} \lesssim \Lambda$



$$\frac{1}{Q_{\rm tr}^2 - \Lambda^2} = -\frac{1}{\Lambda^2}\left[\overbrace{1}^{\text{dim-6}} + \overbrace{\frac{Q_{\rm tr}^2}{\Lambda^2}}^{\text{dim-8}} + \mathcal{O}\left(\frac{Q_{\rm tr}^4}{\Lambda^4}\right)\right]$$

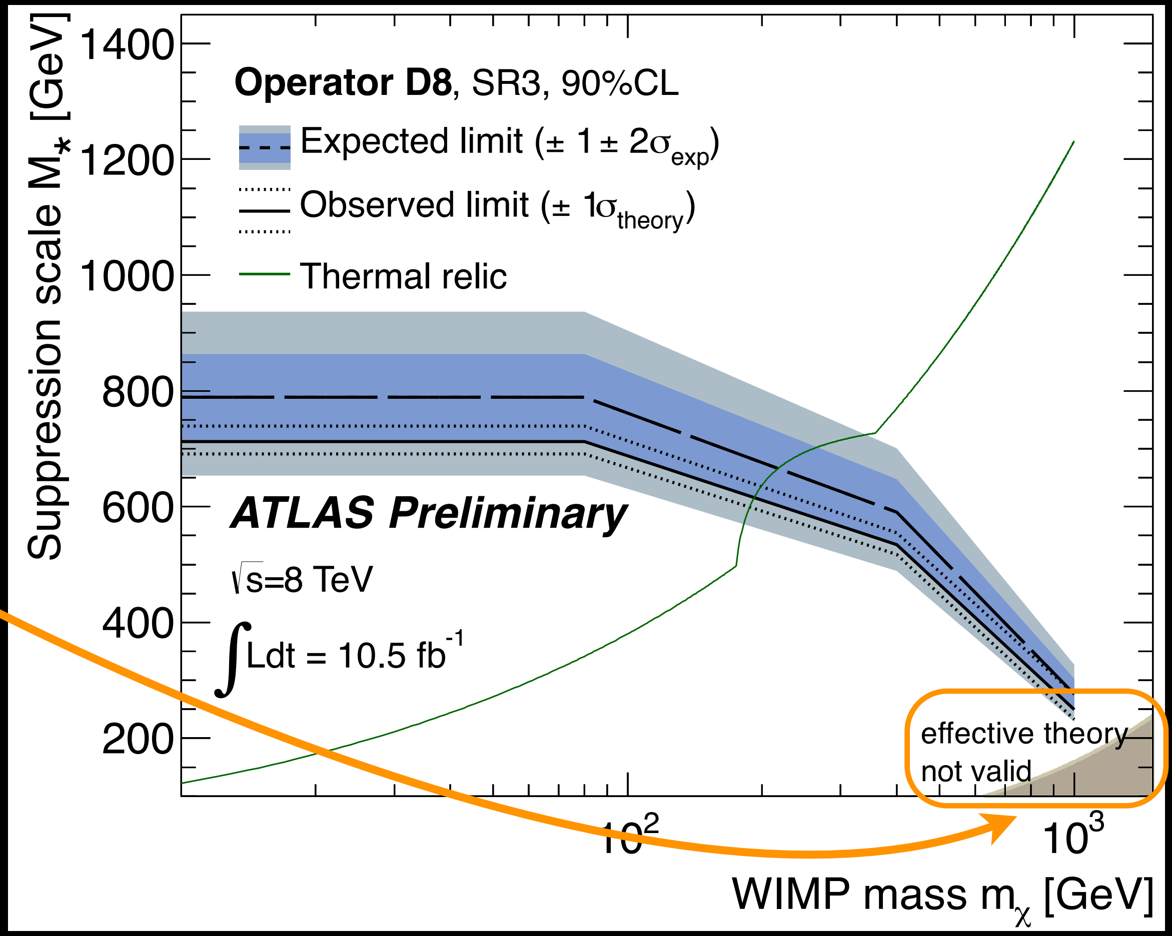
- $Q_{\rm tr}/\Lambda$ measures the badness of the truncation of the tower of effective ops to the lowest dimensional ones

- Usually, lowest order is OK. Situation can be different at LHC.

- Standard lore

mediator mass $M > m_\chi$

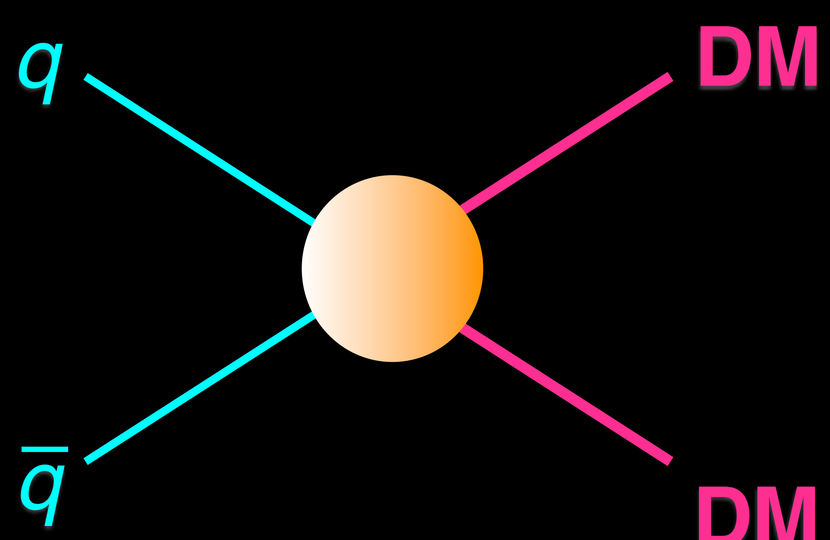
$$\Lambda \simeq \frac{M}{\sqrt{g_{\rm SM}\, g_\chi}} \gtrsim \frac{M}{4\pi} \quad \Bigg\} \quad \Lambda \gtrsim \frac{m_\chi}{4\pi}$$



[ATLAS-CONF-2012-147]

Actual limits can be stronger (depending on the process)

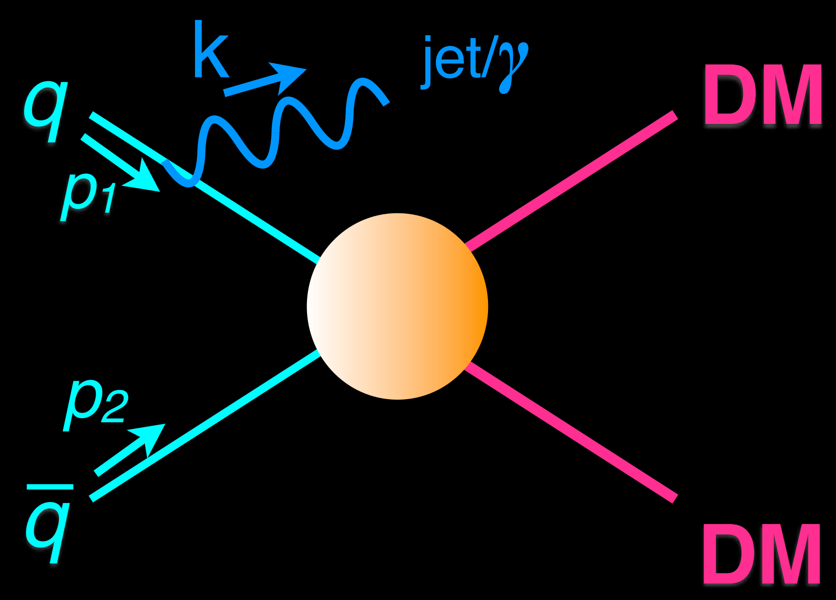
- 2→2 process



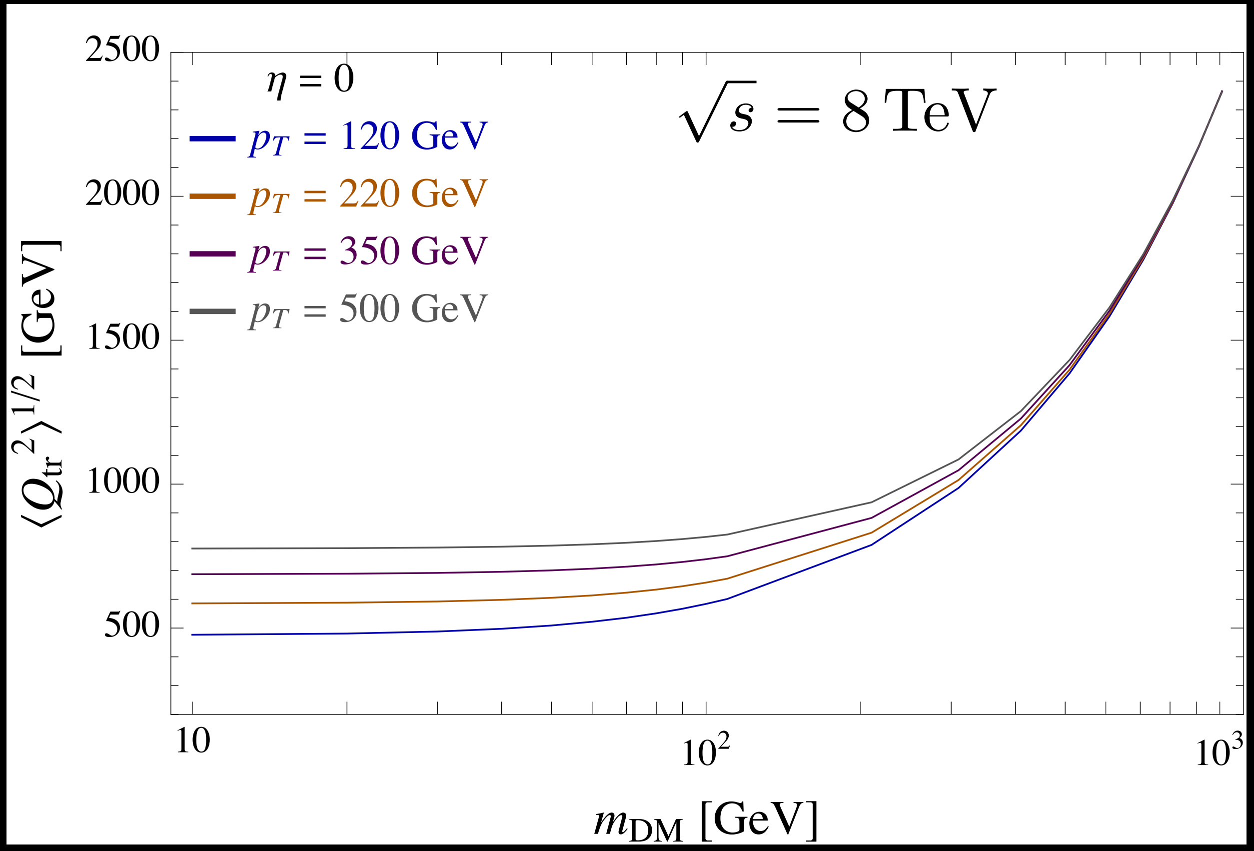
$$Q^2_{\rm tr} \geq 4m_\chi^2 \longrightarrow \Lambda > 2m_\chi$$

below this bound, the contribution of higher-dim ops become important

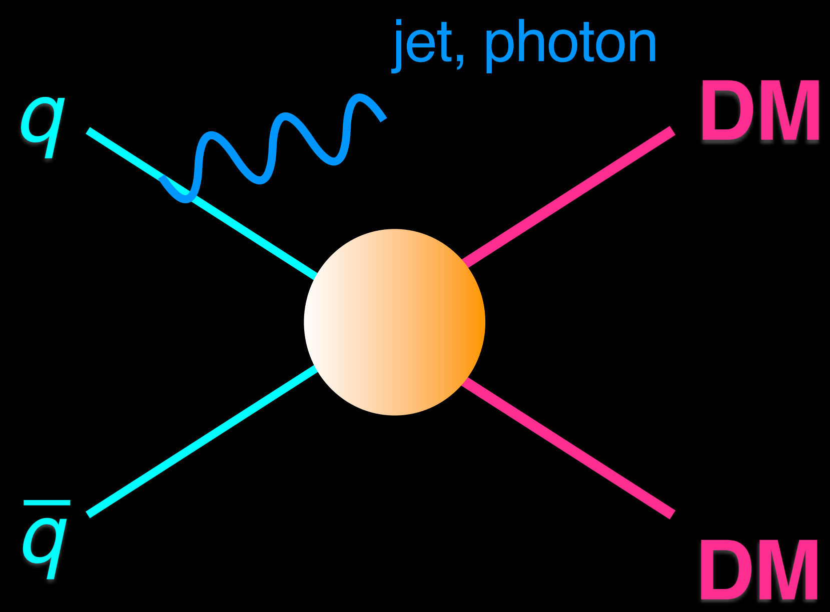
- 2→3 process



$$Q_{\rm tr}^2 \equiv (p_1+p_2-k)^2 = x_1 x_2 s - \sqrt{s}\, p_{\rm T}\left(x_1 e^{-\eta}+x_2 e^{\eta}\right)$$



the transfer momentum is larger for larger DM mass

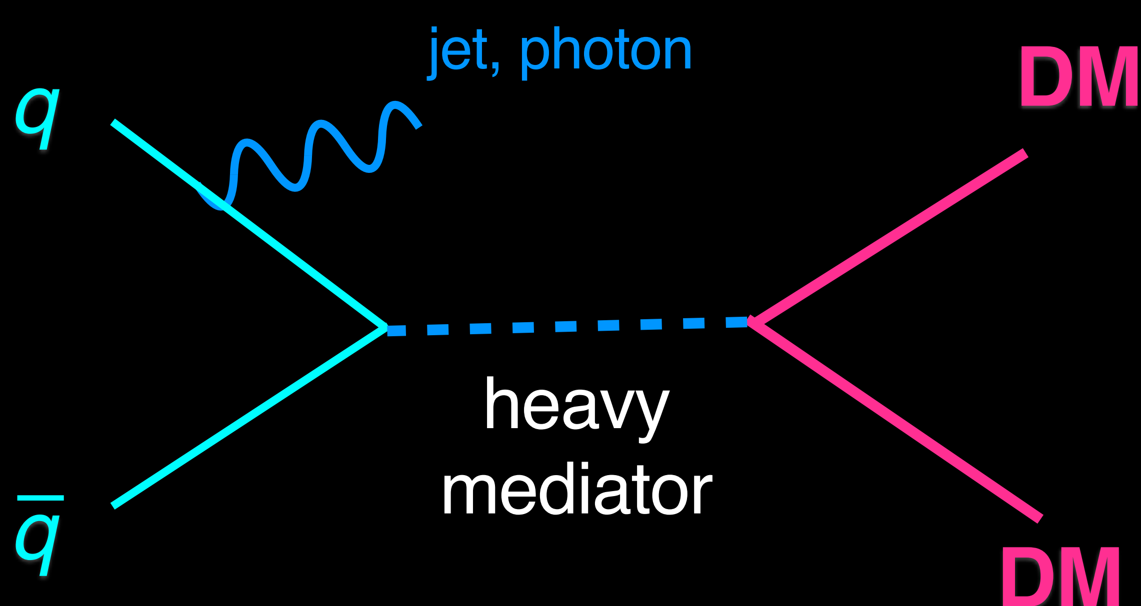


eff. operator $\mathcal{O}_S = \frac{1}{\Lambda^2}(\bar{\chi}\chi)(\bar{q}q)$

parton-level differential cross section:

$$\frac{d^2\hat{\sigma}_{\rm eff}}{dp_T d\eta} = \frac{\alpha_s}{36\pi^2}\frac{1}{p_T}\frac{1}{\Lambda^4}\frac{\left[Q_{\rm tr}^2 - 4m_{\rm DM}^2\right]^{3/2}\left[1+\frac{Q_{\rm tr}^4}{(x_1x_2s)^2}\right]}{Q_{\rm tr}}$$

matching: $\frac{1}{\Lambda^2} = \frac{g_\chi g_q}{M_V^2}$



$$\mathcal{L}_{\rm UV} \supset \frac{1}{2}M^2S^2 - g_q\bar{q}qS - g_\chi\bar{\chi}\chi S$$

parton-level differential cross section:

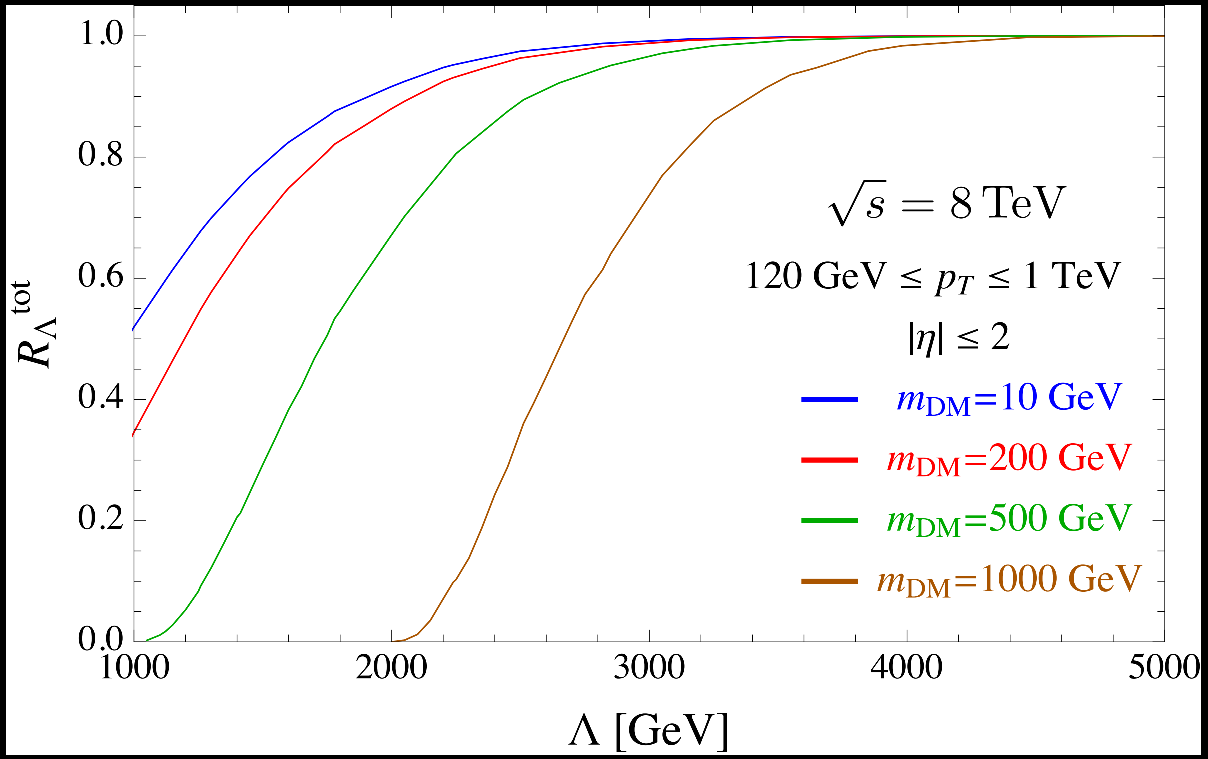
$$\frac{d^2\hat{\sigma}_{\rm UV}}{dp_T d\eta} = \frac{\alpha_s}{36\pi^2}\frac{1}{p_T}\frac{g_q^2 g_\chi^2}{\left[Q_{\rm tr}^2 - M^2\right]^2}\frac{\left[Q_{\rm tr}^2 - 4m_{\rm DM}^2\right]^{3/2}\left[1+\frac{Q_{\rm tr}^4}{(x_1x_2s)^2}\right]}{Q_{\rm tr}}$$

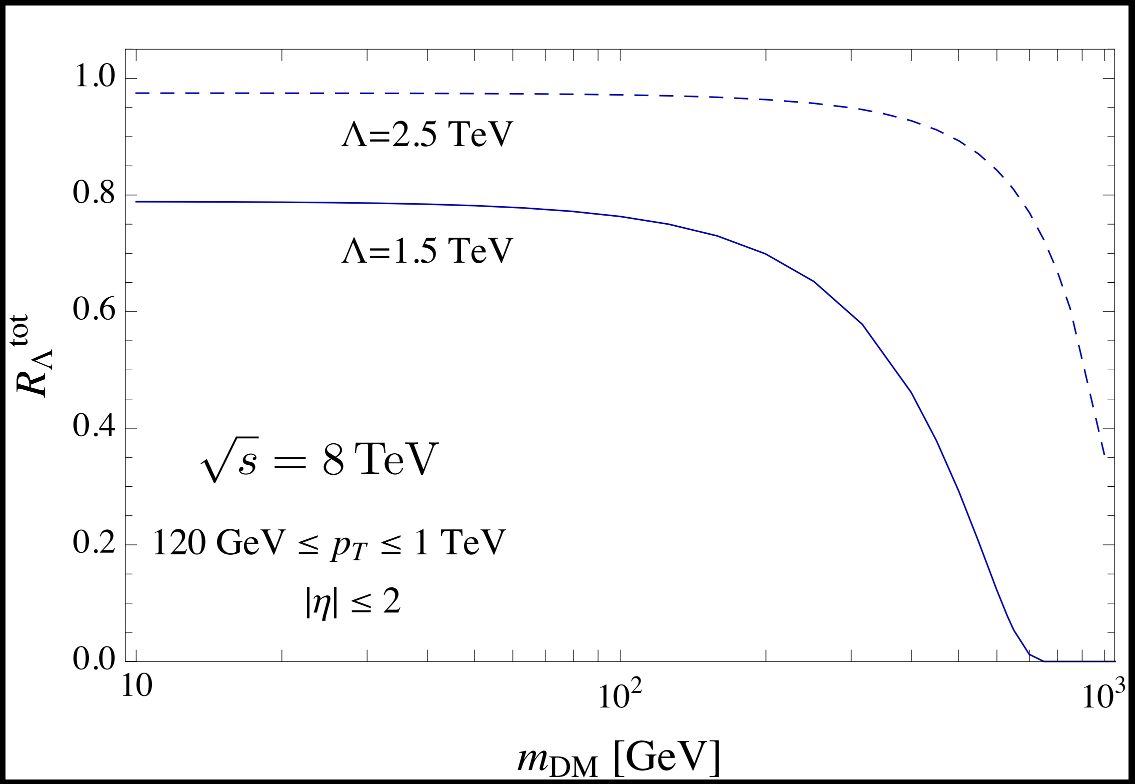
1. In what regions of the parameter space $\{\Lambda, m_{DM}\}$ is the effective description accurate/reliable?

2. What is the difference between interpreting data with an effective operator and with its UV completion?

$$R_\Lambda^{\rm tot} \equiv \frac{\sigma_{\rm eff}\big|_{Q_{\rm tr}<\Lambda}}{\sigma_{\rm eff}}$$

fraction of eff. cross section at low momentum transfer



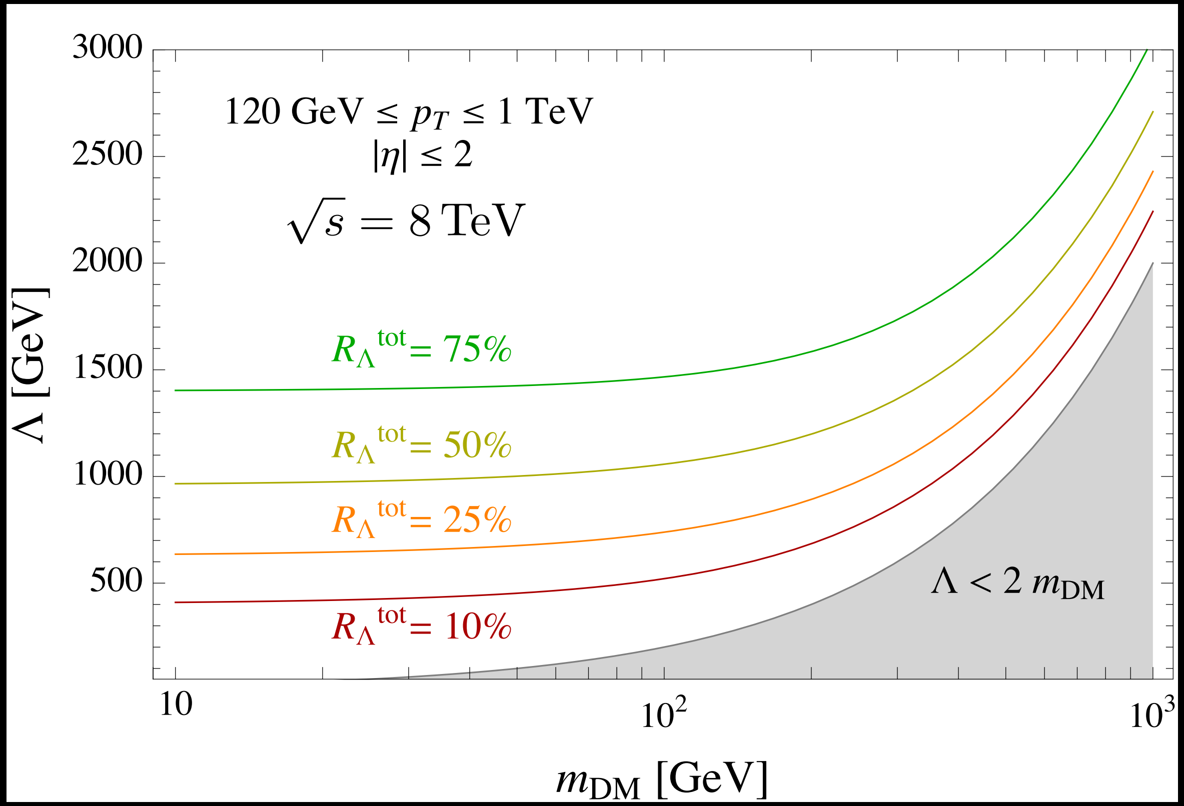


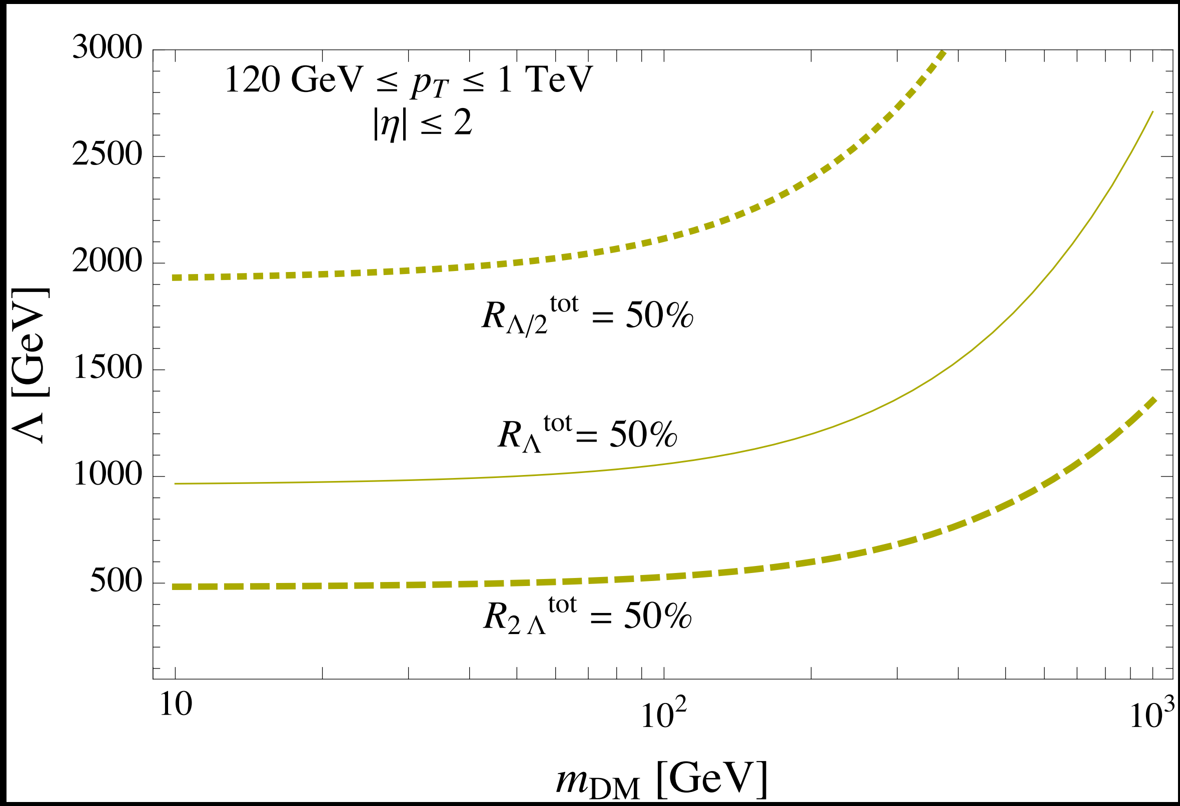
- Ratio ~ 1: negligible contribution from higher-dim ops.
  Accurate cross sections can be extracted without considering the cutoff on the momentum transfer.

- EFT works better for larger Λ and smaller $m_{\rm DM}$

$$R_\Lambda^{\text{tot}} \equiv \frac{\sigma_{\text{eff}}\big|_{Q_{\text{tr}}<\Lambda}}{\sigma_{\text{eff}}}$$

fraction of eff. cross section at low momentum transfer



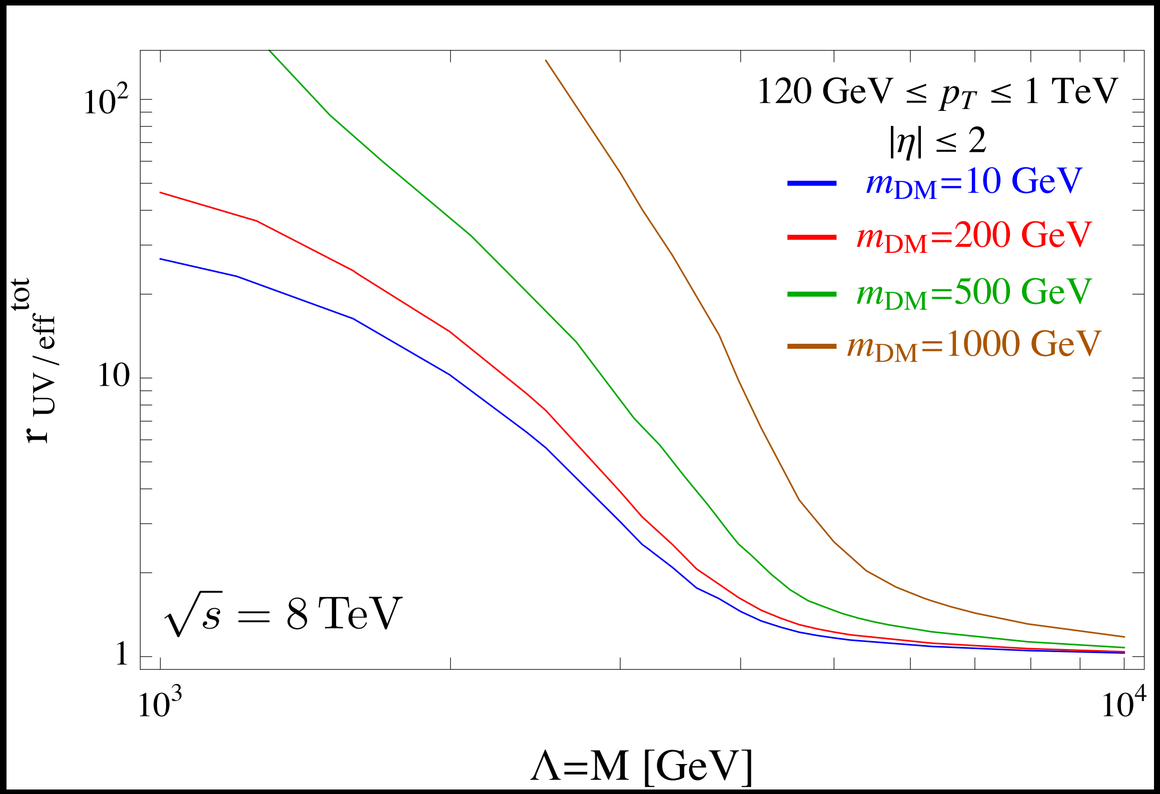


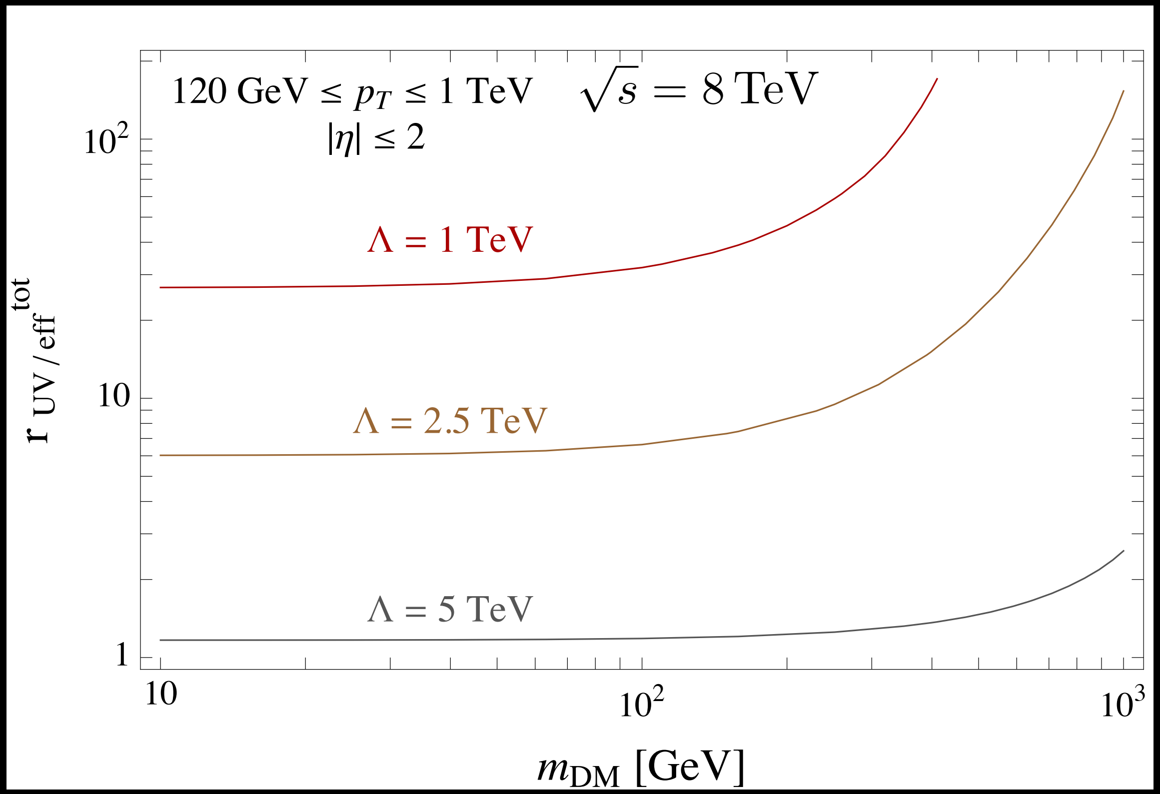
- Cross sections are measured experimentally with ~O(10%) accuracy. Worry about EFT validity is justified.

- The precise definition of cutoff scale is somewhat arbitrary (*Λ/2, 2Λ?*)
  → *O(1)* variations.

$$r^{\text{tot}}_{\text{UV/eff}} \equiv \frac{\sigma_{\text{UV}}}{\sigma_{\text{eff}}}$$

error of using EFT (truncated at dim-6) instead of full theory





- σ_{UV} easily larger than σ_{eff} → mono-jet data can place stringent bounds on heavy mediator masses

- **direct** exclusion bounds from negative searches of heavy mediators?

LHC searches for DM using effective operators must be handled with care

without resorting to an explicit model, info about the validity of EFT can be extracted → take this into account when placing bounds

use explicit UV completions rather than EFT → stronger limits from direct searches of heavy mediators

- The current situation on DM is very confusing...
  but exciting times ahead

- Huge and diverse efforts to detect the (WIMP) Dark Matter

Golden Age of Dark Matter searches

- Discovery in 5-10 years, or abandon the WIMP paradigm...
  (axion revival?)

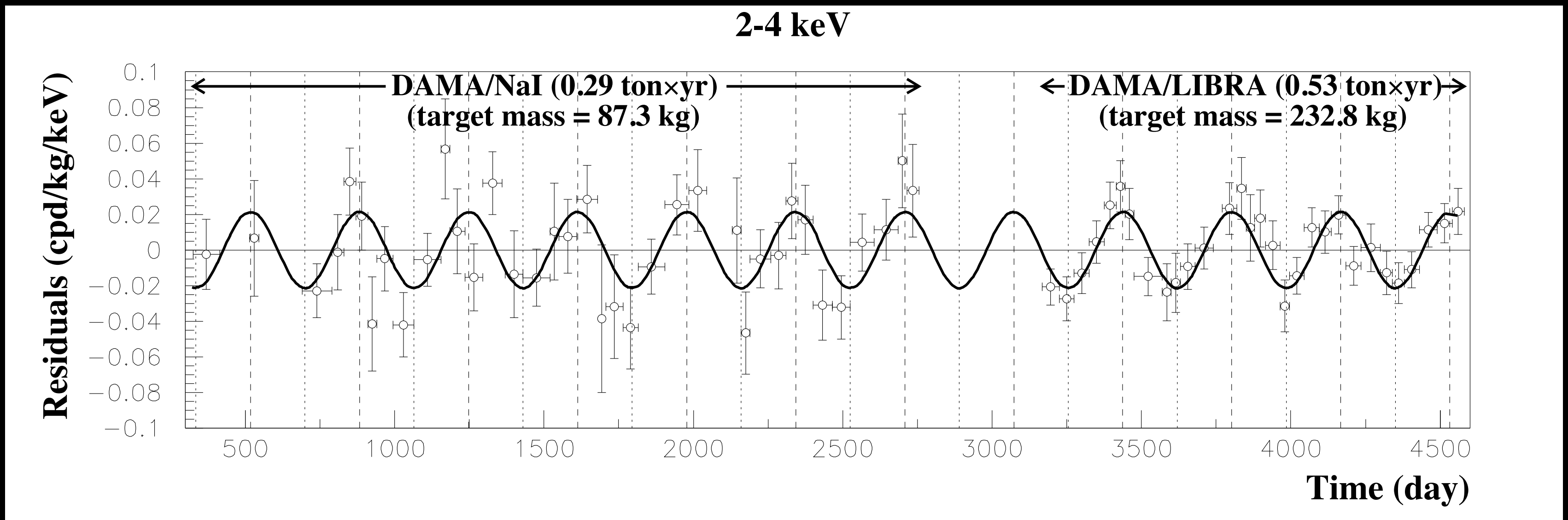
- ....or perhaps after LHC Run-II:
  less motivation to look for DM at the weak scale?

BACK-UP SLIDES

- positive hints (signals)

DAMA/Libra (NaI)

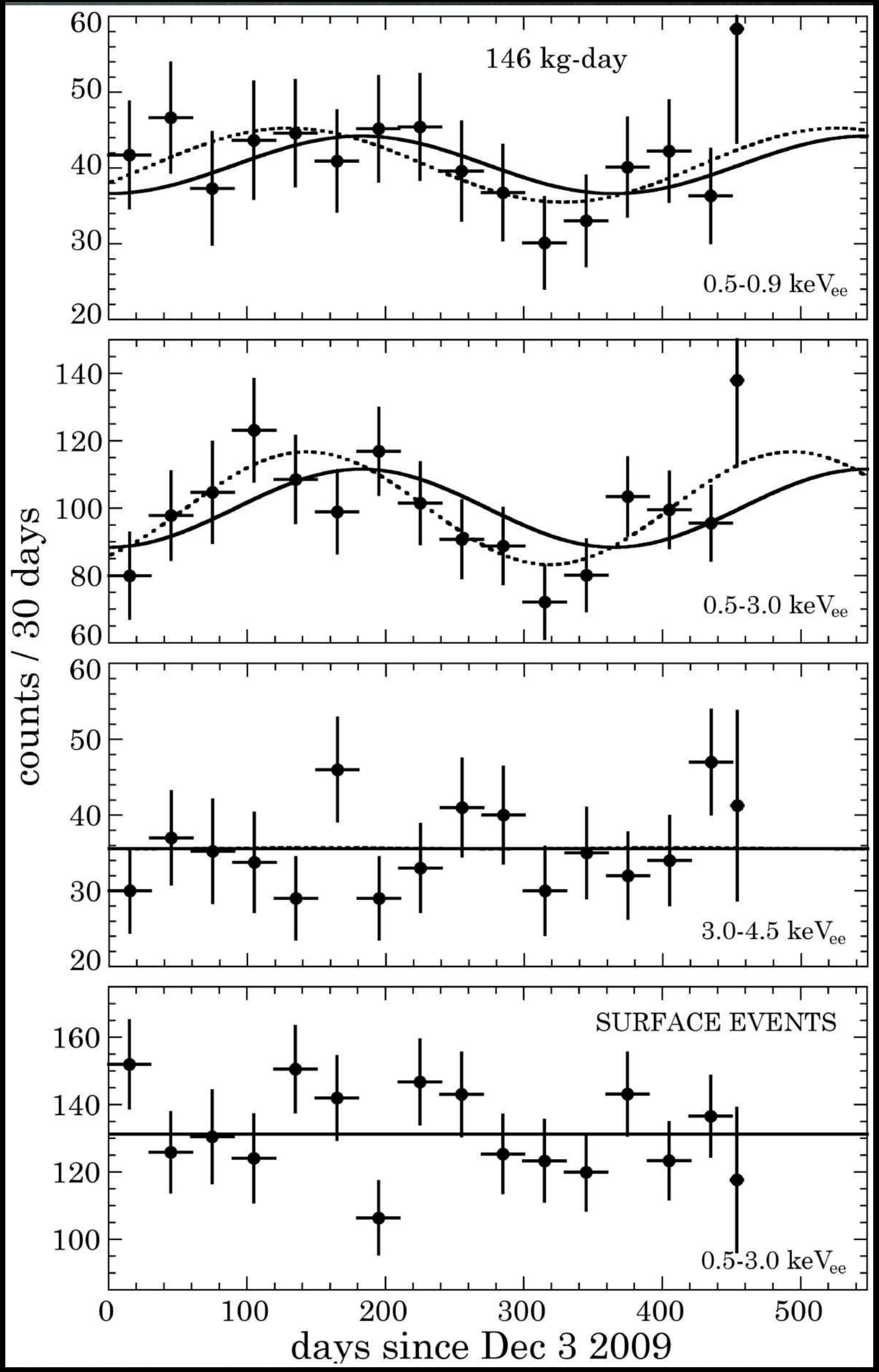
8σ observation of annual modulation



[DAMA Coll - 0804.2741]

CoGeNT (Ge)

2.7σ annual modulation



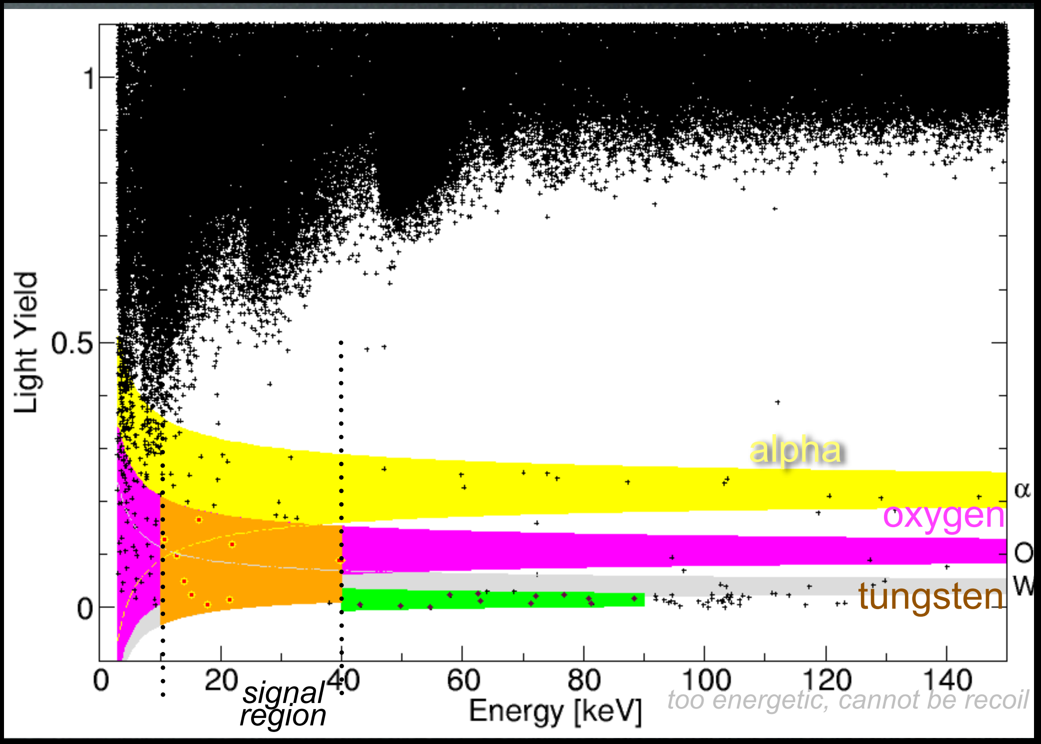
[CoGeNT Coll - 1106.0650]

- positive hints (signals)

CRESST
($CaWO_4$)

67 events, ~4σ

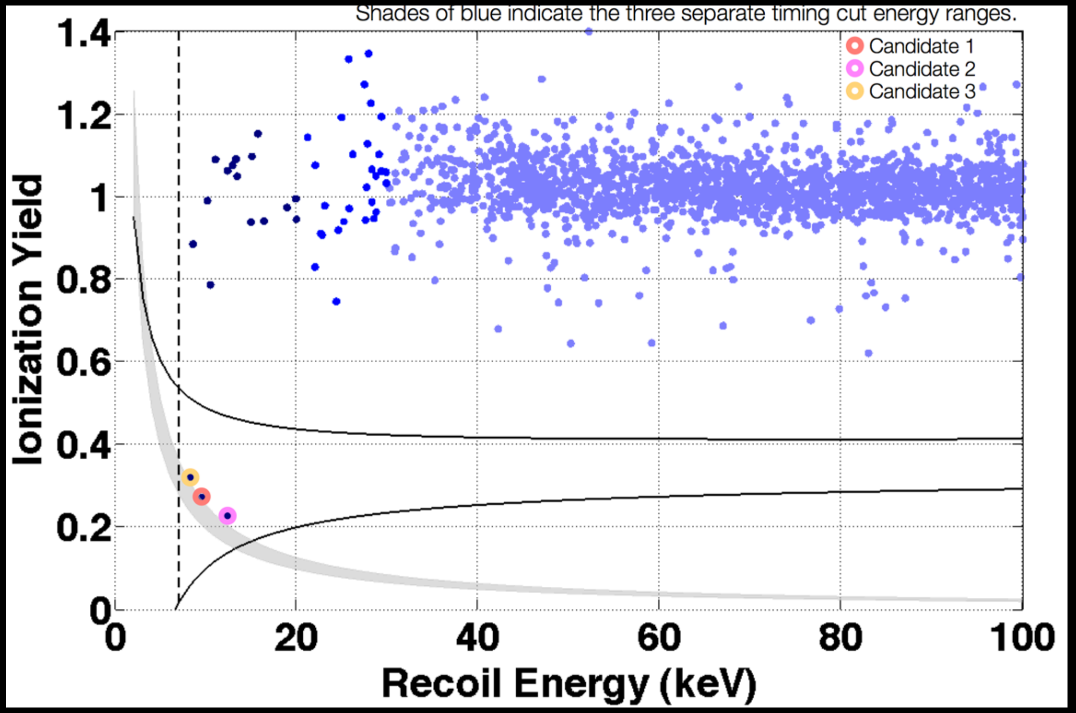
[CRESST - 1109.0702]



CDMS
(Si)

3 events, <3σ

[CDMS - 1304.4279]



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.:

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

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

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

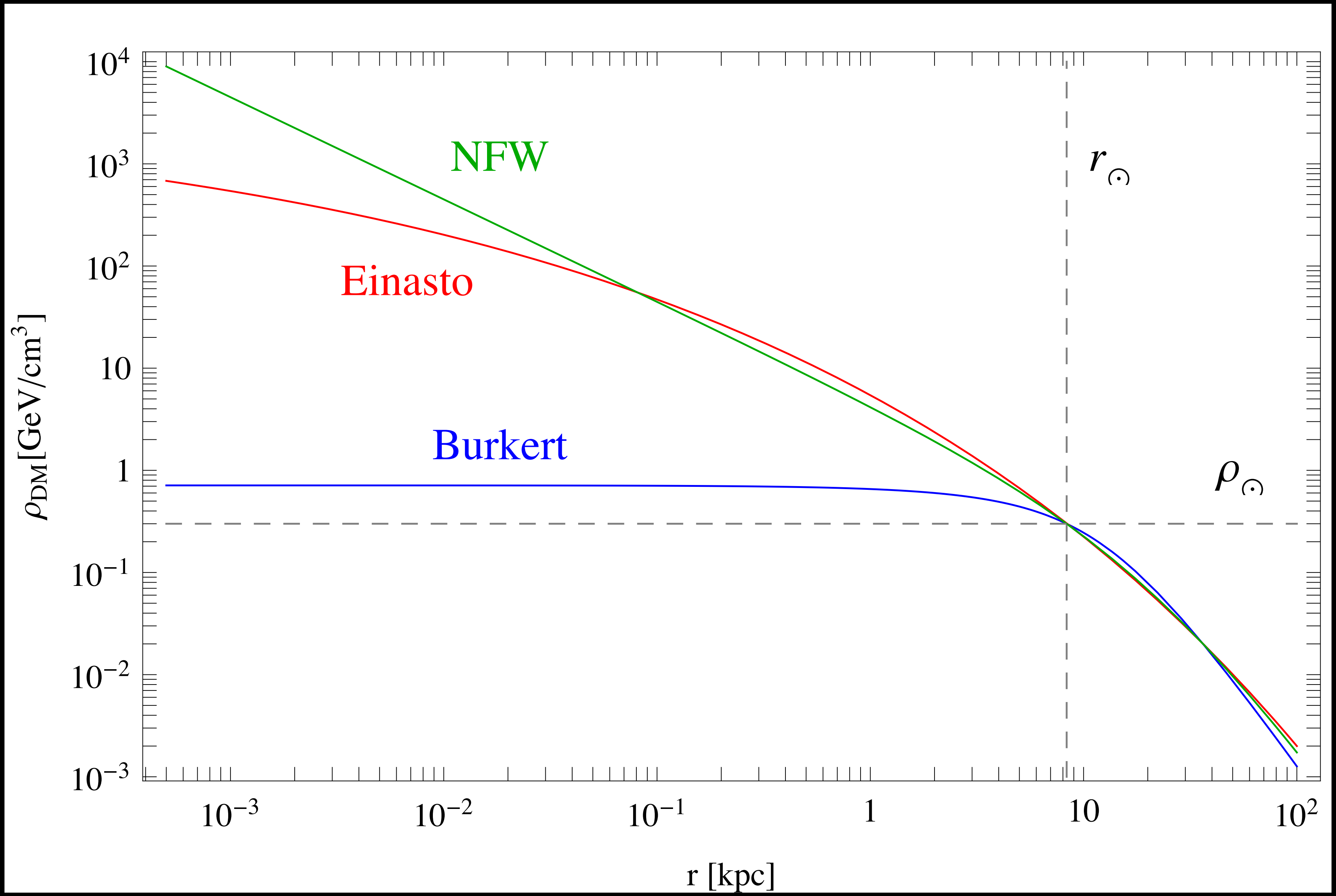
halo profile

energy spectrum of stable particle *i*

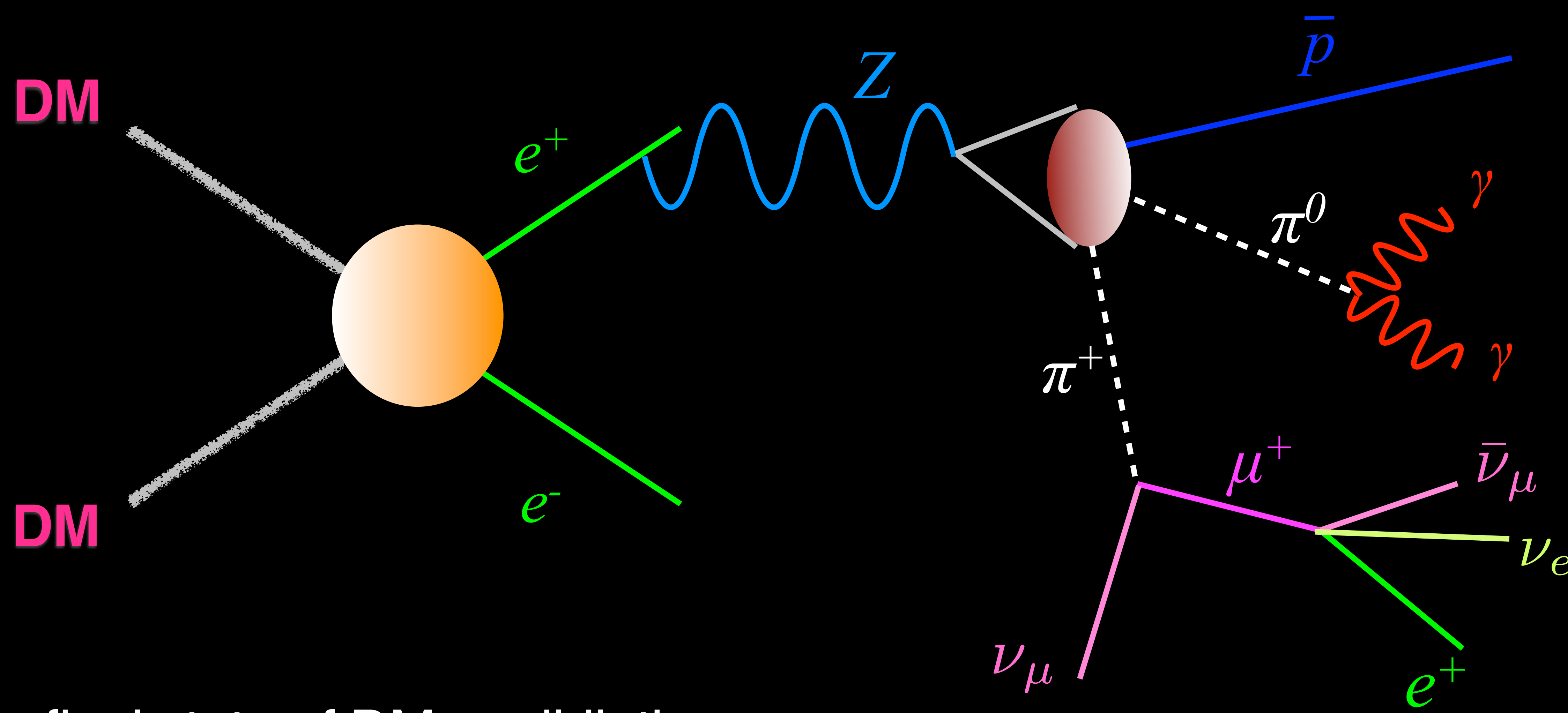
Astrophysics enters into:
- propagation parameters;
- DM halo profile.

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

Halo Profiles



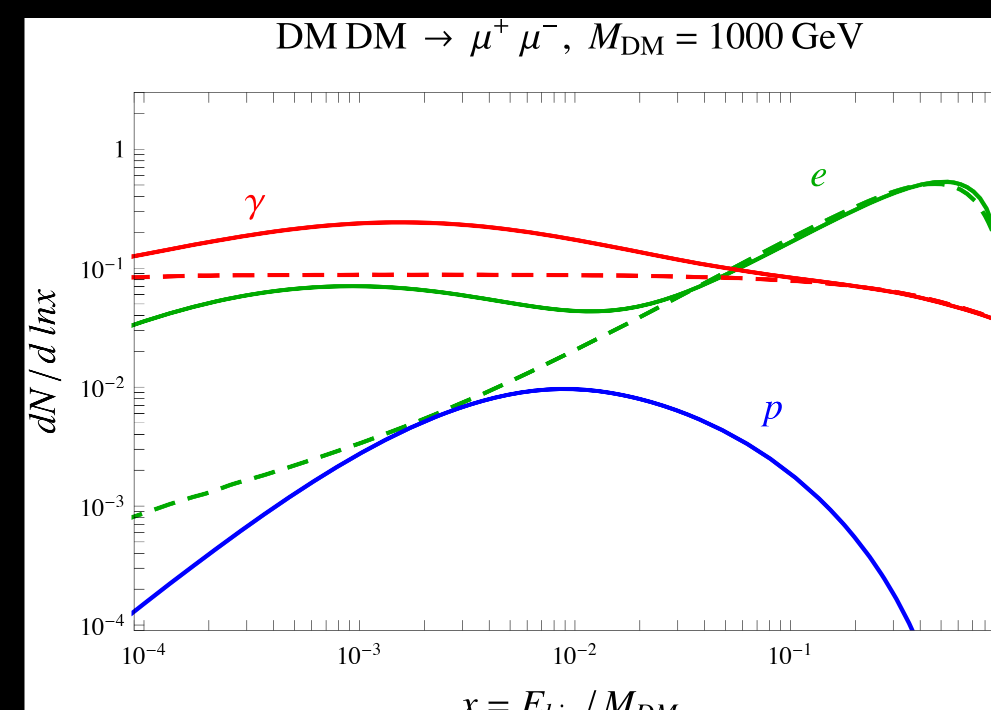
$$\rho(r) = \begin{cases} \rho_s \left[(1+r/r_s)(1+(r/r_s)^2)\right]^{-1}, & r_s = 12.67 \text{ kpc}, \quad \rho_s = 0.712 \text{ GeV/cm}^3, \quad \text{(Burkert)} \\ \rho_s \exp\left[-\frac{2}{0.17}\left[(r/r_s)^{0.17} - 1\right]\right], & r_s = 28.44 \text{ kpc}, \quad \rho_s = 0.033 \text{ GeV/cm}^3,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



- 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



Importance of EW corrections

EW corrections to DM annihilations are important in 3 cases:

1. when the observed fluxes get the largest contribution from low-energy regions of the spectra, largely populated by the products of the EW rad.

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]

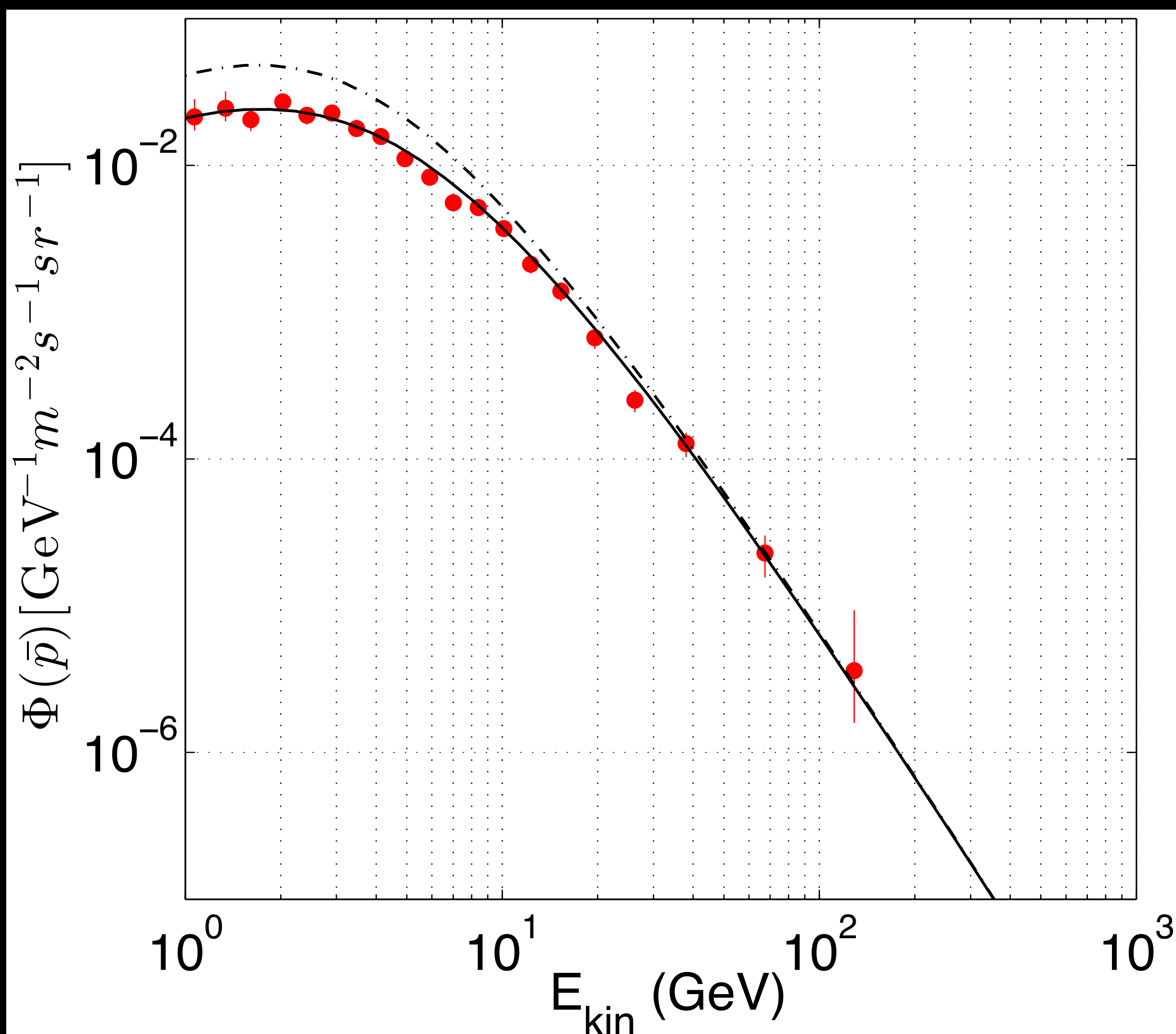
     [DS, Monin, Thamm, Urbano - 1301.1486]

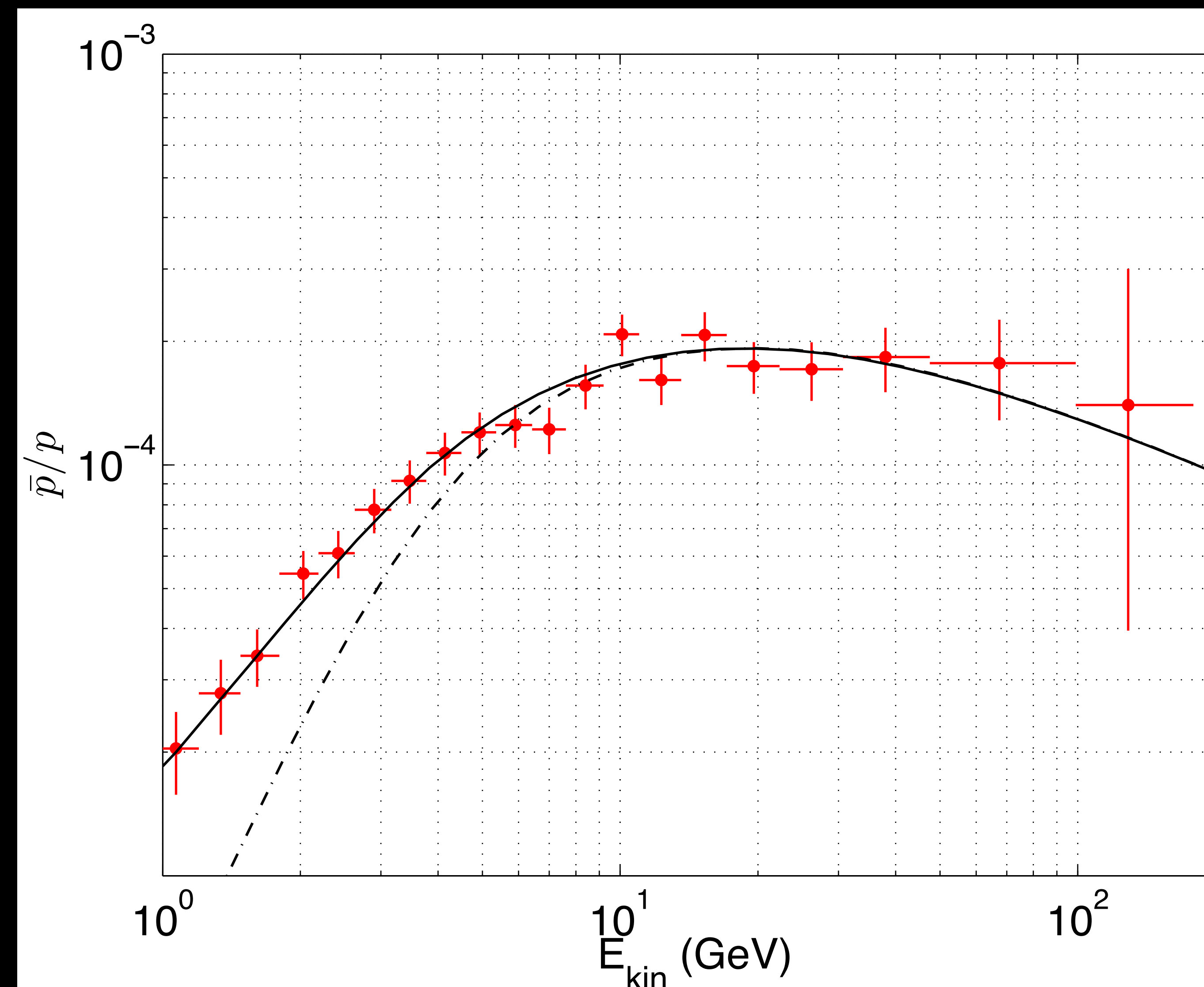
   - DM Majorana fermion/real scalar in an $SU(2)_L$-multiplet.

     [Ciafaloni, Cirelli, Comelli, DS, Riotto, Urbano - 1107.4453]

     [Ciafaloni, Comelli, DS, Riotto, Urbano - 1202.0692]

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





solid/dashed = with/without correcting for solar modulation

Method 1

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

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

then marginalize over *A*, *p* parameters.

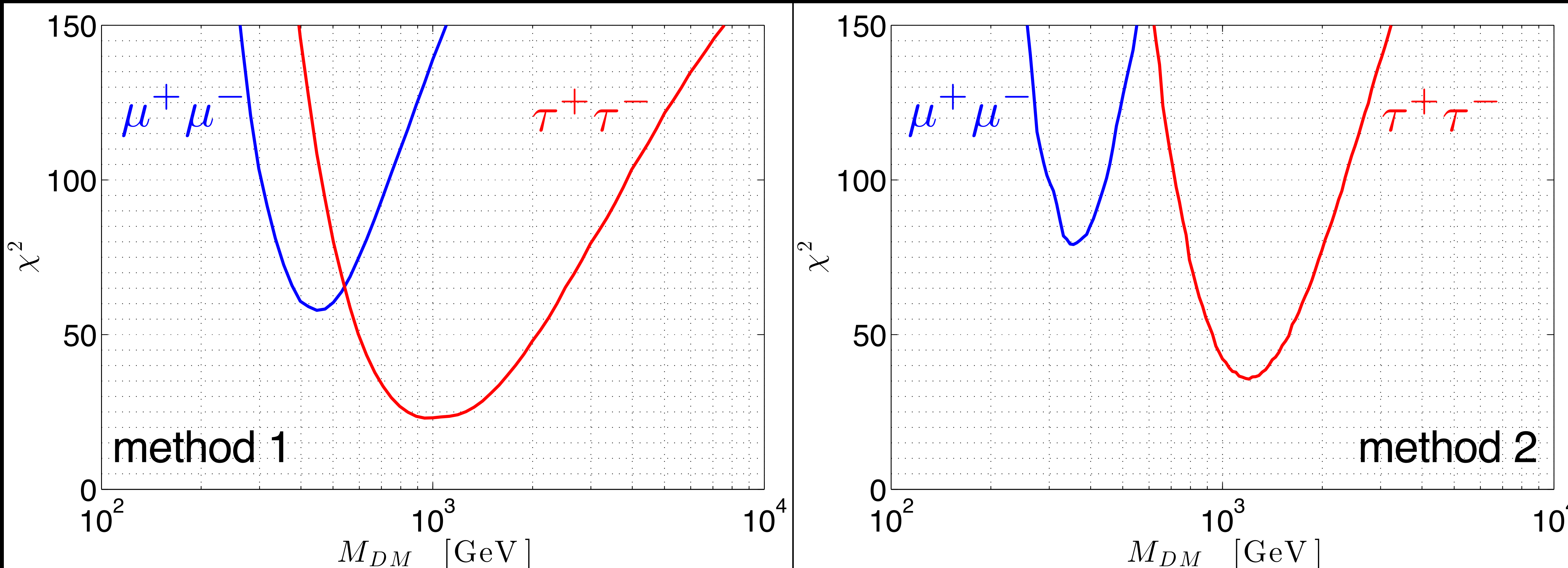
✘ fluxes of different species are treated as uncorrelated;
✓ deal with astrophys. uncert. in a simple and conservative way.

Method 2

Propagate signal and bkg with our own propagation model, which provides a good fit to several data-sets (e^-+e^+, anti-p, B/C).

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

Interpretation of AMS-02 data: Best Fits



- 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

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

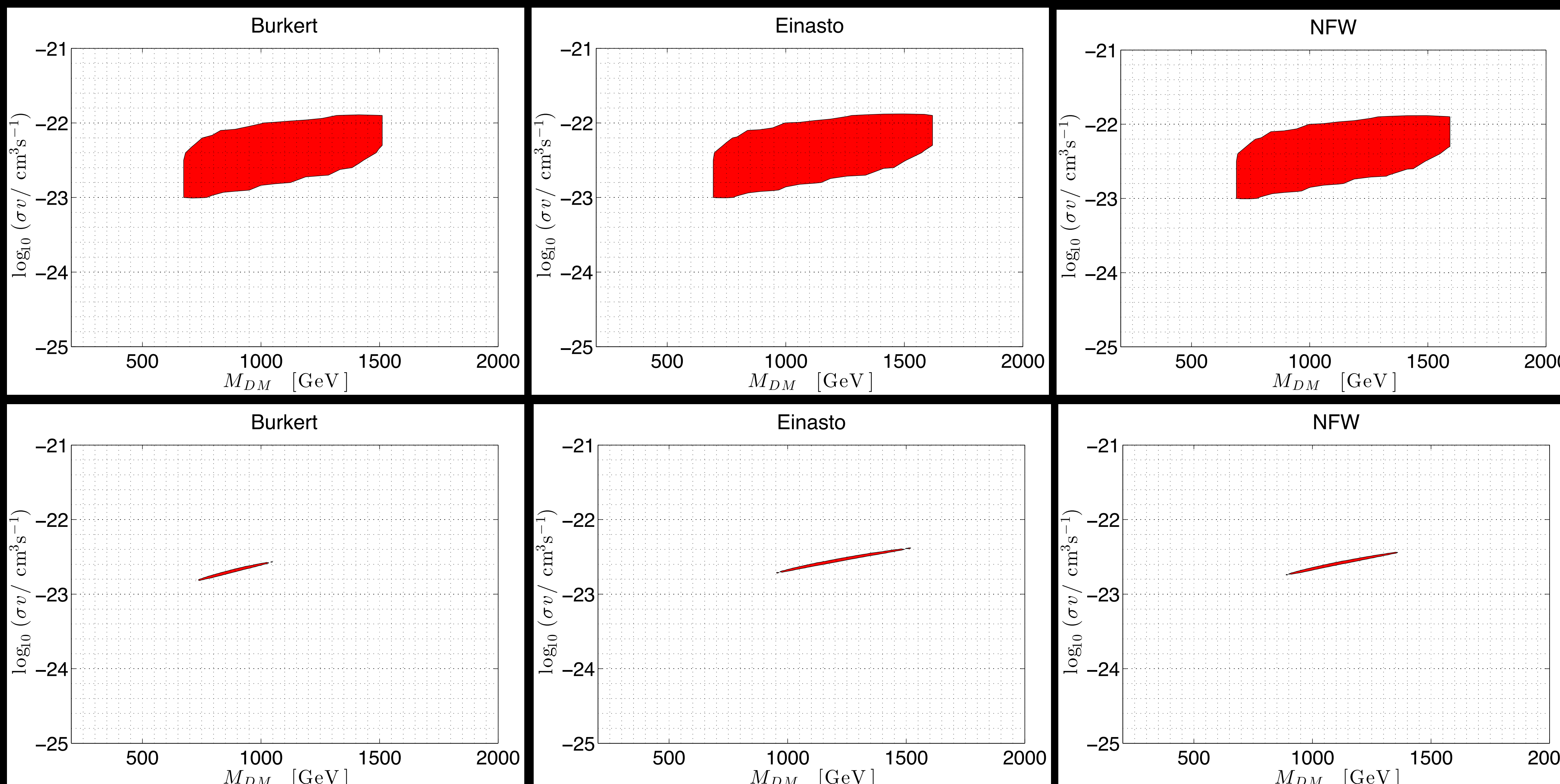
	$\mu^+\mu^-$	$\tau^+\tau^-$
method 1	1.9	0.7
method 2	2.4	1.0

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

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

Method 1

Method 2

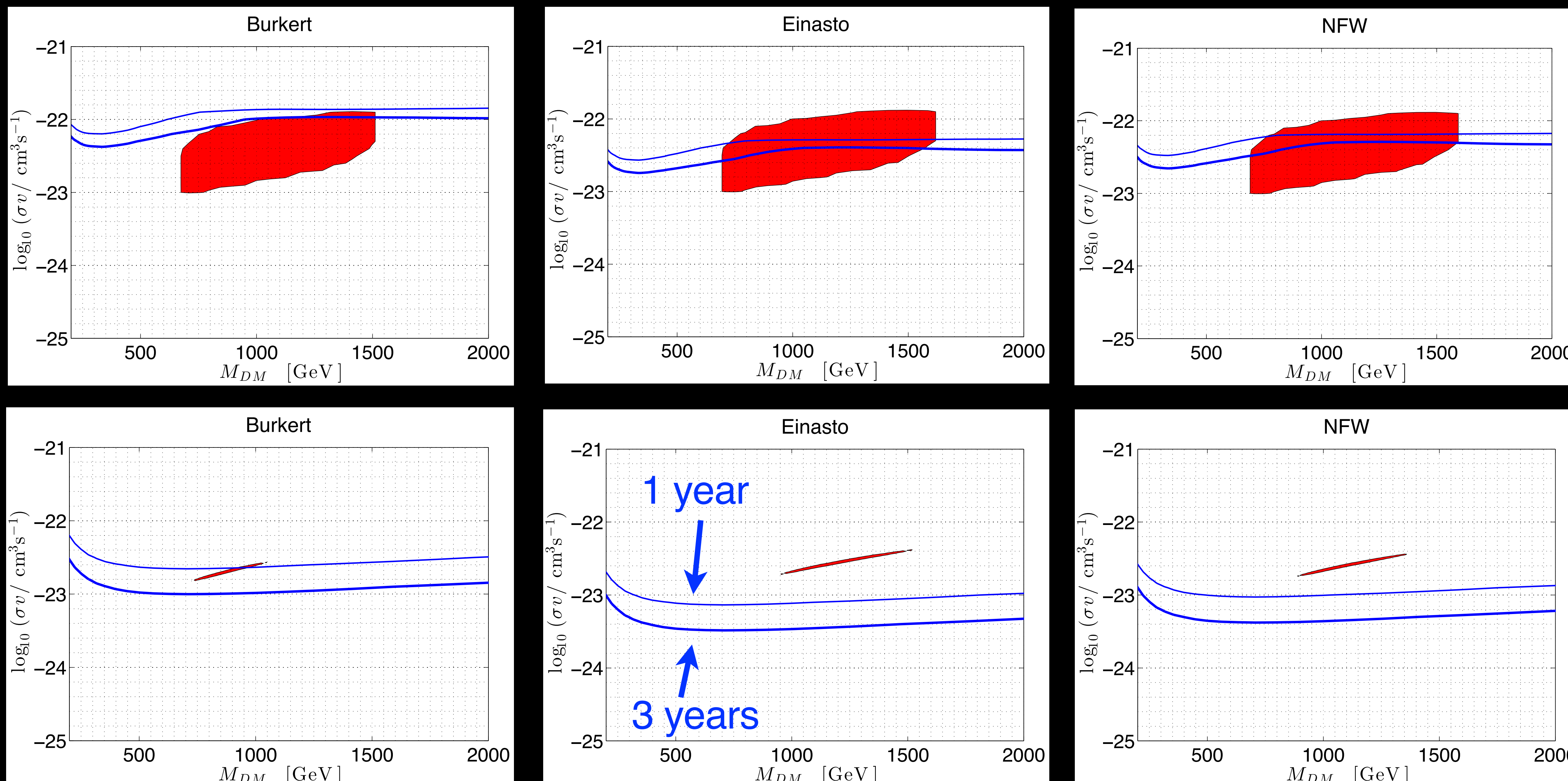


method 2 is more constrained → smaller contours

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

Method 1

Method 2



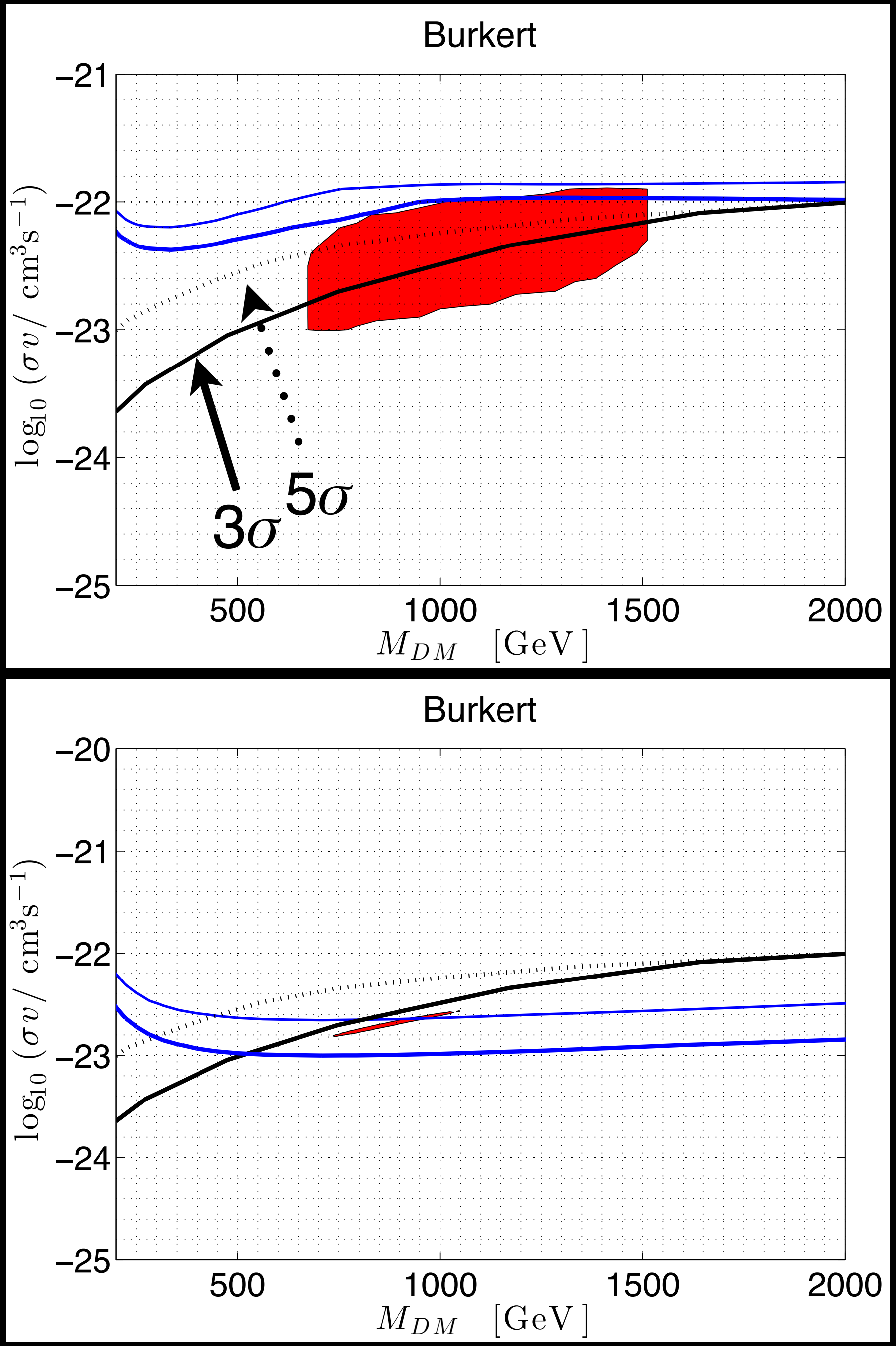
[DS, Riotto, Xue - 1304.1336]

- 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