Balkan Workshop - 26 Apr 2013

The Quest for Dark Matter: update and news

Andrea De Simone

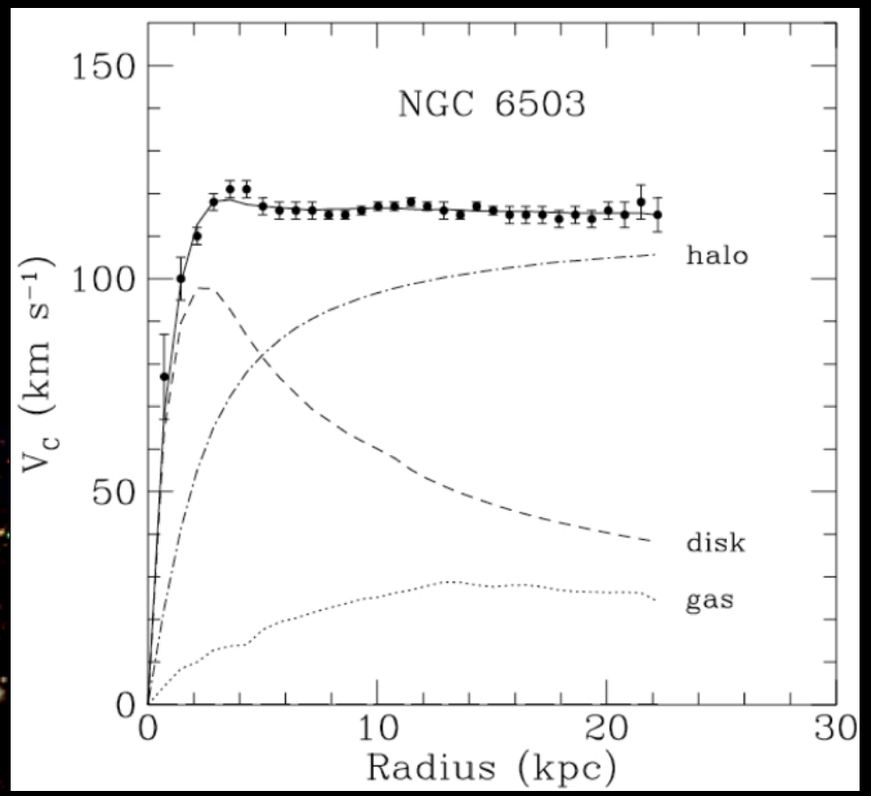
Outline

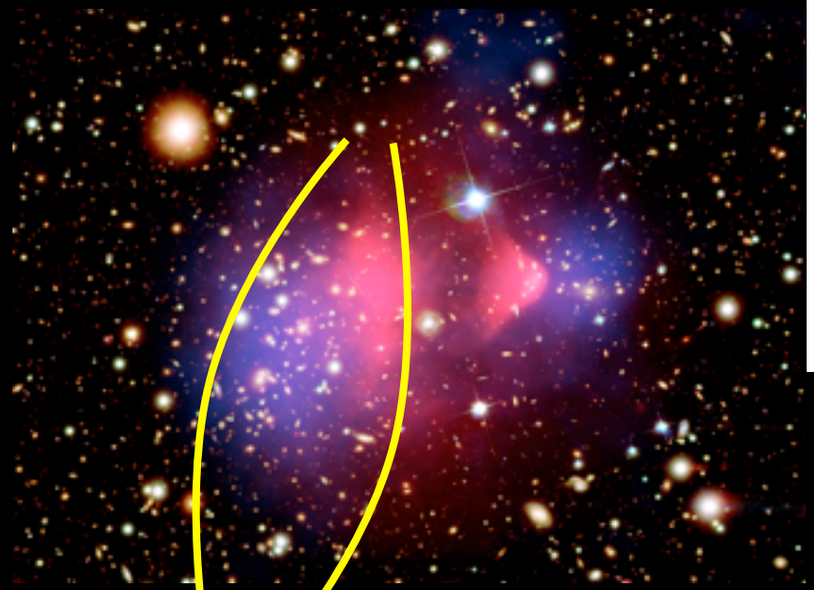
- Status of Dark Matter Searches
- New AMS-02 Data:

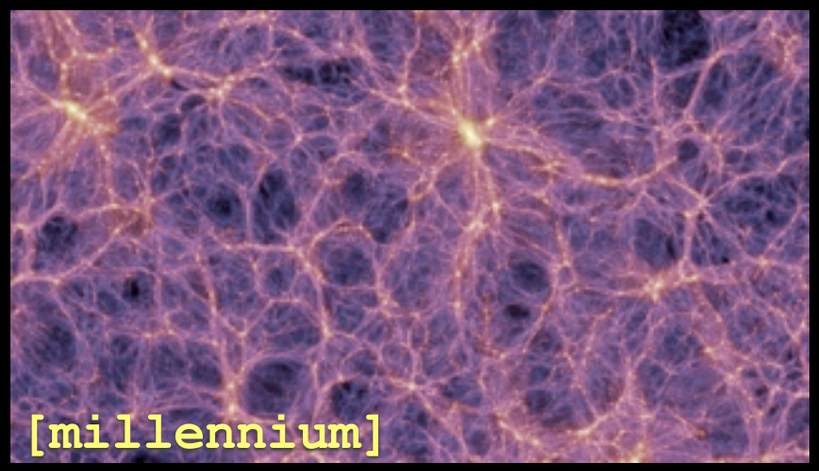
Interpretation and Predictions

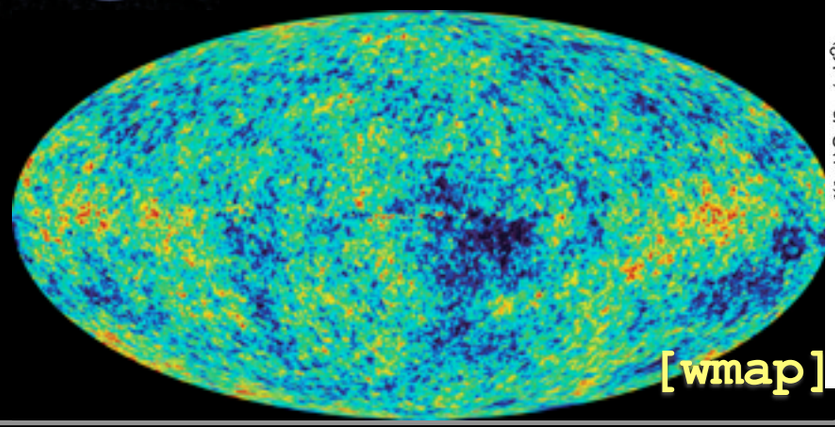
Evidences for DM

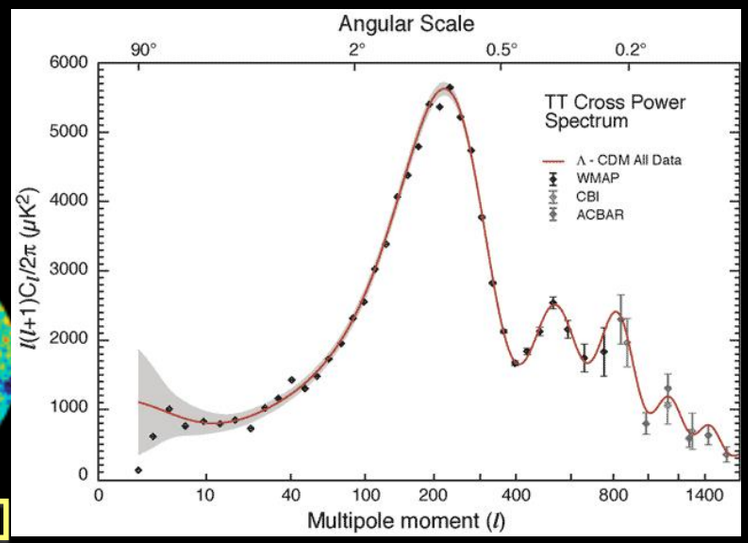
- rotation curves of galaxies
- gravitational lensing
- CMB+LSS











Candidates

(an incomplete list)

WIMP

neutralino
minimal DM
heavy neutrino
inert Higgs doublet
LKP
LTP
...

non-WIMP

axion
gravitino
axino
sterile neutrino
techni-baryon,
Q-balls
...

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Search Strategies

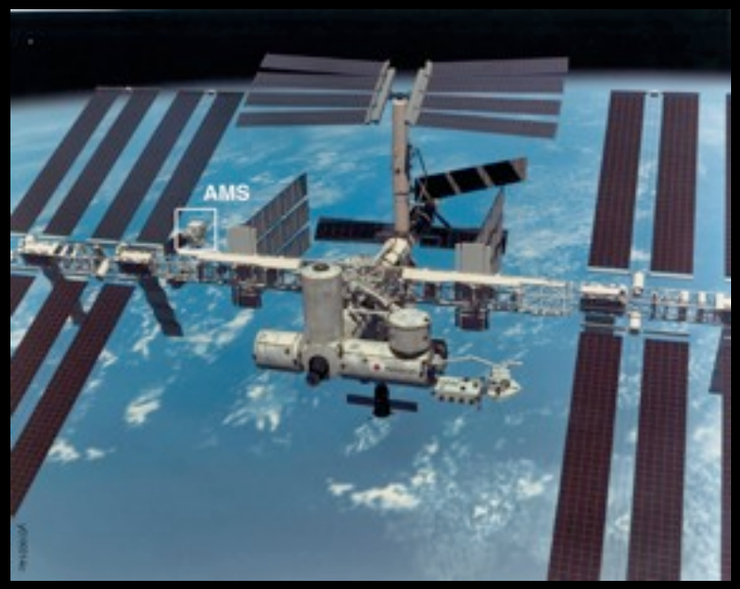
COLLIDER

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

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**

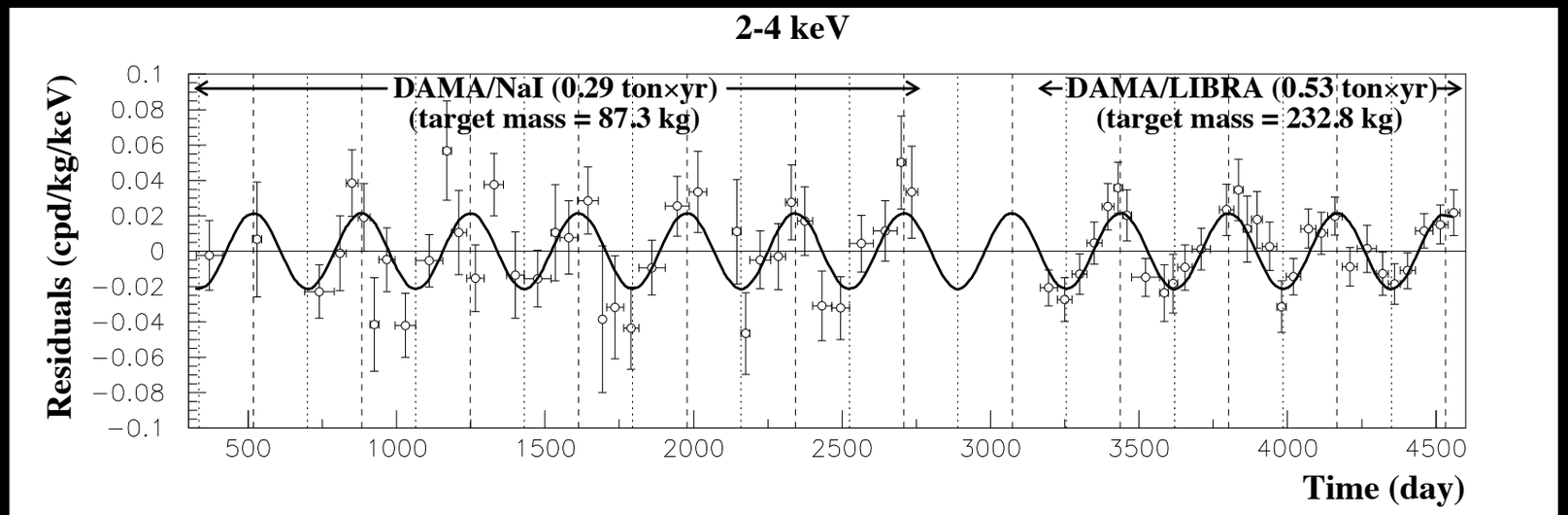
DIRECT DETECTION

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

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

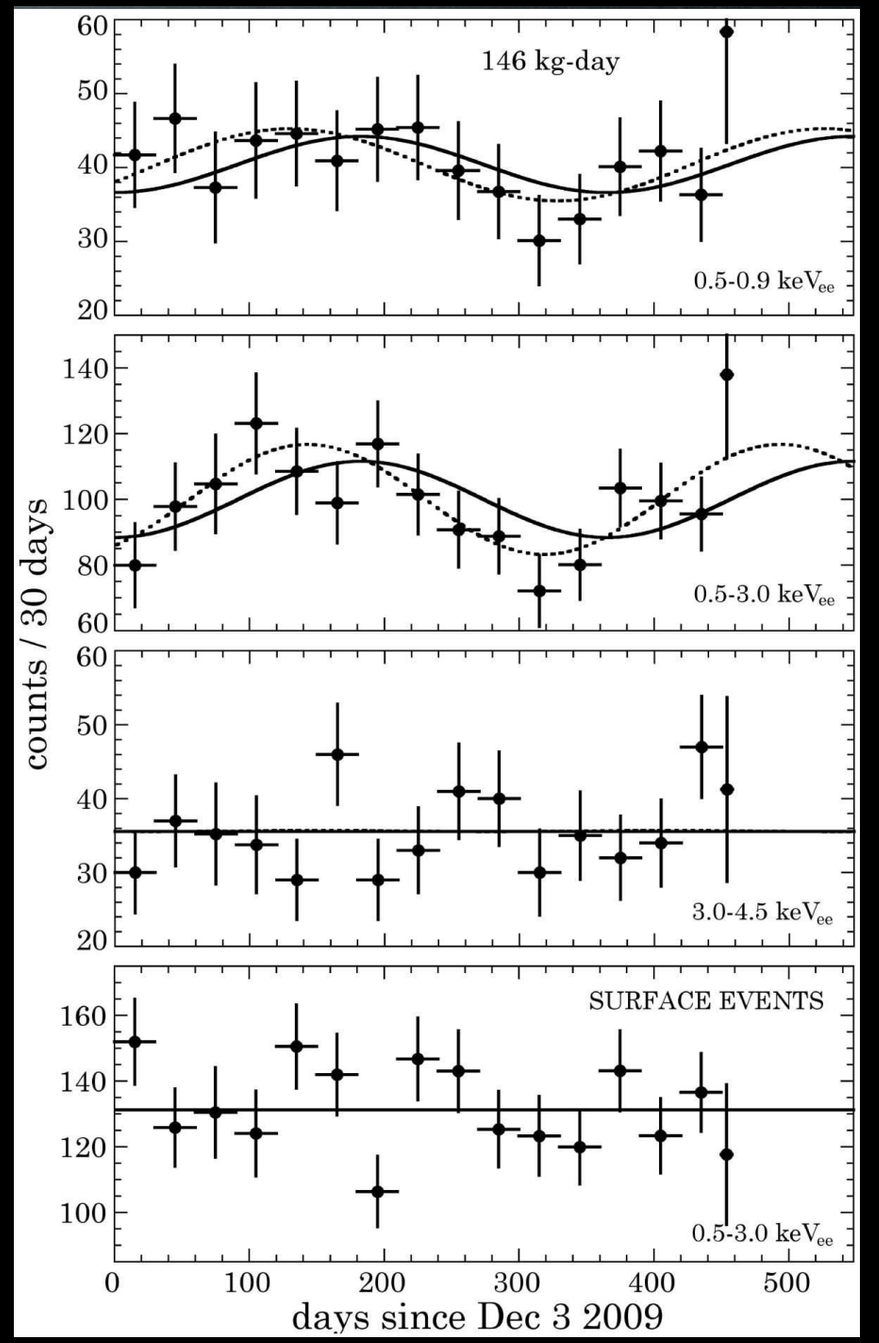
- positive hints (signals)

DAMA/Libra (NaI) 8σ observation of annual modulation



[DAMA Coll - 0804.2741]

CoGeNT (Ge) 2.7σ annual modulation



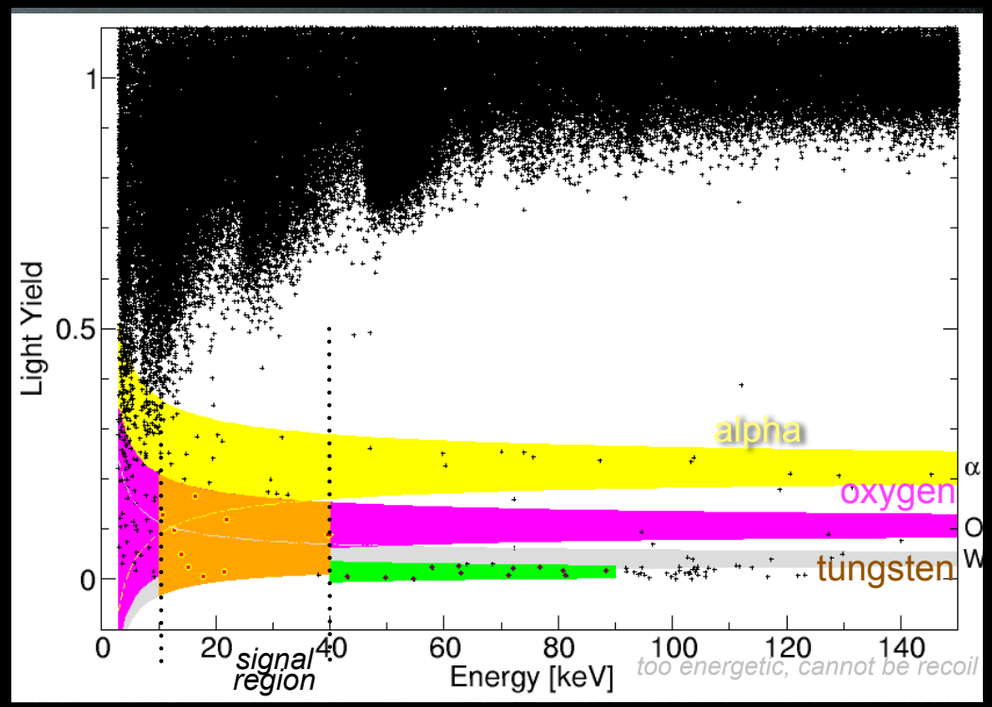
[CoGeNT Coll - 1106.0650]

- positive hints (signals)

CRESST
($CaWO_4$)

67 events, ~4σ

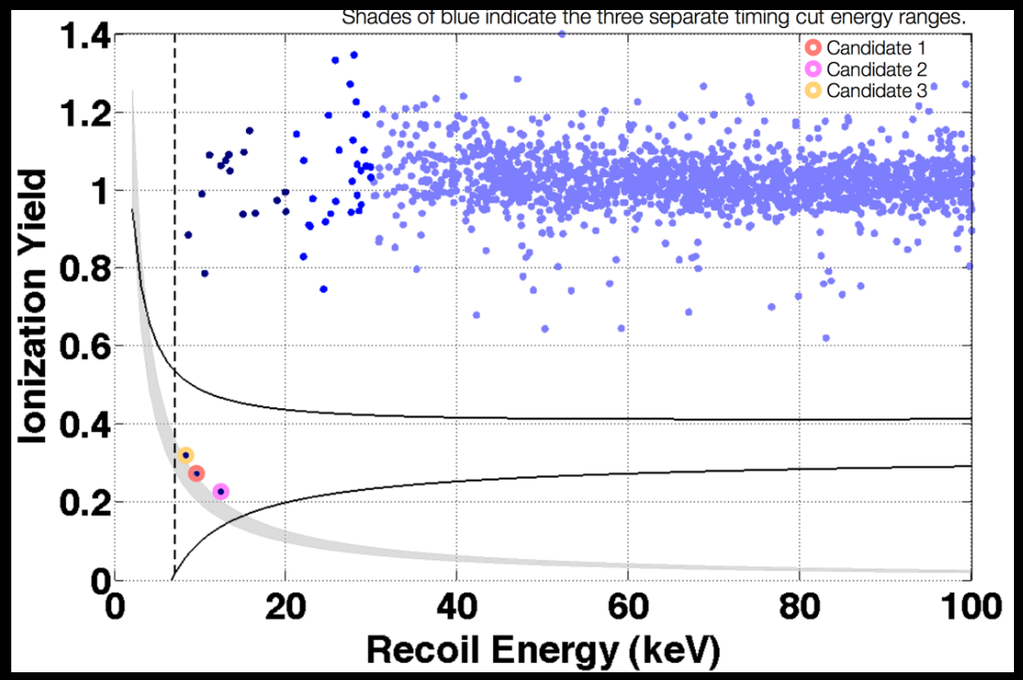
[CRESST - 1109.0702]



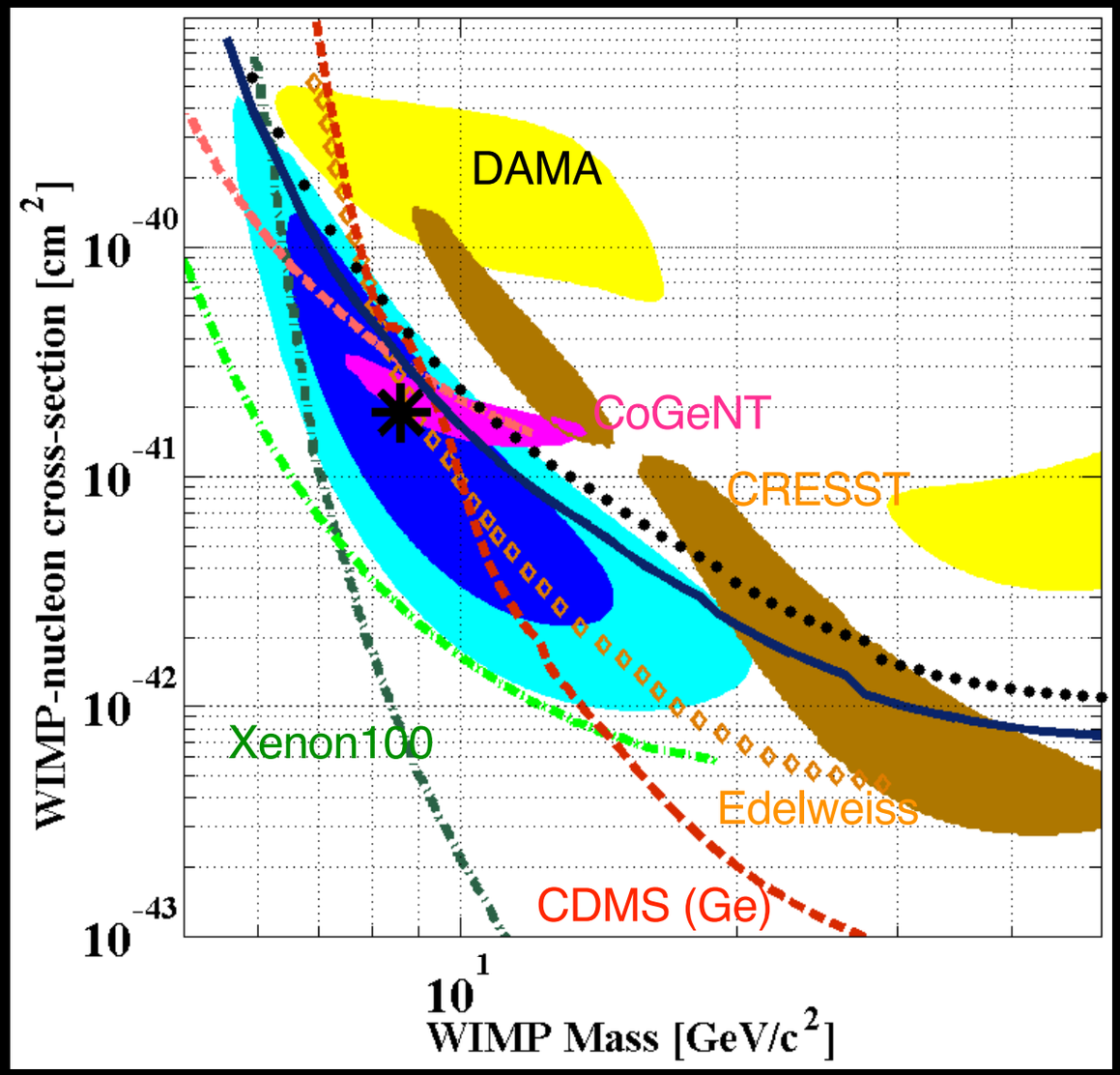
CDMS
(Si)

3 events, <3σ

[CDMS - 1304.4279]



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



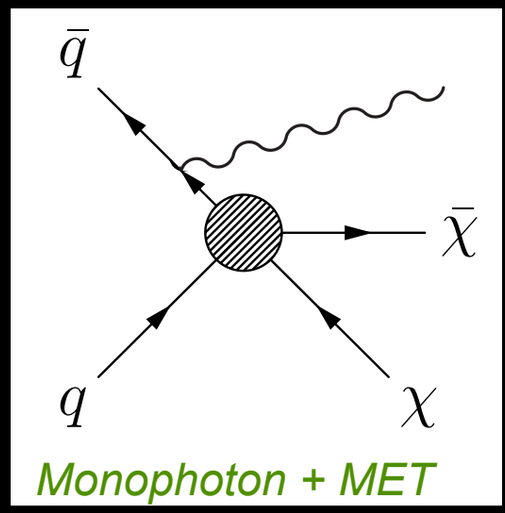
[CDMS - 1304.4279]

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

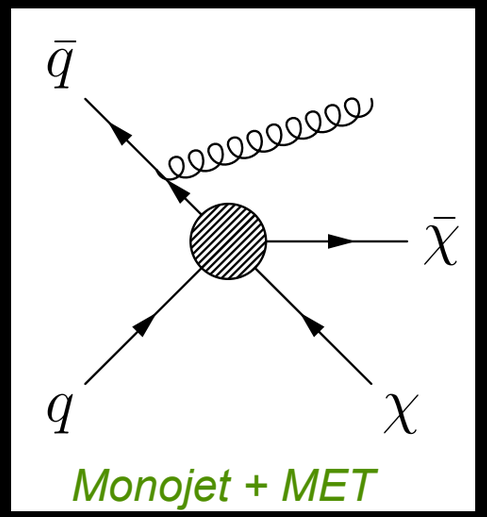
in LHC we trust...

Difficult search, unless correlating MET with other handles (displaced vertex, ISR jets, ISR photons...)

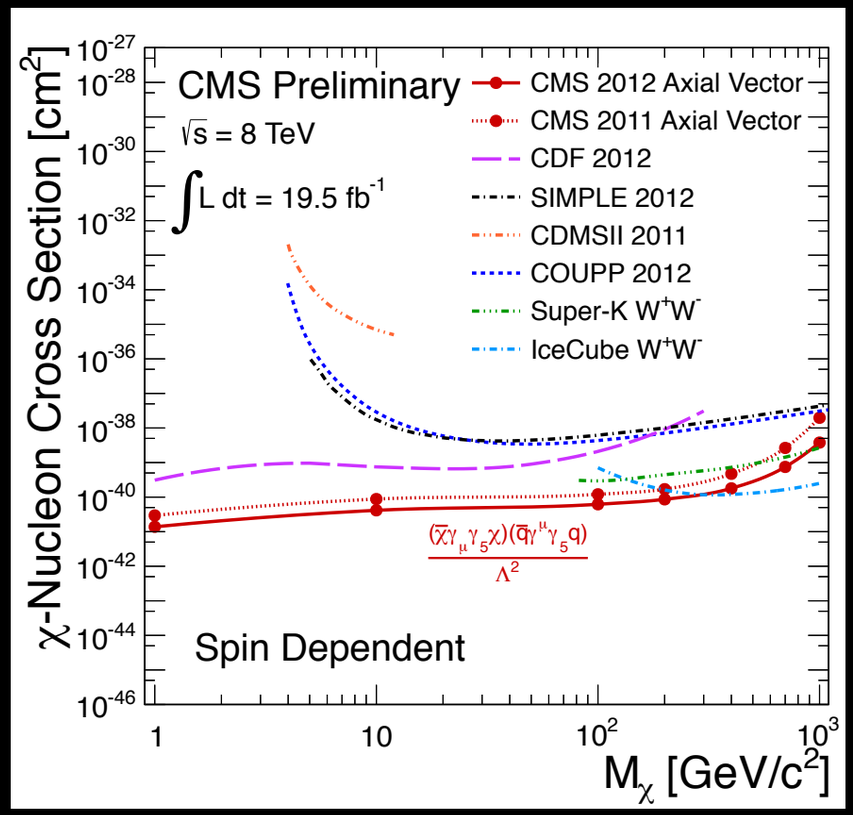
- constrain DM-quarks interactions and translate into limits on scattering cross-section
- complementary/ competitive with direct detection.
- no astrophysical uncertainty.

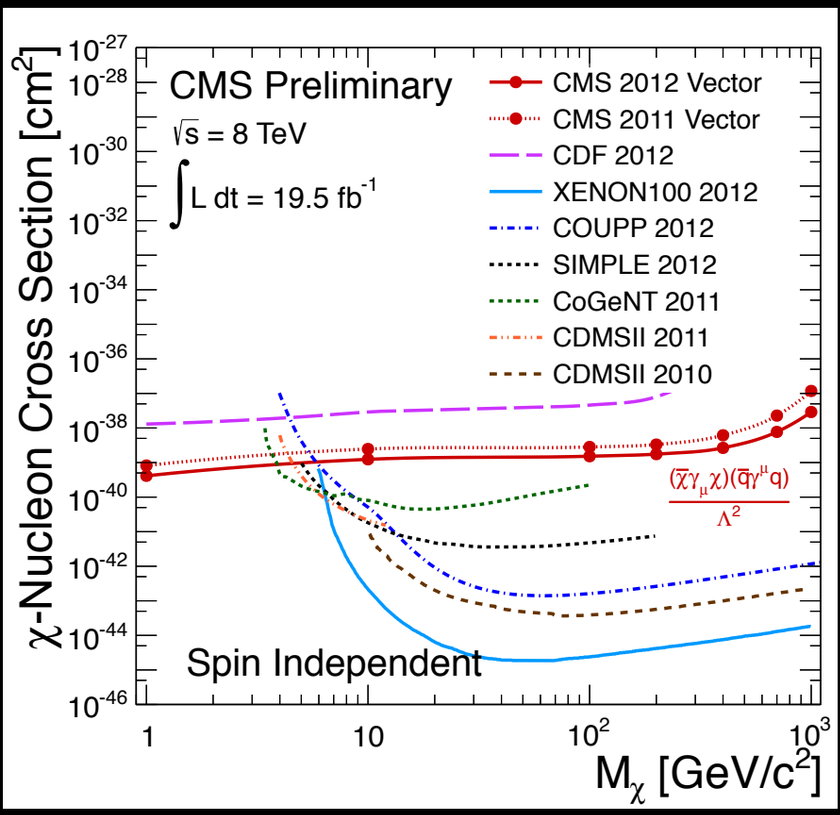


Monophoton + MET



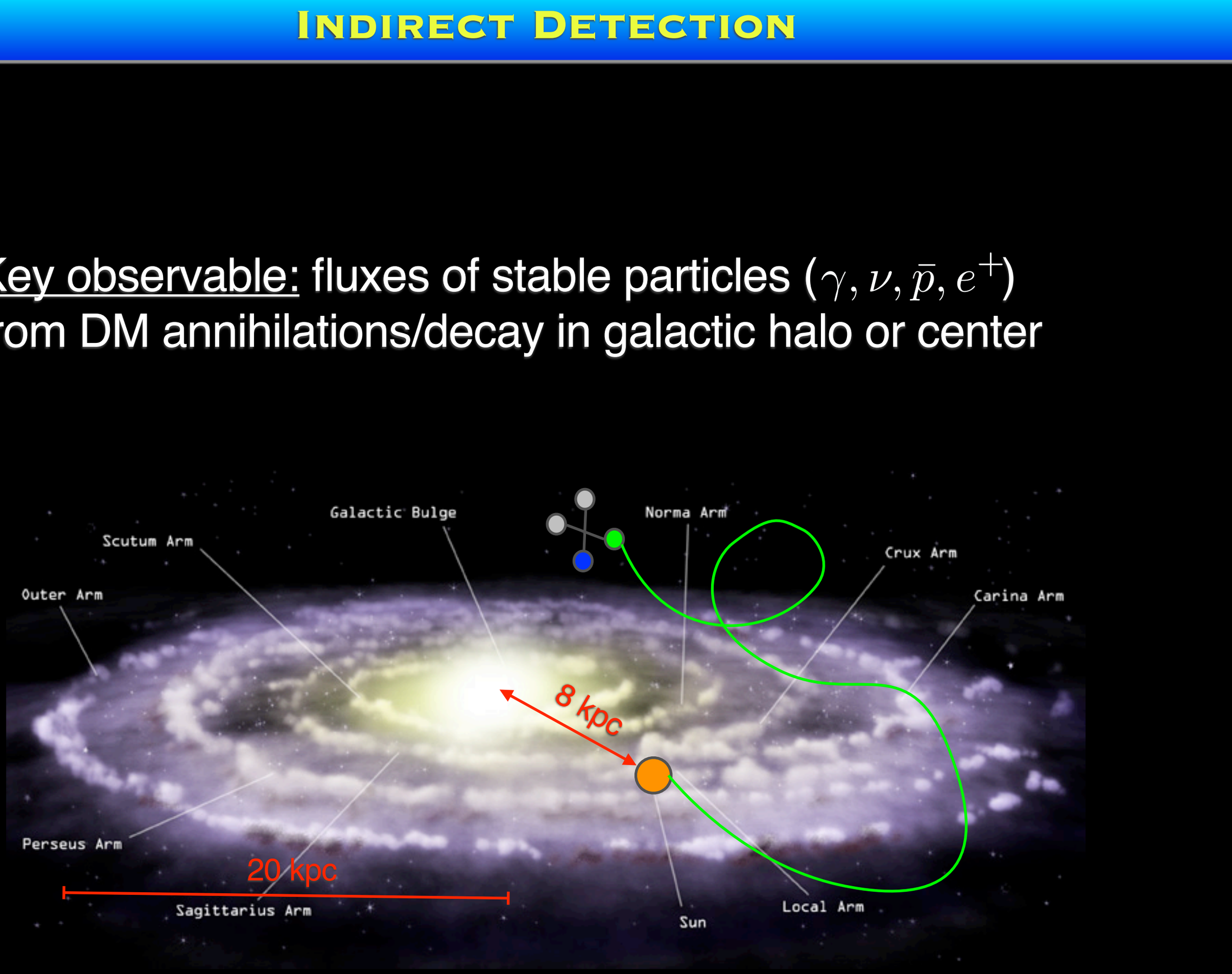
Monojet + MET



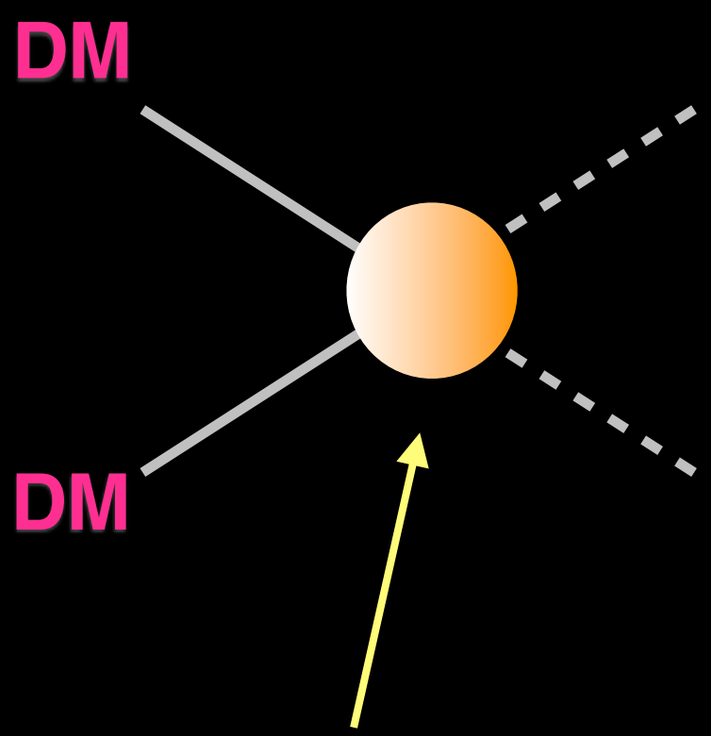


[CMS PAS EXO-12-048]

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



Indirect Detection



DM annihilations in galactic halo/center

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

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

primary channels

SM evolution

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

stable species

astrophysical propagation

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

fluxes at detection

model for DM interactions
$(\mathcal{L})$

radiation/hadronization/decay
(QCD, QED, EW)

DM

DM

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

primary channels

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

SM evolution

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

stable species

particle physics

DM annihilations in galactic halo/center

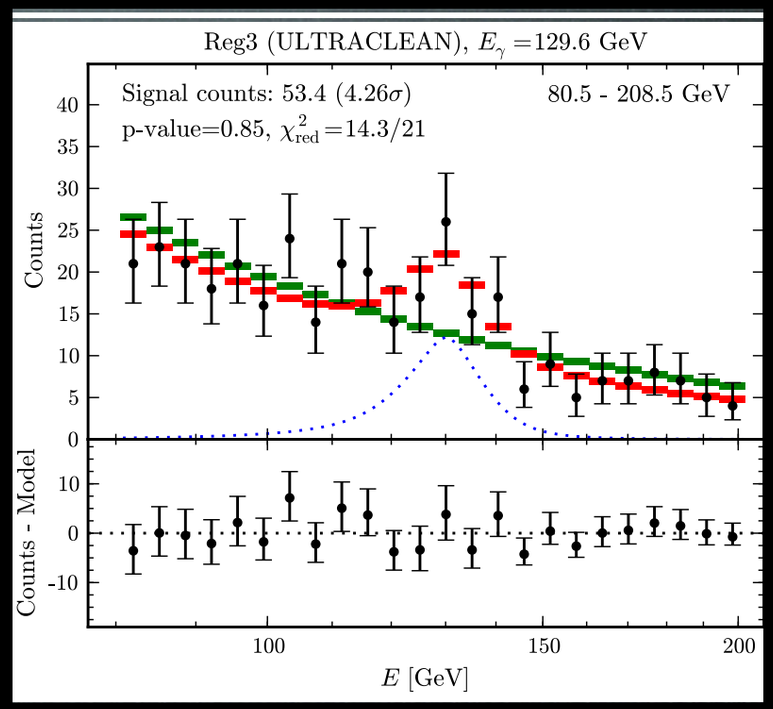
astrophysical propagation

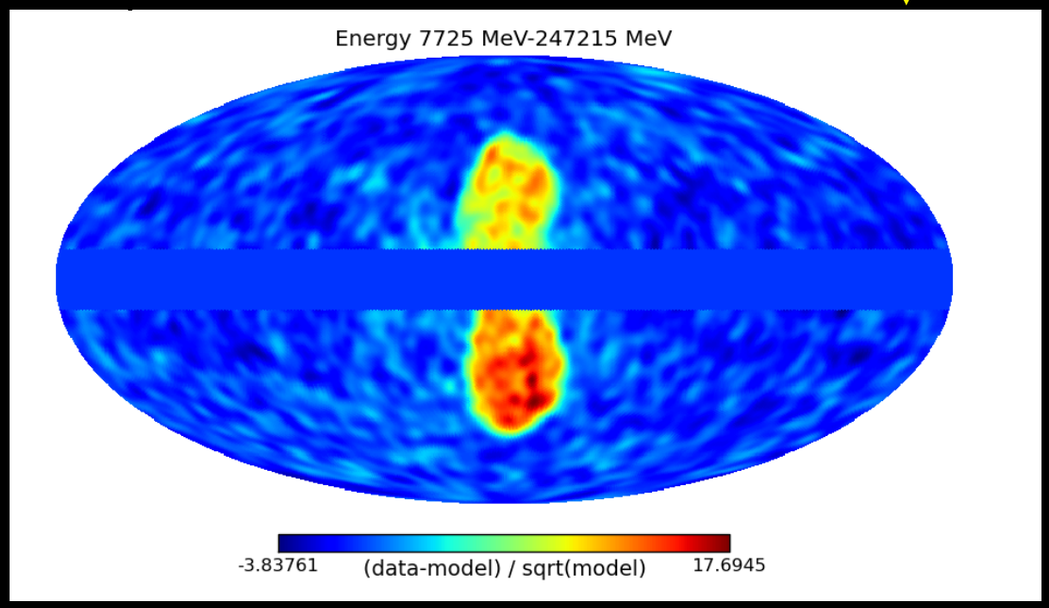
$e^\pm, \gamma, \nu, \bar{\nu}, p, \bar{p}, \dots$

fluxes at detection

Indirect Detection "Anomalies"

- "Anomalies" in gamma rays
  - Fermi 135 GeV line
  - Fermi "bubbles"





see Zaharijas' talk later

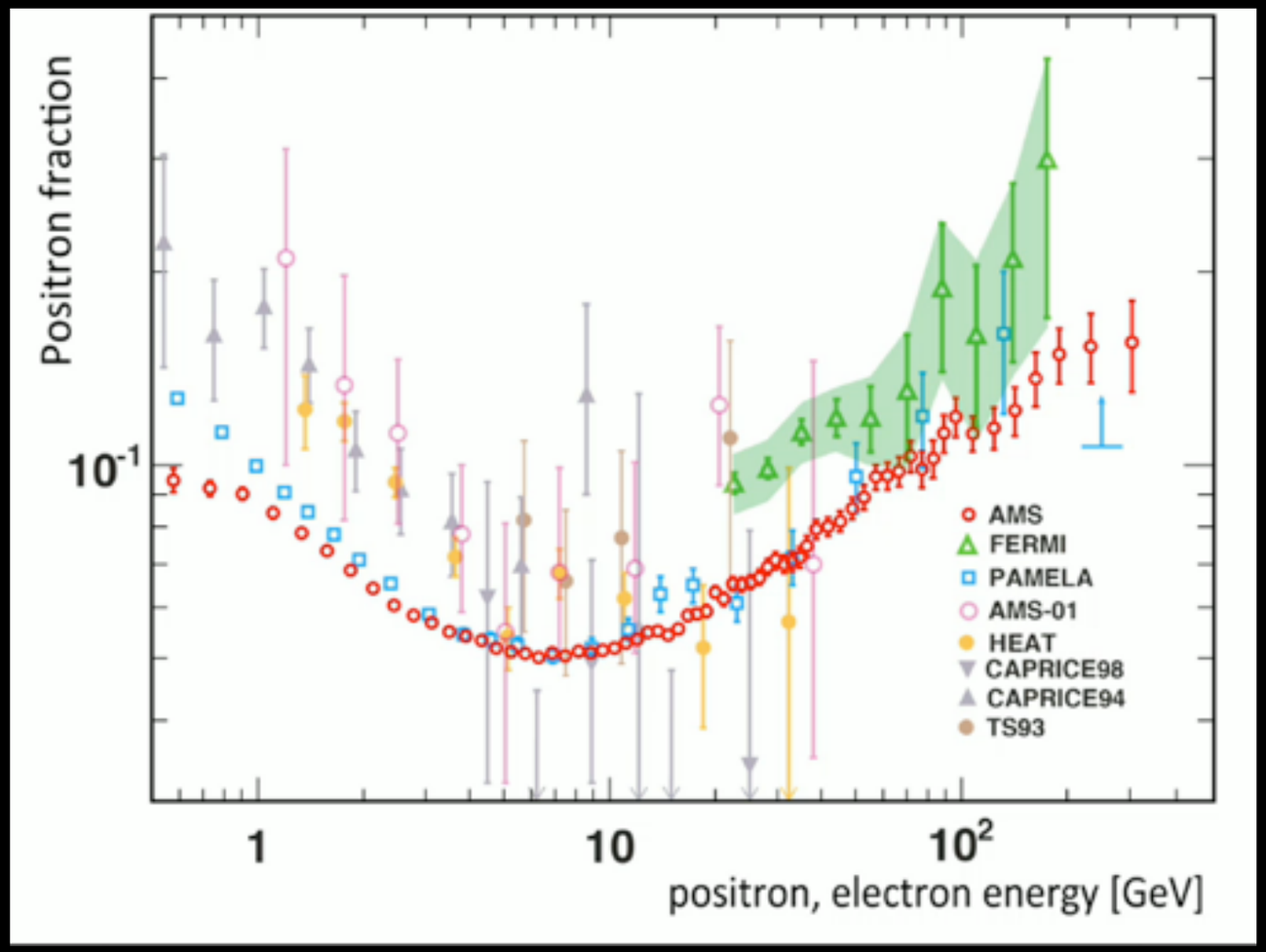
- "Anomaly" in charged cosmic rays (positron fraction $e^+/(e^++e^-)$)

Positron Fraction "anomaly"

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

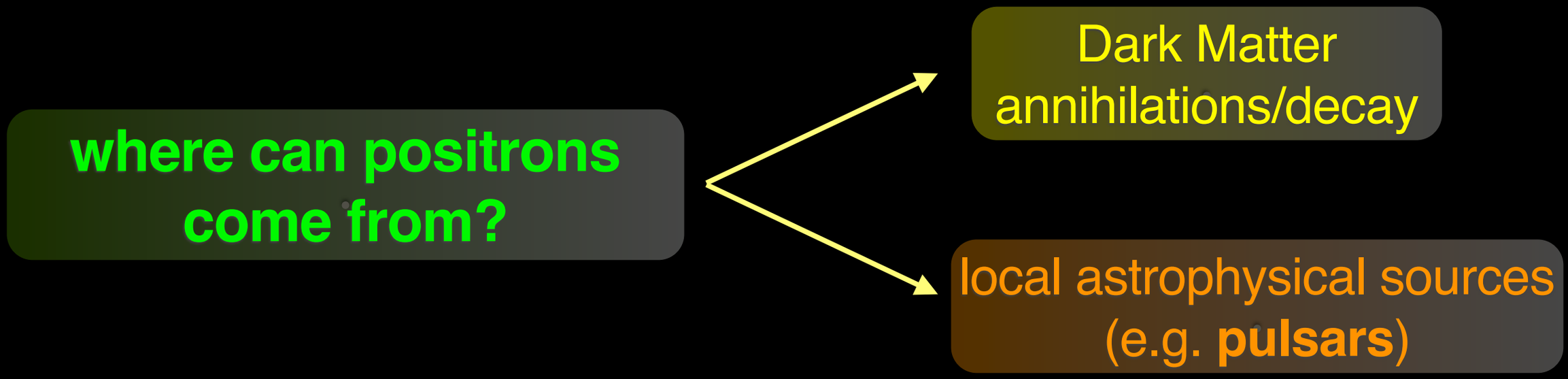
- Excess over "known" bkg, confirming previous **PAMELA** and **Fermi-LAT** measurements.

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



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

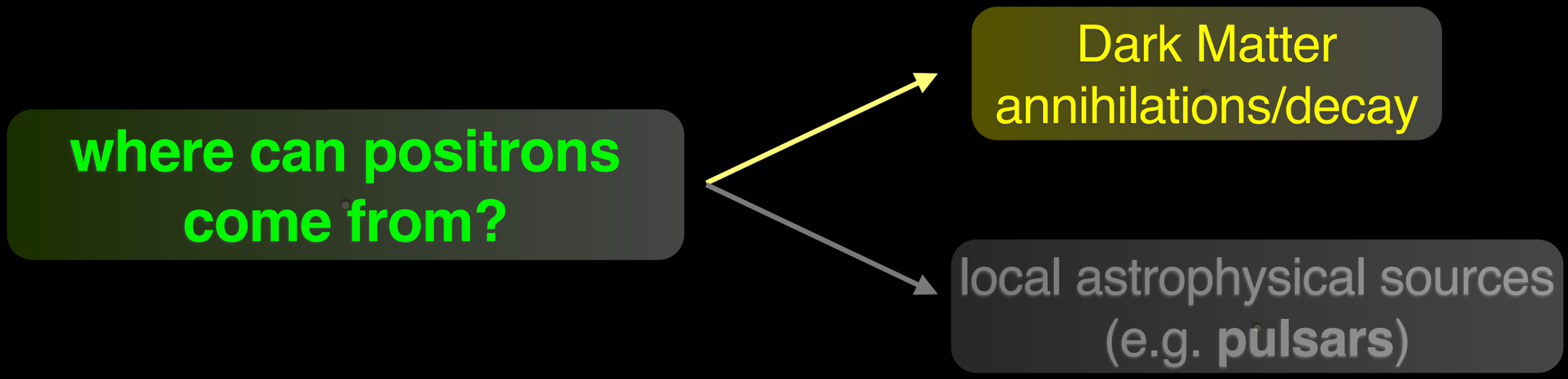
Positron Fraction "anomaly"



- the Dark Matter explanation of the excess is already strongly constrained by other measurements (e.g. gamma-rays)

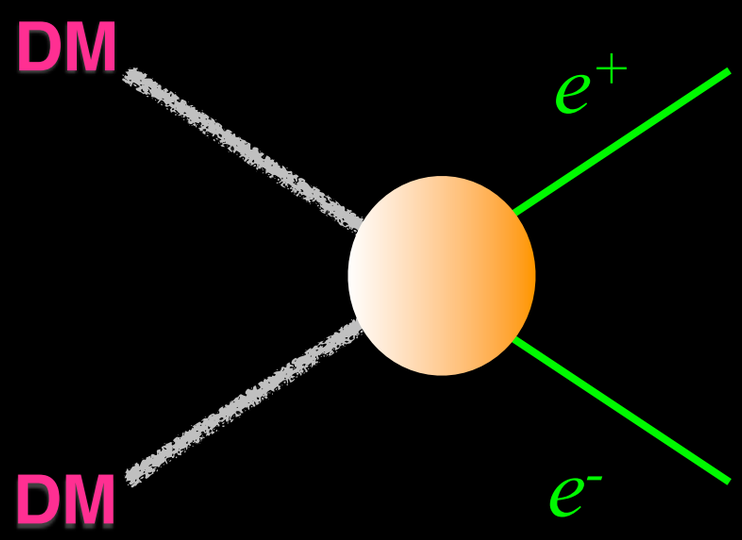
- so the astrophysical explanations look very likely

Positron Fraction "anomaly"



- 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

Electroweak Corrections



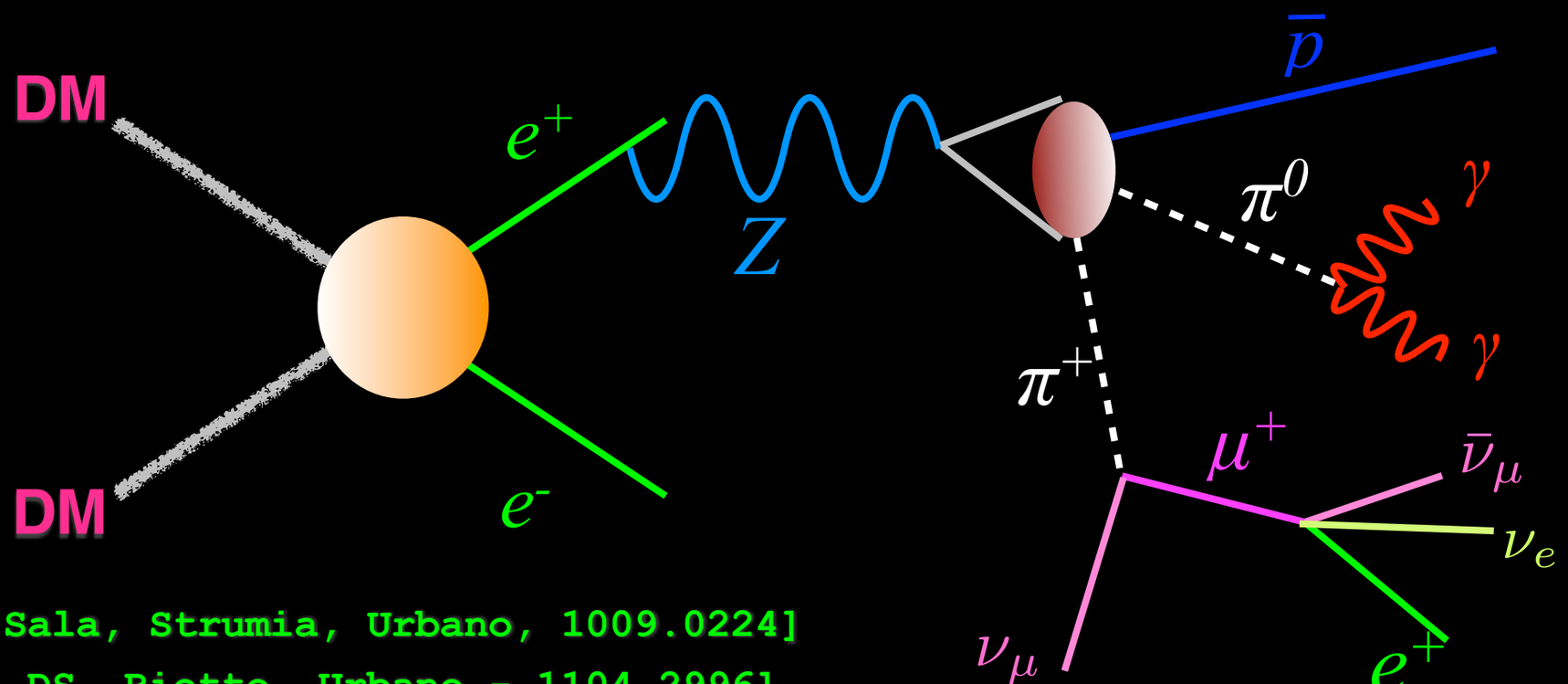
[Ciafaloni, Comelli, Riotto, Sala, Strumia, Urbano, 1009.0224]

[Ciafaloni, Cirelli, Comelli, DS, Riotto, Urbano - 1104.2996]

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

[DS, Monin, Thamm, Urbano - 1301.1486]

Electroweak Corrections



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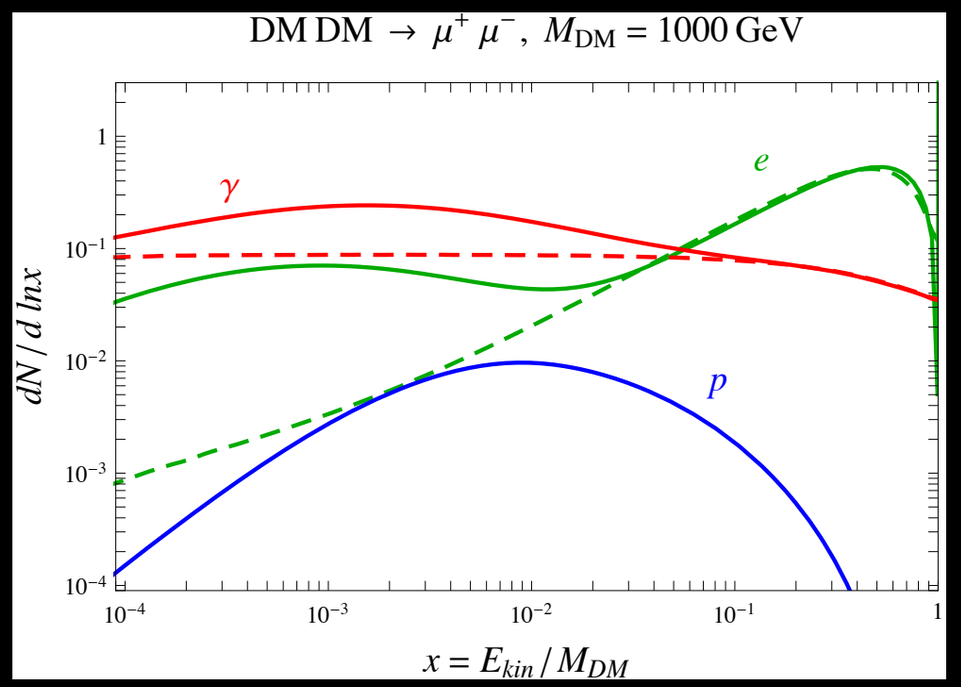
[Ciafaloni, Comelli, DS, Riotto, Urbano - 1202.0692]
[DS, Monin, Thamm, Urbano - 1301.1486]

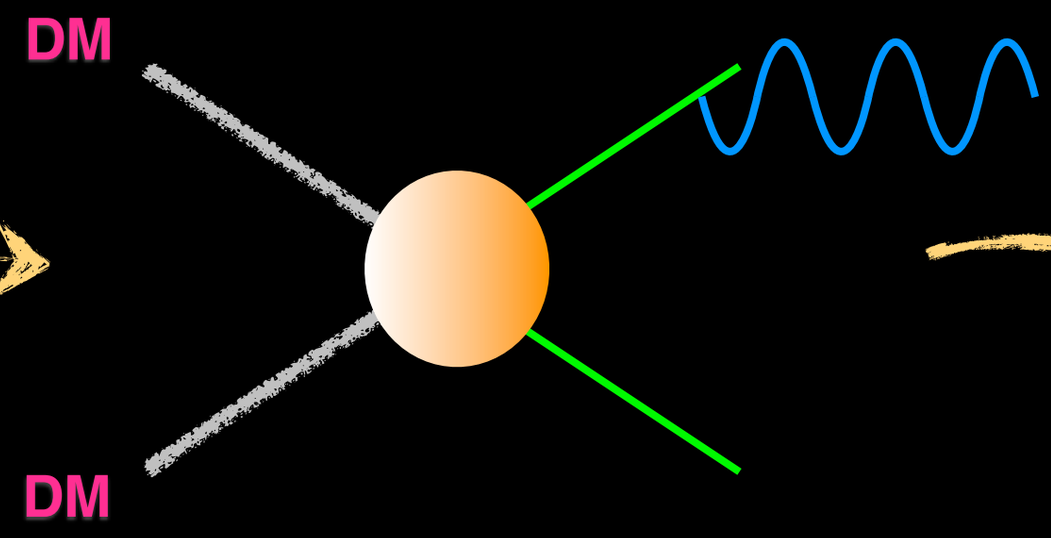
- The final state of DM annihilations can radiate γ,Z,W.
- It is a SM effect, affecting the final fluxes importantly.
- EW interactions connect all SM particles
  → all species will be present in the final state



Correlations among DM signals

assume DM interpretation

fit



EW corrections

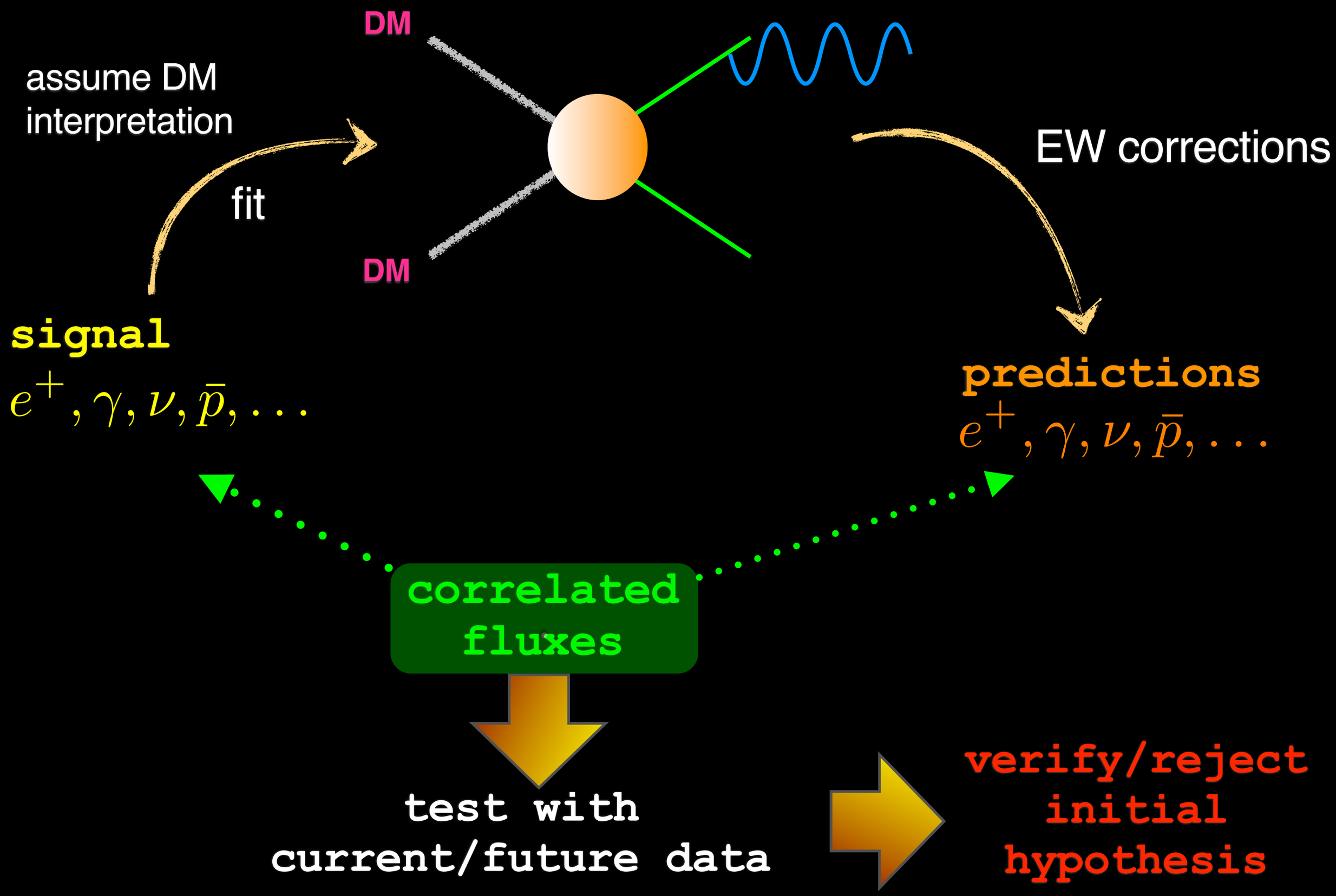
signal

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

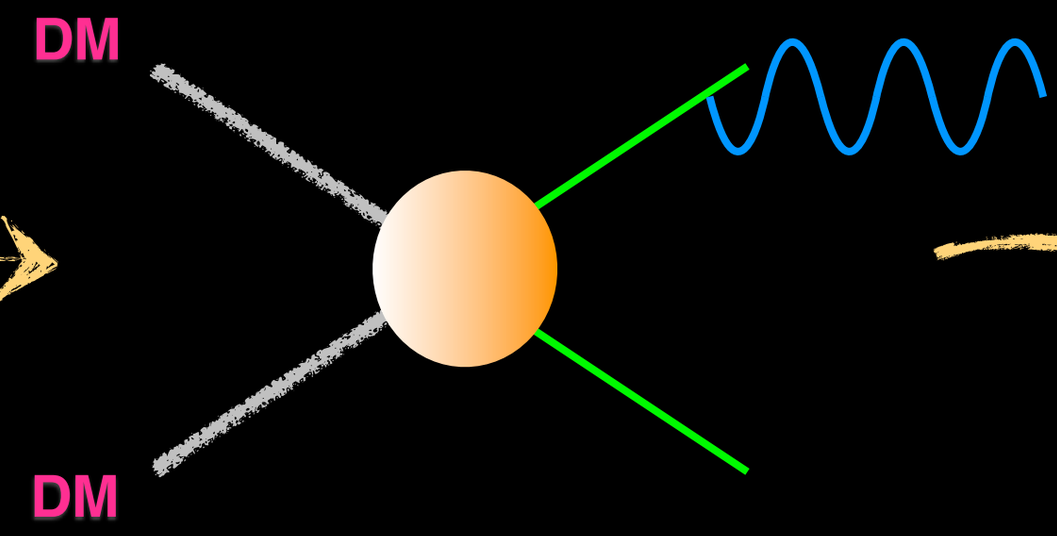
predictions

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

Correlations among DM signals



Correlations among DM signals



assume DM interpretation

fit

signal

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

EW corrections

predictions

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

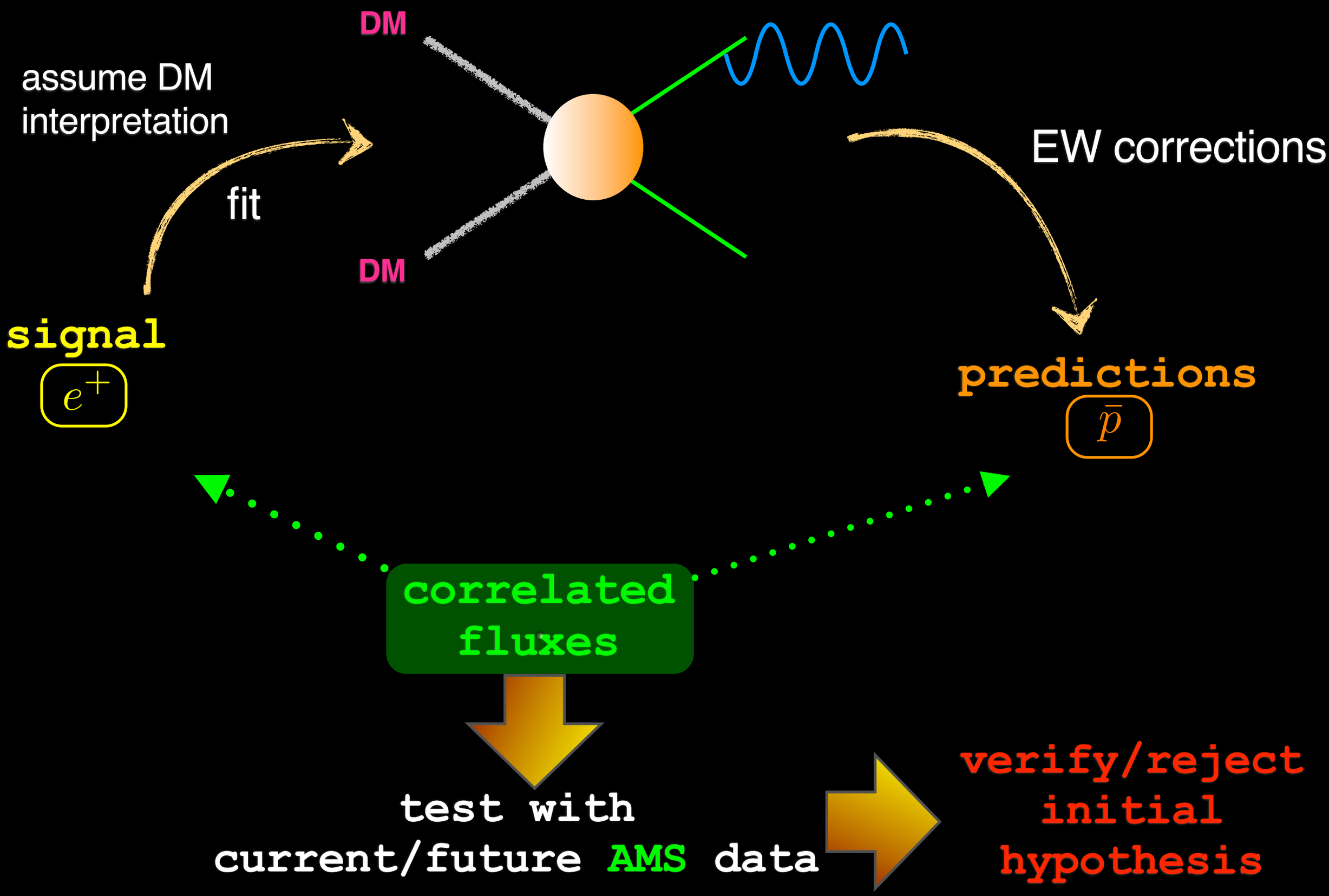
correlated fluxes

- ✓ robust
- ✓ timely

test with current/future data

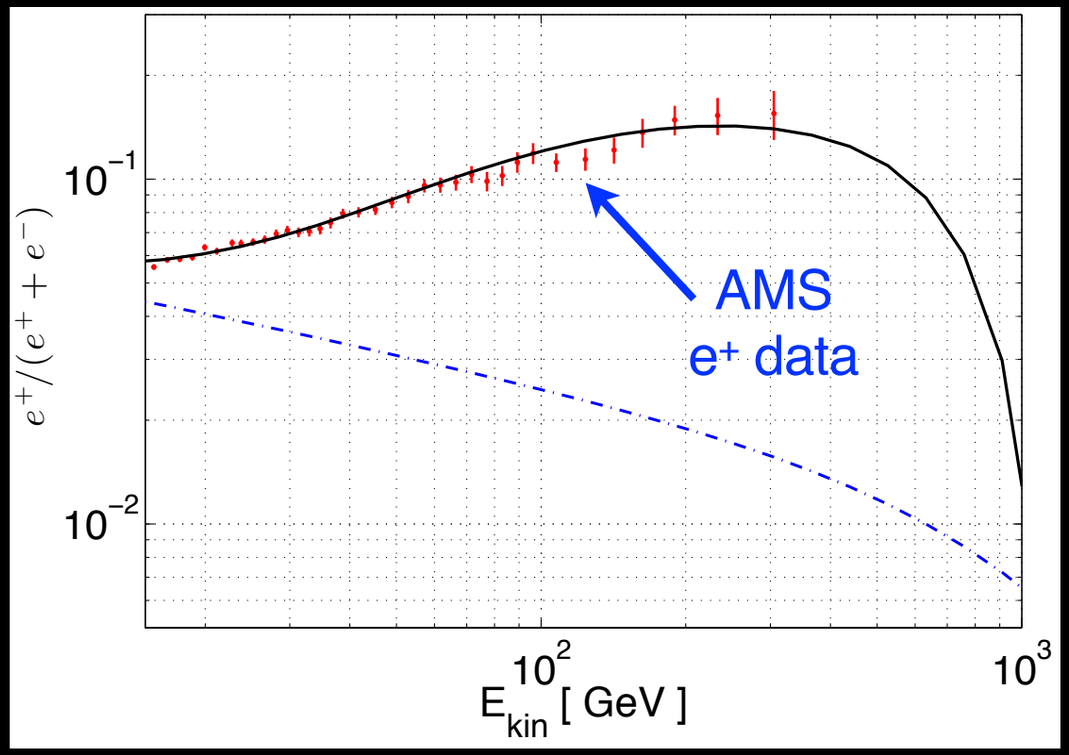
verify/reject initial hypothesis

Correlations among DM signals

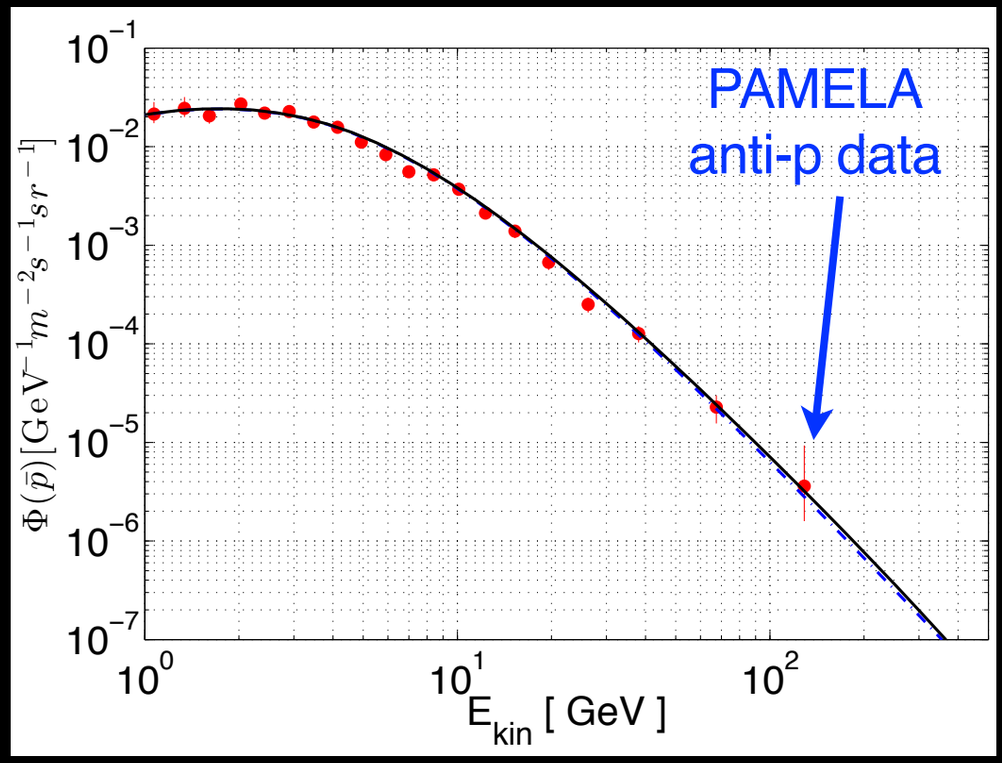


possible interpretation as DM,
without upsetting the anti-p flux

positron fraction



anti-protons



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

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

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

[DS, Riotto, Xue - 1304.1336]

The Importance of Being Propagated

- before claiming any signal, bkg should be under control

- **signal** and **background** fluxes are closely related, because they propagate 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 both signal and background (and for all particle species)

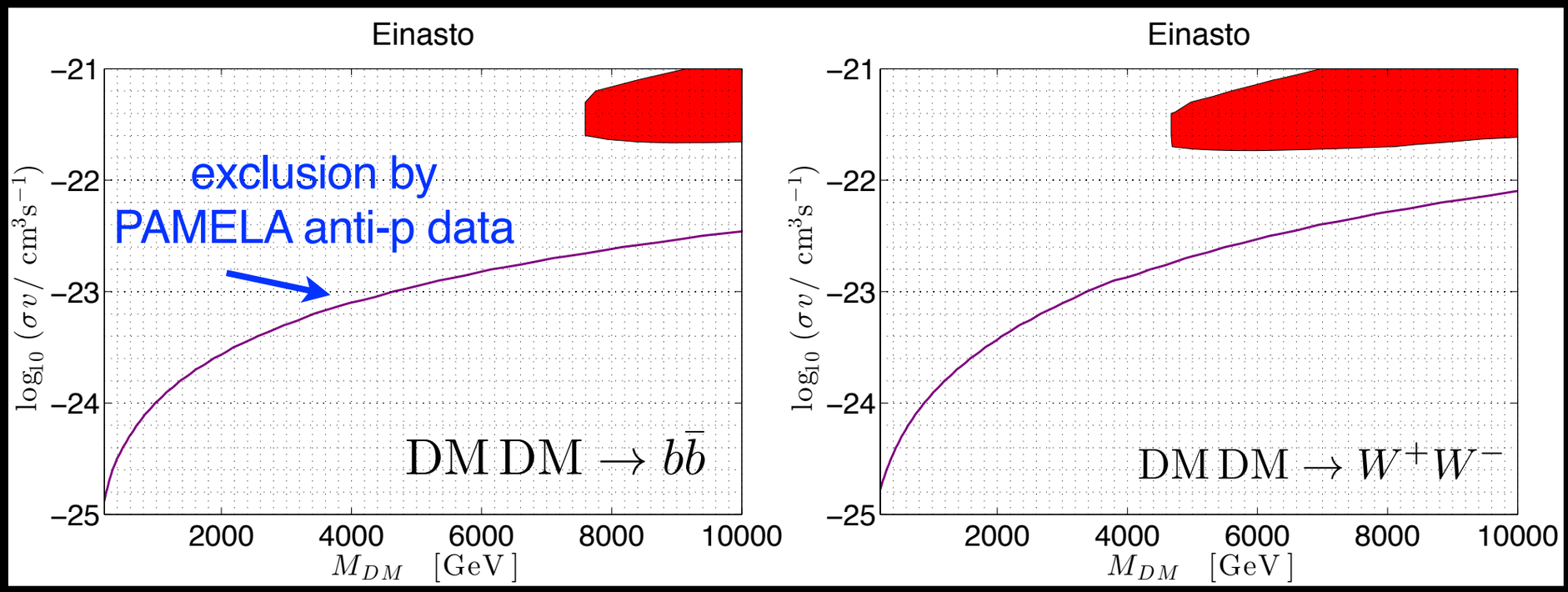
Model-independent analysis of AMS-02 data

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)

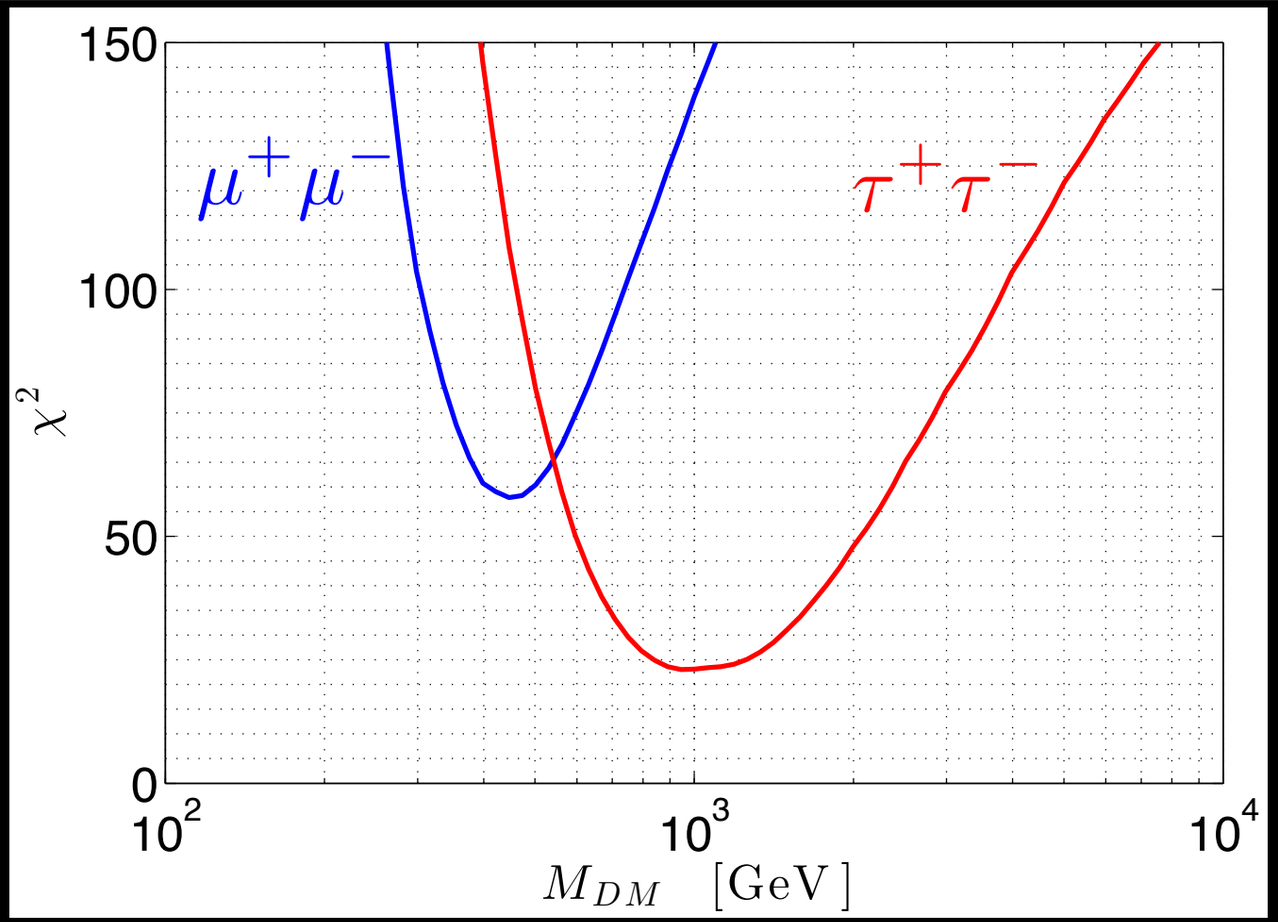
⟶ can easily upset anti-p data

Ex.



only **leptonic** annihilation channels are still allowed

Interpretation of AMS-02 data: Best Fits

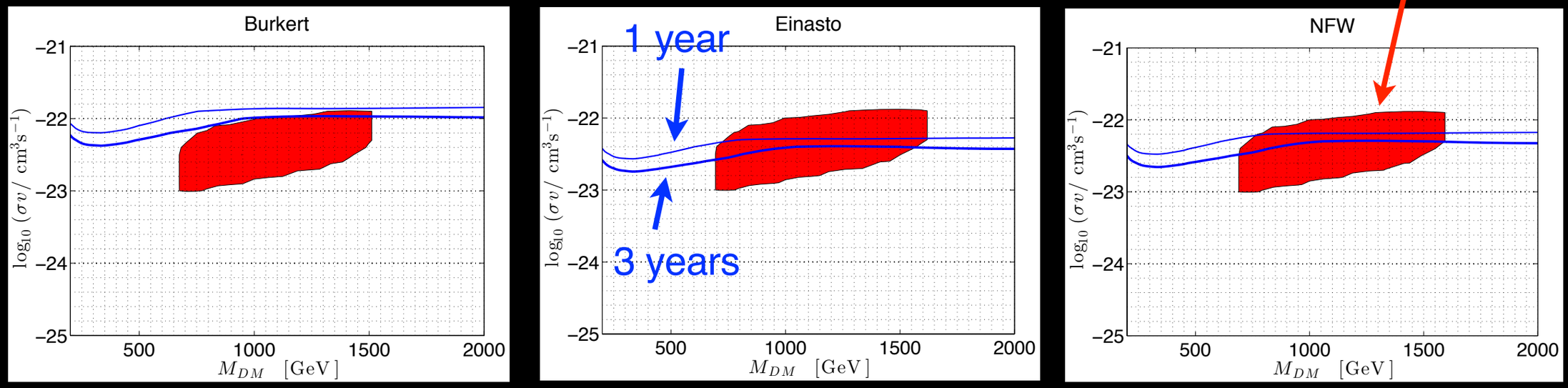


- use only data with E>15 GeV (not affected by solar modulation)
- number of dof: 36-6=30
- e^+e^- gives even higher χ^2

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

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

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

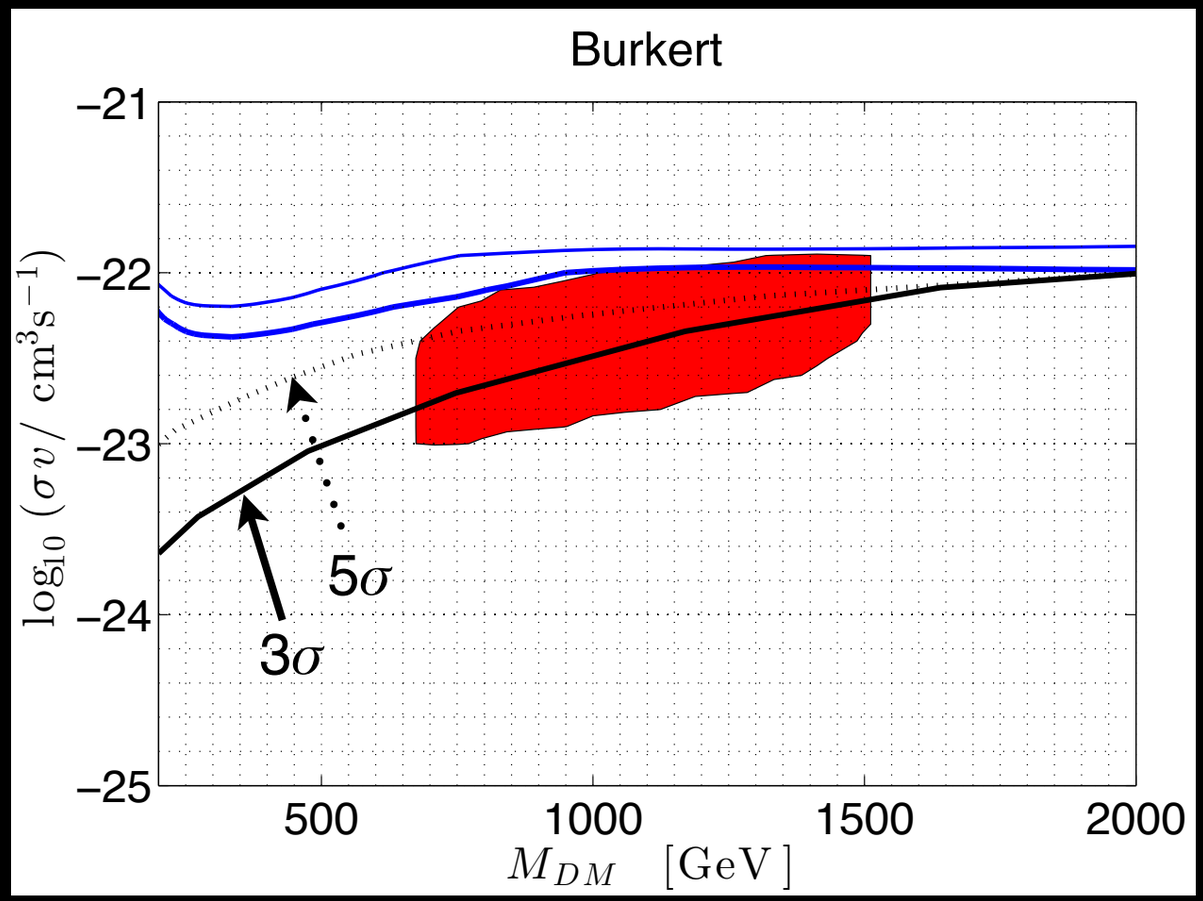


- we simulated projected (mock) data for anti-p, consistent with understanding of detector features from outside the collaboration
- 3 years of AMS-02 anti-p data would be enough to rule out *almost* competely the DM interpretation of the positron rise

Constraints from other Data-sets

taking into account Fermi-LAT diffuse gamma-ray constraints

[Fermi-LAT Coll.- 1205.6474]



best-fit regions for other halo profiles are mostly excluded

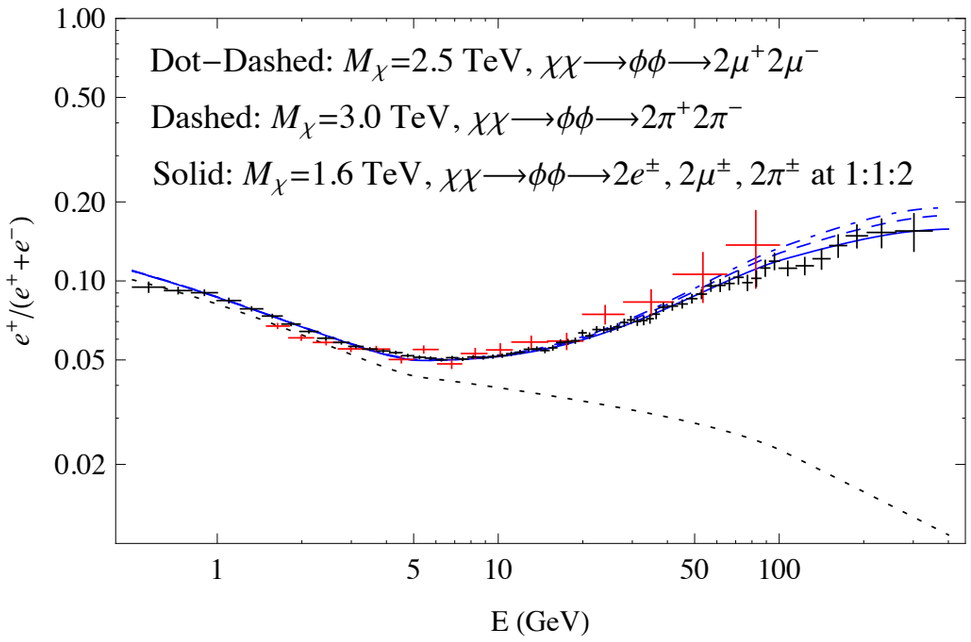
Constraints from other Data-sets

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

positron fraction



$e^+ + e^-$

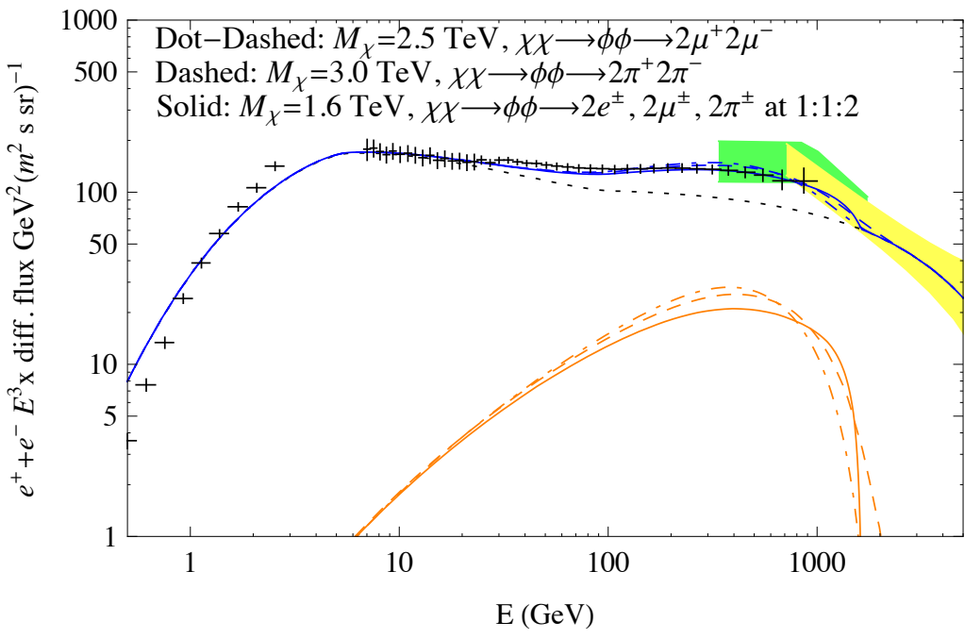


FIG. 6: The same as in Figs. 1, 2, 4 and 5 but for a diffusion zone half-width of $L = 8$ kpc, and for broken power-law spectrum of electrons injected from cosmic ray sources ($dN_{e^-}/dE_{e^-} \propto E_e^{-2.65}$ below 100 GeV and $dN_{e^-}/dE_{e^-} \propto E_e^{-2.3}$ above 100 GeV). The cross sections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

- The current situation on DM is very confusing...

- 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

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

Conclusions

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- Interpretation of AMS-02 recent results

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

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

Golden Age of Dark Matter searches

- discovery in 5-10 years, or abandon the WIMP paradigm...

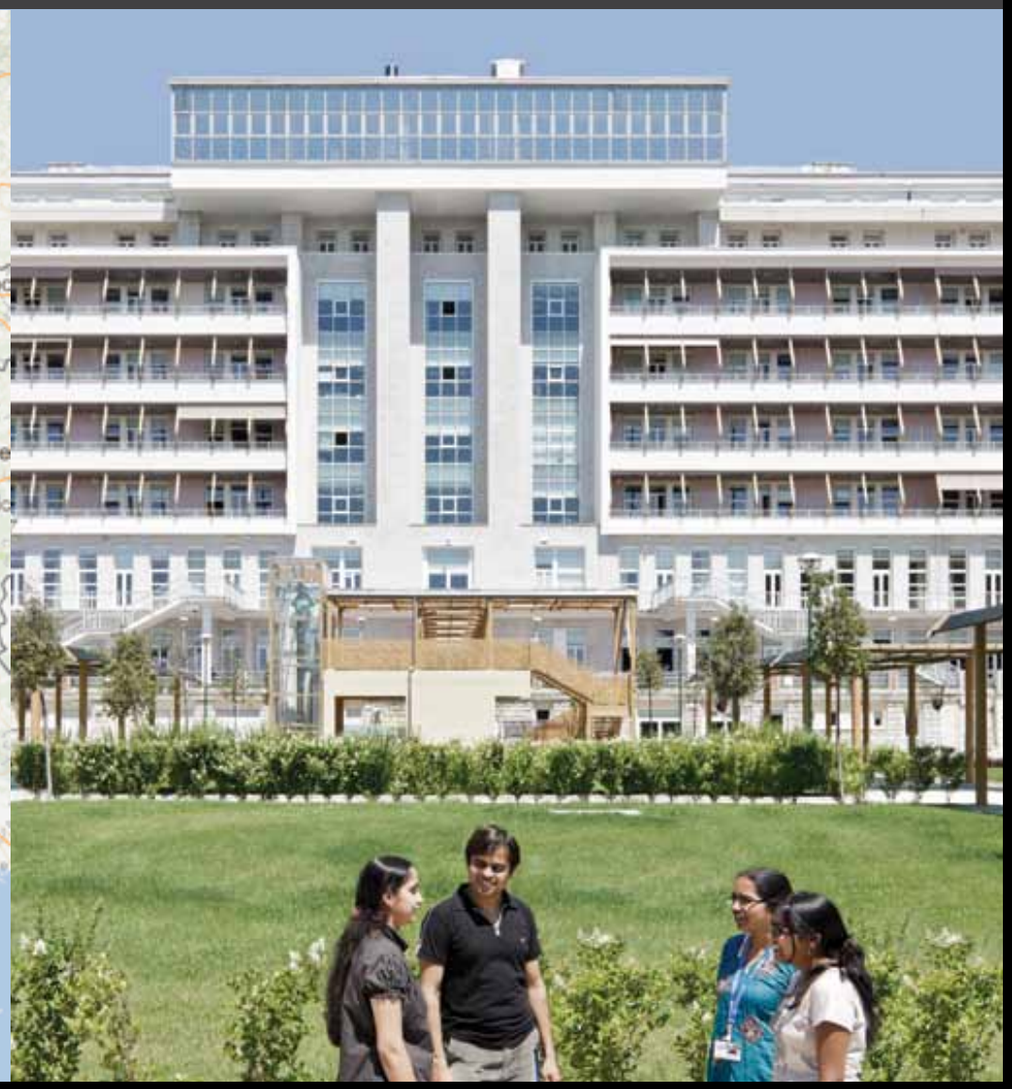
Commercial Break

For prospective graduate students

Scuola Internazionale Superiore di Studi Avanzati

www.sissa.it
SISSA | via Bonomea, 265 | 34136 Trieste | Italy
tel +39 040 3787111 | info@sissa.it

A school where **training** means **research**



AstroParticle Physics at SISSA

Who we are

S. Liberati
(coordinator)

A. De Simone

T. Sotiriou

P. Ullio

+ other SISSA staff

- C. Baccigalupi
- R. Percacci
- S. Petcov
- A. Romanino
- P. Salucci

+ staff from
other institutions

- P. Creminelli (ICTP)
- R. Sheth (ICTP)
- M. Viel (OATS)

+ several post-docs

AstroParticle Physics at SISSA

What we do

Research at the interface of astrophysics, cosmology, gravity and particle physics

- **Cosmology**
  - Baryogenesis
  - CMB, Large Scale Structures
  - Inflation
- **Dark Universe**
  - theory and pheno of Dark Energy and Dark Matter
- **Gravitation Theory**
  - alternative theories of gravity
  - QFT in curved space-times
  - Quantum Gravity
- **Particle Astrophysics**
  - astrophysical neutrinos
  - direct and indirect Dark Matter detection

AstroParticle Physics at SISSA

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How to Join us

Deadline for applications: 24 June

Exams: 4-5 July

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BACK-UP SLIDES

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.:

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

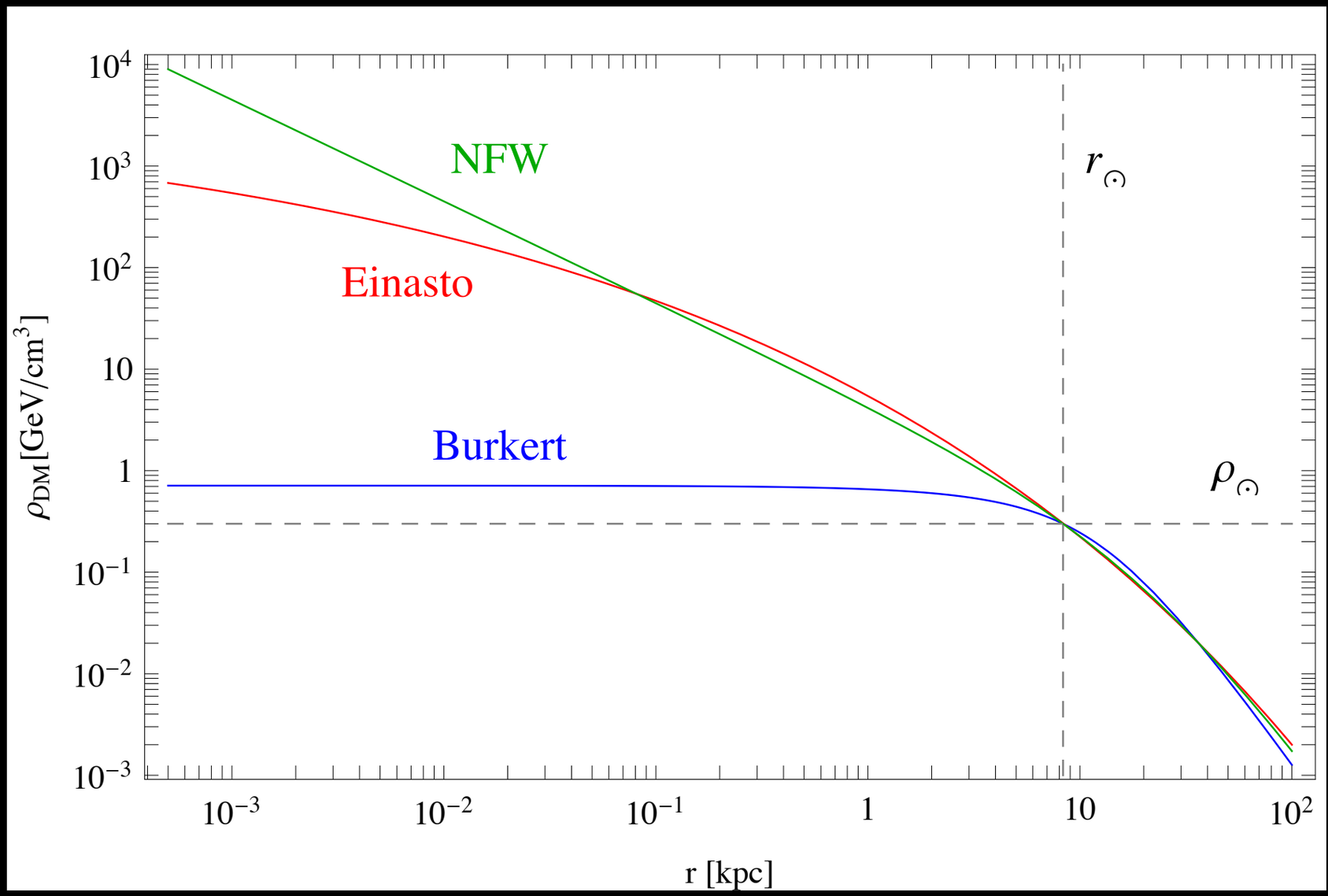
$$-\frac{\partial}{\partial p}\left[\dot{p}n_i - \frac{p}{3}(\nabla\cdot\mathbf{V}_c)\,n_i\right] - \underbrace{\frac{1}{\tau_{sp}}n_i}_{\text{spallation}} - \underbrace{\frac{1}{\tau_f}n_i}_{\text{fragmentation}}$$

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

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

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

Halo Profiles



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

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.

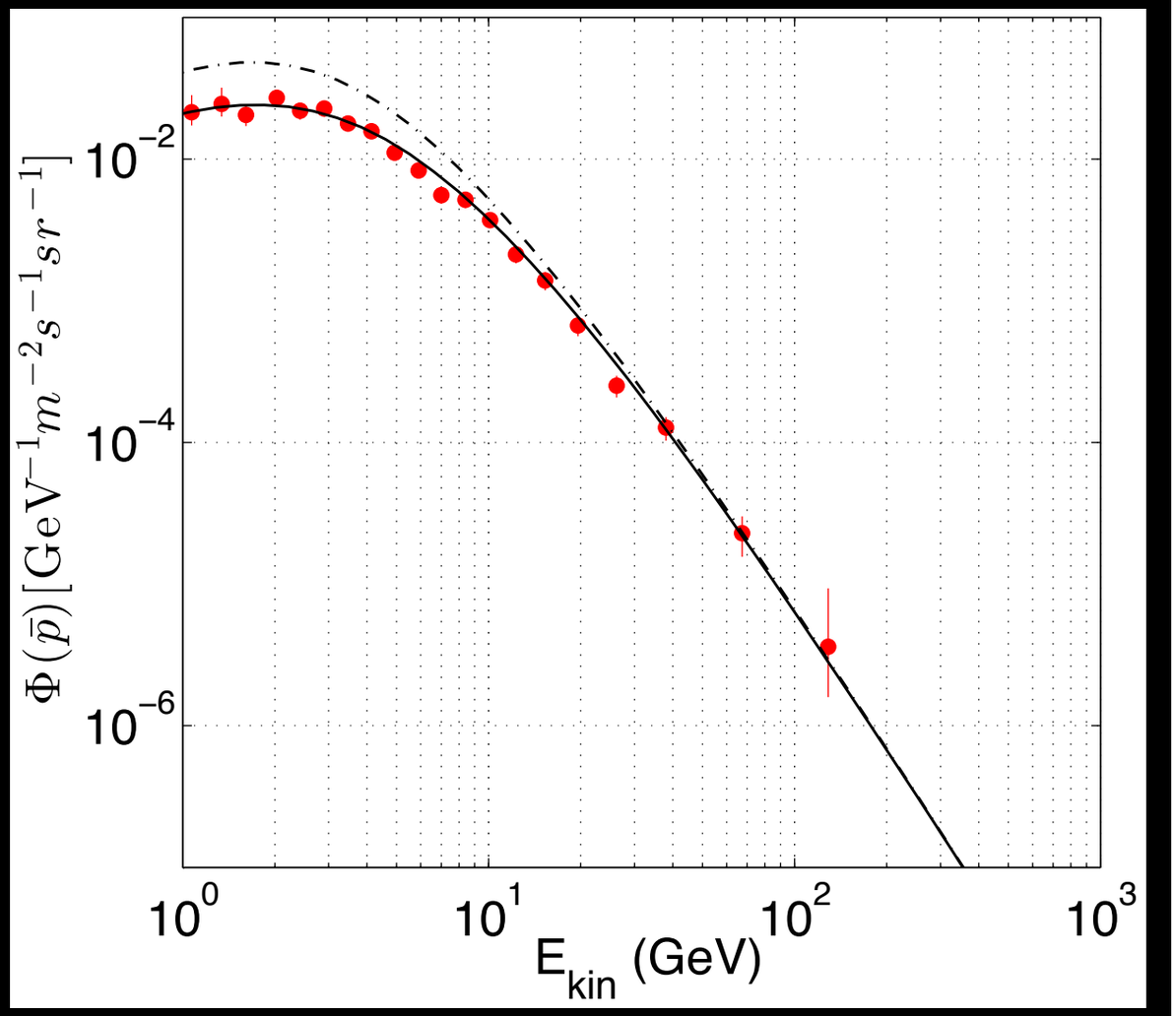
✘ fluxes of different species are treated as uncorrelated;
✓ deal with astrophys. uncert. in a simple and conservative way.

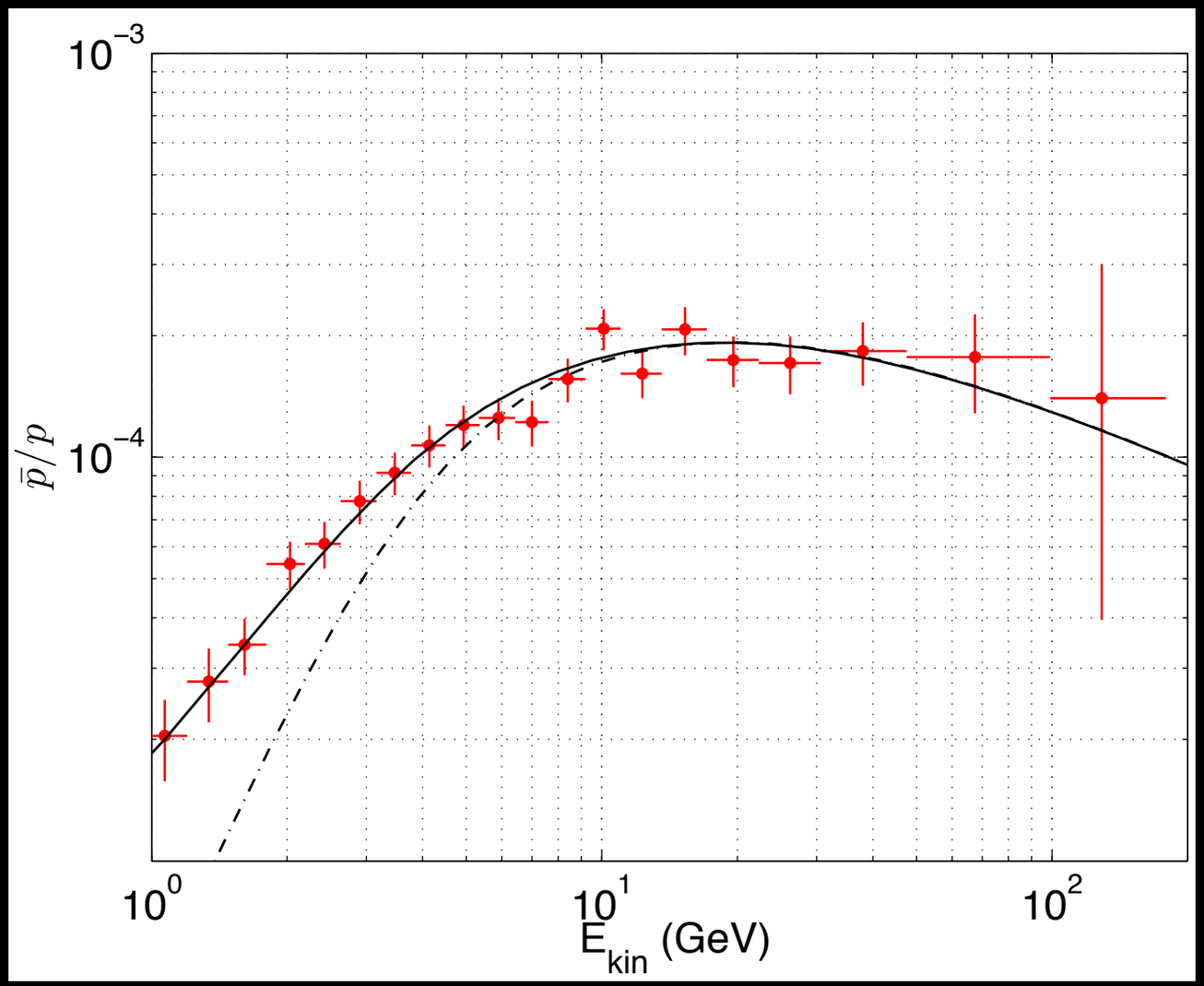
Method 2

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

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

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





solid/dashed = with/without correcting for solar modulation

Importance of EW corrections

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 $\sigma(2 \to 3)$, with soft gauge boson emission, is comparable or even dominant with respect to $\sigma(2 \to 2)$:

   - 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]