LATE DECAYING TWO-COMPONENT DARK MATTER (LD2DM)

CAN EXPLAIN THE AMS-02 POSITRON EXCESS

(WITH A FEW BONUS FEATURES!)

(BASED ON 1609.04821 W/ P. RALEGANKAR AND V. RENTALA)

JATAN BUCH

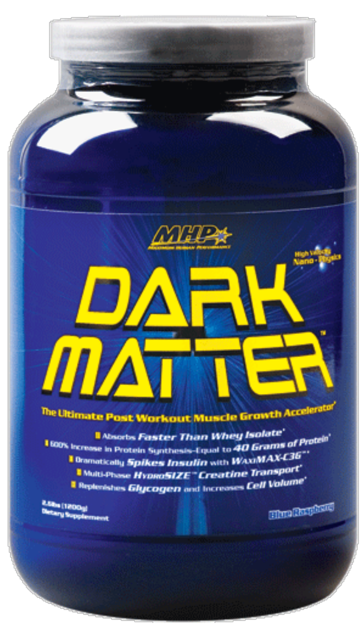
(BROWN U.)

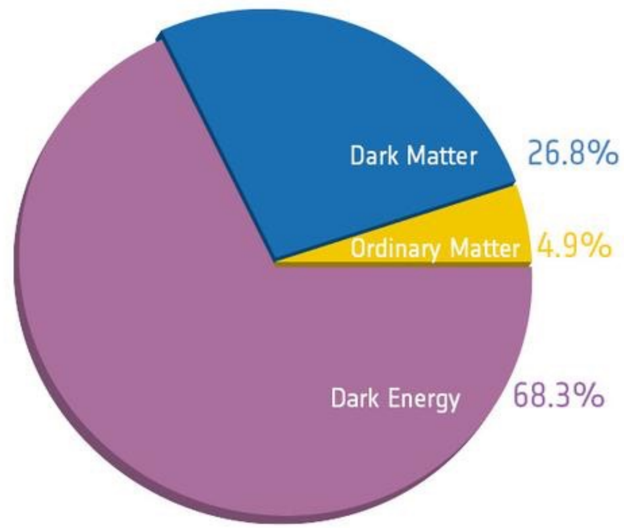
AUGUST 7-11 COLUMBUS, OHIO

TeVPA 2017

THE 'DARK MATTER (DM) EXISTS AND HERE IS PROOF' SLIDE

- Rotation curve data
- Gravitational lensing
- Large scale structure
- CMB anisotropies
- …





Credit: ESA/Planck

- Non-baryonic (dark)
- Non-relativistic (cold)
- Has gravitational interactions.
- Stable (until now?)

PARTICLE DARK MATTER

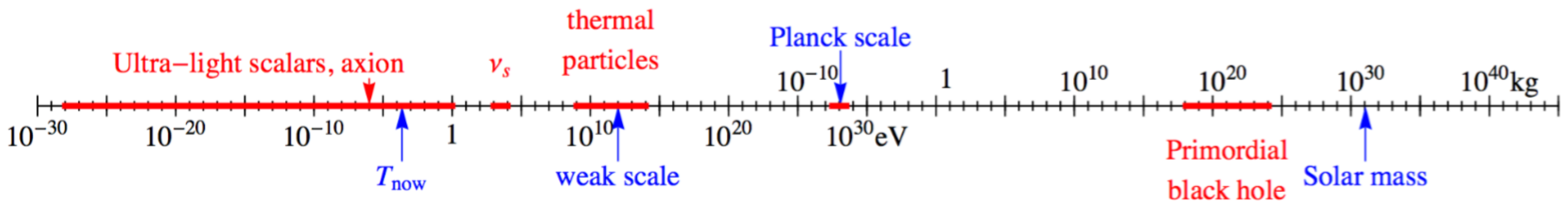
- Weak-scale and heavier DM can arise 'naturally' in some beyond Standard Model (BSM) theories of particle physics.

- Avenue for exploring signatures of DM at colliders, astrophysical probes (indirect detection), underground experiments (direct detection).

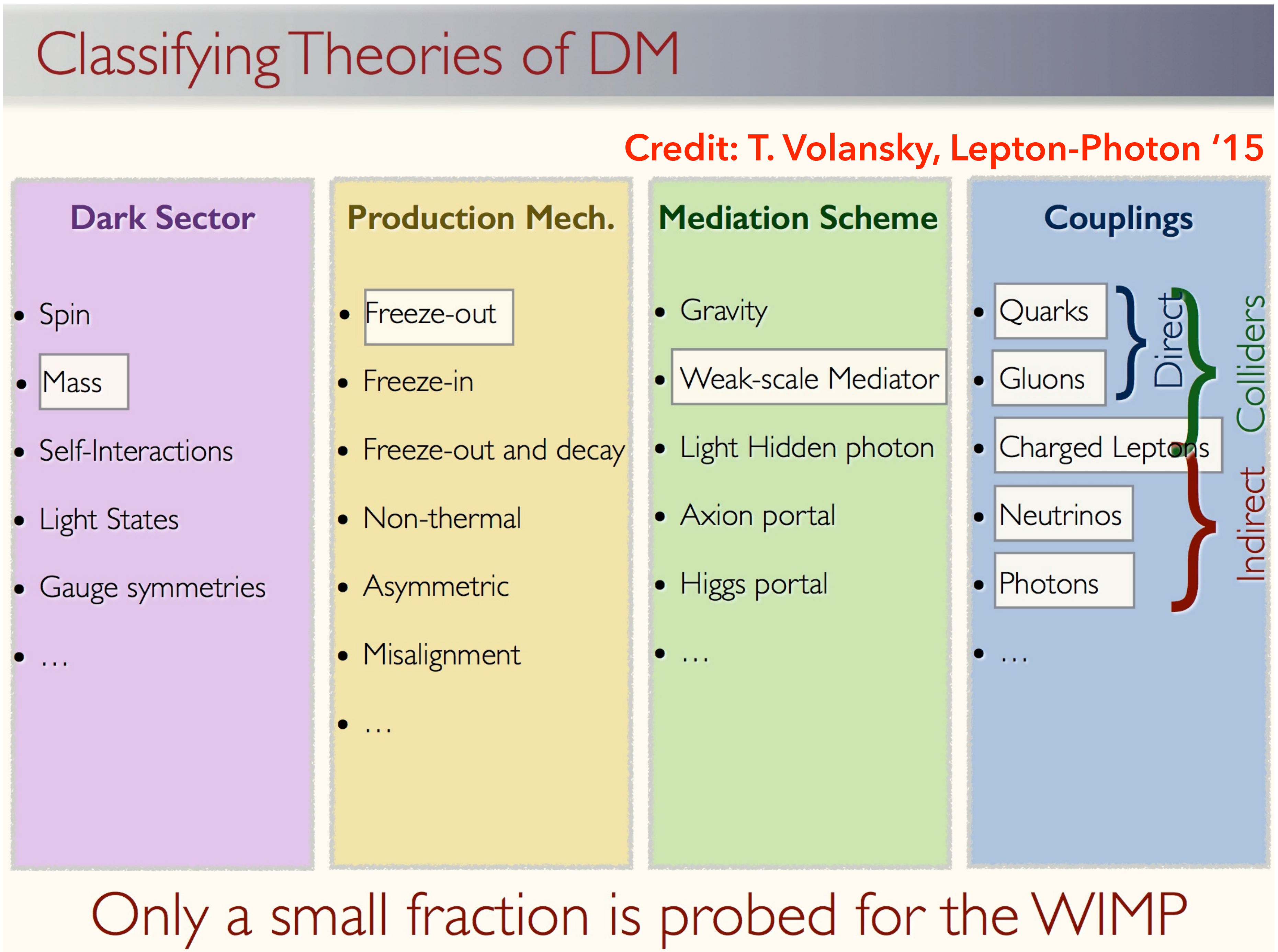
- However, in light of stringent constraints, we need BSM cosmology to explain current signals with DM or devise new searches for it.

- Now, DM candidates span a large parameter space in both mass and cross-section (not shown here).

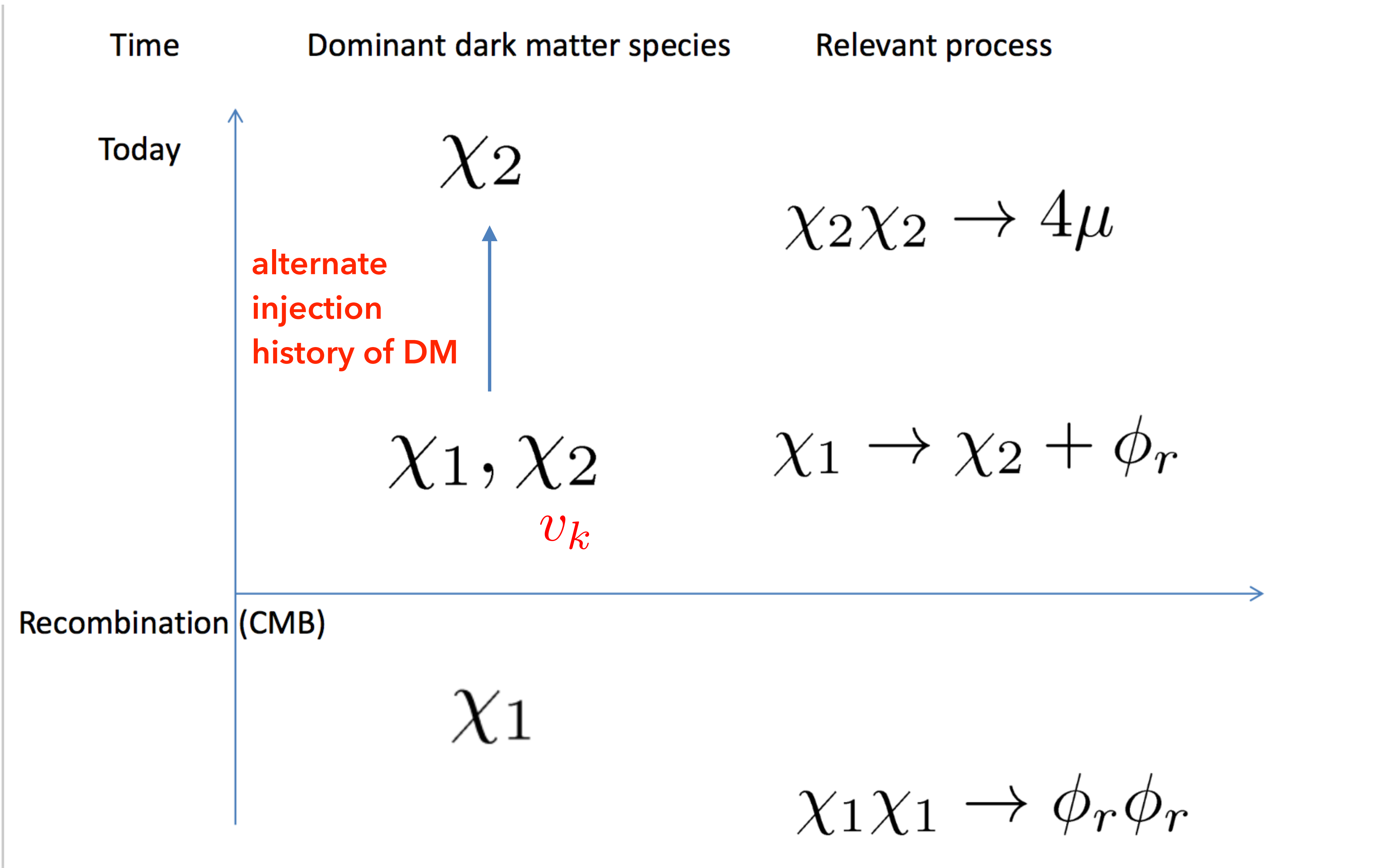
Credit: M. Cirelli



THE WIMP MIRACLE (OR RED HERRING?)



LD2DM SCENARIO



LD2DM SCENARIO

$$\chi_1 \rightarrow \chi_2 + n\phi_r$$

$$\chi_2\chi_2 \rightarrow Z'Z' \rightarrow 4l$$

(a similar, although purely cosmological, scenario was proposed among others by 1003.0419)

- where ϕ is dark radiation and Z' is a dark photon.

- Since χ_2 is the DM today, we fix it's mass and cross-section to the best-fit values that we obtain from fitting the AMS-02 data. The cross-section for χ_1 is set to the thermal value to ensure the right relic abundance.

- The decay lifetime, Γ^{-1}, of χ_1 determines the epoch of energy deposition for the LD2DM scenario and is constrained by the CMB anisotropy spectrum.

cosmologically constrained

- Finally, the mass difference between the two species, Δm, is constrained by Ly-α forest power structure measurements.

OUTLINE FOR TALK:

- Overview of the positron excess
- Constraints from astrophysics and cosmology
- Constraints on the LD2DM scenario
- Interesting cosmological features in the LD2DM scenario
- Summary

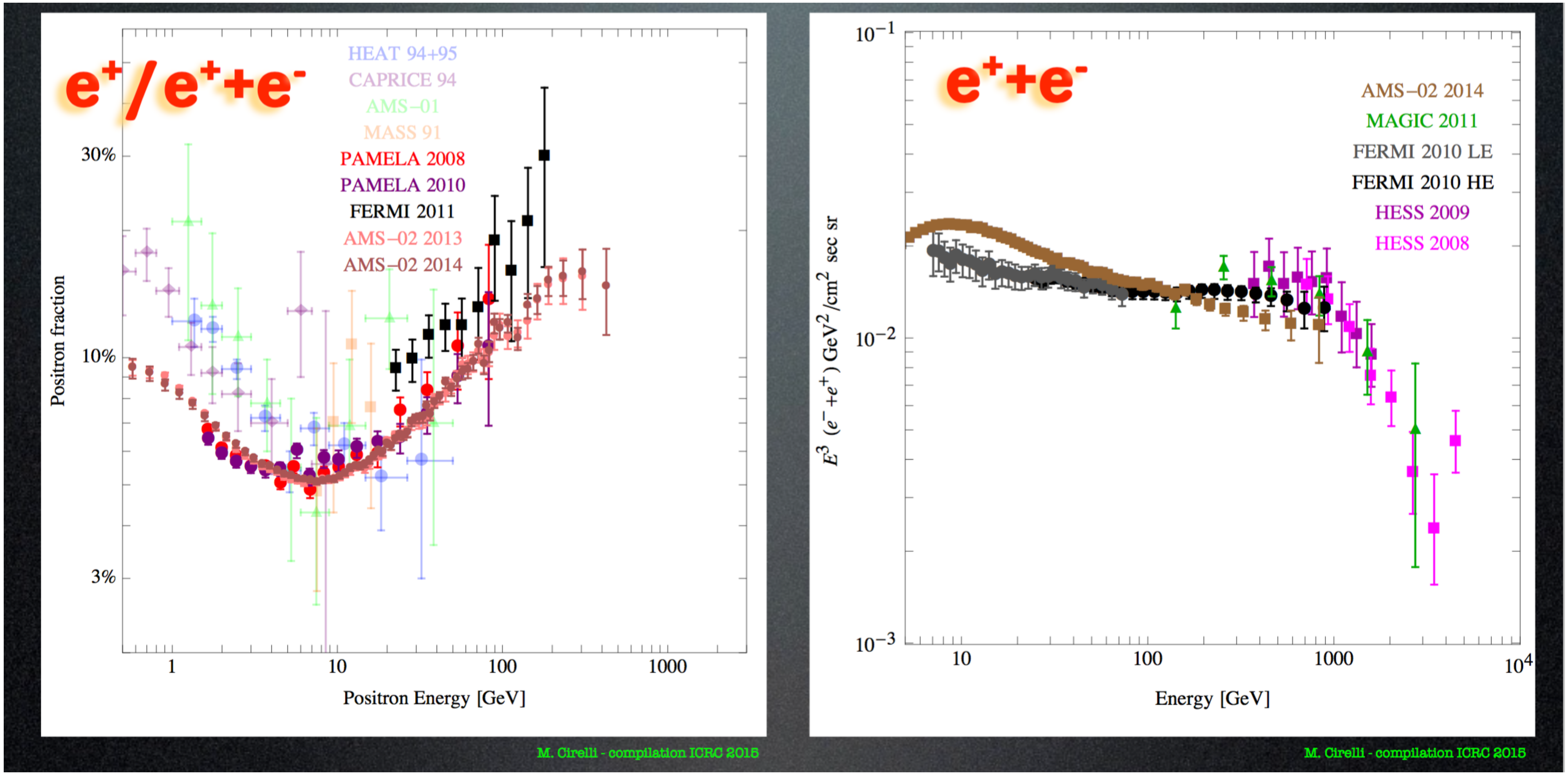
"I see men ordinarily more eager to discover a reason for things than to find out whether the things are so."

– Montaigne*

POSITRON EXCESS: AN OVERVIEW

- Before proceeding, let’s take a moment to appreciate how far along we have come with the data.

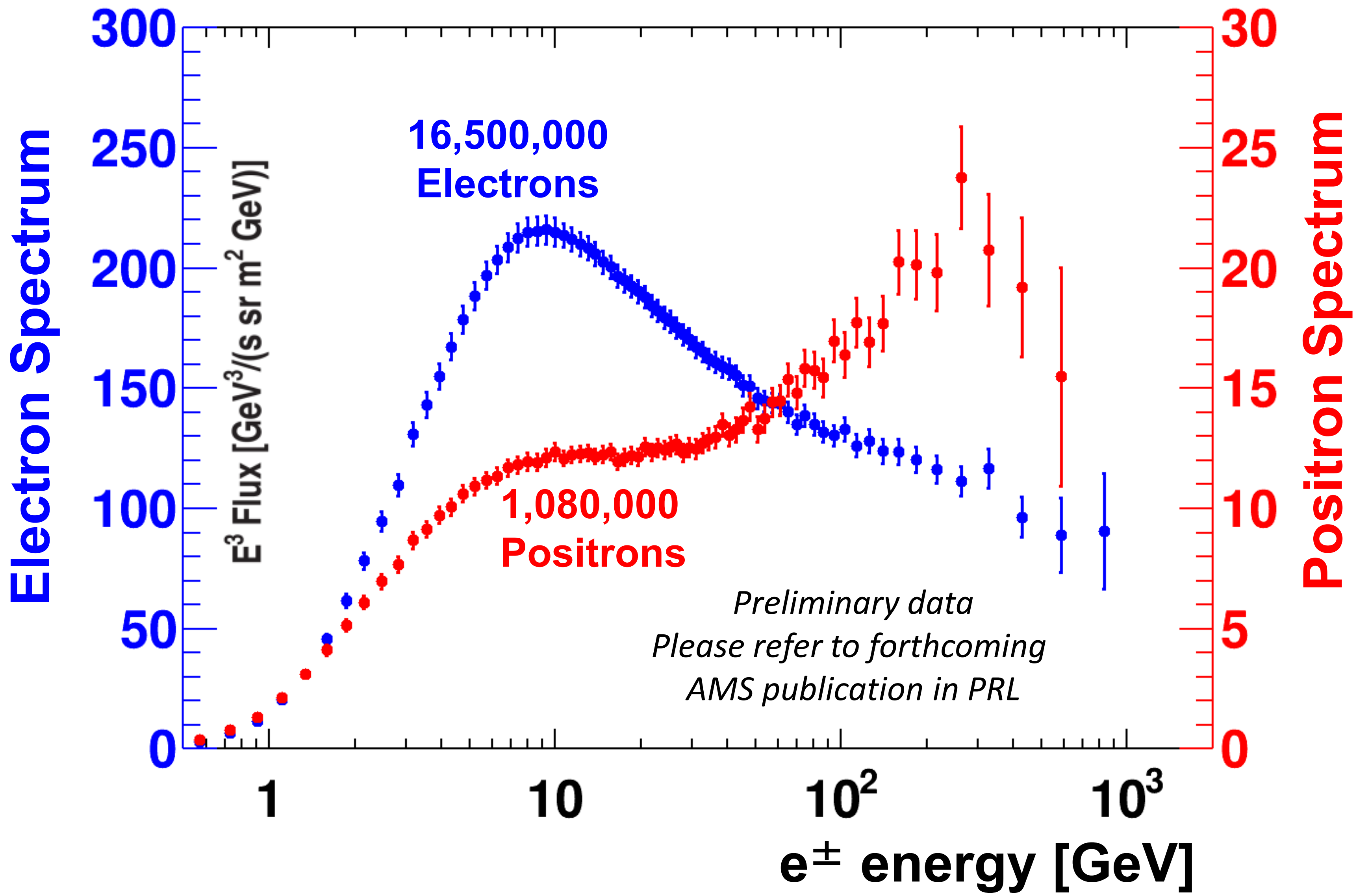
POSITRON EXCESS: AN OVERVIEW



"Believe the AMS result" – P. Michelson (for FERMI), AMS Days at CERN, April 2015

POSITRON EXCESS: AN OVERVIEW

AMS data is precise enough to look into details of Electron and Positron spectra separately



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Yuan-Hann Chang (for AMS collaboration) talk @ TeVPA '17

POSITRON EXCESS: AN OVERVIEW

- Before proceeding, let's take a moment to appreciate how far along we have come with the data.

- In the context of charged cosmic rays, we are entering a new era of precision astrophysics where the emphasis is on:
  a) improving our understanding of astrophysical 'backgrounds' ,

  b) updating our current models of propagation in accordance with the latest complementary data sets, e.g: galactic magnetic field (GMF) models.

- Thus, armed with latest data for the positron flux and updated propagation profiles, we revisited the annihilating DM interpretation of the positron excess.

- However, it is also very likely that this excess is (atleast partially) astrophysical in nature.

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Pulsars as the Sources of High Energy Cosmic Ray Positrons

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Department of Astronomy and Astrophysics, The University of Chicago, USA

Pasquale Blasi
Theoretical Astrophysics, Fermi National Accelerator Laboratory, Batavia, USA
INAF-Osservatorio Astrofisico di Arcetri, Firenze, Italy and
INFN-Laboratori Nazionali del Gran Sasso, Assergi, L'Aquila, Italy

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New limits on dark matter annihilation from AMS cosmic ray positron data

Lars Bergström,[1,*] Torsten Bringmann,[2,†] Ilias Cholis,[3,‡] Dan Hooper,[3,4,§] and Christoph Weniger[5,¶]

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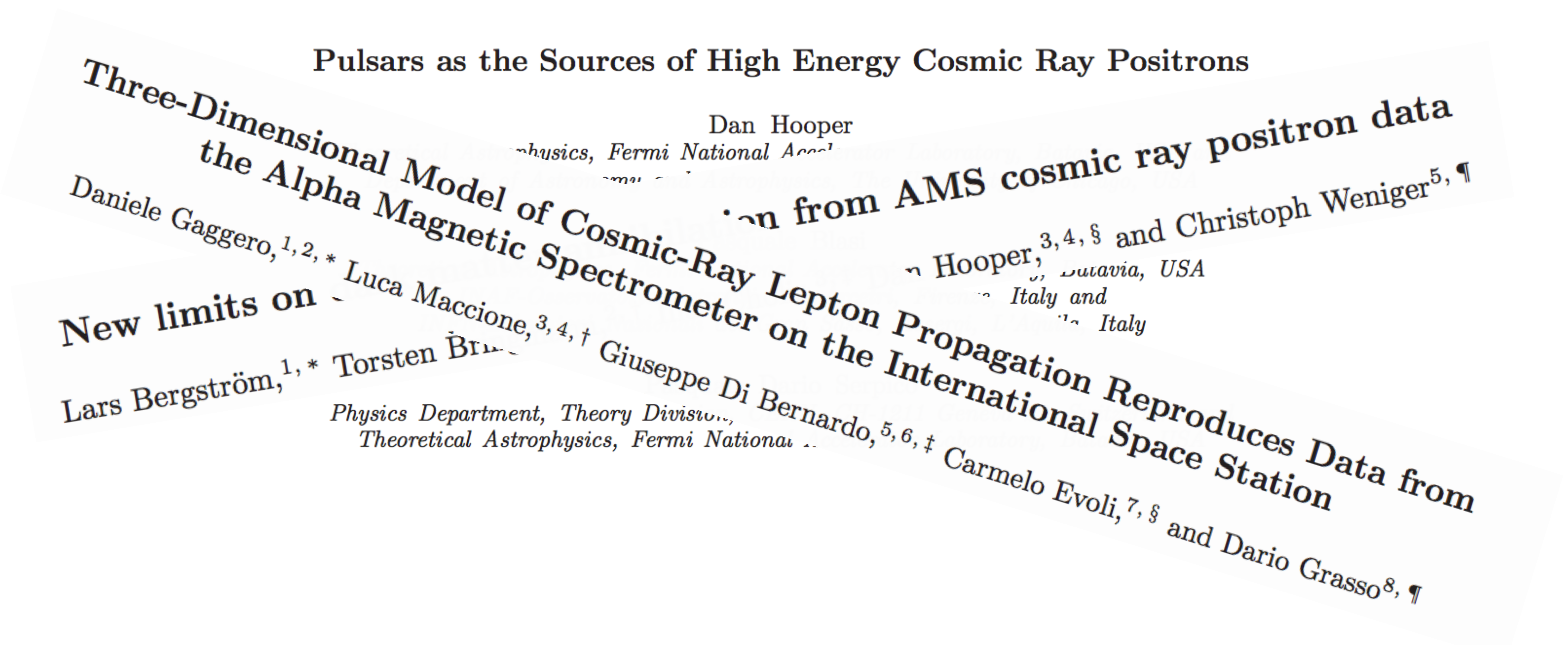

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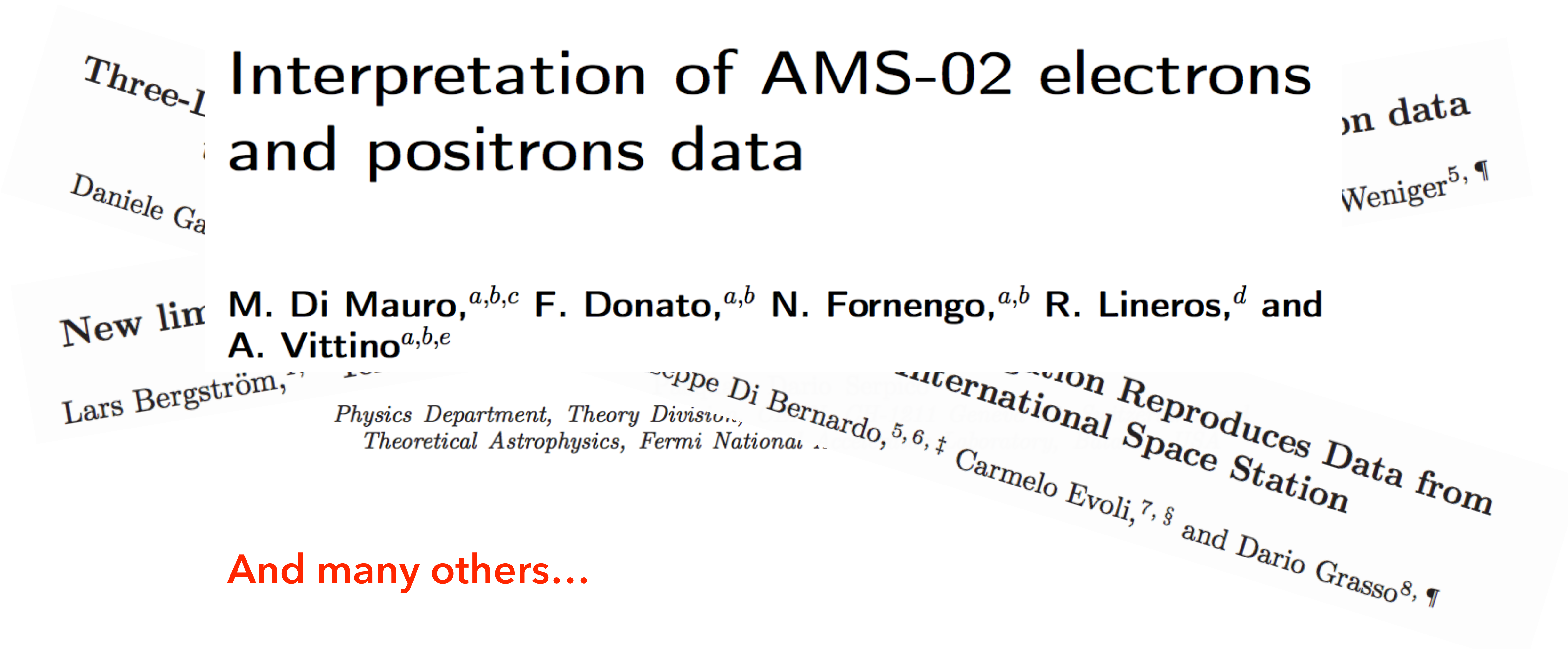


And many others…

RESULTS

* https://github.com/cosmicrays

- We use these ingredients to solve the propagation equation numerically in DRAGON* and obtain the total positron flux:

$$\Phi_{e^+}^{\rm tot}(E) = \Phi_{e^+}^{\rm DM}(E) + c_{e^+}\Phi_{e^+}^{\rm sec}(E)$$

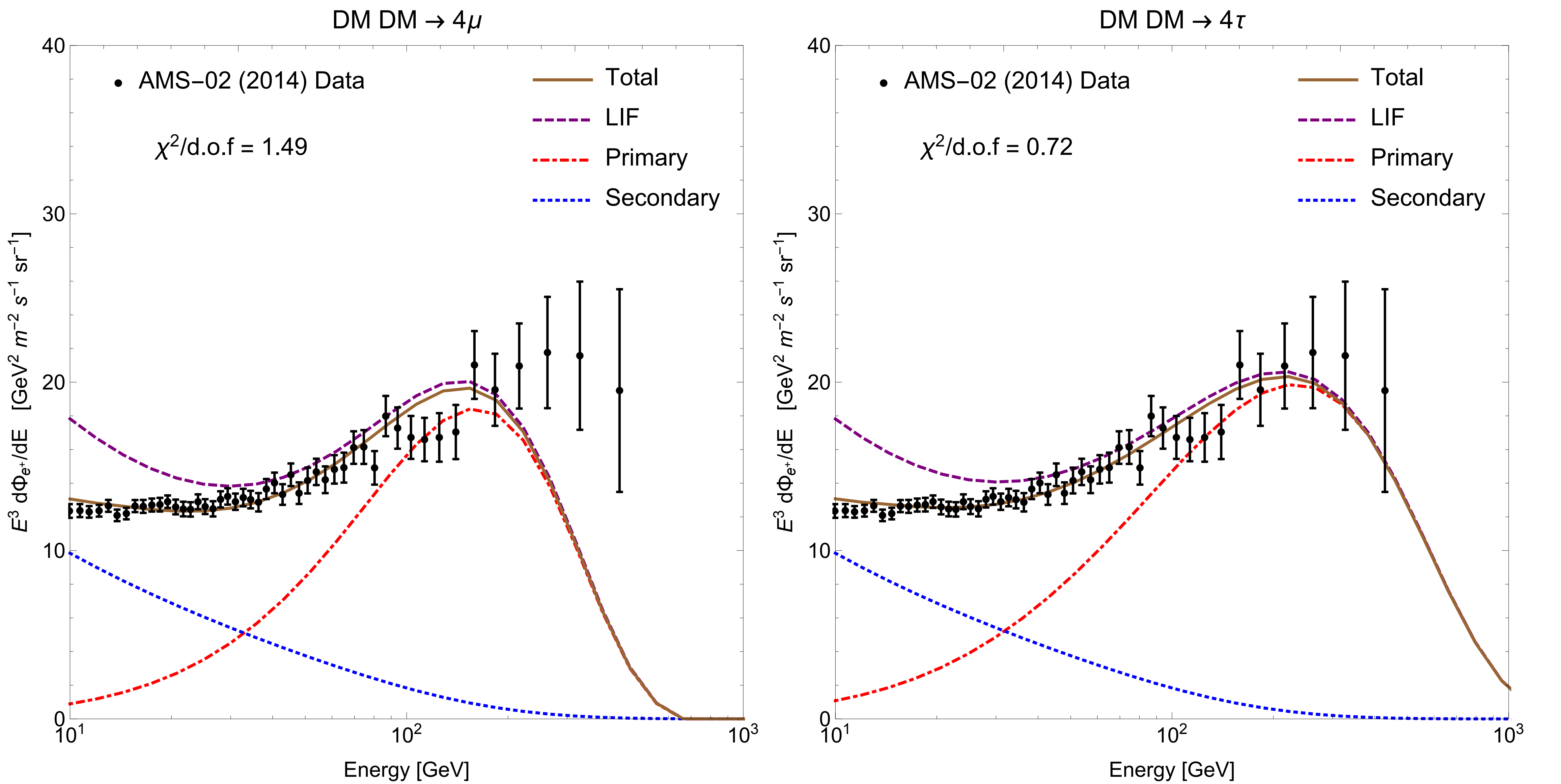
- Including solar modulation with a Fisk potential $\Phi_F = 600\,\mathrm{MV}$,

$$\Phi_{e^+}^{\rm tot,\ modulated}(E) = \frac{E^2}{(E+\phi_{\rm F})^2}\Phi_{e^+}^{\rm tot,\ LIF}(E+\phi_{\rm F})$$

Propagation Model	Channel	m_χ [GeV]	$\langle\sigma v\rangle$ [cm^3/s]	c_{e^+}	$\chi^2_{\rm dof}$
MODA	$\mu^+\mu^-$	340	2.42×10^{-24}	1.80	2.99
	$\tau^+\tau^-$	800	1.73×10^{-23}	1.63	0.68
	$VV\to4\mu$	570	4.57×10^{-24}	1.72	1.49
	$VV\to4\tau$	1700	3.63×10^{-23}	1.70	0.72
MODB	$\mu^+\mu^-$	350	2.42×10^{-24}	2.20	3.11
	$\tau^+\tau^-$	880	1.77×10^{-23}	2.10	0.76
	$VV\to4\mu$	570	2.10×10^{-24}	2.10	1.66
	$VV\to4\tau$	1760	1.70×10^{-23}	2.10	0.80

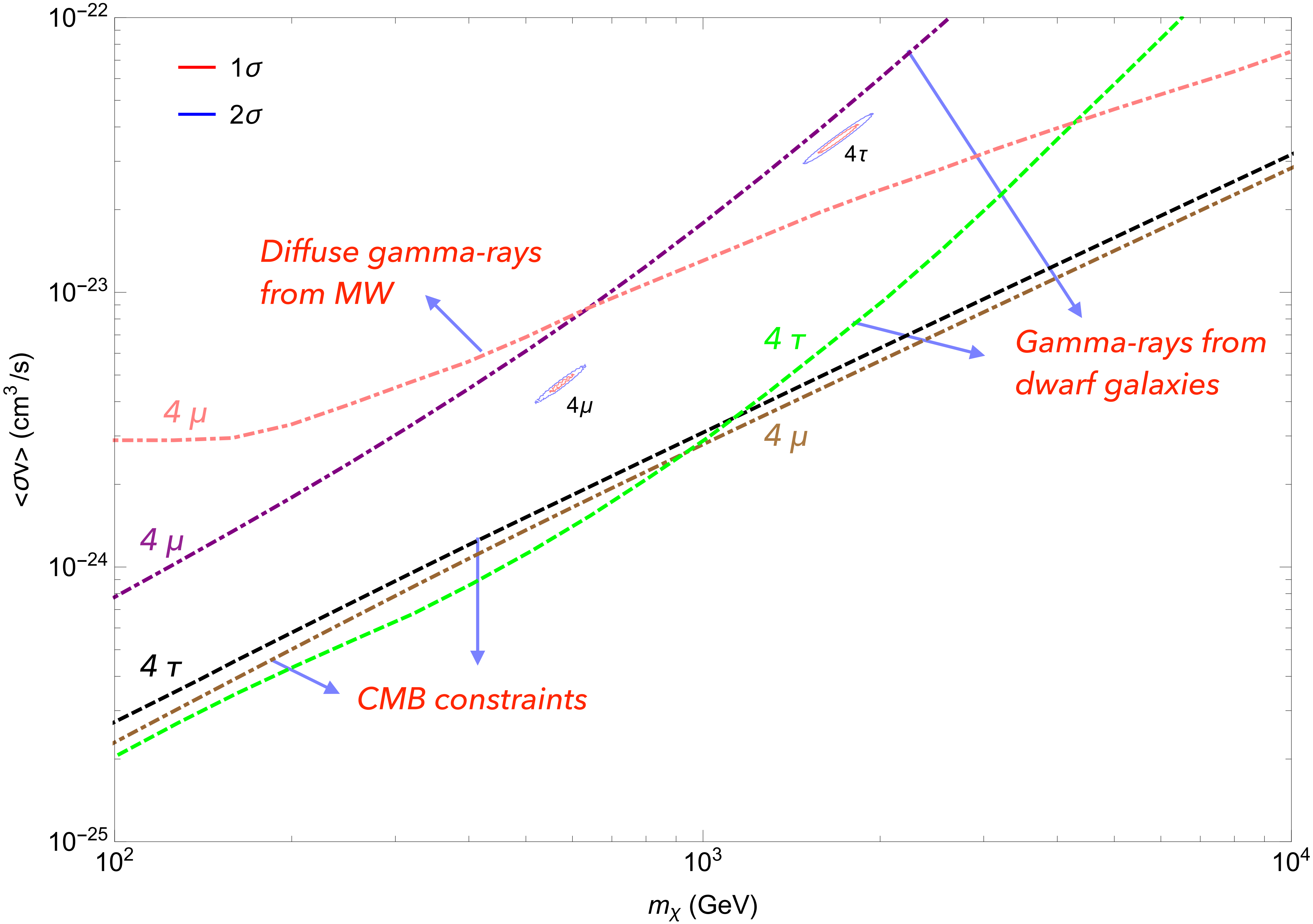
RESULTS

$$\Phi_{e^+}^{\text{tot, modulated}}(E) = \frac{E^2}{(E+\phi_{\text{F}})^2}\Phi_{e^+}^{\text{tot, LIF}}(E+\phi_{\text{F}})$$

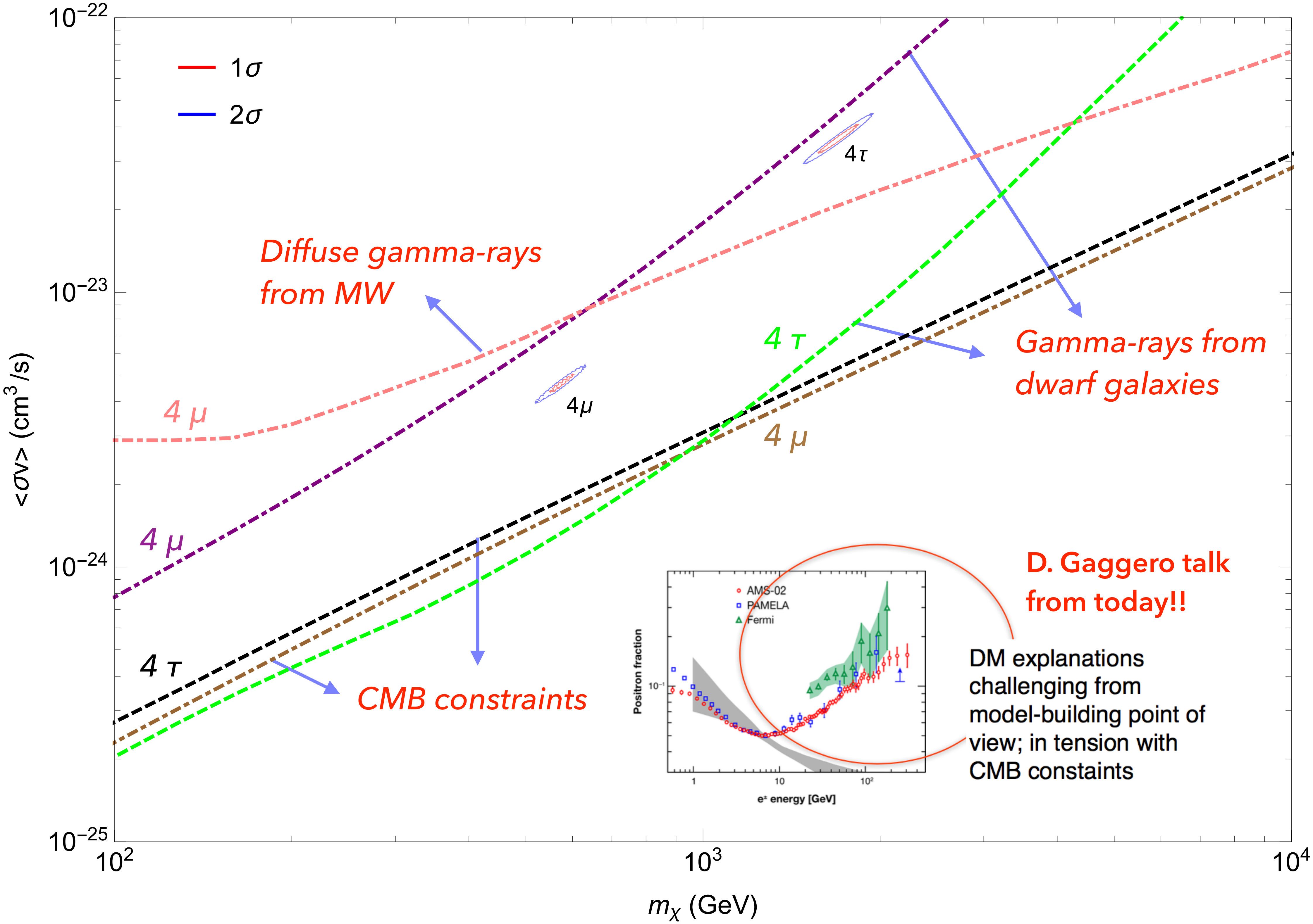


CONSTRAINTS FROM ASTROPHYSICS AND COSMOLOGY

CONSTRAINTS



CONSTRAINTS



BEYOND THE THERMAL WIMP PARADIGM

- While deriving the bounds from CMB, there is an implicit assumption that the s-wave annihilation cross-section remains constant from recombination era to the current epoch.

- This constraints the cosmological evolution of the DM species.

- We are interested not only in exploring alternate production mechanisms in the early universe, but also to probe effects of change in DM characteristics over a cosmological time scale.

- LD2DM is a simple scenario that realizes the above goal while simultaneously explaining the positron excess.

CONSTRAINTS
ON THE LD2DM SCENARIO

LD2DM SCENARIO

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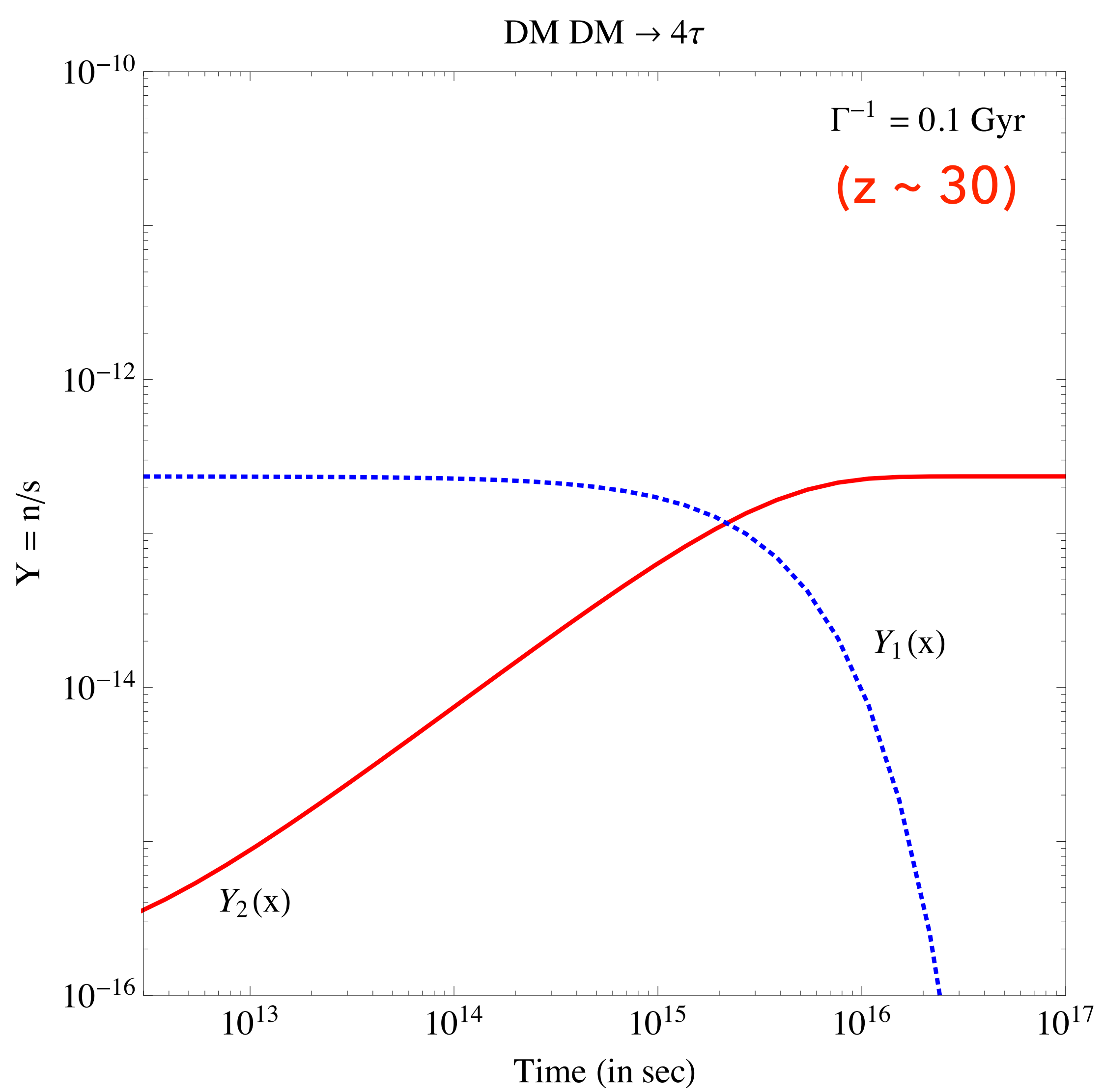
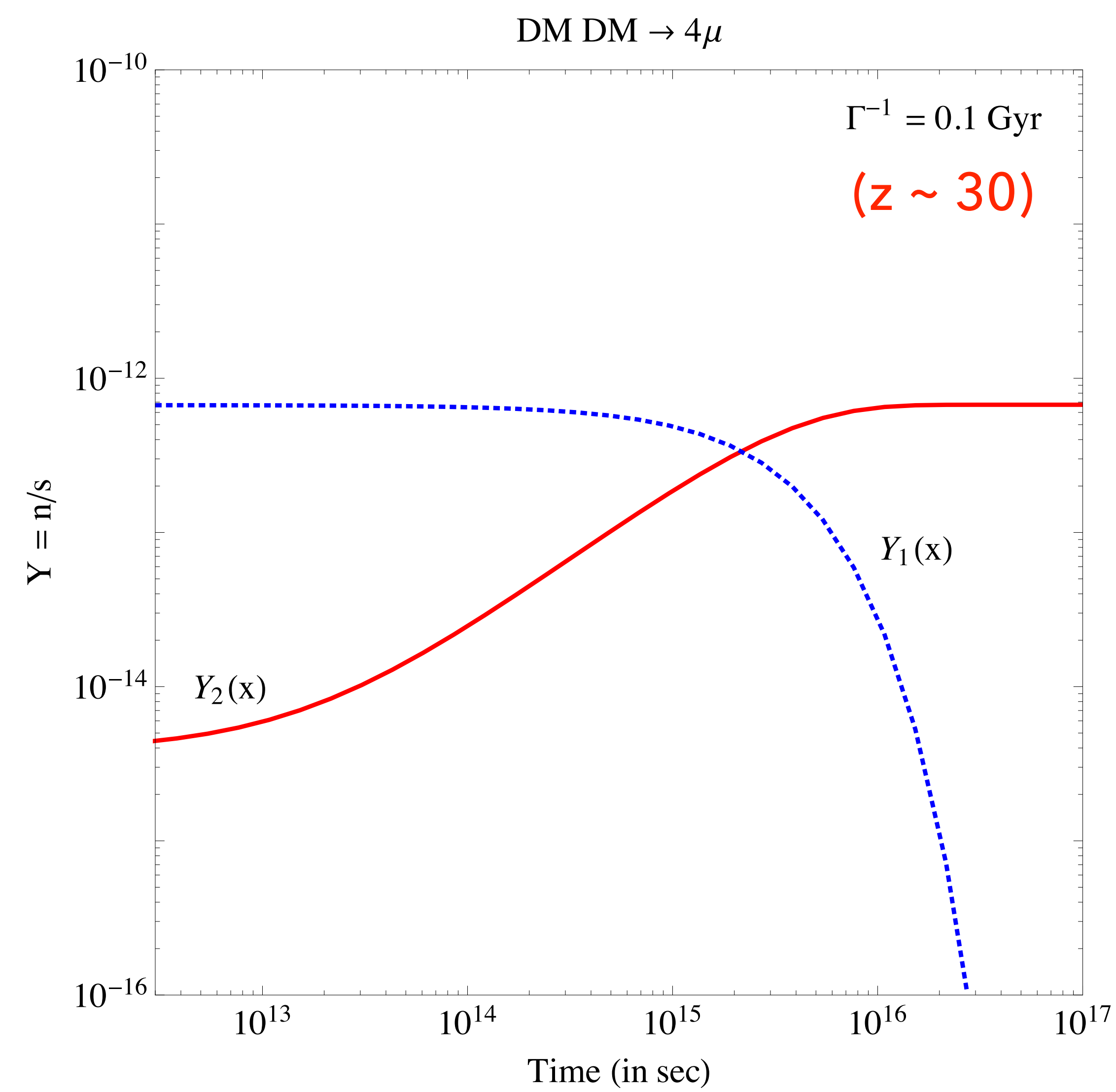
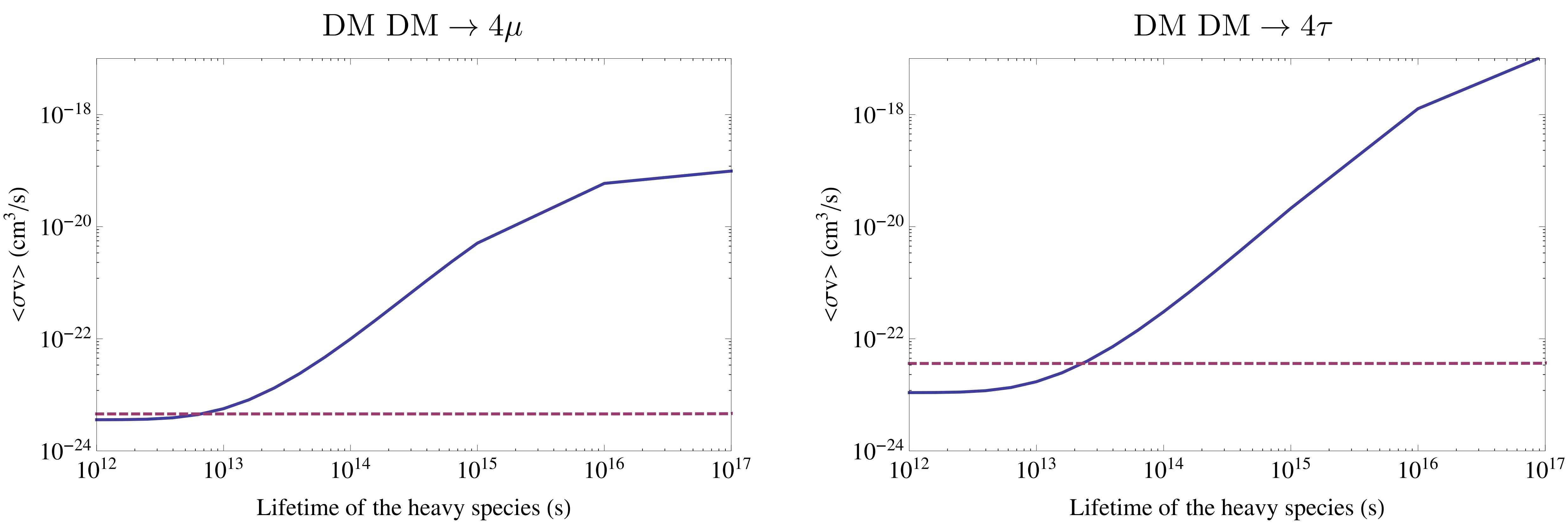




LD2DM CONSTRAINTS

- In the framework of LD2DM, DM decays in the late universe (after z~30) after the onset of halo formation.
- Thus, the heavier DM populates the lighter species, with the higher cross-section, in the late universe such that the relic abundance remains unchanged (we calculate this explicitly!).
- We use publicly available Mathematica recipes to provide a bound on the DM annihilation cross-section by considering the complete shape of its ionization history determined by the LD2DM scenario.
- Such an approach becomes particularly relevant for the LD2DM scenario since it has a unique, red-shift dependent, energy-deposition history.

LIFETIME CONSTRAINTS



- Contraints come from annihilation of lighter species and not decay of the heavier one!

Recipes: 1211.0283, 1506.03811
https://faun.rc.fas.harvard.edu/epsilon//

ΔM CONSTRAINTS

- Ly-α forest measurements constrain the 'kick velocity' imparted to χ_2 upon decay:

$$v_k = \frac{\Delta m}{m} c$$

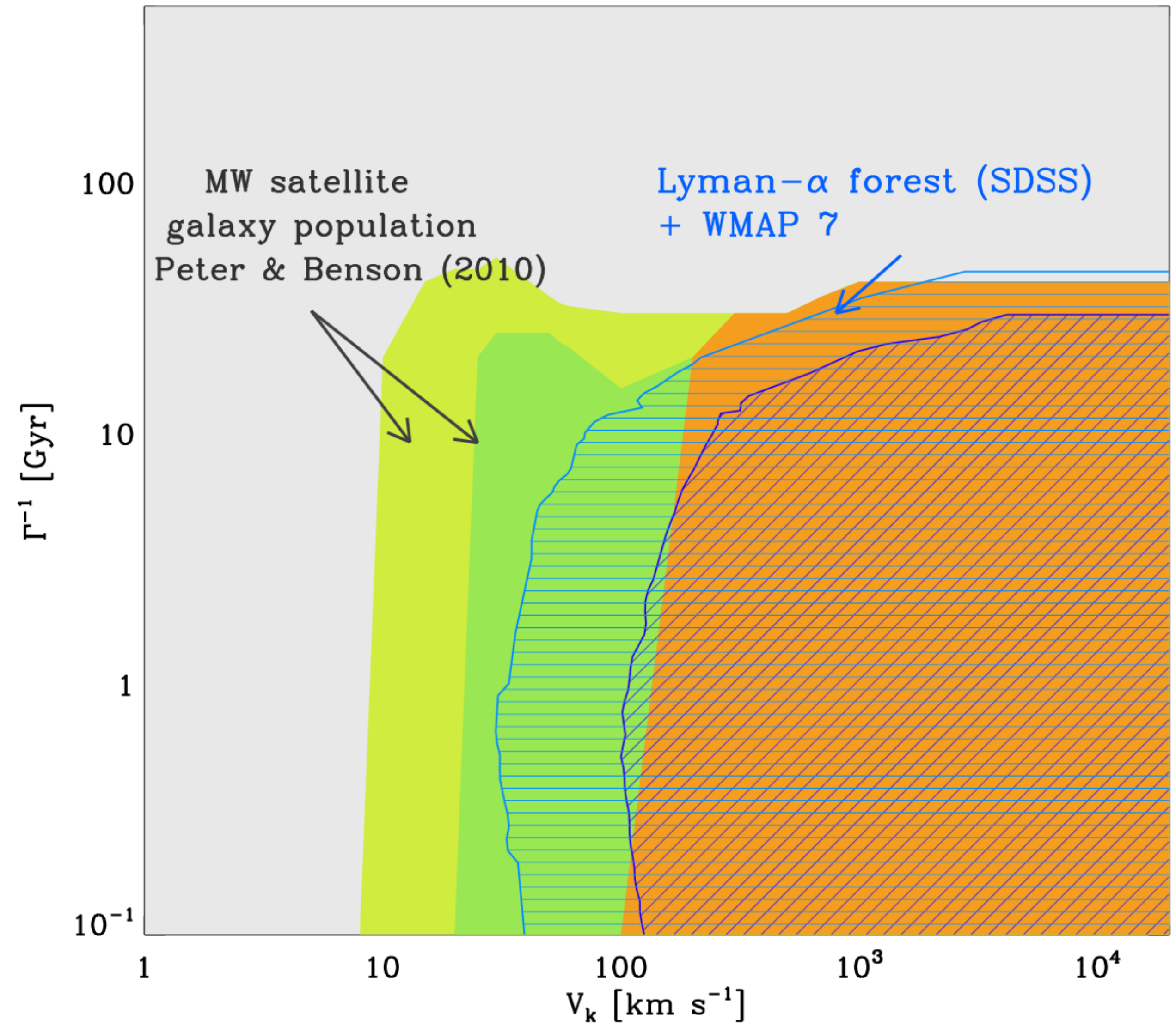
- For $\Gamma^{-1} \lesssim 10\,\mathrm{Gyr}$,

$$v_k \lesssim 40\,\mathrm{km/s}$$

- This translates to a mass difference

$$\Delta m \lesssim 0.1\,\mathrm{GeV}$$

1309.7354



INTERESTING COSMOLOGICAL FEATURES IN THE LD2DM SCENARIO

LD2DM FEATURES

- Kick velocities in the LD2DM scenario are $\mathcal{O}(10)\,\mathrm{km/s}$, which are typical of the maximum circular velocities in dwarf galaxies. Thus, decays of the heavier particle would have a visible impact on galactic halo substructure.

- A detailed numerical study could help narrow down the parameter space for solving some small scale structure anomalies: “missing satellite problem” (not really a problem anymore?) and the ‘too big to fail” problem.

- Moreover, the dark radiation produced in the decays can be interpreted as an extra relativistic degree of freedom, which could resolve the tension between the CMB and local measurements of H_0 and σ_8.

LD2DM FEATURES

- An energy injection due to the annihilation of the daughter can potentially contribute to the reionization of the universe. However, we still need to understand the underlying astrophysics of reionization better!

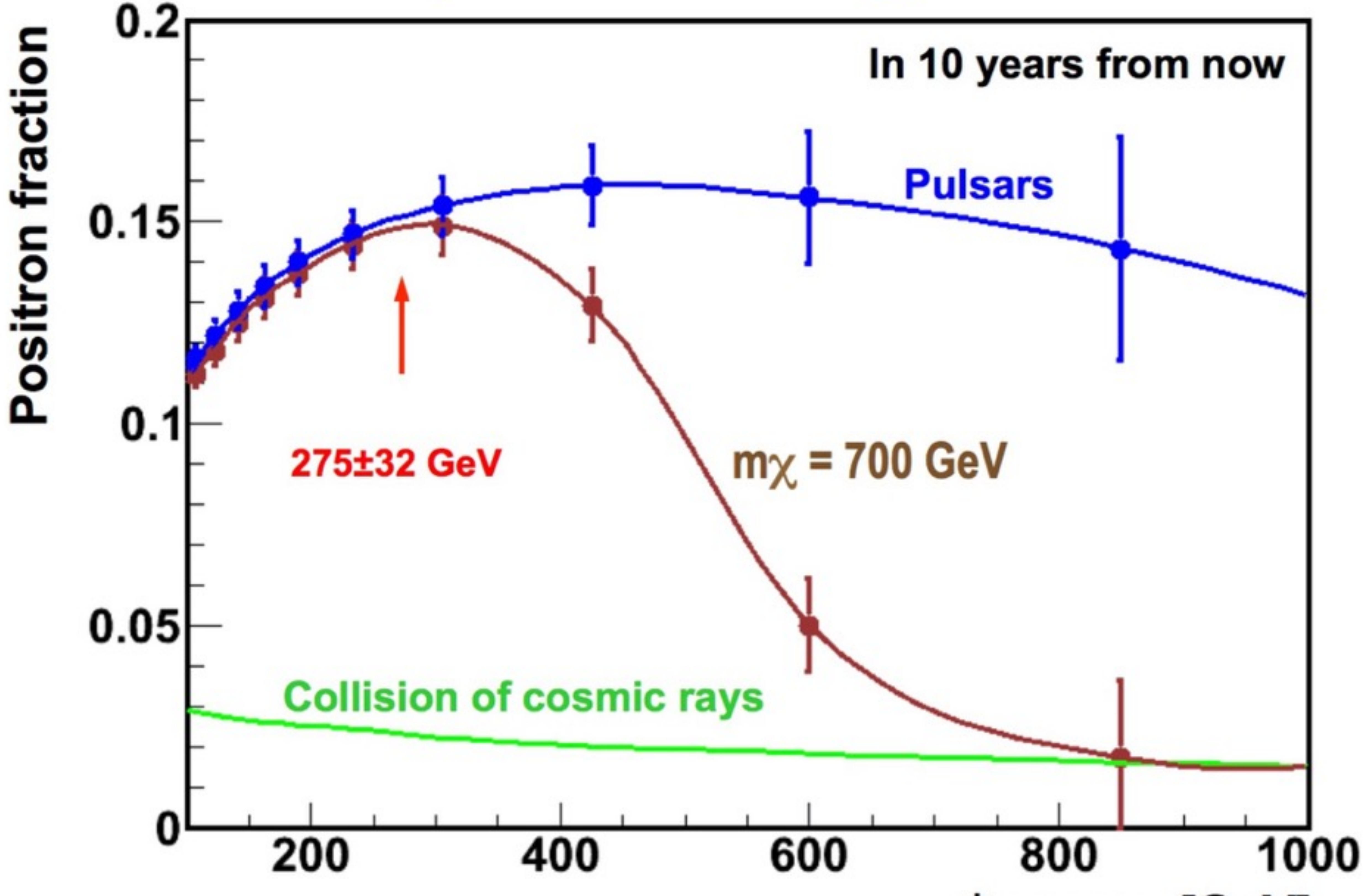
- Precision measurments from current and future 21-cm astronomy experiments like HERA and SKA, especially redshift decomposition for EoR progression, can help us probe peculiar energy injection signatures arising from scenarios like the LD2DM.

SUMMARY

- The positron excess is real, but its origins are still unclear.
- Biggest takeaway: to narrow down the search for DM in cosmic rays, we need to improve our understanding of the astrophysical environment.
- Thermal freeze-out, while simple and elegant, may not be the complete story. Alternate production mechanisms may assist in searches that employ ‘unconventional’ DM candidates.
- Assuming a priori that there is only one particle dark matter candidate in the Universe may be quite restrictive. If the SM is any indication, we should anticipate a rich dark sector as well. In that regard, LD2DM may be incorporated as a scenario for a more elaborate multi-component sector.
- Advent of cosmologically motivated models for DM: motivation to look for signals in hitherto unexplored epochs.

EXTRA SLIDES

(vi) The expected rate at which it falls beyond the turning point.



A. Kounine, AMS Days

CR TRANSPORT: A QUICK PRIMER

- Cosmic Ray (CR) transport for all species is modelled by a diffusion equation:

$$\frac{\partial \psi}{\partial t} = Q(x,p) + \nabla.(D_{xx}\nabla\psi - V_c\,\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\nabla.V_c)\psi\right]$$

Source term

Diffusion term

Diffusive reacceleration

Energy loss coefficient

Convective loss

$$Q(x,p) = \frac{1}{2}\left(\frac{\rho}{M_\chi}\right)^2 \sum_f \langle\sigma v\rangle_f \frac{dN^f_{e^\pm}}{dE}$$

best-fit parameters

Spectrum of e^+ from DM annihilations

$$D_{xx} = D_0\,(R/R_0)^\delta$$

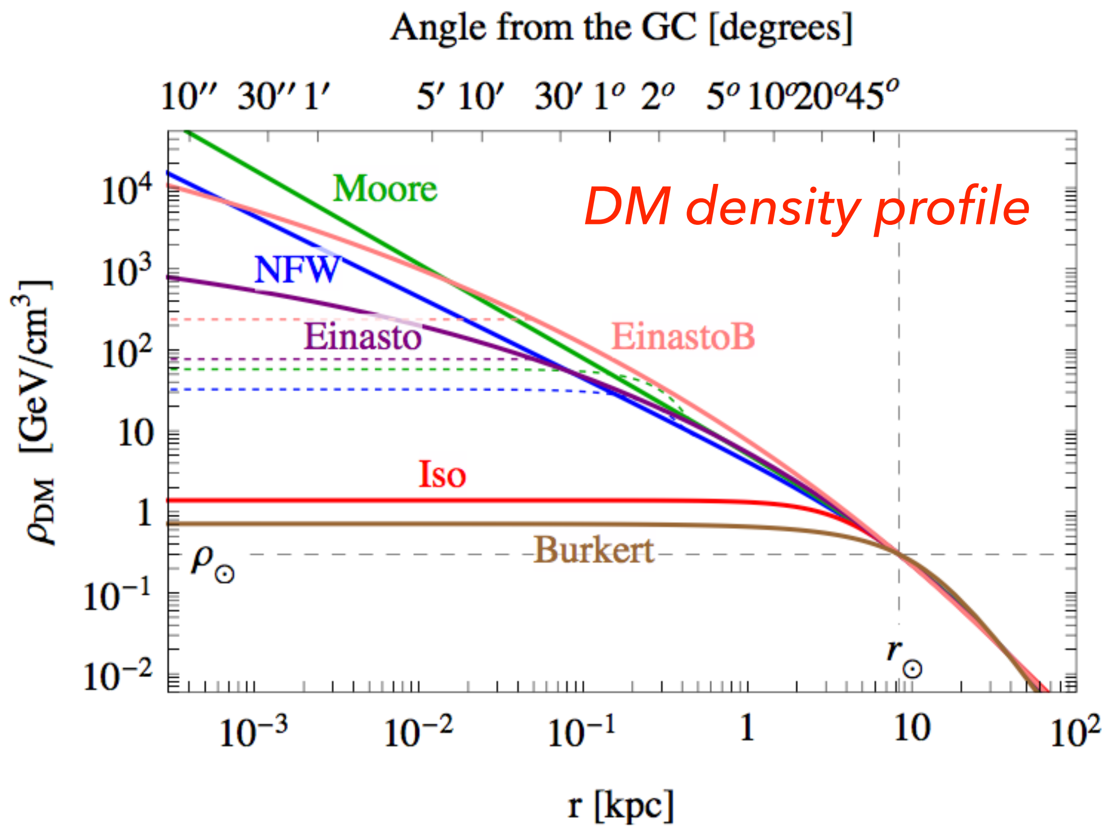
$$D_{pp} = \frac{4p^2 v_A^2}{3\,D_{xx}\delta(4-\delta^2)(4-\delta)}$$

CR TRANSPORT: A QUICK PRIMER

Propagation parameters

Parameters	Model A	Model B
$D_0\,(10^{28}\mathrm{cm}^2/\mathrm{s})$	1.95	6.464
δ	0/0.51	0.29
R_0 (GV)	4.71	4
L (kpc)	2.5	3.2
dV_c/dz (km/s)	4.2	-
v_A (km/s)	-	44.7

MODA: 1409.6248
MODB: 1410.0171



DM density profile

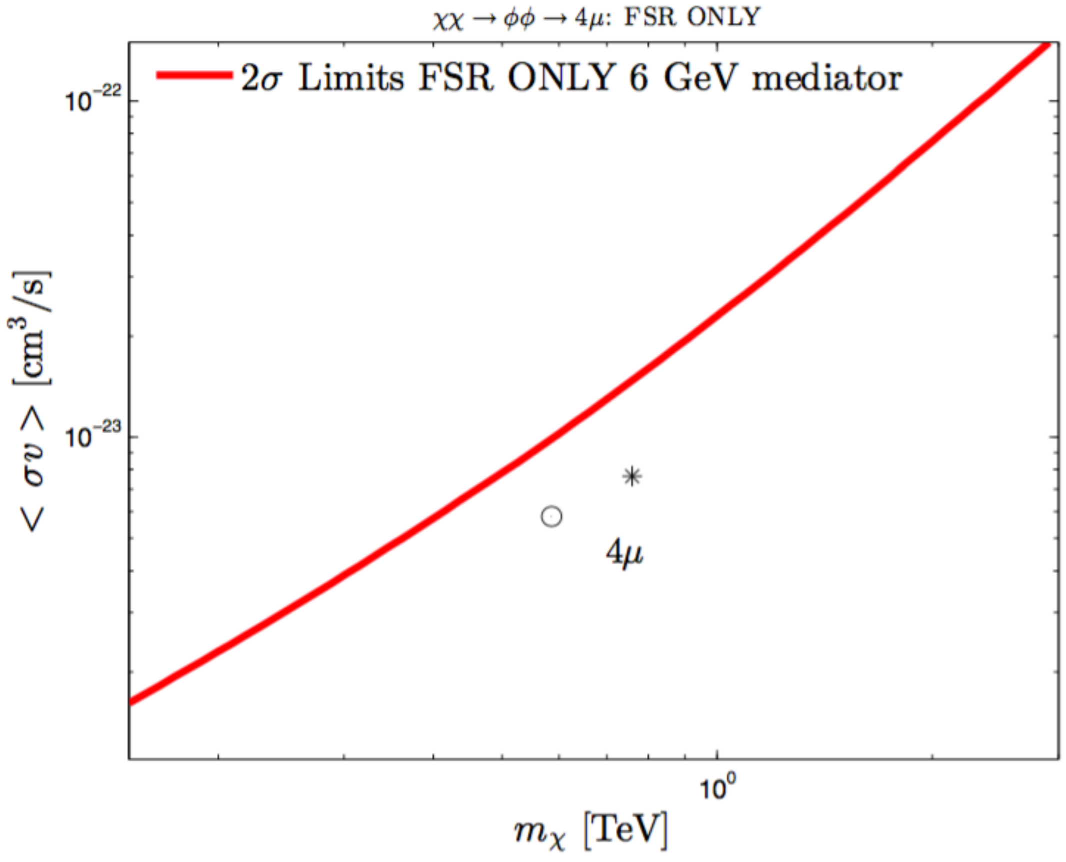
- We also adopt a 21-paramter model for the galactic magnetic field following 0905.2228, 1204.3662

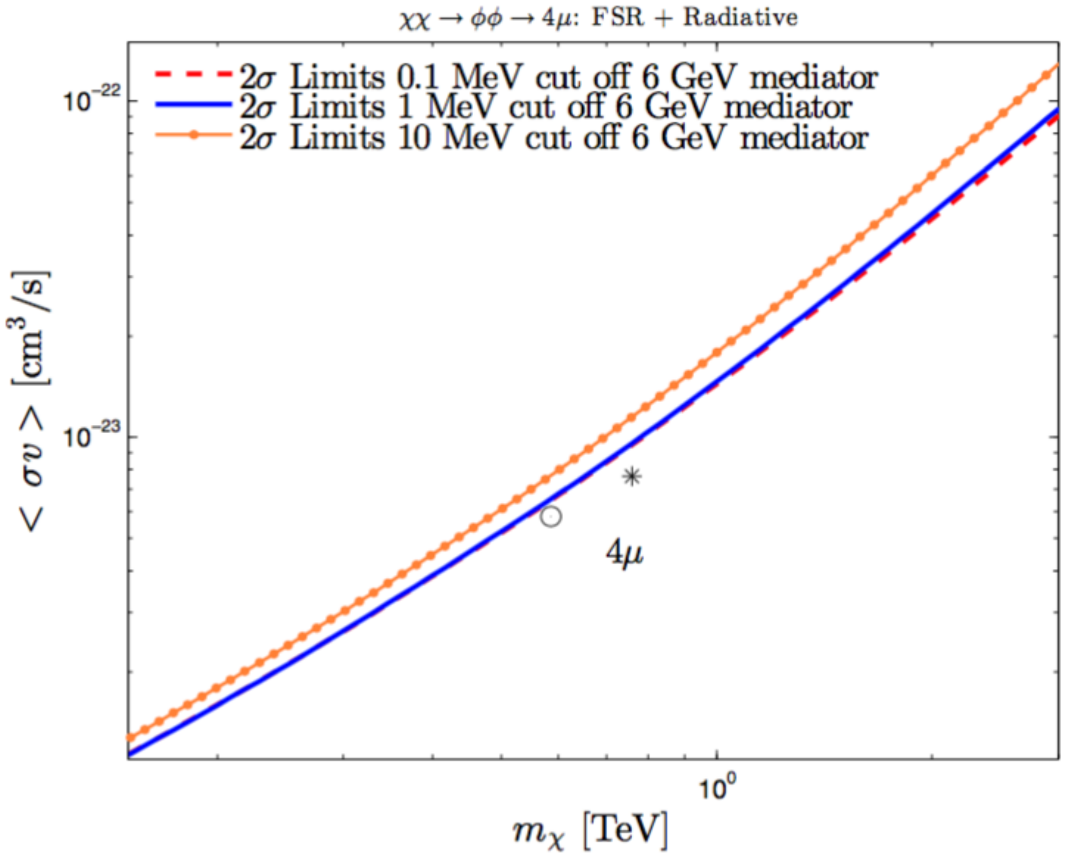
NFW profile: $$\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2} \qquad (\rho_\odot = 0.3\ \mathrm{GeV\ cm}^{-3})$$

TOY MODEL

$$\mathcal{L}_{\text{int}} = -\frac{1}{\Lambda}\overline{\chi}_1\chi_1\phi\phi^* - ig_\phi(\phi^*\partial^\mu\phi - \phi\partial^\mu\phi^*)Z'_\mu - ig\overline{\chi}_2\gamma^\mu\chi_2 Z'_\mu - ig'\overline{\psi}_\ell\gamma^\mu\psi_\ell Z'_\mu + y\overline{\chi}_1\chi_2\phi + \text{ h.c.}$$

GAMMA-RAY CONSTRAINTS





A. Scaffidi et.al. 1604.00744

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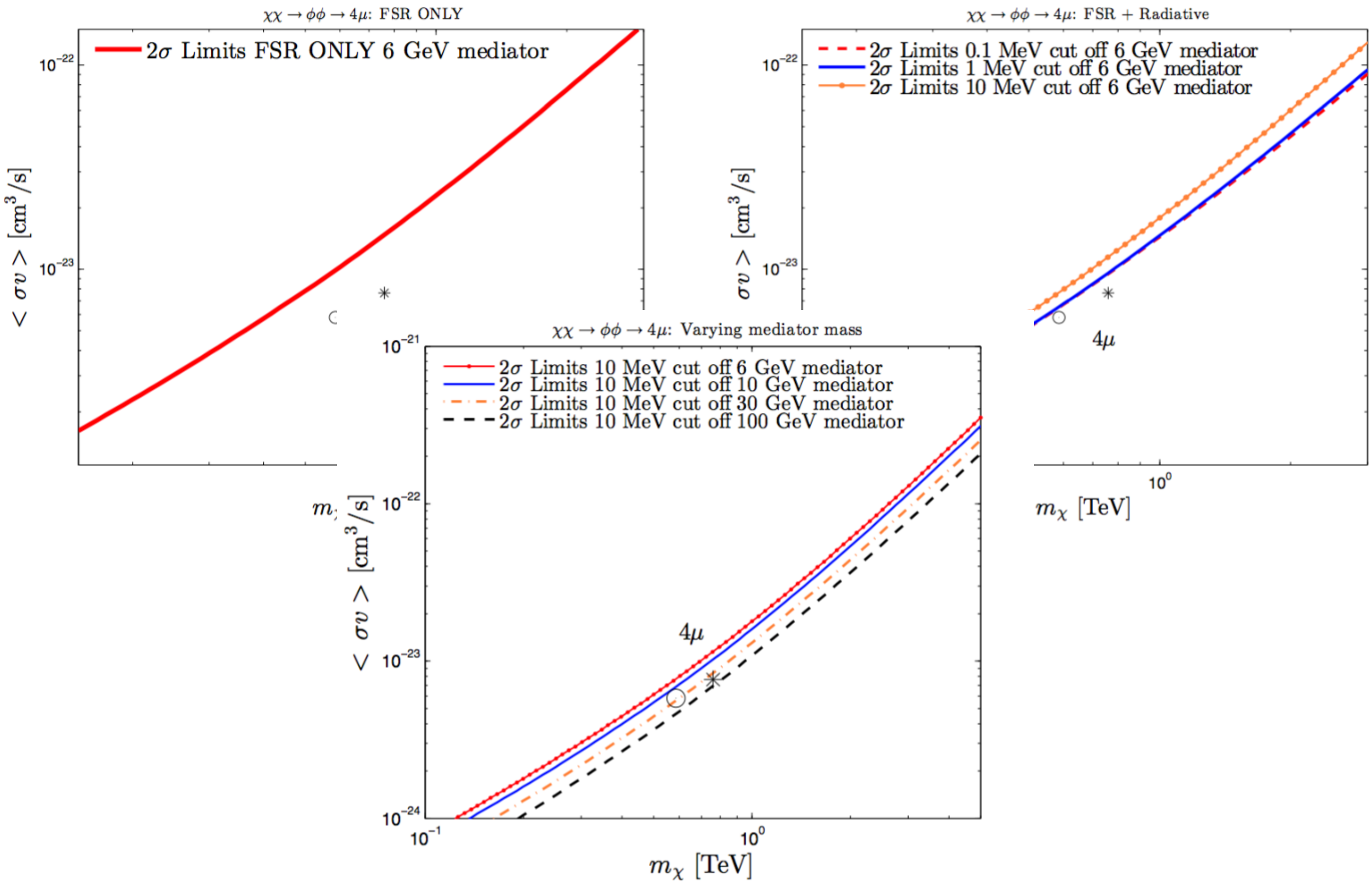

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The Autobiography of Michel Montaigne (1999), Ch: 22