Dynamical Dark Matter and the Positron Excess in Light of AMS

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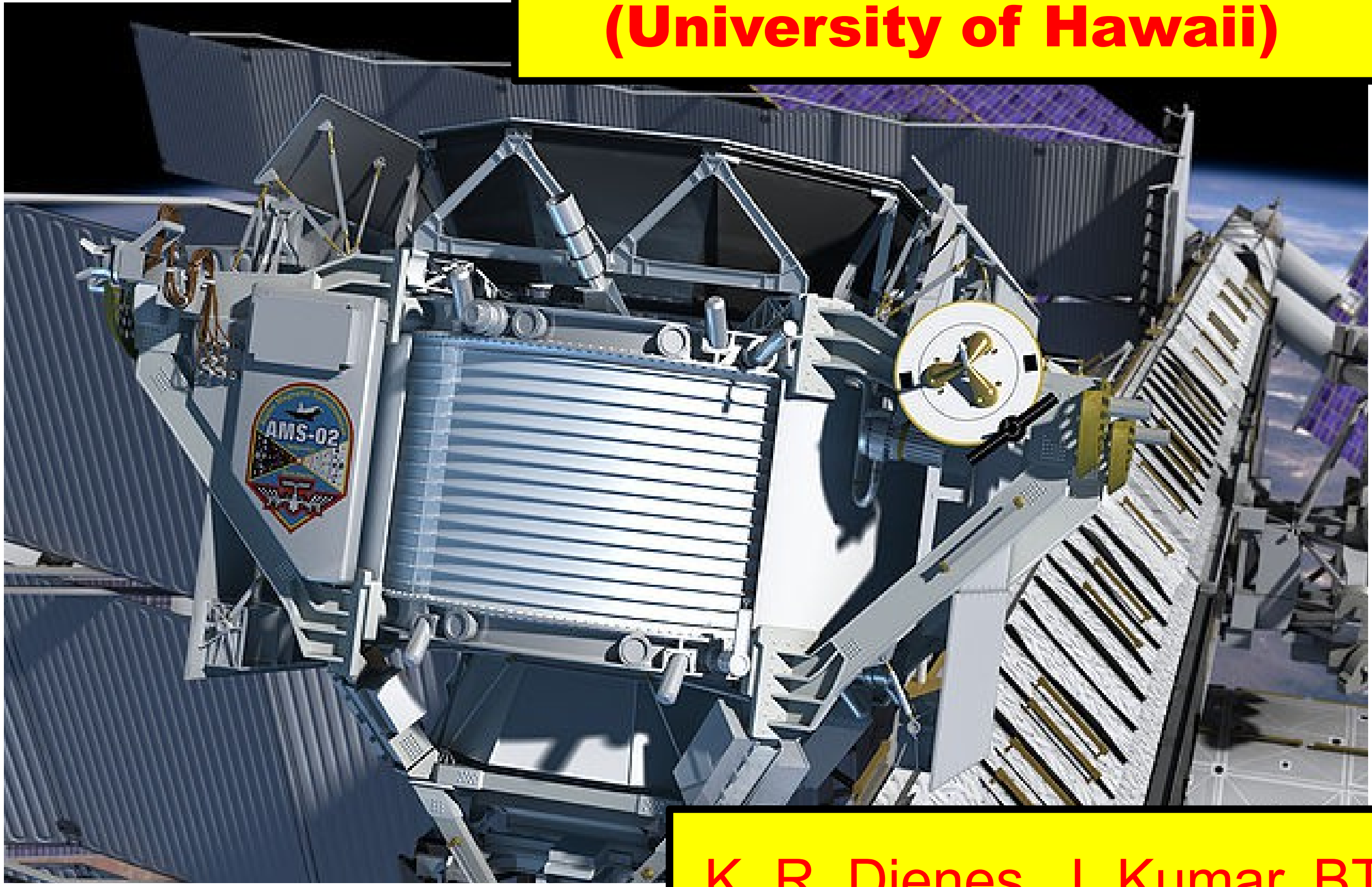
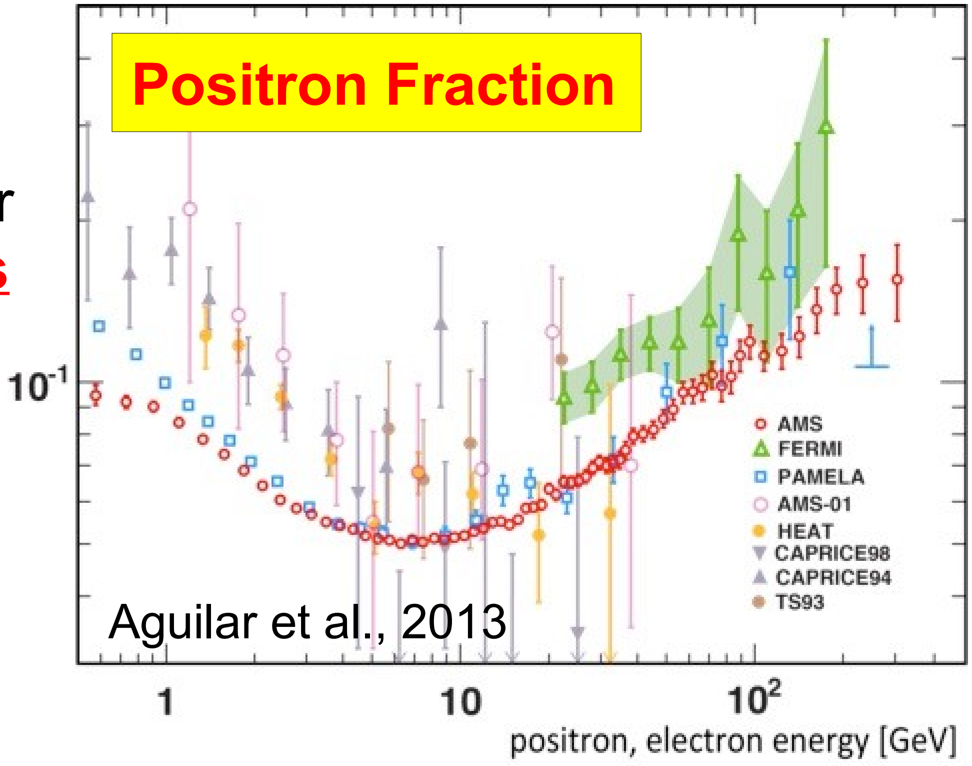


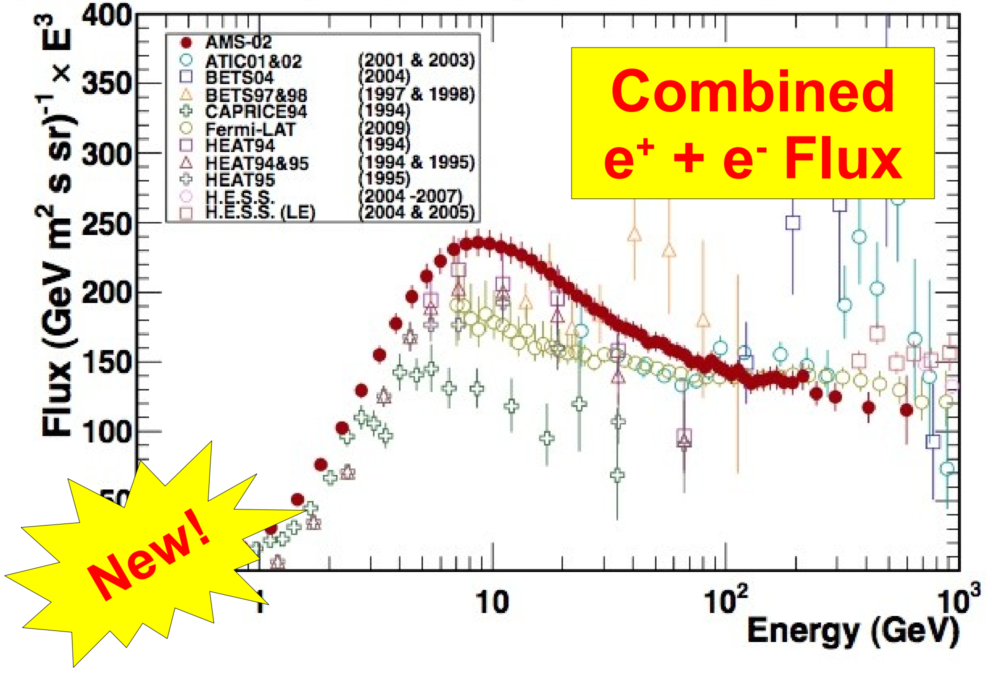
K. R. Dienes, J. Kumar, BT [arXiv:1306.2959]

The Positron Puzzle

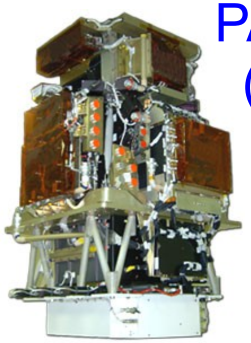
- PAMELA, AMS-02, and a host of other experiments have reported an **excess of cosmic-ray positrons**.
- **Annihilating or decaying dark-matter** in the galactic halo has been advanced as one possible explanation for this data anomaly.
- Alternative explanations involving standard astrophysics (e.g., a population of **pulsars**) have also been advanced. The origin of the positron excess is still unclear.


Positron Fraction

Aguilar et al., 2013


Combined $e^+ + e^-$ Flux

New!


PAMELA (2006)


FERMI (2008)

Dark-matter candidates whose annihilations or decays reproduce the observed positron fraction must respect a battery of additional constraints, many of them quite stringent:

- Limits on the continuum **gamma-ray flux** (from FERMI, etc.)
- Limits on the cosmic-ray **antiproton flux** (from PAMELA, etc.) and other antimatter fluxes
- Consistency with the observed **combined $e^+ + e^-$ flux spectrum** (from FERMI, AMS-02, etc.)
- CMB constraints – and in particular, **reionization limits** – on the annihilation or decay of relic particles in the early universe (from WMAP, PLANCK, etc.)

Traditional dark-matter models can still satisfy these constraints under certain conditions, e.g, if the dark-matter...

- Annihilates to an intermediate state that decays to leptons [Cholis & Hooper, '13]
- Comprises two different particles [Kajiyama, Okada & Toma '13]
- Decays via three-body processes [Ibe et al., '13; Kohri & Sahu, '13]
- Is asymmetric and decays to a pair of different-flavor leptons [Feng & Kang, '13]

...but AMS data have made constructing successful dark-matter models of the positron excess *quite challenging*!

What about other well-motivated dark-matter candidates?

- Competing constraints on the lifetime and abundance of a traditional dark-matter candidate force it to be "hyperstable," with a lifetime $\tau \gtrsim 10^{26}$ s.
- However, a more *general* set of viable dark-matter candidates can be realized as a consequence of this fundamental observation:

A given dark-matter component need not be stable if its abundance at the time of its decay is sufficiently small.

Indeed, a sufficiently small abundance ensures that the disruptive effects of the decay of such a particle will be minimal, and that all constraints from BBN, CMB, etc., will continue to be satisfied.

Thus, it follows that a viable alternative to hyperstability involves a **balancing of decay widths against abundances** across the entire dark sector.

(i.e., states with larger abundances must have smaller widths, but states with smaller abundances can have larger widths)

Dynamical Dark Matter

K. R. Dienes, BT [arXiv:1106.4546, arXiv:1107.0721]

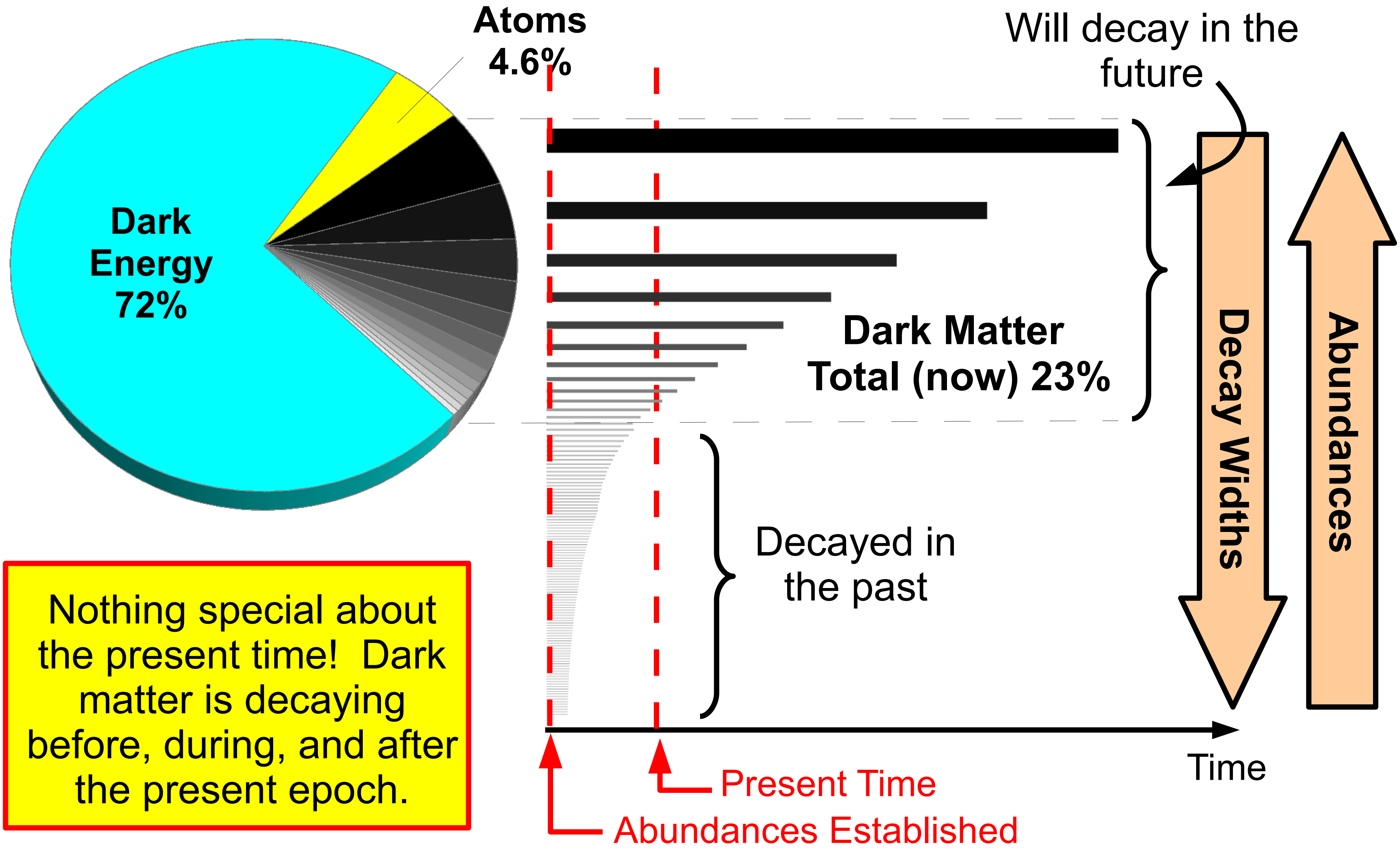
Dynamical Dark Matter (DDM) is a more general framework for dark-matter physics which takes advantage of these possibilities.

In particular, within the DDM framework...

- The dark-matter candidate is an **ensemble** consisting of a vast number of constituent particle species whose collective behavior transcends that of traditional dark-matter candidates.
- Dark-matter stability is not a requirement; rather, the individual abundances of the constituents are **balanced against decay widths** across the ensemble in manner consistent with observational limits.
- Cosmological quantities like the total dark-matter relic abundance, the composition of the dark-matter ensemble, and even the dark-matter equation of state exhibit a **non-trivial time-dependence** beyond that associated with the expansion of the universe.

Such ensembles can be parameterized, e.g., by **scaling relations** which describe how masses, couplings, etc., scale relative to one another across the ensemble as a whole.

DDM Cosmology At a Glance:



Nothing special about the present time! Dark matter is decaying before, during, and after the present epoch.

Not only do models within the DDM framework imply an unusual cosmology, but they can also give rise to **unusual and striking experimental signals**...

- ..at colliders:

  K. R. Dienes, Shufang Su, BT [arXiv:1204.4183]

- ...at direct-detection experiments:

  K. R. Dienes, J. Kumar, [arXiv:1208.0336]

- ...and a a variety of other expreiments.

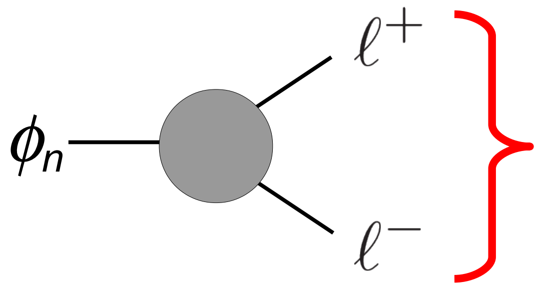
As we shall see, inherent properties of DDM ensembles can also help reconcile many of the phenomenological tensions that make constructing dark-matter models of the positron excess so challenging!

Indeed, these ensembles have several properties which make them particularly apt candidates for explaining the AMS results, such as:

- A **natural softening** of the electron and positron injection spectra.
- An inherent source of cosmic-ray particles – dark-matter decays are an integral part of the DDM framework!

DDM Ensembles and Cosmic Rays

For concreteness, consider the case in which the ensemble constituents ϕ_n are scalar fields which couple to pairs of SM fermions.



Leptonic decays (preferred by antiproton-flux constraints)

$$\ell^\pm = \{e^\pm, \mu^\pm, \tau^\pm\}$$

e.g.,
$$\mathcal{L}_{\rm int} = \frac{c_n}{\Lambda} \left(\partial_\mu \phi_n\right) \overline{\ell} \gamma^\mu \ell$$

Distributing the dark-matter abundance across the ensemble of particles with different masses yields a broad spectrum of lepton injection energies

Effectively softens the e± spectra!

Parametrizing the Ensemble: Scaling Relations

Masses:
$$m_n = m_0 + n^\delta \Delta m$$

Couplings:
$$c_n = c_0 \left(\frac{m_n}{m_0}\right)^\xi$$

Abundances:
$$\Omega_n = \Omega_0 \left(\frac{m_n}{m_0}\right)^\alpha$$

$$\Gamma_n \sim \frac{m_\ell^2 m_0}{\Lambda^2} \left(\frac{m_n}{m_0}\right)^\gamma$$

where $\gamma \equiv 1 + 2\xi$

Surveying the Parameter Space

- In surveying the parameter space of our DDM model, we adopt the following criteria for consistency with observational limits:

> - Consistency with the combined $e^+ + e^-$ flux spectrum observed by FERMI to within 3σ.
> - Consistency with the diffuse extragalactic gama-ray flux observed by FERMI (the most stringent gamma-ray constraint on decaying dark-matter models of this sort).
> - Conistency with PAMELA limits on the antiproton flux to within 3σ (*easily* satisfied for leptophilic DDM ensembles).
> - Consistency with projected Planck CMB reionization limits.

- For each choice of α, γ, and m_0, we survey over values of $\tau_0 \equiv 1/\Gamma_0$ and identify the value which provides the best fit to the AMS positron-fraction data (using a χ^2 statistic) and simultaneously satisfies the above criteria.
- We are primarily interested in the **"continuum" regime**, in which the mass splitting between all relevant modes is much smaller than the energy resolution of the AMS detector. We therefore focus on the benchmark values Δm = 1 GeV, δ = 1.

Reionization Limits

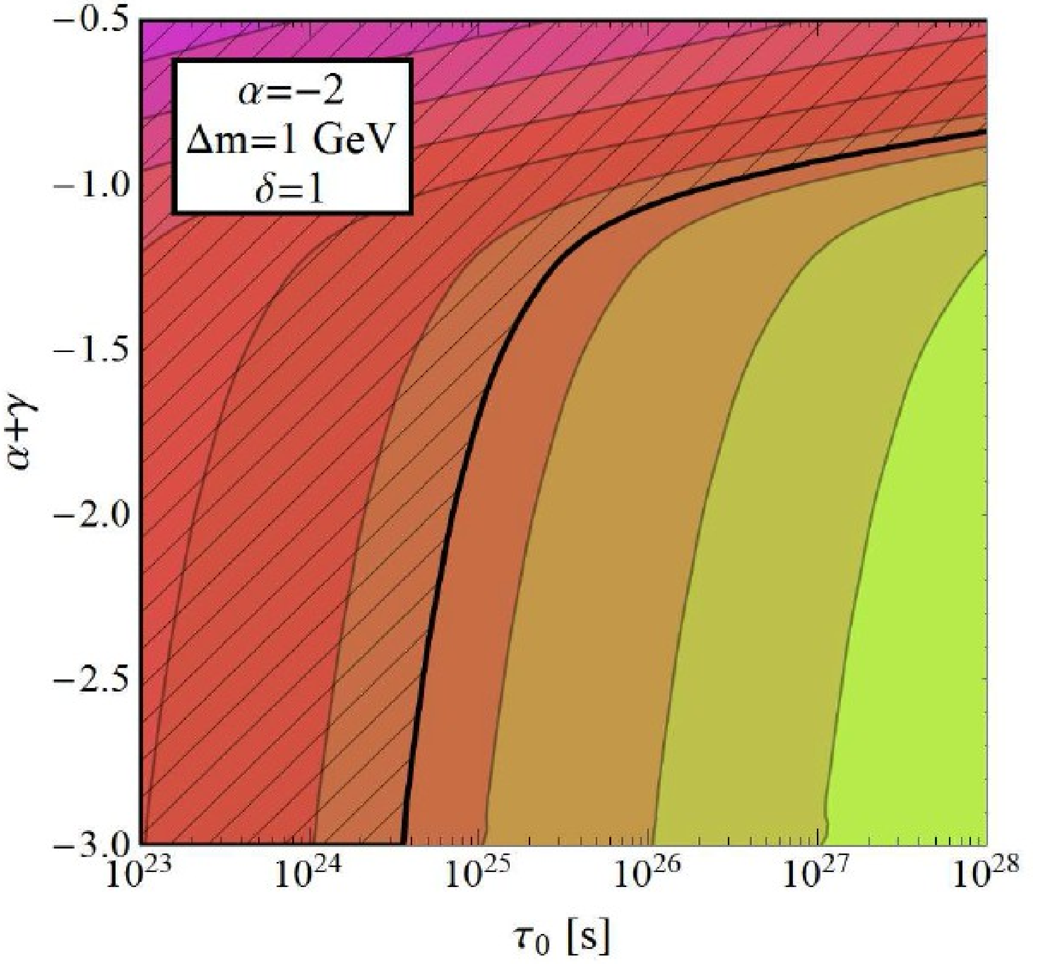
- High-energy photons, electrons, and positrons produced from dark-matter decay can alter the reionization history of the universe, thereby leaving observable imprints on the CMB.

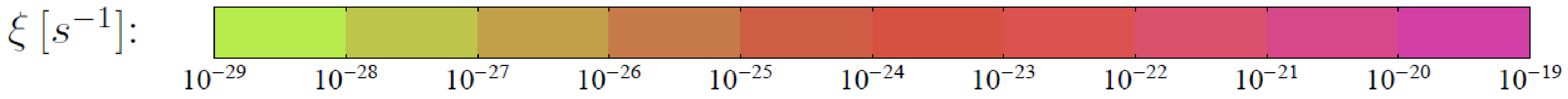
- Limits from Planck, WMAP, etc., on such imprints essentially constrain the total energy injection from dark-matter decays:

$$\xi \equiv \sum_{n=0}^{n_{\max}} \Omega_n \Gamma_n \lesssim 3 \times 10^{-26}\ \mathrm{s}^{-1}$$

Projected Planck limit
(including polarization data)

▨ Excluded Region





As a result of the softening of the $e^{\pm}$ injection spectra, DDM ensembles can reproduce AMS positron-fraction data while simultaneously satisfying these other additional constraints.

Decays primarily to $\mu^+\mu^-$ strongly preferred

The best fit to AMS data is obtained for:

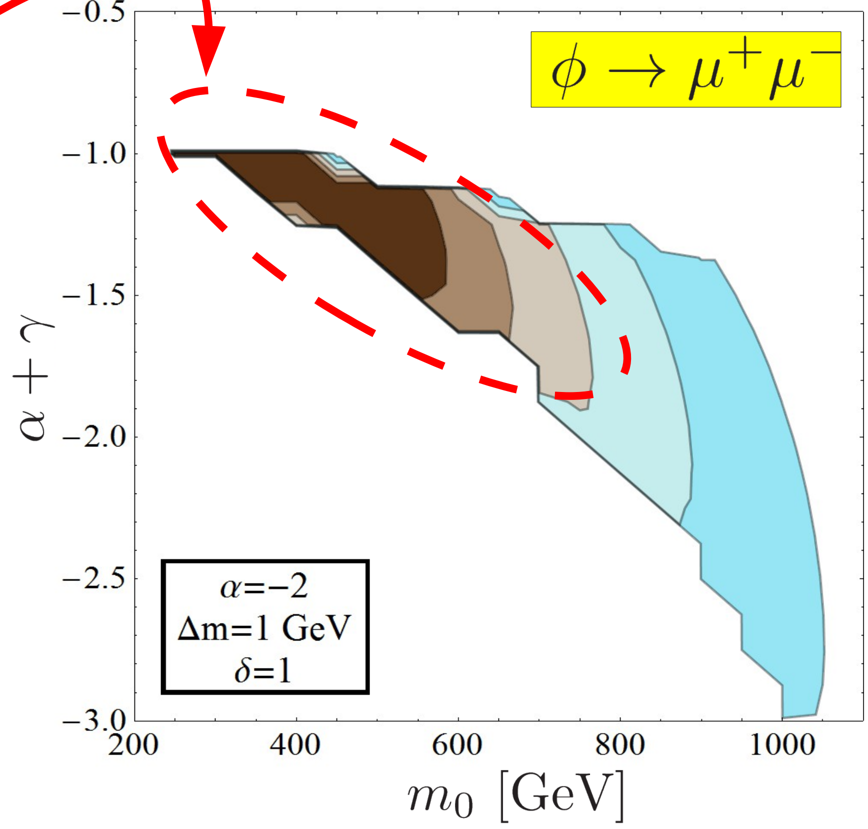
$$200\ \text{GeV} \lesssim m_0 \lesssim 800\ \text{GeV}$$

...and thus when a substantial number of enemble constituents are reasonably light.

This helps ease tensions with gamma-ray constraints relative to traditional dark-matter models with m_χ ~ 1-3 TeV.

Such light ensemble constituents are also far easier to detect via complementary probes of the dark sector (e.g., colliders).

Discrepancy from AMS Positron Fraction



Discrepancy:

(White region: either > 5σ discrepancy or else ruled out by other constraints)

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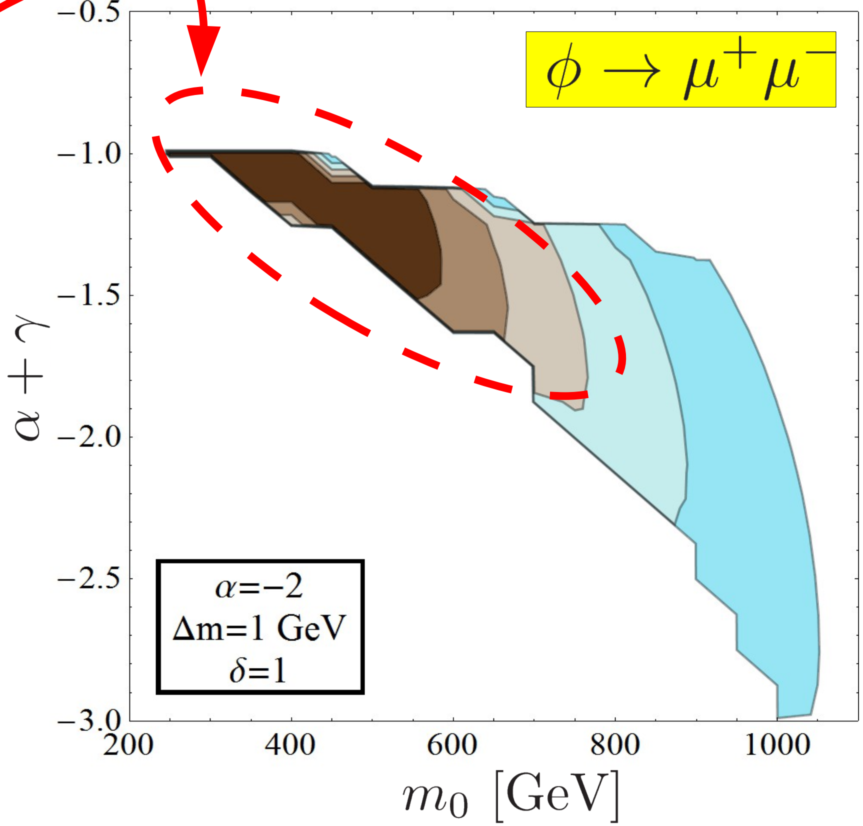

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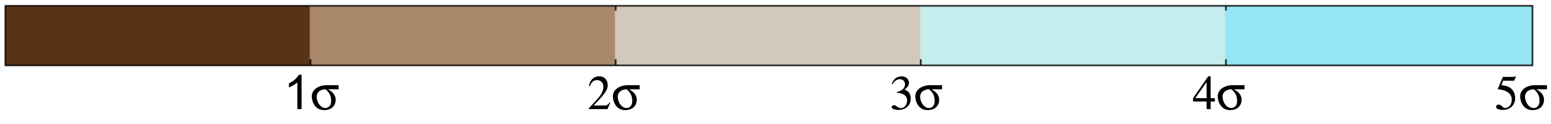

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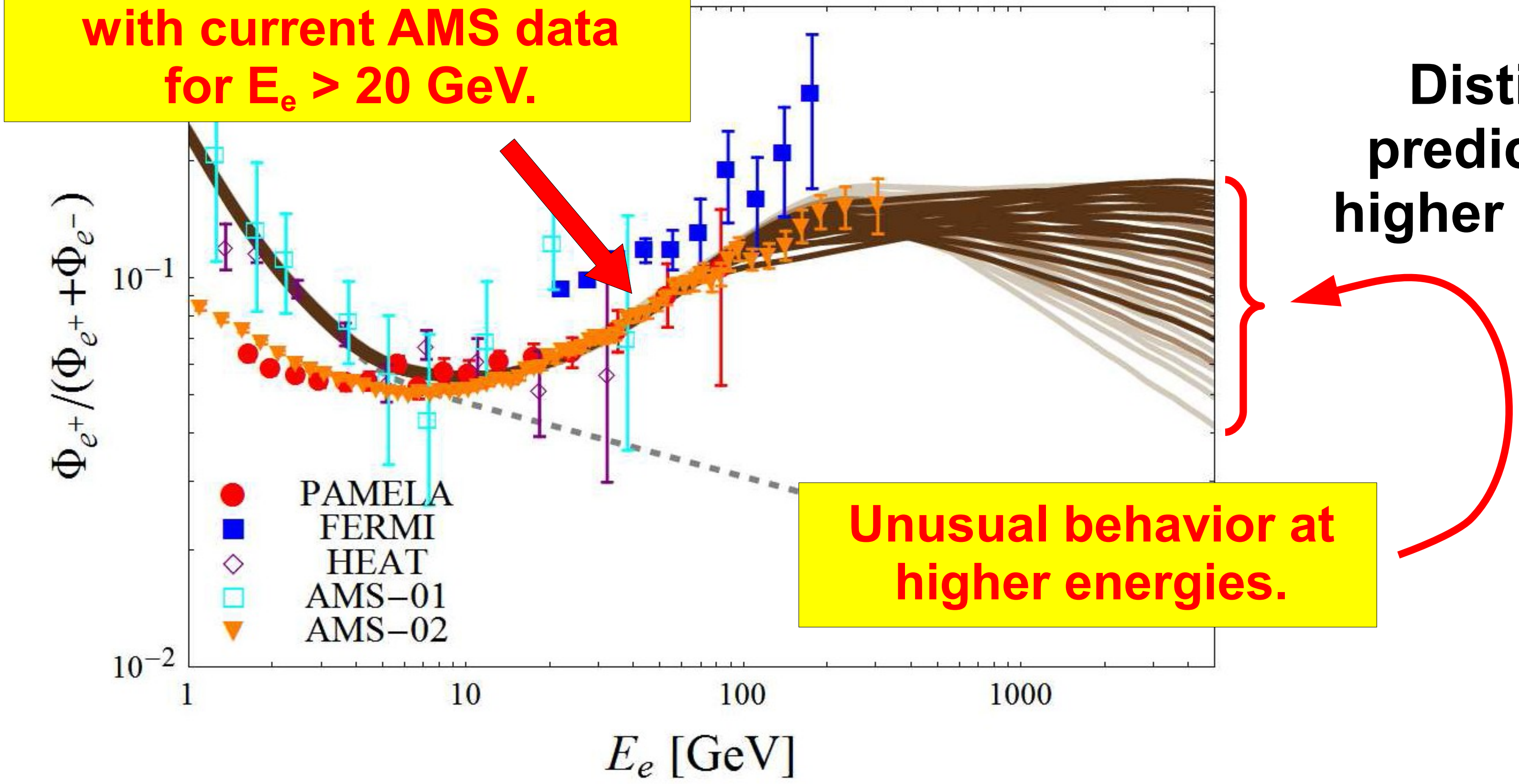
Positron Fractions from DDM Ensembles



Agreement (3σ or better) with current AMS data for $E_e > 20$ GeV.

Distinctive predictions at higher energies!

Unusual behavior at higher energies.

The positron-fraction curves associated with DDM models in the continuum regime yield a concrete prediction for the positron fraction at $E_{e^\pm} < 350$ GeV :

In stark contrast to the pronounced downturn anticipated for typical dark-matter models, DDM models in this regime predict a **plateau** or a **gradual decline** in the positron fraction at high energies.

DDM vs. Pulsars

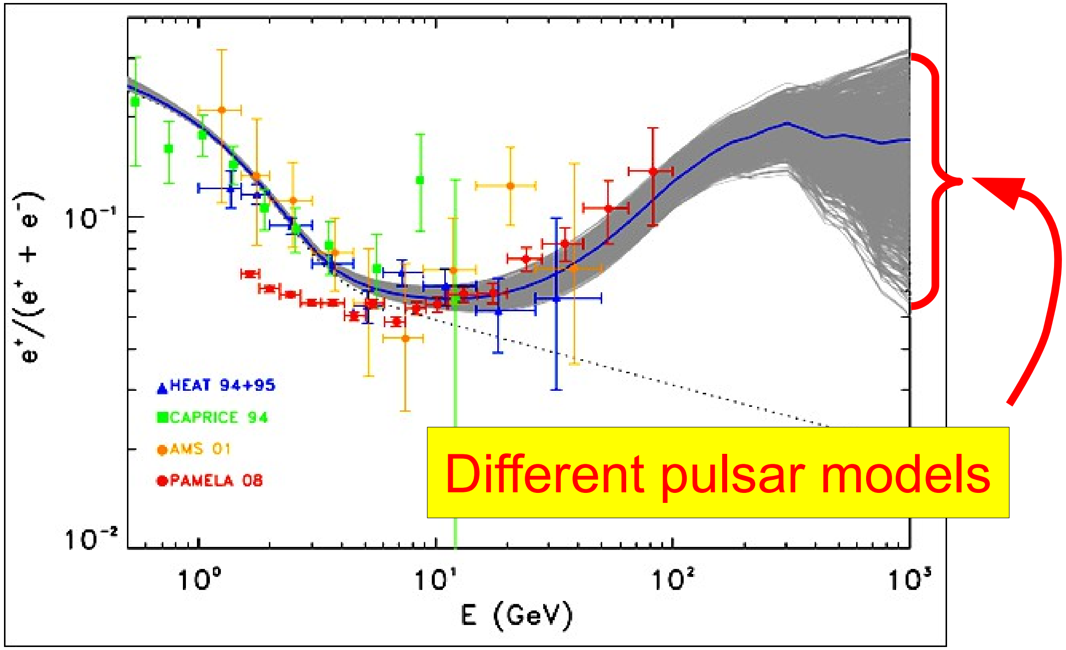
Q: Can't a population of pulsars reproduce the same positron-fraction curves?

A: Yep. Sure can.

Q: Can't a population of pulsars also reproduce essentially any curve you want?

A: Yep. Sure can.

The point is that a large number of positron-fraction curves which one might have thought could only be reproduced by pulsars ***also*** **have a natural dark-matter interpretation in terms of DDM ensembles!**



Different pulsar models

- Probing **anisotropies** in the e$^+$ and e$^-$ fluxes could potentially help distinguish between pulsar populations and DDM ensembles.
- Successful DDM models of the positron excess include many light ensemble constituents which could potentially be dectected using other, **complementary probes** of the dark sector.

Summary

- The DDM framework provides a viable dark-matter explanation of the observed positron excess.
- The distribution of Ω_{DM} across an ensemble of dark-matter fields leads to a natural softening of the $e^{\pm}$ flux spectra and eases tensions with other constrains on dark-matter decays.
- DDM ensembles which reproduce the positron-fraction curve observed by AMS-02 at $E_{e^{\pm}} < 350$ GeV predict a **plateau** or a **gradual decline** in the positron fraction at higher energies.
- Thus, the lack of a downturn in the positron fraction (and the combined $e^+ + e^-$ flux) at high energies does *not* rule out a dark-matter interpretation of the positron excess.

The absence of a downturn in the positron fraction and combined $e^+ + e^-$ flux at high energies doesn't mean that standard astrophysics (e.g., a collection pulsars) is responsible for the positron excess.