Current Status on Dark Matter Motivation for Heavy Photons

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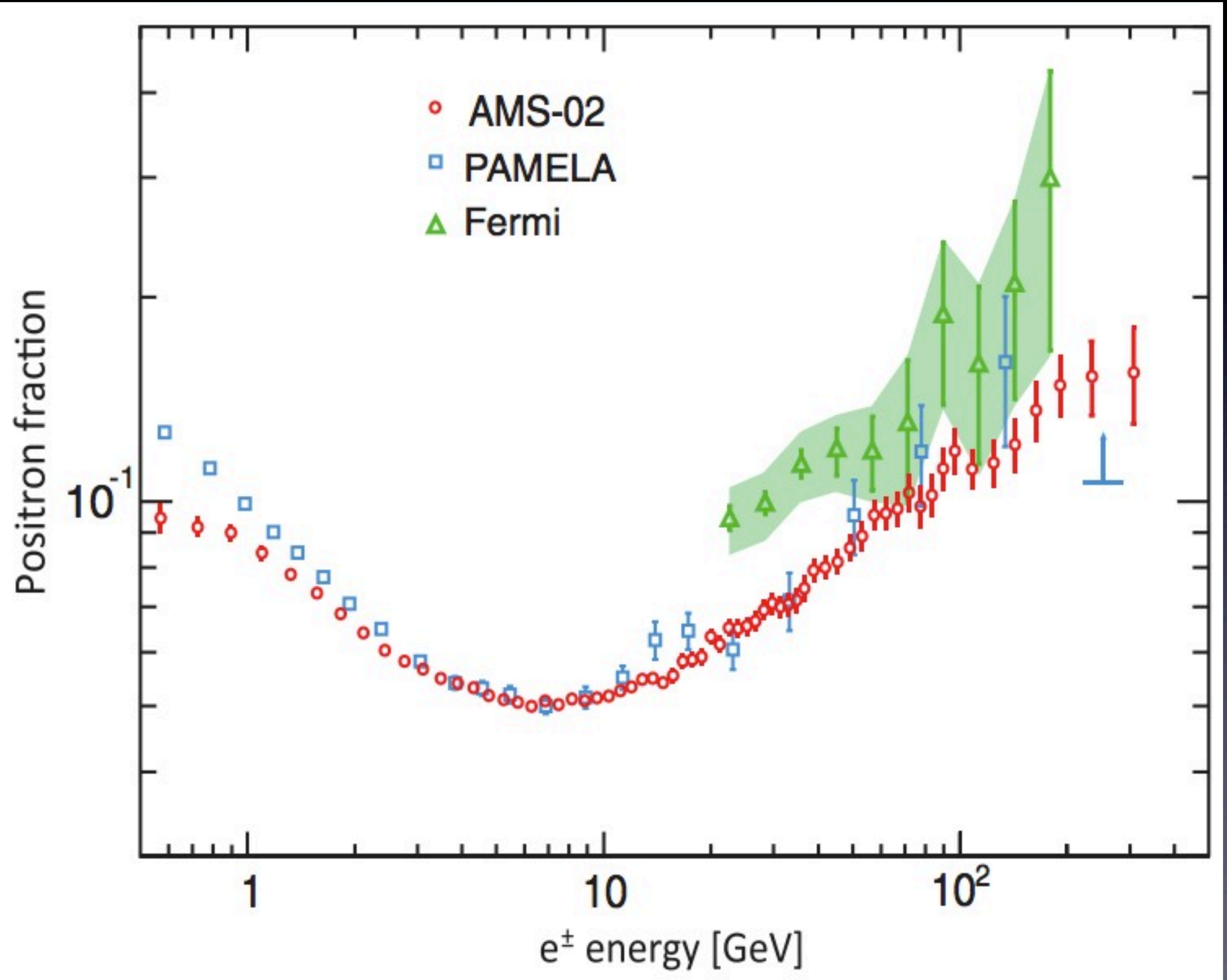
Outline

- Cosmic rays: the positron excess from PAMELA/Fermi/AMS-02
  - New favored parameter space after AMS-02
  - Constraints on the DM interpretation
- Light dark matter
  - Direct detection (and the LHC)
  - Indirect detection: inner galaxy signals
  - Heavy photon hypothesis
- Self-interacting dark matter
  - The status of observed DM distribution on galactic scales, vs ΛCDM
  - Parameter space where light mediators can make a difference

POSITRON FRACTION MEASUREMENTS

PAMELA, Fermi, AMS-02

- Measurement of the $e^+/(e^+ + e^-)$ ratio ("positron fraction") as a function of energy.
- Data below 10 GeV affected by "solar modulation" effect; above 10 GeV, sharp rise is observed.



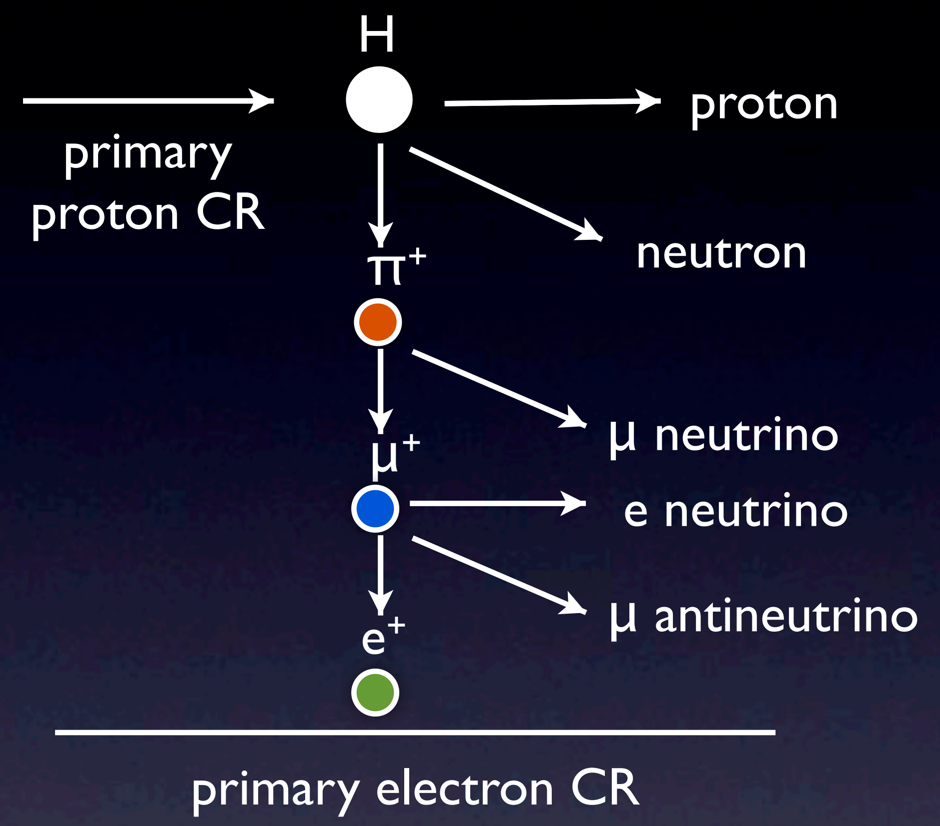
Cosmic ray positrons

Secondary particles = spectrally softer than primaries. Ratio of antimatter/ matter from supernova shocks should fall at high energies.

But dark matter is charge-neutral - in most models, DM annihilation produces particles, antiparticles equally.

Rise in the antimatter fraction at weak-scale energies = potential WIMP annihilation signal.

PAMELA experiment designed to measure this and other CR spectra, succeeded by AMS-02.



Fermi Gamma-Ray Space Telescope: designed to observe gamma rays, but can measure the total electron + positron spectrum; positron fraction analysis uses the Earth's magnetic field to perform charge discrimination.

DM and the positron excess

- Three problems arise with conventional DM interpretation:
  - Signal is too large by a factor of ~100 relative to expected thermal relic cross section.
  - Signal is too hard, rising too quickly with energy - typical e^+ spectra from DM annihilation are produced by a lengthy cascade, and are softer than observed.
  - No corresponding excess is observed in antiprotons; would generally expect both p^+ and e^+ to be produced by WIMP annihilation.
- All three can be evaded by the addition of a new GeV-scale force carrier coupled to dark matter (Arkani-Hamed, Finkbeiner, TRS & Weiner 2008; Pospelov & Ritz 2008).

A new dark force

- Suppose we couple the DM to a new vector A' which mixes with the photon.
- Dominant annihilation channel is now:

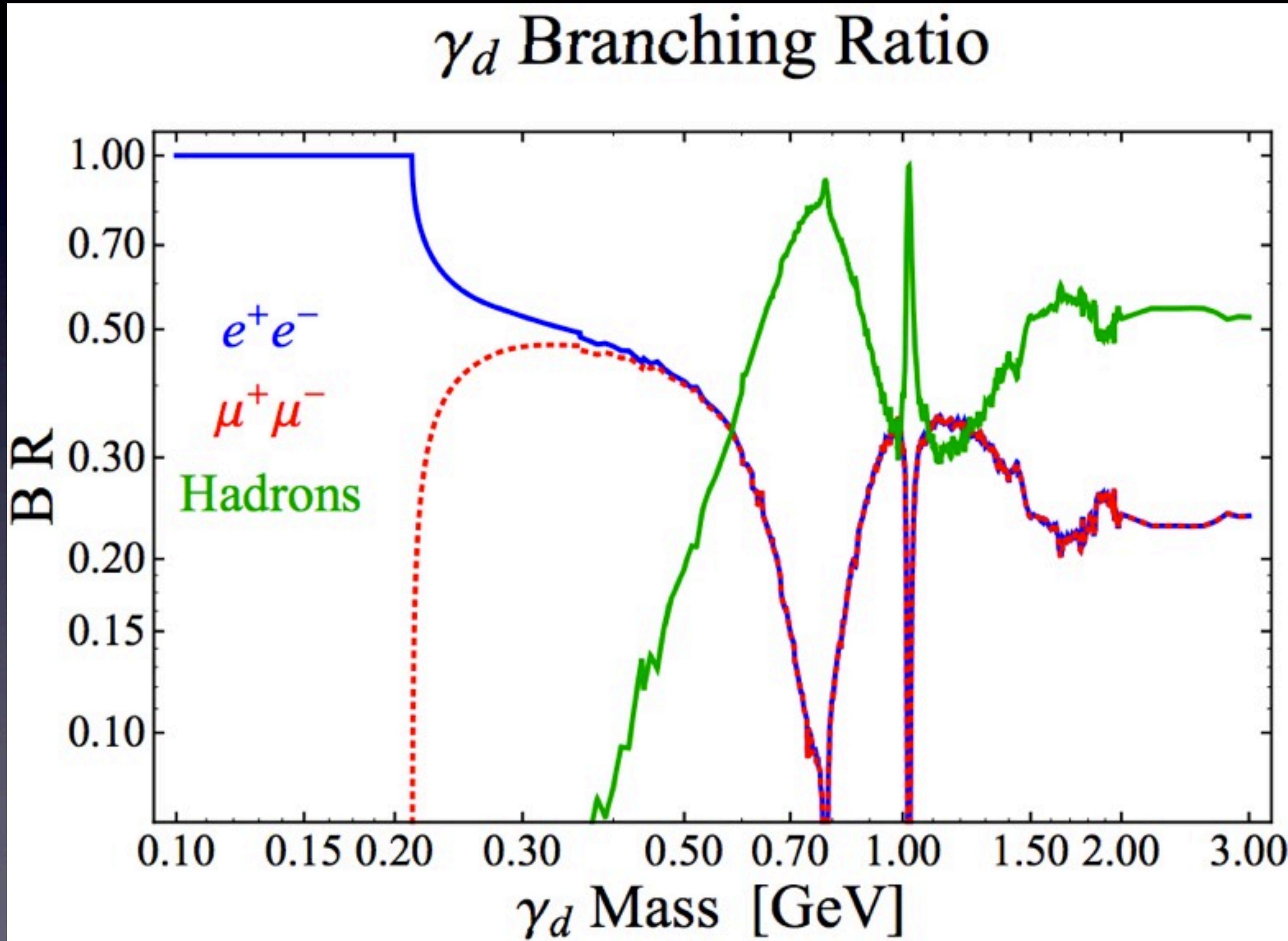
$\chi\chi \rightarrow A'A'$ followed by $A' \rightarrow e^+e^-, \mu^+\mu^- \pi^+\pi^-, \ldots$

- The decay channels of the A' depend on its mass.
- The annihilation rate does not depend on the mixing with the SM, only the χ-A' coupling.
- If the A' is around 100 MeV - 1 GeV in mass then:
  - The relatively short decay chain yields a hard spectrum.
  - The A' cannot decay to proton-antiproton pairs due to its low mass.
  - The long-range (~fm) interaction enhances the annihilation rate at non-relativistic velocities.

Decays of a dark photon

Falkowski et al 1002.2952

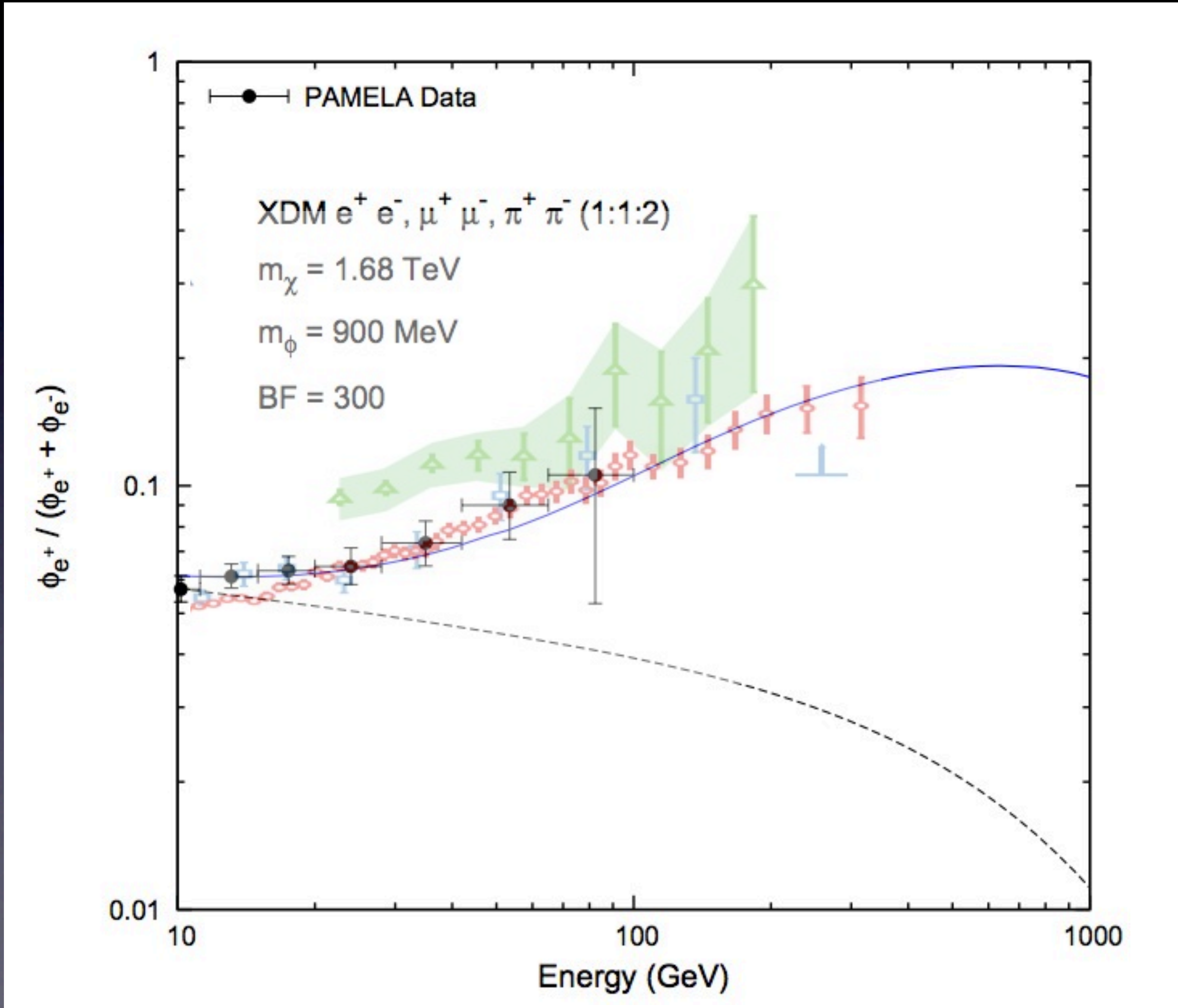
In simplest case, decays are leptonically dominated below ~500 MeV; mixture of leptons and charged pions up to 1 GeV; then additional contributions from ρ, kaons, taus.



Implications of AMS-02

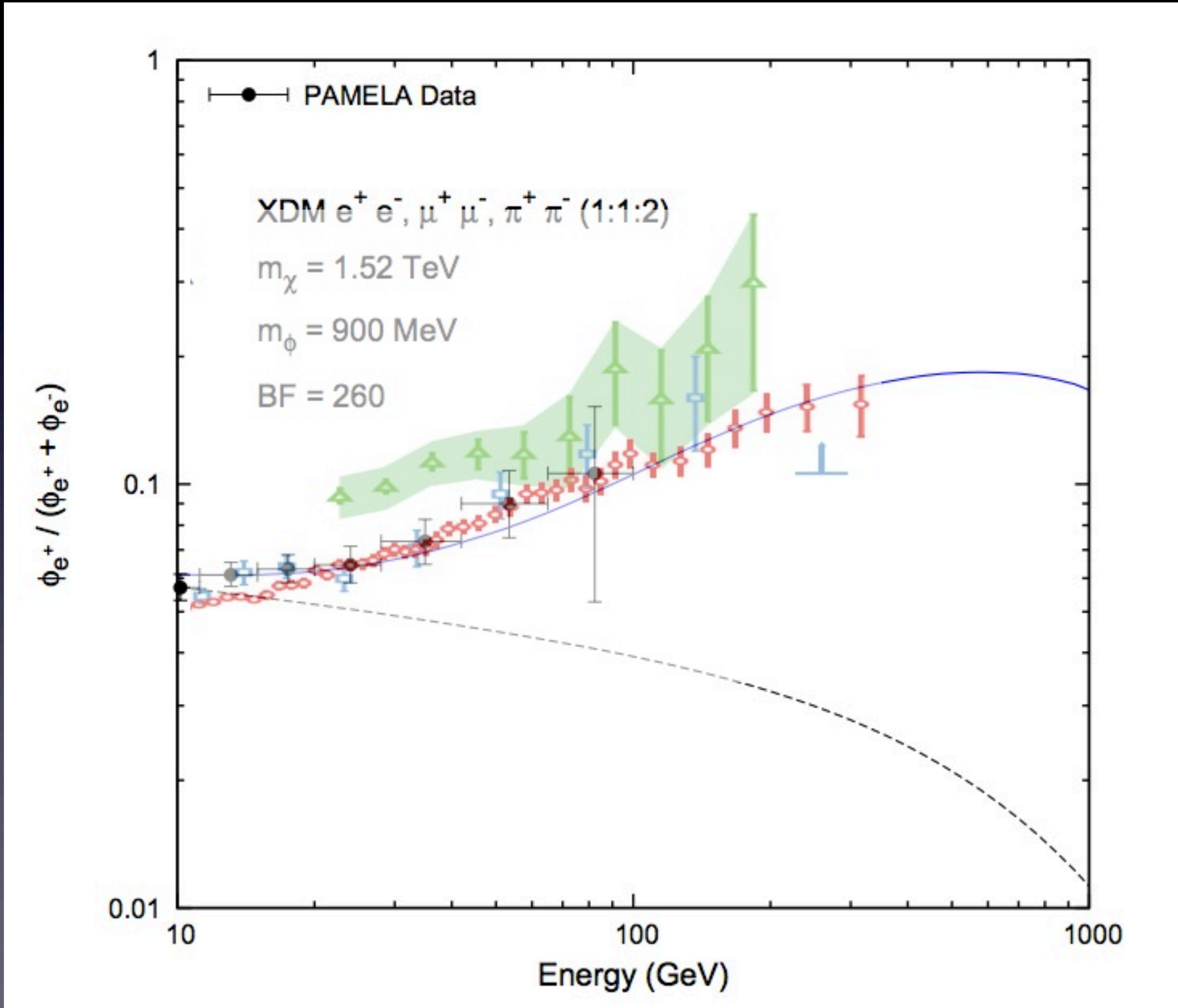
- First reaction: exactly as expected! PAMELA is confirmed! But...
- Hint of flattening at high energy favors softer spectra (multi-particle final states, charged pions, taus) => heavier force carrier masses, or more complex dark sector.
- Possible tension with Fermi e^+e^- measurement if astrophysical background for electrons is a single power law and the new component is half e^+/half e^-.
- Possible asymmetry goes in the direction of $n(e^-) > n(e^+)$, up to a factor of 2 (Masina & Sannino 1304.2800).
- However, above statements depend on assumptions about the e^- background (and hence on cosmic-ray propagation).
- No hint of anisotropy, but not expected given sensitivity of constraints (cannot currently rule out even a single nearby pulsar as the source).

Pre-AMS benchmarks



Finkbeiner, Goodenough, TRS & Weiner 2010

Pre-AMS benchmarks



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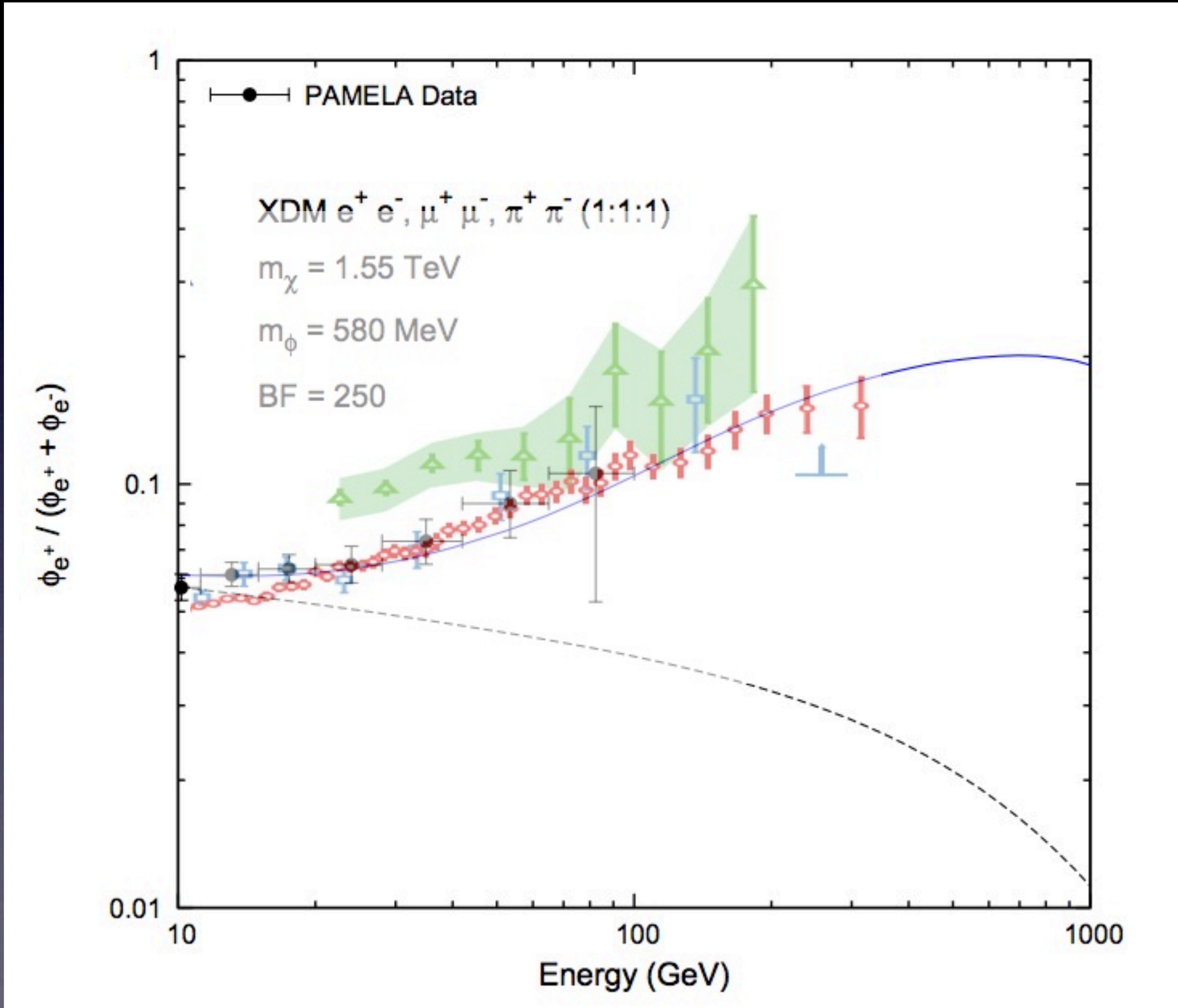
Pre-AMS benchmarks



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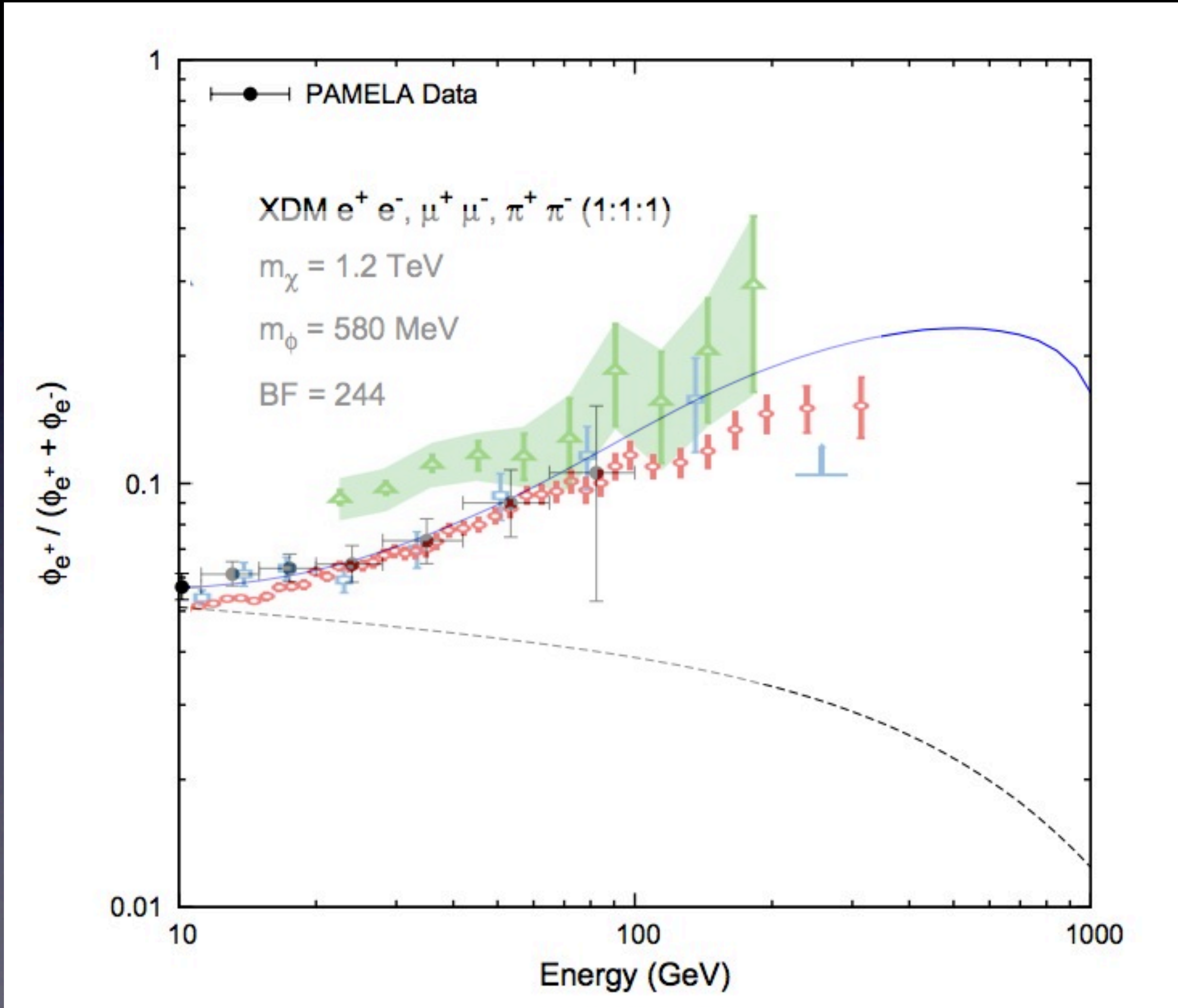

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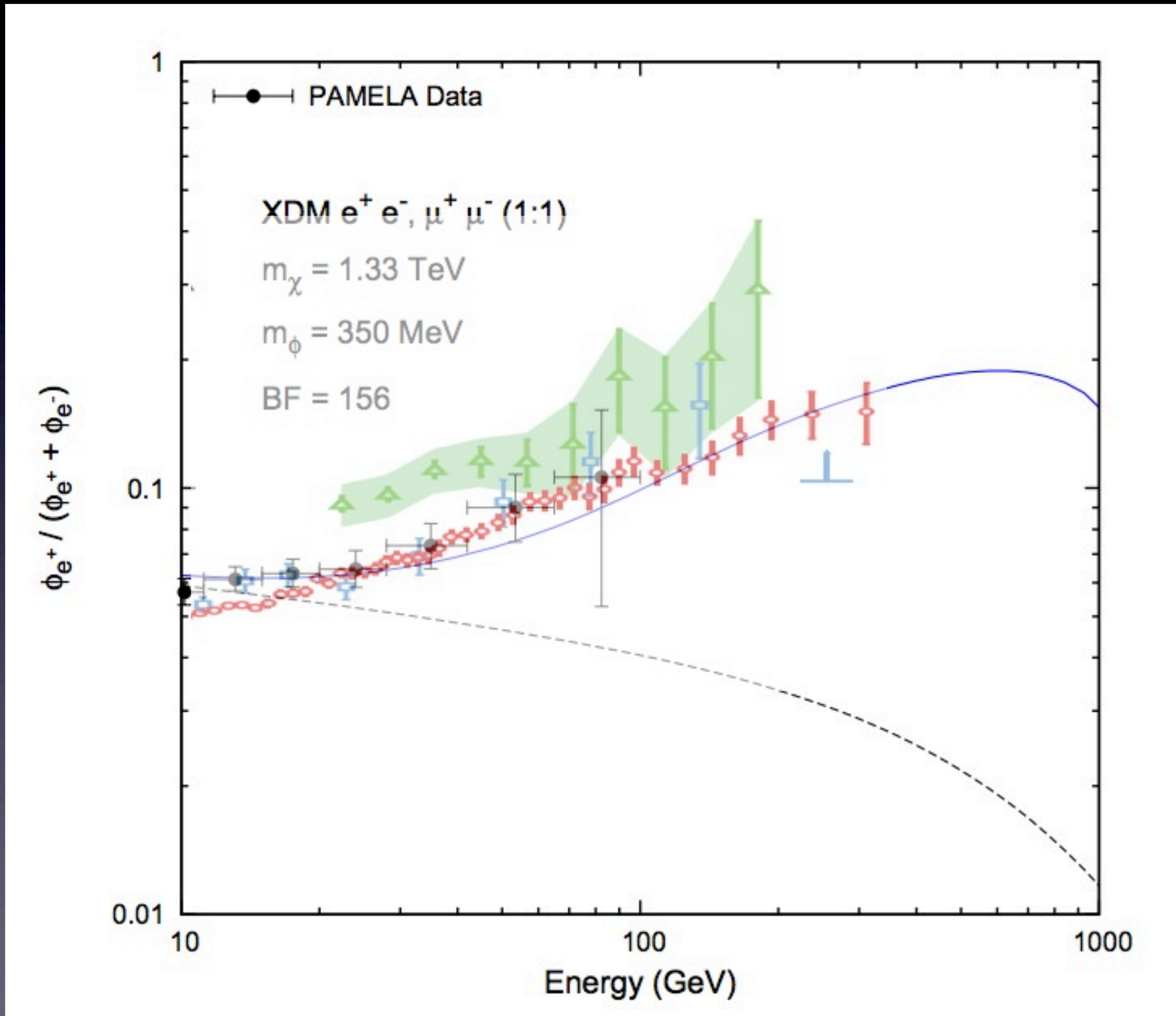

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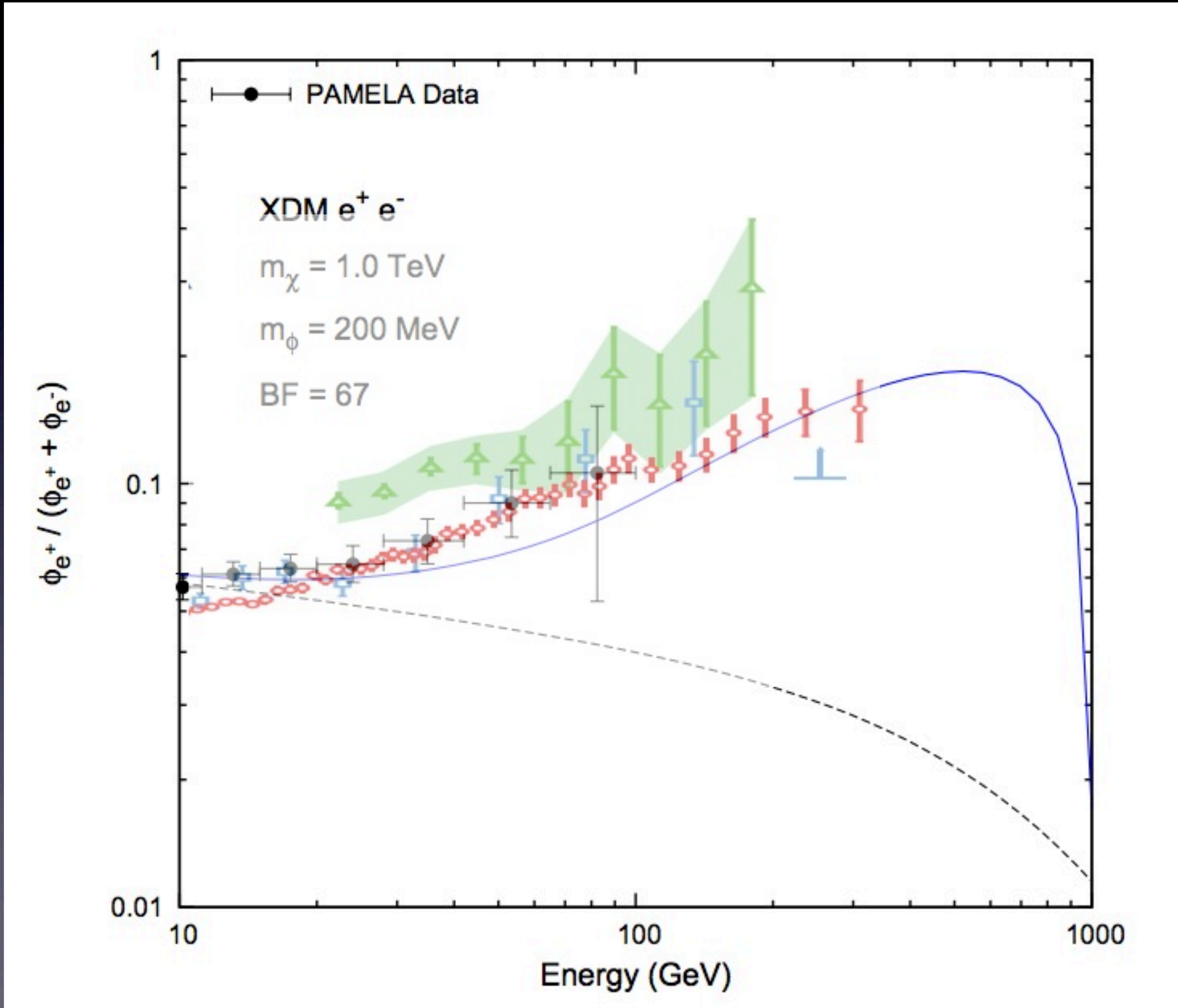


Finkbeiner, Goodenough, TRS & Weiner 2010

Post-AMS analysis

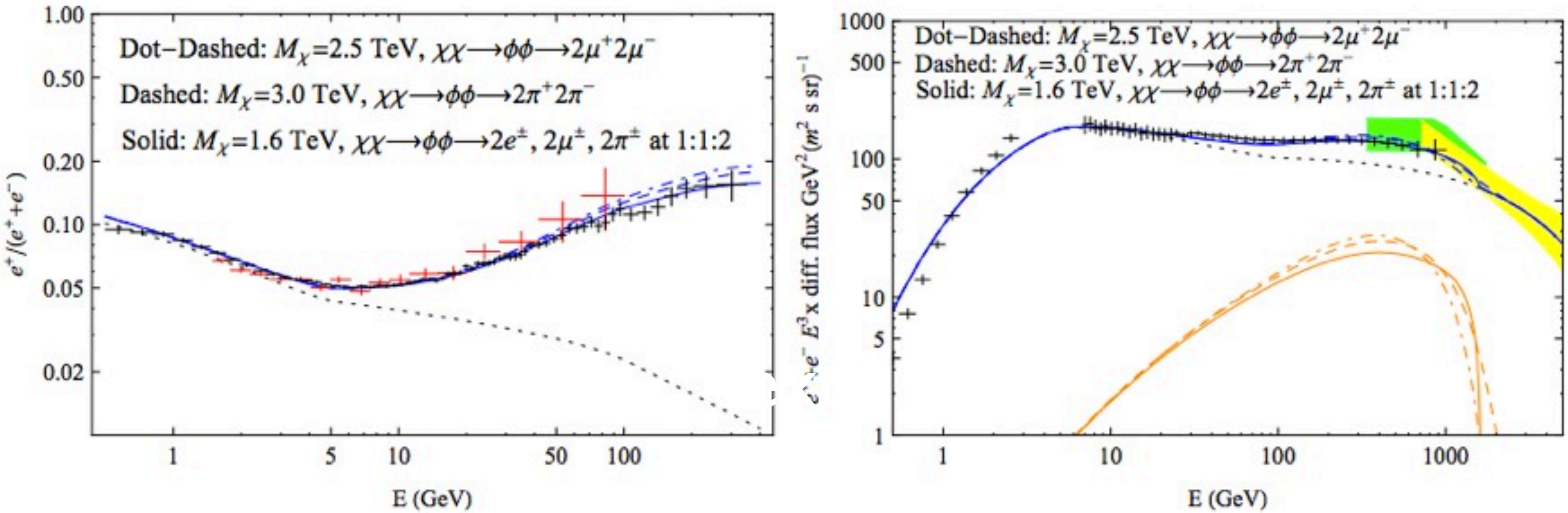


FIG. 6: The same as in Figs. 1, 2, 4 and 5 but for a diffusion zone half-width of $L = 8$ kpc, and for broken power-law spectrum of electrons injected from cosmic ray sources ($dN_{e^-}/dE_{e^-} \propto E_e^{-2.65}$ below 100 GeV and $dN_{e^-}/dE_{e^-} \propto E_e^{-2.3}$ above 100 GeV). The cross sections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

- Direct annihilation to e^+e^-, $\mu^+\mu^-$ can no longer accommodate the data (Yuan et al 1304.1482, Cholis & Hooper 1304.1840).
- Direct annihilation to $\tau^+\tau^-$ (1304.1482) or to an intermediate state decaying to muons and charged pions (1304.1840) can provide a good fit.
- The first possibility appears in conflict with gamma-ray limits from dwarf galaxies (1304.1482).

Gamma-ray constraints

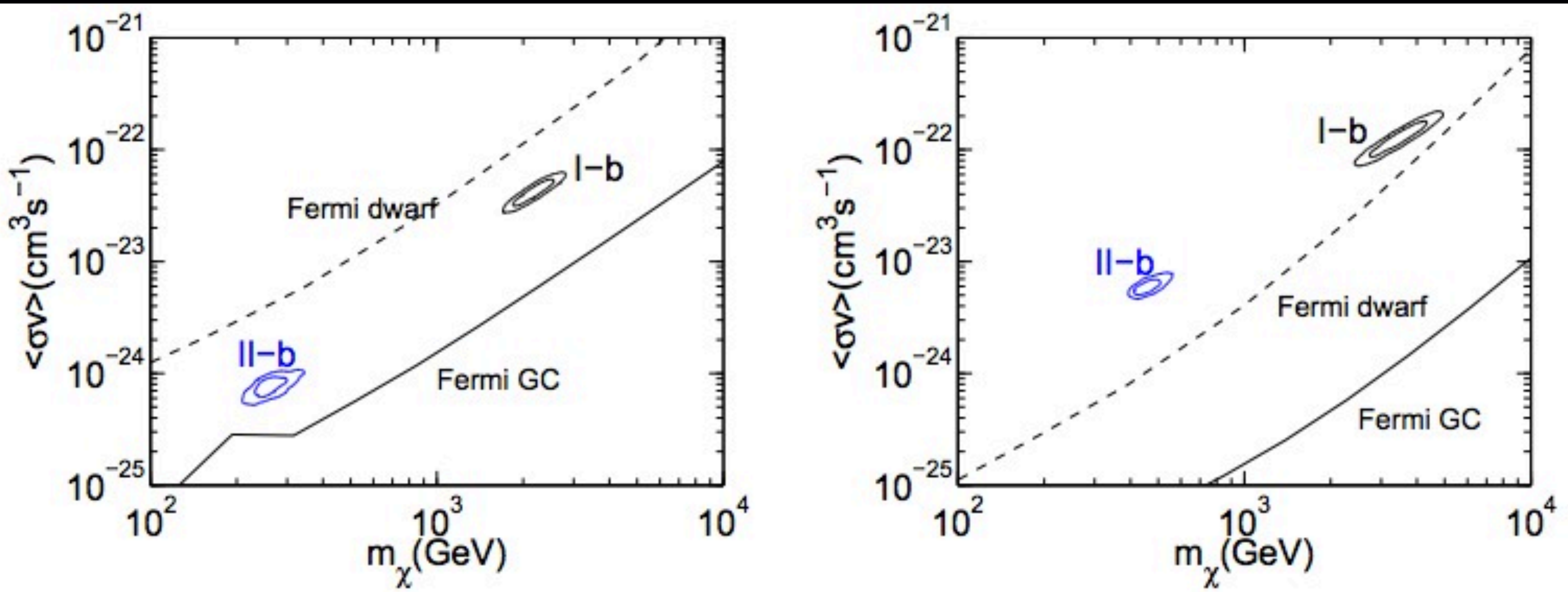


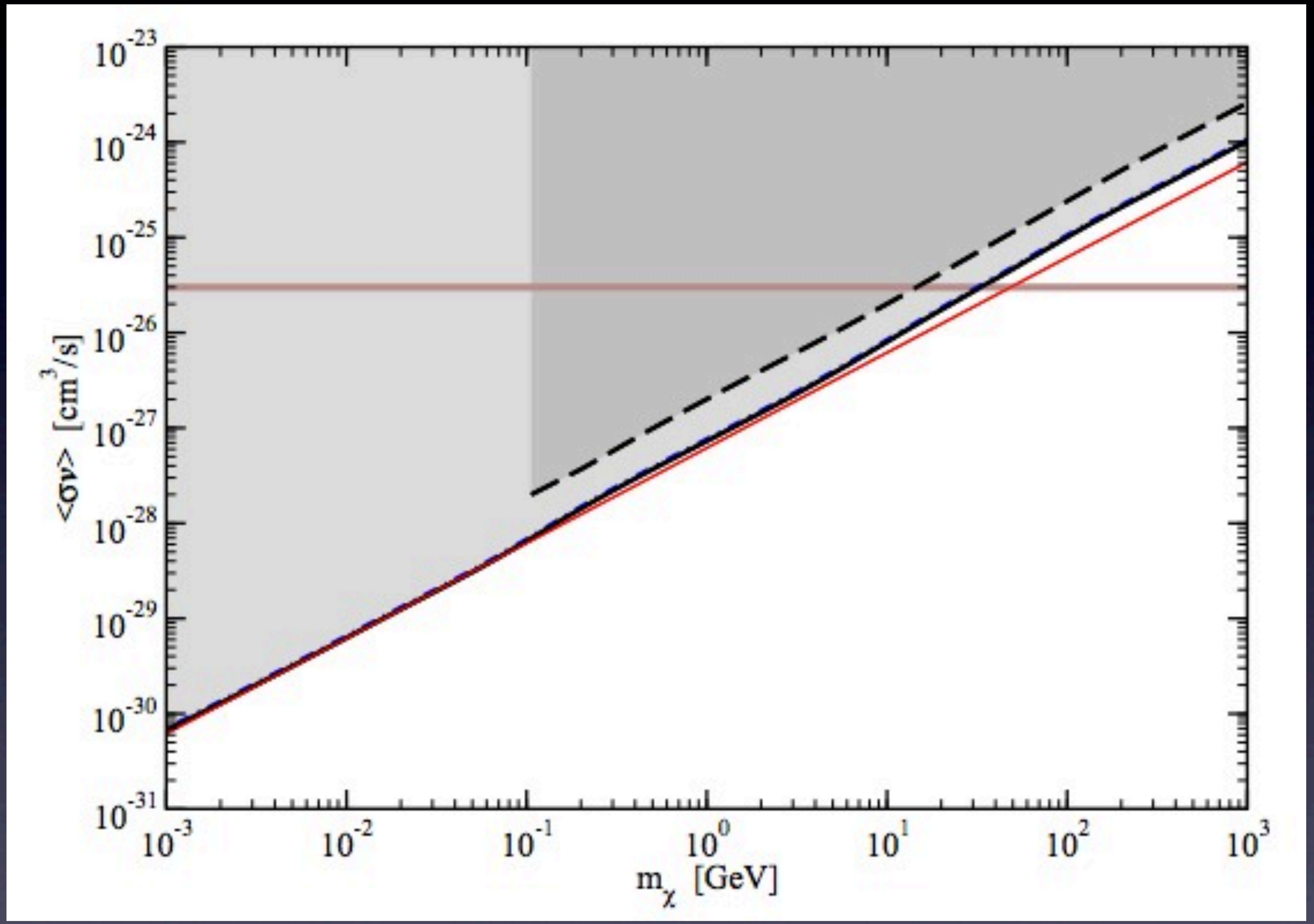
FIG. 10: 1σ and 2σ confidence regions on the DM mass and cross section plane, for the fits I-b and II-b respectively. The left panel is for $\mu^+\mu^-$ channel, and the right panel is for $\tau^+\tau^-$ channel. The solid lines show the 95% upper limit of Fermi γ-ray observations of the Galactic center (with normalization of the local density corrected) [59] and dwarf galaxies [60].

Yuan et al 1304.1482

- Stringent constraints on these scenarios from Fermi studies of dwarf galaxies in gamma rays (uncertainly due to DM density profile is only ~20%). Not very sensitive to e^+e^-, $\mu^+\mu^-$, $\pi^+\pi^-$, as these do not decay producing gammas.
- Galactic Center constraints are nominally stronger but far more dependent on the DM profile (here NFW is assumed).

CMB constraints

- DM annihilation producing e^+e^- can modify the ionization history of the universe during the cosmic dark ages (z~10-1000).
- This in turn modifies the power spectrum of CMB anisotropies: sensitively probed by WMAP, ACT, SPT and now Planck.
- Independent of DM structure formation, relies only on power in e^+e^- and cosmological average DM density - very clean probe of claimed annihilation xsec.
- Planck limits should be about a factor of 3 stronger than these.



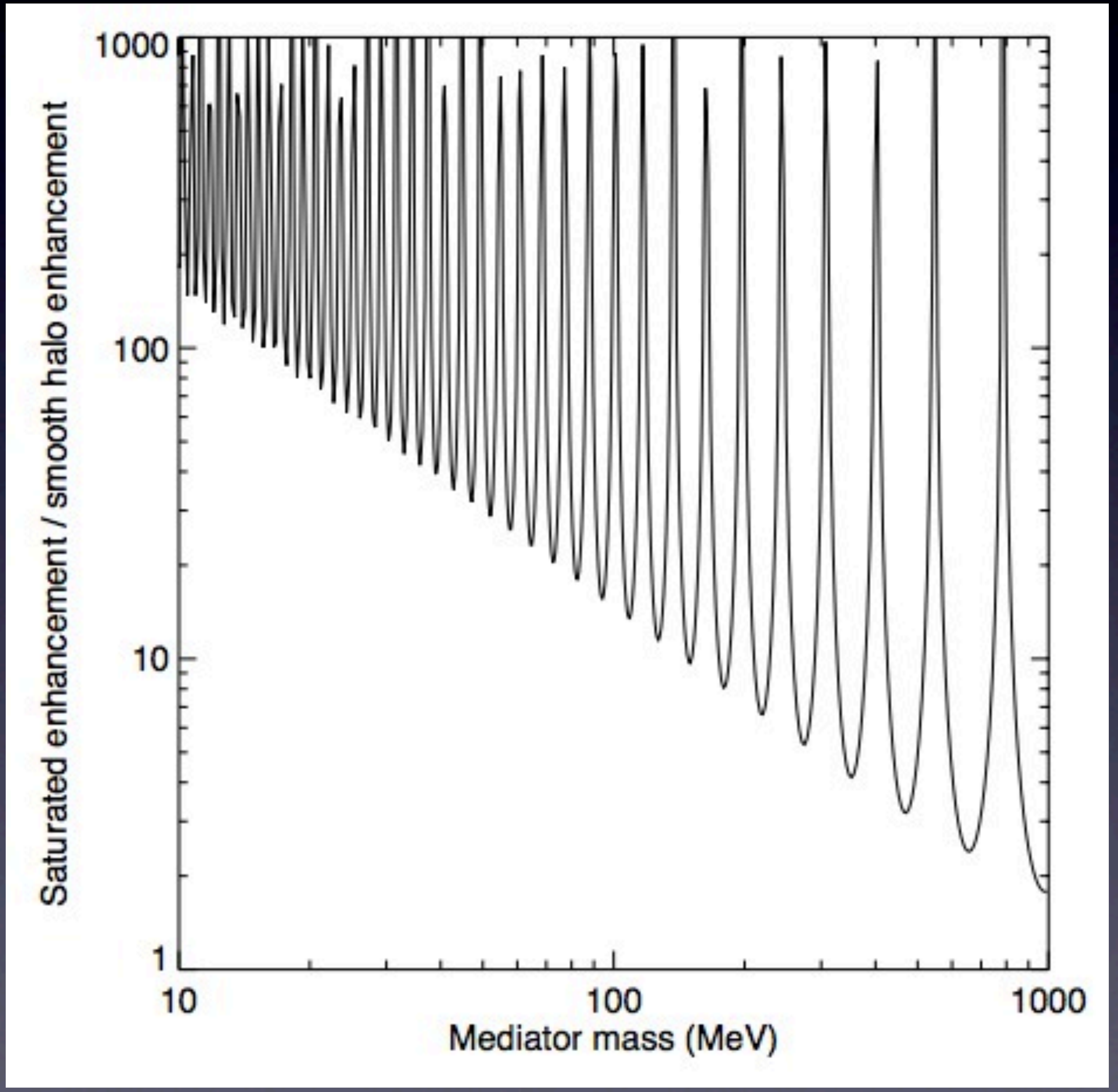
Lopez-Honorez et al 1303.5094

- Electron channel:

$$\langle \sigma v \rangle \lesssim 30 \left(\frac{1\mathrm{TeV}}{m_\chi} \right) \times 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}$$

Interpreting the CMB limits

- Latest CMB constraints (using 2011 ACT and SPT data) in tension with the best-fit cross sections given by Cholis & Hooper 1304.1840.
- Tension at the factor-of-2 level - seem to require O(1-2) local "boost factor" from higher local DM density or substructure.
- Exclusion can be much stronger for models where the cross section is greater at low velocities ($v \sim 10^{-8}$ relevant for CMB constraints, compared to $v \sim 10^{-3}$ for the local halo). Holds true for $v_{local} \sim 10^{-3} < m_{A'}/m_X$.
- Favors heavier force carrier masses.
- Alternative viable scenario: the local signal is dominated by DM substructure, where typical velocities are much smaller.



TRS, Toro & Weiner 1107.3546

Substructure

- DM halos built up hierarchically: lots of smaller clumps of dark matter.
- These bound clumps are cold:
  - Low internal velocities
  - High densities
  - Can contribute non-negligibly to local $\langle \rho^2 \rangle$, could be a factor of a few higher than the main halo
- For $m_{A'}$ < GeV, enhancement may be "saturated" (maximum value) in small subhalos, and during the CMB epoch, but NOT in the Milky Way smooth halo.
- If this gap is large, substructure signal can be >> main halo. Then behaves like large velocity-independent annihilation rate (since enhancement is always saturated).
- Need to account for the signal from small-scale structure in dwarf galaxies, extragalactic diffuse gamma rays, etc, but...
- Reopens viable parameter space at low mediator masses (below ~100 MeV), if sufficient substructure is present.

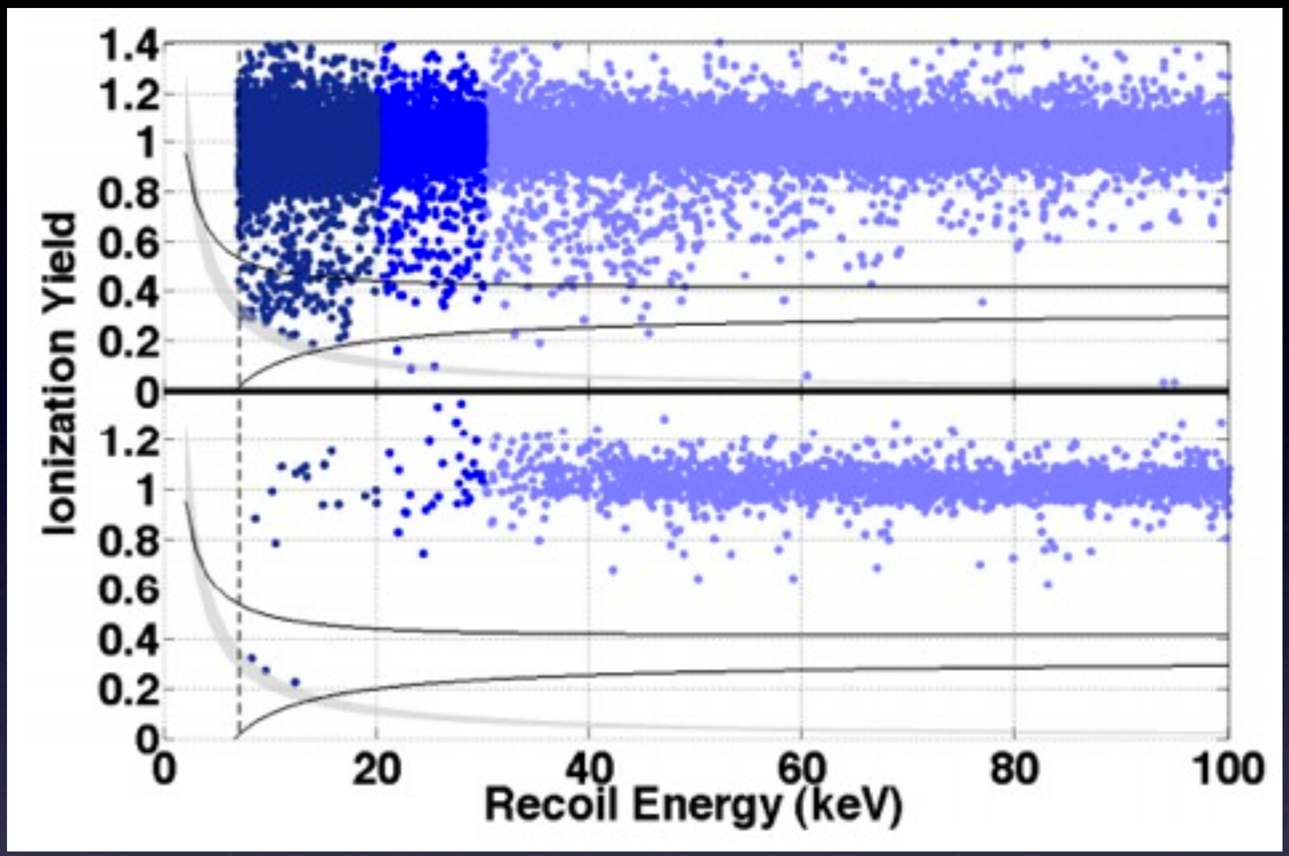
LIGHT DARK MATTER

Light dark matter

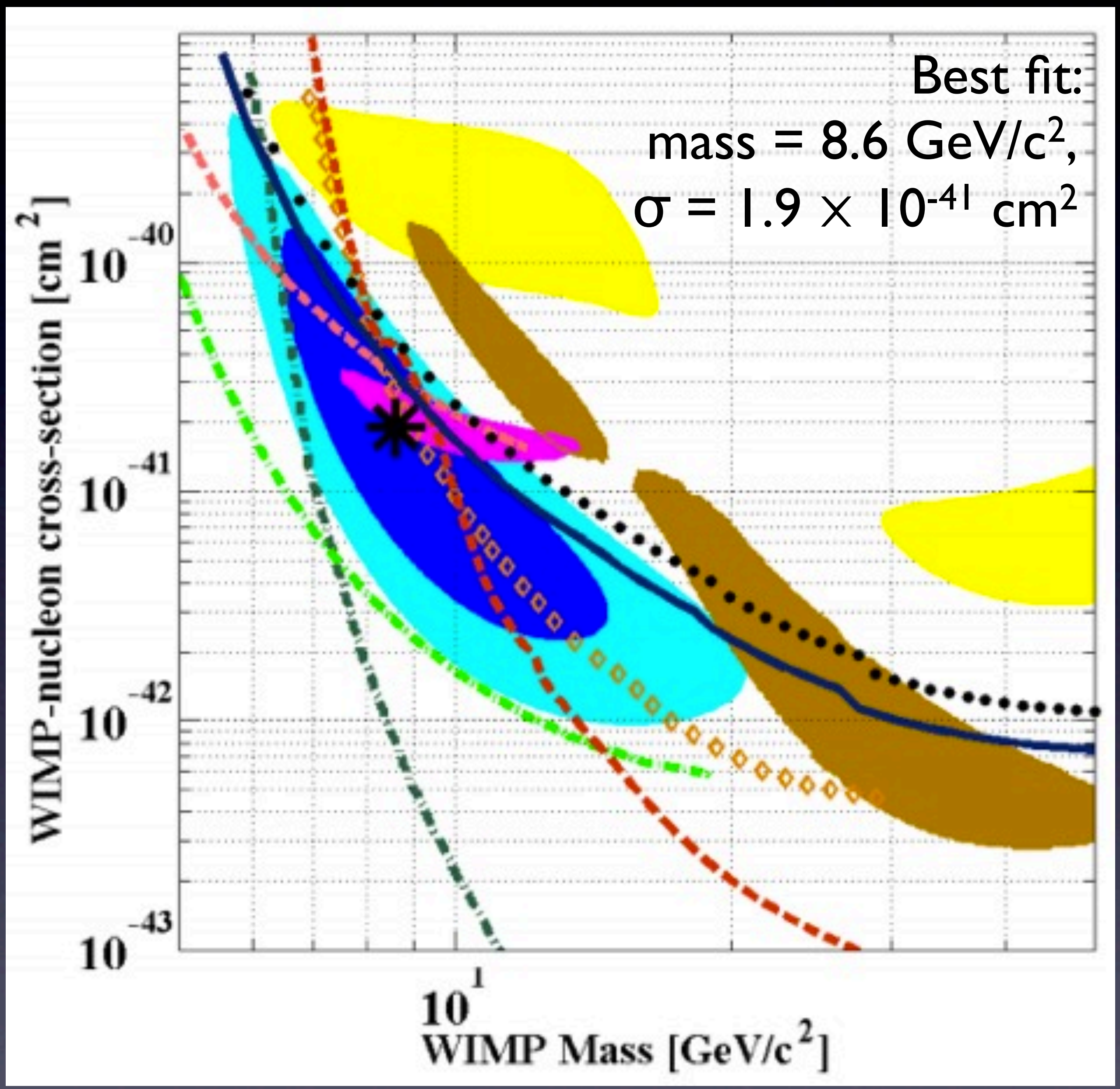
- Explanation for positron excess in terms of DM coupled to a light mediator requires hierarchy of scales; gives novel phenomenology.
- However, also several hints for light dark matter, closer to the interesting mass scale for the A'.
- Light mediators coupled to these light DM particles can naturally yield:
  - A large scattering cross section in direct detection experiments.
  - Spectrally hard lepton and gamma-ray signals from annihilation followed by decay of the mediator.

CDMS-Si

CDMS collaboration, 1304.4279



- CDMS silicon analysis (from 140 kg days of 2007-2008 data) sees three events at 8.2, 9.5 and 12.3 keV recoil energies.
- Estimated background in search region of 0.4 events. Probability of 3 events (no energy information) as a background fluctuation ~5%.
- Fitting event energies, best-fit model favored over background-only at 99.8% confidence.



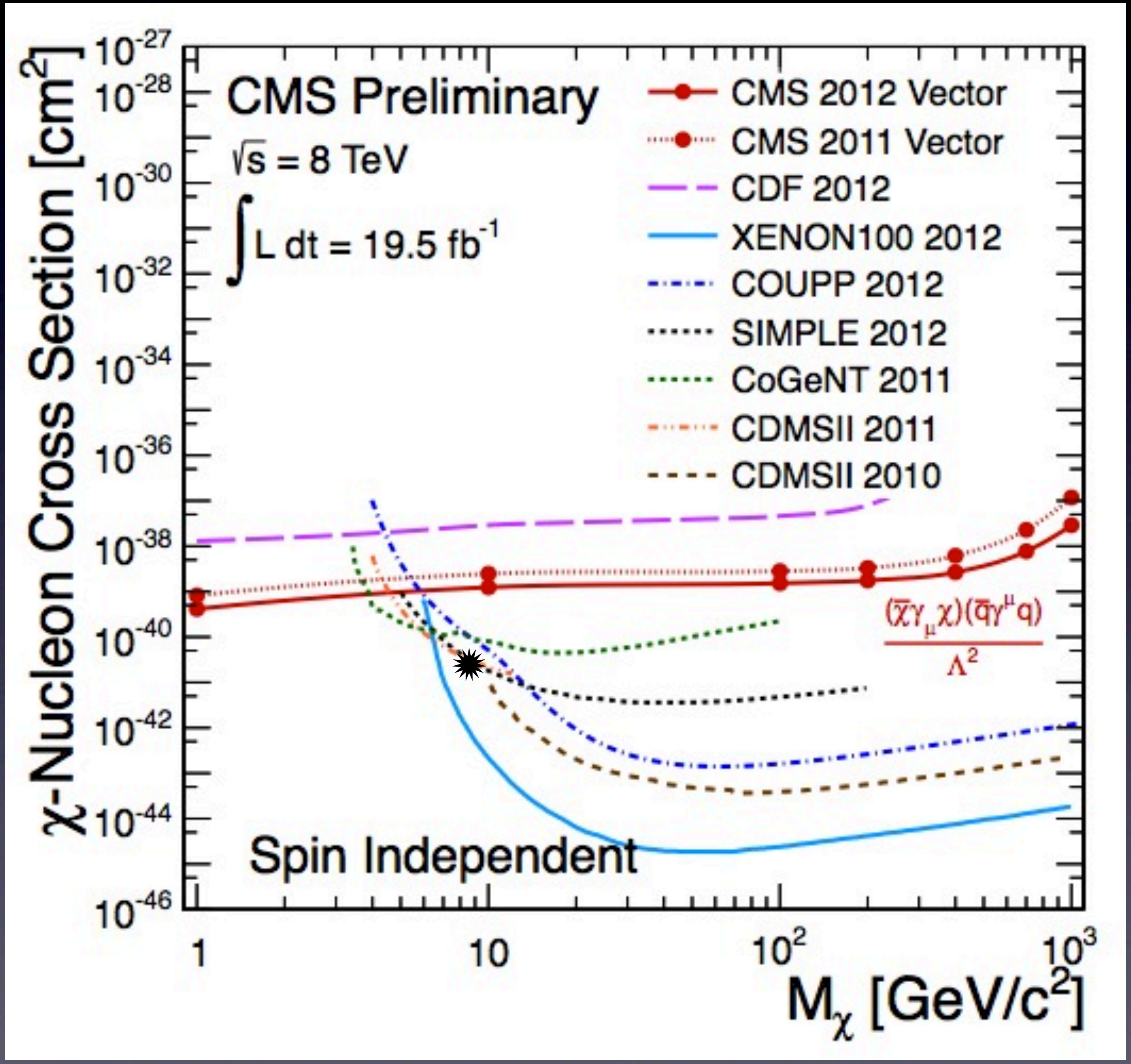
Black dots + blue and cyan contours = this work
Blue solid line = previous CDMS-Si
Dark (light) dashed red = CDMS-II standard (low-threshold) Ge analysis
Orange diamonds = EDELWEISS low threshold
Light dash-dotted green = XENON10 S2-only
Dark dash-dotted green = XENON100
Magenta filled region = CoGeNT (residual surface contamination subtracted)
Yellow filled region = DAMA/LIBRA
Brown filled region = CRESST

Direct detection anomalies & constraints

- Several other long-standing anomalies / candidate signals from DAMA, CoGeNT, CRESST.
- Only CoGeNT favored region appears consistent with current CDMS result.
- XENON results appear in tension with CDMS favored region:
  - For XENON100 this statement depends on the DM velocity distribution. Plausible alternate choices of velocity distribution may mitigate the tension.
  - The XENON10 S2-only analysis is more robustly sensitive to low-energy recoils and can place astrophysics-independent bounds, but has uncertainties in the mapping from recoil energy to ionization (see also Frandsen et al 1304.6066).
  - Isospin-dependent couplings can always remove the constraint from any one element (“xenophobic” dark matter?)

LHC monojet constraints

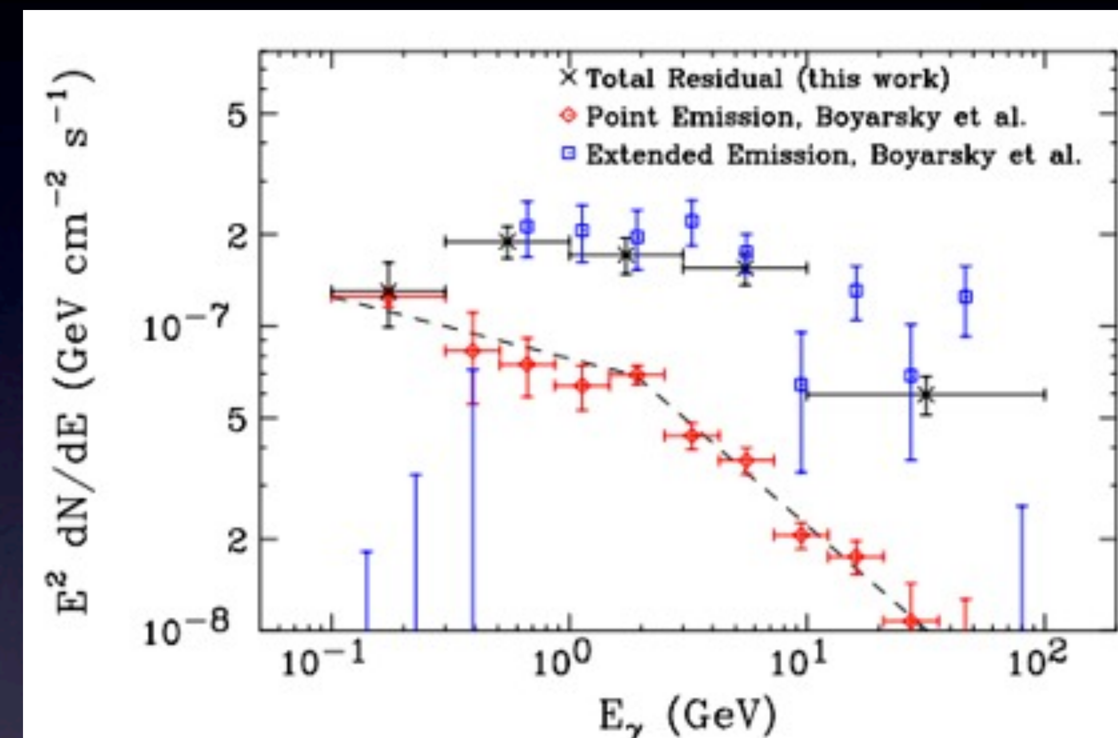
- The LHC provides the best limits on spin-independent couplings between quarks and very light dark matter, but is still roughly 1.5 orders of magnitude above the CDMS best-fit cross section.
- If the LHC limits were improved to nominally rule out this cross section, and the CDMS result was confirmed, would be a signal for light mediators, or some other breakdown of the effective theory.



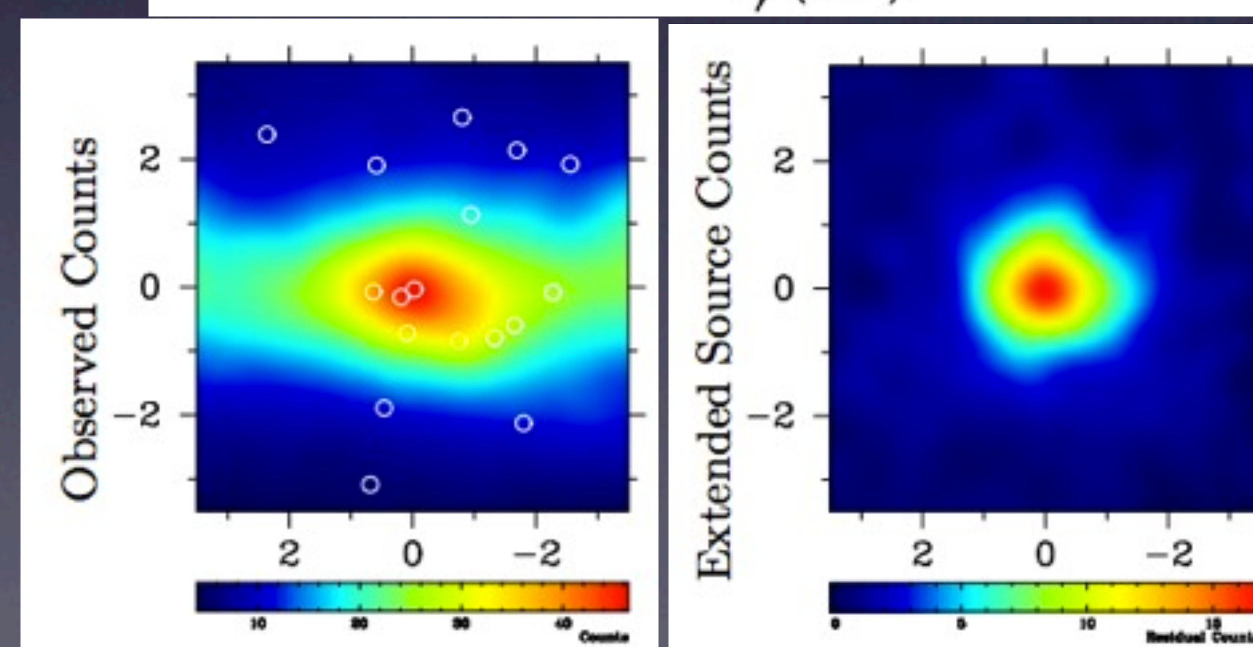
CMS conference note CMS-PAS-EXO-12-048, presented at Moriond

The Galactic Center GeV excess

Hooper & Linden 2011



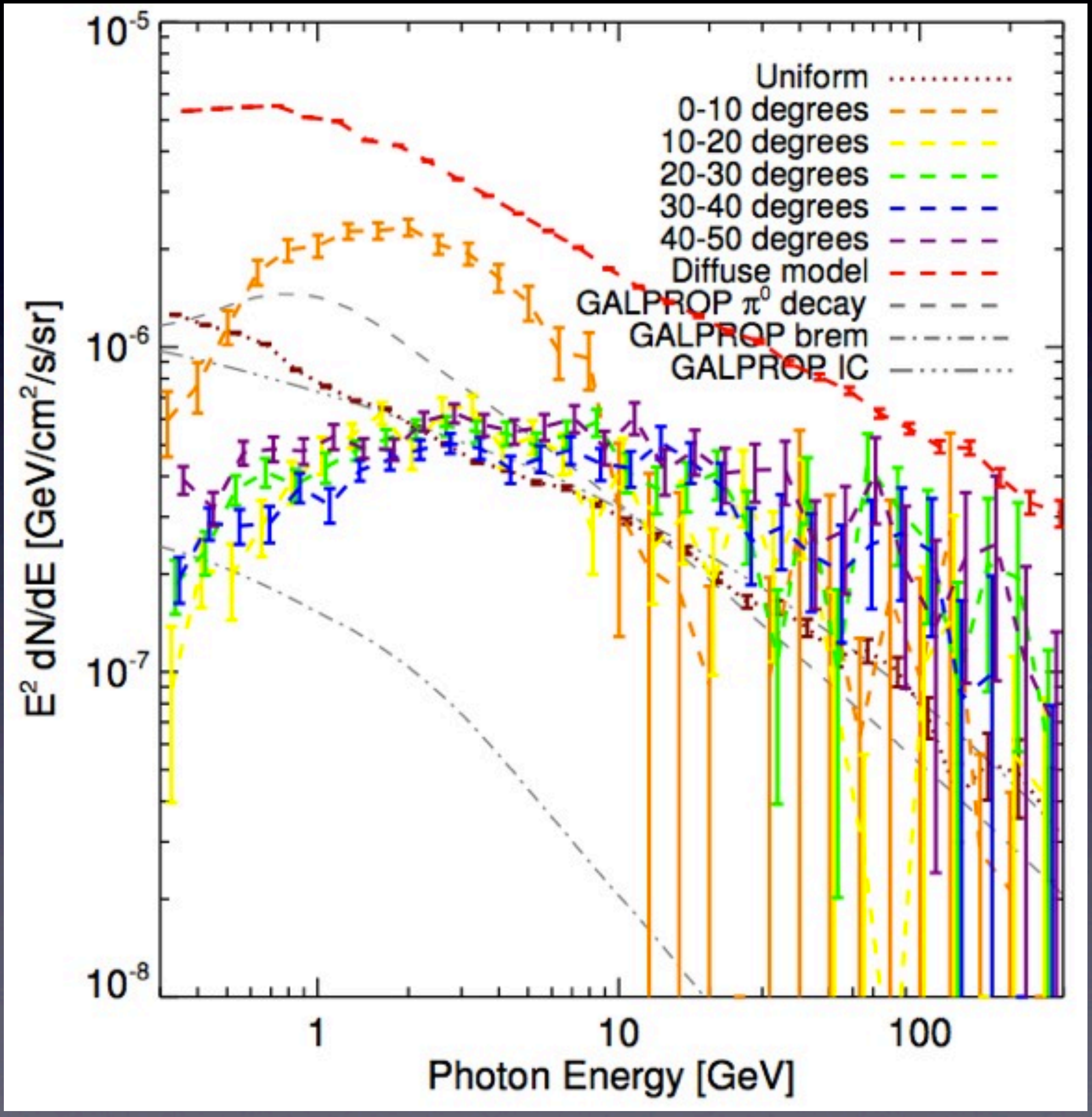
- Claims of a spectral feature in Fermi public data:
  - Peaking at a few GeV,
  - Localized around the Galactic Center.
- First identified by Goodenough and Hooper in 2009-10: not then clearly separable from emission associated with the bright point source at the GC.
- Subsequent studies (Hooper & Linden; Boyarsky, Malyshev & Ruchayskiy; Abazajian & Kaplinghat) found strong evidence for extended (non-point-like) emission, with spherical morphology.



Abazajian & Kaplinghat 2012

The inner Galaxy

- Recent study by Hooper & TRS (1302.6589) finds a consistent signal extending at least 10-20 degrees from the GC.
- Signal appears spectrally consistent with the GC + spatially consistent with the best-fit GC DM model (annihilation from a generalized NFW profile with inner slope γ=1.2).
- Spectrum favors ~10 GeV DM annihilating to leptonic states or ~50 GeV DM annihilating to quarks.
- Systematics at these larger Galactocentric radii should be very different than in the GC.



Light mediators?

- Consistent scenarios with ~10 GeV DM and light force carrier (Hooper, Weiner & Xue 1206.2929).
- Mass of force carrier largely unconstrained by spectrum of GC signal; 100 MeV and 1 GeV both work well, for example.
- Direct detection cross section is strongly dependent on the force carrier mass, but degenerate with the mixing:

$$\sigma_{Xp} = \frac{g_2^2 \sin^2\theta_W g_X^2 \epsilon^2 m_X^2 m_p^2}{\pi m_\phi^4 (m_X + m_p)^2}$$
$$\approx 1.6 \times 10^{-40}\,\mathrm{cm}^2 \left(\frac{\epsilon}{7\times 10^{-5}}\right)^2 \left(\frac{1\,\mathrm{GeV}}{m_\phi}\right)^4.$$

Close to $m_{A'} \sim \sqrt{\epsilon} m_Z$ motivated in some SUSY constructions.

DM SELF-INTERACTION

Dark matter on galactic scales

- Several discrepancies between prediction and observation for CDM, in the distribution of DM on galactic scales.
  - "Missing satellites" - fewer dwarf galaxies observed than predicted, both in the Milky Way and in the field.
  - "Cusp/core" - low-surface-brightness (LSB) ellipsoidal galaxies and dwarf spheroidals of the Milky Way appear to have kpc-scale low-density cores, rather than the 1/r cusps predicted by simulations.
  - "Too big to fail" - massive subhalos of CDM MW-like halos seem too dense to host the bright MW dwarf spheroidals.
- Predictions come from large N-body simulations assuming cold collisionless dark matter - unaccounted-for baryonic physics could help resolve them, and this is an active topic of research. But discrepancies could also be a clue to new dark-sector physics!

Self-interacting dark matter

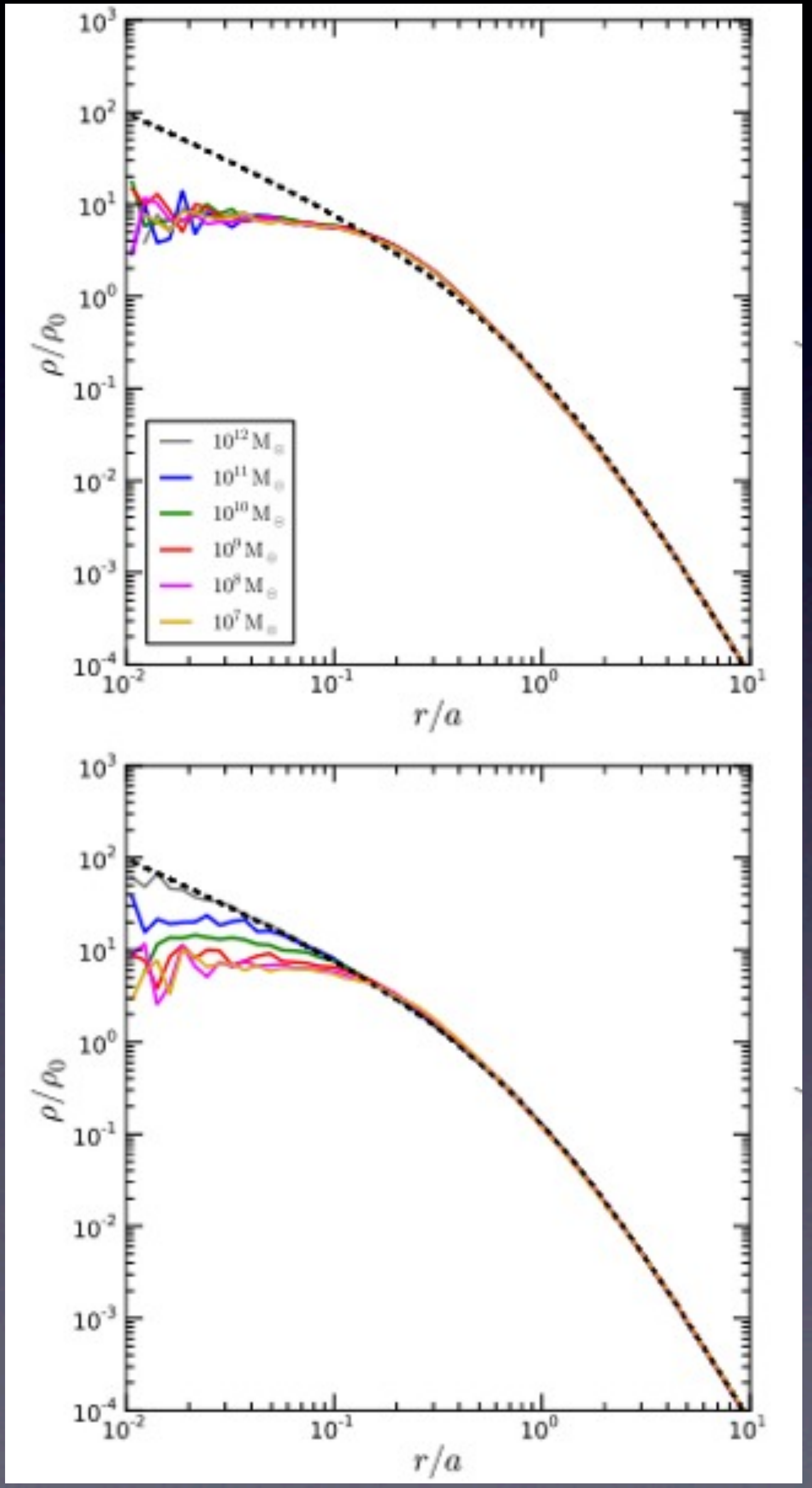
- A light force carrier coupled to DM can induce a non-negligible scattering cross section.
- DM-DM scattering can flatten cusps to cores and potentially deplete substructure.
- Initial studies were all of velocity-independent scattering cross sections: strong constraints from the halo shapes of galaxy clusters.
- But for the scattering cross section mediated by a heavy photon is *not* velocity-independent: it is negligible at high velocities (where kinetic energy >> energy from the long-range potential) and grows at low velocities.
- Thus we expect minimal impact on clusters, where velocities are high, and greater impact on low-mass systems where typical velocities are smaller.

Recent progress on vSIDM

- Vogelsberger, Zavala & Loeb 1201.5892:
  - Elastic scattering does not deplete subhalos substantially because host-subhalo interactions occur at high velocity.
  - Consequently, does not solve missing satellite problem (although inelastic scattering is different - e.g. Loeb & Weiner 2011).
- Small halos develop kpc-scale cores, which also lowers their concentration.
- Consistency with the inferred mass profiles of the Fornax and Sculptor dwarfs requires a cross section at the dwarf velocity scale of:

$$\sigma/m_\chi \sim 0.1 - 1\,\mathrm{cm}^2/\mathrm{g}$$

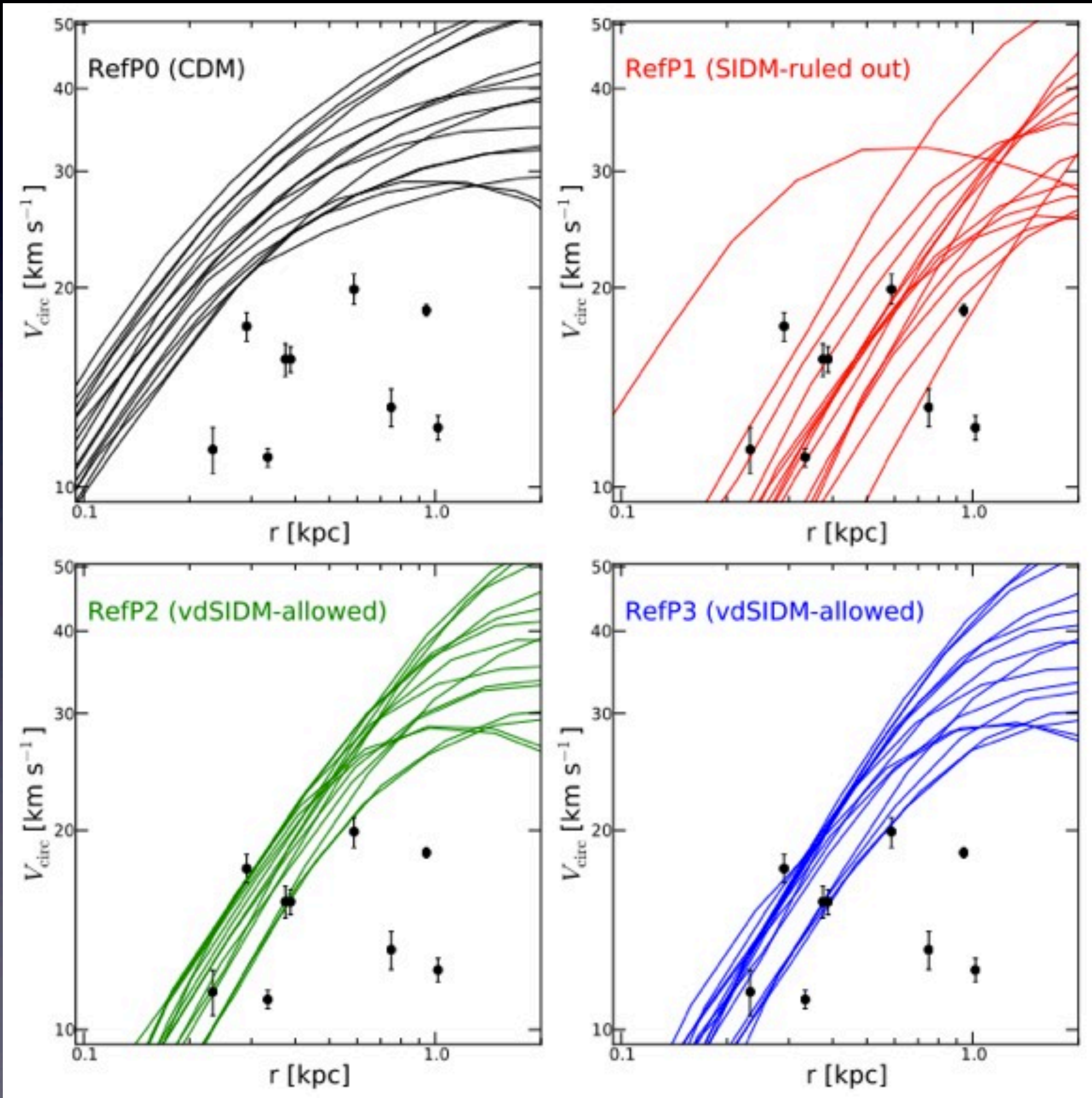
Rocha et al 1208.3025 find 0.1 cm^2/g suffices, using scaling relations (~ equal to the updated constraint from halo shapes for velocity-*independent* SIDM, see Peter et al 1208.3026). Zavala, Vogelsberger and Walker 1211.6426 instead find 1 cm^2/g is required, by direct simulation.



Too big to fail

- Circular velocity profiles for the 15 most massive subhalos in the Aquarius simulation, compared to the observational estimates for the Milky Way dwarf spheroidals.
- In SIDM cases, the simulations do not predict subhalos too concentrated to host any of the bright MW spheroidals.
- Benchmarks here are:

RefP1: $\sigma_T/m_\chi = 10\,\mathrm{cm}^2/\mathrm{g}$
RefP2: $\sigma_T^{\max}/m_\chi = 3.5\,\mathrm{cm}^2/\mathrm{g}, \quad v_{\max} = 30\mathrm{km/s}$
RefP3: $\sigma_T^{\max}/m_\chi = 35\,\mathrm{cm}^2/\mathrm{g}, \quad v_{\max} = 10\mathrm{km/s}$



Mediator mass range

- The maximum momentum transfer cross section is given by,

$$\sigma_T^{\max} \approx \frac{22.7}{m_\phi^2}$$

- Setting this value divided by m_χ to 1 cm^2/g yields,

$$m_\phi \approx 70\text{MeV} \times \sqrt{\text{GeV}/m_\chi}$$

- That is, for GeV-TeV DM masses in this simple (Yukawa potential) model, the force carrier mass should be a few to a few tens of MeV (or lighter) in order to significantly modify DM halos.

Conclusions

- Couplings to heavy photons can drastically alter the phenomenology of cold and otherwise collisionless dark matter - its distribution in the Galaxy, and its direct and indirect signatures.
- If the positron excess observed by PAMELA and confirmed by Fermi and AMS-02 is interpreted as a signal of DM annihilation, the most favored models now involve annihilation to a new light particle that decays into final states including muons and/or charged pions (or perhaps to multi-particle final states).
- Constraints from WMAP9+ACT+SPT are in tension with the best-fit cross sections for AMS-02, at the factor of 2 level (for a local DM density of 0.4 GeV/cm^3); could be alleviated by substructure, uncertainties in the DM density and CR propagation, etc.
- Light (~10 GeV) DM coupled to a GeV-scale dark photon (with a small mixing with the SM photon) can explain recent direct and indirect detection signals in a unified framework.
- Mediators lighter than ~100 MeV can lead to significant modifications to the cores of dwarf spheroidal galaxies, alleviating or solving the core/cusp and "too big to fail" problems.