Limits on Dark Matter and Nearby Astrophysical Sources from the CALET Electron+Positron Spectrum

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ICSEP Waseda University, RISE Waseda University[A],
ASE Waseda University[B]

Holger Motz, Yoichi Asaoka[A], Shoji Torii[A]
and Saptashwa Bhattacharyya[B]

CALET

CALorimetric Electron Telescope

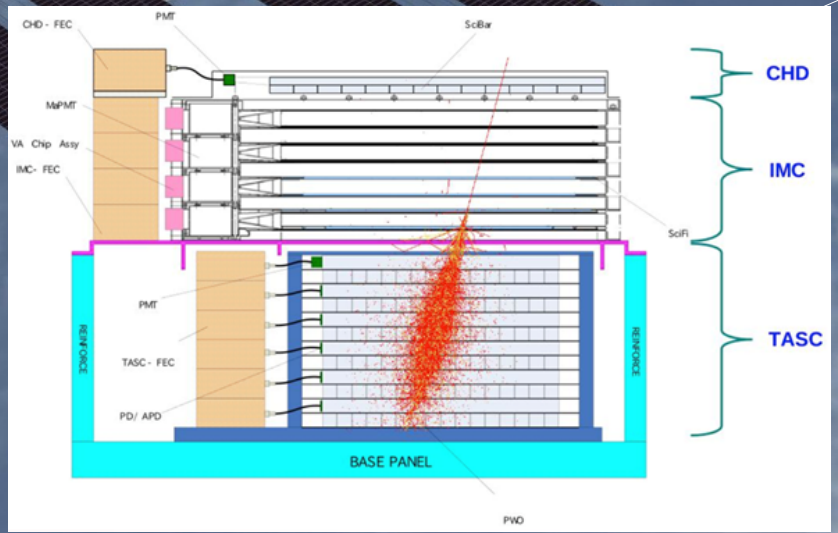
- Collaboration with groups from Japan , USA , Italy

Installed on the ISS in August 2015 and taking data since October 2015 – Electron+Positron spectrum up to 3 TeV measured and published

Japanese Experiment Module Exposed Facility Port 9

GRB Monitor:
- Hard X-Ray
- Soft γ-Ray

More information in plenary talk by Shoji Torii on Monday, 11:30

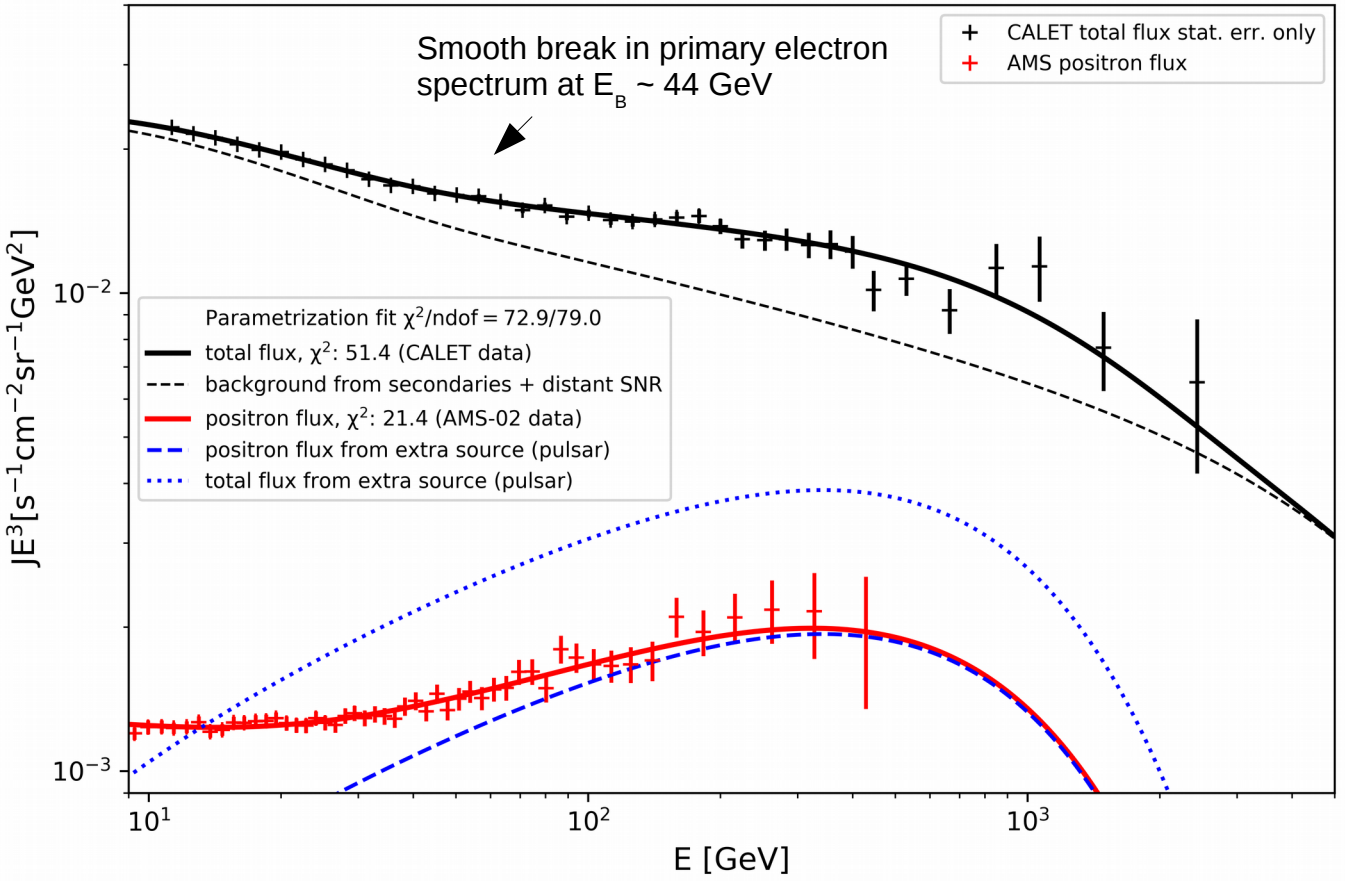


Calorimeter:
- Charge Detector
- Imaging Calorimeter
- Total Absorption Calorimeter
- 30 radiation length thickness in total for fully contained events

- 2% energy resolution
- 1040 cm²×sr aperture
- Proton rejection 10^{-5}

Parametrization for CALET Electron+Positron Spectrum

Starting point for calculation of Dark Matter limits: A well matching fit of a parametrization with a pulsar as the source of the positron excess to **CALET data** (O. Adriani et al. Phys. Rev. Lett. 119, 181101(2017)) and AMS-02 positron flux (M. Aguilar et al. Phys. Rev. Lett. 113, 121102(2014)) for E>10GeV (E<10 GeV: charge dependent solar modulation):



$$\Phi_{ele} = C_e E^{-(\gamma_e - \Delta\gamma_e)} \left(1 + \left(\frac{E}{E_B}\right)^{\frac{\Delta\gamma_e}{s}}\right)^s \left(\frac{C_s}{C_e} E^{-(\gamma_s - \gamma_e)} + e^{-\left(\frac{E}{E_{cut_d}}\right)}\right) + C_{ex} E^{-\gamma_{ex}} e^{-\left(\frac{E}{E_{cut_{ex}}}\right)}$$

$$\Phi_{pos} = C_e E^{-\gamma_e} \left(\frac{C_s}{C_e} E^{-(\gamma_s - \gamma_e)}\right) + C_{ex} E^{-\gamma_{ex}} e^{-\left(\frac{E}{E_{cut_{ex}}}\right)}$$

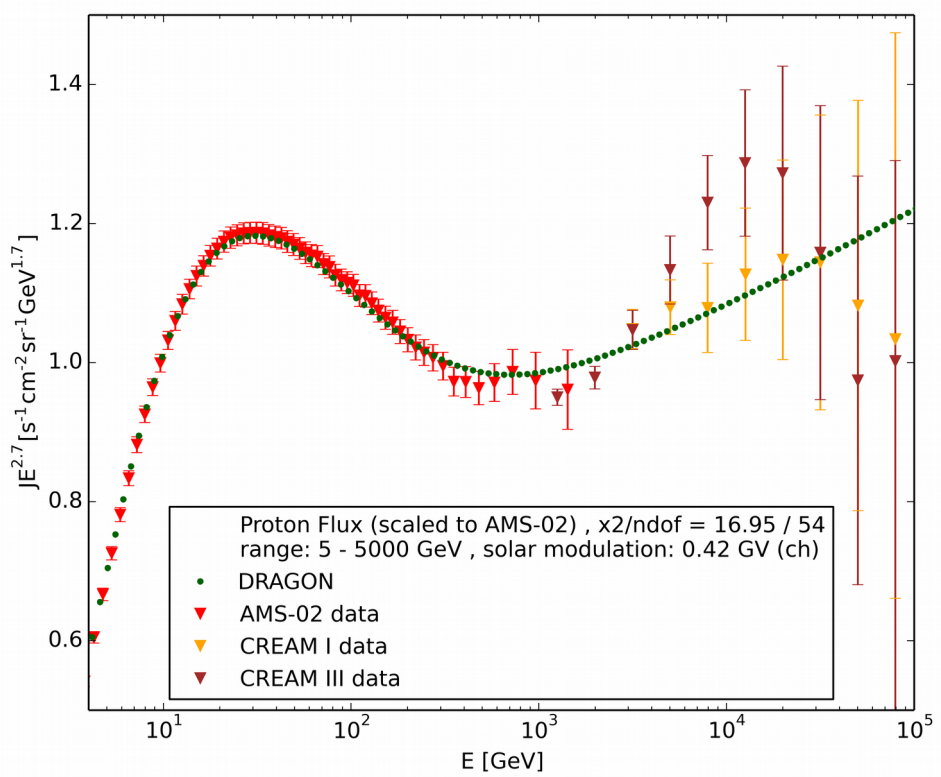
$$\Phi_{tot} = \Phi_{ele} + \Phi_{pos}$$

$\gamma_s - \gamma_e = 0.600$
$\gamma_{ex} - \gamma_e = -0.65$
$C_s/C_e = 0.2$
$C_{ex}/C_e = 0.0078$
$\gamma_e = 3.22$
$E_B = 44.27$ GeV
$E_{cut_{ex}} = 783$ GeV
$C_e = 0.0316$ $cm^{-2}s^{-1}sr^{-1}GeV^{-1}$
$E_{cut_d} = 10000$ GeV
$\Delta\gamma = 0.20$
$\Phi_{ele} = 0.5$GV
$\Phi_{pos} = 0.5$GV
$s = 0.05$

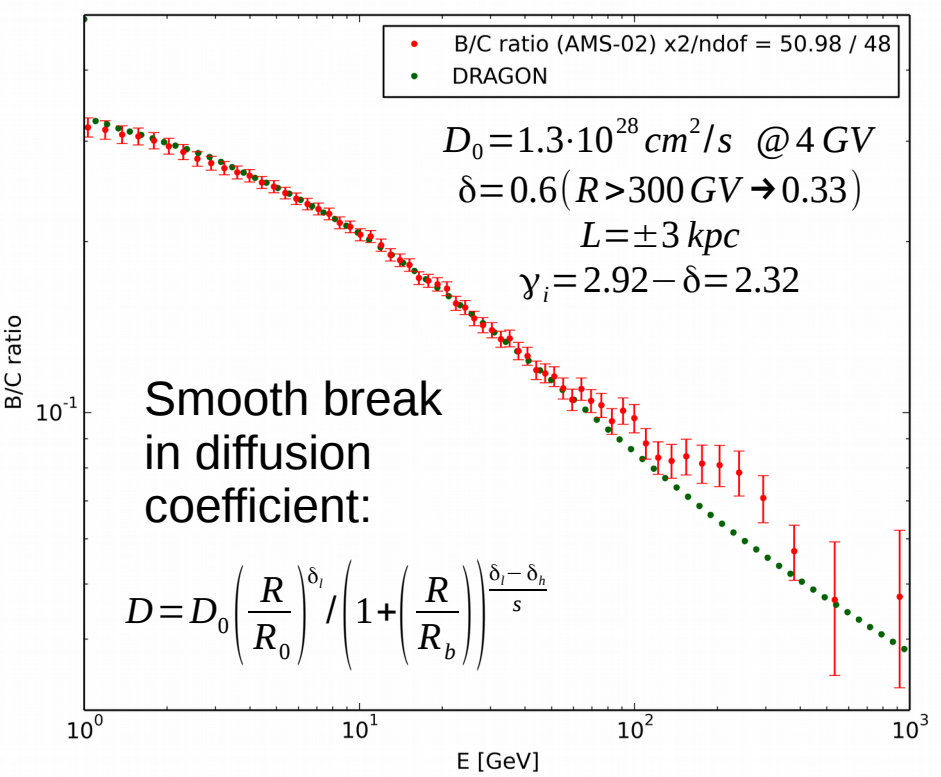
Solar modulation: Force field approximation (same potential for both signs of the charge)

Propagation Model

Proton Spectrum:



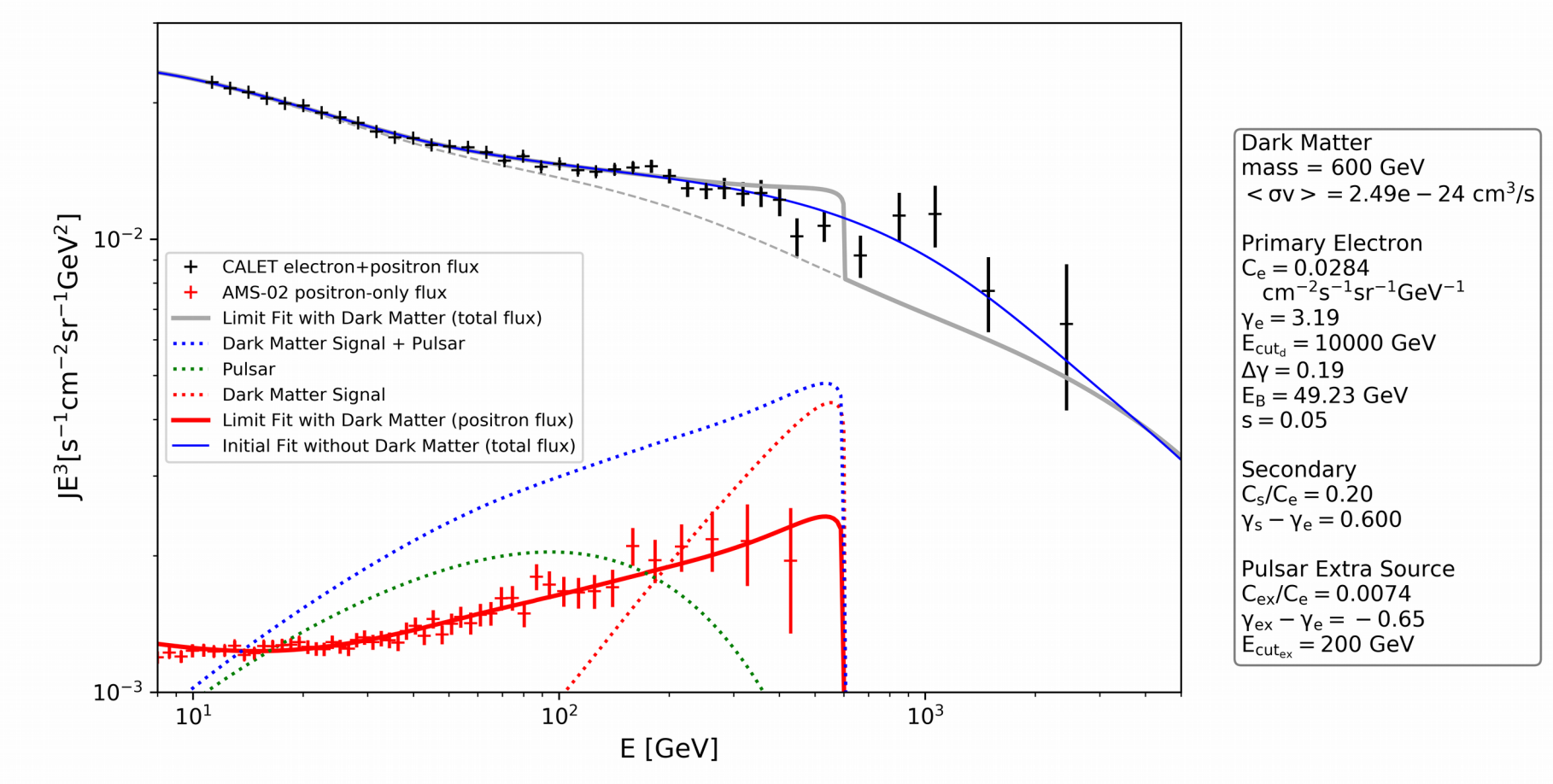
Boron/Carbon ratio:



- Propagation parameters tuned to explain nuclei measurements
- Dark Matter fluxes for NFW profile, local density: 0.3 GeV/cm^3 and annihilation x-section $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm^{3}s^{-1} calculated with PYTHIA and propagated with DRAGON using this model

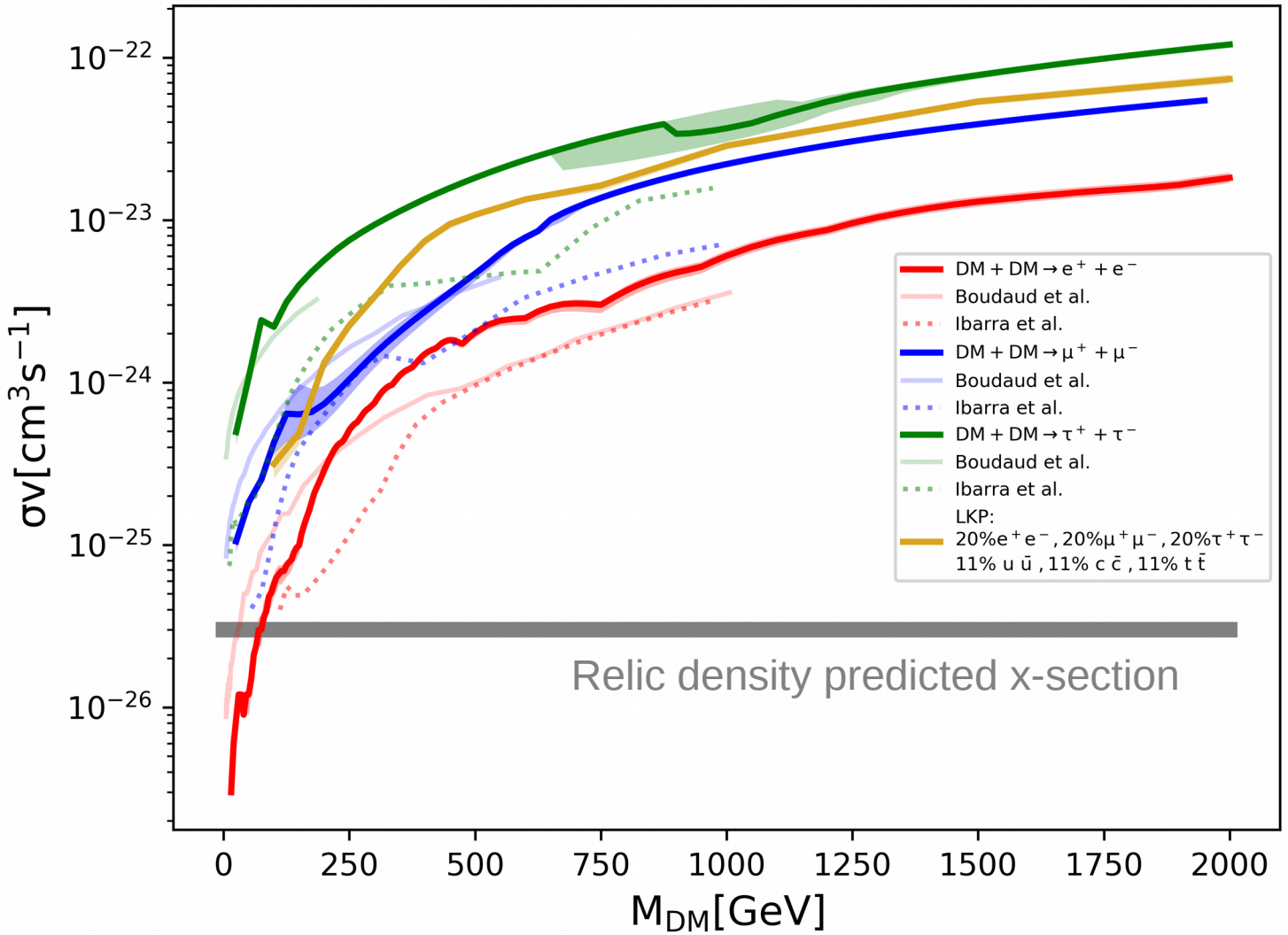
Dark Matter Limit Calculation

- Initial assumption that a nearby pulsar (power law with cut-off electron+positron extra source) is the reason for the positron excess
- Starting from this pulsar-only fit, the Dark Matter term is added and the boost factor increased while repeating the fit each time to adapt other parameters, until 95%CL exclusion limit reached



Limits on Dark Matter Annihilation as a Function of Dark Matter Mass

- Boost factor limits are translated into limits on annihilation cross-section by multiplication with $\langle\sigma v\rangle = 3 \times 10^{-26}\ cm^3 s^{-1}$



Shaded regions: Variation due to solar modulation potential in range 0.3 GV – 0.6 GV

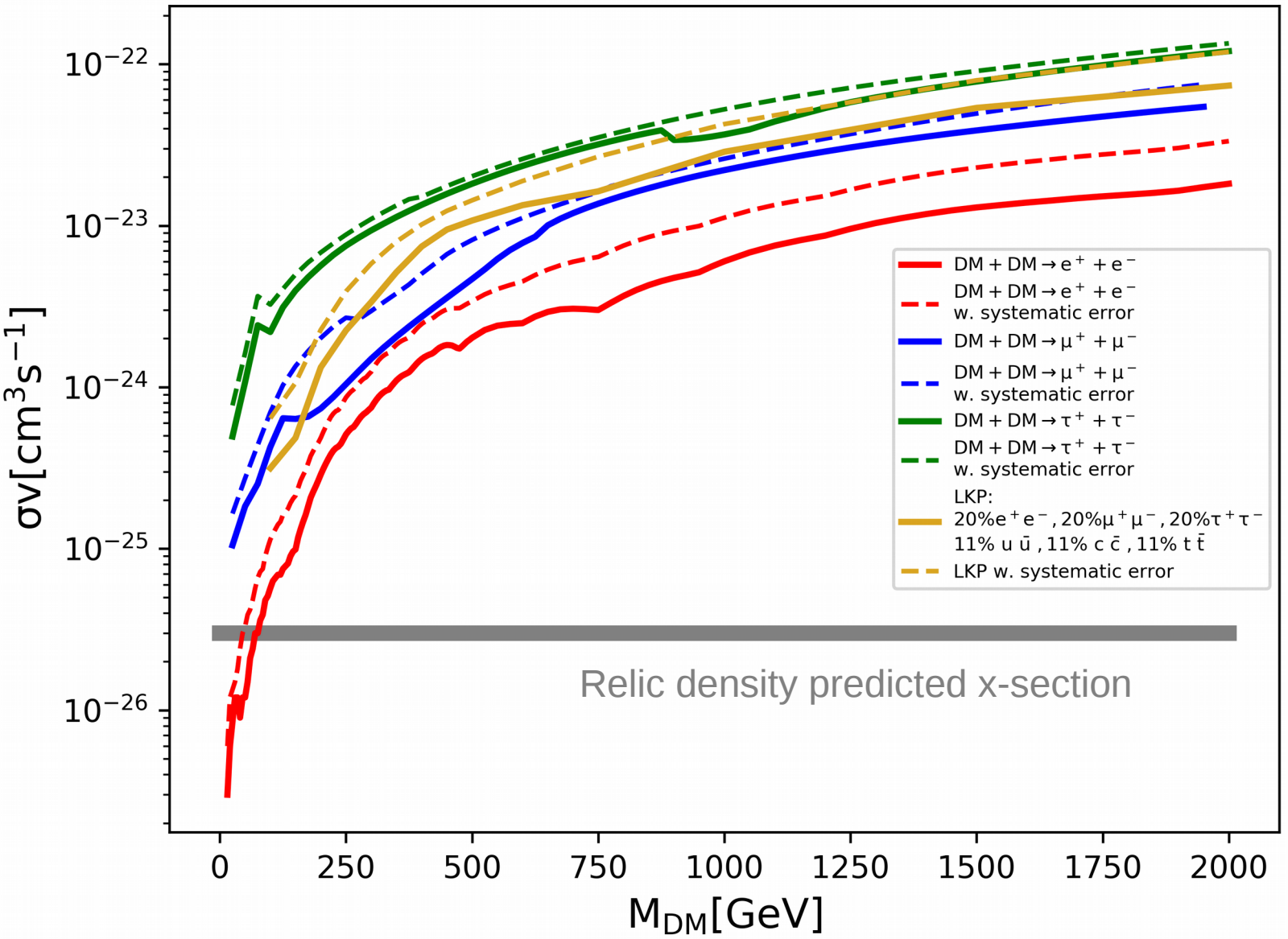
Thin lines: M.Boudaud et al.
Phys. Rev. Lett. 119, 021103 (2017)
ArXiv: 1612.07698

Dotted lines: Ibarra et al.
Phys. Rev. D 89, 063539 (2014)
ArXiv: 1309.2570

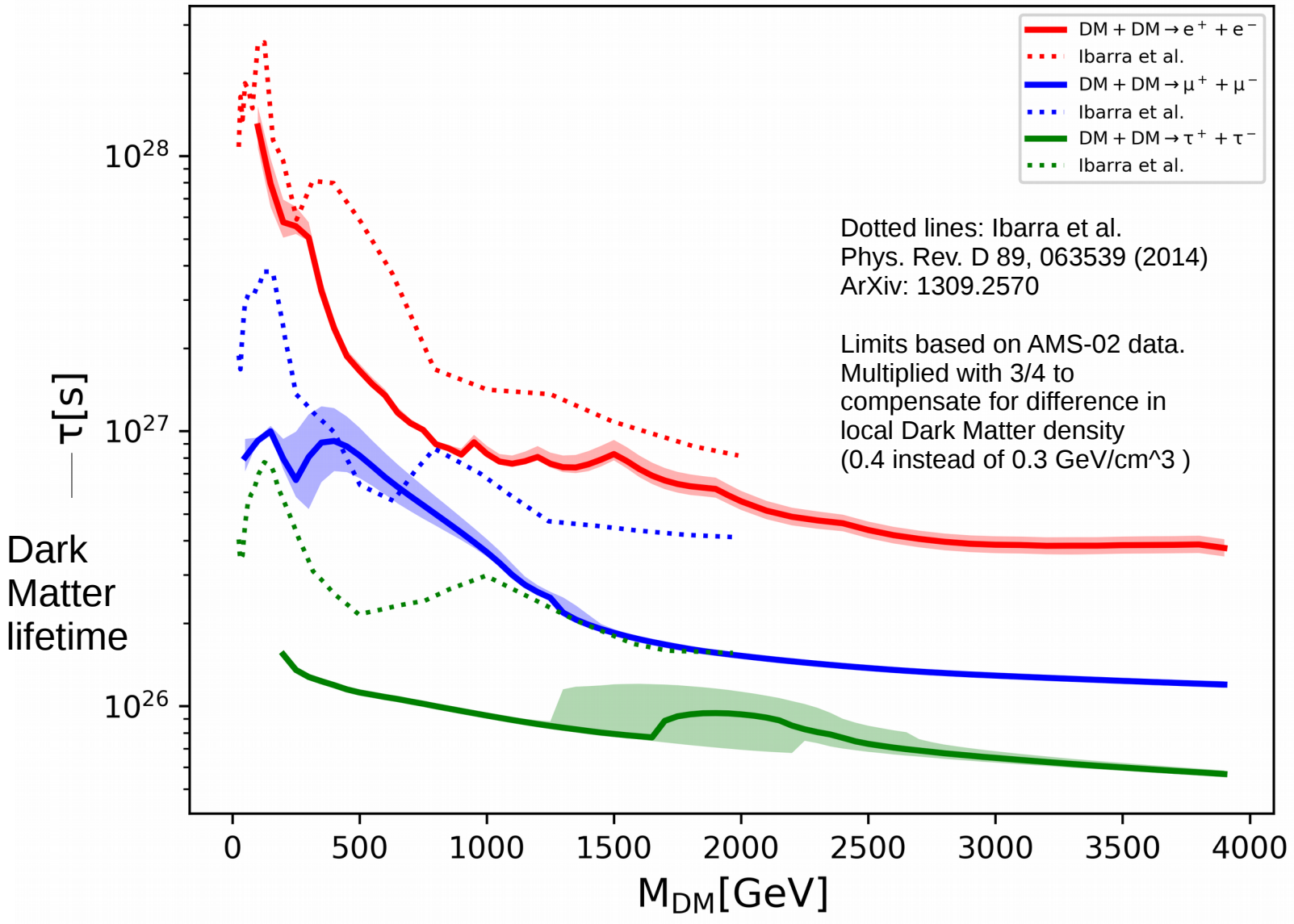
Limits based on AMS-02 data.
Multiplied with 16/9 to compensate for difference in local Dark Matter density (0.4 instead of 0.3 GeV/cm^3)

→ **both use different parametrization of background and extra source**

Limits from CALET Data with Systematic Errors



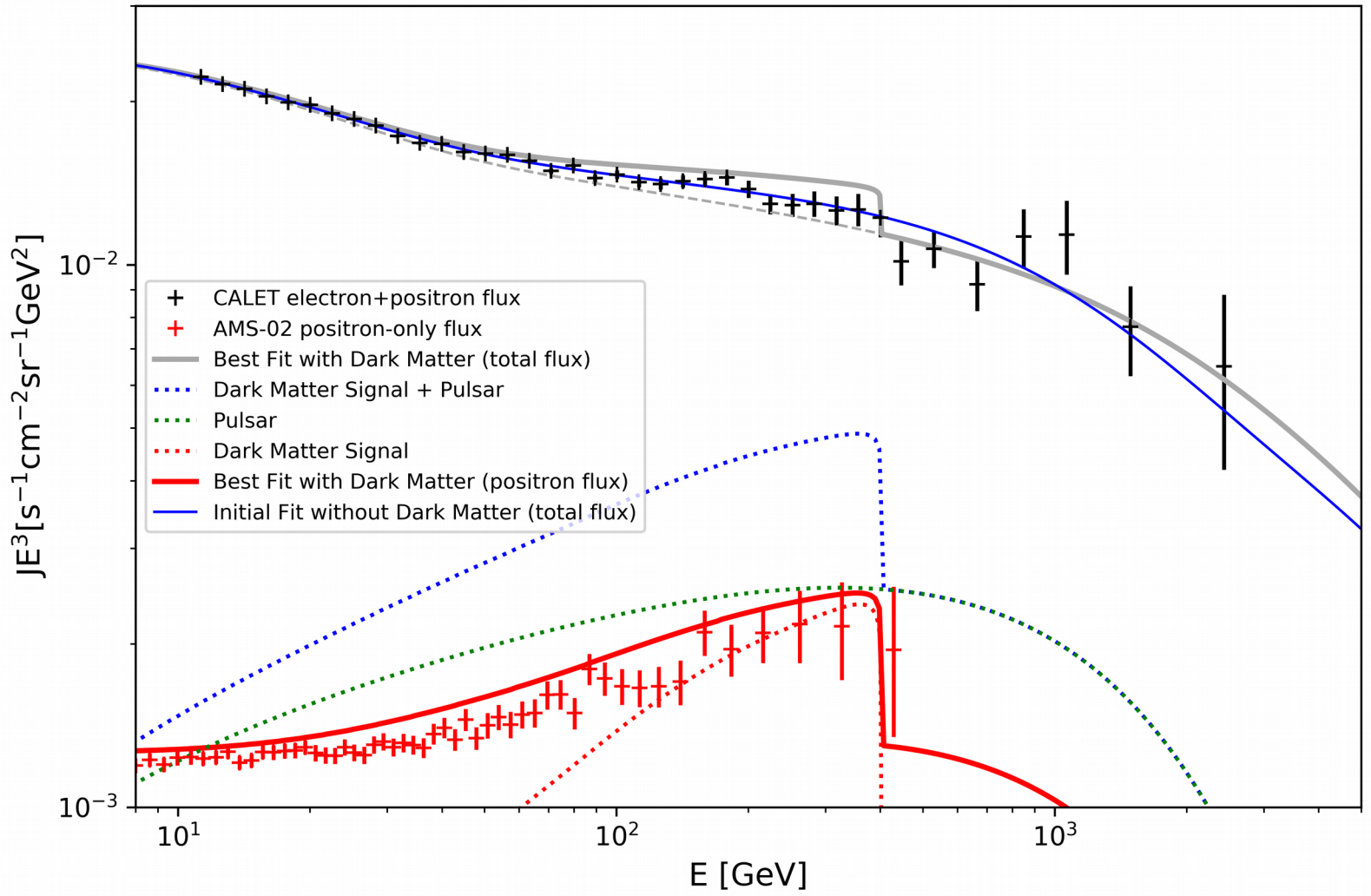
Limits on Dark Matter Decay as a Function of Dark Matter Mass



- Flux from decaying Dark Matter calculated for nominal lifetime
- Scale factor limits are translated into limits on lifetime by dividing through nominal lifetime

Possible Dark Matter Signature

- Addition of the Dark Matter term improves fit in some cases
- Direct annihilation/decay to electron+positron can model “step” at ~400 GeV
  → **400 GeV LKP** annihilation with boost factor ~150 possible explanation



$\chi^2(\mathrm{DM}) = 69.74$
$\chi^2(\mathrm{base}) = 74.41$
$\Delta\chi^2 = 4.67$

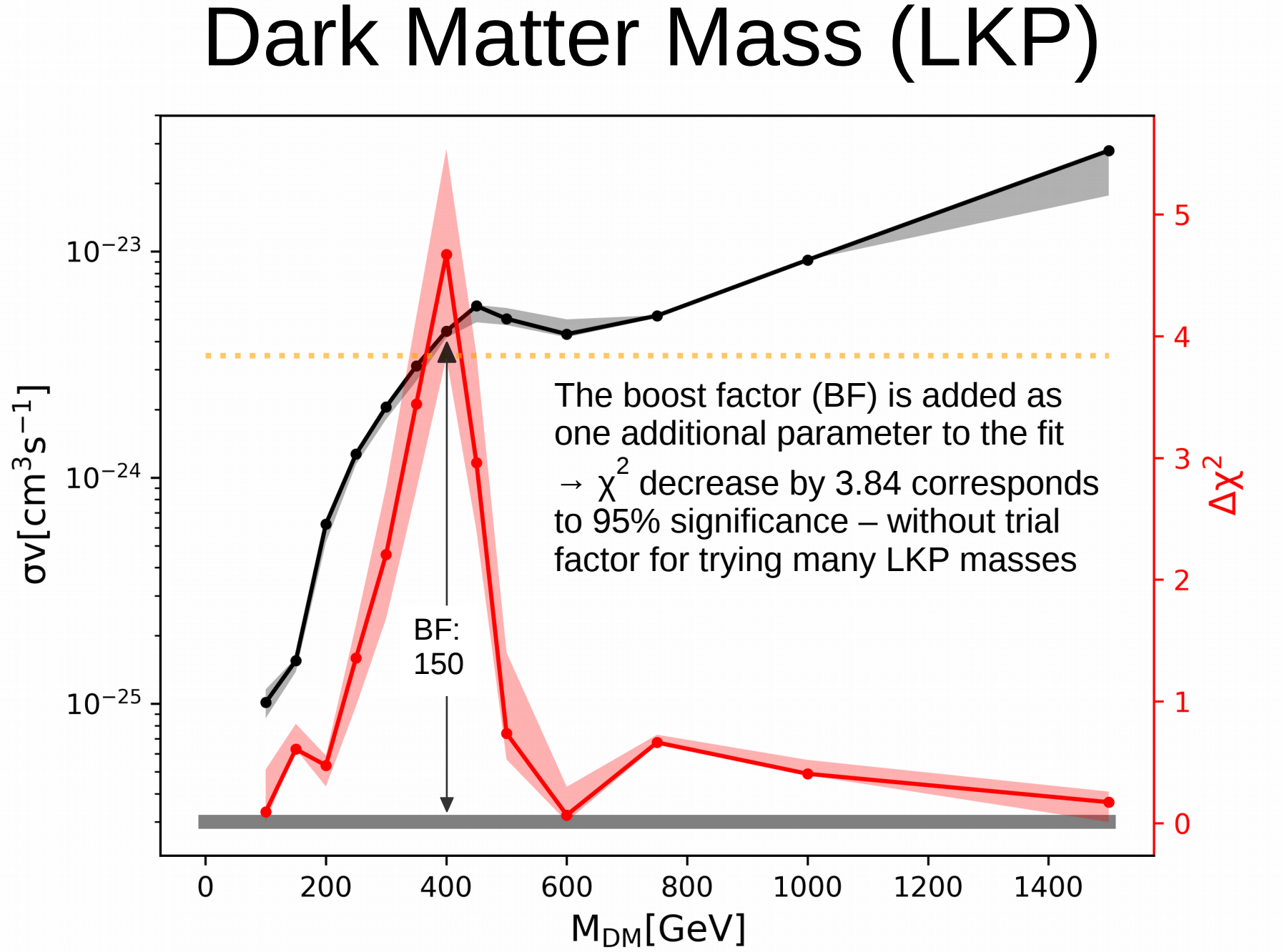
Dark Matter
mass = 400 GeV
$<\sigma v> = 4.45e-24\ \mathrm{cm}^3/\mathrm{s}$

Primary Electron
$C_e = 0.0267$
$\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}^{-1}$
$\gamma_e = 3.18$
$E_{cut_d} = 10000$ GeV
$\Delta\gamma = 0.21$
$E_B = 48.78$ GeV
$s = 0.05$

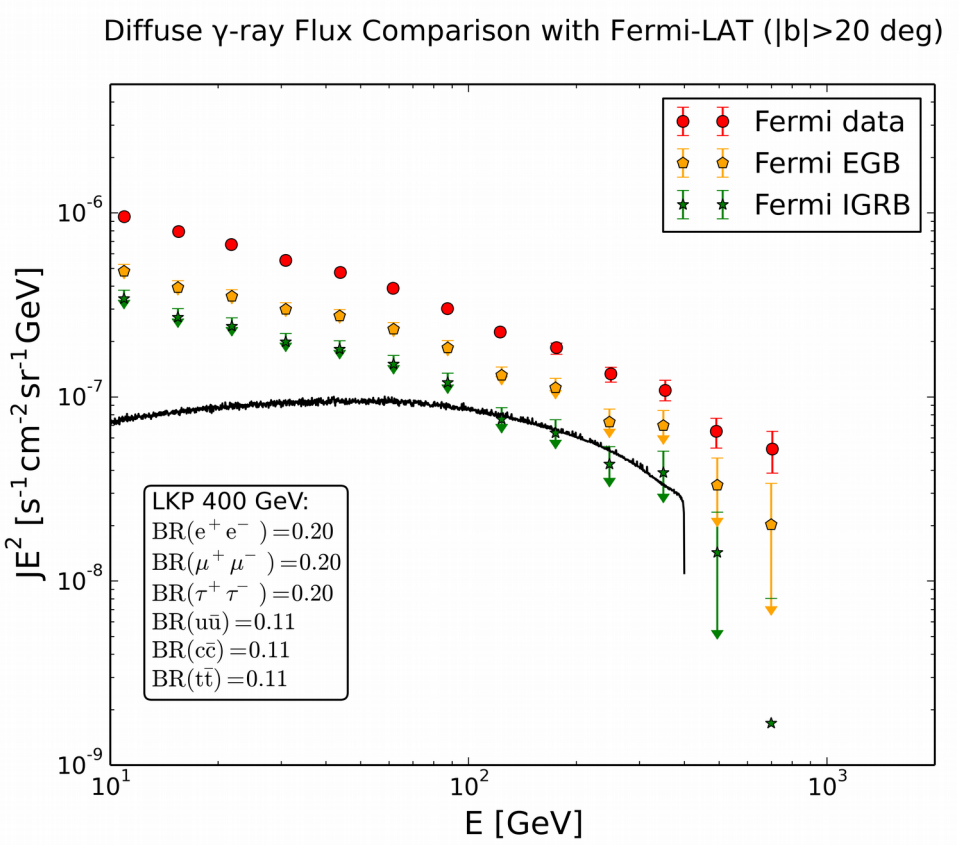
Secondary
$C_s/C_e = 0.15$
$\gamma_s - \gamma_e = 0.600$

Pulsar Extra Source
$C_{ex}/C_e = 0.0165$
$\gamma_{ex} - \gamma_e = -0.40$
$E_{cut_{ex}} = 1400$ GeV

Reduction of χ^2 as a Function of Dark Matter Mass (LKP)

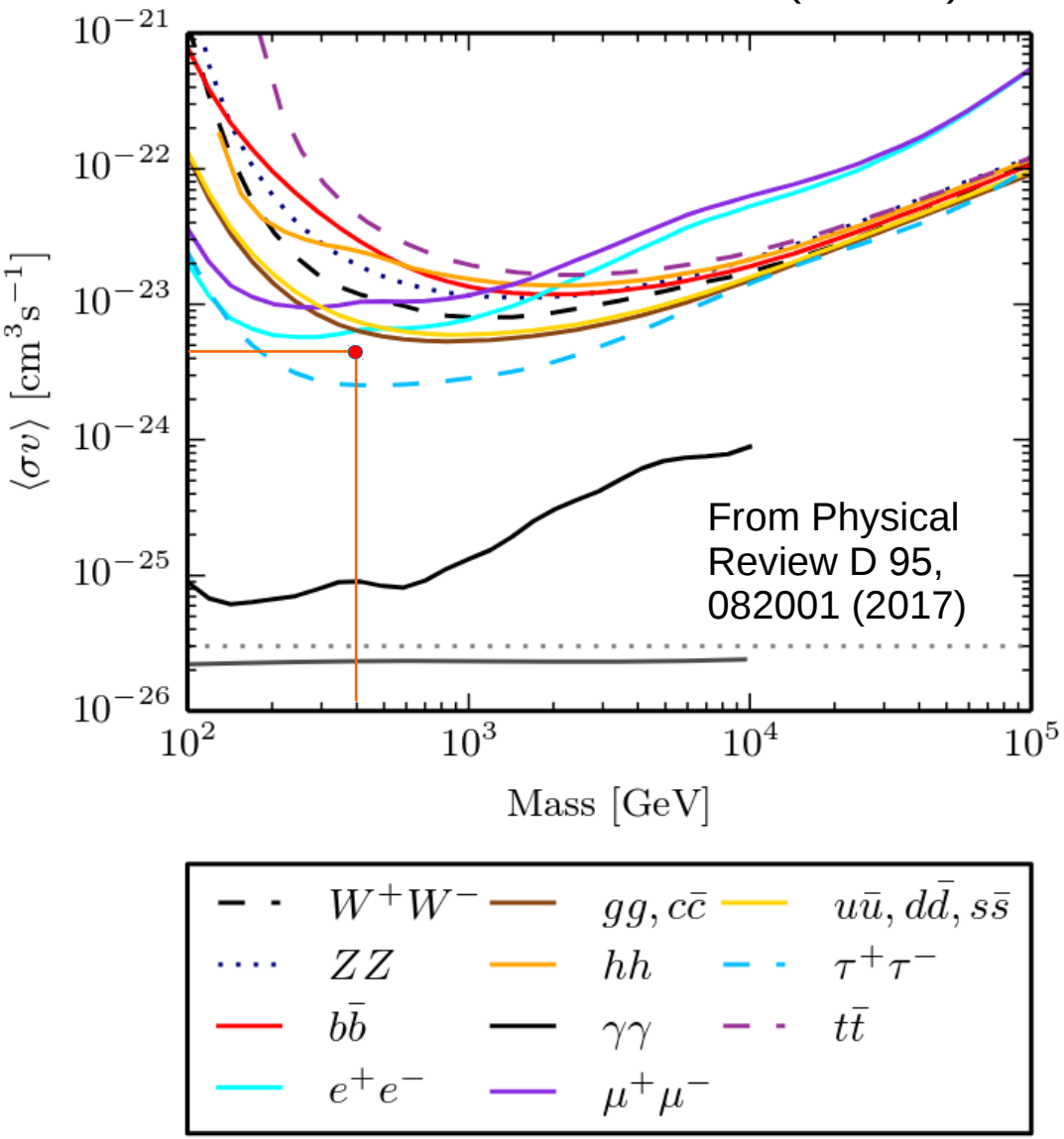


Checking Gamma-ray Constraints



- Gamma-ray emission per annihilation calculated with PYTHIA
- Average diffuse flux for latitude > 20 deg (as Fermi-LAT measurement), NFW halo → not exceeding unexplained diffuse flux measured by Fermi-LAT

Limits from Dwarf Galaxies (Veritas)



Limits on CR Electrons from Vela

- A nearby Supernova remnant (prime candidate: Vela) could dominate the electron flux in the TeV region
- The flux from Vela is calculated with DRAGON from a power-law with cut-off injection spectrum and added to the electron flux in the parametrization
- The parametrization is fitted to CALET total (electron+positron) flux and AMS-02 positron flux data
- From the fit with a nominal energy ($W_{SNR} = 10^{48}$ erg in electron CR of E > 1GeV) the scale factor for the SNR contribution is increased until χ^2 reaches 95%CL → resulting W_{SNR} is the limit set by the CALET measurement
- The spectrum of VELA depends on propagation conditions and on injection parameters

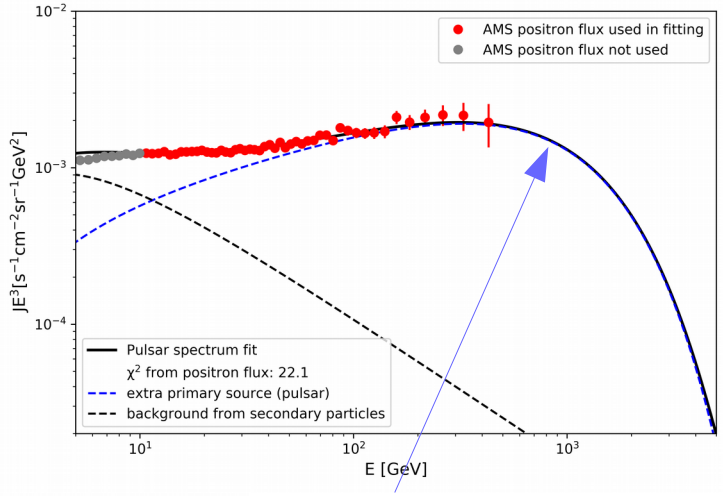
Example Result

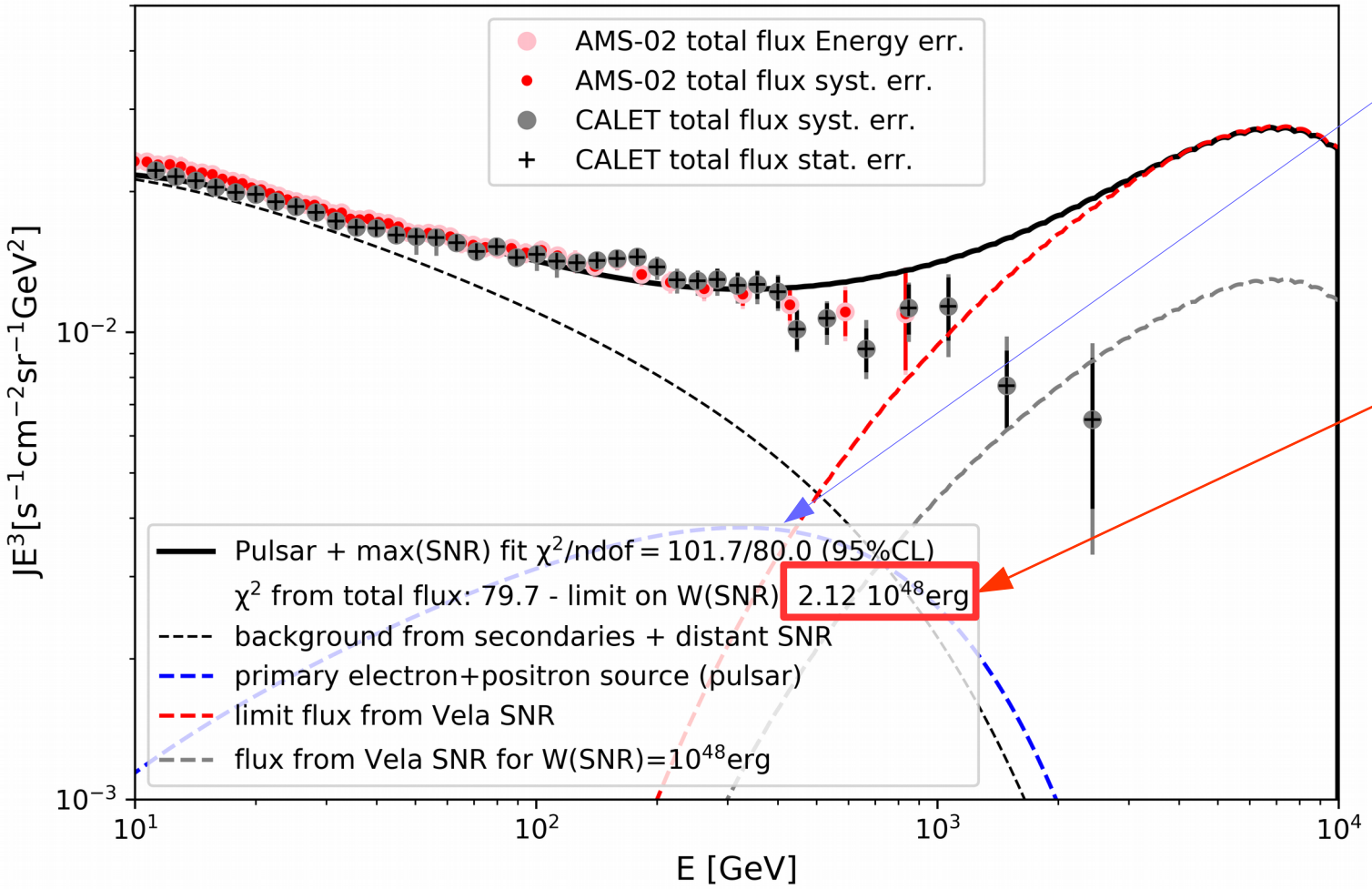
parameters for Vela calculation :

$D_0 = 1.3 \cdot 10^{28}\, cm^2/s \;\; ; \;\; \delta = 0.6 \; (R > 300\, GV \rightarrow 0.33) \;\; ; \;\; L = \pm 3\, kpc$

$\gamma_i = 2.92 - \delta = 2.32 \;\; E_{cut} = 100\, TeV$

instantaneous release of CR from the SNR assumed





Extra primary source for positron excess as part of background → AMS-02 positron flux is also fitted

Limit on energy in electron-CR > 1 GeV emitted by Vela

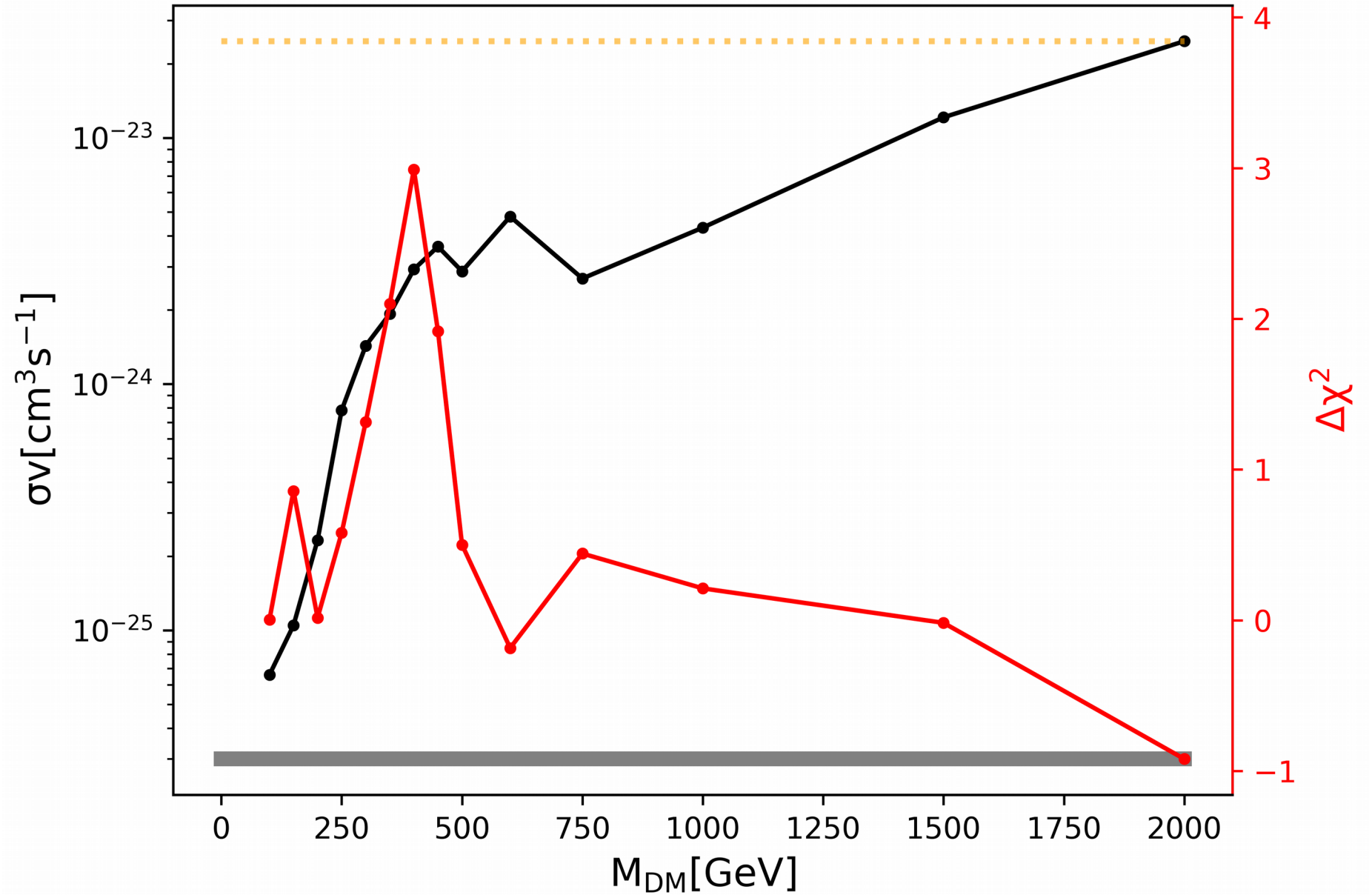
Conclusions and Outlook

- Limits on Dark Matter annihilation and decay have been derived from CALET electron+positron spectrum
- Dark Matter with direct annihilation or decay to electron-positron pairs could model the step in the CALET spectrum around E = 400 GeV e.g. Lightest Kaluza-Klein Particle, passing also gamma-ray constraints
- Limits on CR emission from nearby SNR possible
- One order of magnitude better than current statistics expected from future CALET data with full acceptance

  → improvement of limits and verification of structures
- Systematic errors expected to be reduced by increasingly better modeling of the detector and their influence mitigated by modeling the energy dependence of the error sources

Backup slides

LKP Dark Matter Signature with Systematic Errors



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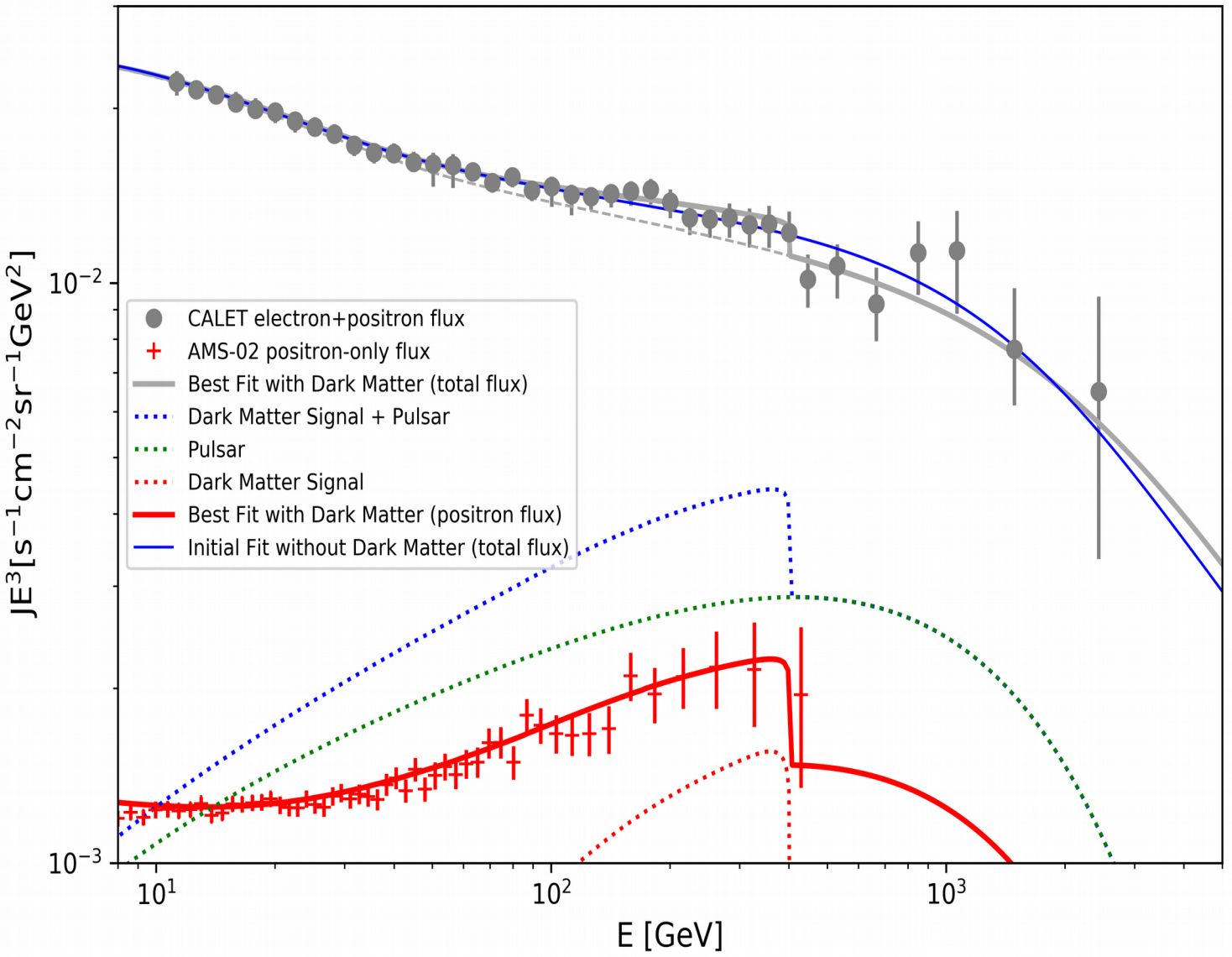

$\chi^2(DM) = 27.53$
$\chi^2(base) = 30.52$
$\Delta\chi^2 = 2.99$

Dark Matter
mass = 400 GeV
$< \sigma v > = 2.92e-24\ cm^3/s$

Primary Electron
$C_e = 0.0305$
$cm^{-2}s^{-1}sr^{-1}GeV^{-1}$
$\gamma_e = 3.21$
$E_{cut_d} = 10000$ GeV
$\Delta\gamma = 0.18$
$E_B = 50.00$ GeV
$s = 0.05$

Secondary
$C_s/C_e = 0.17$
$\gamma_s - \gamma_e = 0.600$

Pulsar Extra Source
$C_{ex}/C_e = 0.0109$
$\gamma_{ex} - \gamma_e = -0.50$
$E_{cut_{ex}} = 1400$ GeV

Reduction of χ^2 as a Function of Dark Matter Mass for Electron+Positron - Channel