Indirect Dark Matter Search with CALET

TeVPA 2016

CERN 2016/9/13

Holger Motz for the CALET collaboration

ICSEP Waseda University

CALET

CALorimetric Electron Telescope

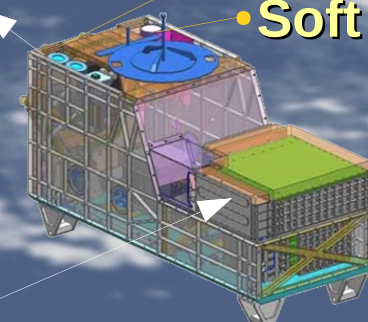
- Collaboration with groups from

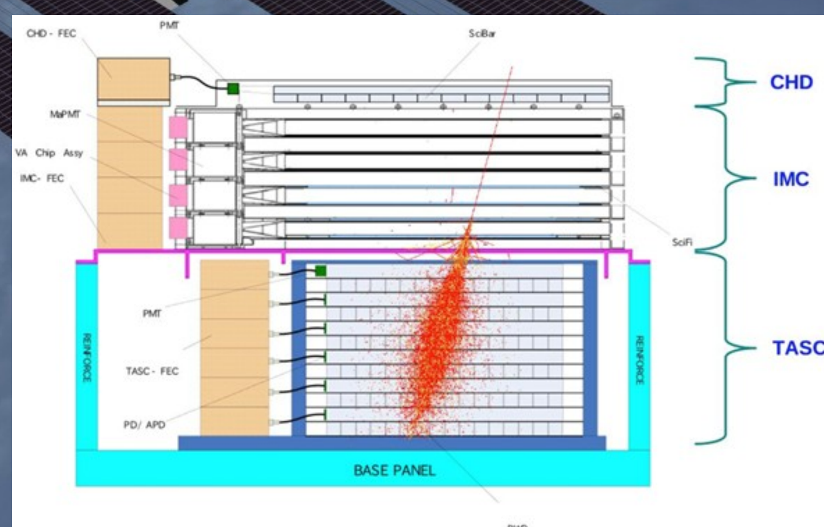
  Japan , USA , Italy

Japanese Experiment Module
Exposed Facility Port 9

CALET was launched in August 2016 aboard HTV-5 and has now been installed on the ISS for 5-years of observation

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





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

- 2% energy resolution
- 1200 $cm^2 \times sr$ aperture
- Proton rejection 10^{-5}

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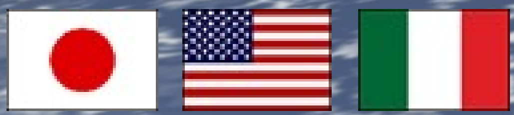

Japanese Experiment Module
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Status and preliminary results from CALET as plenary talk by Shoji Torii on Thursday at 11:30

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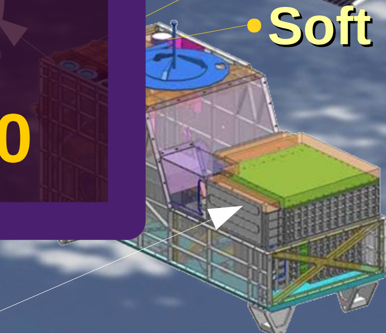

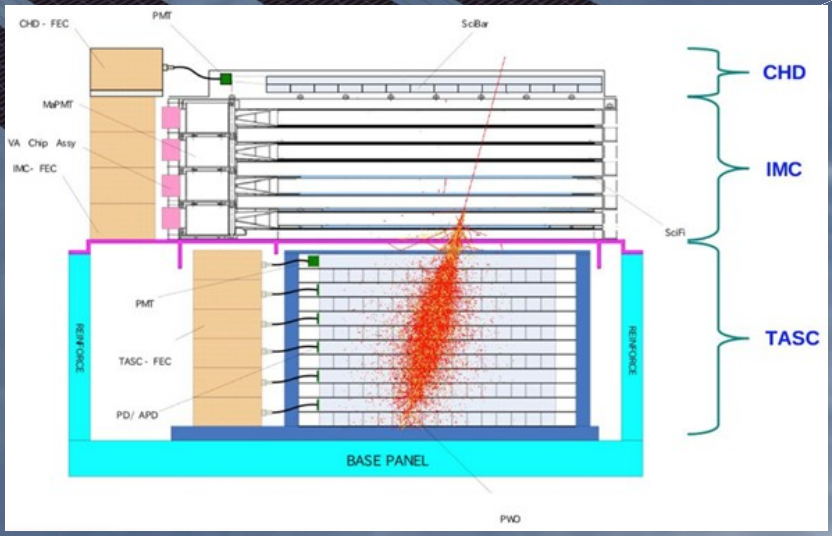

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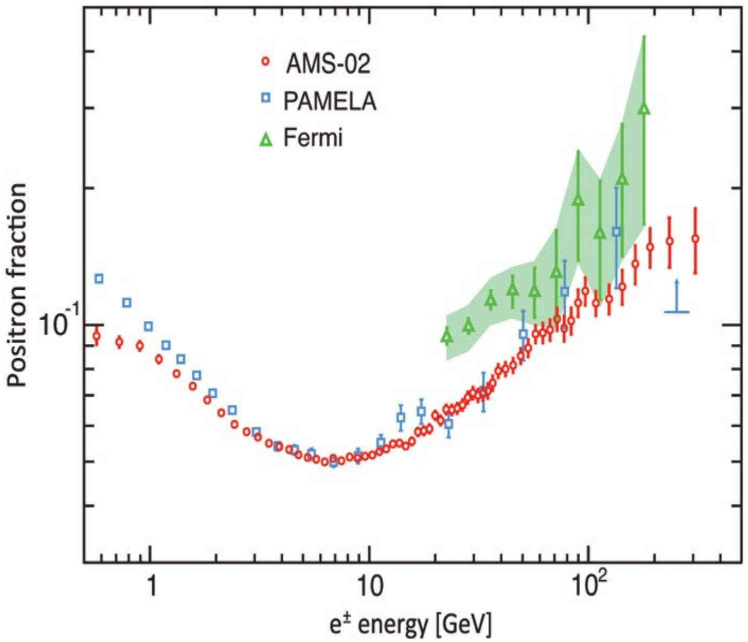
Origin of the Positron Excess

- **Extra Cosmic-Ray Source:**

  Common power law with cut-off proposed by AMS-02 as empirical model fits data well

- Possibly caused by nearby pulsar(s) emitting an equal amount of electrons and positrons **(Pulsar Case)**

- Or by Dark Matter annihilation or decay **(Dark Matter Case)**



- Investigated Questions:

  Dark Matter Case:

  – *Could CALET identify signatures of Dark Matter decay that might explain the positron excess ?*

  Pulsar Case:

  – *What limits can be set from CALET data on Dark Matter Annihilation on top of this nearby pulsar source if taking into account the shape of the Dark Matter spectrum*

Parametrization of Local Spectrum

Coefficient and slope of the primary electron flux

secondary particles (electron + positron → 2)

Exponential cut-off due to energy loss during propagation of primary electrons

$$\Phi_{e^-+e^+}(E)=2\Phi_{extra}(E)+C_e E^{\gamma_e}\left(2\cdot\frac{C_{e^+}}{C_e}\cdot E^{\gamma_{e^+}-\gamma_e}+\exp\left(\frac{-E}{E_{cut_d}}\right)\right)$$

Extra source emitting equal amount of electron & positron

Pulsar Wind Nebula $\Phi_{PWN}(E)=C_s E^{\gamma_s}\cdot\exp\left(\frac{-E}{E_{cut_s}}\right)$

Dark Matter Annihilation $\Phi_{DM}(E)=BF\cdot\Phi_{DM_{base}}(E)$

$(\Phi_{DM_{base}}$ calculated for $<\sigma v>=3\cdot 10^{-26} cm^3 s^{-1})$

Dark Matter Decay $\Phi_{DM}(E)$ proportional to $\frac{1}{\tau}$

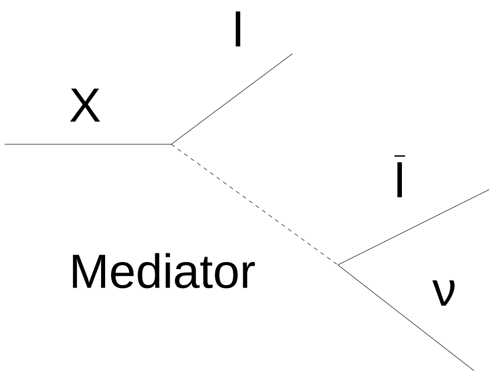
positron flux: $\Phi_{e^+}(E)=\Phi_{extra}(E)+C_e E^{\gamma_e}\left(\frac{C_{e^+}}{C_e}\cdot E^{\gamma_{e^+}-\gamma_e}\right)$

positron fraction = $\dfrac{\text{(positron flux)}}{\text{(electron + positron flux)}}$

For Dark-Matter-only explanation of the positron excess, decaying Dark Matter is favourable, since no Boost Factor would be required in the theory.

Leptonic 3-particle Decay

- Possible decay Mode of Fermionic Dark Matter favoured as explanation of the positron excess



- Spectrum softer than equivalent 2-particle decay because the neutrino caries away part of the energy

  → spectral shape suited to explain the positron excess without including hadronic channels
  → <u>no anti-proton constraints</u>

Theoretical Background

- Gravity Mediated Wino Dark Matter
  - M. Ibe et al. (JHEP 1307 (2013) 063)

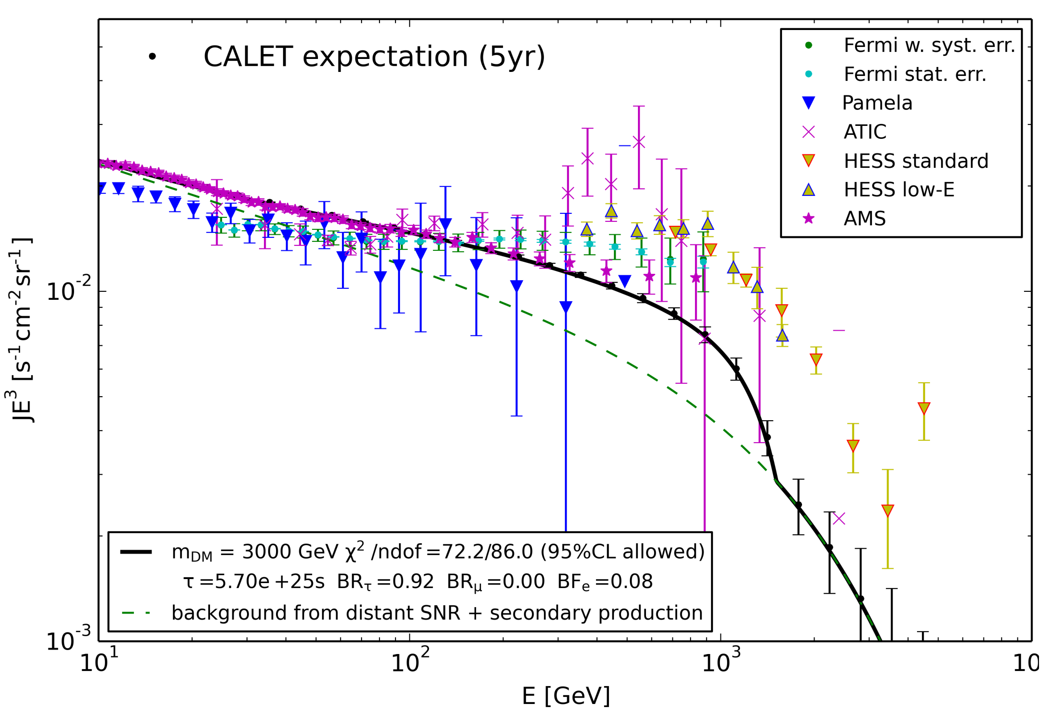
$$50\%\,\widetilde{W}^0 \rightarrow \mu + \nu_\tau + l^\pm + 50\%\,\widetilde{W}^0 \rightarrow \tau + \nu_\mu + l^\pm$$

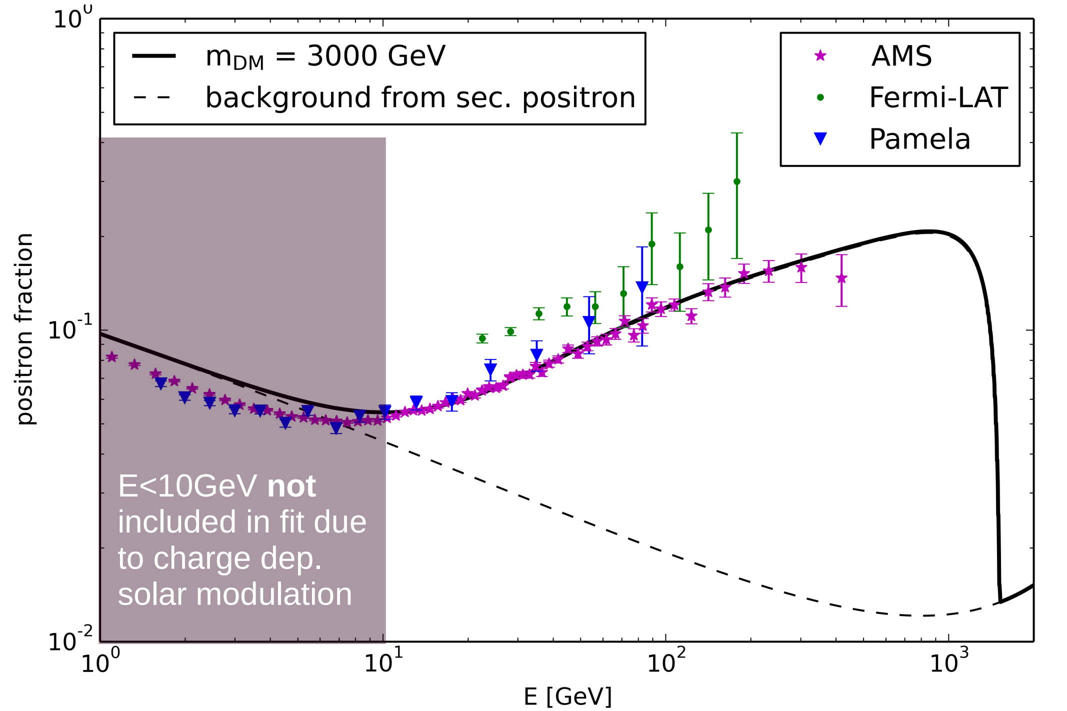
- Fermionic Dark Matter in a 2-Higgs-Doublet Extension of the Standard Model
  - K. Kohri & N. Sahu (Phys. Rev. D 88, 103001)

$$N_L \rightarrow l^\pm + l^\mp + \nu$$

- Both predict a **~3 TeV** Dark Matter candidate whose decay could explain the positron excess

Fit to Current Data (AMS-02)





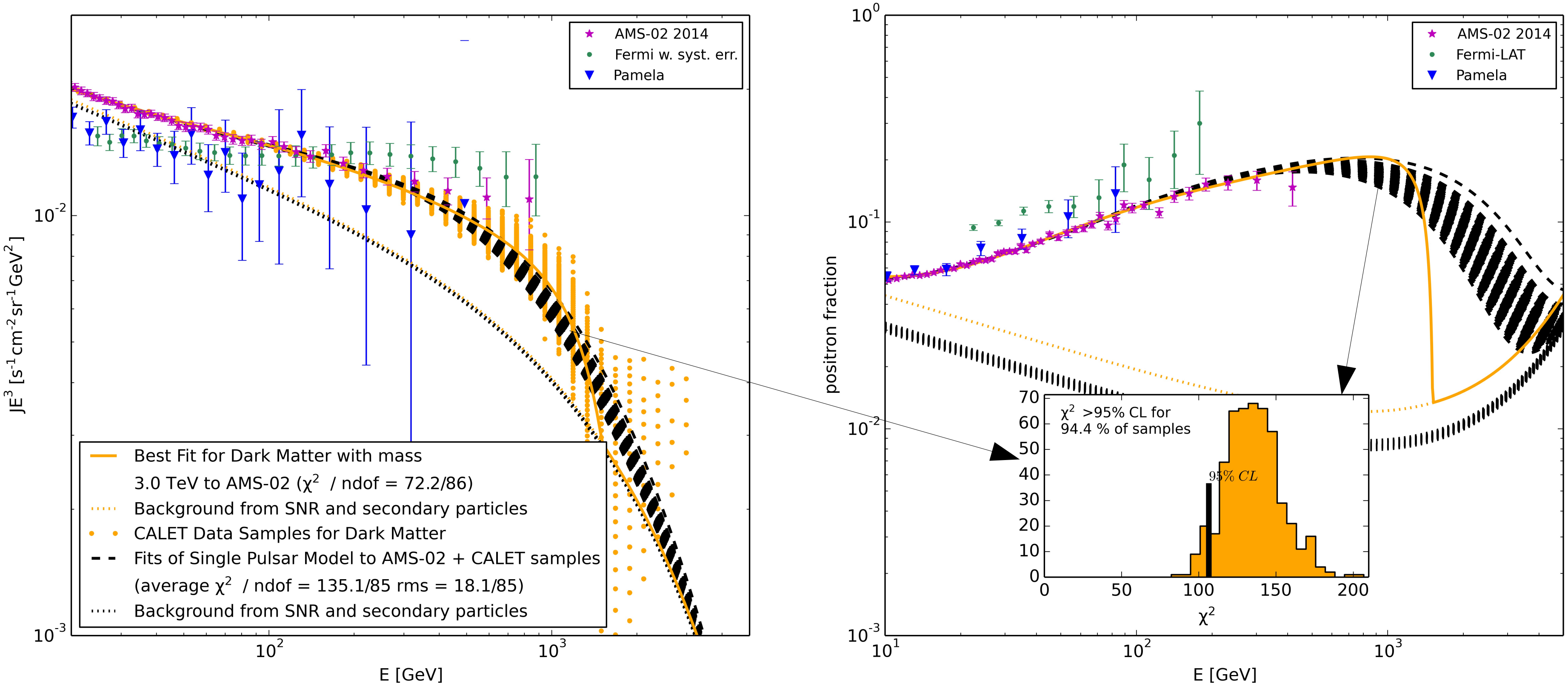
- Electron/positron spectra from 3-particle decay in point-interaction approximation calculated with Pythia and propagated with DRAGON
- Parameters optimized by minimization of χ^2 with regard to the predicted **total flux (left)** and **positron fraction (right)** → allowed model if χ^2 < 95 %CL
- 92% $\chi \rightarrow \tau^+ \tau^- \nu$ + 8% $\chi \rightarrow e^+ e^- \nu$ gives the best fit to AMS-02 data (branching fractions treated as free parameters in the fit)

Prediction for CALET

- Expected flux derived from fit of candidate scenario to current experimental data
- Simulation of 500 statistical samples of expected CALET data for 5 year observation
- Fit of the Single Pulsar scenario to AMS positron fraction + simulated CALET data (done for each of the 500 samples)
- χ^2 distribution of all samples shows whether the scenario can likely be distinguished from a Single Pulsar (or similar smooth spectrum) using CALET data

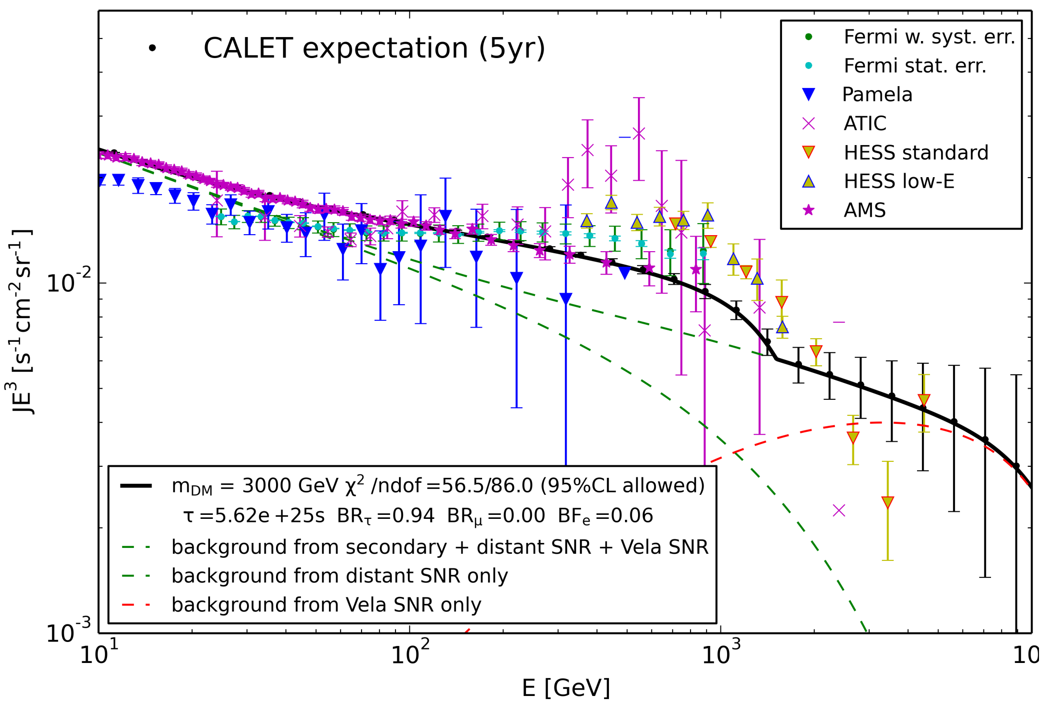
CALET Simulated Data Analysis

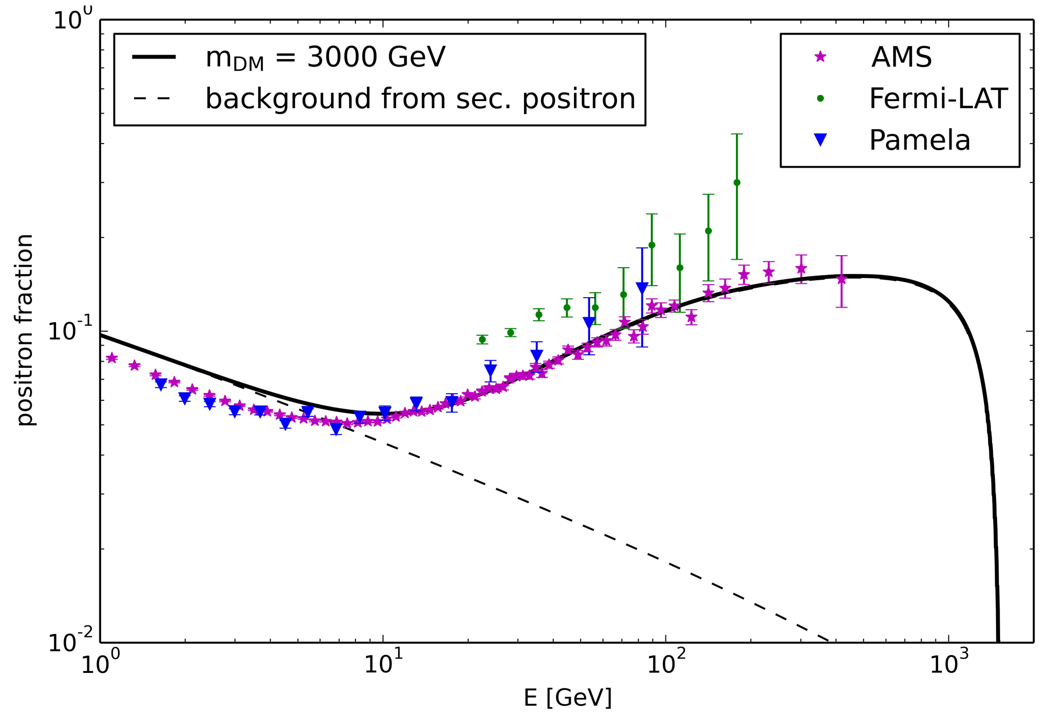
$92\%\ \chi \rightarrow \tau^+ \tau^- \nu \ + \ 8\%\ \chi \rightarrow e^+ e^- \nu$



- χ^2 distribution for all samples shows whether the scenario can likely be distinguished from the Single Pulsar case → for most samples χ^2 > 95% CL

Nearby SNR Included in the Model





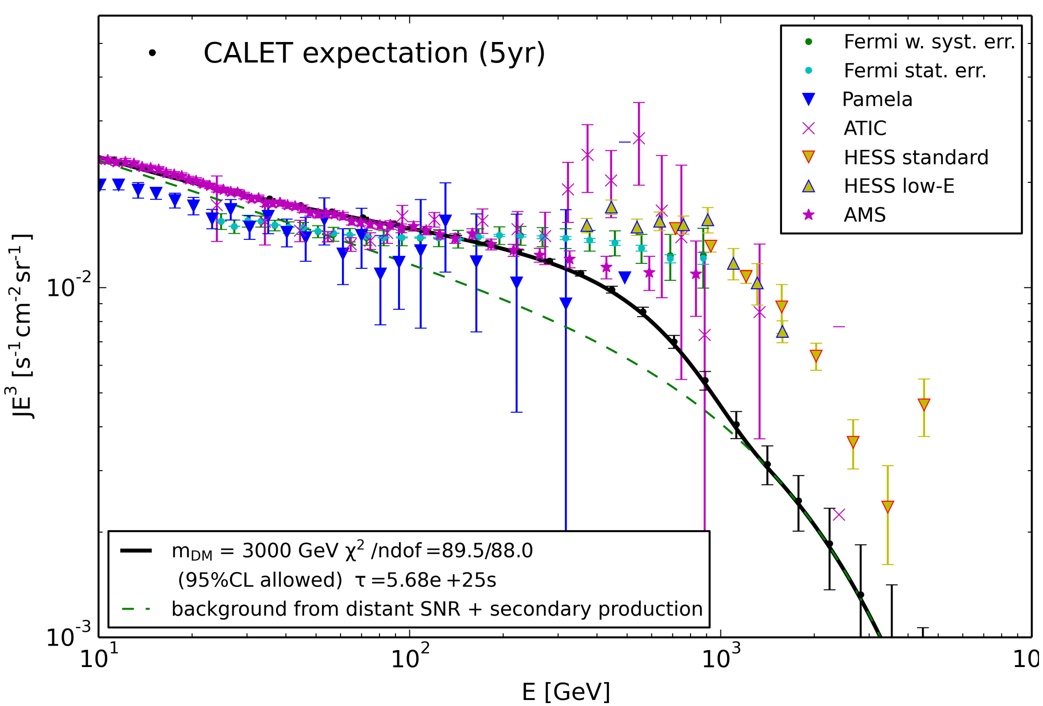
- Nearby SNR as a fixed electron-only component
- The Vela SNR is expected to dominate over all other candidates:

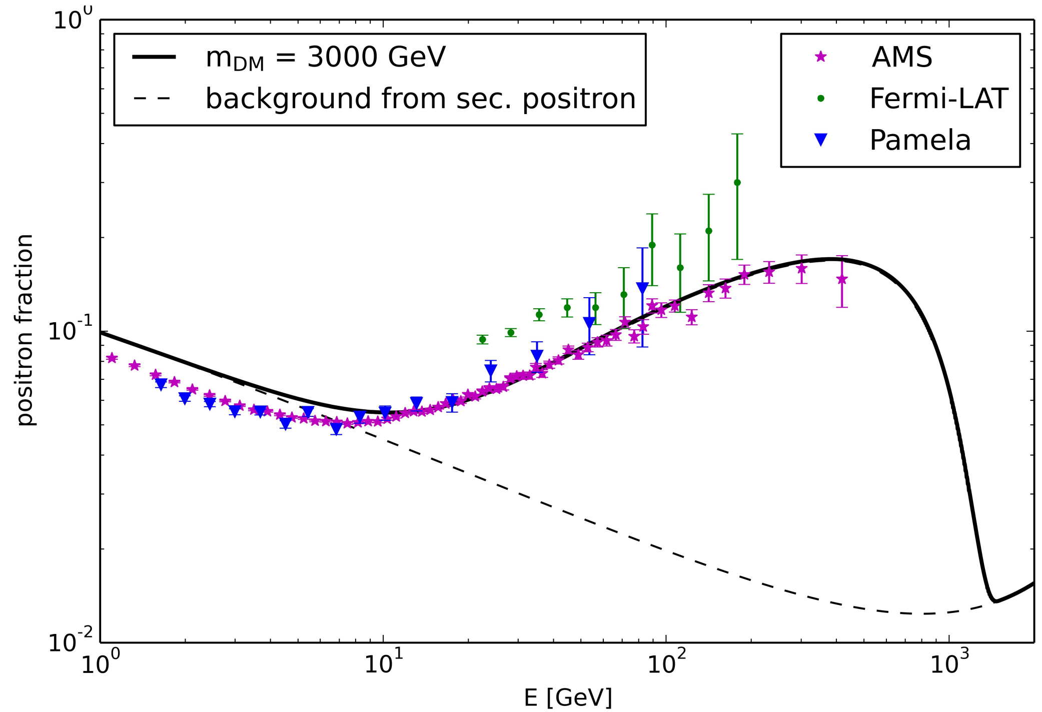
$$E_{CR>1GeV} = 1\cdot 10^{48} \text{ erg – spectrum calculated with DRAGON}$$

- The best fit for the branching fractions becomes:

$$94\% \ \chi \rightarrow \tau^+ \tau^- \nu \ + \ 6\% \ \chi \rightarrow e^+ e^- \nu$$

Decaying Wino Dark Matter





$$50\% \ \ \chi \rightarrow \tau^{+} \nu_{\mu} \tau^{-}_{R} \quad + \quad 50\% \ \ \chi \rightarrow \mu^{+} \nu_{\tau} \tau^{-}_{R}$$

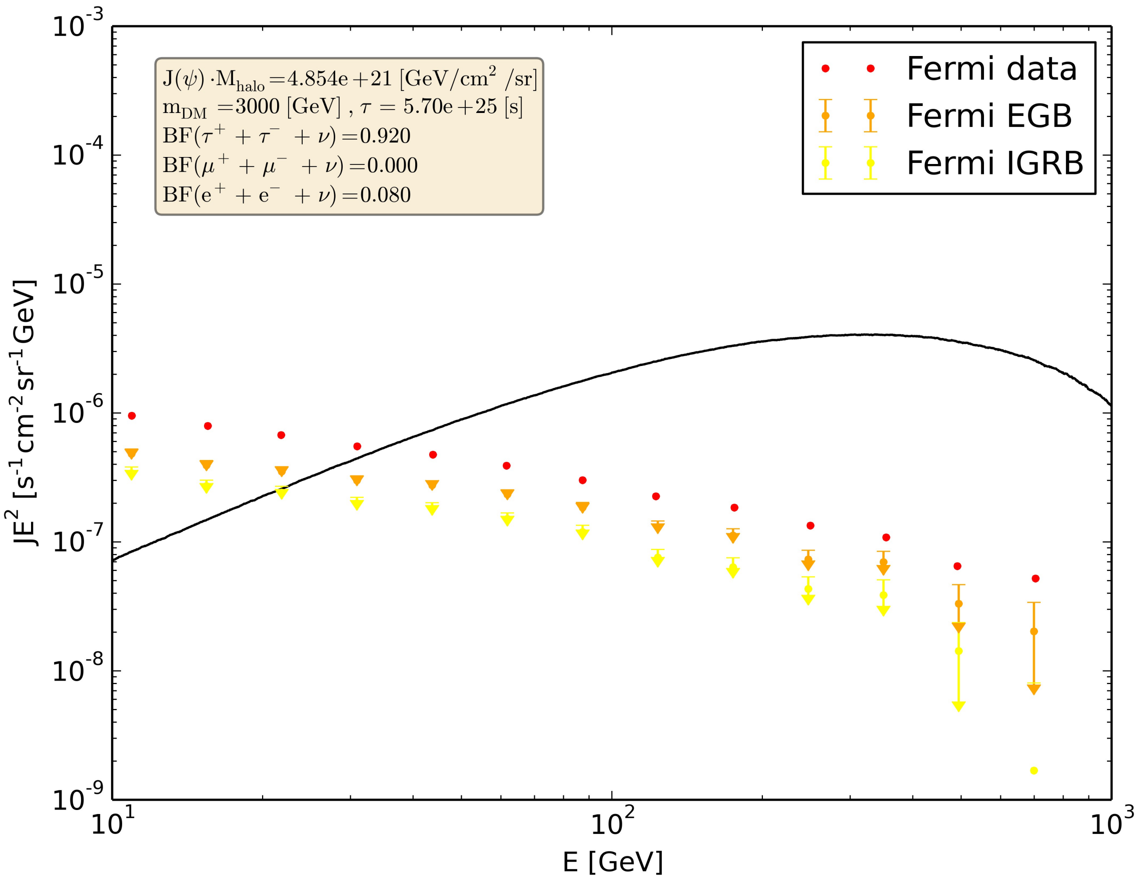
Only the case of the right-handed third lepton being a **τ** gives a good fit to current data

Result Overview

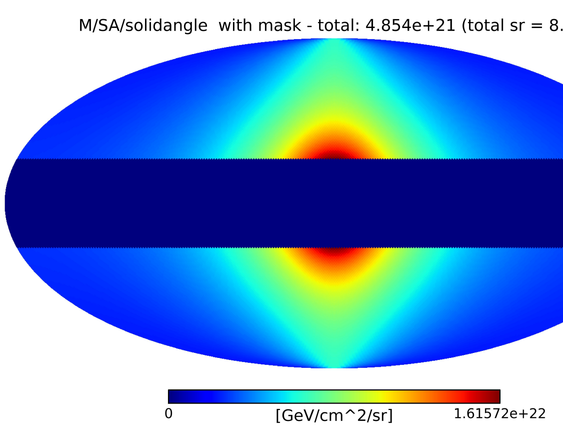
DM mass:	2 TeV	3 TeV	4 TeV
Free Branching Ratios Fit to Current data: X^2 /ndf for AMS-02	**62.1 / 86**	**72.2 / 86**	**87.3 / 86**
CALET simulation: fraction of samples with χ^2 > 95 %CL	**99.2 %**	**94.4 %**	**96.2 %**
Free Branching with Vela Fit to Current data: X^2 /ndf for AMS-02	**49.5 / 86**	**56.5 / 86**	**67.8 / 86**
CALET simulation: fraction of samples with χ^2 > 95 %CL	**82.2 %**	**79.8 %**	**67.2 %**
Wino Decay Fit to Current data: X^2 /ndf for AMS-02	**112.6/88**	**89.5 / 88**	**121.3/88**
CALET simulation: ffraction of samples with χ^2 > 95 %CL	-	**76.0 %**	-
Wino Decay with Vela Fit to Current data: X^2 /ndf for AMS-02	**79.6 / 88**	**70.8 / 88**	**112.8/88**
CALET simulation: fraction of samples with χ^2 > 95 %CL	**98.6 %**	**57.6 %**	-

shown examples

Gamma Constraints

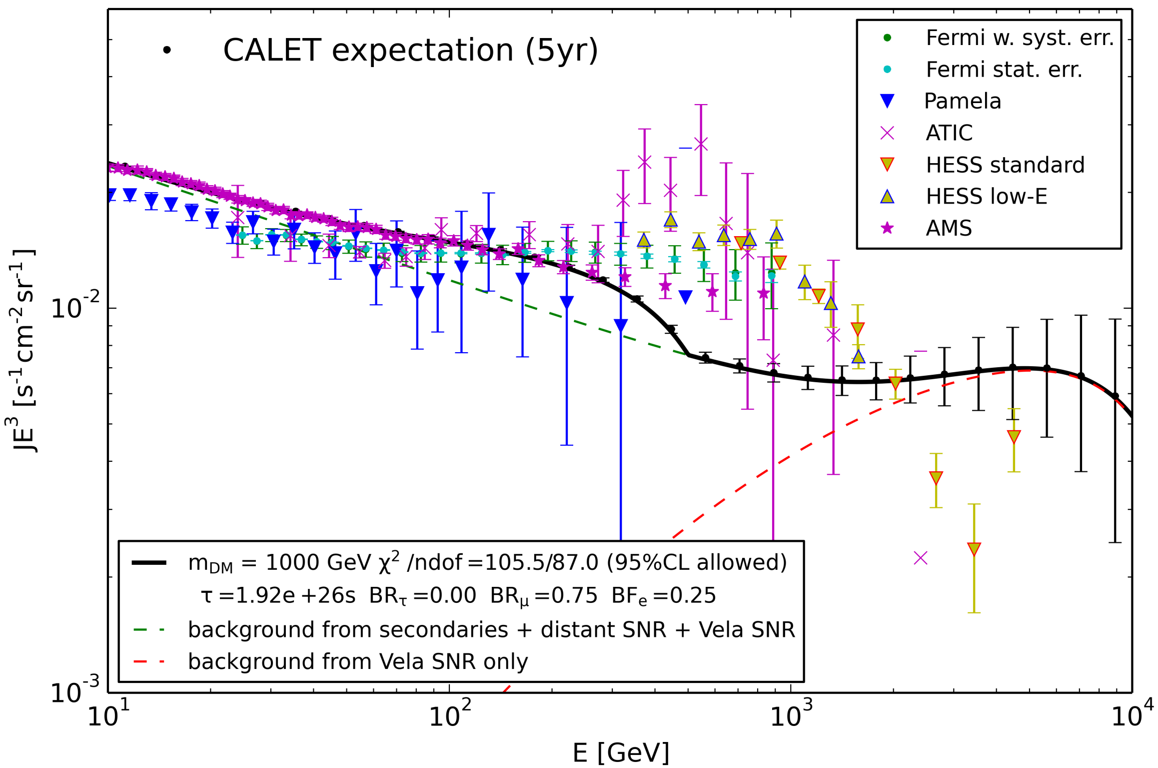


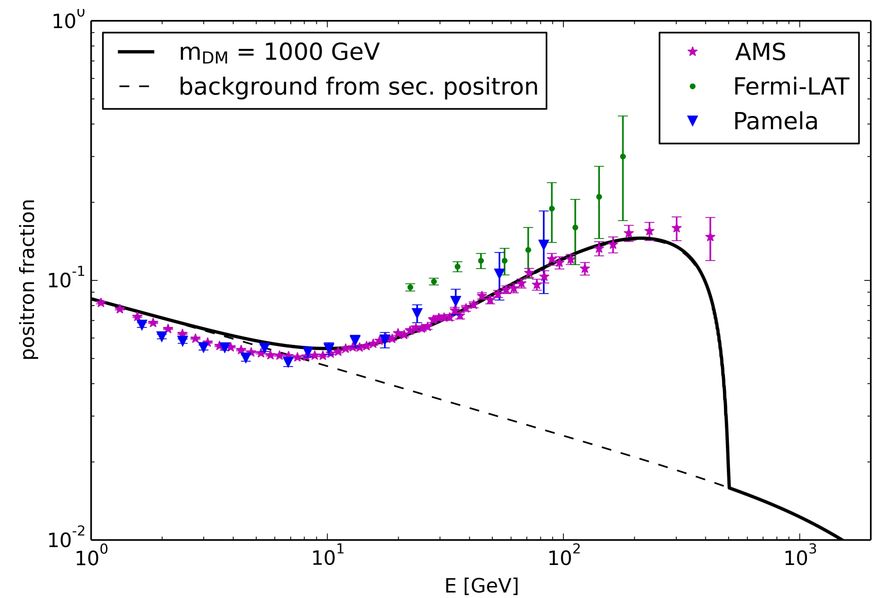
- Gamma flux for galactic latitude (absolute value) larger than 20 degree
- Photons from FSR and those produced in decay of primary decay products (calculated with PYTHIA)
- NFW halo model assumed

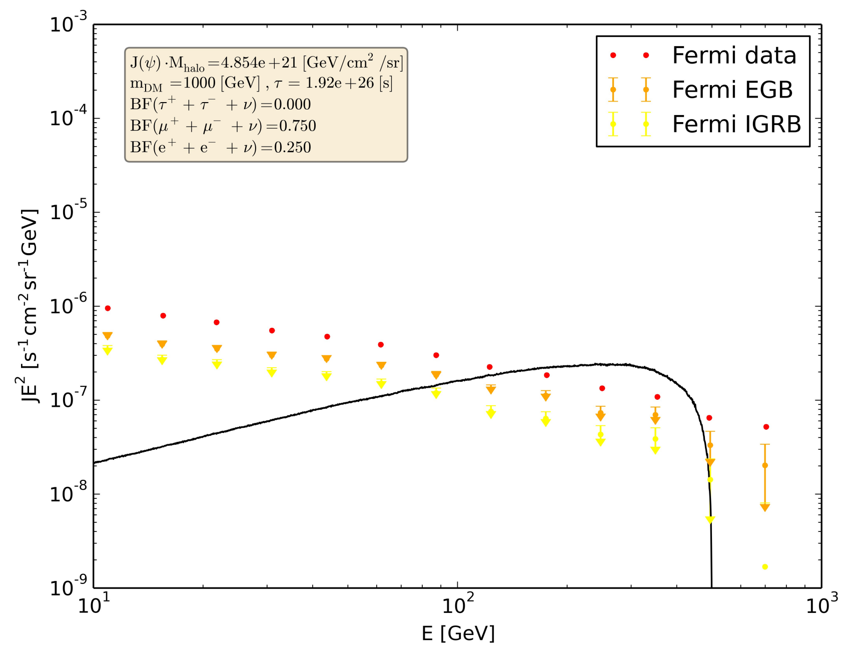


→ For best fit model, expected gamma emission significantly exceeds gamma flux measured by Fermi in the same region

Low Gamma-Flux Scenario



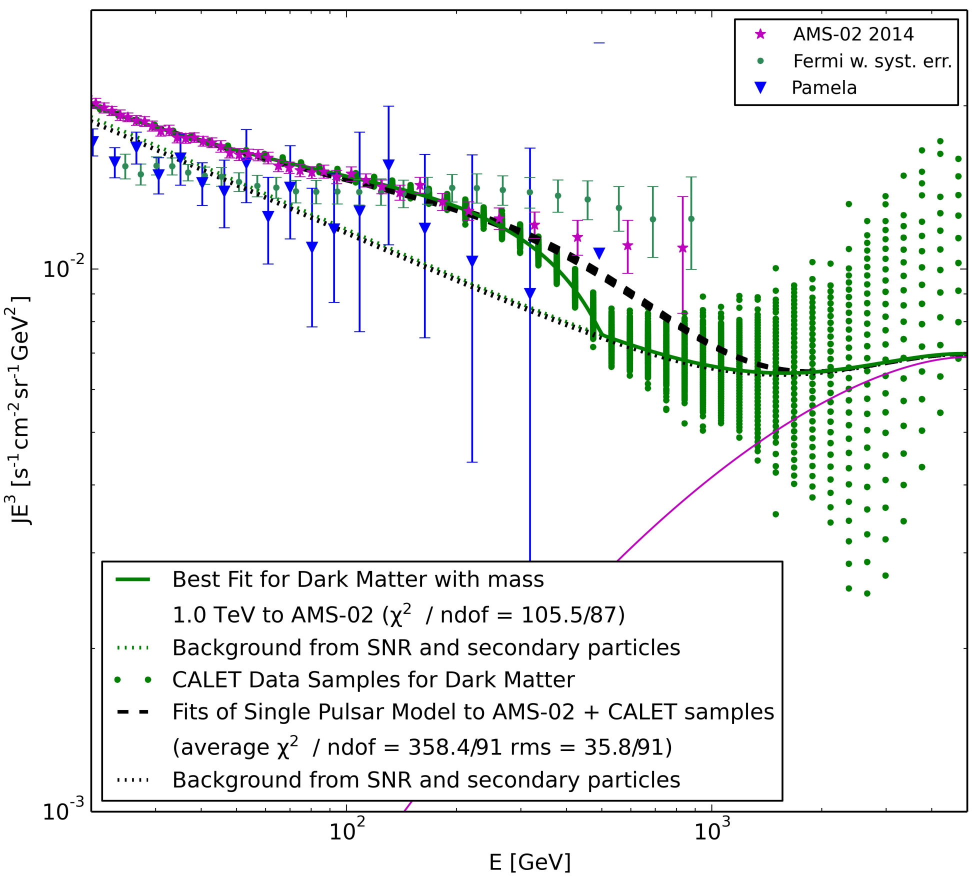


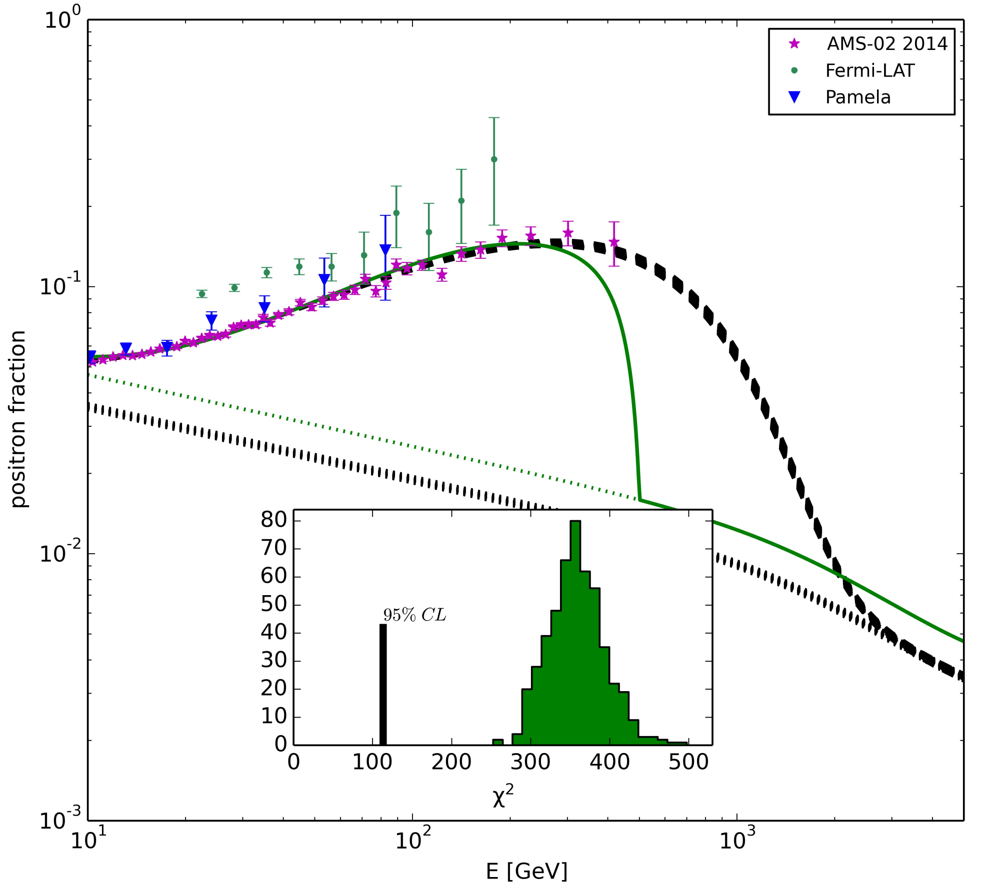


- **1 TeV** Dark Matter Mass
- Extra source provides positron excess only → electron + positron spectrum adjusted by strong contribution from nearby SNR (Vela , $2 \cdot 10^{48}$ erg)
- Decay does not include channel $\chi \rightarrow \tau^+ \tau^- \nu$
- Possibly further reduction of gamma flux by adopting a non-spherical halo profile

Prospects for the Low-Gamma Flux Scenario

$75\%\ \chi \rightarrow \mu^+ \mu^- \nu\ +\ 25\%\ \chi \rightarrow e^+ e^- \nu$





- 100 % of simulated samples have χ^2 > 95% CL
  → distinct drop in spectrum at half the Dark Matter mass

Origin of the Positron Excess

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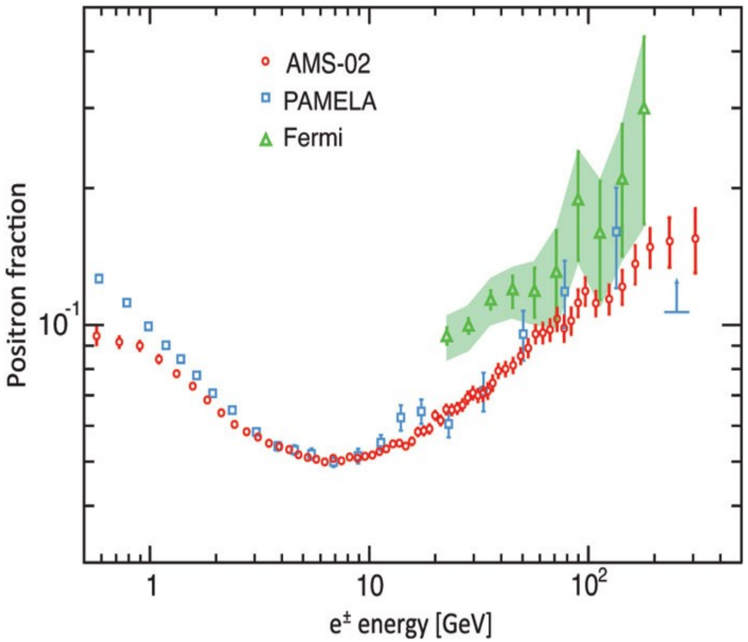

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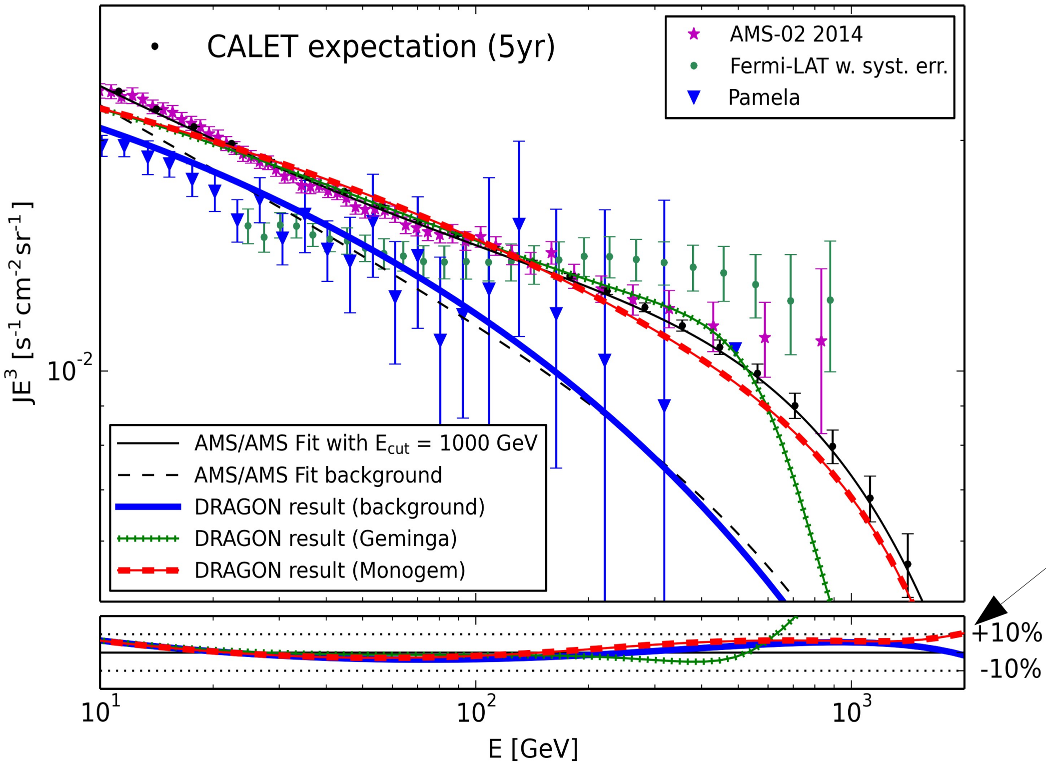
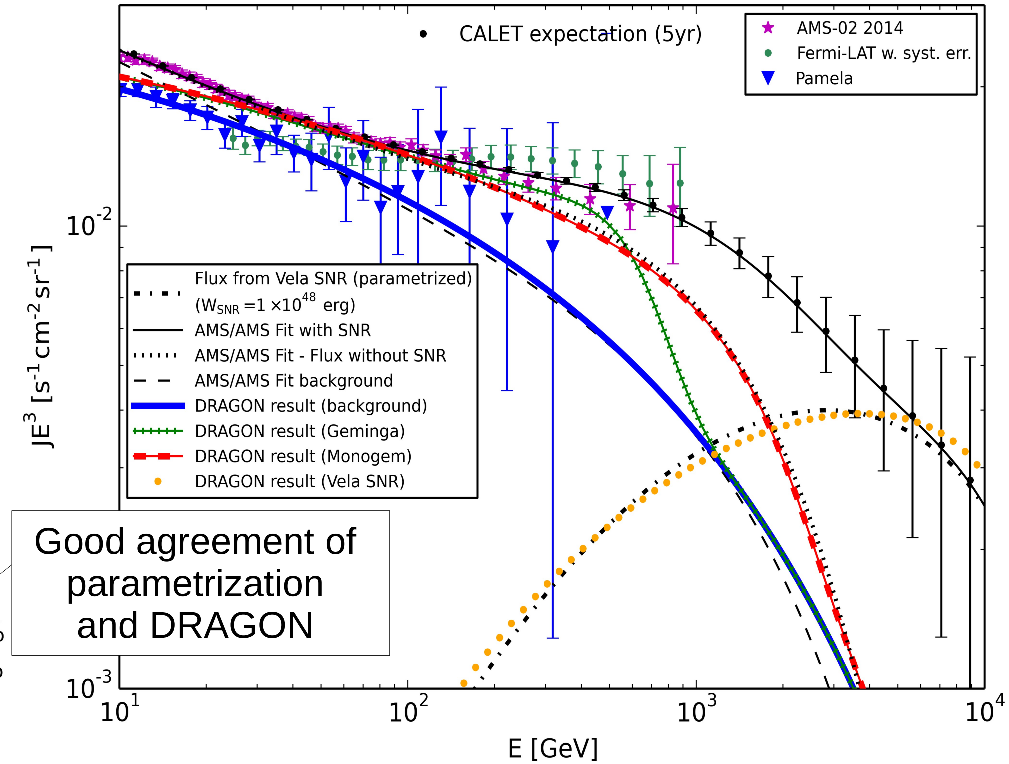
Expected Limit Calculation

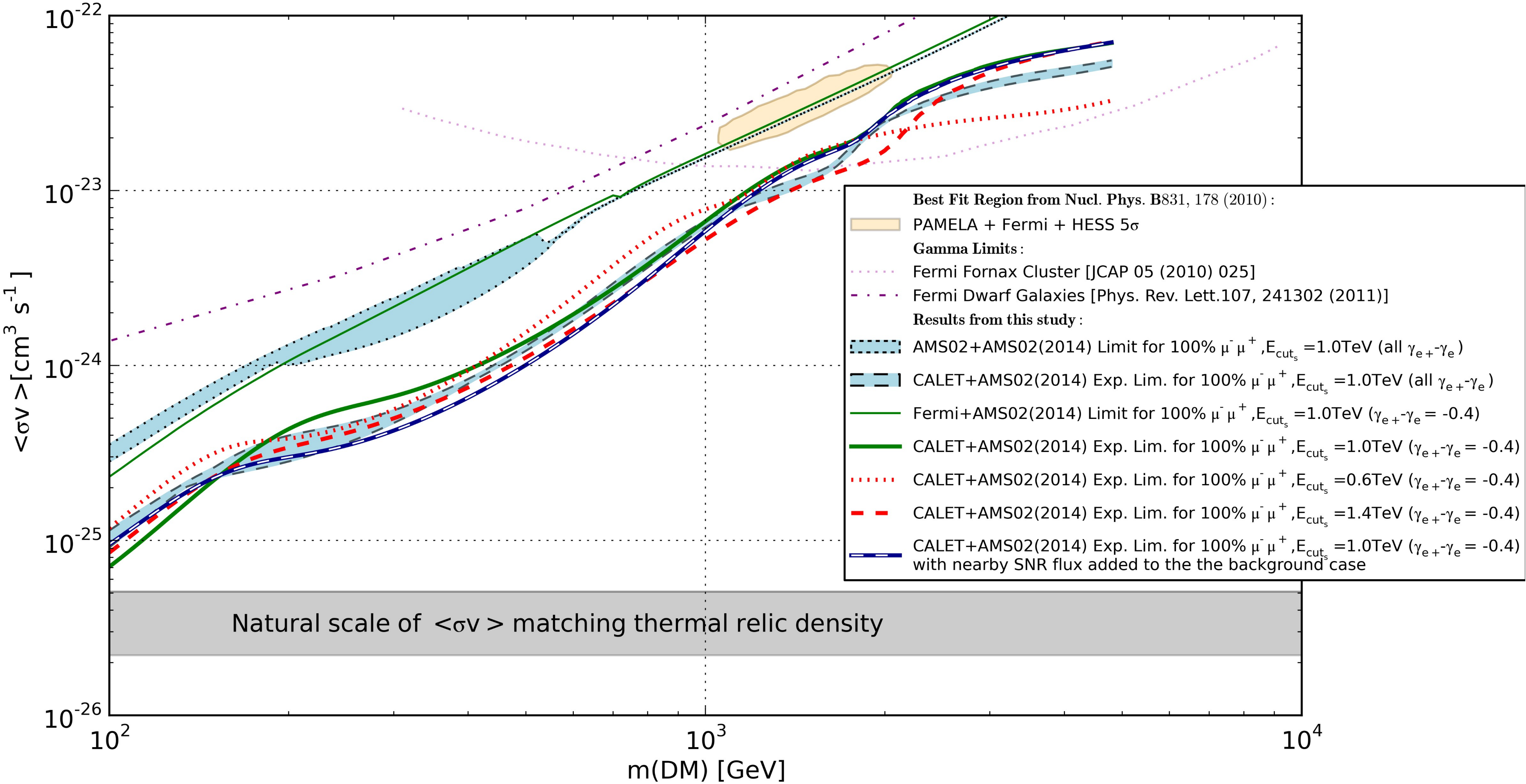




Good agreement of parametrization and DRAGON

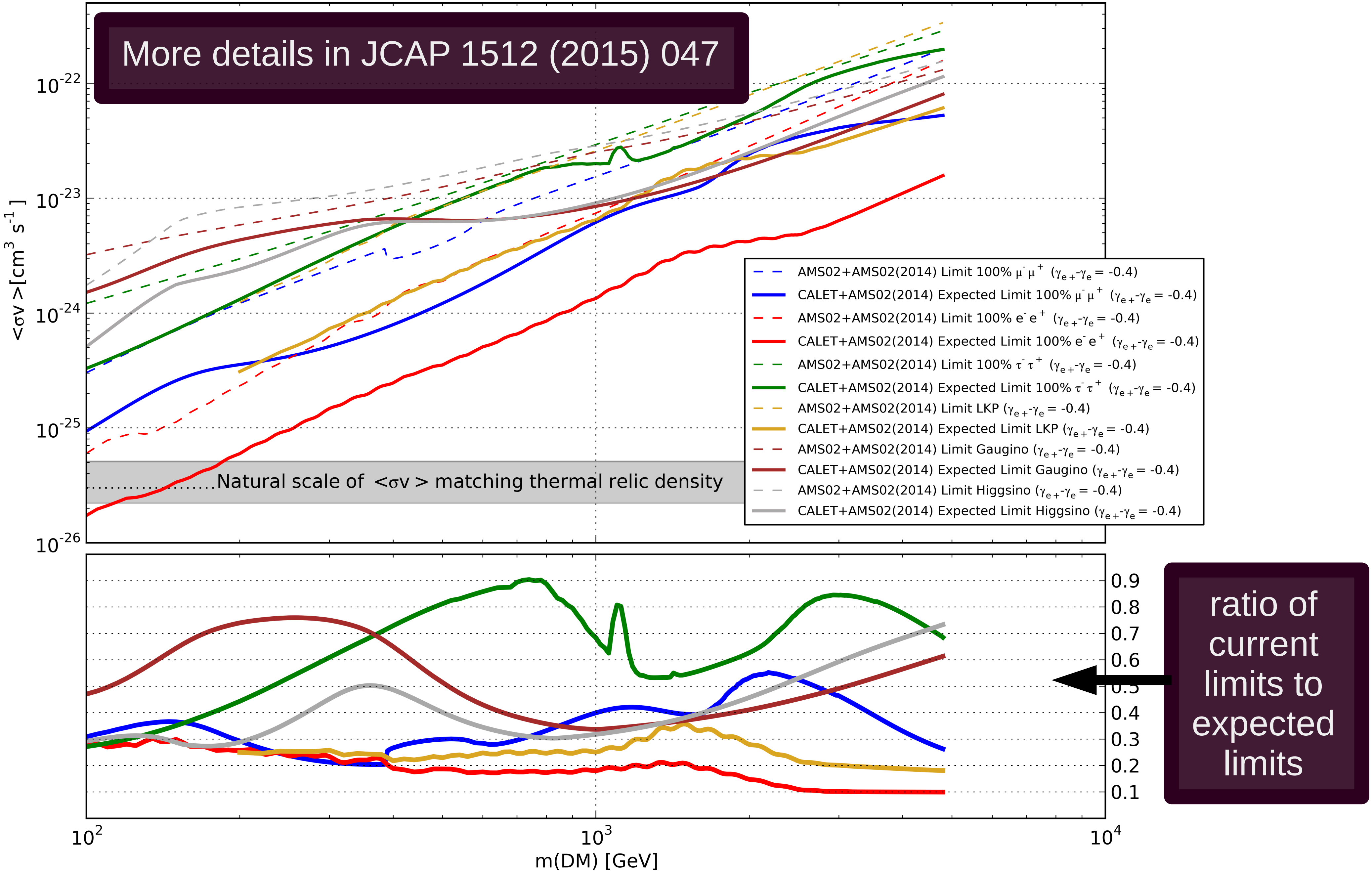
- Statistical samples of 5-year CALET data were simulated for the best fit of the pulsar case to AMs-02 data (with and without additional contribution from Vela SNR)
- Starting from the best pulsar fit, the Dark Matter term is added and the Boost Factor increased until χ^2 reaches the 95% CL exclusion limit → Expected limit

Influence of a Nearby SNR on the Expected Limits ($\mu^+ + \mu^-$ - channel)

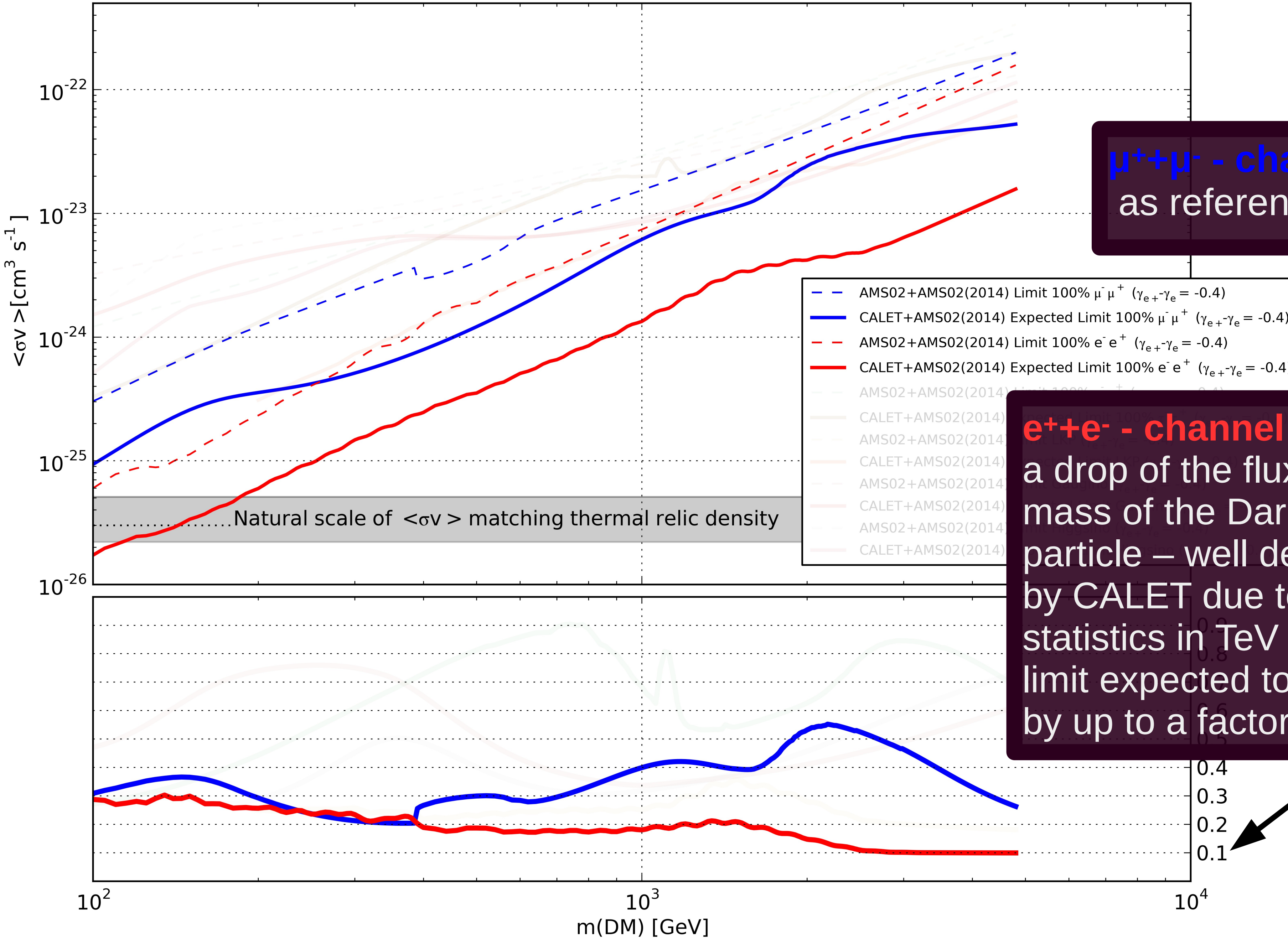


The influence of a nearby SNR as part of the background is small and comparable to other nuisance parameters such as the propagation parameters

Overview of Expected Limits



Annihilation to 100% $e^+ + e^-$

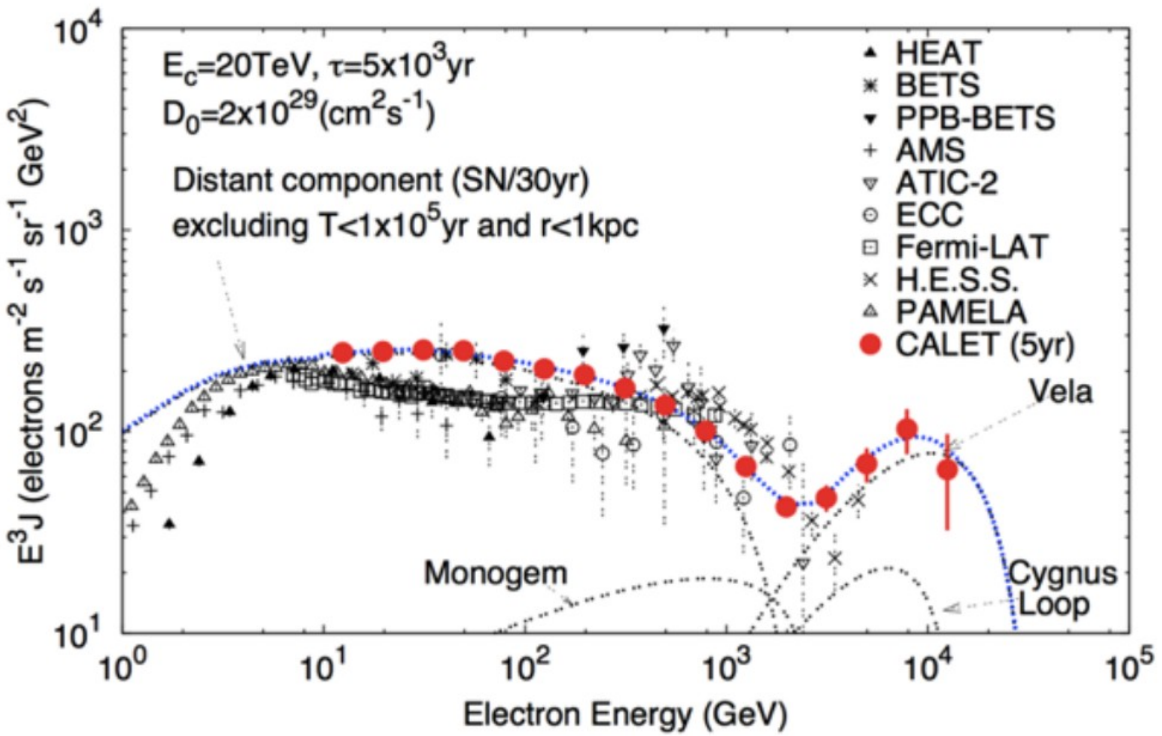


$\mu^+ + \mu^-$ - channel as reference

$e^+ + e^-$ - channel features a drop of the flux at the mass of the Dark Matter particle – well detectable by CALET due to high statistics in TeV region – limit expected to improve by up to a factor of 10

Nearby SNR

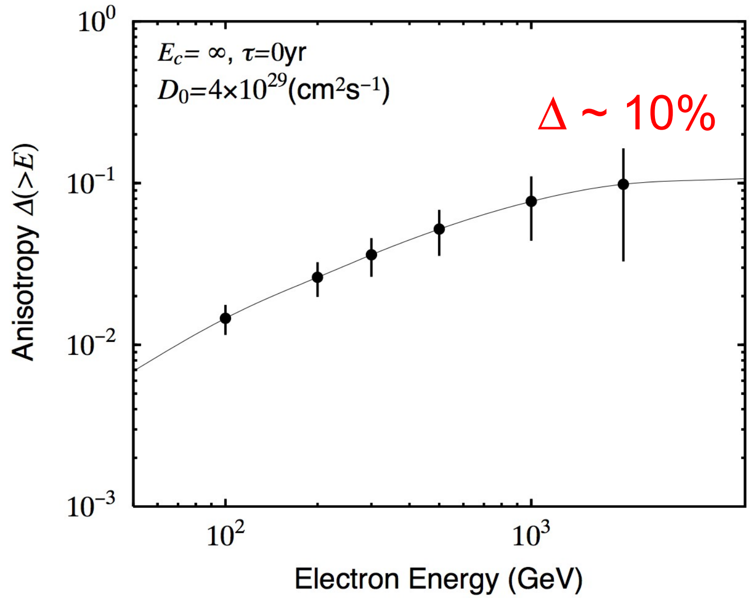
- A nearby SNR (Vela) may be an important part of the background for Dark Matter search
- Identification of a nearby SNR's signature is one of the main targets of the CALET project
- Presence of a distinct signature in the spectrum depends on injection and propagation conditions

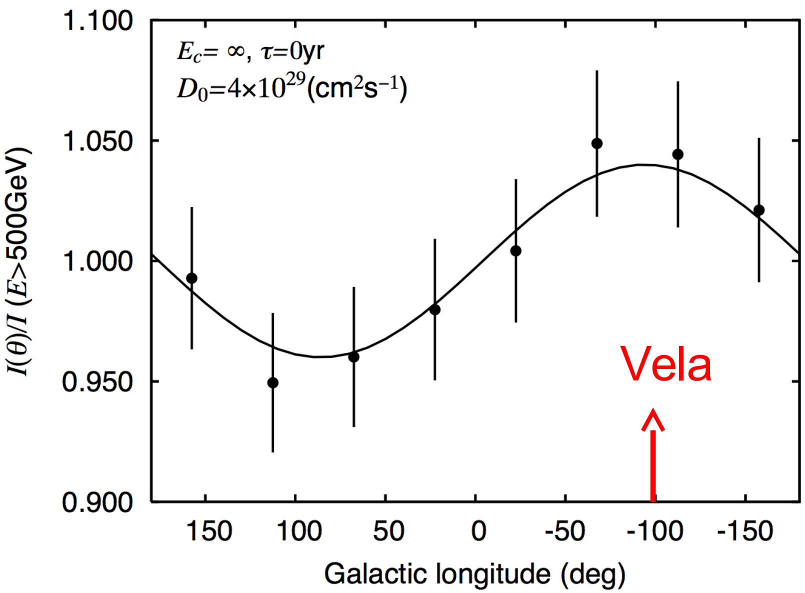


Possible signature of Vela in the TeV-region electron+positron spectrum
Kobayashi et al. ApJ 2004

- In addition to search for spectral features in the TeV-region, cosmic-ray **anisotropy** can be used to identify this nearby point source

Anisotropy from Vela SNR





$$\Delta = \frac{\Phi_{max} - \Phi_{min}}{\Phi_{max} + \Phi_{min}} = \frac{3D}{c} \frac{|\nabla F|}{F}$$

$$D(E) = D_0 \left(\frac{E}{4\,GeV} \right)^{\delta}$$

- Anisotropy increasing with energy, reaches 10 % in TeV region
- Due to better statistics at lower energy, minimum energy of several 100 GeV expected to be optimum
- Refinement of analysis methods ongoing

Summary and Conclusion

- A Dark Matter explanation of the positron excess can most likely be distinguished by spectral shape from a single pulsar, especially for those models potentially fulfilling extragalactic gamma-ray flux constraints
- Limits on Dark Matter annihilation as a potential additional component to a pulsar explanation of the positron excess are expected to be improved significantly, especially for direct annihilation to $e^{+}+e^{-}$
- Detection of a nearby SNR's signature in the TeV region energy spectrum and/or by anisotropy possible
- **CALET has been taking data since one year now, first preliminary results to be released soon!**

→ Plenary talk by Shoji Torii on Thursday 11:30

Backup Slides

Calculation of Decay Spectra with Pythia

- 3-particle decay spectra not published or available from public programs → calculation with Pythia
- Initial momentum distribution of the three outgoing particles has been calculated analytically
- Approximation: mediator is extremely heavy → point-like interaction
- Only handedness of outgoing lepton initial momentum distribution:
- The further decay of outgoing leptons into electrons and positrons was calculated with Pythia 8.2

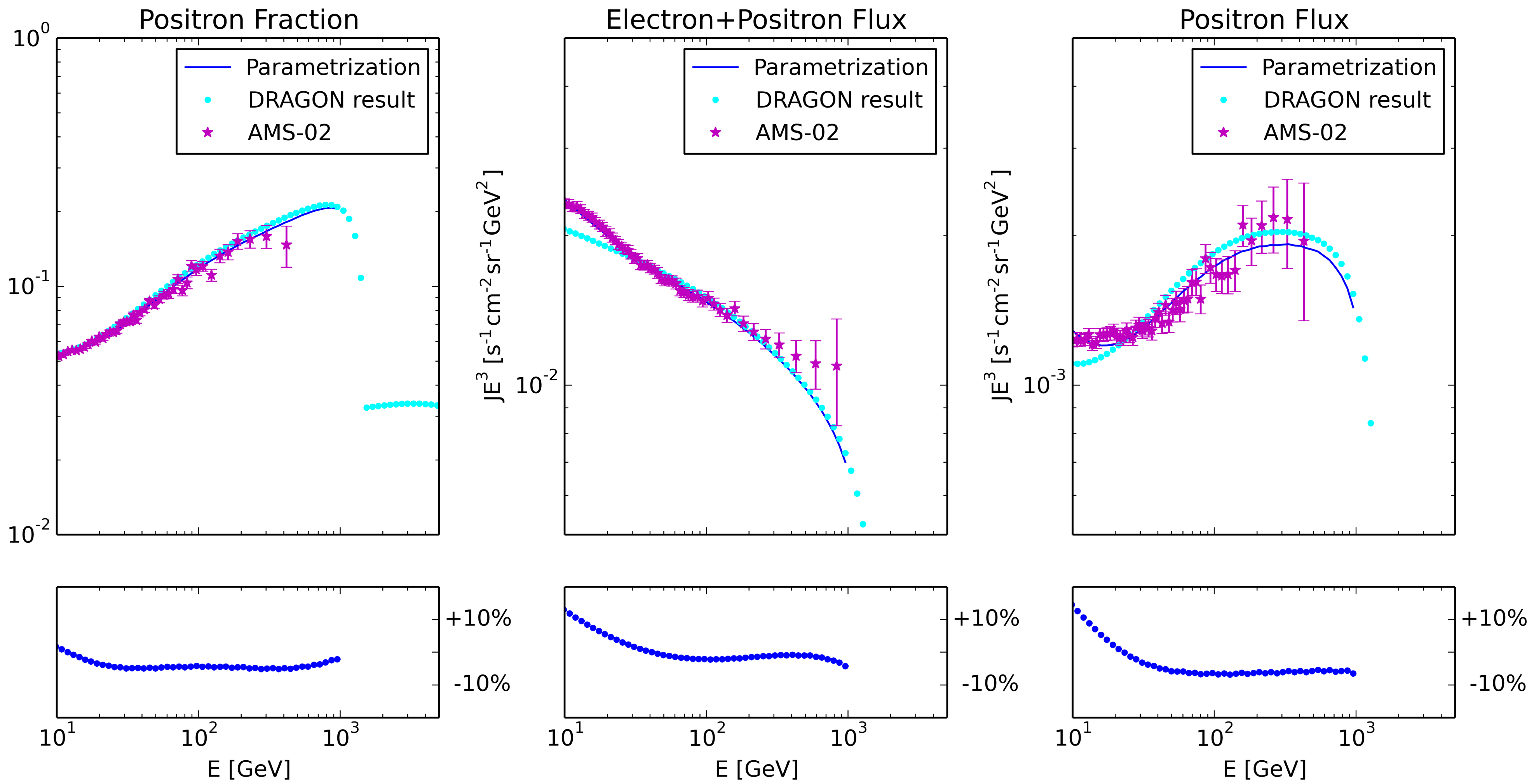
Left-handed:

$$\frac{dP}{dx} = 6x^2 - 4x^3$$

Right-handed:

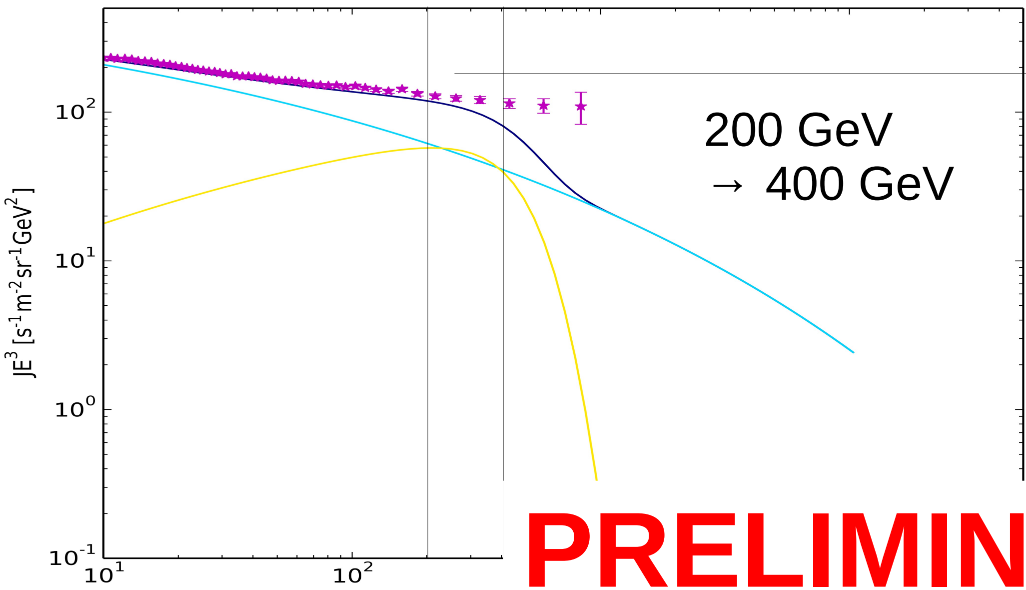
$$\frac{dP}{dx} = 12x - 12x^3$$

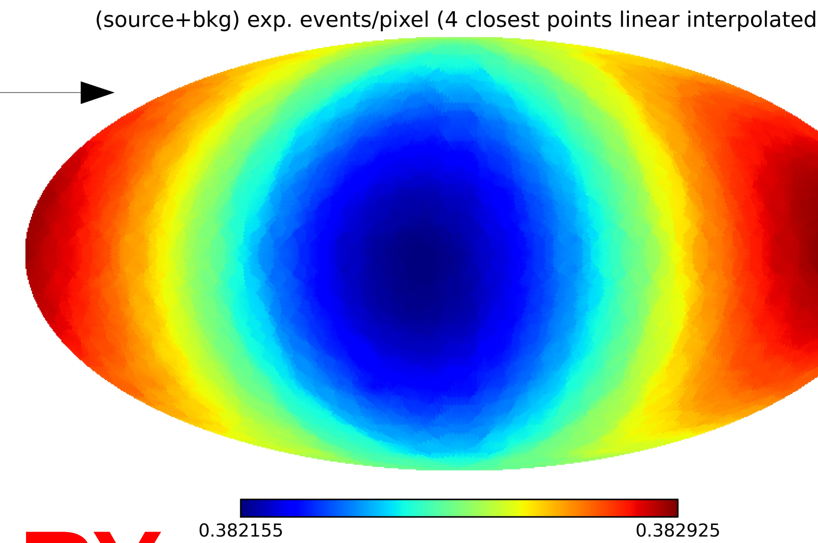
Comparison of the Parametrization with Numerical Calculation



- In the energy range for the fitting (10 GeV – 1 TeV, deviation within 10 %)
- Assumed propagation parameters: $\delta = 0.4$, $D = 3.7\ 10^{28}\ cm^2 s^{-1}$
- Injection power law index for electron spectrum: 2.35

Geminga Pulsar + Vela





PRELIMINARY