# Investigating Leptonic 3-Particle Dark Matter Decay as the Source of the Positron Excess with CALET

JPS Autumn Meeting
Miyazaki 2016/9/21

**21pSP-9**

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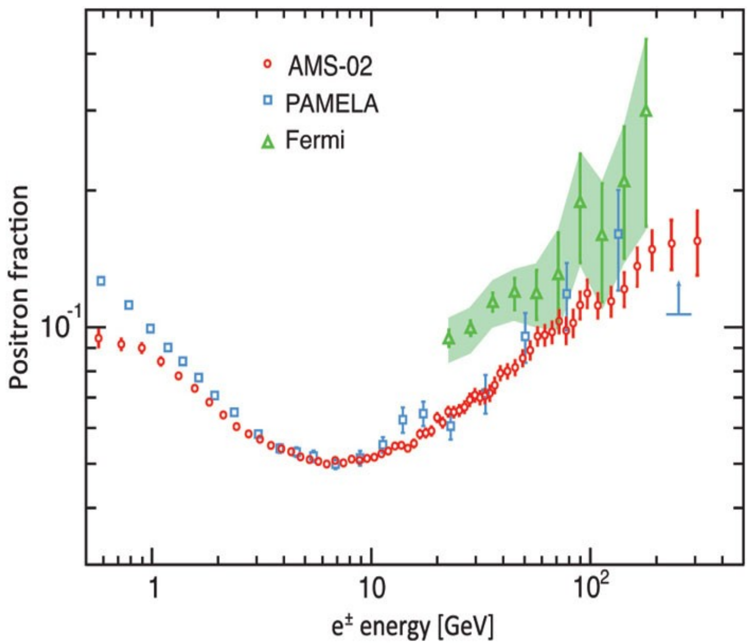
# Origin of the Positron Excess




- Power law with cut-off extra source emitting an equal amount of electrons and positrons proposed by AMS-02 to explain positron excess
- One or more nearby pulsars / pulsar wind nebulae (PWN) could be this extra source → **Pulsar Case**

- **Or by Dark Matter annihilation or decay → Dark Matter Case:** *Can CALET distinguish the spectrum from Dark Matter annihilation or decay from that of a pulsar?*

# 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 $\frac{1}{\tau}$

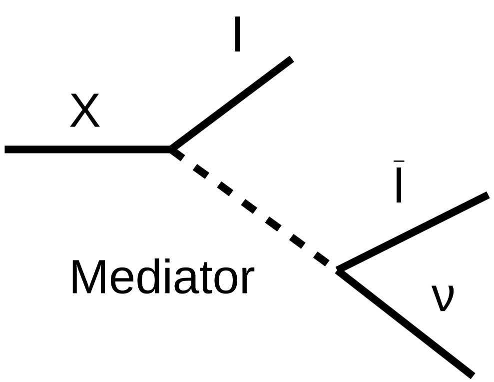
positron flux: $\Phi_{e^+}(E) = \Phi_{extra}(E) + C_e E^{\gamma_e}\left(\frac{C_{e^+}}{C_e}\cdot E^{\gamma_{e^+}-\gamma_e}\right)$

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 carries 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)

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

- 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

# 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 decides initial momentum distribution:
- The further decay of outgoing leptons into electrons and positrons was calculated with PYTHIA 8.2

Left-handed:

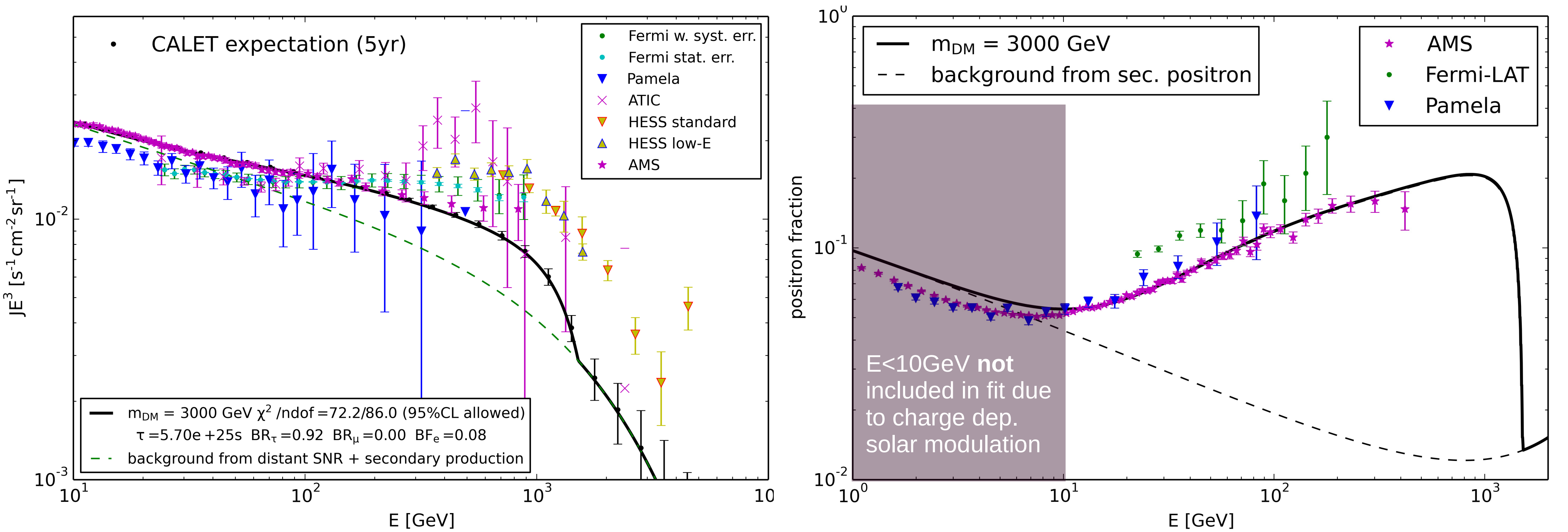
$$\frac{dP}{dx} = 6\,x^2 - 4\,x^3$$

Right-handed:

$$\frac{dP}{dx} = 12\,x^2 - 12\,x^3$$

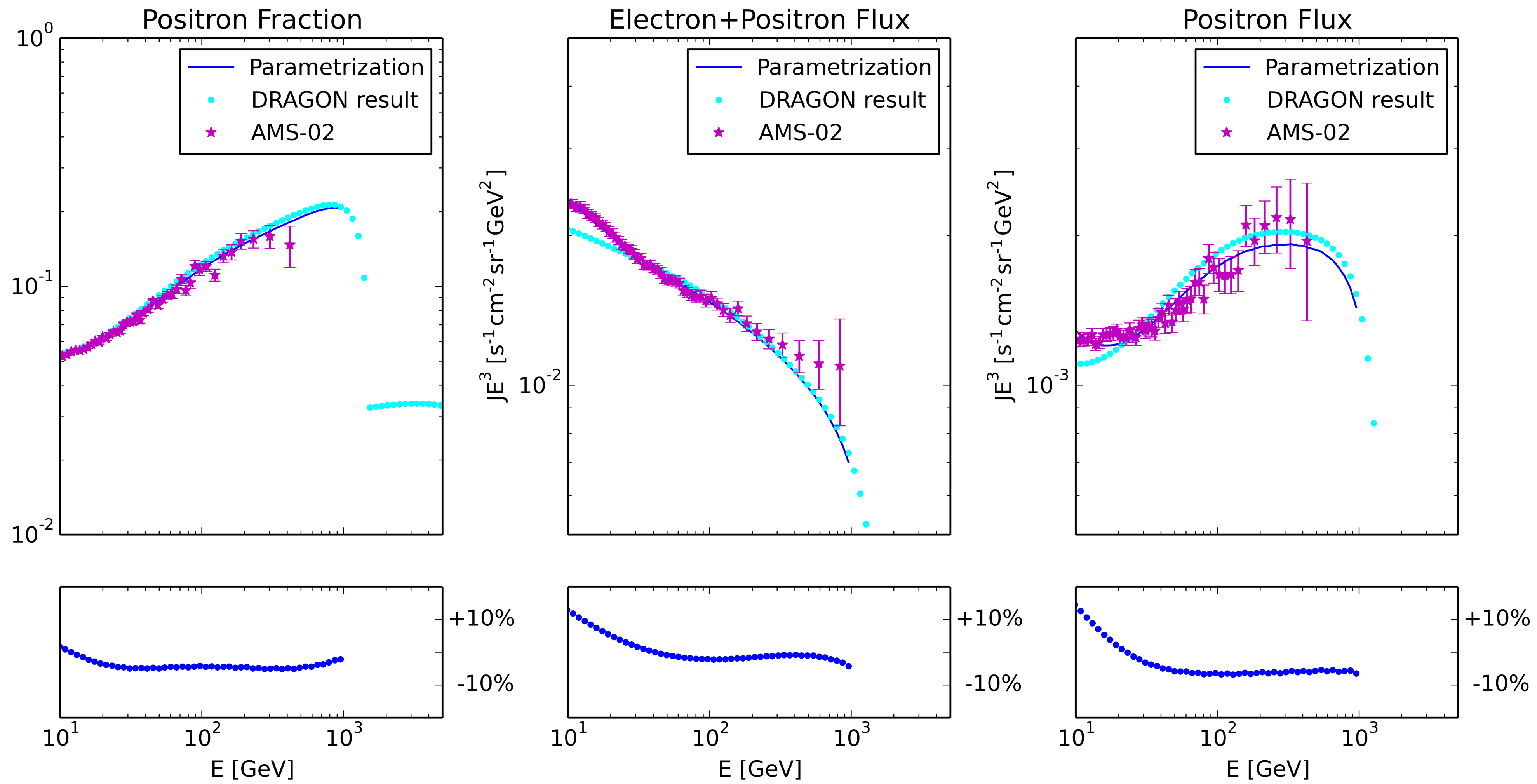
$$x = \frac{2\,E}{m_{DM}}$$

# Fit to Current Data (AMS-02)




- Electron/positron decay spectra propagated with DRAGON
- Parameters optimized by minimization of $\chi^2$ with regard to the predicted **total flux (left)** and **positron fraction (right)**
  → allowed model if $\chi^2$ < 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)

# Comparison of the Parametrization with Numerical Calculation



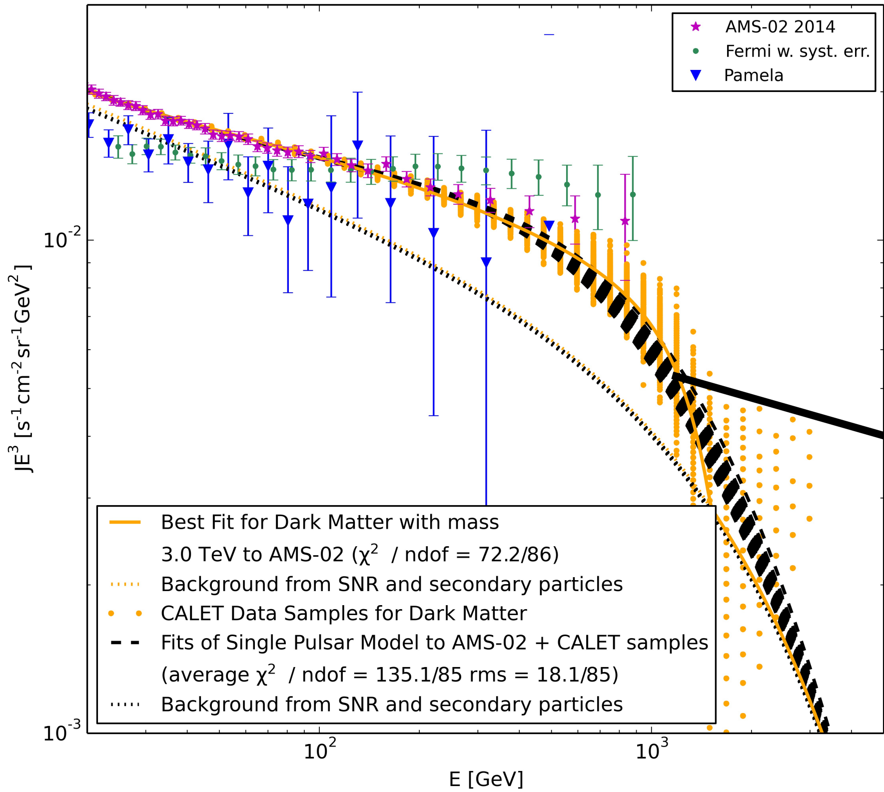

- In the energy range for the fitting (10 GeV – 1 TeV, deviation within 10 %)
- Assumed propagation parameters: $\delta = 0.4$ , $D = 3.7\ 10^{28}\ cm^2 s^{-1}$
- Injection power law index for electron spectrum: 2.35

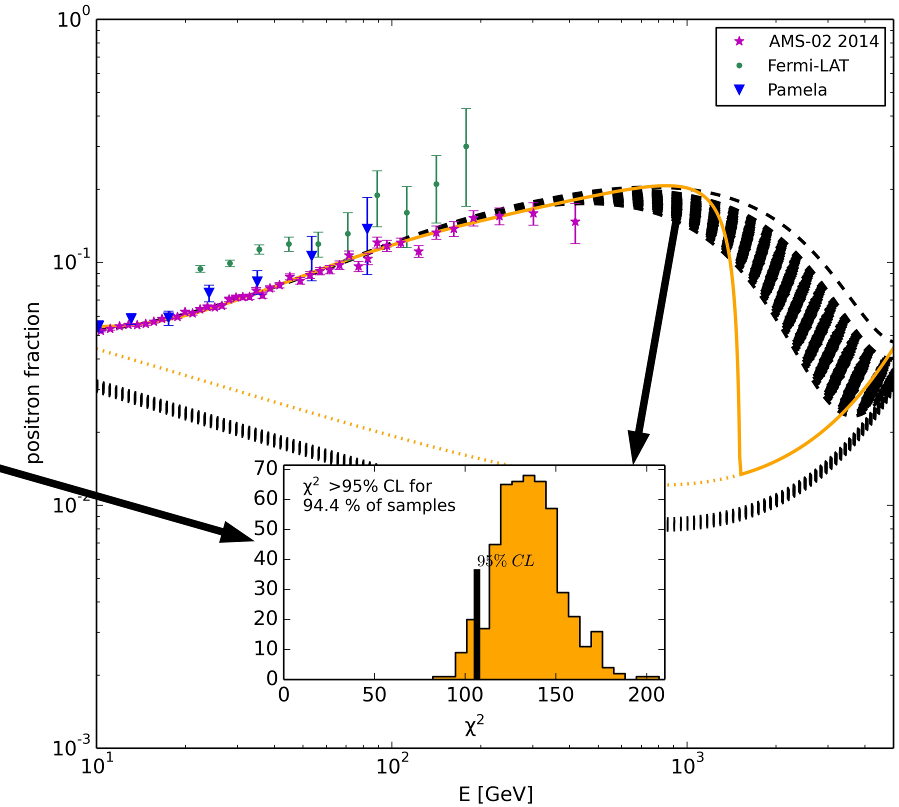
# Prediction for CALET

- 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)
- $\chi^2$ 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

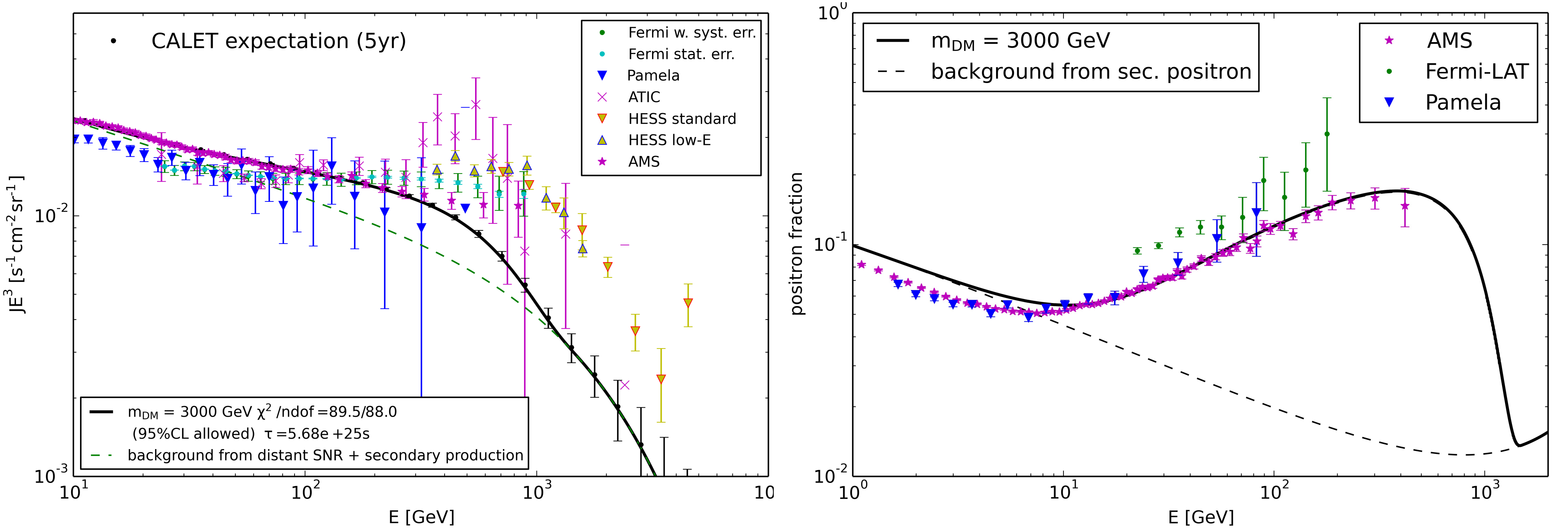
## 92% $\chi \rightarrow \tau^+ \tau^- \nu$ + 8% $\chi \rightarrow e^+ e^- \nu$




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

# Decaying Wino Dark Matter

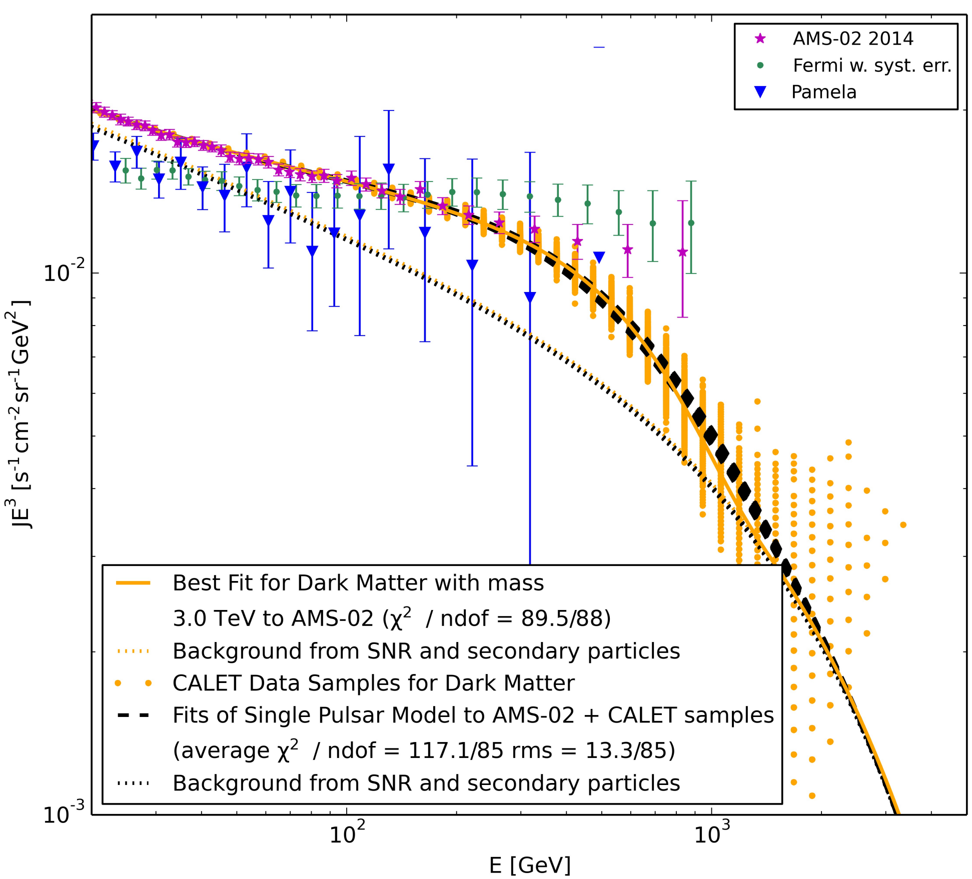


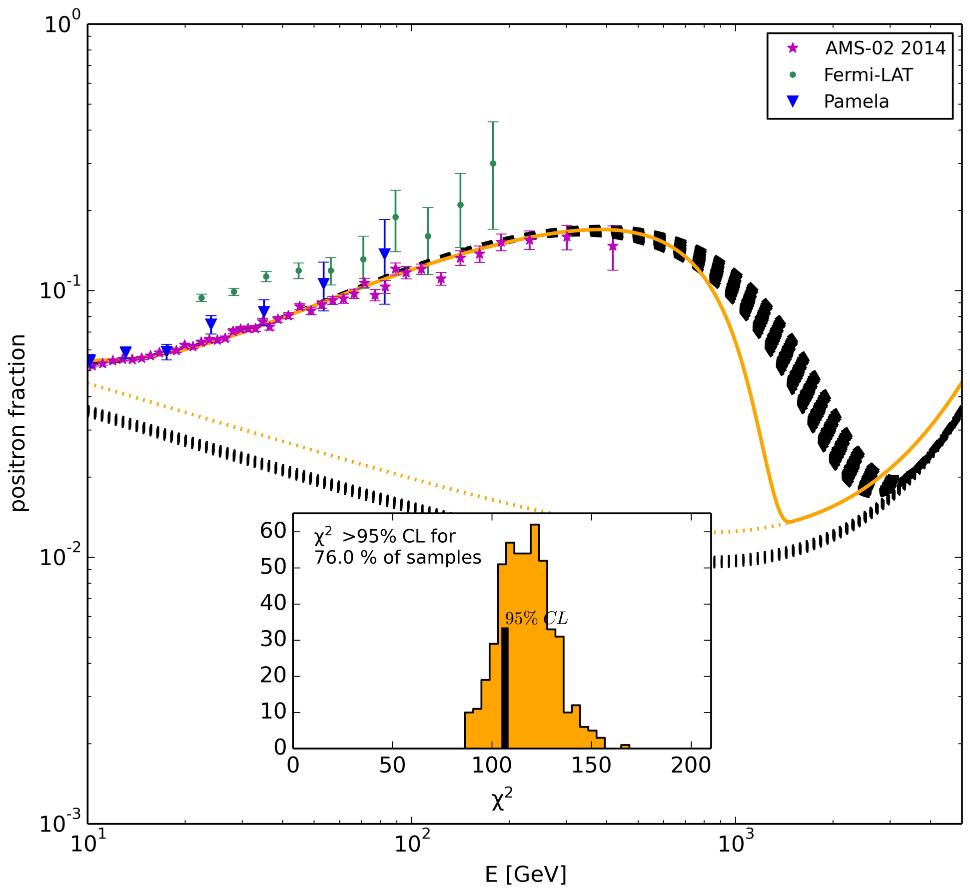

$$50\% \;\; \chi \rightarrow \tau^+ \nu_\mu \tau^-_R \quad + \quad 50\% \;\; \chi \rightarrow \mu^+ \nu_\tau \tau^-_R$$

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

# Discerning Wino Dark Matter Decay from Single Pulsar

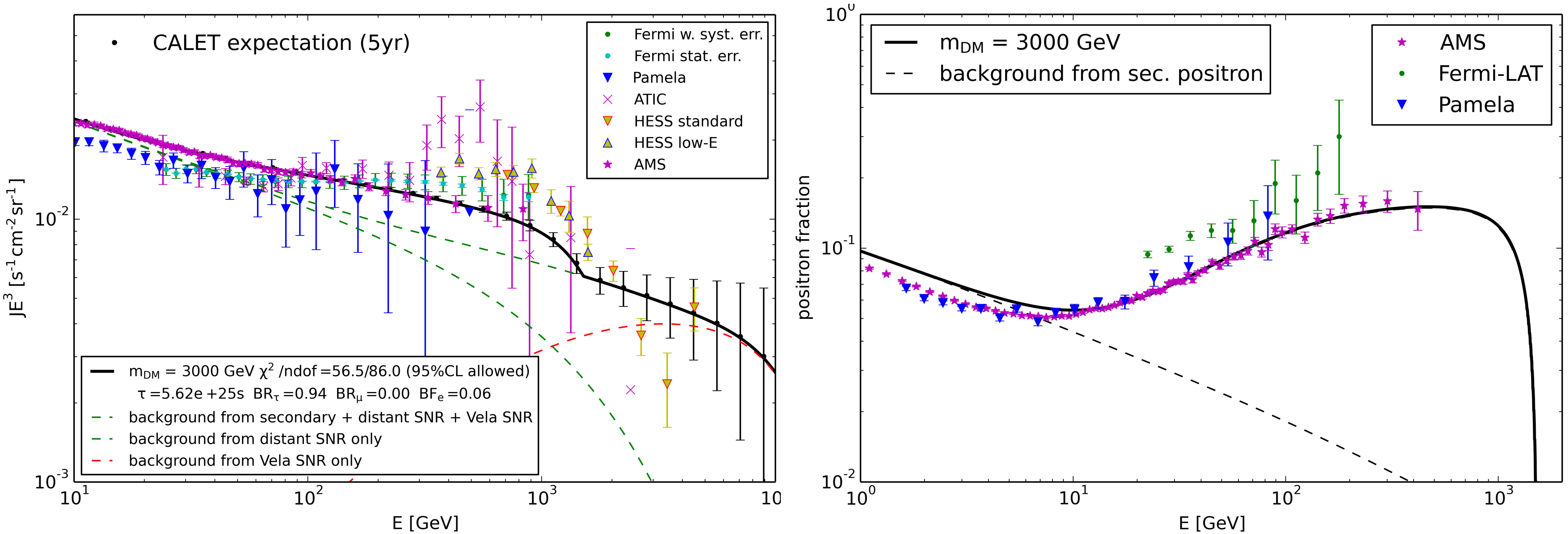
## 50% $\chi \rightarrow \tau^+ \nu_\mu \tau^-_R$ + 50% $\chi \rightarrow \mu^+ \nu_\tau \tau^-_R$




- For this decay mode of Wino Dark Matter, some (24%) samples are indistinguishable from a Single Pulsar.

# Nearby SNR Included in the Model




- Nearby SNR as an electron-only component

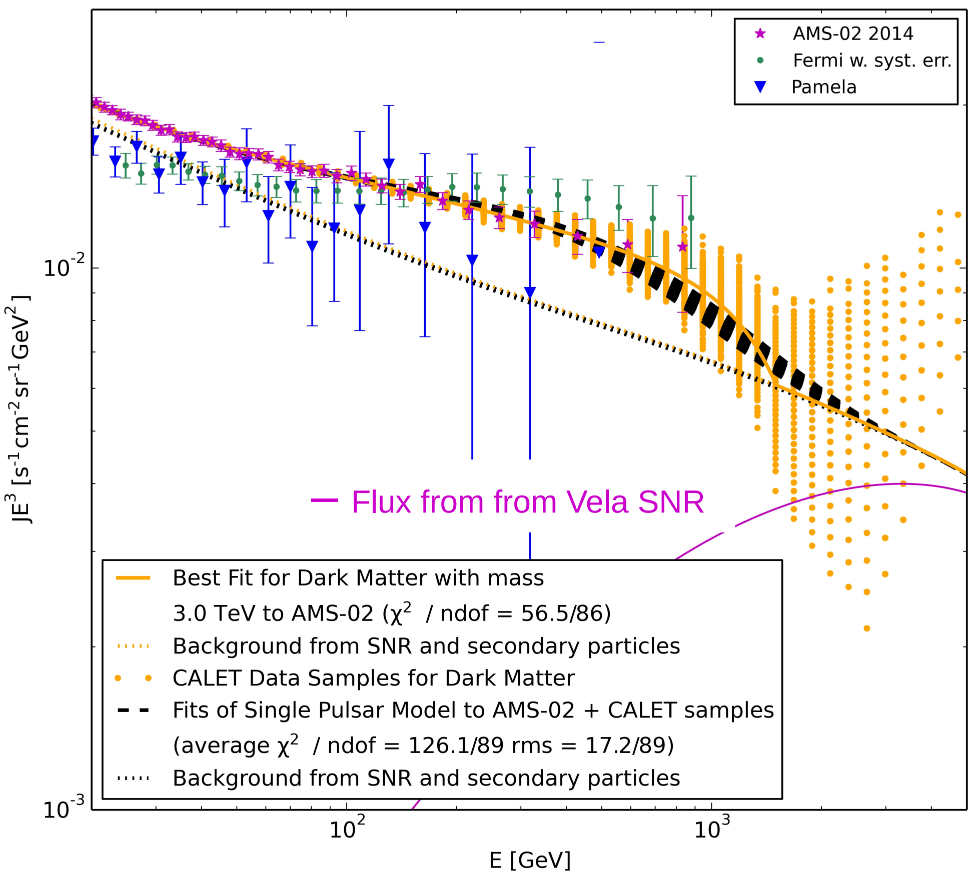
  (Vela , $1{\cdot}10^{48}$ erg – calculated with DRAGON)

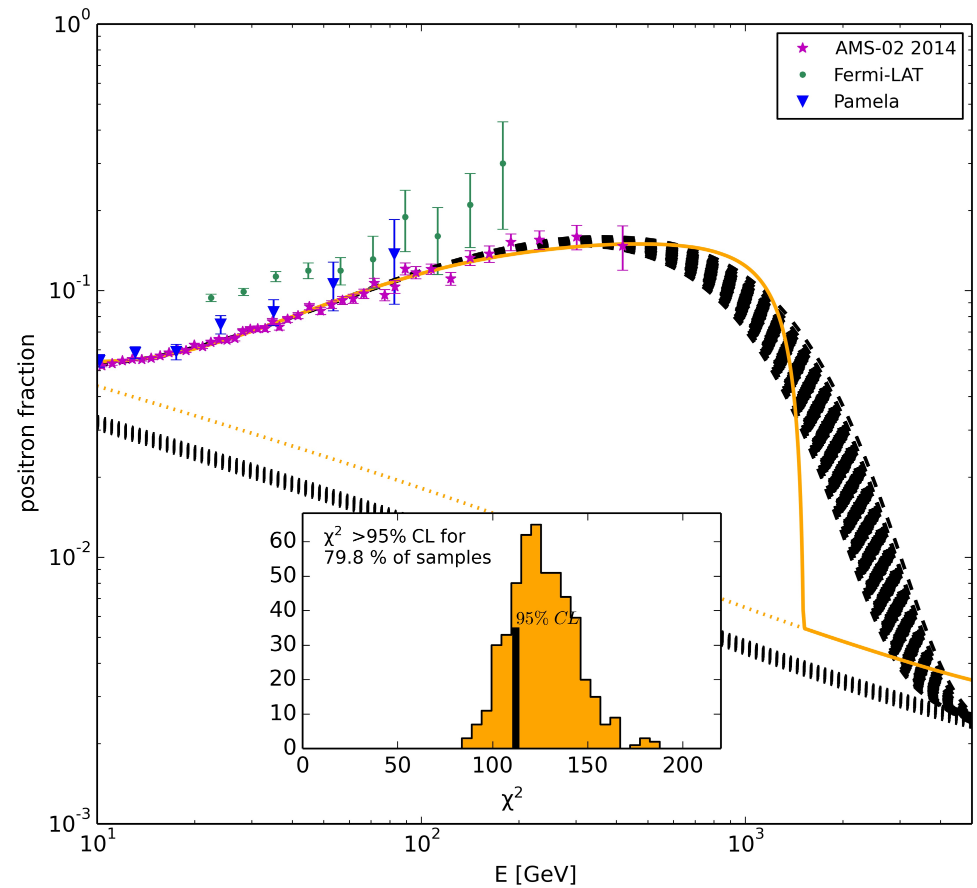
- the best fit for the branching fractions becomes:

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

# Discerning Matter Decay from Single Pulsar with nearby SNR

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




- 79.8 % of simulated samples have $\chi^2$ > 95% CL

# Result Overview

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

shown examples

# Result Overview

| DM mass: | 2 TeV | 3 TeV | 4 TeV |
|---|---|---|---|
| **Free Branching Ratios**<br>Fit to Current data:<br>$X^2$ /ndf for AMS-02 | 62.1 / 86 | 72.2 / 86 | 87.3 / 86 |
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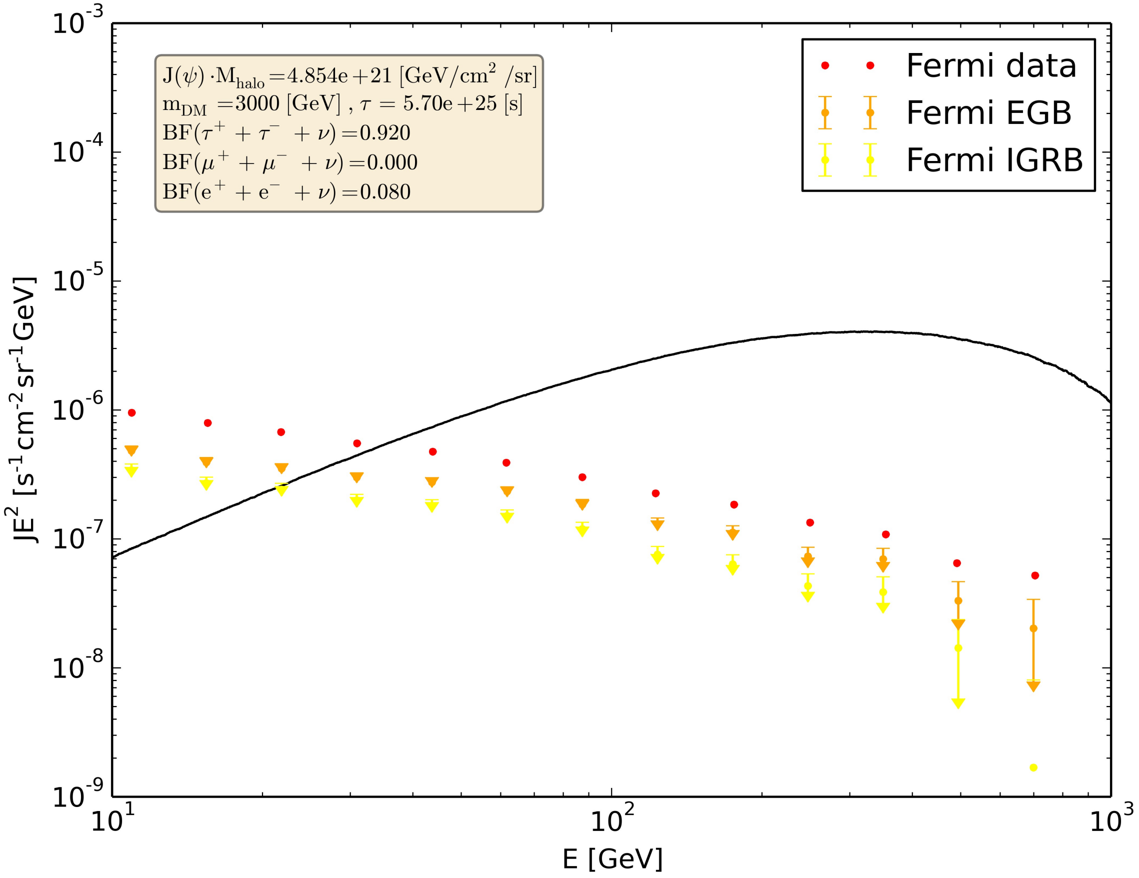
| **Wino Deca**<br>Fit to Curre<br>$X^2$ /ndf for |  | 89.5 / 88 |  |
| CALET sim<br>ffraction of<br>$\chi^2 > 95$ %C |  | 76.0 % |  |
| **Wino Decay with Vela**<br>Fit to Current data:<br>$X^2$ /ndf for AMS-02 | 79.6 / 88 | 70.8 / 88 |  |
| CALET simulation:<br>fraction of samples with<br>$\chi^2 > 95$ %CL | 98.6 % | 57.6 % | - |

shown examples

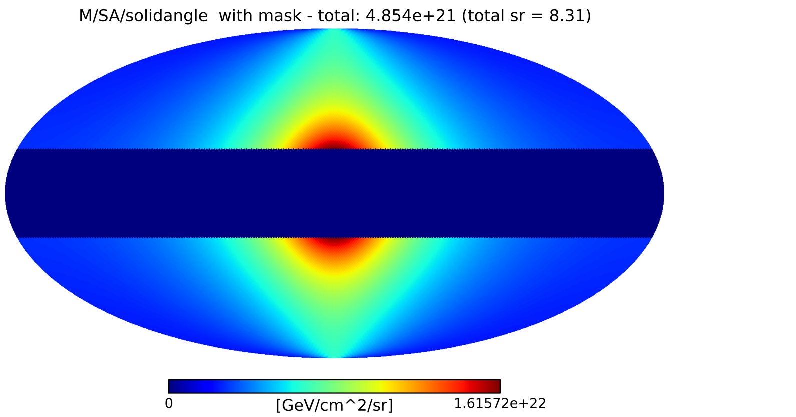
**CALET can most likely discern these models from a single pulsar**

**Discrimination from single pulsar difficult due to similar spectrum**

# Gamma Constraints

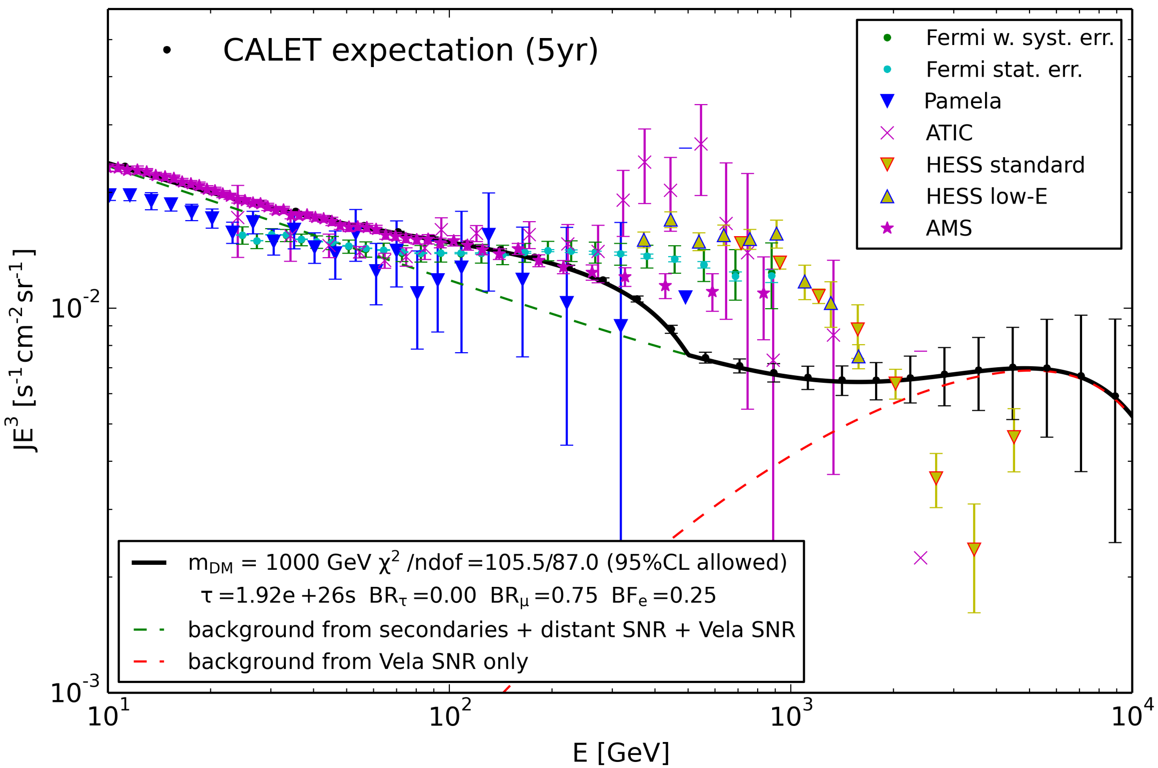


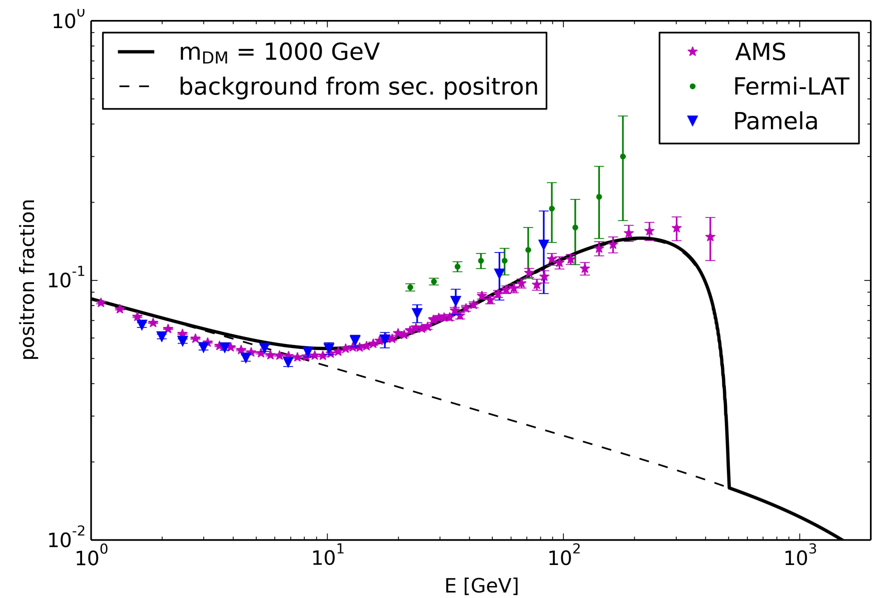

- Gamma flux for galactic latitude (absolute value) larger than 20 degree
- Photons from FSR and those produced in decay of primary decay products (calculated with PYTHIA)
- NFW halo model assumed

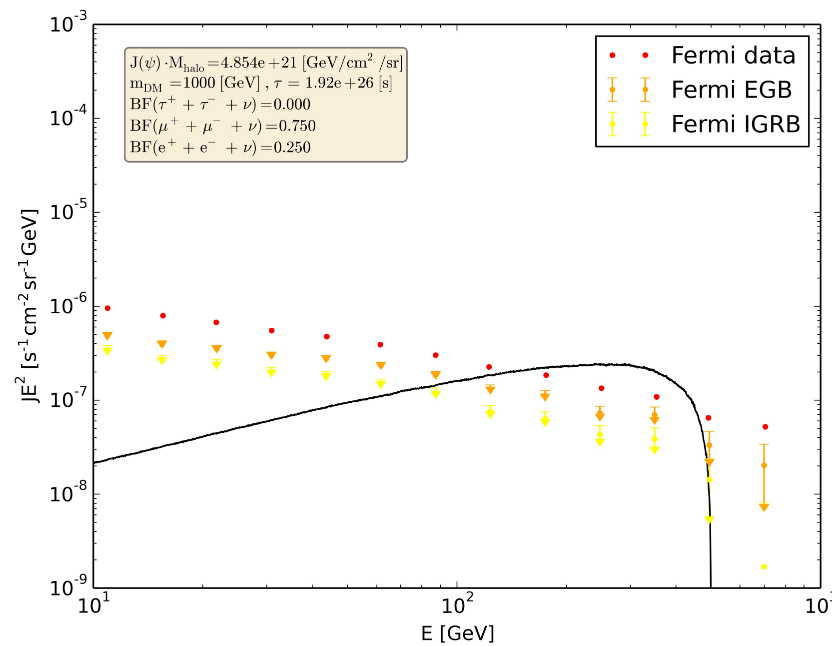



→ For best fit model, expected gamma emission significantly exceeds gamma flux measured by Fermi in the same region

# Low Gamma-Flux Scenario



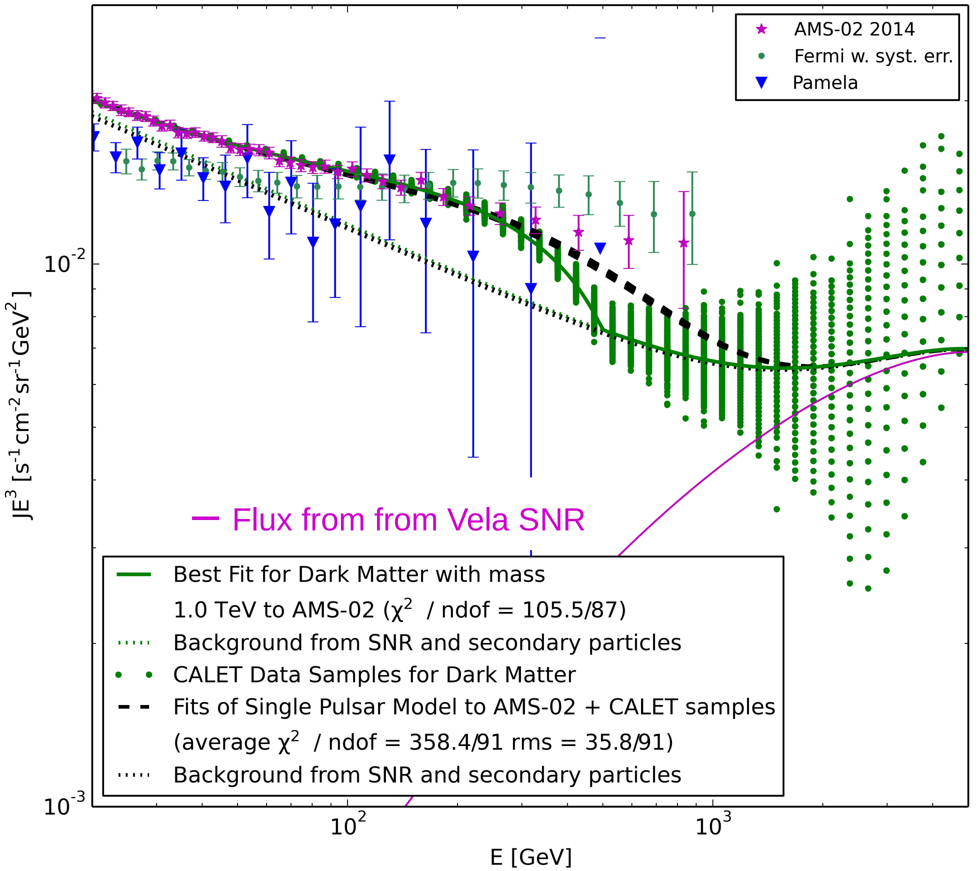



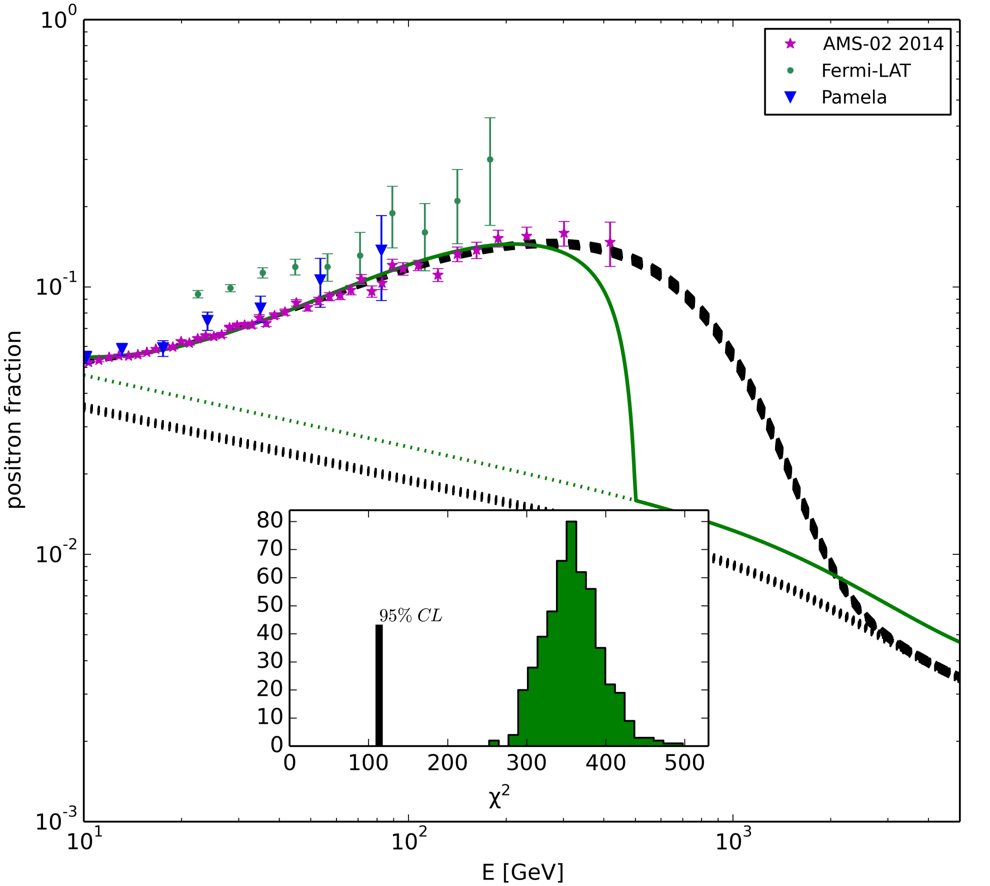




- **1 TeV** Dark Matter Mass
- Extra source provides positron excess only → electron + positron spectrum adjusted by strong contribution from nearby SNR (Vela , $2{\cdot}10^{48}$ erg)
- Decay does not include channel $\chi \rightarrow \tau^+ \tau^- \nu$
- Possibly further reduction of gamma flux by non-spherical 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 $\chi^2$ > 95% CL
  → distinct drop in spectrum at half the DM mass

# Conclusion

- Dark Matter decay into two leptons and a neutrino can in most cases be distinguished from a single PWN as the only source of the positron excess
- Most Dark Matter models fit current data better with the expected flux from a nearby SNR (Vela) included in the background flux.
- Explaining the positron excess with decay of Dark Matter with mass around 1 TeV might be allowed by constraints from Fermi extragalactic gamma flux measurement → decay into muon and electron favoured → clearly detectable by CALET

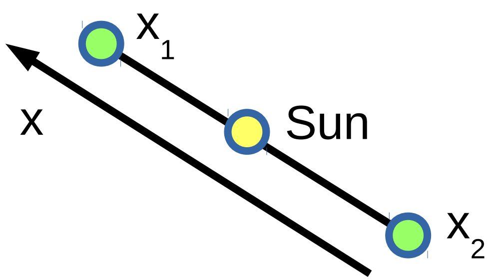
# Backup Slides

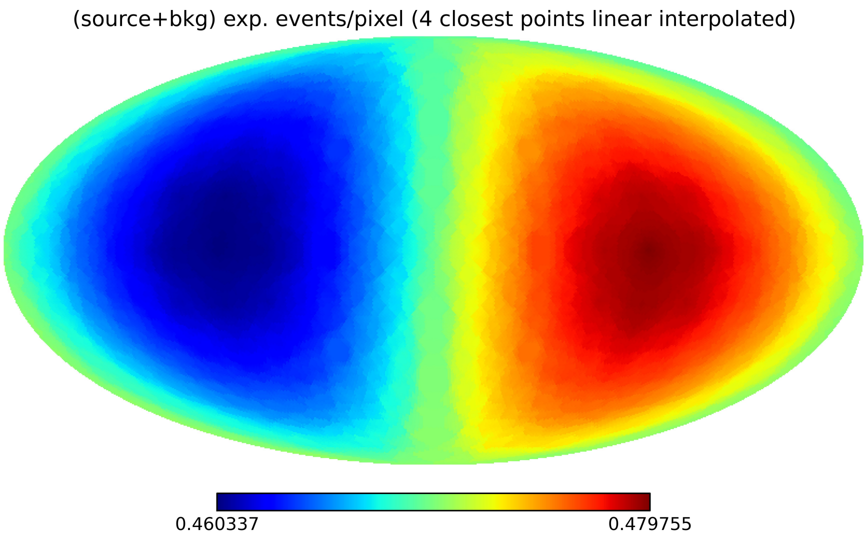
# Nearby SNR Detectability by Anisotropy

**PRELIMINARY**

- Anisotropy calculation with DRAGON:
  - Fine grid around Sun
  - Directional flux calculated from differences in cosmic ray density ***F*** :

$$\Phi_{dir} = \Phi_{avg}\left(1 + \frac{3D}{c}\frac{(F_{x1} - F_{x2})/|x_1 - x_2|}{F_{Sun}}\right)$$



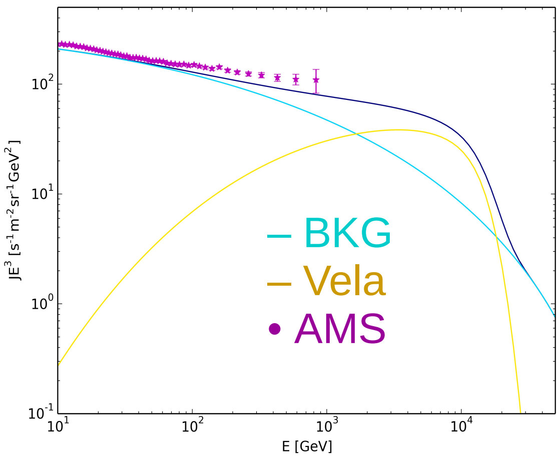



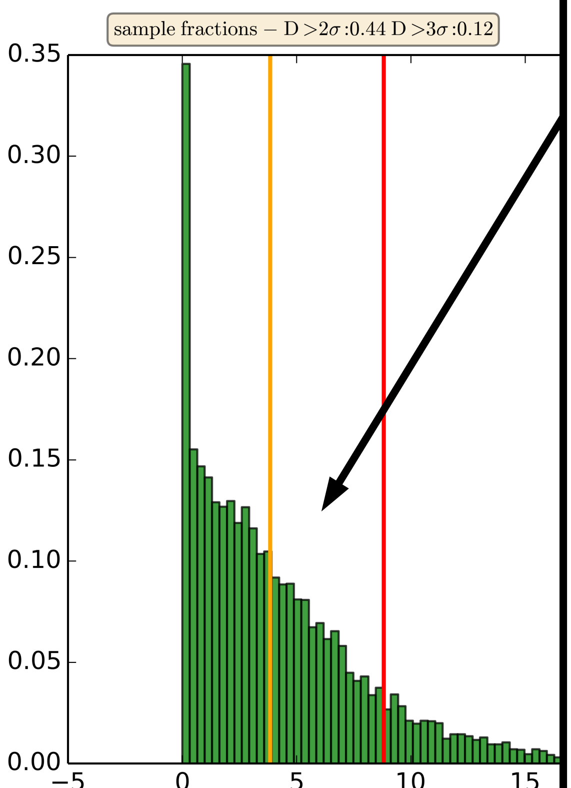

Healpix Map of expected events with E > 200 GeV in CALET for 5-years of data-taking
(Vela SNR + background)

→ Analysis of simulated data samples with likelihood-ratio test to determine CALET's ability to detect the anisotropy signature

# Nearby SNR Detectability by Anisotropy

**PRELIMINARY**




Test statistics distribution for the example case shown to the left
→ probability to detect anisotropy with
**2σ : 44%** , and with
3σ : 12%

Parameters:
$\delta = 0.4$
$D = 6.2\ 10^{28}\ cm^{2}\ s^{-1}$
$\gamma_i = 2.4$
T = 0 yr (instantaneous)

Same parameters and spectrum for Vela as in the background case for DM

- Depending on studied injection and propagation parameters, the probability of detection ranges from

**32% to 82 % (2σ)**

7% to 45 % (3σ)

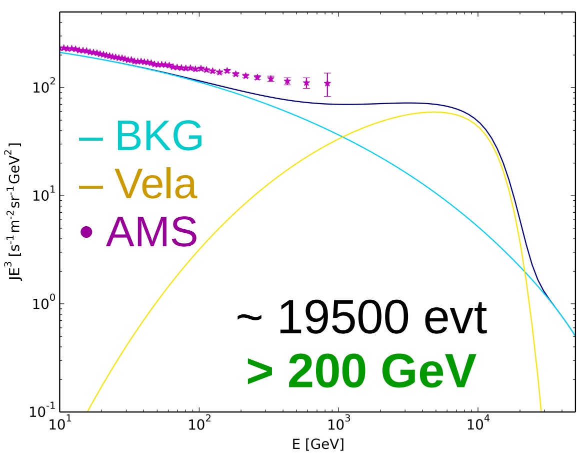
Assuming there is no anisotropy from Vela for this case, a 95 % CL **upper limit of ~ 0.025** above 200 GeV is expected on the anisotropy

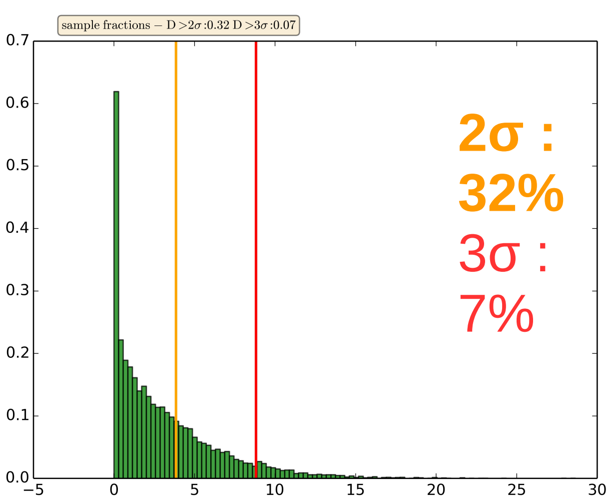
$$\Phi_{max} = (1 + a)\left(\frac{\Phi_{max} + \Phi_{min}}{2}\right)$$

# Spectra and Anisotropy for Different Injection/Propagation

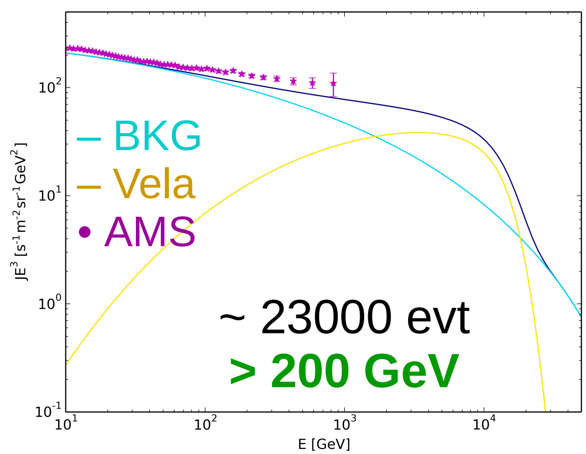
**PRELIMINARY**

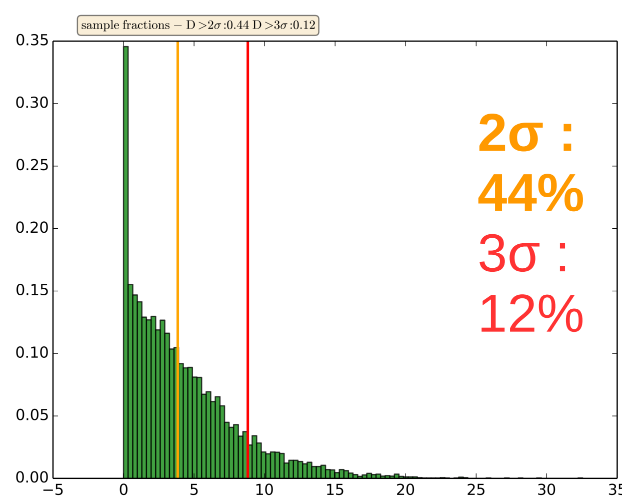
$\delta = 0.4$ , $D_0 = 3.7\ 10^{28}\ \mathrm{cm^2\,s^{-1}}$
$\rightarrow D_{1\mathrm{TeV}} = 33.7\ 10^{28}\ \mathrm{cm^2\,s^{-1}}$
$\gamma_{inj} = 2.4$ , $T = 0$ kyr



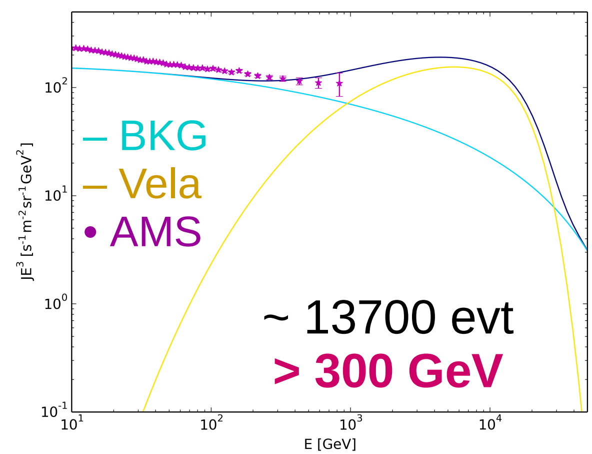



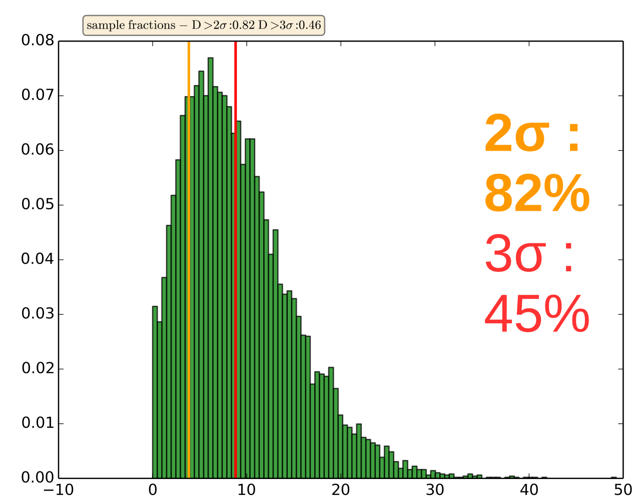

$\delta = 0.4$ , $D_0 = 6.2\ 10^{28}\ \mathrm{cm^2\,s^{-1}}$
$\rightarrow D_{1\mathrm{TeV}} = 36.2\ 10^{28}\ \mathrm{cm^2\,s^{-1}}$
$\gamma_{inj} = 2.4$ , $T = 0$ kyr




$\delta = 0.55$ , $D_0 = 2.2\ 10^{28}\ \mathrm{cm^2\,s^{-1}}$
$\rightarrow D_{1\mathrm{TeV}} = 45.8\ 10^{28}\ \mathrm{cm^2\,s^{-1}}$
$\gamma_{inj} = 2.0$ , $T = 5$ kyr



# Unbinned Analysis

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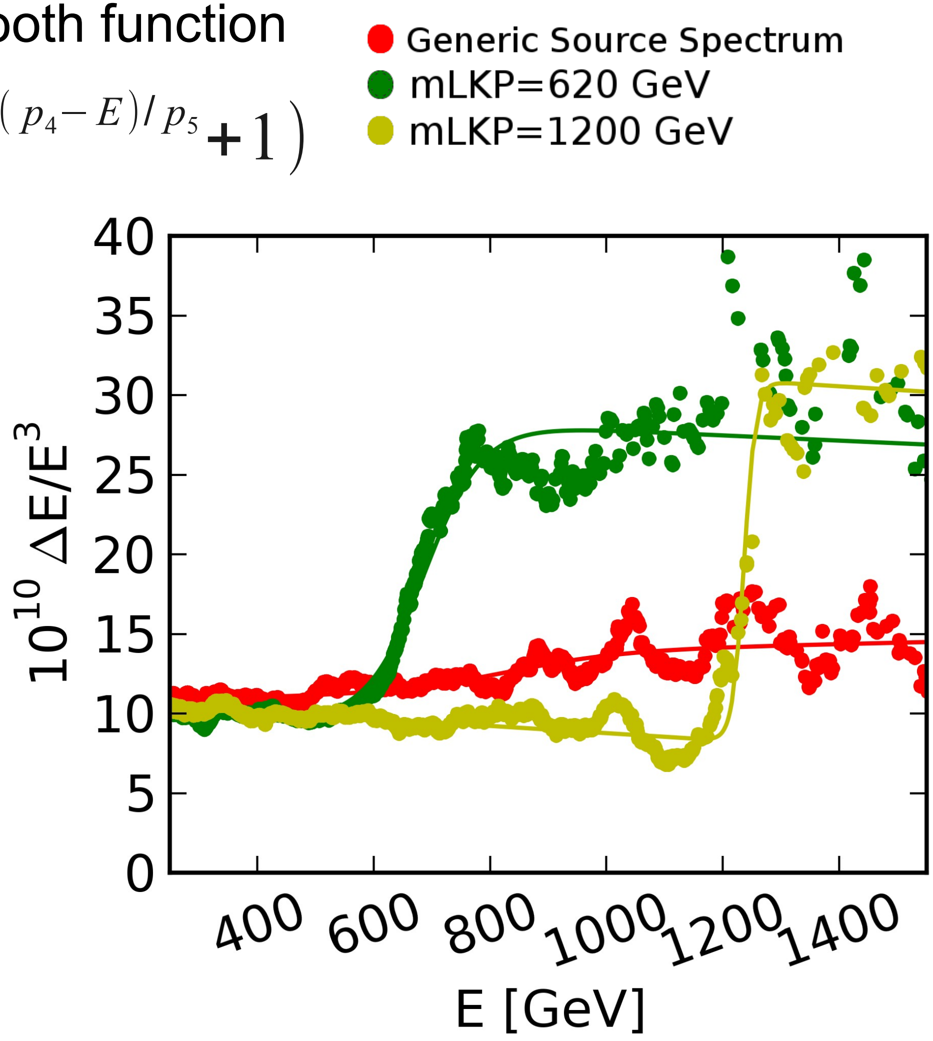
- ΔE(E): Energy difference between energy ordered events (inversely proportional to density of events at energy E)
- -50/+50 GeV sliding average to smooth function

$$10^{10}\,\Delta E / E^3 = p_1 + p_2 \cdot E + p_3 / \left( e^{(p_4 - E)/p_5} + 1 \right)$$




- Analysis by least square fit of parameters in function above
- Step at mass of LKP is identified

=> separation parameter DM/GSS: $p_3/(p_1-6)$ [height of step / base flux]

=> reconstruction of mass possible

$mLKP = p_4 - p_5 - 20$ GeV

[position of the step corrected for its softness]

- Tested with 1000 simulated samples of 2-year CALET data for each case

# Performance of Unbinned Analysis

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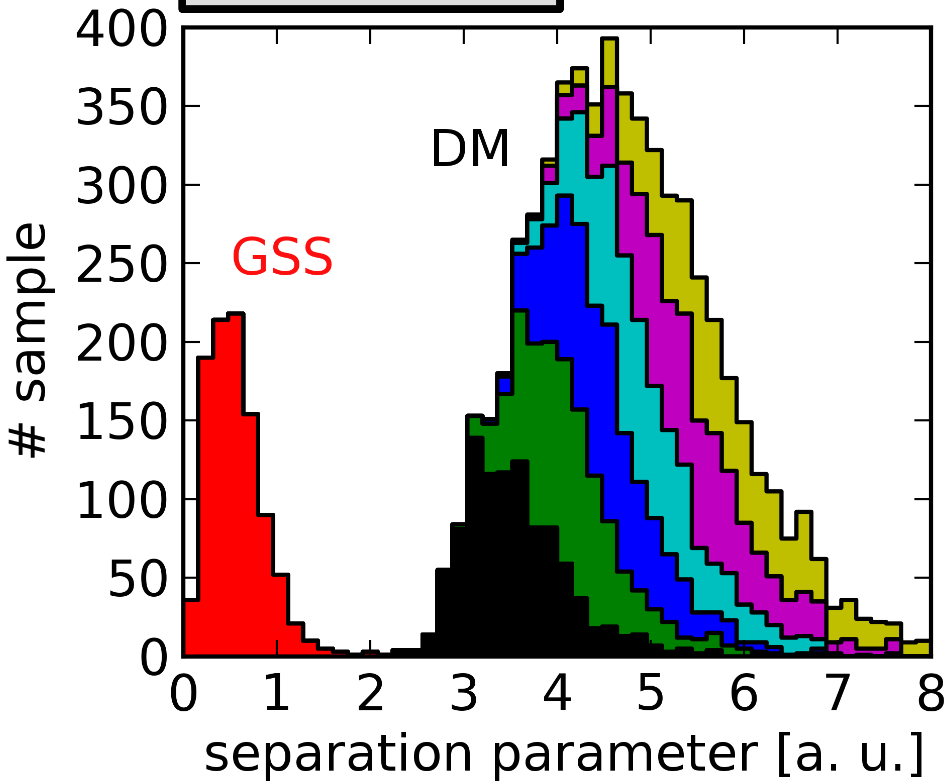


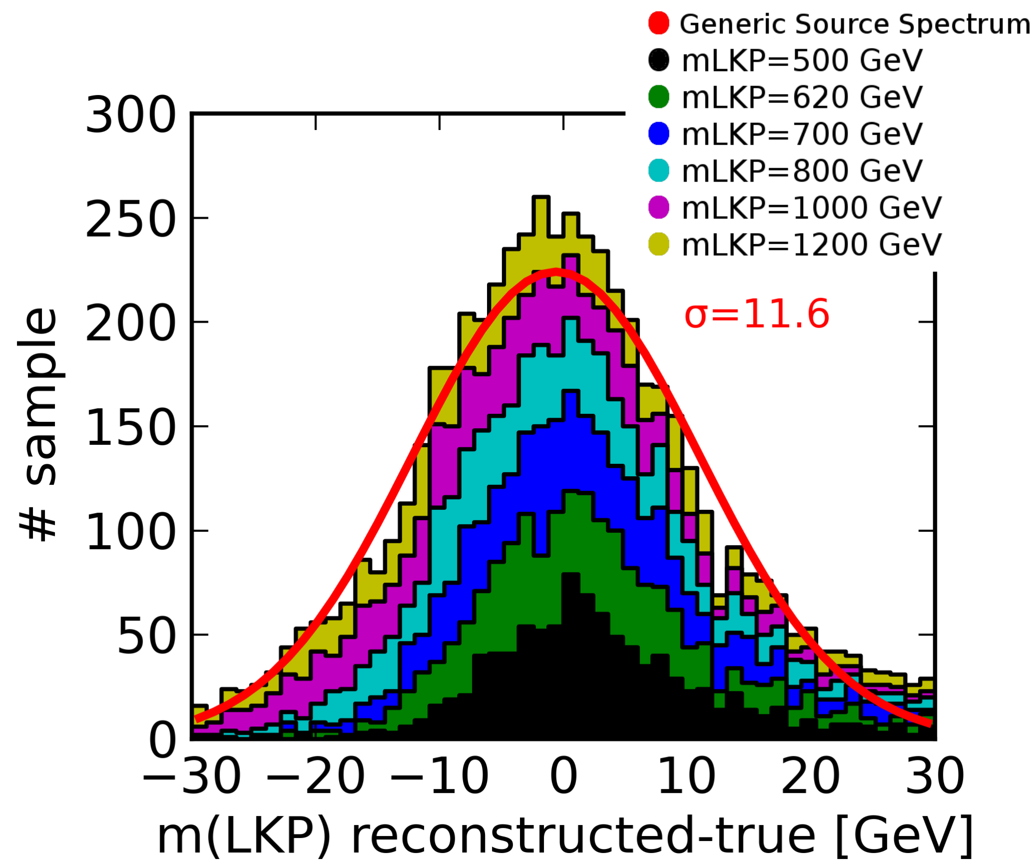


- Clear Separation between local accelerators (Generic Source Spectrum - GSS) and Kaluza Klein Dark Matter Annihilation possible with 2-yr CALET data

- Mass of Lightest Kaluza Klein Particle can be reconstructed with high resolution