Cosmic ray anomalies: recent progress

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Cosmic ray **theory** aims at ...

1. Explaining the locally observed flux

2. Modelling of diffuse backgrounds and application for dark matter searches

3. Defining their environmental effect
   - Providing pressure support
   - Driving Galactic winds
   - Ionising interstellar medium

Cosmic ray **theory** aims at . . .

1. Explaining the locally observed flux

AC RWTH	Mertsch & Vittino
B DESY	Pohl *et al.*
BO RUB	Tjus *et al.*
HD MPIK	Kirk & Giacinti

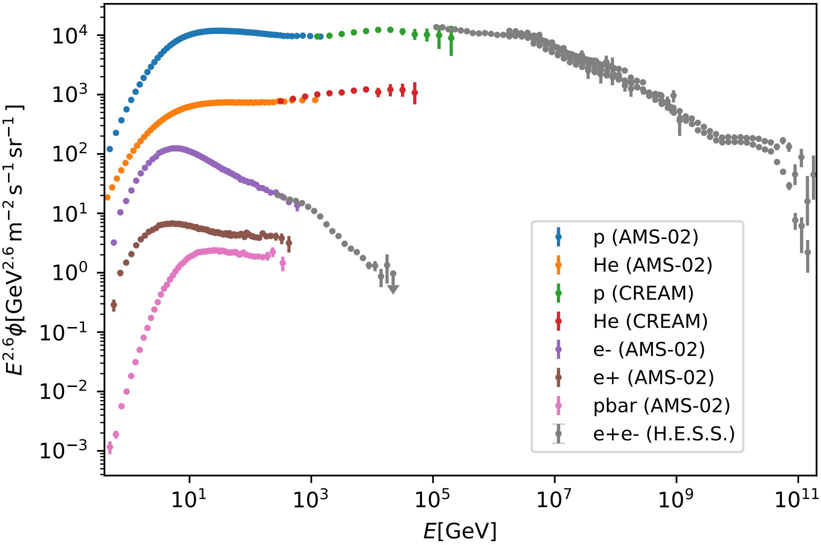
2. Modelling of diffuse backgrounds and application for dark matter searches

AC RWTH	Kraemer *et al.*, Mertsch & Vittino
B DESY	Pohl *et al.*
BN UNI	Kappl, Reinert & Winkler
HH DESY	Sigl *et al.*
KA KIT	de Boer & Gebauer *et al.*, Unger *et al.*
M TUM	Ibarra *et al.*
M MPE	Strong *et al.*
WÜ UNI	Mannheim *et al.*

3. Defining their environmental effect
   - Providing pressure support
   - Driving Galactic winds
   - Ionising interstellar medium

BO RUB	Tjus *et al.*
P AIP	Pfrommer *et al.*

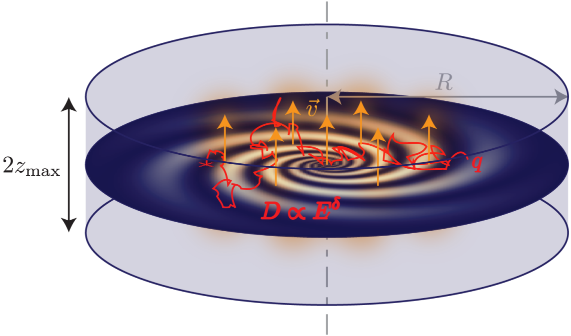
Locally observed fluxes



The transport equation

Ginzburg & Syrovatskii (1964)

$$\frac{\partial \psi_j}{\partial t} - \nabla \cdot (D_{xx} \cdot \nabla \psi_j - \mathbf{u} \psi_j) - \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_j - \frac{\partial}{\partial p} \left(\frac{\mathrm{d}p}{\mathrm{d}t} \psi_j - \frac{p}{3} (\nabla \cdot \mathbf{u}) \psi_j \right)$$
$$= q_j + \sum \left(c \beta n_{\mathrm{gas}} \sigma_{k \to j} + \gamma \tau_{j \to i}^{-1} \right) \psi_k - \left(c \beta n_{\mathrm{gas}} \sigma_i + \gamma \tau_i^{-1} \right) \psi_j$$



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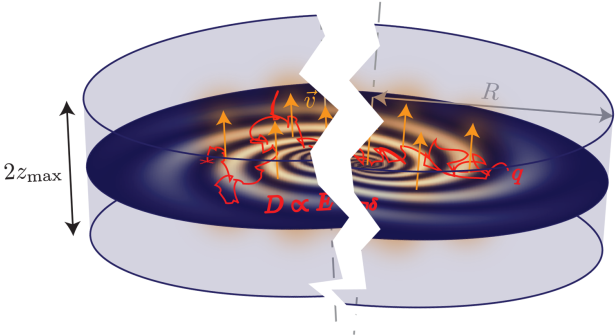


Large amounts of new data

Ways forward

Precision

- Secondary-to-primary ratios depend on:
- astrophysical parameters

→ useful for calibration

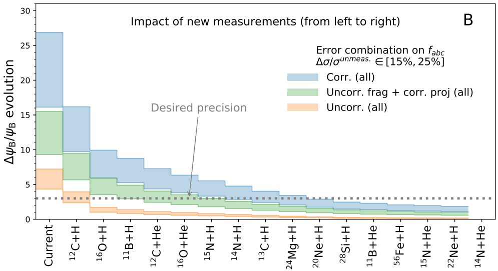
- cross-sections

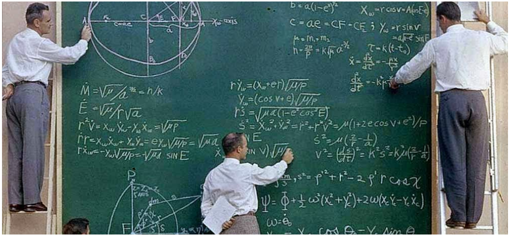
→ need to (re-)measure

Anomalies

- Additional sources
- New dynamics
- Complete overhaul?

KA KIT Unger *et al.* (2018)

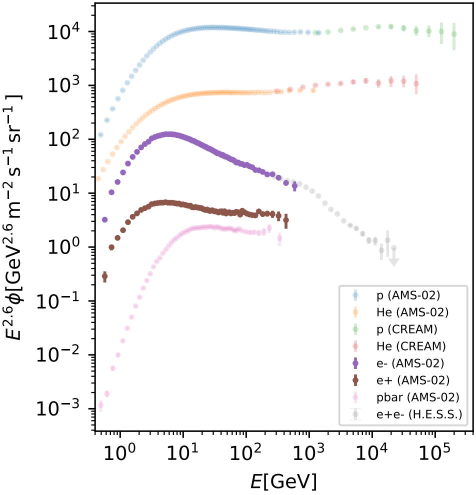




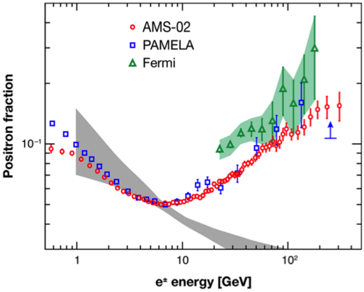
Outline

Outline

1. Positron excess
2. Gamma-ray anomalies
3. Break in the electron spectrum
4. Discrepant hardening
5. Spectral coincidences
6. Conclusion



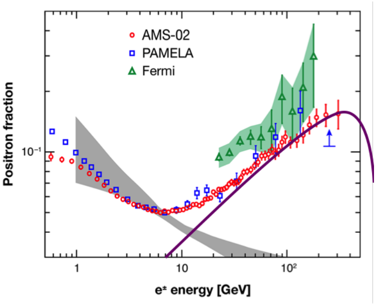
The positron excess – recap



- Cosmic ray nuclei produce soft flux of $\mathrm{e}^{\pm}$ by spallation

$\rightarrow$ Falling positron fraction

The positron excess – recap



- Cosmic ray nuclei produce soft flux of $\mathrm{e}^{\pm}$ by spallation

→ Falling positron fraction

- Rise above $\sim 7\,\mathrm{GeV}$

→ Exotic contributions?

Interpretations:

Dark matter

- Leptophilic, strong boosts needed
- Constraints from CMB and gamma-rays
- Can look for spectral structure?

Pulsars/pulsar wind nebulae

many free parameters:

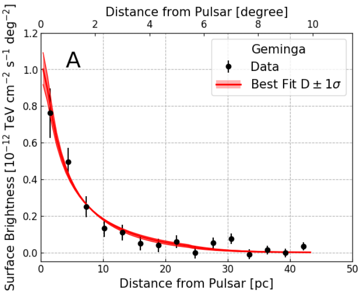
- sources
- efficiency
- spectral index
- cut-off energies

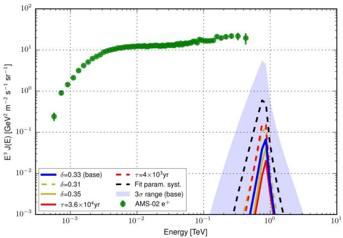
Old supernova remnants

different species strongly correlated

The positron excess – news

Abeysekara *et al.* (2017)





Testing the e^+ excess *in situ*

see also Hooper *et al.* (2017)

- HAWC has observed gamma-ray halo around Geminga

→ from $e^\pm$ responsible for local e^+ excess?

- Can only fit angular profile if diffusion significantly suppressed

→ Geminga cannot contribute locally

The positron excess – news

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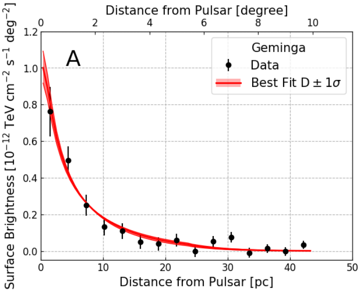

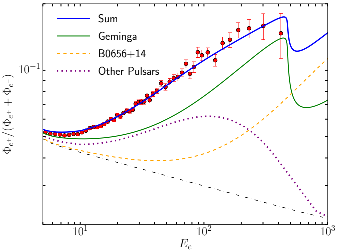

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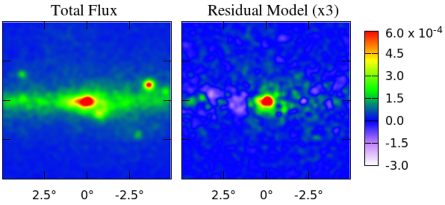
$\rightarrow$ Geminga cannot contribute locally

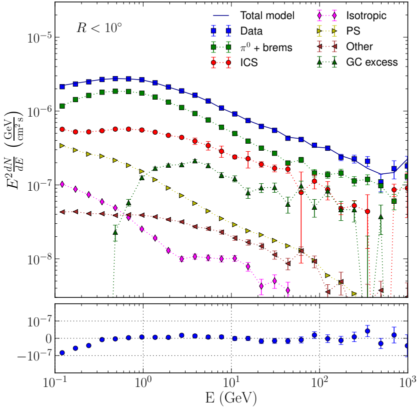
Dissent

Fang *et al.* (2018), Profumo *et al.* (2018), Hooper & Linden (2018)

- $\mathcal{O}(100)$ smaller than D_{xx} from B/C!
- Implies that no TeV $e^\pm$ could be observed!
- Significant contribution with usual D_{xx}

The Galactic centre excess





- removal of astrophysical emission: spatial and spectral template subtraction
- morphology: roughly spherical
- spectrum: log-parabola? power law?

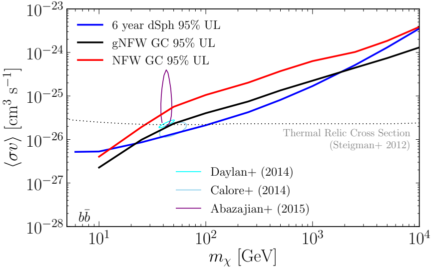
Hooper & Goodenough (2009); Vitale & Morselli (2009); Hooper & Linden PRD (2011); Hooper & Goodenough PLB 2011; Boyarsky, Malyshev, Ruchayskiy PLB 705 (2011) 165; Abazajian & Kaplinghat PRD 2012; Macias & Gordon PRD 2014; Abazajian *et al.* PRD 2014; Daylan *et al.* 2014; Huang, Ensslin, Selig 2015; Carlson *et al.* 2015; Ajello *et al.* 2015; Casandjian Fermi Symp. 2014; de Boer *et al.* 2016; Macias *et al.* 2016; Ackermann *et al.* 2017

Dark matter interpretation?

Dark matter

- $\sim$ thermal cross-section, $m_{\mathrm{DM}} \approx 10$ ($\mathrm{b}\bar{\mathrm{b}}$) or 50 GeV ($\tau^+\tau^-$)
- *Fermi*-LAT coll. finds excesses of similar size along Galactic plane

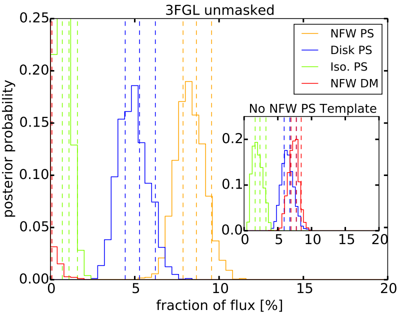
$\Rightarrow$ upper limits



Unresolved sources

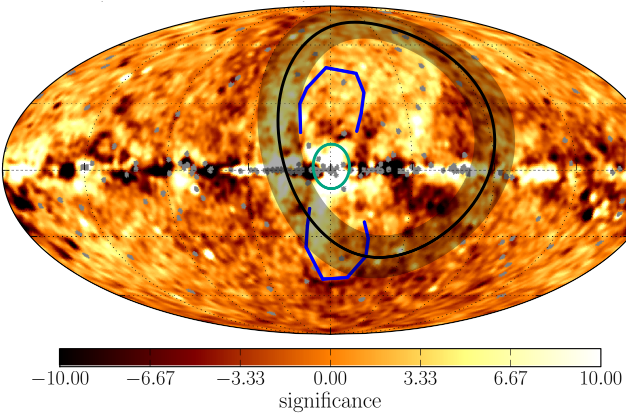
Bartels *et al.* (2015, 2017, 2018), Lee *et al.* (2015)

- spectrum and morhpology also consistent with millisecond pulsars
- can constrain *unresolved* sources
  - with photon-count statistics
  - or wavelet analysis
- follow-up in radio?



The residuals

Ackermann *et al.* 2017



(At least) 3 connected structures

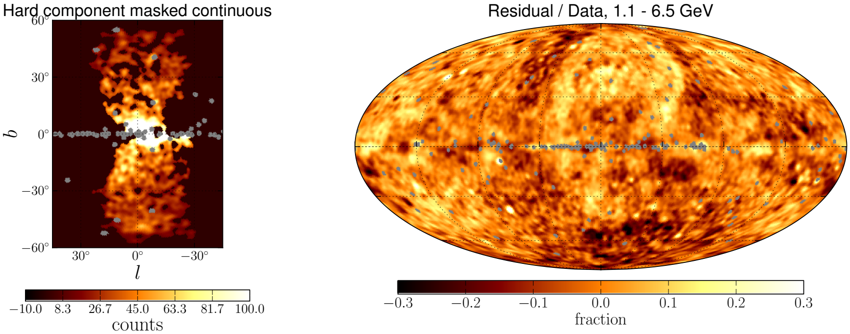
- Fermi bubbles
- Galactic centre excess
- Loop I

Galactic centre - Fermi bubbles connection

Ackermann *et al.* 2017

- Need for a bubbles template closer to Galactic centre

→ Use uniformity of bubbles spectrum above and below $\pm 10^\circ$ latitude



1. Bubbles connect to Galactic centre.
2. Galactic centre excess *significanlty* suppressed.

Fermi bubbles modelling

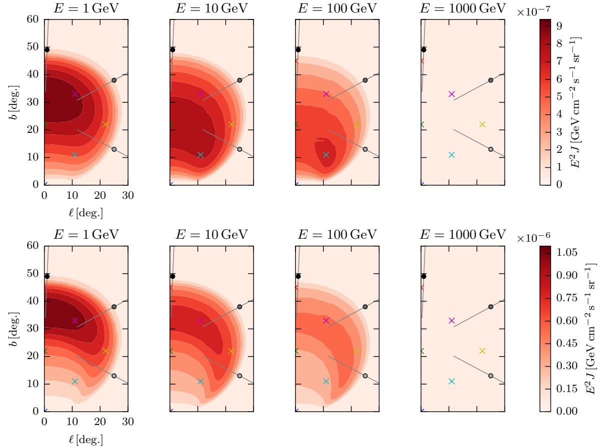
PM & Petrosian (2018)

Is this a generic feature of models? → probably not

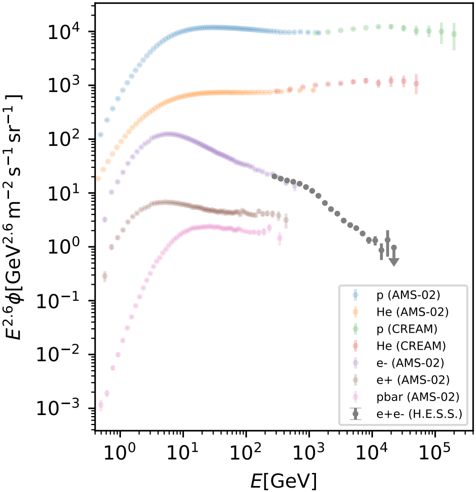
Kinetic simulation of cosmic ray $e^{\pm}$ in large-scale outflow:

model B

model C



Outline



$E^{2.6}\phi[\mathrm{GeV}^{2.6}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}]$
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^0
10^1
10^2
10^3
10^4
10^5
E[GeV]
p (AMS-02)
He (AMS-02)
p (CREAM)
He (CREAM)
e- (AMS-02)
e+ (AMS-02)
pbar (AMS-02)
e+e- (H.E.S.S.)

Green's function

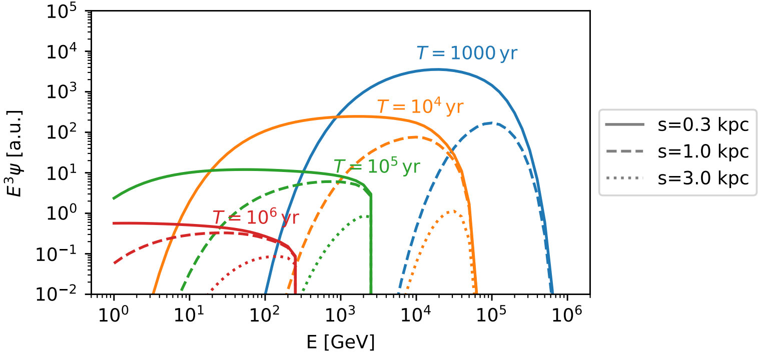
- Simplified transport equation for $e^{\pm}$ spectral density ψ

$$\frac{\partial \psi}{\partial t} - \nabla \cdot \kappa \cdot \nabla \psi + \frac{\partial}{\partial p} \left(b(p) \psi \right) = q(\mathbf{r}, E, t)$$

- Green's function $\psi(d, T, E)$, i.e. solution for

$$q(\mathbf{r}, E, t) = \delta(\mathbf{r} - \mathbf{r}_0) \delta(t - t_0) Q(p) \,,$$

only depends on distance s and age T



with $D_{xx} = D_0 p^{\delta}$, $Q(p_0) \propto p_0^{-\Gamma} \exp[-p_0/p_c]$

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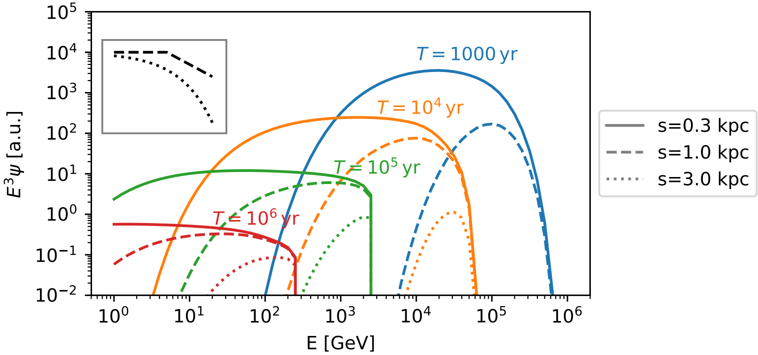

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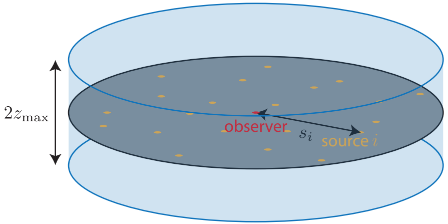
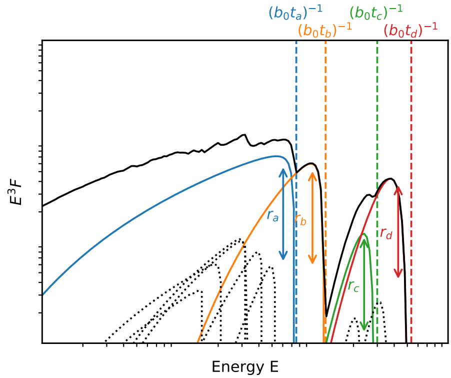
Flux from a population of sources



consider ensemble of sources at distances $\mathbf{r}_i$ and with ages t_i

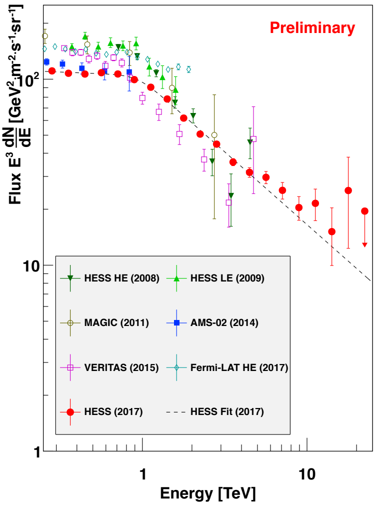


Ignorance of $\mathbf{r}_i$ and t_i $\Rightarrow$ cannot predict $e^{\pm}$ spectrum

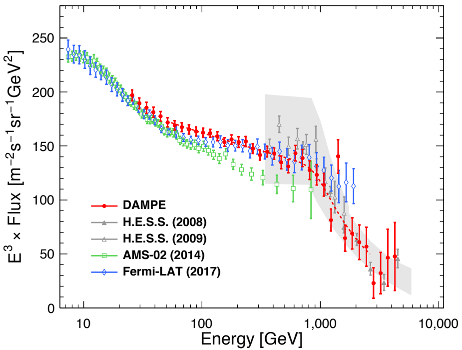
measure $e^{\pm}$ spectrum $\Rightarrow$ learn about $\mathbf{r}_i$ and t_i

The TeV break

Kerszberg *et al.*, ICRC 2017



Ambrosi *et al.* (2017)

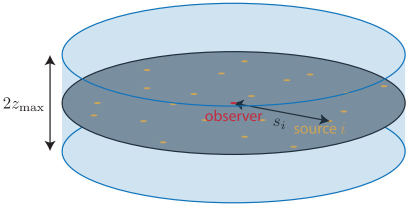


- Is the TeV break compatible with a random ensemble of sources?
- Or is this a cooling break? Lipari (2018)
- Or due to dark matter annihilation?

  Jin, Yue, Zhang, Chen (2018)

A statistical model

PM (2018) AC RWTH



- Contribution from source i to ϕ_k depends on distance s_i and age t_i

→ Spectrum is a random vector: $\phi = \sum_i \phi^i = (\phi_1, \phi_2, \dots \phi_N)^T$

- Statistically characterised by joint distribution $f(\phi_1, \phi_2, \dots \phi_N)$

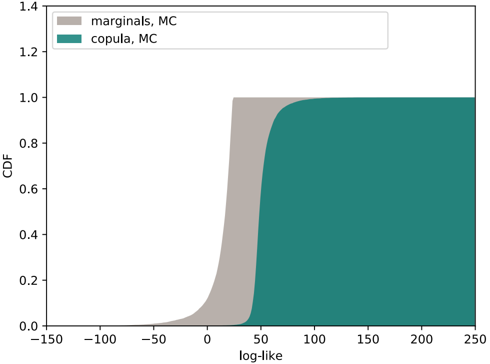
Applications

1. Likelihood of a model: evaluate $f(\hat{\phi}_1, \hat{\phi}_2, \dots \hat{\phi}_N)$ for measured $\hat{\phi}$
2. Extrapolate to higher energies: $f(\phi_{M+1}, \dots \phi_N | \phi_1, \phi_2, \dots \phi_M)$
3. Quickly generate samples from model, e.g. for forecasting

Goodness of fit

PM (2018) AC RWTH

- Distribution of log-likelihoods in MC (source rate $= 2 \times 10^4\ \mathrm{Myr}^{-1}$):



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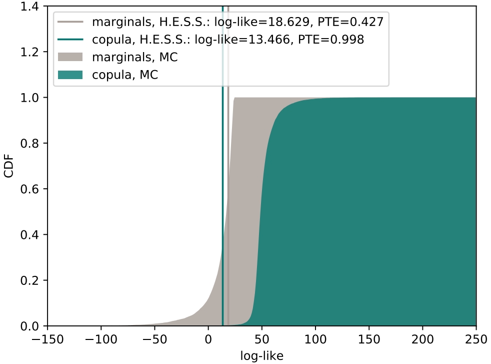


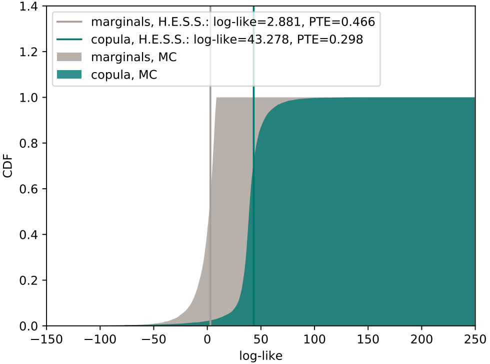
- Compare with log-likelihoods from H.E.S.S. broken power-law:
- Too little fluctuations!

Statistically disfavoured

Goodness of fit

PM (2018) AC RWTH

- Distribution of log-likelihoods in MC (source rate $= 2 \times 10^3\ \mathrm{Myr}^{-1}$):

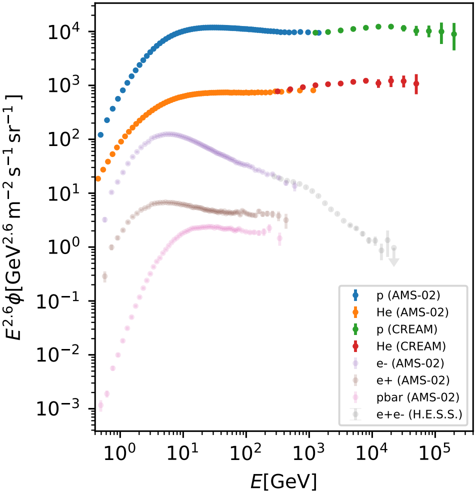


- Compare with log-likelihoods from H.E.S.S. broken power-law:

Statistically compatible

$\rightarrow$ Spatial and temporal correlations between SN events?

Outline



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e+ (AMS-02)
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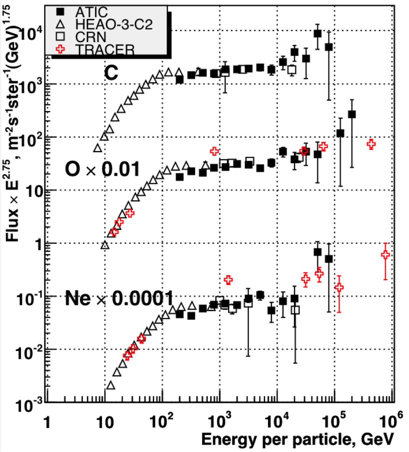
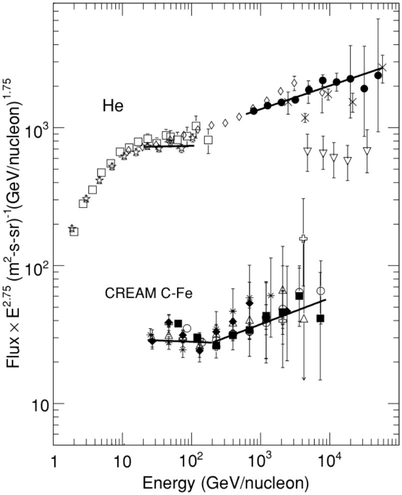
e+e- (H.E.S.S.)

Discrepant hardening I

A. D. Panov et al., astro-ph/0612377

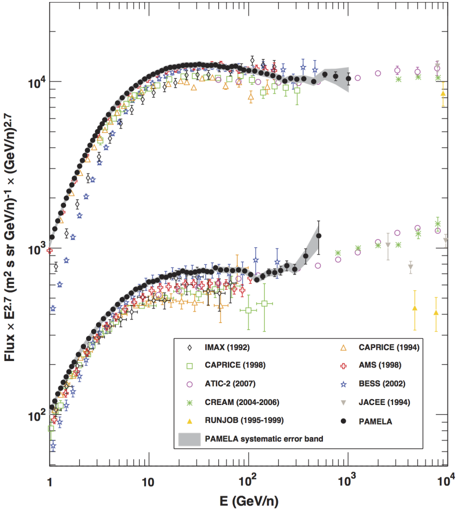


H. S. Ahn et al., ApJ 714, L89 (2010)

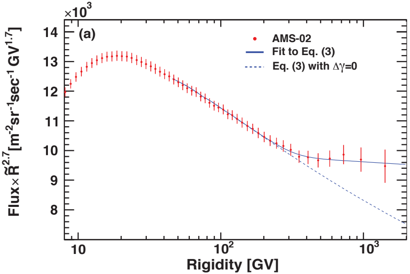


Discrepant hardening II

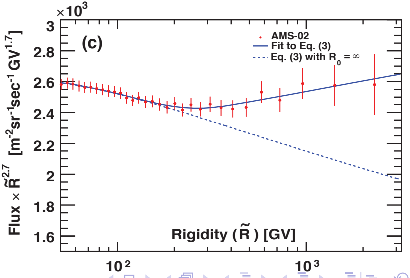
Adriani *et al.*, Science 332 (2011) 69



Aguilar *et al.*, PRL 114 (2015) 171103

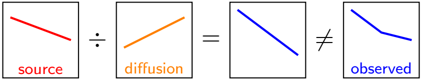


Aguilar *et al.*, PRL 115 (2015) 211101



Discrepant hardening III

Standard picture:

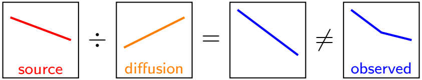


Source effect

- break in source spectrum
  Stanev, Biermann and Gaisser (1993)
  Parizot (2004)
  Ptuskin, Zirakashvili and Seo (2013)

Discrepant hardening III

Standard picture:



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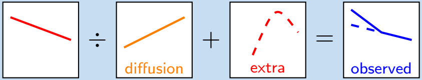
- additional high-energy source(s)
  Bernard *et al.* (2012, 2013)
  Thoudam and Hörandel (2012, 2013)



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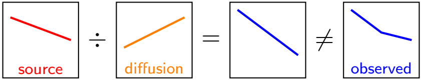

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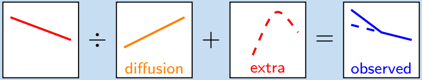
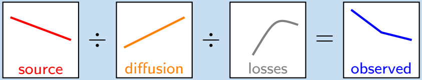


Transport effect

- break in diffusion coefficient
  Blasi, Amato & Serpico, PRL 109 (2012) 061101
  Tomassetti, ApJL 752 (2012) 13

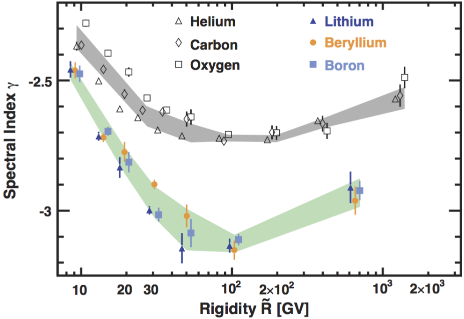
- additional losses
  Krakau & Schlickeiser (2015)



Source or transport?

- Can be distinguished by secondaries Vladimirov *et al.* (2012)
- break in source spectrum: break in secondaries similar

- break in diffusion coefficient: break in secondaries $\sim 2\times$ as strong



Streaming instability and large-scale transport

Blasi, Amato, Serpico (2012); Aloisio and Blasi (2013); Aloisio, Blasi and Serpico (2015)

$$\partial_z \left(D_{zz}(z,p) \partial_z f(z,p) \right) + v_\mathrm{A} \partial_z f(z,p) - \frac{p}{3} \frac{\mathrm{d} v_\mathrm{A}}{\mathrm{d}z} \partial_p f(z,p) = q_\mathrm{CR}(p) \delta(z)$$

$$D_{zz}(z,p) \sim \frac{v r_g}{3} \left. \frac{B_0^2}{k W(k)} \right|_{k=1/r_g}$$

$$\partial_k \left(D_{kk} \partial_k W(z,k) \right) + \partial_z (v_\mathrm{A} W(z,k)) = q_W \delta(z) \delta(k - k_0)$$

- Without CR feedback, recover $W(k) \propto k^{-5/3} \quad \Rightarrow D_{zz}(p) \propto p^{1/3}$

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$$D_{zz}(z, p) \sim \frac{v r_g}{3} \left. \frac{B_0^2}{k W(k)} \right|_{k = 1/r_g}$$

$$\Gamma_{\mathrm{CR}}(z, k) \propto p^4 \partial_z f(z, p)$$

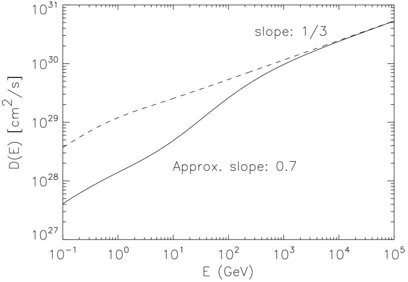
$$\partial_k \left(D_{kk} \partial_k W(z, k) \right) + \partial_z (v_{\mathrm{A}} W(z, k)) = q_W \delta(z) \delta(k - k_0) + \Gamma_{\mathrm{CR}}(z, k) W(z, k)$$

- Without CR feedback, recover $W(k) \propto k^{-5/3}$ $\Rightarrow D_{zz}(p) \propto p^{1/3}$
- self-generated turbulence on small scales, cascaded on large scales

Routinely considered for acceleration
in supernova remnants, e.g. B DESY Pohl *et al.*

Break in diffusion coefficient

Blasi, Amato, Serpico (2012)

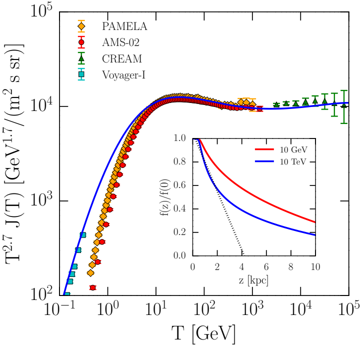


- 2 contributions to turbulence power spectrum:
  - external turbulence (supernova remnants and winds)
  - self-generated turbulence

$\rightarrow$ break in D_{zz}

- can also include spatial dependences

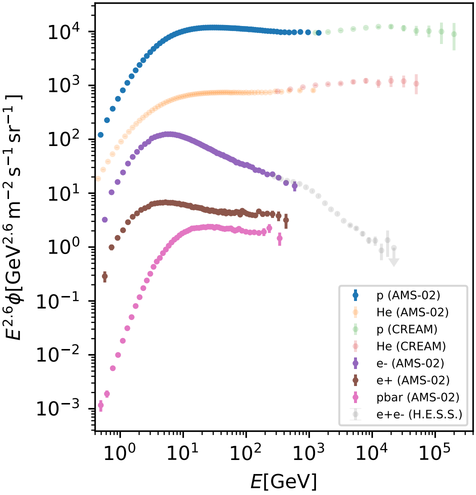
Evoli *et al.* (2018)



Future

- extend to 2D Galaxy
  $\rightarrow$ solve CR gradient problem?
  Evoli et al. (2012)
  Cerri, Vittino et al. (2017) M TUM
- complicated **B**-field geometry

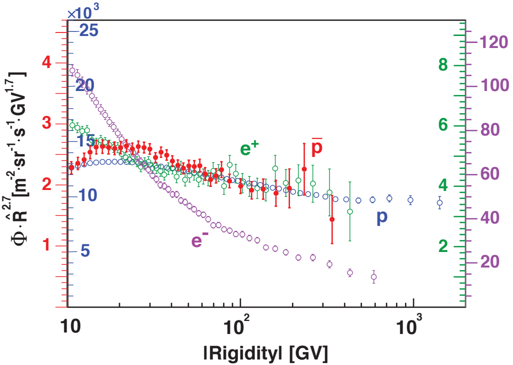
Outline



$E^{2.6}\phi[\mathrm{GeV}^{2.6}\,\mathrm{m}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}]$
$E[\mathrm{GeV}]$
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}
p (AMS-02)
He (AMS-02)
p (CREAM)
He (CREAM)
e- (AMS-02)
e+ (AMS-02)
pbar (AMS-02)
e+e- (H.E.S.S.)

Spectral coincidences

- p: accelerated in sources, diffusive losses
- e^-: (mostly) accelerated in sources, (mostly) radiative losses
- $\bar{\mathrm{p}}$: produced from p, diffusive losses
- e^+: produced from p, mostly radiative losses



Yet, the p, $\bar{\mathrm{p}}$ and e^+ spectra are markably similar!

A common source of e^+ and $\bar{p}$?

Cowsik & Burch (2012); Cowsik & Madziwa-Nussinov (2016); Lipari (2016)

Nested leaky box model

Cowsik & Wilson (1973, 1975)

1. CRs are confined to a near source region: "cocoon"
2. rigidity-dependent escape from cocoon, $\tau_c \searrow \mathcal{R}$
3. rigidity-independent escape from Galaxy $\tau_g \sim$ constant

$\Rightarrow$ observed primary spectra $\sim$ source spectra

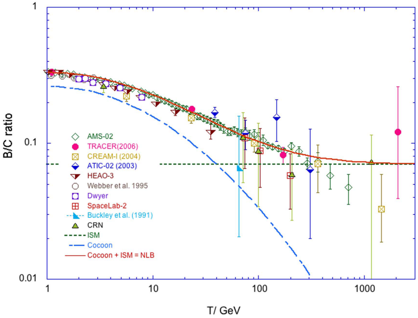
$\Rightarrow$ secondary nuclei have contributions

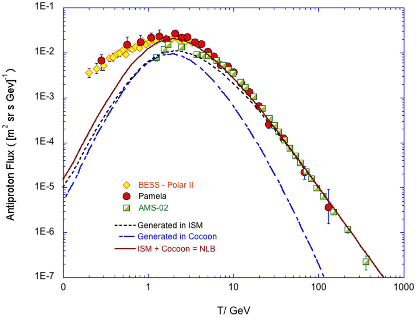
- from cocoon (softer than primaries)
- from Galaxy (same as primaries)

$\Rightarrow$ $\bar{p}$ and e^+ have little contribution from cocoon

Nested leaky box model

Cowsik & Madziwa-Nussinov (2016)



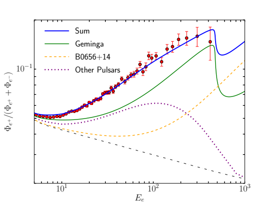


- ☺ low, constant level of anisotropy
- ☺ explains similar spectra of p, $\bar{p}$ and e^+
- ☹ soft source spectra, even softer for e^-
- ☹ break in B/C not observed

Conclusion

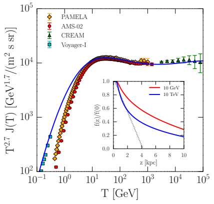
Cosmic ray anomalies point to ...

New sources



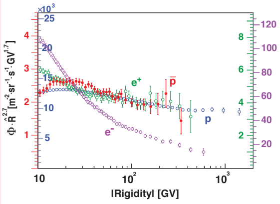
e.g. to explain TeV gamma-ray haloes and local positron flux

New dynamics



e.g. non-linear interplay between turbulence generation and transport

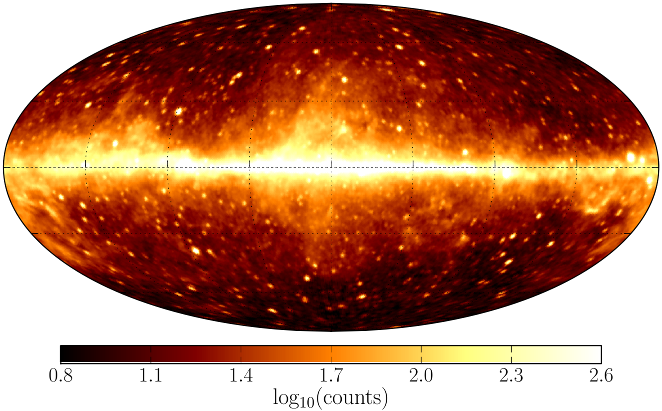
Complete overhaul



e.g. to explain spectral coincidences

Backup

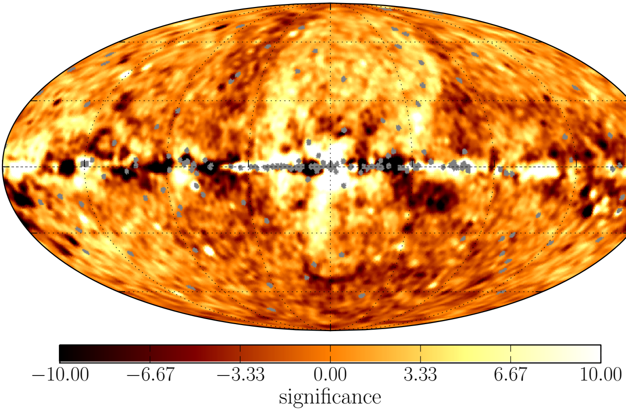
The data



Template fitting

- Linear combination of tracer maps: π^0, inverse Compton, isotropic, pt sources
- Maximise likelihood $\rightarrow$ derive spectra

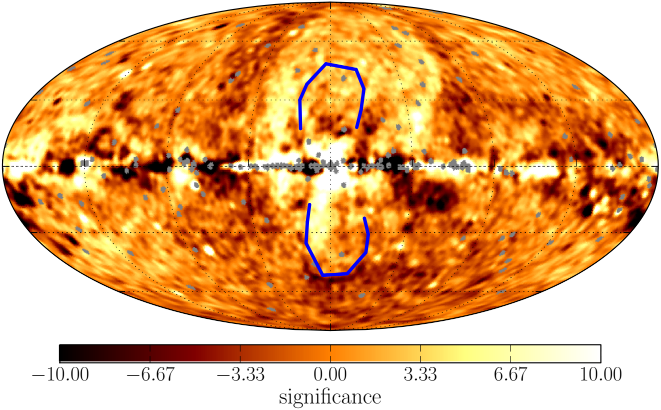
The residuals



(At least) 3 connected structures

- Fermi bubbles
- Galactic centre excess
- Loop I

The residuals



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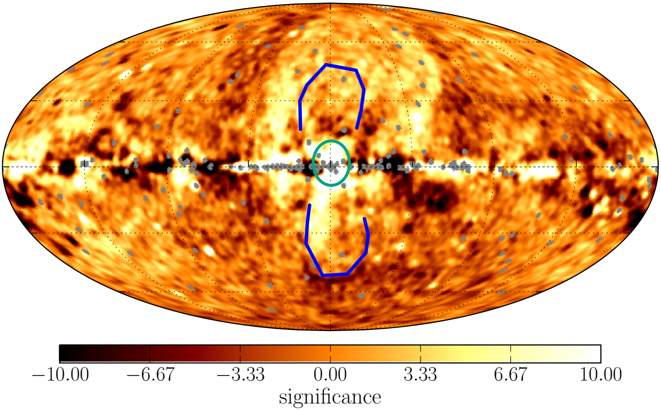
The residuals



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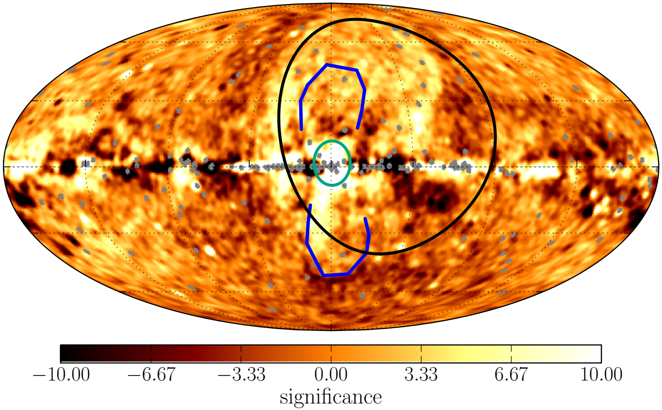
The residuals



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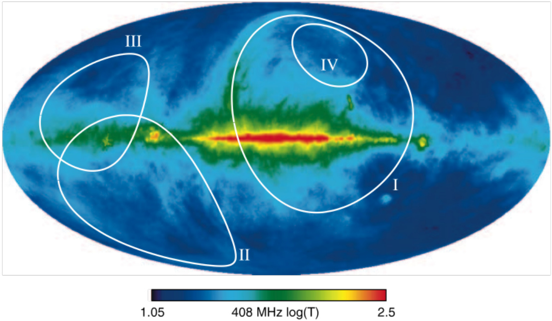
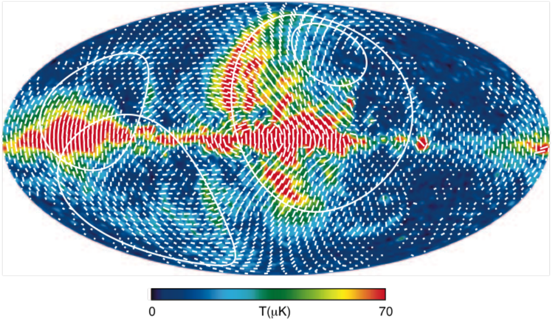
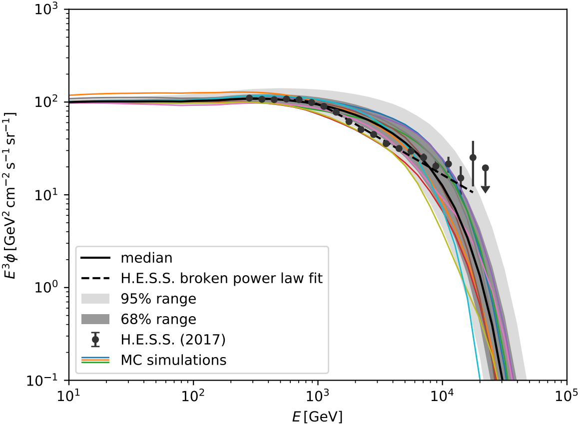
Loop I





MC result, source rate $= 2 \times 10^4 \mathrm{Myr}^{-1}$



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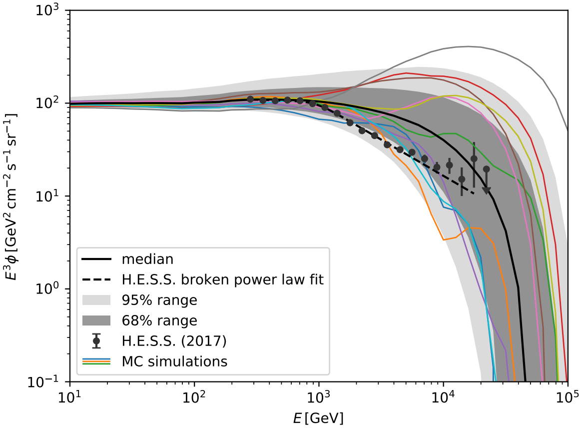
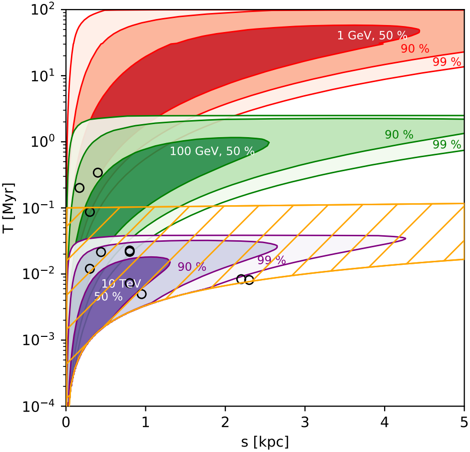


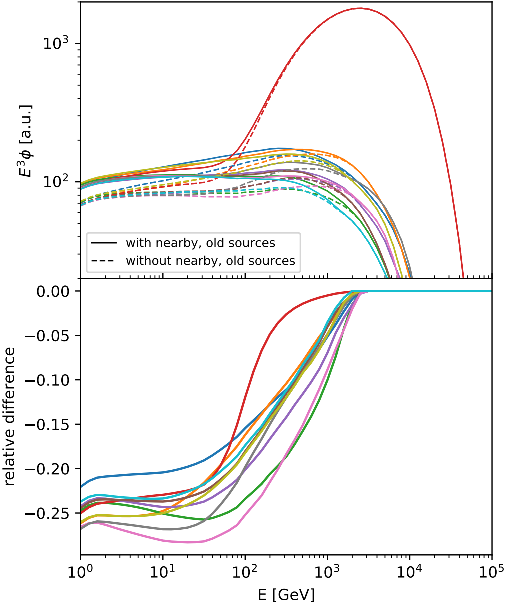
The problem with catalogues

Contributions from various regions for homogenous source density



→ Effect on flux? PM (2018); also Ahlers, PM, Sarkar (2010)

The problem with catalogues



Estimate error due to catalogue incompleteness with MC approach:

- Homogeneous density in disk
- Constant source rate $2 \times 10^4\,\mathrm{Myr}^{-1}\mathrm{galaxy}^{-1}$
- Draw samples *with* and *without* nearby ($< 1\,\mathrm{kpc}$), old ($> 0.1\,\mathrm{Myr}$) sources

Underestimates low-energy flux by up to $\sim 25\,\%$! PM (2018)

Extra source models

- Any hardening explained by superposition of $n \geq 2$ components:
- "known" sources → any multimessenger evidence?
- statistical model: "myriad model"

Statistical ensemble of sources

- analyse distribution of fluxes at fixed energies
- stable distribution with power-law tails, non-Gaussian!
- likelihood of deviations from expectation value $\lesssim 10^{-5}$

Genolini *et al.* (2017)