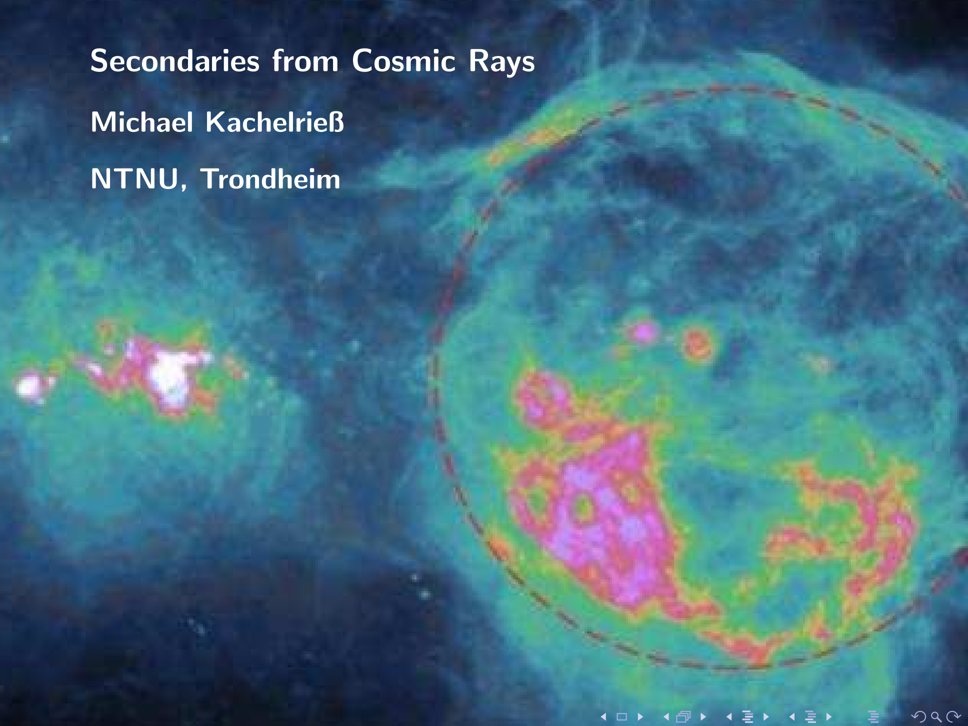
Secondaries from Cosmic Rays

Michael Kachelrieß

NTNU, Trondheim



Outline of the talk

1. Introduction: Galactic Cosmic Rays:
   - standard approach and its weaknesses
2. Propagation in the escape model:
   - replaces diffusion by individual trajectories
   - leads to anisotropic propagation
   - importance of local source(s)
3. Secondary production in interactions on gas
   - uncertainties in $\bar{p}$ production
4. Conclusions

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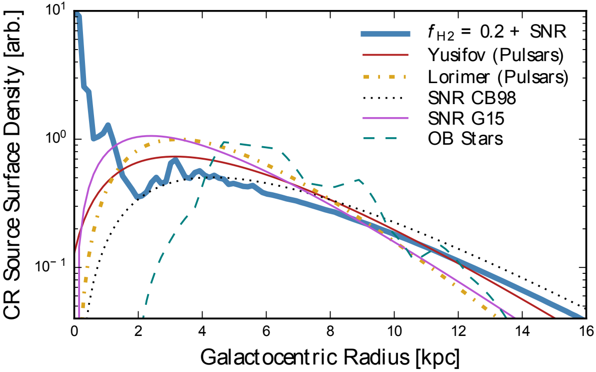
- fit of $n(r)$ to SNR/pulsar/OB star regions, adding gas



[Carlson, Linden, Profumo '16]

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- Galactic magnetic field: regular + turbulent component
  turbulent: fluctuations on scales $l_{\rm min} \sim$ AU to $l_{\rm max} \sim (10-150)$ pc

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- anisotropy $\delta = -3D_{ij}\nabla_i \ln(n) \propto E^{\beta}$

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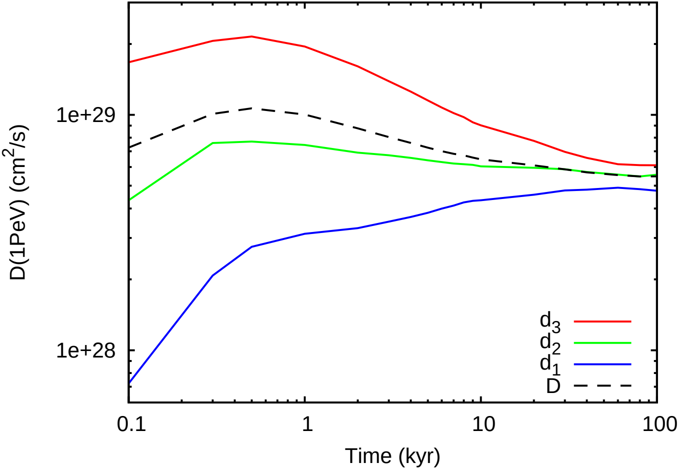
- as preparation, let's calculate diffusion tensor in pure, isotropic turbulent magnetic field

Eigenvalues of $D_{ij} = \langle x_i x_j \rangle / (2t)$ for $E = 10^{15}$ eV

[Giacinti, MK, Semikoz ('12)]



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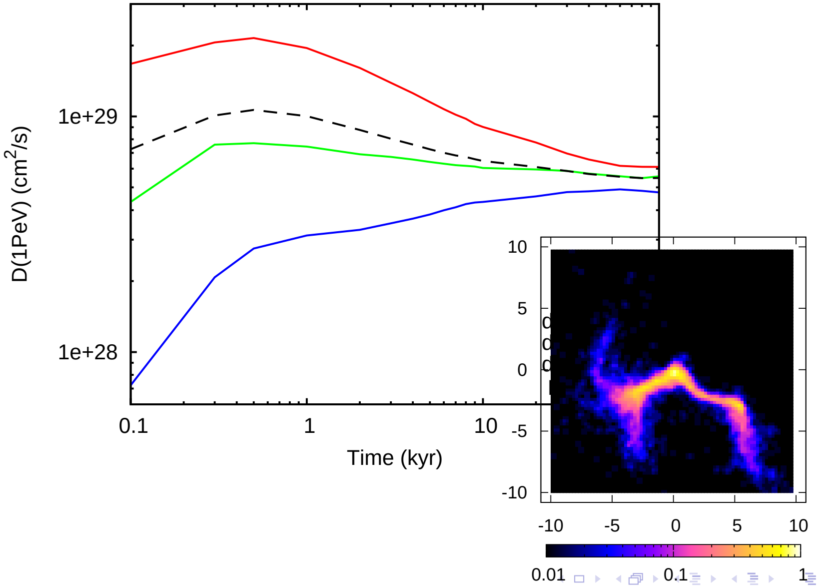

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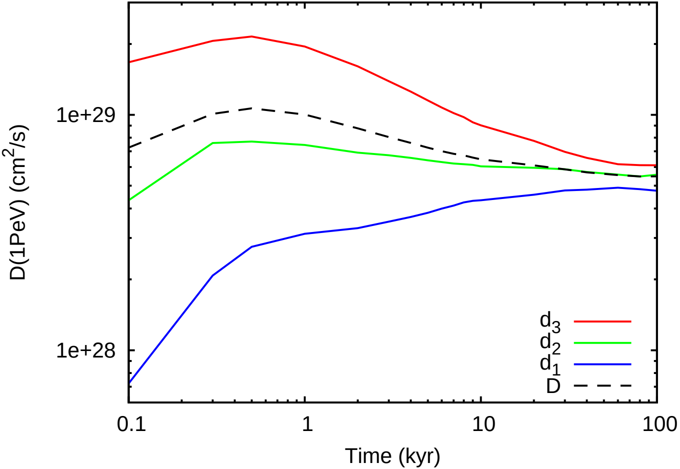

- asymptotic value is ~ 10 smaller than extrapolated "Galprop value"

Fitting the grammage X

- $l_{\rm coh}$ and regular field $\boldsymbol{B}(\boldsymbol{x})$ fixed from observations
  - LOFAR: $l_{\rm coh} \lesssim 10\,{\rm pc}$ in disc
- determine magnitude of $\mathcal{P}(k)$ from grammage $X(E)$

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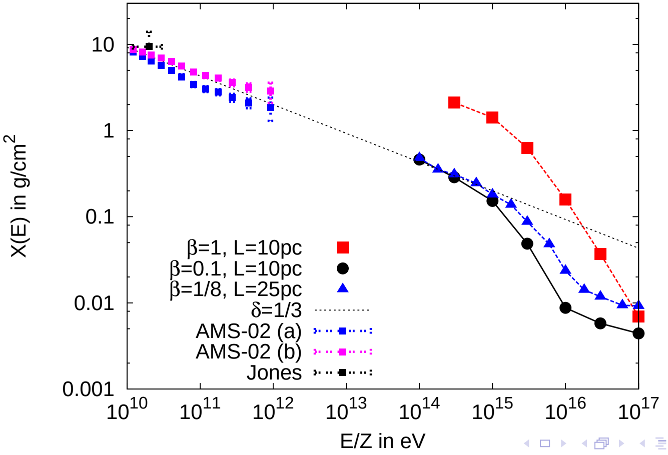

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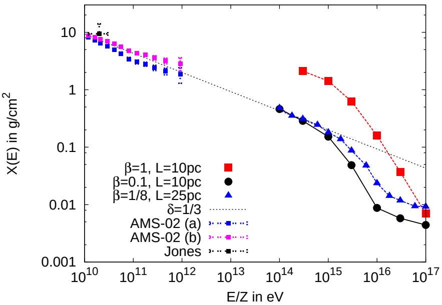

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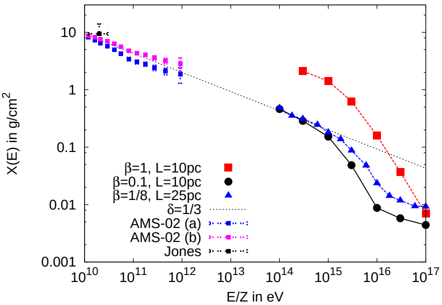

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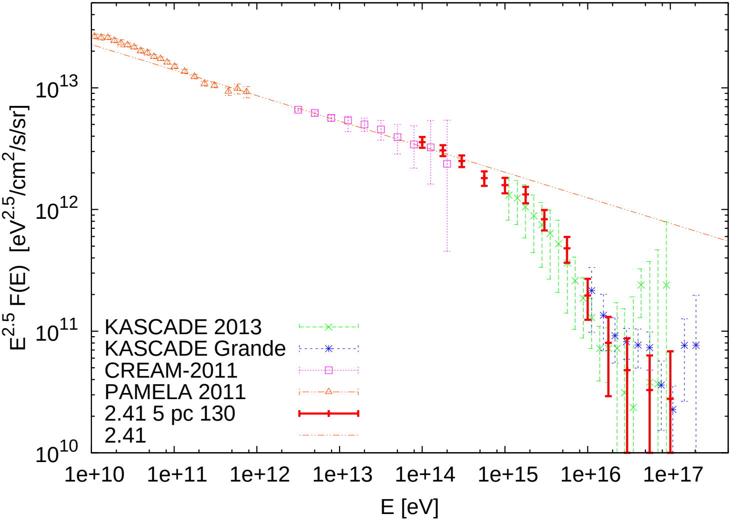
- test: fluxes $I_A(E)$ of all isotopes fixed by low-energy data

Knee from Cosmic Ray Escape: proton energy spectra



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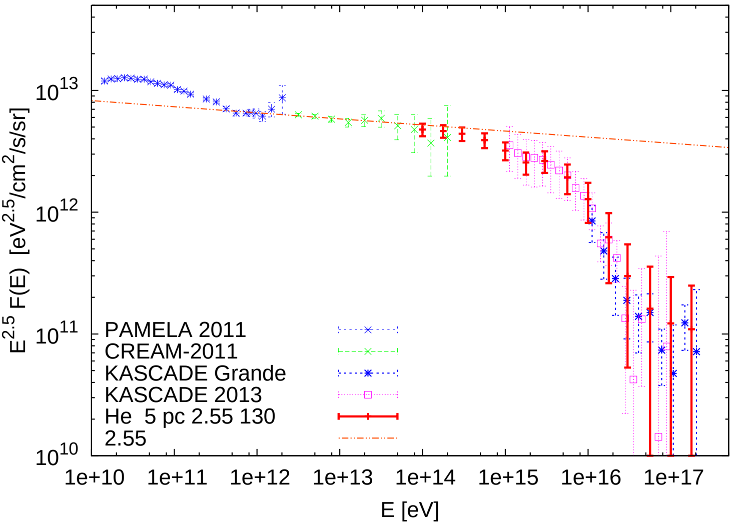
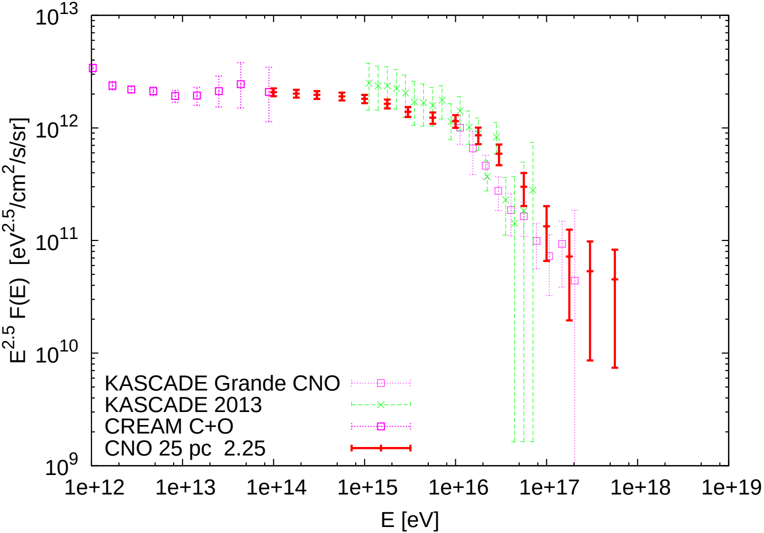
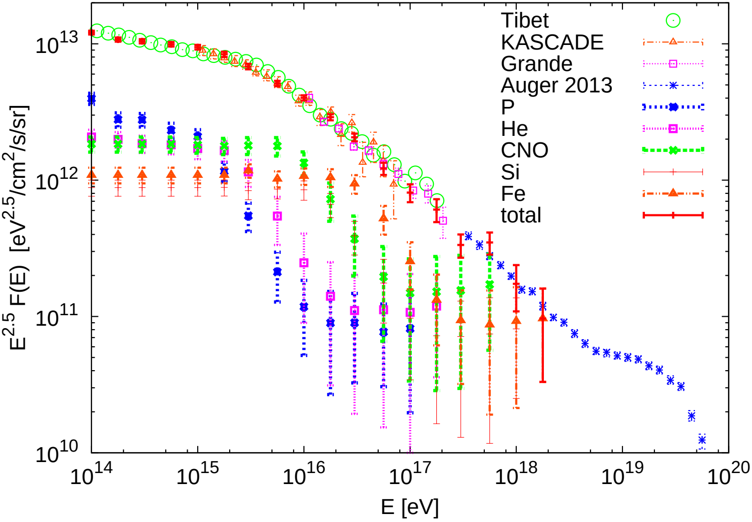


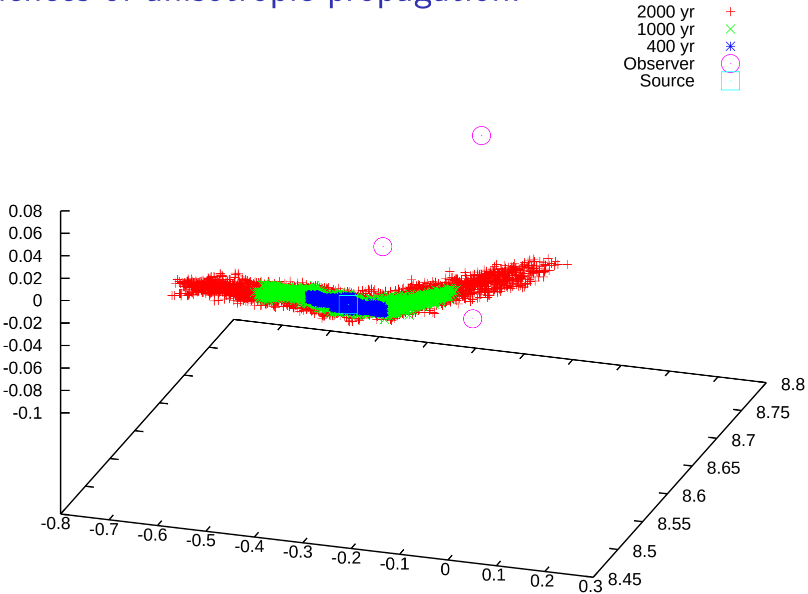
Knee from Cosmic Ray Escape: CNO energy spectra



Knee from Cosmic Ray Escape: total energy spectra



Consequences of anisotropic propagation:



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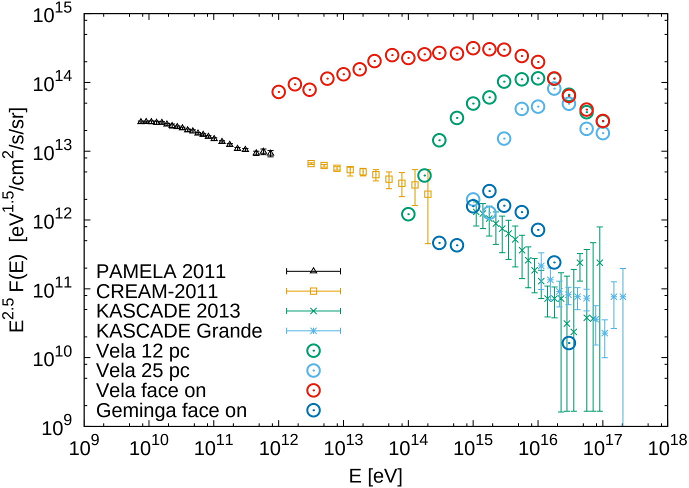

$\Rightarrow$ local sources contribute only, if $d_\perp$ is small

Anisotropy of a single source

- if only turbulent field:
  diffusion = random walk = free quantum particle
- number density is Gaussian with $\sigma^2 = 4DT$
  $$\delta = \frac{3D}{c}\frac{\nabla n}{n} = \frac{3R}{2T}$$
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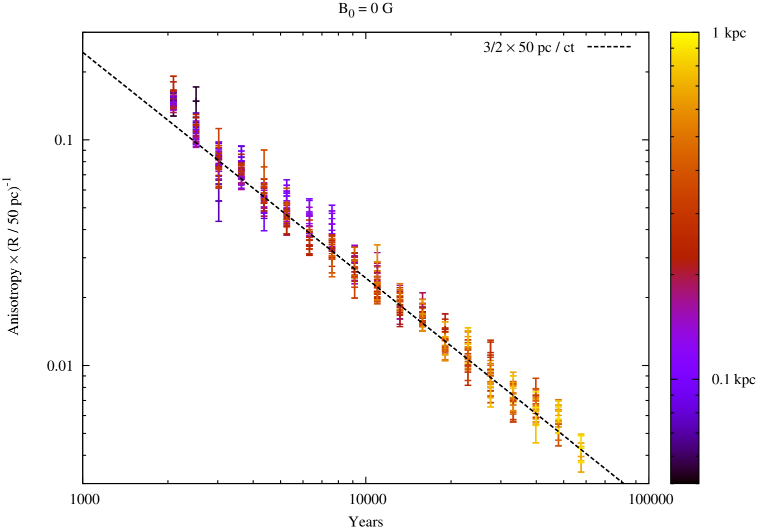
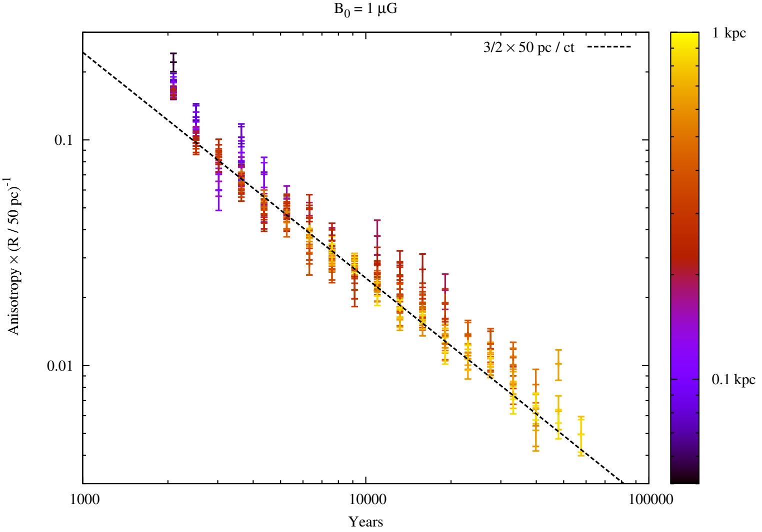


[*Savchenko, MK, Semikoz '15*]

Anisotropy of a single source: plus regular



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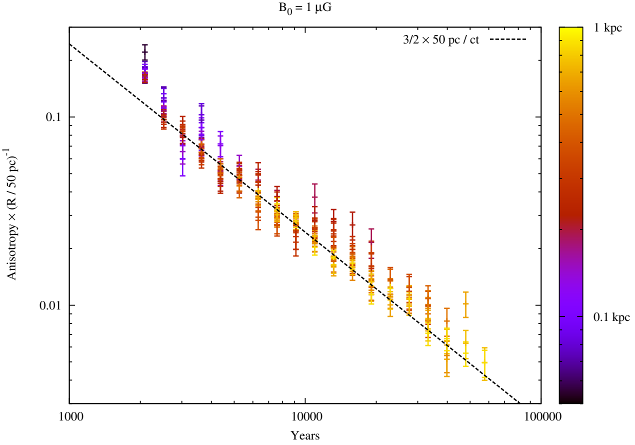
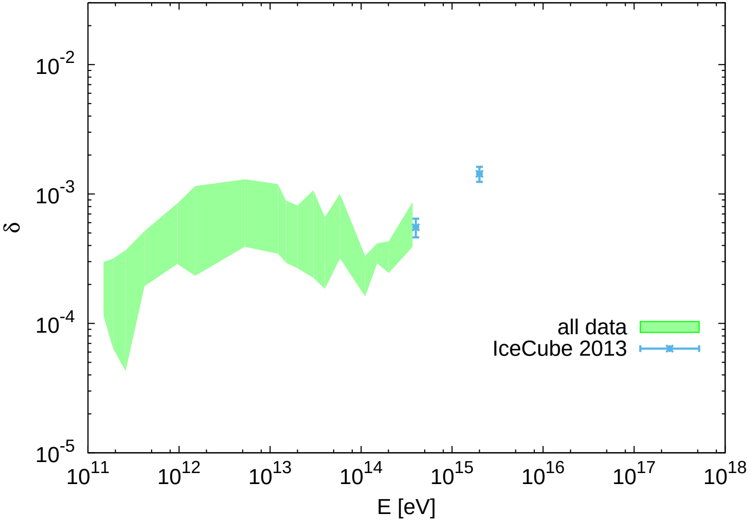


- regular field changes $n(\boldsymbol{x})$, but keeps it Gaussian

  $\Rightarrow$ no change in δ, but $\boldsymbol{\delta} \| \boldsymbol{B}$

Dipole anisotropy:



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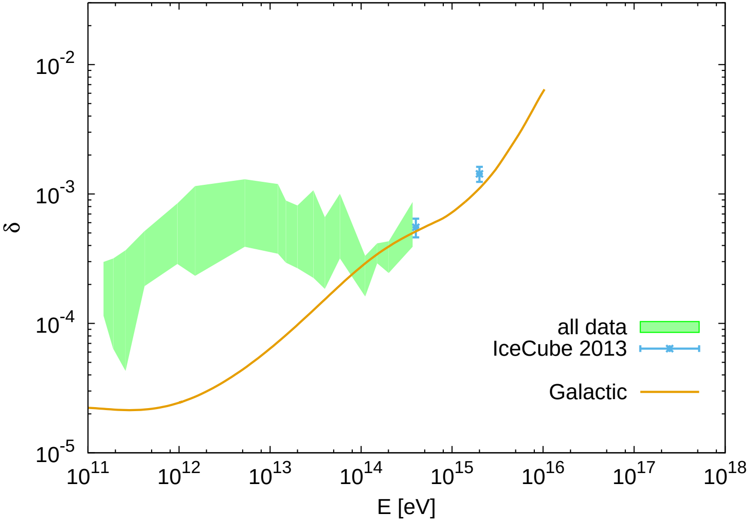

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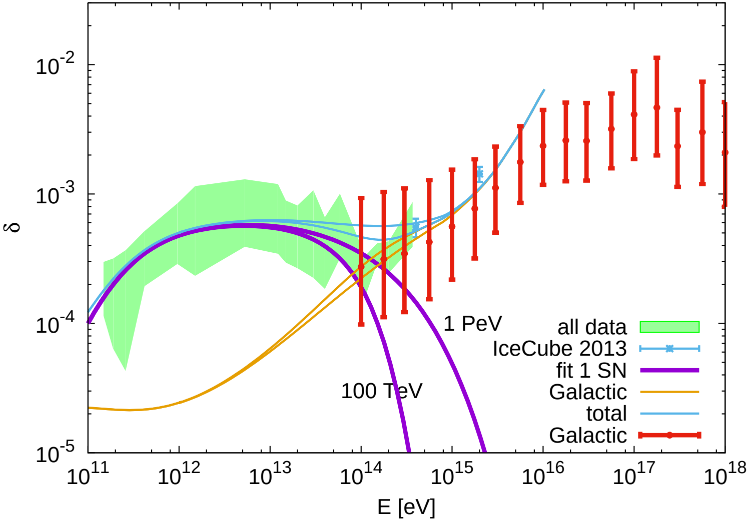

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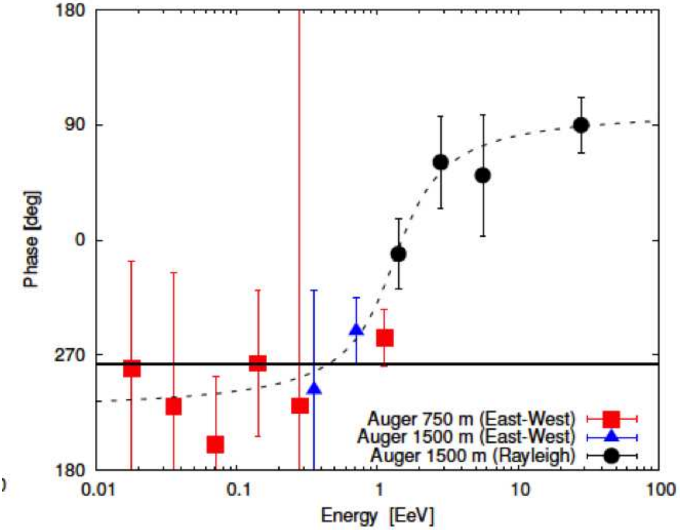
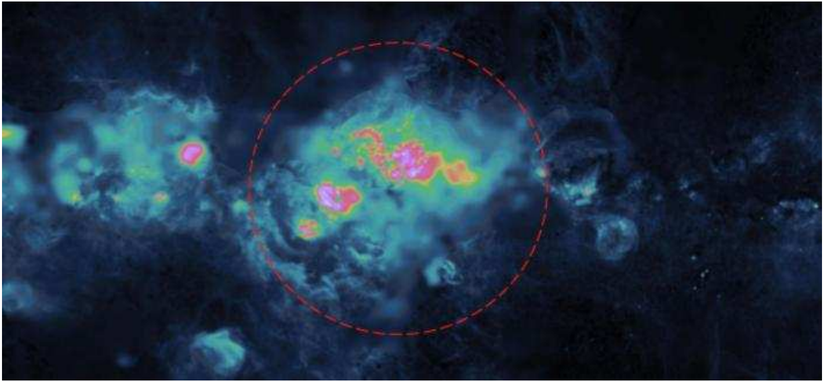
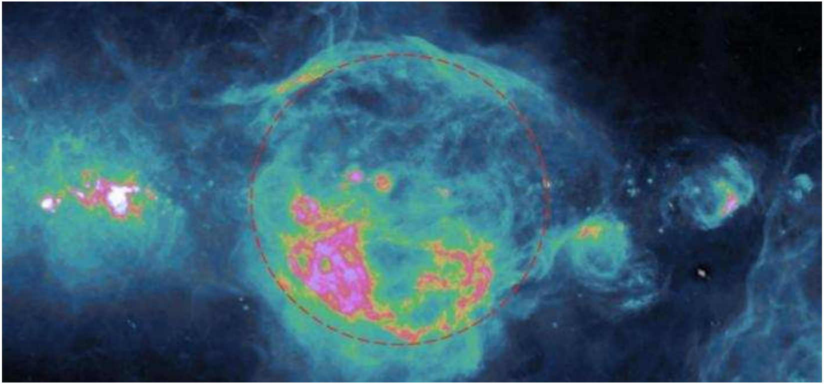


View along local GMF line: towards $l = 79^\circ$



[M. Haverkorn '16]

View along local GMF line: towards $l = 259°$



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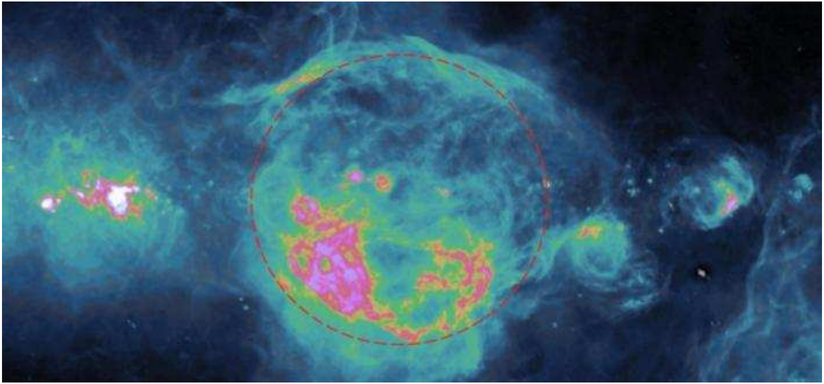

- Gum Nebula:
  - age ~ 2.5 Myr
  - distance $\sim$ 300–400 pc

[*M. Haverkorn '16*]

Single source: other signatures

- 2.4 Myr SN explains anomalous ^{60}Fe sediments [*Ellis+ '96*]

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  - $\bar{p}/p$ ratio fixed by source age $\Rightarrow$ $\bar{p}$ flux is predicted
  - e^+ flux is predicted
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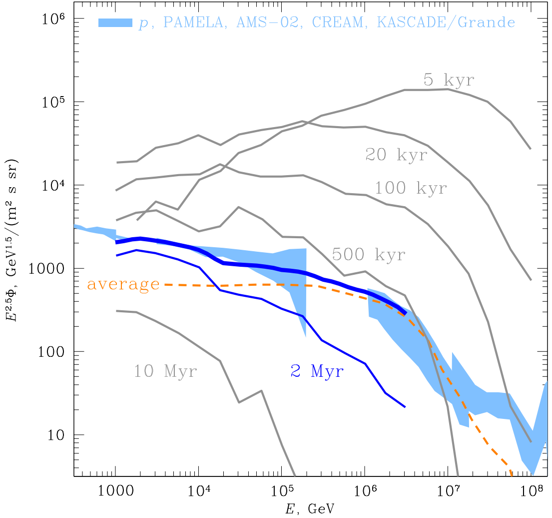
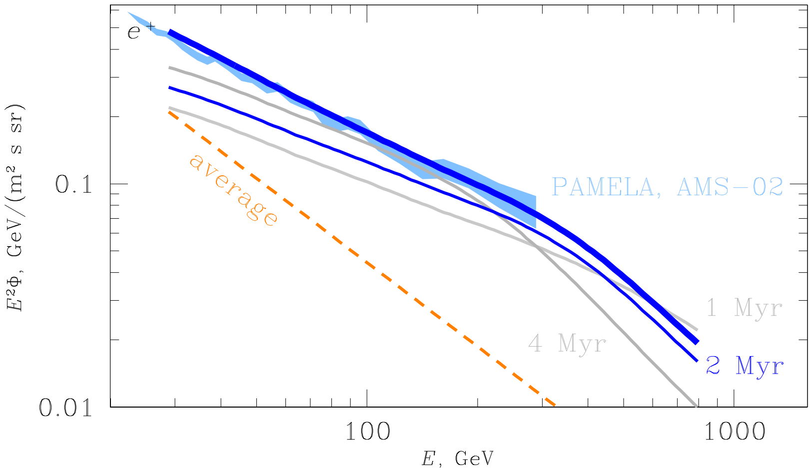
- may responsible for different slopes of local p and nuclei fluxes

Single source: proton flux



[MK, Neronov, Semikoz '15]

Single source: positrons



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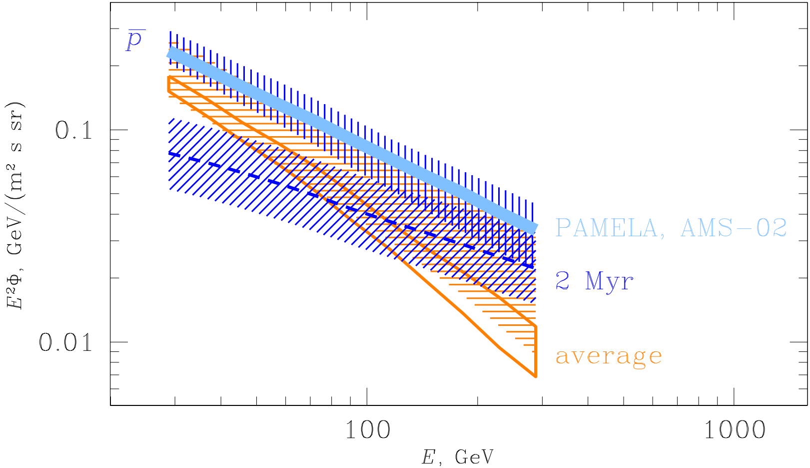
Single source: antiprotons



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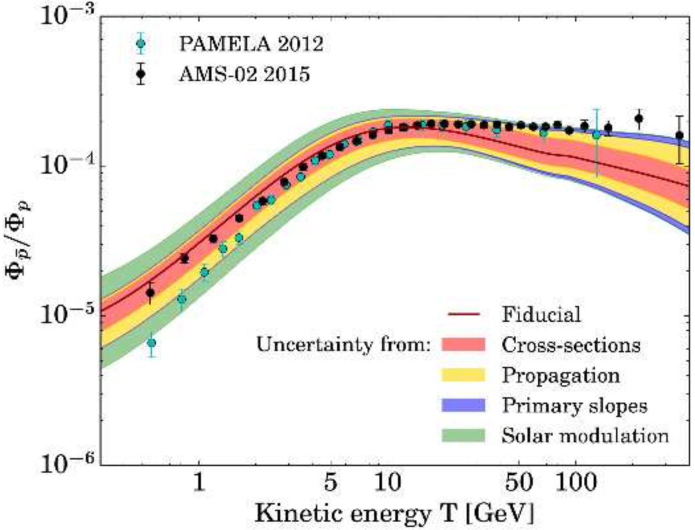
Uncertainties in $\bar{p}$ flux predicition

[Giesen et al. [1504.04276]]



Fitting $\bar{p}$ production vs. modelling

[MK, Moskalenko, Ostapchenko '15]

- common problems:
  - low energies $\cong$ old exp. $\cong$ large, badly documented syst. errors
  - Ex.: some "pp" measurements are rescaled pA data
  - small Ω coverage, typically fixed angle
  - low E not covered
- fitting:
  - required extrapolation depends on quality of fit function
  - based on obsolet Ng&Tang parametrisations
- simulations:
  - models like QGSJet or EPOS calibrated on large data sets (SPS, Tevatron, LHC, Na49, . . . , CR)
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  - require models for soft interactions and hadronisation
  - all hadronisations models have problems with baryons

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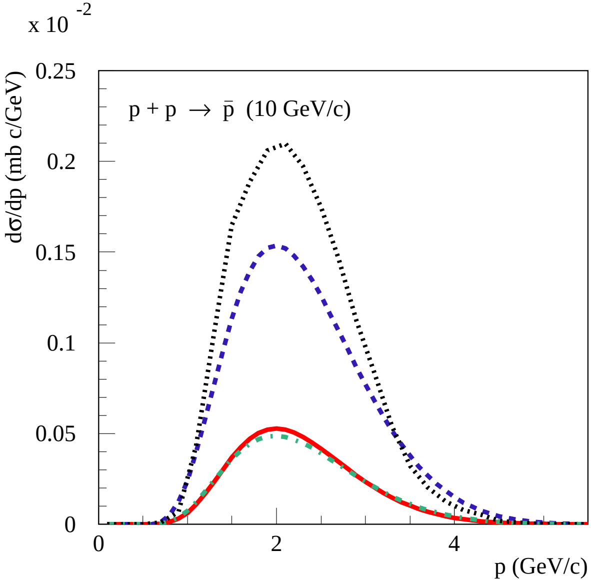
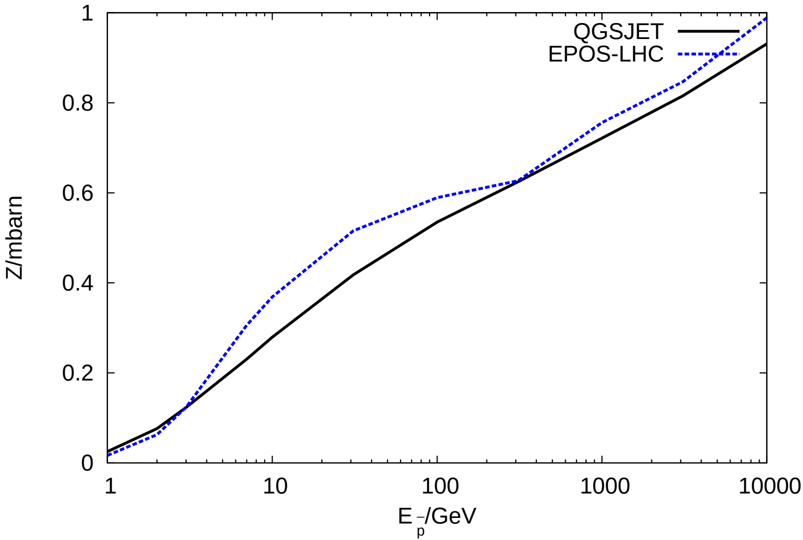
Variation of models: Tan-Ng, Duperray 1, Duperray 2, QGSJET-IIm



Comparison of QCD models ($\alpha = 2$)



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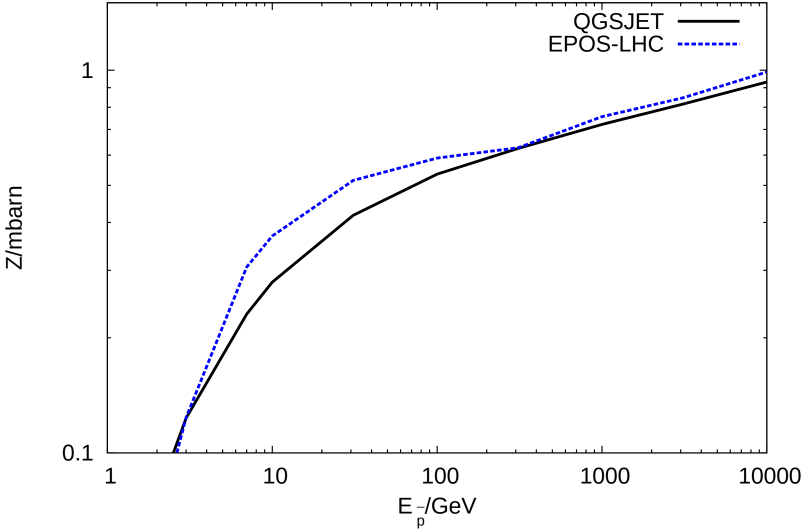
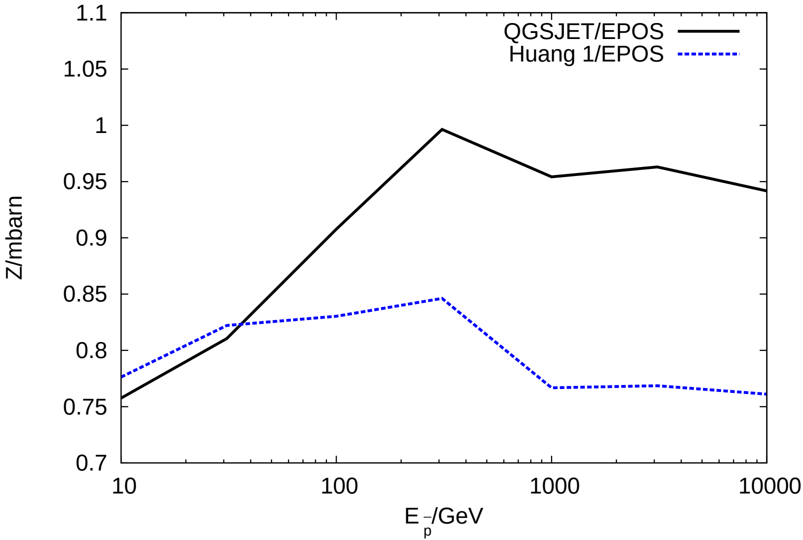
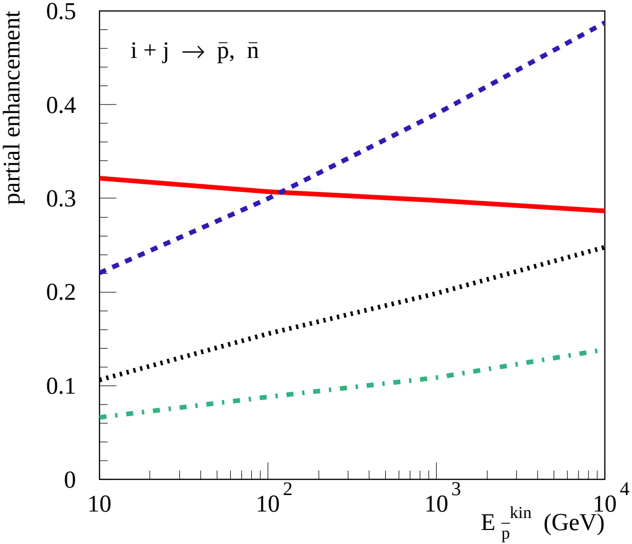


Ratios of Z-factors ($\alpha = 2$)



Nuclear enhancement: p-He, He-p, He-He, rest



Conclusions

1. CR propagation in the escape model
   - reproduces fluxes of CR nuclei for $200\,\mathrm{GeV} \lesssim E/Z \lesssim 10^{17}$ eV
   - suggests small $\mathcal{P}(k)$ and small $l_{\rm coh}$ $\Rightarrow$ anisotropic propagation
2. Single source: anisotropy
   - dipole formula $\delta = 3R/2T$ holds universally in quasi-gaussian regime, $d_\perp$ crucial for flux
   - plateau of δ points to dominance of single source
3. Single source: antimatter
   - consistent explanation of p, $\bar{p}$ and e^+ fluxes
   - consistent with δ – too far for ^{60}Fe?
4. Uncertainty in $\sigma(pp \to \bar{p})$:
   - $E_{\bar{p}} \gtrsim 100$ GeV: models agree within 15%
   - below: no improvement without no exp. data
   - parametrisations: $\varepsilon_{\rm nuc}$ adds additional uncertainty