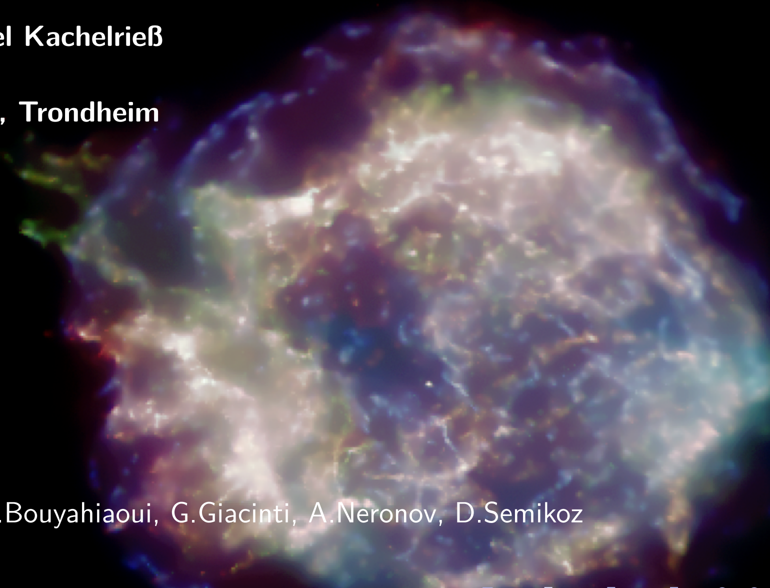
A Fresh Look at Galactic Cosmic Rays

Michael Kachelrieß

NTNU, Trondheim



with M.Bouyahiaoui, G.Giacinti, A.Neronov, D.Semikoz

Outline of the talk

1. Introduction: CR propagation
   - Standard diffusion approach
   - Trajectory approach
   - Consequences of anisotropic diffusion
2. 2–3 Myr local SN
   - Primaries: breaks, non-universality
   - Secondaries: positron excess, antiprotons, B/C
   - Anisotropy
3. Vela and the CR knee
   - Living in the Local Bubble
   - CR fluxes
   - Neutrinos
4. Conclusions

Introduction: CR propagation

1. Extragalactic UHECRs:
    - use model for Galactic Magnetic Field
    - calculate trajectories $x(t)$ of individual CRs via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.
2. Galactic CR, low energies:
    - CRs as relativistic fluid
    - use effective diffusion picture
    - connection to GMF only indirect

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- Galactic magnetic field: regular + turbulent component

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  all fluctuations between $l_{\rm max}$ and $\sim R_L/10$ have to be included
  $\Rightarrow$ makes trajectory approach computationally very expansive

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- slope of power spectrum $\mathcal{P}(k) \propto k^{-\alpha}$ determines energy dependence of diffusion coefficient for $B_{\rm reg} = 0$ as $D(E) \propto E^{\beta}$ as $\beta = 2 - \alpha$:

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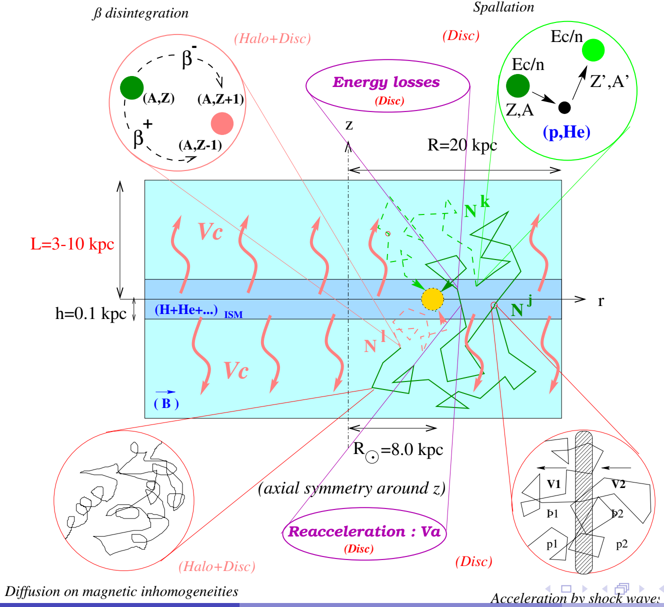
- spectrum of secondaries $dN_s/dE \propto E^{-\delta-\beta-\delta}$
- ratio $N_s/N_p \propto E^{-\delta}$

Standard diffusion approach:



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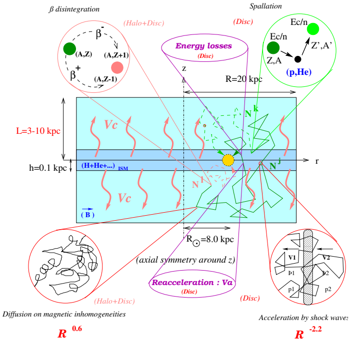

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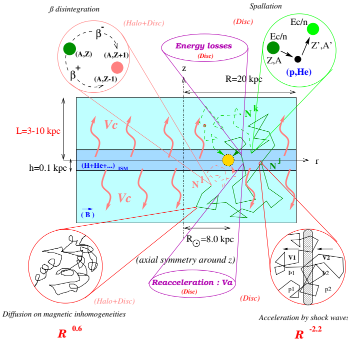

- effective approach invites for simplications:
- often $D_{ij}(E, \boldsymbol{x}) \to D(E), \quad \partial_t = 0$, etc.
- good approximation for many "average" quantities: $I_\gamma(E), \ldots$
- how important are deviations, local effects?

Our approach:

- use model for Galactic magnetic field: Jansson-Farrar, Psirkhov et al.,...
- calculate trajectories $\boldsymbol{x}(t)$ via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.

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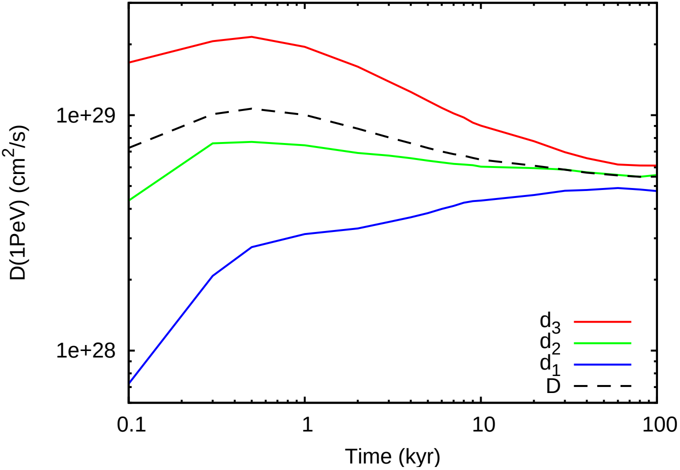
- calculate trajectories $\boldsymbol{x}(t)$ via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.
- as preparation, let's calculate diffusion tensor in pure, isotropic turbulent magnetic field

Eigenvalues of $D_{ij} = \langle x_i x_j \rangle / (2t)$ $E = 10^{15}$ eV, $B_{\rm rms} = 4\mu$G

[*Giacinti, MK, Semikoz ('12)*]



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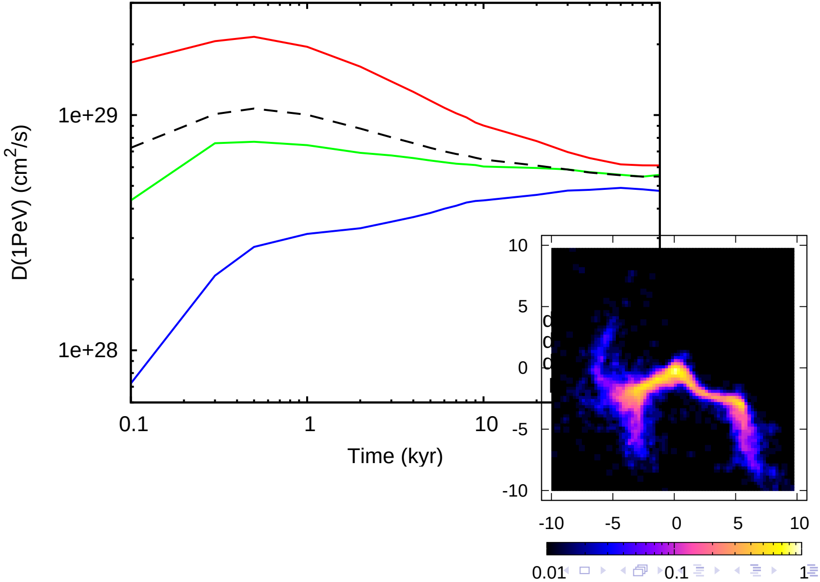

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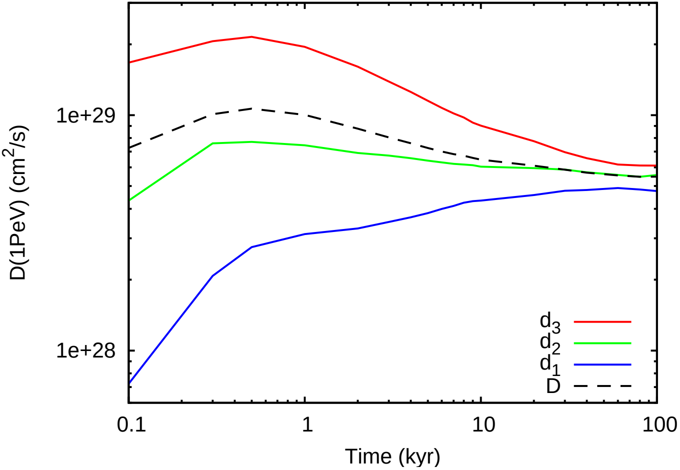

- asymptotic value is ~ 50 smaller than standard value

Is isotropic diffusion possible?

- for isotropic diffusion:

$$D = \frac{cL_0}{3}\left[(R_{\rm L}/L_0)^{2-\alpha} + (R_{\rm L}/L_0)^2\right]$$

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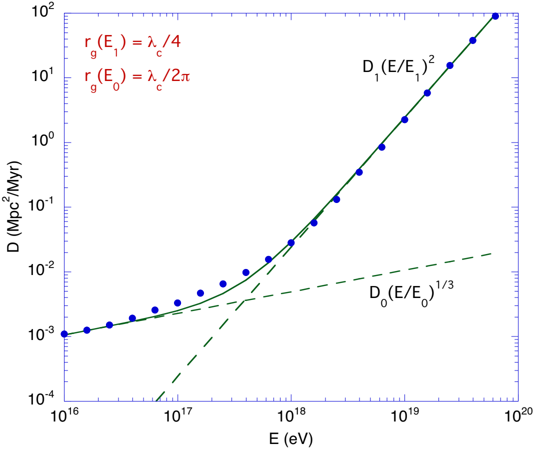

[Parizot '04]

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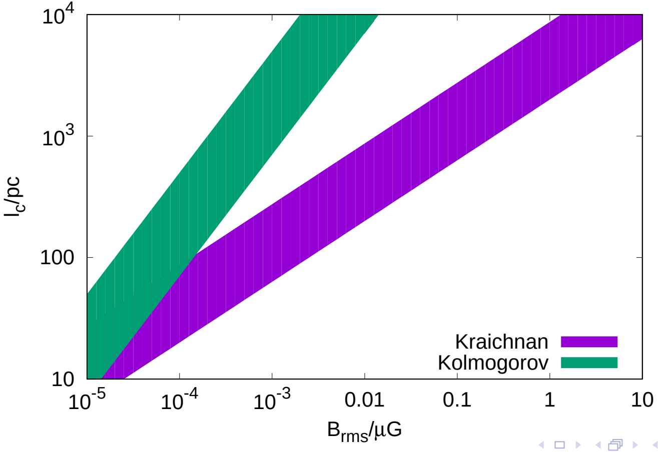

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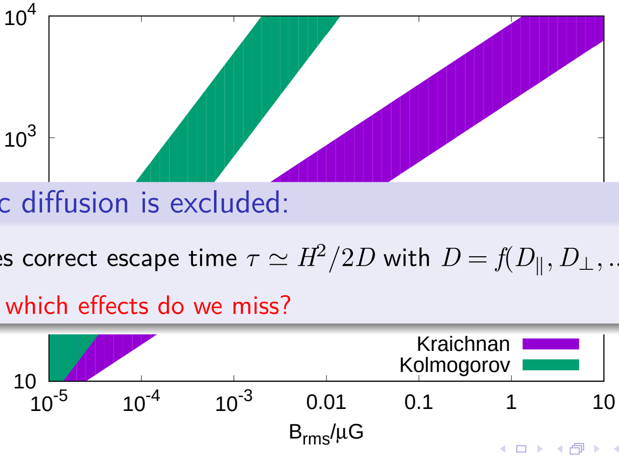

isotropic diffusion is excluded:

- gives correct escape time $\tau \simeq H^2/2D$ with $D = f(D_\parallel, D_\perp, ...)$
- but which effects do we miss?

Anisotropic diffusion – 2 options:

- anisotropic turbulence
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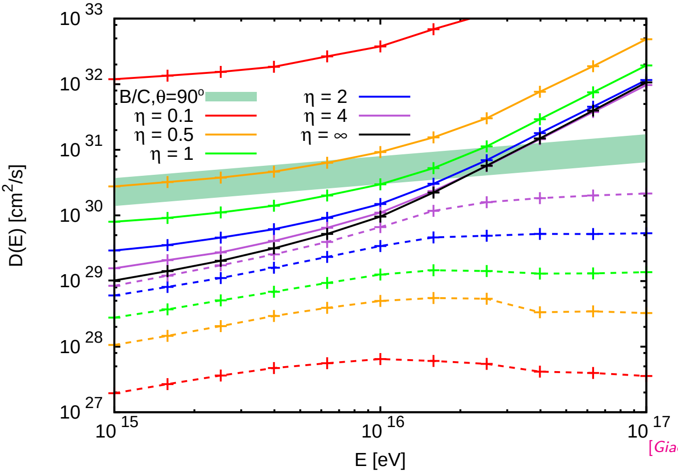

[Giacinti, MK, Semikoz '17]

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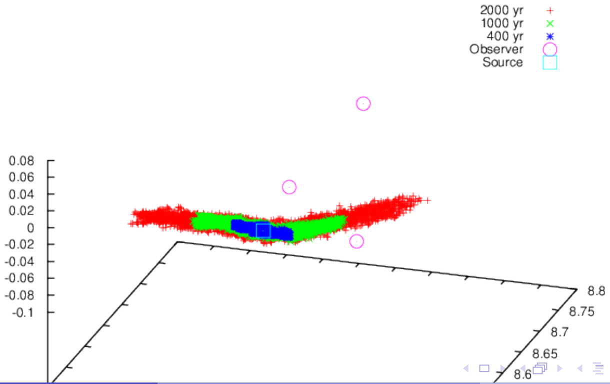

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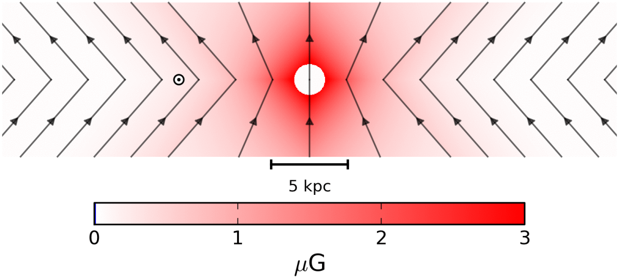

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$\Rightarrow$ $D_{\|} \sin^2\vartheta$ reduces grammage

$\Rightarrow$ relative importance of single sources is changed

How smooth is the CR sea?

- contribution of a single source:

$$I(E) \simeq \frac{c}{4\pi} \frac{Q(E)}{V(t)}$$

with

$$V(t) \simeq \pi^{3/2} D_\perp^{1/2} D_\parallel t^{3/2}$$

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- isotropic diffusion: at $E_* = 10\,\text{TeV}$ and $D_* \equiv D_\perp = D_\parallel = 5 \times 10^{29}\text{cm}^2/\text{s}$

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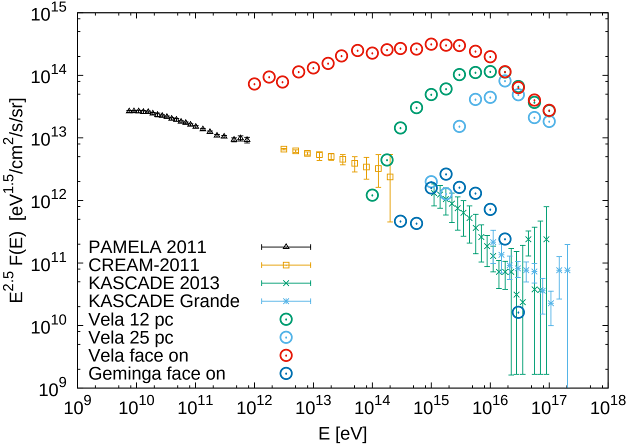
- anisotropic diffusion in JF model with $\eta = 0.25 \Rightarrow D_\parallel \simeq 5D_*$ and $D_\perp \simeq D_*/500$
  - $\Rightarrow$ volume is reduced by $500/\sqrt{5} \simeq 200$
  - $\Rightarrow$ single source can dominate observed flux at 10 TeV

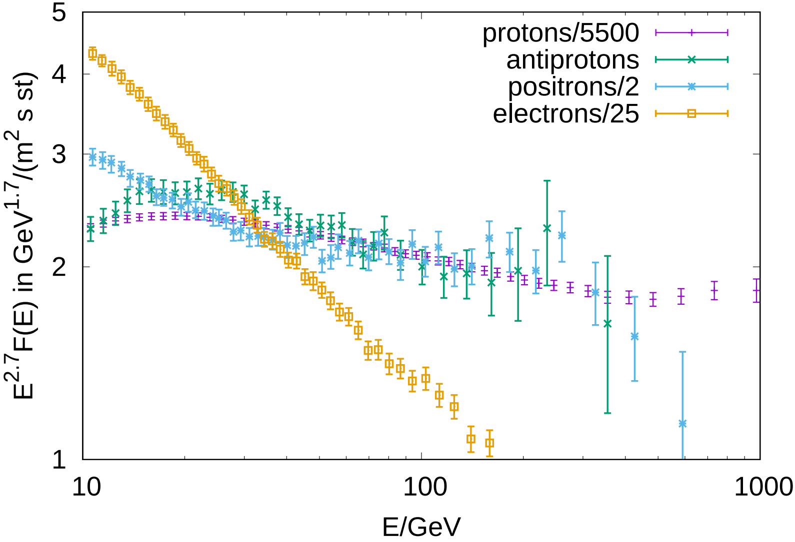
Consequences of anisotropic propagation:



⇒ local sources contribute strongly, if $d_\perp$ is small

⇒ local sources are surpressed, if $d_\perp$ is large

The p, $\bar{p}$, e^+, e^- fluxes:



Signatures of a young, local single source:

- secondary $\bar{p}$ and e^+ flux have same shape as p
  - $\bar{p}$ diffuse as $p \Rightarrow$ leads to constant $\bar{p}/p$ ratio for fixed grammage
  - $\bar{p}/p$ ratio fixed by source age $\Rightarrow$ age is predicted
  - e^+ flux is fixed, break should be consistent with age
  - relative ratio of $\bar{p}$ and e^+ depends only on their Z factors: $R = F_{e^+}/F_{\bar{p}} \simeq 1.8$ for $\alpha = 2.6$

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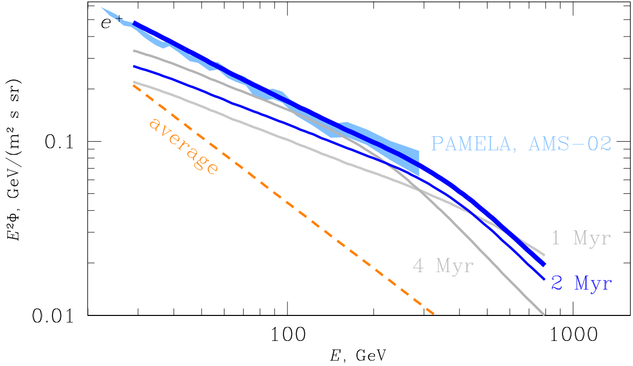

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- 2-3 Myr SN explains anomalous ^{60}Fe sediments [Ellis+ '96,...]
- SNe connected to Local Bubble [Schulreich '17,...]
- what about other CR puzzles?
  - breaks? rigidity dependence?
- B/C consistent? Electrons?
- anisotropy?

Local source: nuclei fluxes

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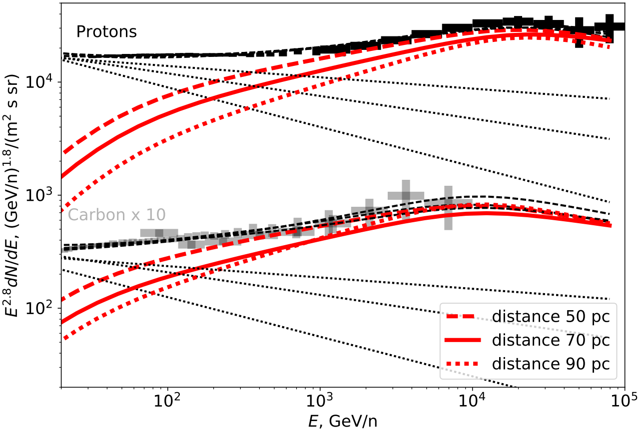
- same shape of rigidity spectra $F_A(\mathcal{R})$ for all nuclei A
- relative normalisation of “local source” $F^{(1)}(\mathcal{R})$ and “average” $F^{(2)}(\mathcal{R})$ varies,

$$F_A(\mathcal{R}) = C_A^{(1)} F^{(1)}(\mathcal{R}) + C_A^{(2)} F^{(2)}(\mathcal{R})$$

Local source: nuclei fluxes

⇒ explains breaks and variation of rigidity spectra



[*MK, Neronov, Semikoz '17*]

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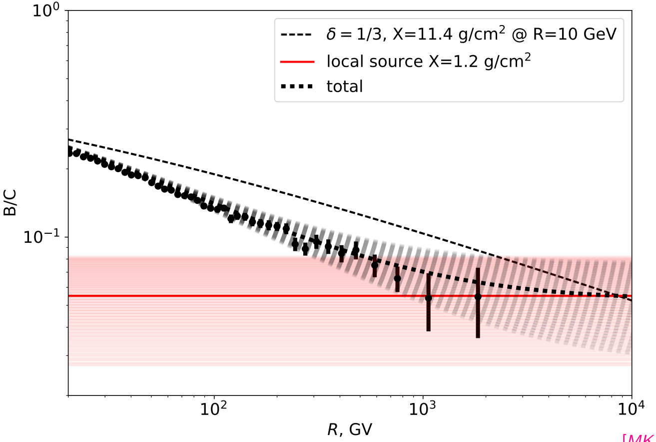
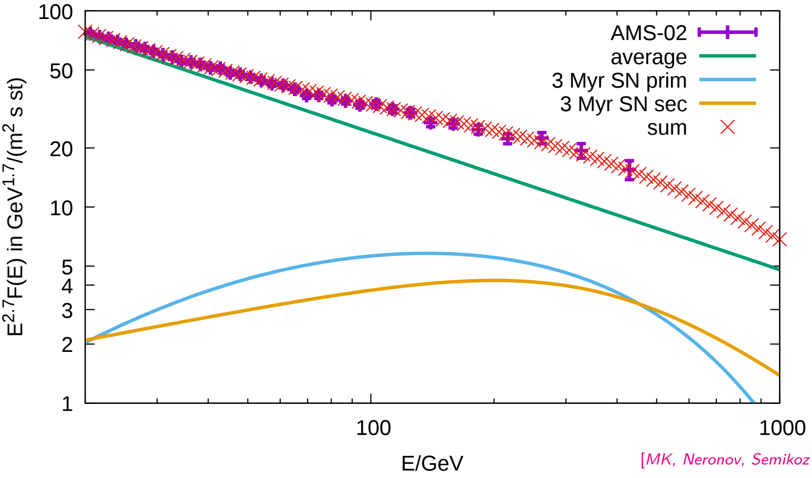


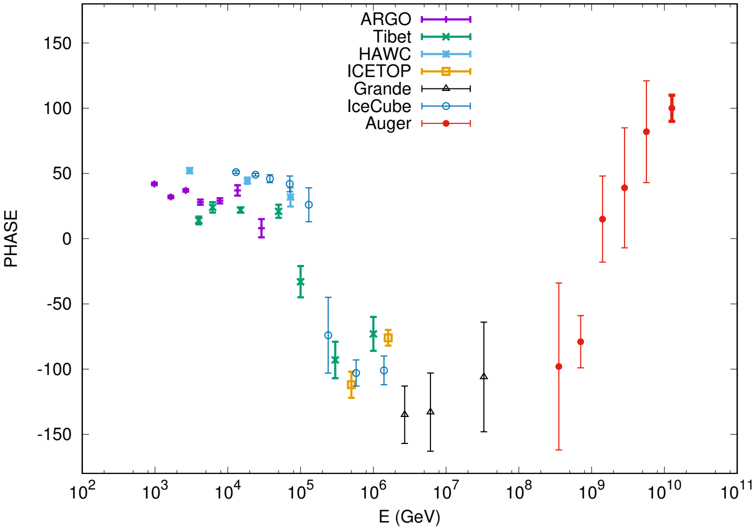
[MK, Neronov, Semikoz '17]

Local source: Electrons

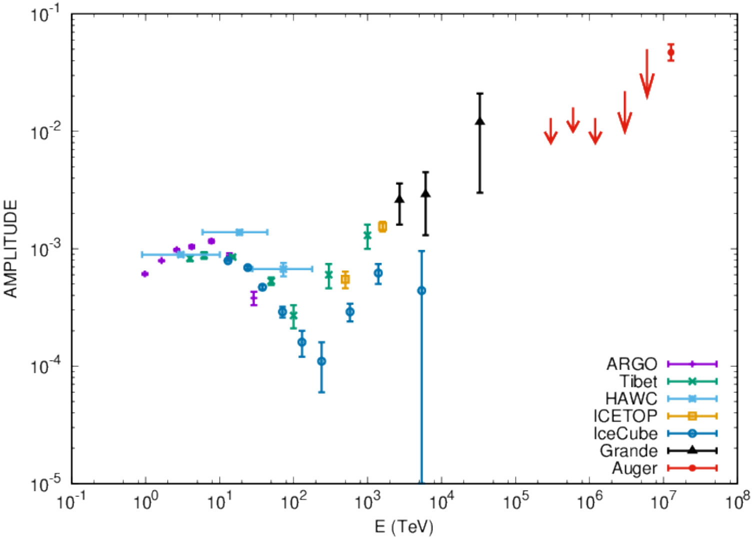


[MK, Neronov, Semikoz '17]

Dipole anisotropy: phase



Dipole anisotropy: amplitude



Anisotropy of a single source

- if only turbulent field:
  diffusion = isotropic random walk = free quantum particle
- number density is Gaussian with $\sigma^2 = 2DT$

$$\delta_i = \frac{3D_{ij}}{c}\frac{\nabla_j n}{n} = \frac{3R}{2T} = 5 \times 10^{-4}\frac{R}{200\text{pc}}\frac{2\text{Myr}}{T}$$

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  - young, nearby source (dominating?) flux, suppression:
    $D_{ij} \propto B_i B_j$ not aligned to ∇n

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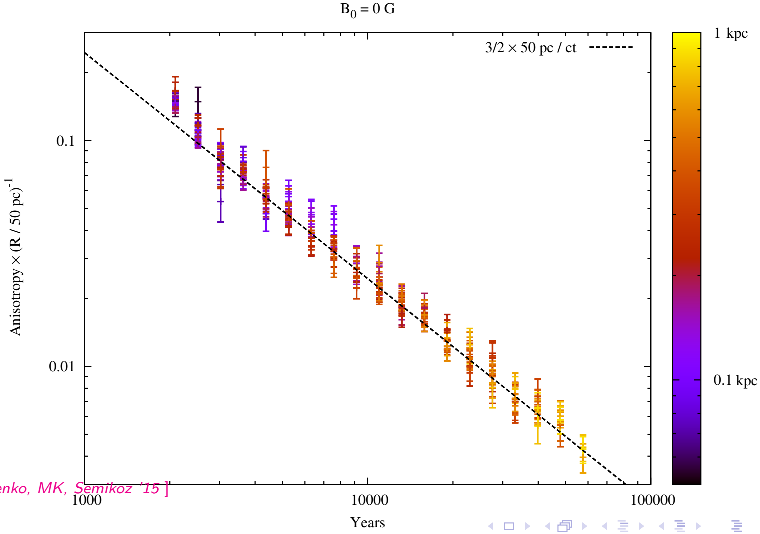
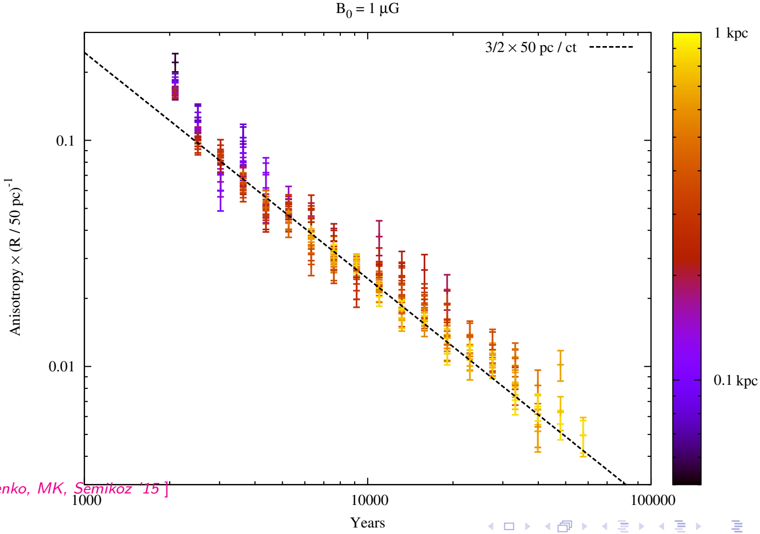
- what happens for general fields?

Anisotropy of a single source: only turbulent field



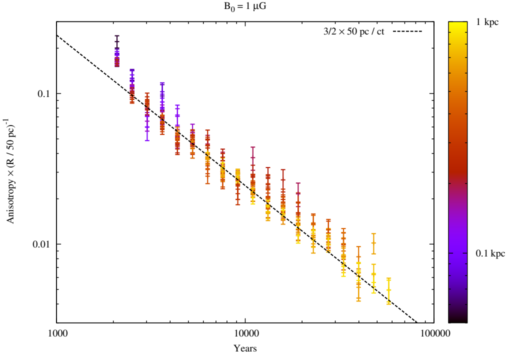
[Savchenko, MK, Semikoz '15]

Anisotropy of a single source: plus regular



[Savchenko, MK, Semikoz '15]

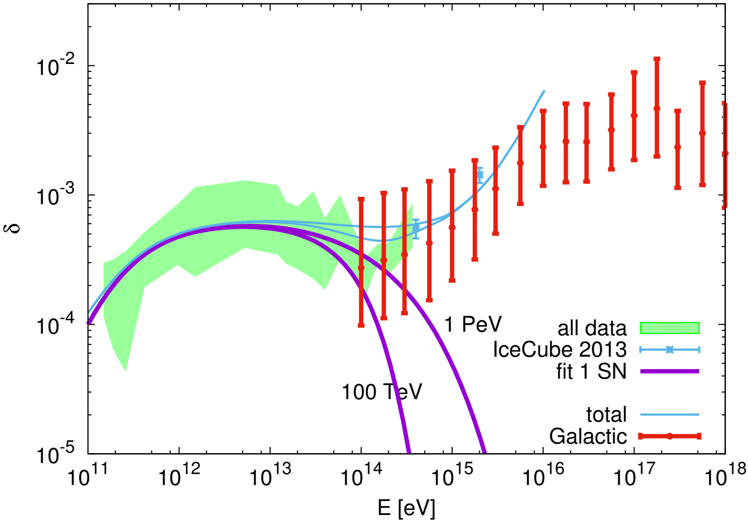
Anisotropy of a single source:



- regular field changes $n(\boldsymbol{x})$, but keeps it Gaussian
- ∇n and D_{ii} are not misaligned

  $\Rightarrow$ no change in δ, no suppression

Dipole anisotropy



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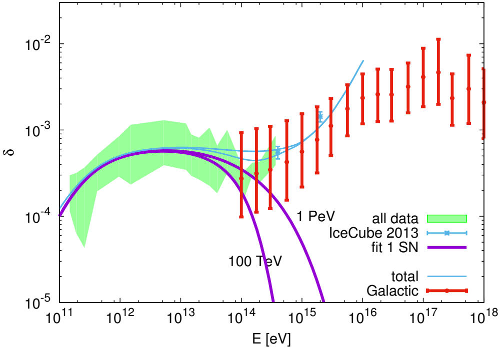
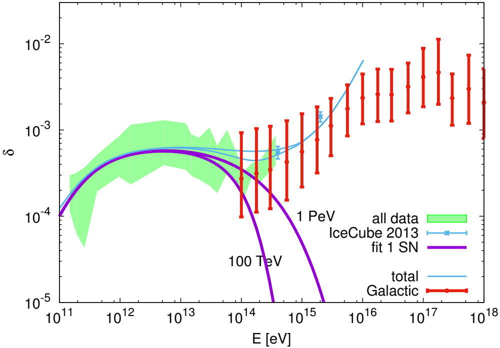


[Savchenko, MK, Semikoz '15]

- suggests low-energy cutoff ⇒ source is off-set
- same cutoff responsible for breaks in spectra

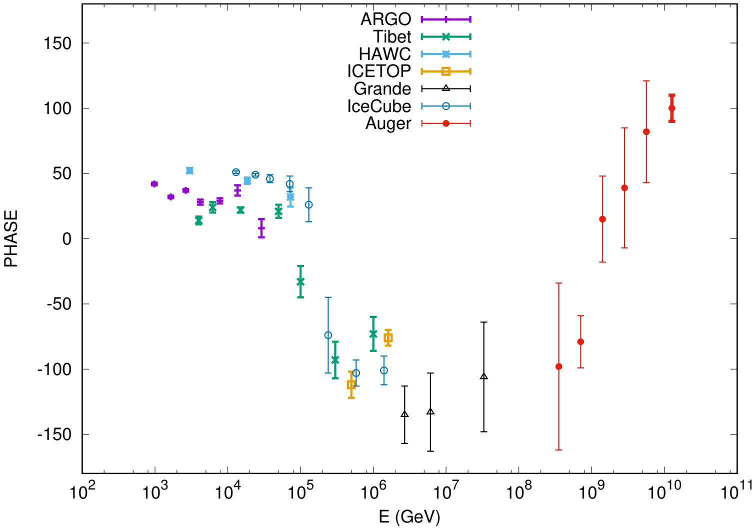
Dipole anisotropy



[Savchenko, MK, Semikoz '15]

- for flip in phase: 2.nd source

Dipole anisotropy: phase flip



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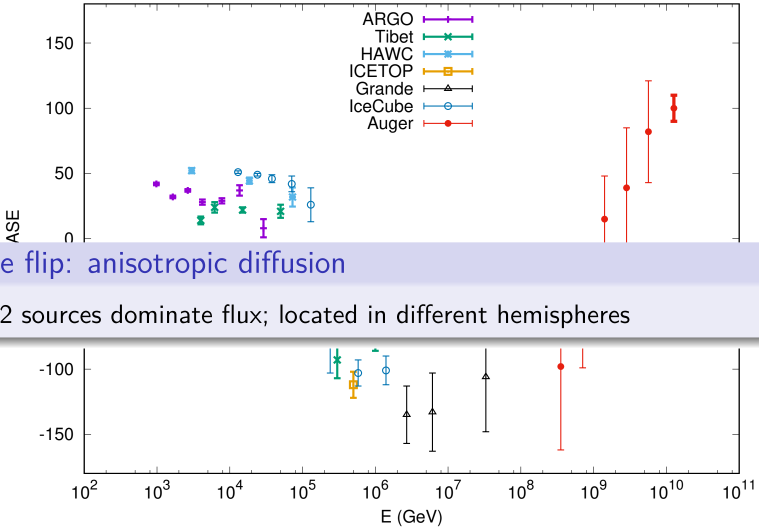


phase flip: anisotropic diffusion

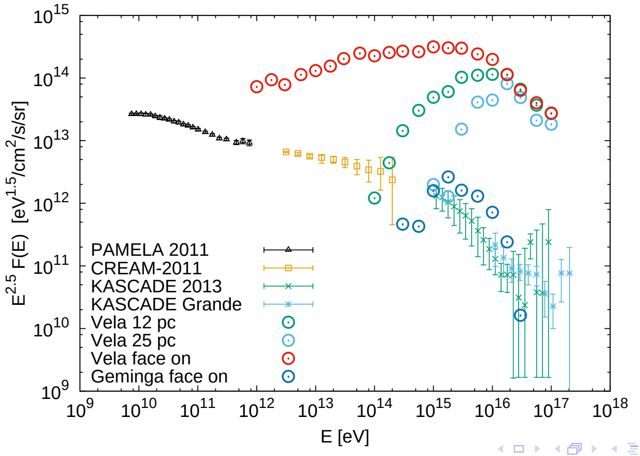
- 2 sources dominate flux; located in different hemispheres

Vela SNR

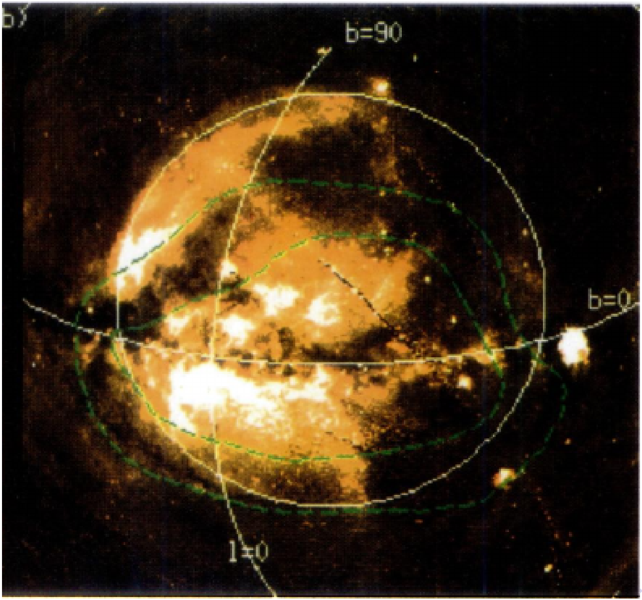
- SNR with $T = 11.000\,\text{yr}$ and $R = 270\,\text{pc}$
- Erlykin & Wolfendale: Vela $E_{\max} \leftrightarrow$ CR knee

Vela SNR

- SNR with $T = 11.000\,\mathrm{yr}$ and $R = 270\,\mathrm{pc}$
- Erlykin & Wolfendale: Vela $E_{\max} \leftrightarrow$ CR knee
- anisotropic diffusion: Sun & Vela connected by field line



Local & Loop I superbubble



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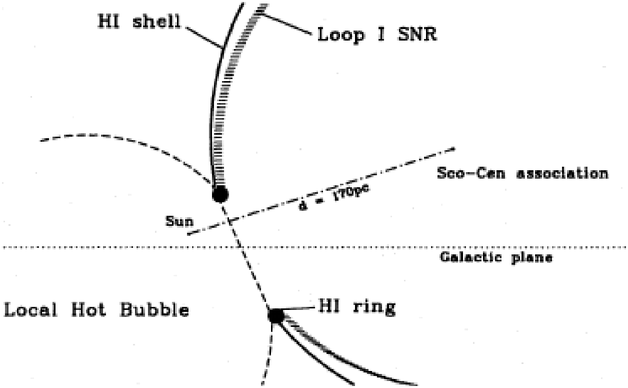
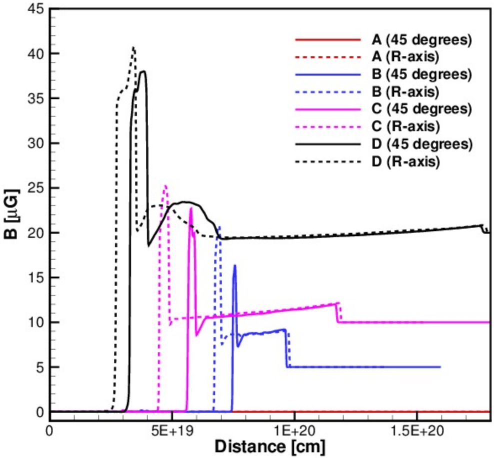
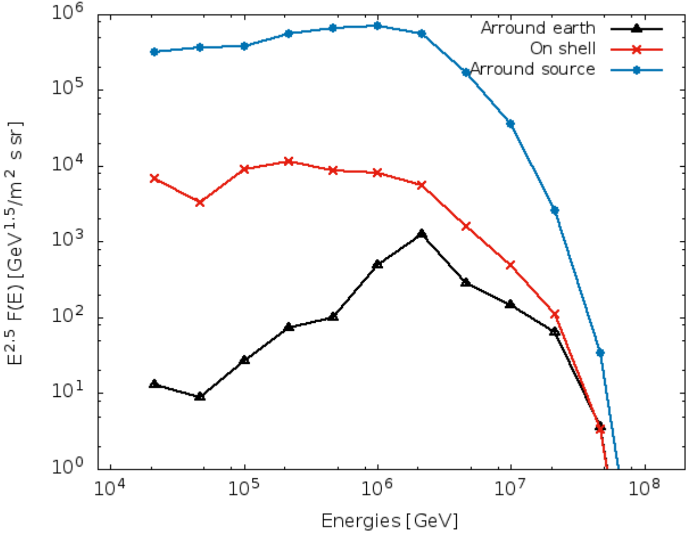


Local & Loop I superbubble

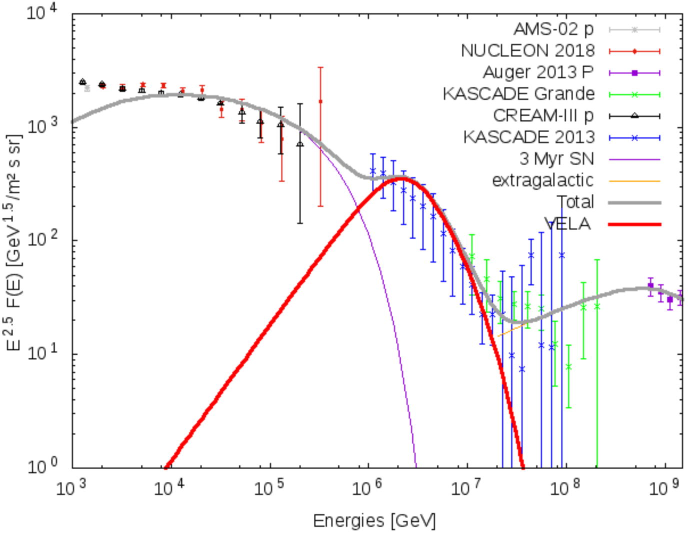


- wall traps particles; acts as a screen

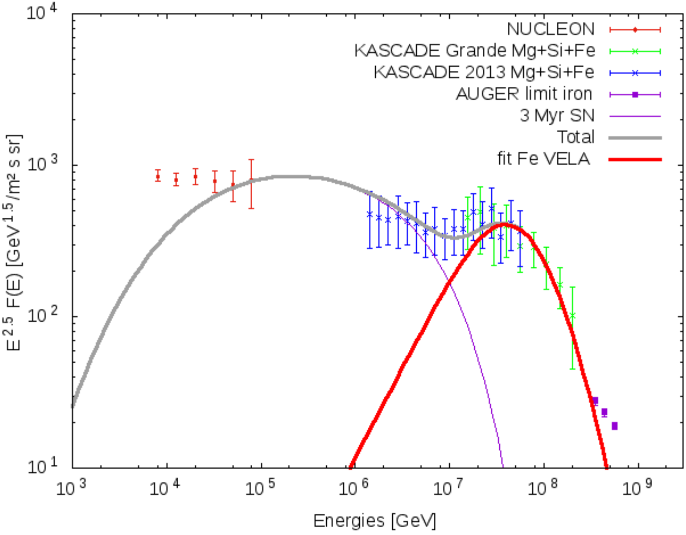
Flux from Vela in Local Superbubble: suppression



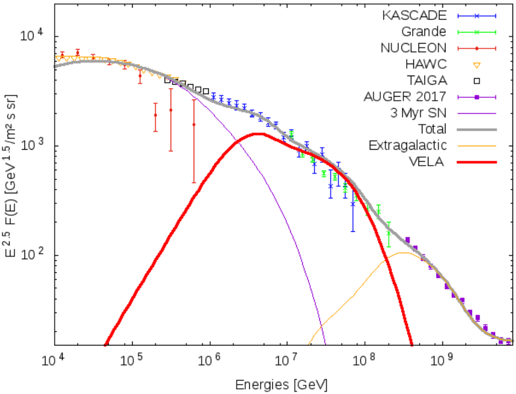
Flux from Vela in Local Superbubble: protons



Flux from Vela in Local Superbubble: Fe+Mg+si

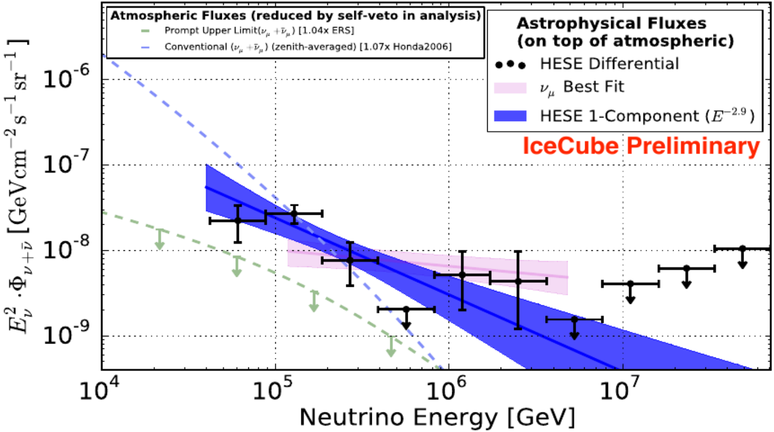


Flux from Vela in Local Superbubble: total

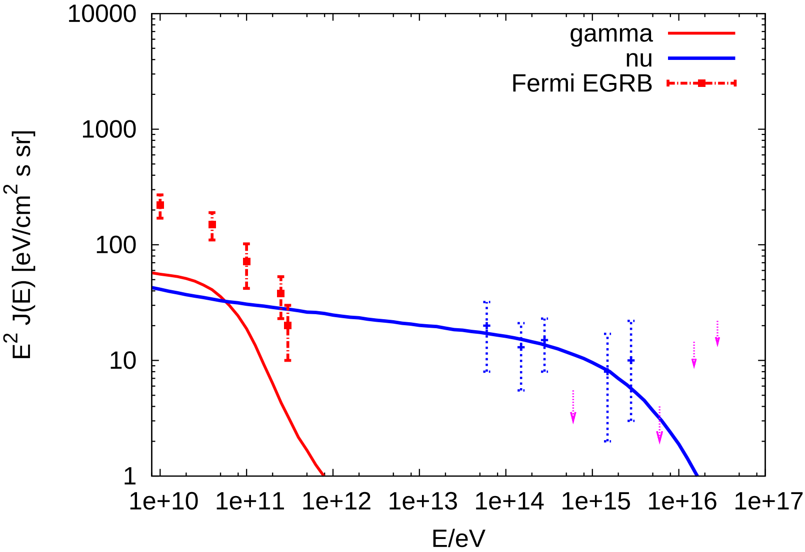


⇒ two local sources dominate Galactic CR flux above 200 GeV

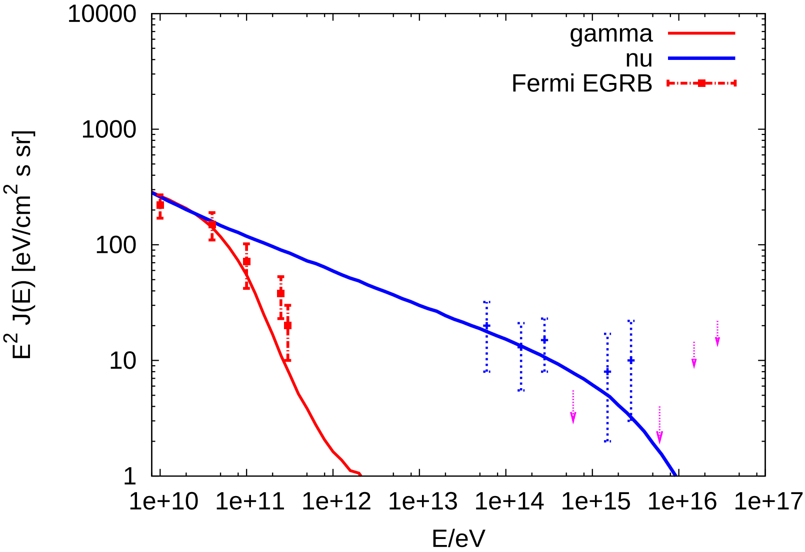
IceCube events: Soft "low-energy" spectrum?



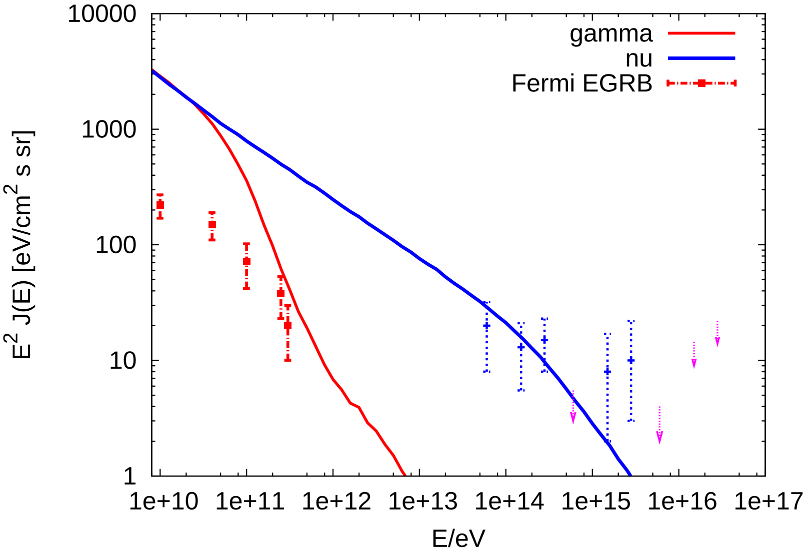
Cascade limit: $\alpha = 2.1$



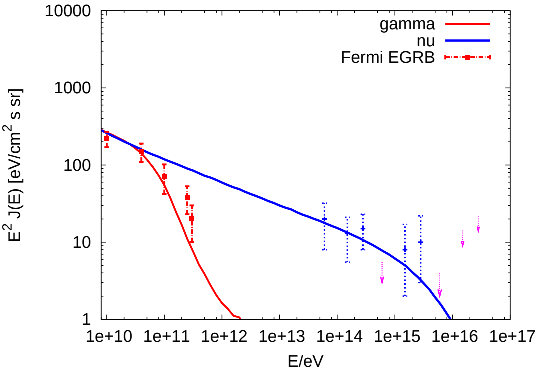
Cascade limit: $\alpha = 2.3$



Cascade limit: $\alpha = 2.5$



Cascade limit:

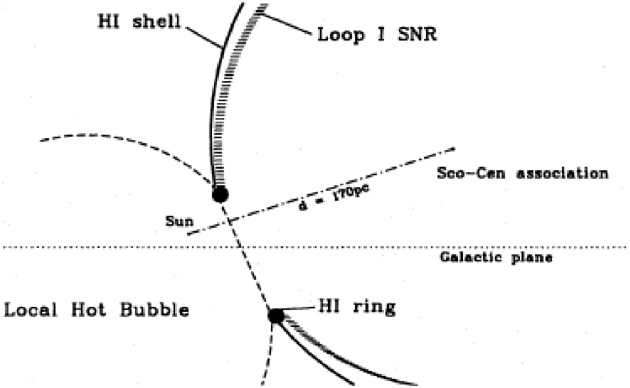


Slope $\alpha \gtrsim 2.2$

- requires "hidden sources" or
- Galactic origin

Sources in Local & Loop I superbubble

[Andersen, MK, Semikoz '17]



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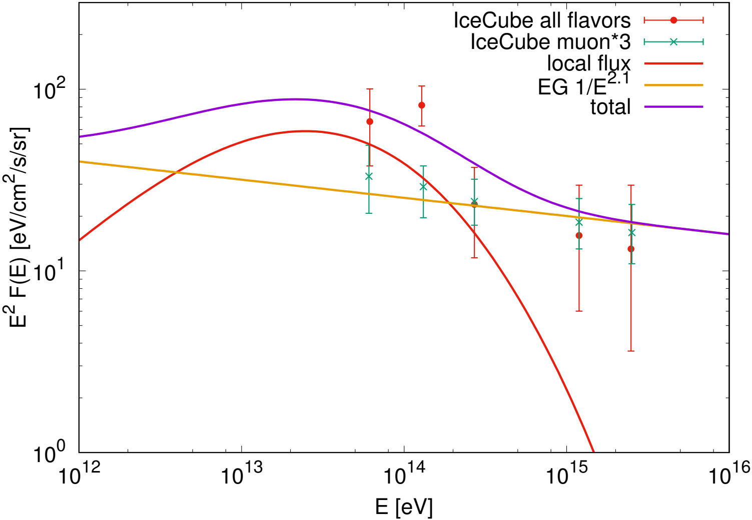
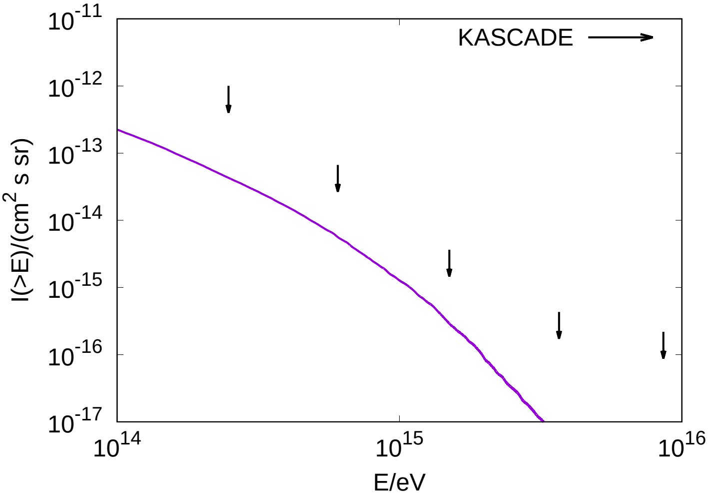
[Andersen, MK, Semikoz '17]



Sources in Local & Loop I superbubble

[Andersen, MK, Semikoz '17]



Conclusions

1. Single source: anisotropy
   - dipole formula $\delta = 3R/2T$ holds universally in quasi-gaussian regime
   - plateau of δ and phase flip point to dominance of 2 single sources
2. Source with $T \sim 2 - 3$ Myr and $R \sim 200$ pc:
   - consistent explanation of $\bar{p}$ and e^+ fluxes, breaks and B/C
   - consistent with ^{60}Fe
3. Vela
   - reproduces fluxes of groups of CR nuclei
   - shape consistent with knee
   - source of soft neutrino component?
4. local geometry of GMF is important: Local Bubble and Loop I

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