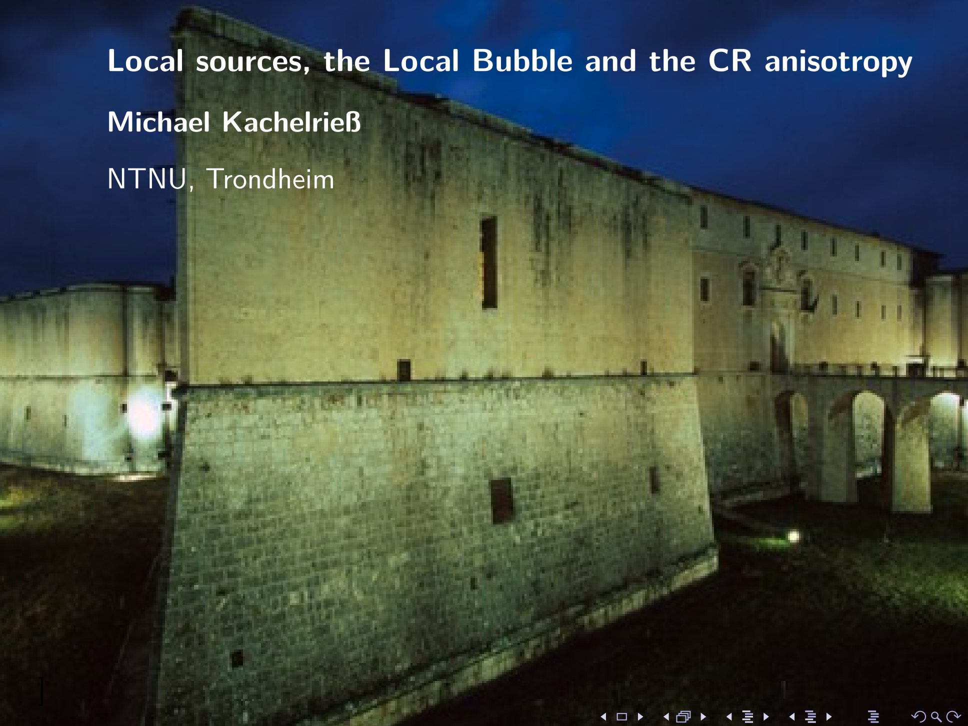
Local sources, the Local Bubble and the CR anisotropy

Michael Kachelrieß

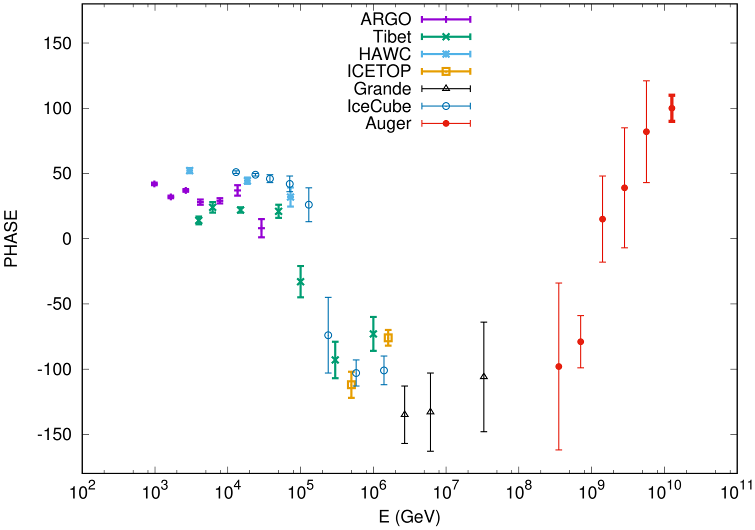
NTNU, Trondheim



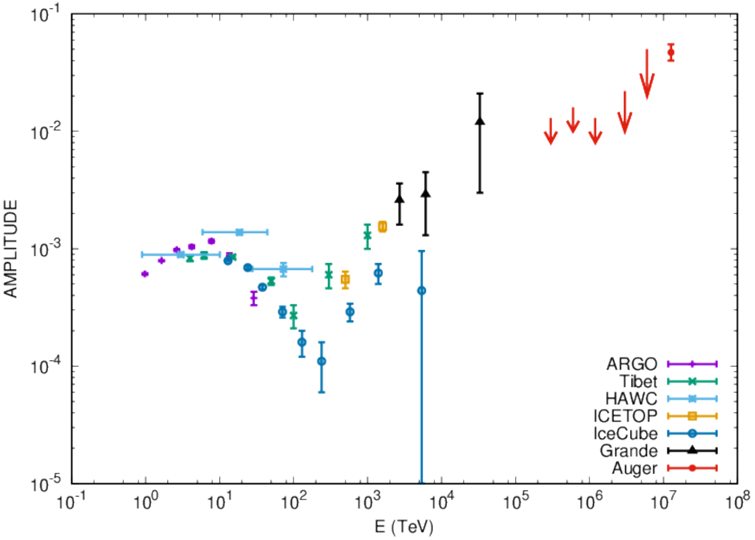
Outline of the talk

1. Introduction
   - Dipole anisotropy: evidence for 2 local sources
2. Anisotropic diffusion
   - Connecting GMF and diffusion
   - Consequences of anisotropic diffusion
3. 2–3 Myr local SN
   - Primaries: breaks, non-universality
   - Secondaries: positron excess, antiprotons, B/C
4. Vela and the Local Bubble
   - CR fluxes
   - Neutrinos and photons
   - CR anisotropy
5. Conclusions

Dipole anisotropy: phase



Dipole anisotropy: amplitude



Anisotropy of a single source

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

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

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- 2 extreme options:
  - old nearby source dominating flux
  - young nearby source (not dominating) flux, suppression:

$$D_{ij} = D_{\parallel} b_i b_j + D_{\perp}(\delta_{ij} - b_i b_j) + \varepsilon_{ijk} e_k D_A \simeq D_{\parallel} b_i b_j$$

not aligned to ∇n

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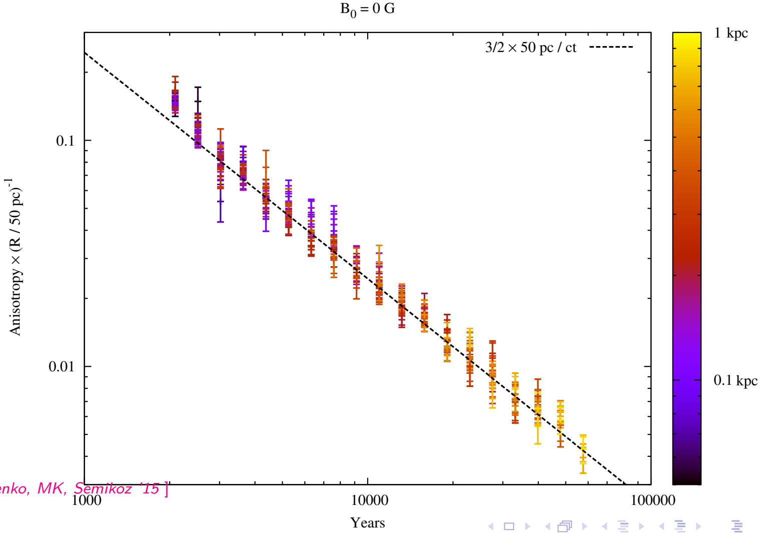
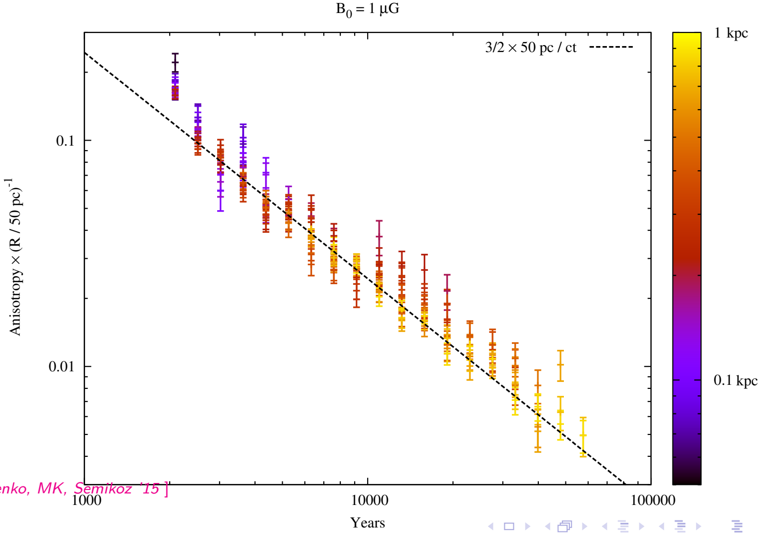
    not aligned to ∇n
- what happens for general fields?

Anisotropy of a single source: only turbulent field



[Savchenko, MK, Semikoz '15]

Anisotropy of a single source: plus regular



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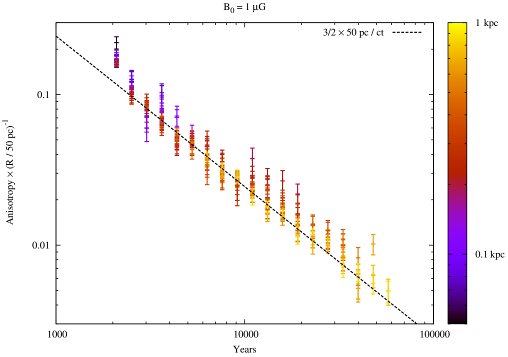

- regular field changes $n(\boldsymbol{x})$, but keeps it Gaussian shape

  $\Rightarrow$ no suppression because of misalignement of ∇n and $D_\parallel$

  $\Rightarrow$ $\delta = 3R/2T$ still holds

Propagation in turbulent magnetic fields: Trajectory approach

- CR above 0.1–1 TeV: neglect non-linear effects

$\Rightarrow$ use prescribed model for Galactic magnetic field

- calculate trajectories $\boldsymbol{x}(t)$ via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.

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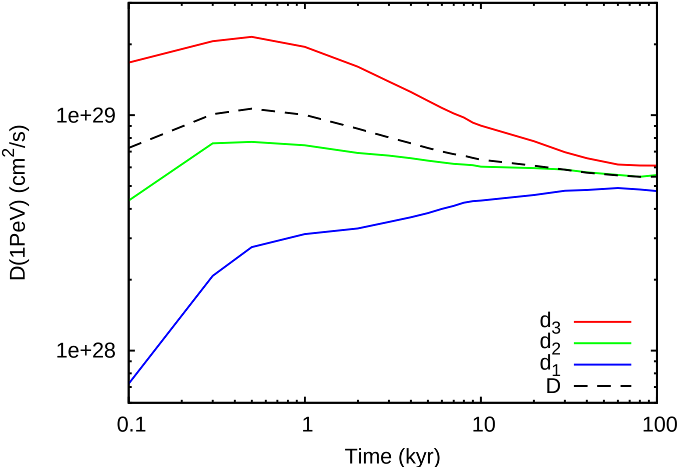
- calculate trajectories $\boldsymbol{x}(t)$ via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.
- as preparation, let's calculate diffusion tensor in pure, isotropic turbulent magnetic field

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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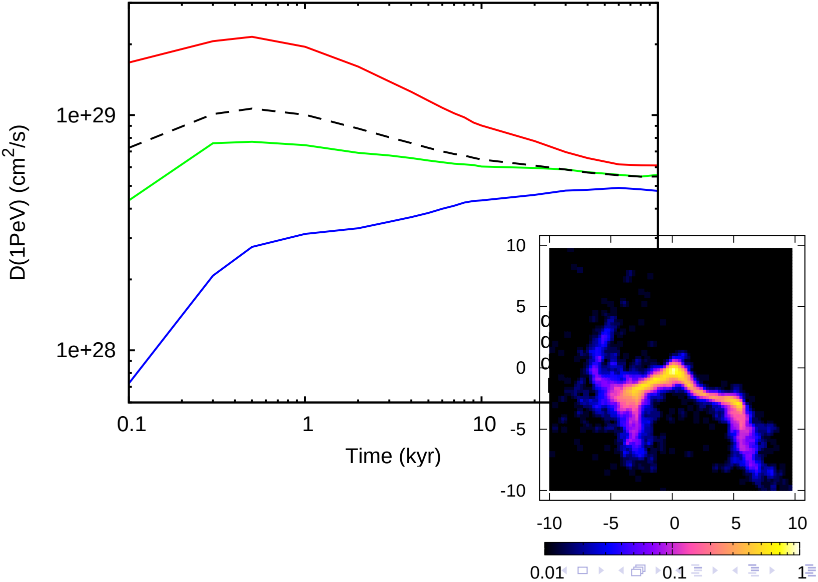

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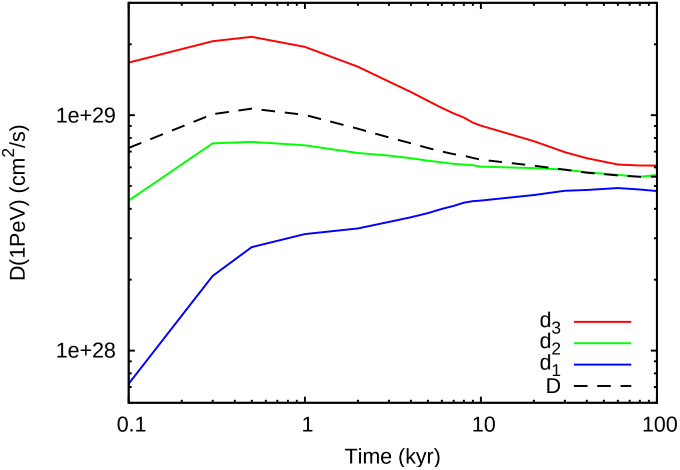

- asymptotic value is ~ 50 smaller than standard value

Is isotropic diffusion possible?

[Giacinti, MK, D. Semikoz '17]

- for isotropic diffusion: for $\alpha = 5/3$

$$D = \frac{cL_0}{3}\left[(R_{\rm L}/L_0)^{2-\alpha} + (R_{\rm L}/L_0)^2\right] \propto B^{-1/3}$$

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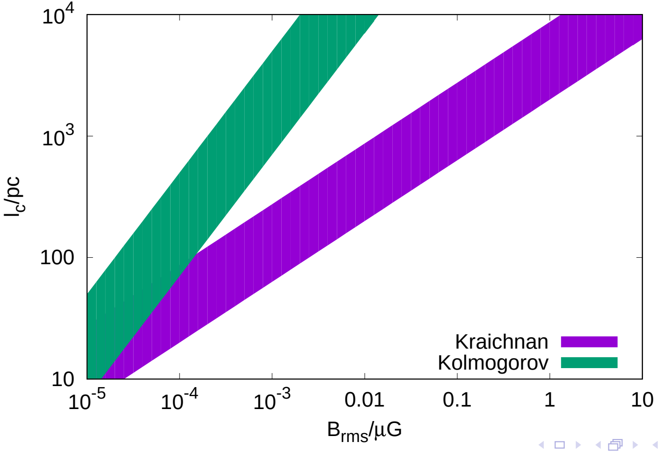

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- anisotropic turbulence
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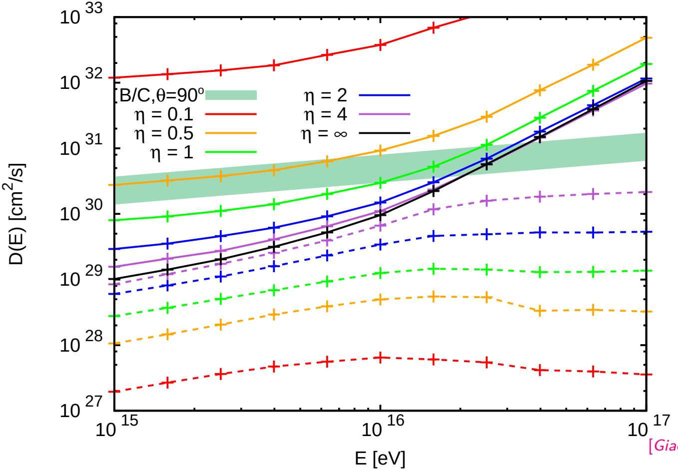

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Anisotropic diffusion – 2 options:

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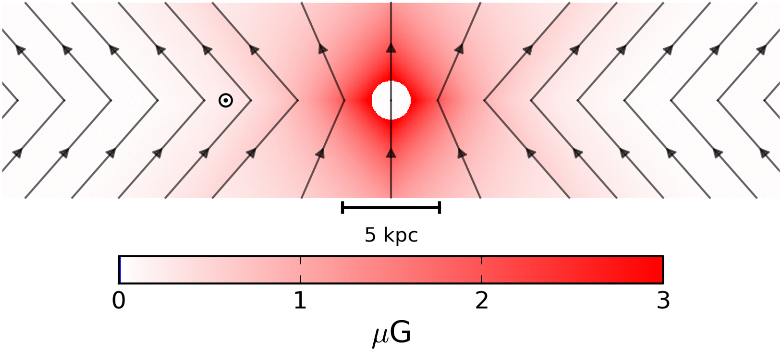
$\Rightarrow$ anisotropic CR propagation

$\Rightarrow$ relative importance of single sources is changed

X-field in JF model:



- propagation along X field eases CR escape

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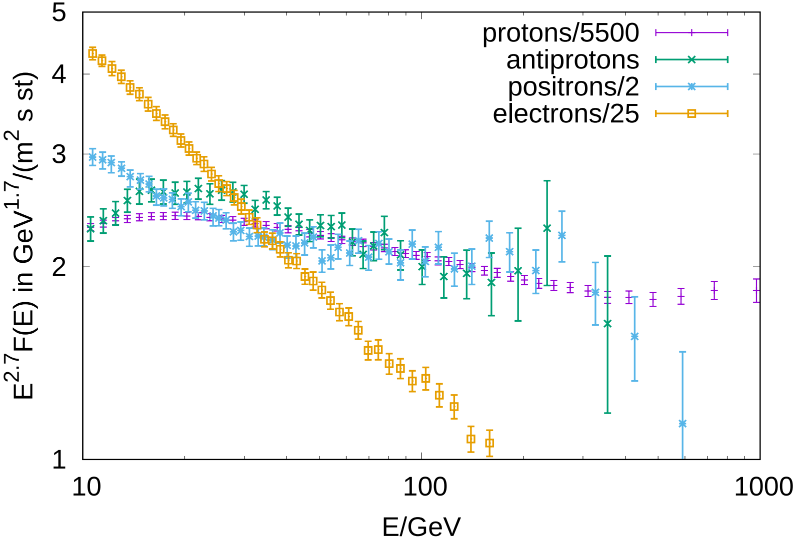
- anisotropic diffusion in JF model with $\eta = 0.25 \Rightarrow D_\| \simeq 5D_*$ and $D_\perp \simeq D_*/500$
  - $\Rightarrow$ volume is reduced by $500/\sqrt{5} \simeq 200$
  - $\Rightarrow$ single source can dominate observed flux at 10 TeV

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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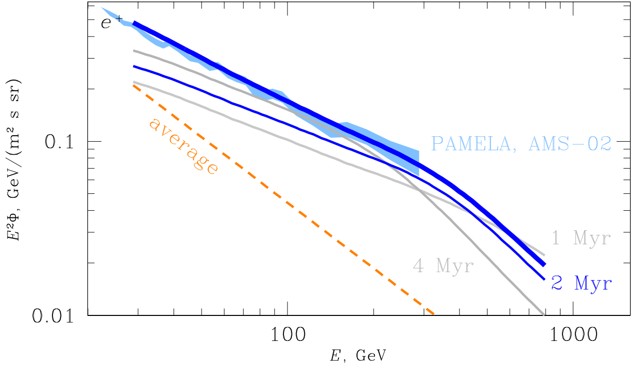

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- SNe connected to Local Bubble [Schulreich '17,…]

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- SNe connected to Local Bubble [Schulreich '17,...]
- what about other CR puzzles?
  - breaks? rigidity dependence?
- B/C consistent?
- anisotropy?

Local source: nuclei fluxes

- same shape of rigidity spectra $F_A(\mathcal{R})$ for all nuclei A

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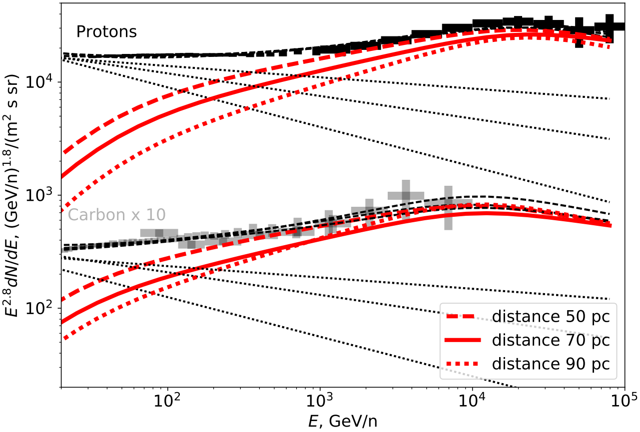
- same shape of rigidity spectra $F_A(\mathcal{R})$ for all nuclei A
- relative normalisation of "local source" $F^{(1)}(\mathcal{R})$ and "average" $F^{(2)}(\mathcal{R})$ varies,

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

Local source: nuclei fluxes

⇒ explains breaks and variation of rigidity spectra



[MK, Neronov, Semikoz '17]

Local source: Secondary nuclei and B/C

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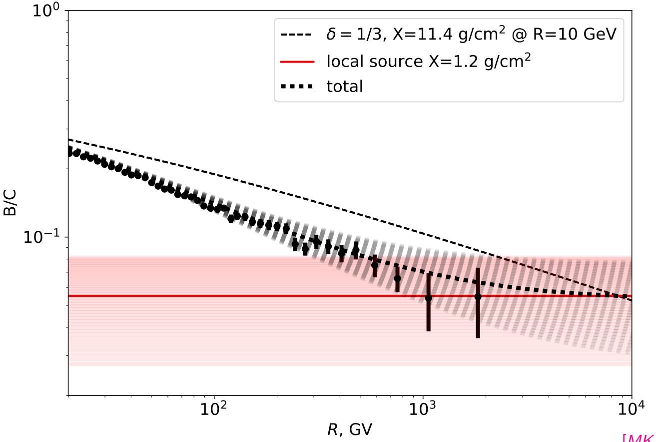

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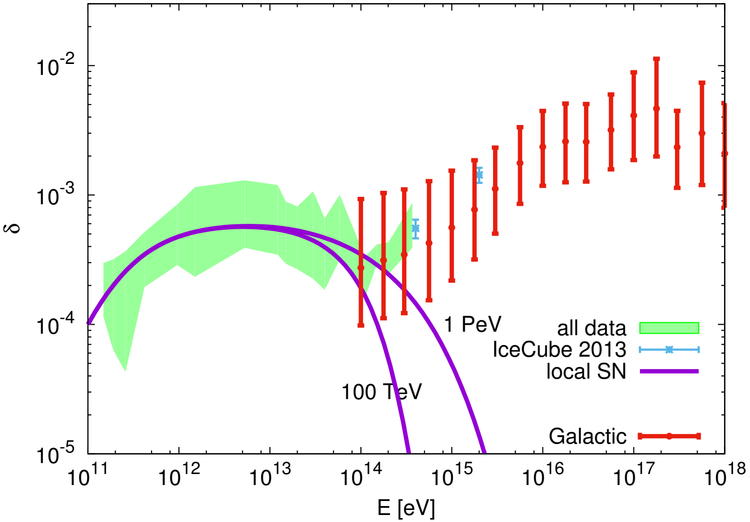
Dipole anisotropy



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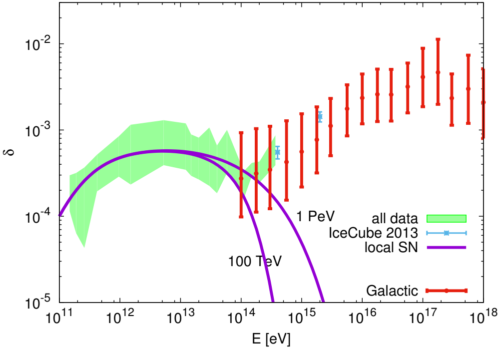
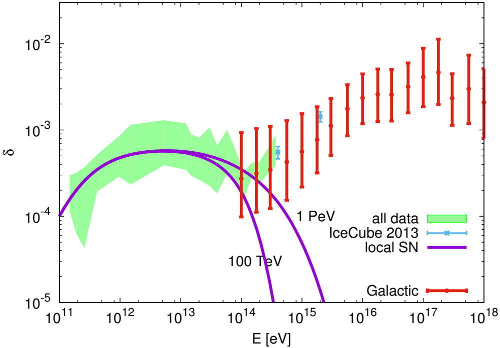


[Savchenko, MK, Semikoz '15]

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

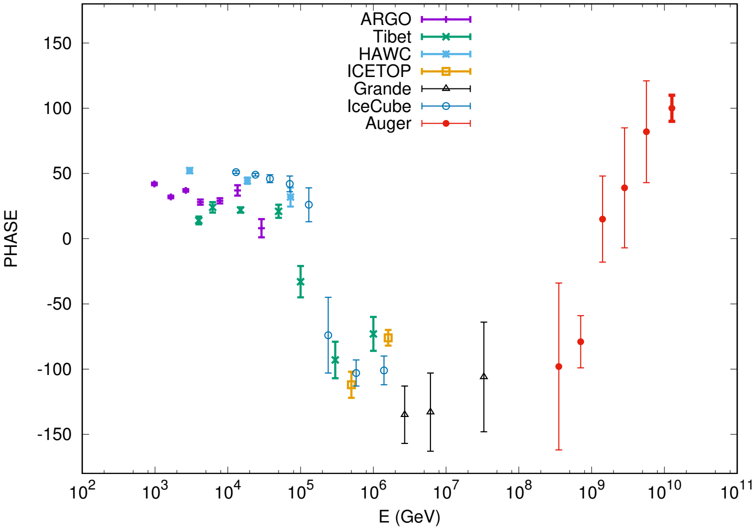
Dipole anisotropy



[Savchenko, MK, Semikoz '15]

- for flip in phase: 2.nd source

Dipole anisotropy: phase flip



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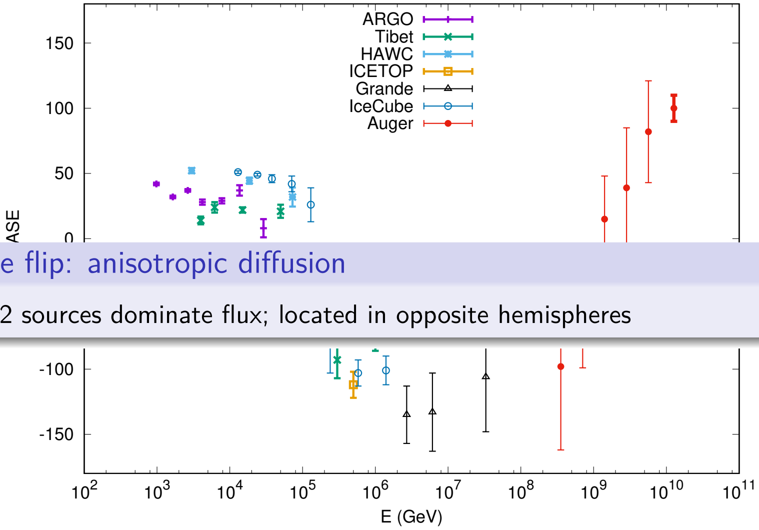

phase flip: anisotropic diffusion

- 2 sources dominate flux; located in opposite hemispheres

Vela SNR

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

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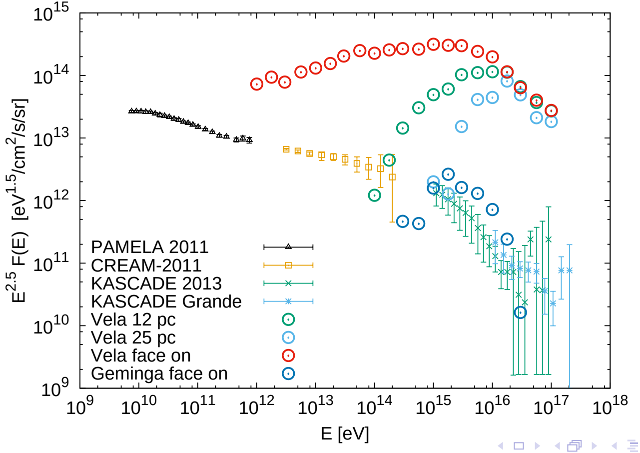
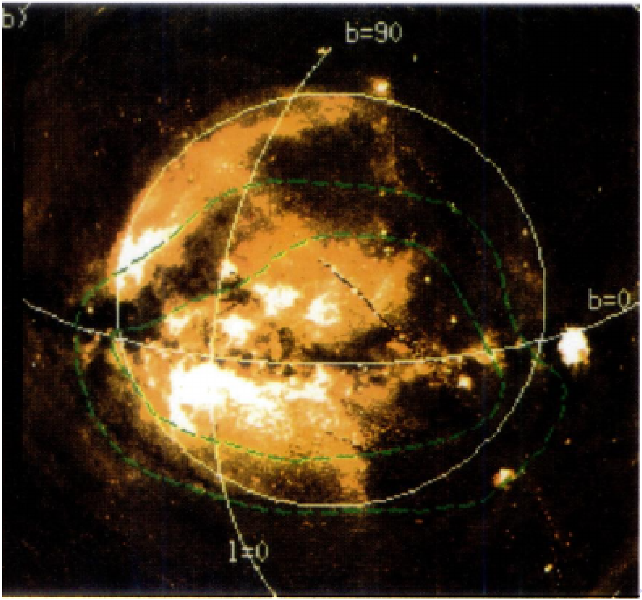
- anisotropic diffusion: Sun & Vela connected by field line



Local & Loop I superbubble



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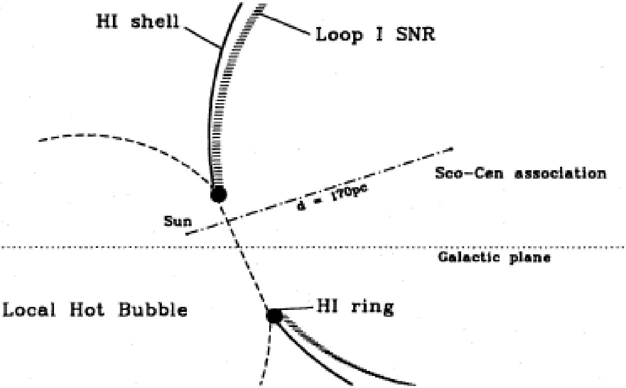

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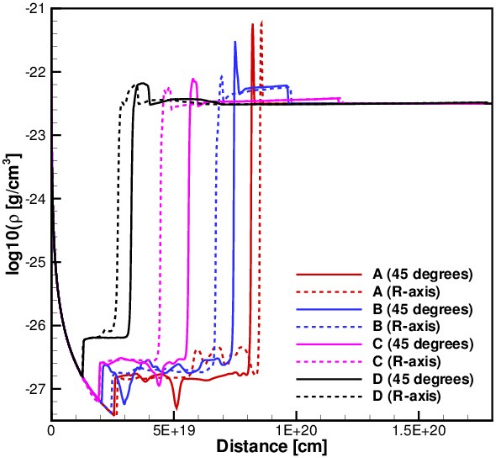
[van Marle, Meliani, Marcowith '15]



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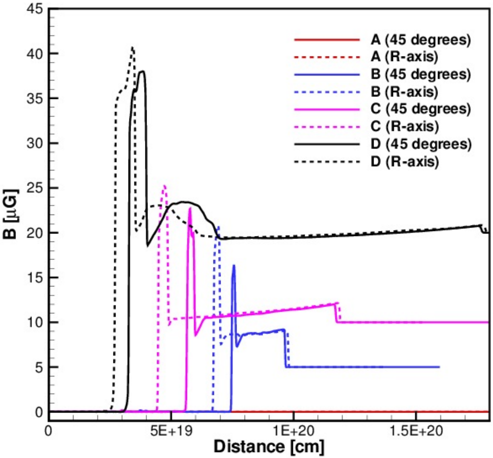
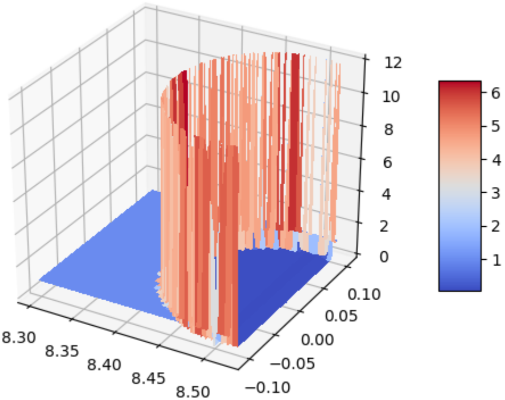


- wall traps particles; acts as a screen

Our toy model

[M.Bouyahiaoui, MK, D.Semikoz '18]



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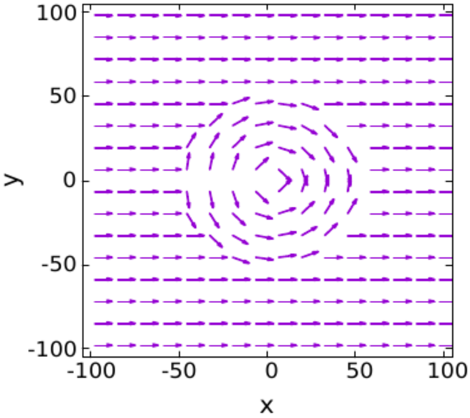
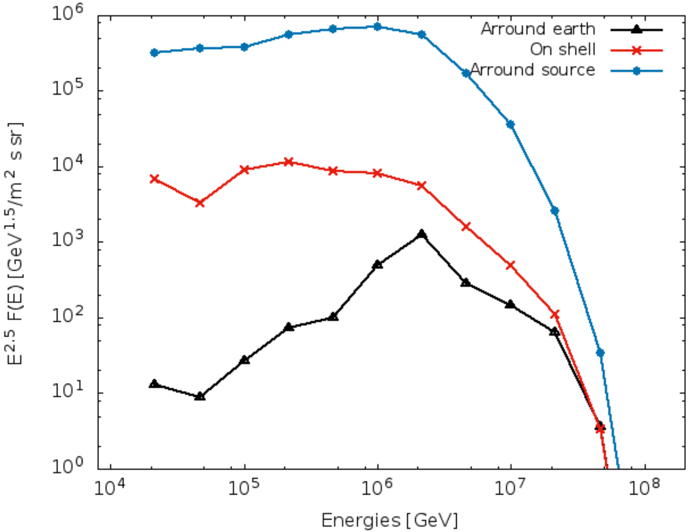


- cylinder symmmetry in z, Vela outside

Flux from Vela in Local Superbubble: suppression



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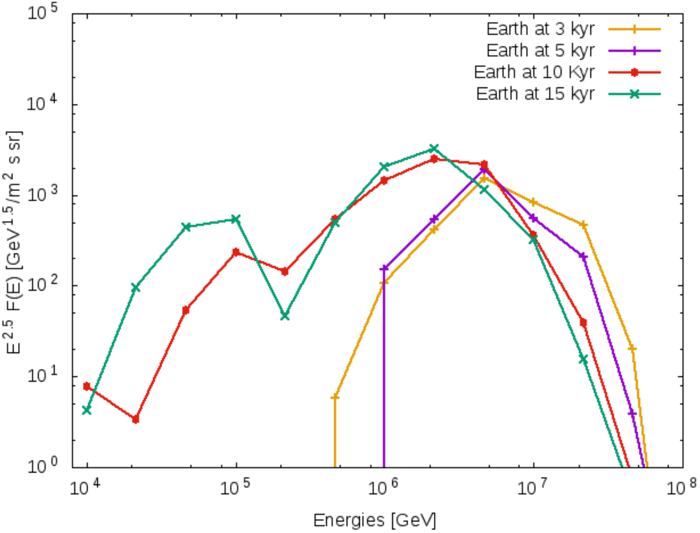

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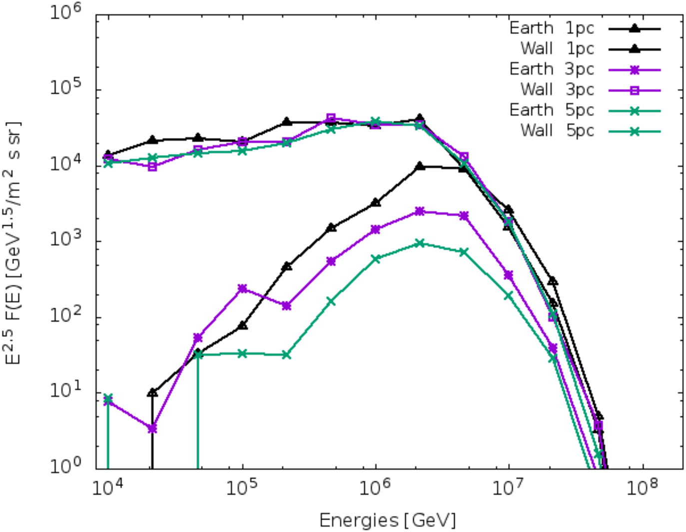
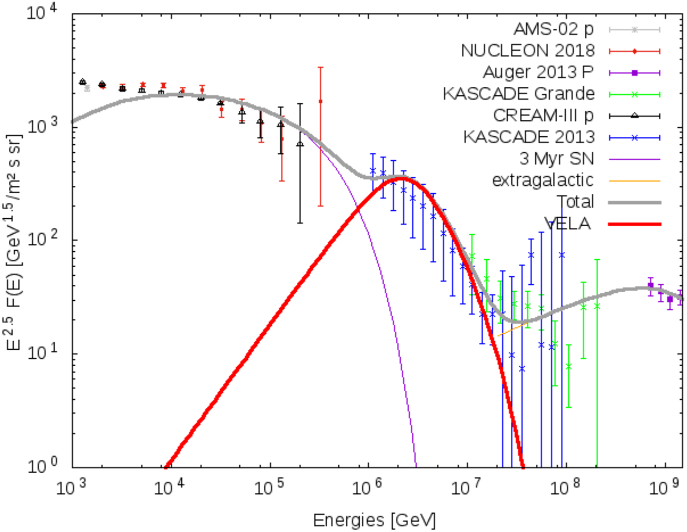
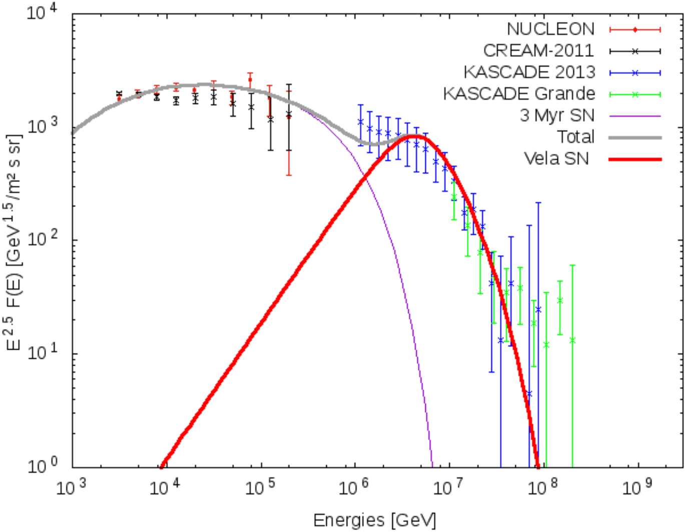


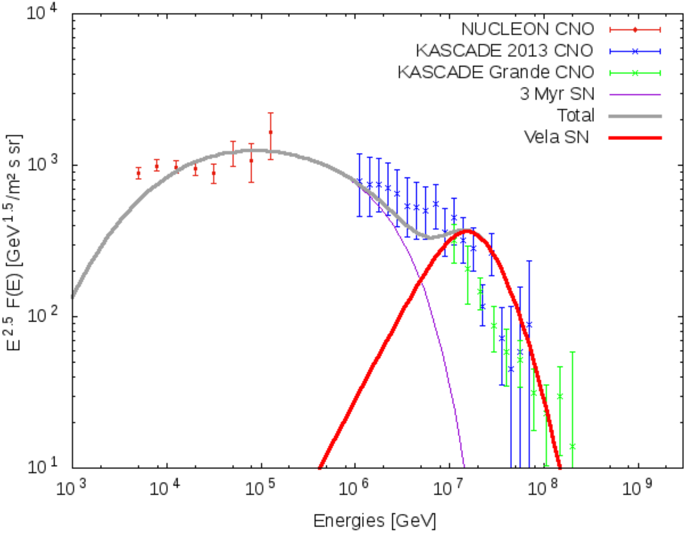
Flux from Vela in Local Superbubble:protons



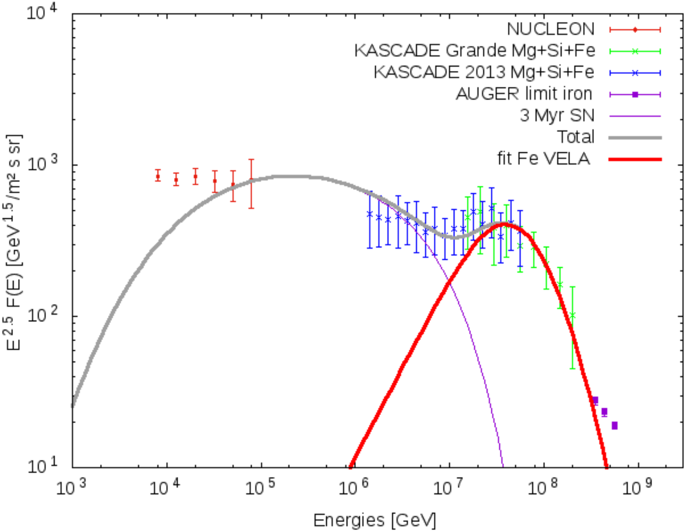
Flux from Vela in Local Superbubble: He



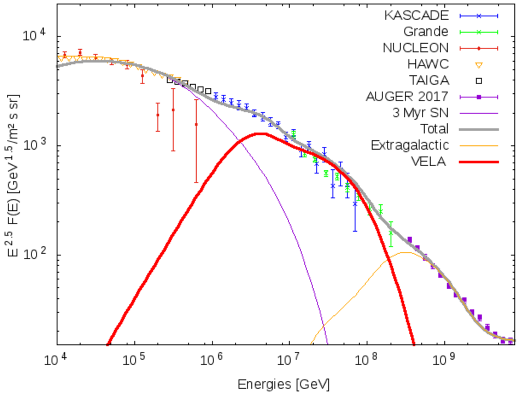
Flux from Vela in Local Superbubble: CNO



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

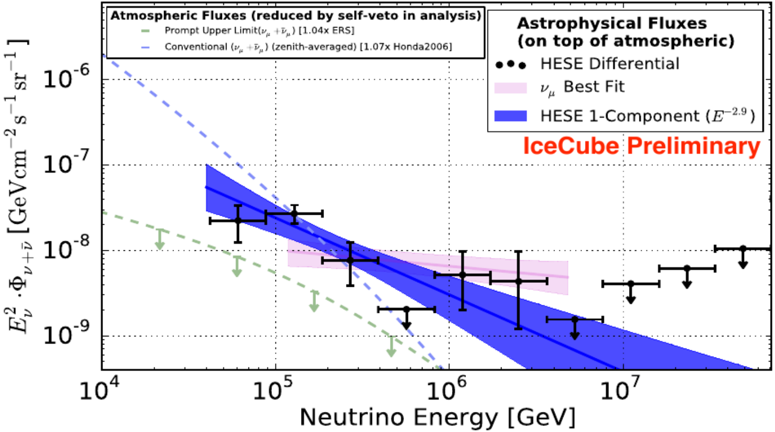


Flux from Vela in Local Superbubble: total



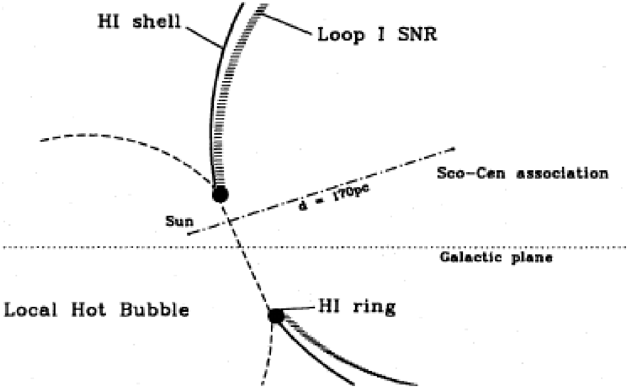
⇒ two local sources dominate Galactic CR flux above 200 GeV

IceCube events: Soft “low-energy” spectrum?



Sources in Local & Loop I superbubble

[Andersen, MK, Semikoz '17]



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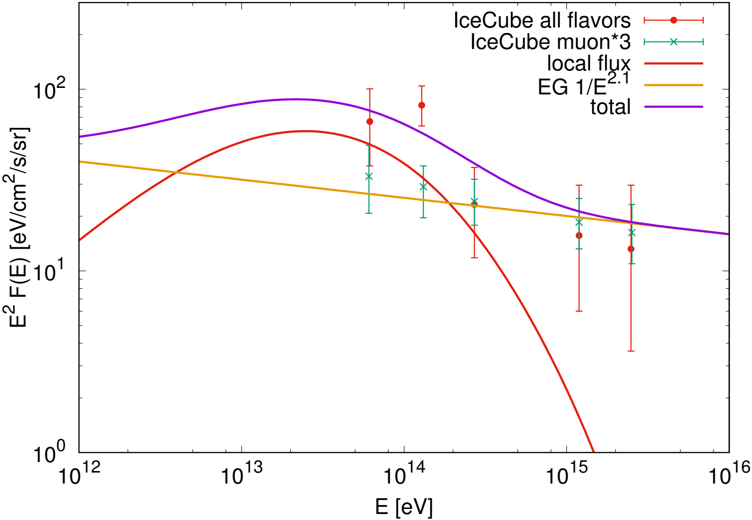

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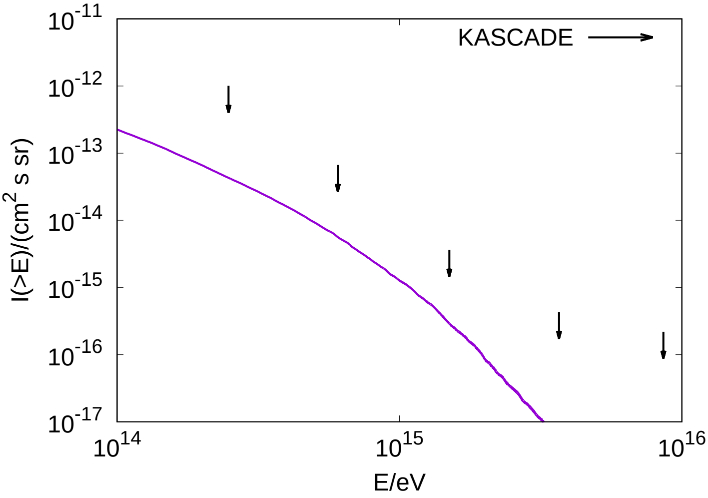

Dipole anisotropy from Vela

- if Vela dominates CR flux around knee, then

$$\delta = \frac{3R}{2T} \simeq 0.1 \, \frac{R}{300\mathrm{pc}} \frac{10\mathrm{kyr}}{T}$$

$\Rightarrow$ overshoots observation by 2 orders of magnitude

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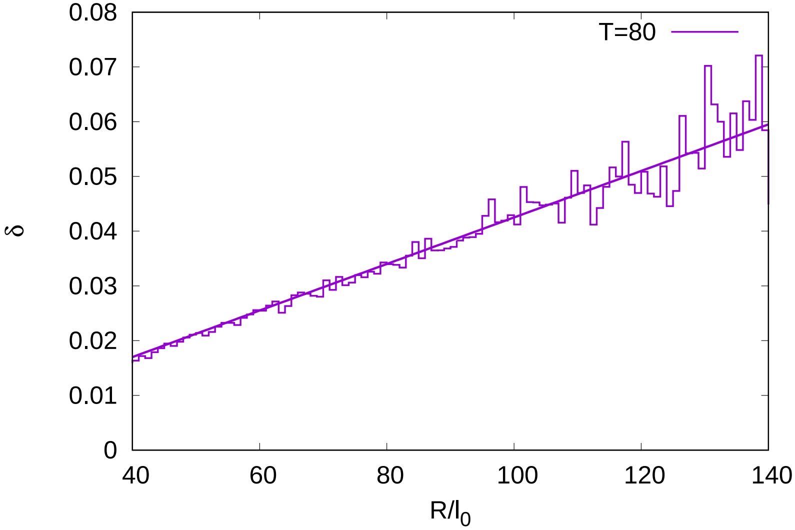
- how does Local Bubble influence this estimate?

Dipole anisotropy in random walk picture

- solving Lorentz equation becomes too expansive
- instead: random walk picture
- anisotropy for stepsize ℓ_0:

$$\delta = \frac{R}{N\ell_0}$$

Dipole anisotropy in random walk picture: tests



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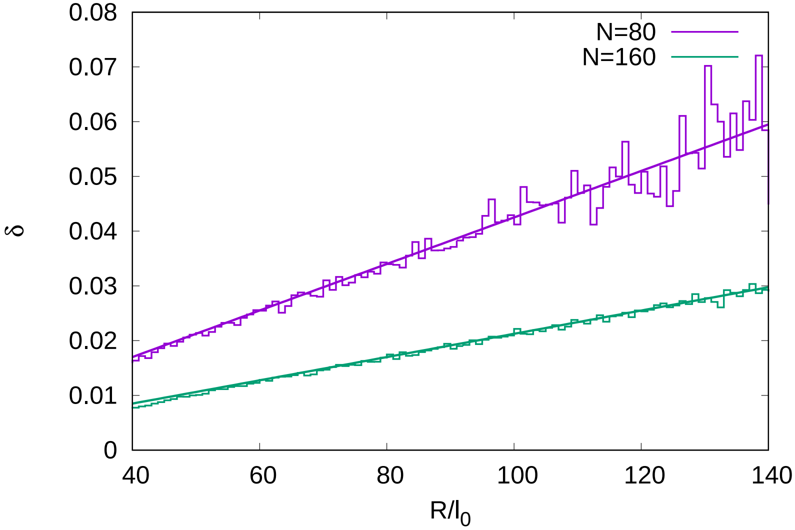
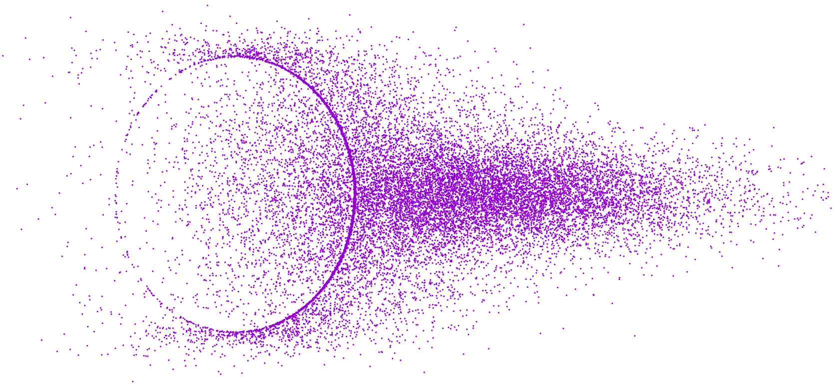


Adding the Local Bubble: particle density



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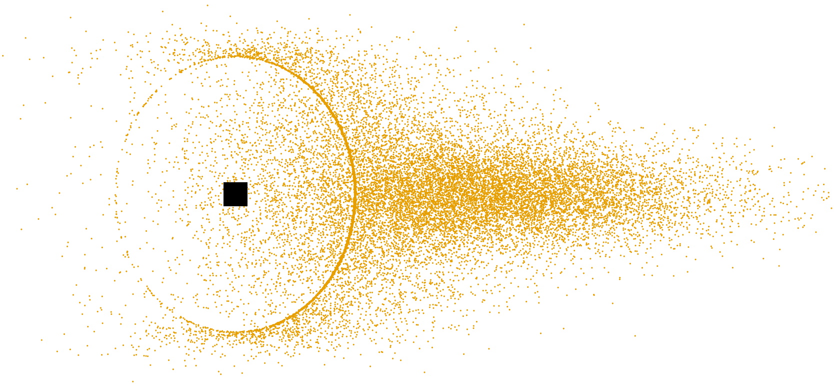

- anisotropy at $T = 12\,\text{kyr}$: $\delta \simeq 0.08$

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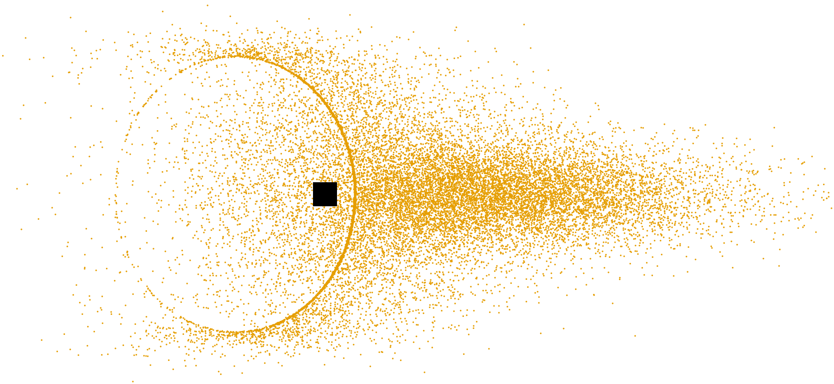

- anisotropy at $T = 12\,\text{kyr}$: $\delta \simeq 0.001$

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
   - knee: low-energy suppression of Local Bubble
   - source of soft neutrino component?
4. local geometry of GMF is important: Local Bubble and Loop I

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