particle acceleration in reconnection regions
the case of cosmic ray excess from the heliotail

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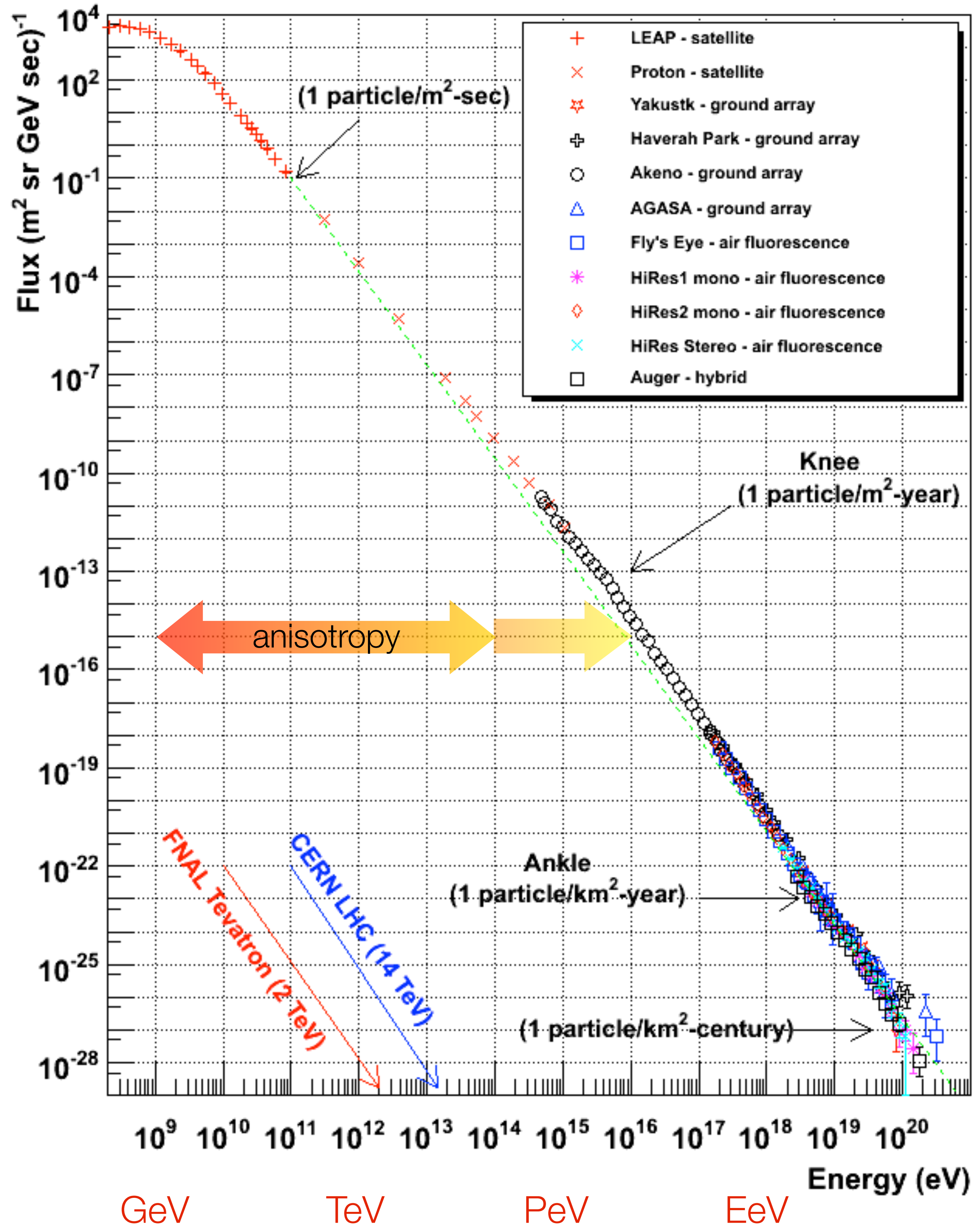
cosmic rays

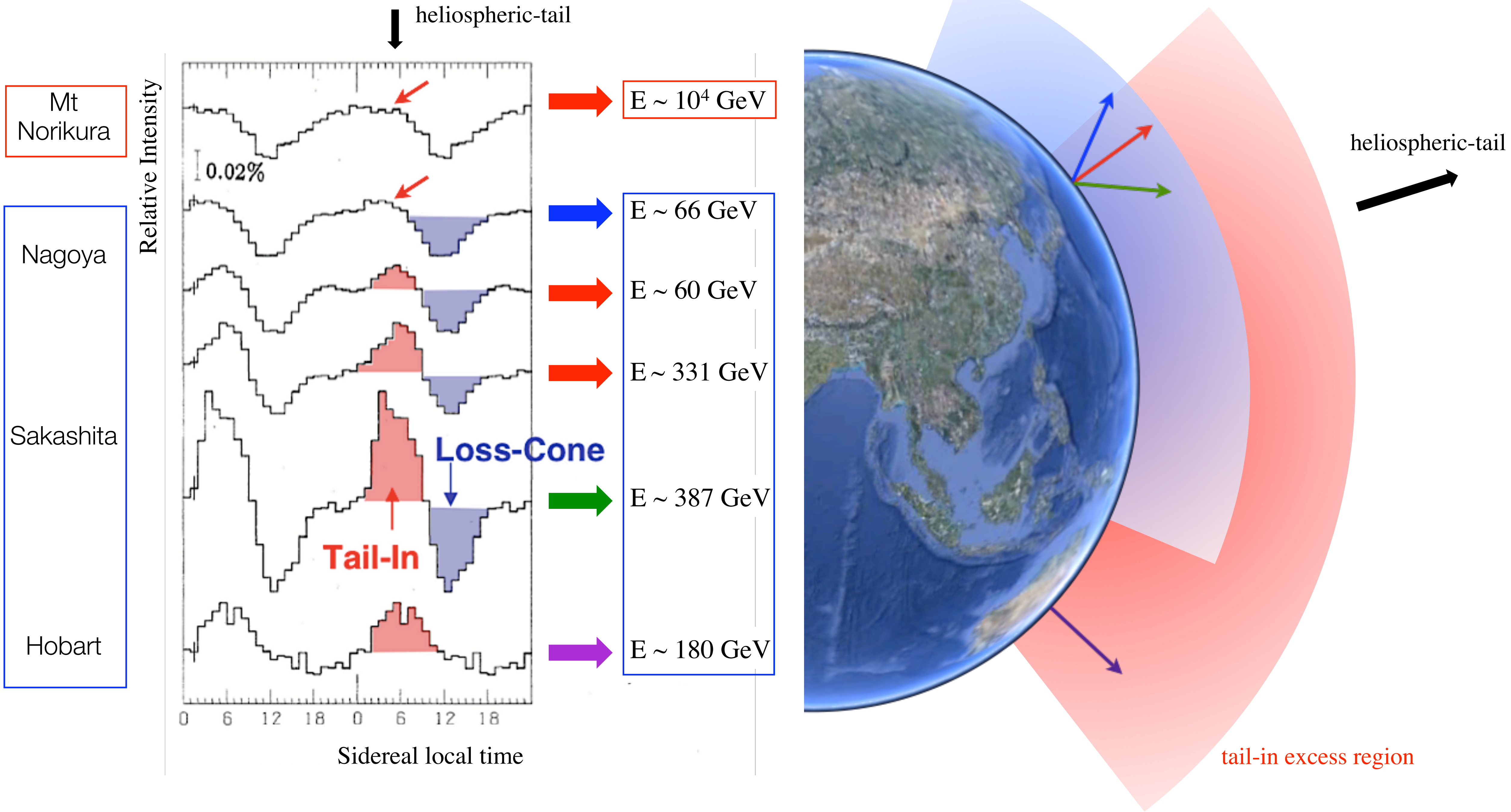
- CR below the knee (~3×10^{15} eV) believed to be galactic
- CR below ~10^{18} eV believed to be predominantly galactic (transition to extra-galactic @ ~10^{18}-10^{19} eV)
- galactic CR believed to be accelerated in expanding shock waves initiated by supernova explosions
- anisotropy in arrival direction expected from discrete sources distribution & propagation

$\Phi_{CR}(E)$



low energy cosmic ray anisotropy in arrival direction

Nagashima et al., J. Geophys. Res., Vol 103, No. A8, Pag. 17,429 (1998)

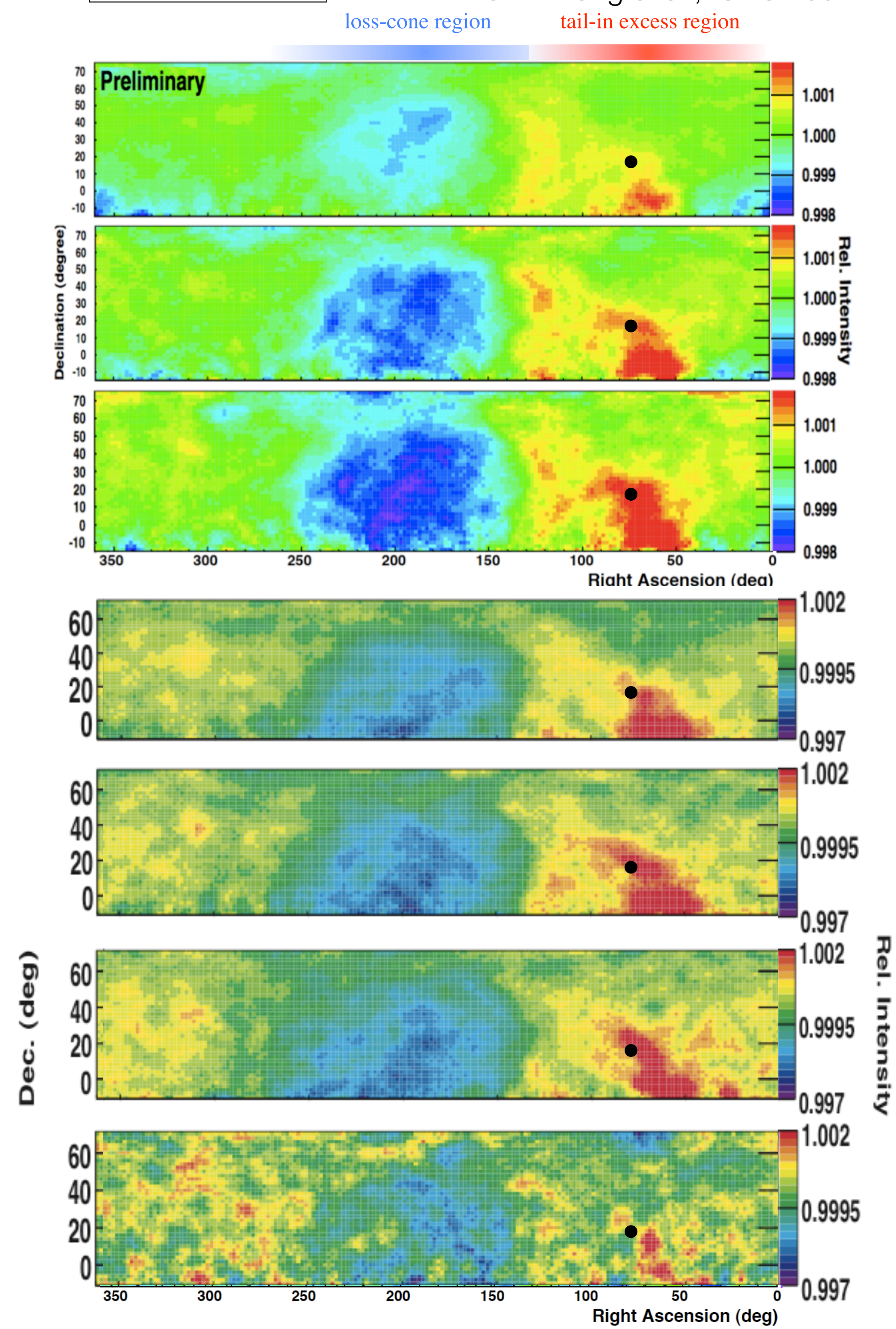


medium / small scale anisotropy

- global amplitude of large scale anisotropy increases with energy up to ~ 1-10 TeV and decreases above it
- origin of anisotropy is unknown
- large scale anisotropy shows **smaller angular features**, some of which highly significant
- small angular features might reveal properties of the boundary region between solar wind and interstellar wind
- isolate small scale features

ARGO YBJ

J.L. Zhang et al., ICRC Łódź - Poland (2009)



0.7 TeV

1.5 TeV

3.9 TeV

4 TeV

6.2 TeV

12 TeV

50 TeV

Tibet-III

Amenomori et al., Science Vol. 314, pp. 439 (2006)

medium / small scale anisotropy

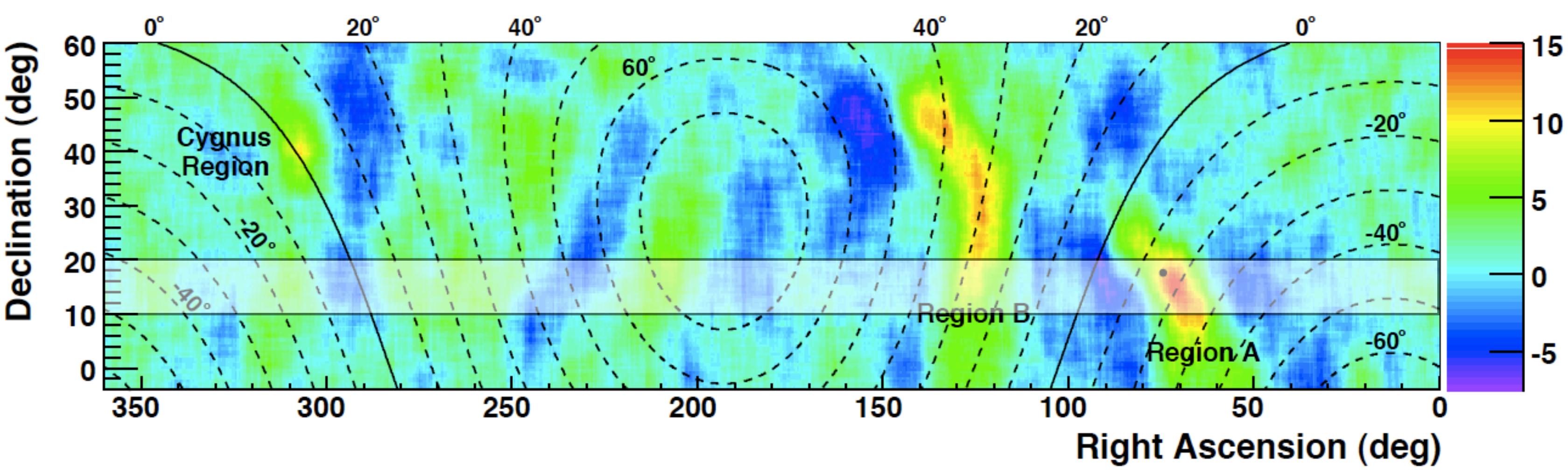
Milagro

$2.2 \cdot 10^{11}$ events
median CR energy ~ 1 TeV = 10^{12} eV
average angular resolution < 1°

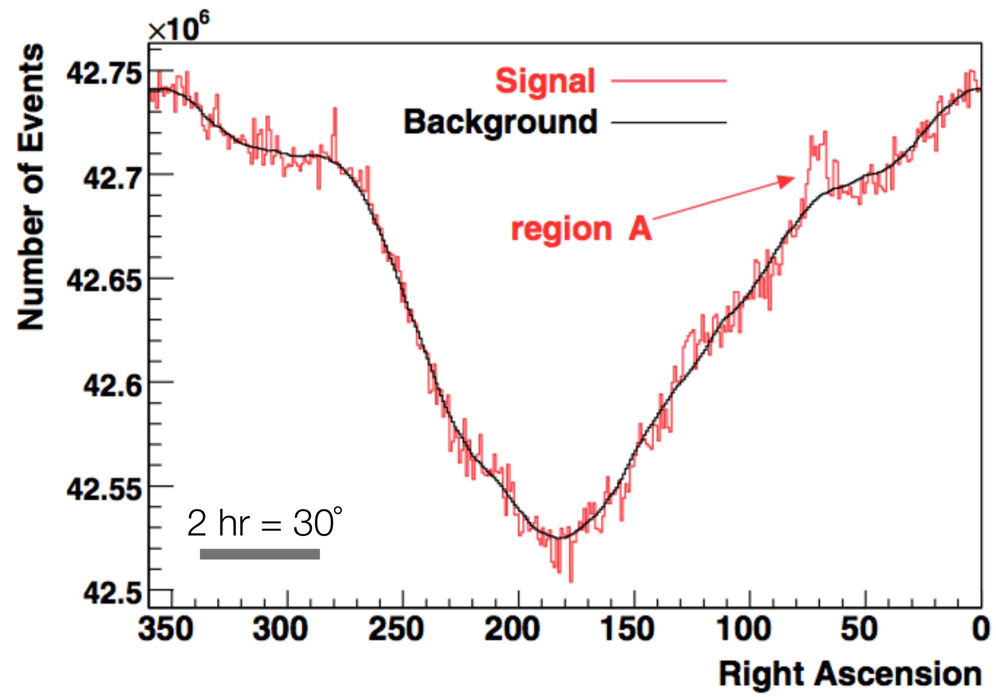
2hr time window
10° smoothing

Abdo A.A. et al., 2008, Phys. Rev. Lett., 101, 221101

- filter all angular features > 30°
- technique used in gamma ray searches



2 hr = 30°



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medium / small scale anisotropy

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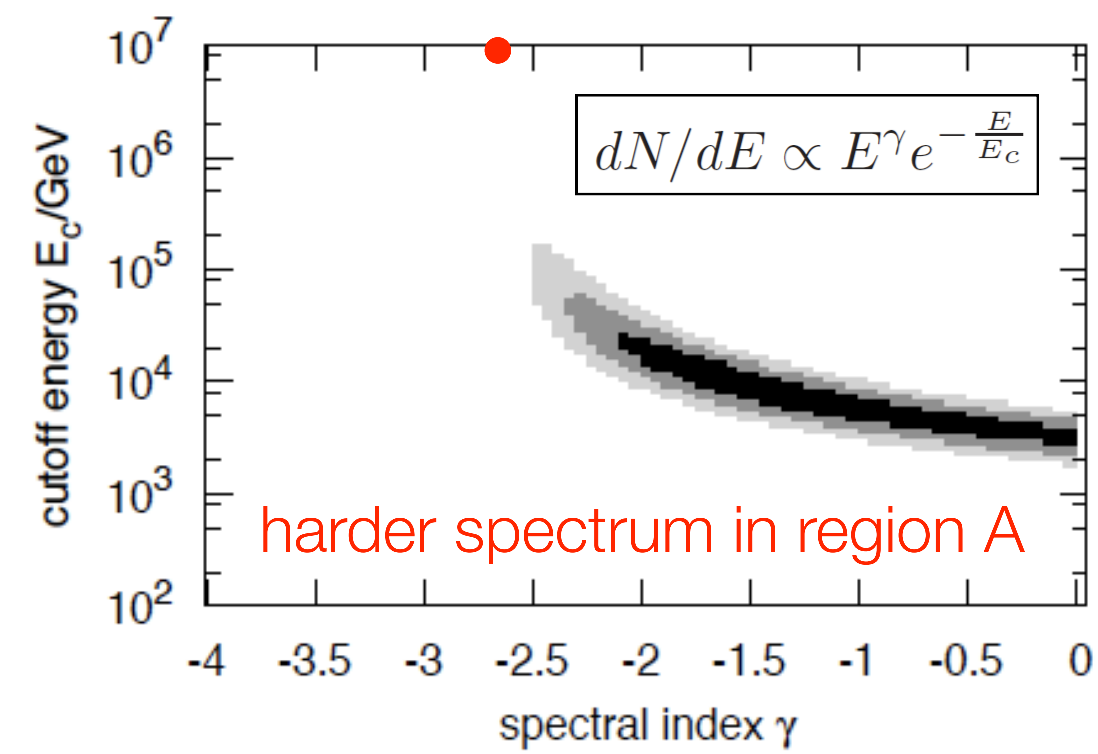
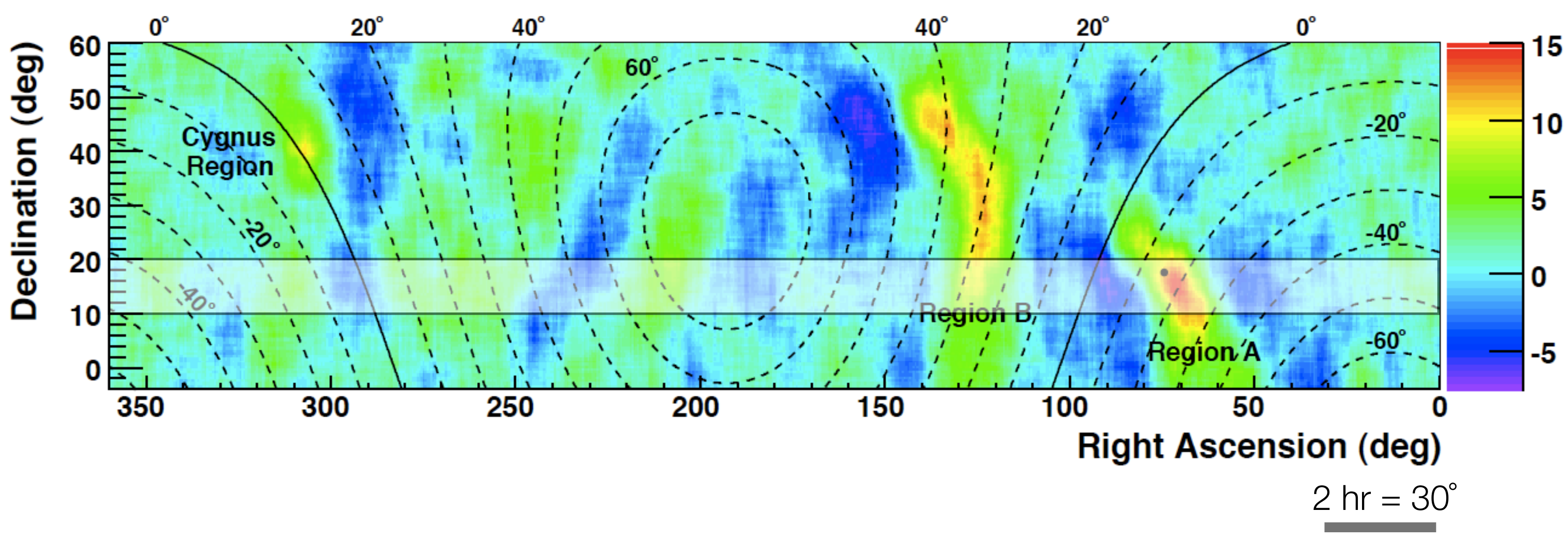
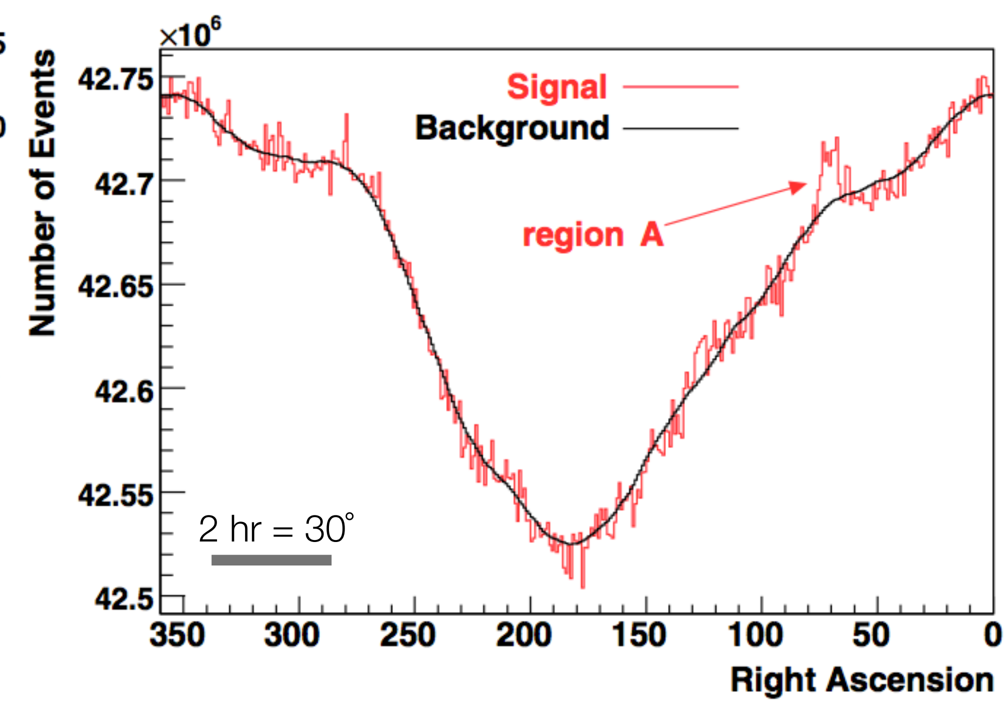






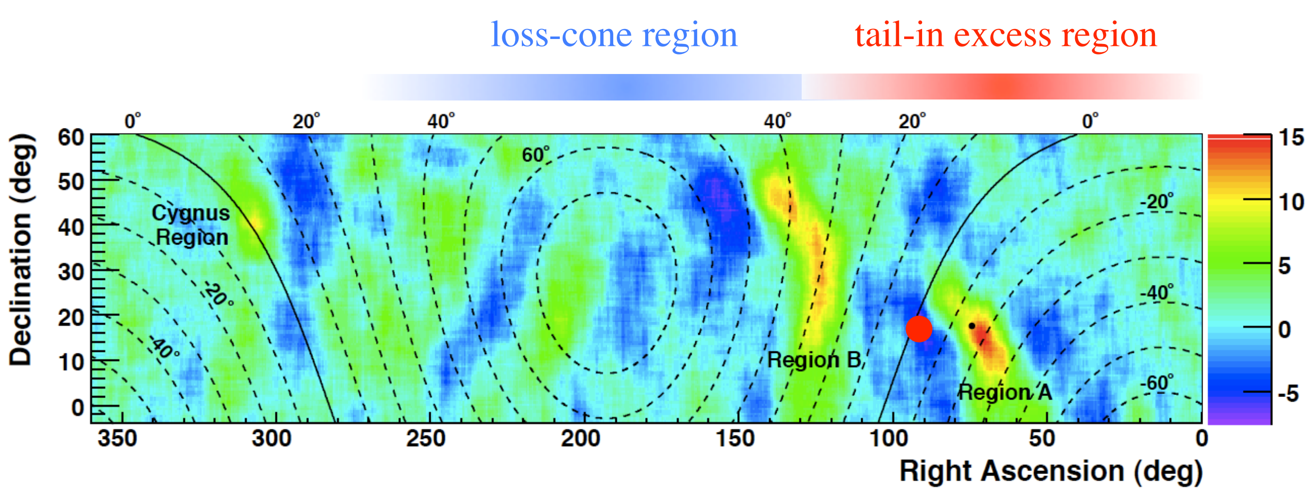
origin of small scale anisotropy : astrophysics ?

- localized excess of cosmic rays from nearby (~150 pc ~ 3×10^7 AU) recent (~ 350 kyr) supernova that gave birth to Geminga Pulsar

- fine tuning of propagation through interstellar medium

- incidentally requires magnetic connection to the faraway source

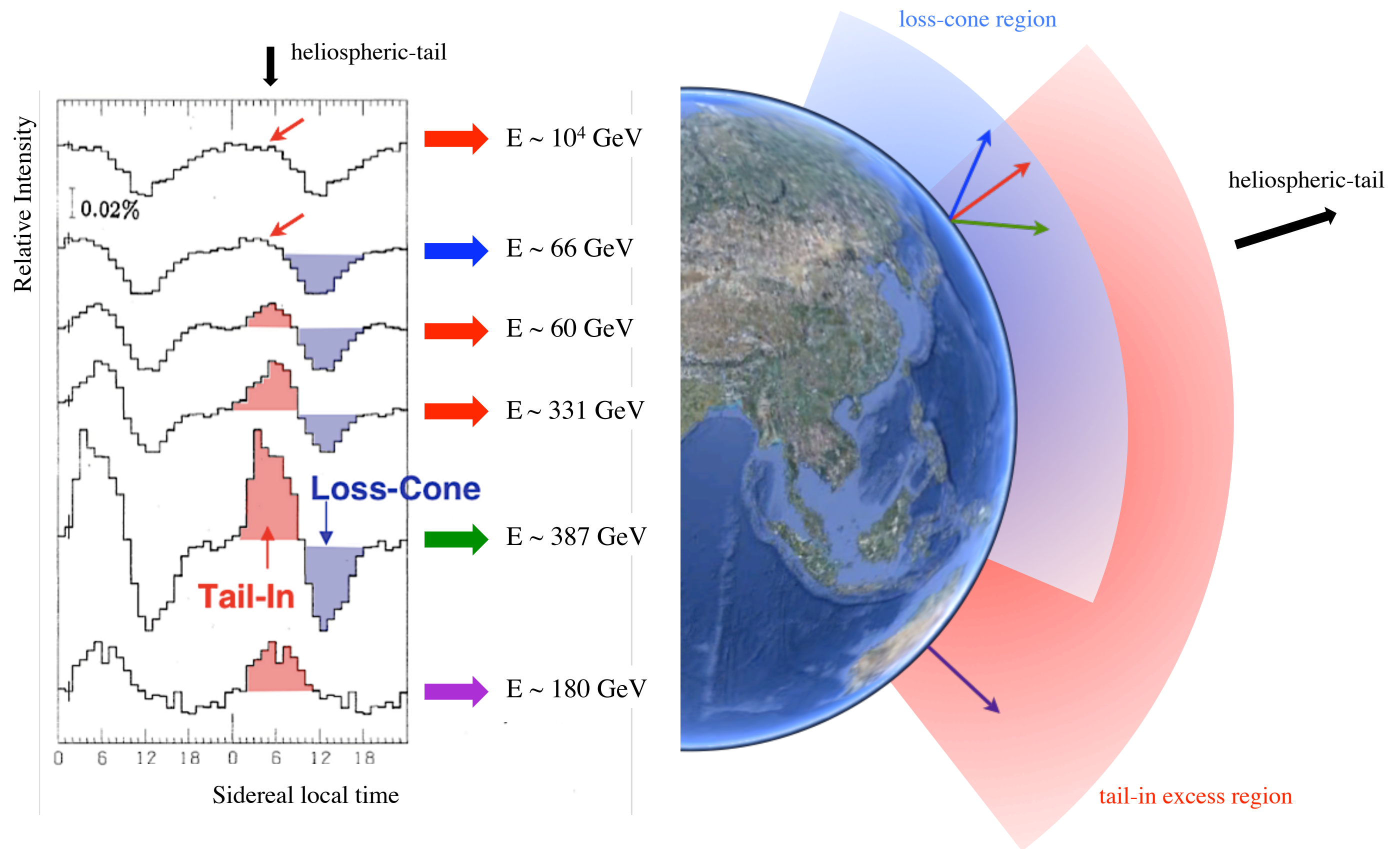
- small scale features likely from local processes



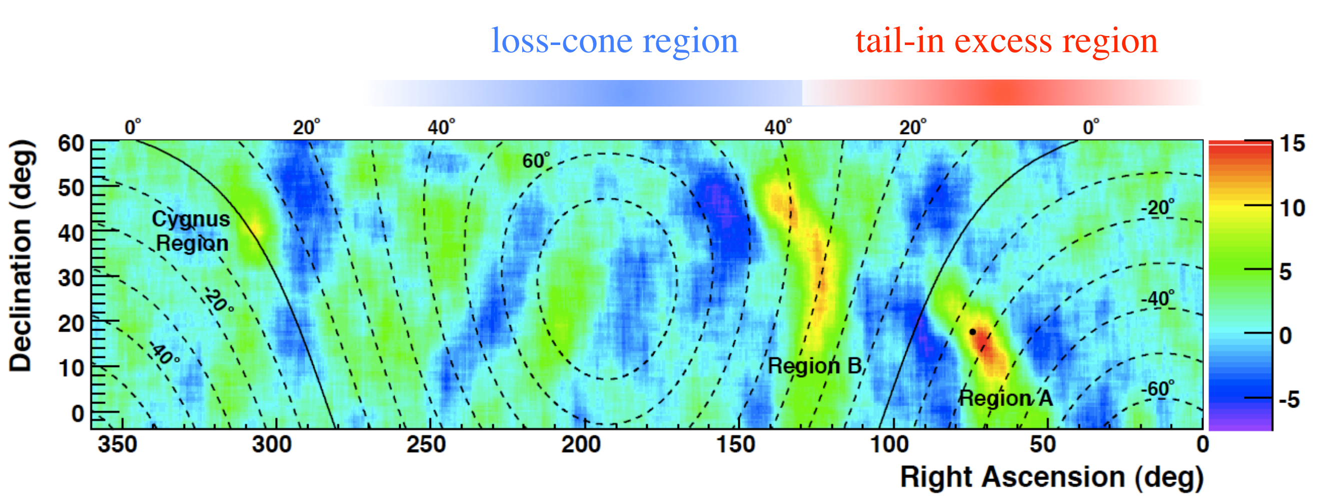
Abdo et al., Phys. Rev. Lett., 101, 221101, 2008

origin of “tail-in anisotropy”

- broad tail-in excess of **sub-TeV** cosmic rays attributed to heliotail
- localized excess of **multi-TeV** cosmic rays from the direction of the heliotail
- medium/small scale modulation to be connected to **nearby** perturbations
- first-order Fermi acceleration in magnetic reconnection regions in the heliotail



Nagashima et al., J. Geophys. Res., Vol 103, No. A8,17429, 1998

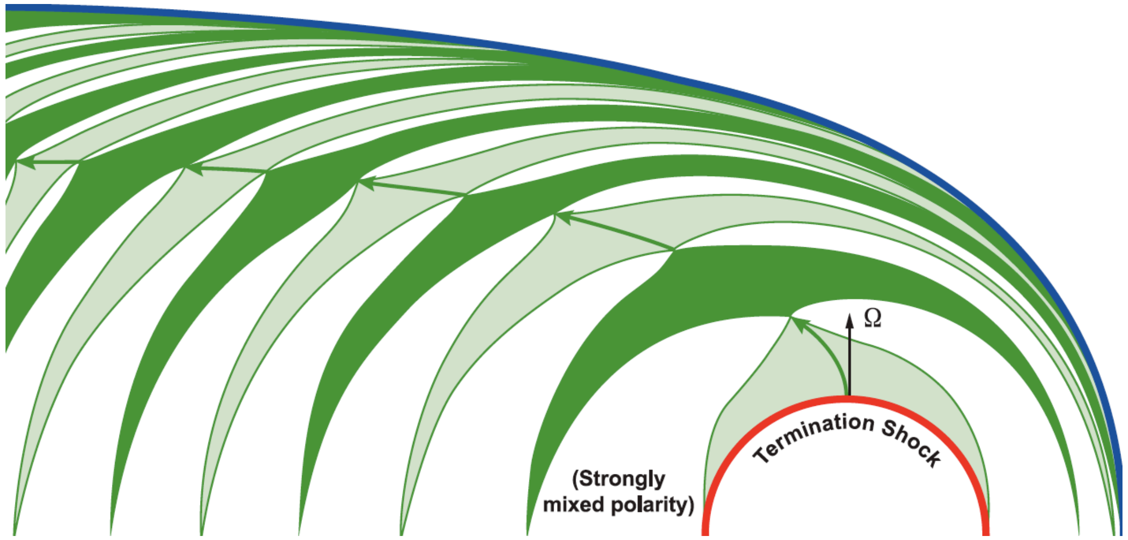


Abdo et al., Phys. Rev. Lett., 101, 221101, 2008

magnetic reconnection @ heliotail

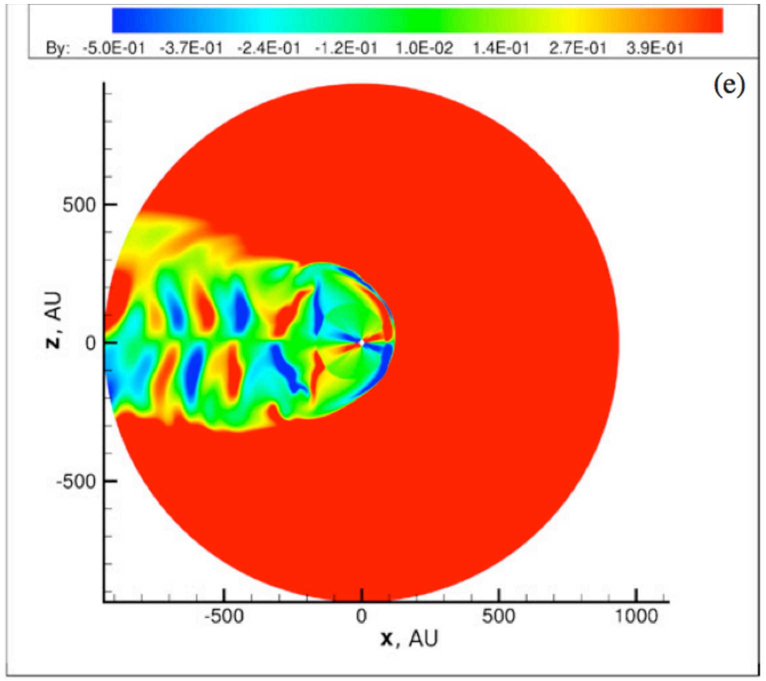
Lazarian & Desiati, ApJ, 722, 188, 2010

- magnetic polarity reversals due to the 11-year solar cycles compressed by the solar wind in the magneto-tail



Pogorelov et al., ApJ, 696, 1478, 2009

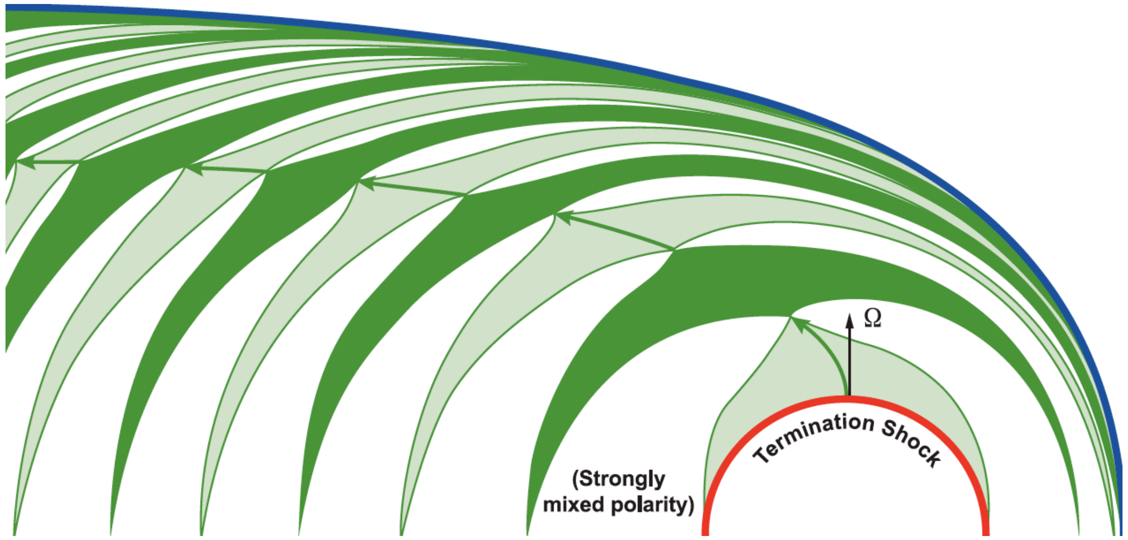
“more realistic” numerical simulation of the turbulent heliosphere and heliotail



magnetic reconnection @ heliotail

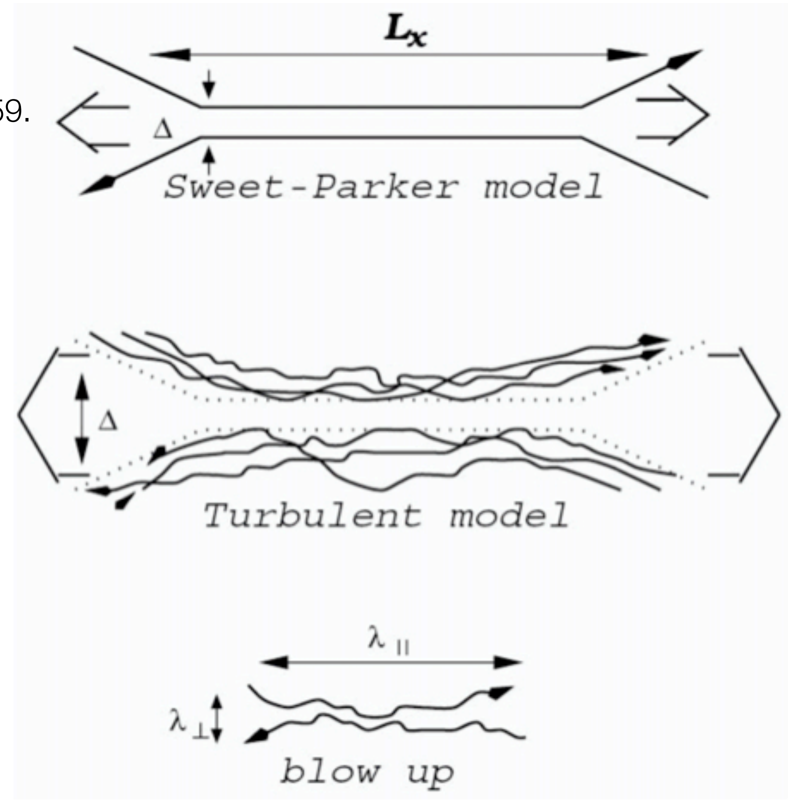
Lazarian & Desiati, ApJ, 722, 188, 2010

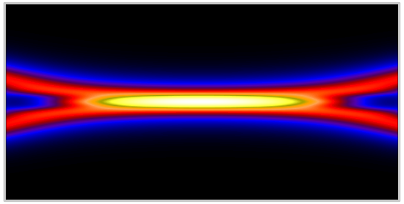
- magnetic polarity reversals due to the 11-year solar cycles compressed by the solar wind in the magneto-tail
- ubiquitous turbulence makes reconnection fast and not affected by ohmic dissipation

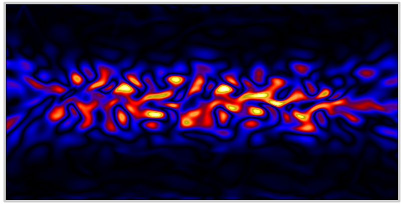


Sweet, IAU Symposium 6, Electromagnetic Phenomena in Cosmical Physics, 123, 1959.
Parker , J. Geophys. Rev., 62, 509, 1957

Lazarian & Vishniac, ApJ, 517, 700, 1999



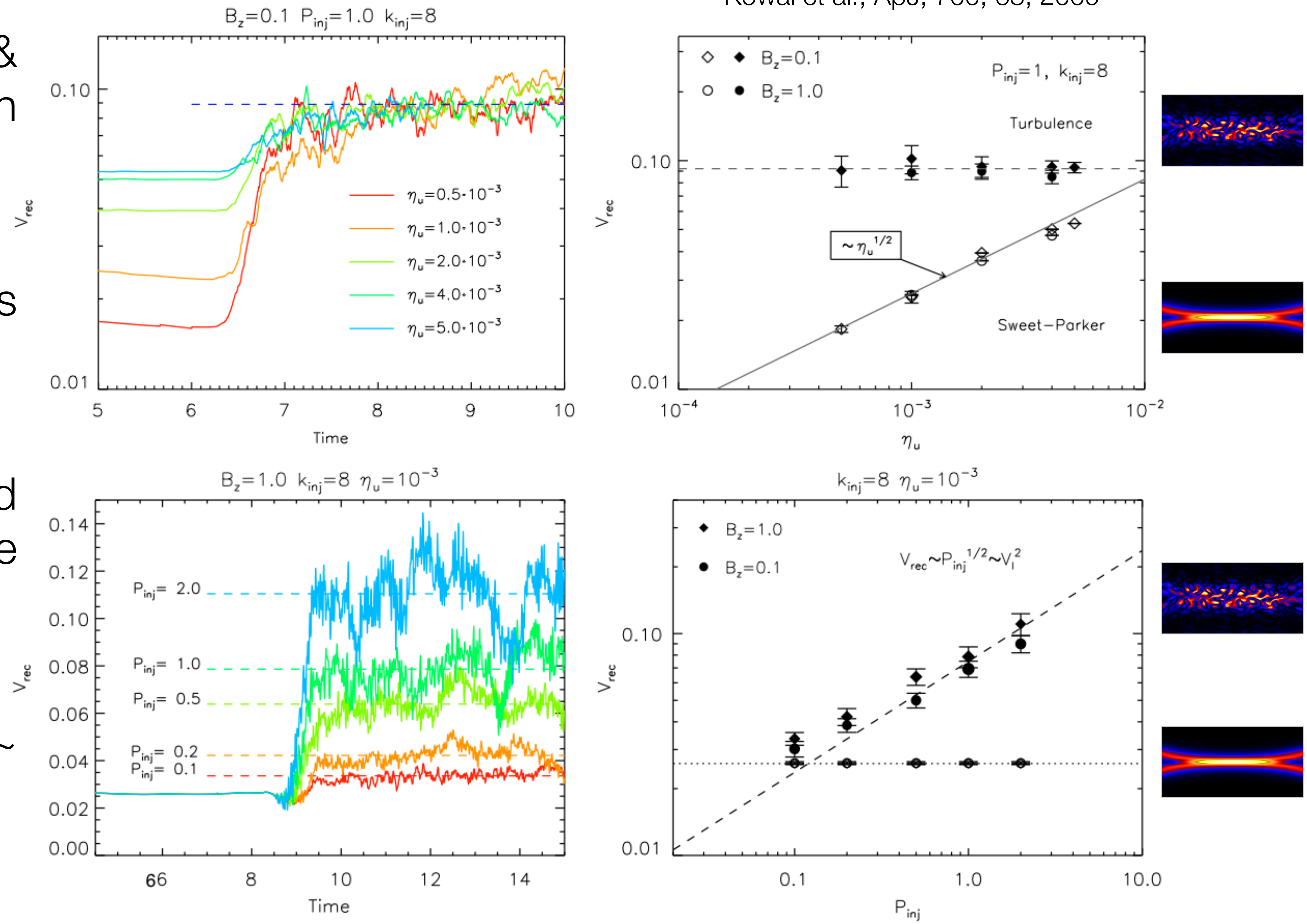




stochastic magnetic reconnection

- verification of Lazarian & Vishniac 1999 with numerical calculations
- reconnection speed does not depend on resistivity
- reconnection speed increases with turbulence injection power
- reconnection speed ~ local turbulent velocity

Kowal et al., ApJ, 700, 63, 2009



acceleration in reconnection regions

- first order Fermi acceleration from volume-filling magnetic reconnection

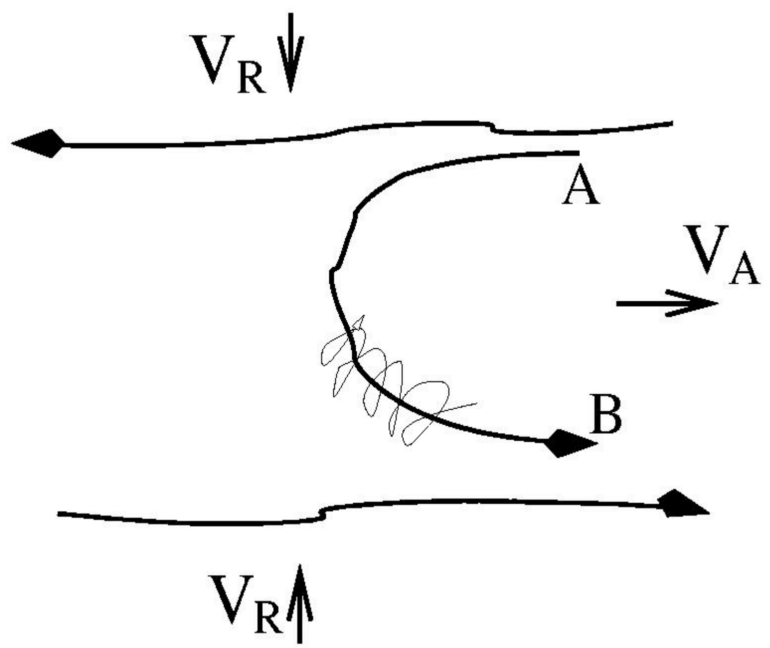
- magnetic mirror @ reconnection as site of acceleration

$$N(E)dE \sim E^{-5/2}dE$$

- magnetic tubes contraction leads to increase of particle energy as long as they are within the contracting magnetic loop

$$E_{max} \approx 10^{13}\ eV \cdot \left(\frac{B}{1\ \mu G}\right) \cdot \left(\frac{L_{zone}}{134\ AU}\right)$$

de Gouveia Dal Pino & Lazarian, 2005



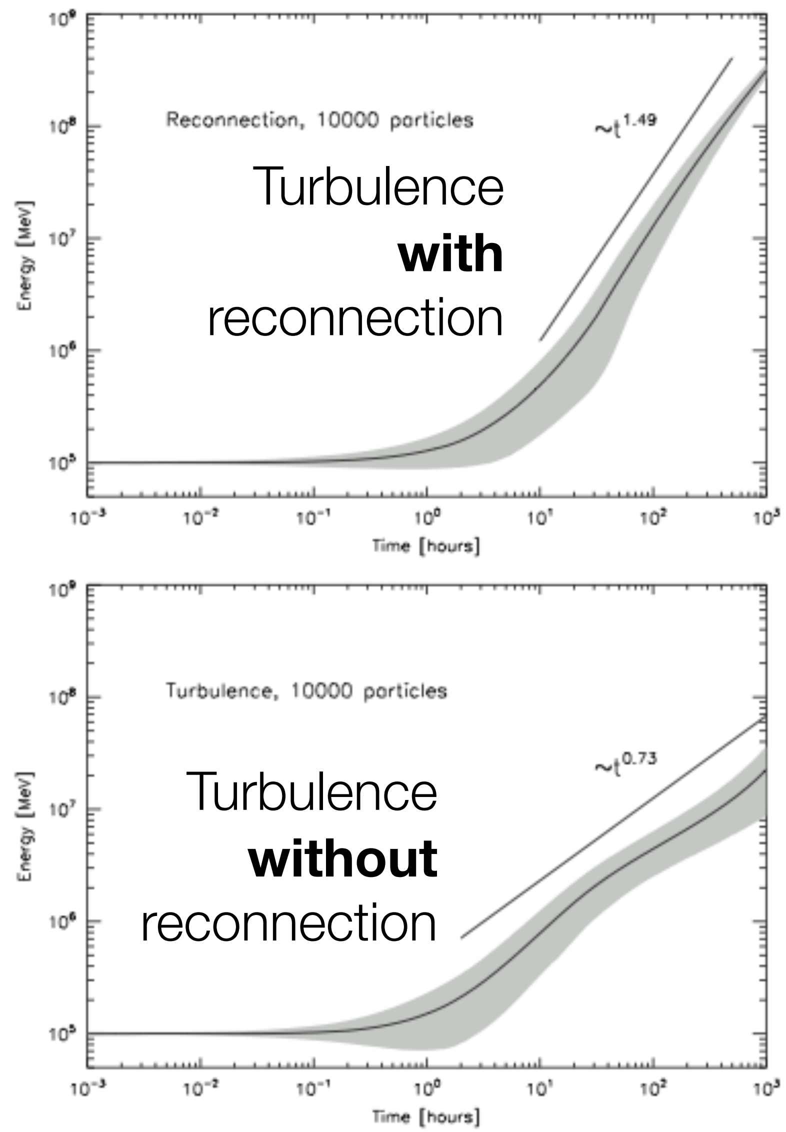
application to pulsars, microquasars, solar flares acceleration

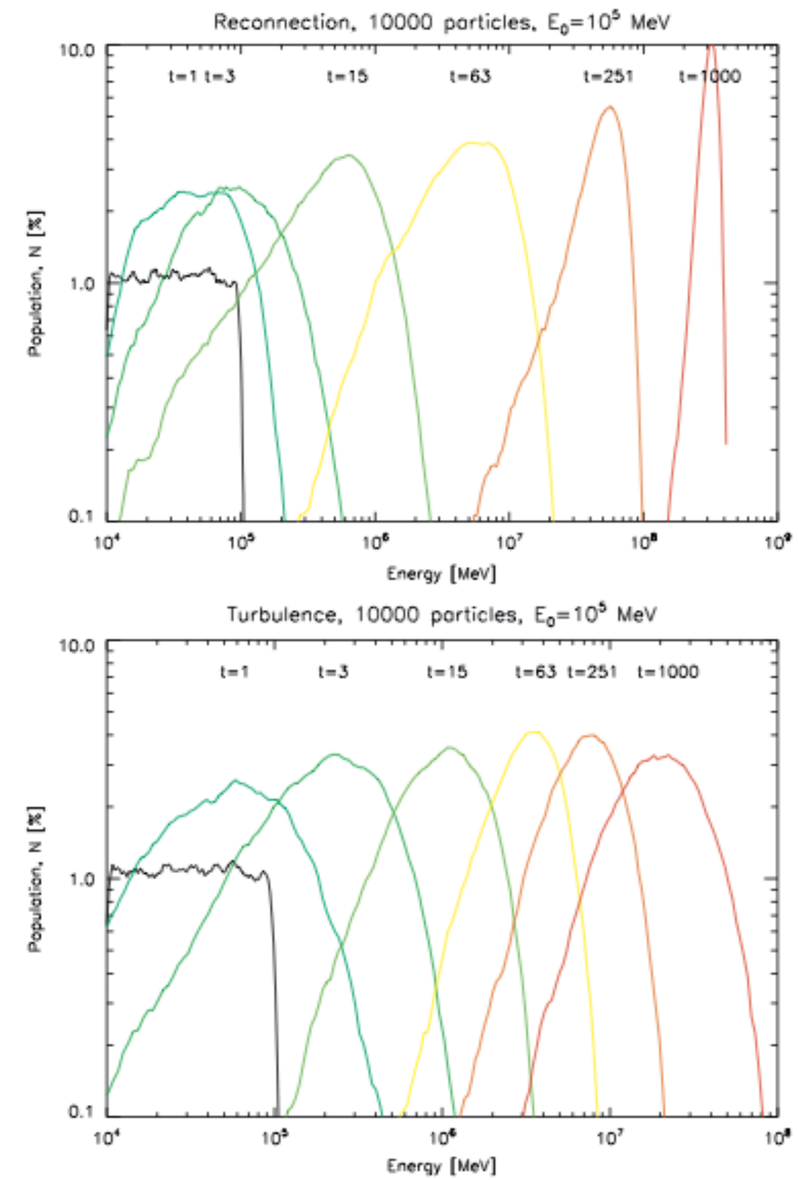
de Gouveia Dal Pino & Lazarian, 2000, 2003, 2005
Lazarian, 2005

acceleration in weakly stochastic reconnection regions

- test particle verification of Lazarian & Vishniac 1999 with numerical calculations
- magnetic energy transferred into energy of contracting loops
- fast reconnection induces efficient acceleration of cosmic rays
- complexity of acceleration: contracting loops & current sheets; 1st order Fermi & drift acceleration

Lazarian et al., Pl. and Sp. Sci. 2010 & Kowal et al., ApJ, 700, 63, 2009





more studies : Kowal et al., arXiv:1103.2984

acceleration in reconnection regions

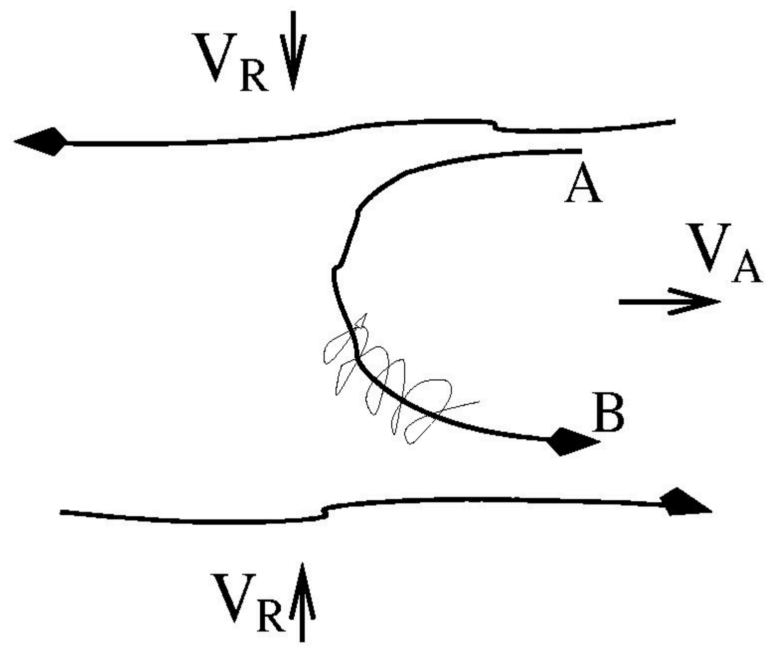
$$N(E)dE \sim E^{-5/2}dE$$

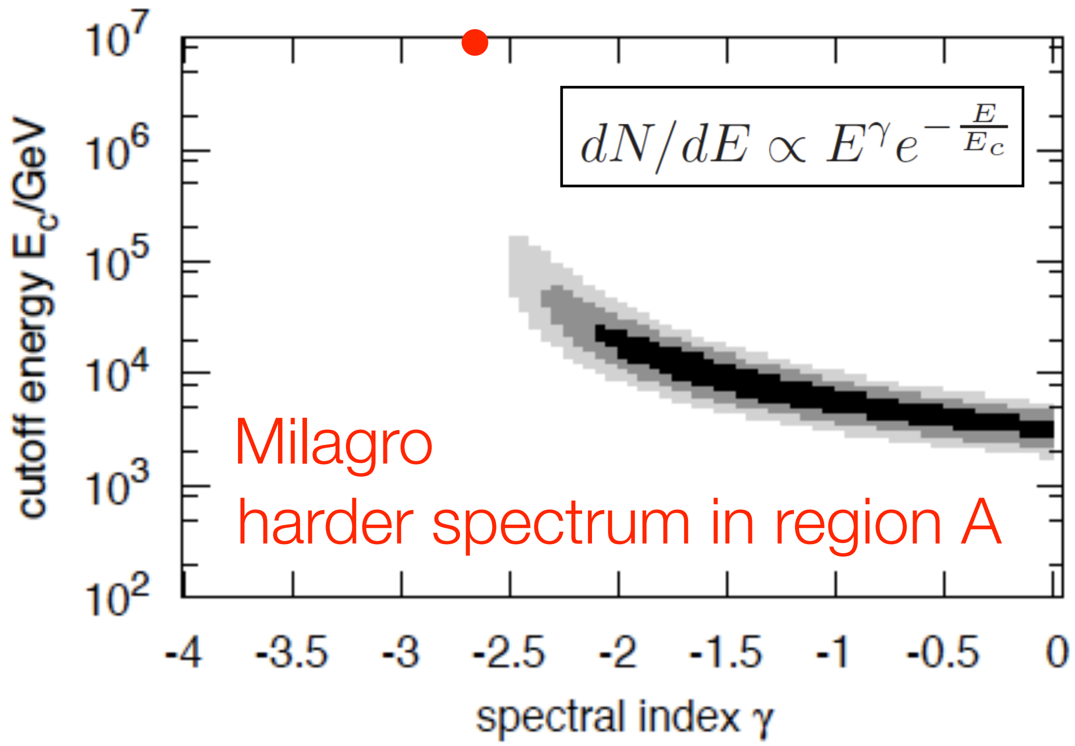
- harder spectrum if **back reaction** of accelerated particle

$$E_{max} \approx 10^{13}\ eV \cdot \left(\frac{B}{1\ \mu G}\right) \cdot \left(\frac{L_{zone}}{134\ AU}\right)$$

- solar wind ≈ 100 km/sec
- E_{max}(1 μG) ≈ 20 TeV

➡ unlikely to expect energies > 10 TeV



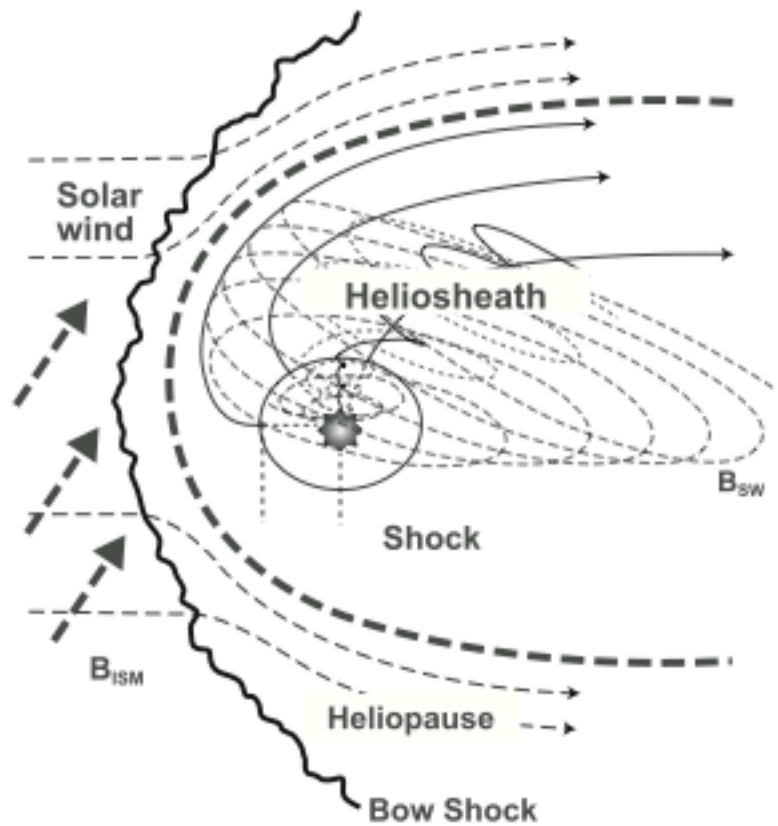


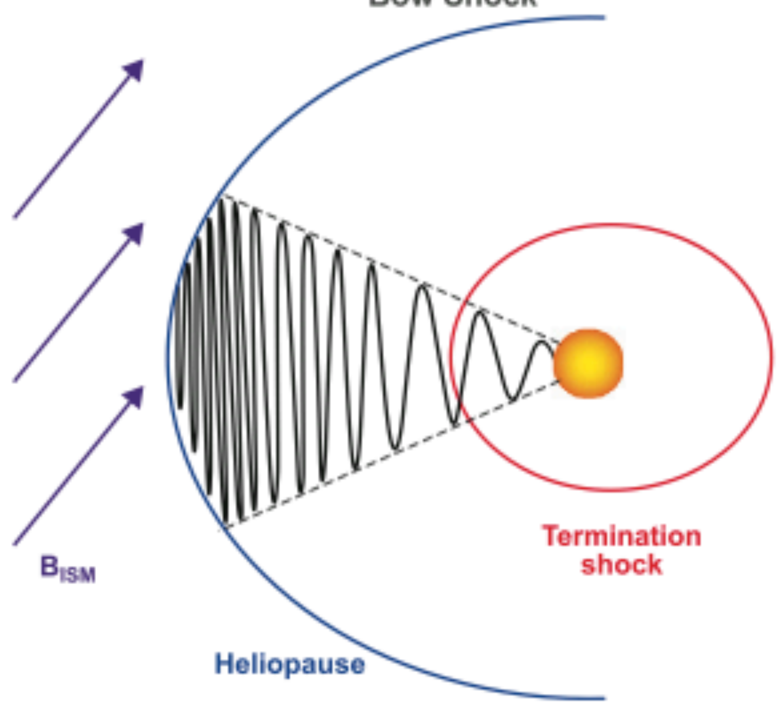
application on anomalous cosmic rays

Lazarian & Opher, ApJ 703, 8, 2009

- magnetic field reversals from Sun's rotation compress at the heliopause
- reconnection and acceleration induced in the heliosheath closer to the heliopause
- Voyager did not observe ACR passed the termination shock
- other models available as well

also Drake et al., ApJ, 709, 963, 2010



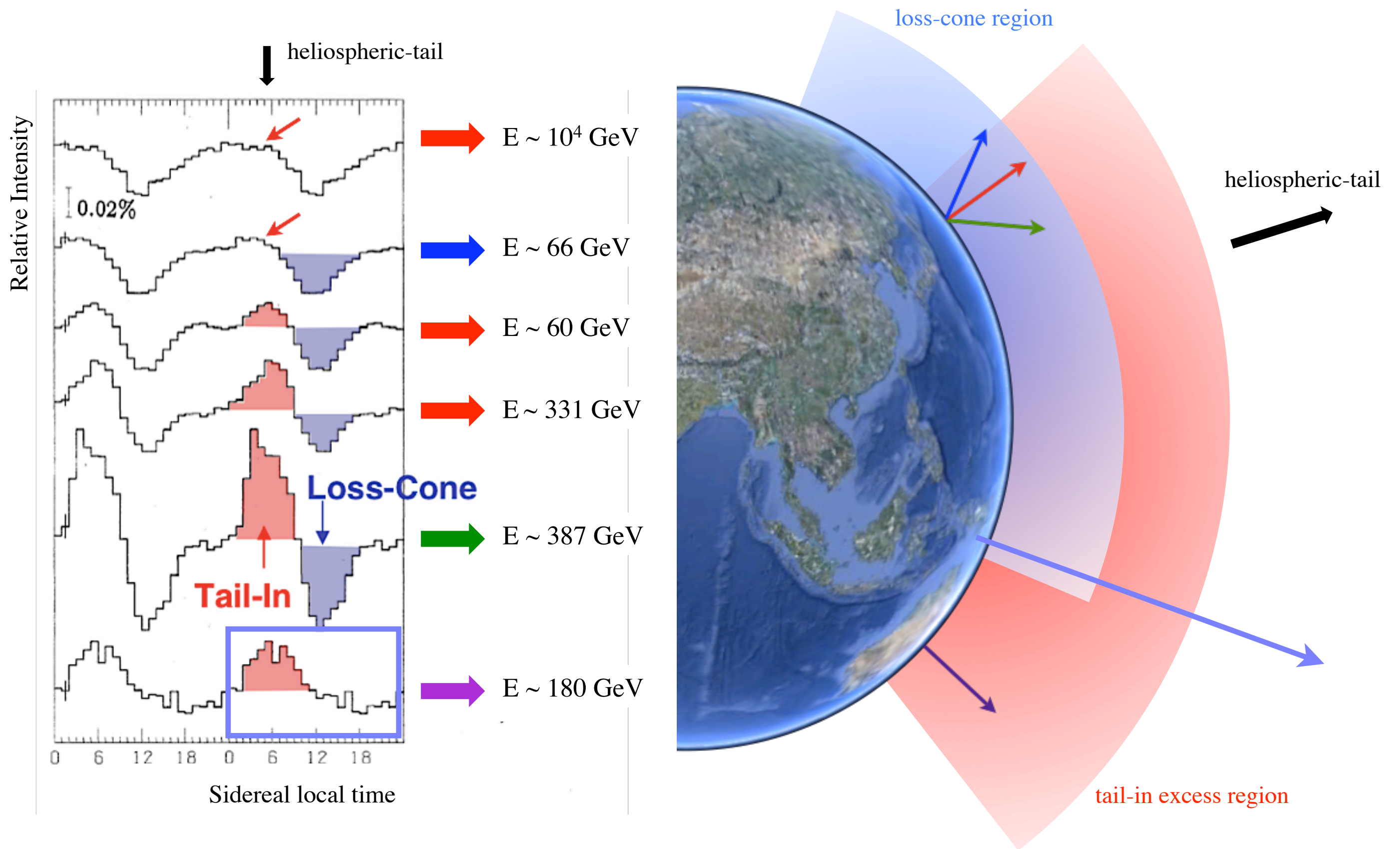


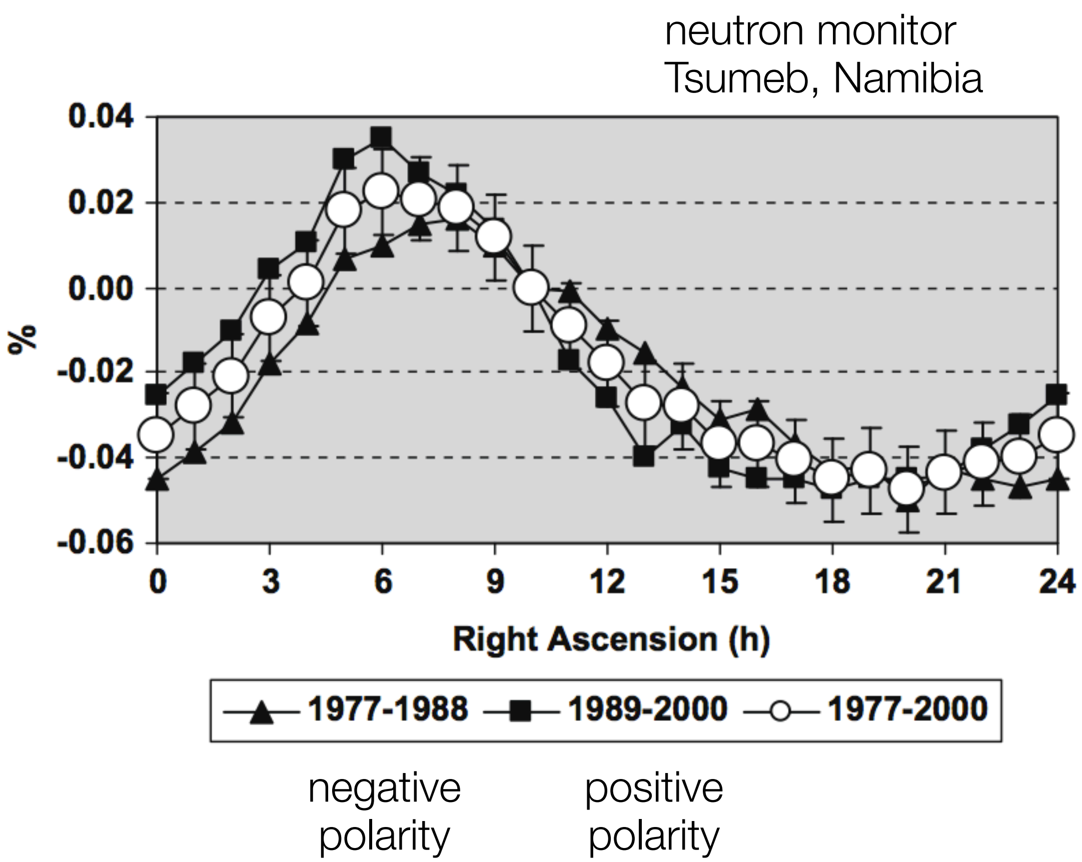
conclusions

- broad tail-in excess of **sub-TeV** cosmic rays and localized excess of **multi-TeV** cosmic rays from the direction of the heliotail could have a common origin
- 1st order Fermi acceleration in magnetic reconnection regions in the heliotail
- HE cosmic rays excess related to reconnection site - LE cosmic rays smeared by scattering
- no need to tune interstellar medium properties
  - on-going numerical calculations to verify whether magnetic reconnection regions in the heliotail may be site of efficient acceleration
  - acceleration mechanisms in stochastic reconnection regions might explain the puzzling localized excess region of multi-TeV cosmic rays

back up slides

origin of small scale anisotropy : heliospheric tail





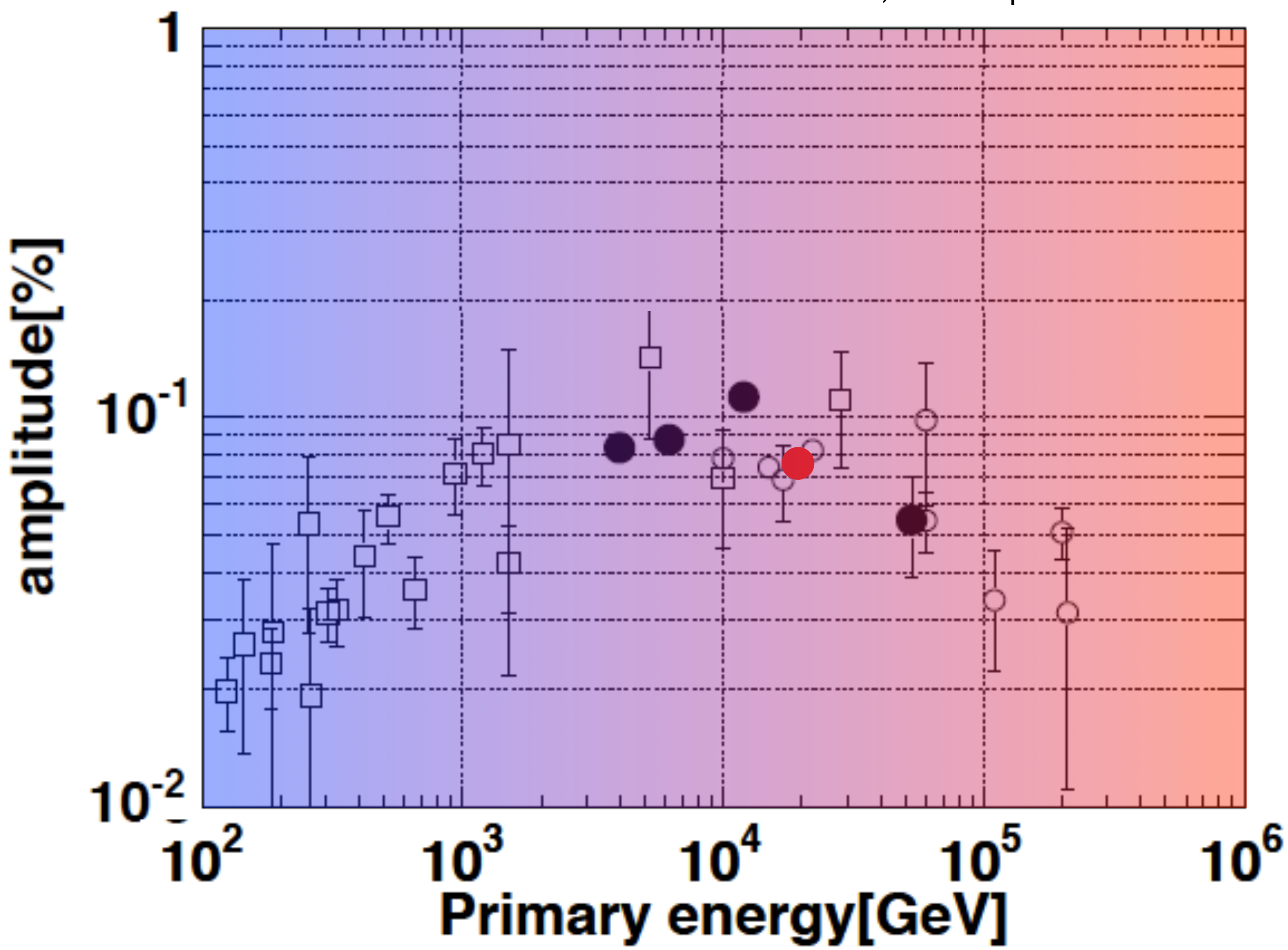
Nagashima et al., J. Geophys. Res., Vol 103, No. A8, Pag. 17,429 (1998)

Karapetyan, Astrop. Phys., 33, 146, 2010

- sub-TeV cosmic ray tail-in excess by some unknown asymmetry caused by the heliotail
- solar magnetic field reversal should affect galactic anisotropy
- origin of excess is “heliospheric”

anisotropy vs energy : probing different causes

Amenomori et al., astro-ph/0505114



(3 μG)

$3 \cdot 10^{-5}$	$3 \cdot 10^{-4}$	$3 \cdot 10^{-3}$	$3 \cdot 10^{-2}$	0.3	gyro-radius (pc)
7	70	700	7,000	70,000	gyro-radius (AU)

tail-in + galactic ← heliospheric influence   galactic influence →