magnetic reconnection as the cause of cosmic ray excess from the heliospheric tail

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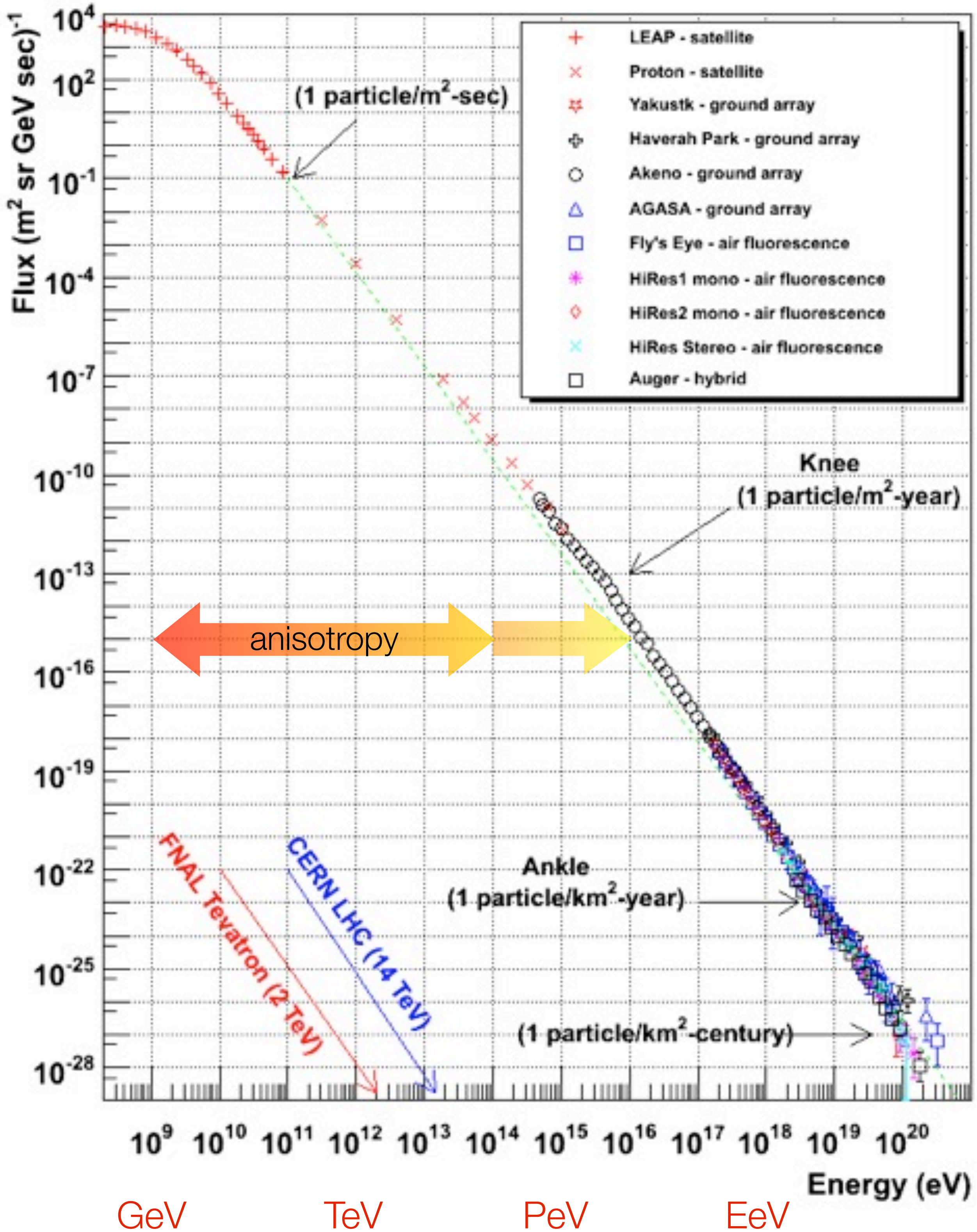
cosmic rays

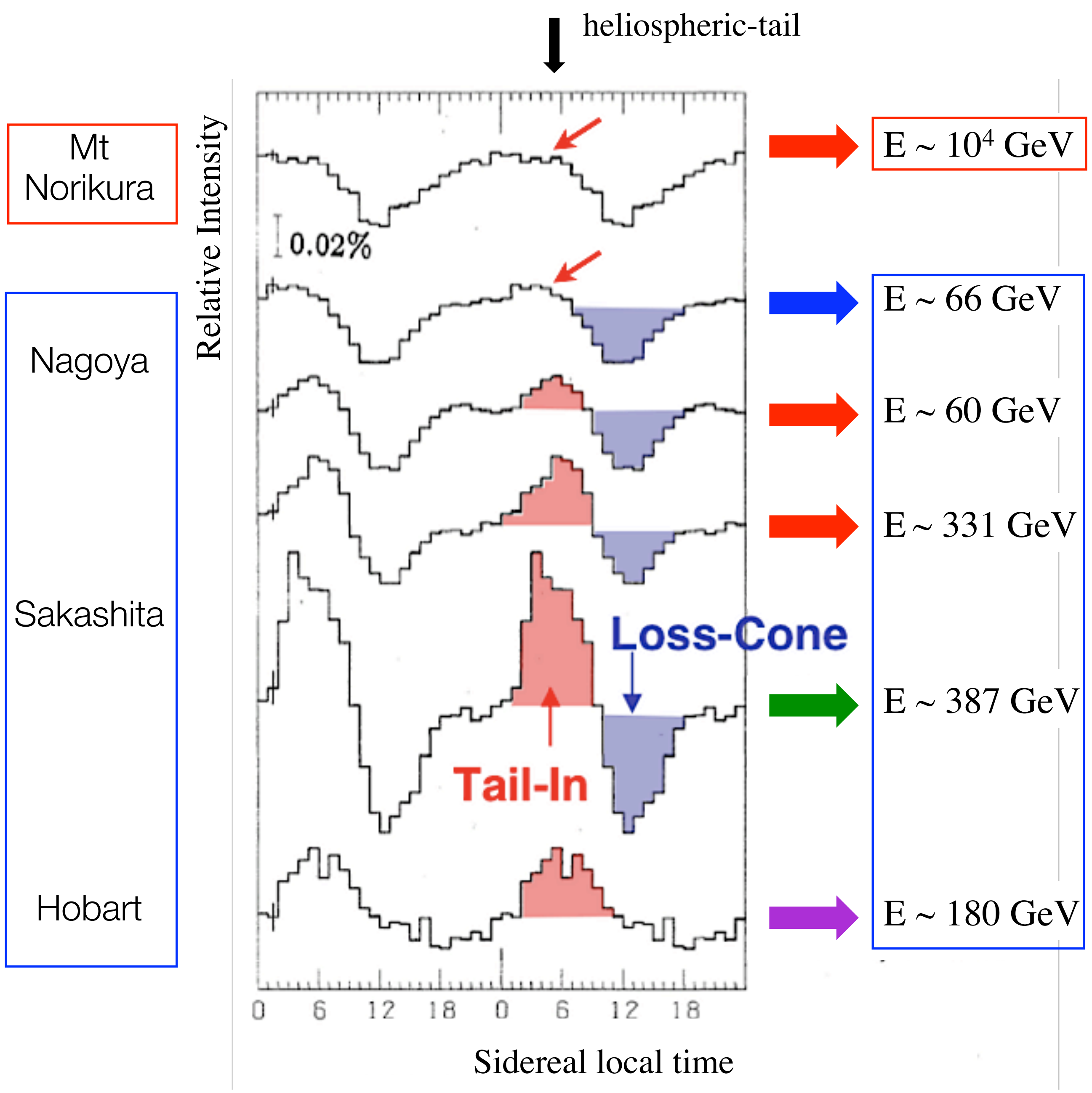
- CR below the knee (~3×10^{15} eV) believed to be galactic: DSA in SNR
- CR below ~10^{18} eV believed to be predominantly galactic (transition to extra-galactic @ ~10^{18}-10^{19} eV)
- anisotropy in arrival direction expected from discrete sources distribution
- CR propagation through ISM likely affected by LIMF and heliosphere, depending on energy

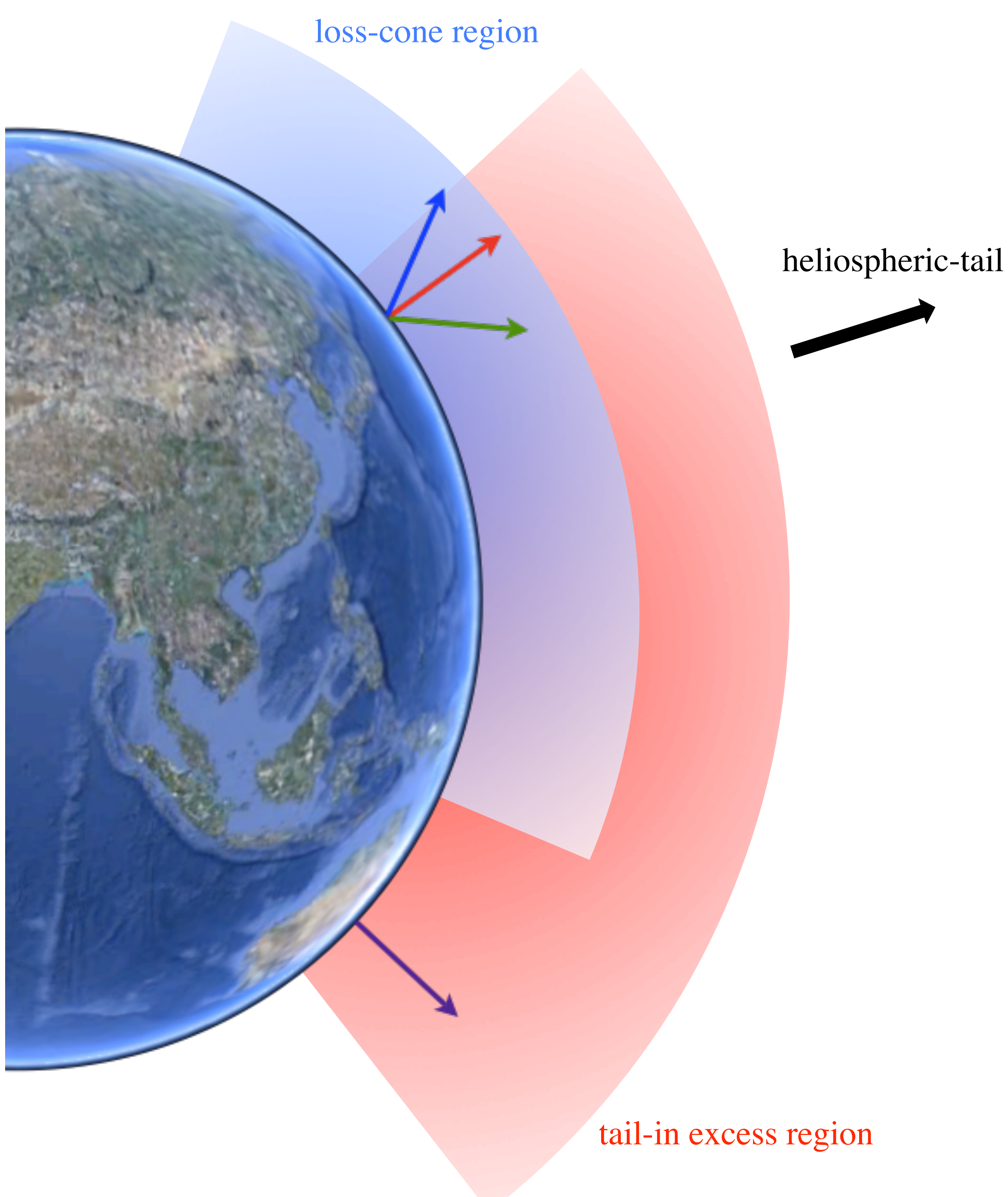
$\Phi_{CR}(E)$



low energy cosmic ray anisotropy in arrival direction

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



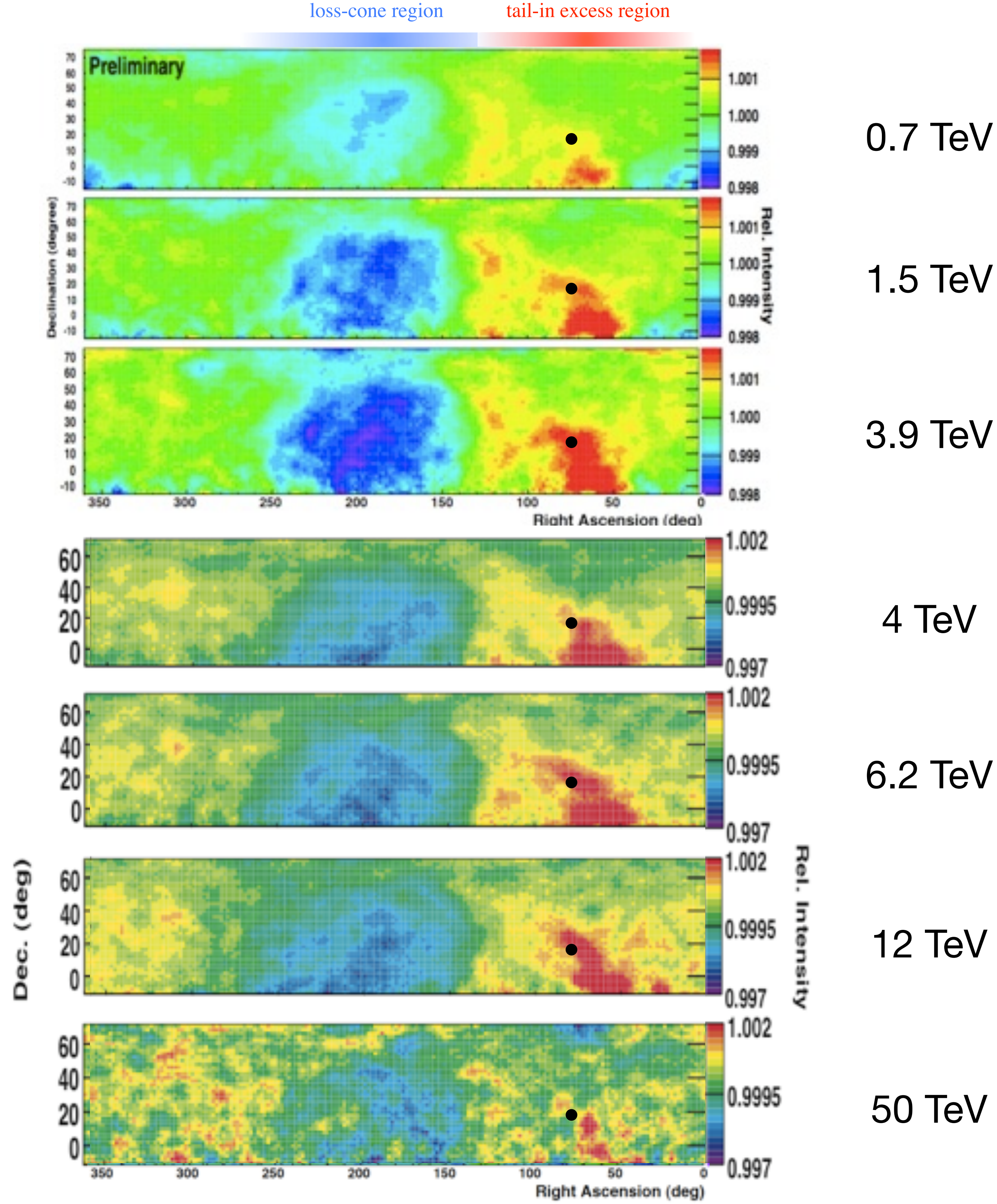


medium / small scale anisotropy

- global amplitude of cosmic ray anisotropy depends on energy
- 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)



Tibet-III

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

medium / small scale anisotropy

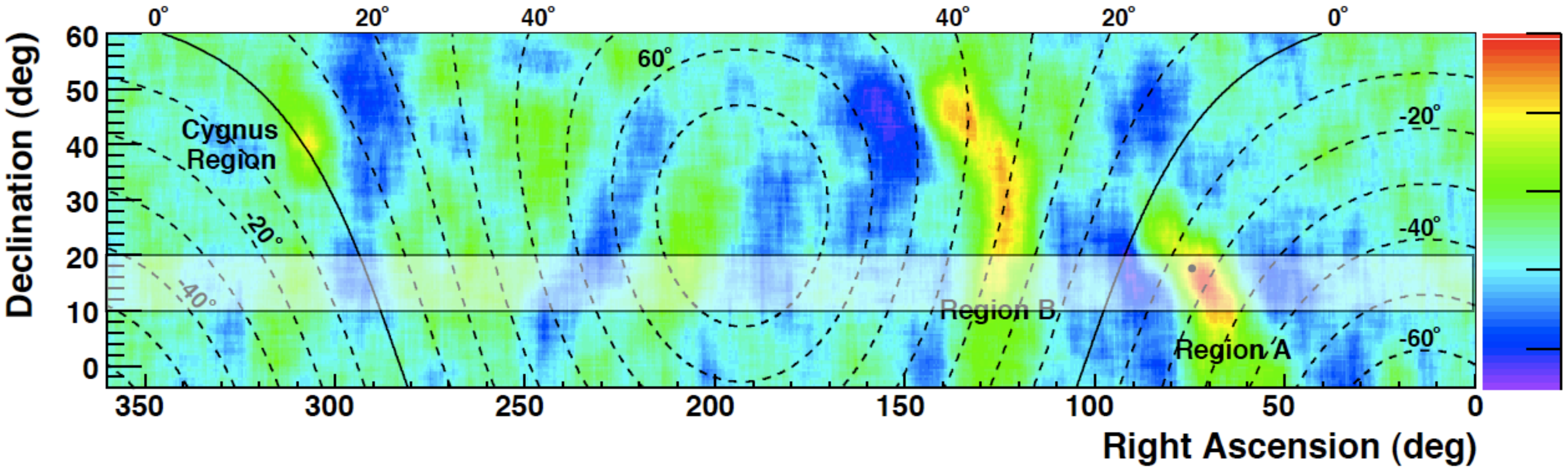
Abdo A.A. et al., 2008, Phys. Rev. Lett., 101, 221101

Milagro

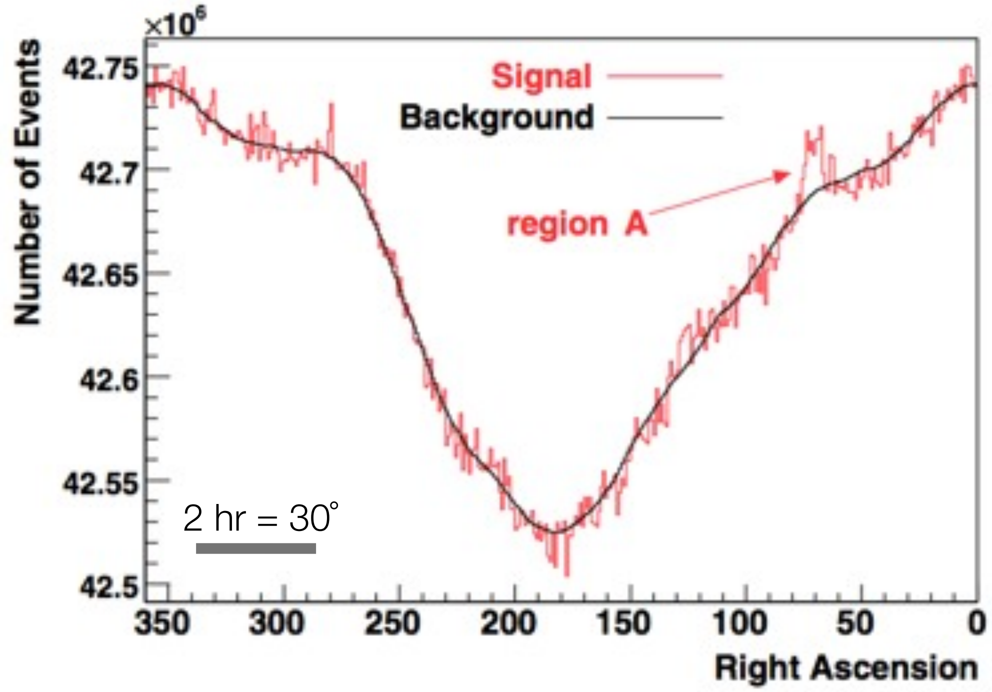
$2.2 \cdot 10^{11}$ events
median CR energy ~ 1 TeV = 10^{12} eV
average angular resolution < 1°

2hr time window
10° smoothing

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



2 hr = 30°



medium / small scale anisotropy

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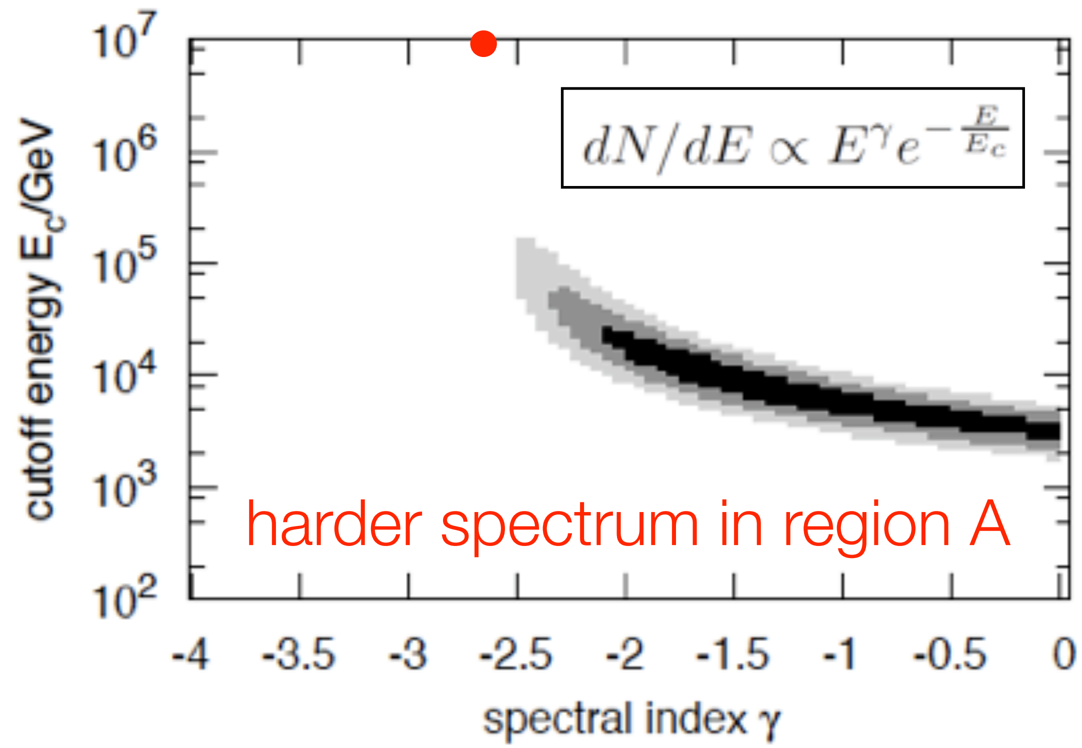

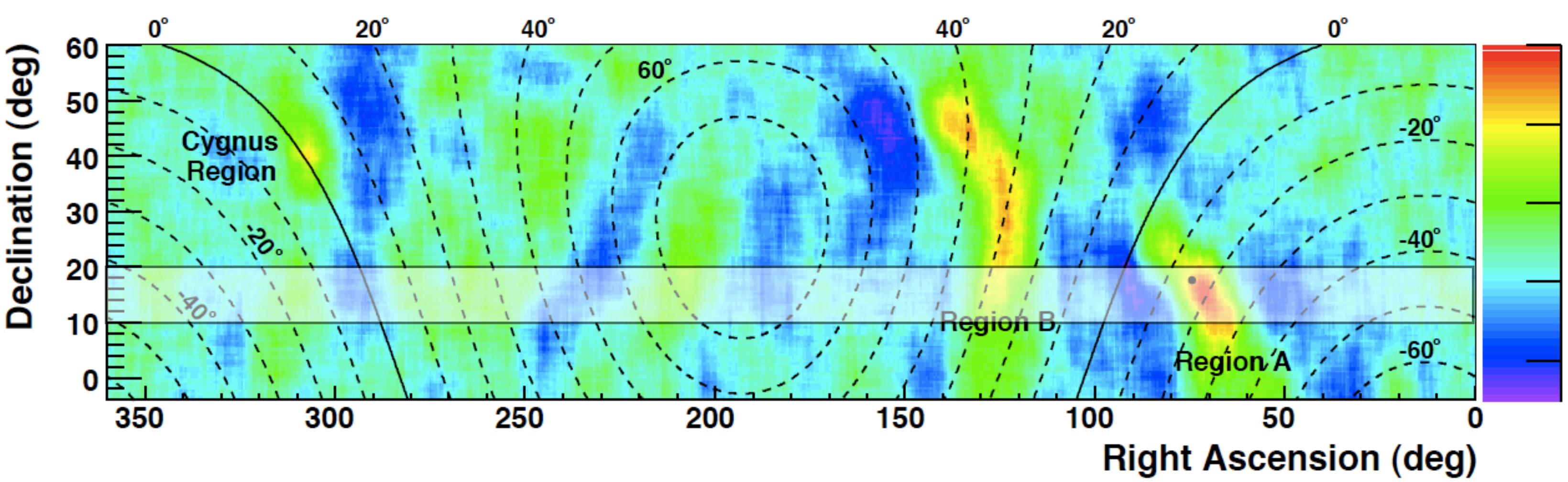

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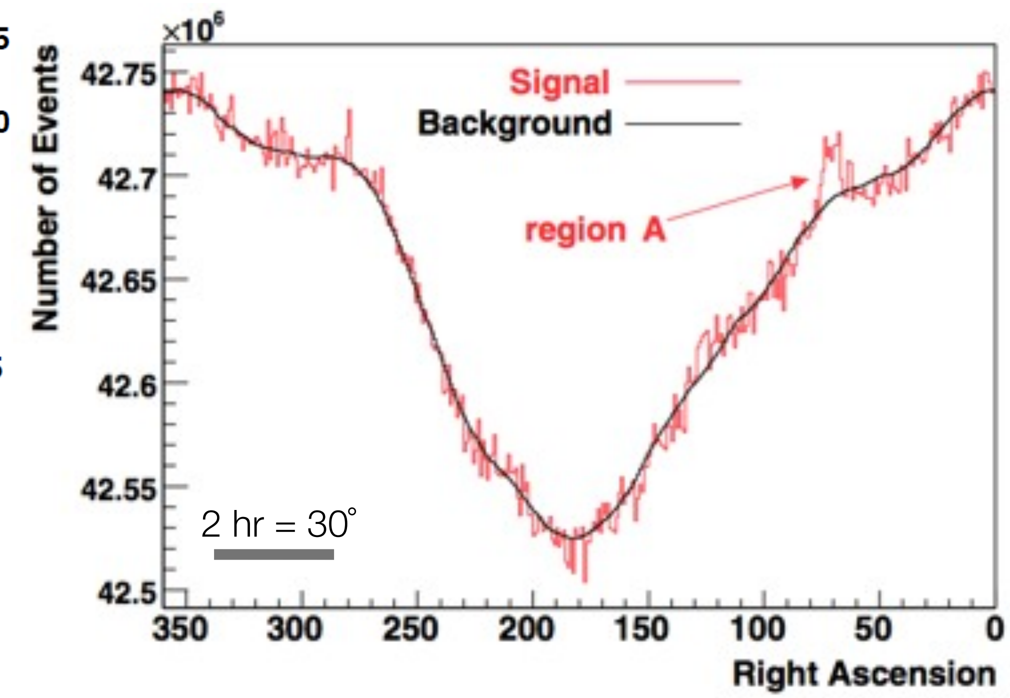
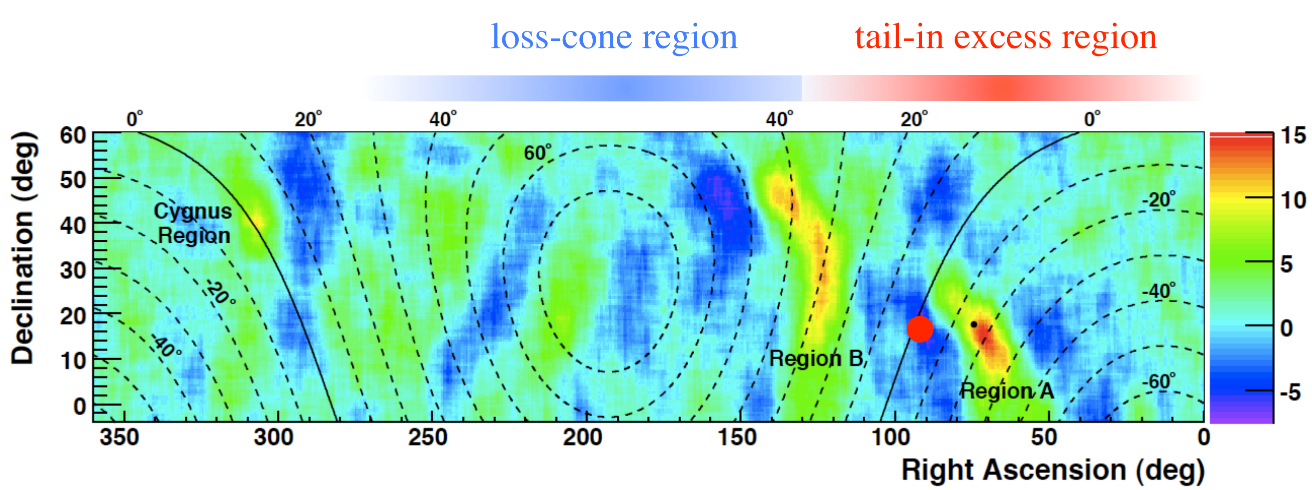


origin of small scale anisotropy : astrophysics ?

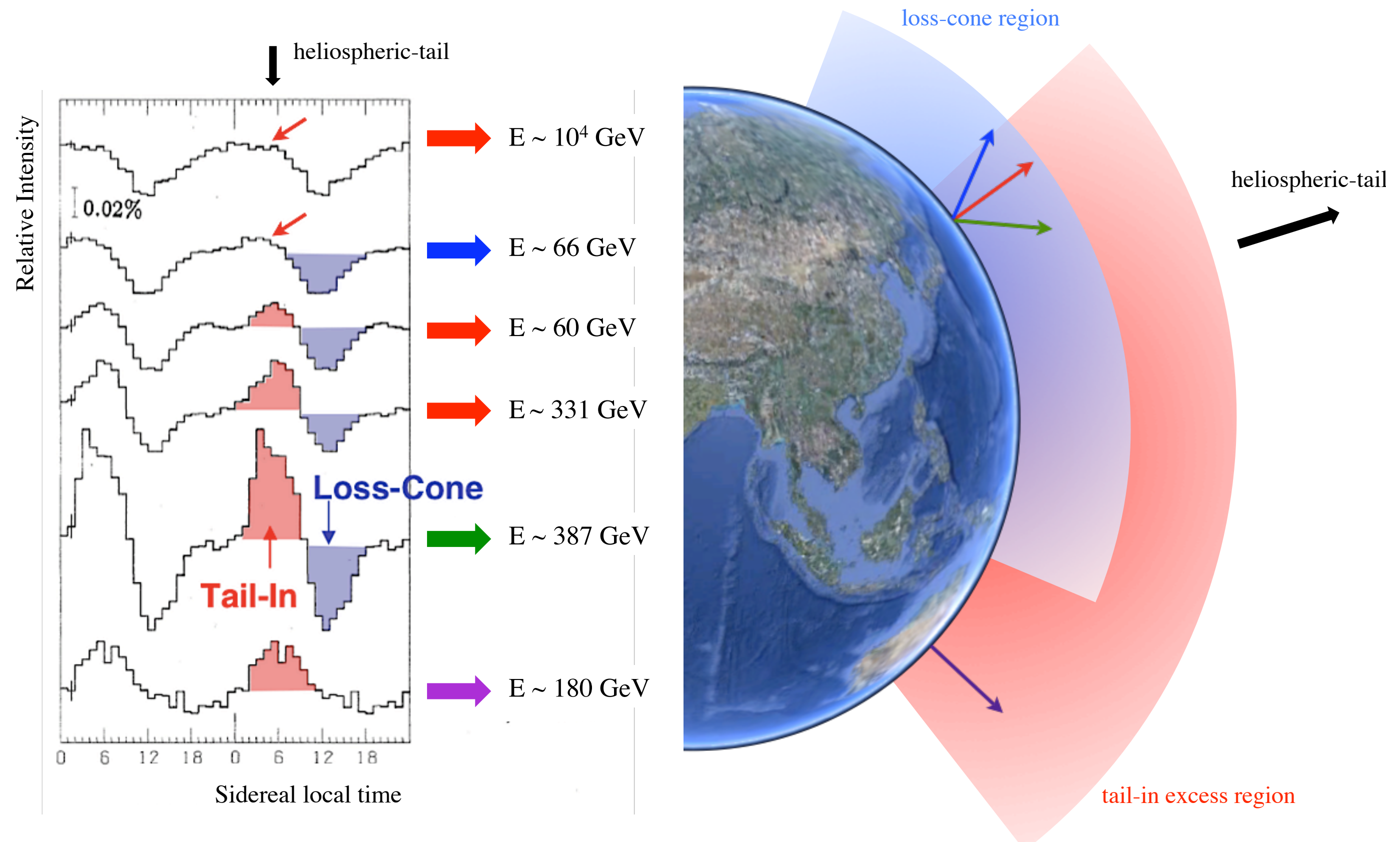
- localized excess of cosmic rays from nearby (~150 pc ~ 3×10^7 AU) recent (~ 350 kyr) supernova that gave birth to Geminga Pulsar
- fine tuning of propagation through interstellar medium
- incidentally requires magnetic connection to the faraway source
- small scale features likely from local processes



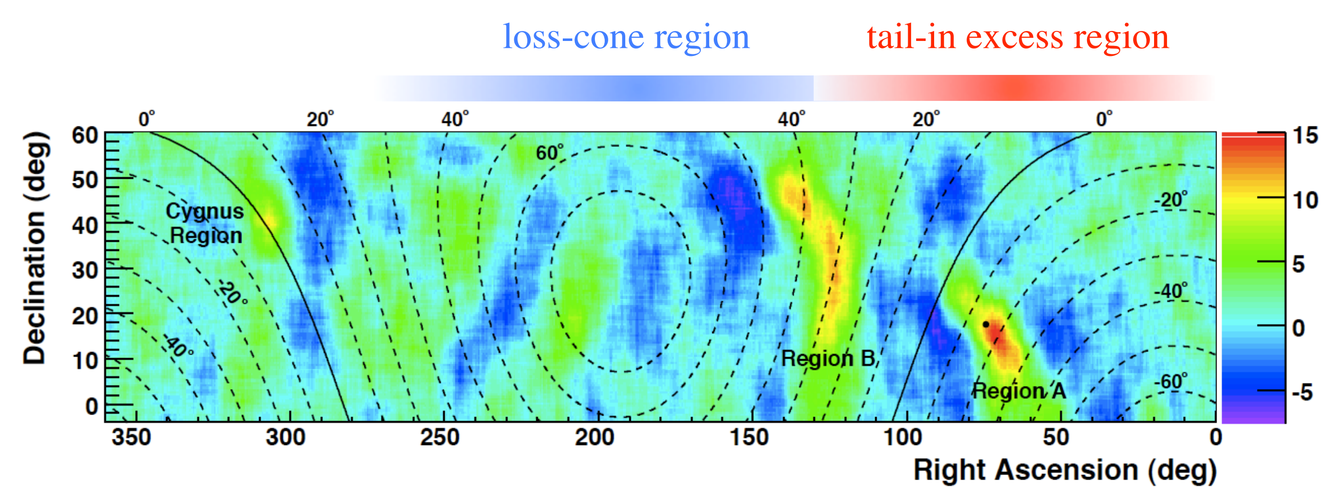
Abdo et al., Phys. Rev. Lett., 101, 221101, 2008

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



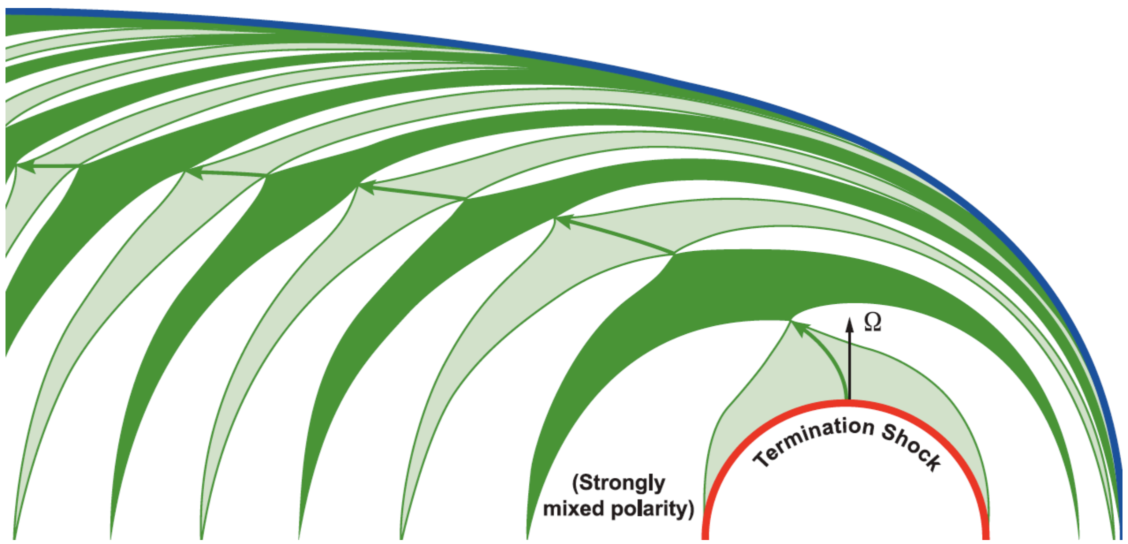
Abdo et al., Phys. Rev. Lett., 101, 221101, 2008

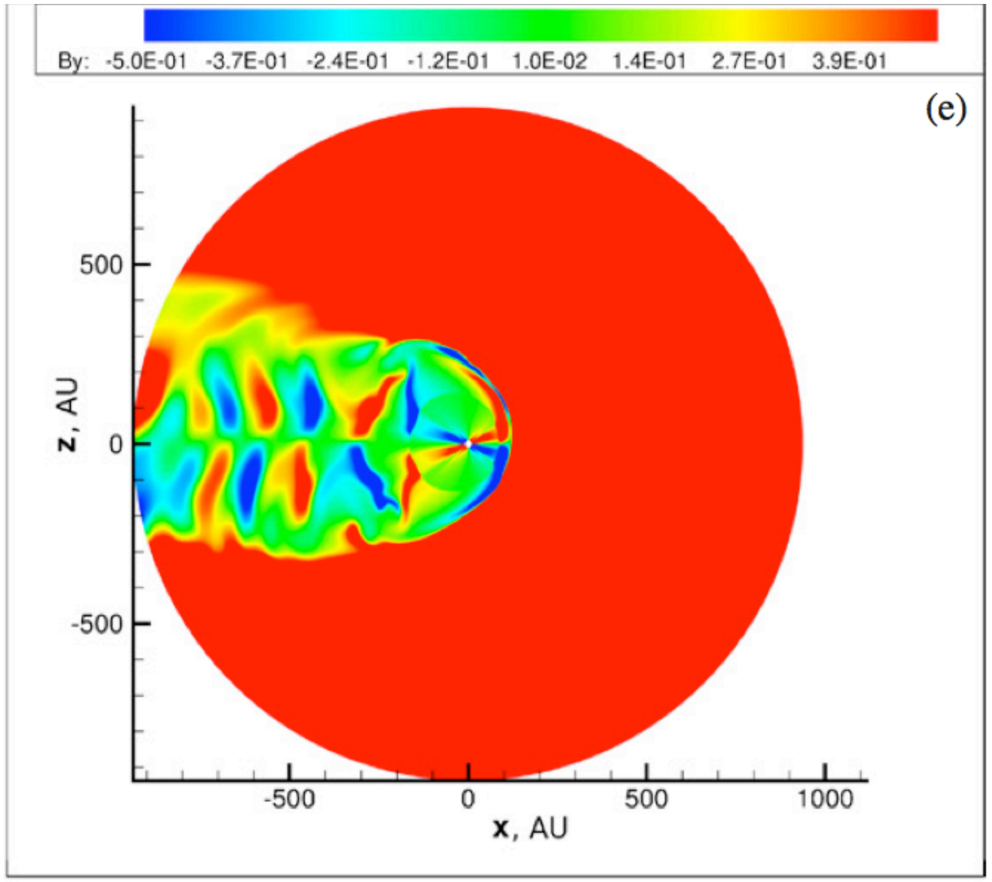
magnetic reconnection @ heliotail

Lazarian & Desiati, ApJ, 722, 188, 2010

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

- dissipative processes convert EM energy into plasma energy & magnetic fields change their topology through magnetic reconnectionß





3D numerical simulation of the turbulent heliosphere and heliotail

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

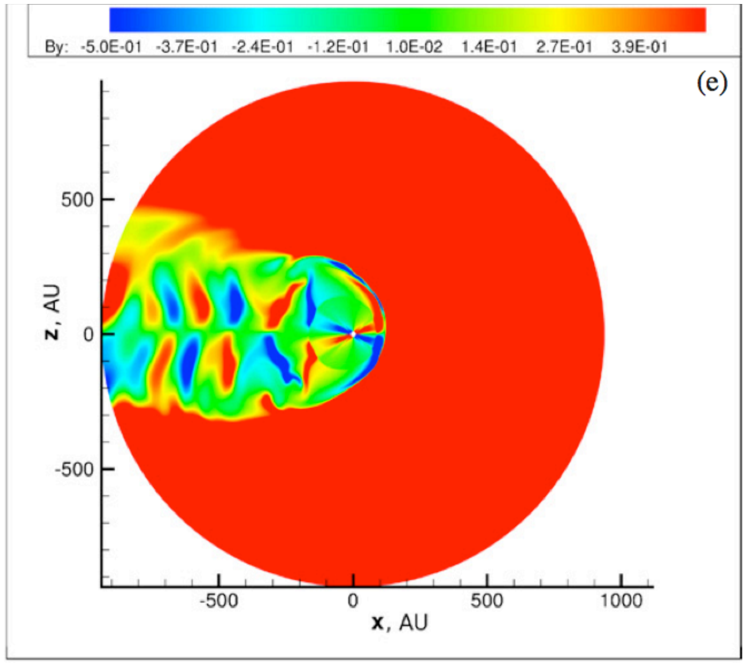
magnetic reconnection @ heliotail

Lazarian & Desiati, ApJ, 722, 188, 2010

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

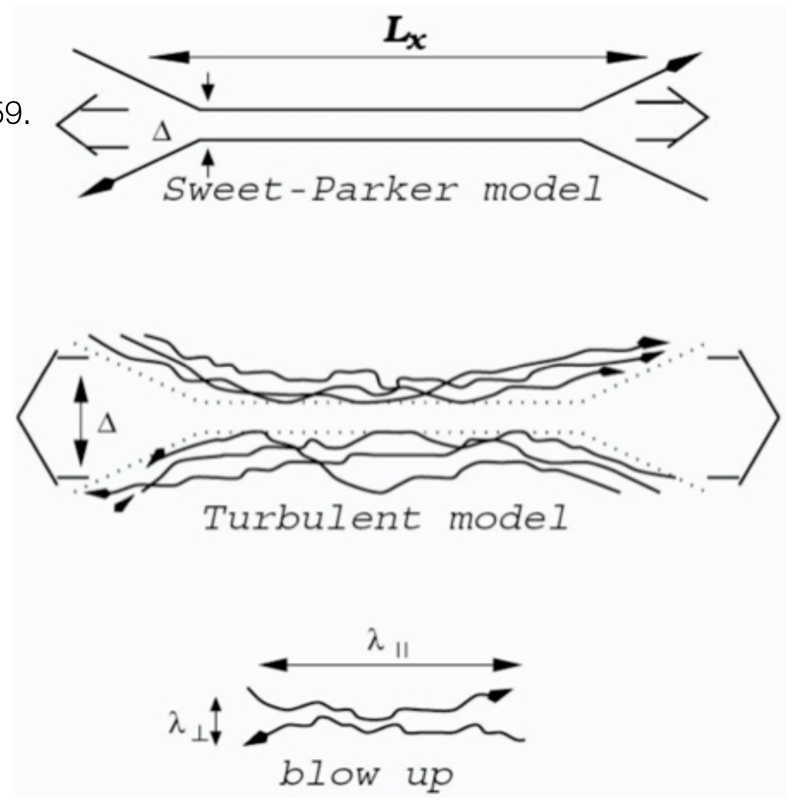
- ubiquitous turbulence makes reconnection fast and not affected by ohmic dissipation

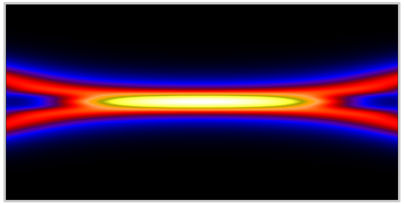
Pogorelov et al., ApJ, 696, 1478, 2009

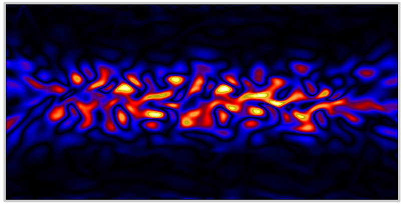


Sweet, IAU Symposium 6, Electromagnetic Phenomena in Cosmical Physics, 123, 1959.
Parker , J. Geophys. Rev., 62, 509, 1957

Lazarian & Vishniac, ApJ, 517, 700, 1999

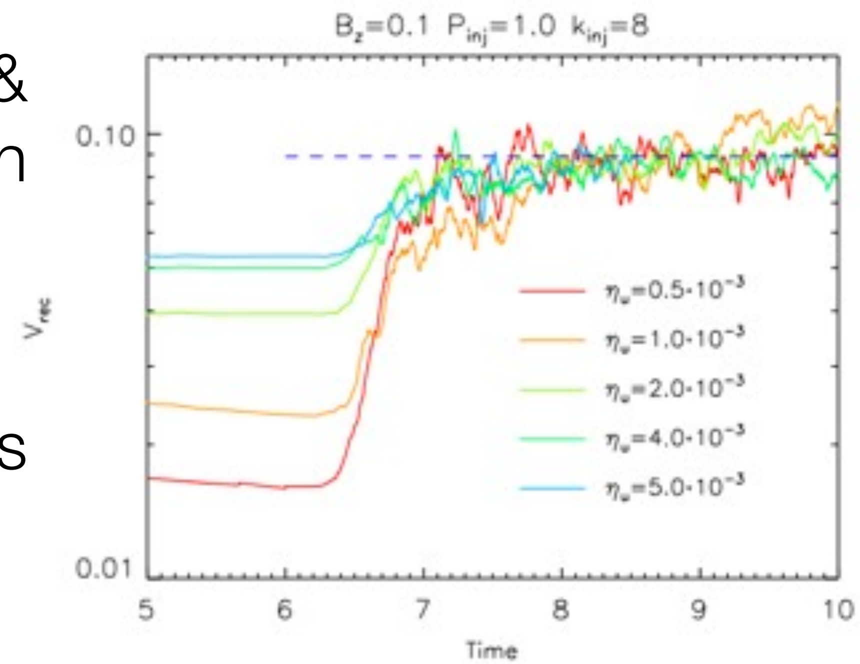




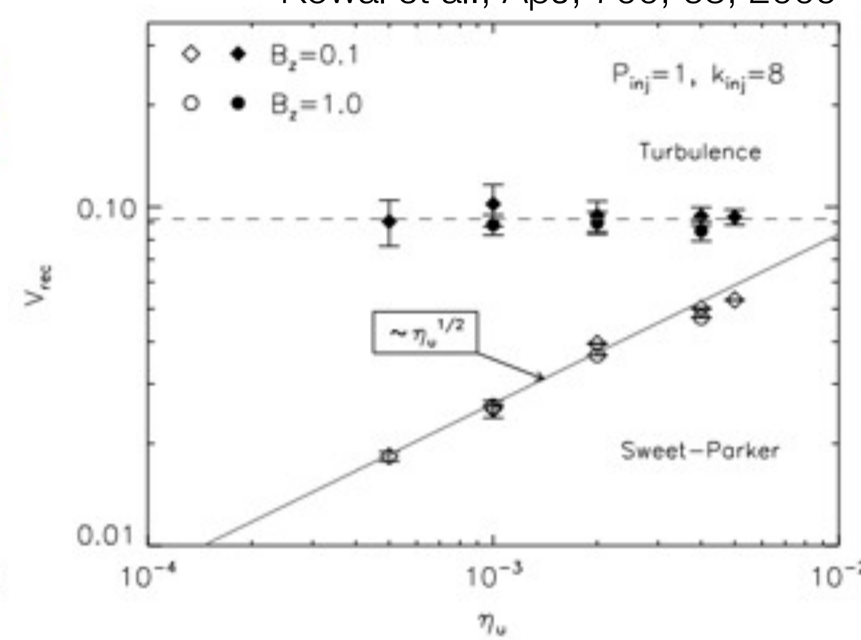


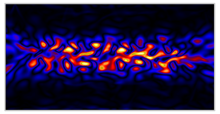
stochastic magnetic reconnection

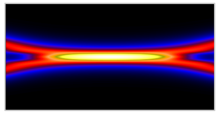
- verification of Lazarian & Vishniac 1999 with numerical calculations
- reconnection speed does not depend on resistivity
- reconnection speed increases with turbulence injection power
- reconnection speed ~ local turbulent velocity

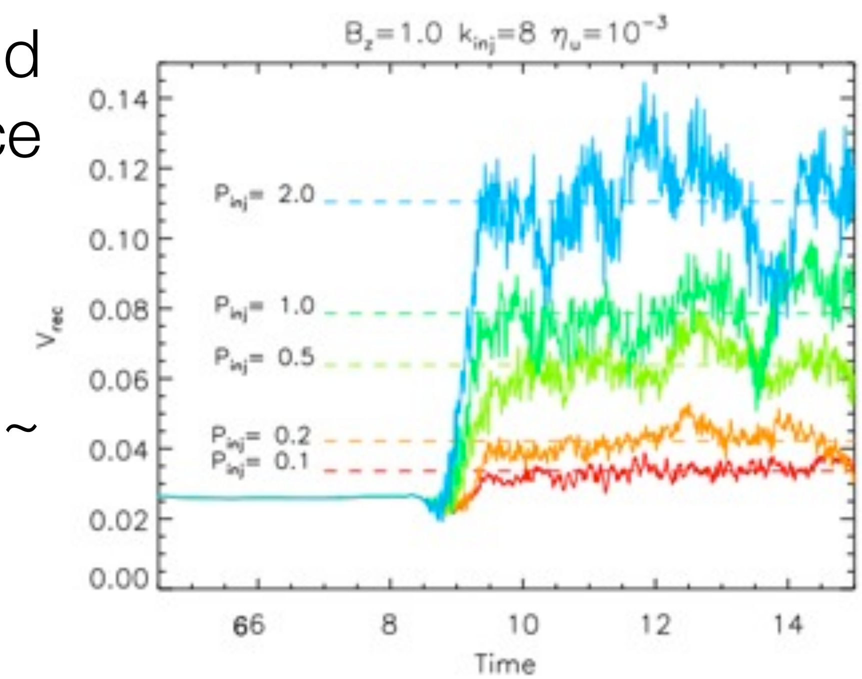


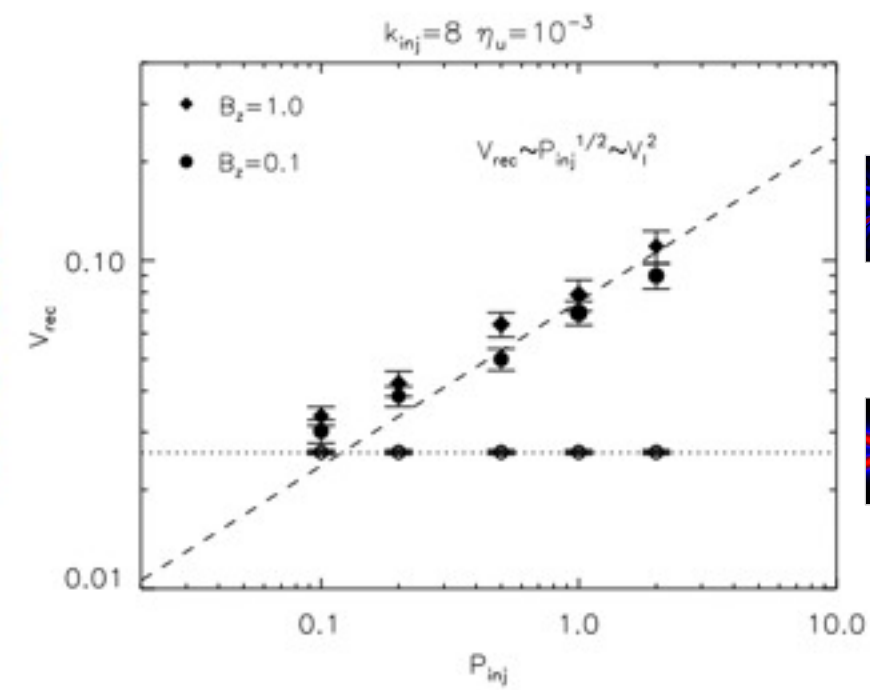
Kowal et al., ApJ, 700, 63, 2009

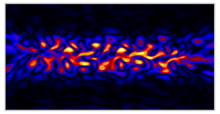


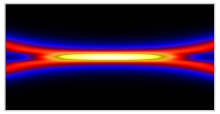












acceleration in reconnection regions

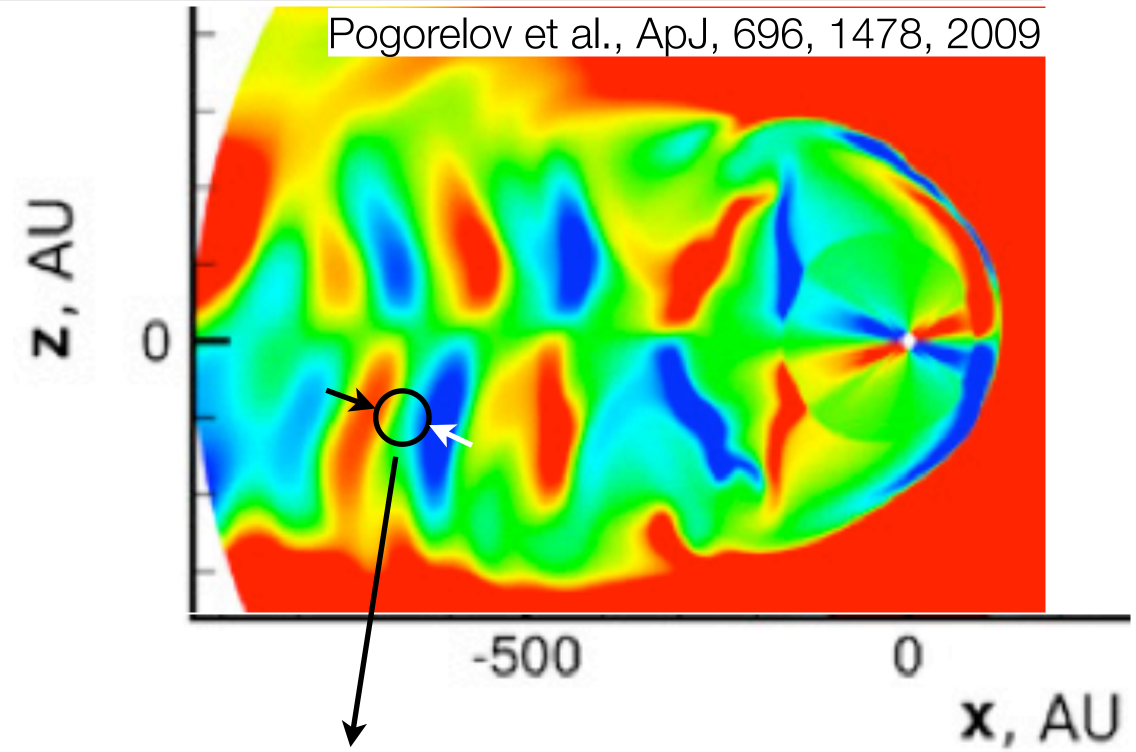
- first order Fermi acceleration from volume-filling magnetic reconnection

- magnetic mirror @ reconnection as site of acceleration *of test particle*

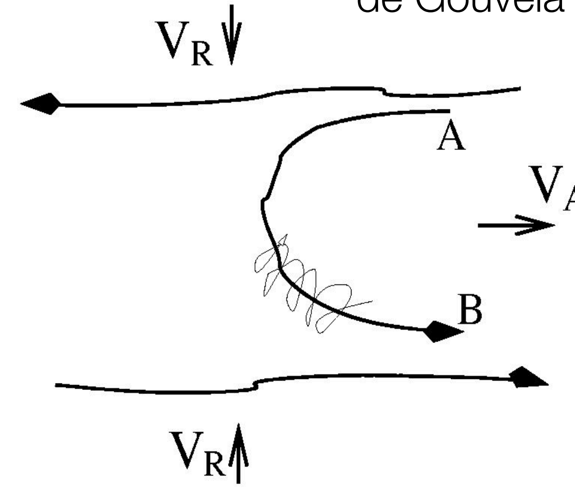
$$N(E)dE \sim E^{-5/2}dE$$

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

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



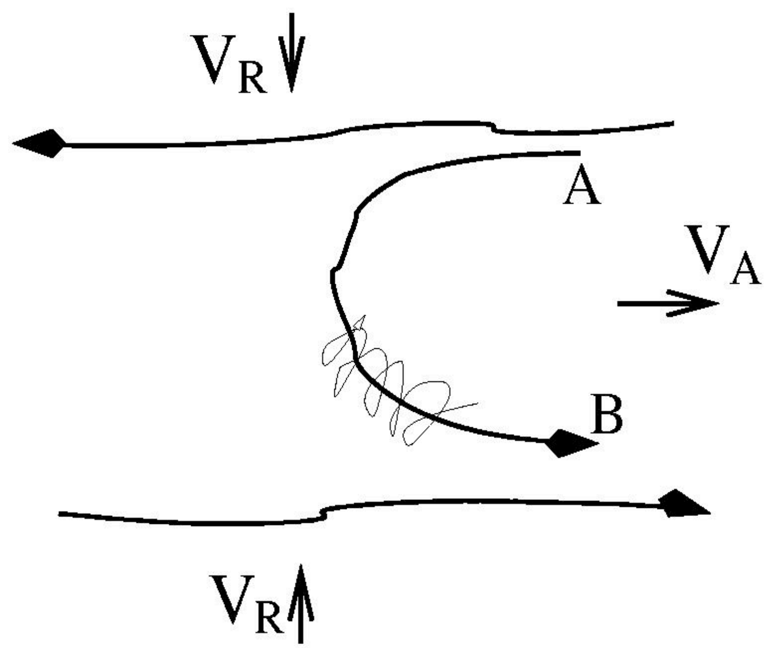
de Gouveia Dal Pino & Lazarian, 2005



application to pulsars, microquasars, solar flares acceleration

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

acceleration in reconnection regions



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

first-order Fermi acceleration of test particle in magnetic mirrors

$$N(E)dE \sim E^{-\frac{3}{2}}dE$$

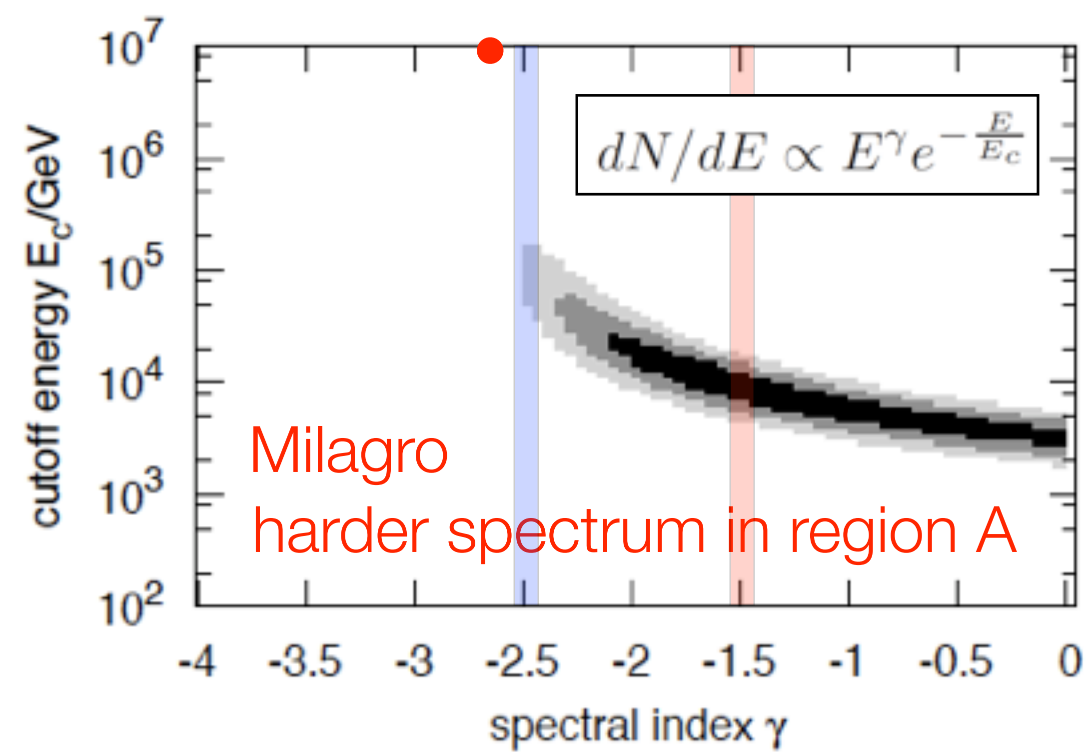
particle back-reaction
Drake et al., Nature, 443, 553, 2006

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

- solar wind down-stream TS ≈ 100 km/sec

$$E_{max} \approx 20\ TeV \cdot \left(\frac{B}{1\mu B}\right)$$

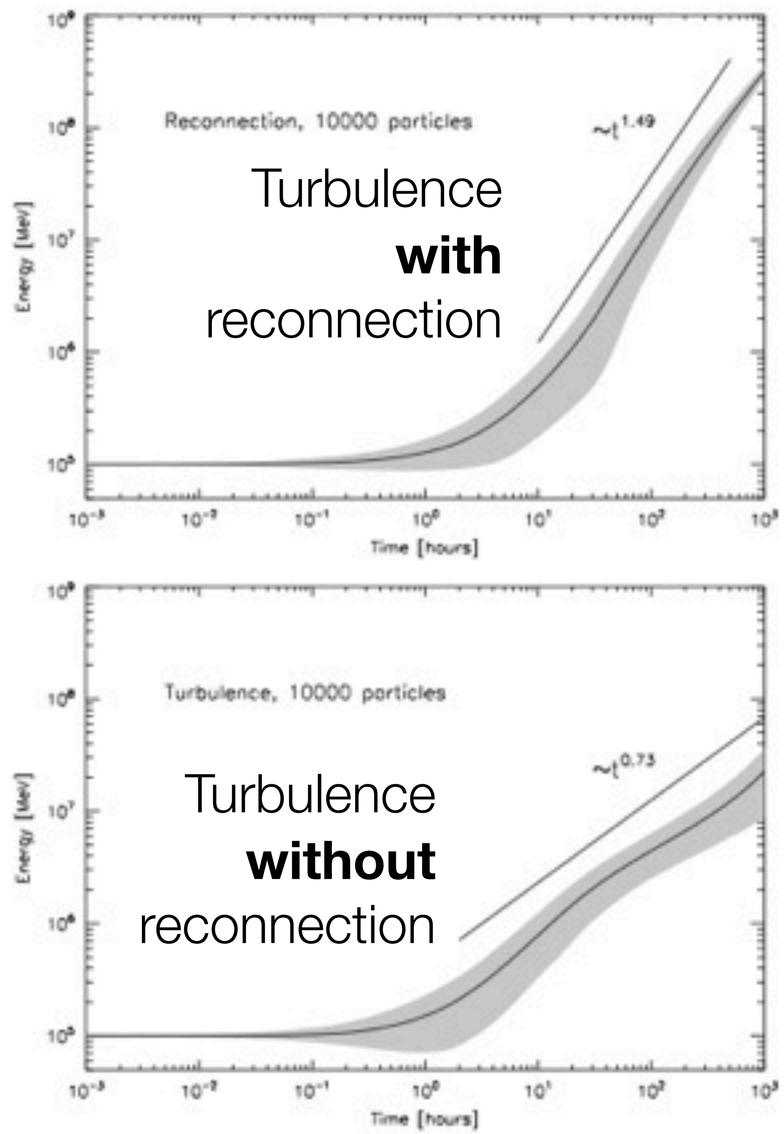
➡ unlikely to expect energies > 10 TeV

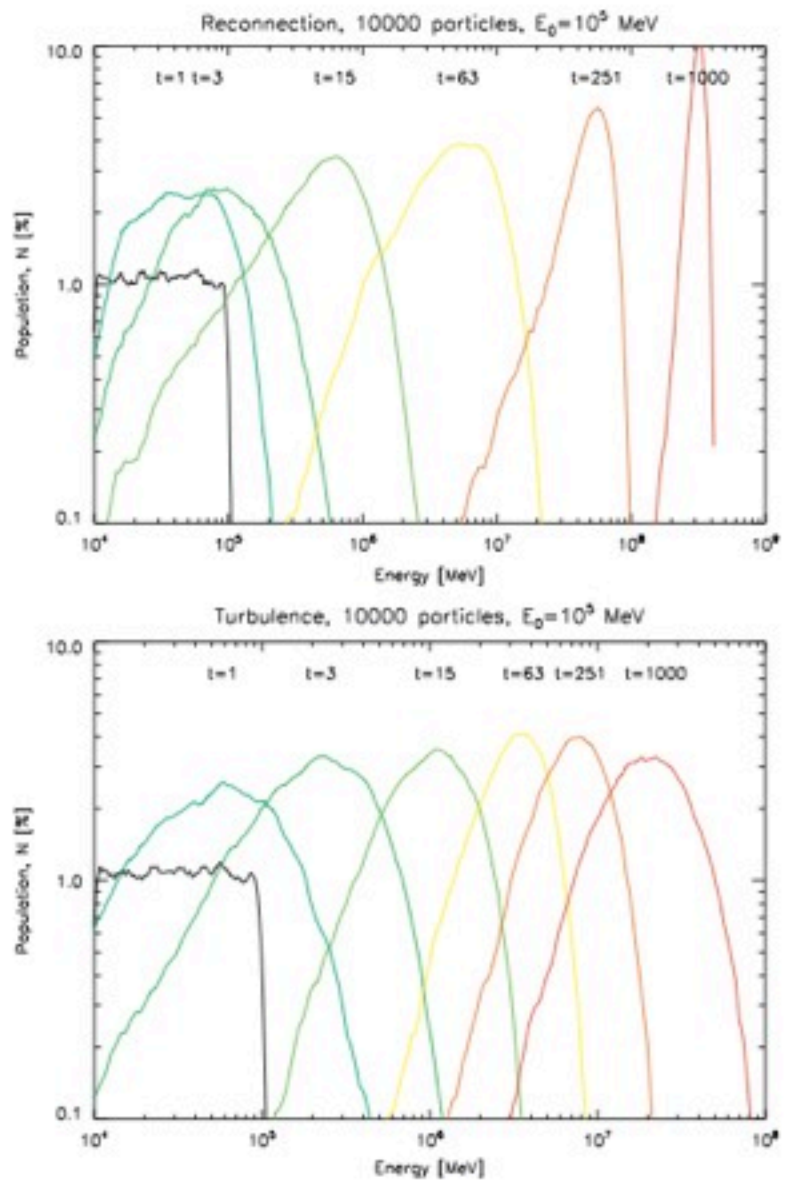


acceleration in weakly stochastic reconnection regions

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

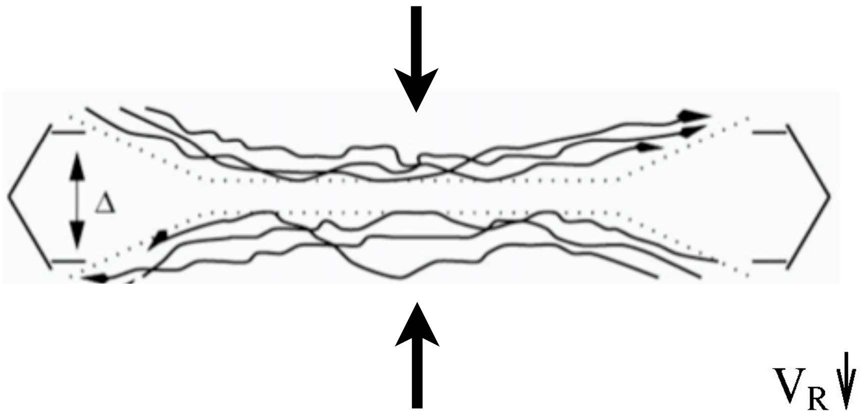
- test particle verification of Lazarian & Vishniac 1999 with numerical calculations
- magnetic energy transferred into energy of contracting loops
- fast reconnection induces efficient acceleration of cosmic rays



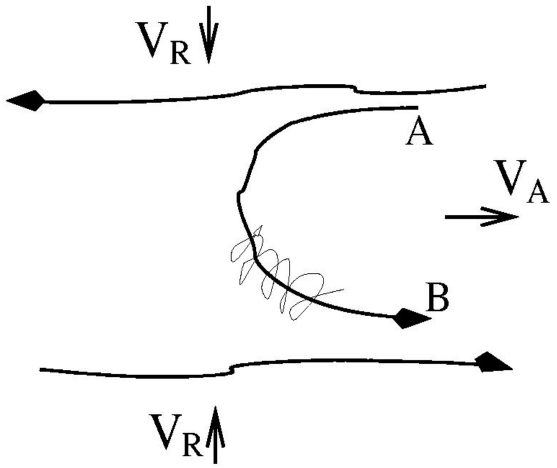


acceleration in weakly stochastic reconnection regions

- fast reconnection produces volume filled with contracting loops & current sheets



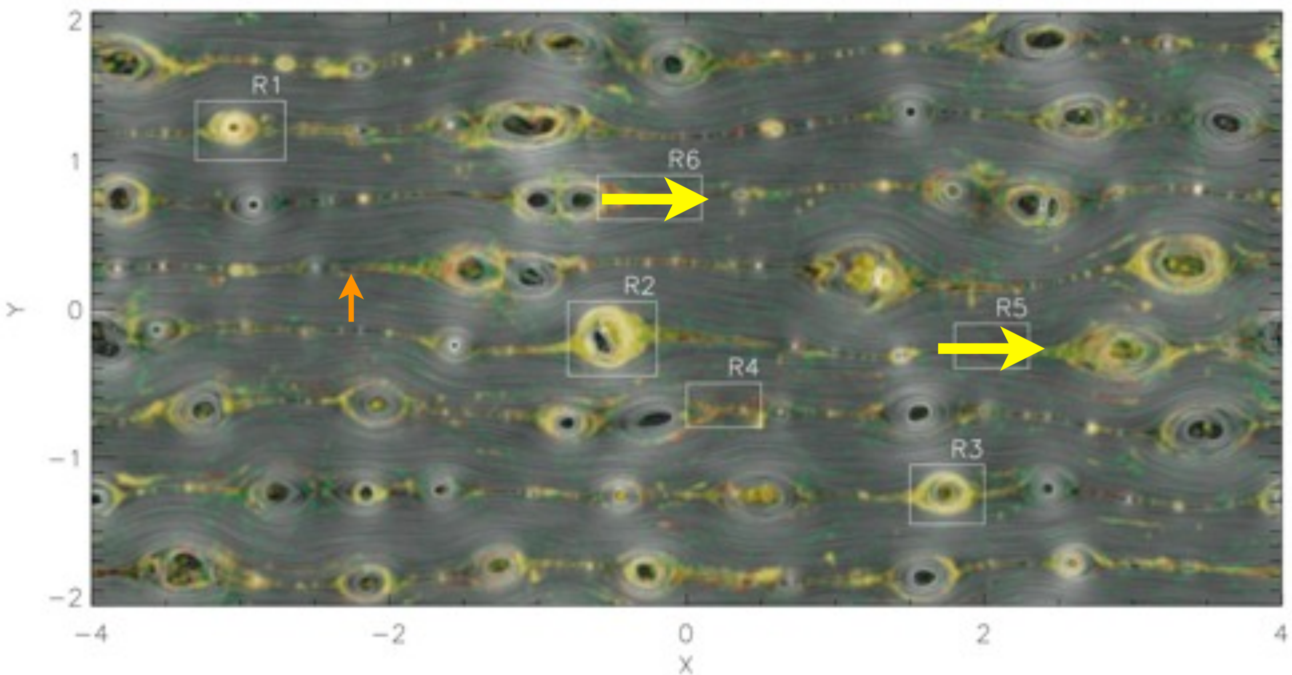
- 1^{st} order Fermi & drift acceleration



  - in contracting loops & currents sheets $\mathbf{v}_{\parallel}$ increases exponentially: **dominant**
  - $\mathbf{v}_{\perp}$ also increases outside those regions via drift acceleration

➡ anisotropy of accelerated CR

nearly non-resistive MHD
Kowal et al., ApJ 735, 102, 2011 (arXiv:1103.2984)



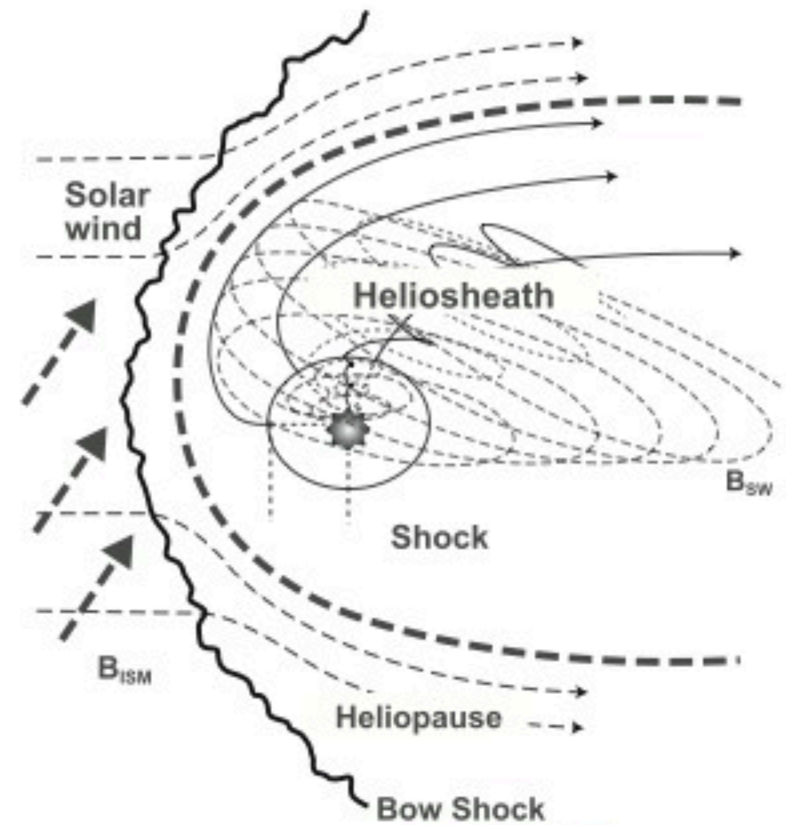
collisionless scenario
Drake et al., Geophys. Res. Lett., 33, 13105, 2006

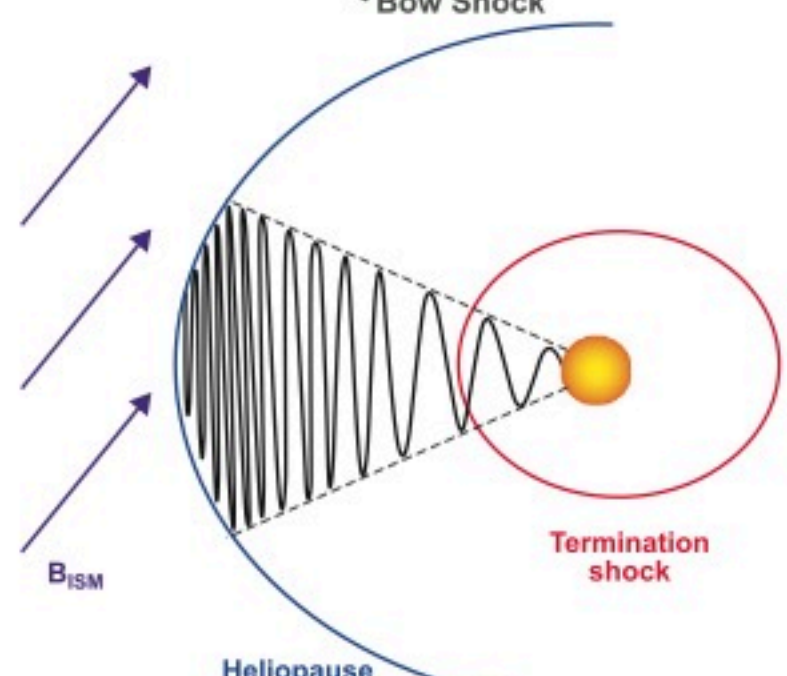
application on anomalous cosmic rays

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

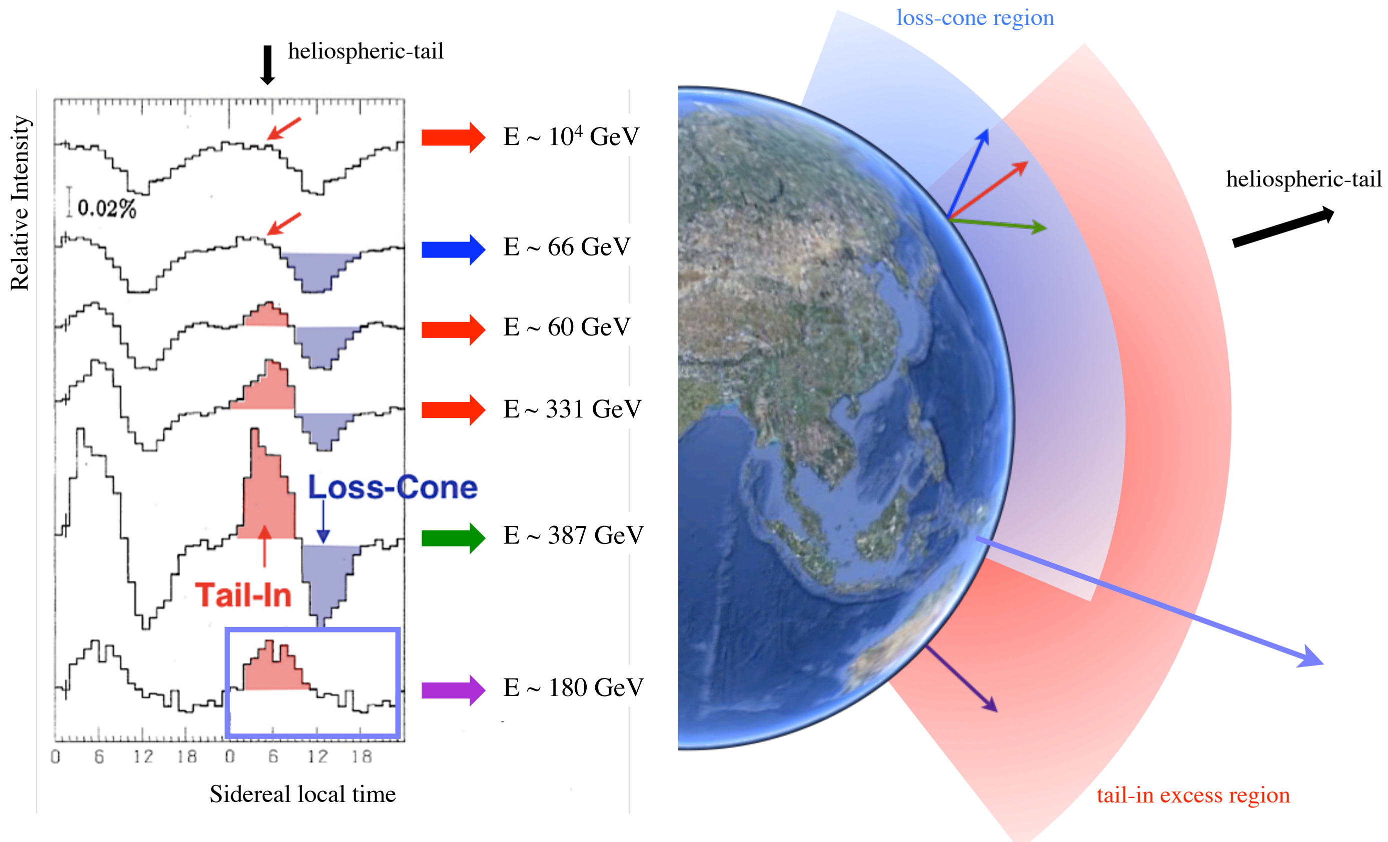
- on-going numerical calculations to verify whether magnetic reconnection regions in the heliotail may be site of efficient acceleration

- acceleration mechanisms in stochastic reconnection regions might explain the puzzling excess region of cosmic rays

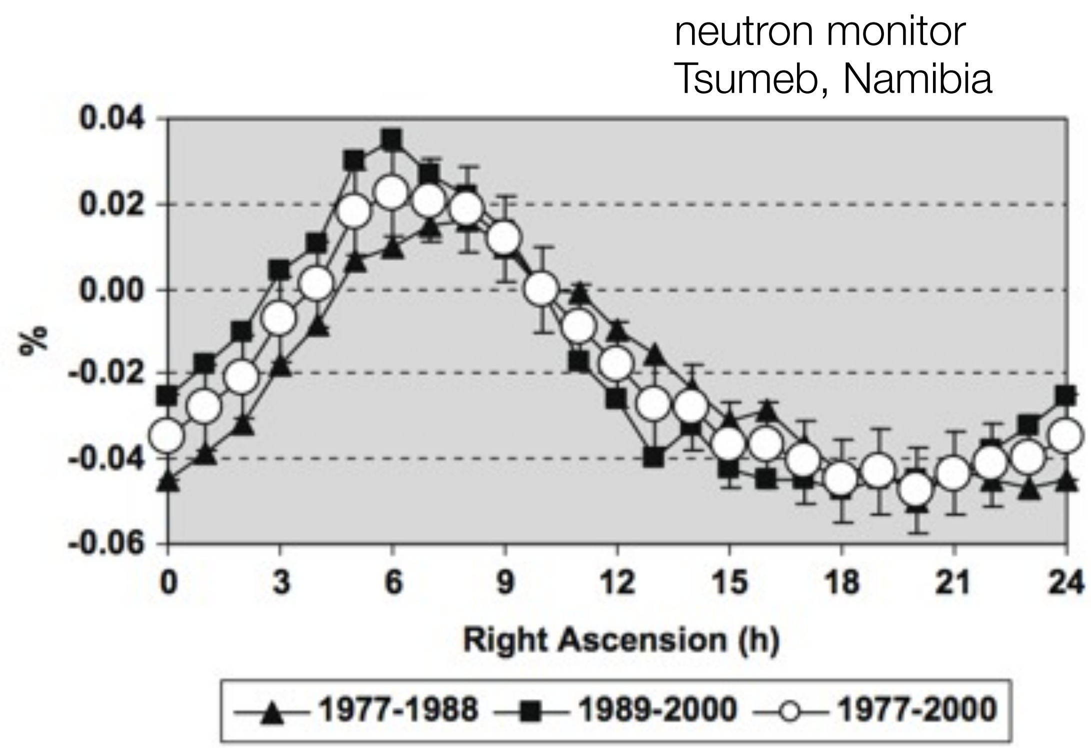
- potential testbed of large-scale acceleration mechanism in stochastic reconnection regions (ACR, heliotail, ...)

- multi-TeV cosmic rays to probe outer heliospheric boundary back up slides

origin of small scale anisotropy : heliospheric tail



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



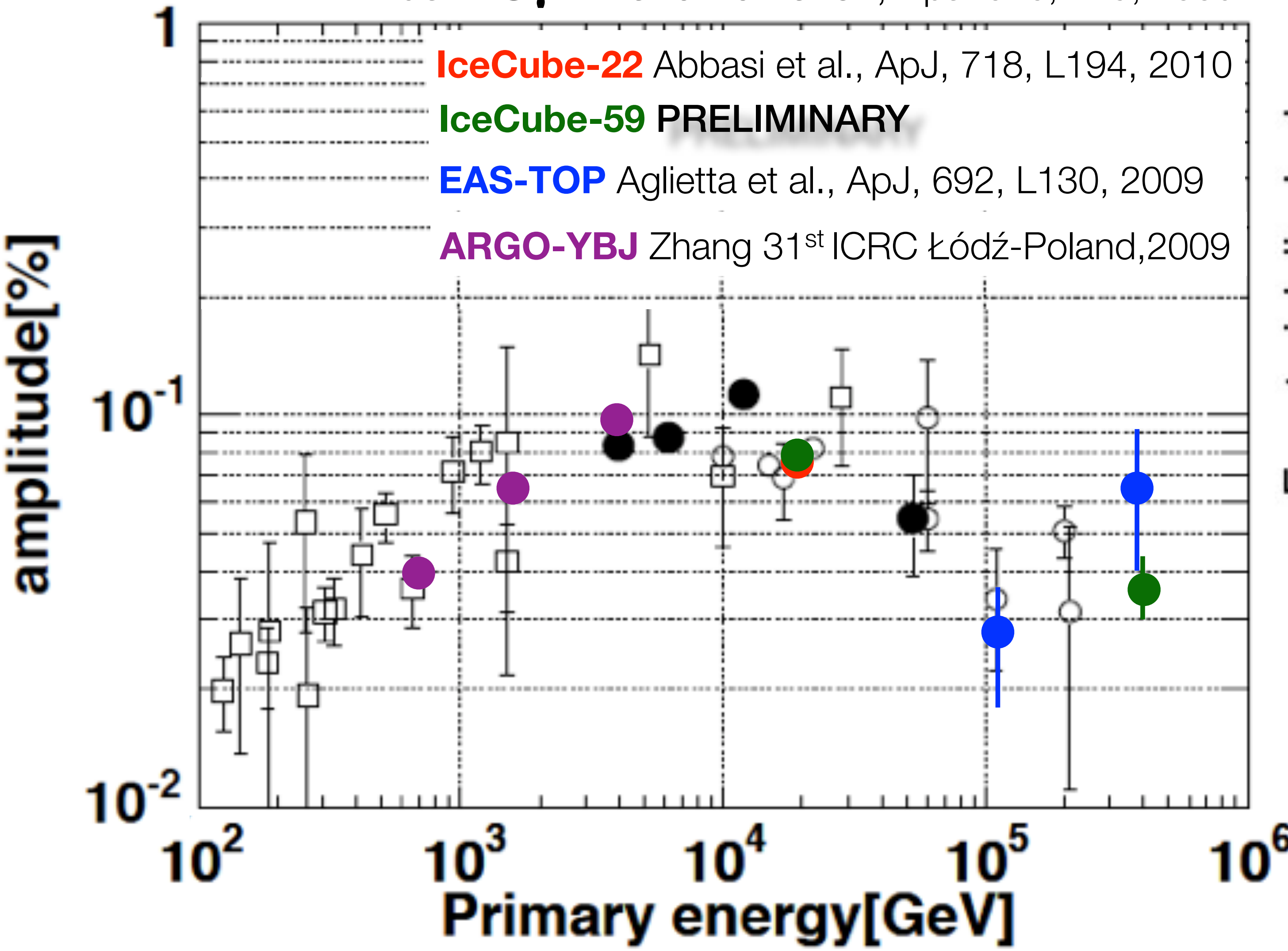
negative polarity   positive polarity

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

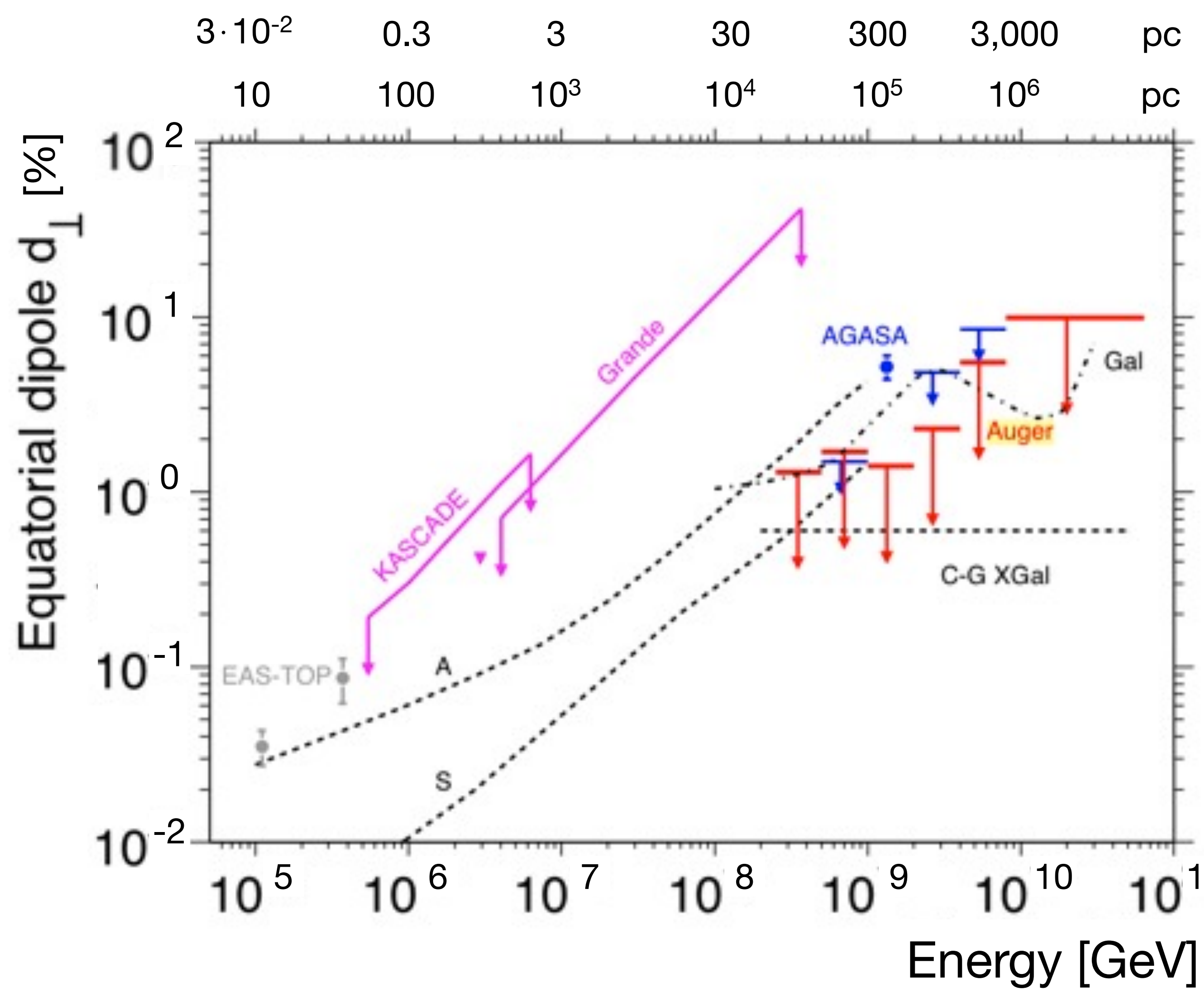
- sub-TeV cosmic ray tail-in excess by some unknown asymmetry caused by the heliotail
- solar magnetic field reversal should affect galactic anisotropy
- origin of excess is “heliospheric”

anisotropy vs energy

Tibet ASγ Amenomori et al., ApJ. 626, L29, 2005



(3 μG)
(~0.01 μG)



Abreu et al., Astrop. Phys., 34, 627, 2011

(3 μG)

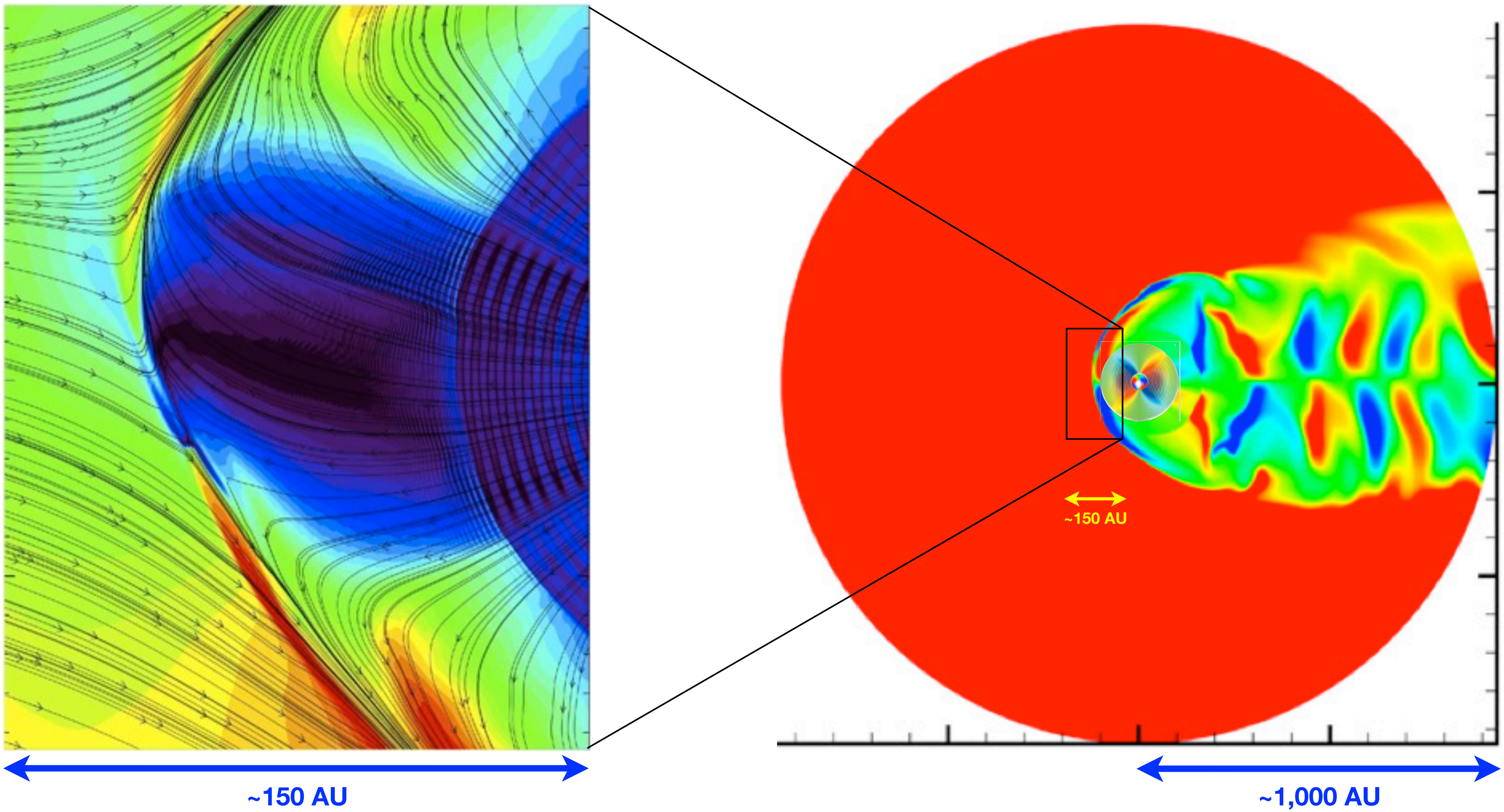
$3 \cdot 10^{-5}$	$3 \cdot 10^{-4}$	$3 \cdot 10^{-3}$	$3 \cdot 10^{-2}$	0.3	gyro-radius (pc)
7	70	700	7,000	70,000	gyro-radius (AU)

heliospheric influence ← → galactic influence

magnetic reconnection in the heliosphere

3D simulations of heliosphere
Opher et al., arXiv:1103.2236

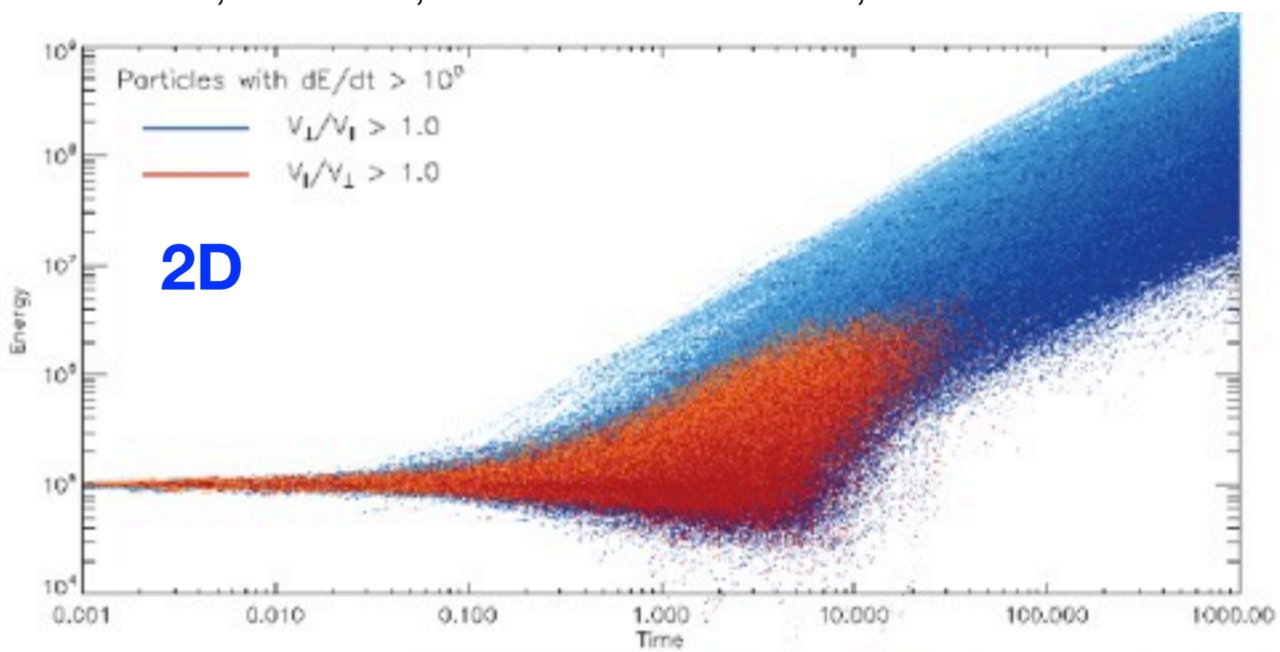
3D simulation of heliosphere/heliotail
Pogorelov et al., ApJ, 696, 1478, 2009

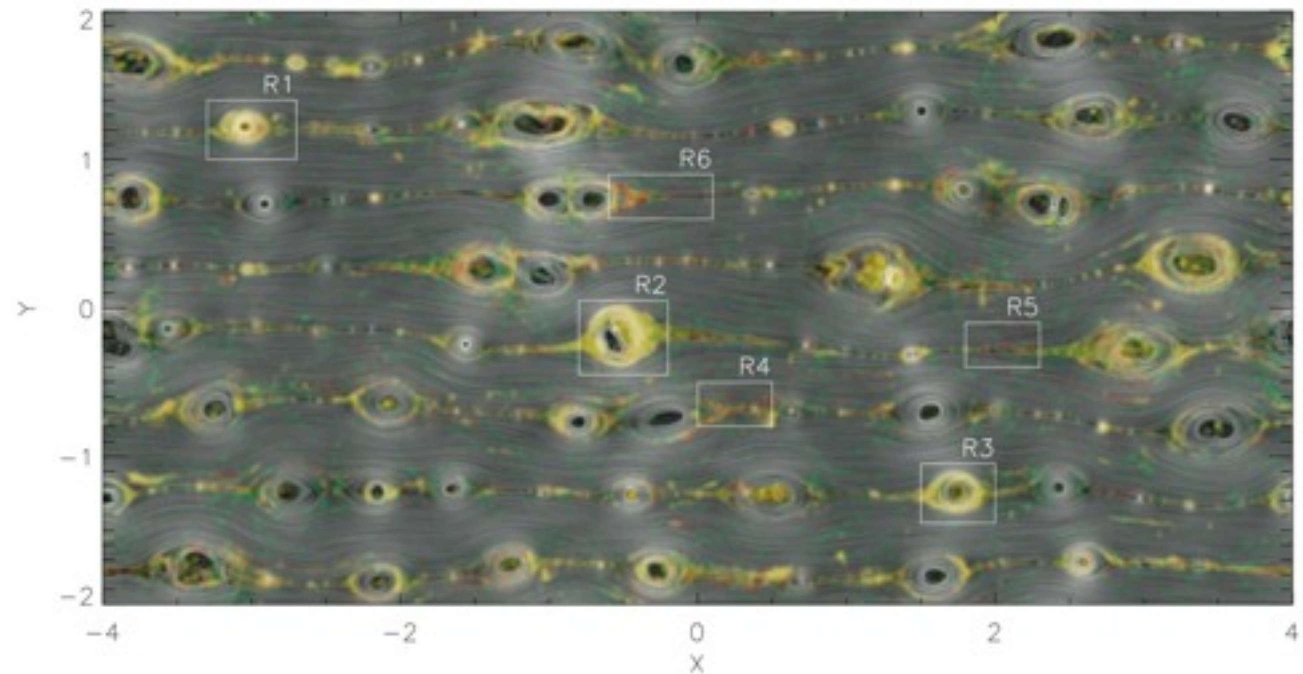


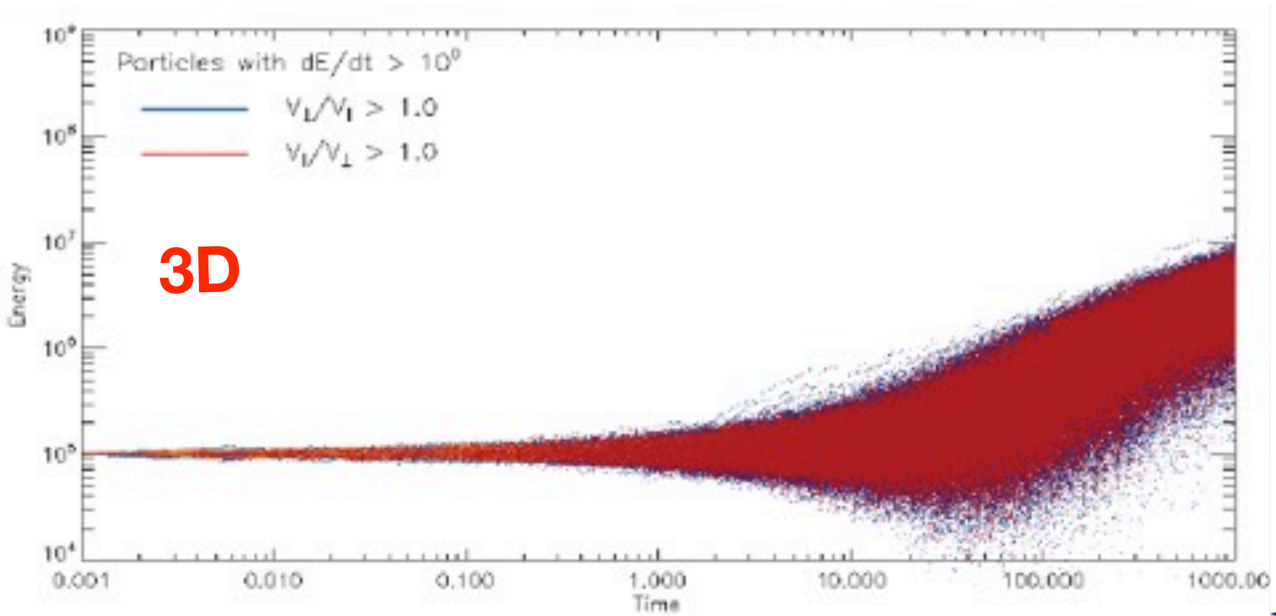
acceleration in weakly stochastic reconnection regions

nearly non-resistive MHD
Kowal et al., ApJ 735, 102, 2011 (arXiv:1103.2984)

Kowal, Lazarian, de Gouveia dal Pino, 2010







- Perpendicular acceleration gets important for **2D** at longer integration times
- Parallel momentum mostly increases for the acceleration in **3D**