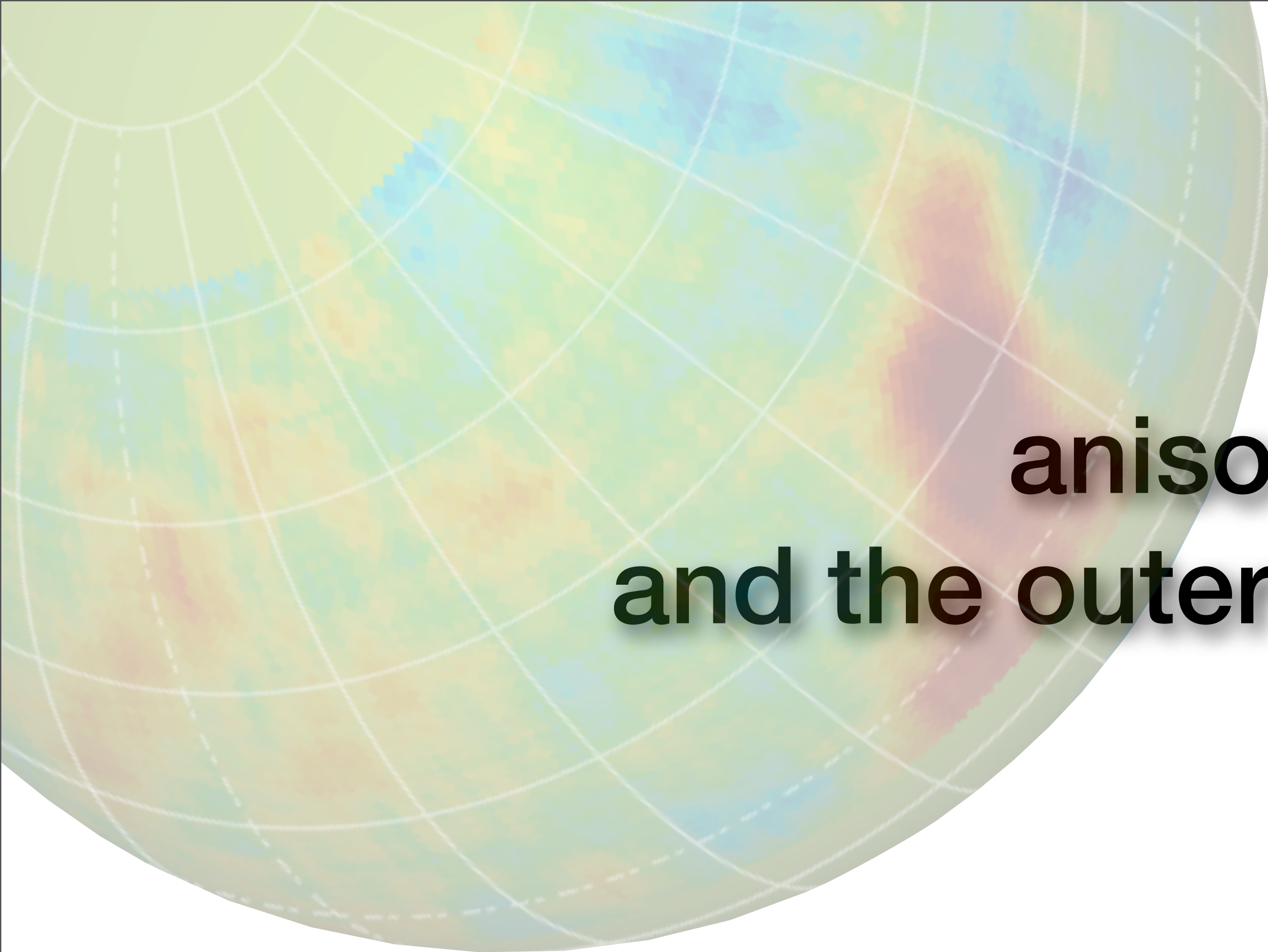


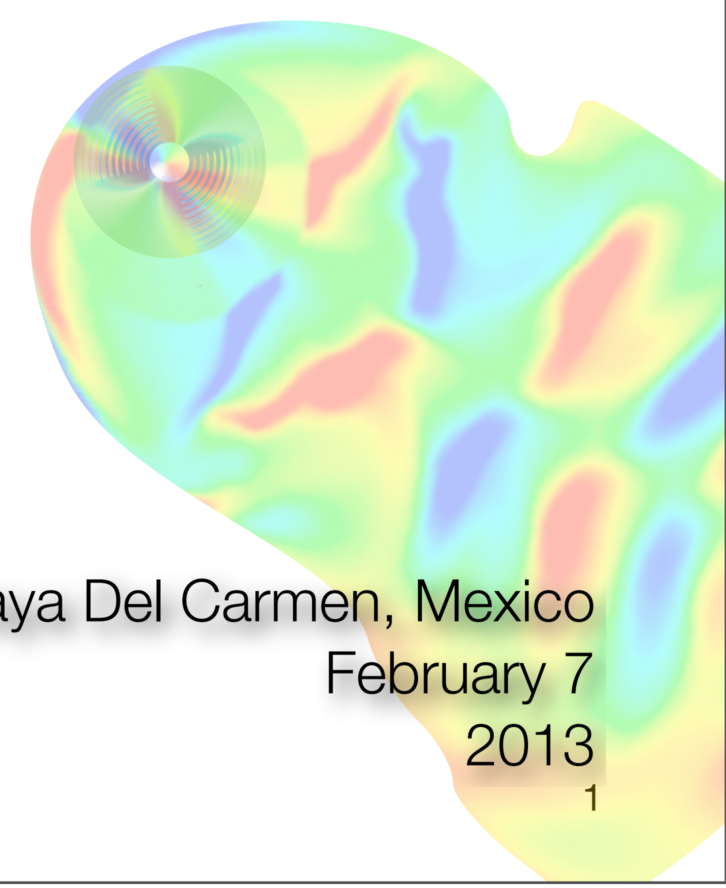
anisotropy of TeV cosmic rays and the outer heliospheric boundaries

Paolo Desiati[1,2] <desiati@wipac.wisc.edu>

Alexander Lazarian[2]

[1] WIPAC - Wisconsin IceCube Particle Astrophysics Center
[2] Department of Astronomy

University of Wisconsin - Madison



MAGNETIC FIELDS IN THE UNIVERSE IV

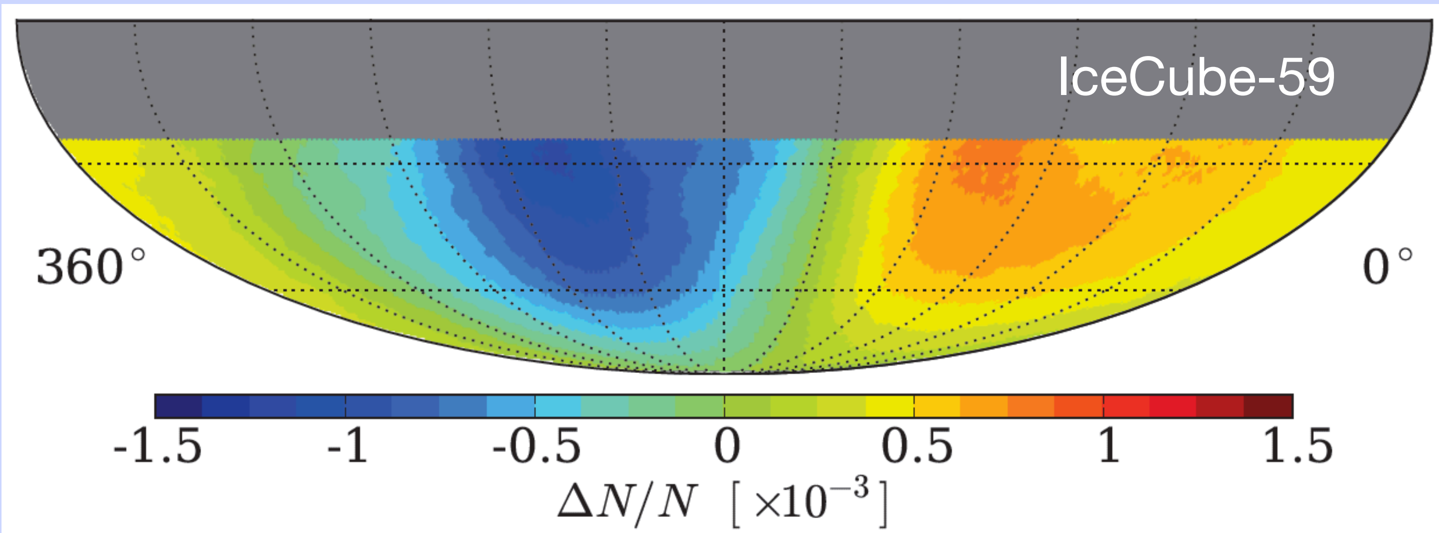
Playa Del Carmen, Mexico
February 7
2013

cosmic ray anisotropy large scale

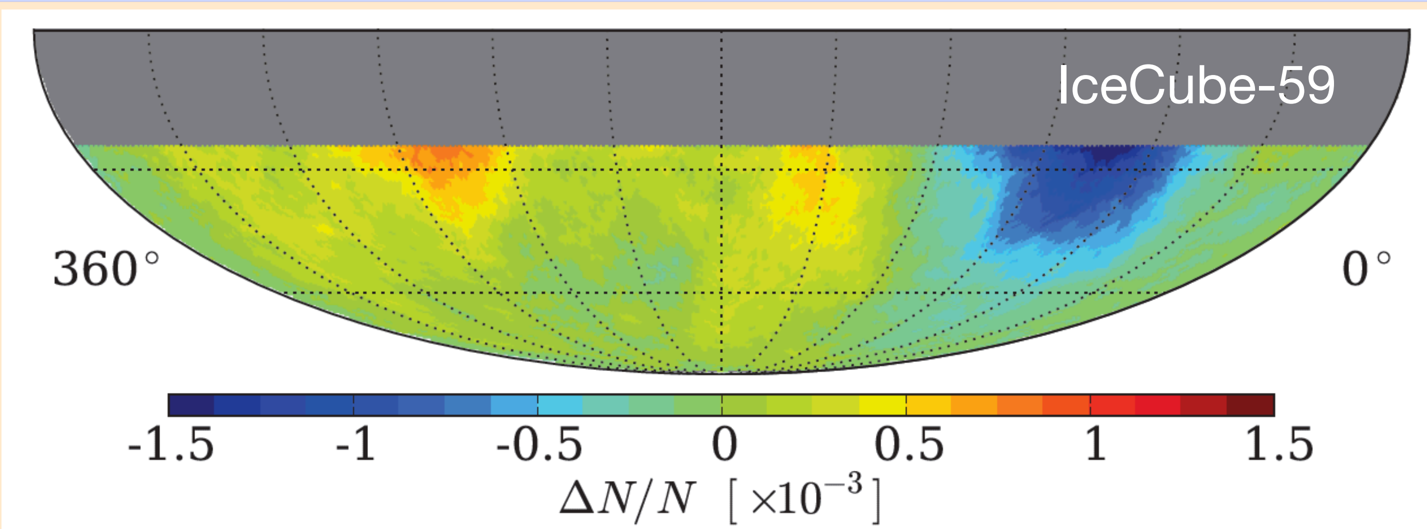
Abbasi et al., ApJ, **718**, L194, 2010
Abbasi et al., ApJ, **746**, 33, 2012
Aartsen et al., arXiv:1210.5278
accepted to ApJ

relative intensity

equatorial coordinates

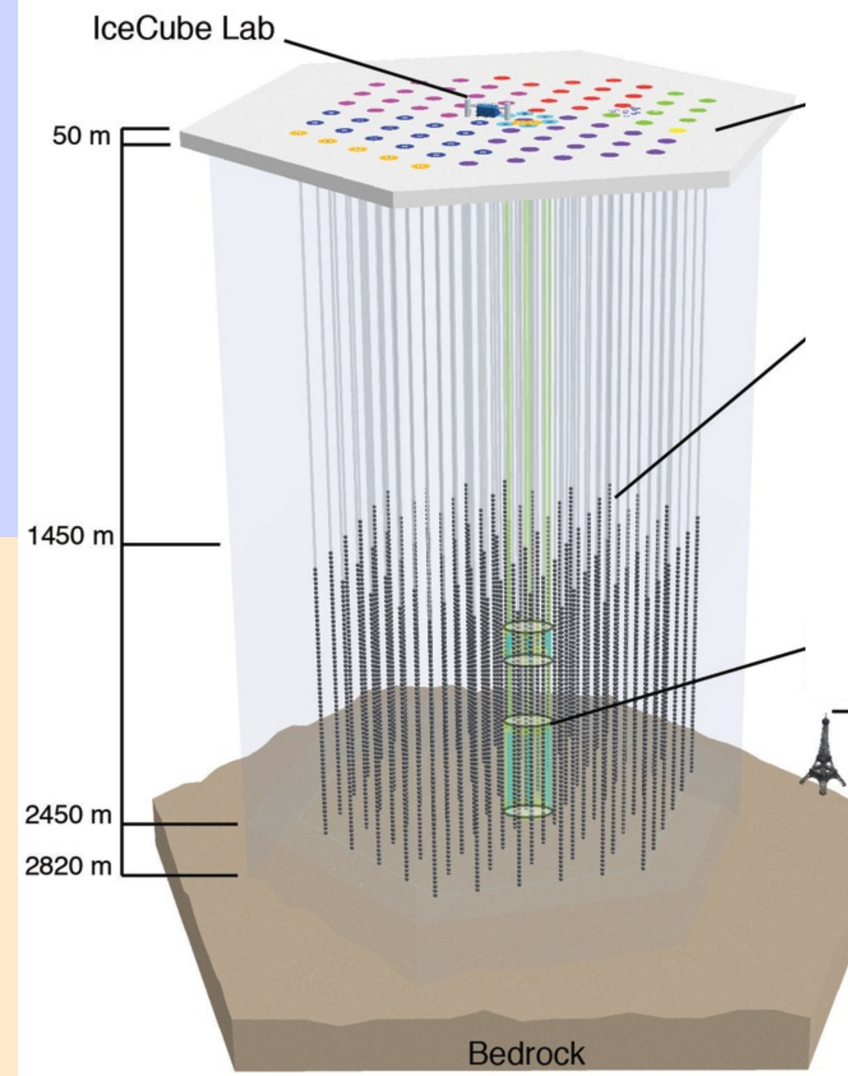


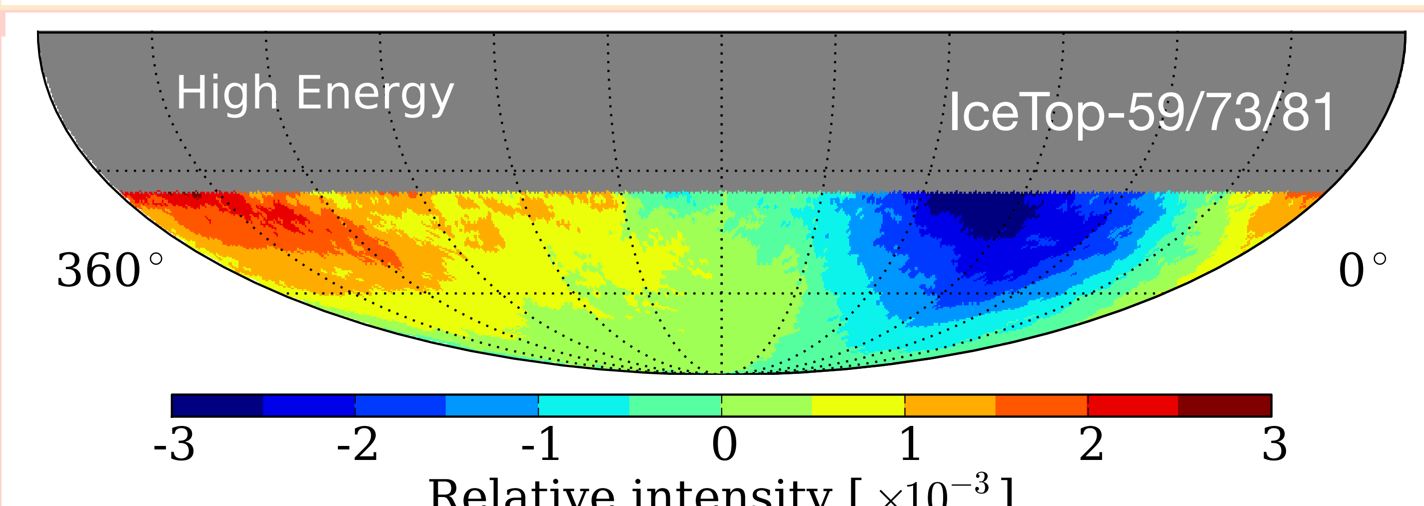
20 TeV



400 TeV

deficit
6.3 σ





2 PeV

deficit
7 σ

$$\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}$$

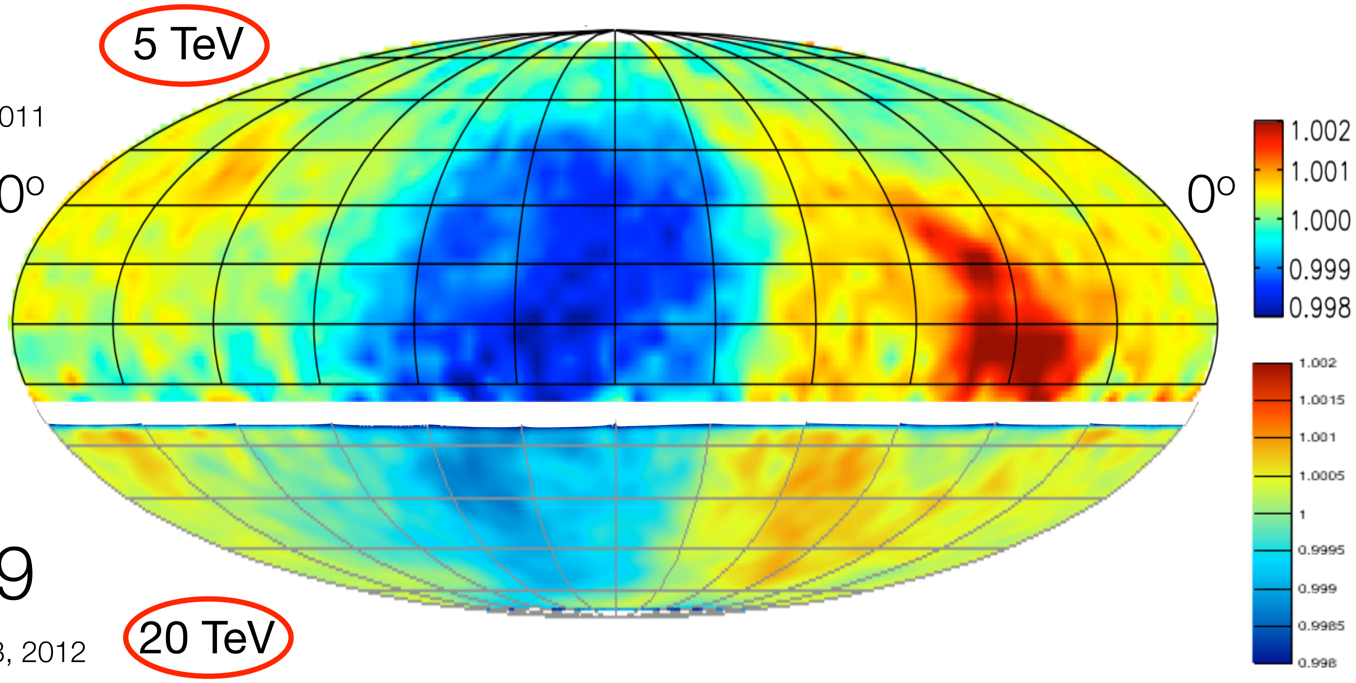
NOT A DIPOLE
ANISOTROPY

cosmic ray anisotropy large scale → small scale

Tibet-III

Amenomori et al., ICRC 2011

5 TeV



equatorial coordinates

relative intensity

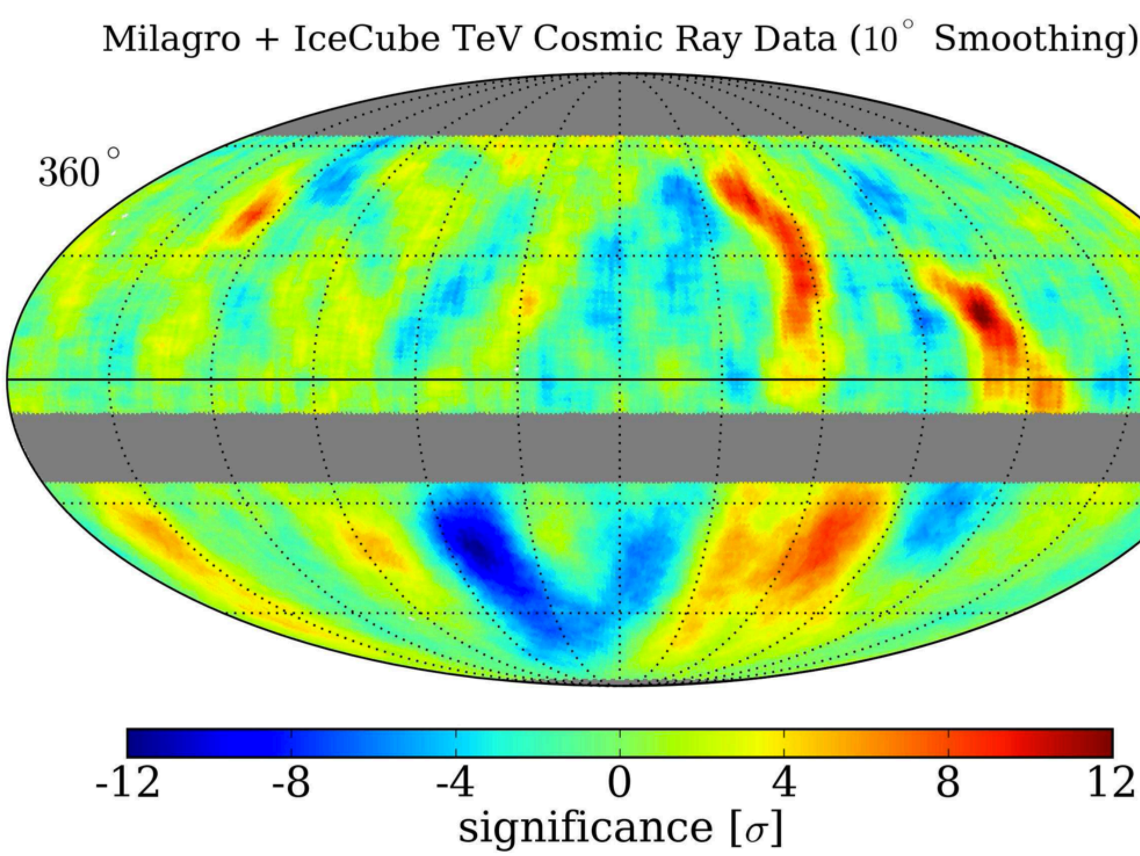
IceCube-59

Abbasi et al., ApJ, **746**, 33, 2012

20 TeV

2 hr = 30°

4 hr = 60°



Milagro

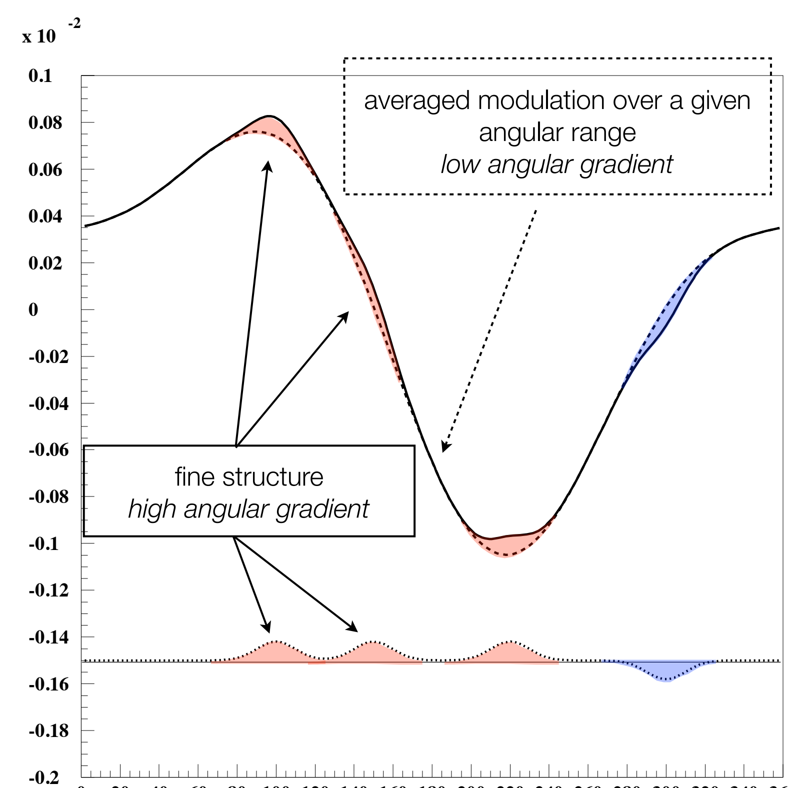
1 TeV

Abdo et al., PRL, **101**, 221101, 2008

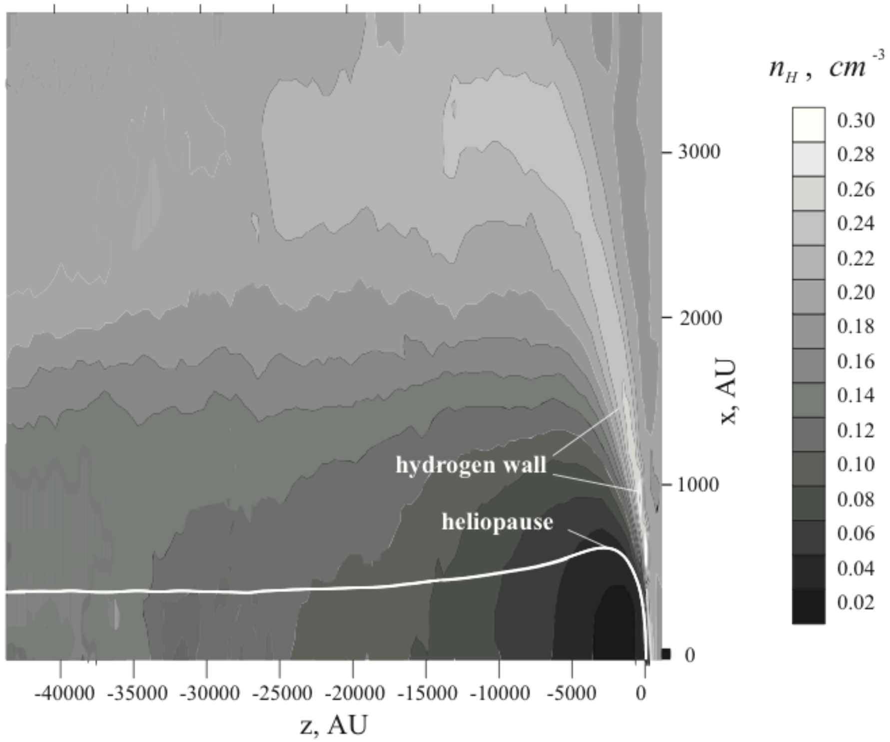
IceCube

20 TeV

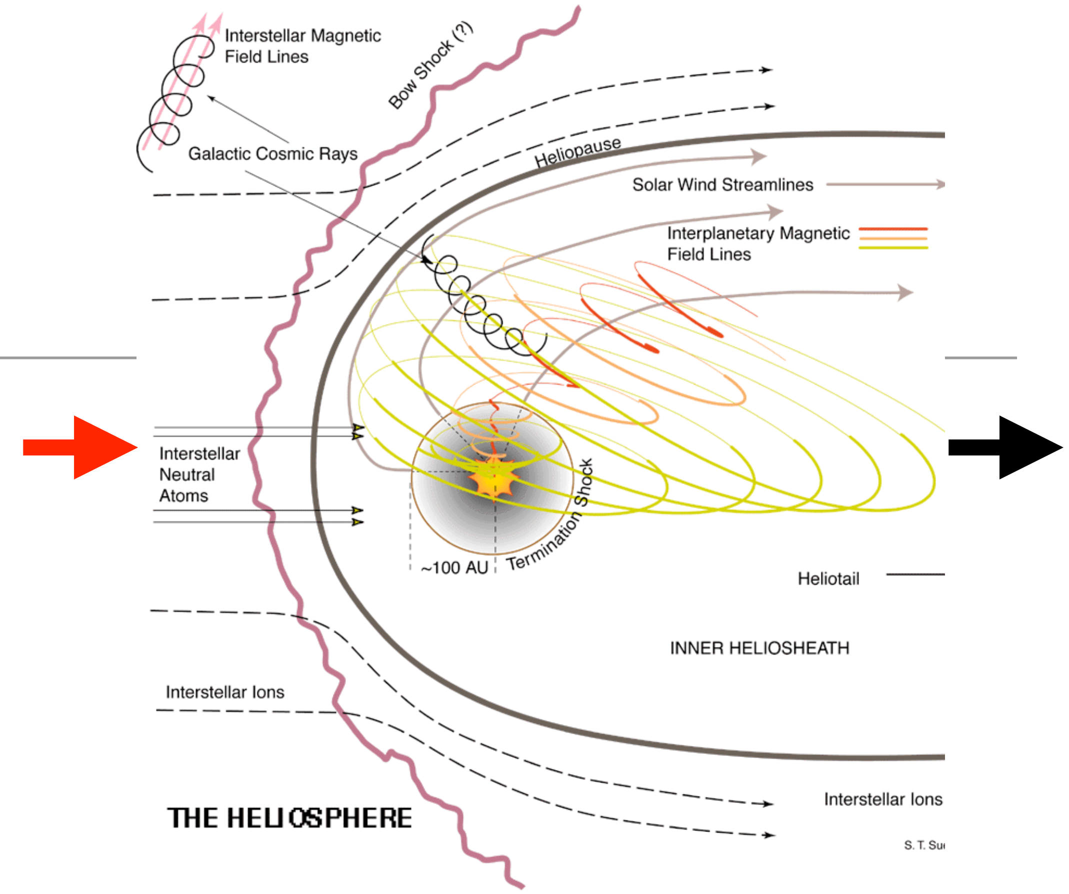
Abbasi et al., ApJ, **740**, 16, 2011

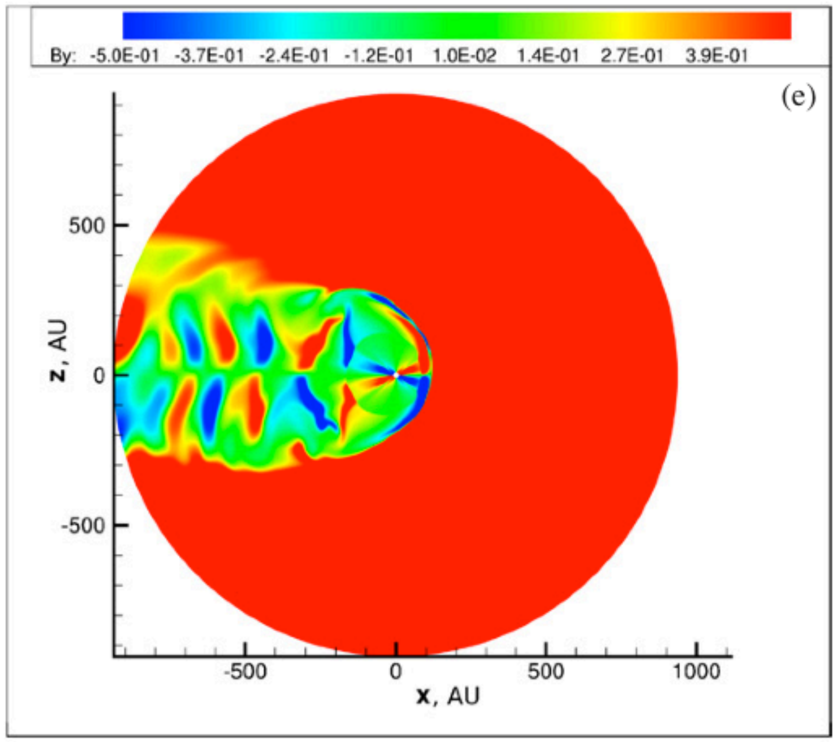


cosmic ray anisotropy
heliospheric influence

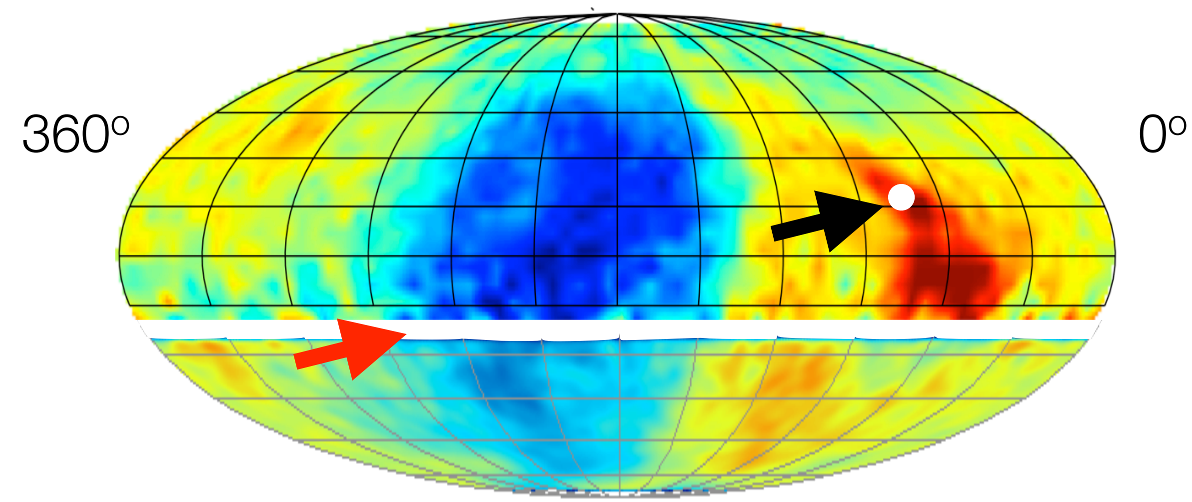


Izmodenov+ 2003





Pogorelov+ 2009



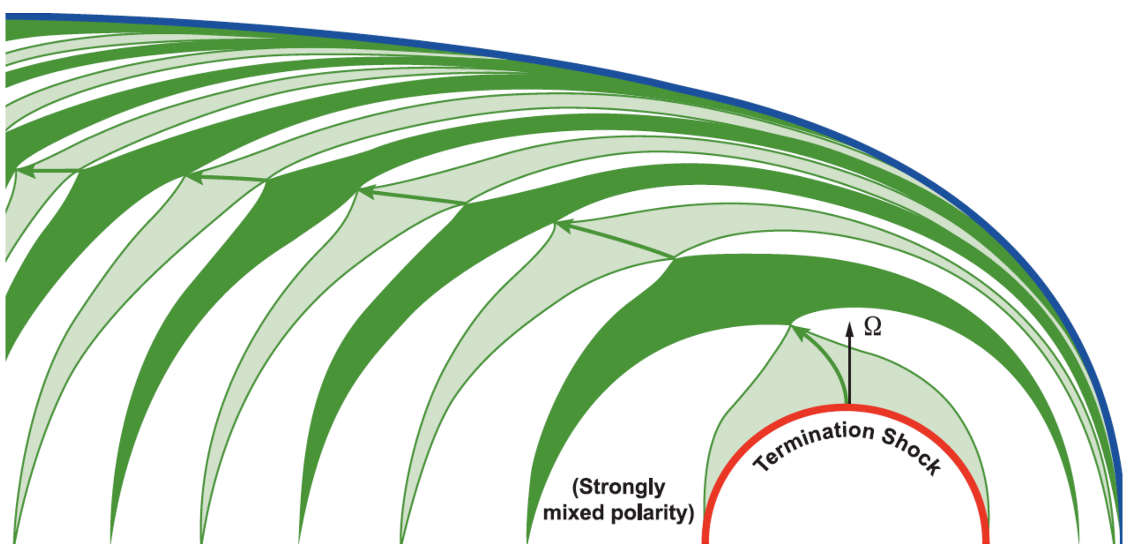
heliospheric size of O(100-10,000) AU influences cosmic rays up to O(10-100) TeV

heliospheric perturbations
solar cycles

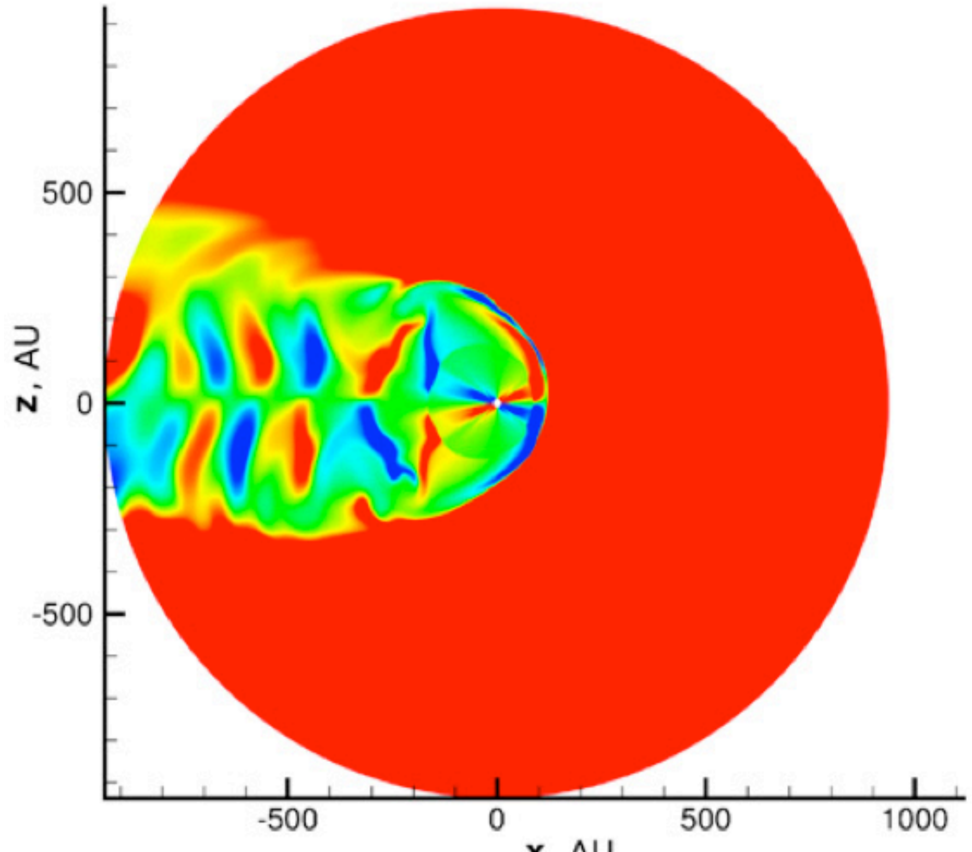
- solar wind modulated over a solar cycle, affecting heliospheric dynamics

Zank & Müller 2003
Pogorelov+ 2009
Washimi+ 2011, 2012

- complex heliotail structure shaped by solar cycles

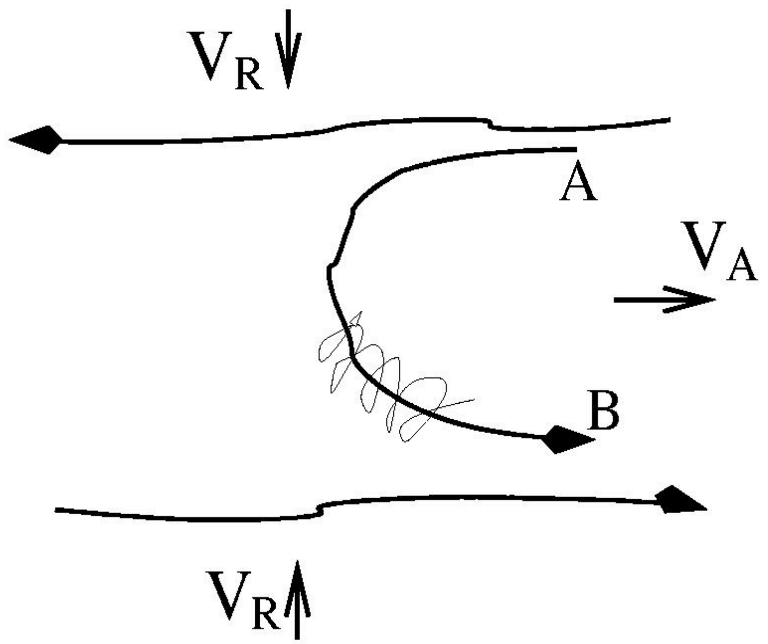


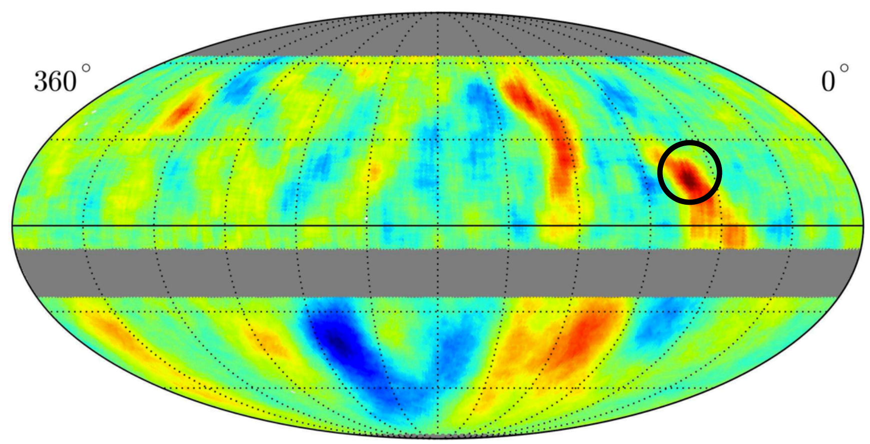
Nerney & Suess 1995



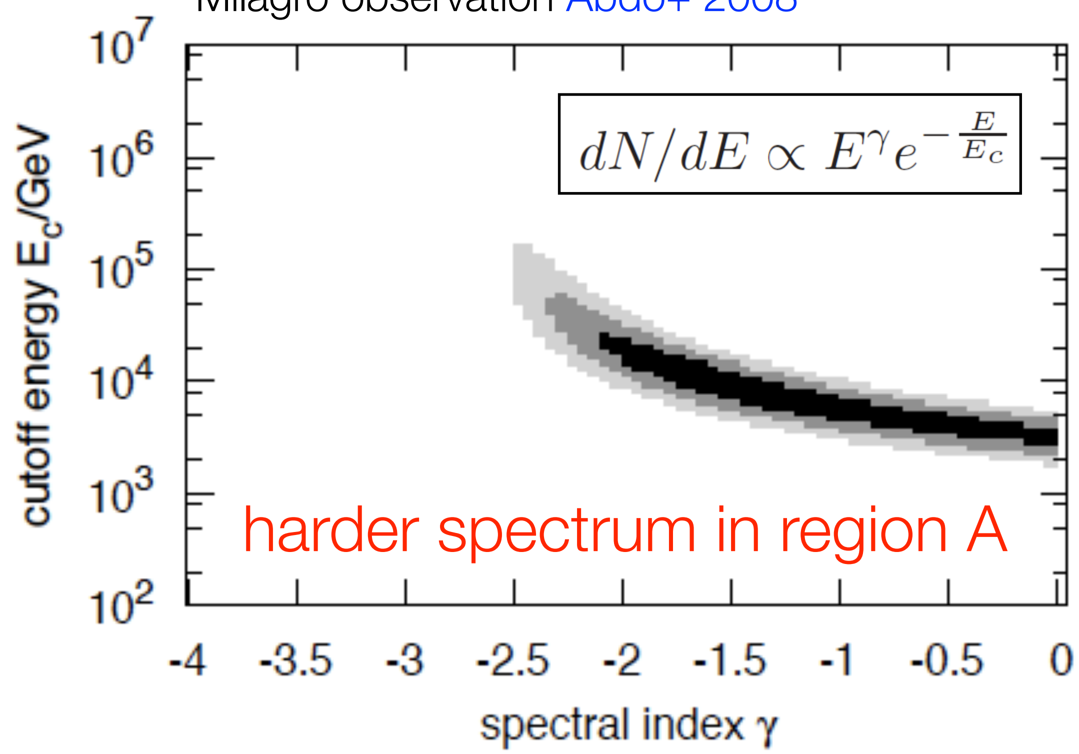
3D simulation of heliosphere/heliotail Pogorelov+ 2009

cosmic ray anisotropy & acceleration
stochastic magnetic reconnection





Milagro observation Abdo+ 2008



turbulent reconnection Lazarian & Vishniac 1999

1st order Fermi acceleration de Gouveia dal Pino & Lazarian 2003, 2005

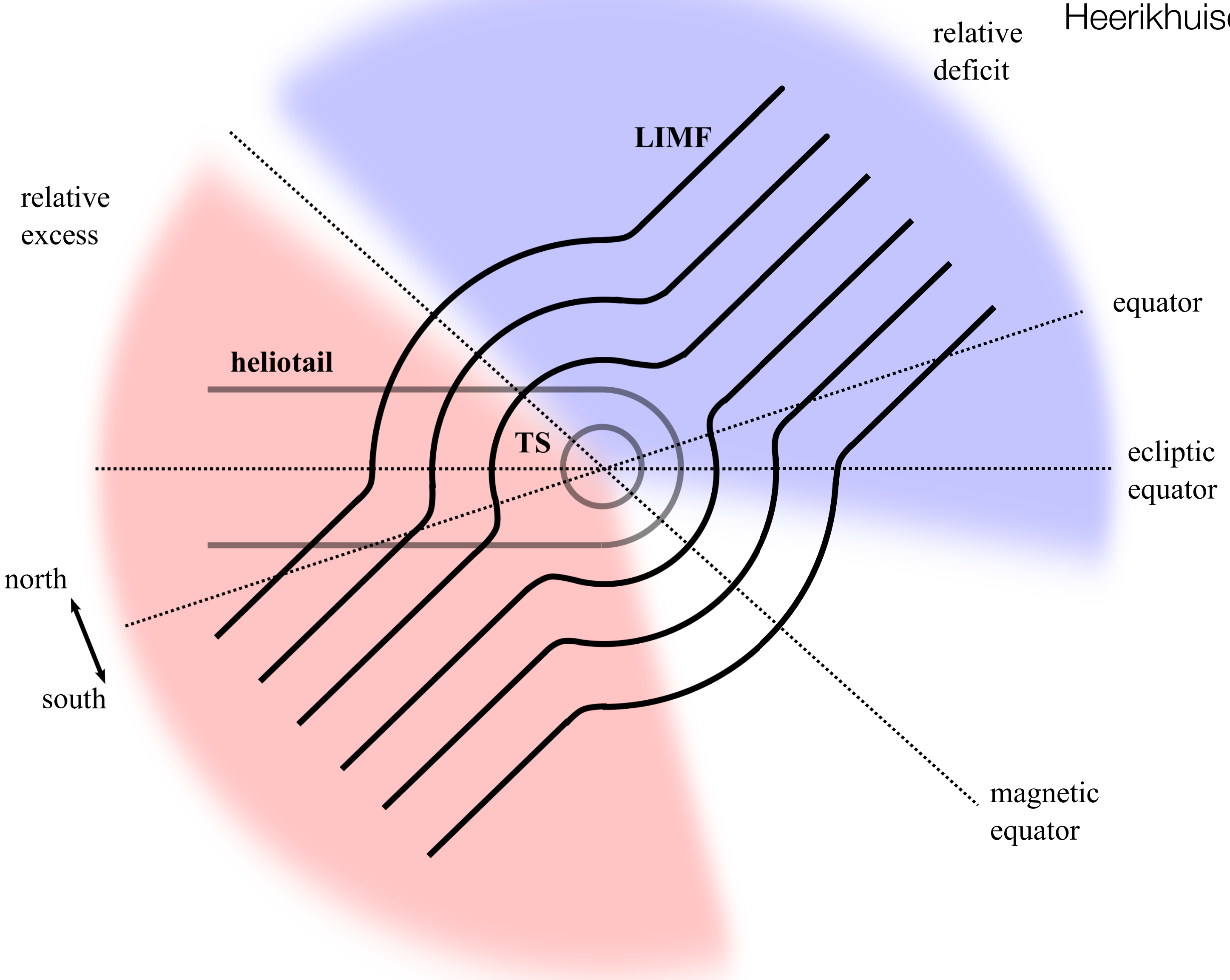
$$E_{max} \approx 0.5 \left(\frac{B}{1\,\mu G}\right) \left(\frac{L_{zone}}{100\,AU}\right) TeV \approx 0.5 - 6\,TeV$$

Lazarian, PD 2010 - PD, Lazarian 2012

- detailed modeling of heliotail very important

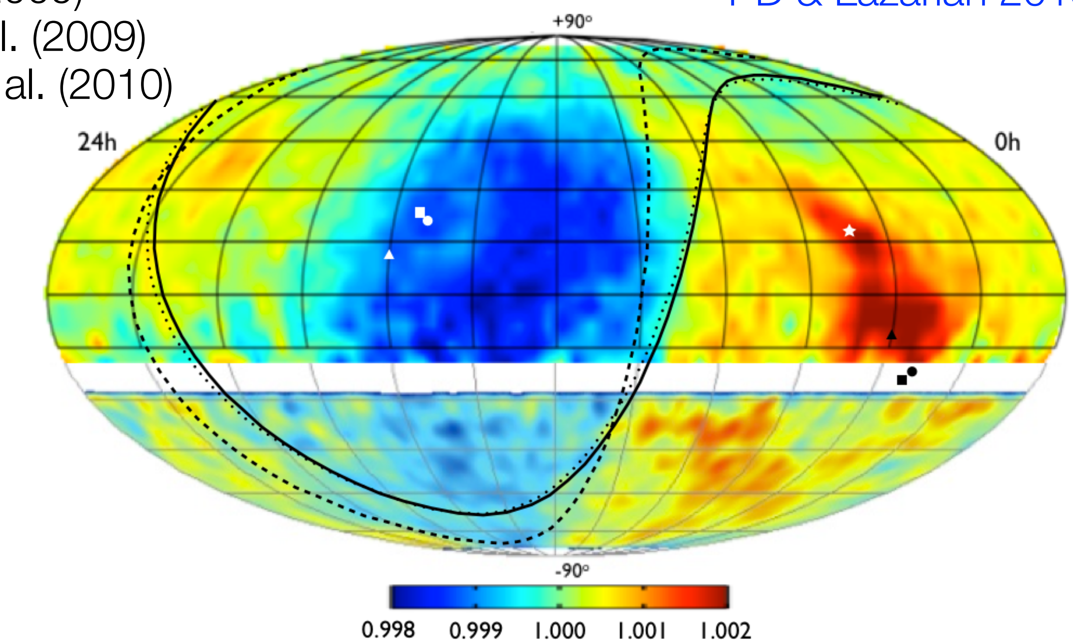
$\gamma < \gamma_{elsewhere}$ at 4.6 σ level
E_C = 3 - 25 TeV

cosmic ray anisotropy & scattering
heliospheric perturbations



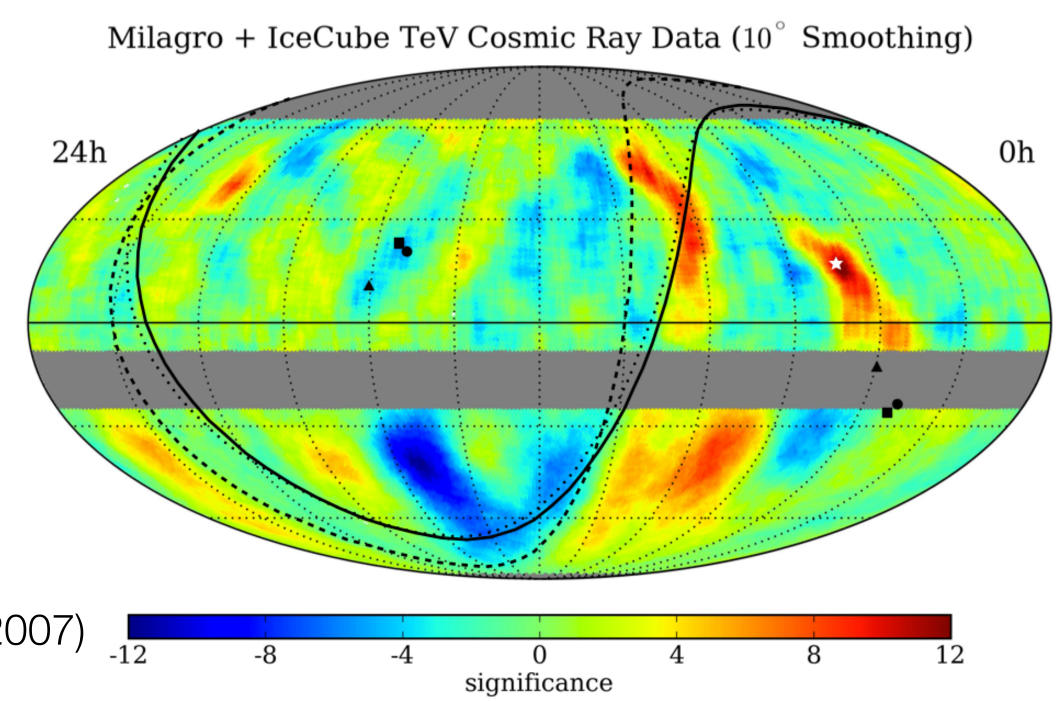
Funsten et al. (2009)
Schwadron et al. (2009)
Heerikhuisen et al. (2010)

PD & Lazarian 2013



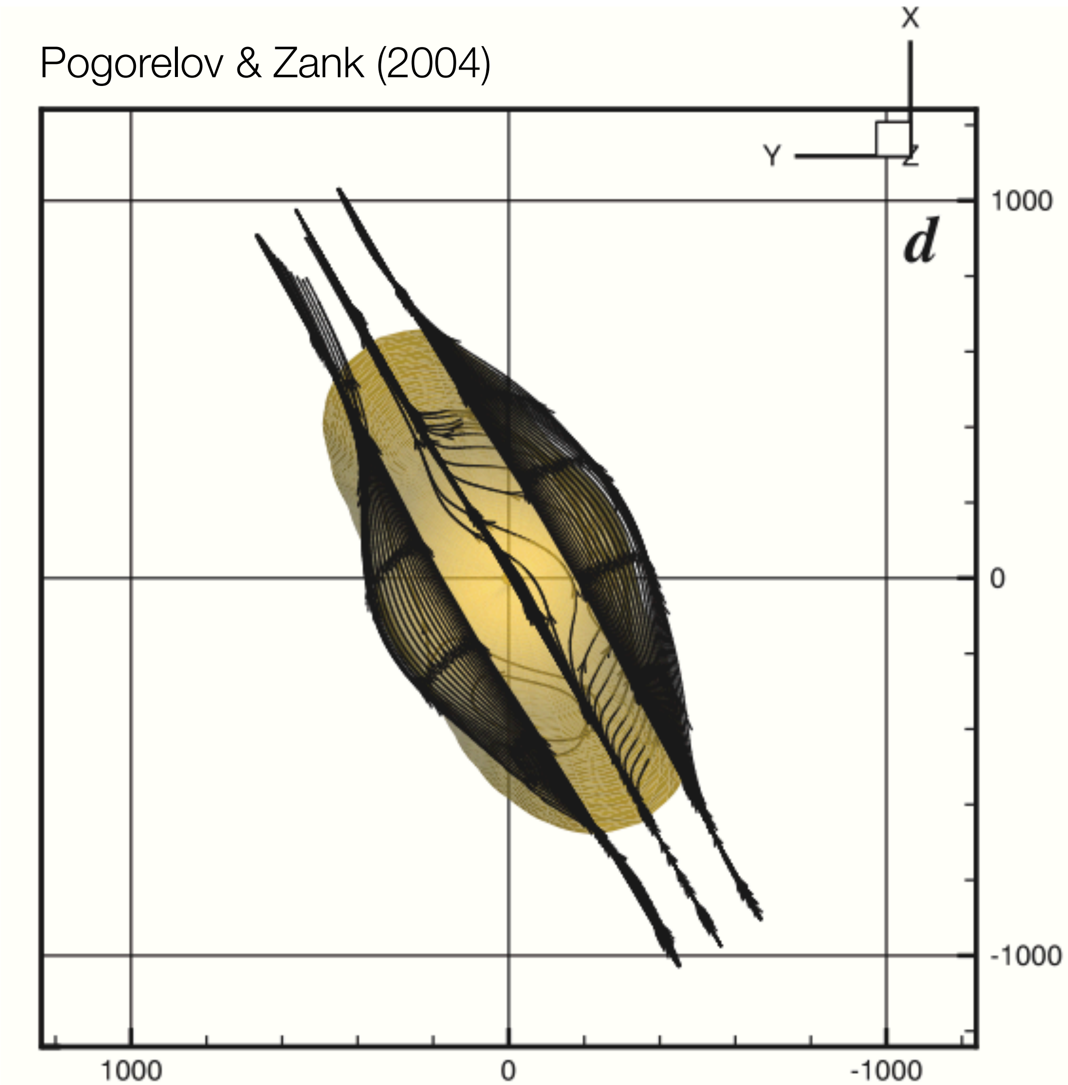
equatorial coordinates

magnetic
equator

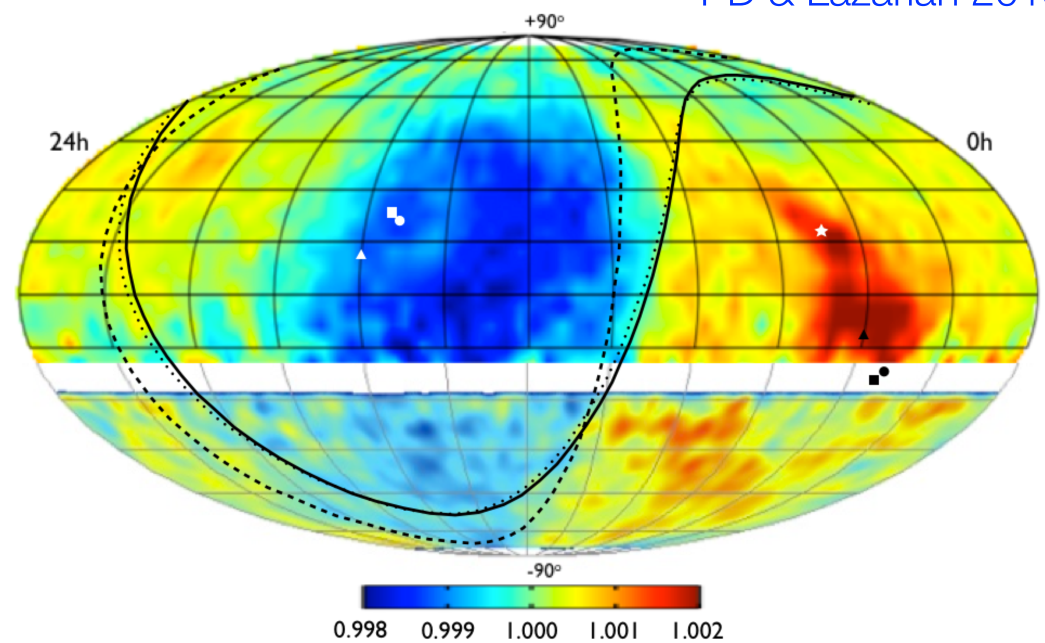


LIMF direction compatible with
- Ca II absorption & H I lines, Frisch (1996)
- radio emission from inner heliosheath, Lallement et al. (2005), Opher et al. (2007)
- polarization measurements, Frisch (2010)

cosmic ray anisotropy & scattering
heliospheric perturbations

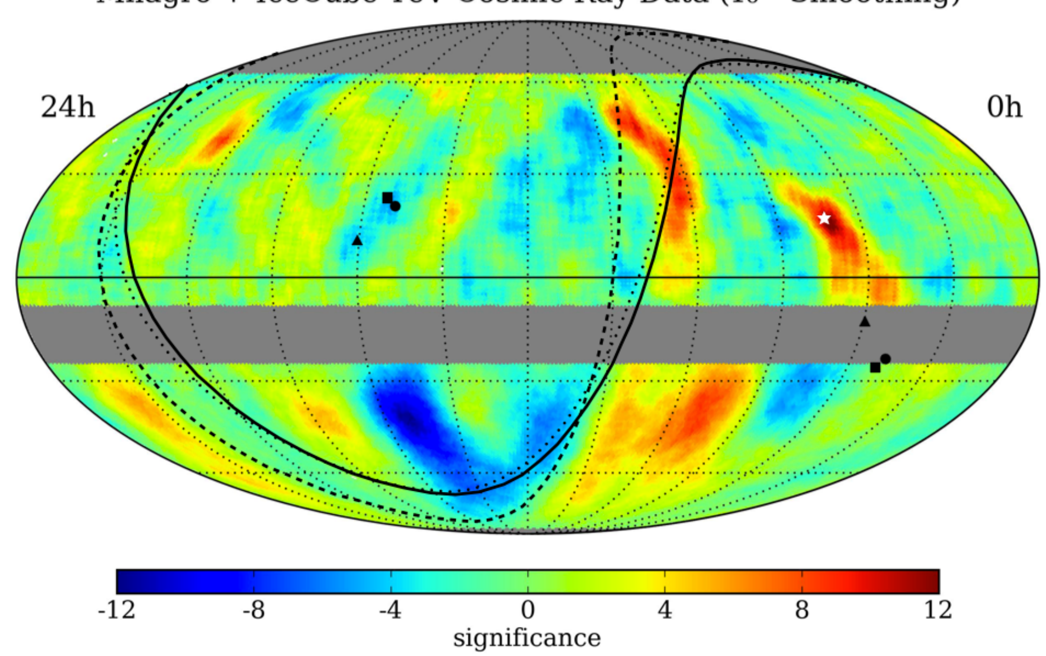


PD & Lazarian 2013

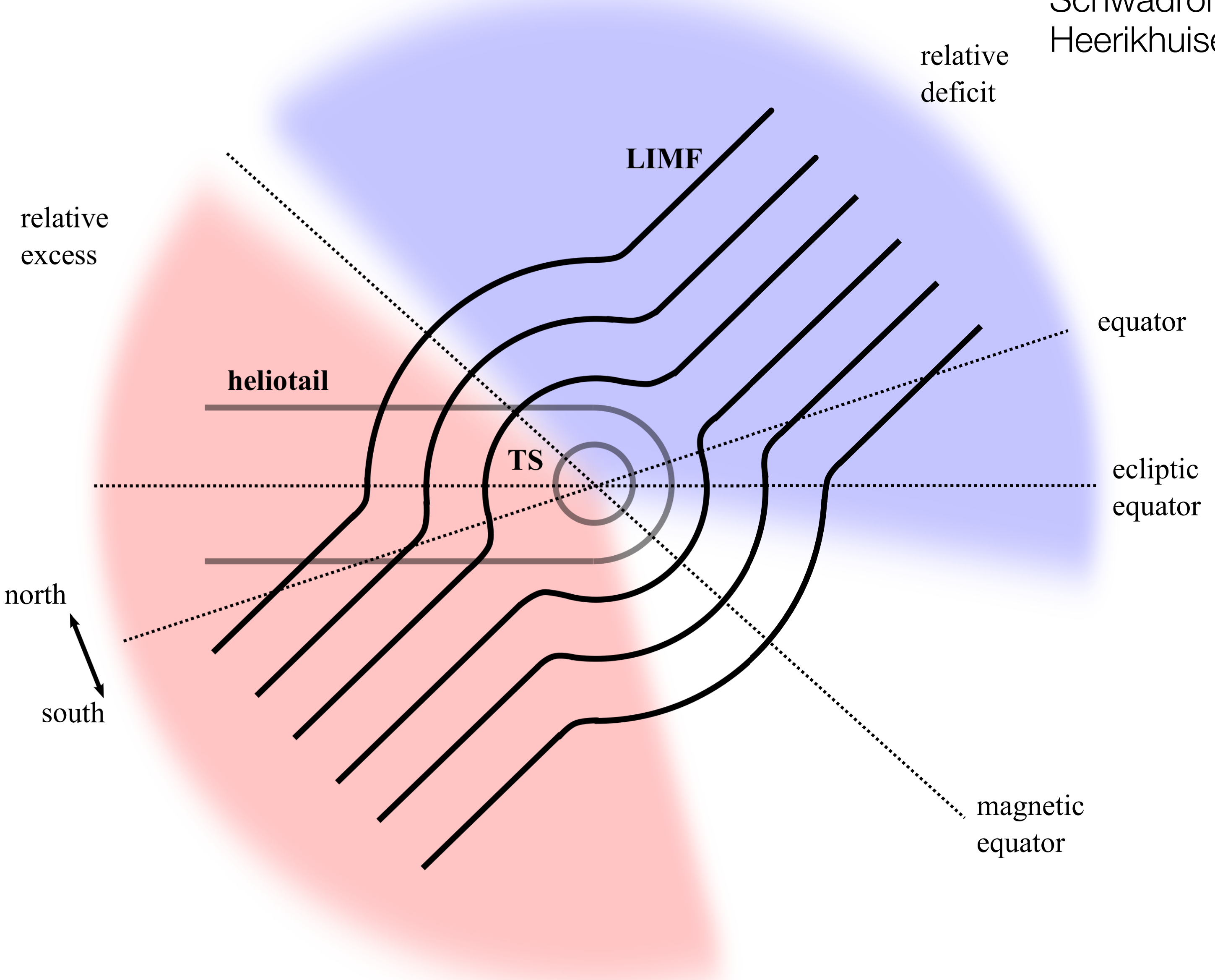


equatorial coordinates

magnetic equator

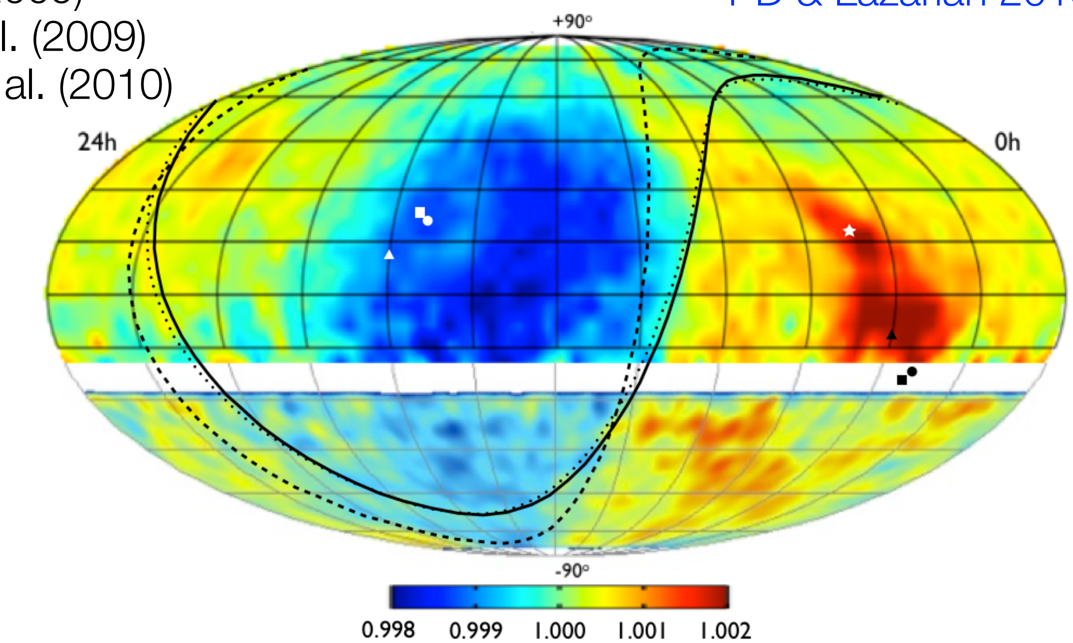


cosmic ray anisotropy & scattering
heliospheric perturbations



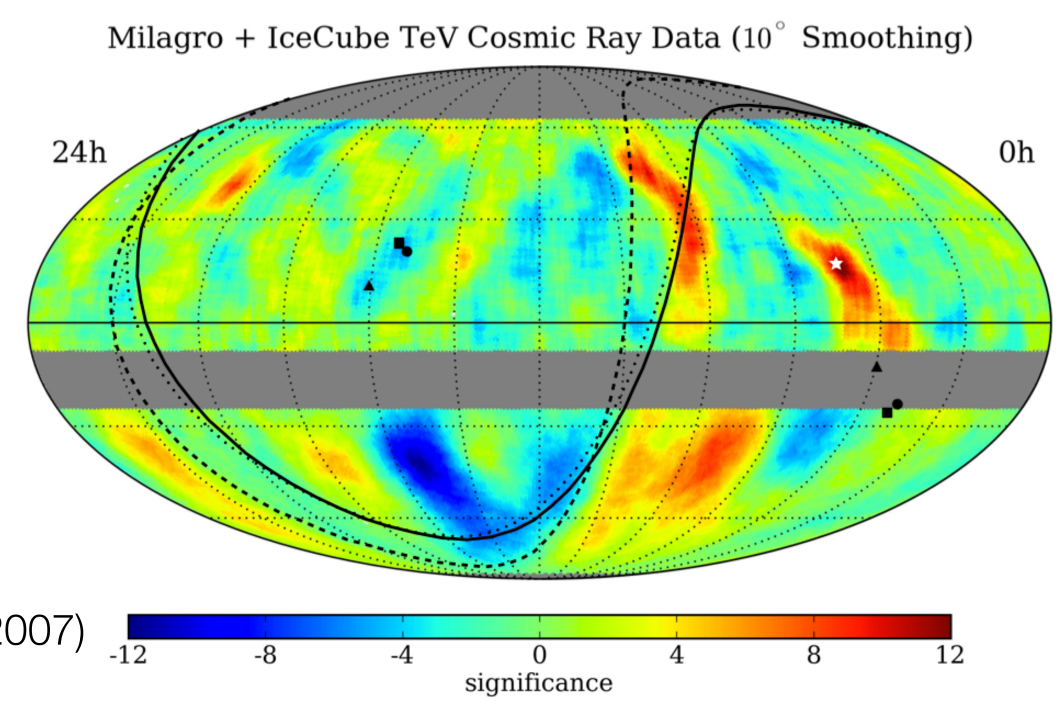
Funsten et al. (2009)
Schwadron et al. (2009)
Heerikhuisen et al. (2010)

PD & Lazarian 2013



equatorial coordinates

magnetic equator



LIMF direction compatible with

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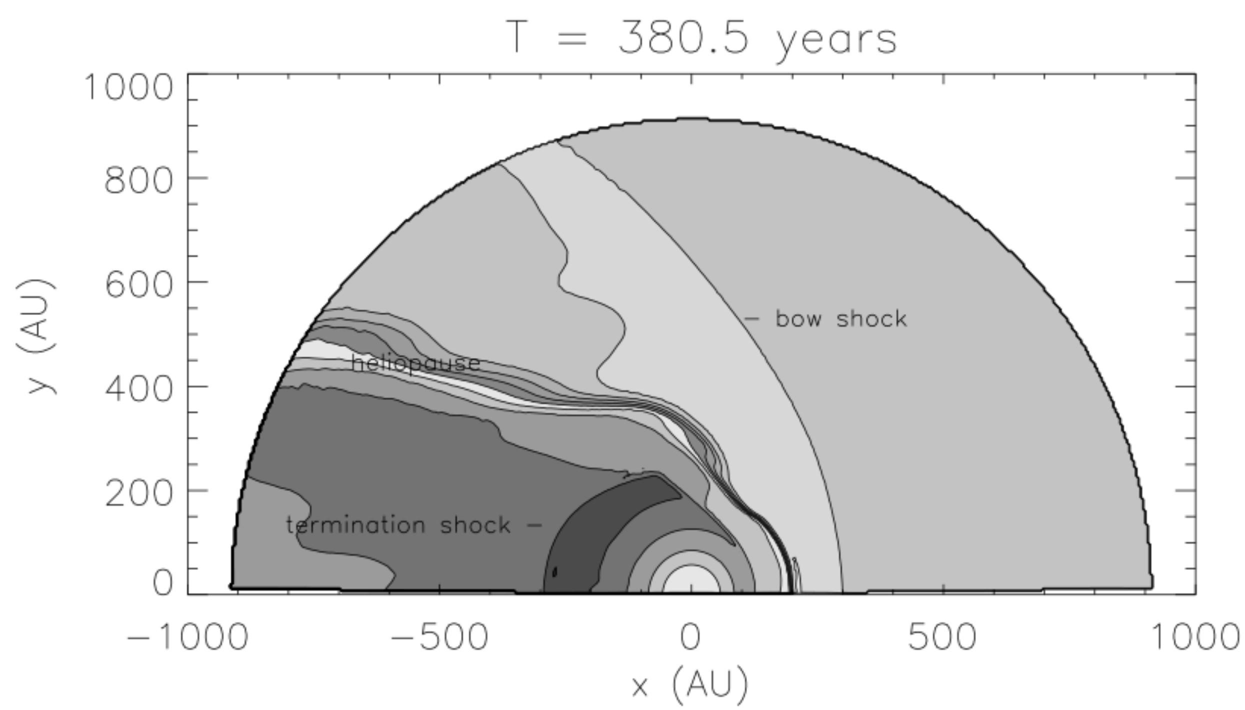
- polarization measurements, Frisch (2010)

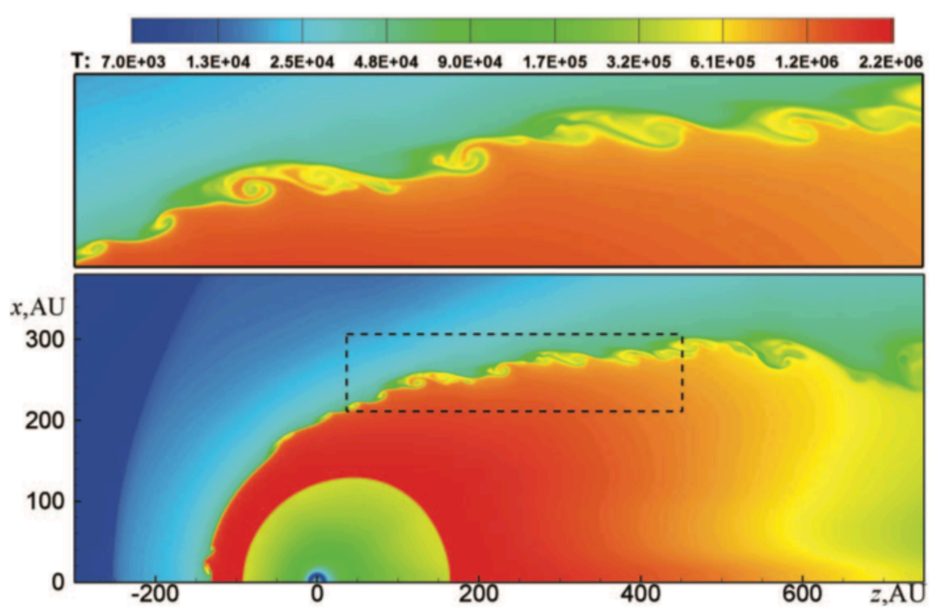
heliospheric perturbations instabilities

- Rayleigh-Taylor instabilities driven and mediated by interstellar neutral atoms



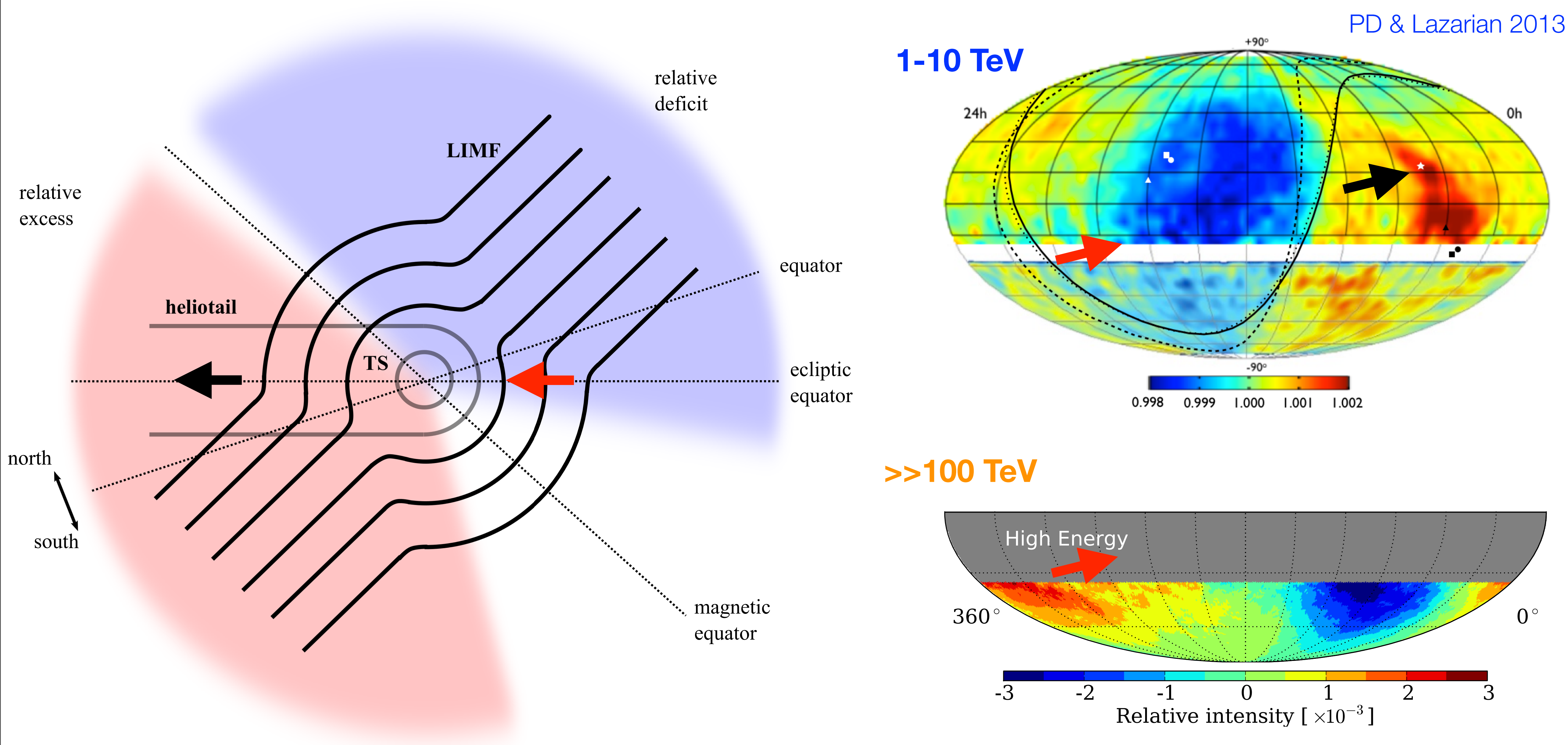
Liewer+ 1996
Zank+ 1996

- plasma-fluid instabilities at the flank of HP by charge exchange processes



Zank 1999
Florinski++ 2005
Borovikov+ 2008
Zank 2009
Shaikh & Zank 2010

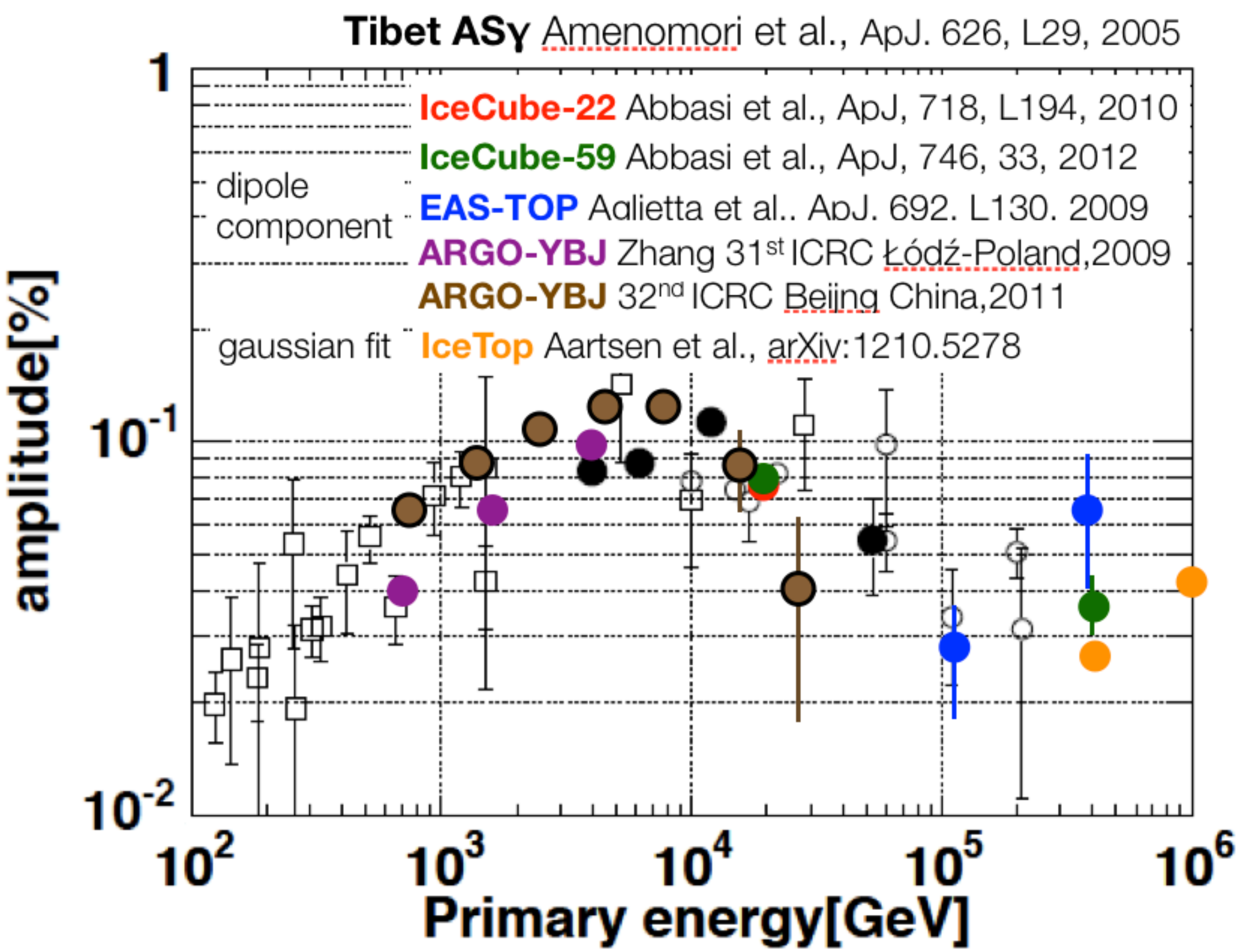
cosmic ray anisotropy
influence of perturbed heliotail



anisotropy re-directed due to *scattering* on magnetic perturbations on the heliospheric boundary

scattering on heliospheric boundary
toy model

- @ energy scale of 10 TeV - proton resonant scattering with perturbations at largest scale - scrambling of cosmic ray arrival directions



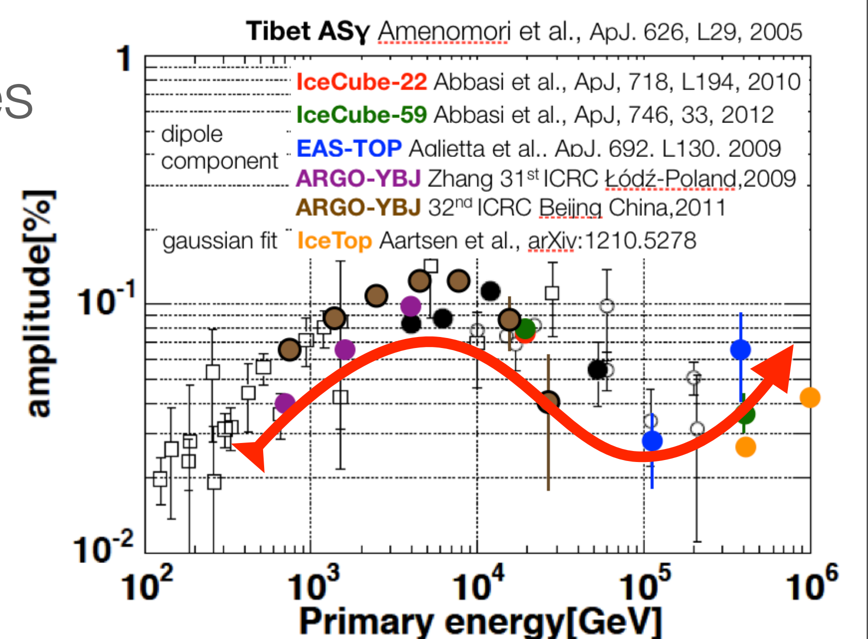
scattering on heliospheric boundary
toy model

- @ energy scale of 10 TeV - proton resonant scattering with perturbations at largest scale - scrambling of cosmic ray arrival directions

- < 10 TeV - resonant scattering with smaller scale perturbations - pitch angle variations from $p^2_\perp/B$ at larger scale

- > 10 TeV - non-resonant scattering with smaller scales - amplitude decreases, intensity gradient become smoother

- > 100 TeV - r_L > heliosphere - heliospheric influence dissipates

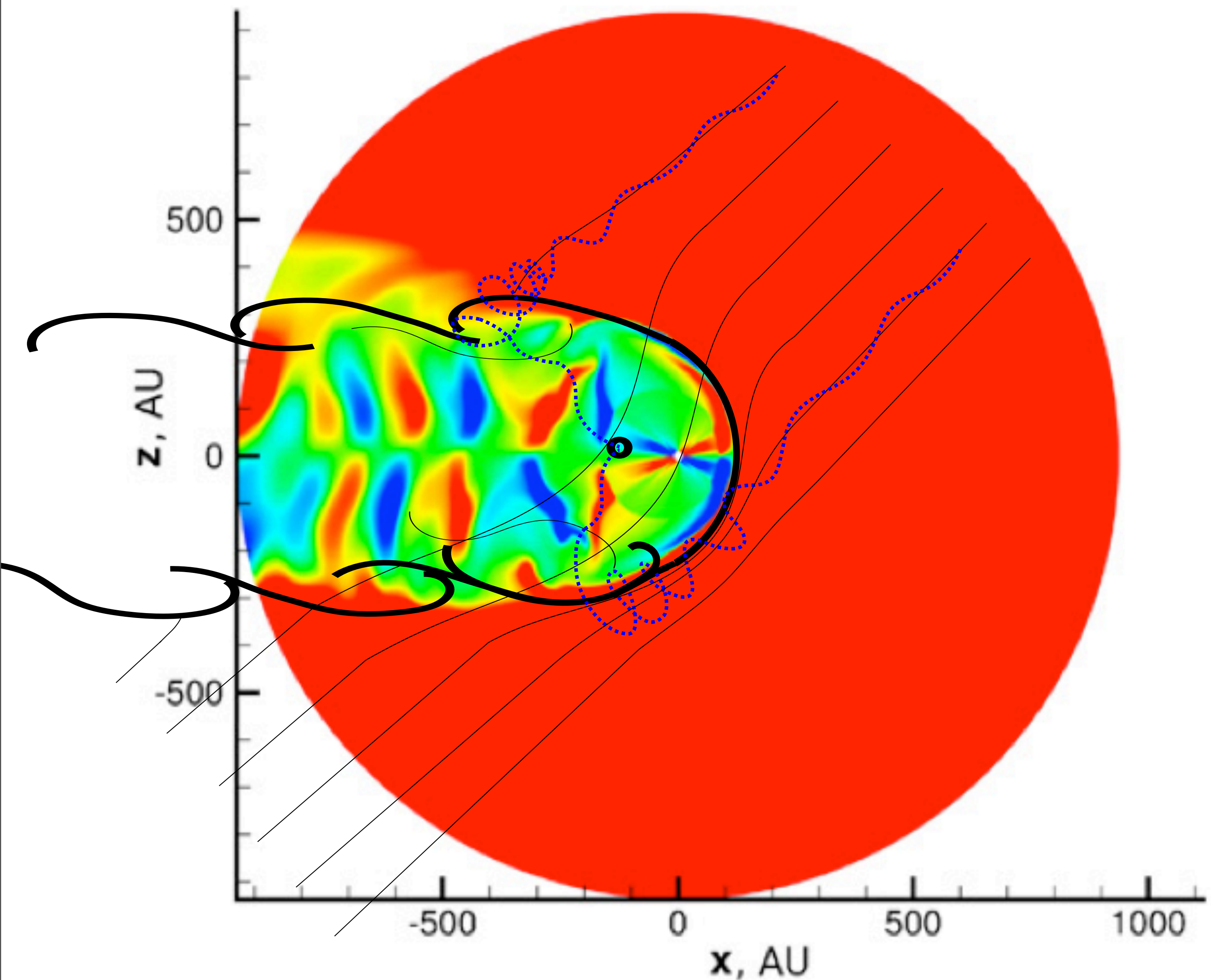


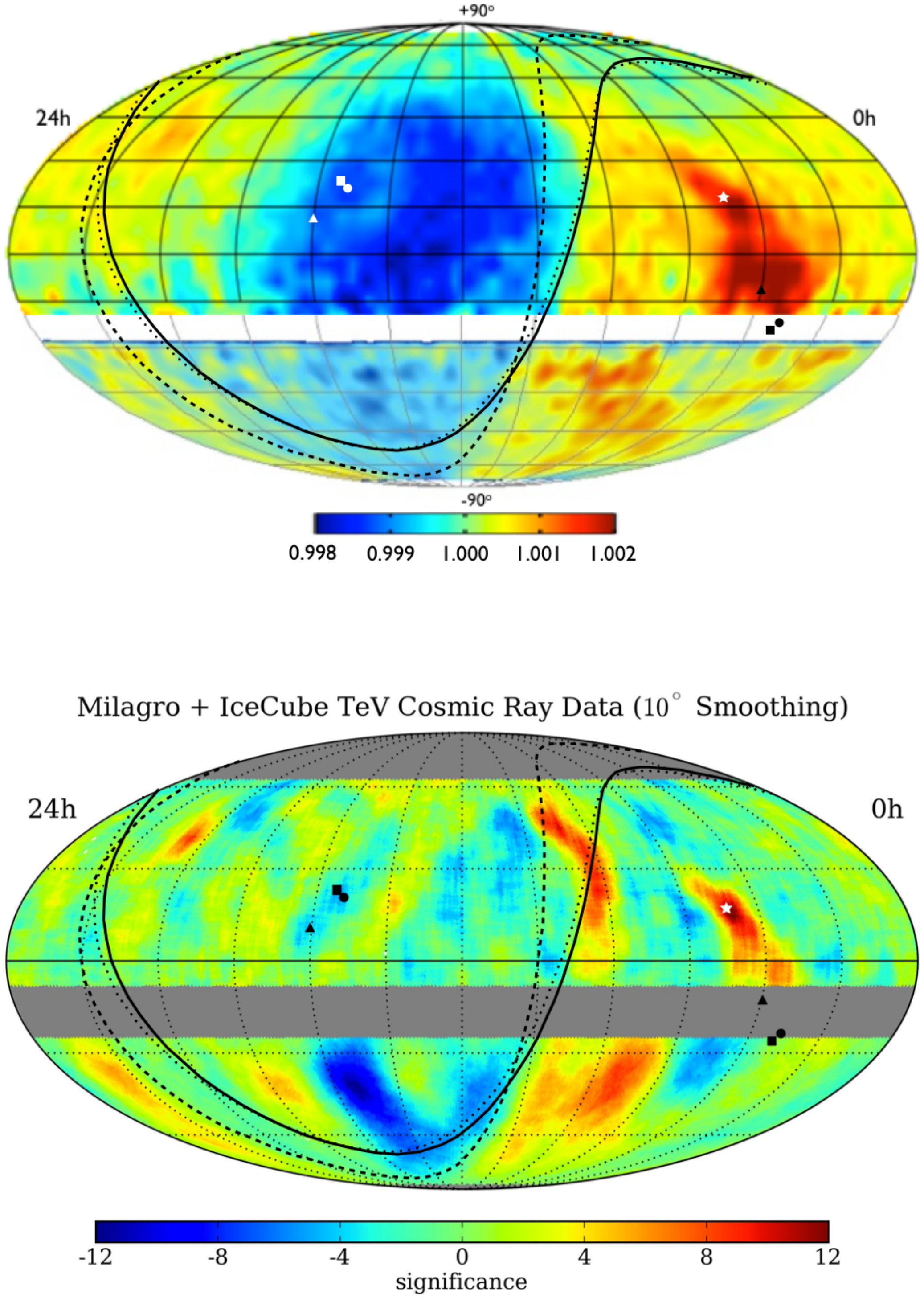
- CR mass composition - smearing of transition scale

- re-directed anisotropy not a dipole

scattering on heliospheric boundary
toy model

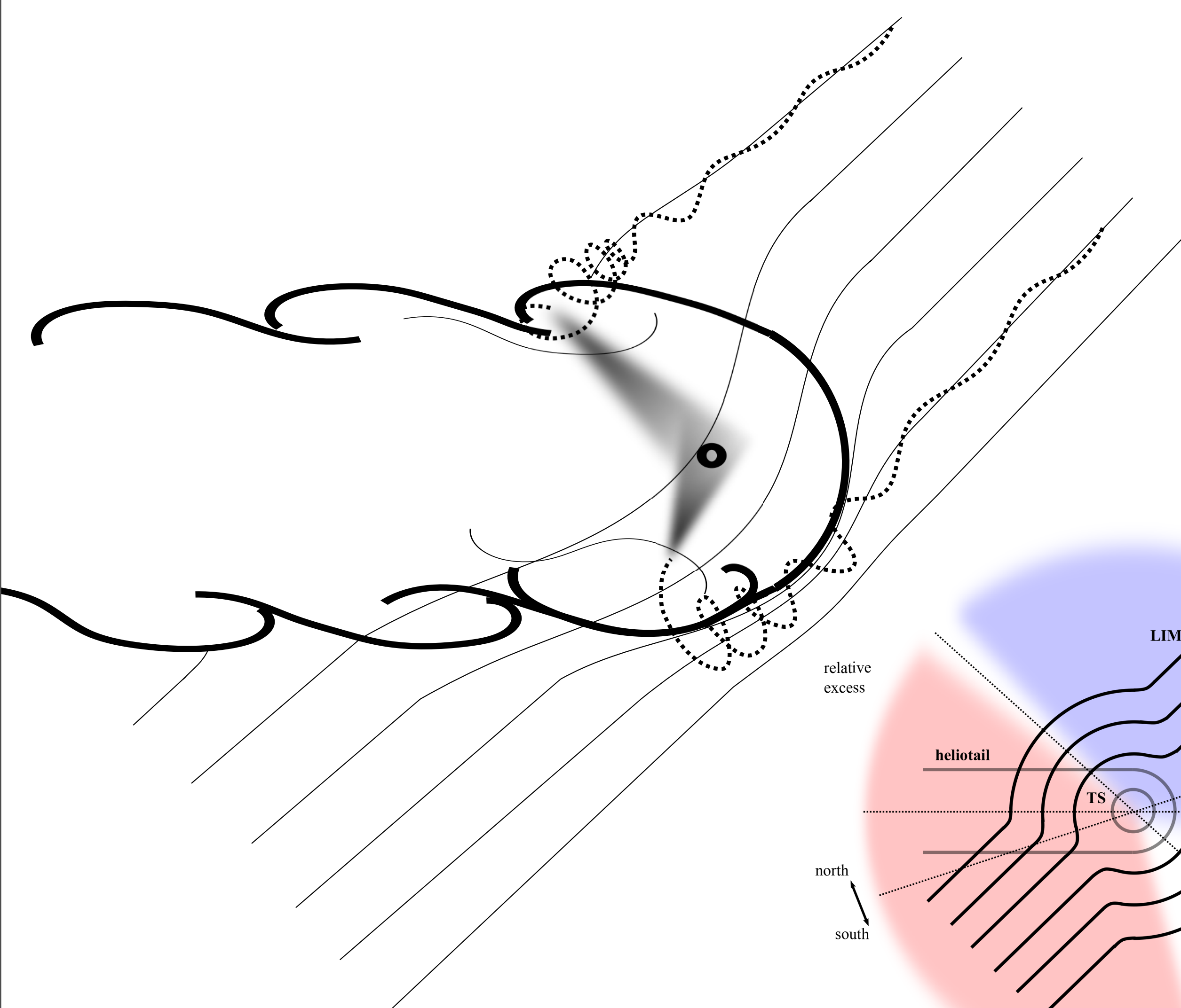
PD & Lazarian 2013

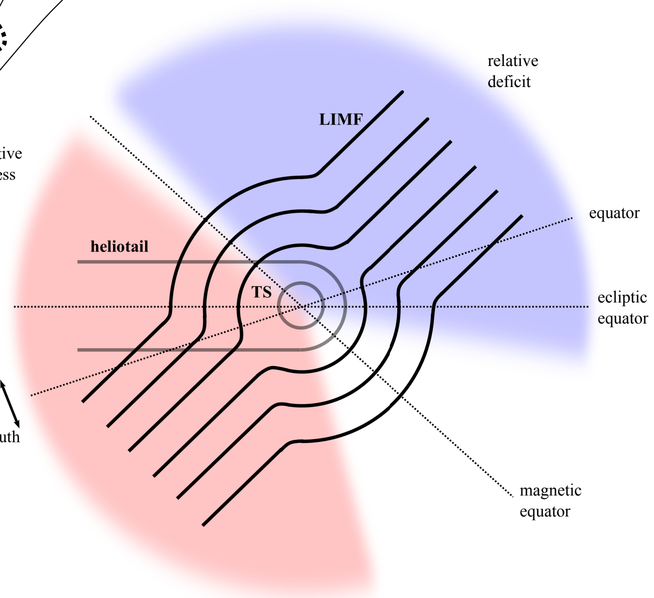


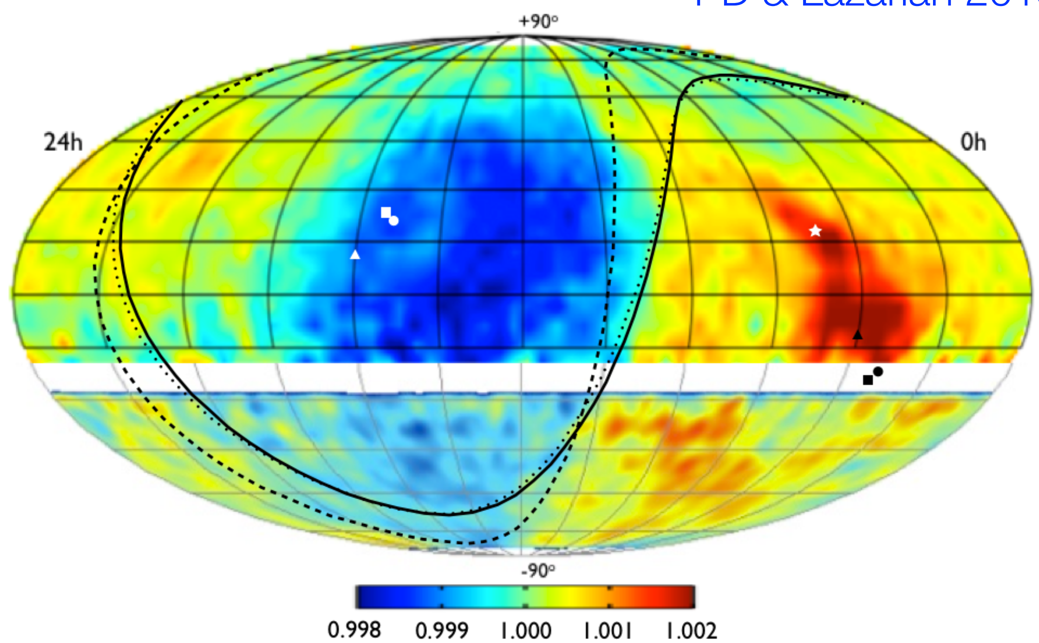


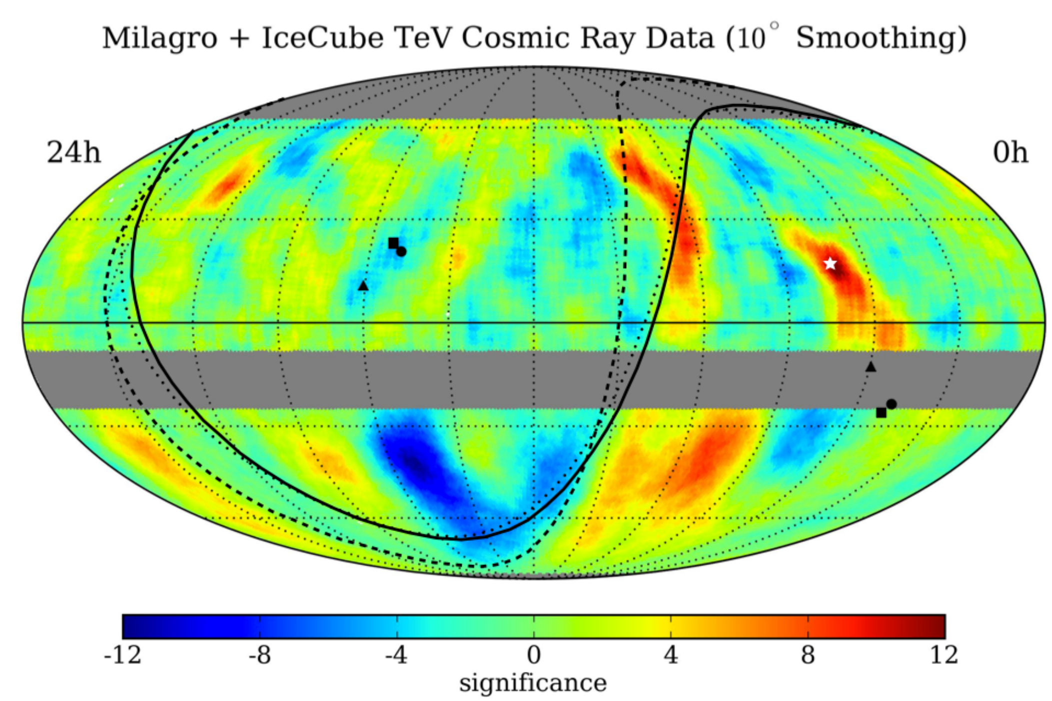
scattering on heliospheric boundary
toy model

PD & Lazarian 2013





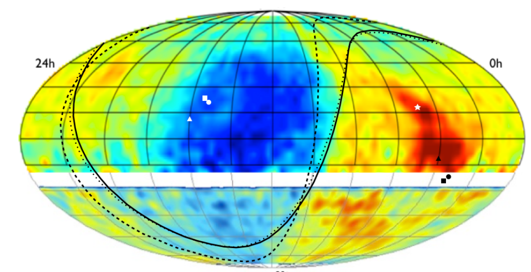


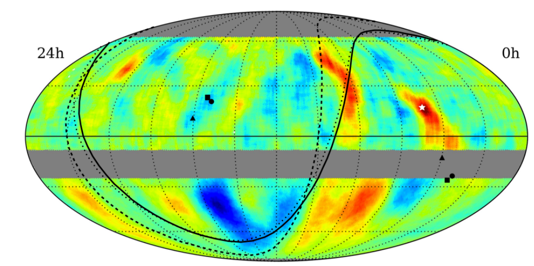


- detailed modeling of heliotail very important

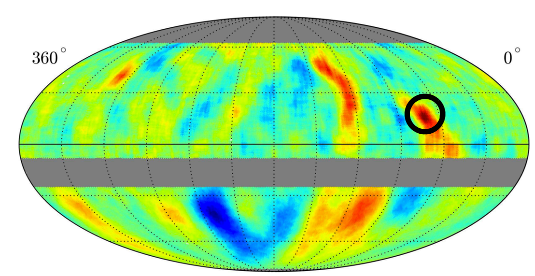
conclusions

- high energy **cosmic ray anisotropy** to probe into their **origin** and **propagation**
- astrophysical scenarios need understanding of local phenomena
- <100 TeV cosmic rays to be affected by heliosphere
- **scattering** with perturbation on heliopause



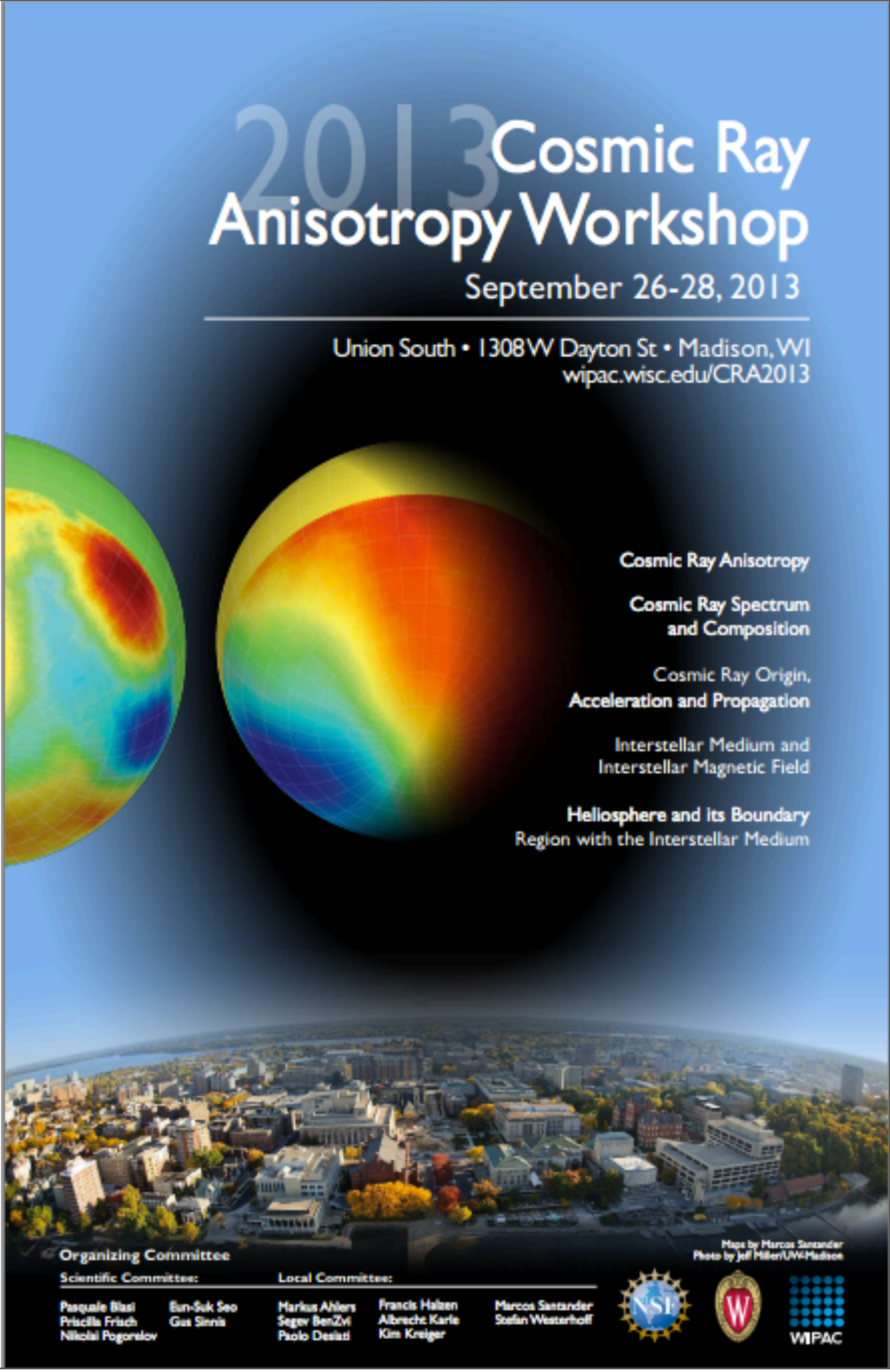


- **re-acceleration** mechanism from heliotail



‣ heliospheric modeling to be extended along **heliotail** with fine resolution: turbulence & global structure. Particle trajectory integration studies will follow → predictive model

thank you

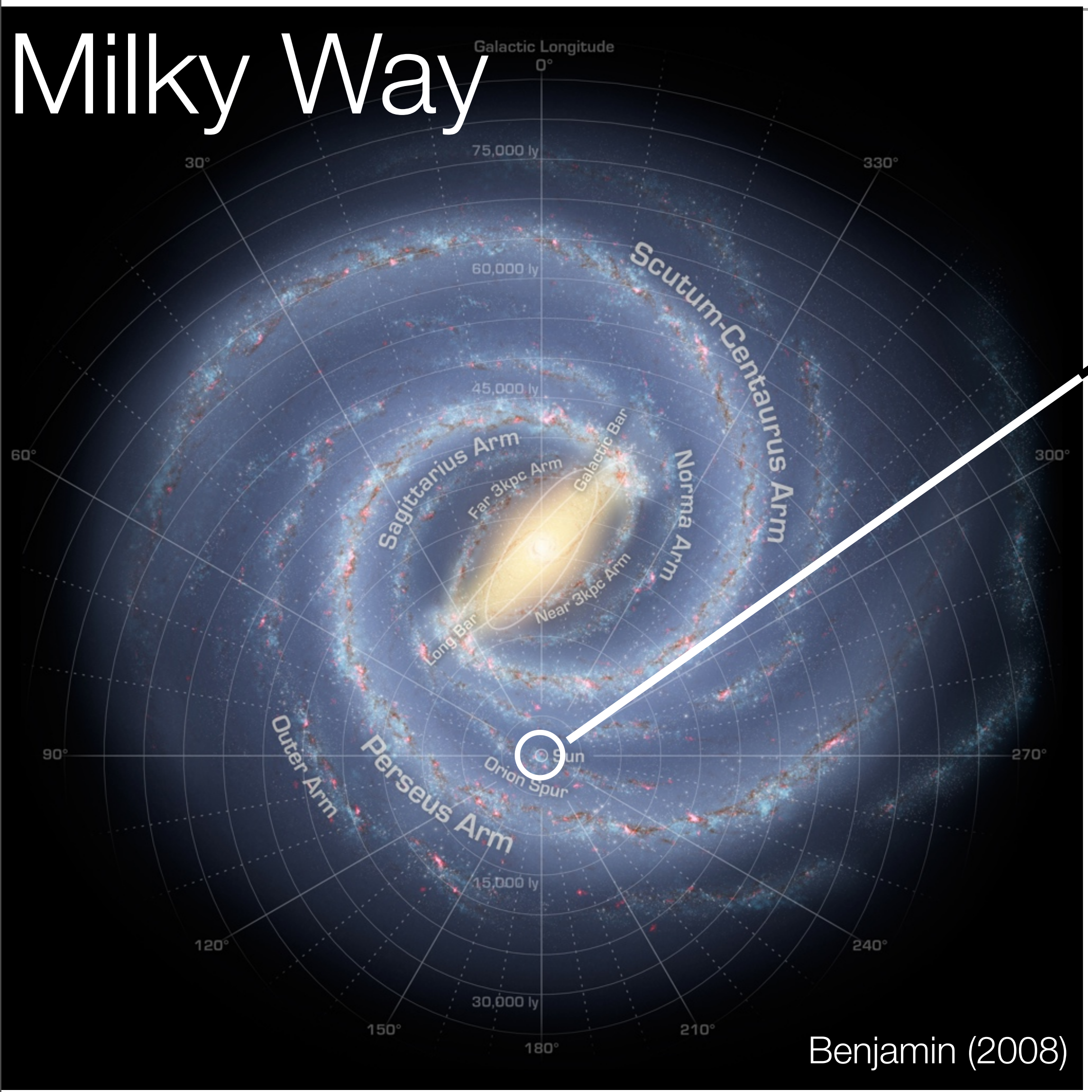


2013 Cosmic Ray Anisotropy Workshop
September 26-28, 2013
Union South • 1308 W Dayton St • Madison, WI
wipac.wisc.edu/CRA2013
Cosmic Ray Anisotropy
Cosmic Ray Spectrum and Composition
Cosmic Ray Origin, Acceleration and Propagation
Interstellar Medium and Interstellar Magnetic Field
Heliosphere and its Boundary Region with the Interstellar Medium
Maps by Marcos Santander
Photo by Jeff Miller/UW-Madison
Organizing Committee
Scientific Committee:
Pasquale Blasi
Priscilla Frisch
Nikolai Pogorelov
Eun-Suk Seo
Gus Sinnis
Local Committee:
Markus Ahlers
Segev BenZvi
Paolo Desiati
Francis Halzen
Albrecht Karle
Kim Kreiger
Marcos Santander
Stefan Westerhoff
NSF
WIPAC

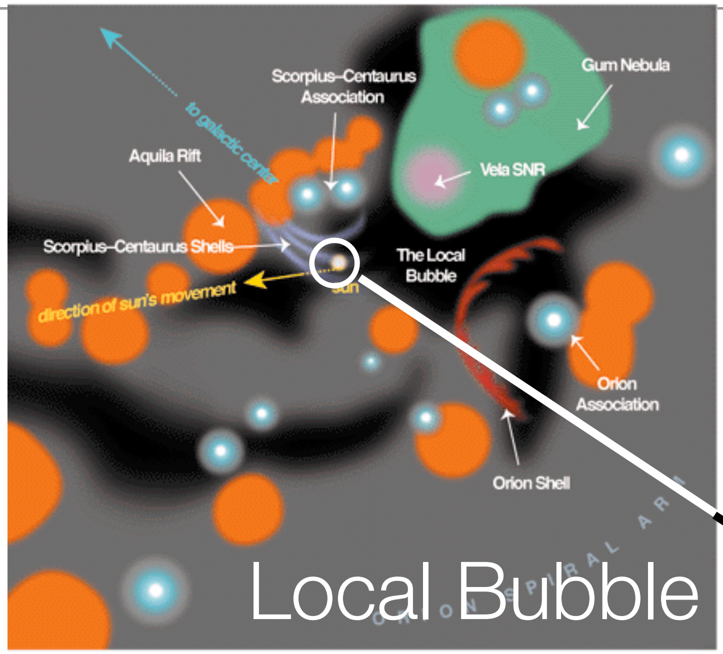
backup

$$R_g \approx \frac{200}{Z}\left(\frac{E}{1\,TeV}\right)\left(\frac{\mu G}{B}\right)\,AU$$

from the Galaxy to our local interstellar medium



< 30,000 pc > (80 EeV)

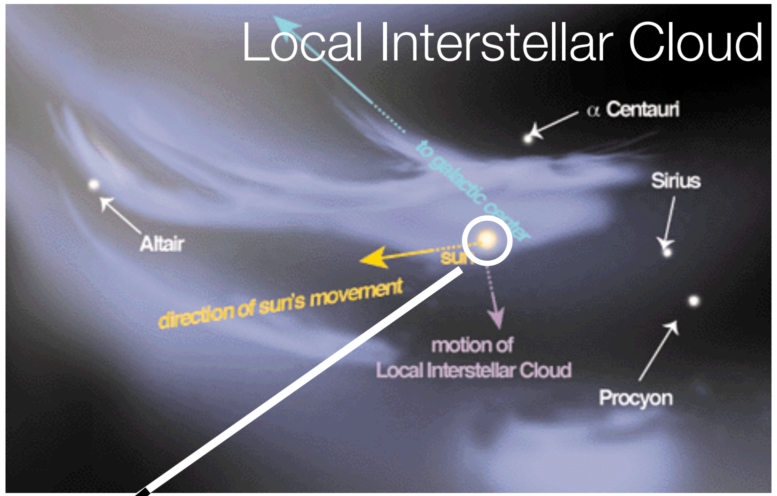


Frisch

molecular clouds diffuse gas

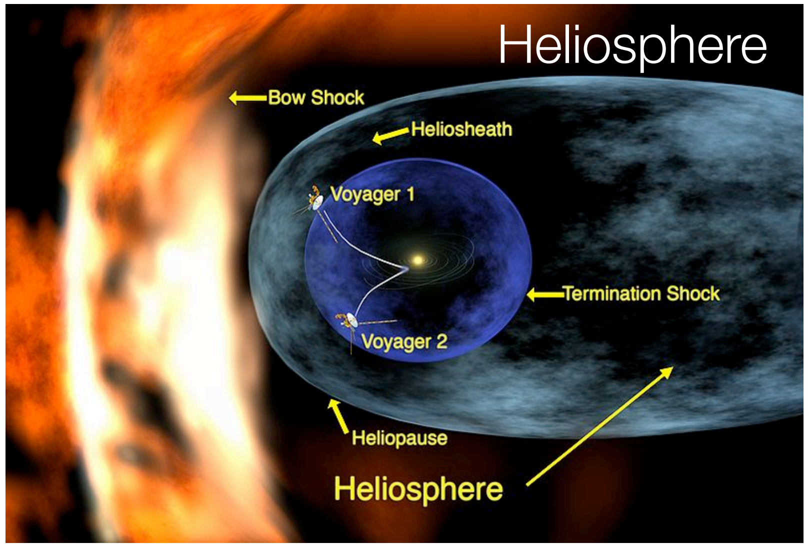
< 500 pc > (1.4 EeV)

Frisch



< 10-50 pc >

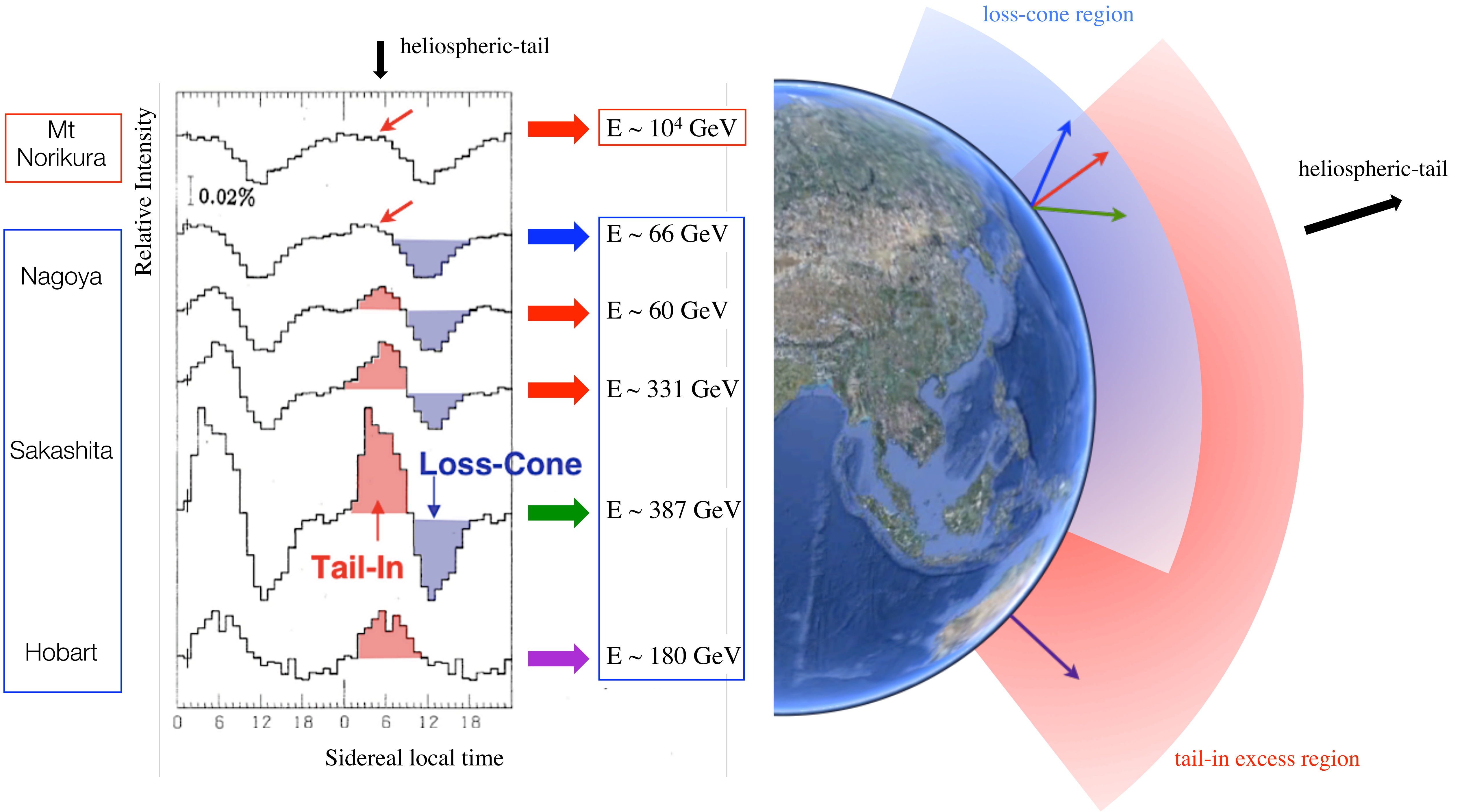
(30 PeV - 140 PeV)



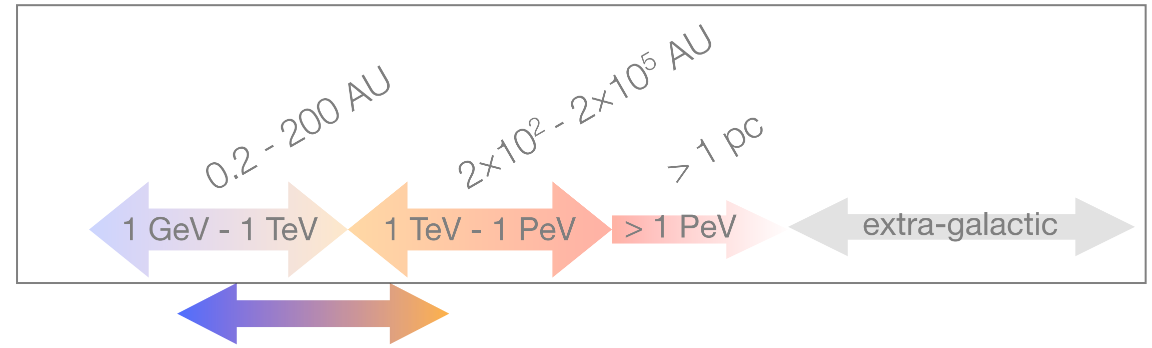
(3 TeV - 140 TeV) < 200 AU - 10^4 AU >

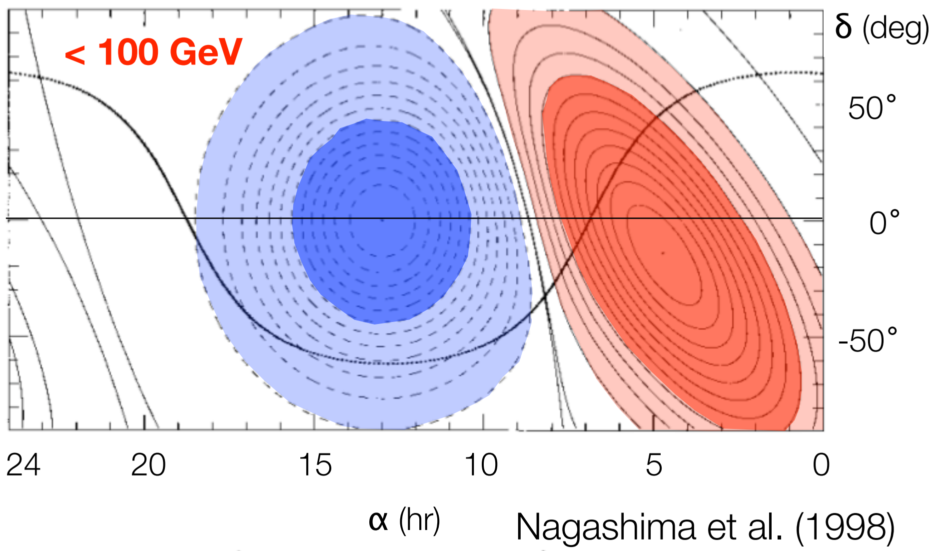
low energy cosmic ray anisotropy in arrival direction

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

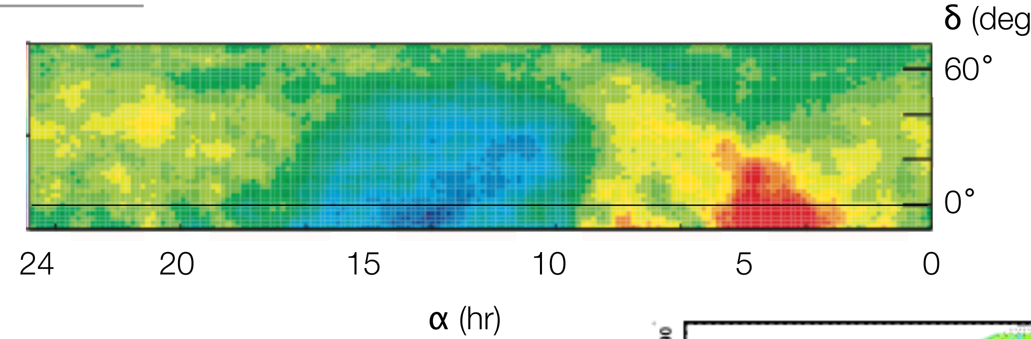


cosmic ray anisotropy

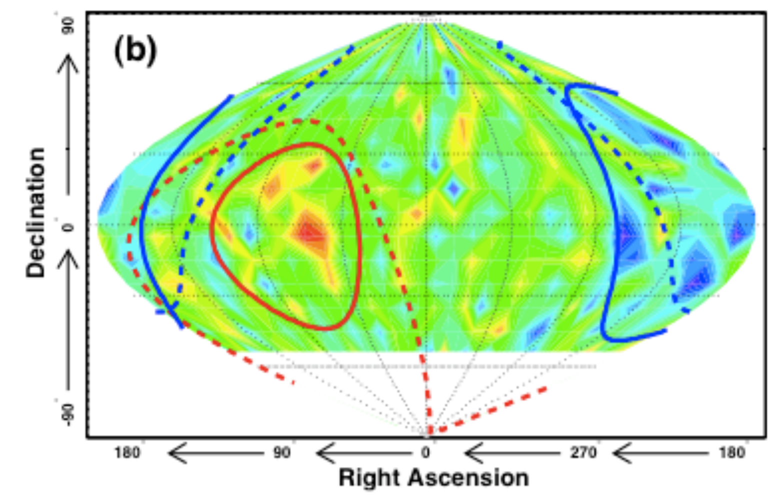




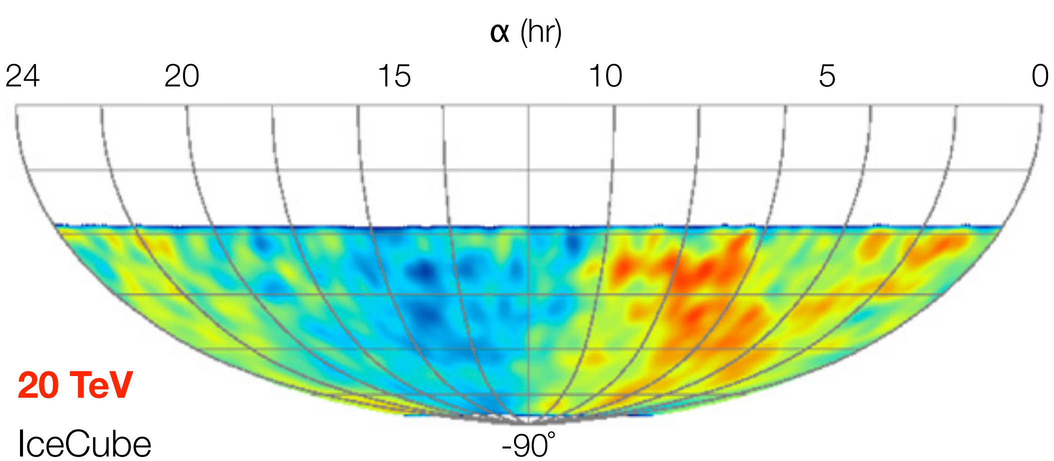
Nagashima et al. (1998)
Hall et al. (1999)



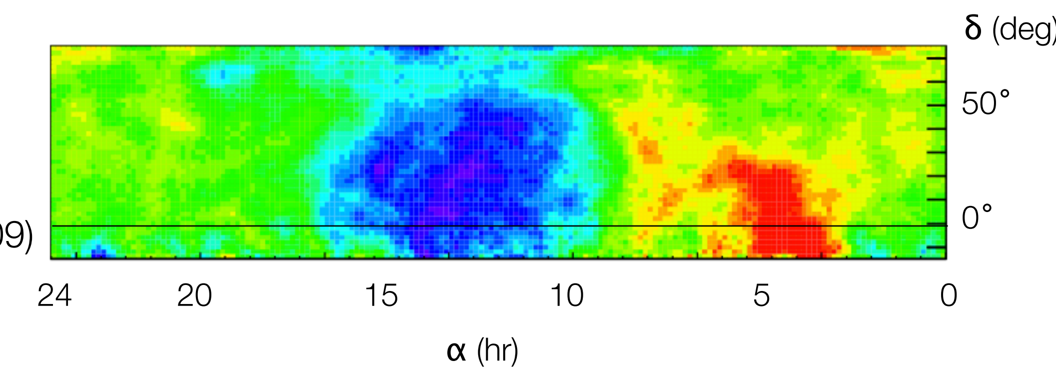
4 TeV
Tibet ASγ
Amenomori et al. (2006)



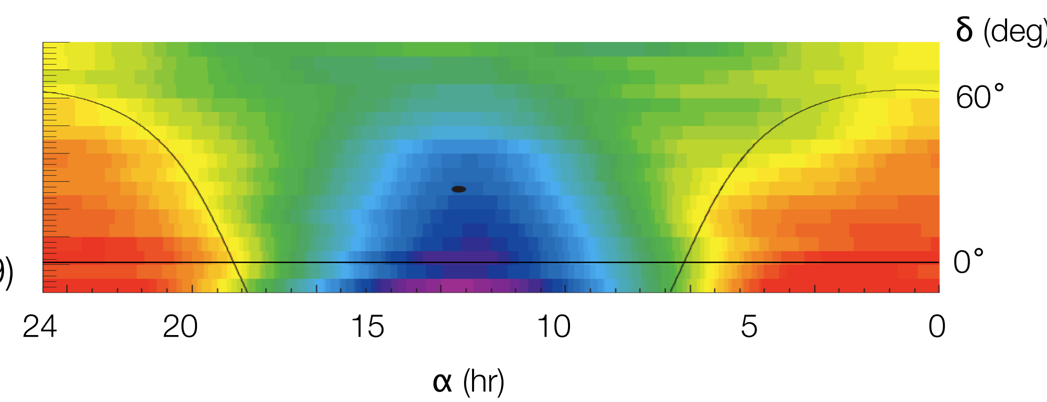
10 TeV
Super Kamiokande
Guillian et al. (2007)



20 TeV
IceCube
Abbasi et al. (2010)



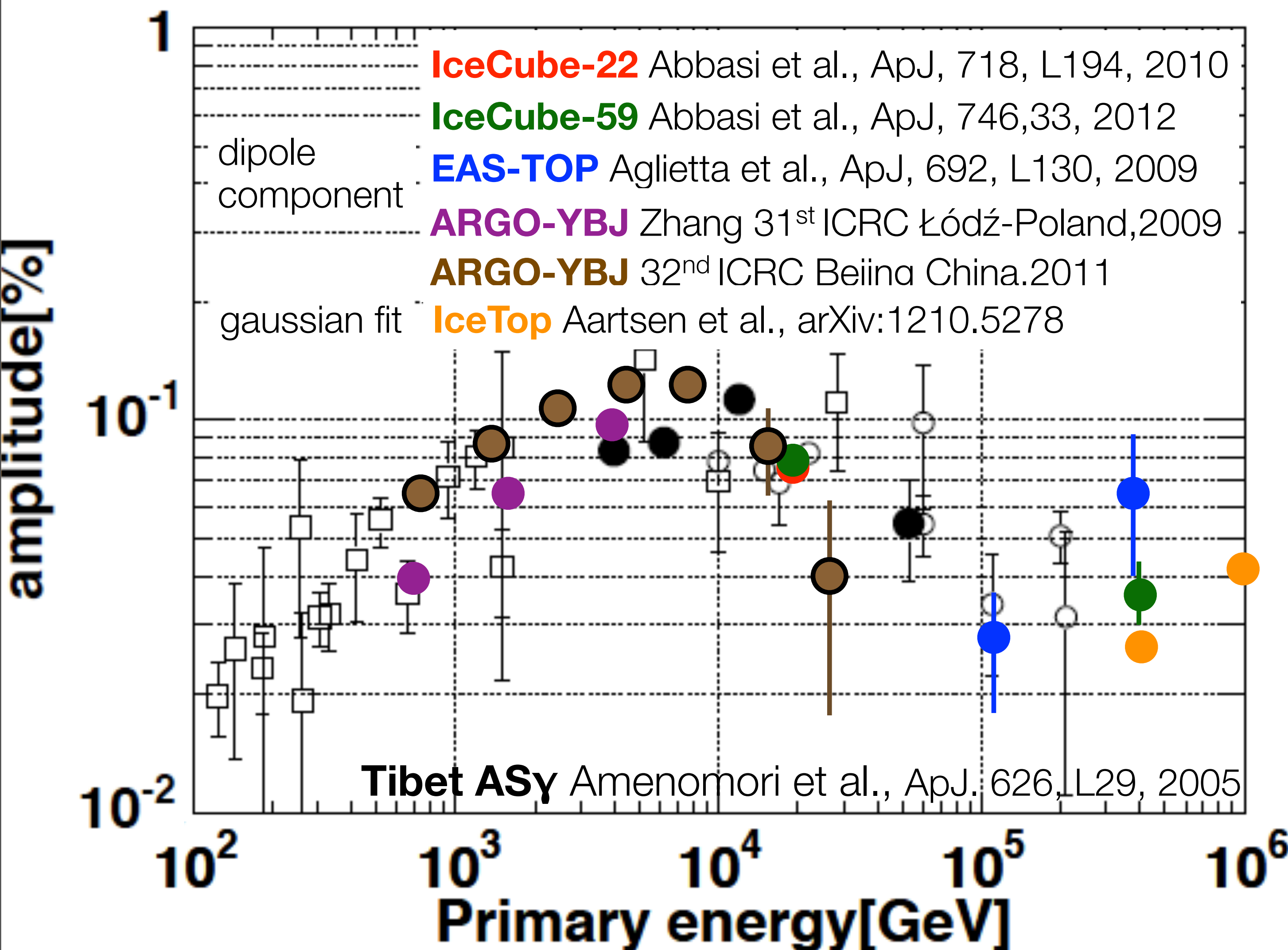
4 TeV
ARGO-YBJ
Zhang et al. (2009)

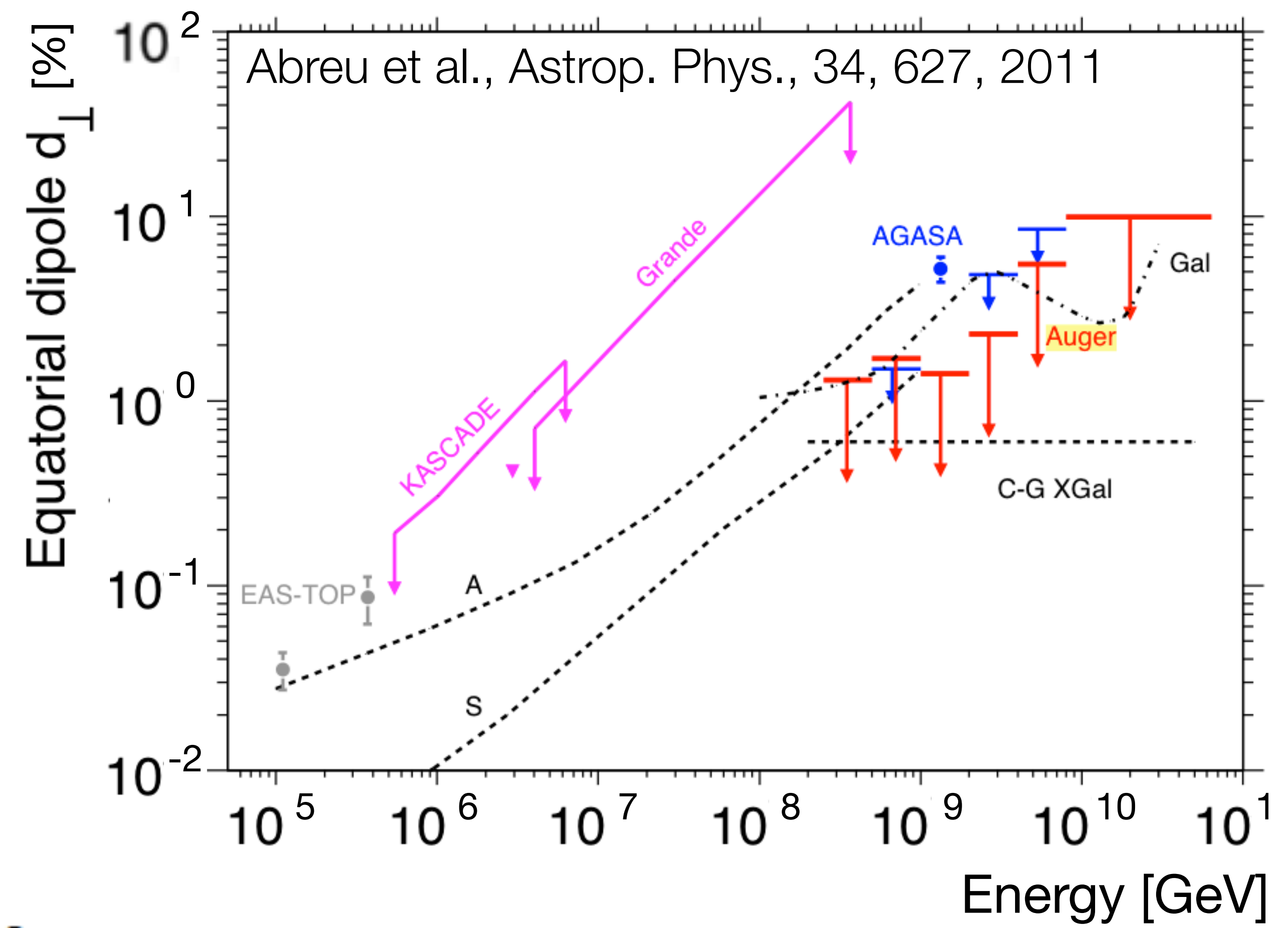


5 TeV
Milagro
Abdo et al. (2009)

equatorial coordinates

cosmic ray anisotropy large scale energy dependency





$$\delta A = \left| \sum_{SNR} \frac{eD(E)}{c} \cdot \frac{\vec{\nabla}\phi_{CR}}{\phi_{CR}}(E) \right|$$

anisotropy amplitude ~ 10^{-4}-10^{-3}

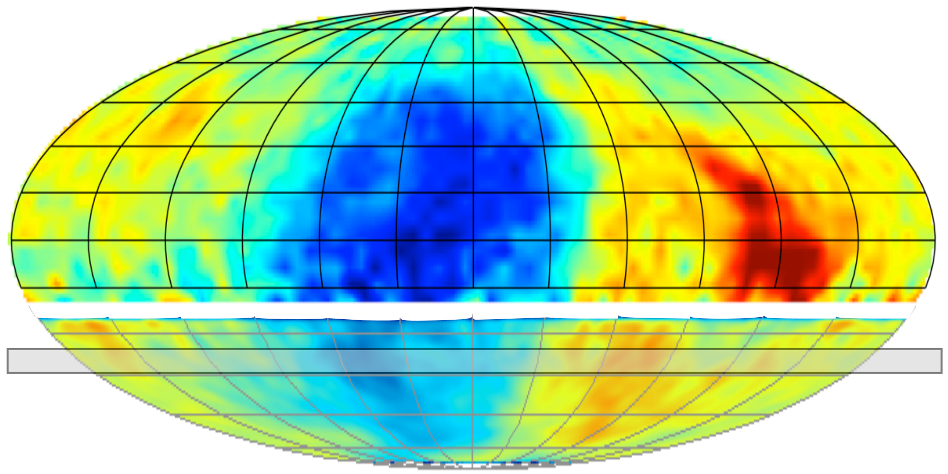
$$D(E) \approx (3-5) \times 10^{28} \cdot E^{0.3-0.6} \quad [cm^2 s^{-1}]$$

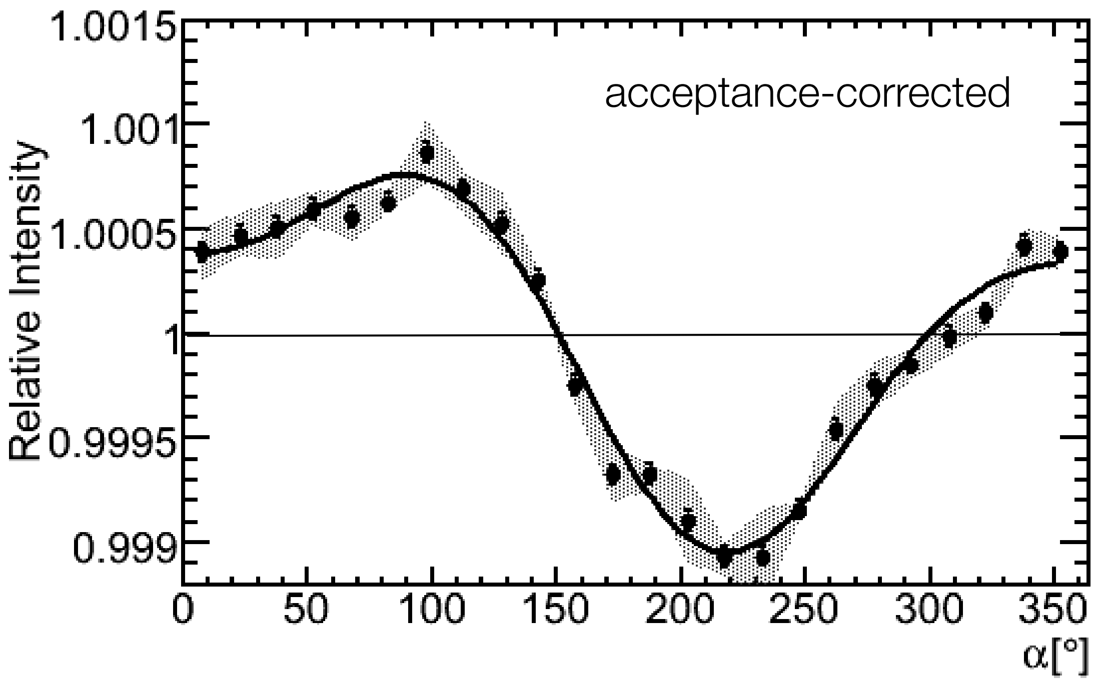
diffusion coefficient

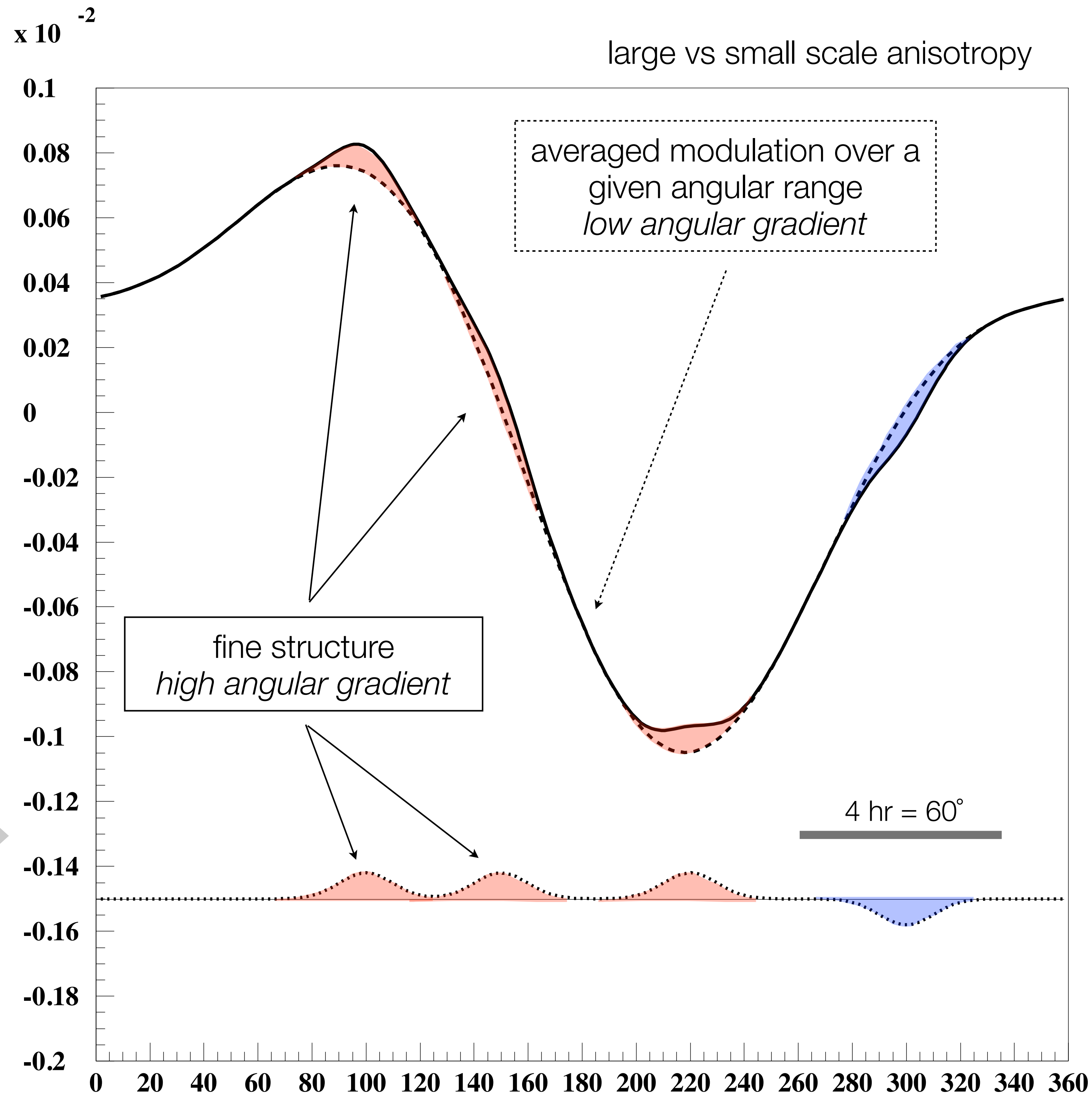
$$\Rightarrow \delta A \propto E^{0.3-0.6}$$

anisotropy increases vs energy

cosmic ray anisotropy
angular scale structure





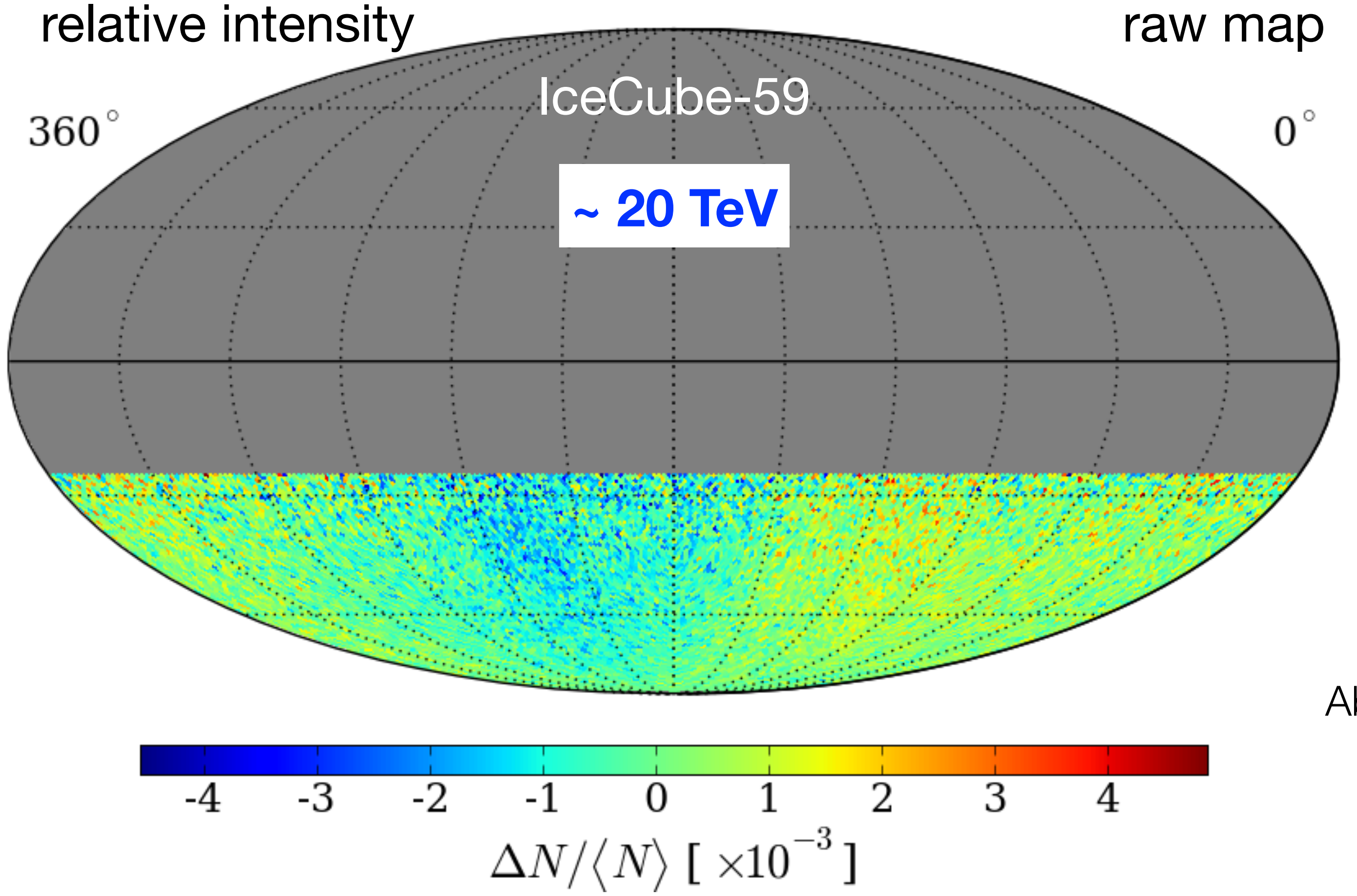


Paolo Desiati

cosmic ray anisotropy small scale
IceCube

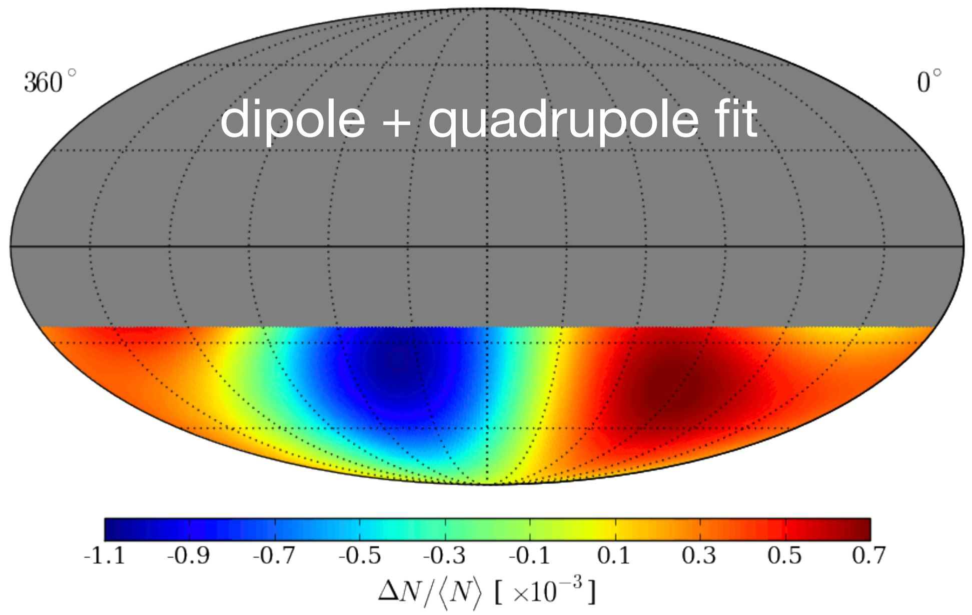
relative intensity

raw map

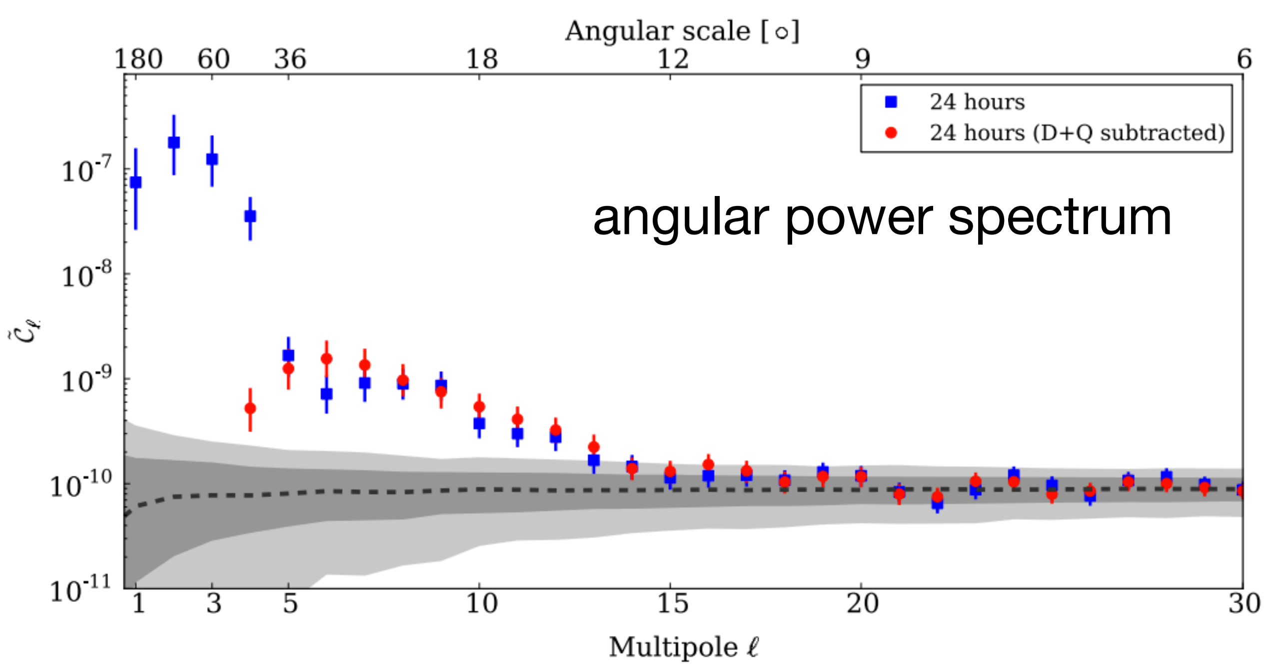


χ^2/ndf = 14743.4 / 14187

Pr(χ^2Indf) = 0.05%



Abbasi et al., ApJ, **740**, 16, 2011



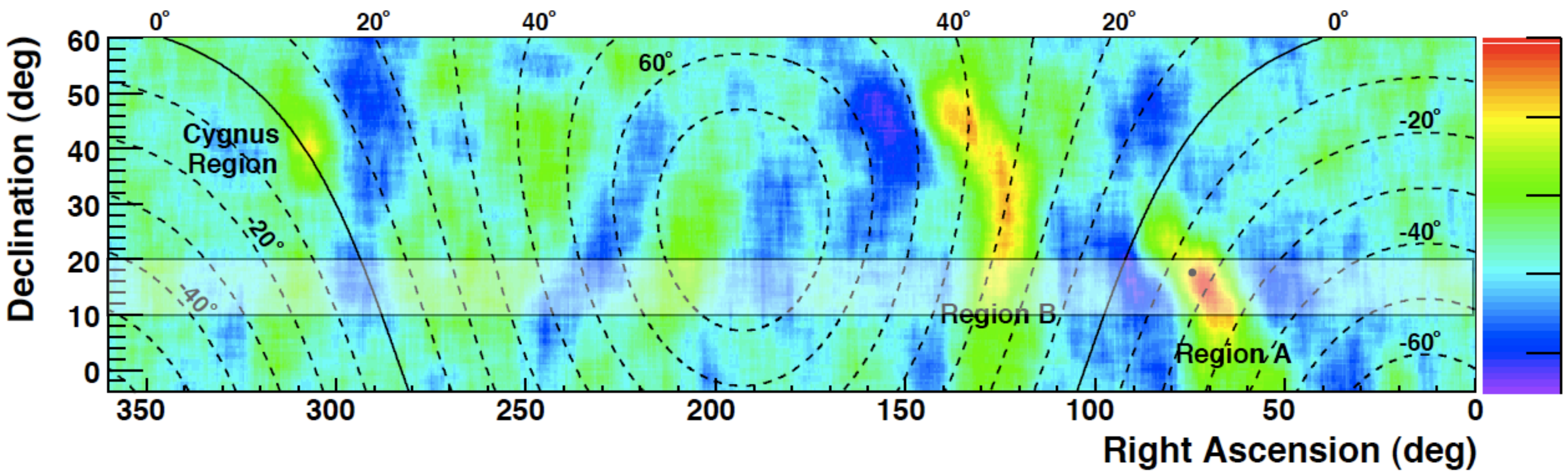
sky map contains correlations at several angular scales

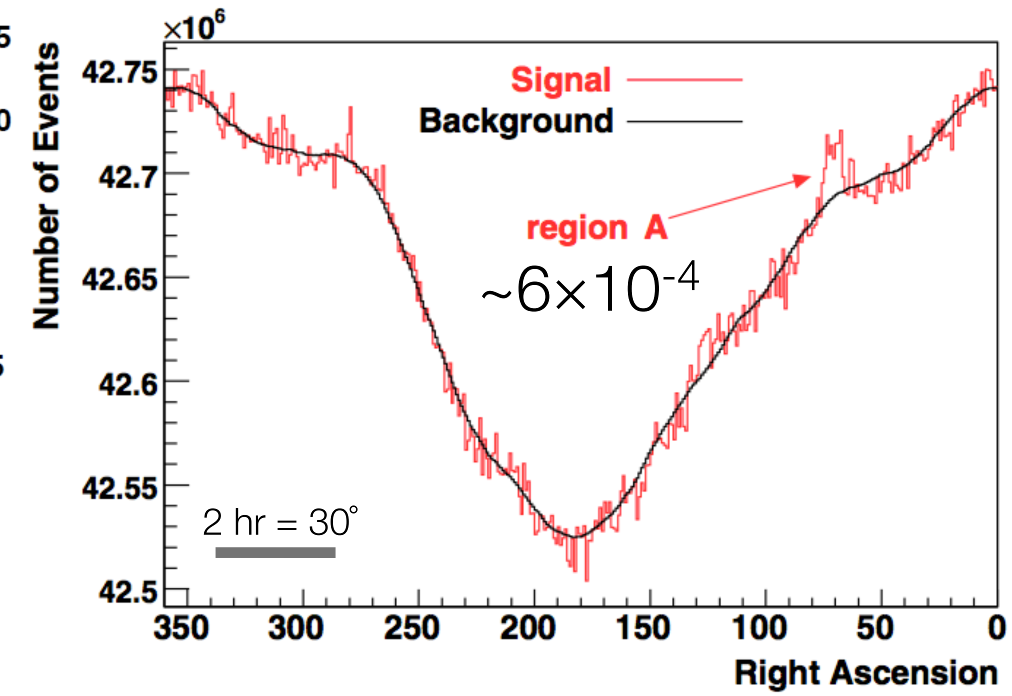
in gray 60% and 95% of simulated isotropic bands

large and small scales *separated* @ ~20 TeV ?

spectral feature associated to anisotropy

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





Milagro

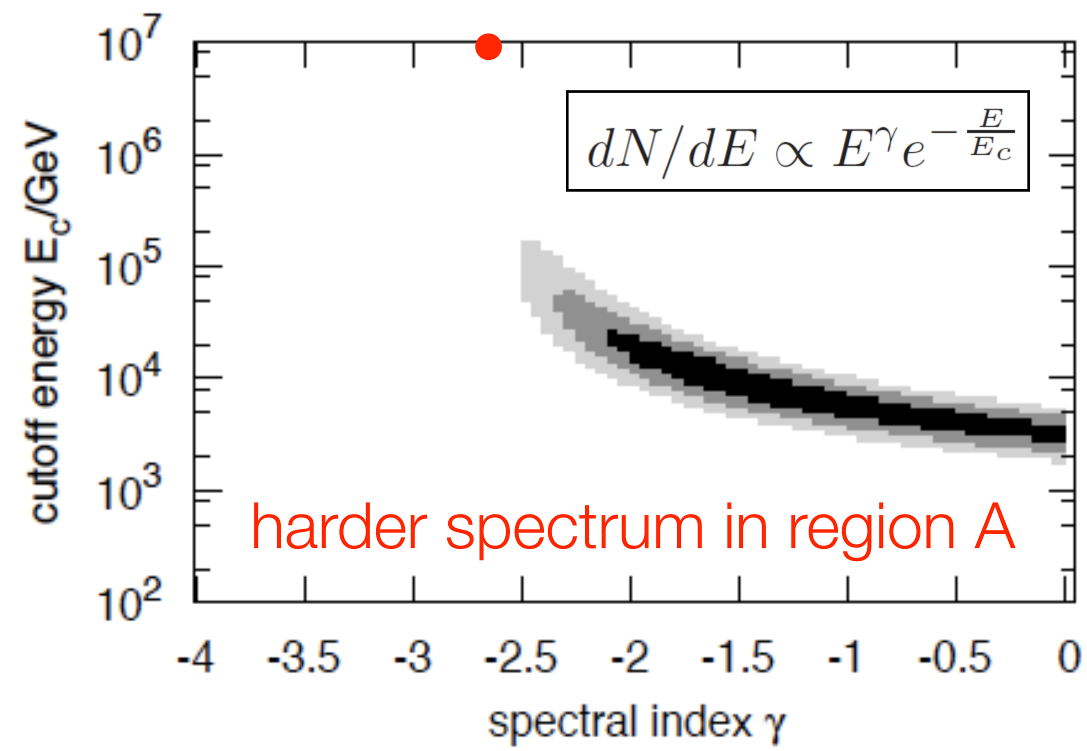
& ARGO-YBJ

Di Sciascio et al., arXiv:1202.3379

harder than average spectrum from region A

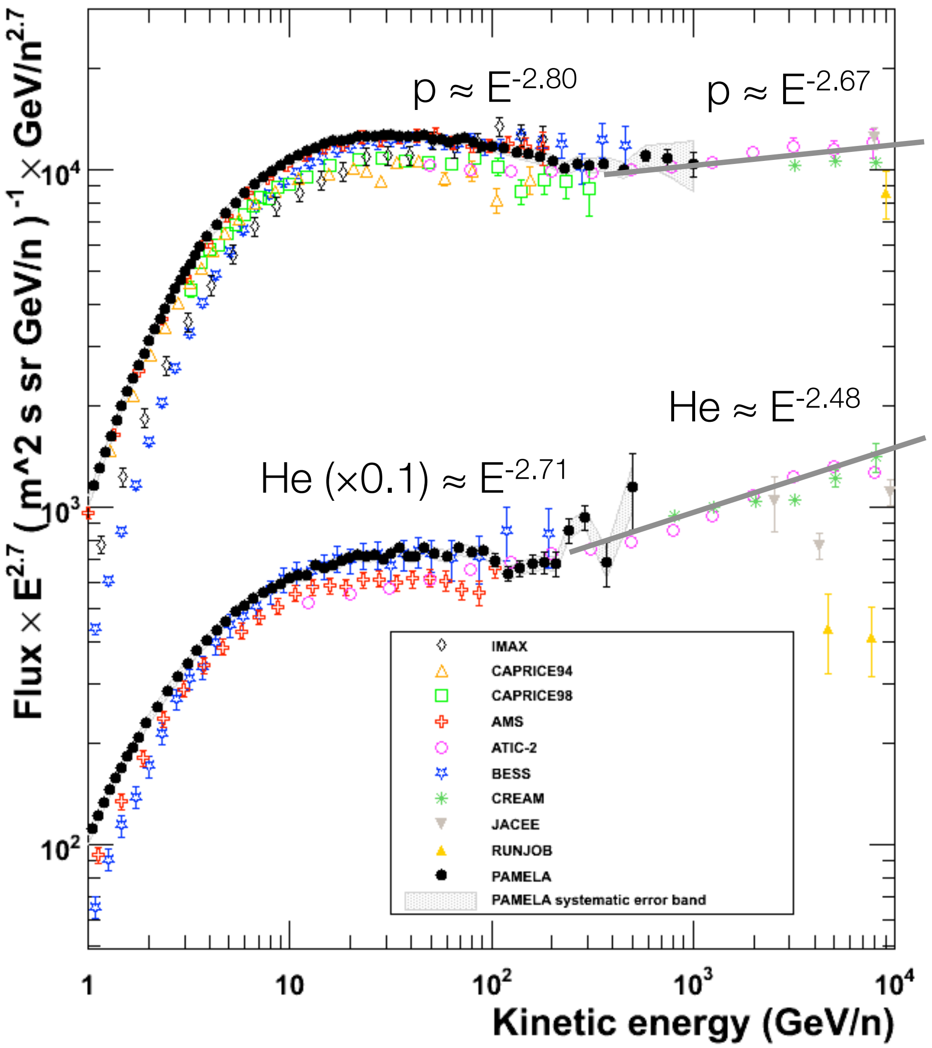
$\gamma < 2.7$ at 4.6 σ level
E_C = 3 - 25 TeV

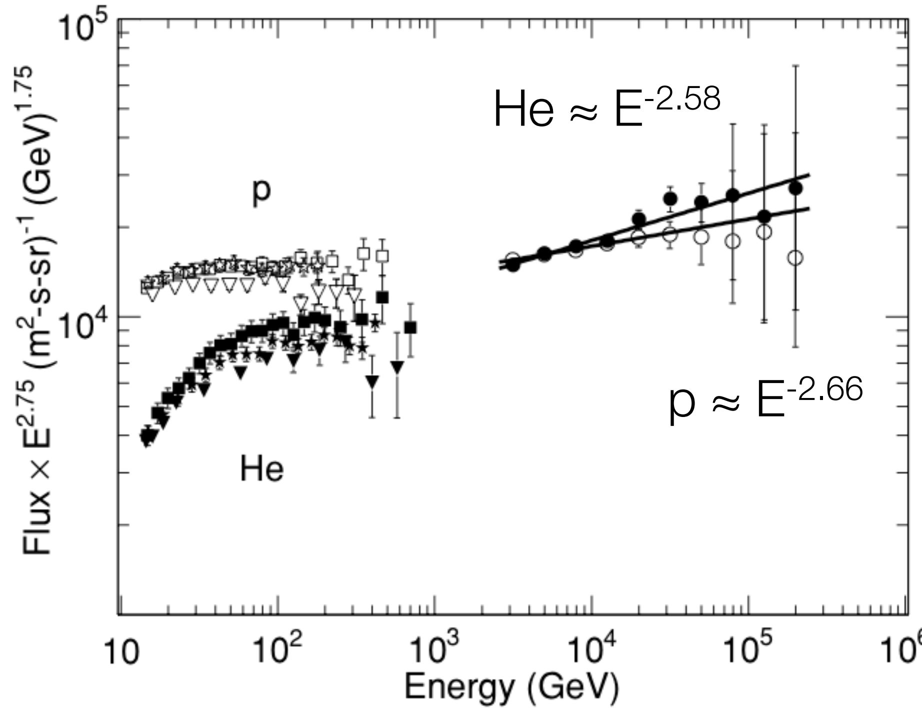
similar to hardening of “diffuse” cosmic rays by Pamela, CREAM, ATIC-2, or something else ?



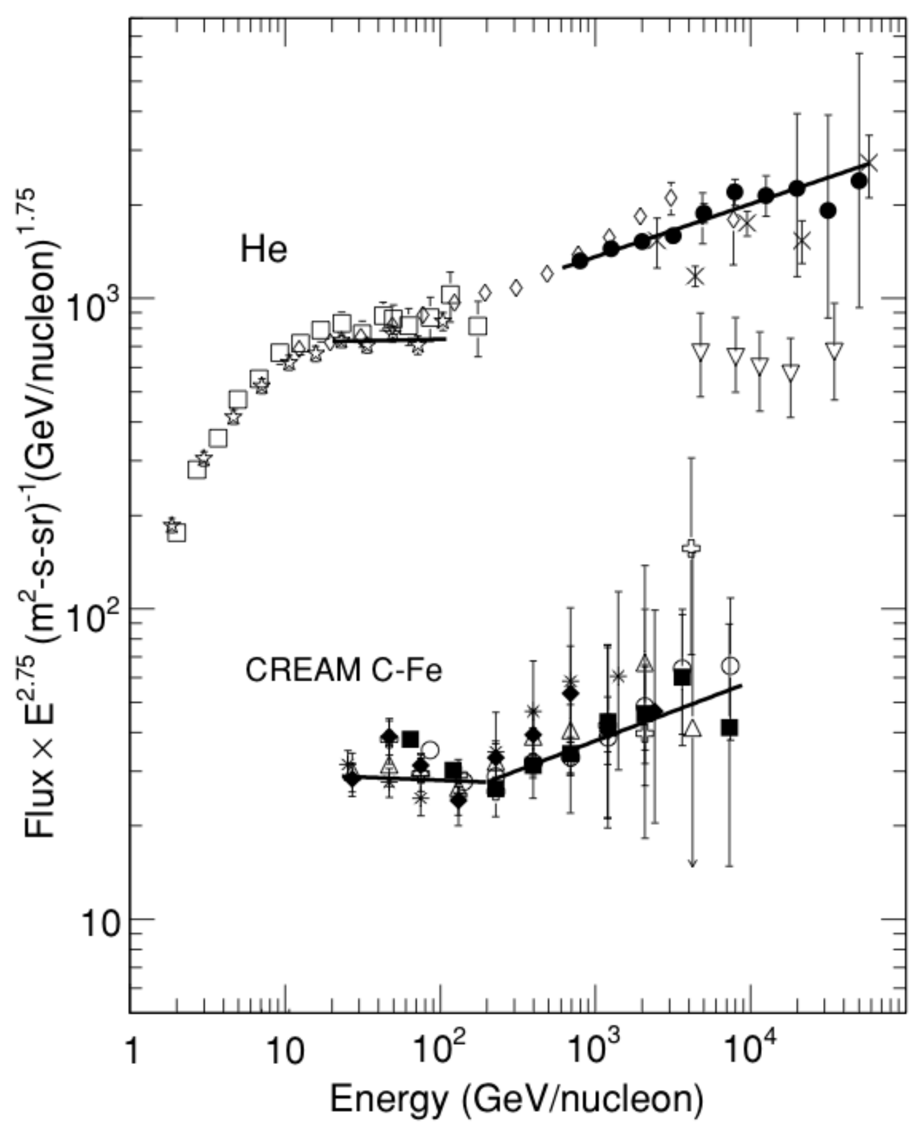
cosmic rays observations
all-particle spectrum

Pamela
Adriani et al. (2011)



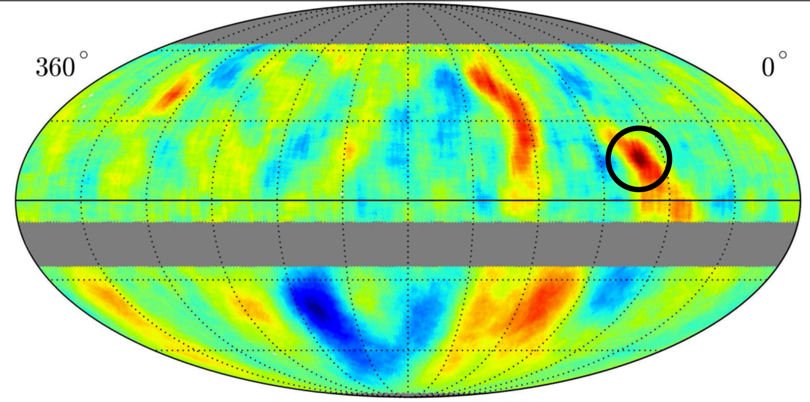


CREAM
Ahn et al. (2010)



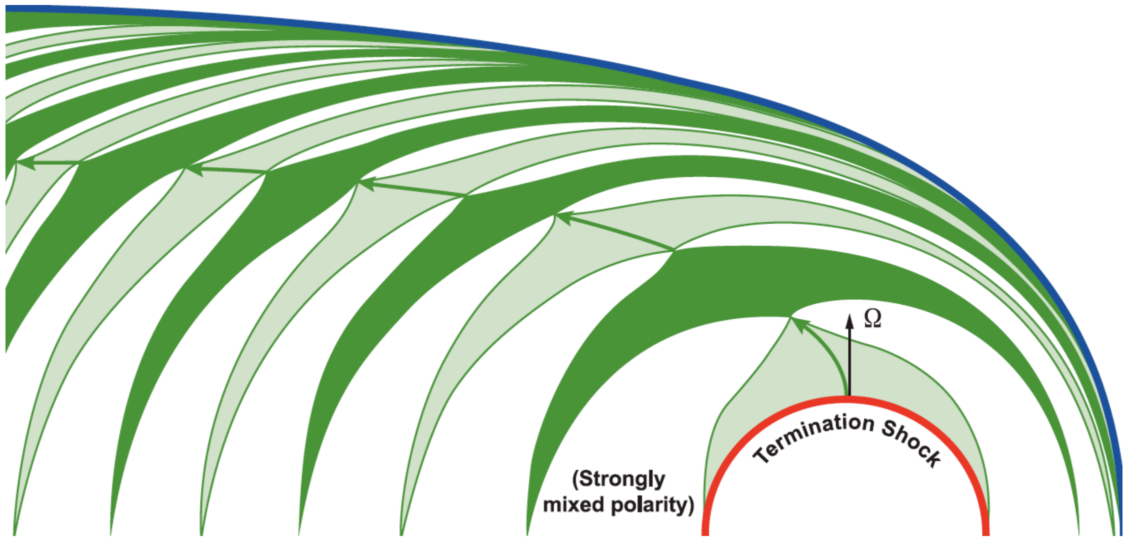
Paolo Desiati

Friday, February 8, 2013



origin of spectral hardening ?

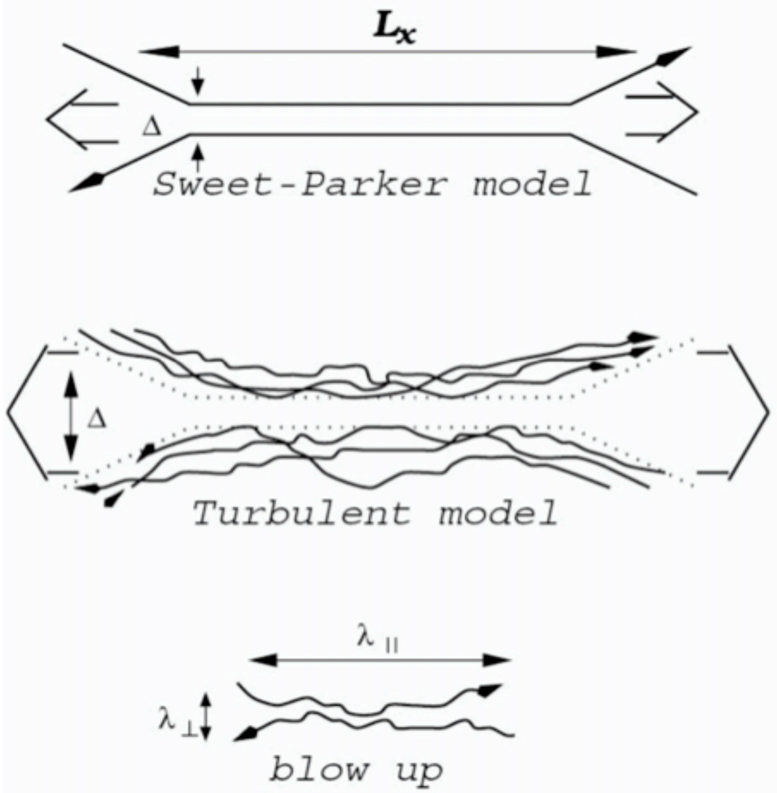
Lazarian & PD, ApJ, 722, 188, 2010

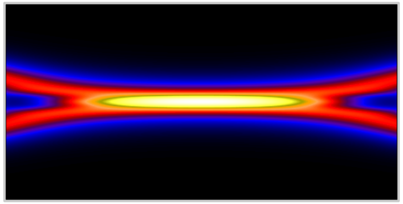


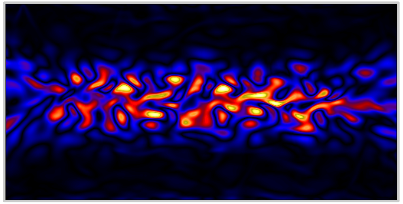
- magnetic polarity reversals due to the 22-year solar cycles produces large scale sectors
- converging of turbulent magnetic field lines can trigger reconnection and make it fast
- magnetic mirror @ single reconnection as site of acceleration (test particle)

Sweet (1959) & Parker (1957)

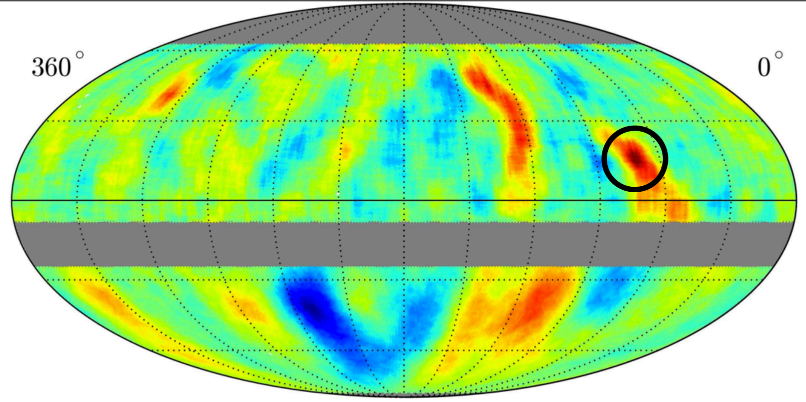
Lazarian & Vishniac, ApJ, 517, 700 (1999)







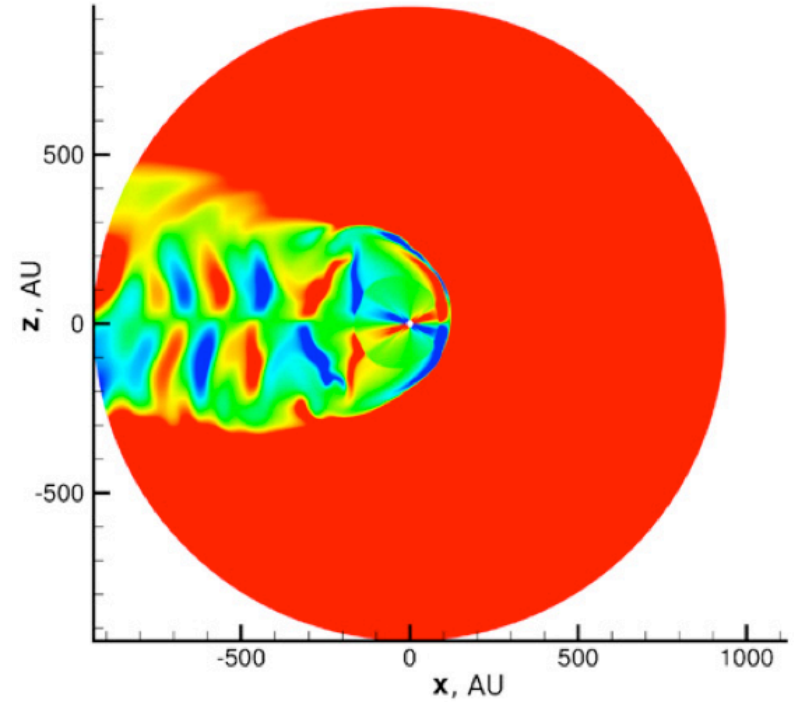
stochastic magnetic reconnection

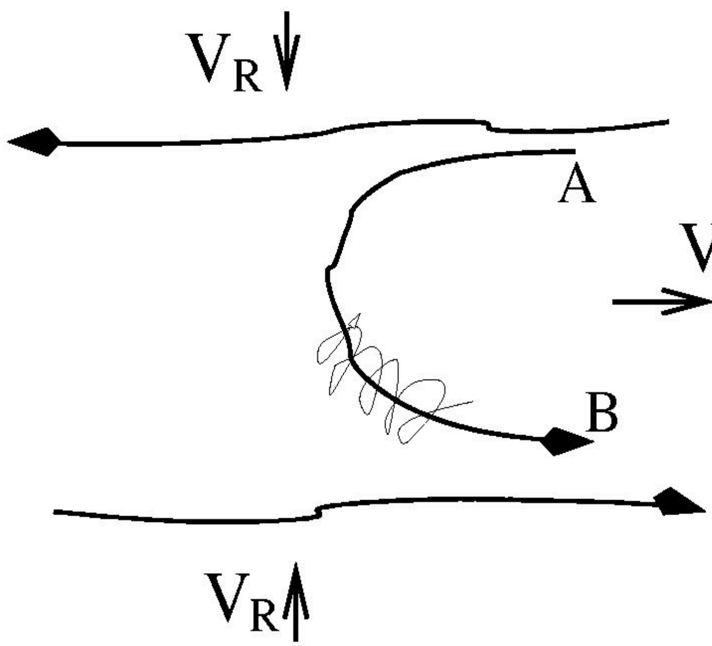


Lazarian & PD, ApJ, 722, 188, 2010

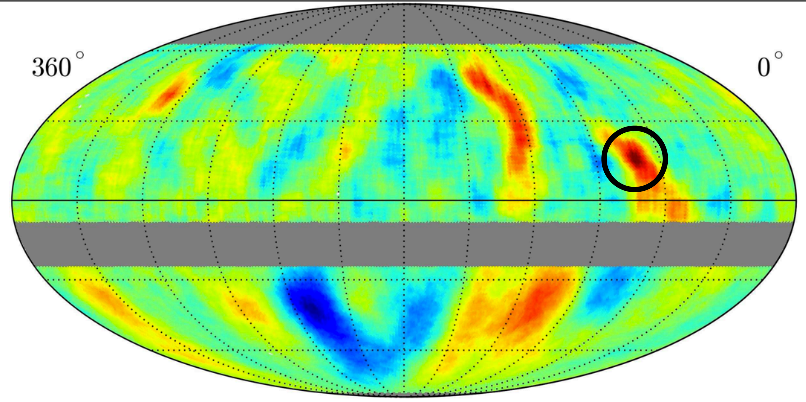
- magnetic polarity reversals due to the 22-year solar cycles produces large scale sectors
- converging of turbulent magnetic field lines can trigger reconnection and make it fast
- magnetic mirror @ single reconnection as site of acceleration (test particle)
- 1st order Fermi acceleration

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

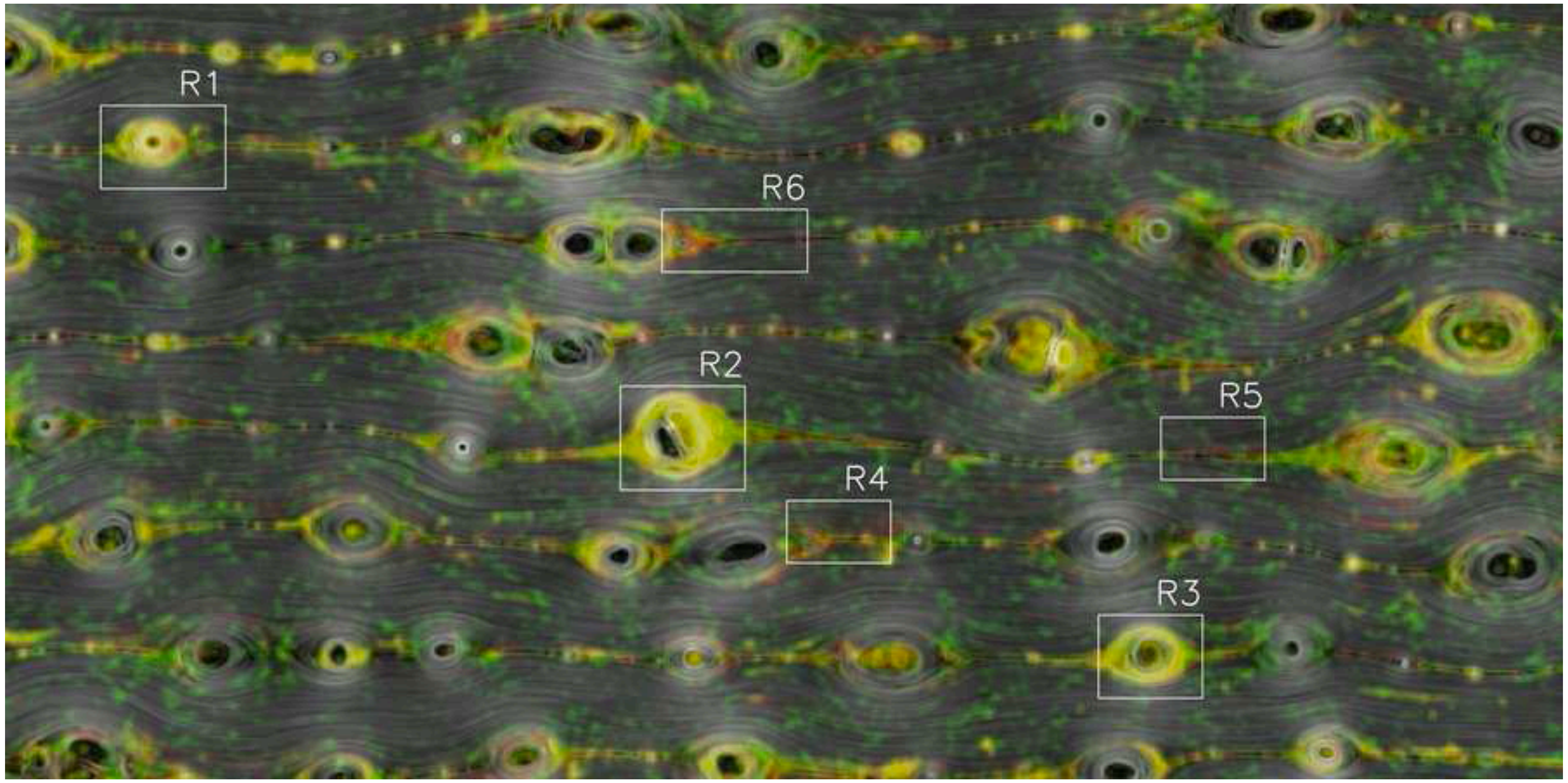




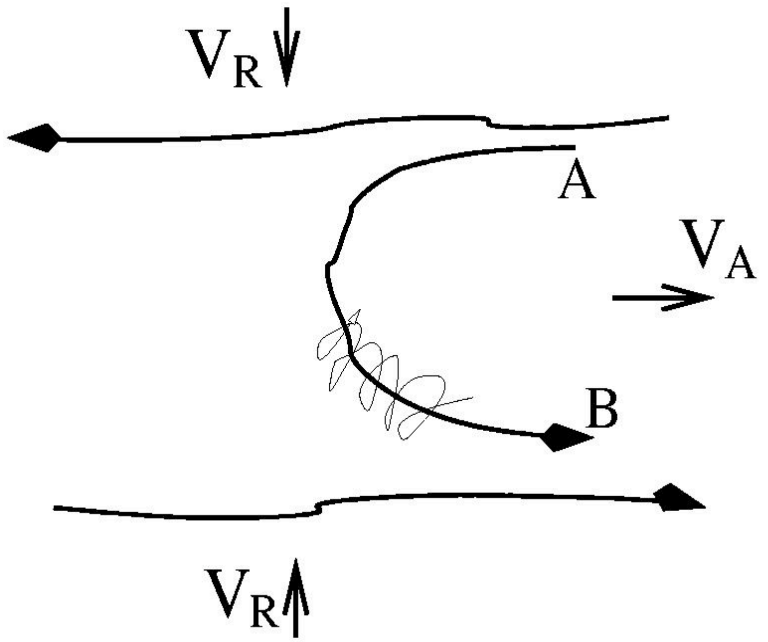
stochastic magnetic reconnection



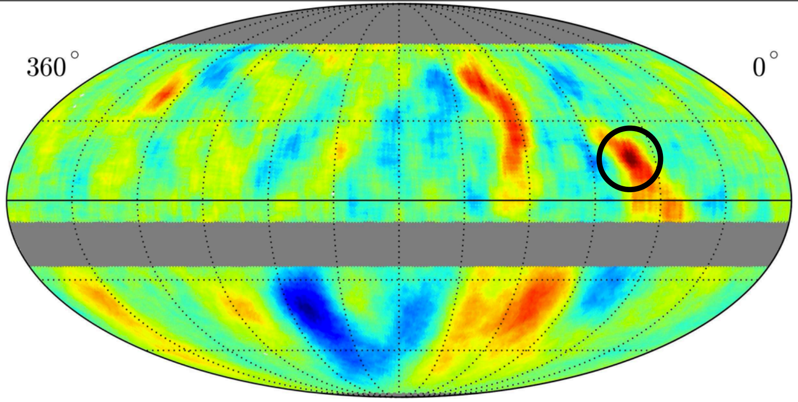
Kowal et al., ApJ 735, 102 (2011)



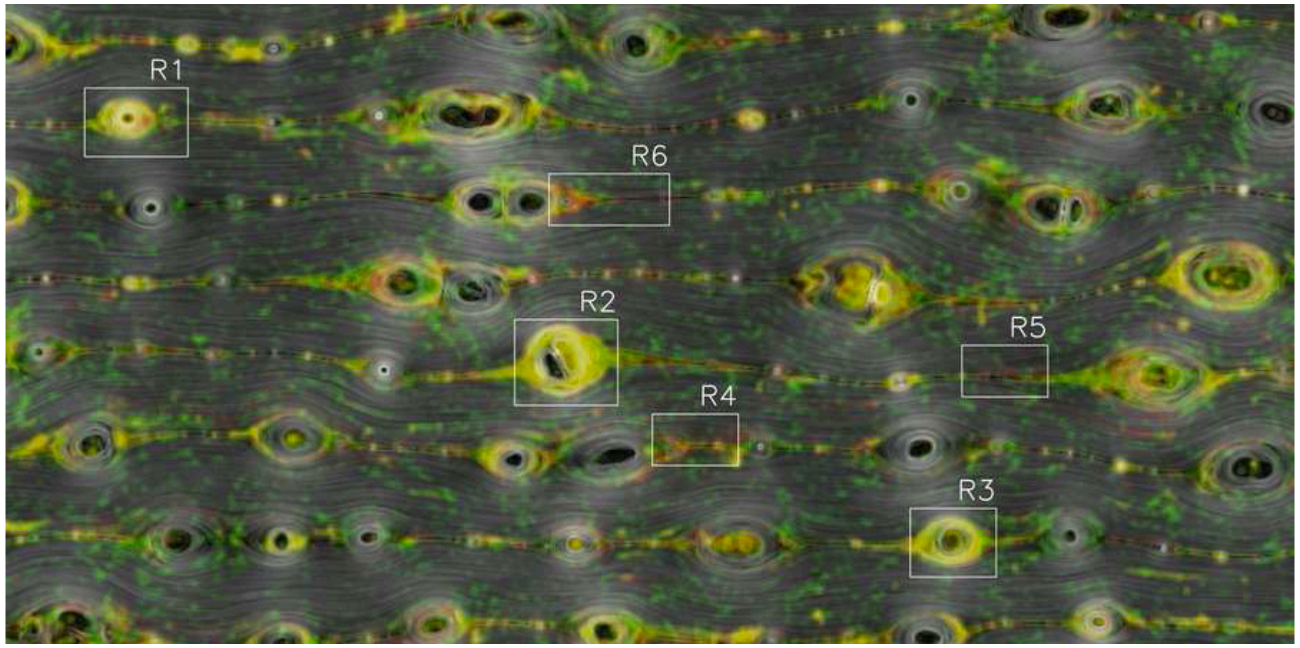
$$N(E)\,dE \sim E^{-5/2}\,dE$$

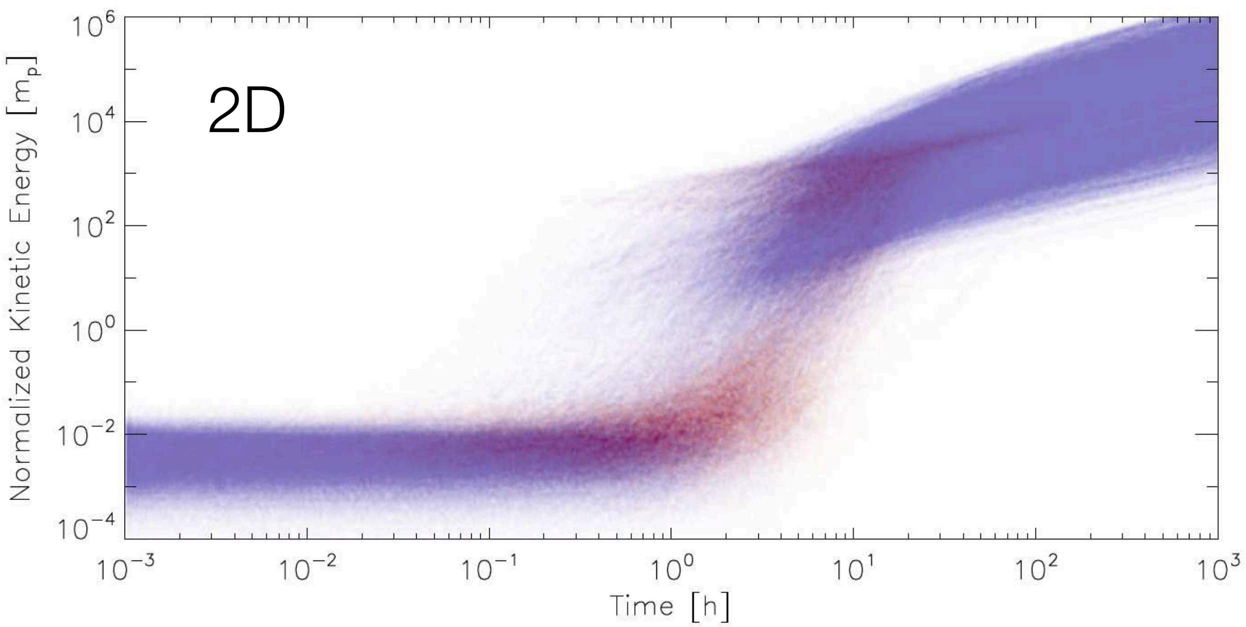


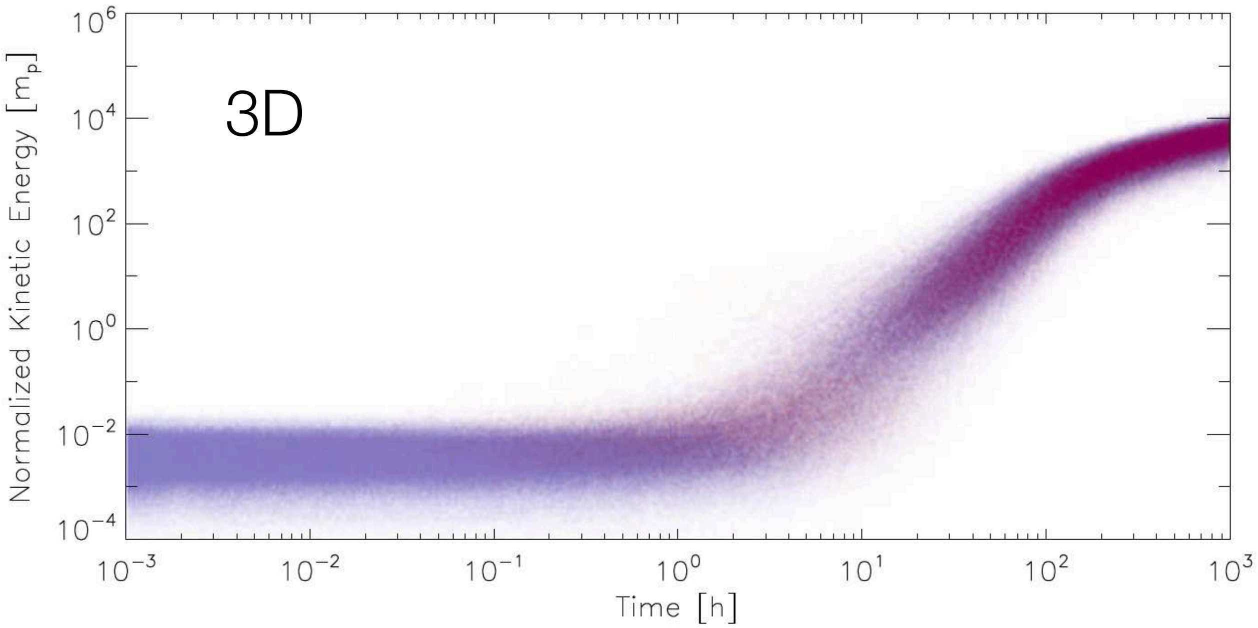
stochastic magnetic reconnection



Kowal et al., ApJ 735, 102 (2011)

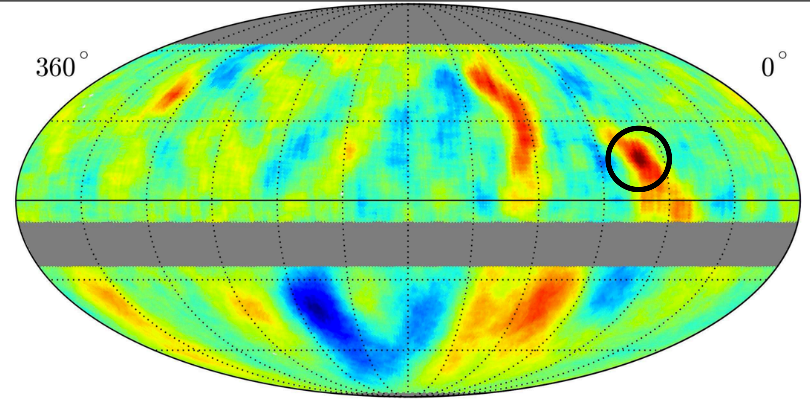






$\mathbf{V}_\perp > \mathbf{V}_\parallel$ $\mathbf{V}_\parallel > \mathbf{V}_\perp$

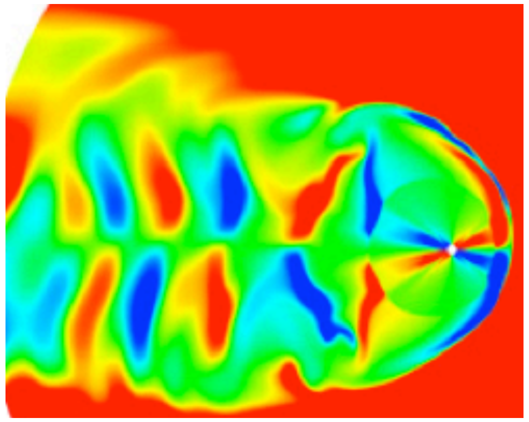
stochastic magnetic reconnection



- 2nd order Fermi acceleration is dominant in purely turbulent plasmas with no converging magnetic flow

Kowal et al., PRL 2012

- if converging flow occurs 1st order Fermi acceleration is the most important



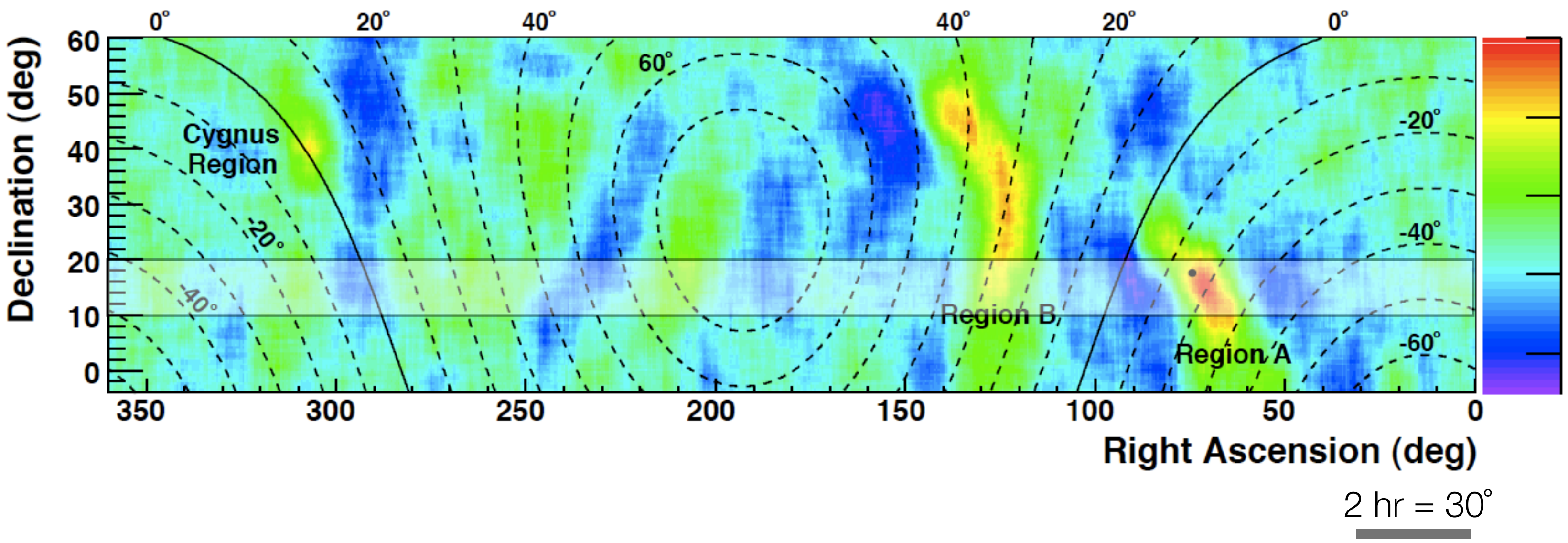
- acceleration by reconnection is efficient if scattering does not isotropize particles. Scattering expected to be minimal along the tail line of sight

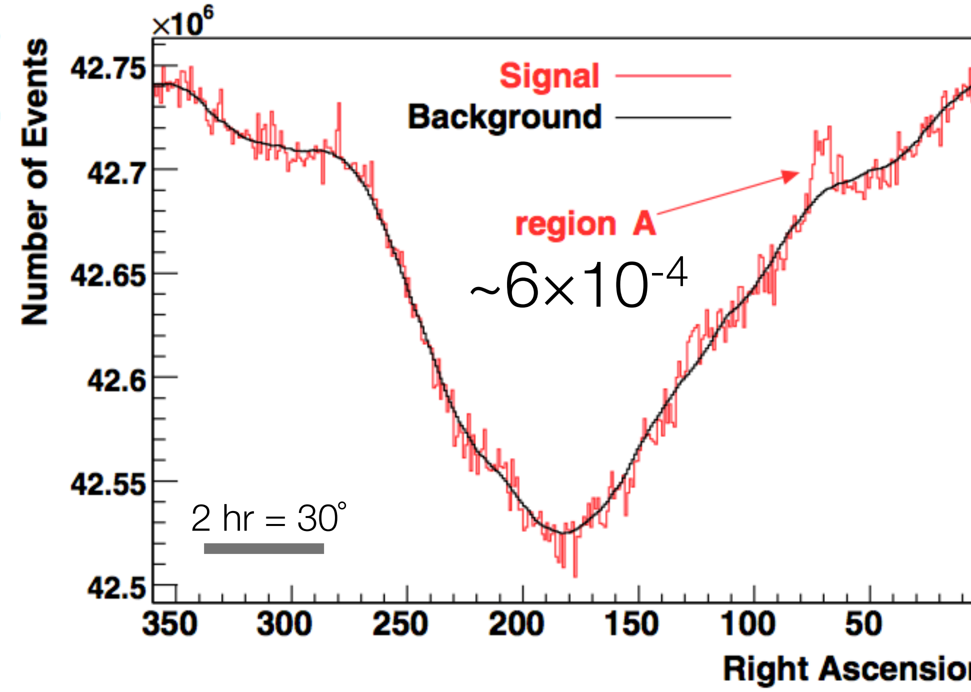
$$E_{max} \approx 0.5 \left(\frac{B}{1\,\mu G}\right)\left(\frac{L_{zone}}{100\,AU}\right) TeV \approx 0.5 - 6\,TeV$$

- cosmic rays re-accelerated as long as trapped in large scale reconnection regions

spectral feature associated to anisotropy

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





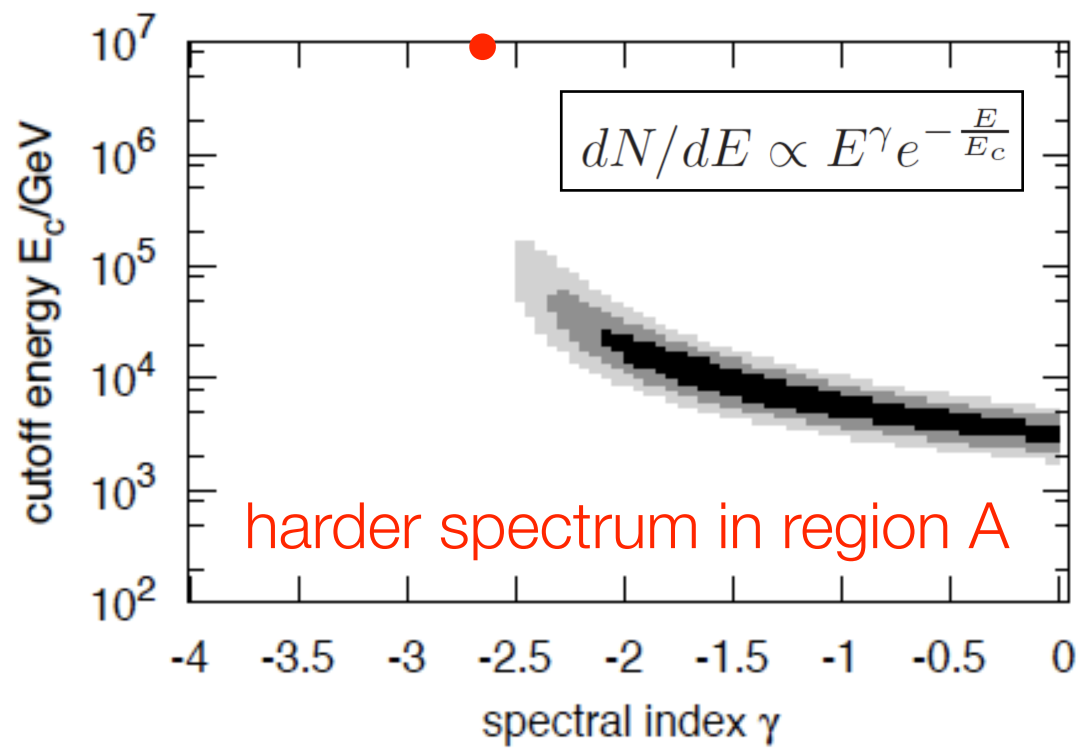
Milagro

γ < 2.7 at 4.6 σ level
E_c = 3 - 25 TeV

E_{flux}(10GeV-10TeV) ~ 10^{-9} - 10^{-8} erg cm^{-2} s^{-1} (γ = 2.7 - 2.0)

$\langle P_{re\text{-}acc} \rangle$ ~ 10^{20} - 10^{22} erg s^{-1}

$\langle P_{solar\ wind} \rangle$ ~ 10^{27} erg s^{-1} (Parker, 1962)



PD, Lazarian, NPG, **19**, 1, 2012

cosmic ray anisotropy
astrophysical origin ?

- stochastic effect of recent nearby CR sources
  - influences spectrum and global arrival direction
  - diffusive scenarios to explain observed features

Dorman+ 1985
Ptuskin+ 2006
Erlykin & Wolfendale 1997, 2001, 2006
Sveshnikova+ 2013
Blasi & Amato 2011, 2012
Pohl & Eichler 2012

Salvati & Sacco 2008
Drury & Aharonian 2008
Salvati 2010

- propagation effects in turbulent ISMF

Battaner+ 2009
Malkov+ 2010

- convection from persistent magnetized flow field from old SNRs

Biermann+ 2012

- breakdown of diffusion regime via scattering with ISMF turbulence

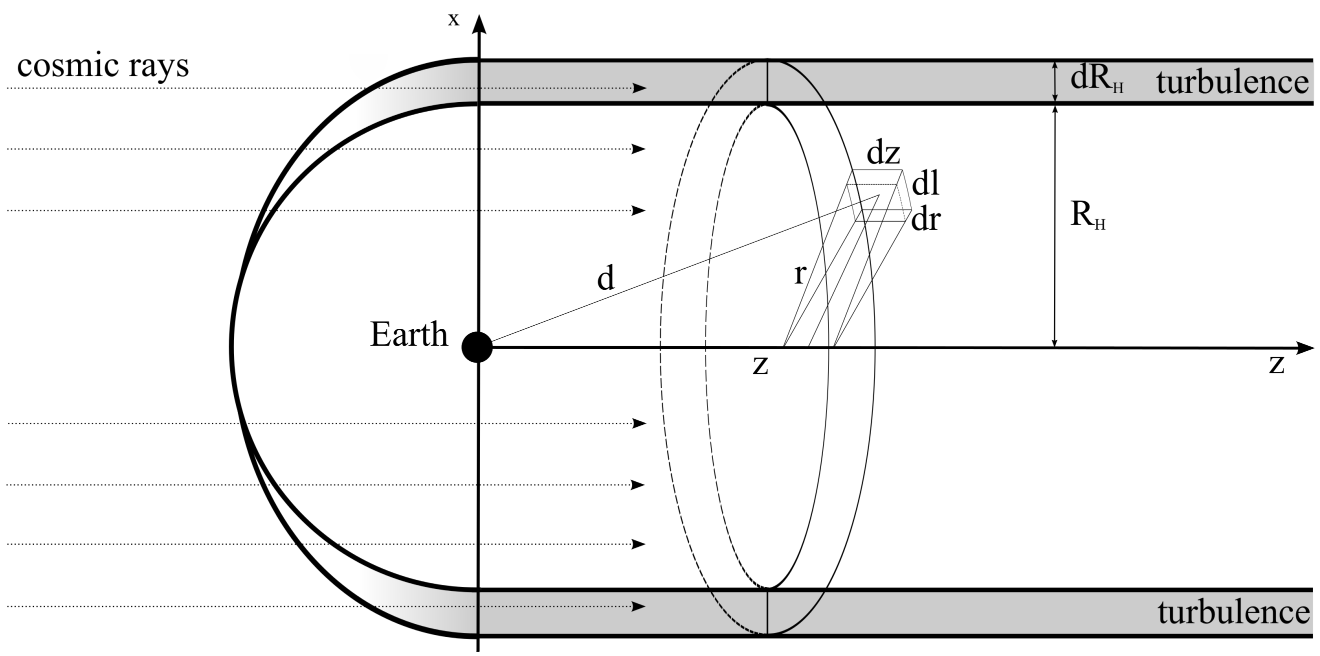
Giacinti & Sigl 2011

- diffusion cannot explain the observed **non-dipolar** topology & **small angular scales**
- limitations on single power-law assumption and spacial dependency of diffusion coeff.

scattering on heliospheric boundary
toy model

PD & Lazarian, ApJ, **762**, 44, 2013

$$N_b = n_{\mathrm{CR}}\, P_s\, R_E^2 \int_{R_H}^{R_H+dR_H} dr \int_0^{2\pi r} dl \int_0^{\infty} \frac{dz}{z^2+r^2}$$
$$= n_{\mathrm{CR}}\, P_s\, \pi^2\, R_E^2\, dR_H,$$



$$N_d = n_{\mathrm{CR}}\, 4\pi\, R_E^2\, c\, \tau.$$

$$\delta = \frac{N_b - N_d}{N_b + N_d} = \frac{N_b/N_d - 1}{N_b/N_d + 1},$$

$$\frac{N_b}{N_d} = \frac{3\pi}{4}\, P_s\, \frac{dR_H}{c\,\tau}.$$

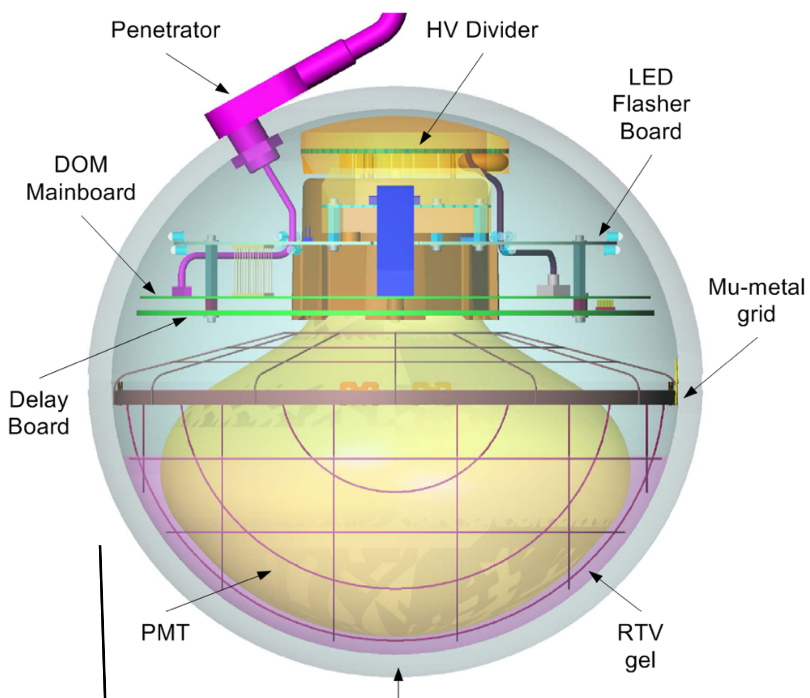
$$\delta \gtrsim 0, \qquad P_s \gtrsim 100/dR_H$$

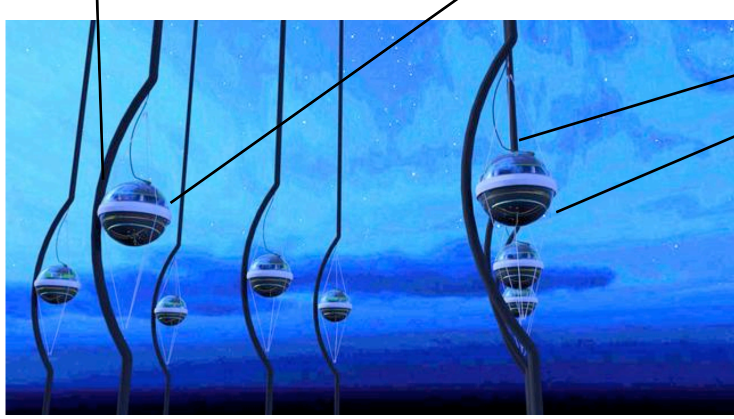
IceCube Observatory

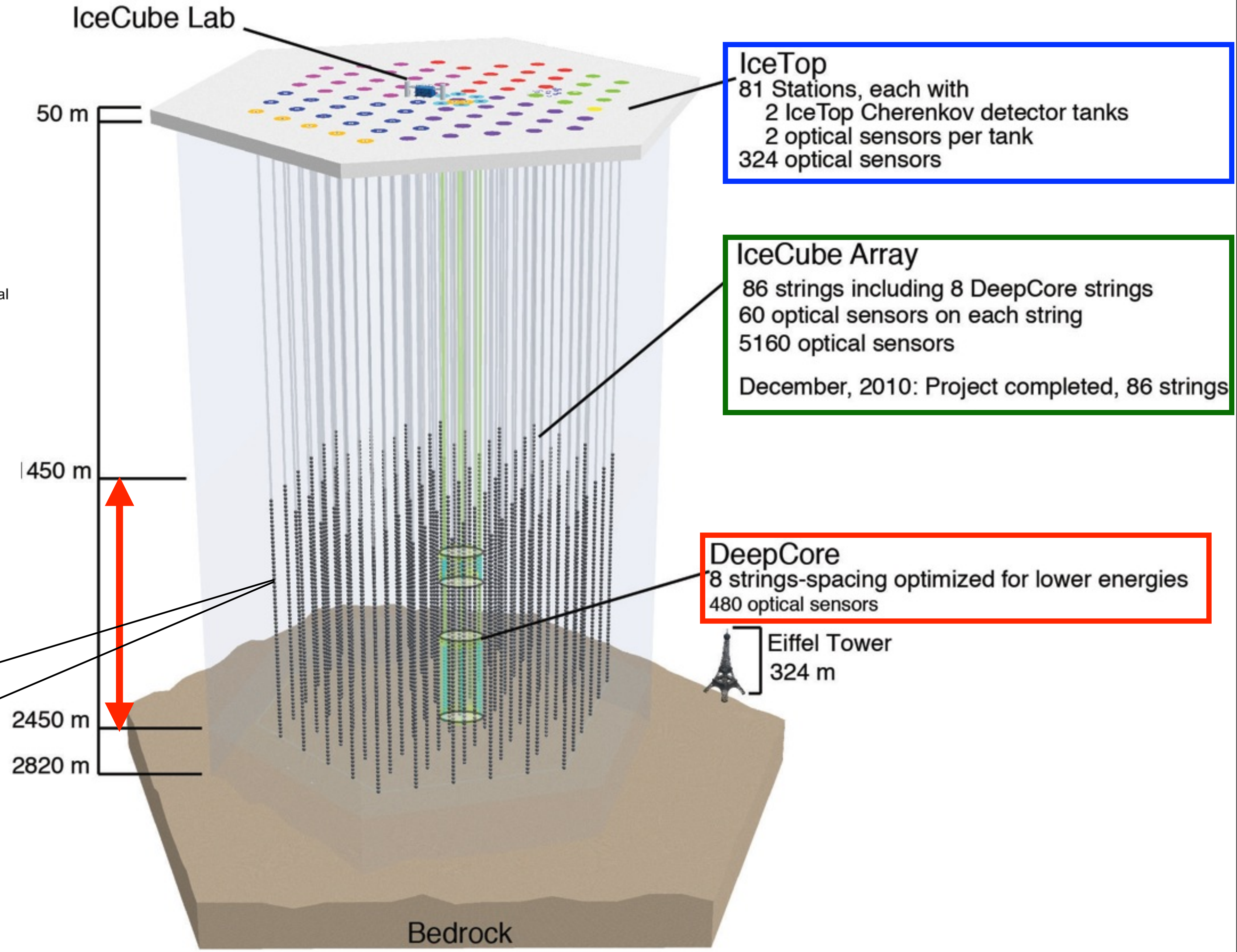
air shower detection @ 2835 m altitude (680 g/cm^2)

muon detection @ 1450-2450 m depth

Digital Optical Module - DOM
with 10” PMT &
local DAQ electronics







detection principle