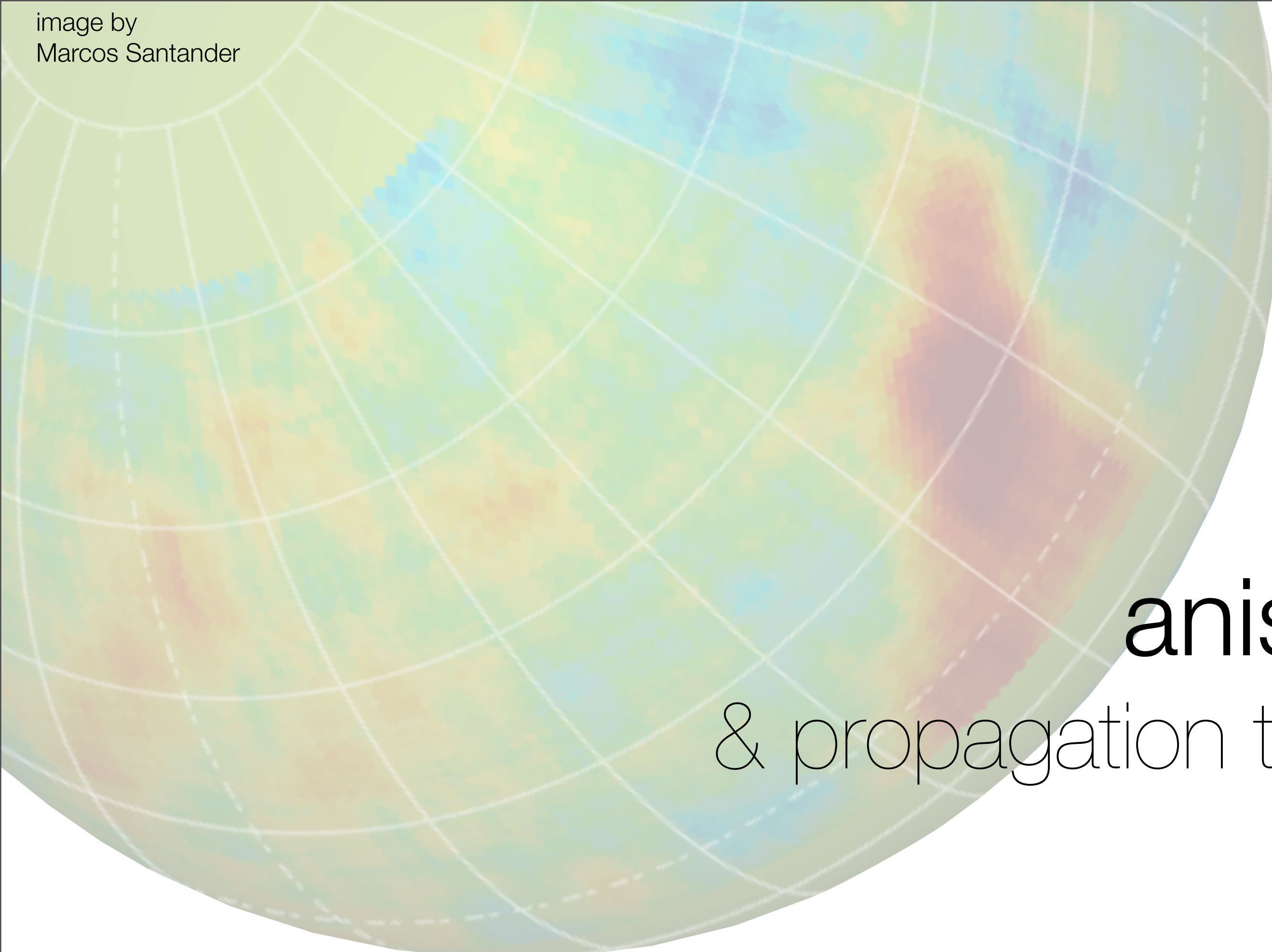
image by
Marcos Santander

May 1, 2013
Midwest Magnetic Fields Workshop
University of Wisconsin, Madison, Wisconsin

anisotropy of TeV cosmic rays
& propagation through the heliospheric boundary

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

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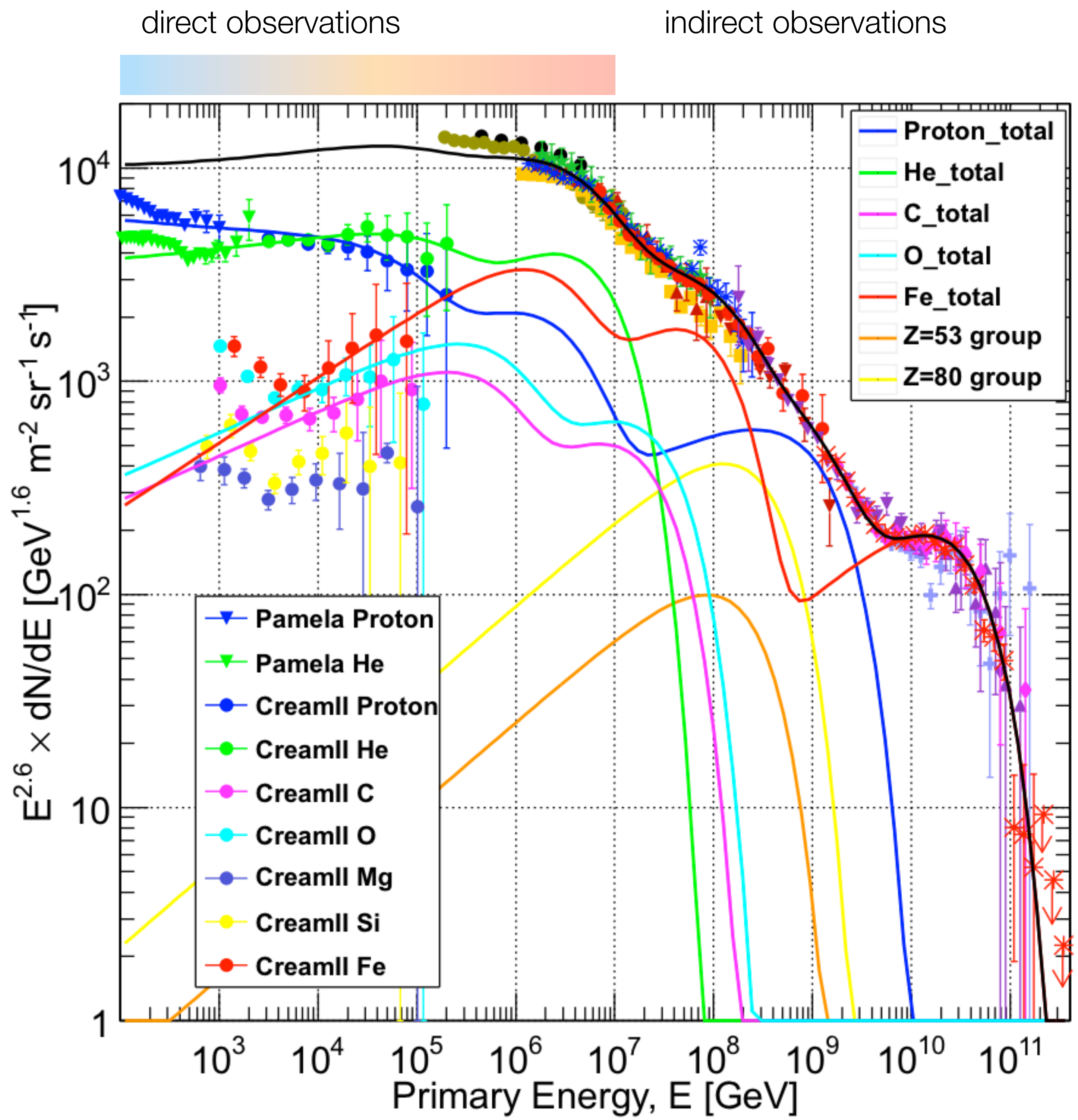
University of Wisconsin - Madison

cosmic rays spectrum

Gaisser, Stanev, Tilav, 2013 - arXiv:1303.3565

- cosmic rays produced in **supernova remnants** below 10^8-10^9 GeV
- **spectral features** from acceleration mechanisms or propagation effects
- **source distribution** in Galaxy and our neighborhood
- **magnetic field** configurations in local interstellar medium
- cosmic ray **anisotropy**



Paolo Desiati

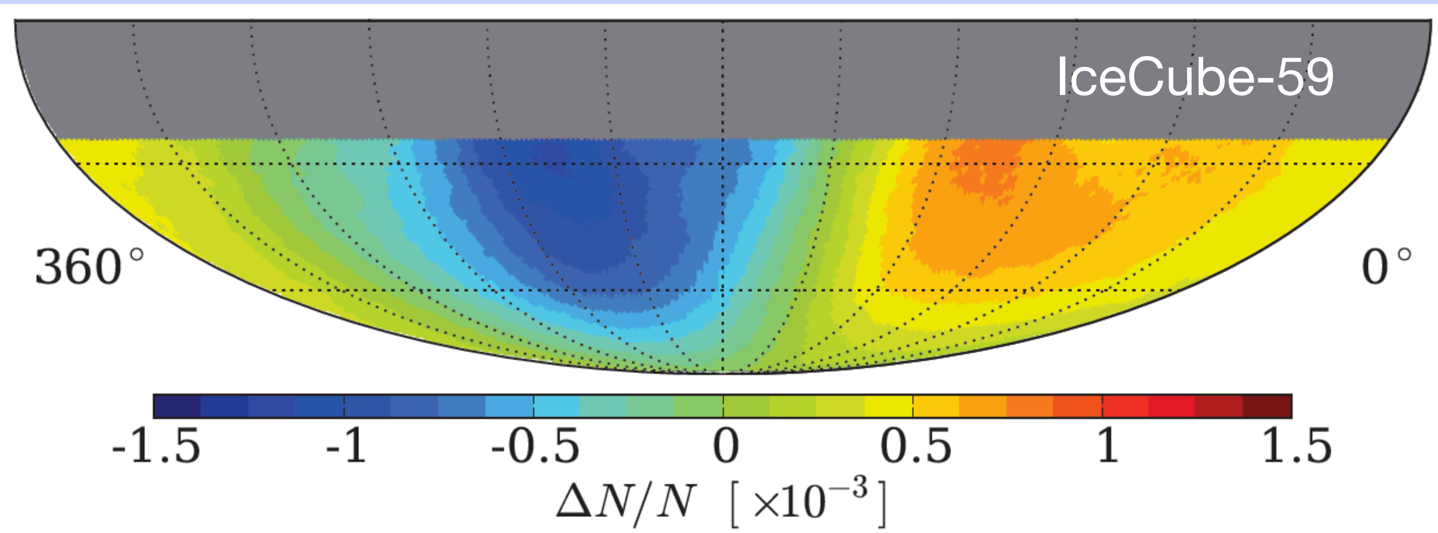
Wednesday, May 1, 2013

cosmic ray arrival direction

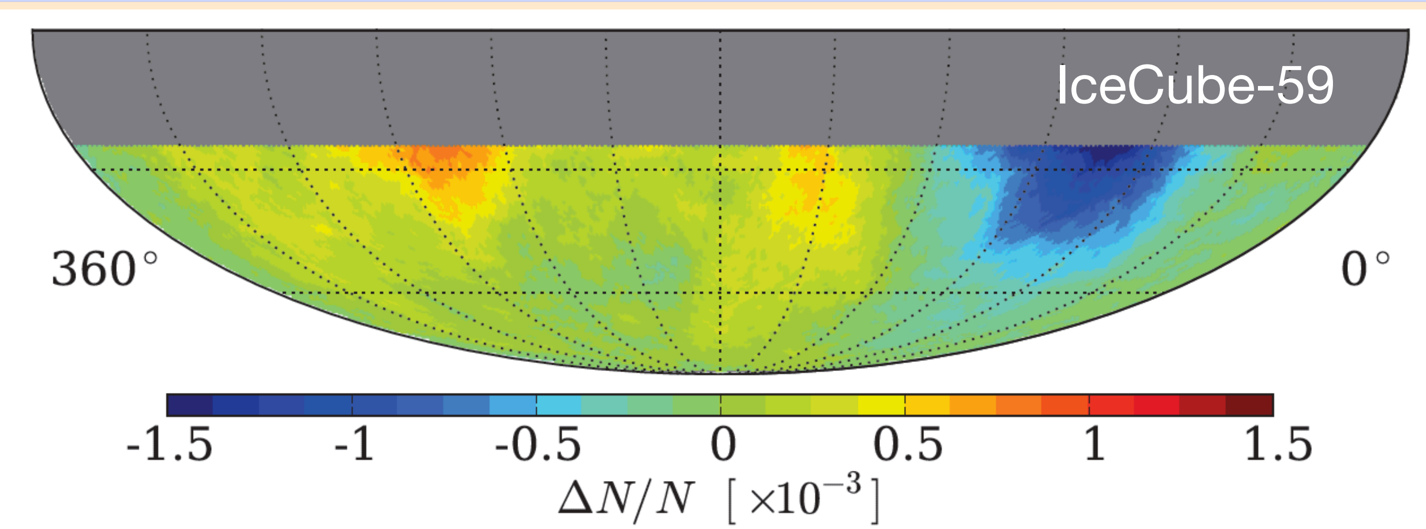
Abbasi et al., ApJ, **718**, L194, 2010
Abbasi et al., ApJ, **746**, 33, 2012
Aartsen et al., ApJ, **765**, 55, 2013

relative intensity

equatorial coordinates

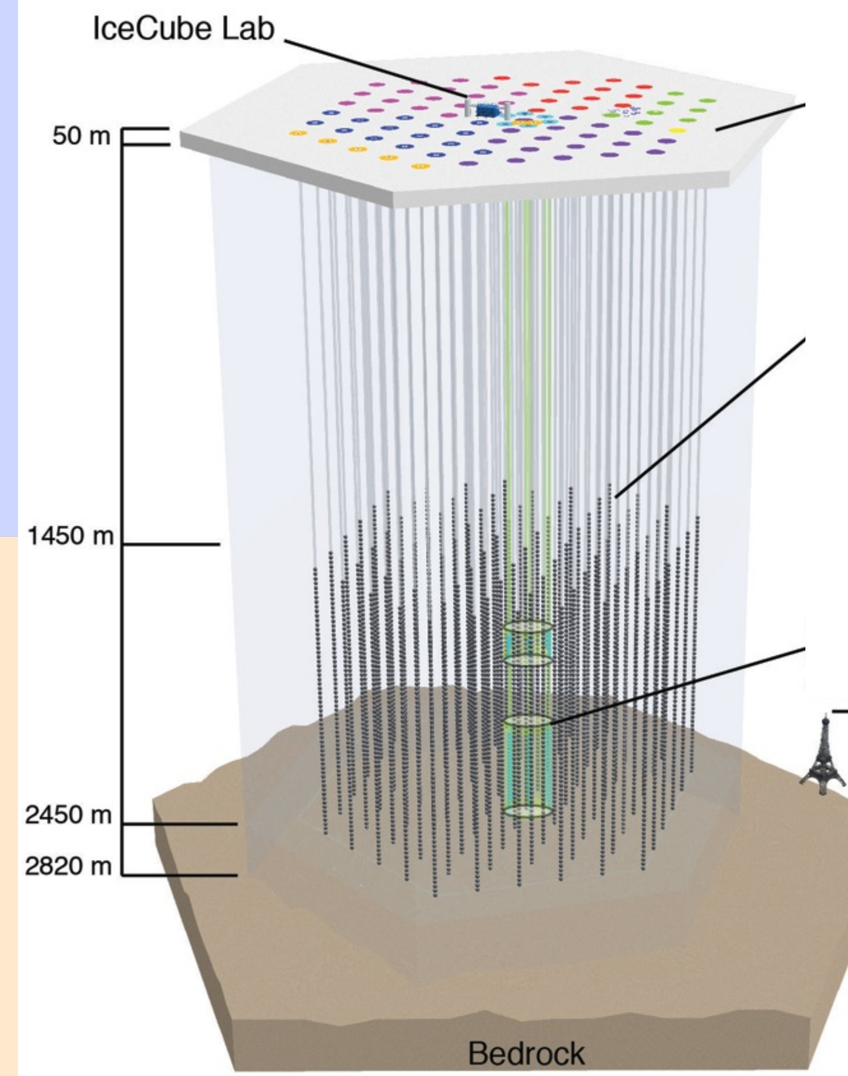


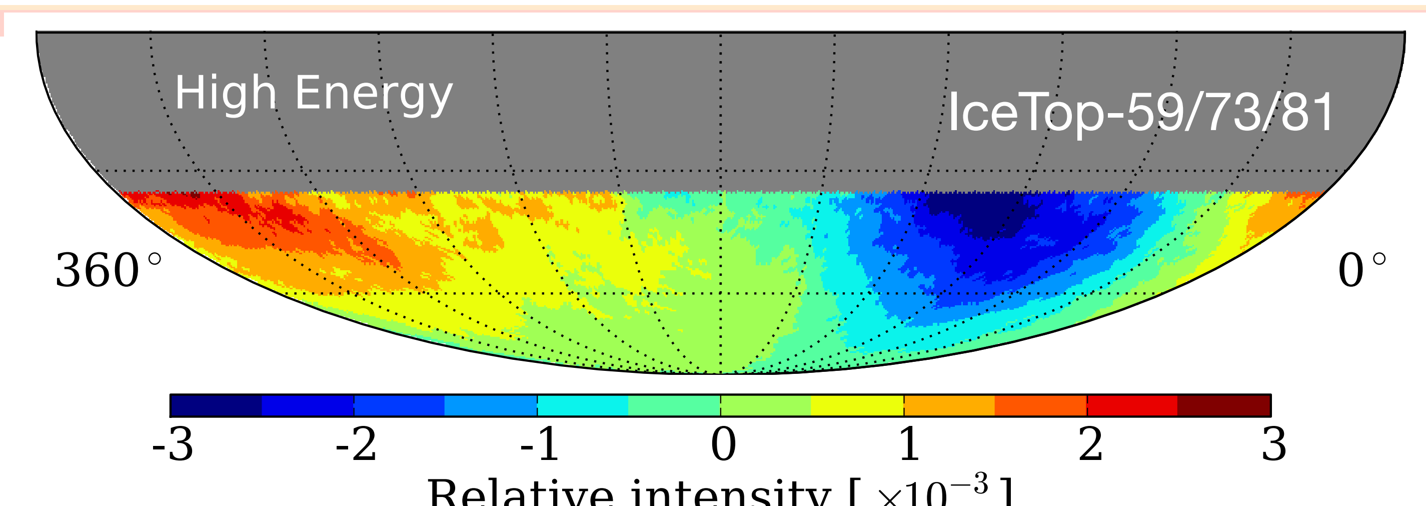
20 TeV



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

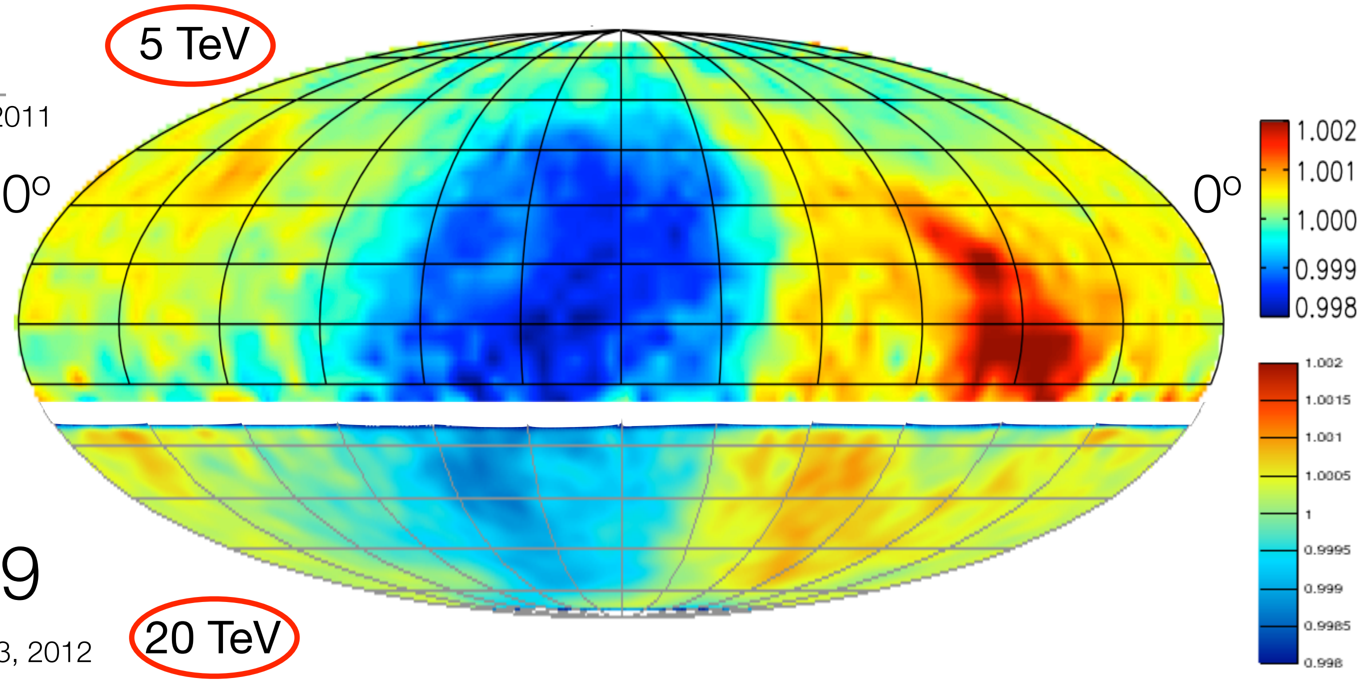
cosmic ray anisotropy large scale → small scale

Tibet-III

Amenomori et al., ICRC 2011

5 TeV

360°



0°

equatorial coordinates

relative intensity

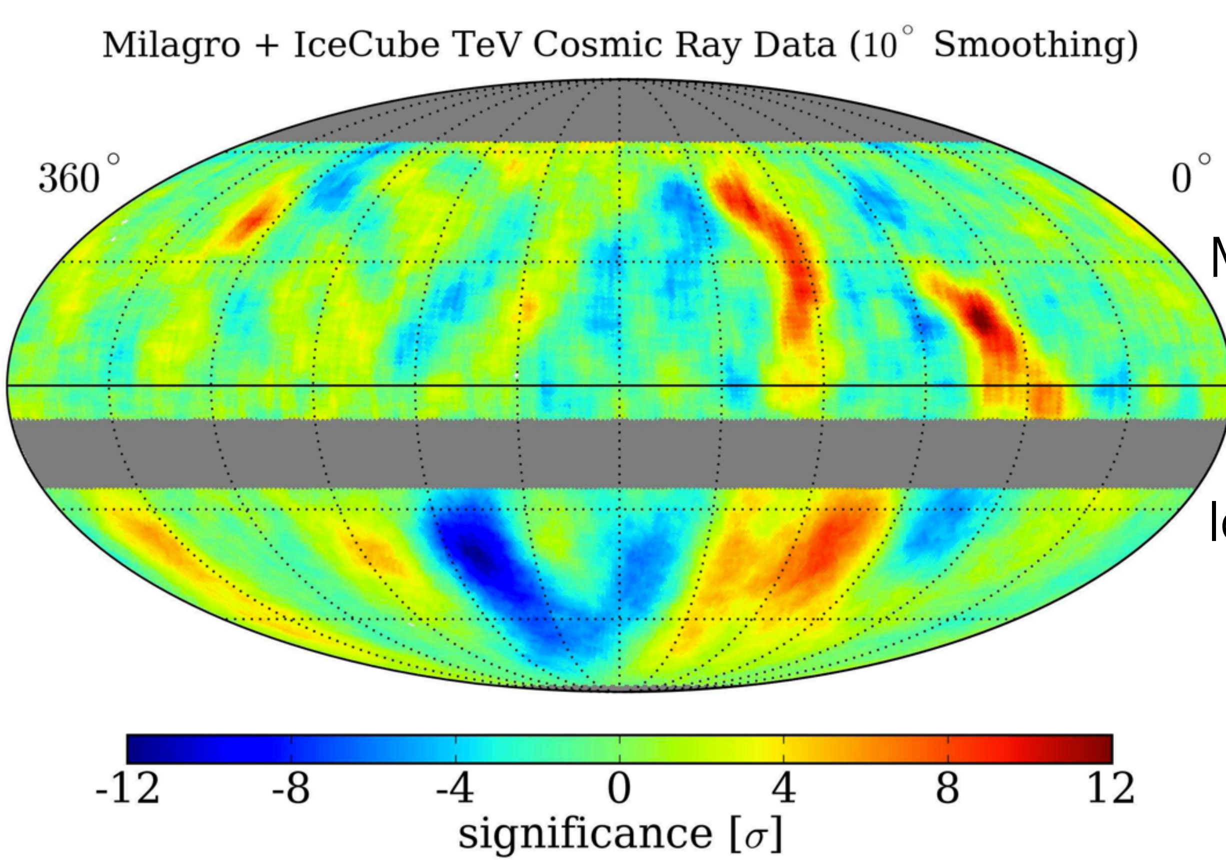
IceCube-59

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

20 TeV

2 hr = 30°

4 hr = 60°



Milagro

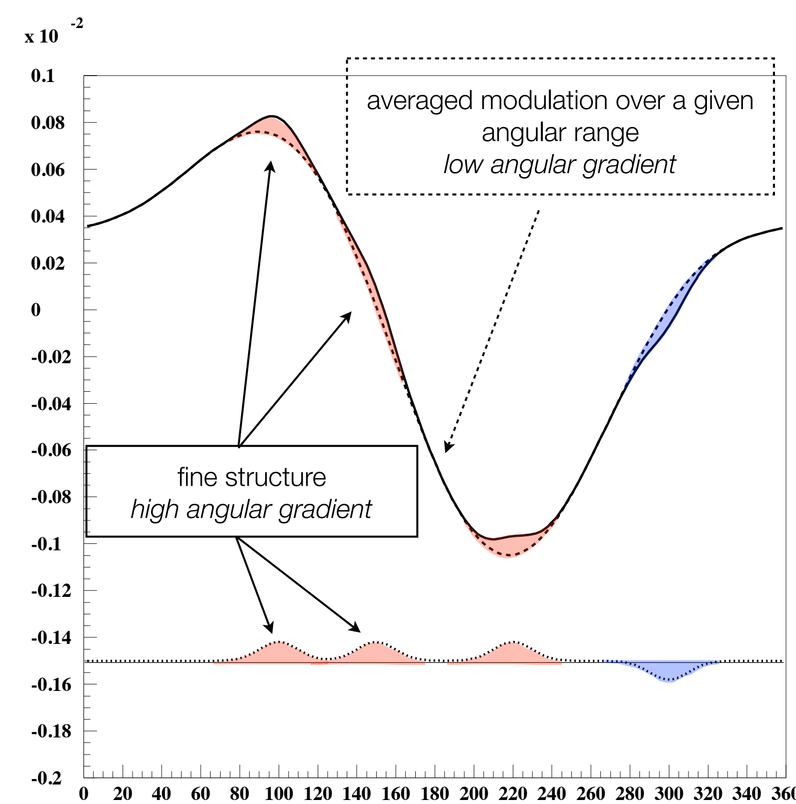
1 TeV

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

IceCube

20 TeV

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

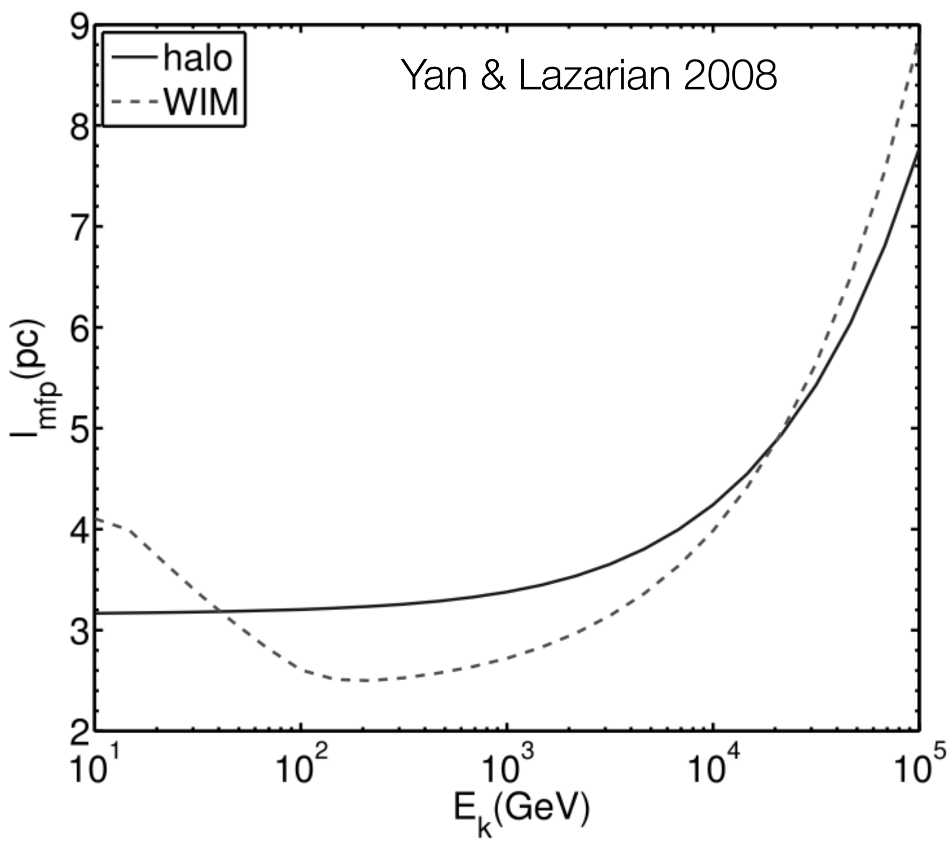


Paolo Desiati

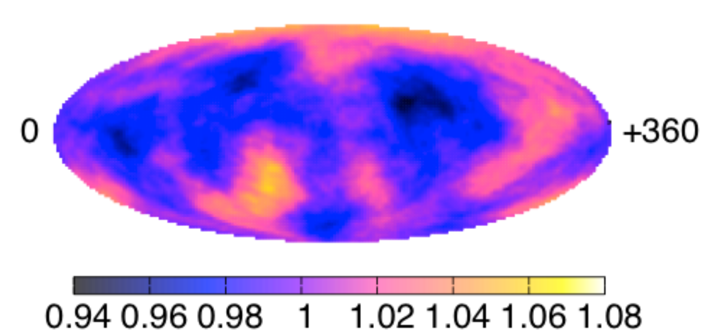
Wednesday, May 1, 2013

cosmic ray propagation
interstellar medium

- gyro-radius $R_L \approx \frac{200}{Z} \frac{E_{TeV}}{B_{\mu G}} [AU]$
- mean free path in ISM



- 1-100 TeV cosmic ray protons have R_L **≈ 70 - 7000 AU** in **B_{ISM} ~ 3 μG**
- **heliosphere** expected to influence cosmic rays below O(100) TeV
- cosmic ray streaming along local IS magnetic field
- **non-diffusive** effects < mean free path



Giacinti & Sigl 2011

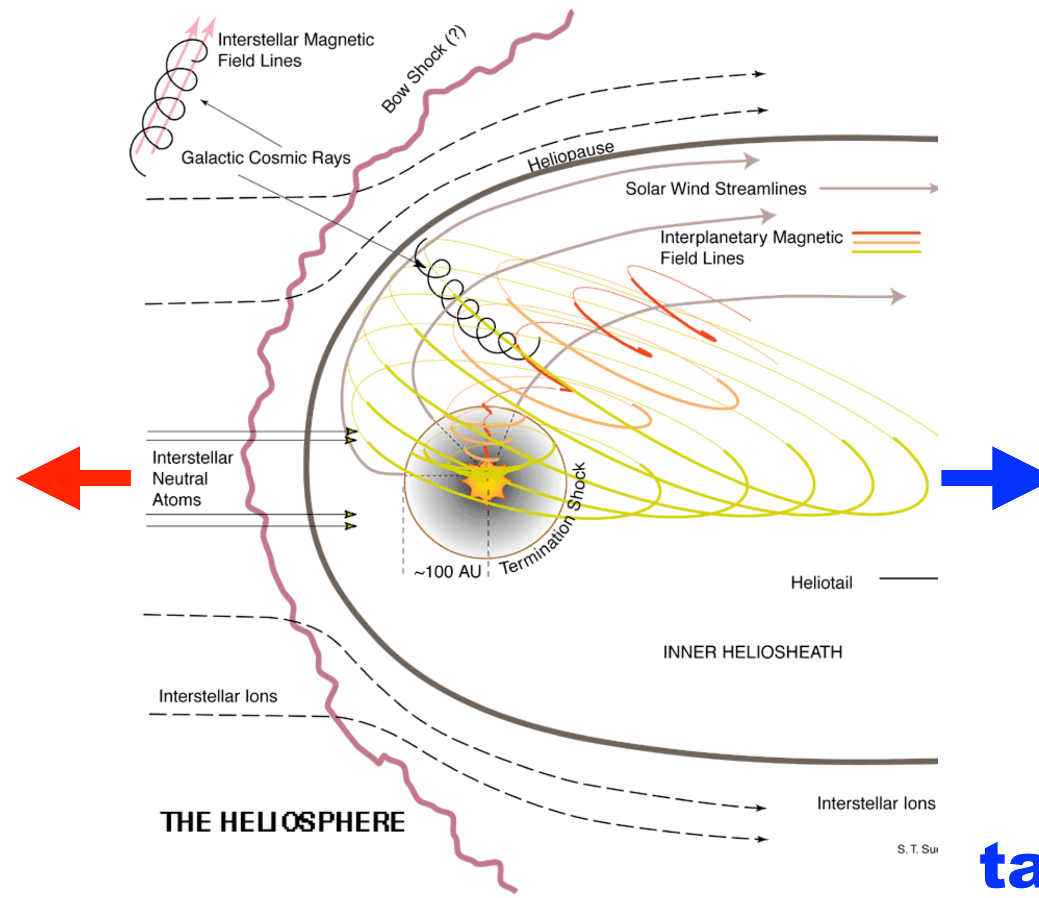
E/Z = 10 PeV

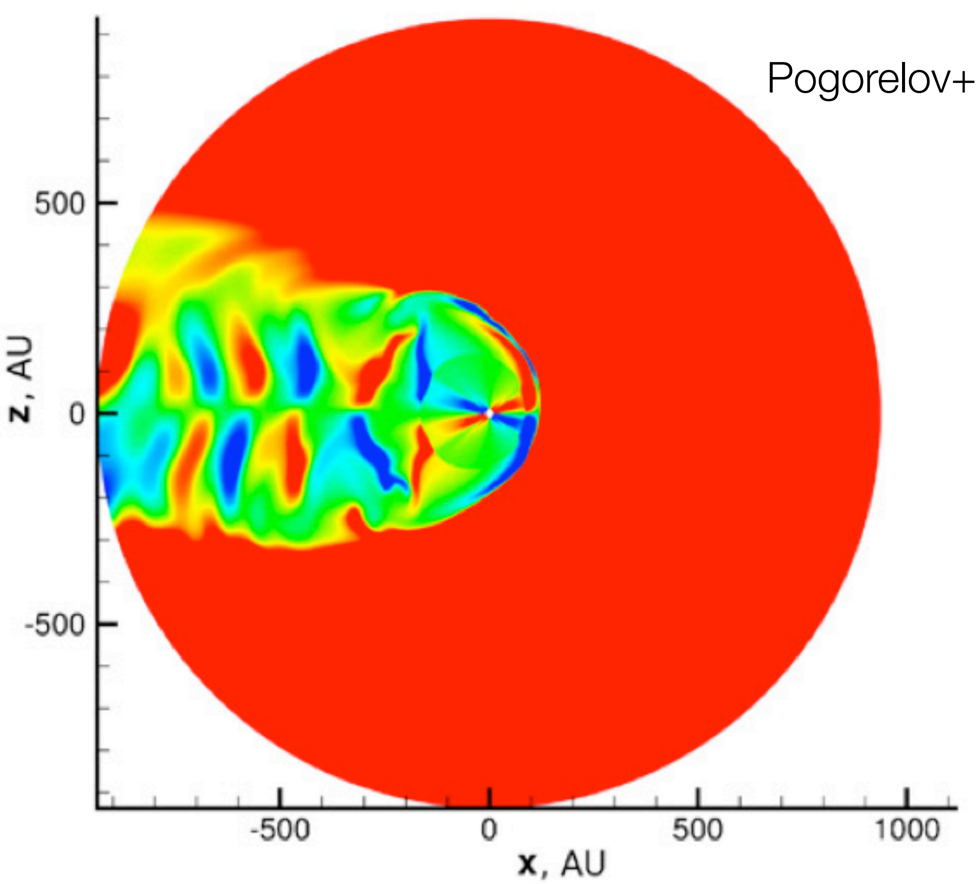
for random realization of B field

cosmic ray anisotropy

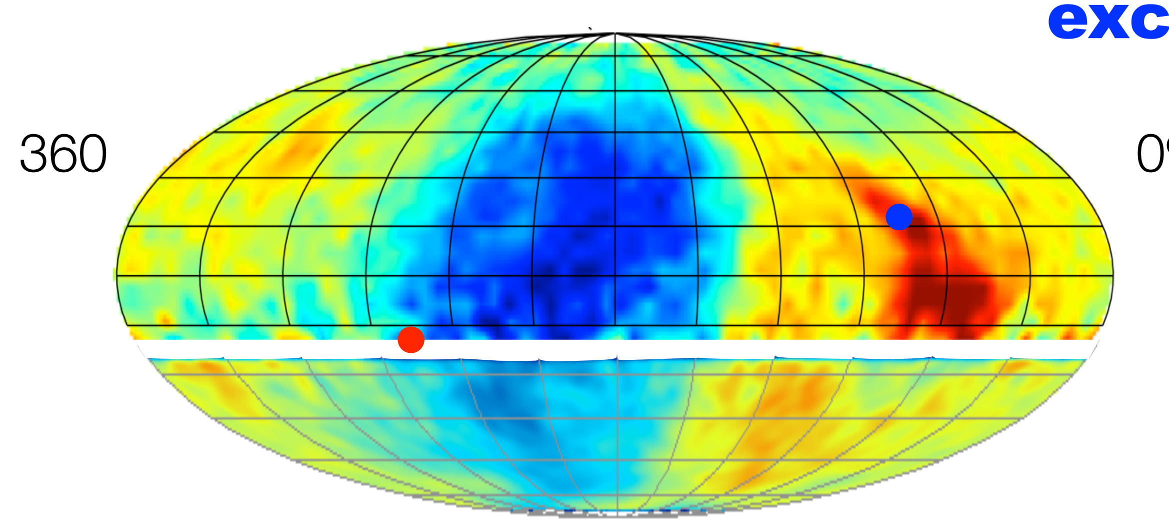
heliospheric influence

- MHD simulations of heliosphere & heliotail
- magnetic **perturbations** on the flanks with significant B amplification





tail-in excess

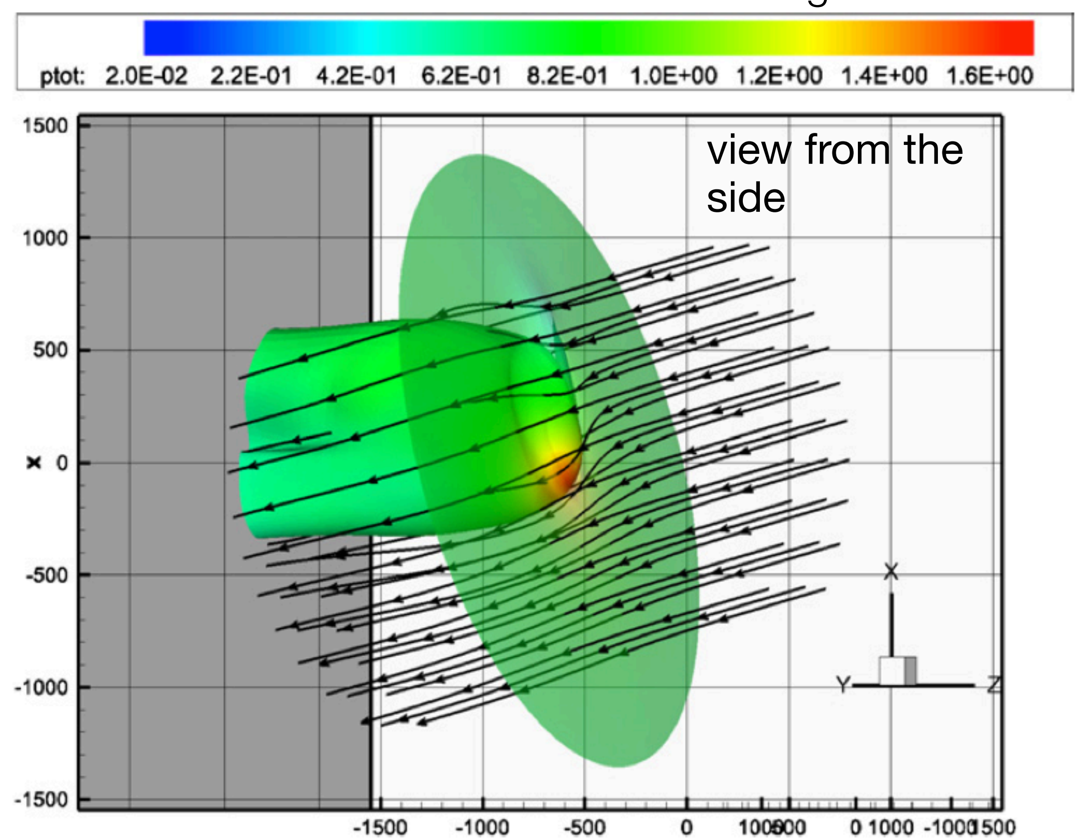


Paolo Desiati

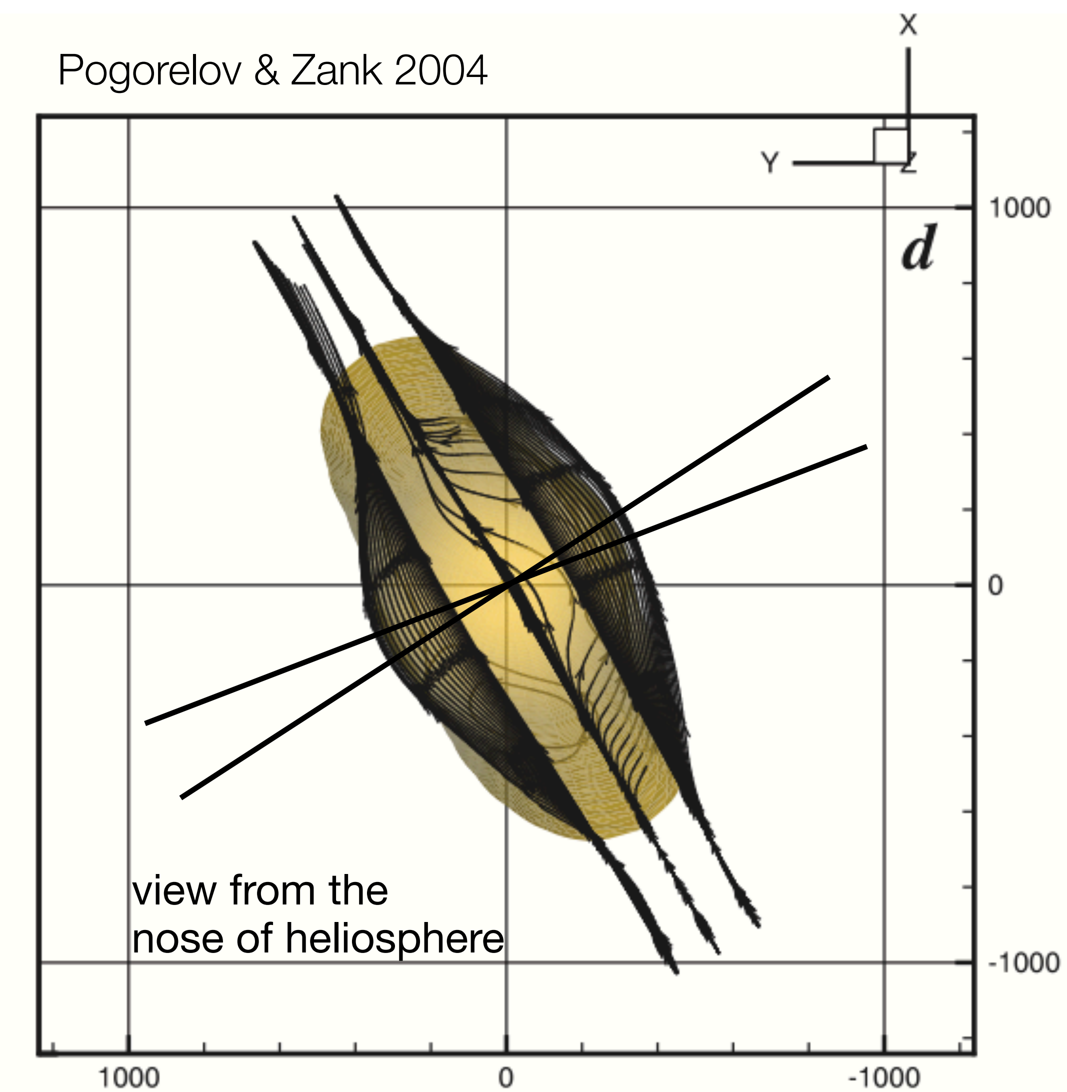
cosmic ray anisotropy
heliospheric influence

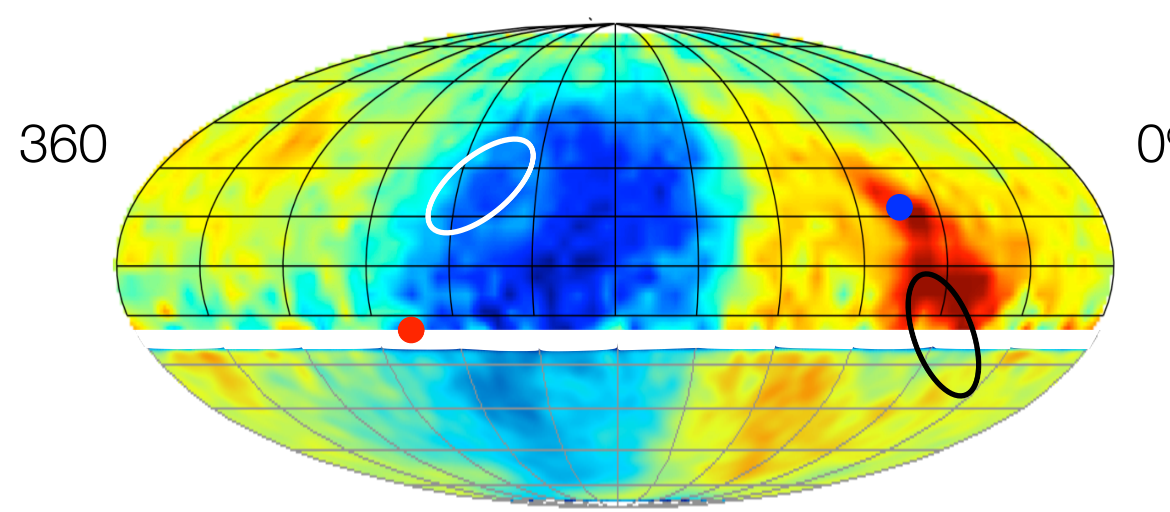
- local IS magnetic field draping the heliosphere

Pogorelov+ 2011



Pogorelov & Zank 2004

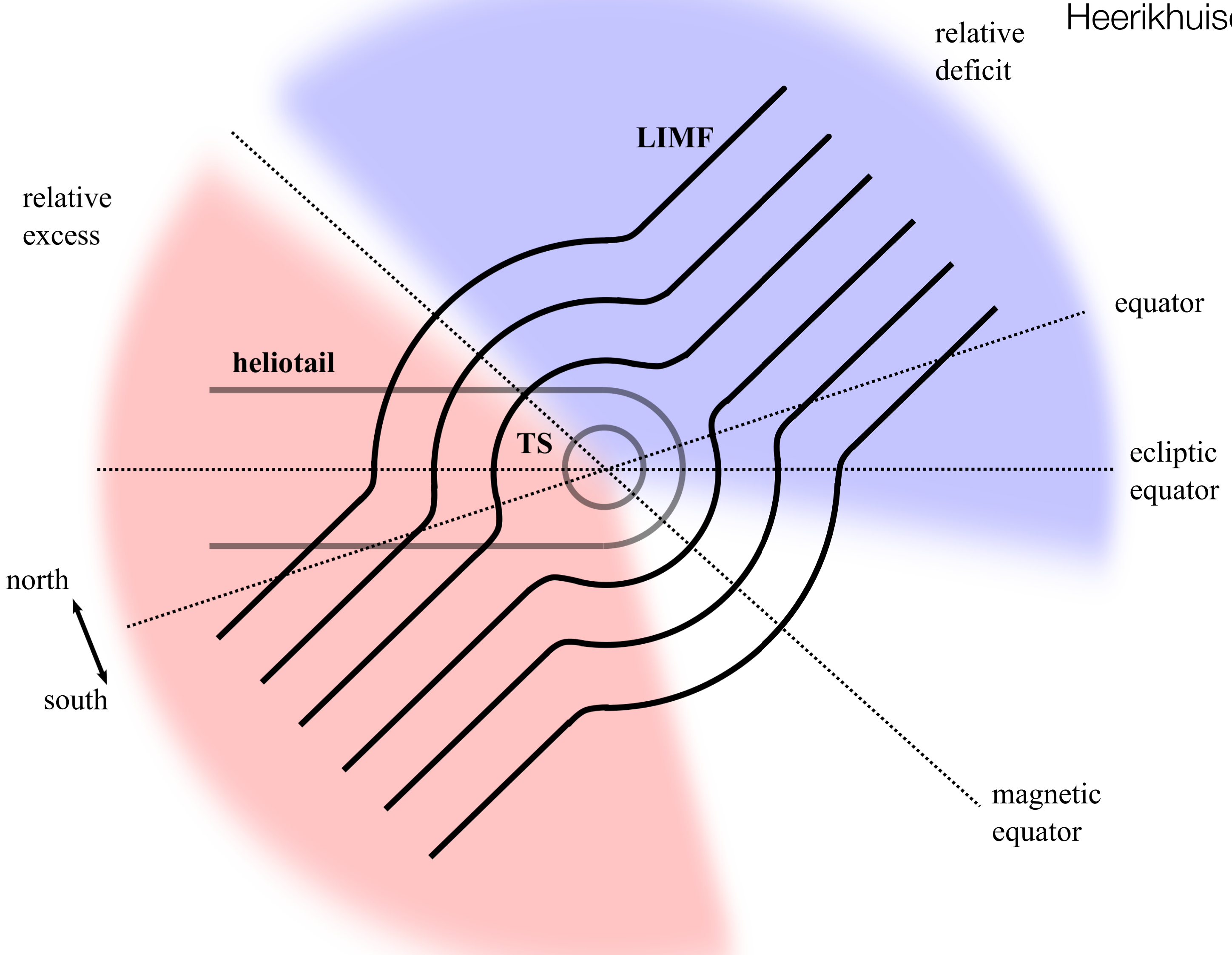




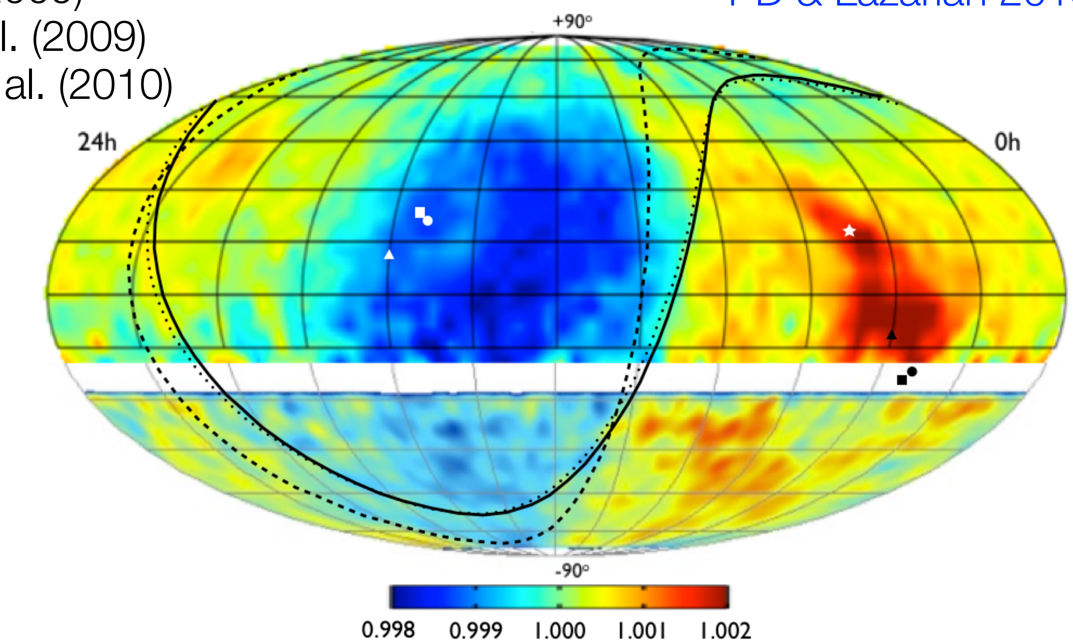
cosmic ray anisotropy & scattering

heliospheric influence

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

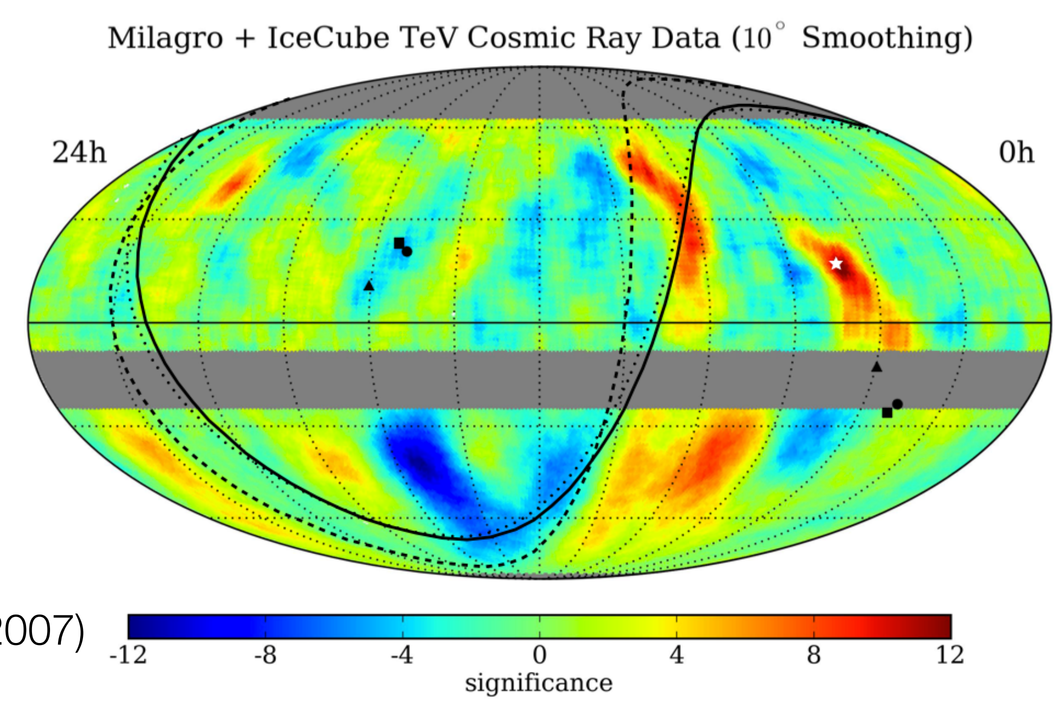


PD & Lazarian 2013



equatorial coordinates

magnetic
equator

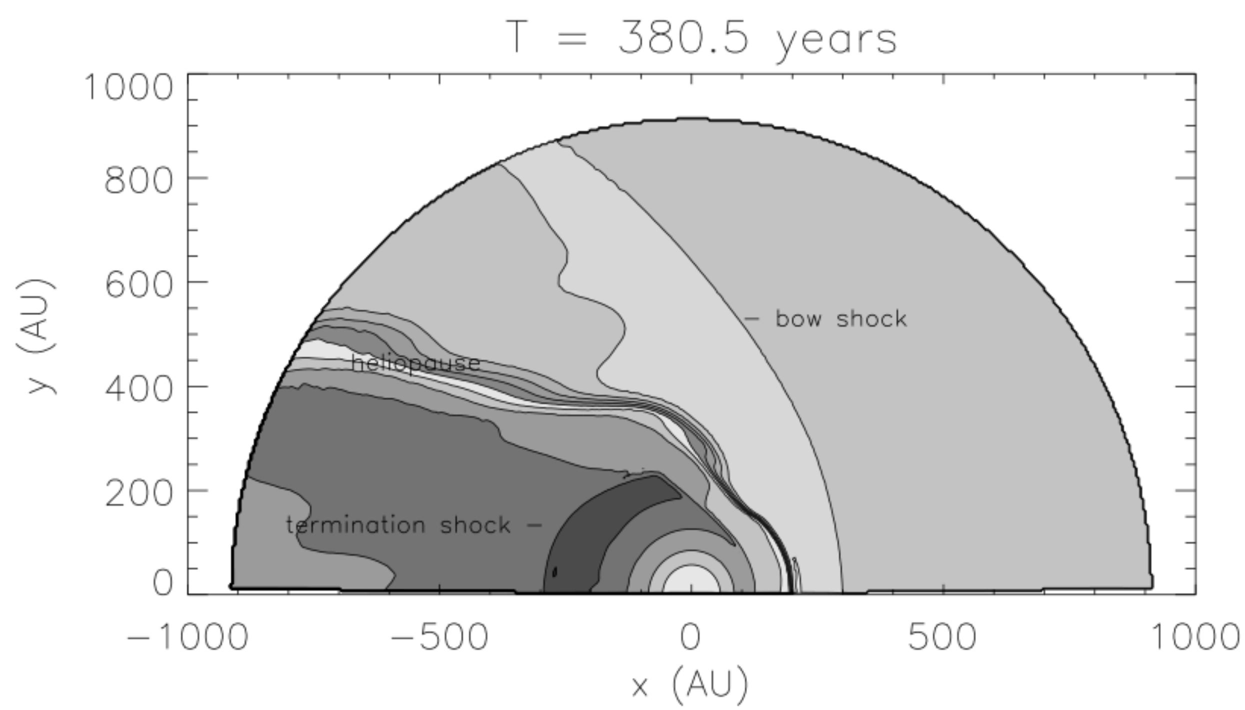


LIMF direction compatible with

- 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)

heliospheric perturbations
instabilities at the heliopause

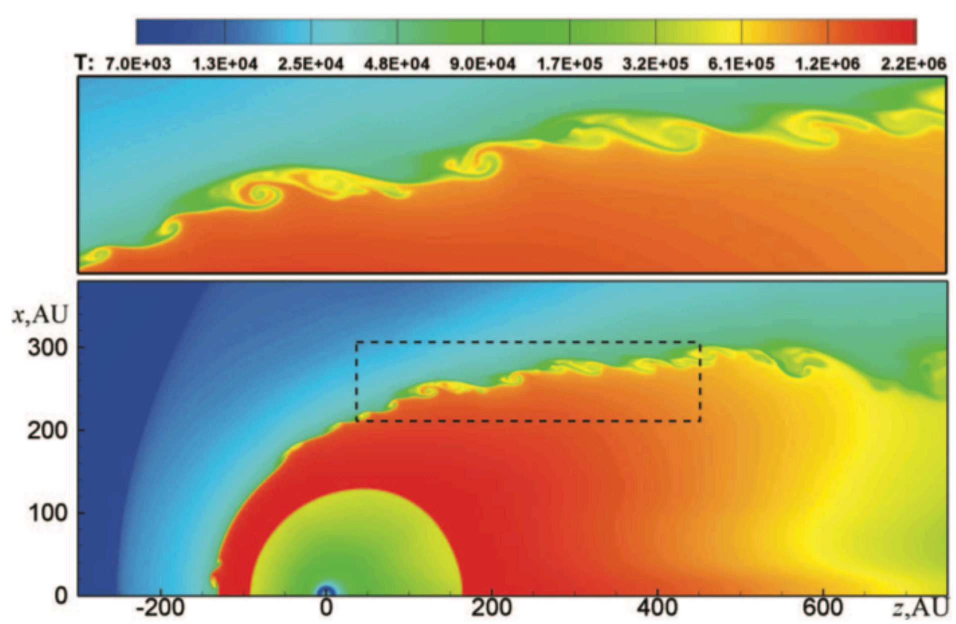
- Rayleigh-Taylor instabilities driven and mediated by interstellar neutral atoms



perturbation scale O(10-100) AU

Liewer+ 1996
Zank+ 1996

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

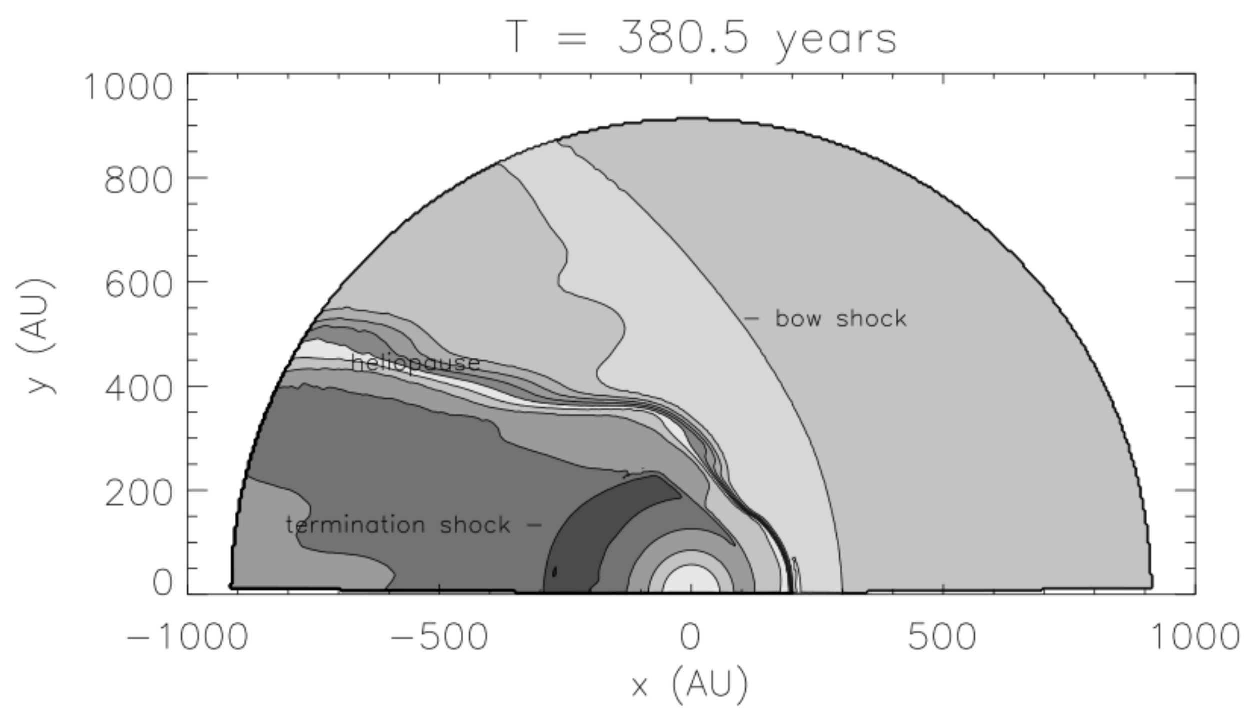


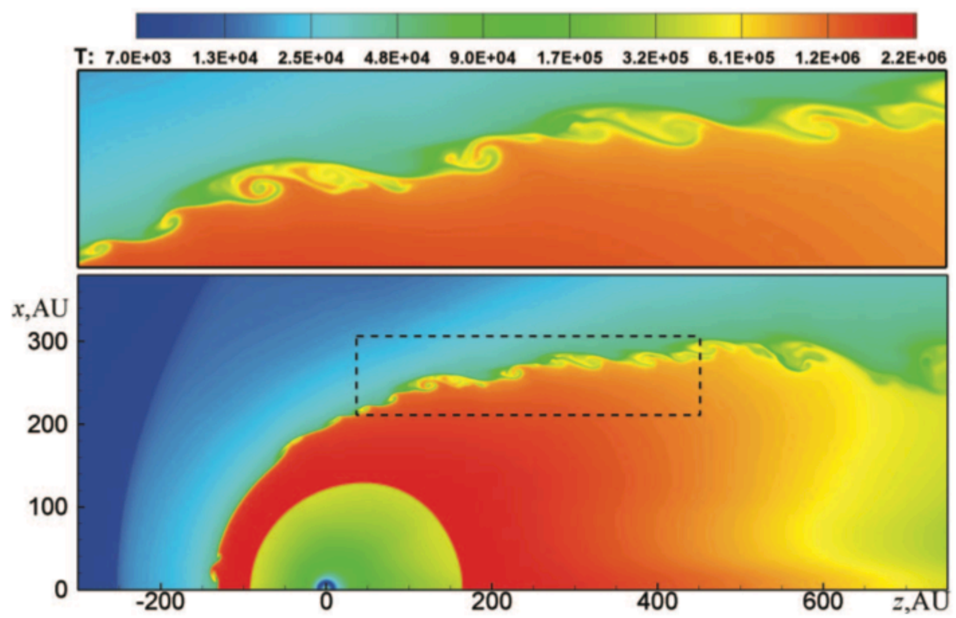
≈ 200-300 AU

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

heliospheric perturbations

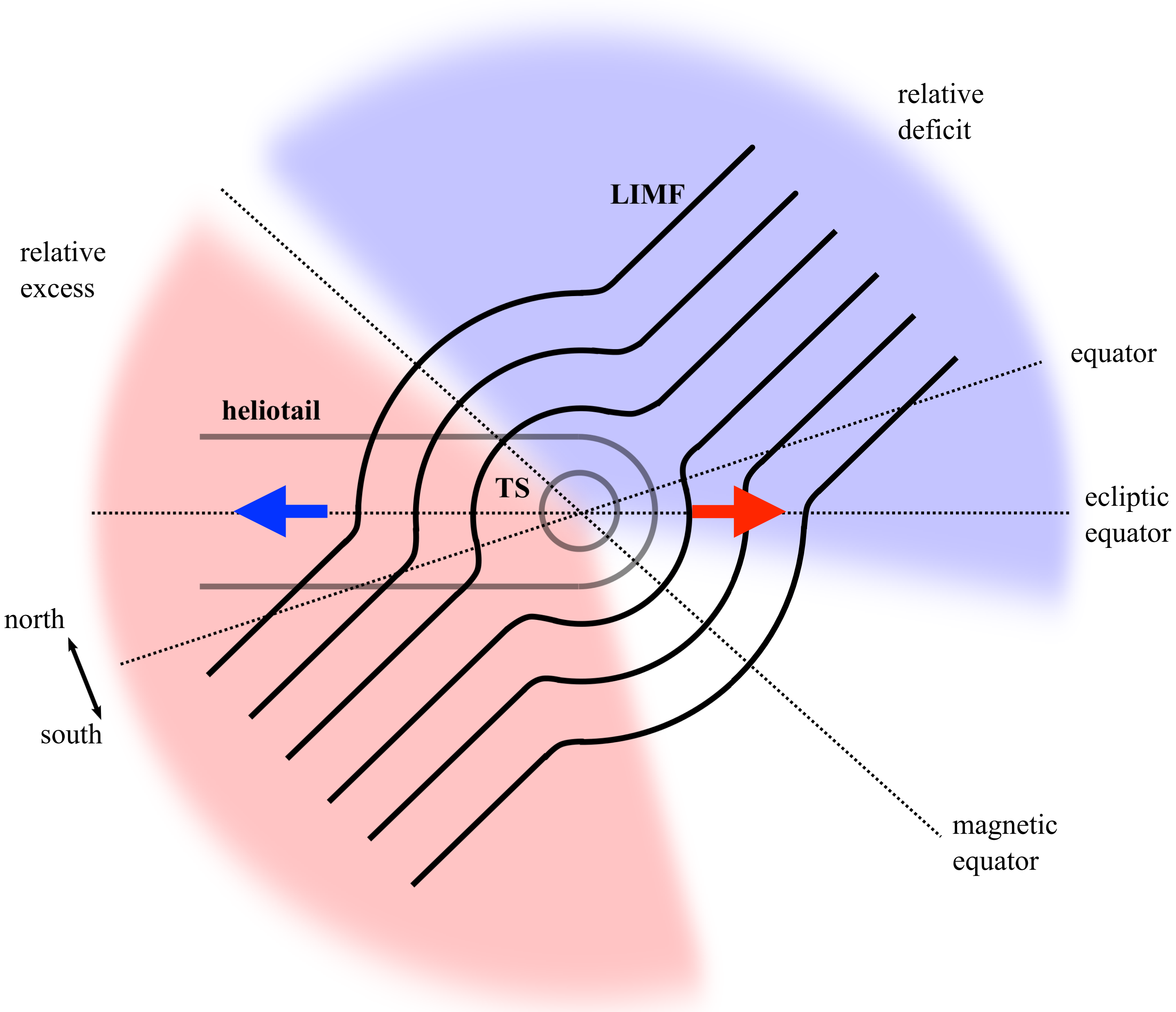
instabilities

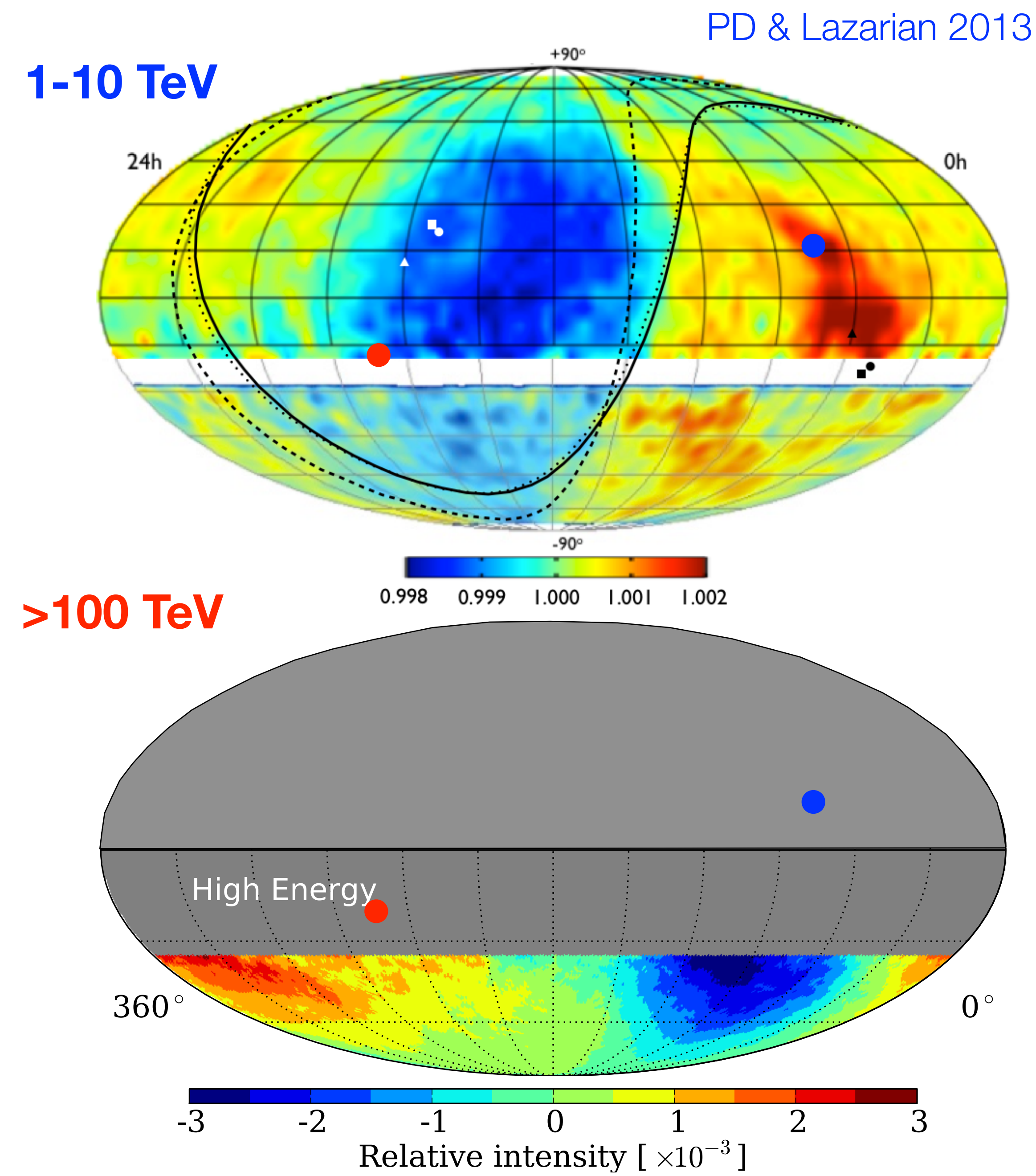




- **resonant scattering** of protons on magnetic perturbations $\delta B \sim B_0$ at scales of $\approx$ 300 AU occurs at $\approx$ **10 TeV**
- perturbations on the flanks of the heliosphere **re-distribute 10 TeV** cosmic rays
- local IS magnetic field and magnetic perturbations along the heliotail responsible for **TeV anisotropy**
- some **small scale features** from gradients generated by scattering

cosmic ray anisotropy
probing heliospheric influence



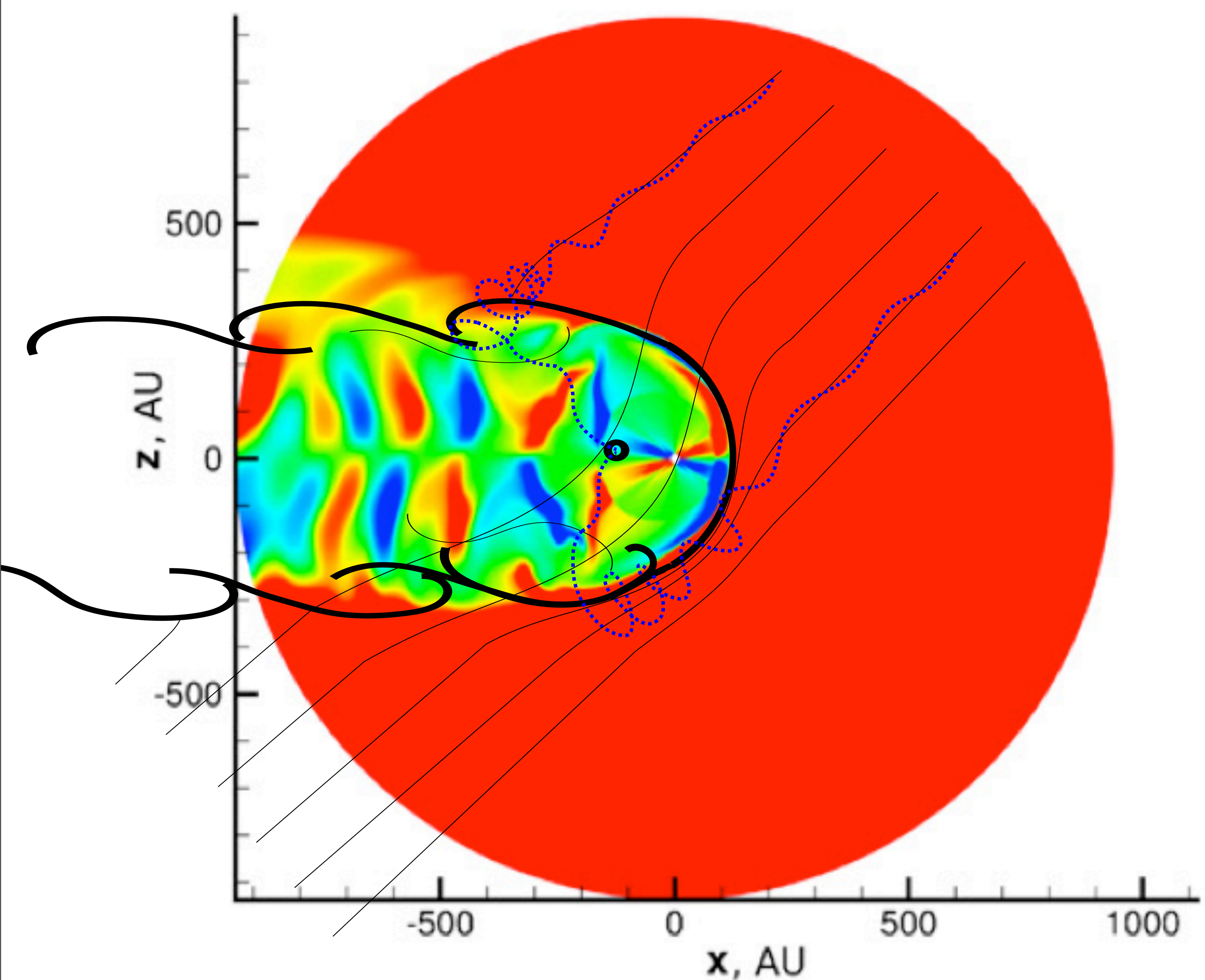


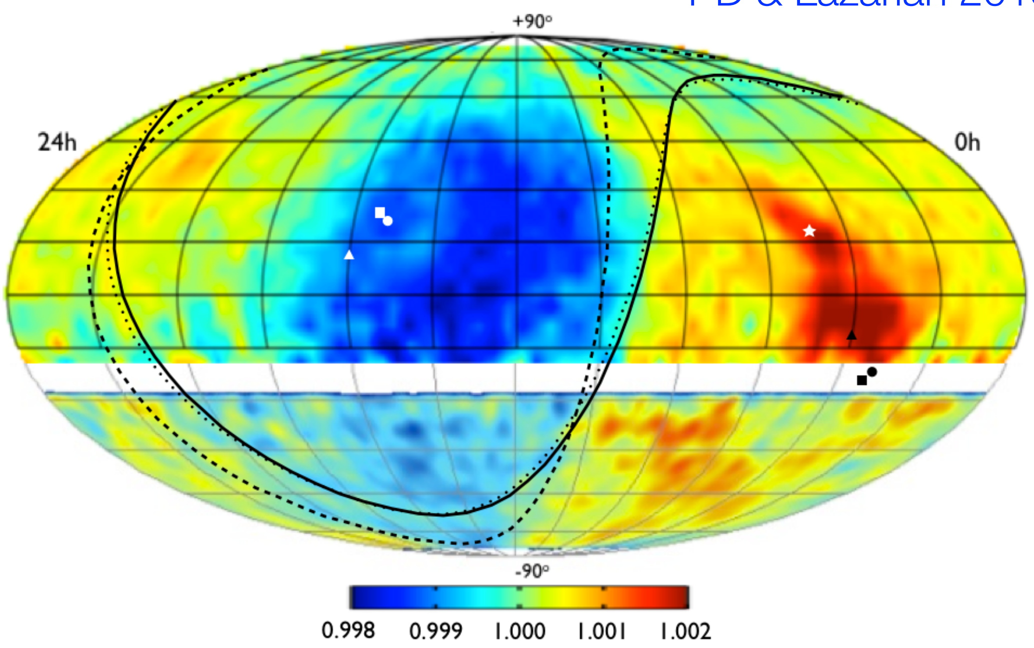
anisotropy re-directed due to ***pitch angle scattering*** on magnetic perturbations on the heliospheric boundary

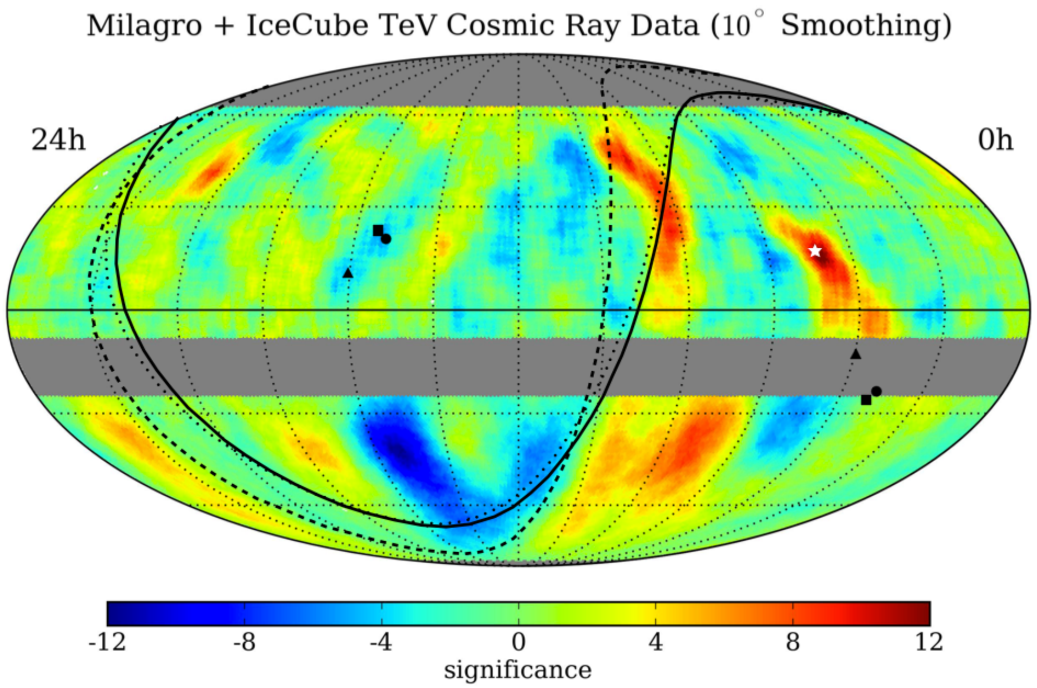
scattering on heliospheric boundary

toy model

PD & Lazarian 2013



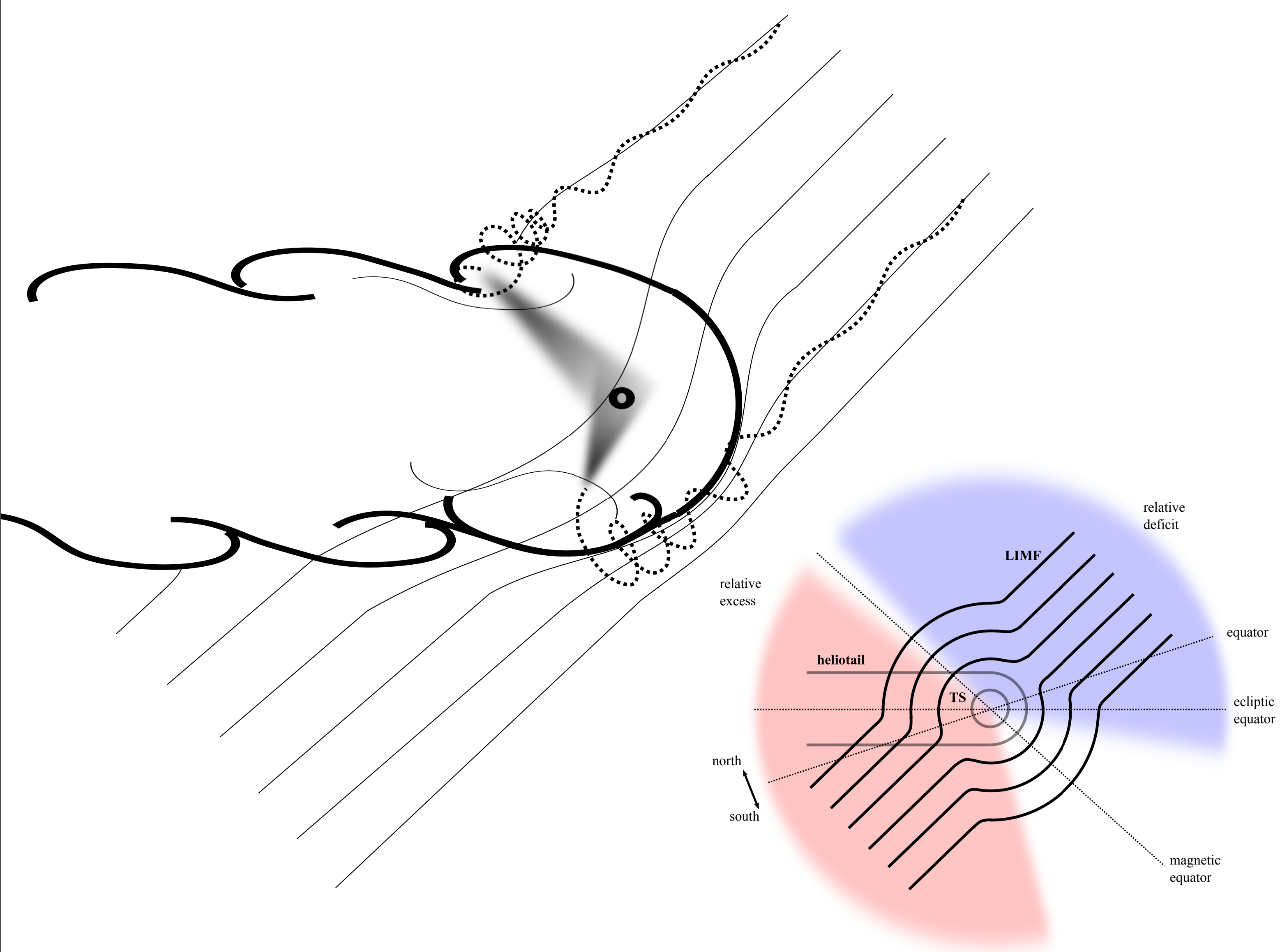


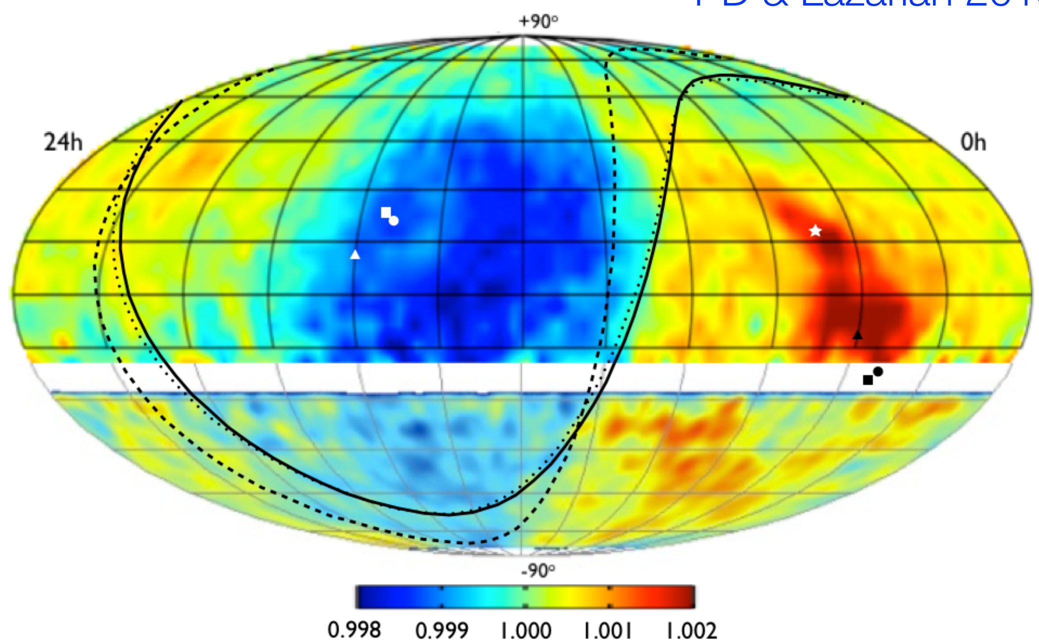


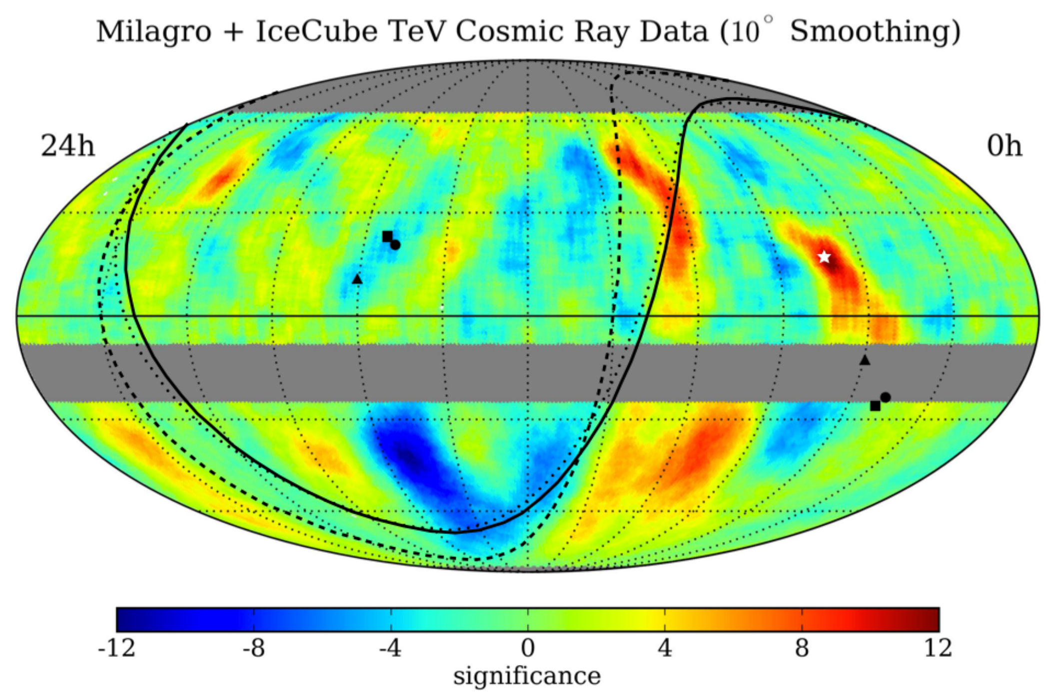
scattering on heliospheric boundary

toy model

PD & Lazarian 2013





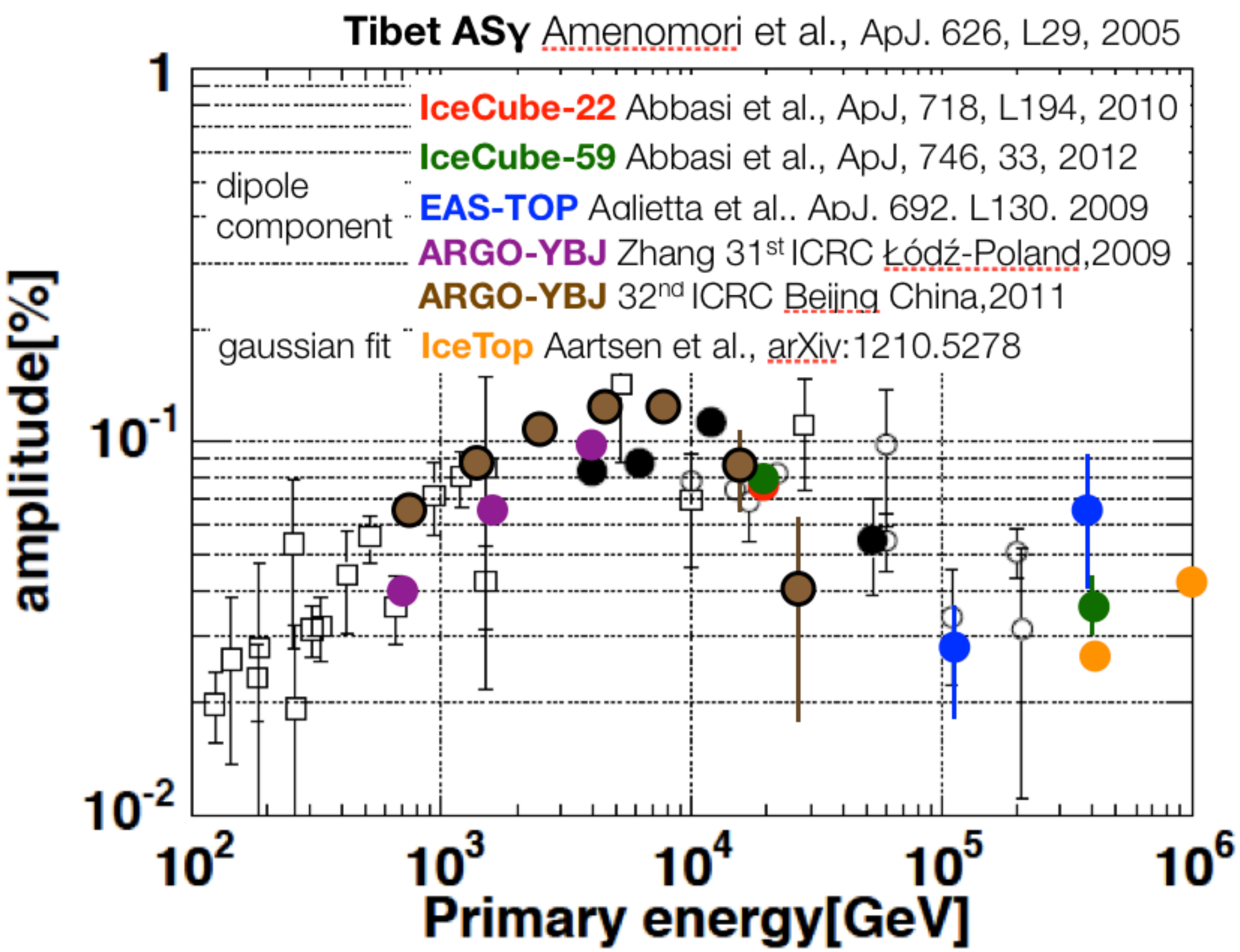


- detailed modeling of heliotail very important

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



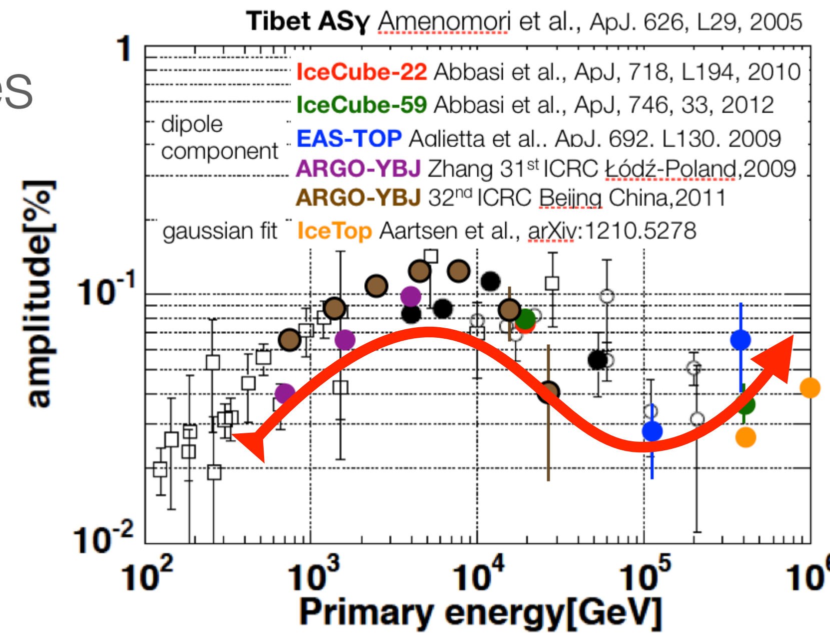
scattering on heliospheric boundary
toy model

- @ 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 - and adiabatic pitch angle variations from $p^2_{\perp}/B$

- > 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

conclusions

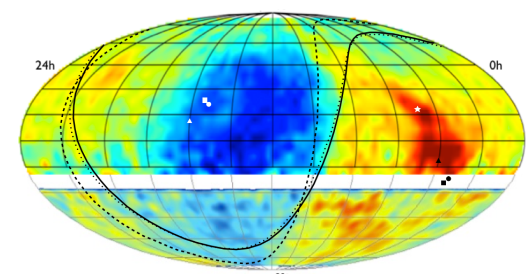
- high energy **cosmic ray anisotropy** to probe into their **origin** and **propagation**

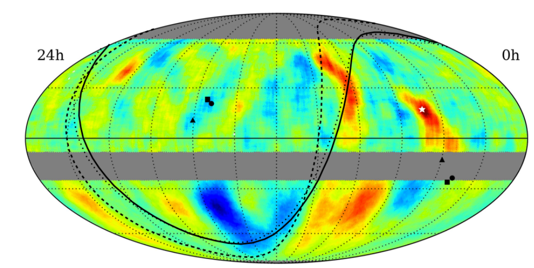
- astrophysical scenarios need understanding of local phenomena

- <100 TeV cosmic rays to be **affected by heliosphere**

PD & Lazarian 2013

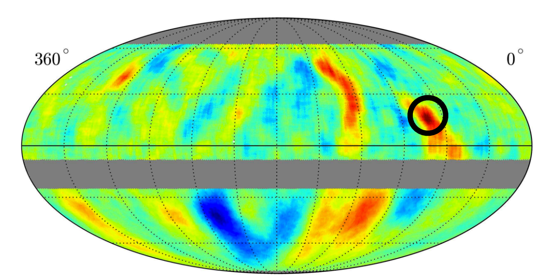
- **scattering** with perturbation on heliopause

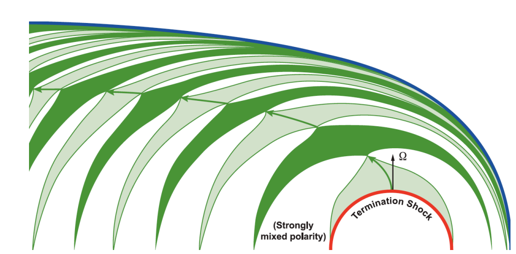




Lazarian & PD 2010 - PD & Lazarian 2012

- **re-acceleration** mechanism in the heliotail





- heliospheric modeling to be extended along **heliotail** with fine resolution: instabilities, 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
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Priscilla Frisch
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Markus Ahlers
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Francis Halzen
Albrecht Karle
Kim Kreiger
Marcos Santander
Stefan Westerhoff
WIPAC

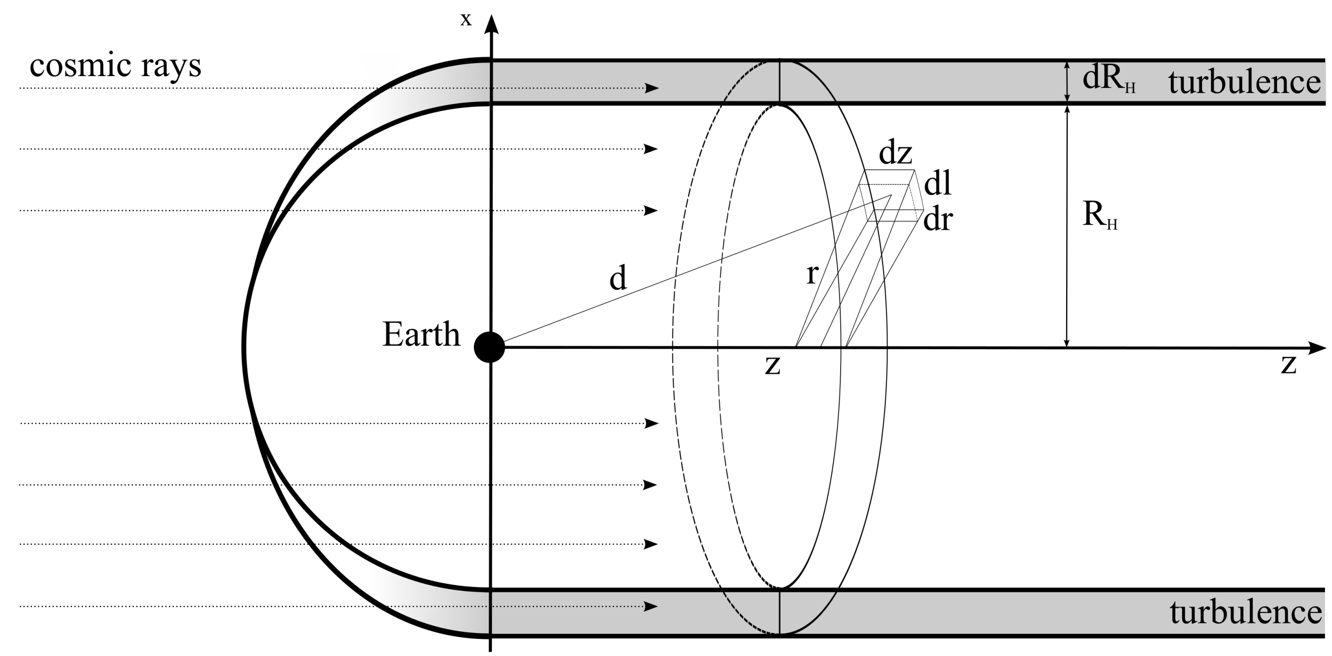
backup

scattering on heliospheric boundary
toy model

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

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

$$= n_{\rm CR}\, P_s\, \pi^2\, R_E^2\, dR_H,$$



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

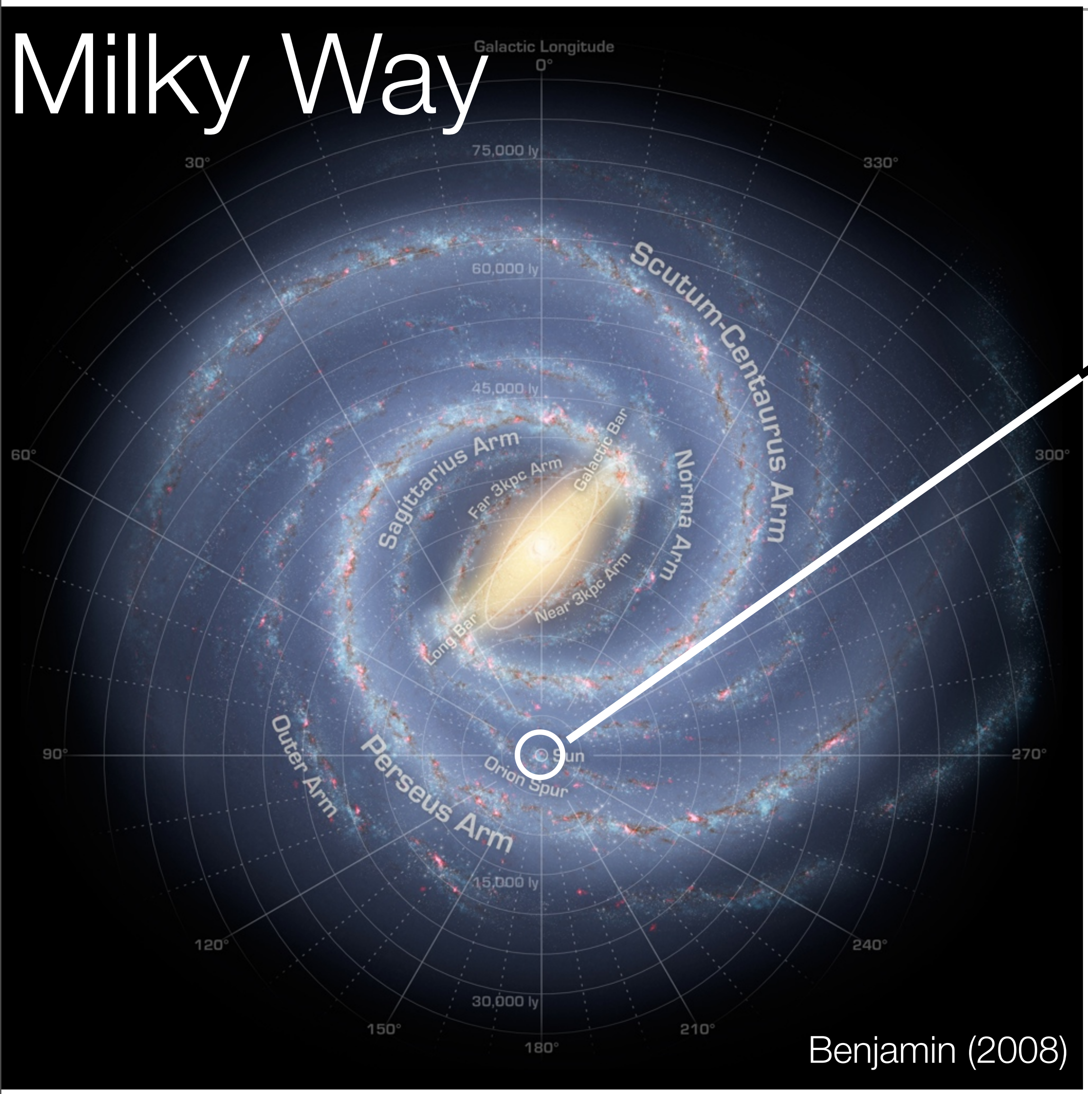
$$\delta = \frac{N_b - N_d}{N_b + N_d} = \frac{N_b/N_d - 1}{N_b/N_d + 1},$$

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

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

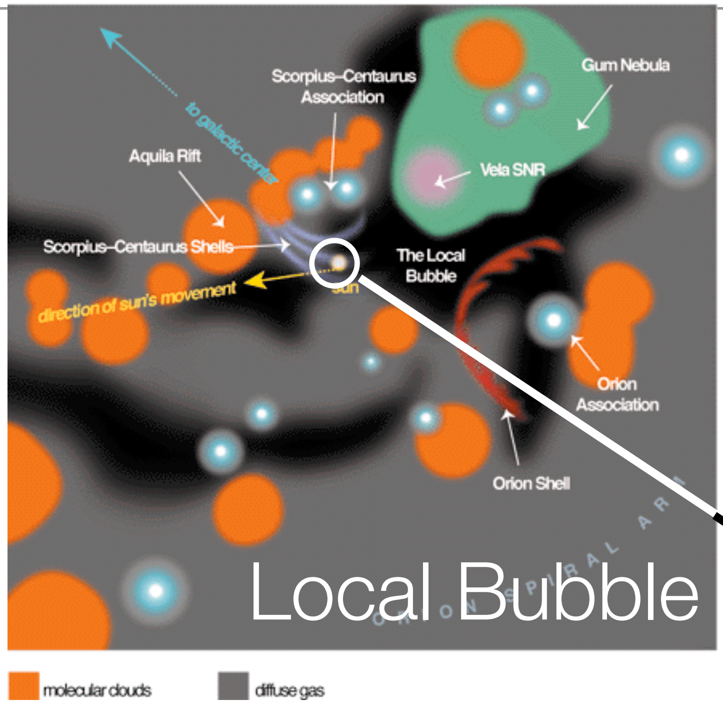
$$R_g \approx \frac{200}{Z}\left(\frac{E}{1\,TeV}\right)\left(\frac{\mu G}{B}\right)\, AU$$

from the Galaxy to our local interstellar medium



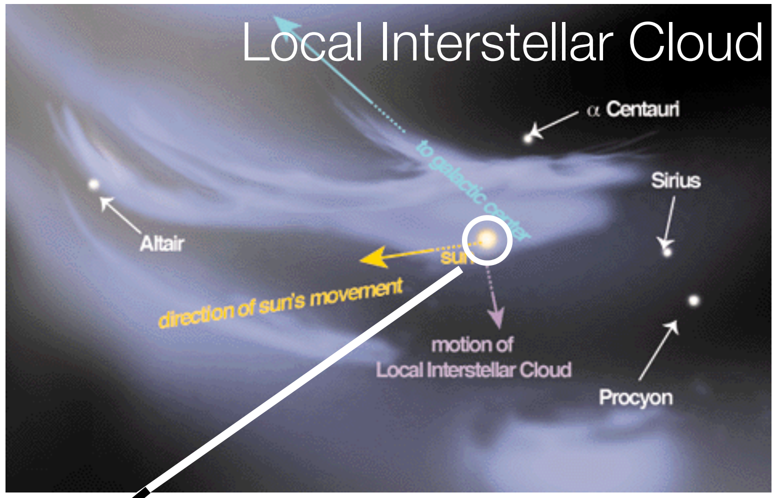
< 30,000 pc > (80 EeV)

Frisch



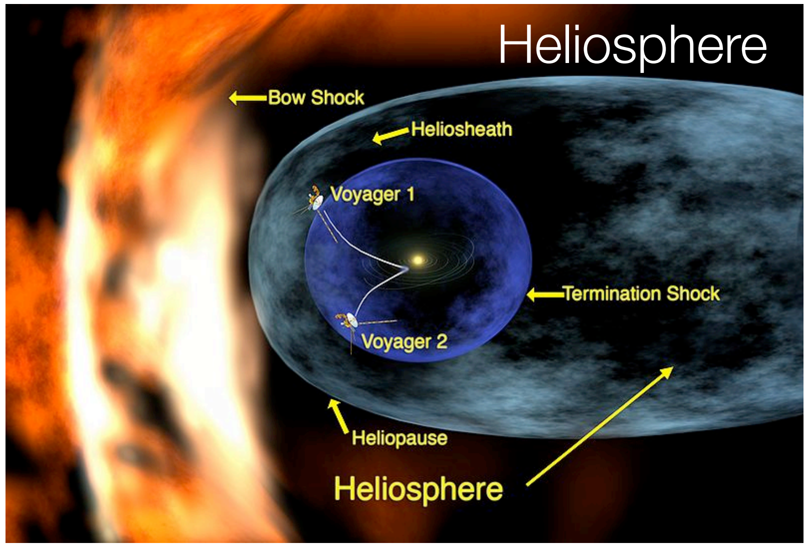
< 500 pc > (1.4 EeV)

Frisch



< 10-50 pc >

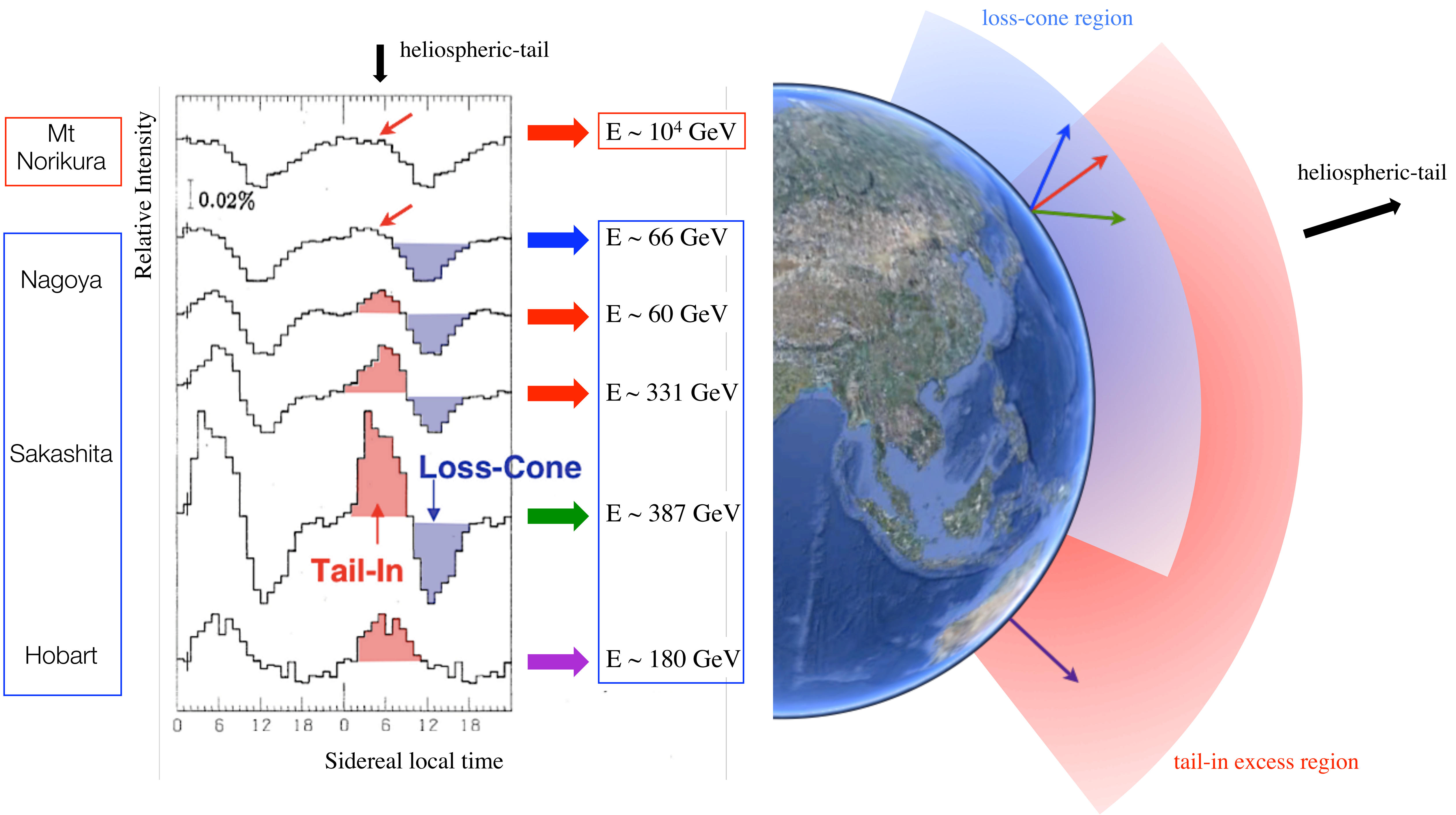
(30 PeV - 140 PeV)



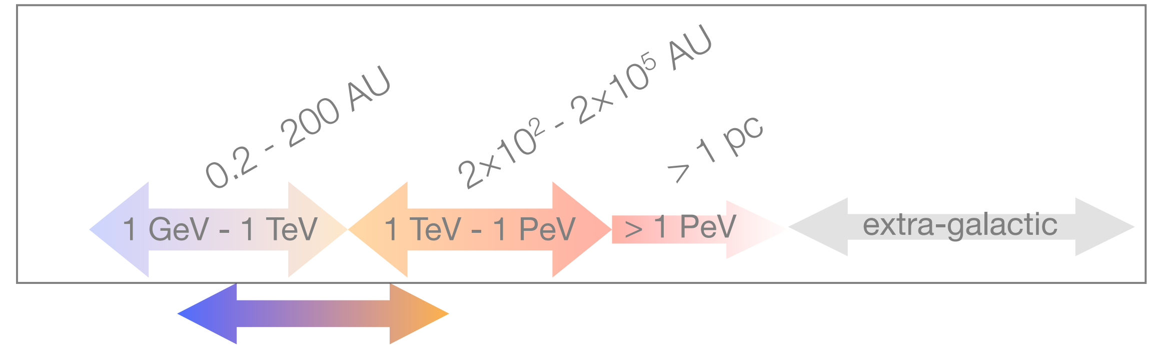
(3 TeV - 140 TeV) < 200 AU - 10^4 AU >

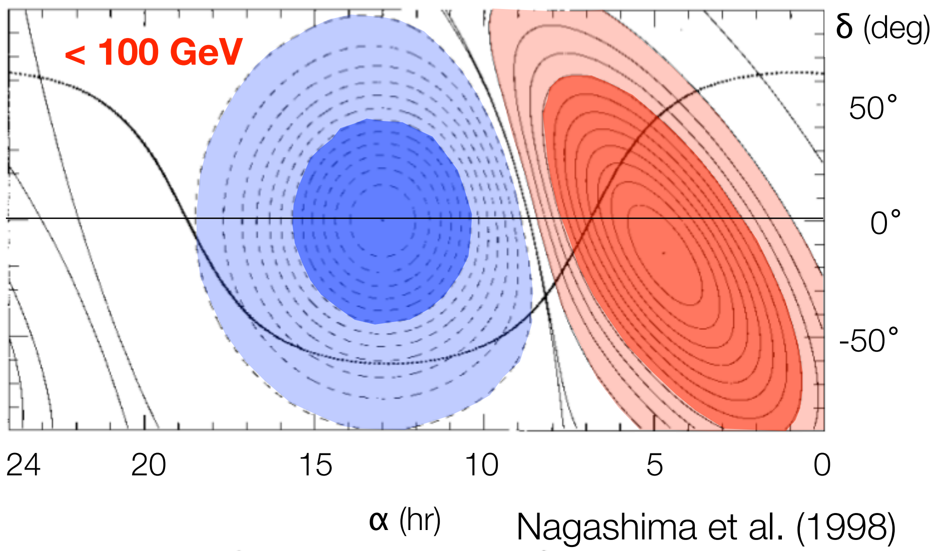
low energy cosmic ray anisotropy in arrival direction

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

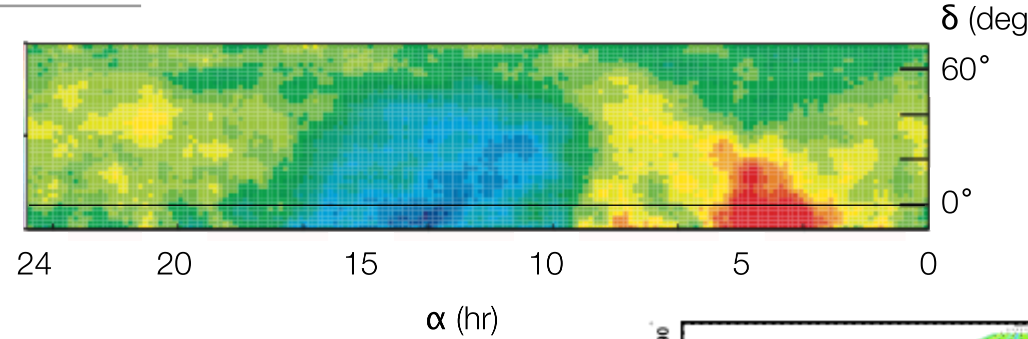


cosmic ray anisotropy

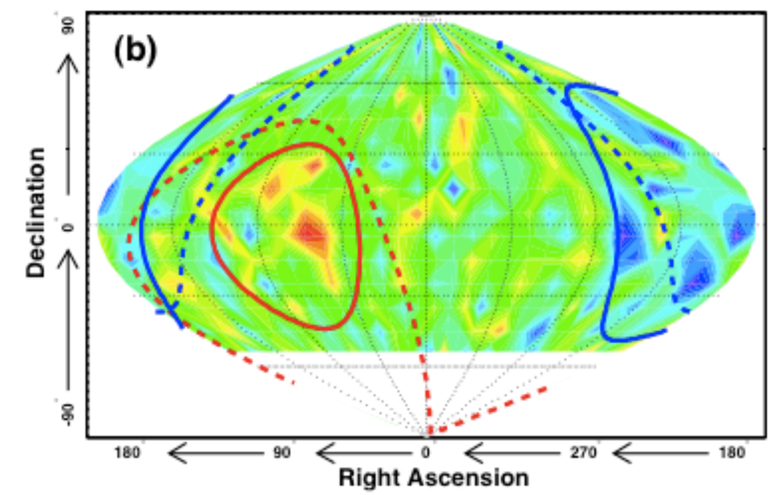




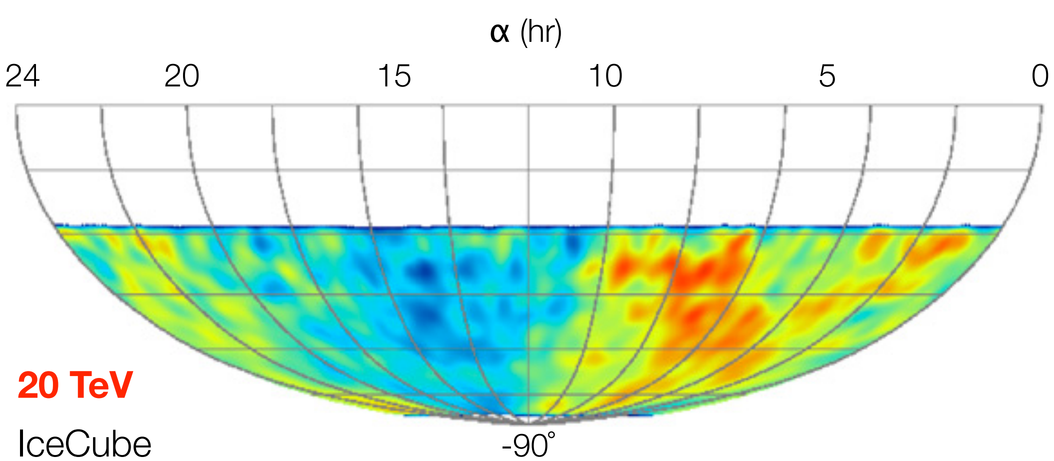
Nagashima et al. (1998)
Hall et al. (1999)



4 TeV
Tibet ASγ
Amenomori et al. (2006)

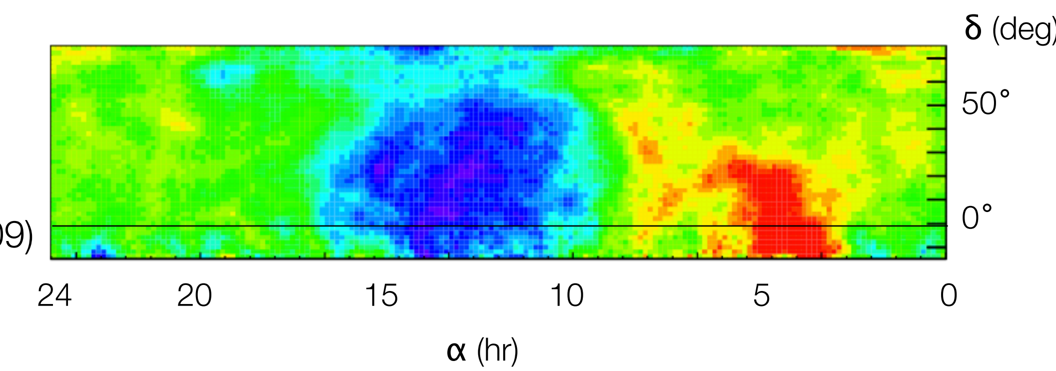


10 TeV
Super Kamiokande
Guillian et al. (2007)

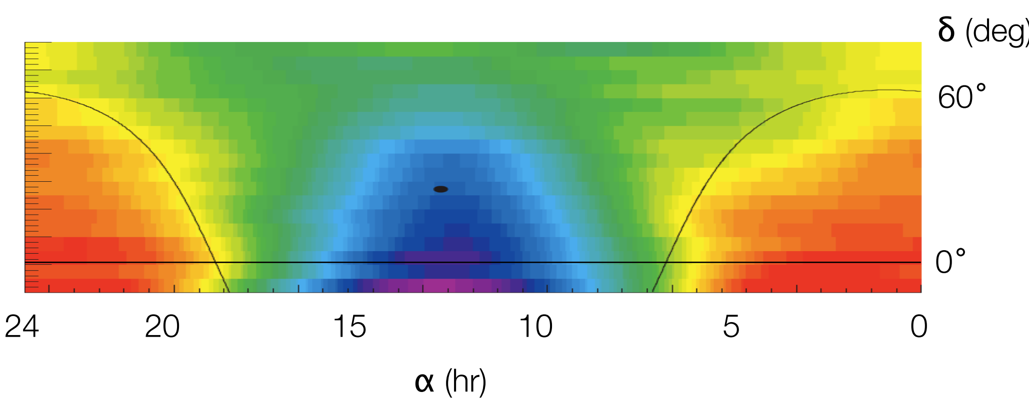


20 TeV
IceCube
Abbasi et al. (2010)

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

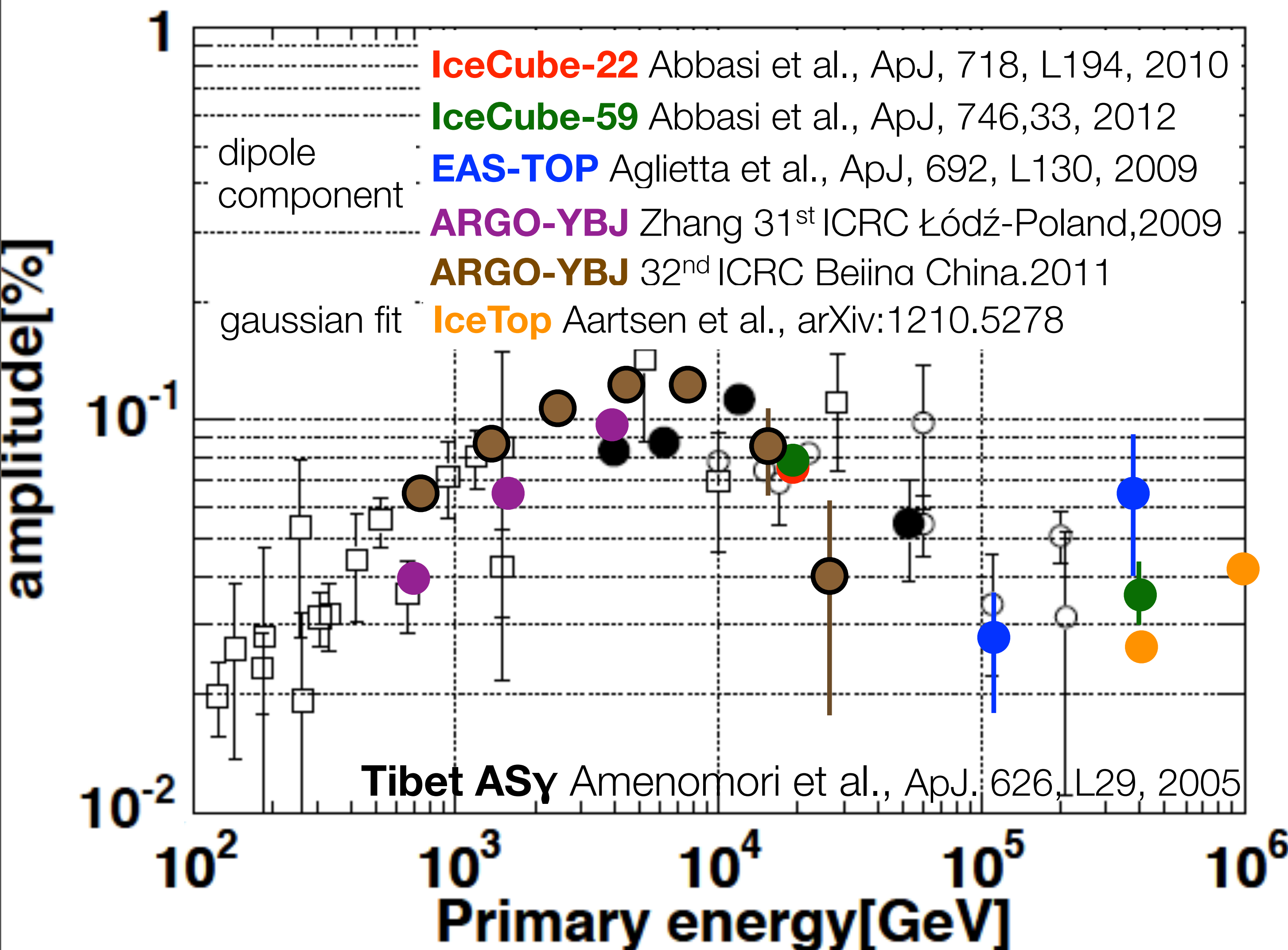


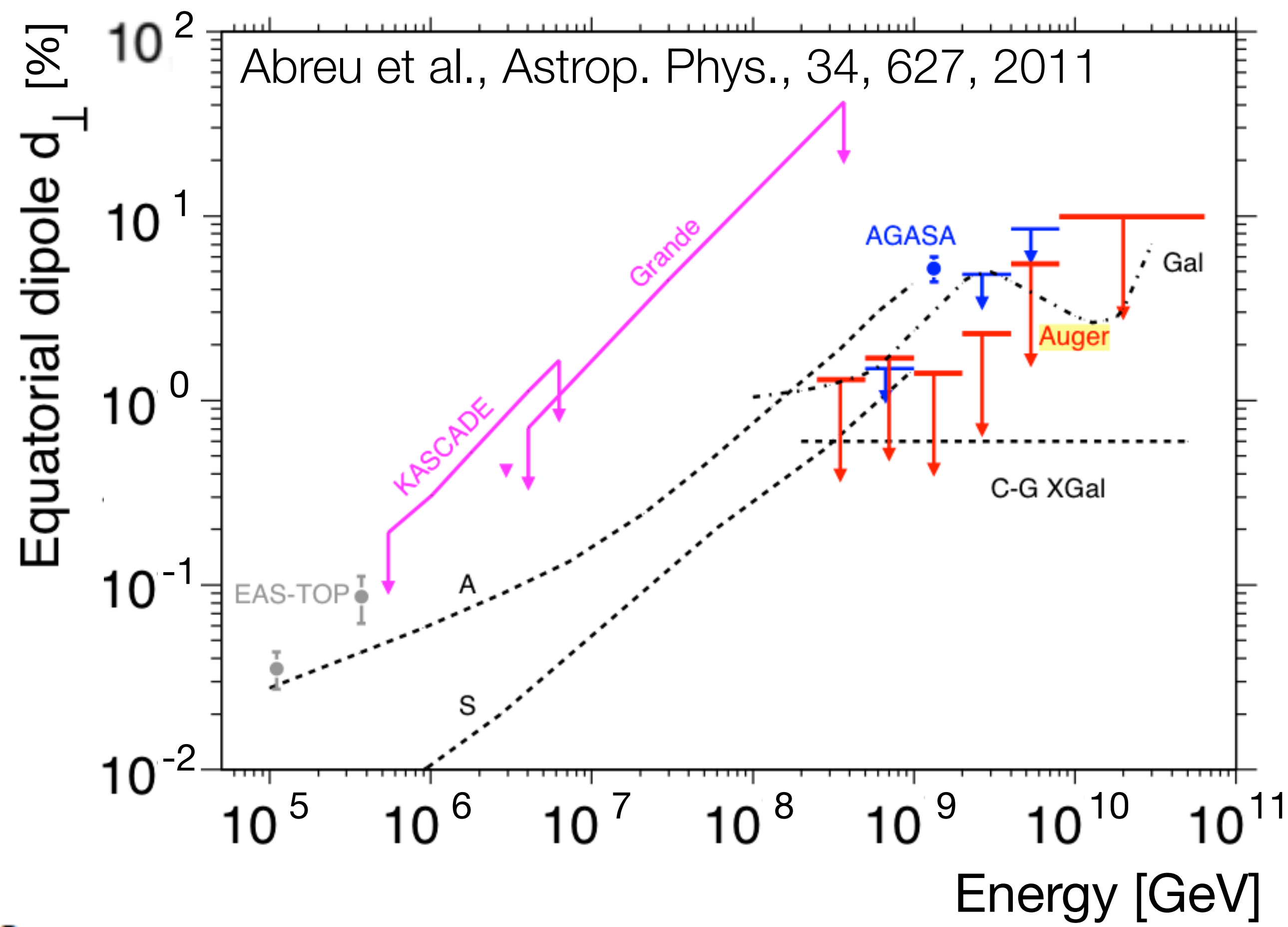
5 TeV
Milagro
Abdo et al. (2009)



equatorial coordinates

cosmic ray anisotropy large scale
energy dependency



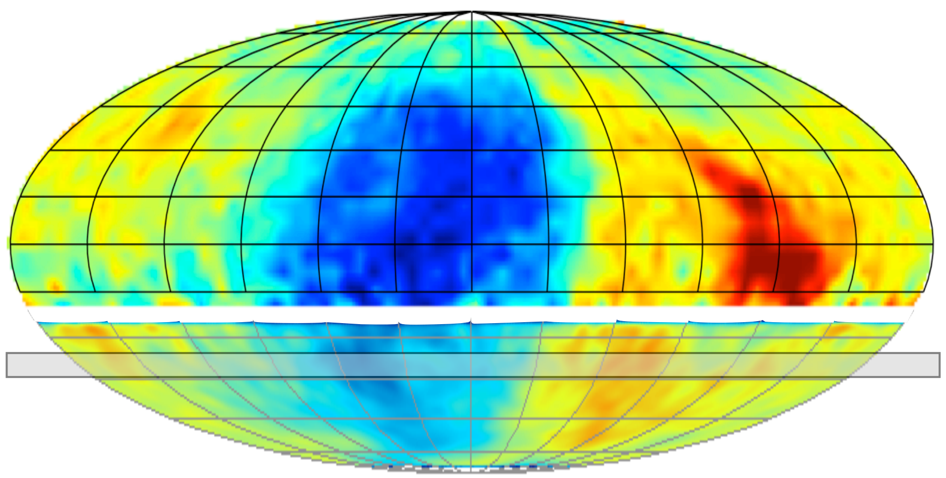


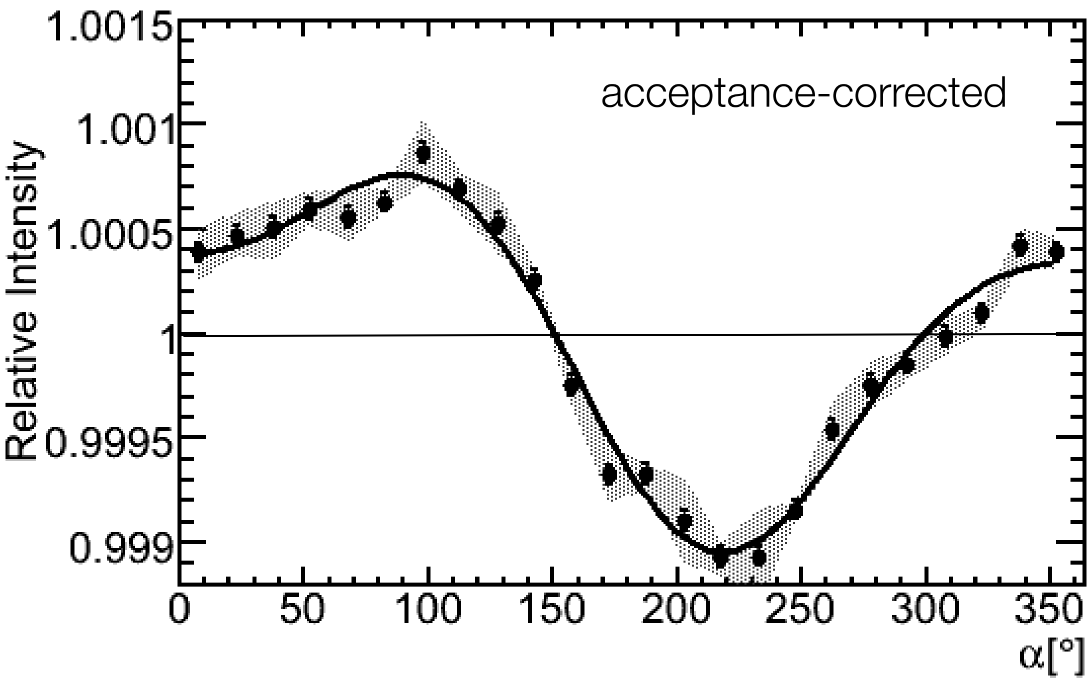
$$\delta A = \left| \sum_{SNR} \frac{eD(E)}{c} \cdot \frac{\vec{\nabla}\phi_{CR}}{\phi_{CR}}(E) \right|$$ anisotropy amplitude ~ 10^{-4}-10^{-3}

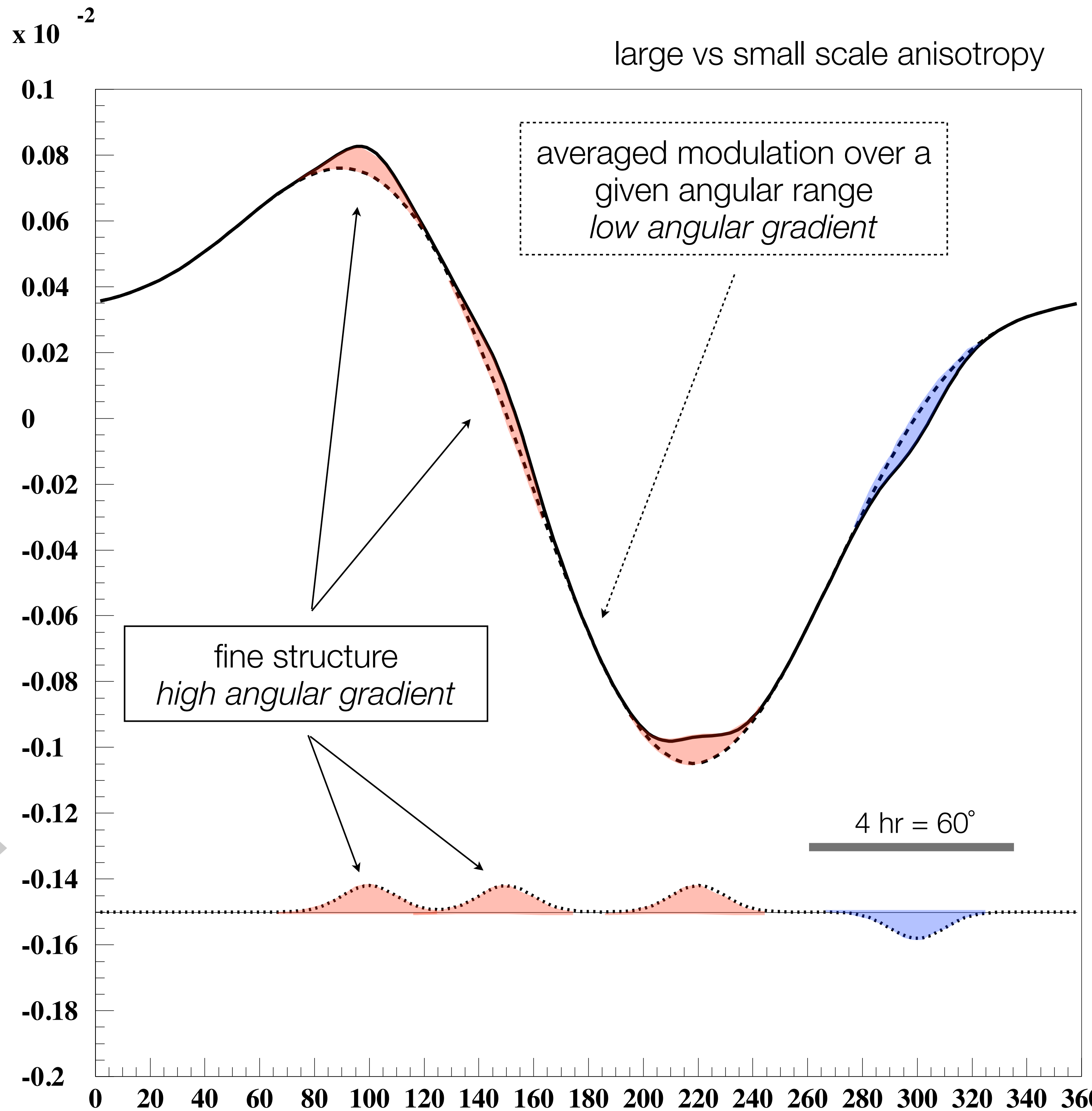
$$D(E) \approx (3-5) \times 10^{28} \cdot E^{0.3-0.6} \quad [cm^2 s^{-1}]$$ diffusion coefficient

$$\Rightarrow \delta A \propto E^{0.3-0.6}$$ anisotropy increases vs energy

cosmic ray anisotropy
angular scale structure





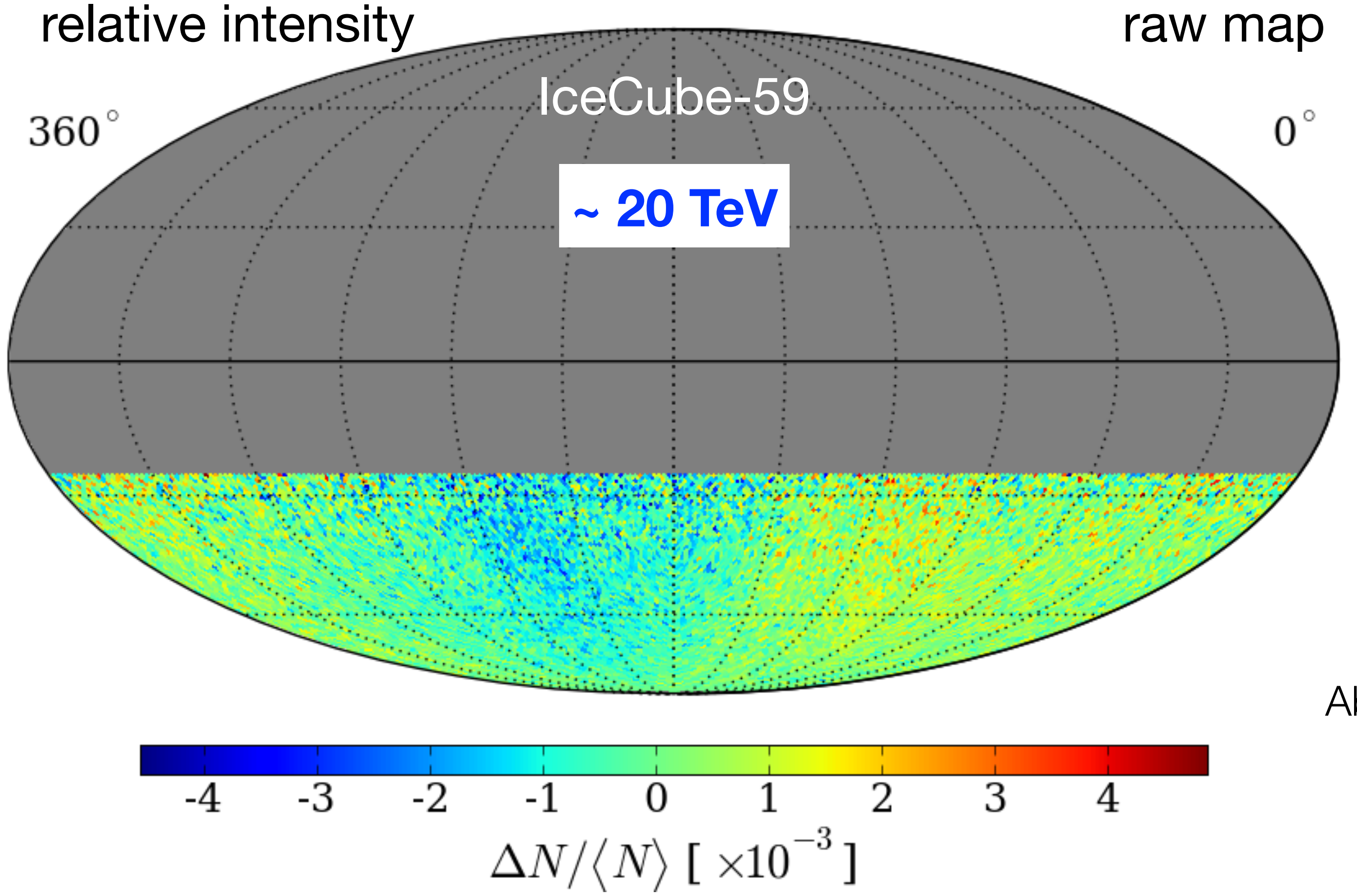


Paolo Desiati

cosmic ray anisotropy small scale
IceCube

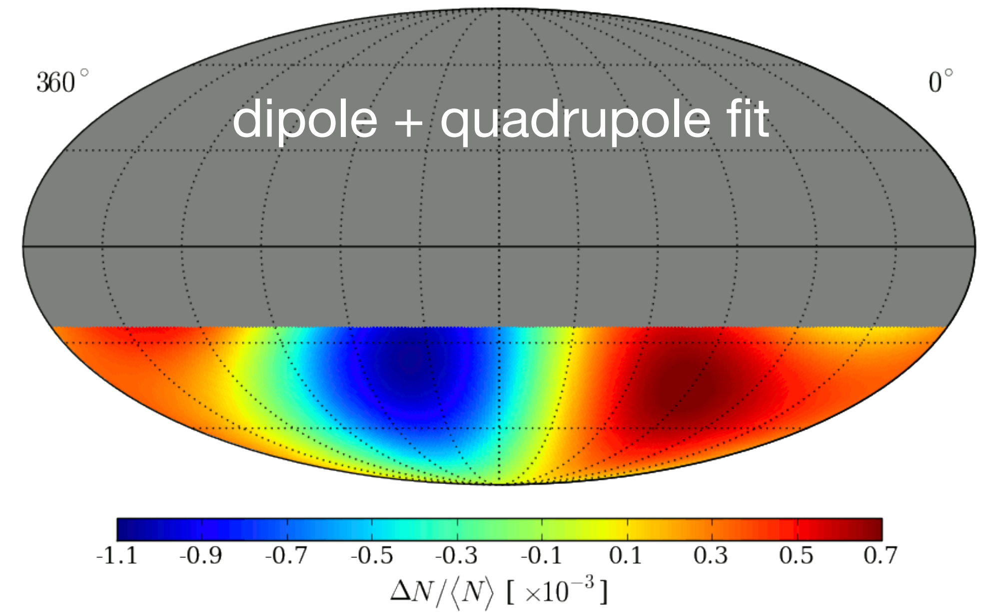
relative intensity

raw map

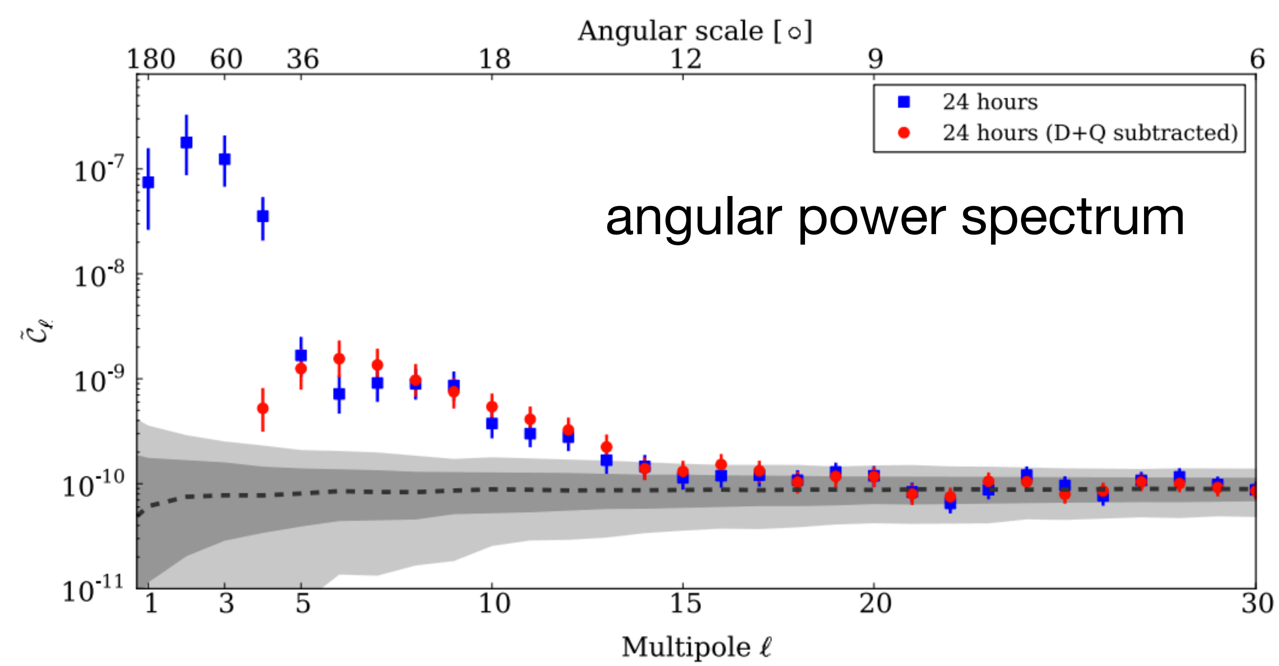


χ^2/ndf = 14743.4 / 14187

Pr(χ^2lndf) = 0.05%



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



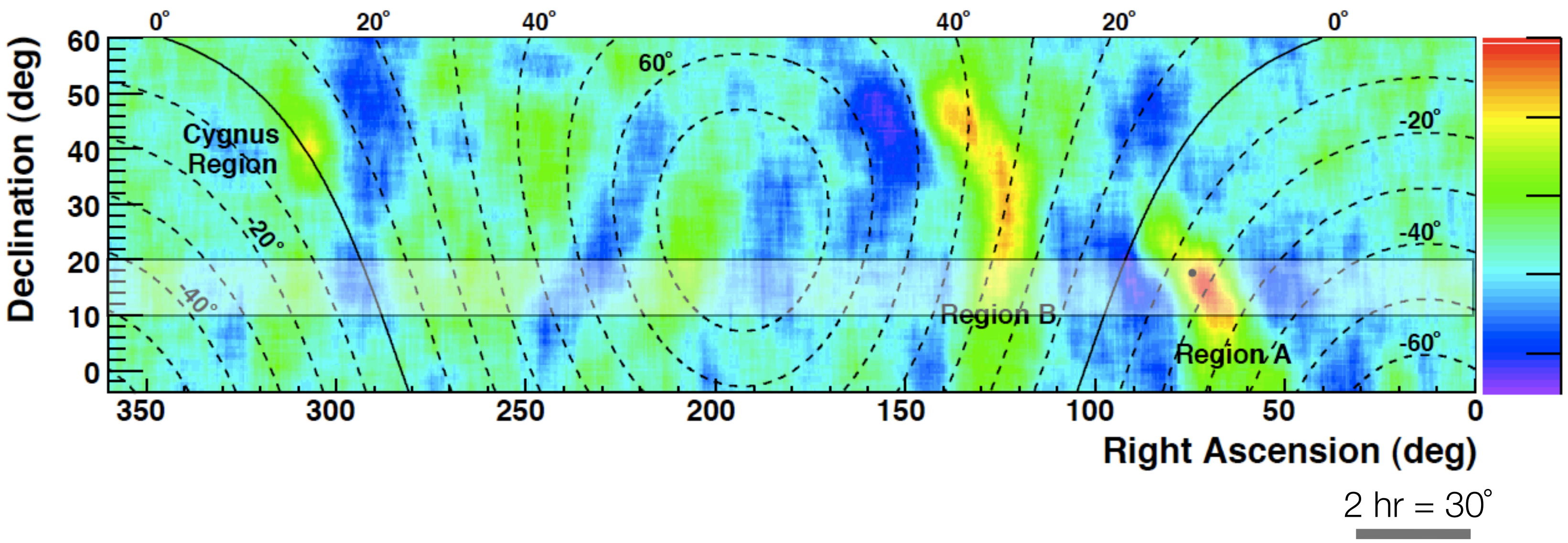
sky map contains correlations at several angular scales

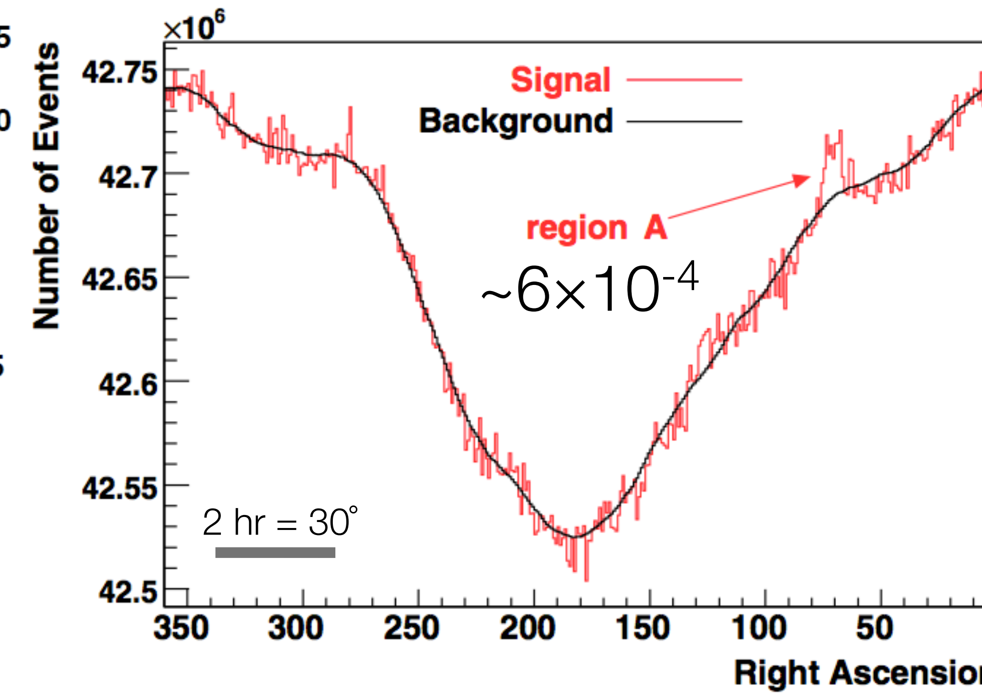
in gray 60% and 95% of simulated isotropic bands

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

spectral feature associated to anisotropy

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





Milagro

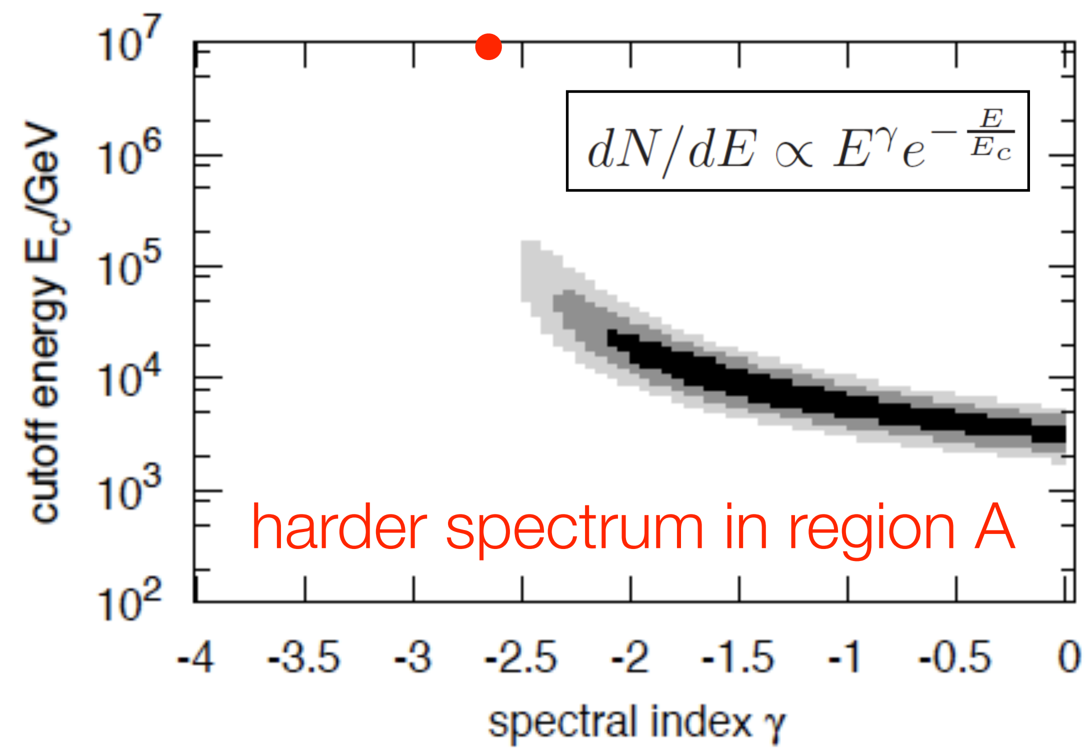
& ARGO-YBJ

Di Sciascio et al., arXiv:1202.3379

harder than average spectrum from region A

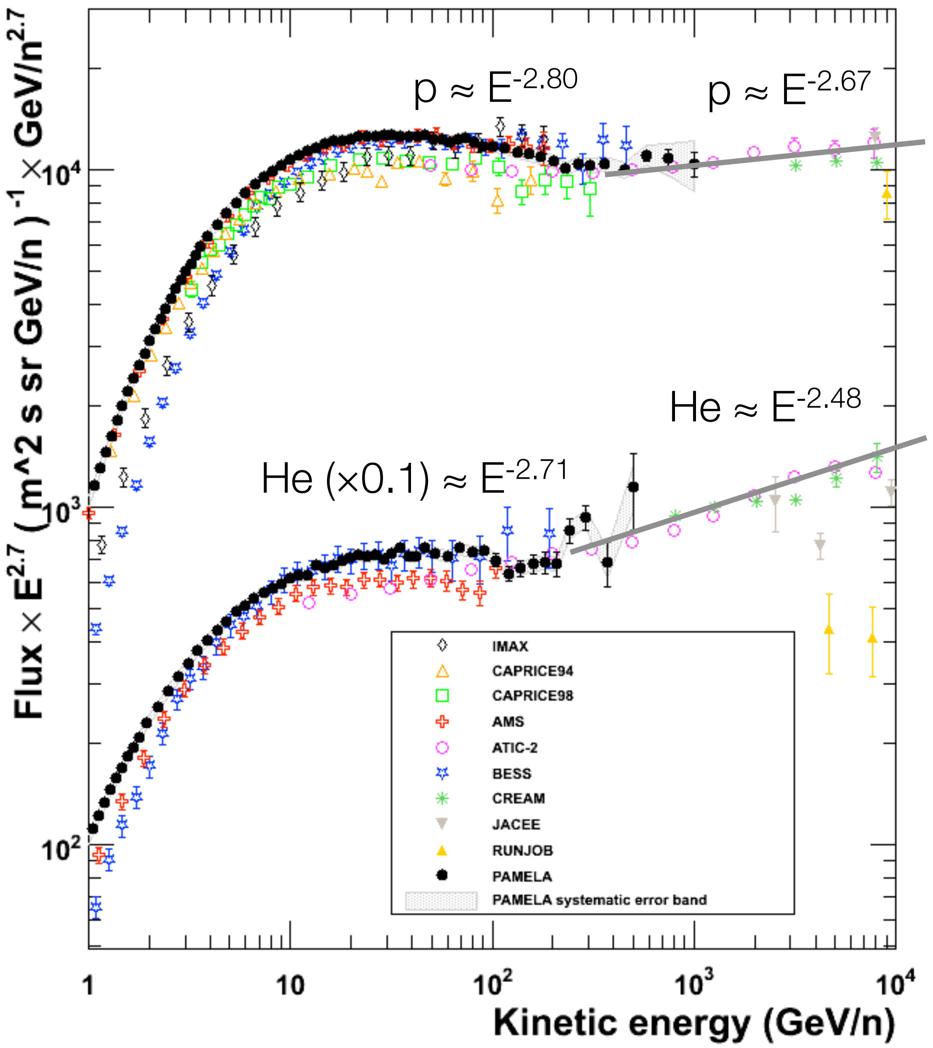
$\gamma < 2.7$ at 4.6 σ level
E_C = 3 - 25 TeV

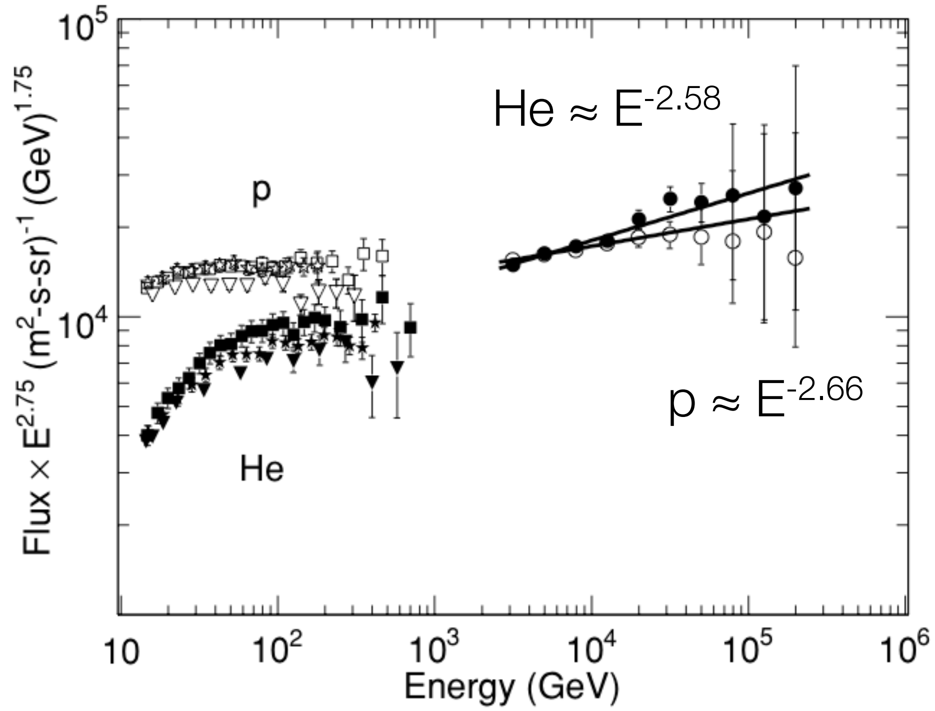
similar to hardening of “diffuse” cosmic rays by Pamela, CREAM, ATIC-2, or something else ?



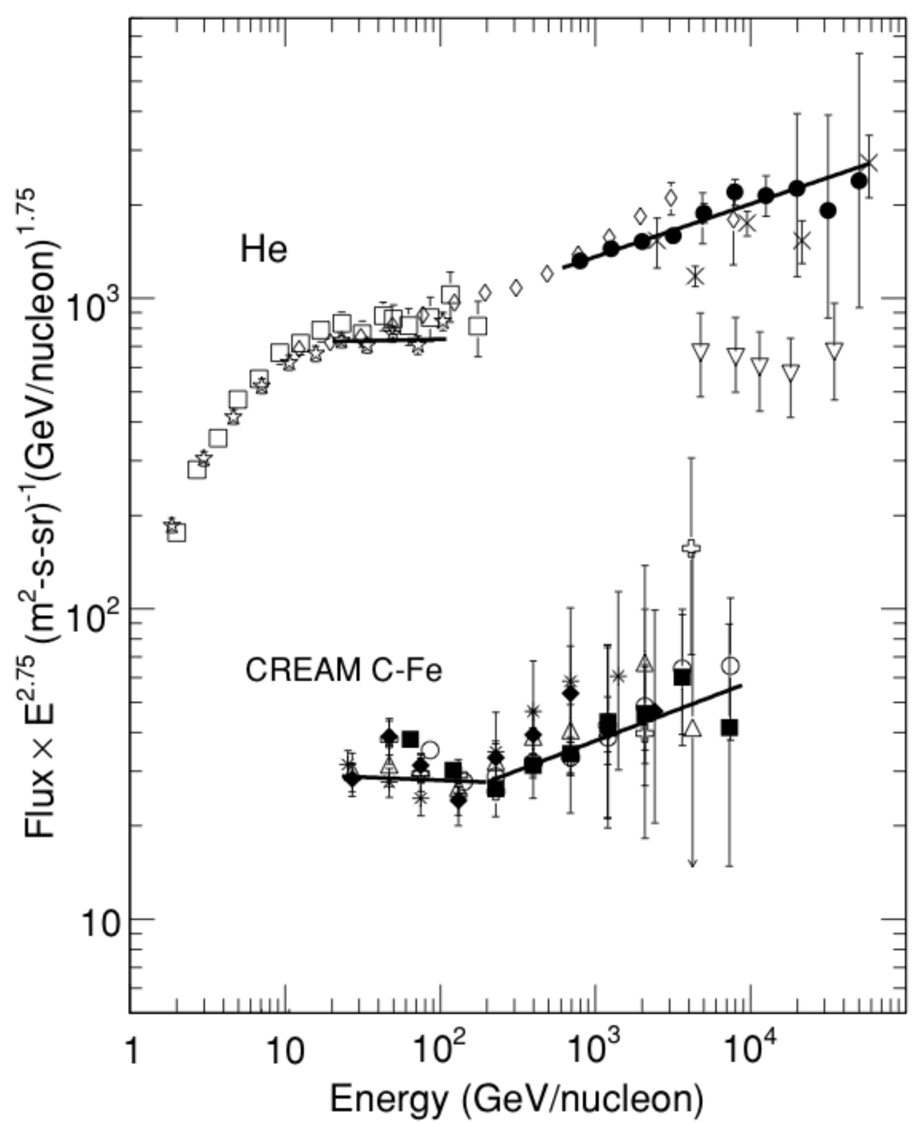
cosmic rays observations
all-particle spectrum

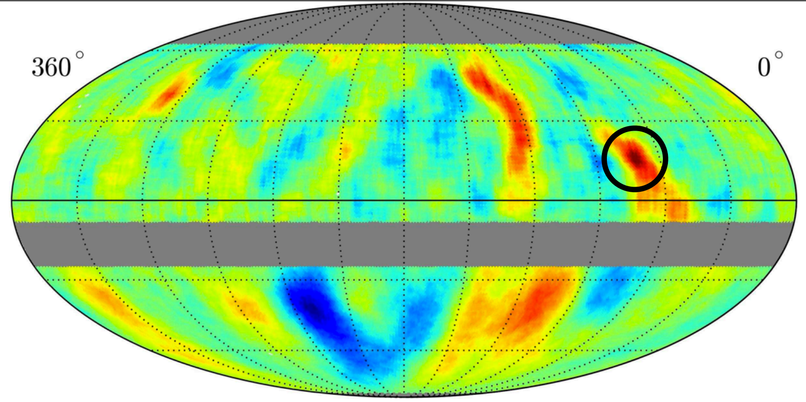
Pamela
Adriani et al. (2011)





CREAM
Ahn et al. (2010)

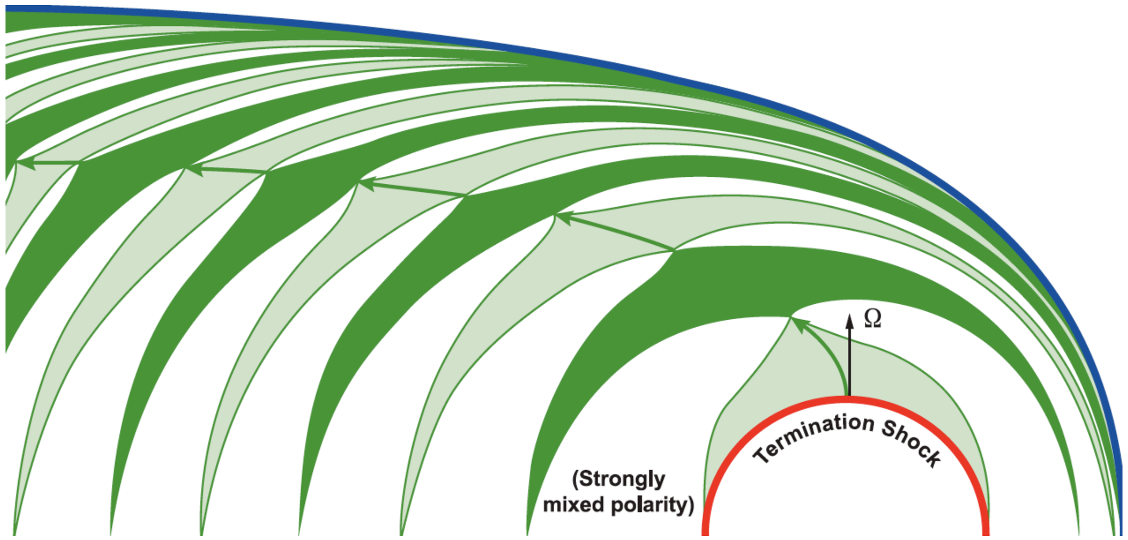




origin of spectral hardening ?

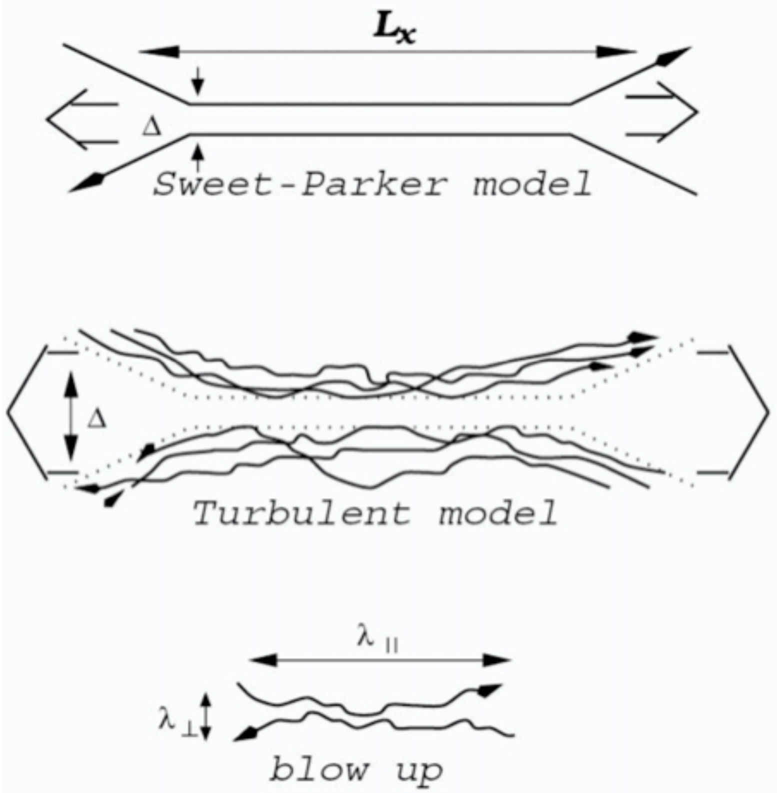
Lazarian & PD, ApJ, 722, 188, 2010

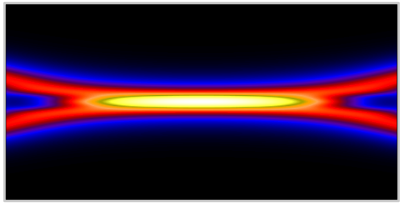
- magnetic polarity reversals due to the 22-year solar cycles produces large scale sectors
- converging of turbulent magnetic field lines can trigger reconnection and make it fast
- magnetic mirror @ single reconnection as site of acceleration (test particle)

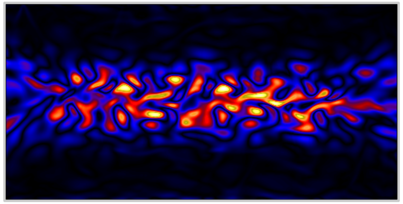


Sweet (1959) & Parker (1957)

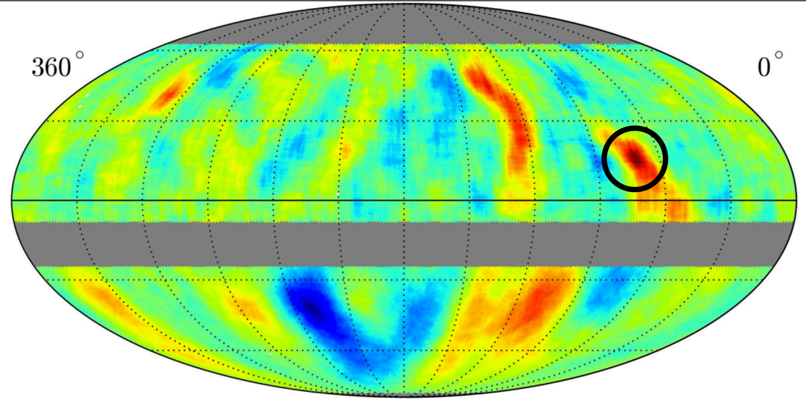
Lazarian & Vishniac, ApJ, 517, 700 (1999)







stochastic magnetic reconnection



Lazarian & PD, ApJ, 722, 188, 2010

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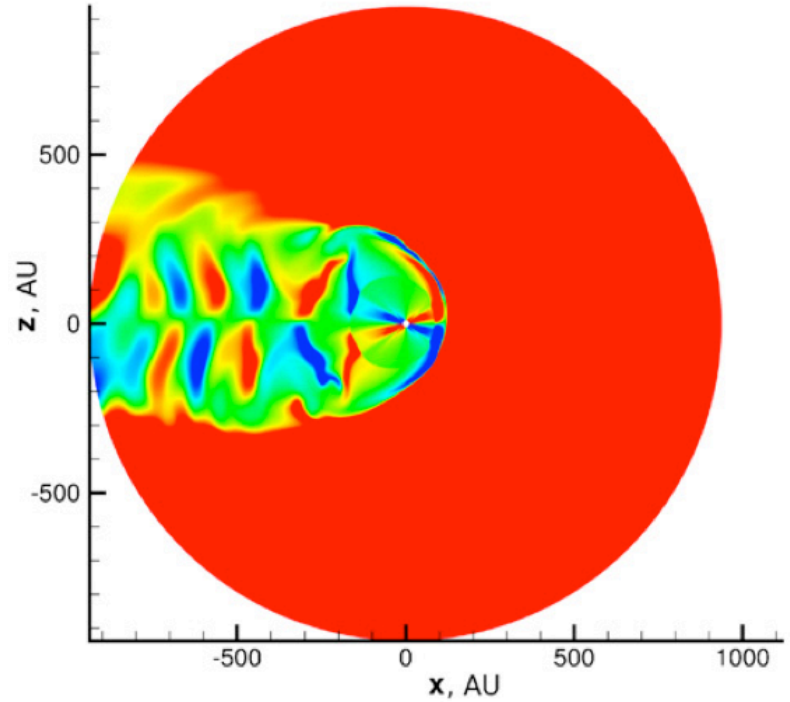
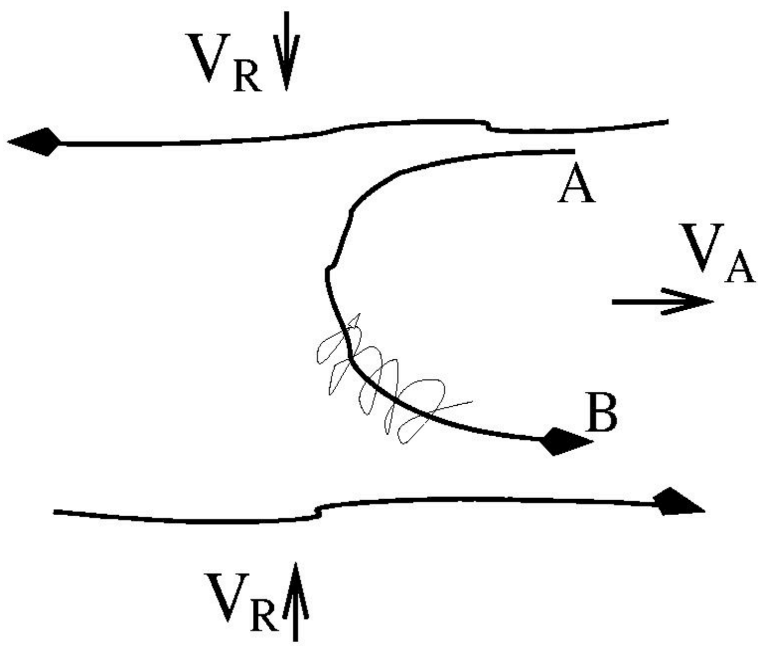
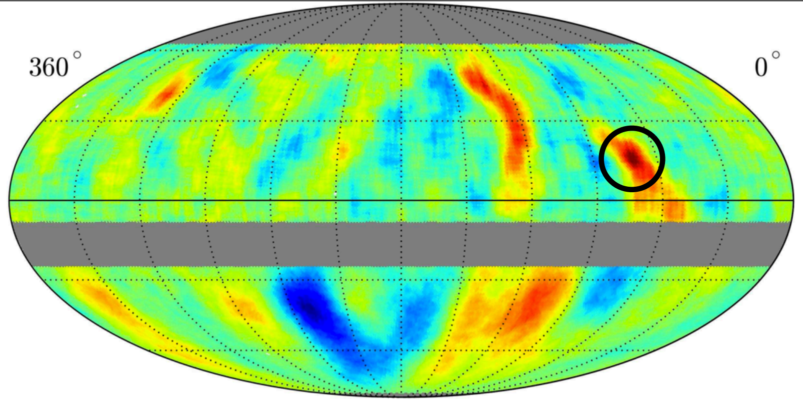


- converging of turbulent magnetic field lines can trigger reconnection and make it fast
- magnetic mirror @ single reconnection as site of acceleration (test particle)
- 1st order Fermi acceleration

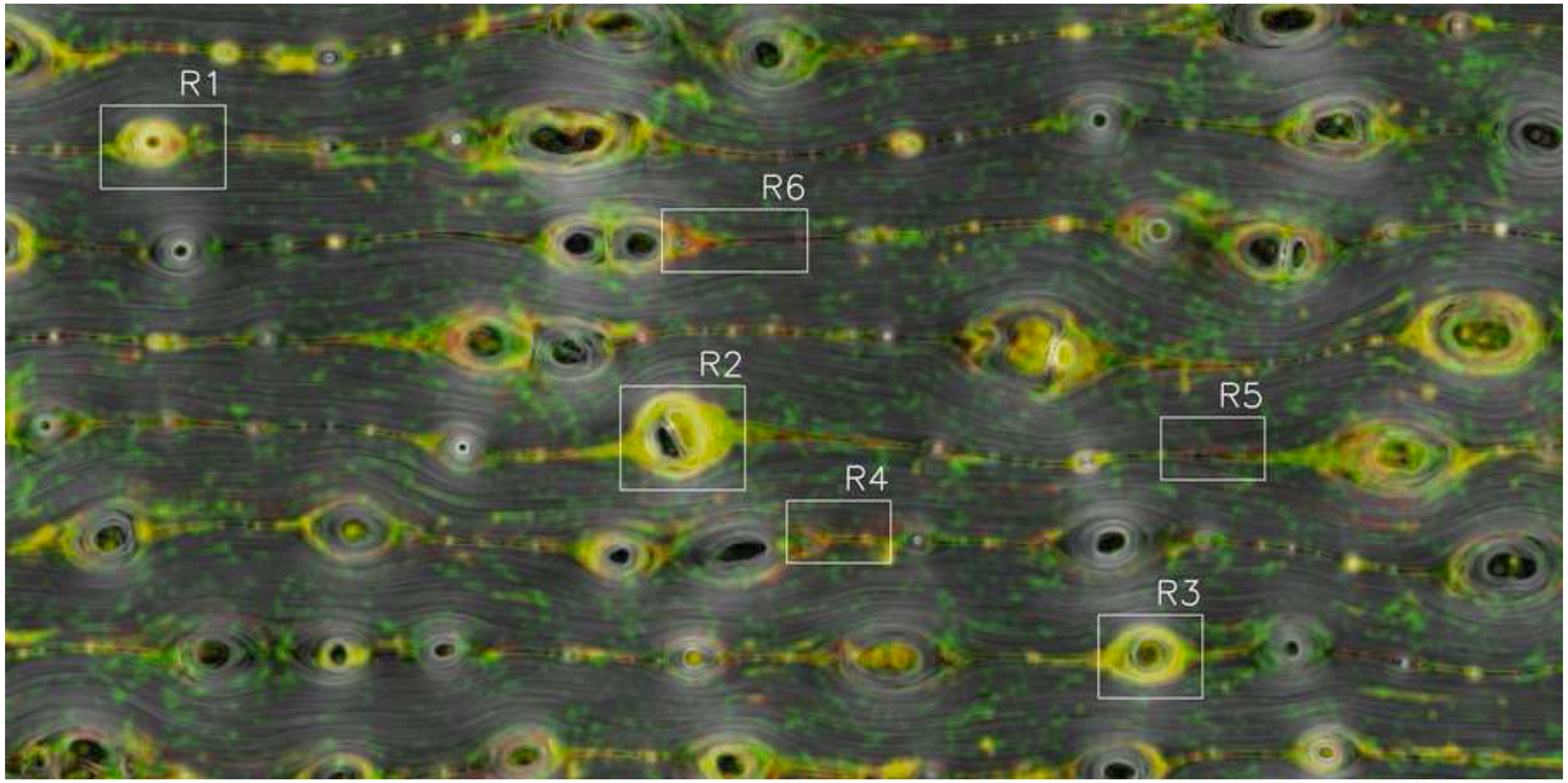
$$N(E)\,dE \sim E^{-5/2}\,dE$$

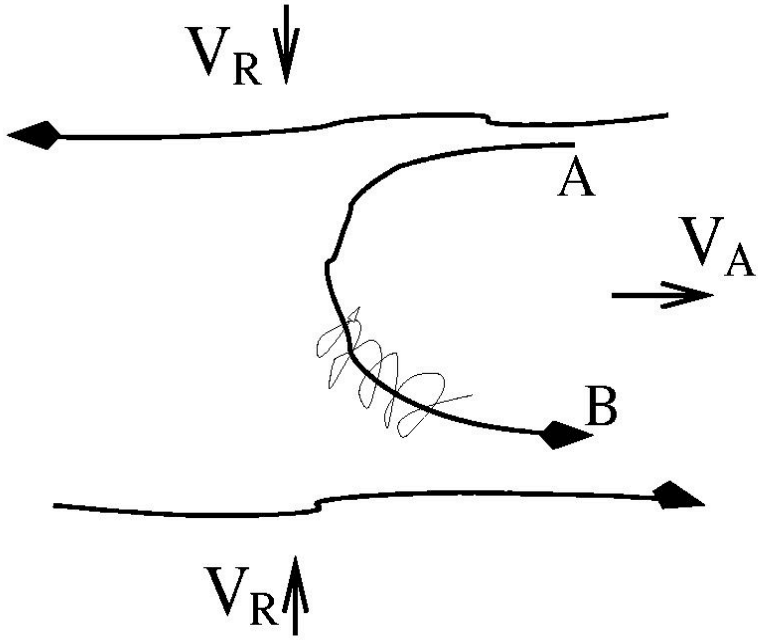




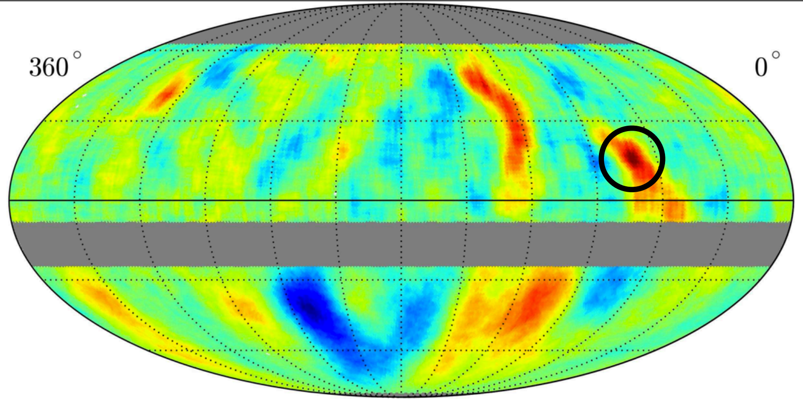
stochastic magnetic reconnection

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



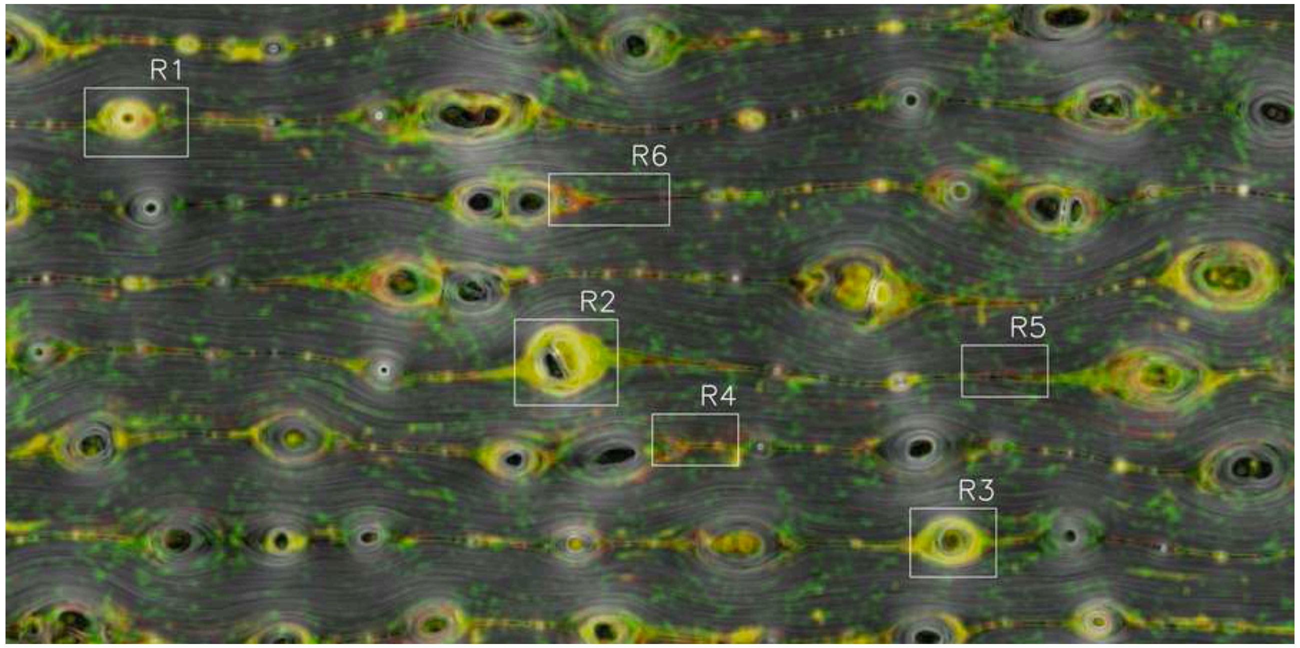


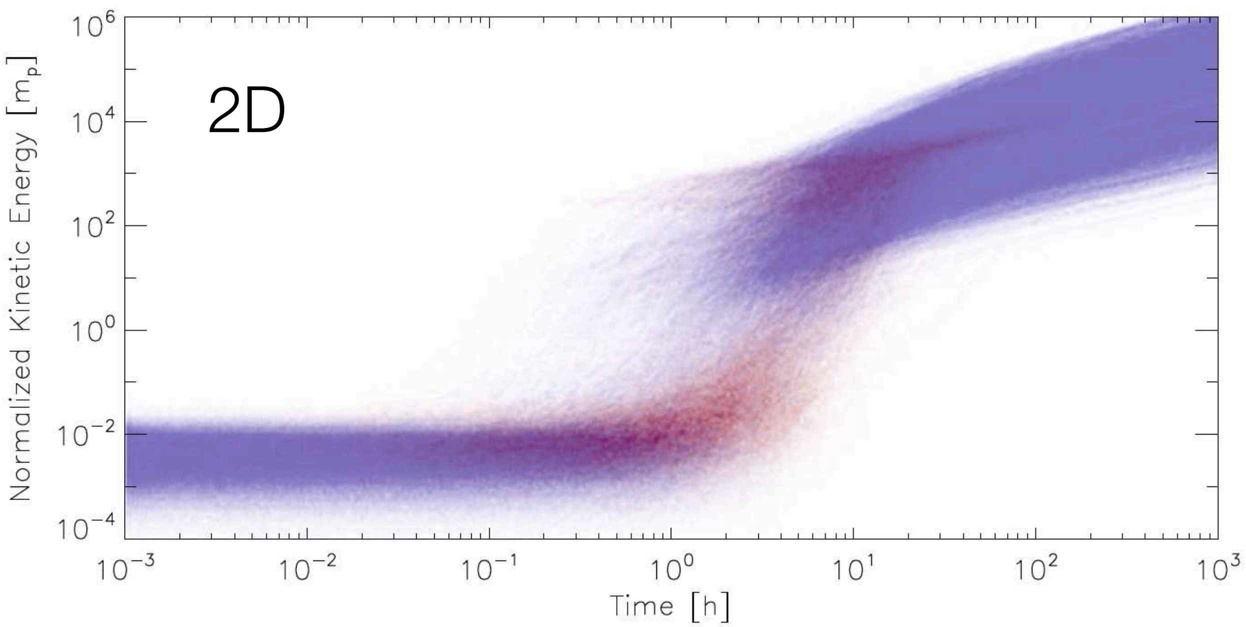
$$N(E)\,dE \sim E^{-5/2}\,dE$$



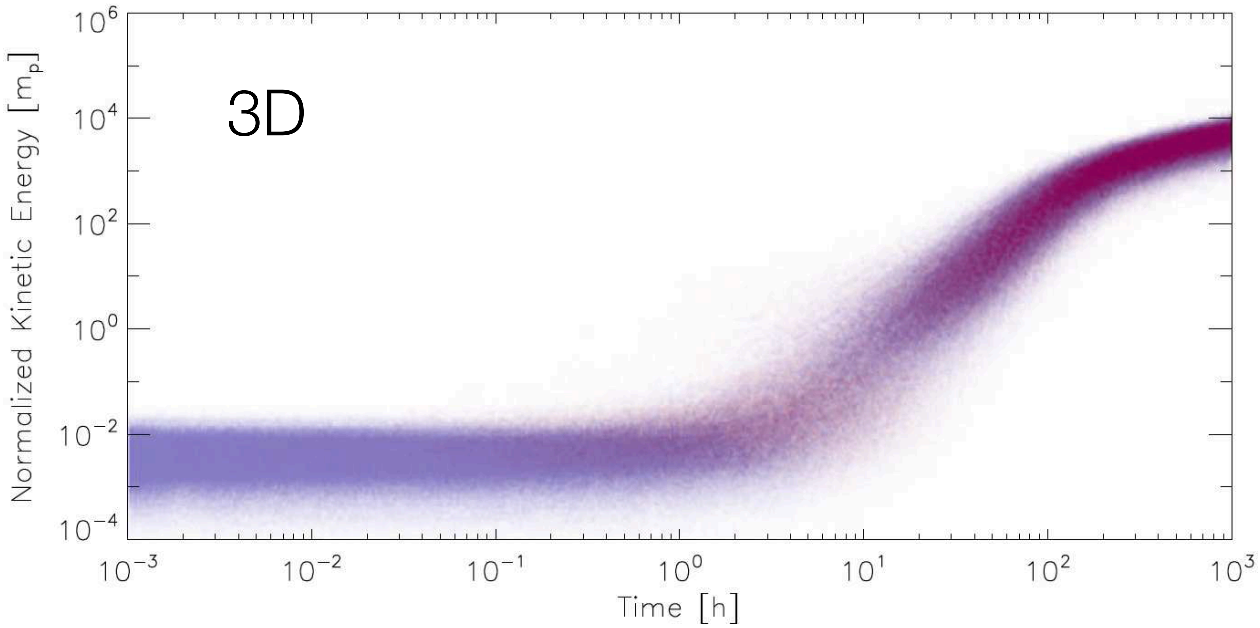
stochastic magnetic reconnection

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



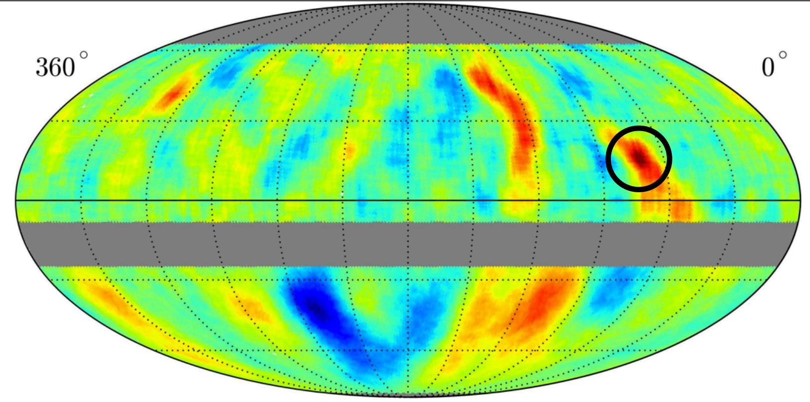


$V_\perp > V_\parallel$



$V_\parallel > V_\perp$

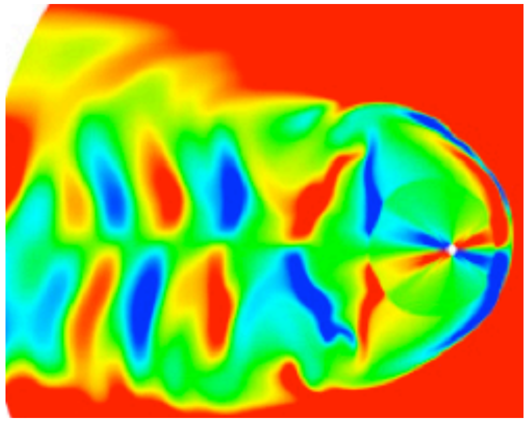
stochastic magnetic reconnection



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

Kowal et al., PRL 2012

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



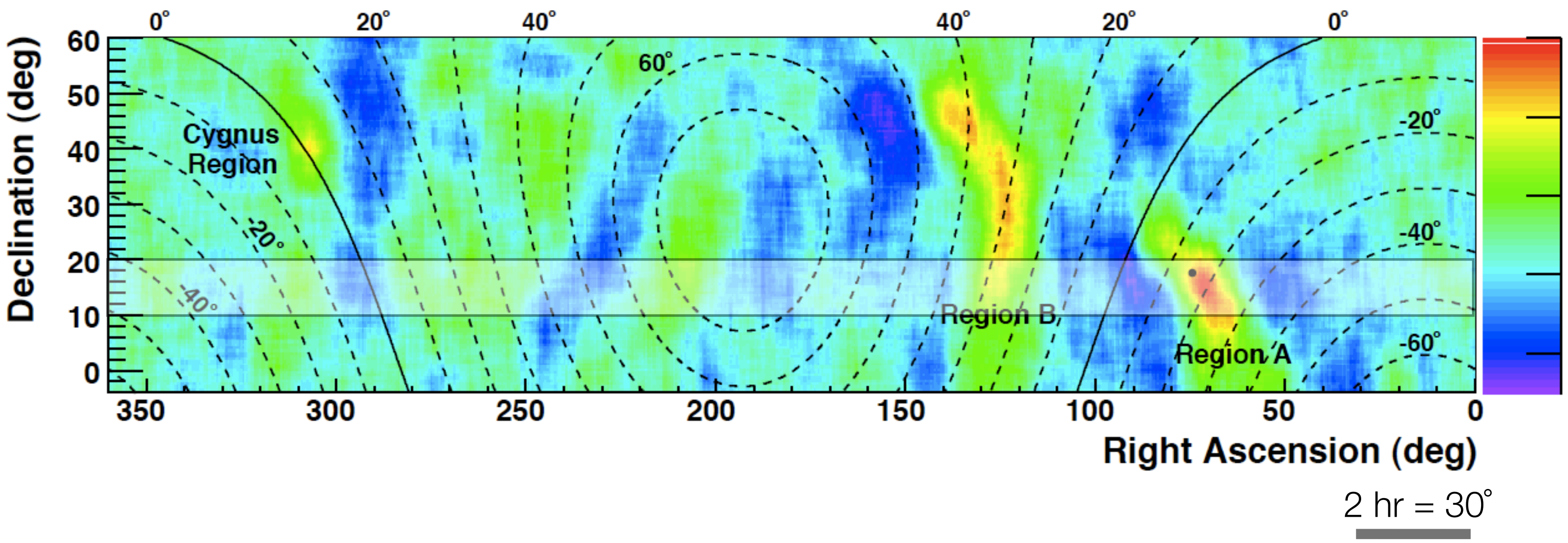
- acceleration by reconnection is efficient if scattering does not isotropize particles. Scattering expected to be minimal along the tail line of sight

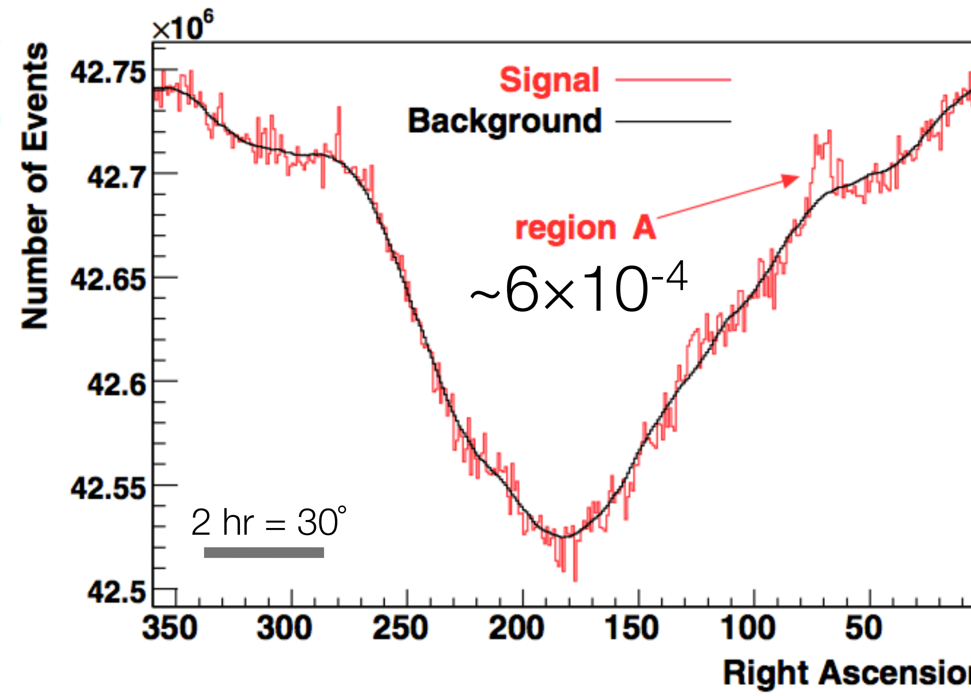
$$E_{max} \approx 0.5 \left(\frac{B}{1\,\mu G}\right) \left(\frac{L_{zone}}{100\,AU}\right) TeV \approx 0.5 - 6\,TeV$$

- 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)





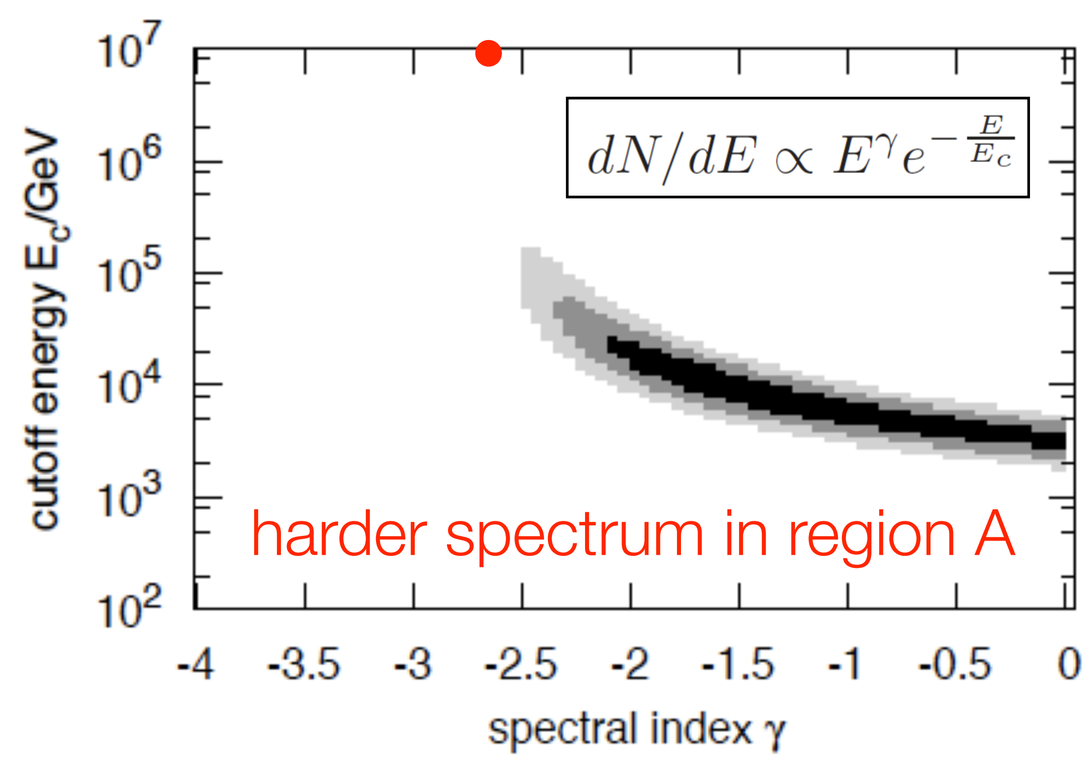
Milagro

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

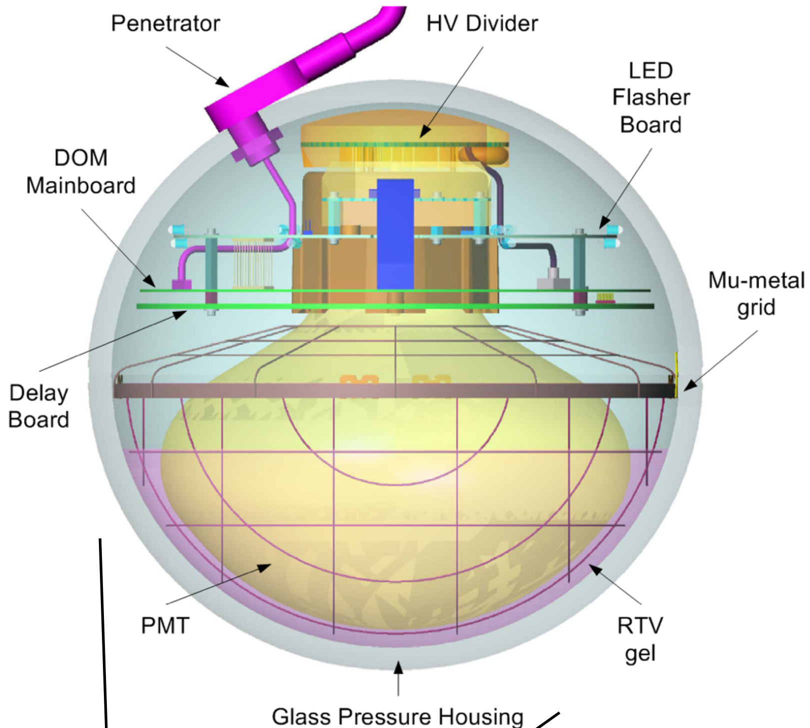
- diffusion cannot explain the observed **non-dipolar** topology & **small angular scales**
- limitations on single power-law assumption and spacial dependency of diffusion coeff.

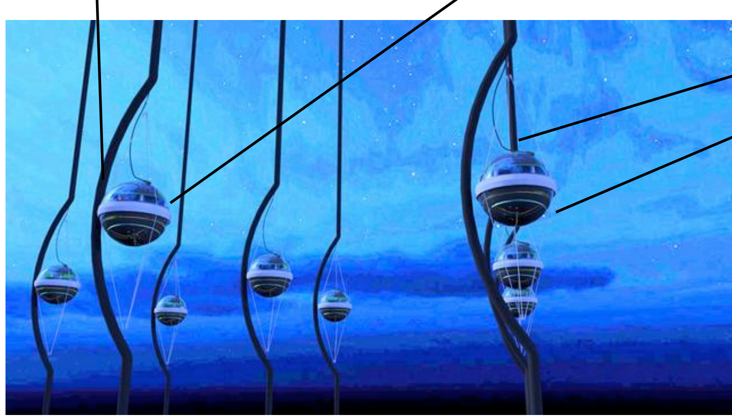
IceCube Observatory

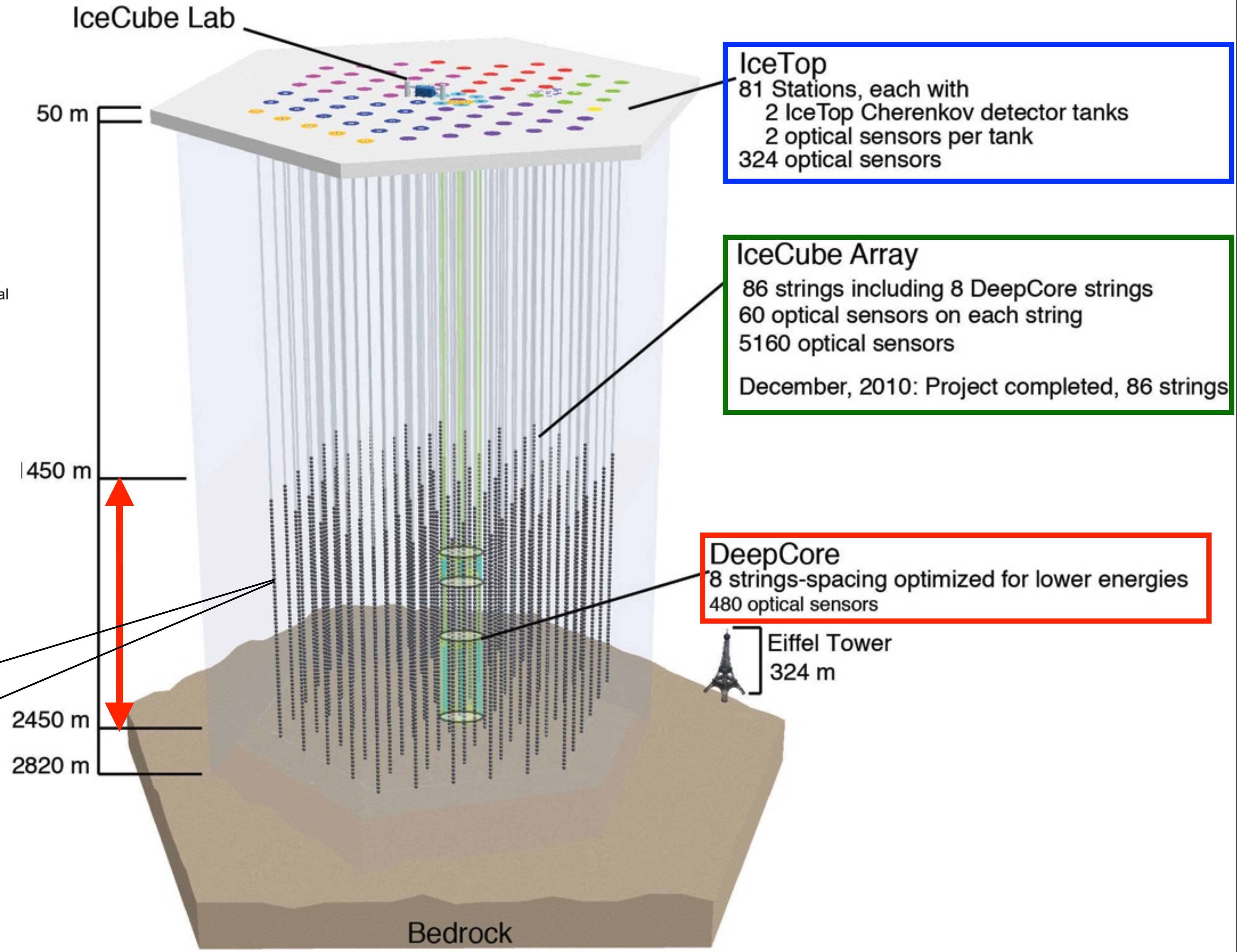
air shower detection @ 2835 m altitude (680 g/cm²)

muon detection @ 1450-2450 m depth

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







detection principle