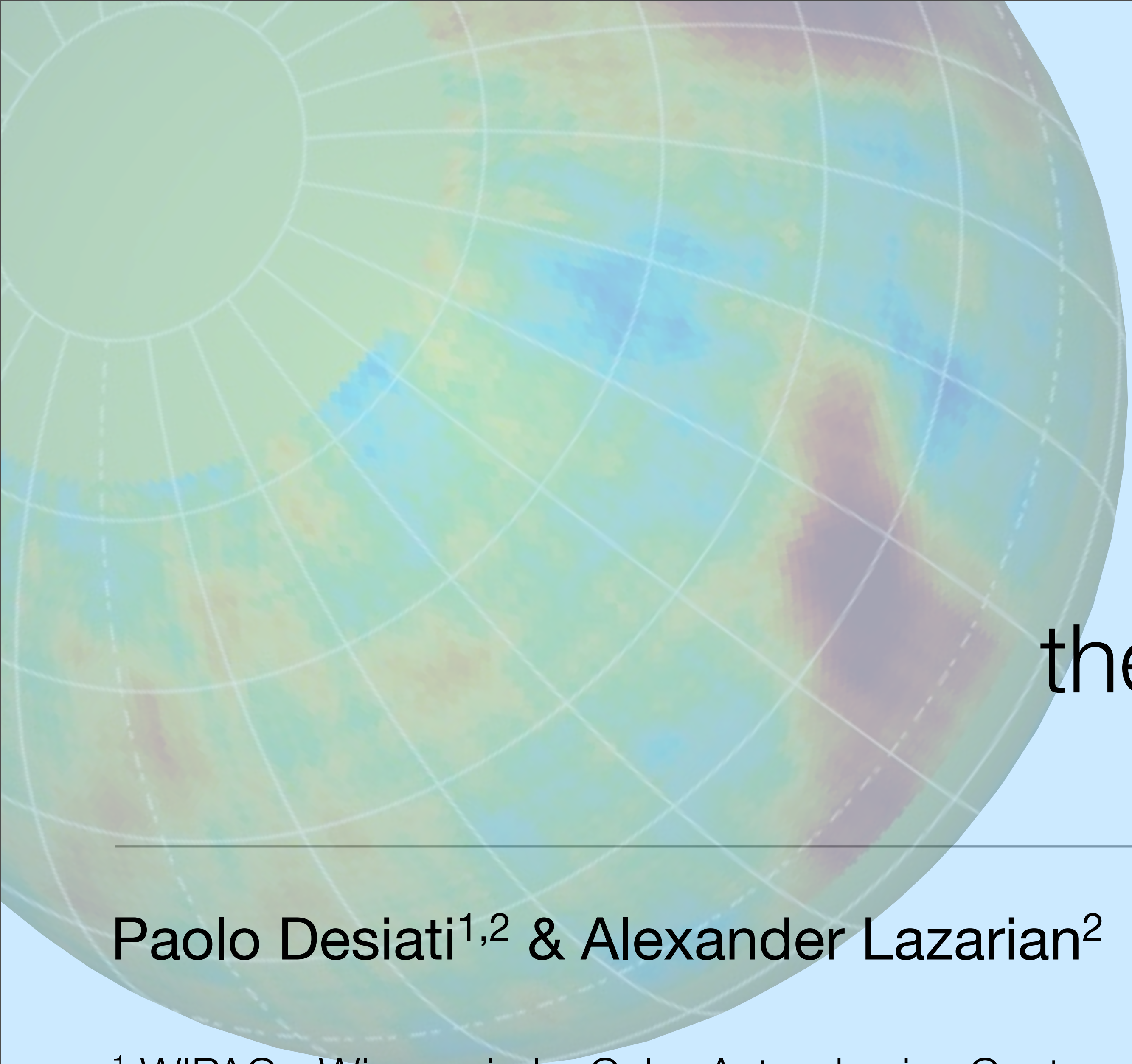
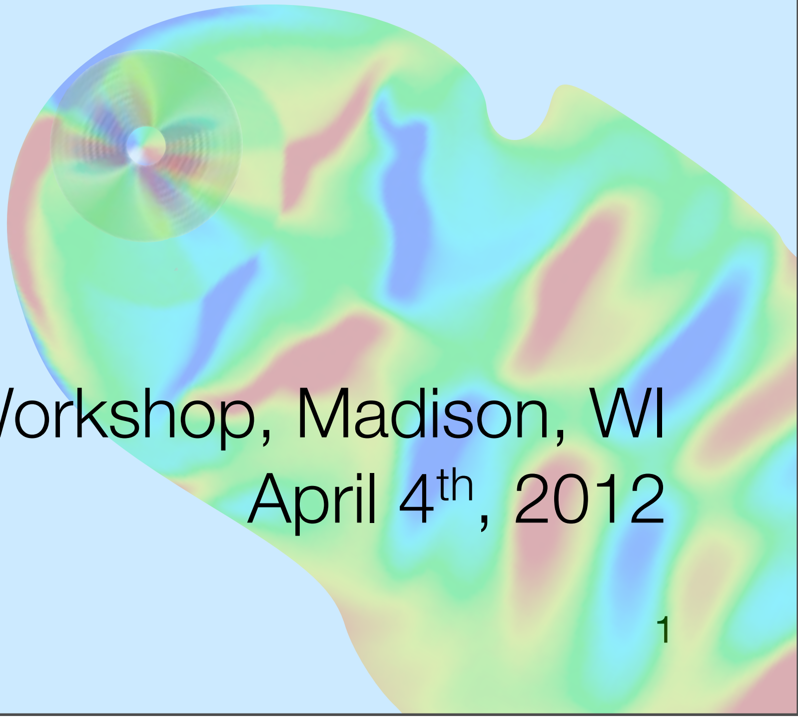


galactic cosmic rays and the turbulent heliospheric tail

Paolo Desiati[1,2] & Alexander Lazarian[2]

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

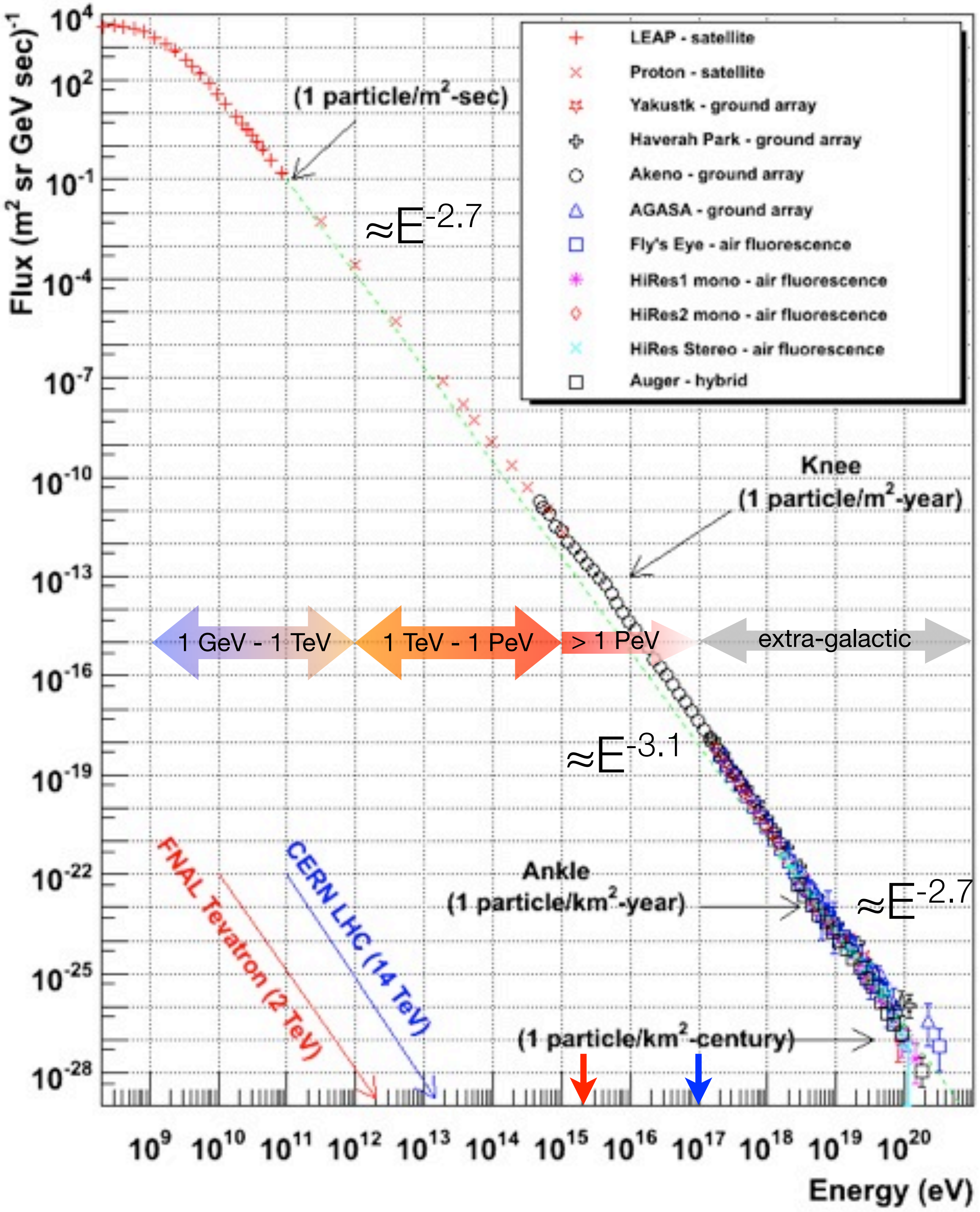
University of Wisconsin - Madison



Midwest Magnetic Fields Workshop, Madison, WI
April 4th, 2012

cosmic rays spectrum

- spectral structure & mass composition hold information on
  - **origin** of cosmic rays
  - **propagation** from *sources* to Earth
- **anisotropy** in arrival distribution
  - energy dependence
  - angular scale



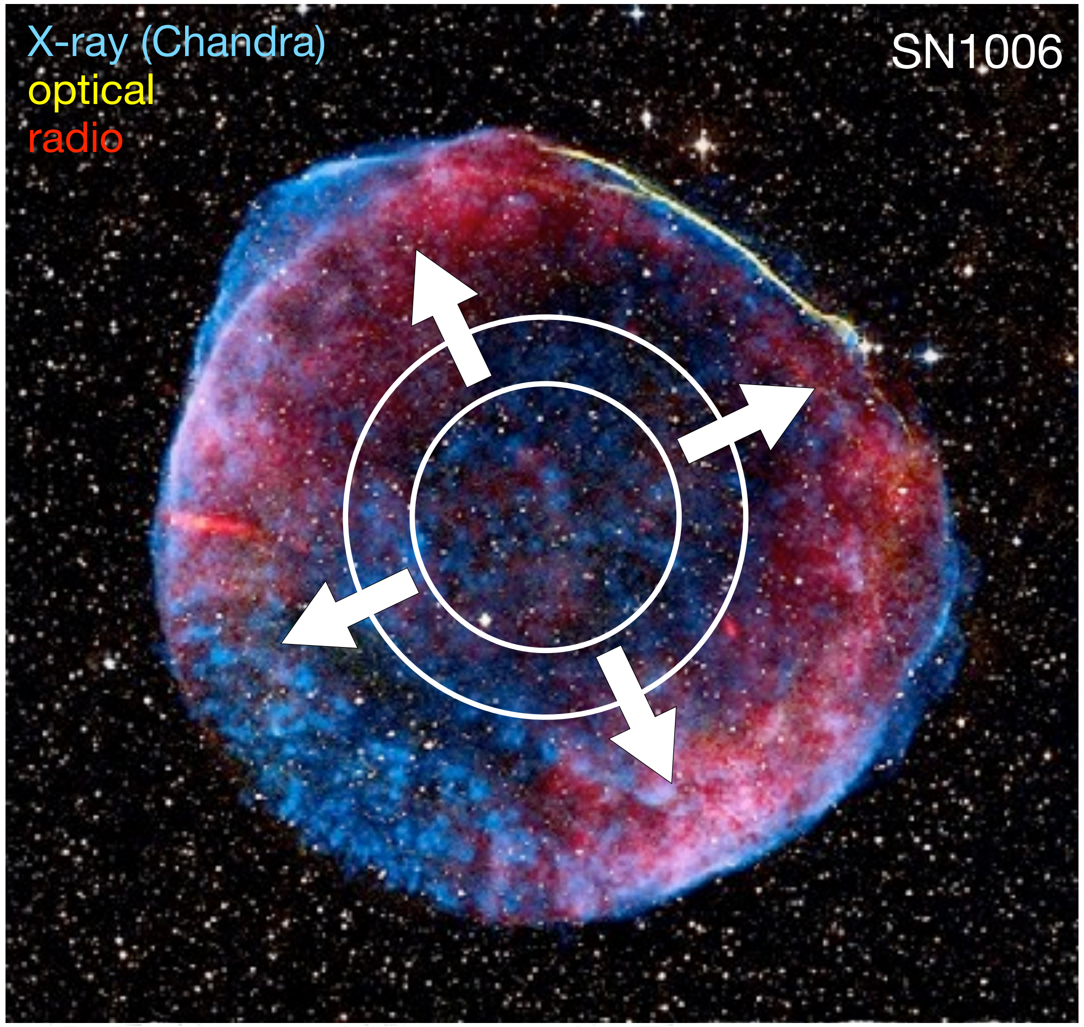
cosmic ray acceleration in supernova remnants

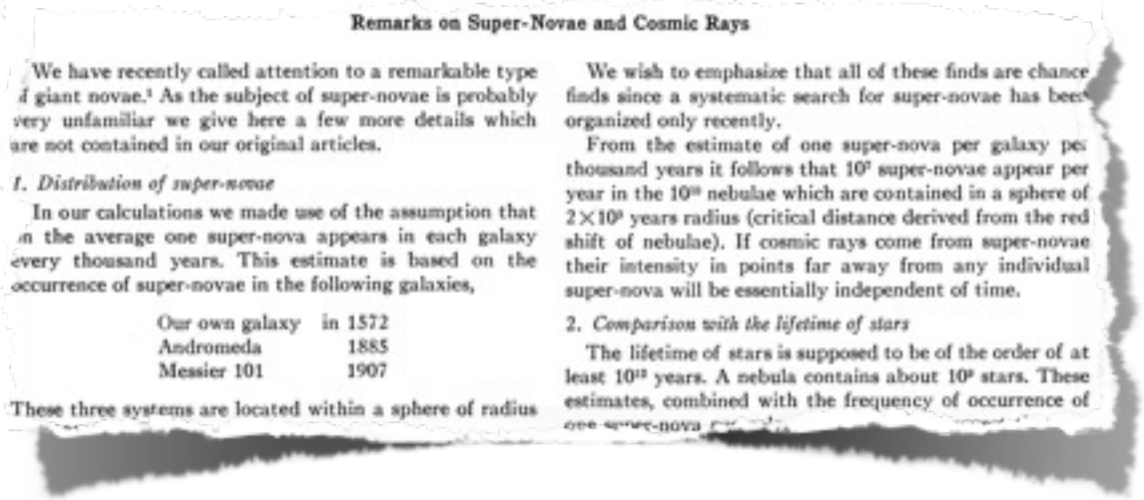
- diffusive shock acceleration in galactic SNR (Baade & Zwicky, 1934 & Fermi, 1949)

$n_{CR}(E) \approx \frac{E^{-\gamma} R_{SN}}{2\pi R_d^2} \cdot \frac{H}{D(E)}$	density of cosmic rays
$D(E) \propto E^{\delta}$	diffusion coefficient
$\phi_{CR} = \frac{c n_{CR}(E)}{4\pi}$	cosmic ray flux

$\phi_{CR} \approx 2.4 \cdot \left(\frac{E_{SN}}{10^{51} erg}\right)$	energy emitted by one SN
$\cdot \epsilon_{CR}$	cosmic ray acceleration efficiency
$\cdot \left(\frac{15kpc}{R_d}\right)^2$	radius of galactic disk
$\cdot \left(\frac{R_{SN}}{30yr}\right)$	rate of supernovae in the Galaxy
$\cdot (\gamma - 2) \cdot 3^{-\delta}$	propagation term
$\cdot \left(\frac{E}{1TeV}\right)^{-\gamma-\delta}$	$[TeV^{-1} m^{-2} s^{-1} sr^{-1}]$

W. Baade & F. Zwicky, Physical Review 46, 76, 1934





Remarks on Super-Novae and Cosmic Rays

We have recently called attention to a remarkable type f giant novae.[1] As the subject of super-novae is probably very unfamiliar we give here a few more details which are not contained in our original articles.

1. Distribution of super-novae

In our calculations we made use of the assumption that n the average one super-nova appears in each galaxy every thousand years. This estimate is based on the occurrence of super-novae in the following galaxies,

Our own galaxy	in 1572
Andromeda	1885
Messier 101	1907

These three systems are located within a sphere of radius

We wish to emphasize that all of these finds are chance finds since a systematic search for super-novae has bee organized only recently.

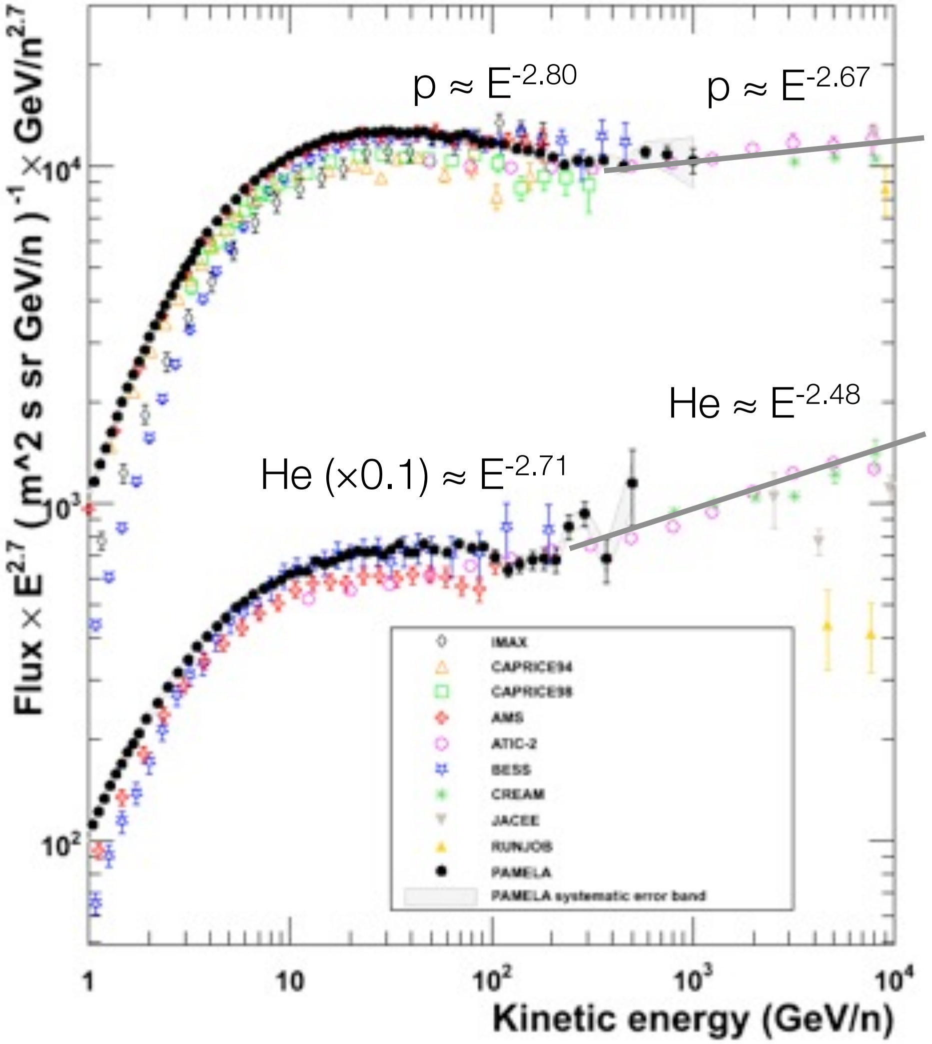
From the estimate of one super-nova per galaxy pe thousand years it follows that 10^7 super-novae appear per year in the 10^{10} nebulae which are contained in a sphere of 2×10^9 years radius (critical distance derived from the red shift of nebulae). If cosmic rays come from super-novae their intensity in points far away from any individual super-nova will be essentially independent of time.

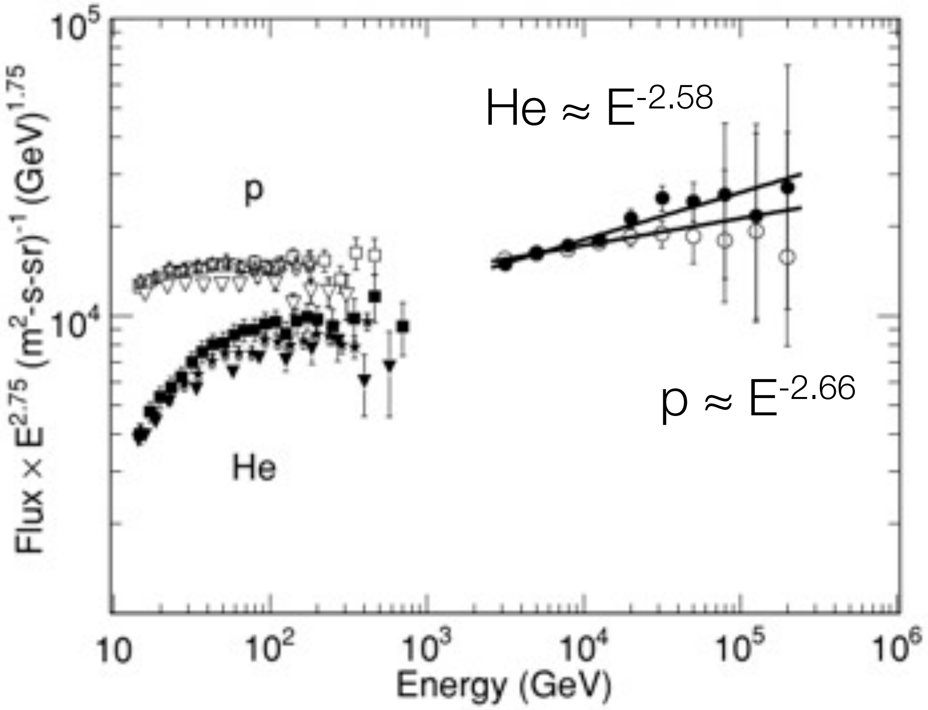
2. Comparison with the lifetime of stars

The lifetime of stars is supposed to be of the order of at least 10^{12} years. A nebula contains about 10^9 stars. These estimates, combined with the frequency of occurrence of

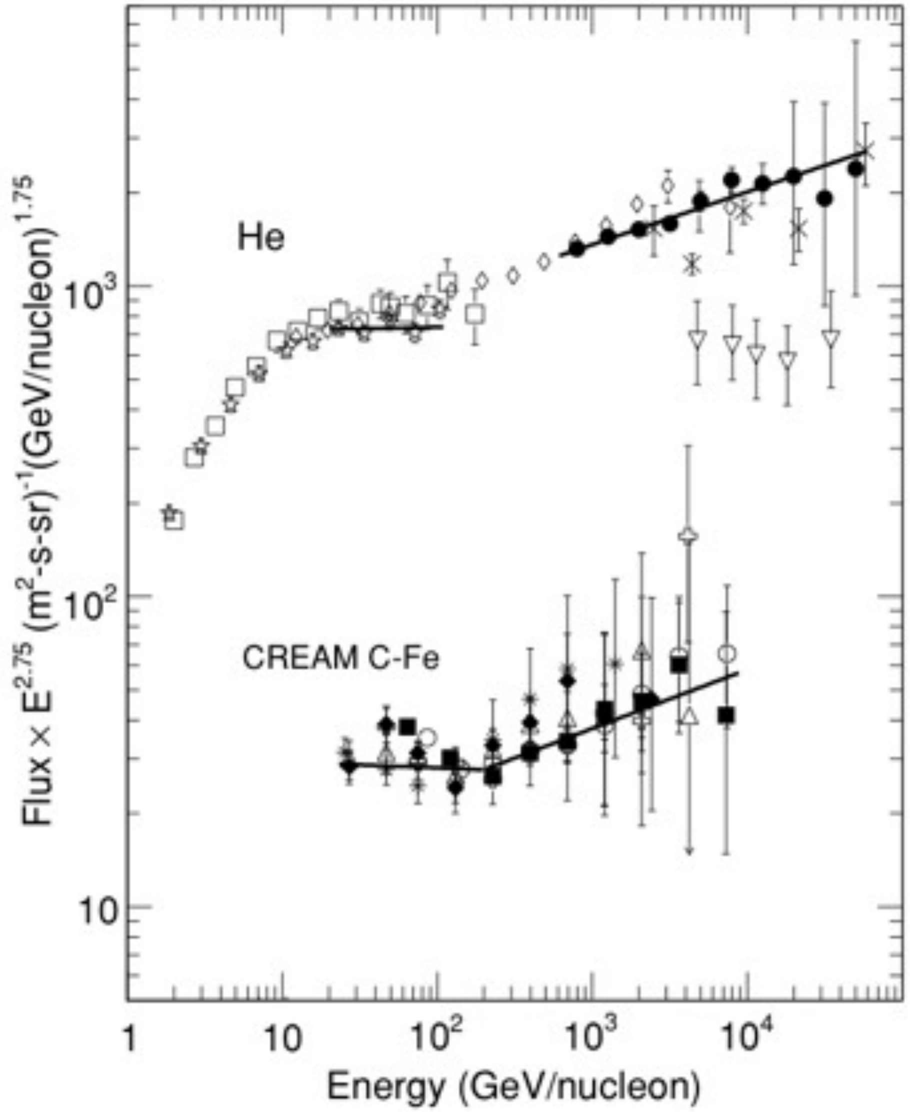
cosmic rays observations all-particle spectrum

Pamela
Adriani et al. (2011)





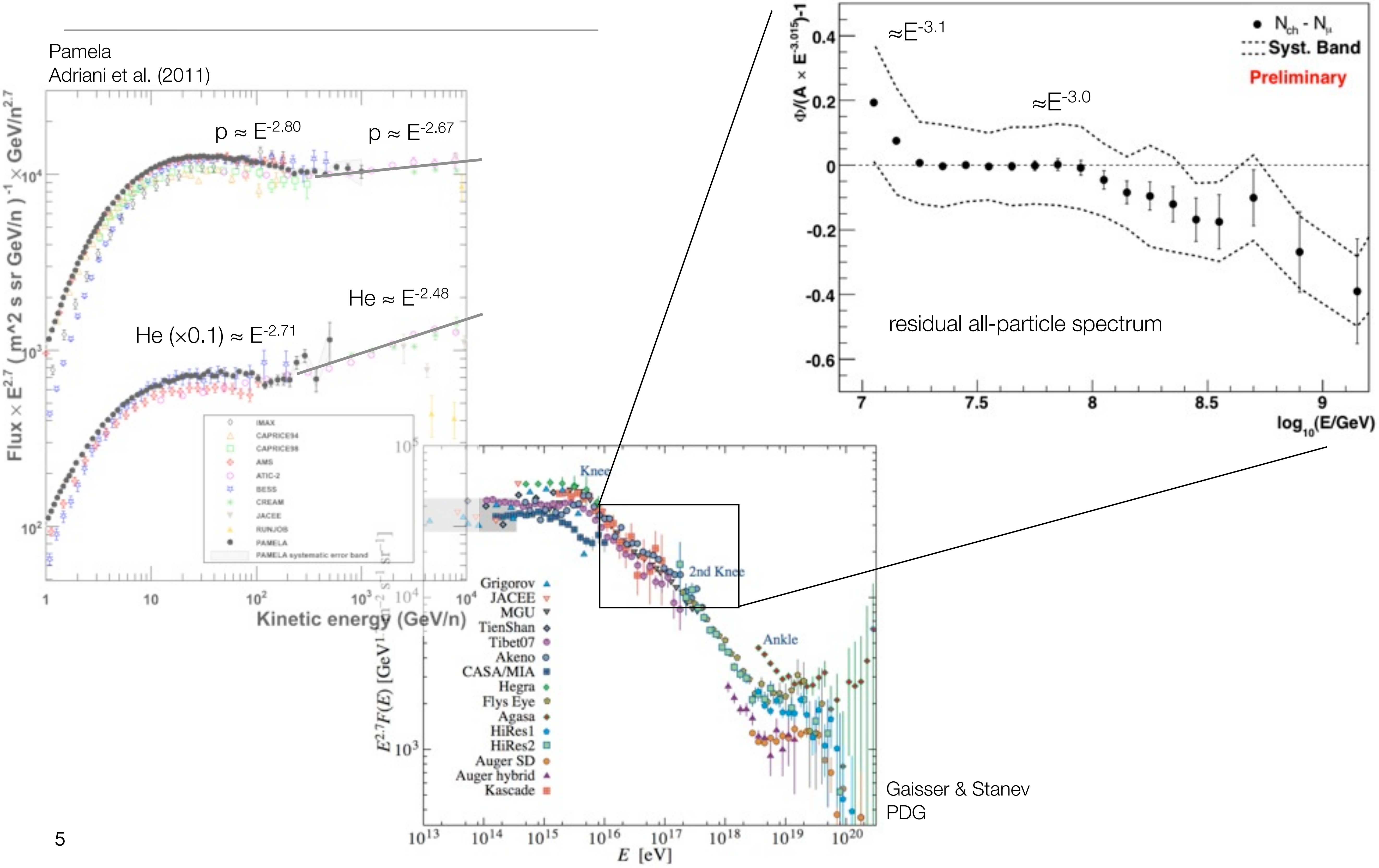
CREAM
Ahn et al. (2010)



cosmic rays observations
all-particle spectrum

KASCADE-Grande
Artega-Velàzquez et al. (2010)

Pamela
Adriani et al. (2011)

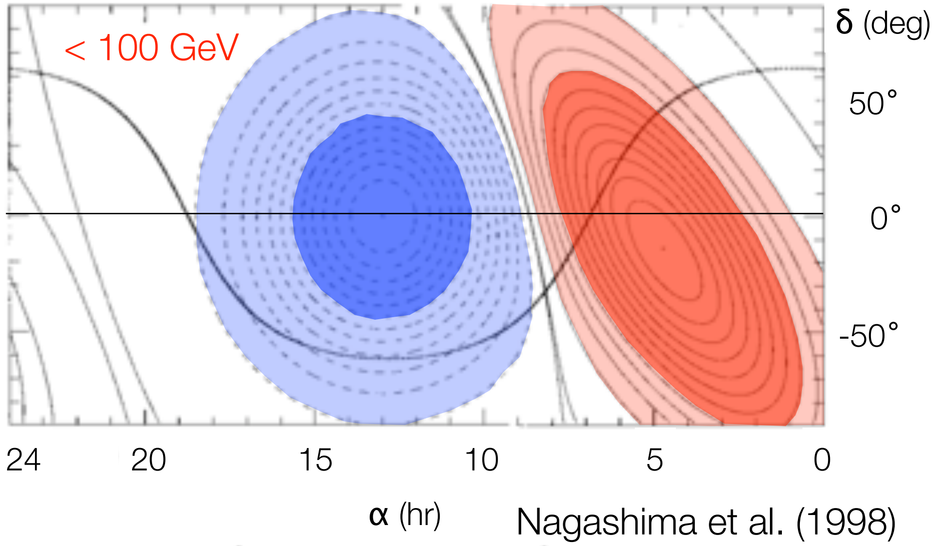


Gaisser & Stanev
PDG

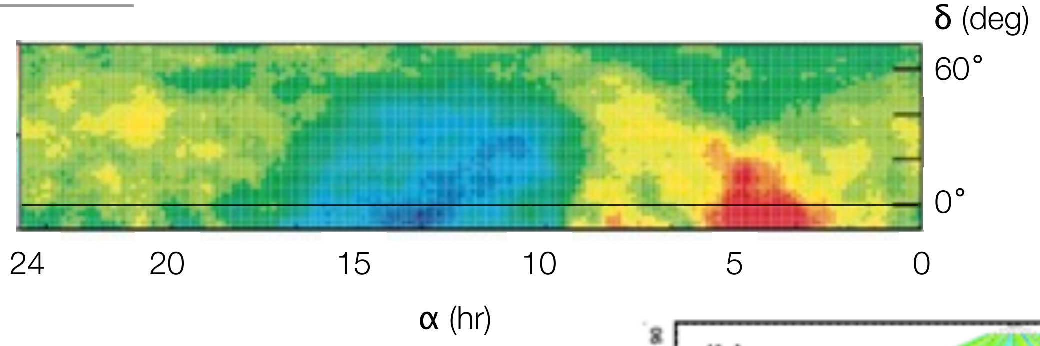
cosmic rays observations

anisotropy

equatorial coordinates

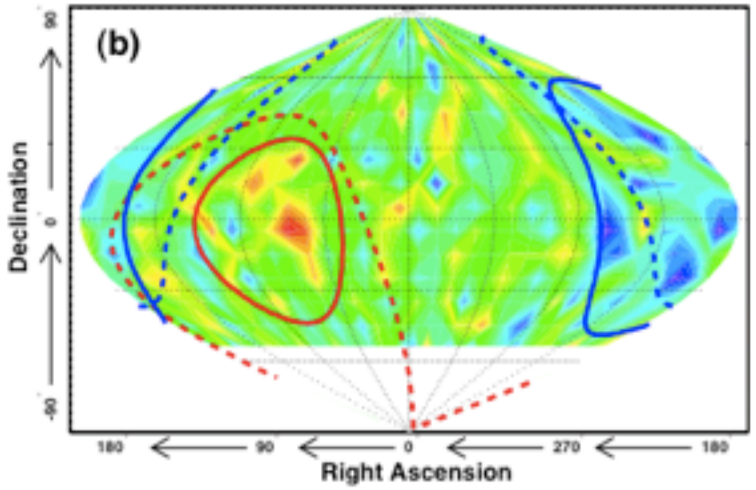


Nagashima et al. (1998)
Hall et al. (1999)



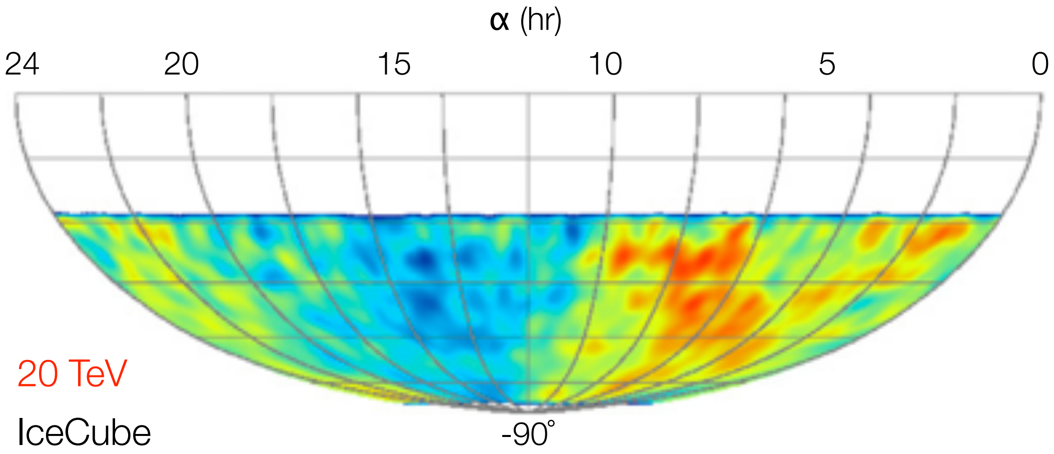
4 TeV

Tibet ASγ
Amenomori et al. (2006)



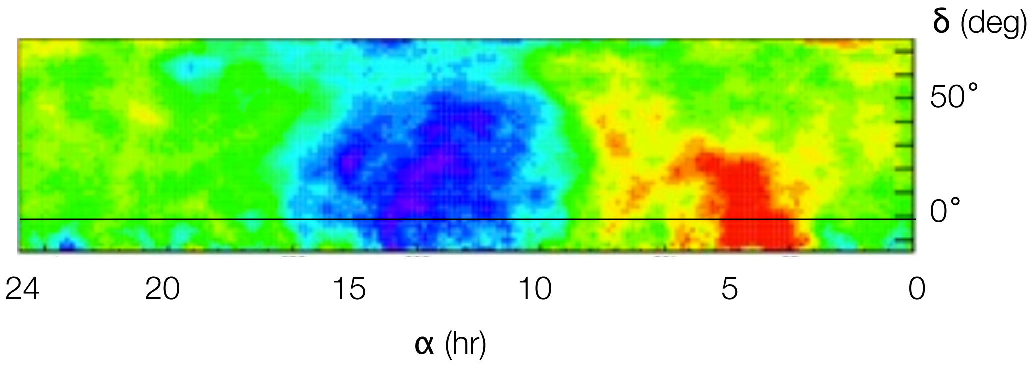
10 TeV

Super Kamiokande
Guillian et al. (2007)



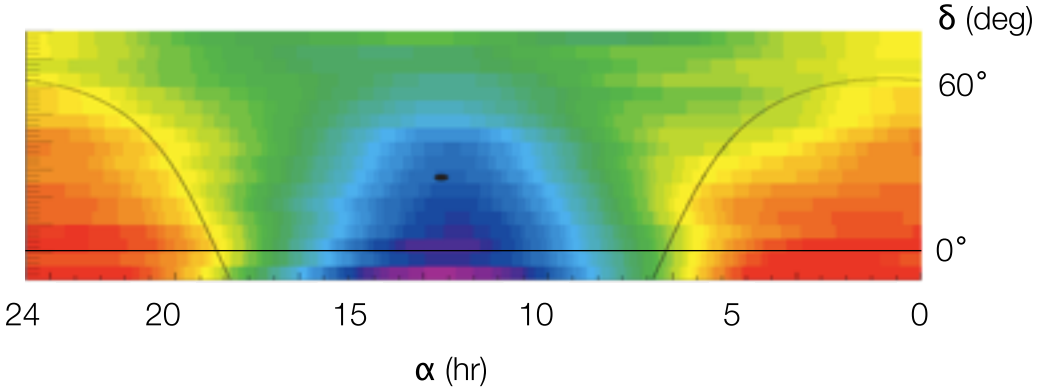
20 TeV

IceCube
Abbasi et al. (2010)



4 TeV

ARGO-YBJ
Zhang et al. (2009)



5 TeV

Milagro
Abdo et al. (2009)

cosmic rays observations anisotropy

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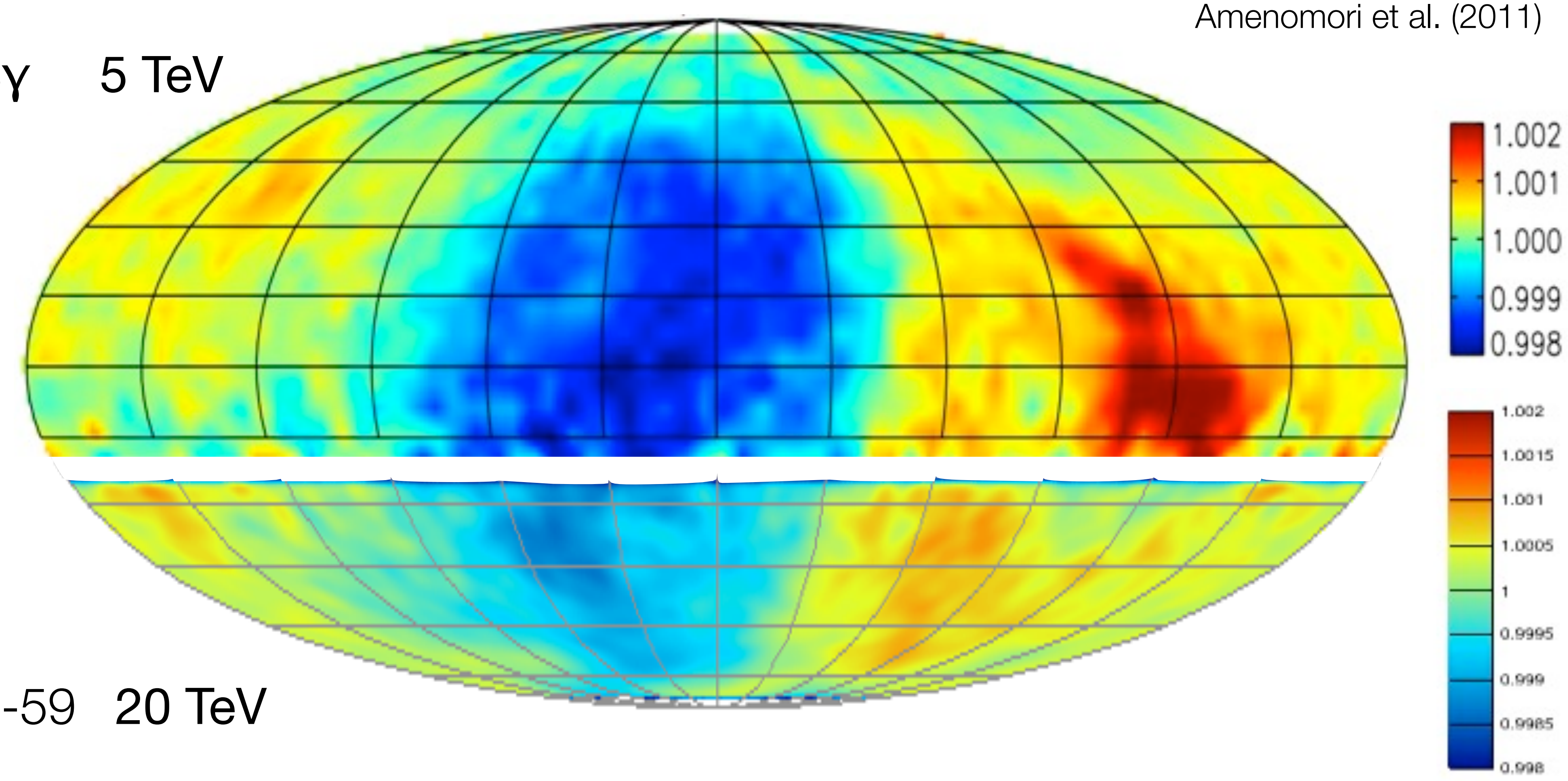
equatorial coordinates relative intensity

Tibet-ASγ **5 TeV**

Amenomori et al. (2011)



IceCube-59 **20 TeV**

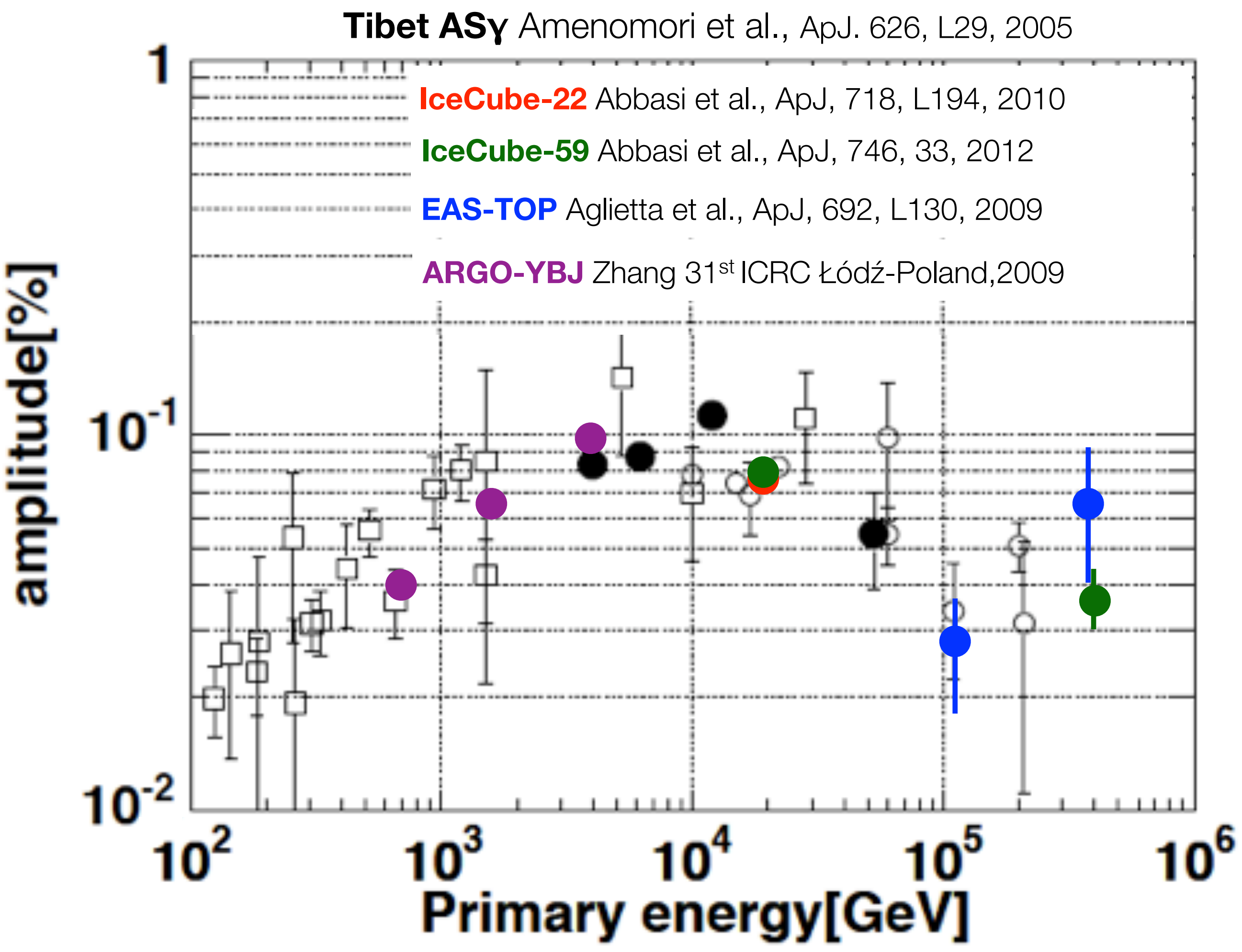
Abbasi et al. (2012)

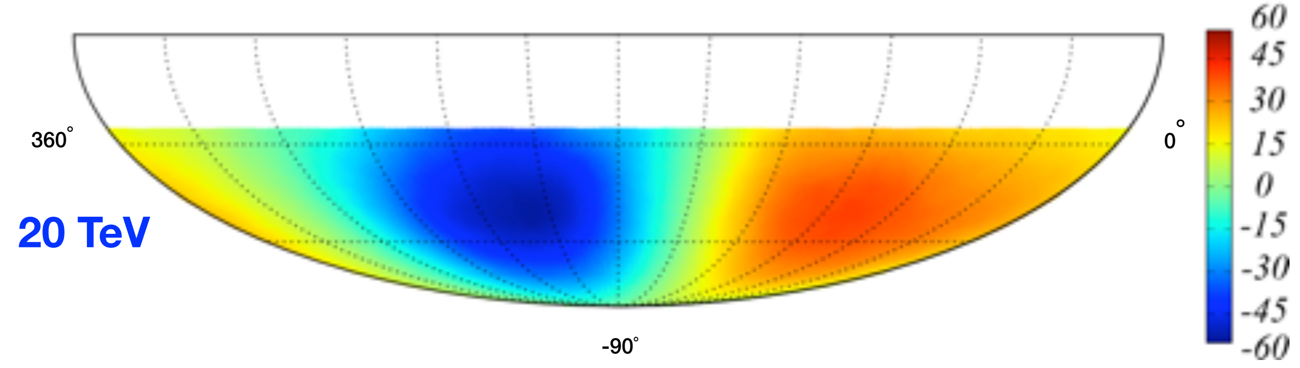
anisotropy vs. energy

- CR anisotropy changes phase ~100 TeV
- global amplitude is modulated

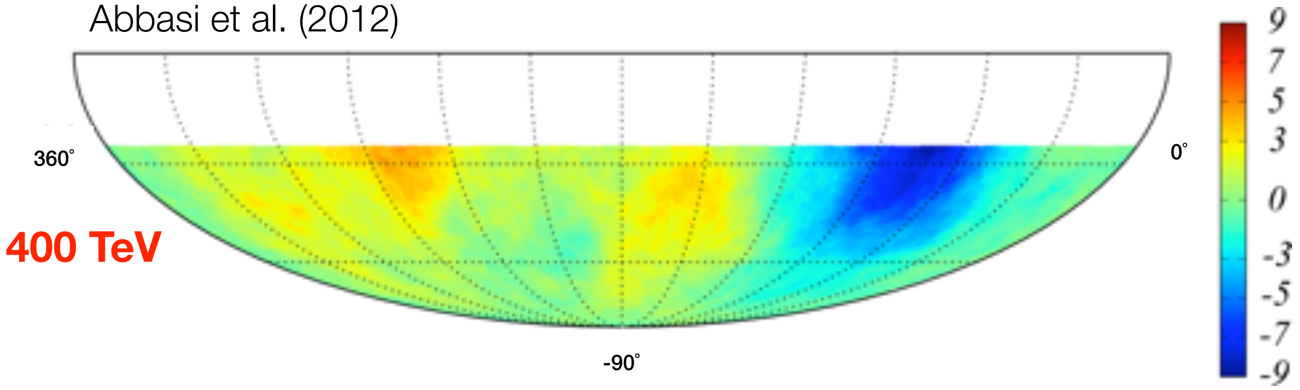
$$\delta_{fluctuations} = \frac{3}{2^{3/2}} \frac{1}{\pi^{1/2}} \frac{D(E)}{Hc}$$

$$D(E) \propto E^{\delta}$$

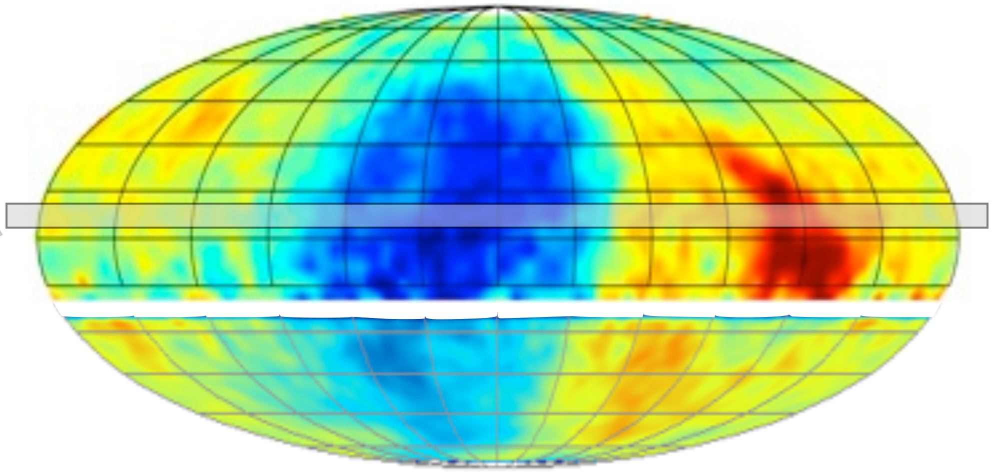


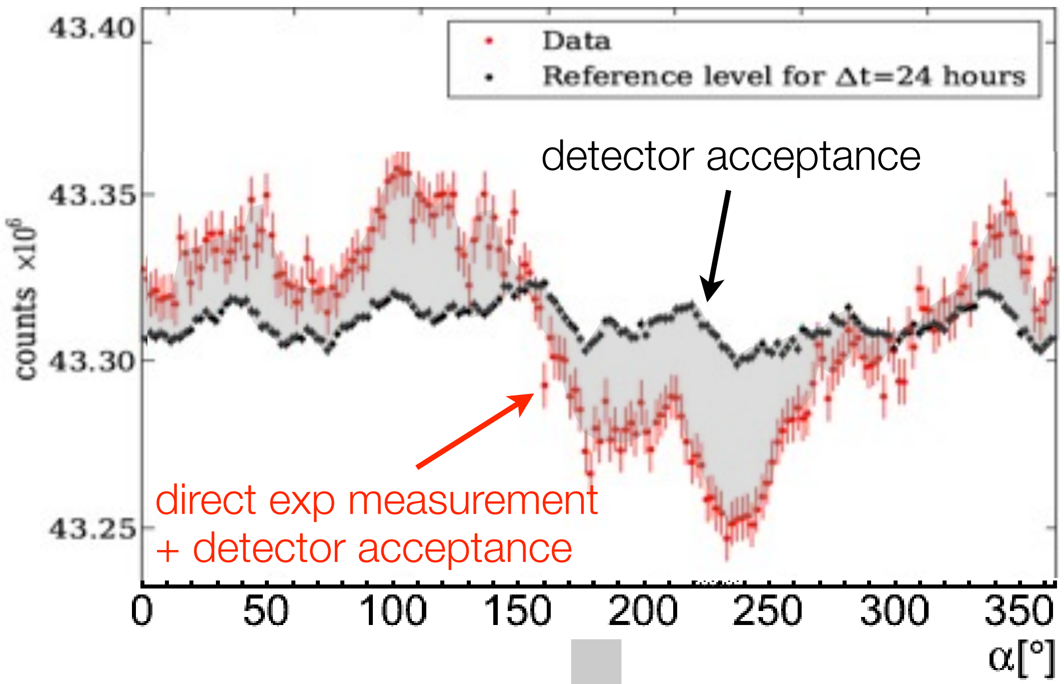


IceCube
Abbasi et al. (2012)



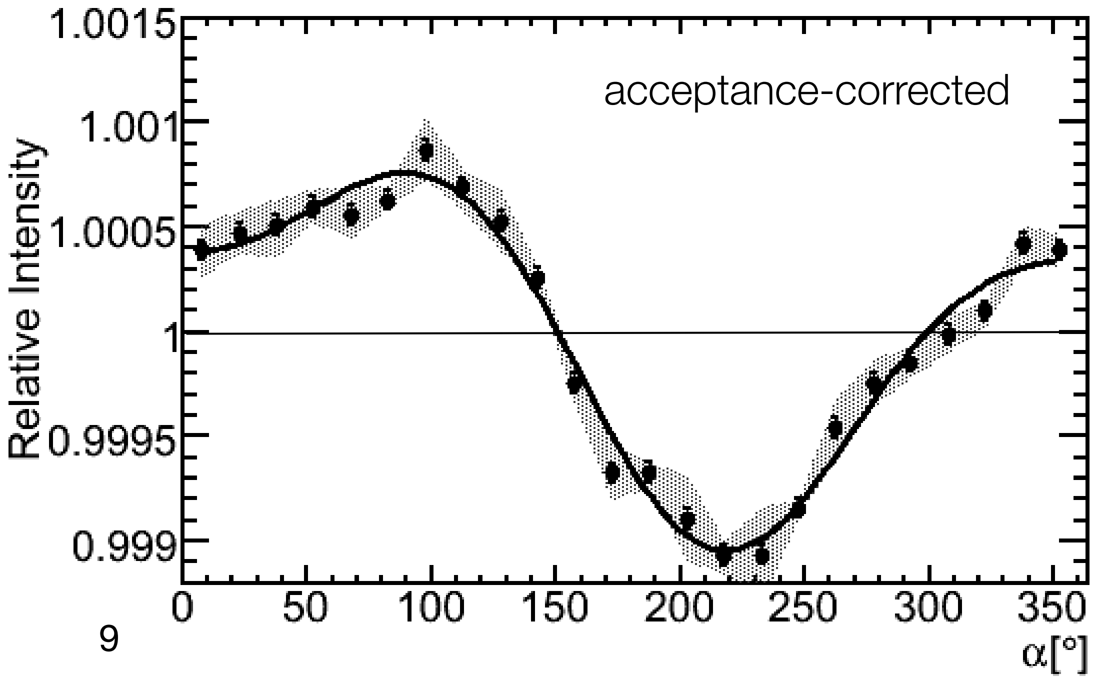
anisotropy vs. angular scale



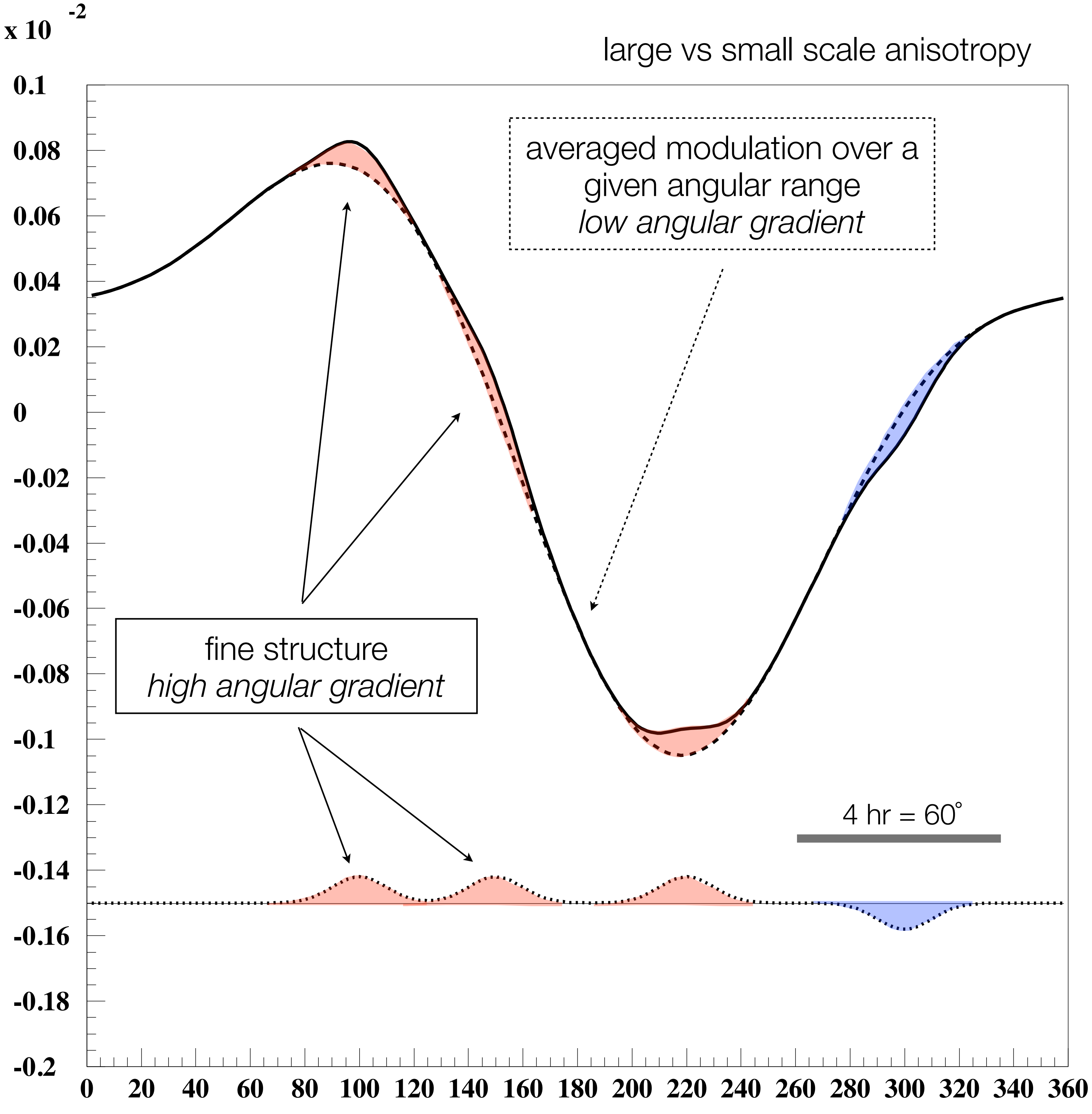


detector acceptance

direct exp measurement
+ detector acceptance



acceptance-corrected



large vs small scale anisotropy

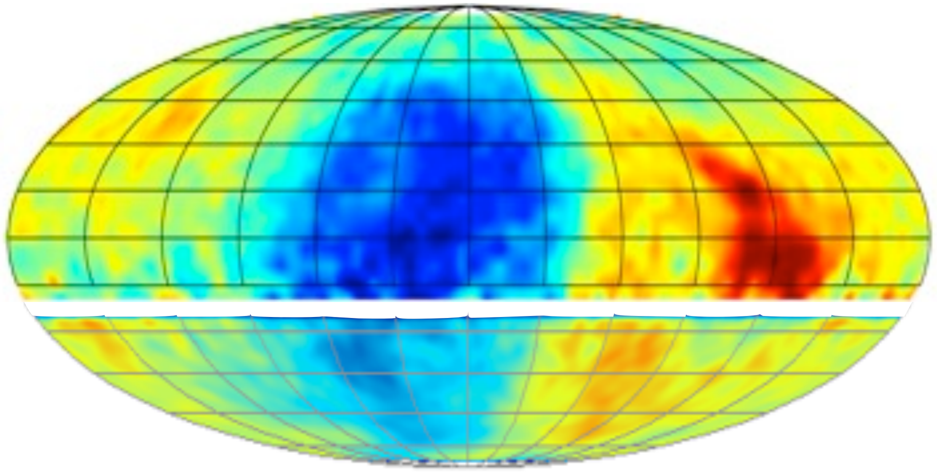
averaged modulation over a
given angular range
low angular gradient

fine structure
high angular gradient

4 hr = 60˚

Paolo Desiati

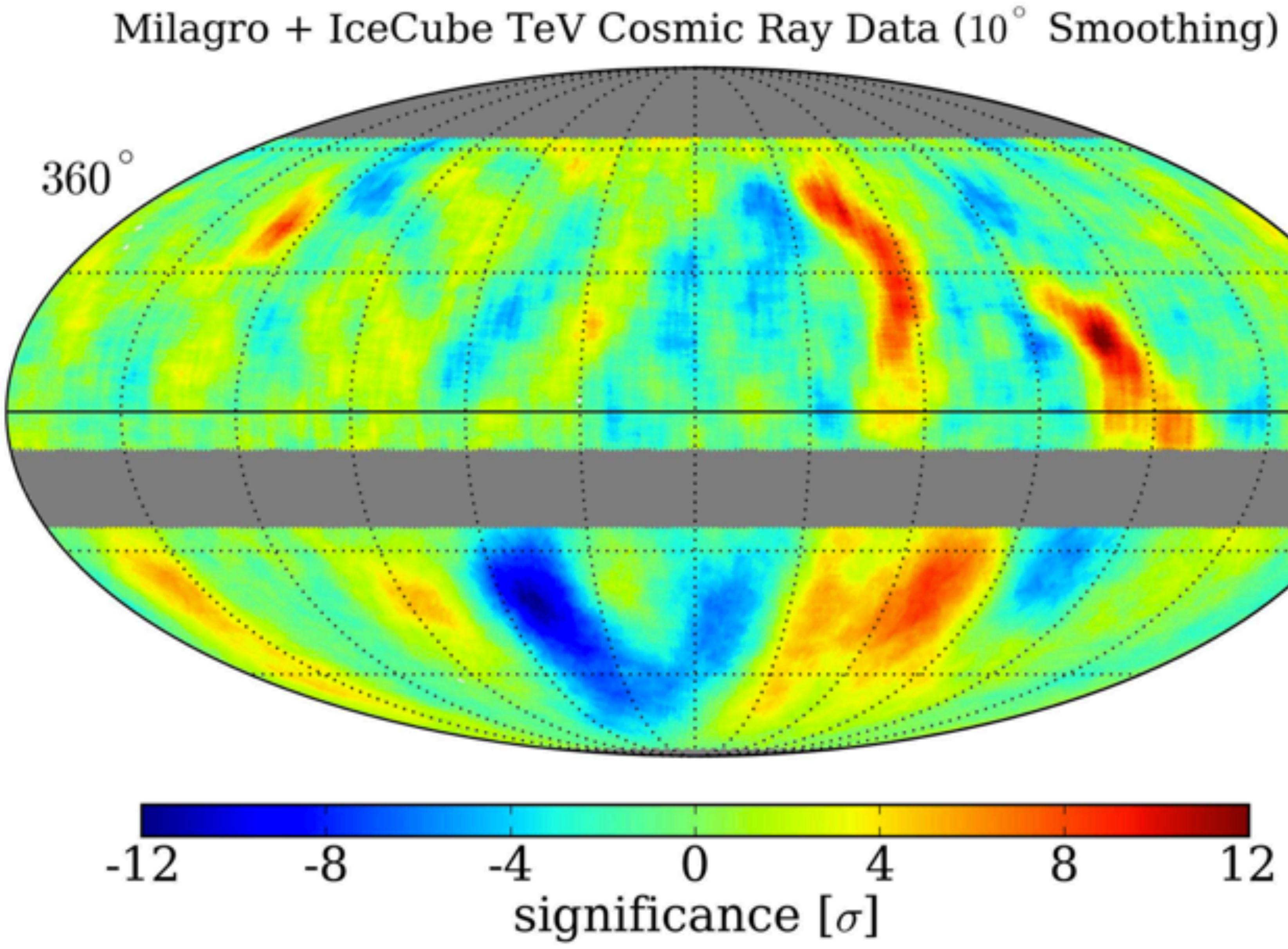
cosmic rays observations anisotropy



equatorial coordinates statistical significance

2 hr = 30°

4 hr = 60°



Milagro 1 TeV

Abdo et al. (2008)

IceCube 20 TeV

Abbasi et al. (2011)

origin of small scale anisotropy ?
astrophysics

- CR from Geminga: ~90-200 pc, 340,000 yr ago

Salvati & Sacco, arXiv:0802.2181
Drury & Aharonian, Astropart. Phys. 29, 420 (2008)

- magnetic connection & propagation in turbulent LIMF

Salvati, Astron. & Astrophys. arXiv:1001.4947

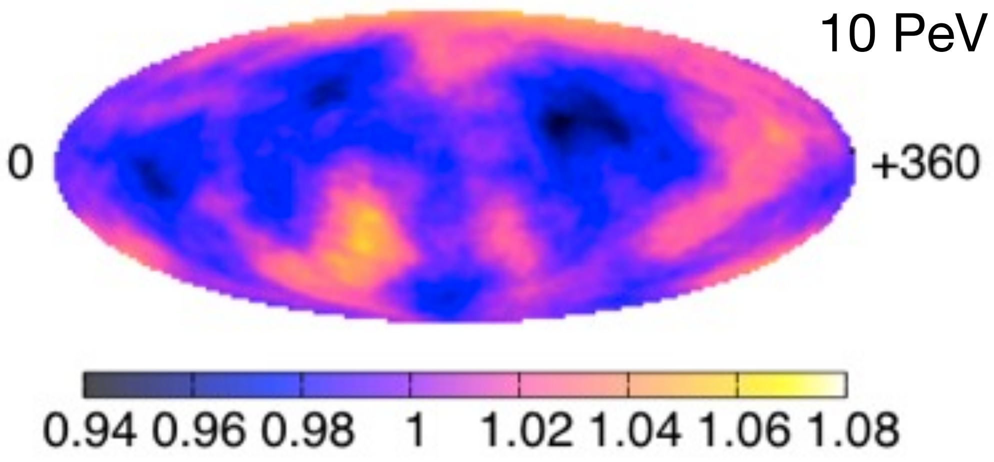
- anisotropic MHD turbulence in the ISM
  - particles streaming along magnetic field lines over ~100 pc (from a source) interact with O(1pc) ISM turbulence
  - pitch angle scattering peaked near the direction of LIMF

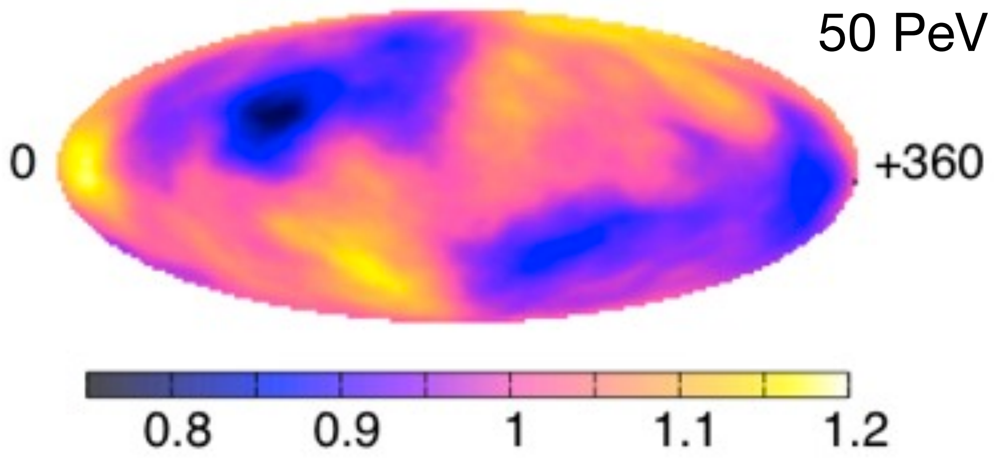
Malkov et al., ApJ 721, 750, 2010

origin of small scale anisotropy ?
effect of turbulence

Giacinti & Sigl, arXiv:1111.2536

- diffusion regime breaks down **within mean free path**
- interaction with **turbulent** interstellar magnetic field
- assuming an underlying dipole anisotropy, fractional localized regions form the effect of magnetic field turbulence
- the residual maps provide an image of magnetic field turbulence < 10’s pc
- cosmic ray energy spectra might also be affected by this propagation effects



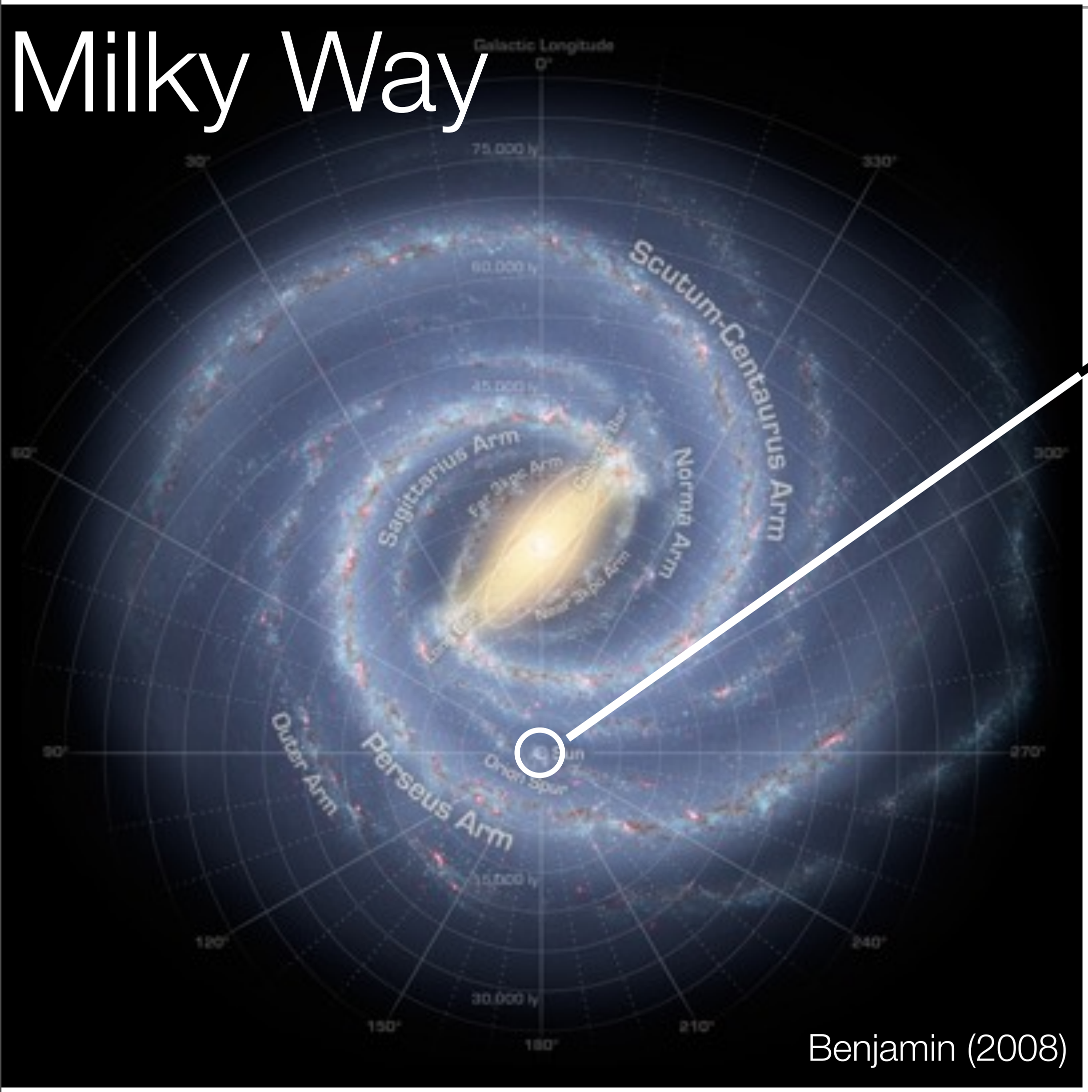


20° smoothing

diffusive propagation models ...

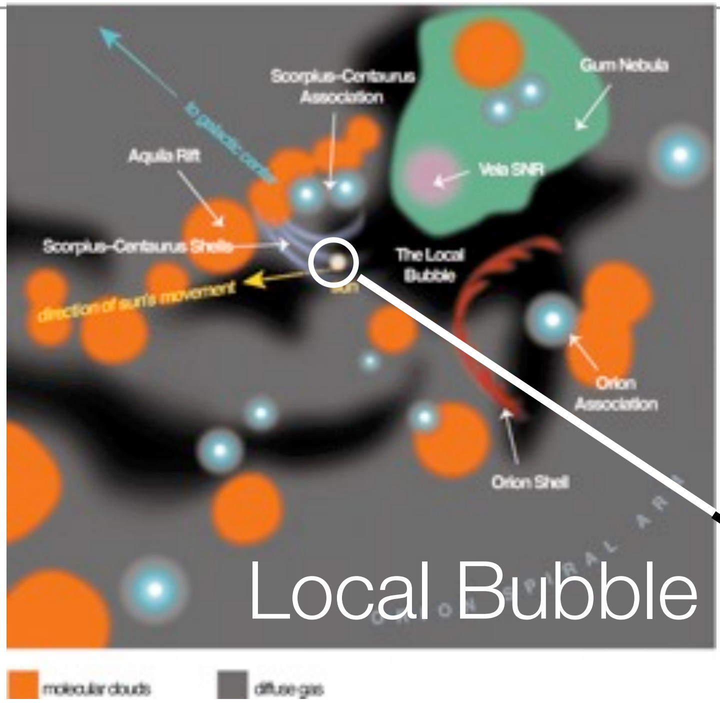
- … assume uniform diffusion coefficient across the Galaxy
- … do not account for energy-dependent interaction with ISM turbulence
- … do not account for magnetic field geometry
- … cannot explain non-dipolar anisotropy structures
- … break down within mean free path

from the Galaxy to our local interstellar medium



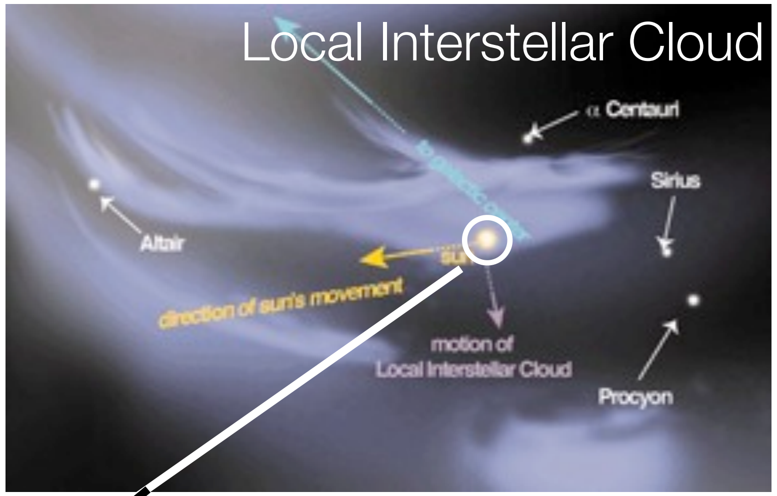
Benjamin (2008)

< 30,000 pc >



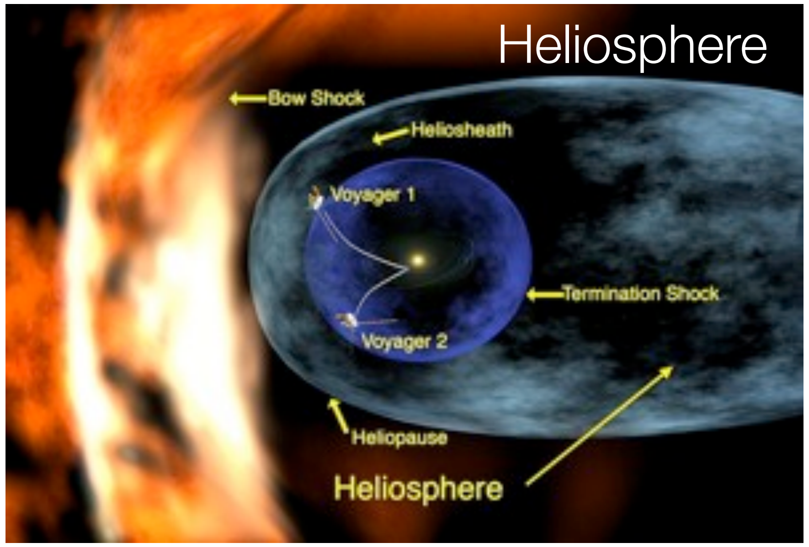
Frisch

< 500 pc >



Frisch

< 10-50 pc >



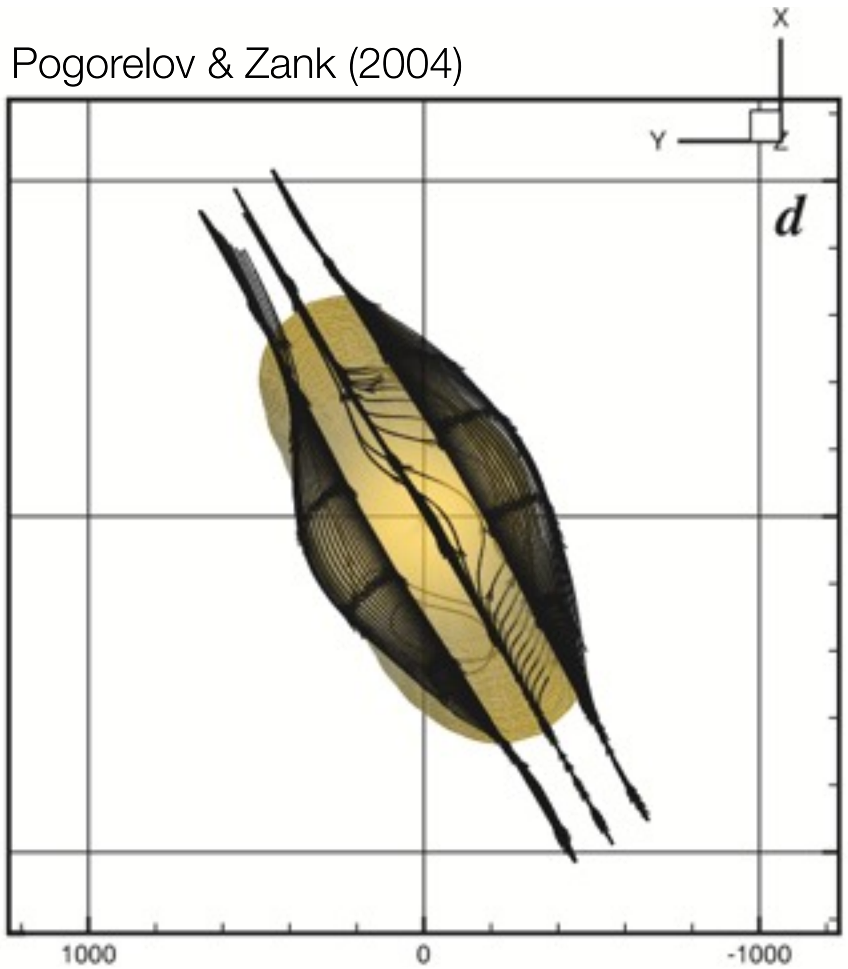
< 0.001 - 0.05 pc >

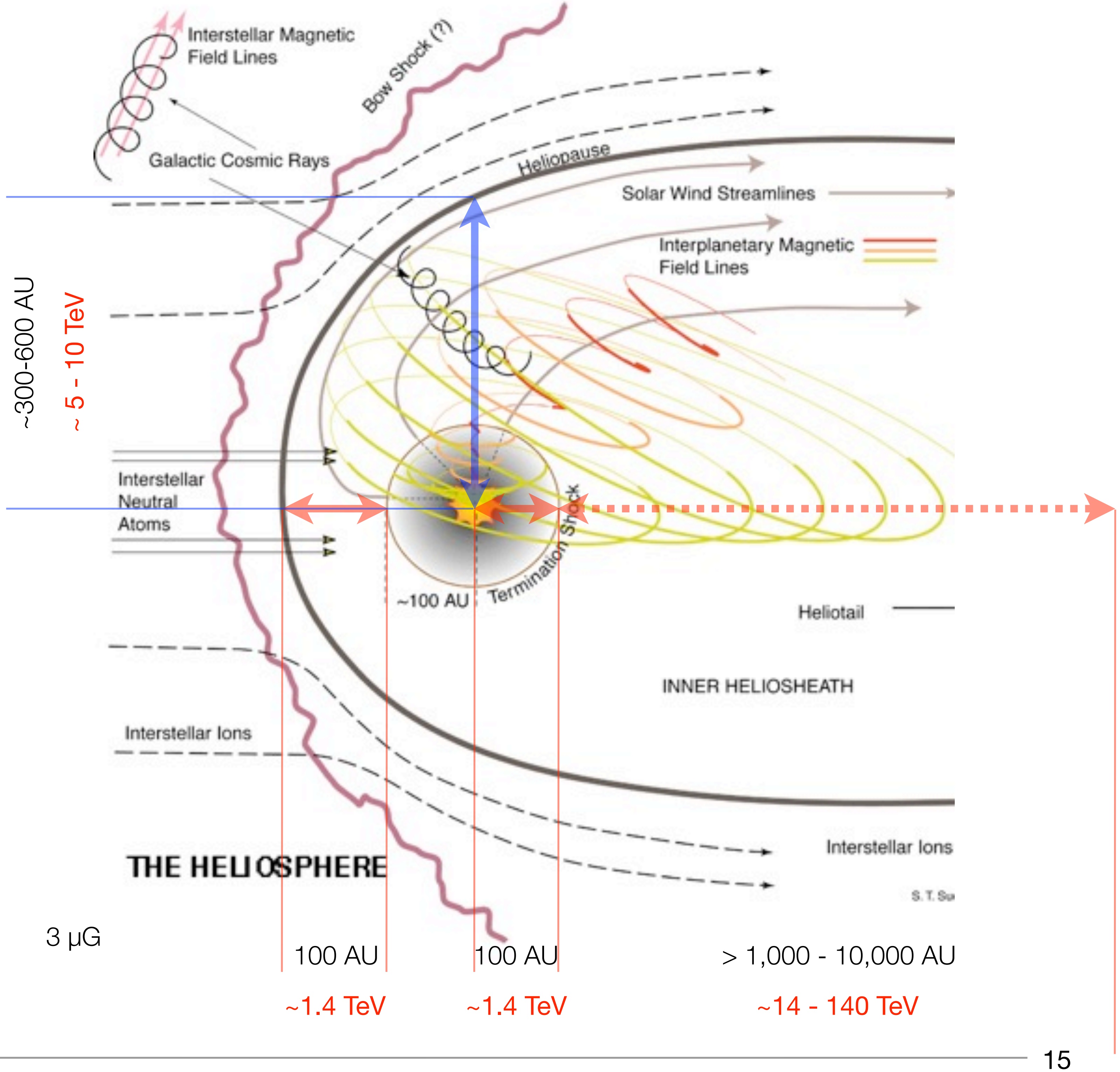
the heliosphere and the LIMF

$$R_g \sim \frac{10^{-3}}{Z}\left(\frac{E}{1\,TeV}\right)\left(\frac{\mu G}{B}\right)\ pc$$

$V_{\text{interstellar flow}} \sim 26$ km/s $\gtrsim V_{\text{Alfén}}$

Pogorelov & Zank (2004)





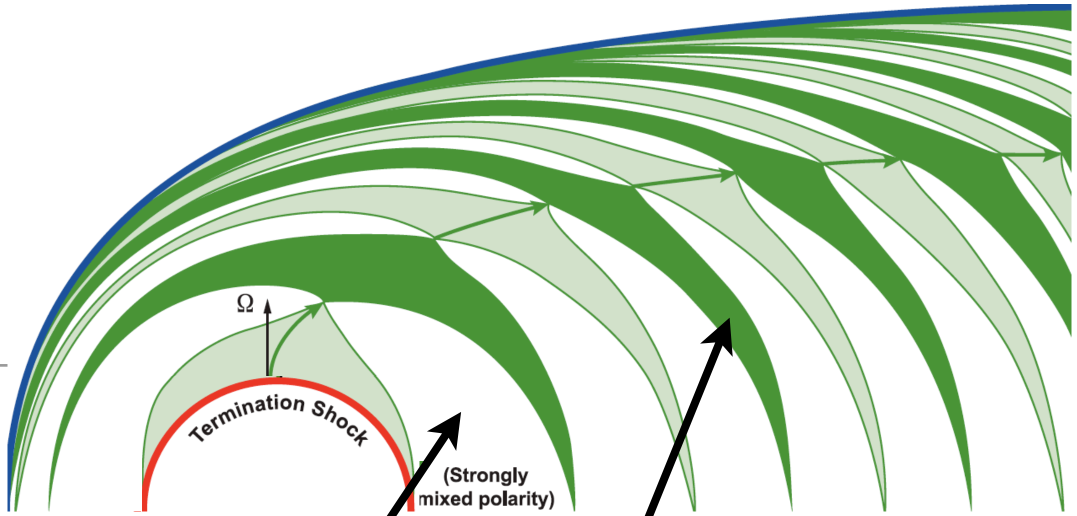
~300-600 AU

~ 5 - 10 TeV

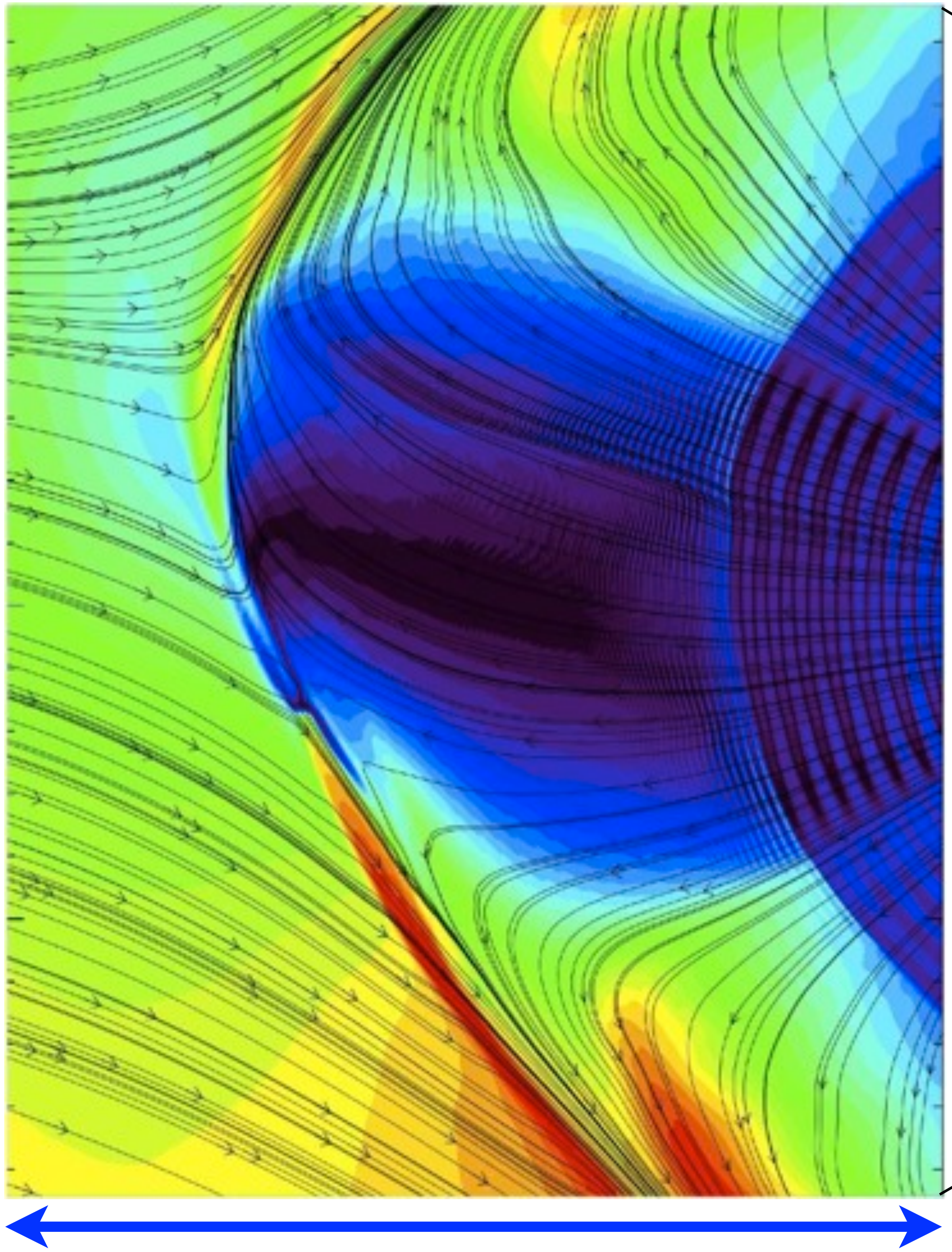
3 µG

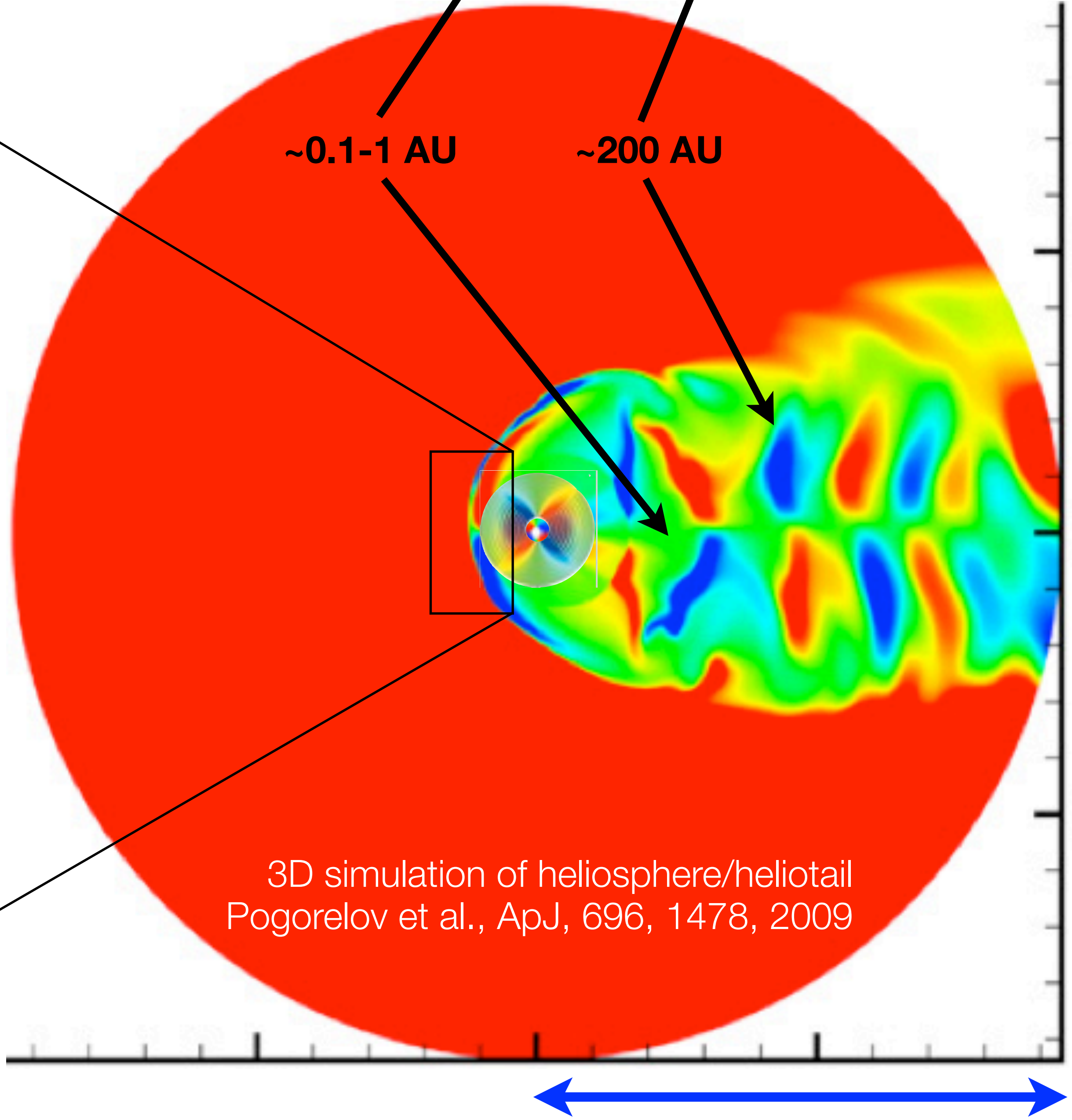
100 AU	100 AU	> 1,000 - 10,000 AU
~1.4 TeV	~1.4 TeV	~14 - 140 TeV

the heliosphere magnetic structure



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





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

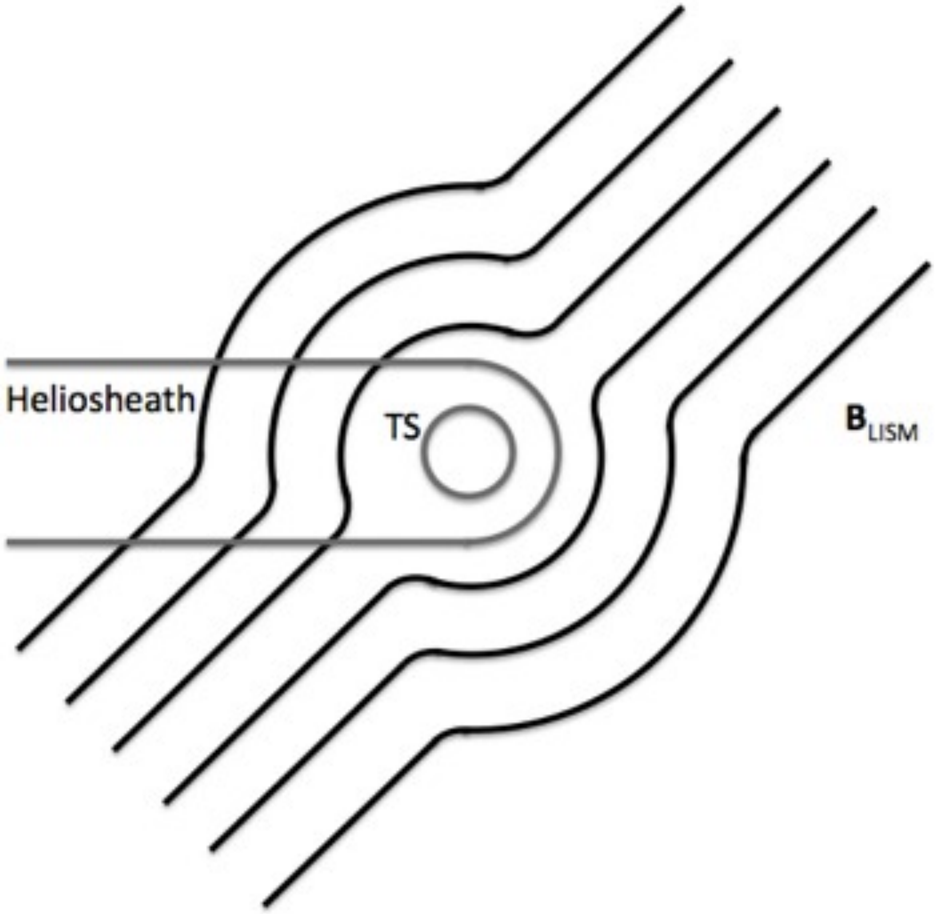
the heliosphere turbulence

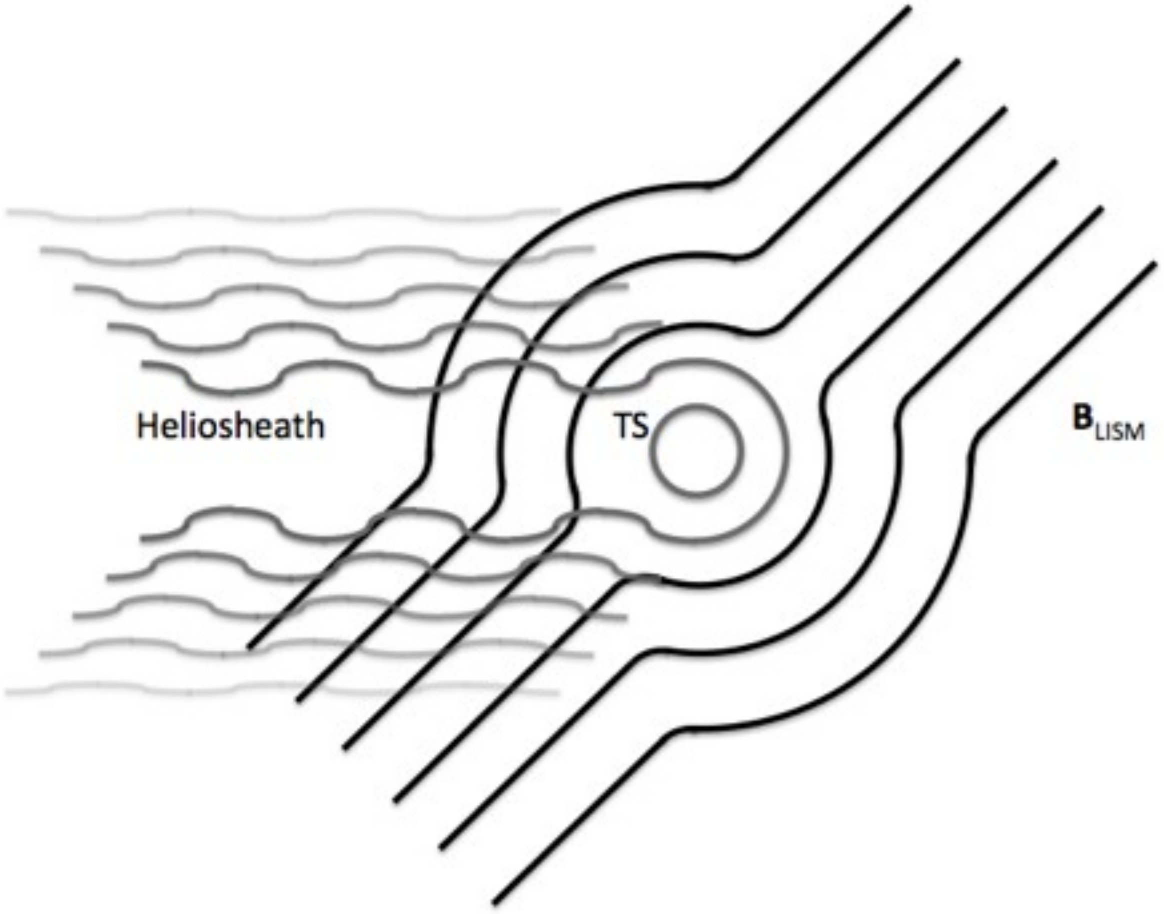
- the wake downstream the interstellar flow develops turbulence from plasma velocity difference across the heliopause (similar to Kelvin-Helmholtz instability)

- charge-exchange processes decelerate the solar wind near the heliopause, producing an effective drag force that pushes the higher ISM density into the heliosheath. This generates Rayleigh-Taylor instability oscillations with amplitude **10's AU** over 100's years - Liewer et al. (1996).

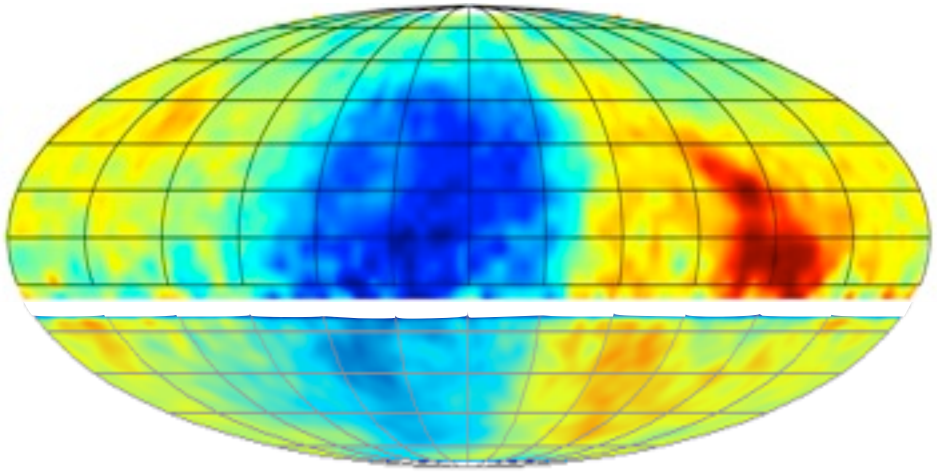
- charge-exchange processes in plasma-neutral fluid model produces alternate growing and damping of Alfvénic, fast and slow turbulence modes, with amplitude **10-100 AU** and slowly propagating downstream along the heliopause - Shaikh & Zank (2010).
    - The 10-100 AU turbulent ripples propagate outward the ISM and are damped by ion-neutral collisions in mfp ~ **300 AU** - Spangler et al. (2011).

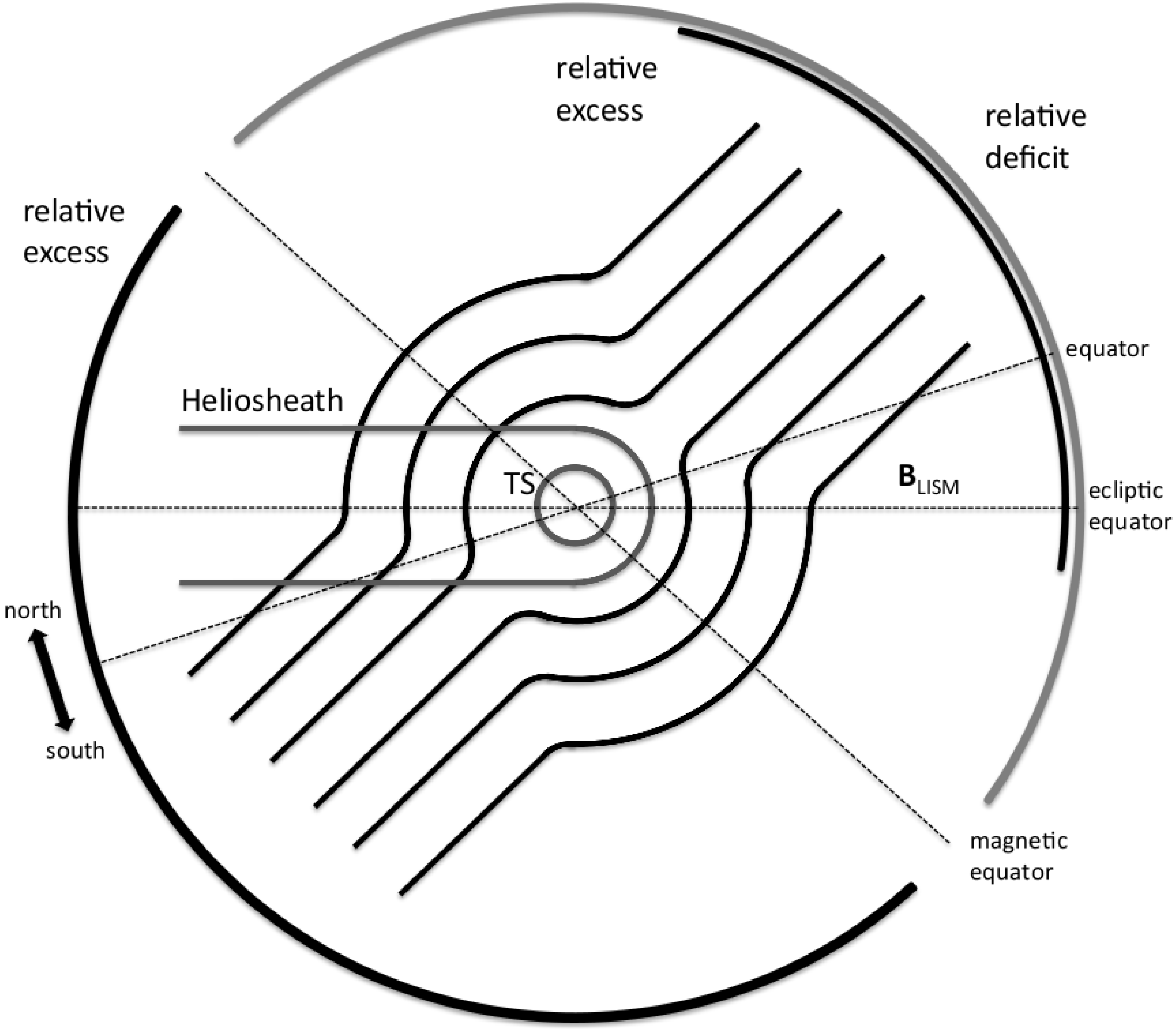
scattering on heliospheric turbulence

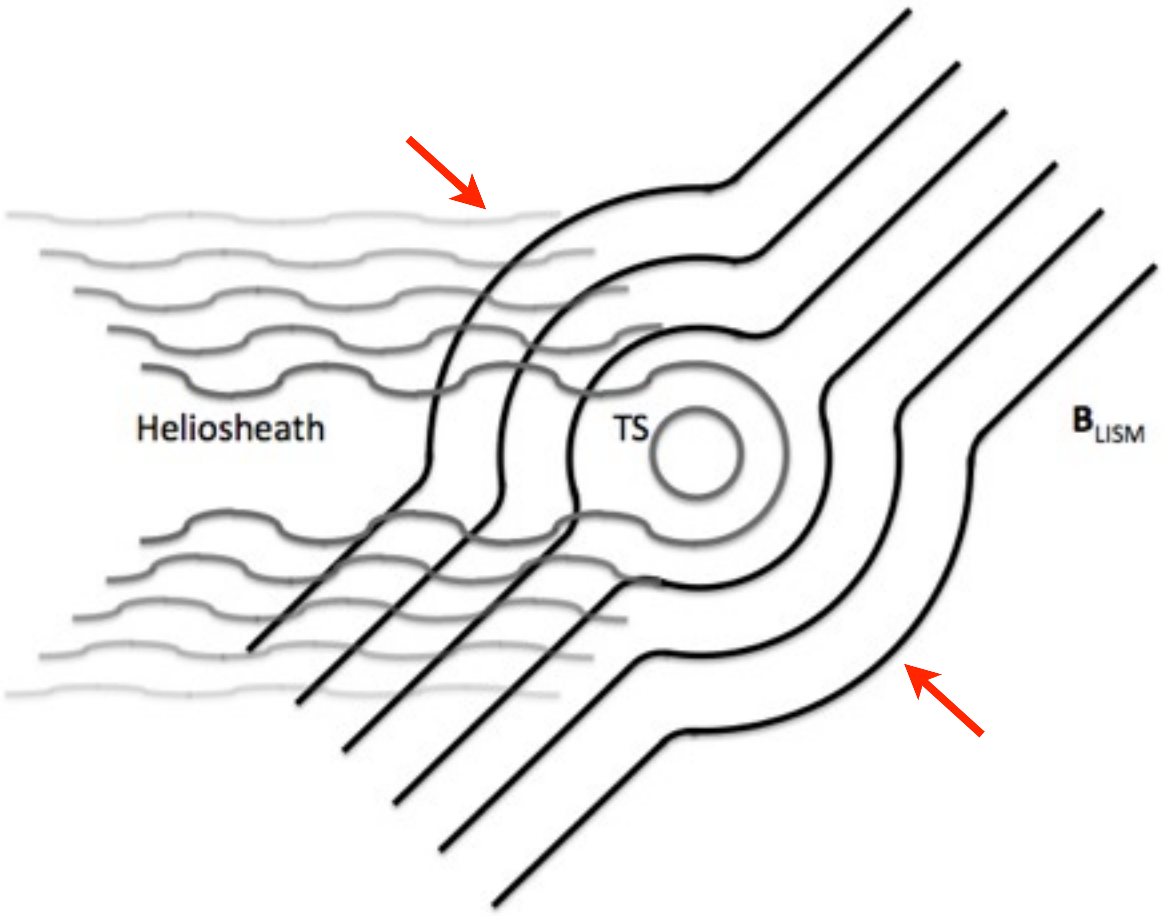




scattering on heliospheric turbulence





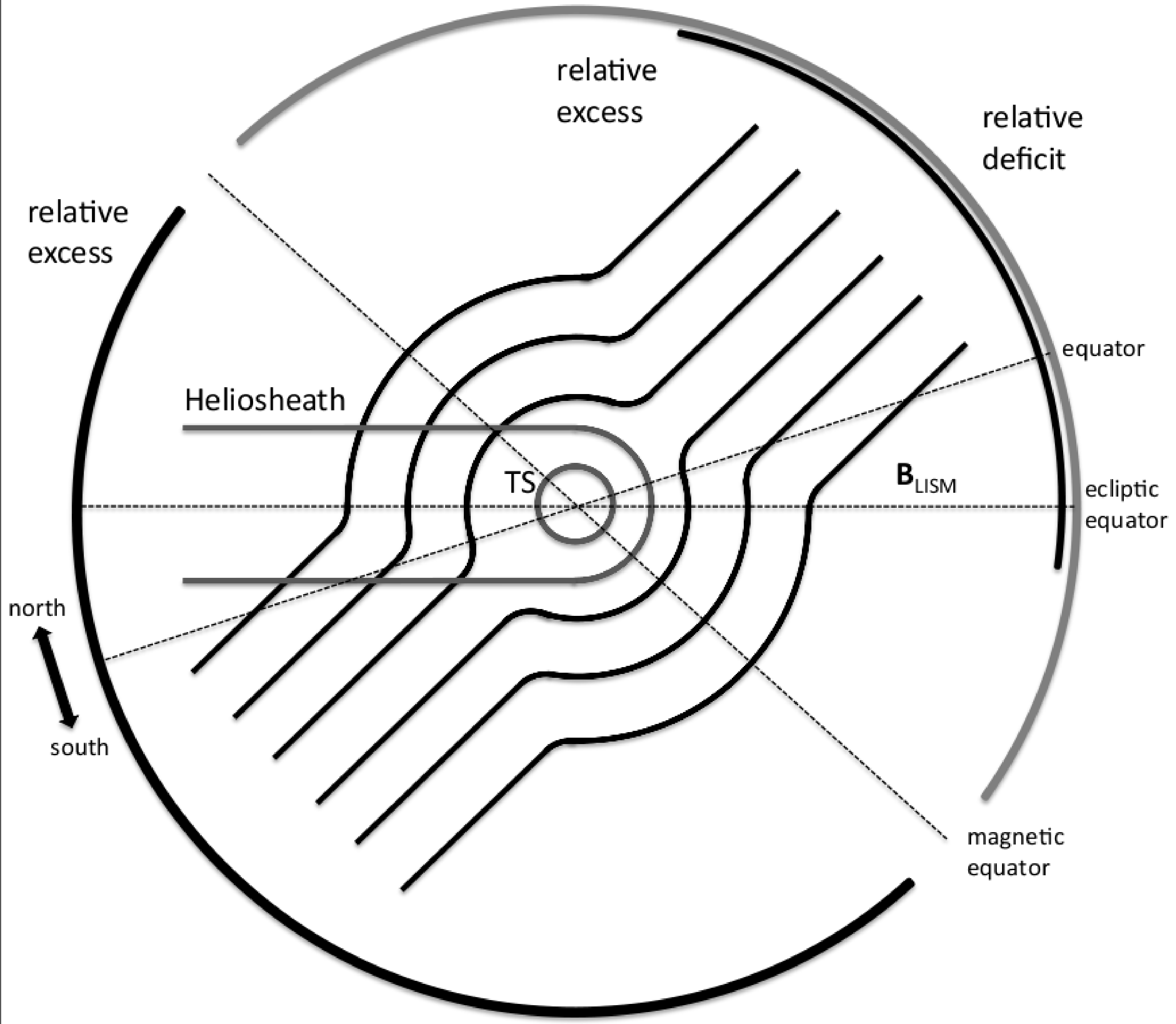


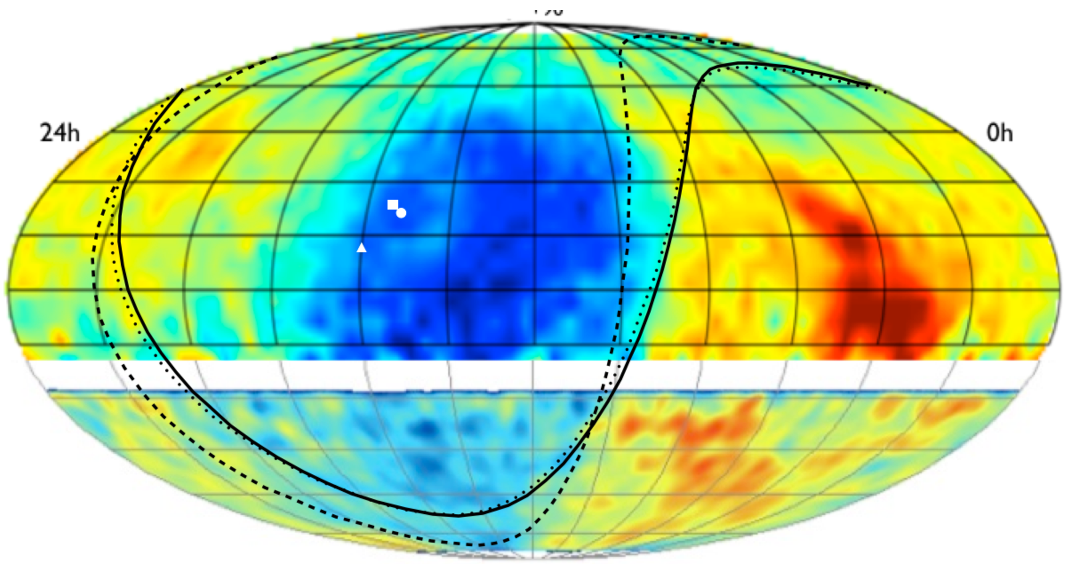
scattering on heliospheric turbulence

- cosmic rays > 100 TeV do not feel the influence of the heliosphere
- cosmic rays < 100 TeV are influenced by the heliosphere from the downstream region
- resonant scattering of 1-10 TeV cosmic rays with 100's AU turbulence ripples re-organizes the arrival direction distribution
- cosmic rays streaming along the LIMF experience the largest effect from the downstream region, and a minimal effect upstream
- perpendicular scattering is critical and determines the gradient region in cosmic ray arrival direction distribution
    - ‣ evaluations and calculations to verify this scenario

scattering on heliospheric turbulence

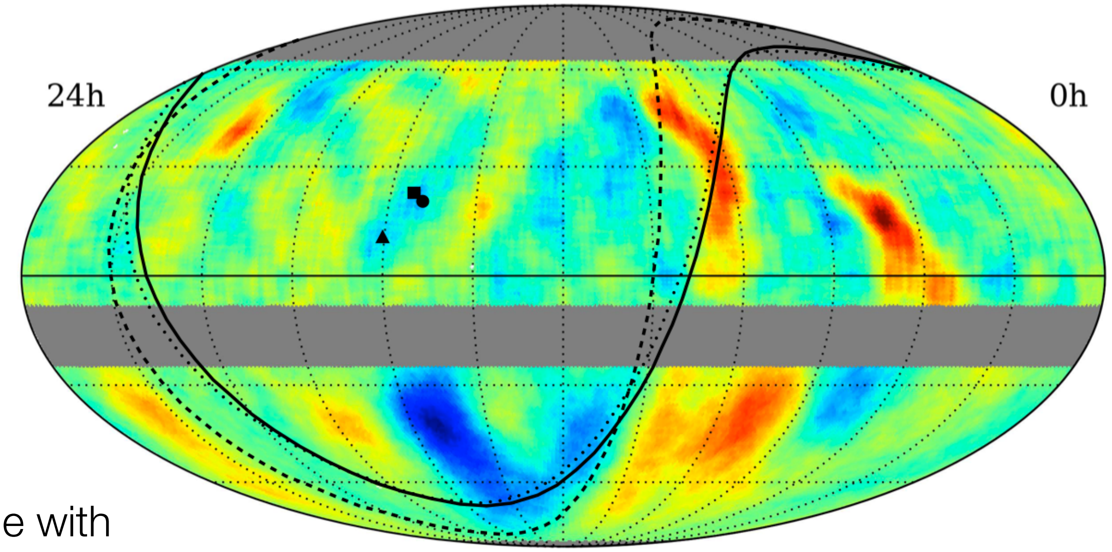
PD & Lazarian, arXiv:1111.3075





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

magnetic equator

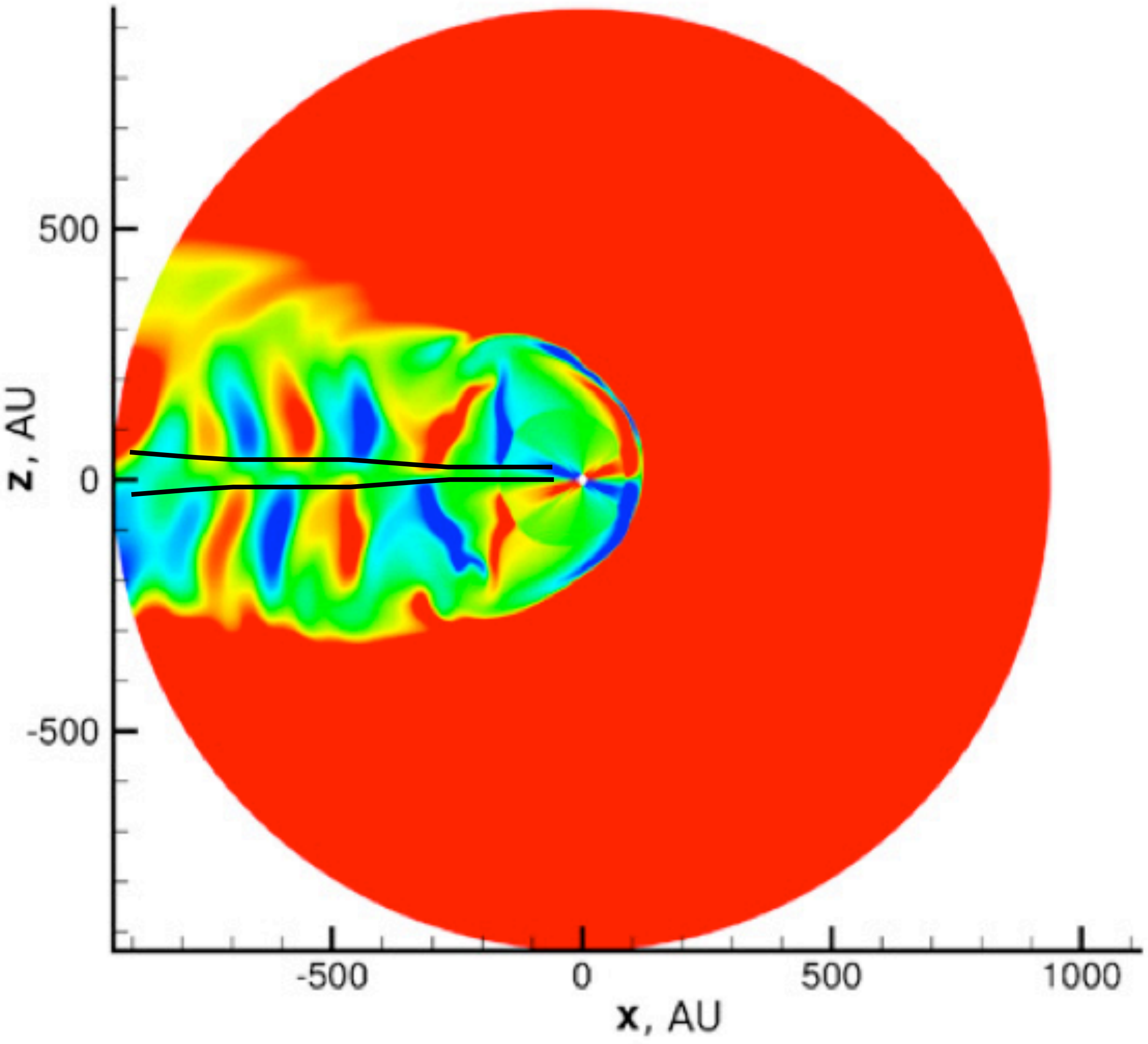


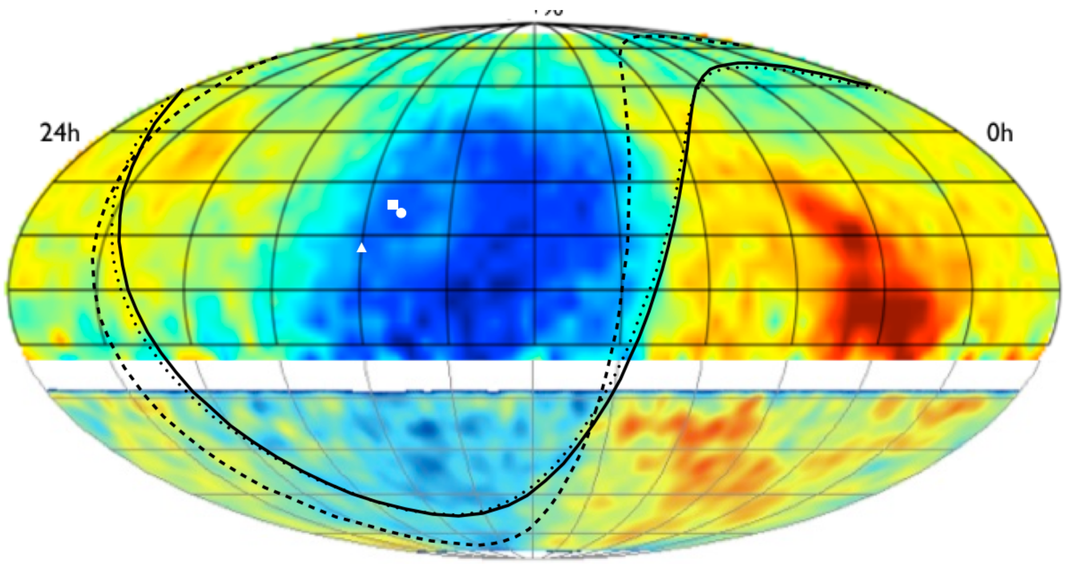
LIMF direction compatible with

- 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)

scattering on heliospheric turbulence

PD & Lazarian, arXiv:1111.3075





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Schwadron et al. (2009)
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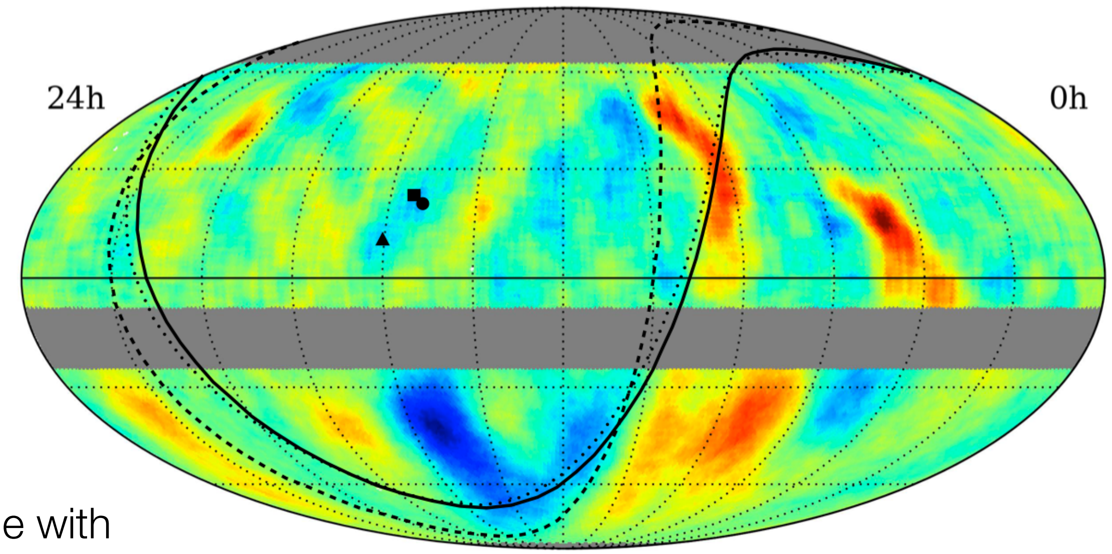
magnetic equator



LIMF direction compatible with

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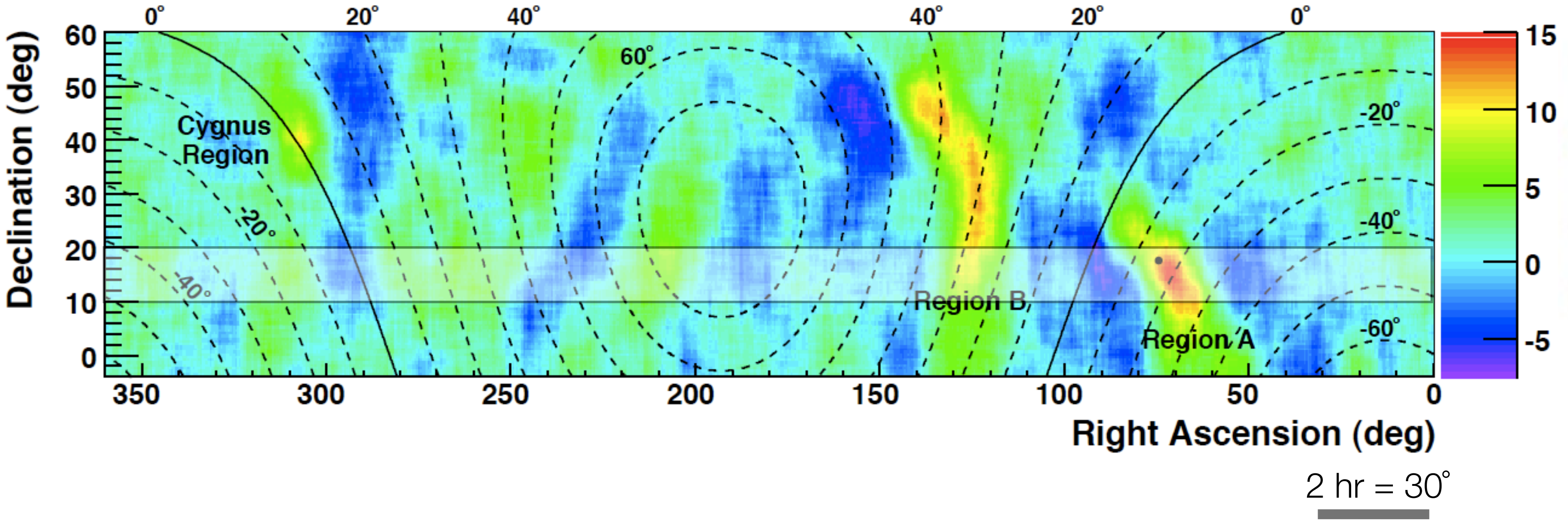
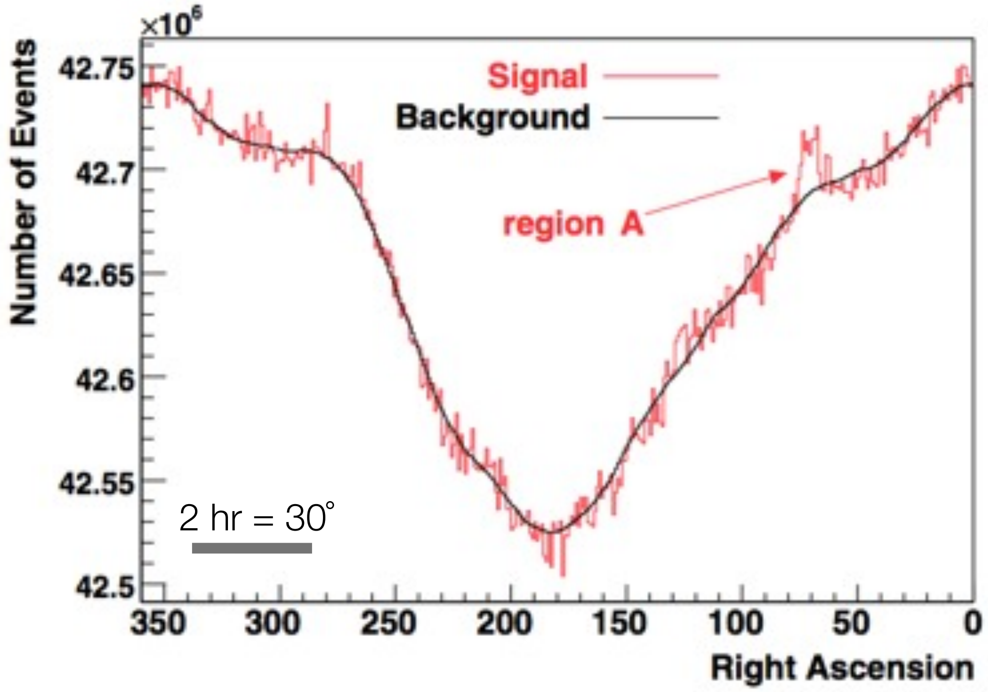
- polarization measurements, Frisch (2010)

spectral feature associated to anisotropy

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



2 hr = 30°



2 hr = 30°

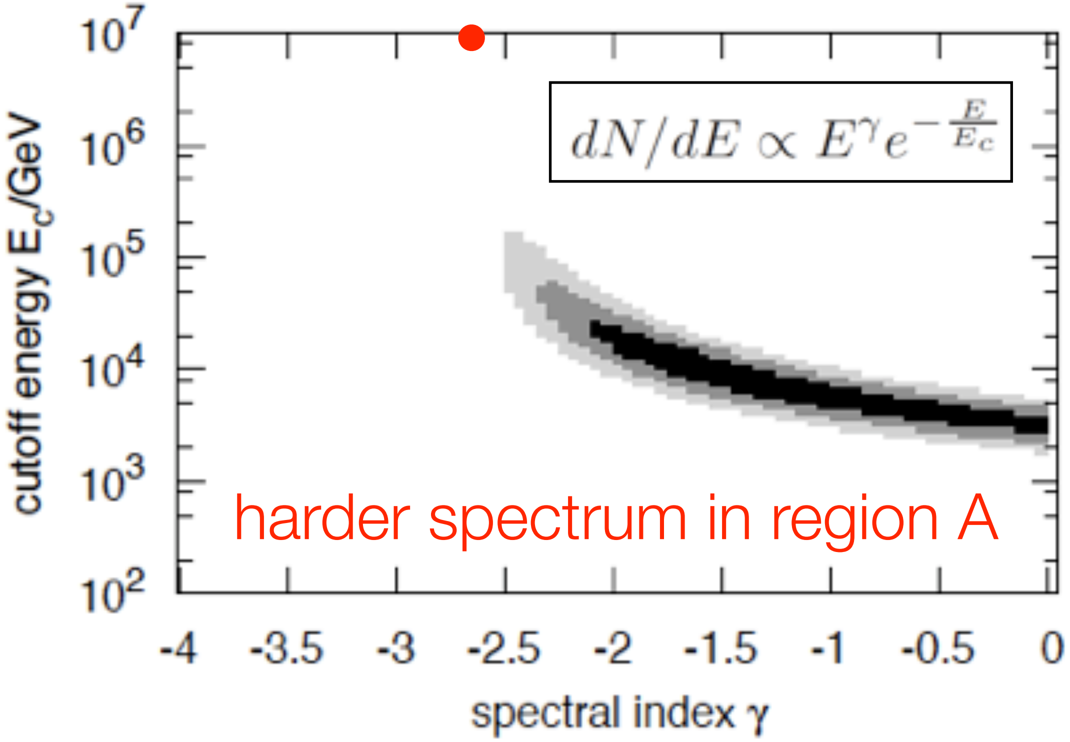
Milagro

& ARGO-YBJ

harder than average spectrum from region A

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

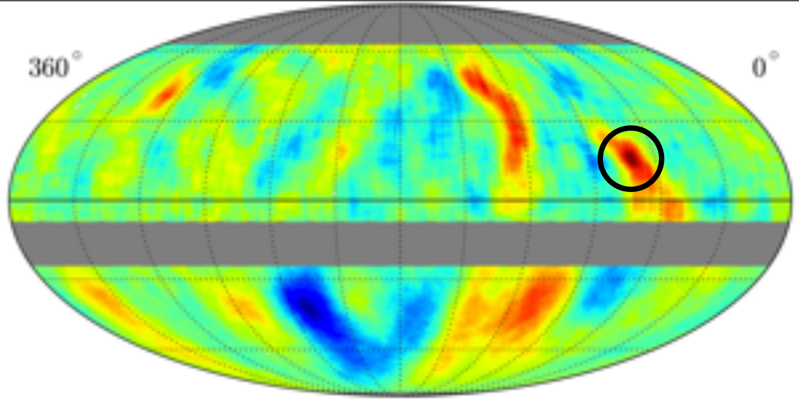
similar to hardening of “diffuse” cosmic rays by Pamela, CREAM, ATIC-2



$dN/dE \propto E^{\gamma} e^{-\frac{E}{E_c}}$

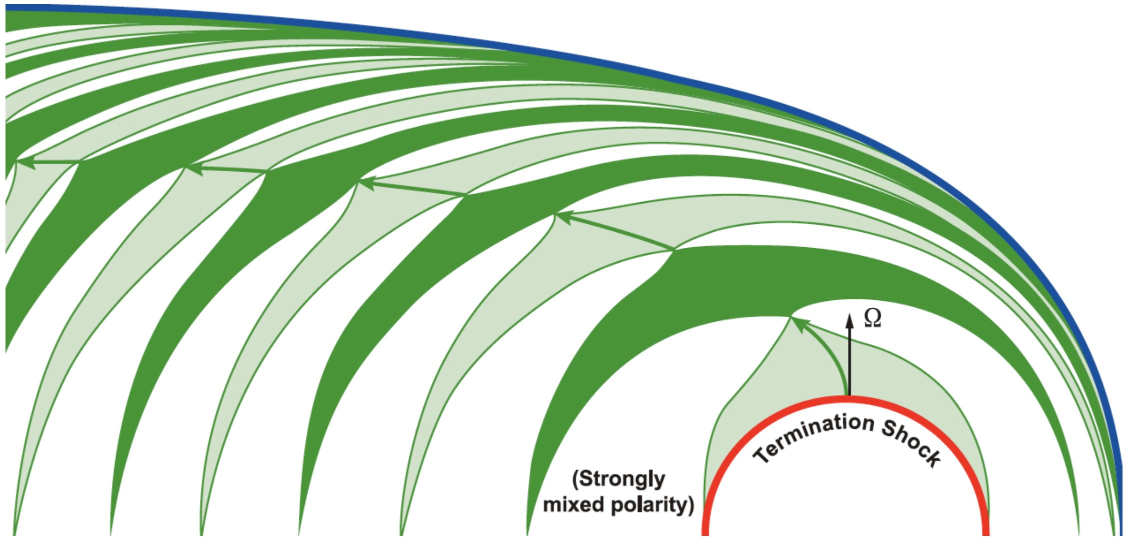
harder spectrum in region A

origin of spectral hardening ?



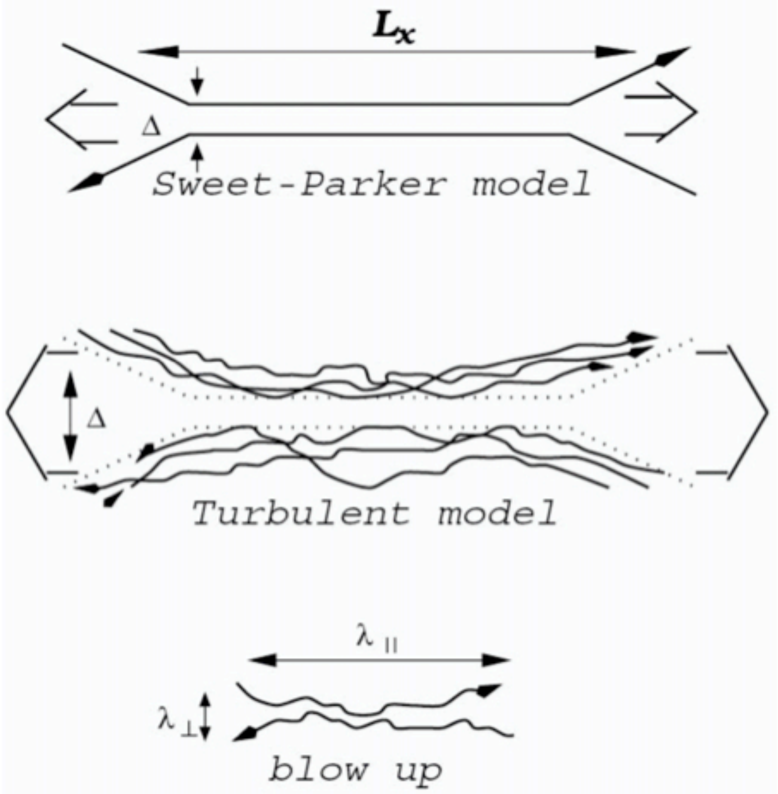
Lazarian & PD, ApJ, 722, 188, 2010

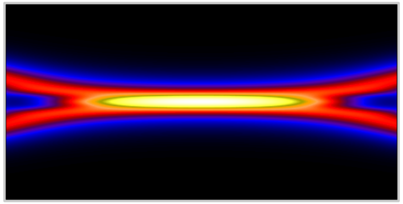
- magnetic polarity reversals due to the 11-year solar cycles compressed by the solar wind in the magneto-tail
- turbulence makes reconnection fast and not affected by ohmic dissipation
- magnetic mirror @ single reconnection as site of acceleration (test particle)

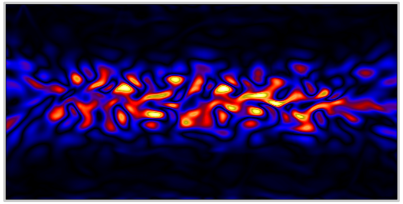


Sweet (1959) Parker (1957)

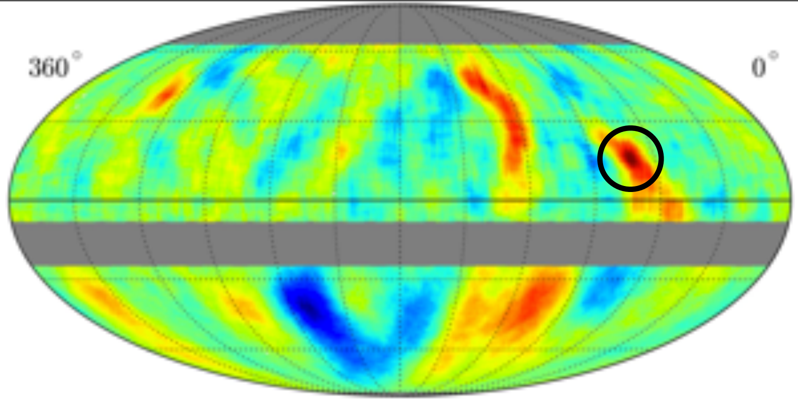
Lazarian & Vishniac, ApJ, 517, 700, 1999





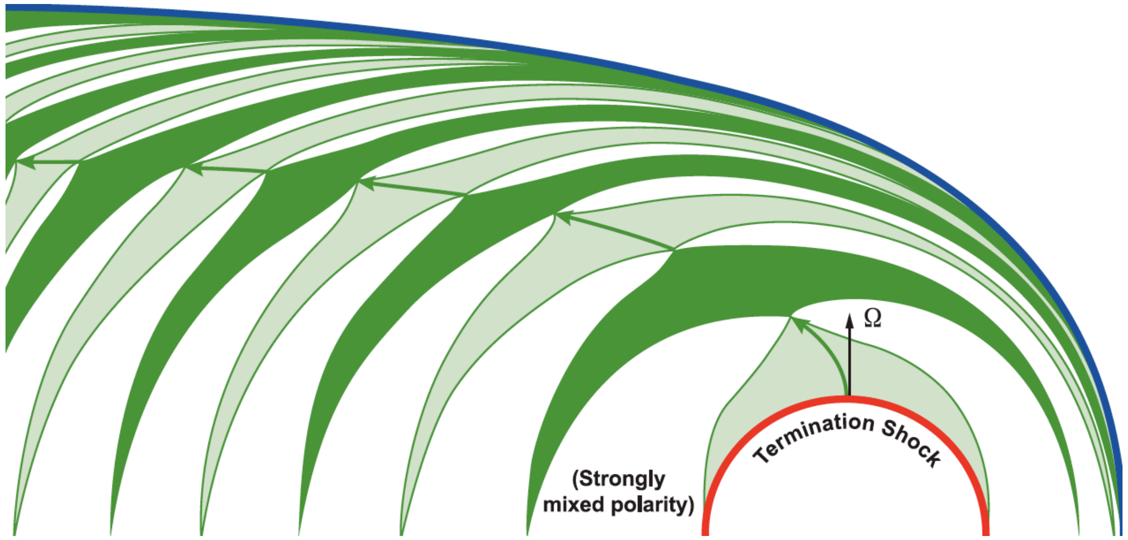


origin of spectral hardening ?



Lazarian & PD, ApJ, 722, 188, 2010

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



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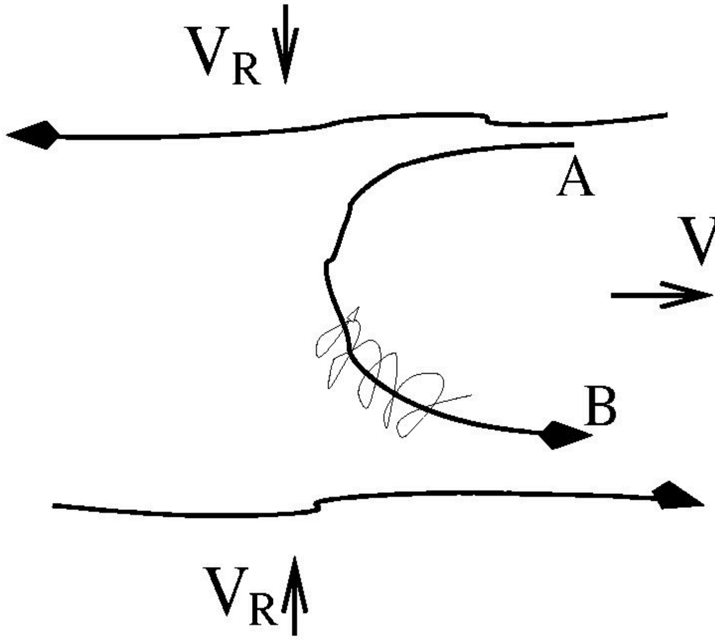
$$N(E)dE \sim E^{-5/2}dE$$

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



Conclusions

- < 100 TeV cosmic ray anisotropy generated by interaction with the very local interstellar medium
- scattering with turbulence inside and in the outer heliospheric boundary to play an important role to explain large scale and small scale TeV cosmic ray anisotropy
- might explain change of cosmic ray anisotropy between 20 TeV and 400 TeV
- spectral hardening observed by Milagro & ARGO-YBJ from the downstream direction from re-acceleration of a fraction of cosmic rays in stochastic magnetic reconnection within the heliotail
- similar hardening observed by Pamela and CREAM could be related to the heliotail, although astrophysical explanations @ source and from propagation are possible