# cosmic rays and stochastic magnetic reconnection in the heliotail

## and large scale heliospheric effects on high energy cosmic rays

D1.3-0006-12

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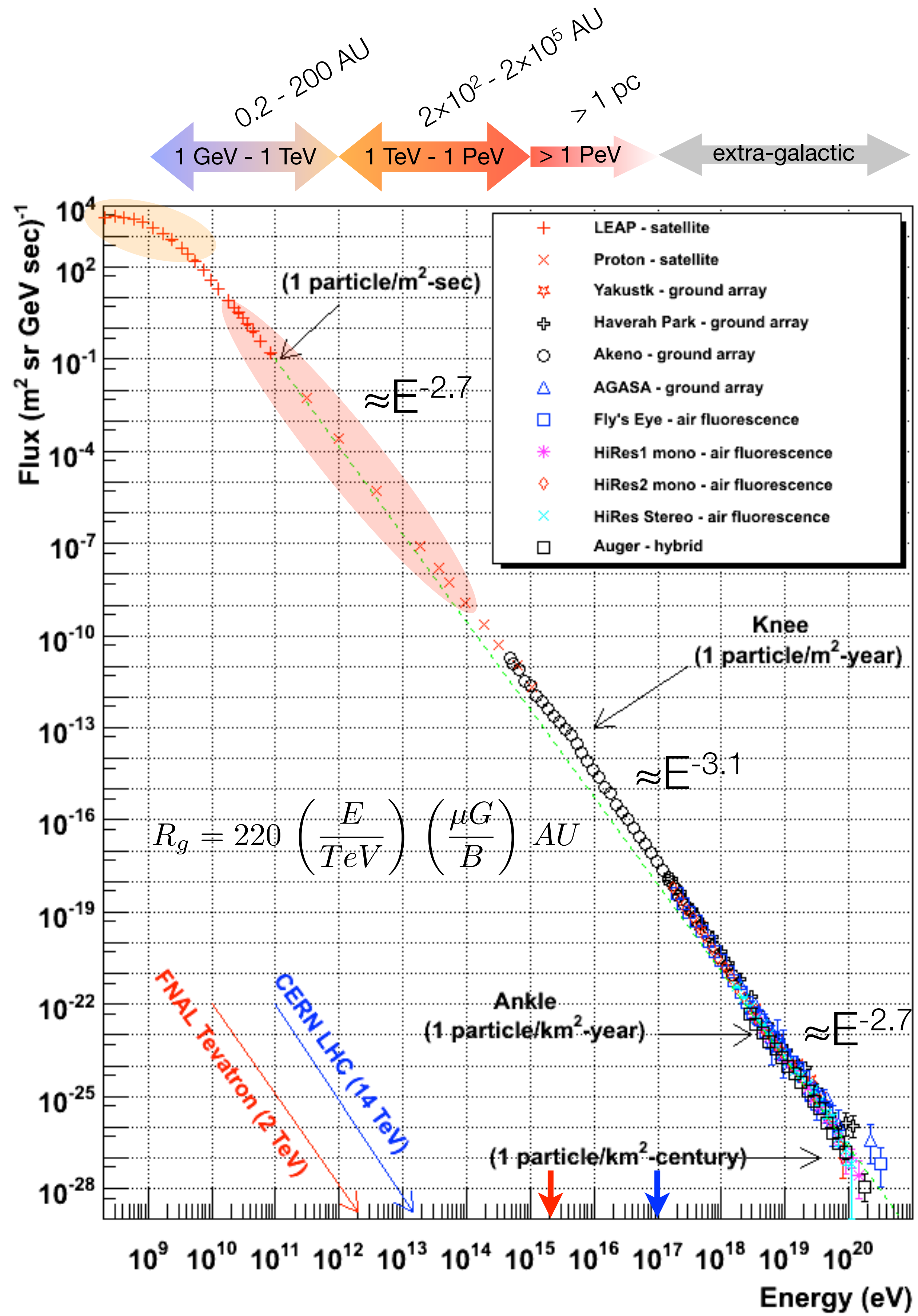
# outline

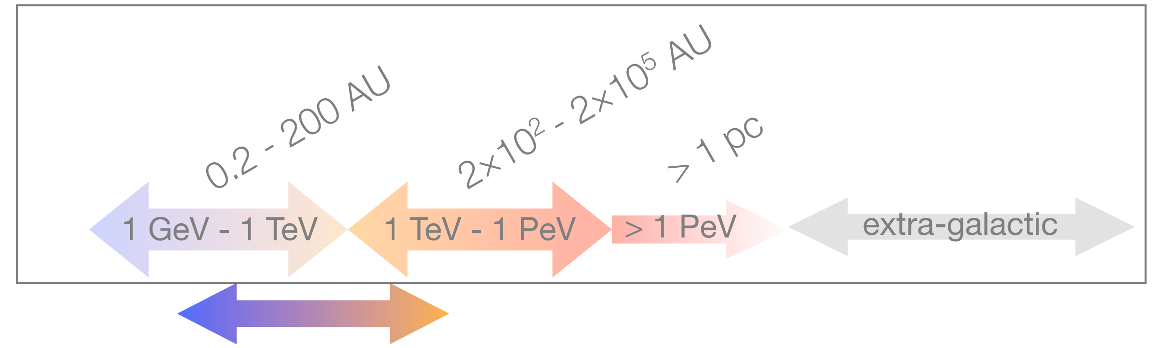
- **anomalies in high energy cosmic rays**
  - large and small scale anisotropy
  - energy dependence of anisotropy
- **heliosphere structure and turbulence**
  - propagation through the heliosphere and non diffusive processes
- **scattering processes and cosmic ray re-acceleration**
  - stochastic magnetic reconnection

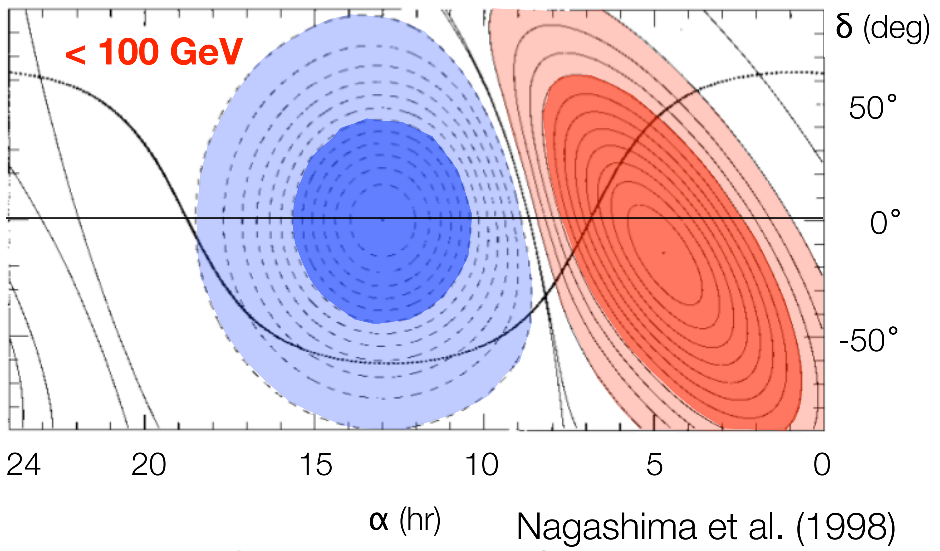
# cosmic rays

- spectrum & composition
  - **origin** of cosmic rays
  - **propagation** from *sources* to Earth
- < 10 GeV
  - solar modulation & heliospheric effects
- 10 GeV - 100 TeV
  - large scale heliospheric effects
  - heliotail

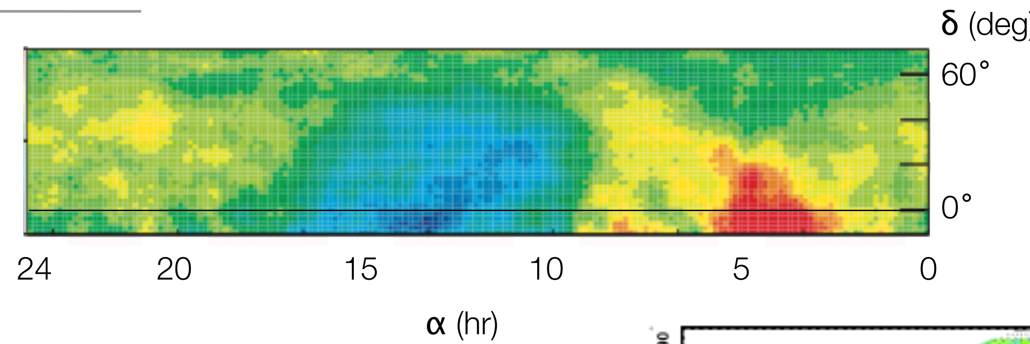


# cosmic ray anisotropy

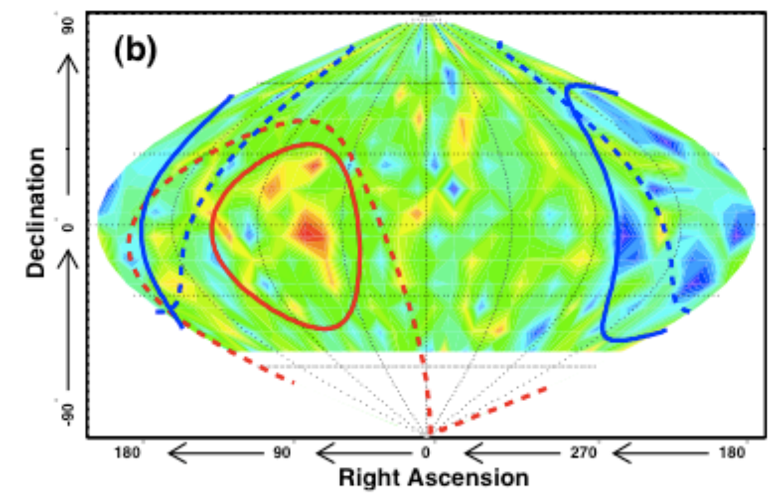


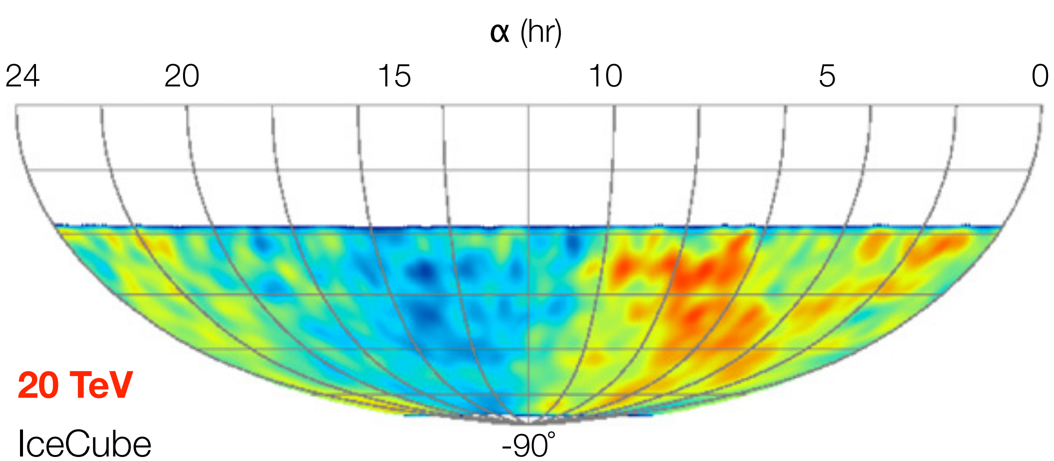

Nagashima et al. (1998)
Hall et al. (1999)




**4 TeV**
Tibet ASγ
Amenomori et al. (2006)

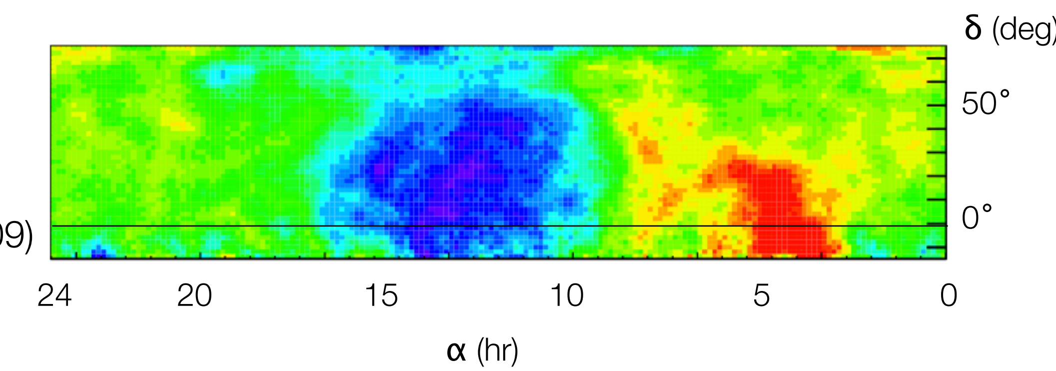



**10 TeV**
Super Kamiokande
Guillian et al. (2007)

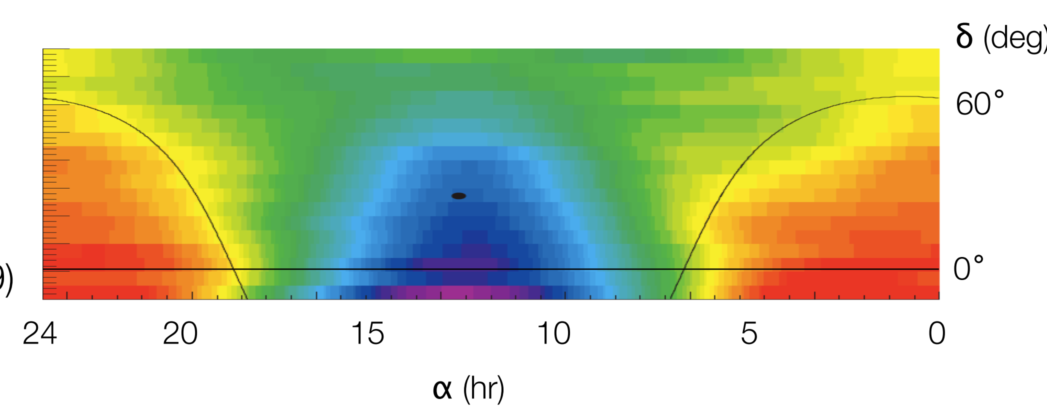



**20 TeV**
IceCube
Abbasi et al. (2010)

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




**5 TeV**
Milagro
Abdo et al. (2009)



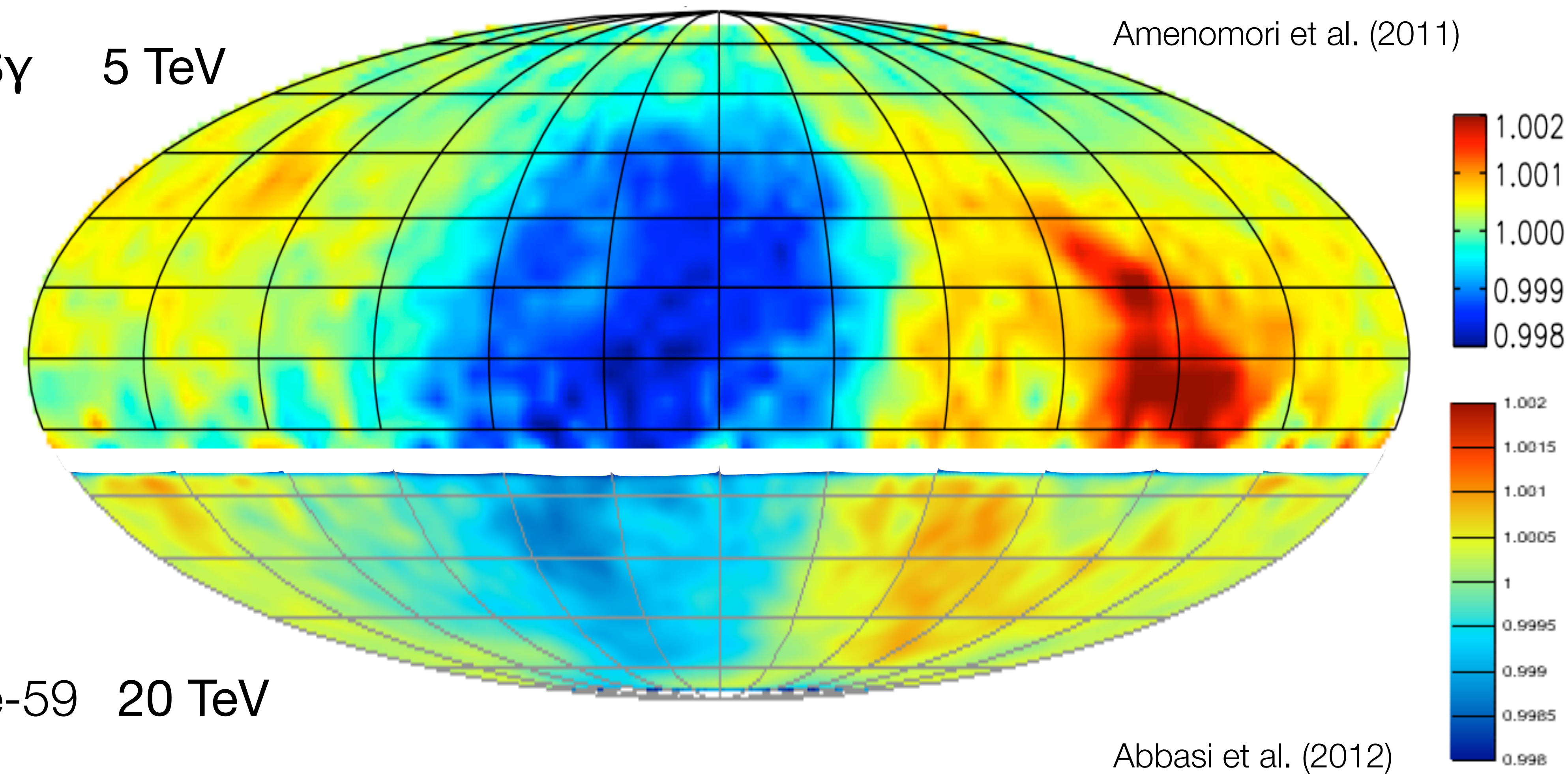

equatorial coordinates

# cosmic ray anisotropy

equatorial coordinates    relative intensity

Tibet-ASγ    5 TeV

Amenomori et al. (2011)



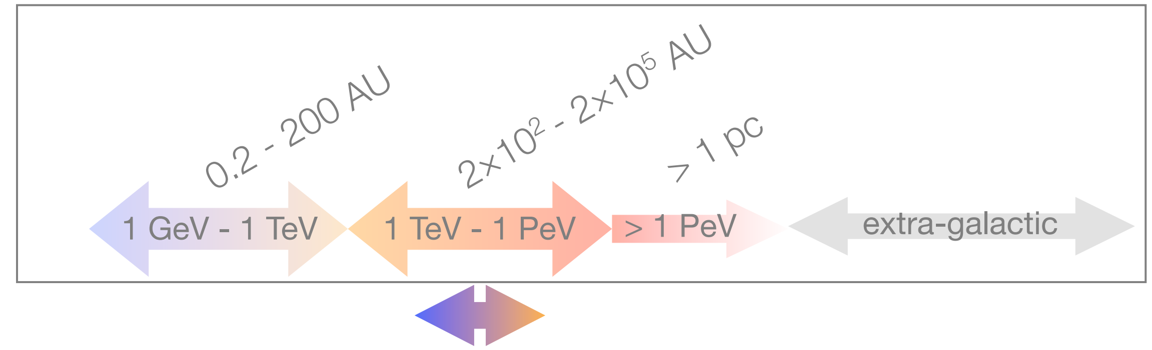

IceCube-59   20 TeV

Abbasi et al. (2012)

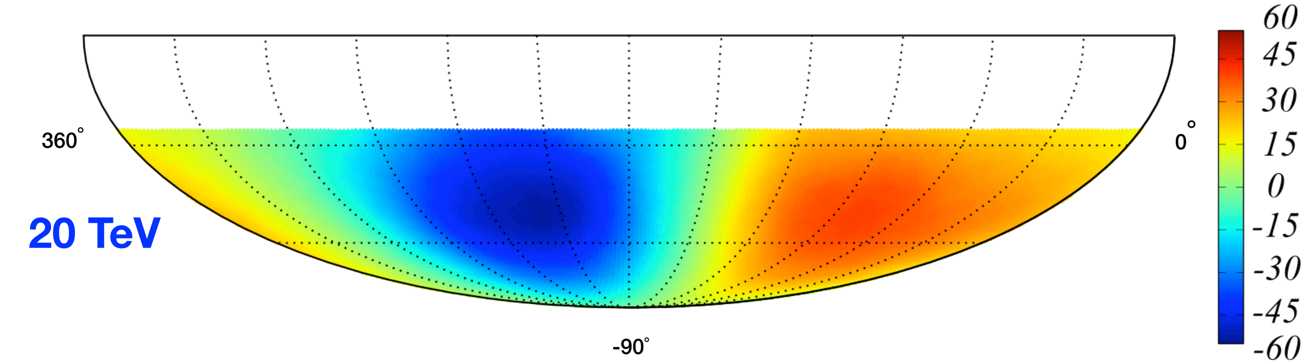
all-sky view of global large scale anisotropy

small scale differences from energy response (the most interesting part)

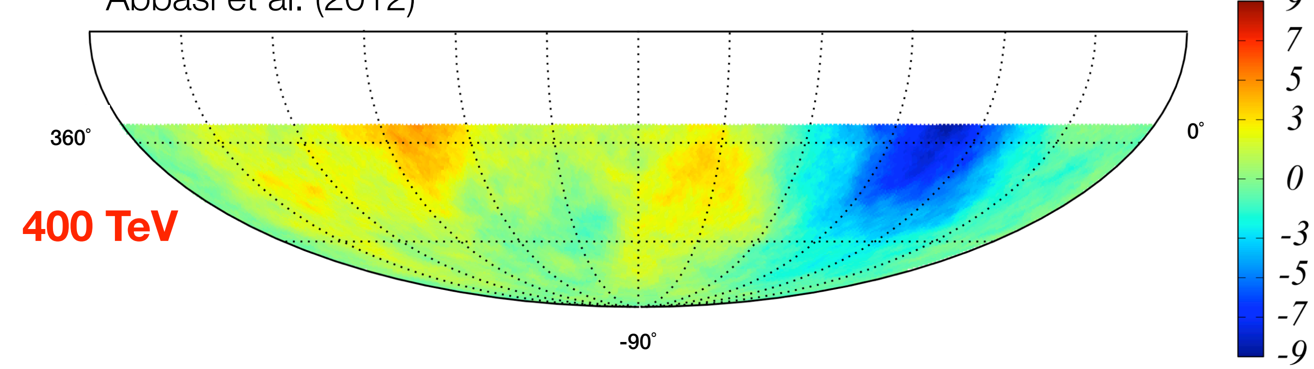
# anisotropy vs. energy



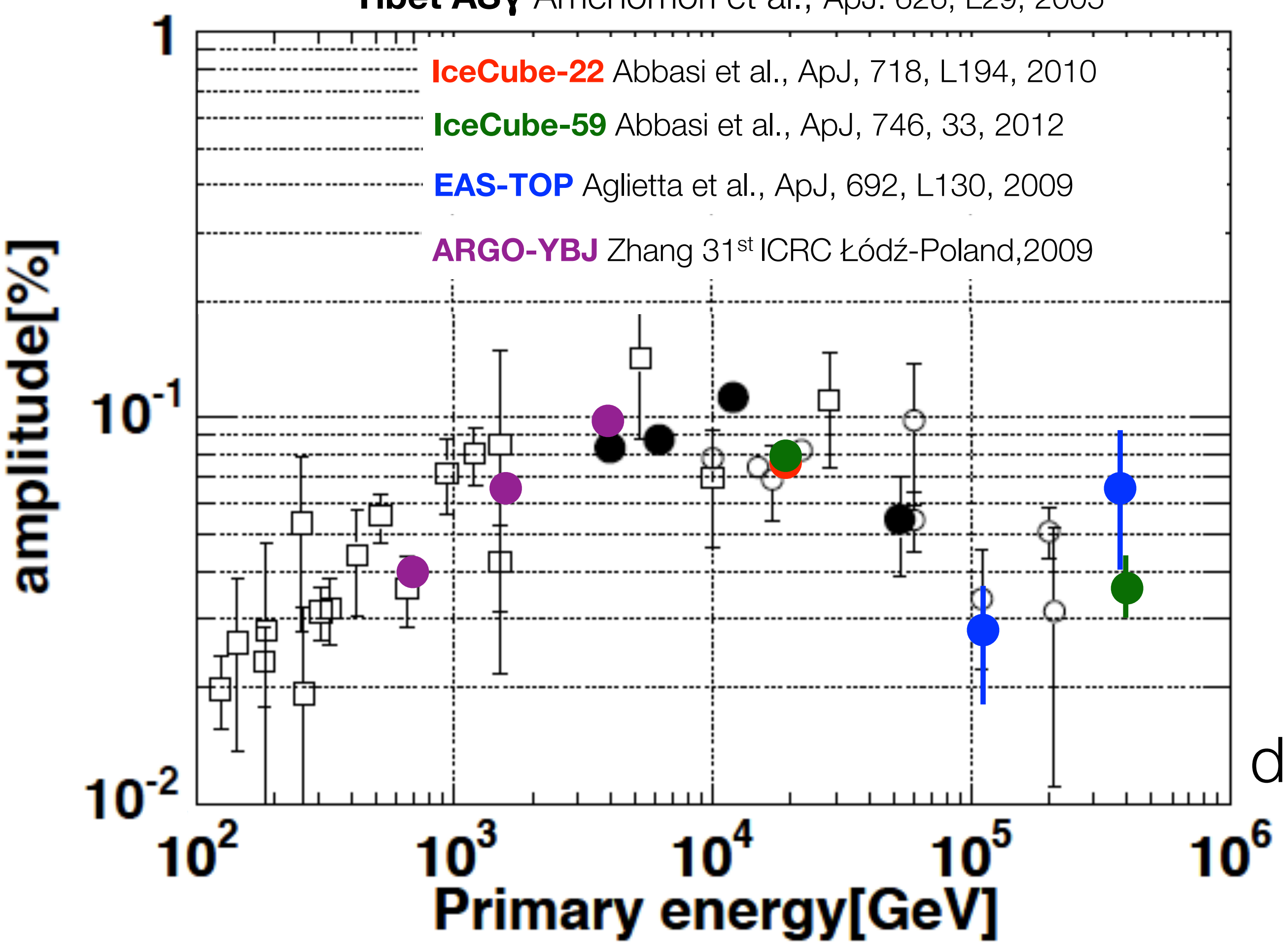

- anisotropy changes phase @ ~100 TeV
- global amplitude is modulated




IceCube
Abbasi et al. (2012)

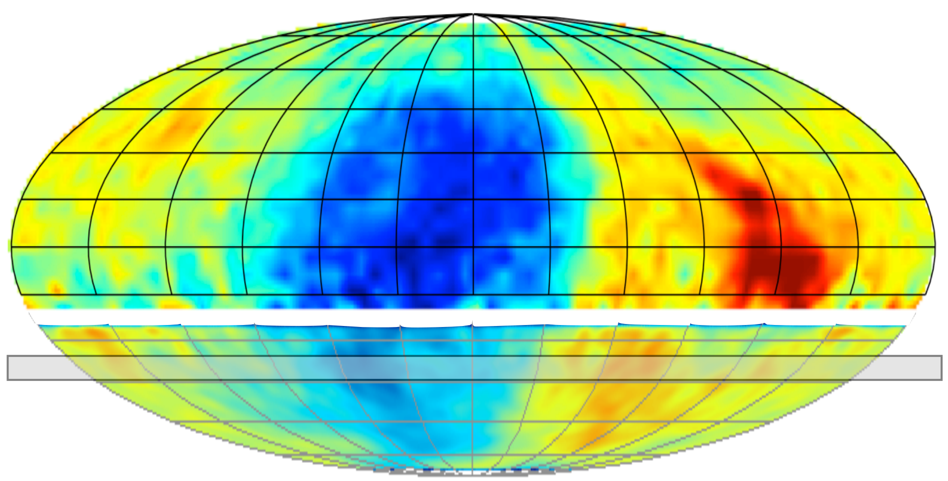


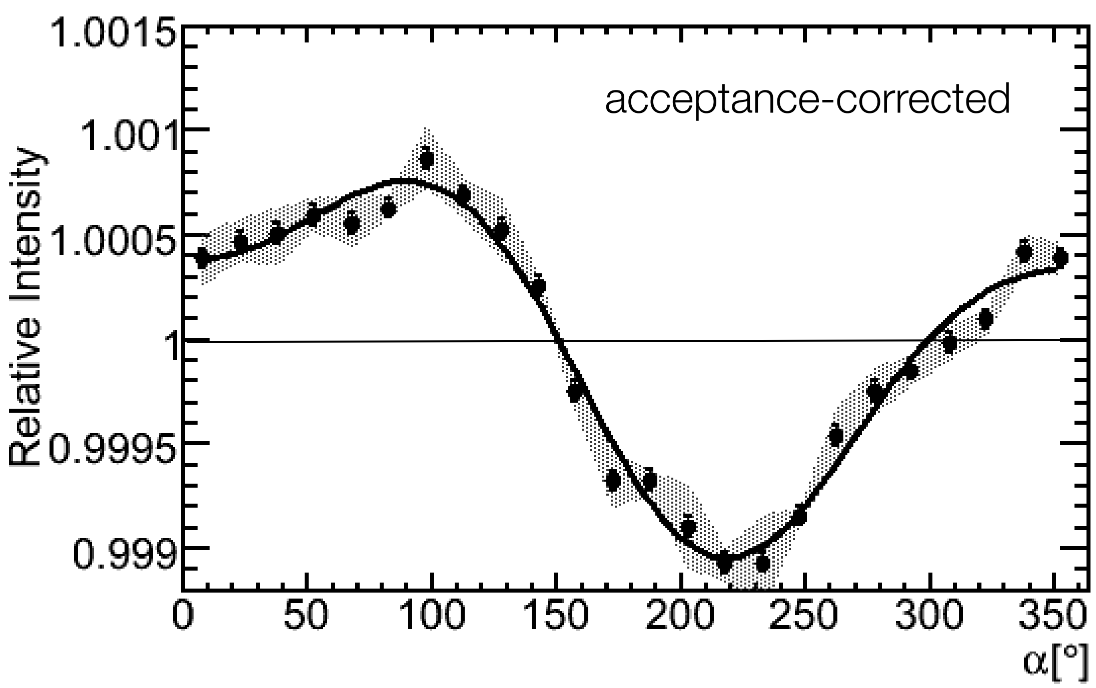

**Tibet ASγ** Amenomori et al., ApJ. 626, L29, 2005

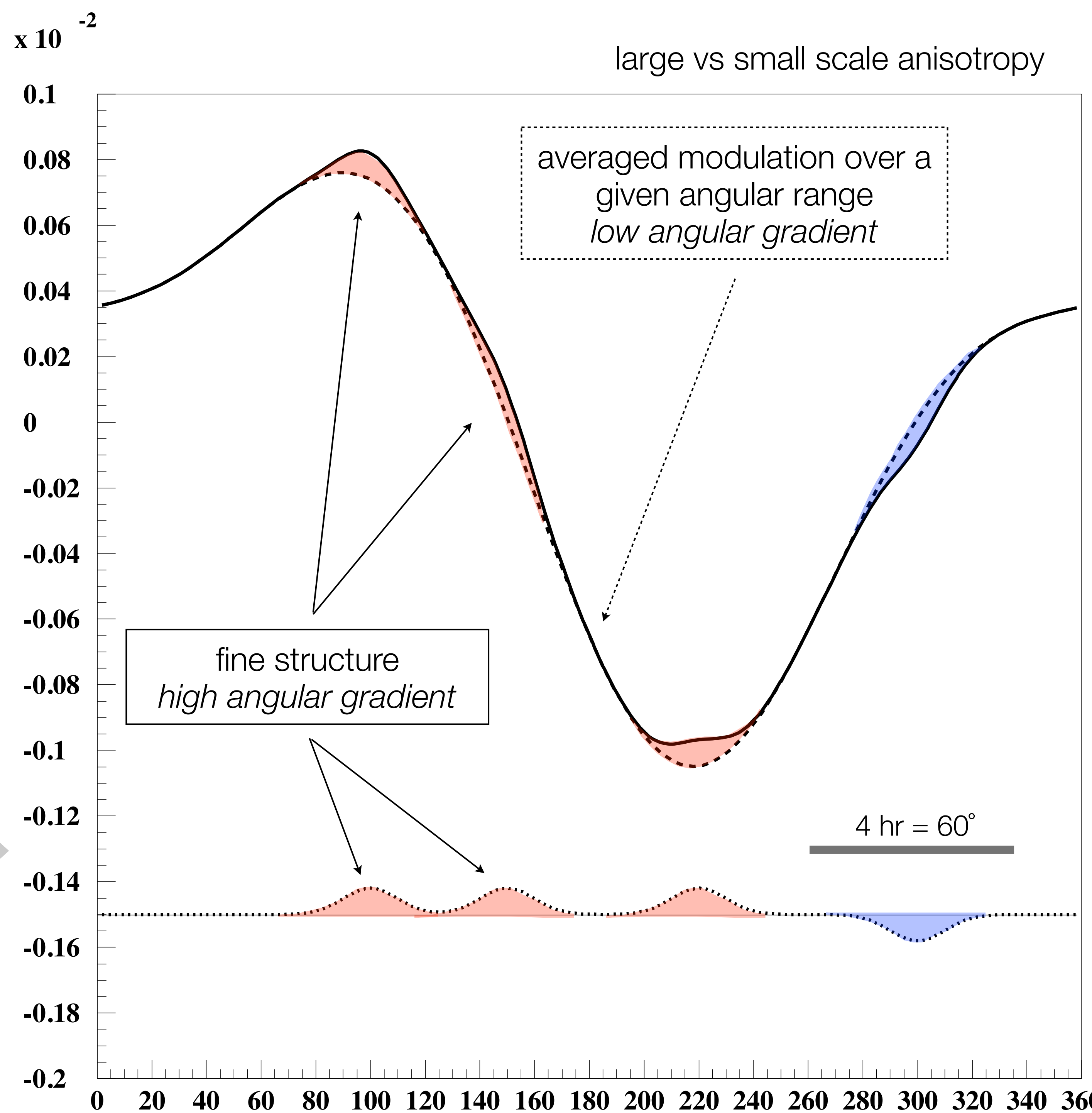



dipole component of large scale anisotropy

# anisotropy vs. angular scale



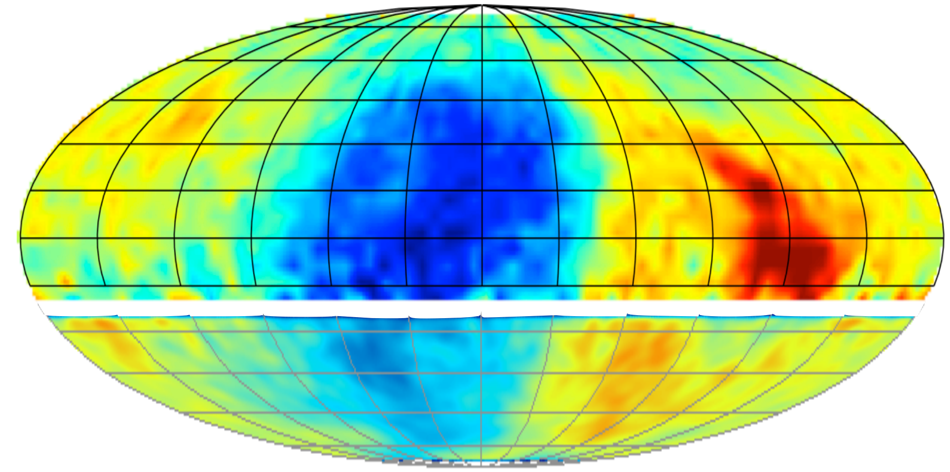





Paolo Desiati

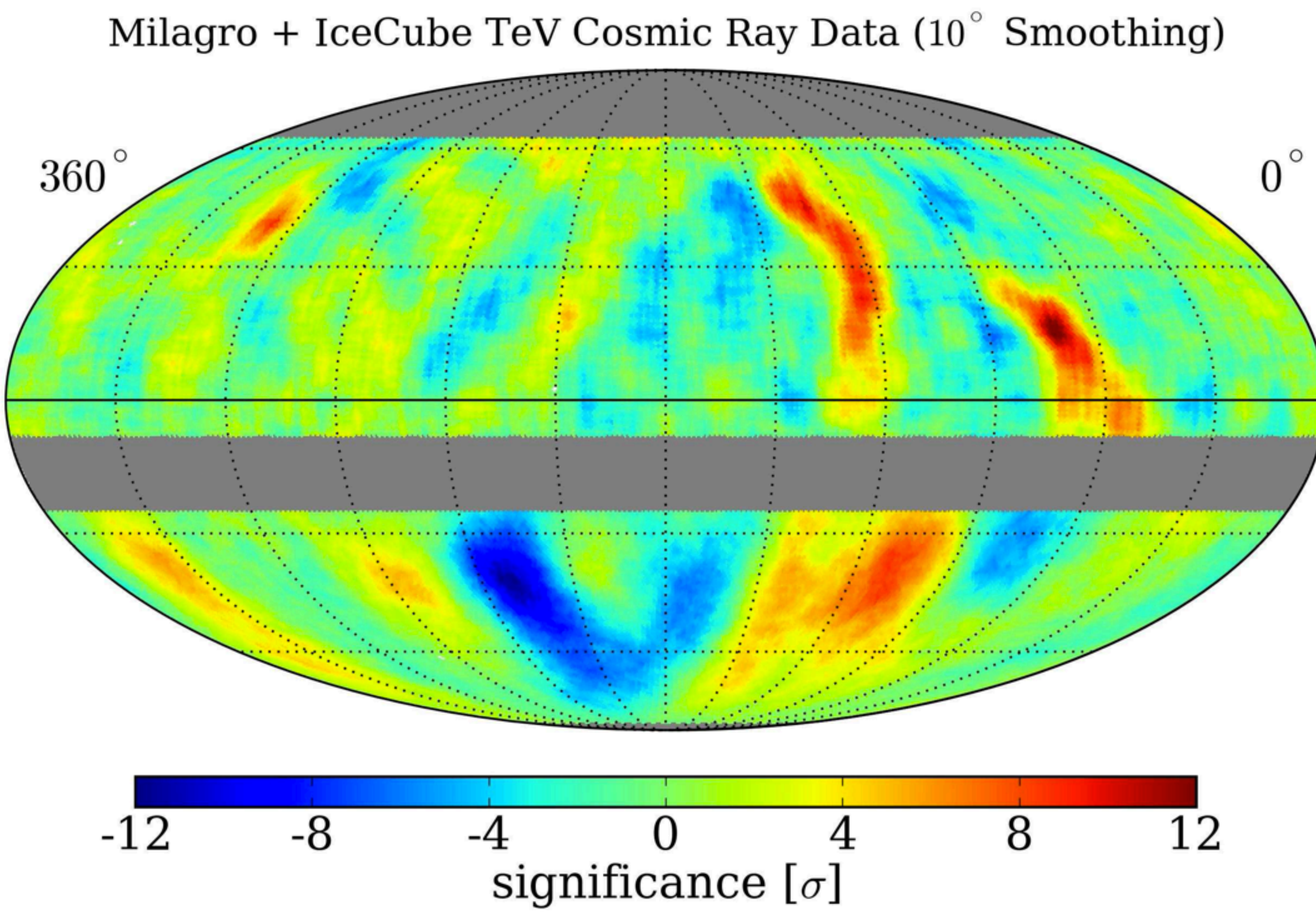
# anisotropy vs. angular scale



equatorial coordinates    statistical significance

2 hr = 30°

4 hr = 60°




Milagro 1 TeV
Abdo et al. (2008)

IceCube 20 TeV
Abbasi et al. (2011)

the understanding of these maps is important

# origin of small scale anisotropy ?
# *astrophysics*

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

Salvati & Sacco, A&A 485, 527 (2008)
Drury & Aharonian, Astropart. Phys. 29, 420 (2008)

Salvati, Astron. & Astrophys. arXiv:1001.4947

- magnetic tube & propagation in turbulent LIMF

- anisotropic MHD turbulence in the ISM

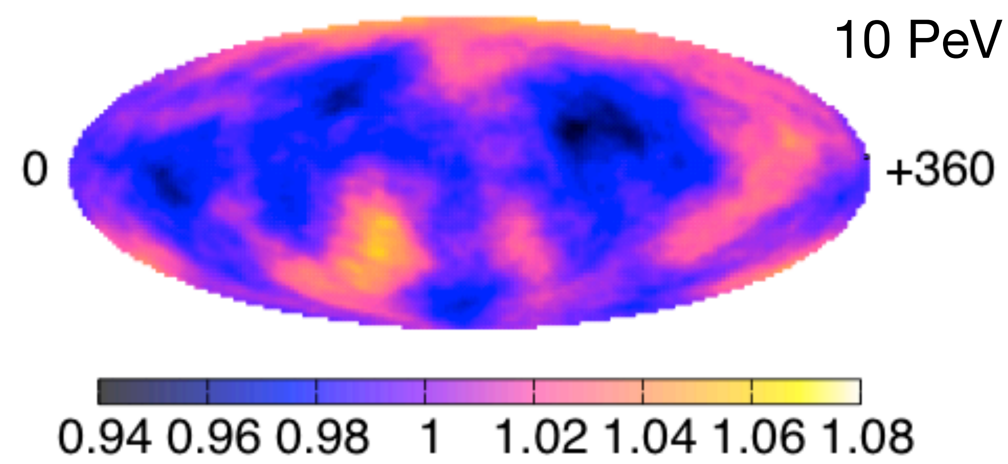
Malkov et al., ApJ 721, 750, 2010

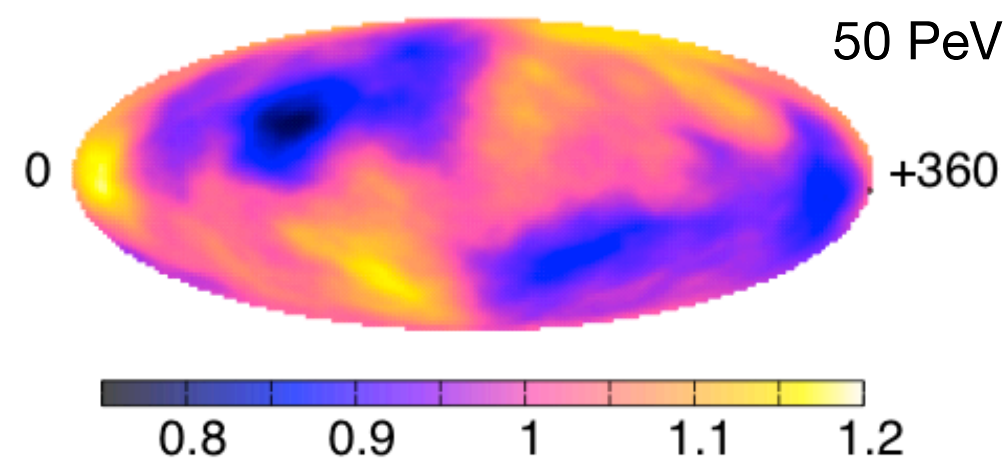
  - particles streaming along magnetic field lines over ~100 pc (from a source) interact with O(1pc) ISM turbulence
  - pitch angle scattering peaked near the direction of LIMF

# origin of small scale anisotropy ?
# *effect of interstellar turbulence*

Giacinti & Sigl, arXiv:1111.2536

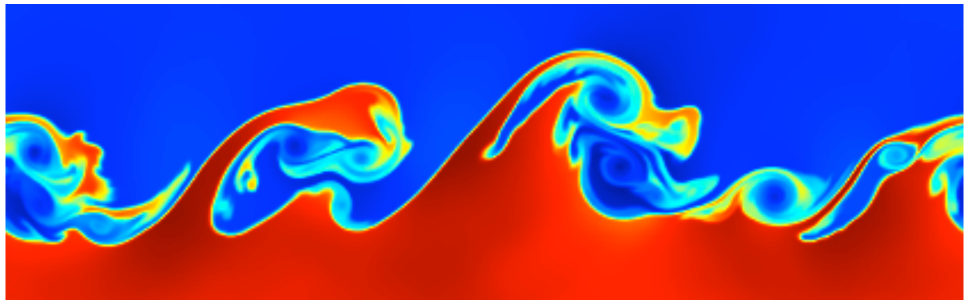
- diffusion regime breaks down **within mean free path**
- interaction with **turbulent** interstellar magnetic field
- assuming an underlying dipole anisotropy, fractional localized regions form the effect of magnetic field turbulence
- the residual maps provide an image of magnetic field turbulence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



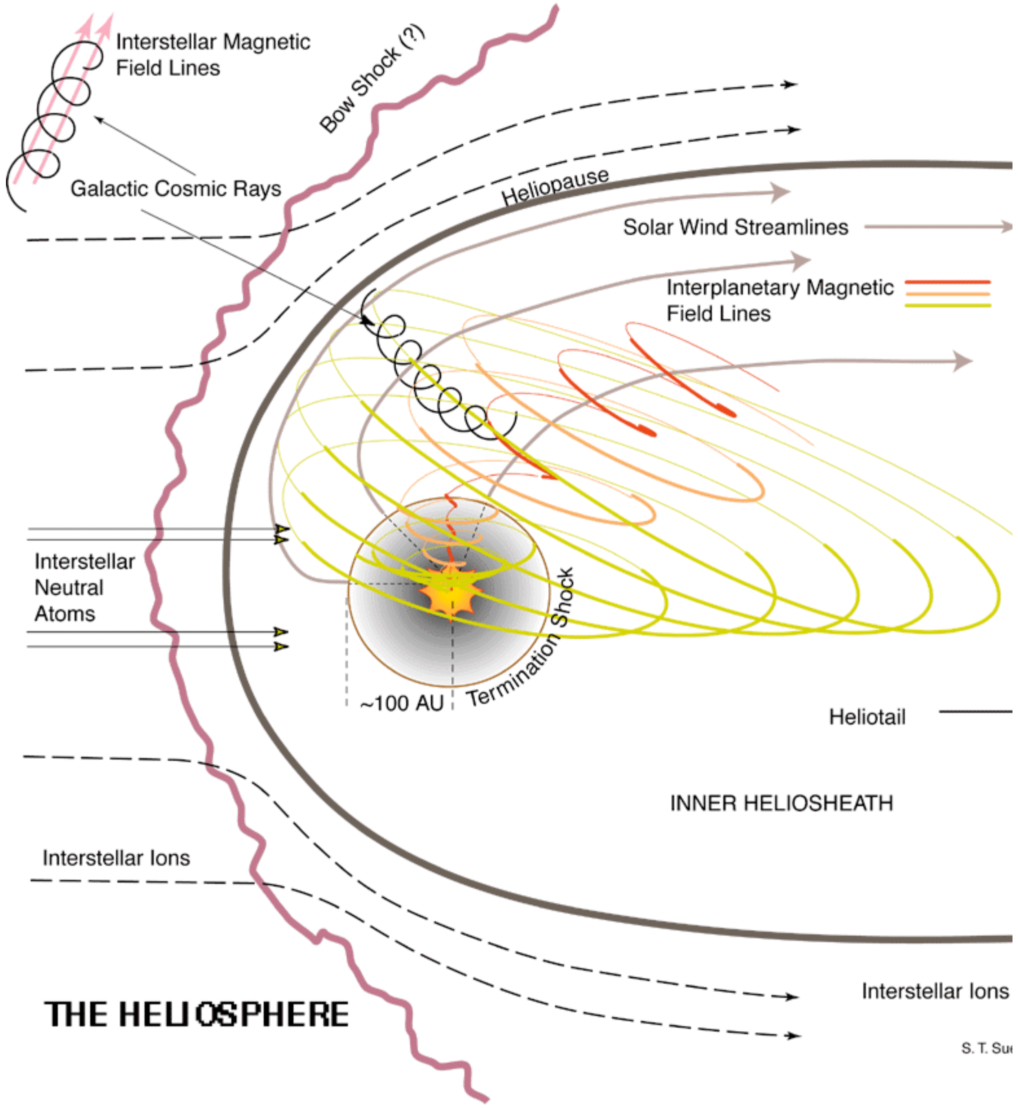




20° smoothing

# origin of small scale anisotropy ?
# *effect of heliospheric perturbation*



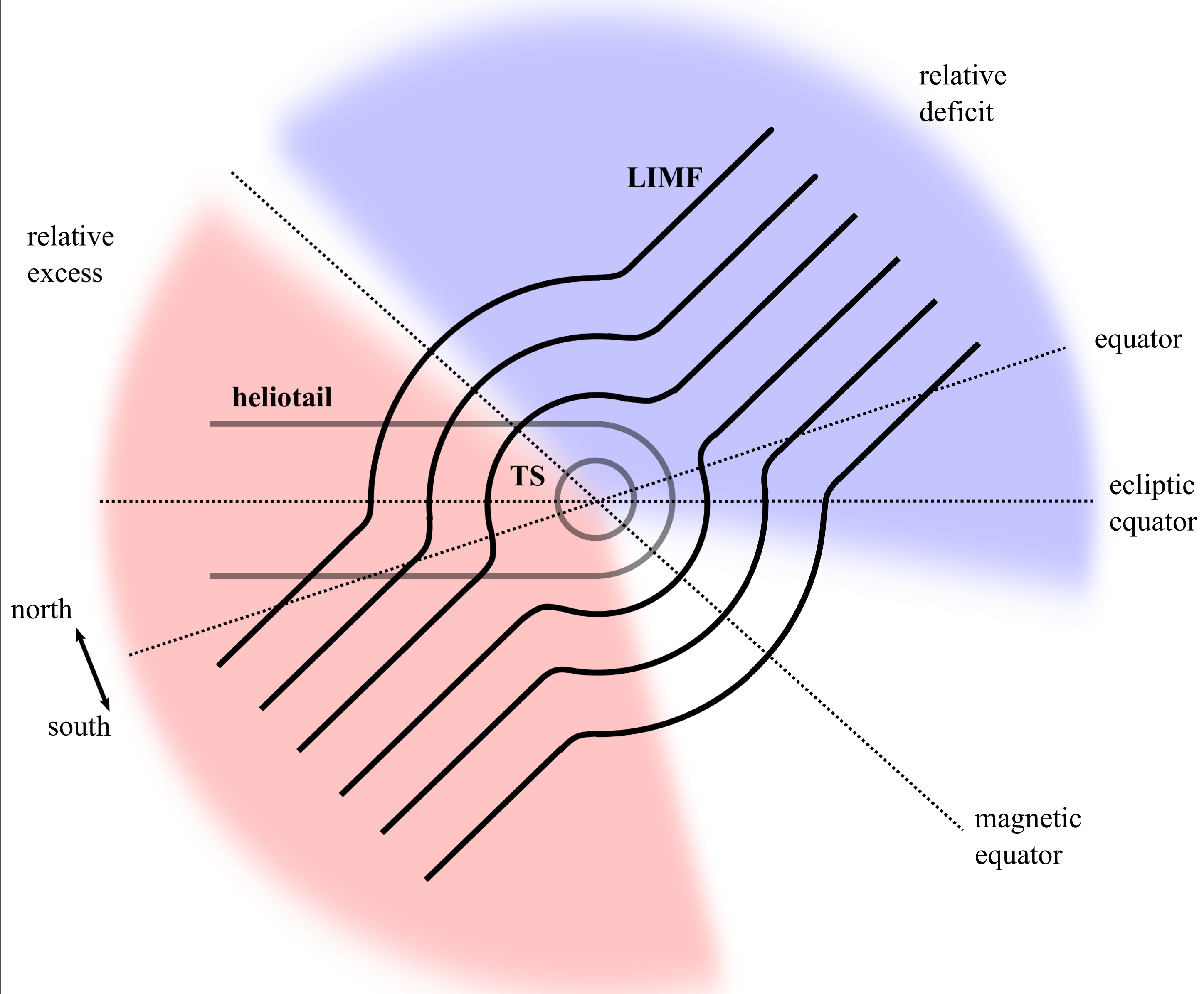
- diffusion regime breaks down **within mean free path**
- $\lambda_{mfp}$ ~ 10 pc @ 100 TeV (Yan & Lazarian, 2008)
- perturbations inside heliosphere and on the flanks into the LISM
- 1-10 TeV cosmic rays in a 3 μG magnetic field
    - $R_g$ ~ 70 - 700 AU
    - scattering on perturbations along the flanks
- < 100 TeV affected by heliotail (~ 1000's AU)

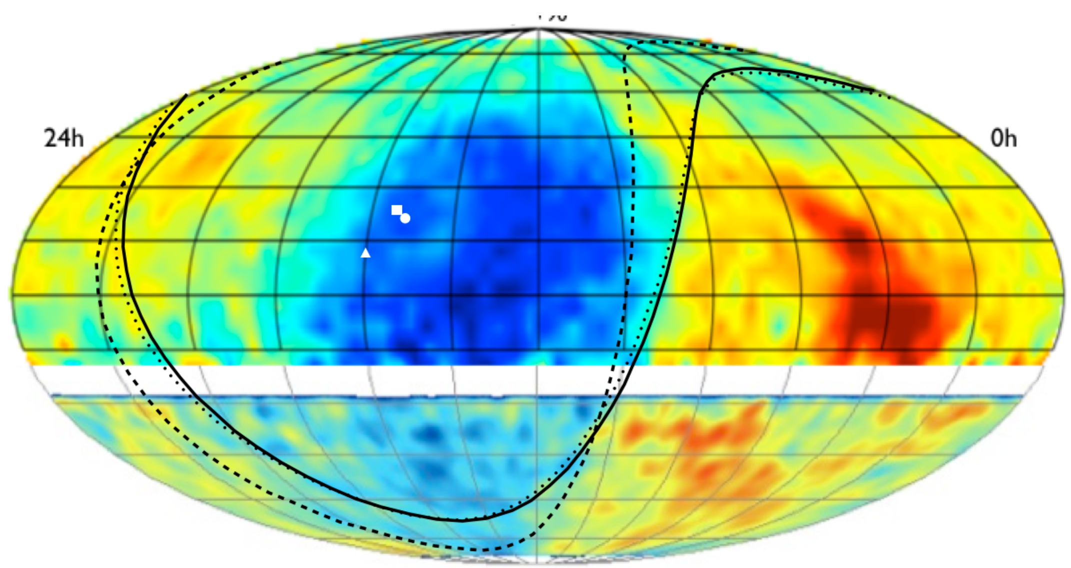



$$R_g = 220 \left(\frac{E}{TeV}\right) \left(\frac{\mu G}{B}\right) AU$$

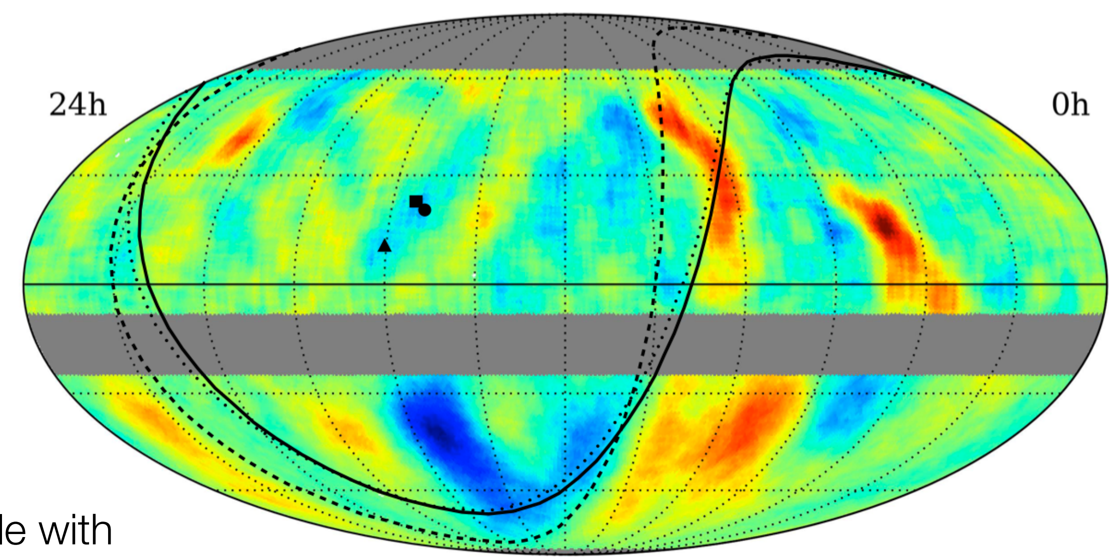
# TeV CR anisotropy and the heliosphere + LIMF

PD & Lazarian, submitted to ApJ




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




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)

# the heliosphere perturbations

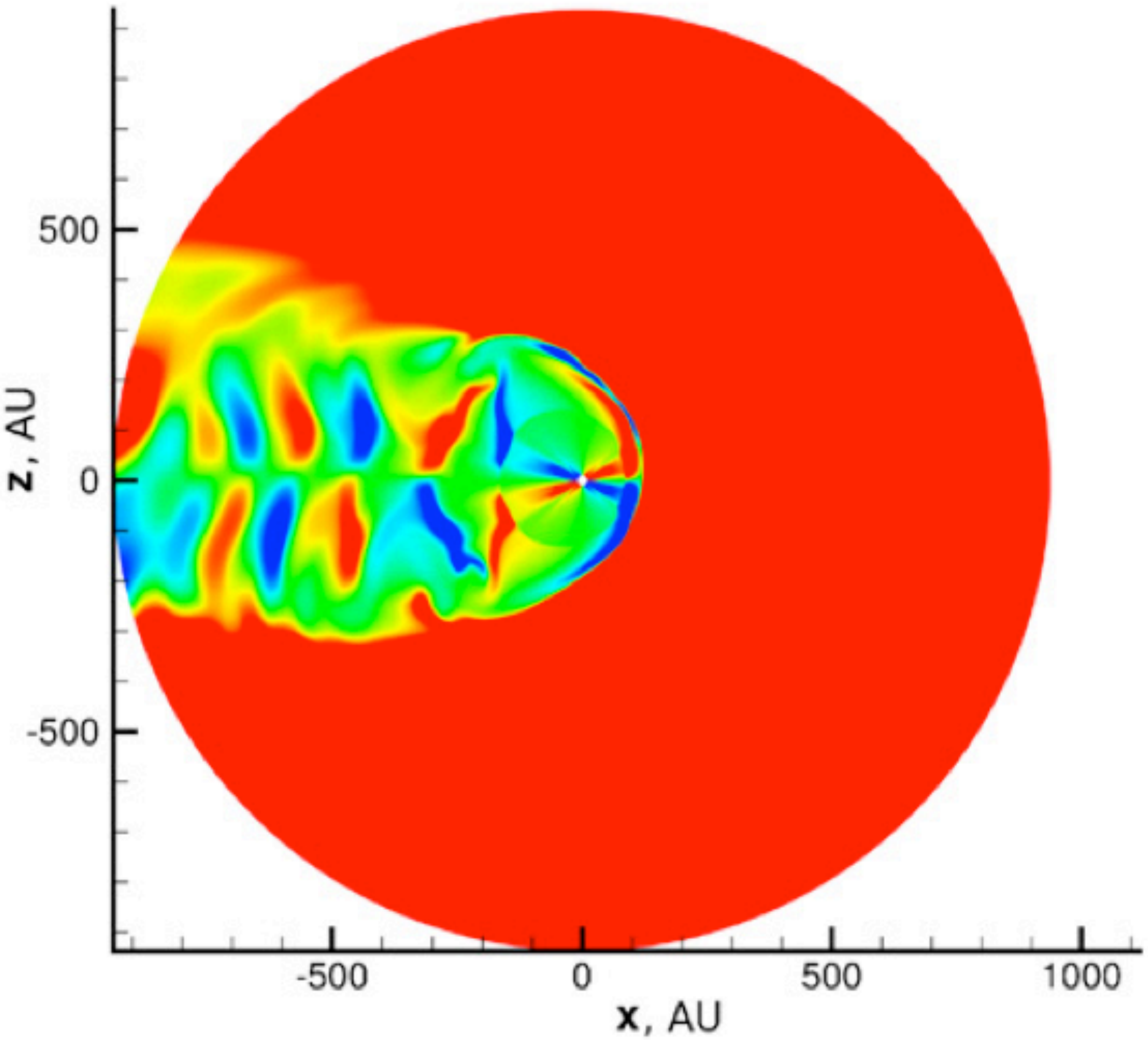
- the wake downstream the interstellar flow develops turbulence perturbations on the flanks of the heliopause similar to Kelvin-Helmholtz instabilities (super-Alfvénic motion)

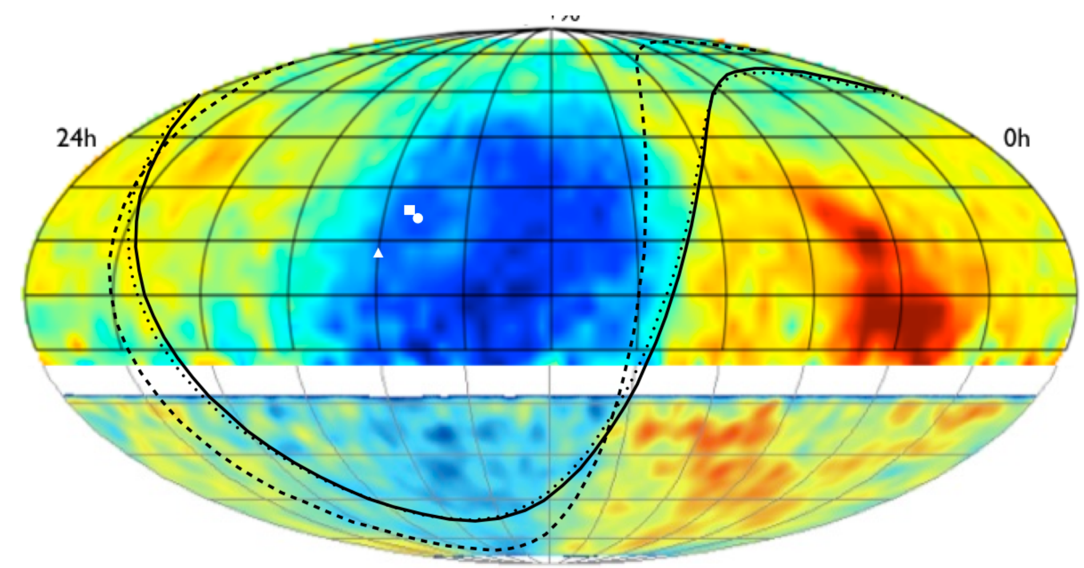
- charge-exchange processes decelerate the solar wind near the heliopause, producing an effective drag force that pushes the higher ISM density into the heliosheath at the stagnation point. This generates Rayleigh-Taylor instability oscillations with amplitude **10's AU** over 100's years - Liewer et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

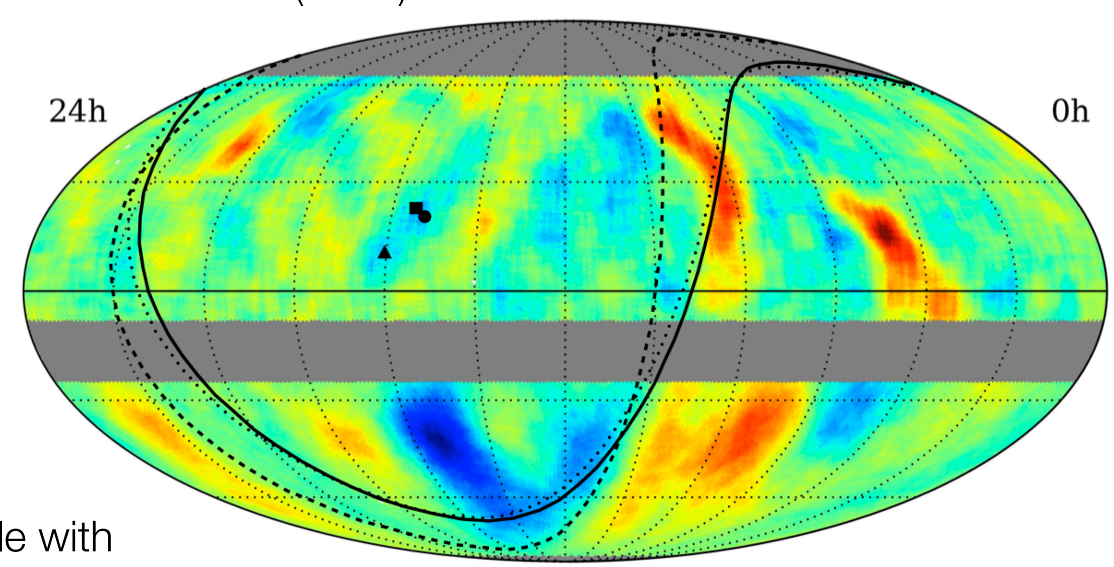
PD & Lazarian, subm. to ApJ




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

magnetic equator

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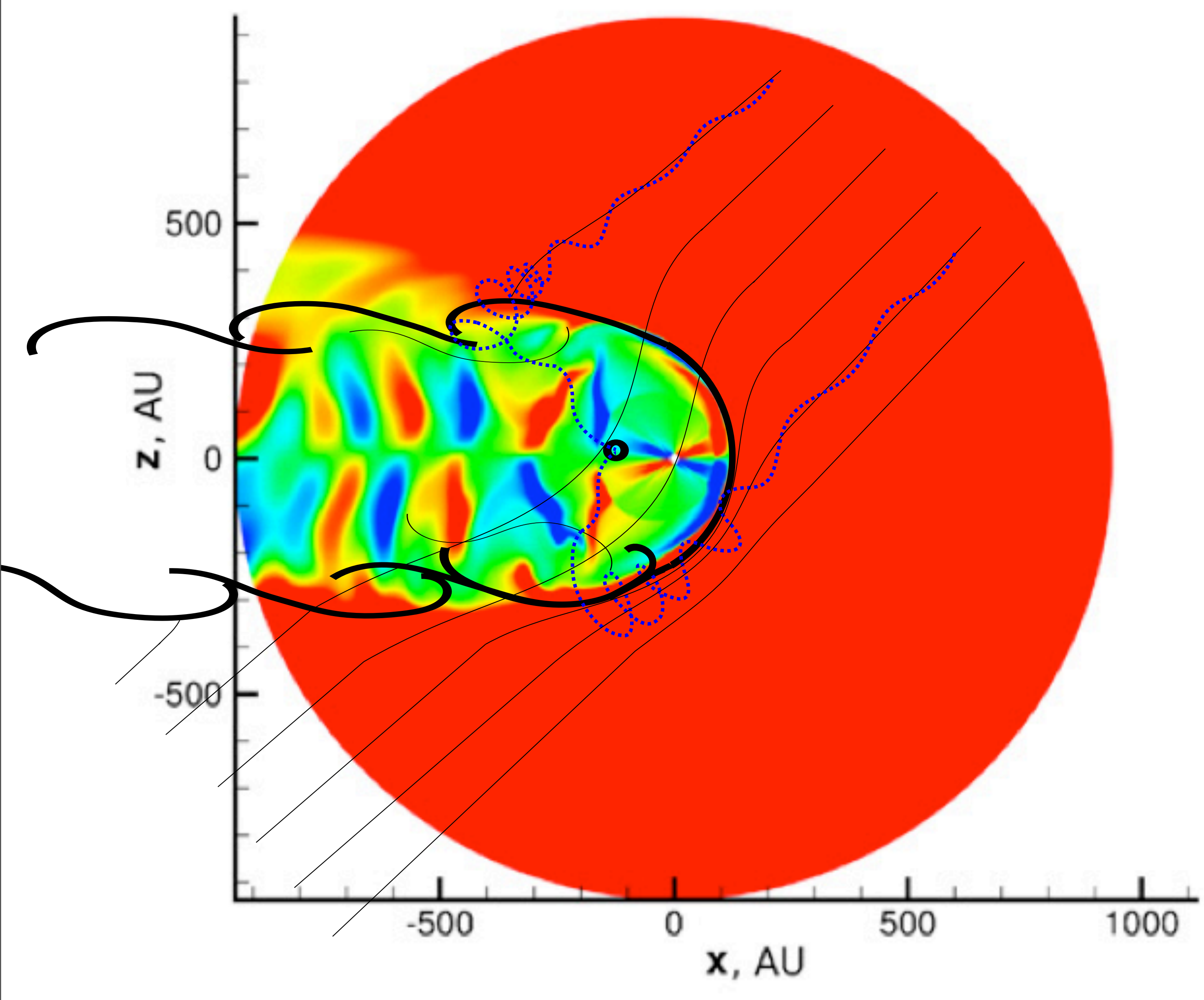


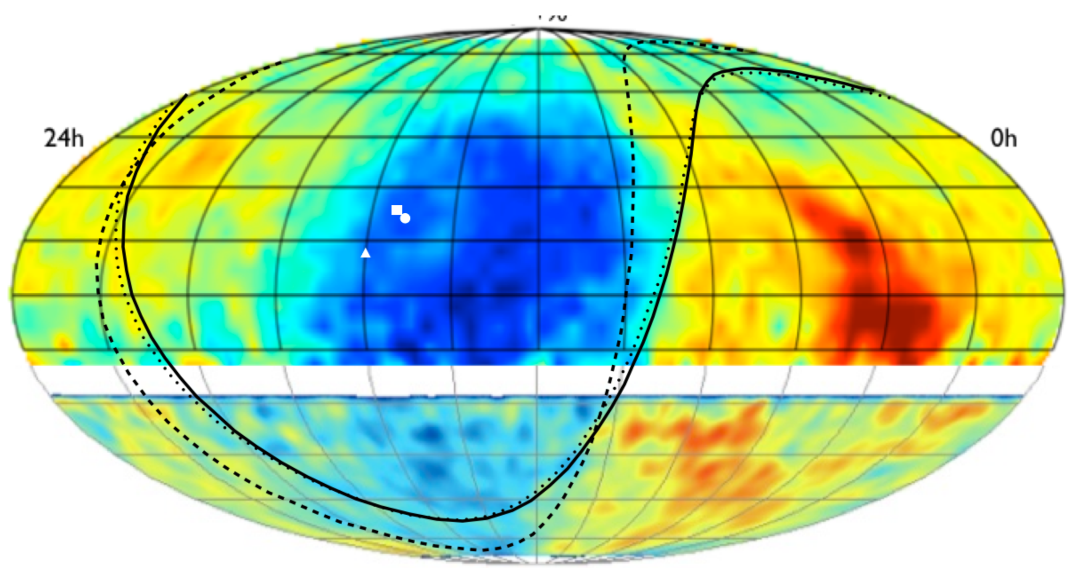


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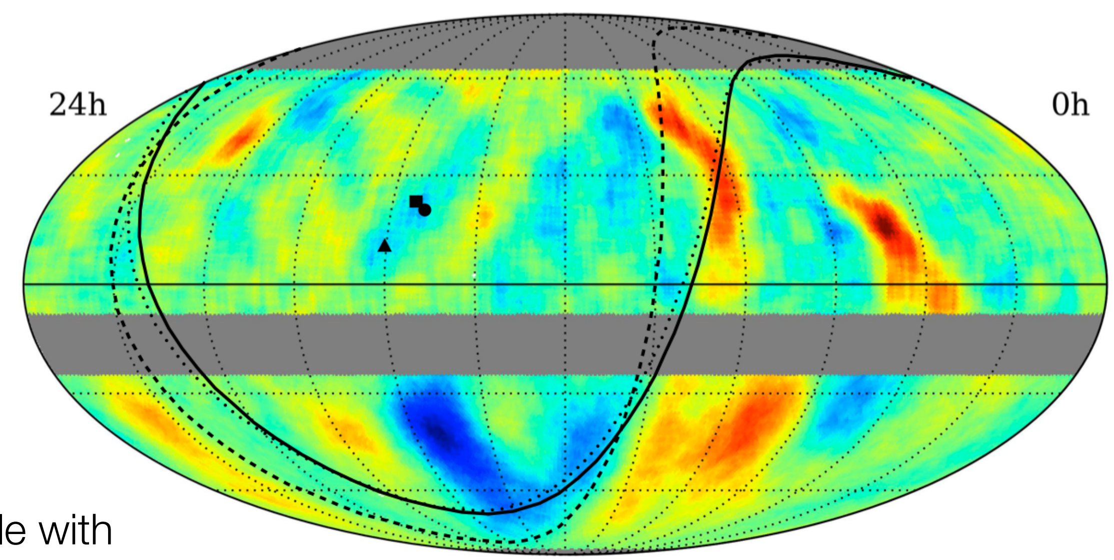


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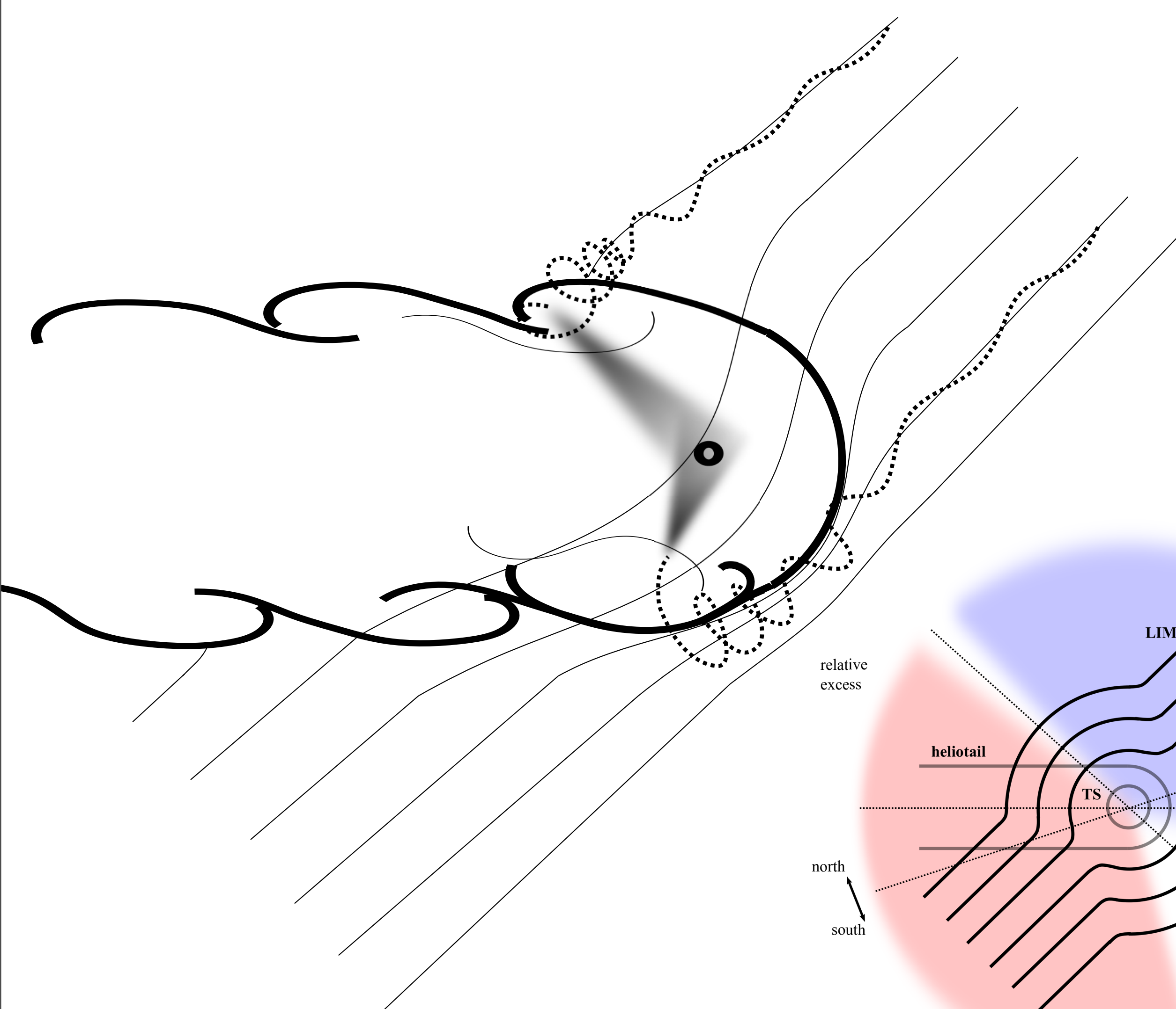

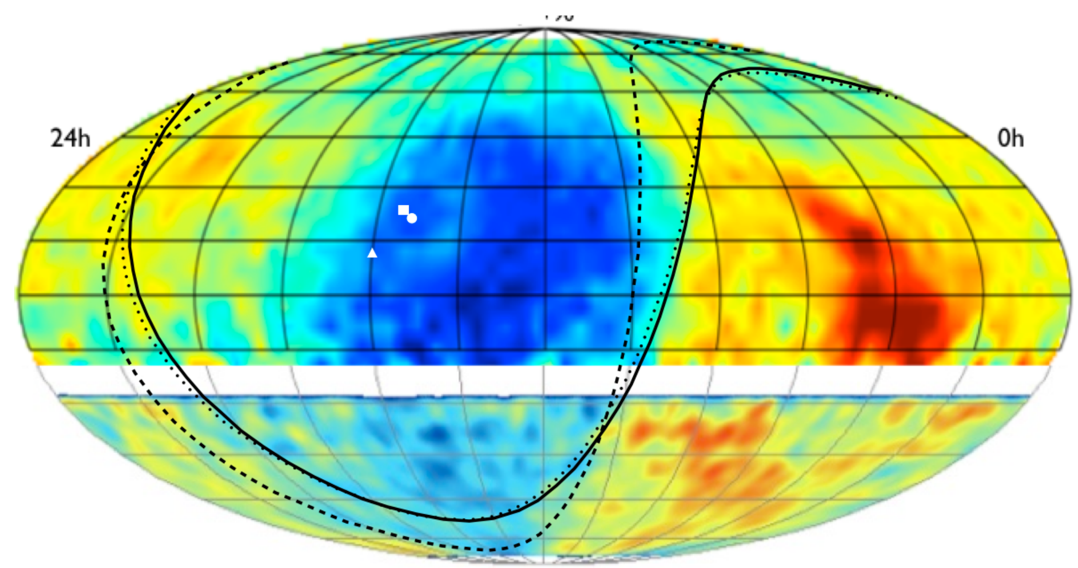


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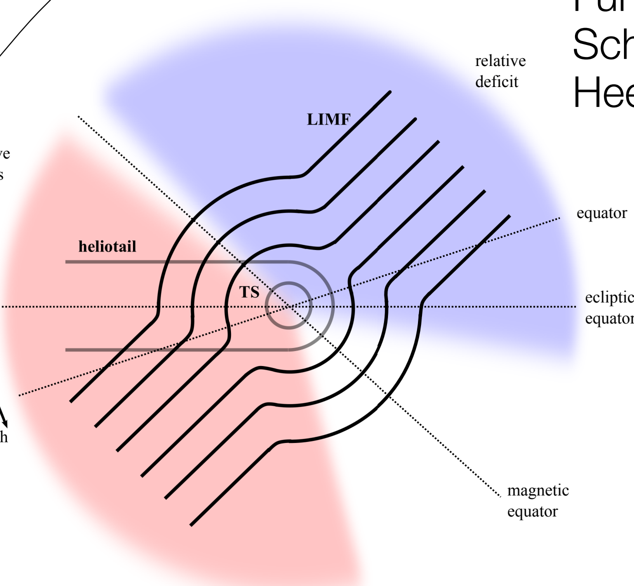


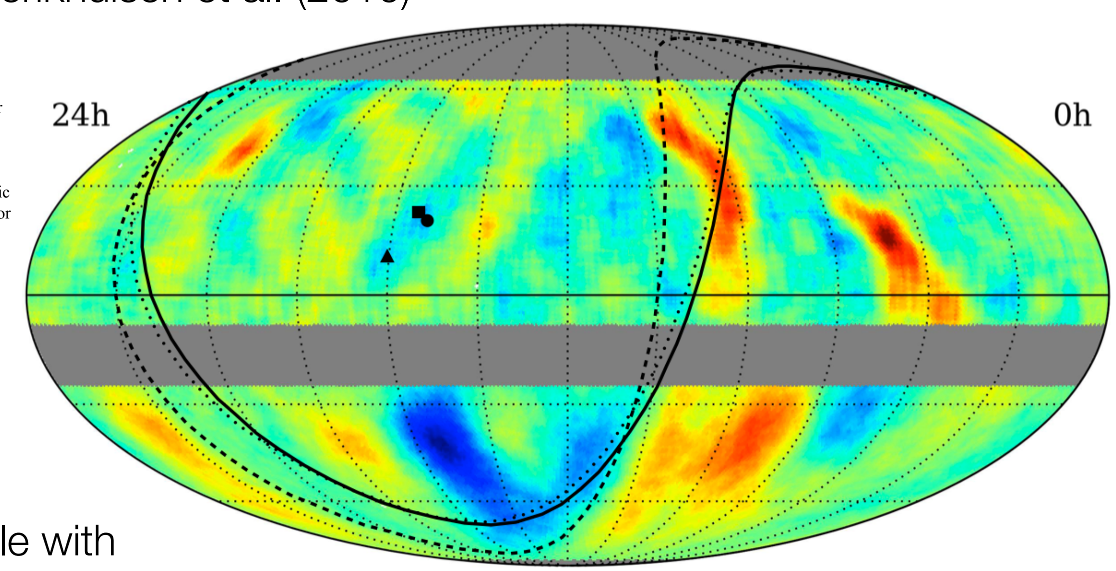


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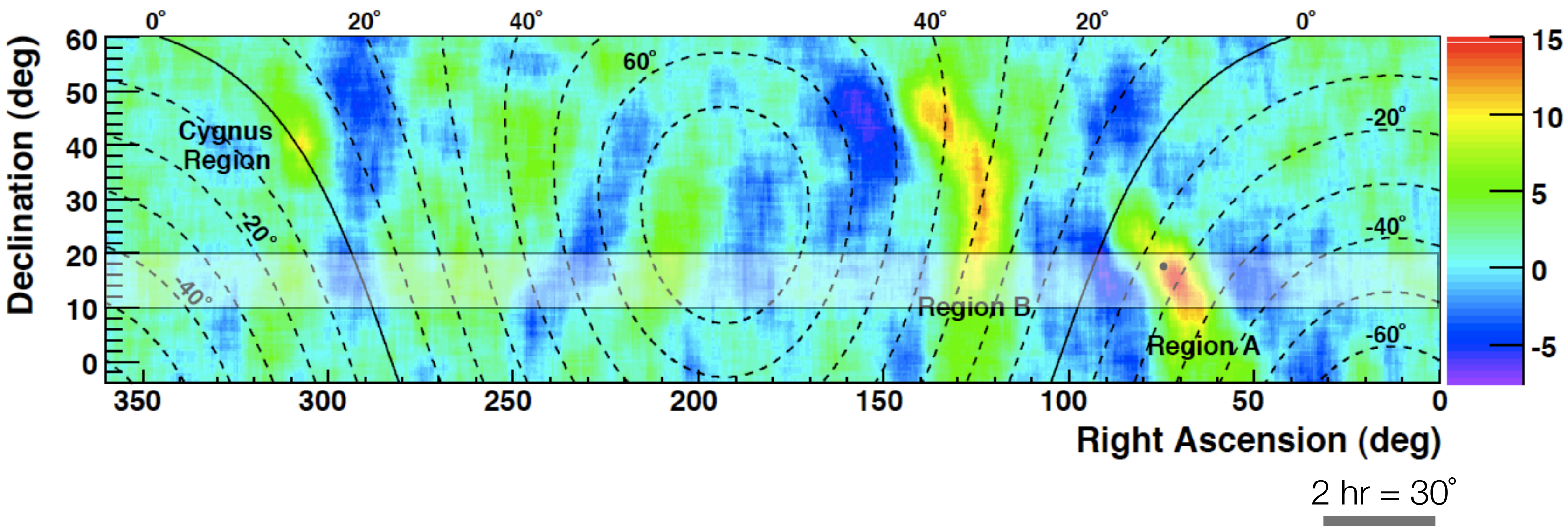
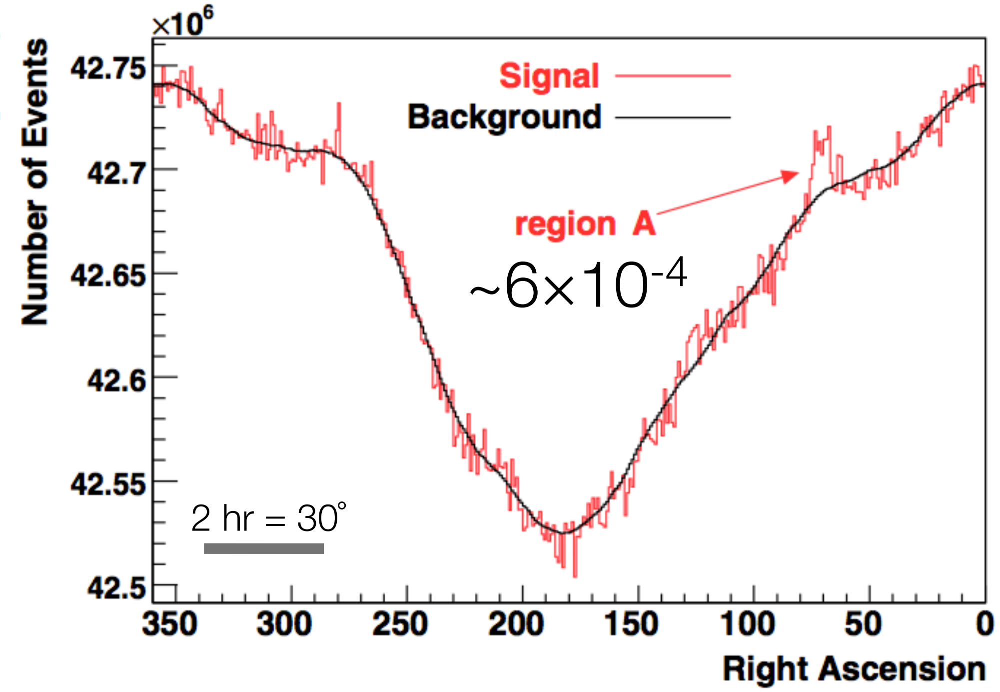
# scattering on heliospheric turbulence

- 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
- perturbations at heliopause trail on the flank due to super-Alfvénic motion
- 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
    - evaluations and calculations to verify this scenario

# spectral feature associated to anisotropy

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




# Milagro

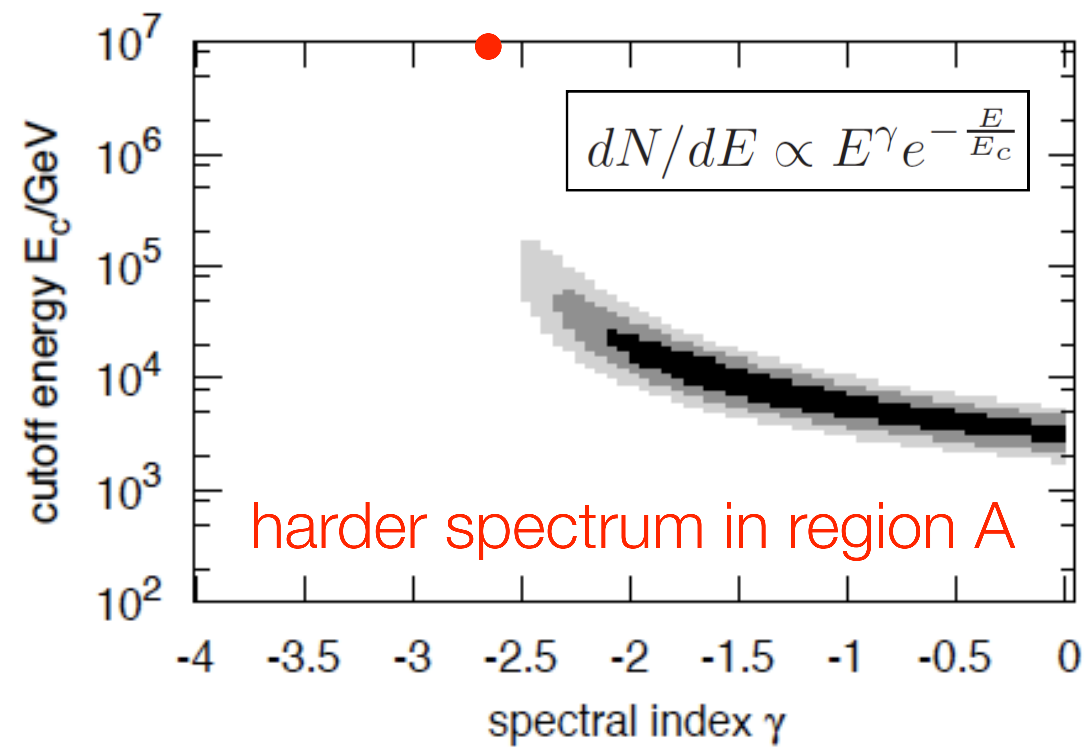
& ARGO-YBJ

Di Sciascio et al., arXiv:1202.3379

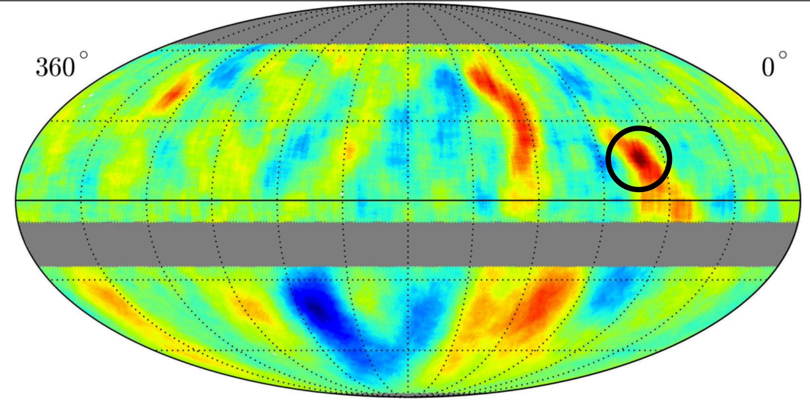
harder than average spectrum from region A

γ < 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 ?

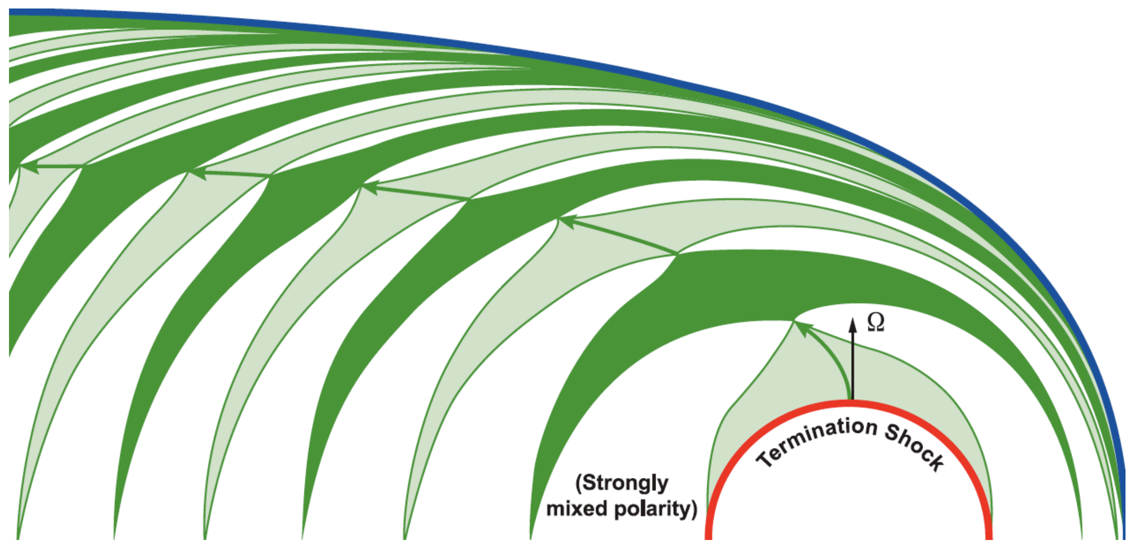


# origin of spectral hardening ?




Lazarian & PD, ApJ, 722, 188, 2010

- magnetic polarity reversals due to the 22-year solar cycles produces large scale sectors

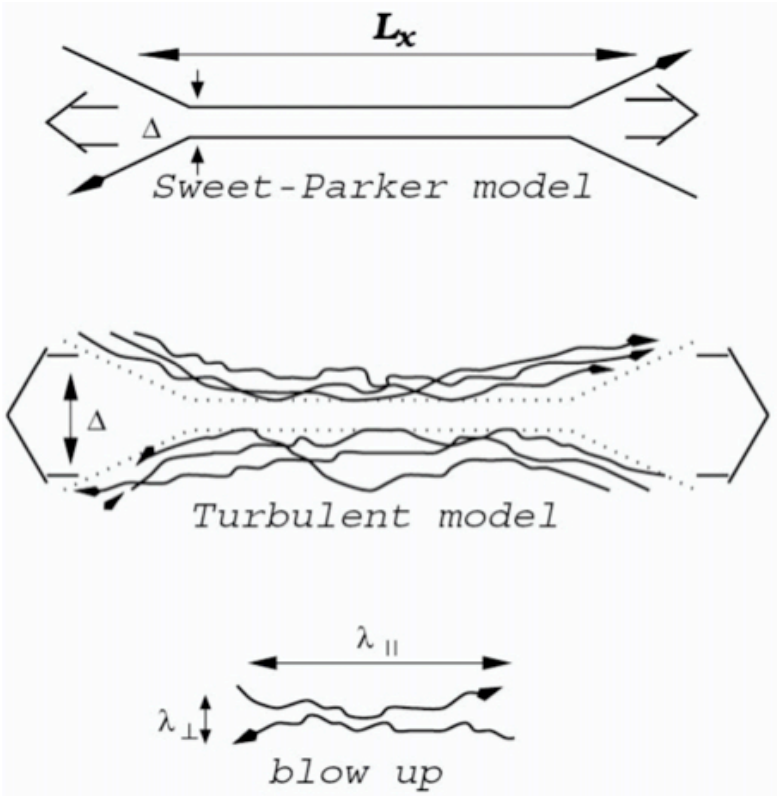


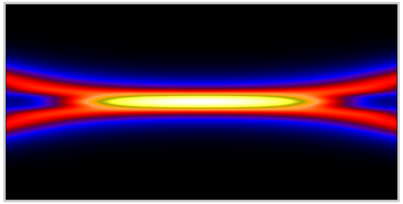

- converging of turbulent magnetic field lines can trigger reconnection and make it fast

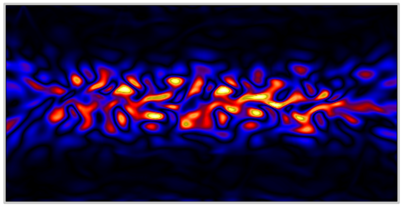
- magnetic mirror @ single reconnection as site of acceleration (test particle)

Sweet (1959) & Parker (1957)

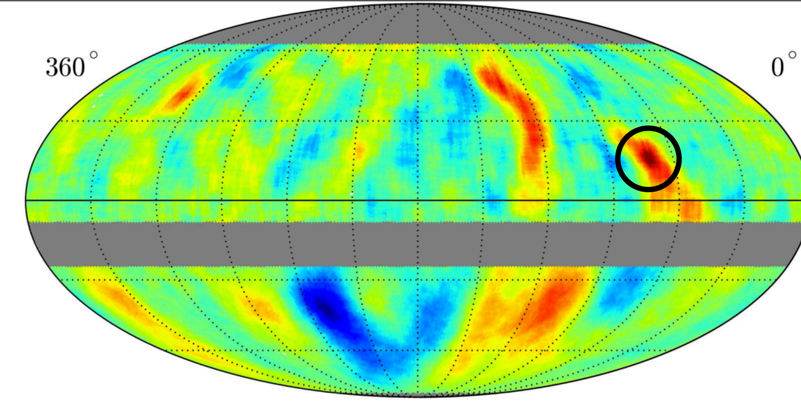
Lazarian & Vishniac, ApJ, 517, 700 (1999)





# stochastic magnetic reconnection

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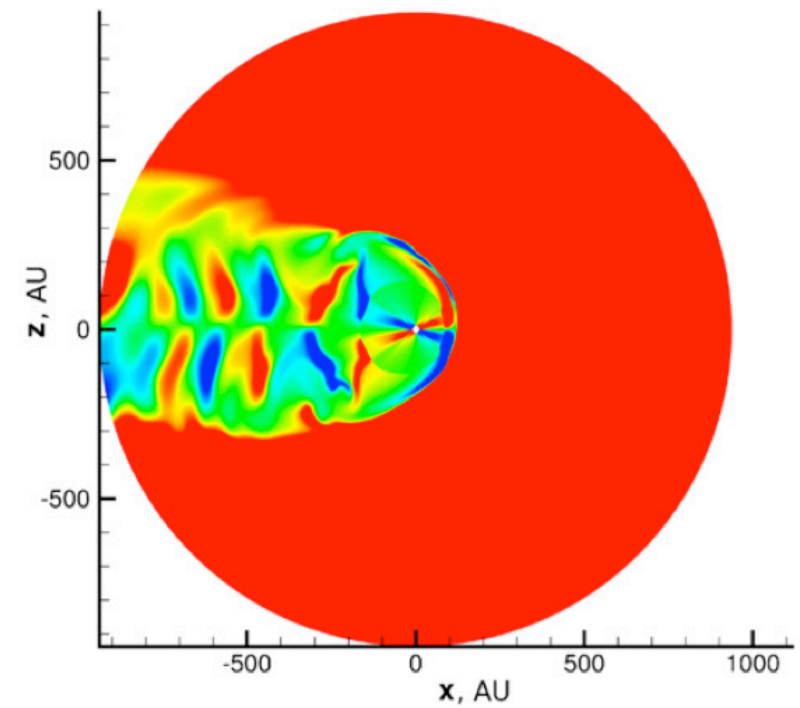
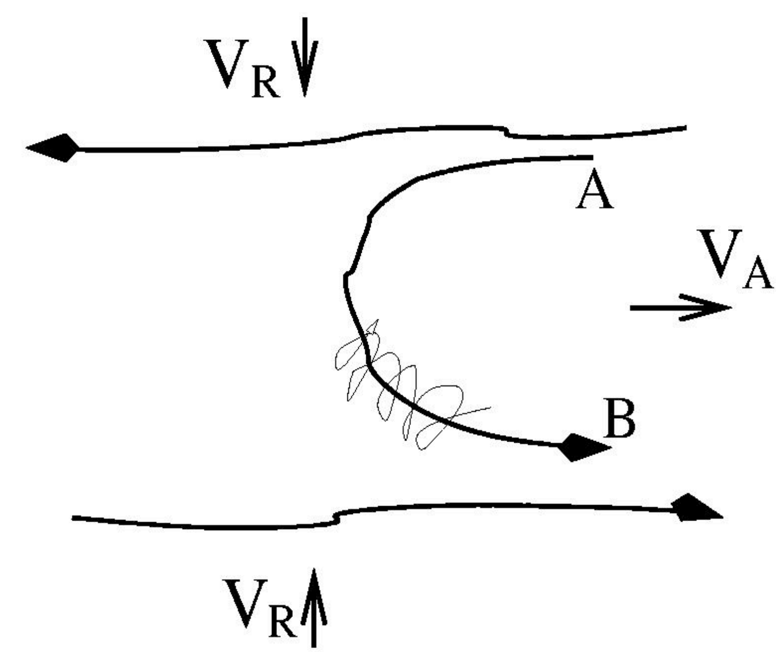
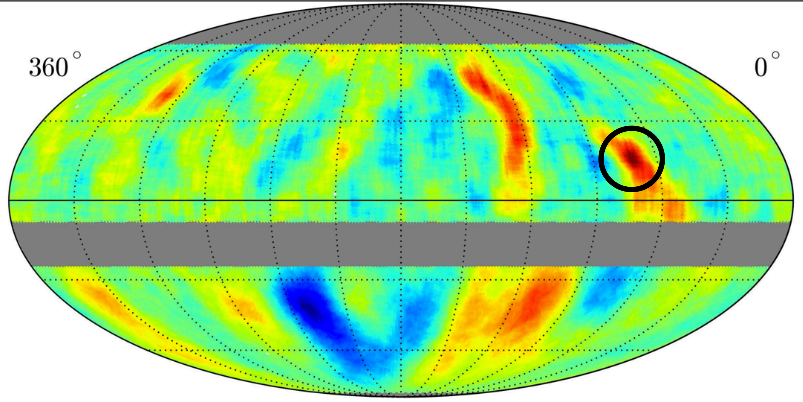
- magnetic polarity reversals due to the 22-year solar cycles produces large scale sectors
- converging of turbulent magnetic field lines can trigger reconnection and make it fast
- magnetic mirror @ single reconnection as site of acceleration (test particle)
- 1st order Fermi acceleration

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

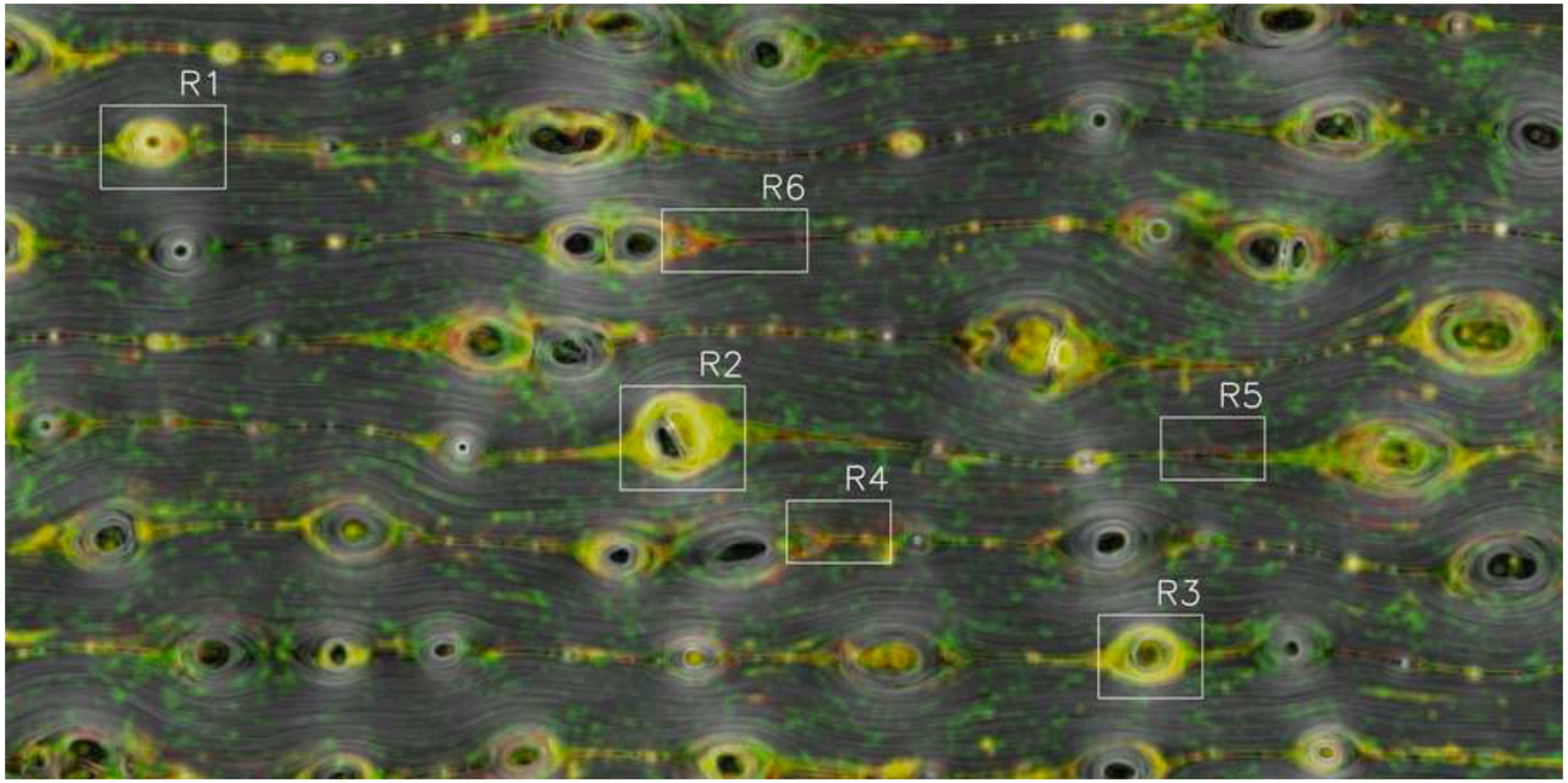


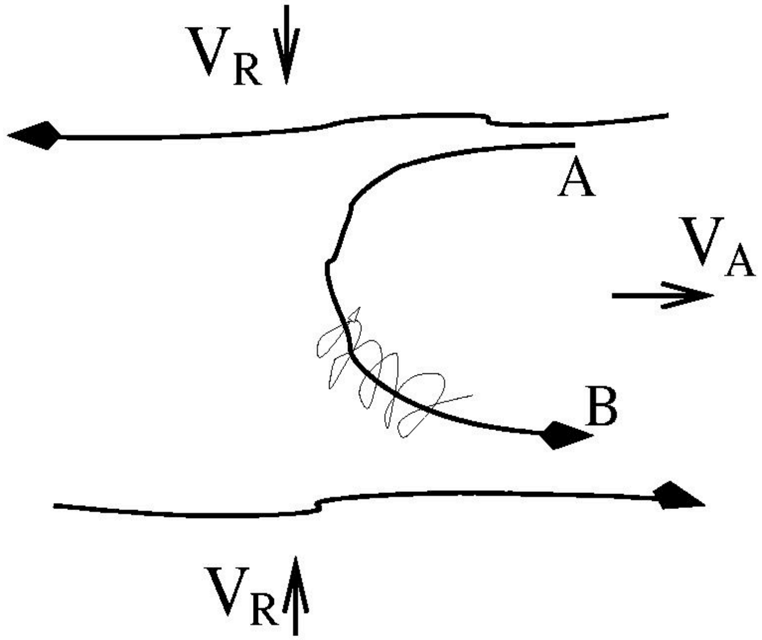


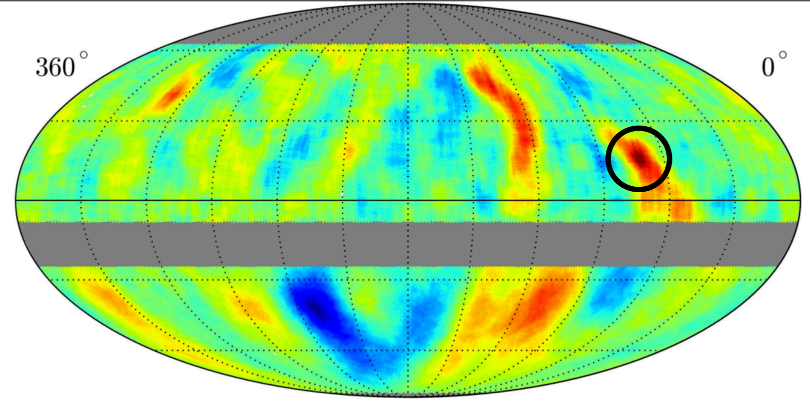

# stochastic magnetic reconnection

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




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



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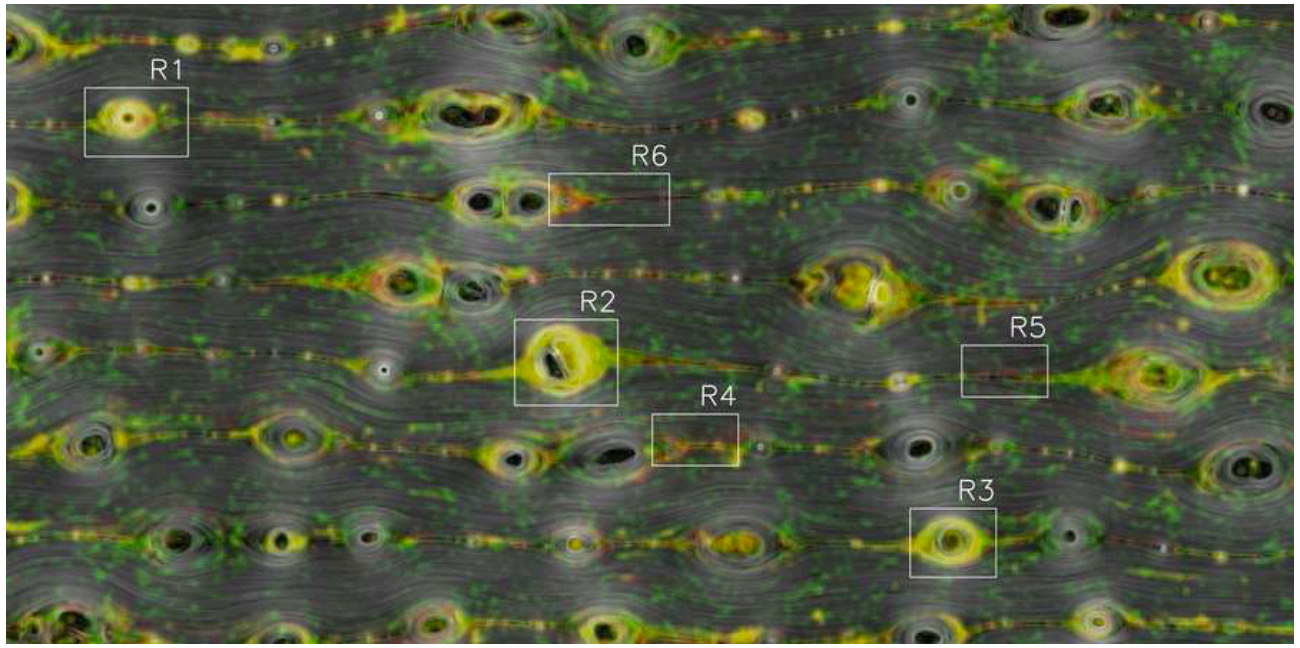
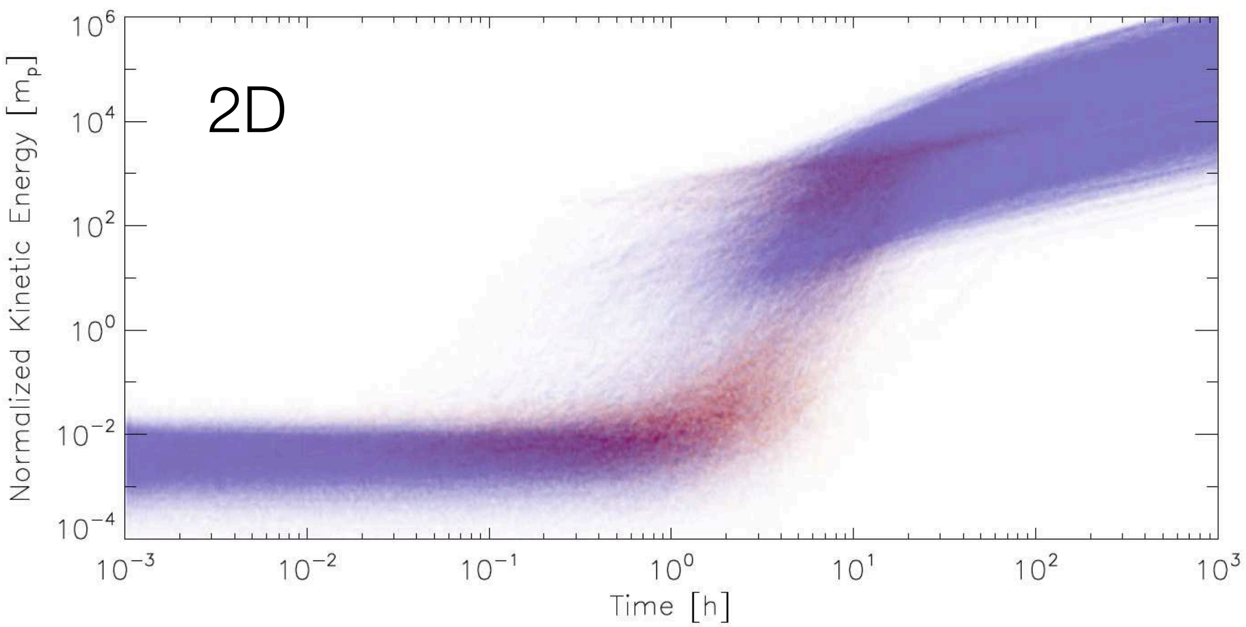
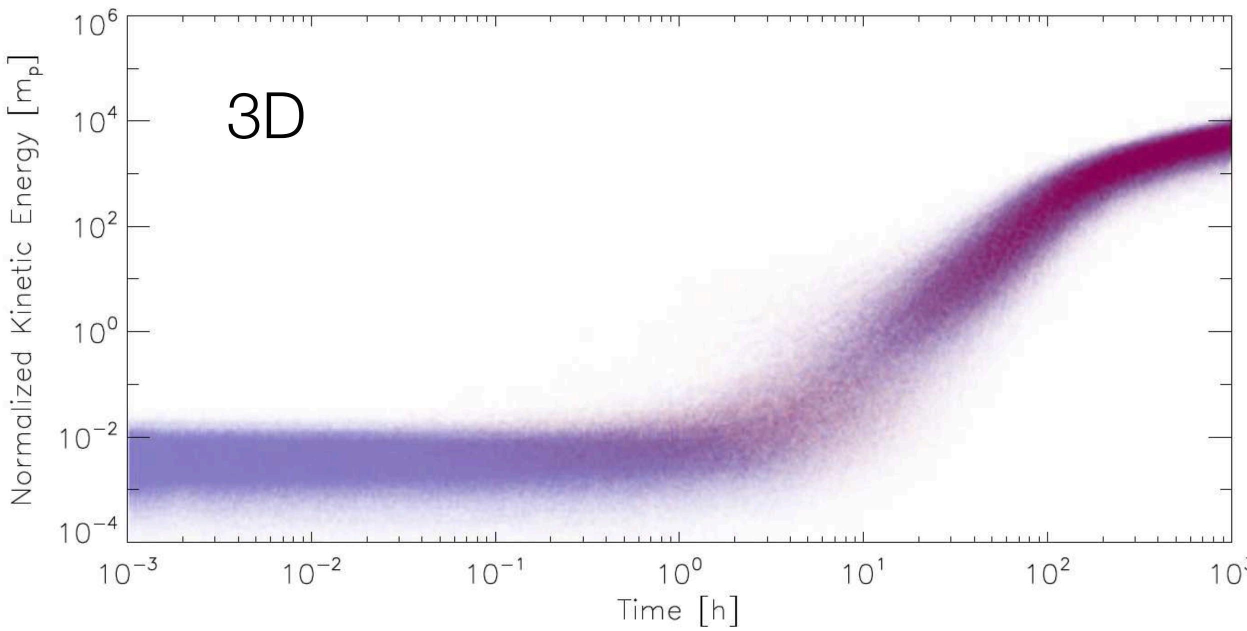


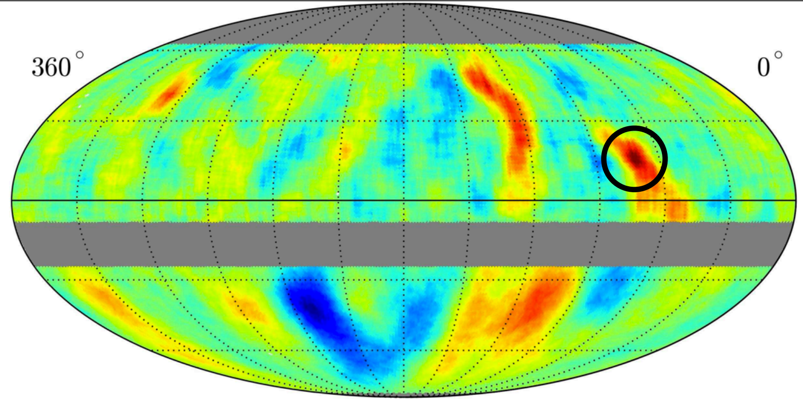




$V_\perp > V_\parallel$

$V_\parallel > V_\perp$

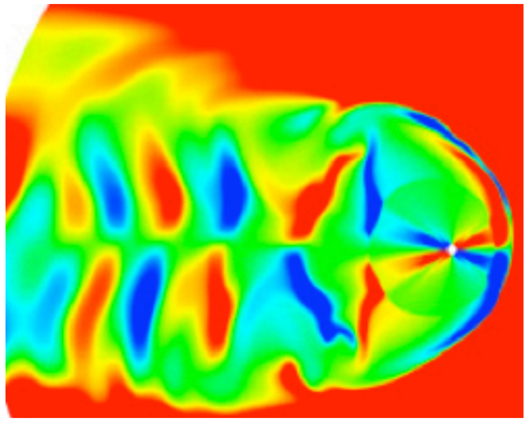
# stochastic magnetic reconnection




- $2^{nd}$ 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

# Conclusions

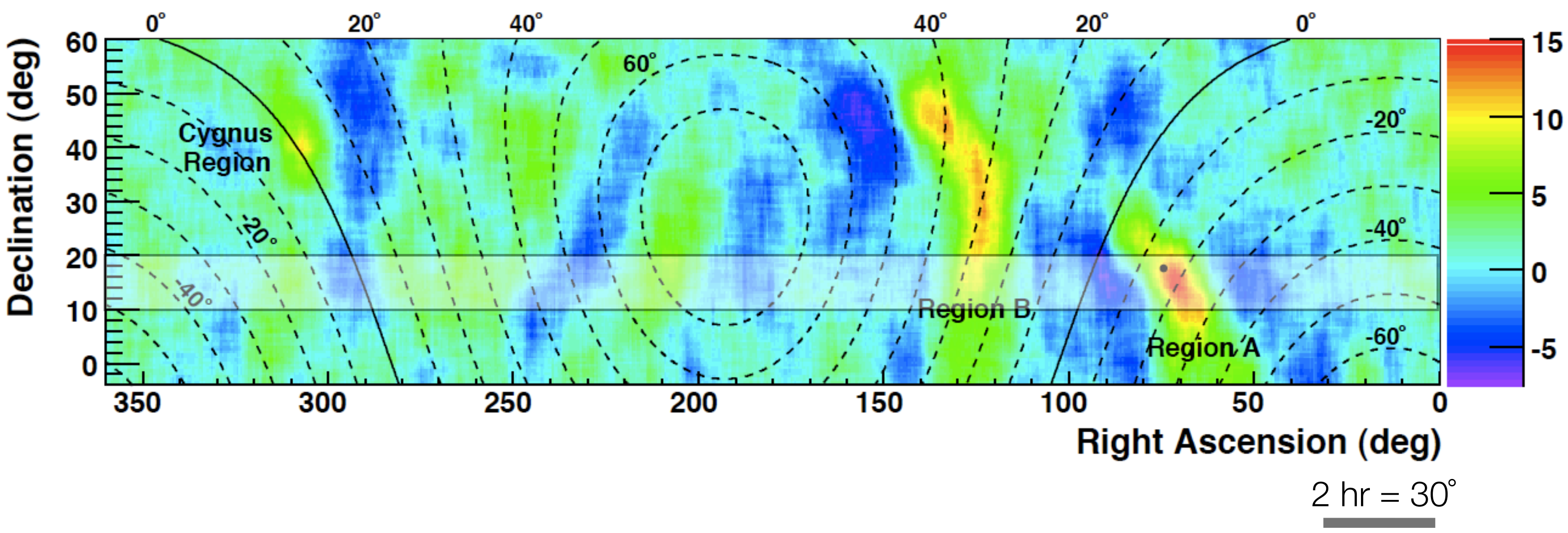
- large scale heliosphere to influence < 100 TeV cosmic rays in relation to the LIMF
- more experimental cosmic ray data to improve, confirm and refine observations
  - expect 22-yr modulation of TeV cosmic ray anisotropy from heliotail ?
- finer heliospheric MHD simulations to study turbulence in heliotail and on heliopause
  - long term space-probes into the far heliotail ?
- study of acceleration in stochastic magnetic reconnection regions undergoing
- new frontier in heliospheric study

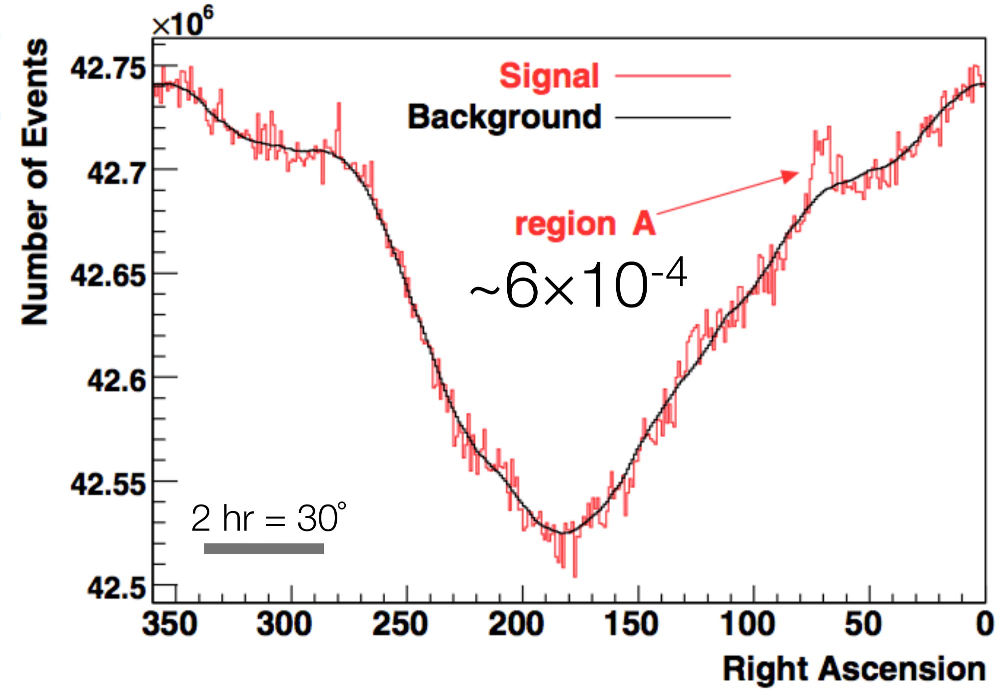
# thank you

# backup

# spectral feature associated to anisotropy

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



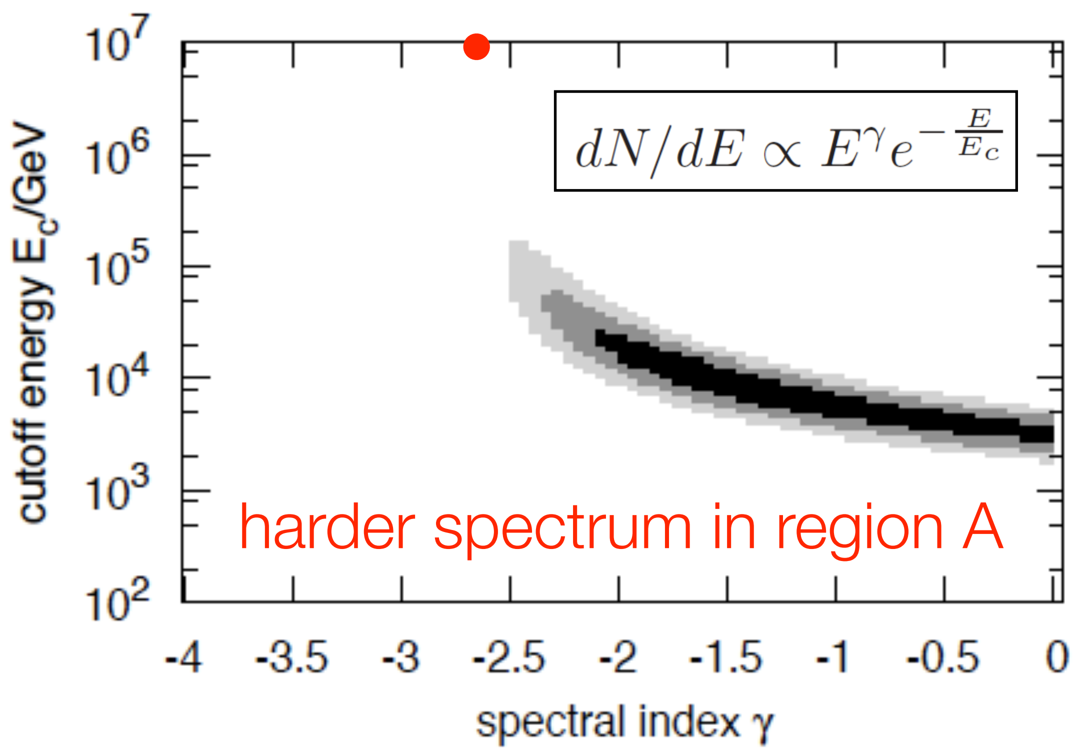

## Milagro

$\gamma < 2.7$ at 4.6 $\sigma$ level
$E_c$ = 3 - 25 TeV

$E_{flux}$(10GeV-10TeV) ~ $10^{-9}$ - $10^{-8}$ erg cm$^{-2}$ s$^{-1}$ ($\gamma$ = 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, accepted in NPG, 2012