Astrophysics with
the IceCube Observatory …

… and life snapshots from the South Pole

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lectures outline

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neutrino telescopes & the IceCube Observatory

observing the Universe

neutrino observations

cosmic ray observations

astrophysics & life at South Pole

outline

astrophysics and interdisciplinary sciences

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qualitative notion of propagation

cosmic ray astrophysics

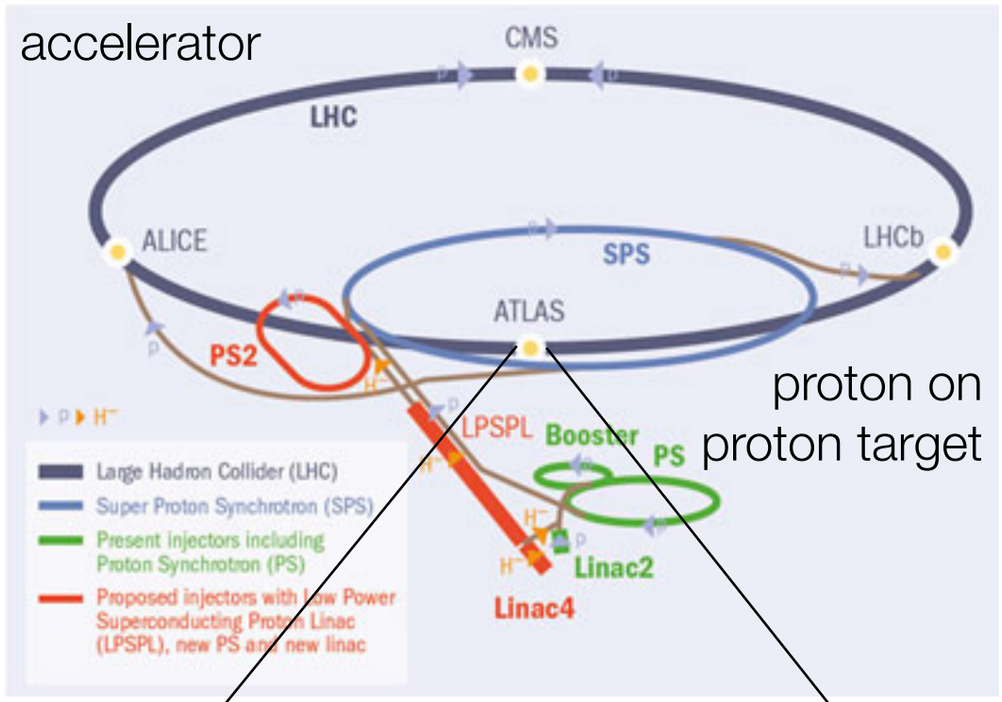
neutrino astrophysics

life at the South Pole

interdisciplinary science (time permitting)

cosmic rays
a natural laboratory

accelerator

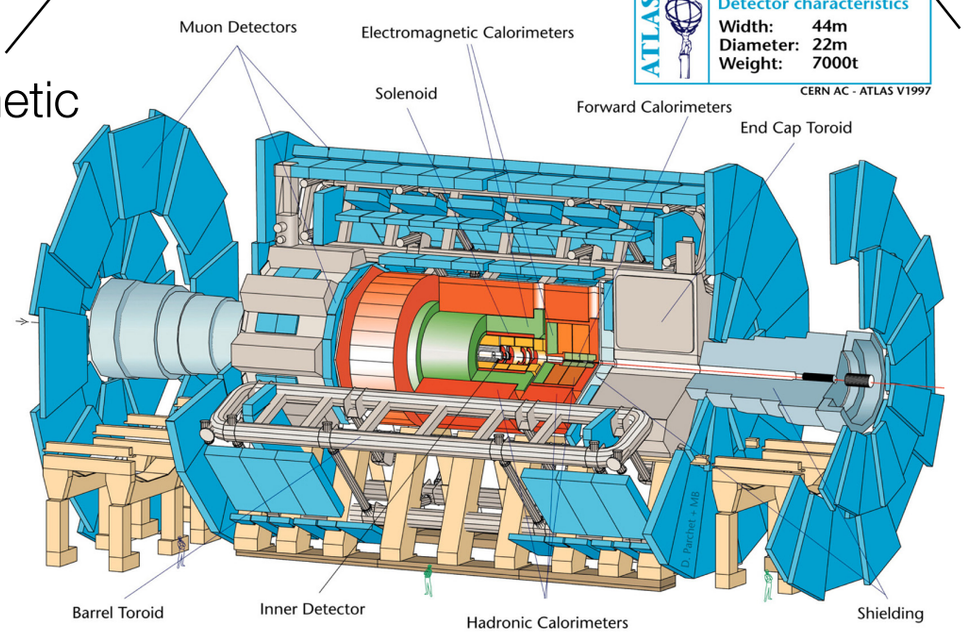


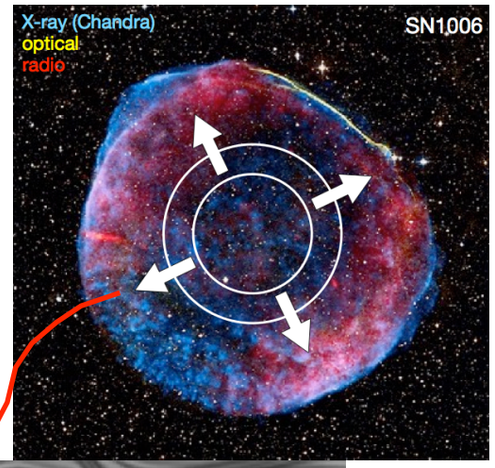
proton on proton target

propagation

magnetic fields

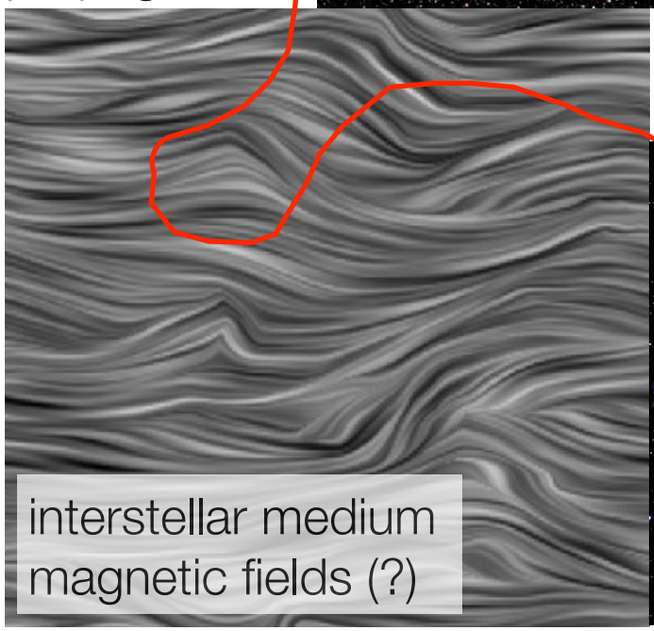
detection



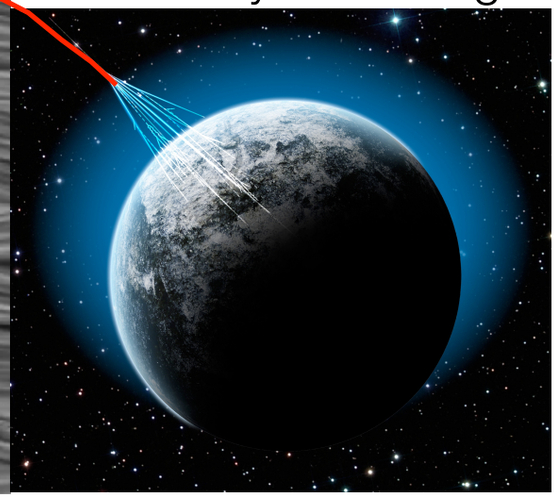


accelerator (?)

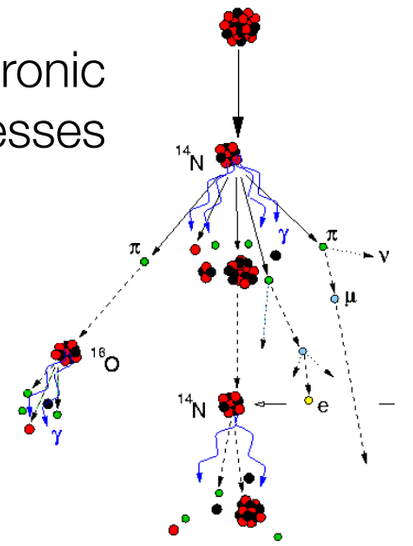
propagation



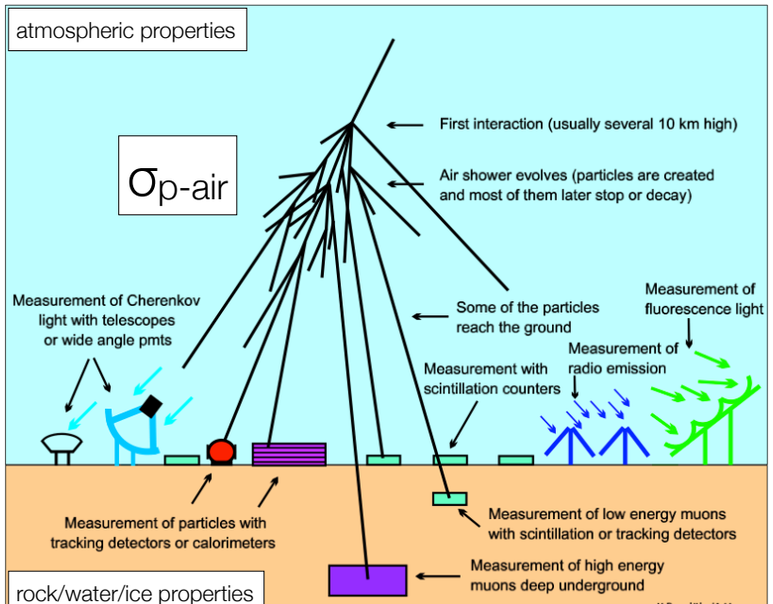
Earth atmosphere
dynamic target



nuclear & hadronic processes



detection



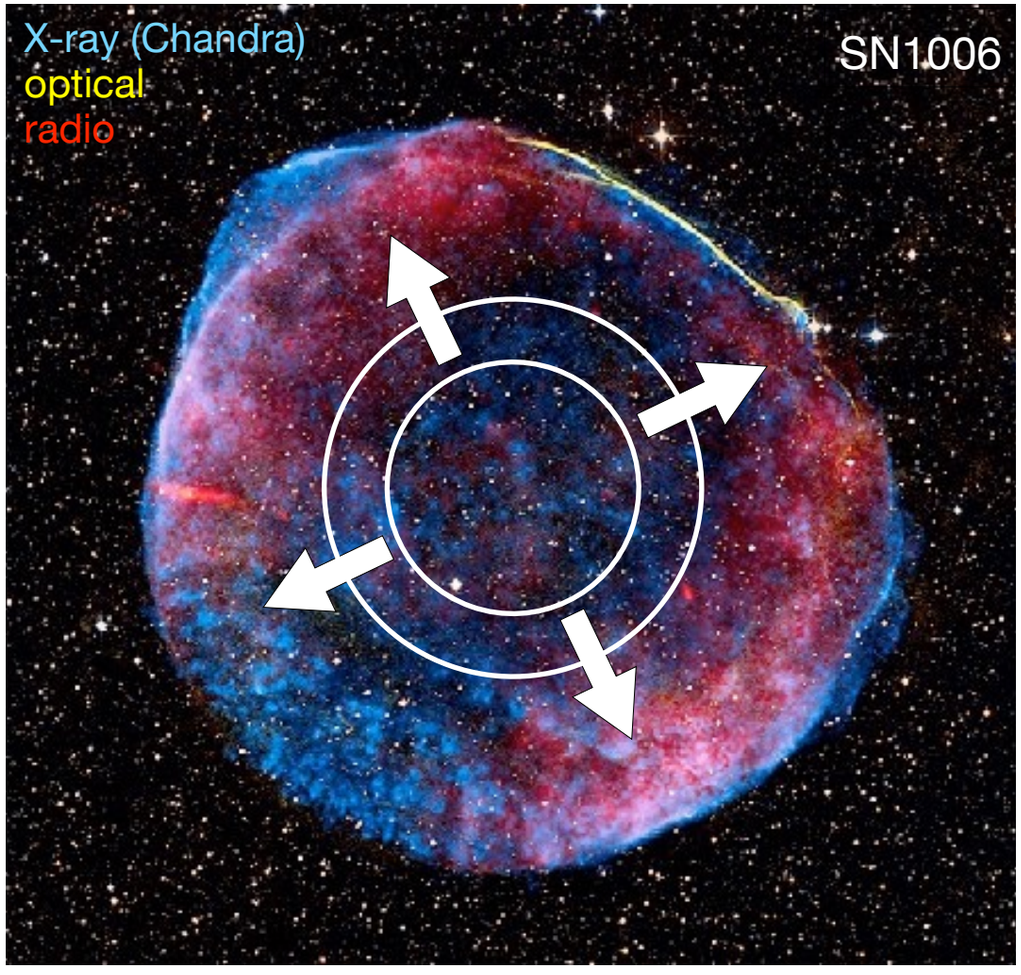
cosmic ray acceleration in supernova remnants

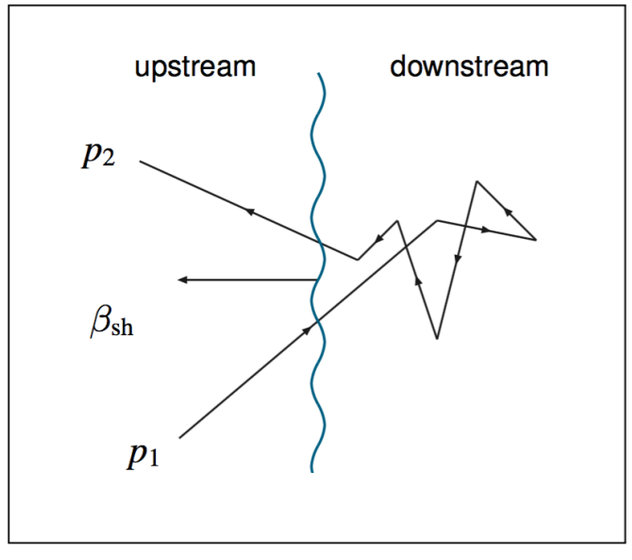
- energy density of cosmic rays **below the knee** consistent with **10%** of energy emitted by SNR every **30 years** in the Galaxy

- composition of **low energy** cosmic rays consistent with **OB Associations**

- diffusive shock acceleration and $\mathbf{E^{-2}}$

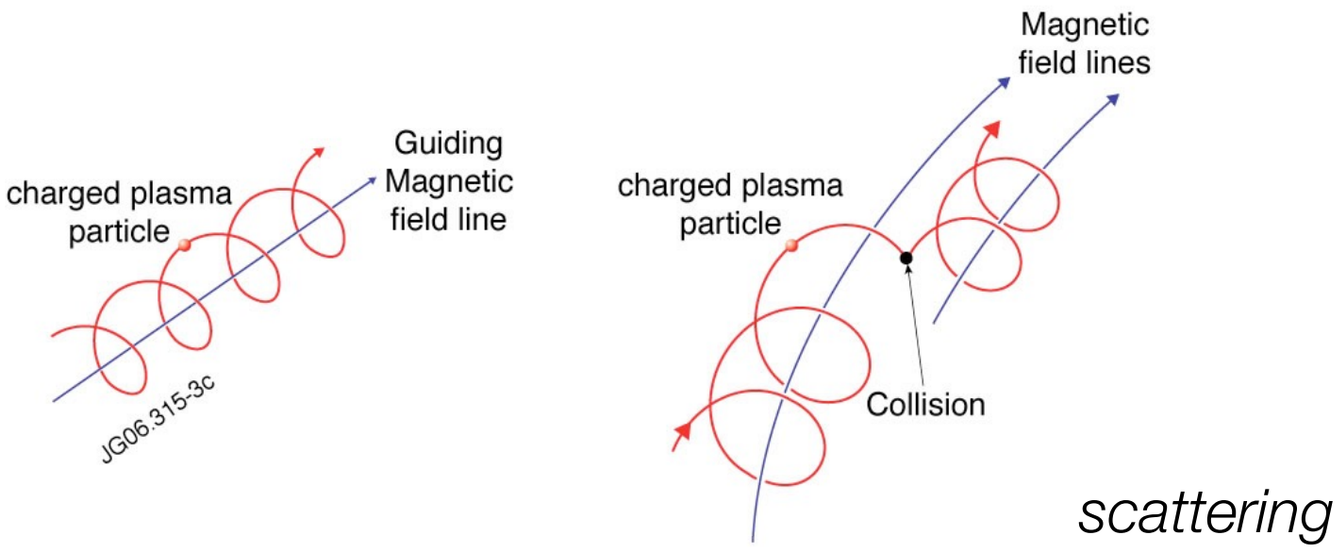
- some particles interacts and some escape and **propagate** across the interstellar medium





cosmic ray propagation in interstellar medium

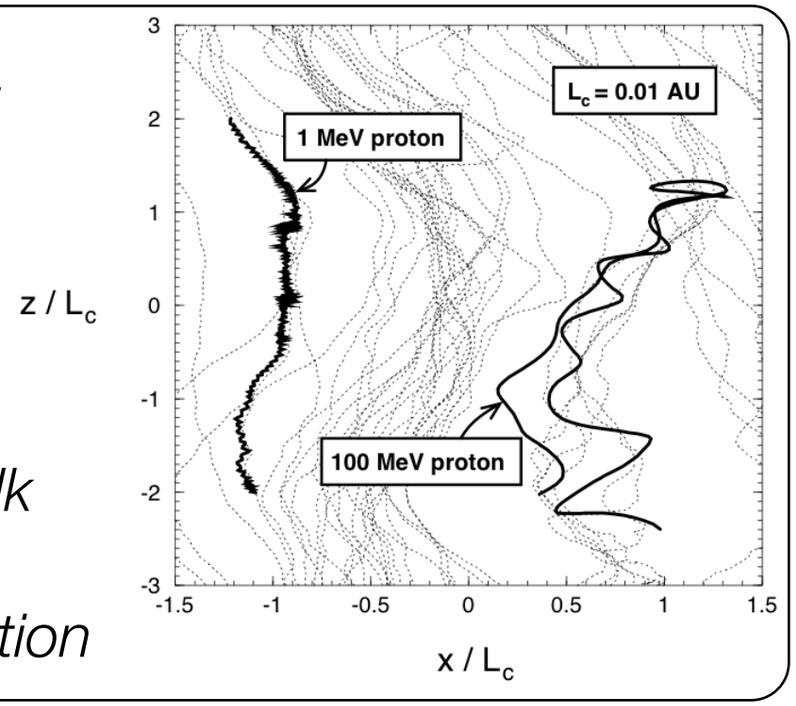
qualitative discussion



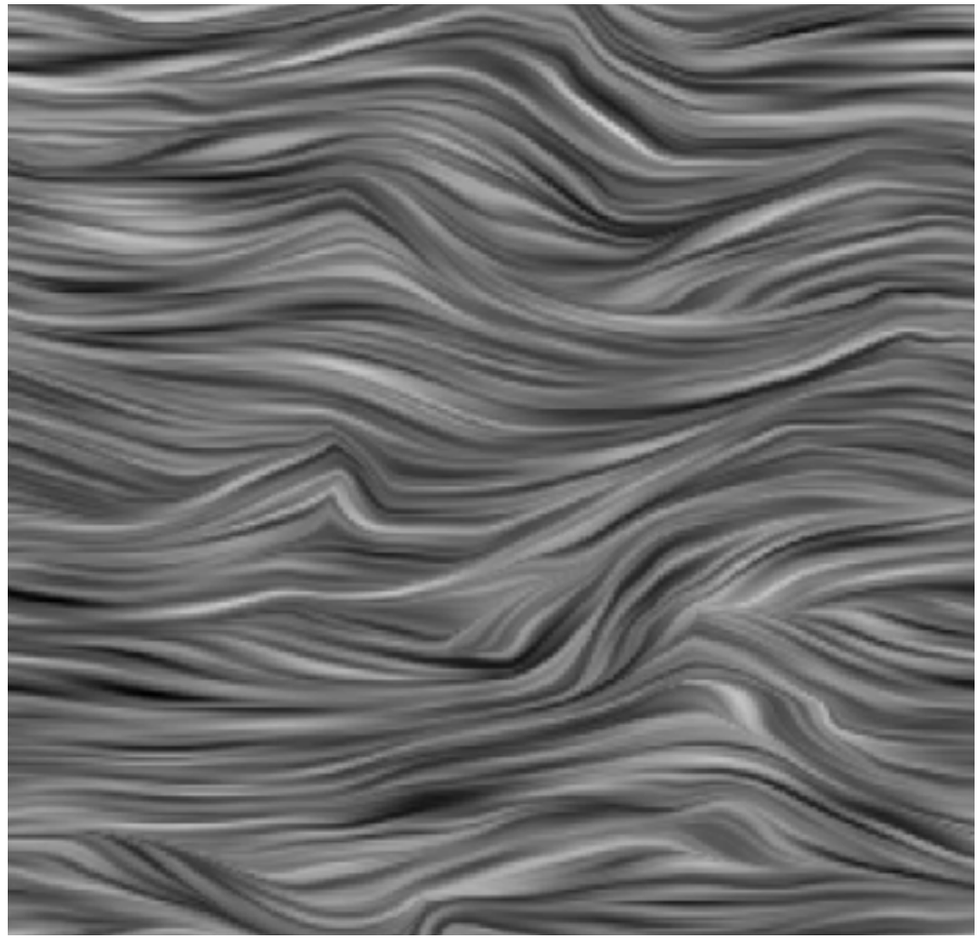
scattering

collisionless scattering

field line random walk
&
cross fieldline propagation

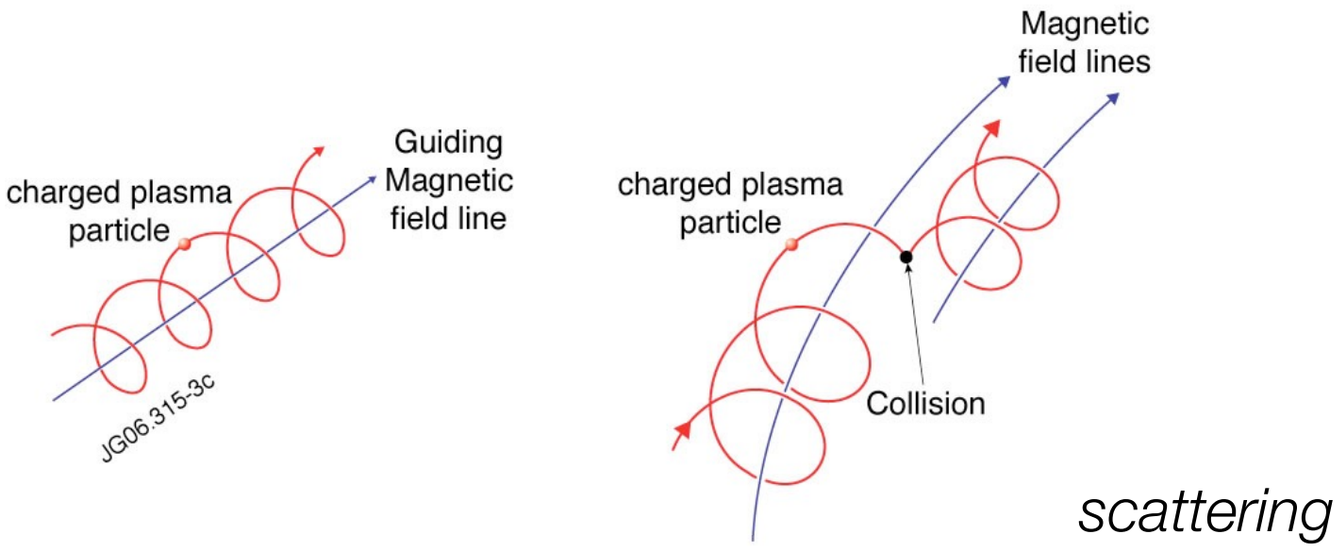


astrophysical
turbulence properties

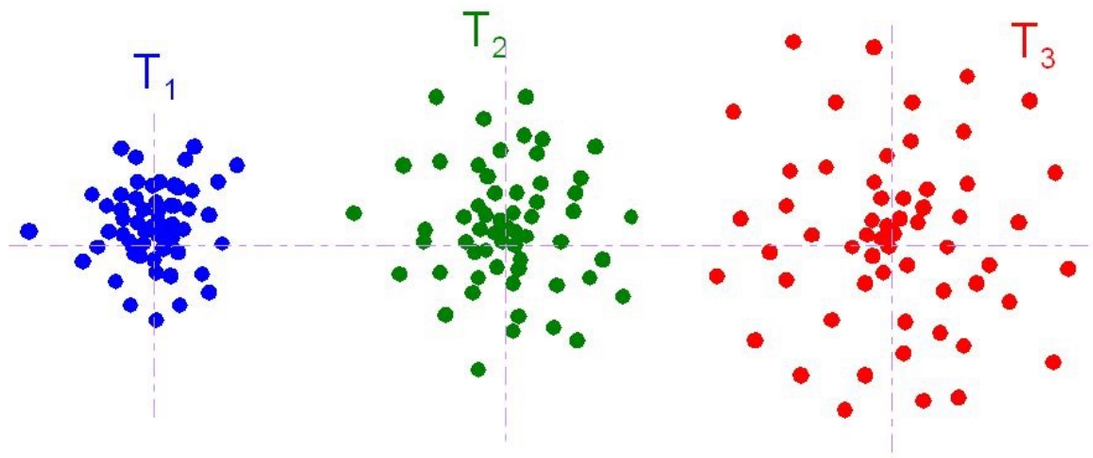


cosmic ray propagation in interstellar medium

qualitative discussion



scattering



collisionless scattering

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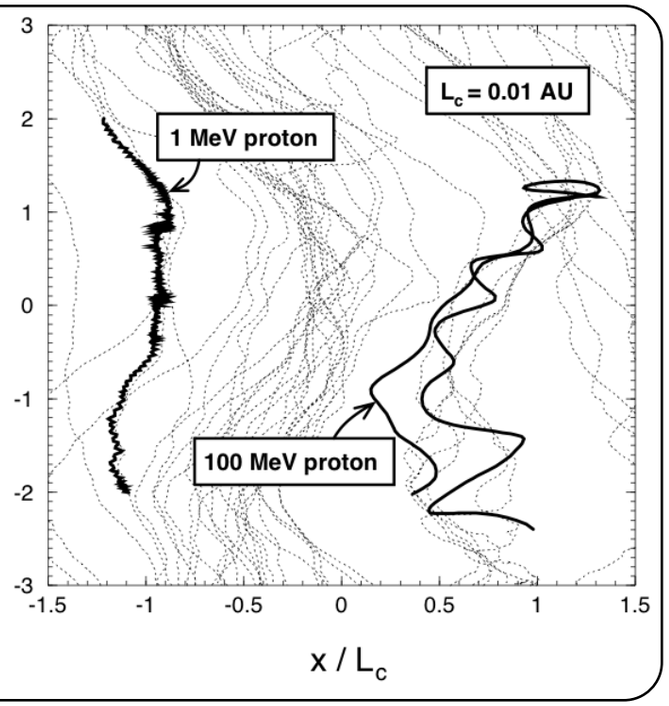


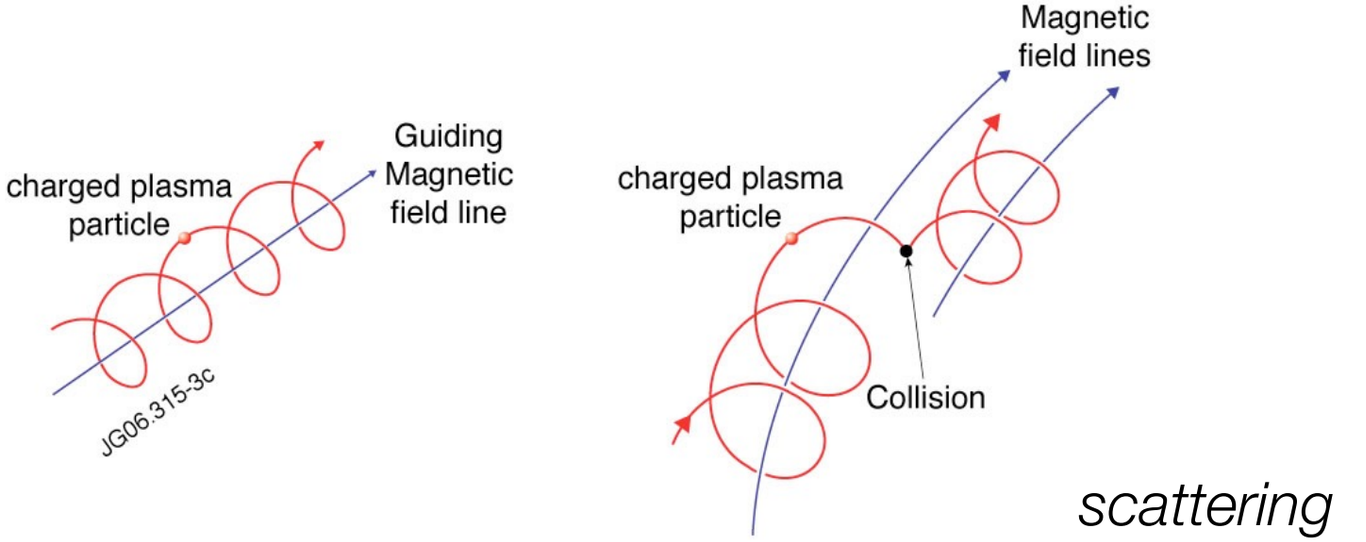
ballistic motion $\vec{r} = \vec{r}_0 + \vec{v} \cdot t$

for an ensemble of particles $\langle \vec{r} \rangle^2_{\mathrm{bal}} \propto t^2$

with effect of scattering, after τ_{sca} $\langle \vec{r} \rangle^2_{\mathrm{dif}} \propto t$

cosmic ray propagation in interstellar medium

qualitative discussion



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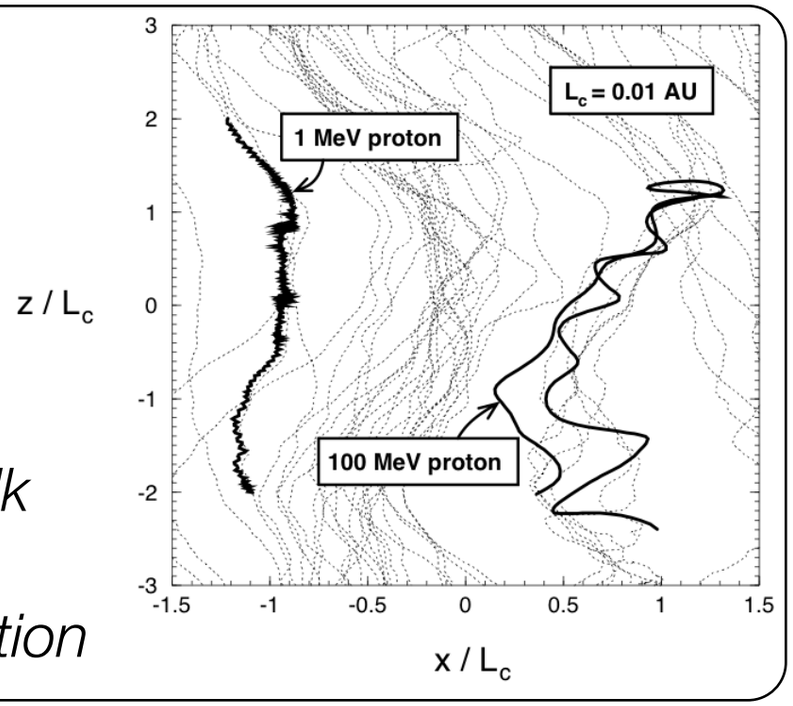
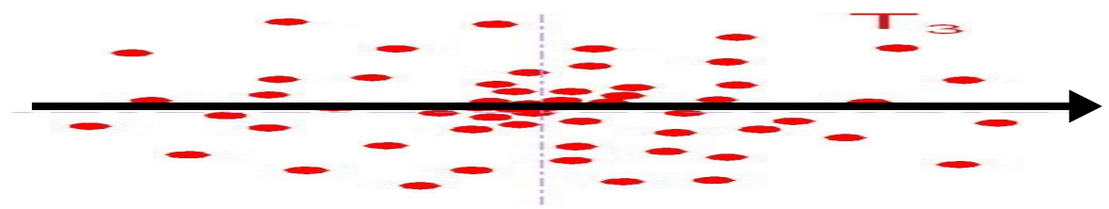


$\langle \vec{B} \rangle_{\rm mag}$



diffusion coefficient

$$\langle \vec{r} \rangle^2_{\rm dif} \propto t$$ **diffusion time** $\tau_{\rm dif}$

$$D_{\parallel,\perp} \propto \frac{\langle r^2_{\parallel,\perp} \rangle}{t} \sim {\rm const} \qquad D_\perp < D_\parallel$$

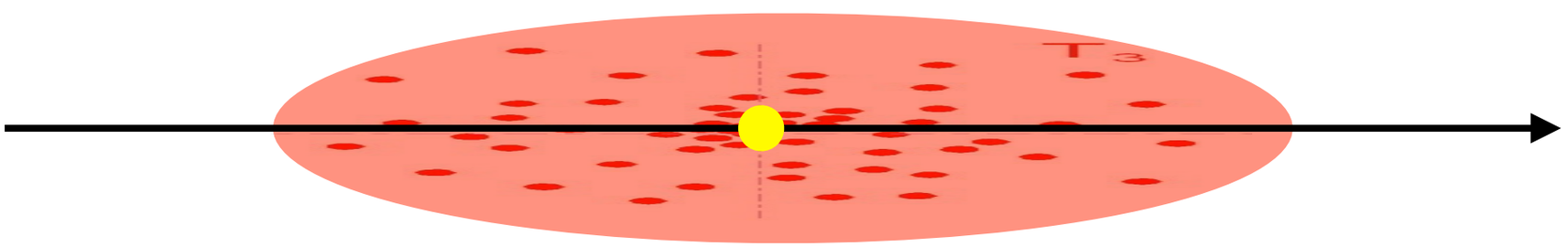
$$D(E) \approx D_0 \cdot E^\delta$$

cosmic ray propagation in interstellar medium

qualitative discussion

diffusion coefficient $D(E) \approx D_0 \cdot E^{\delta}$

$\langle \vec{B} \rangle_{\rm mag}$

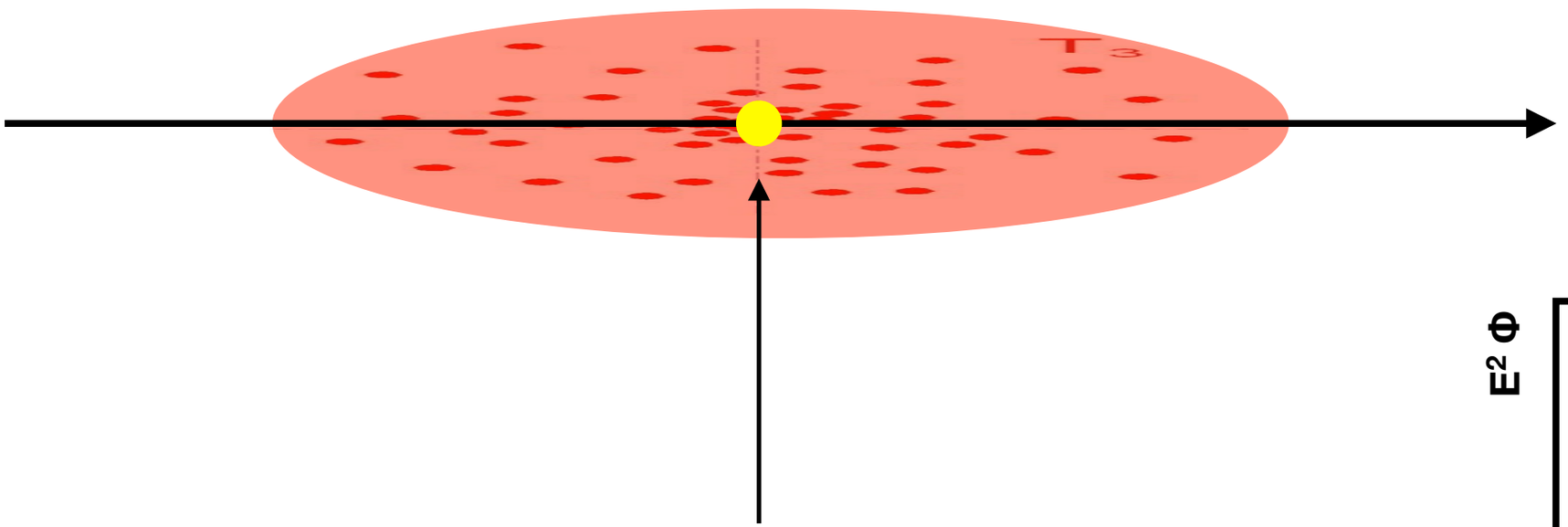


cosmic ray propagation in interstellar medium

qualitative discussion

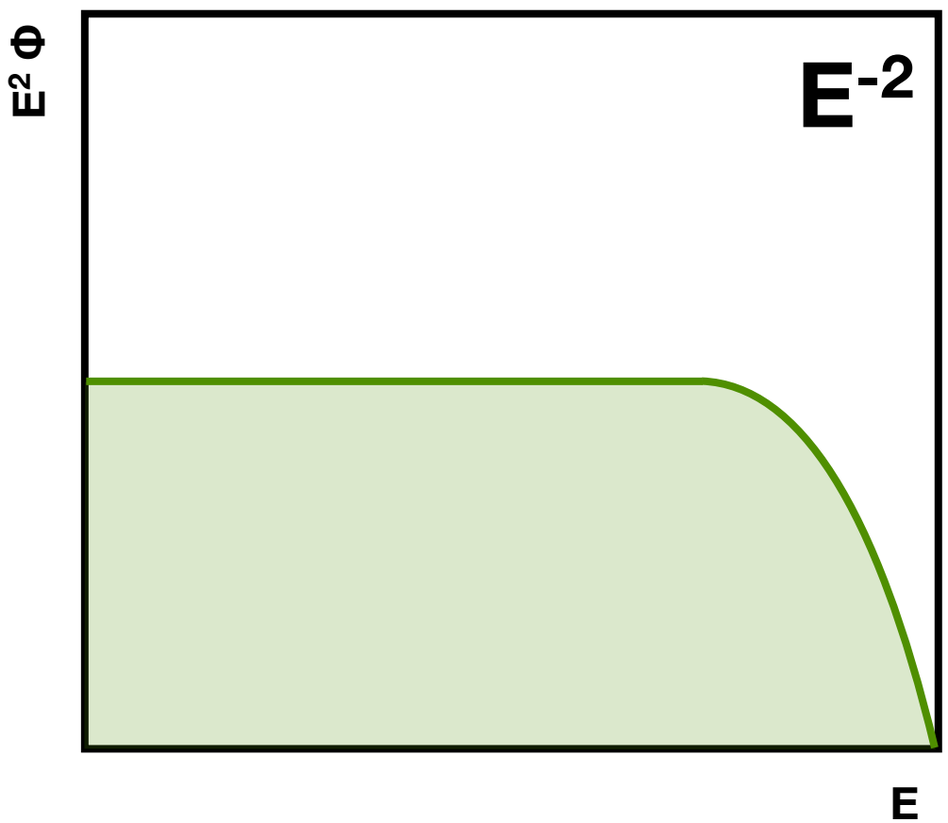
diffusion coefficient $D(E) \approx D_0 \cdot E^{\delta}$

$\langle \vec{B} \rangle_{\mathrm{mag}}$



at the source

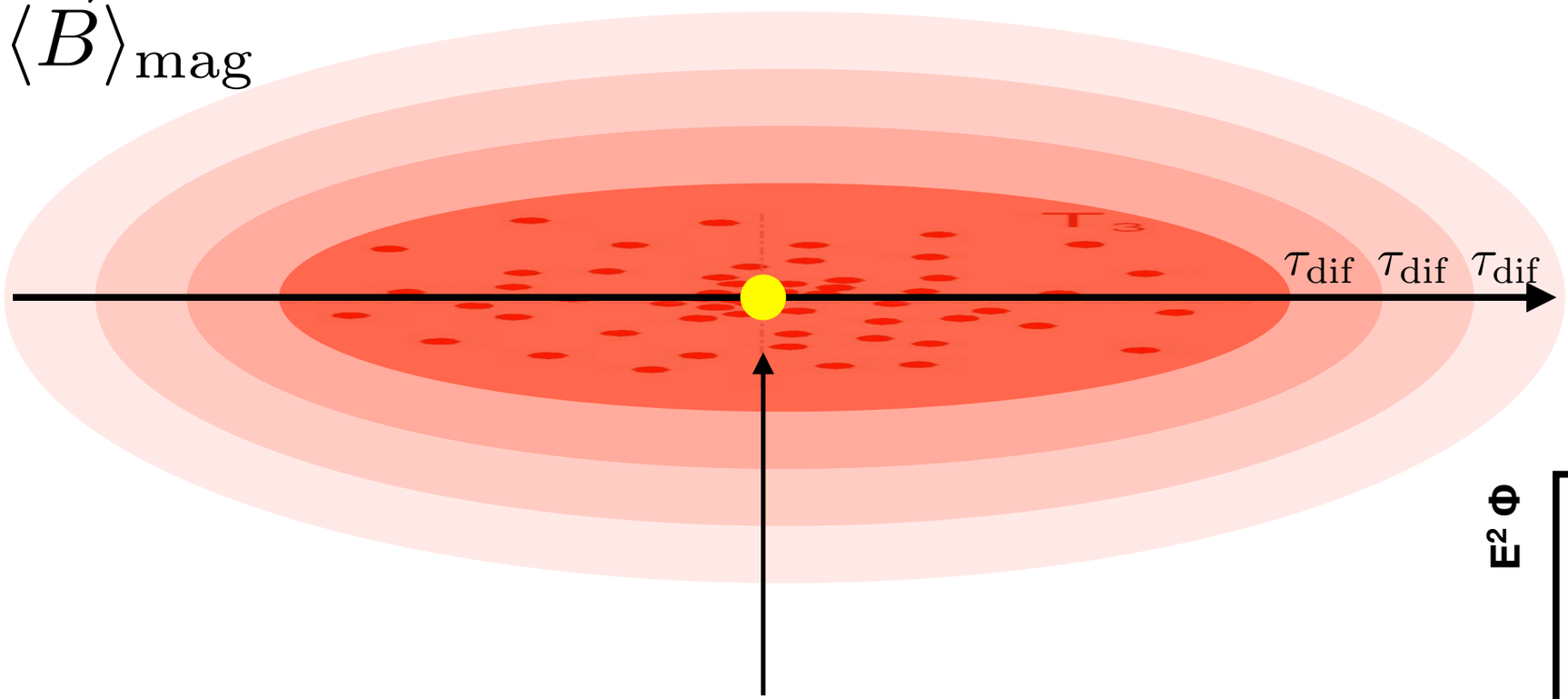
$E^{-\gamma}$ (γ=2)



cosmic ray propagation in interstellar medium

qualitative discussion

diffusion coefficient $D(E) \approx D_0 \cdot E^{\delta}$



at the source

$E^{-\gamma}$ (γ=2)

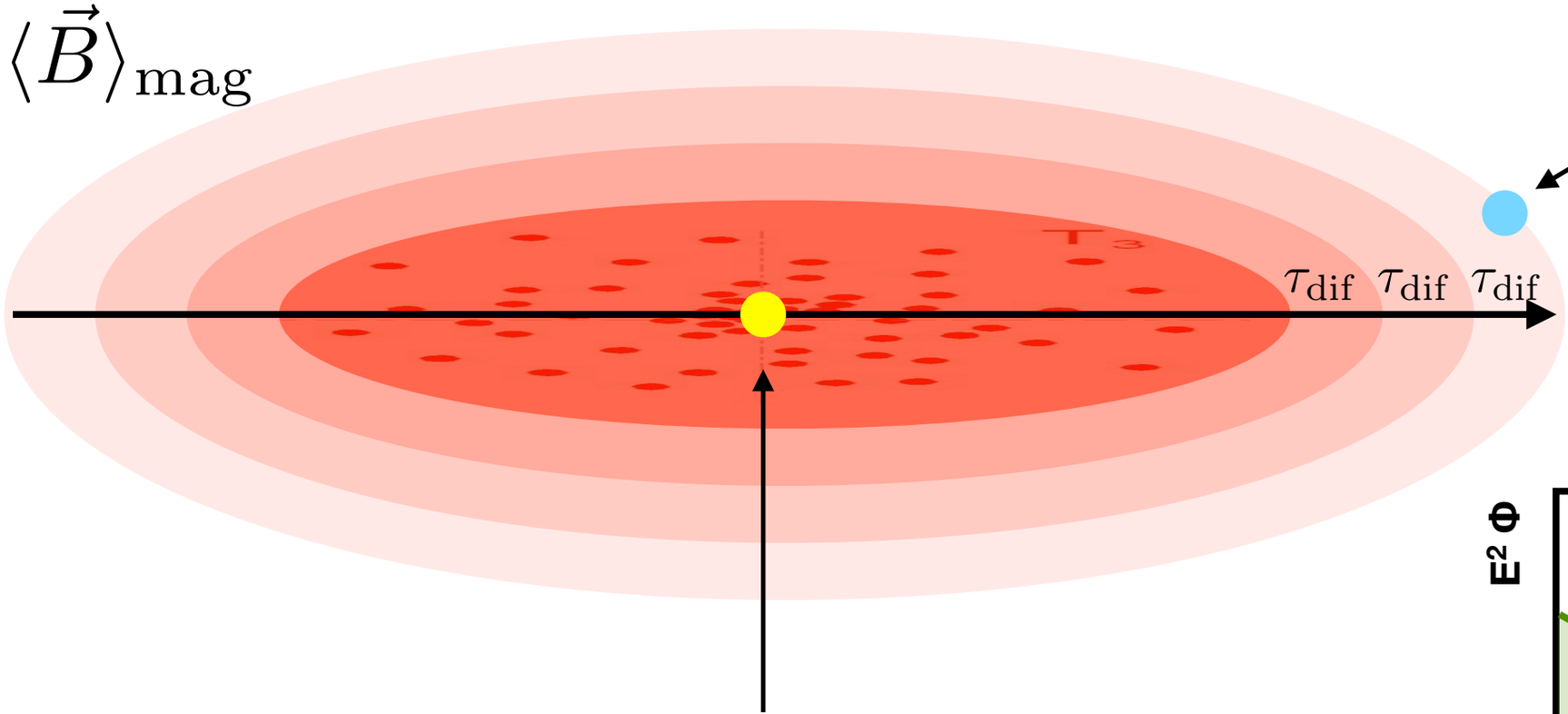
cosmic ray propagation in interstellar medium

qualitative discussion

diffusion coefficient $D(E) \approx D_0 \cdot E^{\delta}$

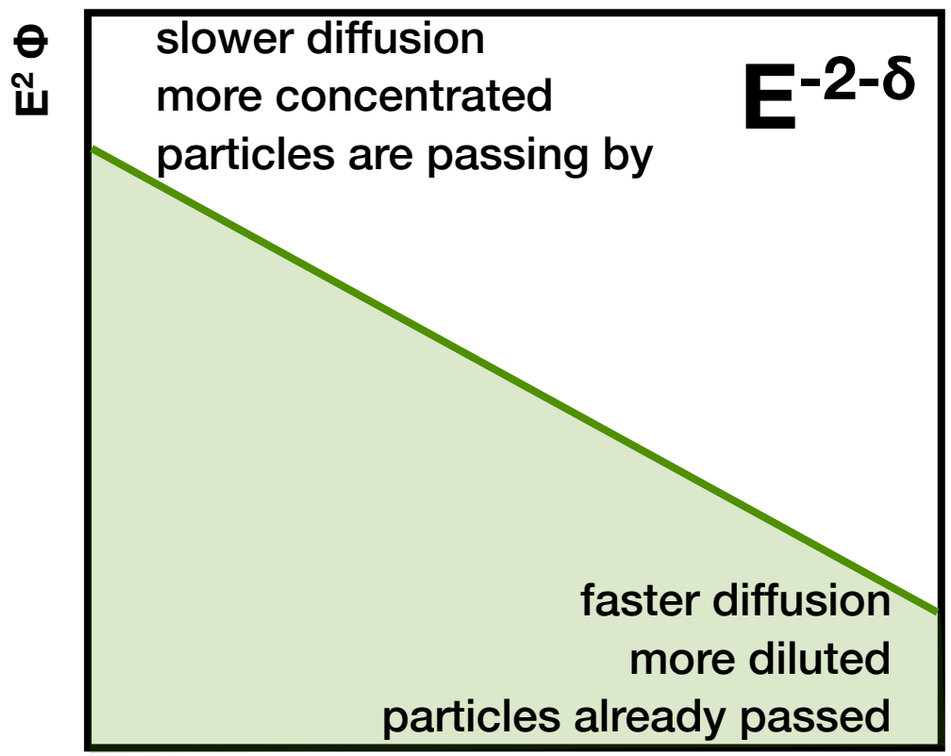
after many diffusion lengths

$E^{-\gamma-\delta}$



at the source

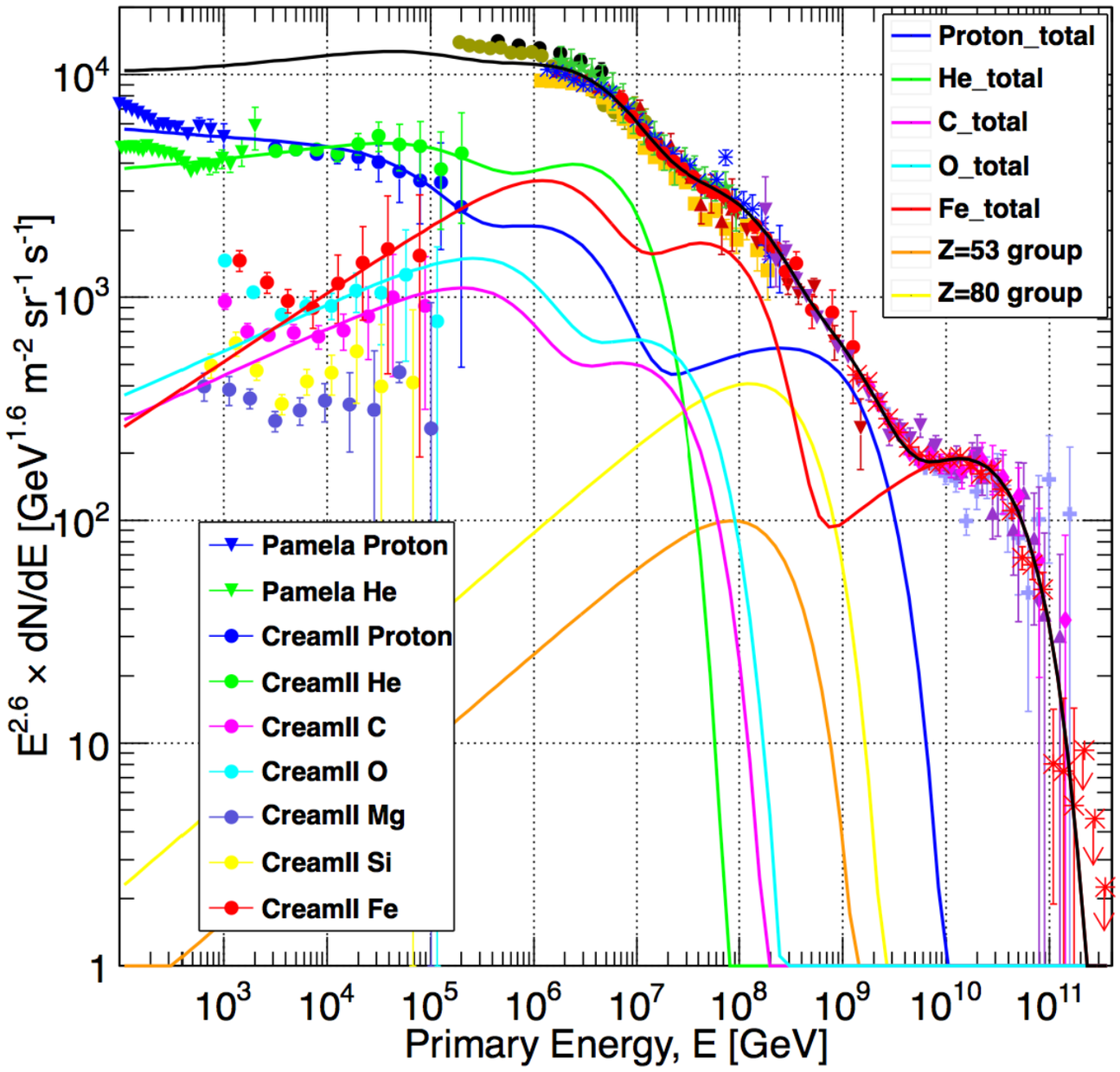
$E^{-\gamma}$ (γ=2)



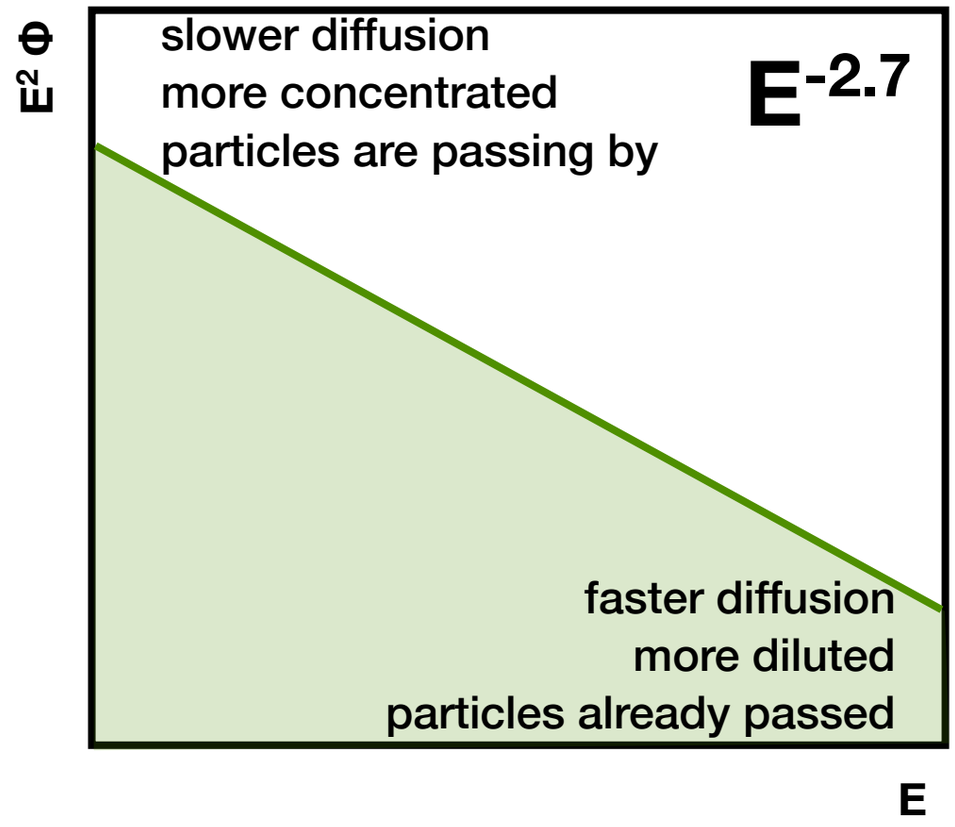
cosmic ray propagation in interstellar medium

qualitative discussion

$E^{-2.7}$



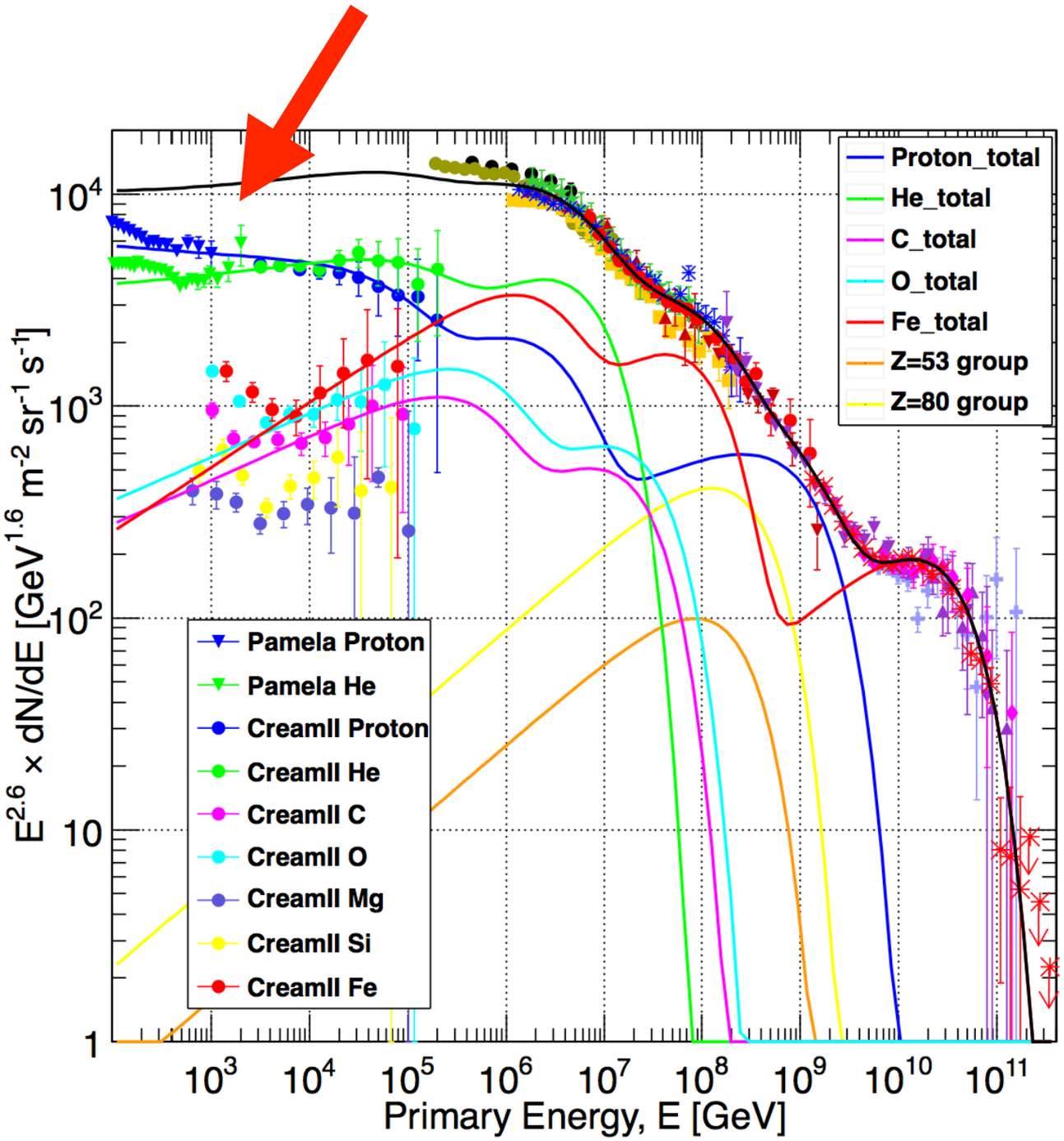
$\delta = 0.7$ (?)

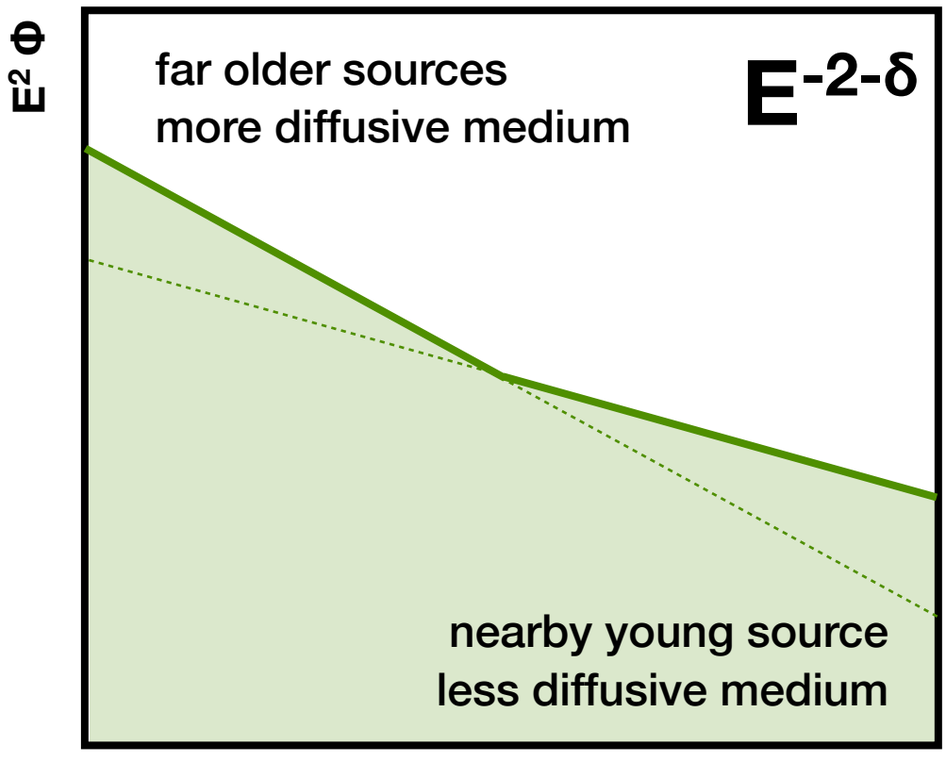


$$\delta \sim 0.3 - 0.6 \Longrightarrow \gamma \sim 2.4 - 2.1$$

cosmic ray propagation in interstellar medium

qualitative discussion





- a nearby “recent” source would have a “flatter” spectrum (no full diffusion?)
- diffusion coefficient can change as a function of the location in the Galaxy

cosmic rays spectrum
direct observations

- **anomaly** cosmic ray spectra
- **anomaly** in anti-proton & positron fraction

effect of a nearby source of cosmic rays

OR

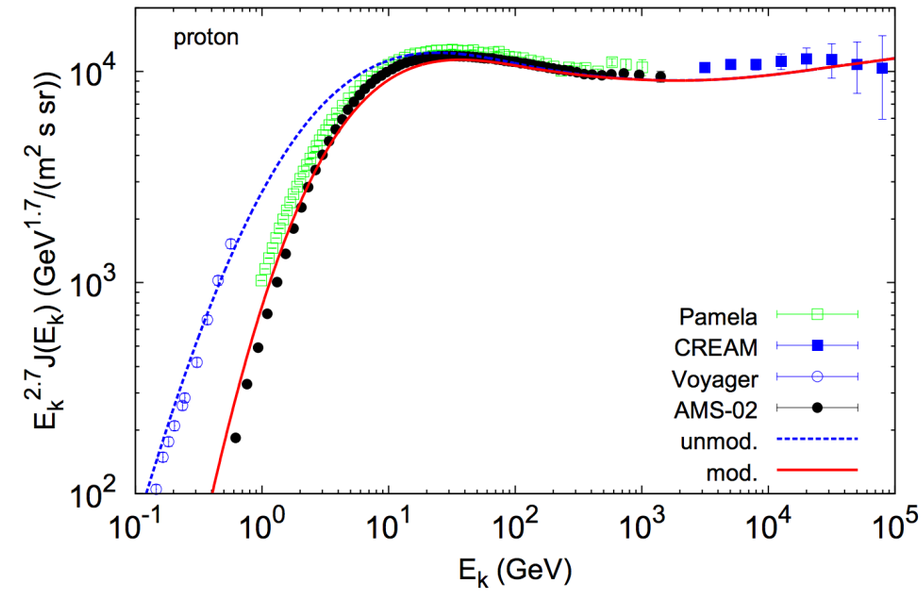
different propagation properties

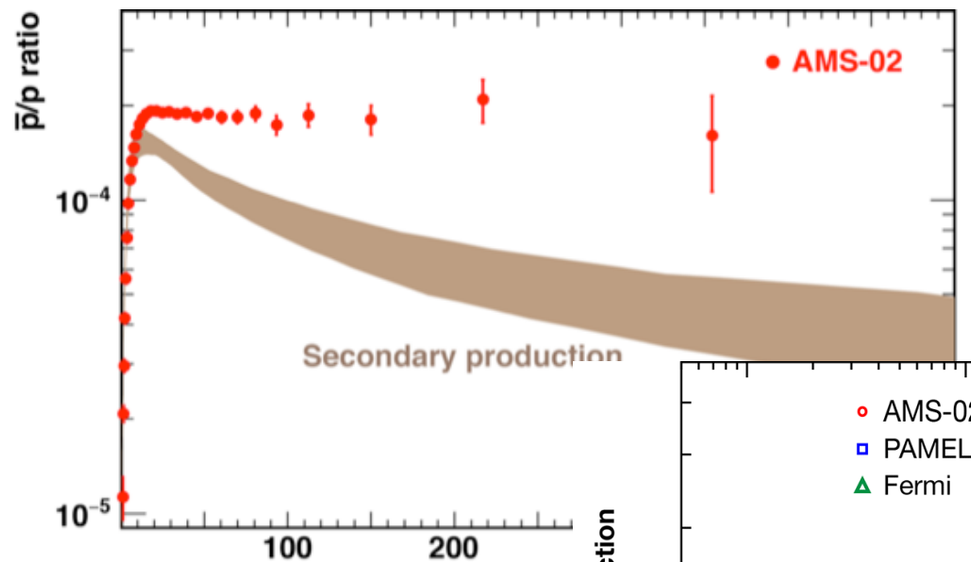
OR

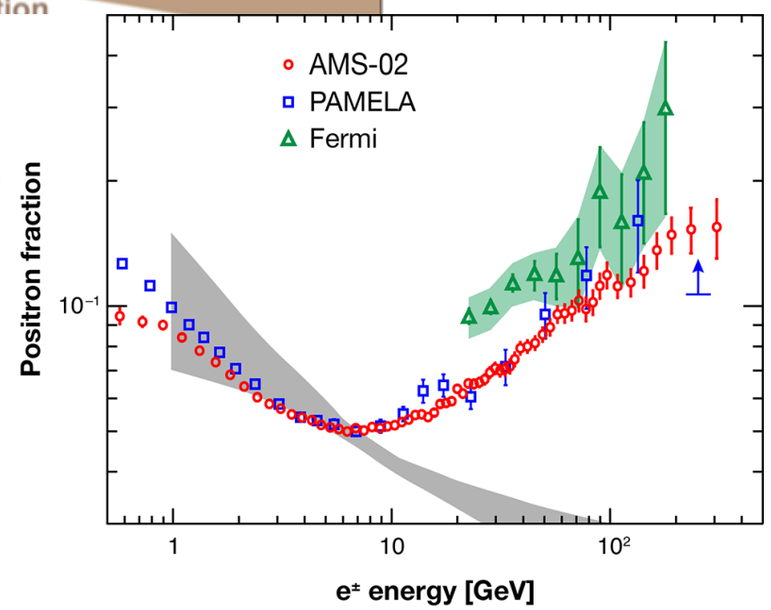
dark matter

OR

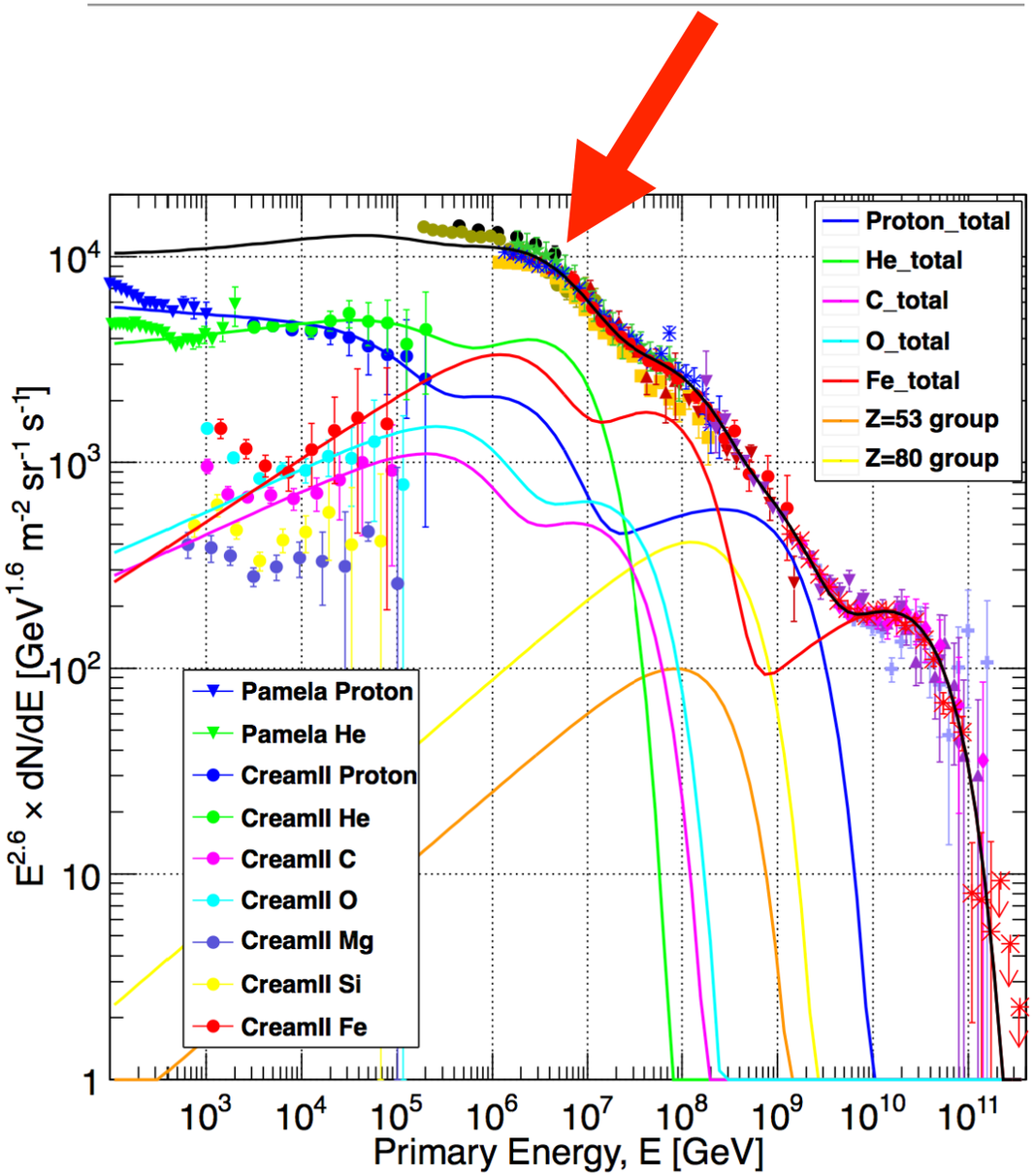
?







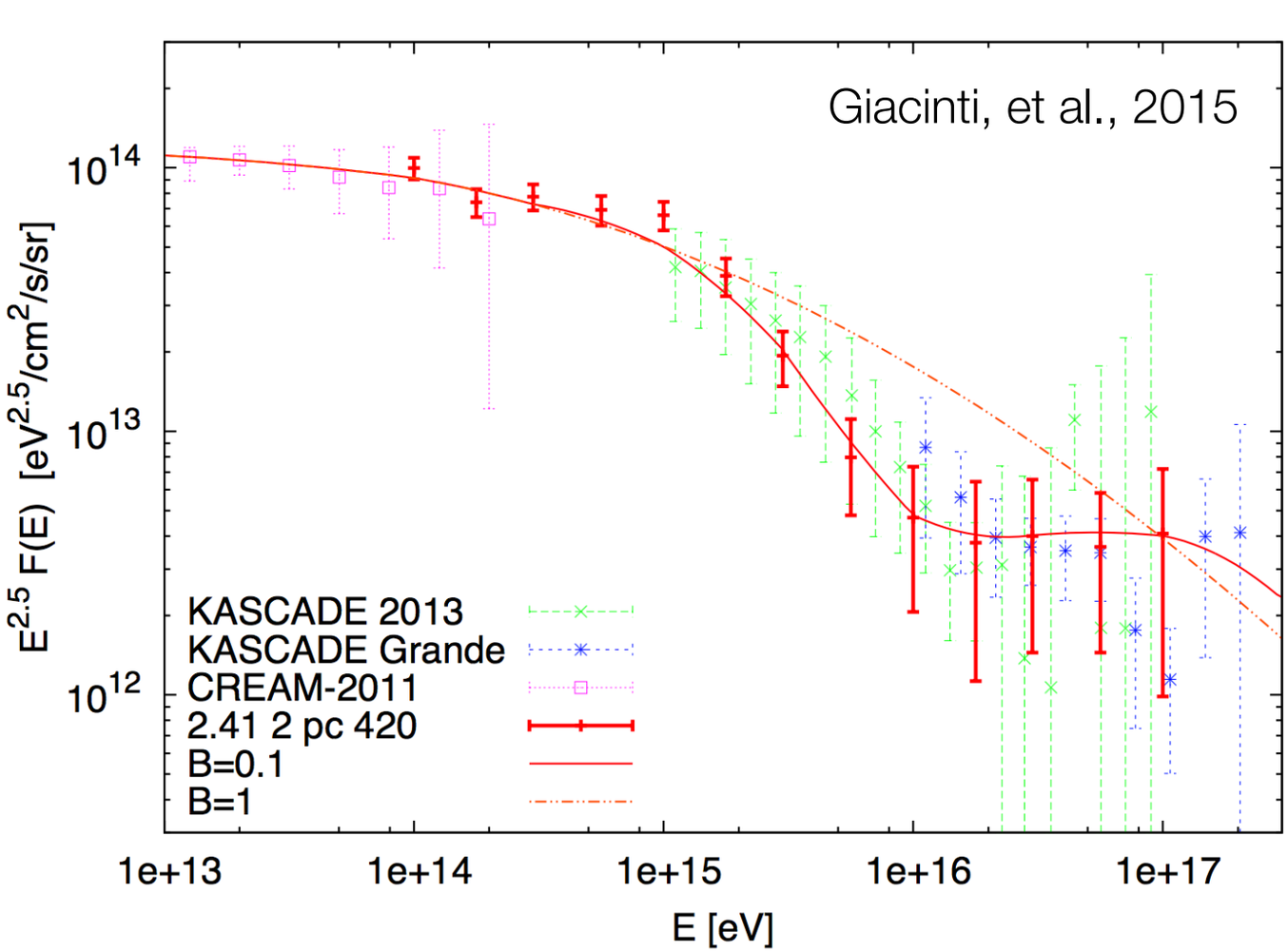
cosmic ray propagation in interstellar medium



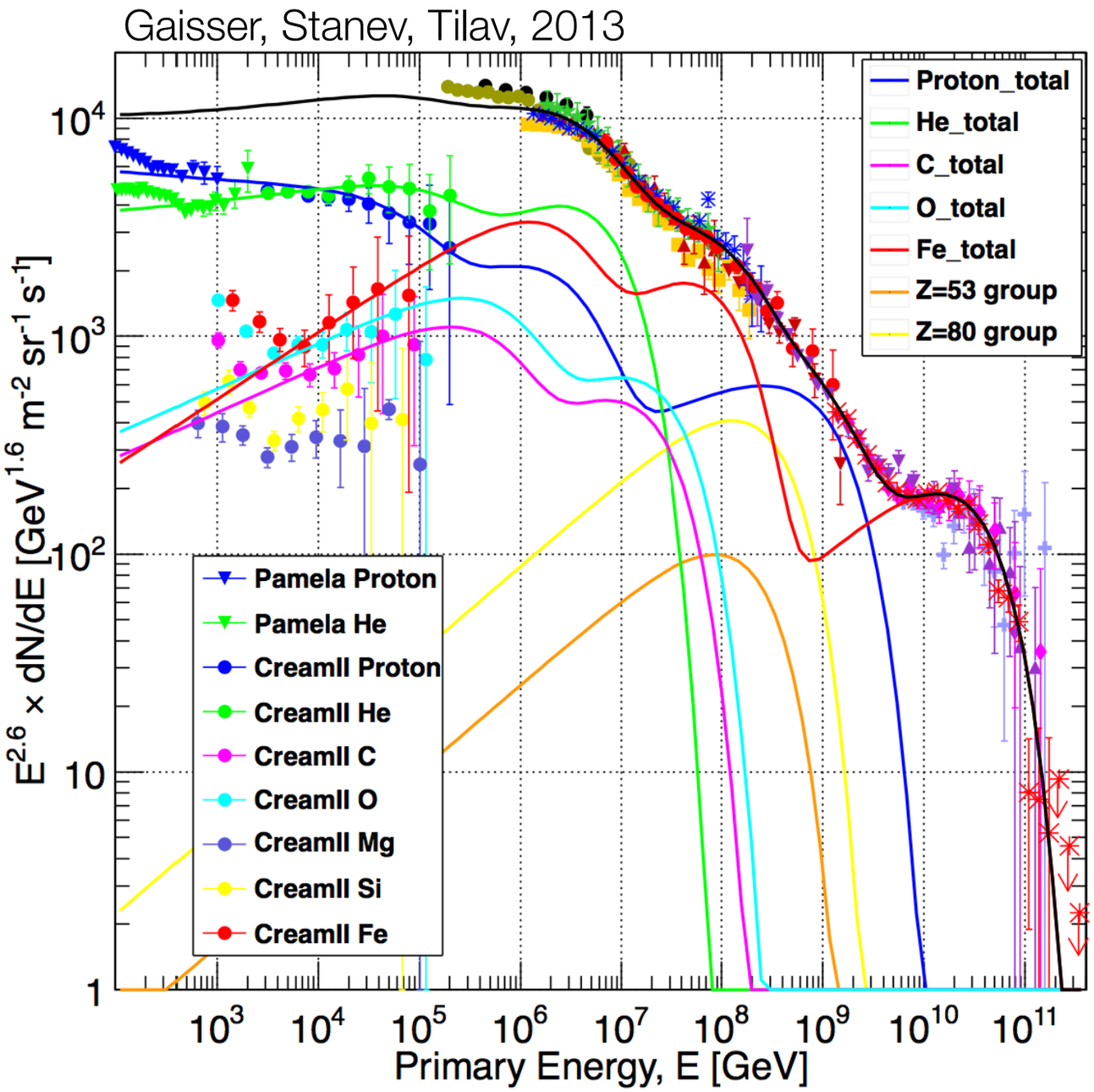
Gaisser, Stanev, Tilav, 2013

- the **knee** of cosmic rays and spectral **features** from **escape** from the Galaxy

- determines the level of **turbulence**



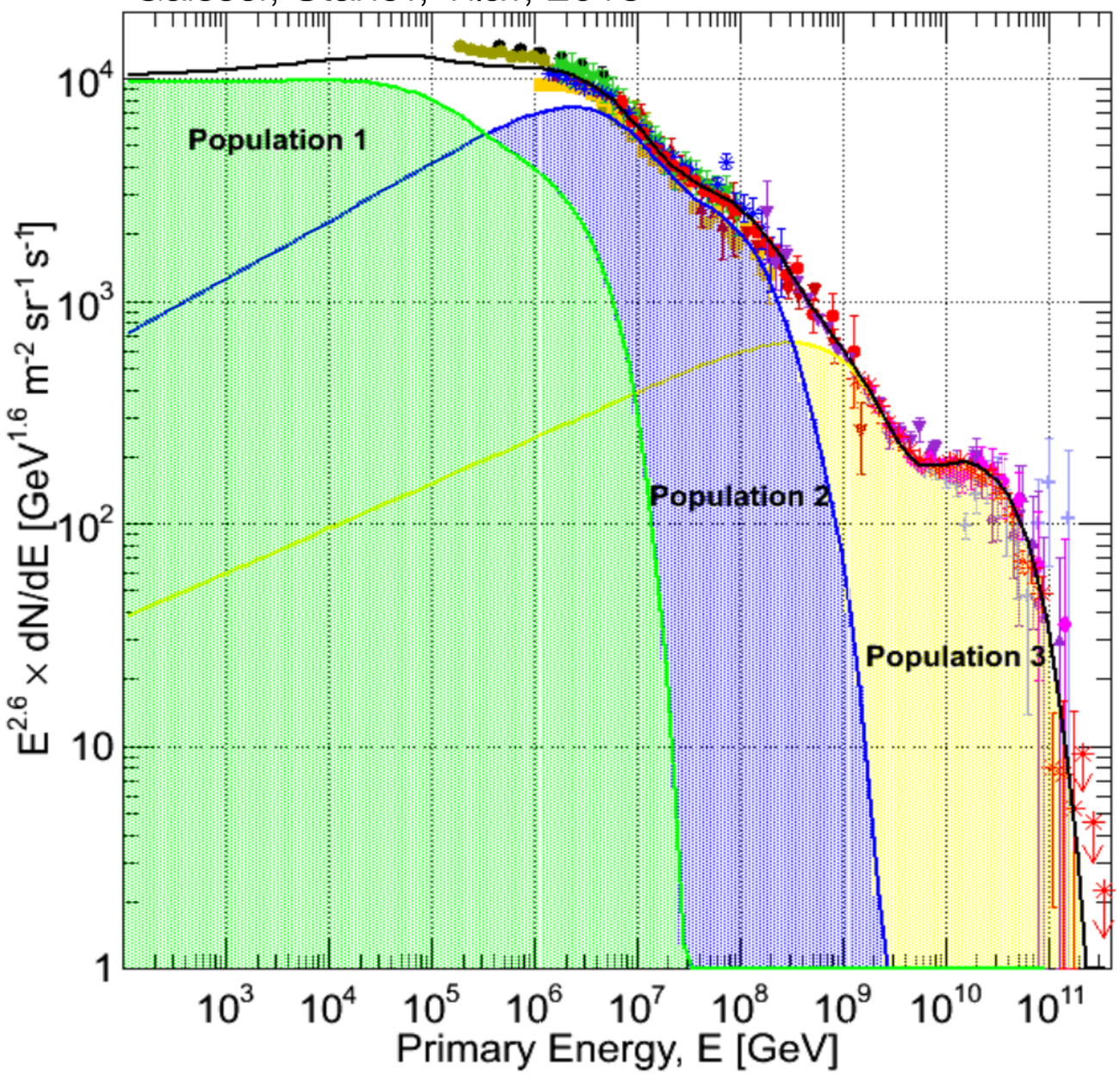
cosmic ray propagation in interstellar medium



- cosmic ray spectrum **shaped** by acceleration at the **source**

cosmic ray propagation in interstellar medium

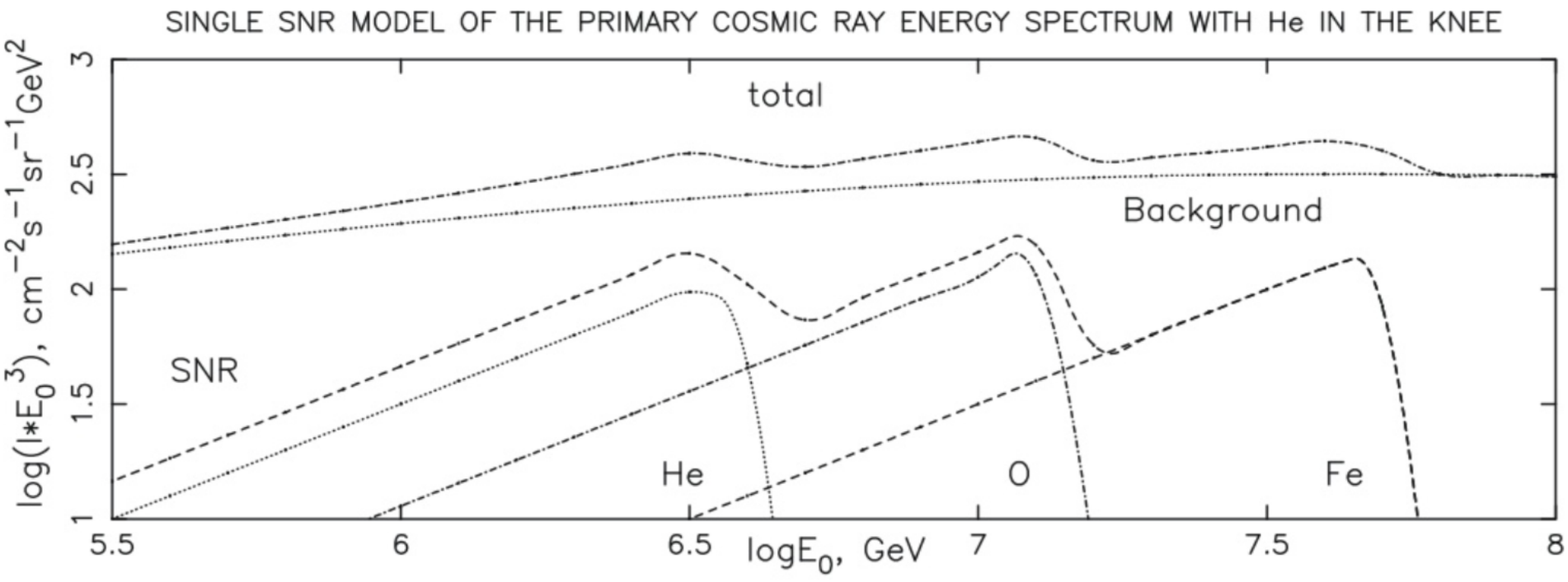
Gaisser, Stanev, Tilav, 2013



- cosmic ray spectrum **shaped** by acceleration at the **source**
- different **populations** of sources with different power (Peter's cycle)
- **hard** energy spectra cumulate to produce **softer** all-particle spectrum
- **knee** from transition of populations

cosmic ray propagation in interstellar medium

- cosmic ray spectrum **shaped** by a **single source** producing the knee

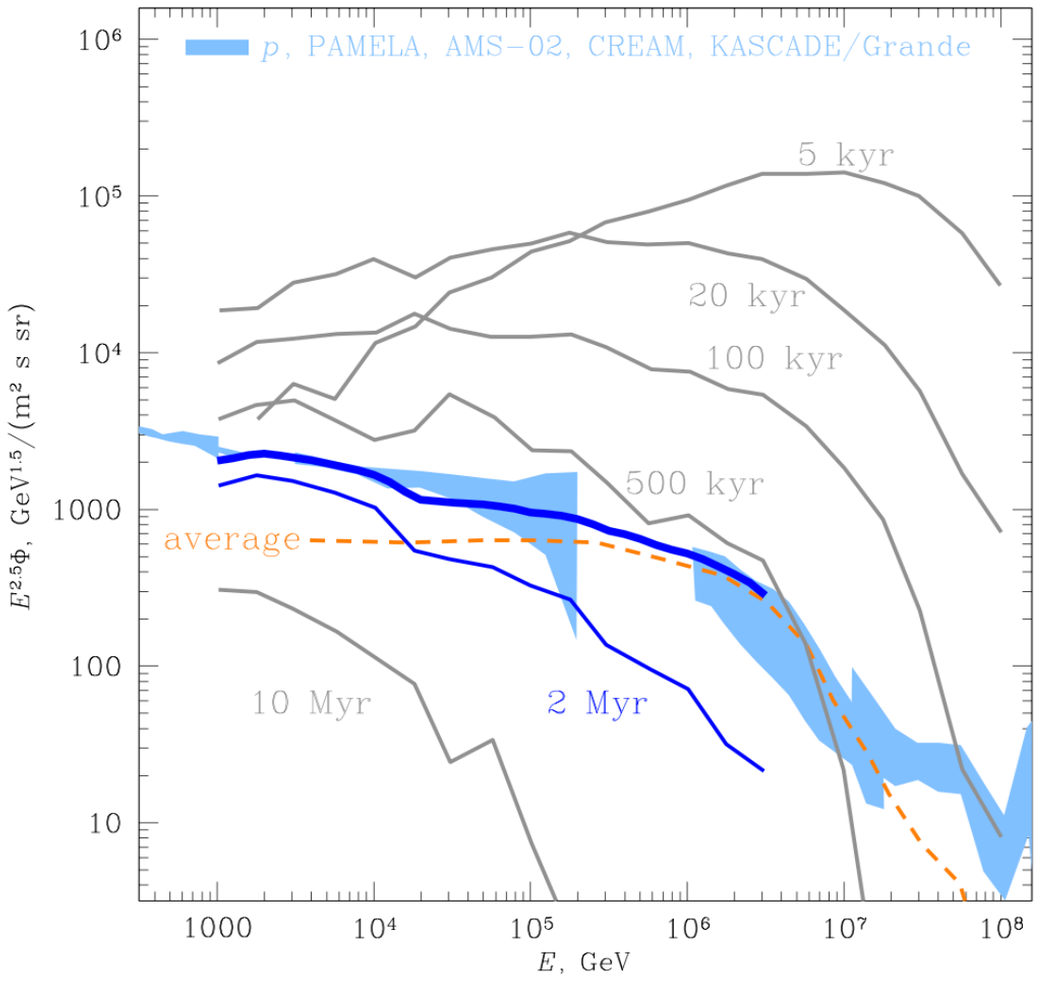


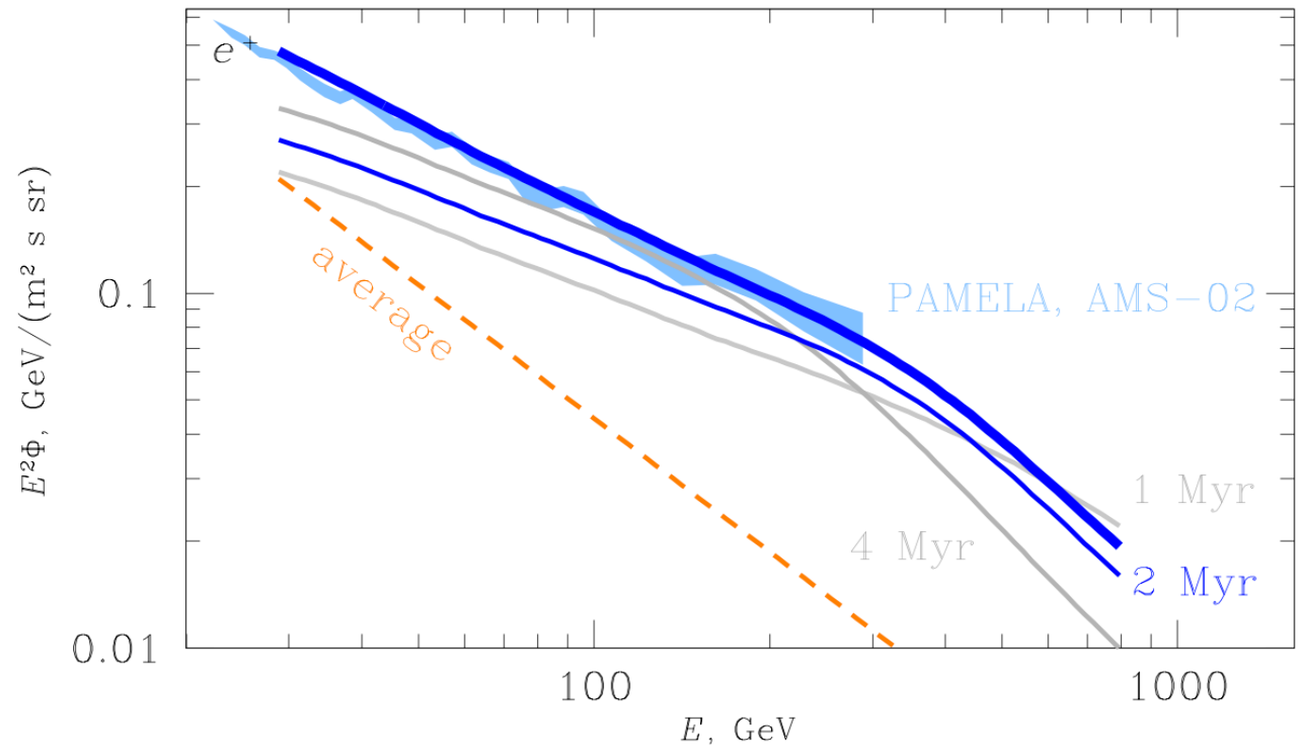
Erlykin, Wolfendale, 2006

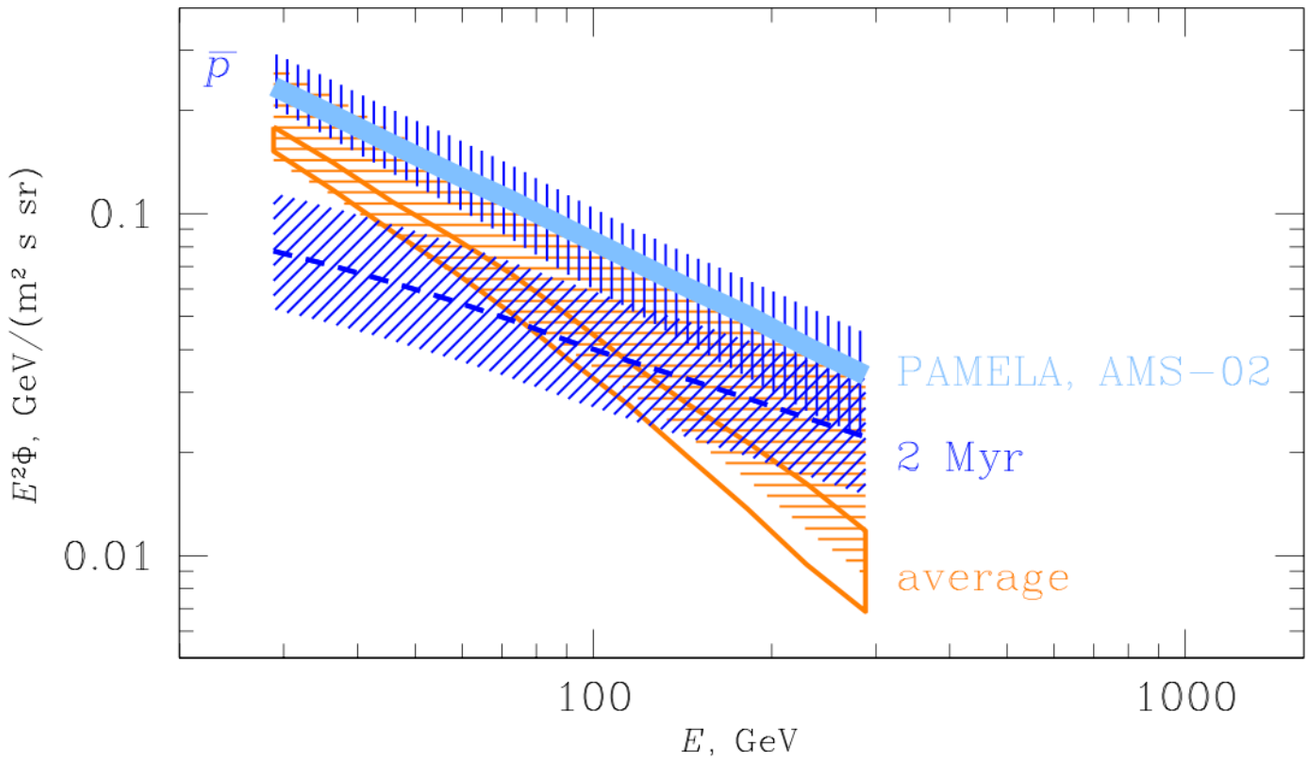
astrophysical neutrinos

2 million years old nearby supernova

Kachelriesß et al., 2015



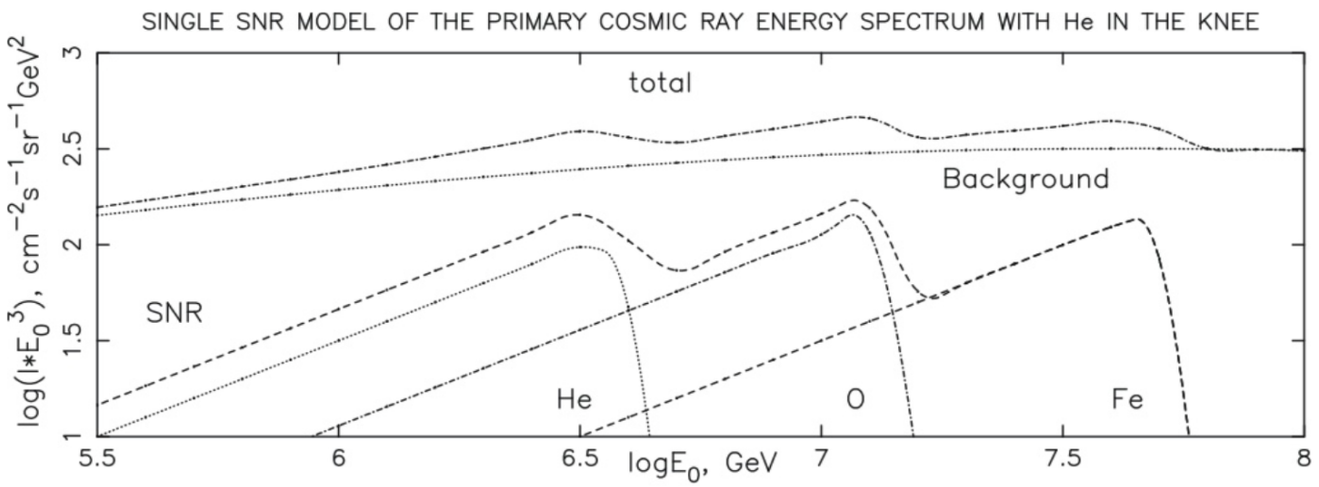




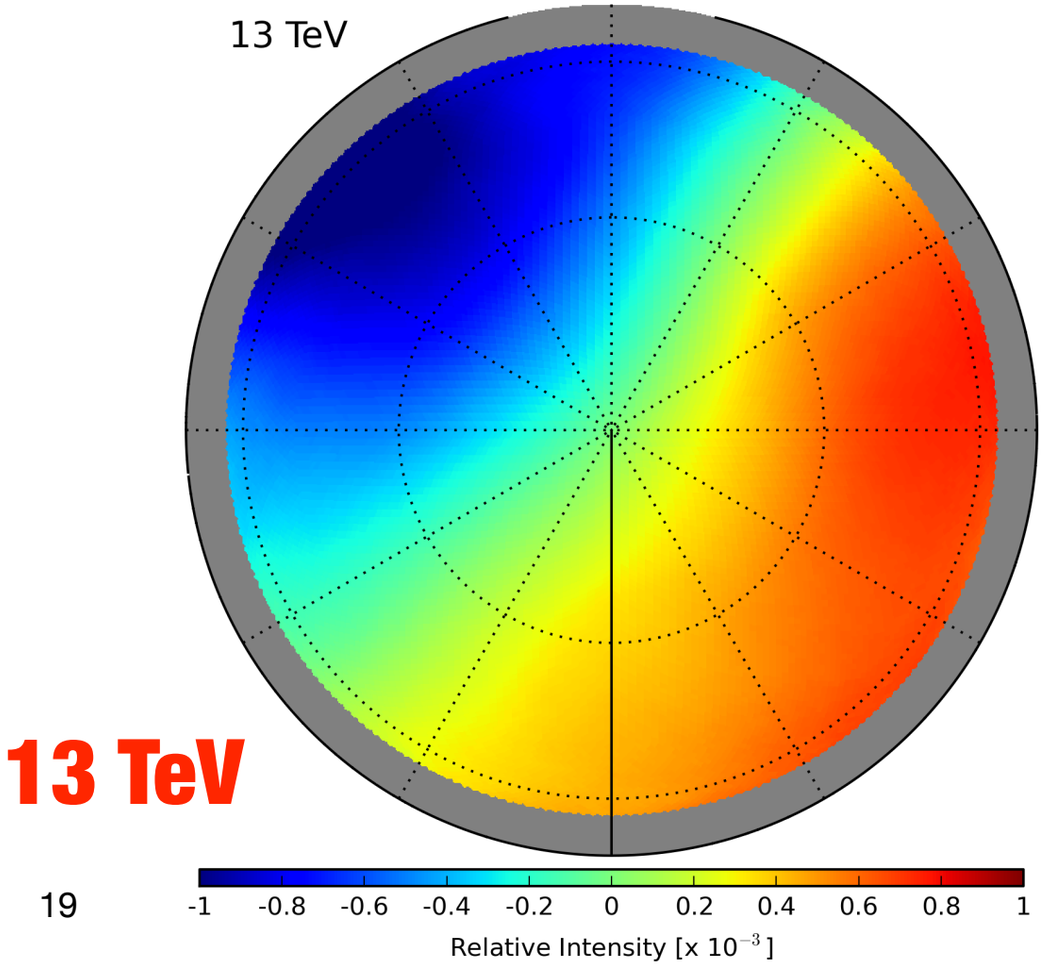
- 2 million years old supernova as the origin of the observed anomalies: **ANISOTROPY?**

cosmic ray propagation in interstellar medium

Erlykin, Wolfendale, 2006



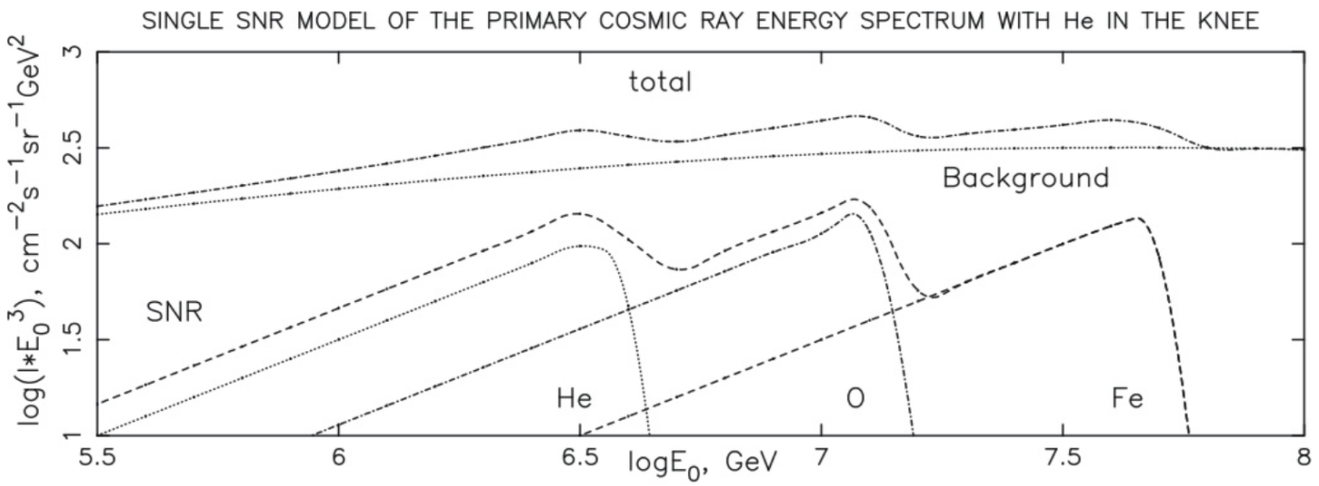
- cosmic ray spectrum **shaped** by a **single source** producing the knee

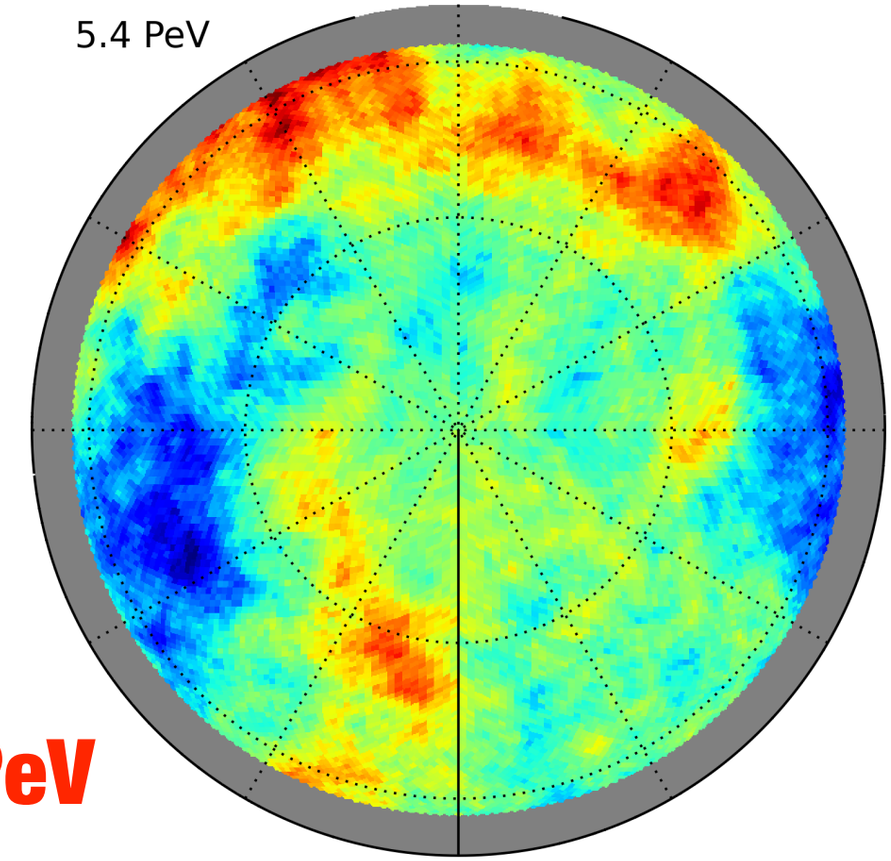


- **anisotropy** from the contributing source
- **evolution** of anisotropy with energy from changing relative contribution from different sources…
- …or from $\mathbf{B_{ISM}}$ at different distances ?
- energy dependence in **disagreement** with simple diffusion scenario

cosmic ray propagation in interstellar medium

Erlykin, Wolfendale, 2006





5.4 PeV

- cosmic ray spectrum **shaped** by a **single source** producing the knee
- **anisotropy** from the contributing source
- **evolution** of anisotropy with energy from changing relative contribution from different sources…
- …or from $\mathbf{B_{ISM}}$ at different distances ?
- energy dependence in **disagreement** with simple diffusion scenario

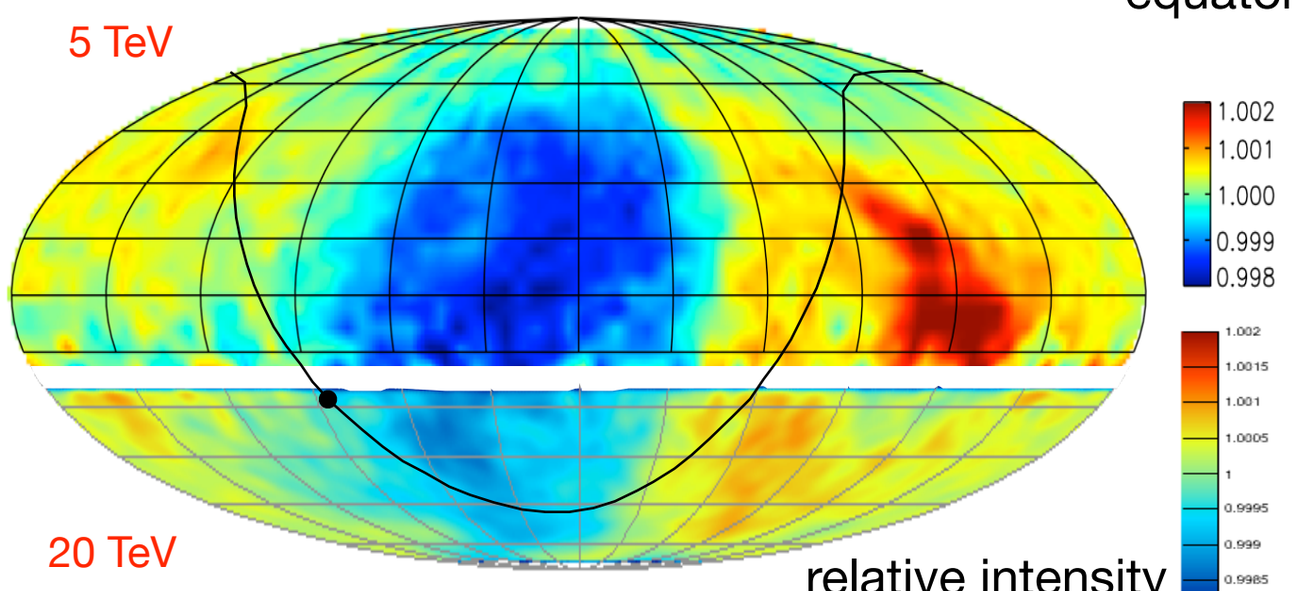
TeV sidereal anisotropy

Tibet-III

Amenomori et al., ICRC 2011

IceCube-59

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

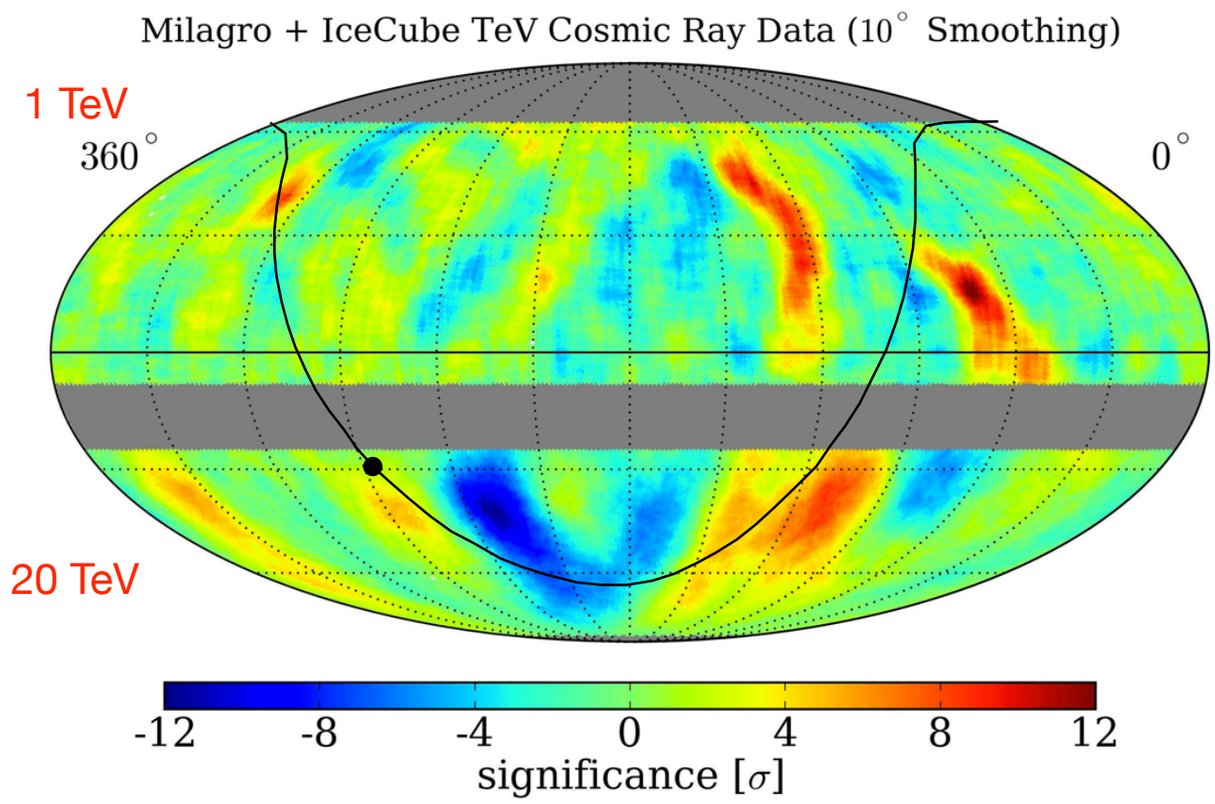


Milagro

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

IceCube-59

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

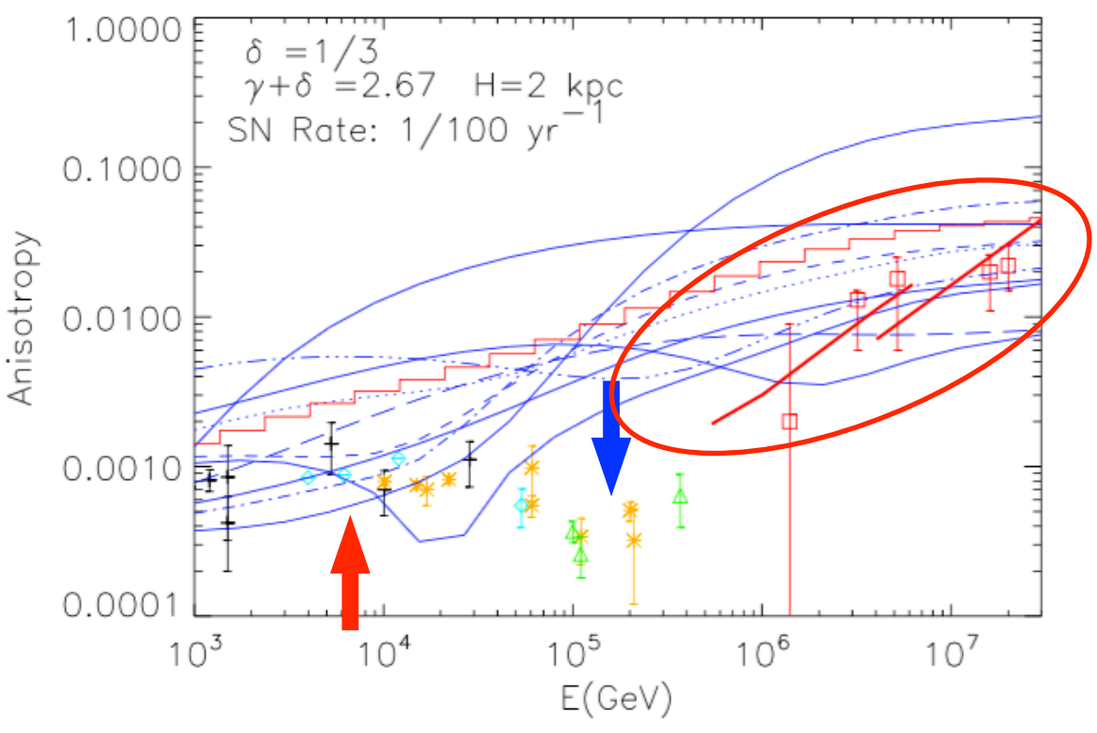


astrophysics of cosmic ray anisotropy
probing sources & propagation of cosmic rays ?

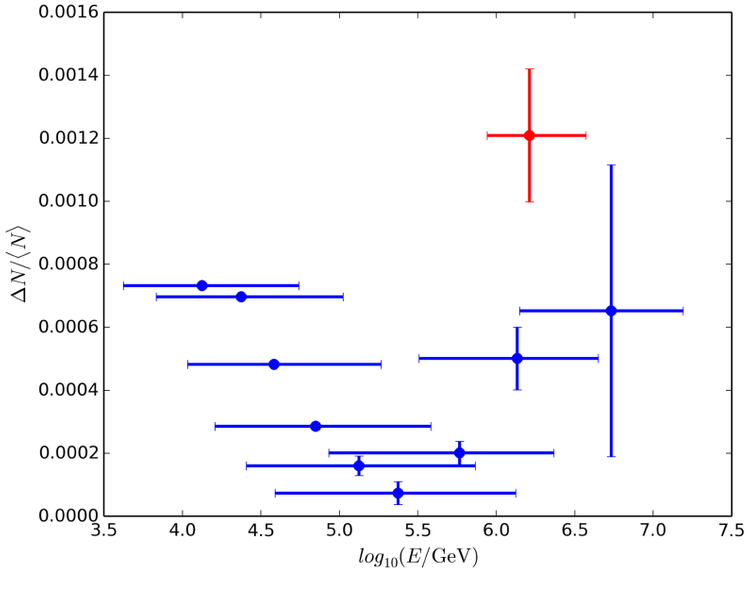
- stochastic effect of **nearby & recent sources** & temporal correlations

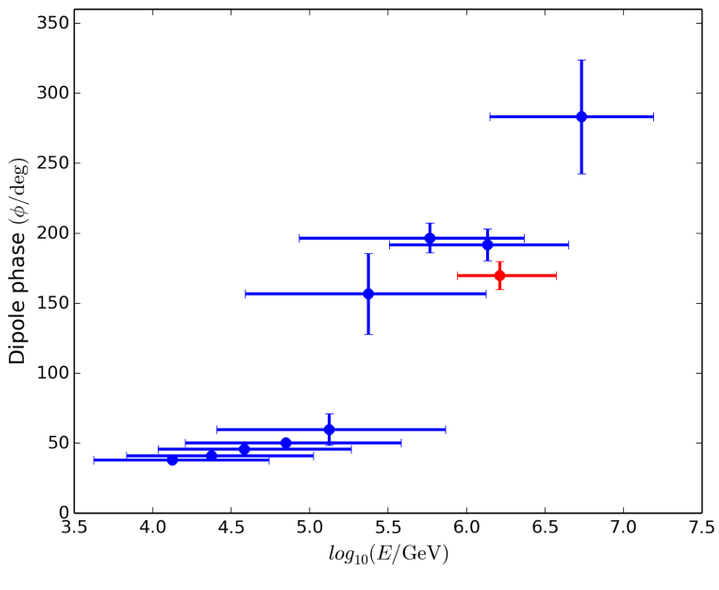
Erlykin & Wolfendale, Astropart. 2006
Blasi & Amato, 2011
Ptuskin+, 2012
Pohl & Eichler, 2012
Sveshnikova+, 2013
Kumar & Eichler, 2014
Mertsch & Funk, 2014

dipole amplitude **Blasi & Amato, 2011**



IceCube



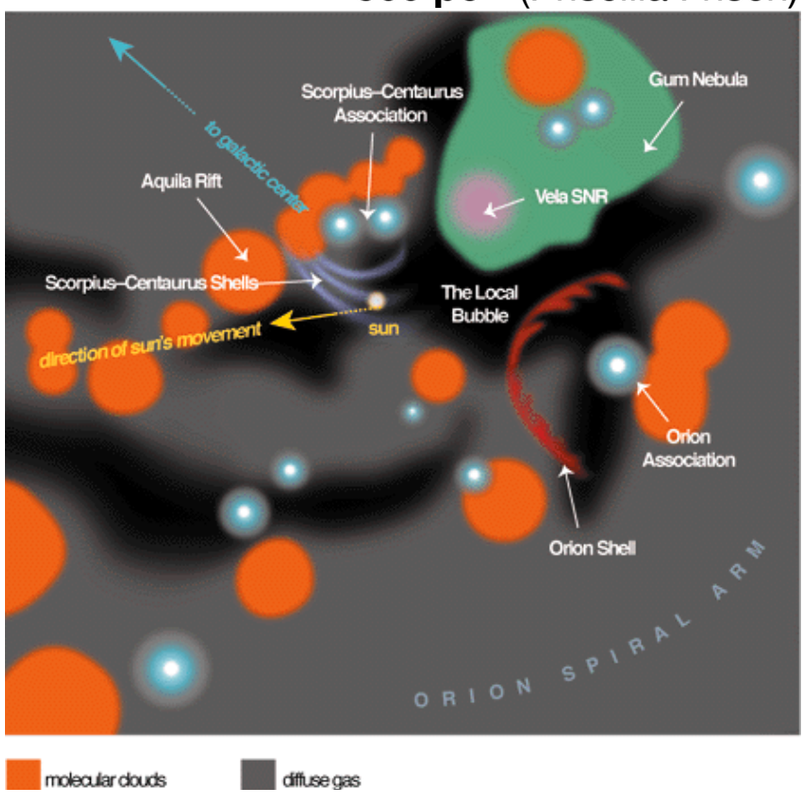


cosmic ray anisotropy
local interstellar medium

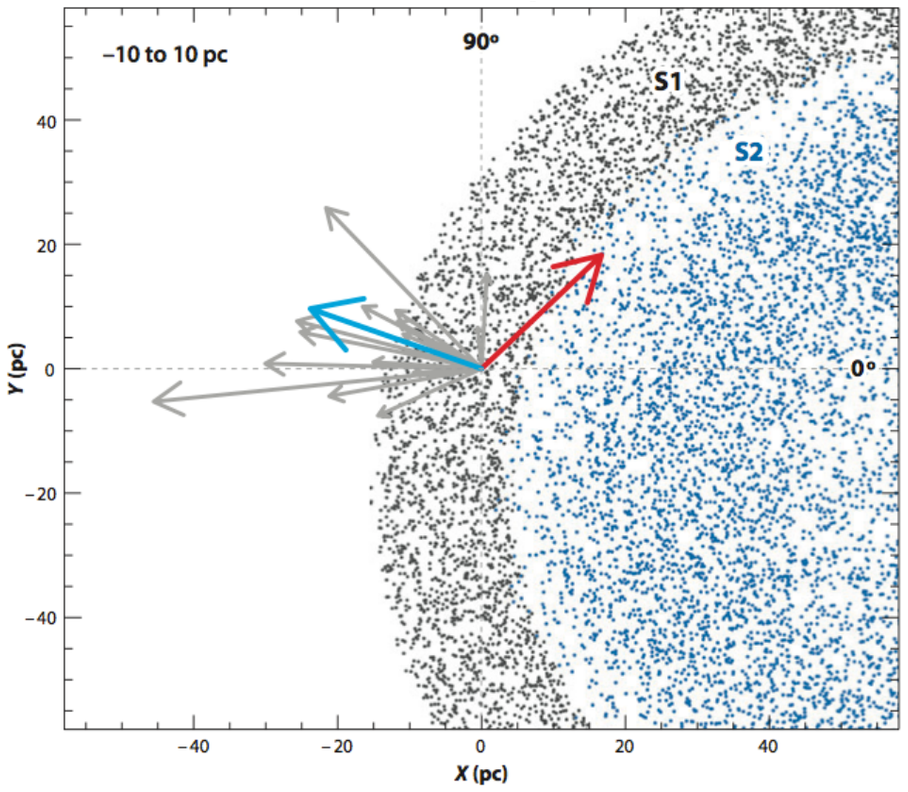
local ISMF shaped by LOOP I expansion sub-shell (with center ~60 pc away in Scorpius-Centaurus OB Association)

local cloudlets fragments of the shell moving at similar velocities

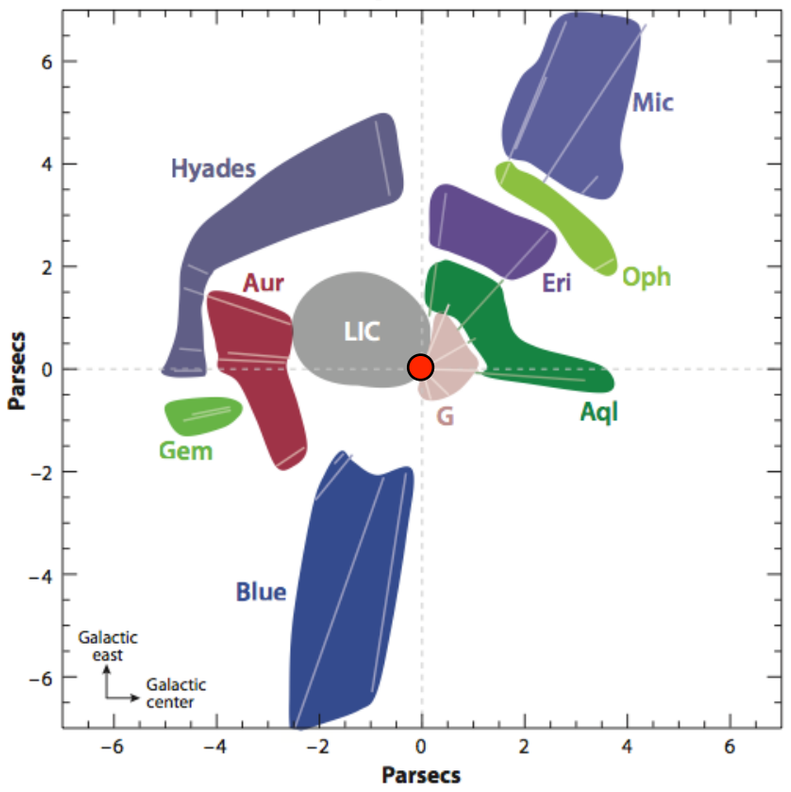
500 pc - (Priscilla Frisch)



100 pc - Wolleben, 2007



14 pc - Frisch+, 2011, 14



- interstellar magnetic field affected by inhomogeneities

  Redfield & Linsky, 2008

  Frisch+, 2011

- local ISMF relatively uniform over spacial scales of order 60-100 pc (**inter-arm**)

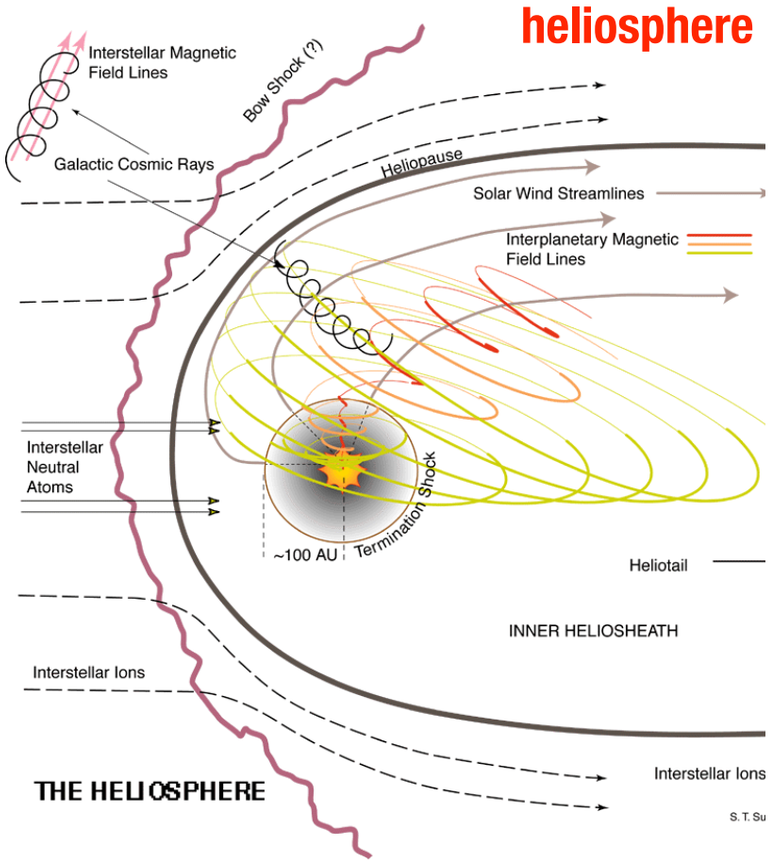
  Frisch+, 2012

- magnetic turbulence affects propagation and diffusion properties

  Giacalone & Jokipii, 1994, 99
  Yan, Lazarian, 2002,04,08

cosmic ray anisotropy
heliosphere

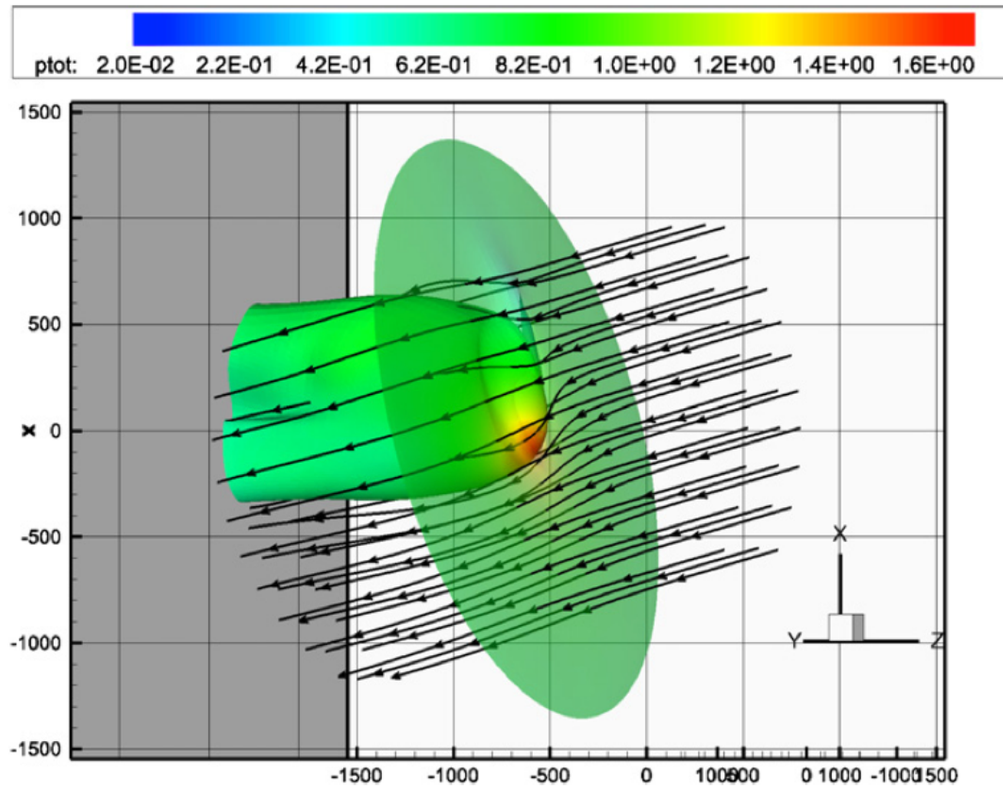
$$r_L \approx \frac{200}{Z} \frac{E(TeV)}{B(\mu G)} AU$$



heliotail

local ISMF draping around heliosphere

Pogorelov+ 2011

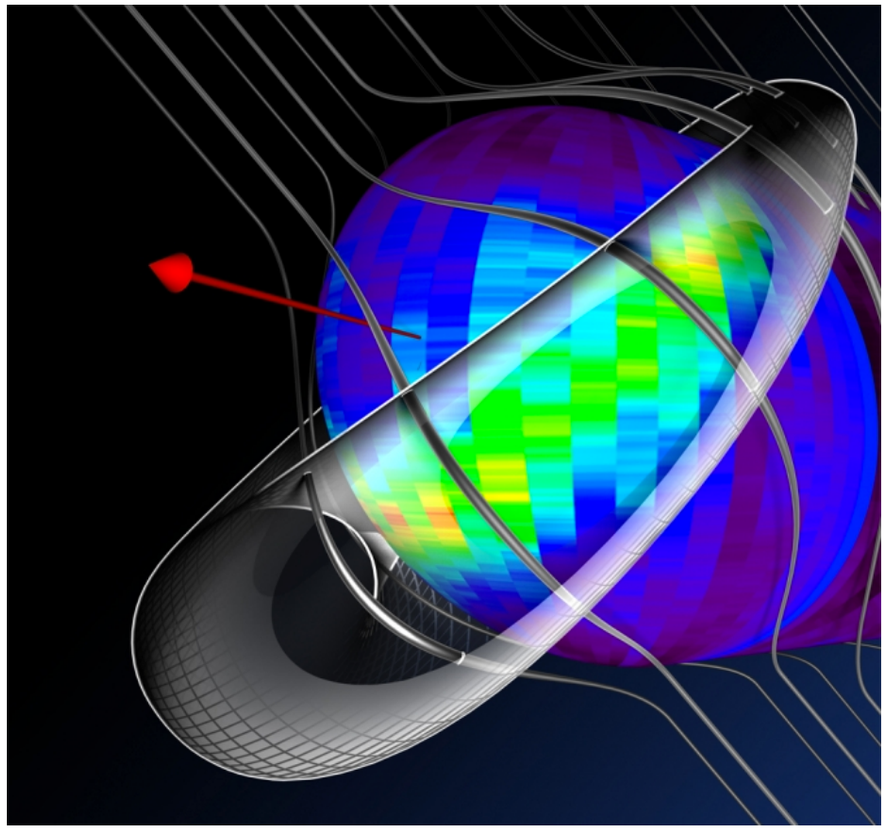


- heliosphere as O(100-1000) AU **magnetic perturbation of local ISMF** PD & Lazarian, 2013
- influence on ≲ 10 TeV protons ($R_L \lesssim 600$ AU)
- cosmic rays >100's TeV influenced by interstellar magnetic field (**change of anisotropy**)

anisotropy and local galactic environment

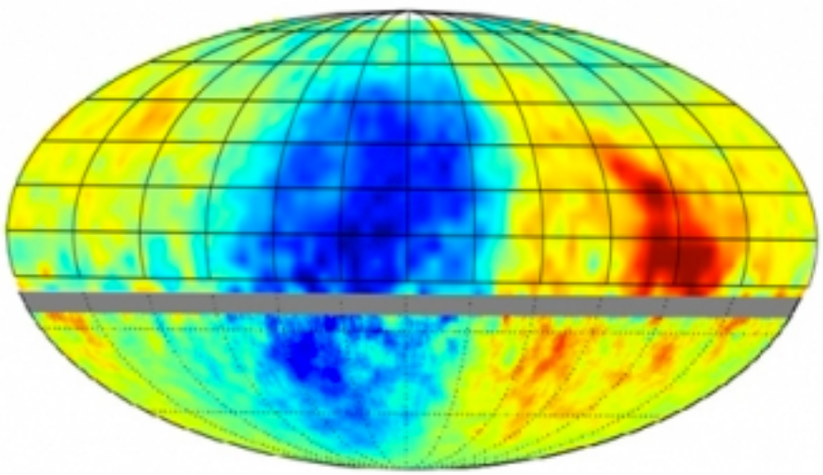
low to high energy connection

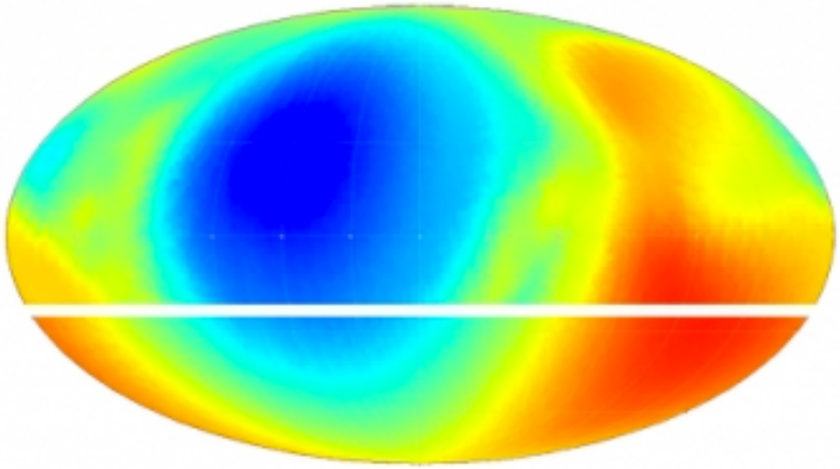
- IBEX observations of keV Energetic Neutral Atoms
- determination of interstellar flow direction
- determination of interstellar magnetic field direction



- large scale heliosphere to induce **perturbations** in arrival direction of TeV cosmic rays

Schwadron, Adams, Christian, PD, Frisch, Funsten, Jokipii, McComas, Möbius, Zank, Science, 1245026 (2014)

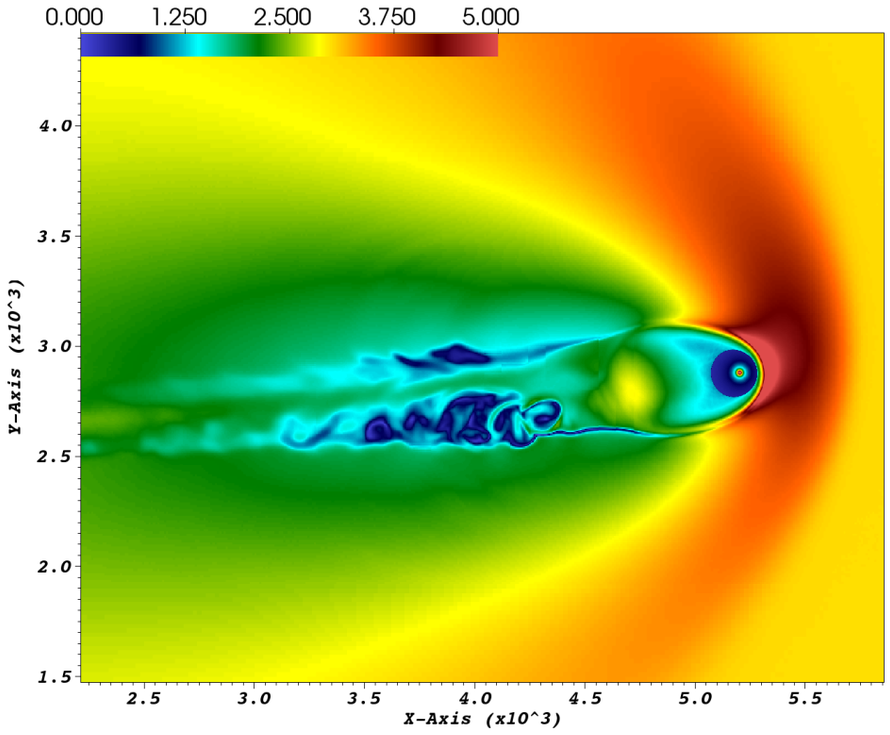




Zhang, Zuo & Pogorelov ApJ 790, 5 (2014)

cosmic ray anisotropy

probing heliospheric magnetic structure

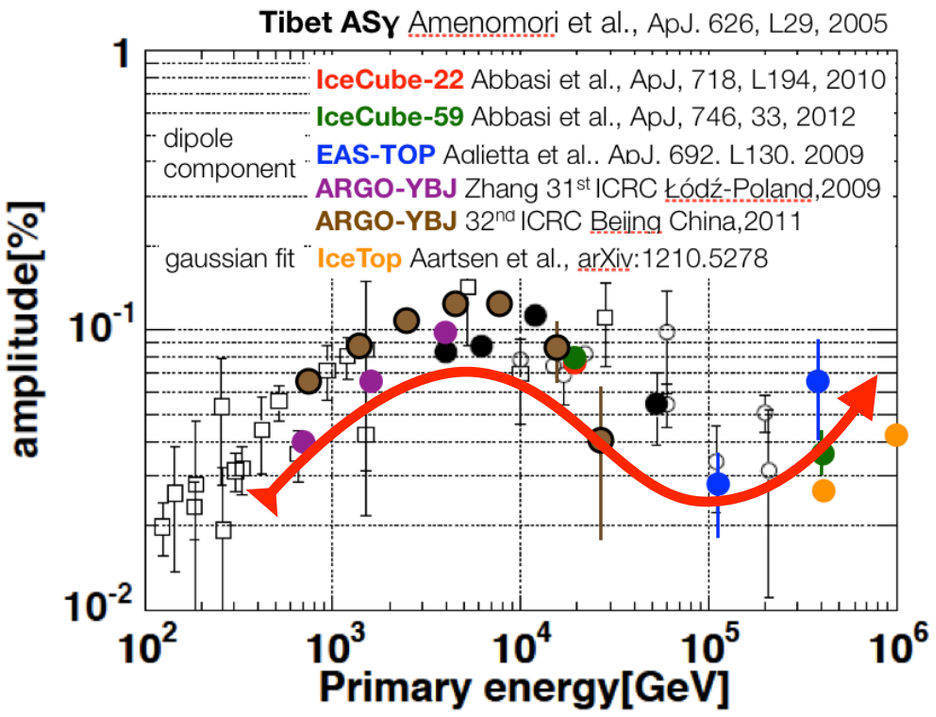


Borovikov, Heerikhuisen, Pogorelov

strong scattering effect from downstream instabilities on the flanks of heliotail

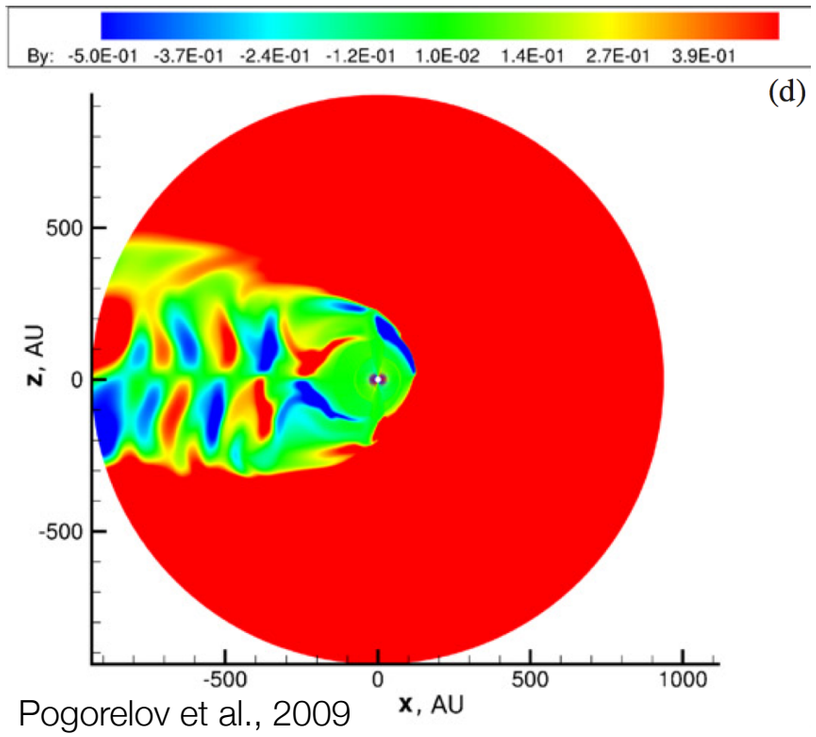
PD & Lazarian 2013

López-Barquero, Farber, Xu, PD, Lazarian, Pogorelov (in preparation)



small angular features from particle gradient distributions correlated with large scale heliospheric geometry

cosmic ray anisotropy
small scale anisotropy



Pogorelov et al., 2009

effects of magnetic polarity reversals from solar cycles

magnetic reconnection

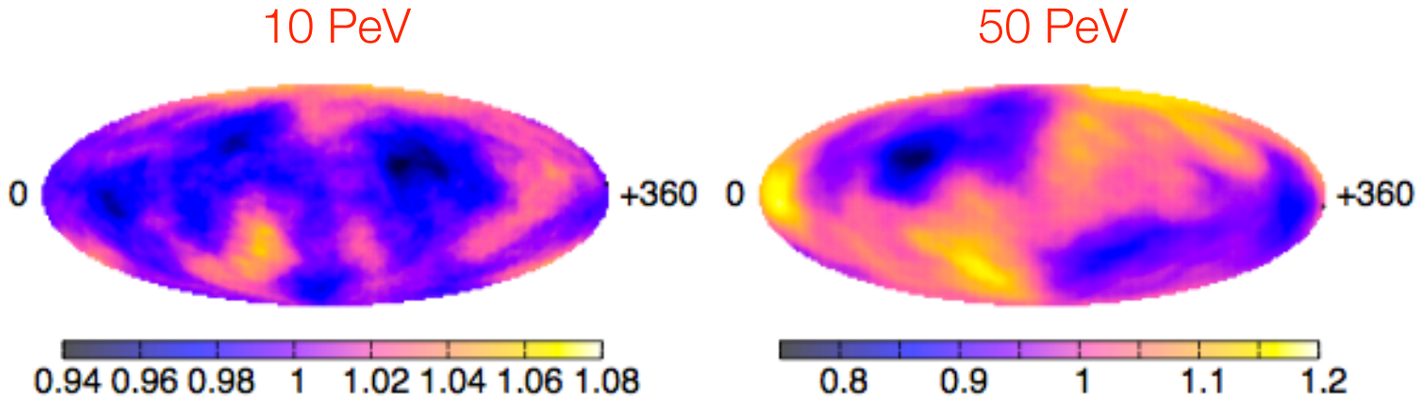
Lazarian & PD 2010
PD & Lazarian 2012

spectral features in some localized excess regions

anisotropy features from **dark matter** clumps Harding, 2013

Giacinti & Sigl, 2012

Biermann+, 2012



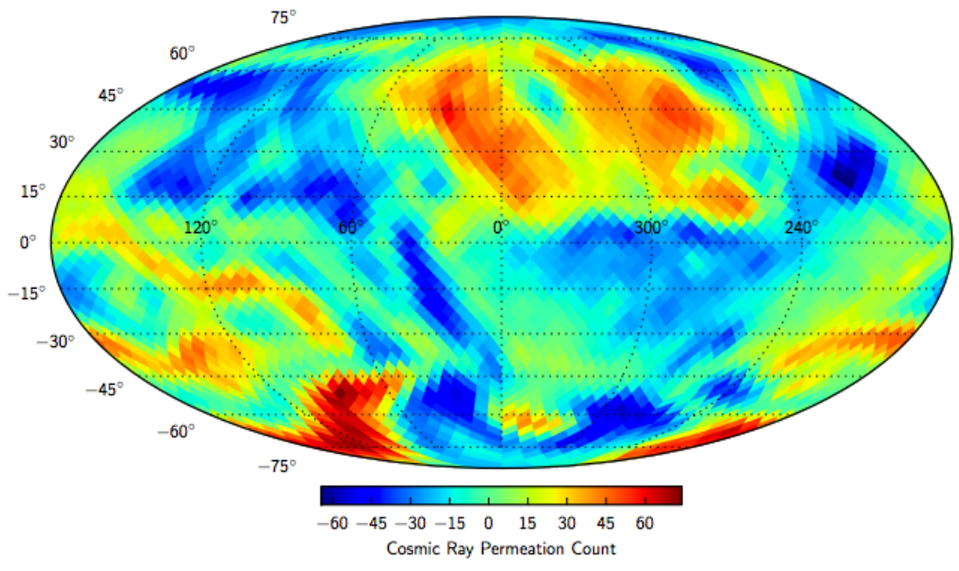
effects of **magnetic turbulence** on small angular scale distribution of cosmic ray arrival directions

cosmic ray anisotropy
small scale anisotropy

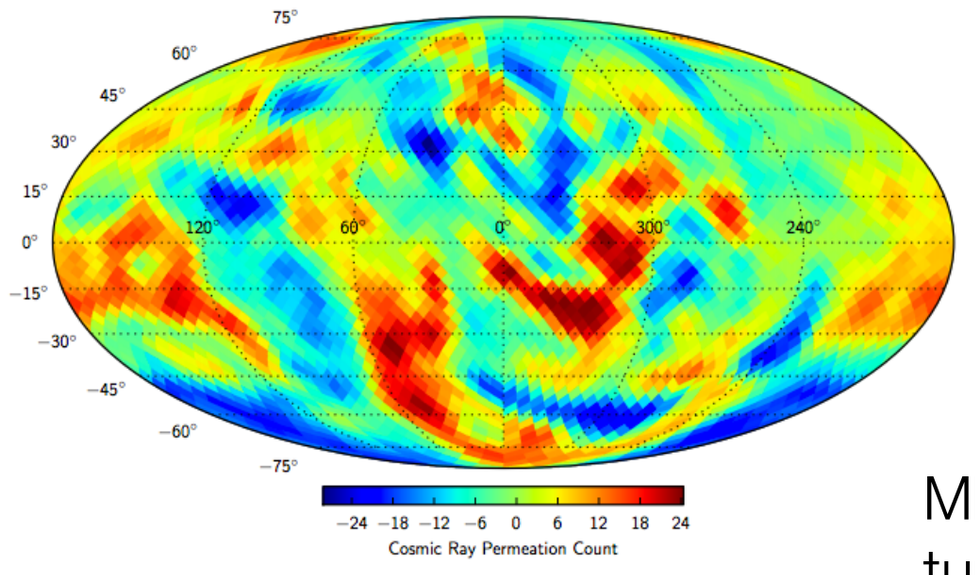
López-Barquero, Farber, Xu, PD, Lazarian (arXiv:1509.00892)

Ahlers, 2014

Ahlers & Mertsch, 2015

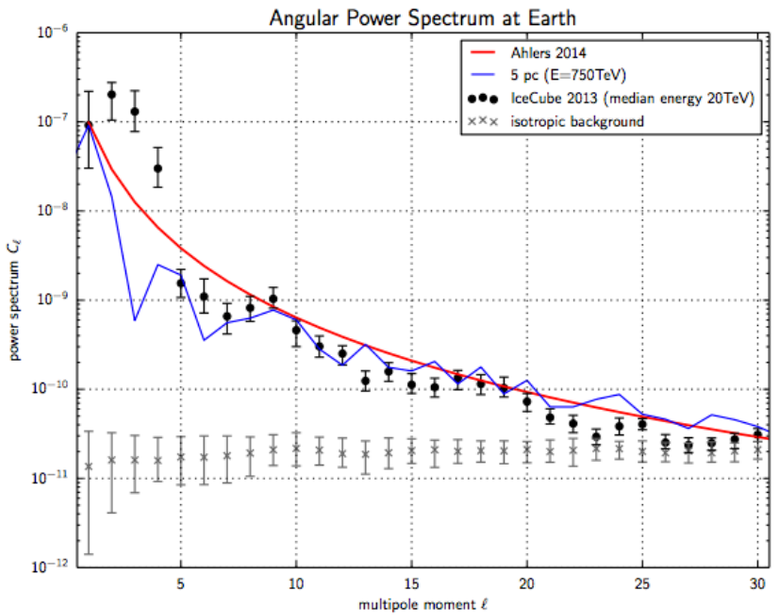


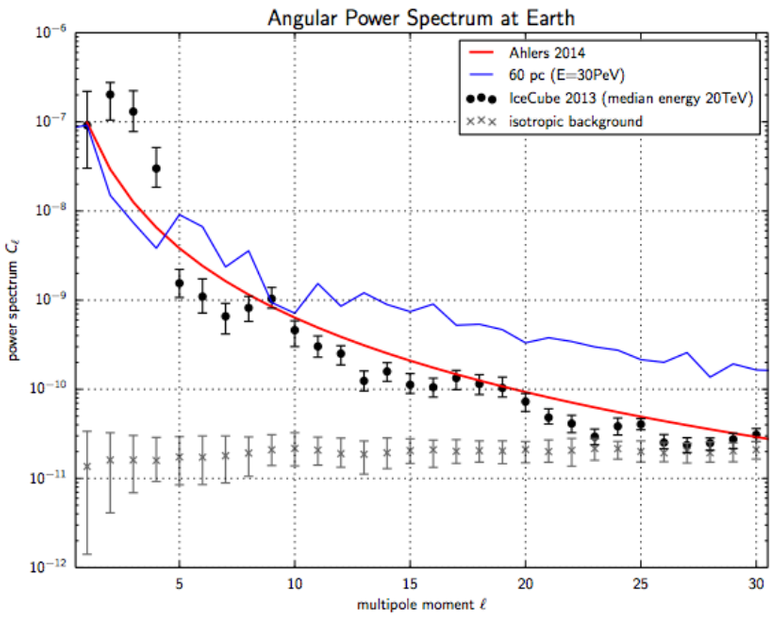
750 TeV



30 PeV

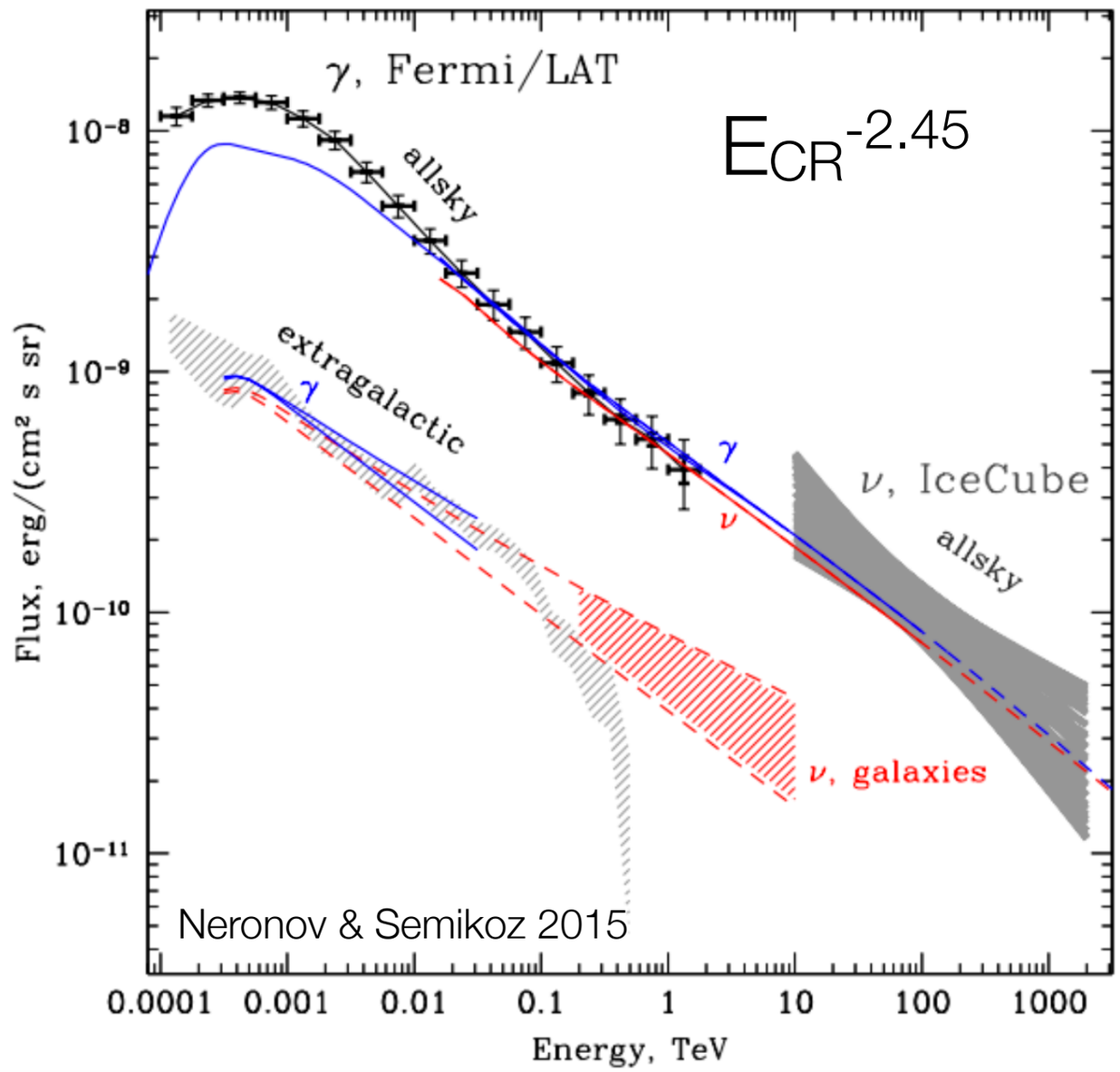
MHD compressible turbulence snapshot with dB/B ~ 0.7





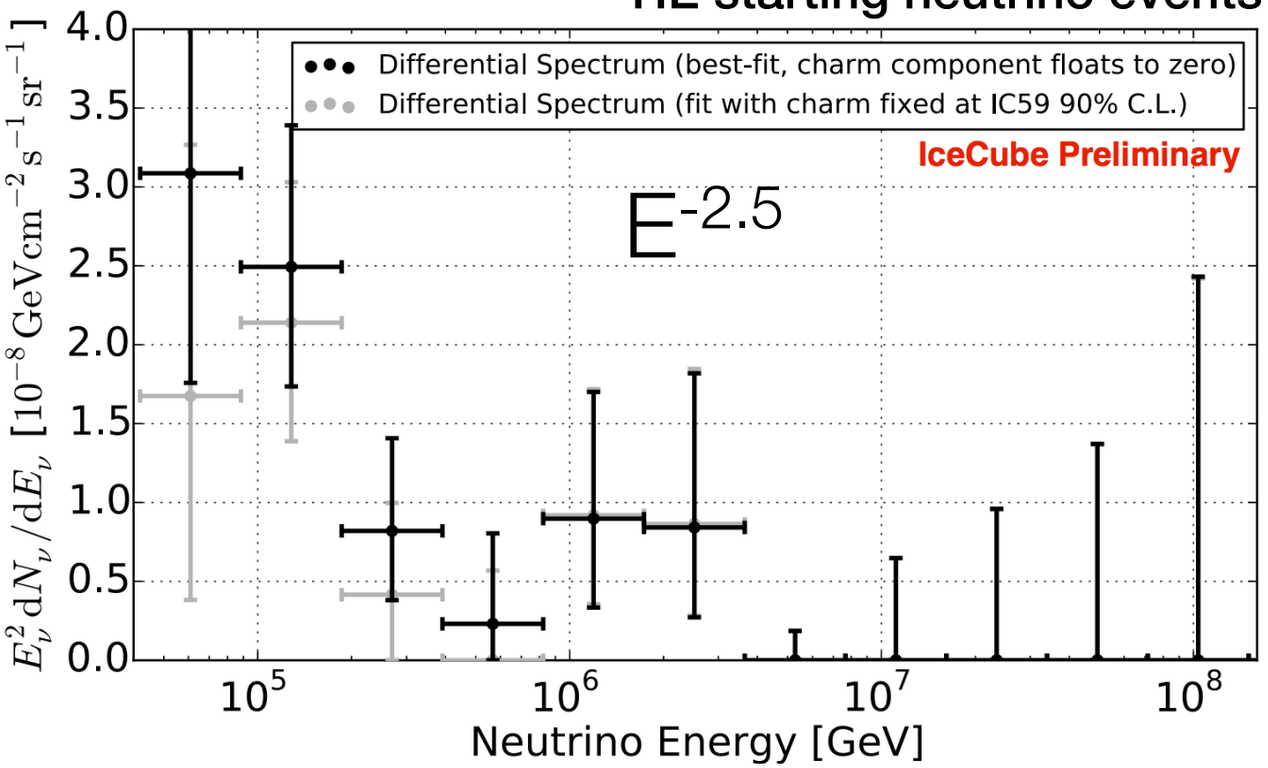
effects of **magnetic turbulence** on small angular scale distribution of cosmic ray arrival directions

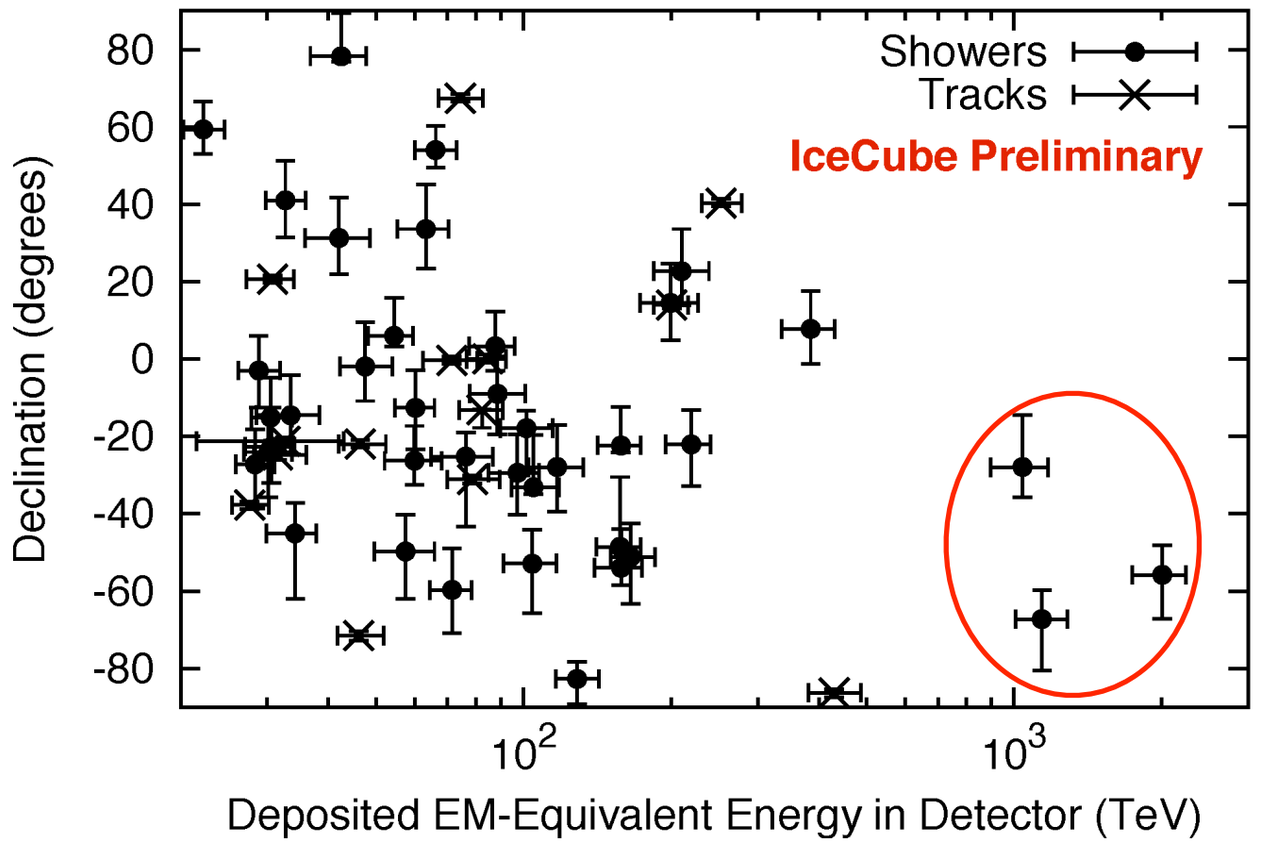
astrophysical neutrinos
galactic origin



galactic cosmic rays with cut-off of 10 PeV ?

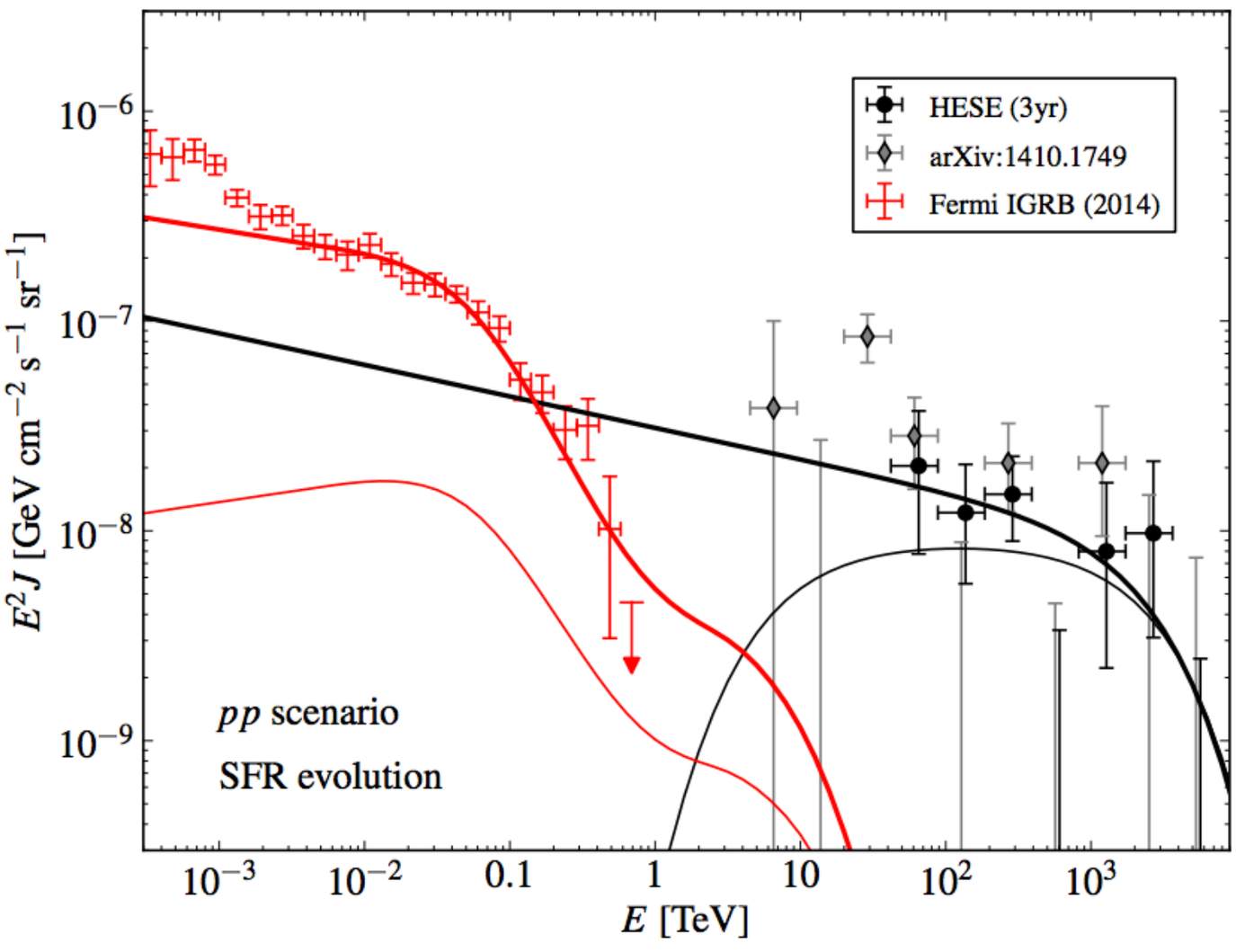
HE starting neutrino events





astrophysical neutrinos
extra-galactic origin

Murase et al., 2014



- γ-rays & ν's from pp interactions
- extra-galactic emission (cascaded in EBL): $E^{-2.1}$ - $E^{-2.2}$
- these cosmic ray sources contribute to 30%-40% of diffuse γ-ray background @100 GeV
- low energy tail of GeV-TeV neutrino/γ-ray spectra
- sources can be opaque in γ-ray
- ν to probe dense environments

astrophysical neutrinos
starburst galaxies ?

M. Ahlers

Messier 82

$$E^2\phi_\gamma(E) \simeq 3.3 \times 10^{-13} \left(\frac{E}{\text{TeV}}\right)^{-0.5} \frac{\text{TeV}}{\text{cm}^2\text{s}}$$

$$E^2\phi_\nu(E) \lesssim 3 \times 10^{-12} \frac{\text{TeV}}{\text{cm}^2\text{s}}$$

[IceCube 4yr]

NGC 253

$$E^2\phi_\gamma(E) \simeq 9.6 \times 10^{-13} \left(\frac{E}{\text{TeV}}\right)^{-0.14} \frac{\text{TeV}}{\text{cm}^2\text{s}}$$

no neutrino limit

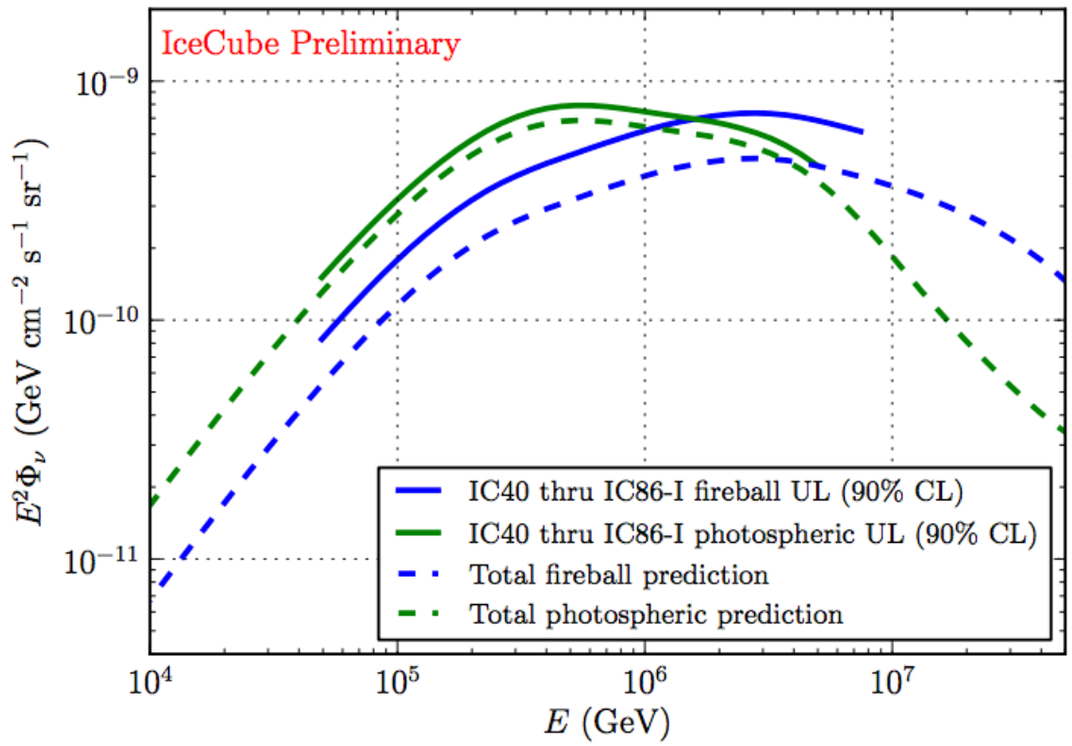
expected from *pp* interactions: $E_\nu^2 \phi_{\nu_\mu}(E_\nu) \simeq \frac{1}{2} E_\gamma^2 \phi_\gamma(E_\gamma)$

astrophysical neutrinos

other sources ? NOT GRB and blazars!

M. Ahlers

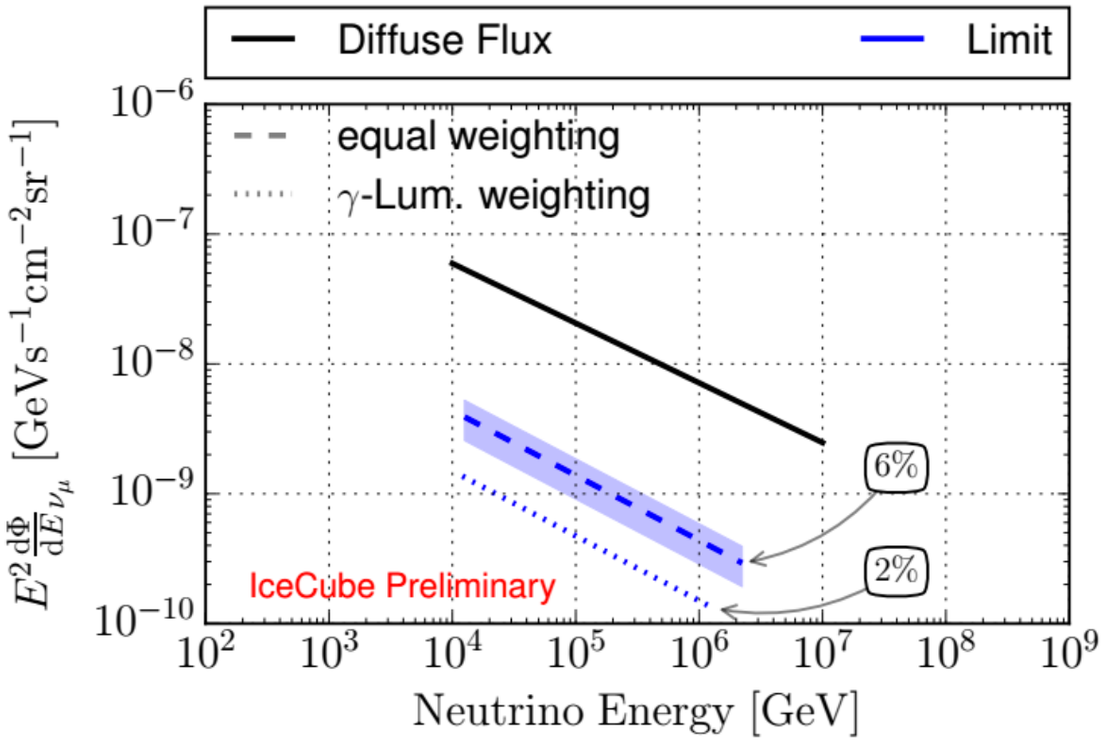
GRB Stacking



[M.Richman ICRC'13; arXiv:1412.6510]

- ν_μ emission following the GRB "fireball" model
- 492 GRBs (2008–2012) in IceCube's FoV reported with GCN and Fermi GBM

Blazar Stacking



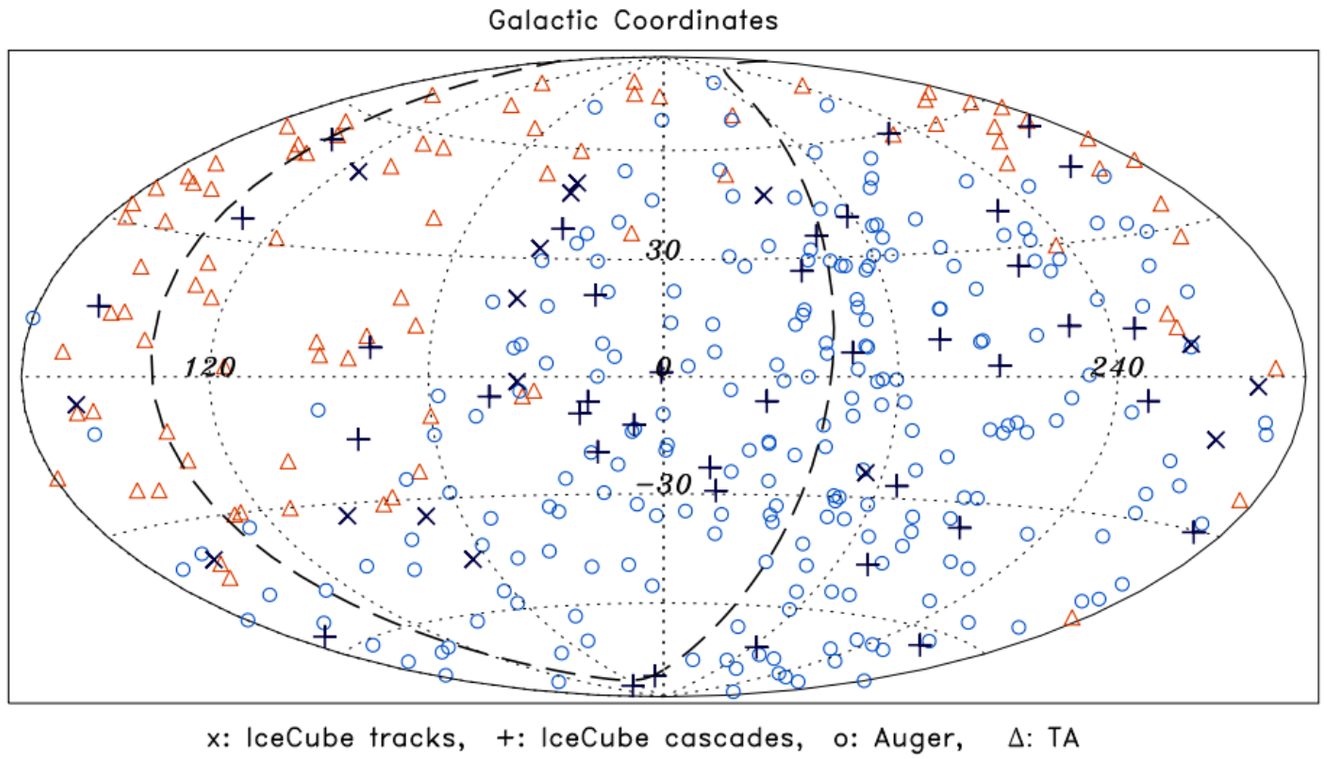
[Th.Gluesenkamp RICAP'14; arXiv:1502.03104]

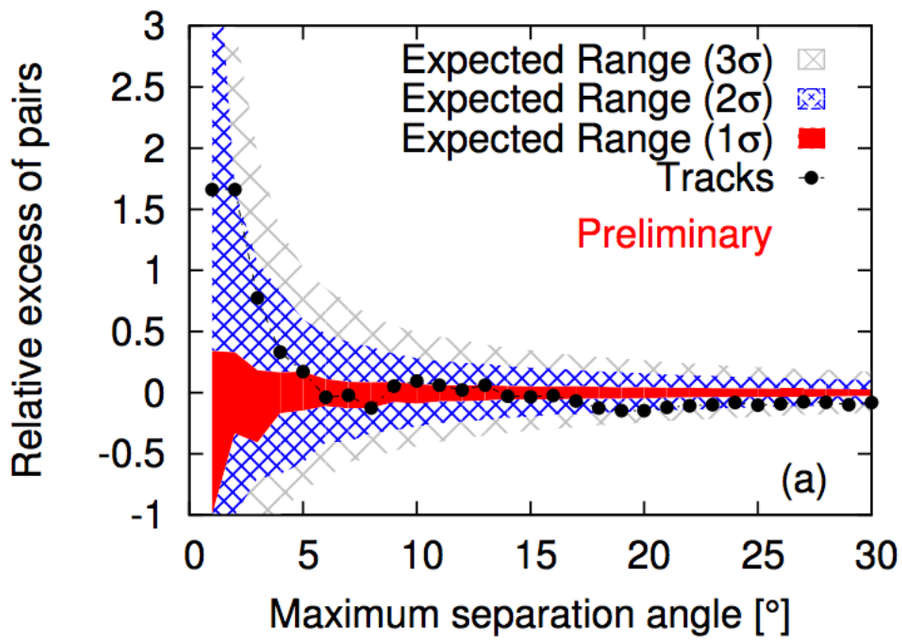
- Fermi blazar stacking
- plot shows limit on 310 FSRQ
- all 2LAC blazar limits of similar strength

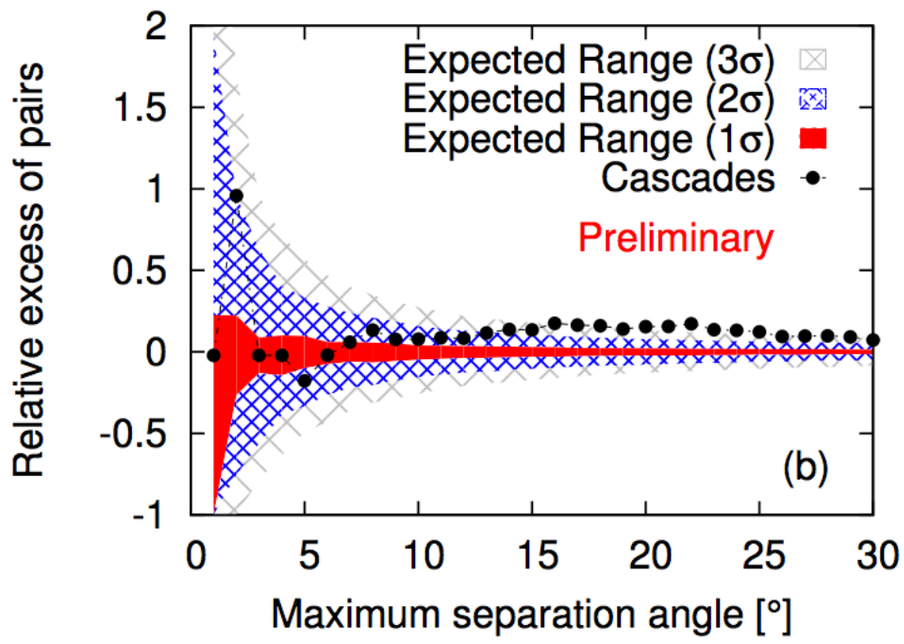
astrophysical neutrinos
correlations with UHECR from Auger ?

IceCube
Auger
TA

ICRC 2015

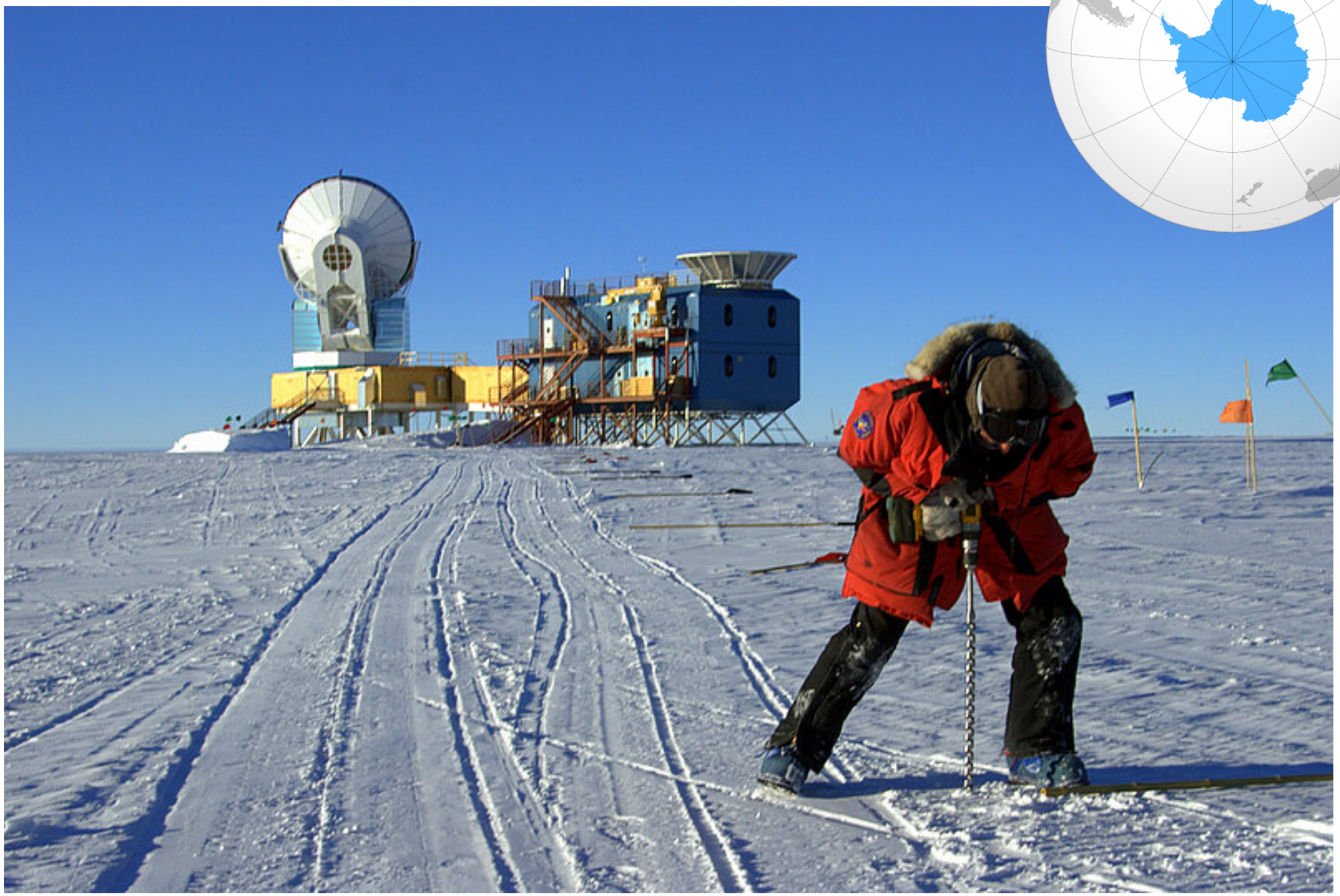






“life at the South Pole”

science
at the bottom of the World

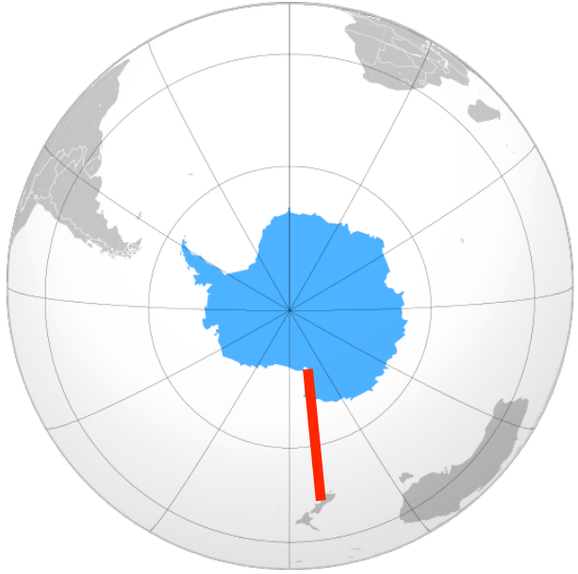


traveling
to the South Pole


Cape Reinga
NORTHLAND
Kaitaia
Paihia
Whangarei
Dargaville
Great Barrier Island
AUCKLAND
Auckland
THE COROMANDEL
Whitianga
BAY OF PLENTY
Tauranga
WAIKATO/
WAITOMO
Hamilton
Whakatane
Waitomo
Caves
ROTORUA
EASTLAND
Rotorua
LAKE TAUPO/
RUAPEHU
Gisborne
Taupo
TARANAKI/
WANGANUI
New Plymouth
Napier
Wanganui
HAWKE'S BAY
RANGITIKEI/
HOROWHENUA/
MANAWATU/
TARARUA
Palmerston North
NELSON
Collingwood
Masterton
Nelson
Picton
WELLINGTON/
WAIRARAPA
Wellington
Westport
Blenheim
MARLBOROUGH
Greymouth
Kaikoura
WEST COAST
Hanmer Springs
Franz Josef
Mt Hutt
CHRISTCHURCH &
CANTERBURY
Haast
SOUTHERN
LAKES
Lake
Tekapo
Geraldine
Timaru
Milford
Sound
Wanaka
Queenstown
Oamaru
Alexandra
Te Anau
Dunedin
Gore
OTAGO &
SOUTHLAND
Invercargill
Stewart Island

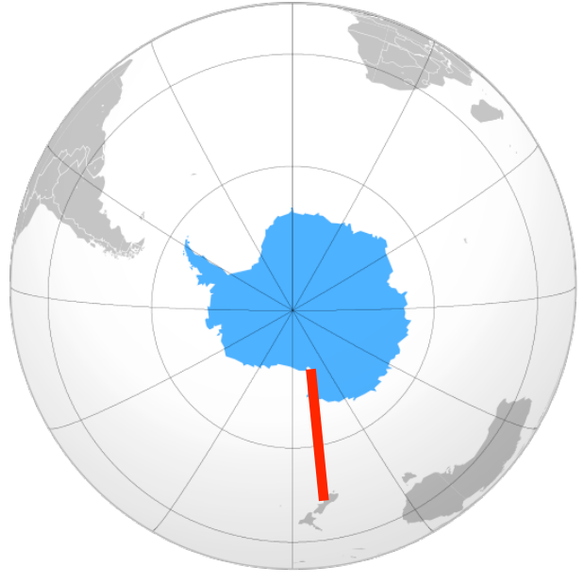

in Christchurch

traveling to the South Pole



in Christchurch

traveling to the South Pole

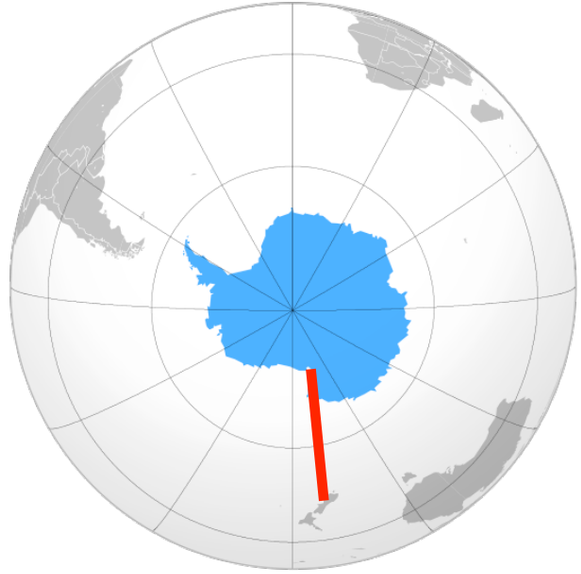


taking off ...

… and relaxing

traveling to the South Pole

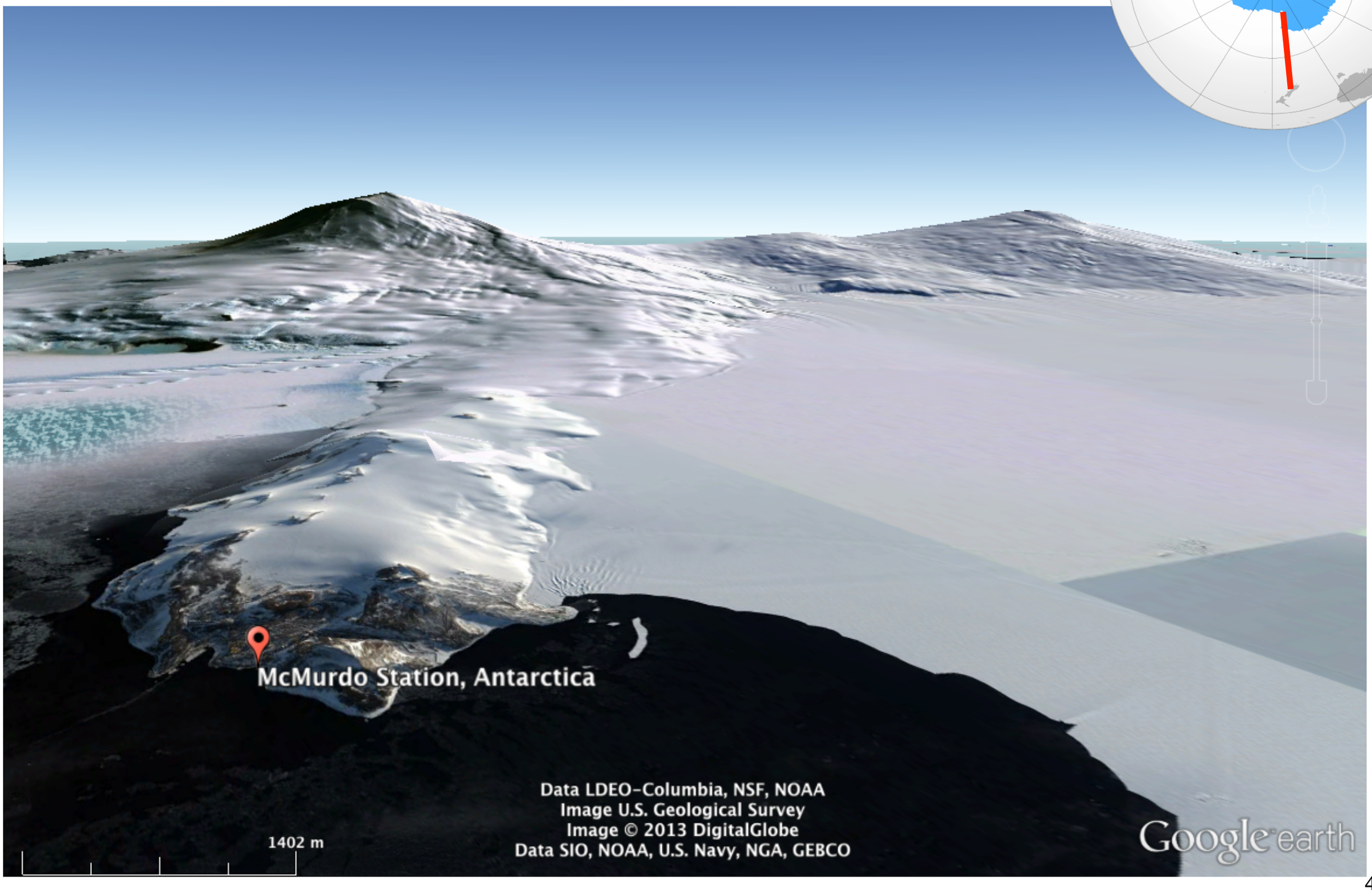
arriving in McMurdo ...




© Carol Walker / naturepl.com


Photo: Glenn Browning

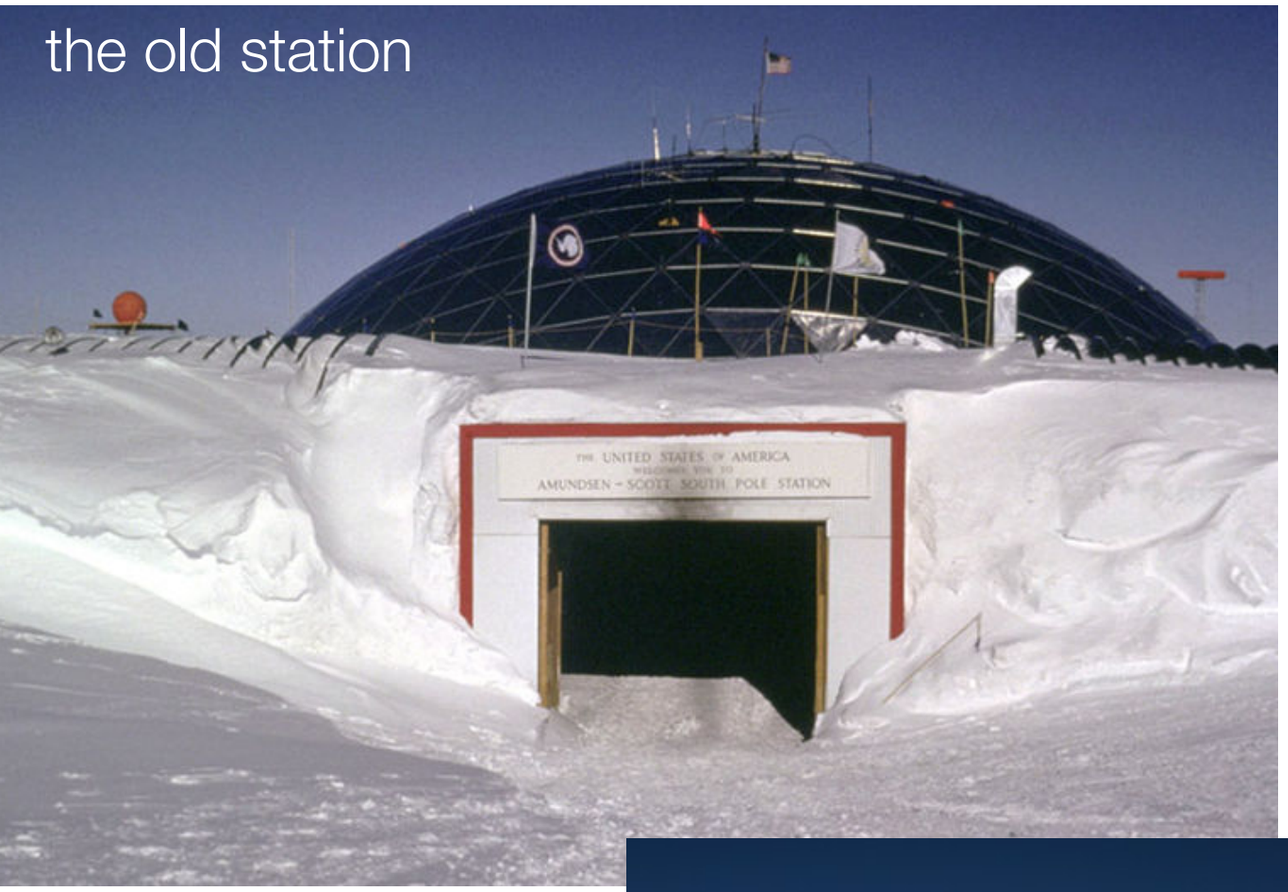
traveling to the South Pole



traveling to the South Pole

arriving to the South Pole

arriving to the South Pole

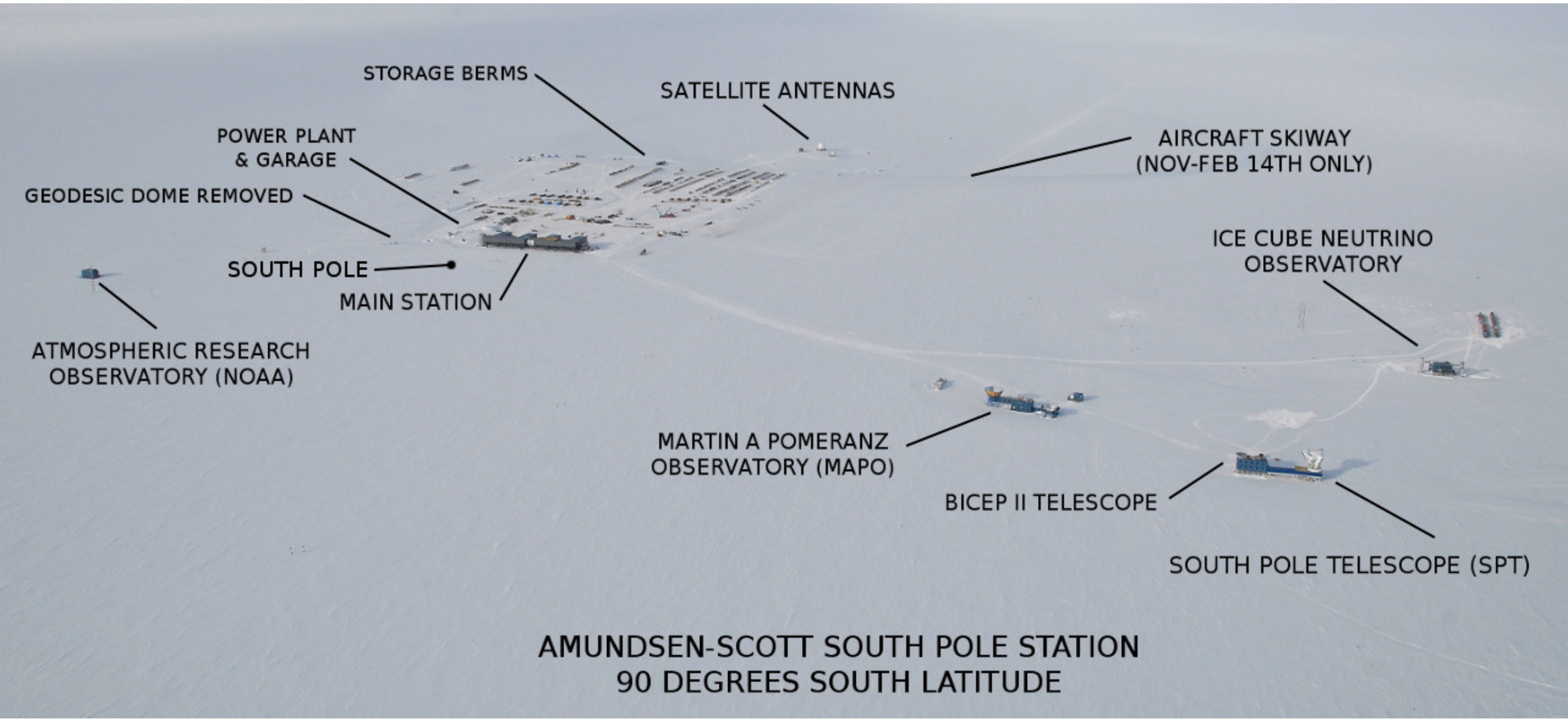


the old station


under the Dome

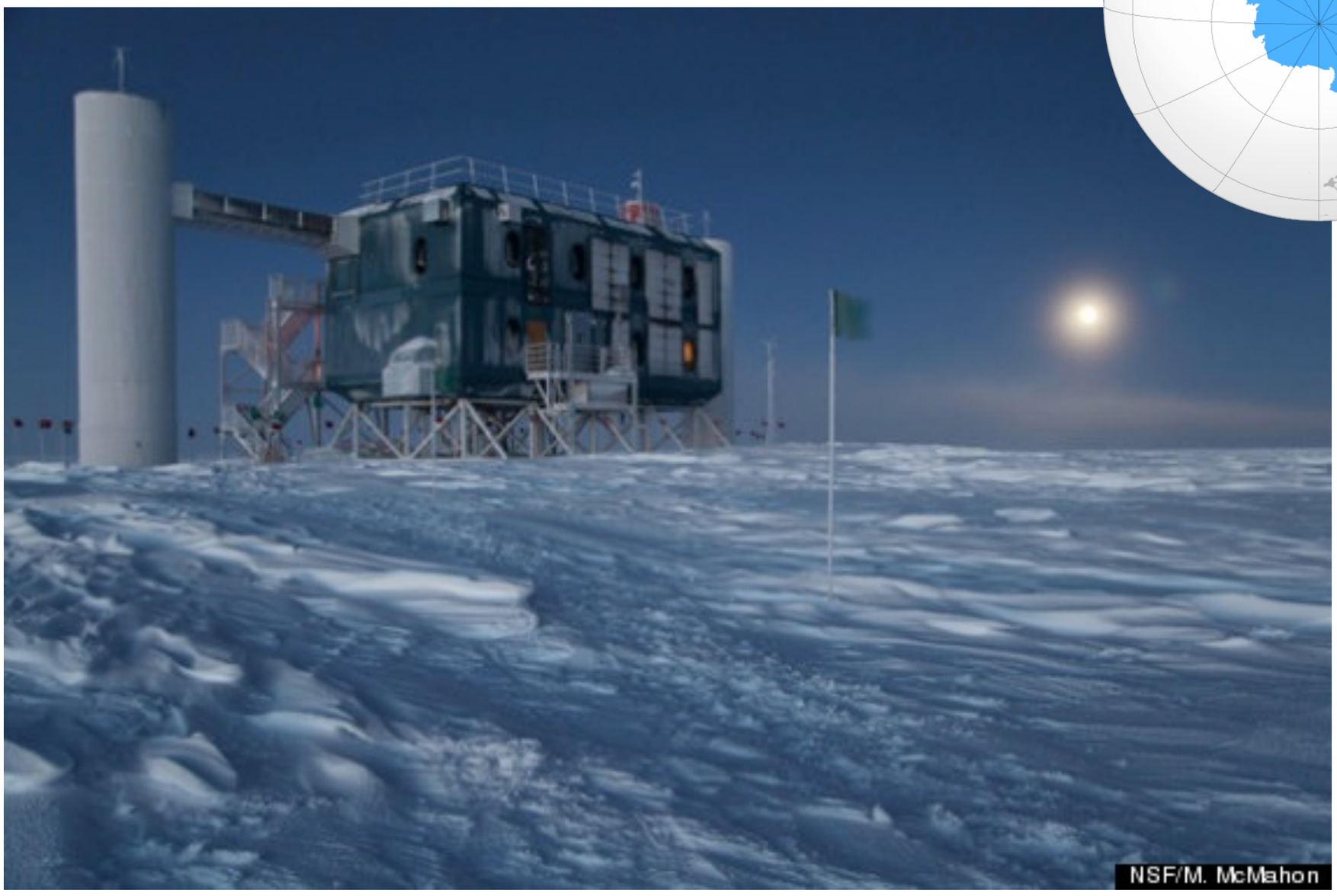
the new station

arriving to the South Pole

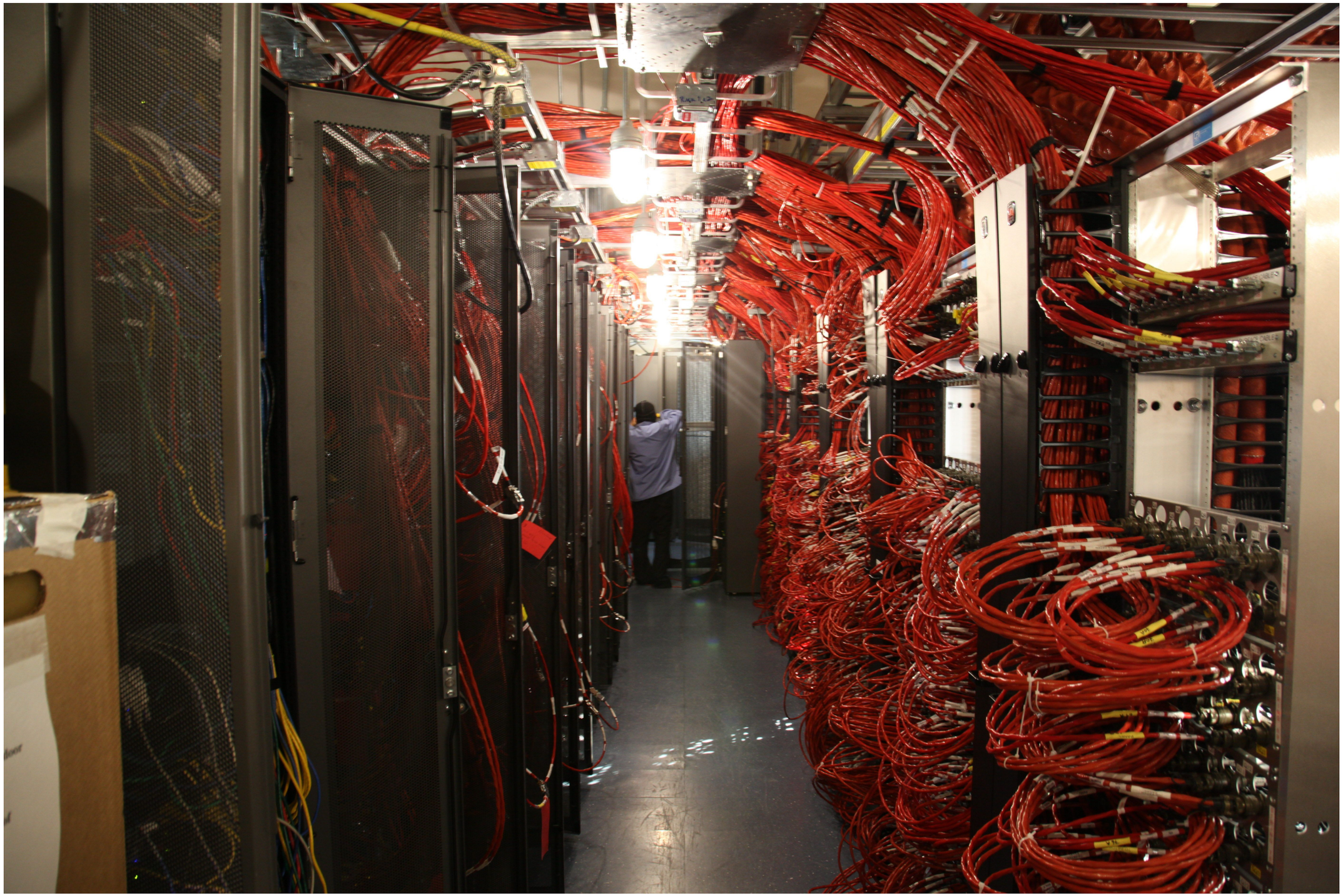


living
at the South Pole

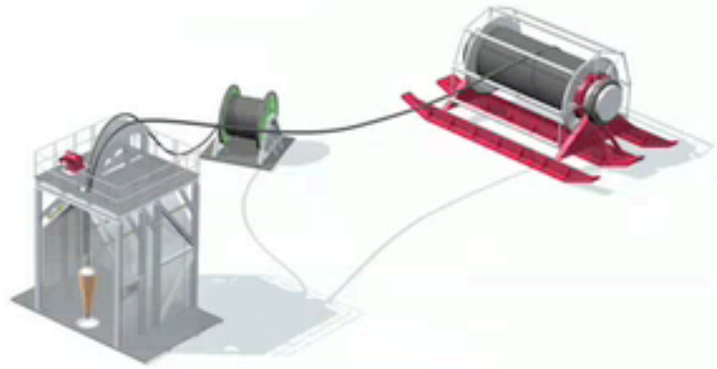
how do we investigate the origin of cosmic rays ?



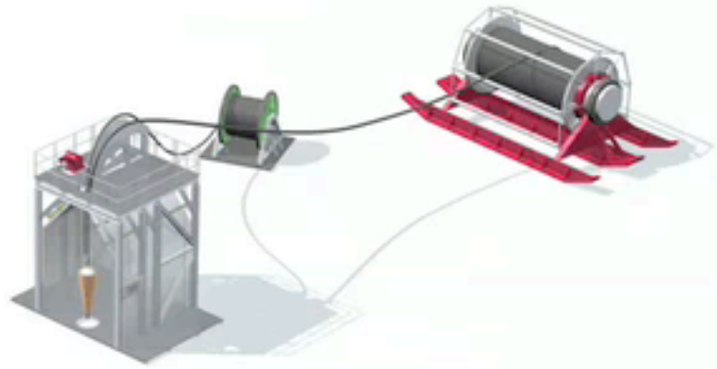
IceCube collecting events



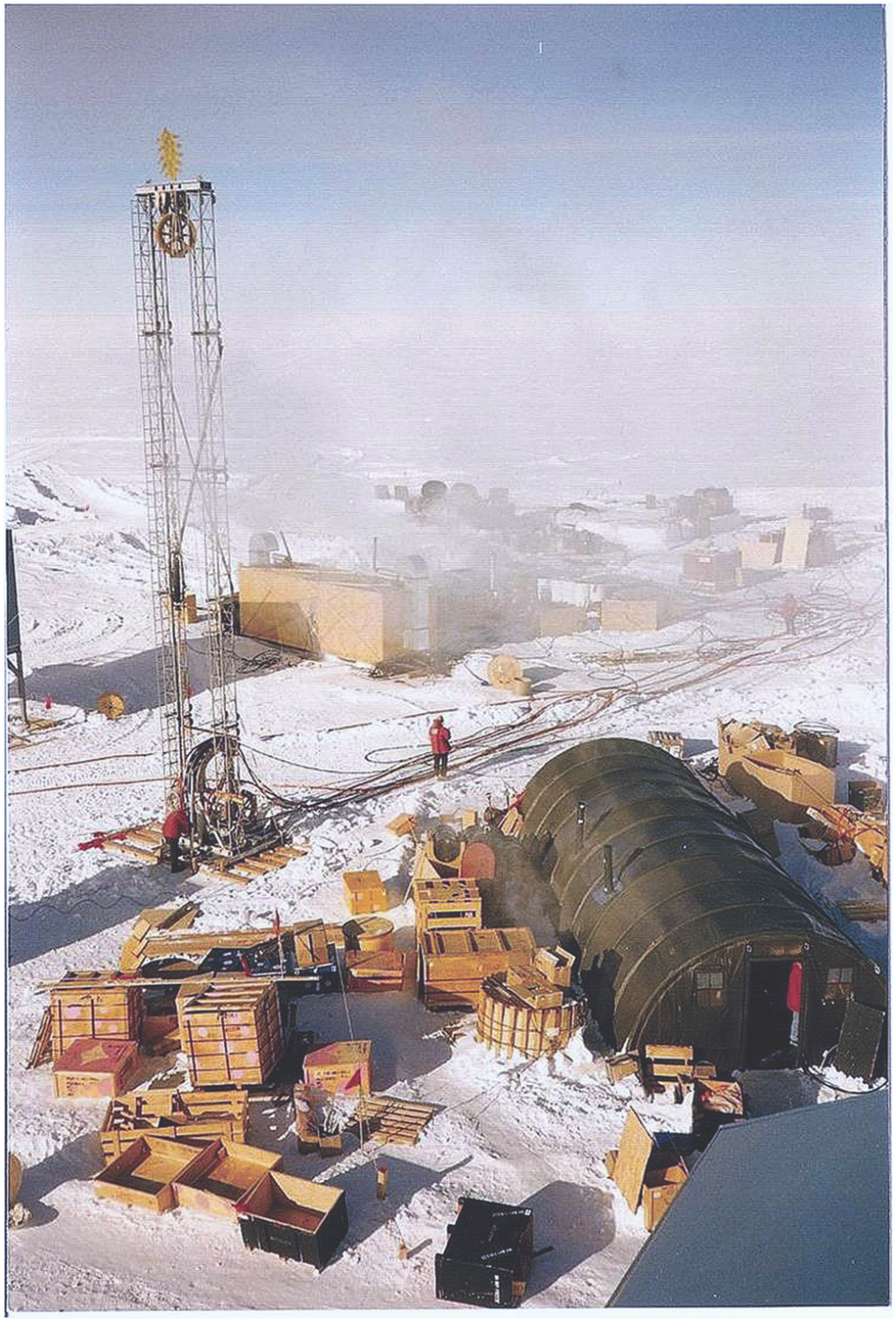
drilling holes at the South Pole



drilling holes at the South Pole

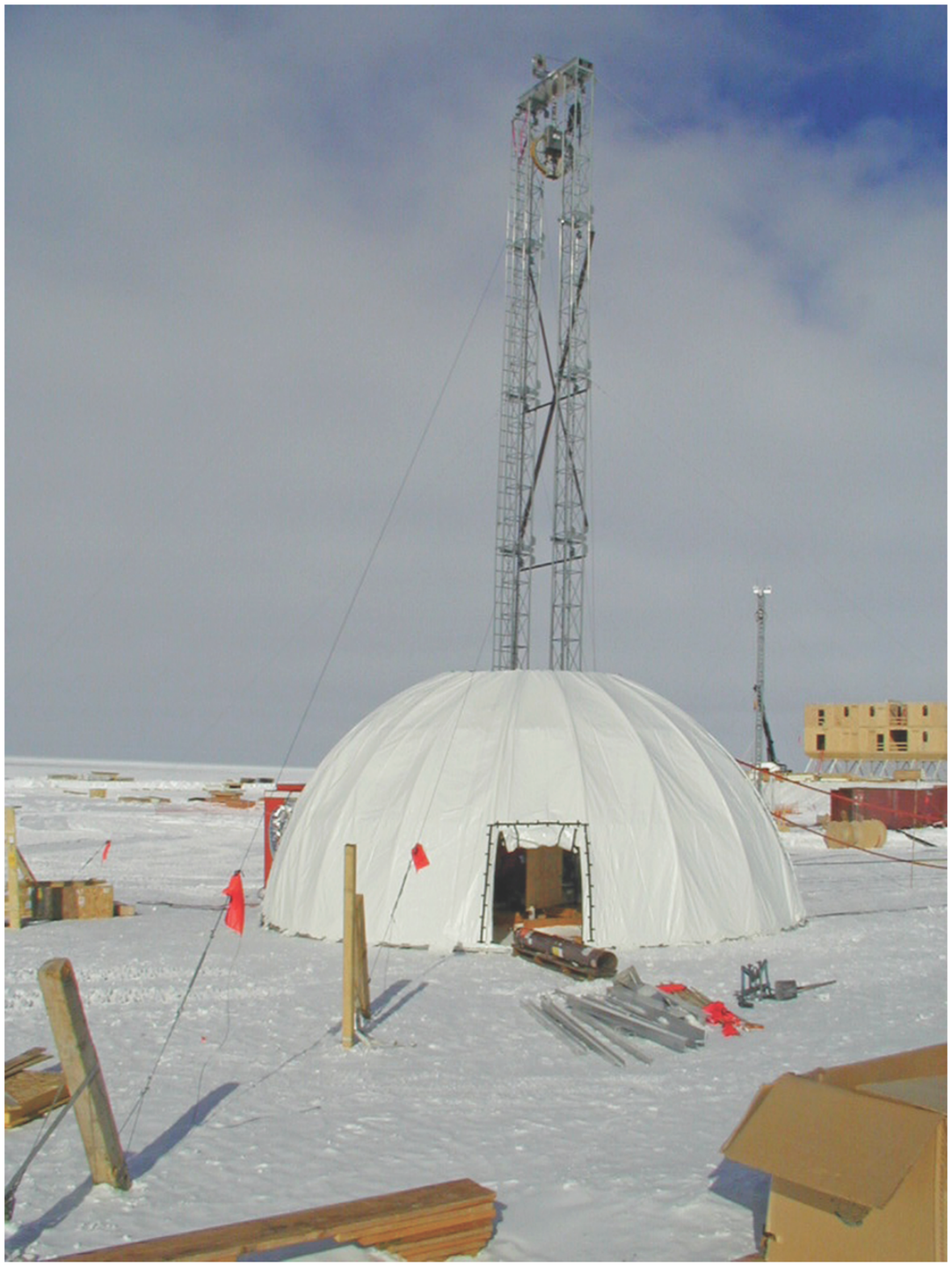


AMANDA - 1996

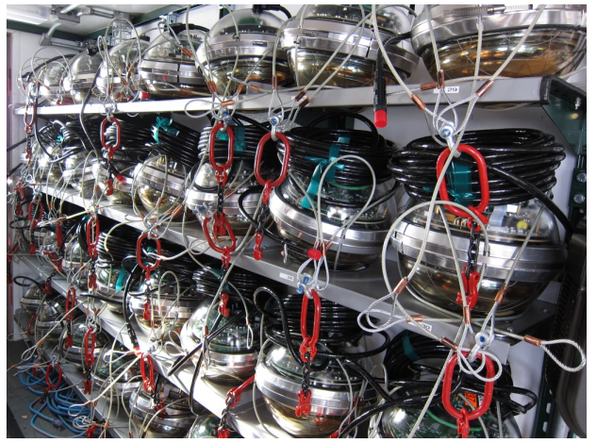


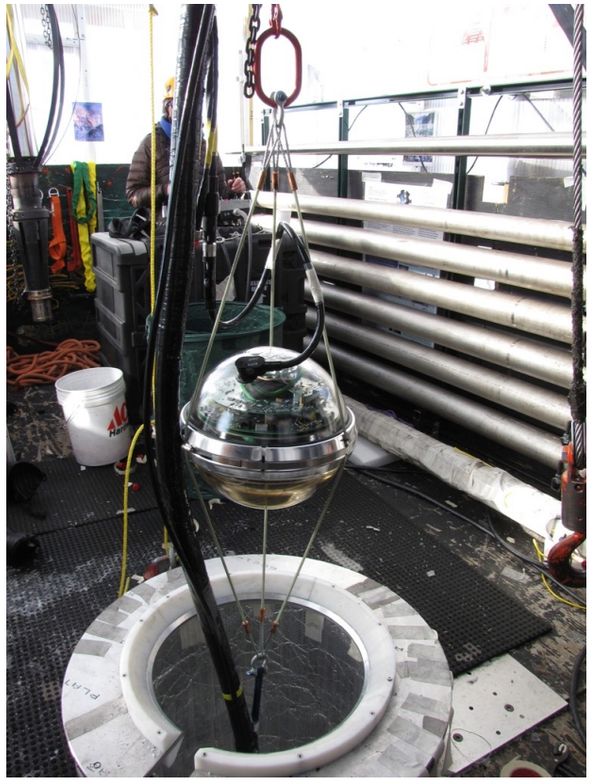
IceCube - 2011

AMANDA - 1996



IceCube - 2011

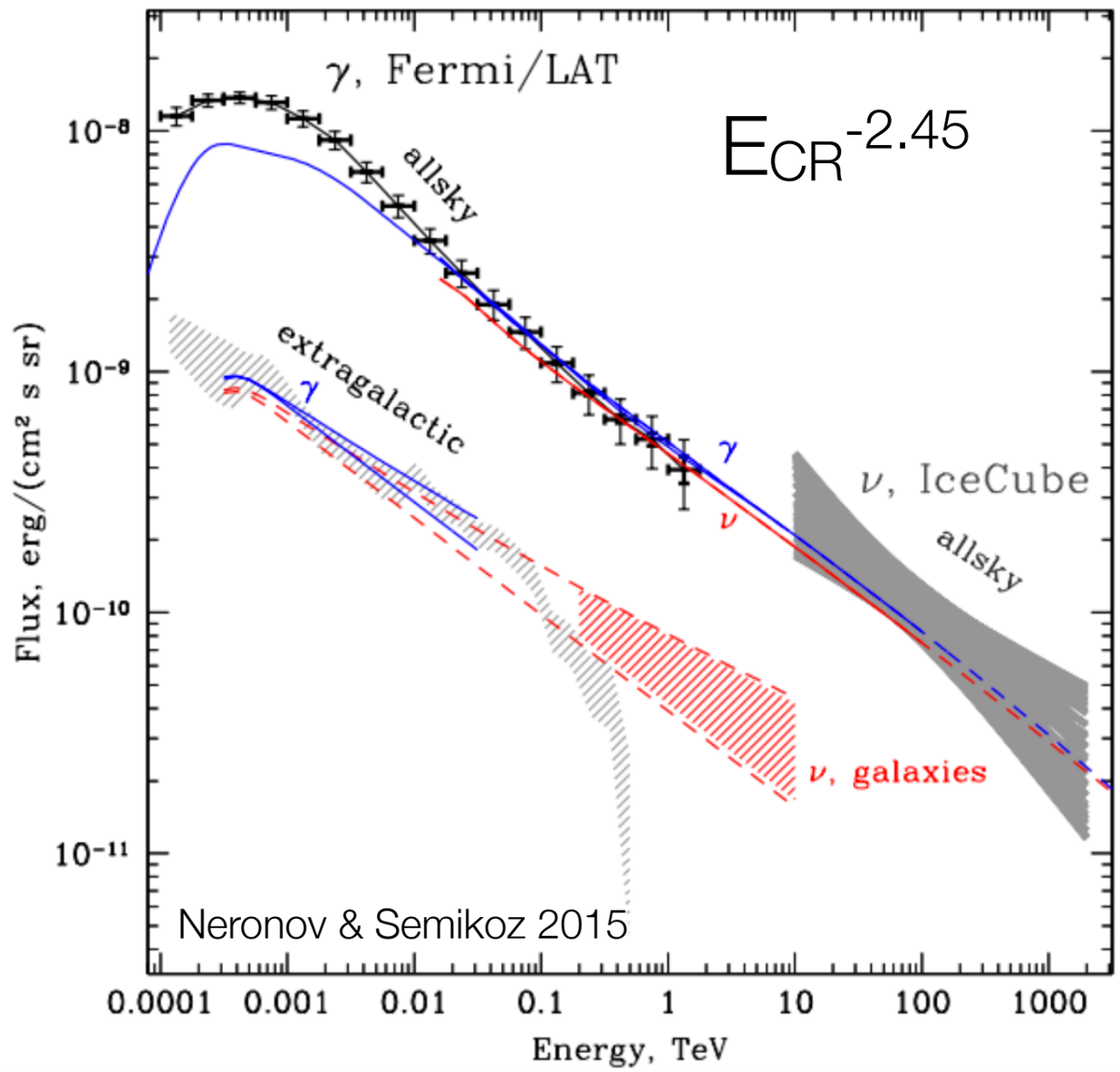




MUCHAS GRACIAS A TODOS USTEDES

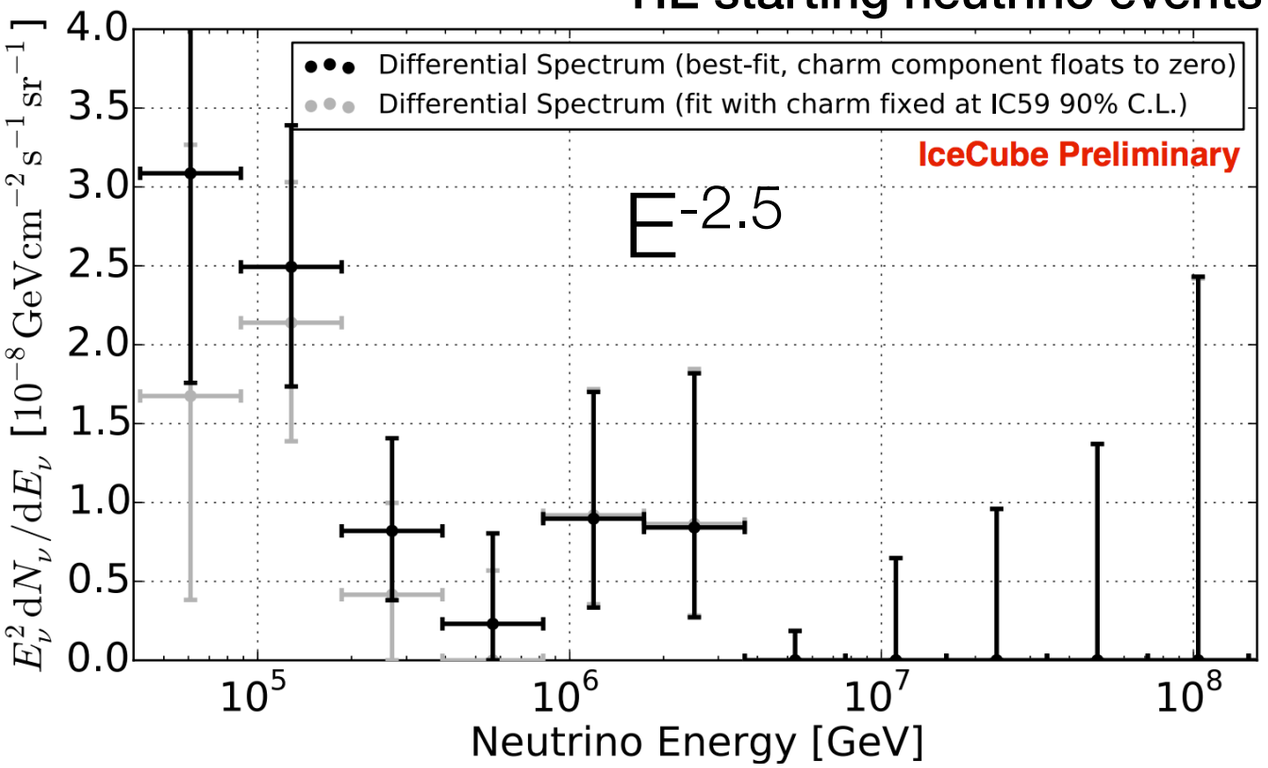
MUCHAS GRACIAS A TODOS USTEDES

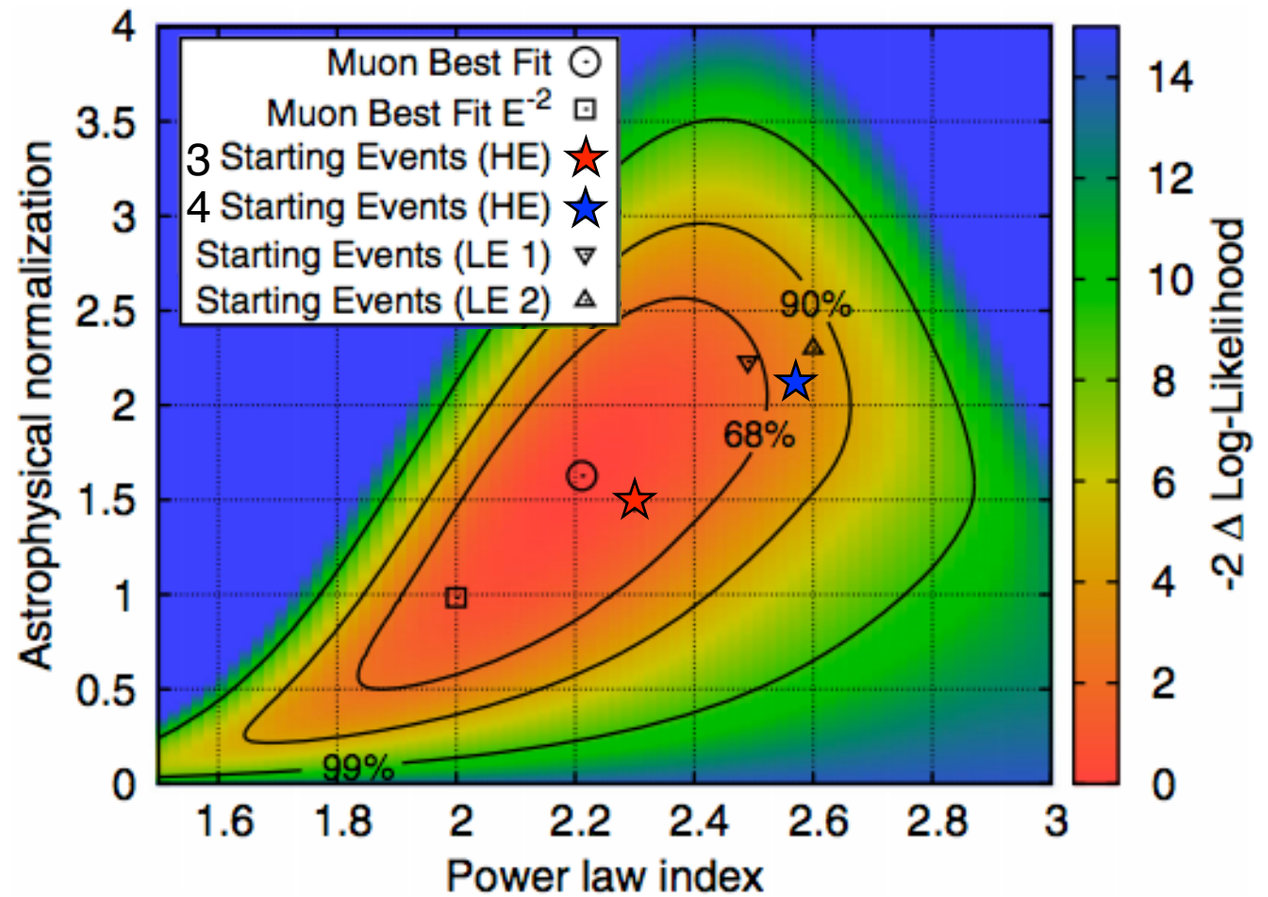
astrophysical neutrinos
galactic origin



galactic cosmic rays with cut-off of 10 PeV ?

HE starting neutrino events

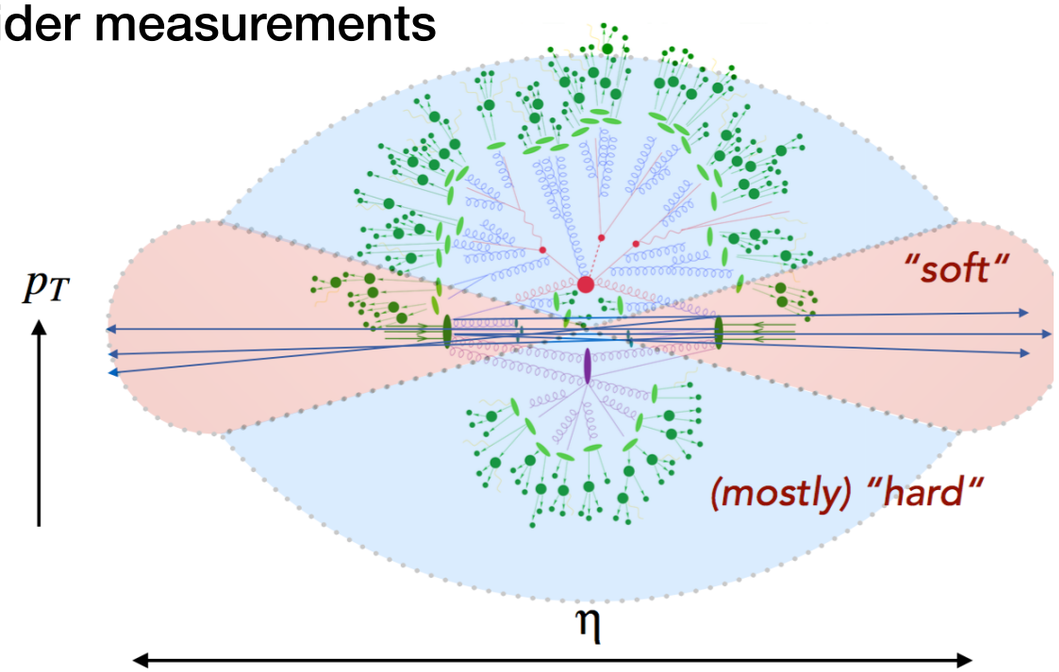


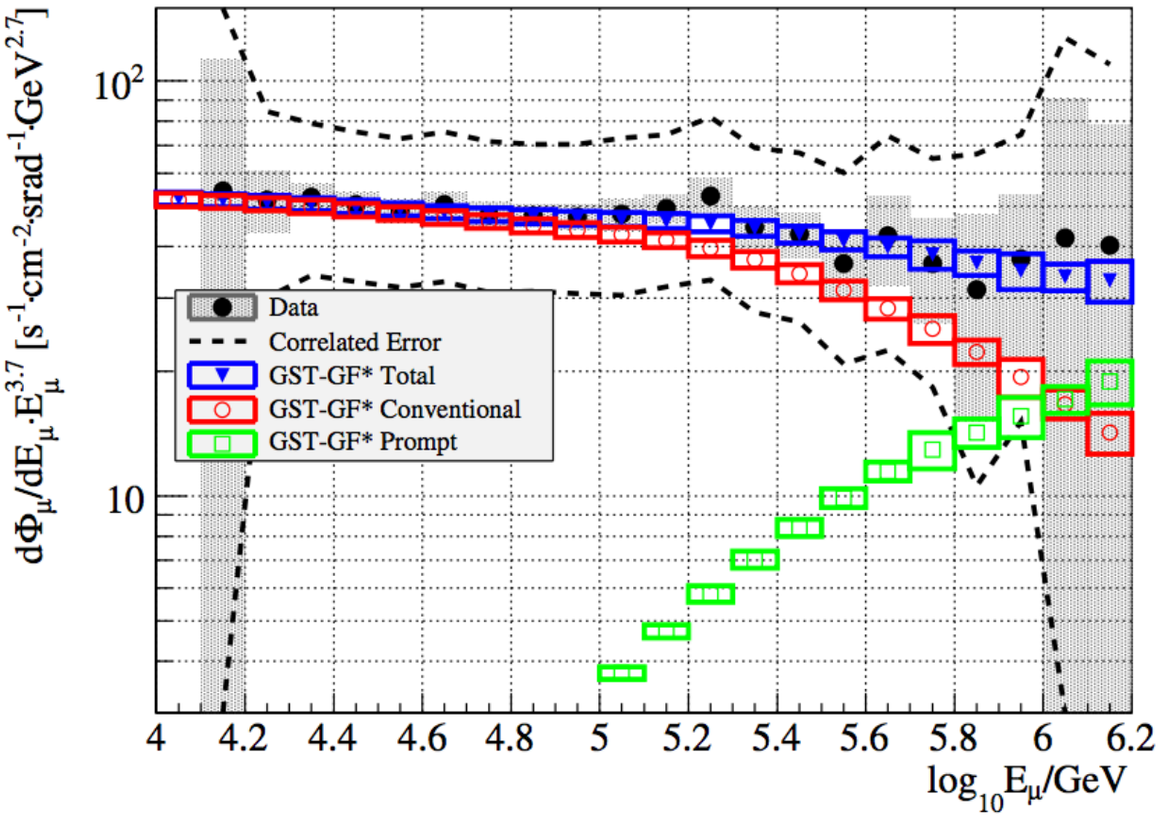


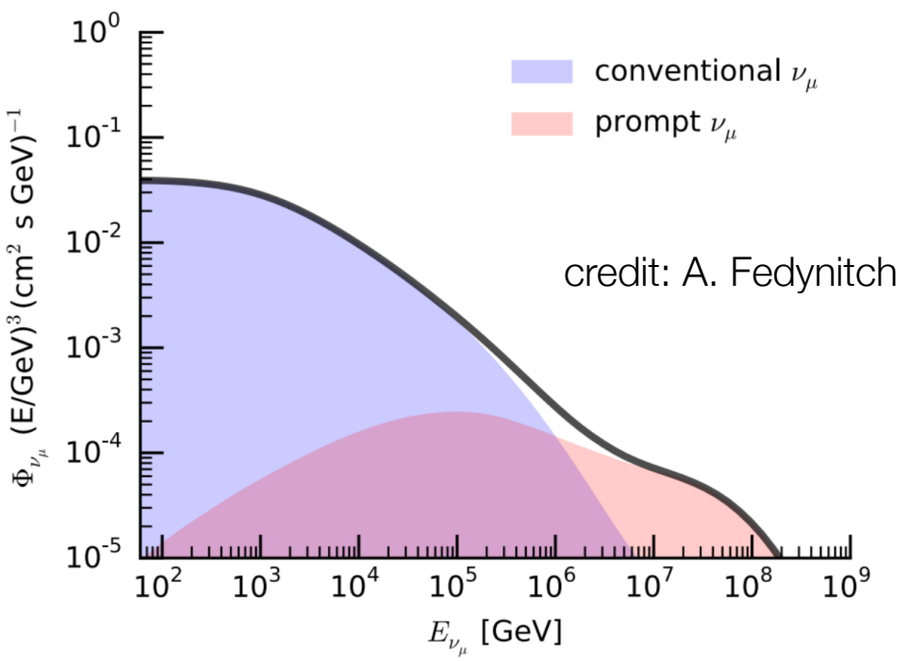
other sciences with IceCube

particle physics (atmospheric ν & μ)

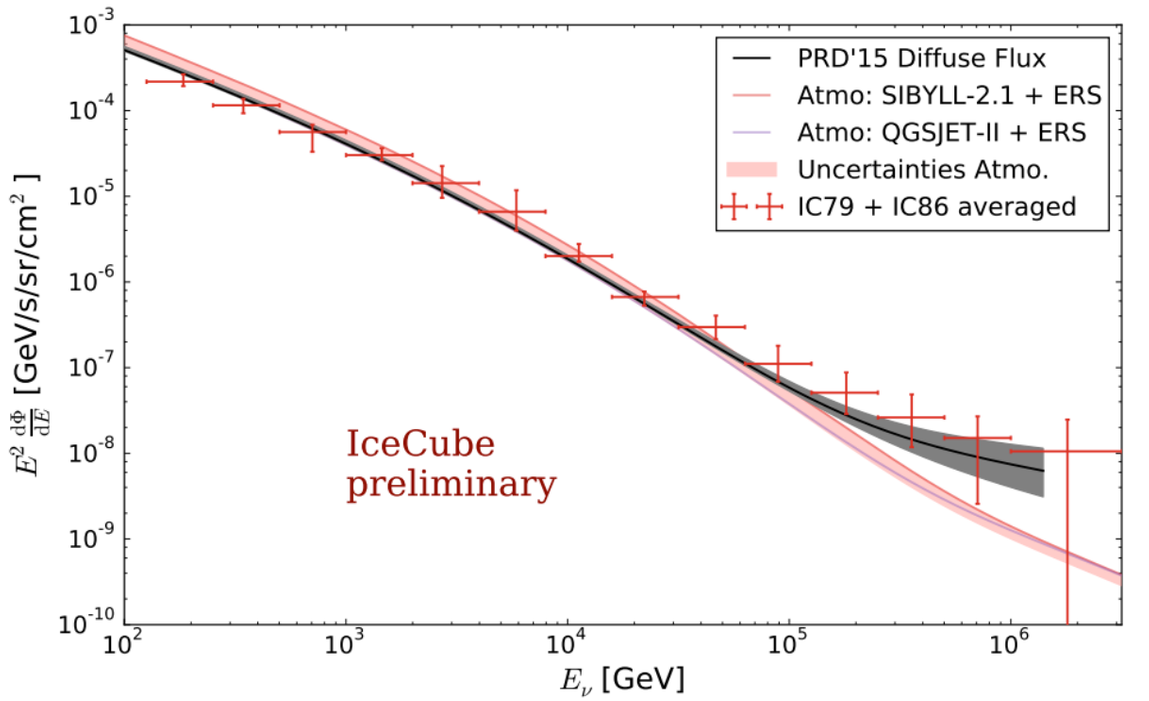
collider measurements





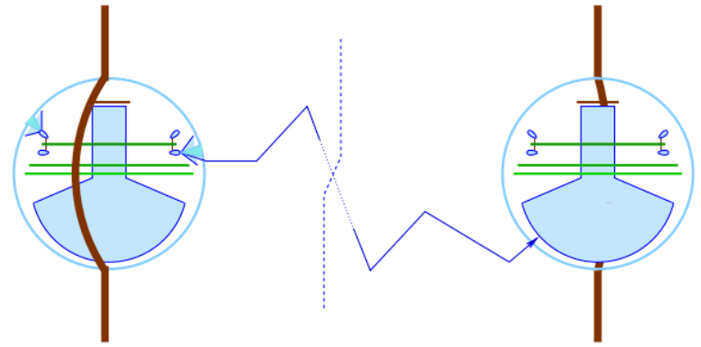


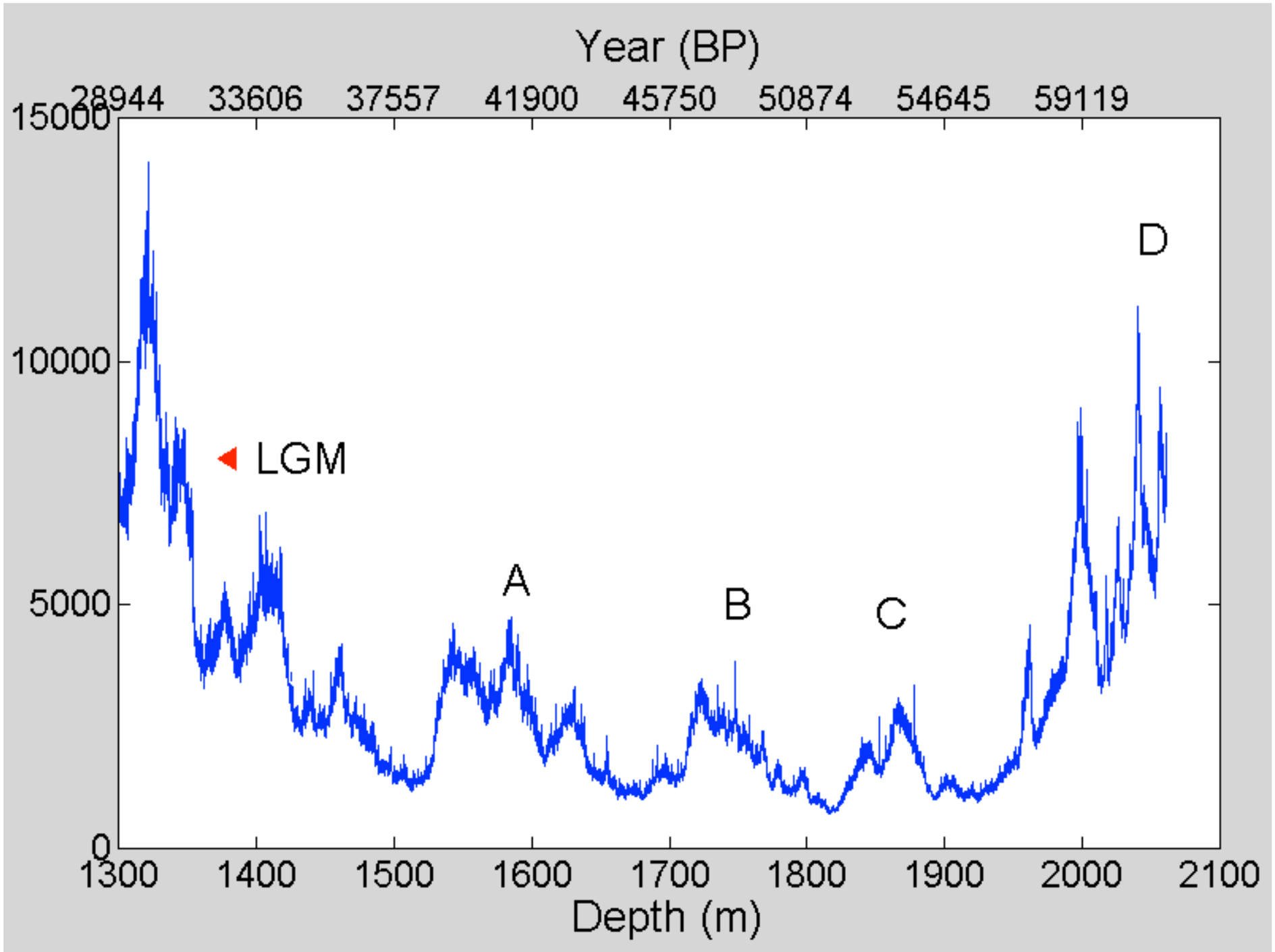
credit: A. Fedynitch

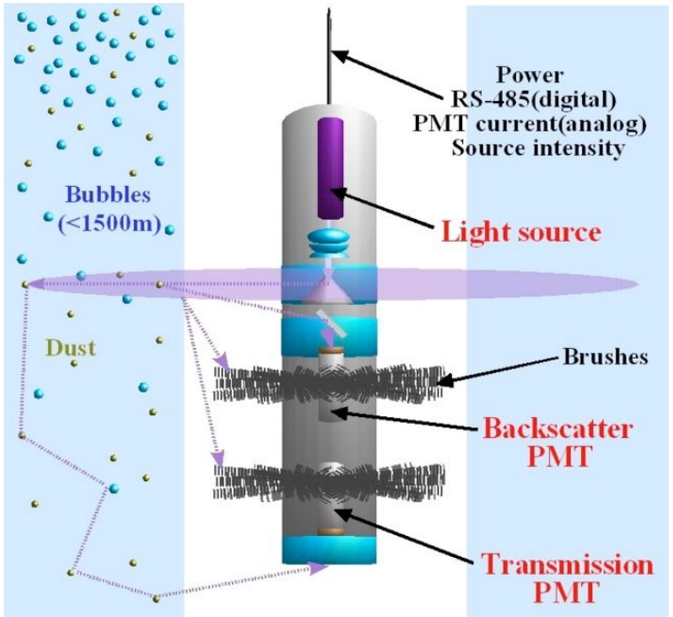


other sciences with IceCube

antarctic glaciology

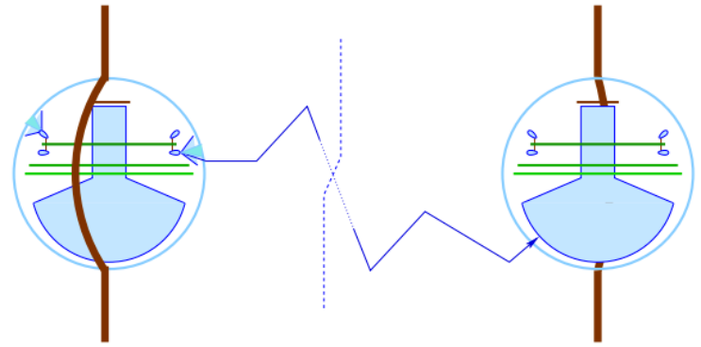


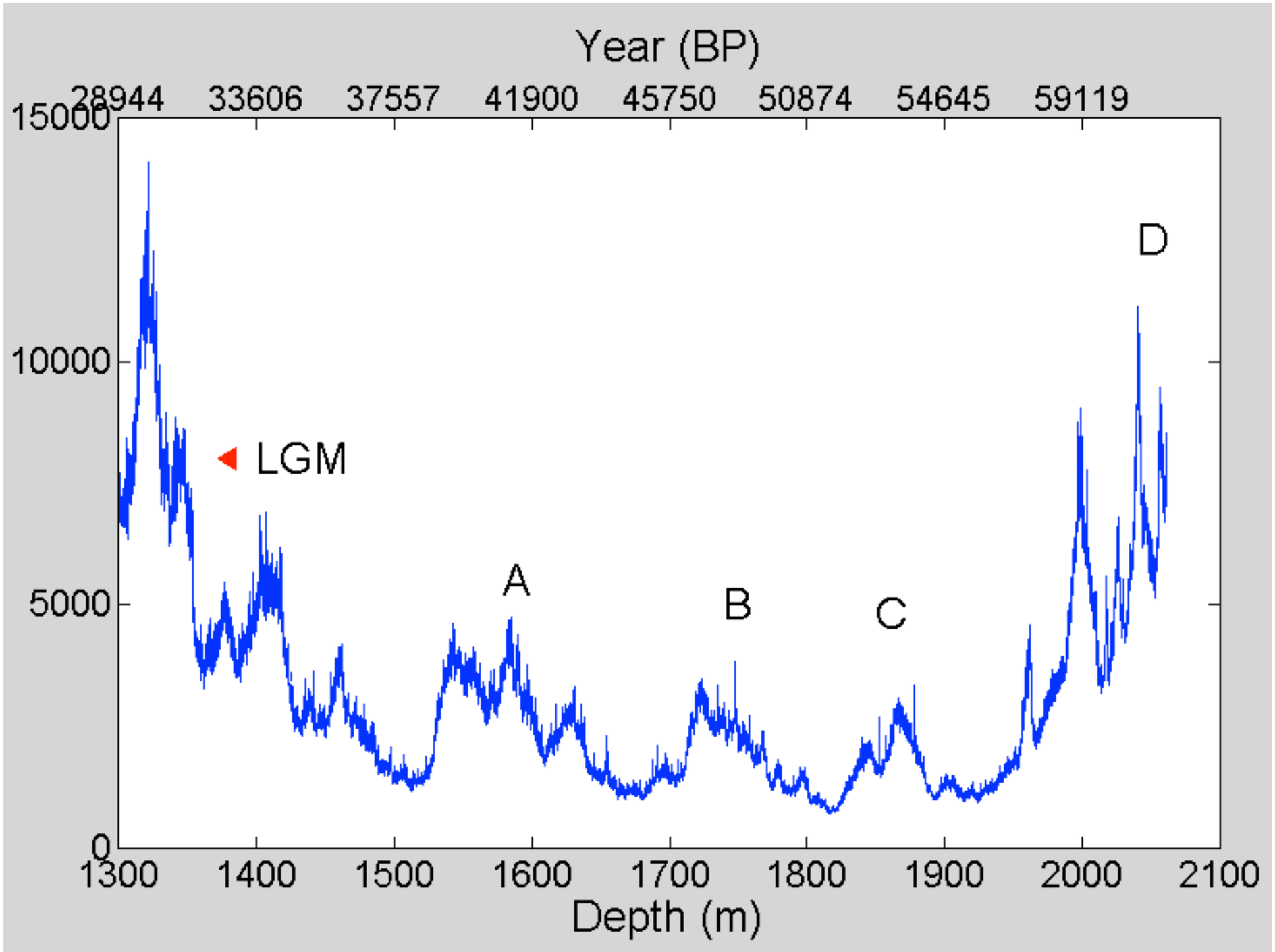


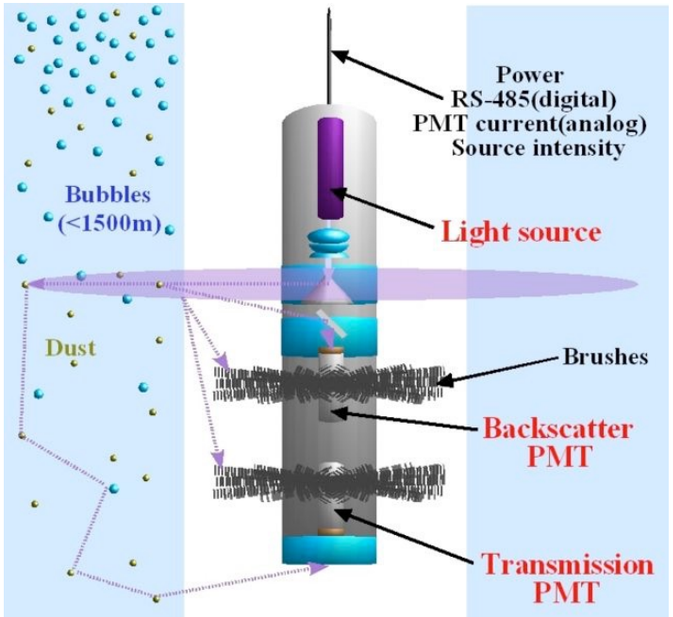


other sciences with IceCube

antarctic glaciology

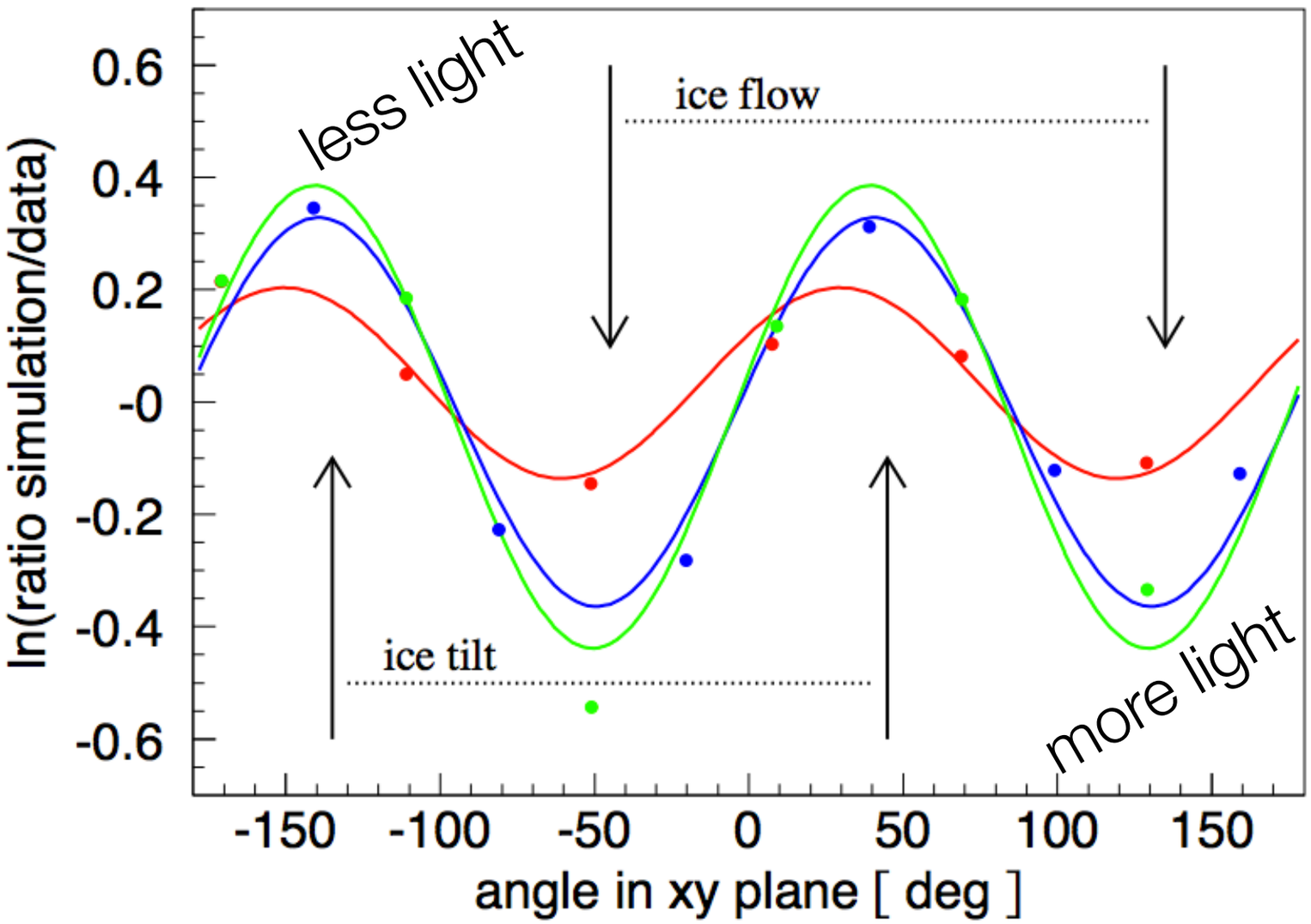


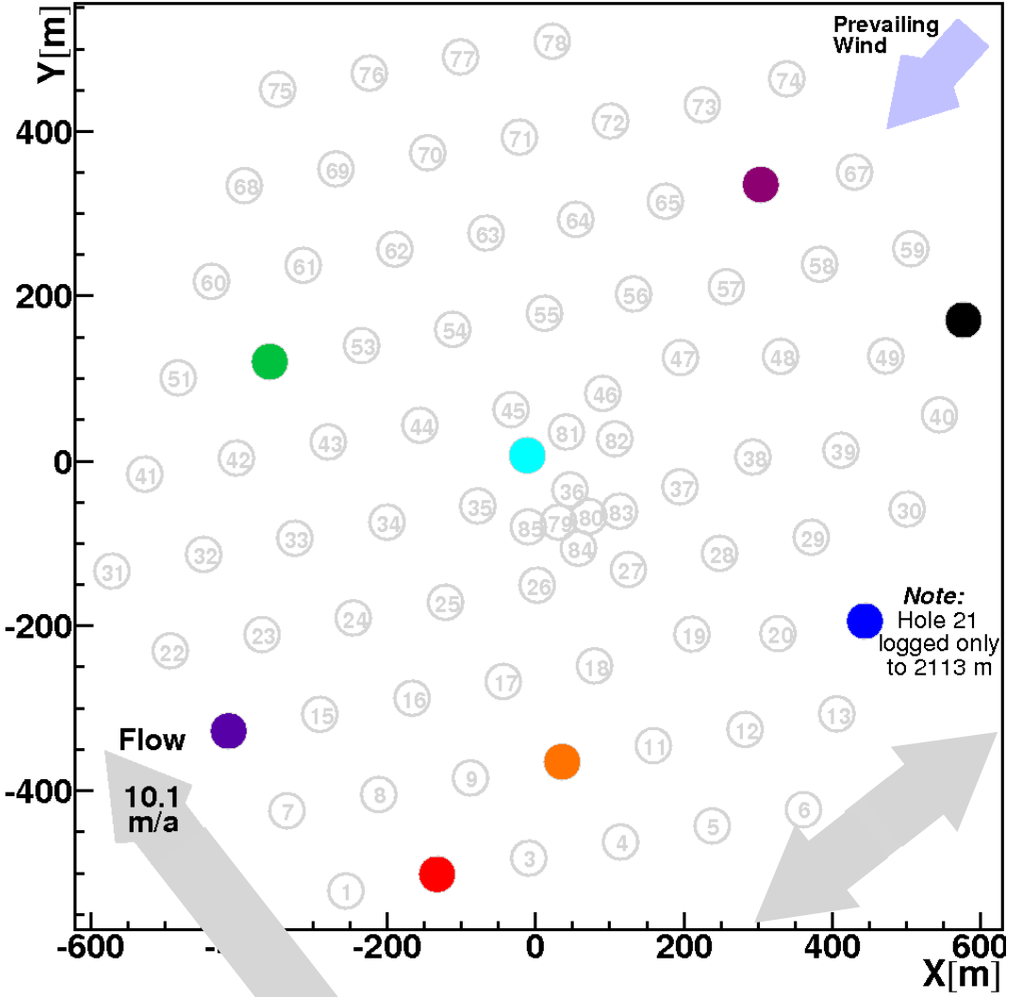




other sciences with IceCube

antarctic glaciology



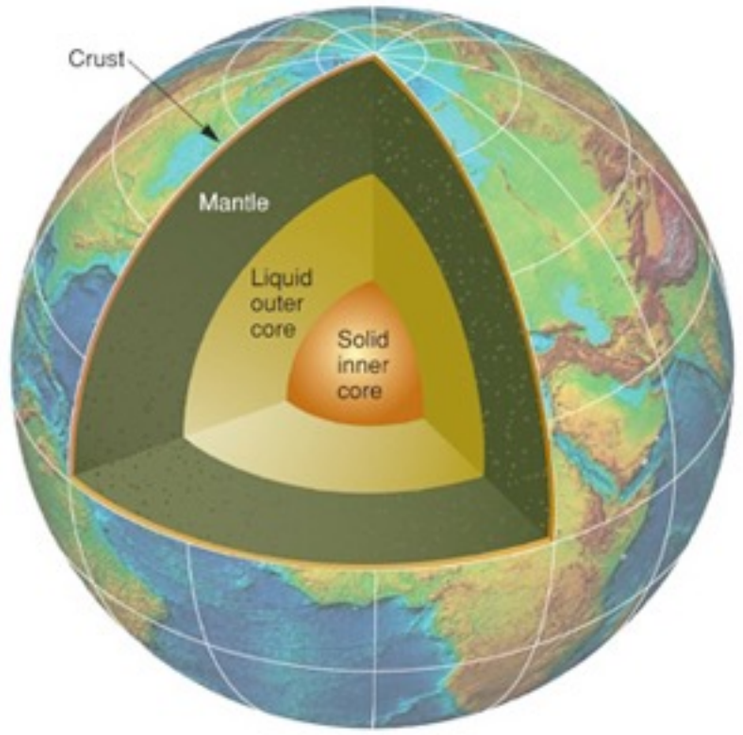


ice flow

ice tilt

other sciences with IceCube
Earth sciences

- inner structure of Earth studies with seismic wave analysis



- dependence on geophysical models: density, chemical composition

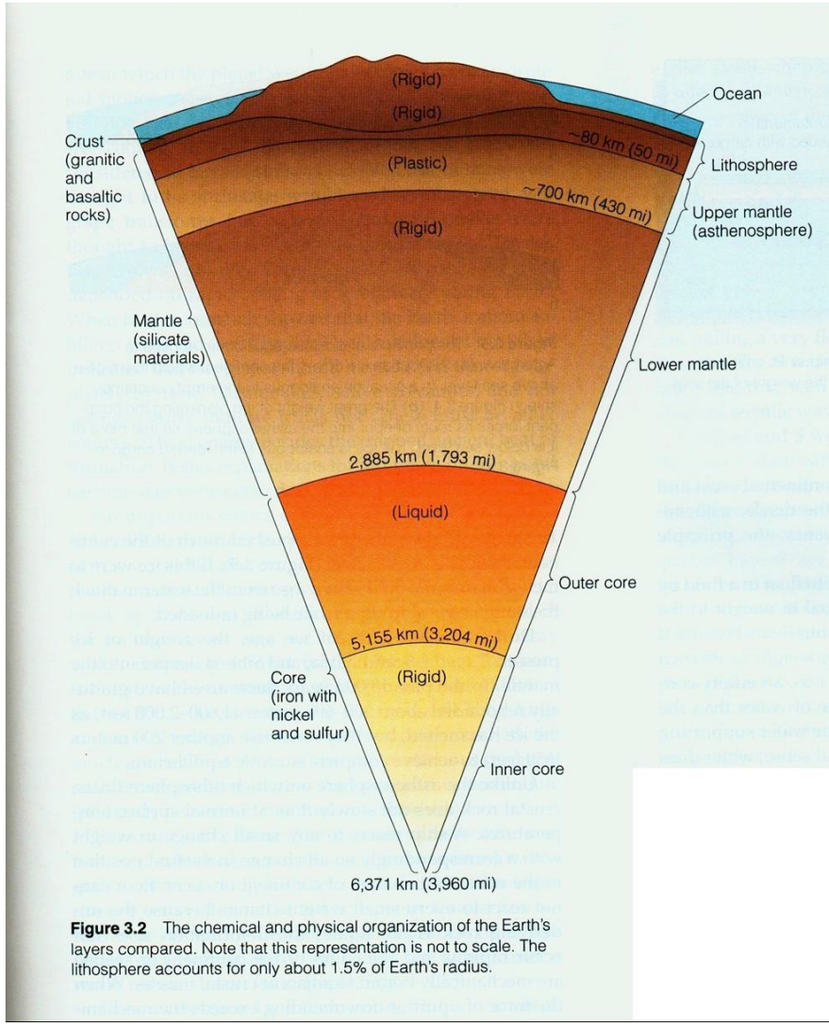


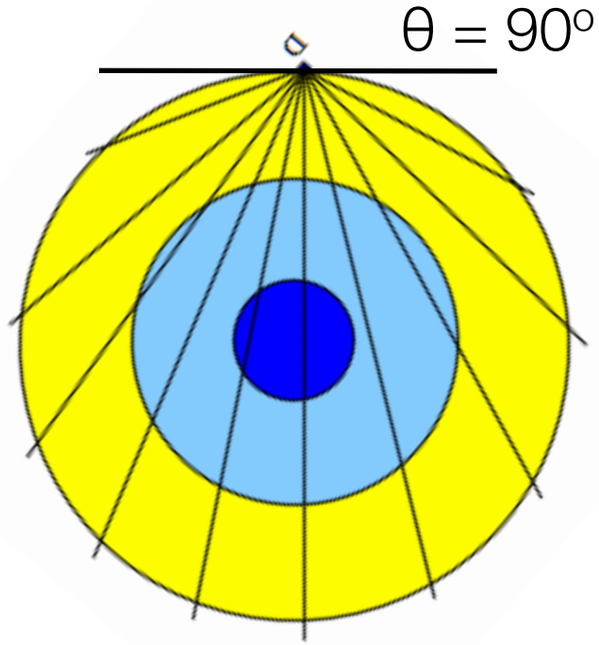
Figure 3.2 The chemical and physical organization of the Earth's layers compared. Note that this representation is not to scale. The lithosphere accounts for only about 1.5% of Earth's radius.

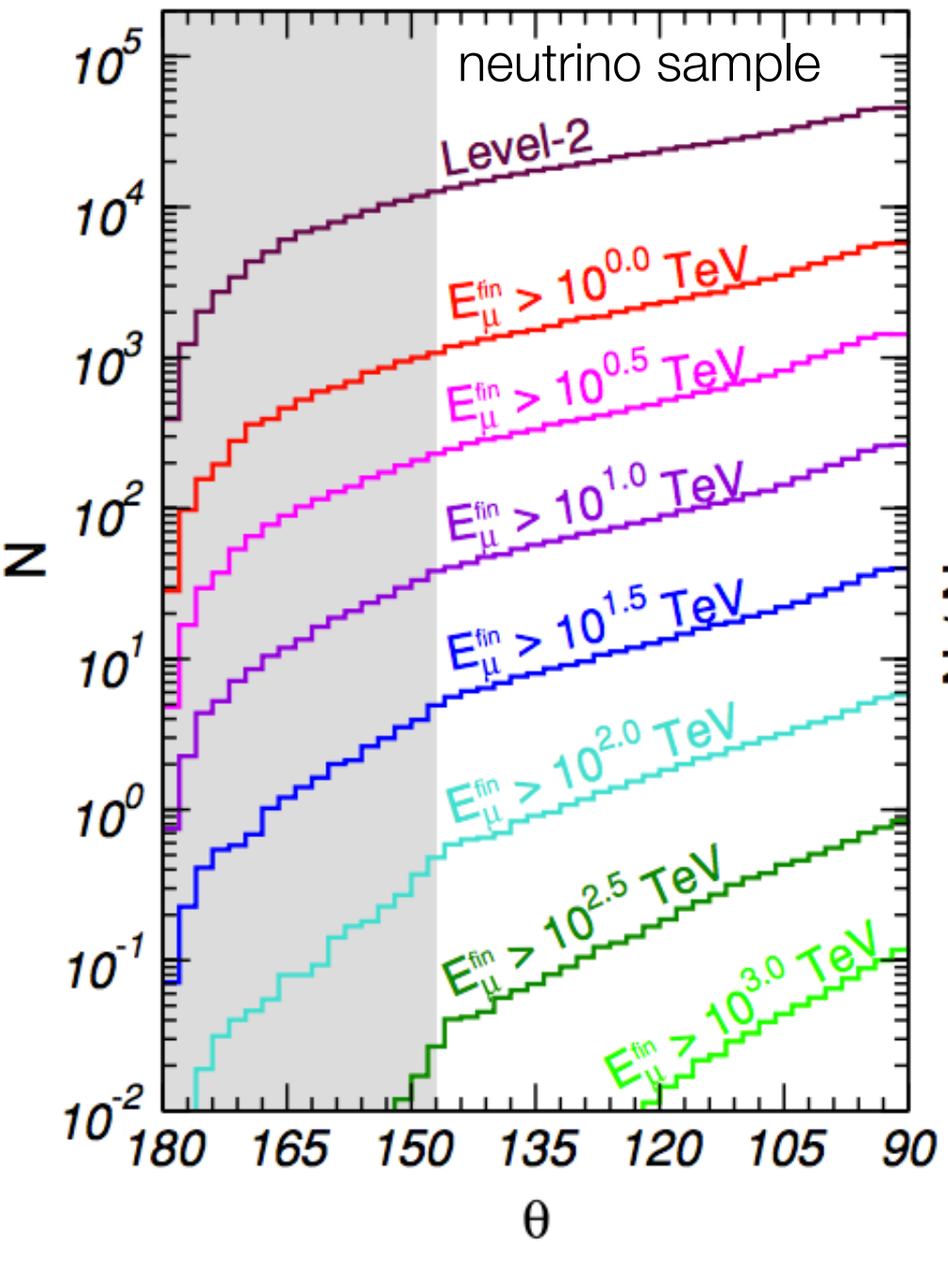
- neutrino radiography - **absorption** at high energy depends on atomic density

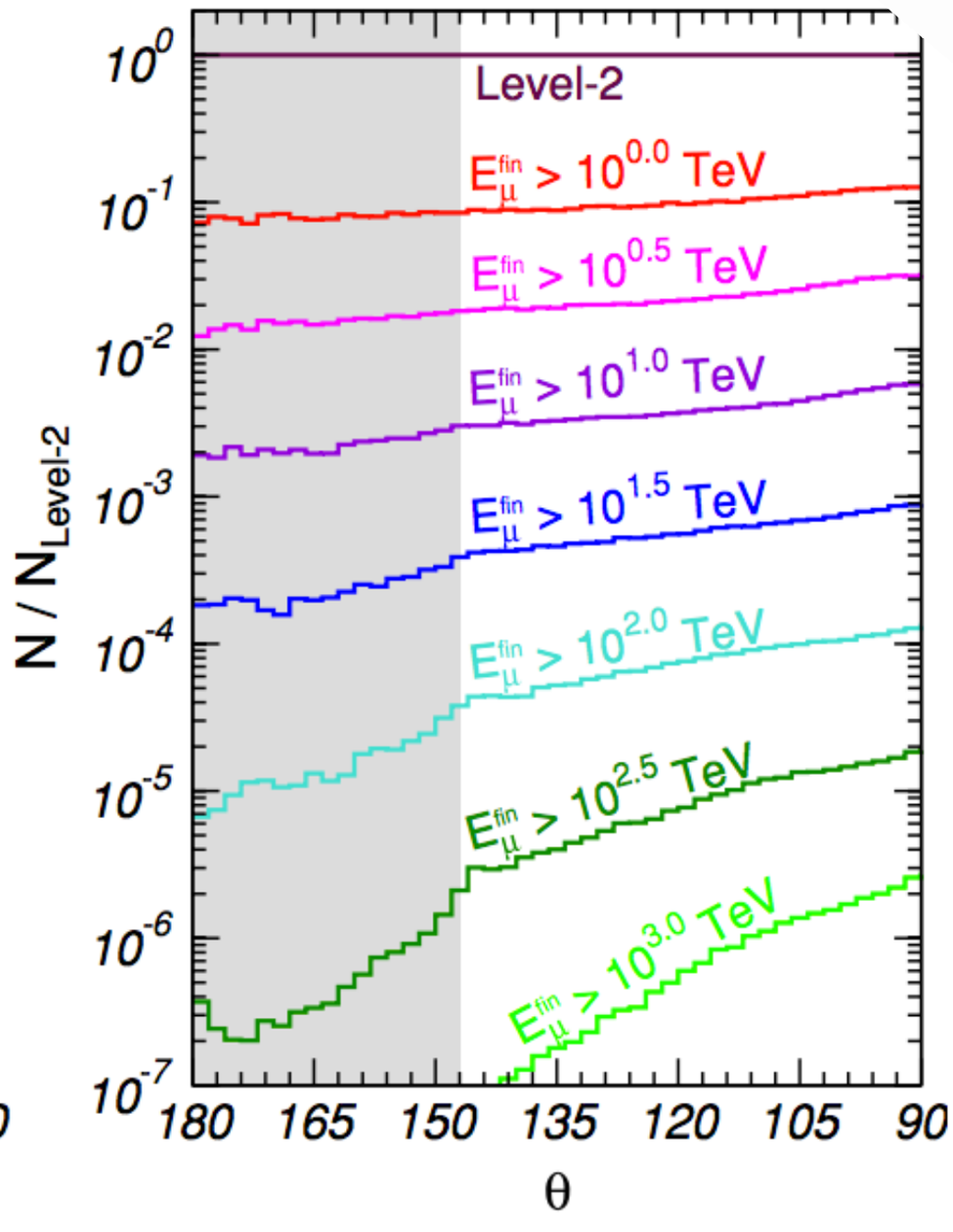
- neutrino tomography - **oscillations** at low energy depends on chemical composition

other sciences with IceCube

Earth sciences

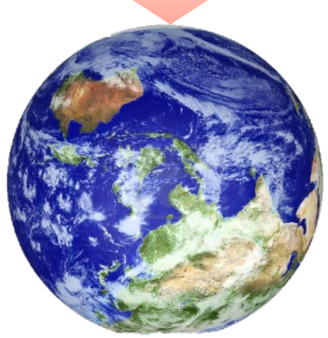




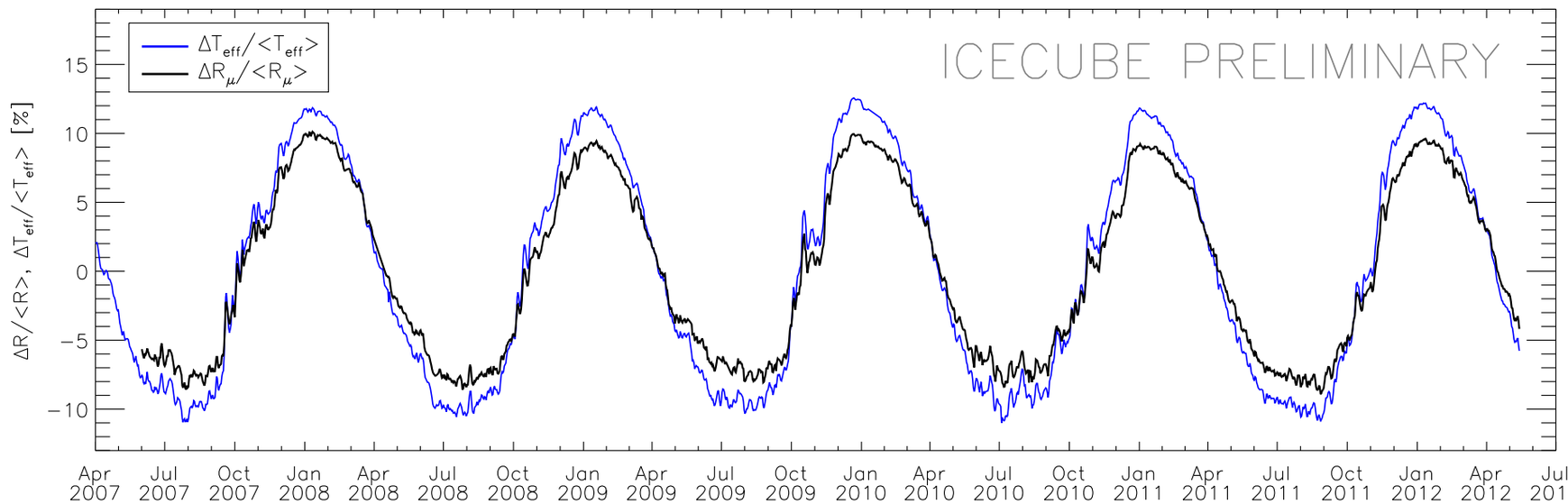


other sciences with IceCube

atmospheric sciences (stratospheric temperature)



μ

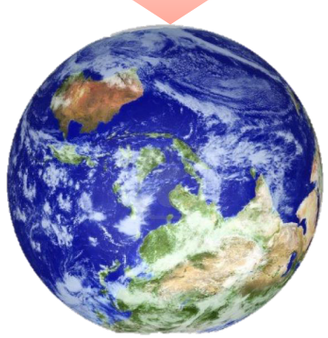


ICRC 2009
ICRC 2011

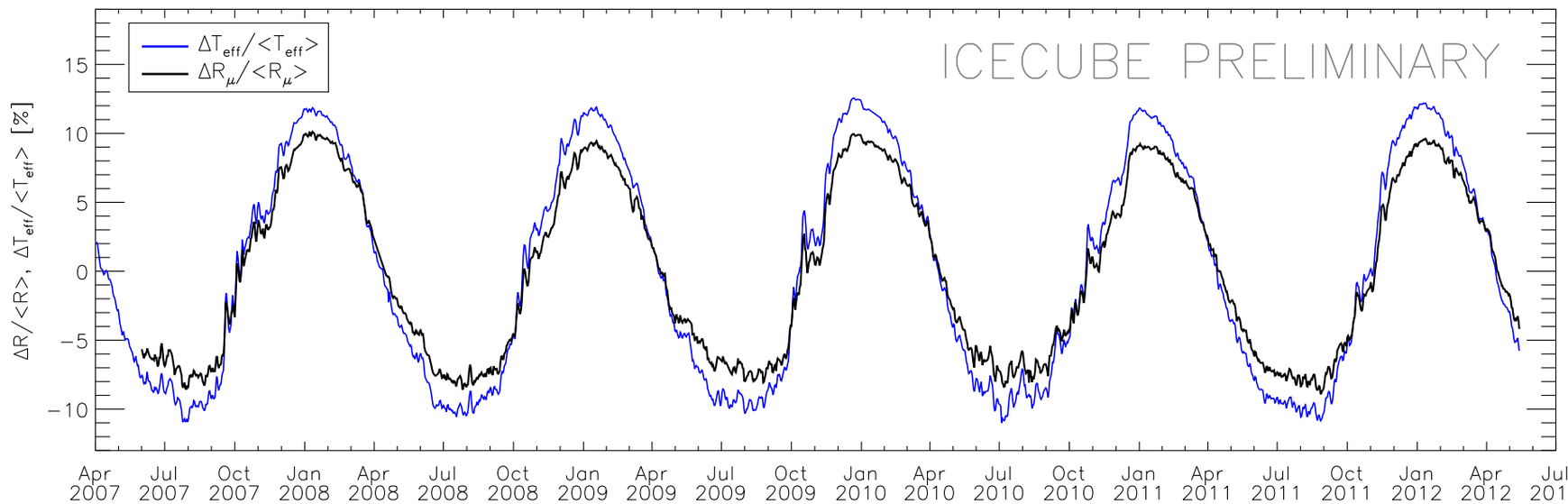
- long (year) & short term (days) variations of stratospheric temperature
- temperature resolution ~1 K (statistics ~0.2 K)

other sciences with IceCube

atmospheric sciences (stratospheric temperature)

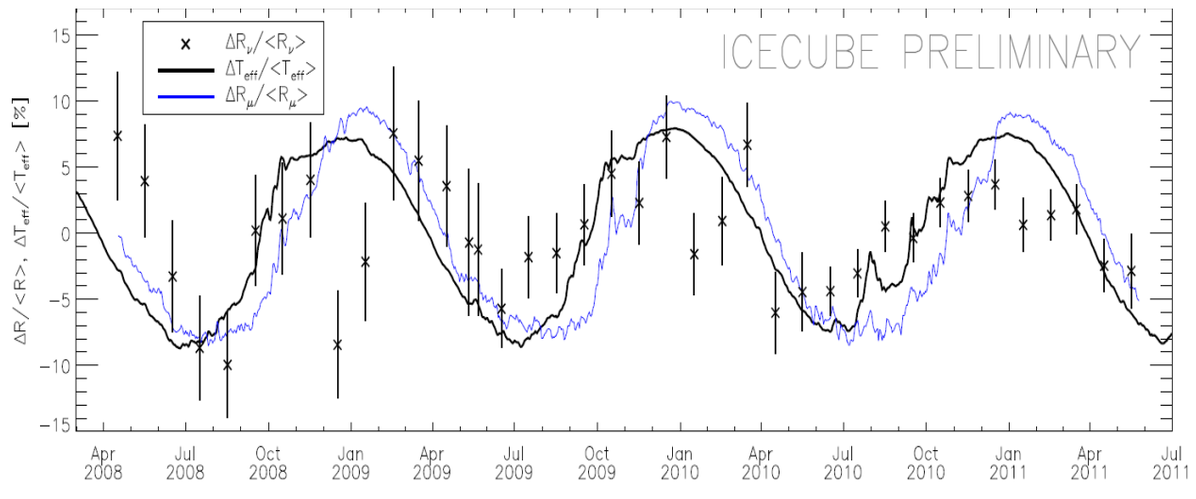


μ



ICRC 2009
ICRC 2011

ν_μ

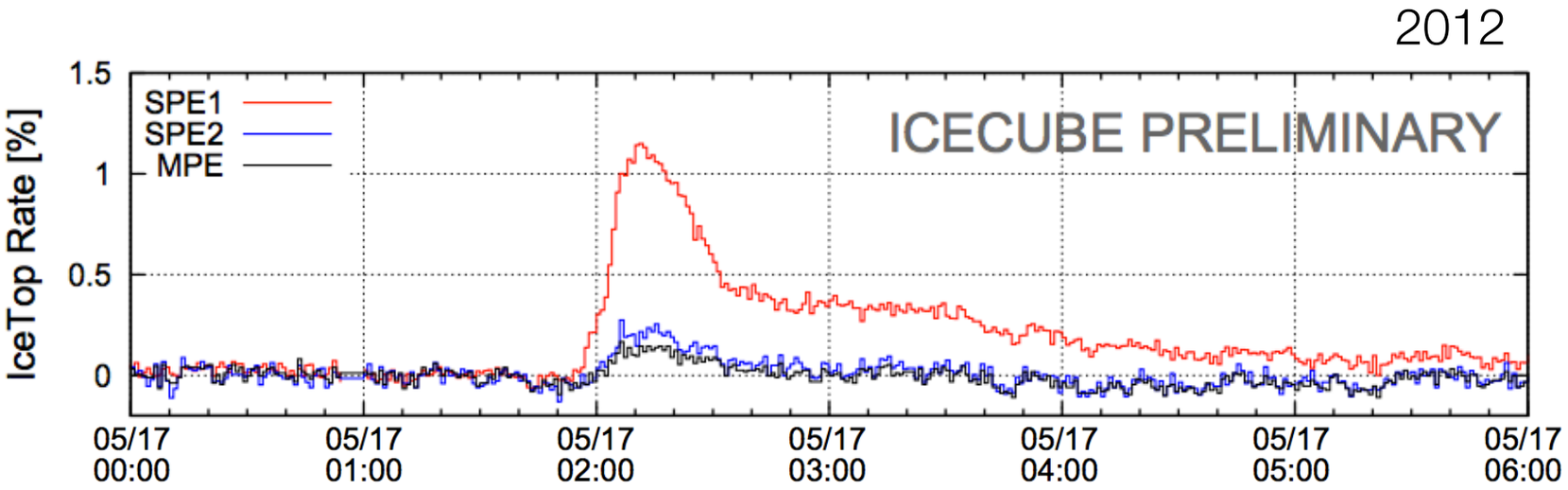


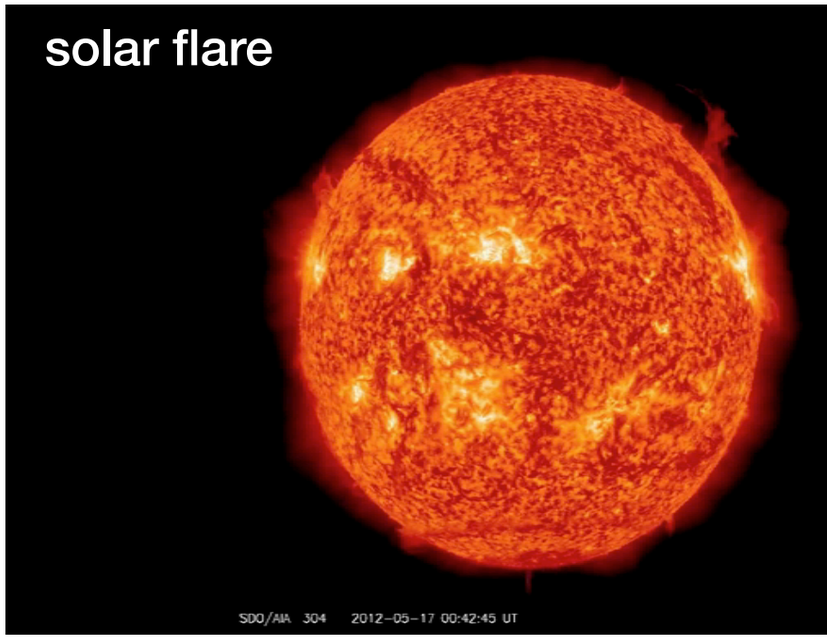
ICRC 2013

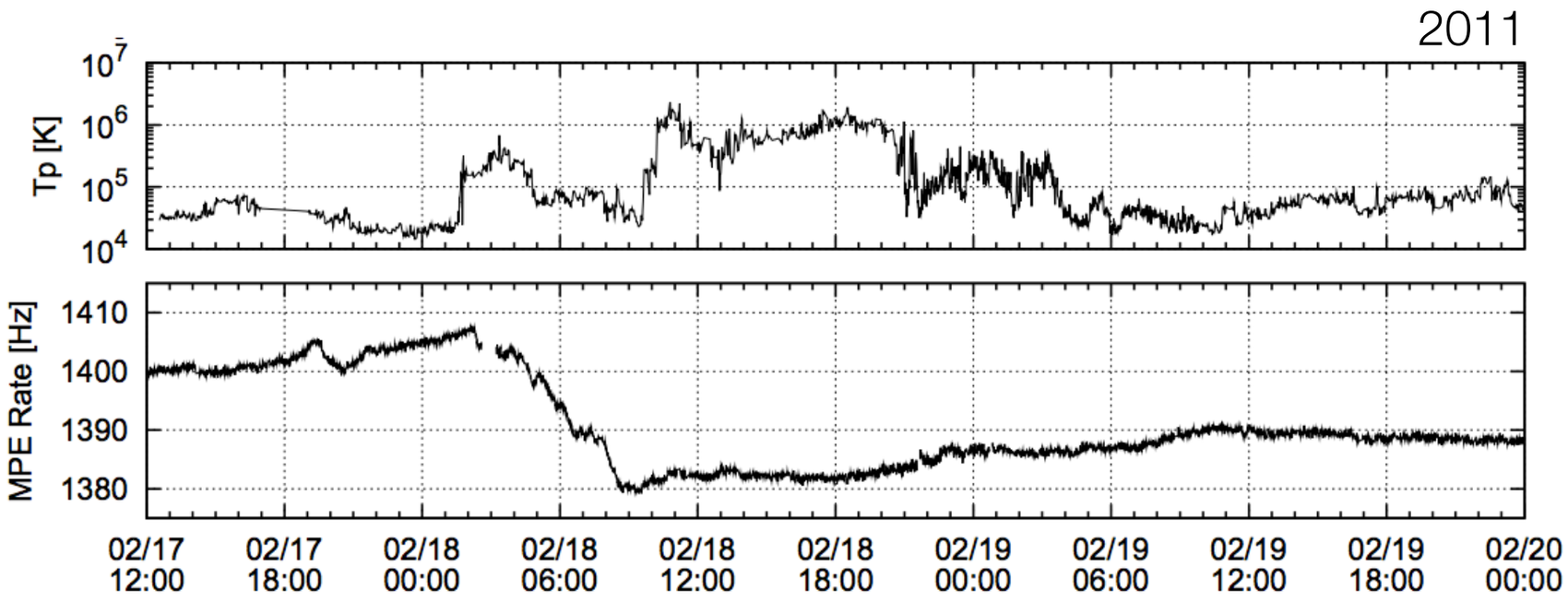
- long (year) & short term (days) variations of stratospheric temperature
- temperature resolution ~1 K (statistics ~0.2 K)

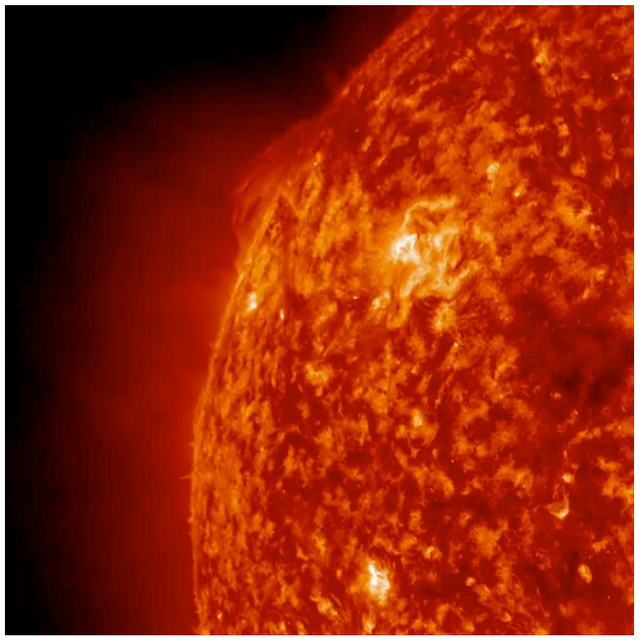
other sciences with IceCube

heliospheric science





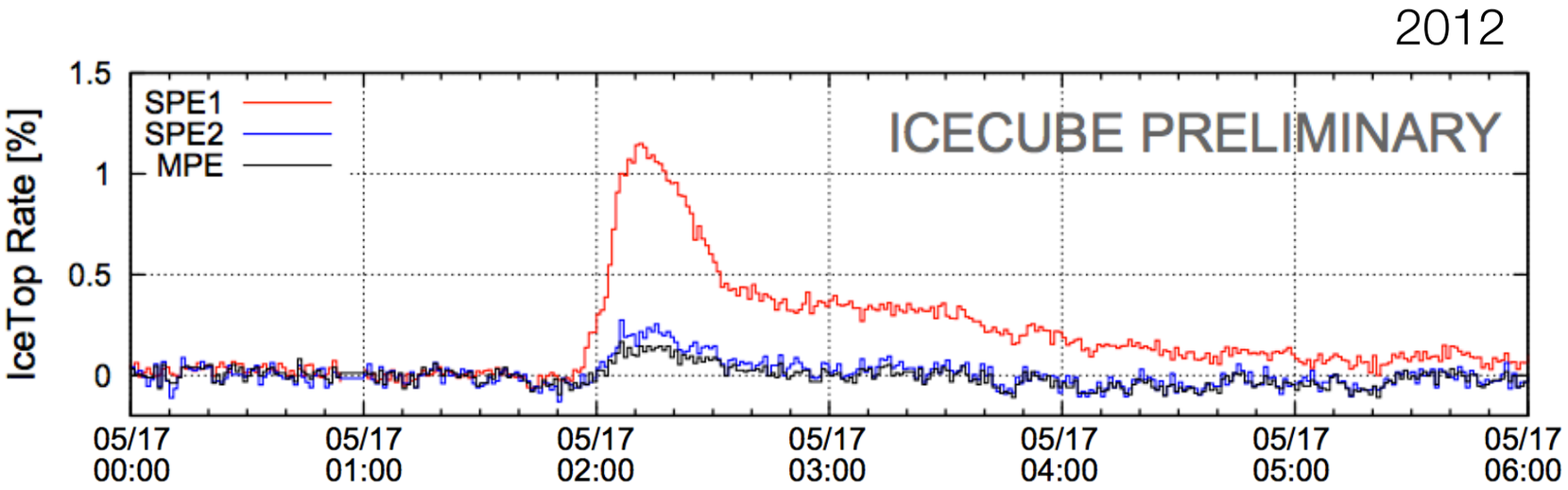


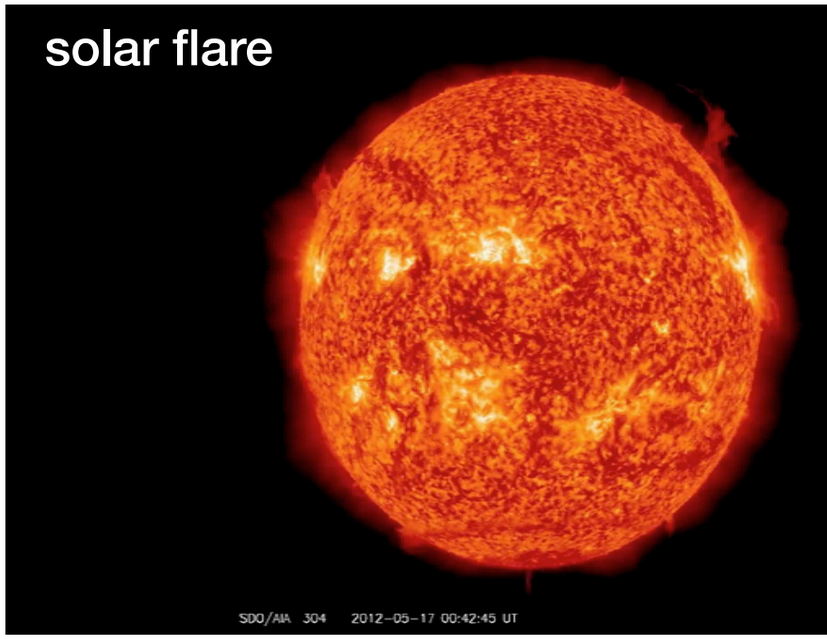


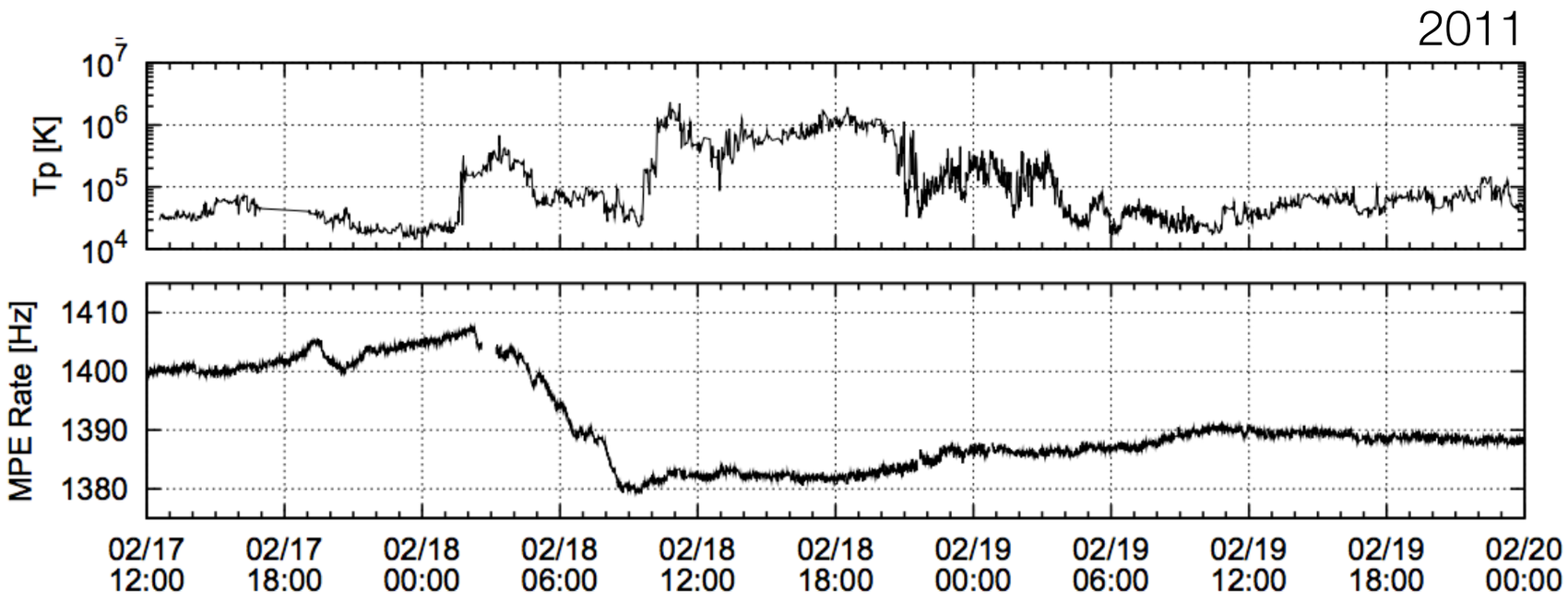
coronal mass ejection

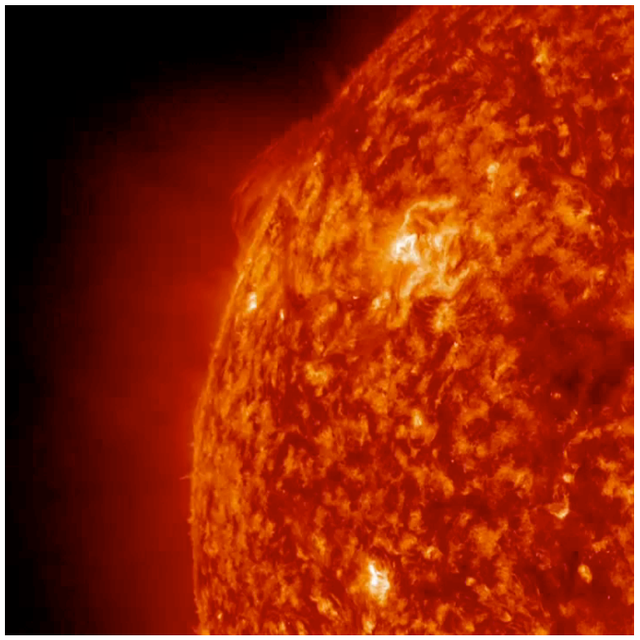
other sciences with IceCube

heliospheric science









coronal mass ejection

other sciences with IceCube

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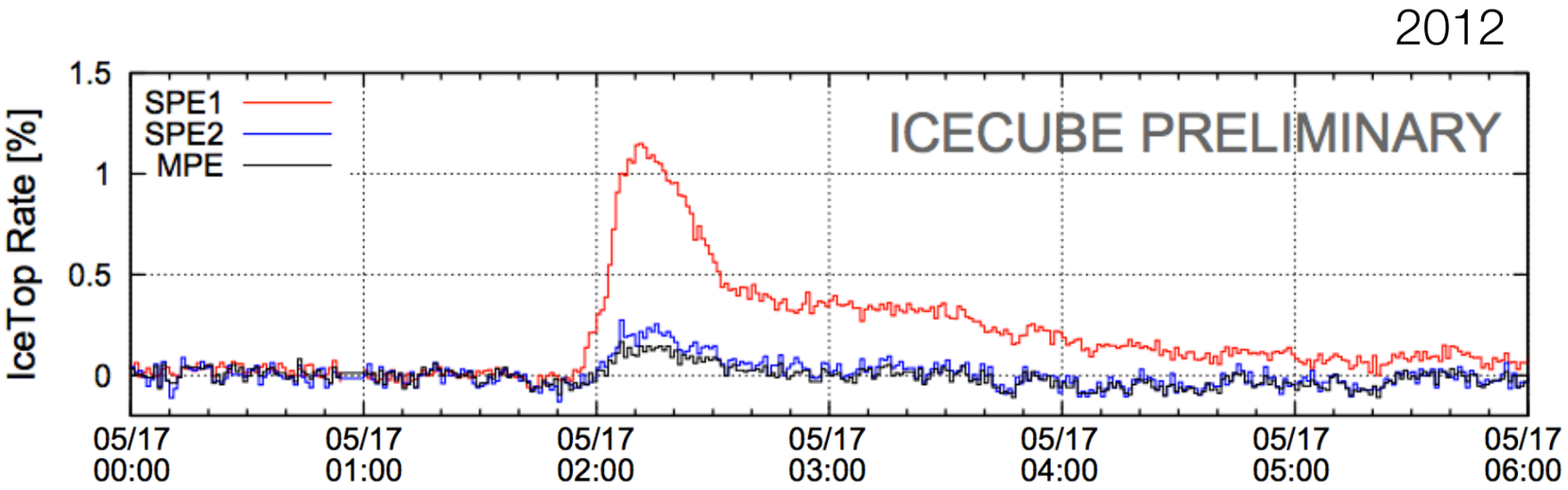

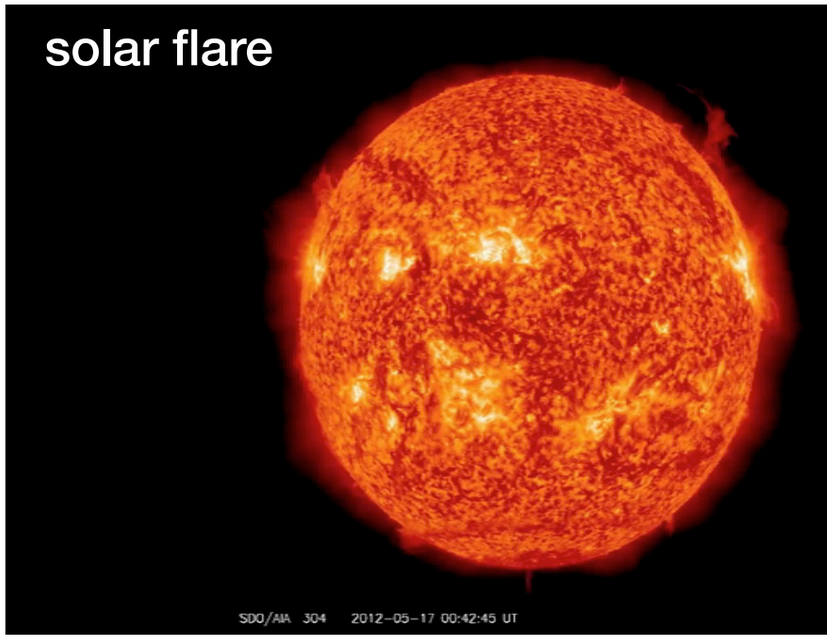

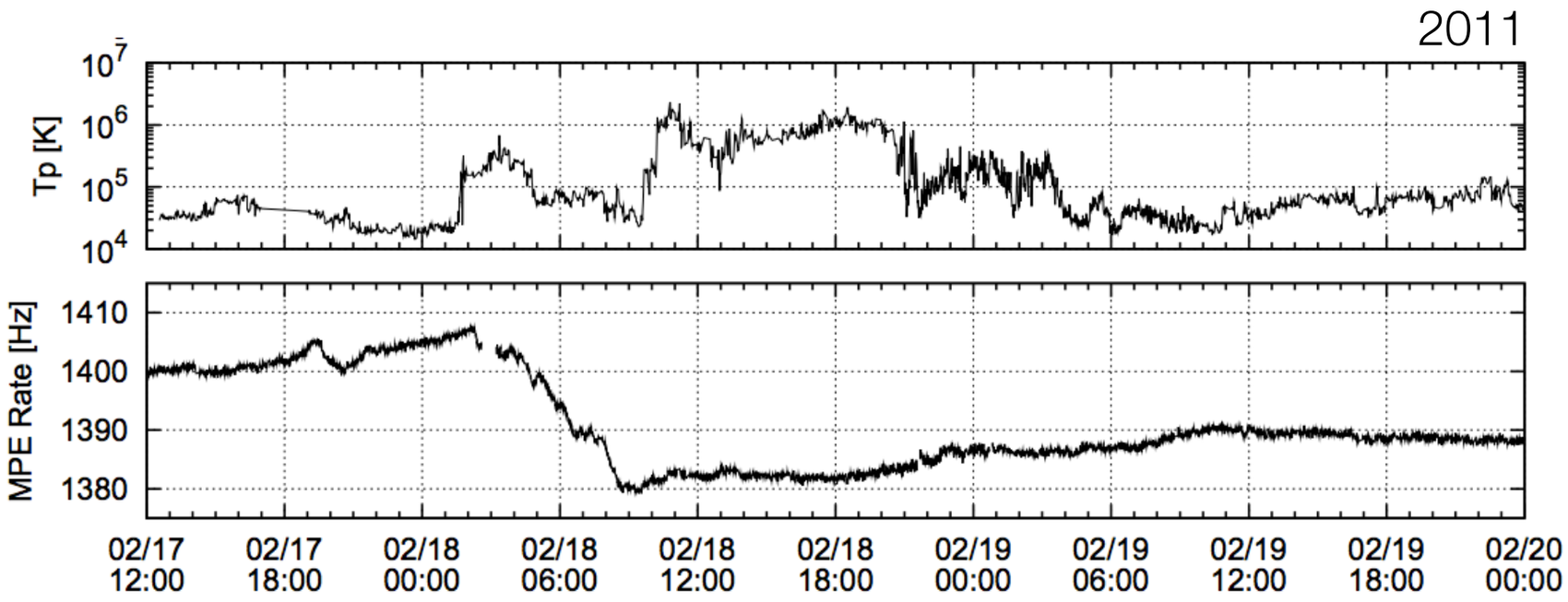

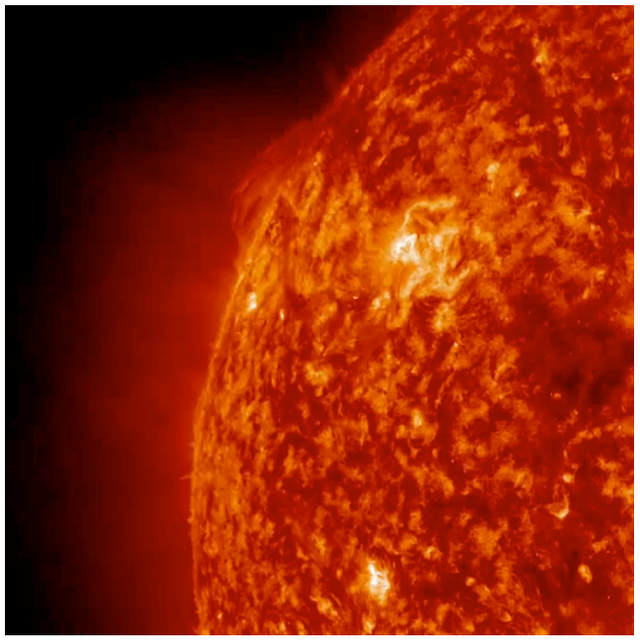

coronal mass ejection