A self-consistent model for the Galactic cosmic ray, antiproton and positron spectra

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APC, Paris

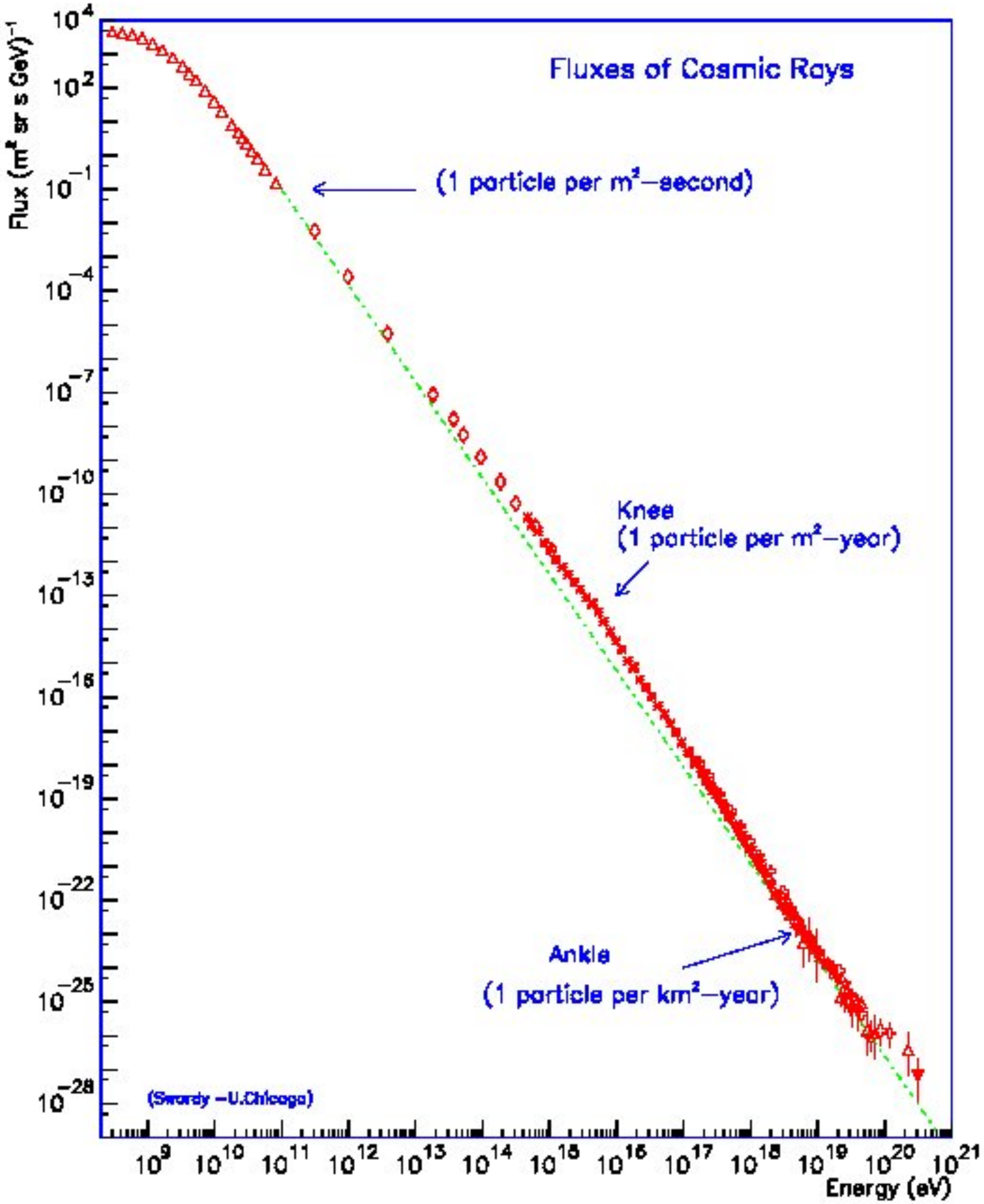
With G.Giacinti and M.Kachelriess, A.Neronov, and V.Savchenko

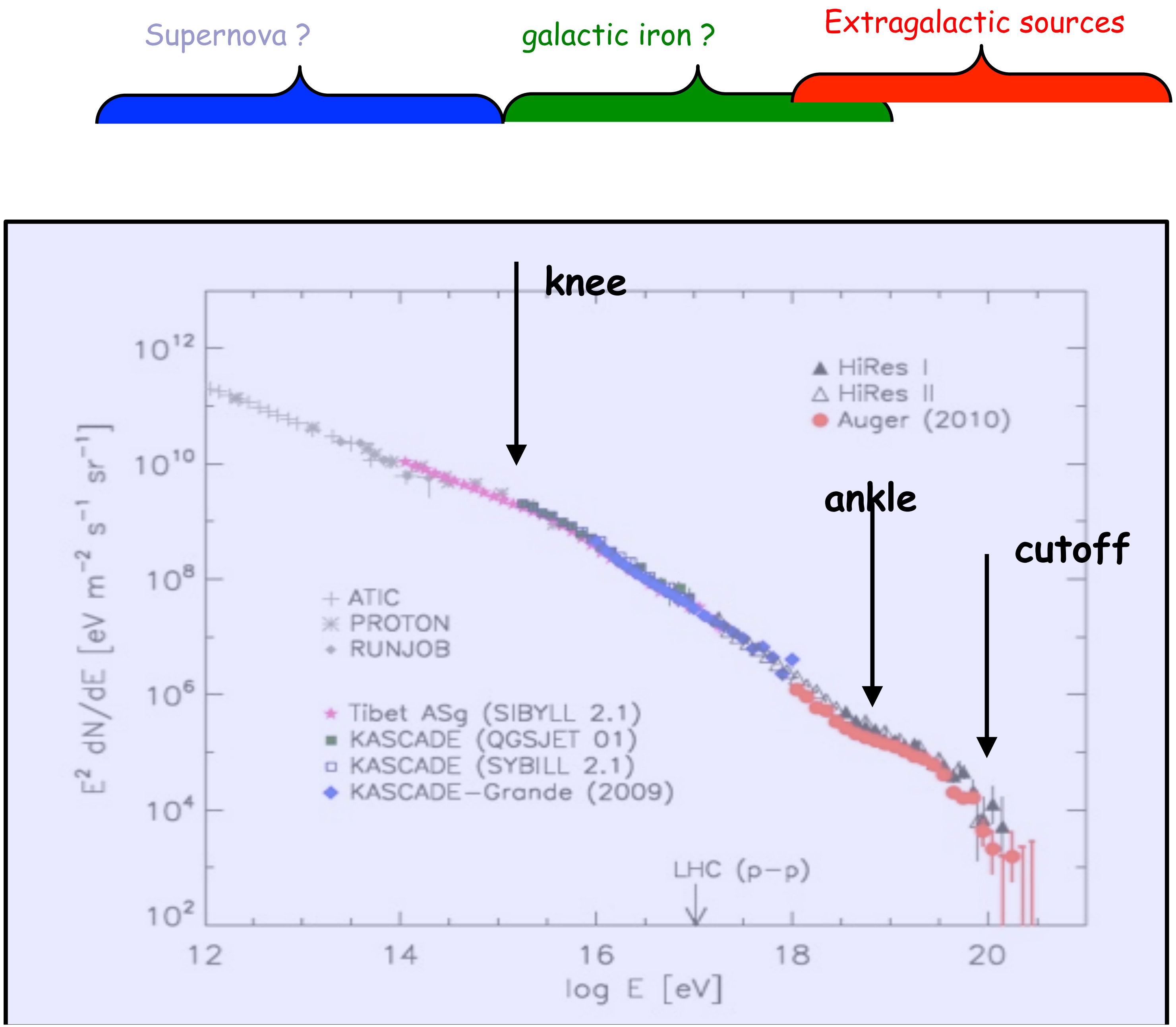
arxiv: 1307.2158, 1403.3380, 1412.1690 1502.01608, 1504.06472 and 1505.02720

Overview:

- *Introduction: cosmic rays*
- *Galactic Magnetic Field*
- *Cosmic ray escape from Galaxy: Knee region*
- *Galactic to extra-galactic cosmic ray transition*
- *Neutrinos in ICECUBE: galactic contribution*
- *Nearby 'recent' source: protons, secondary positrons and anti-protons*
- *Anisotropy*
- *Consclusions*

Galactic cosmic rays


Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
(Swordy – U.Chicago)
Flux (m² sr s GeV)⁻¹
Energy (eV)


Supernova ?
galactic iron ?
Extragalactic sources
knee
ankle
cutoff
HiRes I
HiRes II
Auger (2010)
ATIC
PROTON
RUNJOB
Tibet ASg (SIBYLL 2.1)
KASCADE (QGSJET 01)
KASCADE (SYBILL 2.1)
KASCADE−Grande (2009)
LHC (p−p)
E^2 dN/dE [eV m^{-2} s^{-1} sr^{-1}]
10^{12}
10^{10}
10^8
10^6
10^4
10^2
12
14
16
18
20
log E [eV]

Direct detection of cosmic rays

Stratospheric Balloons: from few hrs to months

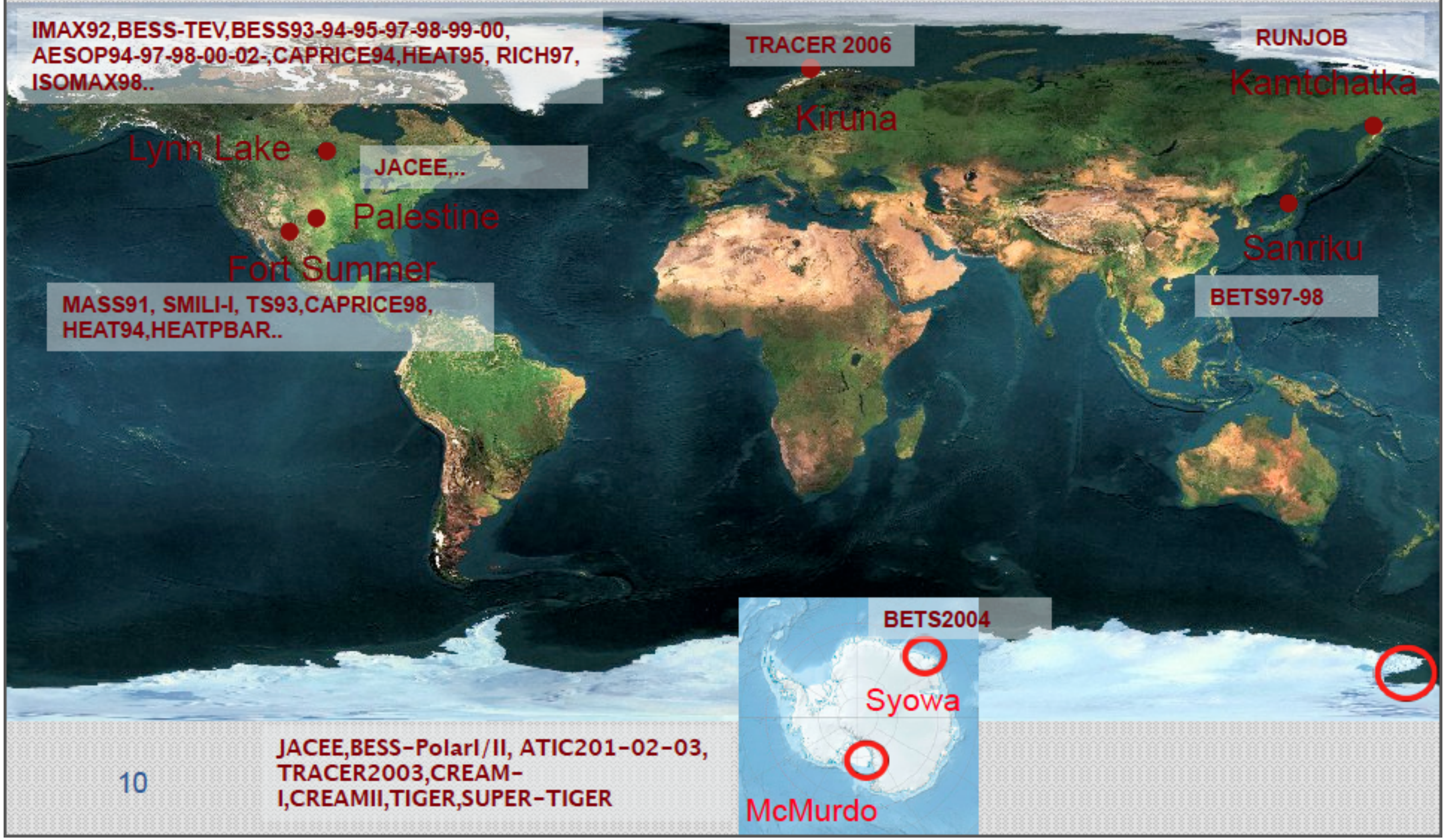
Magnetic Spectrometers

...

- BESS/POLAR/TEV (11 Flights)
- WIZARD (6,Flights)
- HEAT/PBAR (4,Flights)

Calorimetry, TRD +..

- RUNJOB (62 day, 10 Flights)
- TRACER (18 days, 3 Flights)
- CREAM (161 days,6 Flights)
- ATIC (53 days, 3 Flights)
- TIGER/S-TIGER (2/55 days)



Space:

Long missions (years)
Small payloads
Low energies..

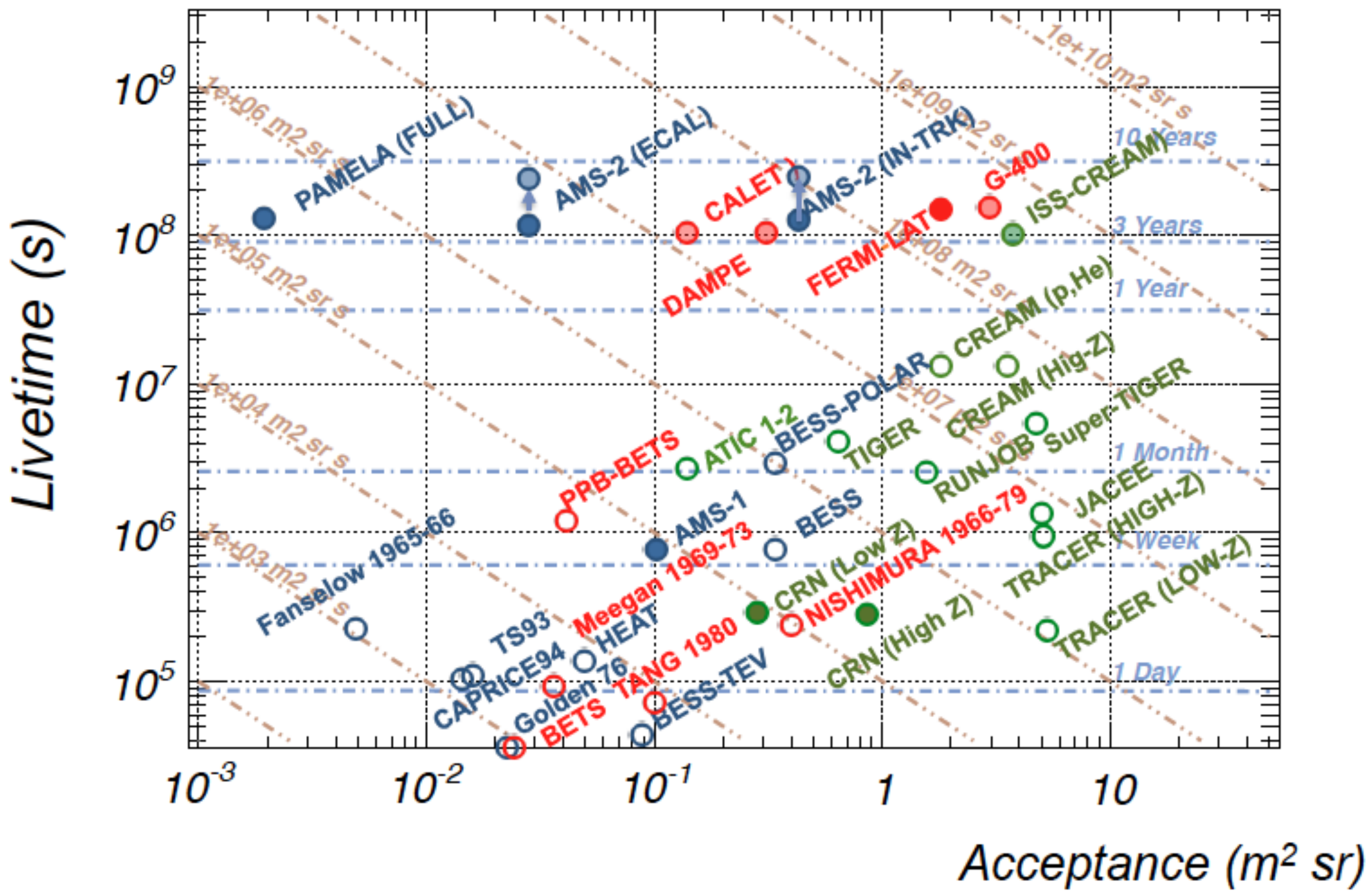
IMP series < GeV/n
ACE-CRIS/SIS Ekin < GeV/n
VOYAGER-HET/CRS < 100 MeV/n
ULYSSES-HET (nuclei) < 100 MeV/n
ULYSSES-KET (electrons) < 10 GeV
CRRES/ONR < (nuclei) 600 MeV/n
HEAO3-C2 (nuclei) < 40 GeV/n

Short missions (days)/ Largerpayloads

CRN on Challenger
(3.5 days 1985)

AMS-01 on Discovery
(8 days, 1998)

Long missions
Large payloads



○ No B field, different techniques with main focus on Z

○ No B field, different techniques with main focus on e,γ

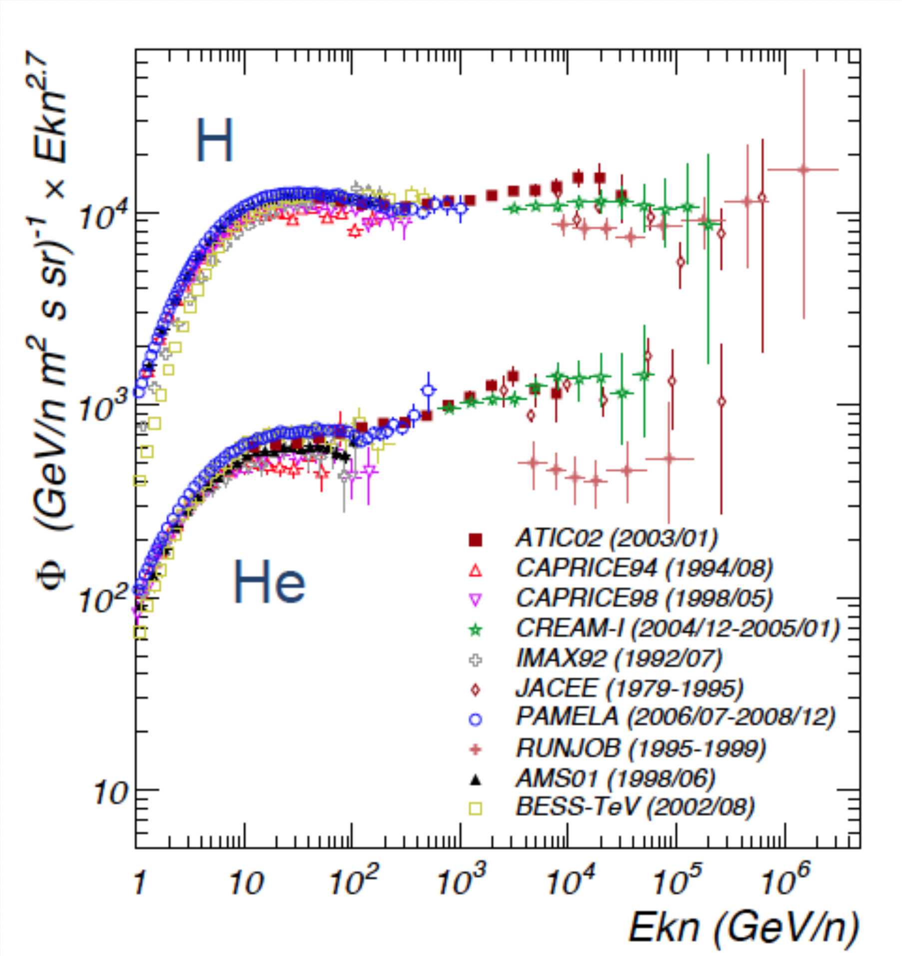
○ Magnetic spectrometers

○ Balloon

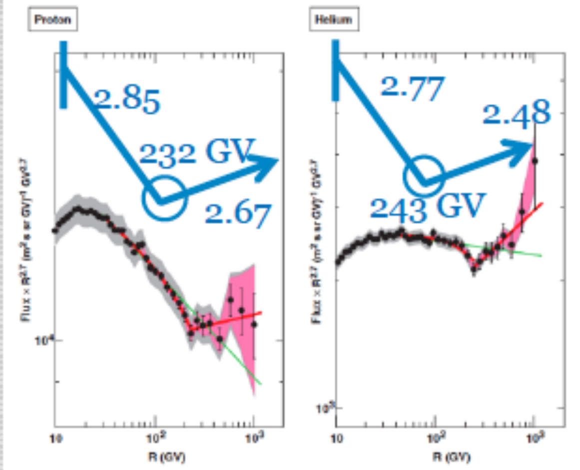
● Space

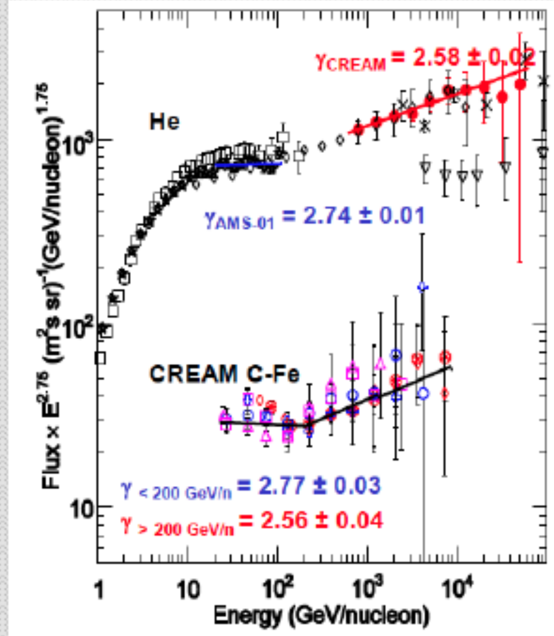
● Space (planned)

p/He spectra



Adriani, Science 32,69 (2011)

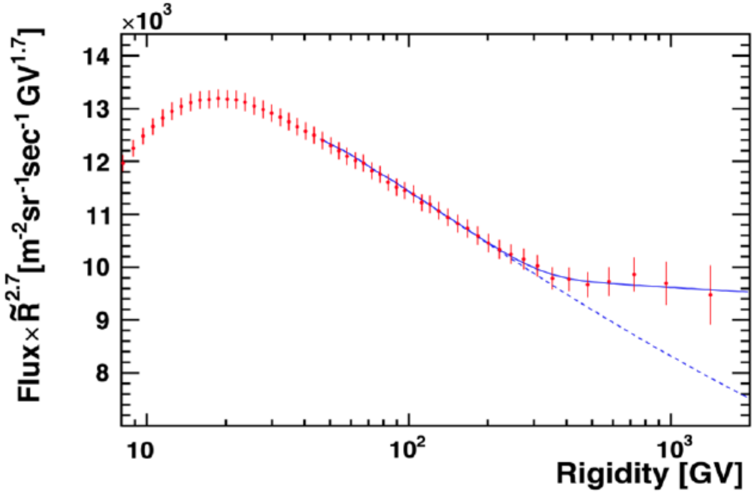




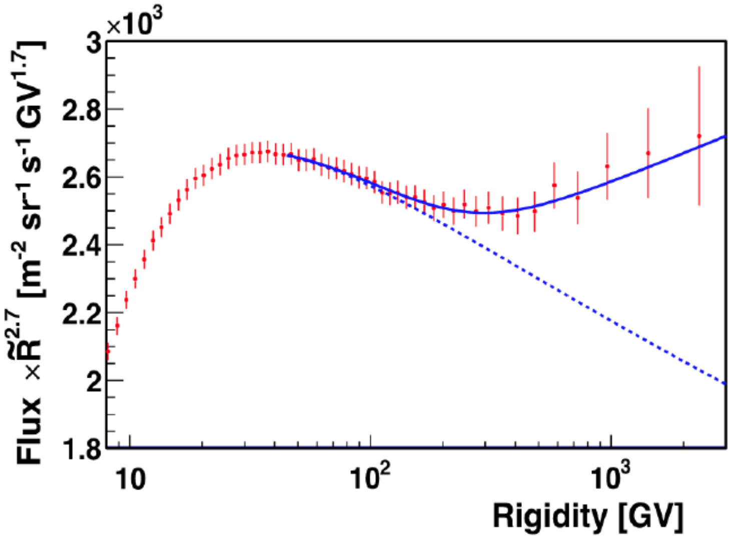
Still waiting for full CREAM statistics
AMS-02 publication soon….(< 2015)

AMS-2 results

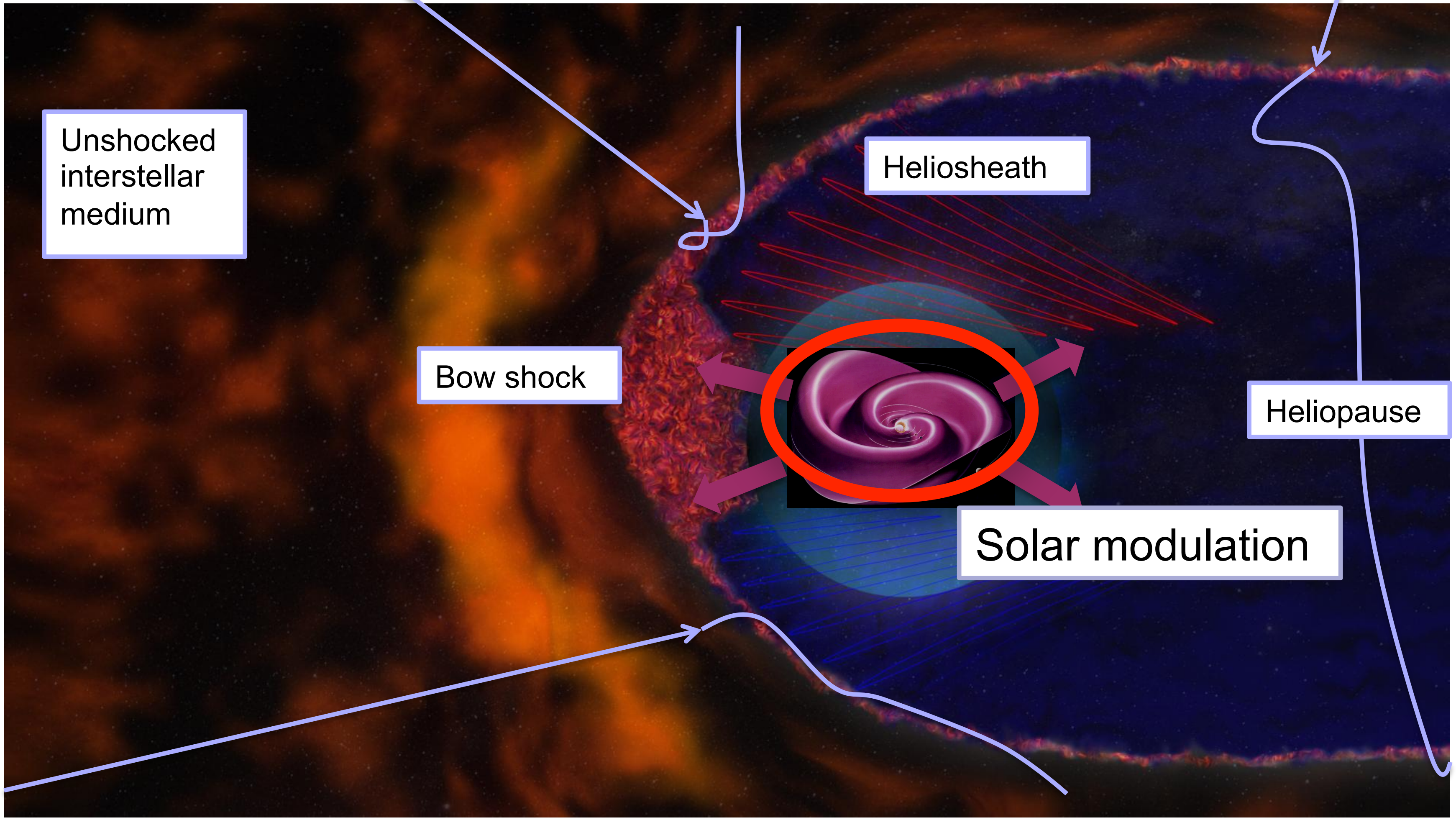
AMS-2 protons



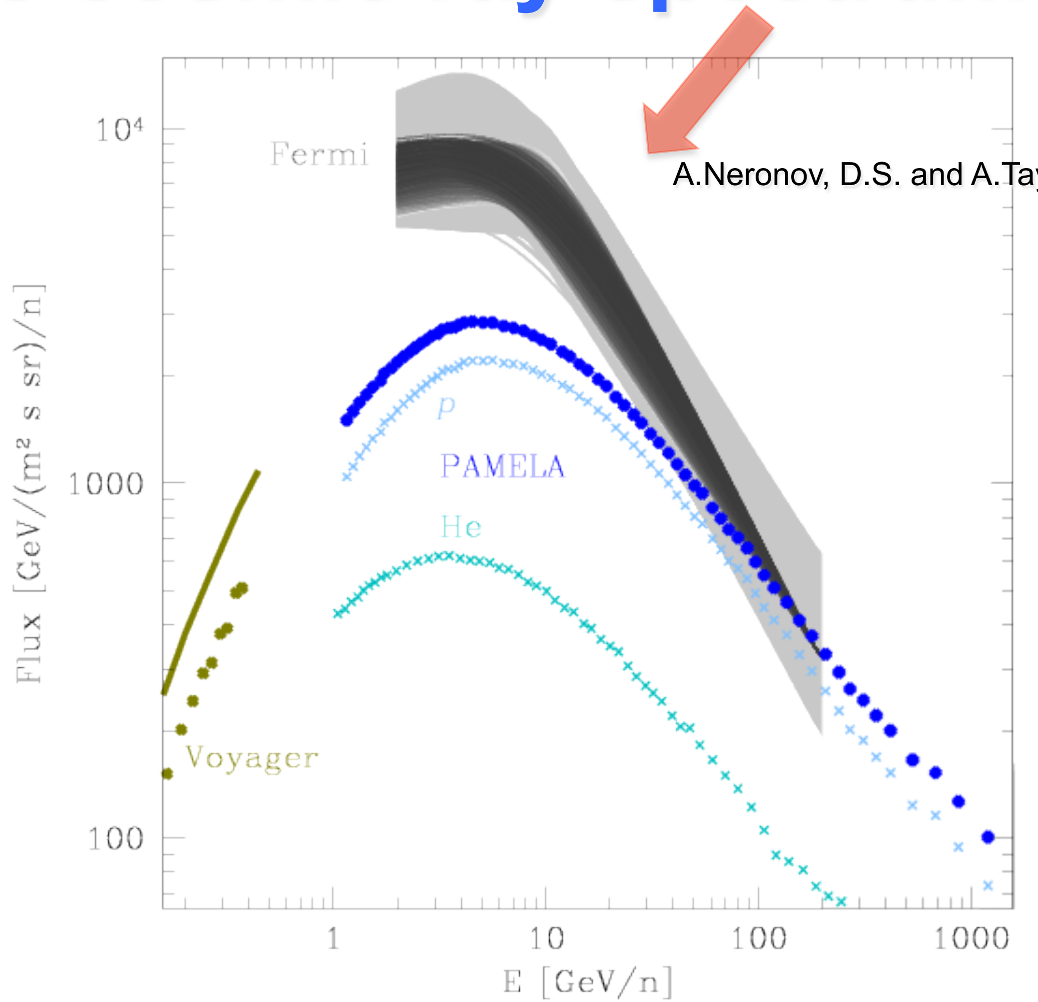
AMS-2 He



Cosmic Rays in the Solar system



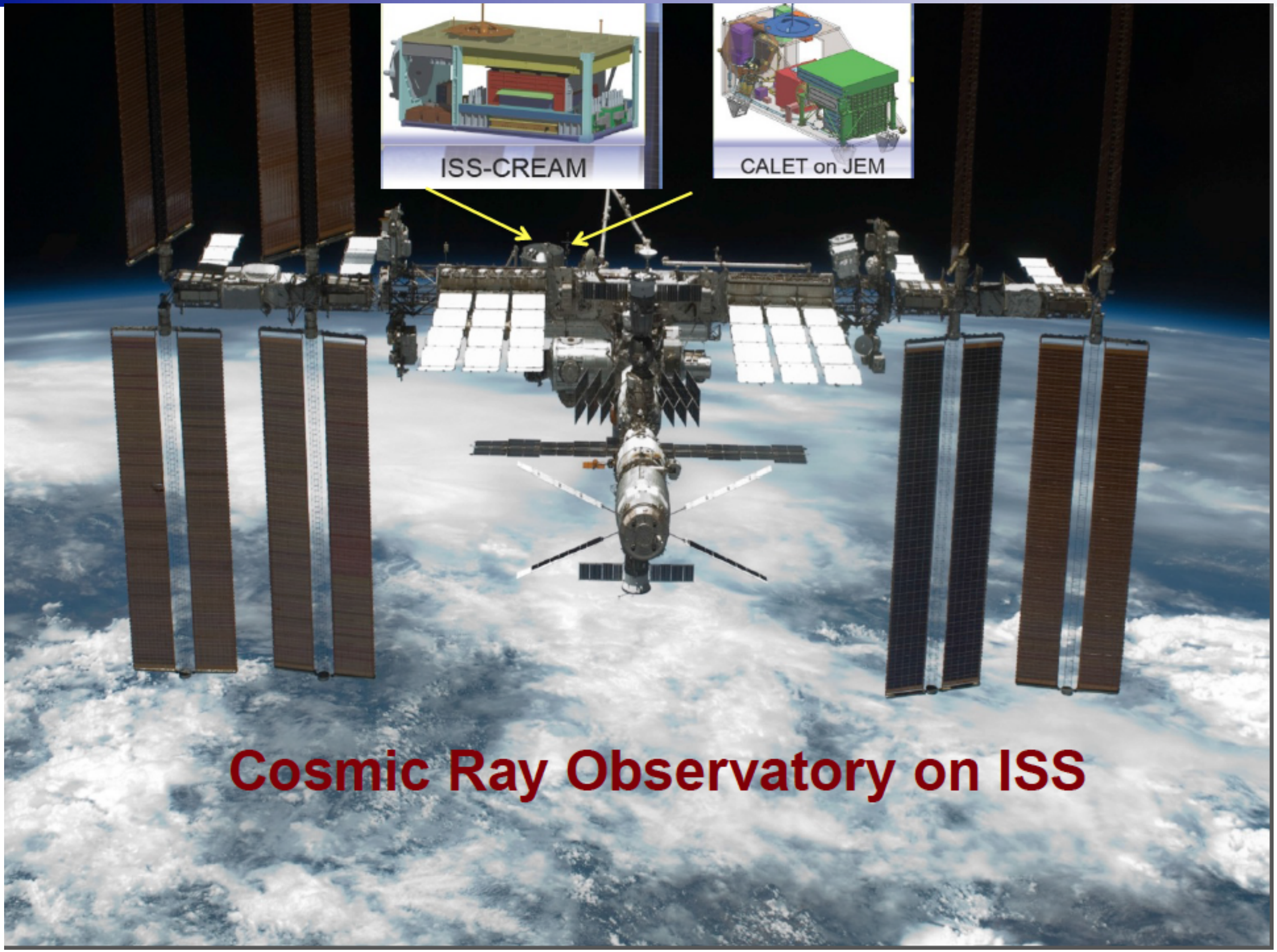
Galactic cosmic ray spectrum

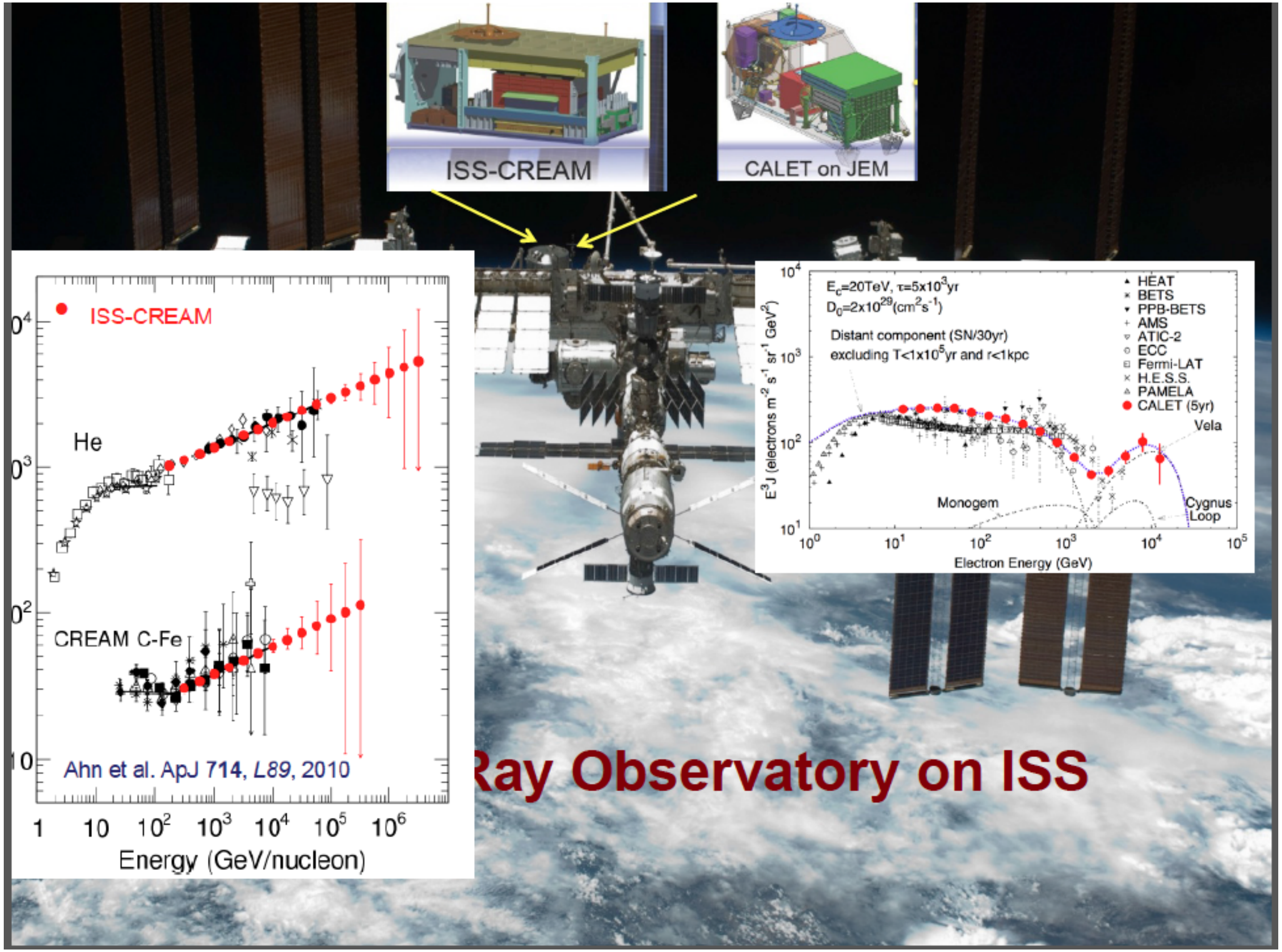


A.Neronov, D.S. and A.Taylor, PRL, 108, 051105 (2012)

Measurement of the spectrum of Galactic CRs not affected by the Heliospheric effects could be deduced from the gamma-ray spectrum of the Giant Molecular clouds.

Galactic cosmic ray spectrum has a strong break at the energy ~few GeV.


ISS-CREAM
CALET on JEM
Cosmic Ray Observatory on ISS



ISS-CREAM
CALET on JEM
ISS-CREAM
He
CREAM C-Fe
Ahn et al. ApJ 714, L89, 2010
Energy (GeV/nucleon)
Ray Observatory on ISS
E3J (electrons m-2 s-1 sr-1 GeV2)
Distant component (SN/30yr)
HEAT
BETS
PPB-BETS
AMS
ATIC-2
ECC
Fermi-LAT
H.E.S.S.
PAMELA
CALET (5yr)
Vela
Monogem
Cygnus Loop
Electron Energy (GeV)

Direct detection of cosmic rays

- *Best way to get information on particle spectra*
- *Can be affected by local Solar system MF at E<200 GeV*
- *Show harder power law spectra 1/E^2.5 or 2.55 for all nuclei, except protons are with alpha=2.7*
- *Can not go to knee (3 PeV energy) due to small statistics. One need in ground experiments.*

Indirect detection of cosmic rays

KASCADE experiment

40000 m² 10^{15}-10^{17} eV

Measure electron and muon size at Karlsruhe, Germany (near sea level).
Energy spectra of 5 primary mass groups are obtained from two dimensional Ne-Nμ spectrum by unfolding method (P,He,CNO,Si,Fe).

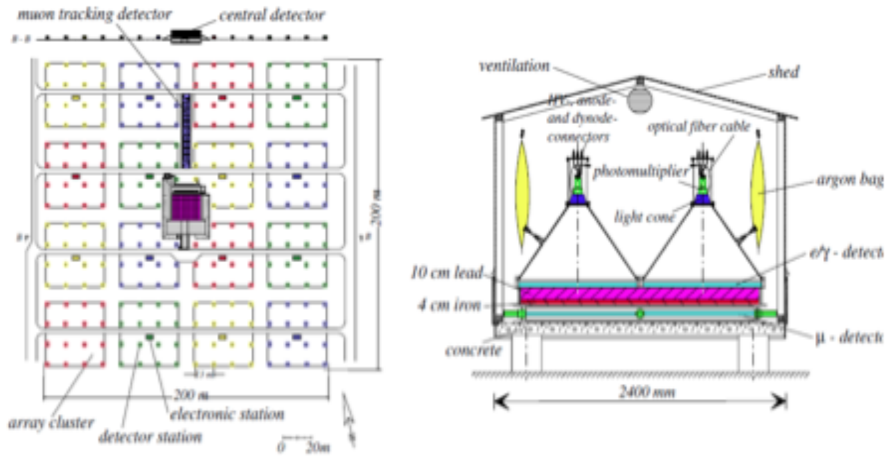


Fig. 1. Left: layout of the KASCADE air shower experiment; Right: sketch of a detector station with shielded and unshielded scintillation detectors.

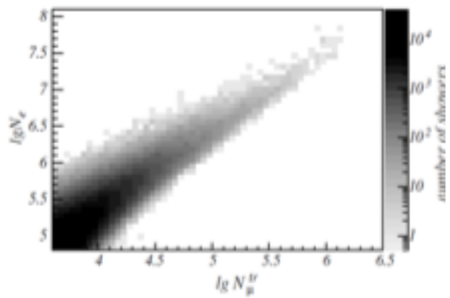
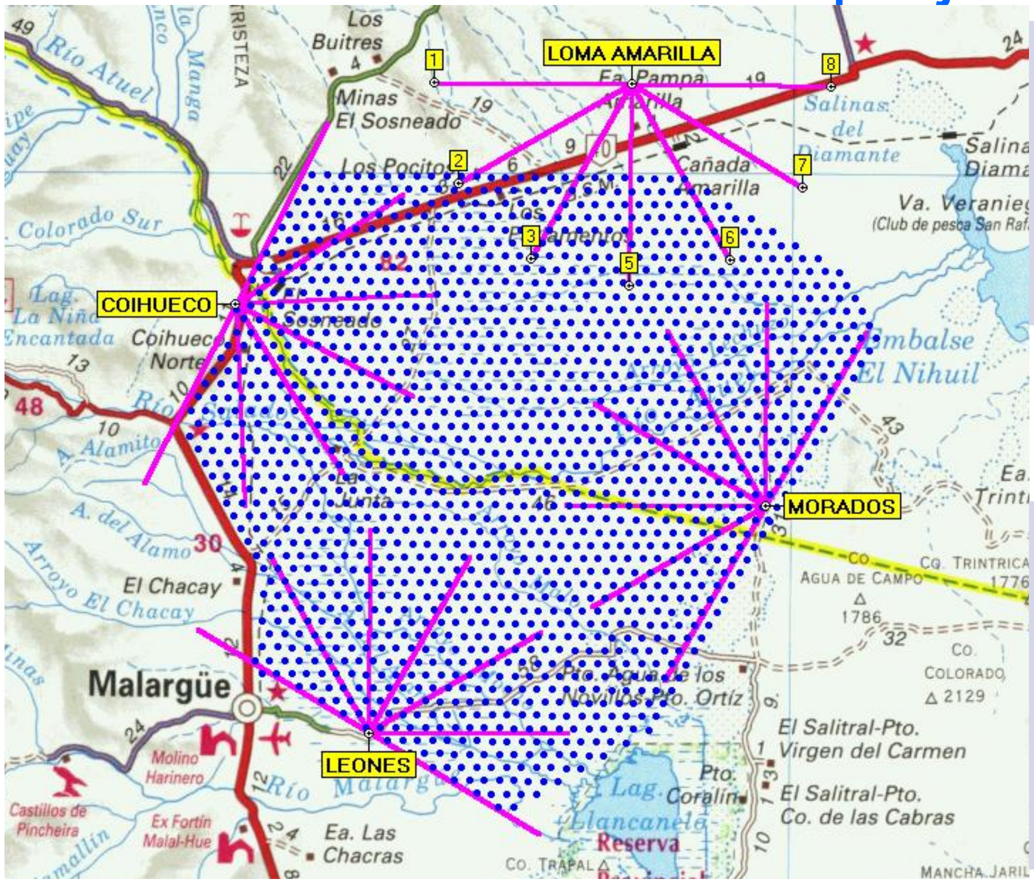


Fig. 2. Two-dimensional shower size spectrum used in th analysis. The range in lg N_e and lg N_μ^{tr} is chosen to avoi influences of inefficiencies.

Pierre Auger Observatory

South site in Argentina almost finished
North site – project



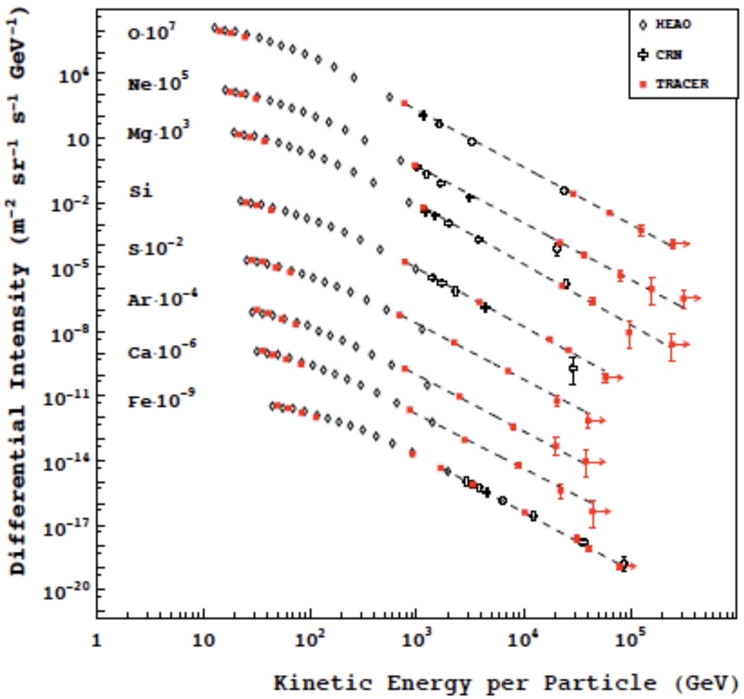
Surface Array

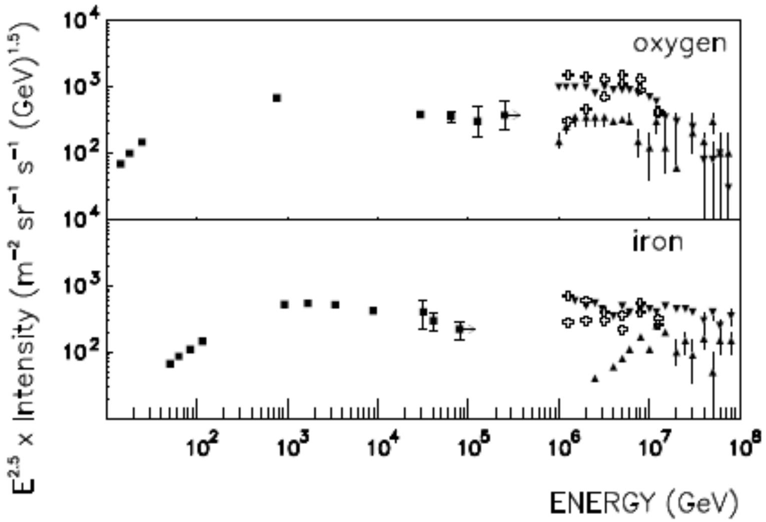
- ***1600 detector stations***
- ***1.5 Km spacing***
- ***3000 Km^2 (30xAGASA)***

Fluorescence Detectors

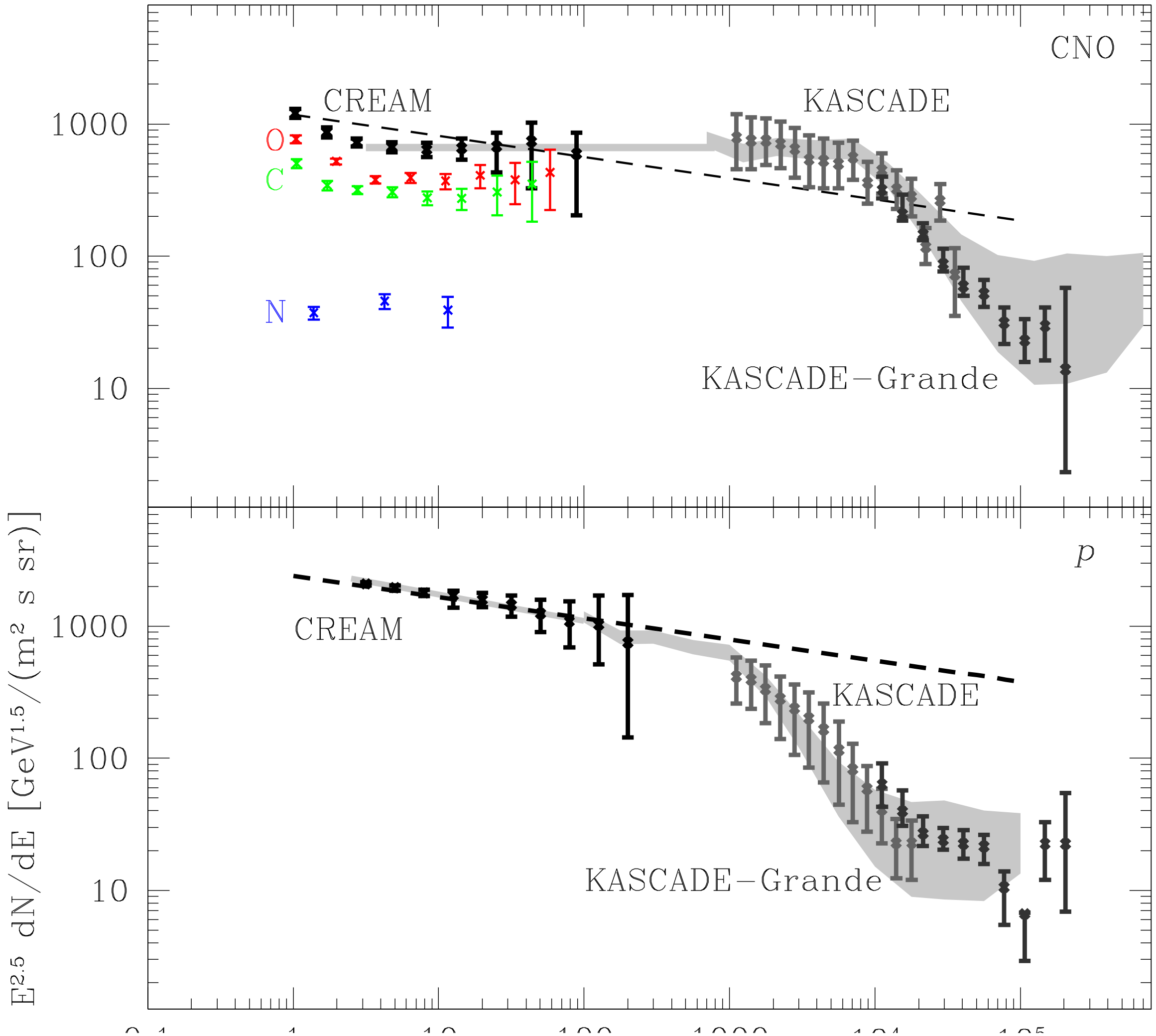
- ***4 Telescope enclosures***
- ***6 Telescopes per enclosure***
- ***24 Telescopes total***

Spectra of individual nuclei

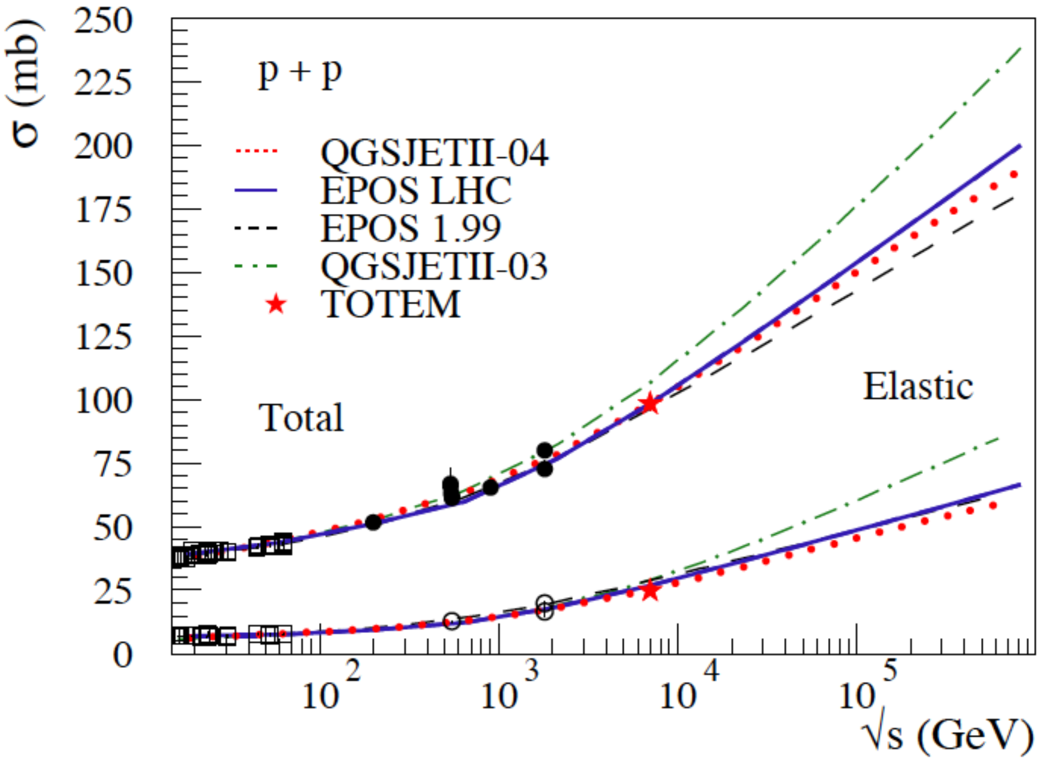




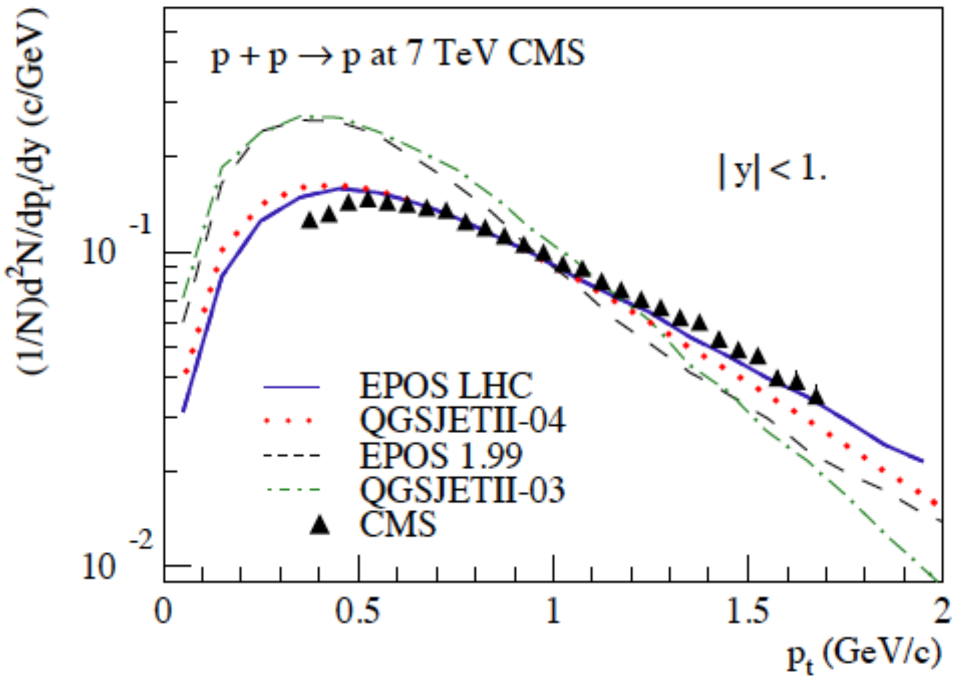
Proton and CNO spectra



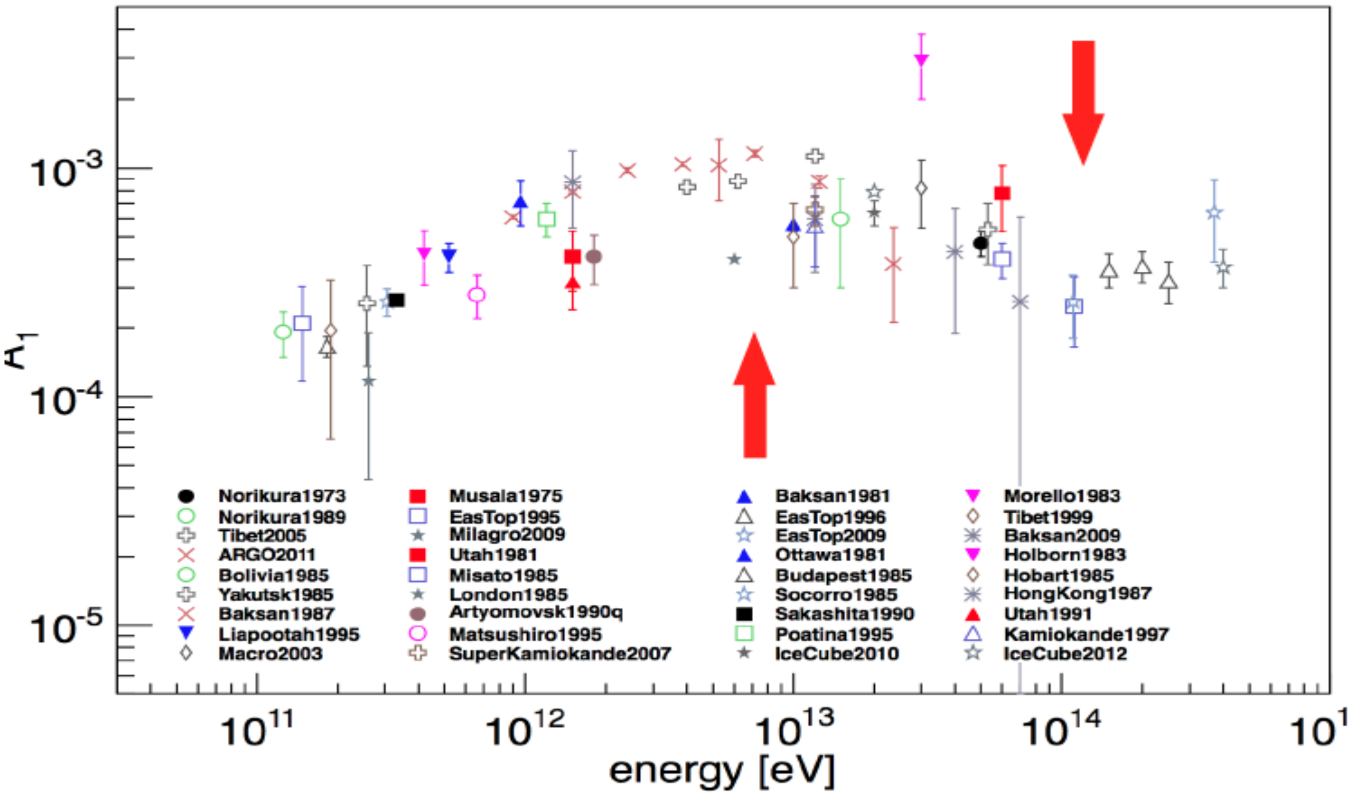
Total cross section



Distribution of secondaries

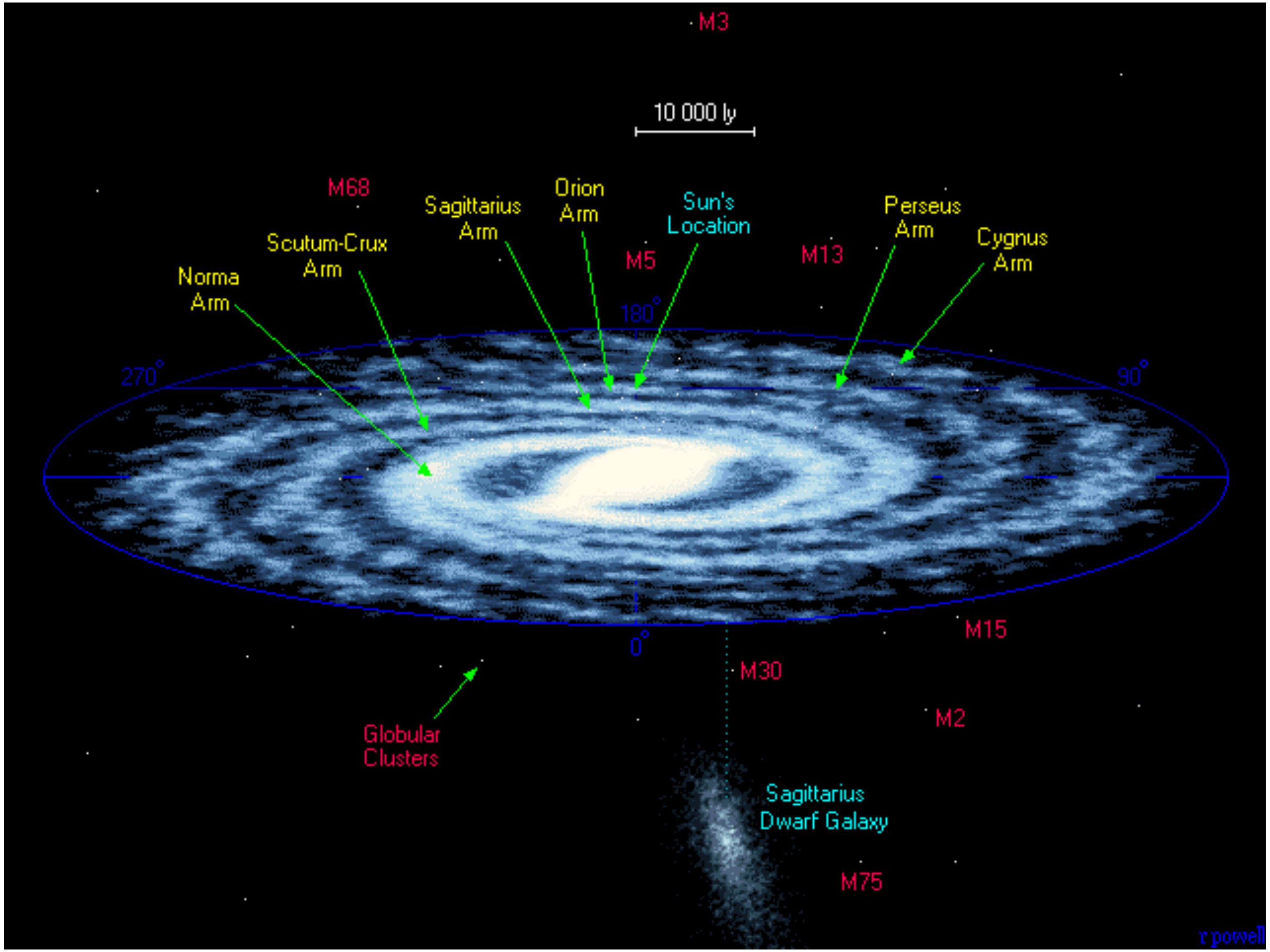


Dipole anisotropy



Galactic magnetic field

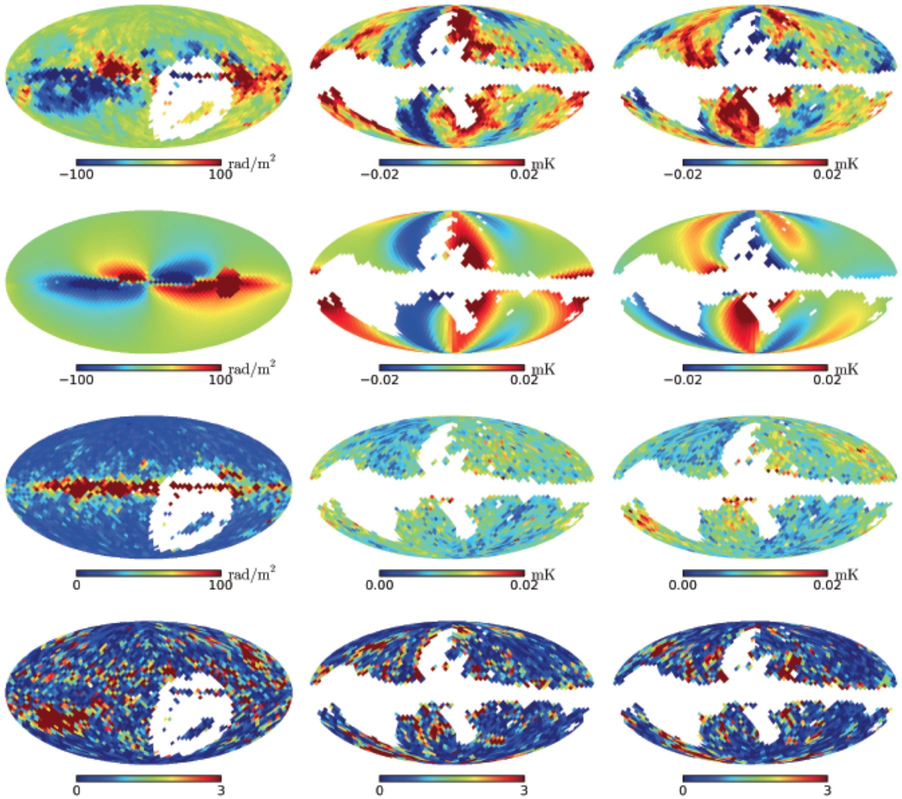
MILKY WAY GALAXY



Galactic magnetic field

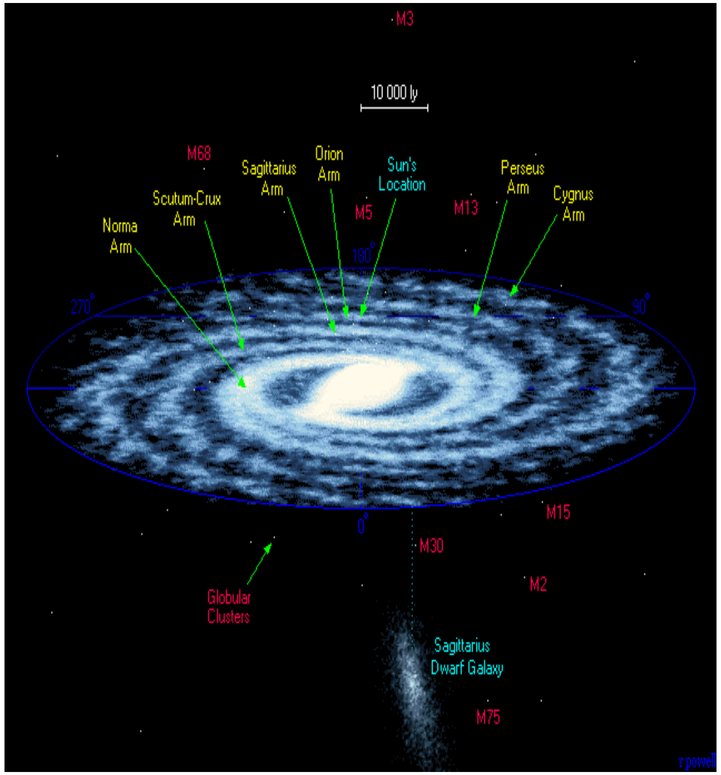
- B = B_disk (regular) + B_disk (turbulent) + B_halo(regular) + B_halo (turbulent)

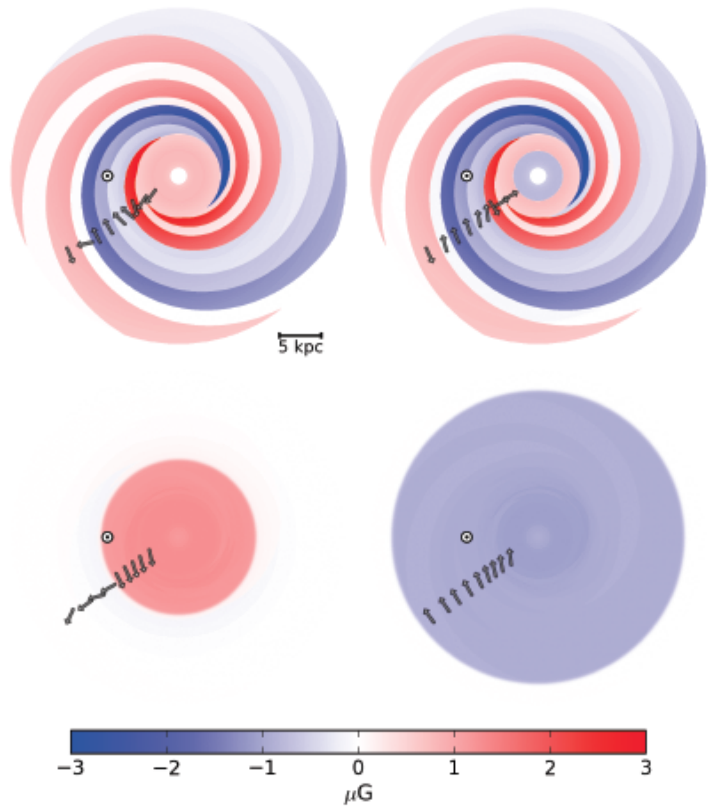
Synchrotron/RM maps



From R.Jansson & G.Farrar, arXiv:1204.3662

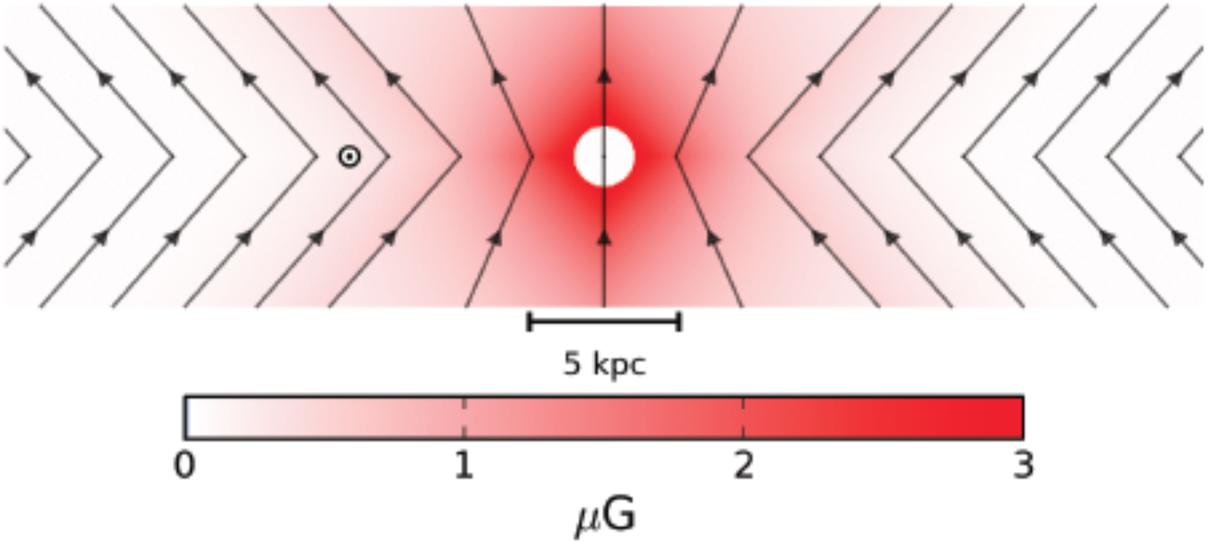
Galactic magnetic field: disk





R.Jansson & G.Farrar, arXiv:1204.3662

Galactic magnetic field halo: x-shape



R.Jansson & G.Farrar, arXiv:1204.3662

GMF regular field parameters

Table 1
Best-fit GMF parameters with $1-\sigma$ intervals.

Field	Best fit Parameters	Description
Disk	$b_1 = 0.1 \pm 1.8\,\mu$G	field strengths at $r = 5$ kpc
	$b_2 = 3.0 \pm 0.6\,\mu$G	
	$b_3 = -0.9 \pm 0.8\,\mu$G	
	$b_4 = -0.8 \pm 0.3\,\mu$G	
	$b_5 = -2.0 \pm 0.1\,\mu$G	
	$b_6 = -4.2 \pm 0.5\,\mu$G	
	$b_7 = 0.0 \pm 1.8\,\mu$G	
	$b_8 = 2.7 \pm 1.8\,\mu$G	inferred from $b_1, ..., b_7$
	$b_{\rm ring} = 0.1 \pm 0.1\,\mu$G	ring at 3 kpc $< r <$ 5 kpc
	$h_{\rm disk} = 0.40 \pm 0.03$ kpc	disk/halo transition
	$w_{\rm disk} = 0.27 \pm 0.08$ kpc	transition width
Toroidal halo	$B_{\rm n} = 1.4 \pm 0.1\,\mu$G	northern halo
	$B_{\rm s} = -1.1 \pm 0.1\,\mu$G	southern halo
	$r_{\rm n} = 9.22 \pm 0.08$ kpc	transition radius, north
	$r_{\rm s} > 16.7$ kpc	transition radius, south
	$w_{\rm h} = 0.20 \pm 0.12$ kpc	transition width
	$z_0 = 5.3 \pm 1.6$ kpc	vertical scale height
X halo	$B_{\rm X} = 4.6 \pm 0.3\,\mu$G	field strength at origin
	$\Theta^0_{\rm X} = 49 \pm 1°$	elev. angle at $z = 0, r > r^c_{\rm X}$
	$r^c_{\rm X} = 4.8 \pm 0.2$ kpc	radius where $\Theta_{\rm X} = \Theta^0_{\rm X}$
	$r_{\rm X} = 2.9 \pm 0.1$ kpc	exponential scale length
striation	$\gamma = 2.92 \pm 0.14$	striation and/or $n_{\rm cre}$ rescaling

R.Jansson & G.Farrar, arXiv:1204.3662

Galactic magnetic field

- B = B_disk (regular) + B_disk (turbulent) + B_halo(regular) + B_halo (turbulent)

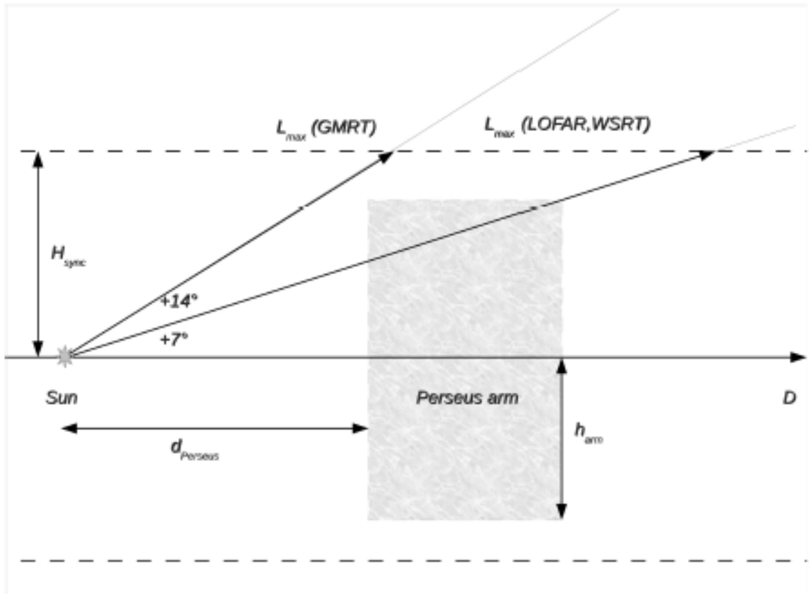
Galactic magnetic field: turbulent component

- Field with $\langle B(r) \rangle = 0 \qquad \langle B(r)^2 \rangle \equiv B_{\rm rms}^2 > 0.$
- Power spectrum $\mathcal{P}(k) \propto k^{-\alpha}, \qquad |B(k)|^2 \propto k^{-\alpha-2}$
- With index $\alpha = 5/3,\ 3/2$ for Kolmogorov/Kraichnan cases
- Correlation length

$$L_c = \frac{L_{\rm max}}{2} \frac{\alpha - 1}{\alpha} \frac{1 - (L_{\rm min}/L_{\rm max})^{\alpha}}{1 - (L_{\rm min}/L_{\rm max})^{\alpha-1}} .$$

- Where
- $L_{\rm min} = 1\,{\rm AU}$ Lmax=25-100 pc

LOFAR measurement of maximum scale of turbulent GMF in disk



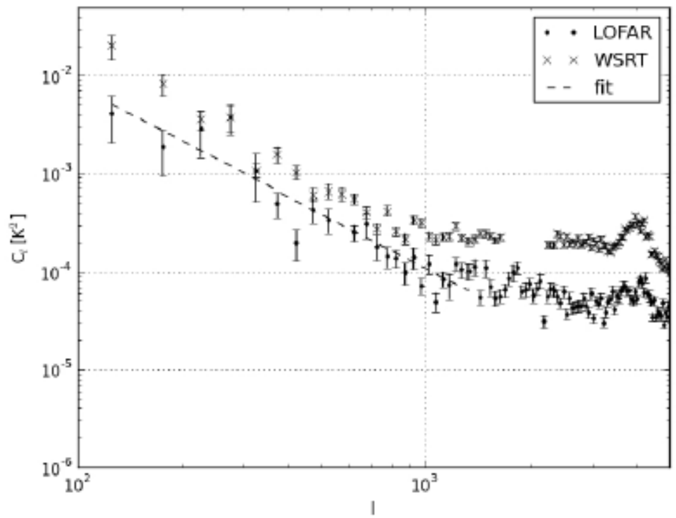


Fig. 9. Power spectra of total intensity from the LOFAR (dots) and WSRT (crosses) observations. The error bars indicate statistical errors at 1σ. The fitted power law (dashed line) with a spectral index $\alpha = -1.84 \pm 0.19$ for $\ell \in [100, 1300]$ is also shown.

arXiv: 1308.2804

Lmax ~ 20 pc +-6 pc in disk

Galactic magnetic field: turbulent component

- For G.Farrar model there is dedicated paper on turbulent component arXiv: 1210.7820

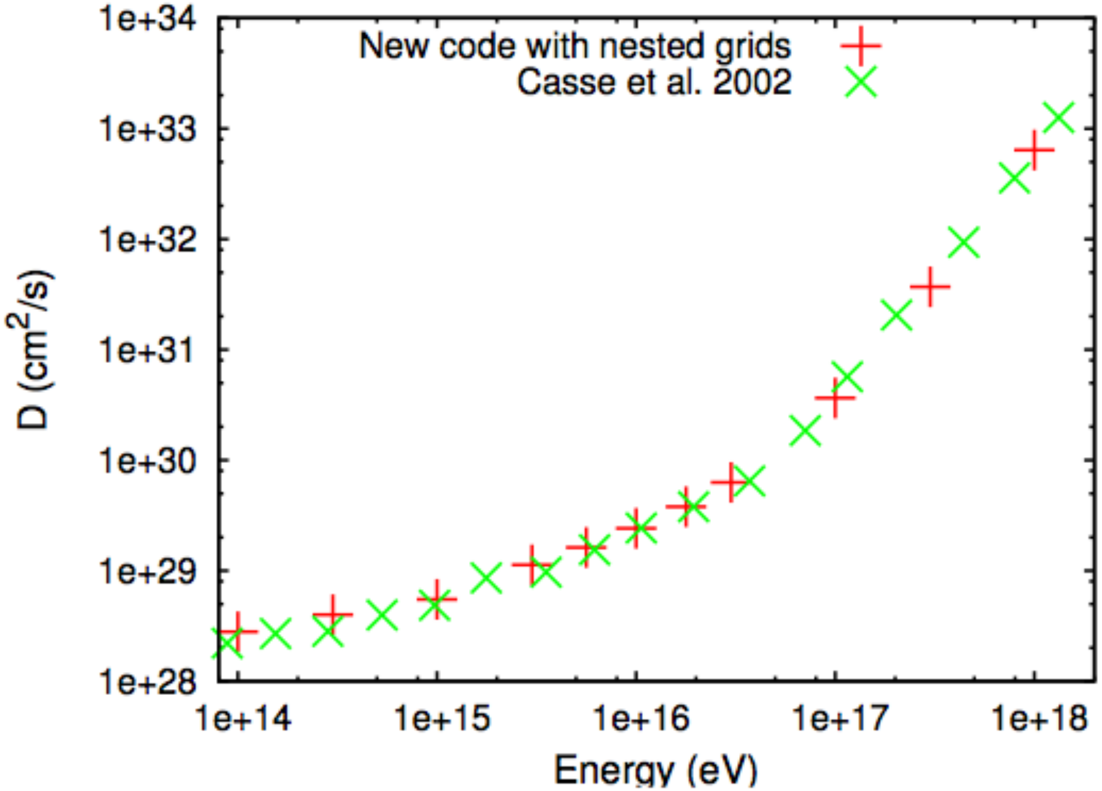
- For Pshirkov et al only deflection map in arXiv:1304.3217

$$B_{\rm rms}(r,z) = B(r)\exp\left(-\frac{|z|}{z_0}\right)$$

$B(r) = B_0 = 6\ \mu G$ $z_0 = 1.8$ kpc

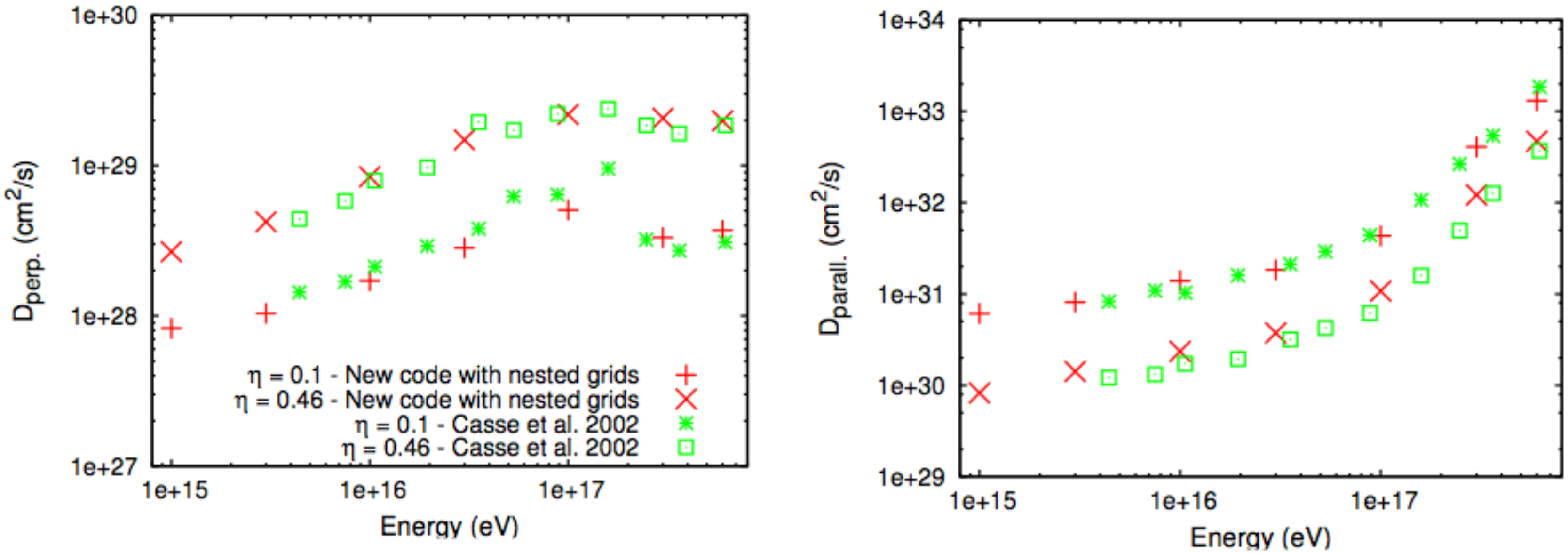
Thanks to G.Farrar and P.Tinyakov for discussion

Only turbulent diffusion



G.Giacinti et al, arXiv:1112.5599

Regular and turbulent diffusion



Escape model

ESCAPE MODEL:

- Idea: V. L. Ginzburg and S. I. Syrovatskii, *1962-1964; small angle diffusion approximation*
- Developement: V. S. Ptuskin et al., Astron. Astrophys. 268, 726 (1993); J. Candia, E. Roulet and L. N. Epele, JHEP 0212, 033 (2002); J. Candia, S. Mollerach and E. Roulet, JCAP 0305, 003 (2003). *Hall diffusion approximation*

Cosmic Ray Knee

.

- change of interactions at multi-TeV energies: excluded by LHC
- maximal energy of dominant CR sources – Hillas model
- knee at $R_L(E/Z) \simeq l_{\rm coh}$:

  $\Rightarrow$ change in diffusion from $D(E) \sim E^{1/3}$ to
  - Hall diffusion $D(E) \sim E$
  - small-angle scattering $D(E) \sim E^2$
  - something intermediate?

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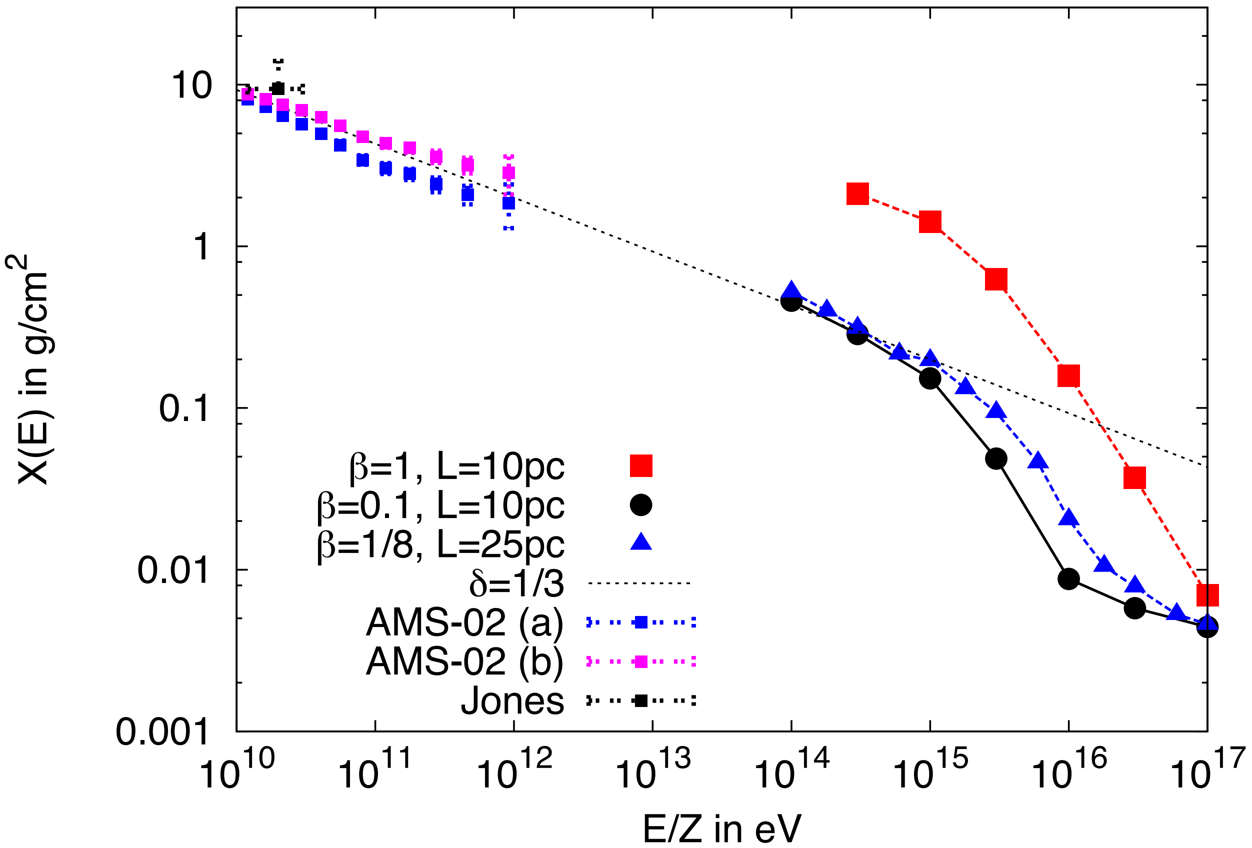
our approach:

- use model for Galactic magnetic field
- calculate trajectories $\boldsymbol{x}(t)$ via $\boldsymbol{F}_L = q\boldsymbol{v} \times \boldsymbol{B}$.

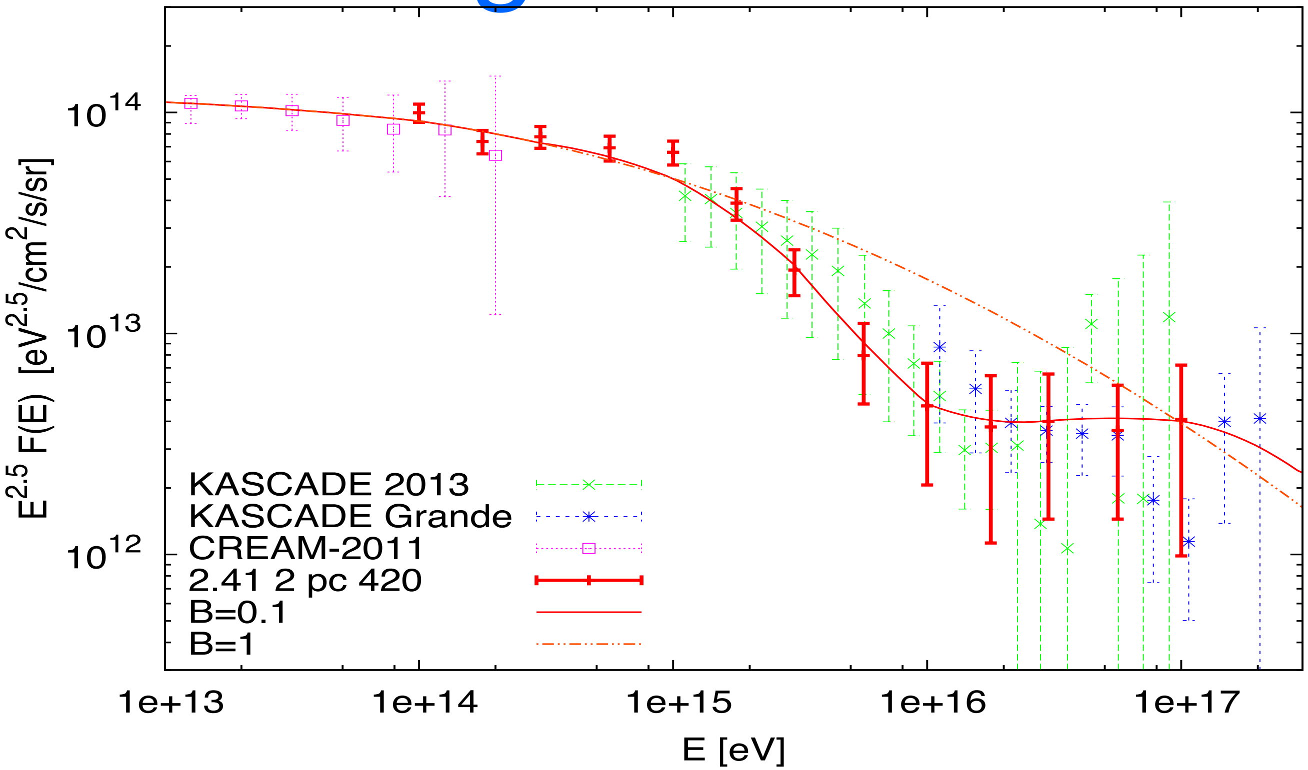
Grammage: amplitude of Bturb



$\Rightarrow$ prefers weak random fields

$\Rightarrow$ fluxes $I_A(E)$ of all isotopes fixed by low-energy data

Escape model does not work with large turbulent field

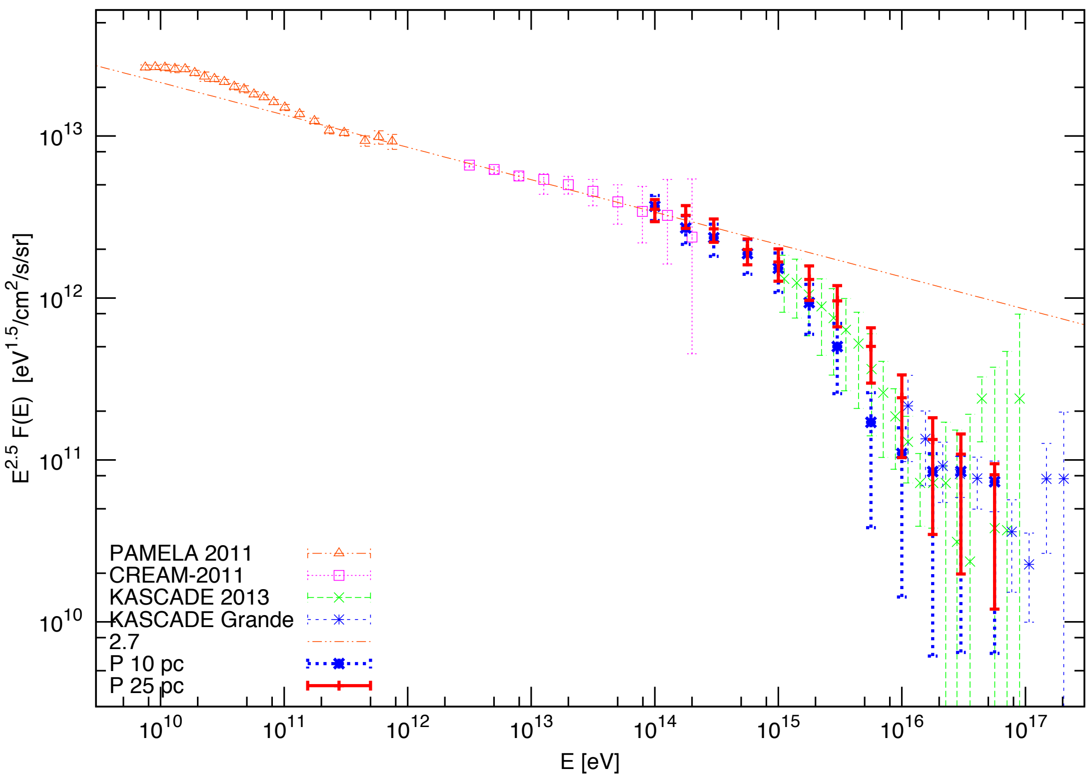


Magnetic field will be reduced by factor ~6 in next generation models. Thanks to G.Farrar for discussion.

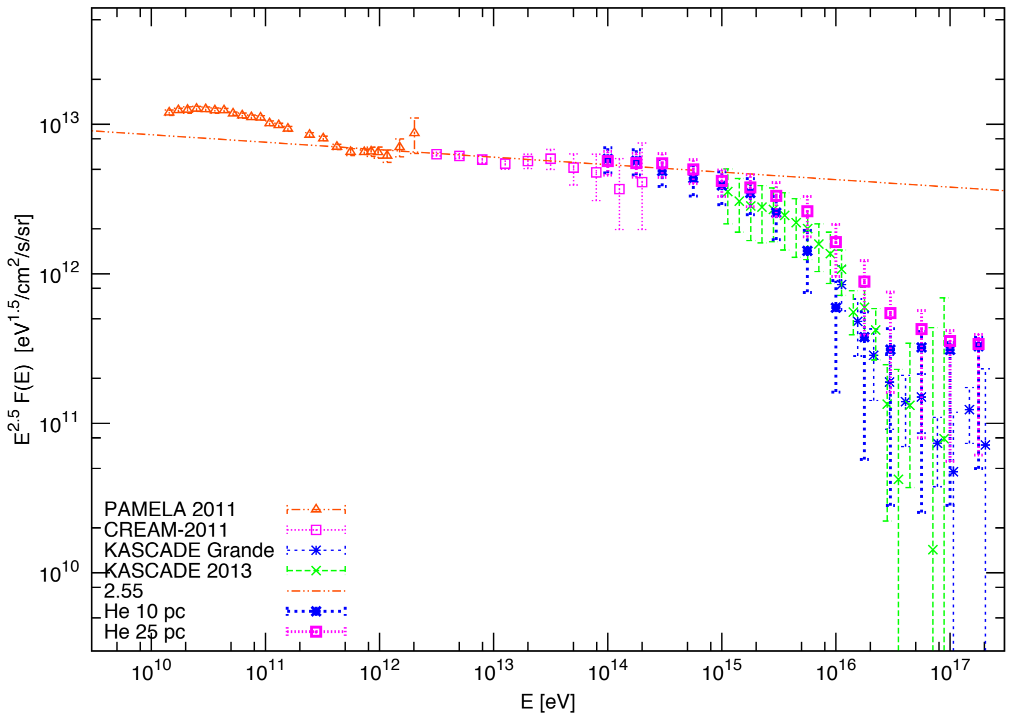
Model

- Sources with power law spectrum fitted to CREAM data at TeV region. $1/E^{\alpha}$
- Emax $=10^{17}$ eV $\alpha=2.4$ protons $\alpha=2.2$ nuclei
- Distributed as SN in Galaxy
- Turbulent field in disk with Kolmogorov turbulence and Lmax =25 pc
- GMF of Jansson & Farrar with reduced turbulent field amplitude in 8 times.

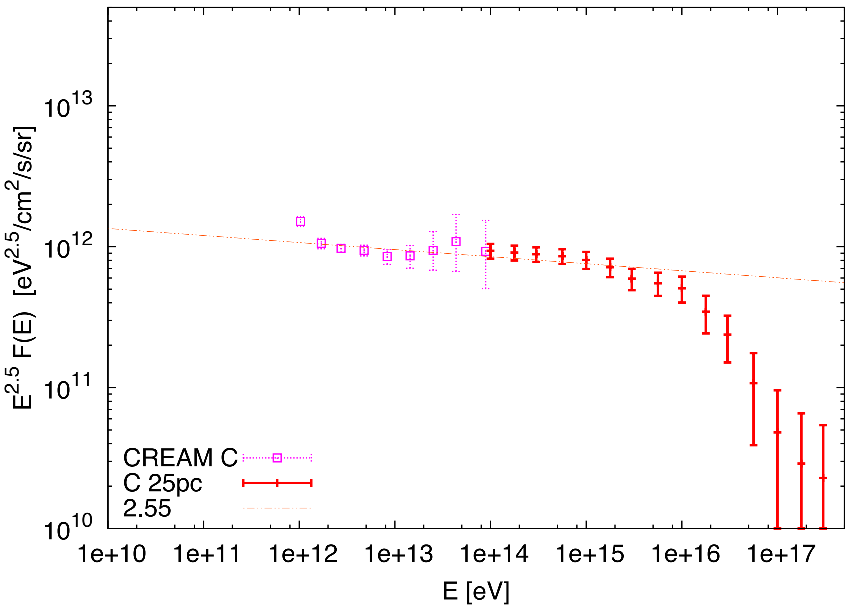
Cosmic Ray Knee: protons

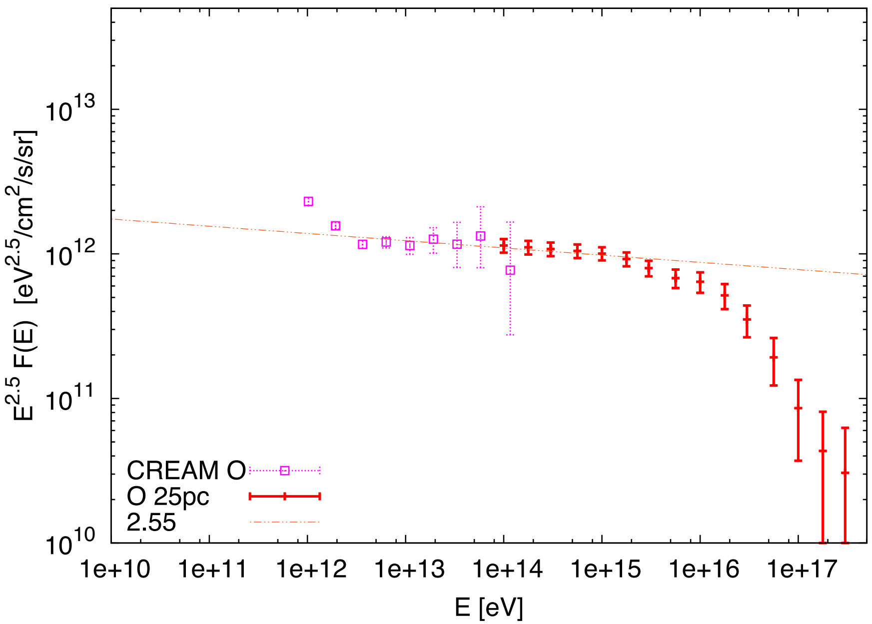


Cosmic Ray Knee: He

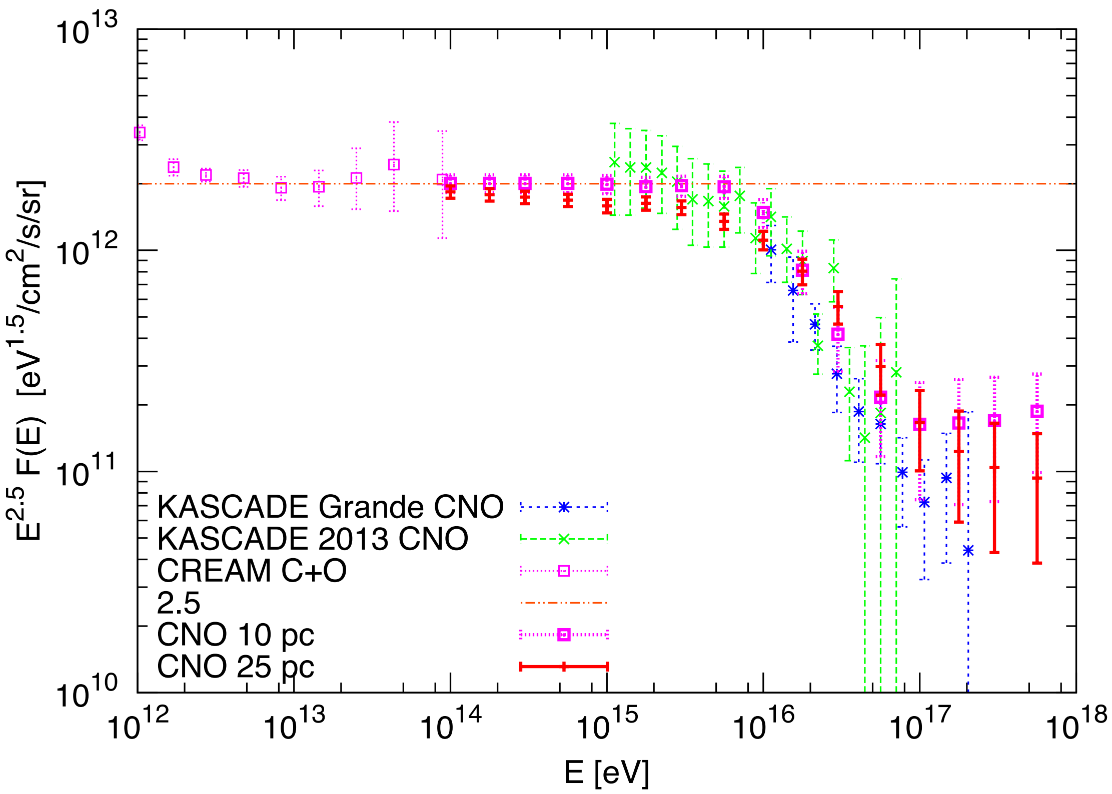


Cosmic Ray Knee: C and O

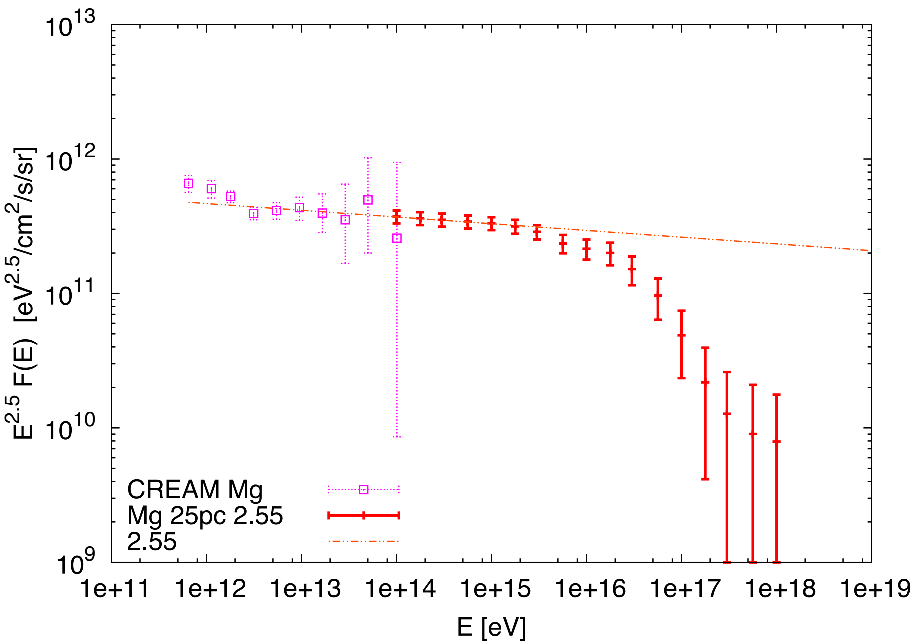


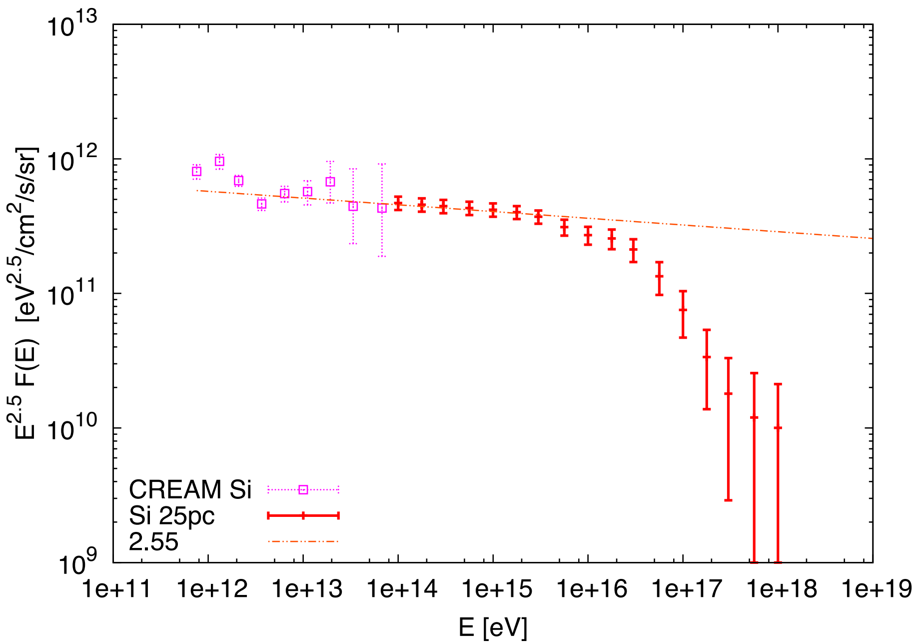


Cosmic Ray Knee: CNO

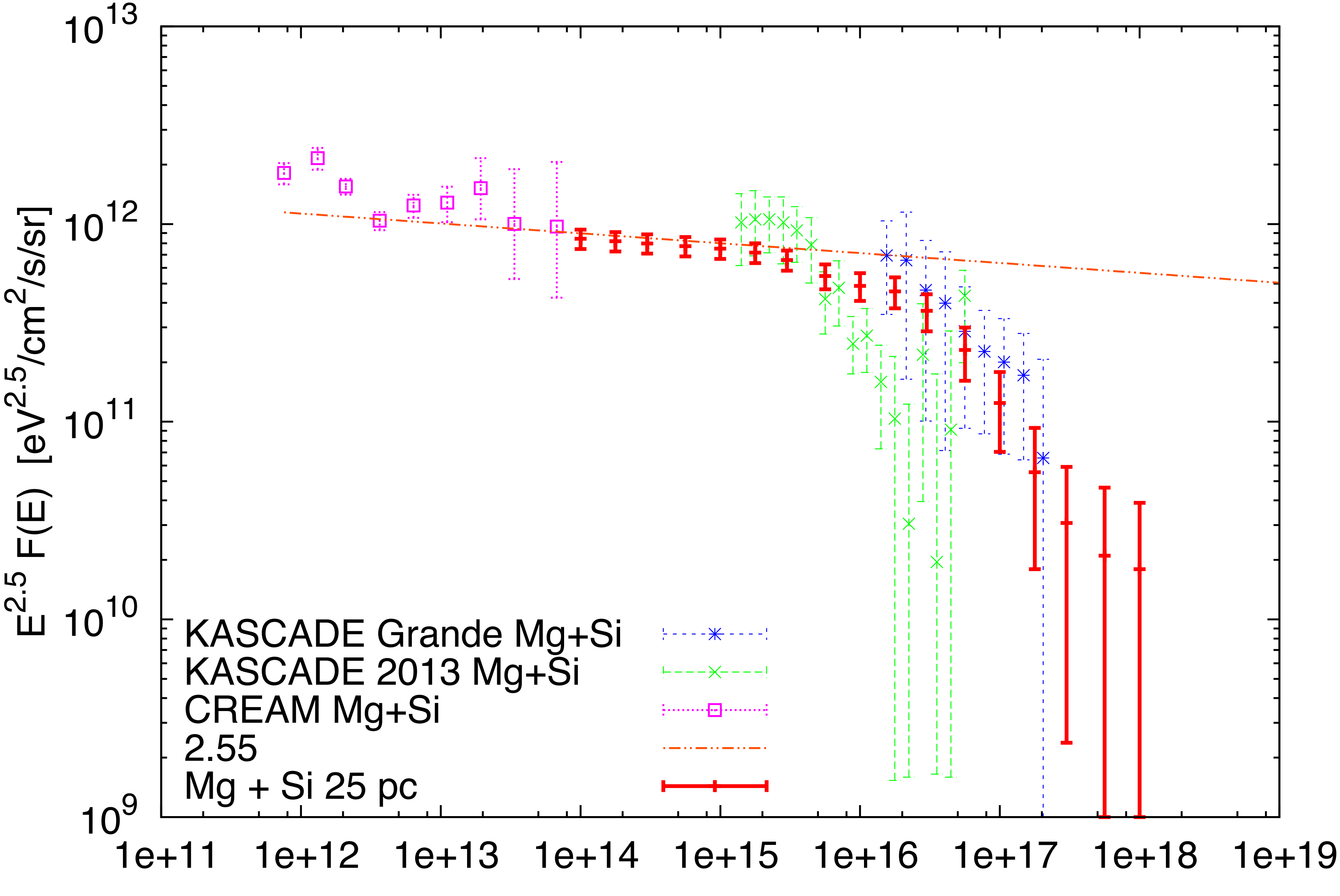


Cosmic Ray Knee: Mg and Si

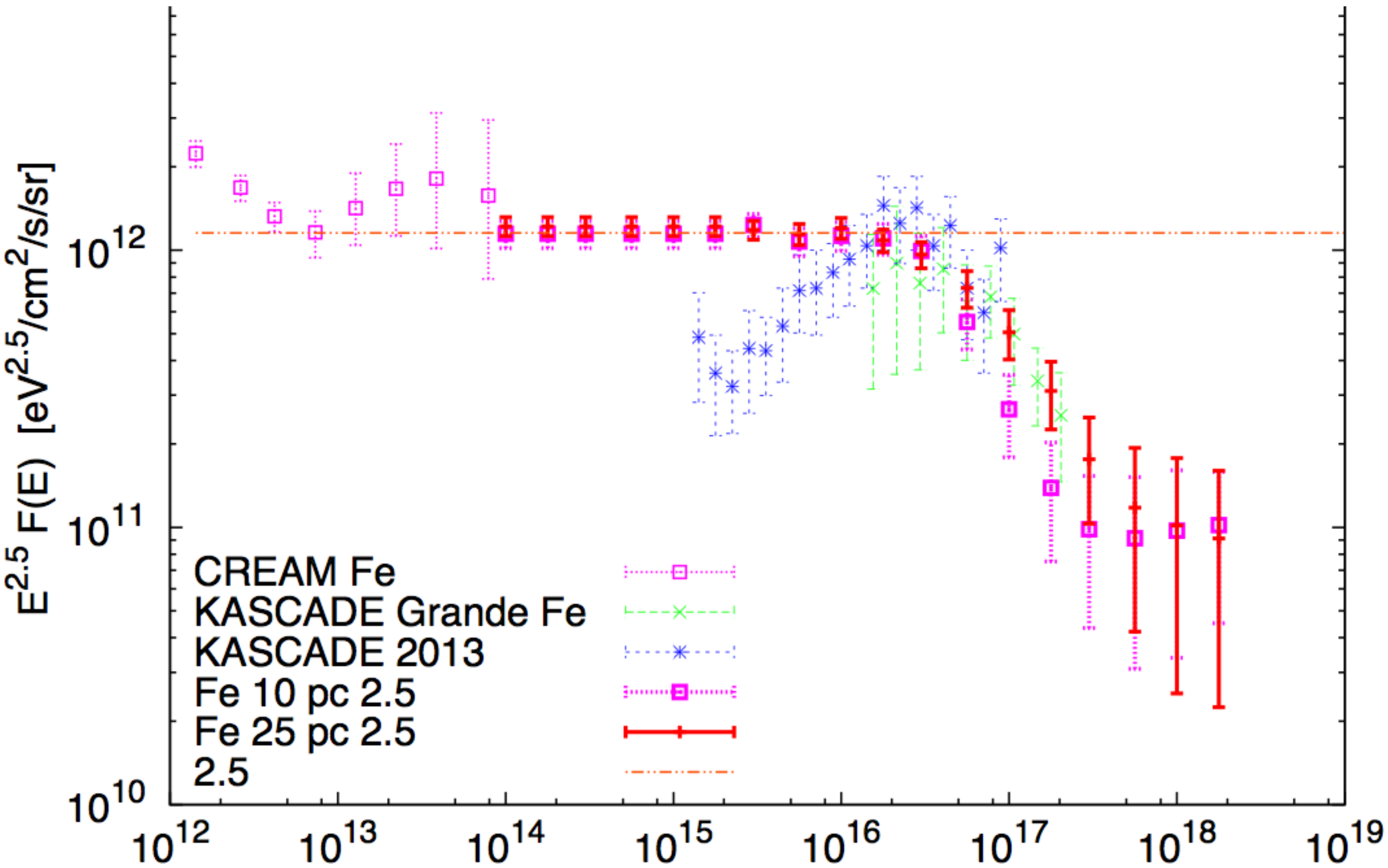




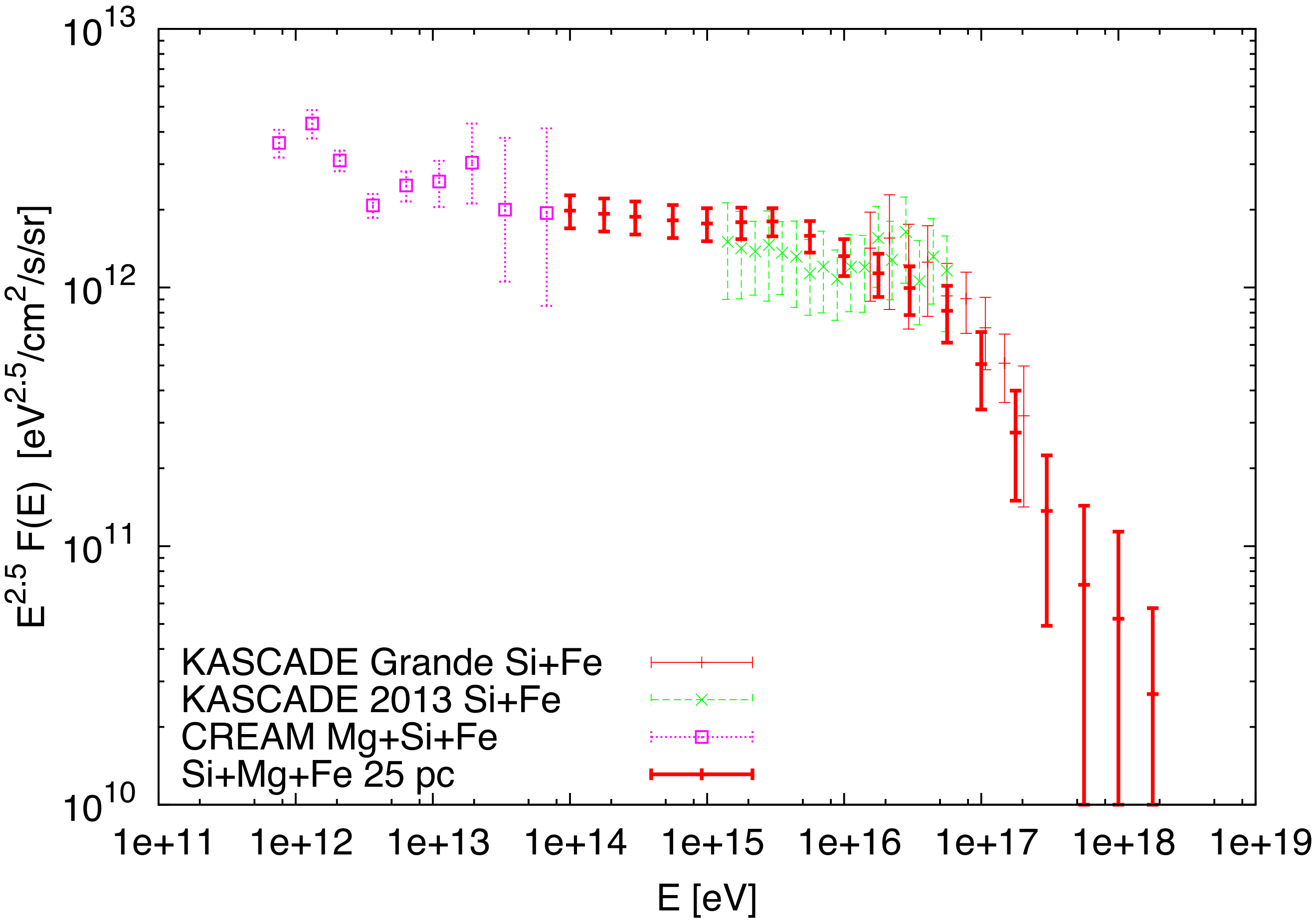
Cosmic Ray Knee: Mg+Si



Cosmic Ray Knee: Fe

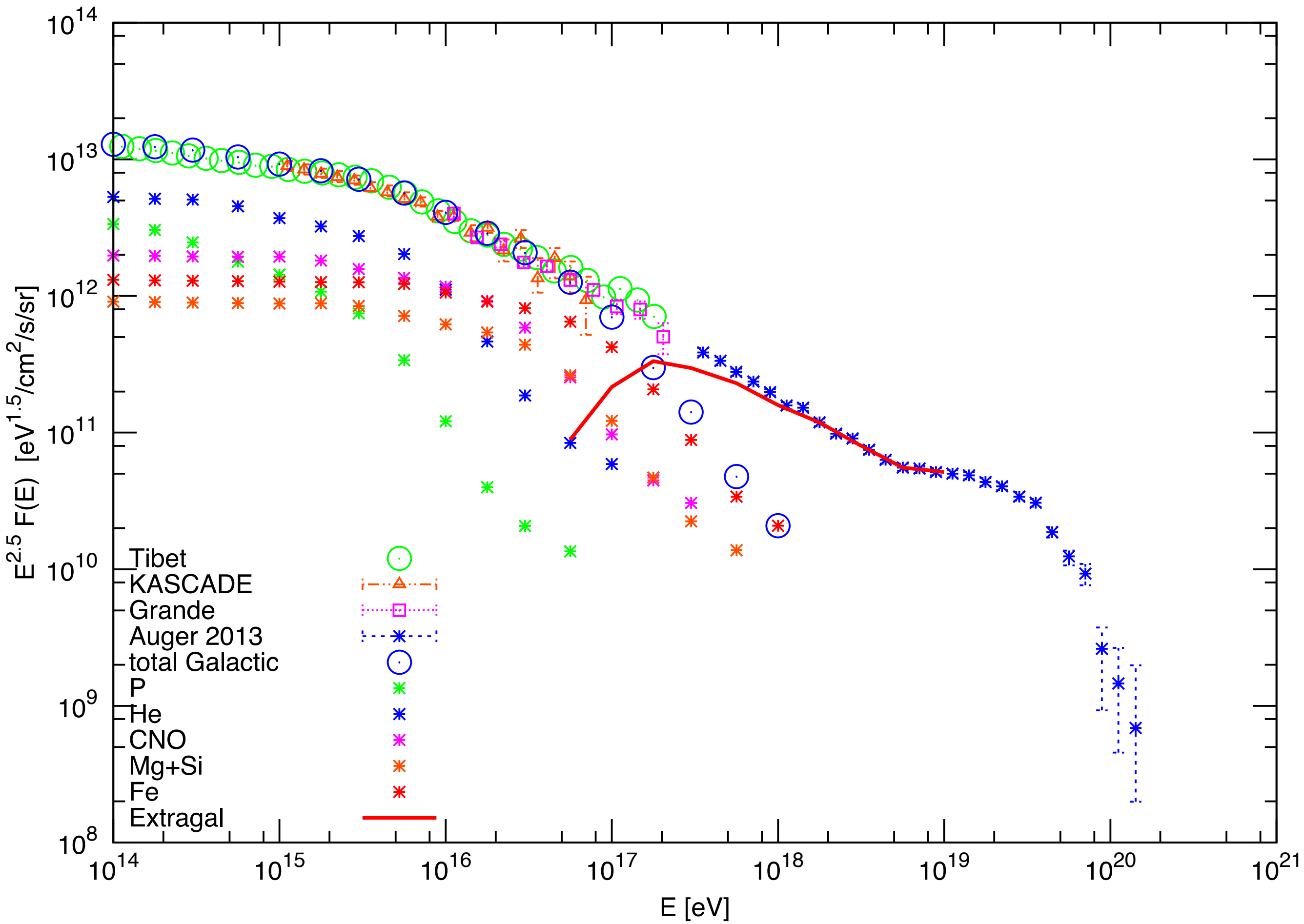


Cosmic Ray Knee: Mg+Si+Fe



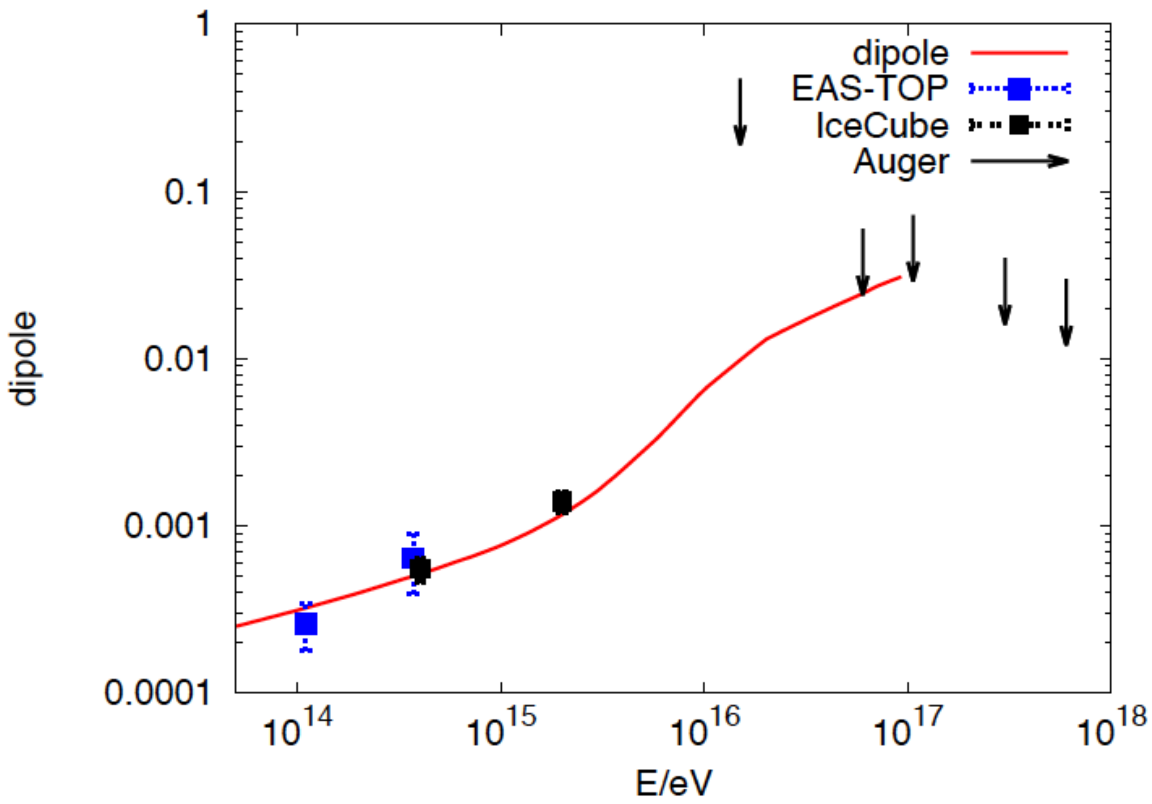
Thanks to Andreas Haungs for discussion

Cosmic Ray Knee: all particles



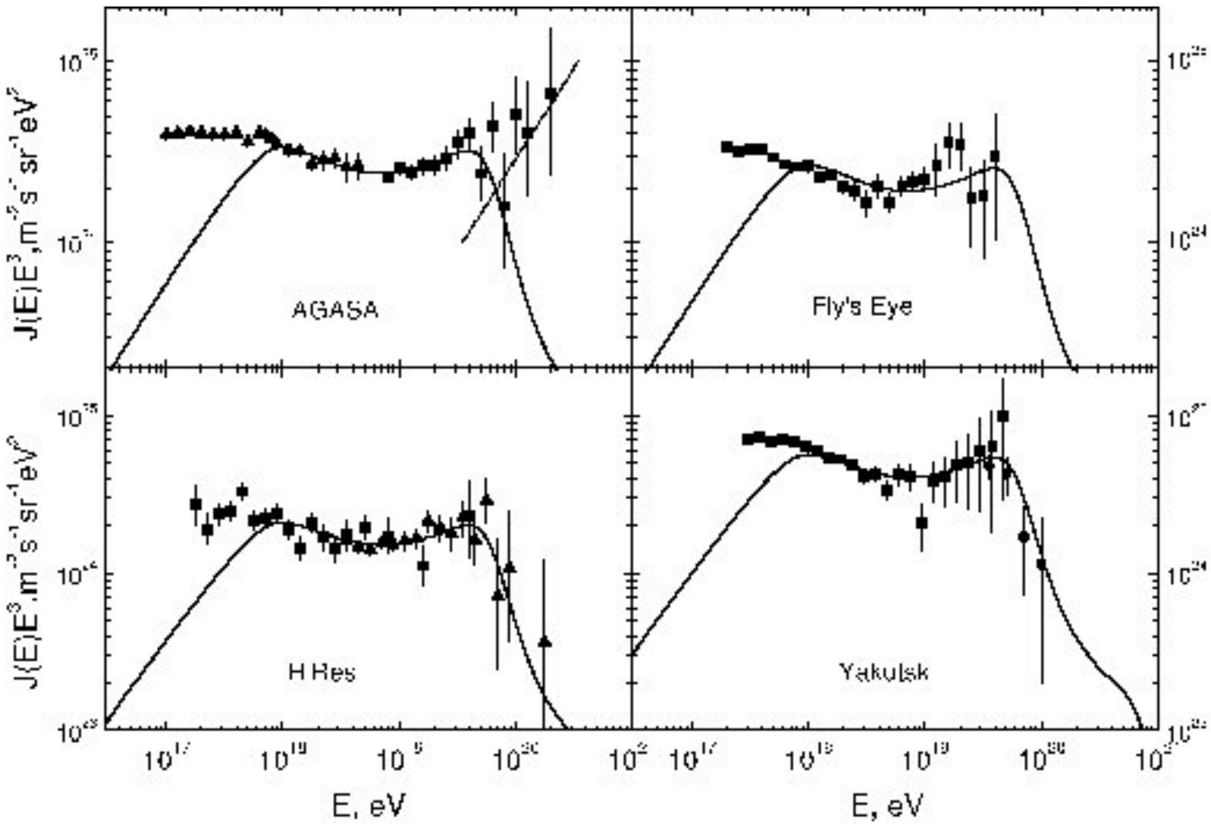
Anisotropy in arrival directions

Cosmic Ray Knee: anisotropy



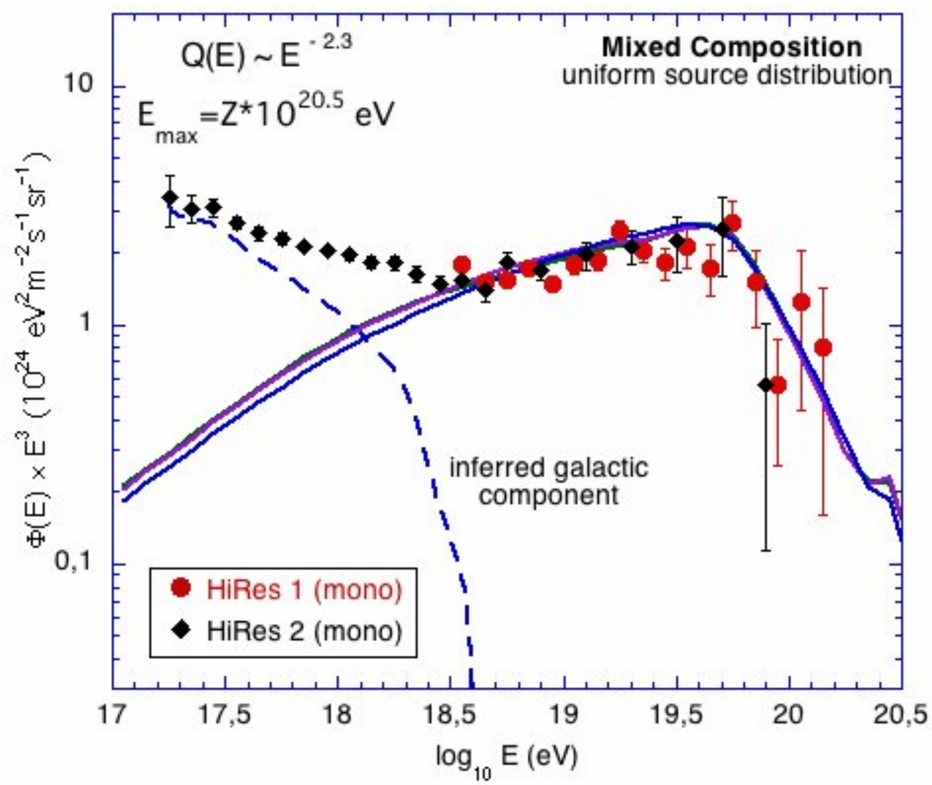
Transition from galactic to extragalactic cosmic rays

Dip model: Protons can fit UHECR data



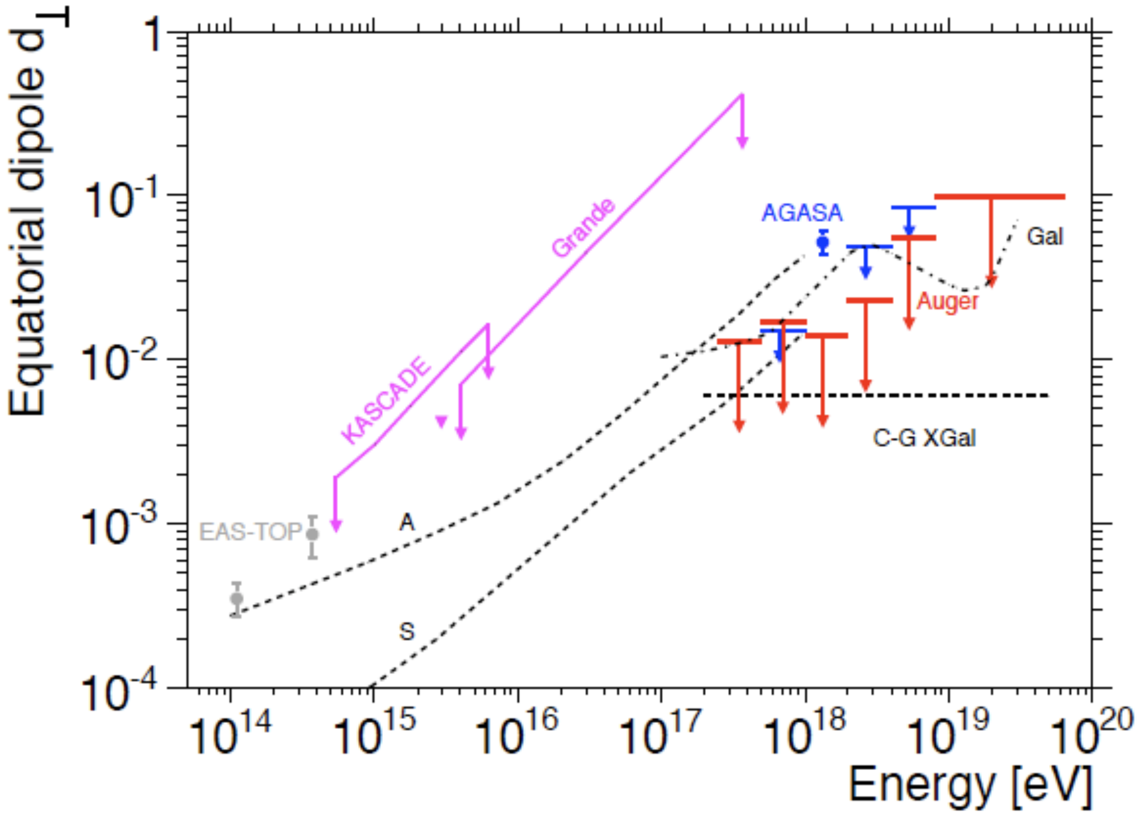
V.Berezinsky , astro-ph/0509069

Mixed composition model



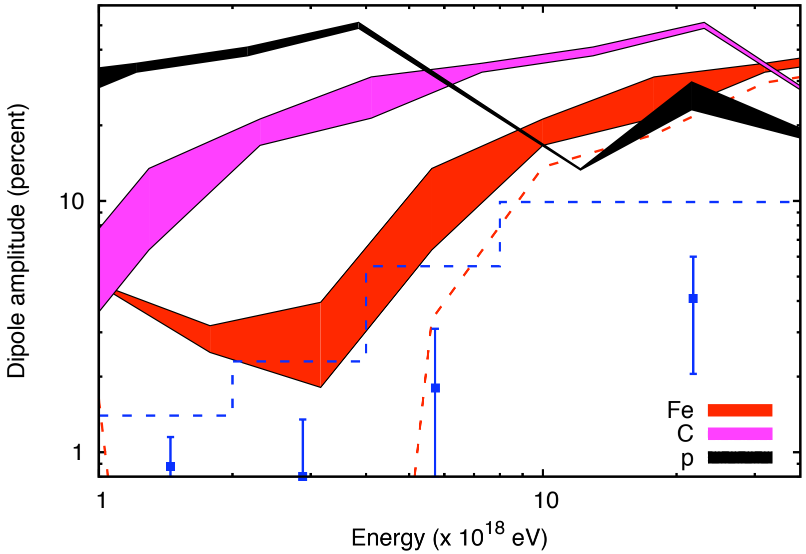
D.Allard, E.Parizot and A.Olinto, astro-ph/0512345

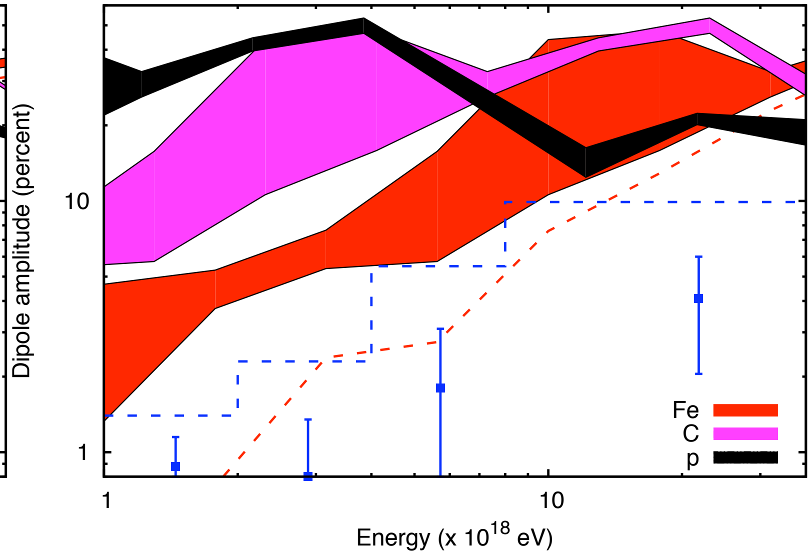
Anisotropy dipole



Pierre Auger Collaboration, arXiv:1103.2721

Dependence on parameters



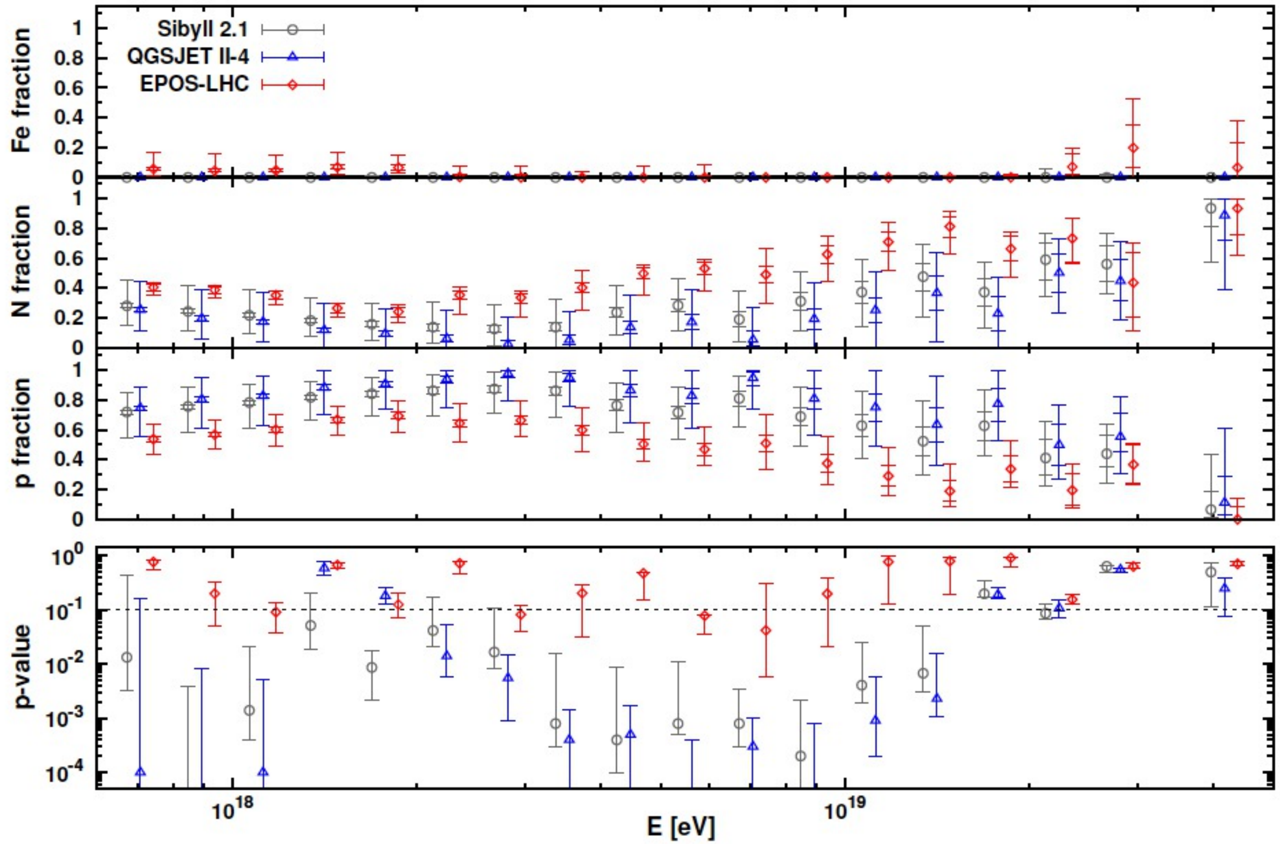


Turb. Magn. Field spectrum
Kolmogorov/Kraichnan

Lmax = 100-300 pc

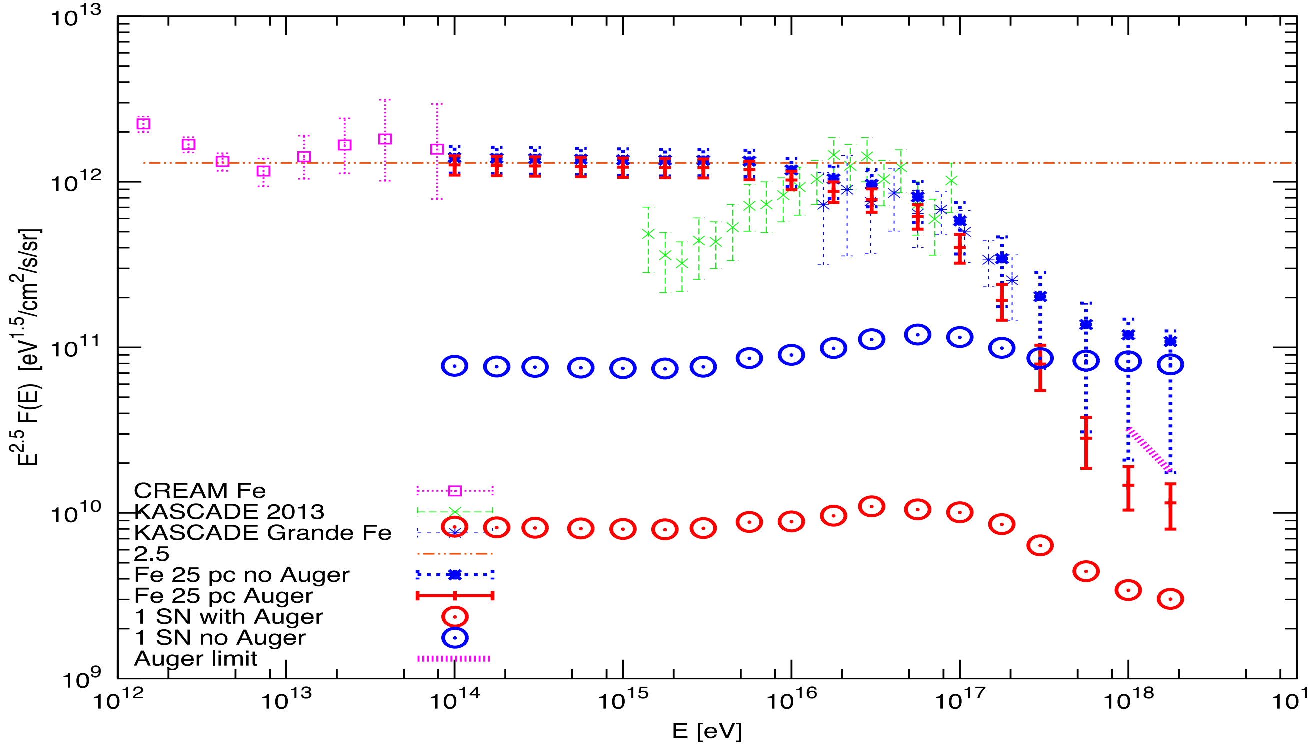
G.Giacinti et al, **arXiv:1112.5599**

Auger cosmposition measurements

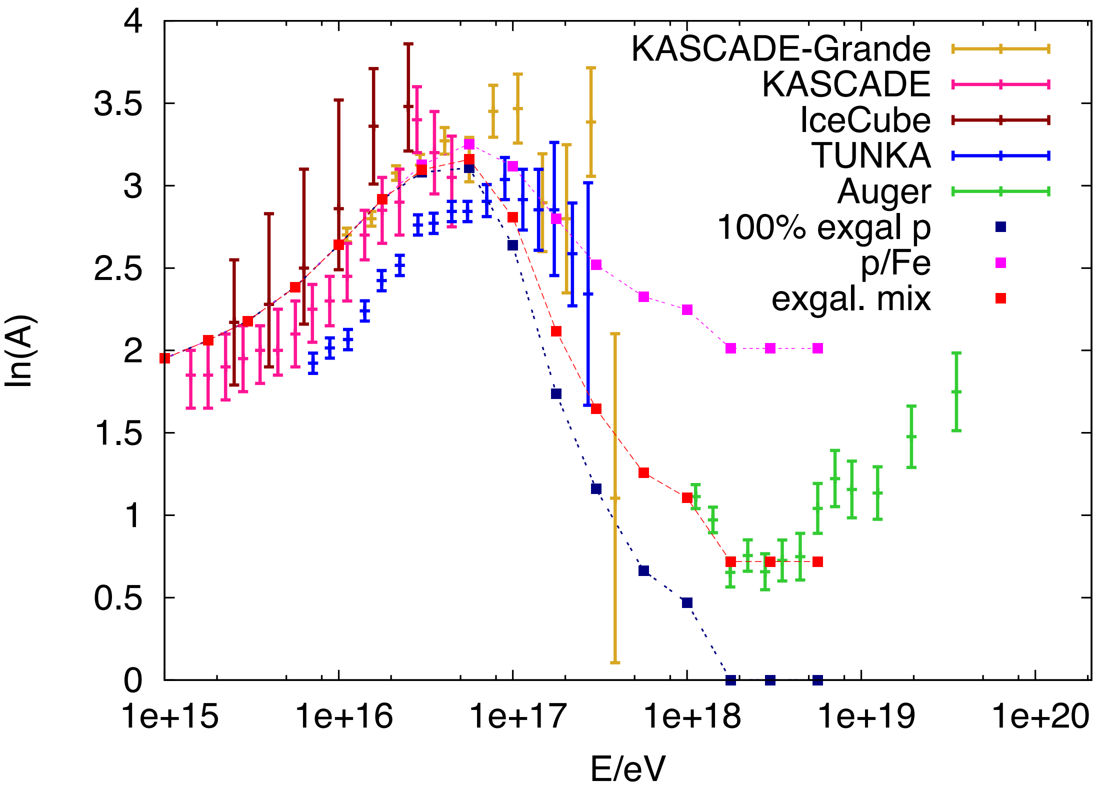


Auger Collaboration, **arXiv:1409.5083**

Auger limit on Fe fraction

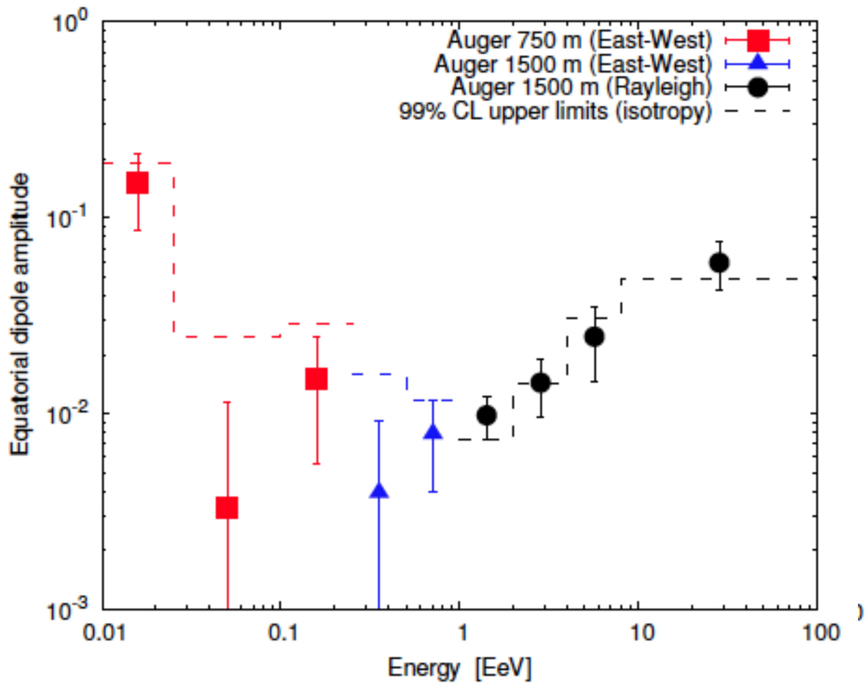


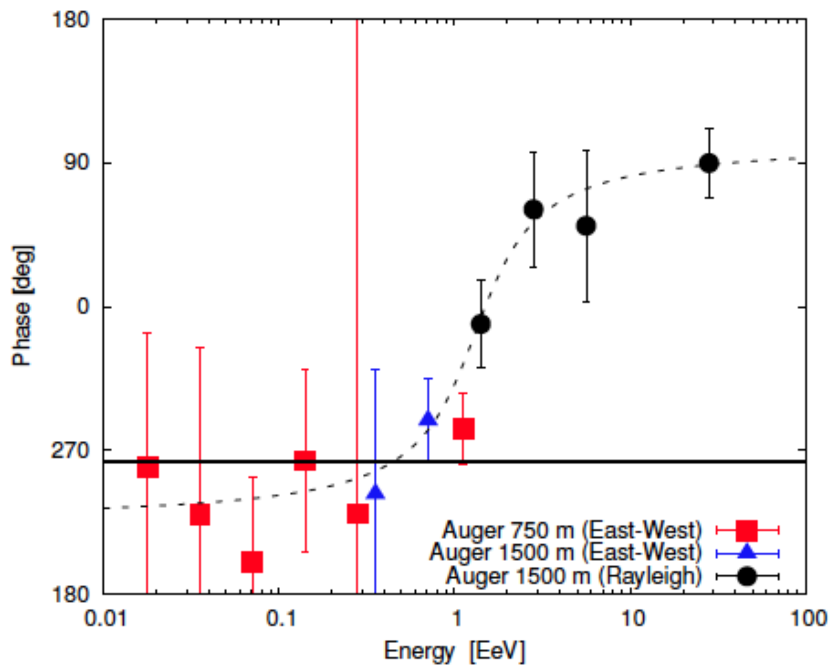
LnA plot



4
3.5
3
2.5
2
1.5
1
0.5
0
ln(A)
1e+15
1e+16
1e+17
1e+18
1e+19
1e+20
E/eV
KASCADE-Grande
KASCADE
IceCube
TUNKA
Auger
100% exgal p
p/Fe
exgal. mix

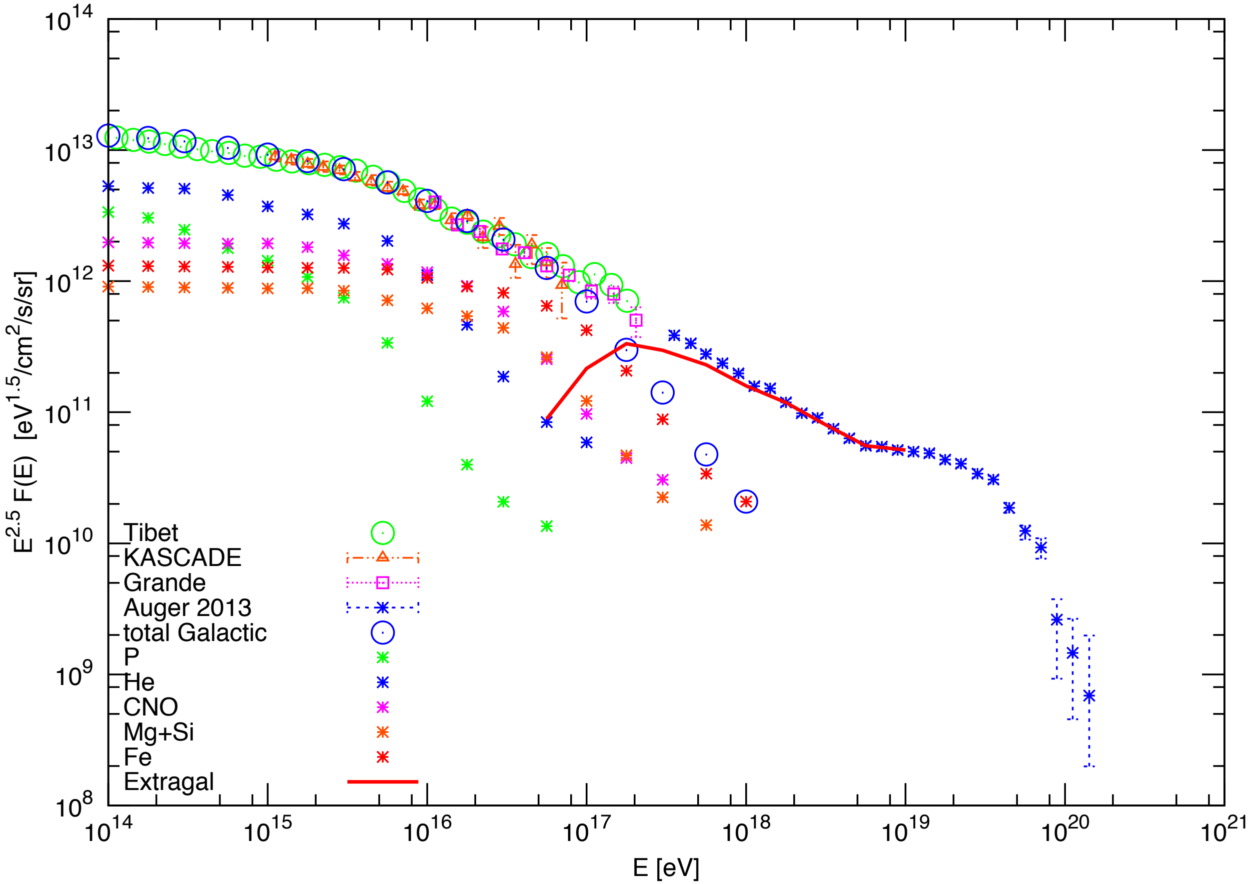
Auger dipole measurements



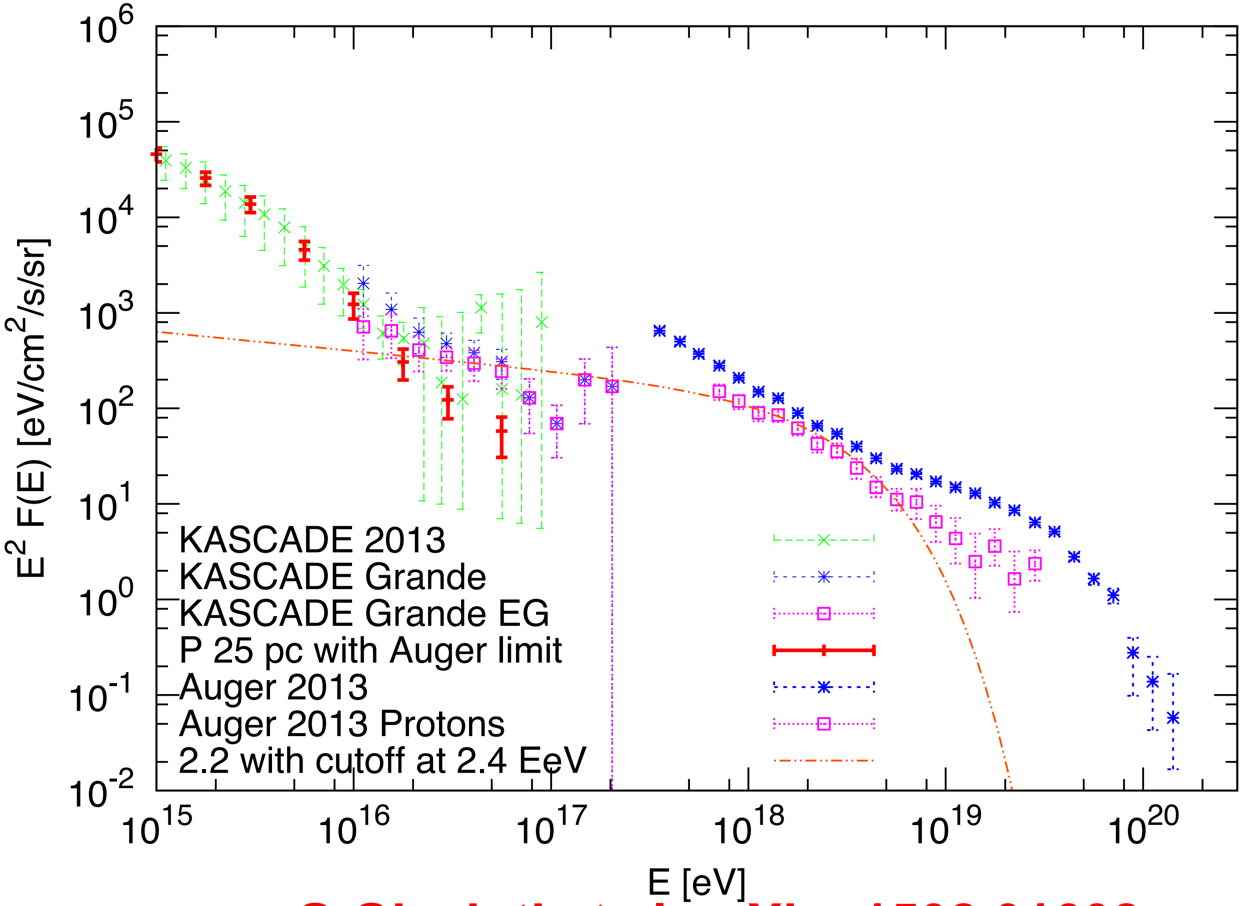


Auger Collaboration, **arXiv:1310.4620**

Contribution of extra-Galactic sources



Contribution of extra-Galactic protons to cosmic ray proton flux



G.Giacinti et al, arXiv: 1502.01608

Detection of astrophysical neutrino flux by ICECUBE

Pion production

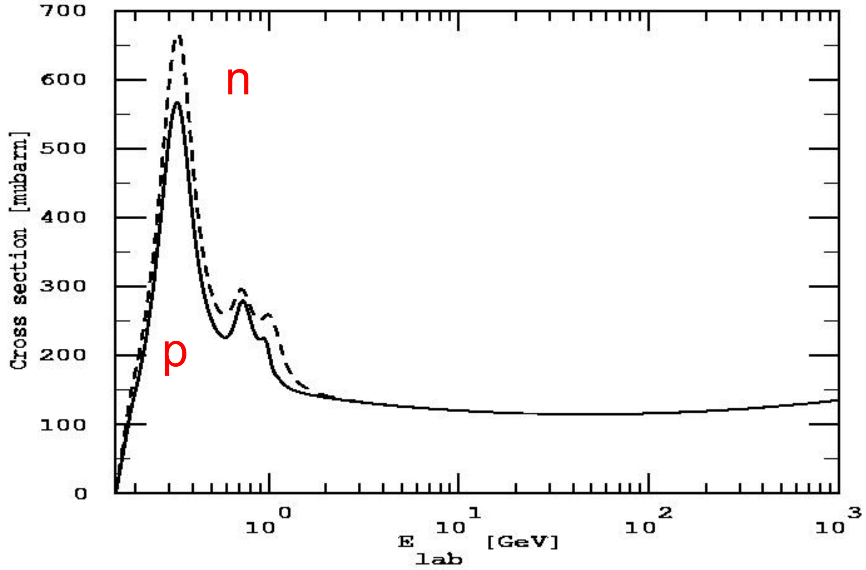
$$N + \gamma_b \Rightarrow N' + \sum \pi^i$$

$$N + A_b \Rightarrow N' + \sum \pi^i$$

$$\pi^0 \Rightarrow 2\gamma$$

$$\pi^\pm \Rightarrow \mu^\pm + \nu_\mu$$

$$\mu^\pm \Rightarrow e^\pm + \bar{\nu}_e + \nu_\mu$$

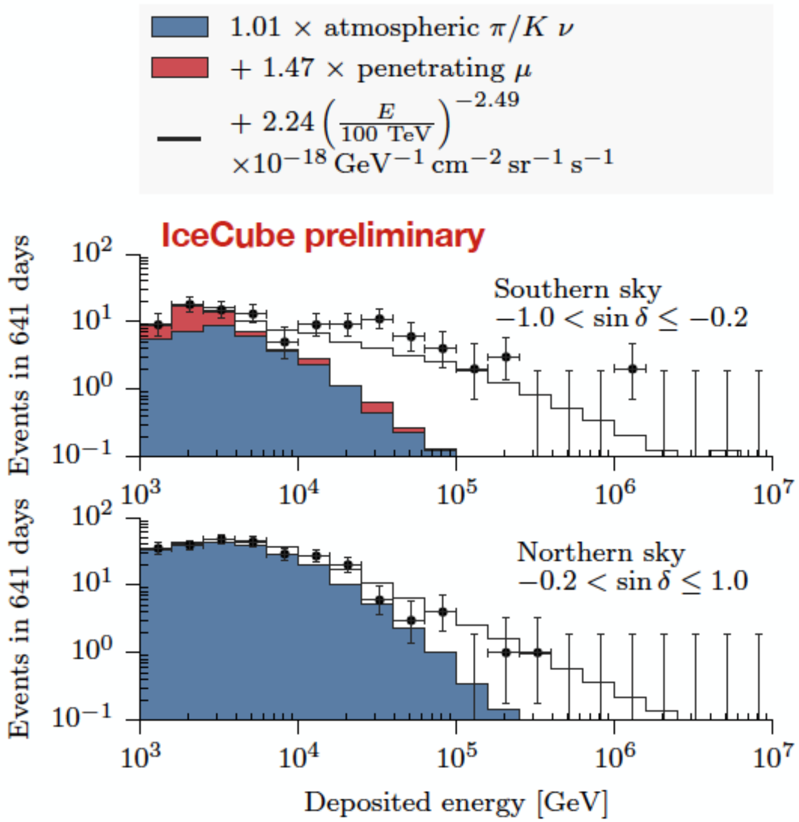


$$n \Rightarrow p + e^- + \bar{\nu}_e$$

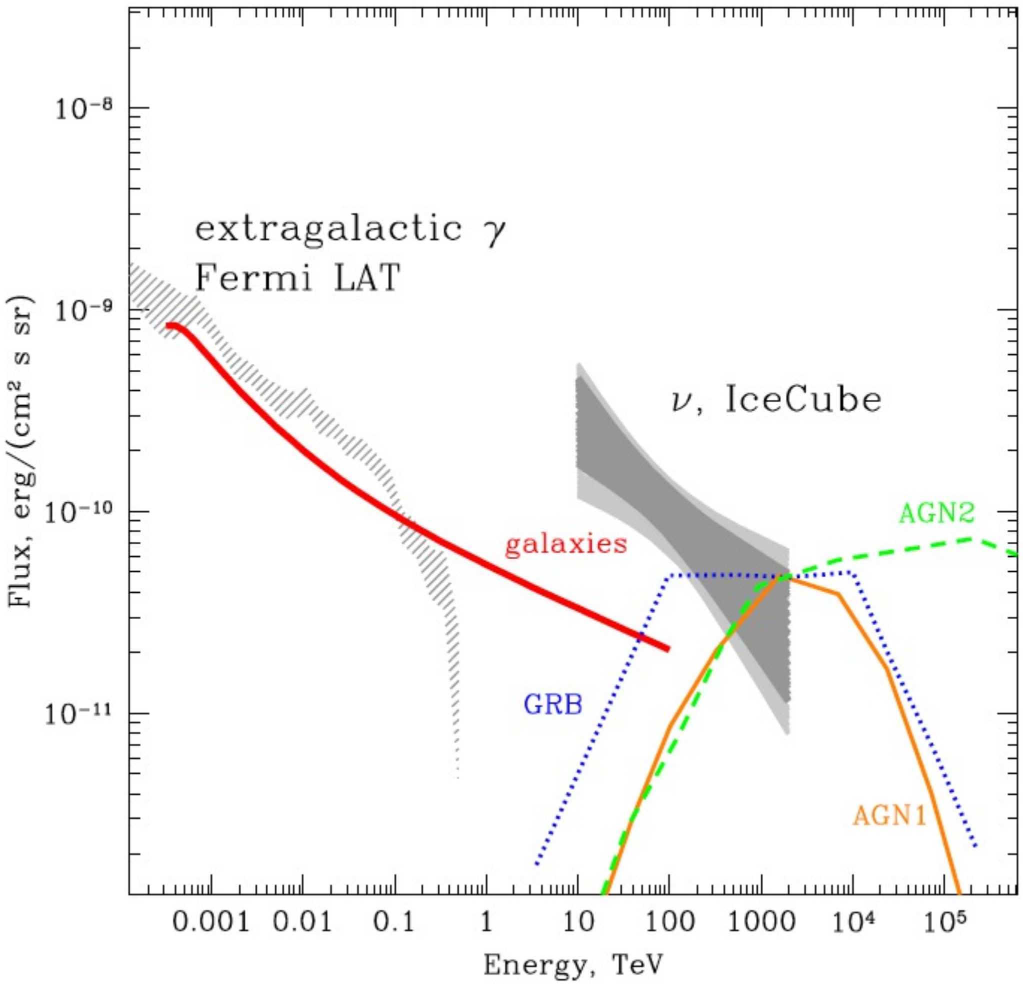
Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_\gamma^{tot} \sim E_\nu^{tot}$

Results: energy spectrum

- 283 cascade and 105 track events in 2 years of data
- 106 > 10 TeV, 9 > 100 TeV (7 of those already in high-energy starting event sample)
- Conventional atmospheric neutrino flux observed at expected level with starting events

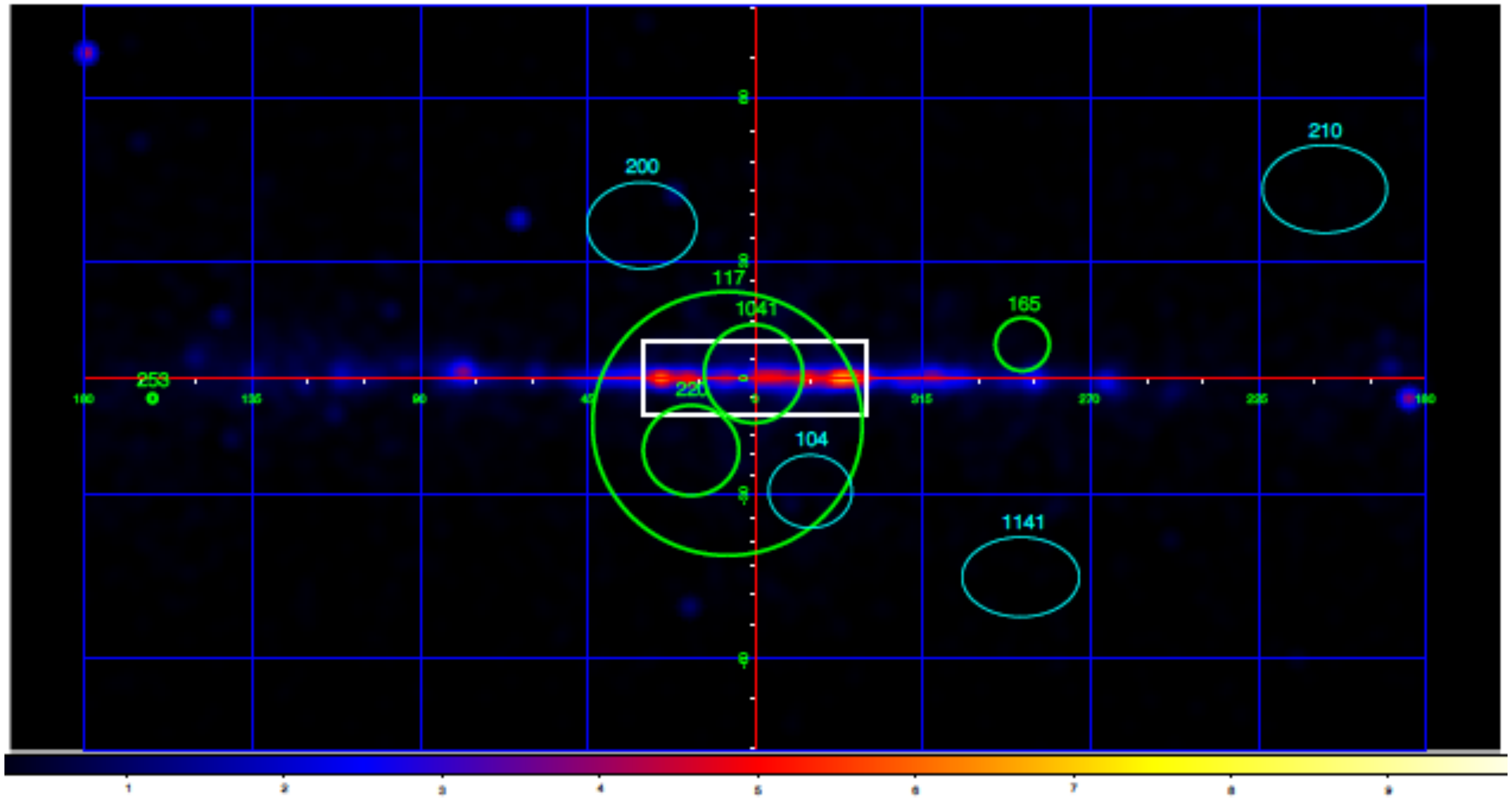


IceCube + Fermi LAT



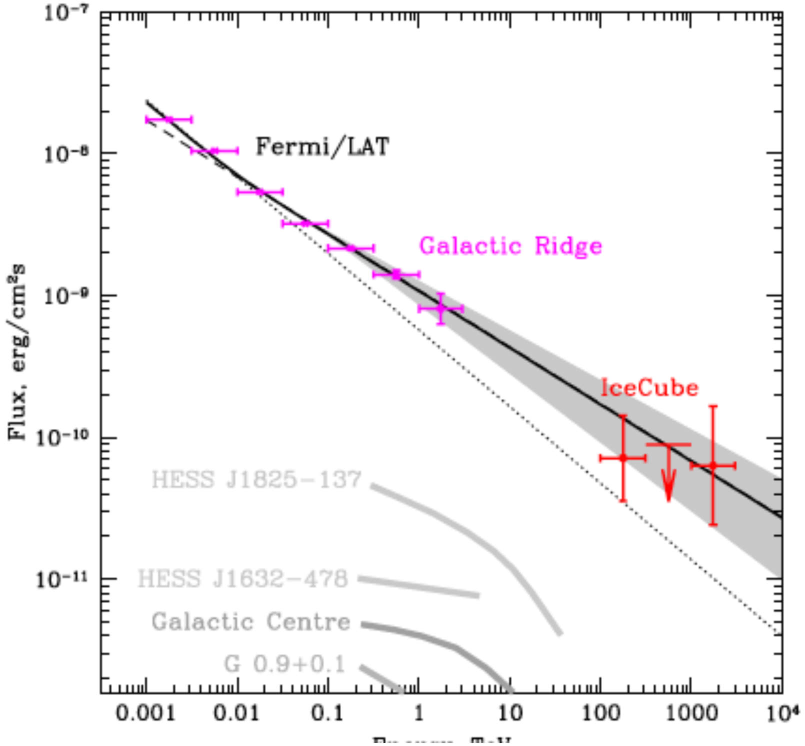
A.Neronov, D.S. arXiv:1412.1690

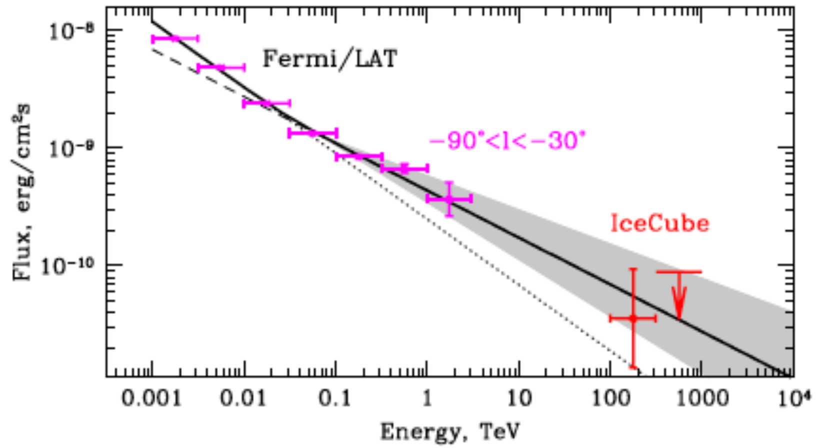
Half of ICECUBE events E>100 TeV are in Galactic plane. Are they correlate with gamma-rays?



Neronov, D.S. and Tchernin, Phys.Rev. D89 (2014) 103002

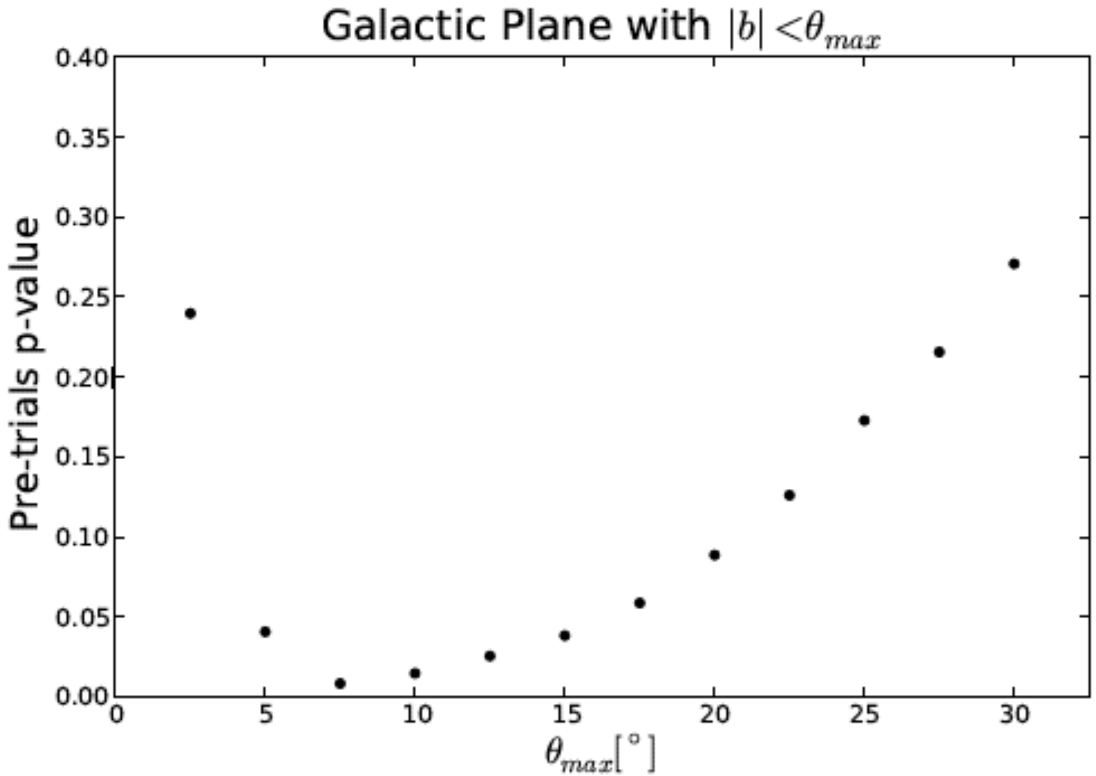
Real multimessenger fluxes, alpha=2.5





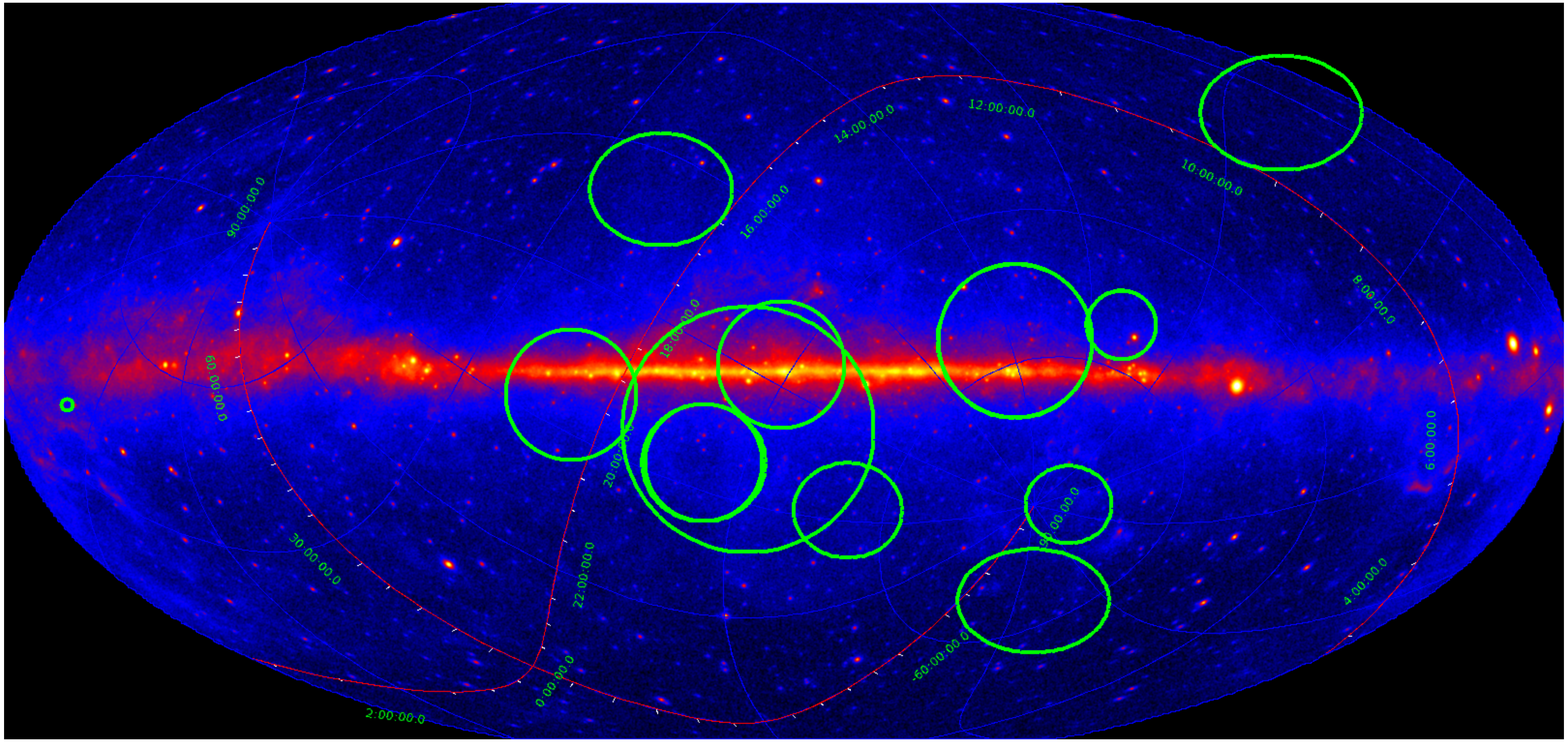
Neronov, D.S. and Tchernin, Phys.Rev. D89 (2014) 103002

IceCube galactic plane 3 years: 2% by chance – small statistics

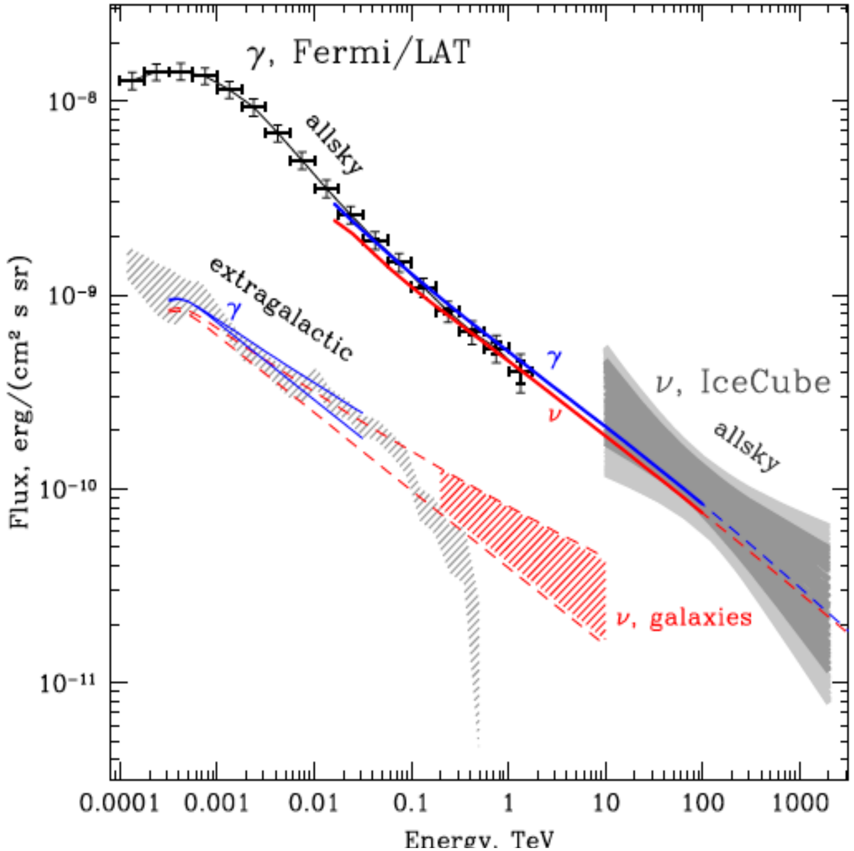


ICECUBE collaboration, 1405.5303

IceCube neutrino sky map 3 years E> 100 TeV

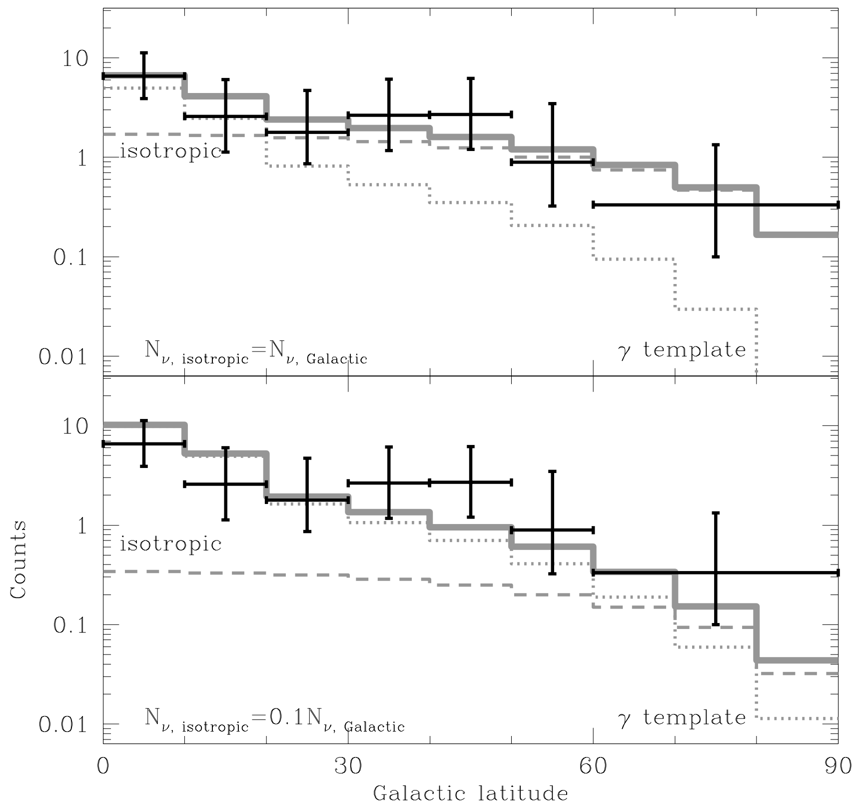


IceCube + Fermi LAT all sky: protons 1/E^2.5

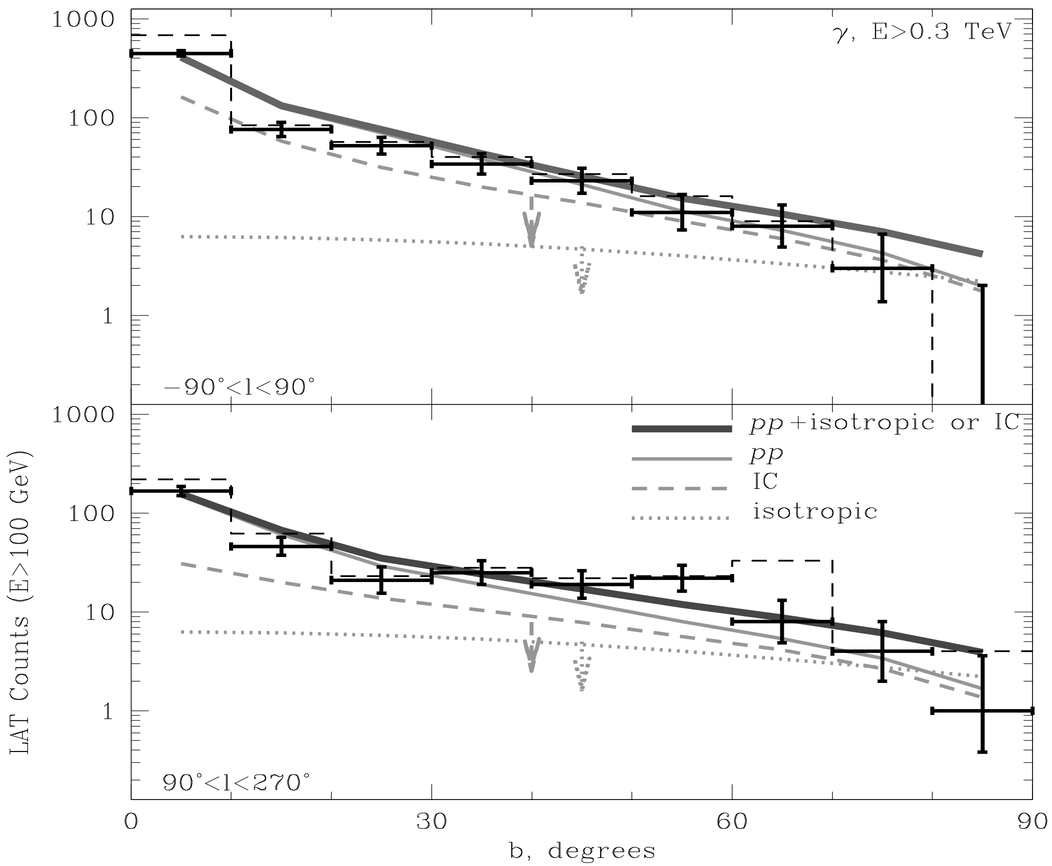


A.Neronov, D.S. arXiv:1412.1690

Profile neutrino

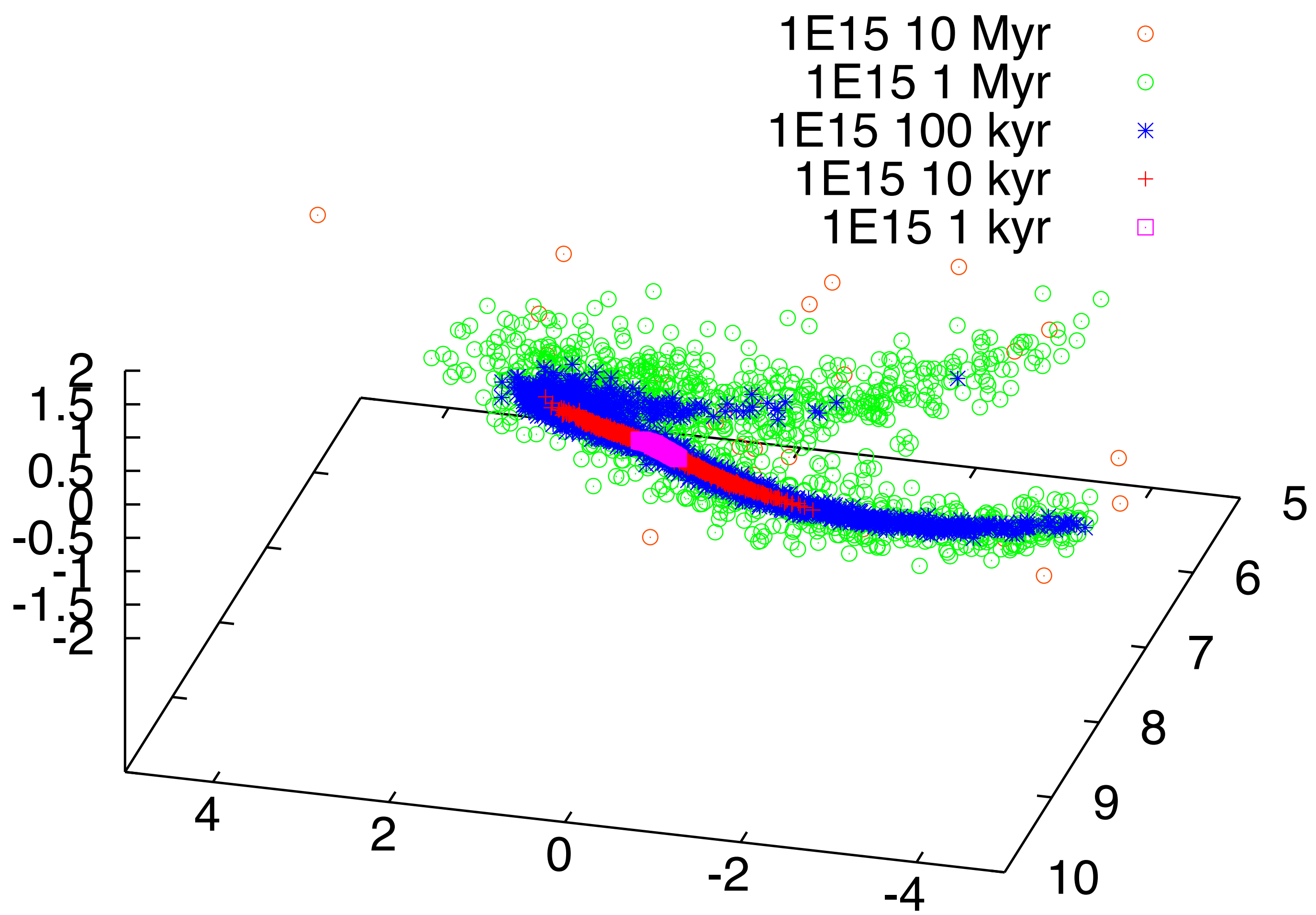


Profile gamma

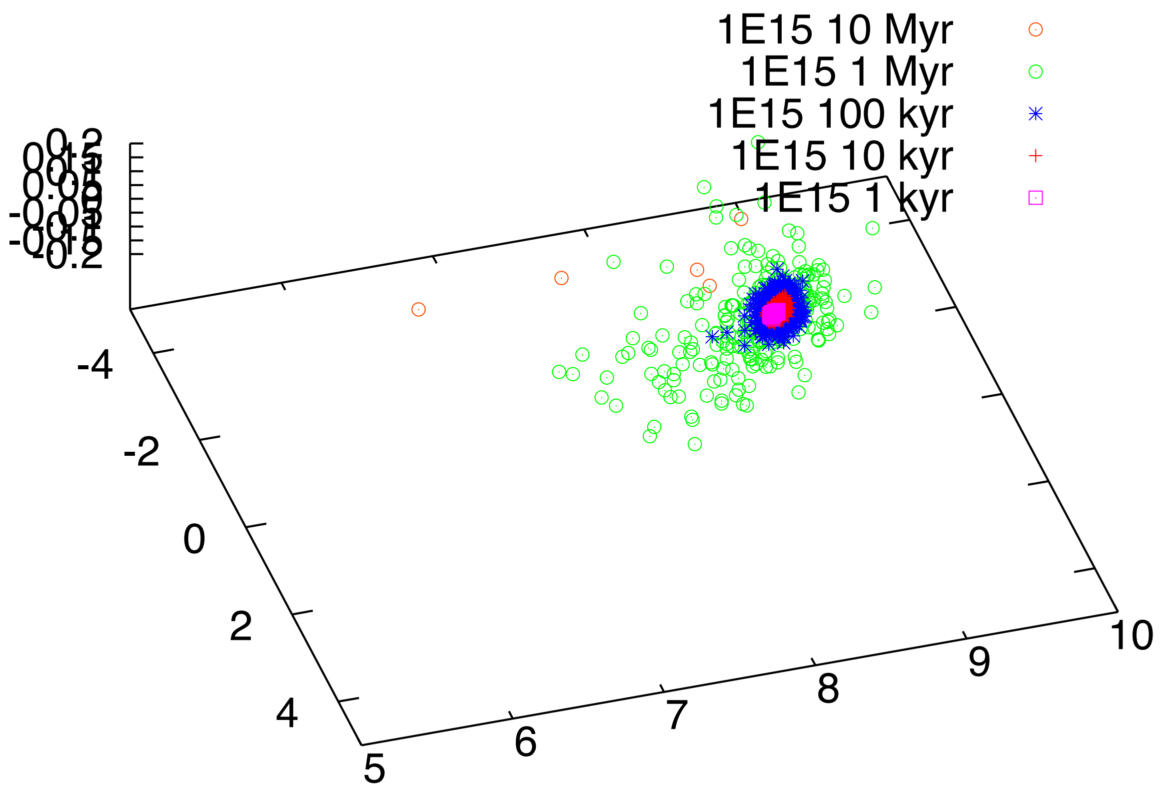


2 Myr old SN: protons, positrons and anti-protons

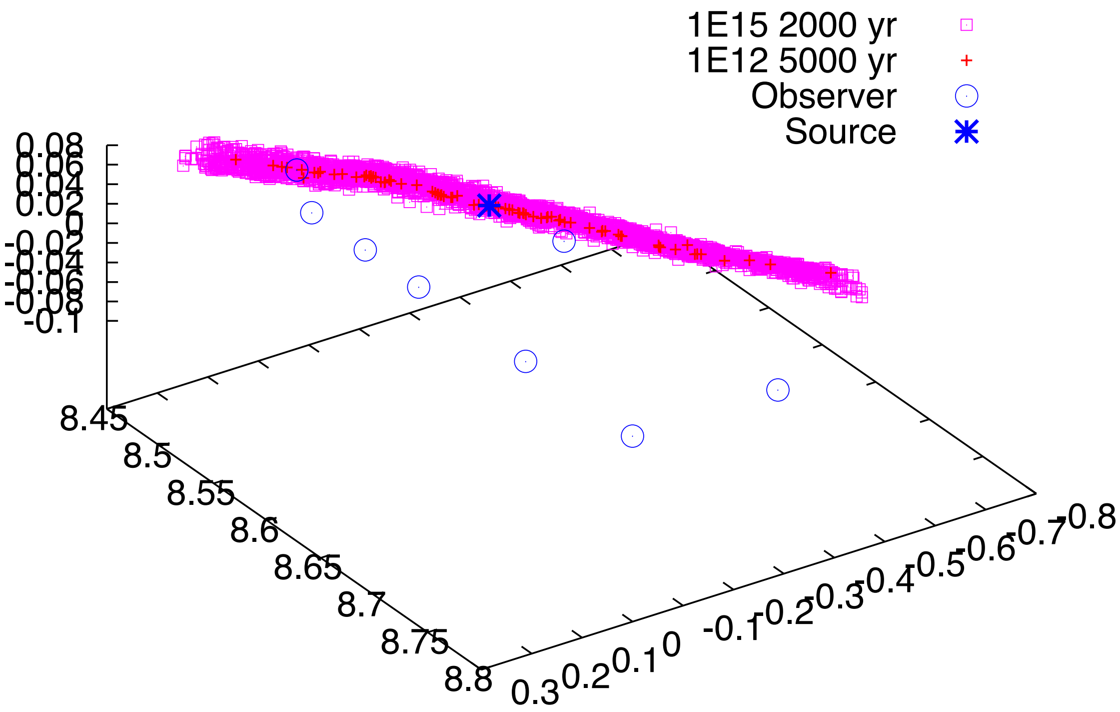
Proton flux from SN at 1 PeV



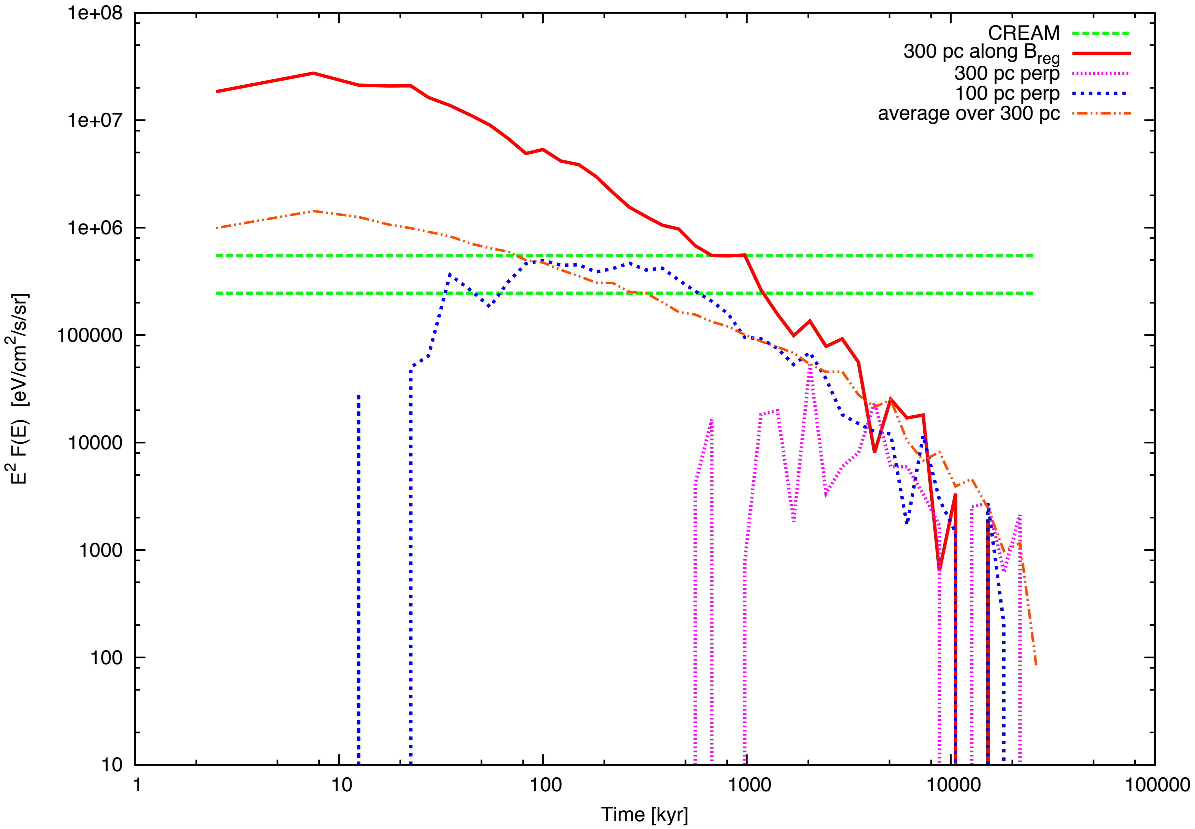
Proton flux from SN at 1 PeV



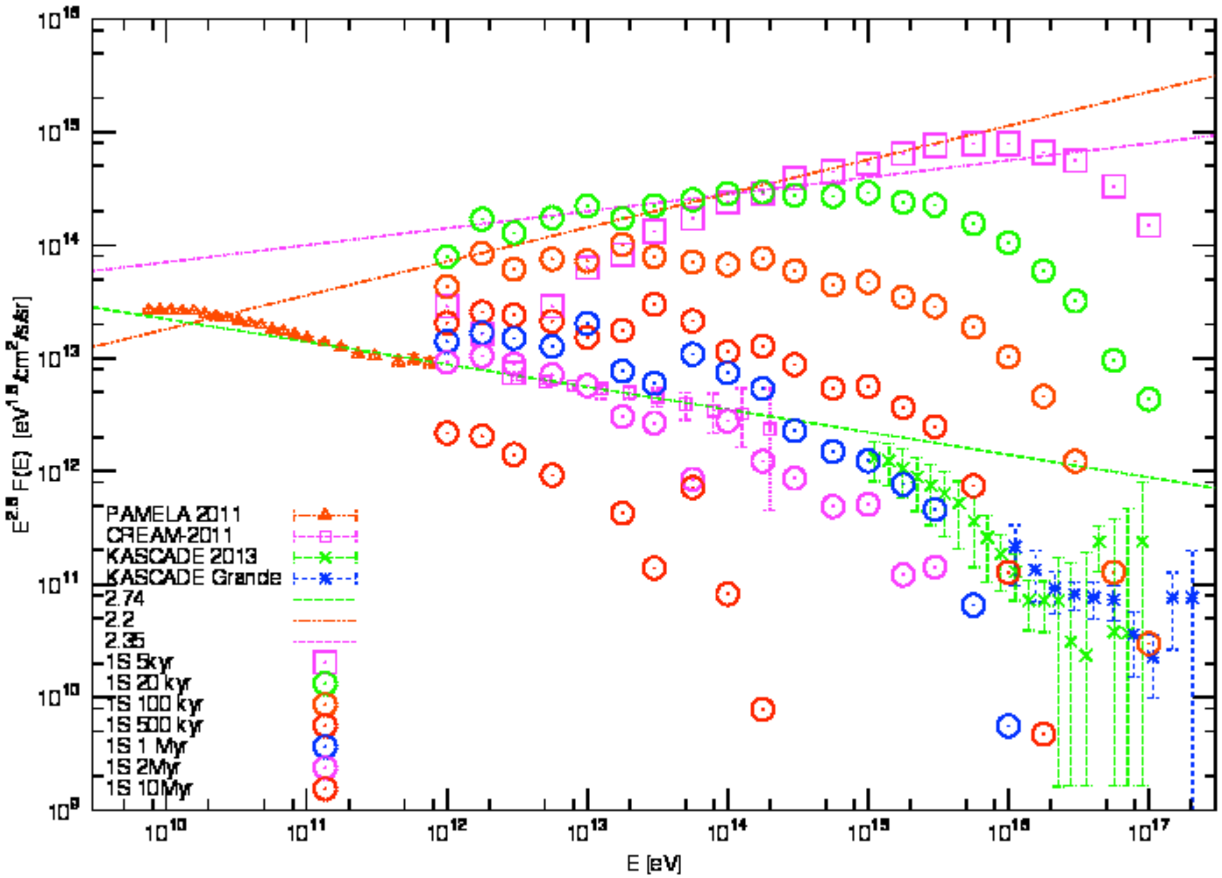
Proton flux from 1 SN: early time



Flux at 100 TeV

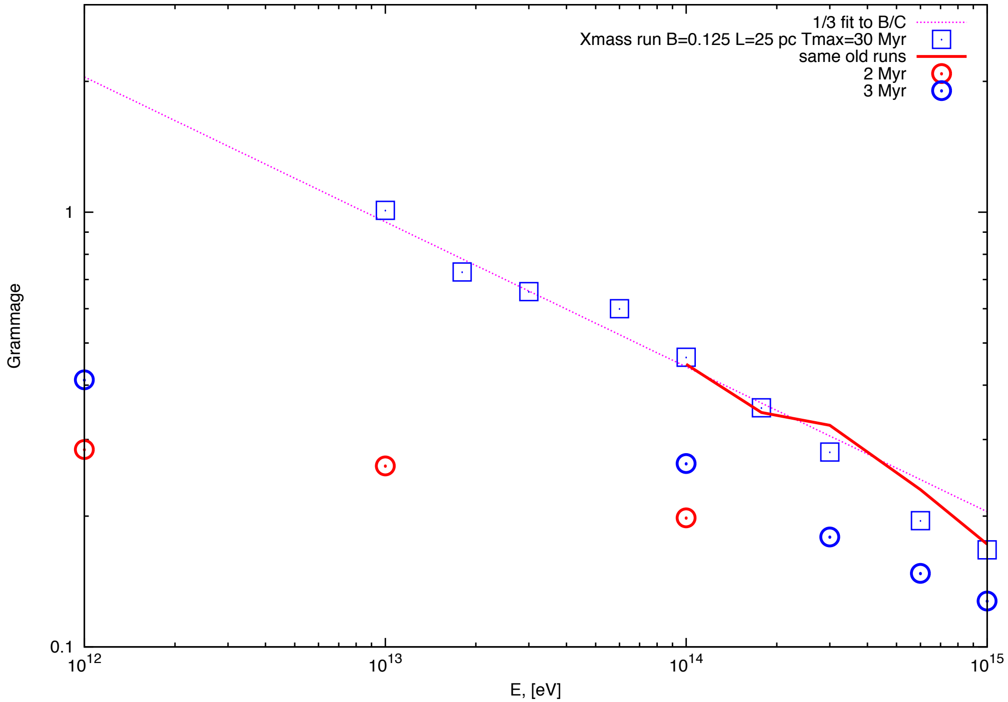


Proton flux from 1 SN



M.Kachelriess, A. Neronov and D.Semikoz, arXiv:1504.06472

Grammage to create secondaries



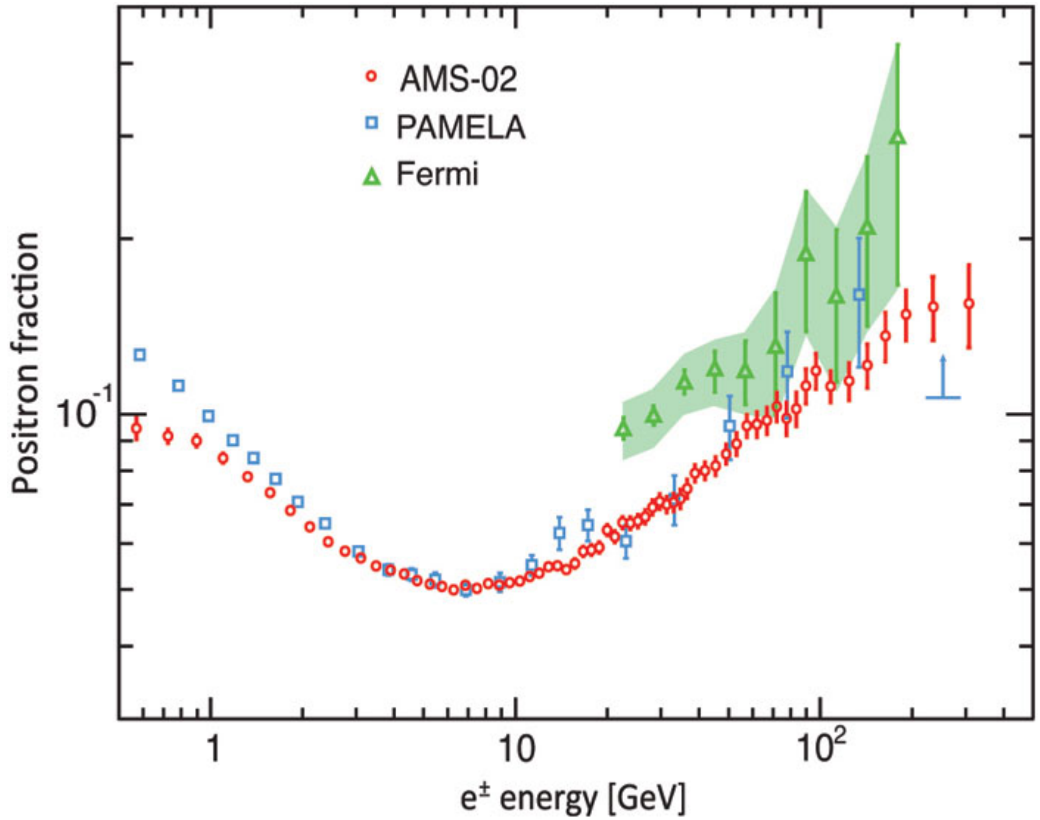
For energies E < 10^{14} eV, the grammage is nearly energy independent, X ≃ 0.3 g/cm2 , for a source of the age T = 2 Myr. This mean that one expect

$$\gamma_{e^+} \simeq \tilde{\gamma}_p \simeq 2.7 - 2.8.$$

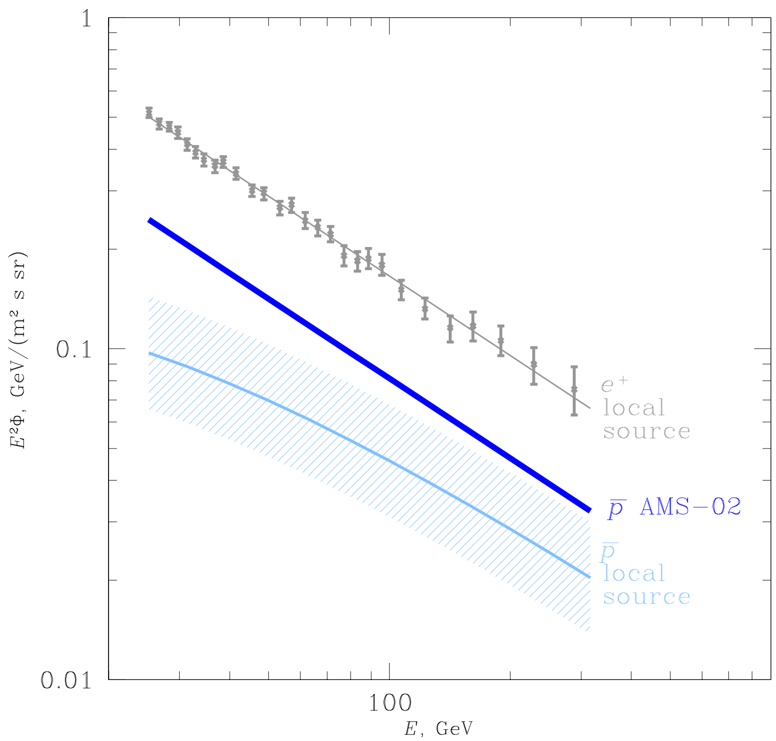
Secondary positrons and antiprotons

- For calculation of secondaries we used post-LHC model QGSJET-II-04m in most recent modification M. Kachelrieß et al., Ap. J. 803, 54 (2015)

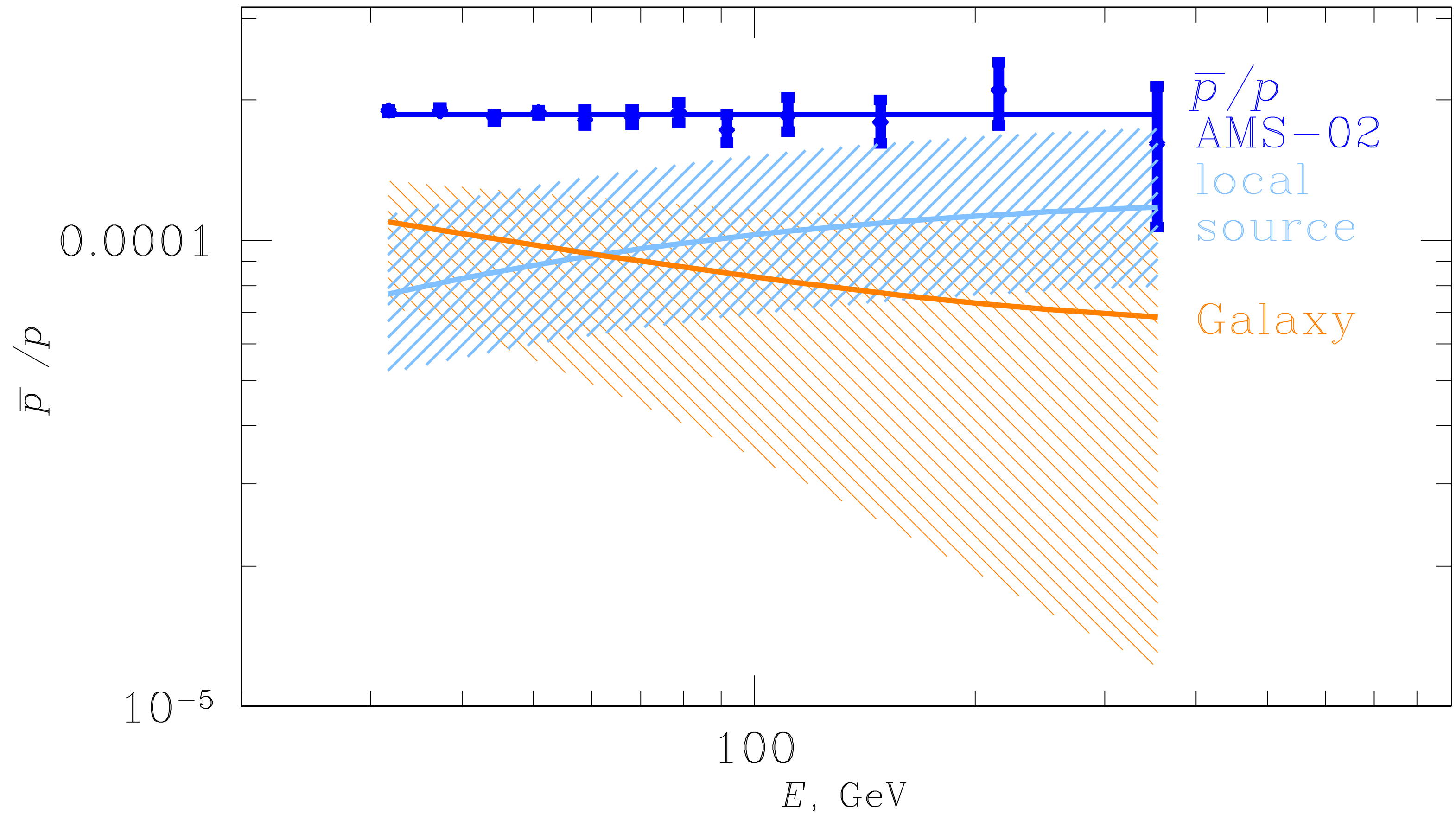
Positron to (electron + positron) ratio



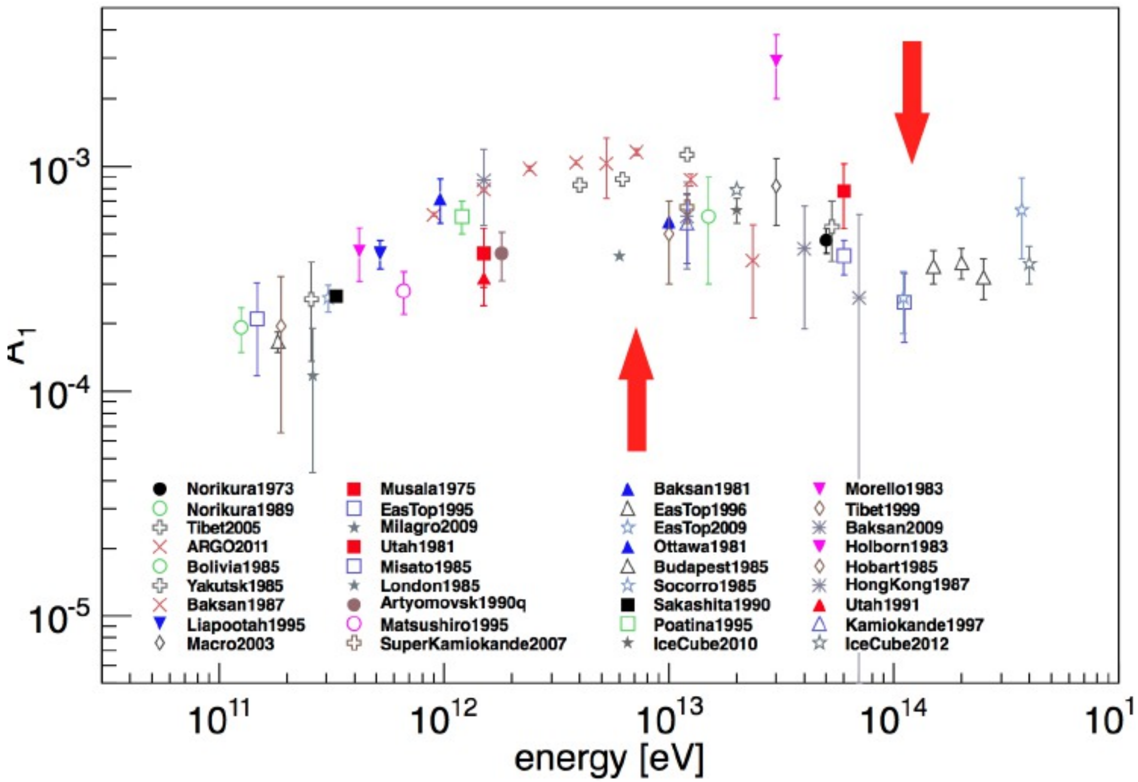
Positron flux and antiprotons from AMS-II



Antriprotons

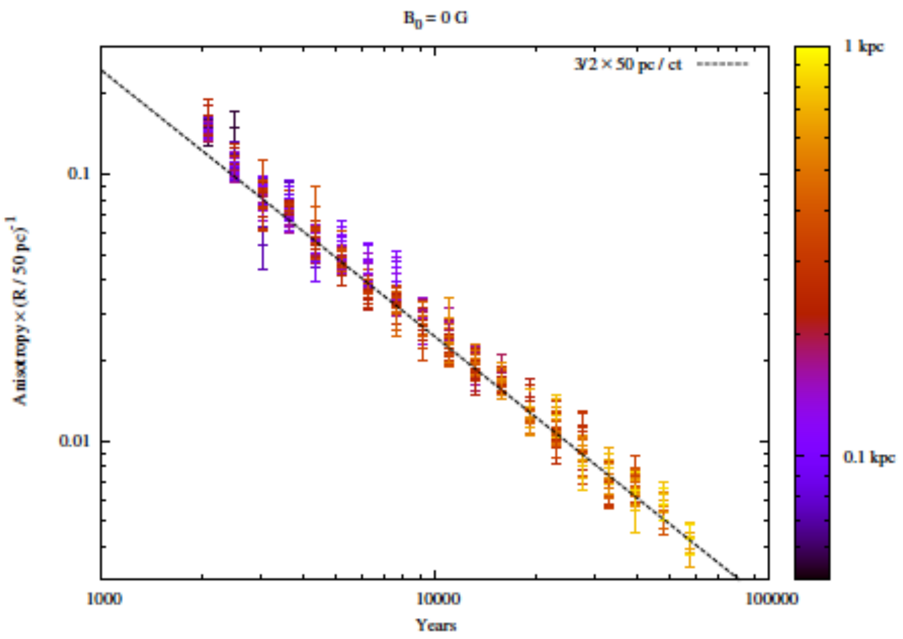


Anisotropy

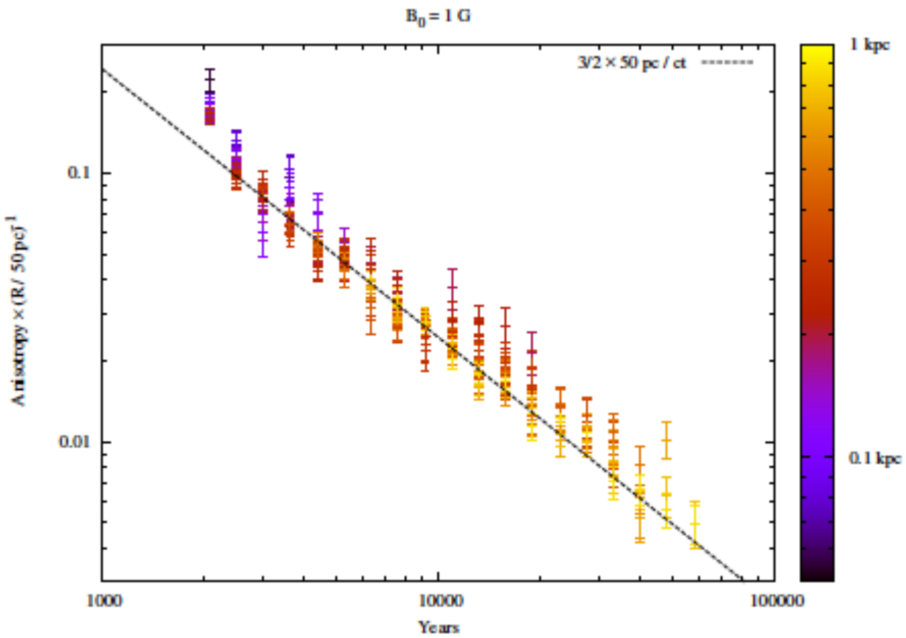


10^{-3}
10^{-4}
10^{-5}
A_1
10^{11}
10^{12}
10^{13}
10^{14}
energy [eV]
Norikura1973
Norikura1989
Tibet2005
ARGO2011
Bolivia1985
Yakutsk1985
Baksan1987
Liapootah1995
Macro2003
Musala1975
EasTop1995
Milagro2009
Utah1981
Misato1985
London1985
Artyomovsk1990q
Matsushiro1995
SuperKamiokande2007
Baksan1981
EasTop1996
EasTop2009
Ottawa1981
Budapest1985
Socorro1985
Sakashita1990
Poatina1995
IceCube2010
Morello1983
Tibet1999
Baksan2009
Holborn1983
Hobart1985
HongKong1987
Utah1991
Kamiokande1997
IceCube2012

Anisotropy

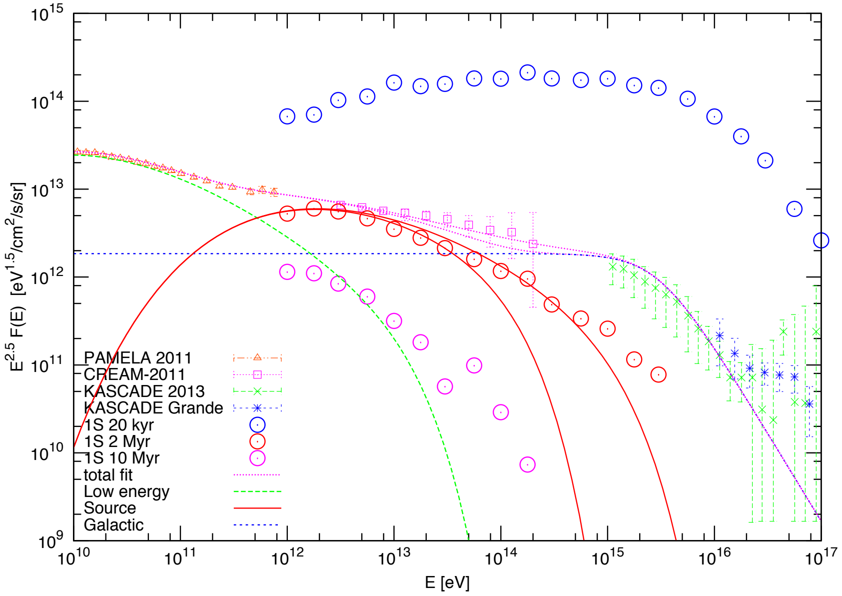


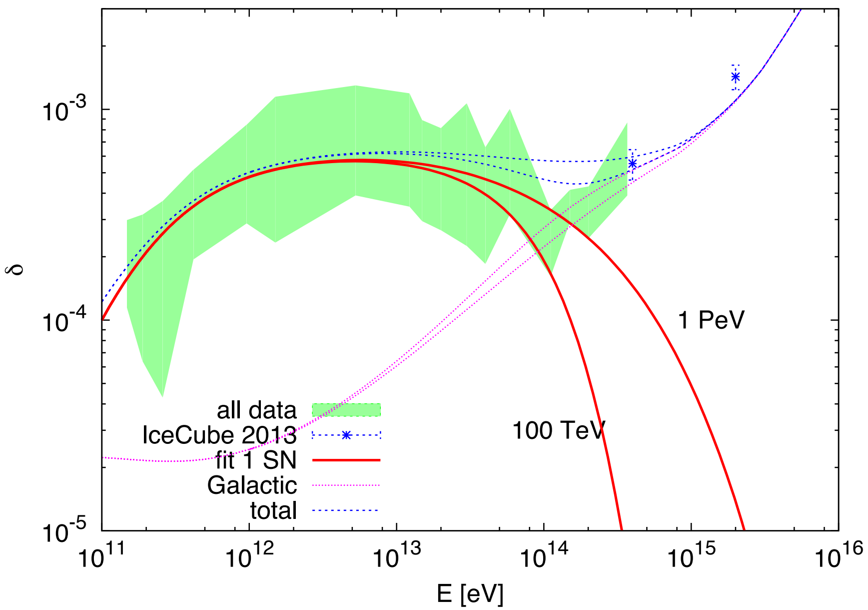
B_0 = 0 G
3/2 × 50 pc / ct
Anisotropy × (R / 50 pc)$^{-1}$
0.1
0.01
1000
10000
100000
Years
1 kpc
0.1 kpc



B_0 = 1 G
3/2 × 50 pc / ct
Anisotropy × (R / 50 pc)$^{-1}$
0.1
0.01
1000
10000
100000
Years
1 kpc
0.1 kpc

Anisotropy and flux





Conclusions

- *We have phenomenological understanding of Galactic cosmic rays from TeV*Z to 0.1 EeV energies.*
- *First diffuse neutrino flux measurements contain galactic and extragalactic components.*
- *Galactic component consistent with diffuse galactic flux by Fermi and proton power law 2.5*

- *This is consistent with nuclei spectra except of LOCAL protons.*
- *Local 2.7 proton flux is local due to 1-2 Myr old nearby source. Same source responsible to positron and anti-proton excess and anomalies in dipole anisotropy*
- *Contribution of sources seen in EG cosmic ray proton spectrum at 0.03 -3 EeV and can dominate EG gamma-ray and neutrino backgrounds*