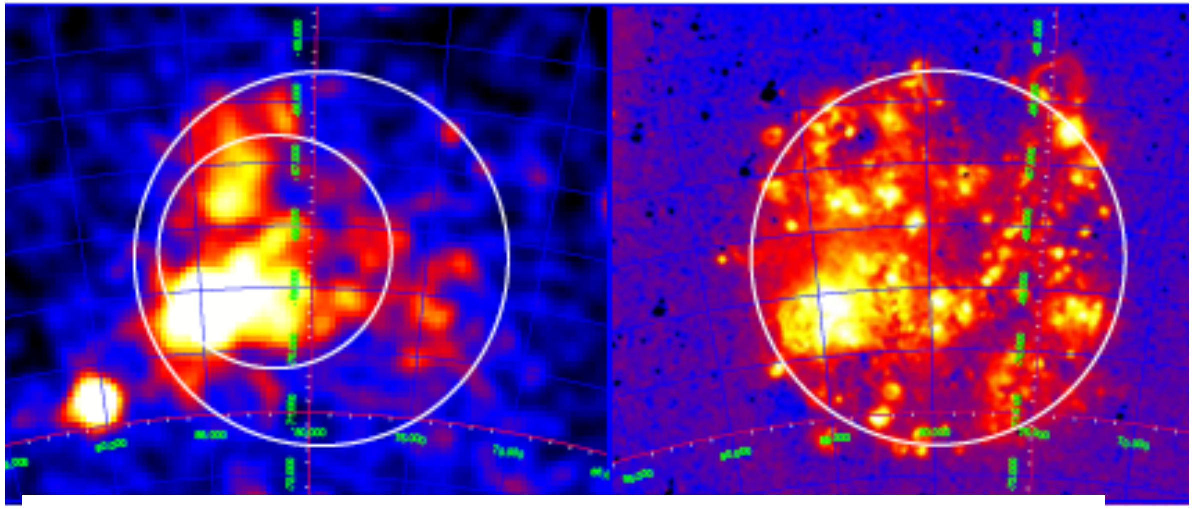
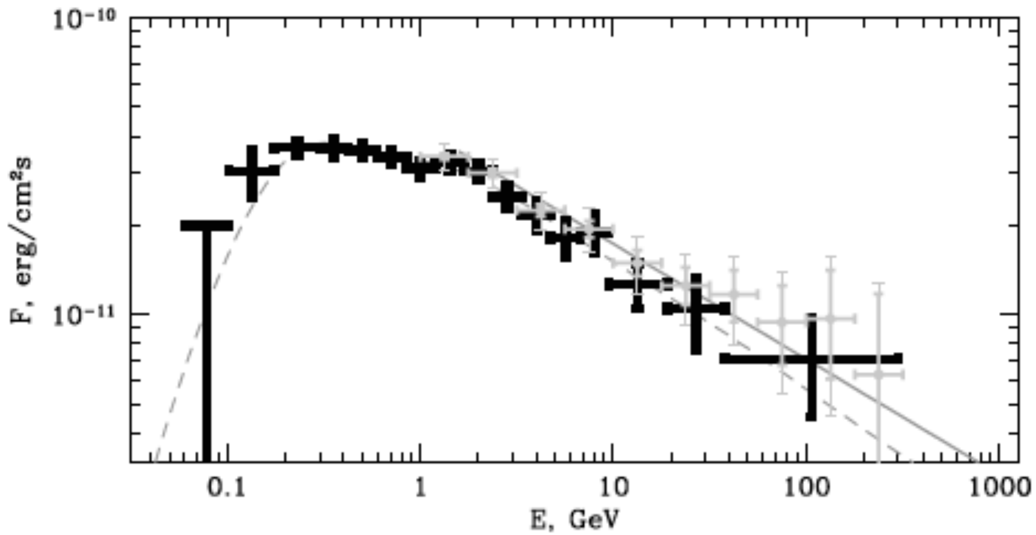
In LMC average proton spectrum 2.45



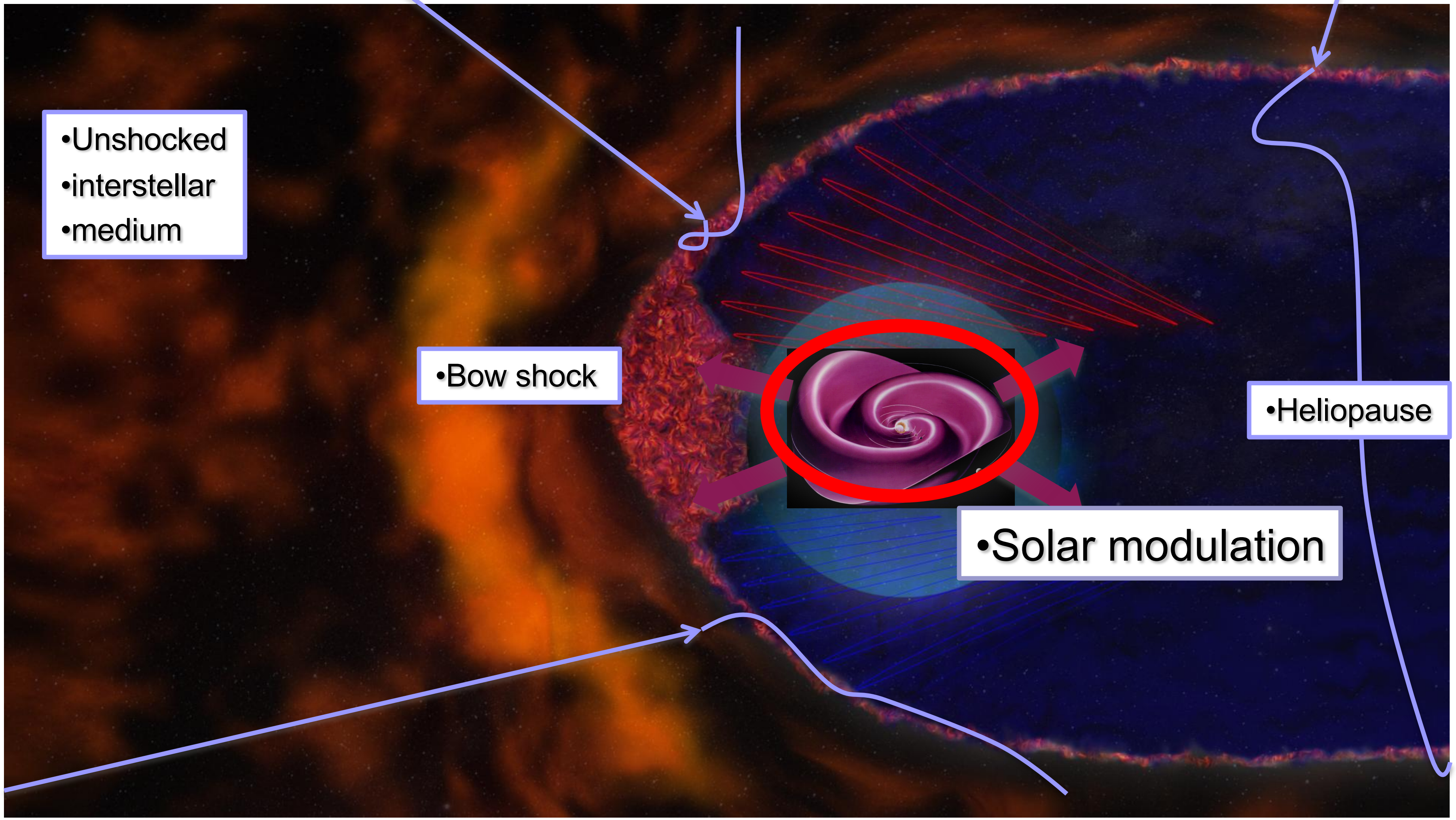


- **A.Neronov and D.Malishev, arXiv: 1505.07601**

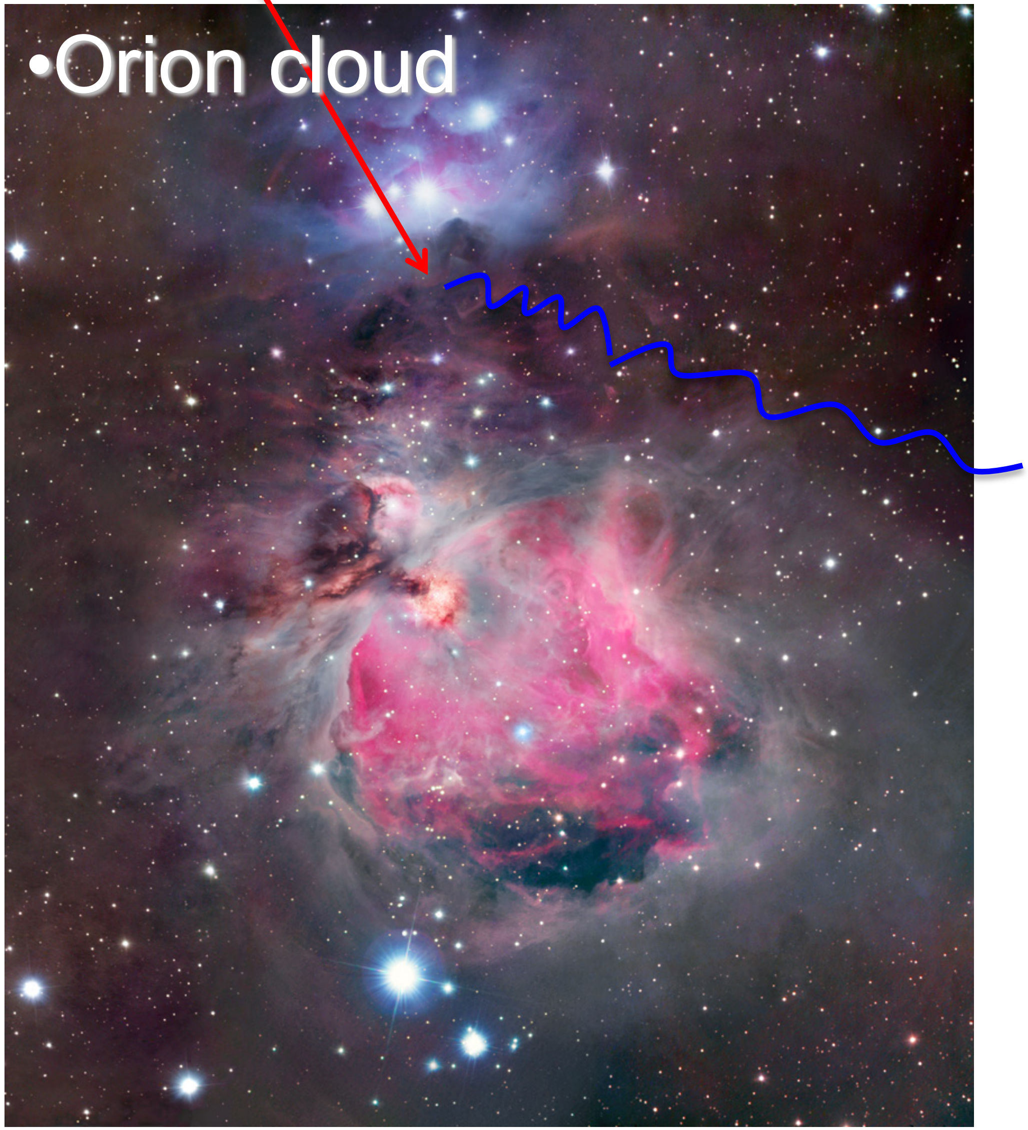
Assumptions of the model

- *Regular magnetic fields does not affect propagation of CR, one can neglect them*
- *Spectrum is the same in all galaxy. It is as measured here 1/E^2.7*
- *Sources are frequent enough that CR are in steady state regime, no variation of fluxes in time*

•Cosmic Rays in the Solar system



•CR detectors outside the Heliosphere



•GMCs are objects of the mass $\sim 10^5\ M_{Sun}$ and size ~ 10 pc, i.e. of the matter density $n \sim 10^3 - 10^4\ cm^{-3}$.

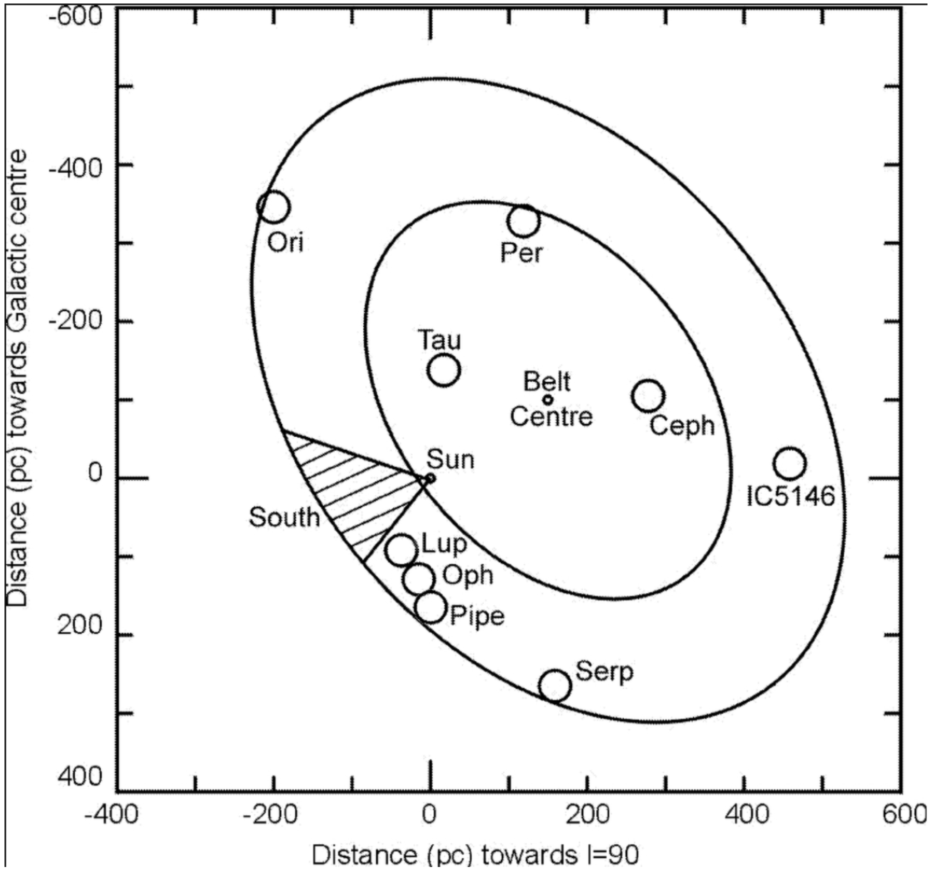
•CRs diffusing through the ISM cross the GMCs on the time scales of $t \sim 10^3 - 10^4$ yr.

•During this time CRs interact with the GMC matter with probability $p \sim ct\sigma n \sim 0.1$.

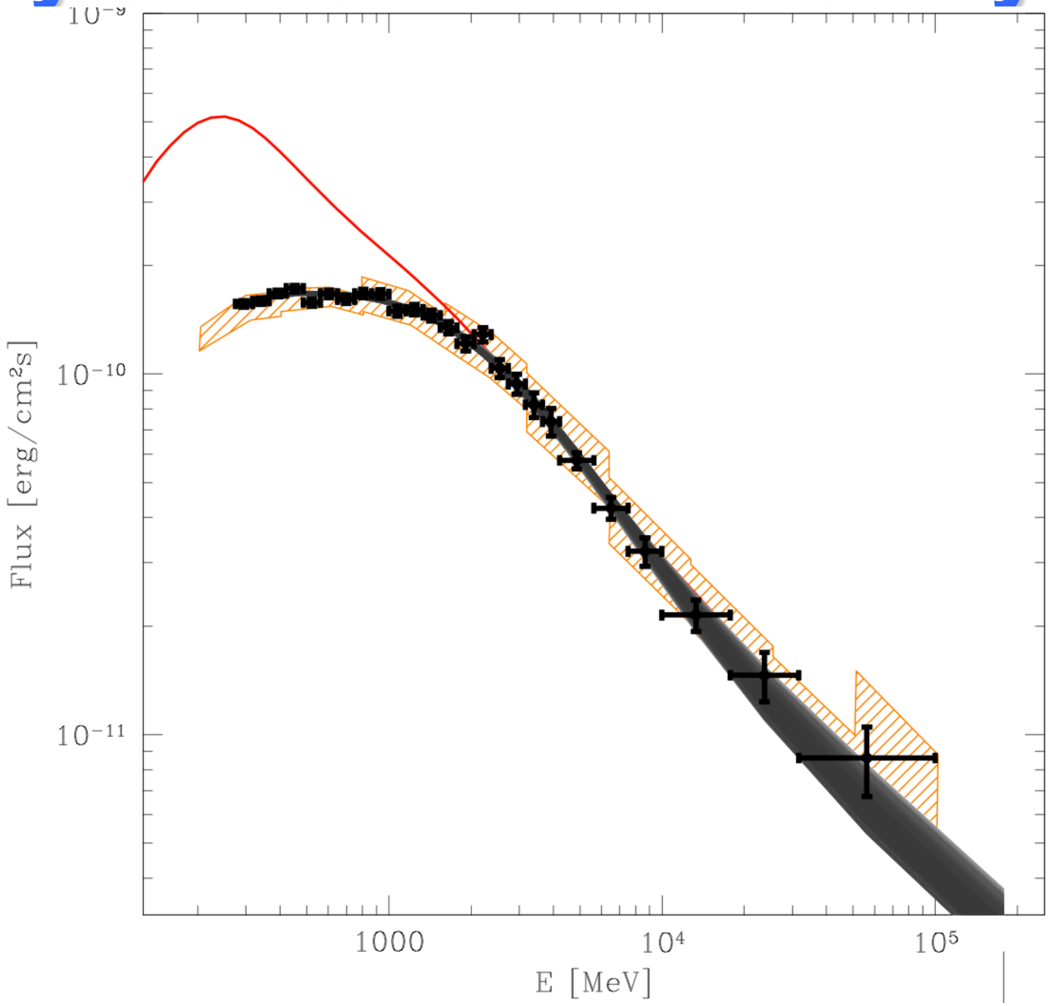
•CR interaction in the GMCs lead to the gamma-ray emission (from neutral pion production and decay).

•Large mass concentrations in the ISM could be used as "natural" CR detectors. Such mass concentrations are e.g. nearby Giant Molecular Clouds (GMC).

Gould belt clouds



•Gamma-ray emission from nearby GMCs



•The gamma-ray spectrum of GMCs repeats the spectrum of emission from local ISM (diffuse Galactic emission at high Galactic latitudes).

•Gamma-ray emission from nearby GMCs

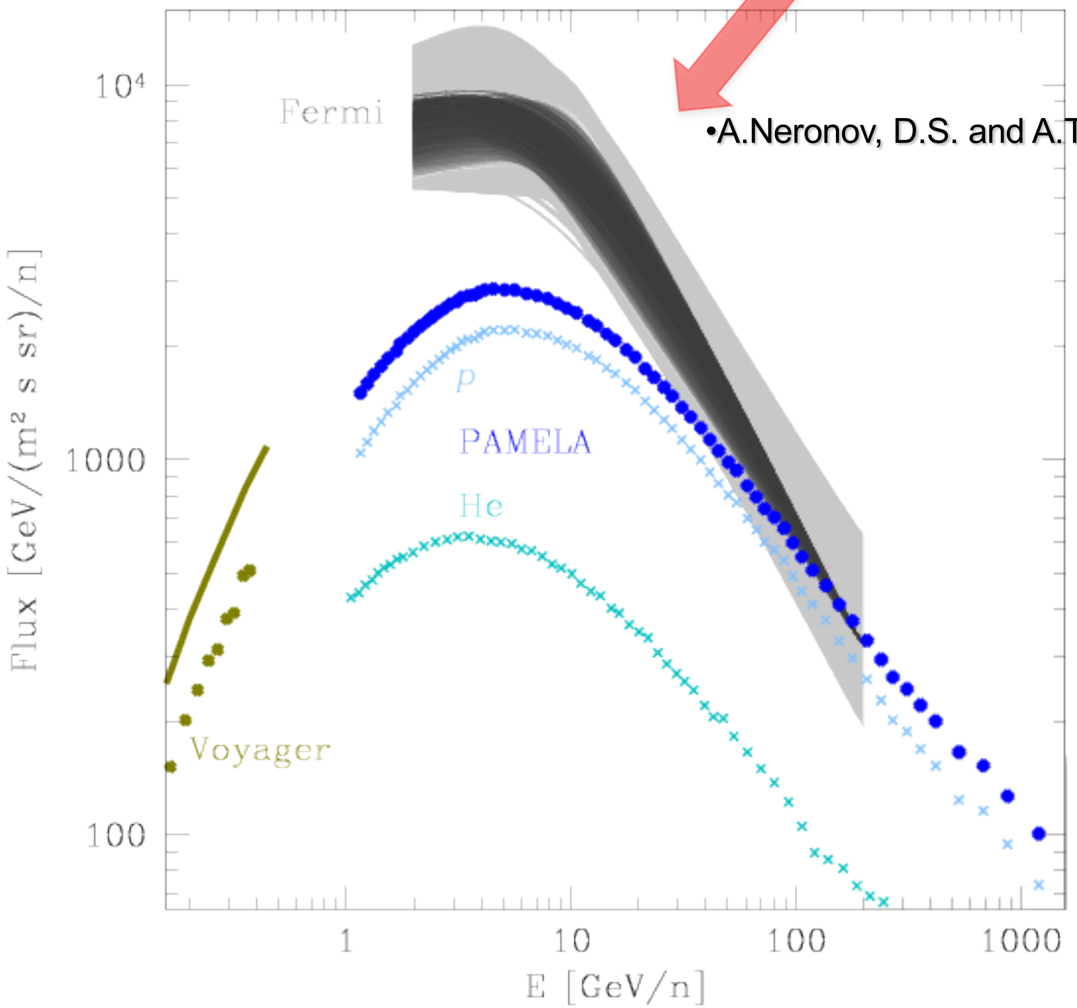
$$dN_{\rm CR}/dE = N_0\, E^{-\bar{\beta}_{\rm CR}}$$

$$\begin{aligned}\frac{E_\gamma^2\, dN_\gamma}{dE_\gamma} &\propto E_\gamma^2 \int_{E_\gamma}^{E_{\rm max}} dE'\, \frac{dN_{\rm CR}}{dE'}\, \frac{d\sigma^{pp\to\gamma}(E', E_\gamma)}{dE_\gamma} \\ &\propto E_\gamma^{2-\beta_{\rm CR}} \int_0^1 dx_E\, \frac{x_E^{\beta_{\rm CR}-1}\, d\sigma^{pp\to\gamma}(E_\gamma/x_E, x_E)}{dx_E} \\ &\equiv E_\gamma^{2-\beta_{\rm CR}}\, \tilde{Z}_\gamma(E_\gamma)\,, \qquad (1)\end{aligned}$$

$$x_E = E_\gamma/E'$$

T. Kamae, N. Karlsson, T. Mizuno, T. Abe, T. Koi, Astrophys. J. **647** (2006) 692; Erratum-ibid. **662** (2007) 779; N. Karlsson and T. Kamae, *ibid.* **674** (2008) 278.

•Galactic cosmic ray spectrum

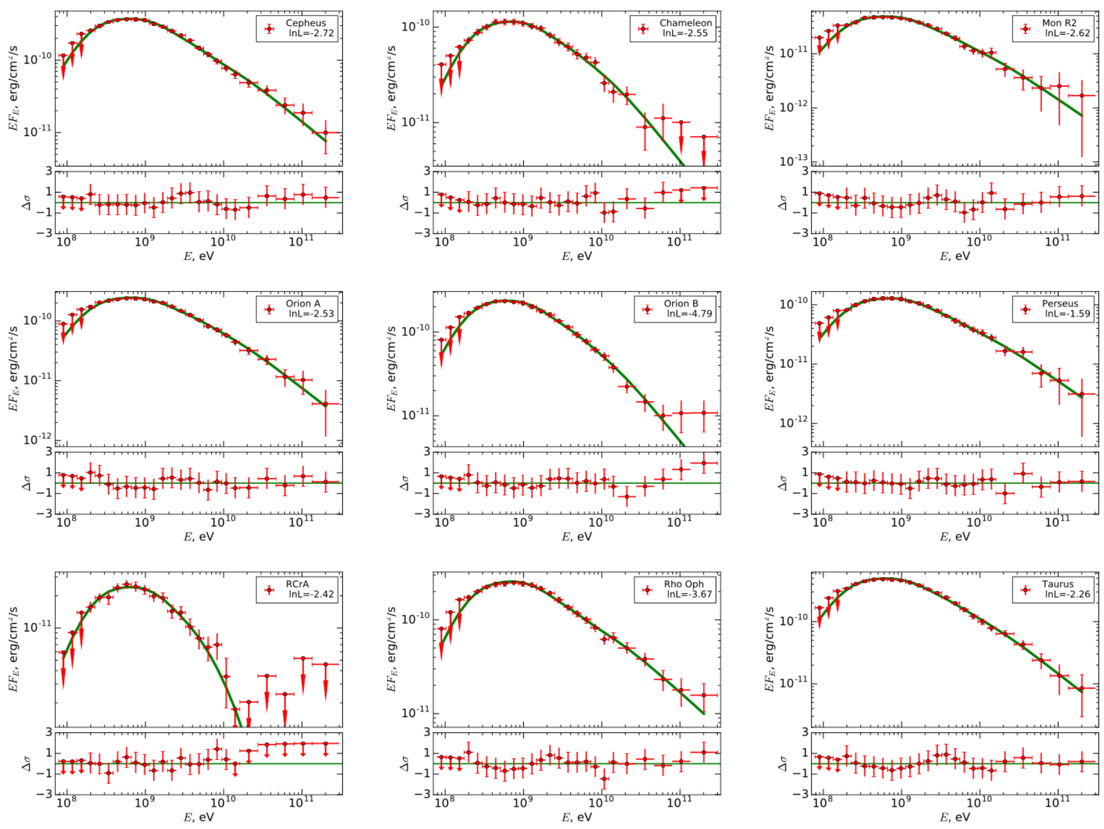


•A.Neronov, D.S. and A.Taylor, PRL, 108, 051105 (2012)

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

•Galactic cosmic ray spectrum has a strong break at the energy ~ 10 GeV.

Progress since 2012?



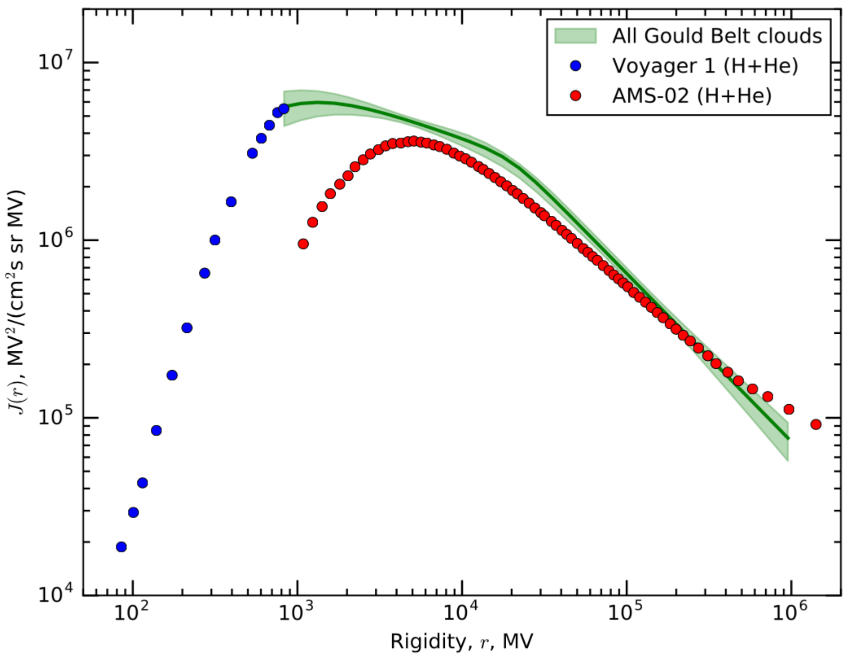
- A.Neronov, D.Malyshev & D.S. 1705.02200

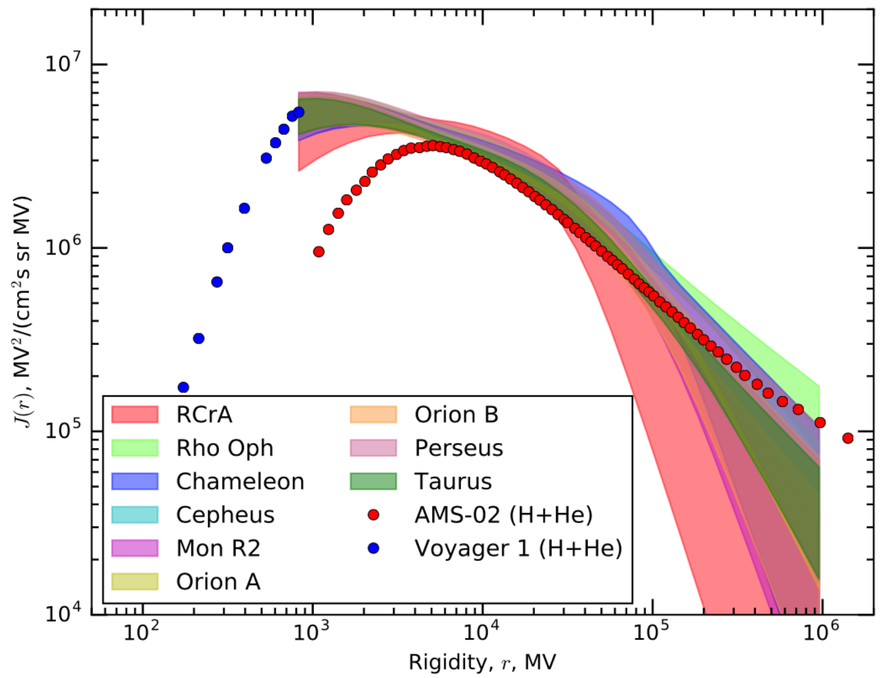
Individual clouds resolved

Name	$N_0, 10^{44}$ 1/eV	i_1	r_{br}, GV	i_2	s
R CrA	$0.24^{+0.04}_{-0.06}$	$2.33^{+0.08}_{-0.21}$	$33.72^{+17.33}_{-11.02}$	$4.82^{+0.11}_{-0.88}$	16.06 (>1.03)
Rho Oph	$2.44^{+0.35}_{-0.25}$	$2.31^{+0.08}_{-0.09}$	$17.72^{+21.49}_{-4.94}$	$2.78^{+0.17}_{-0.05}$	20.61 (>0.84)
Perseus	$1.21^{+0.18}_{-0.14}$	$2.29^{+0.08}_{-0.11}$	$20.75^{+32.81}_{-5.77}$	$2.95^{+0.42}_{-0.07}$	9.55 (>0.88)
Chameleon	$1.13^{+0.13}_{-0.14}$	$2.33^{+0.06}_{-0.11}$	$32.75^{+47.33}_{-10.00}$	$3.07^{+0.75}_{-0.14}$	11.19 (>0.88)
Cepheus	$3.97^{+0.43}_{-0.42}$	$2.36^{+0.06}_{-0.10}$	$18.06^{+13.10}_{-4.24}$	$2.92^{+0.18}_{-0.05}$	71.02 (>1.02)
Taurus	$5.40^{+0.53}_{-0.54}$	$2.38^{+0.06}_{-0.09}$	$21.87^{+19.36}_{-4.33}$	$3.02^{+0.28}_{-0.06}$	56.46 (>1.05)
Orion A	$2.54^{+0.32}_{-0.23}$	$2.35^{+0.07}_{-0.08}$	$27.03^{+31.30}_{-5.58}$	$3.05^{+0.38}_{-0.07}$	230.94 (>1.00)
Orion B	$2.73^{+0.25}_{-0.25}$	$2.41^{+0.05}_{-0.08}$	$30.52^{+32.24}_{-6.64}$	$3.19^{+0.53}_{-0.10}$	17.90 (>1.09)
Mon R2	$0.54^{+0.08}_{-0.06}$	$2.38^{+0.08}_{-0.11}$	$22.47^{+51.55}_{-6.14}$	$3.02^{+0.76}_{-0.10}$	89.20 (>0.80)
All	$19.41^{+2.11}_{-1.87}$	$2.33^{+0.06}_{-0.08}$	$18.35^{+6.48}_{-3.57}$	$2.92^{+0.07}_{-0.04}$	62.52 (>1.50)

• A.Neronov, D.Malyshev & D.S. 1705.02200

Local kpc cosmic ray spectrum



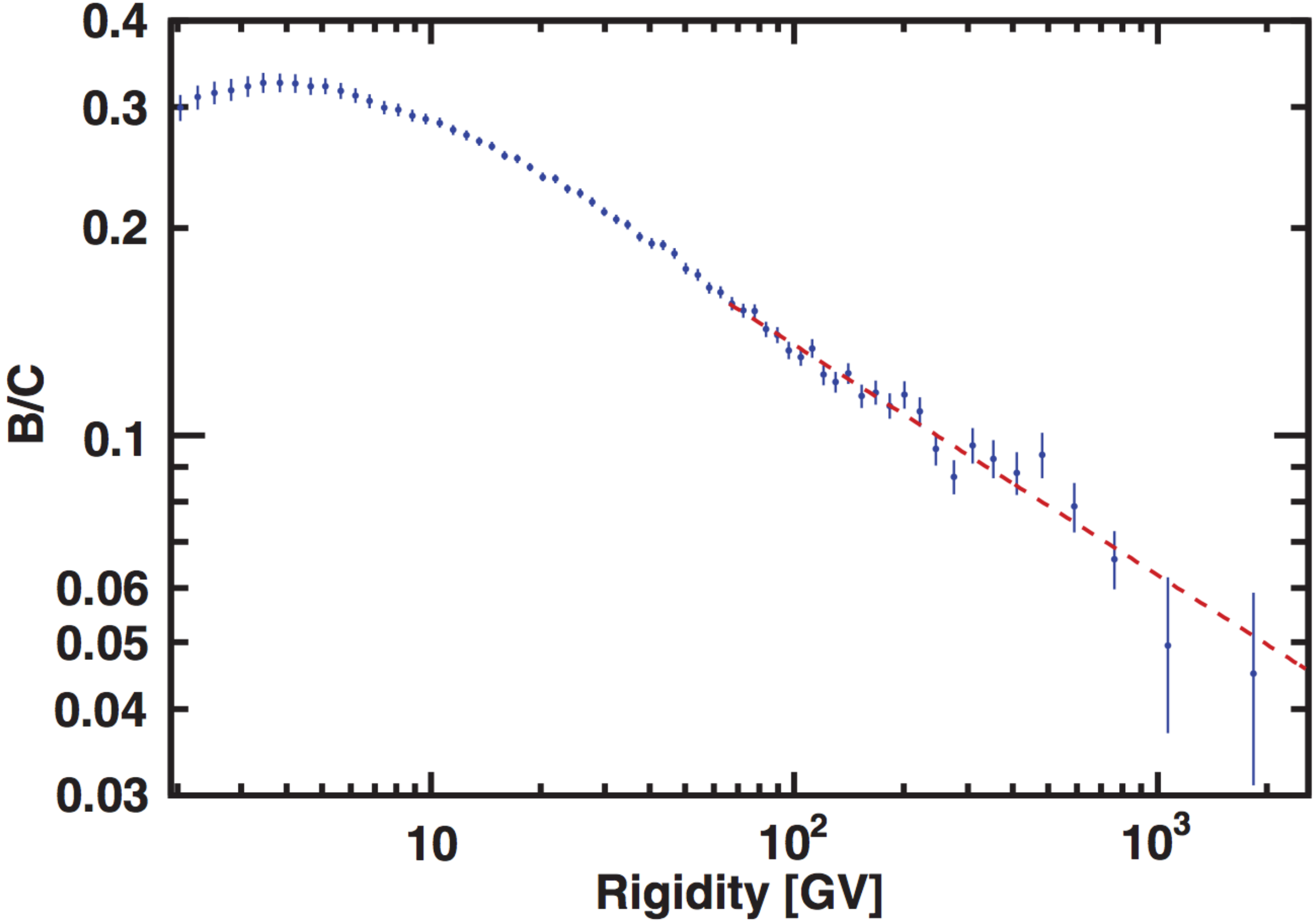


- Sources locally can not support steady state regime above 30 GeV.
- In central galaxy it is OK up to 300 GeV or above
- A.Neronov, D.Malyshev & D.S. 1705.02200

Predictions of the model

- *Spectrum is the same in all galaxy 1/E^2.7: Since accelerated spectrum is 1/E^2 or 1/E^2.2 magnetic field turbulence is Kreichnan with delta=0.5*

- AMS-2 collaboration PRL 117, 231102 (2016)
-

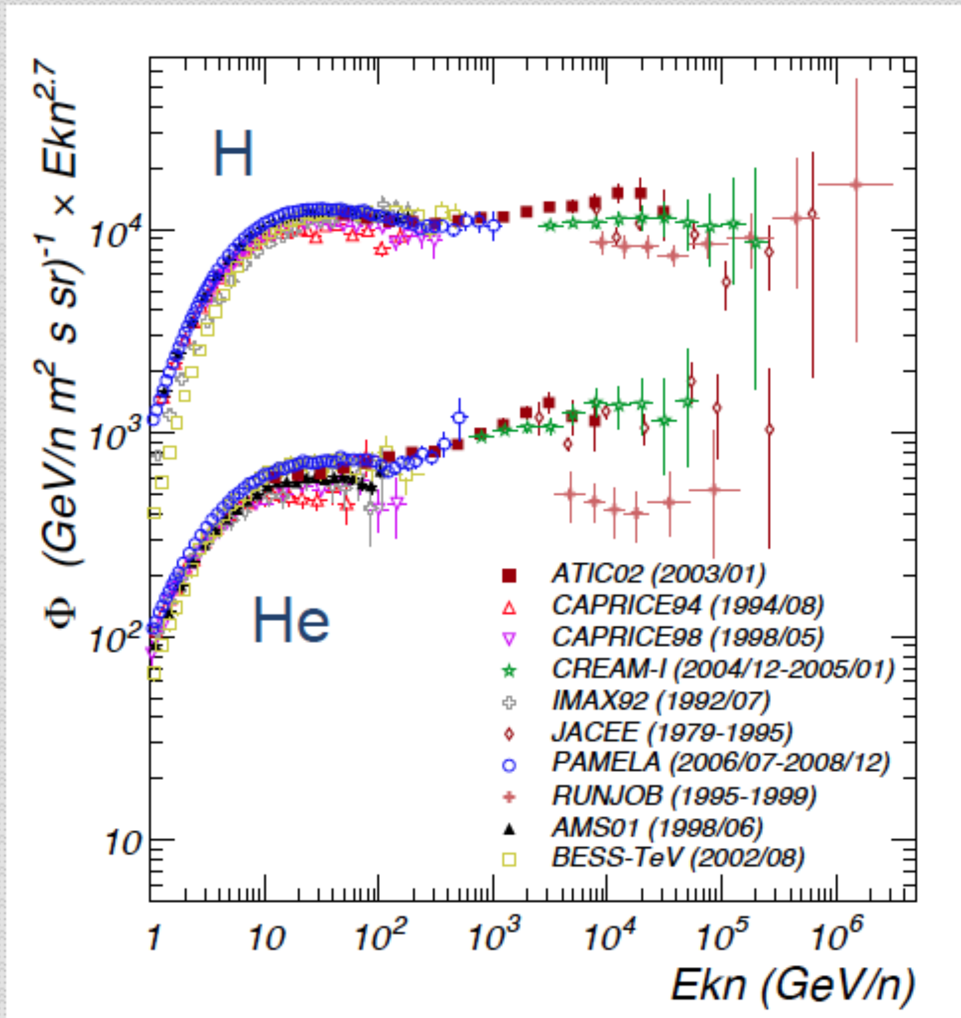


- Delta=1/ 3 Kolmogorov Turbulence

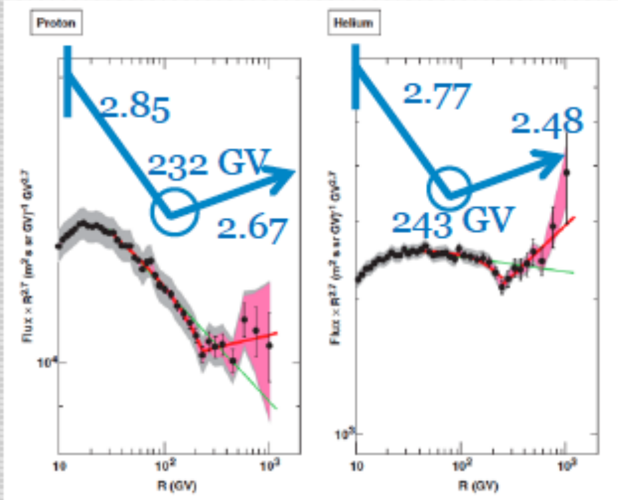
Predictions of the model

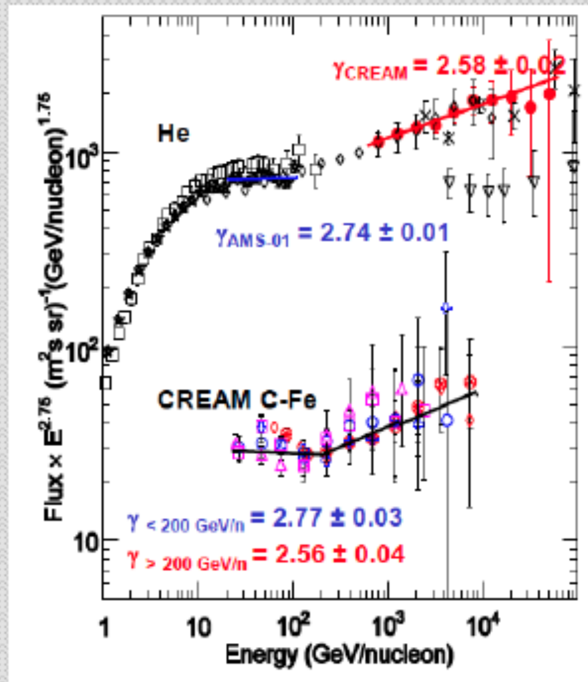
- *Spectrum is the same in all galaxy 1/E^2.7: Since accelerated spectrum is 1/E^2 or 1/E^2.2 magnetic field turbulence is Kreichnan with delta=0.5*
- *Spectra of all nuclei same as one of proton rescaled by regidity R=p/Z*

p/He spectra



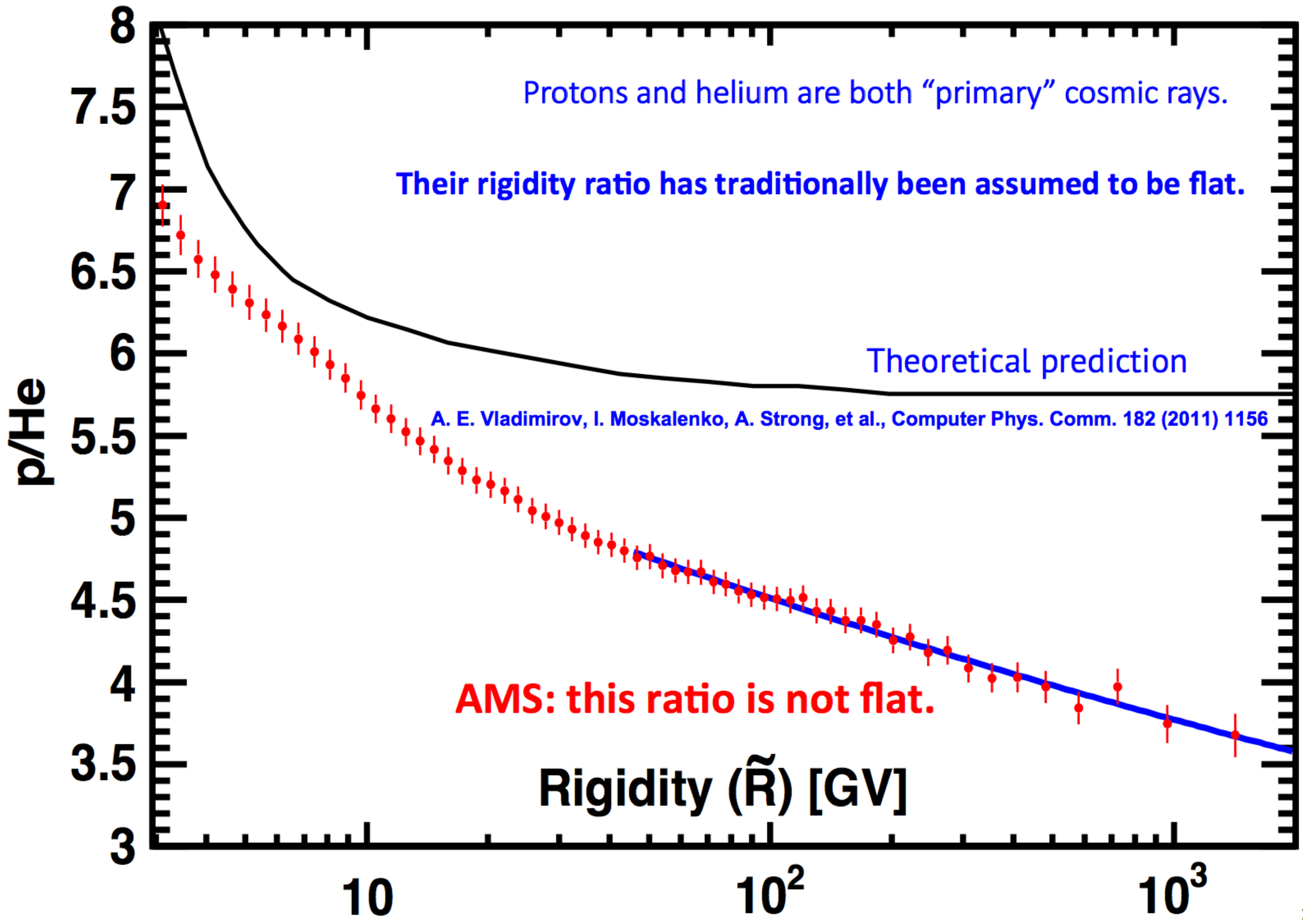
Adriani, Science 32,69 (2011)



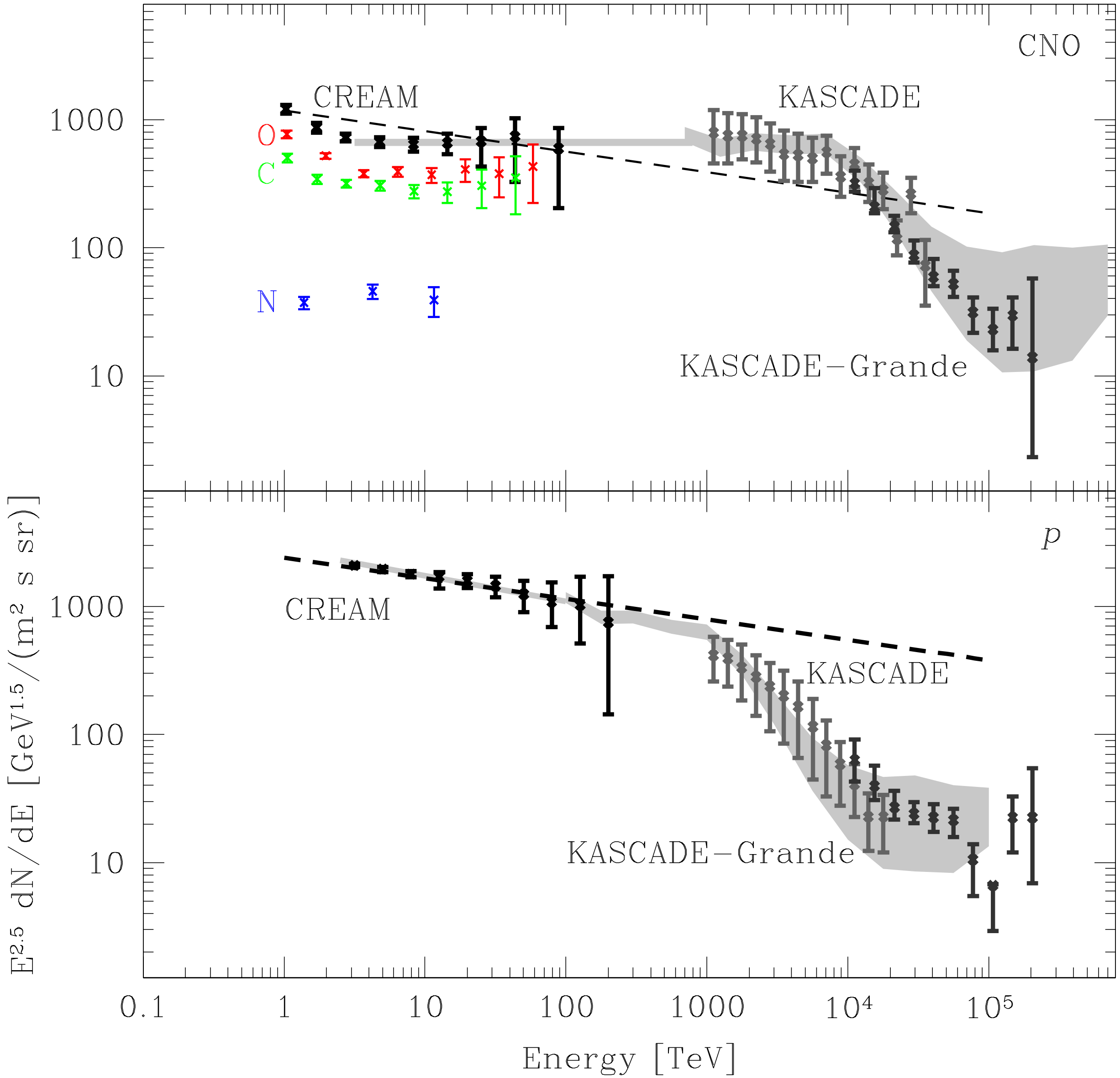


Still waiting for full CREAM statistics
AMS-02 publication soon….(< 2015)

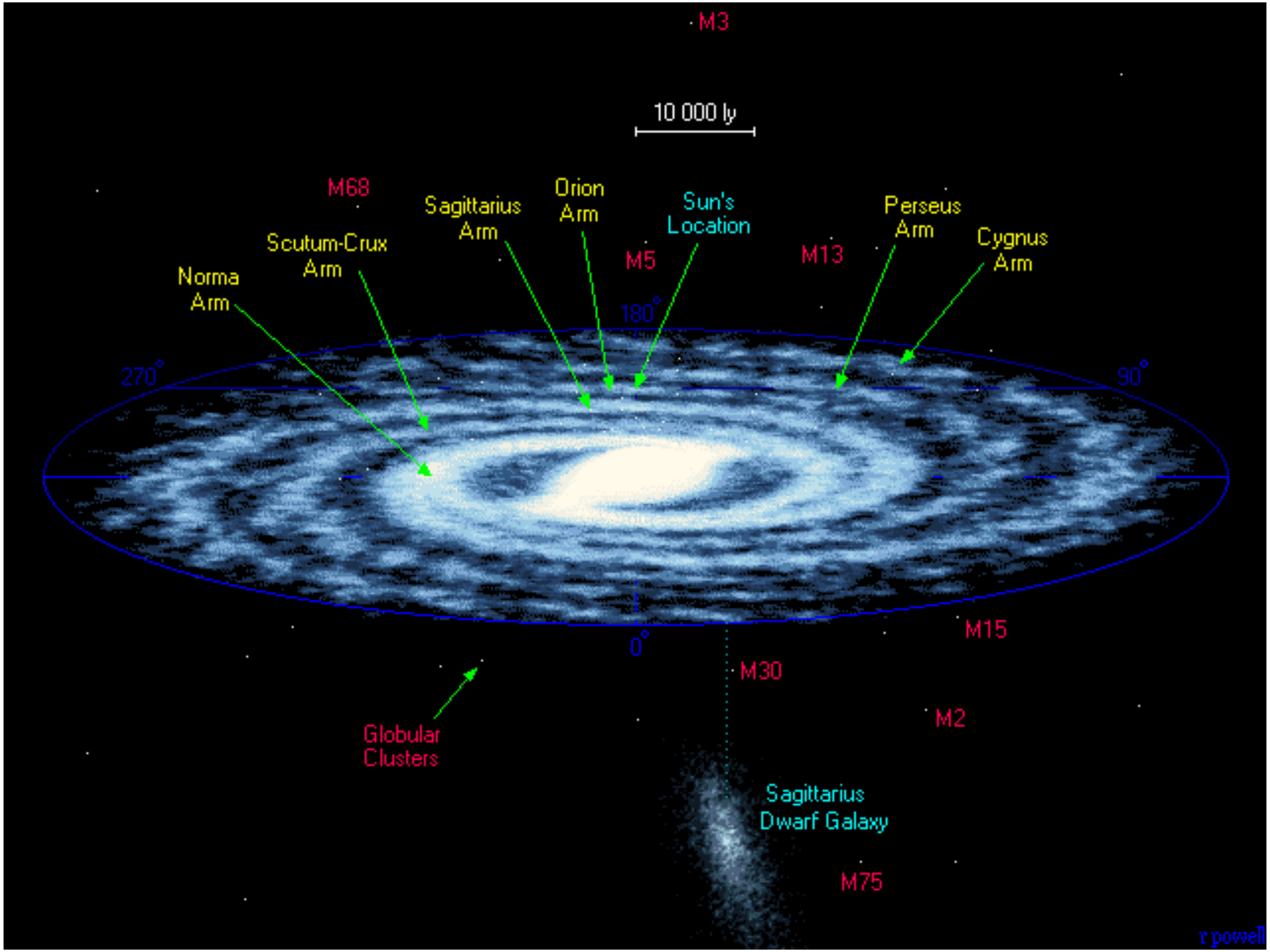
The AMS proton/Helium flux ratio



Proton and CNO spectra



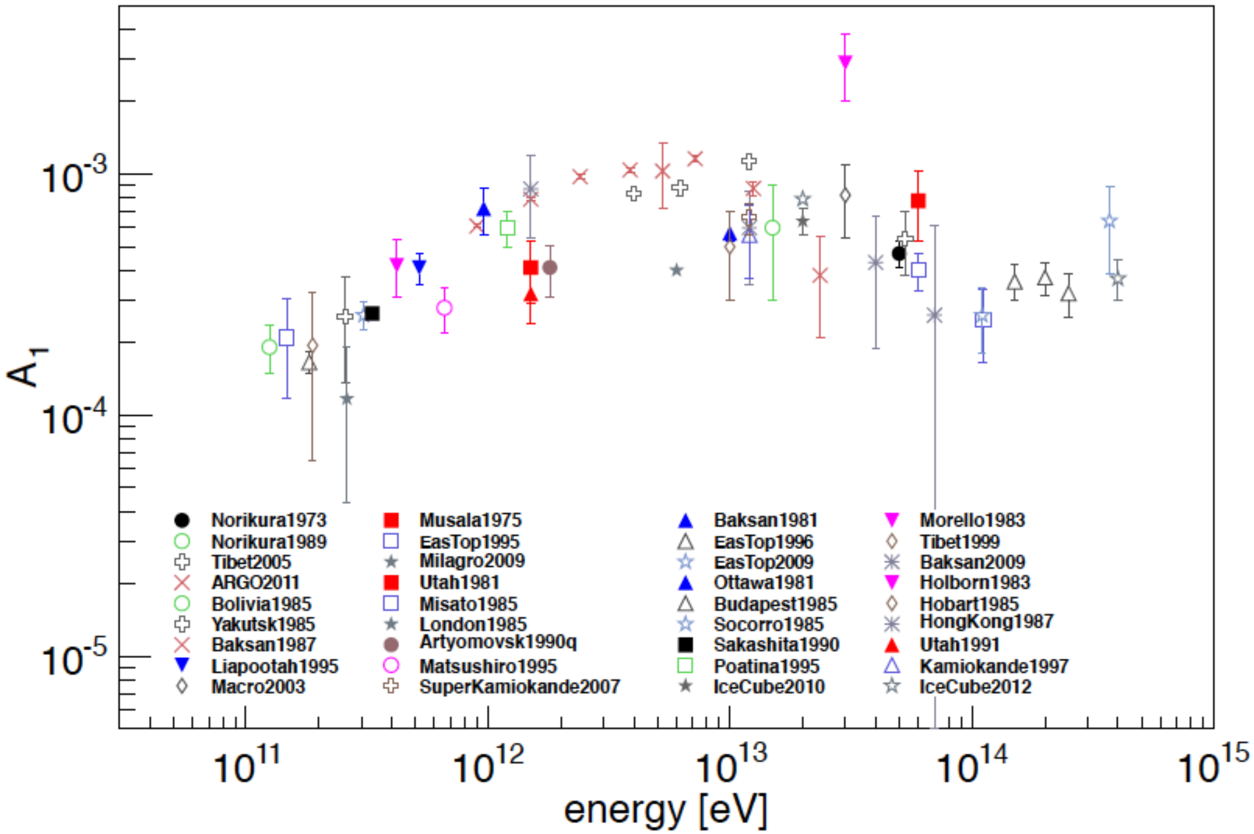
MILKY WAY GALAXY



Predictions of the model

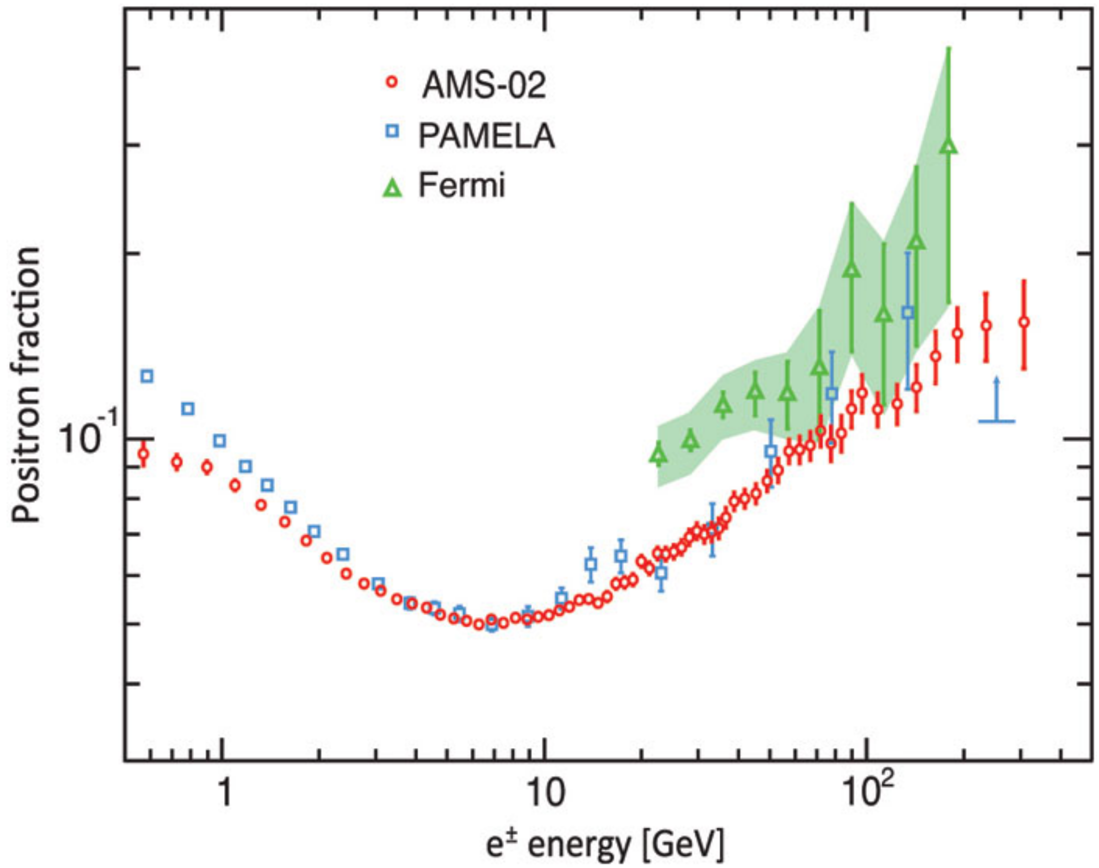
- *Because higher energy cosmic rays escape faster from Galaxy:*
  - *anisotropy is growing function of energy*
  - *Secondary fluxes drop relative to primary fluxes: positron and anti-proton fluxes should drop if compared to proton flux*

Dipole anisotropy of cosmic rays

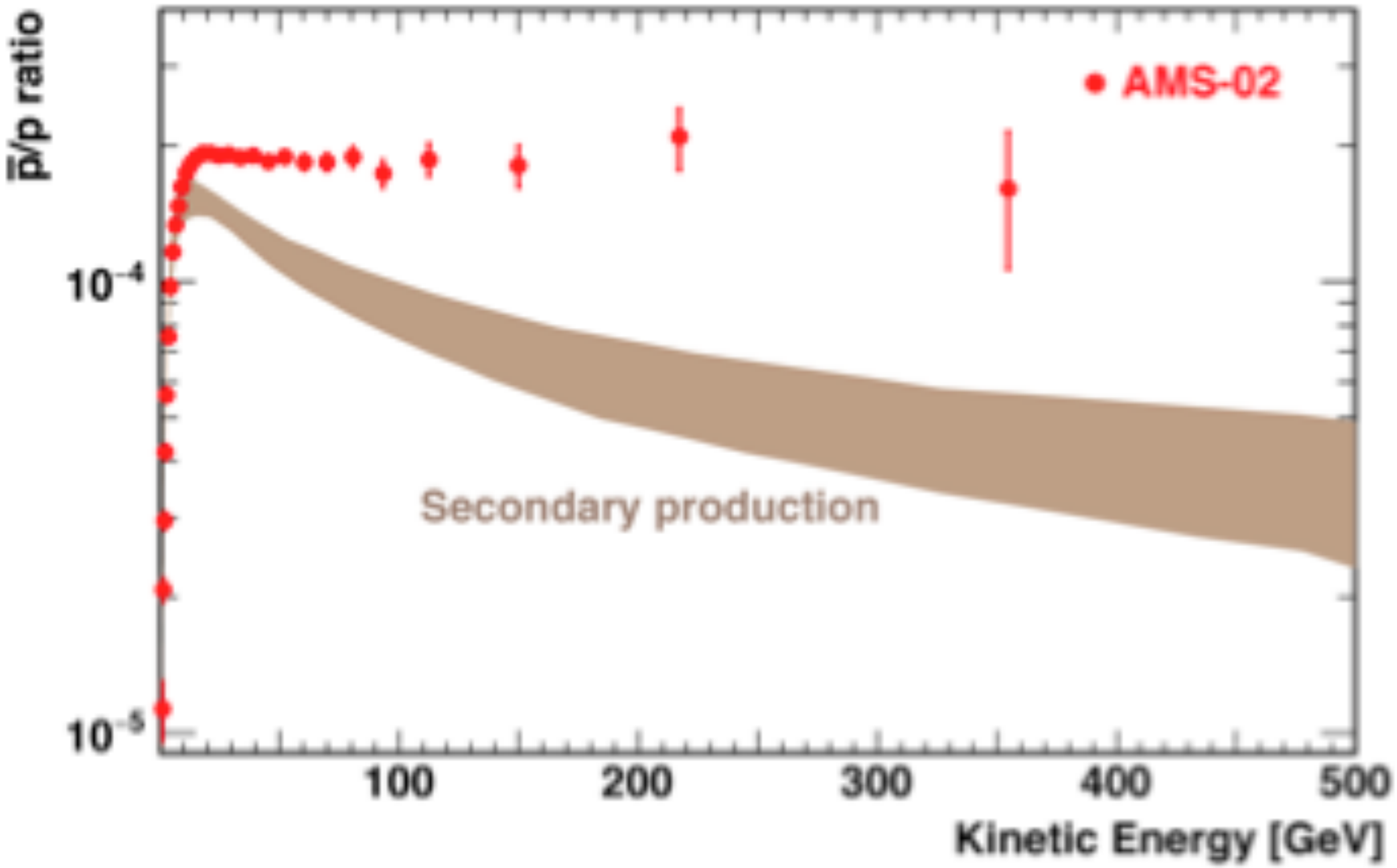


- **G.Di Sciascio and R. Iuppa, arXiv: 1407.2144**

Positron to (electron + positron) ratio by PAMELA, Fermi, AMS-2



Antriprotons by AMS-2



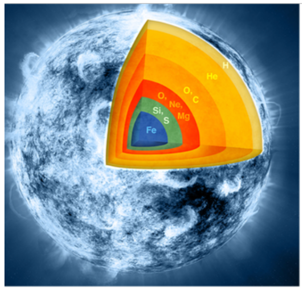
Problems of galactic cosmic rays

- *Measured spectra of nuclei affected by Solar system for E<200 GeV*
- *Show harder power law spectra 1/E^2.5 or 2.55 for all nuclei for E>200 GeV up to PeV, except protons are with alpha=2.7*
- *Acceleration consistent with 2.4-2.5 spectrum, 2.7 difficult to explain*

Problems of galactic cosmic rays

- *Models can not explain plateau in dipole anisotropy*
- *Too many positrons at high energy: Dark Matter, pulsars?*
- *There is excess in antiproton spectrum*

Fe60 from nearby source



Supernovae are Radioactivity Factories

- **medium-lived radioactivities: ^{60}Fe, ^{26}Al, ^{53}Mn, ^{41}Ca, ^{97}Tc(?), ^{146}Sm(?)**

- **^{60}Fe: made by neutron captures**

  "weak s-process"

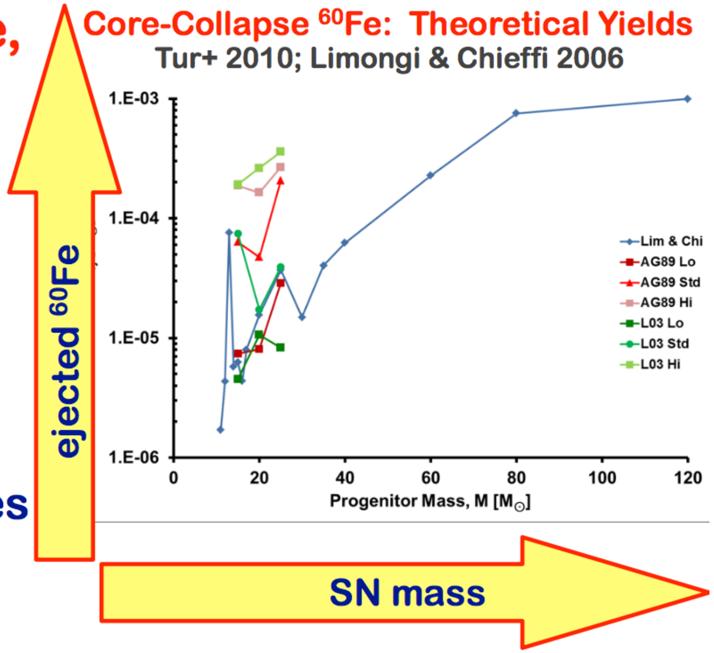
  $$^{59}\mathrm{Fe}(n,\gamma)^{60}\mathrm{Fe}$$

  large theoretical uncertainties in yield

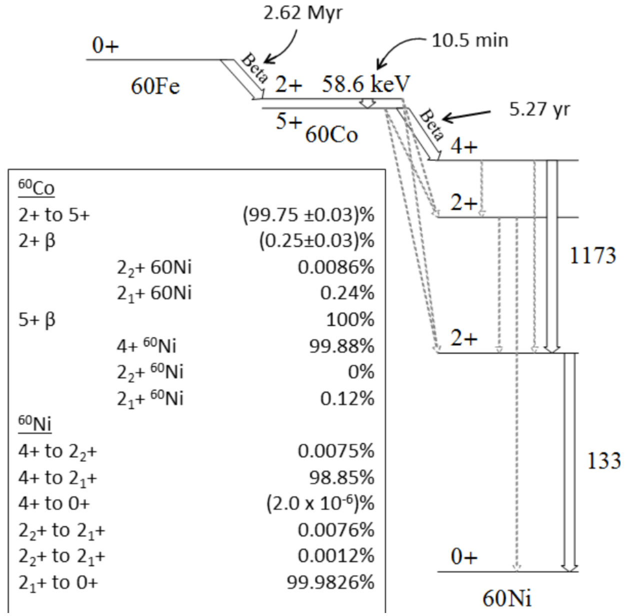
  sensitive to stellar evolution, nuke rates

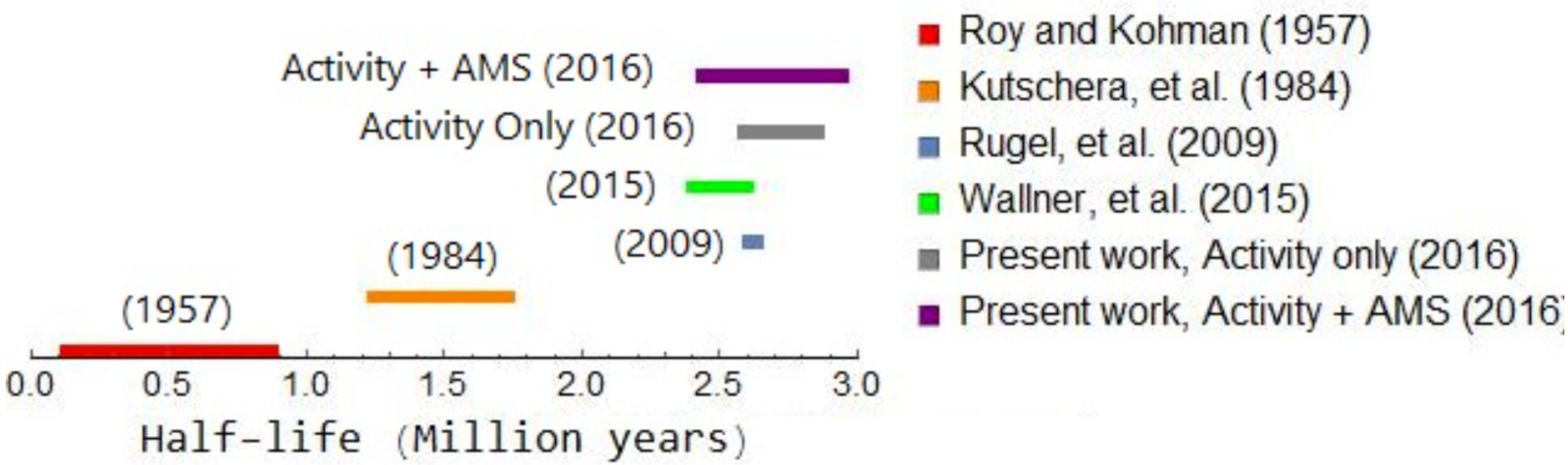
  accuracy ~order of magnitude

- **r-process? ^{182}Hf, ^{244}Pu**



Fe60 lifetime





What if $d_{\rm SN} > 10$ pc ⇨ $r_{\rm shock} > 1$ AU?

- gas-phase SN debris excluded from Earth

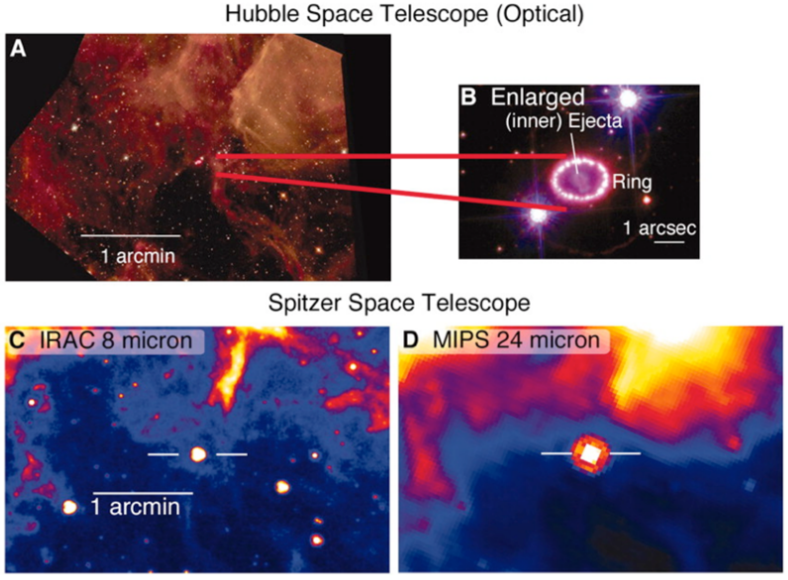
But SN radioisotopes all are refractory elements ⇨ dust grains

SN1987A:

- ~100% (!) of Fe in dust after 20 years

SN dust reaches Earth even if gas does not

- dust decouples from gas at shocks
- radioisotope delivery efficiency set by dust survival fraction



SN1987A dust: Matsuura+ 2011

Deep Ocean Crust

Knie et al. (1999)

- **ferromanganese (FeMn) crust**
- **Pacific Ocean**
- **growth: ~ 1 mm/Myr**

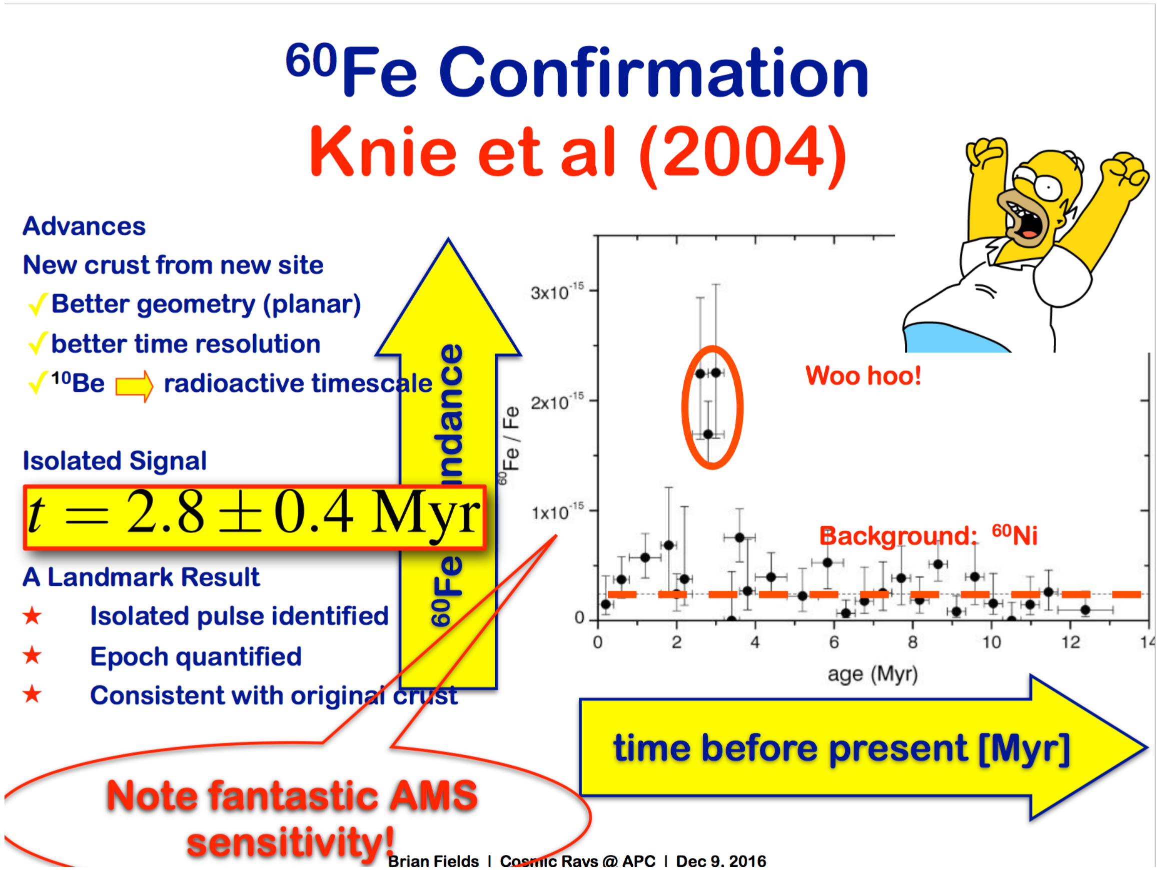
AMS ⇨ live ^{60}Fe, $\tau_{60} = 2.6\ \mathrm{Myr}$!

Expect: one radioactive layer

1999: ^{60}Fe in multiple layers!?

- **detectable signal exists**
- **but not time-resolved**


Geological Signatures
Brian Fields | Cosmic Rays @ APC


60Fe Confirmation
Knie et al (2004)
Advances
New crust from new site
√ Better geometry (planar)
√ better time resolution
√ 10Be radioactive timescale
Isolated Signal
t = 2.8 ± 0.4 Myr
A Landmark Result
★ Isolated pulse identified
★ Epoch quantified
★ Consistent with original crust
60Fe abundance
60Fe / Fe
3x10^-15
2x10^-15
1x10^-15
0
0 2 4 6 8 10 12 14
age (Myr)
Woo hoo!
Background: 60Ni
time before present [Myr]
Note fantastic AMS sensitivity!
Brian Fields | Cosmic Rays @ APC | Dec 9, 2016

Whodunit?

Fry, BDF, & Ellis 2015

Turn the problem around:

$$N_{60,\mathrm{obs}} \sim \frac{M_{60,\mathrm{eject}}}{D^2}$$

$$D \sim \sqrt{M_{60,\mathrm{eject}} / N_{60,\mathrm{obs}}}$$

"radioactivity distance" from ^{60}Fe yield

What makes ^{60}Fe?

- core-collapse supernovae
- ~~Type Ia supernovae~~
- ~~AGB stars~~
- ~~kilonovae~~

SN distance:

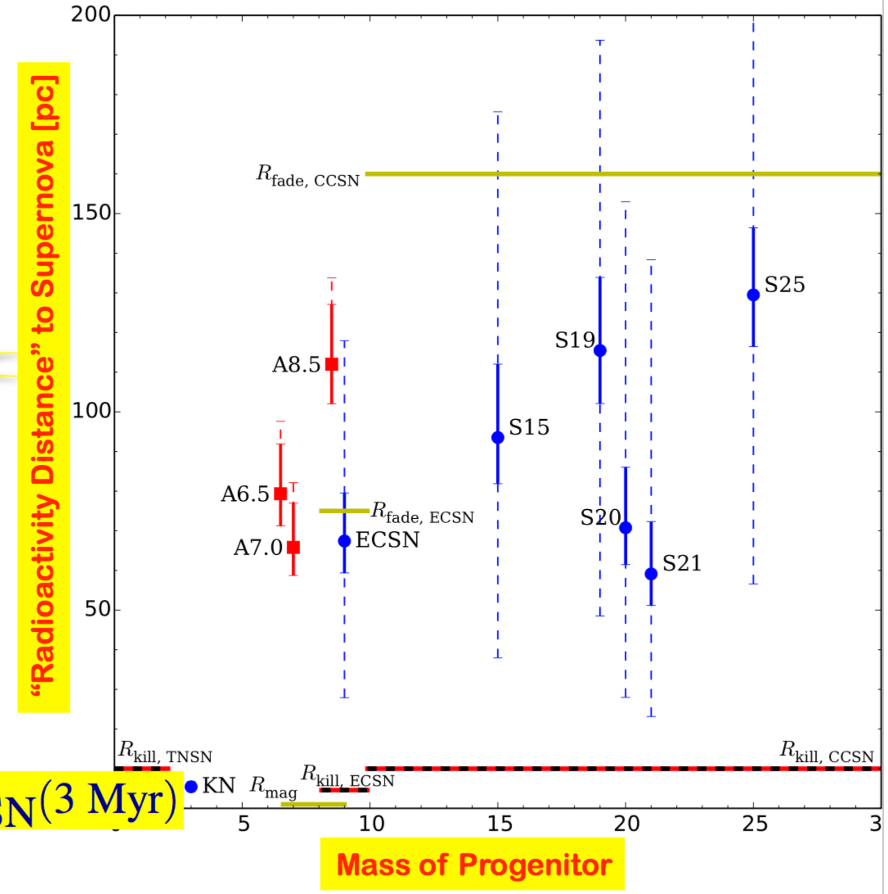
$$d(\mathrm{SN}) \sim 20 - 100\ \mathrm{pc}$$

Encouraging:

★ astronomical distances not built in!

★ $d(^{60}\mathrm{Fe}) \approx d(\mathrm{SN} \rightarrow \mathrm{Earth}) \approx d_{\mathrm{SN}}(3\ \mathrm{Myr})$

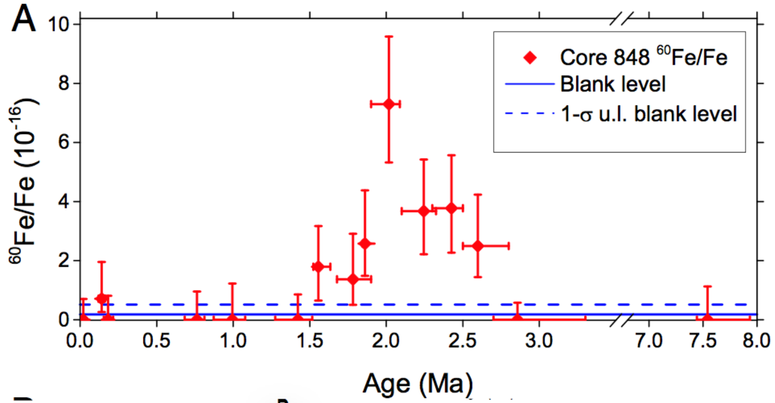
⇨ nontrivial consistency!

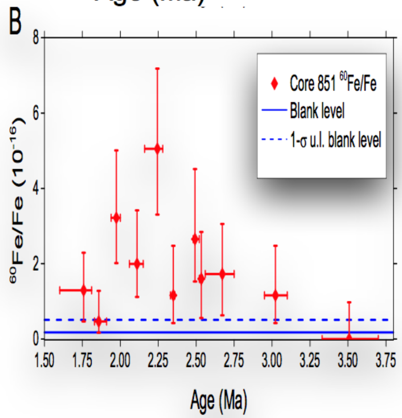


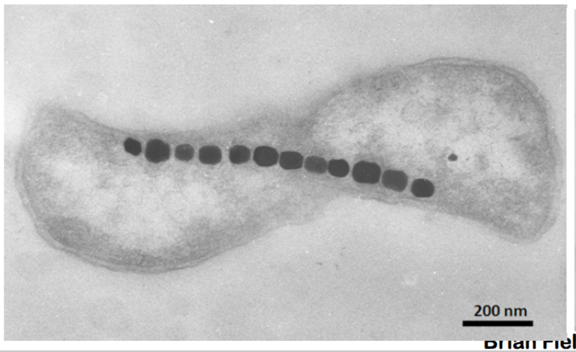
Radioactive Fossil Bacteria

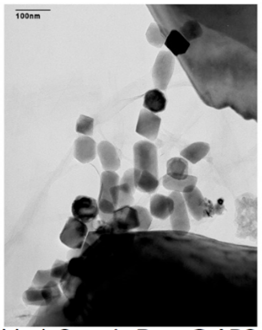
Ludwig, Bishop, et al 2016

- Deep-ocean sediments
- Select small grains of magnetite Fe_3O_4
- Fossilized remains of magnetotactic bacteria



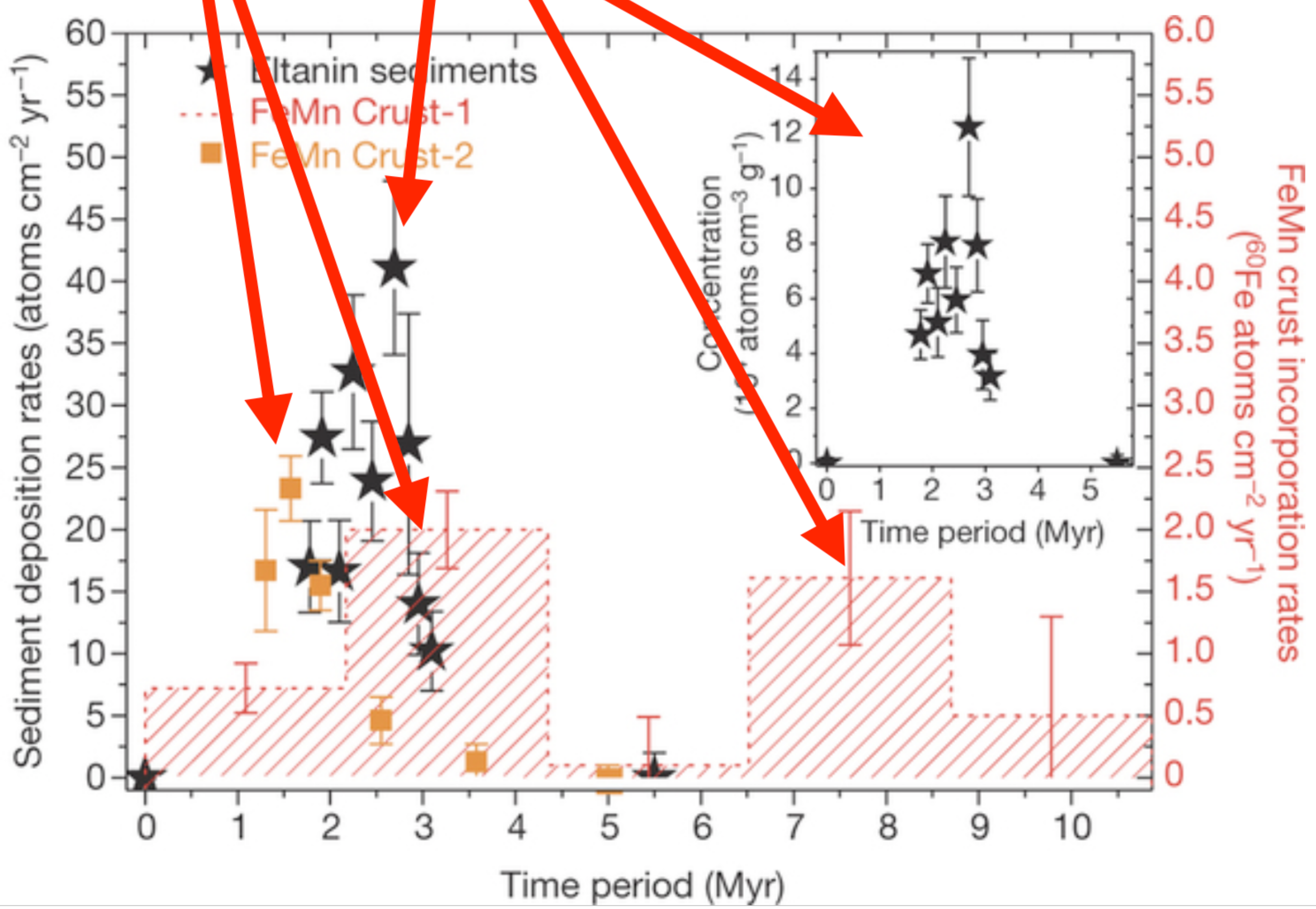






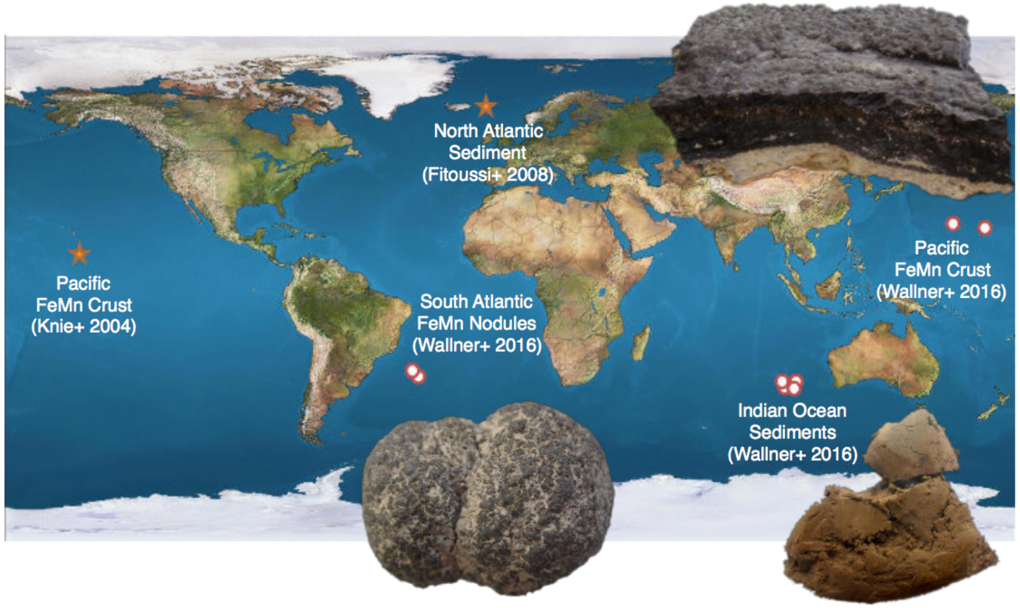
Wallner+ 2016 Nature

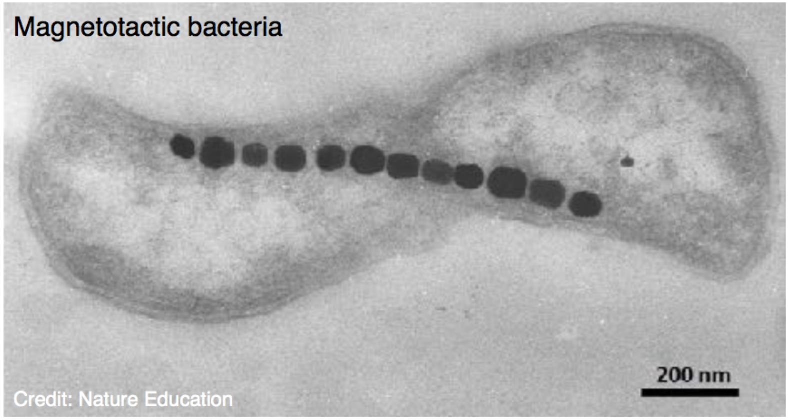
- ★ confirmation of 60Fe crust signal at ~3 Myr
- ★ sedimentary time profile: ~1 Myr width?!
- ★ indication of second ^{60}Fe pulse ~8 Myr

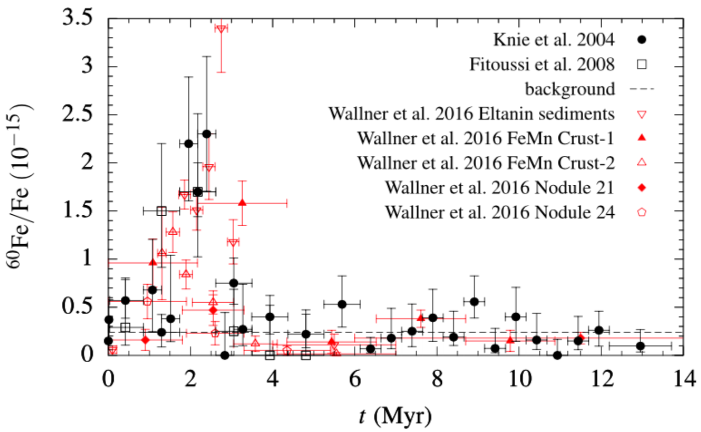


Latest developments

^{60}Fe anomaly is global, extended in time (Wallner+2016; Ludwig+ 2016), and even exists on the Moon (Fimiani+ 2016).





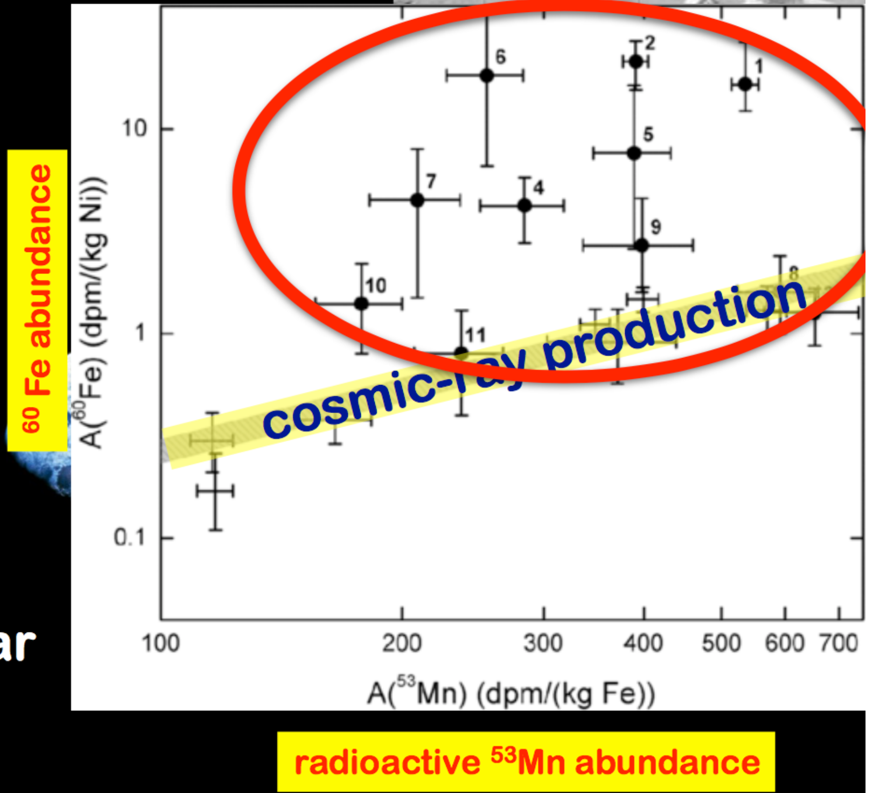


The Moon!

Lunar Soil

- ★ consistency check for deep-ocean signal
- ★ but: nontrivial background: cosmic-ray activation of lunar regolith

$$\mathrm{CR} + \mathrm{Ni} \rightarrow {}^{60}\mathrm{Fe} + \cdots$$
$$\mathrm{CR} + \mathrm{Fe} \rightarrow {}^{53}\mathrm{Mn} + \cdots$$



Fimiani+ 2016 PRL

- ★ ^{60}Fe excess in top layer of lunar drill core
- ★ signal (surface density) consistent with deep ocean

Outlook

Live ^{60}Fe seen globally and on the Moon

- ★ signal in deep ocean crusts, nodules, sediments find
- ★ confirmed pulse ~2-3 Myr ago
- ★ evidence for pulse at ~8 Myr
- ★ evidence for lunar signal
- ★ Source of Local Bubble?

Birth of "Supernova Archaeology"

Implications across disciplines:
cosmic rays, nucleosynthesis, stellar evolution, bio evolution, astrobiol

Future Research

- Supernova(e) origin and direction
  - ★ lunar distribution
  - ★ cosmic-ray anisotropies
  - ★ neutron star/pulsar correlation
- more, different samples:
  - ✓ other isotopes
  - ✓ other media (fossil bacteria)
  - ✓ other sites: Moon!
- other epochs? Mass extinction correlations?
- stay tuned… BDF Euro sabbatical AY 2017-2018

Nachbarsternsupernovaexplosionsgefahr

or

Attack of the Death Star!

Ill efects if a supernova too close

possible source of mass extinction

- Shklovskii; Russell & Tucker 71; Ruderman 74; Melott group

Ionizing radiation

- initial gamma, X, UV rays destroy stratospheric ozone

  Ruderman 74; Ellis & Schramm 94
- solar UV kills bottom of food chain

  Crutzen & Bruhl 96; Gehrels etal 03;

  Melott & Thomas groups; Smith, Sclao, & Wheeler 04
- cosmic rays arrive with blast, double whammy
- ionization damage, muon radiation

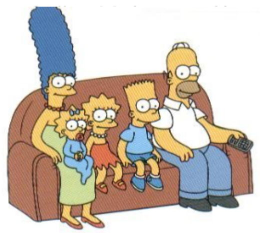
Neutrinos

- neutrino-nucleon elastic scatterin

  "linear energy transfer"

  ⇨ DNA damage

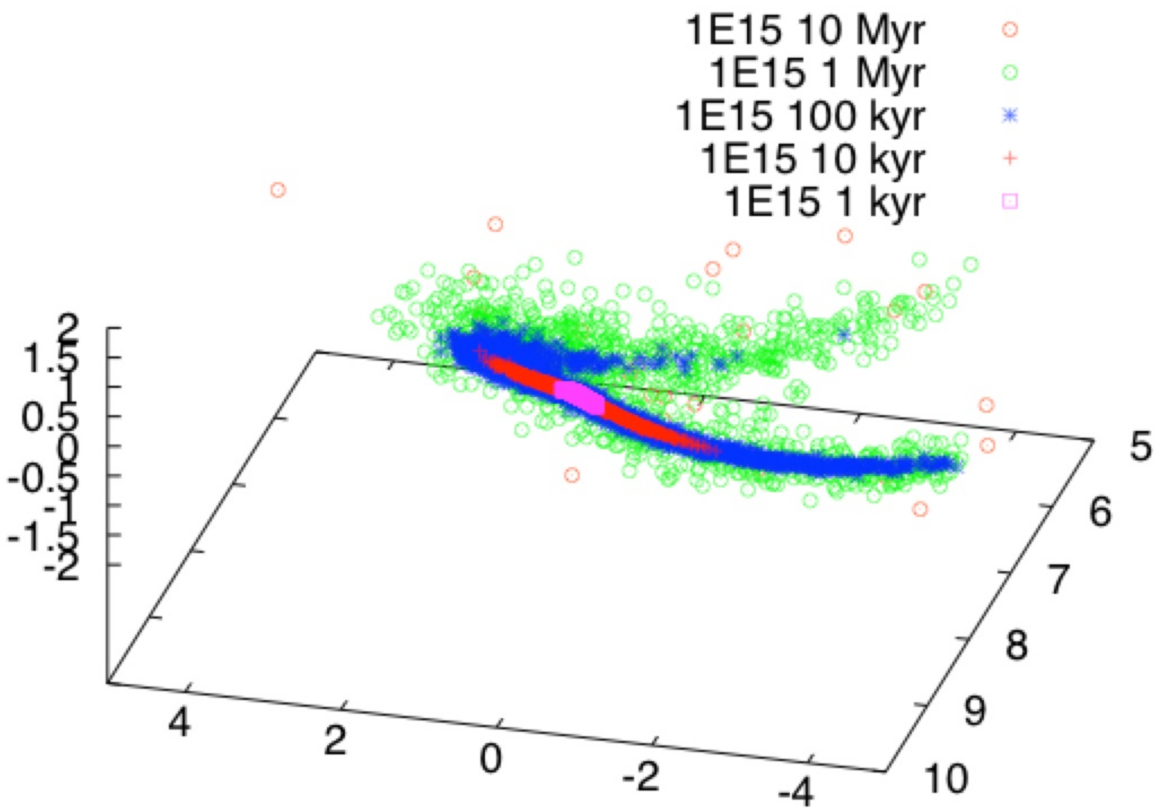
)2



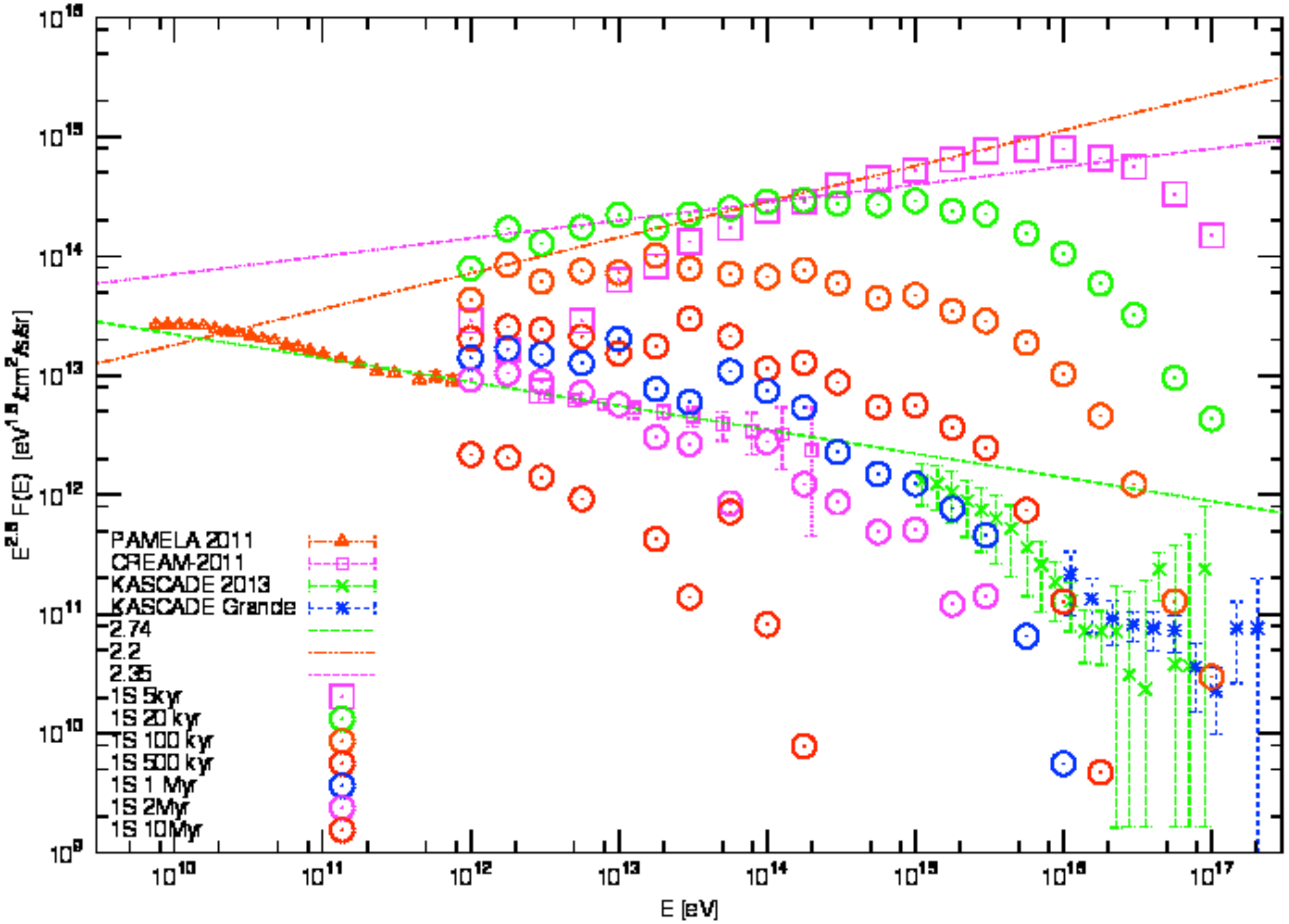
Minimum safe distance: ~8 pc

2-3 Myr old SN: protons, positrons and anti-protons

Proton flux from SN at 1 PeV



Proton flux from nearby SN



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

Two regimes of anisotropy:

- Anisoptropy:

$$\delta_a = \frac{3}{c}\frac{j_a}{n} = -\frac{3D_{ab}}{c}\frac{\nabla_b n}{n}$$

- Steady state disk:

$$\delta_{\rm fl} \approx \frac{3}{2^{5/2}\pi^{1/2} c \sigma_{\rm sn}^{1/2} H \tau} = \frac{3D}{2^{3/2} cH} \propto (E/Z)^a$$

- Single source: n~exp(-r²/4DT)

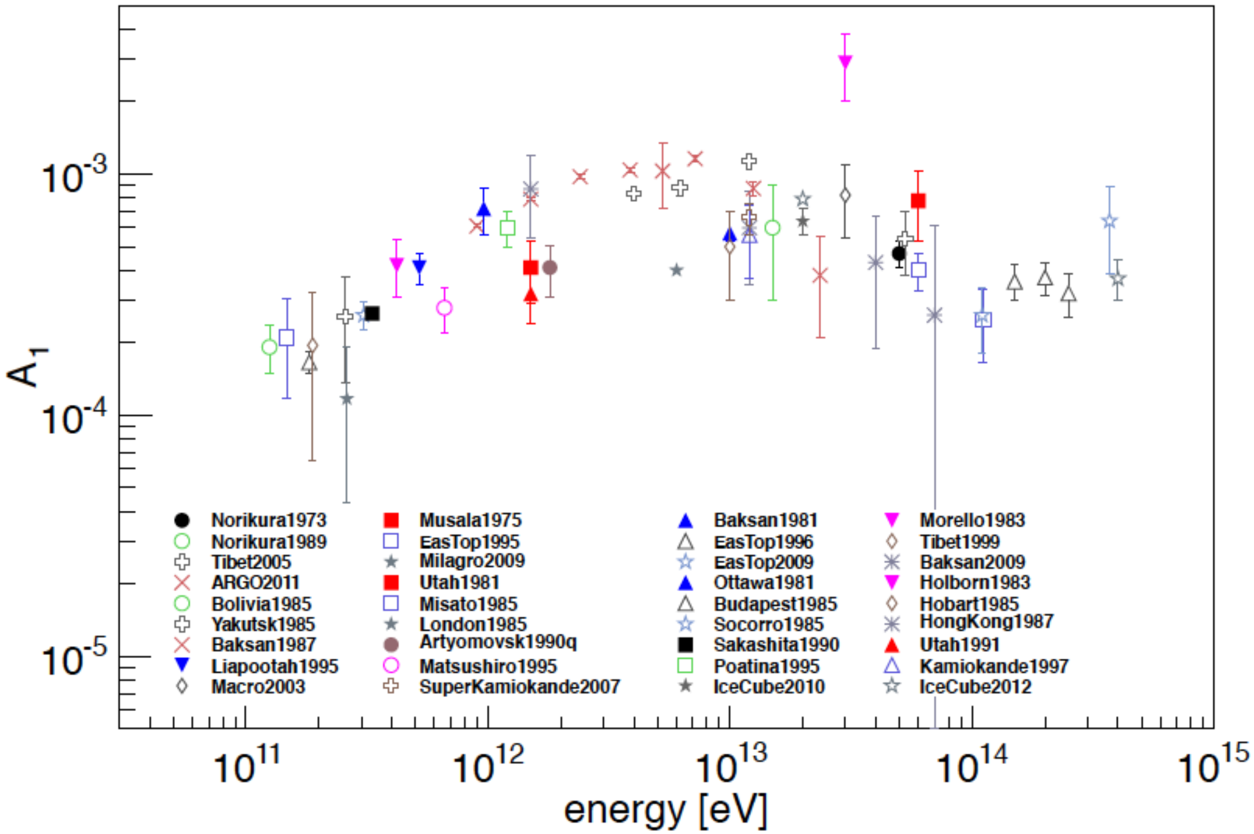
$$\delta = 3R/(2cT),$$

-

- Source which give part of flux $f_s = I_s(E)/I_{\rm tot},$

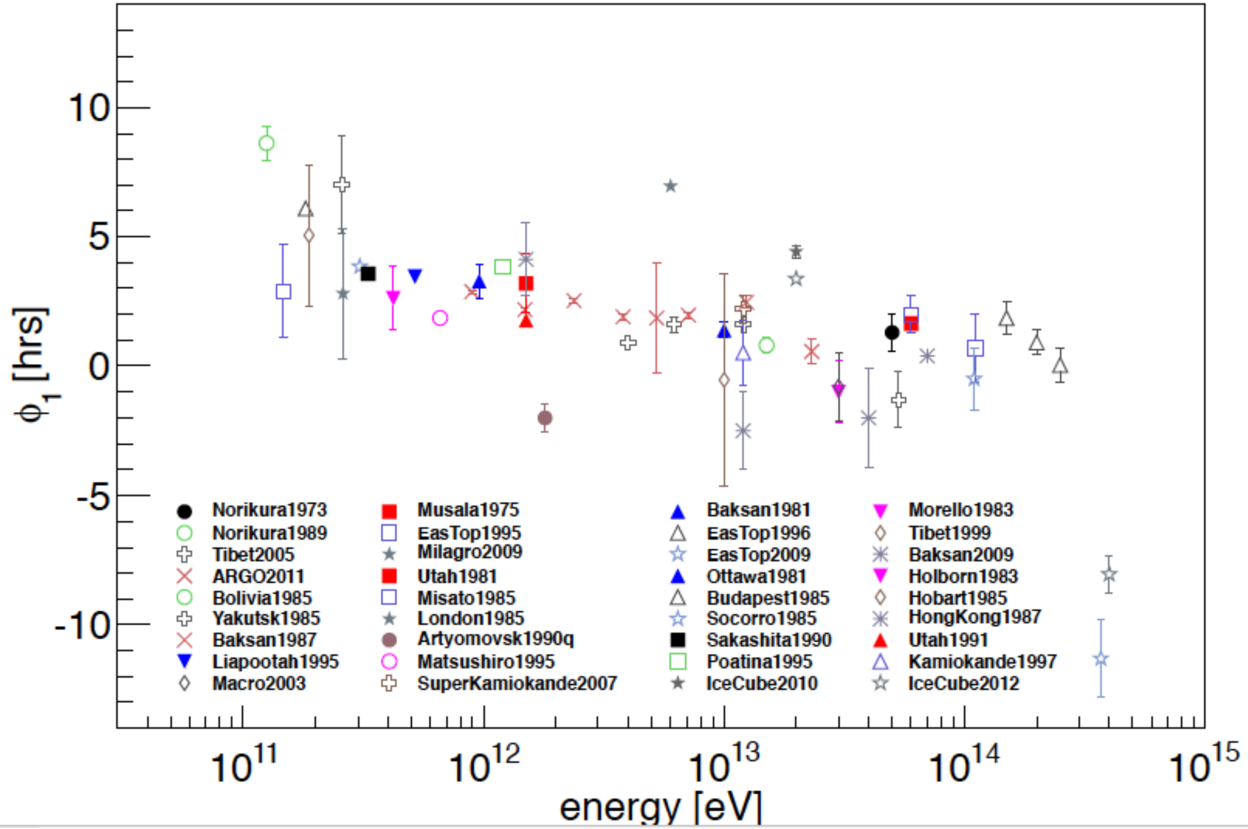
$$\delta_s = 3 f_i R/(2cT).$$

Dipole anisotropy of cosmic rays



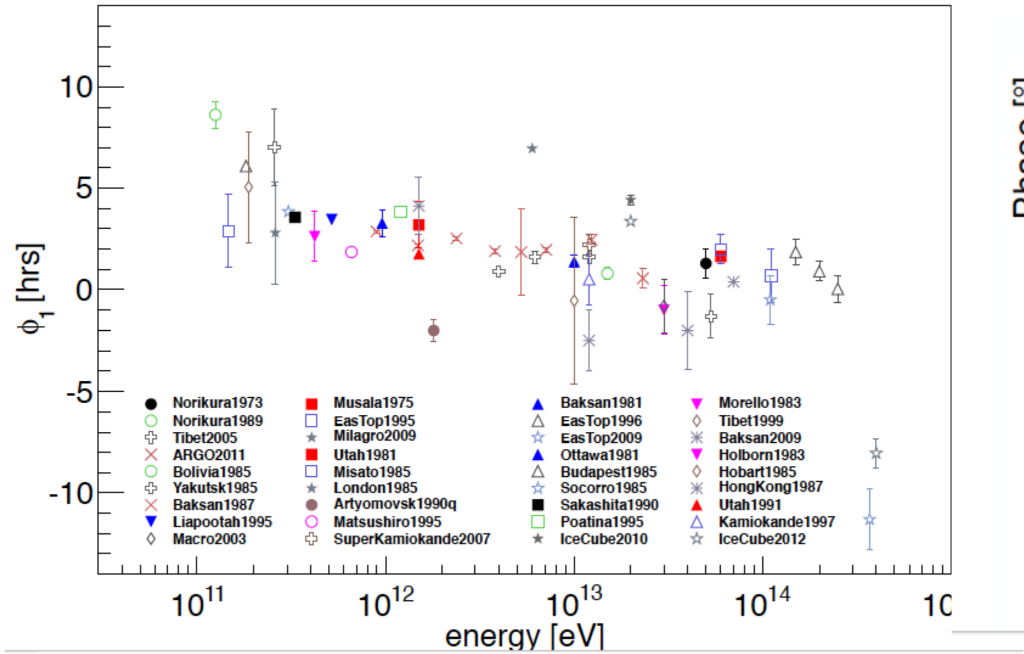
- **G.Di Sciascio and R. Iuppa, arXiv: 1407.2144**

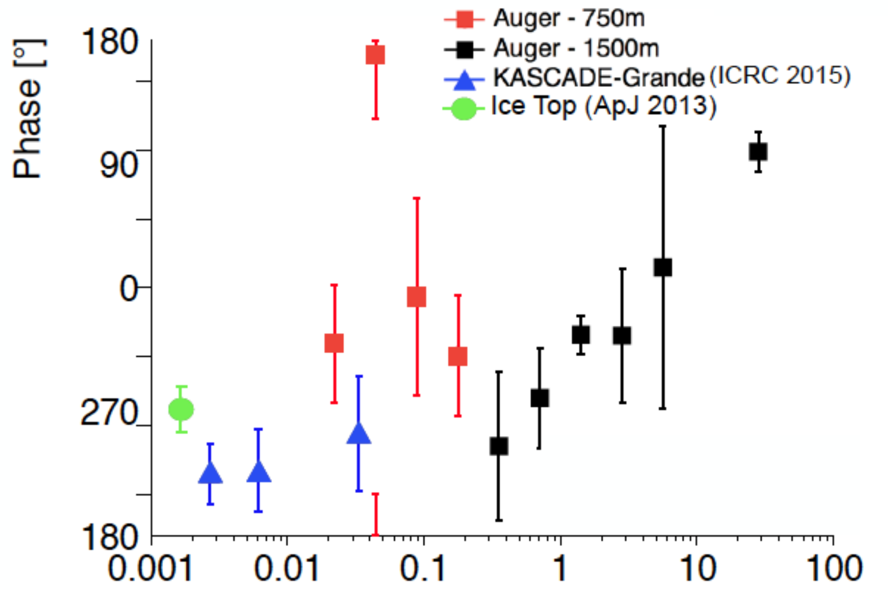
Dipole phase of cosmic rays



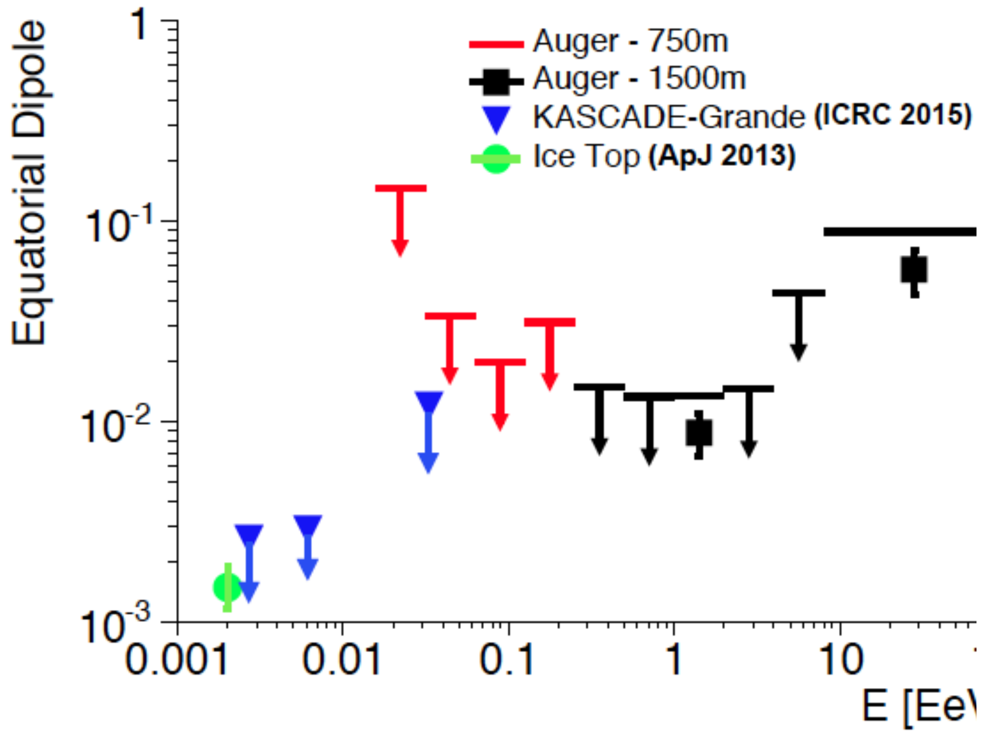
- **G.Di Sciascio and R. Iuppa, arXiv: 1407.2144**

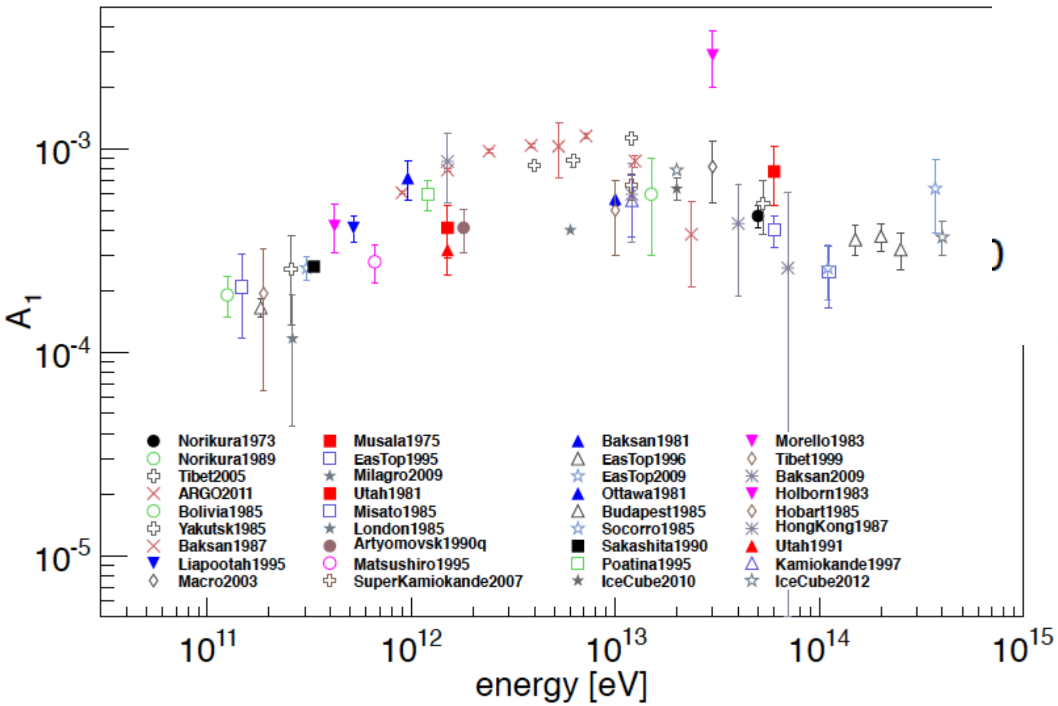
Dipole phase of cosmic rays



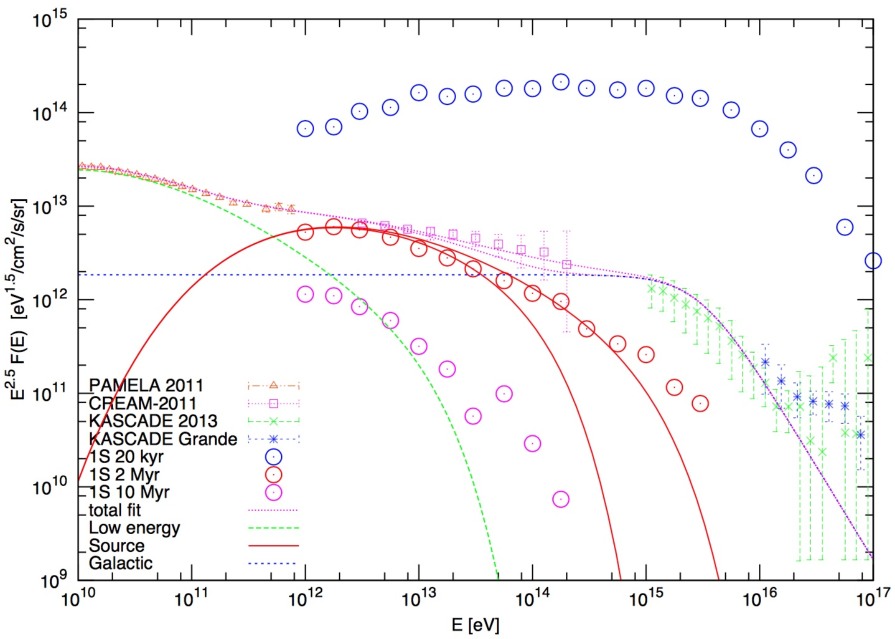


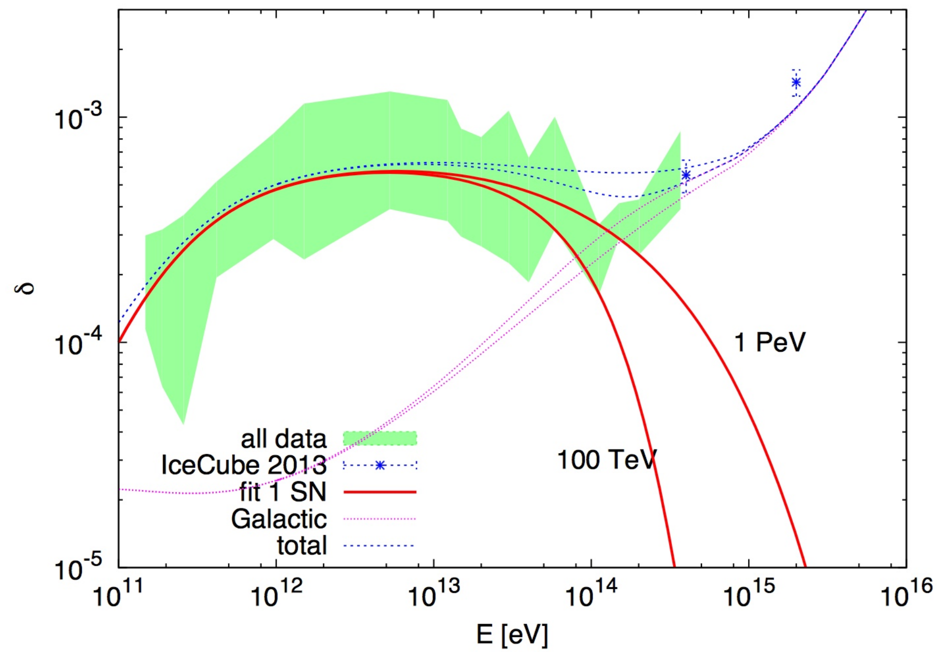
Dipole anisotropy of cosmic ra





Anisotropy and flux from 2 Myr SN

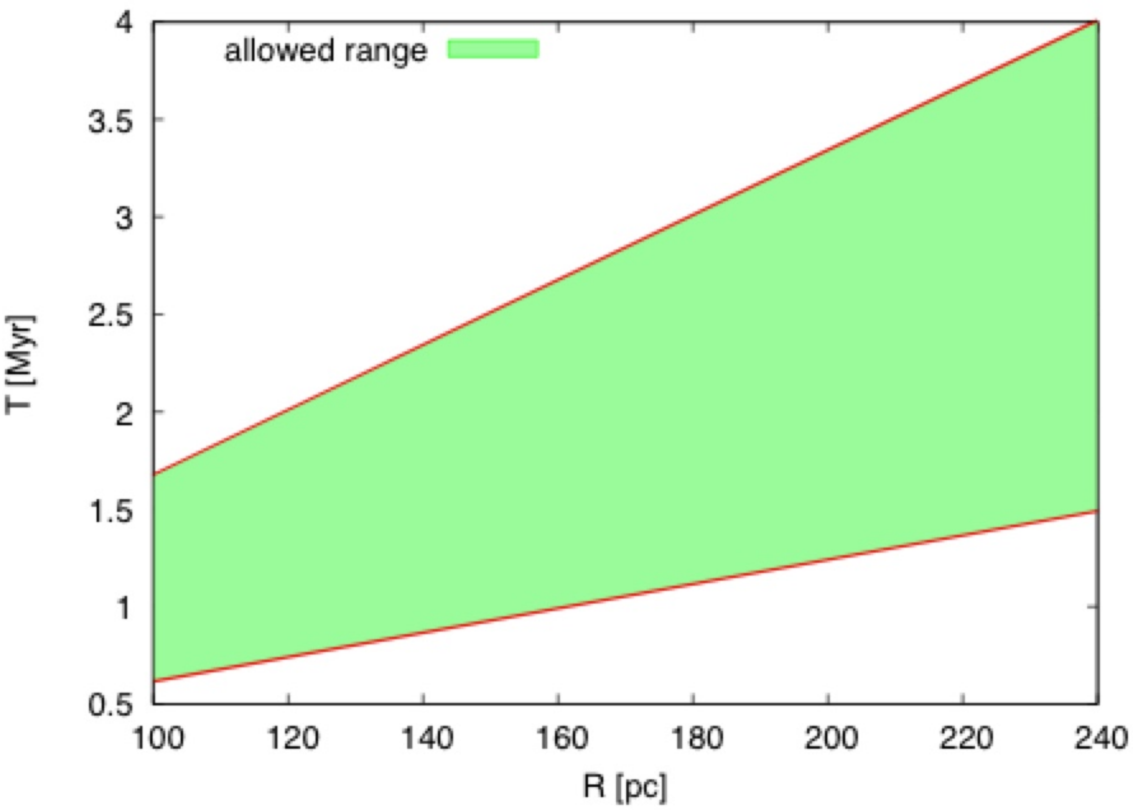




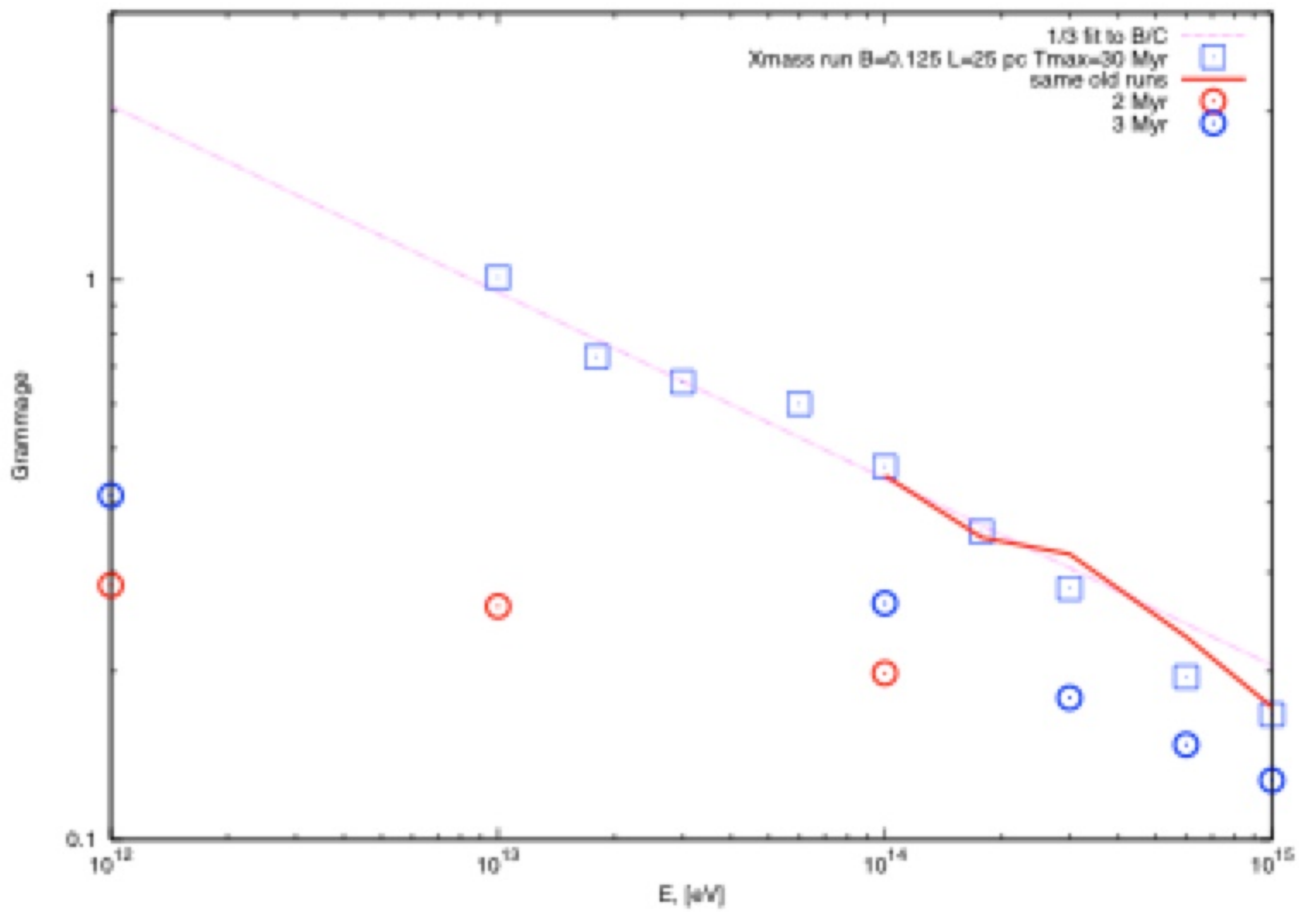
•A=3/2 R/T

- V.Savchenko, M.Kachelriess, and D.Semikoz, arXiv:1505.02720

Anisotropy and parameters of SN



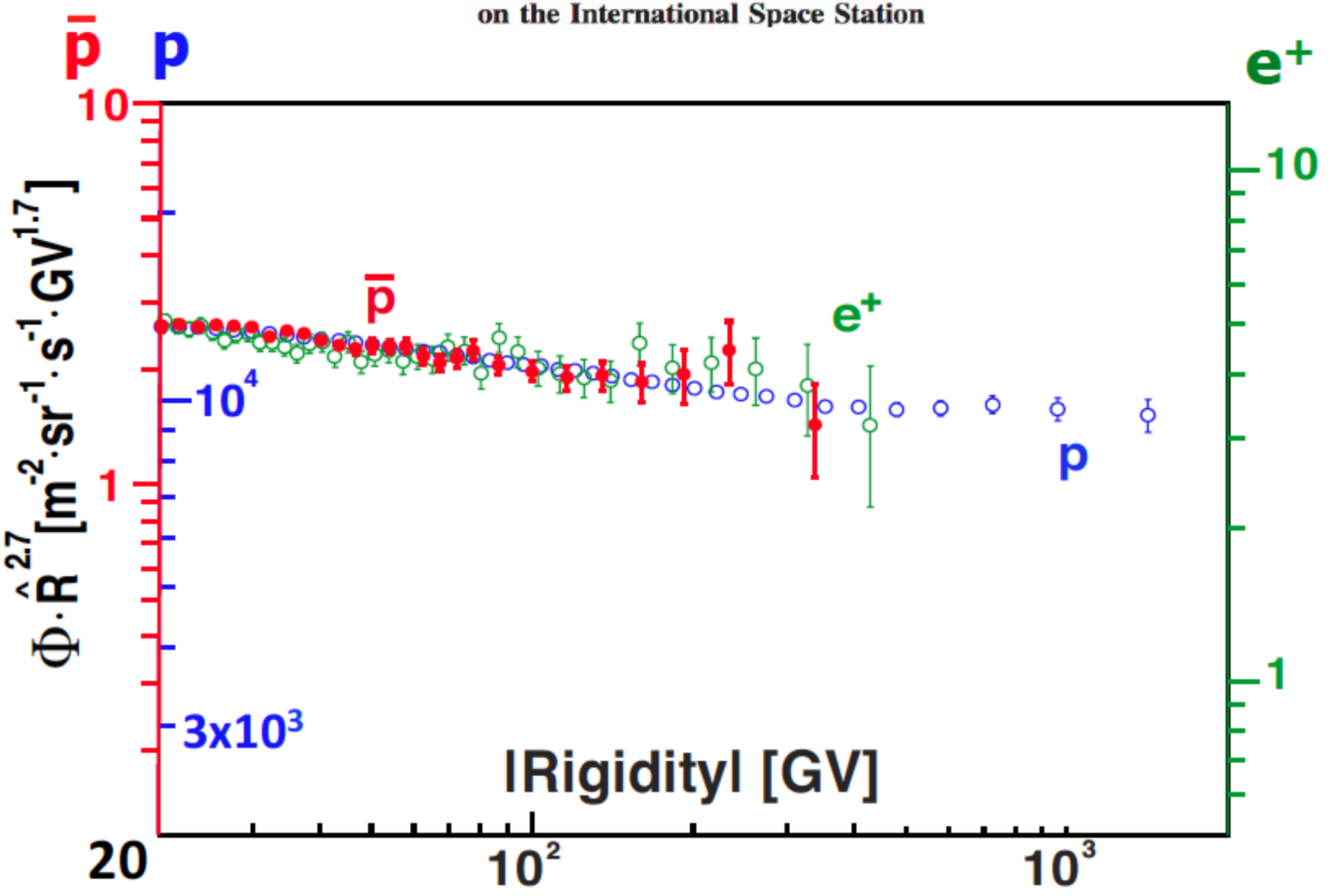
Grammage to create secondaries



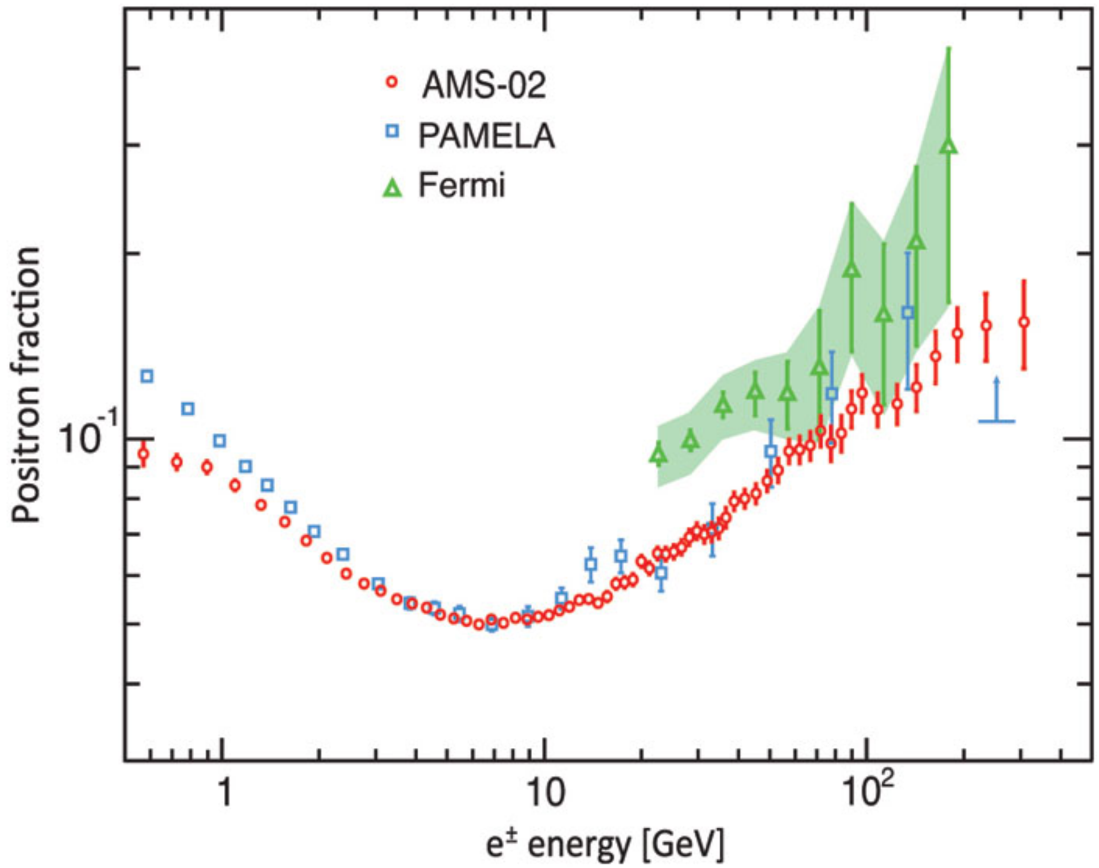
The antiproton flux compared to other particle fluxes

PRL 117, 091103 (2016) PHYSICAL REVIEW LETTERS week ending 26 AUGUST 2016

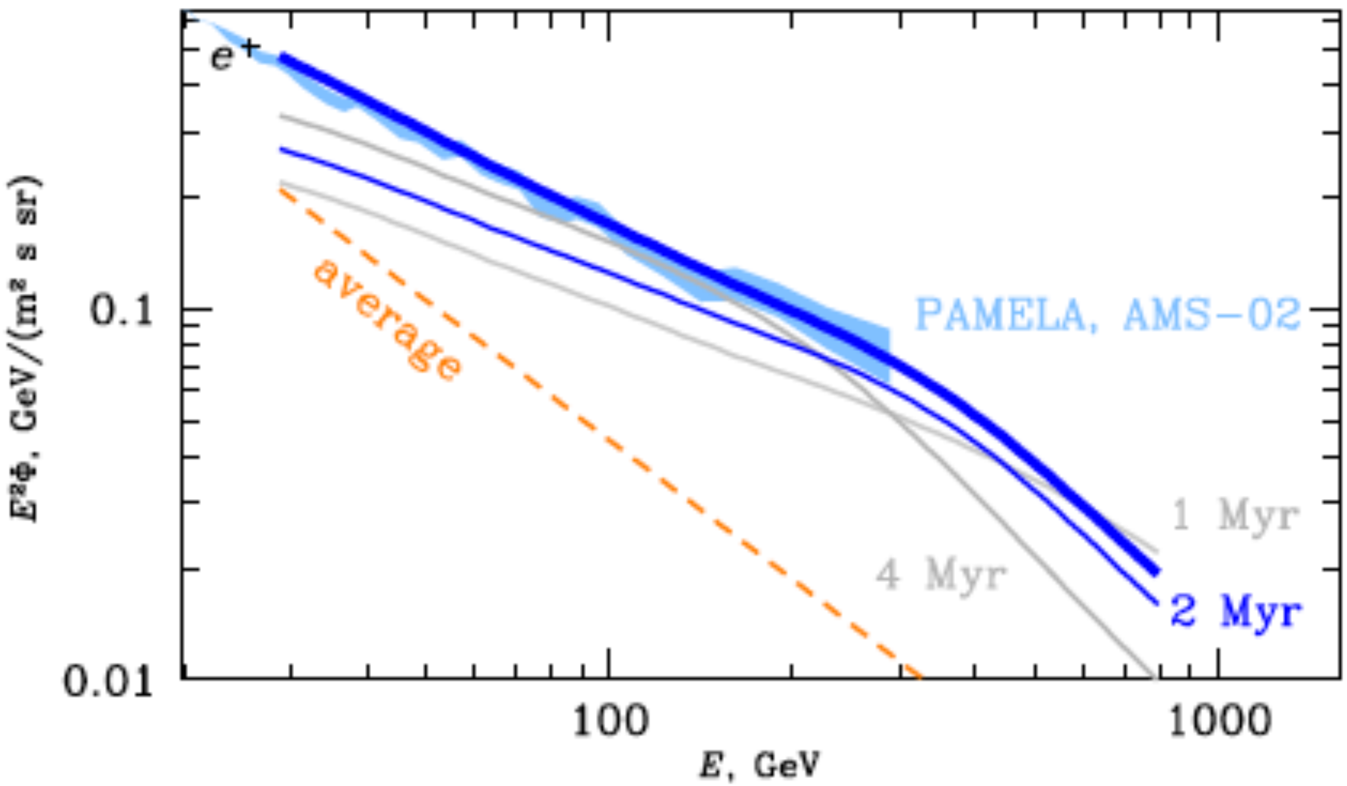
Antiproton Flux, Antiproton-to-Proton Flux Ratio, and Properties of Elementary Particle Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station



Positron to (electron + positron) ratio

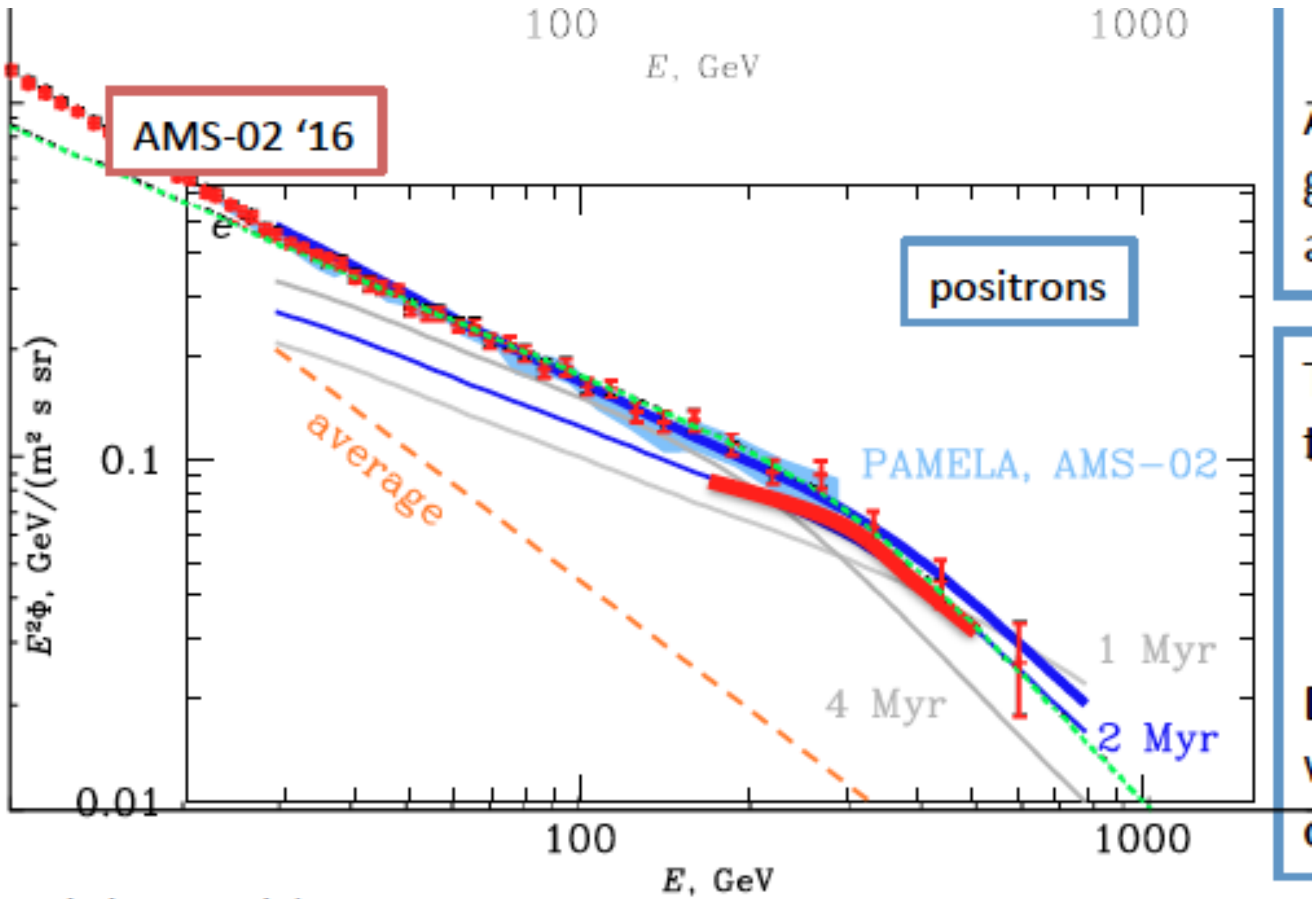


Positron flux PAMELA/AMS-II



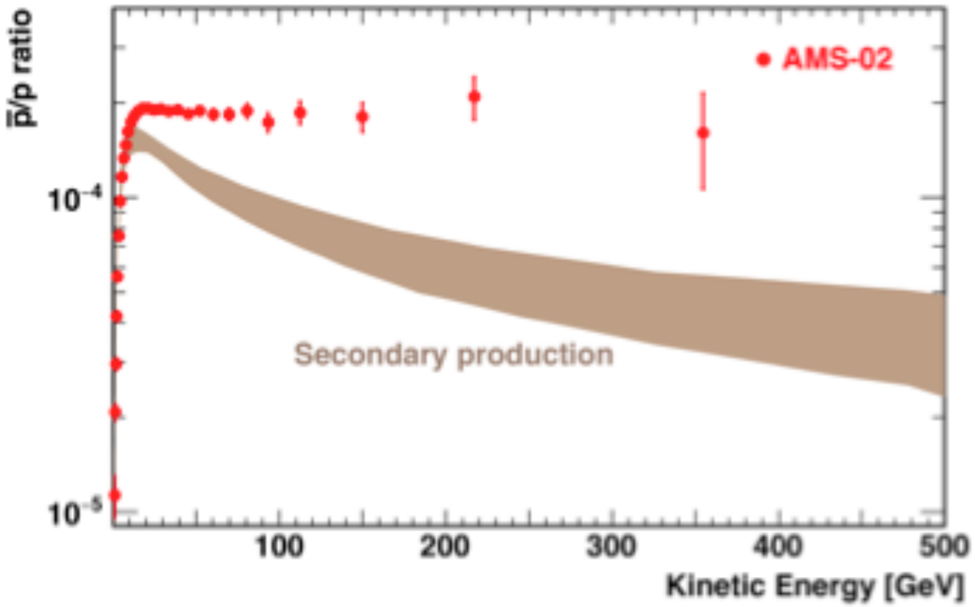
- M.Kachelriess, A. Neronov and D.Semikoz, arXiv:1504.06472

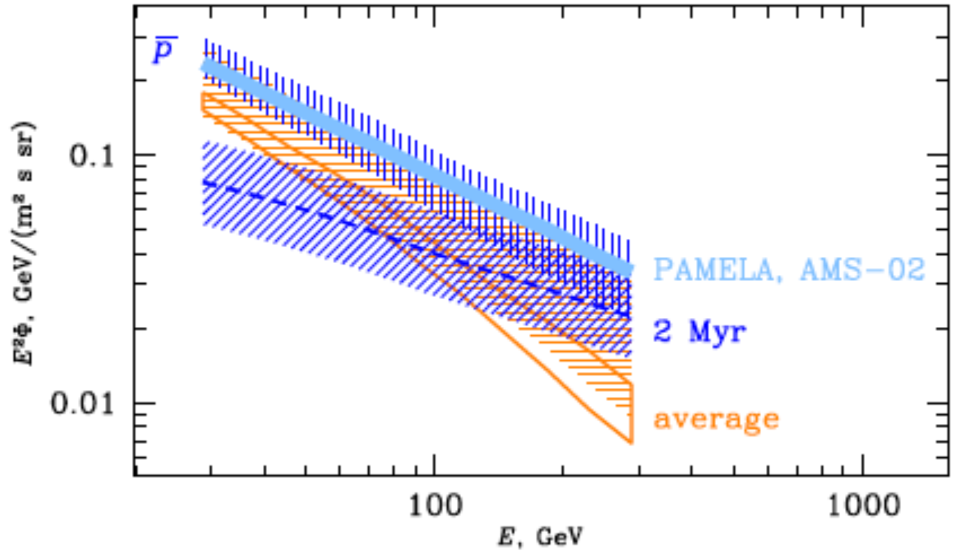
Positron flux PAMELA/AMS-II



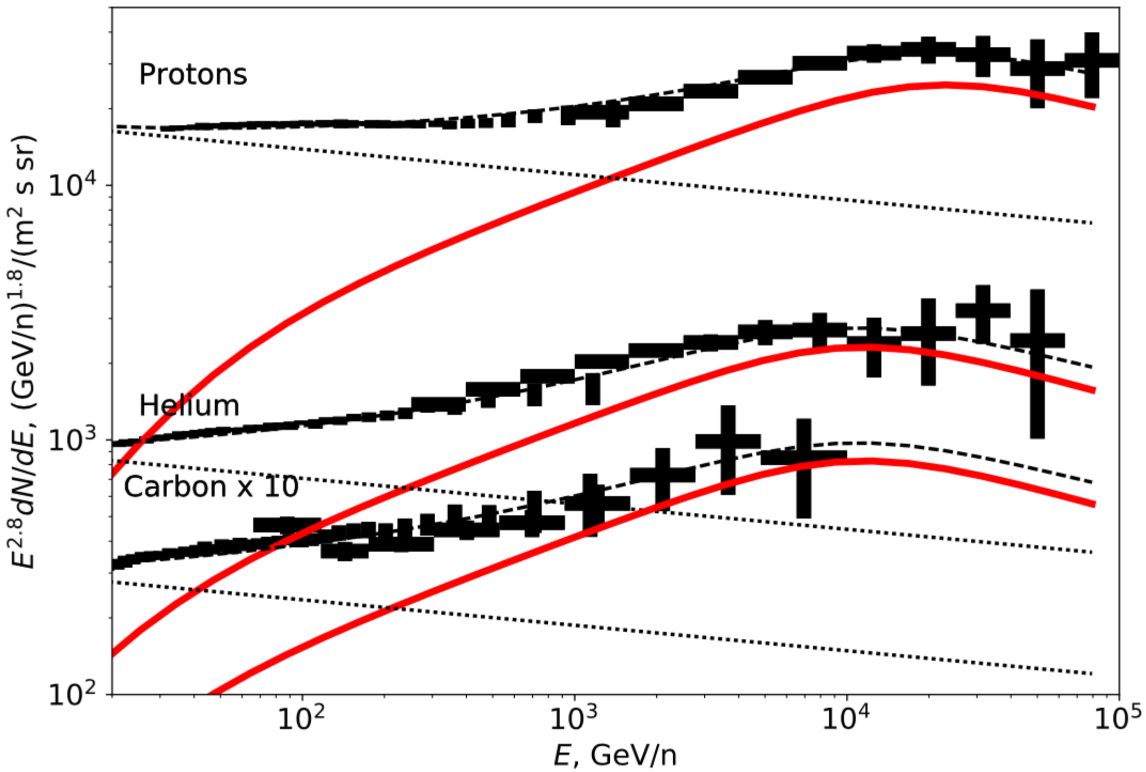
Kachelriess et al. '15

Antriprotons



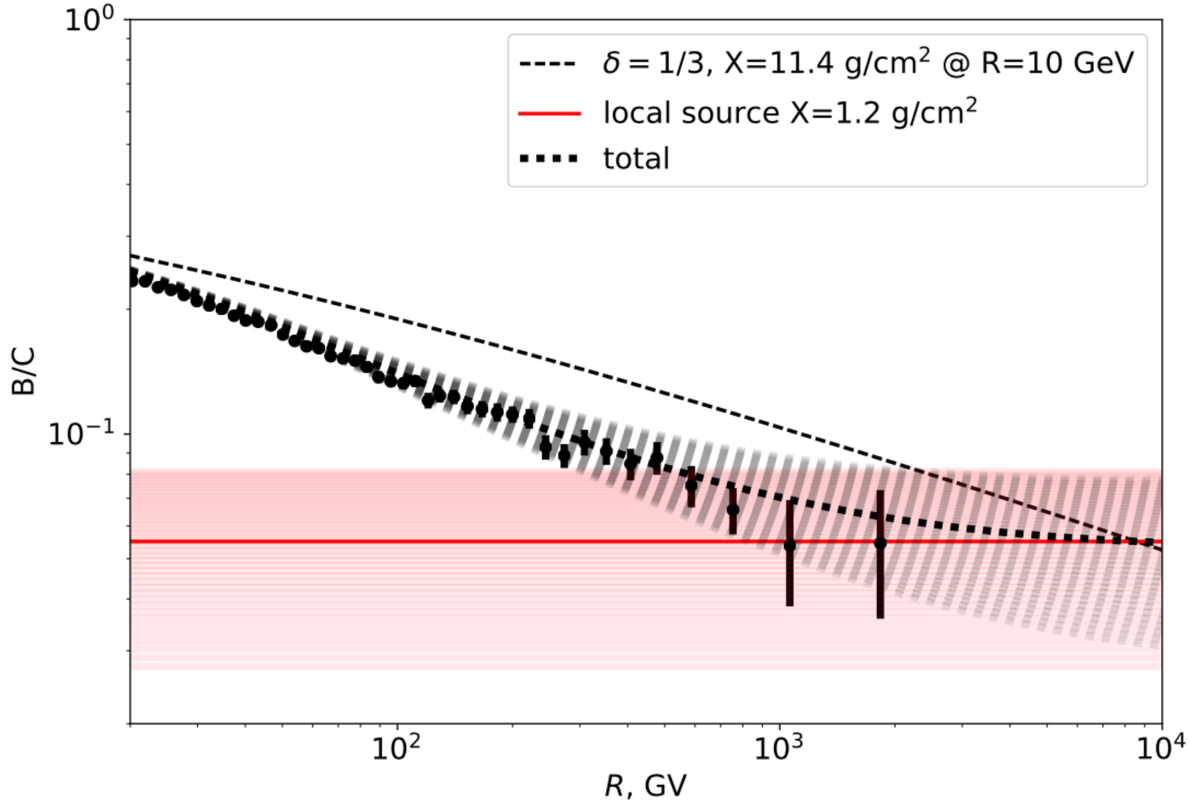


Nuclei



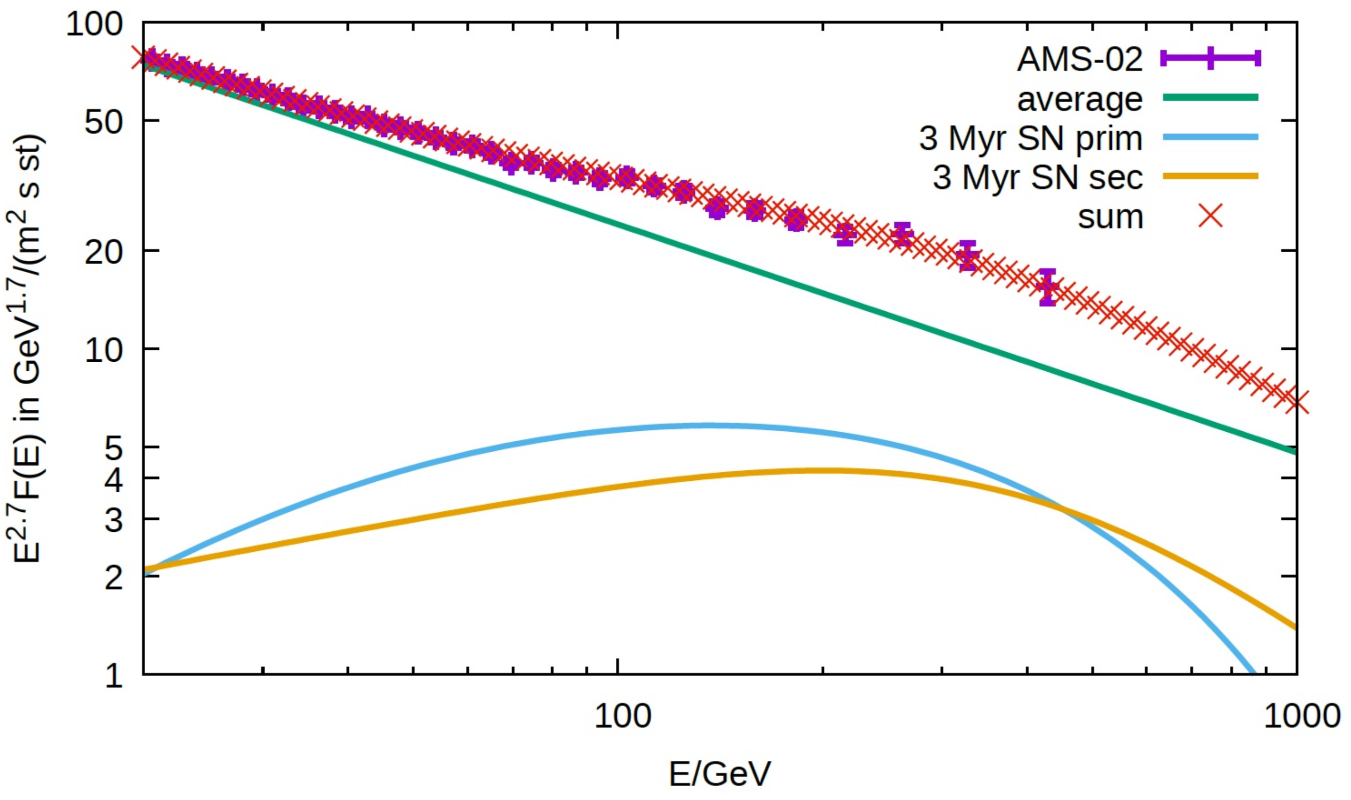
- Ratio of nuclei fluxes at TeV energies differs from one at GeV
- 2 Myr SN solve problem (M.Kachelriess, A.Neronov and D.S. 1710.02321)

Prediction: plateau in B/C



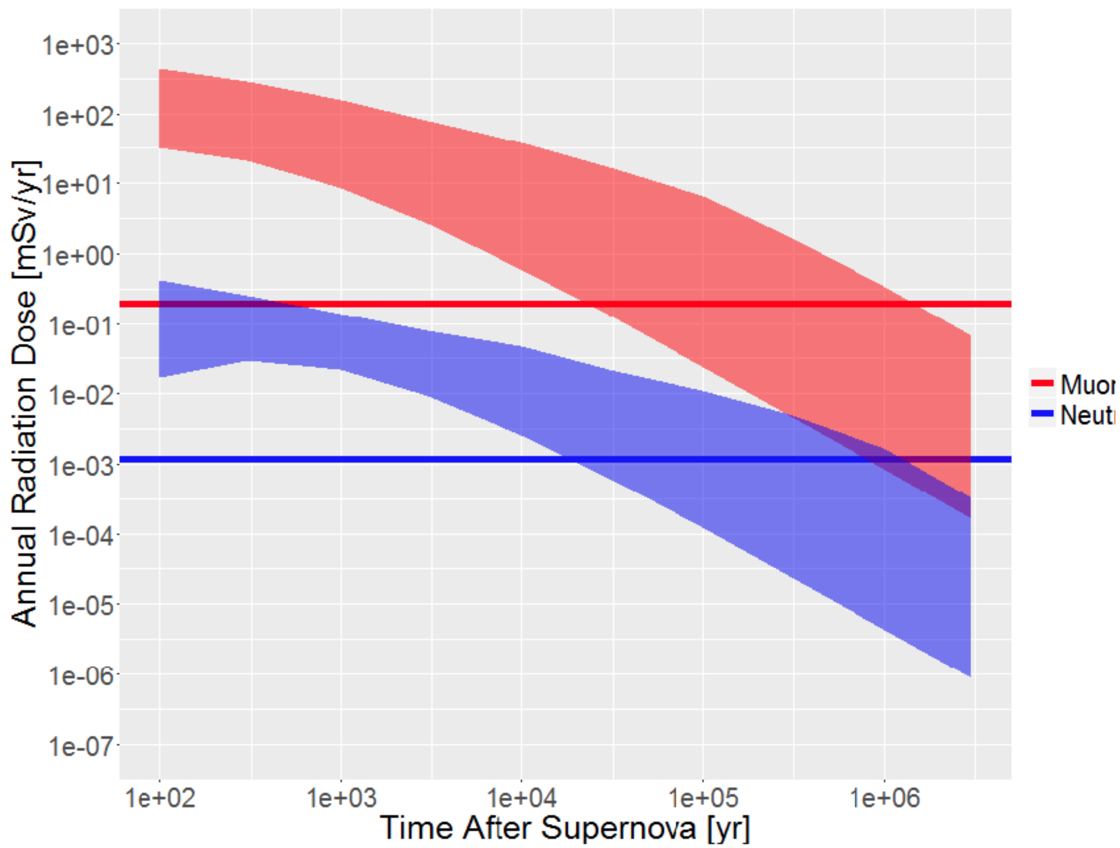
• M.Kachelriess, A.Neronov and D.S., 1710.02321

Electron spectrum



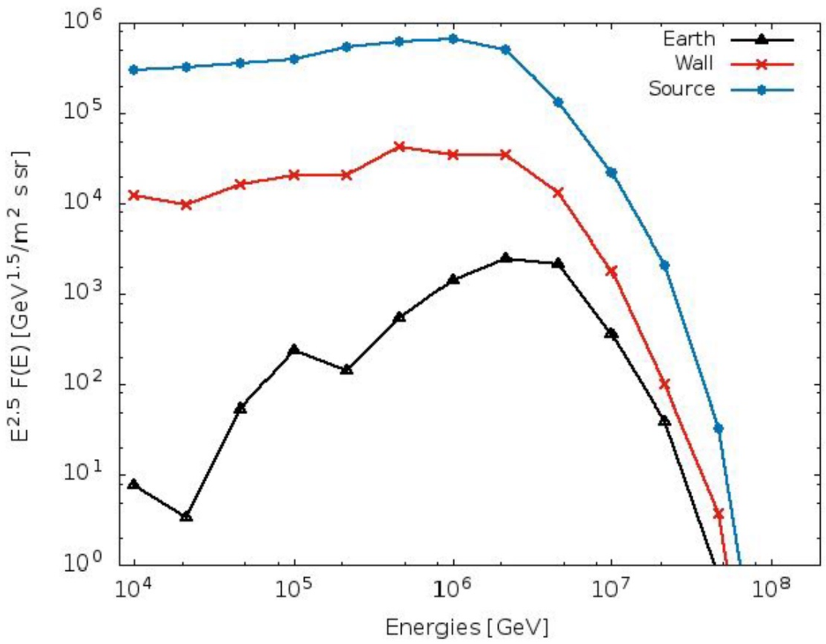
•M.Kachelriess, A.Neronov and D.S., 1710.02321

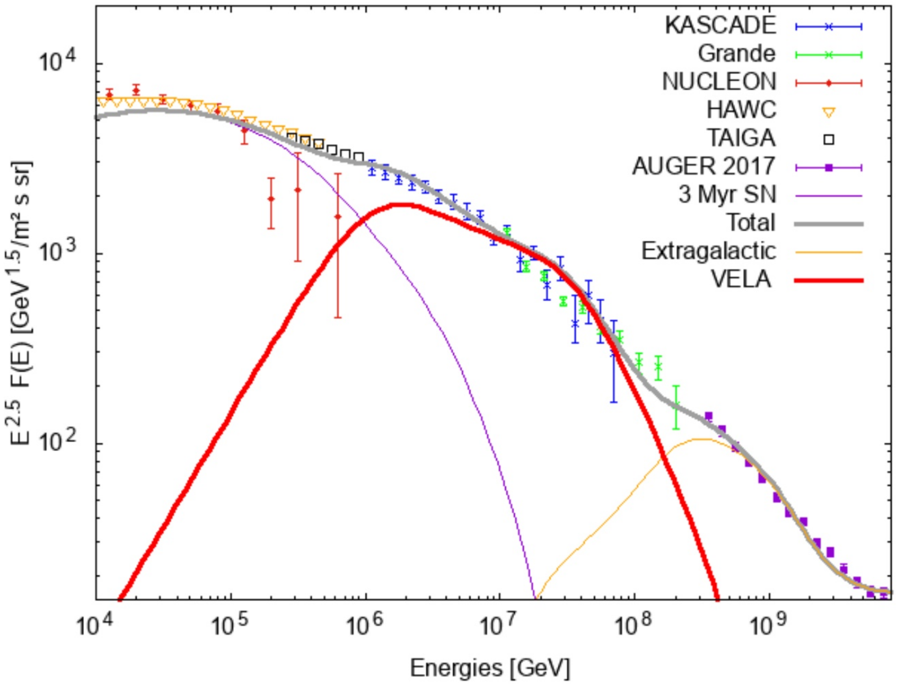
Radiation at Earth from local SN



• Melott et al 1702.0436

Spectrum in presence of Local bubble





- M.Bouyahiaoui, M.Kachelriess and D.S., arXiv:1812.03522

Conclusions

- *Assumption that spectrum of cosmic rays is the same for all galaxy does not work. Spectrum is 1/E^2.4 consistent with acceleration and Kolmogorov turbulence.*
- *Steady state regime for cosmic rays locally breakes at 20 GeV*
- *Above this energy contributions of individual sources are important*

Conclusions

- *Local 2.7 proton flux is local due to 2-3 Myr old nearby source. Same source responsible for p to He flux variation, positron and anti-proton excess and plateau anomaly in the dipole anisotropy*
- *This source provided enhanced radiation on Earth during 0.3-1 Myr: climate change and mutations*

Conclusions: galaxy

- *We have phenomenological understanding of Galactic cosmic rays from 100 GeV*Z to 10*PeV*Z energies.*
- *Neutrinos and gamma-rays in galactic plane both consistent with galactic CR spectrum $1/E^{2.5}$ (next lectures)*
- *Local 2.7 proton flux is local due to 2-3 Myr old nearby source. Same source responsible to p to He ratio, positron and anti-proton excess and plateau anomaly in the dipole anisotropy*
- *Same source probably affected climate and life at Earth due to increased radiation during 1 Myr*

UHECR spectrum and GZK cutoff

Main CR energy loss processes

INTERACTIONS

Protons

$$p + \gamma_{\mathrm{CMB}} \rightarrow p + e^{+} + e^{-}$$

$$p + \gamma_{\mathrm{CMB}} \rightarrow N + \mathrm{pions}$$

Nuclei

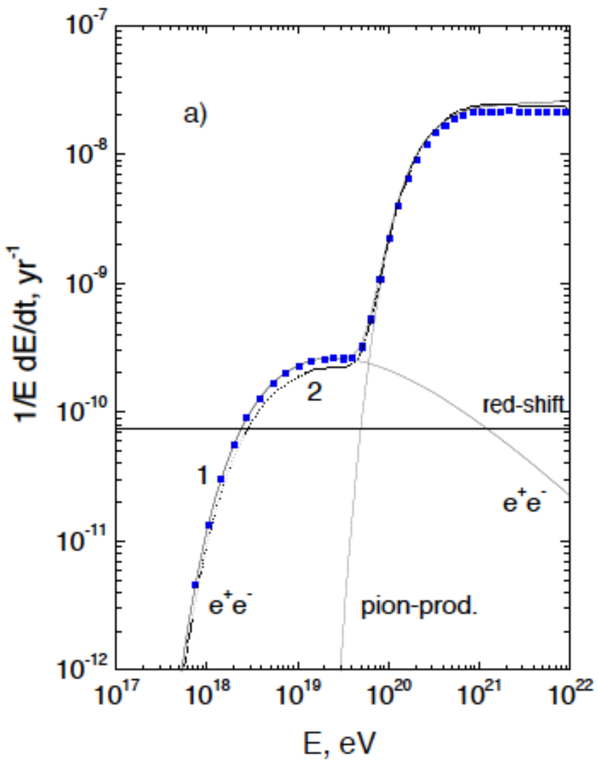
$$Z + \gamma_{\mathrm{CMB}} \rightarrow Z + e^{+} + e^{-}$$

$$A + \gamma_{\mathrm{CMB}} \rightarrow (A-1) + N$$

$$A + \gamma_{\mathrm{CMB}} \rightarrow A' + N + \mathrm{pions}$$

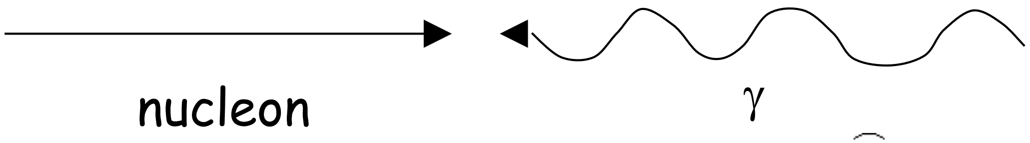
Photons

$$\gamma + \gamma_{\mathrm{bcgr}} \rightarrow e^{+} + e^{-}$$

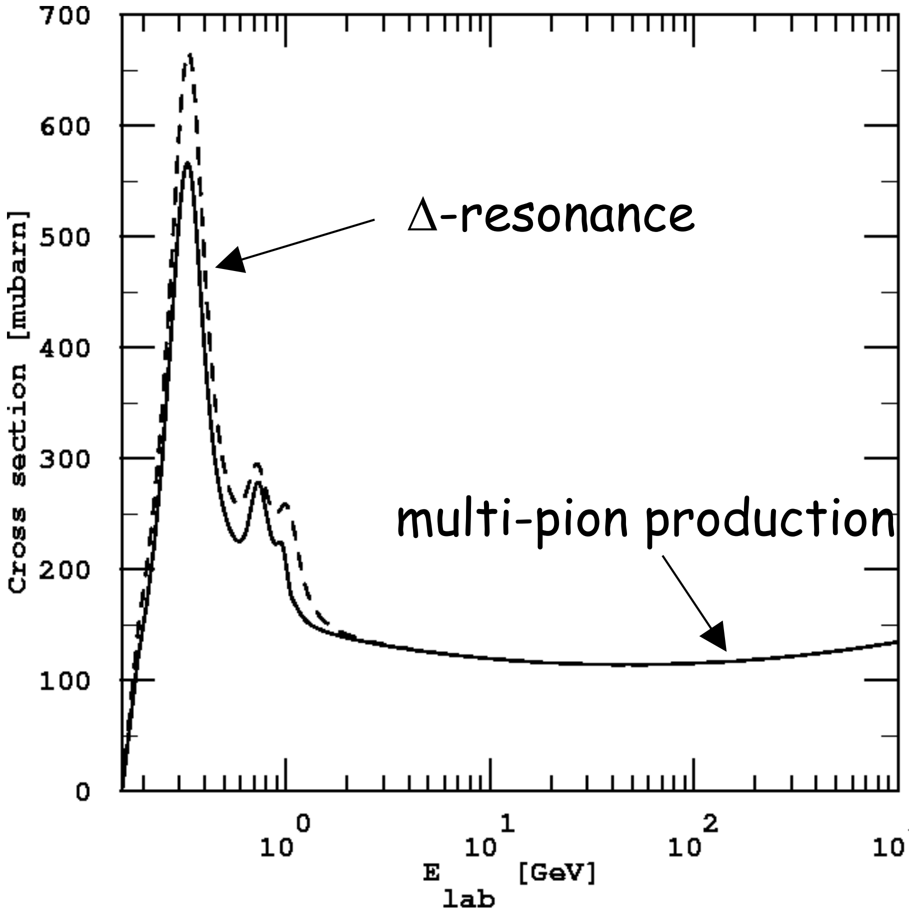


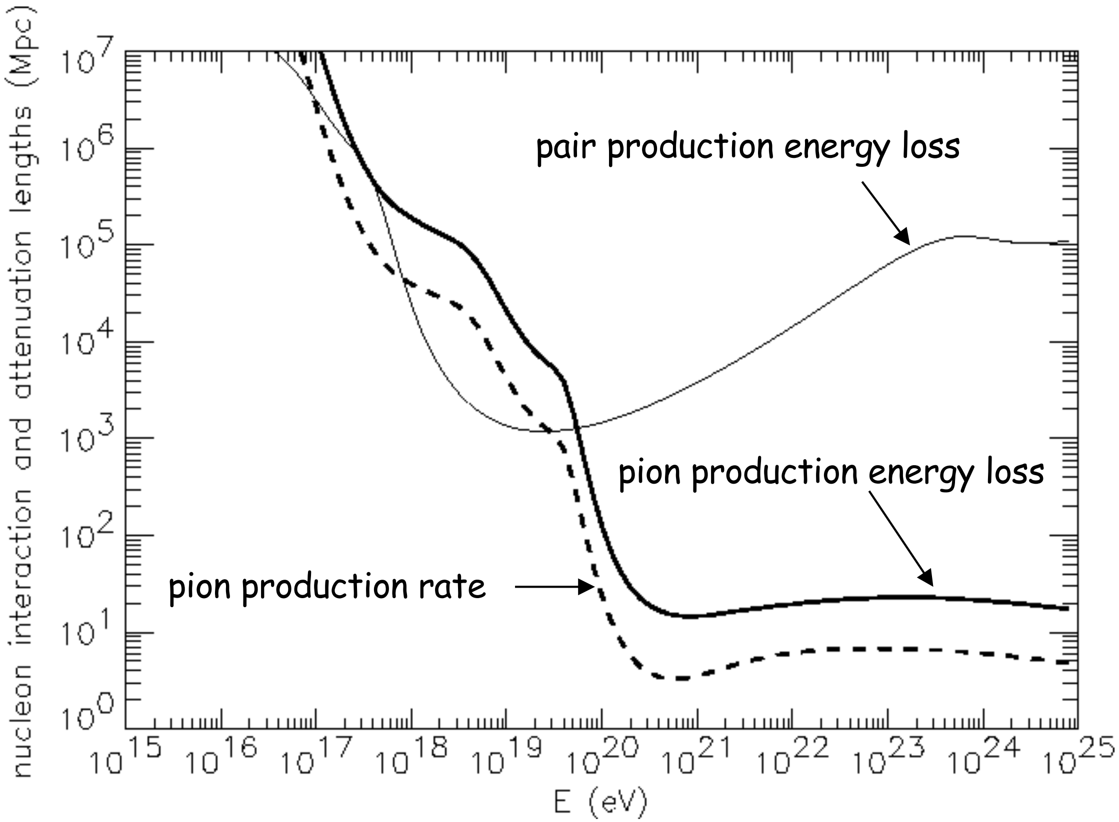
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



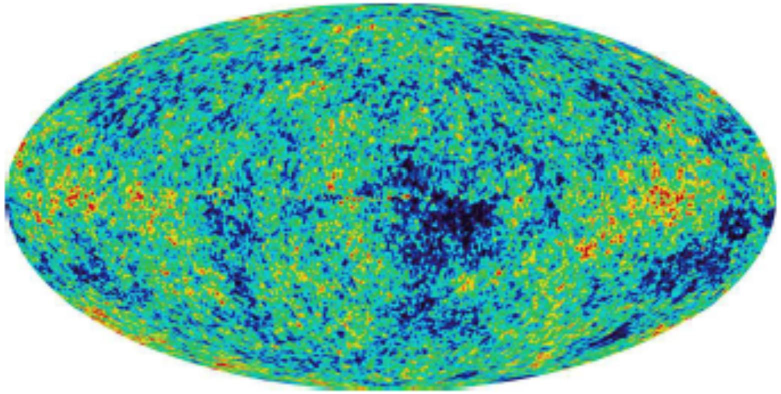
$$E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 6 \cdot 10^{19}\,\mathrm{eV}$$



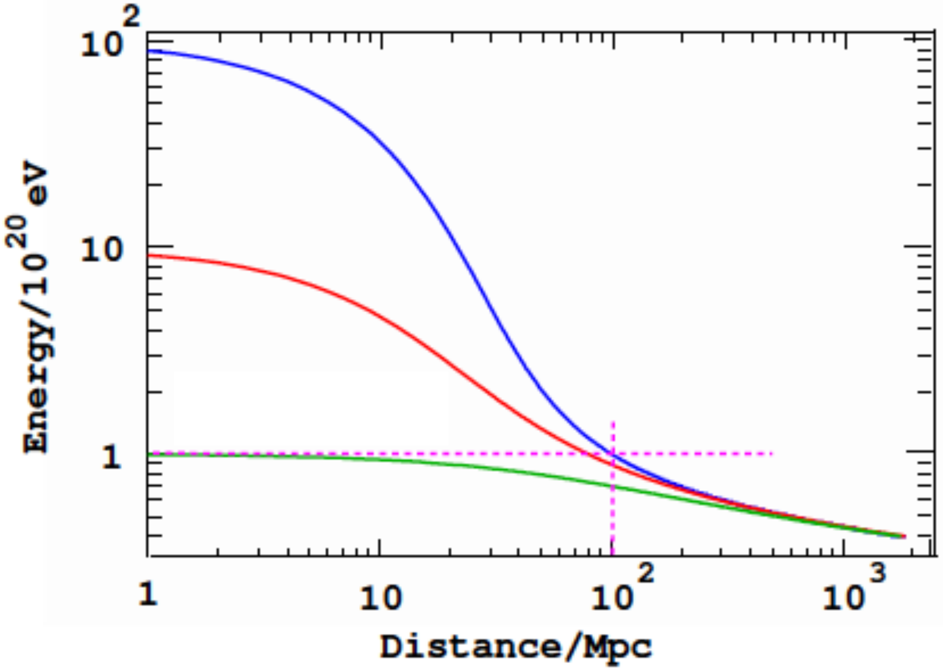


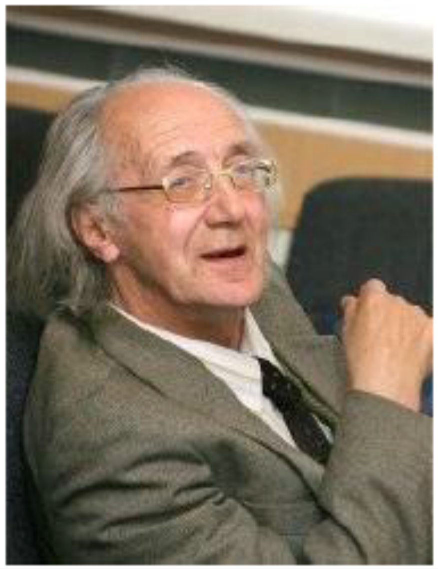
⇒sources must be in cosmological backyard within 50-100 Mpc from Earth (compare to the Universe size ~ 5000 Mpc)

Greisen-Zatsepin-Kuzmin Effect

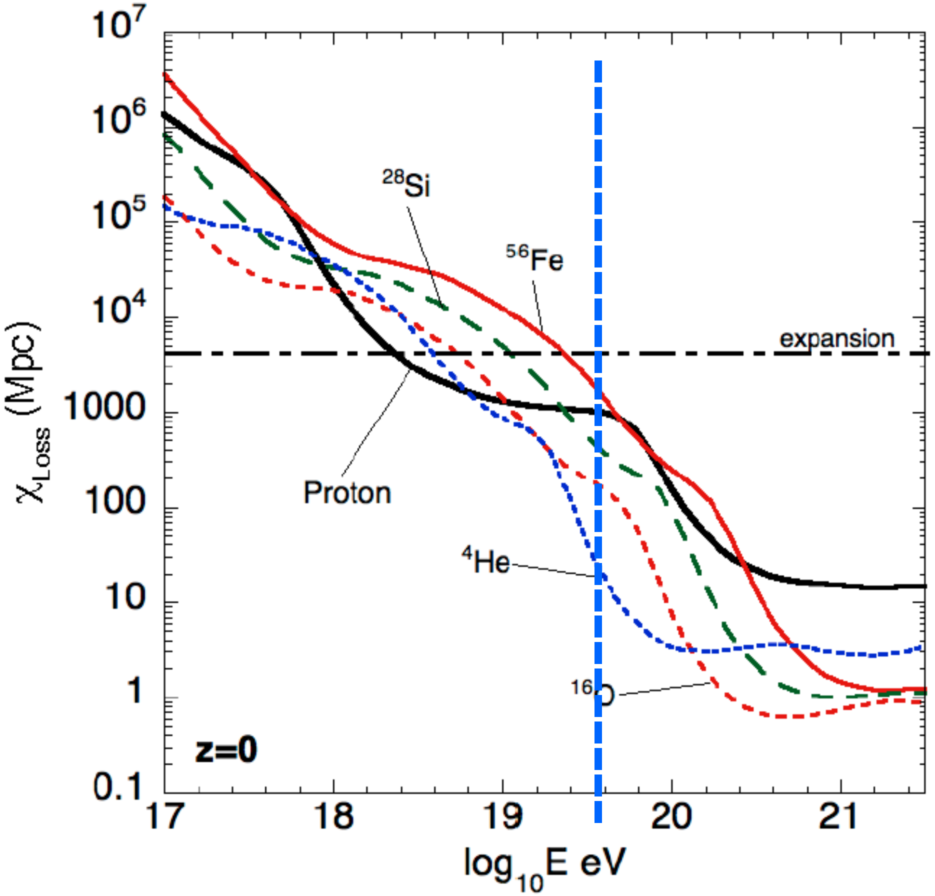


$$p + \gamma_{\mathrm{CMB}} \rightarrow N + \pi$$



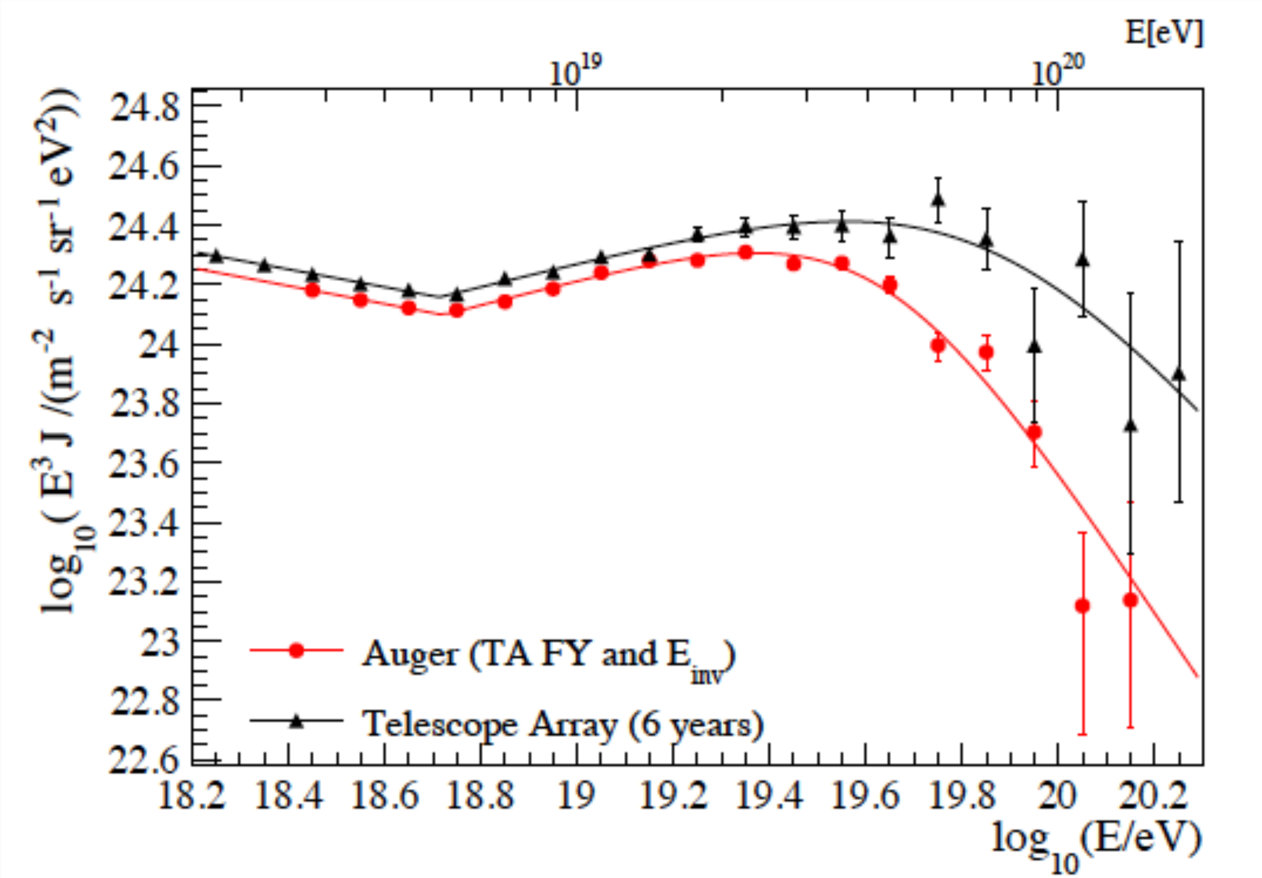


Same true for heavy nuclei: IR background is important



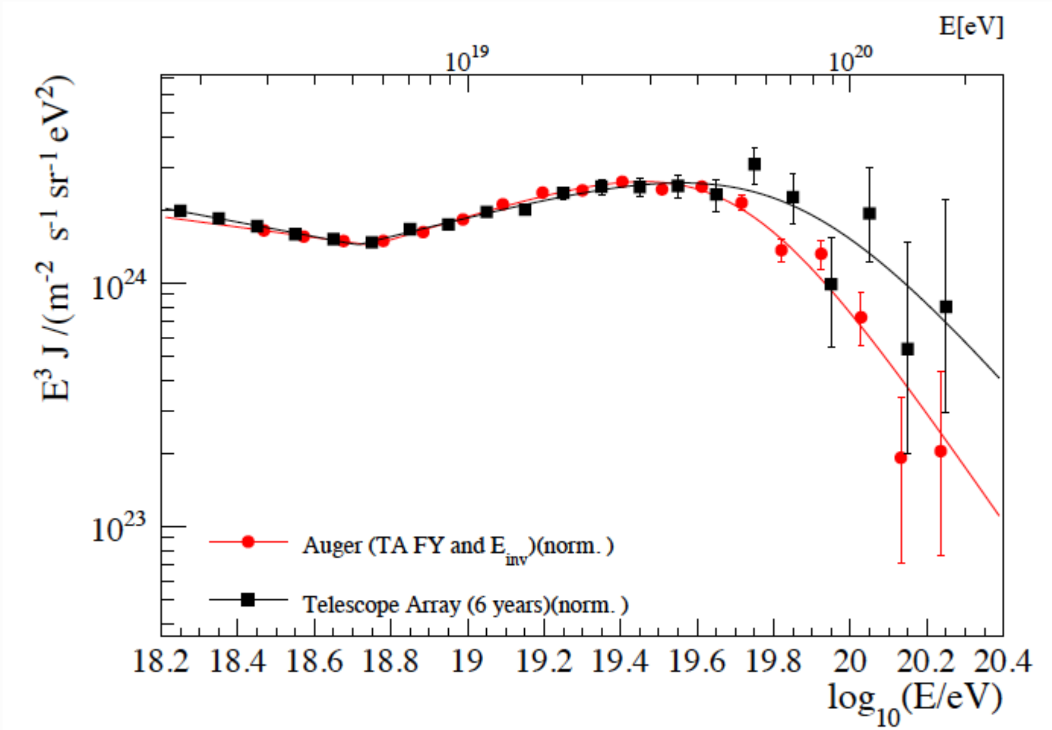
D.Allard, **arXiv:1111.3290**

Auger/TA Energy Spectrum



UHECR 2014

Auger/TA Energy Spectrum

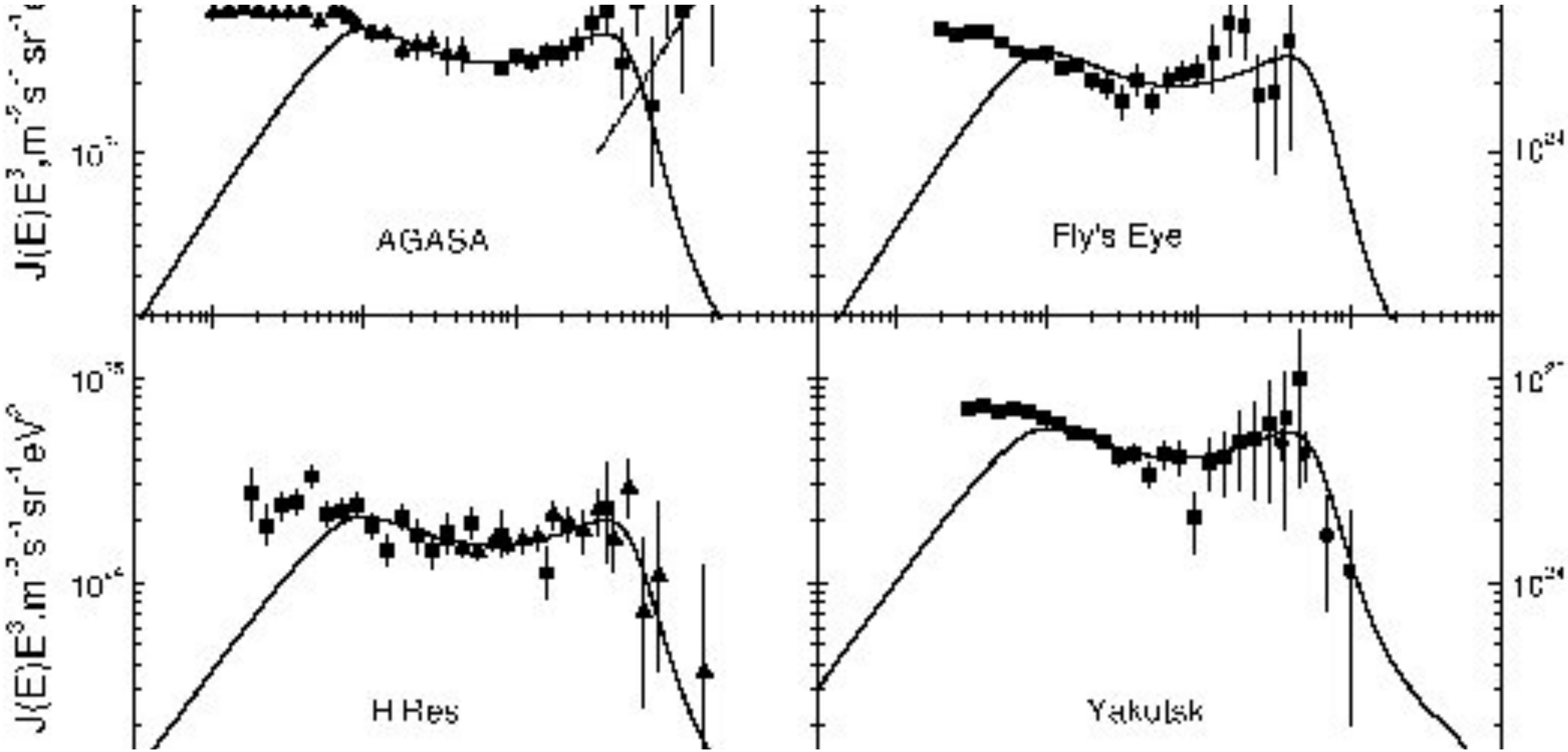


$$\lg(E) = a + b \cdot \lg(E),\ \chi^2/\mathrm{ndof} = 0.75(\mathrm{Prob} = 0.85)$$

UHECR 2014

Theoretical models and composition at highest energies

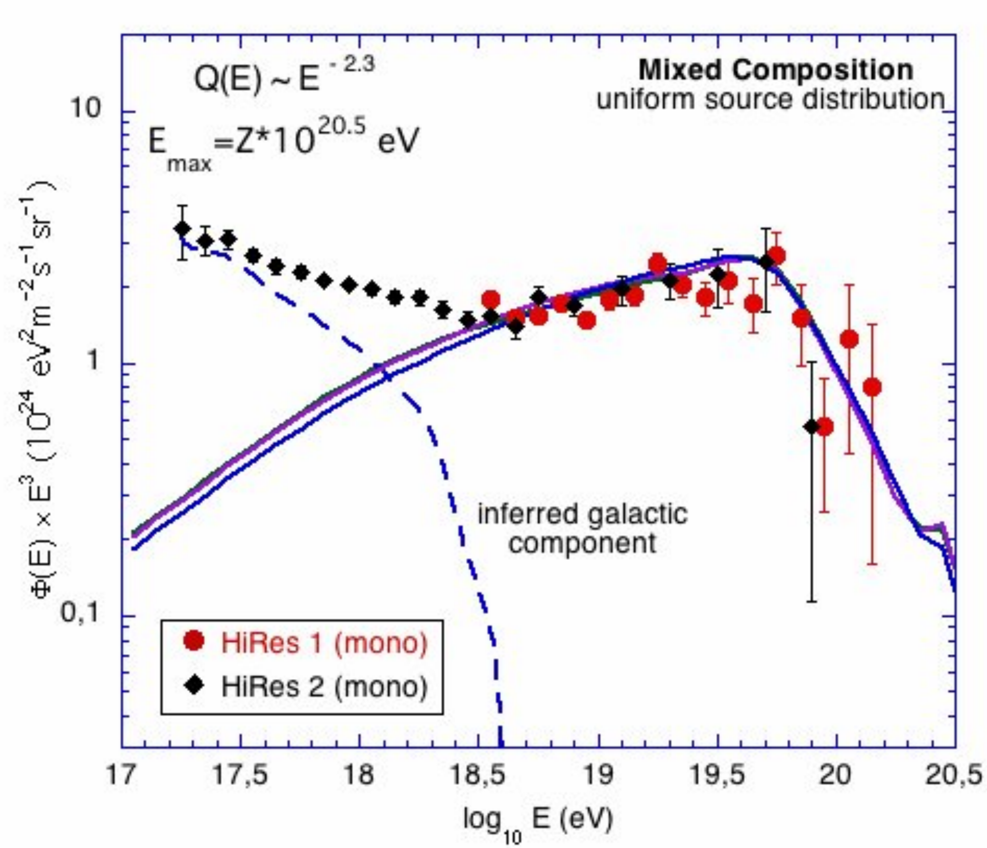
Protons can fit UHECR data



V.Berezinsky , astro-ph/0509069

problem: composition

Mixed composition model

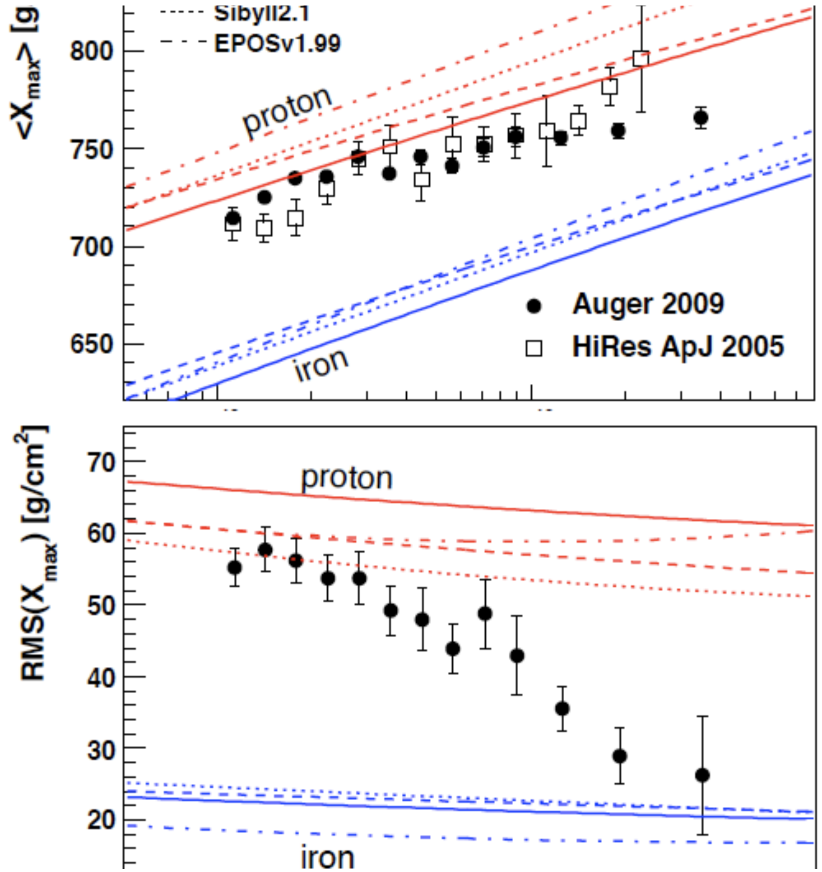


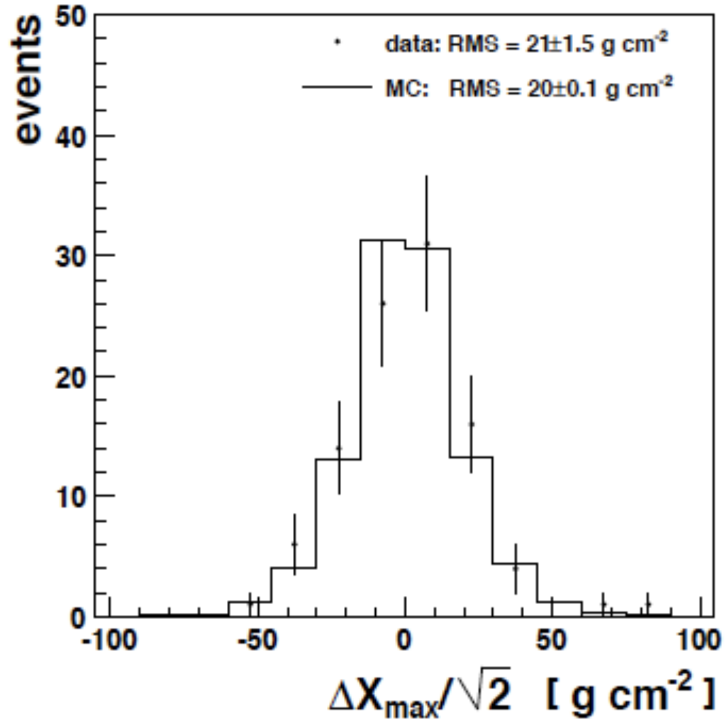
D.Allard, E.Parizot and A.Olinto, astro-ph/0512345

Problems: 1) escape of the nuclei from the source

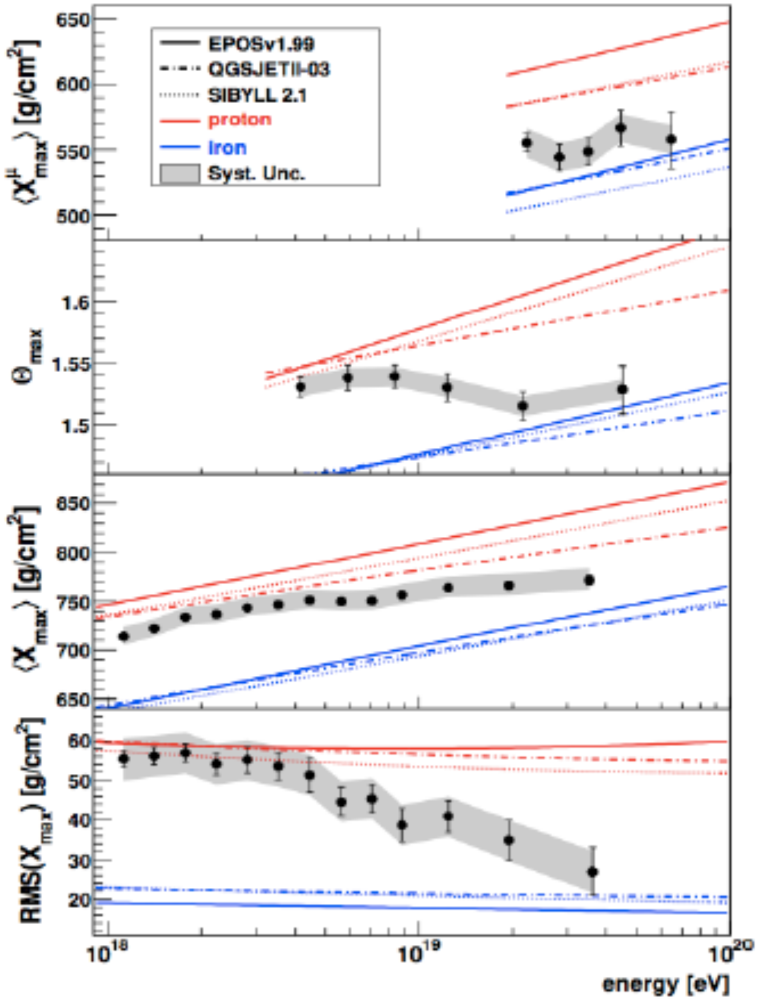
2) How to accelerate Fe in our Galaxy

Auger composition 2009: nuclei!



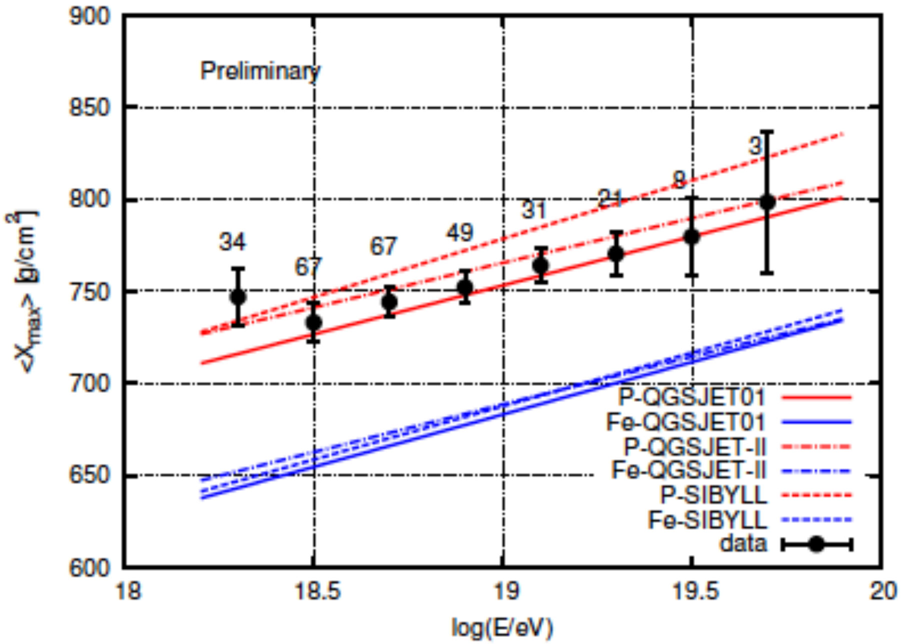


PAO - heavy nuclei

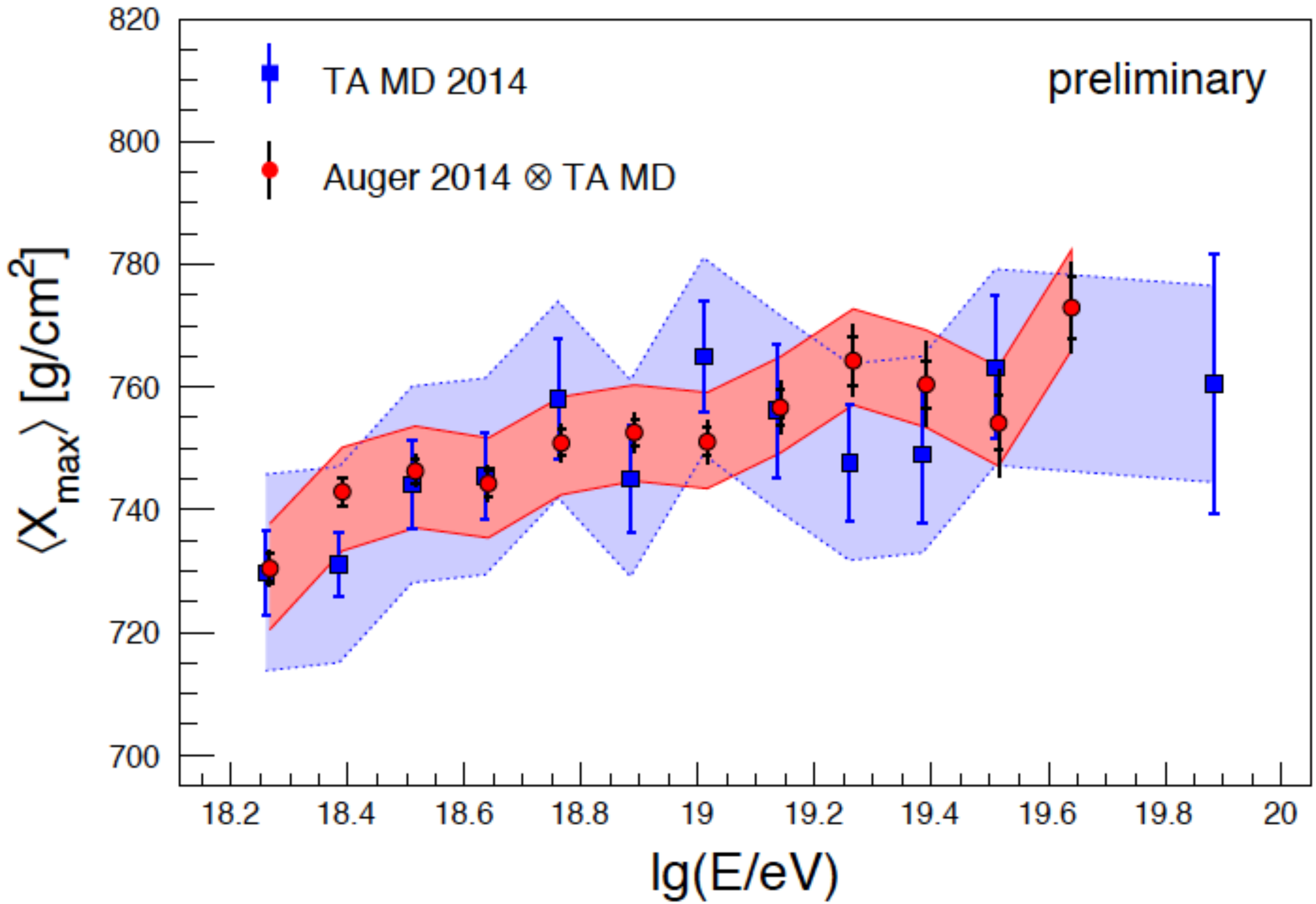


H. Wahlberg (PAO, this conference)

TA- protons

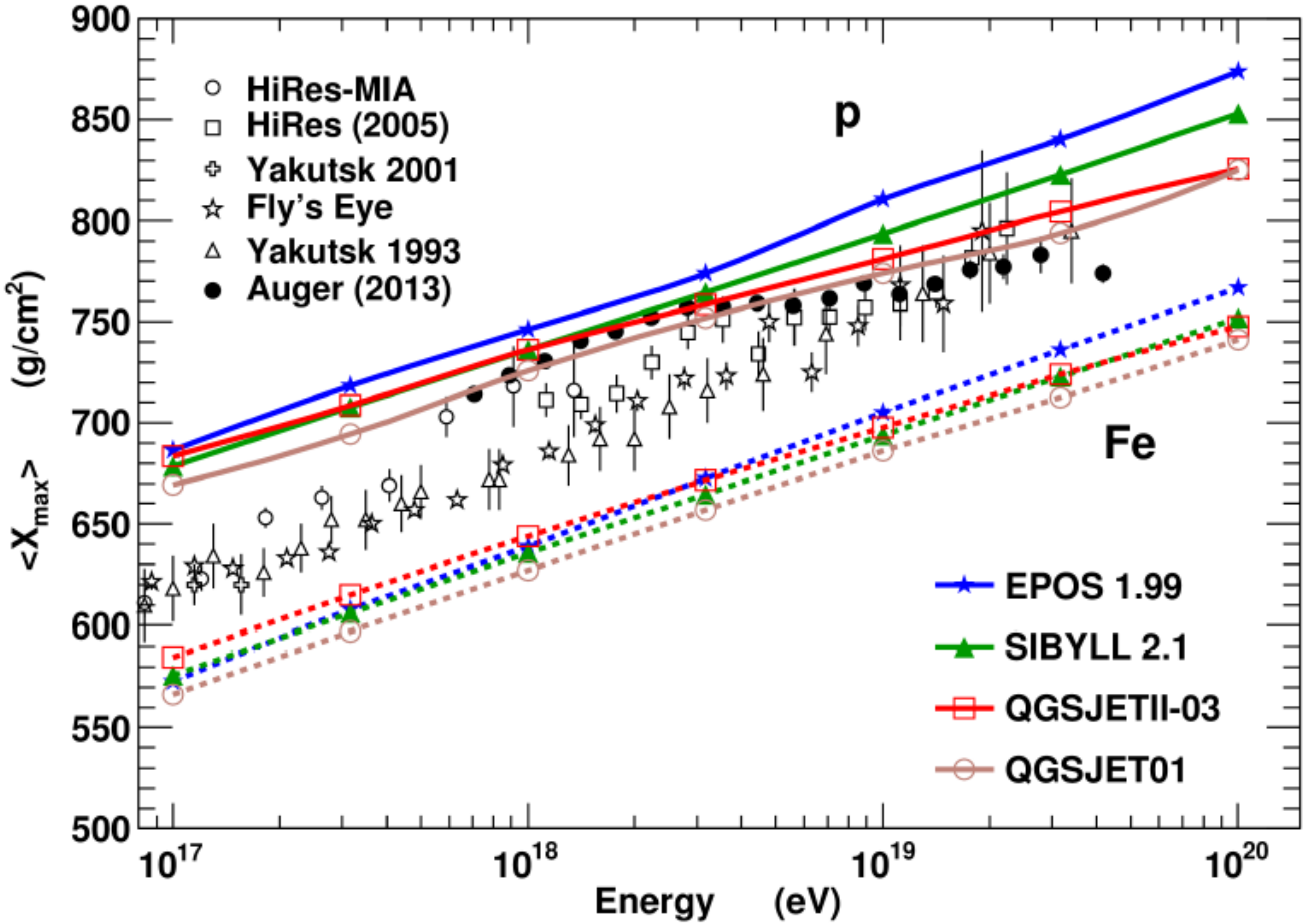


TA collaboration, 2010

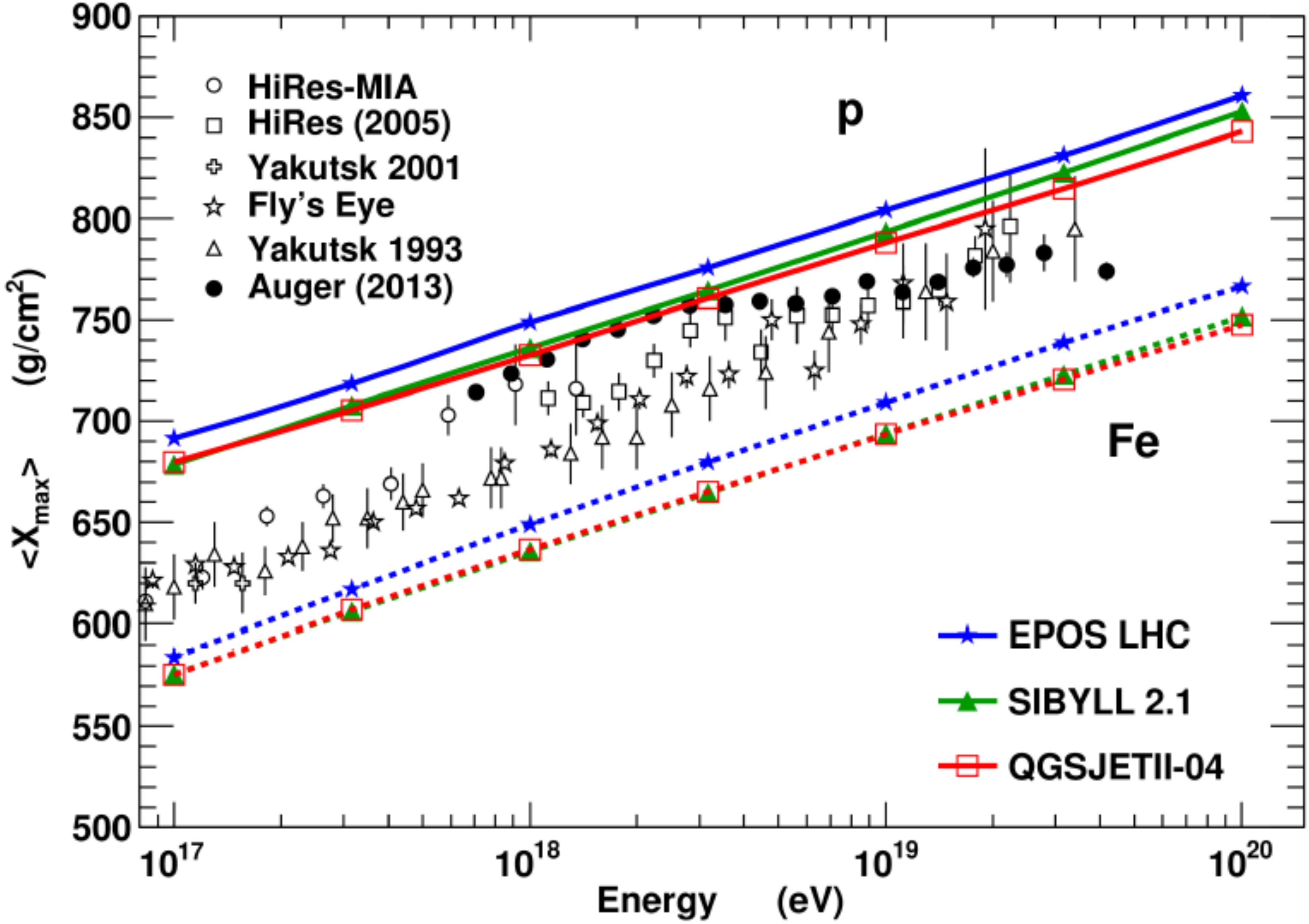


TA MD 2014
Auger 2014 ⊗ TA MD
preliminary
⟨X_max⟩ [g/cm²]
lg(E/eV)
820
800
780
760
740
720
700
18.2
18.4
18.6
18.8
19
19.2
19.4
19.6
19.8
20

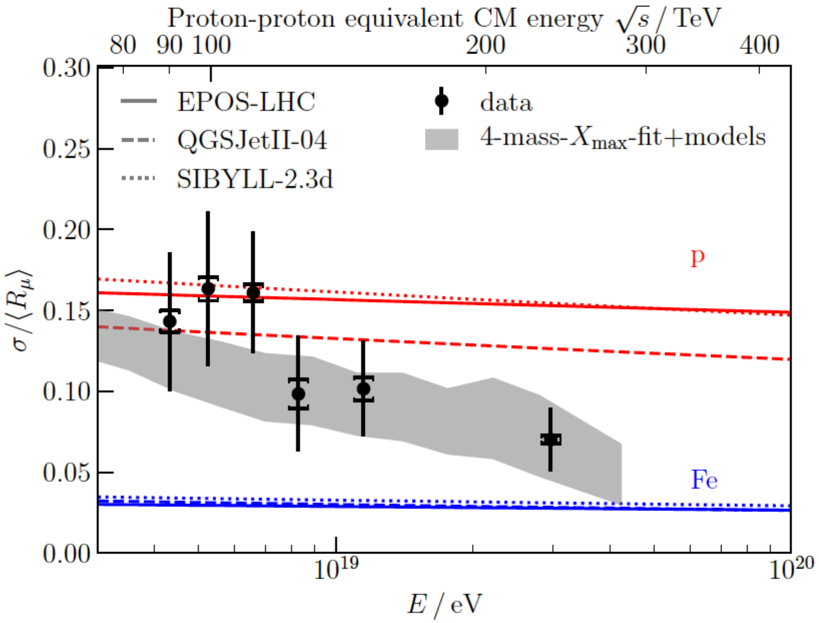
EAS with Old CR Models : X_{max}

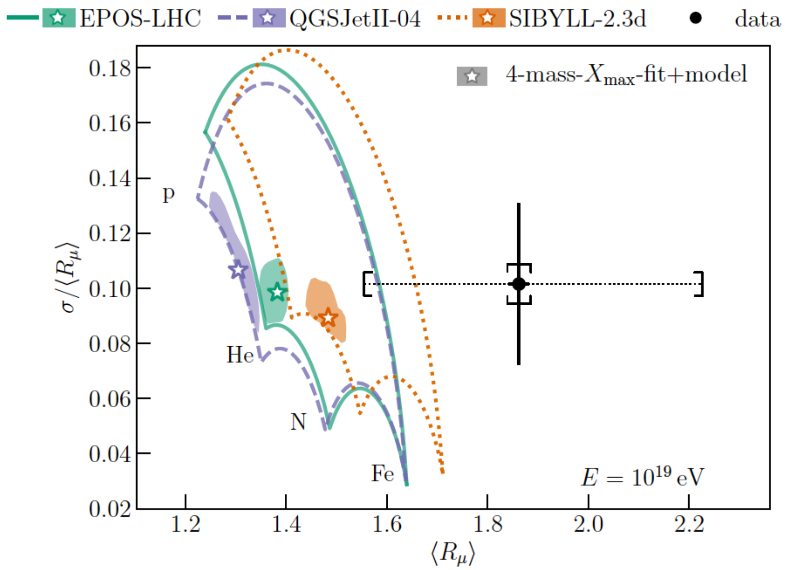


EAS with Re-tuned CR Models : X_{max}



Muon excess

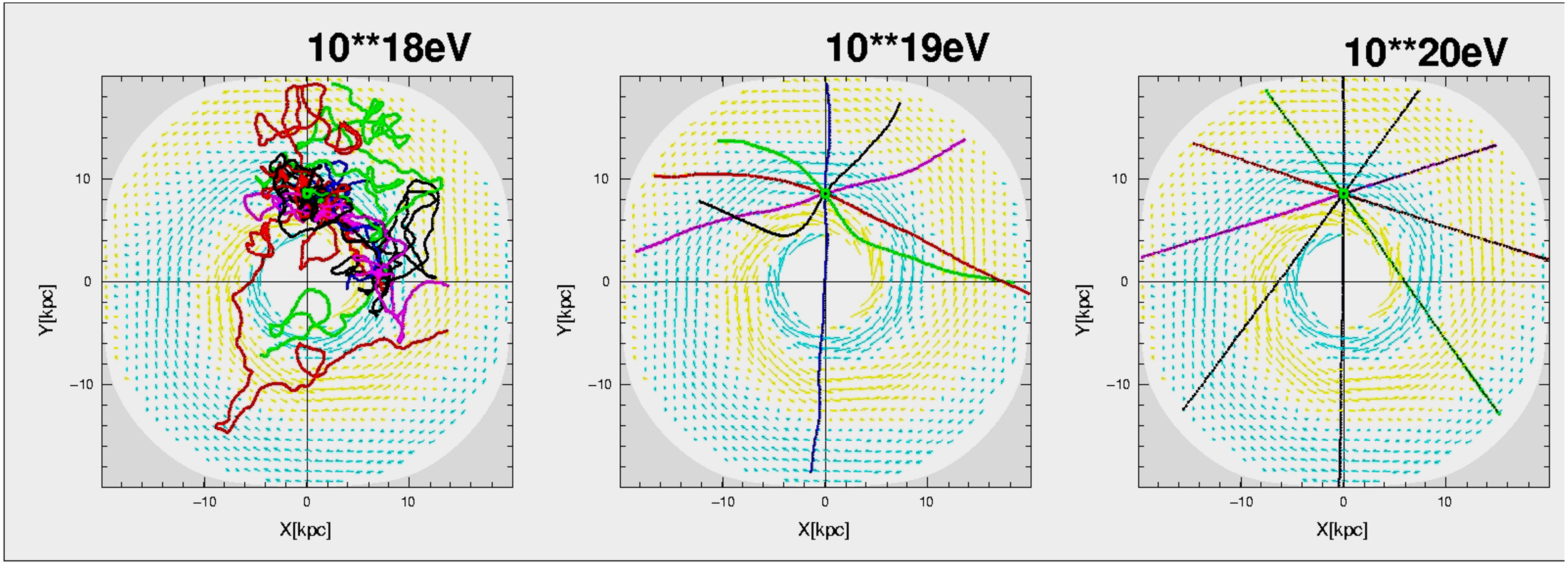

Proton-proton equivalent CM energy $\sqrt{s}$ / TeV
80 90 100 200 300 400
EPOS-LHC
QGSJetII-04
SIBYLL-2.3d
data
4-mass-X_{max}-fit+models
p
Fe
$\sigma / \langle R_\mu \rangle$
0.30
0.25
0.20
0.15
0.10
0.05
0.00
10^{19}
10^{20}
E / eV


EPOS-LHC
QGSJetII-04
SIBYLL-2.3d
data
4-mass-X_{max}-fit+model
p
He
N
Fe
$E = 10^{19}$ eV
$\sigma / \langle R_\mu \rangle$
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
1.2
1.4
1.6
1.8
2.0
2.2
$\langle R_\mu \rangle$

Arrival directions of UHECR and magnetic fields.

UHECR propagation in Milky Way

- Deflection angle ~ 1-2 degrees at 10^{20}eV for protons
  - Astronomy by hadronic particles?



Deflections by EGMF

By K.Dolag, D.Grasso, V.Springel, and I.Tkachev

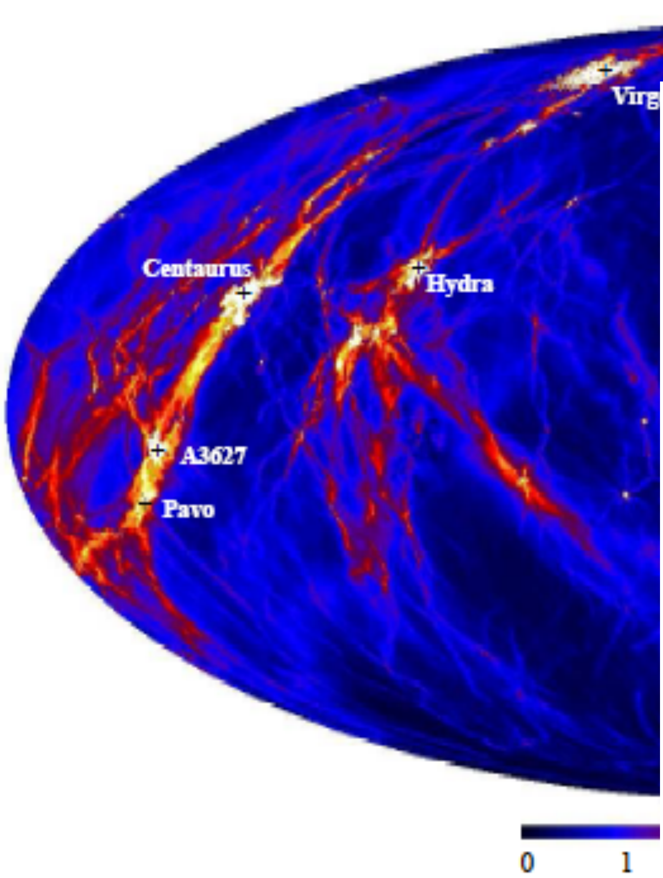


FIG. 1: Full sky map (area preserving projection) of c
scale. All structure within a radius of 107 Mpc aroun
with the galactic anti-center in the middle of the ma
corresponding halos in the simulation.

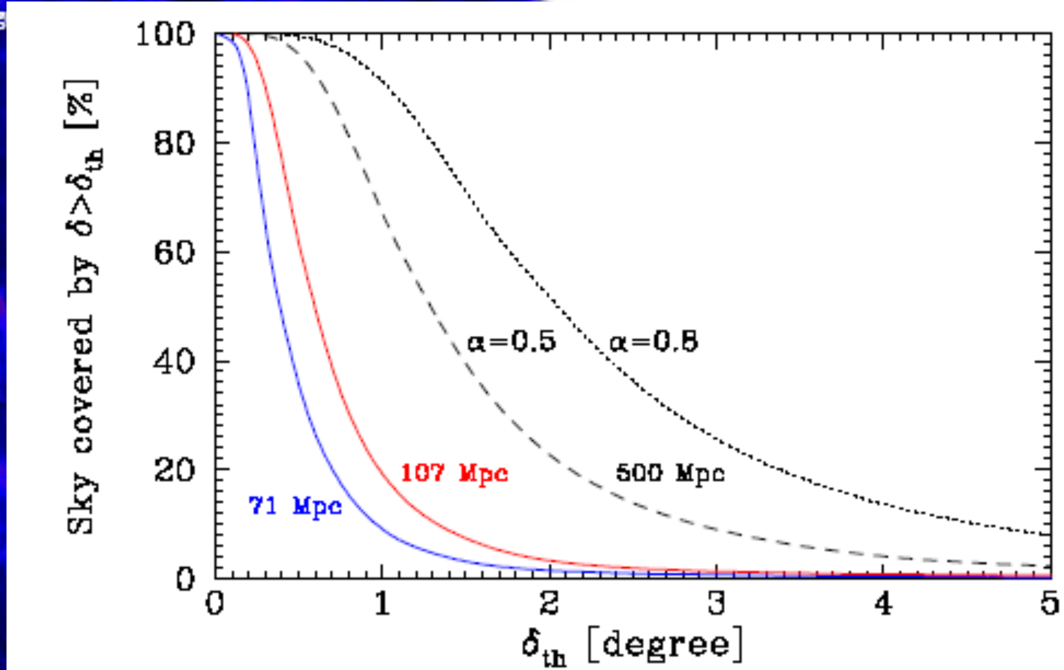
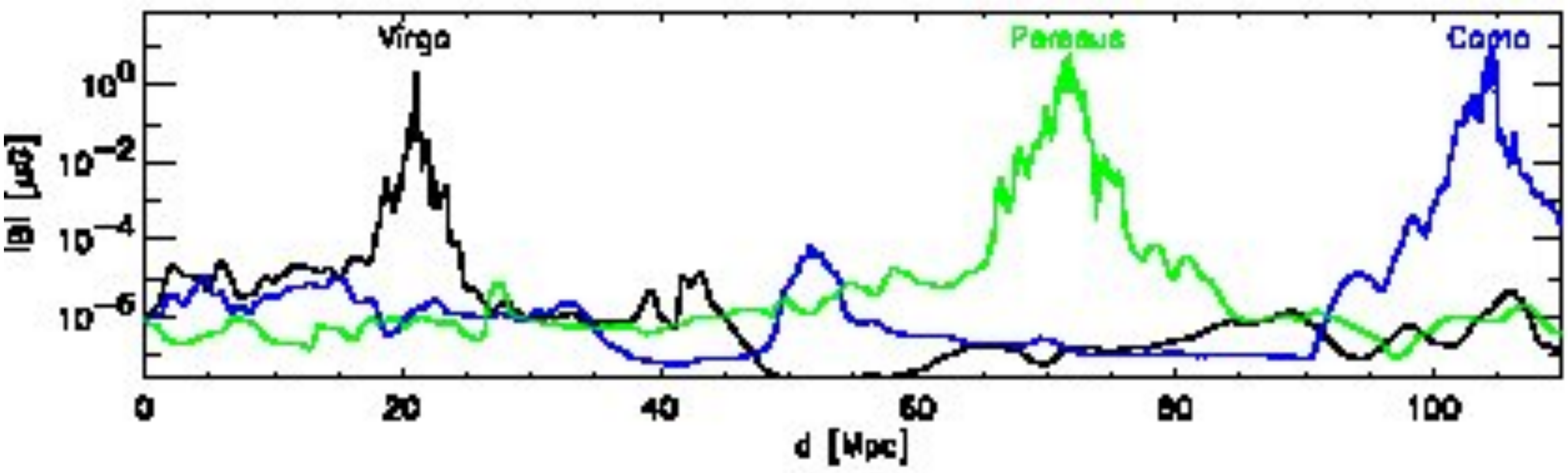


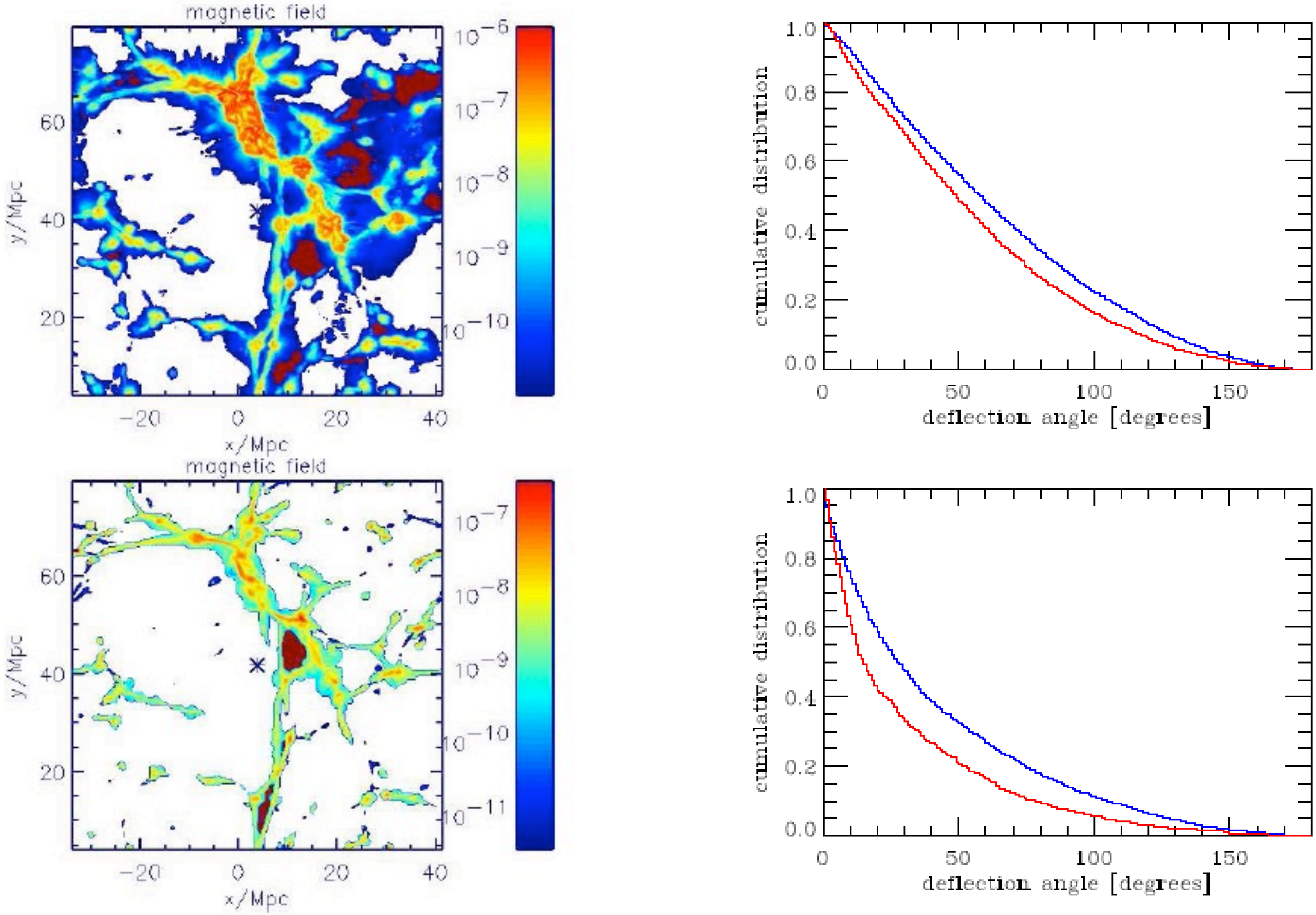
FIG. 2: Cumulative fraction of the sky with deflection angle larger than δ_{th}, for several values of propagation distance (solid lines). We also include an extrapolation to 500 Mpc, assuming self similarity with $\alpha = 0.5$ (dashed line) or $\alpha = 0.8$ (dotted line). The assumed UHECR energy for all lines is 4.0×10^{19} eV.

Magnetic field in several directions from Earth for constrained simulation

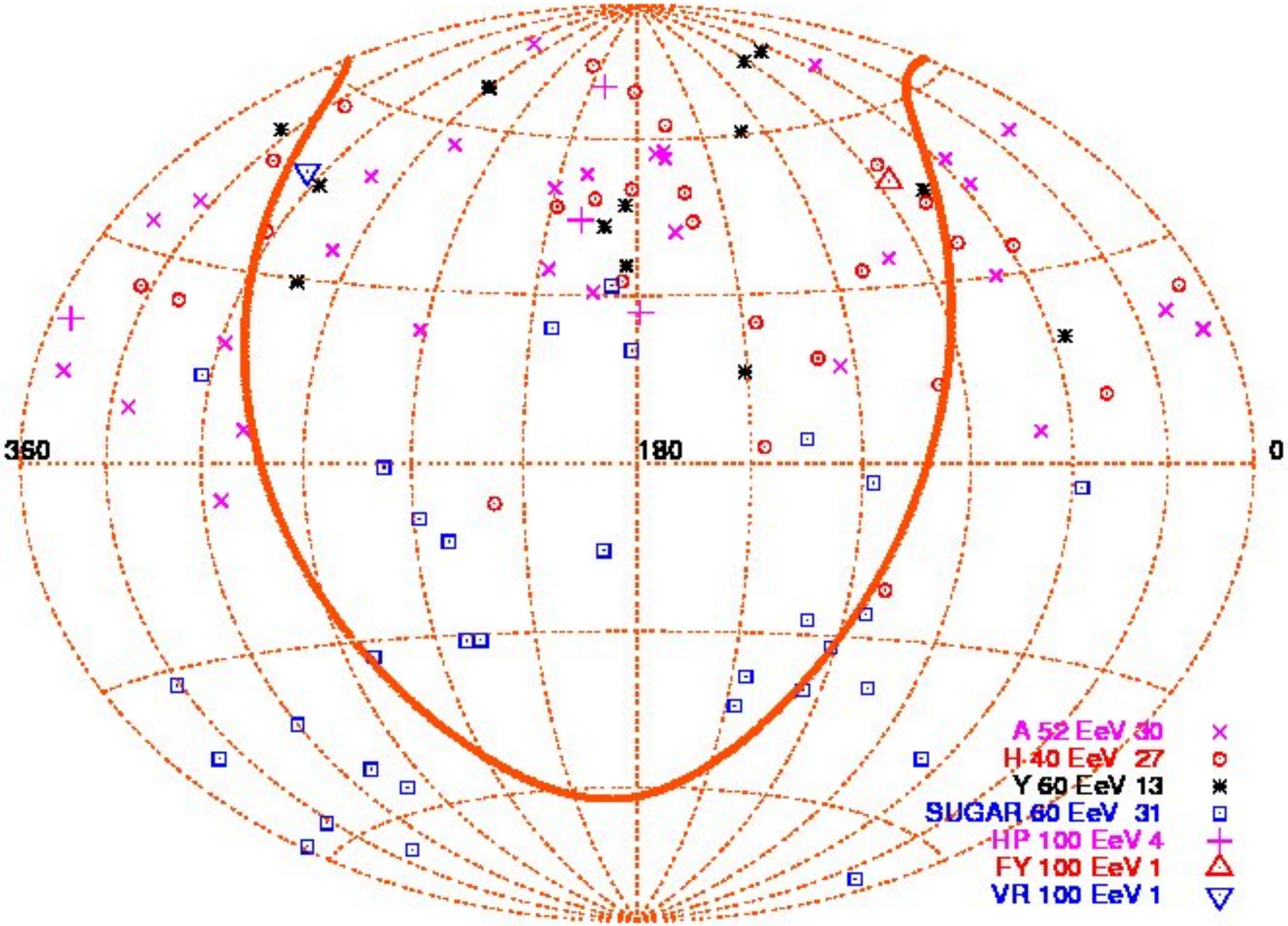


Dolag et al, astro-ph/0410419

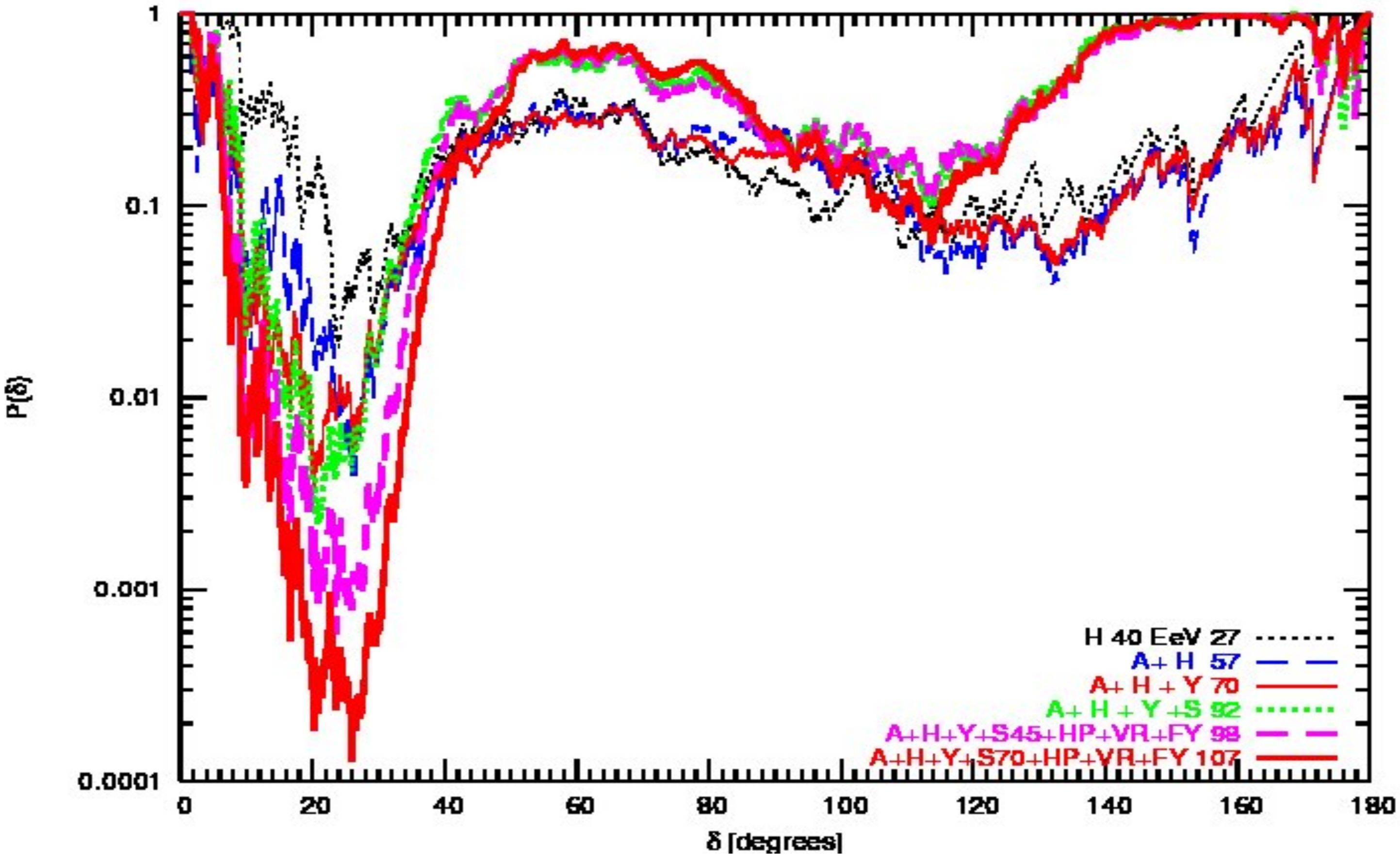
EGMF by G. Sigl et al. astro-ph/0401084



Arrival directions for E>40 EeV in HiRes (E>52 EeV in AGASA)



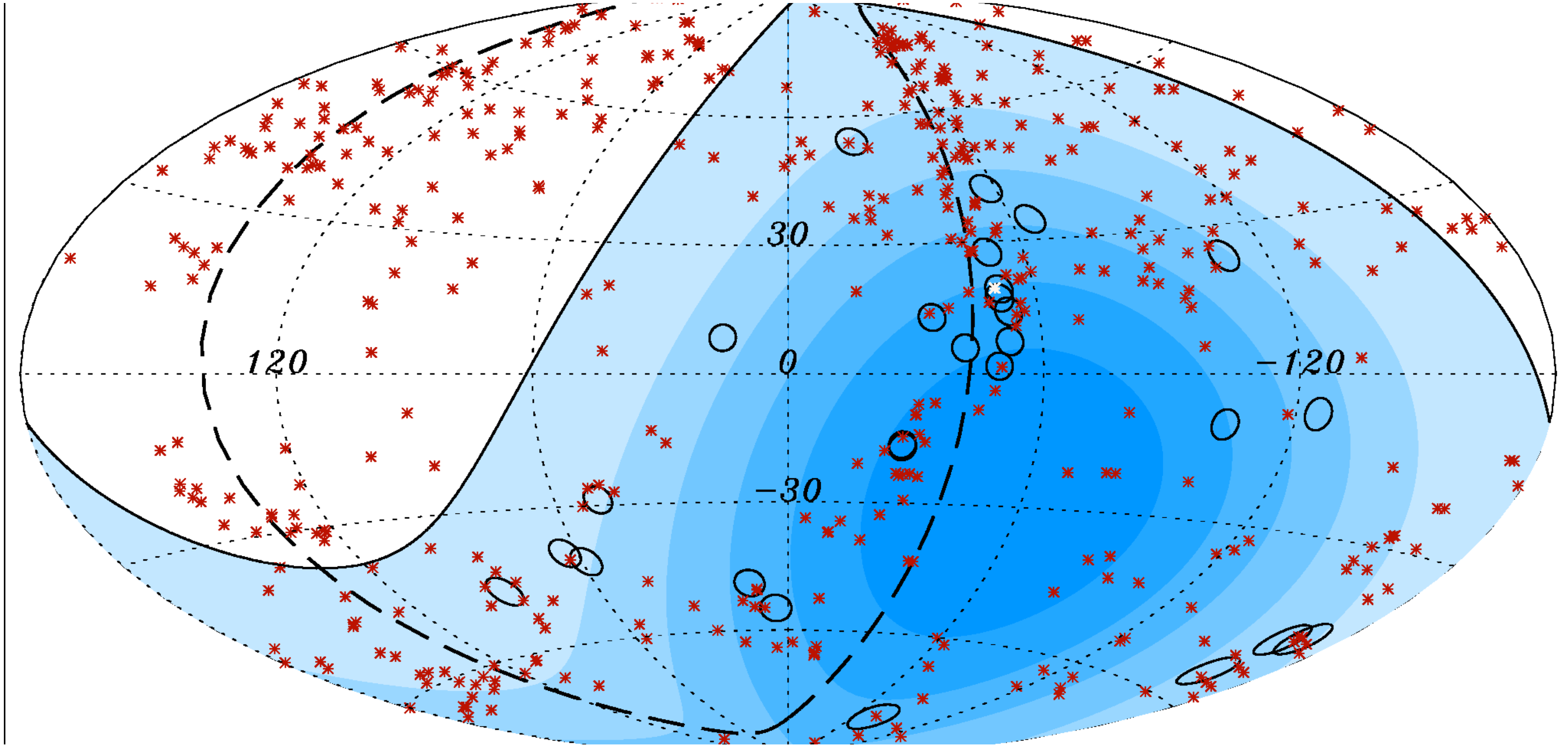
Probability of correlation



3 σ after penalty on angle

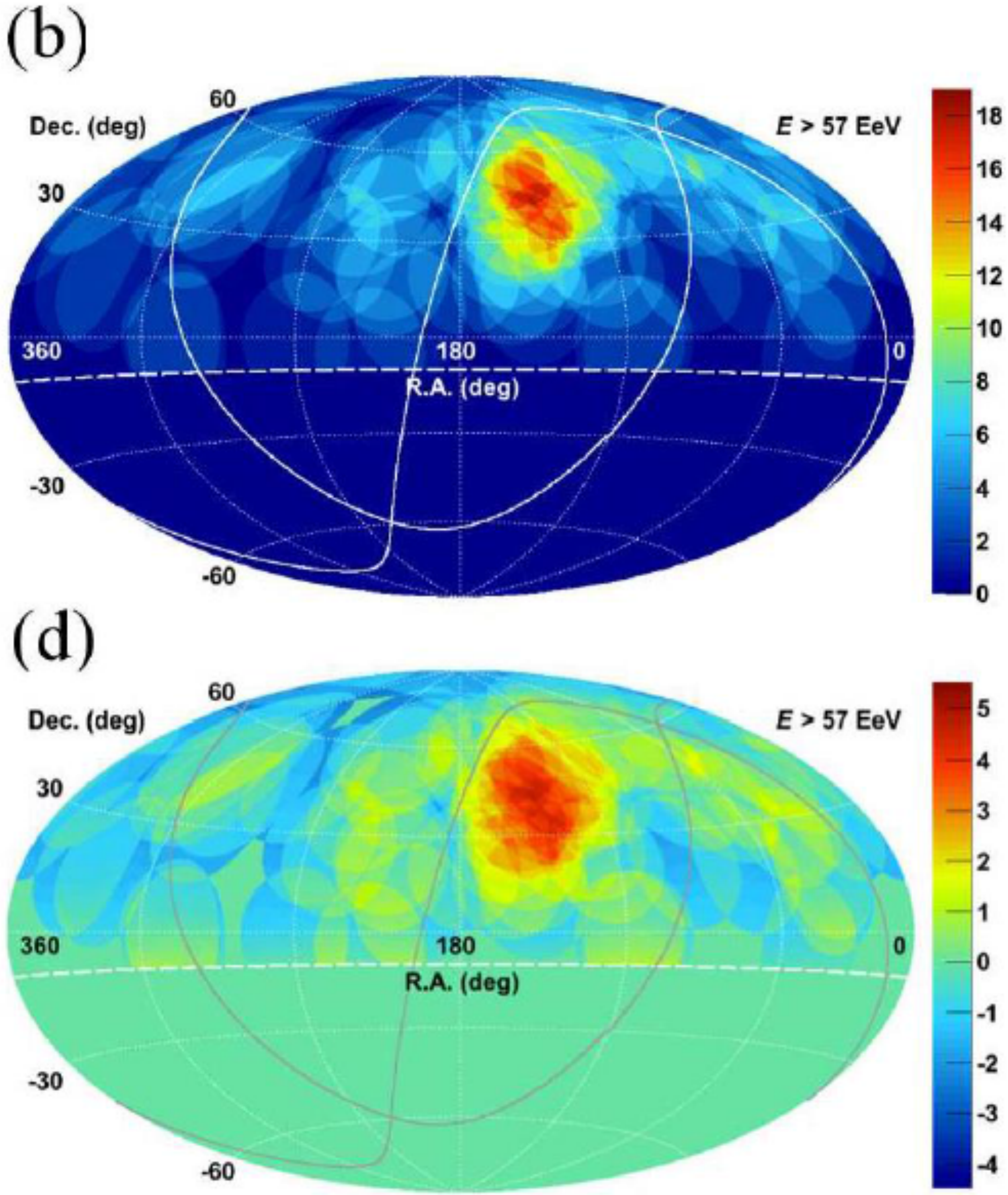
M.Kachelriess and D.S. astro-ph/0512498

Arrival directions for E>57 EeV in Auger



Statistics with Galactic plane cut

- Z<=0.018 R=75 Mpc: 425 AGN |b|>12 degrees
- 6 events in Galactic plane only one correlate
- Out of Galactic plane 21 event /19 correlate 90%.
- Only new events: 11/9 correlate P=0.0002
- In later data no correlations



Telescope Array

10^6 total events over 6 years

87 events > 57 EeV , < 60°

Shown: events within 20° of each point

Hot Spot at
RA= **148.4°** and dec= **+44.5°**
(*Mrk 421 is in the vicinity …)*

4.3 σ significance compared to isotropic fluctuation

R. Abbasi et al., Ap. J (Lett) ***790*** *(2014) L21; arXiv:1404.5890 [astro-ph.HE]*

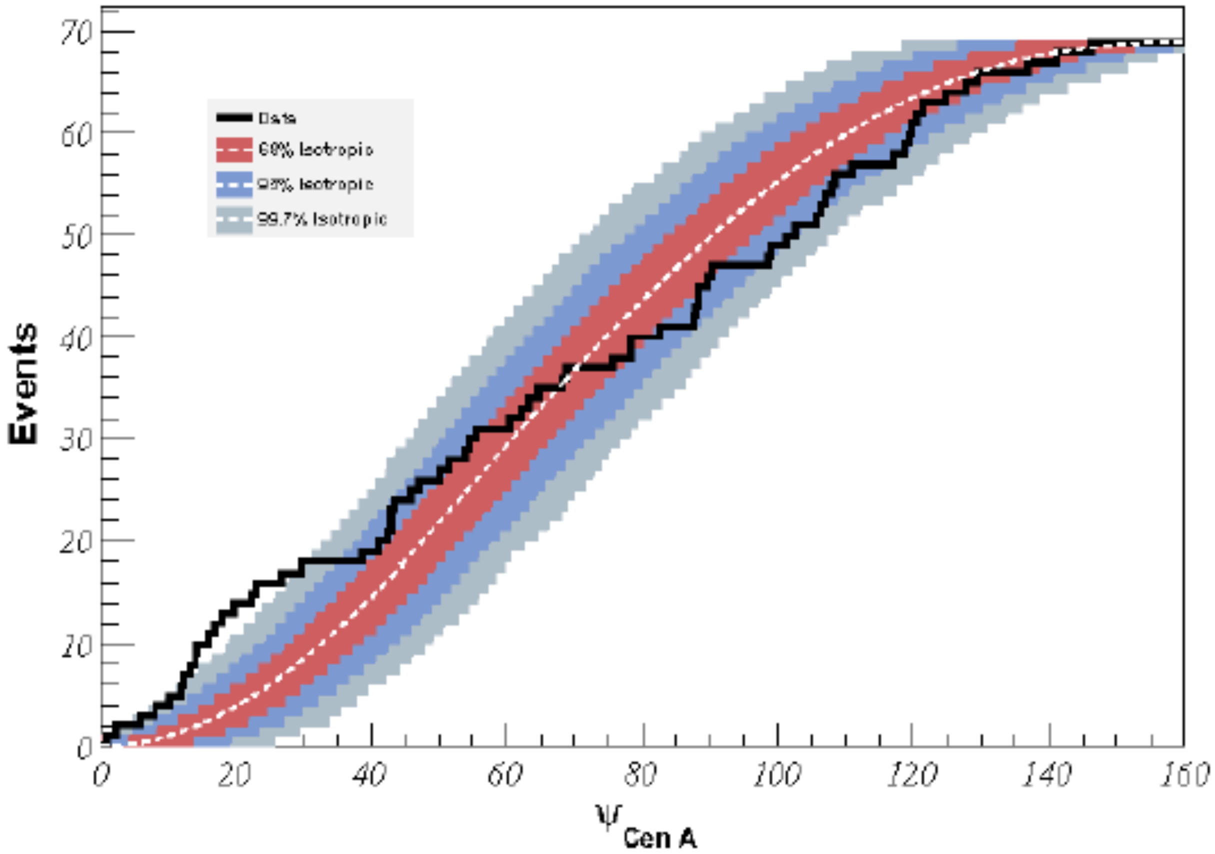


Fig. 9. Cumulative number of events with $E \geqslant 55$ EeV as a function of angular distance from the direction of Cen A. The bands correspond to the 68%, 95% and 99.7% dispersion expected for an isotropic flux.

Pierre Auger Observatory

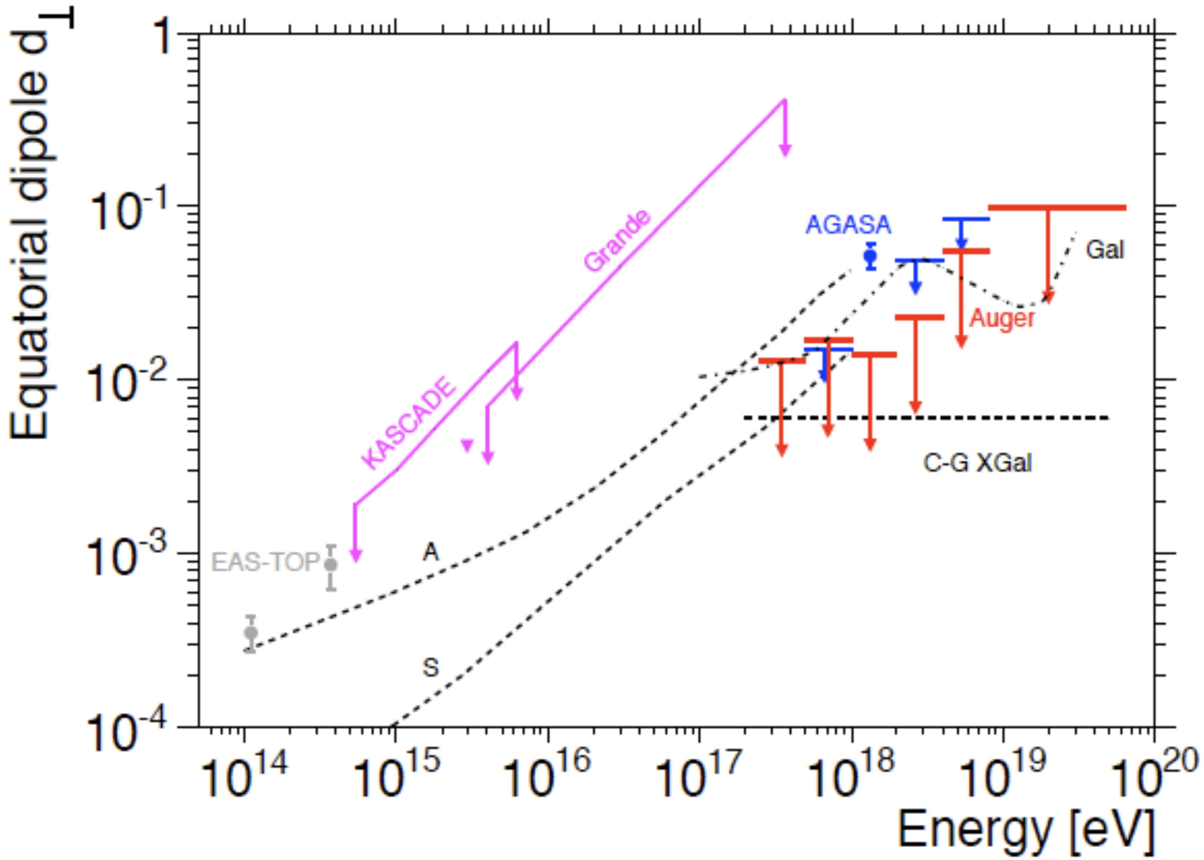
Events > 55 EeV

Excess from directions "near" (~20°) **Cen-A**

P. Abreu et al. , Astropart. Phys. ***34*** *(2010) 314.*

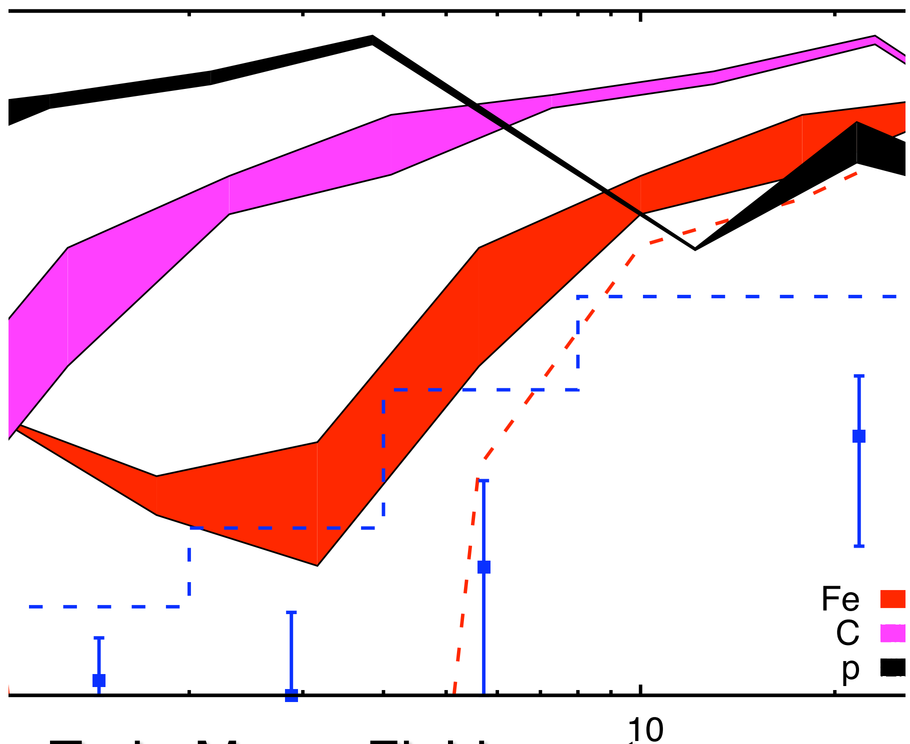
Transition from galactic to extragalactic cosmic rays

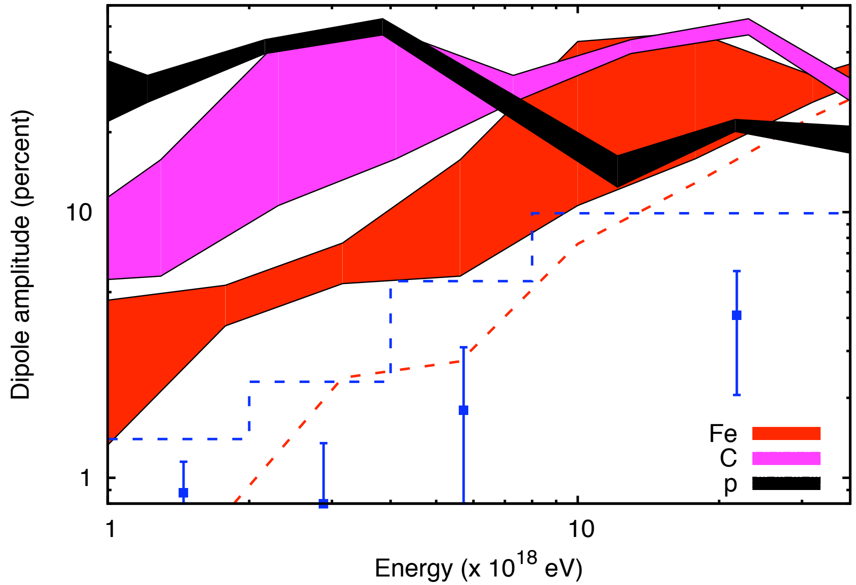
Anisotropy dipole



- **Pierre Auger Collaboration, arXiv:1103.2721**

Dependence on parameters

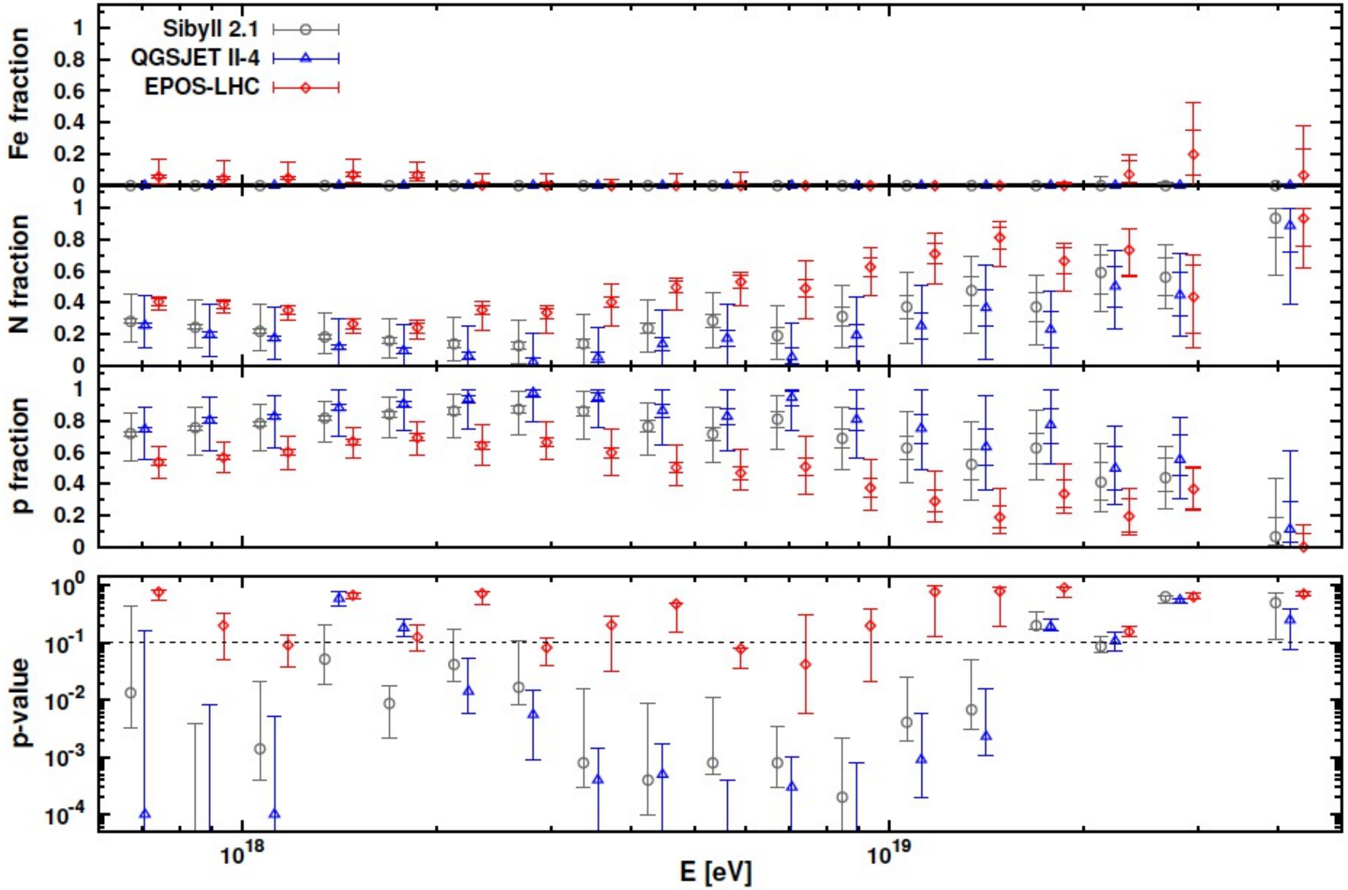




- Turb. Magn. Field spectrum
- Kolmogorov/Kraichnan
- Lmax = 100-300 pc

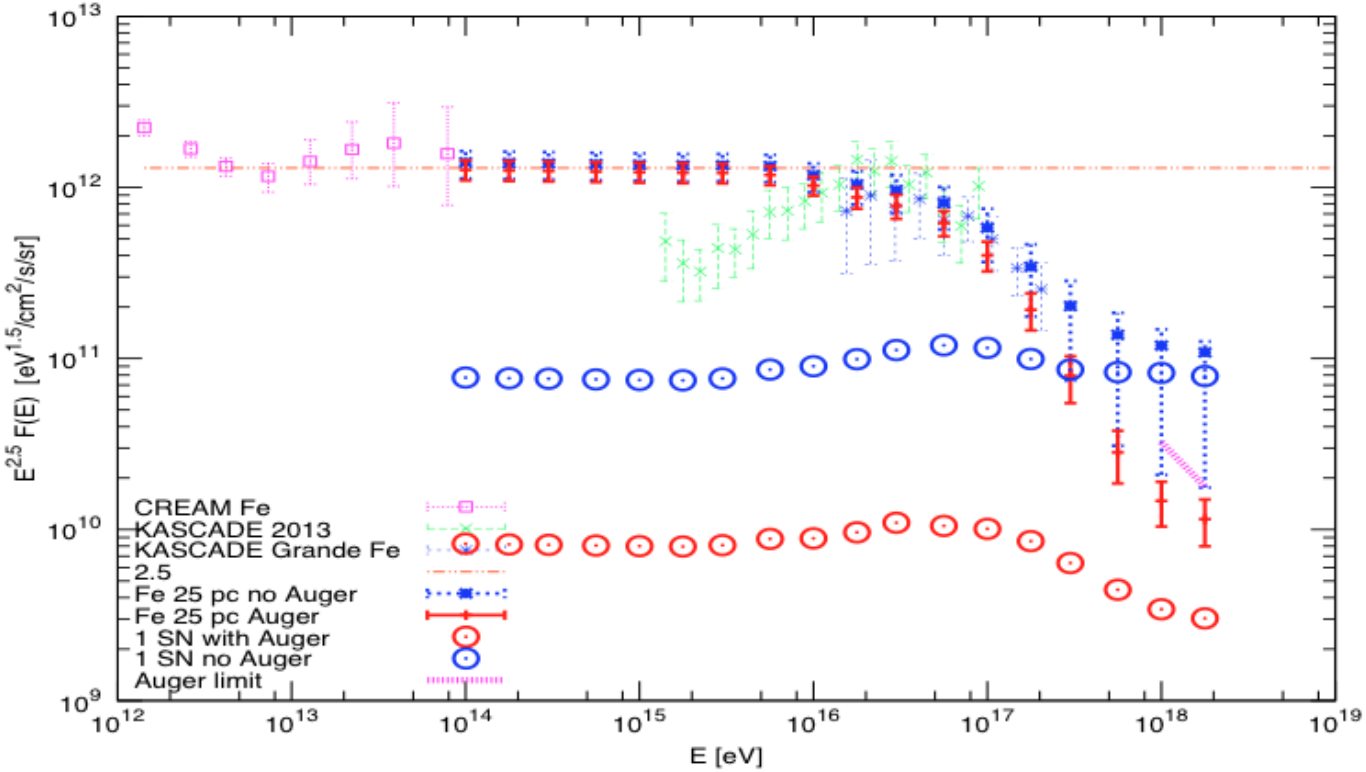
- G.Giacinti et al, **arXiv:1112.5599**

Auger cosmposition measurements

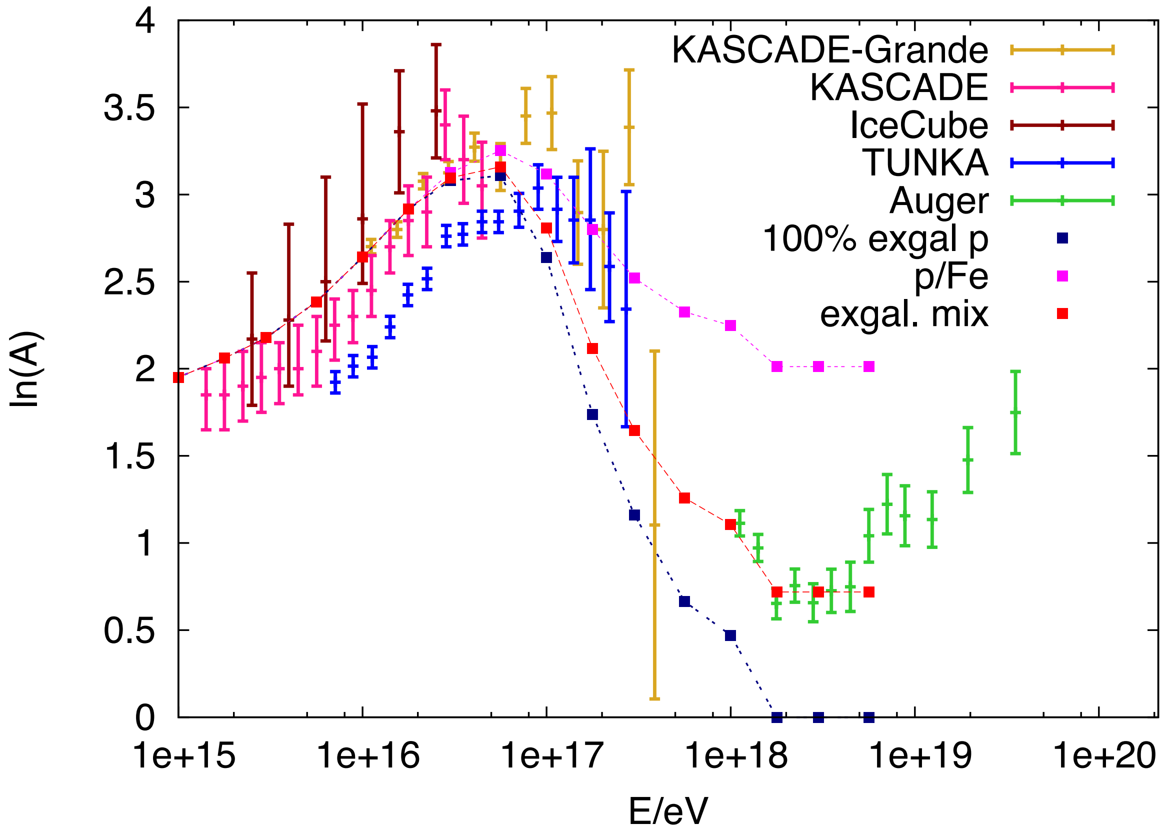


- Auger Collaboration, **arXiv:1409.5083**

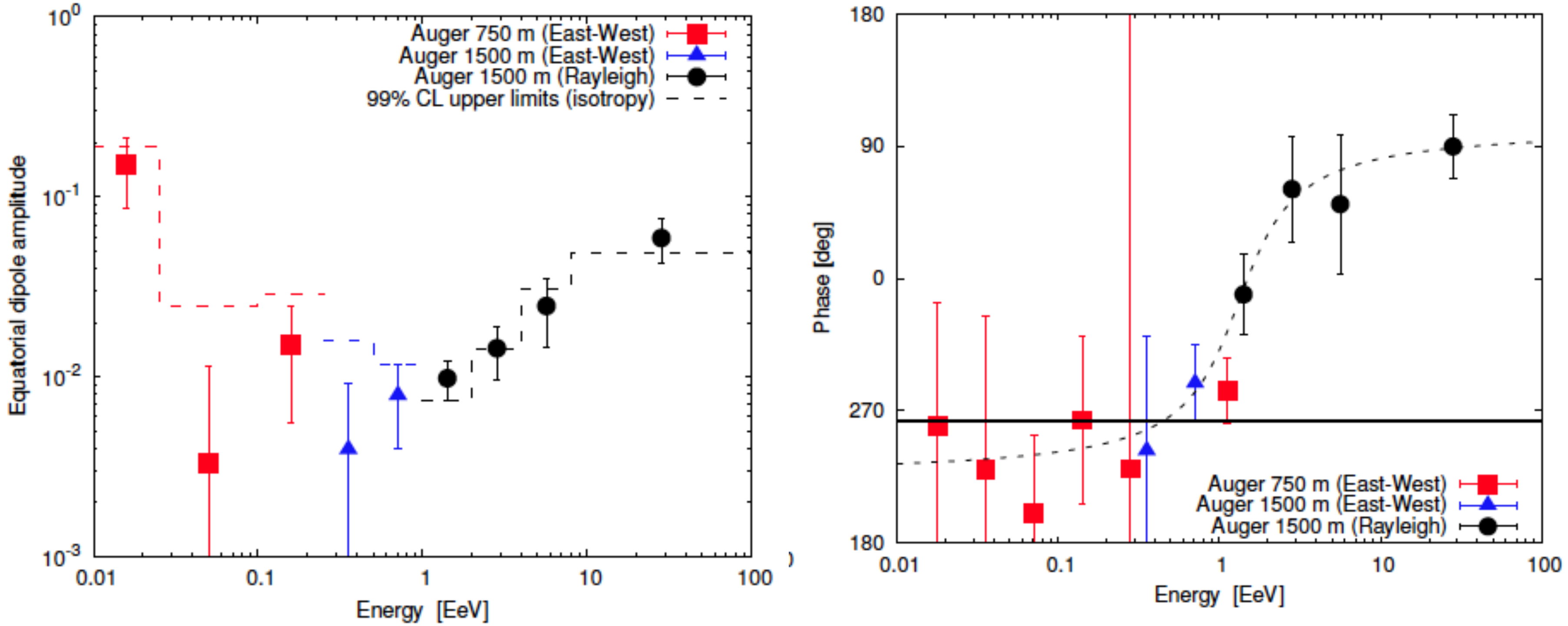
Auger limit on Fe fraction



LnA plot

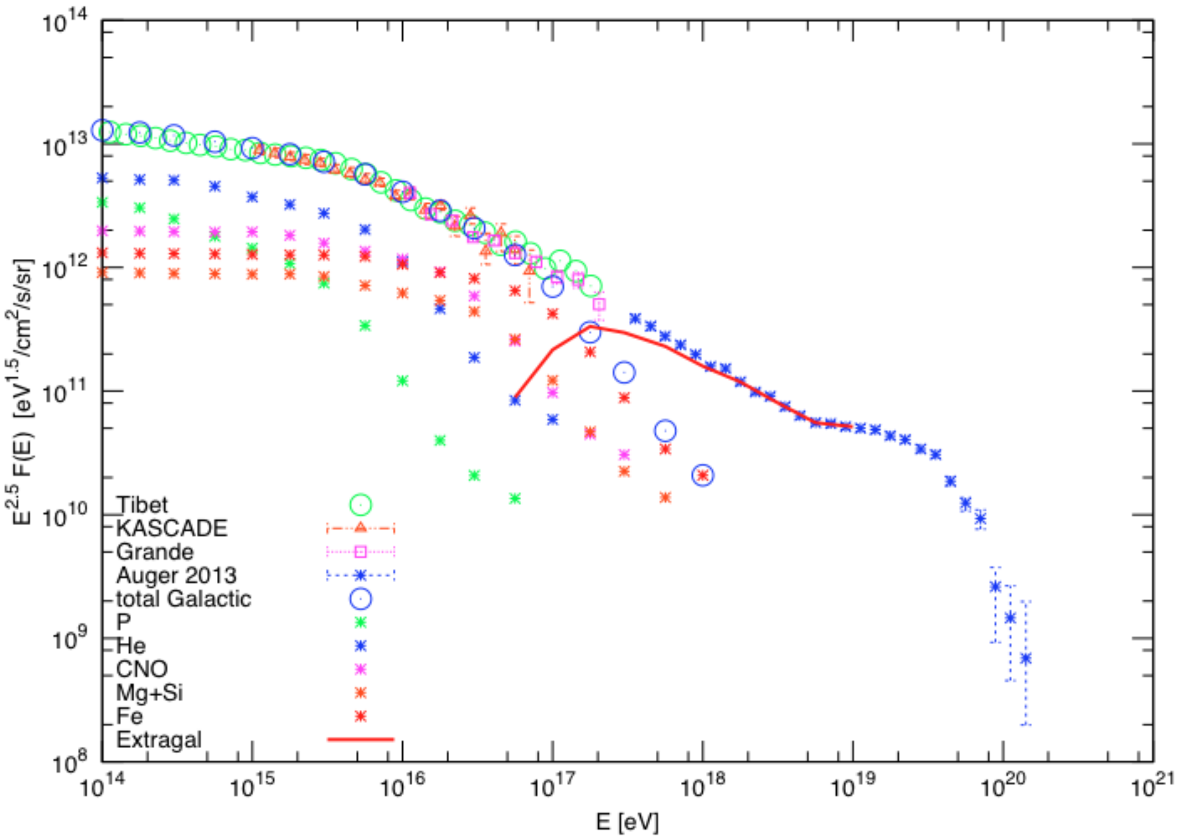

KASCADE-Grande
KASCADE
IceCube
TUNKA
Auger
100% exgal p
p/Fe
exgal. mix
ln(A)
E/eV
0
0.5
1
1.5
2
2.5
3
3.5
4
1e+15
1e+16
1e+17
1e+18
1e+19
1e+20

Auger dipole measurements

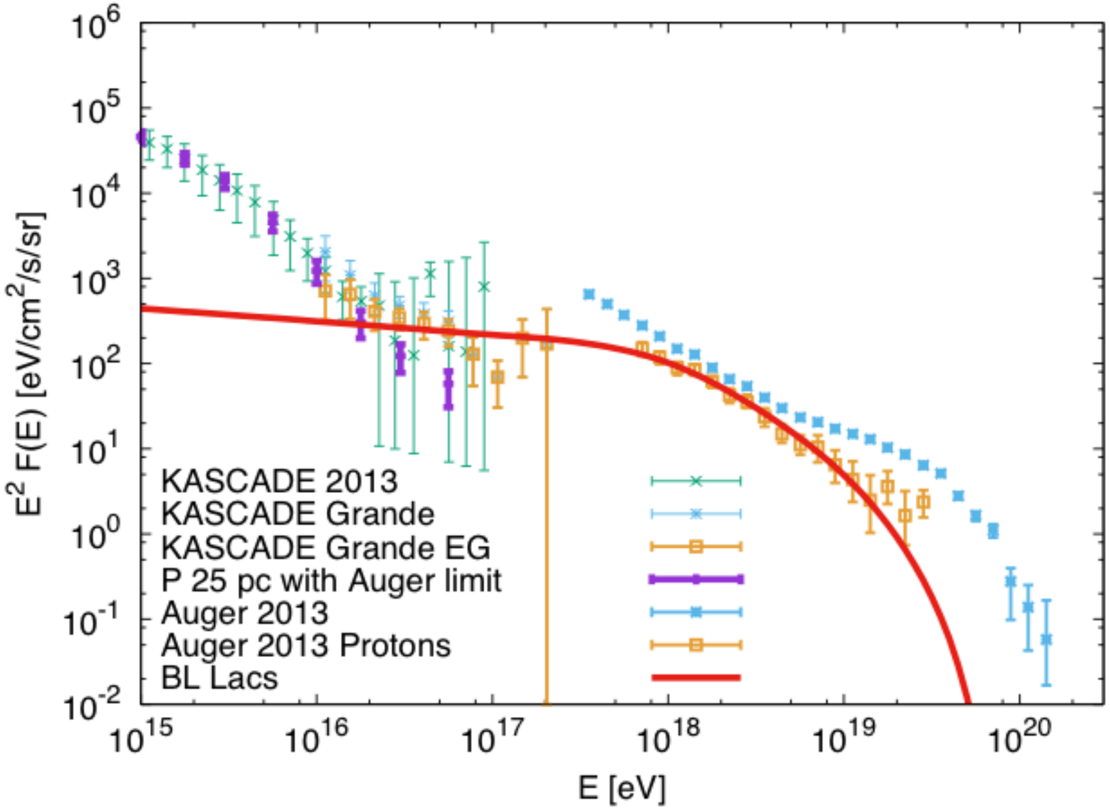


- Auger Collaboration, **arXiv:1310.4620**

Contribution of extra-Galactic sources



UHECR proton flux from extragalactic sources

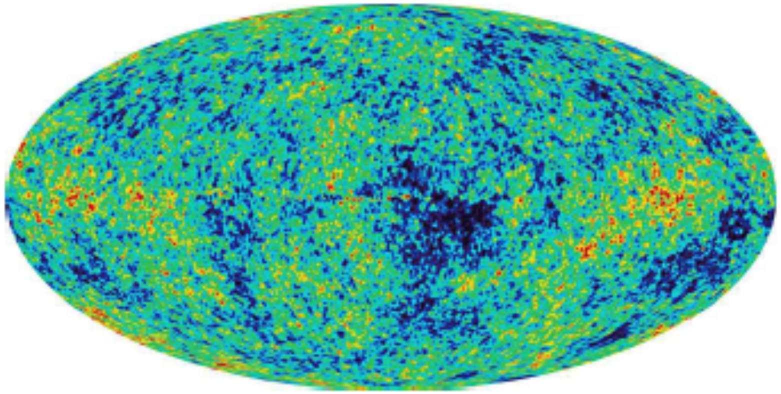


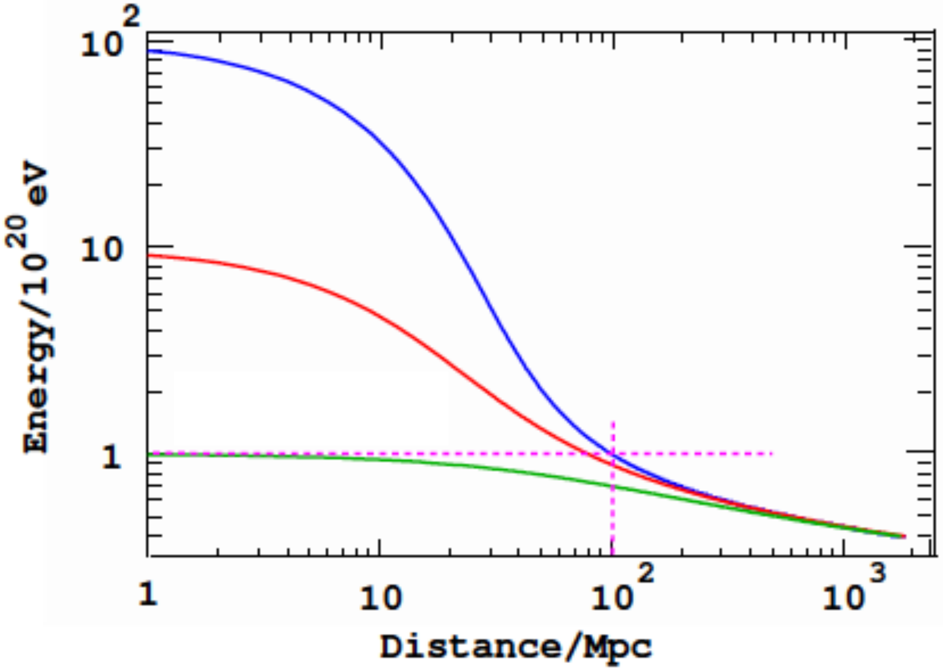
Conclusions extragalactic CR

- Cutoff in UHECR spectrum exist. UHECR come from astrophysical sources
- UHECR composition mixed. Only significant anisotropy is TA hot spot. Not easy to find sources.
- Transition from Galactic to extra-Galactic cosmic rays is from 30 PeV (protons) to 1 EeV (heavy nuclei)
- For understanding of UHECR sources one need to add information on neutrinos and gamma-rays (see next lectures)

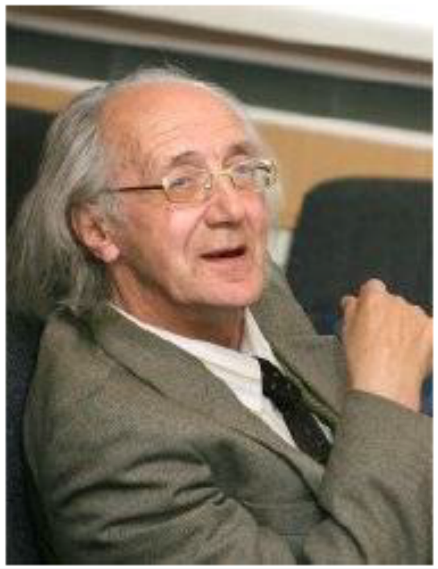
Seminar:
GZK cutoff

Greisen-Zatsepin-Kuzmin Effect



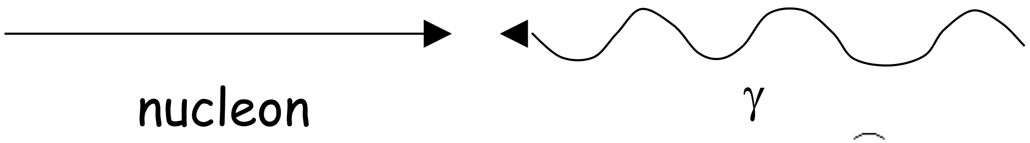


$$p + \gamma_{\mathrm{CMB}} \to N + \pi$$

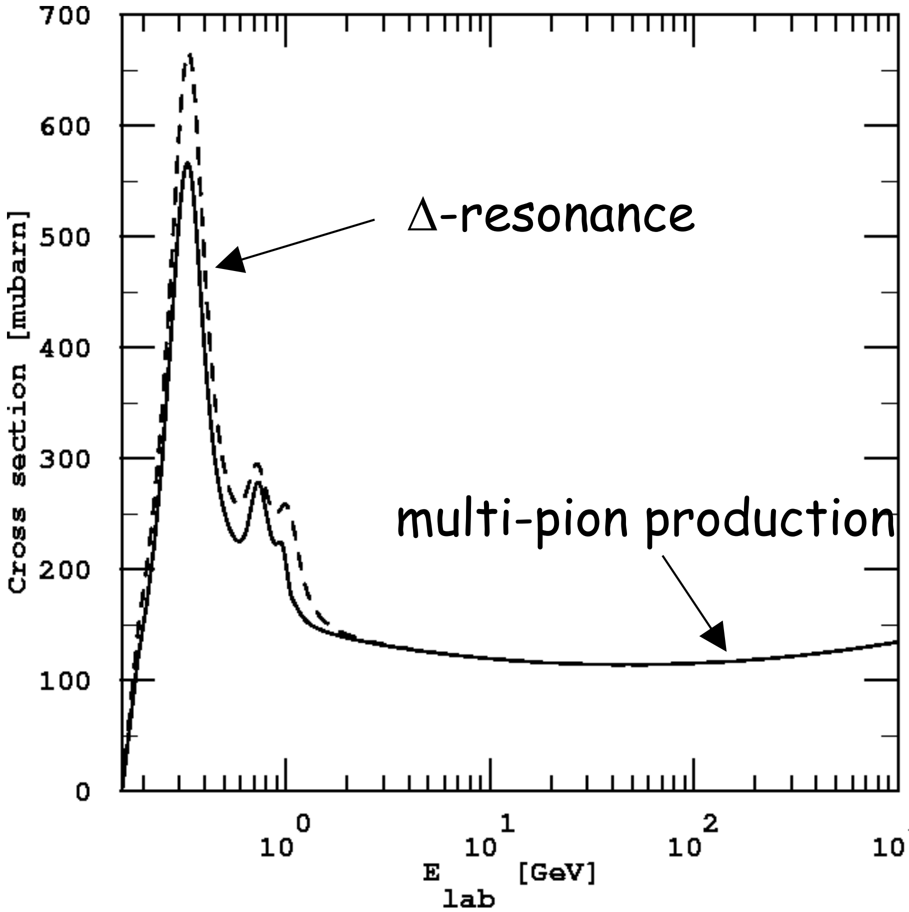


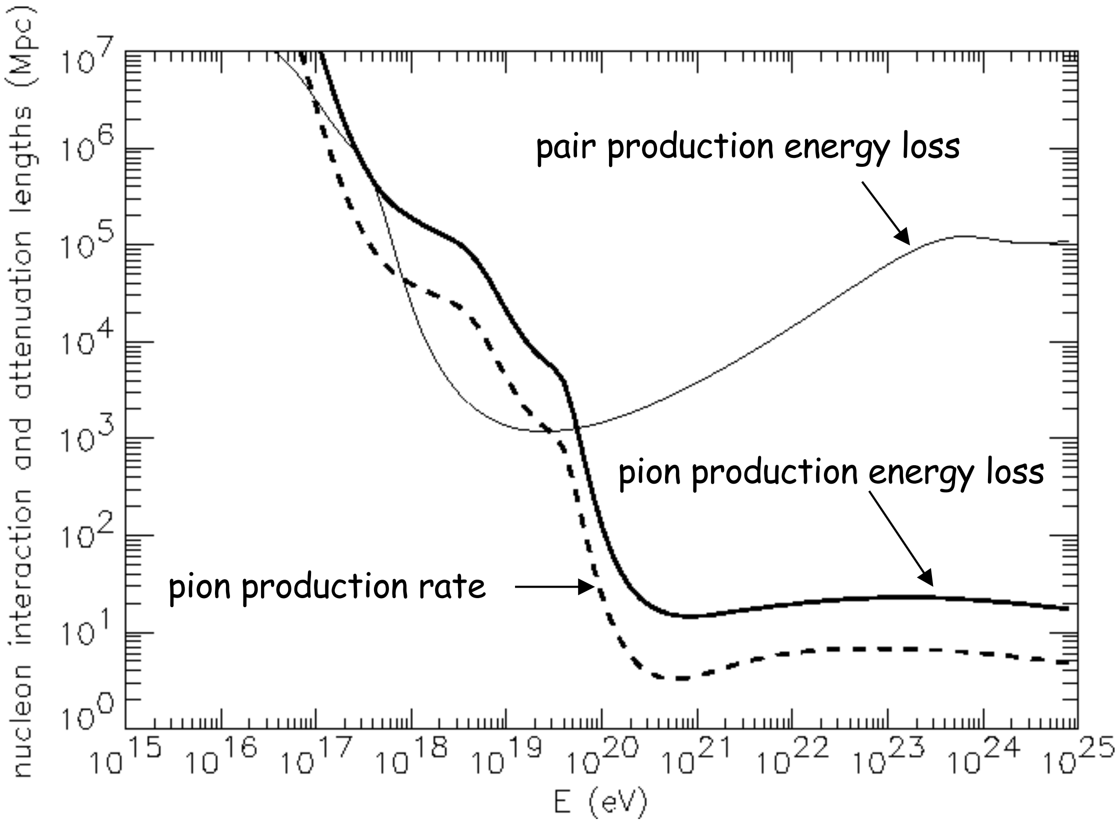
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



$$E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 6\cdot 10^{19}\,\text{eV}$$





⇒sources must be in cosmological backyard within 50-100 Mpc from Earth (compare to the Universe size ~ 5000 Mpc)

Calculation of the required UHECR proton energy for pion photoproduction

- The approach is to calculate the proton energy, E_p, required for pion photoproduction using conservation of 4-momenta, *P*.

$$\gamma + p \to p\pi^0$$

$$\text{Lab} \to \text{Center of mass}$$

- Considering the left hand side in the lab frame and the right hand side in the center-of-mass frame, where
  - E_p = UHECR proton energy (the unknown)
  - $E\gamma$ = average CMB photon energy = 6.34x10-4 eV [4]
  - m_p = 938.27 MeV/c2
  - $m_{\pi 0}$ = 134.97 MeV/c2
  - P = 4-momentum

$$(P_{p\mu} + P_{\gamma\mu})^2 = P_{TOT\mu} P^{\mu}_{TOT}$$

$$P_{p\mu} P^{\mu}_{p} + 2P_{p\mu} P^{\mu}_{\gamma} + P_{\gamma\mu} P^{\mu}_{\gamma} = P_{TOT\mu} P^{\mu}_{TOT}$$

$$(m_p c^2)^2 + (2E_p E_\gamma) + (m_\gamma c^2)^2 = \left((m_p + m_{\pi^0})c^2\right)^2$$

$$m_\gamma c^2 = 0, \text{because it's a photon}$$

$$E_p = \frac{m_{\pi^0}}{2E_\gamma}\left(2m_p + m_{\pi^0}\right)$$

$$E_p = \frac{(134.97 MeV/c^2)c^2}{2(6.34x10^{-4} eV)}\left(\frac{(2 * 938.27 MeV) + 134.97 MeV)}{c^2} c^2\right)$$

$$E_p \approx 2x10^{20} eV$$

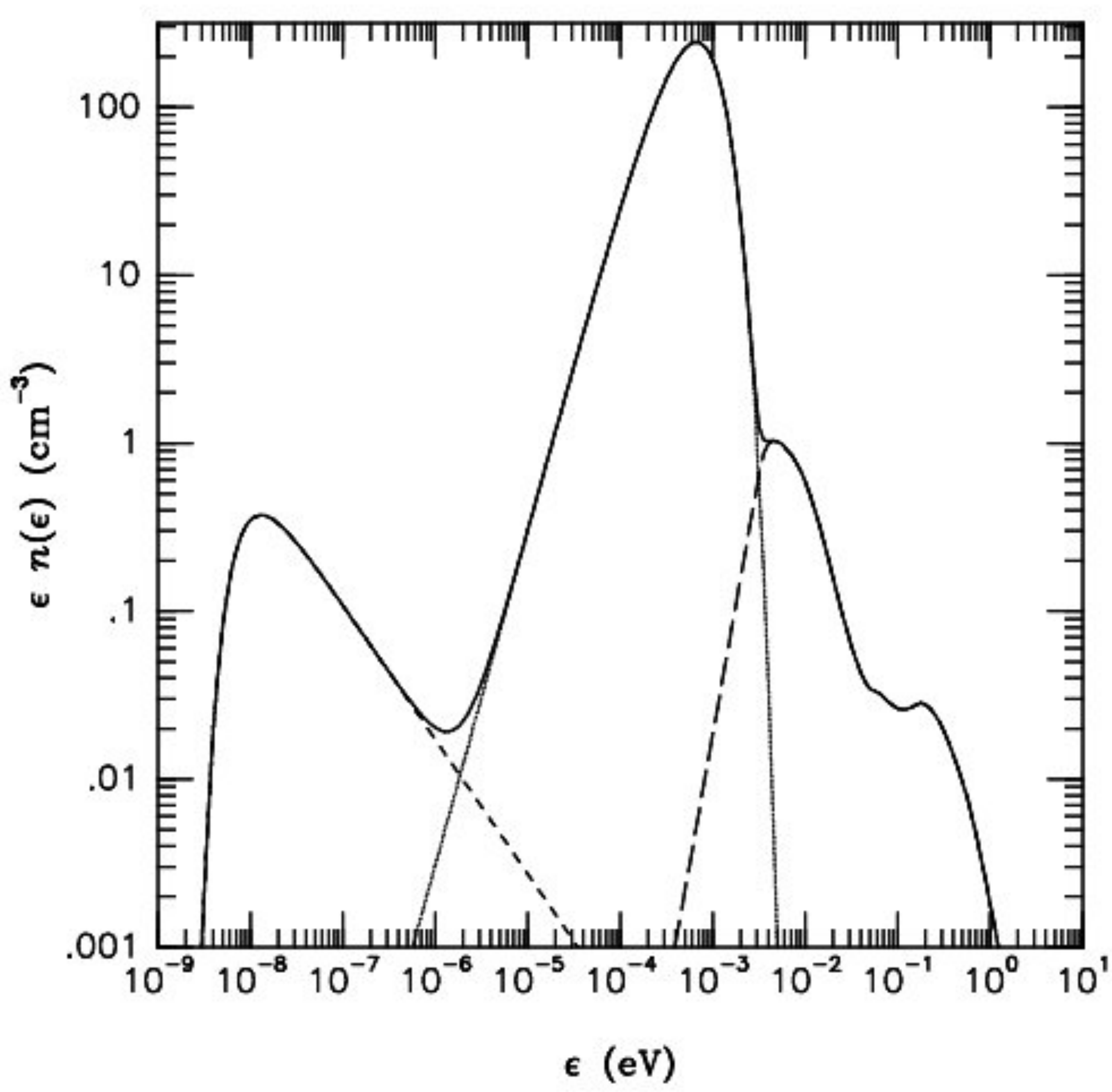
- Conclusion: E_p~2x10^{20} eV

Cutoff energy and threshold energy

$$E = \frac{2m_N m_\pi + m_\pi^2}{2\varepsilon(1-\cos(\alpha))}$$

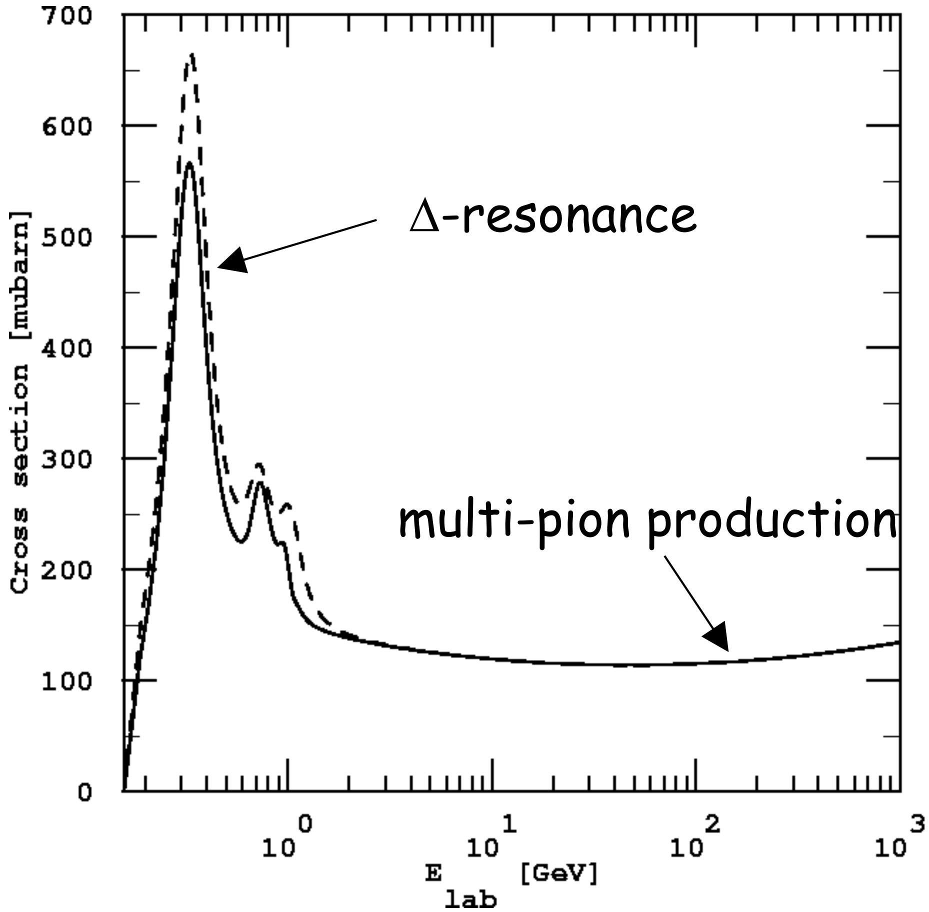
$$E_{\text{th}} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon_{\text{max}}} \approx 6\cdot 10^{19}\,\text{eV}$$

$$E_{av} = \frac{2m_N m_\pi + m_\pi^2}{2\varepsilon_{av}} \approx 2\cdot 10^{20}\,\text{eV}$$



100
10
1
.1
.01
.001
10^-9 10^-8 10^-7 10^-6 10^-5 10^-4 10^-3 10^-2 10^-1 10^0 10^1
ε n(ε) (cm^-3)
ε (eV)

$$\Delta E / E = M_{pi} / M_P = 1/6 \qquad \Delta E_{multi} / E = Sum_i p^i_{pi} / M_P = 1/2$$



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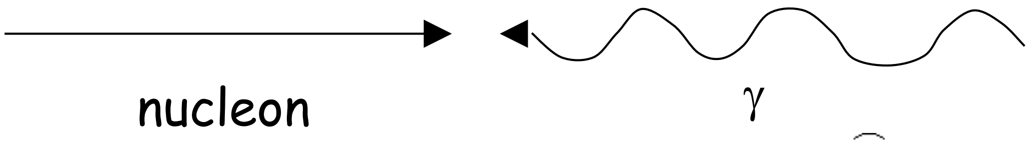
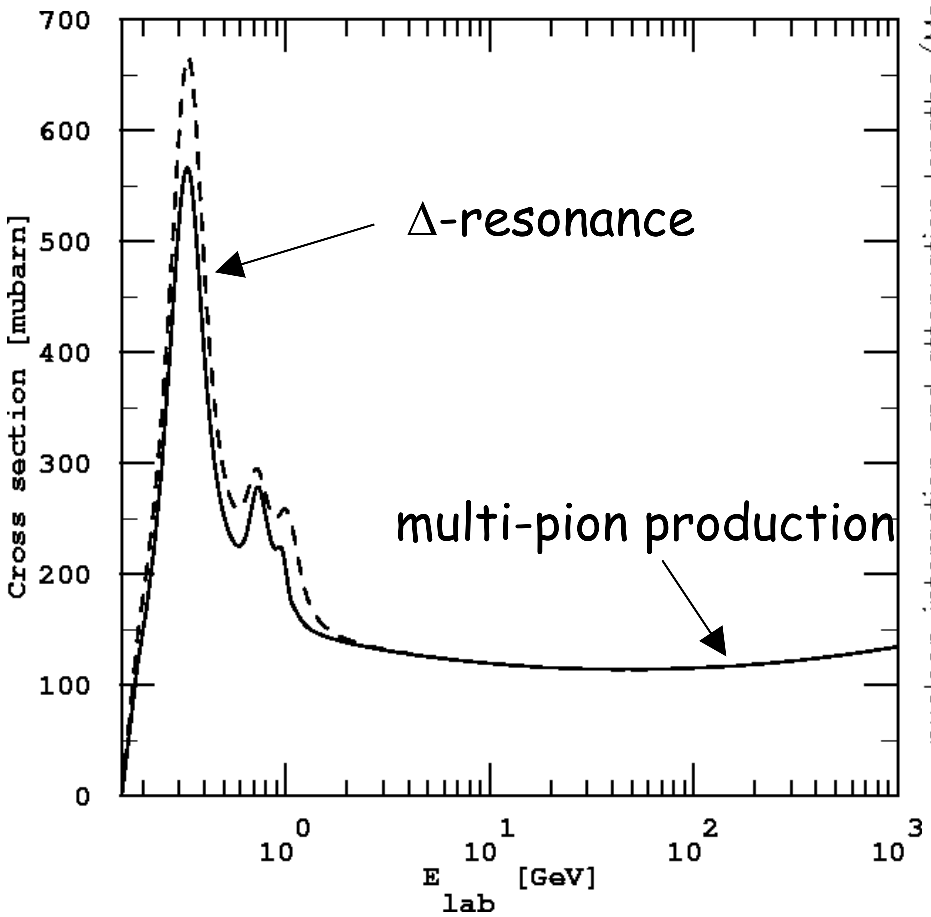
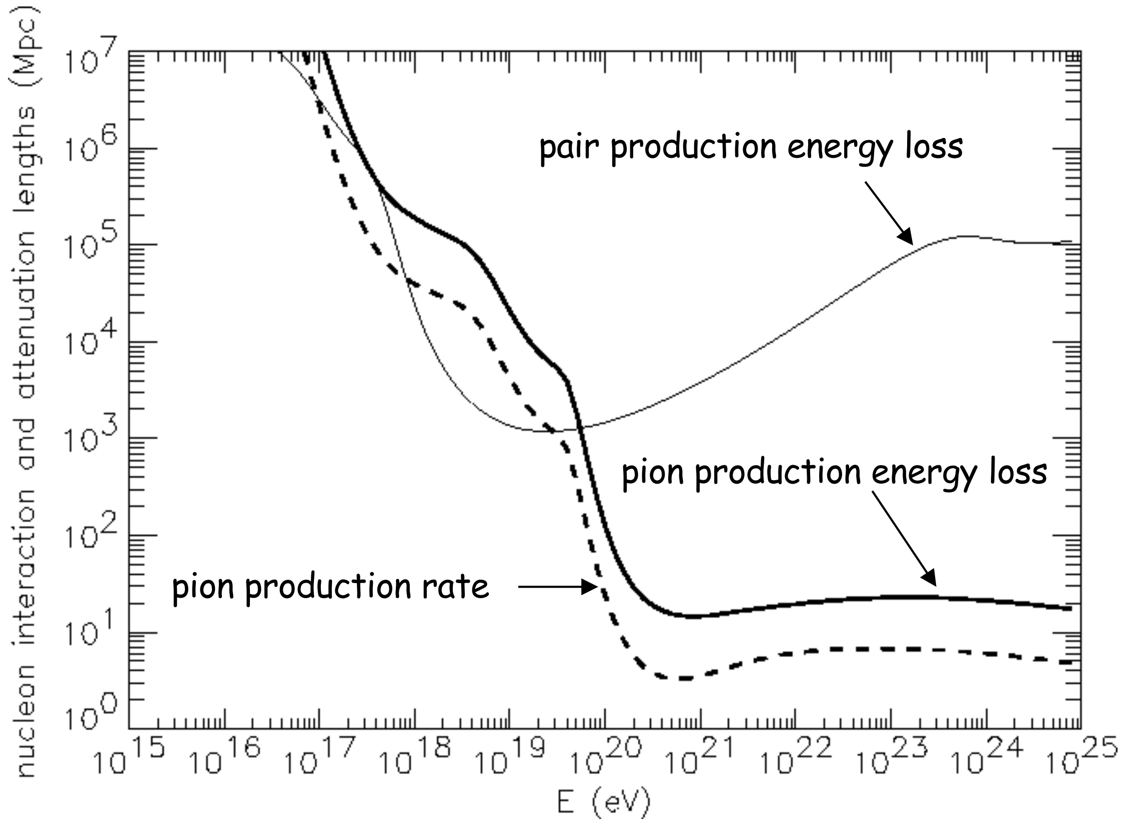


$$E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 6\cdot 10^{19}\,\mathrm{eV}$$





⇒sources must be in cosmological backyard within 50-100 Mpc from Earth (compare to the Universe size ~ 5000 Mpc)

Distance

$$R_{\text{int}} * sigma * n_{cmb} = 1$$

$$R_{\text{int}} = 1/(sigma * n_{cmb}) = 1/(6e-28cm^2 * 400/cm^3)$$

$$R_{\text{int}} = 4*10^{24}\,cm$$

$$R_{at} = R_{\text{int}}(E/dE) = 10\,Mpc$$

$$R_{multi} = 20\,Mpc$$