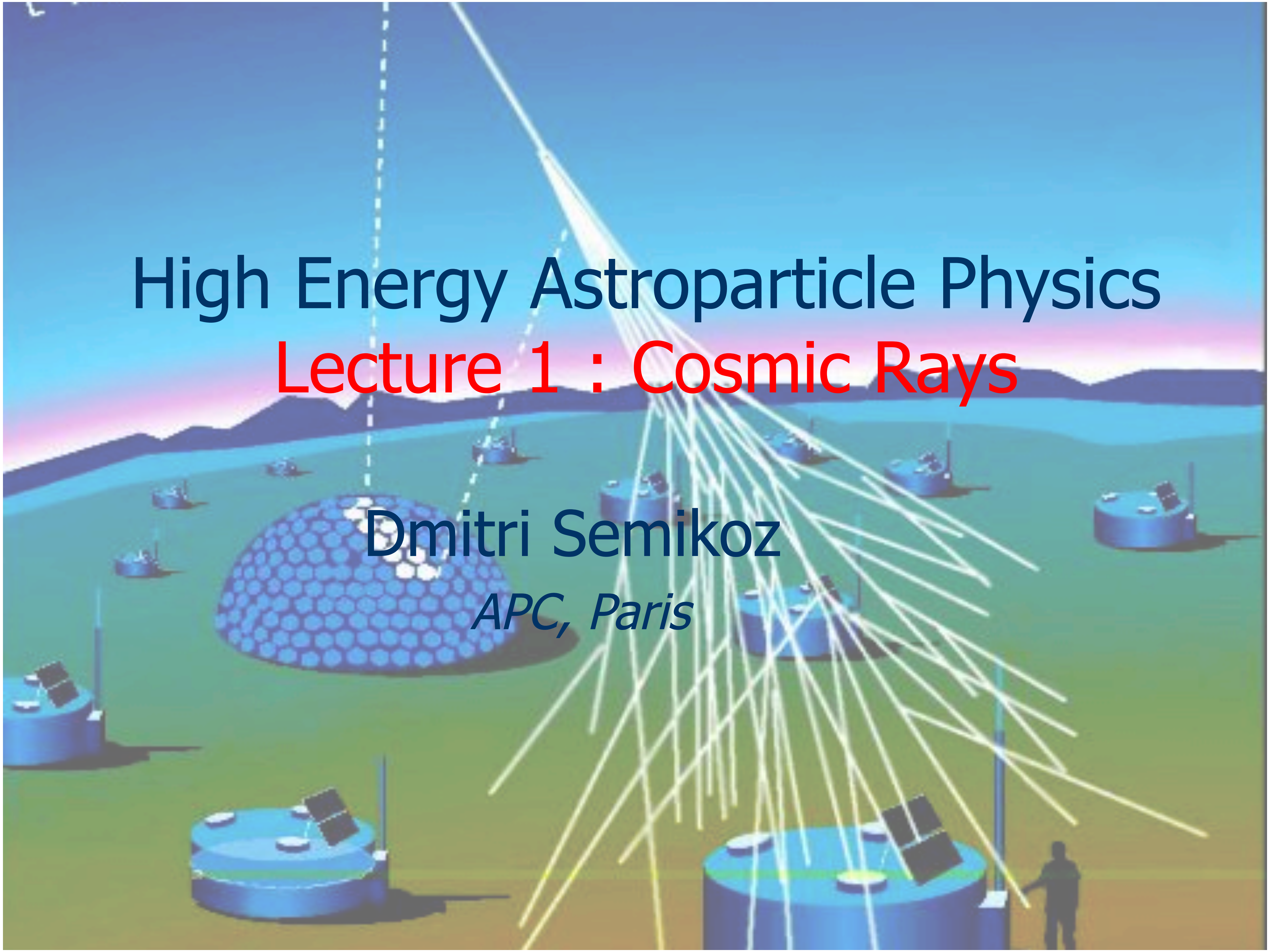


High Energy Astroparticle Physics

Lecture 1 : Cosmic Rays

Dmitri Semikoz

APC, Paris

Astroparticle physics

Particle physics

- Known experimental devices
- Investigation of secondaries from well-defined initial conditions
- Search for unknown phenomena

Astrophysics

- Unknown accelerators
- Elecrodynamics: we understand it well
- Measurement of photons: well understood
- Modelling of sources (inverse problem)

Some units in cosmology and astrophysics

- 1 pc = 3.3 light years = 3.3*c*yr=3*10^{18} cm distance between stars
- 20 kpc = 6*10^{22} cm radius of Milky Way galaxy
- 1 Mpc = 10^6 pc =3*10^{24} cm distance between galaxies
- R_{GZK} =100 Mpc =3*10^{26} cm distance which UHECR protons can travel
- 5 Gpc = 1.5*10^{28} cm size of visible Universe today

Plan:

- *Introduction: historical remarks*
- *Measurements of cosmic rays*
  - *Direct measurements E<100 TeV*
  - *Indirect measurements E> 100 TeV*
  - *UHECR measurements, connection to LHC*
- *Acceleration of cosmic rays*
  - *Fermi acceleration*
  - *Acceleration by electric field near pulsar or black hole*

Plan:

- *Galactic cosmic rays*
  - *Galactic magnetic field*
  - *Knee in spectrum and mass composition*
  - *Theoretical model example: Escape model*
  - *Anisotropy of cosmic rays*
  - *Secondary antiparticles*
  - *Sources of Galactic cosmic rays*

Plan:

- *Extragalactic cosmic rays*
  - *Spectrum of cosmic rays, GZK effect*
  - *Mass composition*
  - *Anisotropy, search for sources of UHECR*
- *Transition from Galactic to extragalactic cosmic rays*
- *Conclusions*

INTRODUCTION

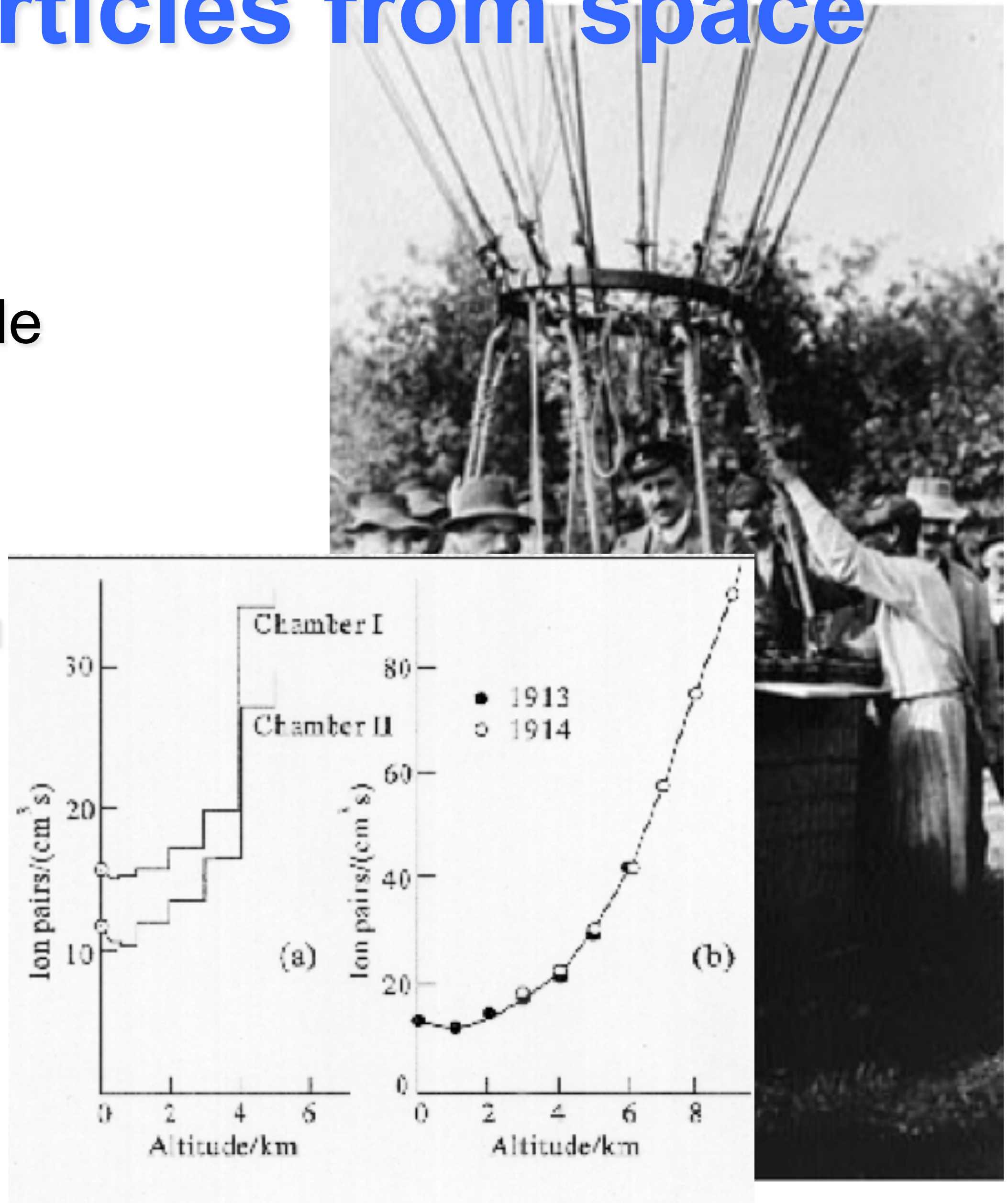
Cosmic rays: historical remarks

- *E*arly radiation detectors (ionization chambers, electroscopes) showed a « dark current » in the absence of sources.
- 1903: Rutherford suggested that most of dark current comes from radioactivity
- 1910: Wulf measured dark current down by factor 2 at top of Eiffel Tower: come from Earth
- *1912: Victor Hess discovered radiation coming to atmosphere from above*

•High-energy particles from space

•Cosmic Rays (CR) are charged high-energy particles coming from outside the atmosphere.

•Discovered 104 yr ago by V.Hess in 1912, via detection of increase of the rate of discharge of an electrometer with increase of the altitude.



Cosmic rays: historical remarks

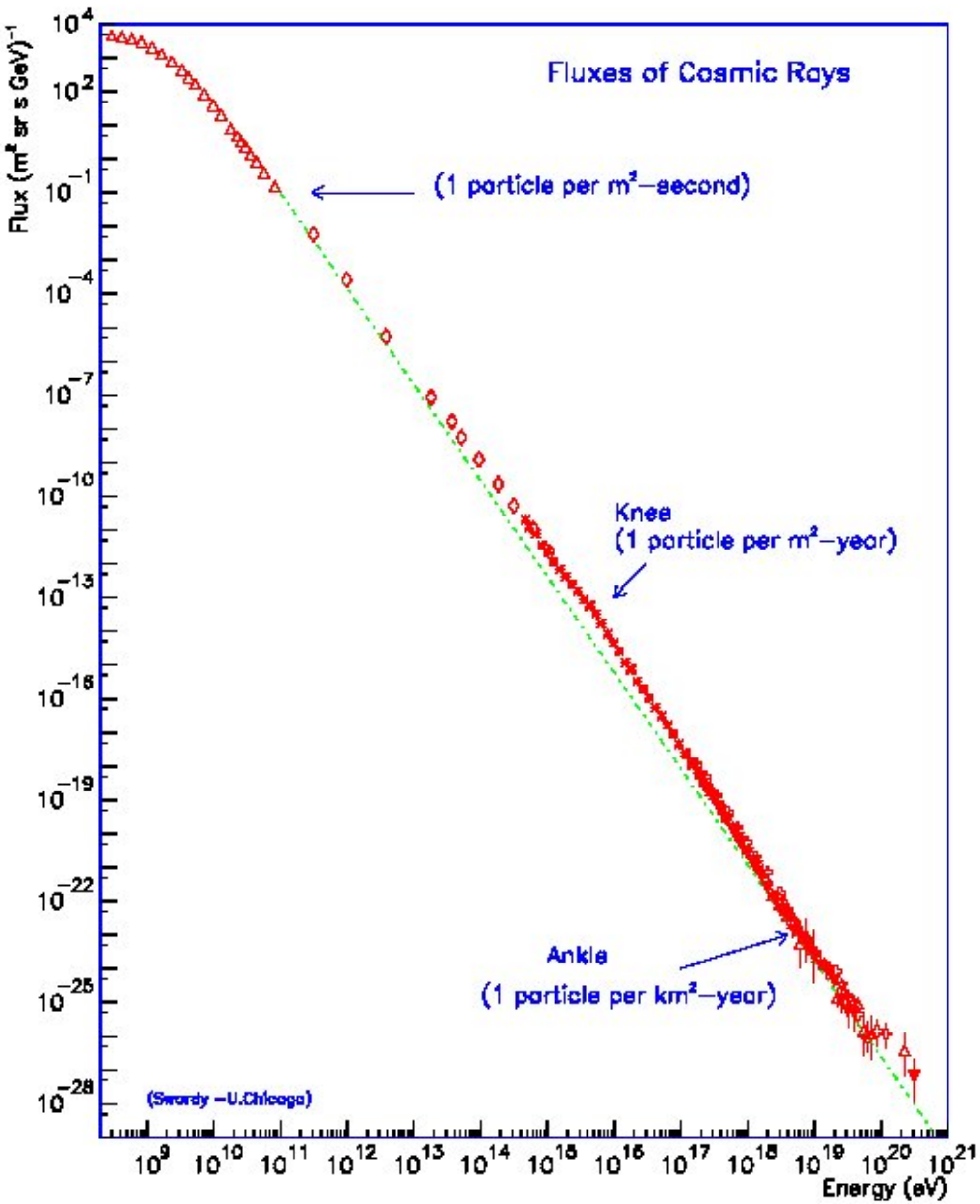
- *1929: Anderson discovered positron*
- *1932: Primaries of radiation got name “cosmic rays” under assumption that they are photons*
- *1934 It was proved that primaries are positively charged particles*
- *1936 Discovery of muon*
- *1938 Pierre Auger observed extensive air showers*
- *1947 Discovery of charge pions*
- *1947-50 Discovery of strange particles*
- *1952-54 Accelerator physics started*

Cosmic rays: historical remarks

- *1954 First measurement of extensive air showers by Harvard College Observatory*
- *1958 Discovery of CR knee in Moscow University (*Kulikov and Khristiansen)
- *1963 first showers with energies $E>10^{19}$ eV*
- *1965 CMB discovered*
- *1966 Greizen, Zatsepin and Kuzmin predict cutoff in the cosmic ray spectrum from interactions with CMB at $E\sim10^{20}$ eV*
- *1981-1993 Fly's Eye experiment prove fluorescent technique. First event with $E>10^{20}$ eV*

Cosmic rays: historical remarks

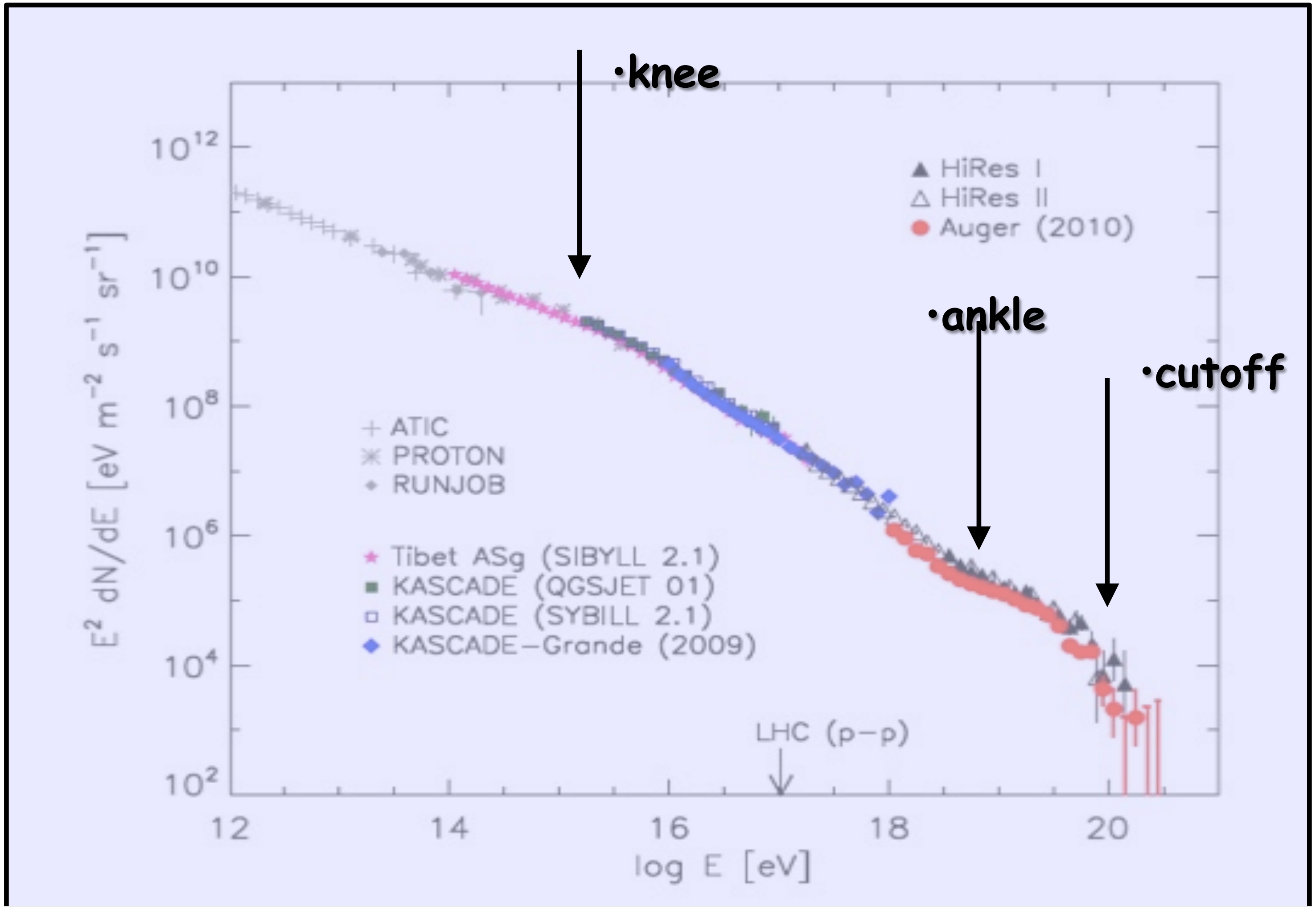
- *1994-1996 First measurements of cutoff region by AGASA experiment: no cutoff in spectrum: big theoretical effort beyond Standard Model (SHDM, LIV, etc.)*
- *2001 HiRes experiment see cutoff.*
- *2007 Construction of Pierre Auger Observatory finished. Precision measurements started and cutoff confirmed.*
- *Modern situation*


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)
10⁴
10²
10⁻¹
10⁻⁴
10⁻⁷
10⁻¹⁰
10⁻¹³
10⁻¹⁶
10⁻¹⁹
10⁻²²
10⁻²⁵
10⁻²⁸
10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰ 10²¹

•Supernova ?

•galactic iron ?

•Extragalactic sources



Direct measurements of Cosmic rays

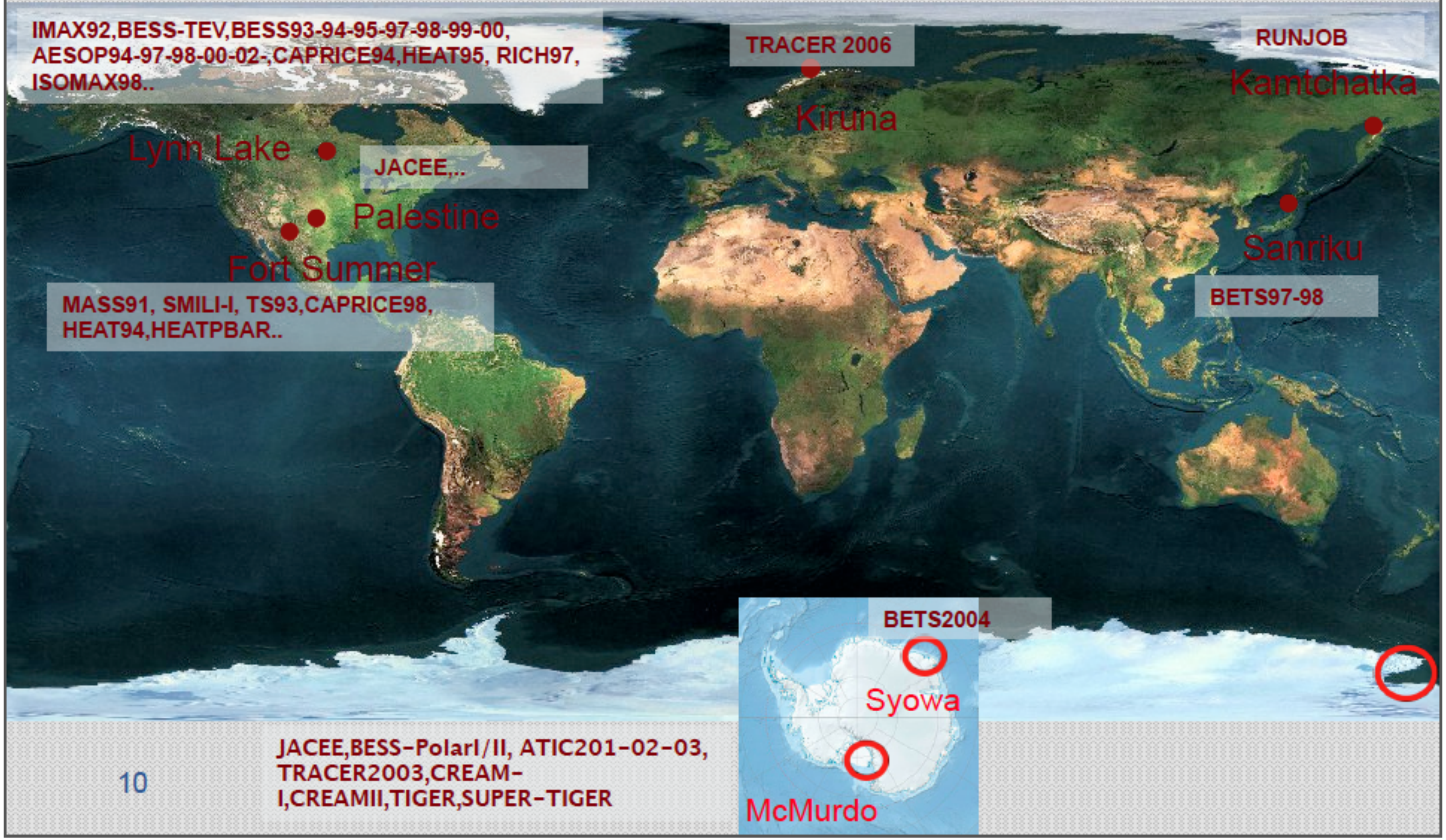
Stratospheric Balloons: from few hrs to months

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:

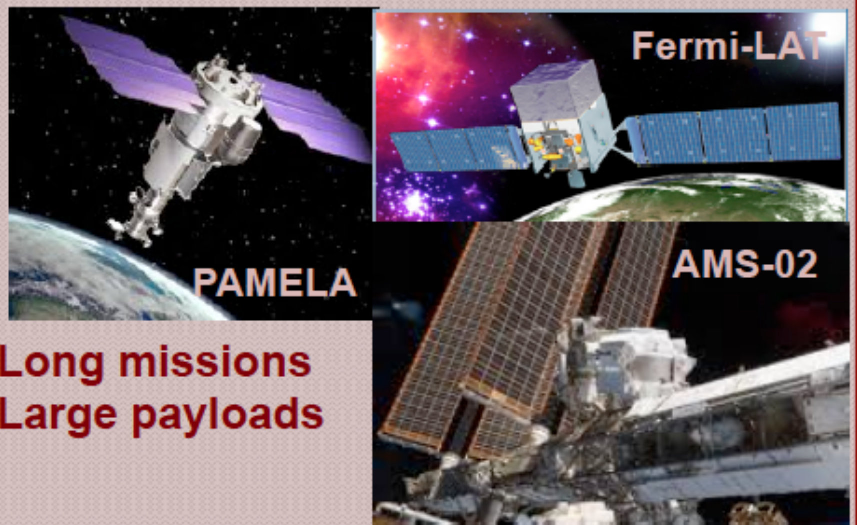
Long missions (years)
Small payloads
Low energies..

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

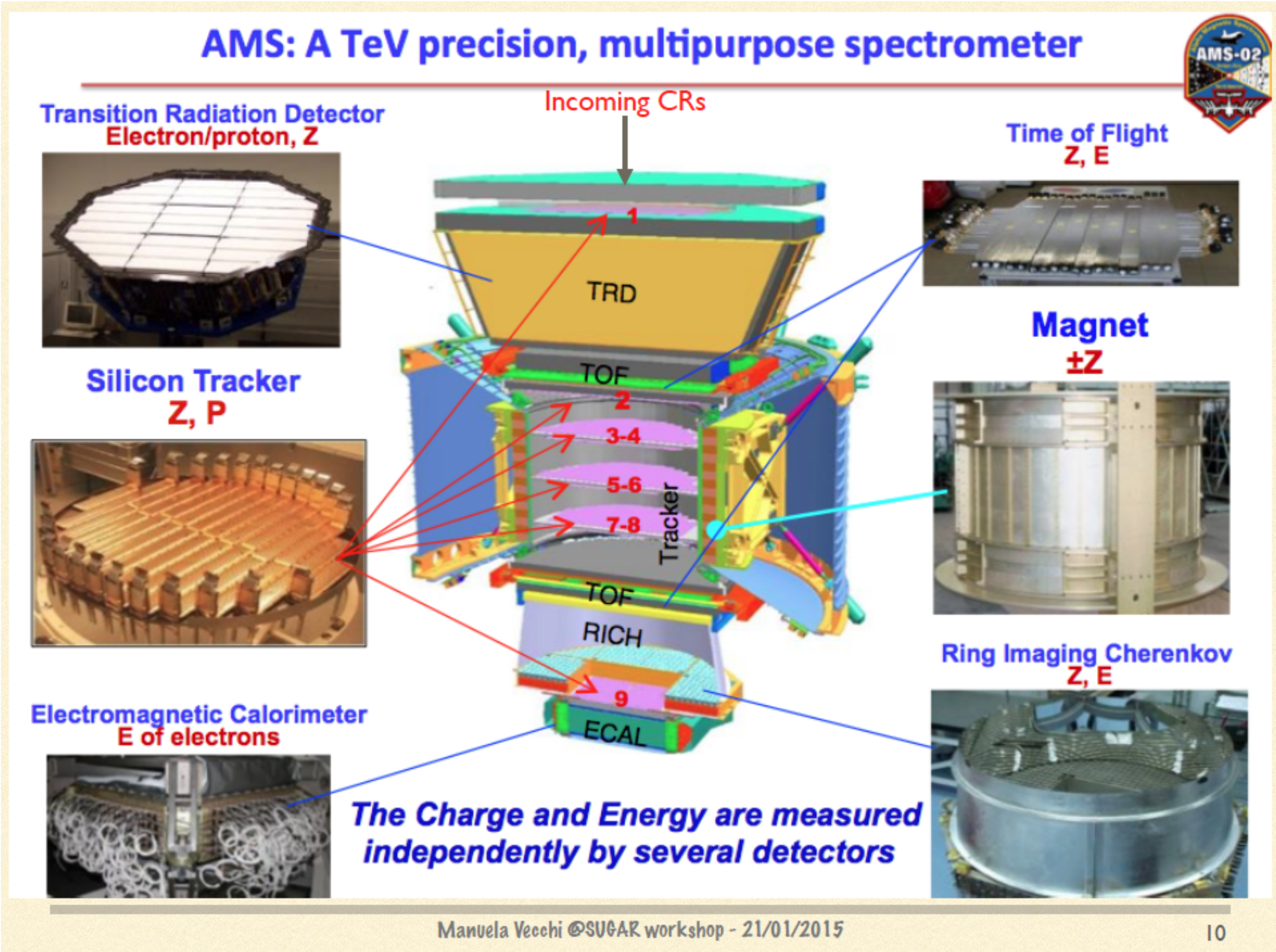
Short missions (days)/ Largerpayloads

CRN on Challenger
(3.5 days 1985)

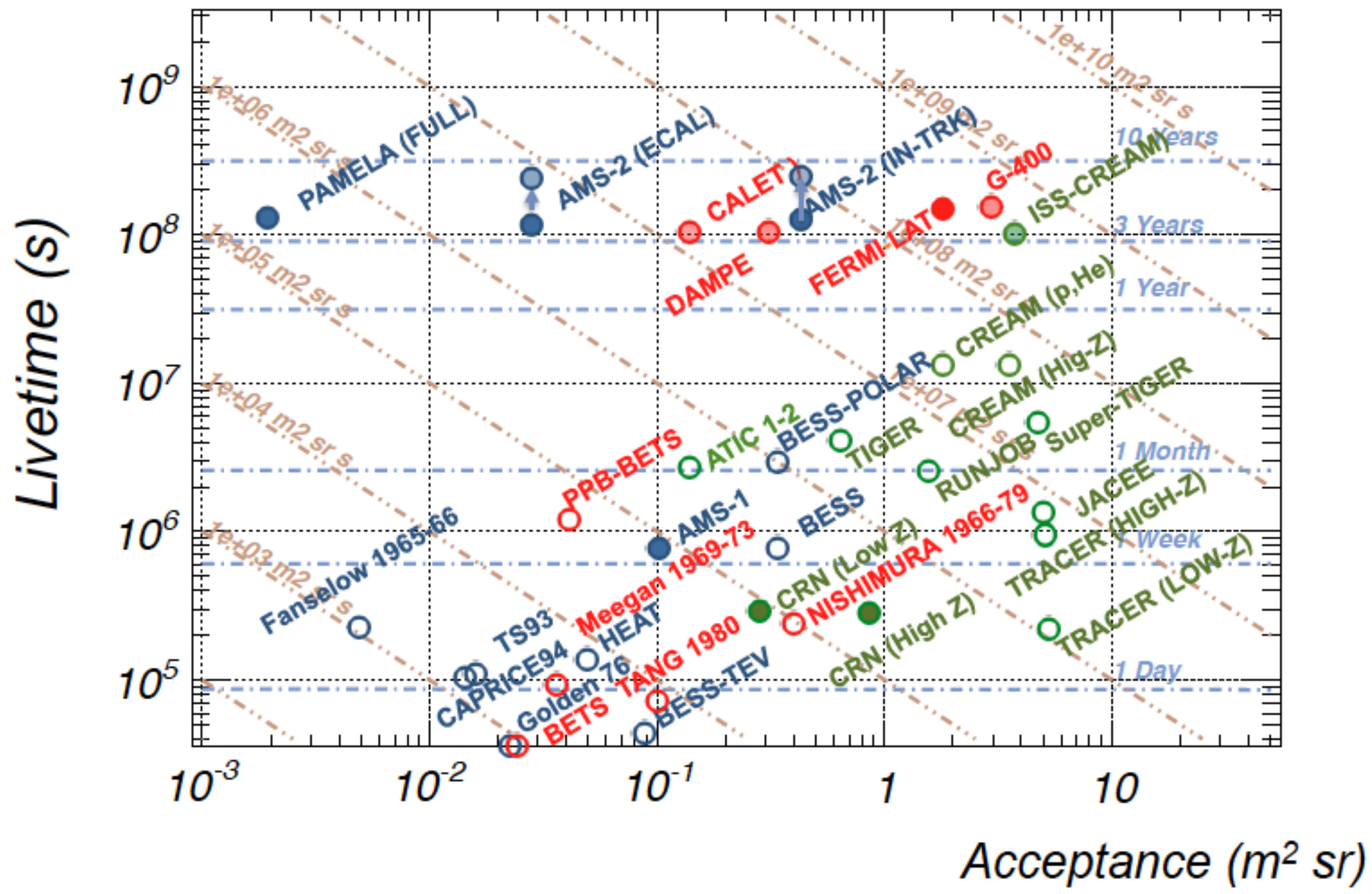
AMS-01 on Discovery
(8 days, 1998)



Long missions
Large payloads



AMS: A TeV precision, multipurpose spectrometer
AMS-02
Incoming CRs
Transition Radiation Detector
Electron/proton, Z
Time of Flight
Z, E
TRD
1
TOF
2
3-4
5-6
7-8
Tracker
TOF
RICH
9
ECAL
Silicon Tracker
Z, P
Magnet
±Z
Ring Imaging Cherenkov
Z, E
Electromagnetic Calorimeter
E of electrons
The Charge and Energy are measured
independently by several detectors
Manuela Vecchi @SUGAR workshop - 21/01/2015
10



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

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

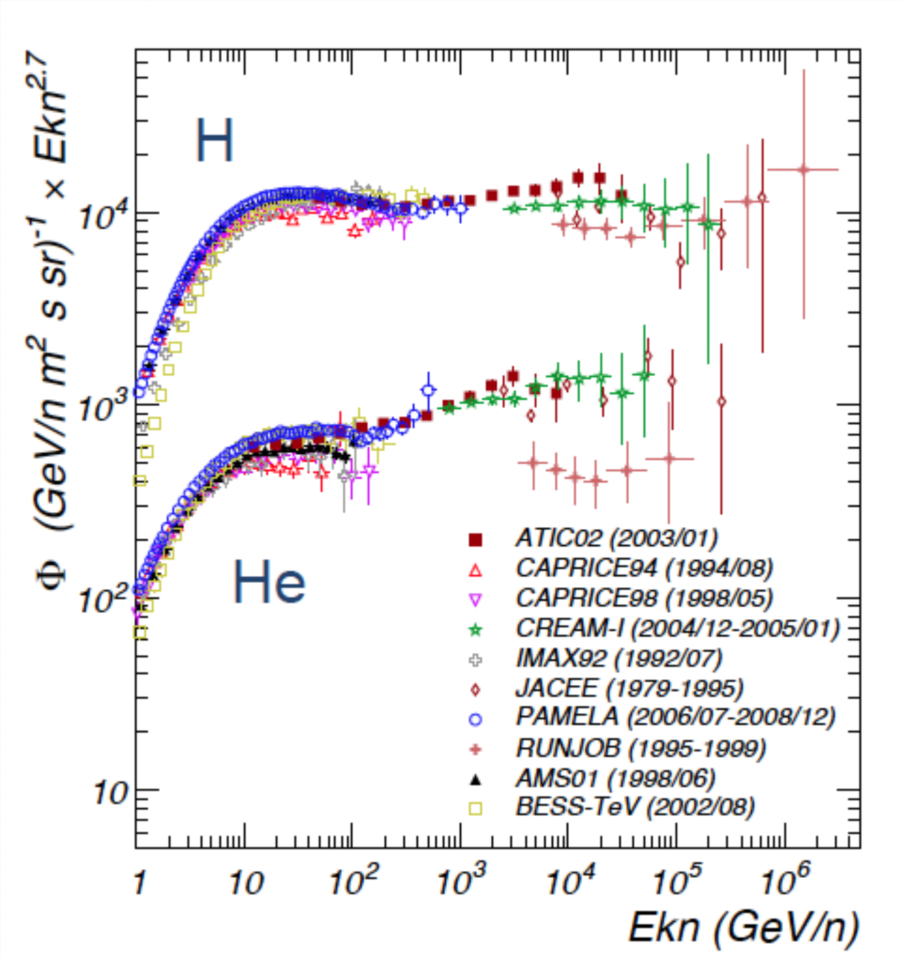
O Magnetic spectrometers

O Balloon

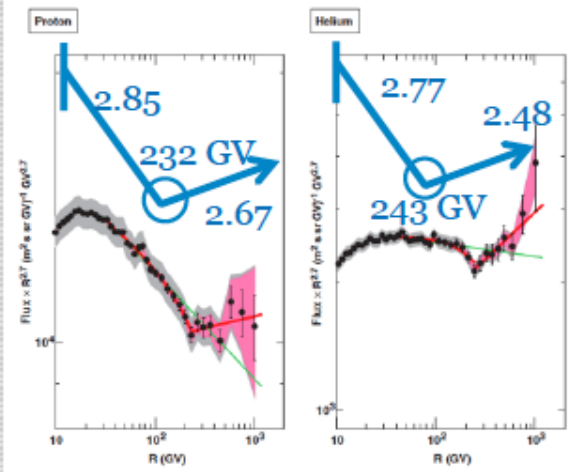
● Space

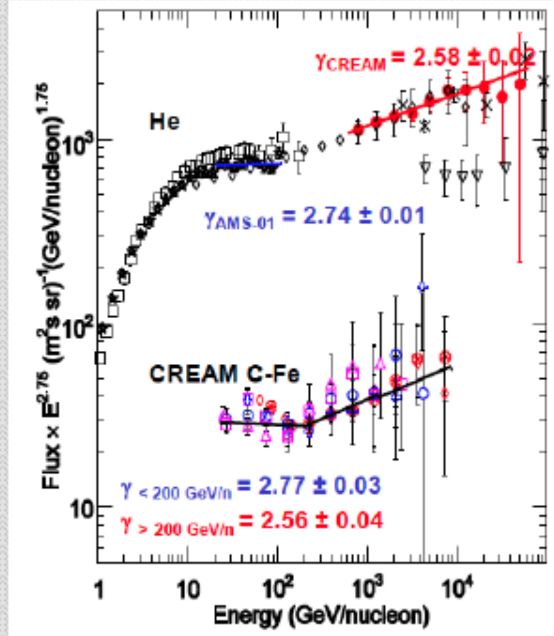
● Space (planned)

p/He spectra



Adriani, Science 32,69 (2011)

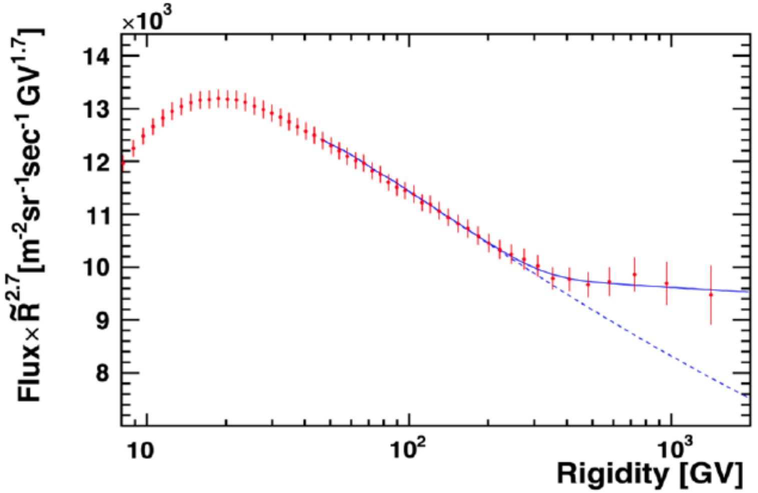




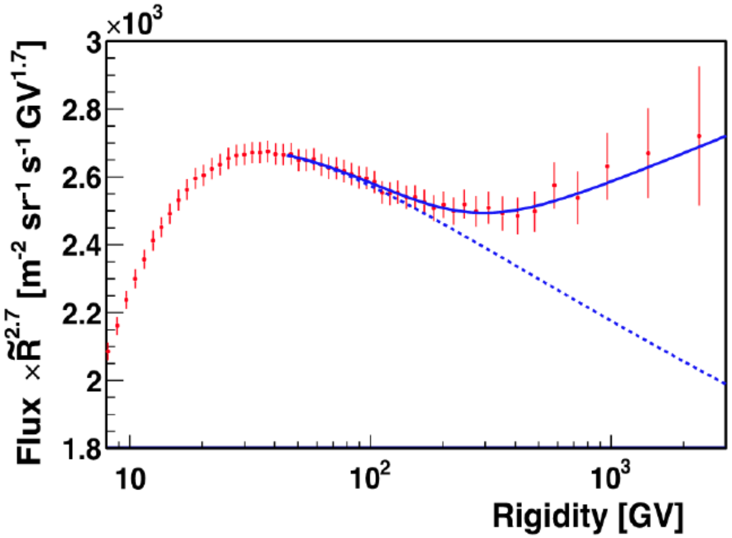
Still waiting for full CREAM statistics
AMS-02 publication soon….(< 2015)

AMS-2 results P 2.85 ->2.7 He 2.85-> 2.6

AMS-2 protons



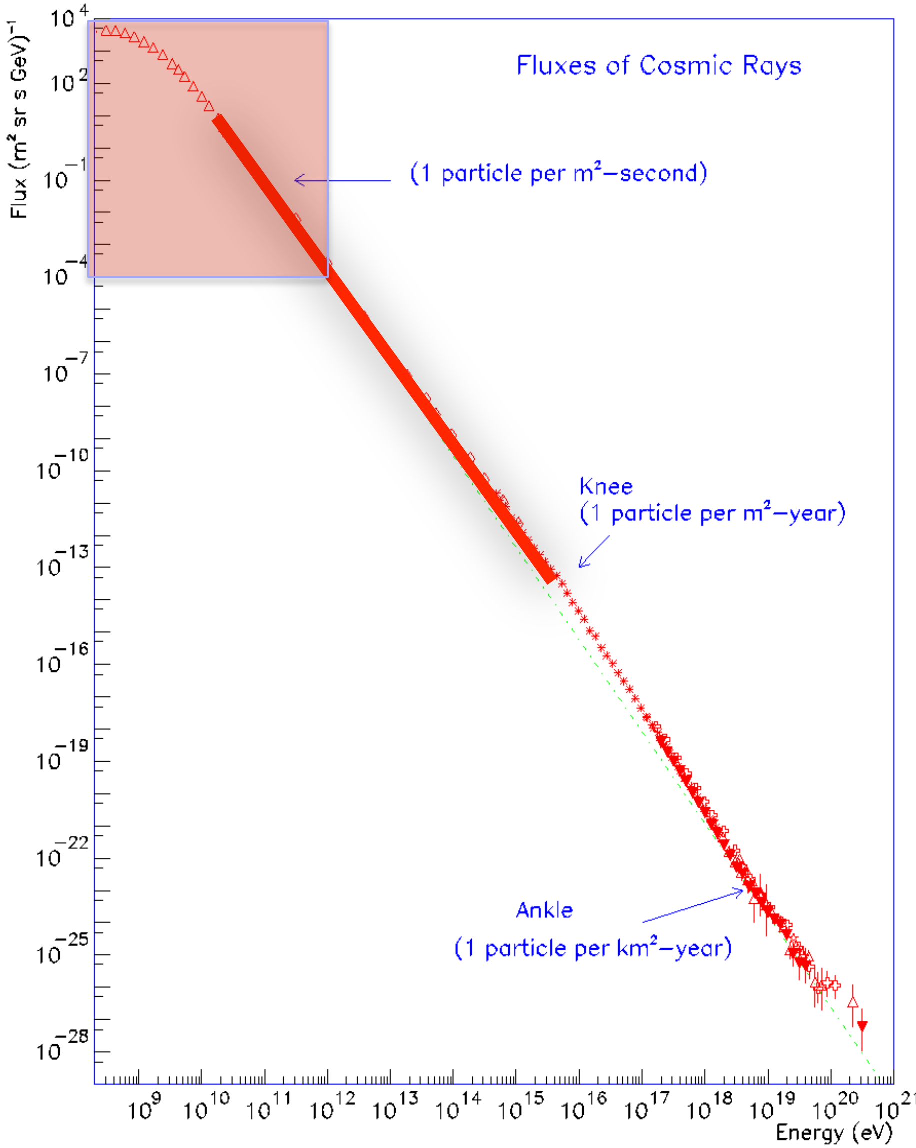
AMS-2 He



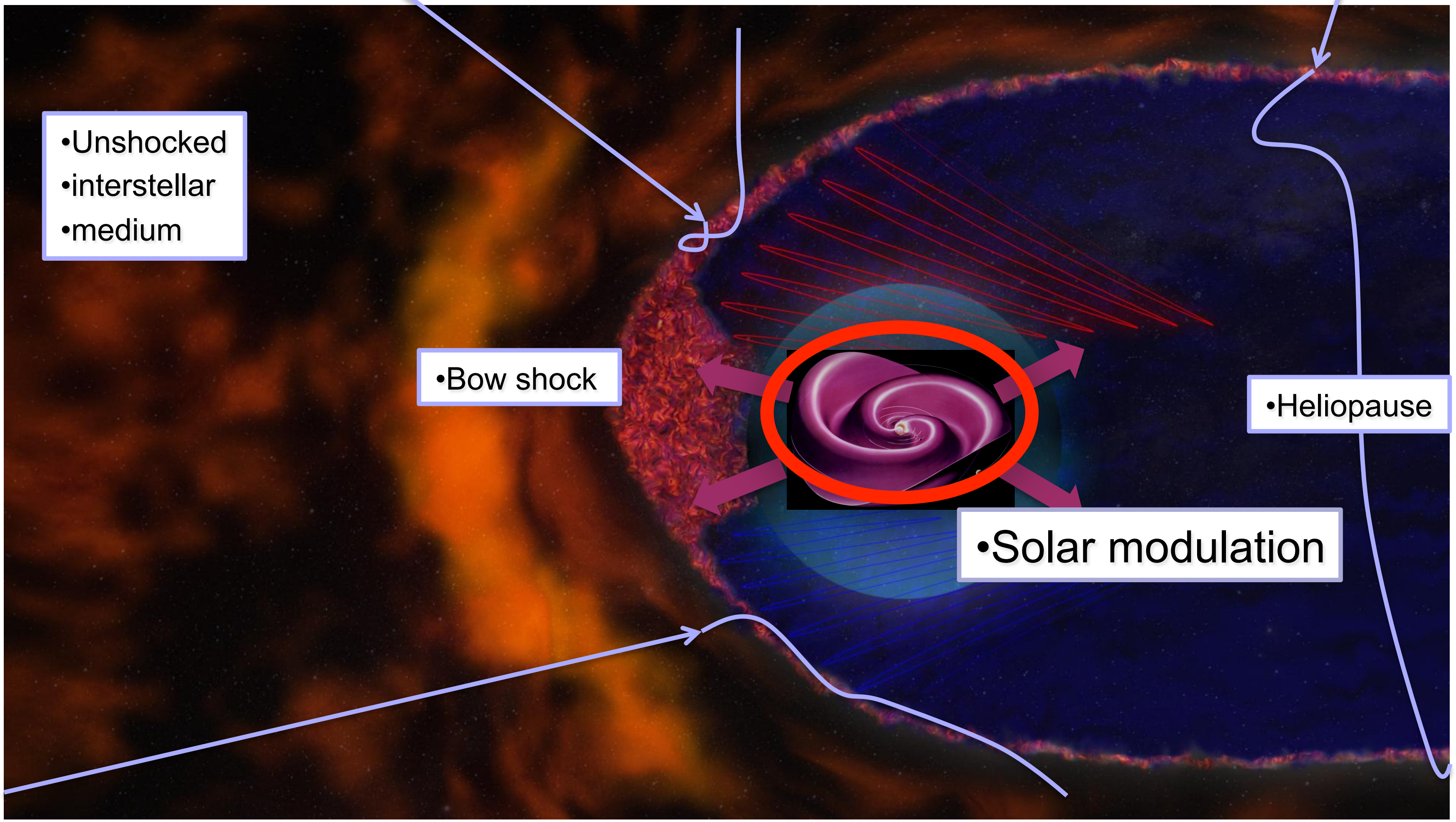
- CR flux at the energies <100 GeV is affected by the interplanetary magnetic field and depends on the solar activity

$$R_L = \frac{E_{CR}}{ZeB} \approx 2\left[\frac{E_{CR}}{10^{11}\,\mathrm{eV}}\right]\left[\frac{B_{IPM}}{10^{-5}\ \mathrm{G}}\right]^{-1}\ \mathrm{AU}$$

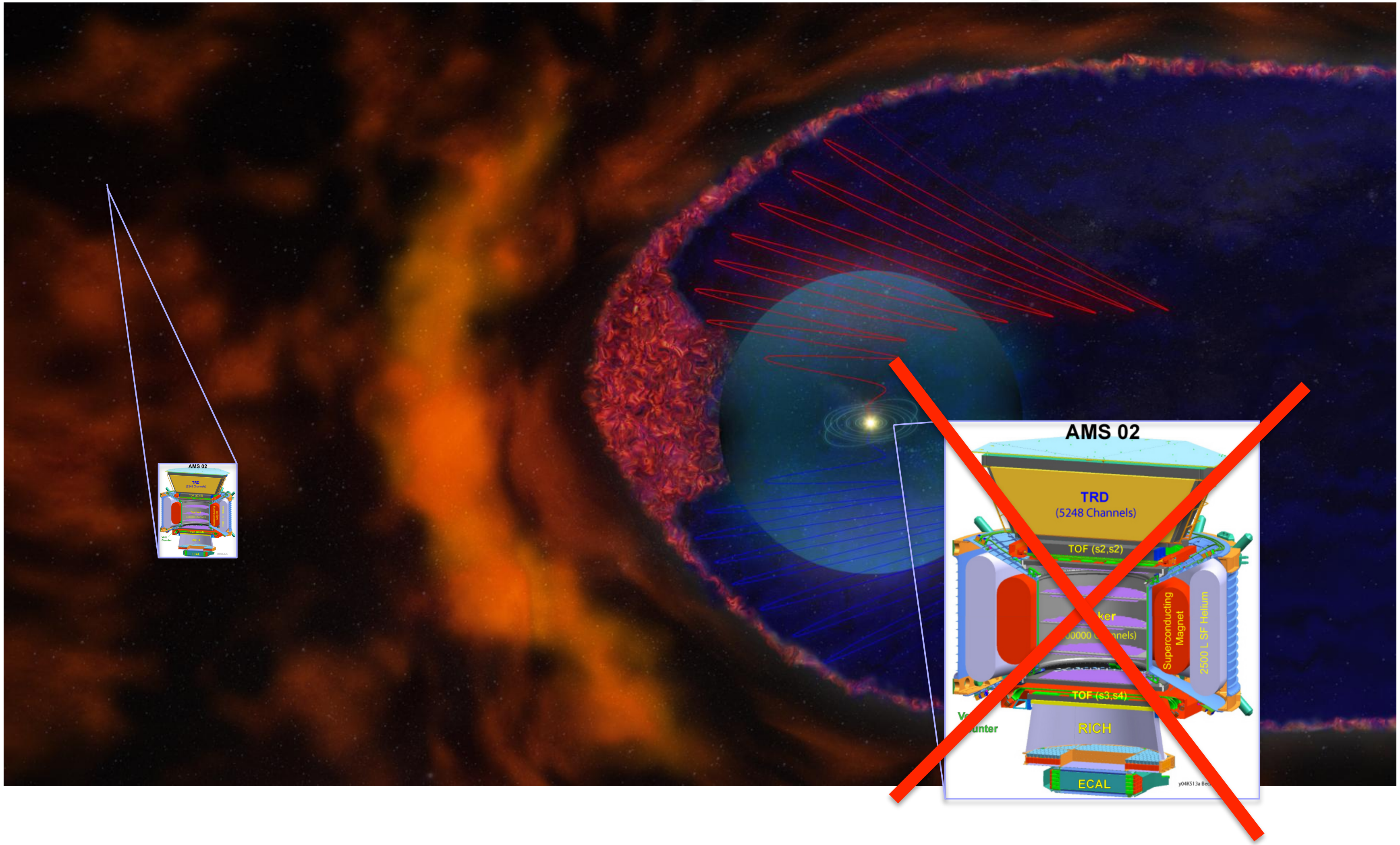
- At the lowest energies (<10 GeV) Solar modulation is observed



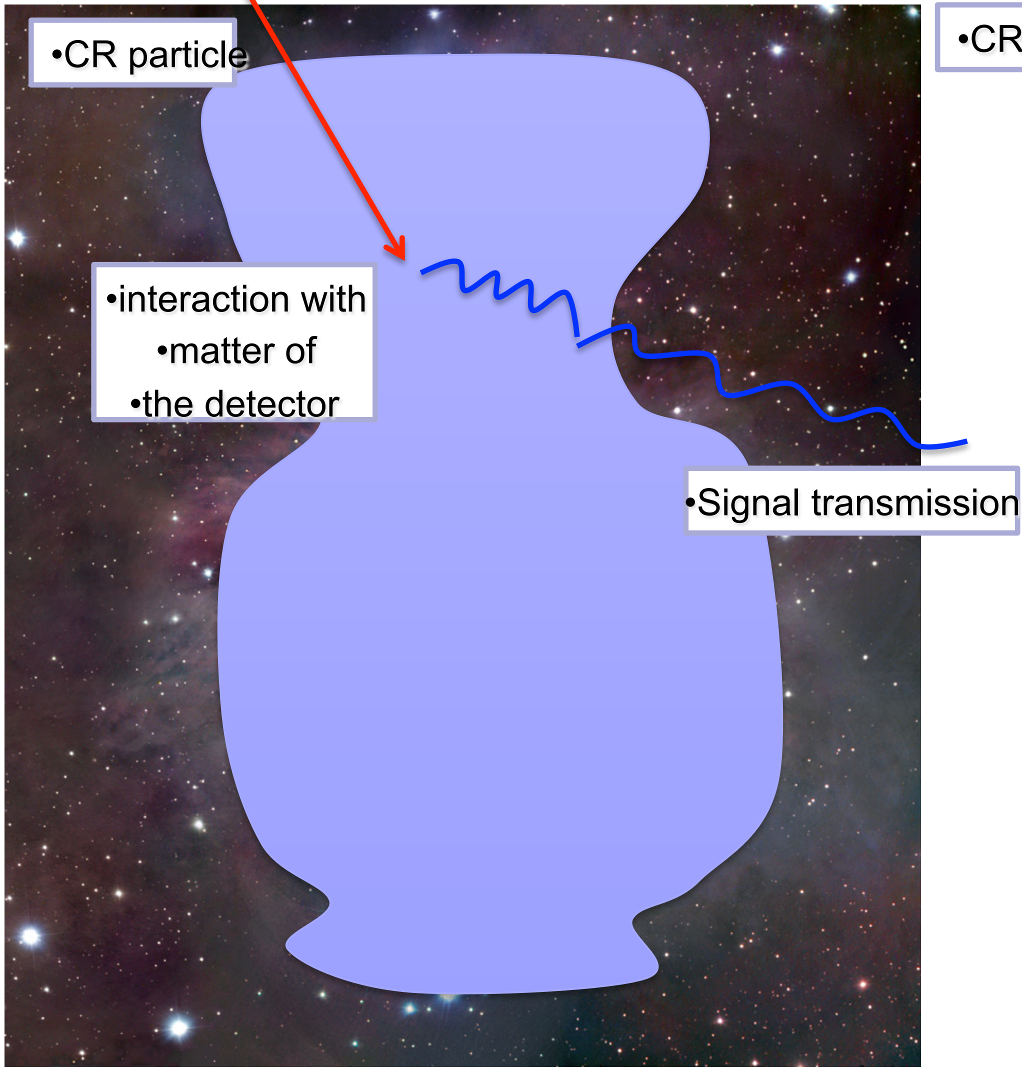
•Cosmic Rays in the Solar system

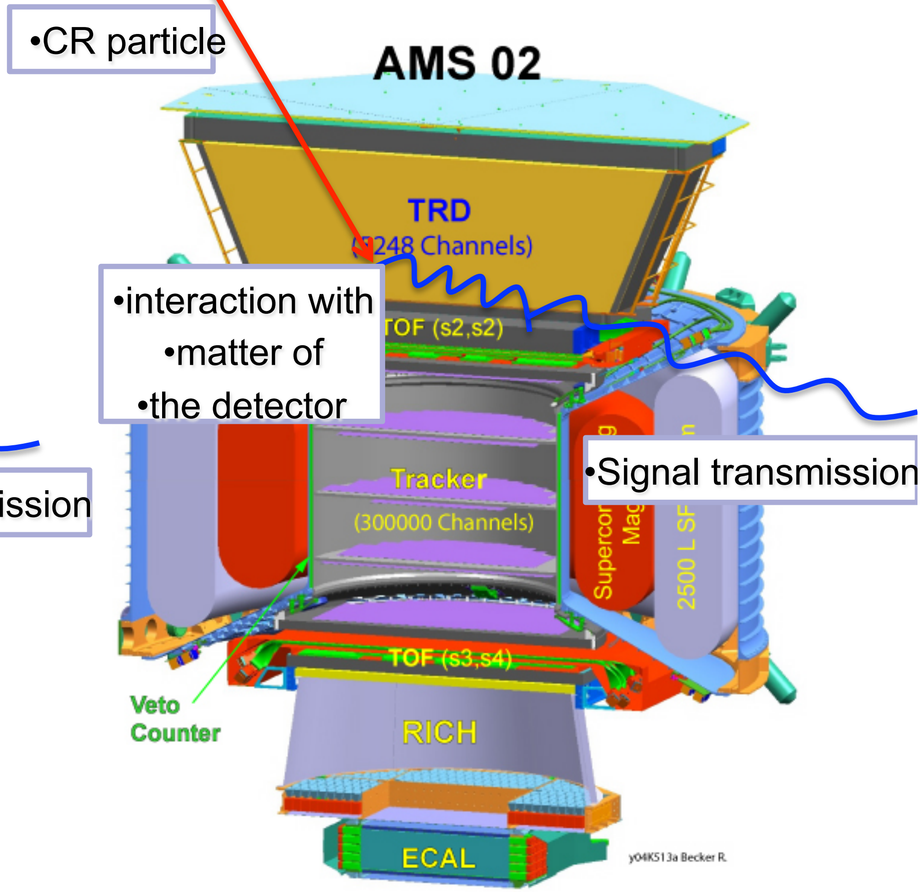


•Measurement of CR spectrum unaffected by the Heliosphere



•CR detectors outside the Heliosphere





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

•CR detectors outside the Heliosphere

F.Aharonian book

•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}.

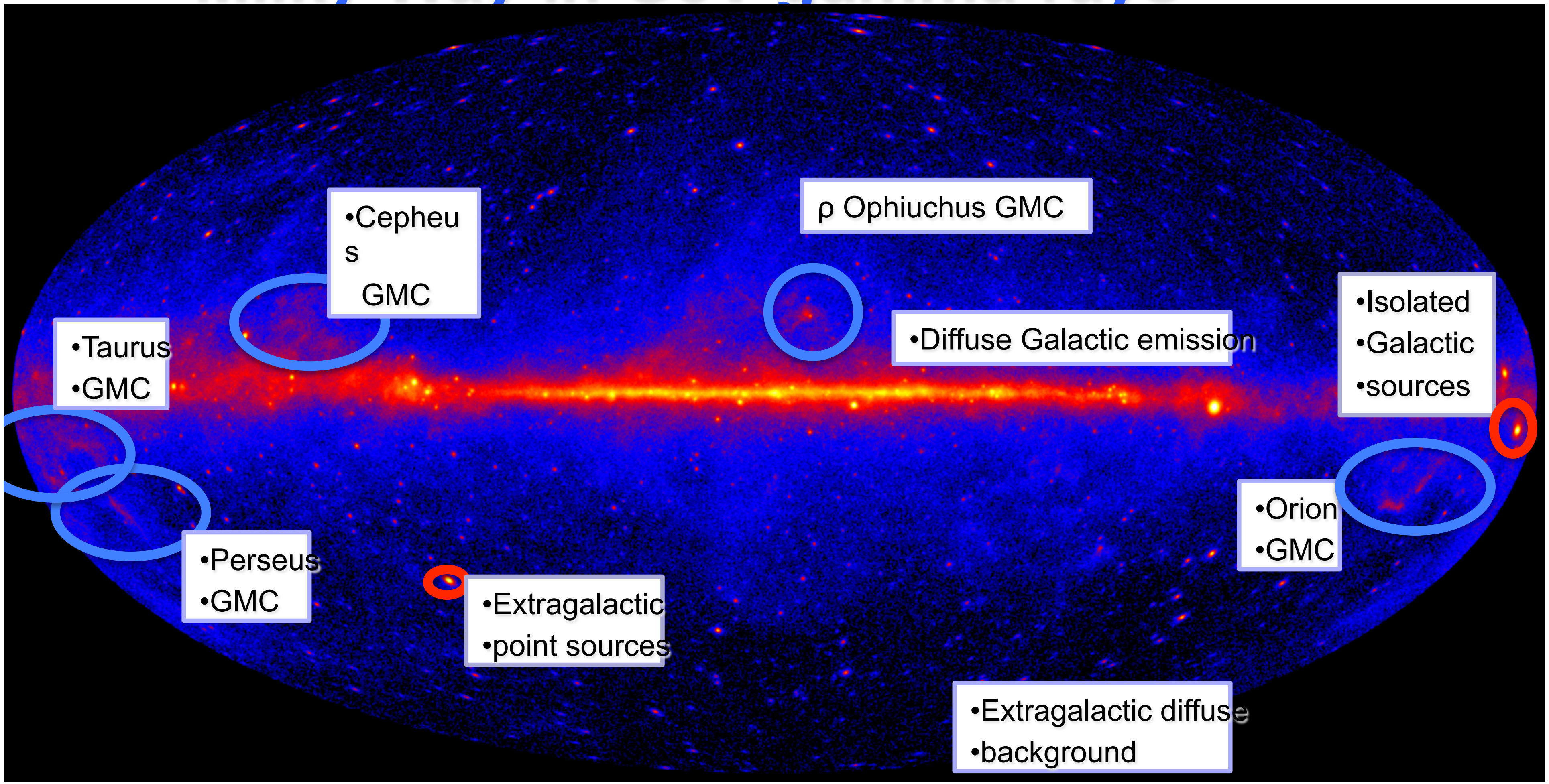
•CRs diffusing through the ISM cross the GMCs on the time scales of $t \sim 10^3 - 10^4$ yr.

•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).

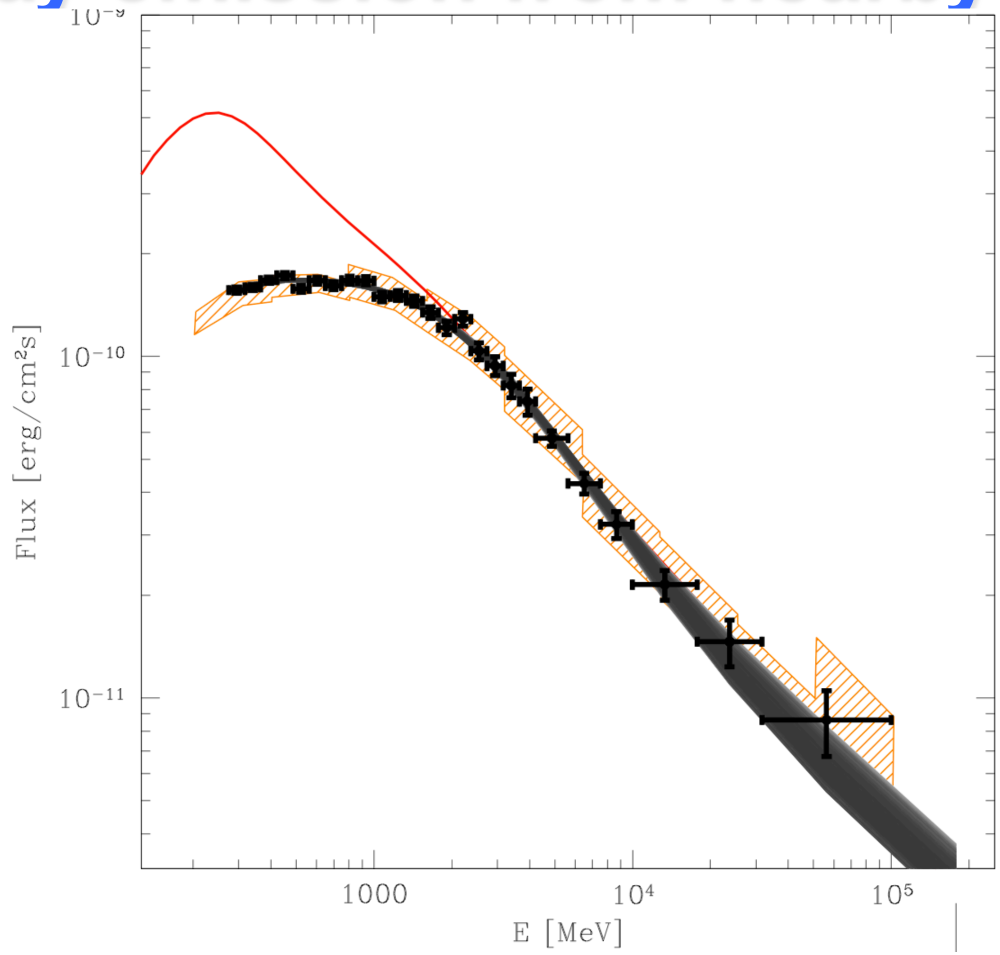
•Large mass concentrations in the ISM could be used as "natural" CR detectors. Such mass concentrations are e.g. nearby Giant Molecular Clouds (GMC).

Milky Way in GeV gamma-rays



•Nearby GMCs are rather strong gamma-ray sources, first detected by CosB, later by EGRET and most recently by Fermi/LAT.

•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

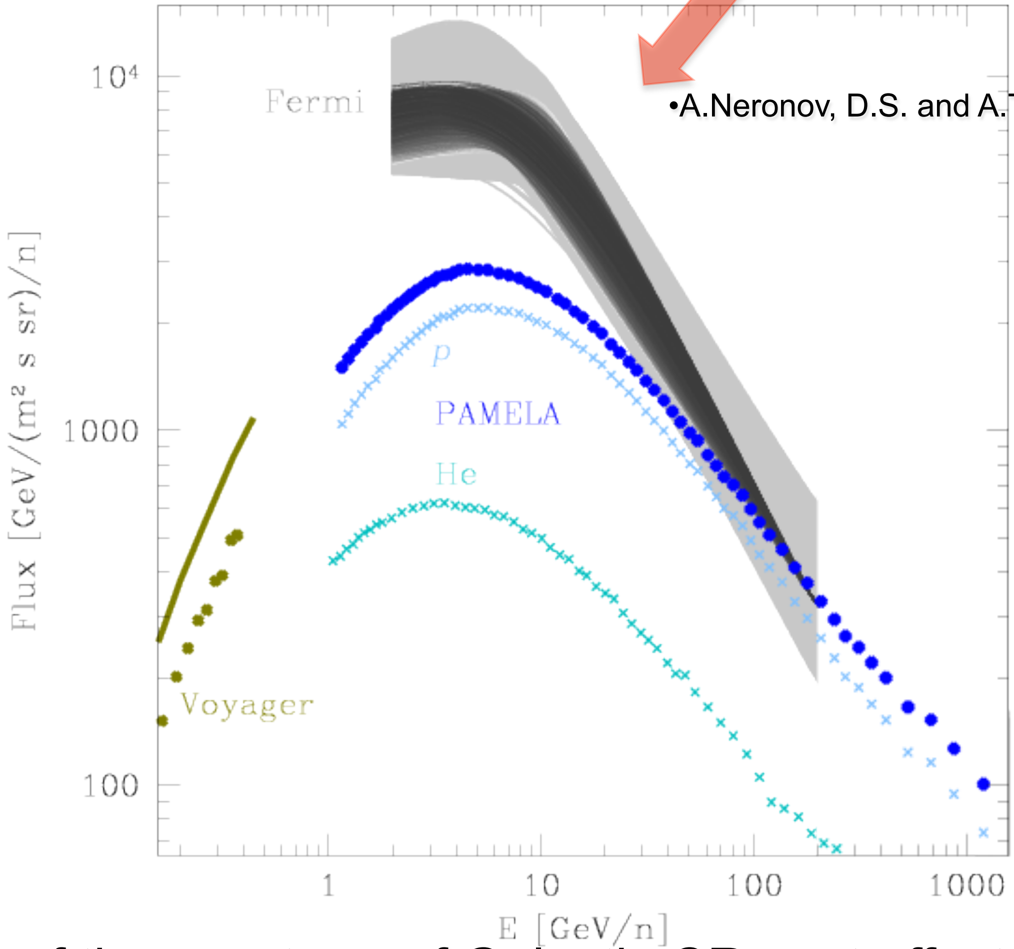
$$dN_{\rm CR}/dE = N_0\, E^{-\tilde{\beta}_{\rm CR}}$$

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

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

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.

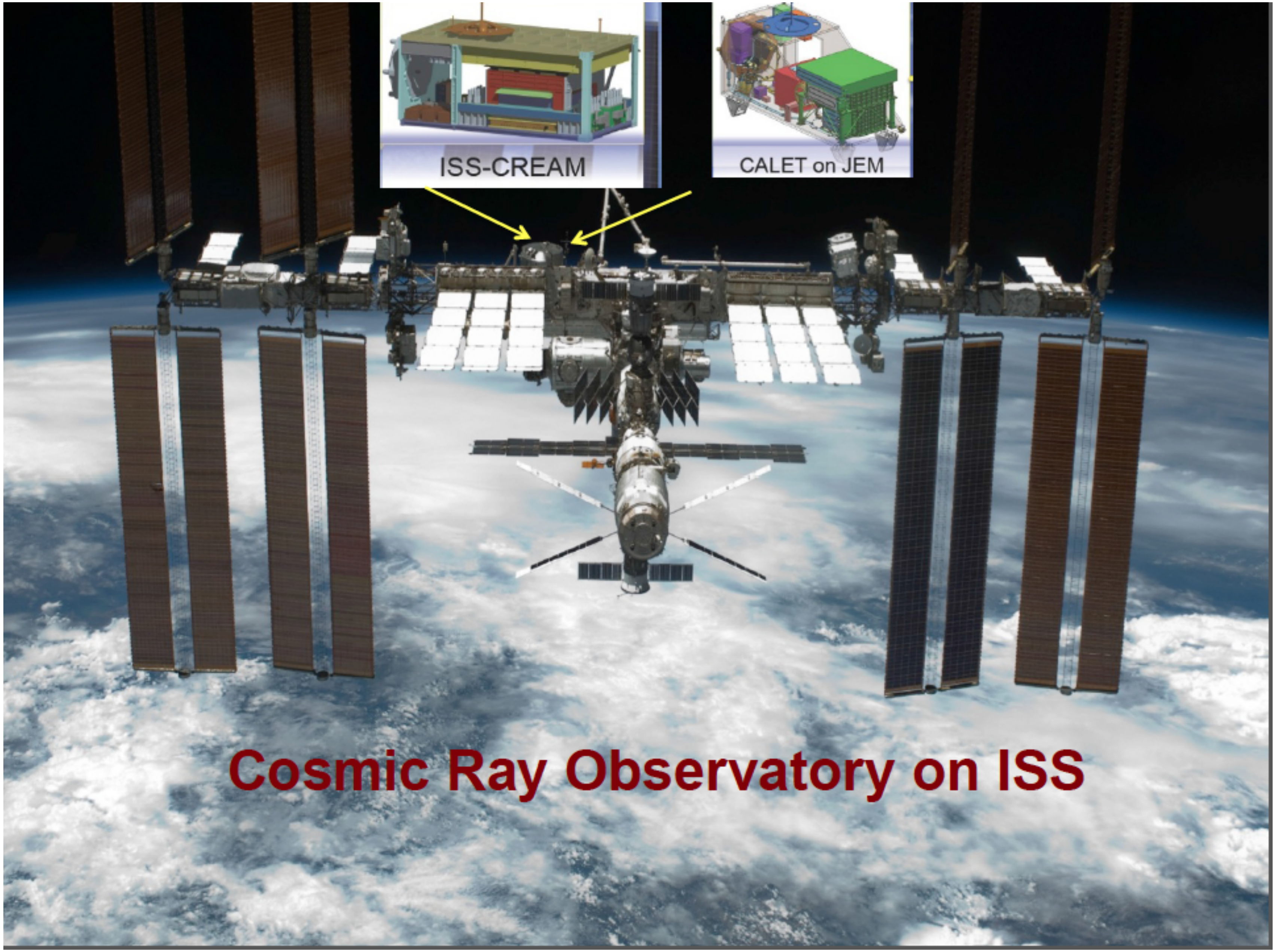
•Galactic cosmic ray spectrum

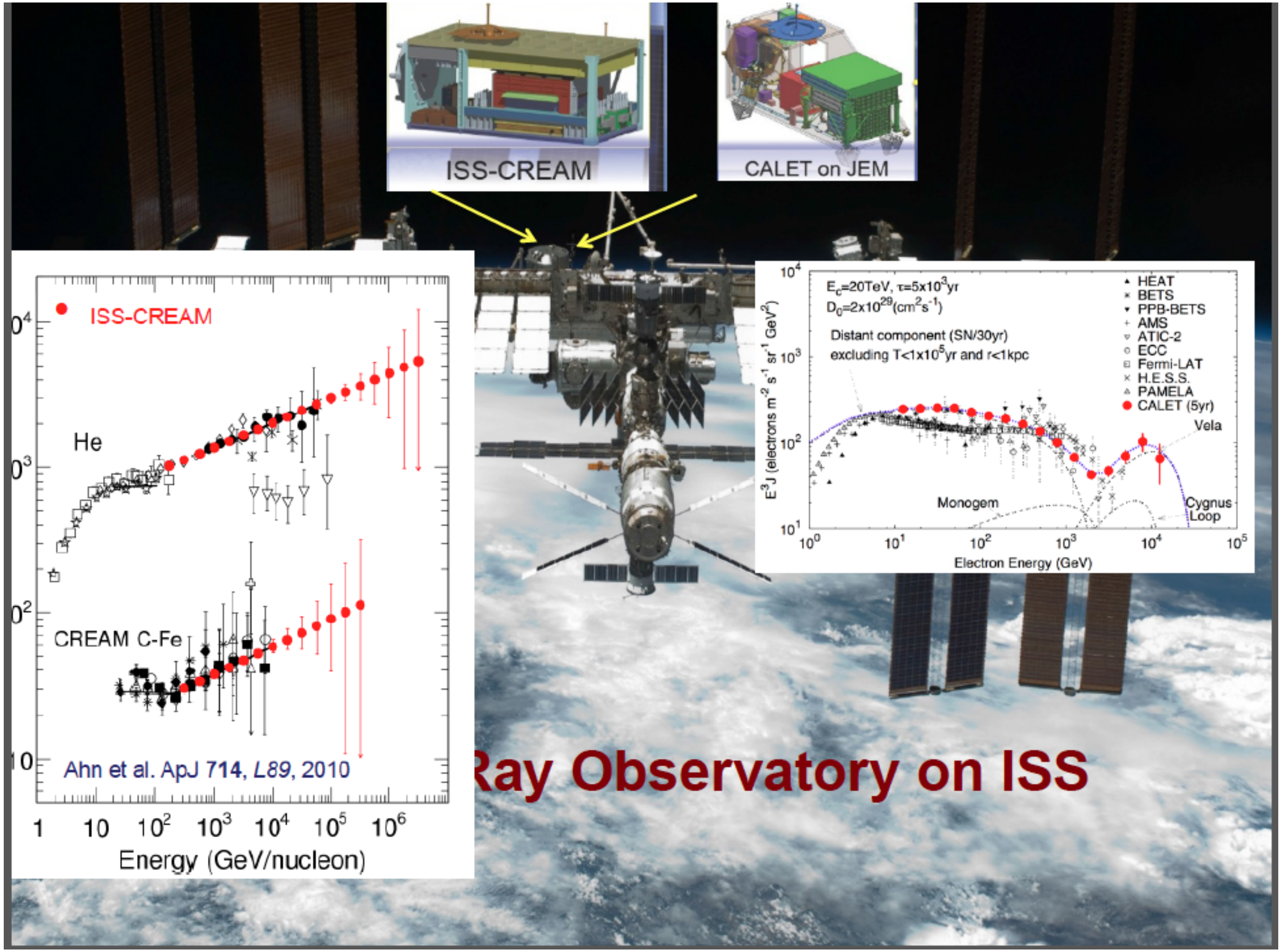


•A.Neronov, D.S. and A.Taylor, PRL, 108, 051105 (2012)

•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.


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
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)

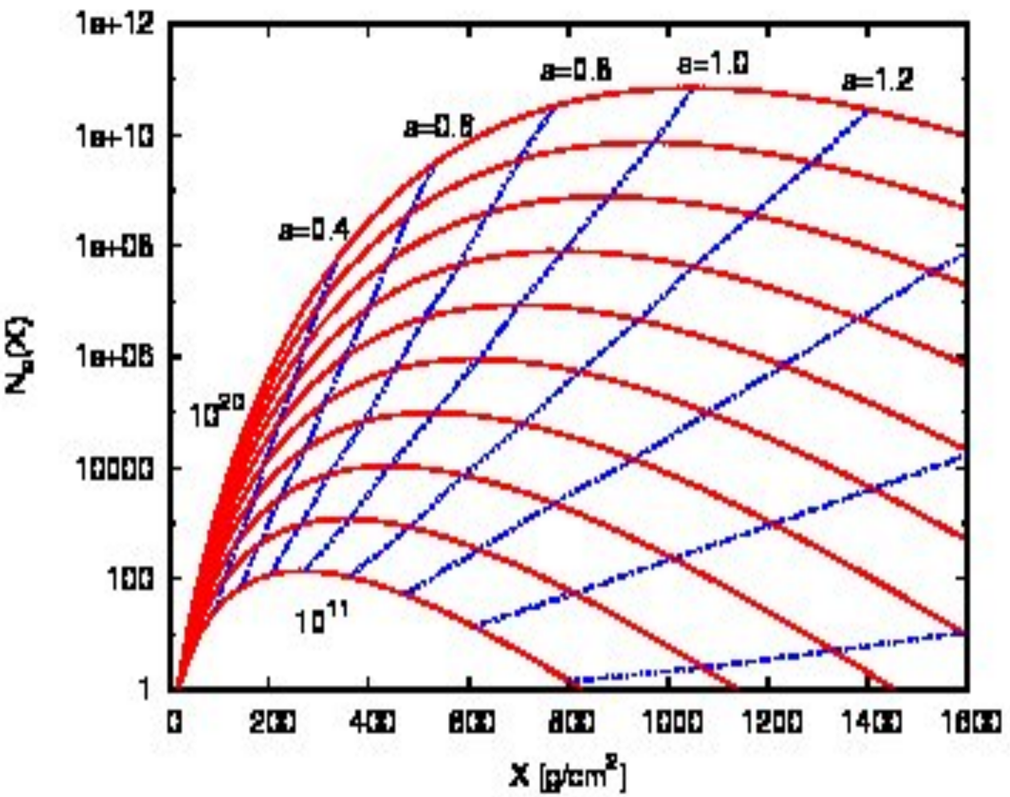
Direct detection of cosmic rays

- *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 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 measurements of Cosmic rays

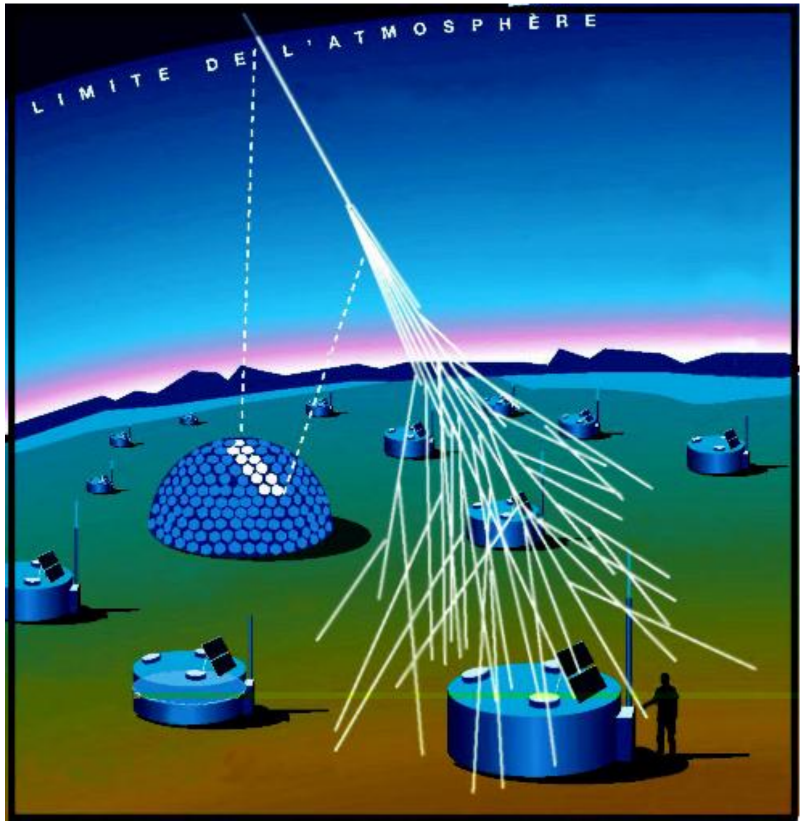
UHECR measurement

- Depth of atmosphere is 1000 g/cm^2
- Proton of 10^{20} eV energy interact within 60-80 g/cm^2. Center mass energy is 300 TeV: much larger then LHC!
- Shower develops with final number 10^{10-11} of low energy particles.



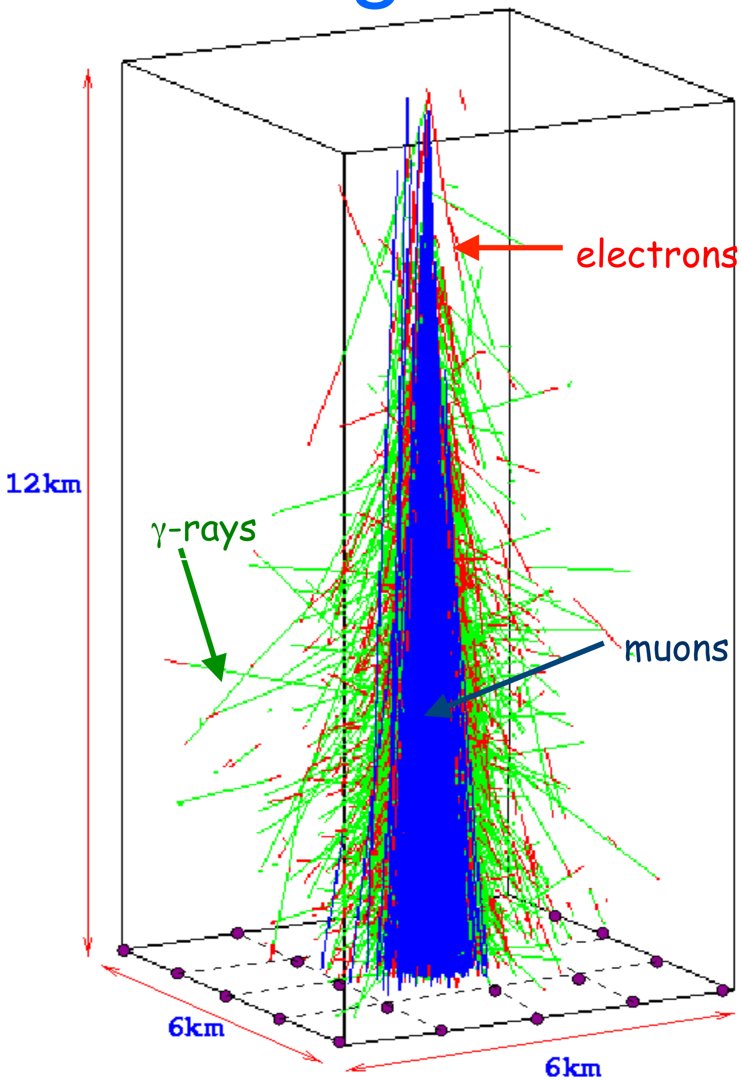
Parameters to measure:

- Energy of primary particle
- Arrival direction.
- Type of primary particle (proton, nuclei, photon, neutrino, new particle)
- Properties of primary particle: total cross section.



Detection of showers on ground

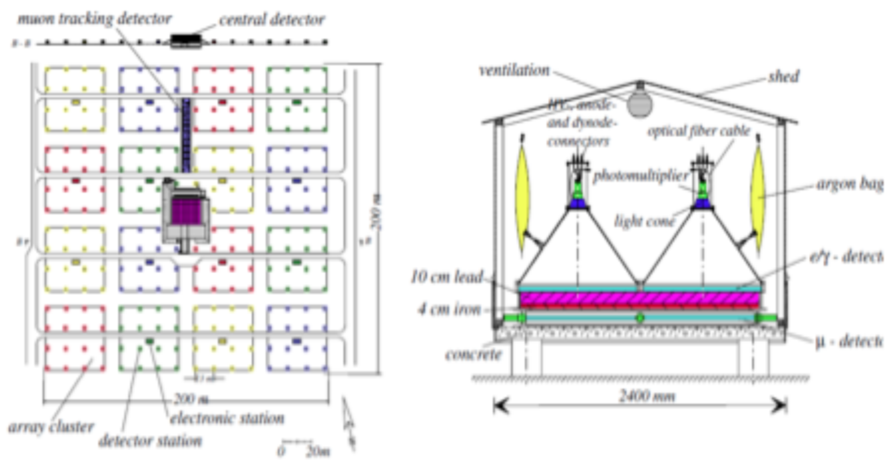
- Ground array measure footstep of the shower. Final particles at ground level are gamma-rays, electrons, positrons and muons.
- Typically 10^{10-11} photons, electrons and positrons in area 20-50 km^2. It is enough to have detectors with area of few m^2 per km^2. Number of low energy particles is connected to primary energy.
- Space/time structure of signal give information on arrival direction.
- Number of muons compared to number of electrons give information on primary particle kind.



KASCADE experiment

40000 m^2 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).



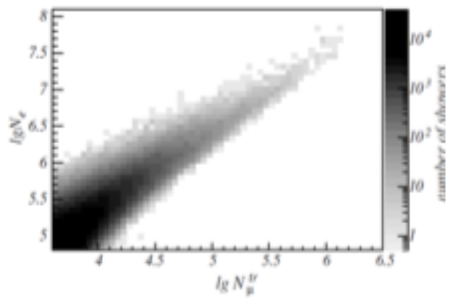


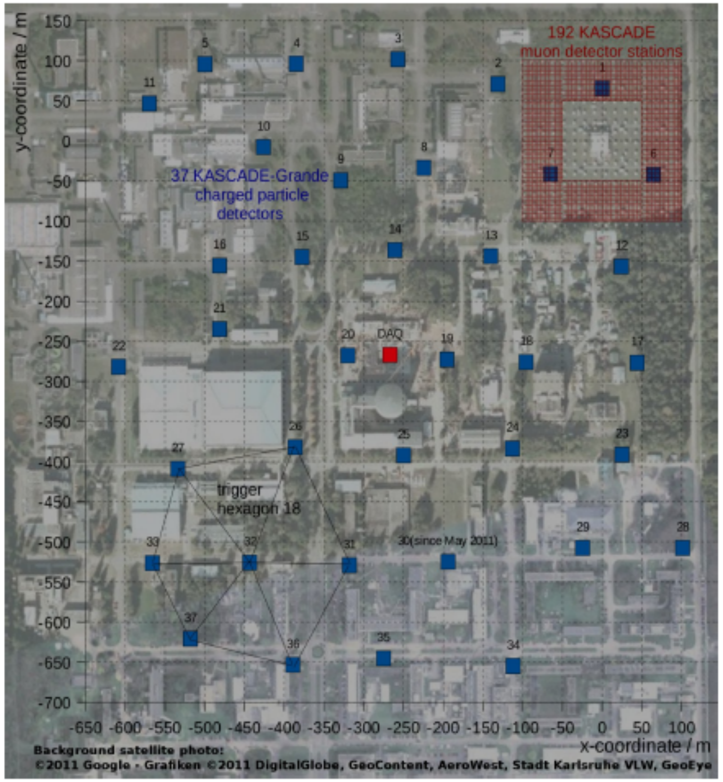
Fig. 2. Two-dimensional shower size spectrum used in th analysis. The range in lg N_e and lg N_μ^{tr} is chosen to avoi influences of inefficiencies.

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

Operated before 2000

KASCADE-Grande

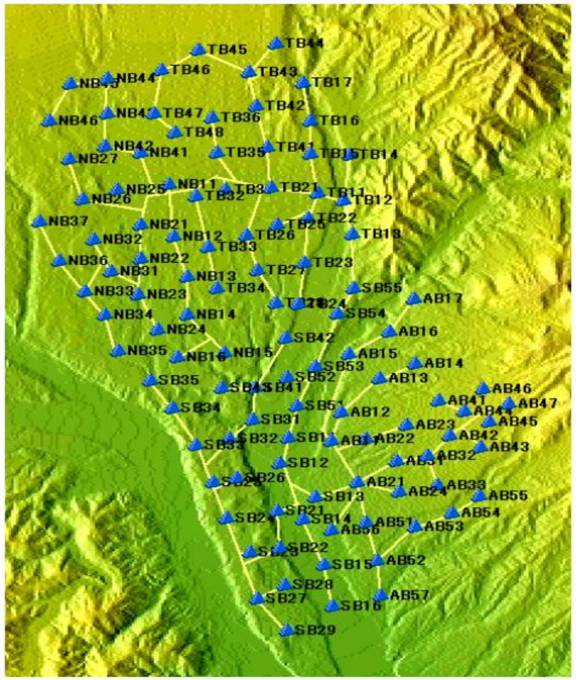
- KASCADE-Grande covered an area of about 1 km^2 and studied energy range 10^{16} eV-10^{18} eV
- Operated 2003- 2013.



AGASA

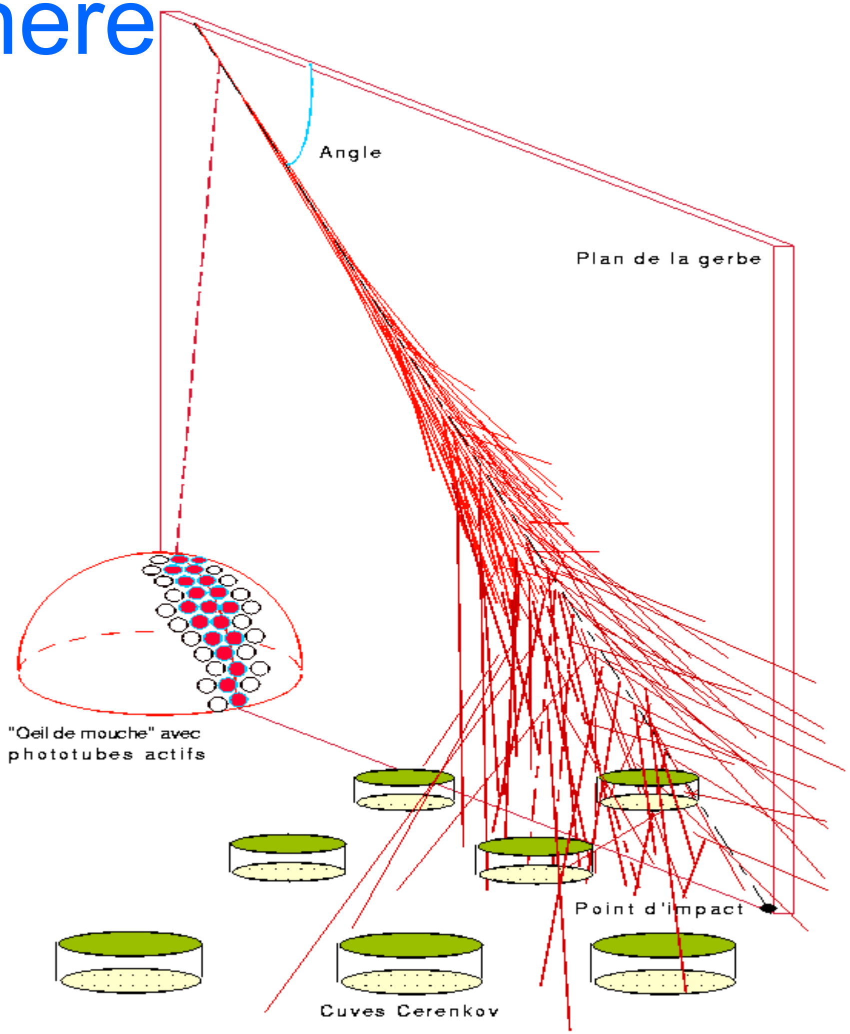
- AGASA covers an area of about 100 km^2 and consists of 111 detectors on the ground (surface detectors) and 27 detectors under absorbers (muon detectors). Each surface detector is placed with a nearest-neighbor separation of about 1 km.
- Operated 1993- 2003.

Akeno Giant Air Shower Array

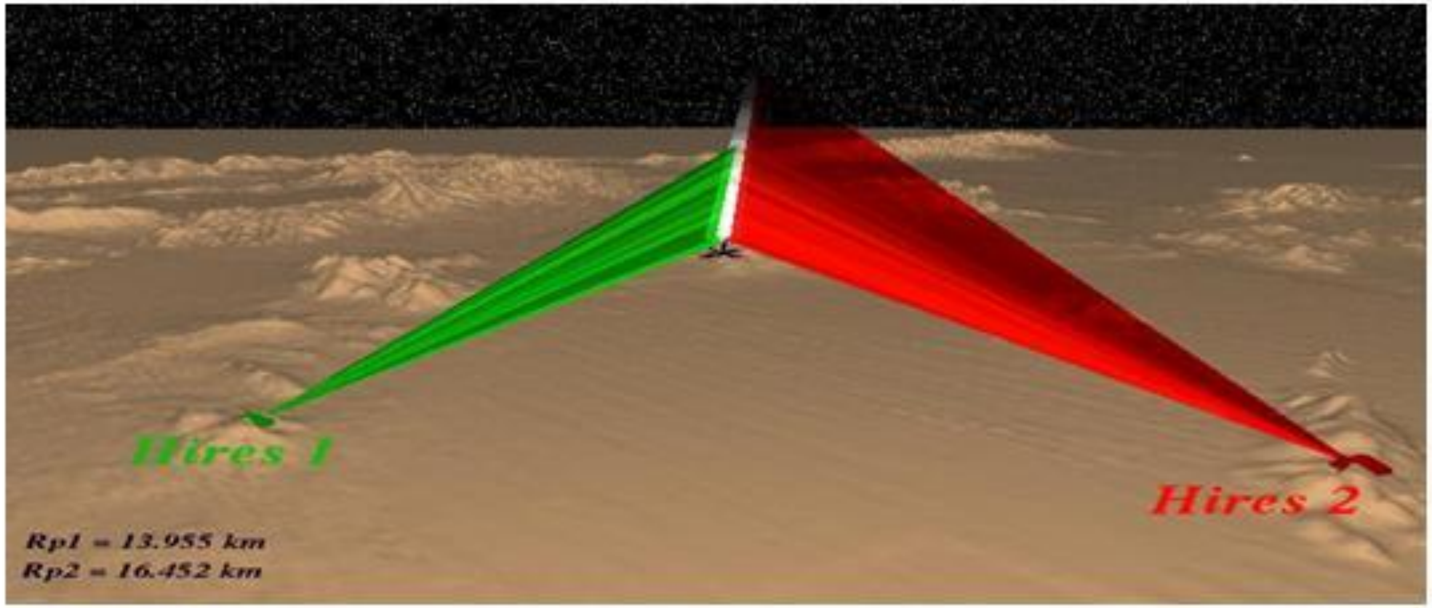


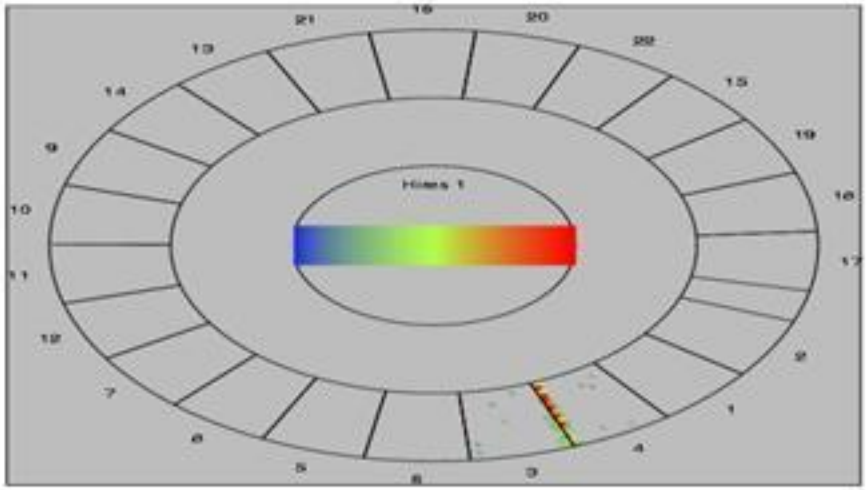
Detection of shower development in atmosphere

- Fly's Eye technique mesure fluorescence emision of N_2 by collection of mirrors: shape of the shower.
- Total amount of light connected to energy of primary particle.
- Time structure of signal gives information on arrival direction.
- Depth in atmosphere with maximum signal give information on primary particle kind.

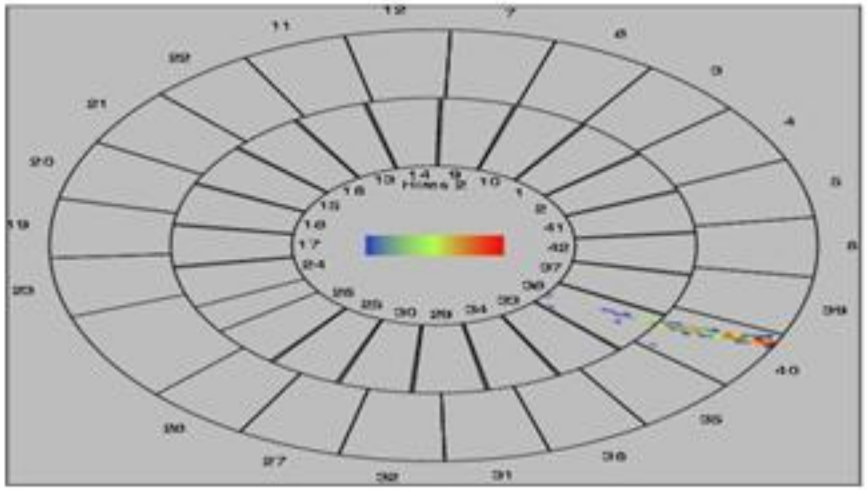


Stereo Event E ~50 EeV





HiRes1



HiRes2

High Resolution Fly’s Eye: HiRes

- HiRes 1 and HiRes 2 sit on two small mountains in western Utah, with a separation of 13 km.
- HiRes 1 has 21 three meter diameter mirrors which are arranged to view the sky between elevations of 3 and 16 degrees over the full azimuth range;
- HiRes 2 has 42 mirrors which image the sky between elevations of 3 and 30 degrees over 360 degrees of azimuth.
- Operated in stereo mode 1999-2006.

Auger Observatory

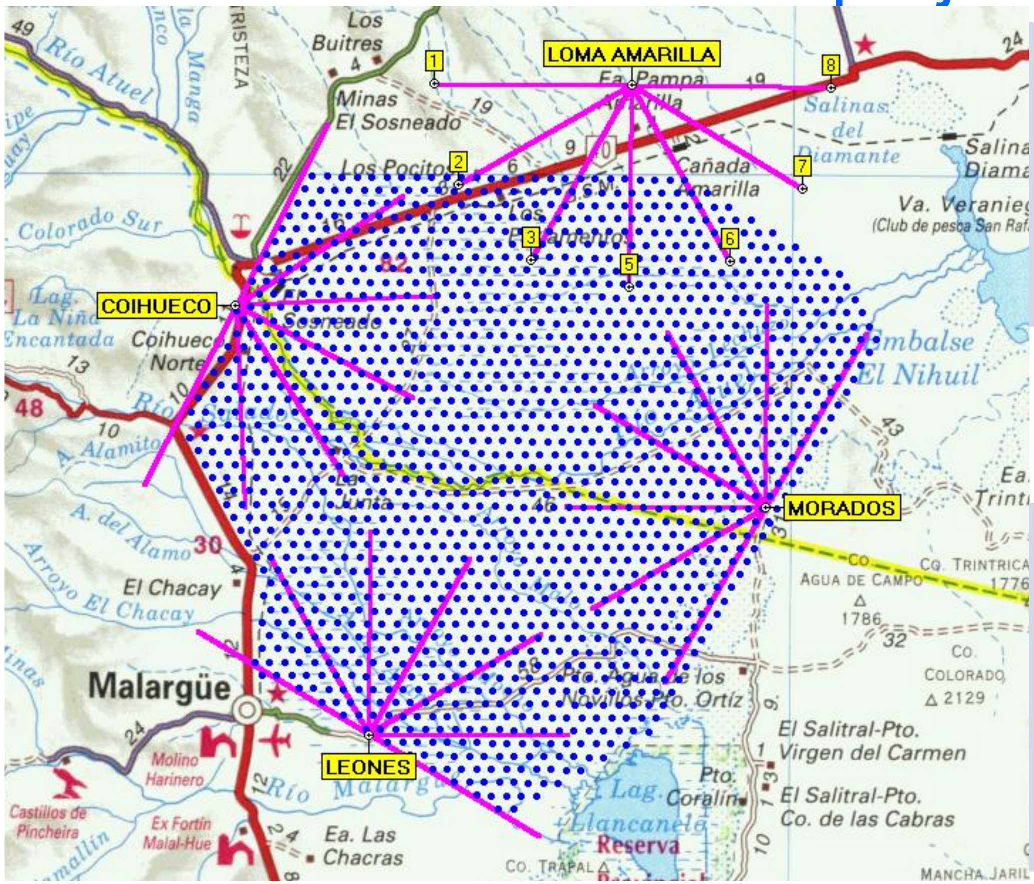
rt involving more than 450
2 institutions in 17 countries:

stralia, Bolivia, Brazil, Czech Republic,
nany, Italy, Mexico, Netherlands, Poland,
venia, Spain, United Kingdom, USA,

PIERRE AUGER OBSERVATORY
MALARGÜE
MENDOZA
ARGENTINA

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

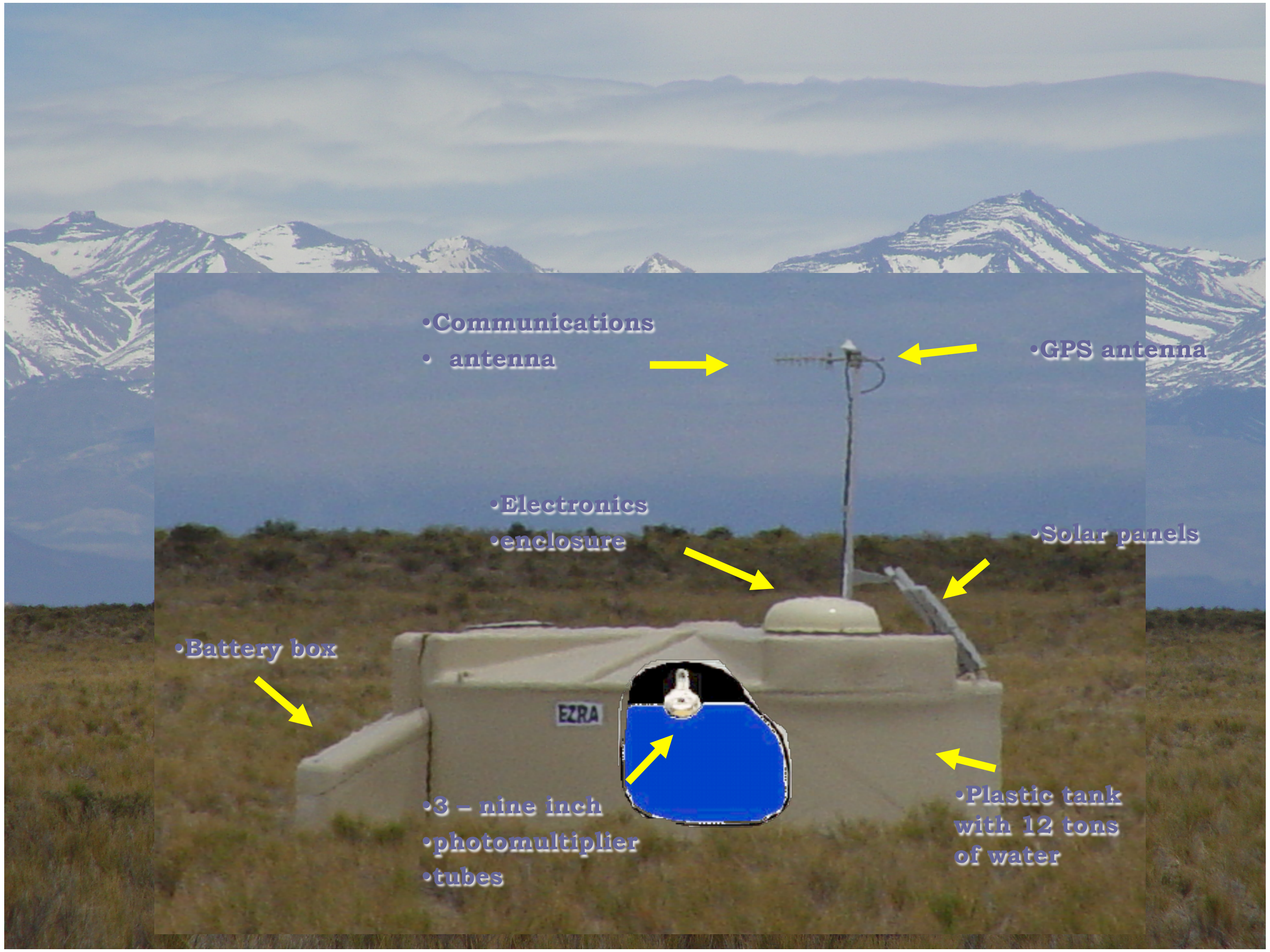
4 Telescope enclosures

6 Telescopes per enclosure

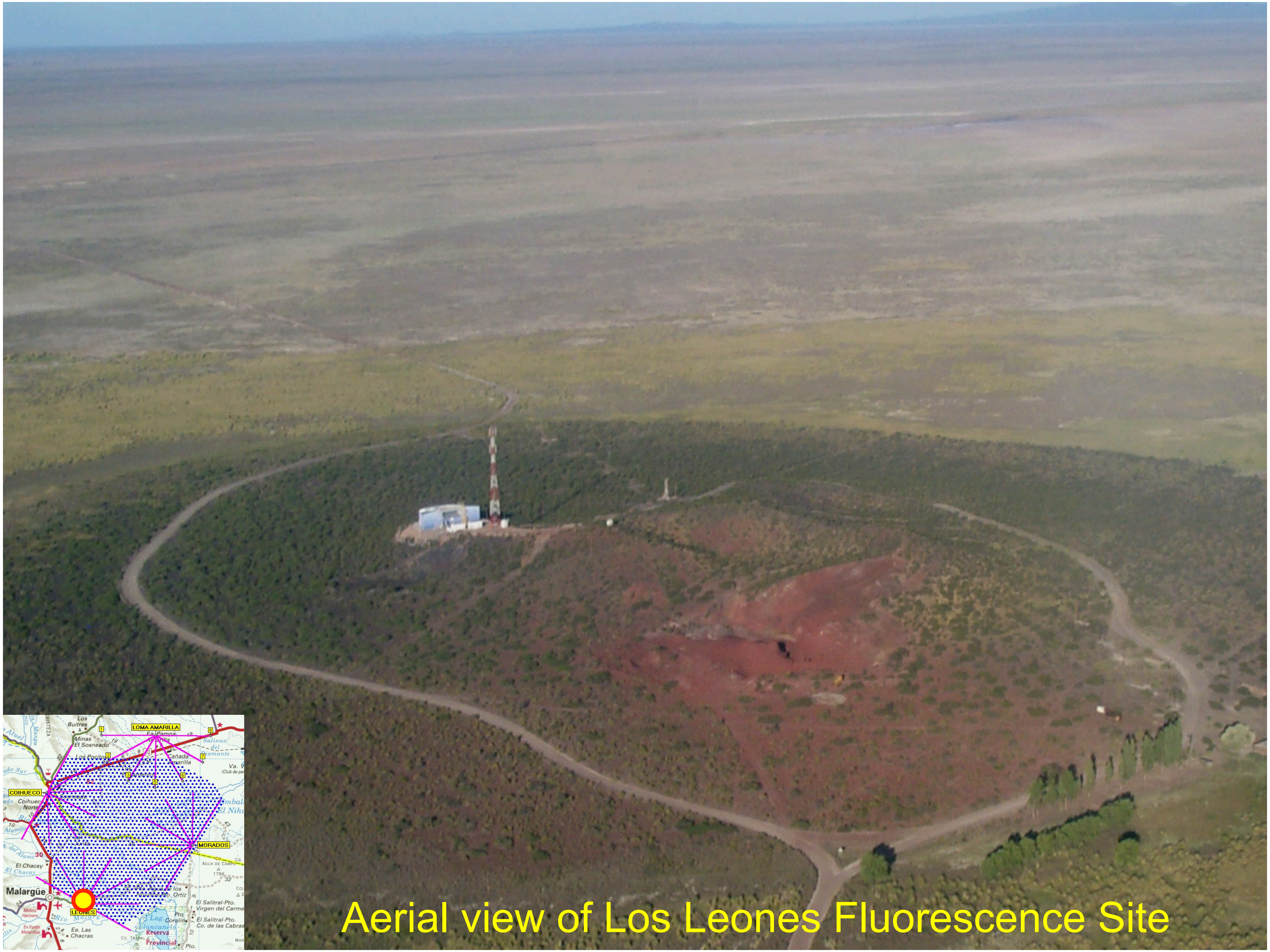
24 Telescopes total

Tanks aligned seen from Los Leones

The Surface Array

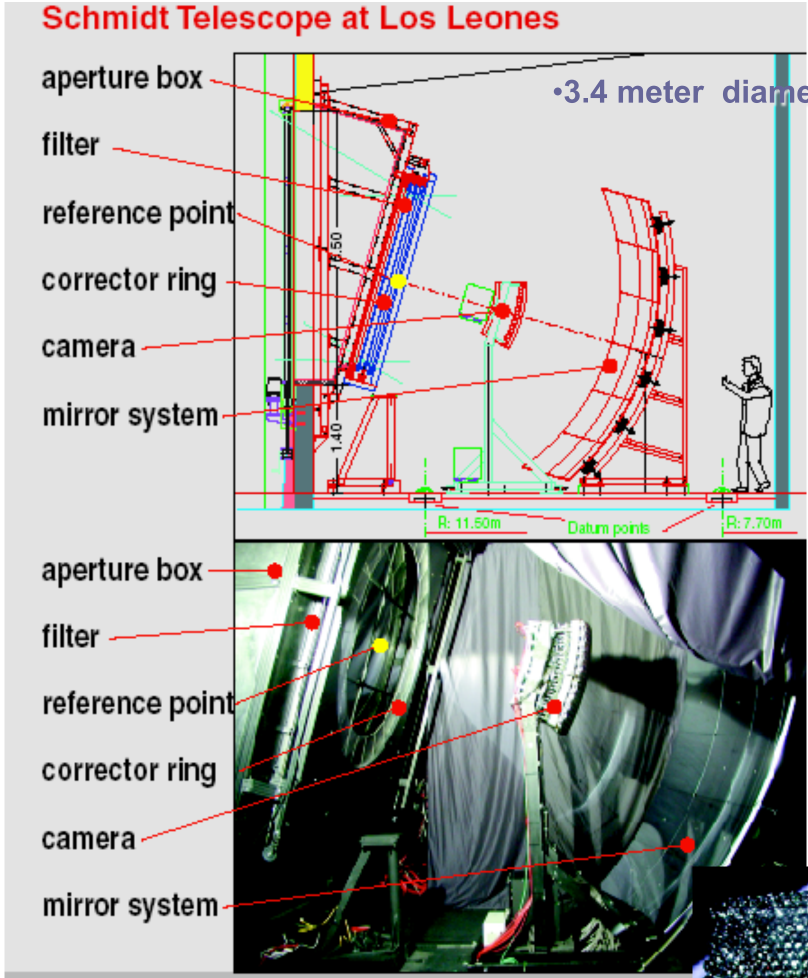


SAGNAP – April 2004
P. Mantsch



Aerial view of Los Leones Fluorescence Site

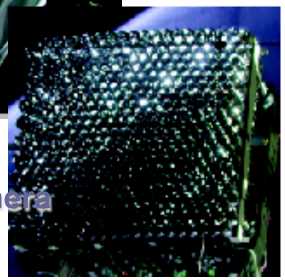
•The Fluorescence Detectors



•3.4 meter diameter mirrors

•Los Leones

•Coihueco



•440 pixels per camera

•Los Morados – under construction

SAGNAP – April 2004
P. Mantsch

Telescope Array

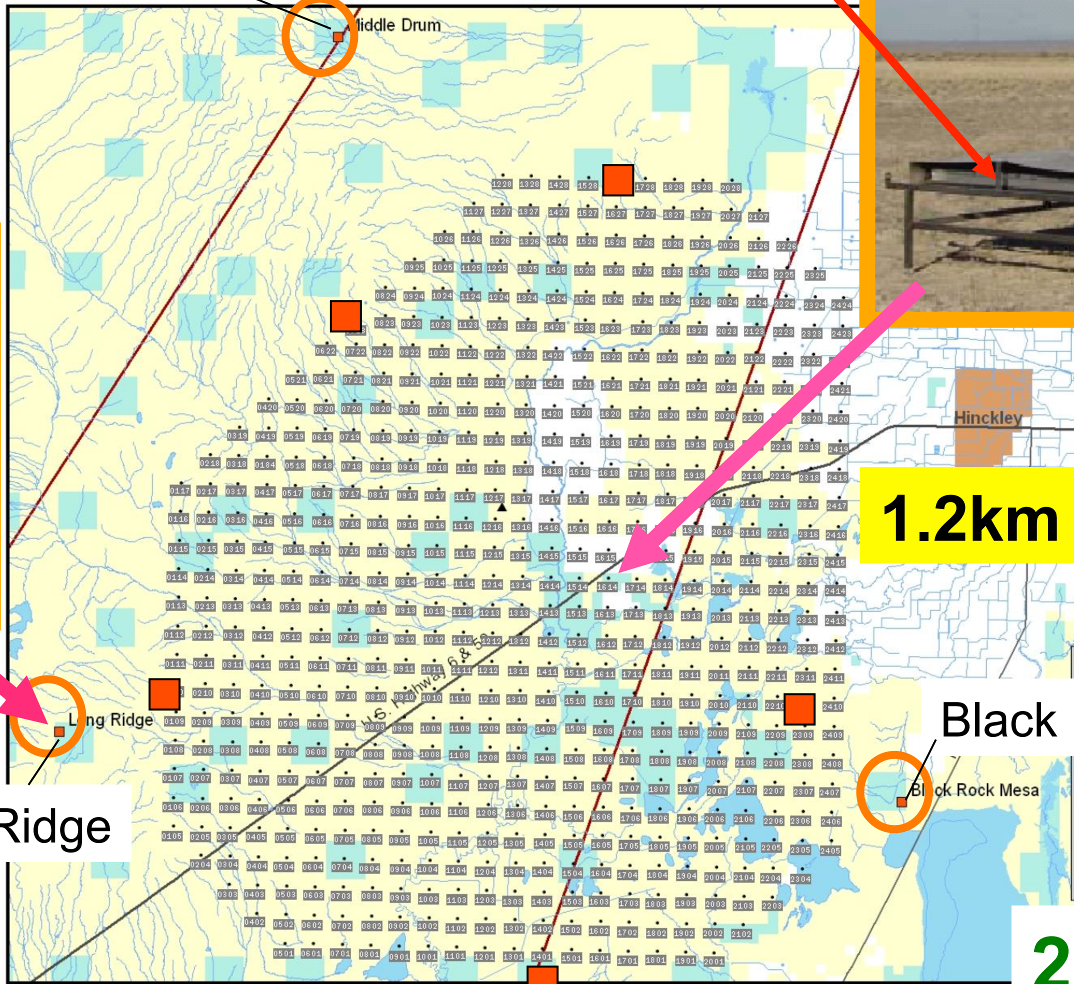
576 plastic scintillation Surface Detectors (SD)

3m^2 1.2cm t
two layers

Atmospheric fluorescence telescope
3 stations FD

5 communication towers

Middle Drum



1.2km spacing

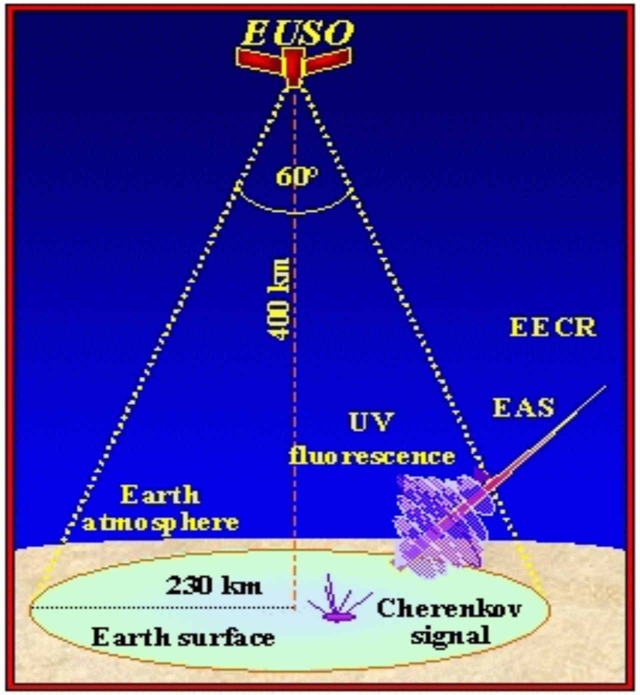
Black Rock Mesa

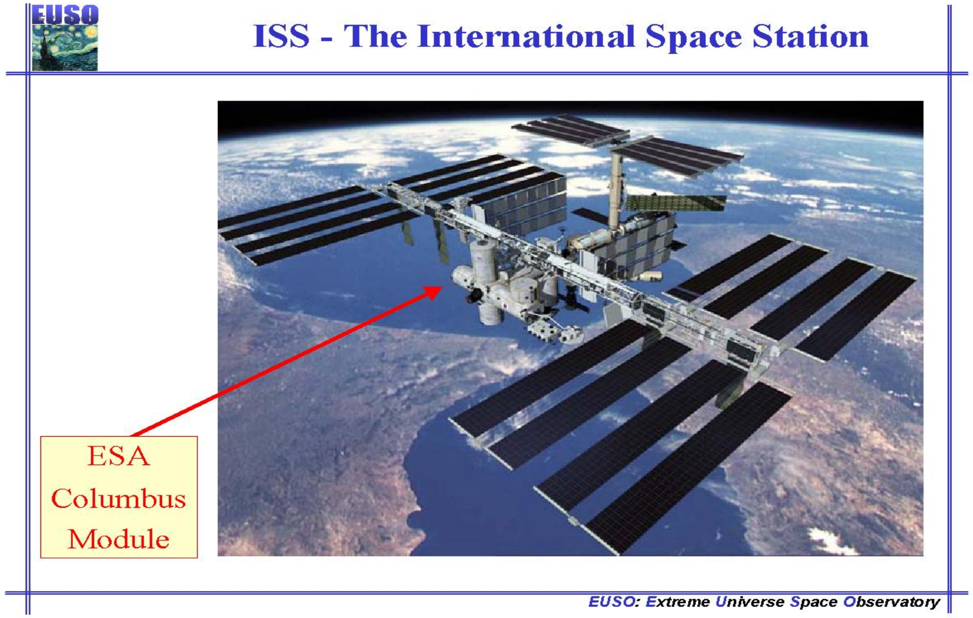
Long Ridge

20km

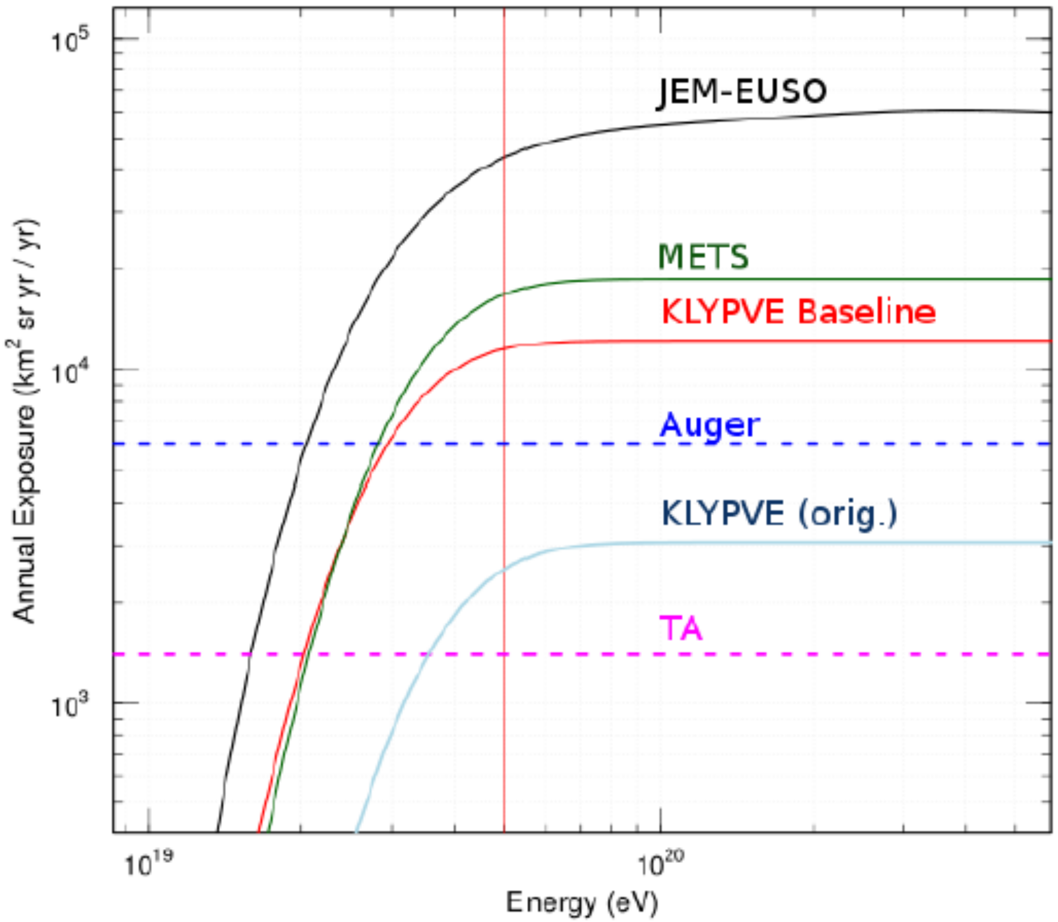
Sensitivity of SD : ~9 x AGASA

Extreme Universe Space Observatory: JEM-EUSO (project)



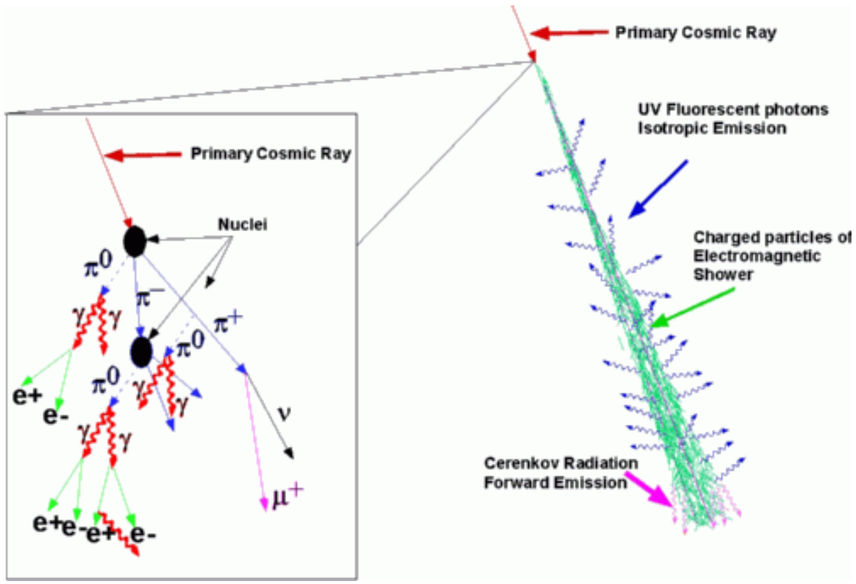


Exposure of space experiments

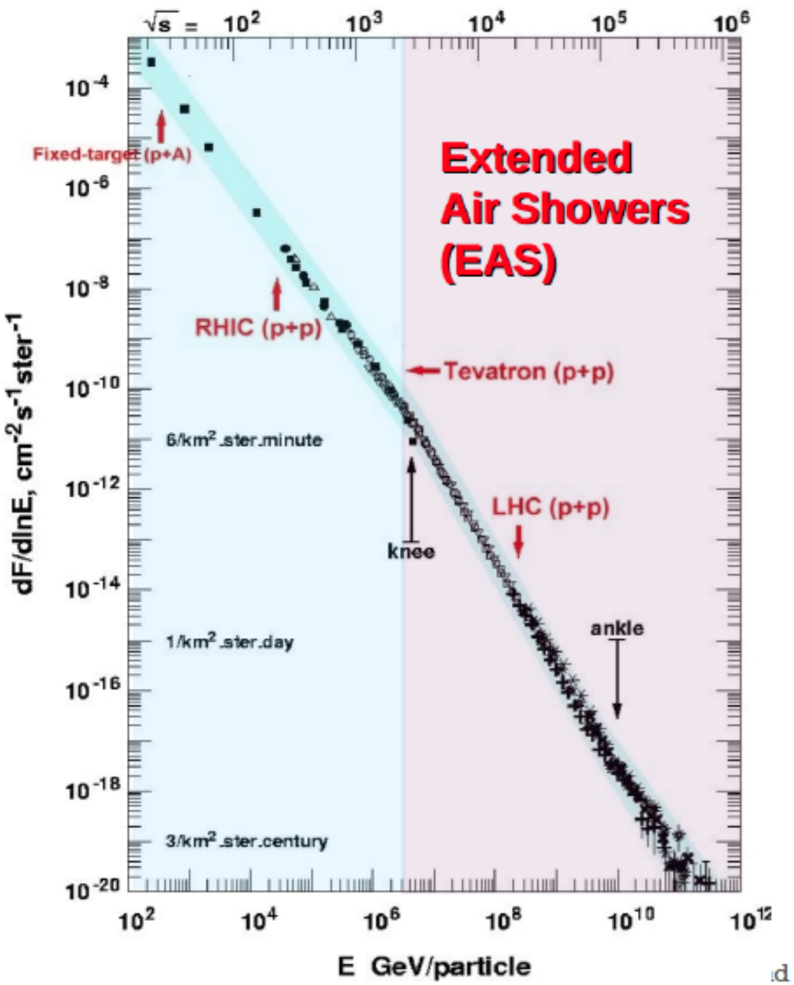


Shower structure: theoretical uncertainty

- Extrapolation of accelerator data to high energies with different approaches can give uncertainty up to 20 % in energy estimate for same shower and 100% important for chemical composition study.



+ The role of the accelerators experiments



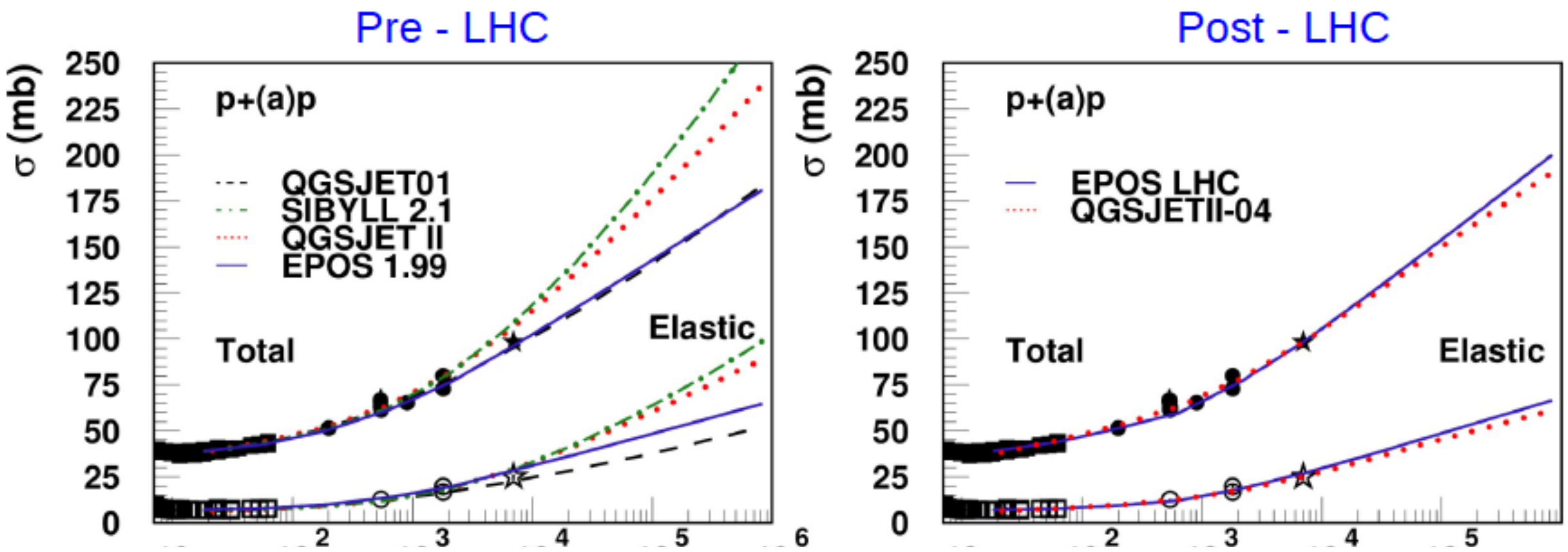
Accelerator based experiments are the most powerful available tools to determine the high energy hadronic interactions characteristics

→ Hadronic interactions models tuning

LHC 13 TeV → 9.10^{16} eV
Unique opportunity to calibrate the models in the 'above knee' region

PP cross section

- extrapolation to pA or to high energy (model dependent)
  - different amplitude and scheme
- different extrapolations

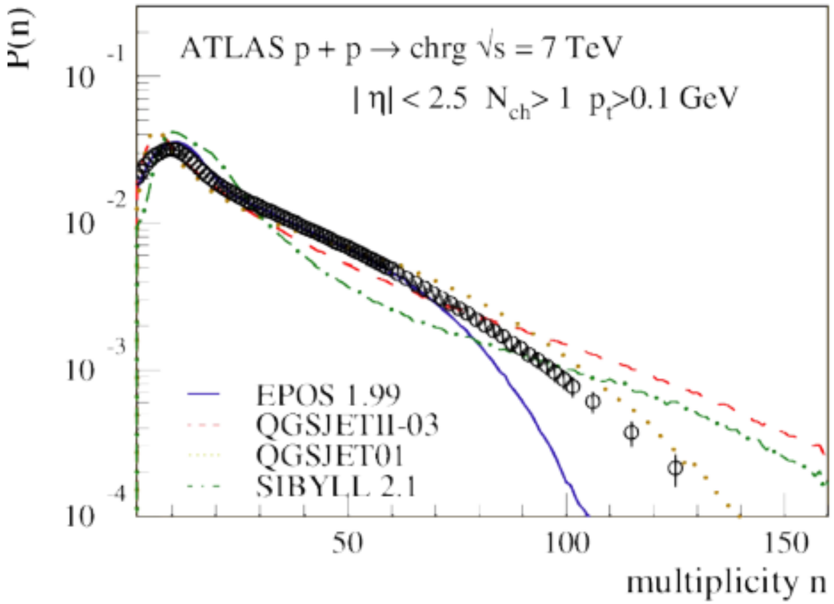


Multiplicity Distribution

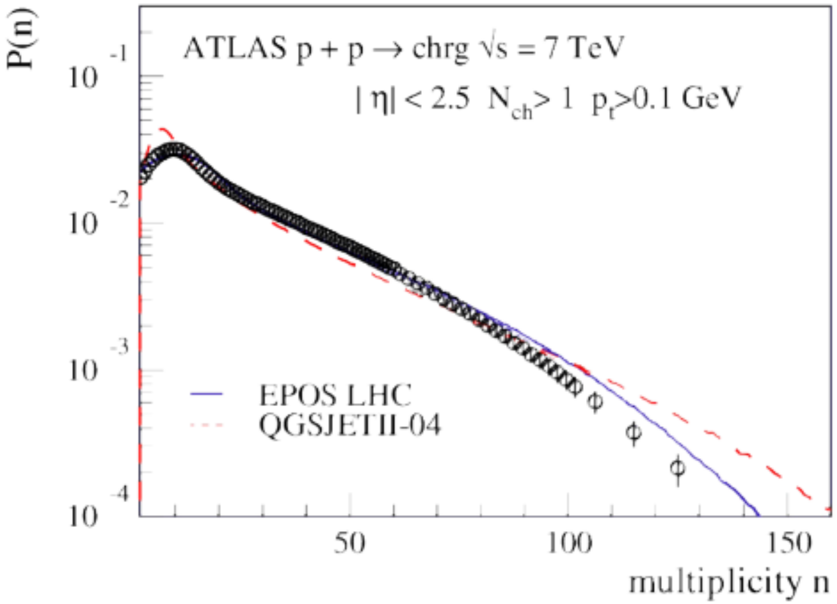
- Consistent results
  - Better mean after corrections
    - difference remains in shape
  - Better tail of multiplicity distributions
    - corrections in EPOS LHC (flow) and QGSJETII-04 (minimum string size)

LHC data in the range defined by Pre-LHC models : no unexpected results in basic distributions

Pre - LHC



Post - LHC



Conclusions: indirect detection of cosmic rays

- Spectrum of cosmic rays at Earth is well measured from sub-GeV energies to 10^{20} eV.
- Shower development in atmosphere measured with 2 main technics: array of ground-based stations and fluorescence telescopes.
- Measurement of mass composition requires modeling of shower development in atmosphere. LHC already helped and will allow to make big progress in near future
- Good measurement of arrival directions of UHECR allows search for UHECR sources.

Acceleration of Cosmic Rays

ALL ACCELERATION MECHANISMS ARE ELECTROMAGNETIC IN NATURE

MAGNETIC FIELD CANNOT MAKE WORK ON CHARGED PARTICLES THEREFORE ELECTRIC FIELDS ARE NEEDED FOR ACCELERATION TO OCCUR

REGULAR ACCELERATION

THE ELECTRIC FIELD IS LARGE SCALE:

$$\langle \vec{E} \rangle \neq 0$$

STOCHASTIC ACCELERATION

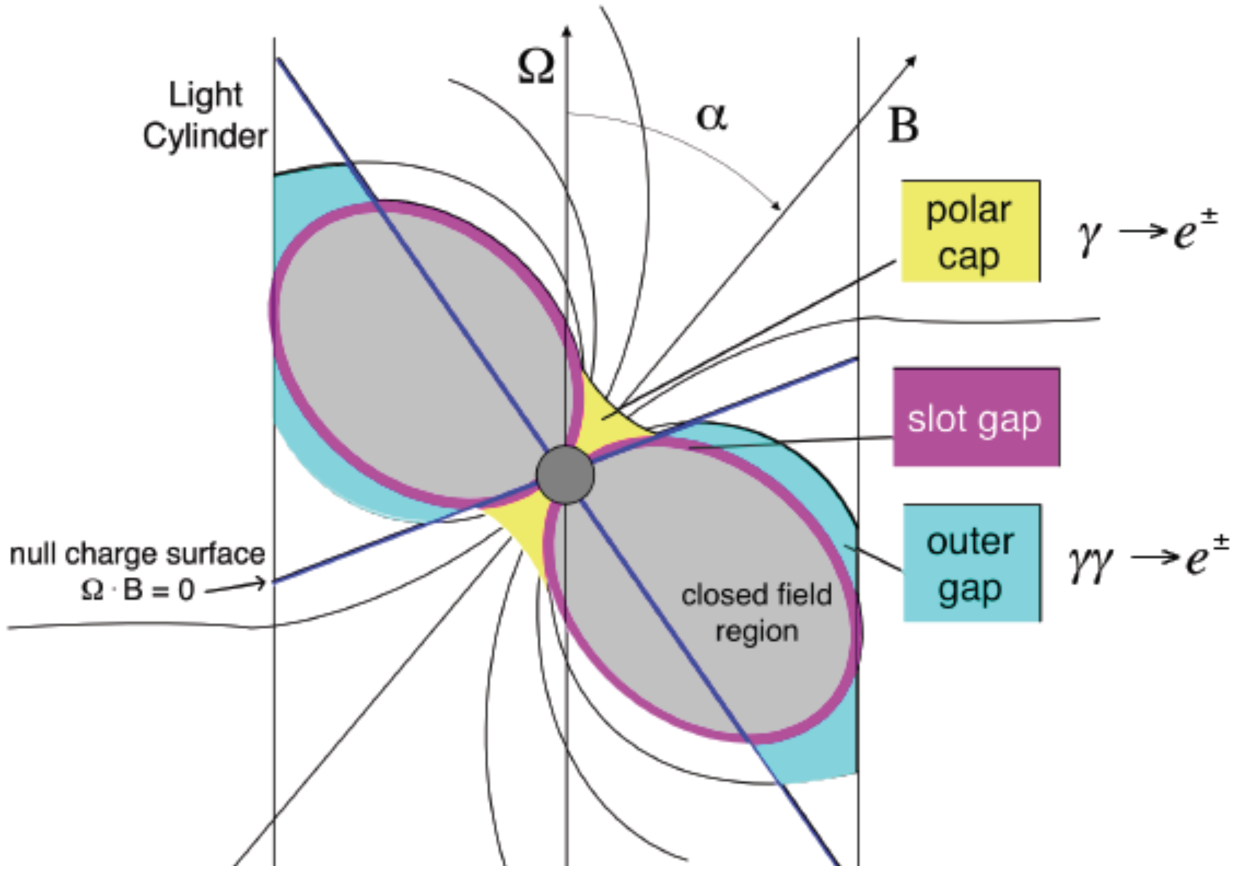
THE ELECTRIC FIELD IS SMALL SCALE:

$$\langle \vec{E} \rangle = 0 \quad \langle \vec{E}^2 \rangle \neq 0$$

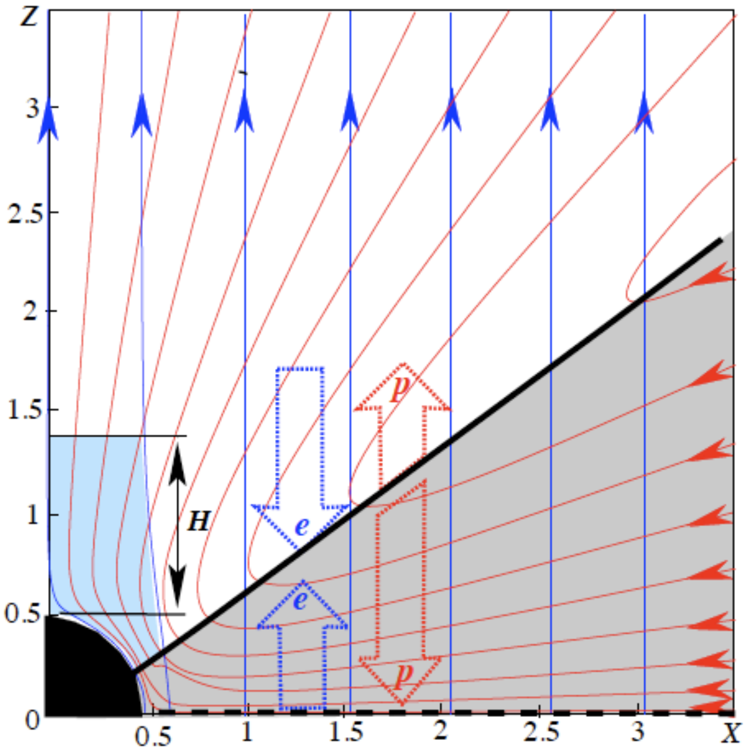
From lectures of P.Blasi

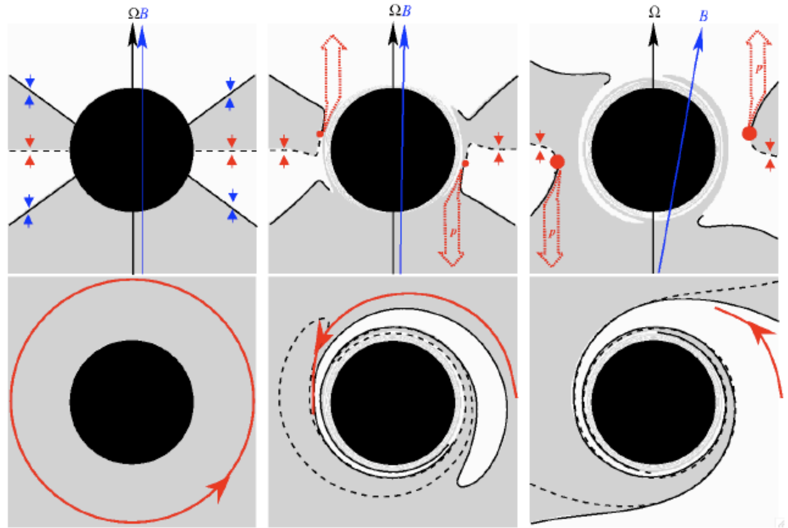
Acceleration by electric field

Pulsar accelerator geometries



Acceleration near Black Hole in the electric field

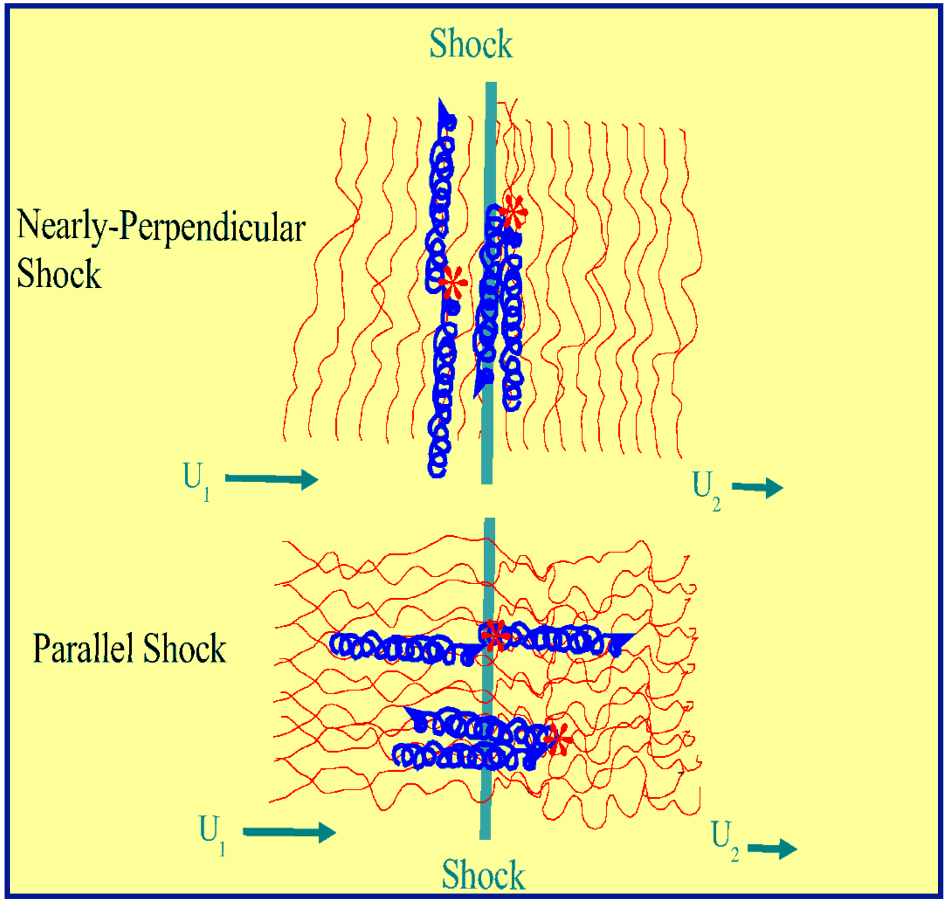




Wald, 1972

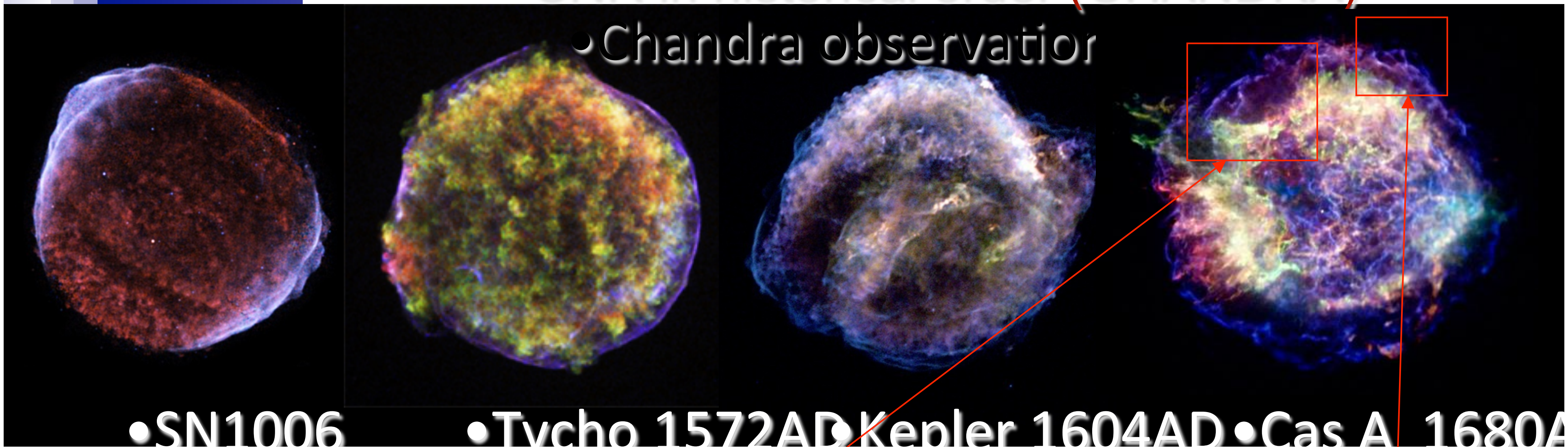
Diffusive Shock Acceleration

- Discovered by four independent teams:
  - *Krymsky (1977), Axford et al (1977), Bell (1978), Blandford & Ostriker (1978)*
- Requires that particles diffuse across a diverging flow (a shock)
- Also requires some form of trapping near the shock



MEPHI,

•SNR in historical order (CHANDRA)

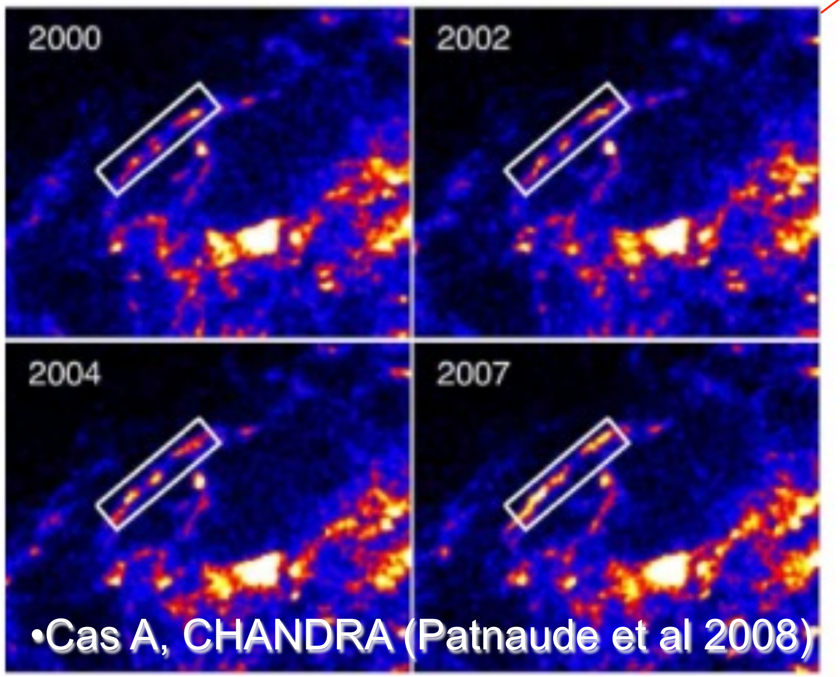


•NASA/CXC/Rutgers/
•J.Hughes et al.

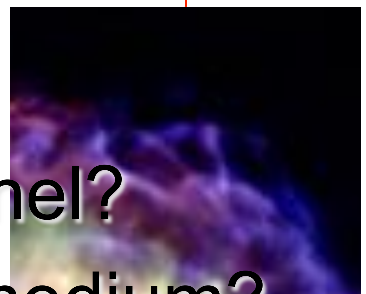
•NASA/CXC/Rutgers/
•J.Warren & J.Hughes et al.

•NASA/CXC/NCSU/
•S.Reynolds et al.

•NASA/CXC/MIT/UMass Amhers
•M.D.Stage et al.



•Cas A, CHANDRA (Patnaude et al 2008)

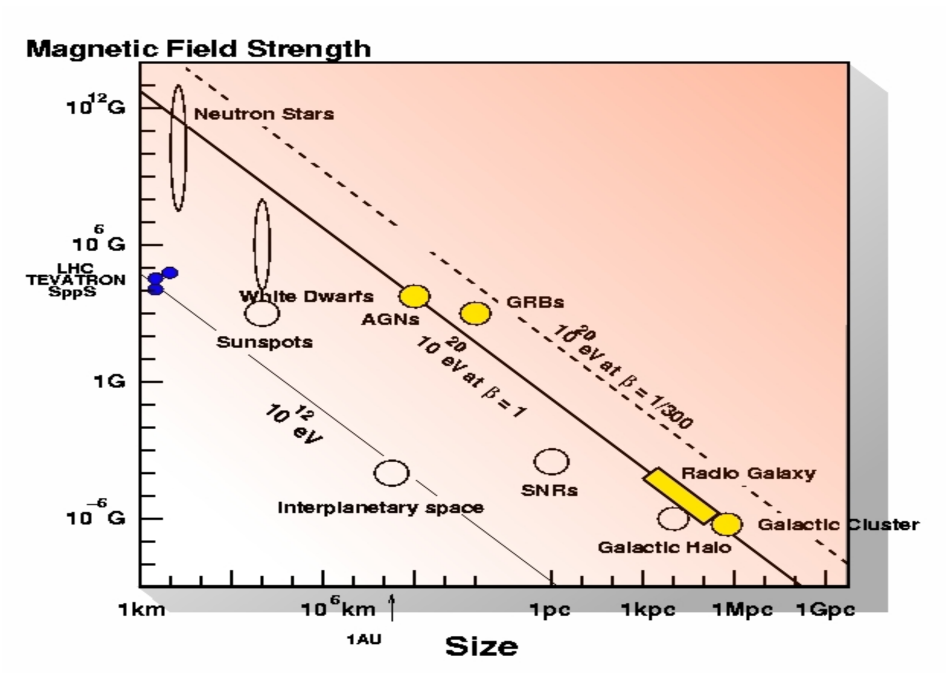


- •High speed shrapnel?
- •Clumpy ambient medium?
- •CR-driven instability?

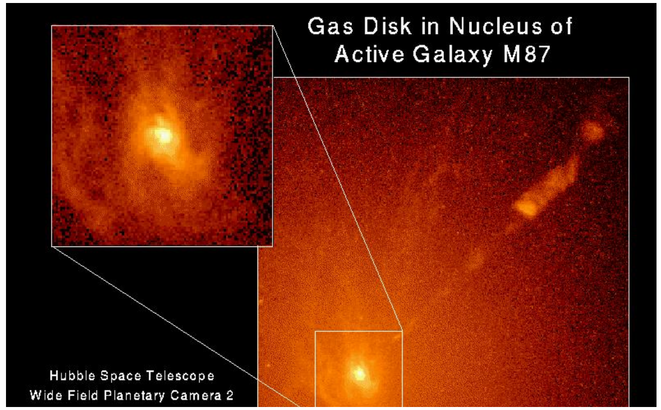
•Shock structure maps out

•pre-shock features (B, ρ…)

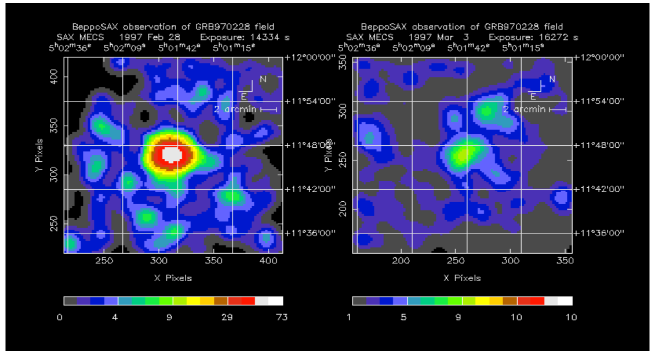
Acceleration of UHECR



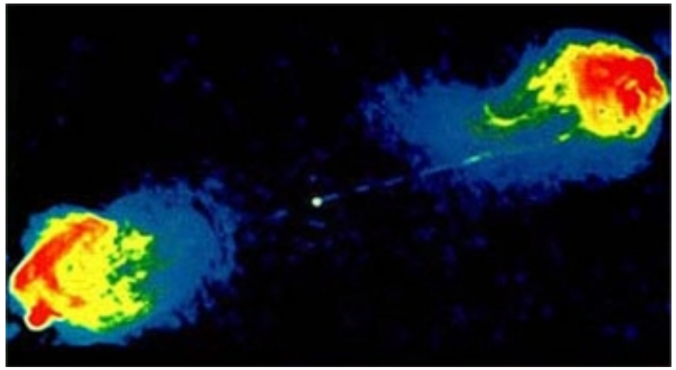
A.G.N.



GRB



Radio Galaxy Lobe



- Hillas 1984
- Shock acceleration $1/E^{\alpha}$ $\alpha >= 2$
- Electric field acceleration line at E_{max}
- Many other types

Acceleration with energy losses

- Maximum energy

$$\mathcal{E}_{\max}(B,R) = \begin{cases} \mathcal{E}_{\rm H}(B,R), & B \le B_0(R); \\ \mathcal{E}_{\rm loss}(B,R), & B > B_0(R), \end{cases}$$

- Where $B_0(R) = 3.16 \times 10^{-3}\ \mathrm{G}\ \dfrac{A^{4/3}}{Z^{5/3}} \left(\dfrac{R}{\mathrm{kpc}}\right)^{-2/3} \eta^{1/3};$

Acceleration with energy losses

- Hillas maximum energy

$$\mathcal{E}_{\mathrm{H}}(B,R) = 9.25 \times 10^{23}\ \mathrm{eV}\ Z \left(\frac{R}{\mathrm{kpc}}\right)\left(\frac{B}{\mathrm{G}}\right)$$

- Diffusive acceleration:

$$\mathcal{E}_{\mathrm{loss}}(B,R) = \mathcal{E}_{\mathrm{d}}(B,R) = 2.91 \times 10^{16}\ \mathrm{eV}\ \frac{A^4}{Z^4}\left(\frac{R}{\mathrm{kpc}}\right)^{-1}\left(\frac{B}{\mathrm{G}}\right)^{-2}$$

Acceleration with energy losses

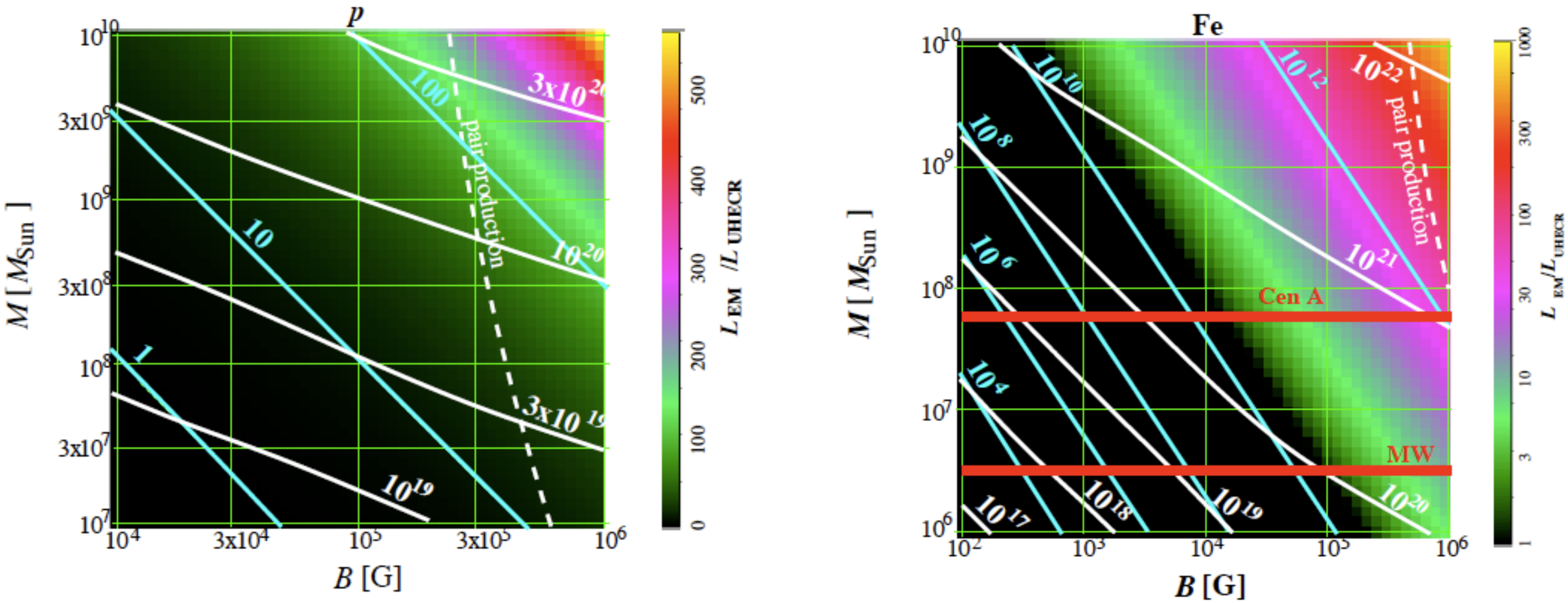
- Inductive with synchrotron loses (jets)

$$\mathcal{E}_{\rm loss}(B,R) = \mathcal{E}_{\rm s}(B,R) = 1.64\times 10^{20}\ {\rm eV}\ \frac{A^2}{Z^{3/2}}\left(\frac{B}{\rm G}\right)^{-1/2}\eta^{1/2}$$

- Inductive with curvature losses (cores)

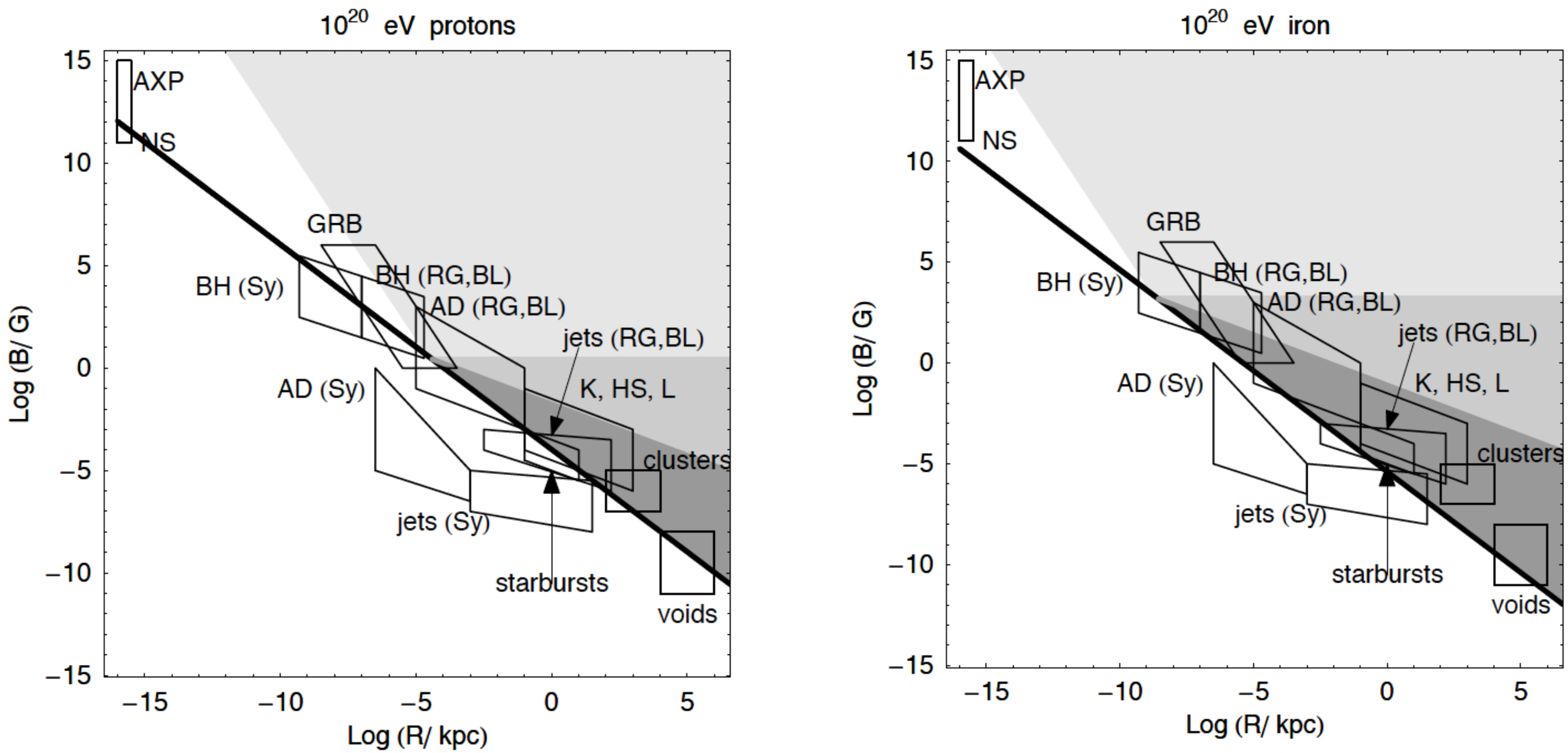
$$\mathcal{E}_{\rm loss}(B,R) = \mathcal{E}_{\rm c}(B,R) = 1.23\times 10^{22}\ {\rm eV}\ \frac{A}{Z^{1/4}}\left(\frac{R}{\rm kpc}\right)^{1/2}\left(\frac{B}{\rm G}\right)^{1/4}\eta^{1/4}$$

Acceleration near Black Hole in the electric field



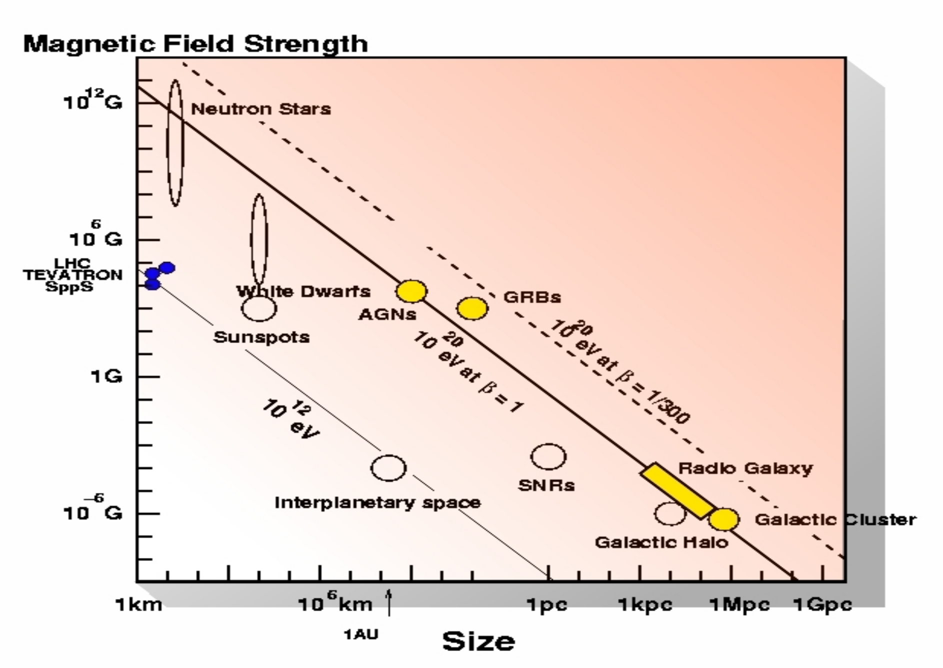
A.Neronov, D.S. and I.Tkachev astro-ph/0712.1737

Acceleration with energy losses

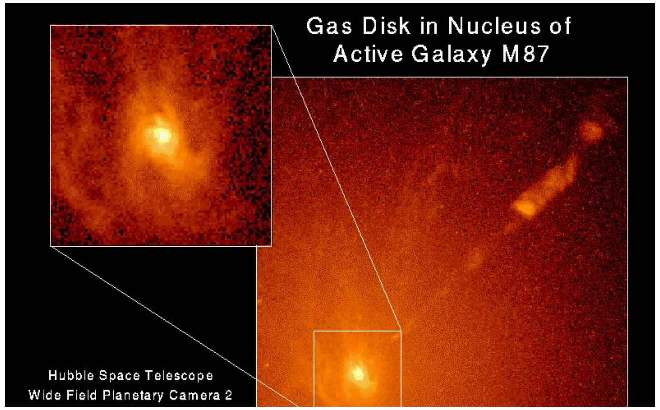


K.Ptitsina and S.Troitsky, **arXiv:0808.0367**

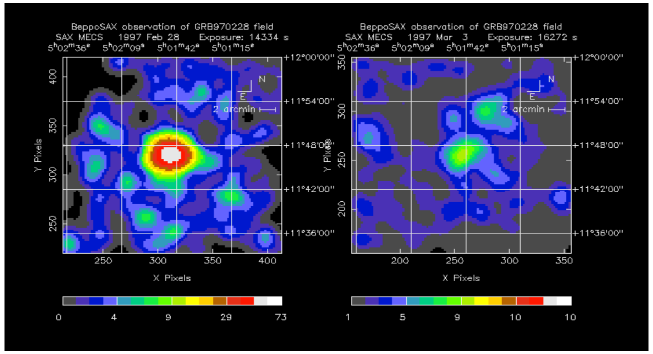
Acceleration of UHECR



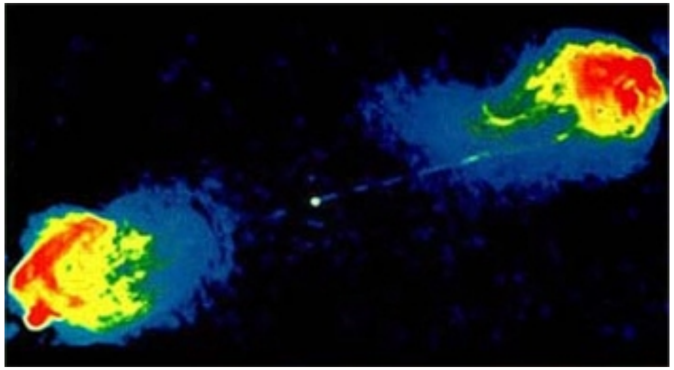
A.G.N.



GRB



Radio Galaxy Lobe

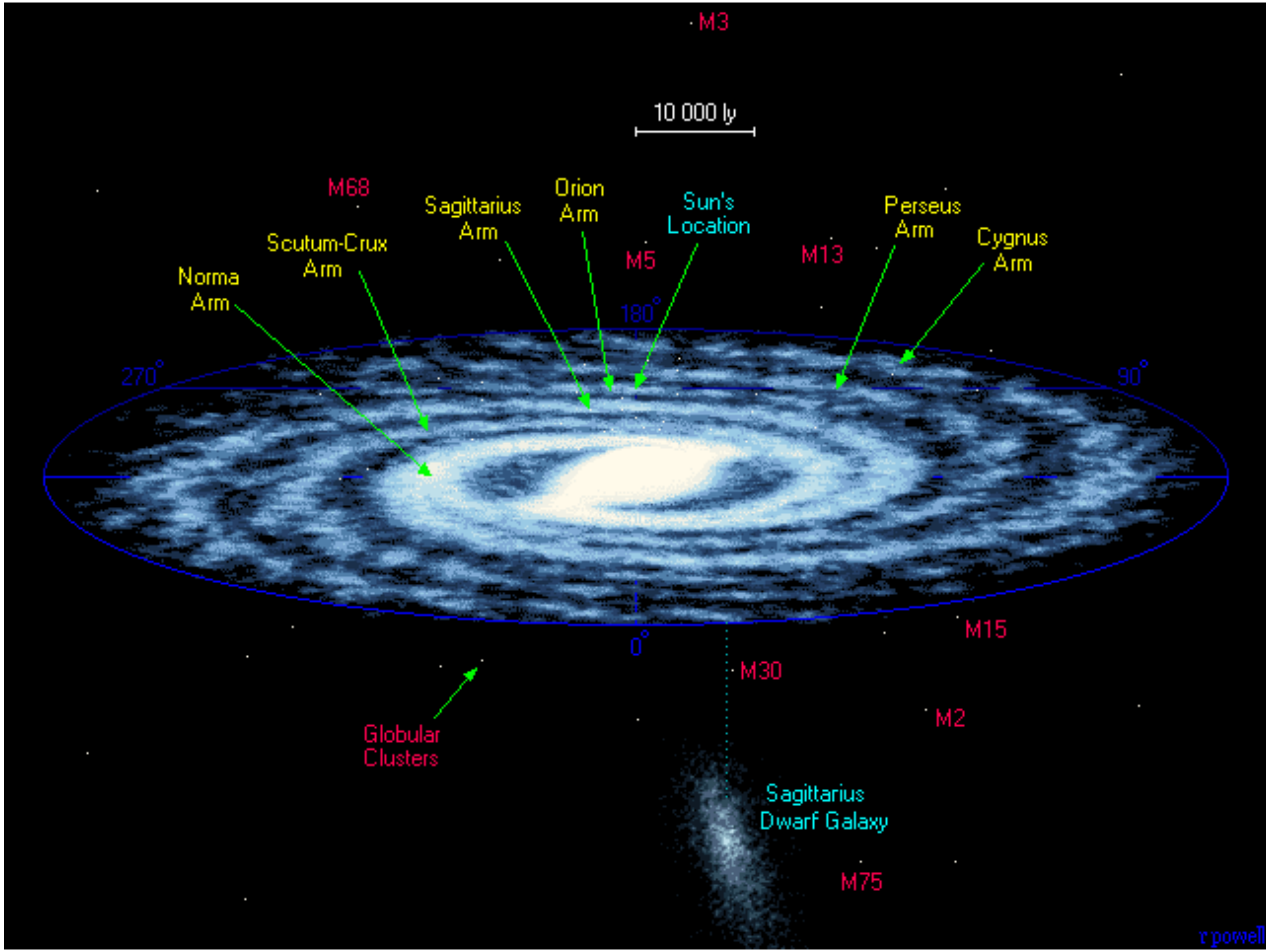


- Shock acceleration $1/E^{\alpha}$ $\alpha>=2$
- Electric field acceleration line at E_{max}
- Converter acceleration can be both

Galactic cosmic rays

Galactic magnetic field

MILKY WAY GALAXY



Galactic magnetic field

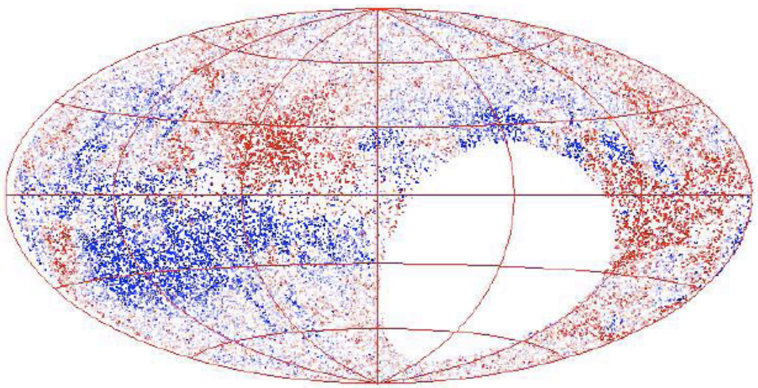
- B = B_disk (regular) + B_disk (turbulent) + B_halo(regular) + B_halo (turbulent)

Rotation measure

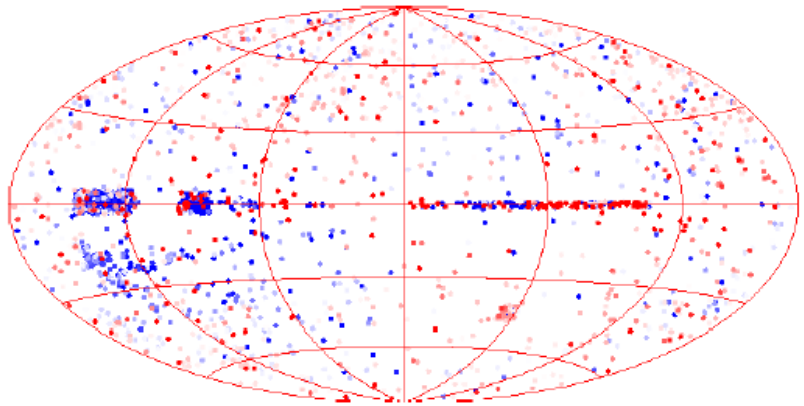
$$\mathrm{RM} \simeq 0.81 \int_0^L \left(\frac{n_e(l)}{\mathrm{cm}^{-3}}\right)\left(\frac{B_{\|}(l)}{\mu\mathrm{G}}\right)\left(\frac{\mathrm{d}l}{\mathrm{pc}}\right)$$

$$\theta \ = \ \theta_0 + \mathrm{RM}\,\lambda^2$$

Galactic magnetic field measurement: RM



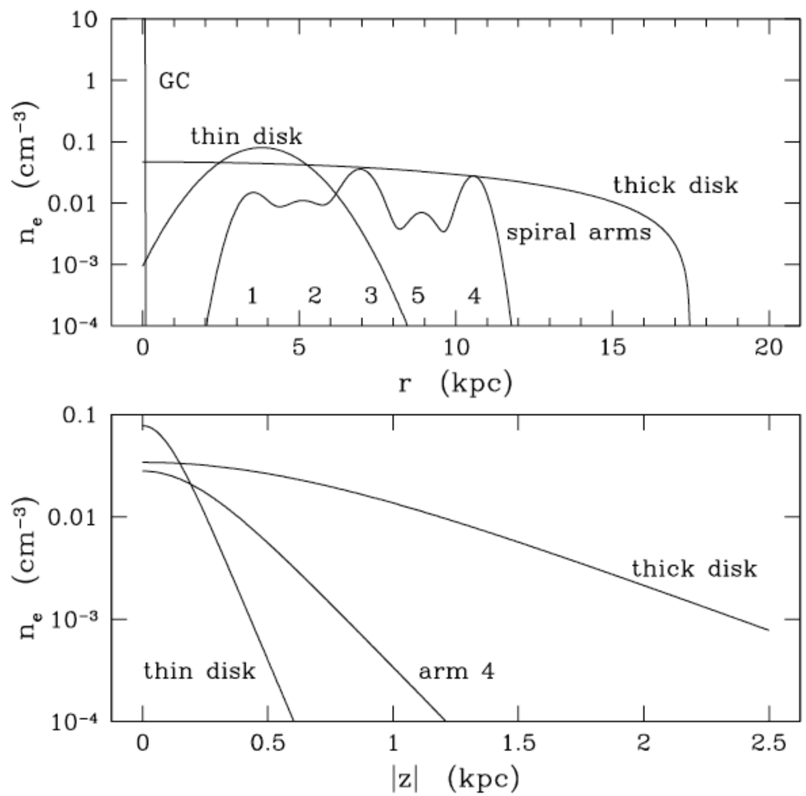
NVSS



Ph.Kronberg & Newton-McGee (2011)

From Pshirkov et al, **arXiv:1103.0814**

Free electrons 2001 model



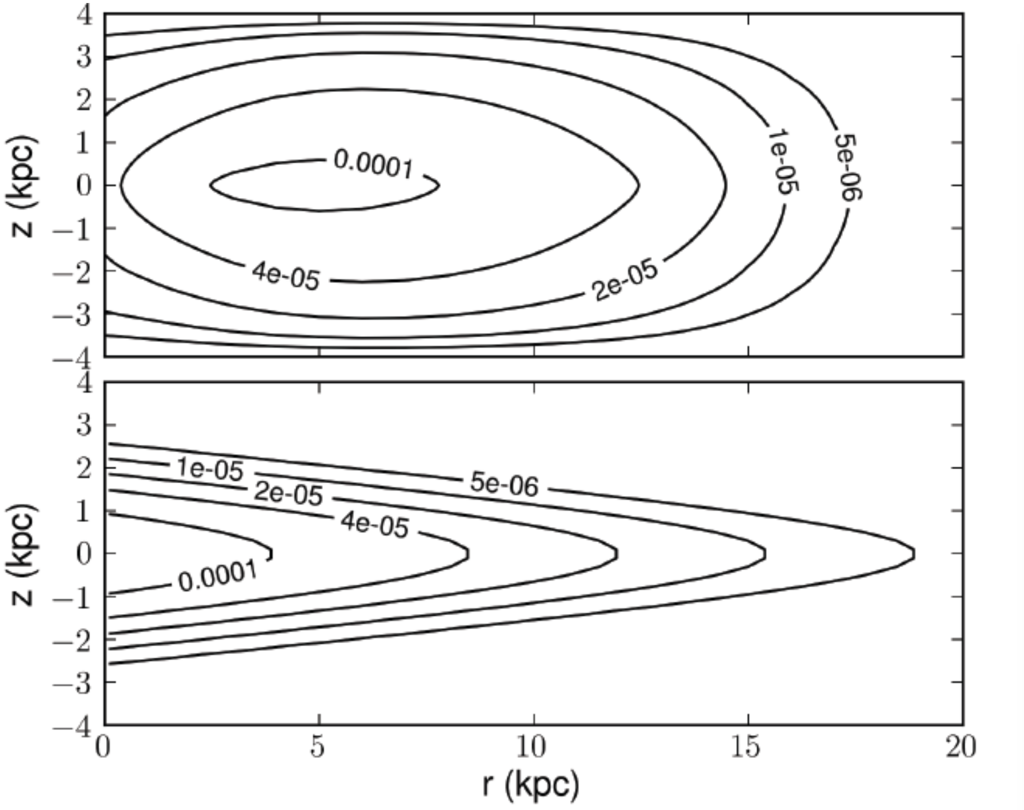
J.Cordes and T.Lazio, **astro-ph/0207156**

Polarized synchrotron emission

$$j_\nu \propto n_{cre} B_\perp^{\frac{1+s}{2}} \nu^{\frac{1-s}{2}}.$$

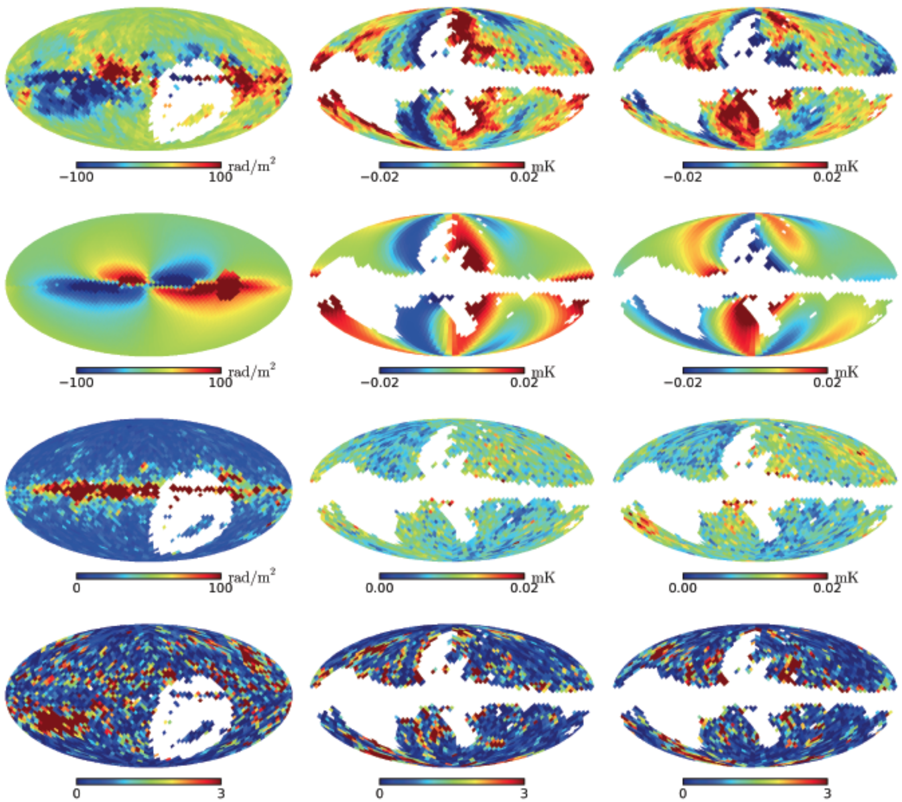
$$s = 3$$

Relativistic electrons



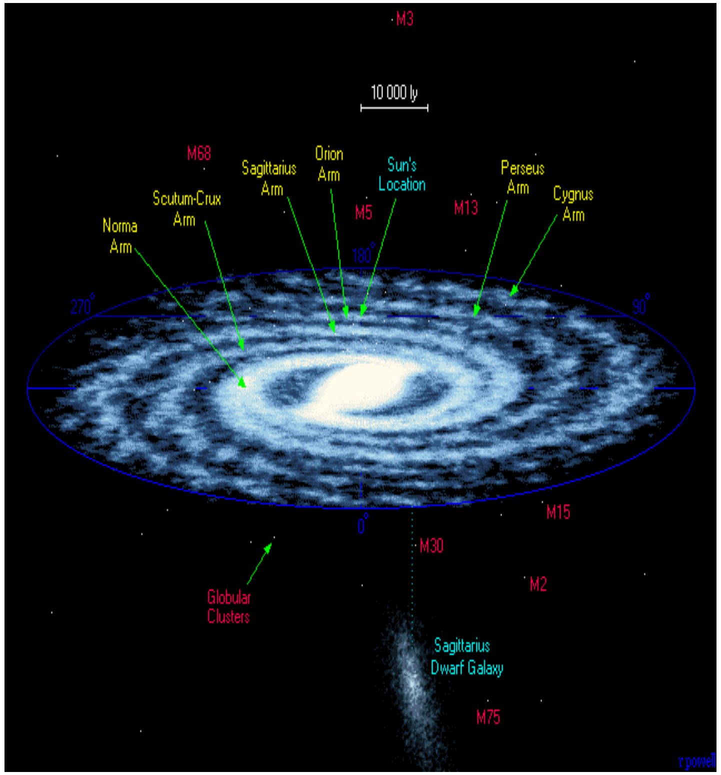
From R.Jansson & G.Farrar, arXiv:1204.3662

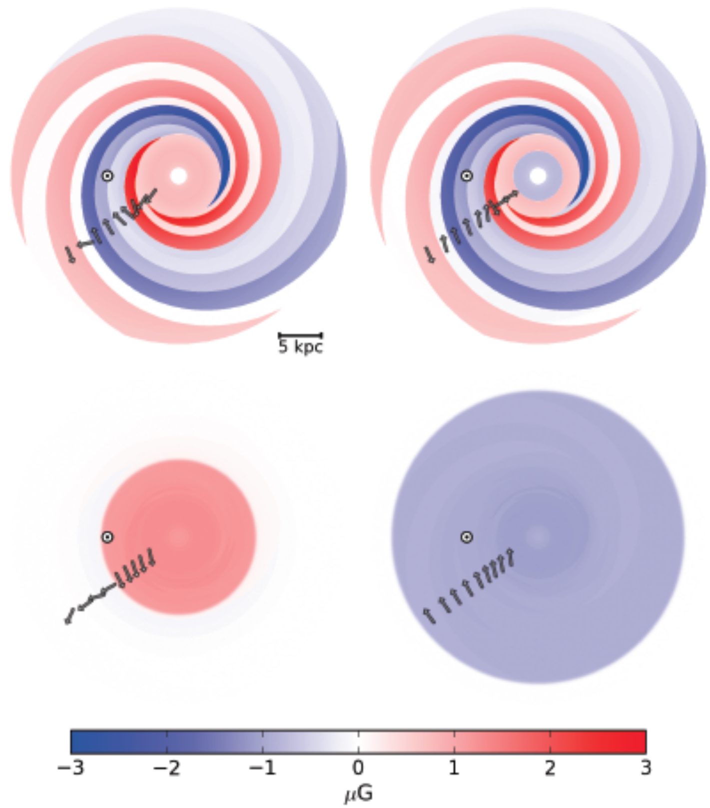
Synchrotron/RM maps



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

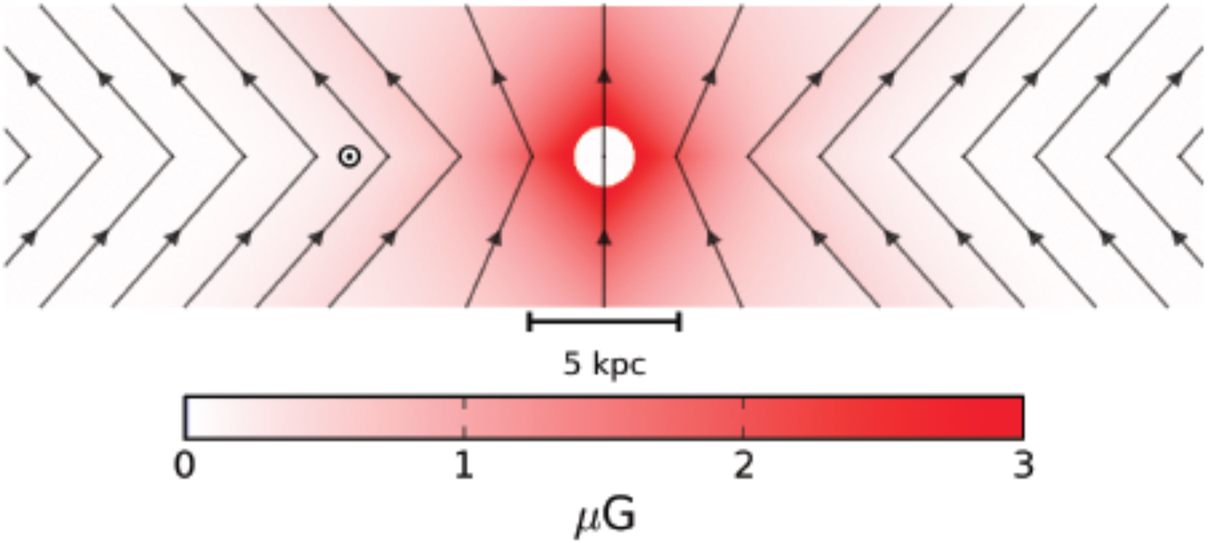
Galactic magnetic field: disk





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
	$\Theta^0_{\rm X} = 49 \pm 1^\circ$	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)

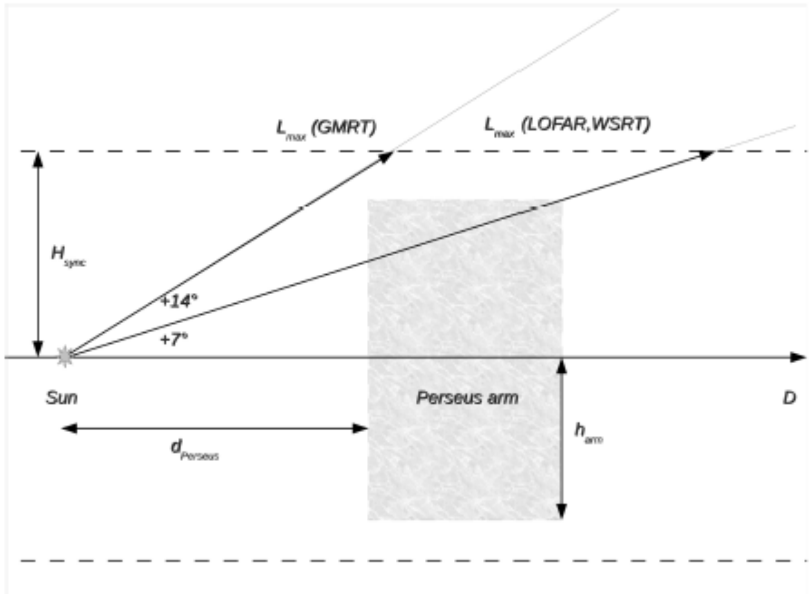
Galactic magnetic field: turbulent component

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

LOFAR measurement of maximum scale of turbulent GMF in disk



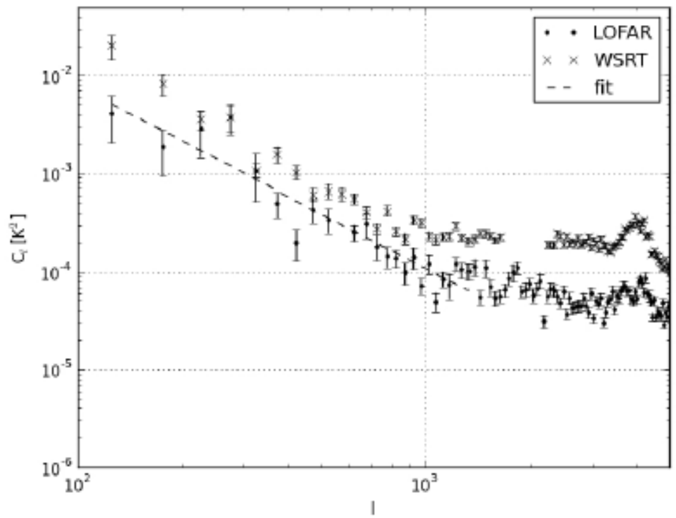


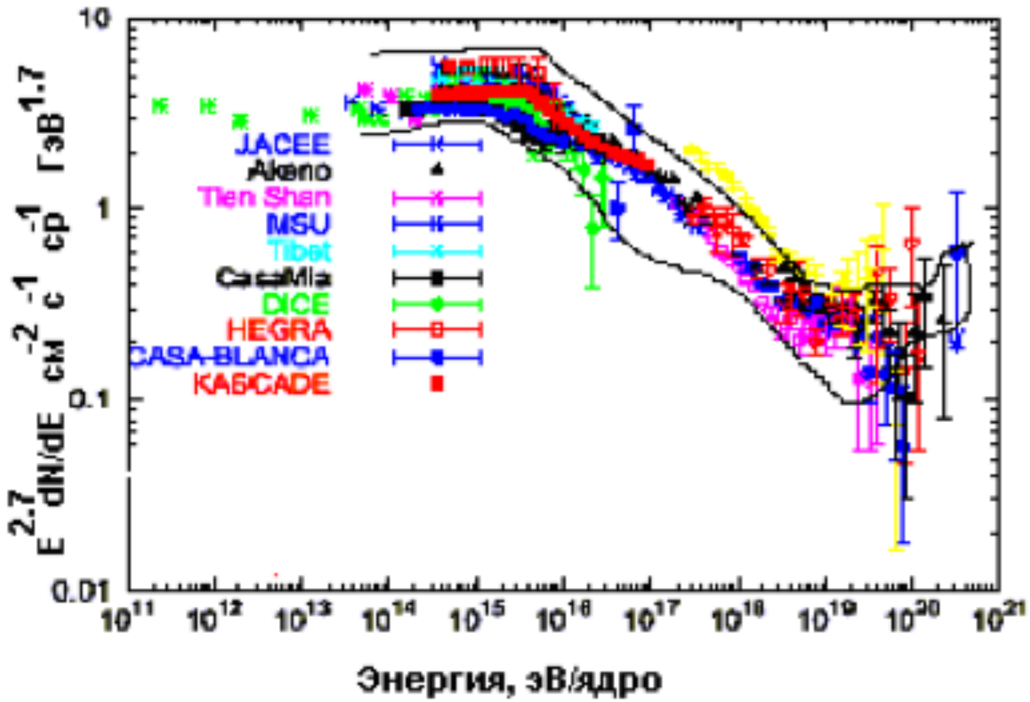
Fig. 9. Power spectra of total intensity from the LOFAR (dots) and WSRT (crosses) observations. The error bars indicate statistical errors at 1σ. The fitted power law (dashed line) with a spectral index $\alpha = -1.84 \pm 0.19$ for $\ell \in [100, 1300]$ is also shown.

arXiv: 1308.2804

Lmax ~ 20 pc +-6 pc in disk

Cosmic ray spectrum: knee

Knee in CR spectrum



Knee was discovered by Kulikov and Khristiansen in data of MSU Experiment in 1958

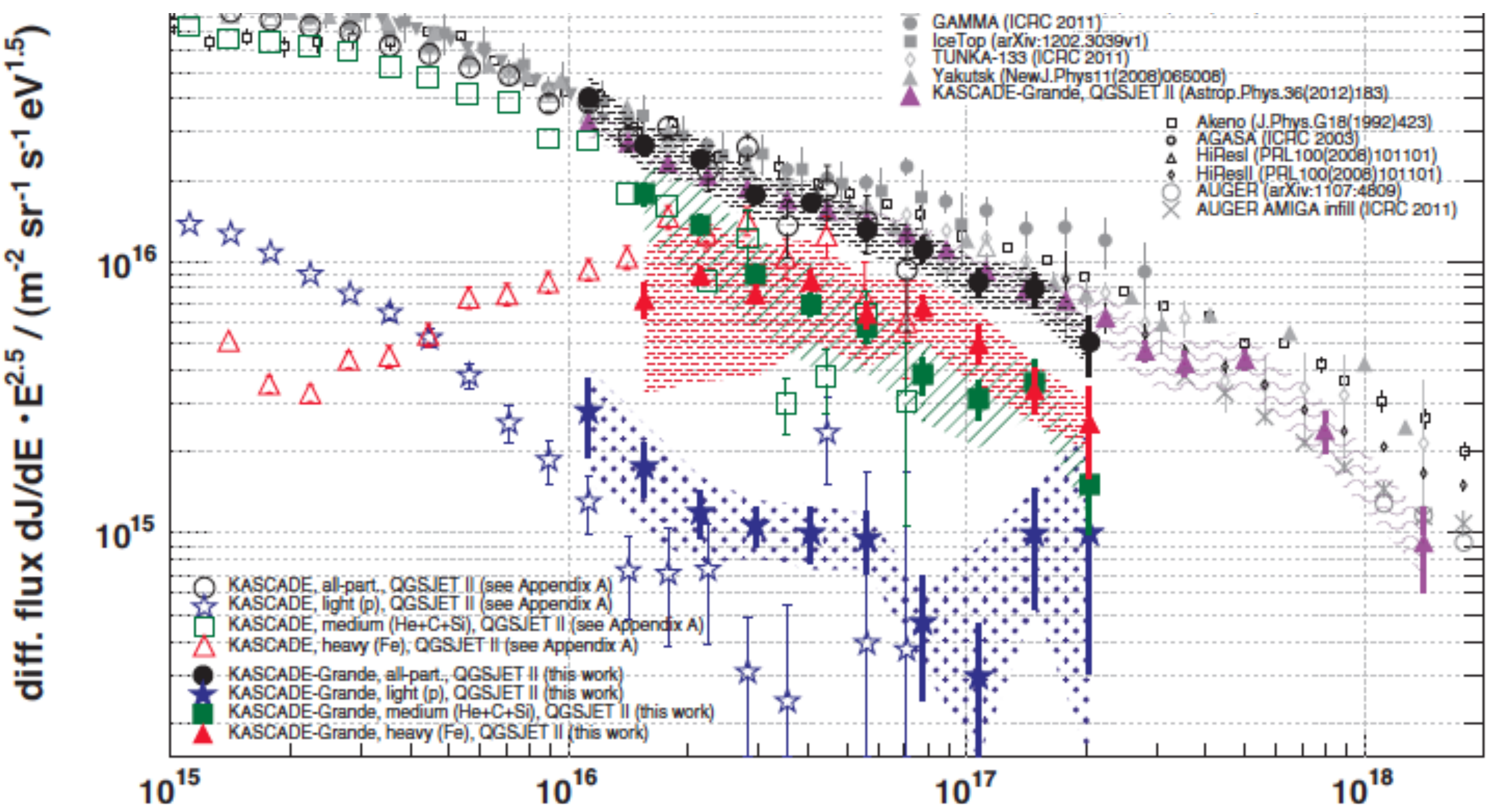
It was confirmed by all new independent eperiments

• For long time it was 2 explanations: astrophysical and particle physics one. In partile physics explanation it was assumed that either interaction changes or new particle dominates. Tevatron and LHC finally killed this interpretation.

Astrophysical interpretation of knee

- Knee is due to maximal energy of dominant sources. Problem: knee is too charp
- Single source dominate everything around knee Problem: dipole anisotropy is too small
- Knee due to change in the propagation properties in interstellar medium Problem: majority of sources have to accelerate above knee

Cosmic Ray Knee: mass composition



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

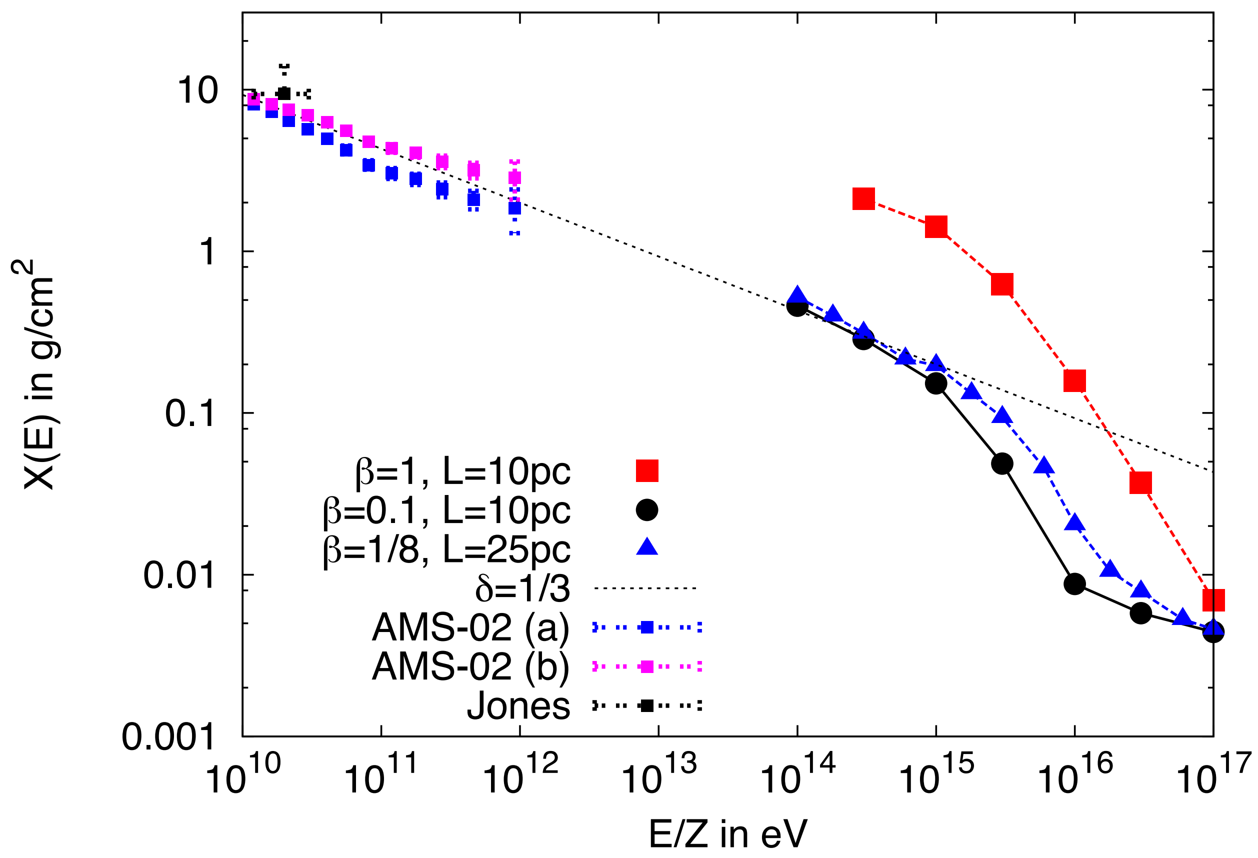
- change of interactions at multi-TeV energies: excluded by LHC
- maximal energy of dominant CR sources – Hillas model
- knee at $R_L(E/Z) \simeq l_{\rm coh}$:

  $\Rightarrow$ 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?

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



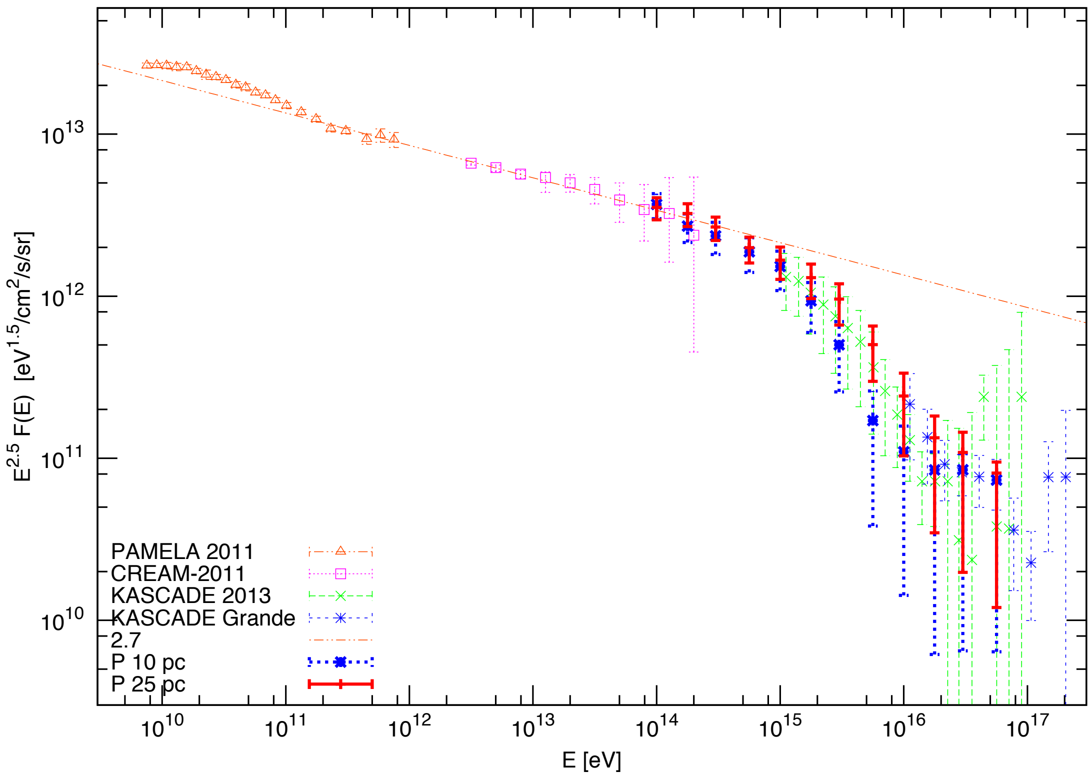
$\Rightarrow$ prefers weak random fields

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

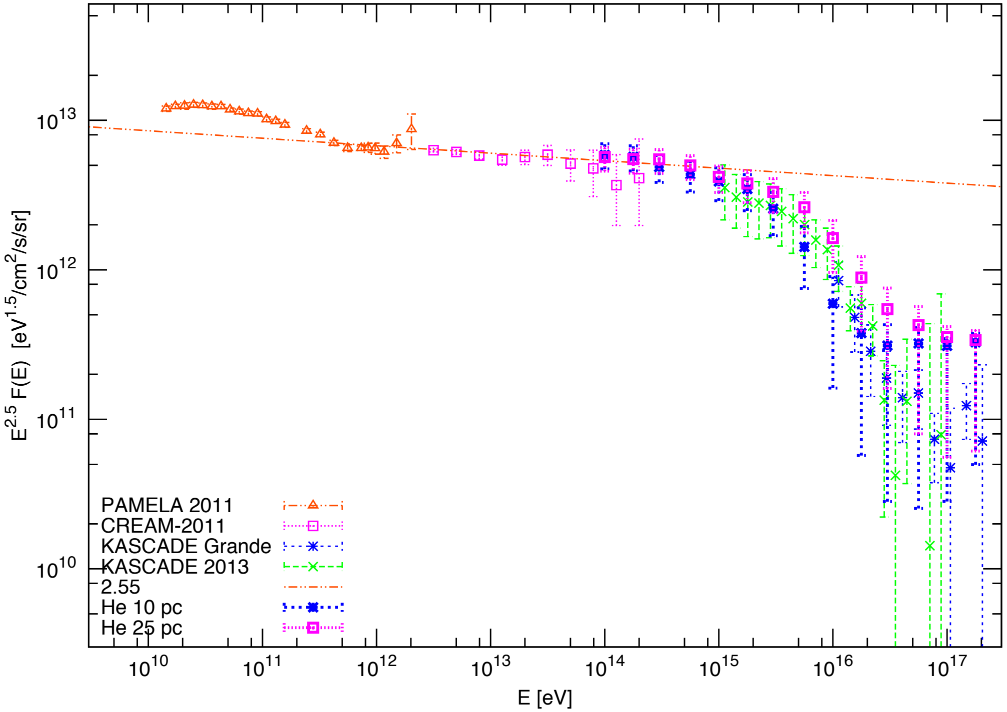
Model

- 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.

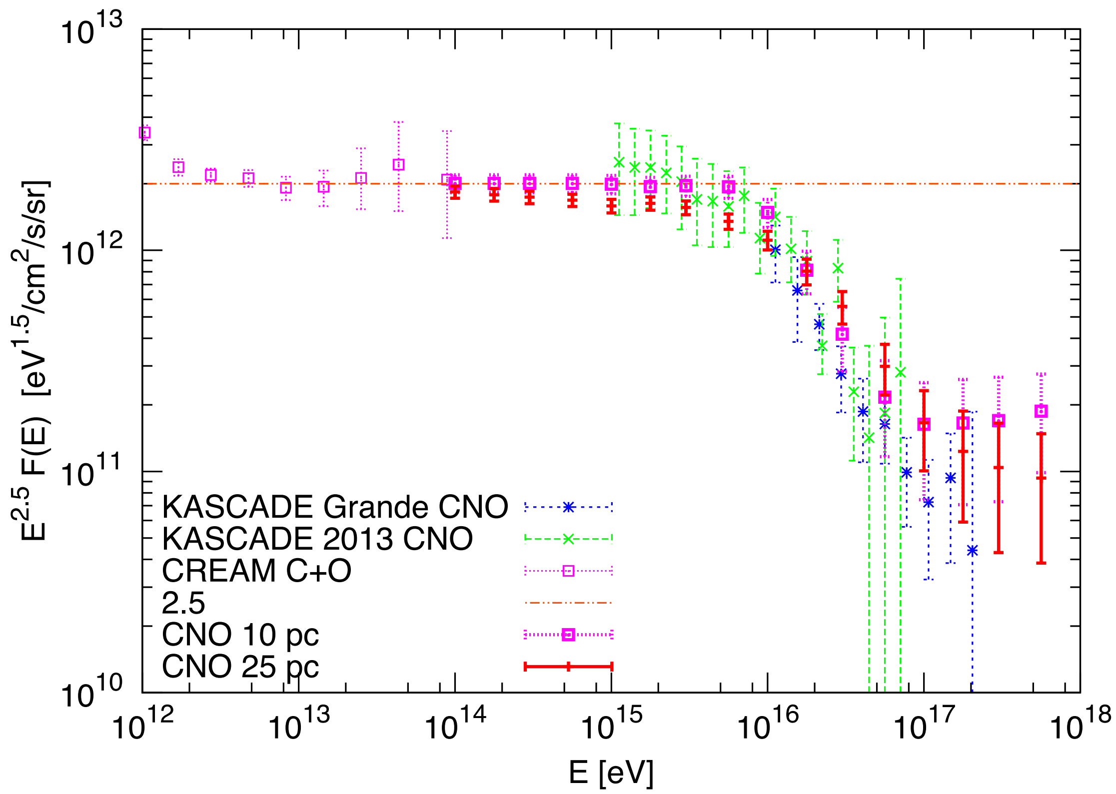
Cosmic Ray Knee: protons



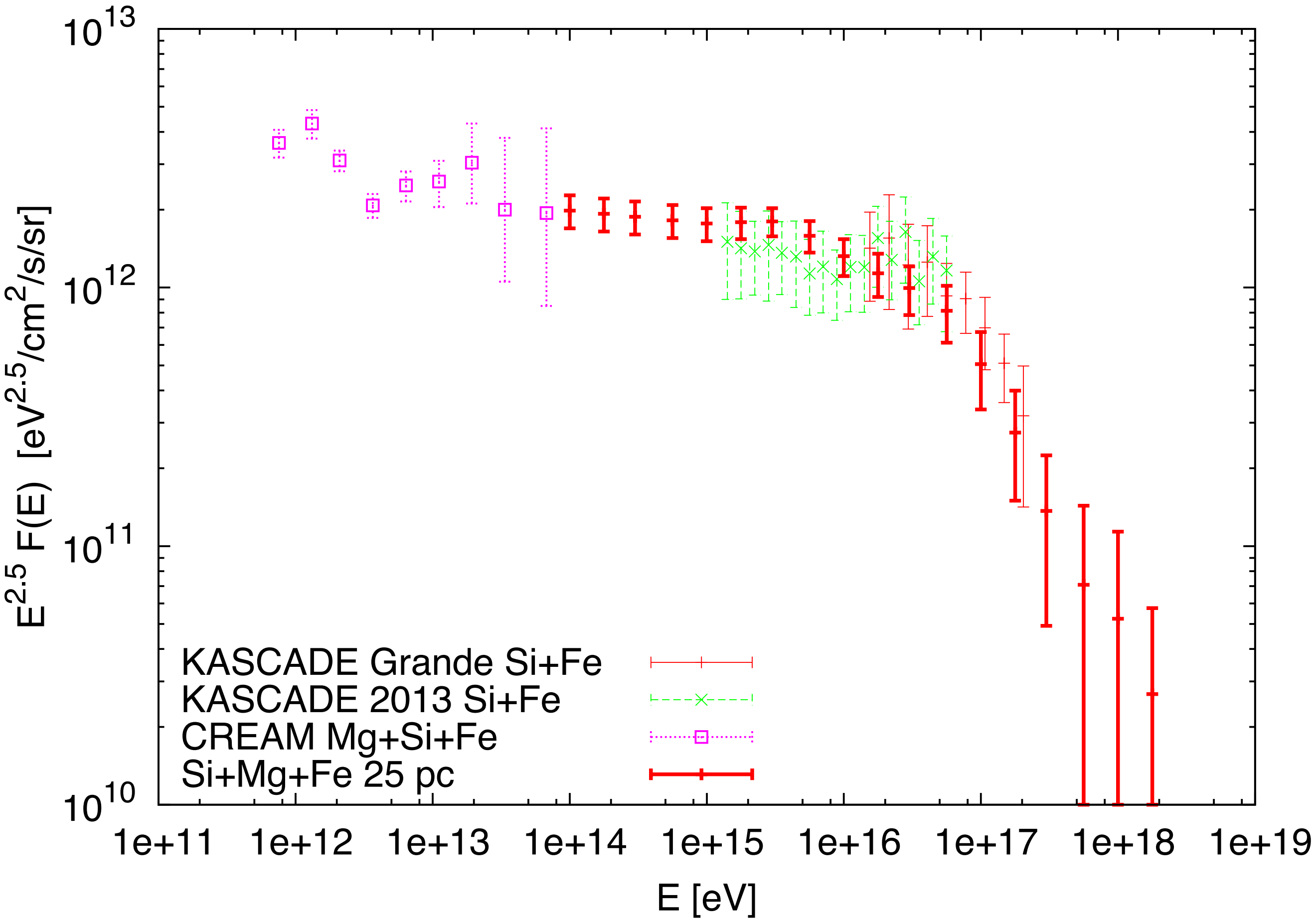
Cosmic Ray Knee: He



Cosmic Ray Knee: CNO

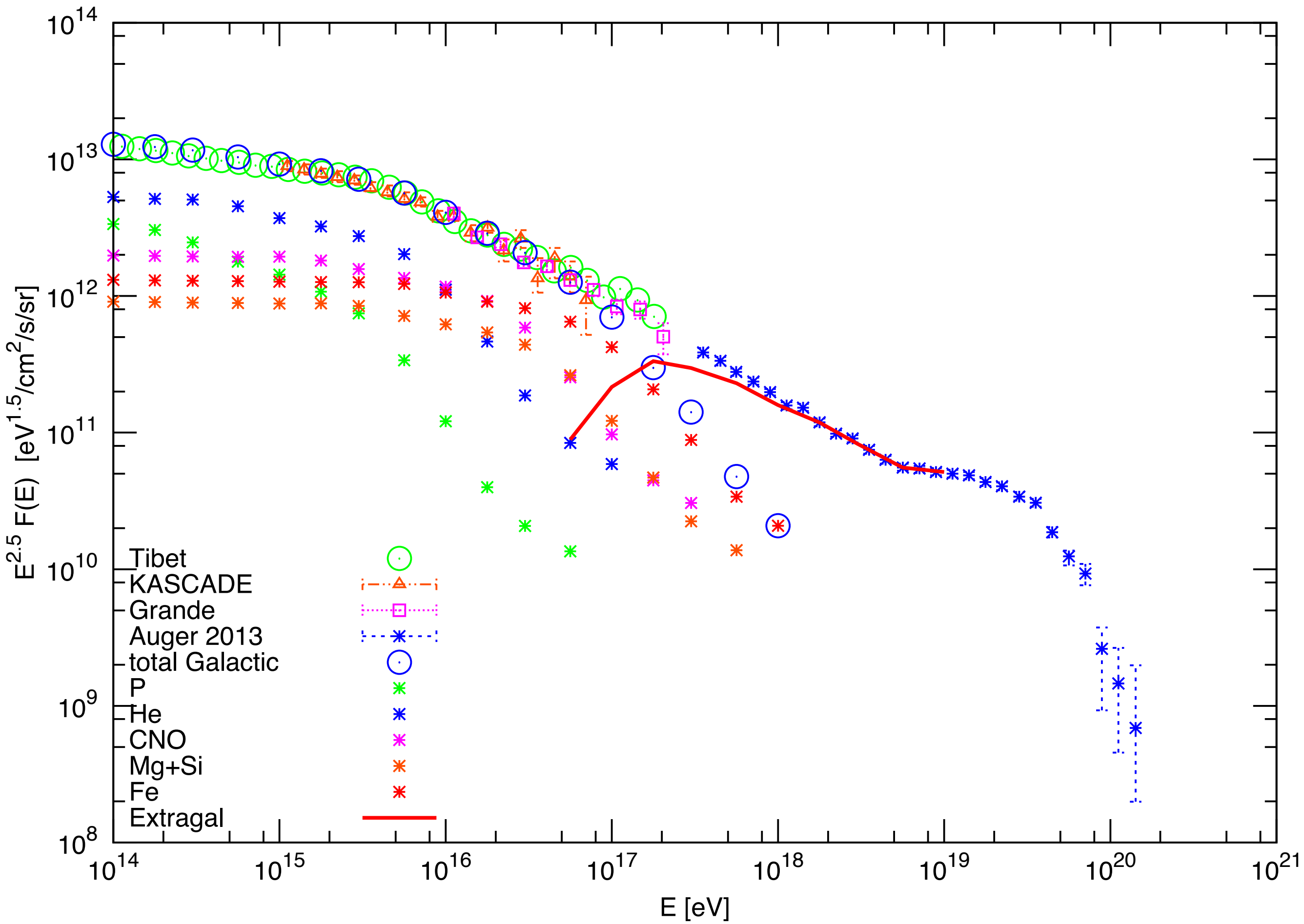


Cosmic Ray Knee: Mg+Si+Fe



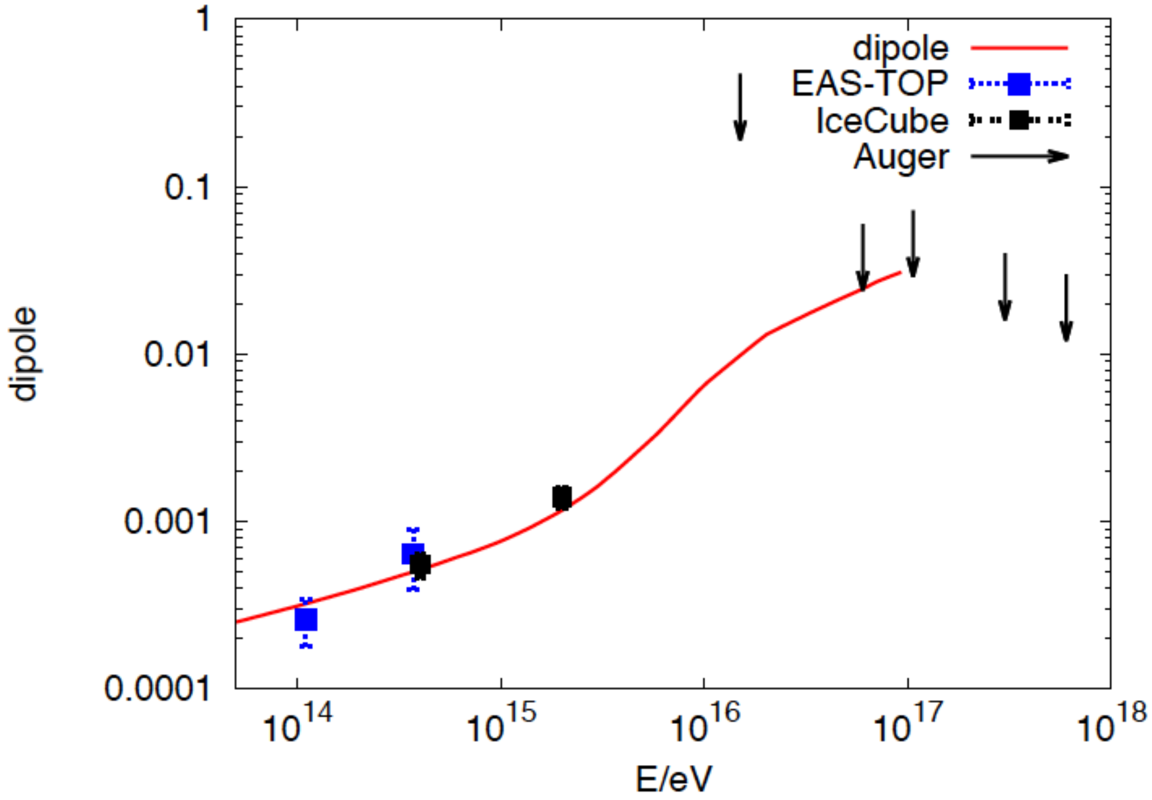
•Thanks to Andreas Haungs for discussion

Cosmic Ray Knee: all particles



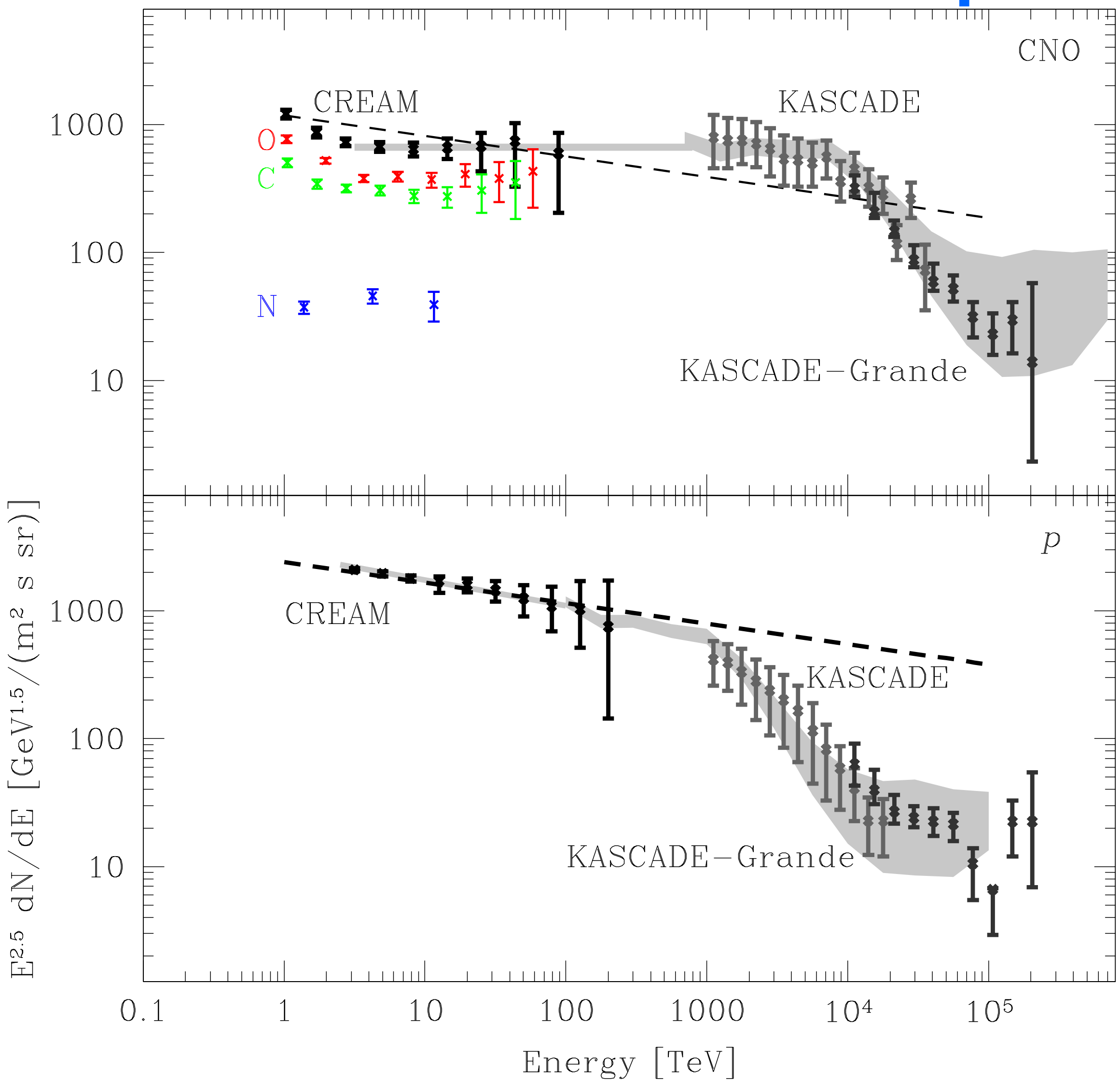
Anisotropy in arrival directions

Cosmic Ray Knee: anisotropy

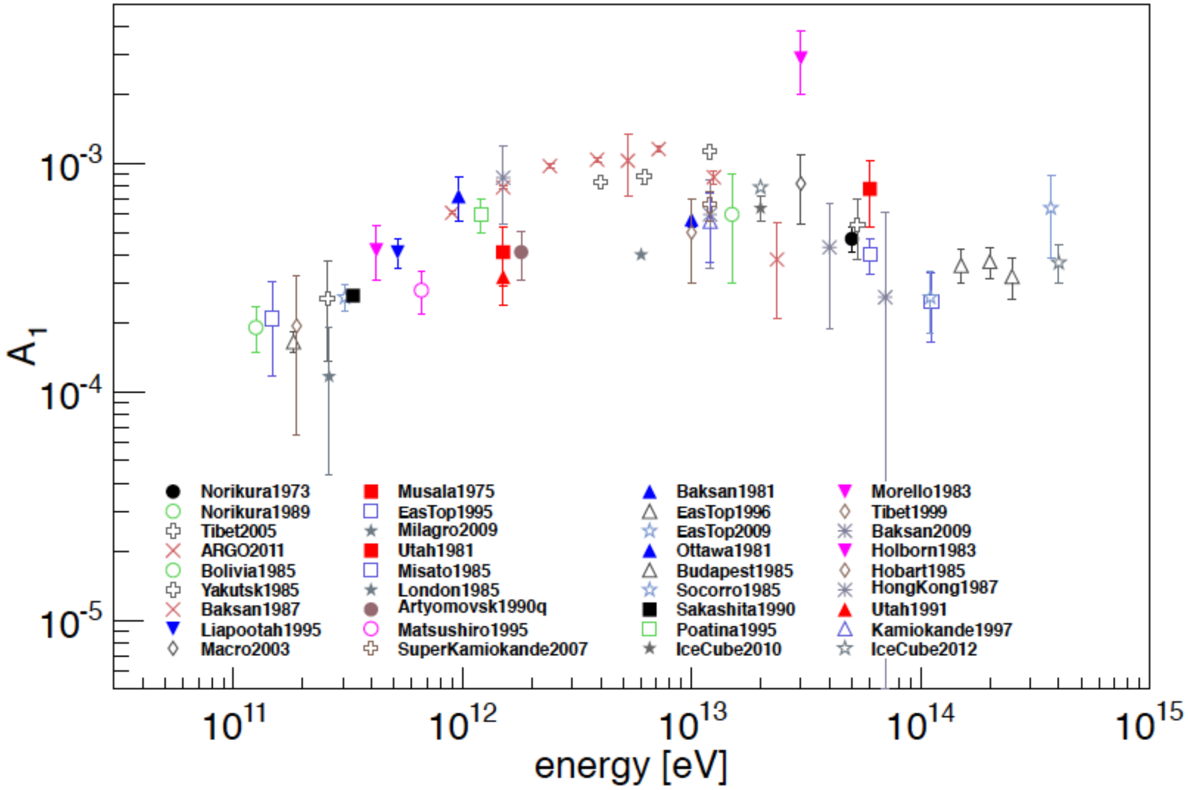


Problems of galactic cosmic ray models

Proton and CNO spectra

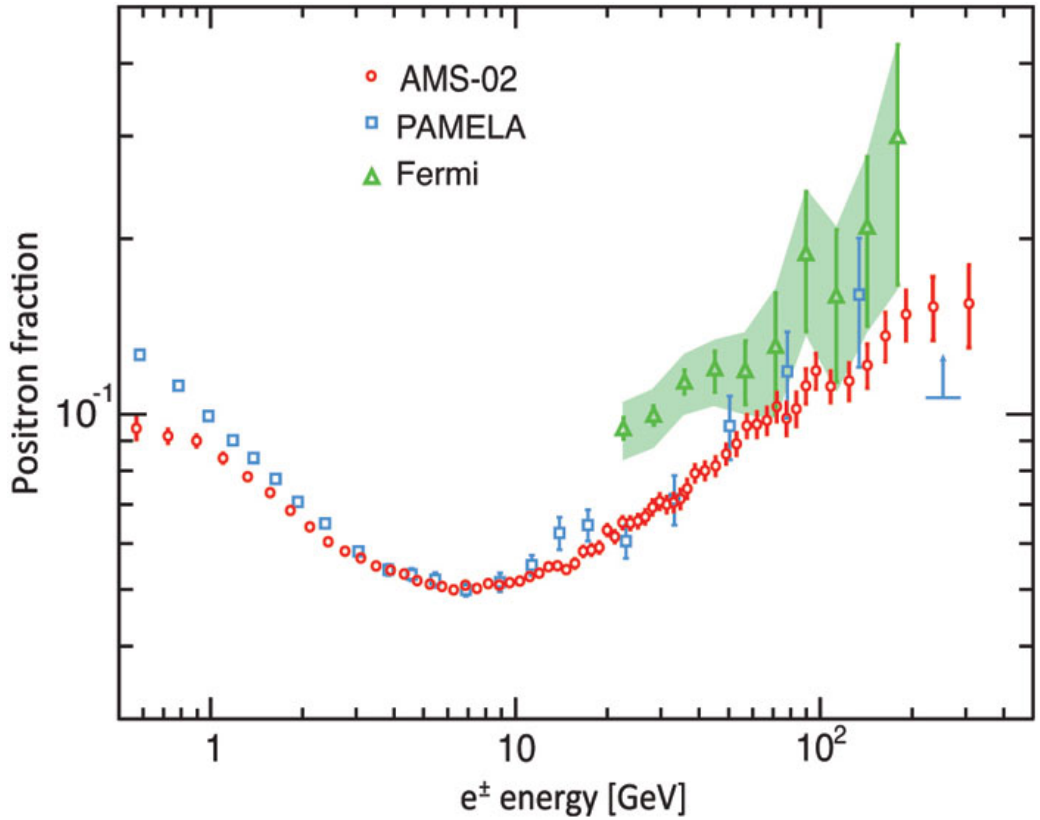


Dipole anisotropy of cosmic rays

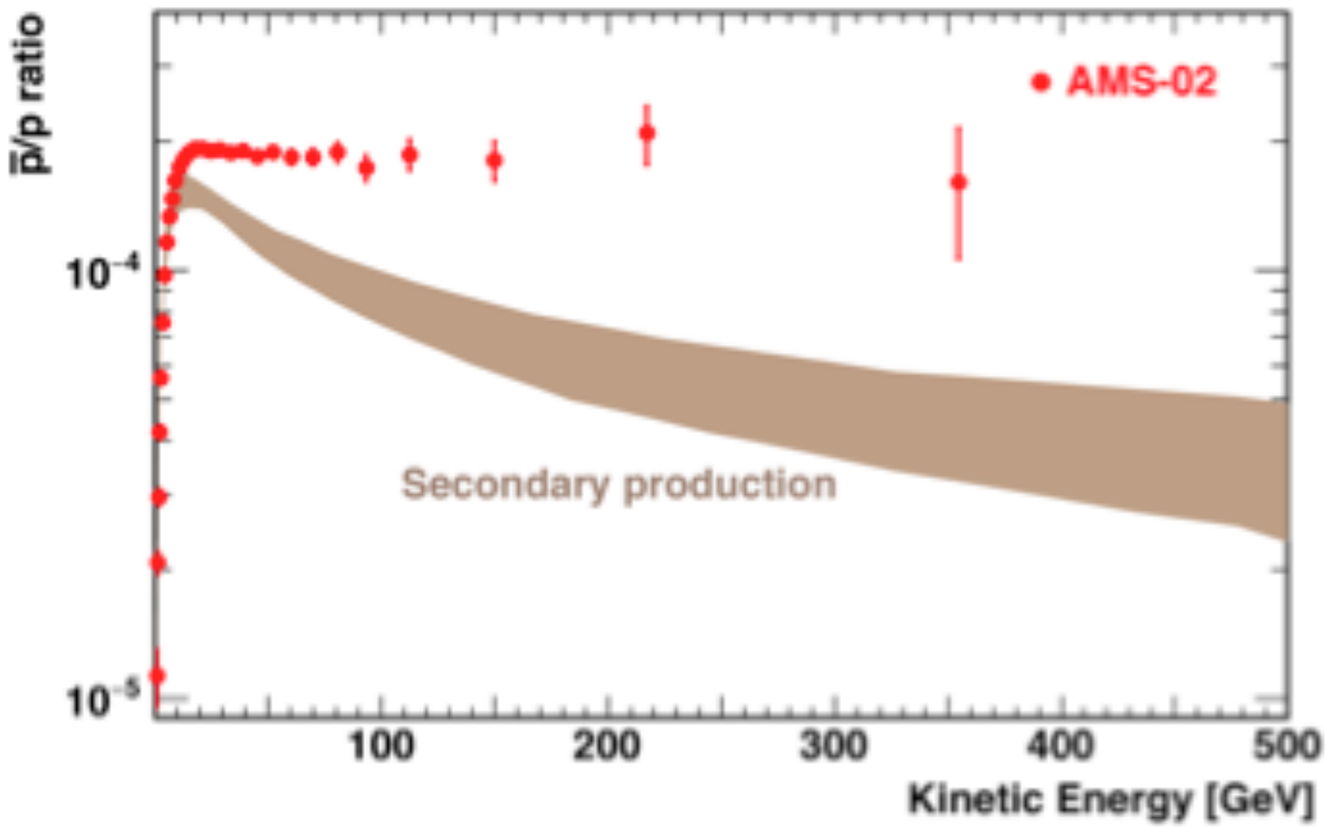


- **G.Di Sciascio and R. Iuppa, arXiv: 1407.2144**

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

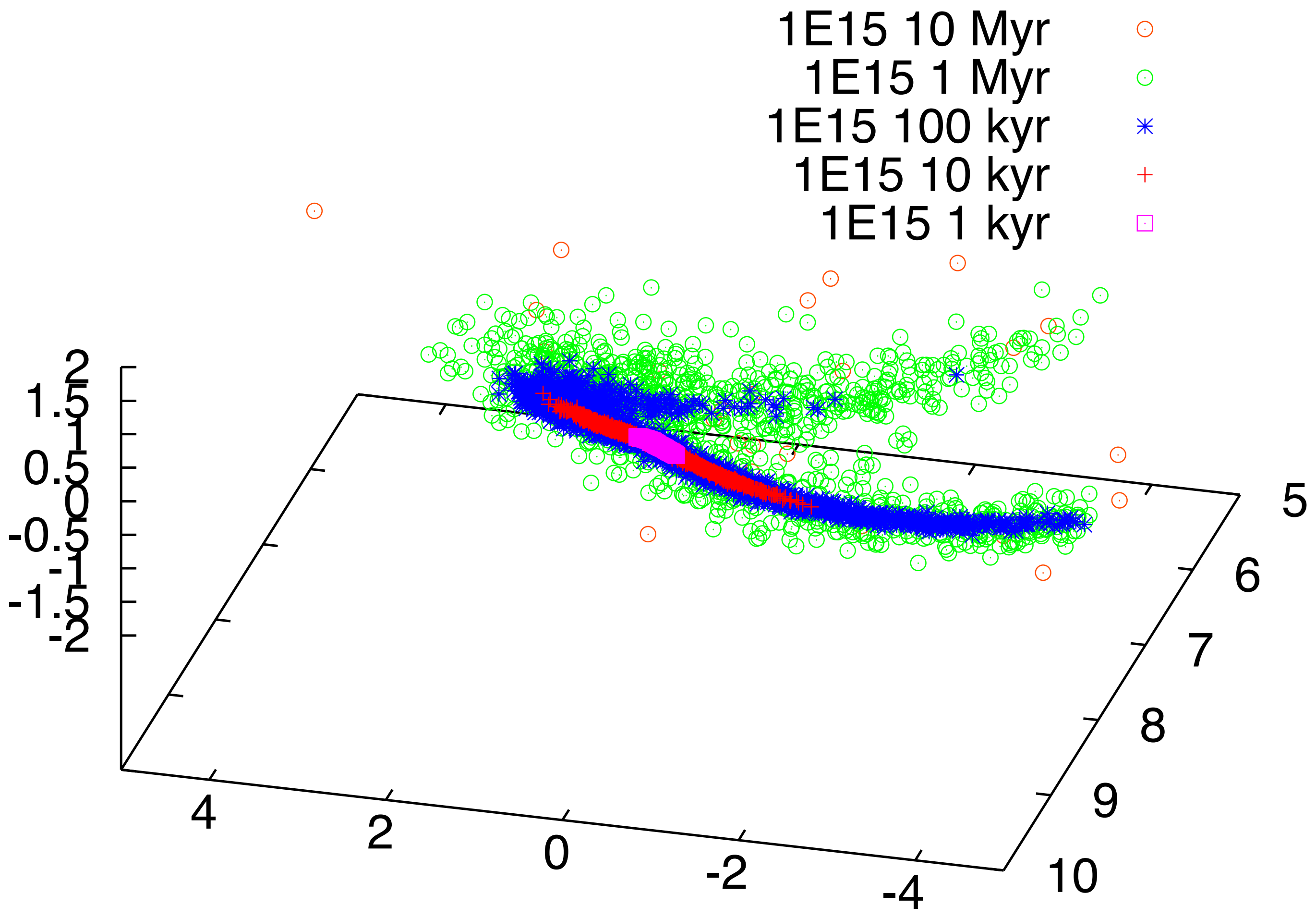


Anti-protons by AMS-2

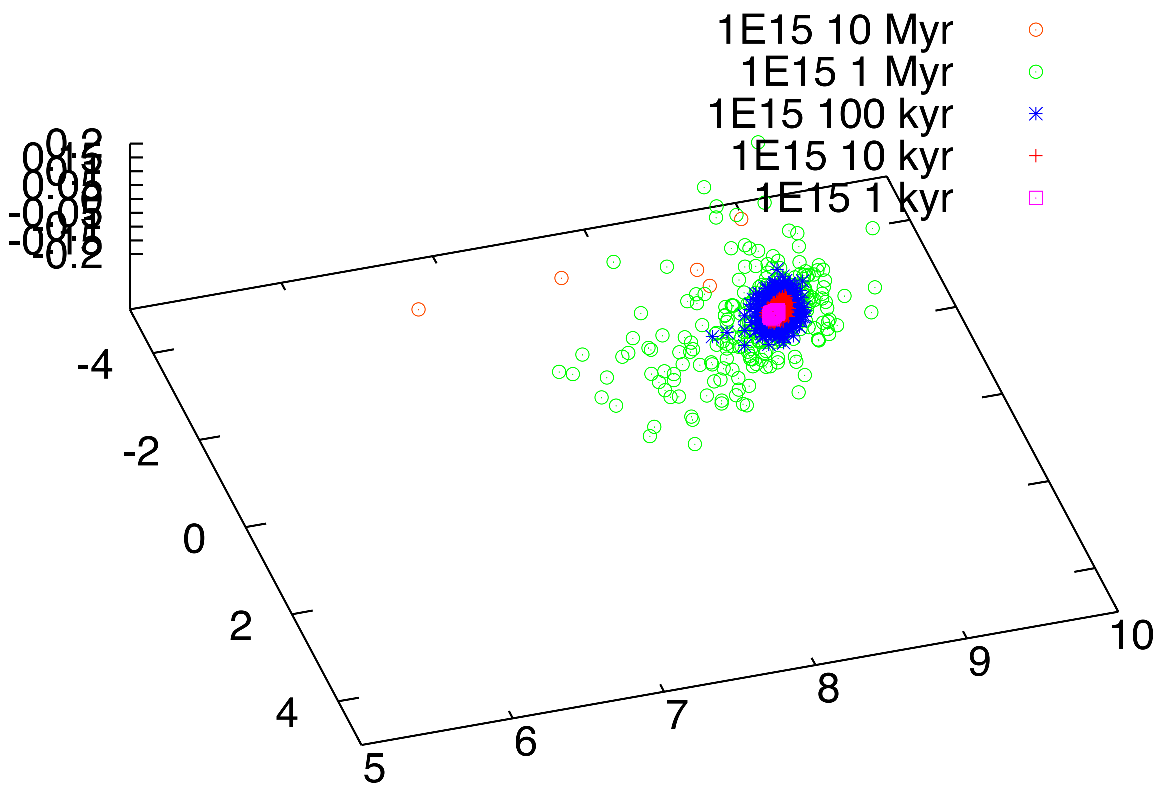


2 Myr old SN: protons, positrons and anti-protons

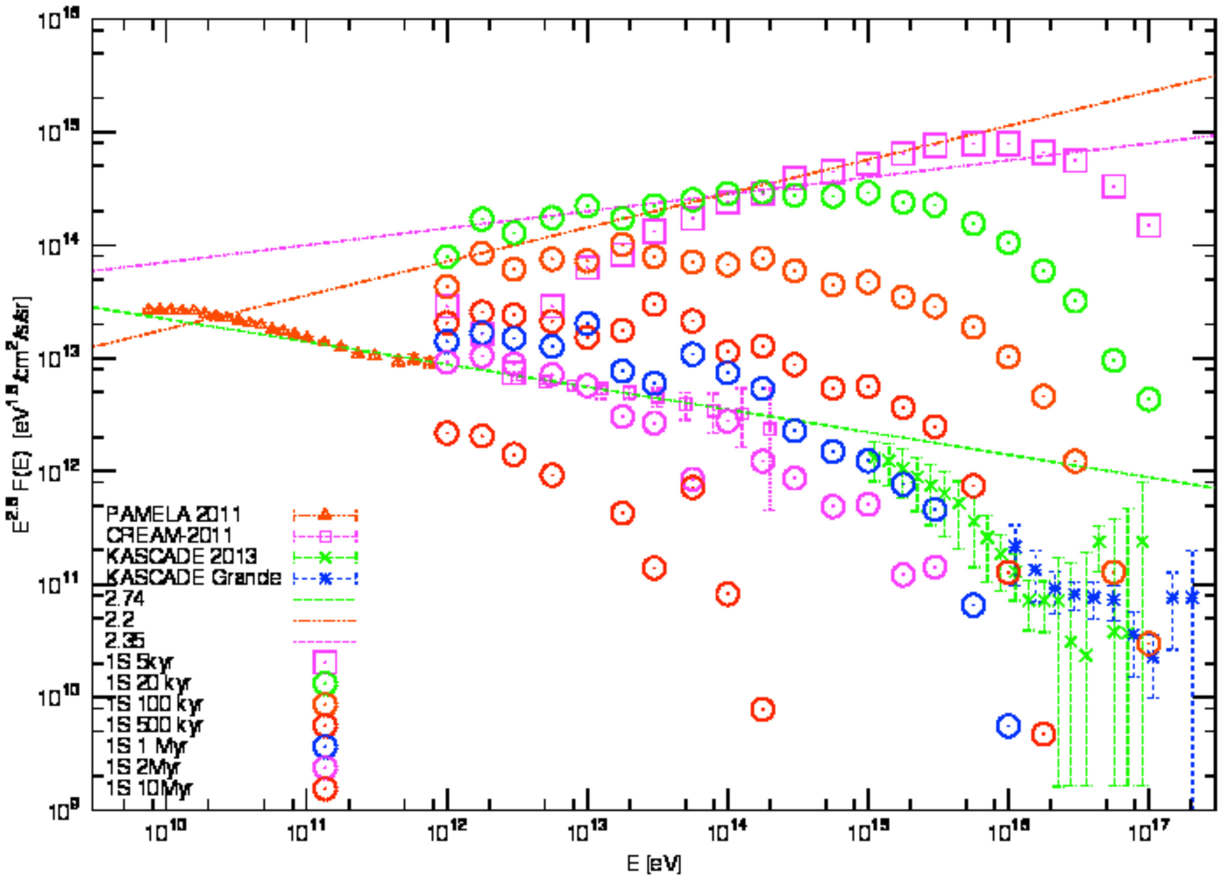
Proton flux from SN at 1 PeV



Proton flux from SN at 1 PeV



Proton flux from 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(-r^2/4DT)

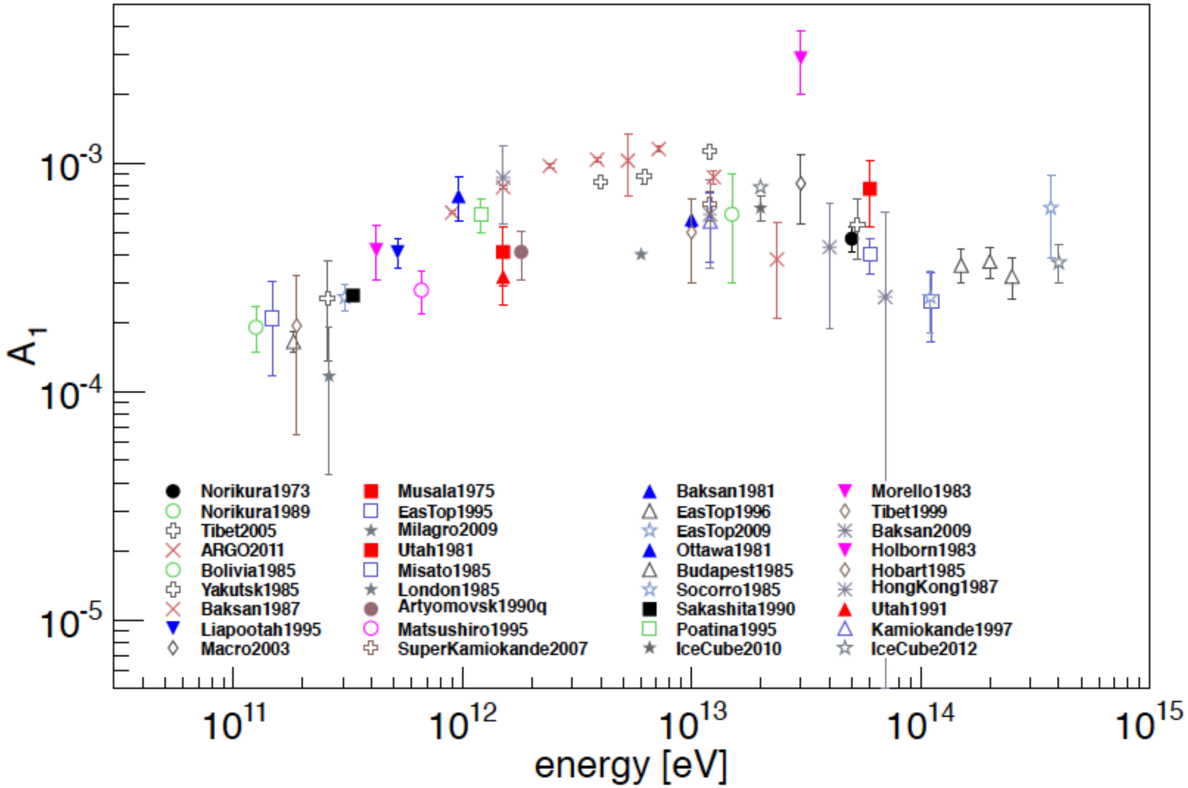
$$\delta = 3R/(2cT),$$

-

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

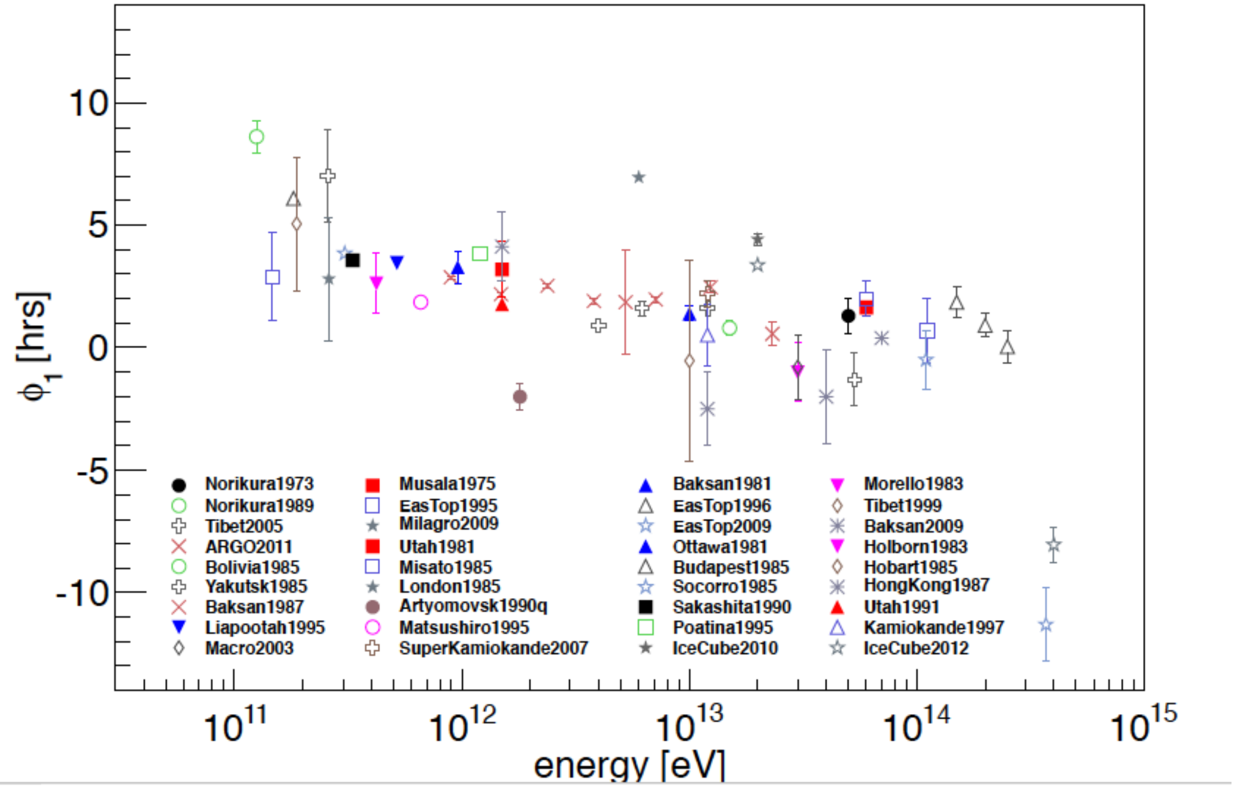
$$\delta_s = 3f_iR/(2cT).$$

Dipole anisotropy of cosmic rays



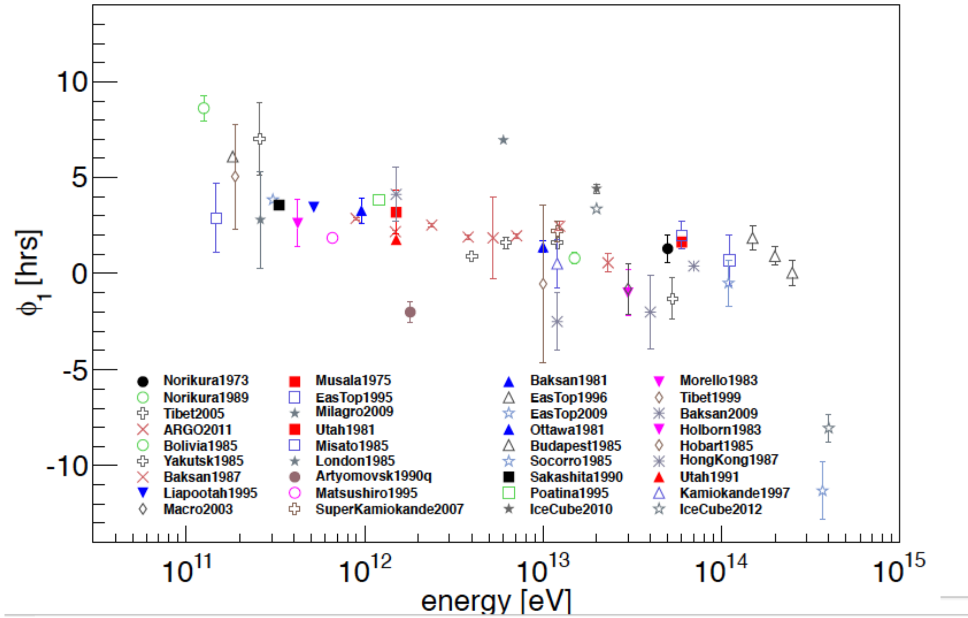
- **G.Di Sciascio and R. Iuppa, arXiv: 1407.2144**

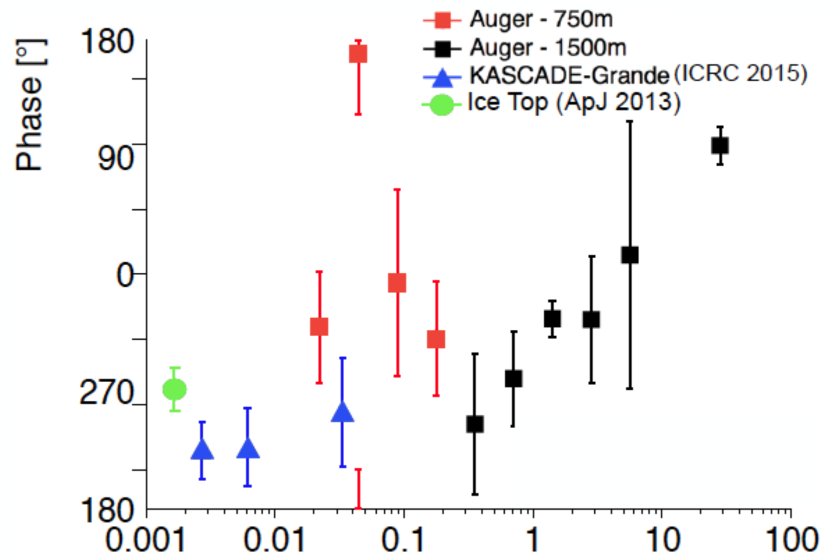
Dipole phase of cosmic rays



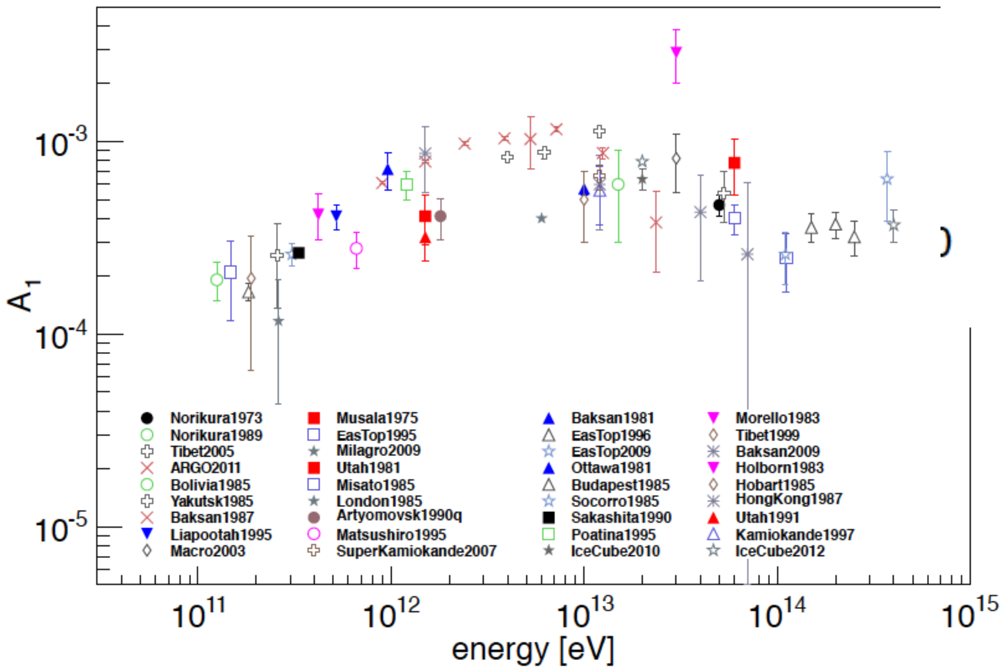
- **G.Di Sciascio and R. Iuppa, arXiv: 1407.2144**

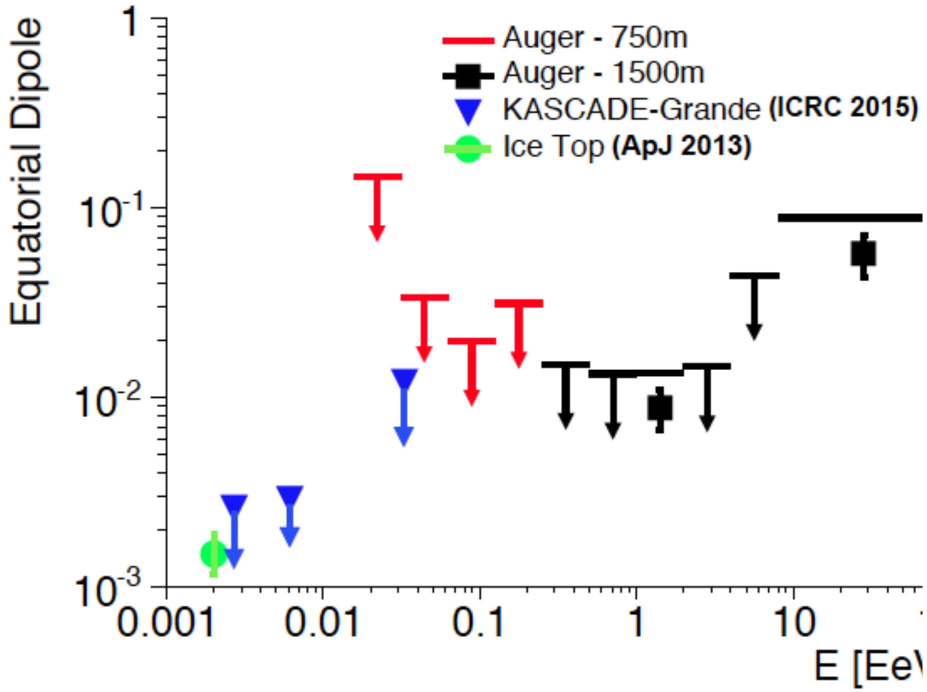
Dipole phase of cosmic rays



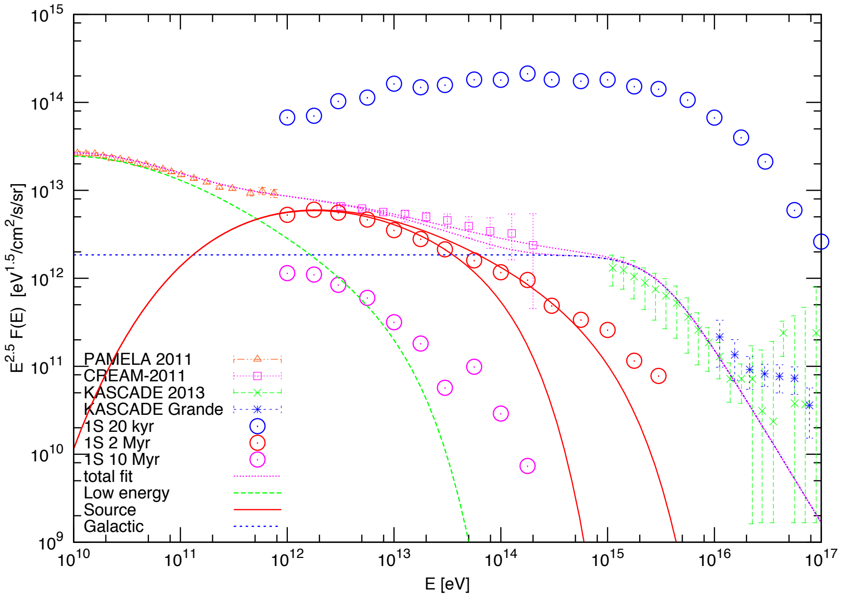


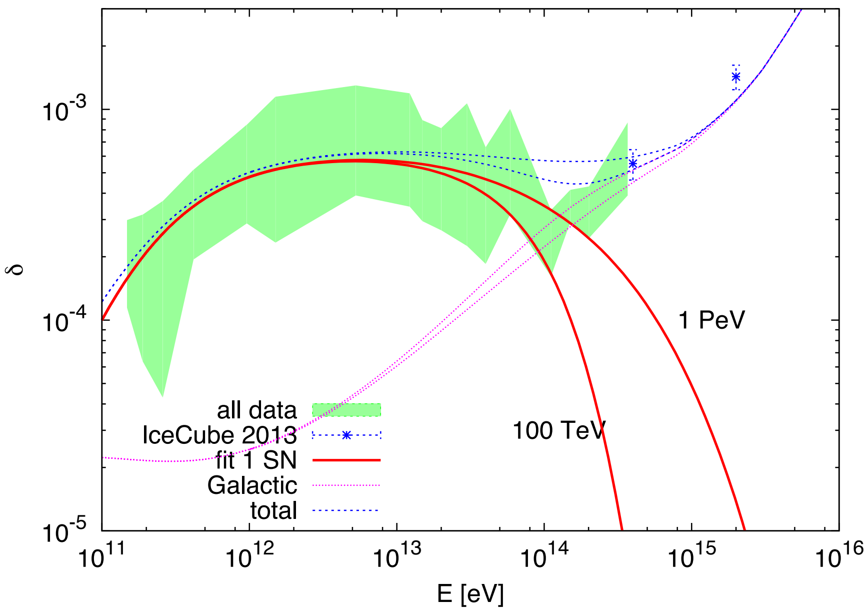
Dipole anisotro





Anisotropy and flux from 2 Myr SN

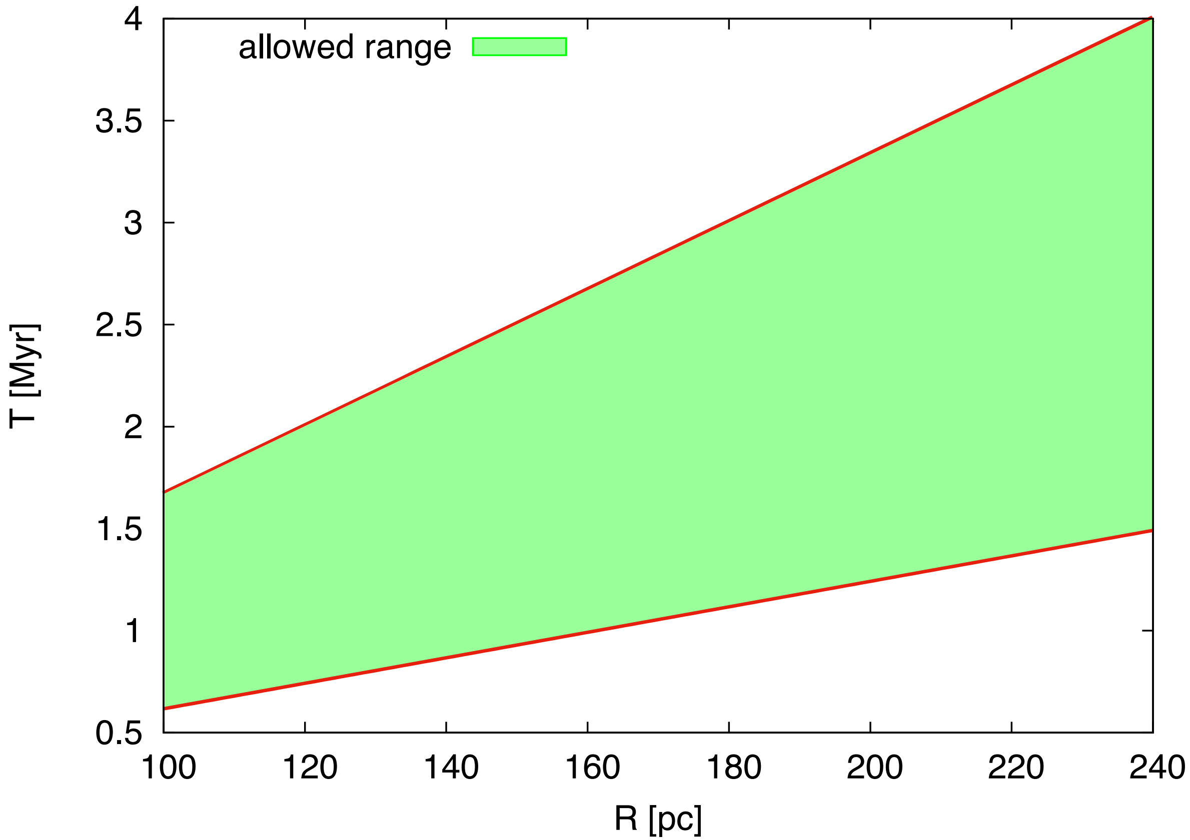




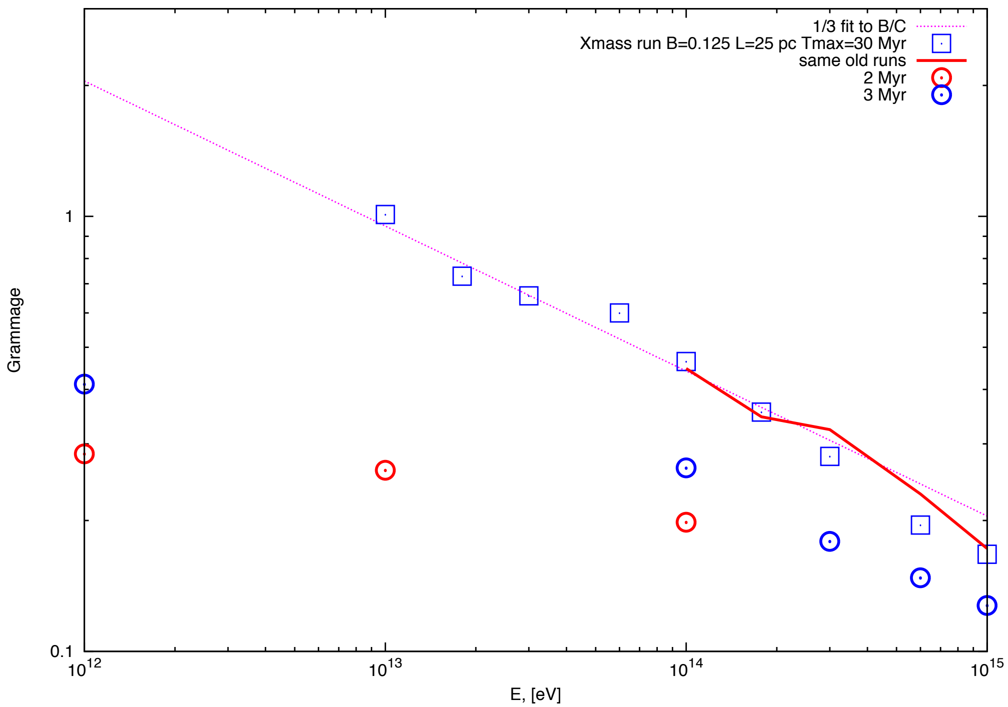
•A=3/2 R/T

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

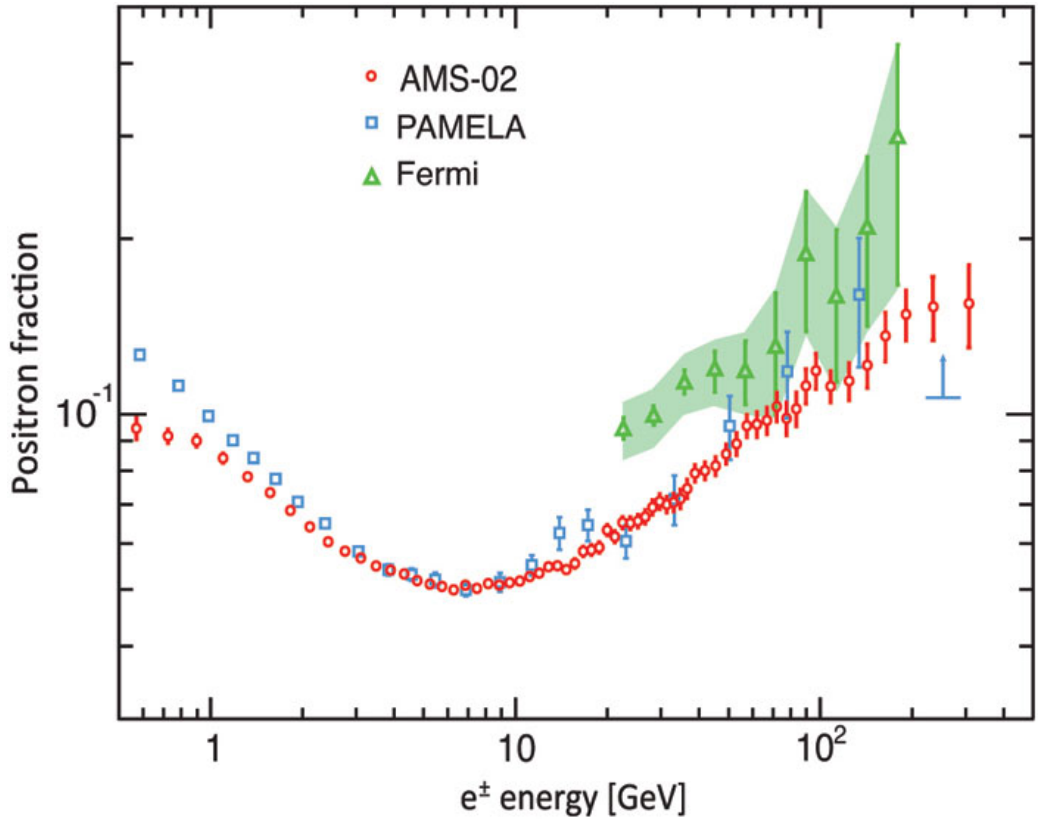
Anisotropy and parameters of SN



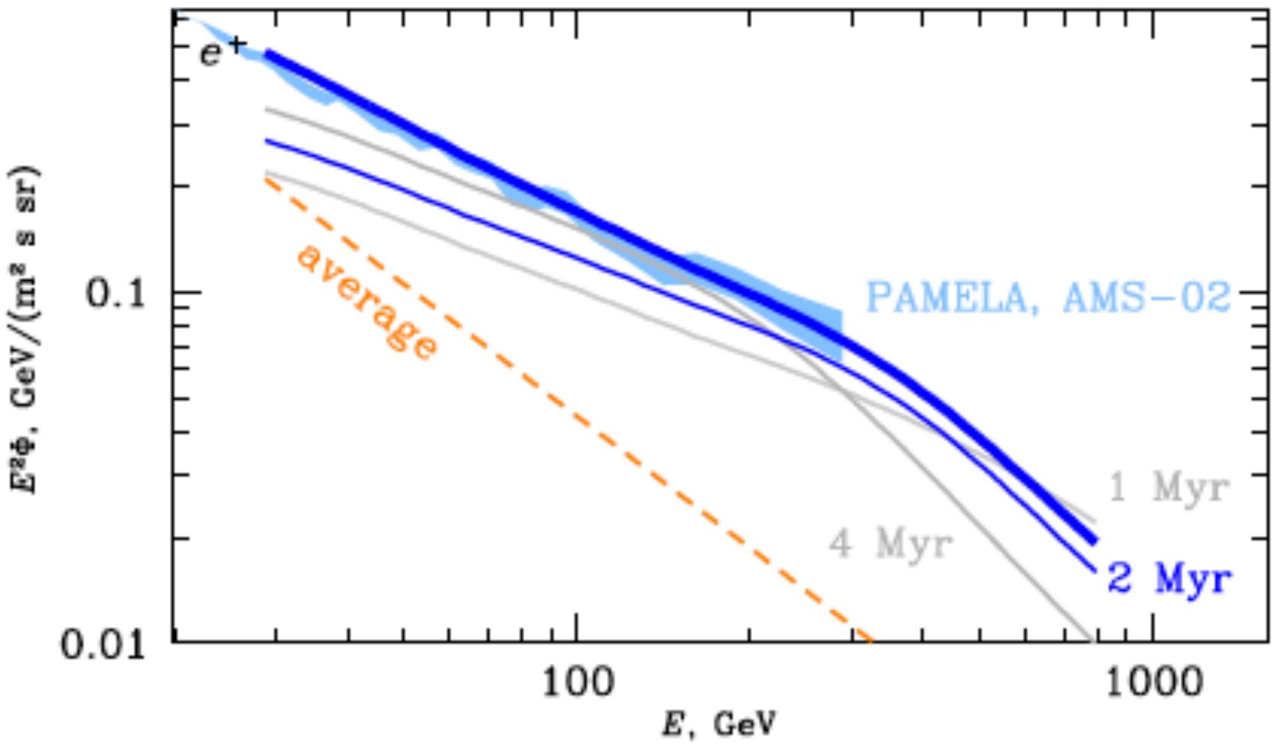
Grammage to create secondaries



Positron to (electron + positron) ratio

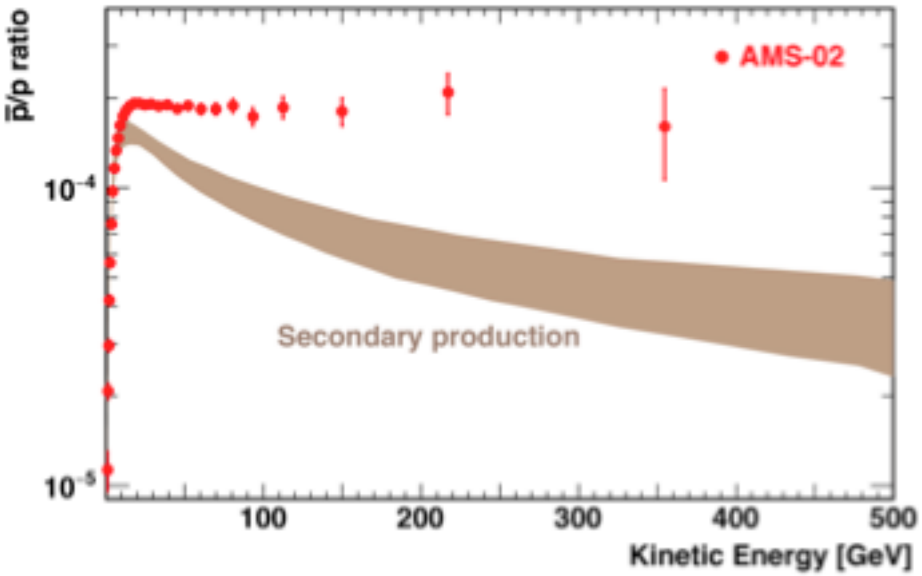


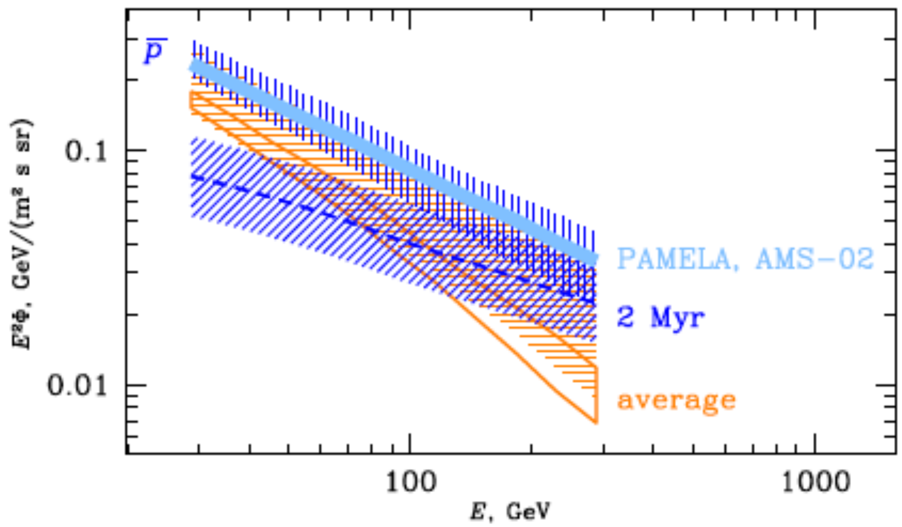
Positron flux PAMELA/AMS-II



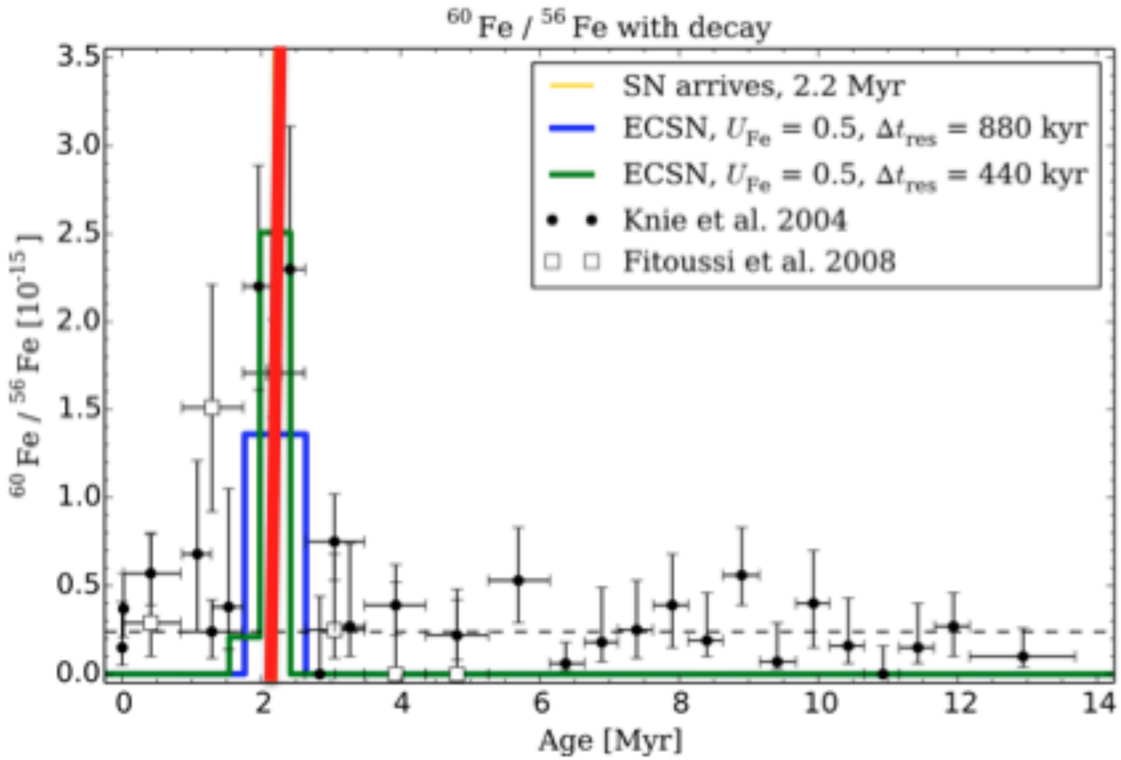
- M.Kachelriess, A. Neronov and D.Semikoz, arXiv:1504.06472

Antriprotons





Nearby SN from Fe60 in ocean crust



•Knie et al. ‘99, ’04, Fry et al. ‘15

Conclusions: galaxy

- *We have phenomenological understanding of Galactic cosmic rays from TeV*Z to 10*PeV*Z energies.*
- *Neutrinos and gamma-rays both consistent with galactic CR spectrum 1/$E^{2.5}$ (next lectures)*
- *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 plateau anomaly in the dipole anisotropy*

UHECR spectrum and GZK cutoff

Main CR energy loss processes

INTERACTIONS

Protons

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

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

Nuclei

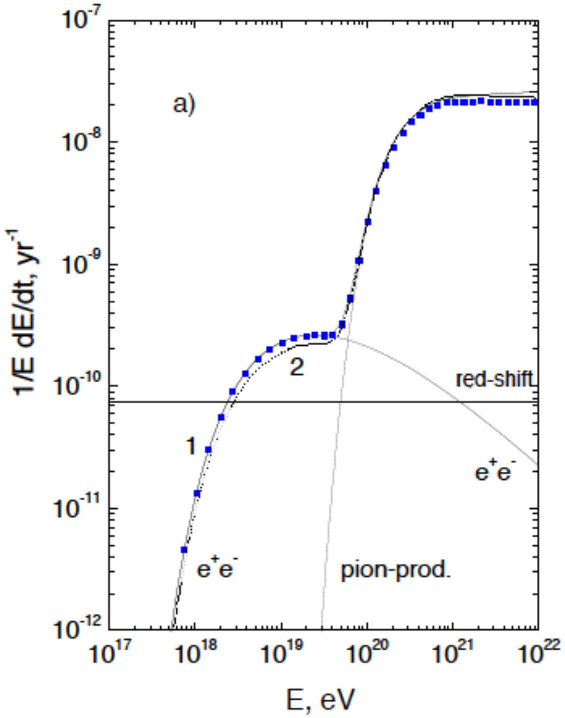
$$Z + \gamma_{\mathrm{CMB}} \to Z + e^{+} + e^{-}$$

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

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

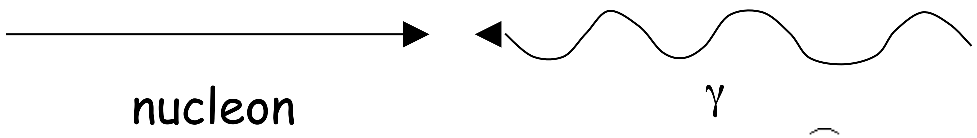
Photons

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

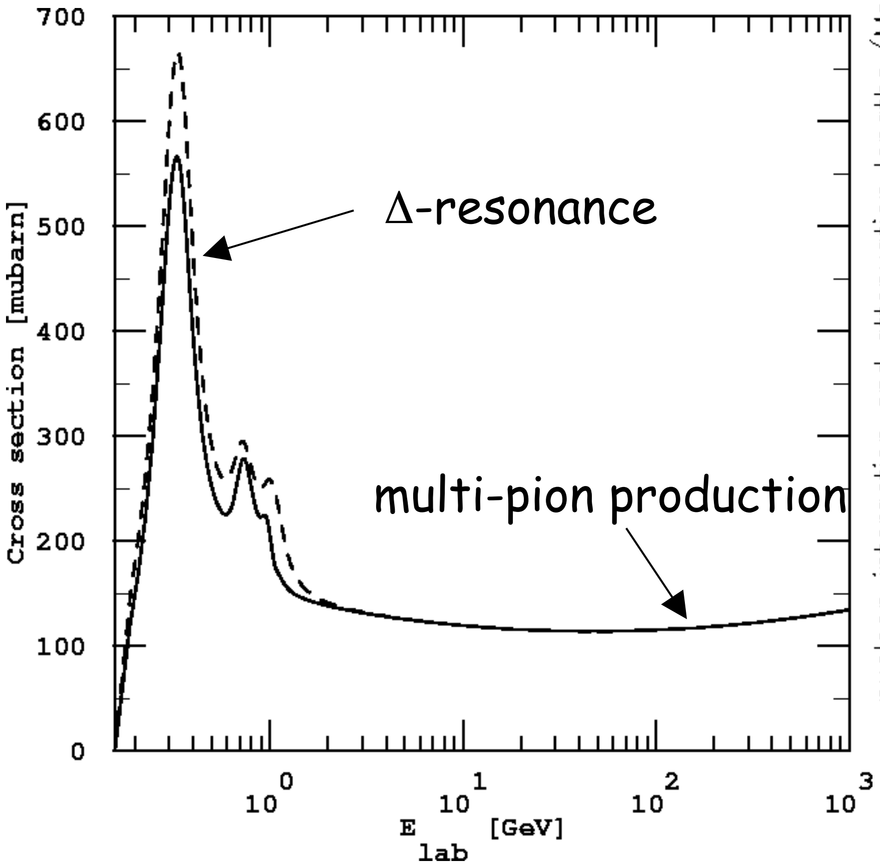


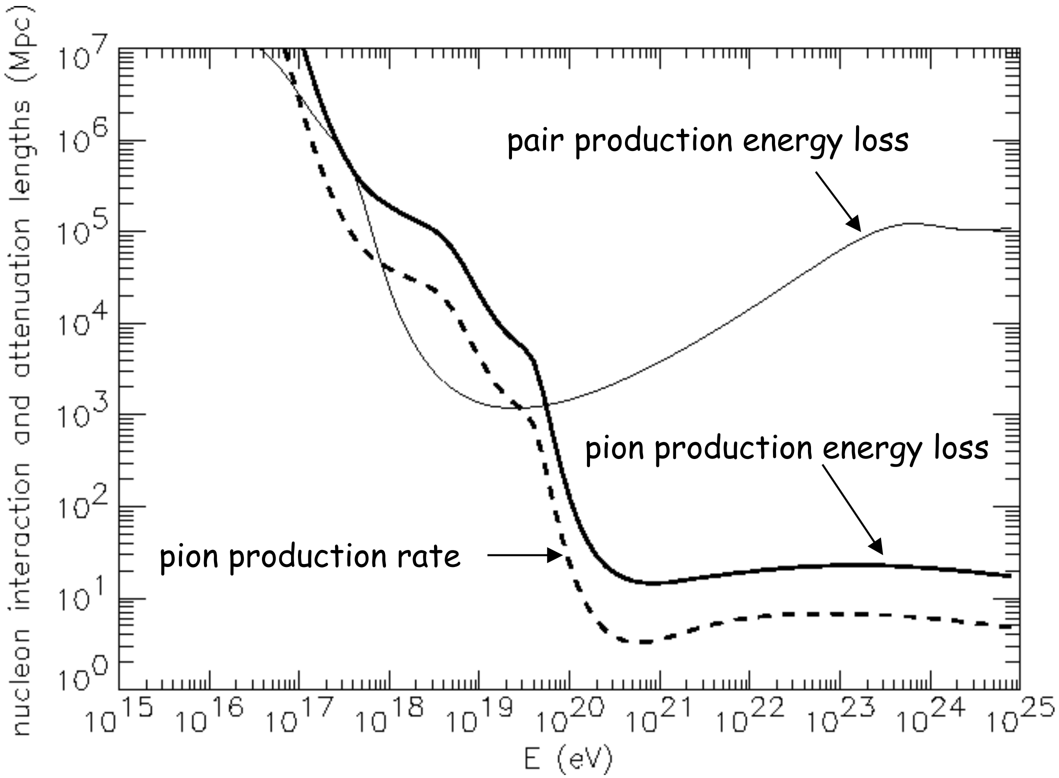
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



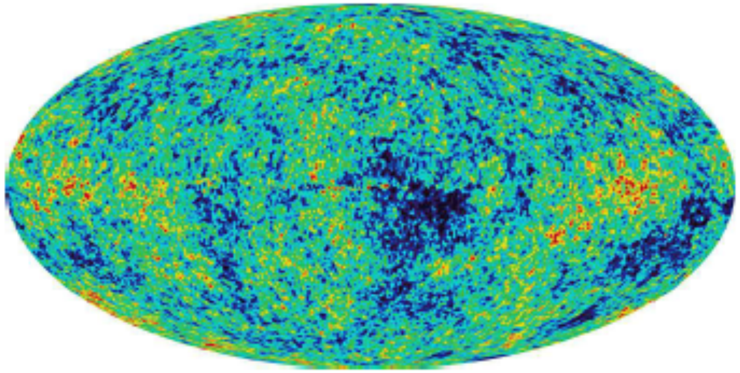
$$E_{\rm th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 4\cdot 10^{19}\,\mathrm{eV}$$



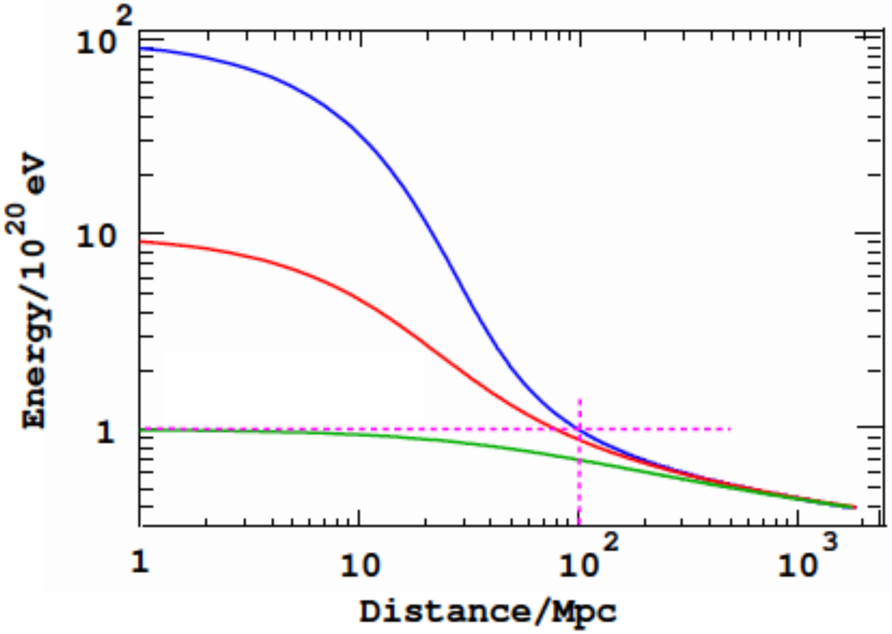


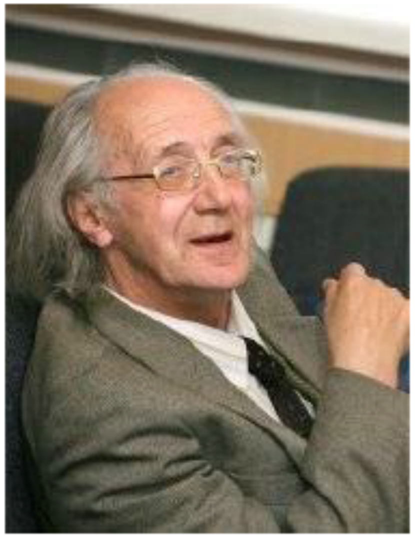
⇒sources must be in cosmological backyard
within 50-100 Mpc from Earth
(compare to the Universe size ~ 5000 Mpc)

Greisen-Zatsepin-Kuzmin Effect

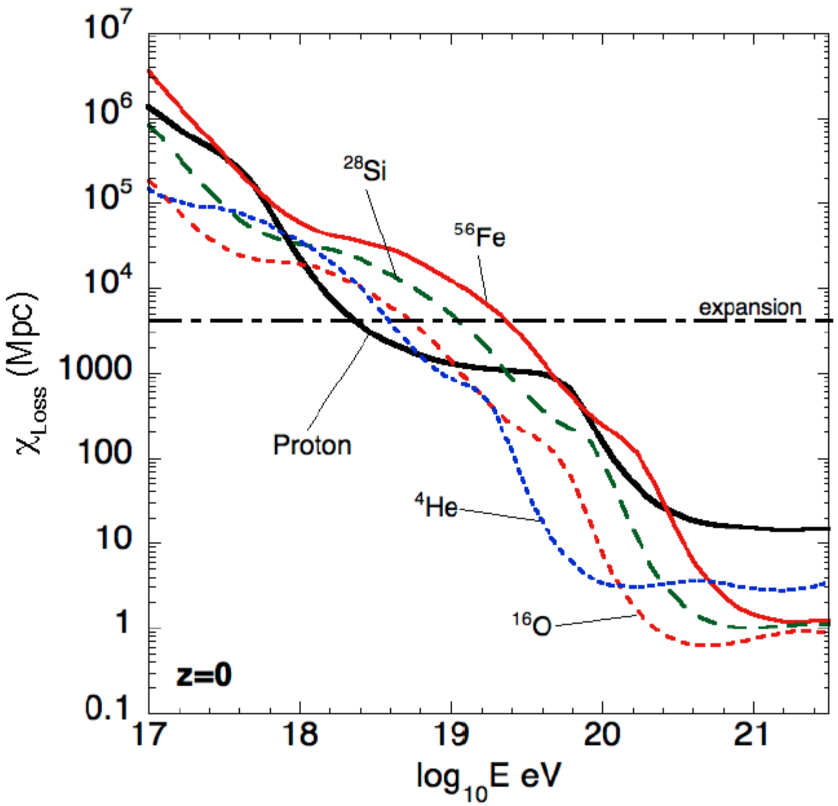


$$p + \gamma_{\mathrm{CMB}} \to N + \pi$$



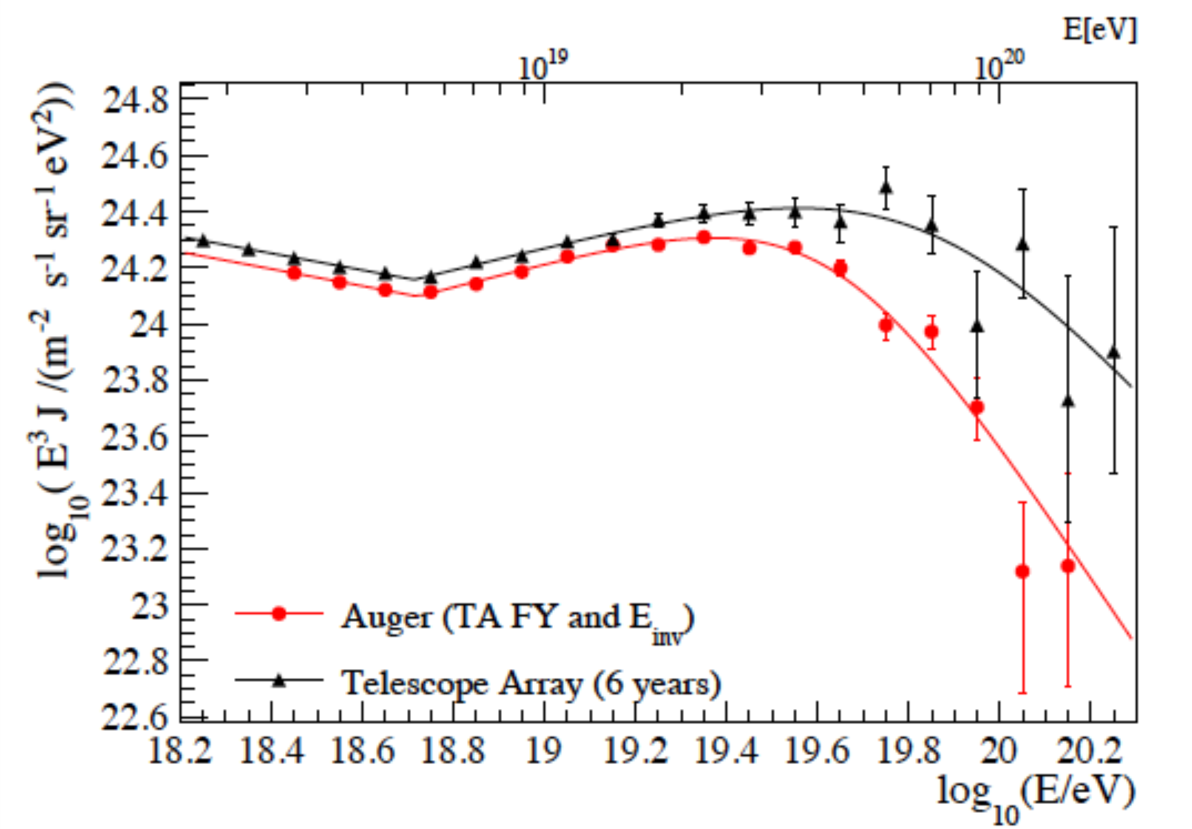


Same true for heavy nuclei: IR background is important



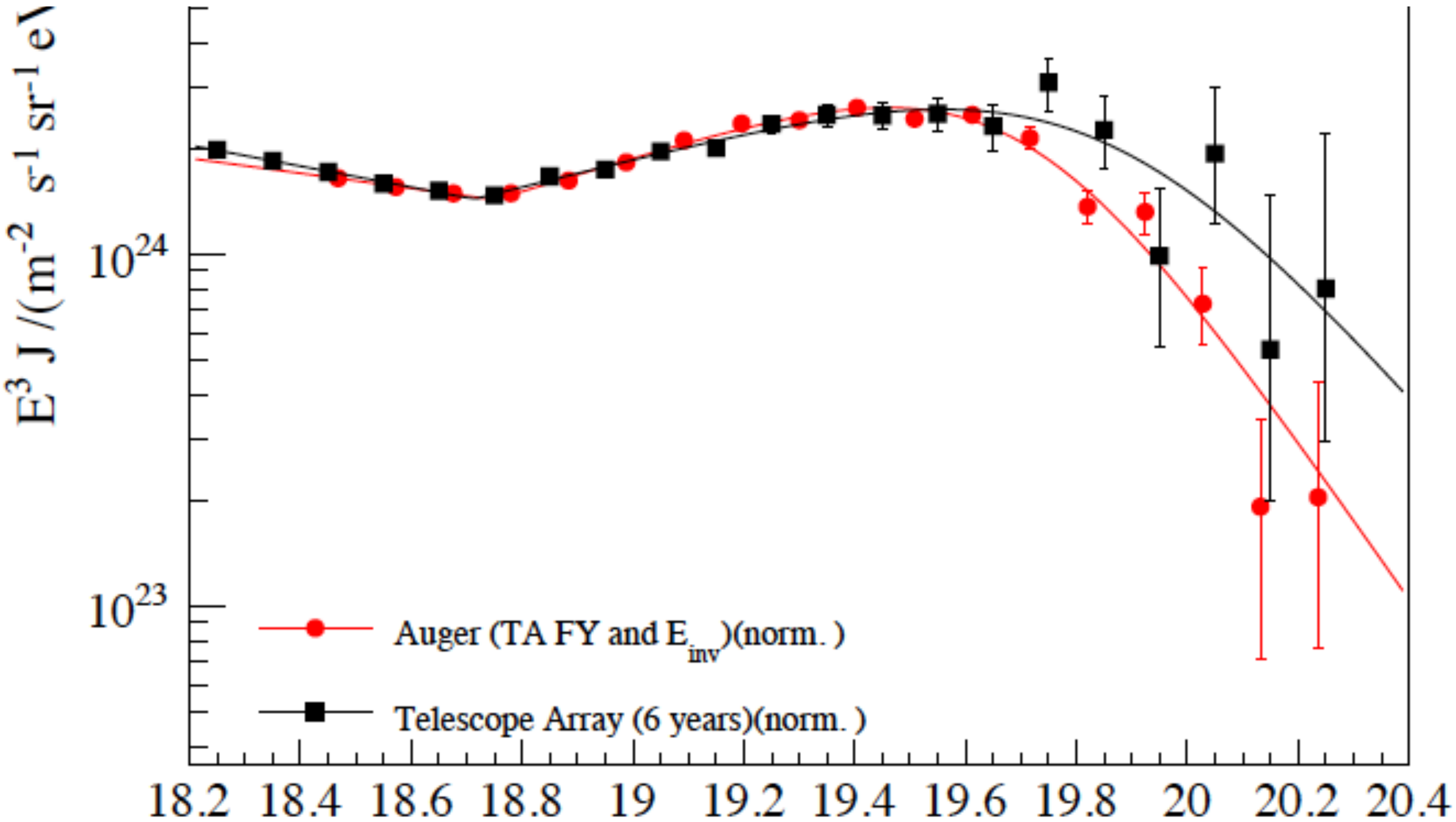
D.Allard, **arXiv:1111.3290**

Auger/TA Energy Spectrum



UHECR 2014

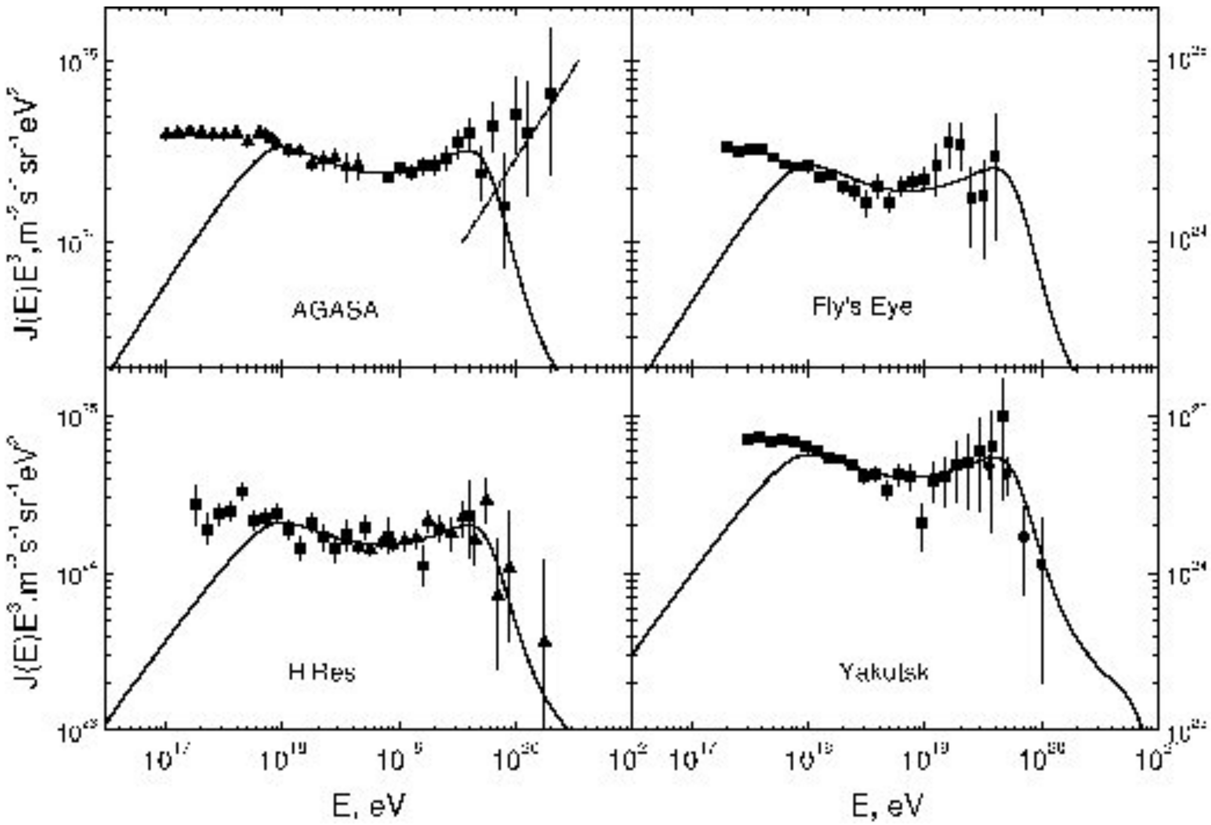
Auger/TA Energy Spectrum



UHECR 2014

Theoretical models and composition at highest energies

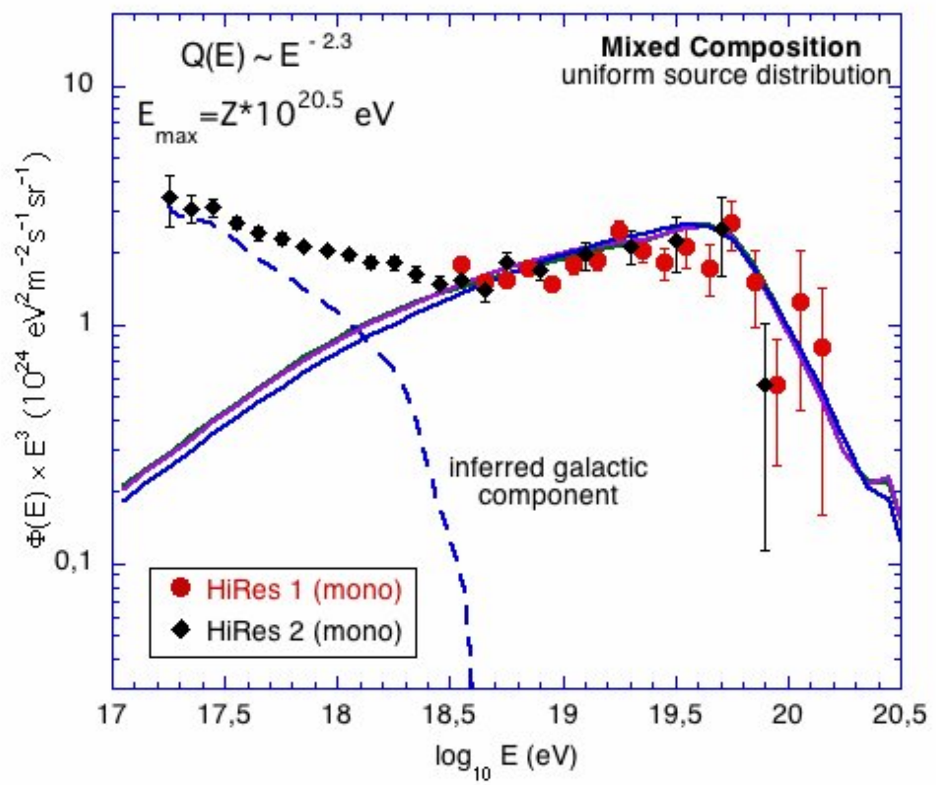
Protons can fit UHECR data



V.Berezinsky , astro-ph/0509069

problem: composition

Mixed composition model

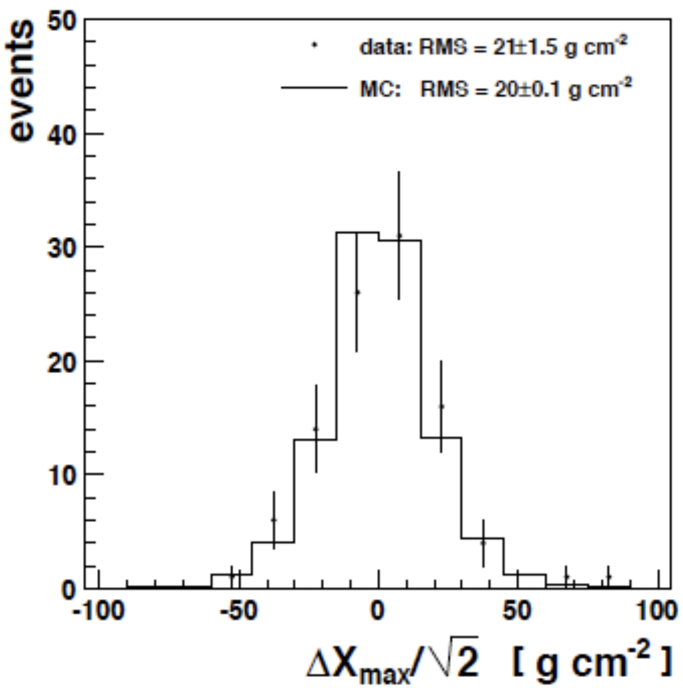


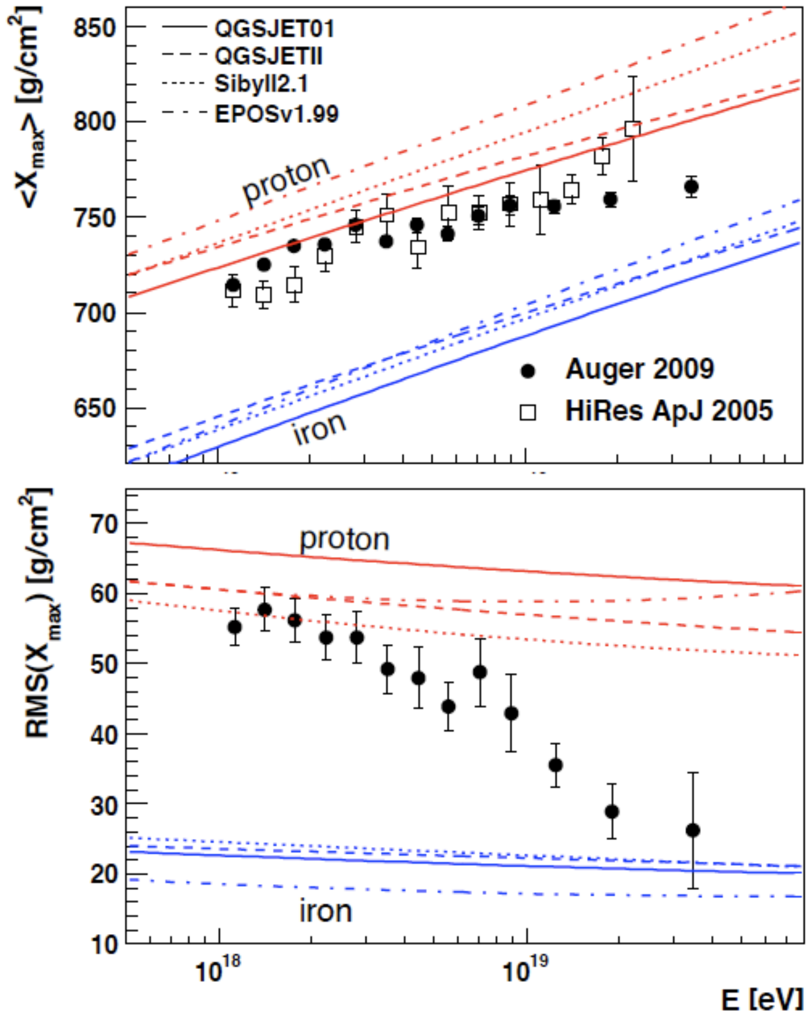
D.Allard, E.Parizot and A.Olinto, astro-ph/0512345

Problems: 1) escape of the nuclei from the source

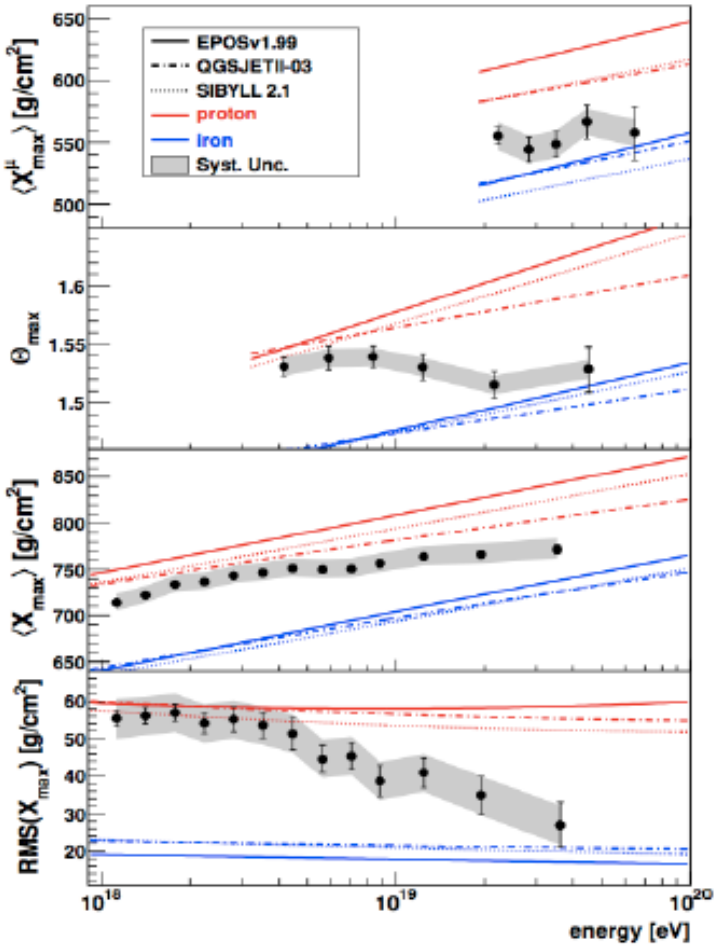
2) How to accelerate Fe in our Galaxy

Auger composition 2009: nuclei!



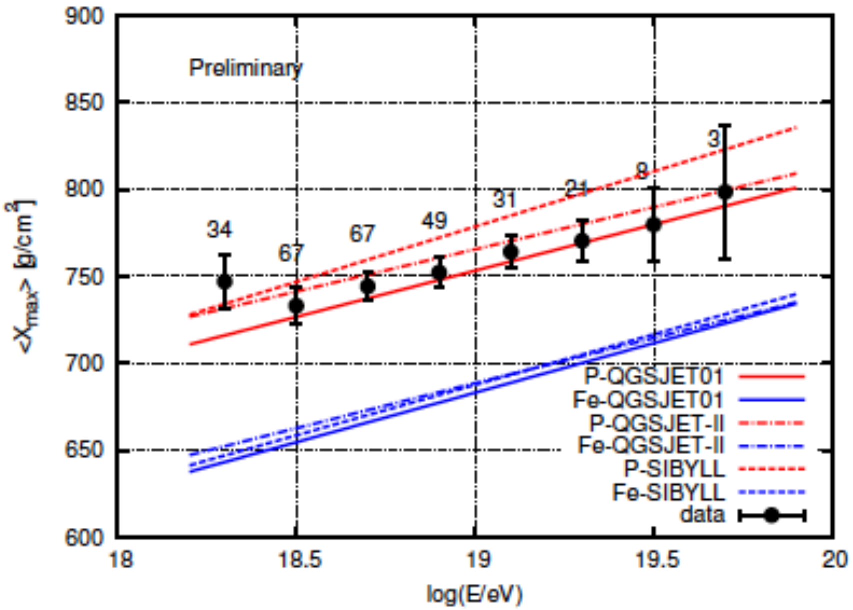


PAO - heavy nuclei

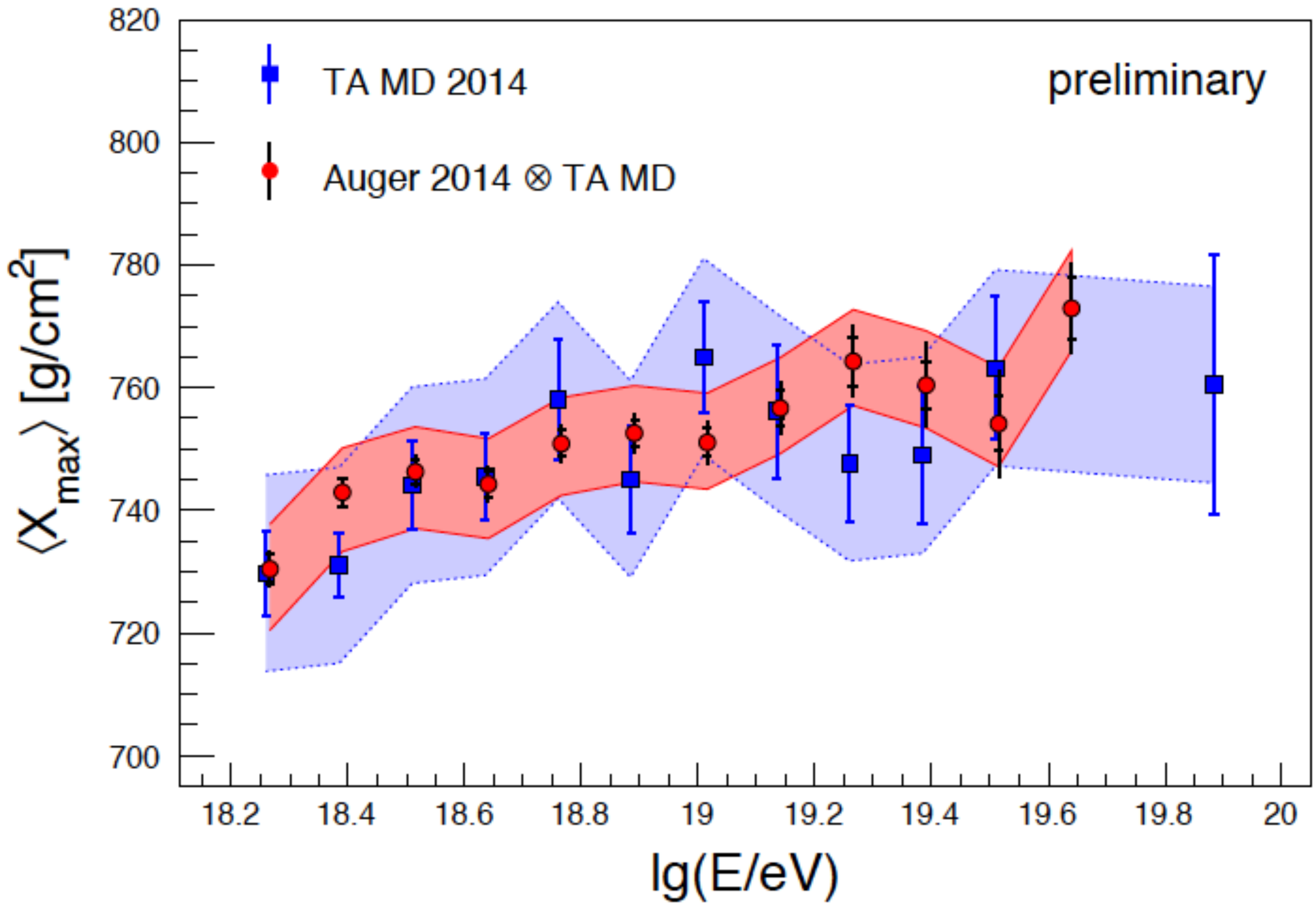


H. Wahlberg (PAO, this conference)

TA- protons

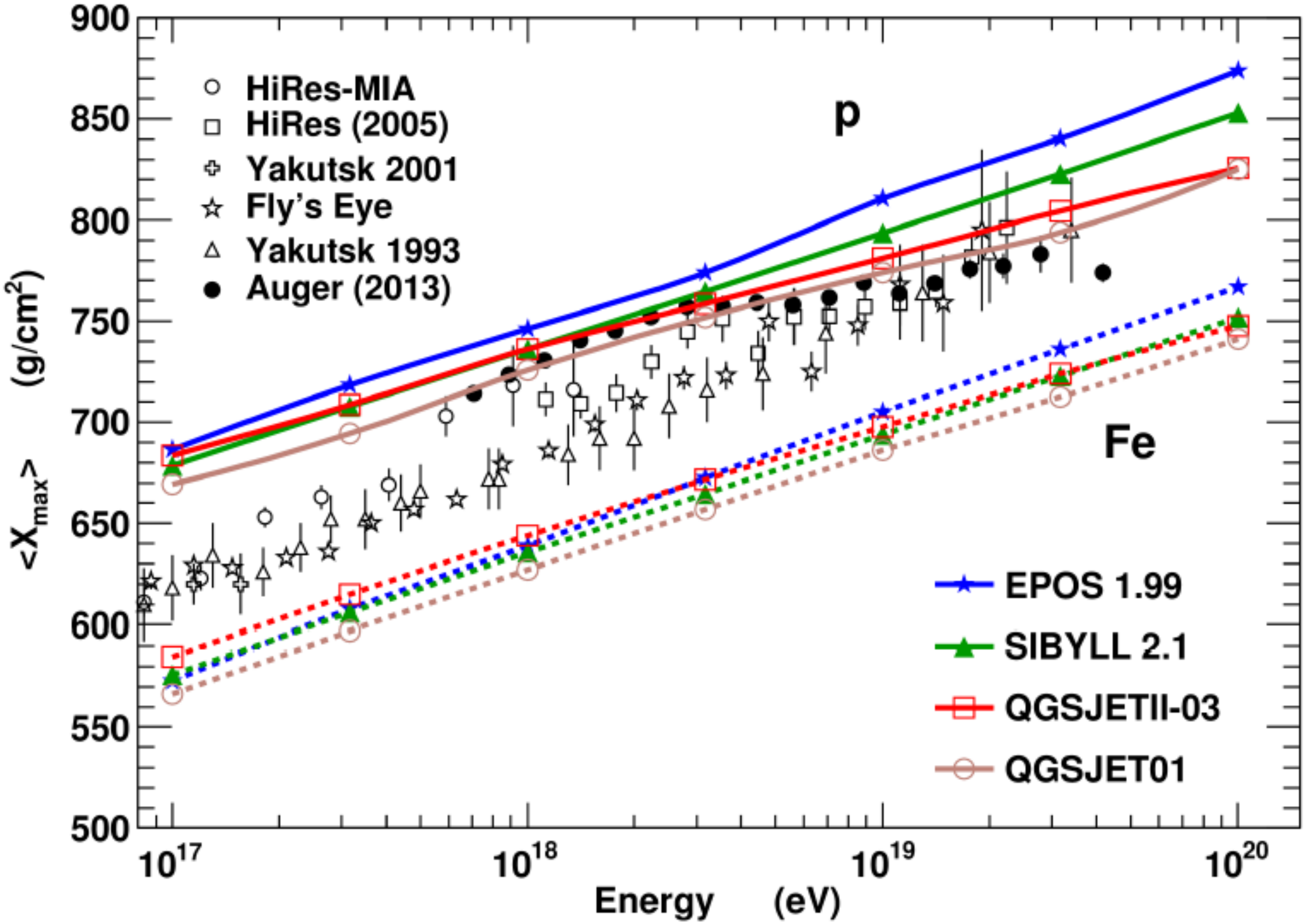


TA collaboration, 2010

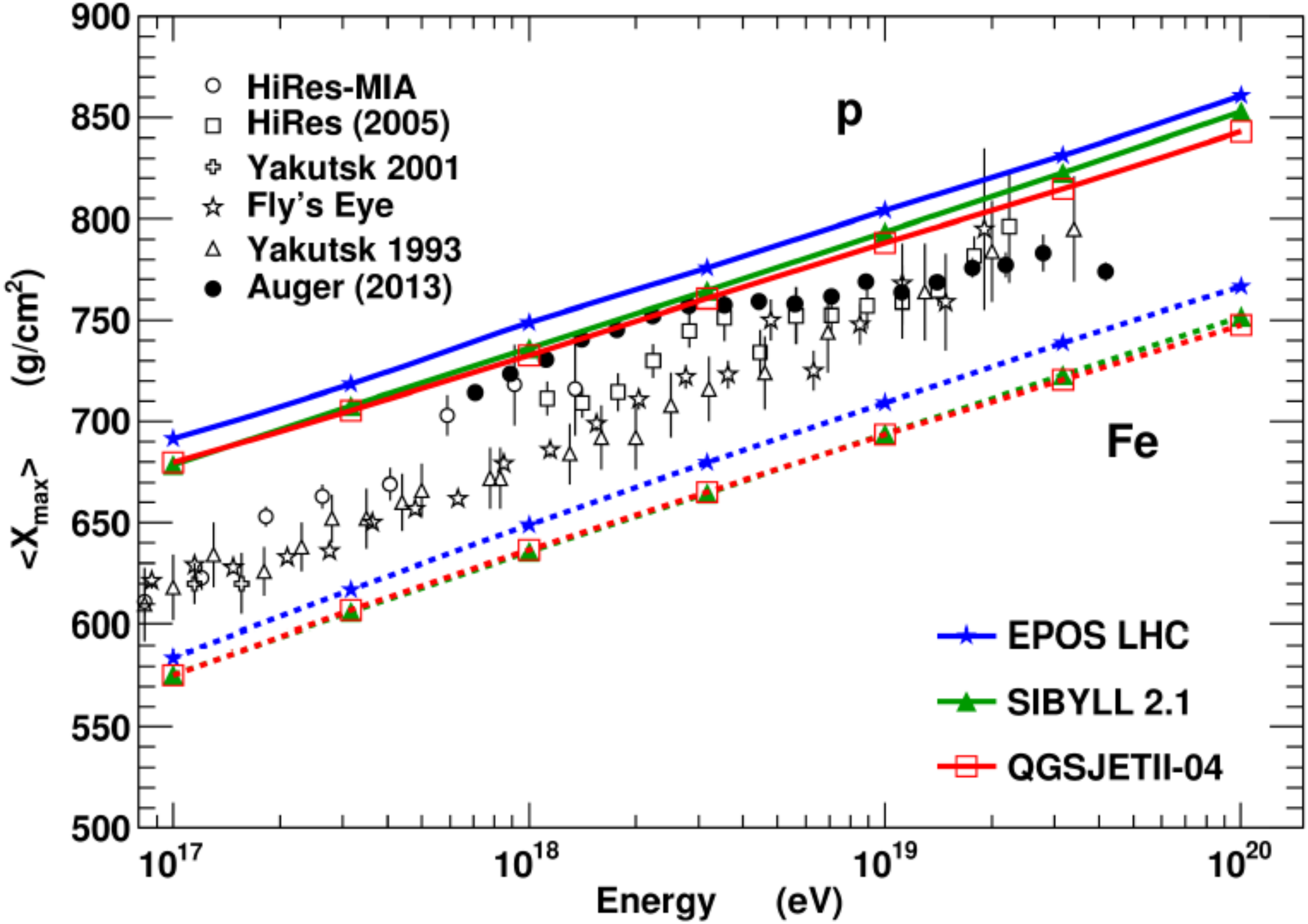


TA MD 2014
Auger 2014 ⊗ TA MD
preliminary
⟨X_max⟩ [g/cm²]
820
800
780
760
740
720
700
18.2
18.4
18.6
18.8
19
19.2
19.4
19.6
19.8
20
lg(E/eV)

EAS with Old CR Models : X_{max}



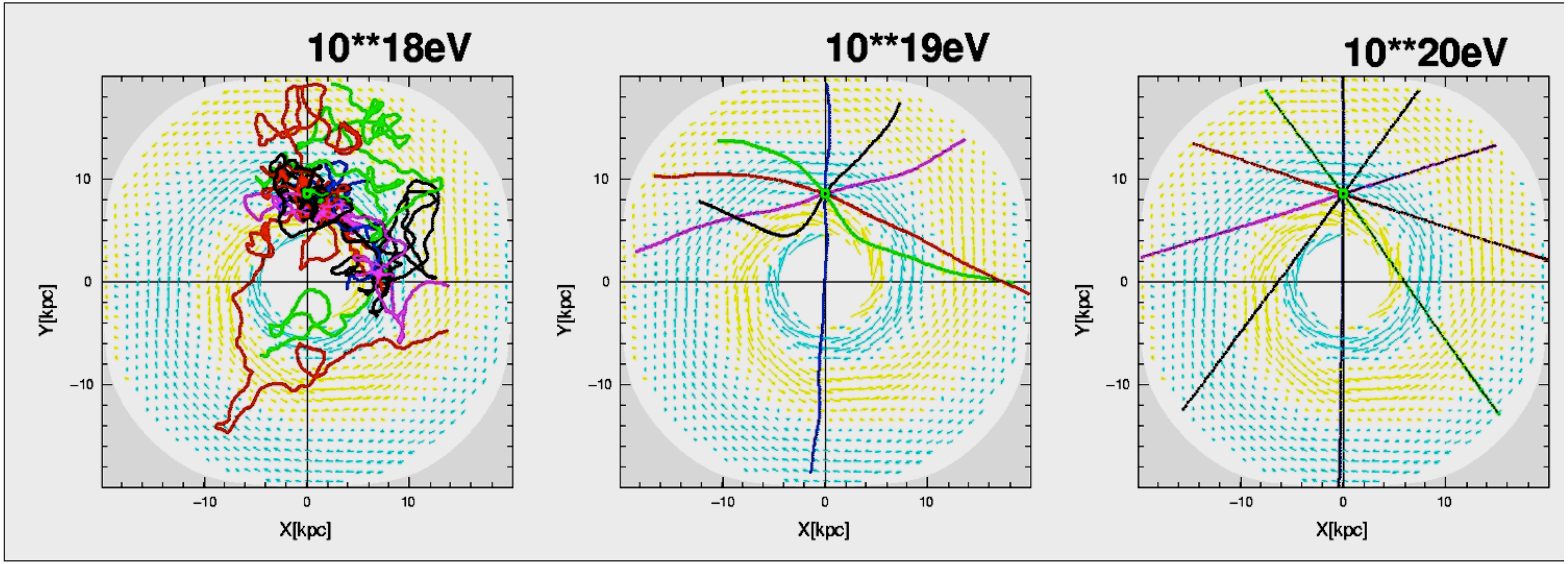
EAS with Re-tuned CR Models : X_{max}



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

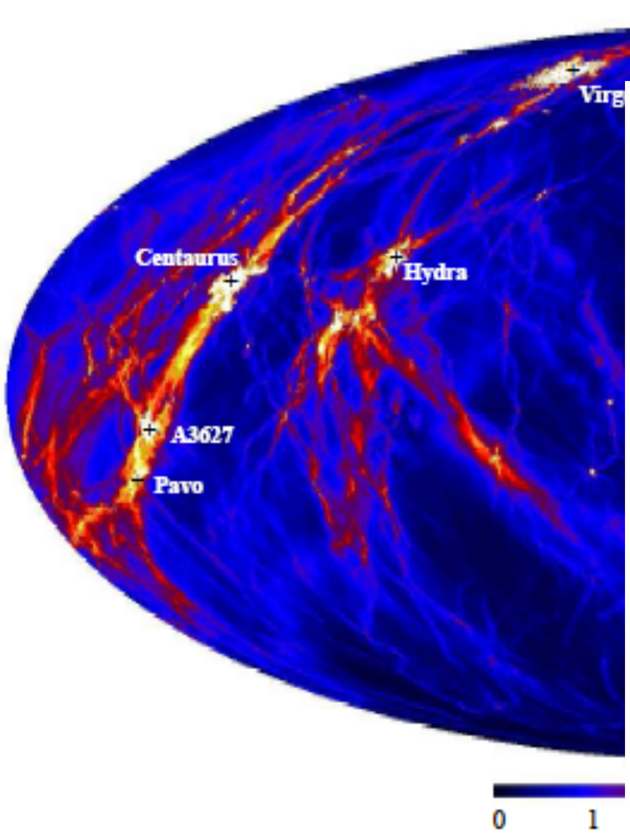


FIG. 1: Full sky map (area preserving projection) of c
scale. All structure within a radius of 107 Mpc aroun
with the galactic anti-center in the middle of the ma
corresponding halos in the simulation.

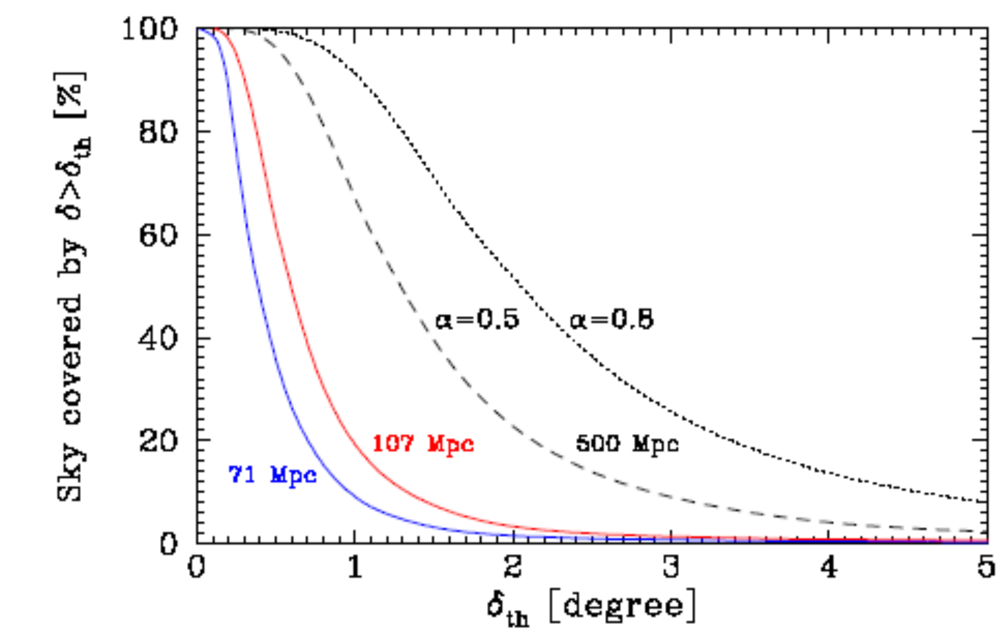
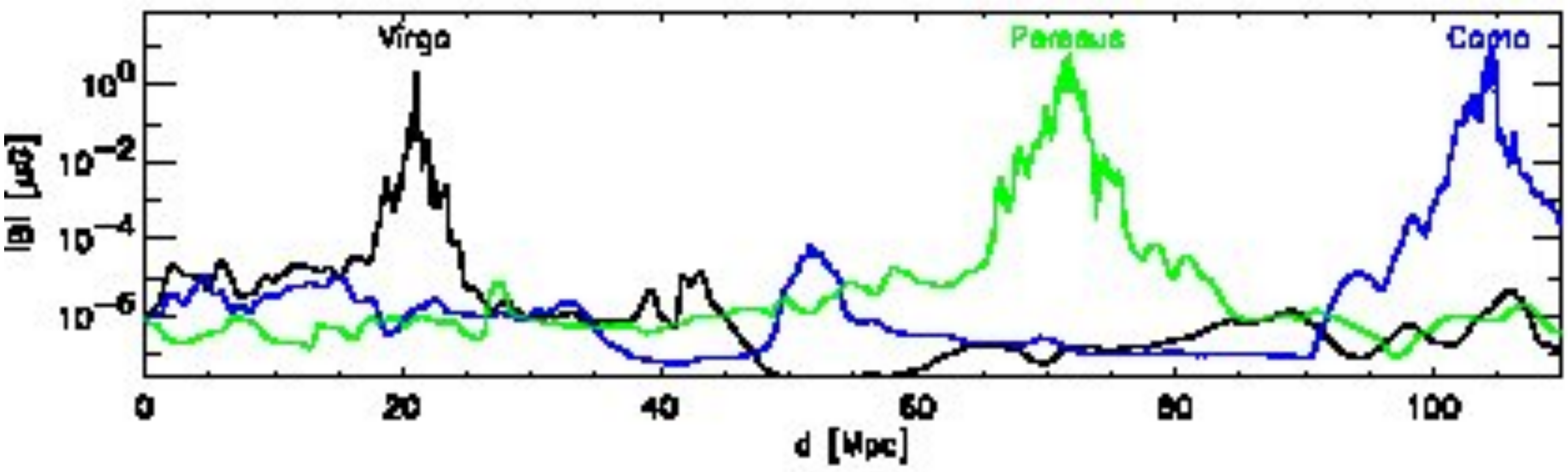


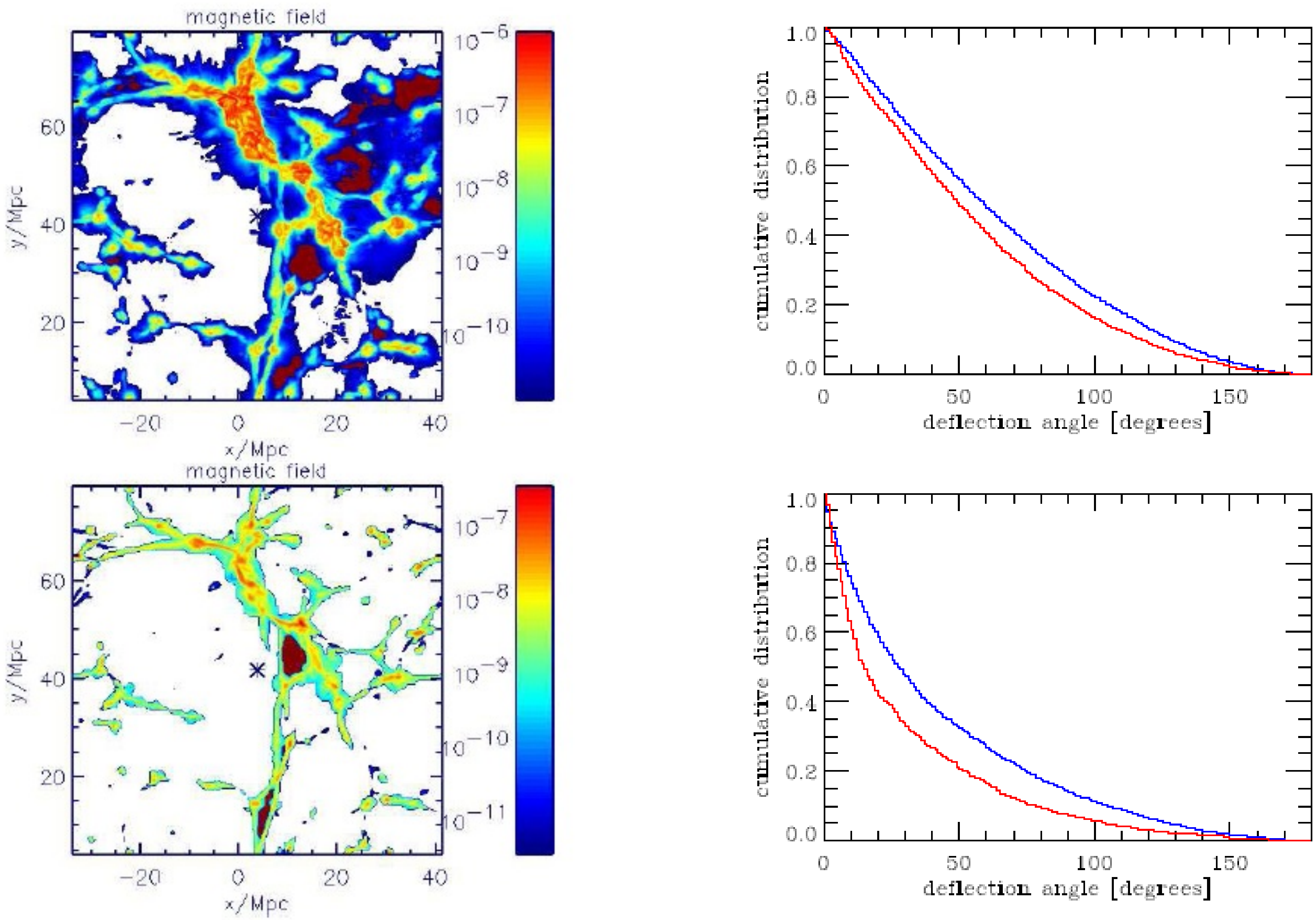
FIG. 2: Cumulative fraction of the sky with deflection angle larger than δ_{th}, for several values of propagation distance (solid lines). We also include an extrapolation to 500 Mpc, assuming self similarity with $\alpha = 0.5$ (dashed line) or $\alpha = 0.8$ (dotted line). The assumed UHECR energy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

Magnetic field in several directions from Earth for constrained simulation

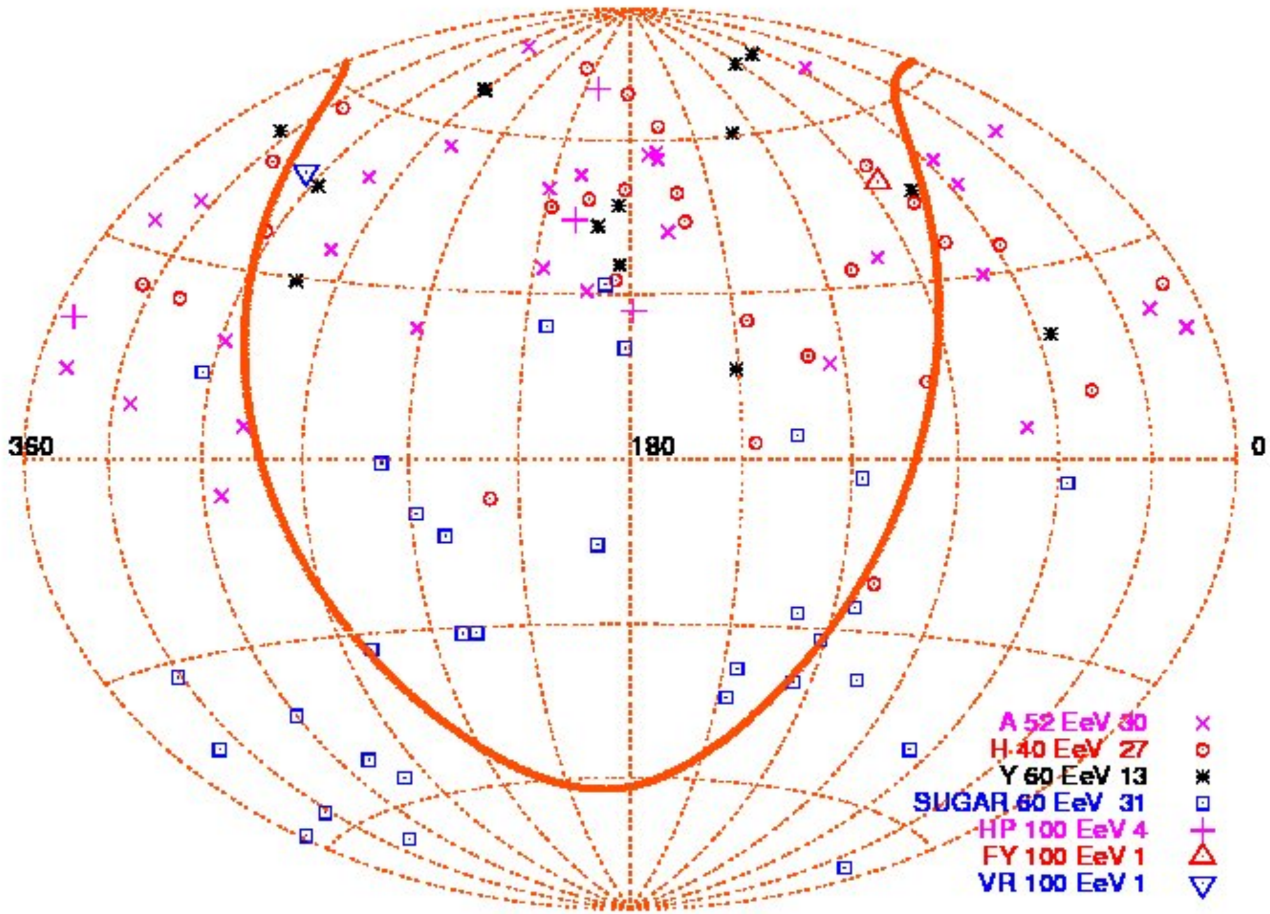


Dolag et al, astro-ph/0410419

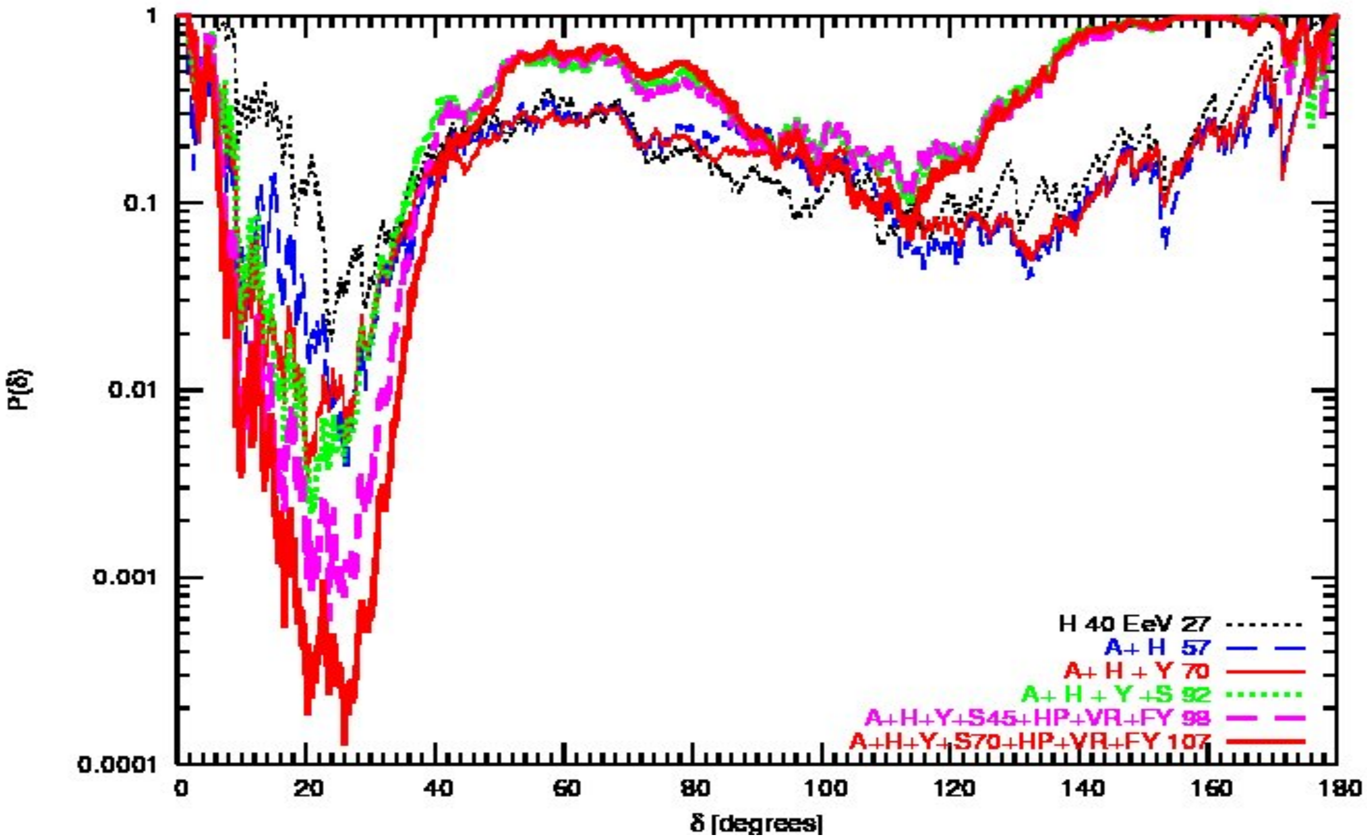
EGMF by G. Sigl et al. astro-ph/0401084



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



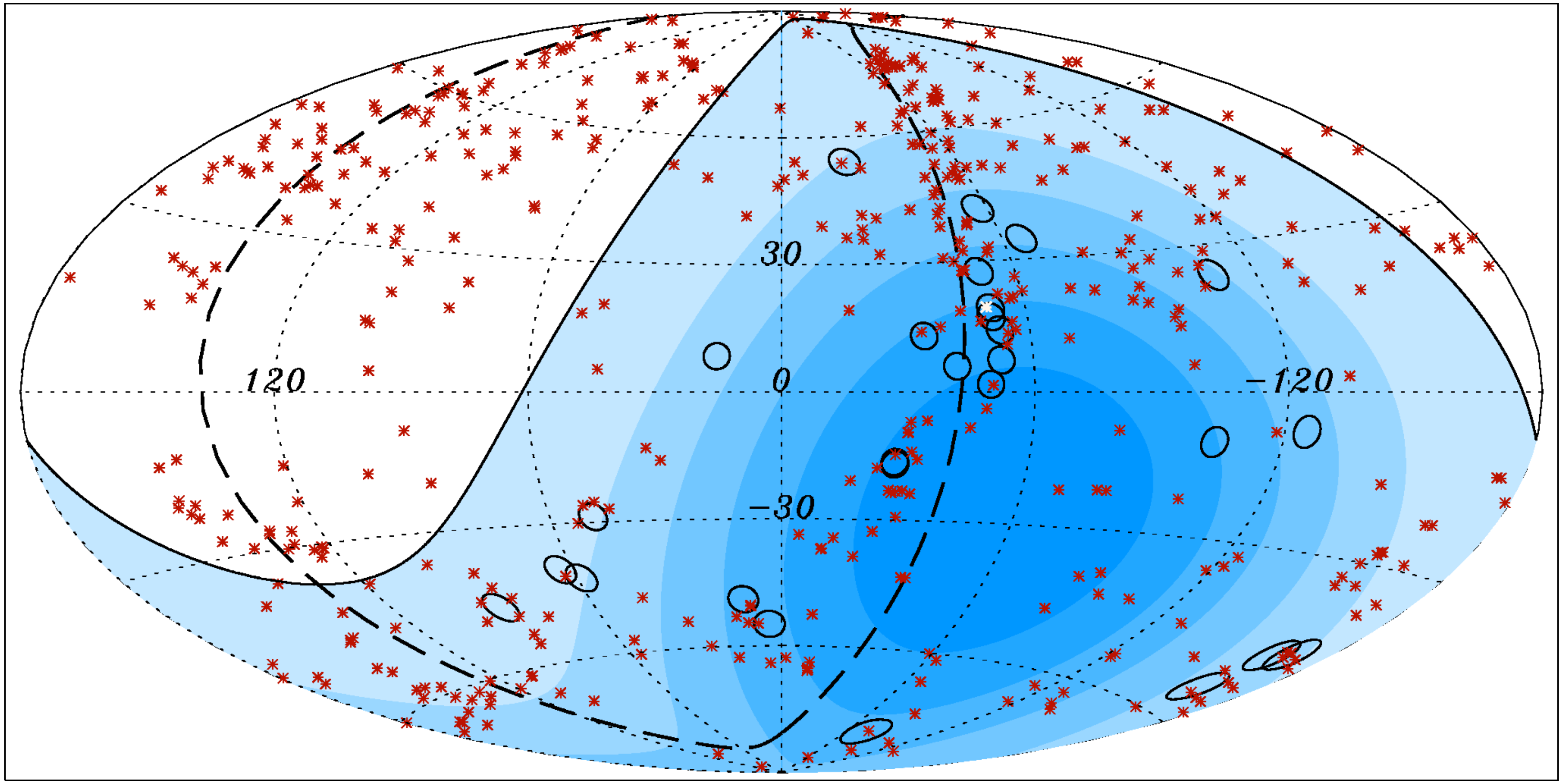
Probability of correlation



3 σ after penalty on angle

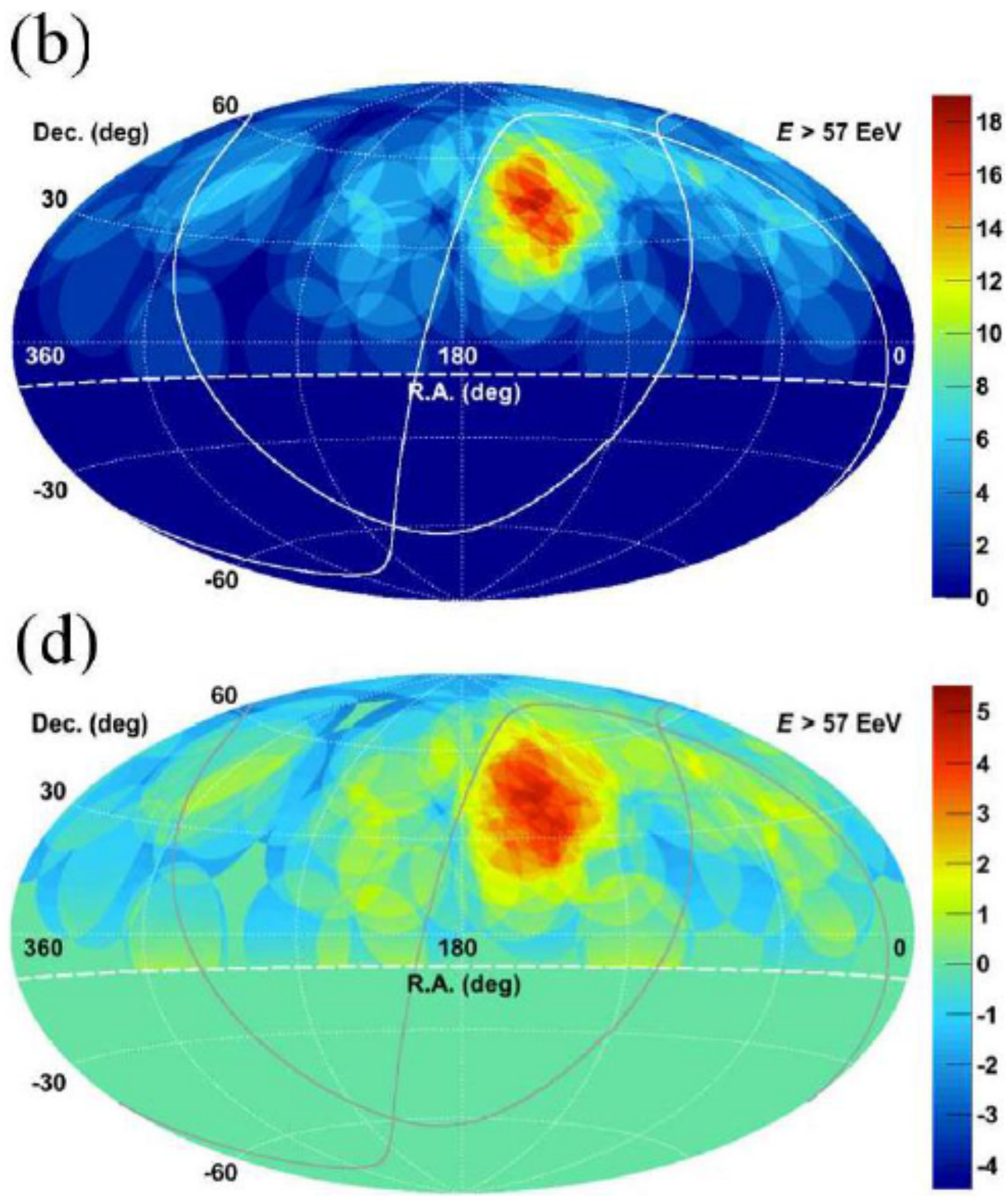
M.Kachelriess and D.S. astro-ph/0512498

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 , < 60º

Shown: events within 20º of each point

Hot Spot at
RA= **148.4º** and dec= **+44.5º**
(*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]*

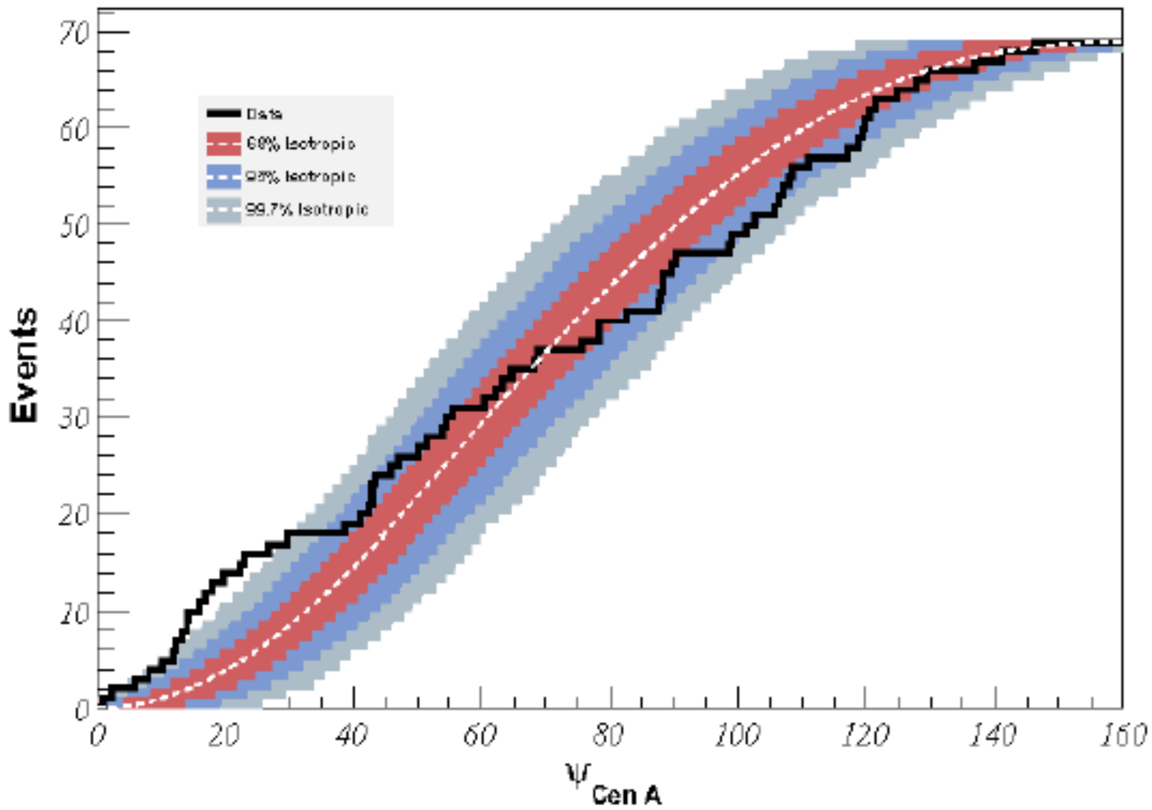


Fig. 9. Cumulative number of events with $E \geqslant 55$ EeV as a function of angular distance from the direction of Cen A. The bands correspond to the 68%, 95% and 99.7% dispersion expected for an isotropic flux.

Pierre Auger Observatory

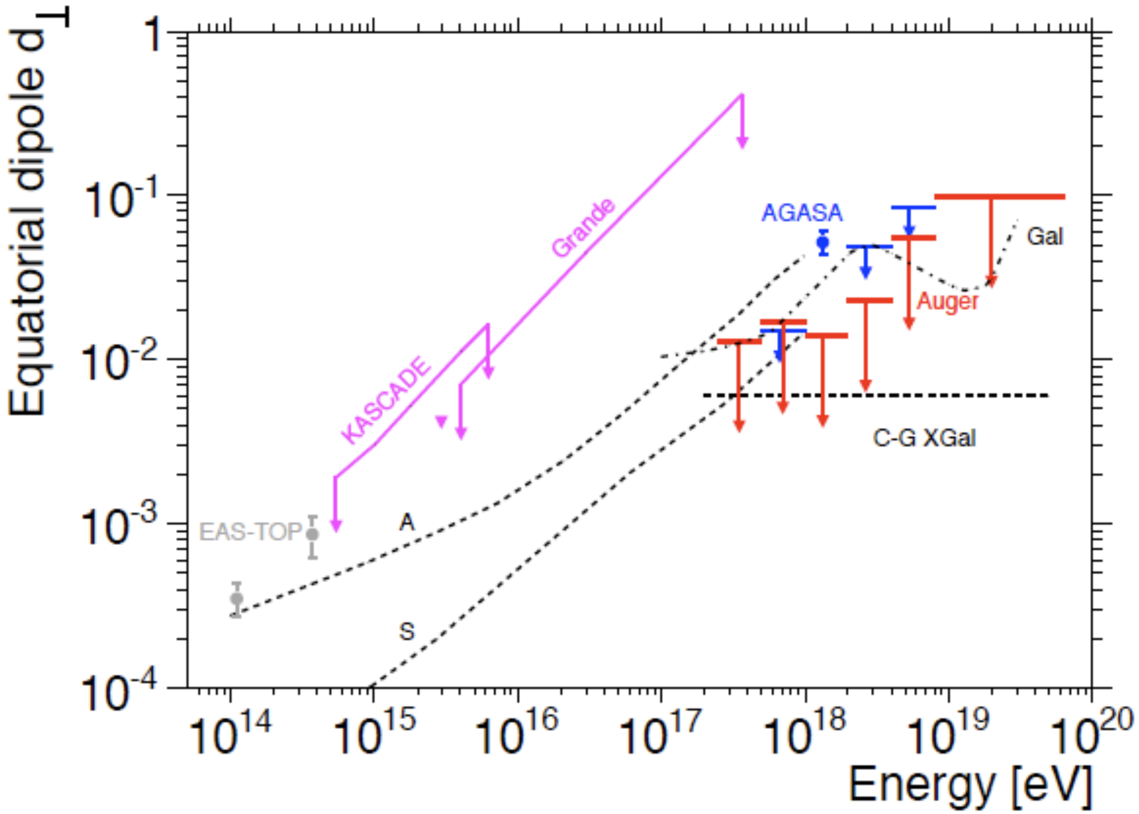
Events > 55 EeV

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

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

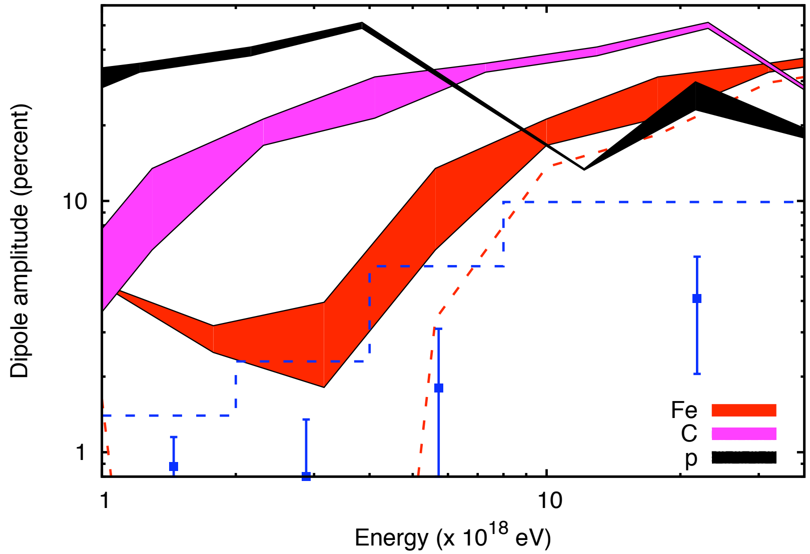
Transition from galactic to extragalactic cosmic rays

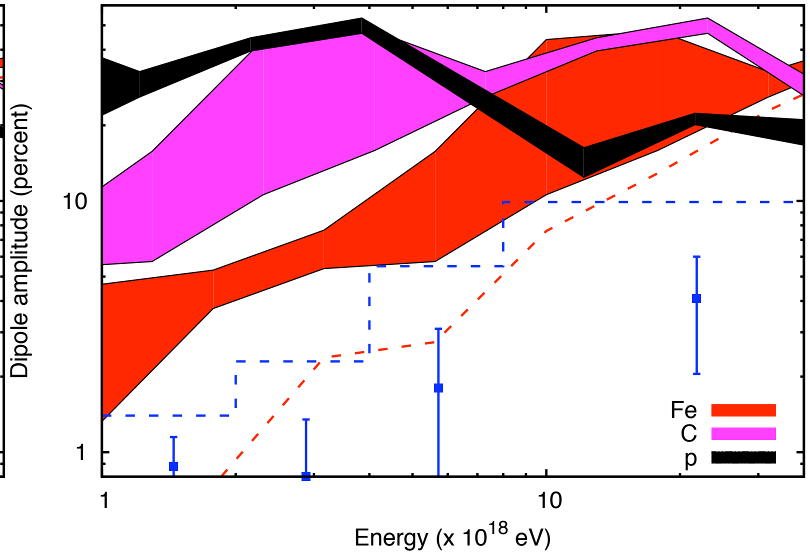
Anisotropy dipole



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

Dependence on parameters



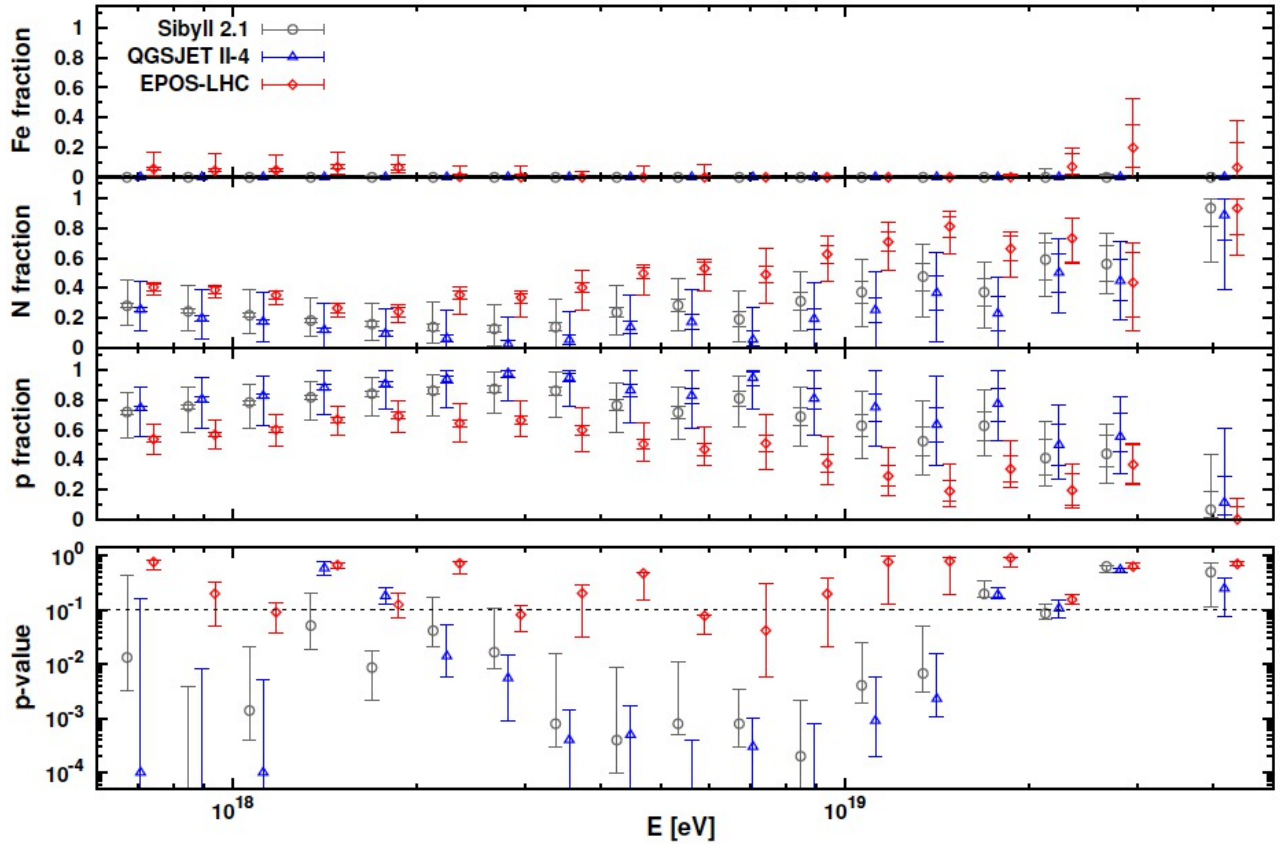


- Turb. Magn. Field spectrum
- Kolmogorov/Kraichnan

- Lmax = 100-300 pc

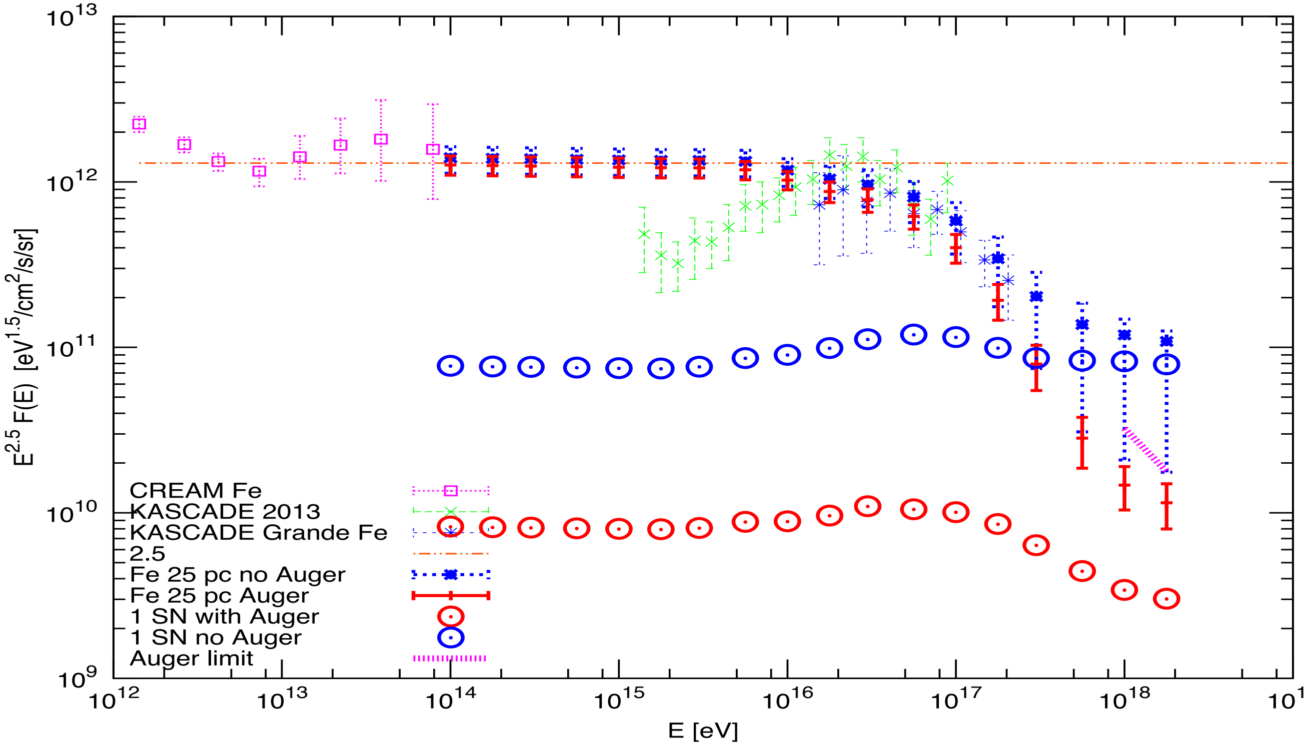
- G.Giacinti et al, **arXiv:1112.5599**

Auger cosmposition measurements

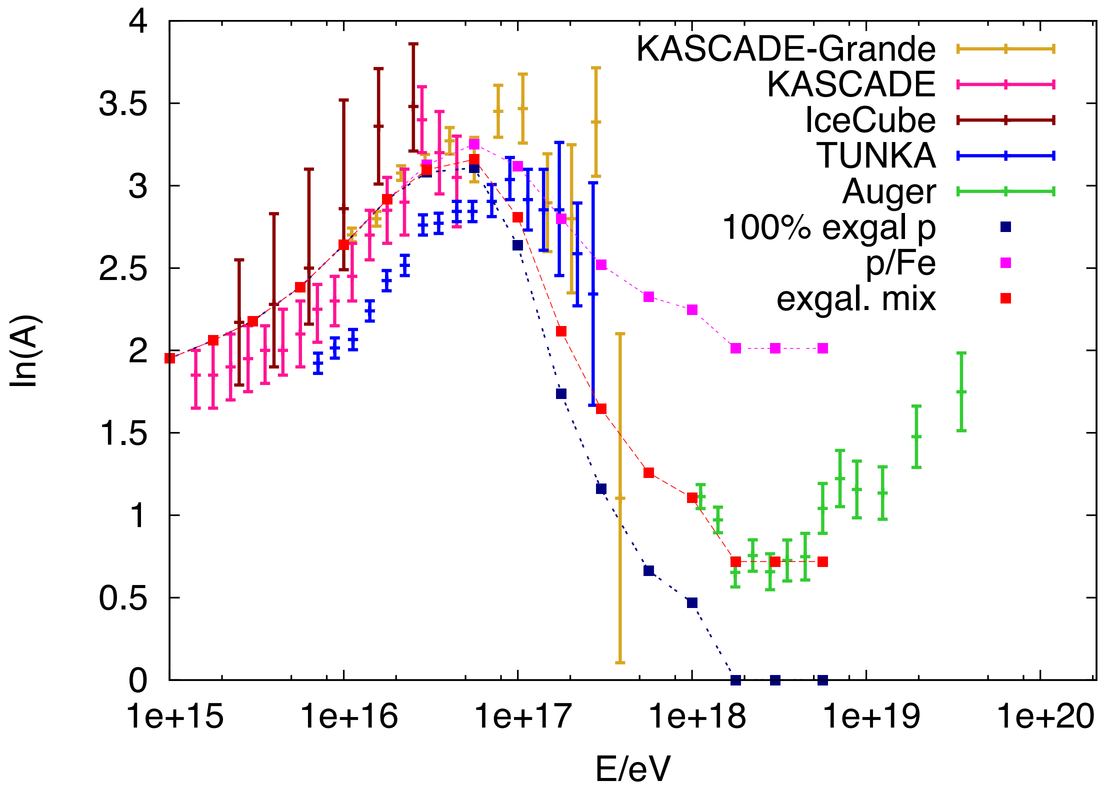


- **Auger Collaboration, arXiv:1409.5083**

Auger limit on Fe fraction

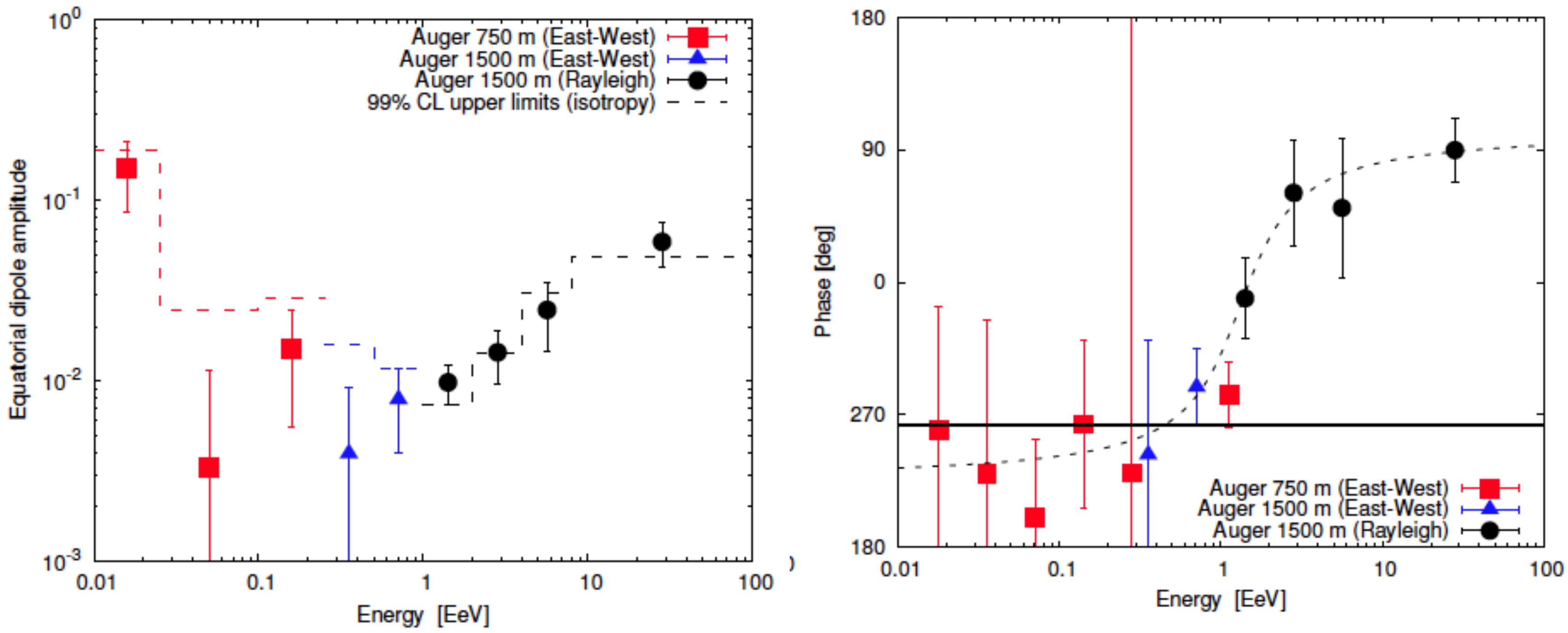


LnA plot



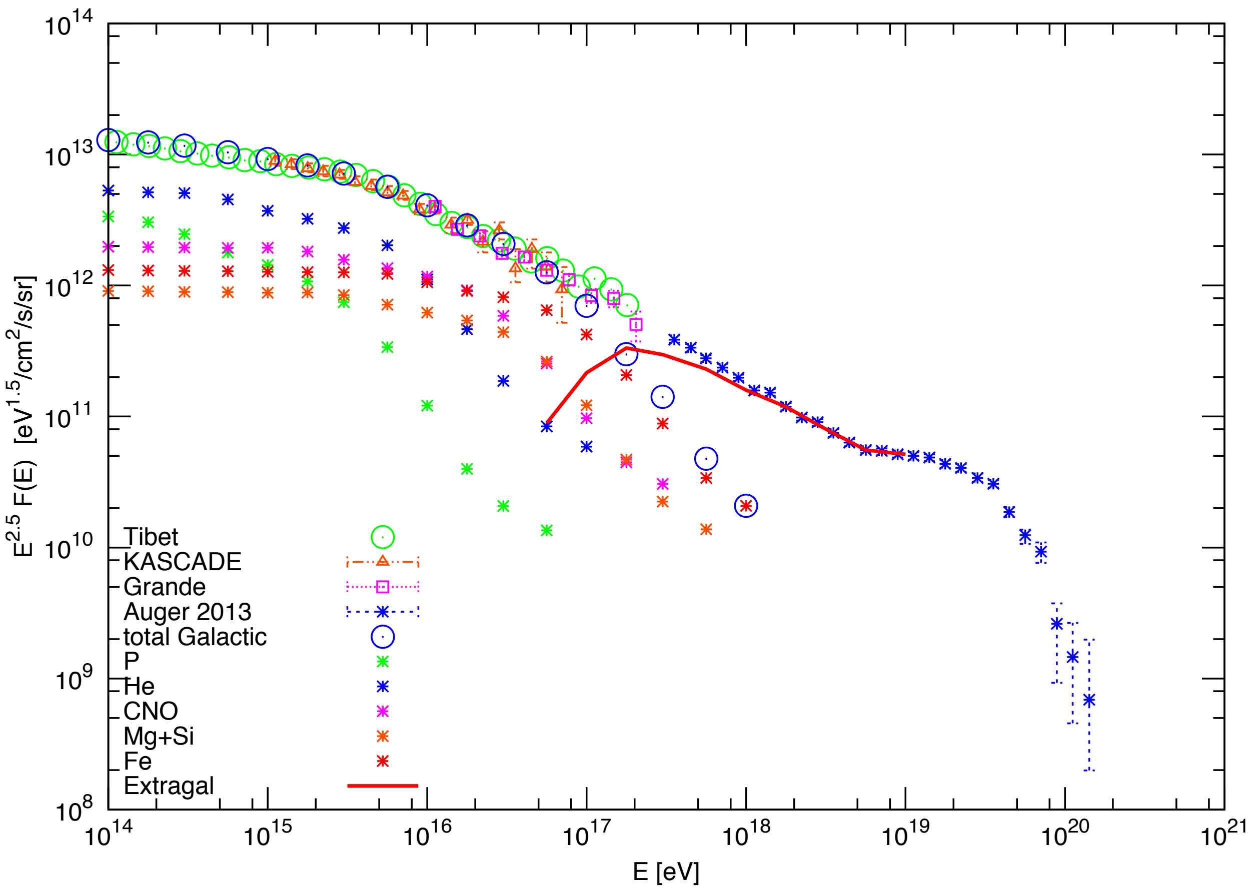
4
3.5
3
2.5
2
1.5
1
0.5
0
ln(A)
1e+15
1e+16
1e+17
1e+18
1e+19
1e+20
E/eV
KASCADE-Grande
KASCADE
IceCube
TUNKA
Auger
100% exgal p
p/Fe
exgal. mix

Auger dipole measurements

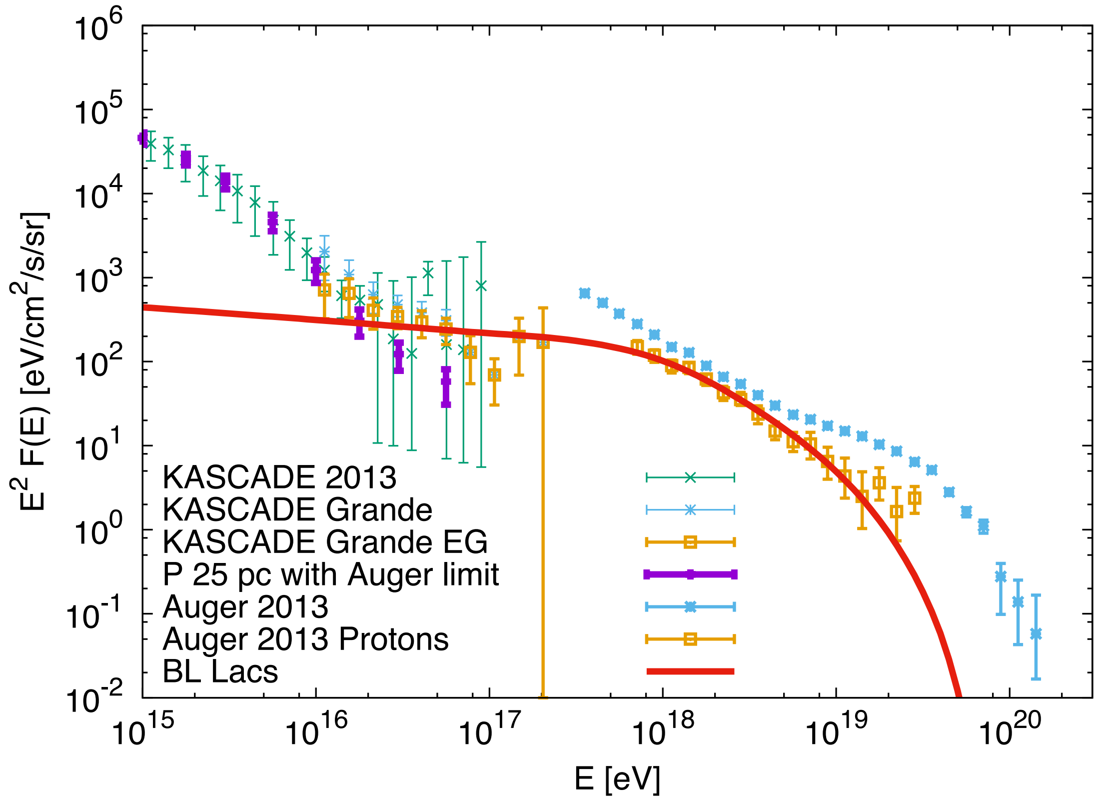


- Auger Collaboration, arXiv:1310.4620

Contribution of extra-Galactic sources



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 (ee next lectures)