High Energy Astroparticle Physics

Lecture 1 : Cosmic Rays

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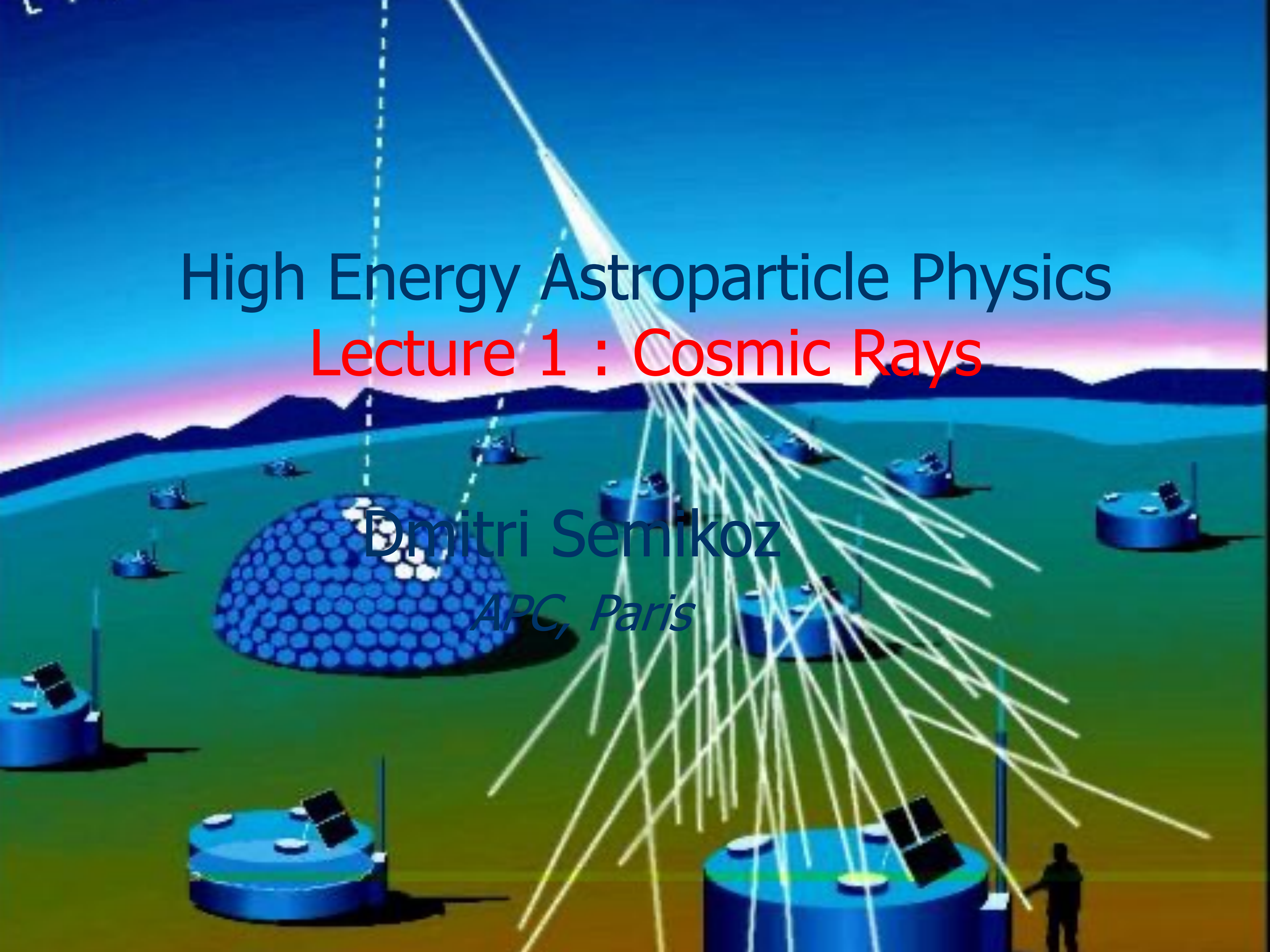


Astroparticle physics

Particle physics

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

Astrophysics

- Unknown accelerators
- Electrodynamics: 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*
  - *Model from 90th: steady state flux in all Galaxy*
  - *Problems of steady state model*
  - *Source of Fe 60*
  - *Nearby SN as solution of cosmic ray anomalies: towards new model 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

Electroscopes discharge spontaneously. Why?

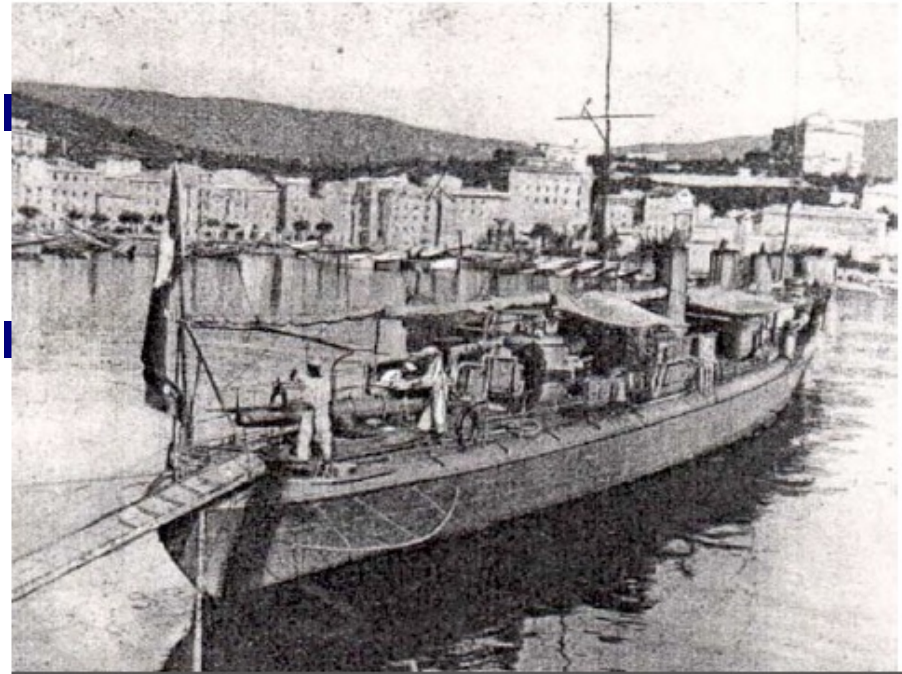
- 1785: Coulomb found that electroscopes can spontaneously discharge by the action of the air and not by defective insulation
- 1835: Faraday confirms the observation by Coulomb, with better insulation technology
- 1879: Crookes measures that the speed of discharge of an electroscope decreased when pressure was reduced (conclusion: direct agent is the ionized air)

100 years later: cause might be radioactivity

- 1896: spontaneous radioactivity discovered by Becquerel
- 1898: Marie (31) & Pierre Curie discover that the Polonium and Radium undergo transmutations generating radioactivity (radioactive decays)
  - Nobel prize for the discovery of the radioactive elements Radium and Polonium: the 2nd Nobel prize to M. Curie, in 1911
  - In the presence of a radioactive material, a charged electroscope promptly discharges
  - Some elements are able to emit charged particles, that in turn can cause the discharge of the electroscopes.
  - The discharge rate of an electroscope was then used to gauge the level of radioactivity

Domenico Pacini's break-through

- Domenico Pacini (1878-1934), meteorologist in Roma and then professor in Bari, makes measurements in 1907-1911, first comparing the rate of ionization on mountains at different altitudes, over a lake, and over the sea
  - Comparing measurements on the ground and on a sea a few km off the coast in Livorno, a 30% reduction of radioactivity
  - A hint that the soil is not (the only) responsible of radiation: *in the hypothesis that the origin of penetrating radiations is only in the soil … it is not possible to explain the results obtained* (Pacini 1910; quoted by Hess)



- In June 1911, the winning idea: immersing an electroscope 3m deep in the sea (at Livorno and later in Bracciano) Pacini, 33-y-old, finds a significant (20% at 4.3σ) reduction of the radioactivity

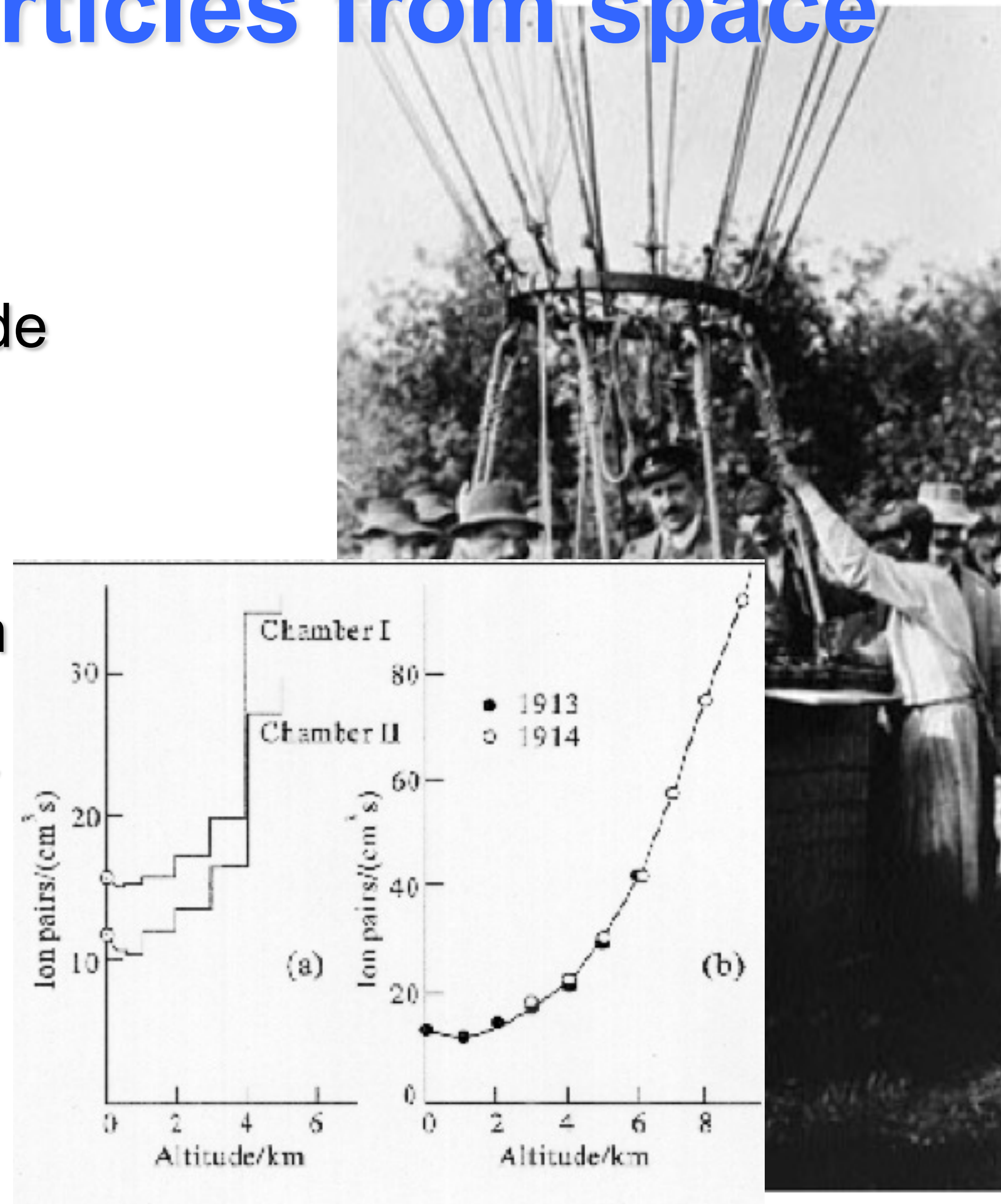
Cosmic rays: historical remarks

- *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
- 1911: Pacini: radiactivity reduced under water
- *1912: Victor Hess discovered radiation coming to atmosphere from above*

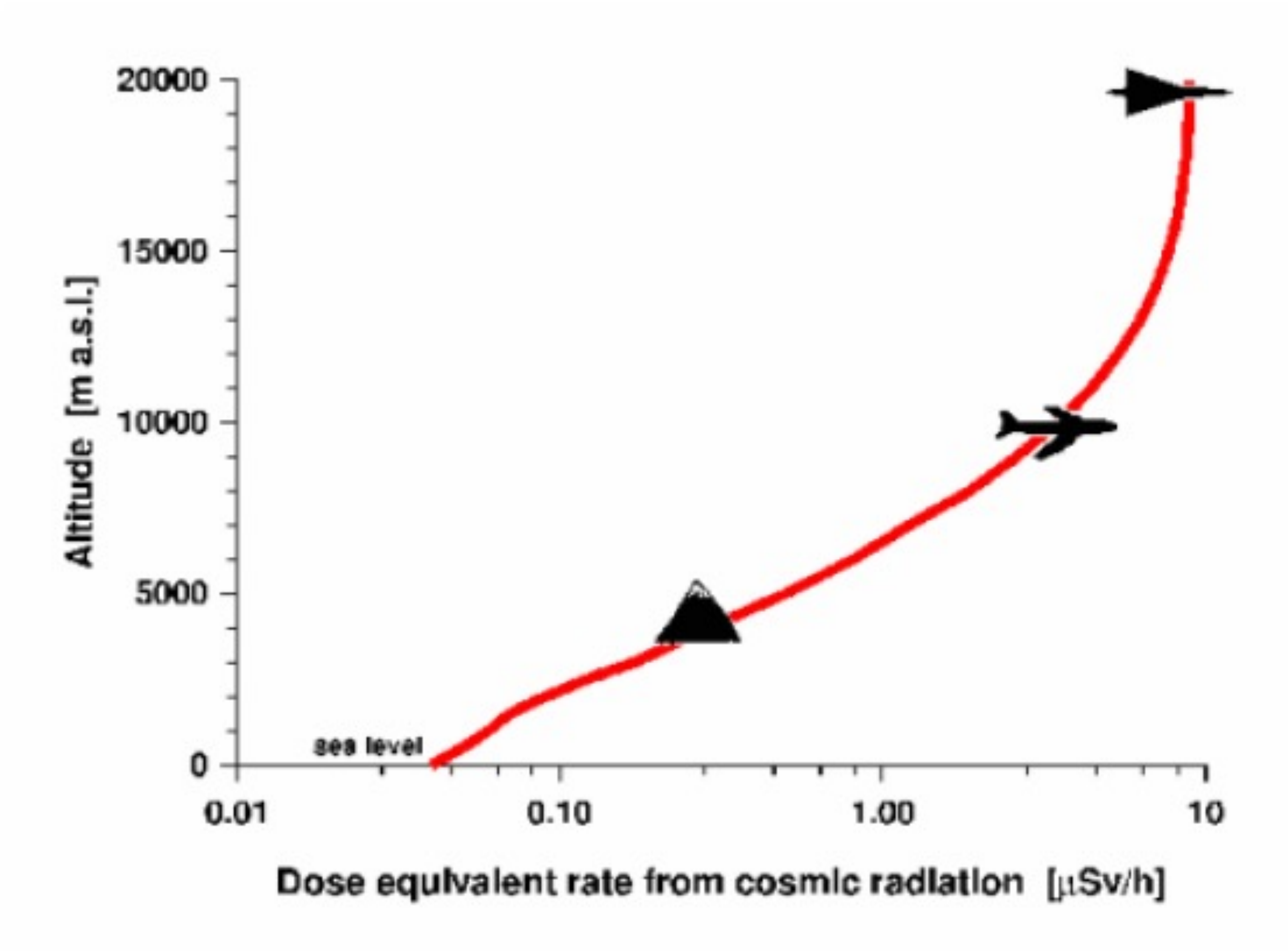
•High-energy particles from space

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

•Discovered 106 yr ago by V.Hess in 1912, via detection of increase of the rate of discharge of an electrometer with increase of the altitude.

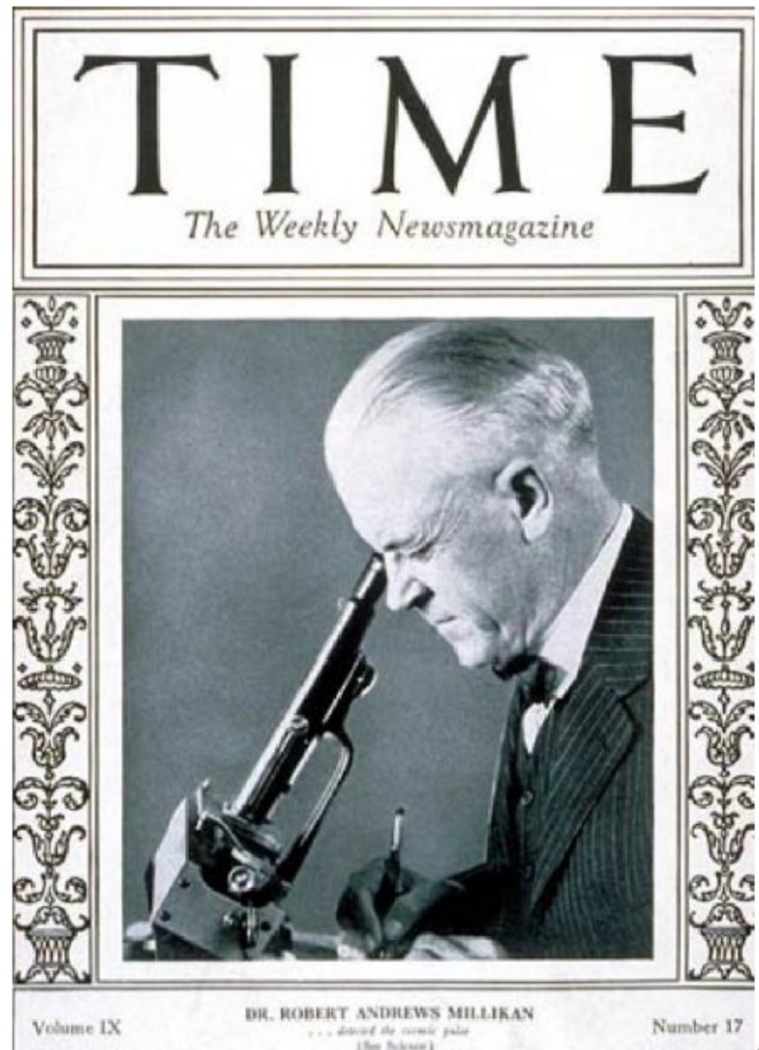


Radiation from cosmic rays



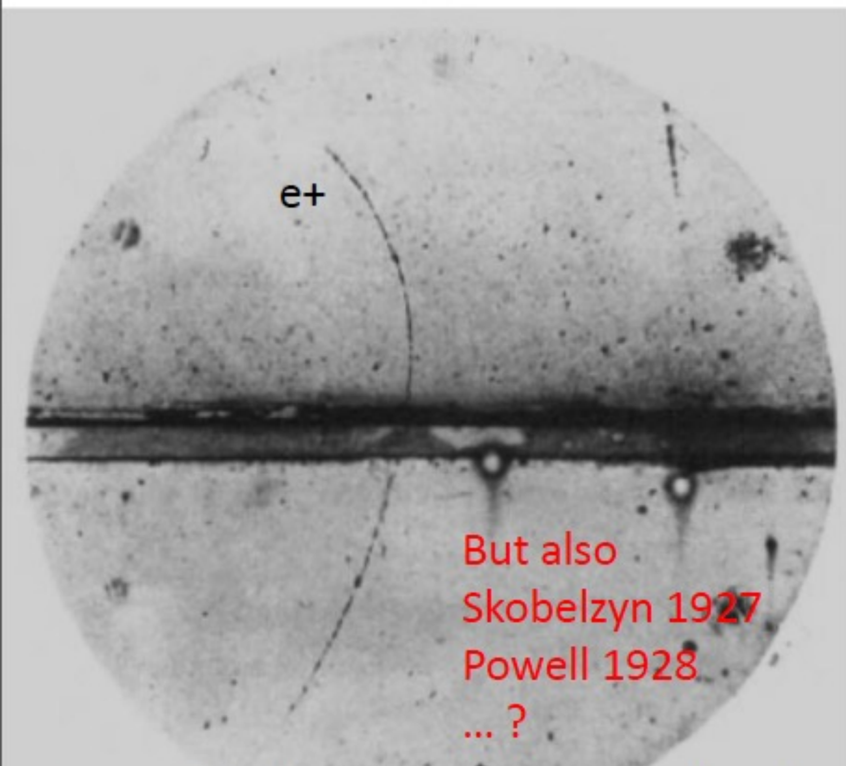
Truth reestablished (but merit stolen)

- In 1926, however, Millikan and Cameron carried out absorption measurements of the radiation at various depths in lakes at high altitudes
  - They reproduced Pacini's depth effect, and they concluded that these particles shoot through space equally in all directions, calling them "cosmic rays"
  - In the conclusive Phys. Rev. article, they ignored Wulf, Gockel, Pacini, Hess
- Millikan was handling with energy and skill the communication with media, and in the US the discovery of cosmic rays became, according to the public opinion, a success of American science
  - Millikan argued that the cosmic rays were the "birth cries of atoms" in our galaxy



Antimatter (the antielectron, or positron: Anderson 1933)

- *Consistent with Weil's interpretation of Dirac's equation (1927-28) …*



- Picture taken by Anderson in 1932 of a cloud chamber (Nobel to Wilson in 1927) in the presence of a magnetic field
- The band across the middle is a Pb plate, which slows down the particles. The momentum of the track after crossing the plate is smaller than before
- From the direction in which the path curves one can deduce that the particle is positively charged
- Mass can be deduced from the long range of the track - a proton would have come to rest in a shorter distance

=> It is a positive electron!

At the same time, gamma -> e+e- (Occhialini & Blackett)

A note: Dirac's equation announced in '28 in Cambridge; at the same conference Skobelzyn spoke about some unexplainable "wrong charge" events.

V.Hess Nobel prize in 1934

Prize in physics, shared with Anderson. Hess was nominated by Clay, Compton:

- *The time has now arrived, it seems to me, when we can say that the so-called cosmic rays have their origin at remote distances from the Earth [...] and that the use of the rays has by now led to results of such importance that they may be considered a discovery of the first magnitude. [...] It is, I believe, correct to say that Hess was the first to establish the increase of the ionization observed in electroscopes with increasing*

Cosmic rays: historical remarks

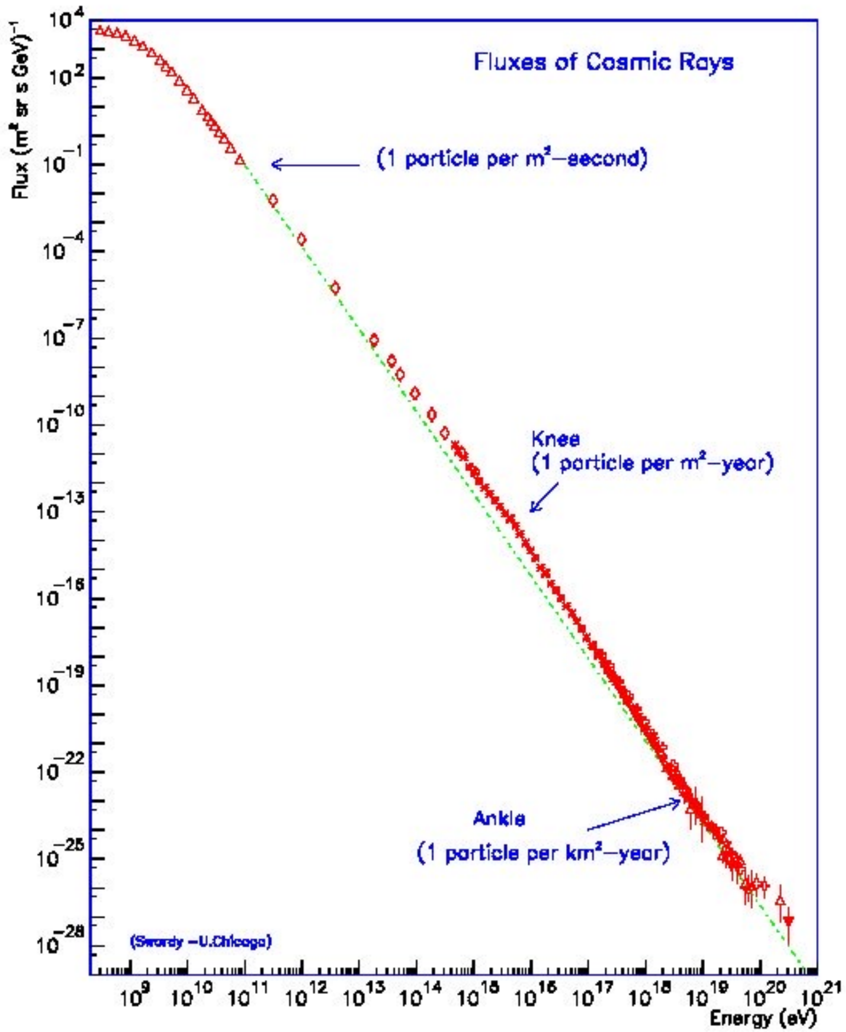
- *1926: Primaries of radiation got name "cosmic rays" under assumption that they are photons*
- *1929: Anderson discovered positron*
- *1934 It was proved that primaries are positively charged particles*
- *1936 Discovery of muon*
- *1938 Pierre Auger observed extensive air showers*
- *1947 Discovery of charge pions*
- *1947-50 Discovery of strange particles*
- *1952-54 Accelerator physics started*

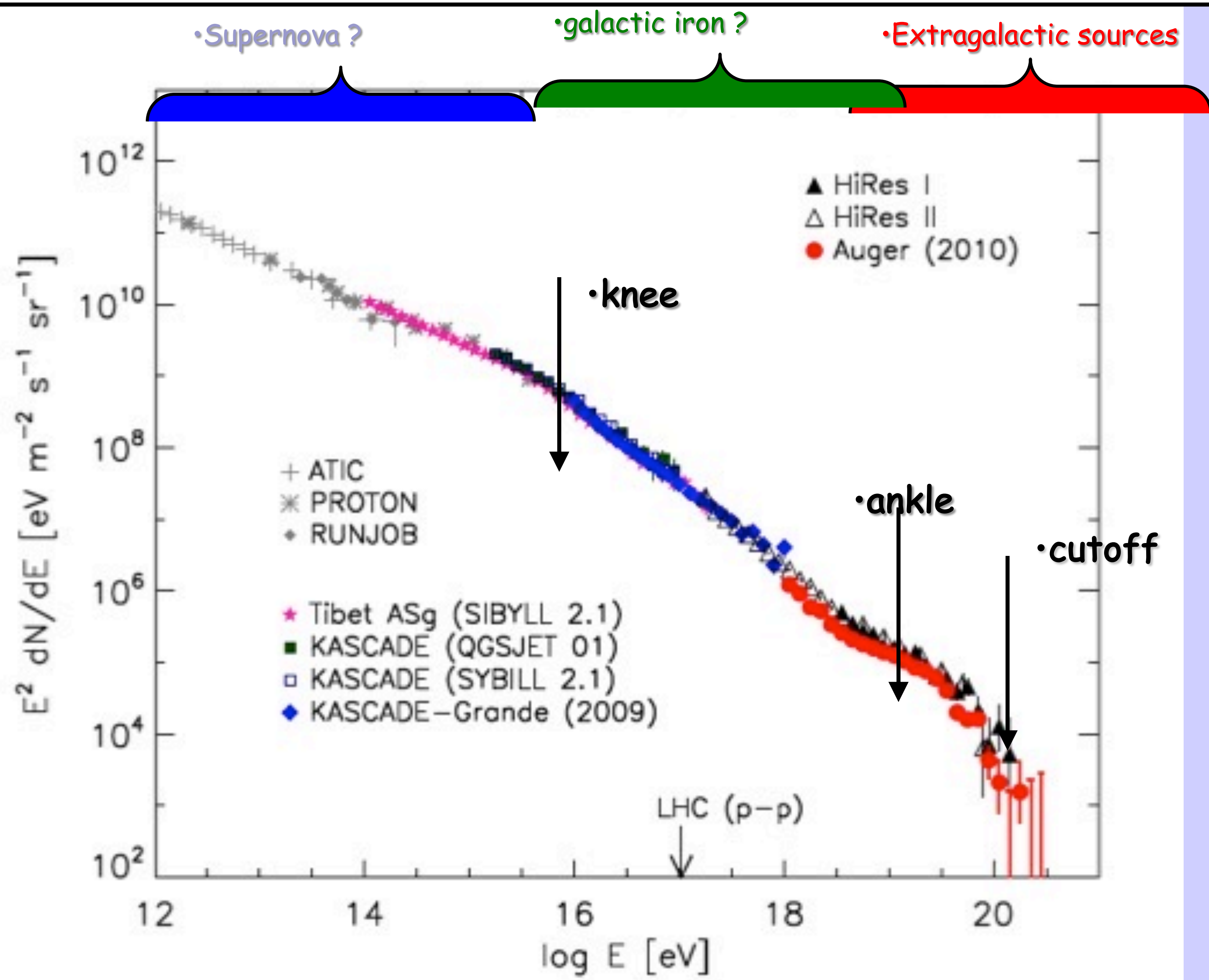
Cosmic rays: historical remarks

- *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

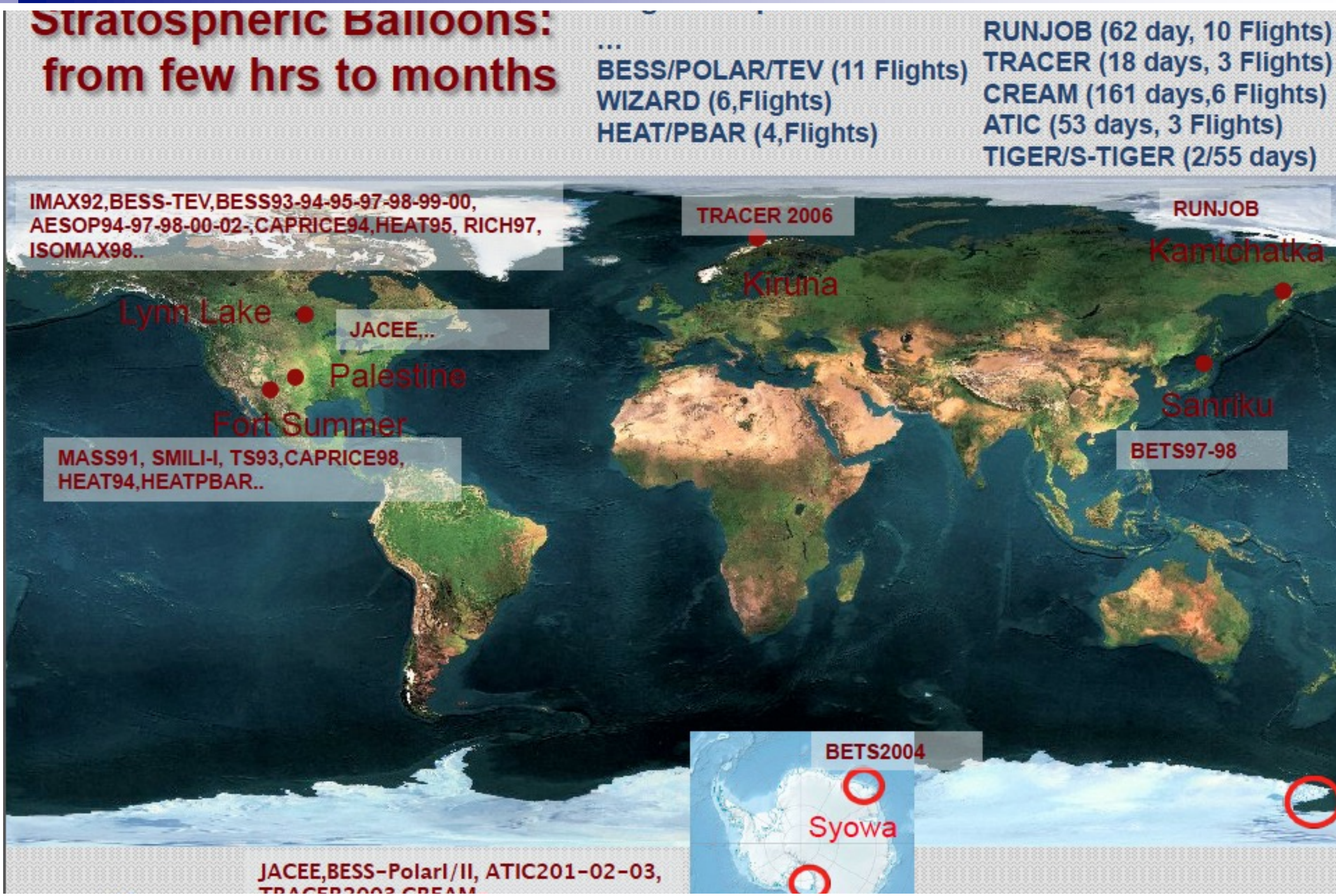
- *1994-1996 First measurements of cutoff region by AGASA experiment: no cutoff in spectrum: big theoretical effort beyond Standard Model (SHDM, LIV, etc.)*
- *2001 HiRes experiment see cutoff.*
- *2007 Construction of Pierre Auger Observatory finished. Precision measurements started and cutoff confirmed.*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

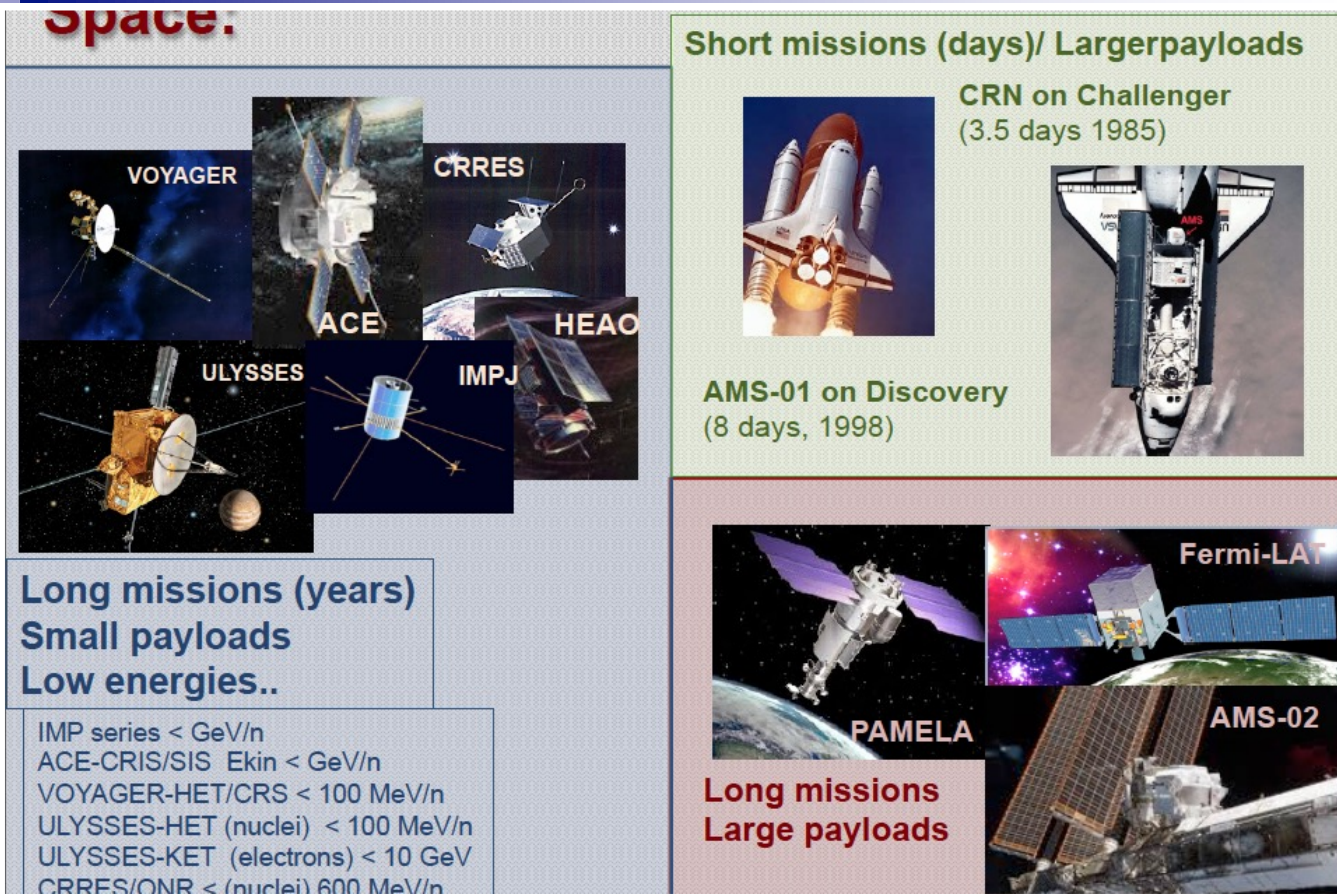

Fluxes of Cosmic Rays
Flux (m² sr s GeV)⁻¹
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
(Swordy – U.Chicago)
Energy (eV)

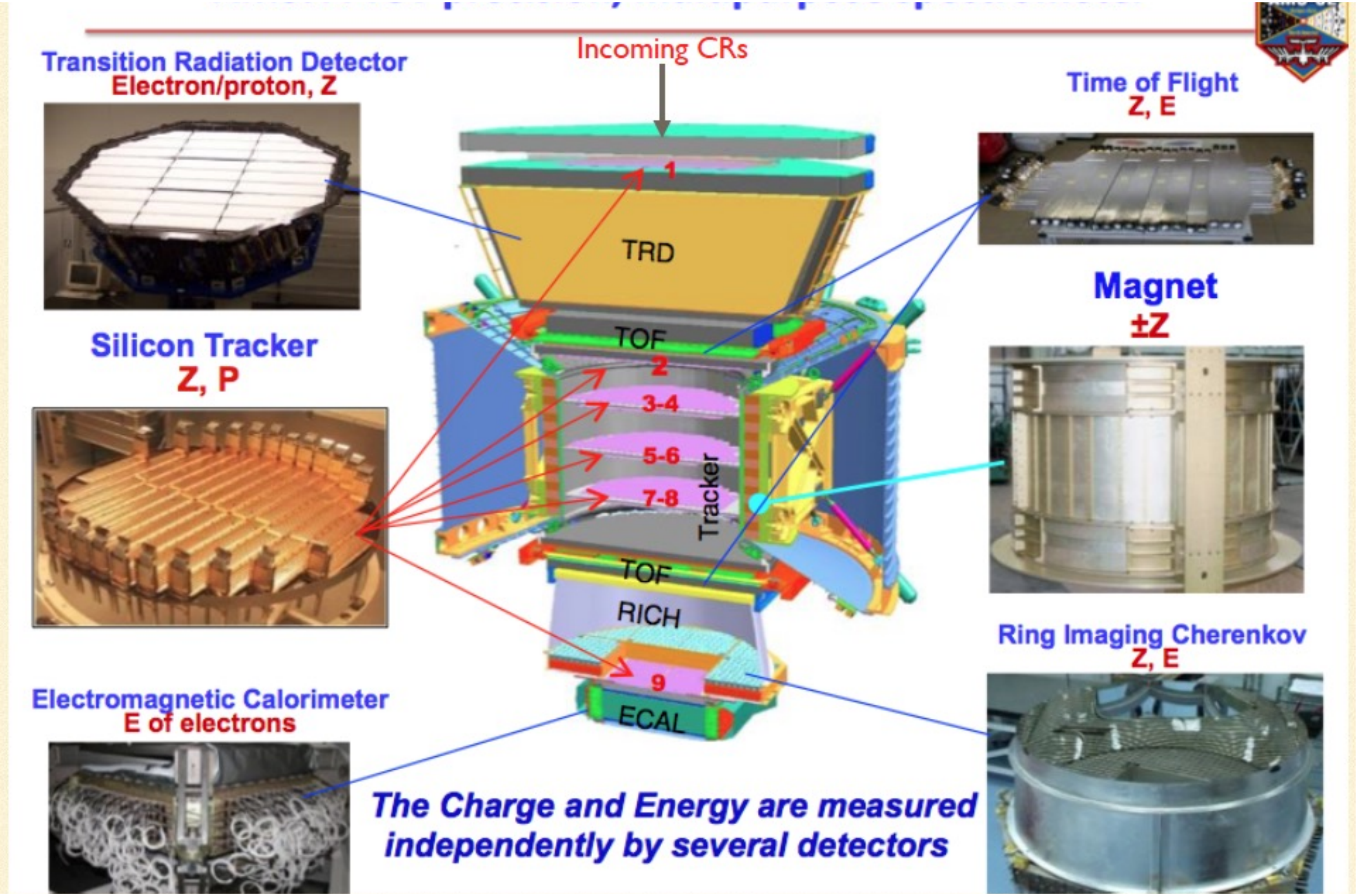


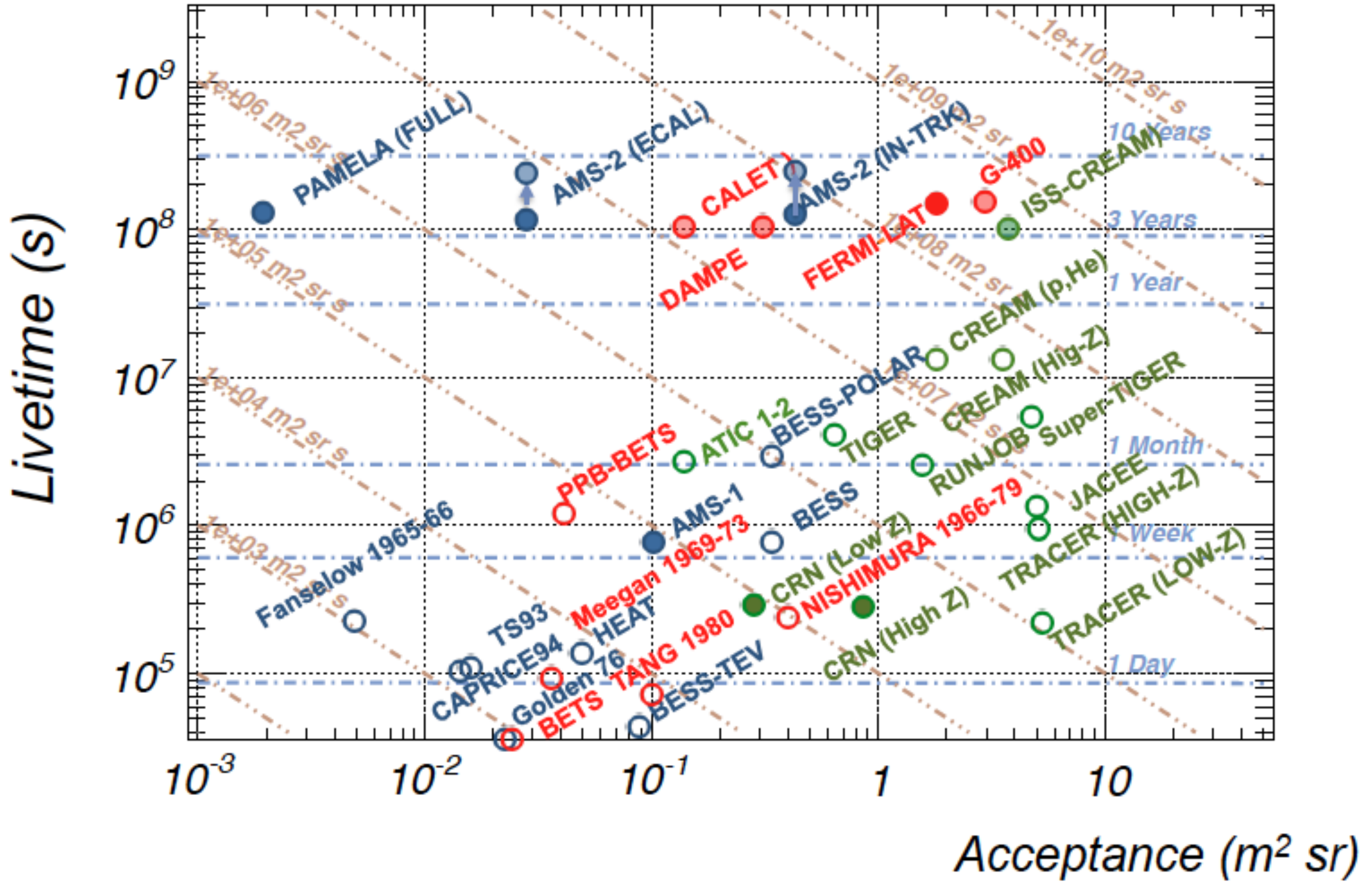
•Supernova ?
•galactic iron ?
•Extragalactic sources
•knee
•ankle
•cutoff
HiRes I
HiRes II
Auger (2010)
ATIC
PROTON
RUNJOB
Tibet ASg (SIBYLL 2.1)
KASCADE (QGSJET 01)
KASCADE (SYBILL 2.1)
KASCADE−Grande (2009)
LHC (p−p)
E^2 dN/dE [eV m^{-2} s^{-1} sr^{-1}]
10^{12}
10^{10}
10^{8}
10^{6}
10^{4}
10^{2}
12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

Direct measurements of Cosmic rays


Stratospheric Balloons:
from few hrs to months
...
BESS/POLAR/TEV (11 Flights)
WIZARD (6,Flights)
HEAT/PBAR (4,Flights)
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)
IMAX92,BESS-TEV,BESS93-94-95-97-98-99-00,
AESOP94-97-98-00-02-,CAPRICE94,HEAT95, RICH97,
ISOMAX98..
TRACER 2006
Kiruna
RUNJOB
Kamtchatka
Lynn Lake
JACEE,..
Palestine
Fort Summer
MASS91, SMILI-I, TS93,CAPRICE98,
HEAT94,HEATPBAR..
Sanriku
BETS97-98
BETS2004
Syowa
JACEE,BESS-PolarI/II, ATIC201-02-03,


Space:
Short missions (days)/ Largerpayloads
CRN on Challenger
(3.5 days 1985)
AMS-01 on Discovery
(8 days, 1998)
VOYAGER
ACE
CRRES
HEAO
ULYSSES
IMPJ
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
Fermi-LAT
PAMELA
AMS-02
Long missions
Large payloads

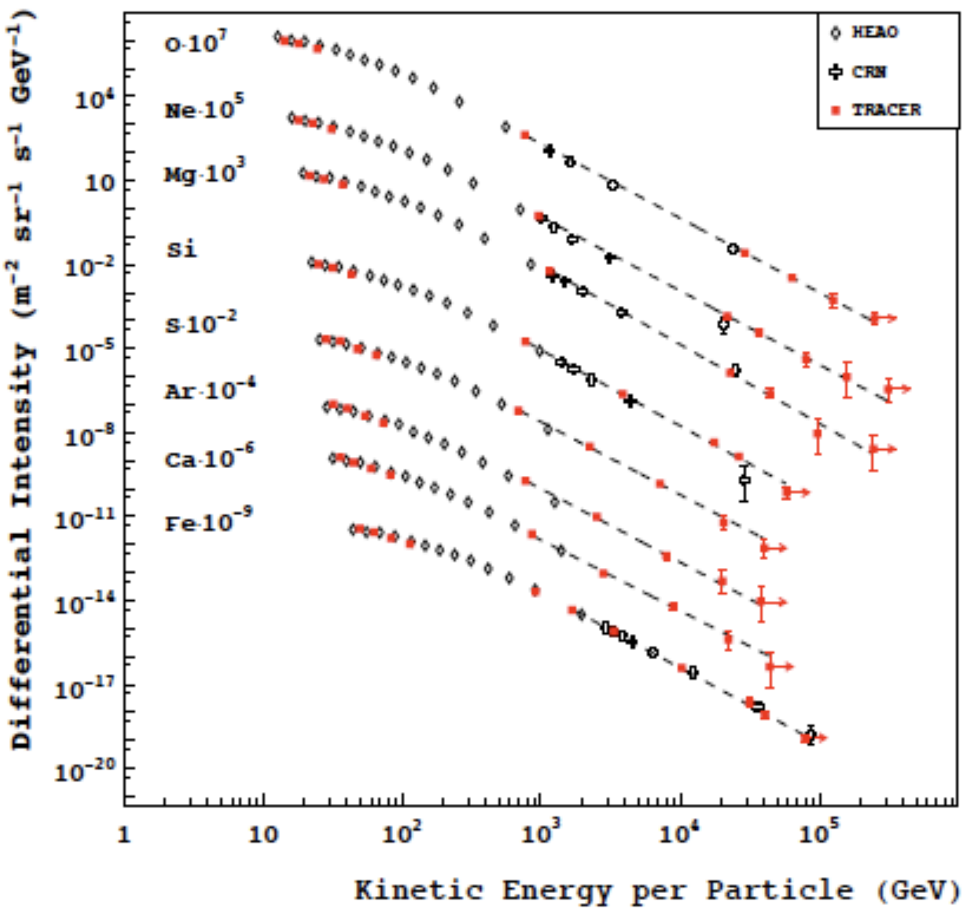

Incoming CRs
Transition Radiation Detector
Electron/proton, Z
Time of Flight
Z, E
TRD
Magnet
±Z
Silicon Tracker
Z, P
TOF
1
2
3-4
5-6
7-8
Tracker
TOF
RICH
9
ECAL
Ring Imaging Cherenkov
Z, E
Electromagnetic Calorimeter
E of electrons
The Charge and Energy are measured independently by several detectors



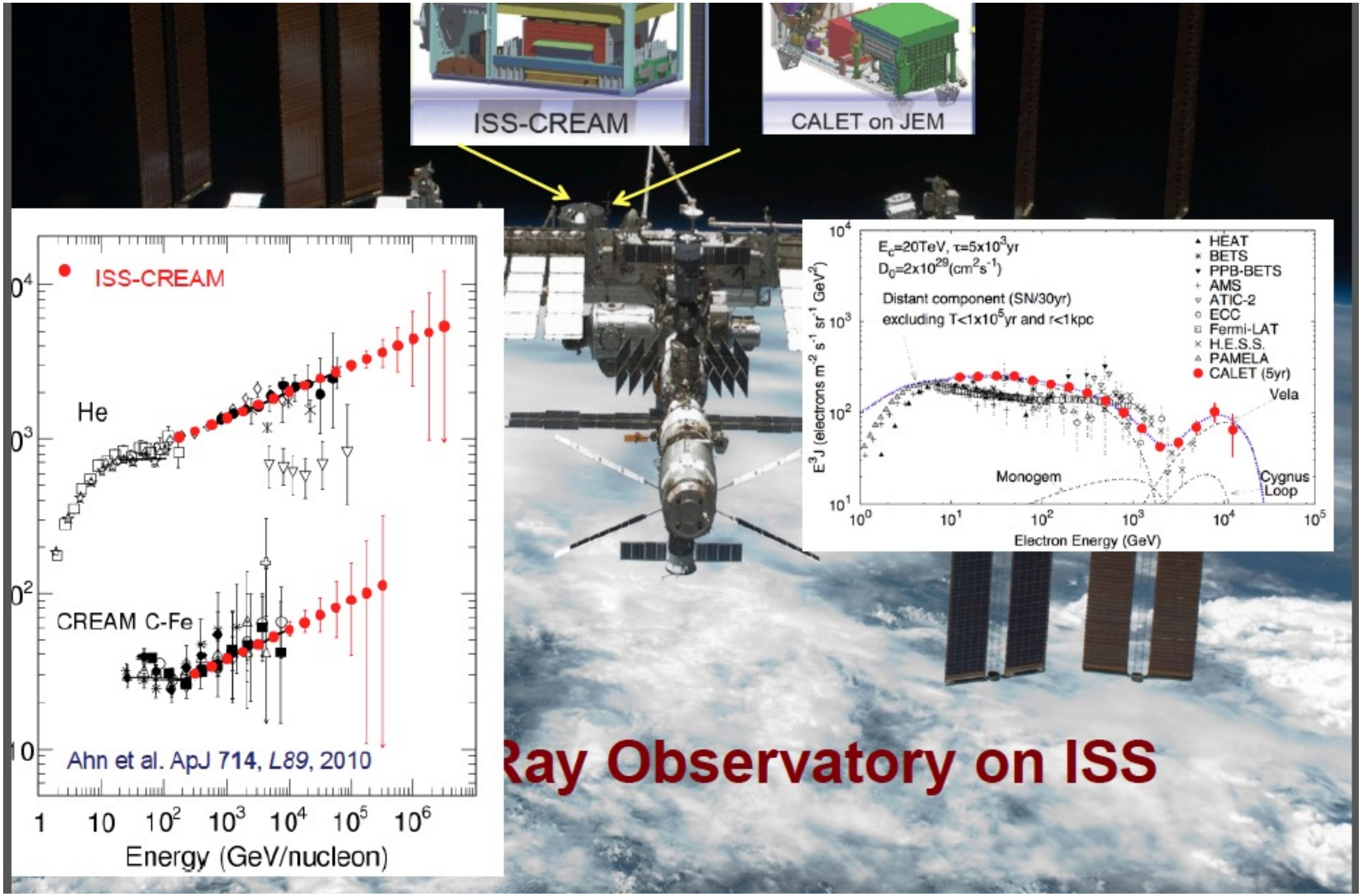
- No B field, different techniques with main focus on Z
- No B field, different techniques with main focus on e,γ
- Magnetic spectrometers

- Balloon
- Space
- Space (planned)

Spectra of individual nuclei




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)
E_c=20TeV, τ=5x10^3yr
D_0=2x10^29(cm^2s^-1)
Distant component (SN/30yr)
excluding T<1x10^5yr and r<1kpc
HEAT
BETS
PPB-BETS
AMS
ATIC-2
ECC
Fermi-LAT
H.E.S.S.
PAMELA
CALET (5yr)
Vela
Monogem
Cygnus Loop
E^3J (electrons m^-2 s^-1 sr^-1 GeV^2)
Electron Energy (GeV)
Ray Observatory on ISS

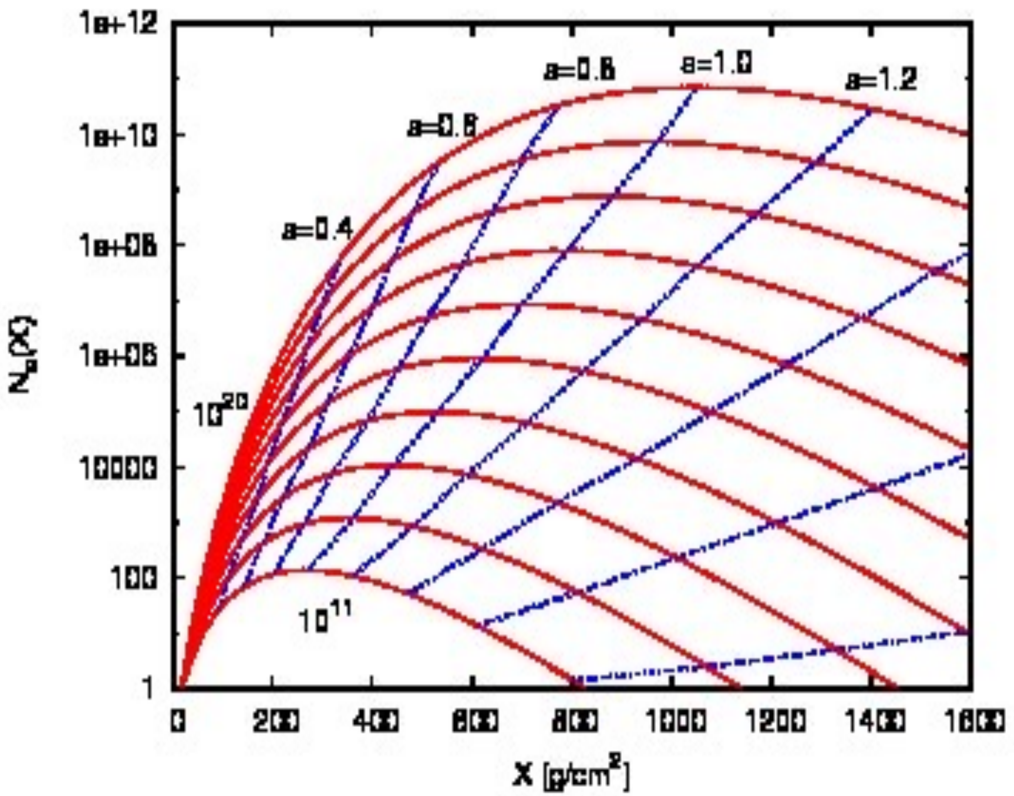
Direct detection of cosmic rays

- *Best way to get information on particle spectra*
- *Can be affected by local Solar system MF at E<200 GeV*
- *Can not go to knee (30 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.



Extensive air showers from cosmic rays

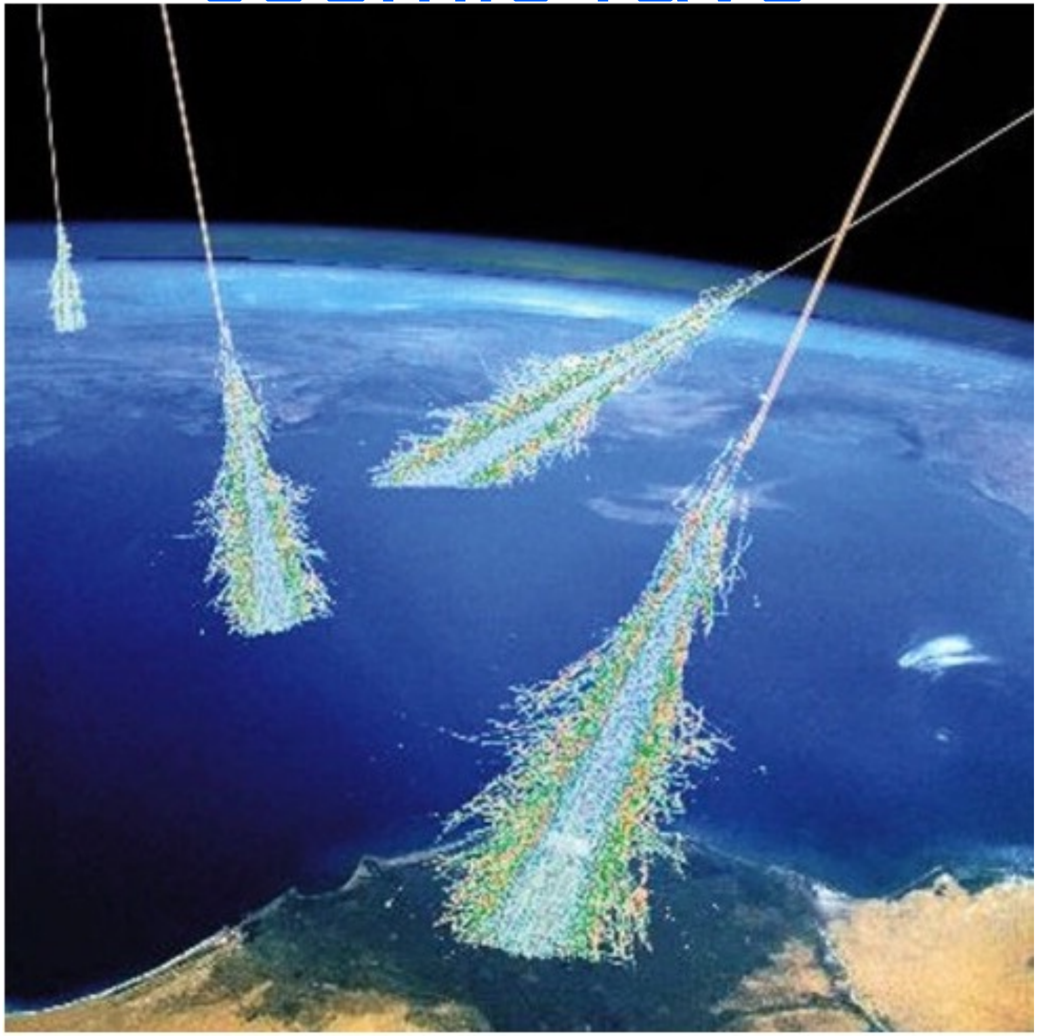
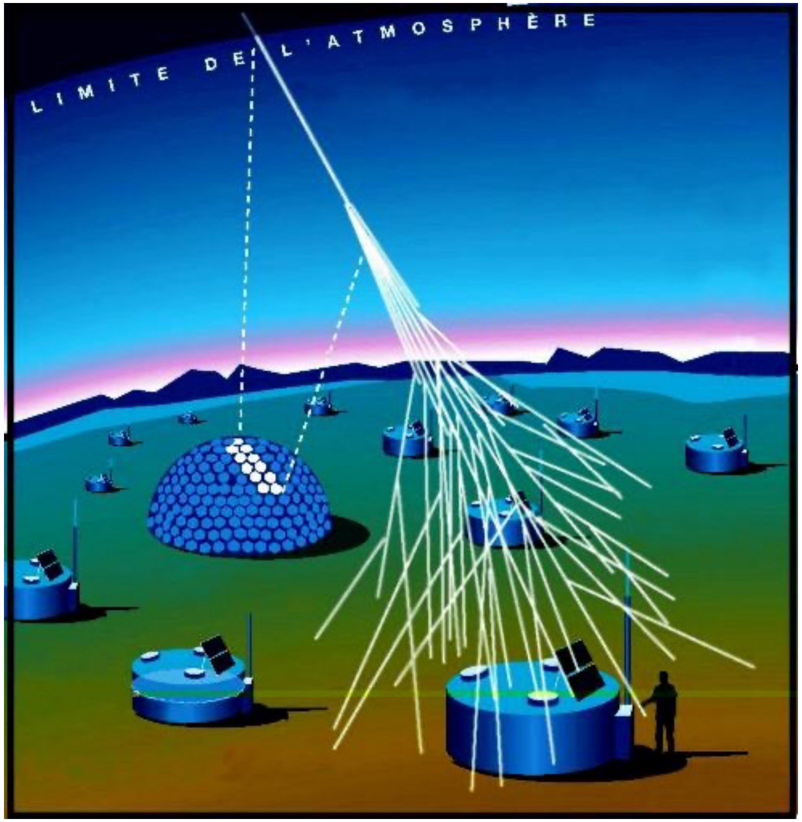


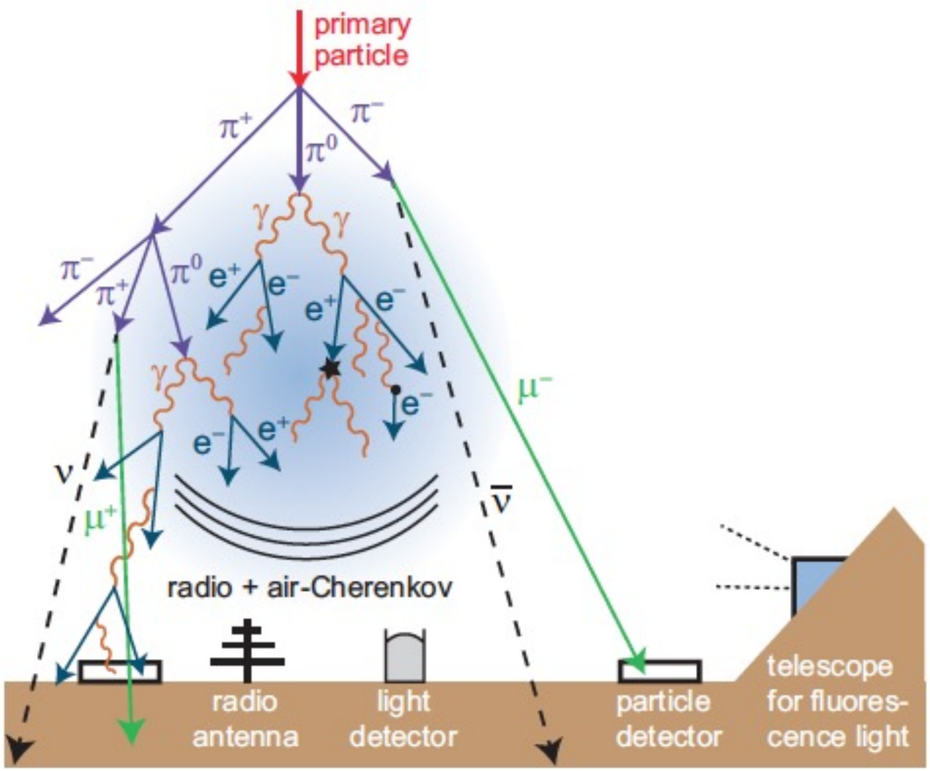
Illustration of extensive air-showers induced by UHECRs. Image credit: auger.org

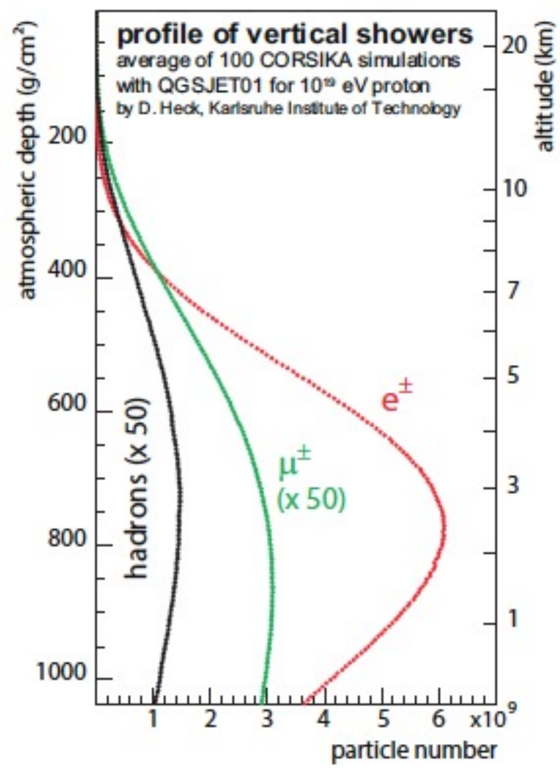
Parameters to measure:

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



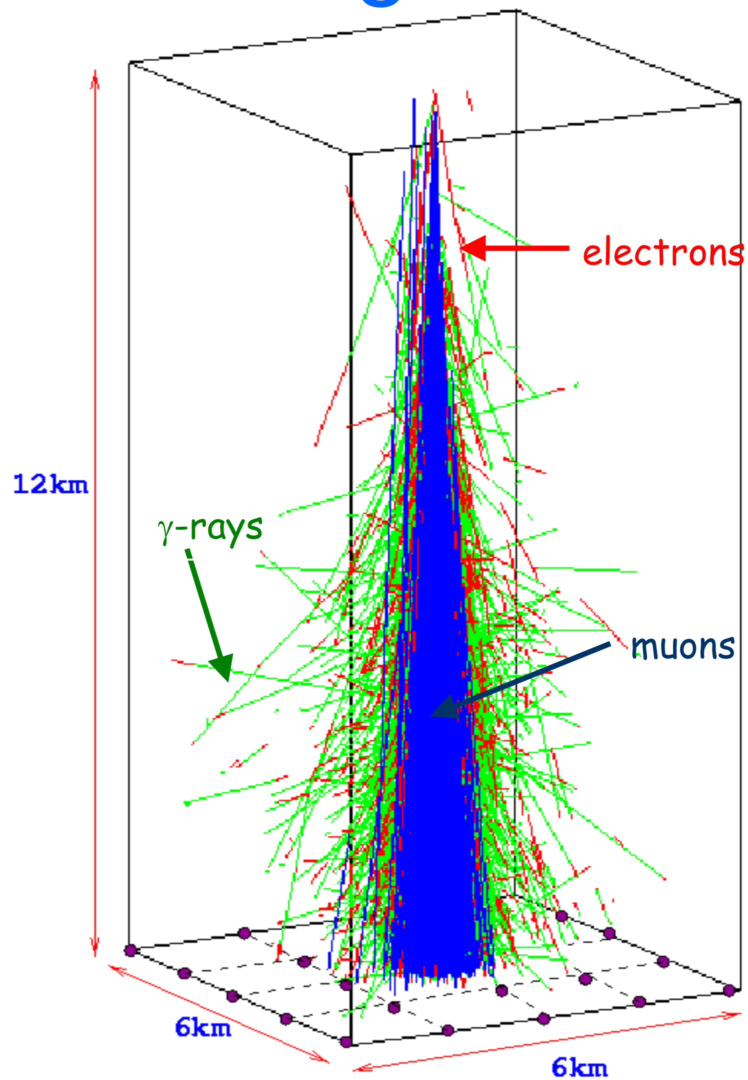
Detection techniques





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).

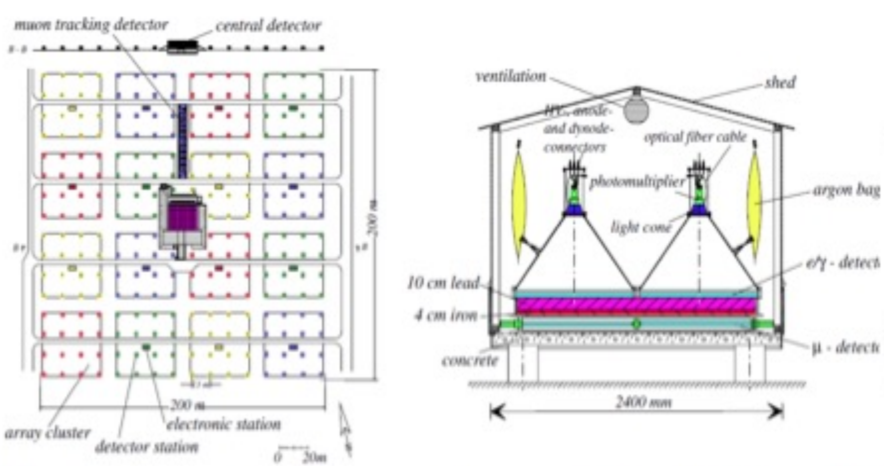


Fig. 1. Left: layout of the KASCADE air shower experiment; Right: sketch of a detector station with shielded and unshielded scintillation detectors.

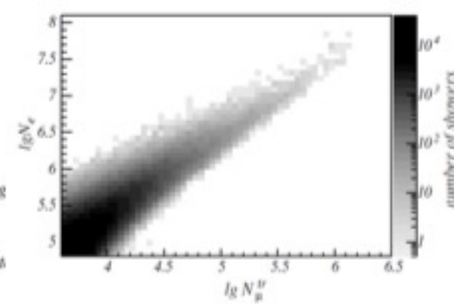
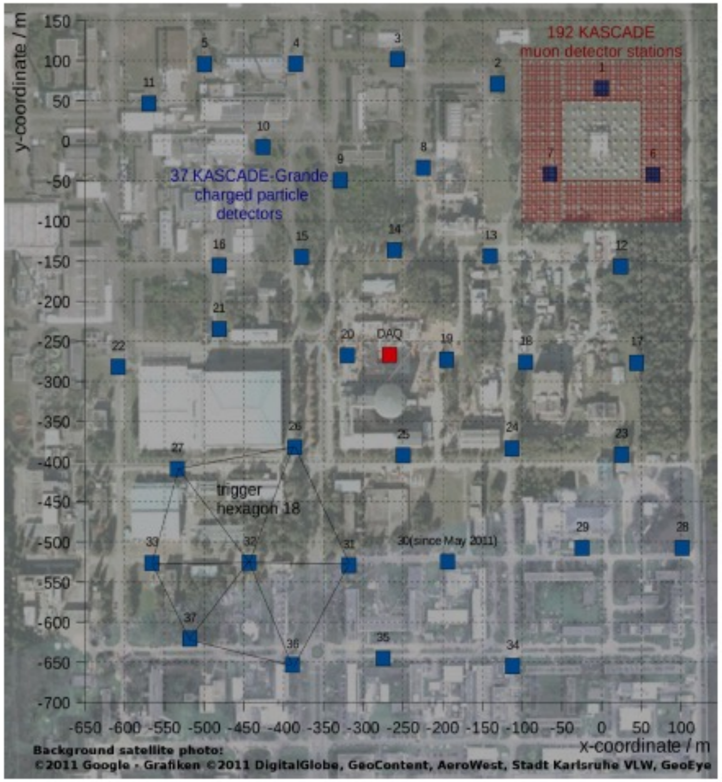


Fig. 2. Two-dimensional shower size spectrum used in th analysis. The range in $\lg N_e$ and $\lg N_\mu^{tr}$ is chosen to avoi influences of inefficiencies.

Operated before 2000

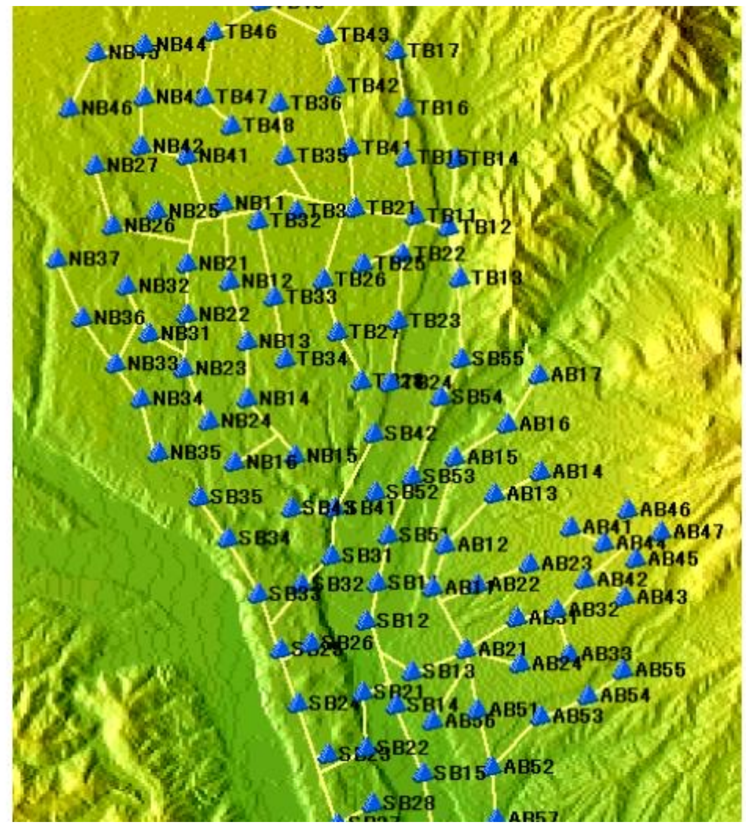
KASCADE-Grande

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



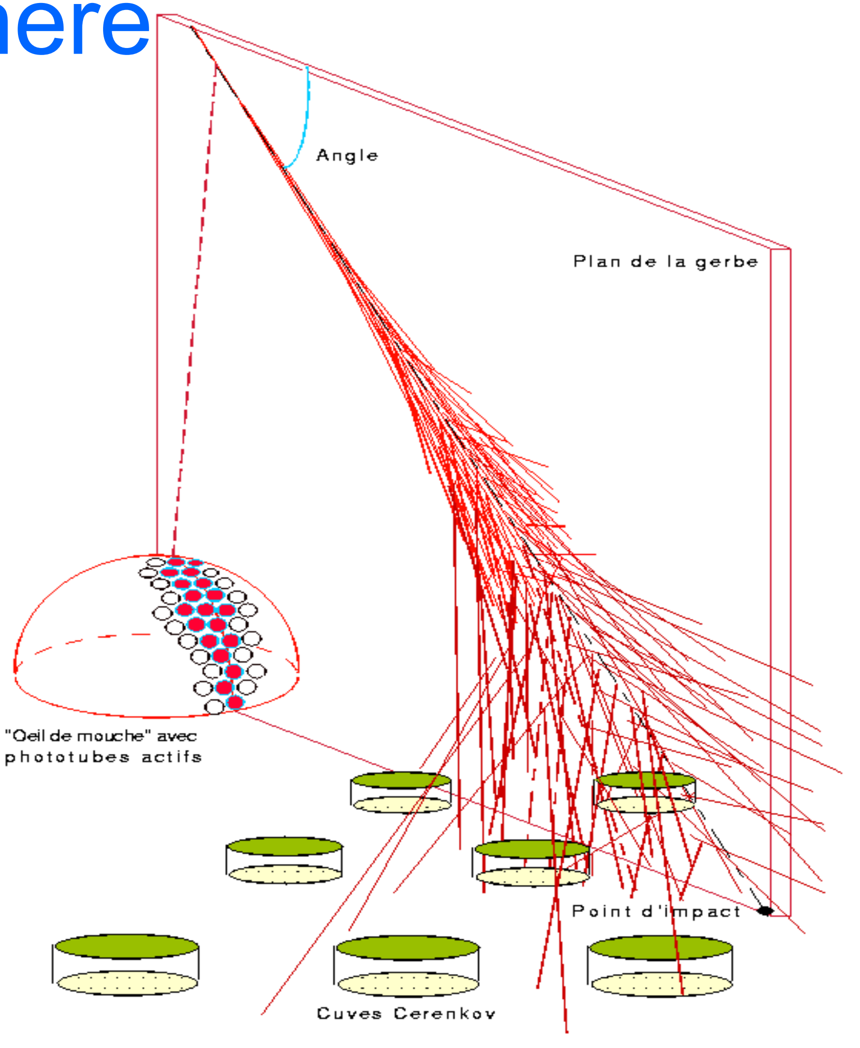
AGASA

- 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.

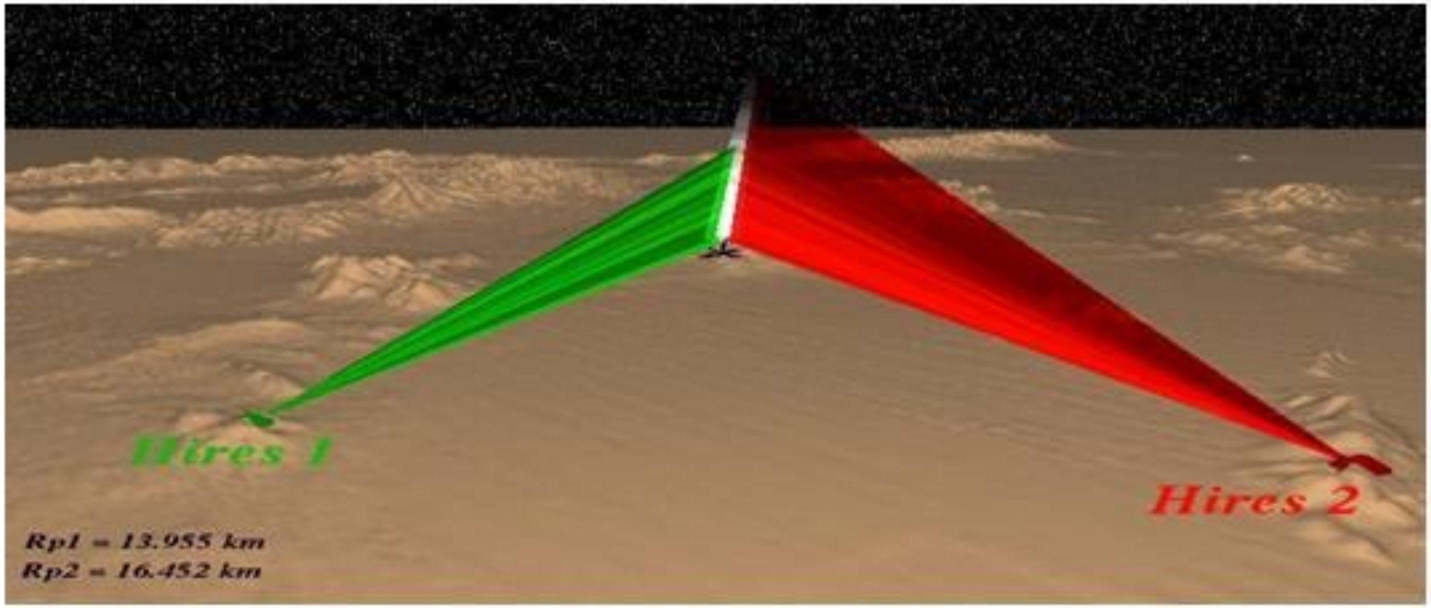


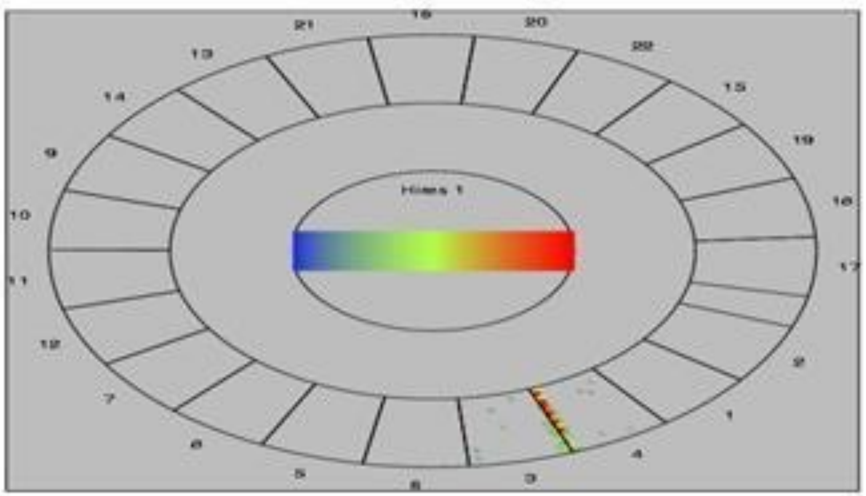
Detection of shower development in atmosphere

- 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.

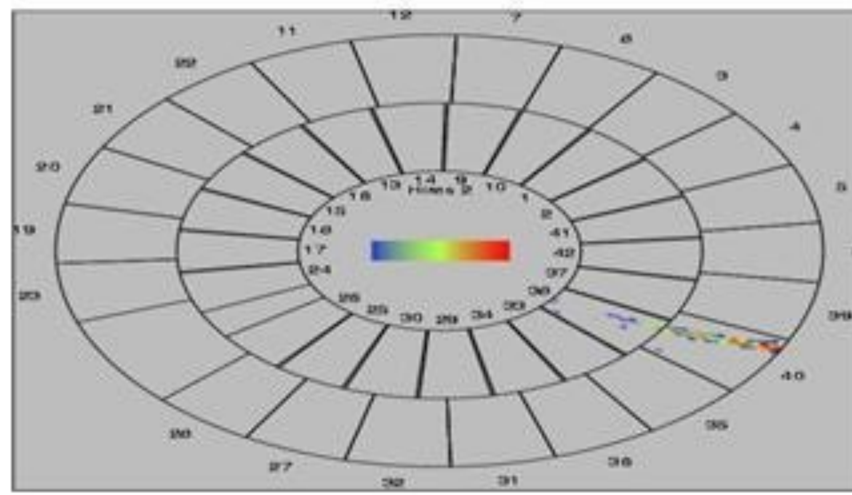


Stereo Event E ~50 EeV





HiRes1



HiRes2

High Resolution Fly’s Eye: HiRes

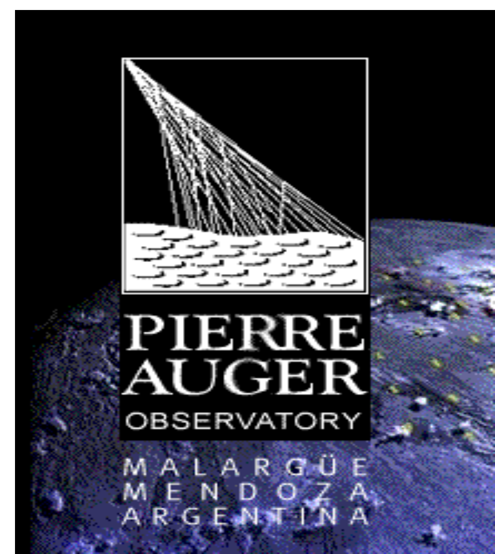
- HiRes 1 and HiRes 2 sit on two small mountains in western Utah, with a separation of 13 km.
- HiRes 1 has 21 three meter diameter mirrors which are arranged to view the sky between elevations of 3 and 16 degrees over the full azimuth range;
- HiRes 2 has 42 mirrors which image the sky between elevations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

- Operated in stereo mode 1999-2006.

Auger Observatory

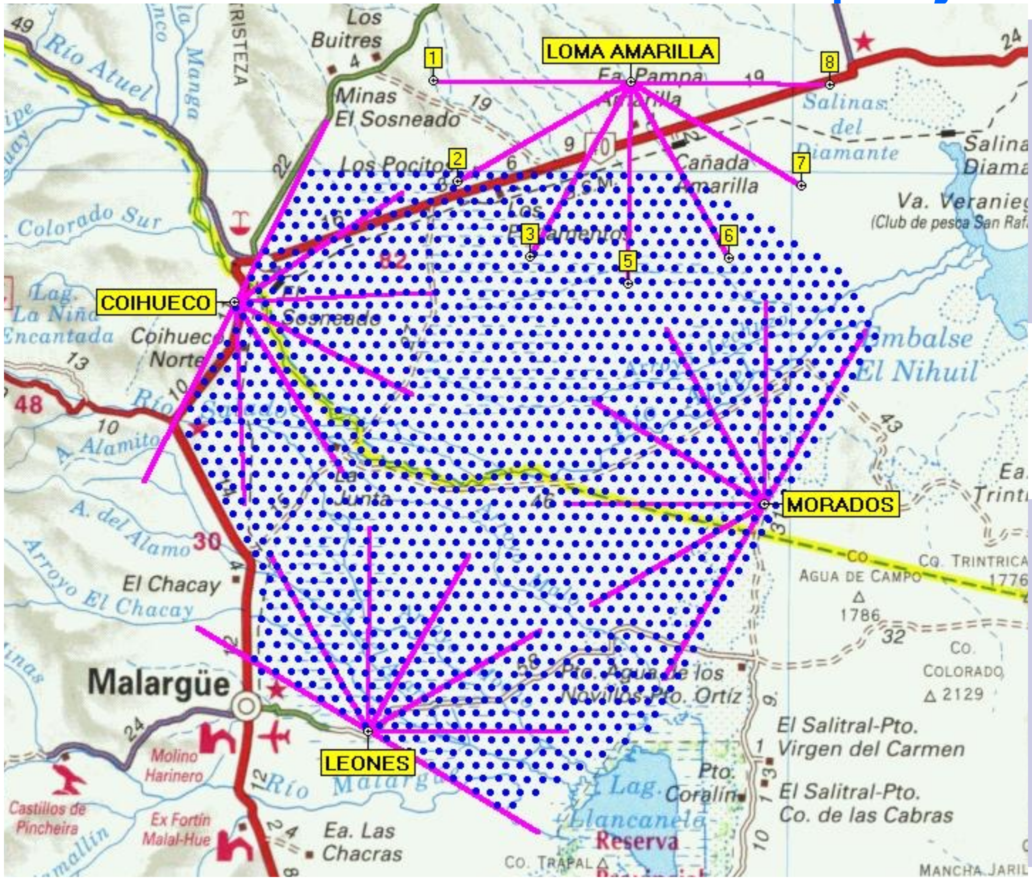
ort involving more than 450
2 institutions in 17 countries:

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



Pierre Auger Observatory

South site in Argentina almost finished
North site – project



Surface Array

1600 detector stations

1.5 Km spacing

3000 Km^2 (30xAGASA)

Fluorescence Detectors

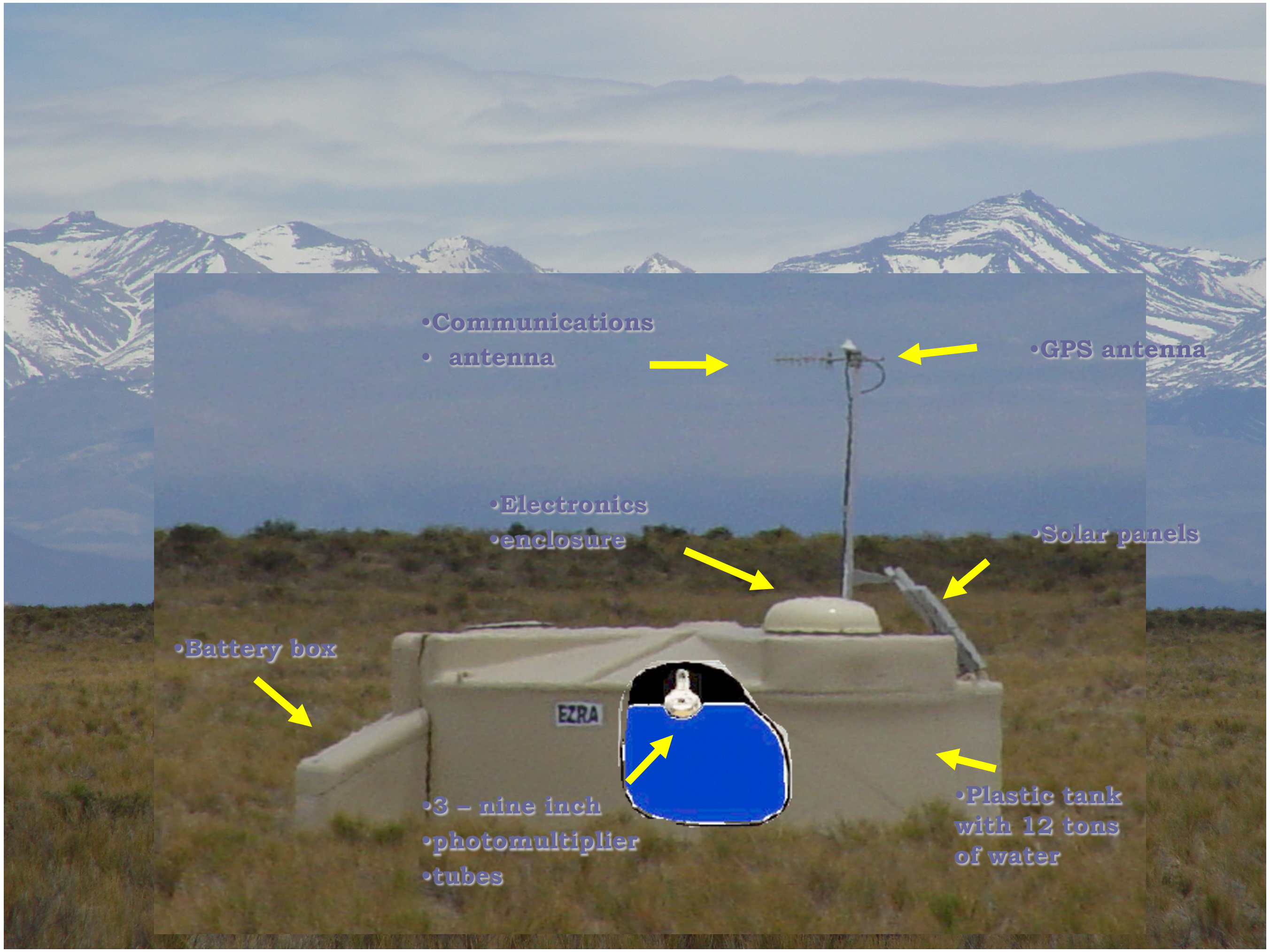
4 Telescope enclosures

6 Telescopes per enclosure

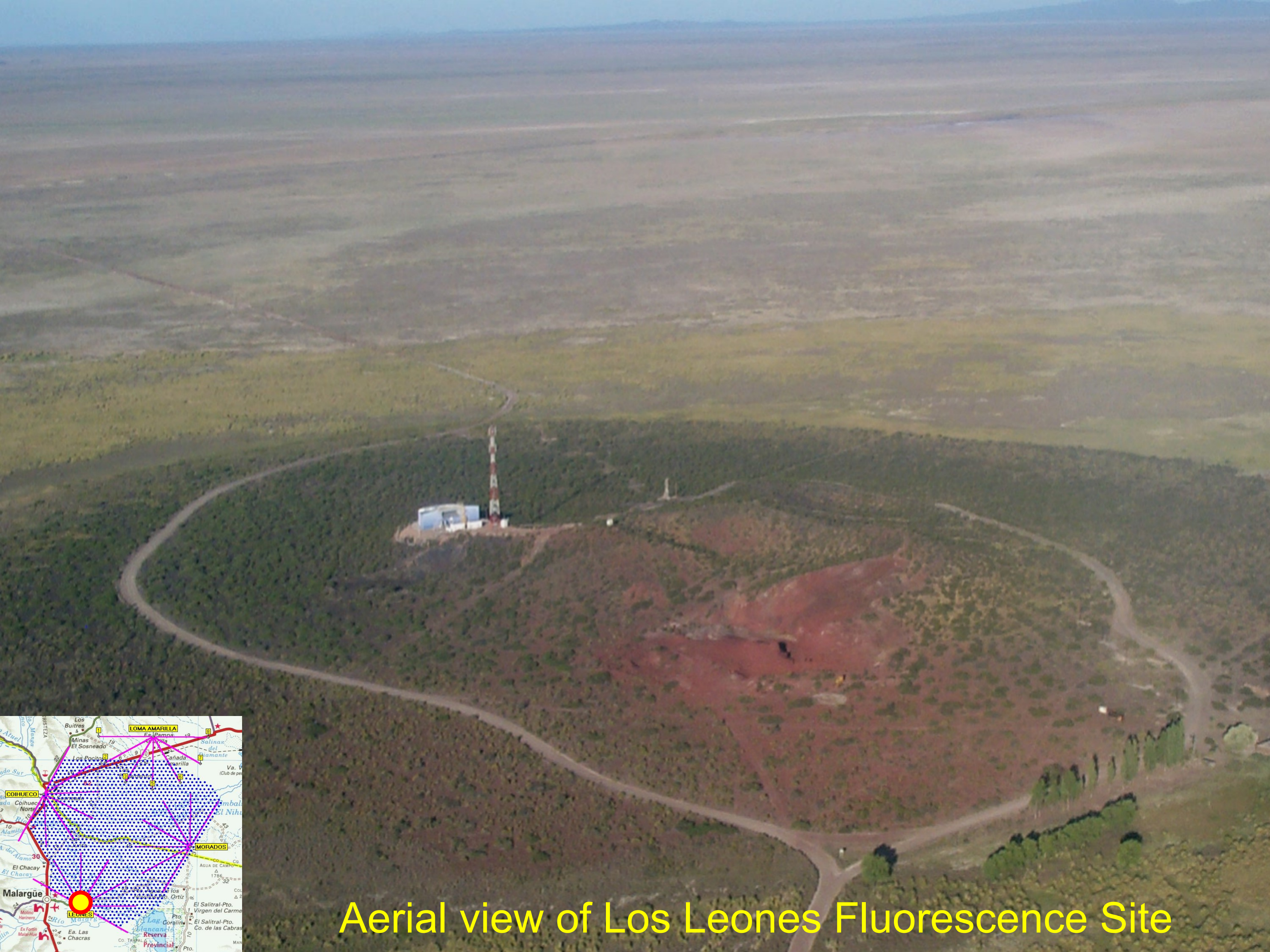
24 Telescopes total

Tanks aligned seen from Los Leones

The Surface Array

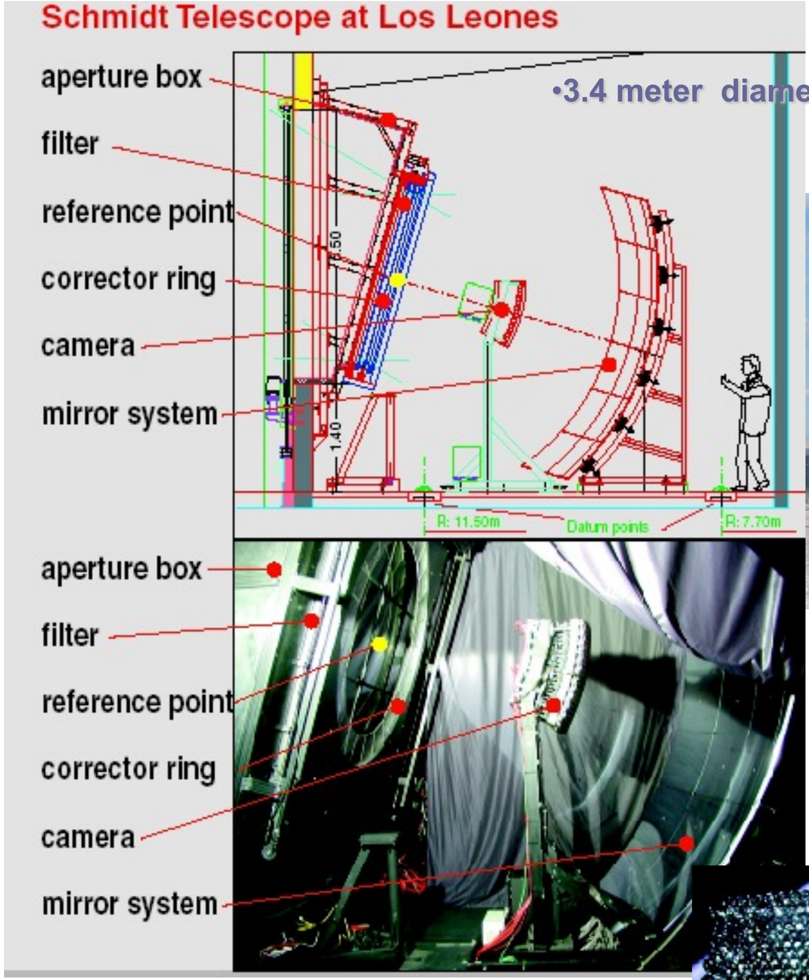


SAGNAP – April 2004
P. Mantsch



Aerial view of Los Leones Fluorescence Site

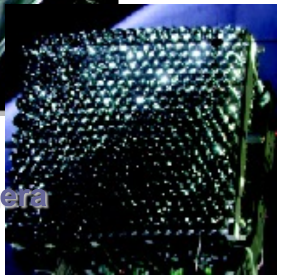
•The Fluorescence Detectors



•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)

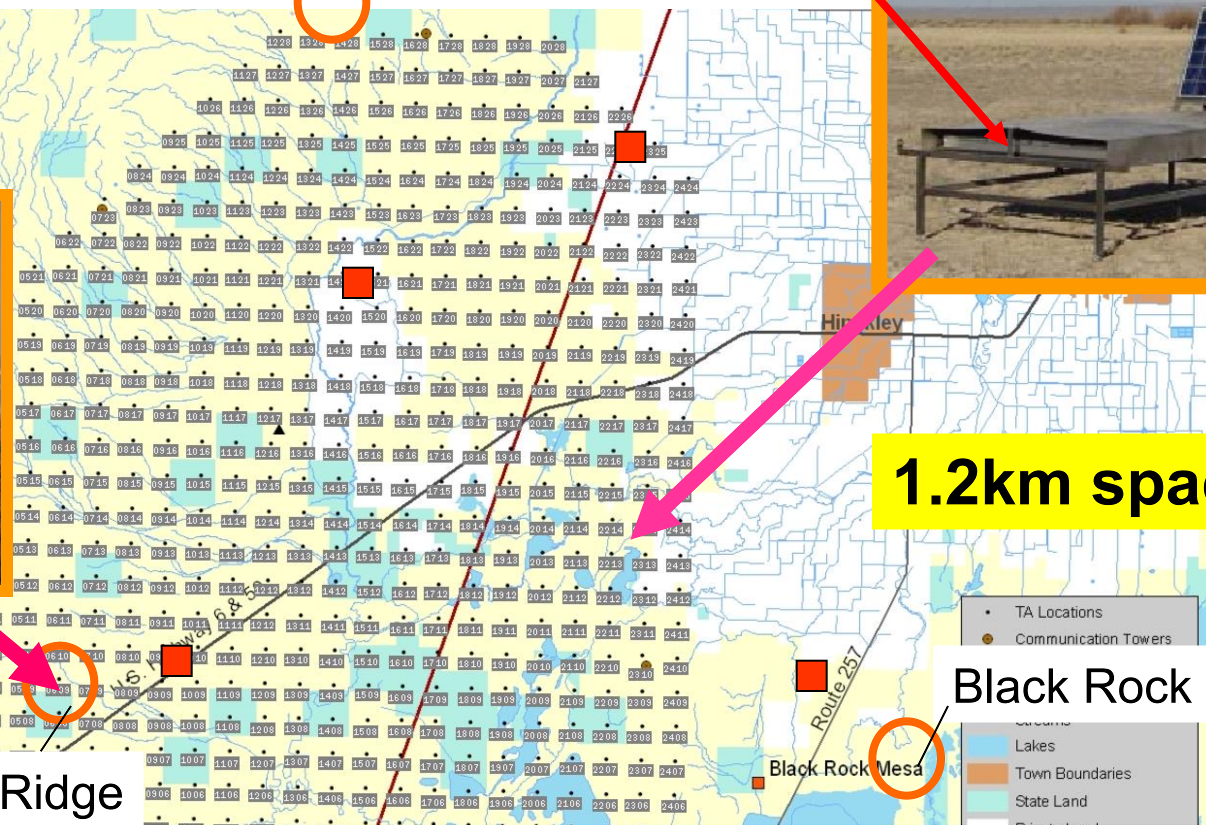
Atmospheric fluorescence telescope
3 stations **FD**

5 communication towers

$3m^2$ 1.2cm t
two layers

SD

Middle Drum



Long Ridge

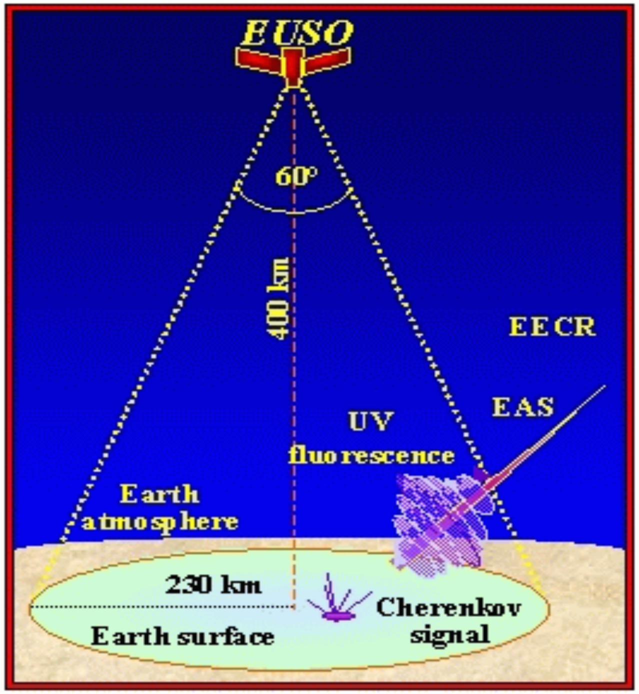
Black Rock Mesa

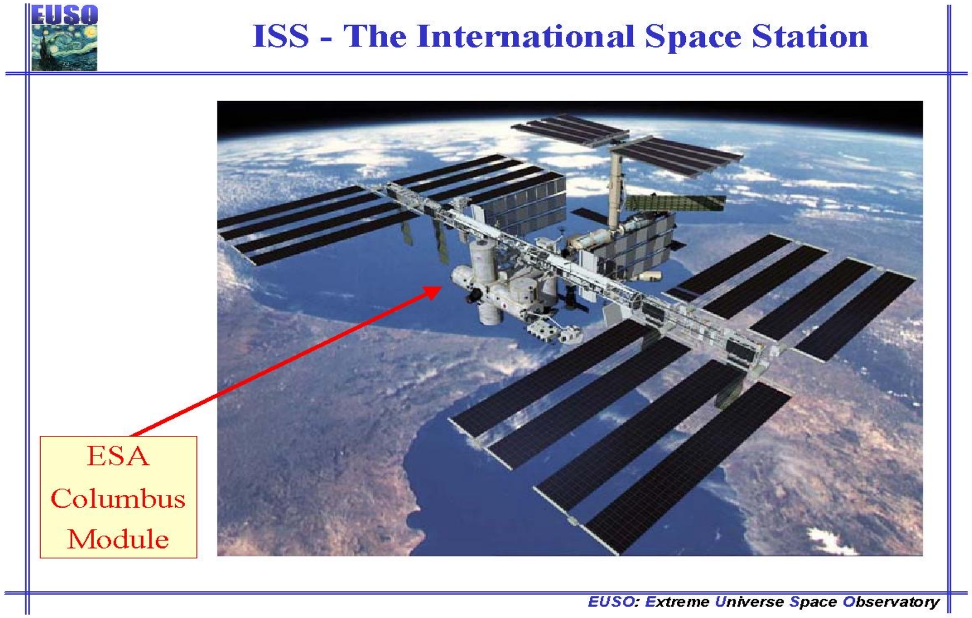
1.2km spacing

20km

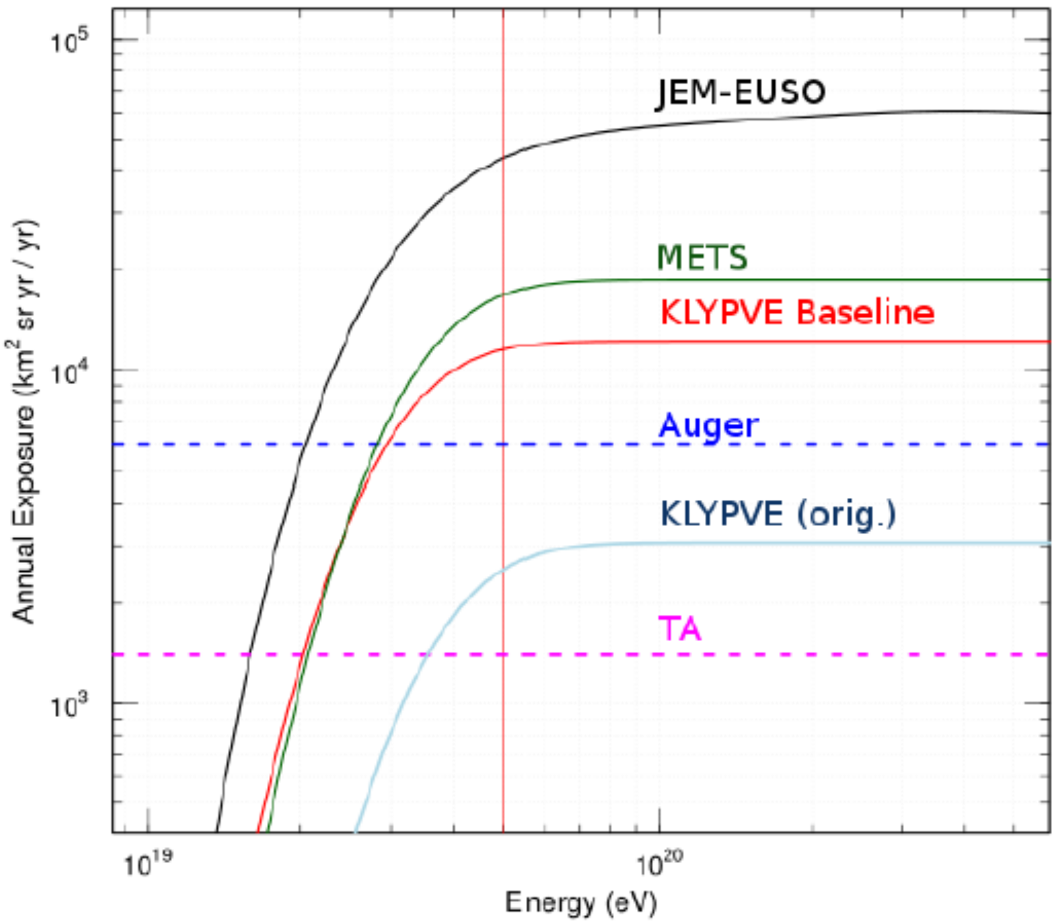
Sensitivity of SD : ~9 x AGASA

Extreme Universe Space Observatory: JEM-EUSO (project)



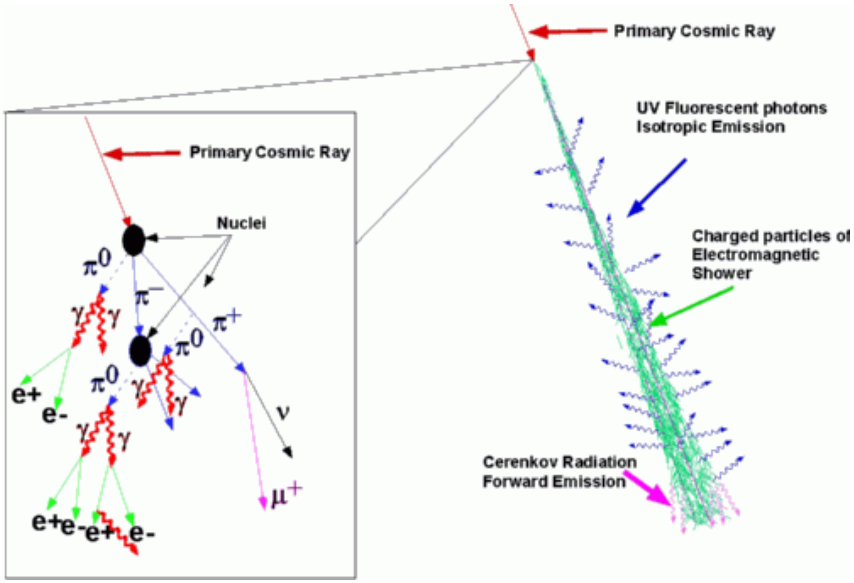


Exposure of space experiments

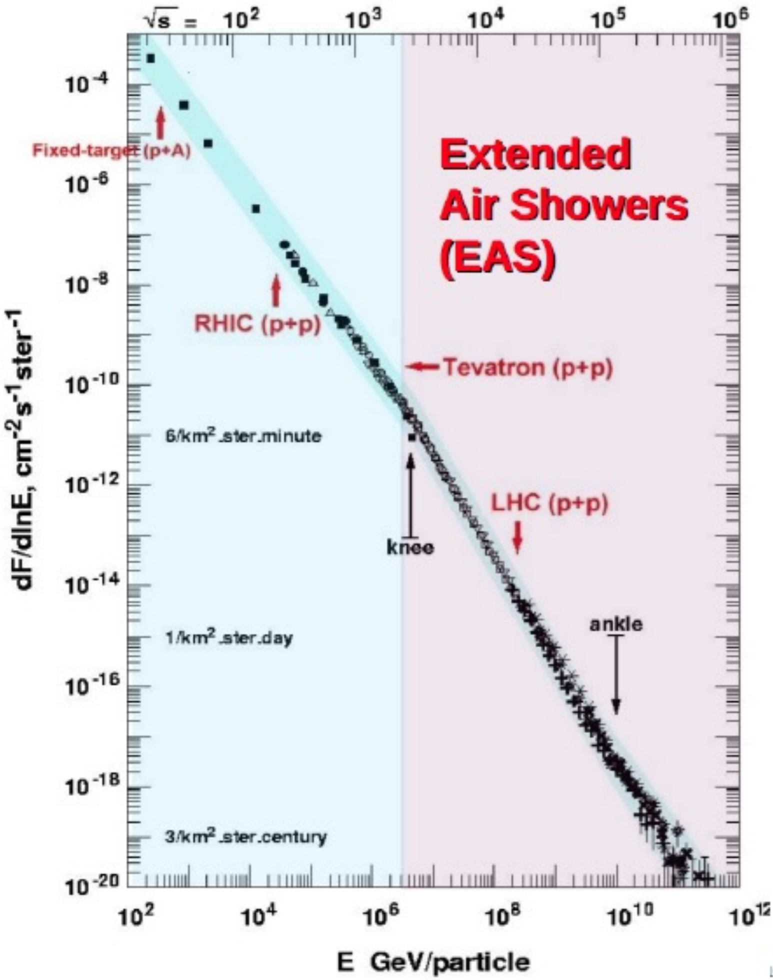


Shower structure: theoretical uncertanty

- 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

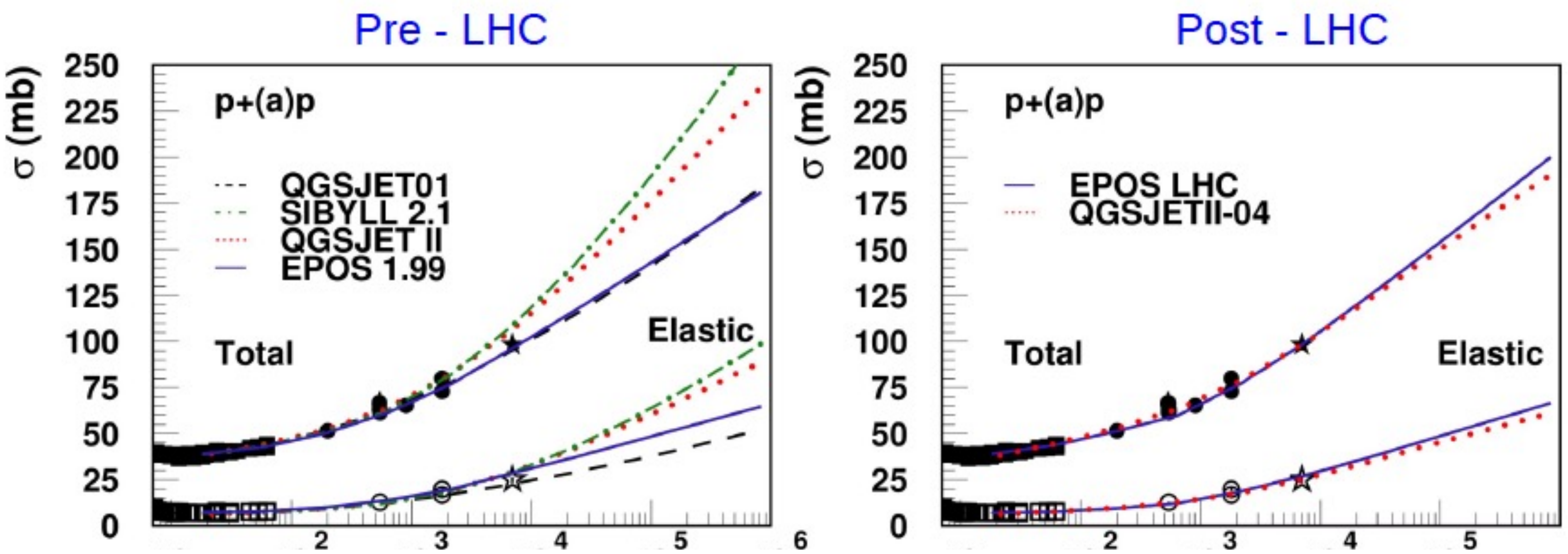


Accelerator based experiments are the most powerful available tools to determine the high energy hadronic interactions characteristics
→ Hadronic interactions models tuning

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

PP cross section

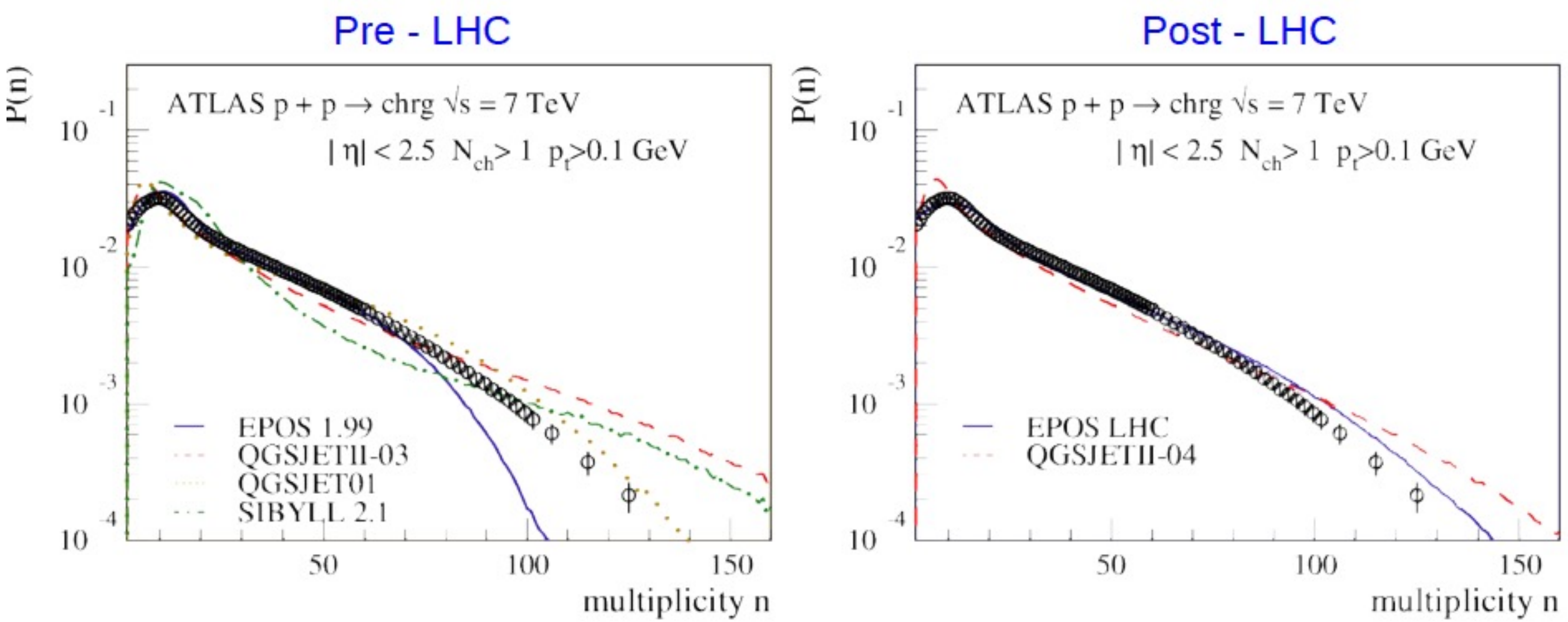
- extrapolation to pA or to high energy (model dependent)
  - different amplitude and scheme
- different extrapolations



Multiplicity Distribution

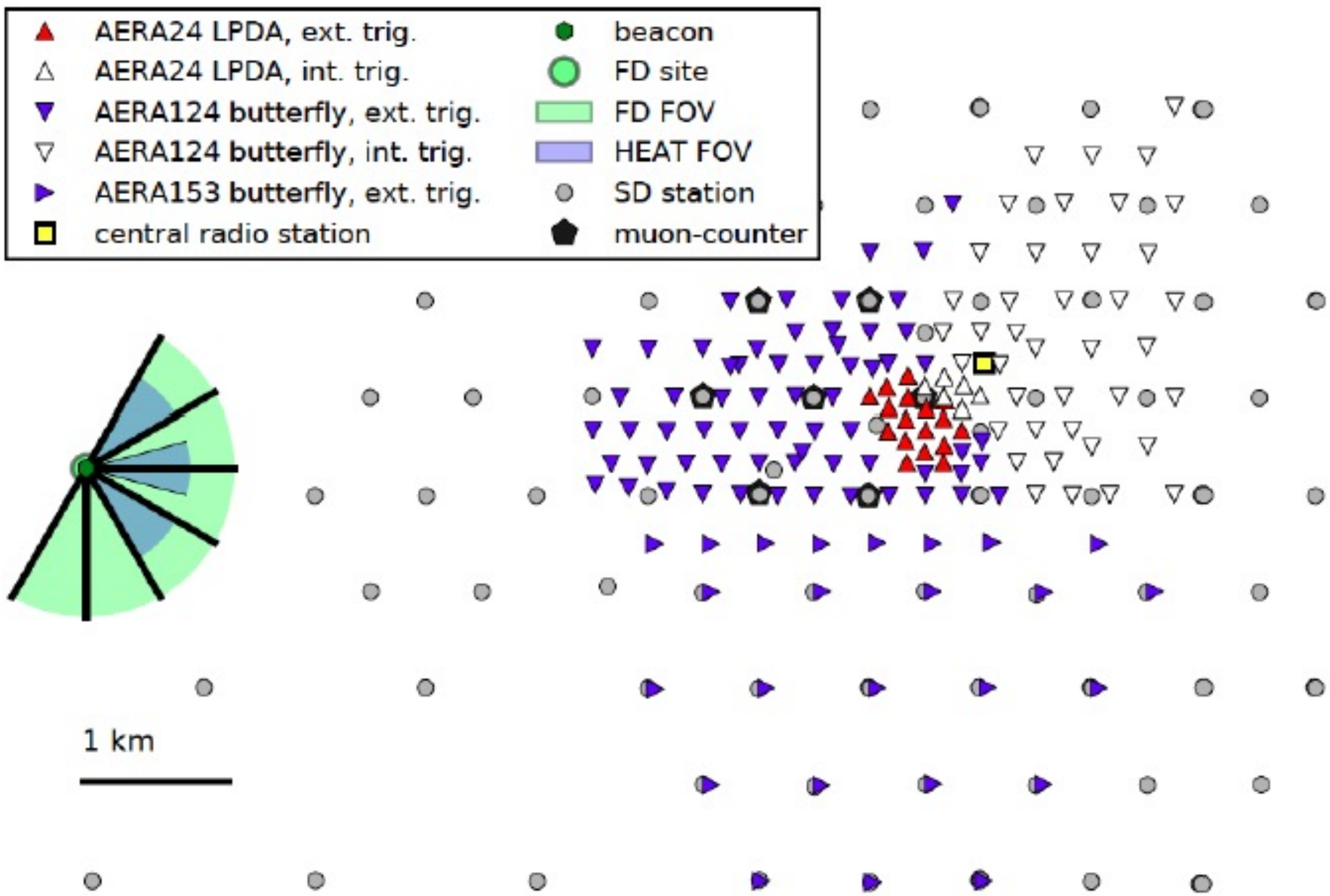
- Consistent results
  - ➜ Better mean after corrections
    - difference remains in shape
  - ➜ Better tail of multiplicity distributions
    - corrections in EPOS LHC (flow) and QGSJETII-04 (minimum string size)

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

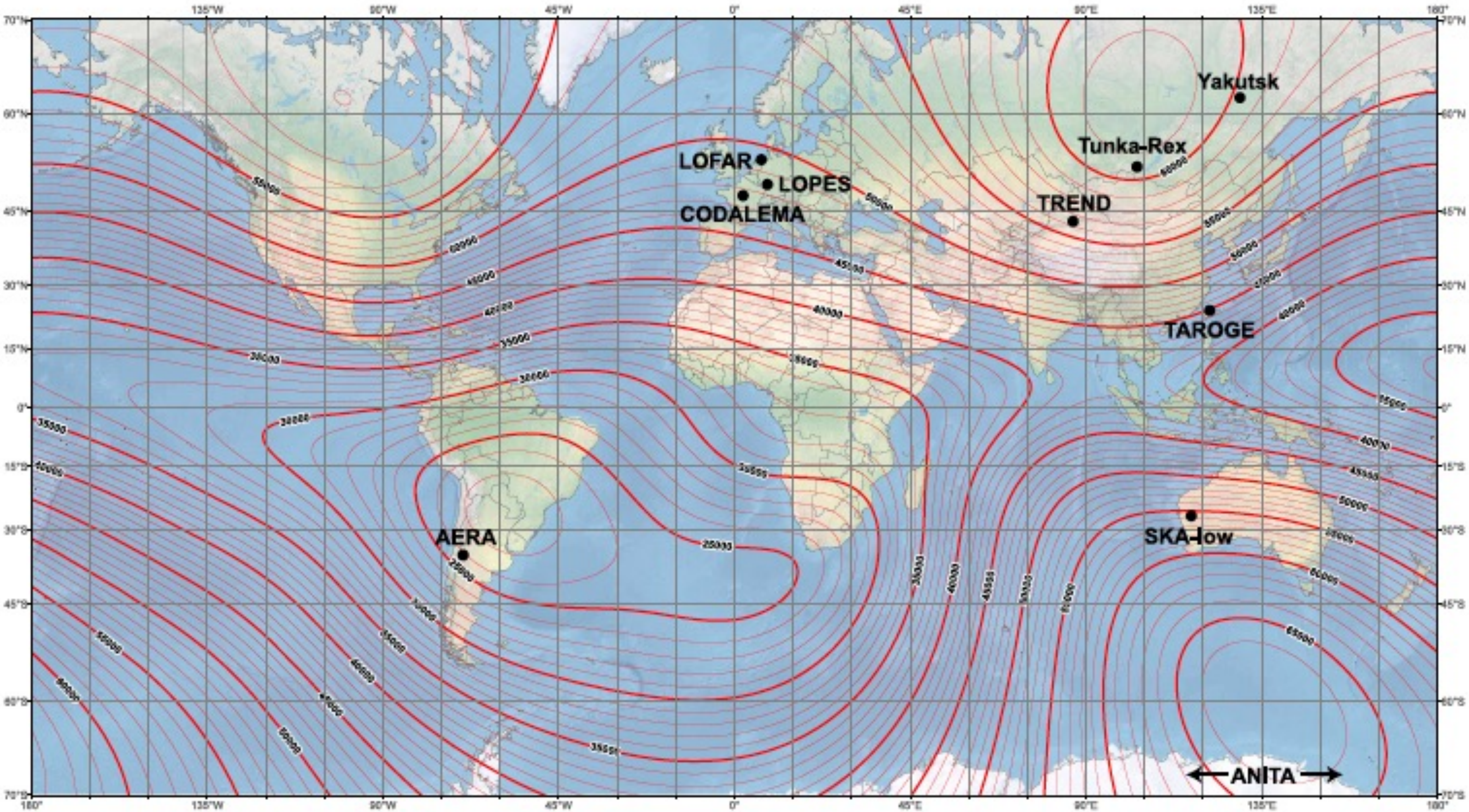


Radio detection of Cosmic Rays

Radio detectors in Auger



Radio detectors Earth



Underlying map (Mercator projection):
Main Geomagnetic Field Total Intensity with contour intervals of 1000 nT according to US/UK World Magnetic Model - Epoch 2015.0

developed by NOAA/NGDC & CIRES http://ngdc.noaa.gov/geomag/WMM

Map reviewed by NGA and BGS Published December 2014

Overlayed: **Location of radio experiments for cosmic-ray air showers** added on underlying map by Frank G. Schröder Karlsruhe Institute of Technology (KIT), Germany

Radio detectors

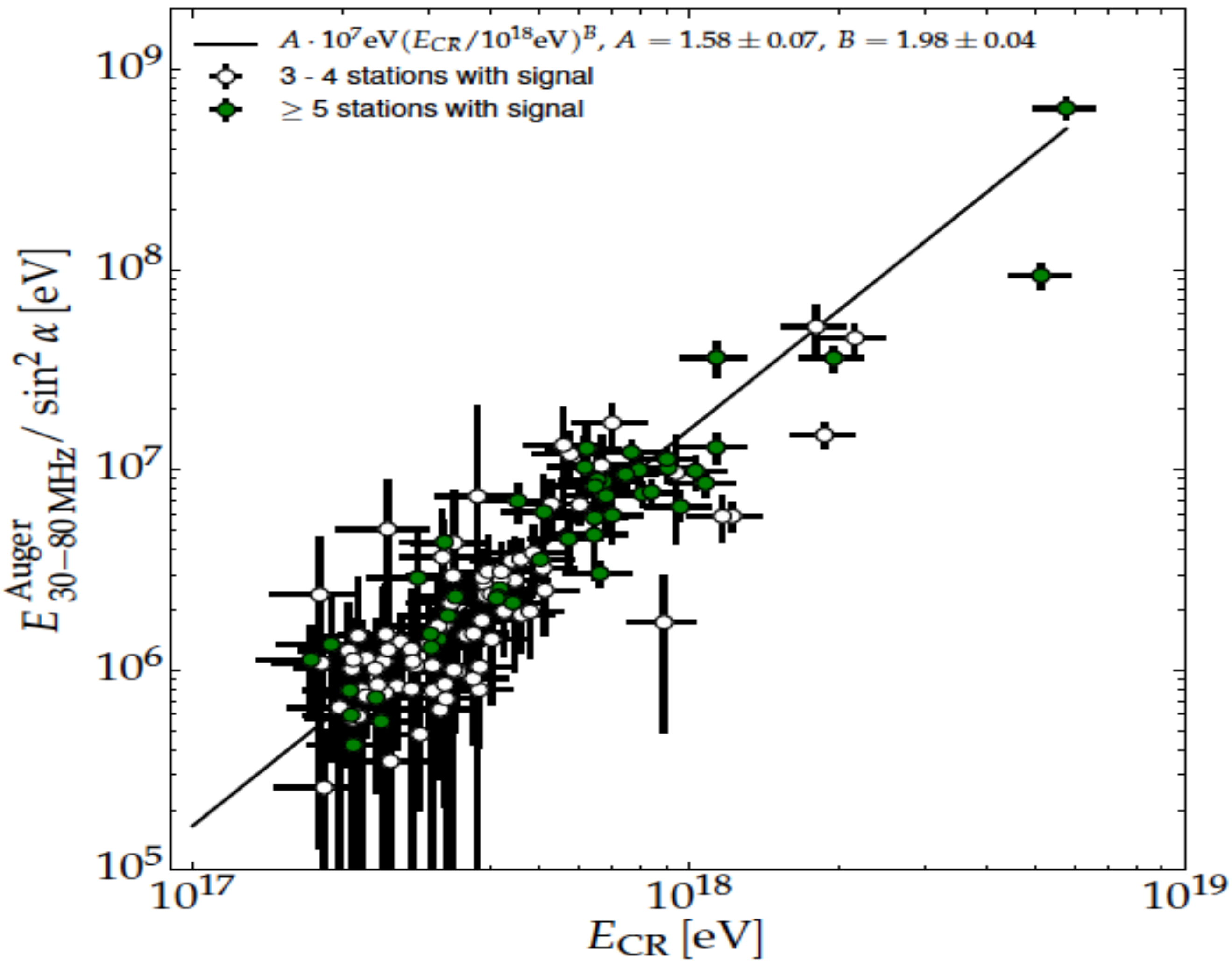
(a) Inverted v-shape dipole at LOPES

(b) Butterfly at CODALEMA

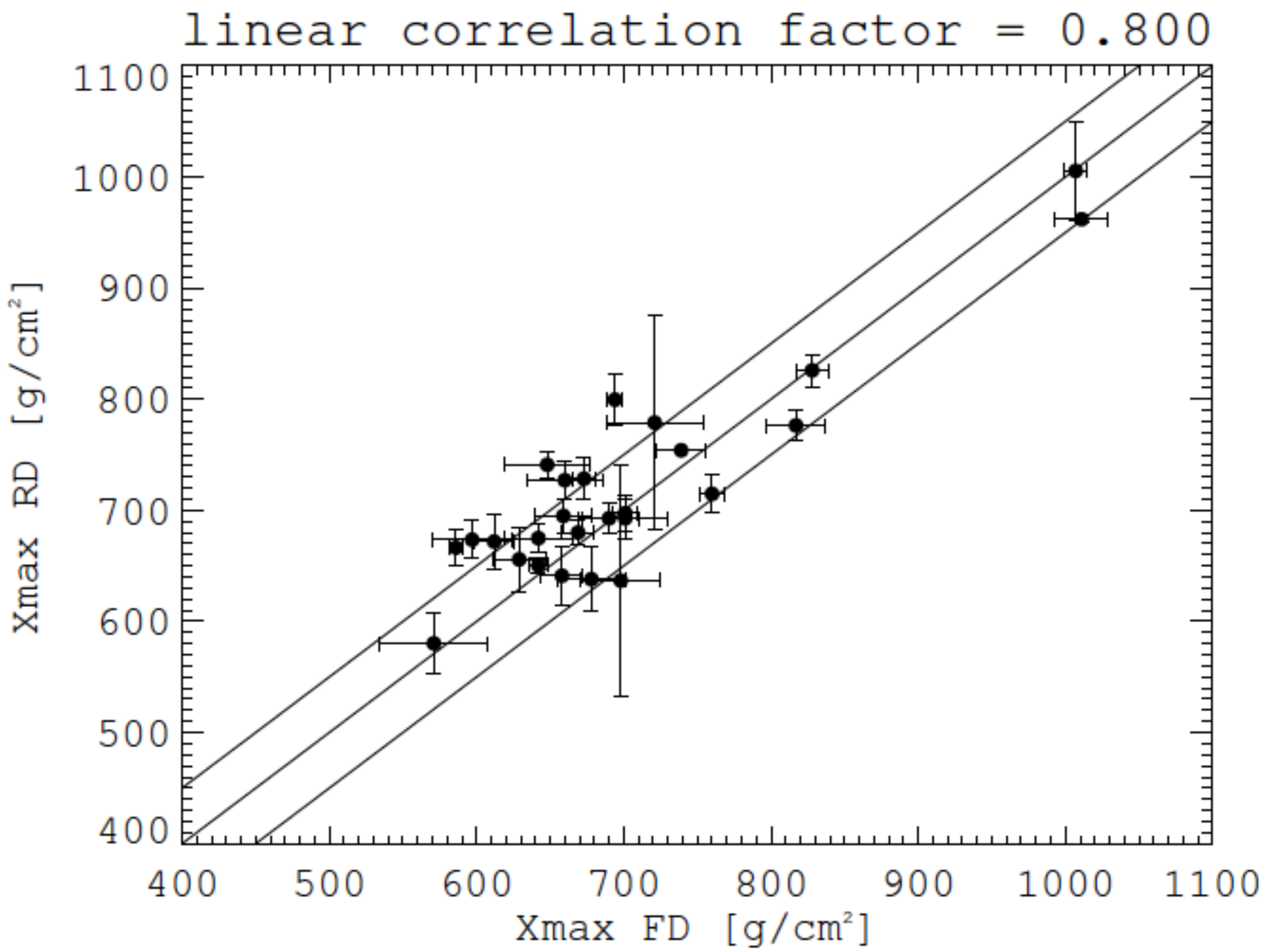
(c) LPDA at AERA

(d) SALLA at Tunka-Rex

Energy by radio detection



Xmax radio detection



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. New Radio technique is under development.
- 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

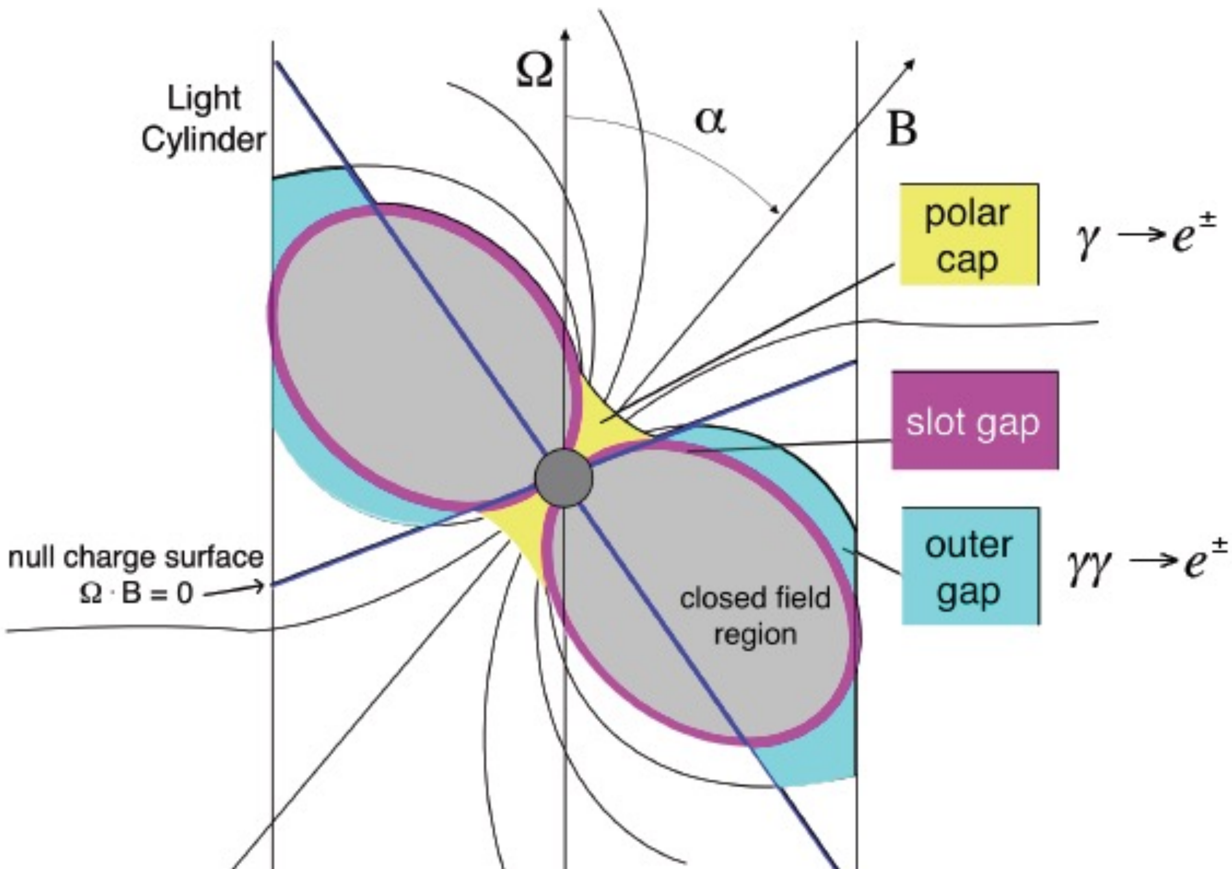
THE ELECTRIC FIELD IS SMALL SCALE:

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

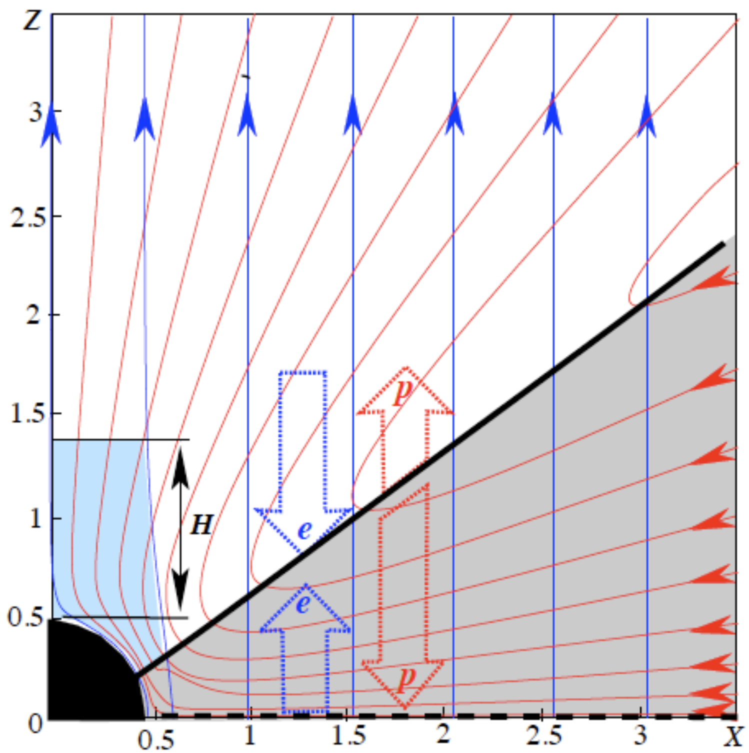
From lectures of P.Blasi

Acceleration by electric field

Pulsar accelerator geometries



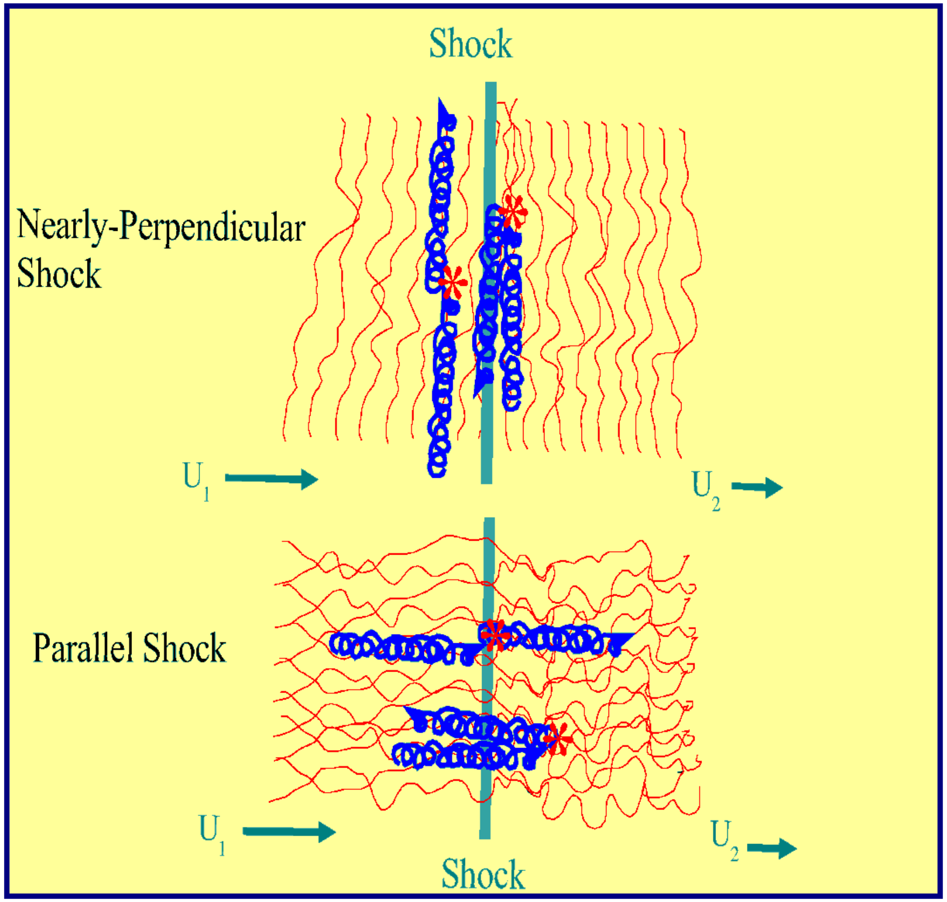
Acceleration near Black Hole in the electric field



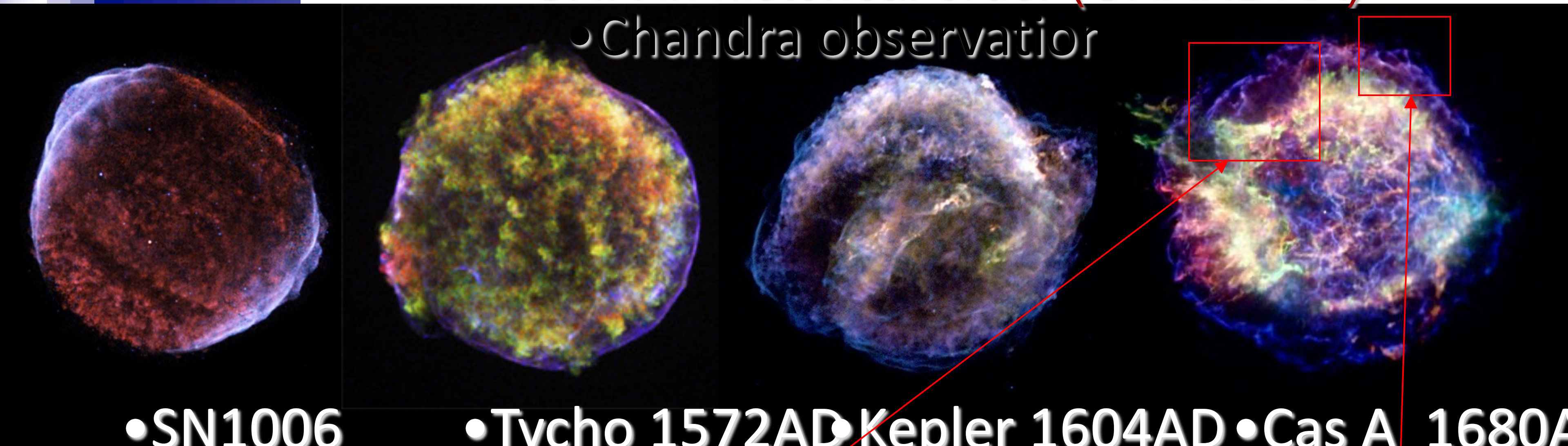
Wald, 1972

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



•SNR in historical order (CHANDRA)

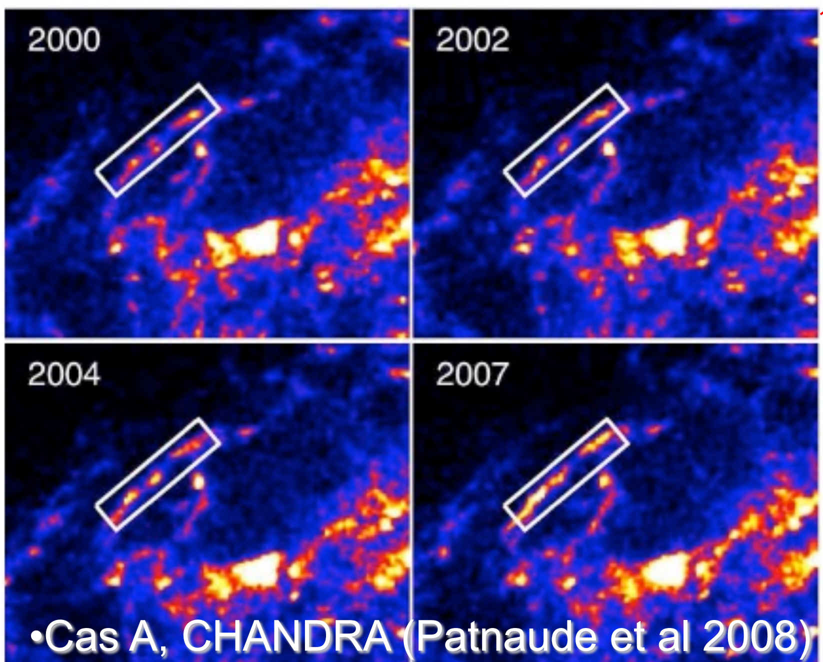


•NASA/CXC/Rutgers/
•J.Hughes et al.

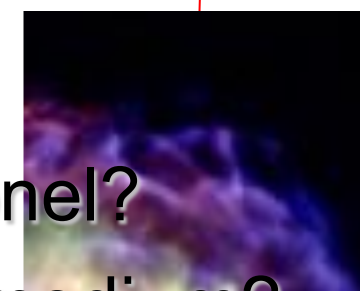
•NASA/CXC/Rutgers/
•J.Warren & J.Hughes et al.

•NASA/CXC/NCSU/
•S.Reynolds et al.

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



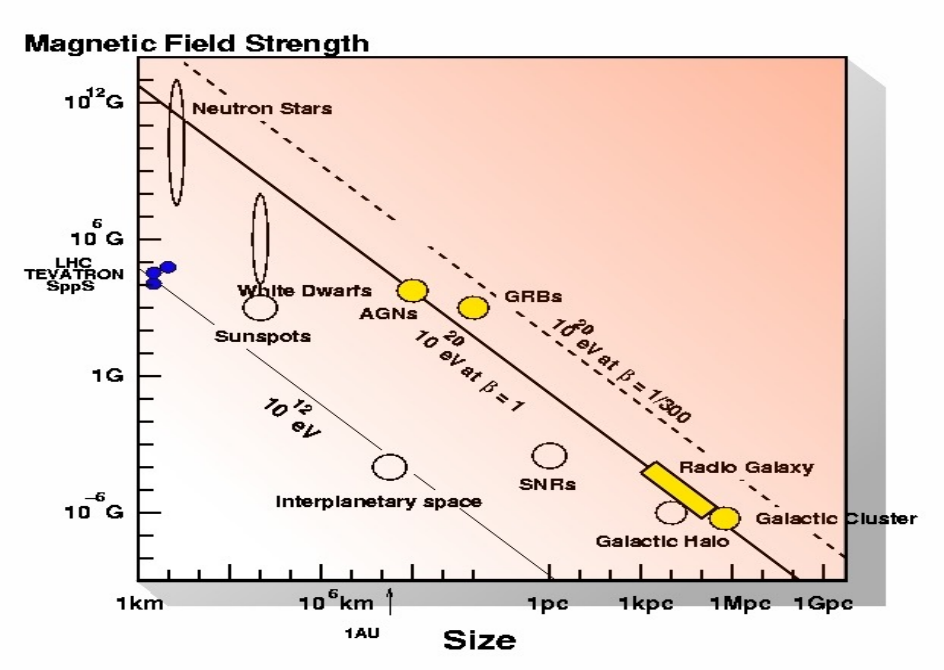
•Cas A, CHANDRA (Patnaude et al 2008)



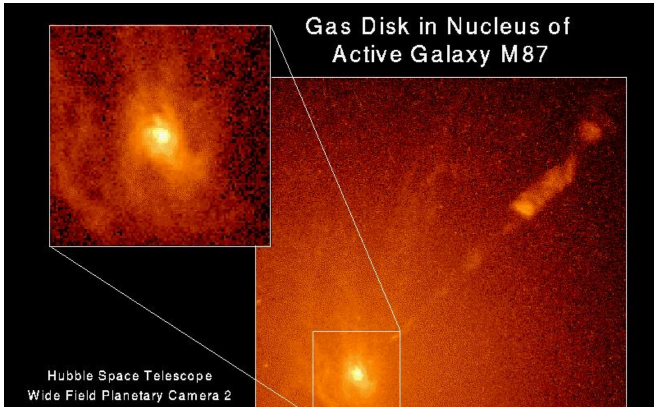
- High speed shrapnel?
- Clumpy ambient medium?
- CR-driven instability?

•Shock structure maps out
•pre-shock features (B, ρ...)

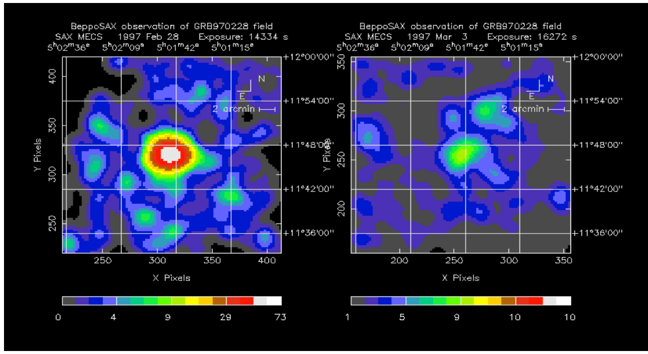
Acceleration of UHECR



A.G.N.

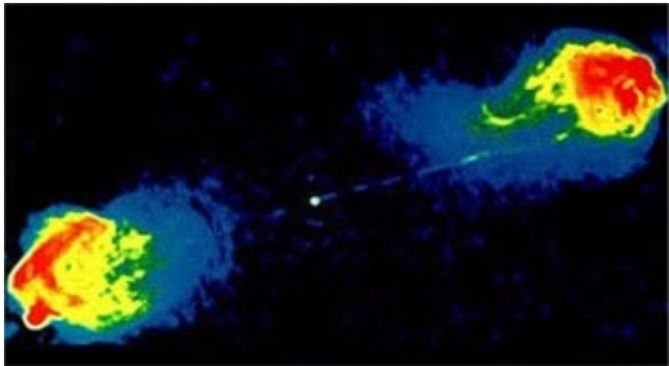


GRB



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

Radio Galaxy Lobe



Acceleration with energy losses

- Maximum energy

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

- Where

$$B_0(R) = 3.16 \times 10^{-3}\ {\rm G}\ \frac{A^{4/3}}{Z^{5/3}} \left(\frac{R}{\rm kpc}\right)^{-2/3} \eta^{1/3},$$

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

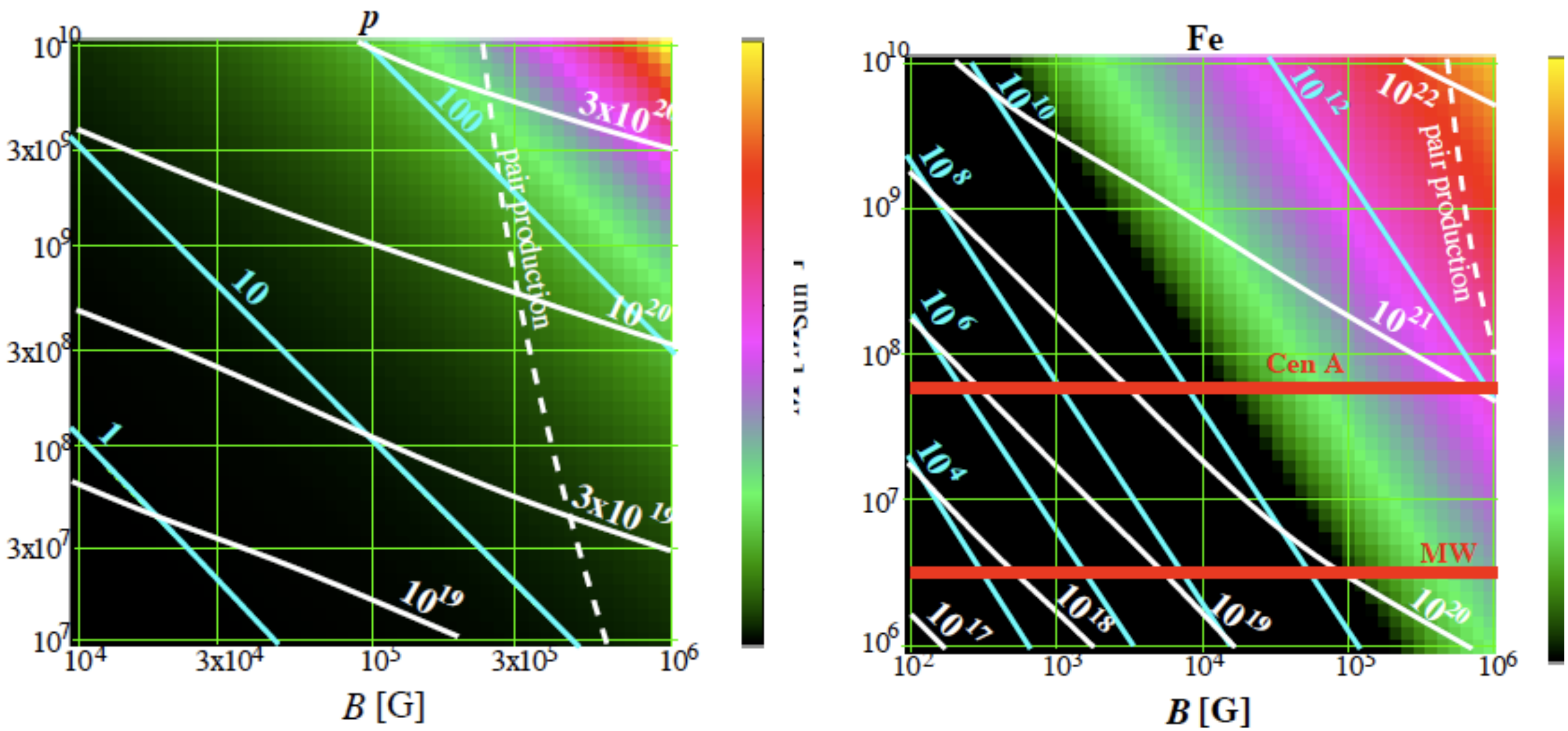
- Inductive with synchrotron loses (jets)

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

- Inductive with curvature losses (cores)

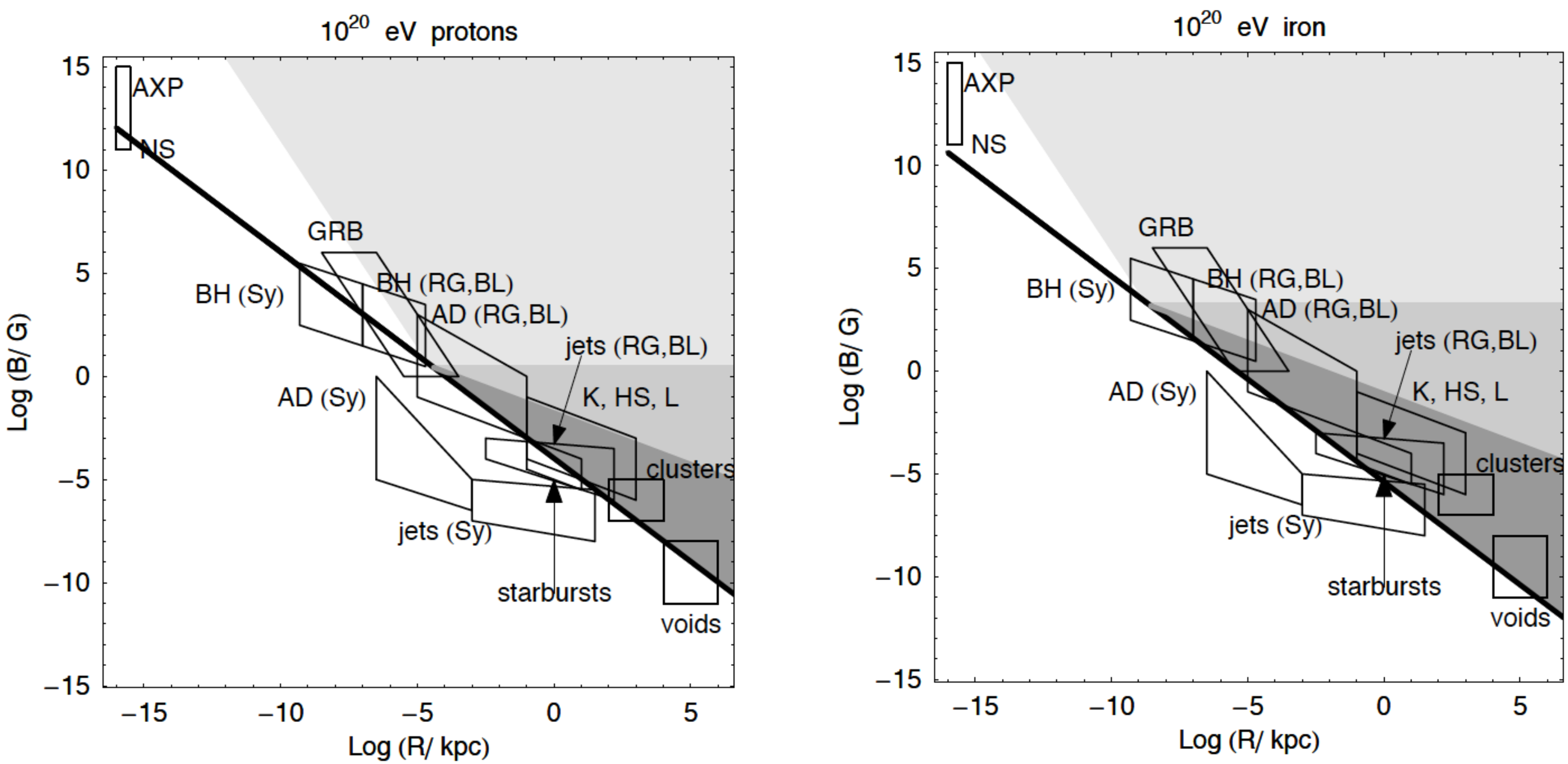
$$\mathcal{E}_{\rm loss}(B,R) = \mathcal{E}_{\rm c}(B,R) = 1.23 \times 10^{22}\ \mathrm{eV}\ \frac{A}{Z^{1/4}} \left(\frac{R}{\mathrm{kpc}}\right)^{1/2} \left(\frac{B}{\mathrm{G}}\right)^{1/4} \eta^{1/4}$$

Acceleration near Black Hole in the electric field



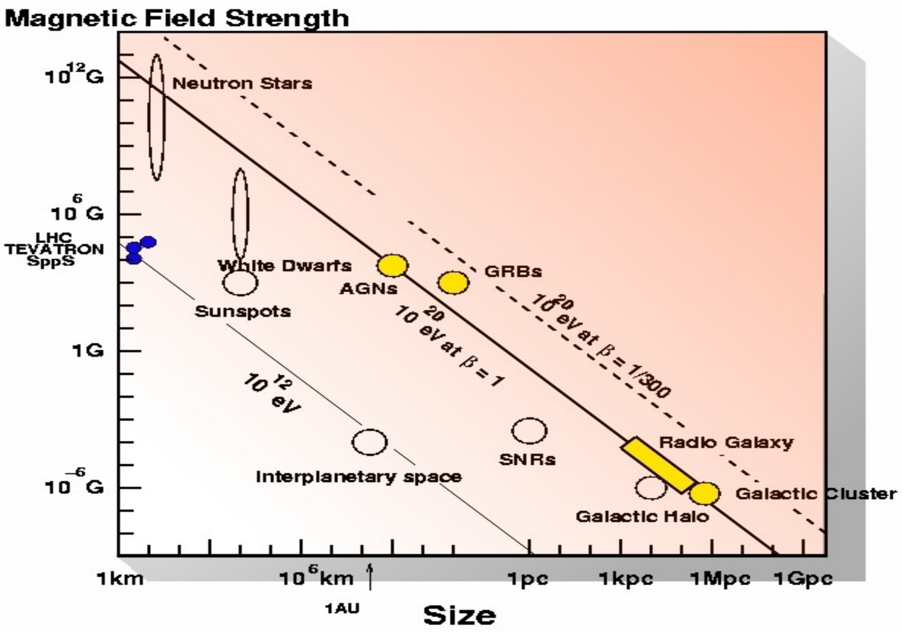
A.Neronov, D.S. and I.Tkachev astro-ph/0712.1737

Acceleration with energy losses



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

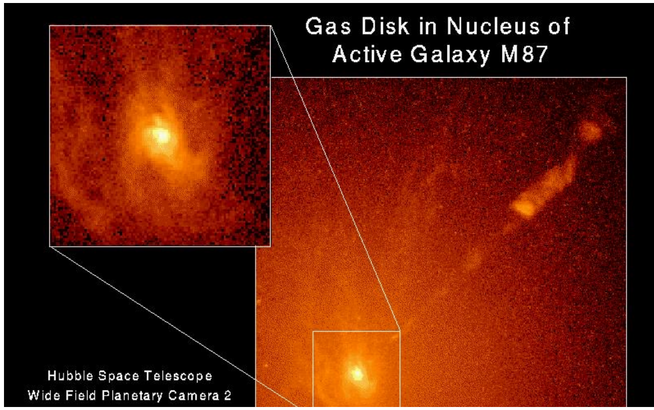
Acceleration of UHECR



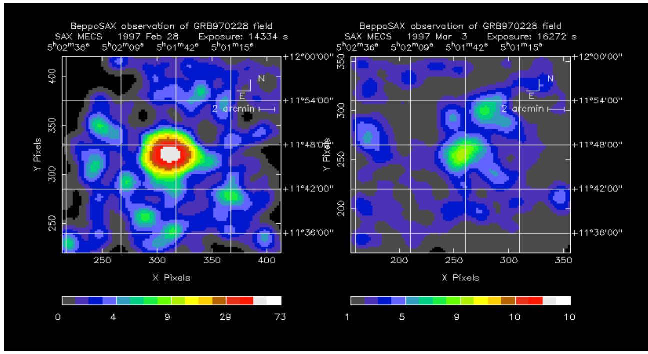
- Shock acceleration $1/E^{\alpha}$ $\alpha >= 2$

- Electric field acceleration line at E_{max}
- Converter acceleration can be both

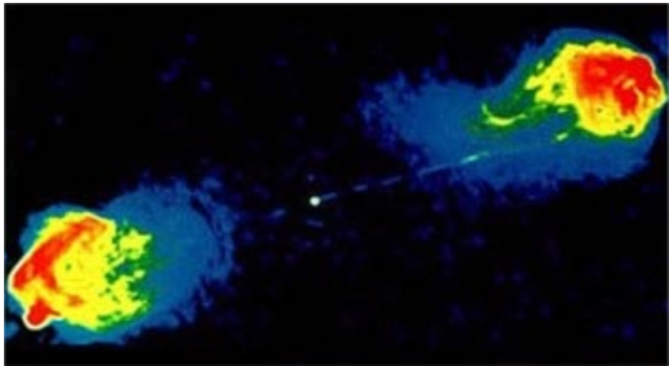
A.G.N.



GRB

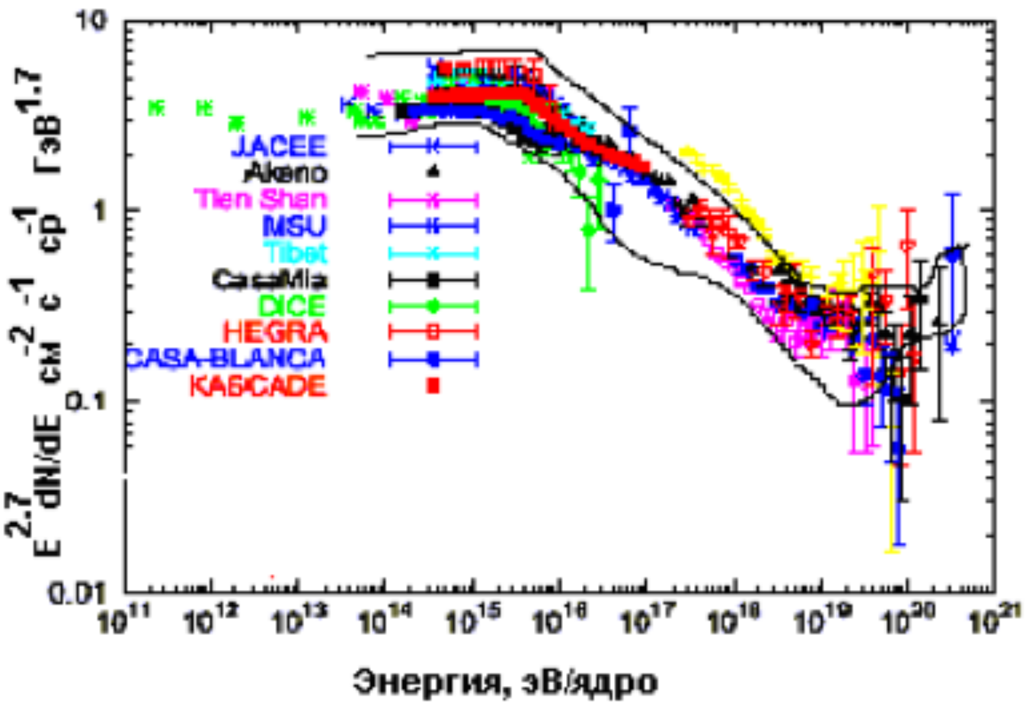


Radio Galaxy Lobe



Galactic cosmic rays

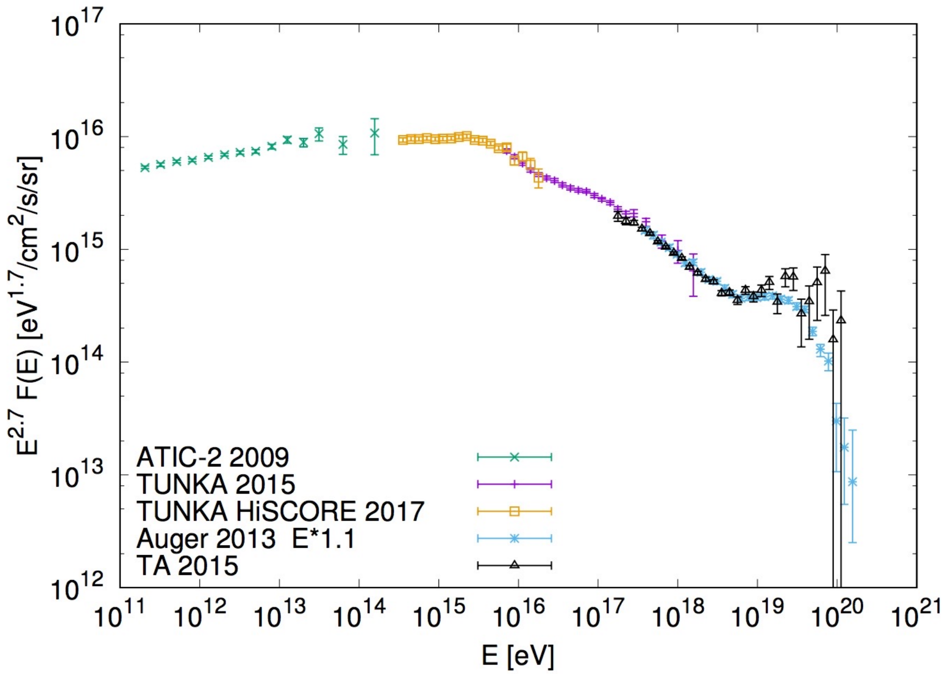
Knee in CR spectrum



- 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.

Knee in CR spectrum



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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: Sources with 1/100 SN rate have to accelerate above knee

Transport Equations ~90 (no. of CR species)

$$\frac{\partial \psi(\vec{r},p,t)}{\partial t} = q(\vec{r},p)$$ •sources (SNR, nuclear reactions…)

•diffusion $$+\vec{\nabla}\cdot[D_{xx}\vec{\nabla}\psi - \vec{V}\psi]$$

•convection
(Galactic wind)

•diffusive reacceleration
(diffusion in the momentum space) $$+\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^2}\right]$$

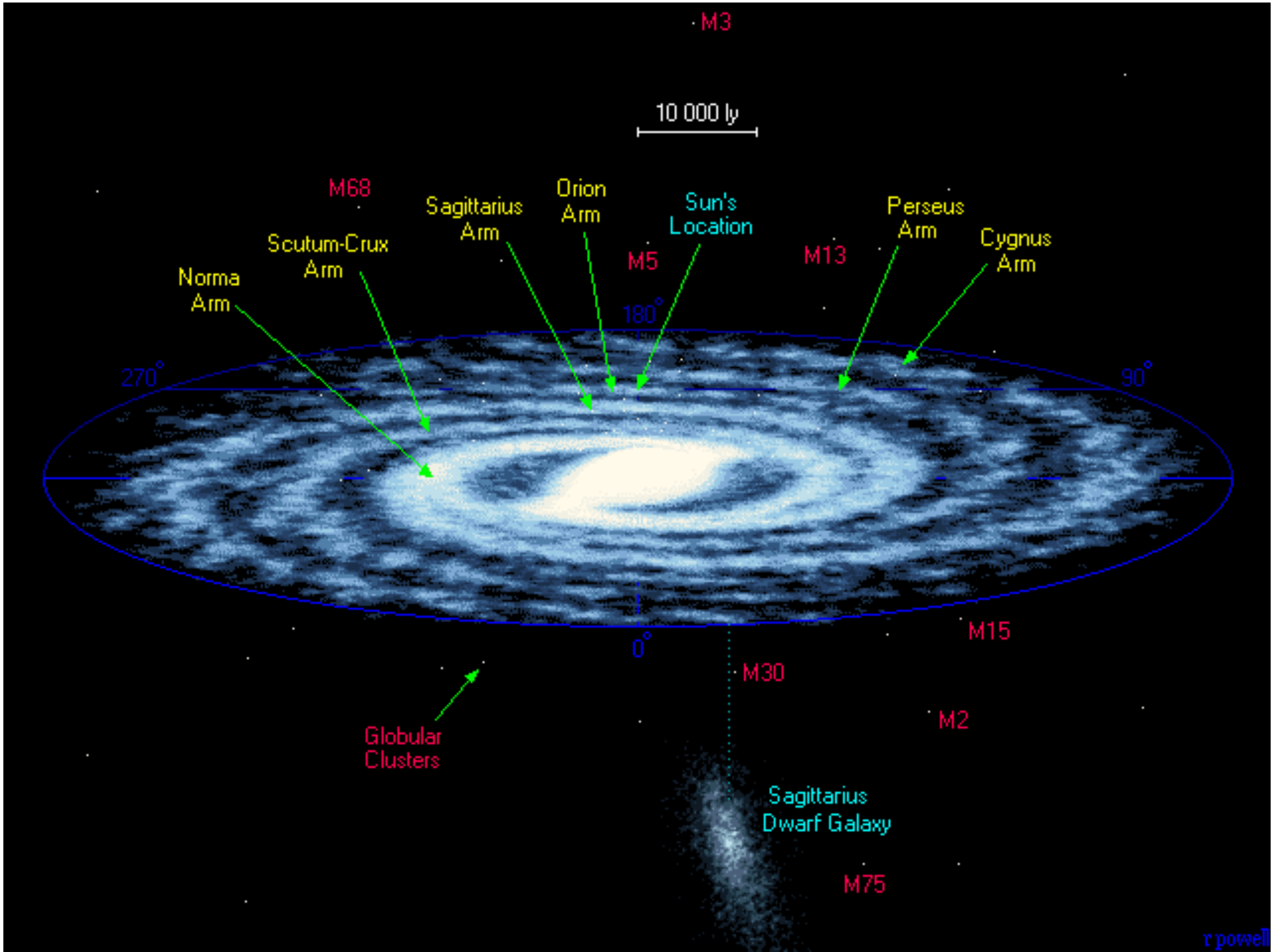
•E-loss $$-\frac{\partial}{\partial p}\left[\frac{dp}{dt}\psi - \frac{1}{3}p\vec{\nabla}\cdot\vec{V}\psi\right]$$

•fragmentation $$-\frac{\psi}{\tau_f} - \frac{\psi}{\tau_d}$$ •radioactive decay

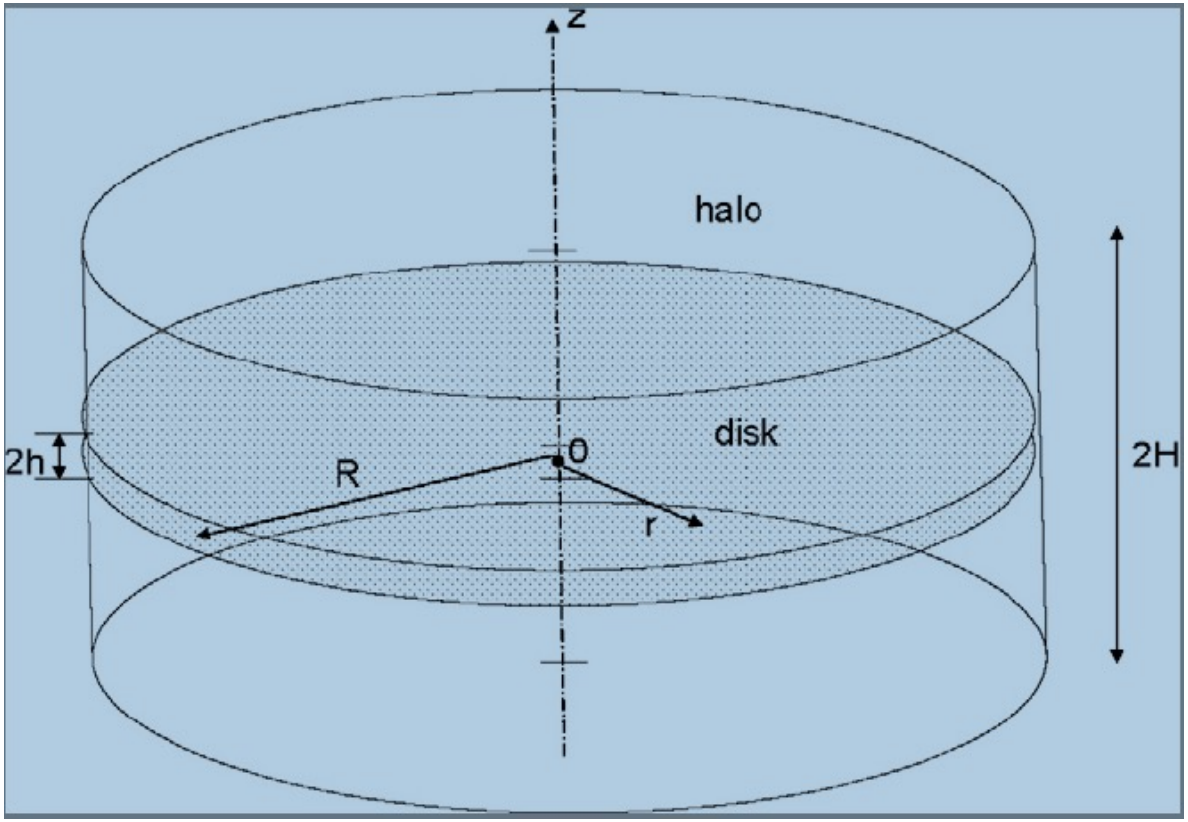
- + boundary conditions

*ψ(**r**,p,t) – density per total momentum*

MILKY WAY GALAXY



Sources and Galactic magnetic field



- Ptuskin, **Astropart. Phys. 2011**

GALPROP model of CR Propagation in the Galaxy

- Gas distribution (energy losses, π^0, brems)
- Interstellar radiation field (IC, $e^{\pm}$ energy losses)
- Nuclear & particle production cross sections
- Gamma-ray production: brems, IC, π^0
- Energy losses: ionization, Coulomb, brems, IC, synch
- Solve transport equations for all CR species
- Fix propagation parameters
- “Precise” Astrophysics

Assumptions of the model

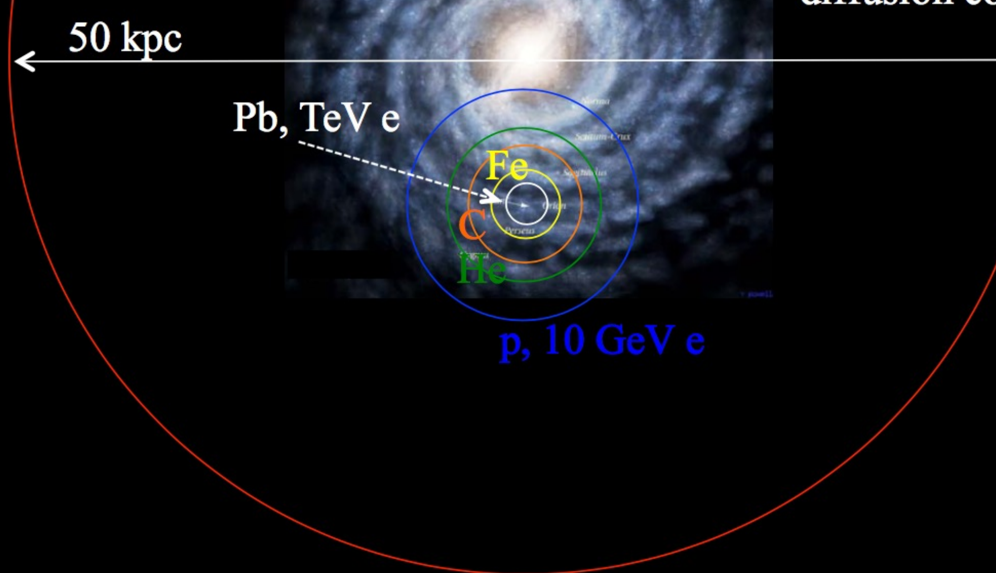
- *Regular magnetic fields does not affect propagation of CR, one can neglect them*
- *Spectrum is the same in all galaxy. It is as measured on Earth 1/E^2.7*
- *Sources are frequent enough that CR are in steady state regime, no variation of fluxes in time*

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*
- *Regular magnetic fields does not affect propagation of CR, one can neglect them: Propagation of cosmic rays is spherically symmetric. Required diffusion coefficient is very high.*

Direct probes of CR propagation

- Direct measurements probe a very small volume of the Galaxy
- Light & heavy nuclei probe different propagation volume
- The propagation distances are shown for nuclei for rigidity ~1 GV, and for electrons ~1 TeV
- $\delta \sim 0.33$ – index of the rigidity dependence of the diffusion coefficient



Effective propagation distance:

$\langle X \rangle \sim \sqrt{6D\tau} \sim 2.7 \text{ kpc } R^{\delta/2} (A/12)^{-1/3}$

Helium: ~ 3.6 kpc $R^{\delta/2}$
Carbon: ~ 2.7 kpc $R^{\delta/2}$
Iron: ~ 1.6 kpc $R^{\delta/2}$
Lead ~ 1.0 kpc $R^{\delta/2}$
(anti-) protons: ~ 5.6 kpc $R^{\delta/2}$
Electrons ~ 1 kpc $E_{12}^{-\delta/2}$

γ-rays: probe CR p (pbar) and $e^{\pm}$ spectra in the whole Galaxy ~50 kpc across

Predictions of the model

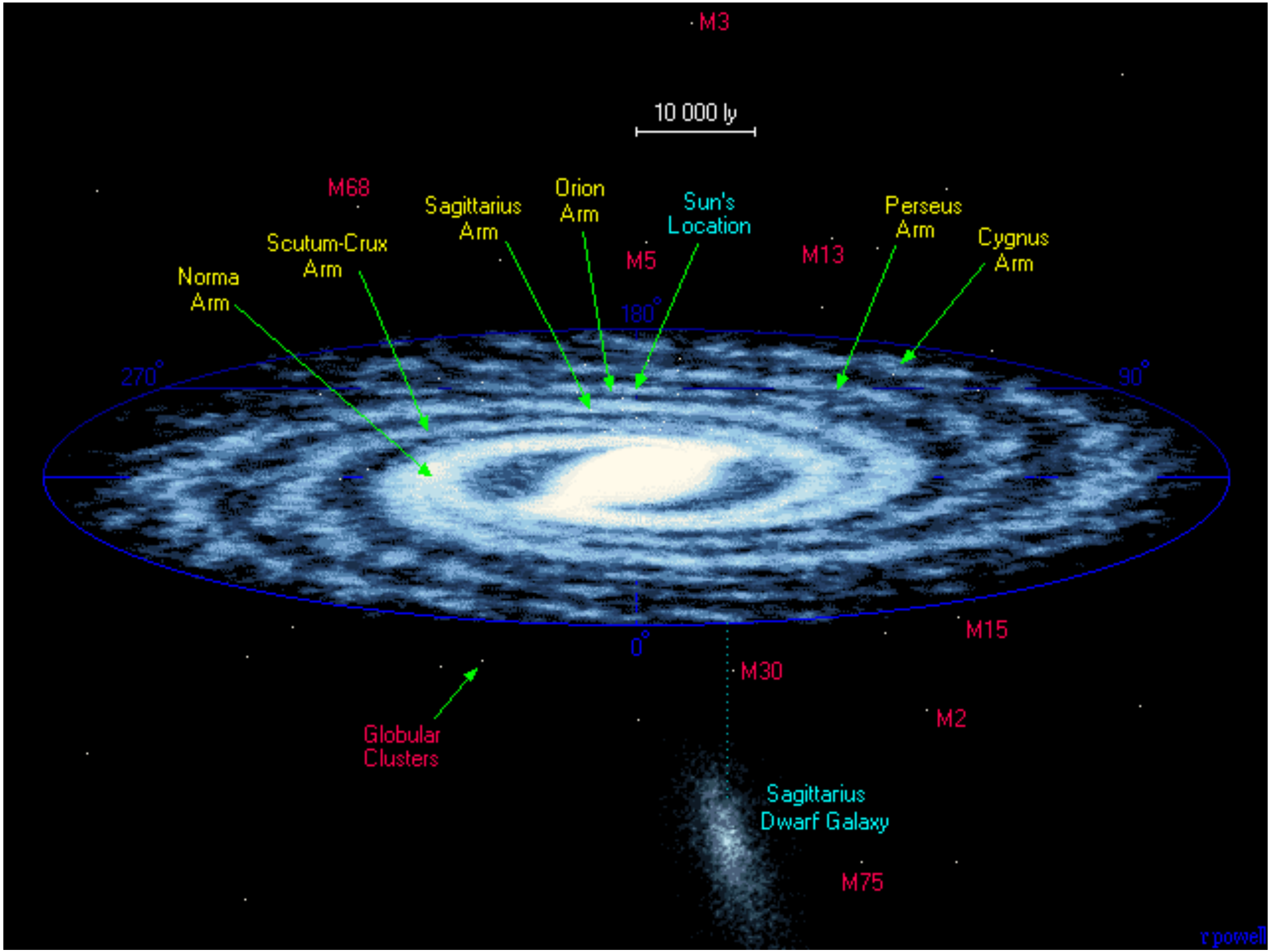
- *Because higher energy cosmic rays escape faster from Galaxy:*
  - *anisotropy is growing function of energy*
  - *Secondary fluxes drop relative to primary fluxes: positron and anti-proton fluxes should drop if compared to proton flux*

Problems of isotropic galactic cosmic ray model

Assumptions of the model

- *Regular magnetic fields does not affect propagation of CR, one can neglect them*

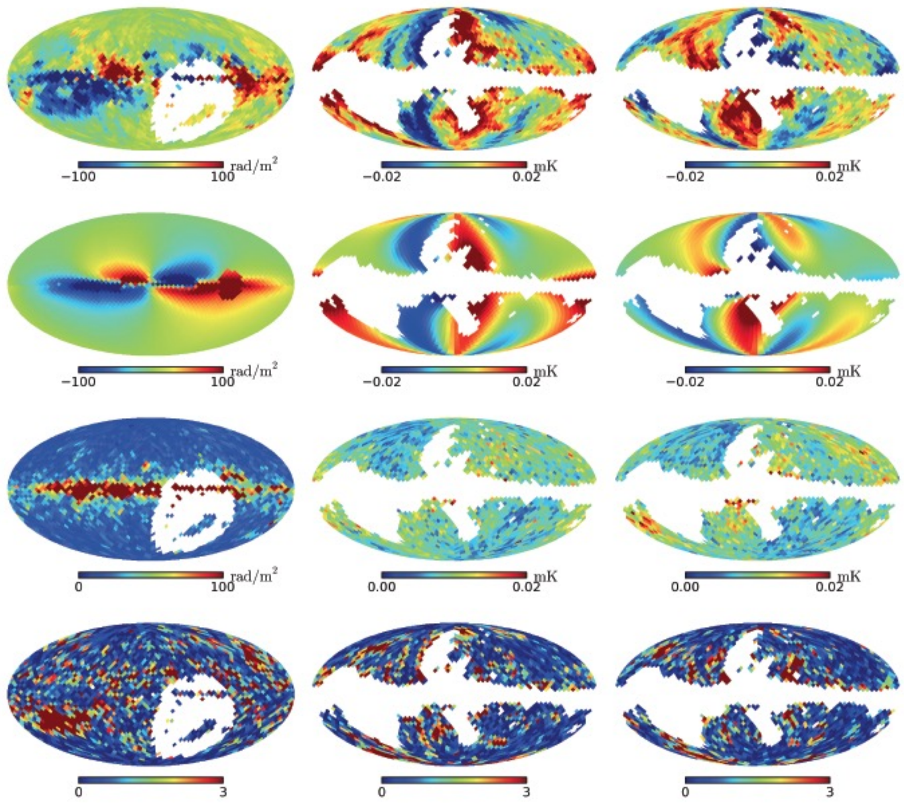
MILKY WAY GALAXY



Galactic magnetic field

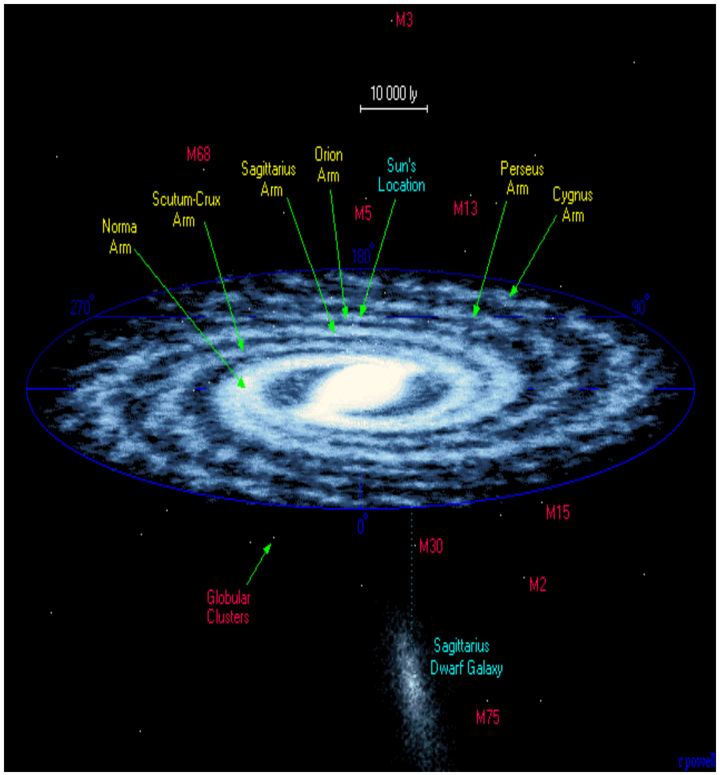
- B = B_disk (regular) + B_disk (turbulent) + B_halo(regular) + B_halo (turbulent)

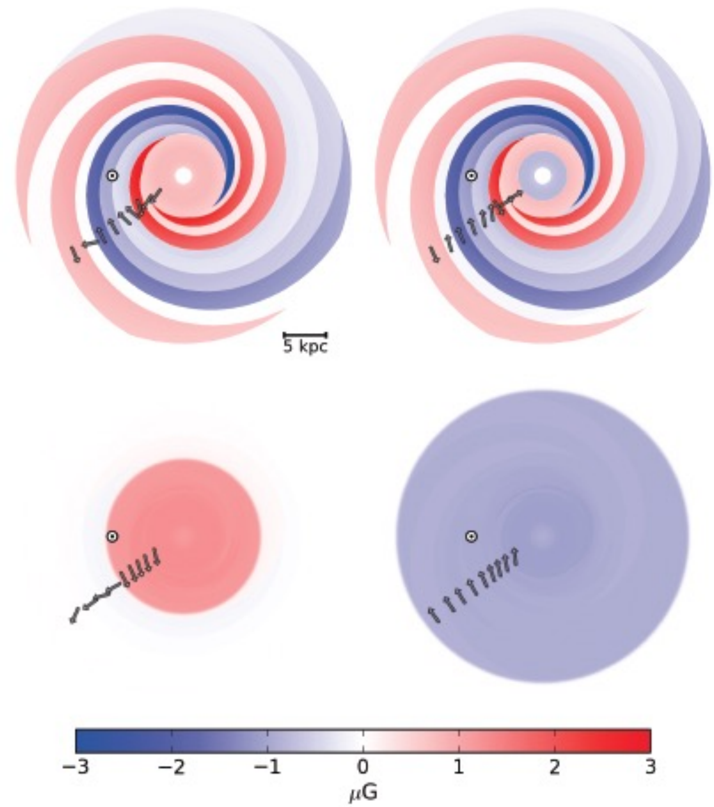
Synchrotron/RM maps



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

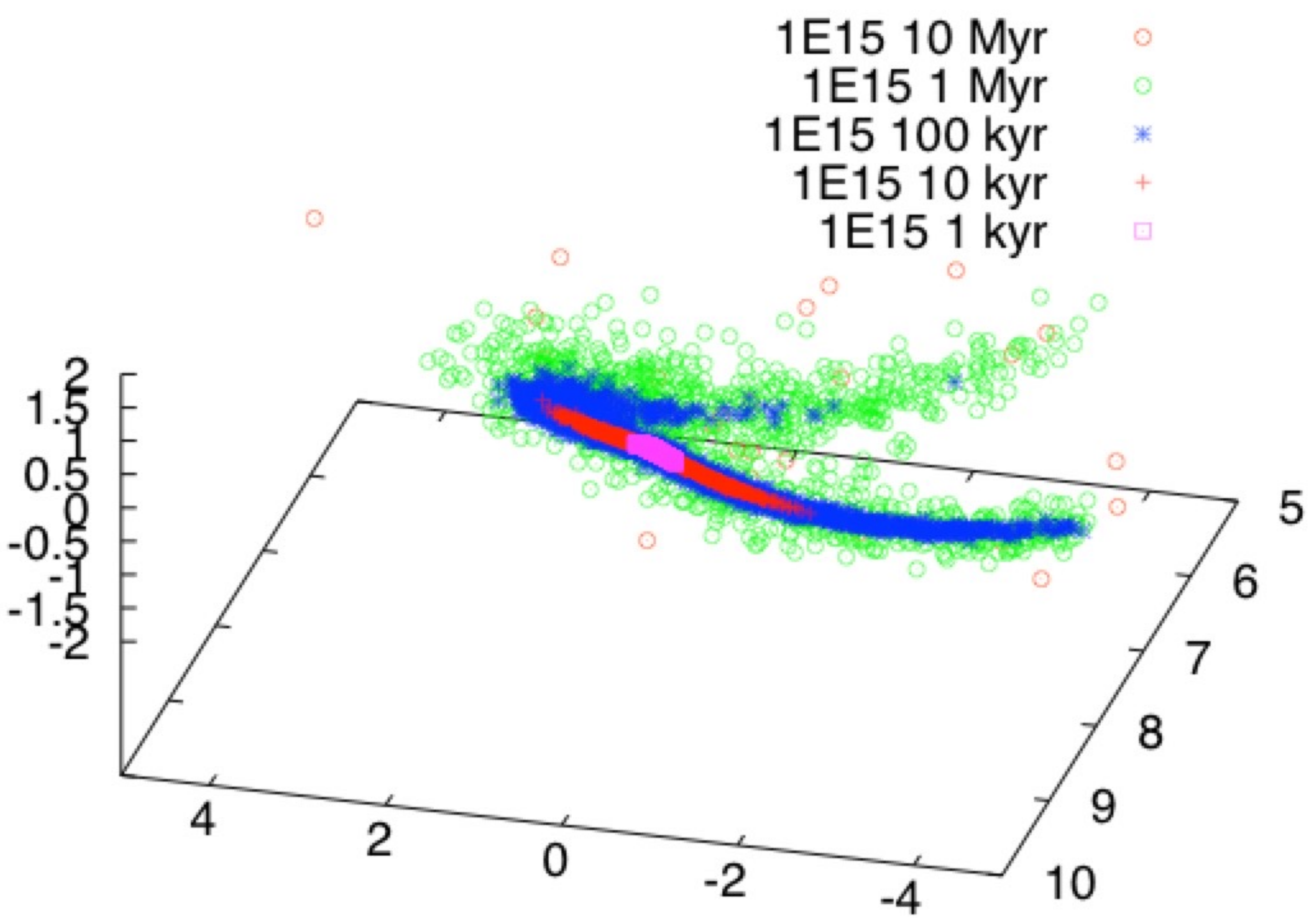
Galactic magnetic field: disk



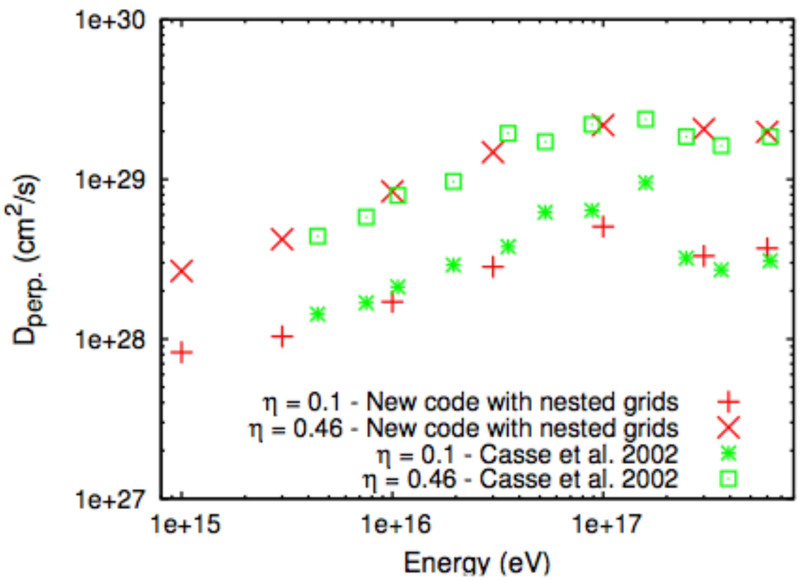


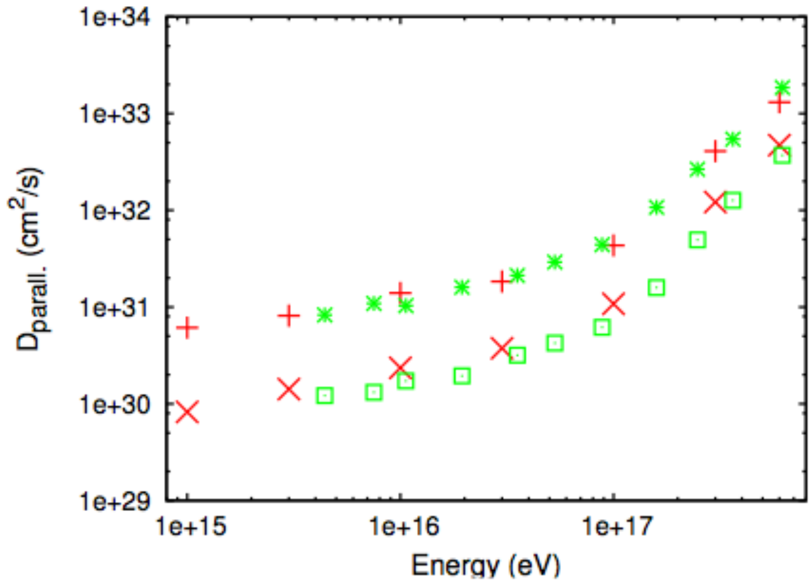
- R.Jansson & G.Farrar, arXiv:1204.3662

Proton flux from SN at 1 PeV

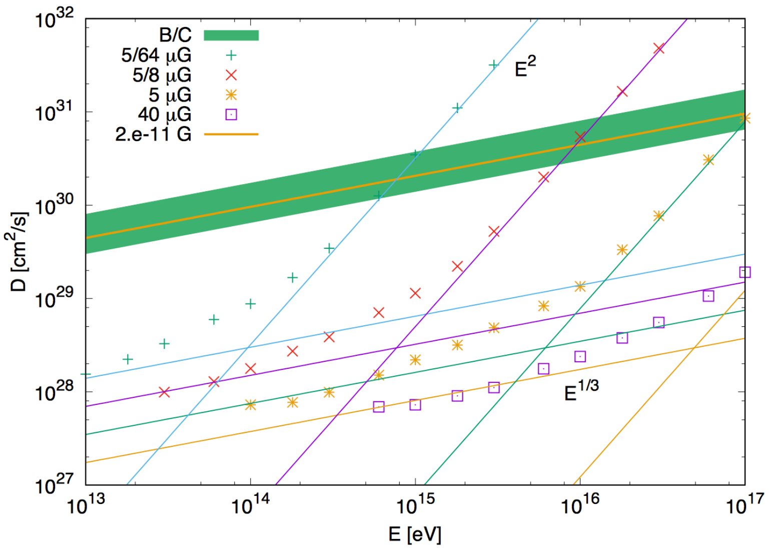


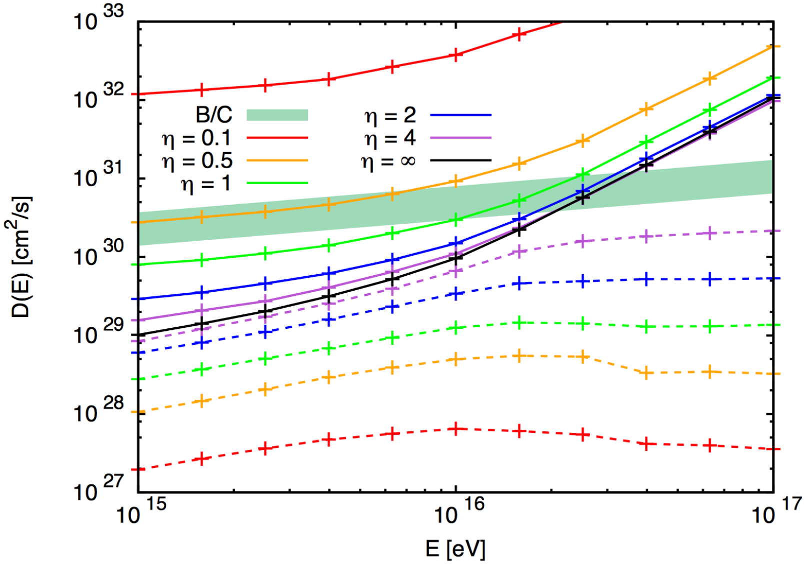
Regular and turbulent diffusion





Regular and turbulent diffusion





•Giacinti et al, 1710.08205

Assumptions of the model

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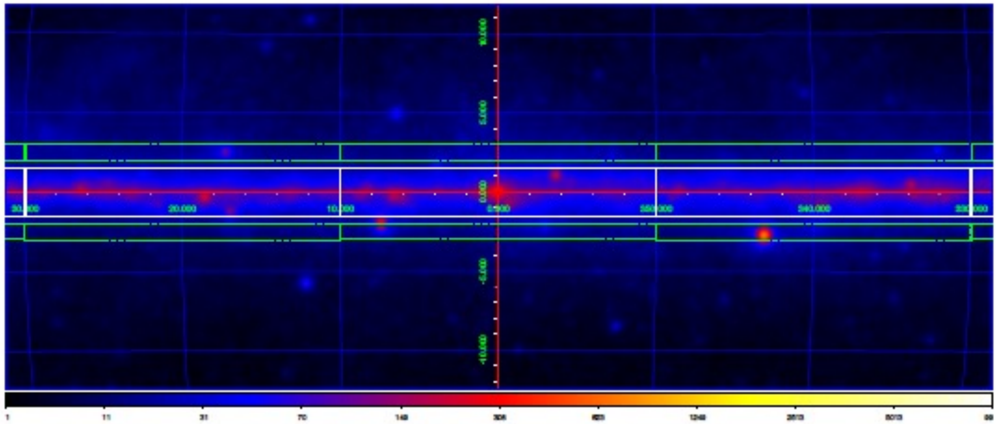
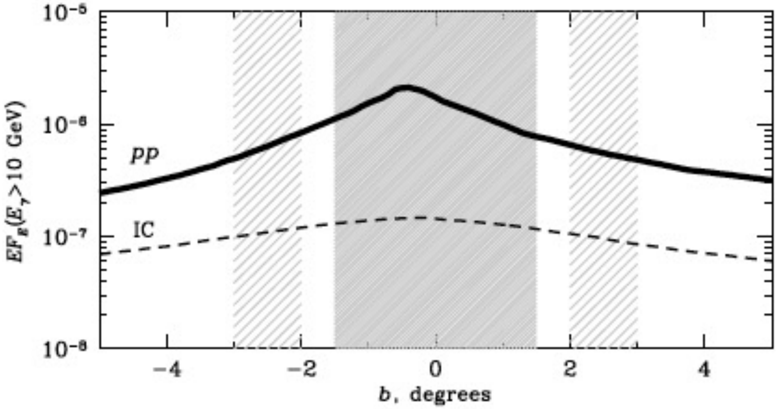
CR spectrum in MW and LMC from gamma-rays

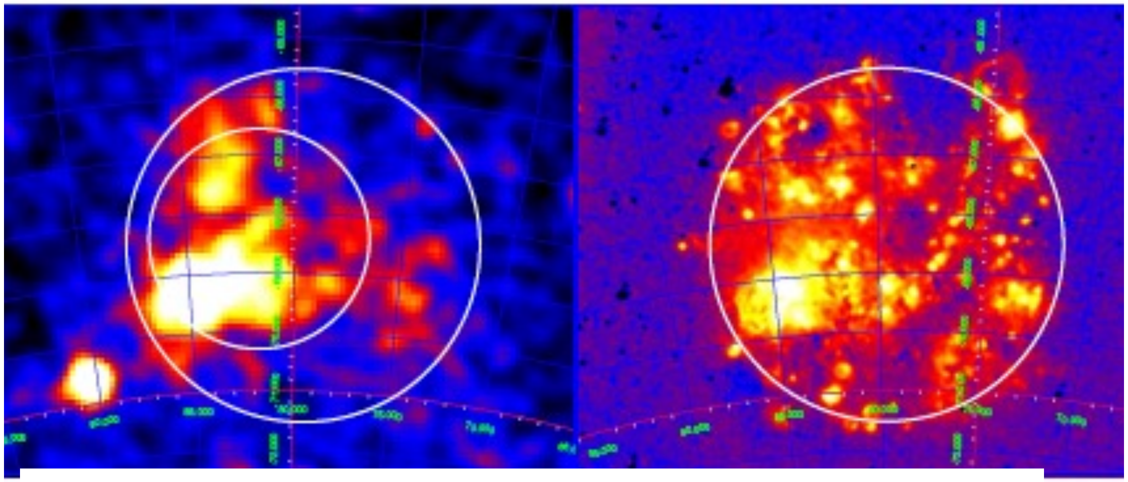
Milky Way inner Galaxy
Fermi E>10 GeV

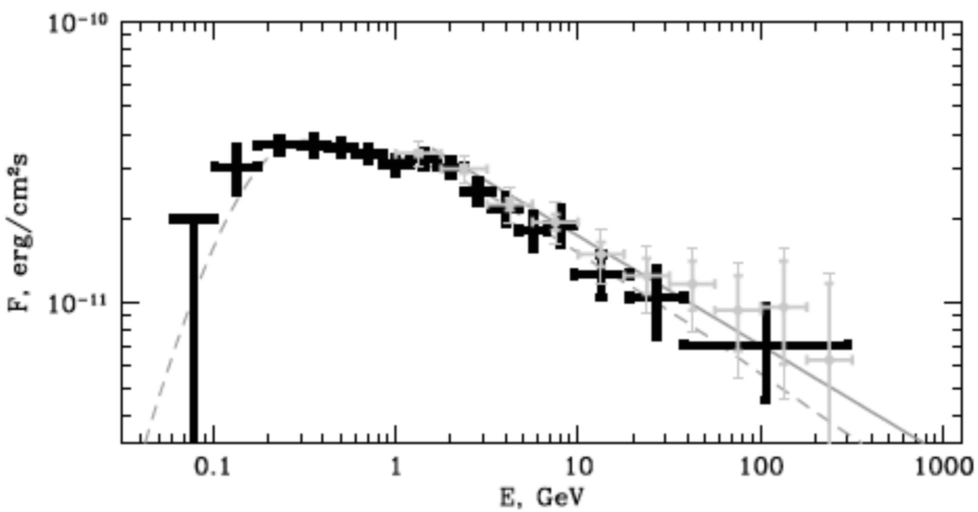




- **A.Neronov and D.Malishev, arXiv: 1505.07601**

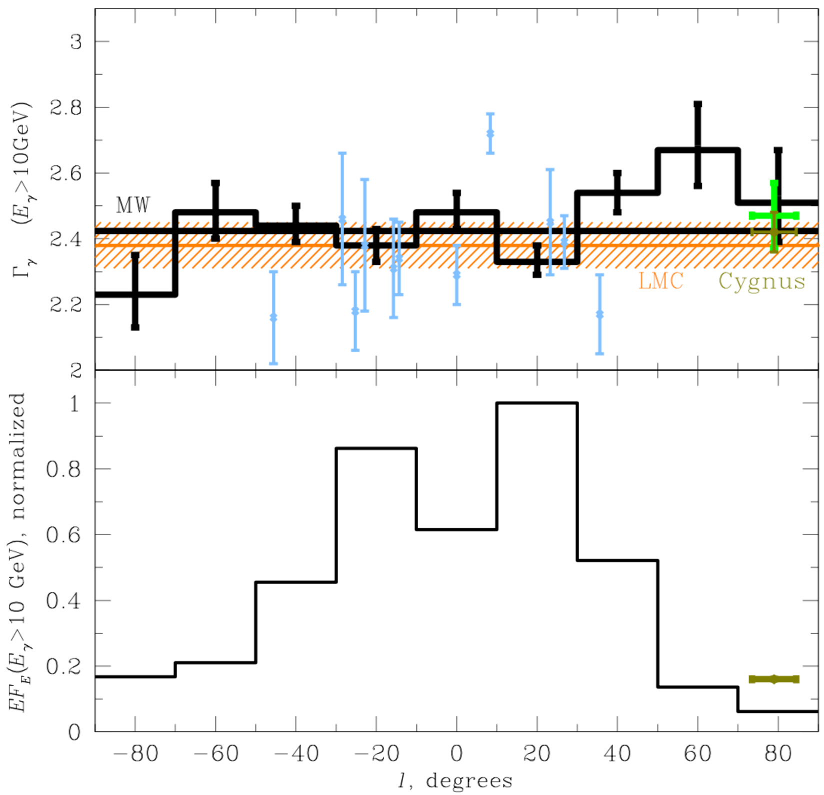
In LMC average proton spectrum 2.45

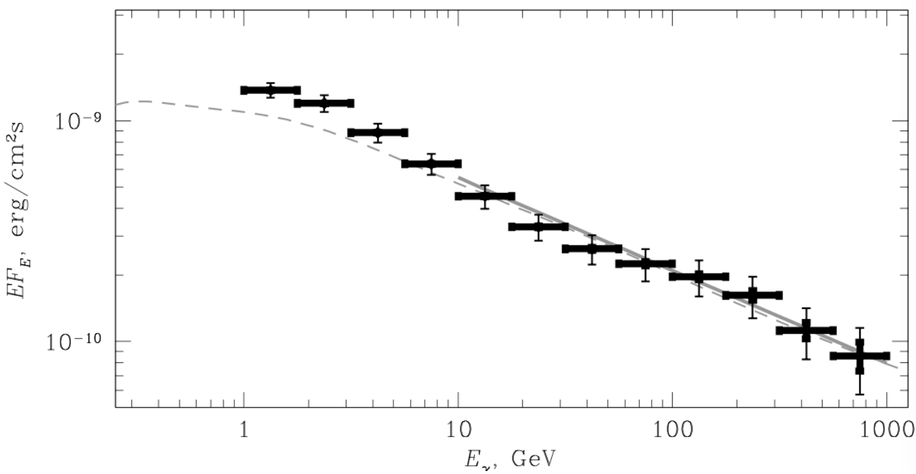




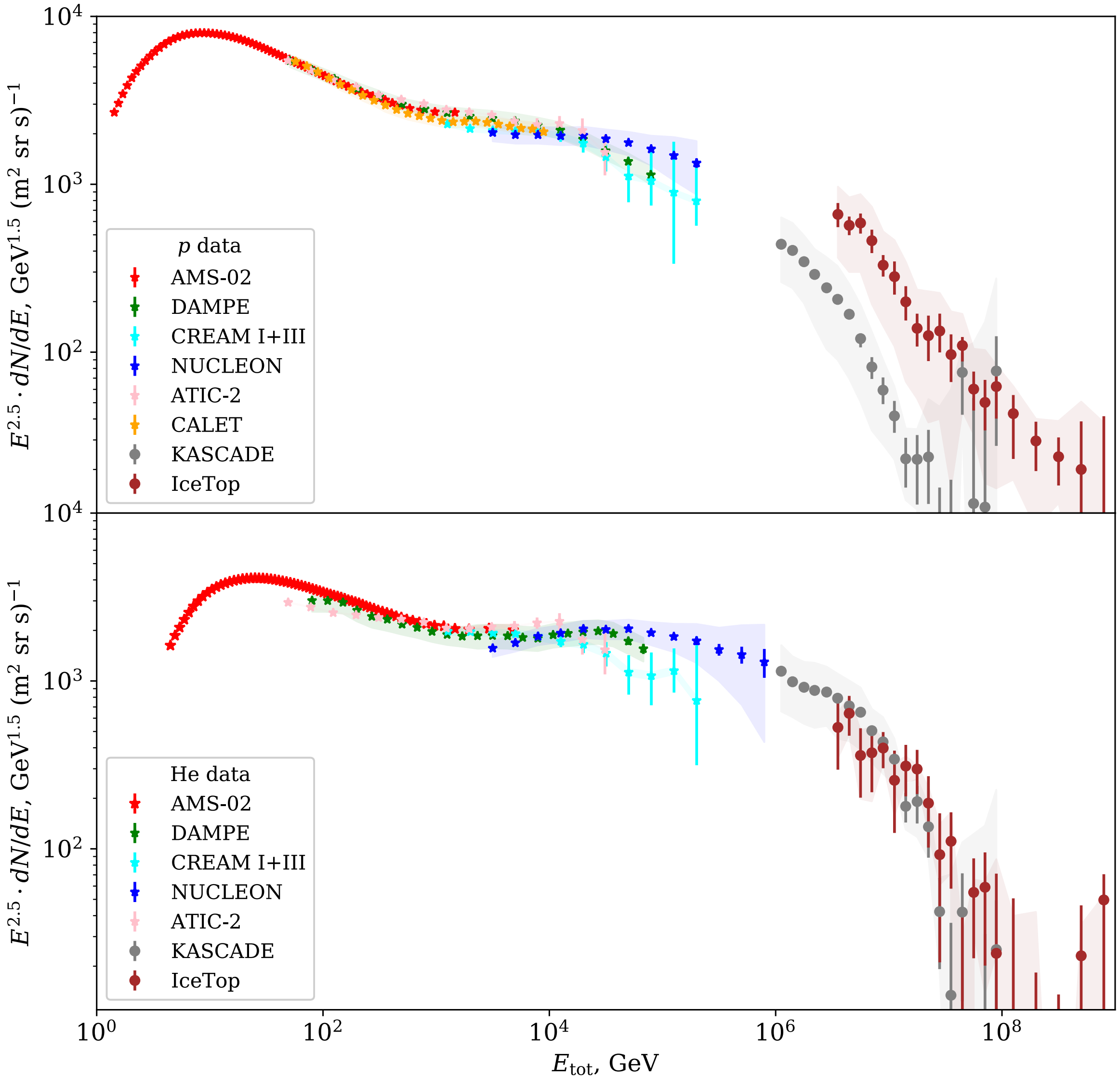
- **A.Neronov and D.Malishev, arXiv: 1505.07601**

Milky Way inner Galaxy
Fermi E>10 GeV: spectrum 2.4

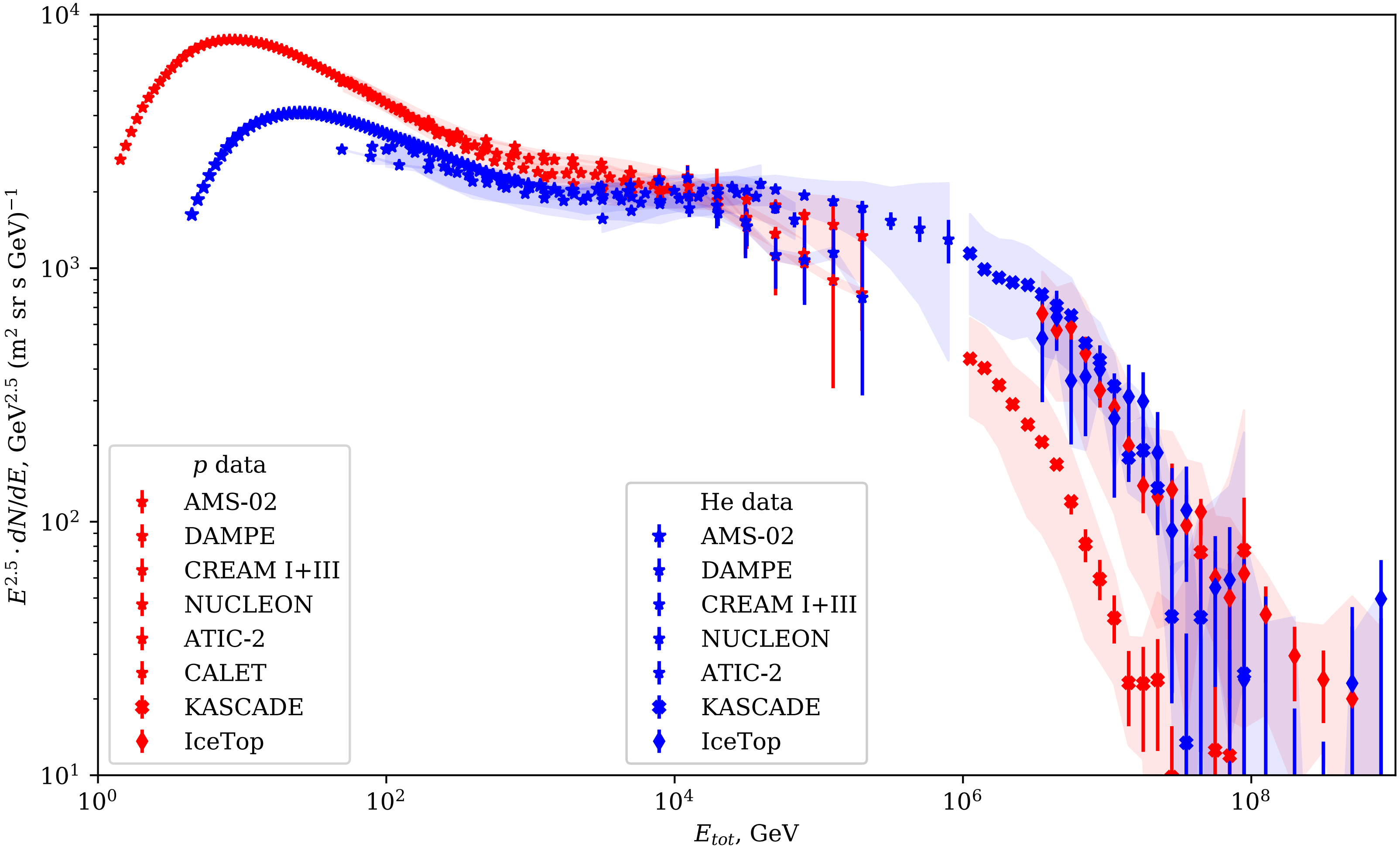




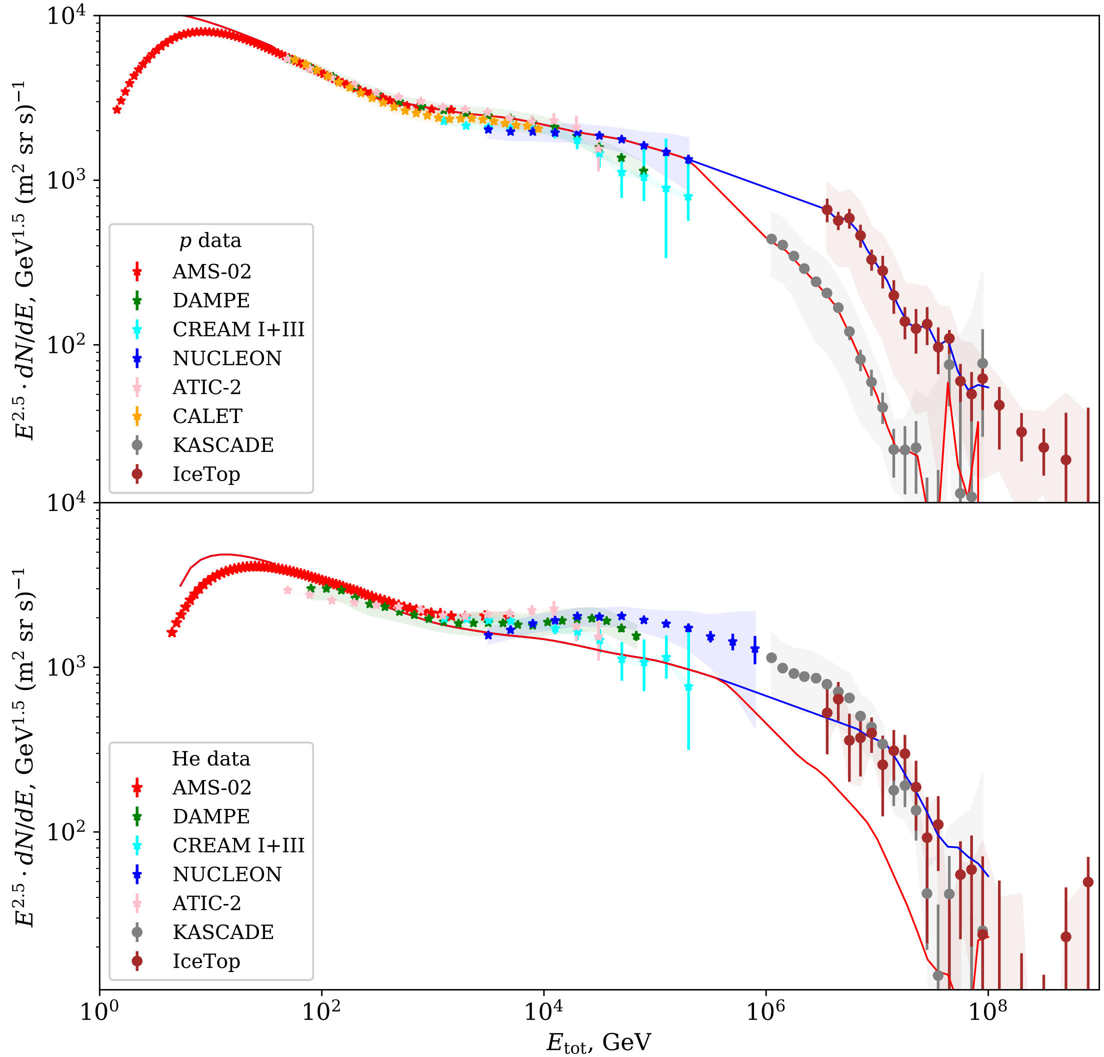
Local cosmic ray flux



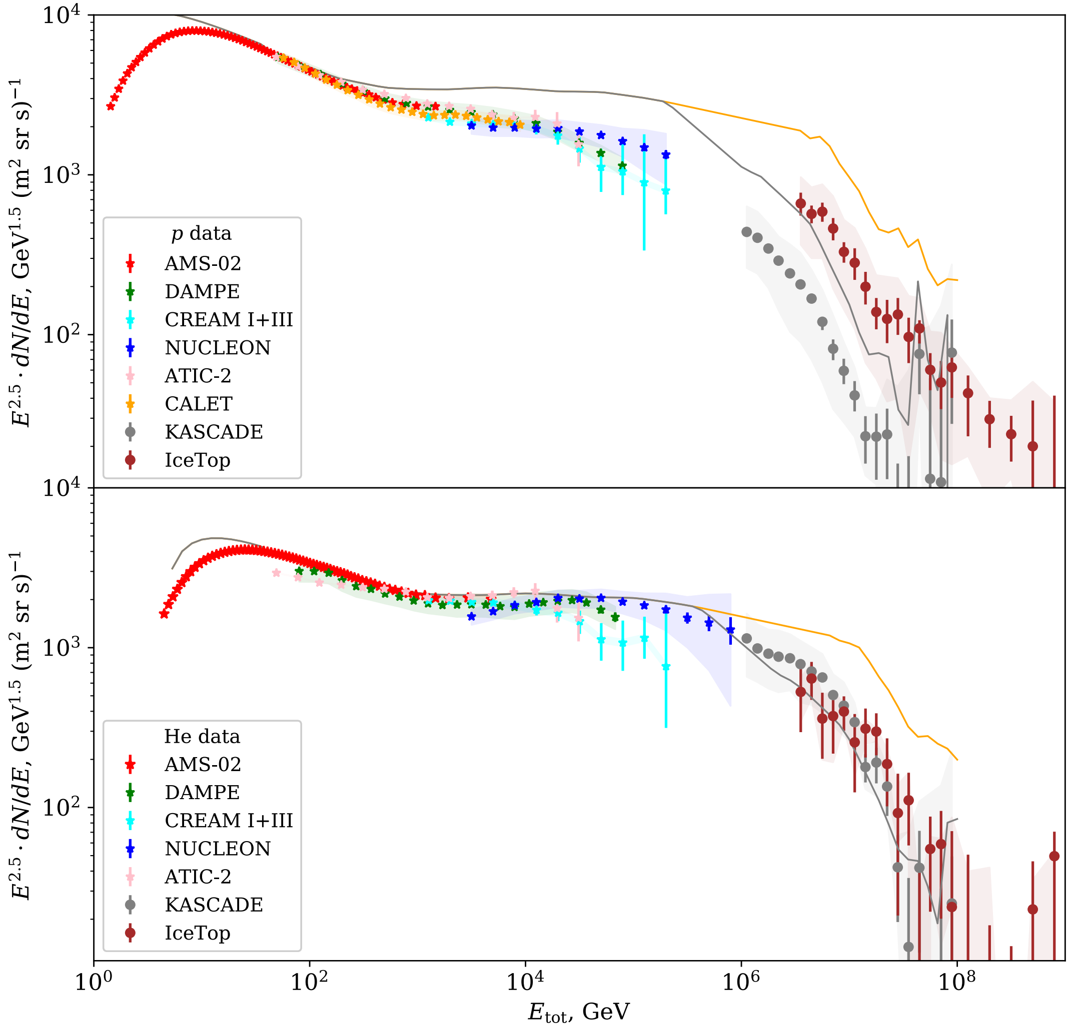
Local cosmic ray flux



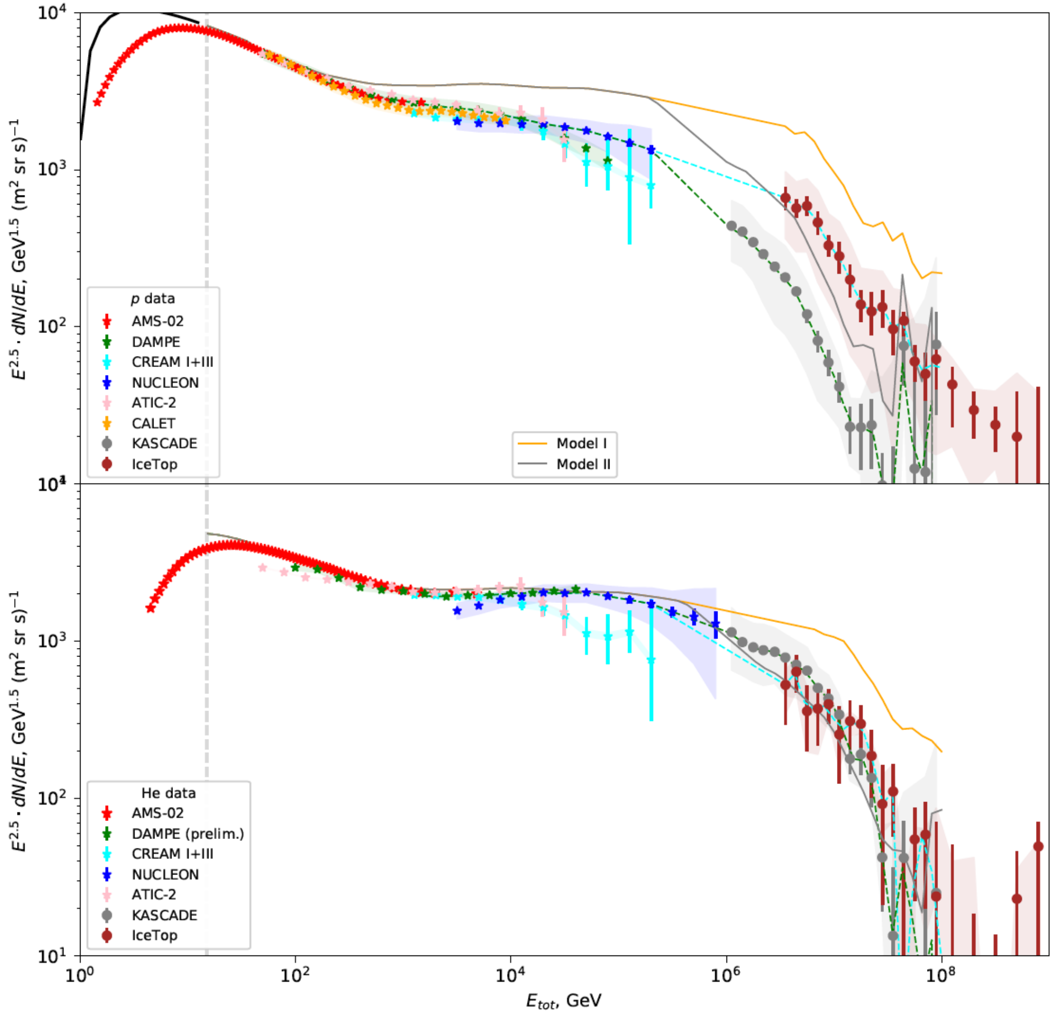
Cosmic ray flux in outer Galaxy is soft as local proton flux



Cosmic ray flux in outer Galaxy is hard as local He flux

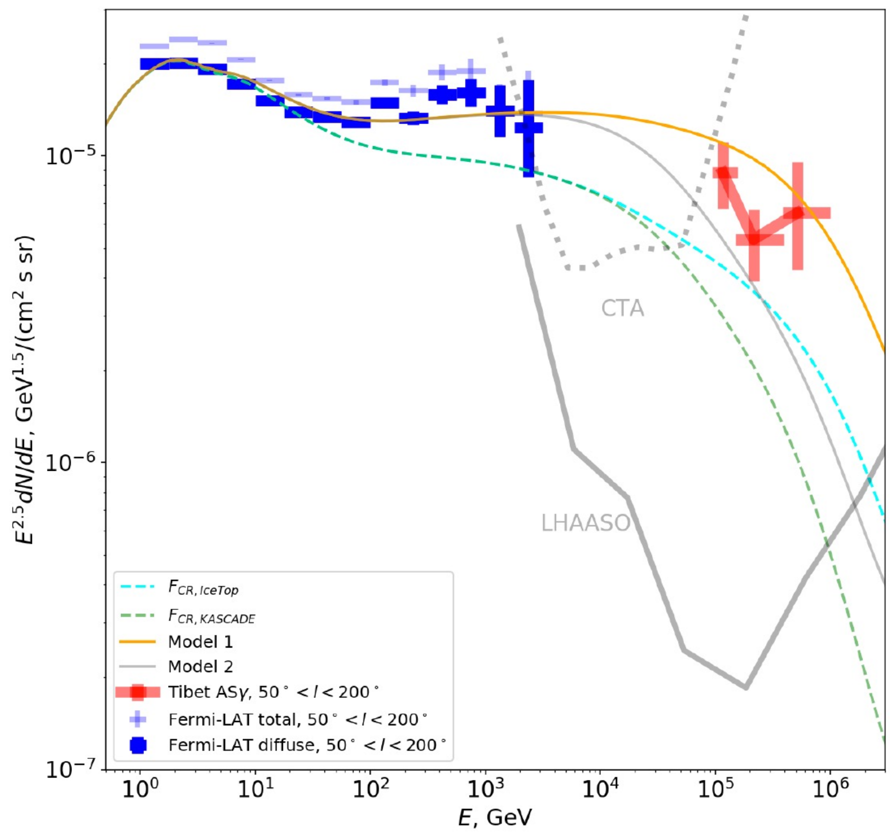


Cosmic ray flux models in outer Galaxy



•S.Koldobskiy, A.Neronov and D.Semikoz, arXiv:2

Gamma-ray flux in outer Galaxy

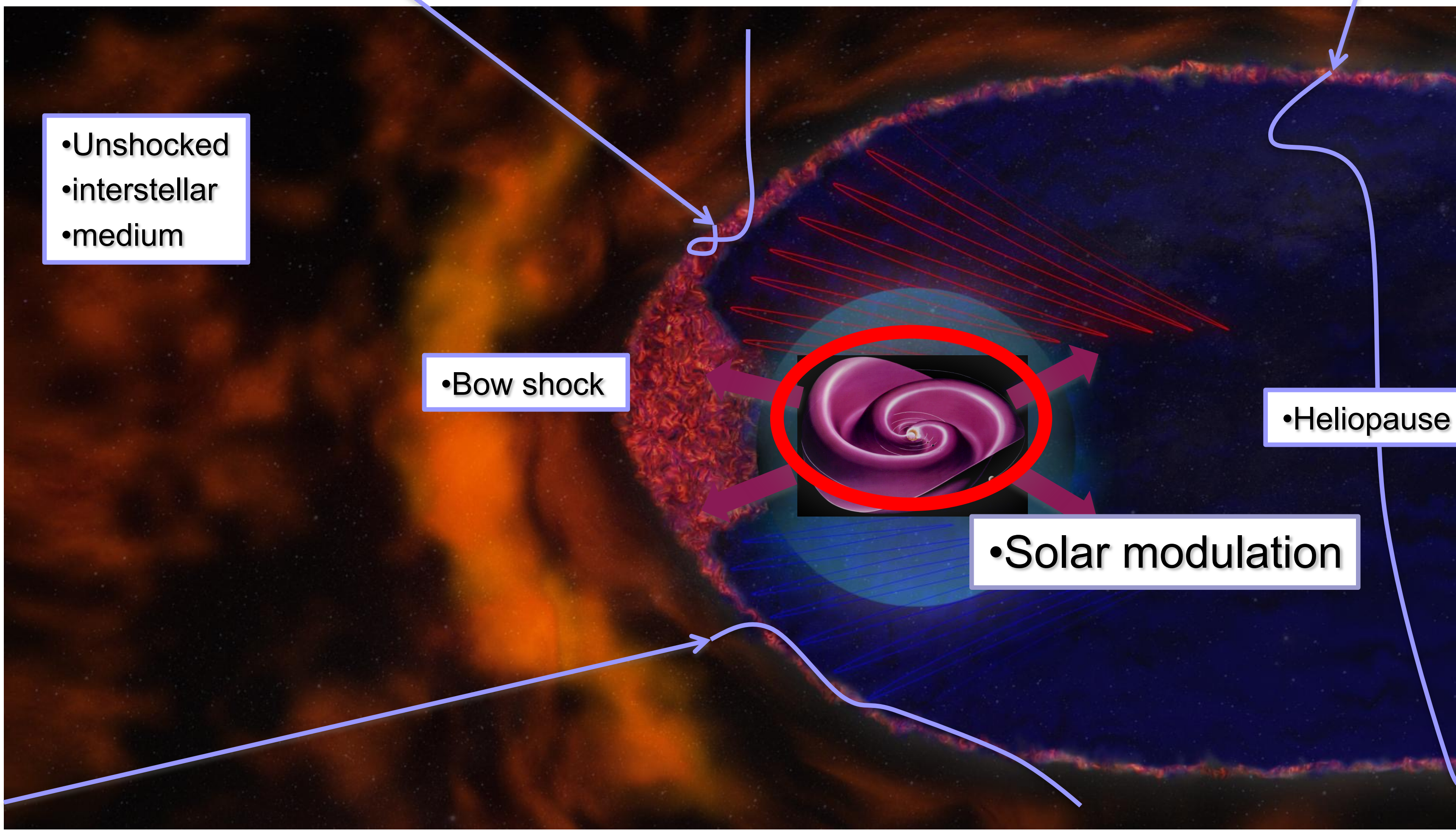


•S.Koldobskiy, A.Neronov and D.Semikoz, arXiv:21

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 $n \sim 10^3 - 10^4\ \mathrm{cm}^{-3}$.

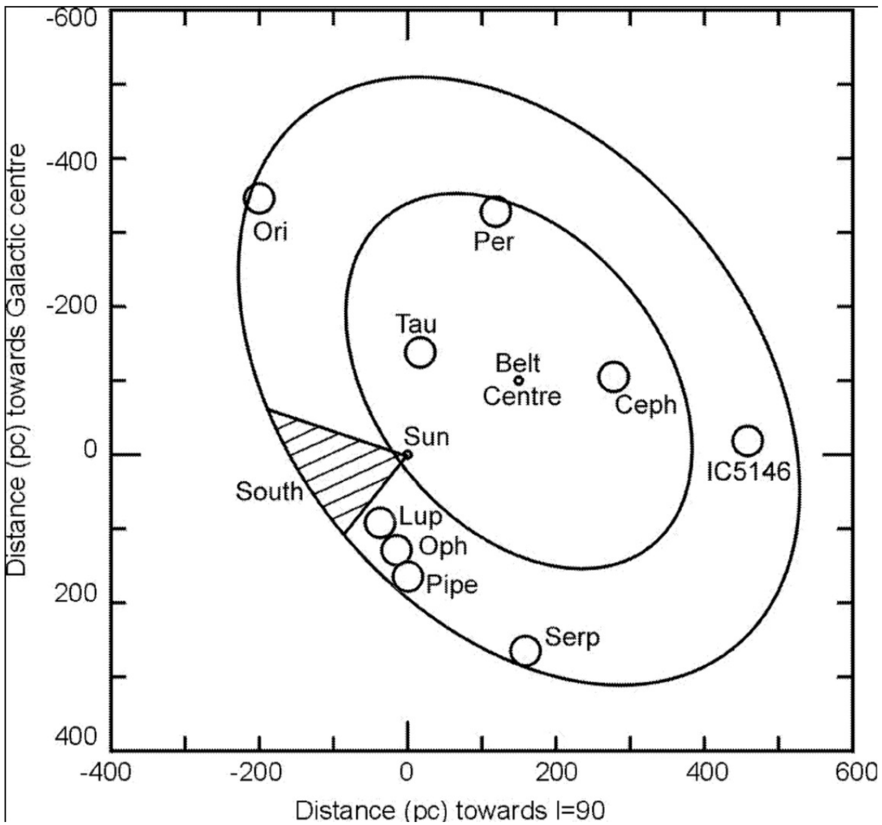
•CRs diffusing through the ISM cross the GMCs on the time scales of $t \sim 10^3 - 10^4$ yr.

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

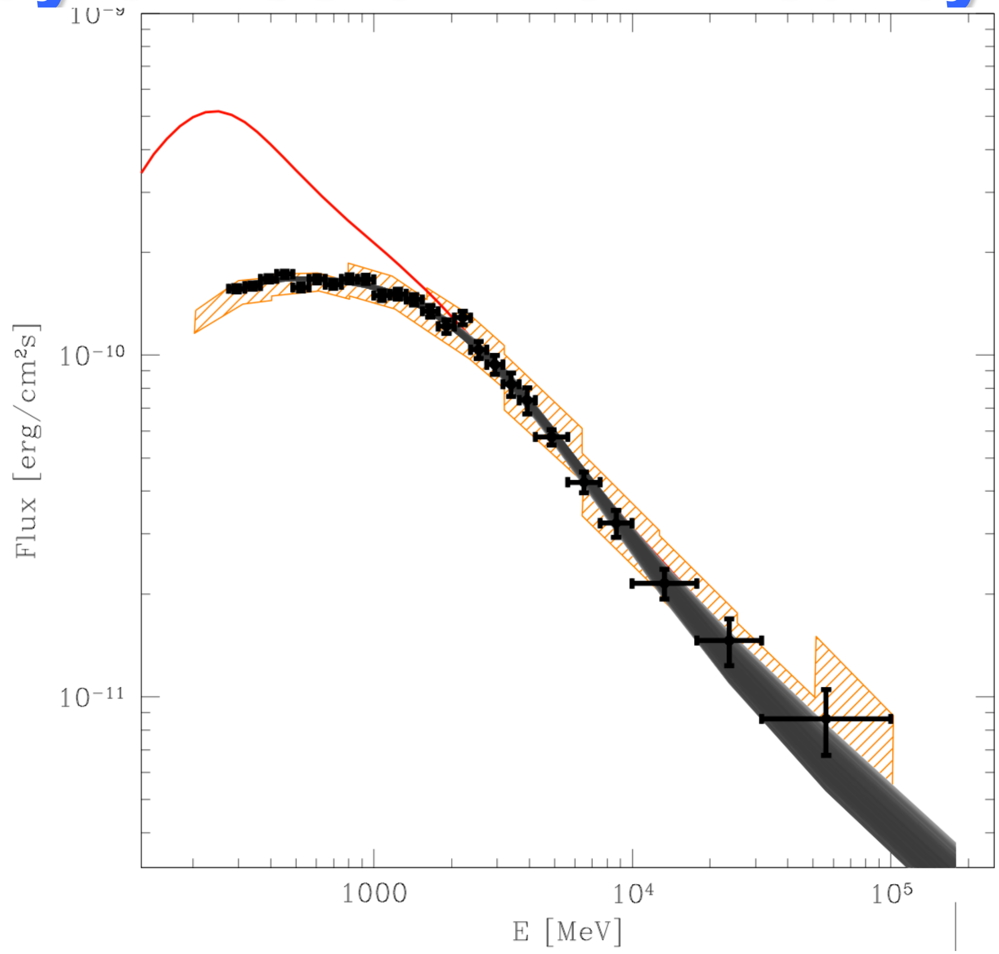
•CR interaction in the GMCs lead to the gamma-ray emission (from neutral pion production and decay).

•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

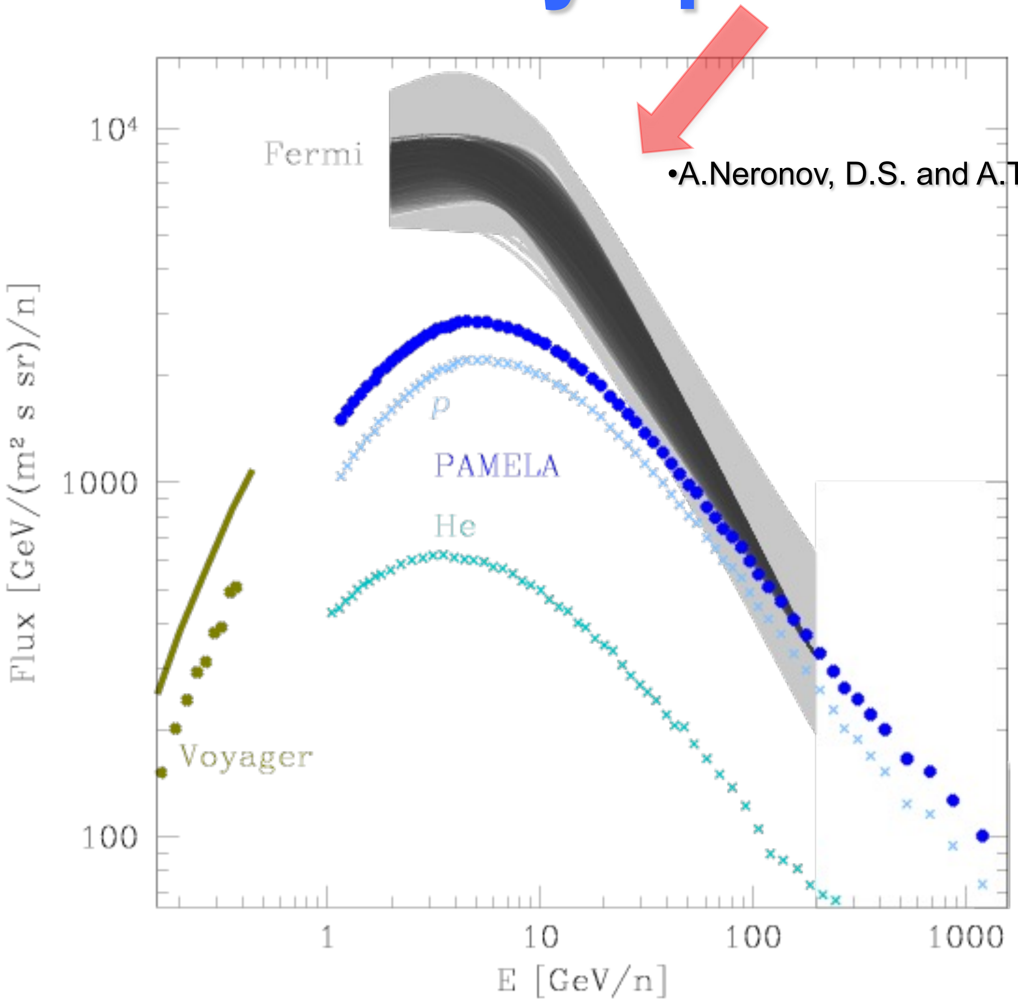
$$dN_{\rm CR}/dE = N_0\, E^{-\bar{\beta}_{\rm CR}}$$

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

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

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

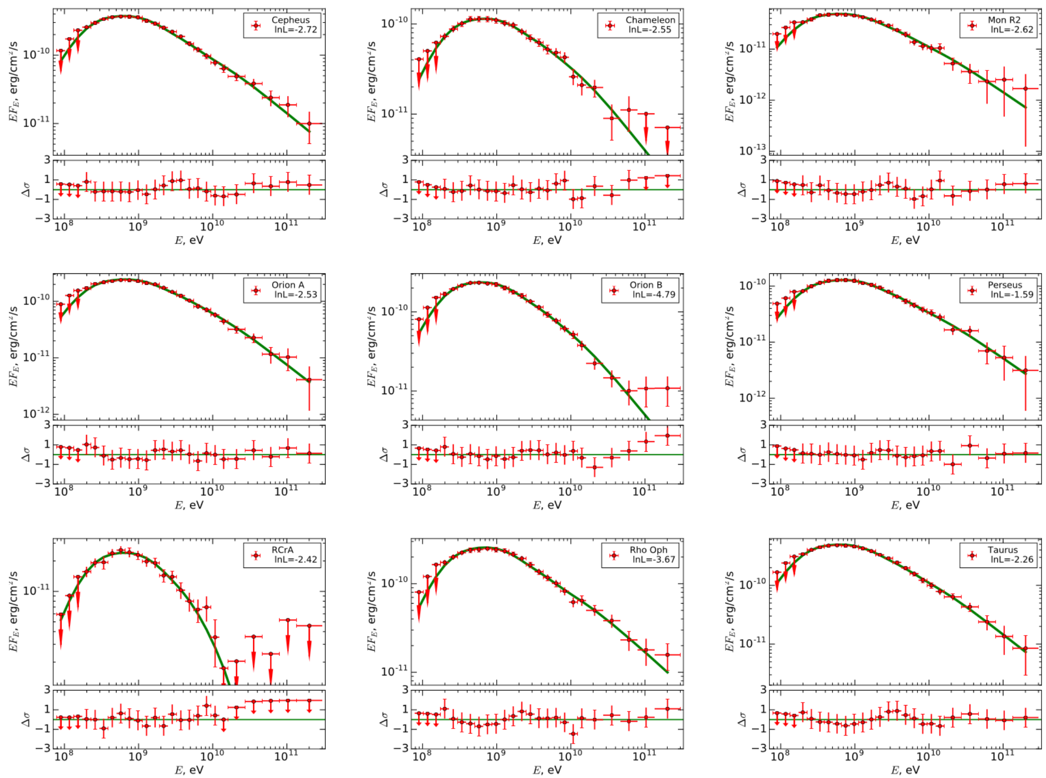


•A.Neronov, D.S. and A.Taylor, PRL, 108, 051105 (2012)

•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?



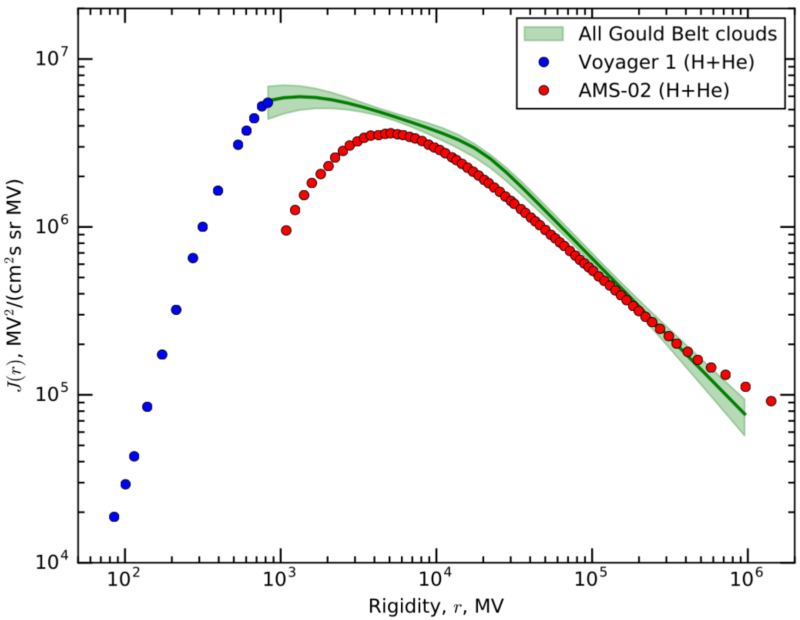
- A.Neronov, D.Malyshev & D.S. 1705.02200

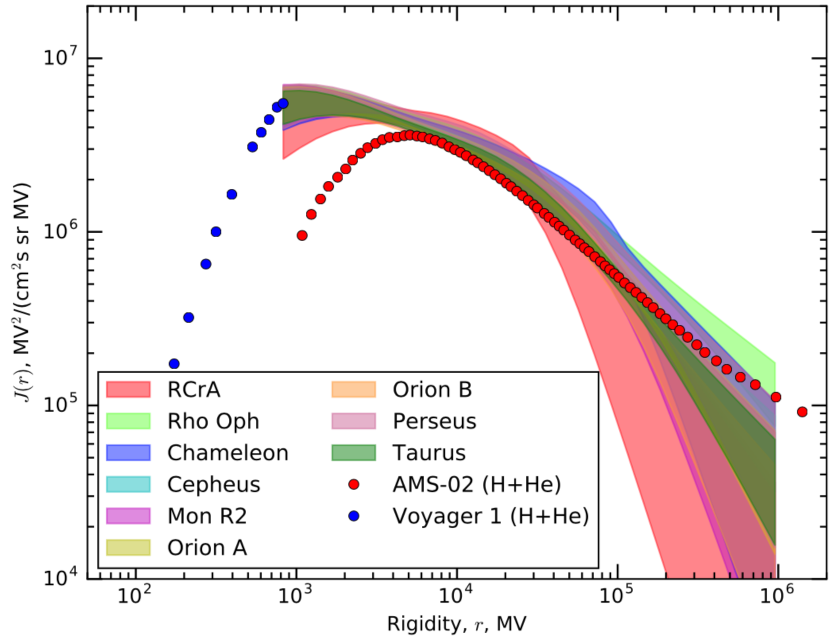
Individual clouds resolved

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





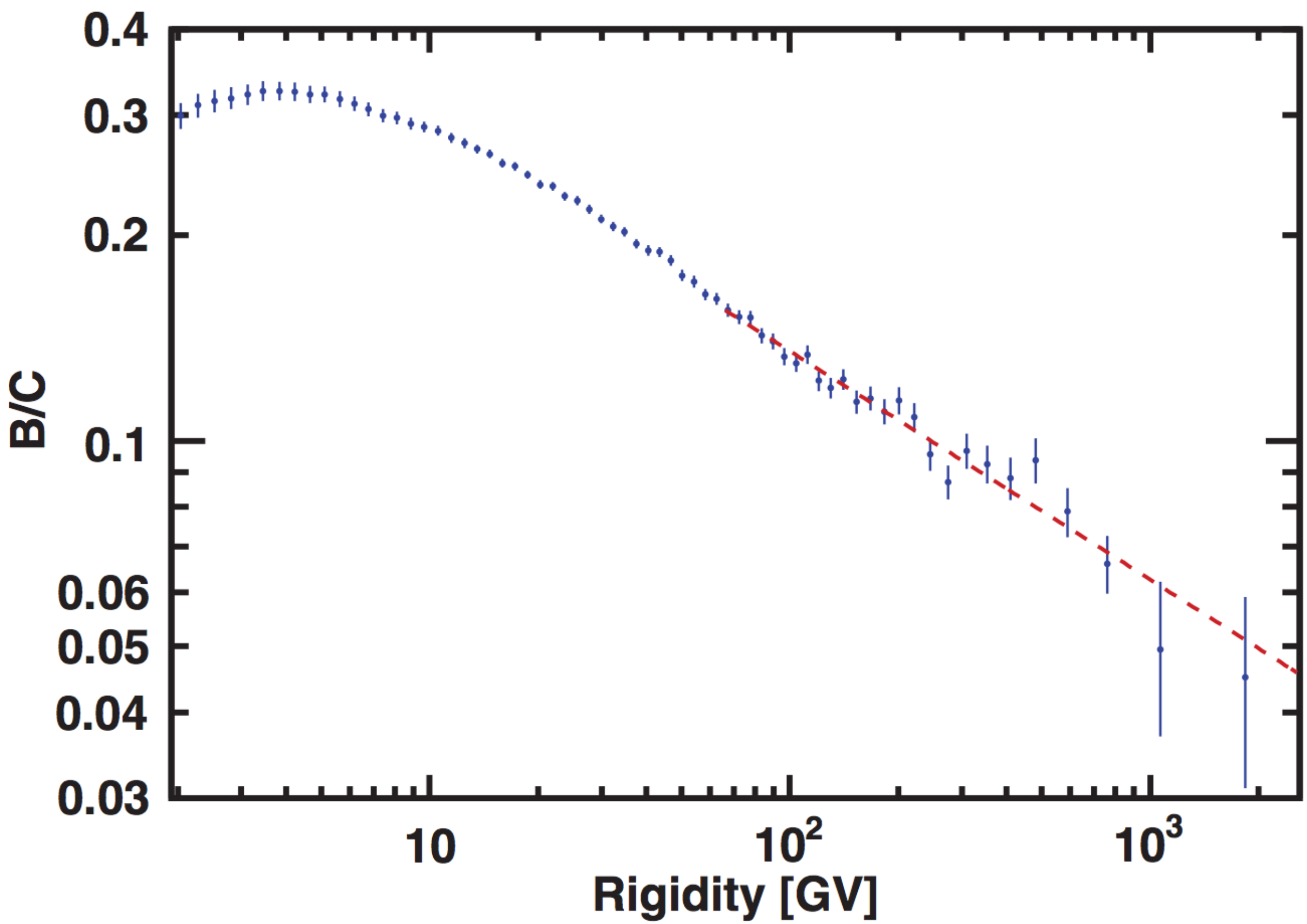
- Sources locally can not support steady state regime above 30 GeV.
- In central galaxy it is OK up to 300 GeV or above

- 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)
-



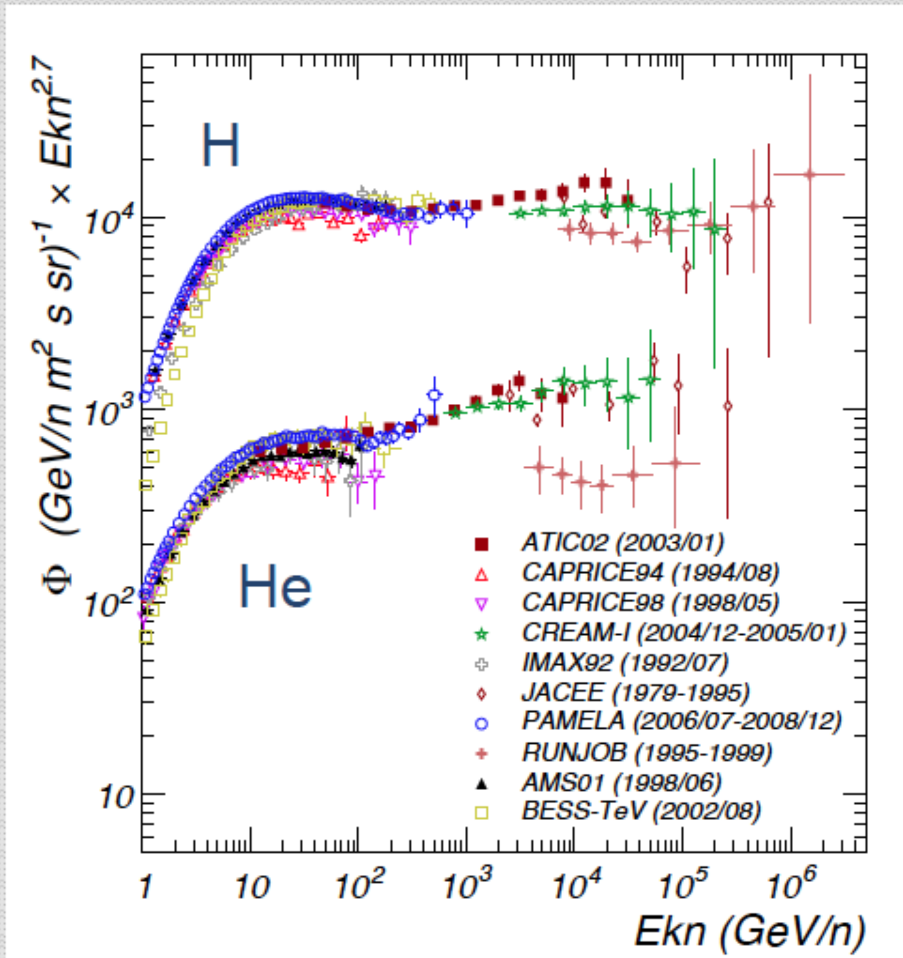
- Delta=1/ 3 Kolmogorov Turbulence

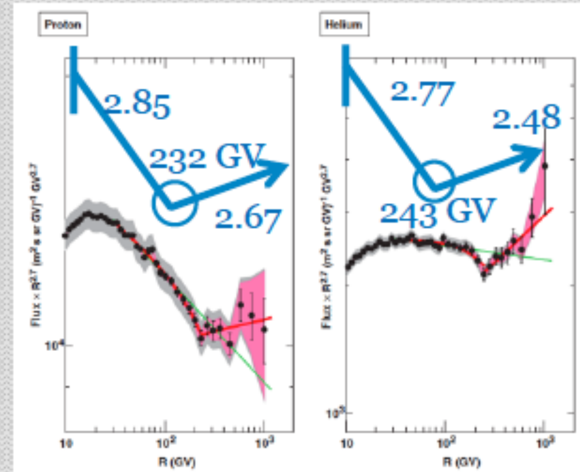
Predictions of the model

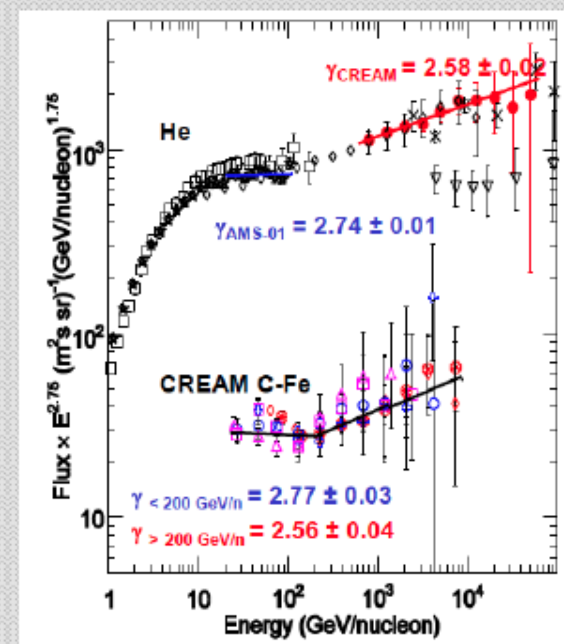
- *Spectrum is the same in all galaxy 1/E^2.7: Since accelerated spectrum is 1/E^2 or 1/E^2.2 magnetic field turbulence is Kreichnan with delta=0.5*
- *Spectra of all nuclei same as one of proton rescaled by regidity R=p/Z*

p/He spectra

Adriani, Science 32,69 (2011)



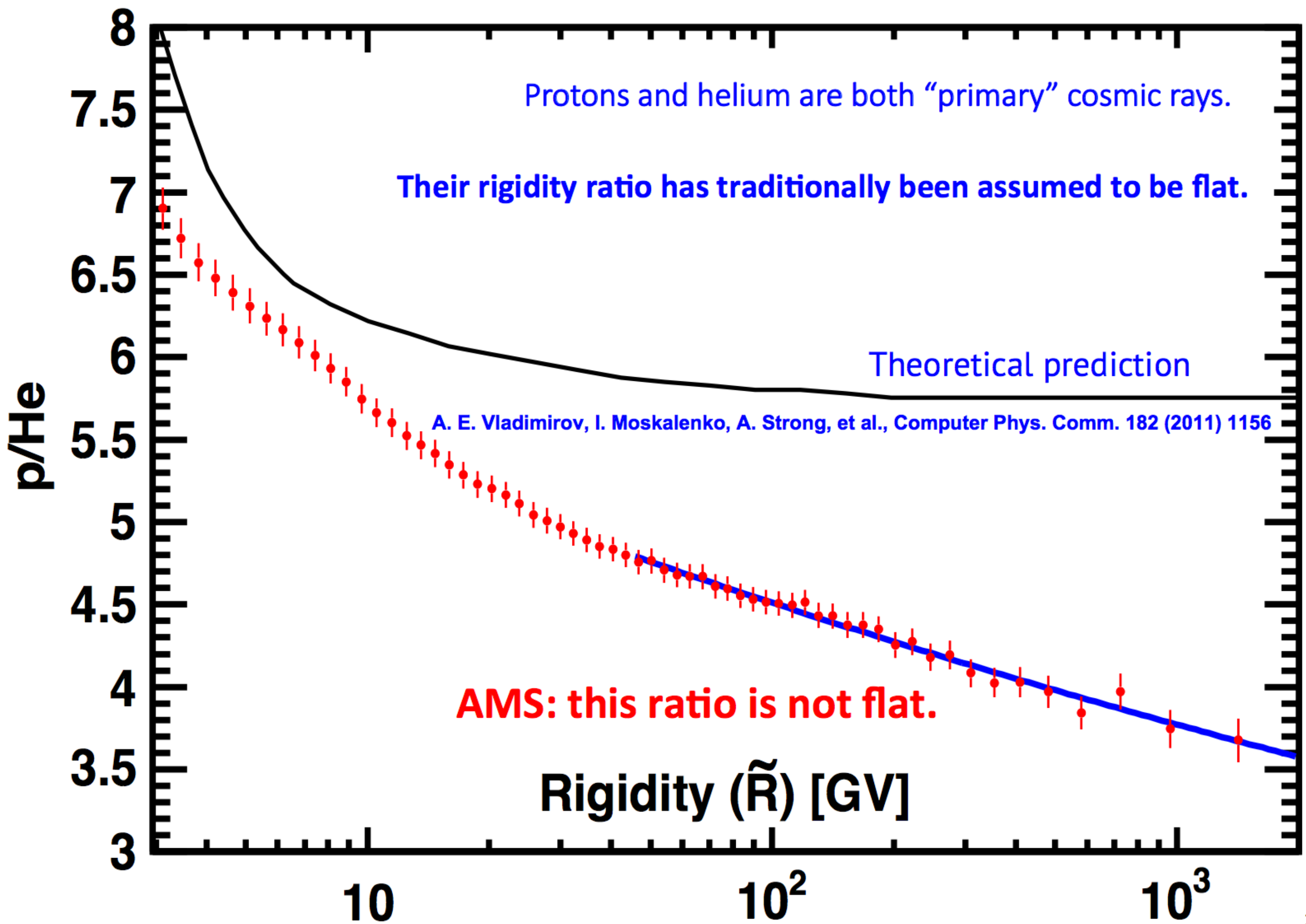




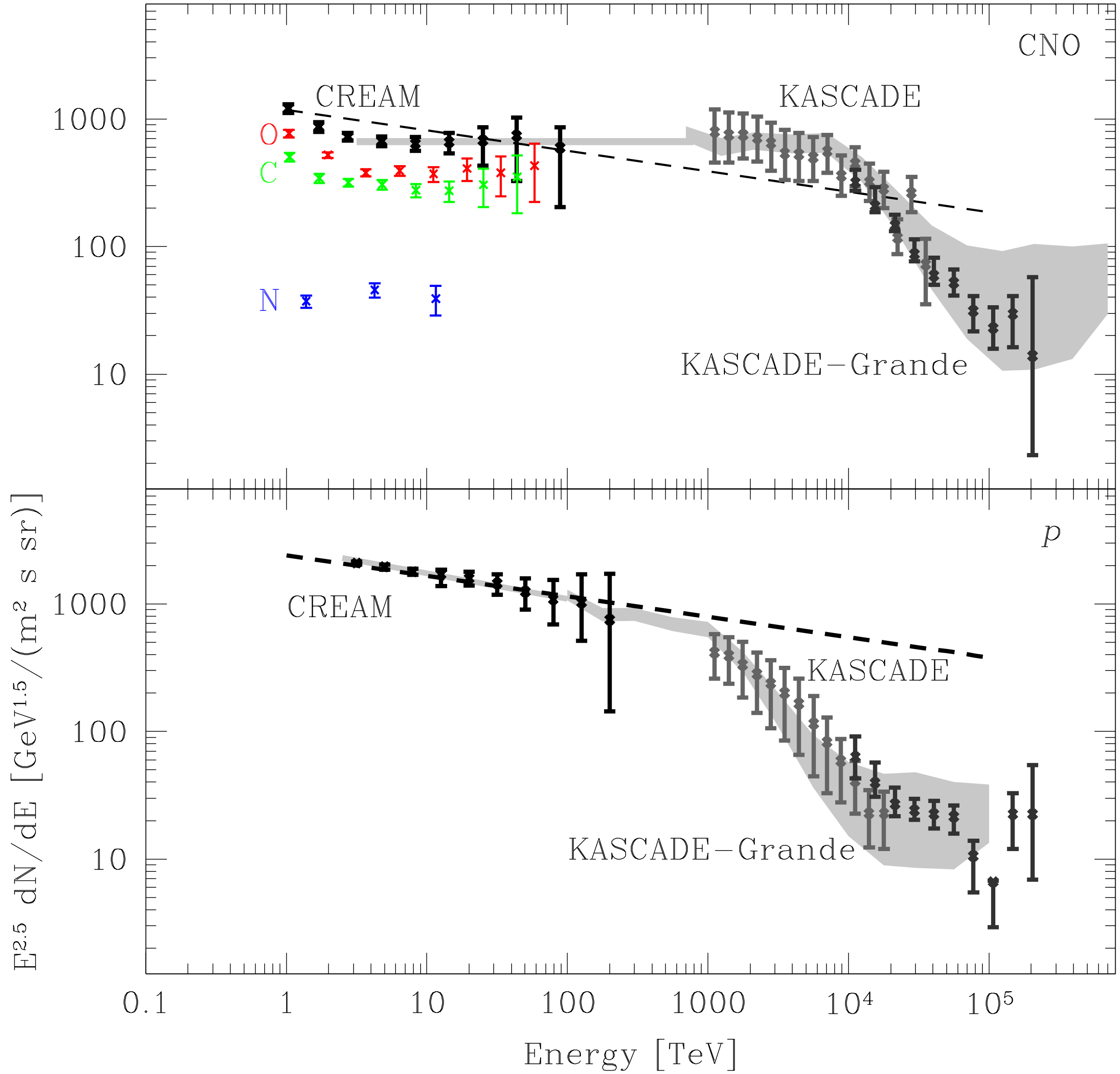
Still waiting for full CREAM statistics

AMS-02 publication soon….(< 2015)

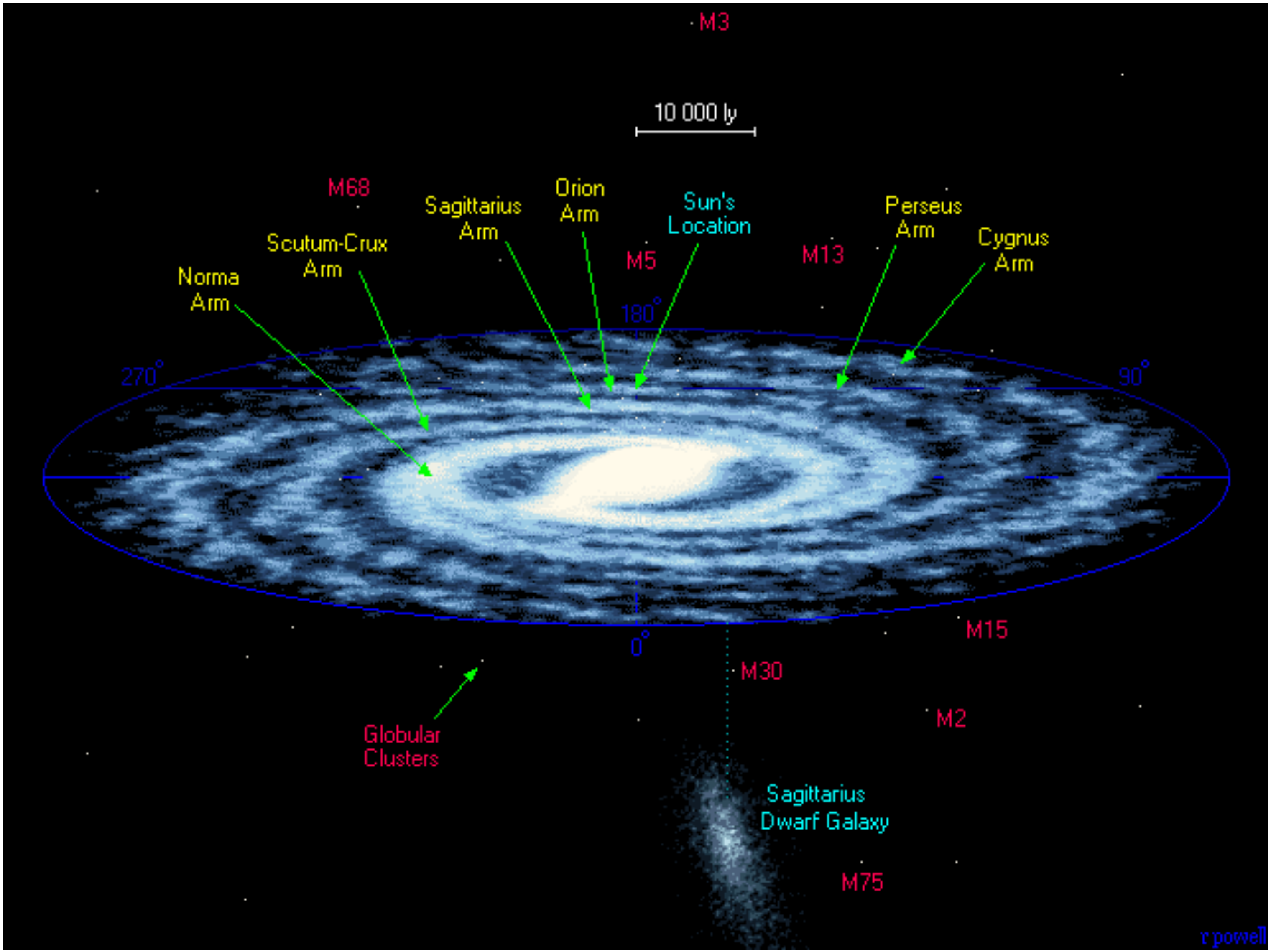
The AMS proton/Helium flux ratio



Proton and CNO spectra



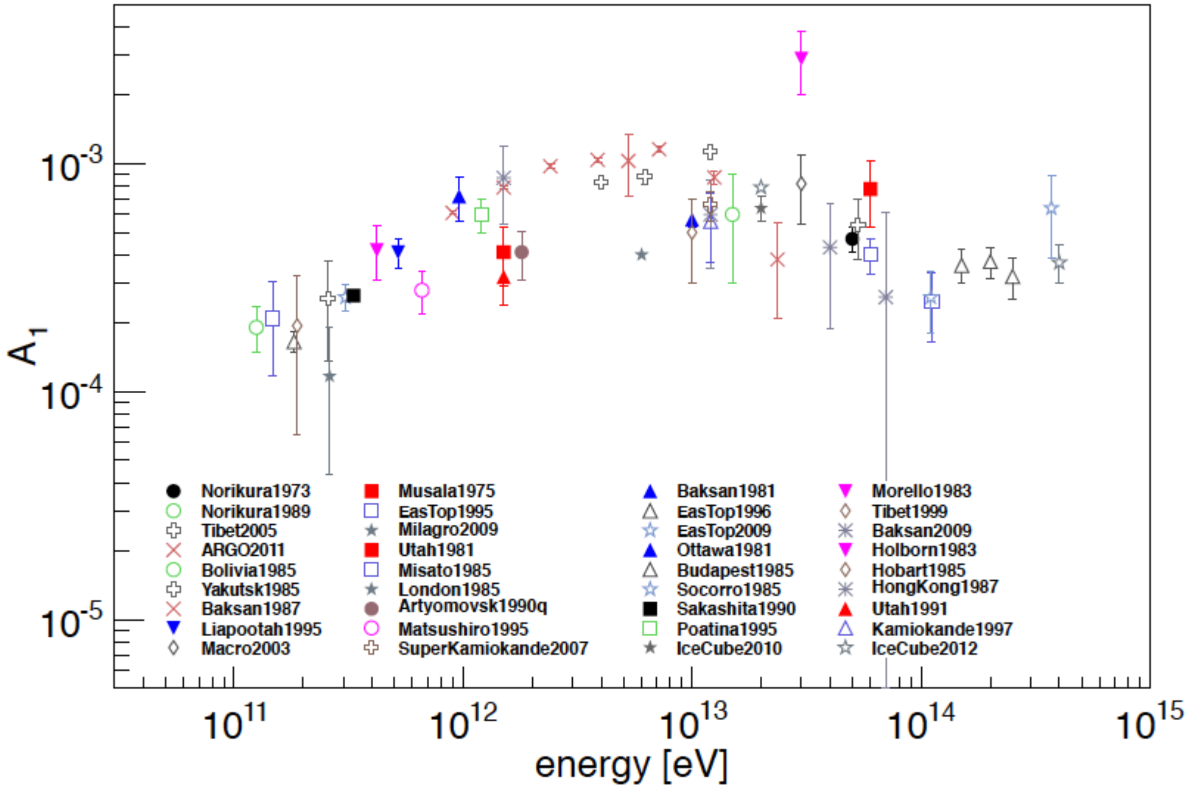
MILKY WAY GALAXY



Predictions of the model

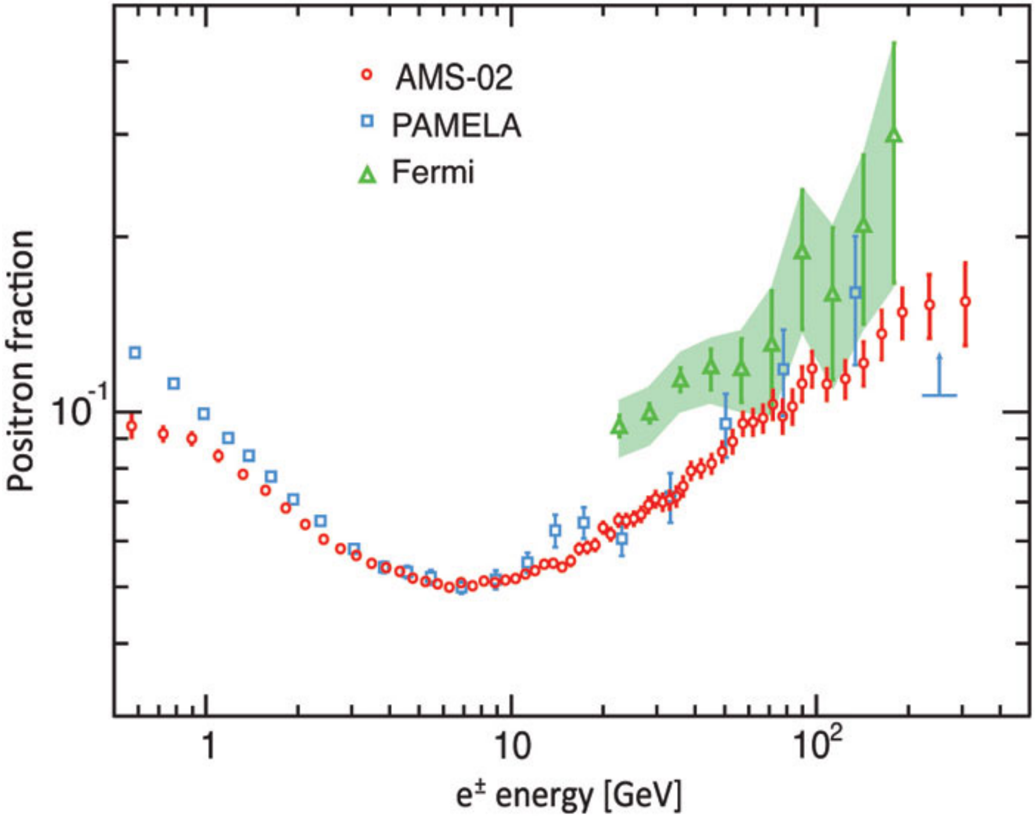
- *Because higher energy cosmic rays escape faster from Galaxy:*
  - *anisotropy is growing function of energy*
  - *Secondary fluxes drop relative to primary fluxes: positron and anti-proton fluxes should drop if compared to proton flux*

Dipole anisotropy of cosmic rays

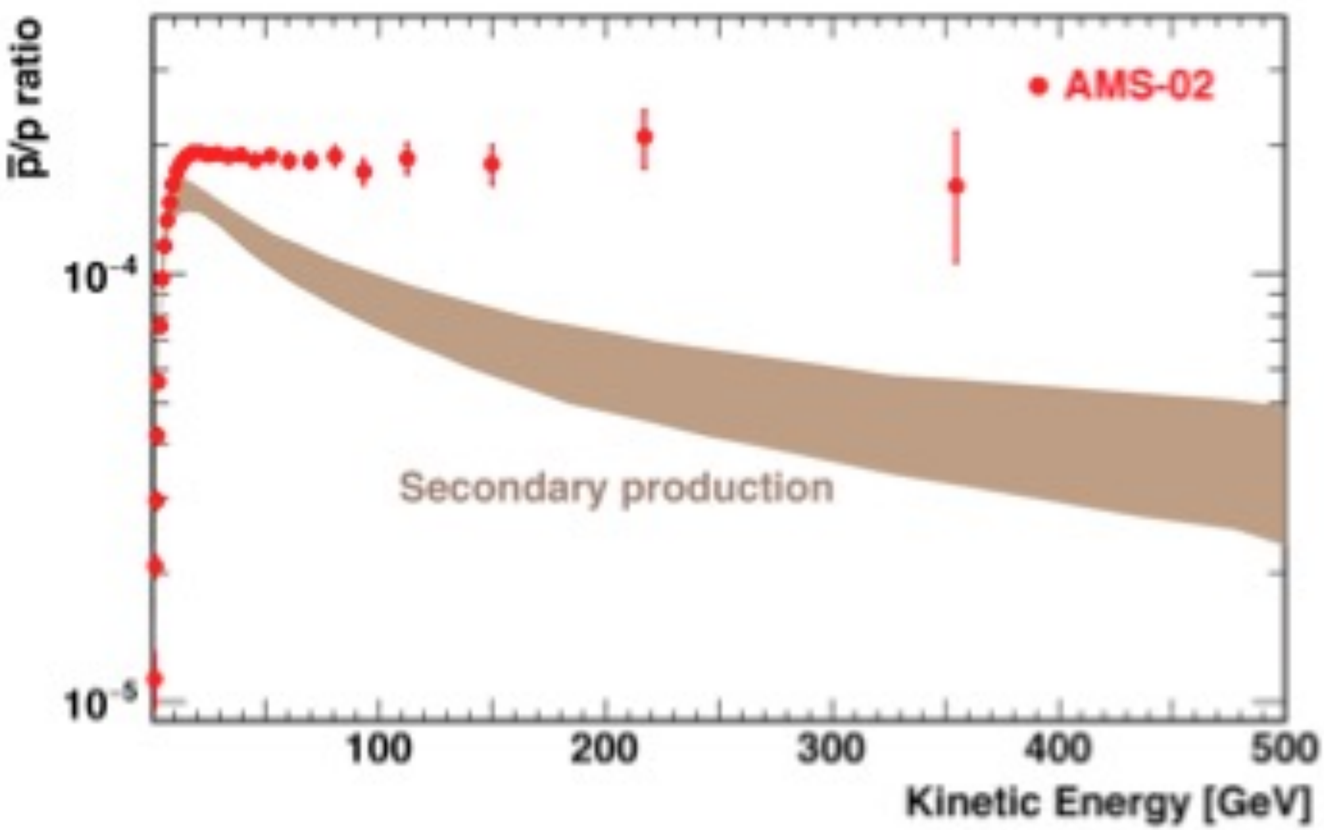


- **G.Di Sciascio and R. Iuppa, arXiv: 1407.2144**

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



Antriprotons by AMS-2



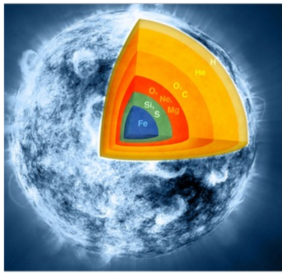
Problems of galactic cosmic rays

- *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

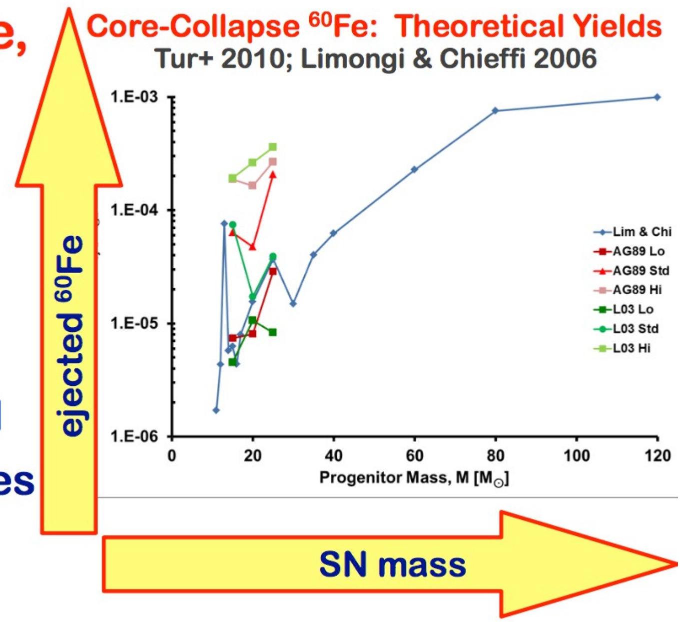
  "weak s-process"

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

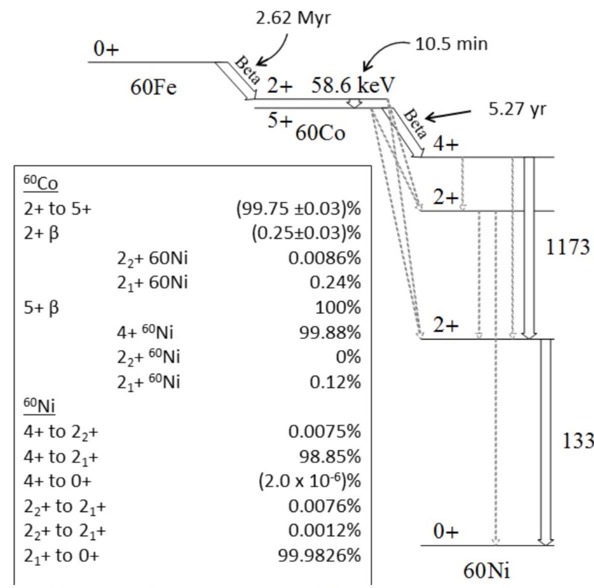
  large theoretical uncertainties in yield

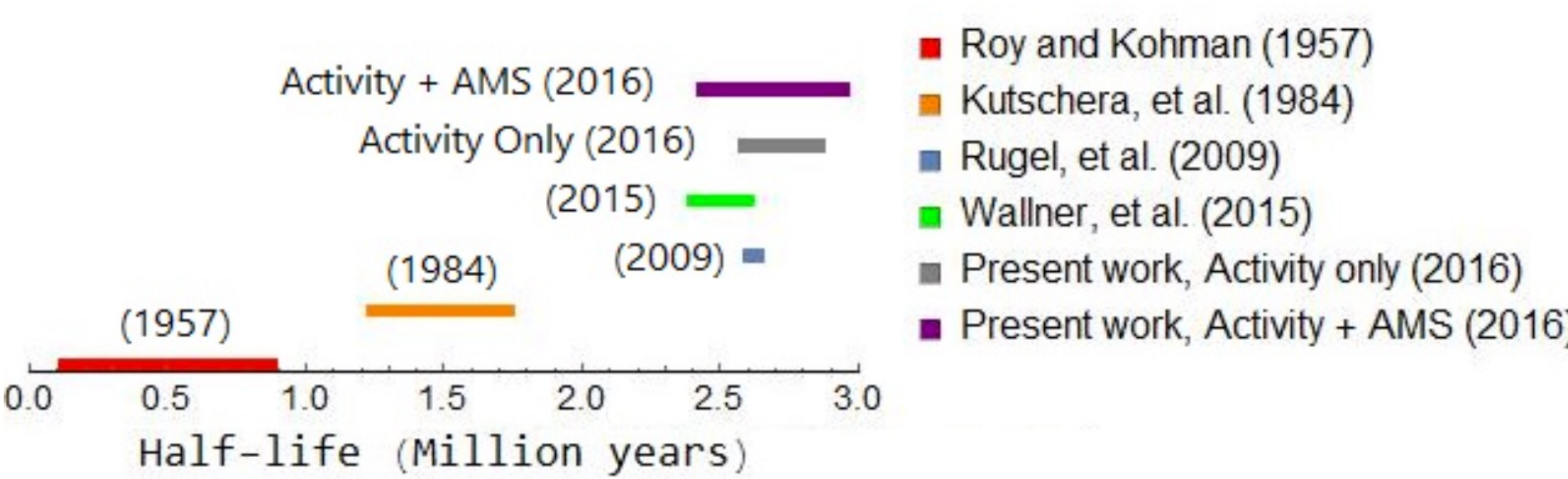
  sensitive to stellar evolution, nuke rates

  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

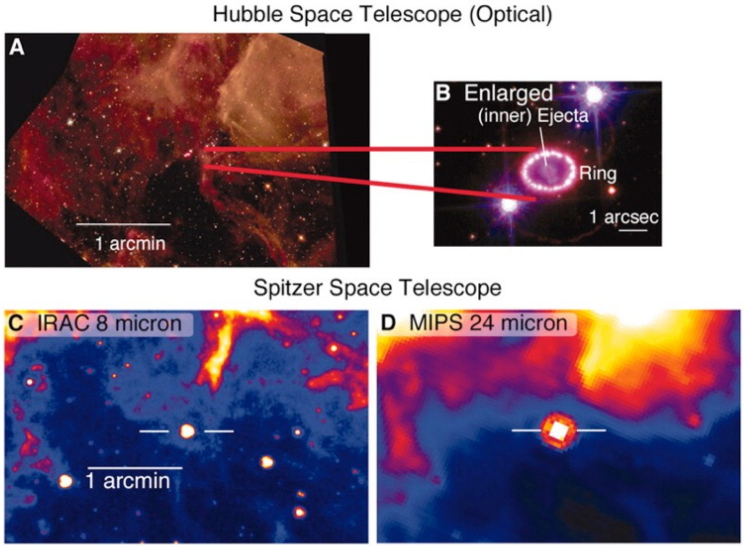
But SN radioisotopes all are refractory elements ⇨ dust grains

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

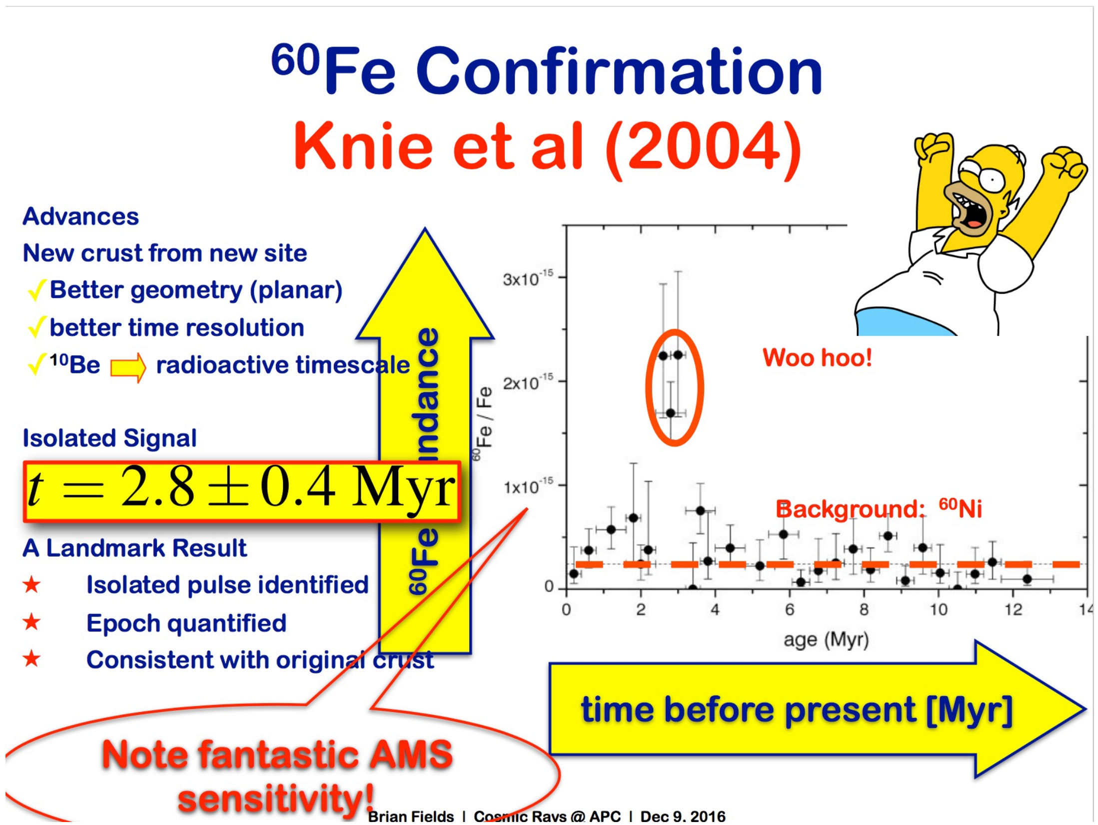
AMS ⇨ live ^{60}Fe, $\tau_{60} = 2.6\ \mathrm{Myr}$!

Expect: one radioactive layer

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

- detectable signal exists
- but not time-resolved


Geological Signatures
Brian Fields | Cosmic Rays @ APC | Dec. 2016


60Fe Confirmation
Knie et al (2004)
Advances
New crust from new site
√ Better geometry (planar)
√ better time resolution
√ 10Be radioactive timescale
Isolated Signal
$t = 2.8 \pm 0.4$ 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 I Cosmic Rays @ APC I Dec 9, 2016

Whodunit?

Fry, BDF, & Ellis 2015

Turn the problem around:

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

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

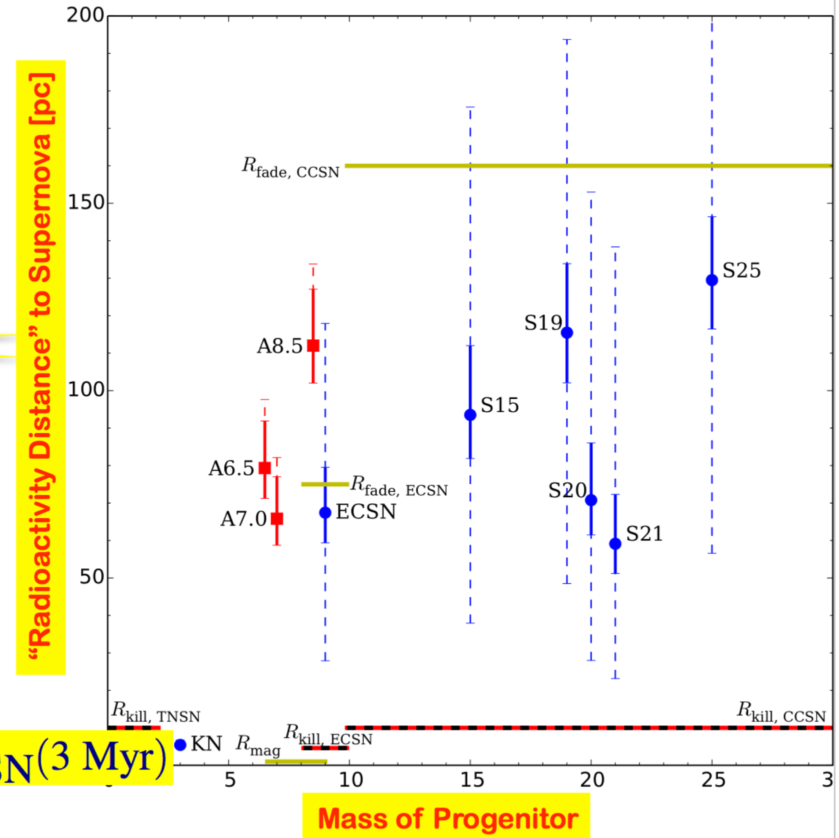
"radioactivity distance" from ^{60}Fe yield

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!

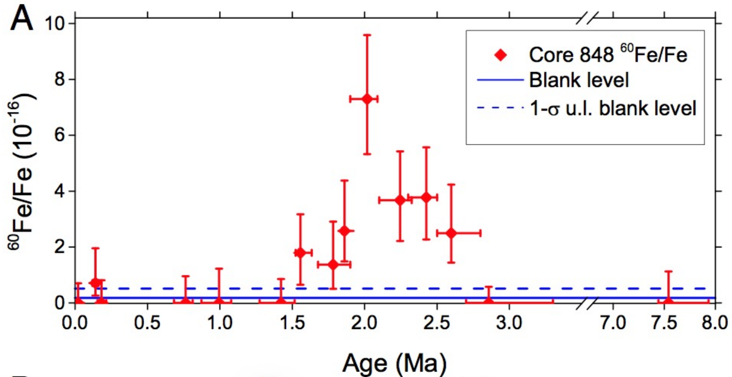
★ $d(^{60}\mathrm{Fe}) \approx d(\mathrm{SN} \rightarrow \mathrm{Earth}) \approx d_{\mathrm{SN}}(3\ \mathrm{Myr})$

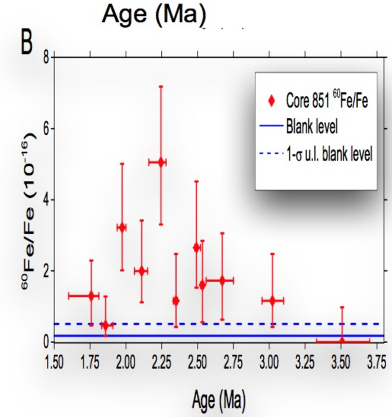
⇨ nontrivial consistency!

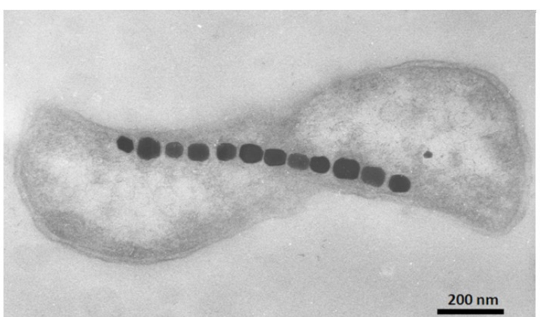
Radioactive Fossil Bacteria

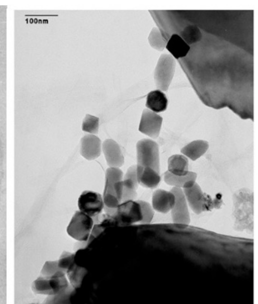
Ludwig, Bishop, et al 2016

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



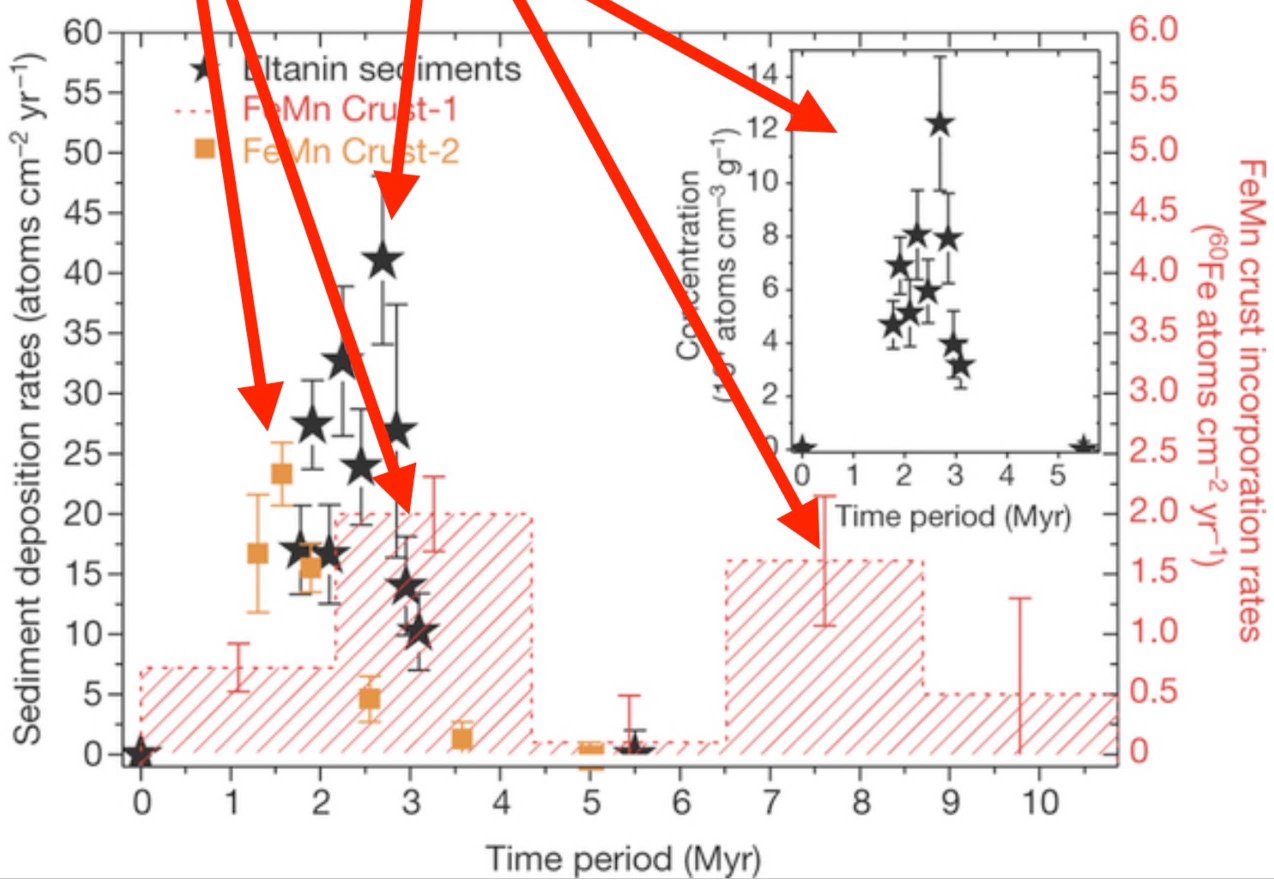






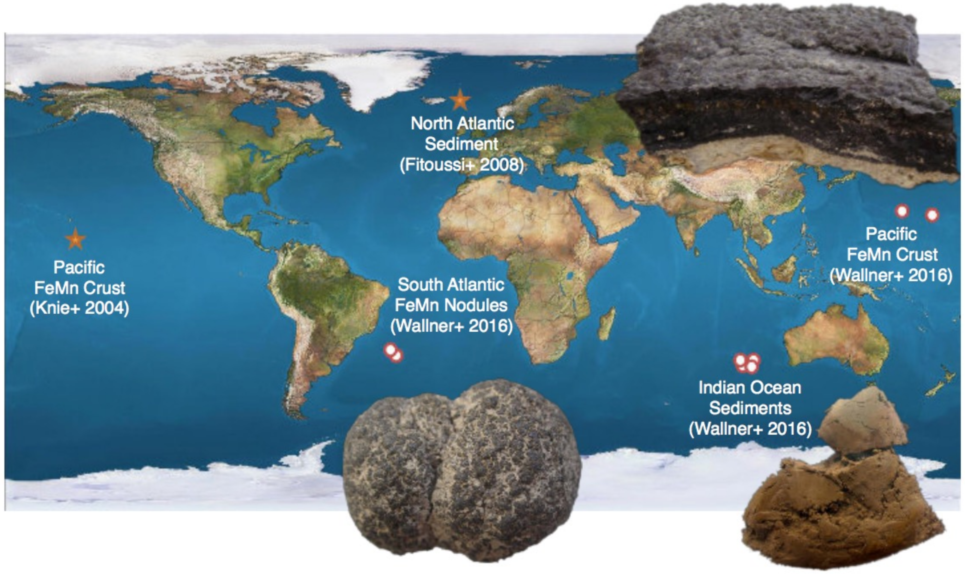
Wallner+ 2016 Nature

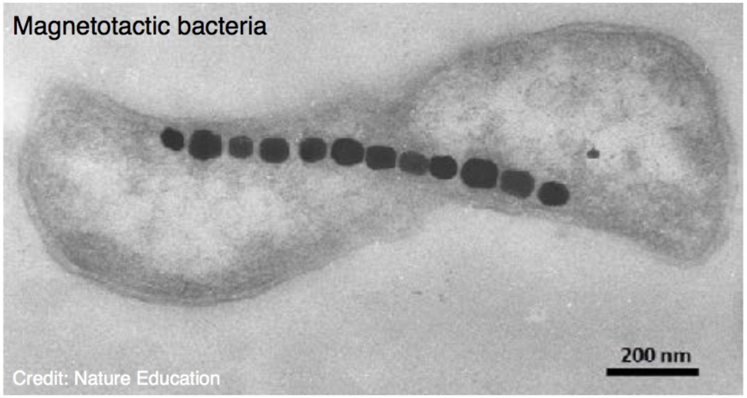
- ★ confirmation of 60Fe crust signal at ~3 Myr
- ★ sedimentary time profile: ~1 Myr width?!
- ★ indication of second ^{60}Fe pulse ~8 Myr

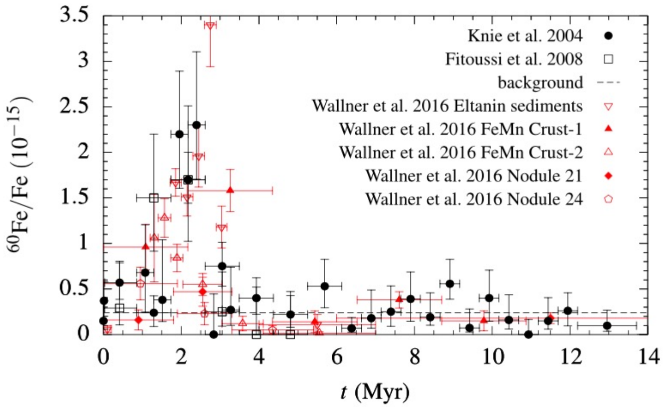


Latest developments

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







The Moon!

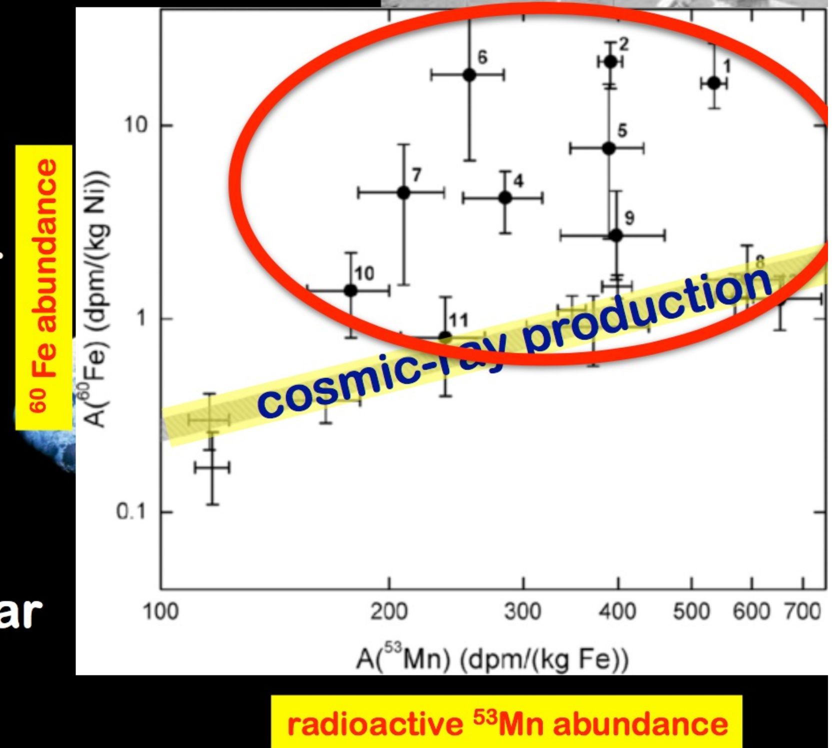
Lunar Soil

- ★ 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

Thank You!

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

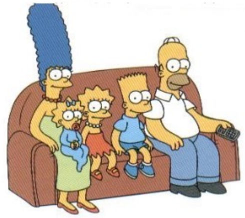
- Shklovskii; Russell & Tucker 71; Ruderman 74; Melott group

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

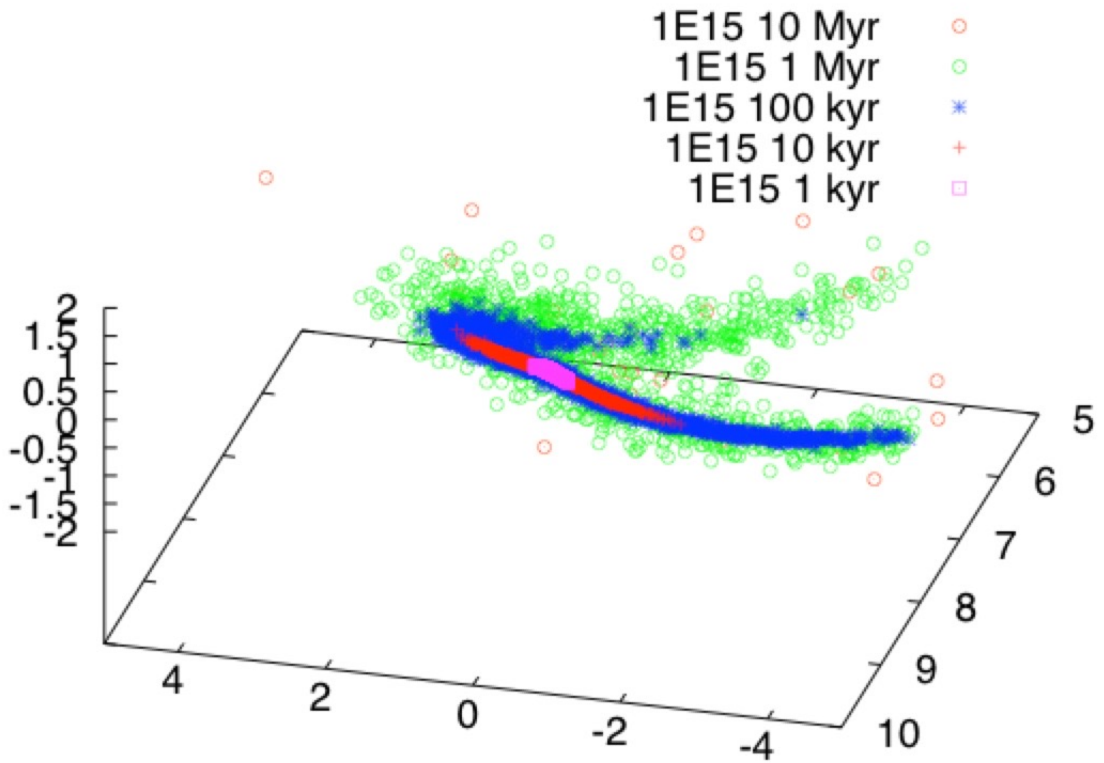
- neutrino-nucleon elastic scatteri
  "linear energy transfer"
  ⇨ DNA damage
)2



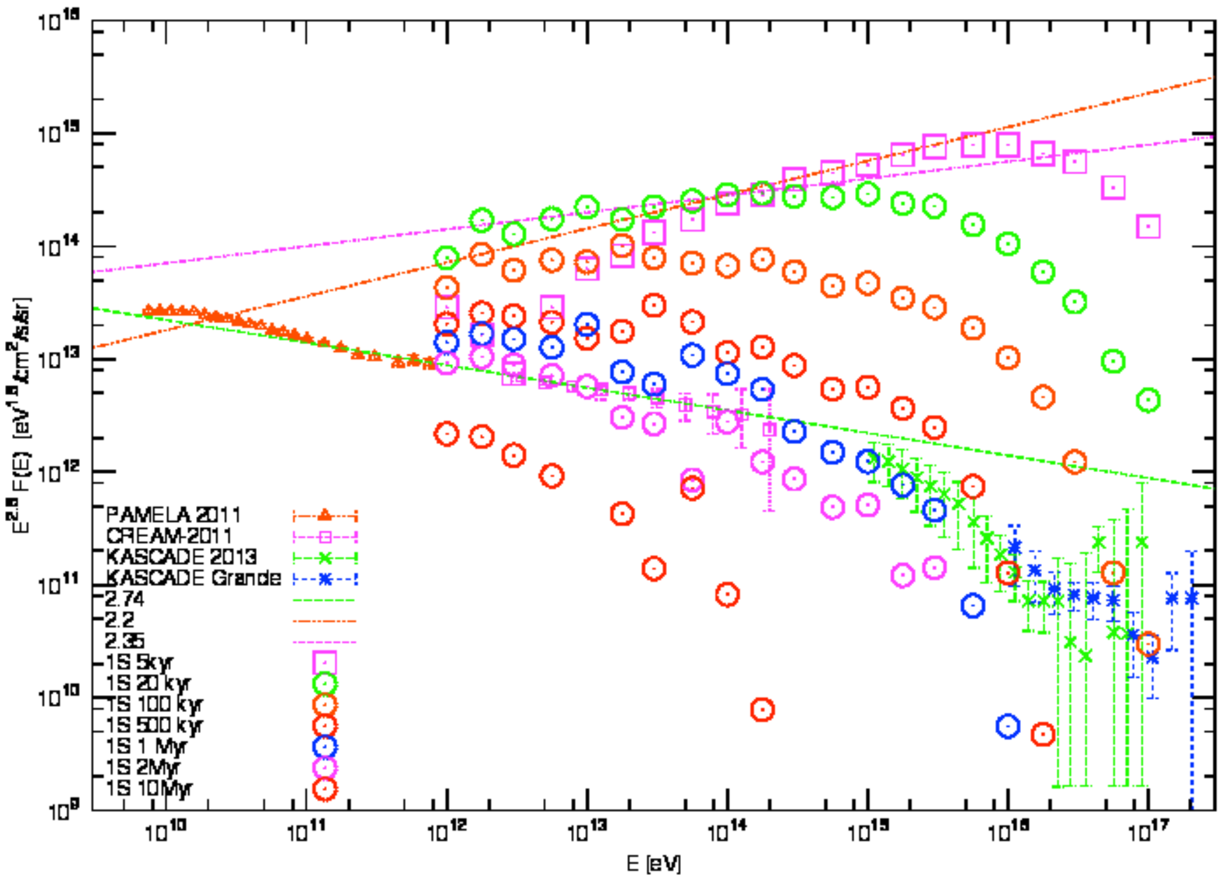
Minimum safe distance: ~8 pc

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)

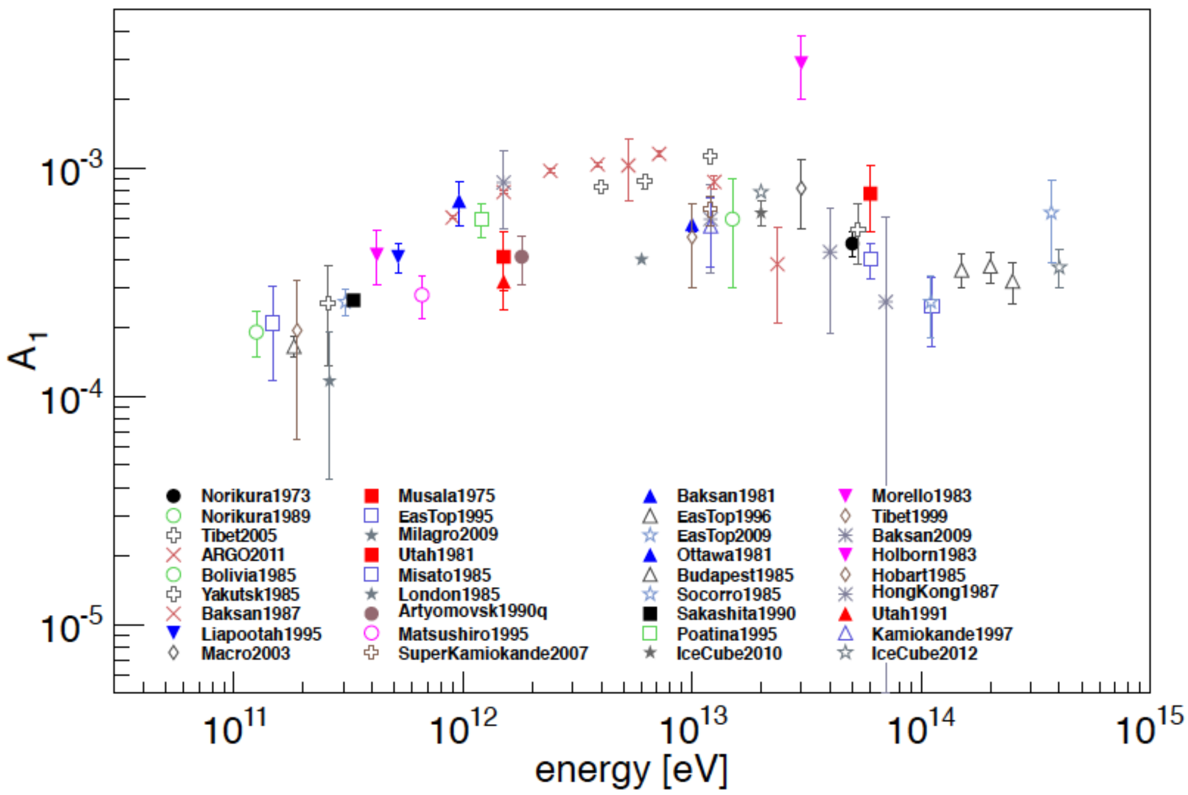
$$\delta = 3R/(2cT),$$

-

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

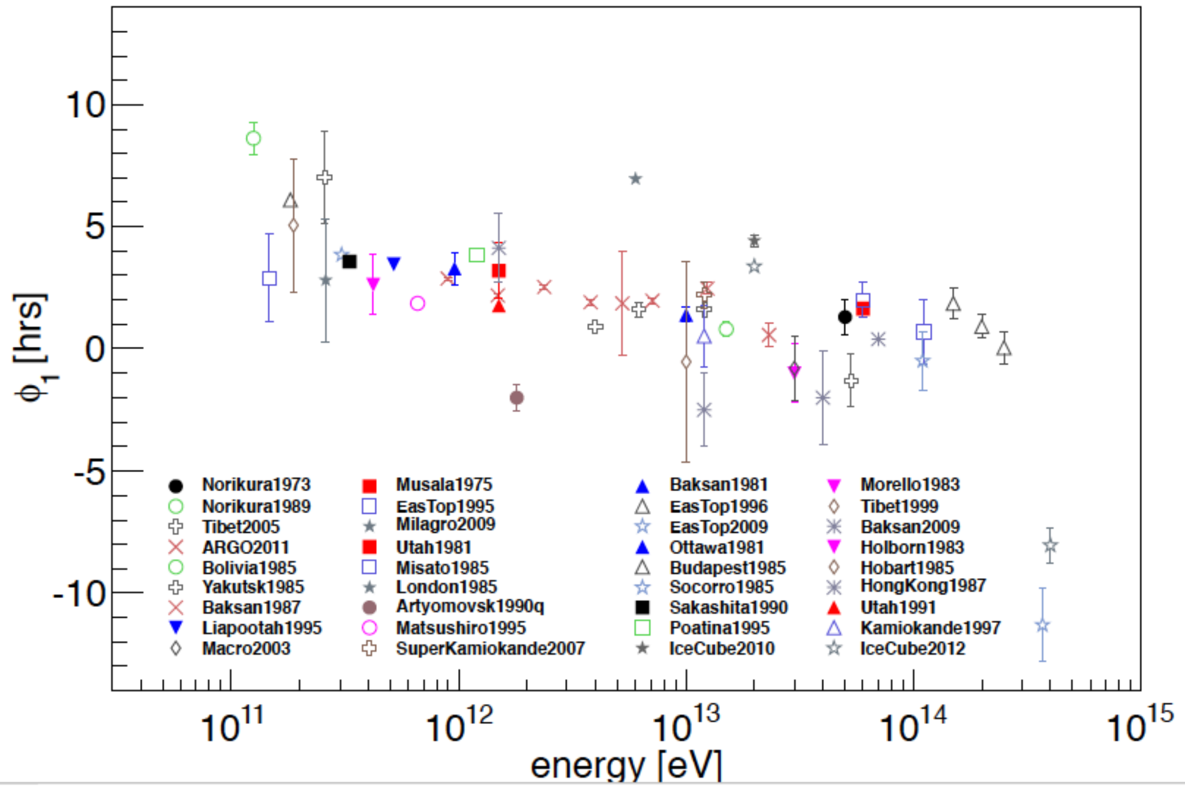
$$\delta_s = 3f_i R/(2cT).$$

Dipole anisotropy of cosmic rays



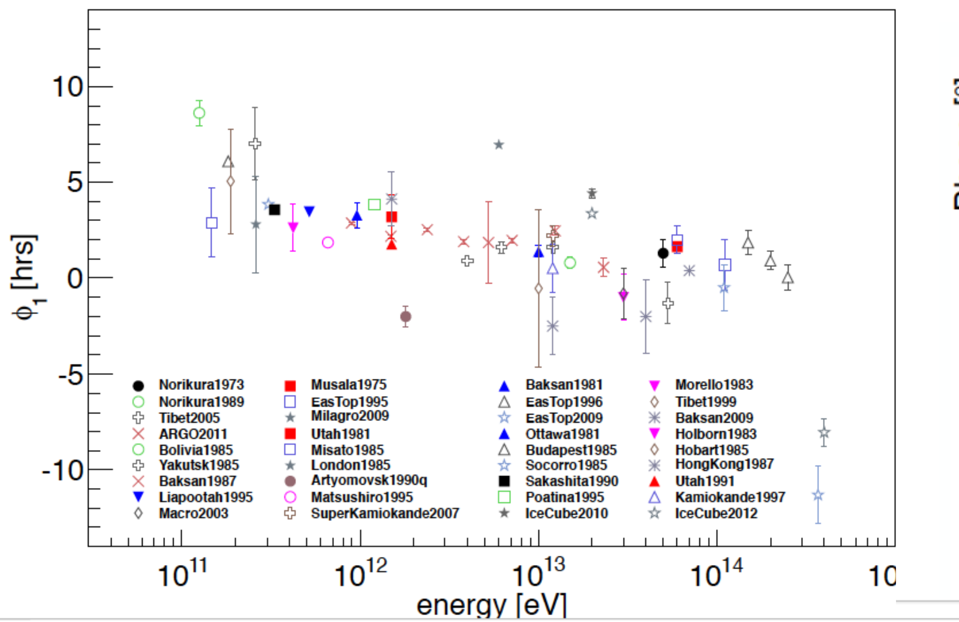
- **G.Di Sciascio and R. Iuppa, arXiv: 1407.2144**

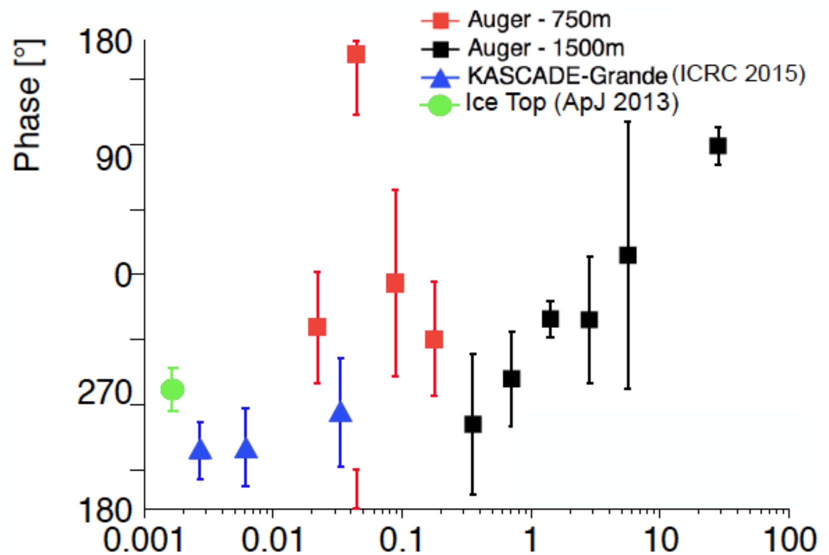
Dipole phase of cosmic rays



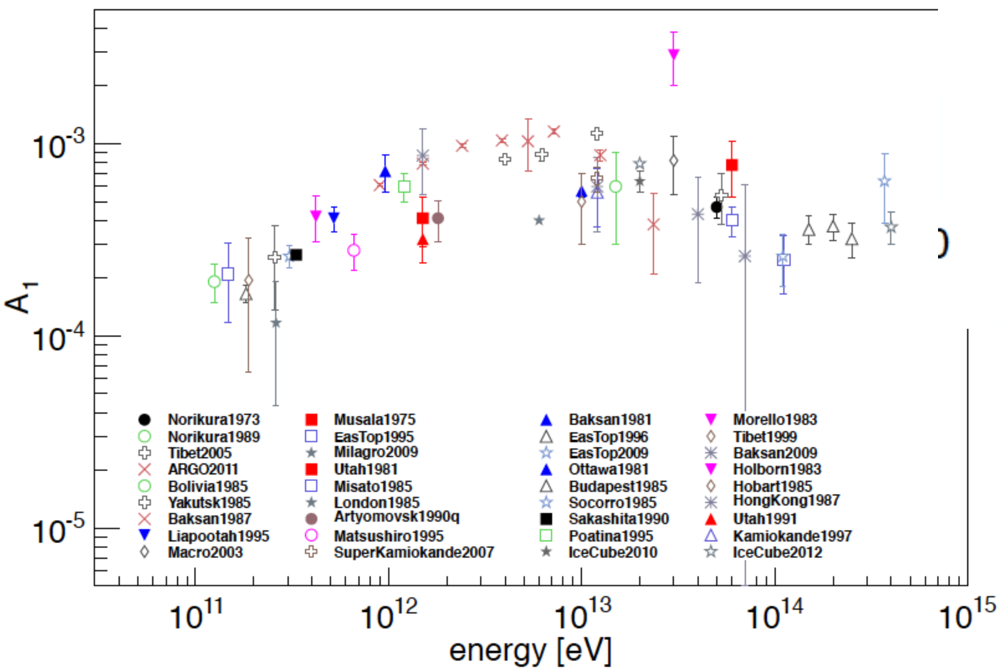
- **G.Di Sciascio and R. Iuppa, arXiv: 1407.2144**

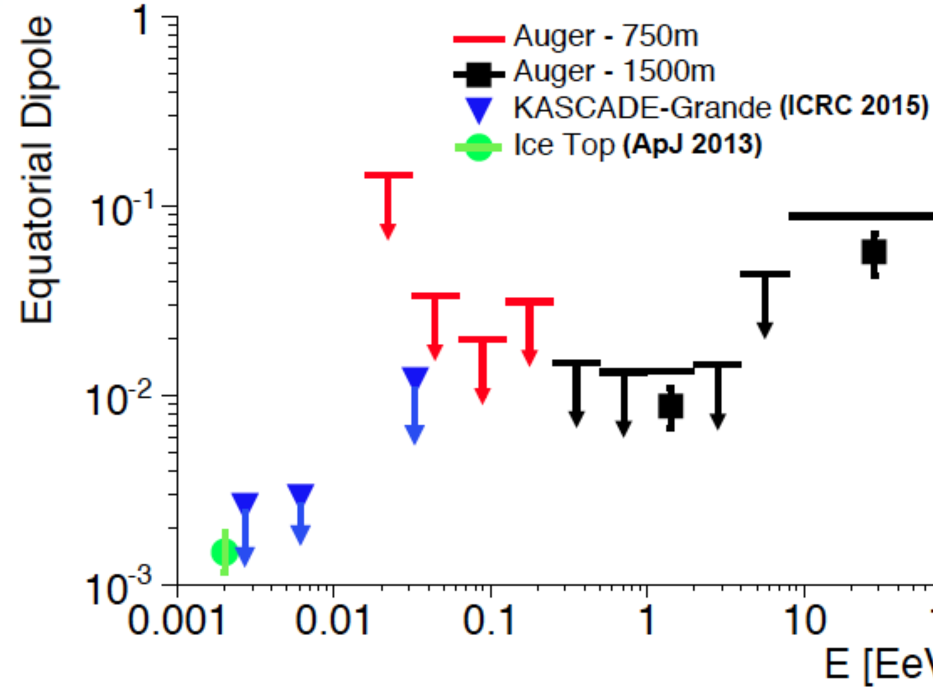
Dipole phase of cosmic rays



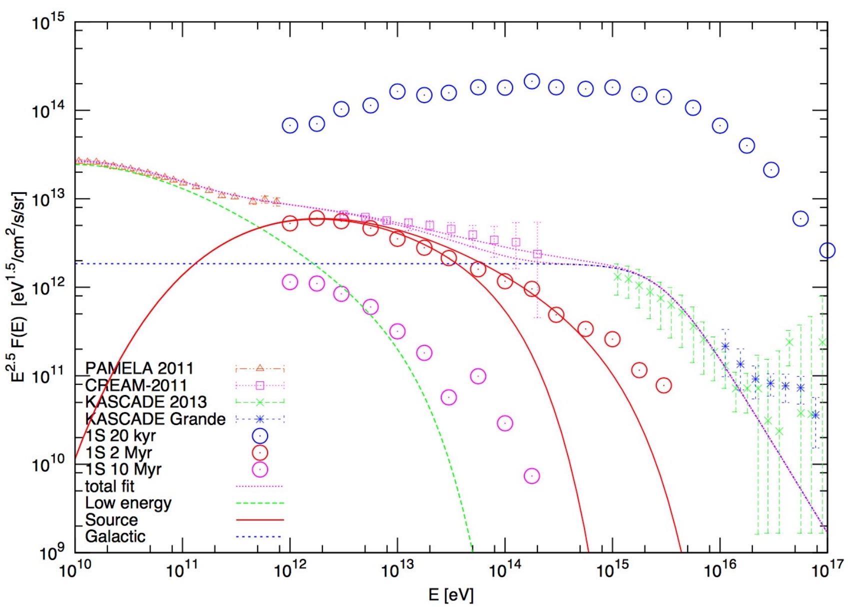


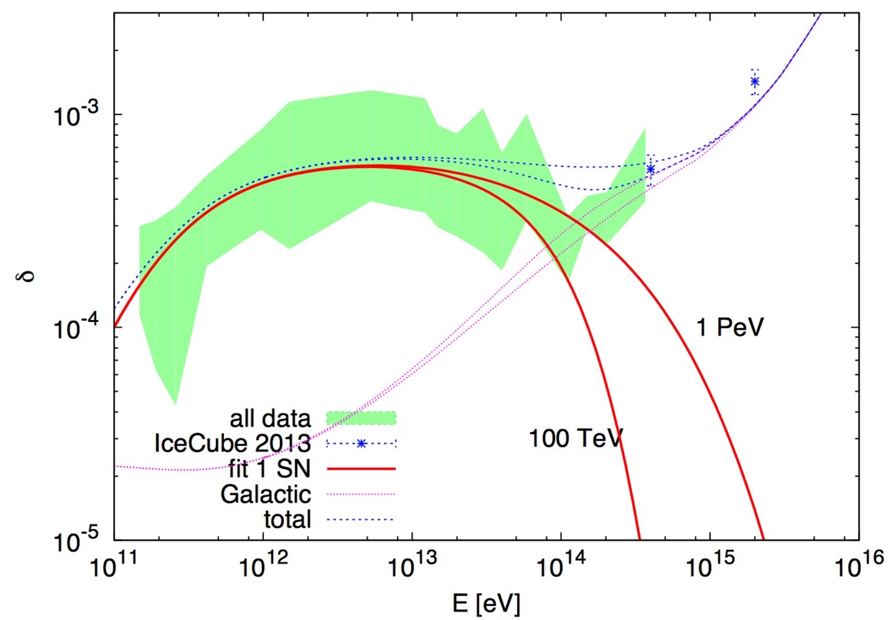
Dipole anisotropy of cosmic ra





Anisotropy and flux from 2 Myr SN

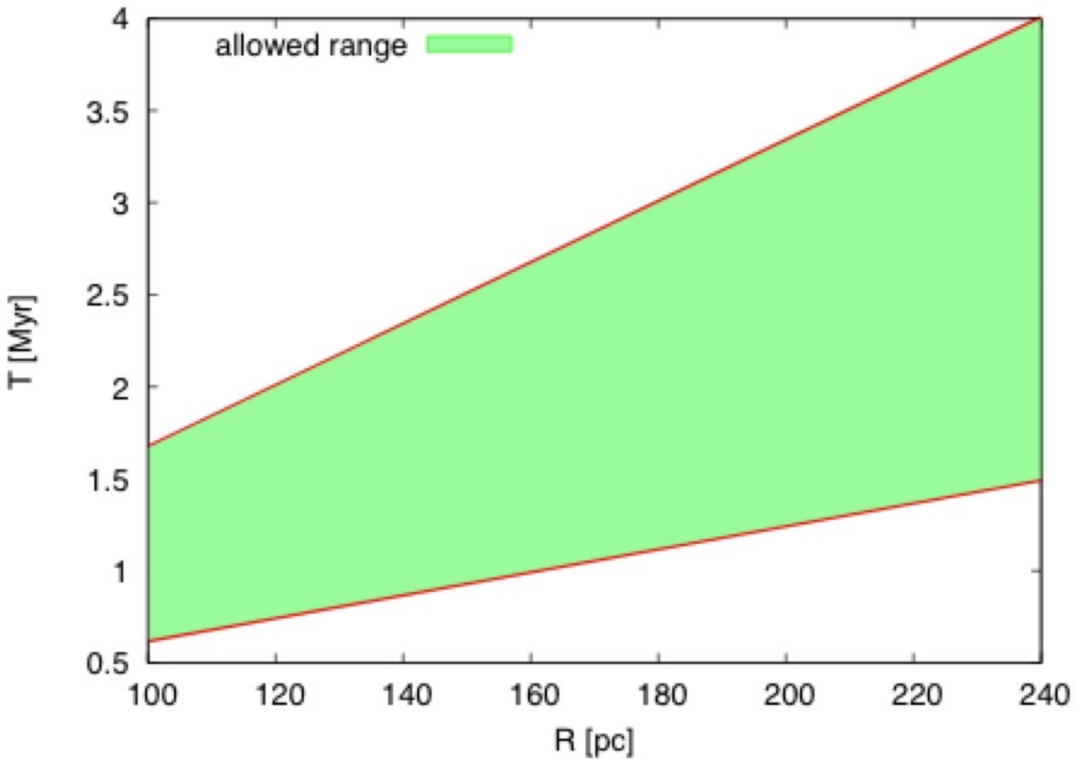




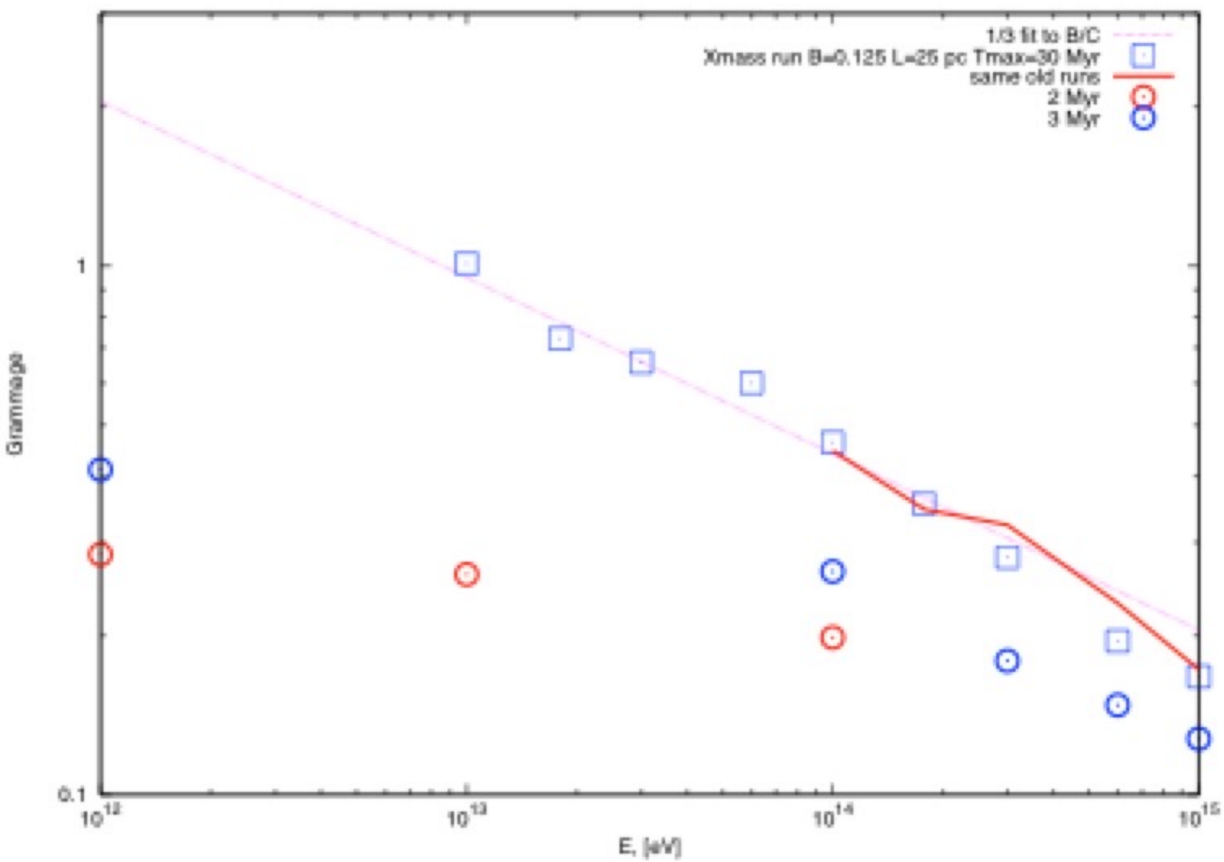
- A=3/2 R/T

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

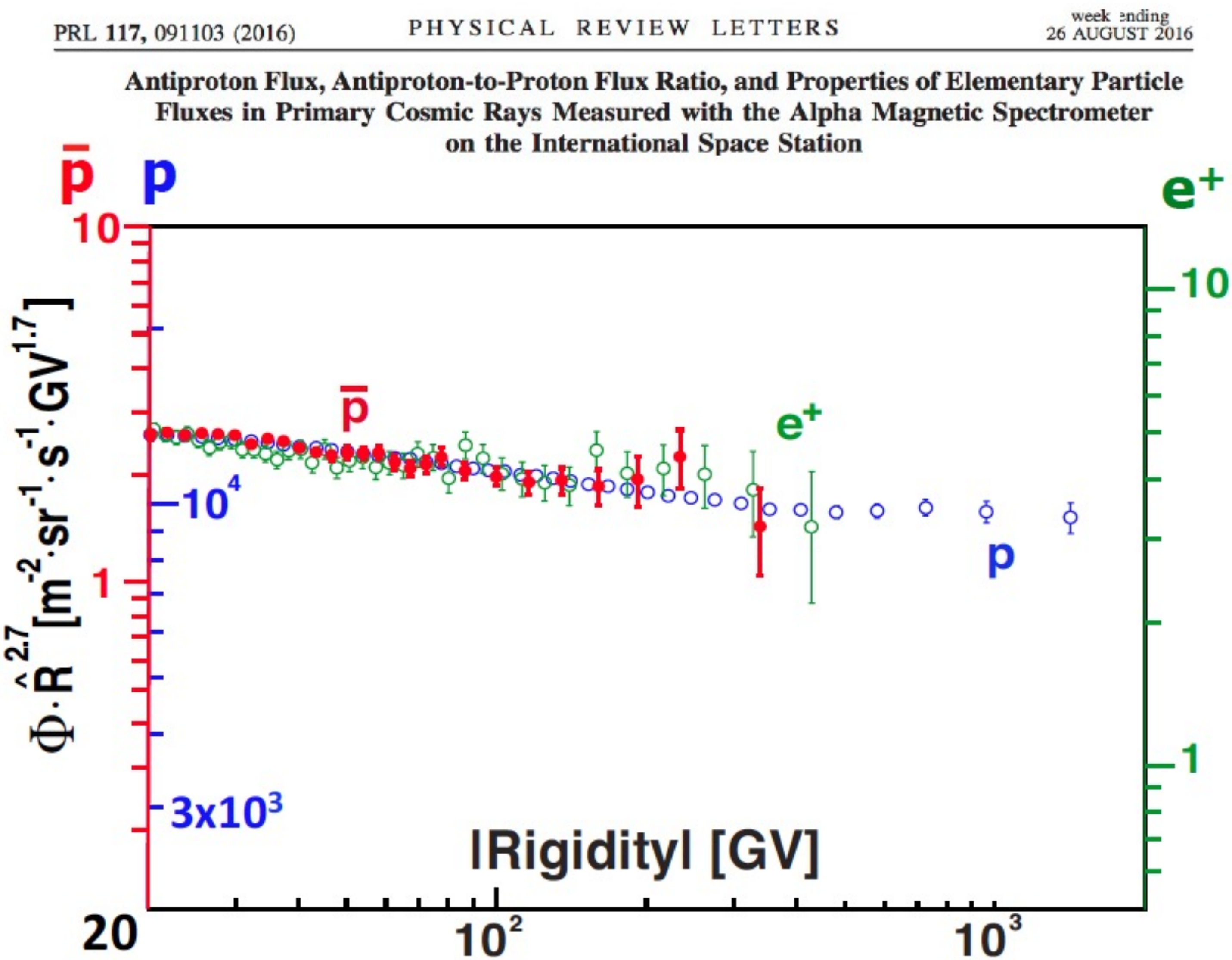
Anisotropy and parameters of SN



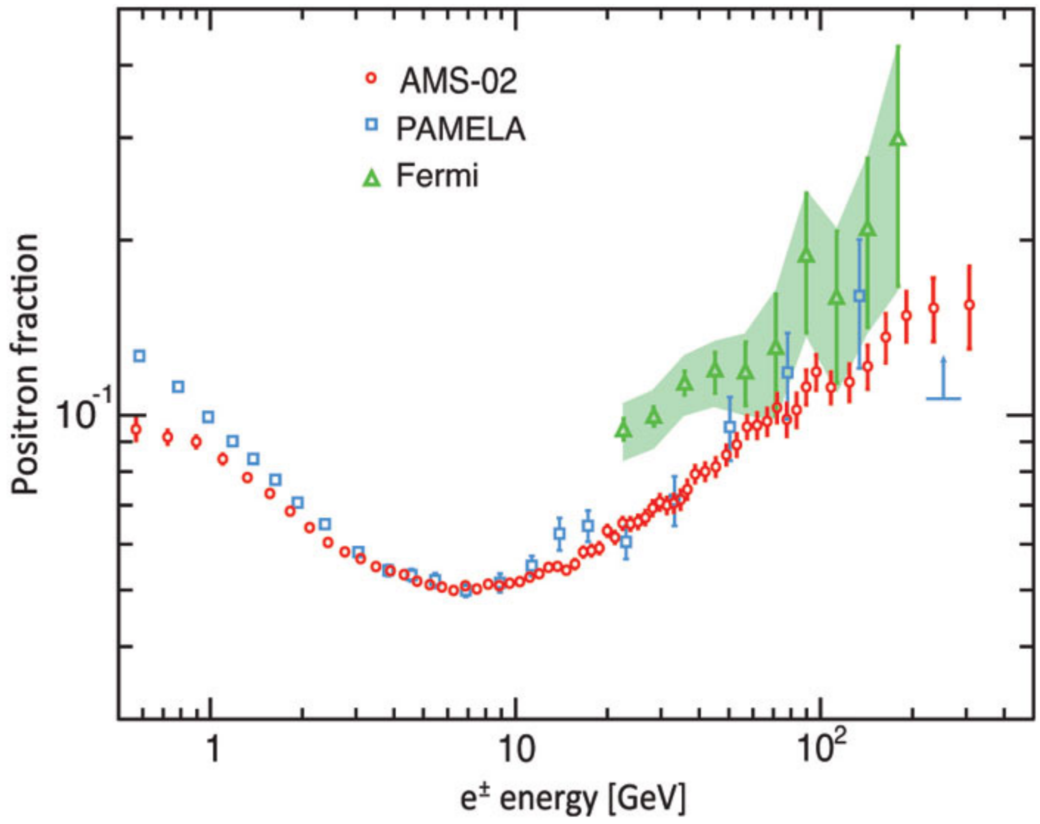
Grammage to create secondaries



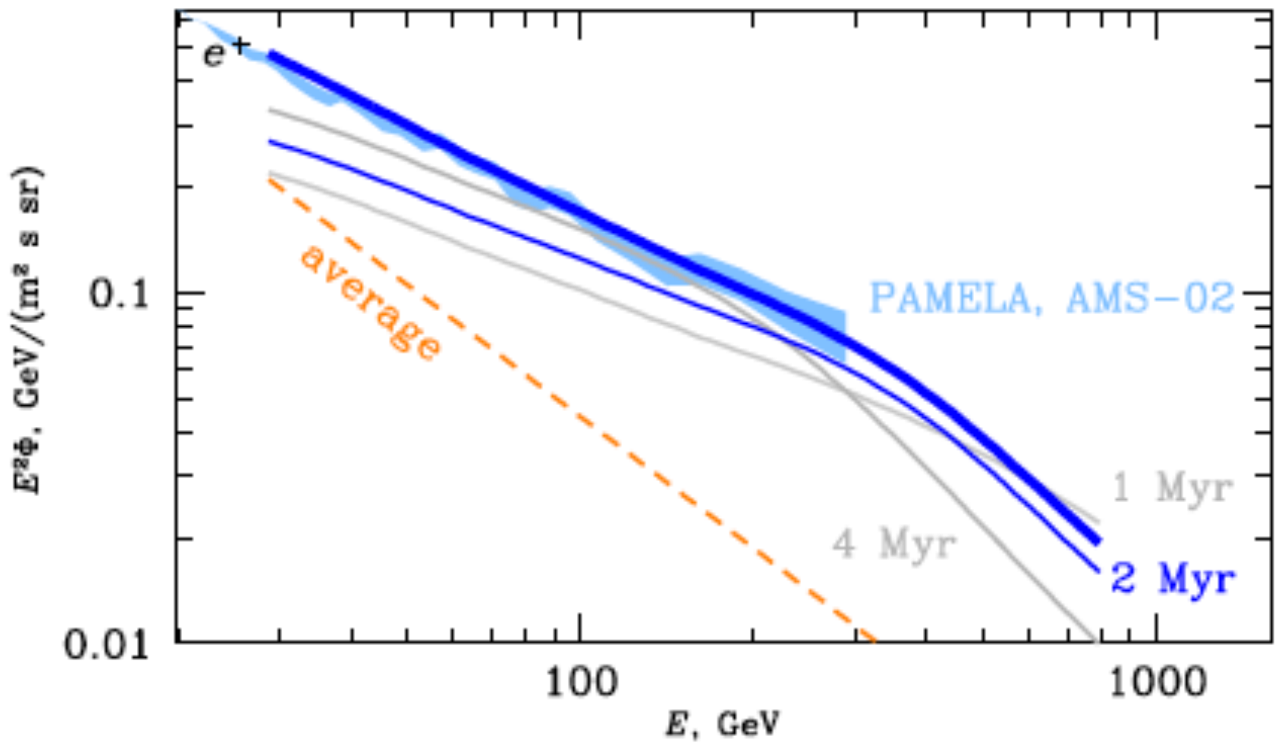
The antiproton flux compared to other particle fluxes



Positron to (electron + positron) ratio

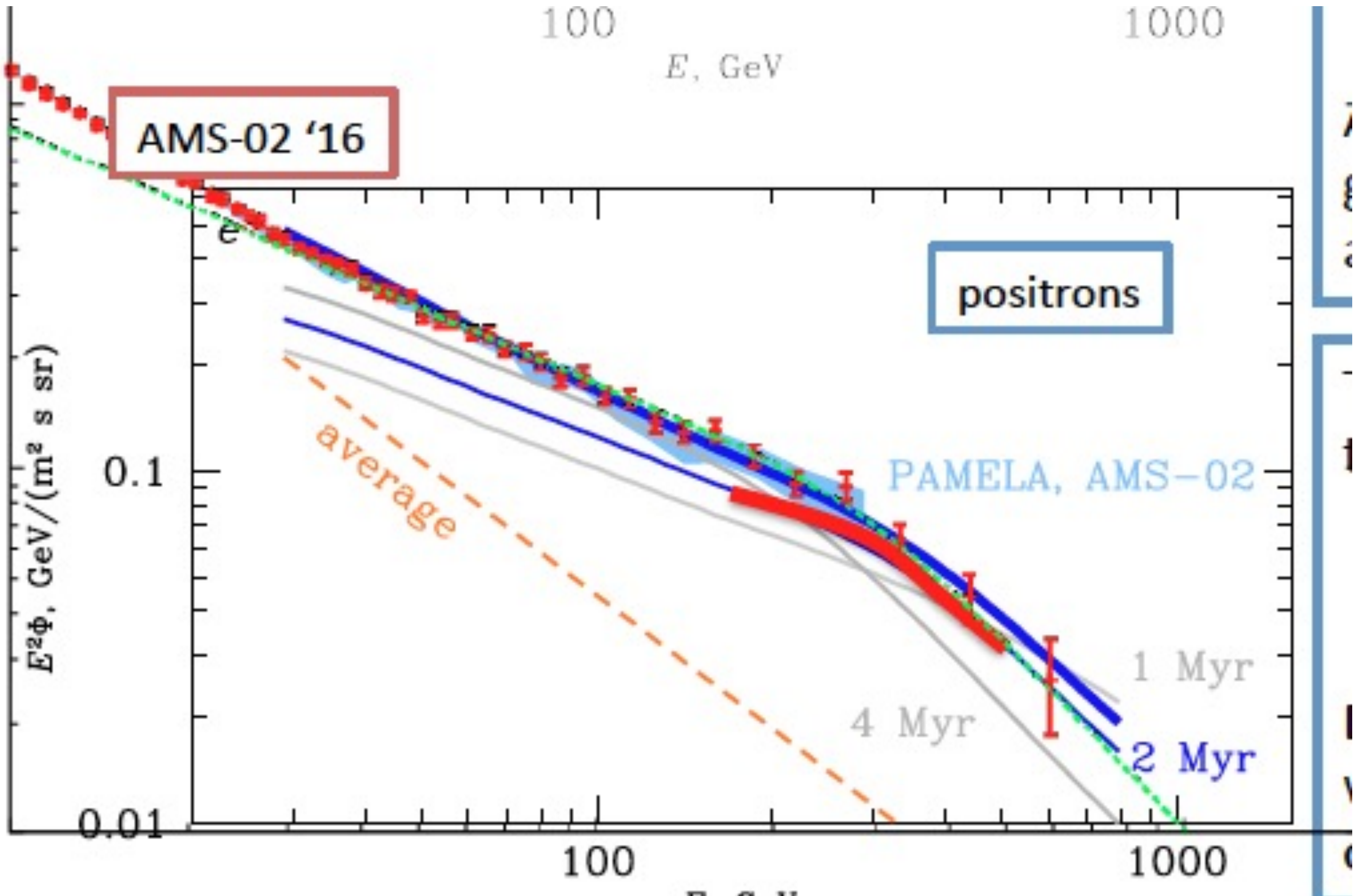


Positron flux PAMELA/AMS-II



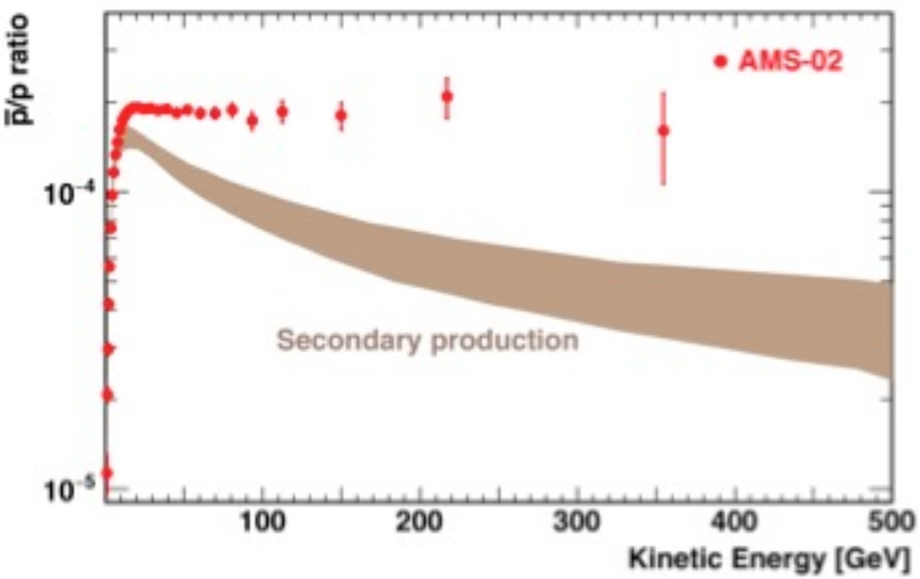
- M.Kachelriess, A. Neronov and D.Semikoz, arXiv:1504.06472

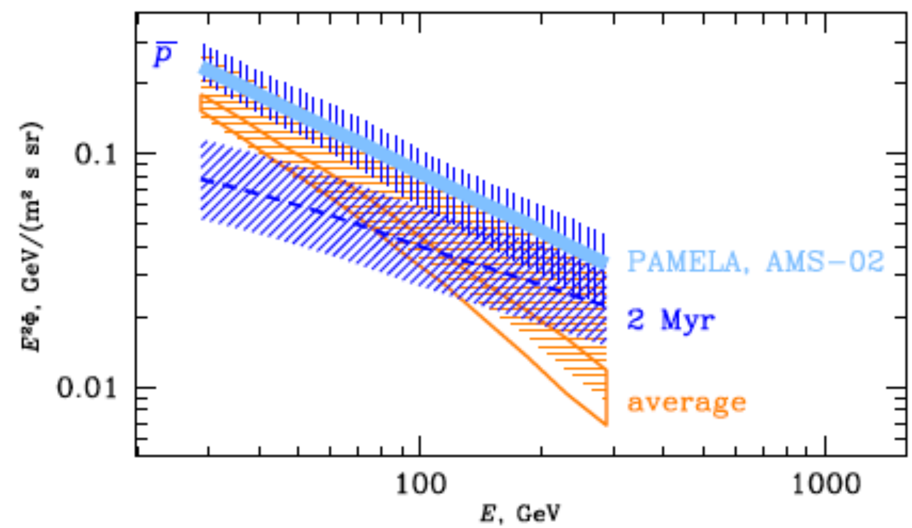
Positron flux PAMELA/AMS-II



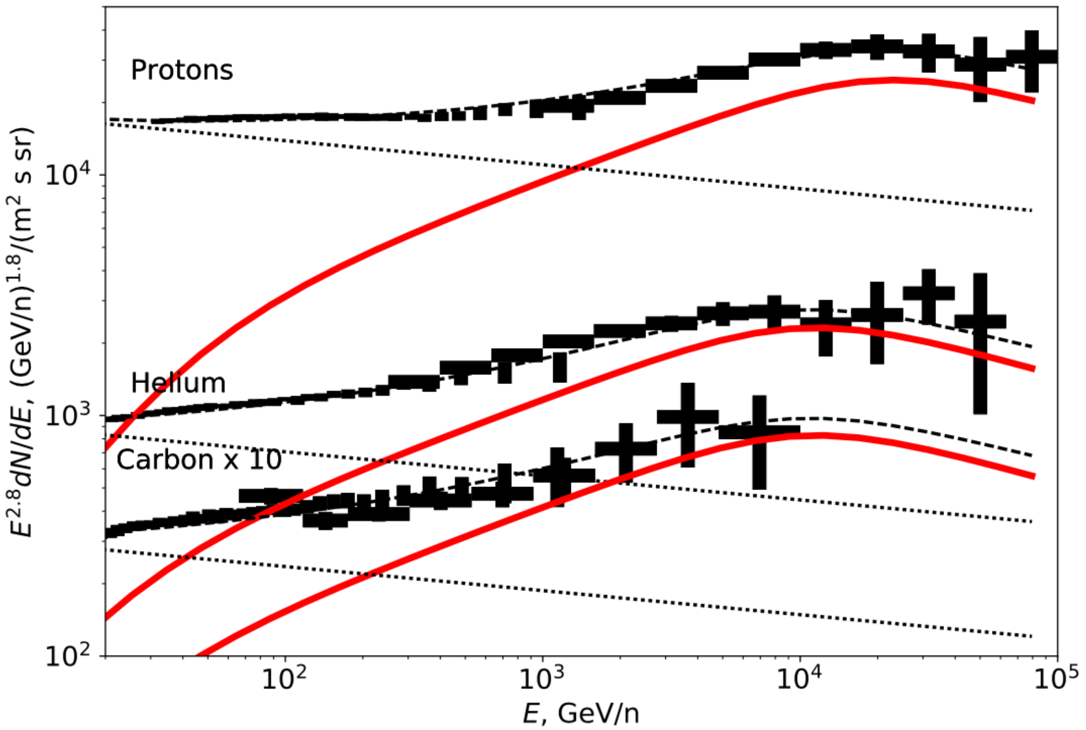
Kachelriess et al. '15

Antriprotons



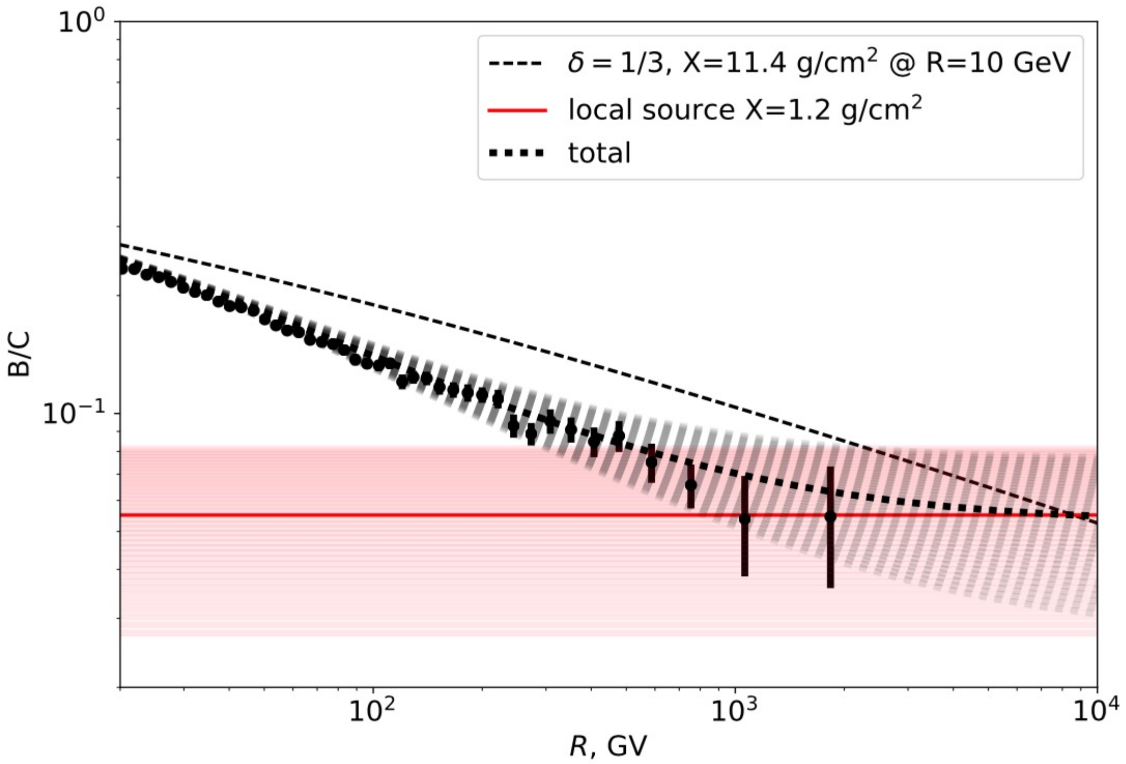


Nuclei



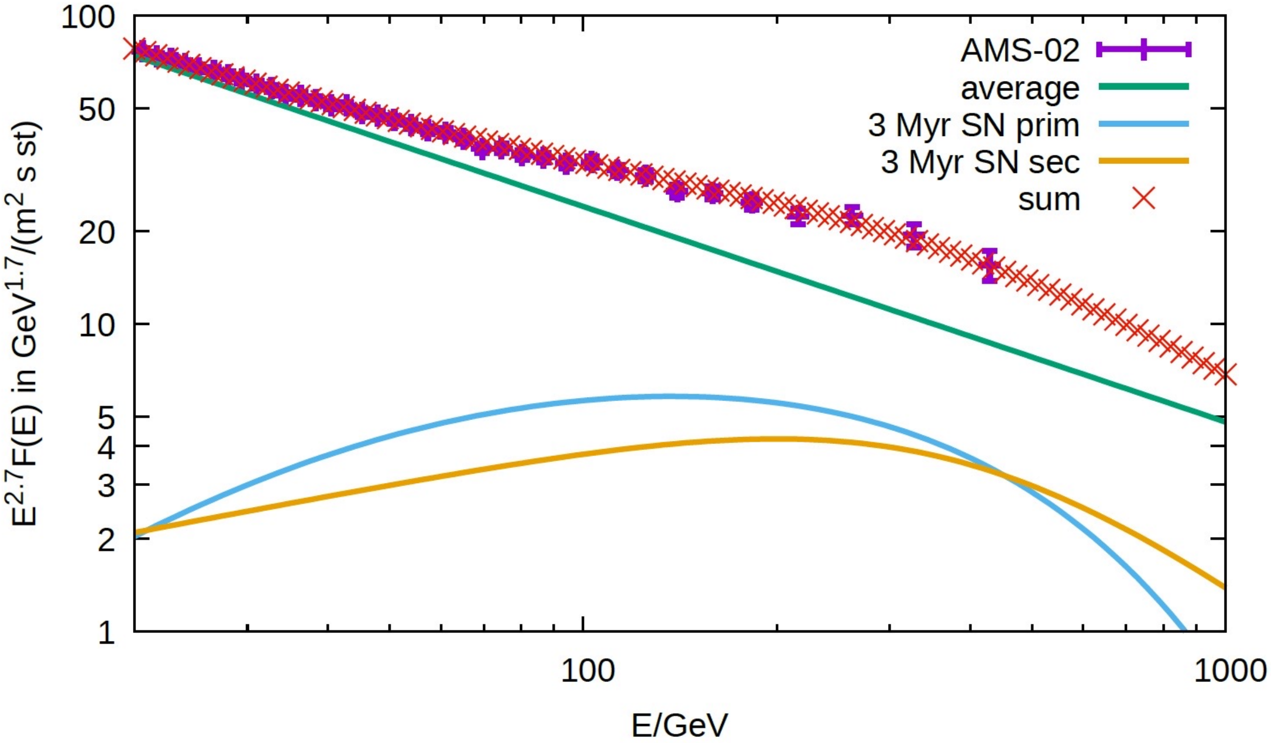
- Ratio of nuclei fluxes at TeV energies differs from one at GeV
- 2 Myr SN solve problem (M.Kachelriess, A.Neronov and D.S. 1710.02321)

Prediction: plateau in B/C



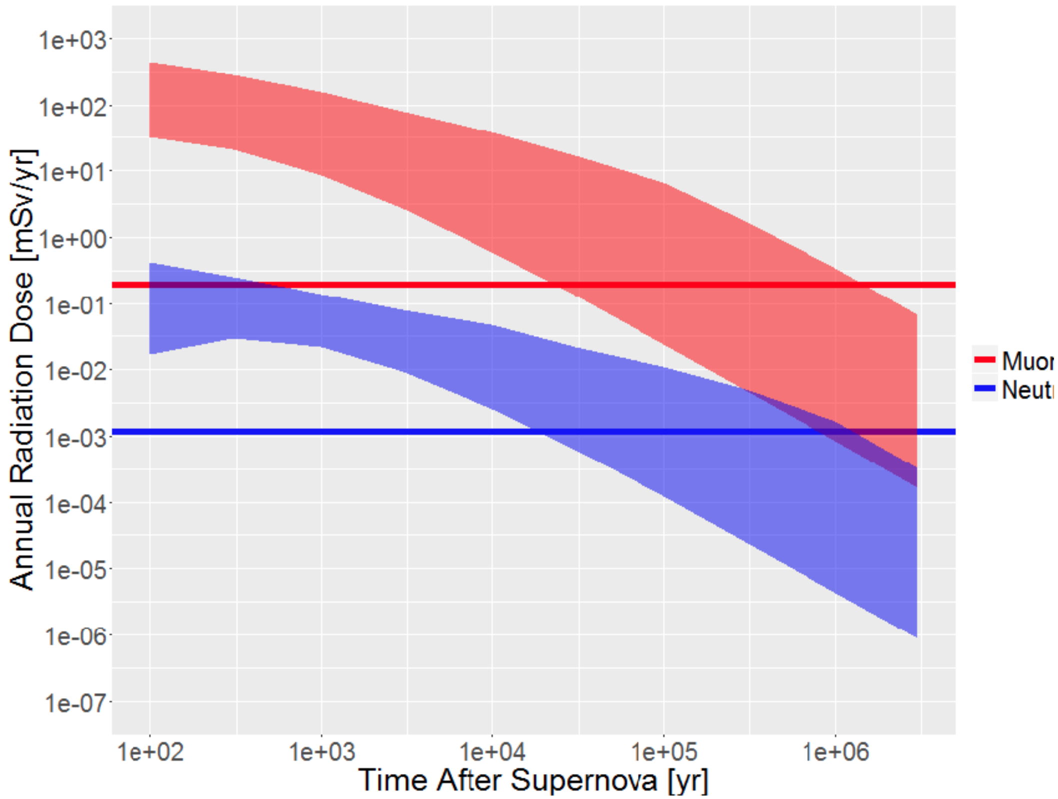
- M.Kachelriess, A.Neronov and D.S., 1710.02321

Electron spectrum



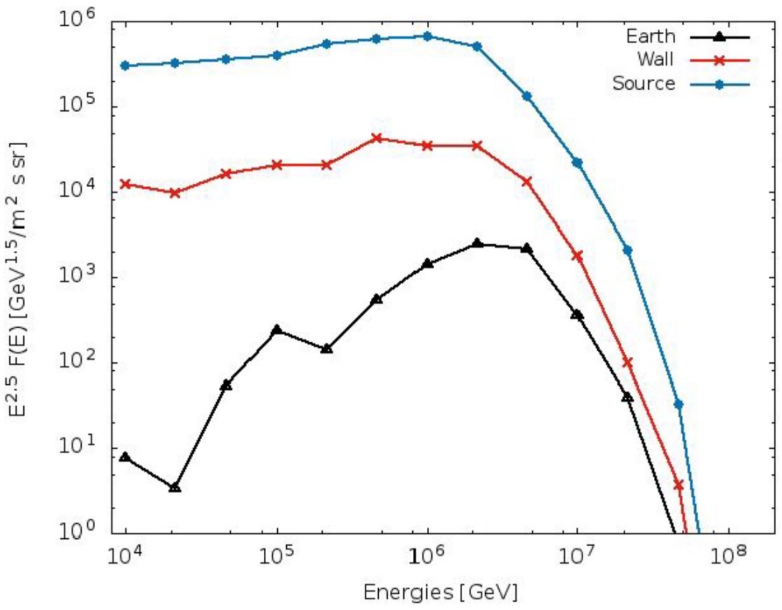
- M.Kachelriess, A.Neronov and D.S., 1710.02321

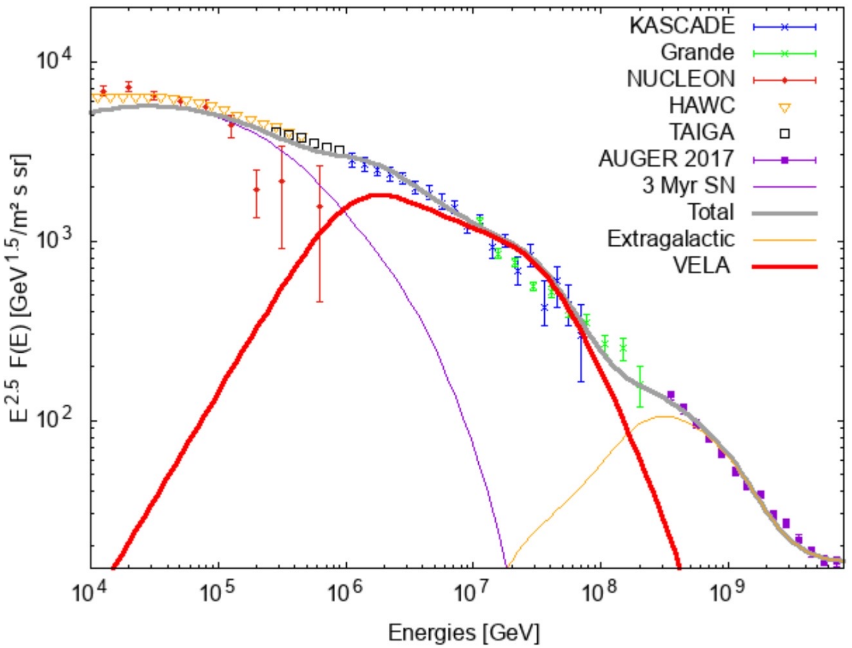
Radiation at Earth from local SN



•Melott et al 1702.0436

Spectrum in presence of Local bubble





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

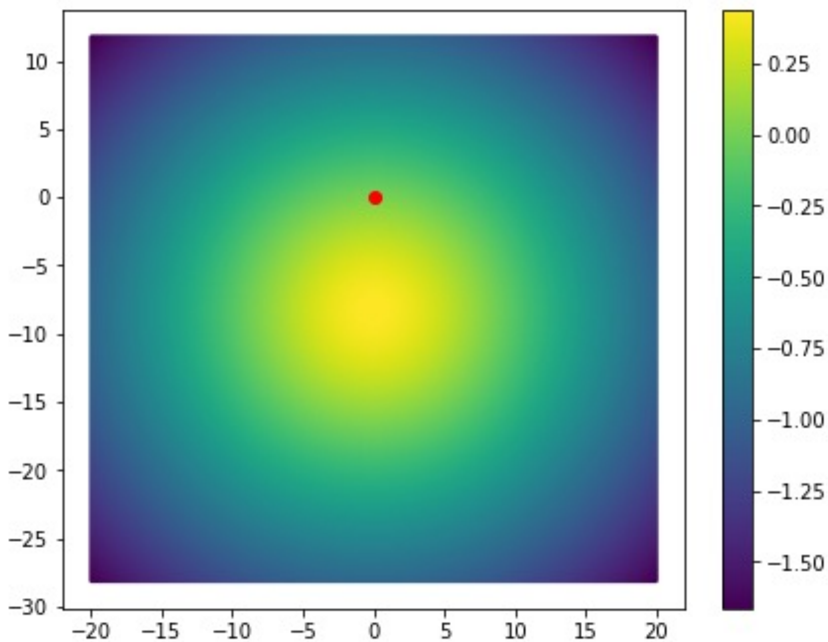
Conclusions

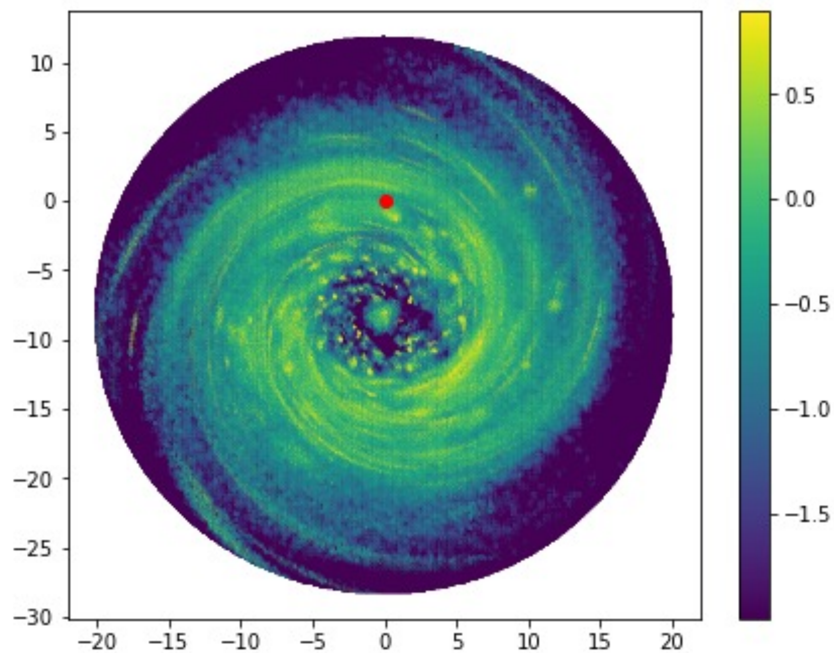
- *Assumption that spectrum of cosmic rays is the same for all galaxy does not work. Spectrum is 1/E^2.4 consistent with acceleration and Kolmogorov turbulence.*
- *Steady state regime for cosmic rays locally breakes at 20 GeV*
- *Above this energy contributions of individual sources are important*

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*

PeV Cosmic rays in Galaxy





• G.Giacinti, S.Koldobsky, A.Neronov and D.S., 2023

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

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

$$p + \gamma_{\rm CMB} \rightarrow N + \text{pions}$$

Nuclei

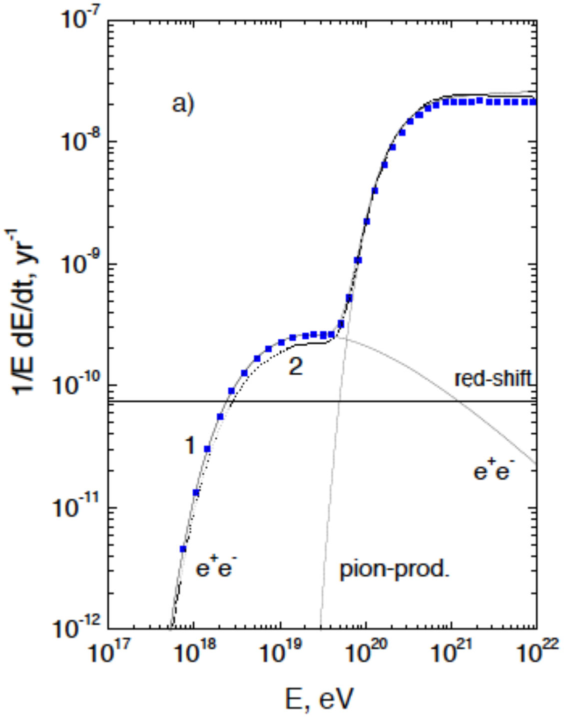
$$Z + \gamma_{\rm CMB} \rightarrow Z + e^+ + e^-$$

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

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

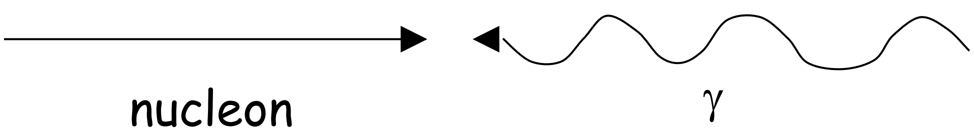
Photons

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

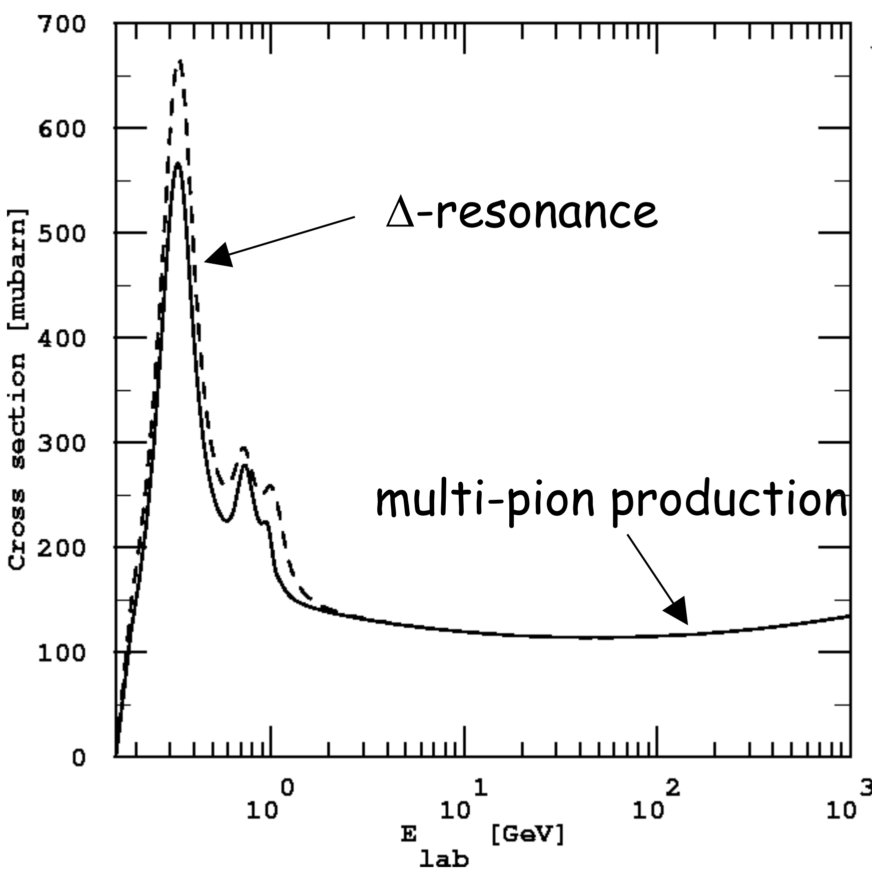


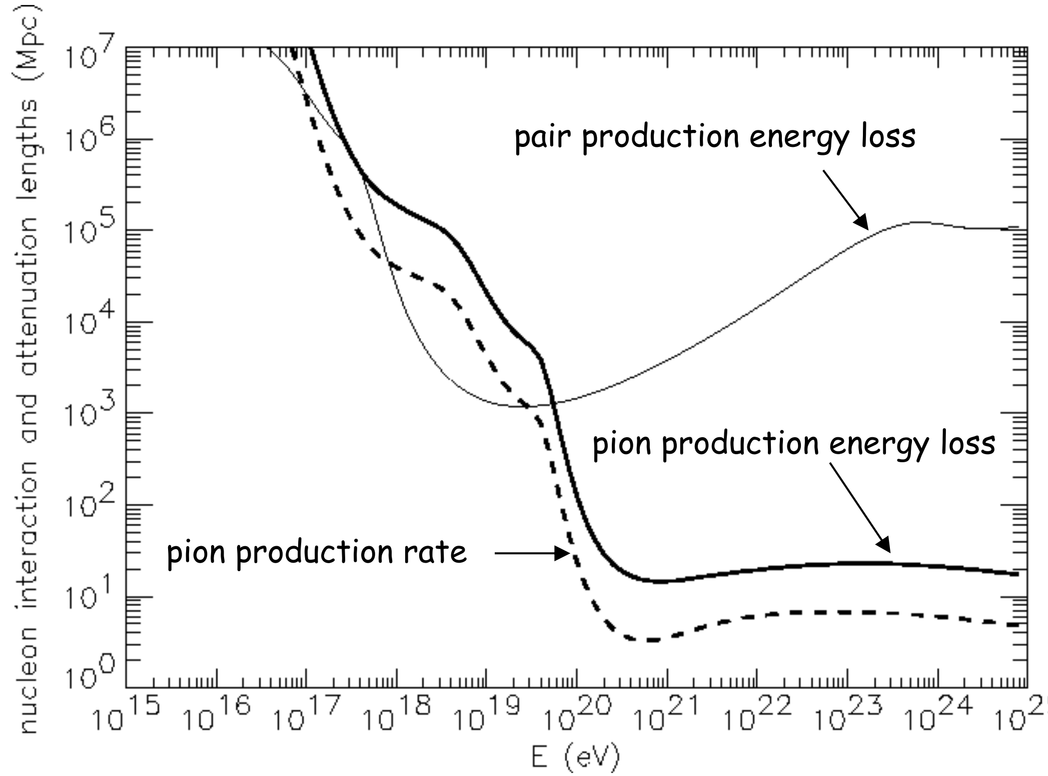
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



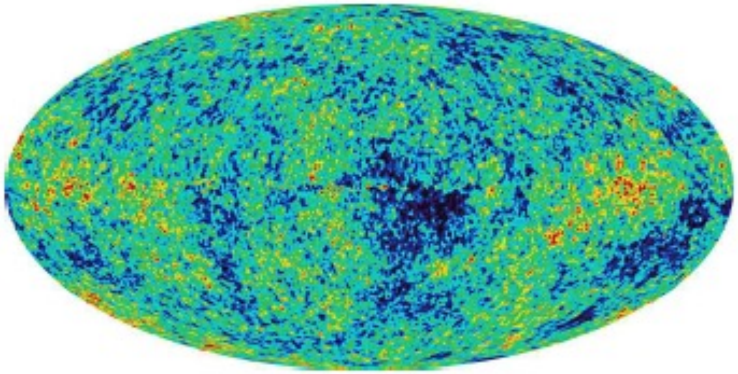
$$E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 6 \cdot 10^{19}\,\mathrm{eV}$$

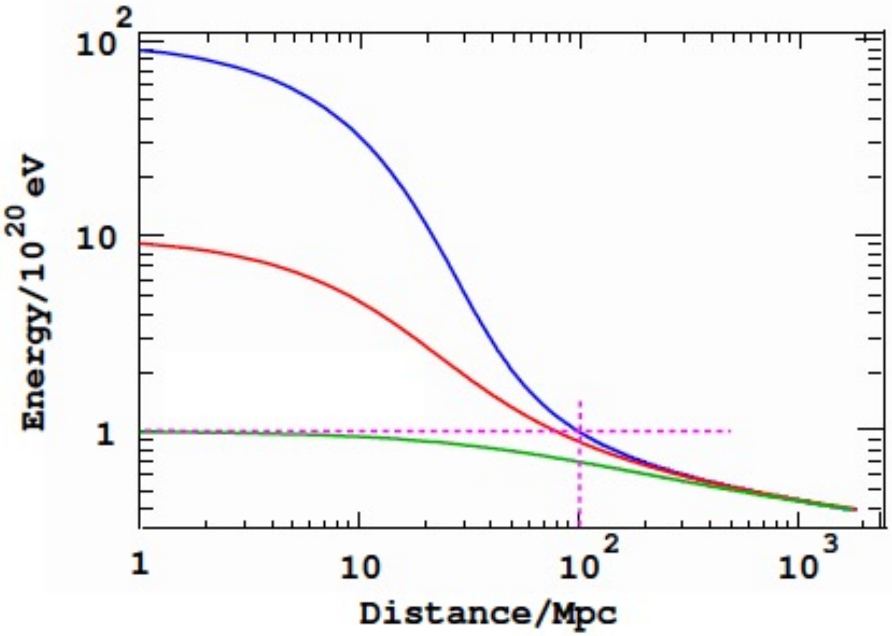




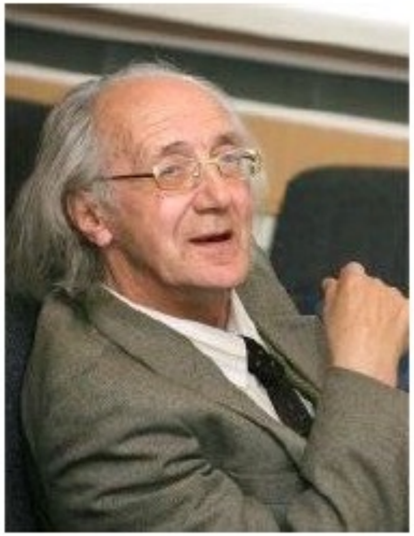
⇒sources must be in cosmological backyard within 50-100 Mpc from Earth (compare to the Universe size ~ 5000 Mpc)

Greisen-Zatsepin-Kuzmin Effect

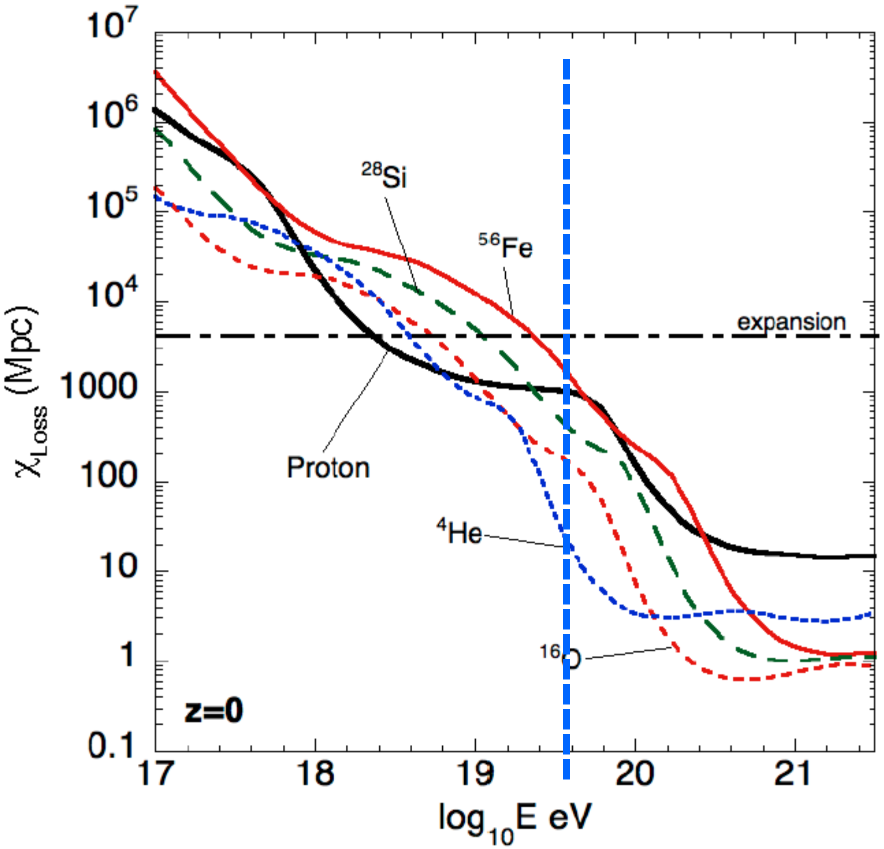




$$p + \gamma_{\rm CMB} \rightarrow N + \pi$$

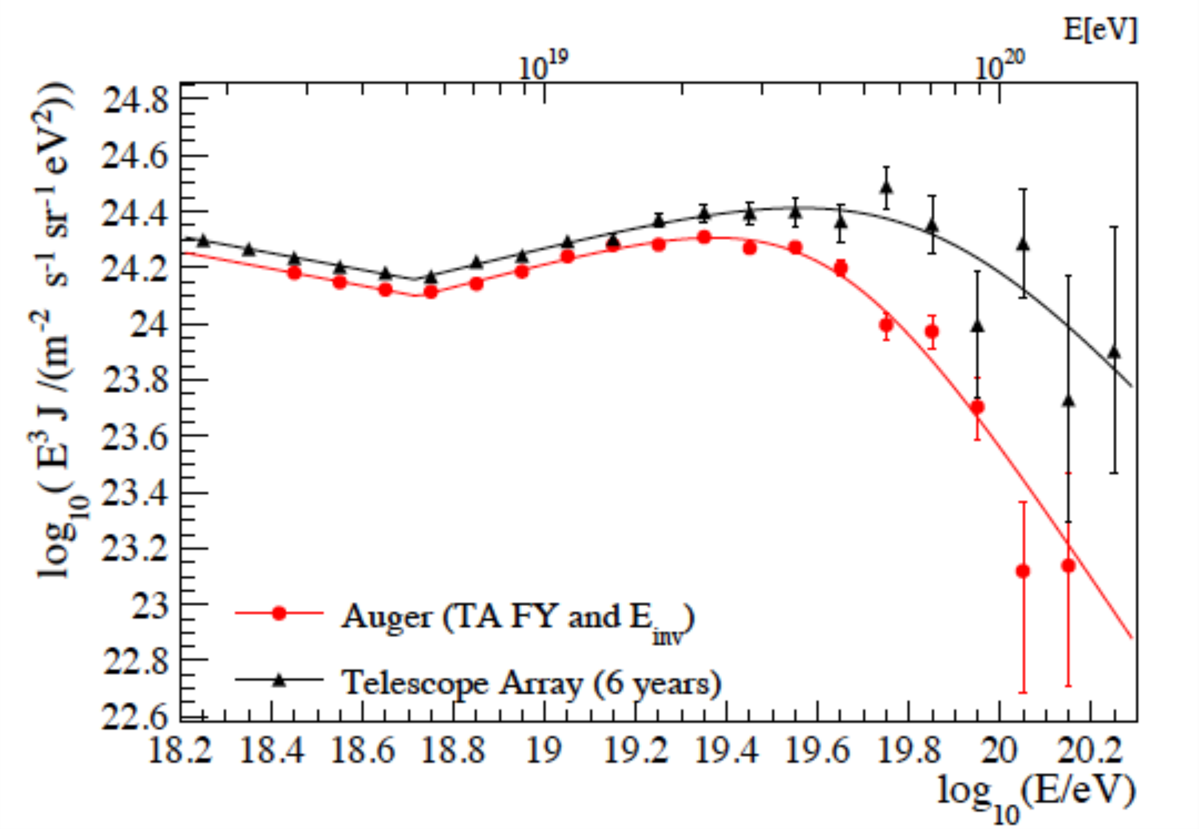


Same true for heavy nuclei: IR background is important



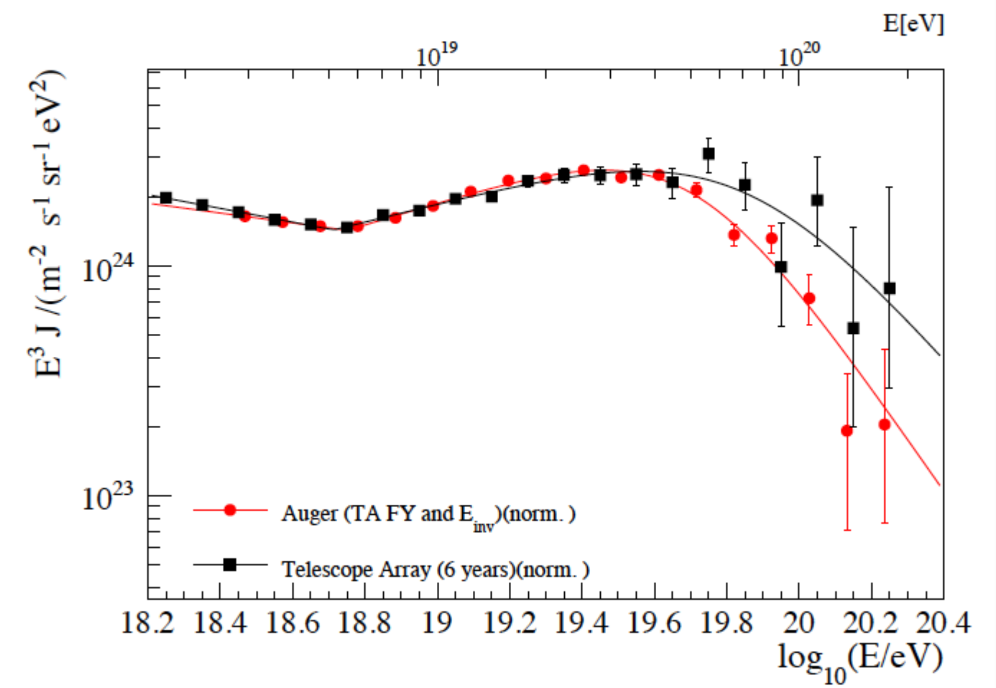
D.Allard, **arXiv:1111.3290**

Auger/TA Energy Spectrum



UHECR 2014

Auger/TA Energy Spectrum

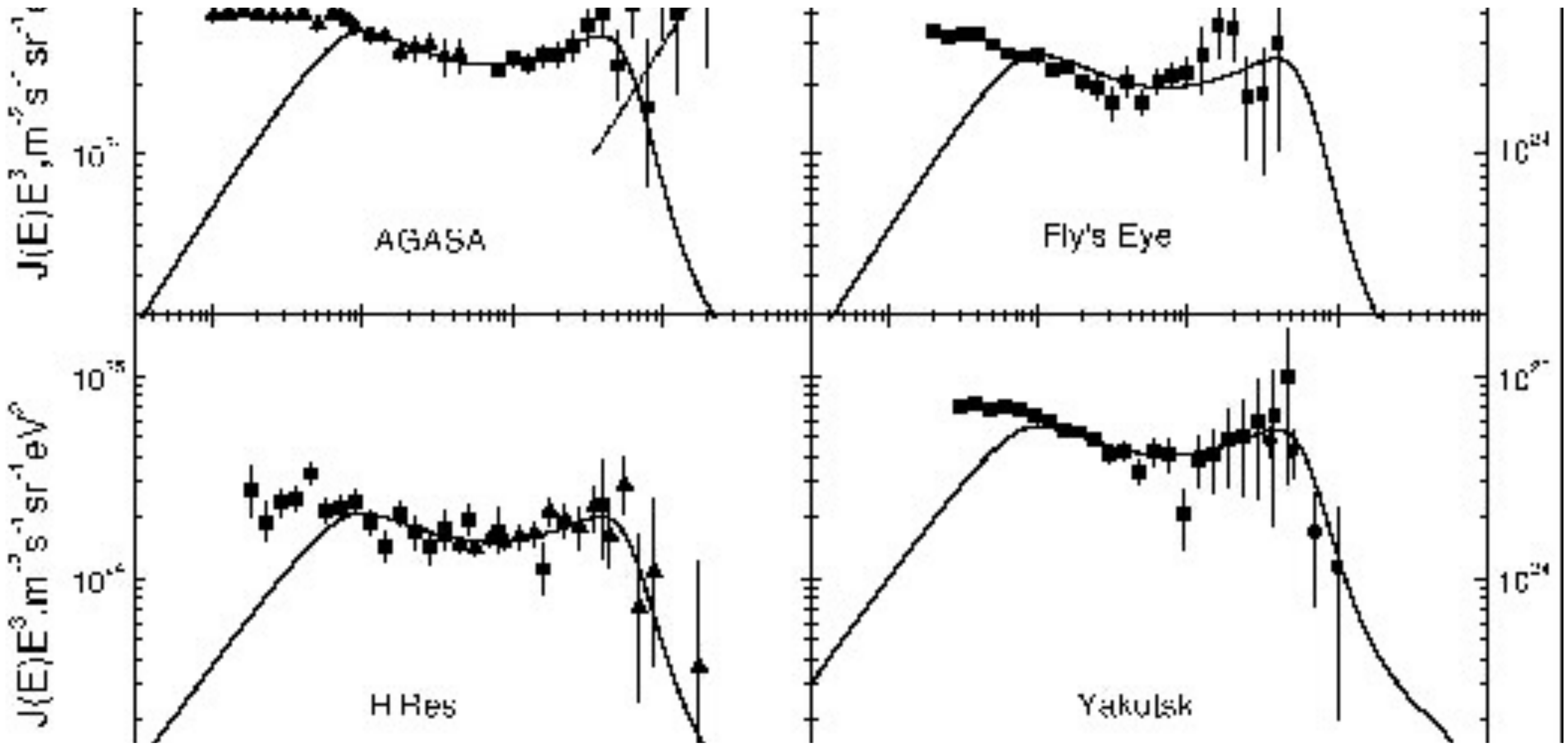


$\lg(E) = a + b \cdot \lg(E)$, $\chi^2/\mathrm{ndof} = 0.75(\mathrm{Prob} = 0.85)$

UHECR 2014

Theoretical models and composition at highest energies

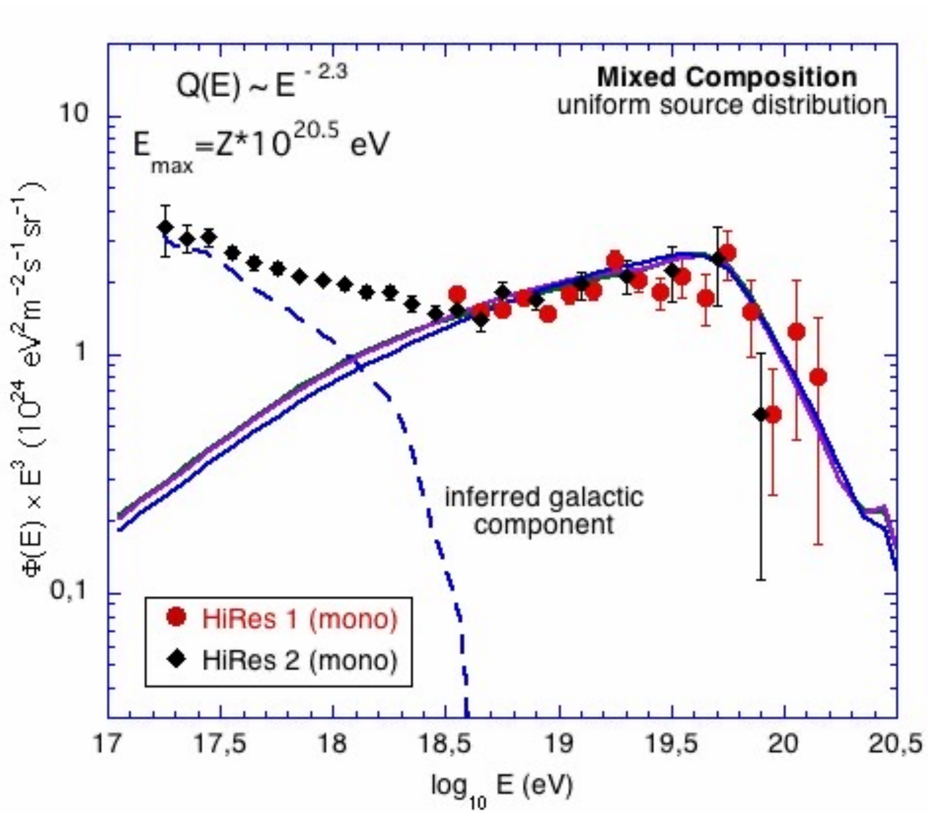
Protons can fit UHECR data



V.Berezinsky , astro-ph/0509069

problem: composition

Mixed composition model

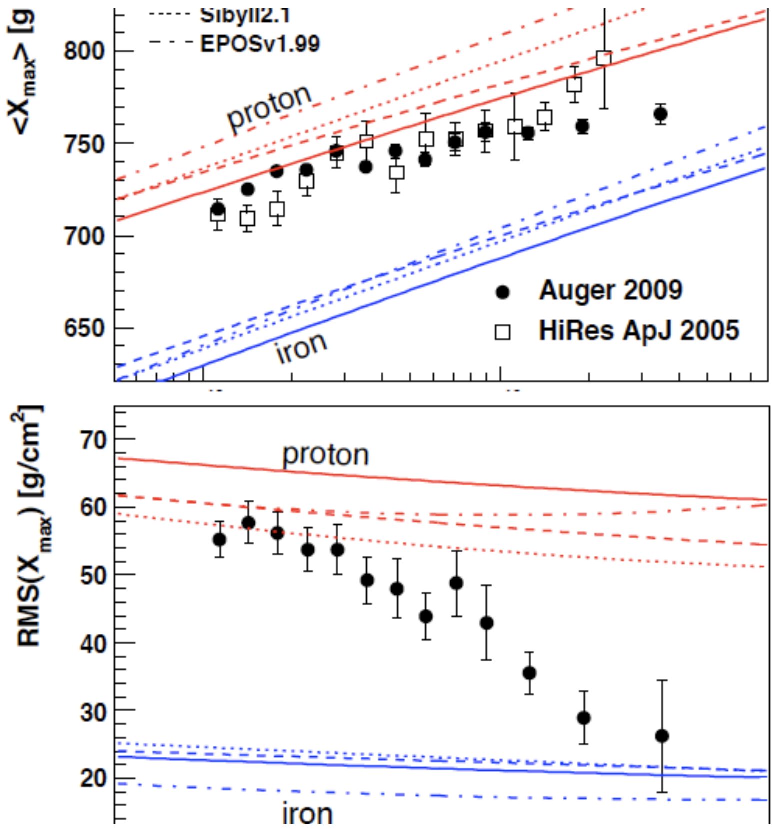


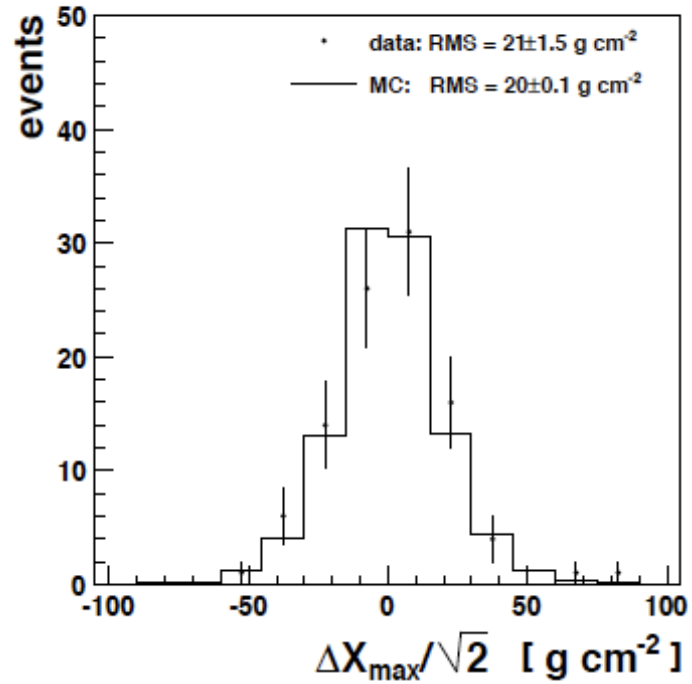
D.Allard, E.Parizot and A.Olinto, astro-ph/0512345

Problems: 1) escape of the nuclei from the source

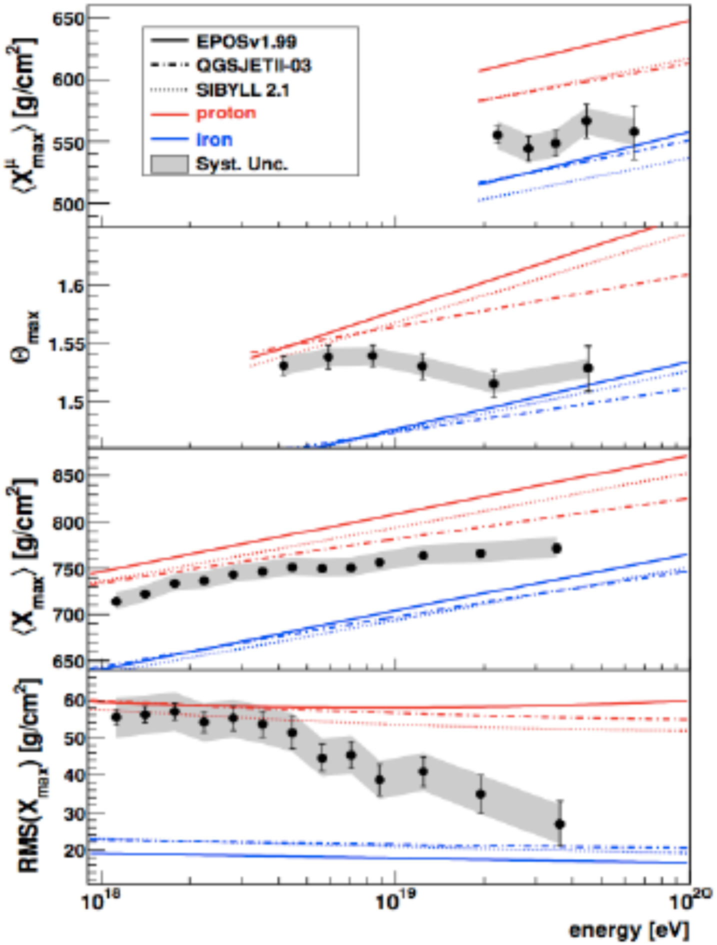
2) How to accelerate Fe in our Galaxy

Auger composition 2009: nuclei!



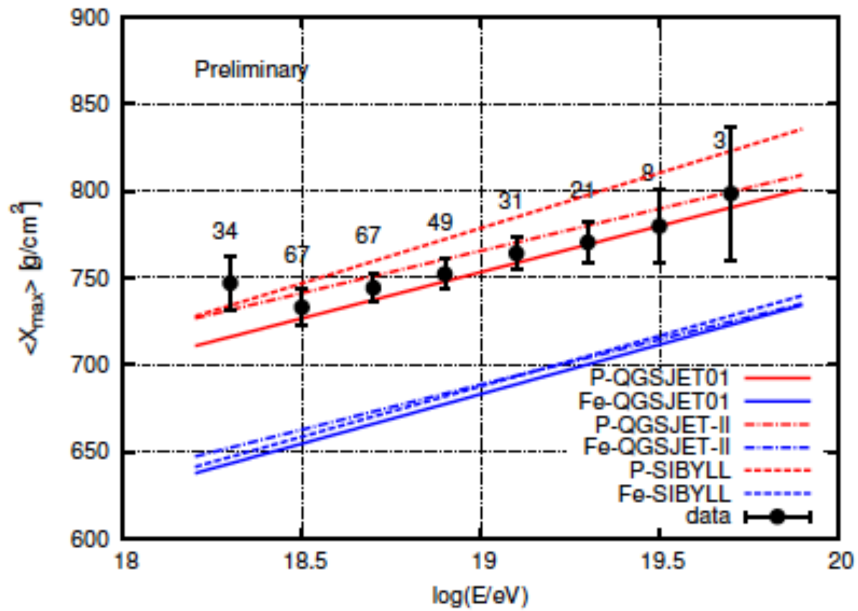


PAO - heavy nuclei

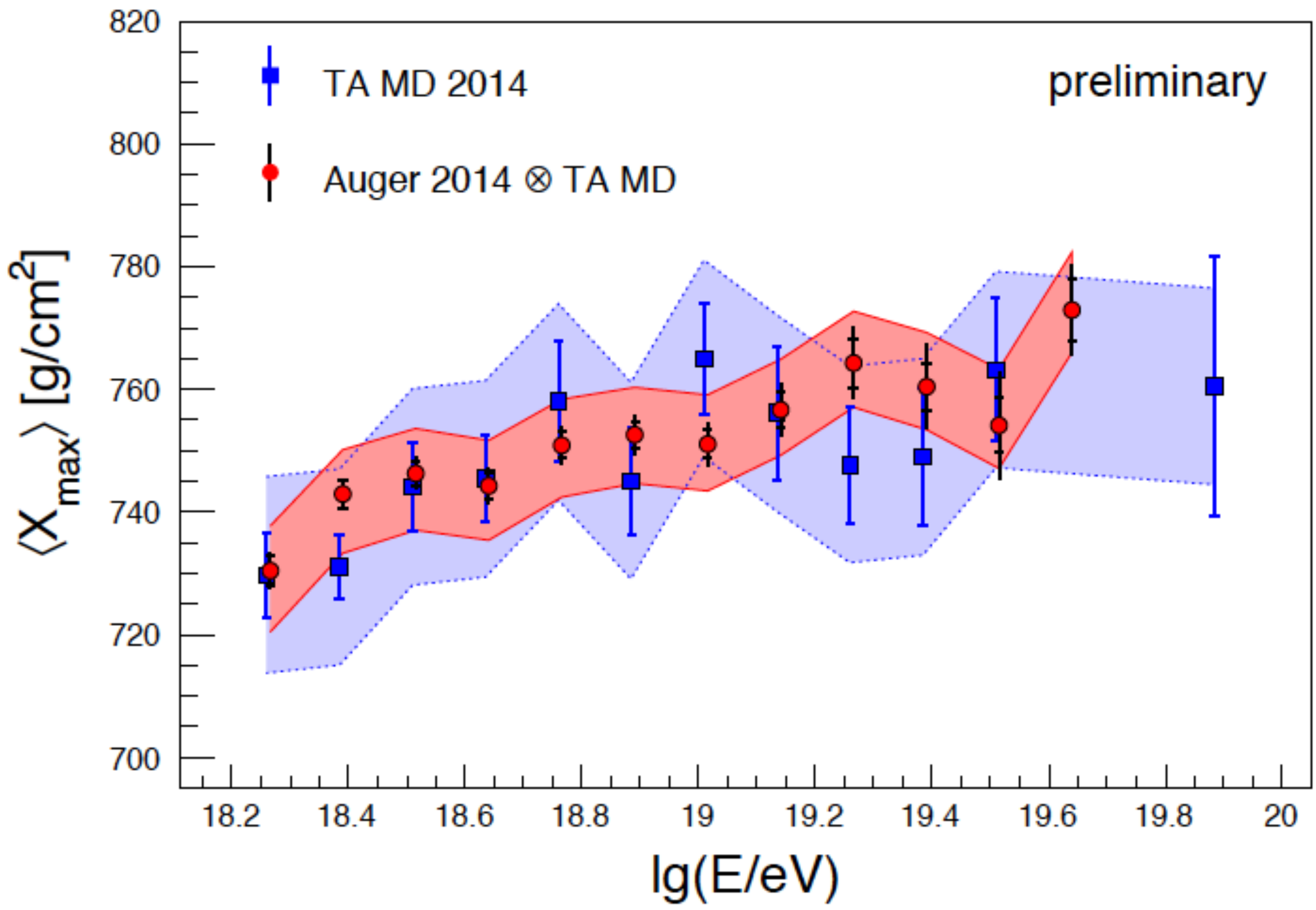


H. Wahlberg (PAO, this conference)

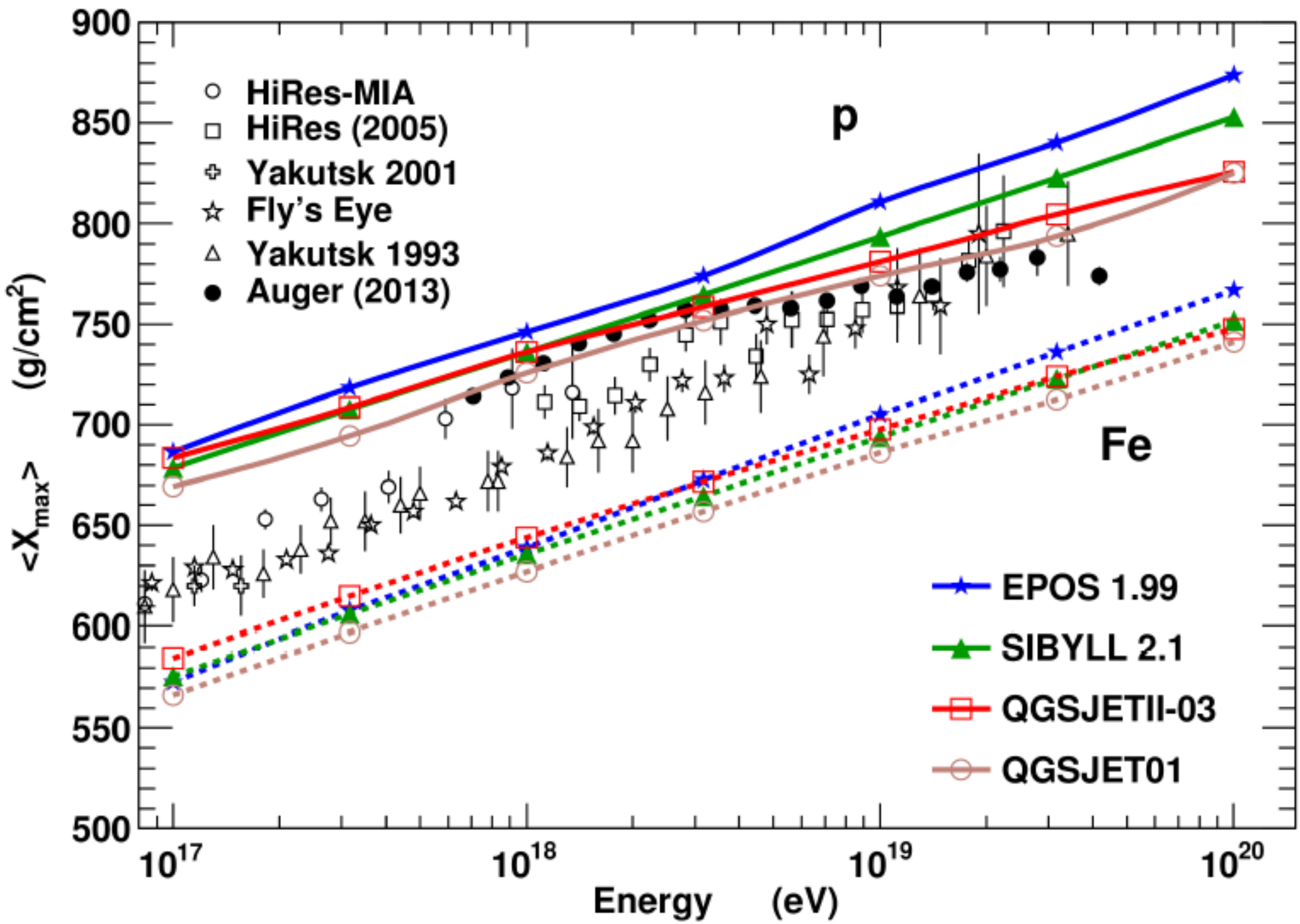
TA- protons



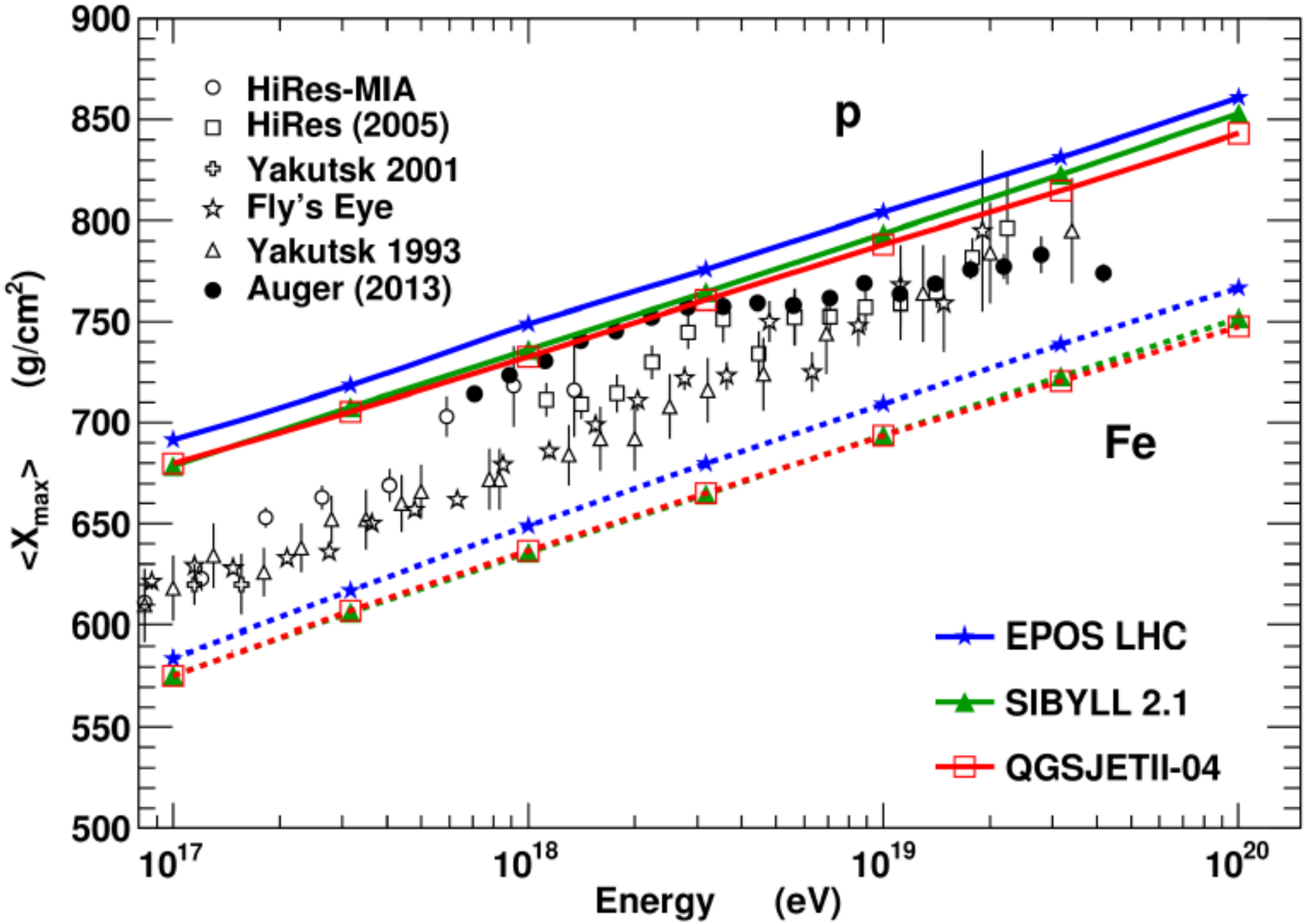
TA collaboration, 2010


TA MD 2014
Auger 2014 ⊗ TA MD
preliminary
⟨X_max⟩ [g/cm²]
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)

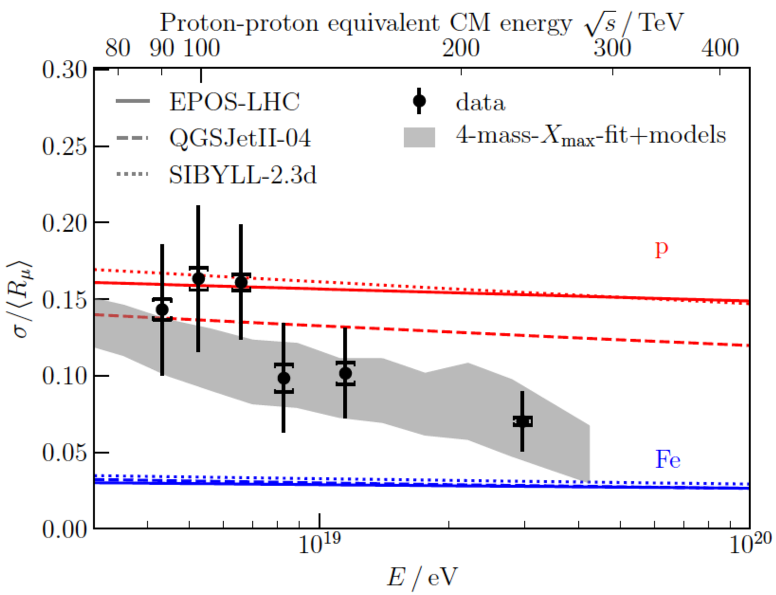
EAS with Old CR Models : X_{max}

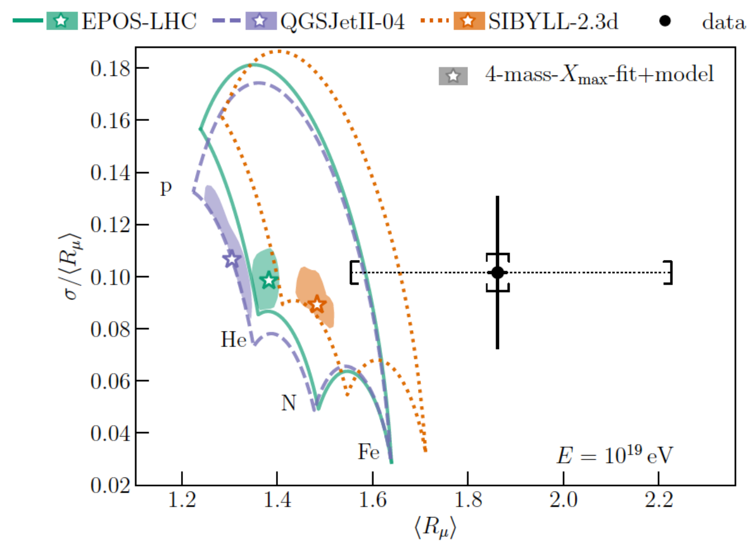


EAS with Re-tuned CR Models : X_{max}



Muon excess

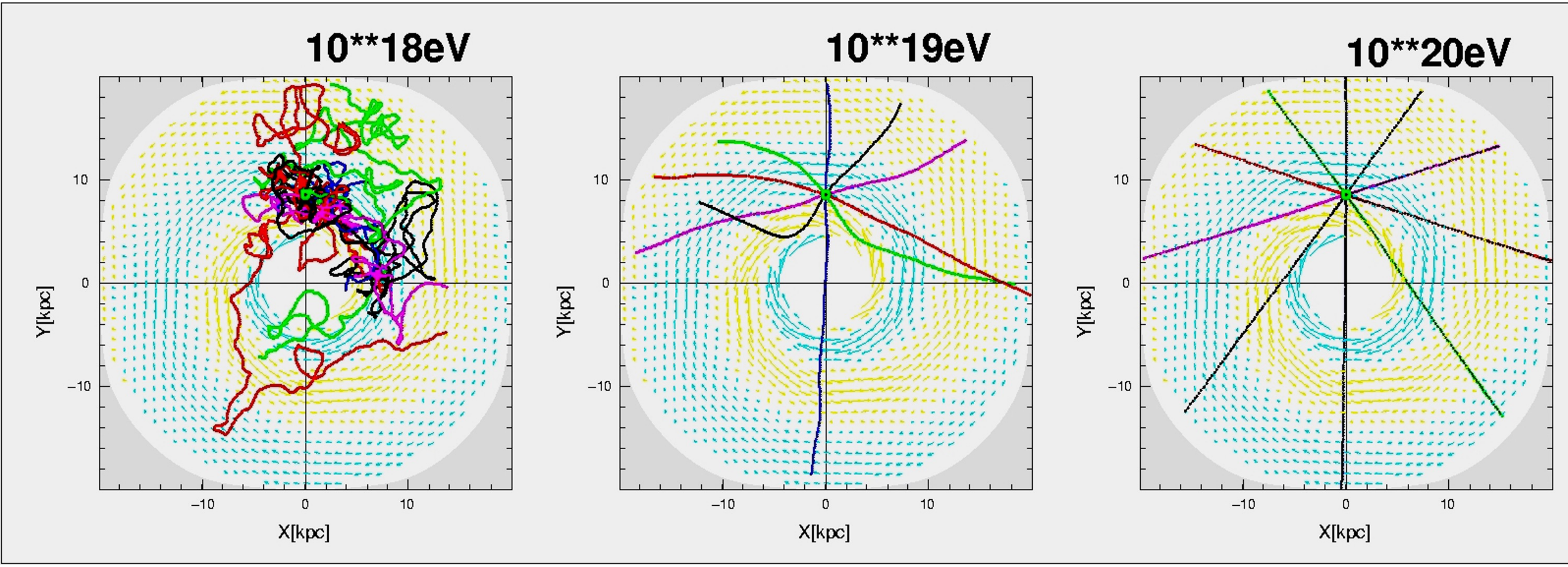

Proton-proton equivalent CM energy $\sqrt{s}$ / TeV
80 90 100
200
300
400
EPOS-LHC
QGSJetII-04
SIBYLL-2.3d
data
4-mass-X_{max}-fit+models
p
Fe
$\sigma / \langle R_\mu \rangle$
E / eV
10^{19}
10^{20}


EPOS-LHC
QGSJetII-04
SIBYLL-2.3d
data
4-mass-X_{max}-fit+model
p
He
N
Fe
$E = 10^{19}$ eV
$\sigma / \langle R_\mu \rangle$
$\langle R_\mu \rangle$

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

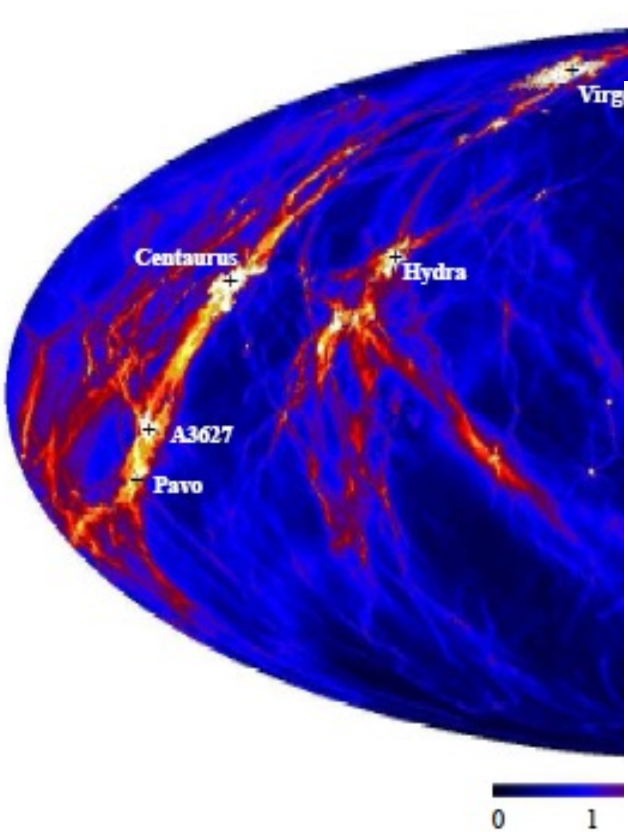


FIG. 1: Full sky map (area preserving projection) of d
scale. All structure within a radius of 107 Mpc aroun
with the galactic anti-center in the middle of the ma
corresponding halos in the simulation.

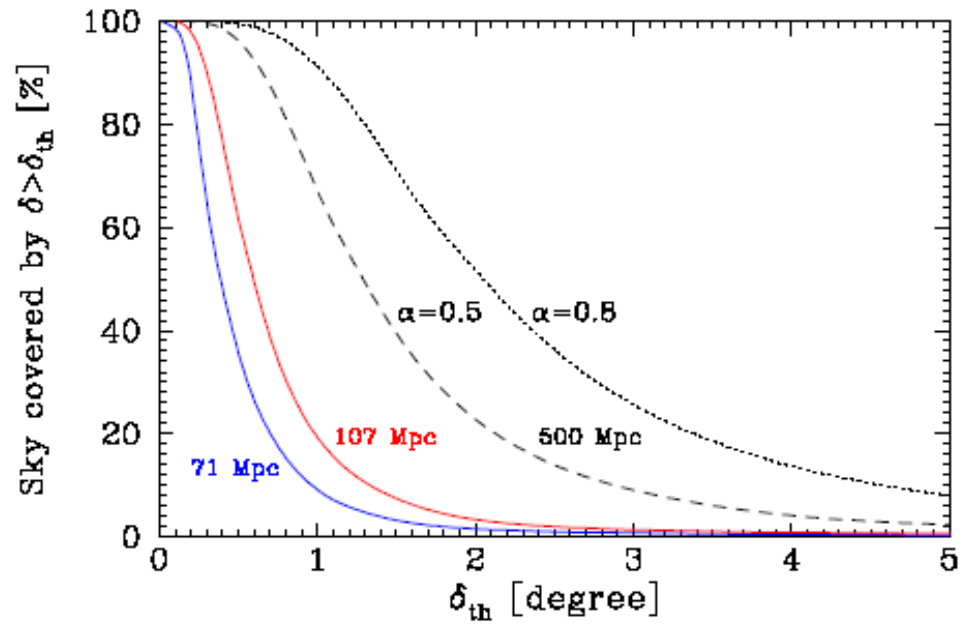
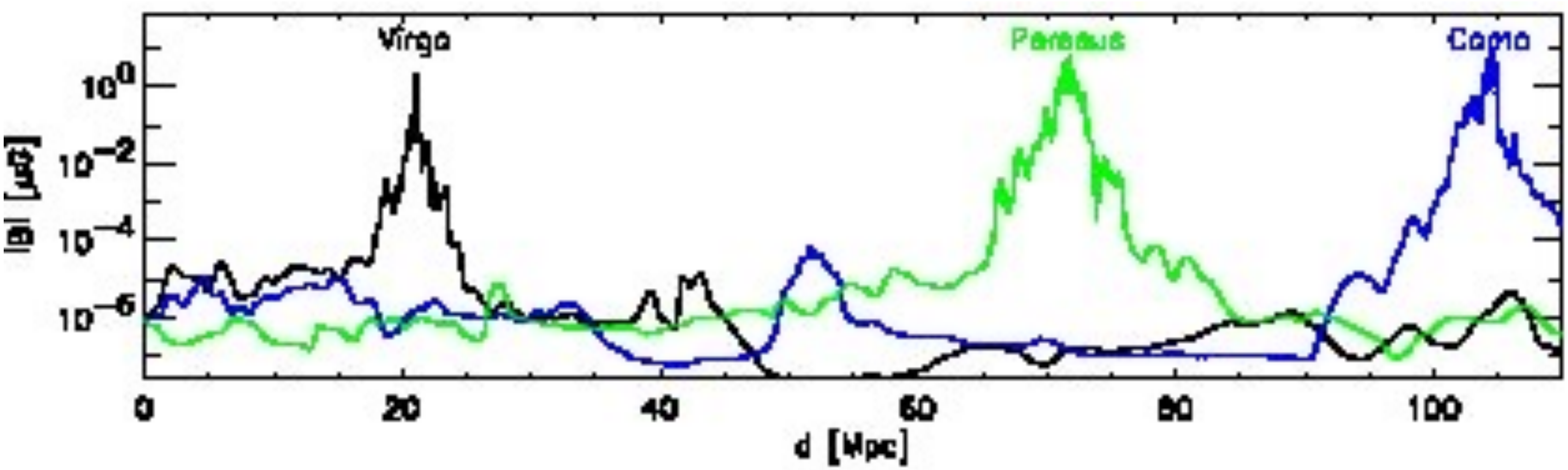


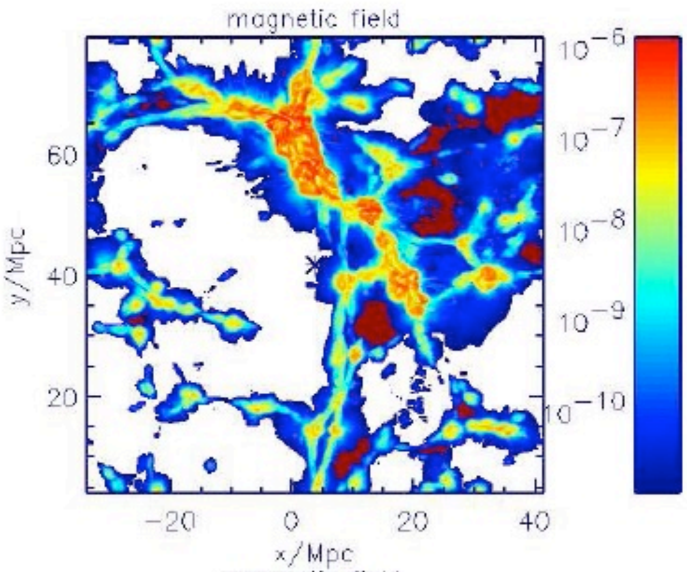
FIG. 2: Cumulative fraction of the sky with deflection angle larger than δ_{th}, for several values of propagation distance (solid lines). We also include an extrapolation to 500 Mpc, assuming self similarity with $\alpha = 0.5$ (dashed line) or $\alpha = 0.8$ (dotted line). The assumed UHECR energy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

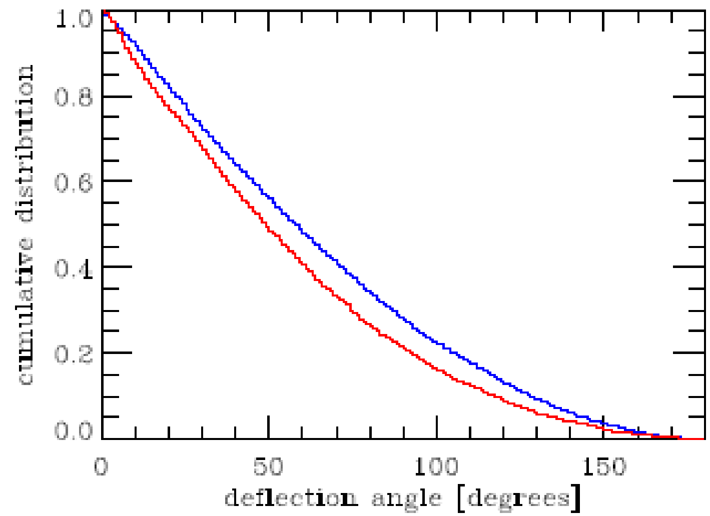
Magnetic field in several directions from Earth for constrained simulation

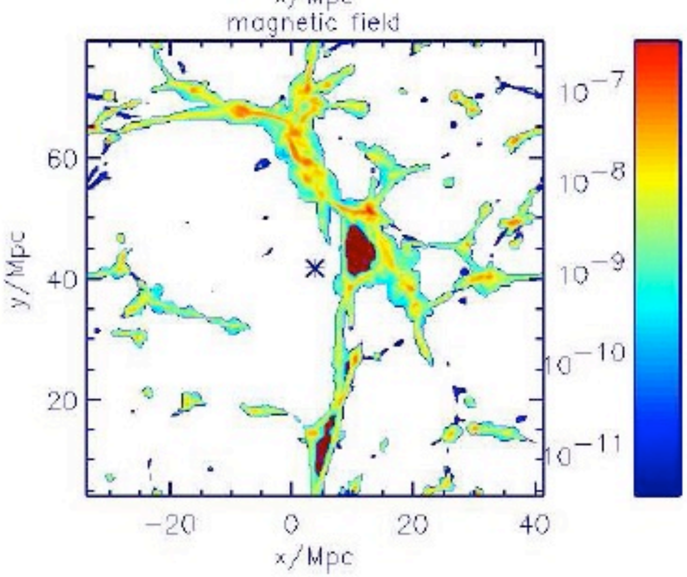


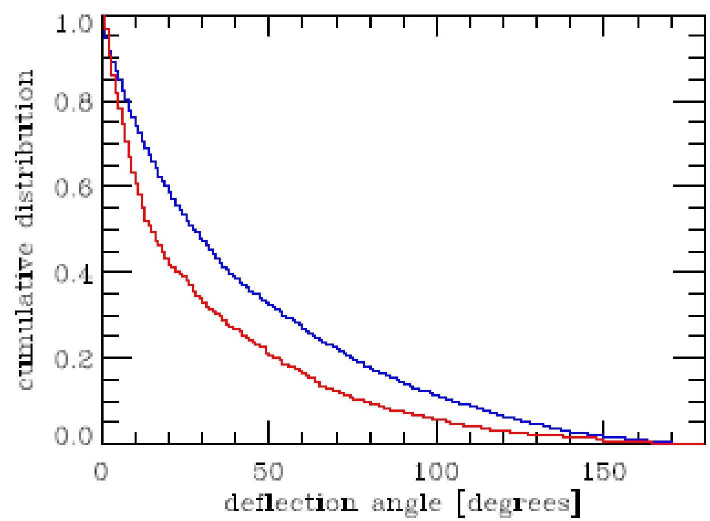
Dolag et al, astro-ph/0410419

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

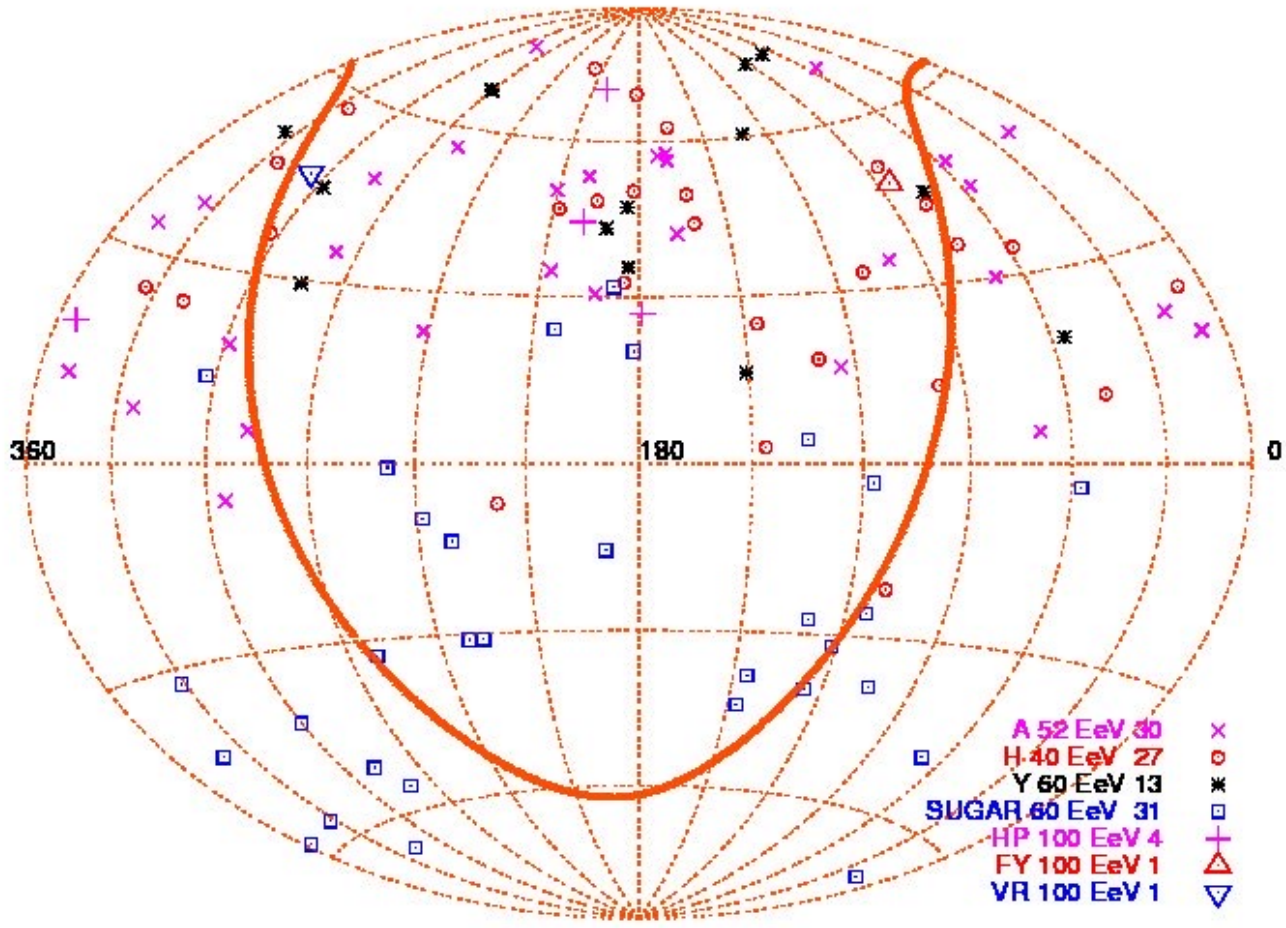




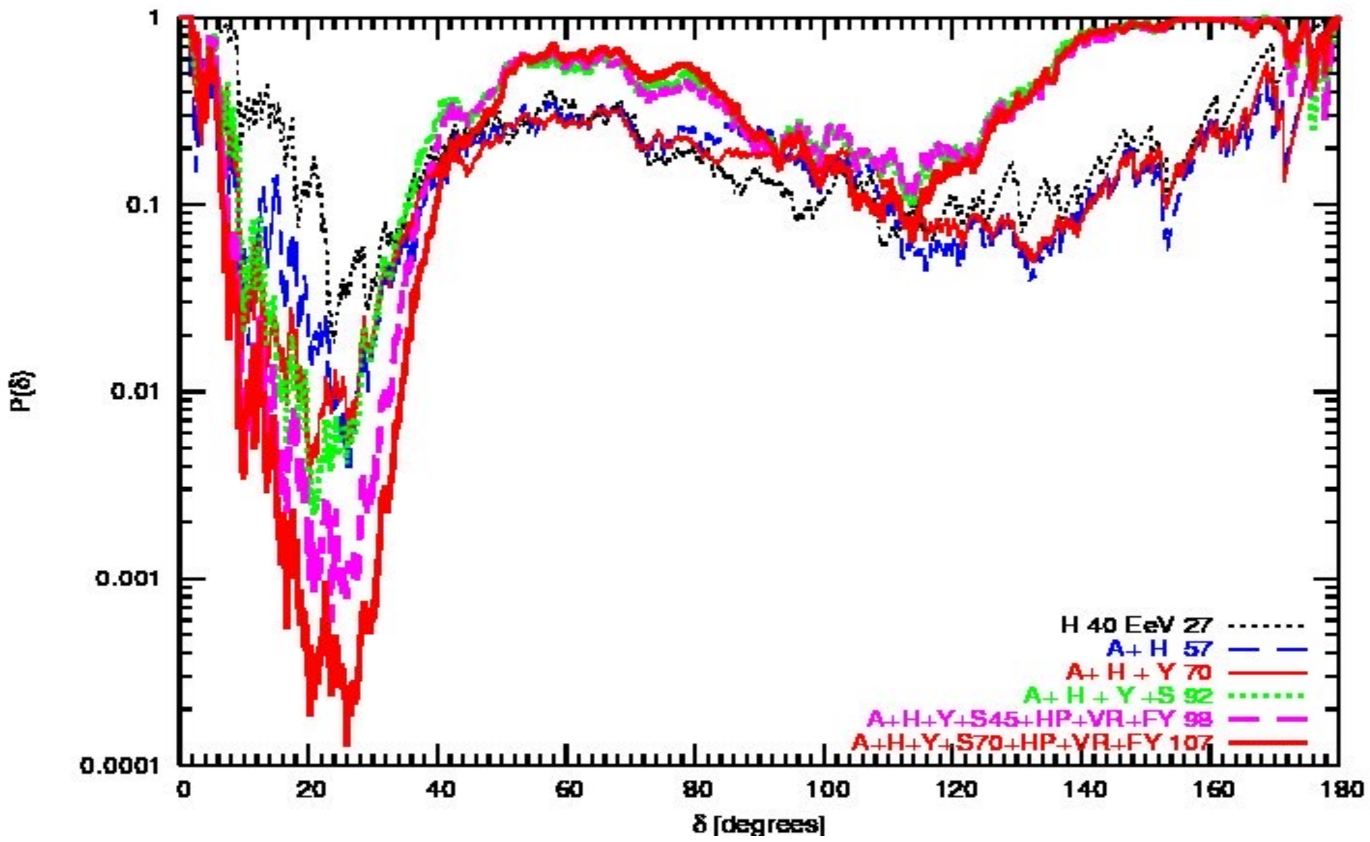




Arrival directions for E>40 EeV in HiRes (E>52 EeV in AGASA)



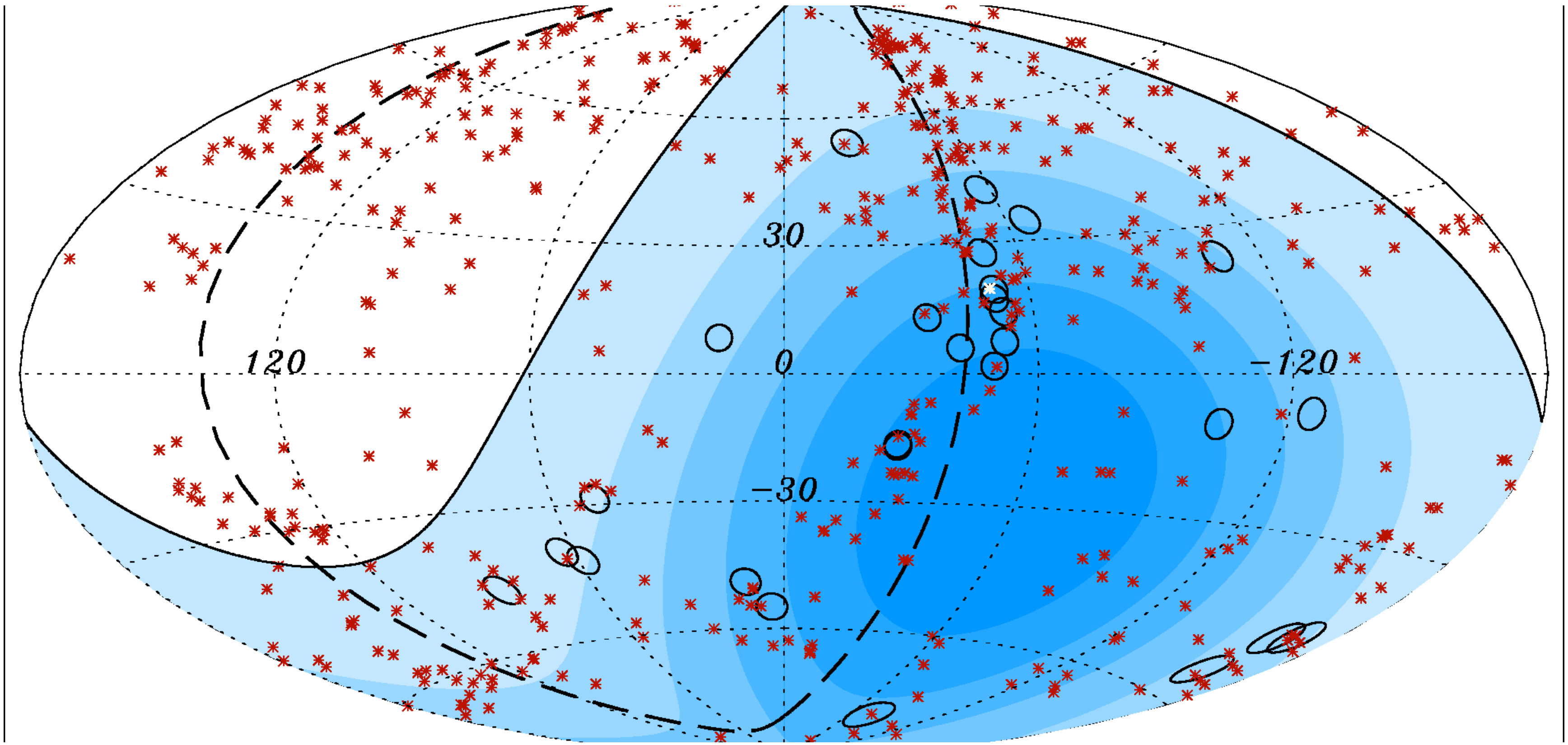
Probability of correlation



3 σ after penalty on angle

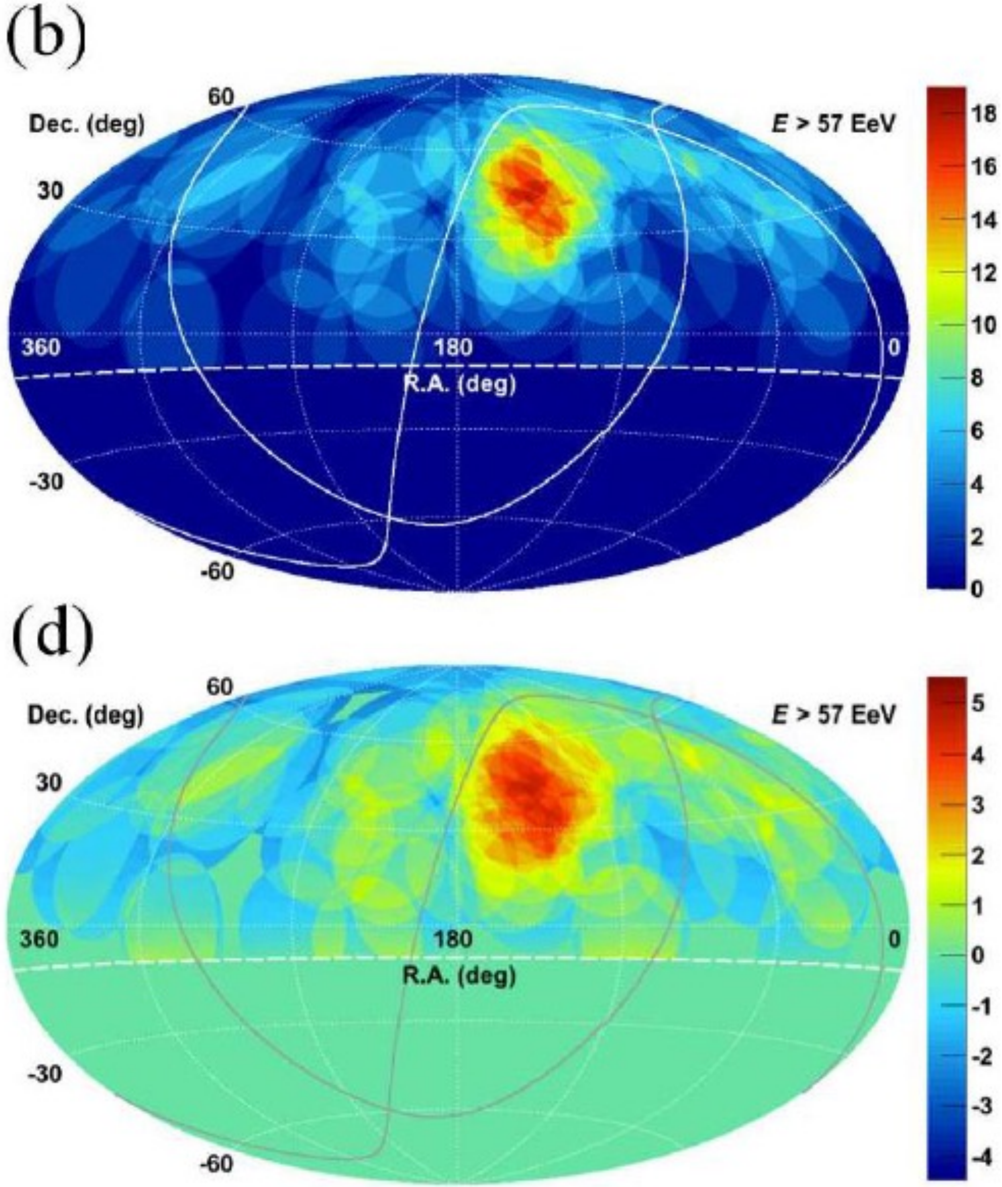
M.Kachelriess and D.S. astro-ph/0512498

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

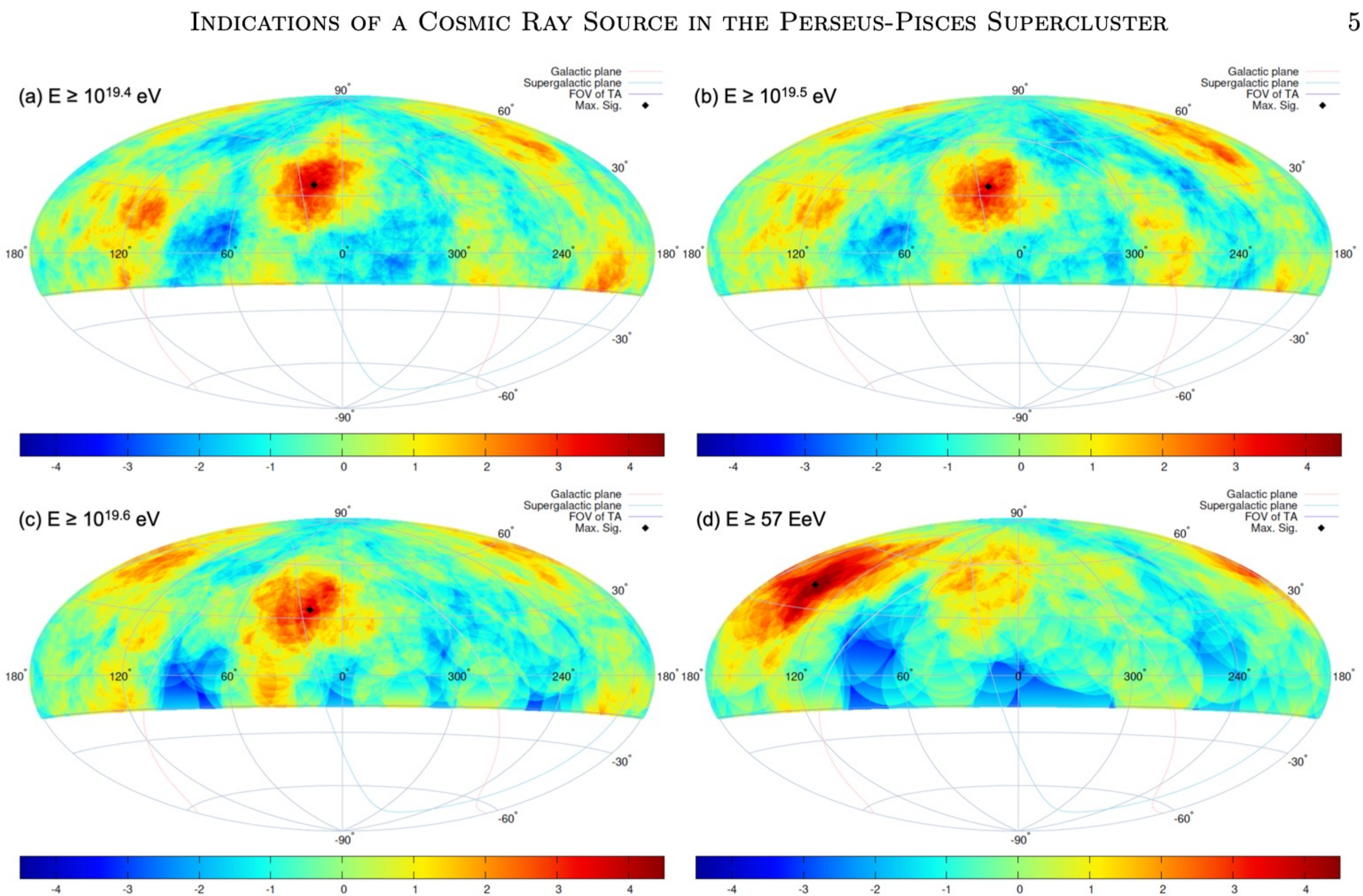
87 events > 57 EeV , < 60°

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]*



TA collaboration, 2110.14827

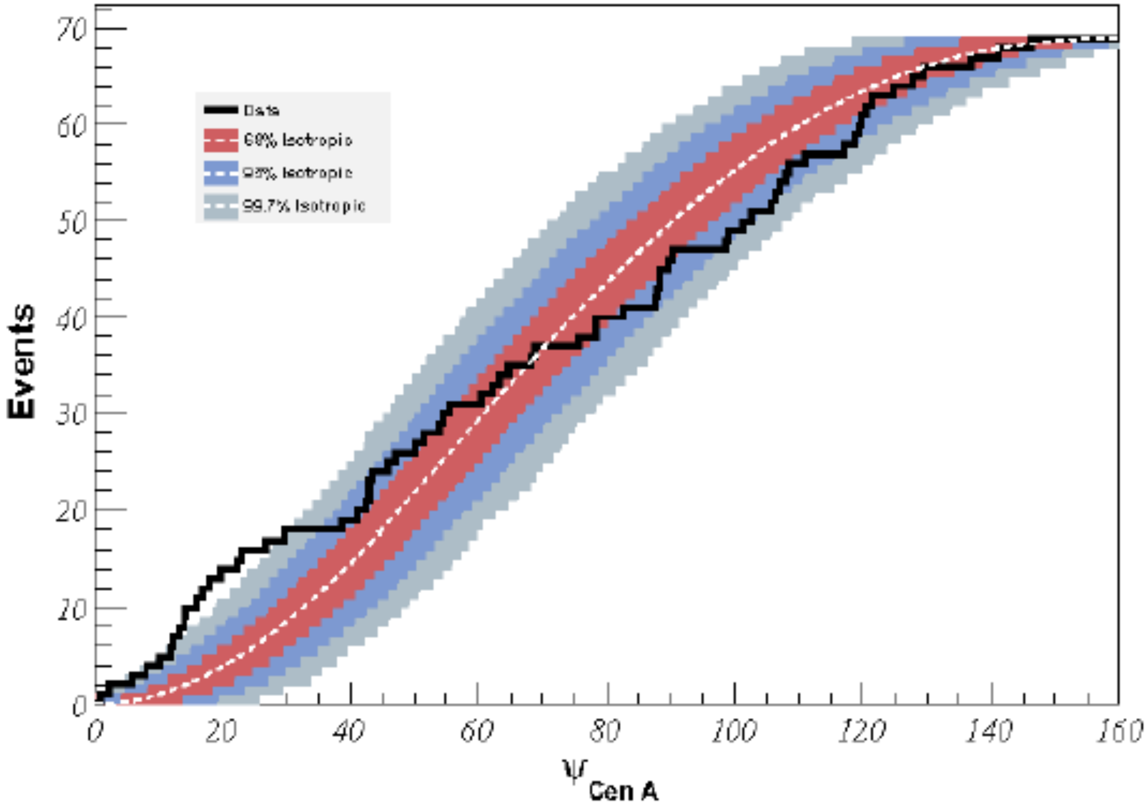


Fig. 9. Cumulative number of events with $E \geqslant 55$ EeV as a function of angular distance from the direction of Cen A. The bands correspond to the 68%, 95% and 99.7% dispersion expected for an isotropic flux.

Pierre Auger Observatory

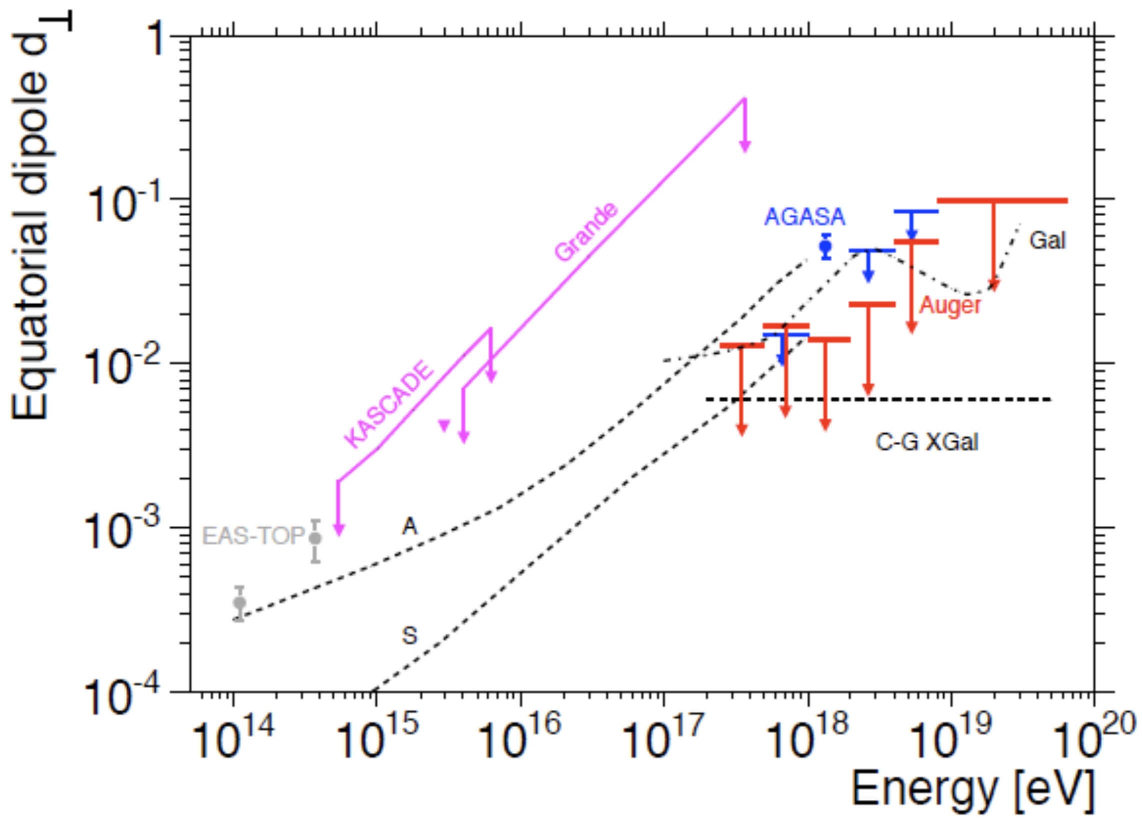
Events > 55 EeV

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

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

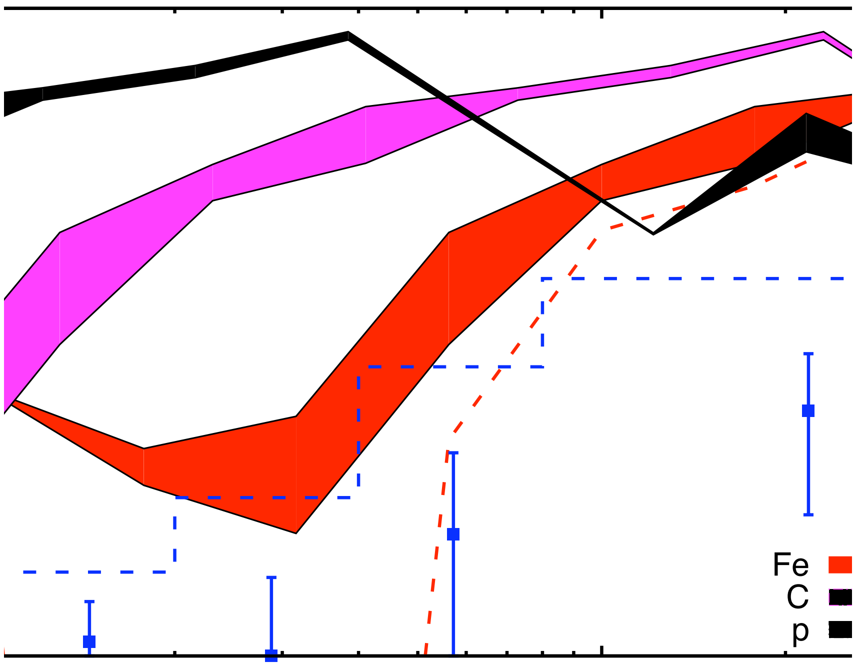
Transition from galactic to extragalactic cosmic rays

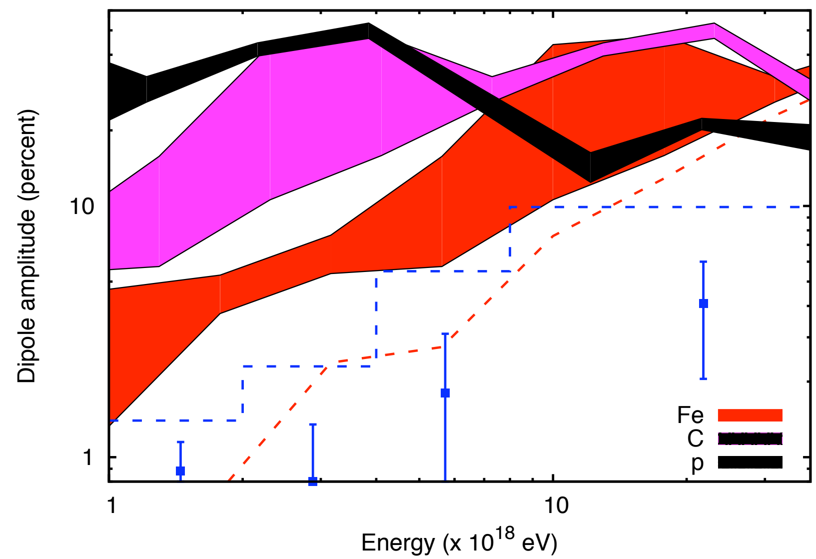
Anisotropy dipole



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

Dependence on parameters



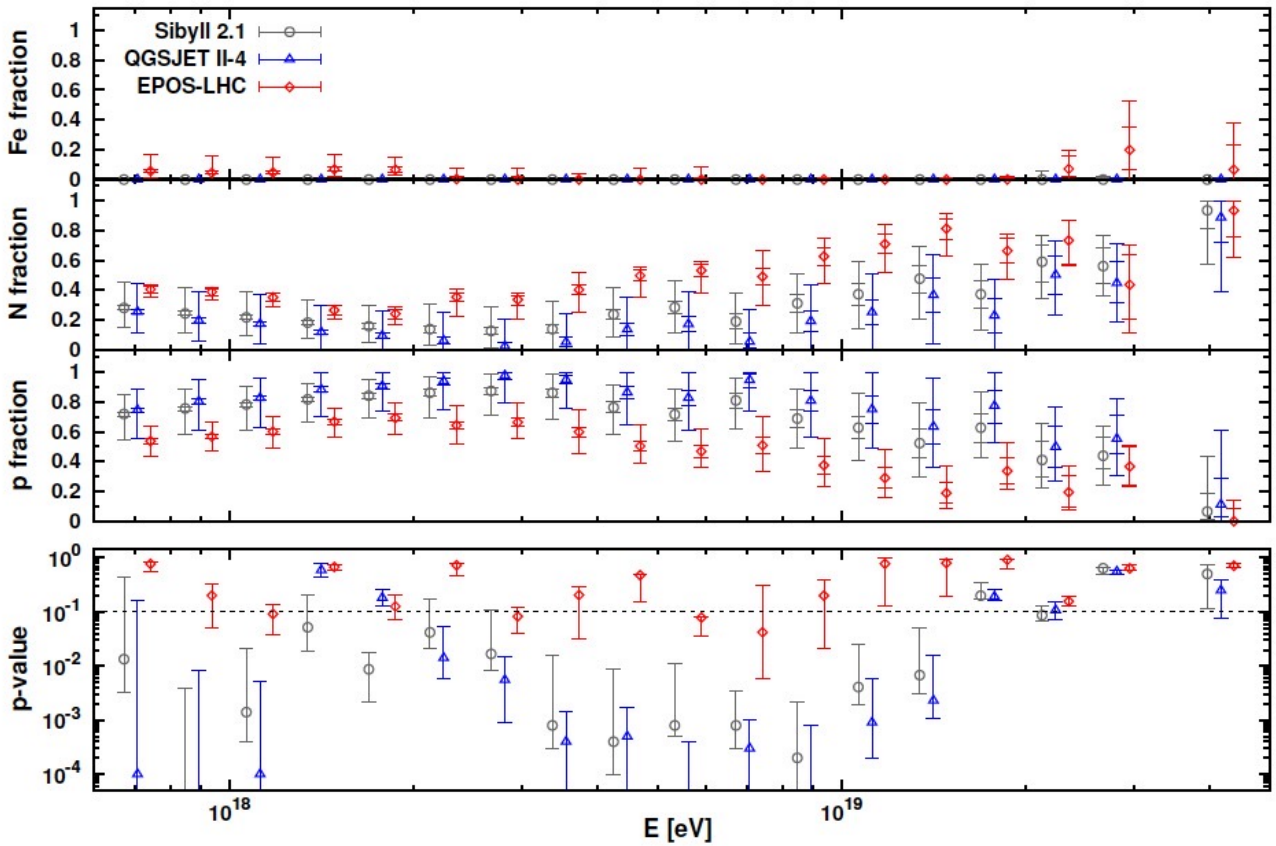


- Turb. Magn. Field spectrum
- Kolmogorov/Kraichnan

- Lmax = 100-300 pc

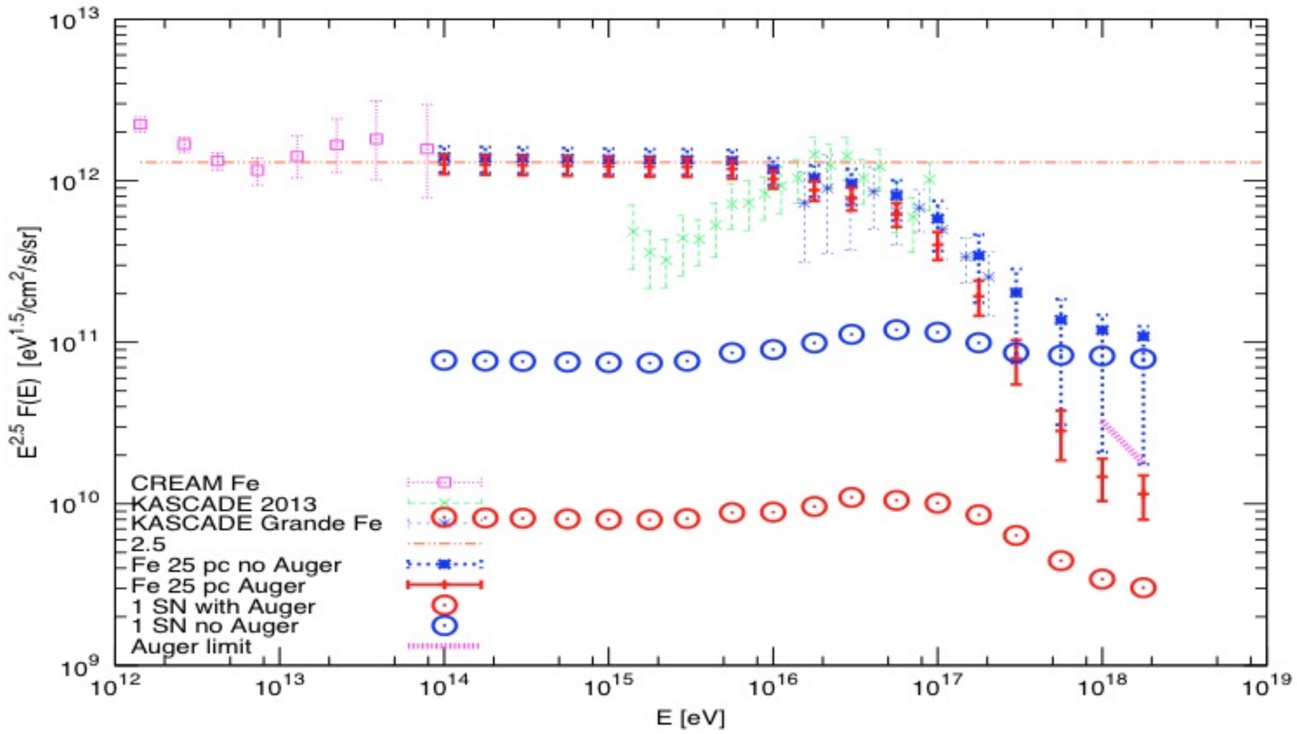
- G.Giacinti et al, arXiv:1112.5599

Auger cosmposition measurements

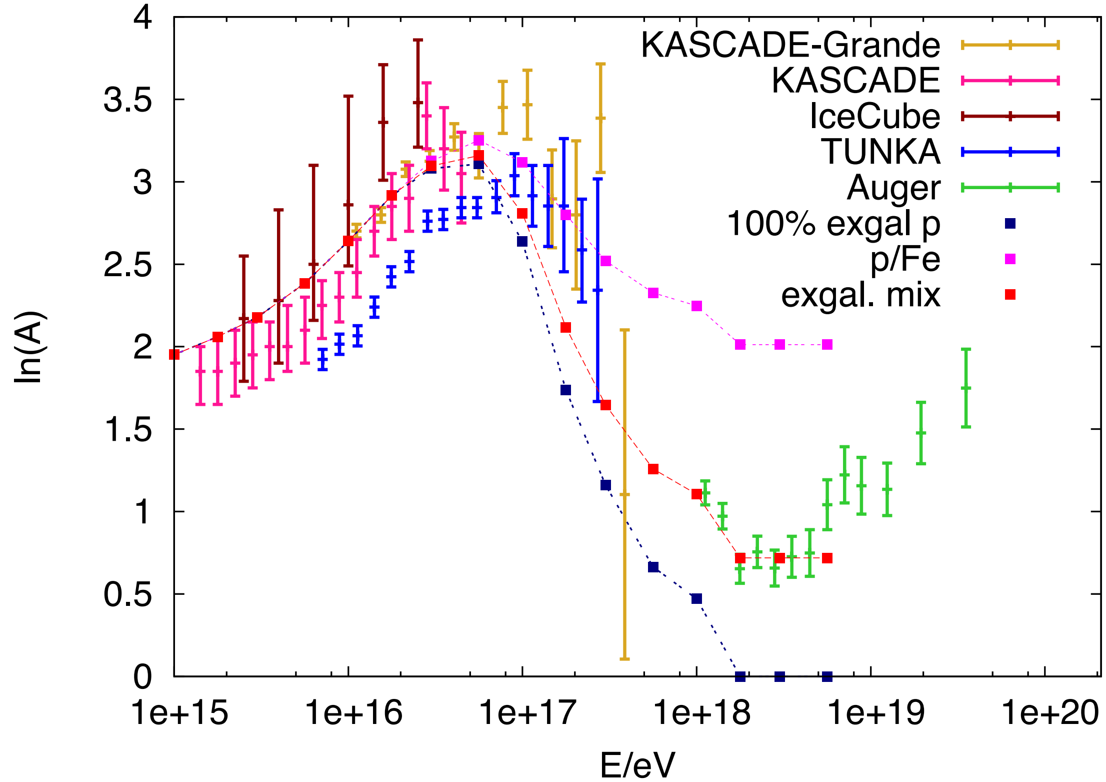


- Auger Collaboration, **arXiv:1409.5083**

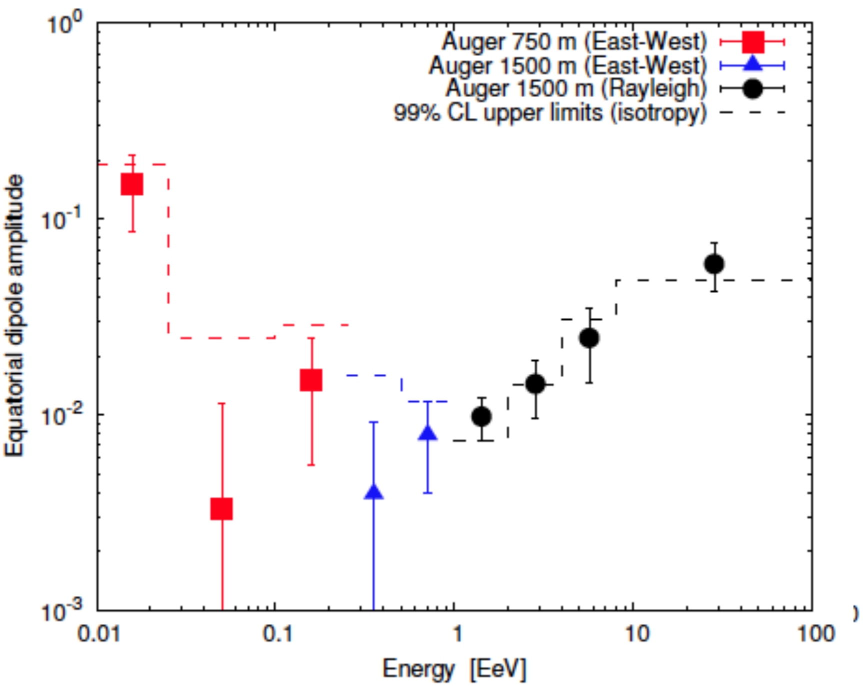
Auger limit on Fe fraction

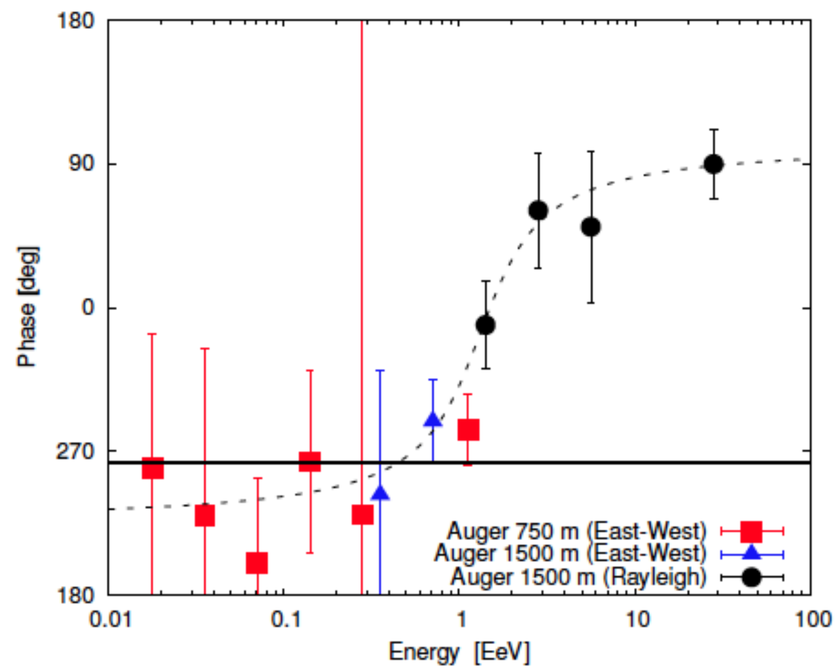


LnA plot


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

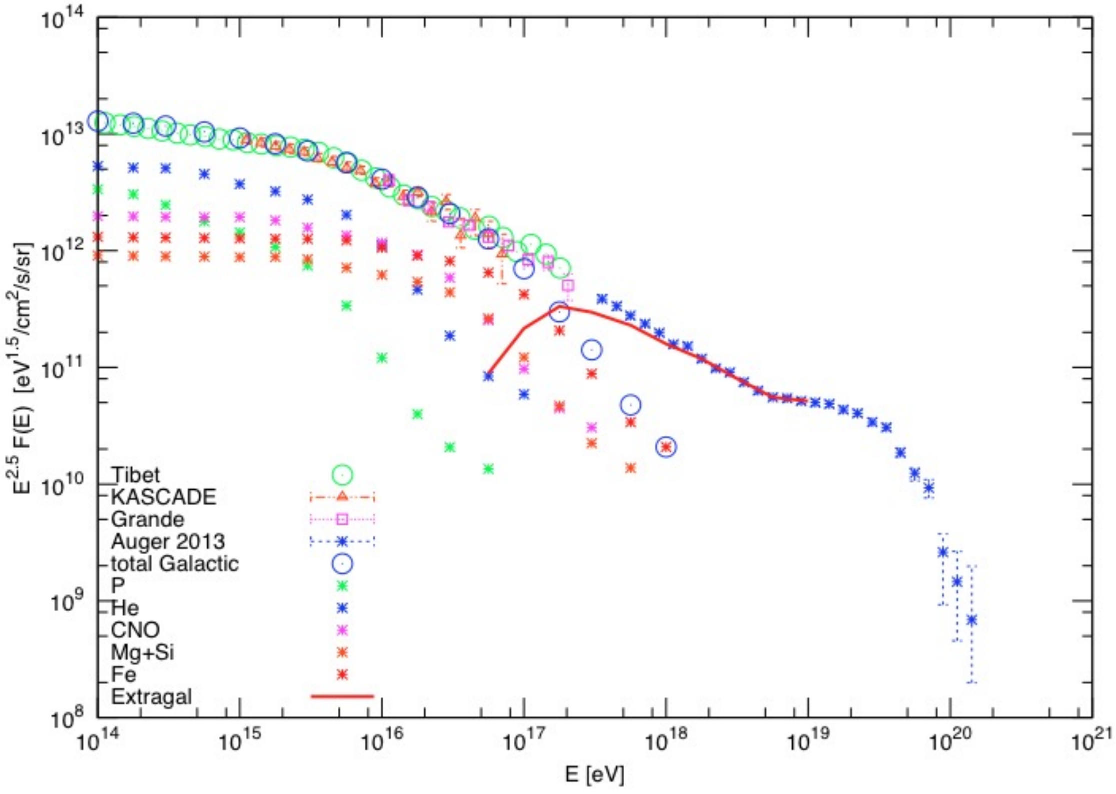
Auger dipole measurements



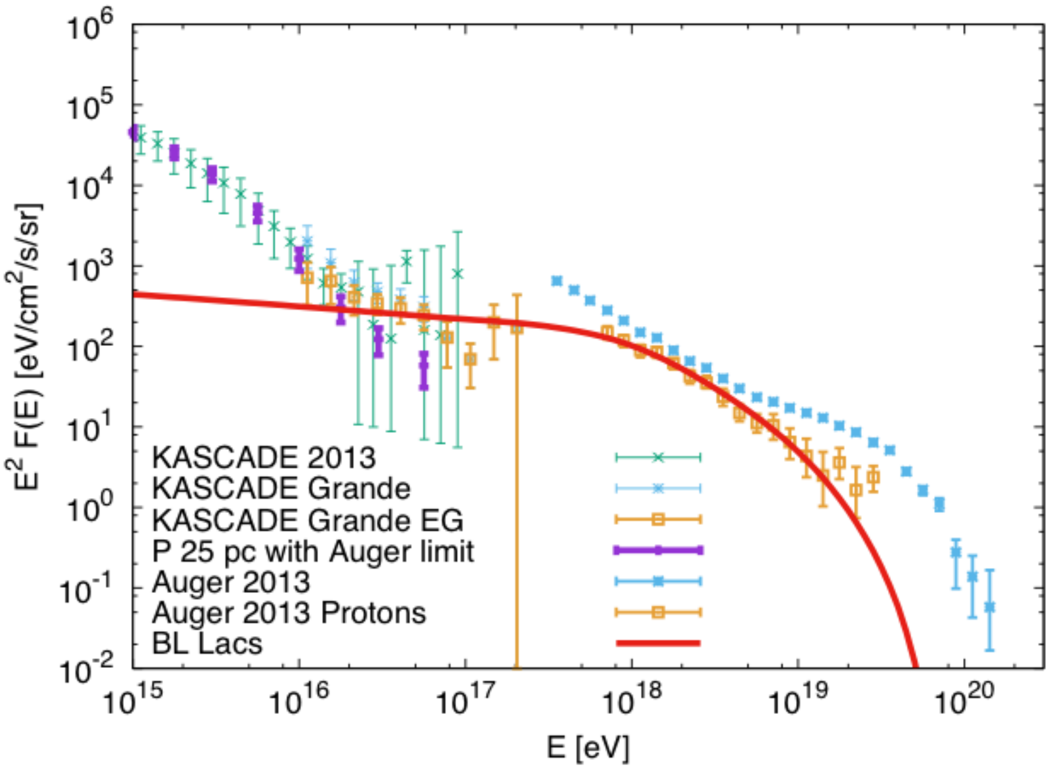


- **Auger Collaboration, arXiv:1310.4620**

Contribution of extra-Galactic sources



UHECR proton flux from extragalactic sources

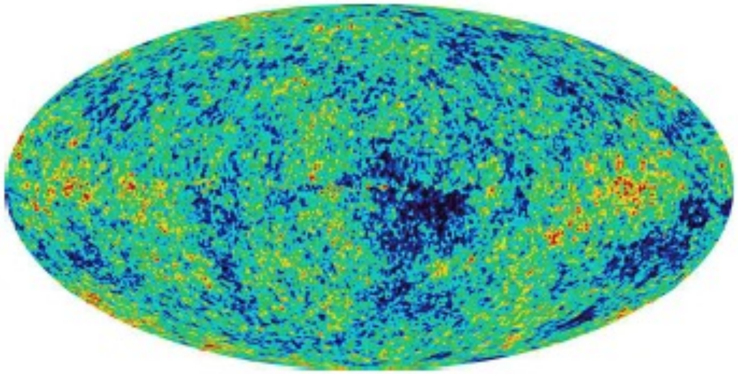


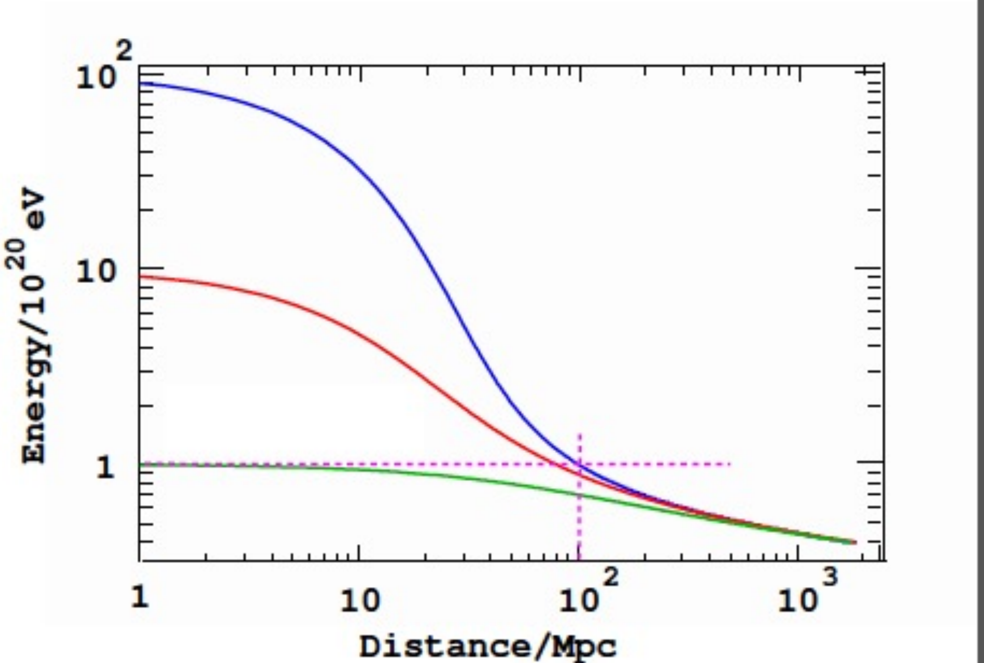
Conclusions extragalactic CR

- 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)

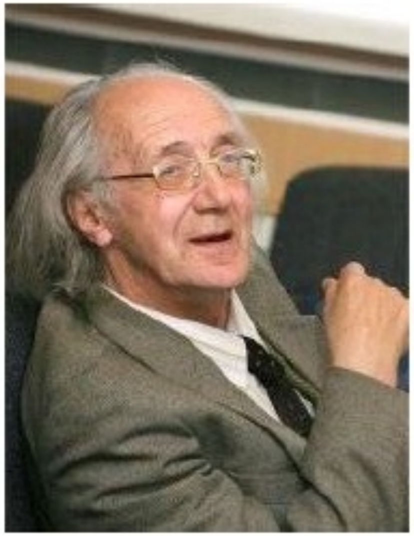
Seminar:
GZK cutoff

Greisen-Zatsepin-Kuzmin Effect



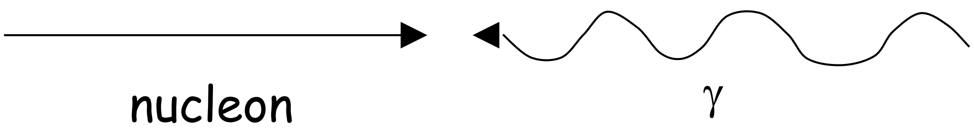


$$p + \gamma_{\mathrm{CMB}} \to N + \pi$$

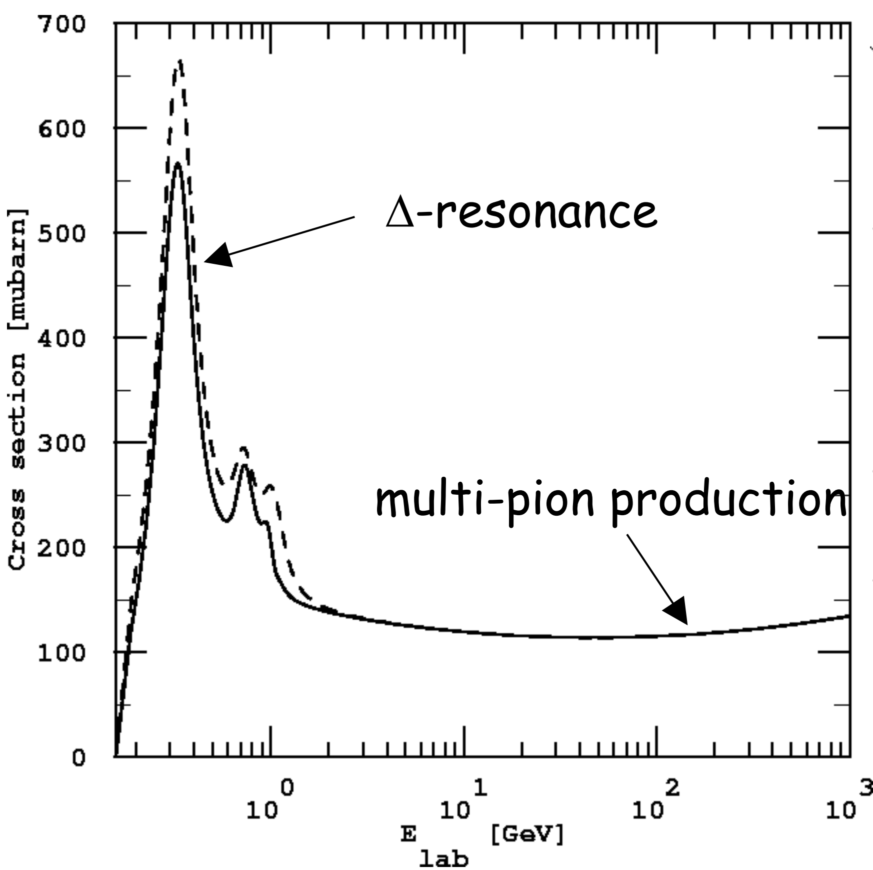


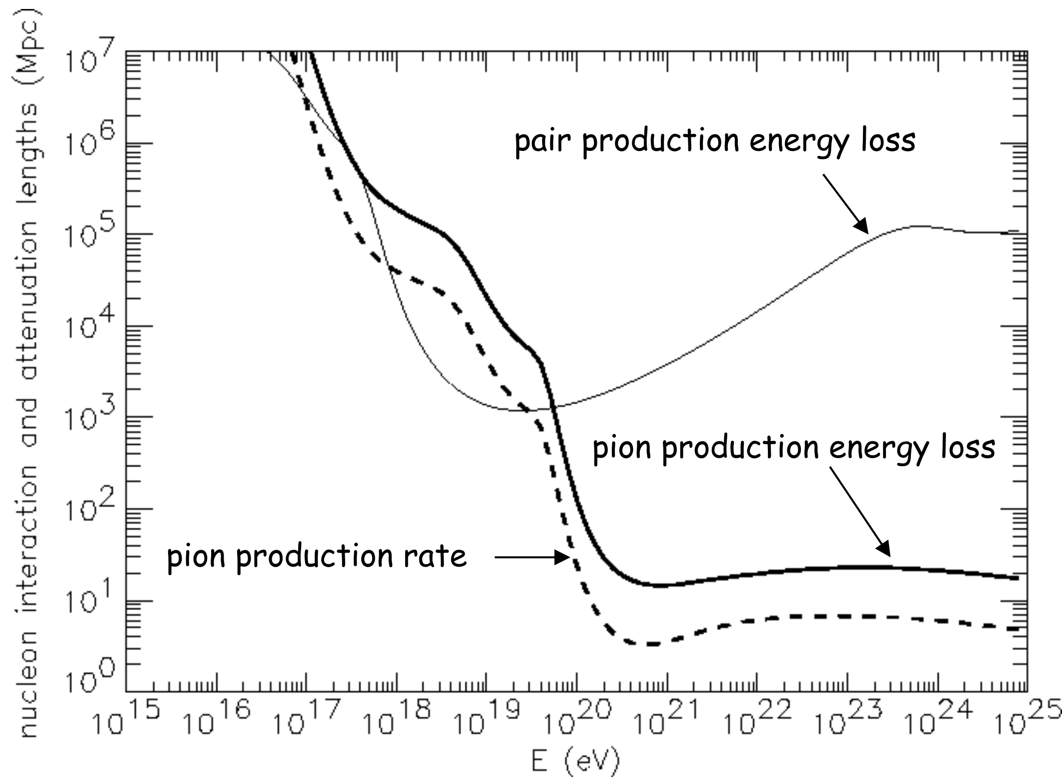
The Greisen-Zatsepin-Kuzmin (GZK) effect

Nucleons can produce pions on the cosmic microwave background



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





⇒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.

- 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

- Conclusion: E_p~2x10[20] eV

$$\gamma + p \rightarrow p\pi^0$$
$$\text{Lab} \rightarrow \text{Center of mass}$$

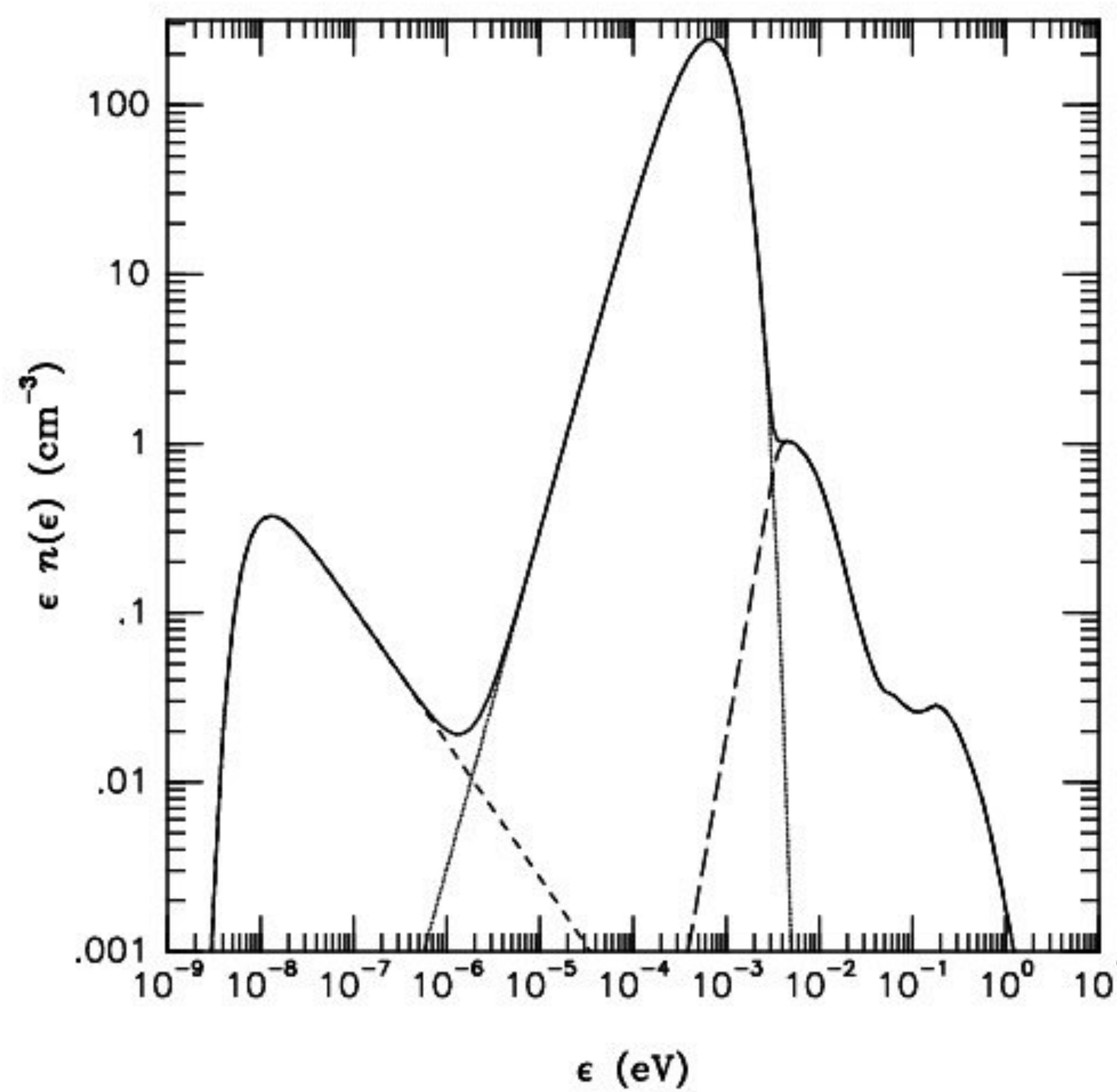
$$(P_{p\mu} + P_{\gamma\mu})^2 = P_{TOT\mu} P^{\mu}_{TOT}$$
$$P_{p\mu} P^{\mu}_{p} + 2P_{p\mu} P^{\mu}_{\gamma} + P_{\gamma\mu} P^{\mu}_{\gamma} = P_{TOT\mu} P^{\mu}_{TOT}$$
$$(m_p c^2)^2 + (2E_p E_\gamma) + (m_\gamma c^2)^2 = \left(\left(m_p + m_{\pi^0}\right)c^2\right)^2$$
$$m_\gamma c^2 = 0, \text{because it's a photon}$$
$$E_p = \frac{m_{\pi^0}}{2E_\gamma}\left(2m_p + m_{\pi^0}\right)$$
$$E_p = \frac{(134.97 MeV/c^2)c^2}{2(6.34x10^{-4} eV)}\left(\frac{(2*938.27 MeV) + 134.97 MeV)}{c^2}c^2\right)$$
$$E_p \approx 2x10^{20} eV$$

Cutoff energy and threshold energy

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

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

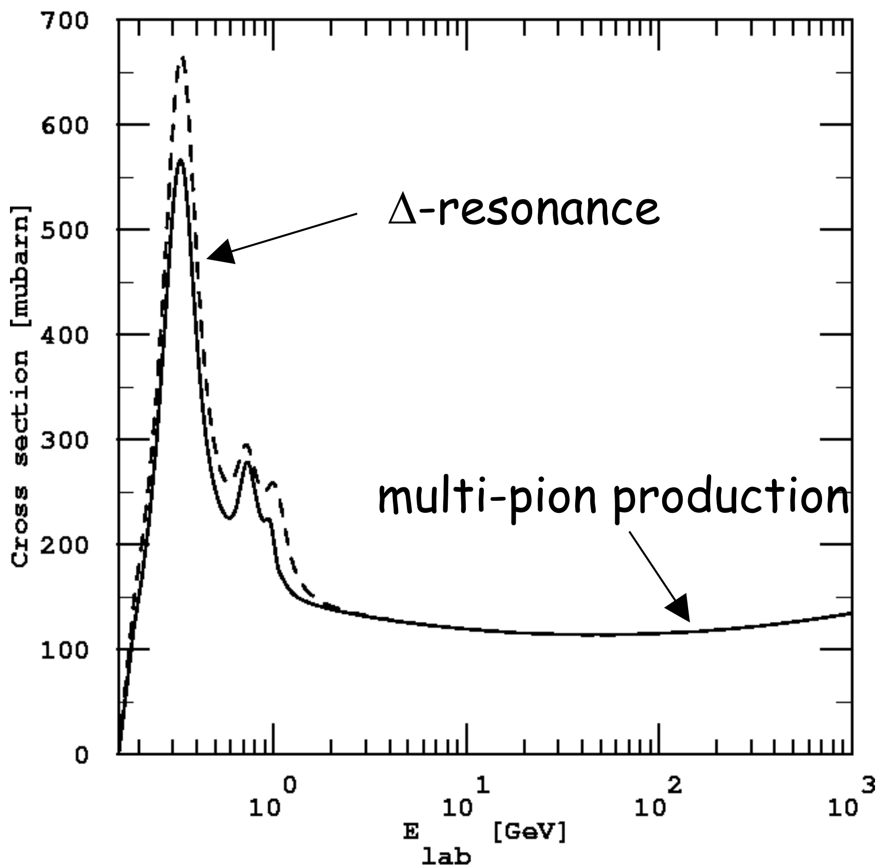
$$E_{av} = \frac{2m_N m_\pi + m_\pi^2}{2\varepsilon_{av}} \approx 2\cdot 10^{20}\,\mathrm{eV}$$



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)

$$\Delta E / E = M_{pi} / M_P = 1/6$$

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



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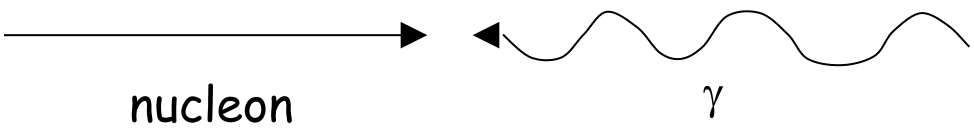
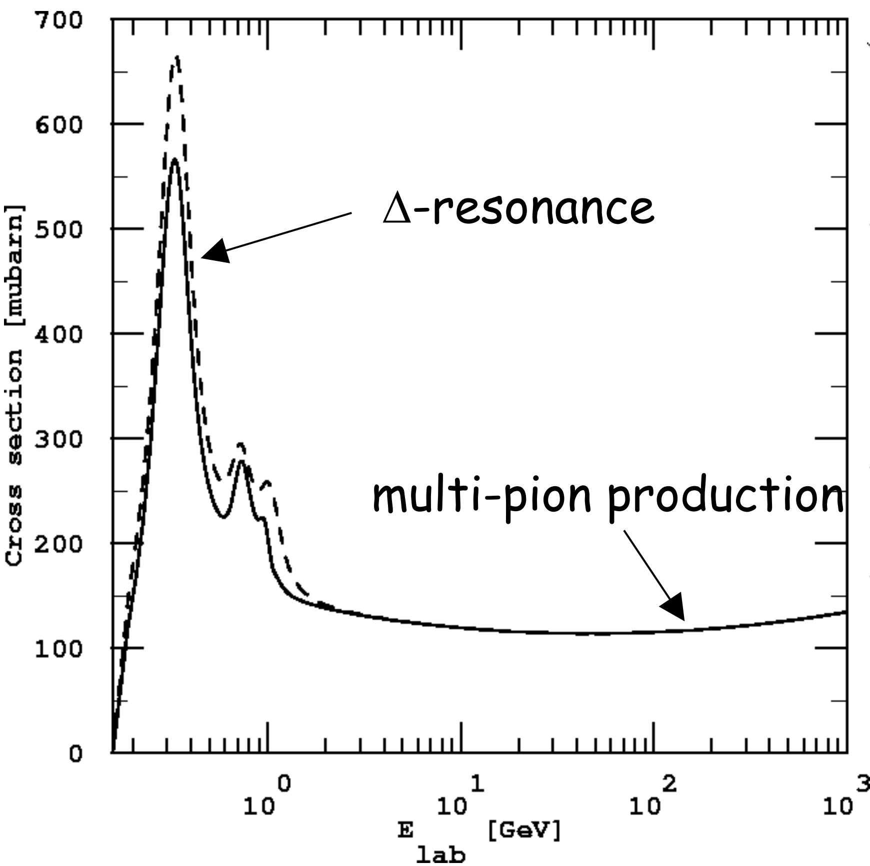
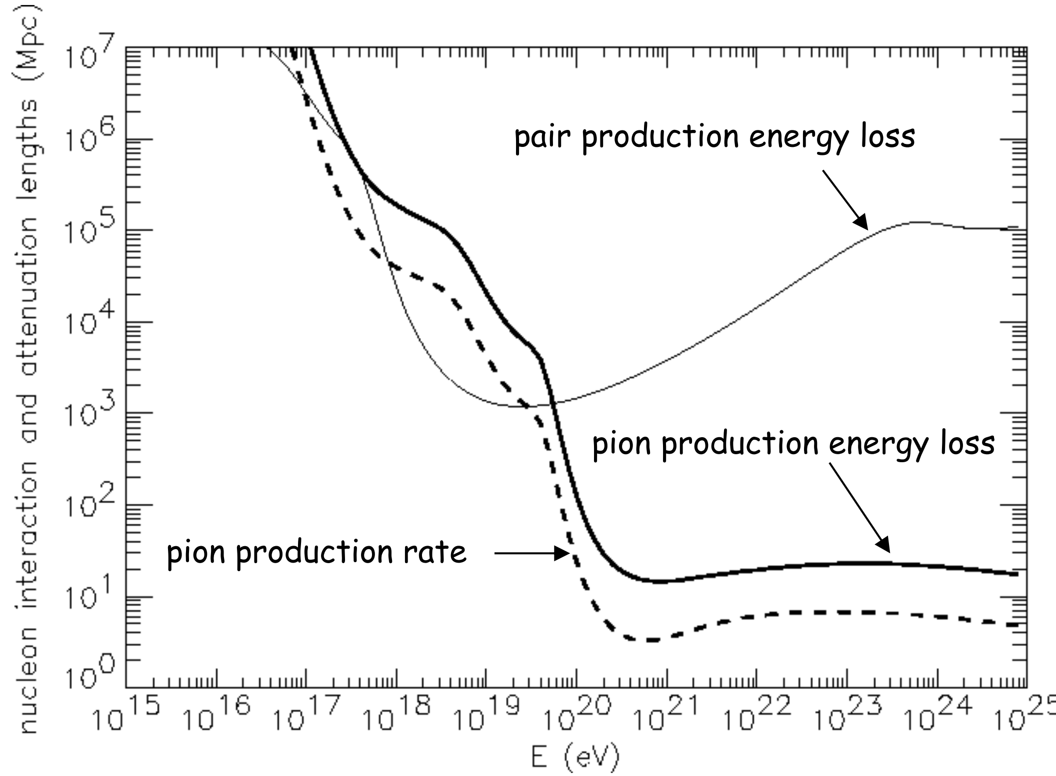


$$E_{th} = \frac{2m_N m_\pi + m_\pi^2}{4\varepsilon} \approx 6 \cdot 10^{19}\,\mathrm{eV}$$





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

Distance

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

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

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

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

$$R_{multi} = 20Mpc$$