Signatures of nearby supernova in cosmic ray data

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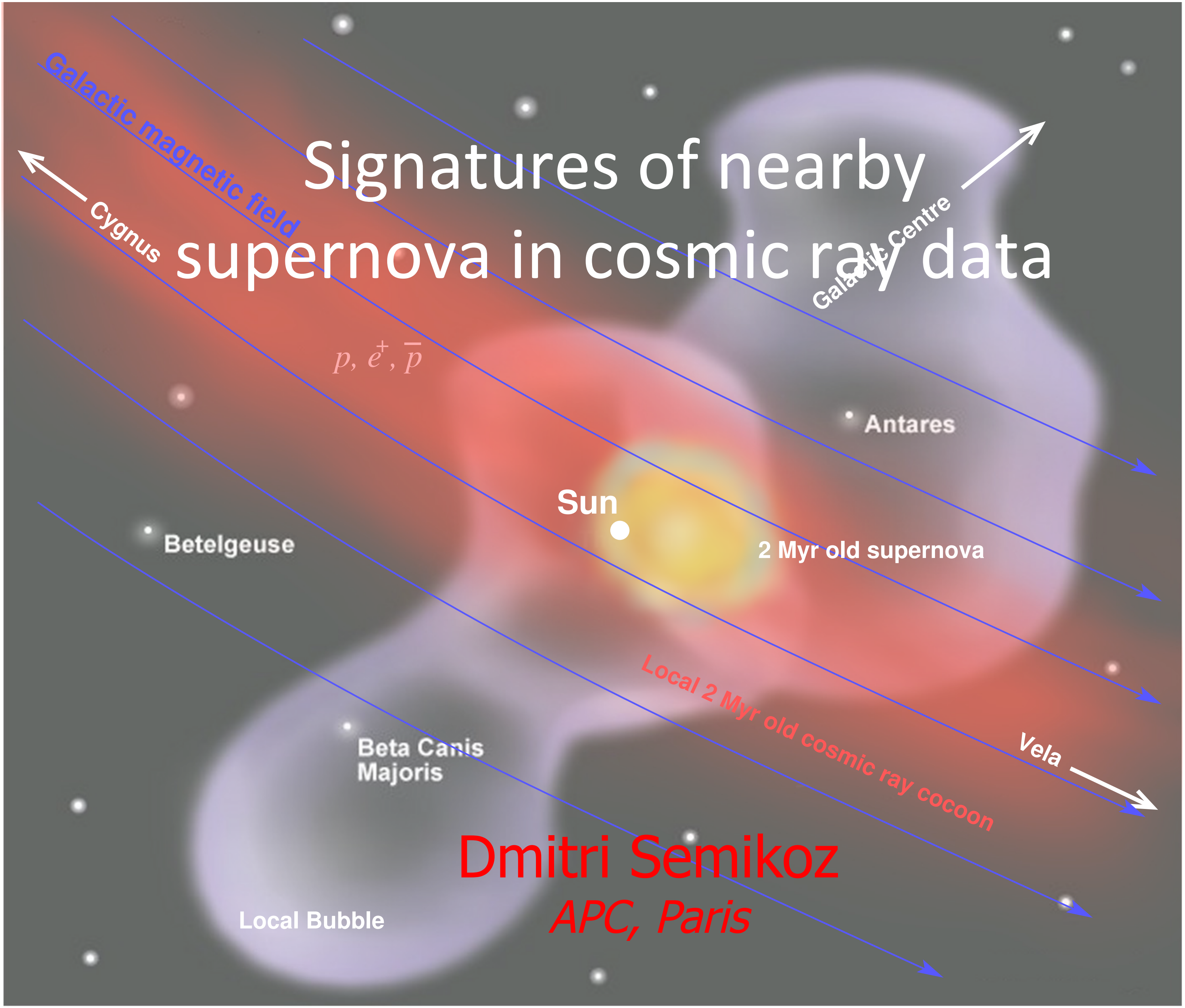
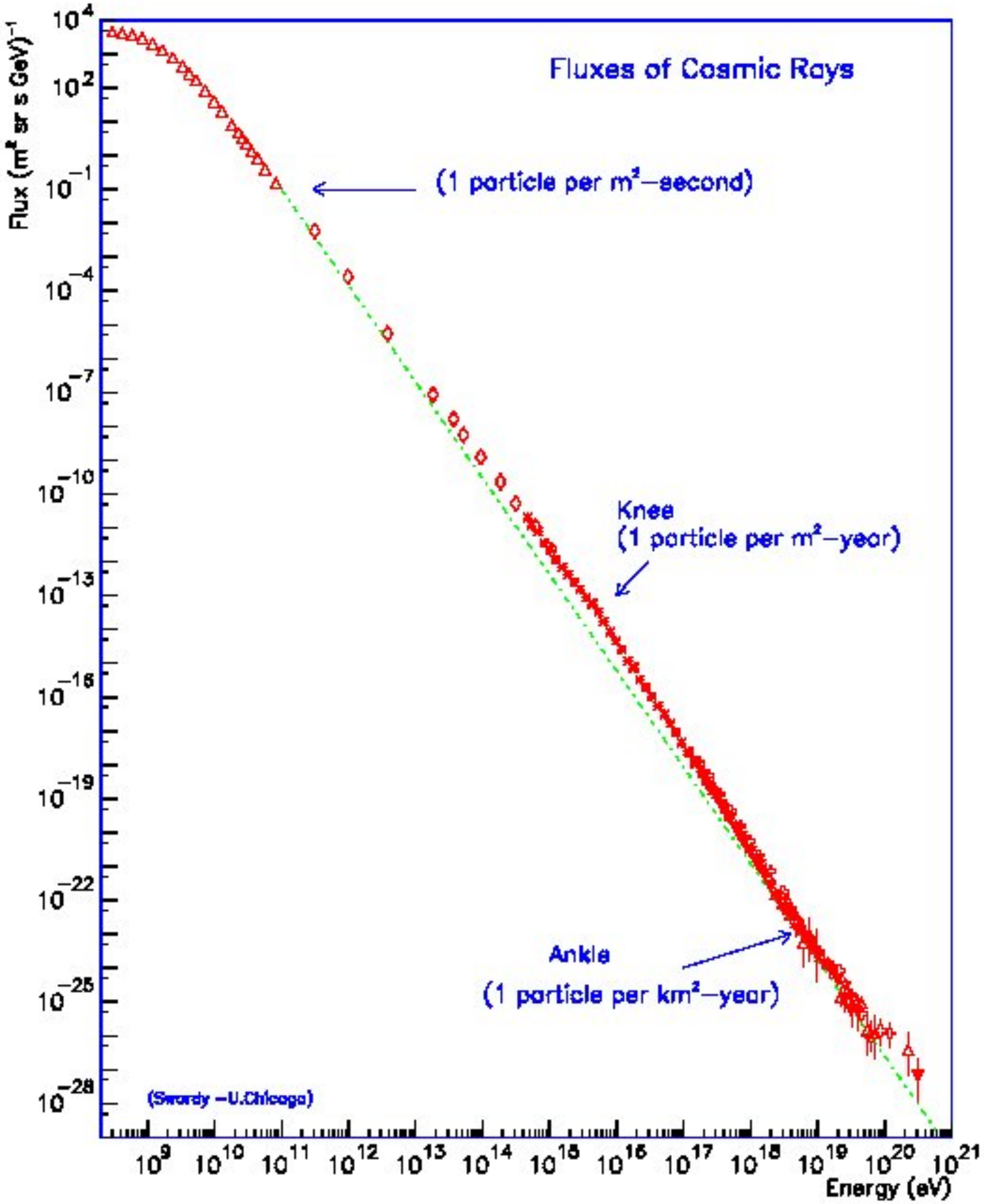
APC, Paris

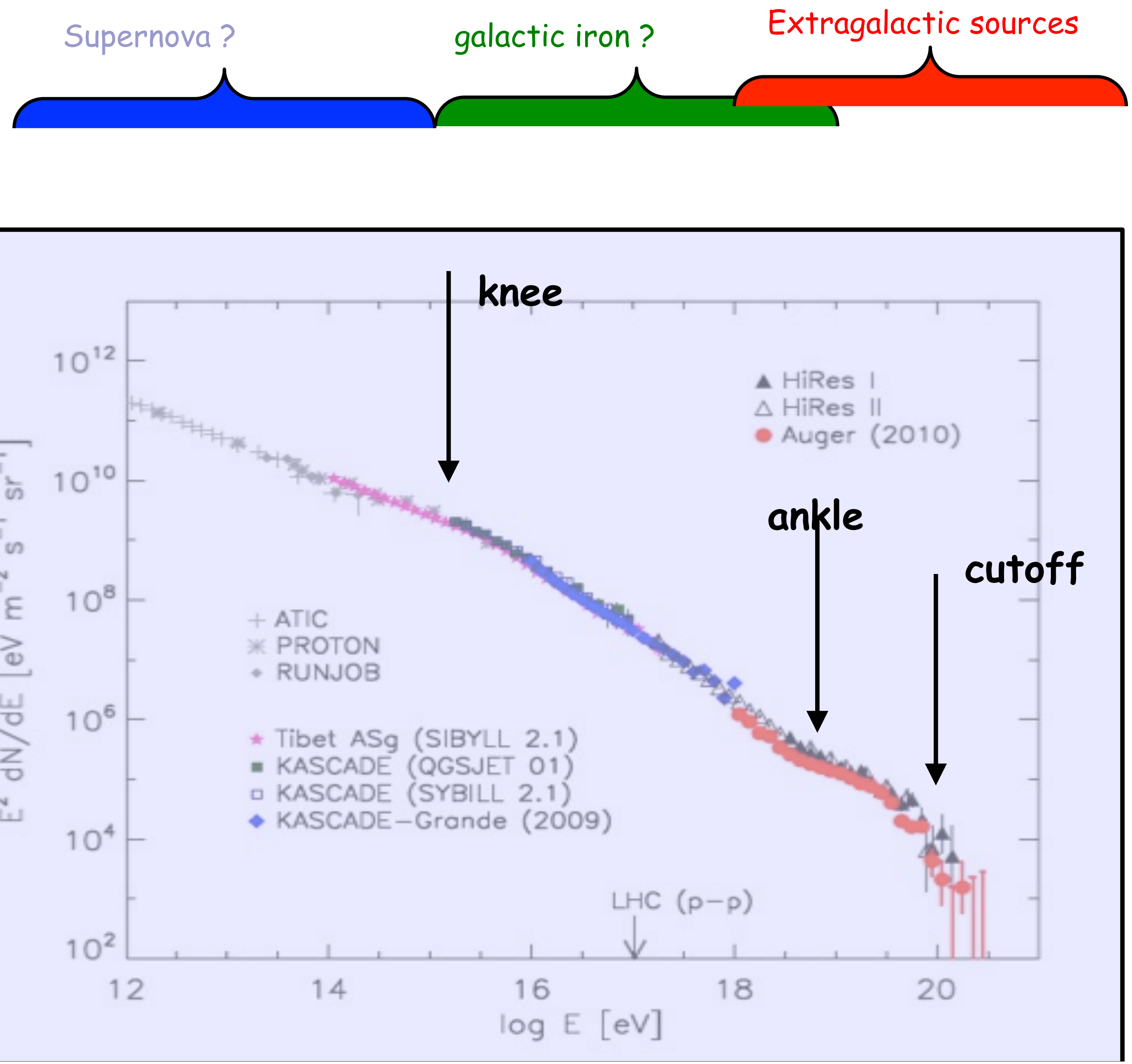


Overview:

- *Introduction: galactic cosmic rays*
- *Problems with modeling of galactic cosmic rays*
- *CR spectrum from gamma-rays and neutrino data*
- *Fe60 anomaly and nearby source*
- *Nearby 'recent' source: proton spectrum and anisotropy, secondary positrons and anti-protons*
- *Conclusions*

Introduction: galactic cosmic rays

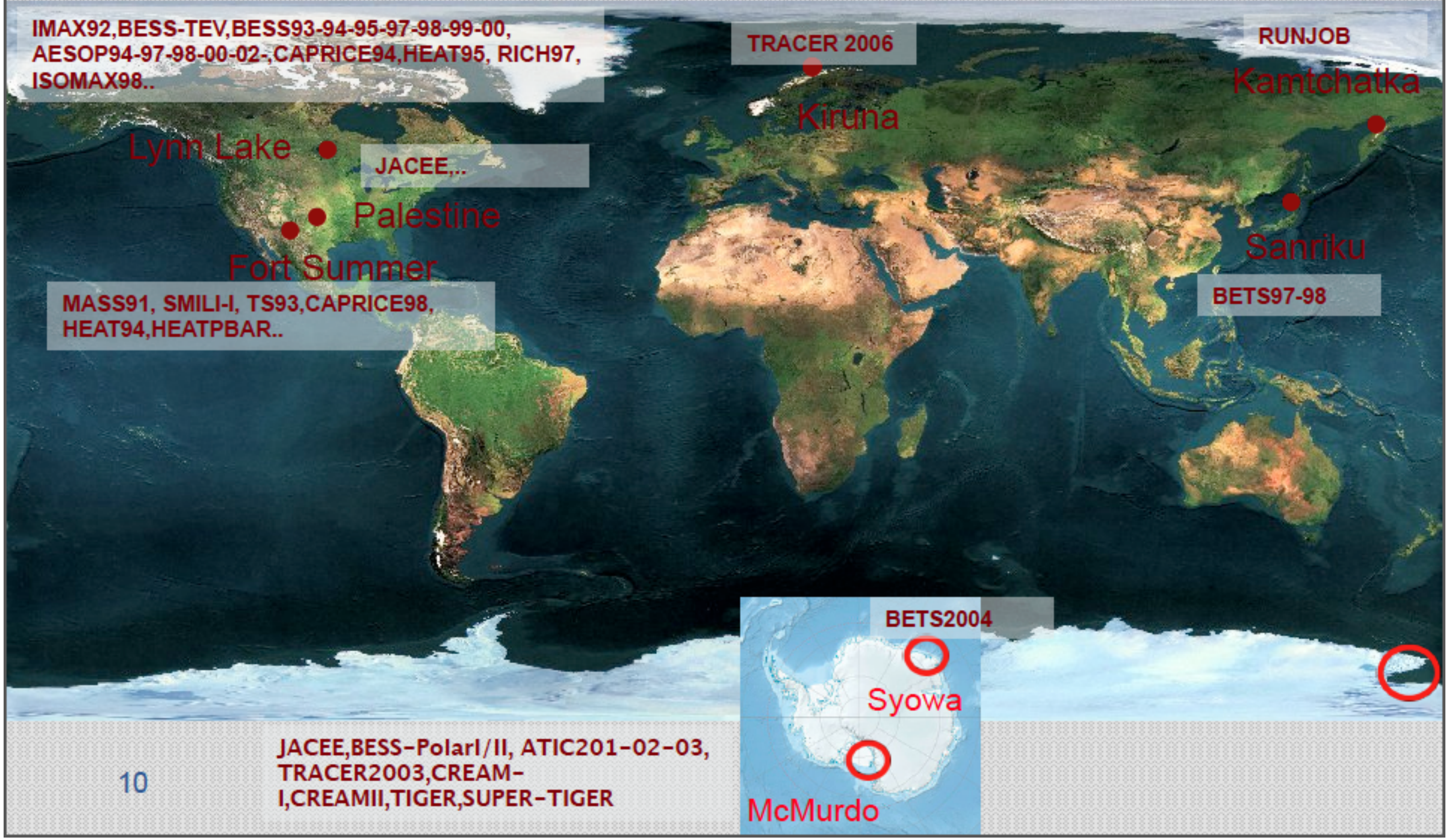

Fluxes of Cosmic Rays
(1 particle per m²–second)
Knee
(1 particle per m²–year)
Ankle
(1 particle per km²–year)
(Swordy – U.Chicago)
Flux (m² sr s GeV)⁻¹
Energy (eV)
10^4
10^2
10^-1
10^-4
10^-7
10^-10
10^-13
10^-16
10^-19
10^-22
10^-25
10^-28
10^9
10^10
10^11
10^12
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21


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}]
log E [eV]
10^{12}
10^{10}
10^8
10^6
10^4
10^2
12
14
16
18
20

Stratospheric Balloons: from few hrs to months

Magnetic Spectrometers
...
BESS/POLAR/TEV (11 Flights)
WIZARD (6,Flights)
HEAT/PBAR (4,Flights)

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



Space:

Long missions (years)
Small payloads
Low energies..

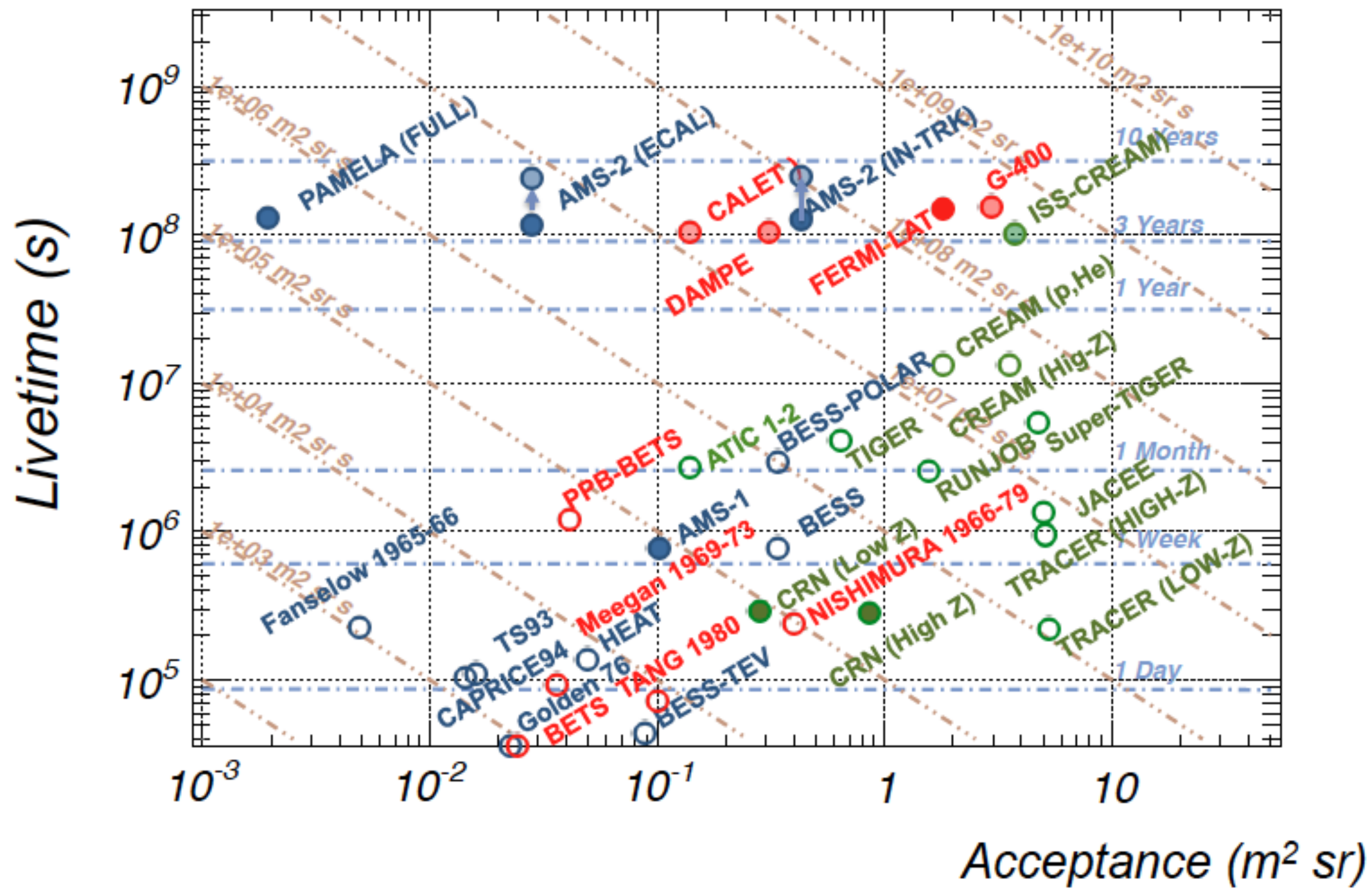
IMP series < GeV/n
ACE-CRIS/SIS Ekin < GeV/n
VOYAGER-HET/CRS < 100 MeV/n
ULYSSES-HET (nuclei) < 100 MeV/n
ULYSSES-KET (electrons) < 10 GeV
CRRES/ONR < (nuclei) 600 MeV/n
HEAO3-C2 (nuclei) < 40 GeV/n

Short missions (days)/ Largerpayloads

CRN on Challenger
(3.5 days 1985)

AMS-01 on Discovery
(8 days, 1998)

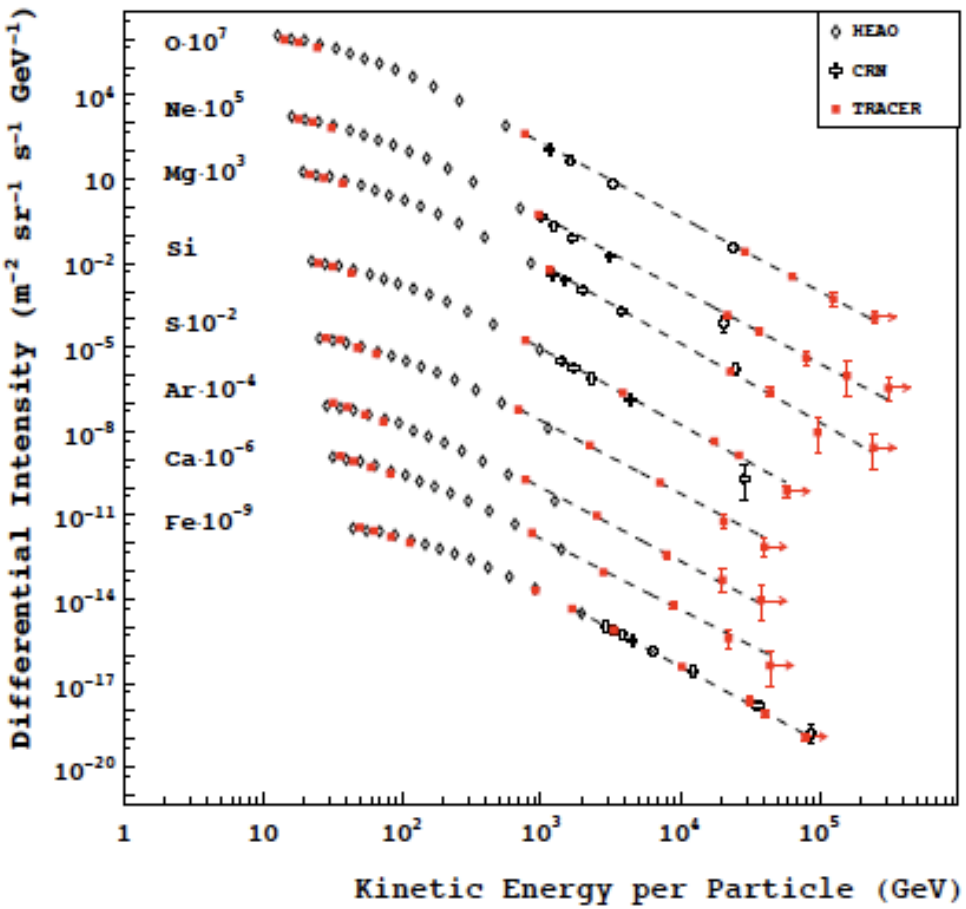
Long missions
Large payloads



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

○ Balloon
● Space
● Space (planned)

Spectra of individual nuclei



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).

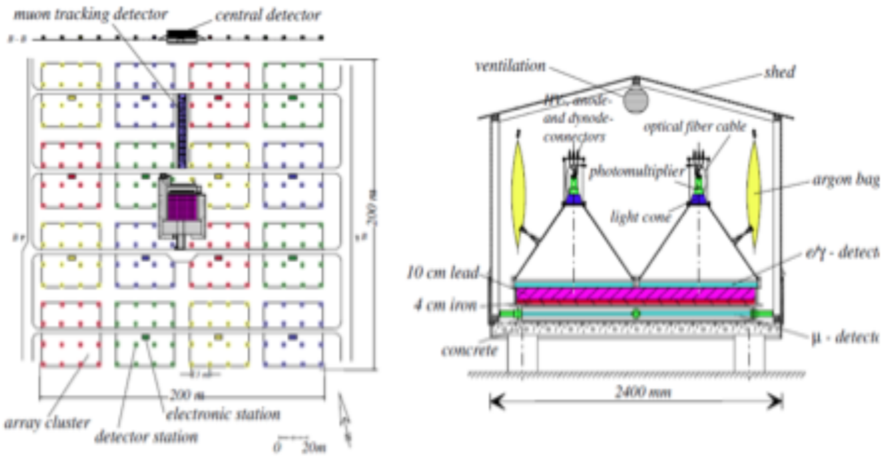


Fig. 1. Left: layout of the KASCADE air shower experiment; Right: sketch of a detector station with shielded and unshielded scintillation detectors.

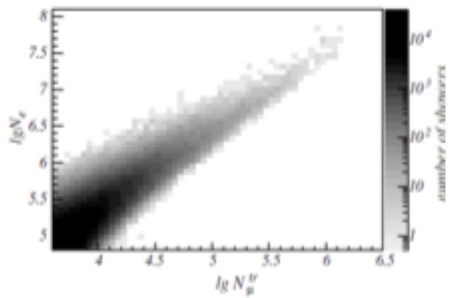
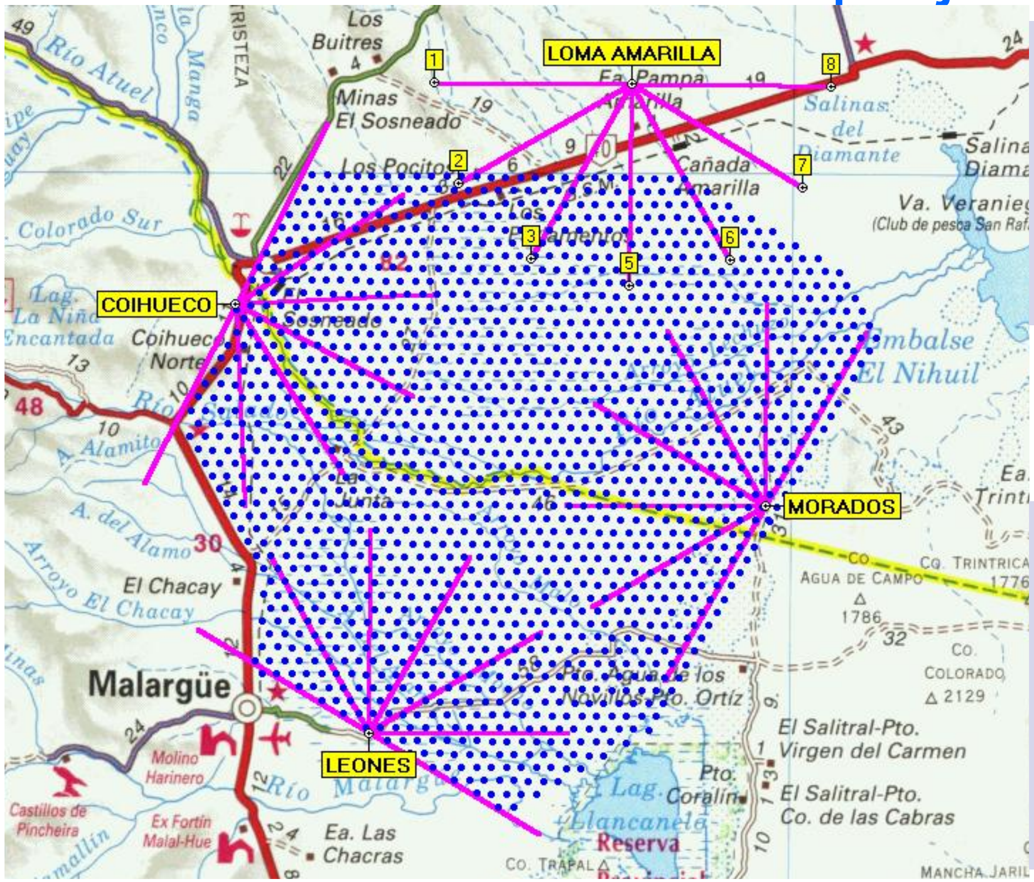


Fig. 2. Two-dimensional shower size spectrum used in th analysis. The range in $\lg N_e$ and $\lg N_\mu^{tr}$ is chosen to avoi influences of inefficiencies.

Pierre Auger Observatory

South site in Argentina almost finished
North site – project



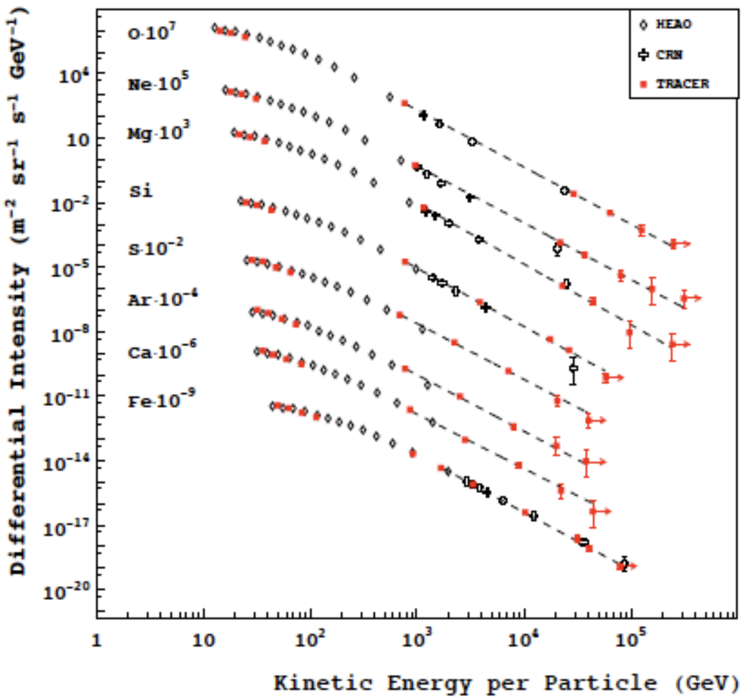
Surface Array

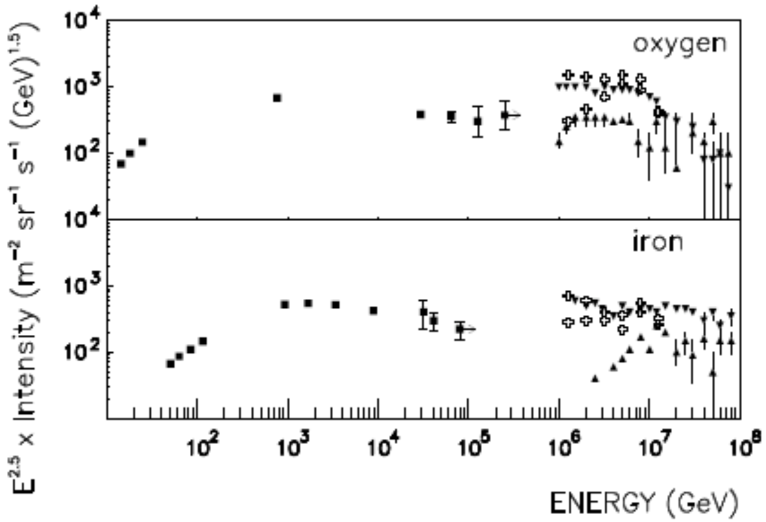
- *1600 detector stations*
- *1.5 Km spacing*
- *3000 Km^2 (30xAGASA)*

Fluorescence Detectors

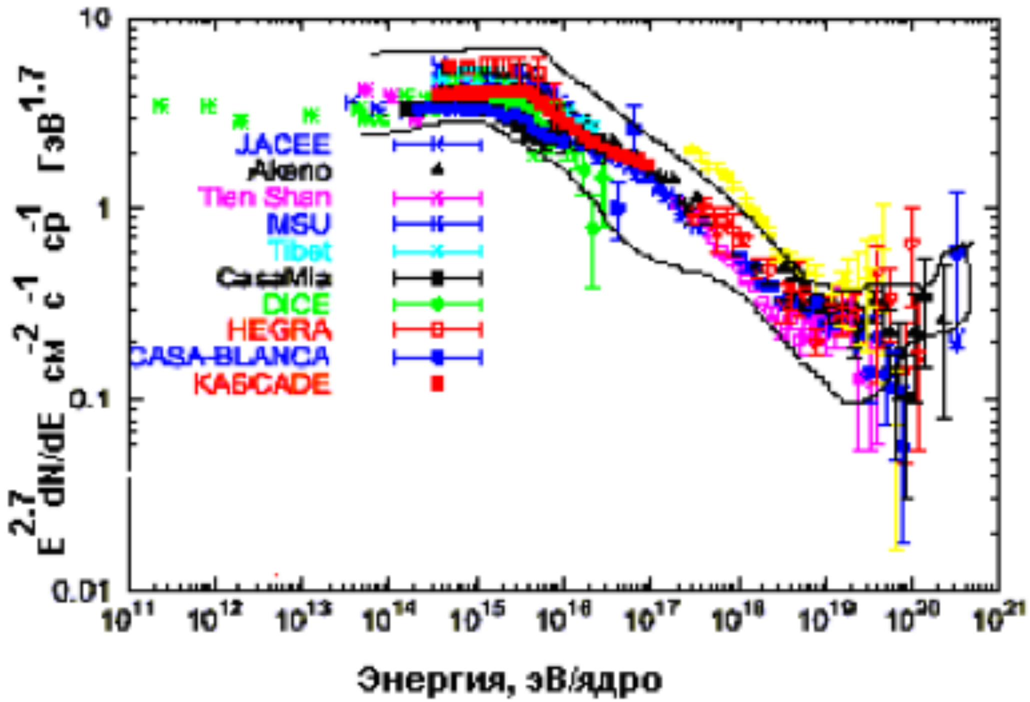
- *4 Telescope enclosures*
- *6 Telescopes per enclosure*
- *24 Telescopes total*

Spectra of individual nuclei





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

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

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

convection (Galactic wind)

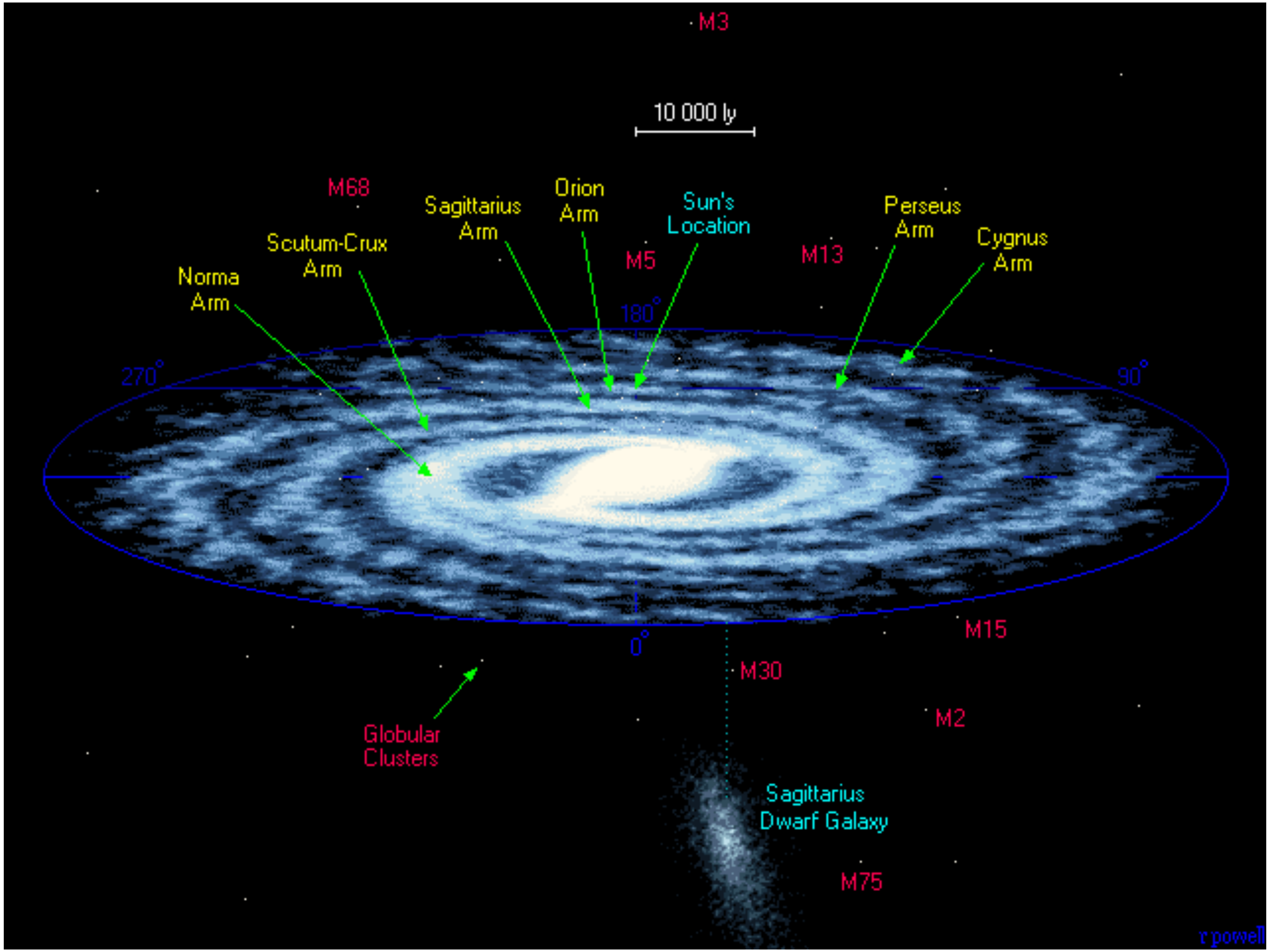
E-loss $$-\frac{\partial}{\partial p}\left[\frac{dp}{dt}\psi - \frac{1}{3}p\vec{\nabla}\cdot\vec{V}\psi\right]$$

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

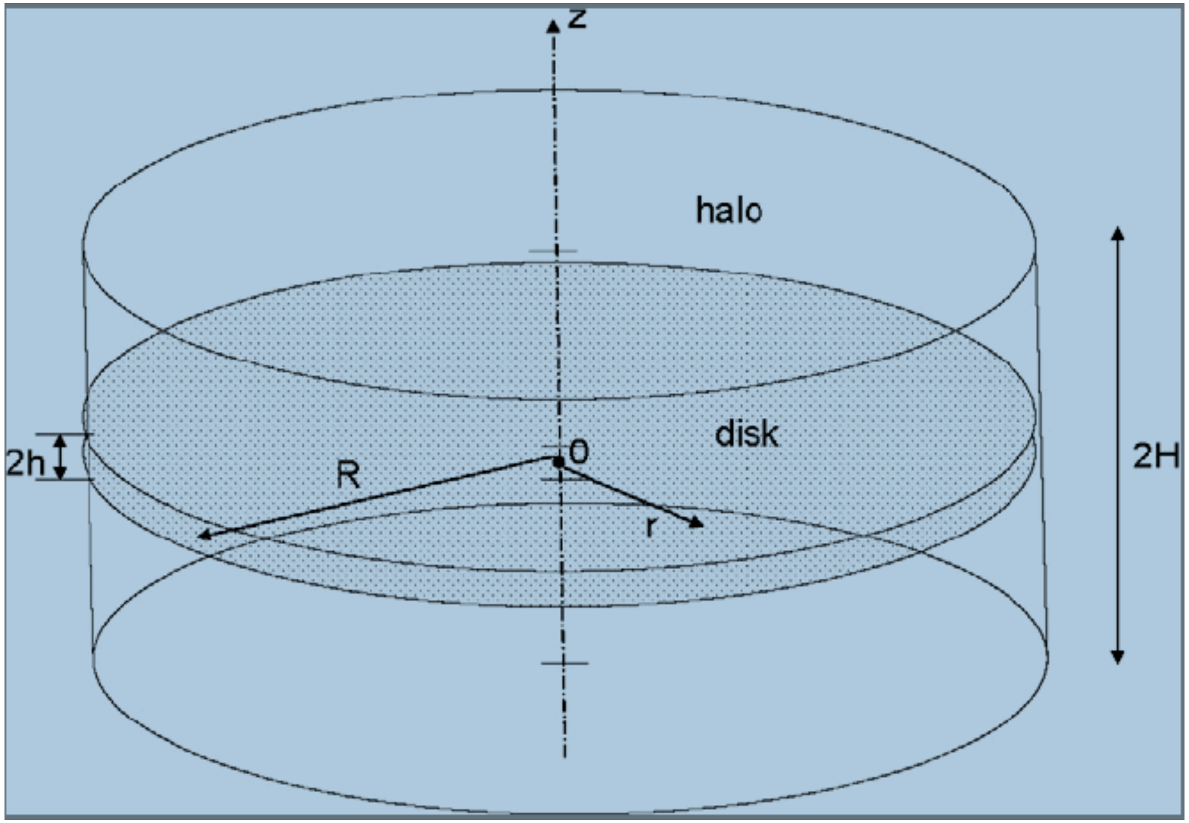
+ boundary conditions

$\psi(\mathbf{r},p,t)$ – 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

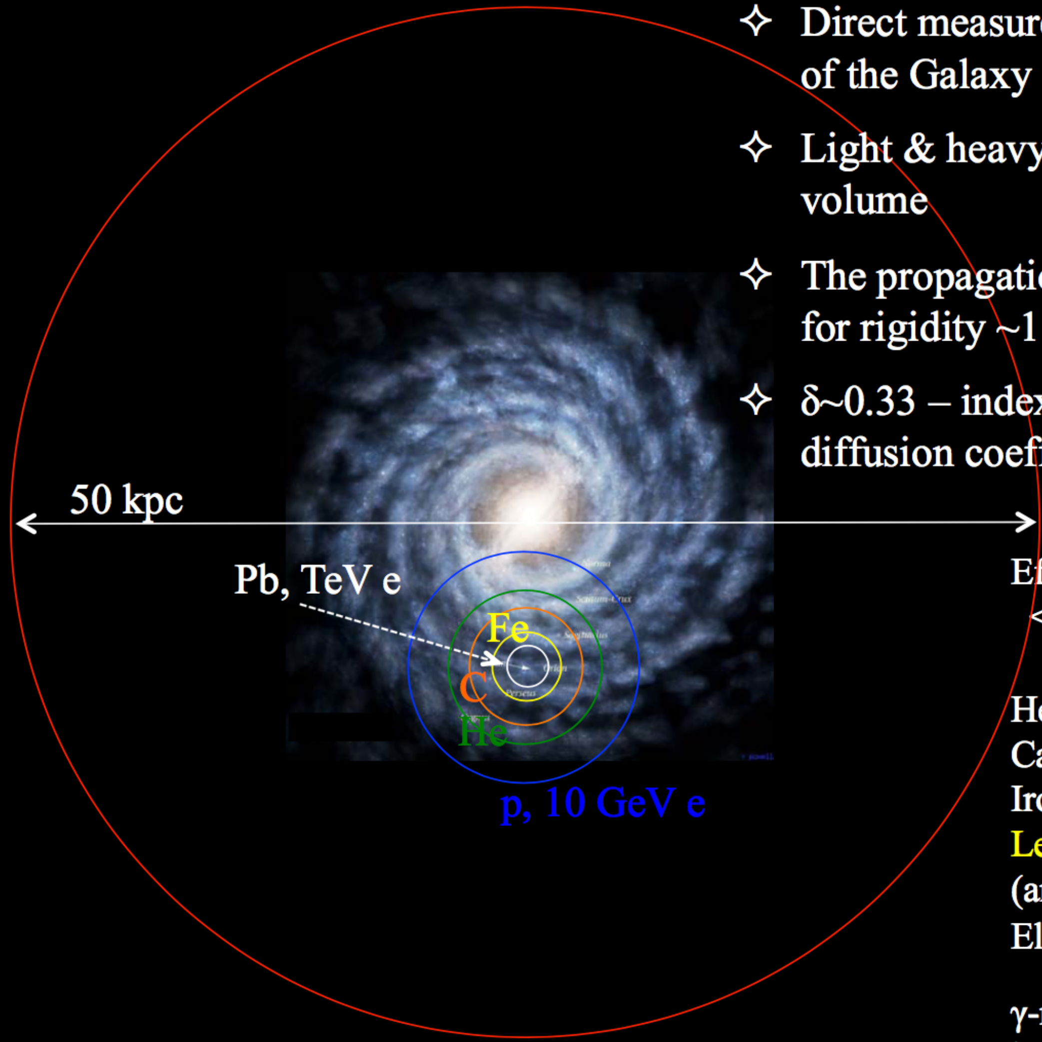
- *Regular magnetic fields does not affect propagation of CR, one can neglect them*
- *Spectrum is the same in all galaxy. It is as measured here 1/E^2.7*
- *Sources are frequent enough that CR are in steady state regime, no variation of fluxes in time*

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
- δ~0.33 – index of the rigidity dependence of the diffusion coefficient



Effective propagation distance:
$\langle X\rangle \sim \sqrt{6D\tau} \sim 2.7\ \mathrm{kpc}\ R^{\delta/2}\,(A/12)^{-1/3}$

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± spectra in the whole Galaxy ~50 kpc across

Predictions of the model

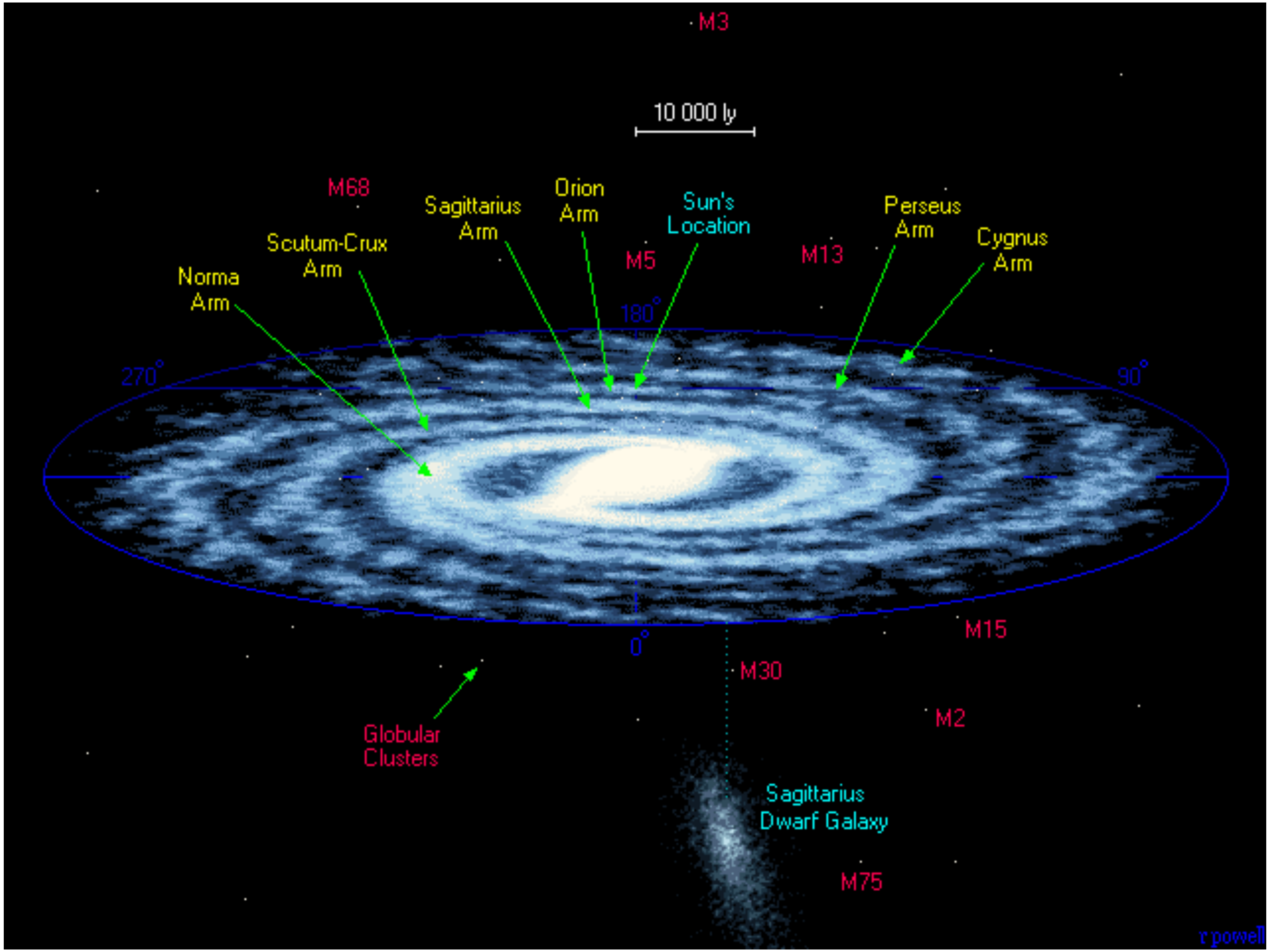
- *Because higher energy cosmic rays escape faster from Galaxy:*
  - *anisotropy is growing function of energy*
  - *Secondary fluxes drop relative to primary fluxes: positron and anti-proton fluxes should drop if compared to proton flux*

Problems of galactic cosmic ray model

Assumptions of the model

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

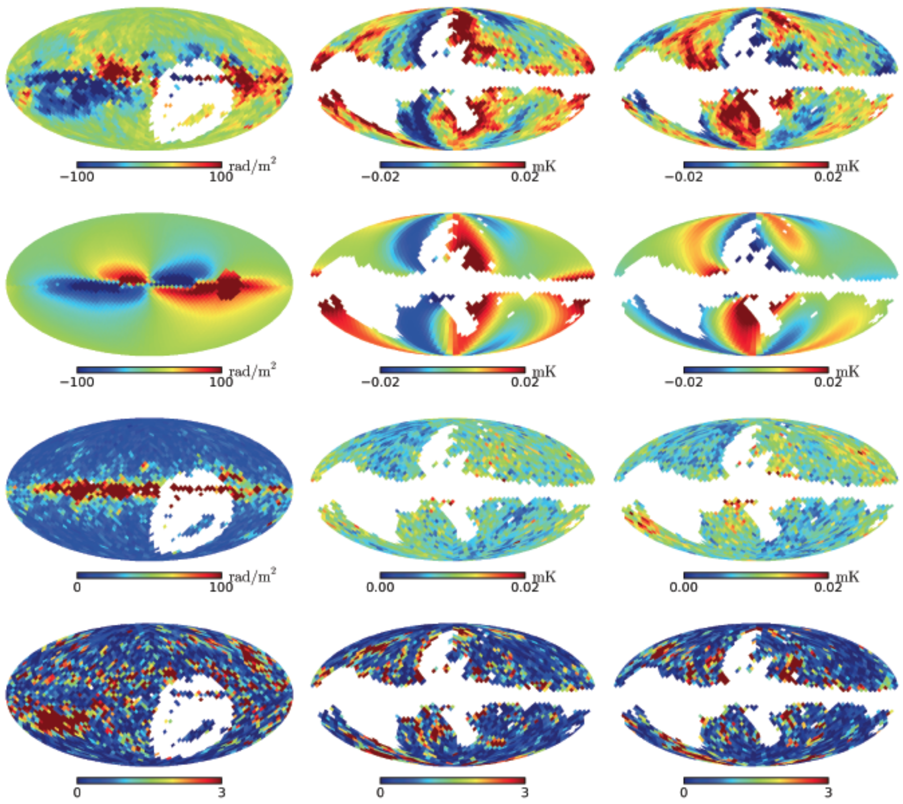
MILKY WAY GALAXY



Galactic magnetic field

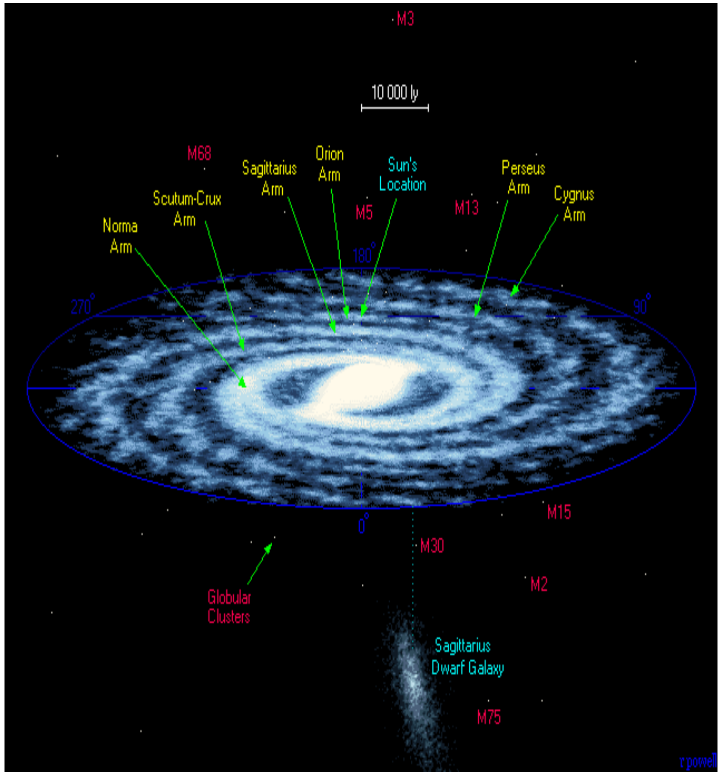
- B = B_disk (regular) + B_disk (turbulent) + B_halo(regular) + B_halo (turbulent)

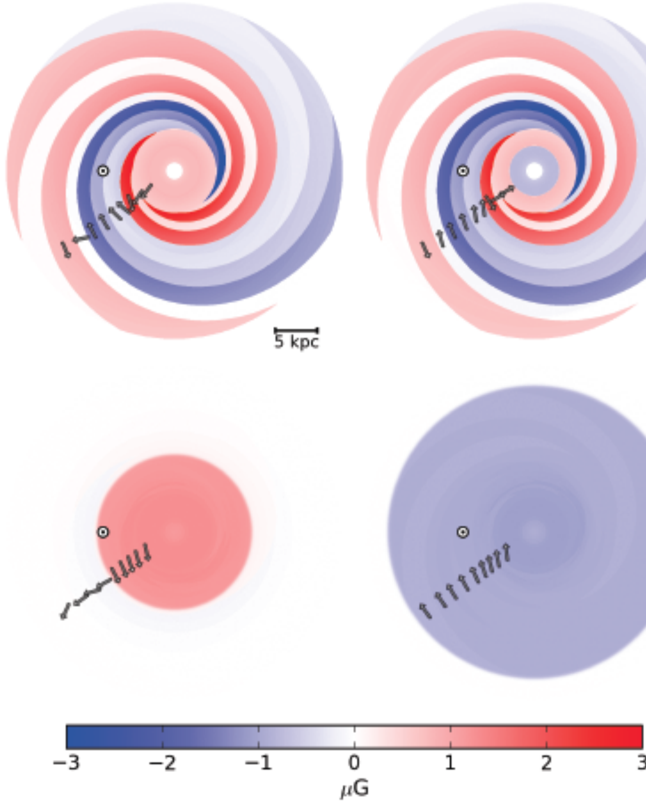
Synchrotron/RM maps



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

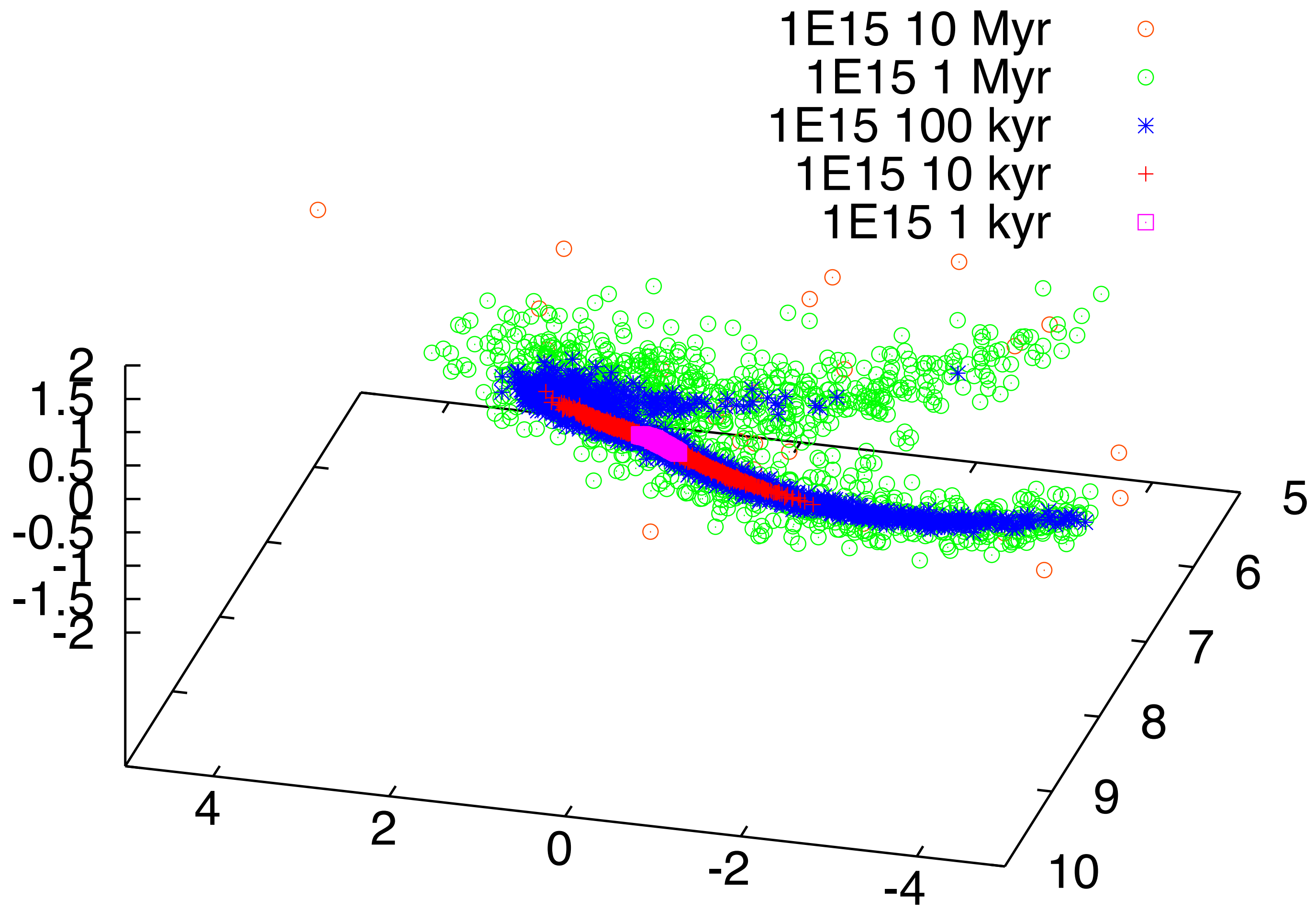
Galactic magnetic field: disk



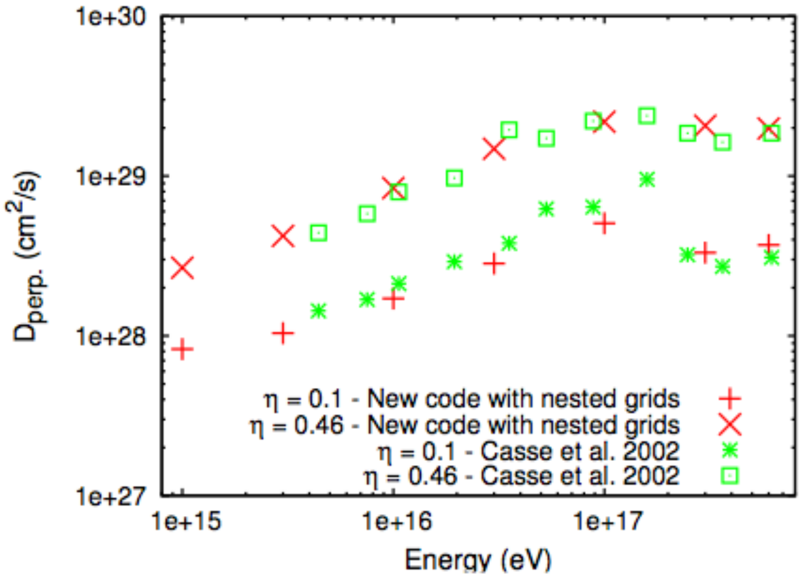


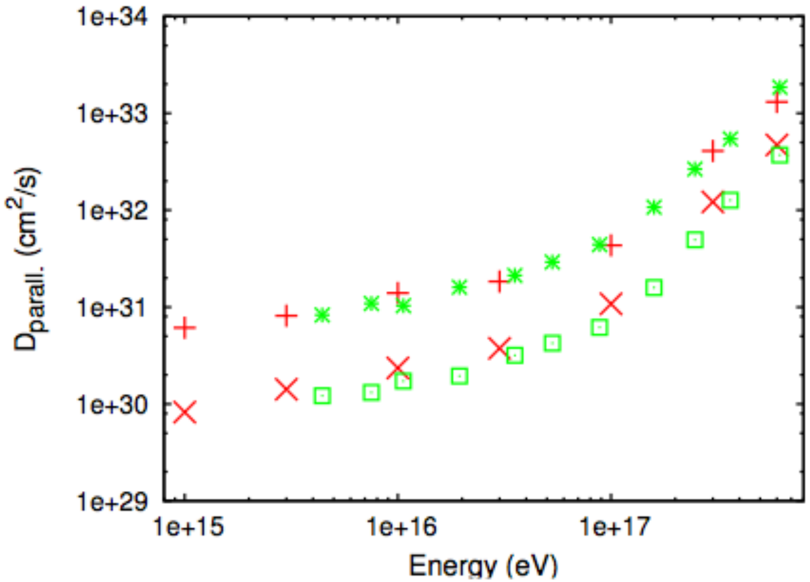
R.Jansson & G.Farrar, arXiv:1204.3662

Proton flux from SN at 1 PeV

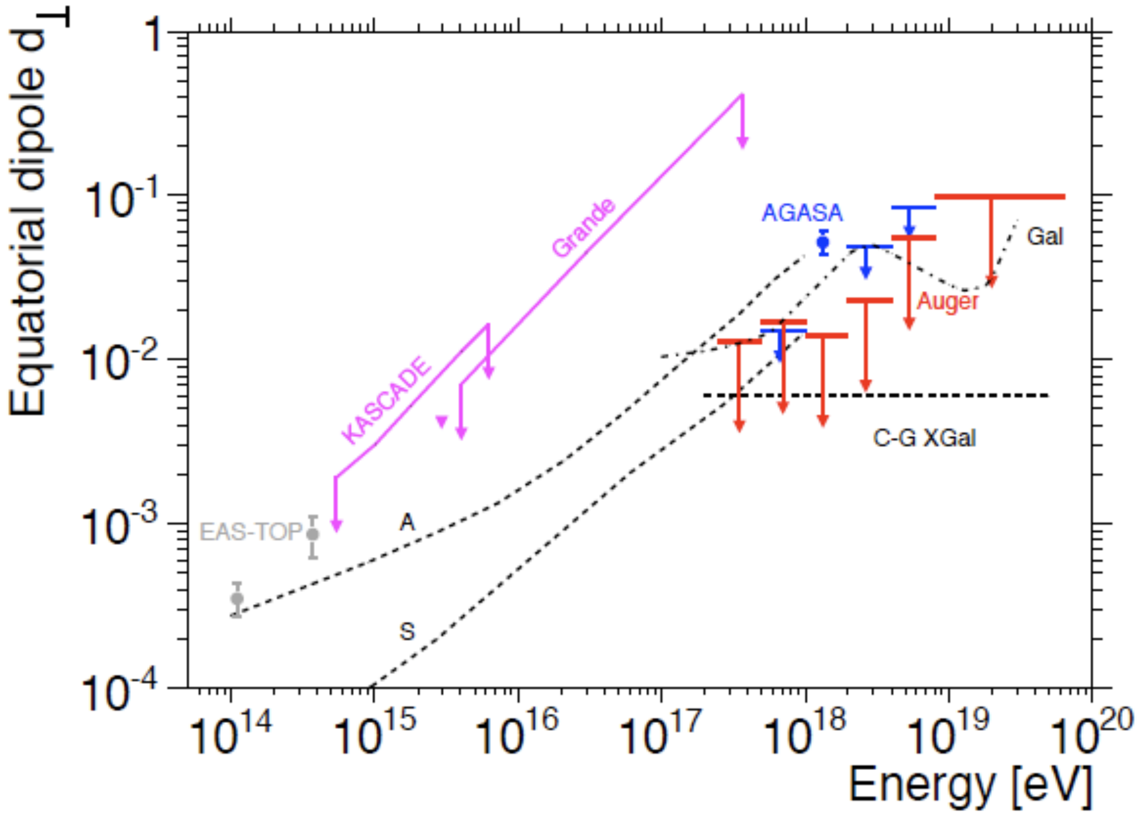


Regular and turbulent diffusion





Anisotropy dipole



Pierre Auger Collaboration, arXiv:1103.2721

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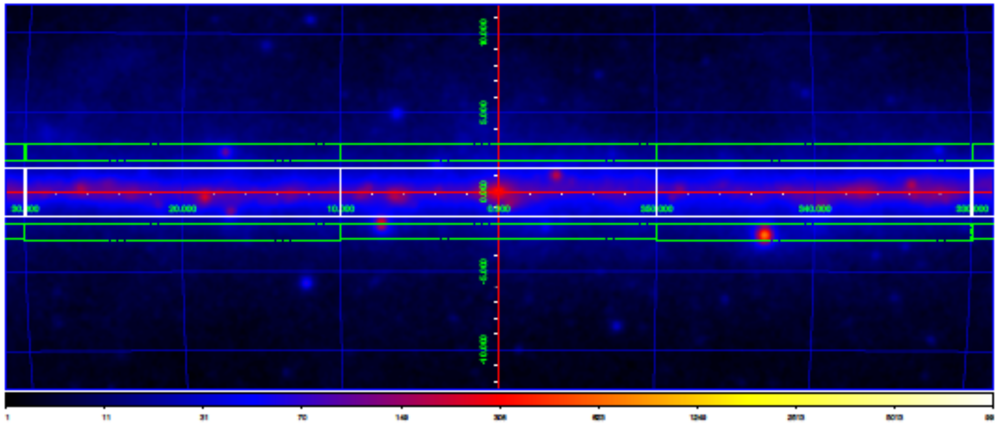
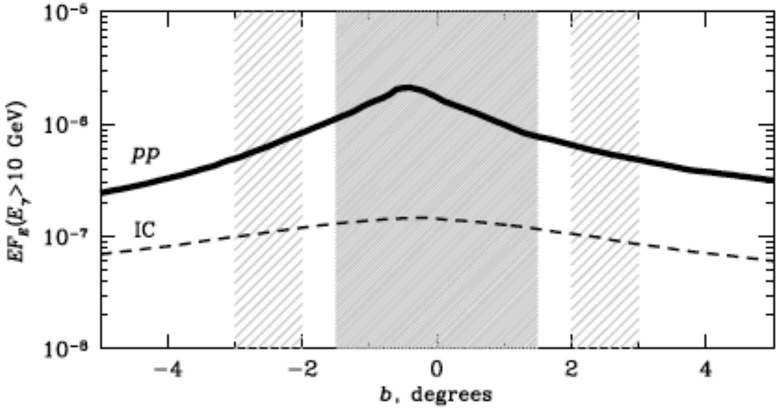
CR spectrum in MW and LMC from gamma-rays

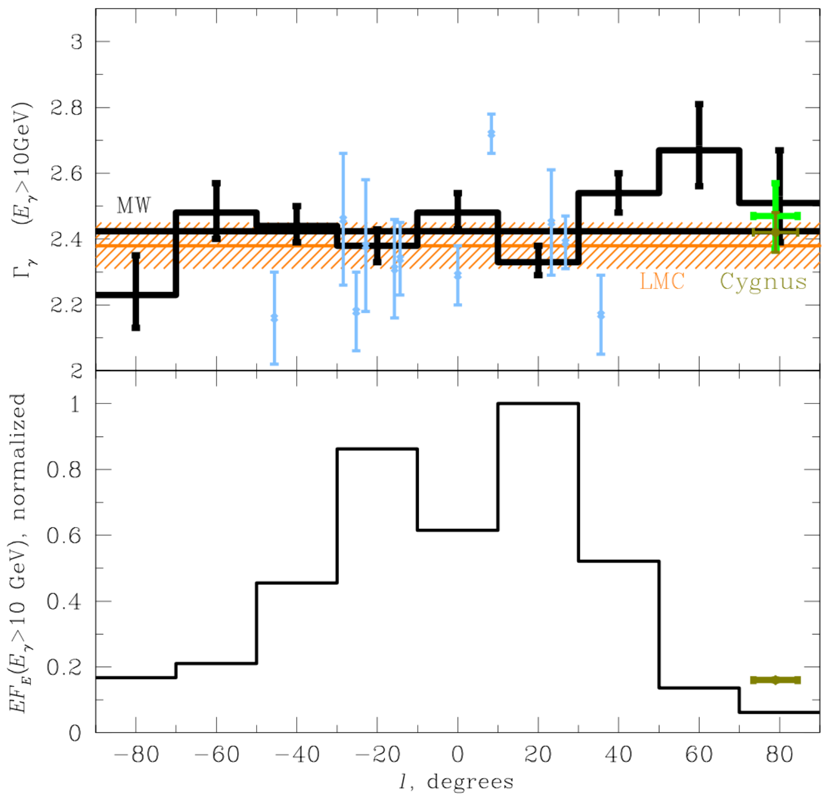
Milky Way inner Galaxy Fermi E>10 GeV

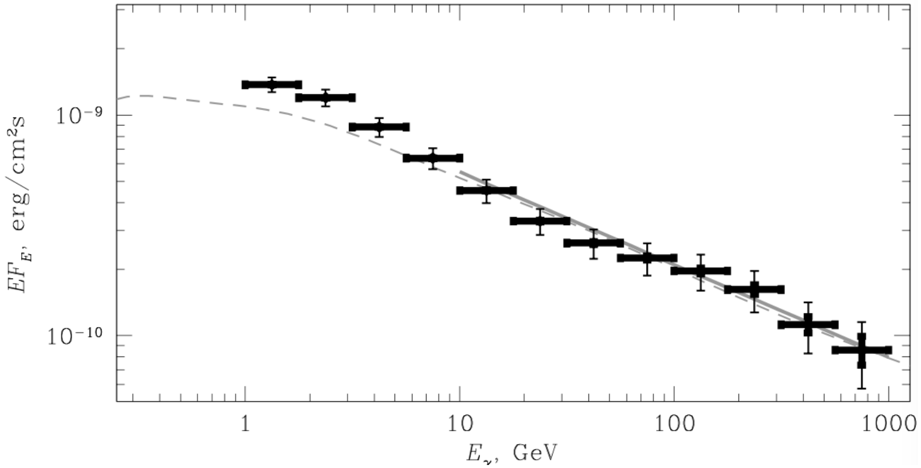




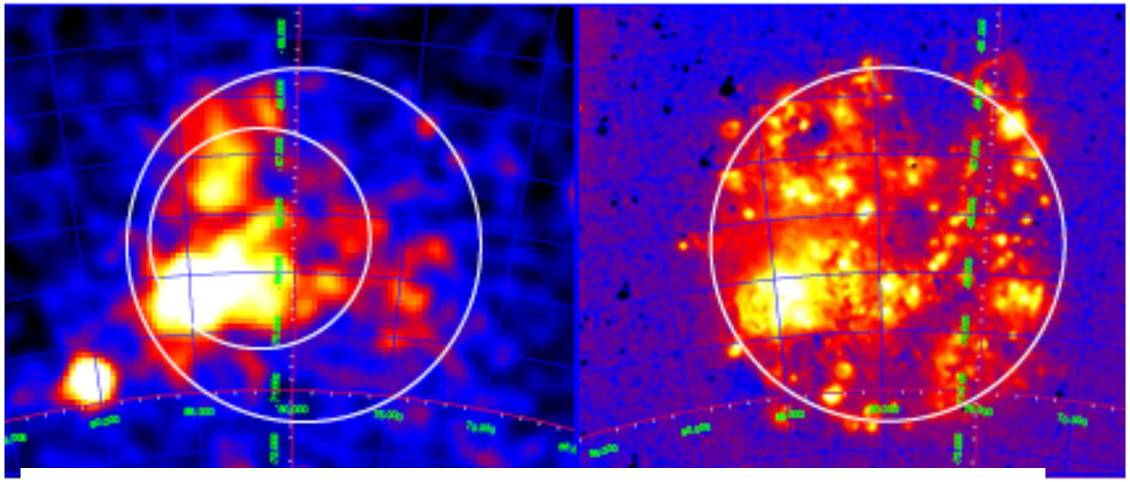
A.Neronov and D.Malishev, arXiv: 1505.07601

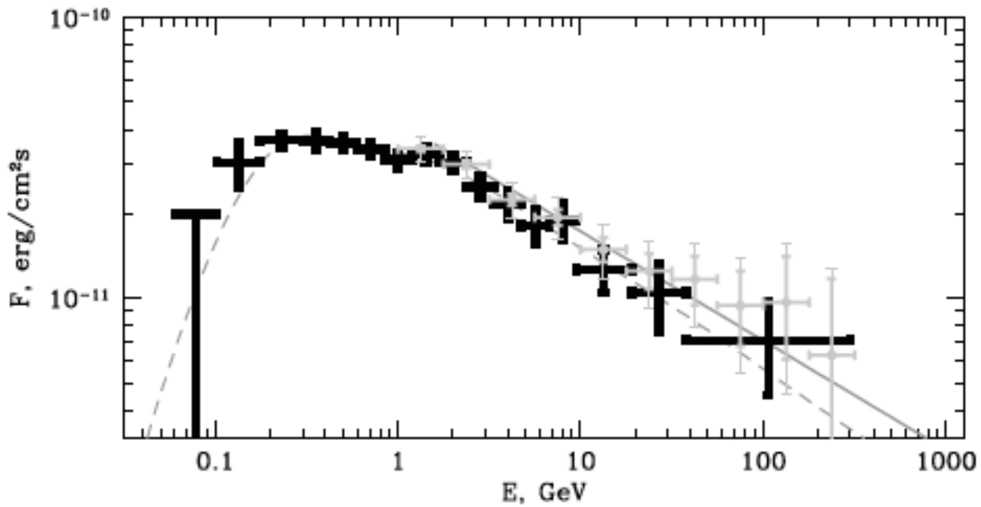
Milky Way inner Galaxy
Fermi E>10 GeV: spectrum 2.4





In LMC average proton spectrum 2.45





A.Neronov and D.Malishev, arXiv: 1505.07601

CR spectrum from astrophysical neutrinos

Pion production

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

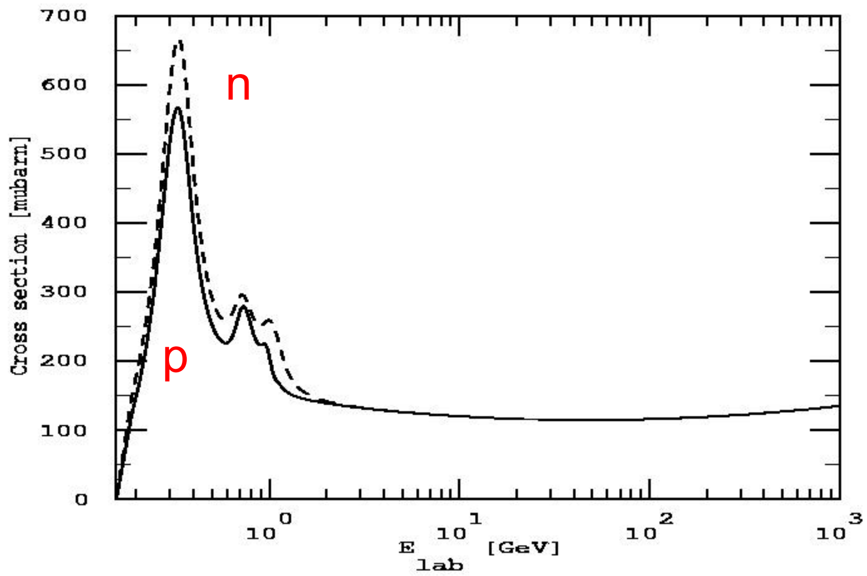
$$N + A_b \Rightarrow N' + \sum \pi^i$$

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

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

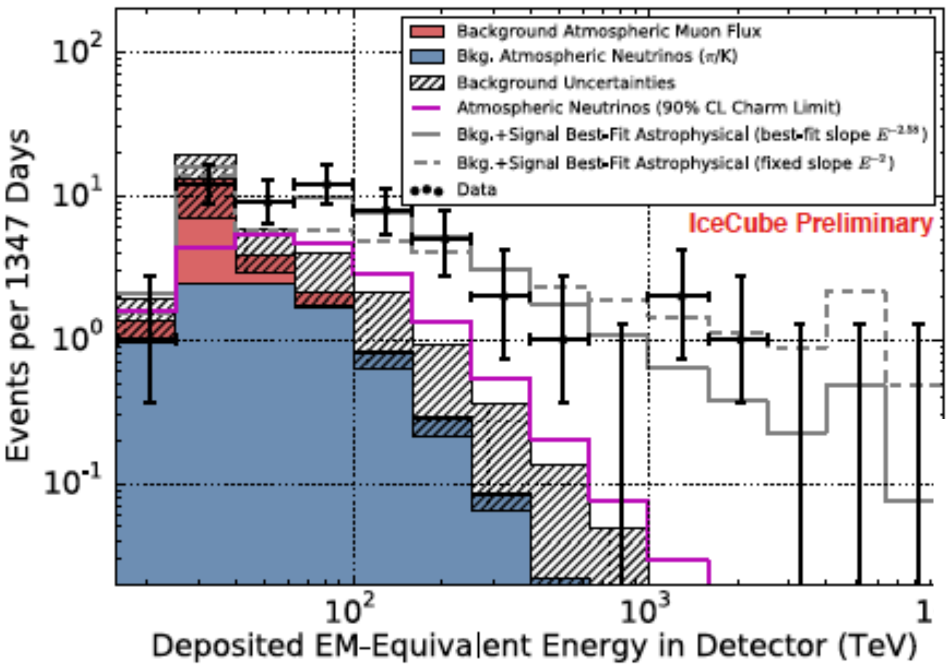
$$\mu^\pm \Rightarrow e^\pm + \overline{\nu}_e + \nu_\mu$$

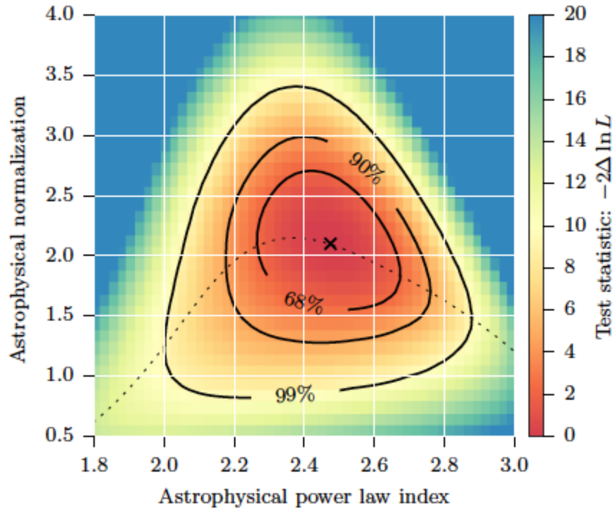
$$n \Rightarrow p + e^- + \overline{\nu}_e$$

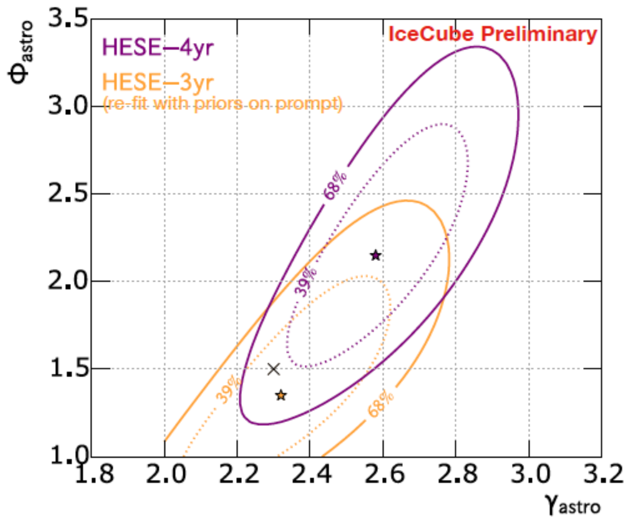


Conclusion: proton, photon and neutrino fluxes are connected in well-defined way. If we know one of them we can predict other ones: $E_\gamma^{tot} \sim E_\nu^{tot}$

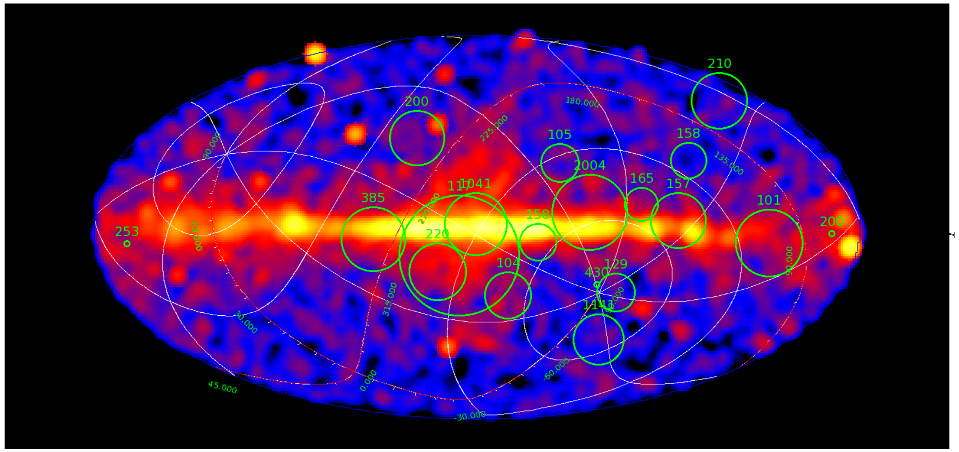
IceCube data 4 yrs

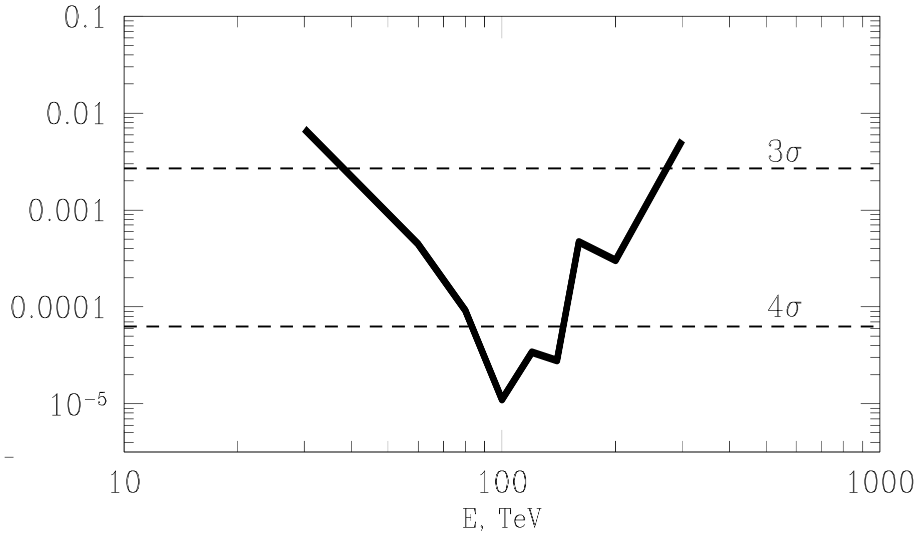






Evidence of Galactic component in 4 year IceCube data E>100 TeV

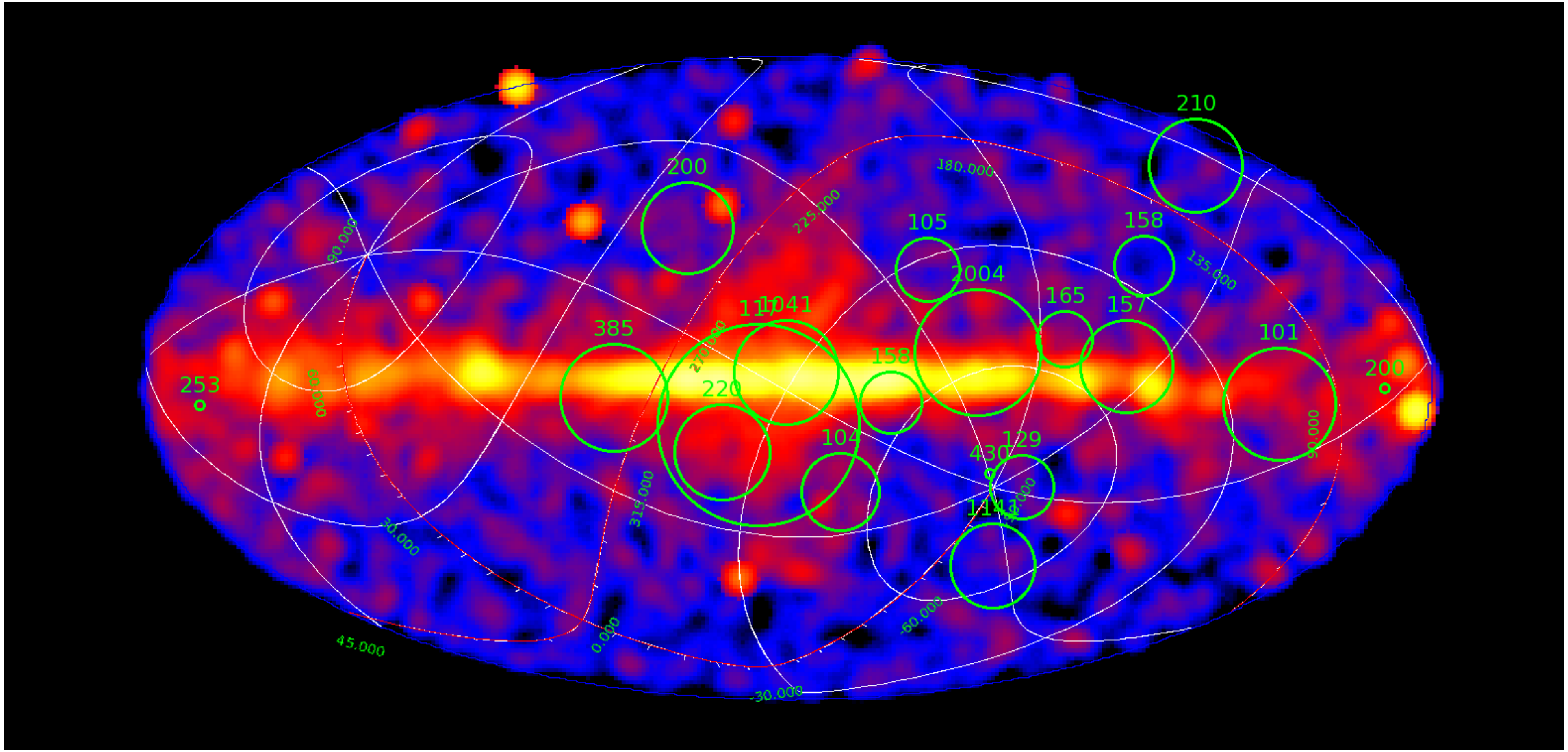




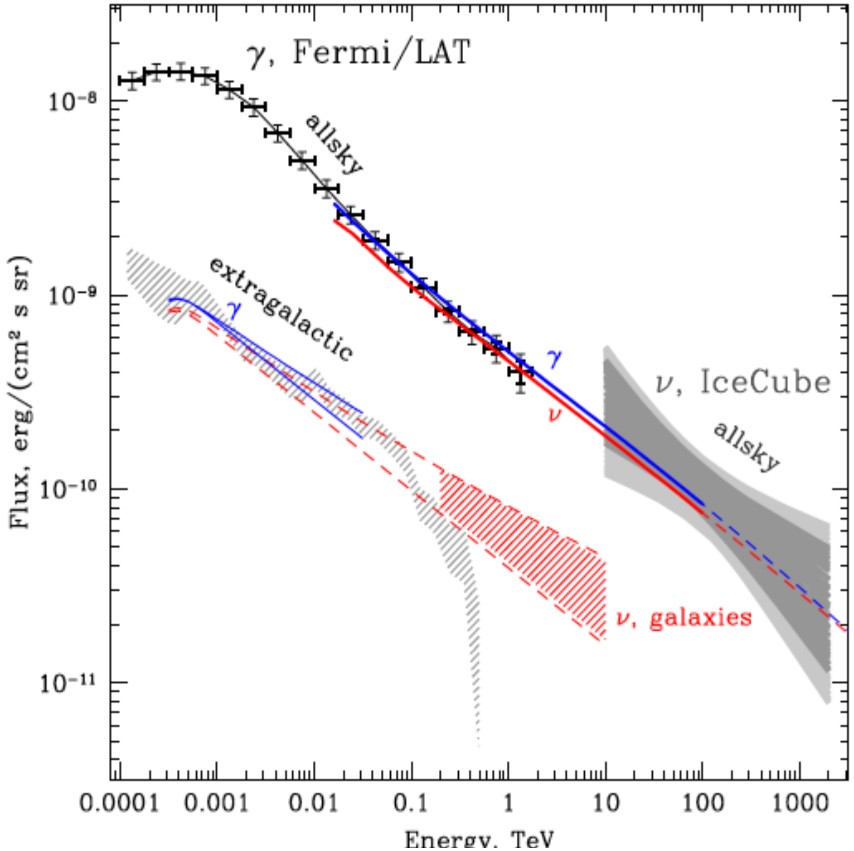
Post-trial probability is 1.7 * 10^{-3}

A. Neronov & D.S. arXiv: 1509.03522

IceCube neutrino sky map 4 years E> 100 TeV and Fermi E>100 GeV 5 degree smoothed



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



A.Neronov, D.S. arXiv:1412.1690

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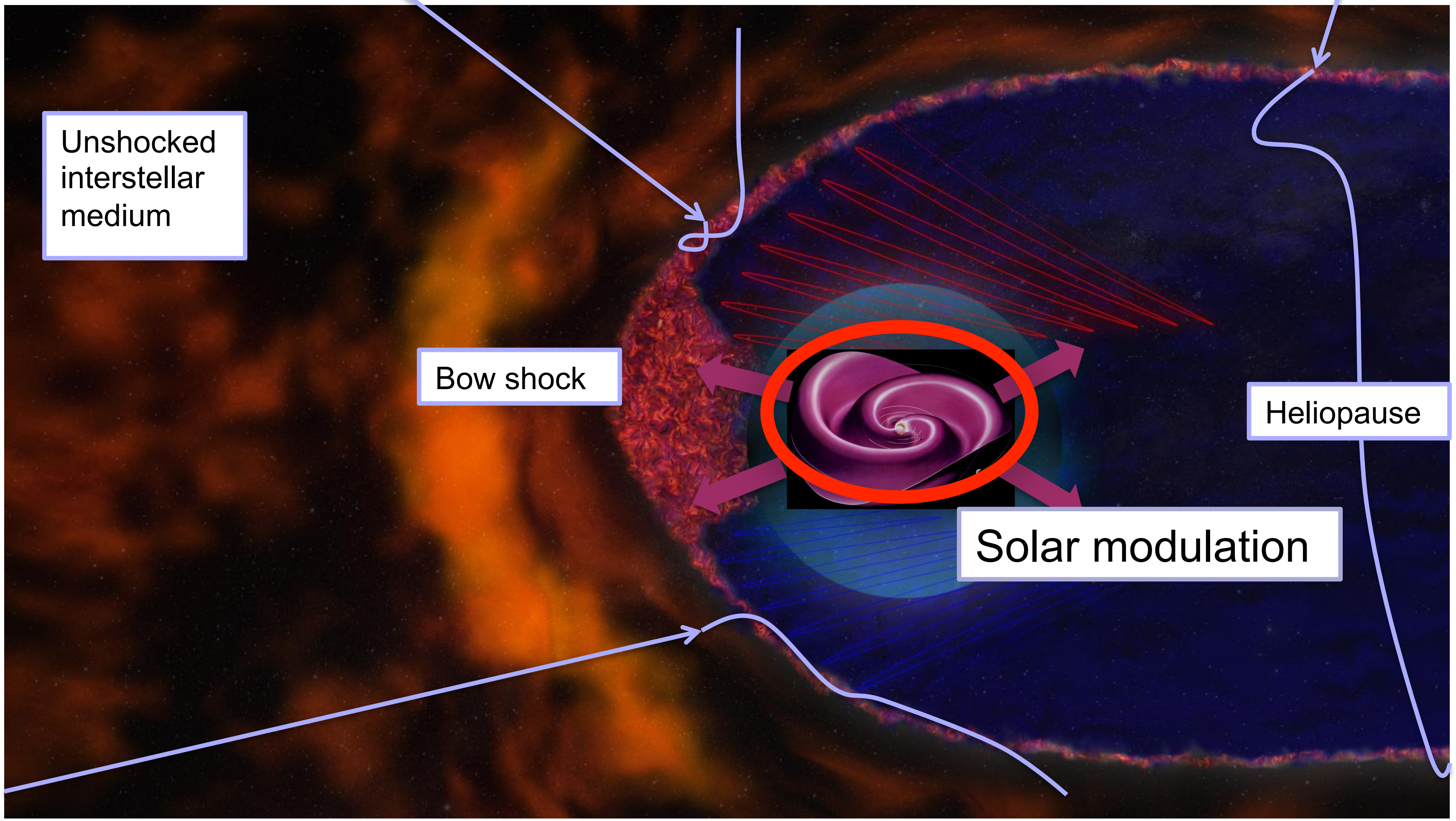
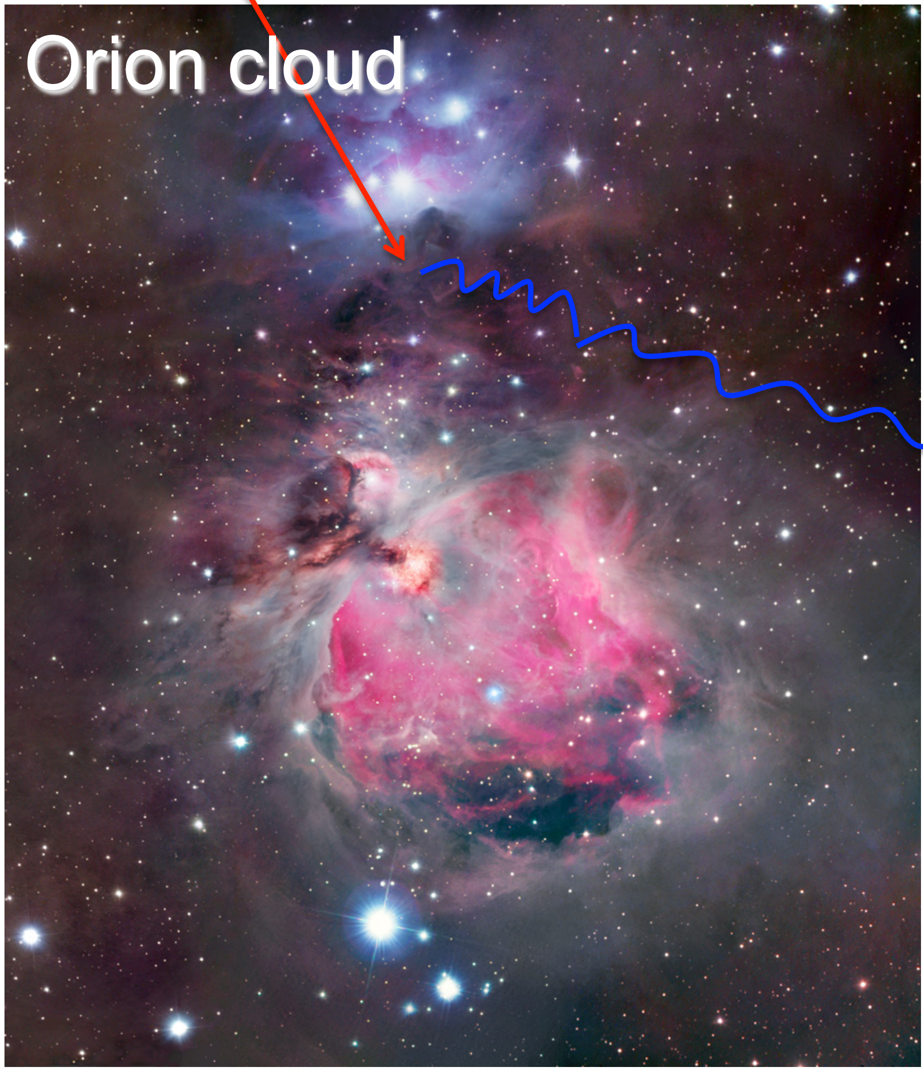
- *Spectrum is the same in all galaxy. It is as measured here 1/E^2.7*
- *Sources are frequent enough that CR are in steady state regime, no variation of fluxes in time*

Cosmic Rays in the Solar system



CR detectors outside the Heliosphere



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

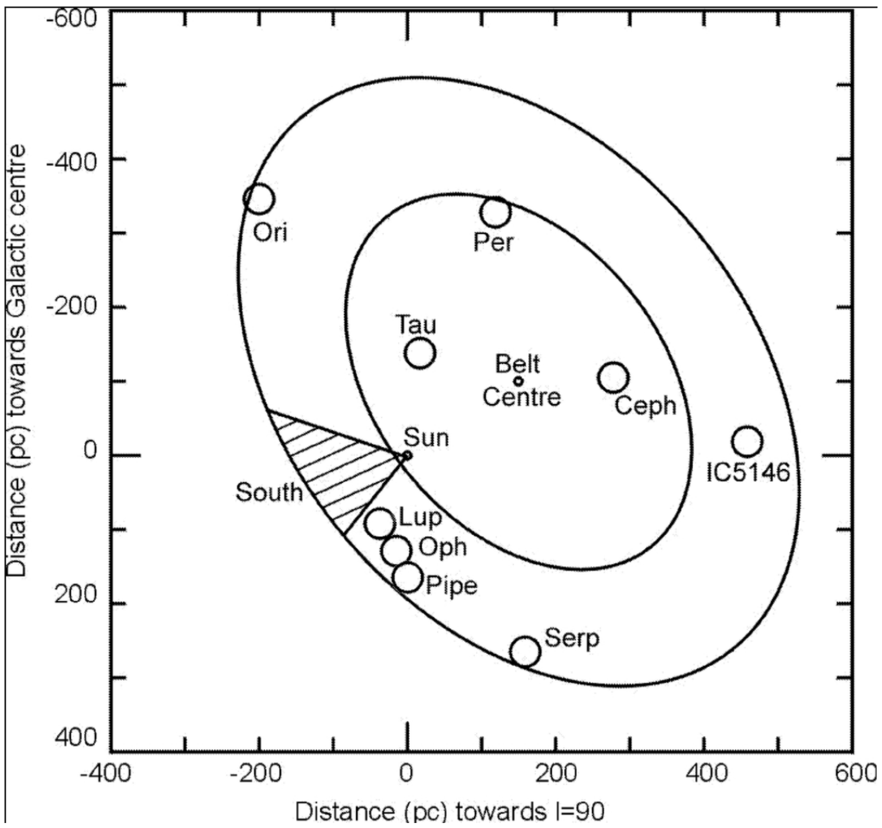
CRs diffusing through the ISM cross the GMCs on the time scales of $t \sim 10^3 - 10^4$ yr.

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

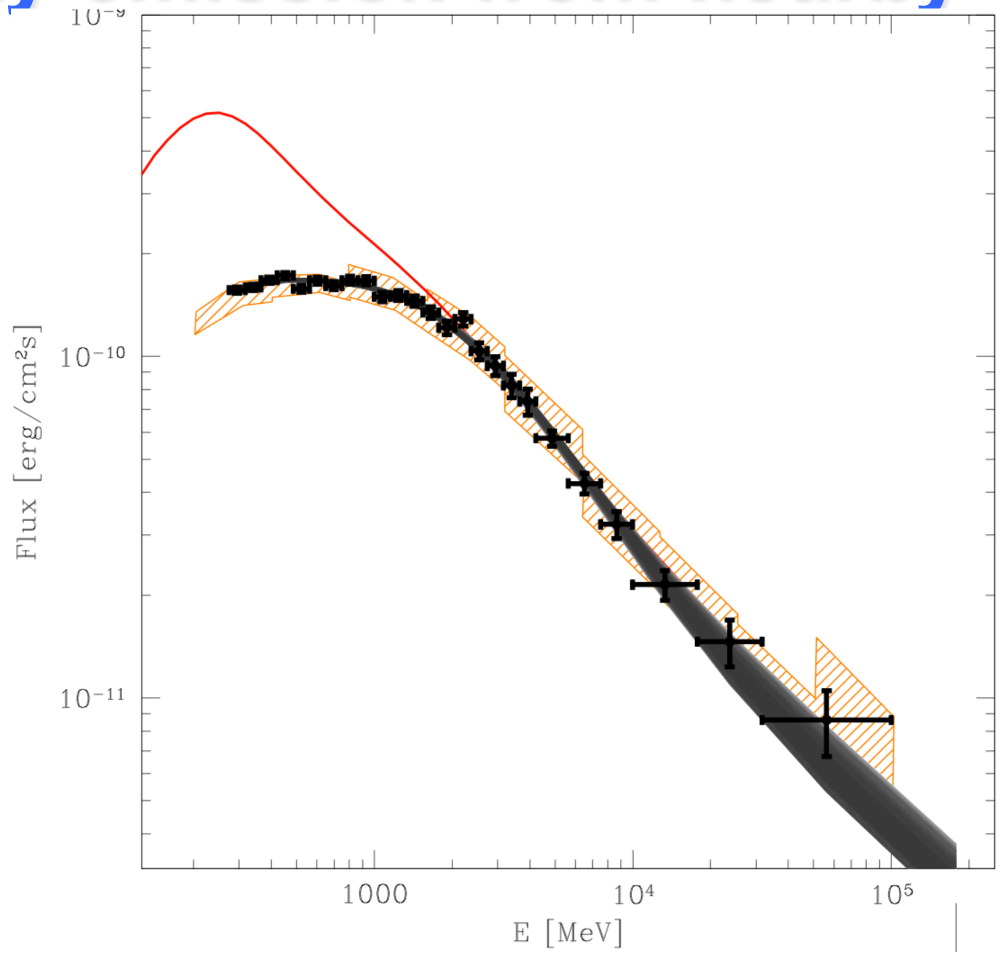
CR interaction in the GMCs lead to the gamma-ray emission (from neutral pion production and decay).

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

Gould belt clouds



Gamma-ray emission from nearby GMCs



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

Gamma-ray emission from nearby GMCs

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

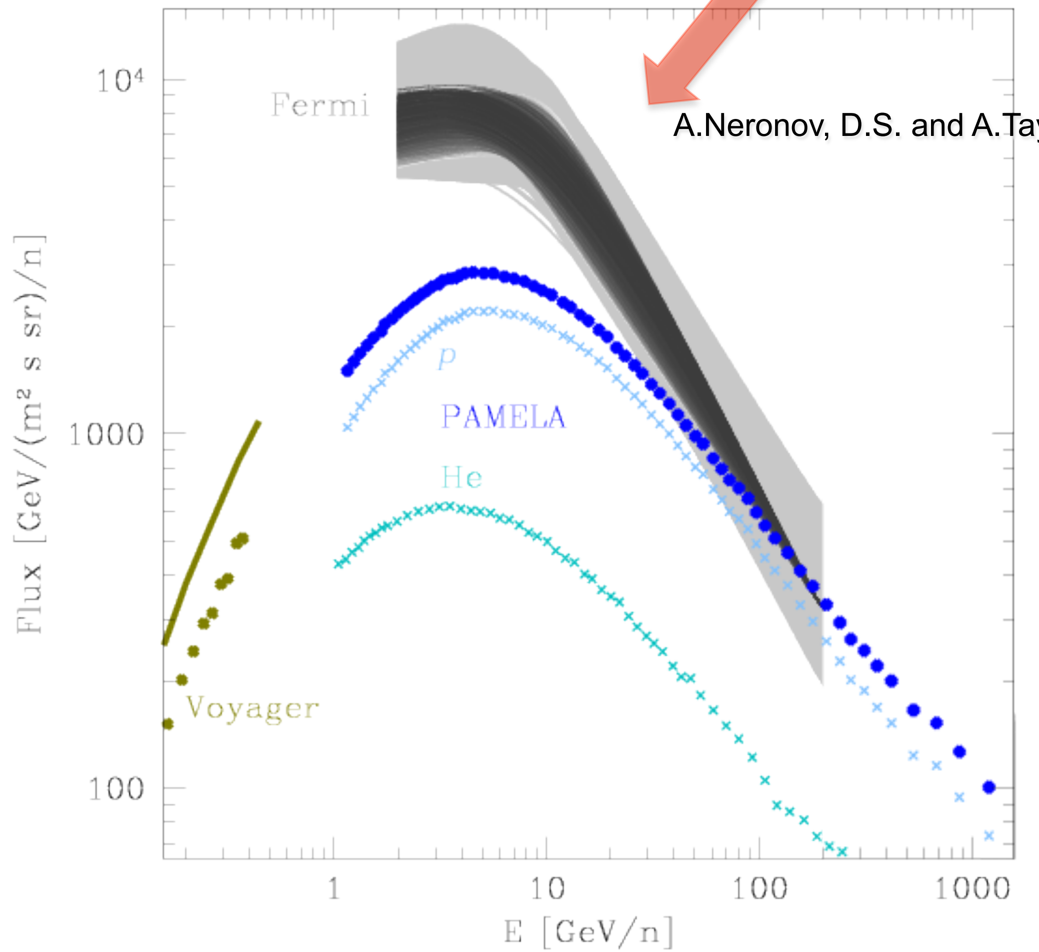
$$\begin{aligned} \frac{E_\gamma^2\, dN_\gamma}{dE_\gamma} &\propto E_\gamma^2 \int_{E_\gamma}^{E_{\rm max}} dE' \, \frac{dN_{\rm CR}}{dE'} \, \frac{d\sigma^{pp\to\gamma}(E', E_\gamma)}{dE_\gamma} \\ &\propto E_\gamma^{2-\beta_{\rm CR}} \int_0^1 dx_E \, \frac{x_E^{\beta_{\rm CR}-1}\, d\sigma^{pp\to\gamma}(E_\gamma/x_E,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

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

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.

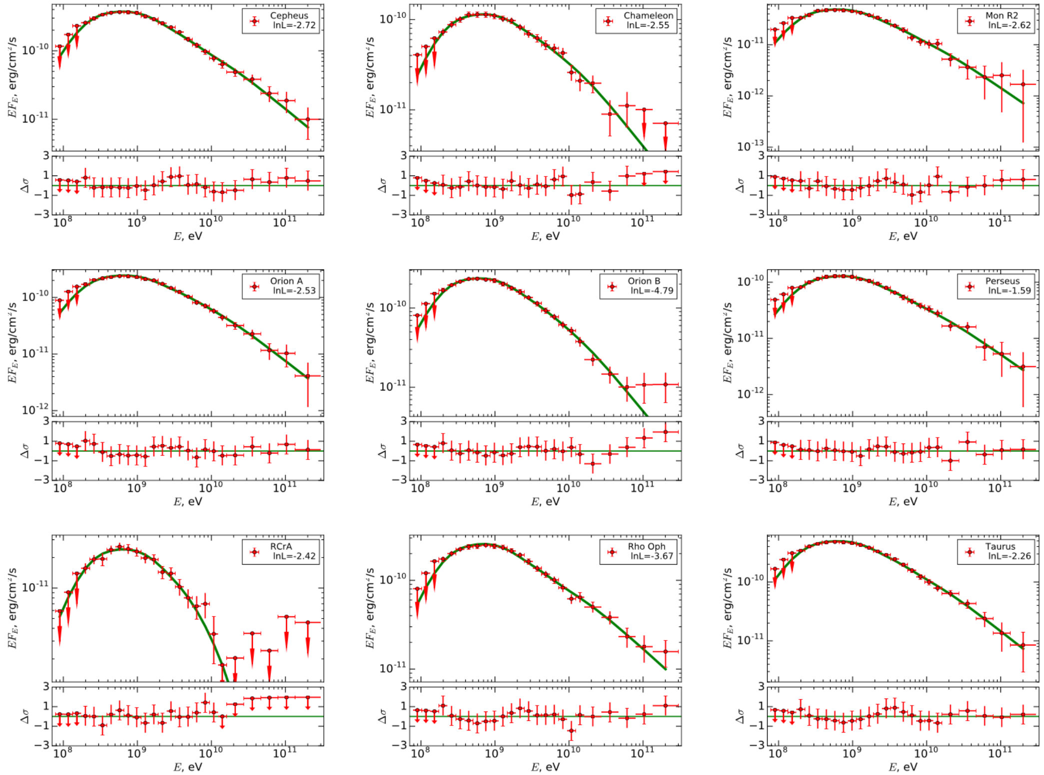
Galactic cosmic ray spectrum

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?



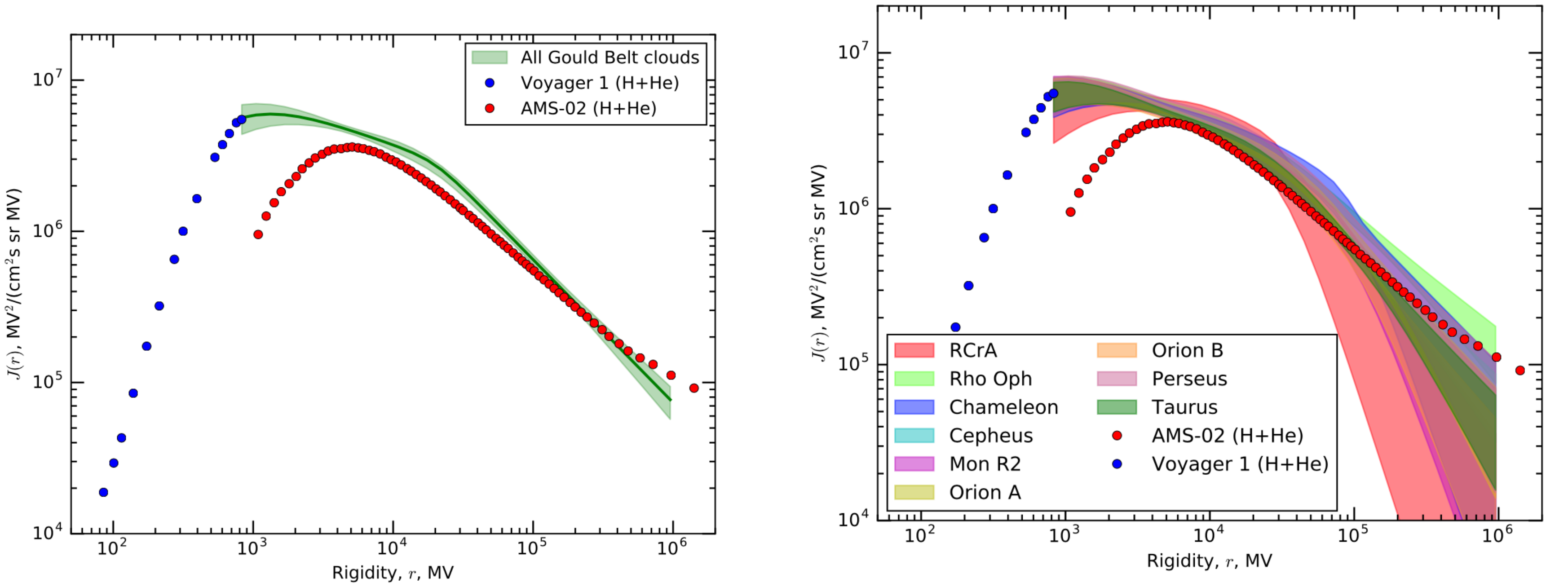
A.Neronov, D.Malyshev & D.S. 1705.02200

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



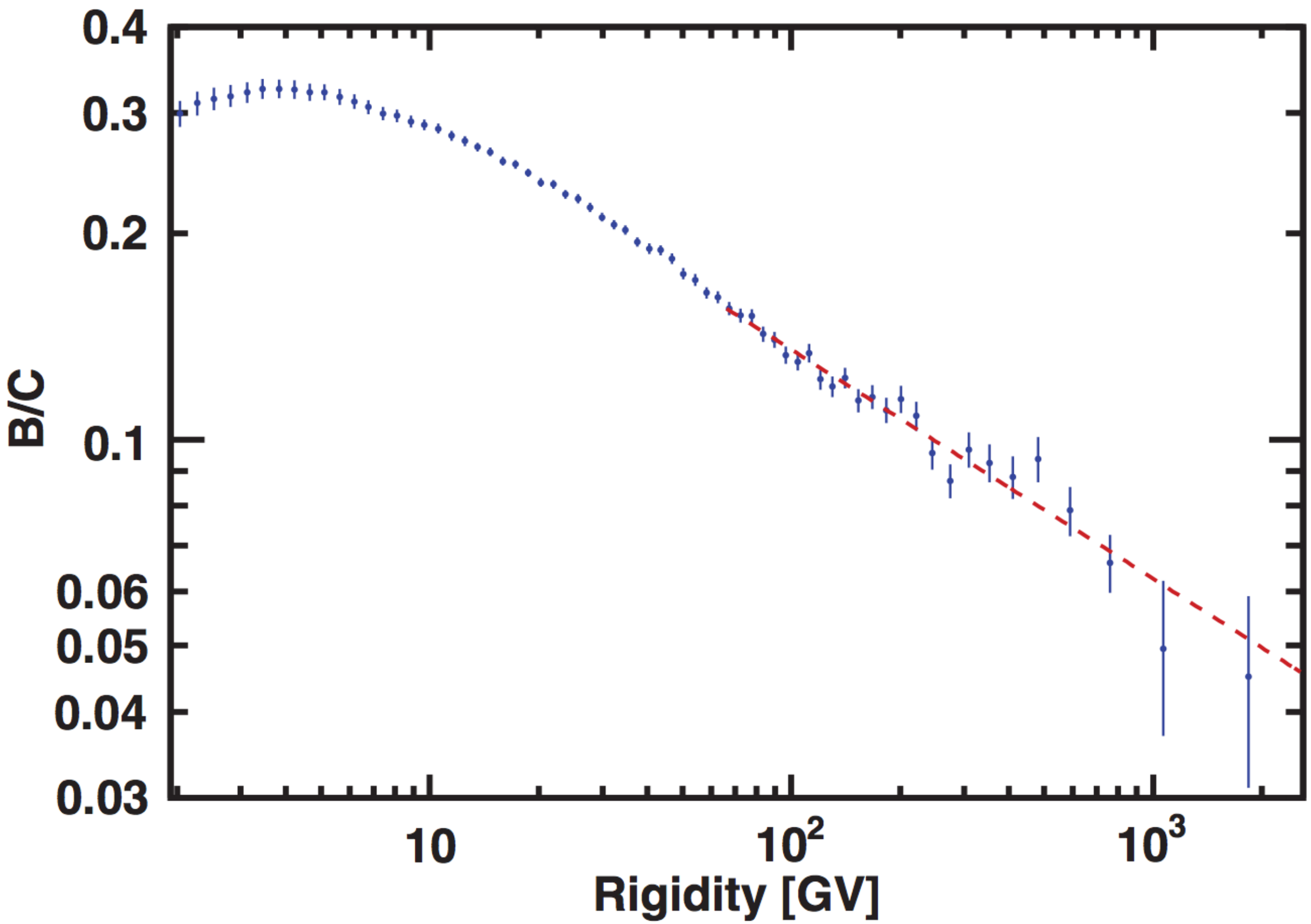
Sources locally can not support steady state regime above 30 GeV.
In central galaxy it is OK up to 300 GeV or above

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)

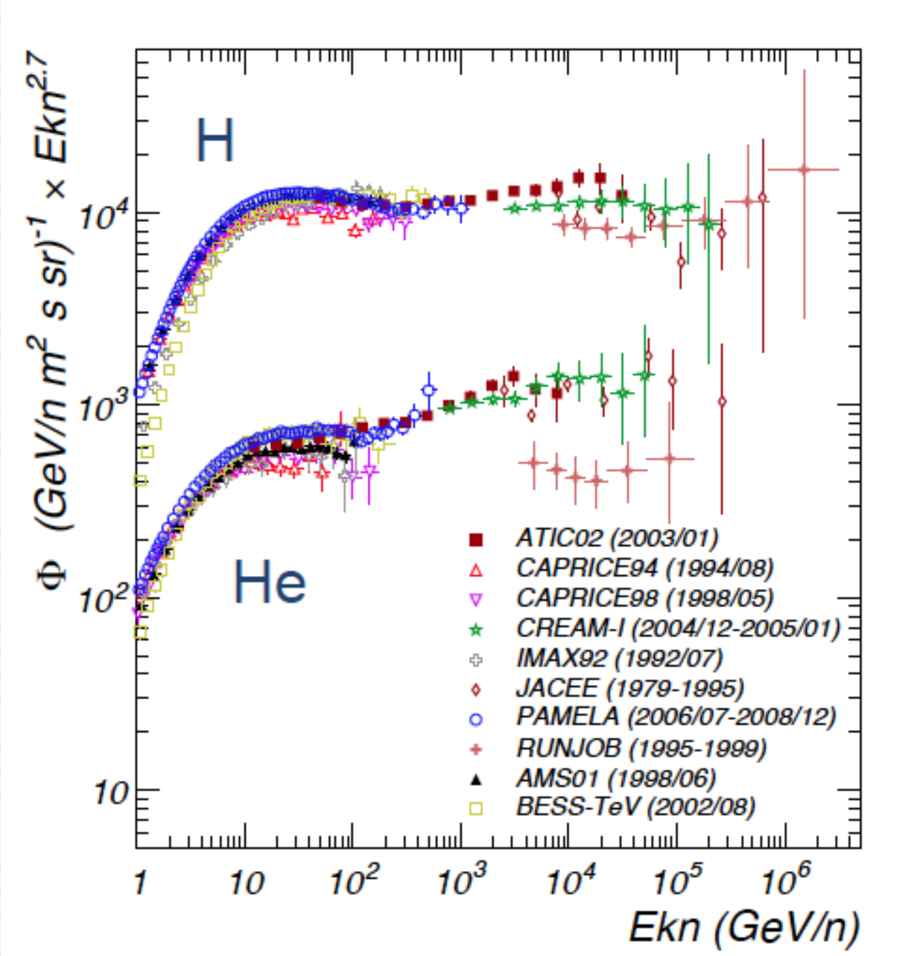


Delta=1/ 3 Kolmogorov Turbulence

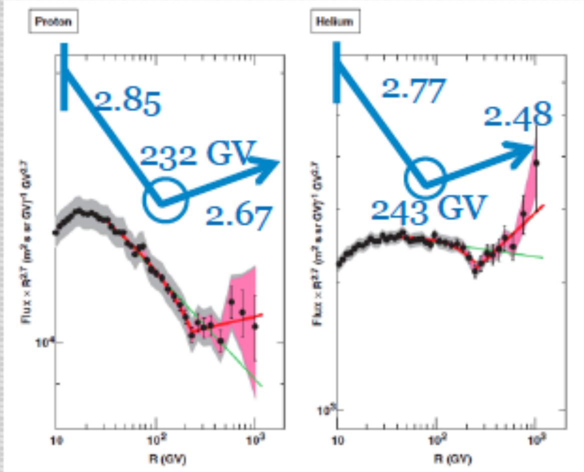
Predictions of the model

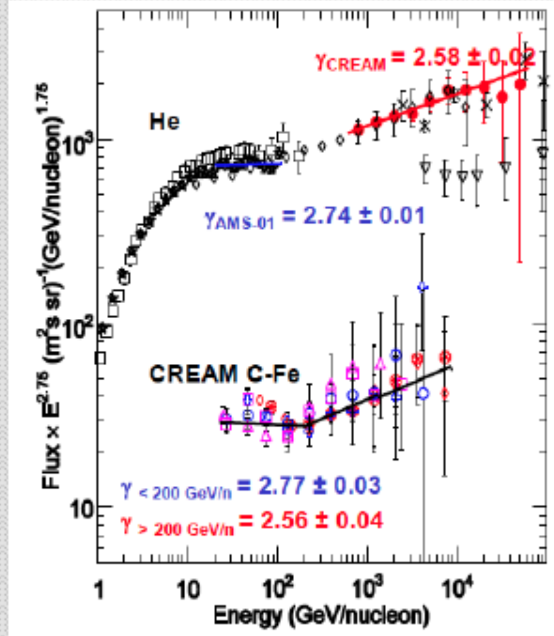
- *Spectrum is the same in all galaxy 1/E^2.7: Since accelerated spectrum is 1/E^2 or 1/E^2.2 magnetic field turbulence is Kreichnan with delta=0.5*
- *Spectra of all nuclei same as one of proton rescaled by regidity R=p/Z*

p/He spectra



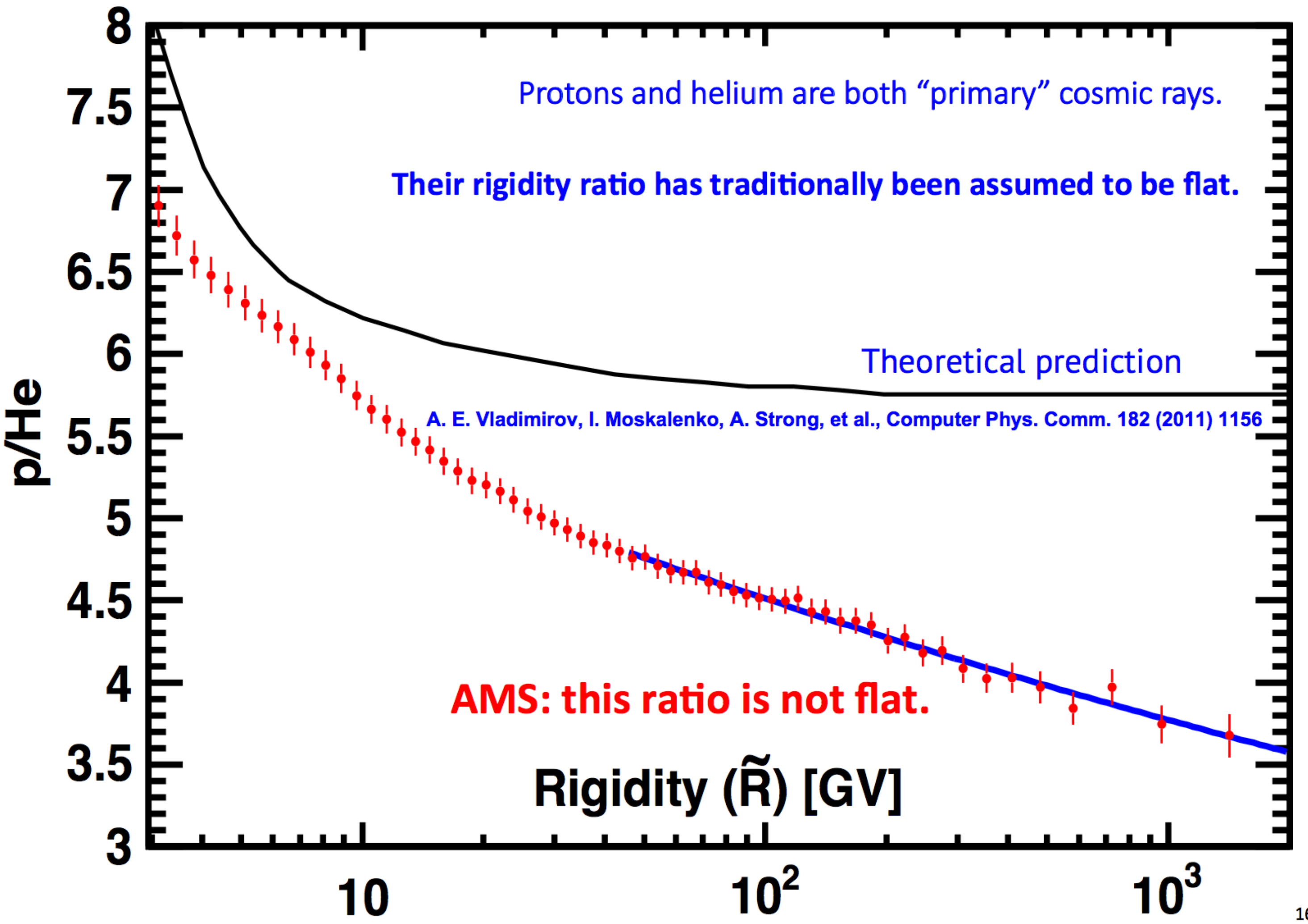
Adriani, Science 32,69 (2011)



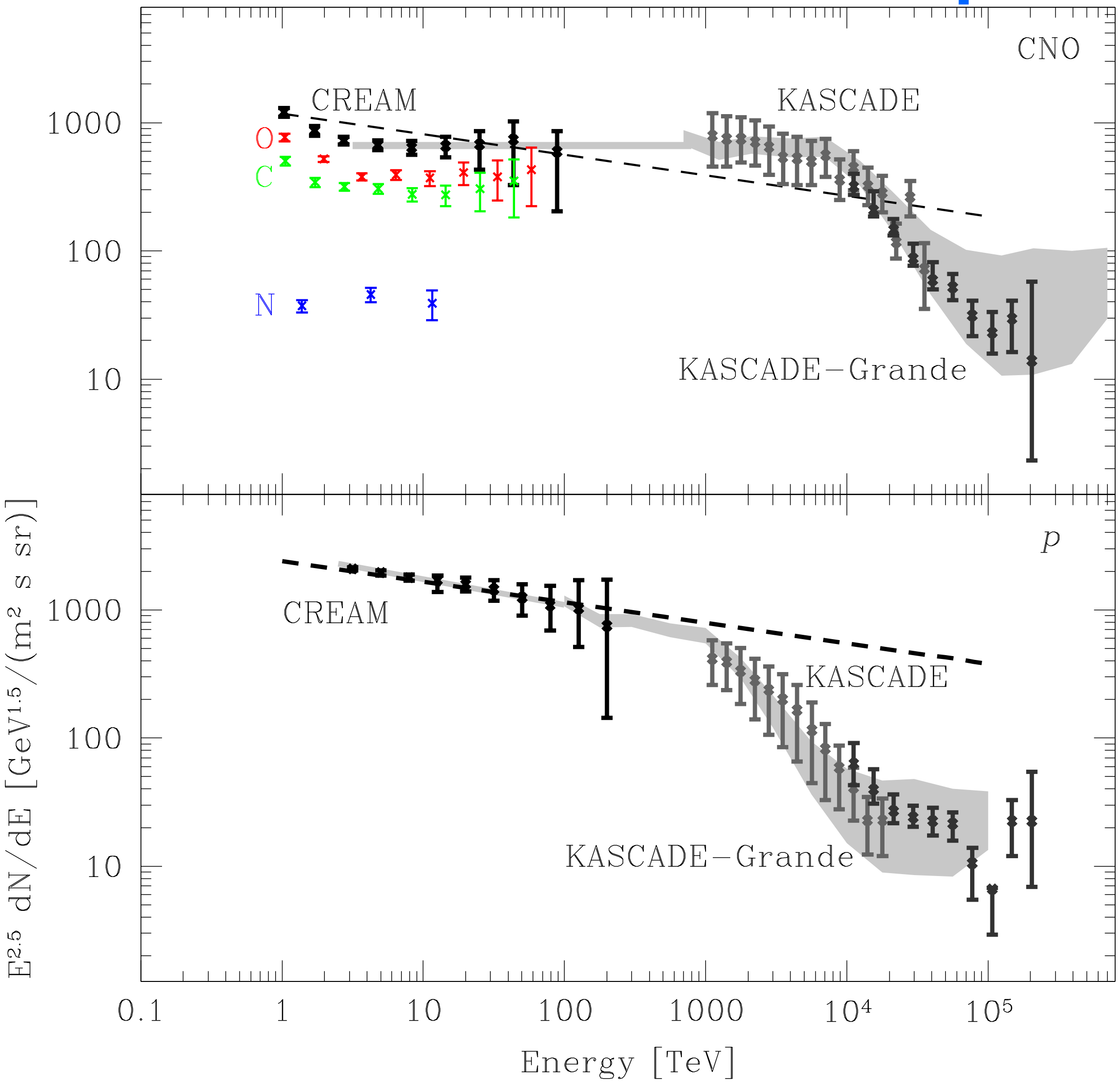


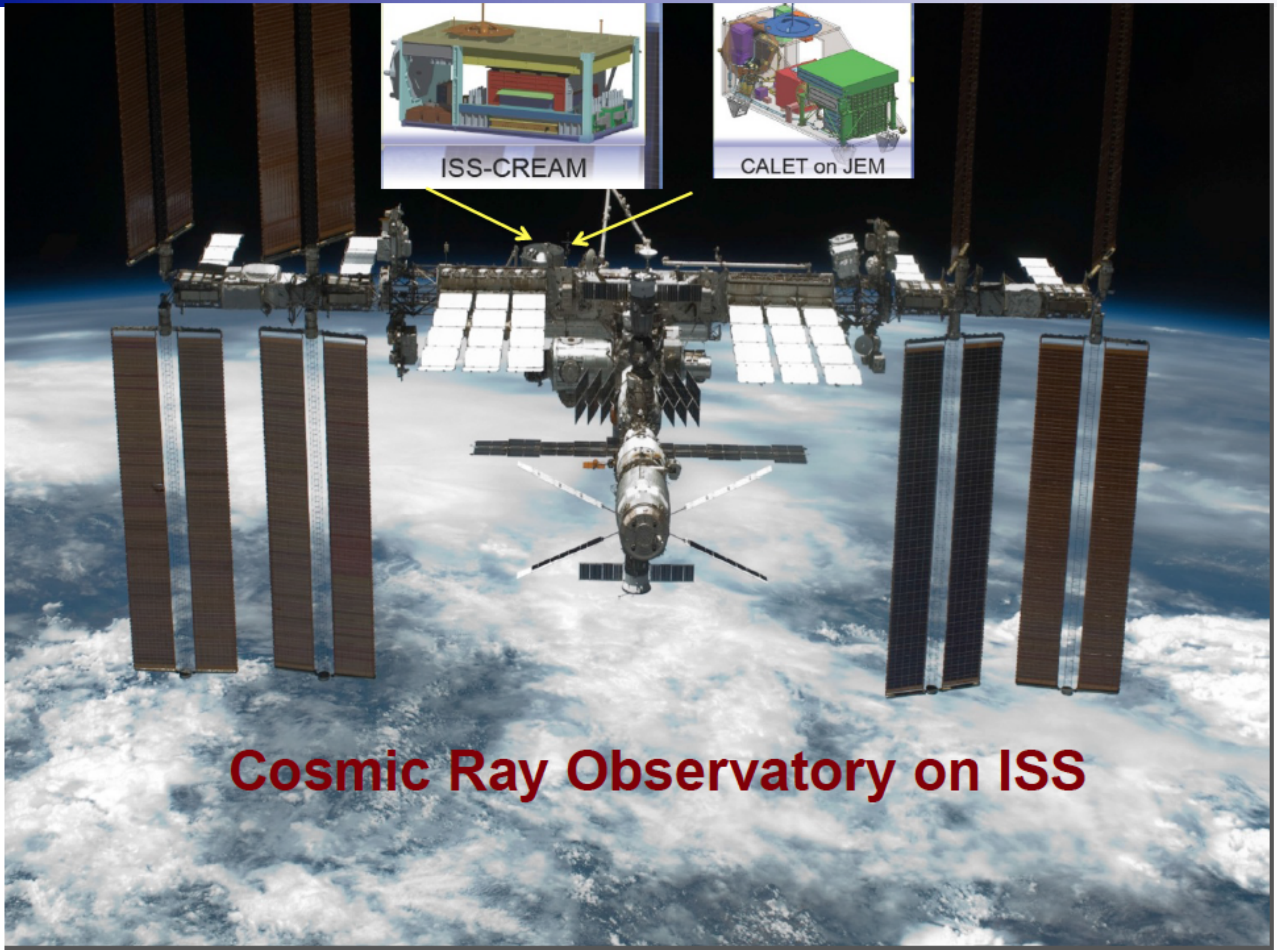
Still waiting for full CREAM statistics
AMS-02 publication soon….(< 2015)

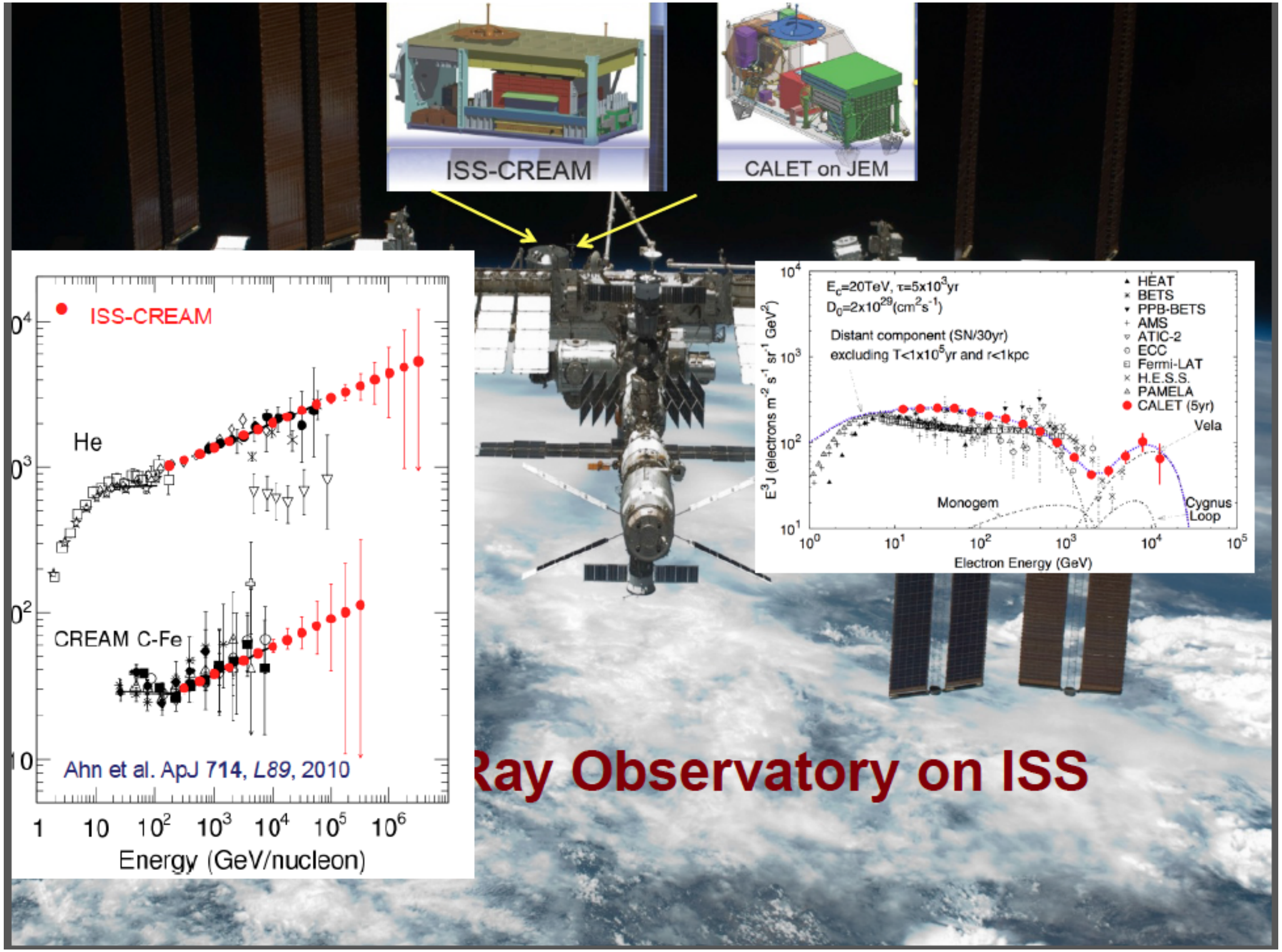
The AMS proton/Helium flux ratio



Proton and CNO spectra

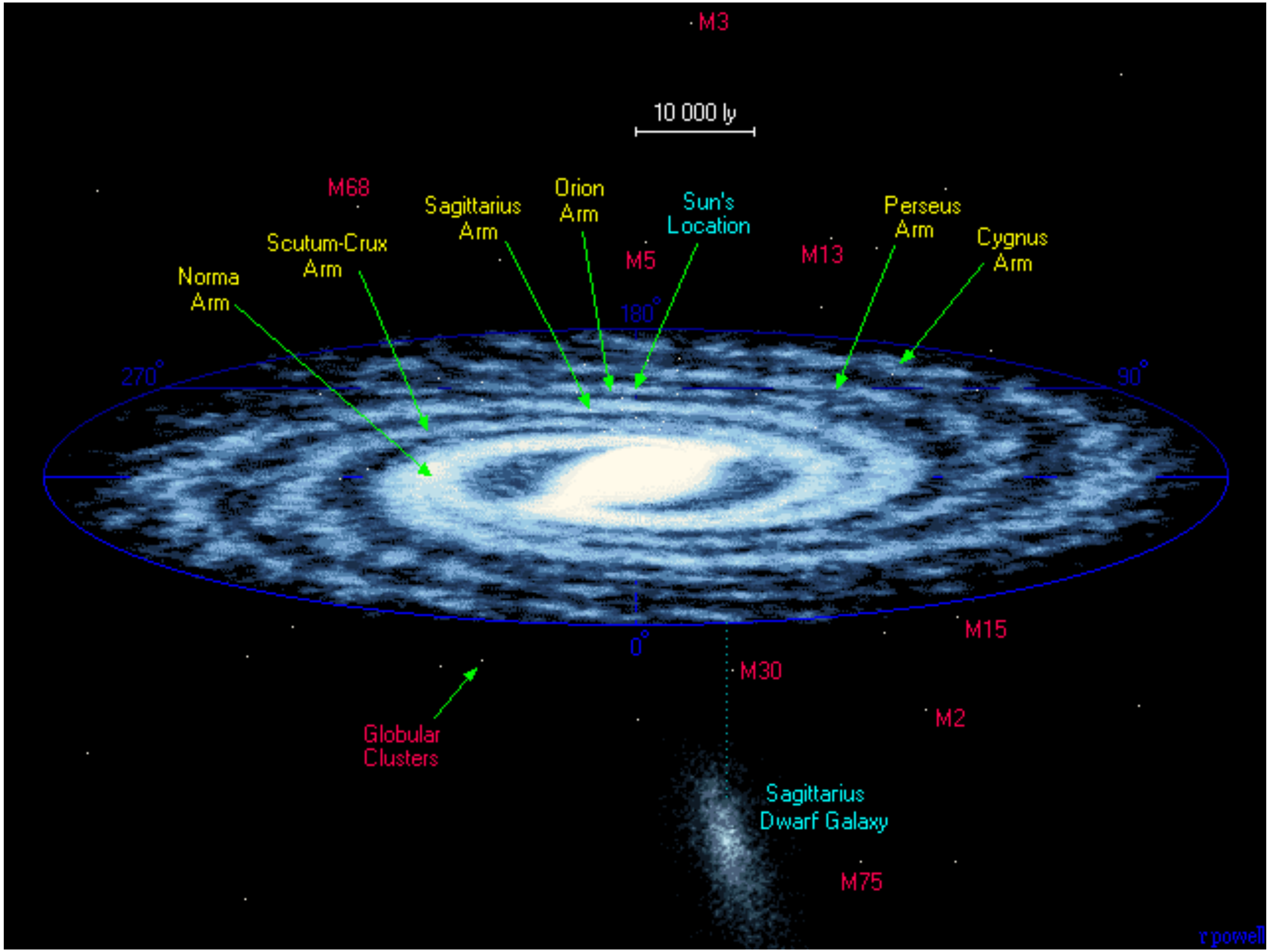



ISS-CREAM
CALET on JEM
Cosmic Ray Observatory on ISS



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
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)

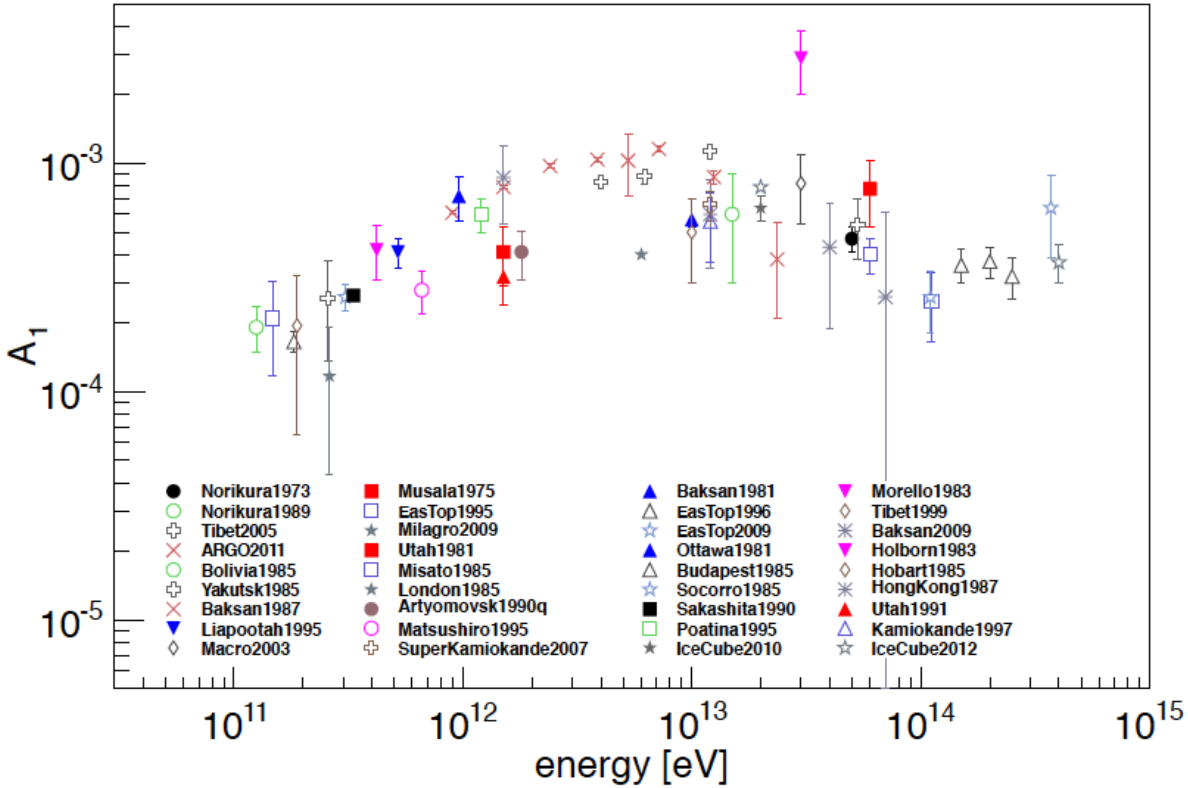
MILKY WAY GALAXY



Predictions of the model

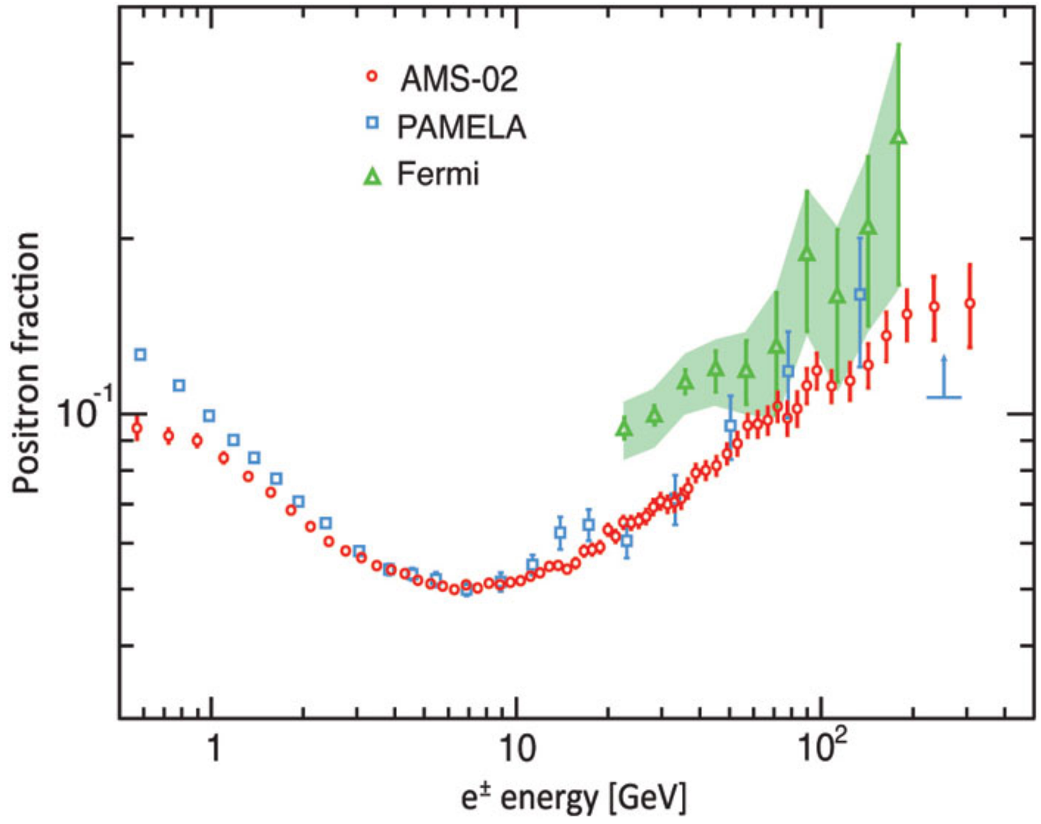
- *Because higher energy cosmic rays escape faster from Galaxy:*
  - *anisotropy is growing function of energy*
  - *Secondary fluxes drop relative to primary fluxes: positron and anti-proton fluxes should drop if compared to proton flux*

Dipole anisotropy of cosmic rays

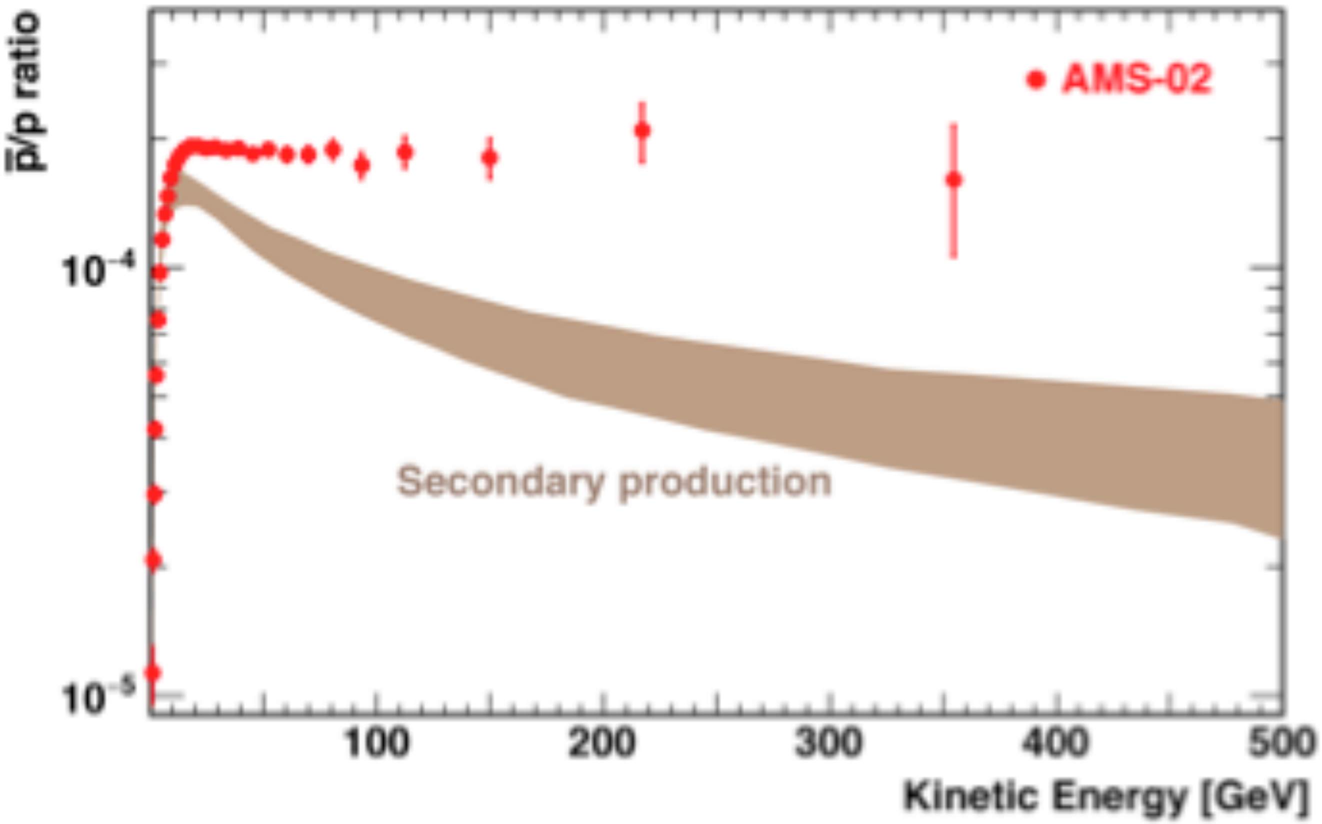


G.Di Sciascio and R. Iuppa, arXiv: 1407.2144

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



Antriprotons by AMS-2



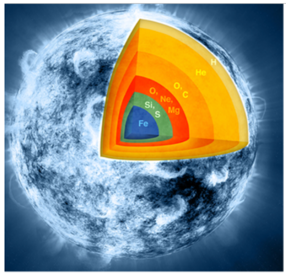
Problems of galactic cosmic rays

- *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

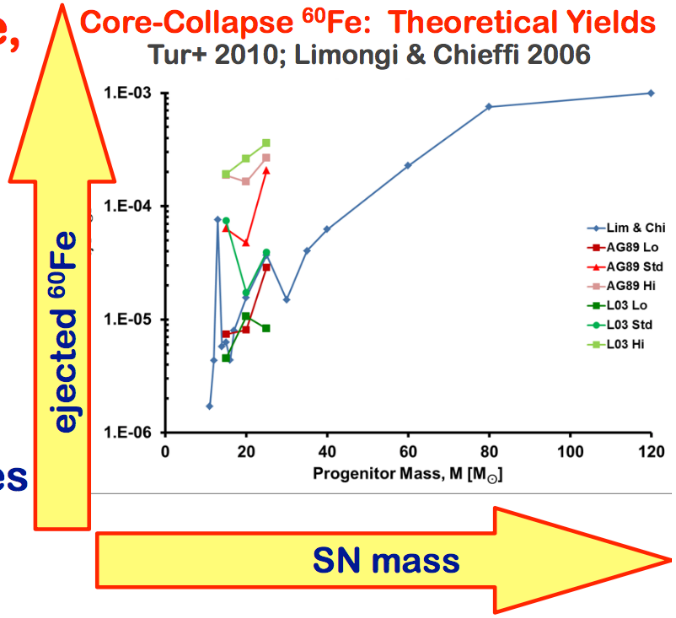
- *Models can not explain plateau in dipole anisotropy*
- *Too many positrons at high energy: Dark Matter, pulsars?*
- *There is excess in antiproton spectrum*

Fe60 from nearby source

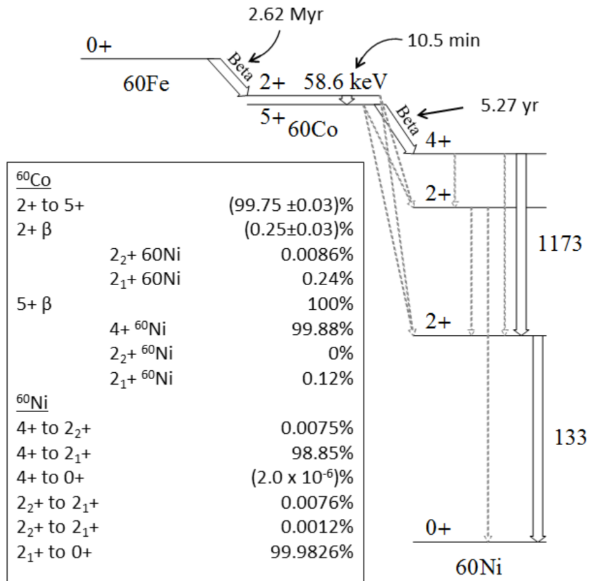


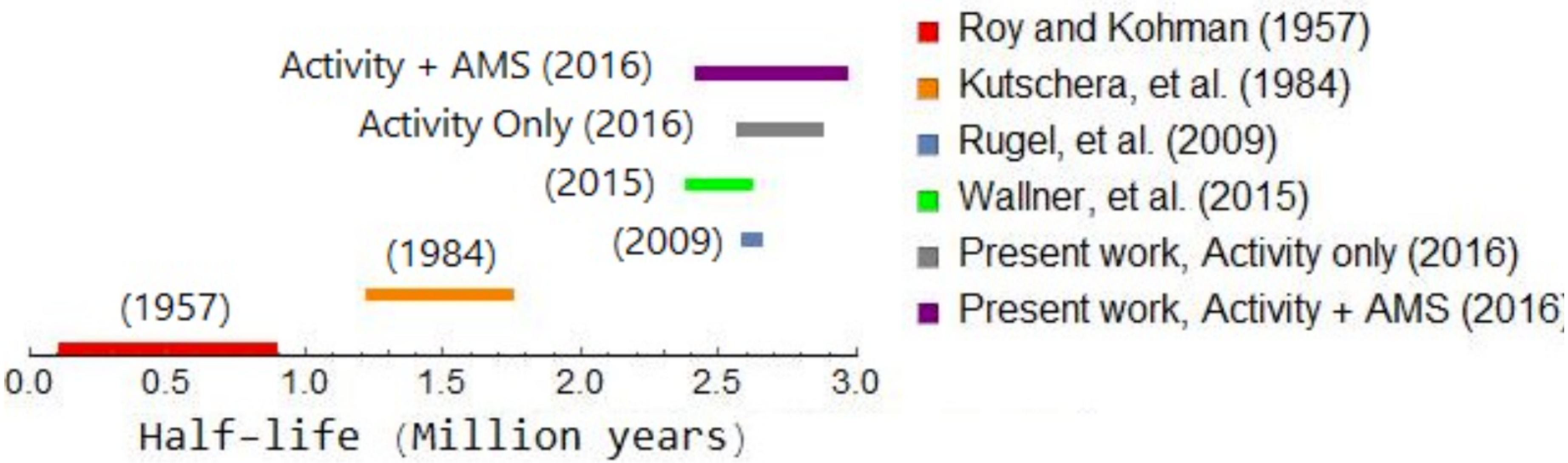
Supernovae are Radioactivity Factories

- 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 $d_{\text{SN}} > 10 \text{ pc}$ ⇨ $r_{\text{shock}} > 1 \text{ AU}$?

- gas-phase SN debris excluded from Earth

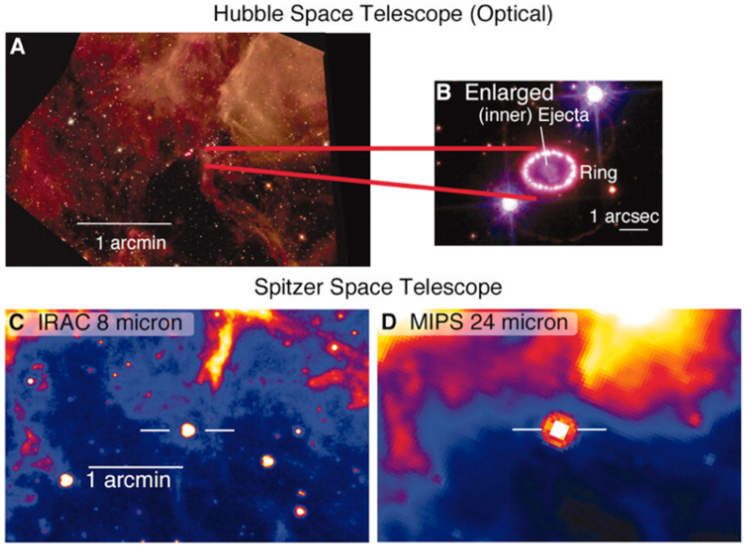
But SN radioisotopes all are refractory elements ⇨ dust grains

SN1987A:

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

SN dust reaches Earth even if gas does not

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



SN1987A dust: Matsuura+ 2011

Deep Ocean Crust

Knie et al. (1999)

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

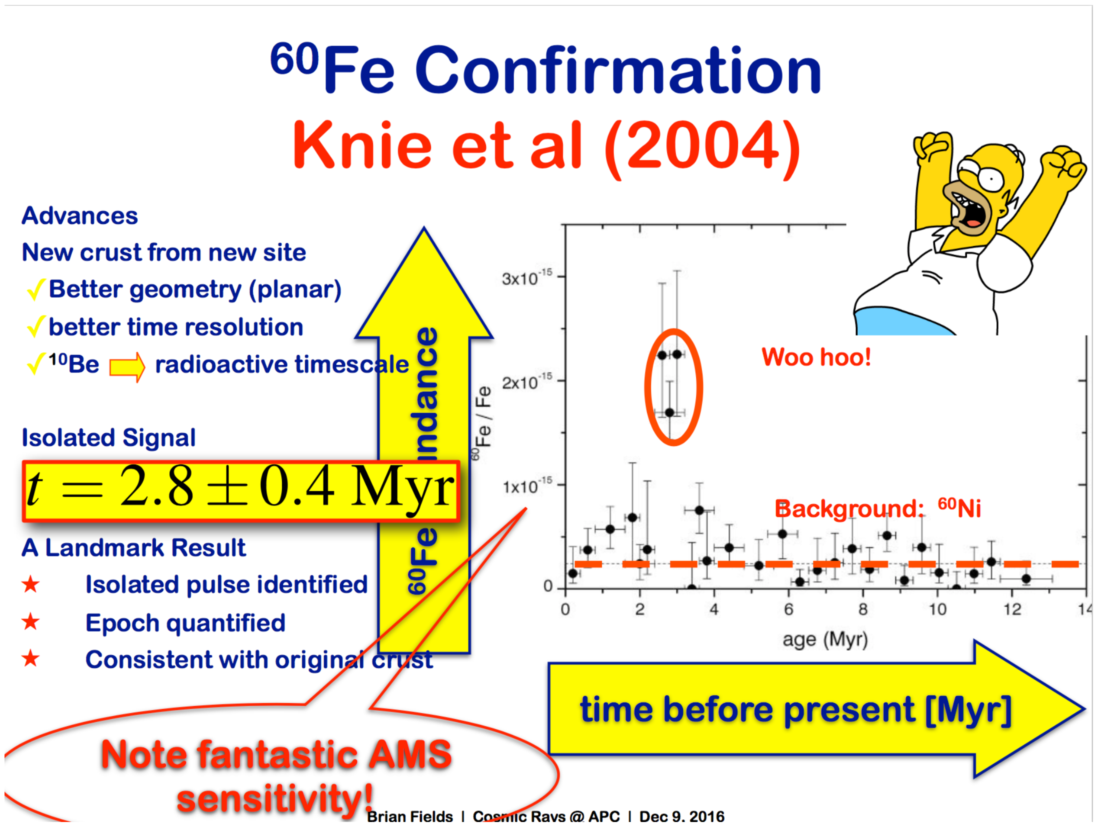
AMS ⇨ live ^{60}Fe, $\tau_{60} = 2.6\ \mathrm{Myr}$!

Expect: one radioactive layer

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

- detectable signal exists
- but not time-resolved


Geological Signatures
Brian Fields | Cosmic Rays @ APC


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

Whodunit?

Fry, BDF, & Ellis 2015

Turn the problem around:

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

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

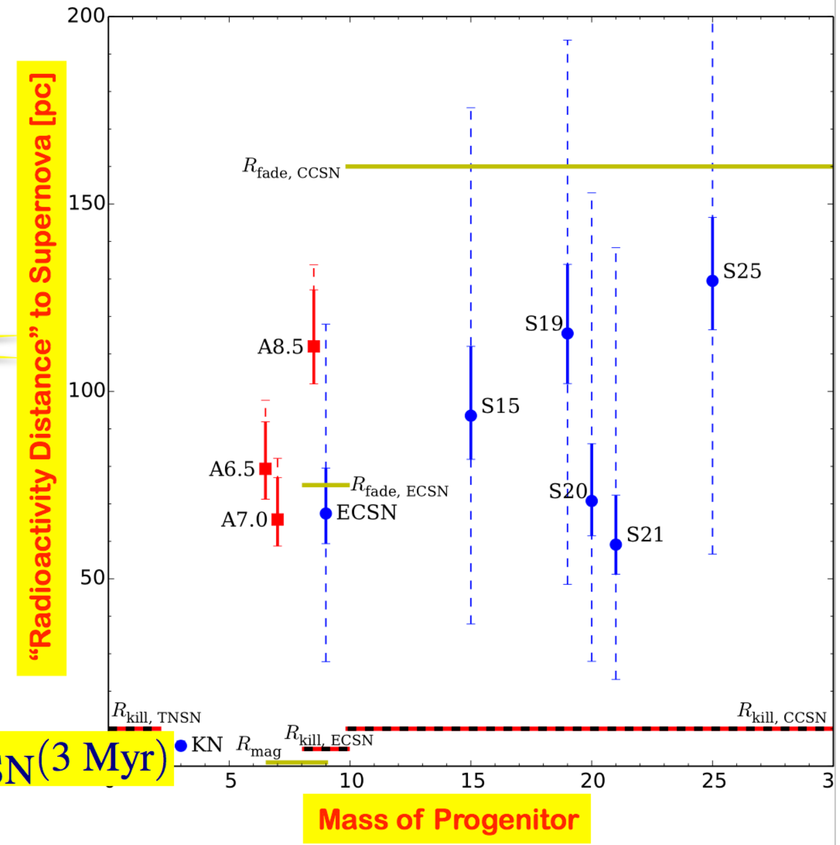
"radioactivity distance" from ^{60}Fe yield

What makes ^{60}Fe?

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

SN distance:

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



Encouraging:

★ astronomical distances not built in!

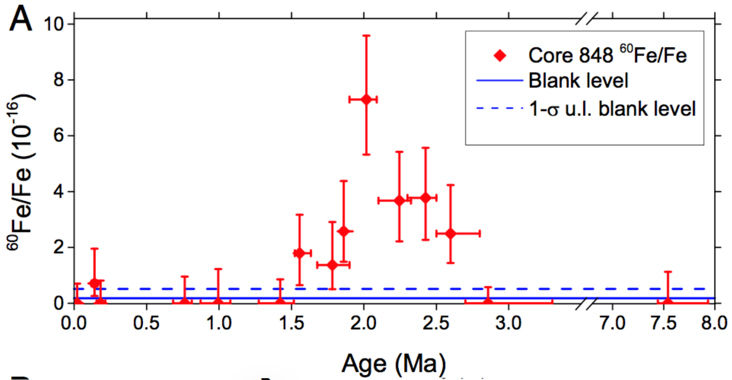
★ $d(^{60}\mathrm{Fe}) \approx d(\mathrm{SN} \rightarrow \mathrm{Earth}) \approx d_{\mathrm{SN}}(3\ \mathrm{Myr})$

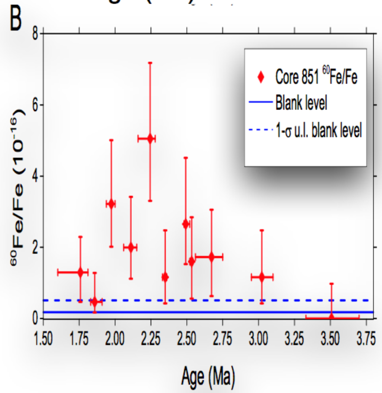
⇨ nontrivial consistency!

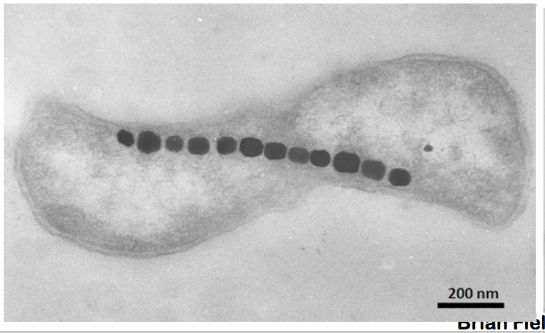
Radioactive Fossil Bacteria

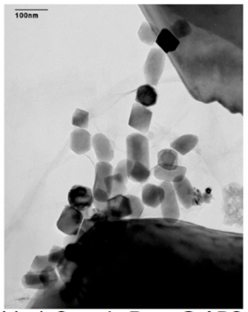
Ludwig, Bishop, et al 2016

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



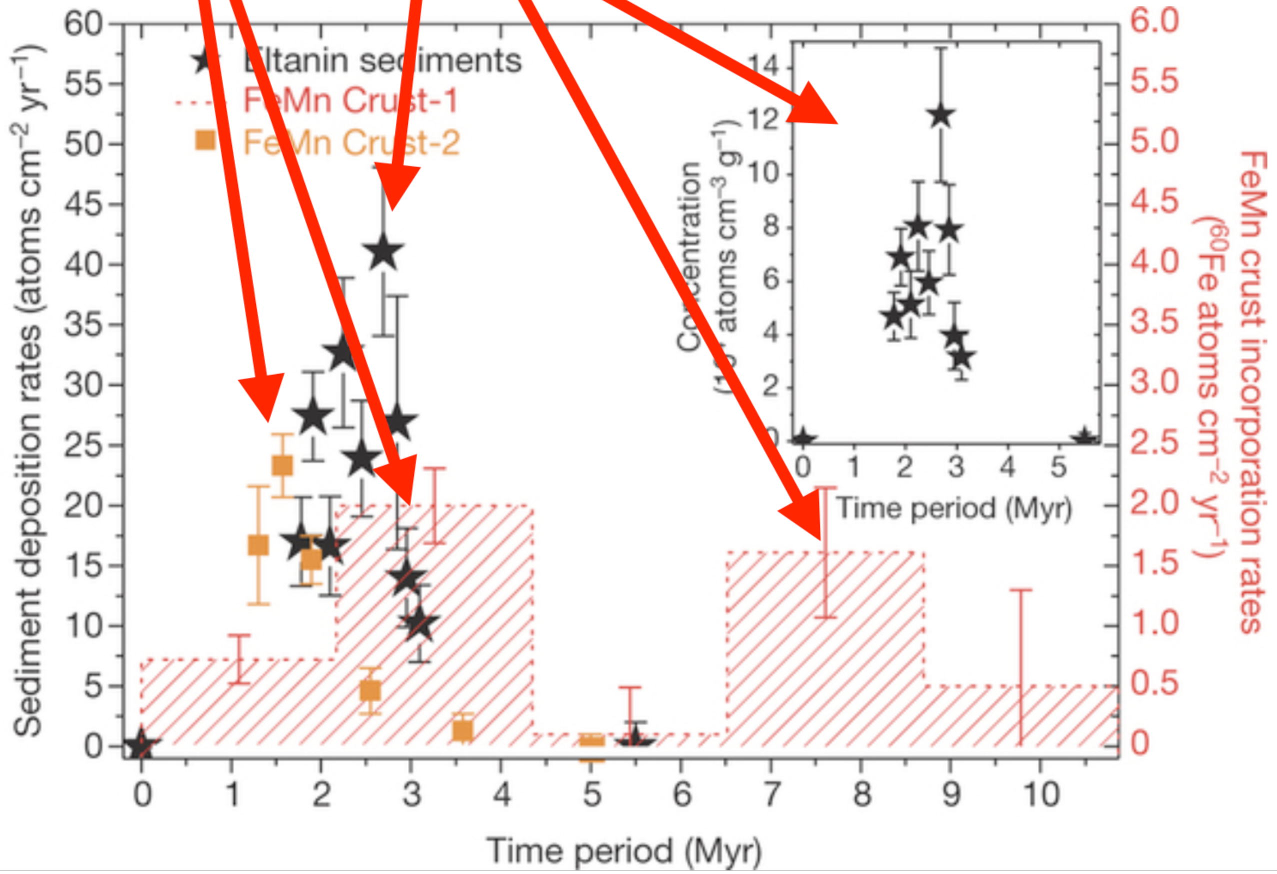






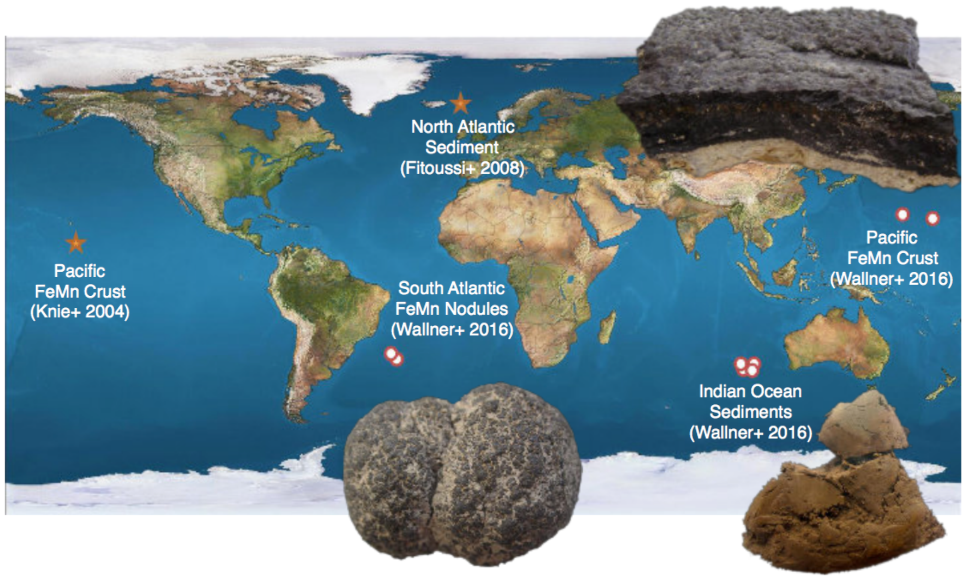
Wallner+ 2016 Nature

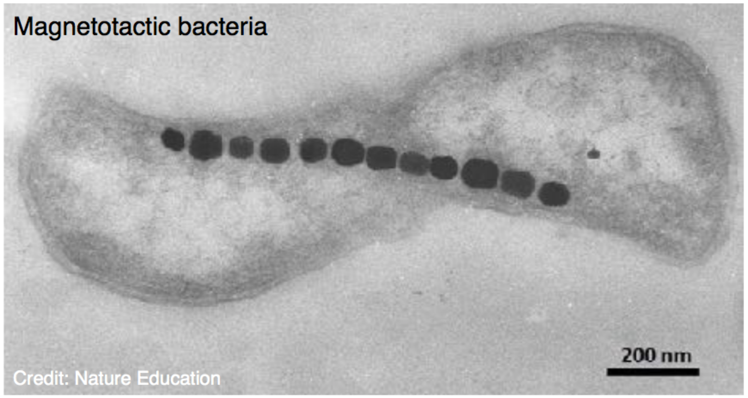
- ★ confirmation of 60Fe crust signal at ~3 Myr
- ★ sedimentary time profile: ~1 Myr width?!
- ★ indication of second ^{60}Fe pulse ~8 Myr

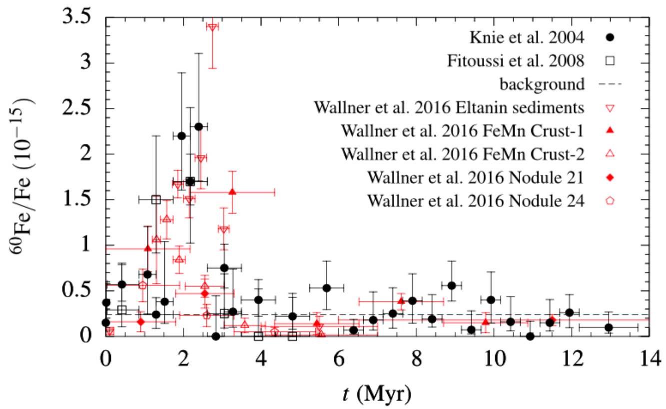


Latest developments

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







The Moon!

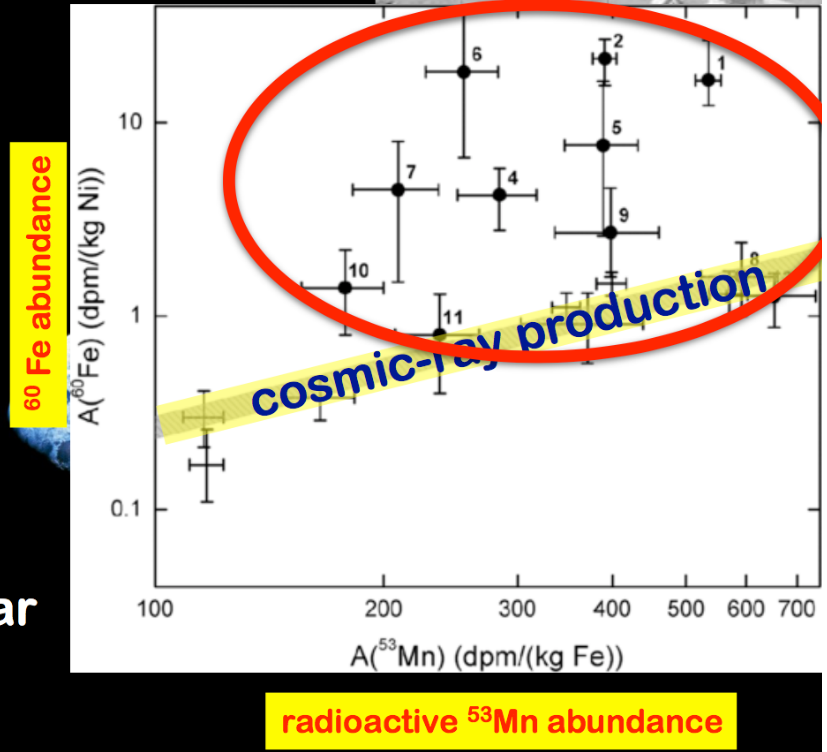
Lunar Soil

- ★ 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

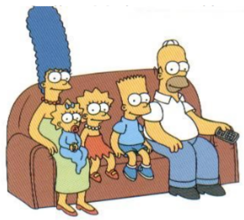
  Ruderman 74; Ellis & Schramm 94
- solar UV kills bottom of food chain

  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

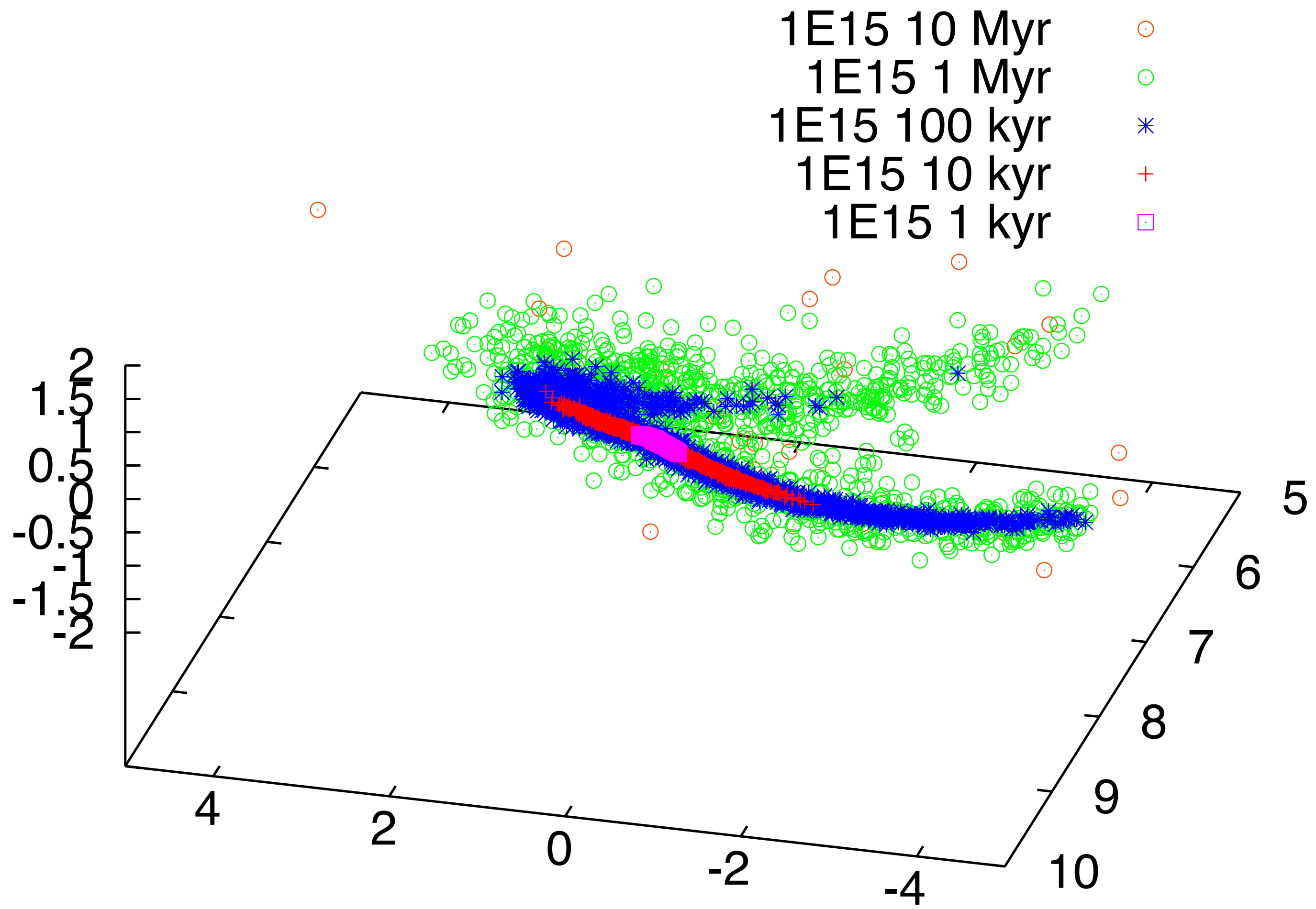
)2



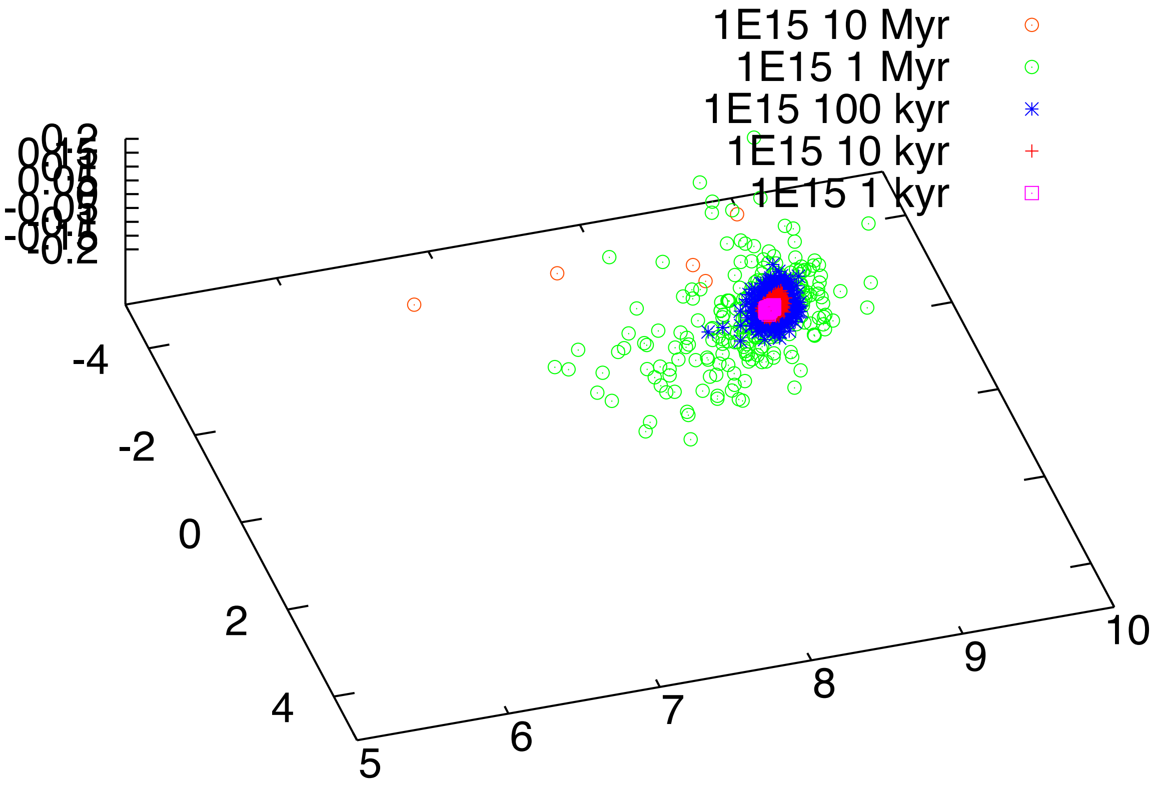
Minimum safe distance: ~8 pc

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

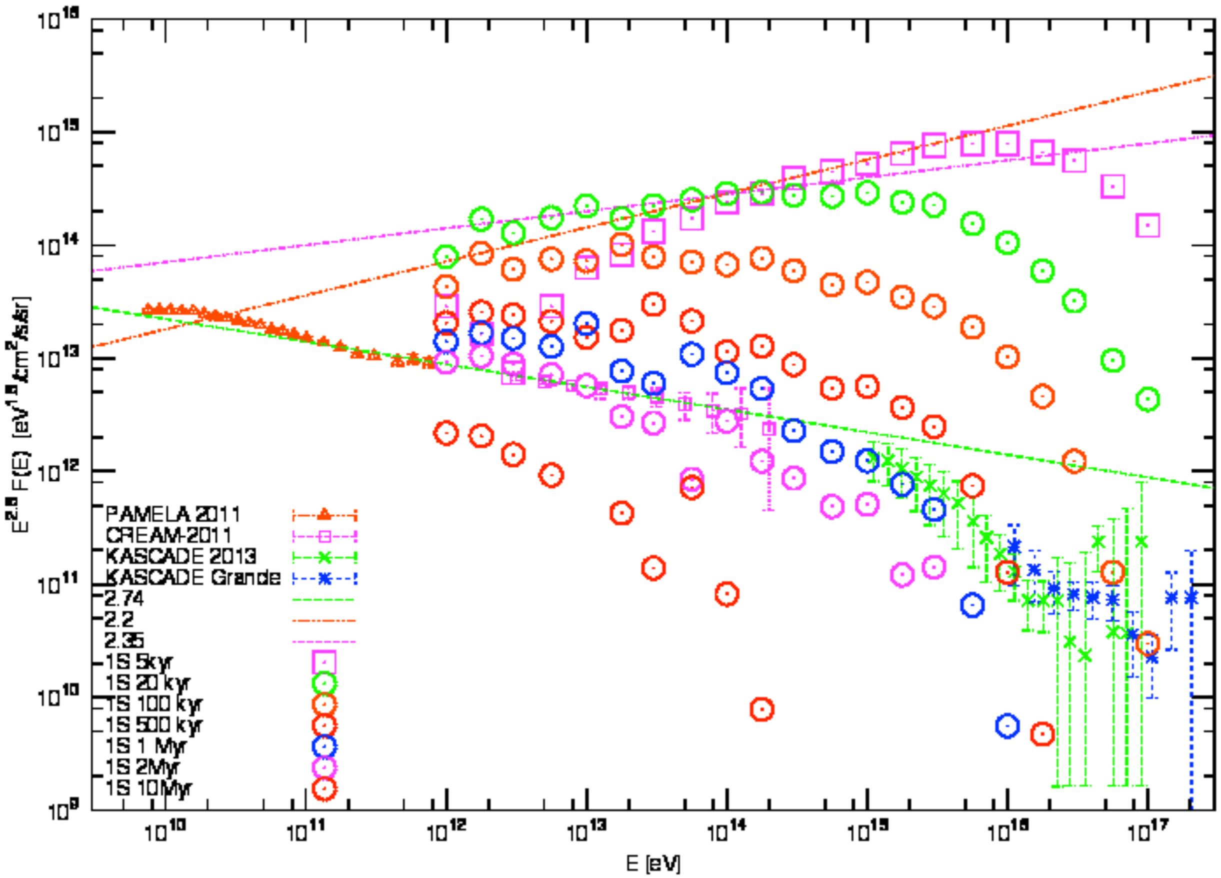
Proton flux from SN at 1 PeV



Proton flux from 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:

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

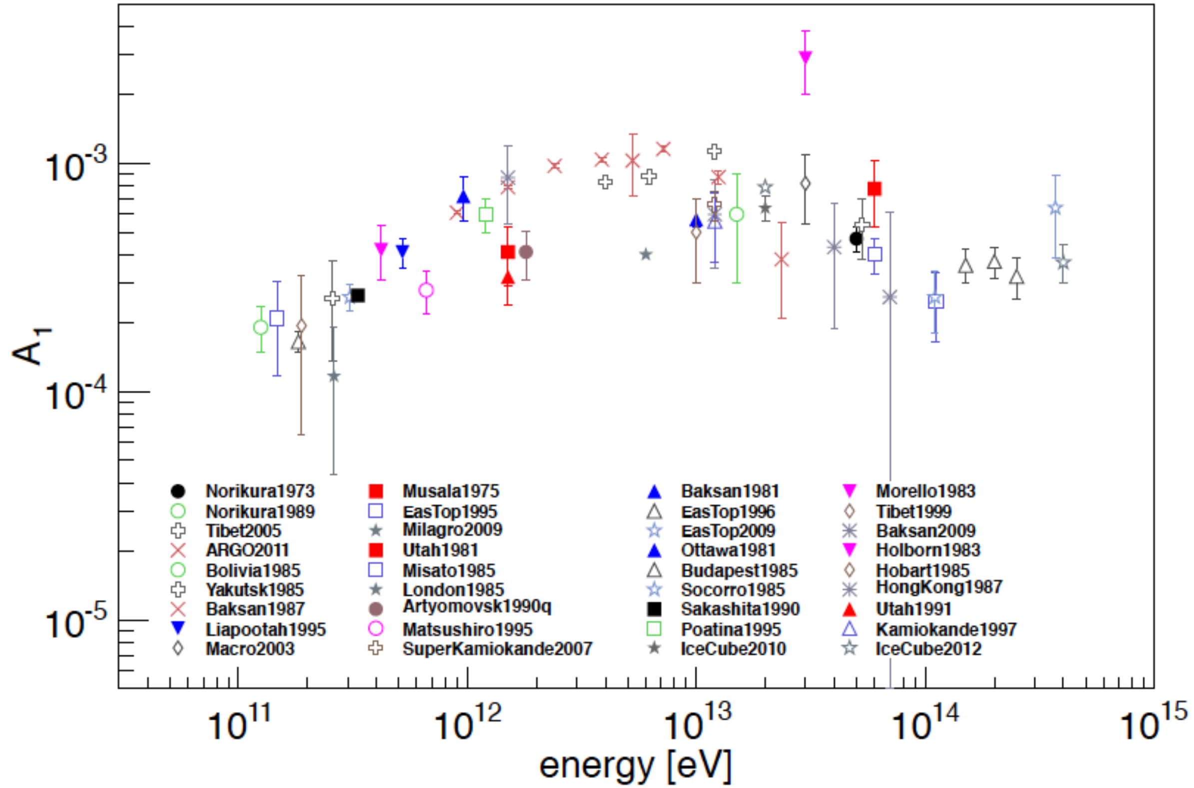
- Single source: n~exp(-r^2/4DT)

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

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

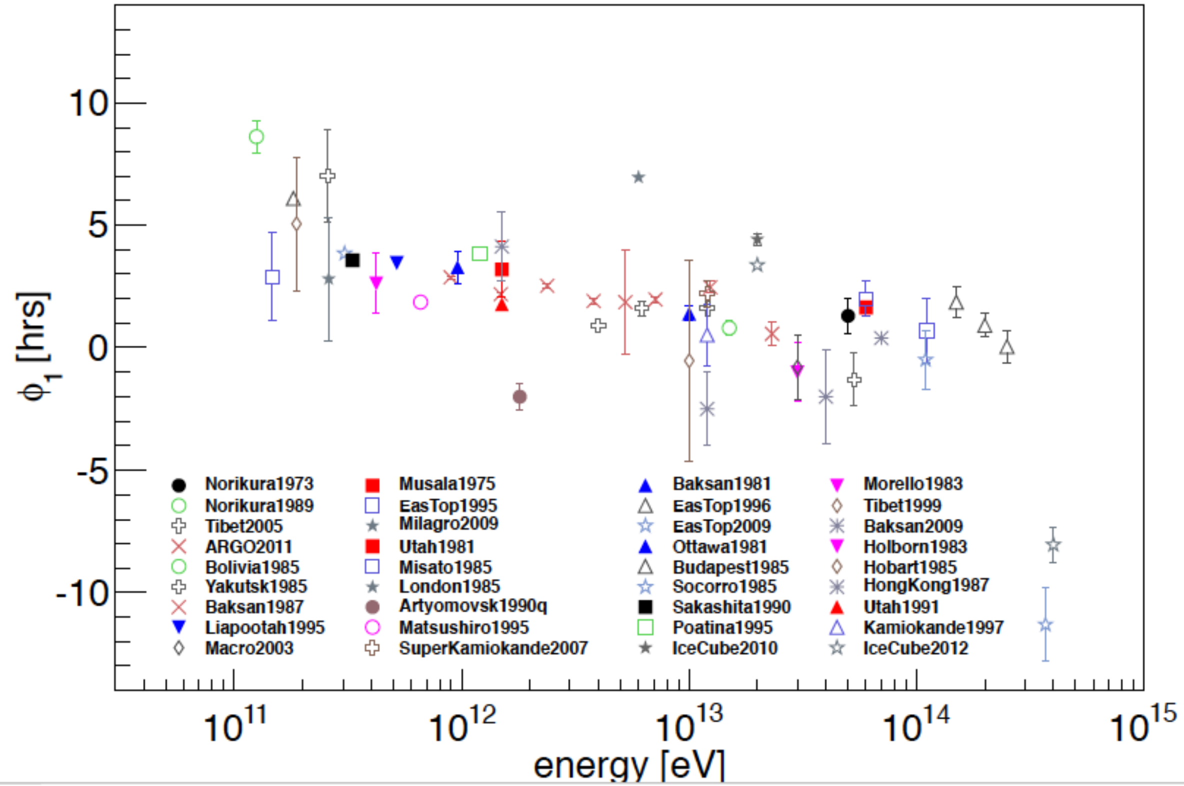
$$\delta_s = 3f_i R/(2cT).$$

Dipole anisotropy of cosmic rays



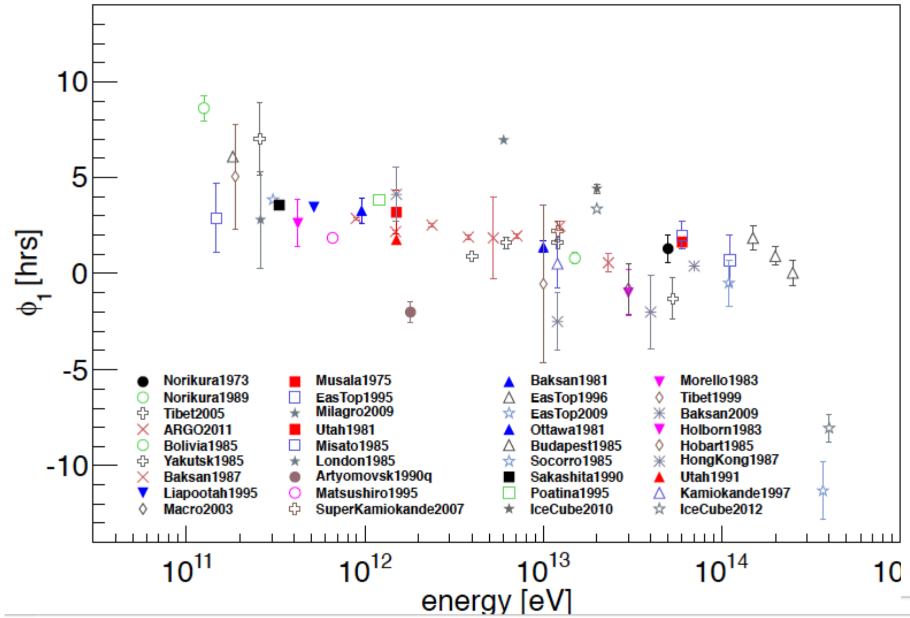
G.Di Sciascio and R. Iuppa, arXiv: 1407.2144

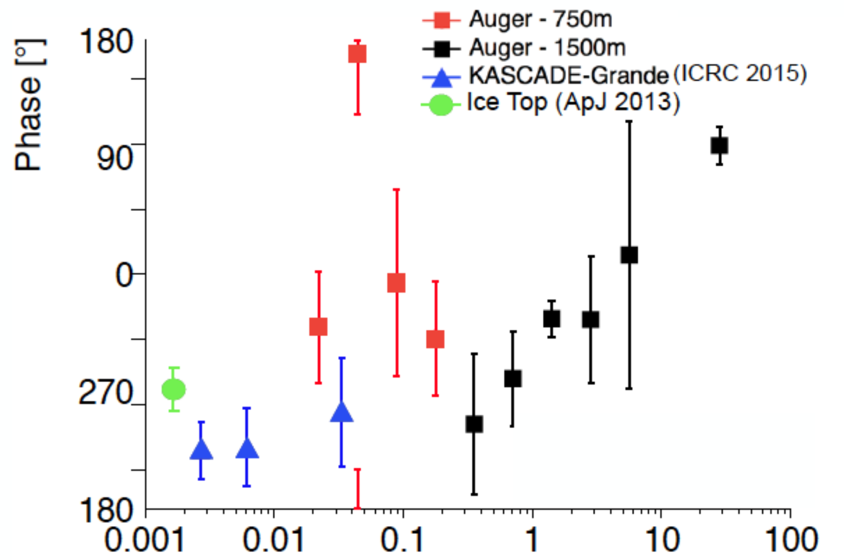
Dipole phase of cosmic rays



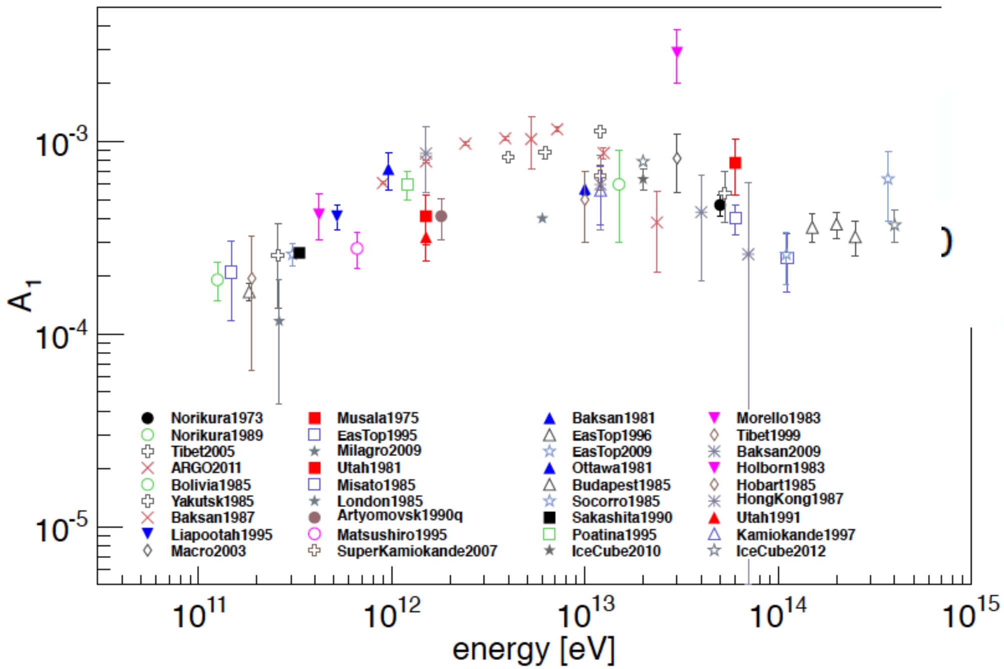
G.Di Sciascio and R. Iuppa, arXiv: 1407.2144

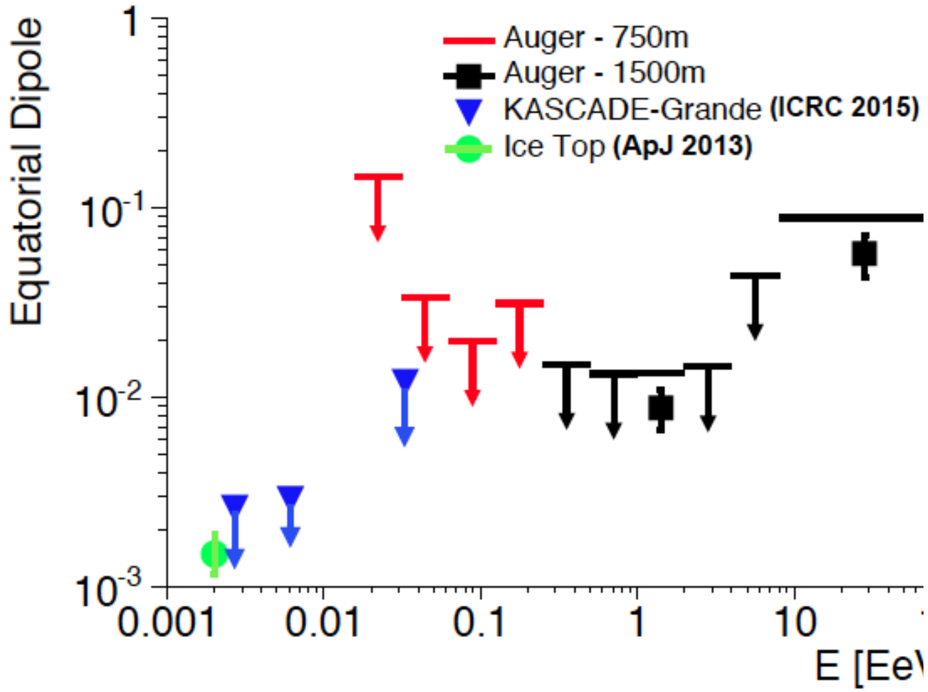
Dipole phase of cosmic rays



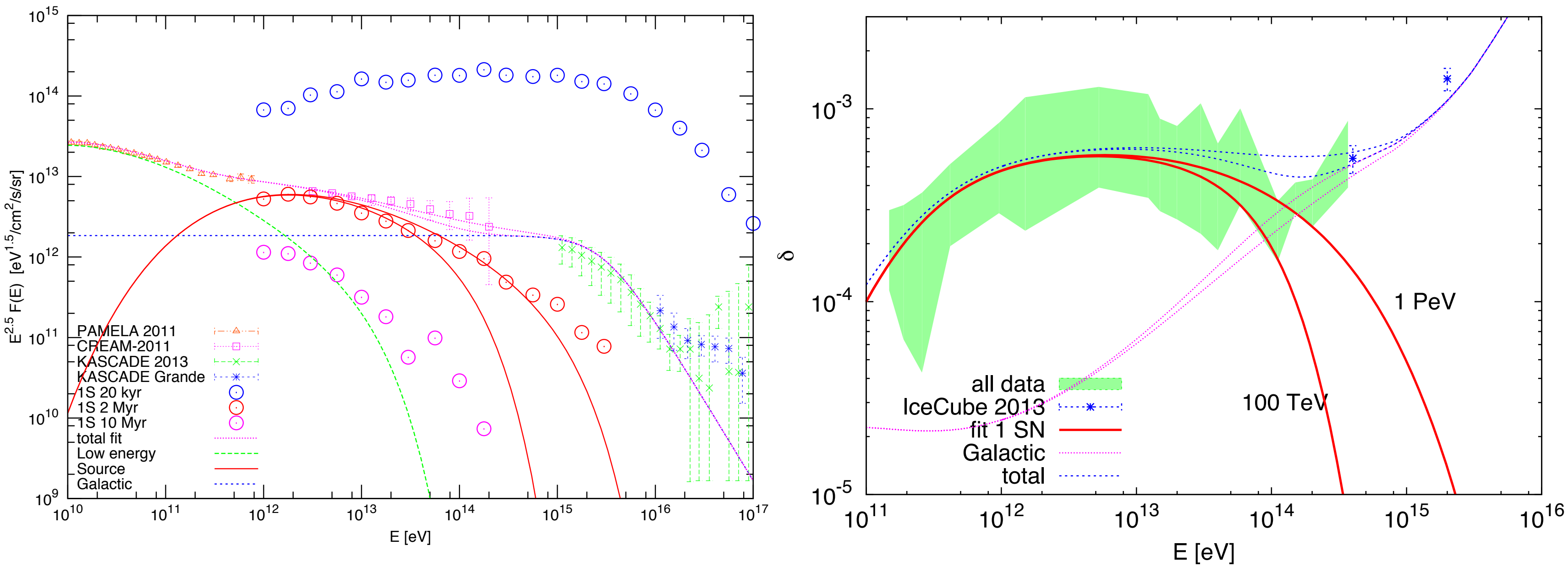


Dipole anisotro





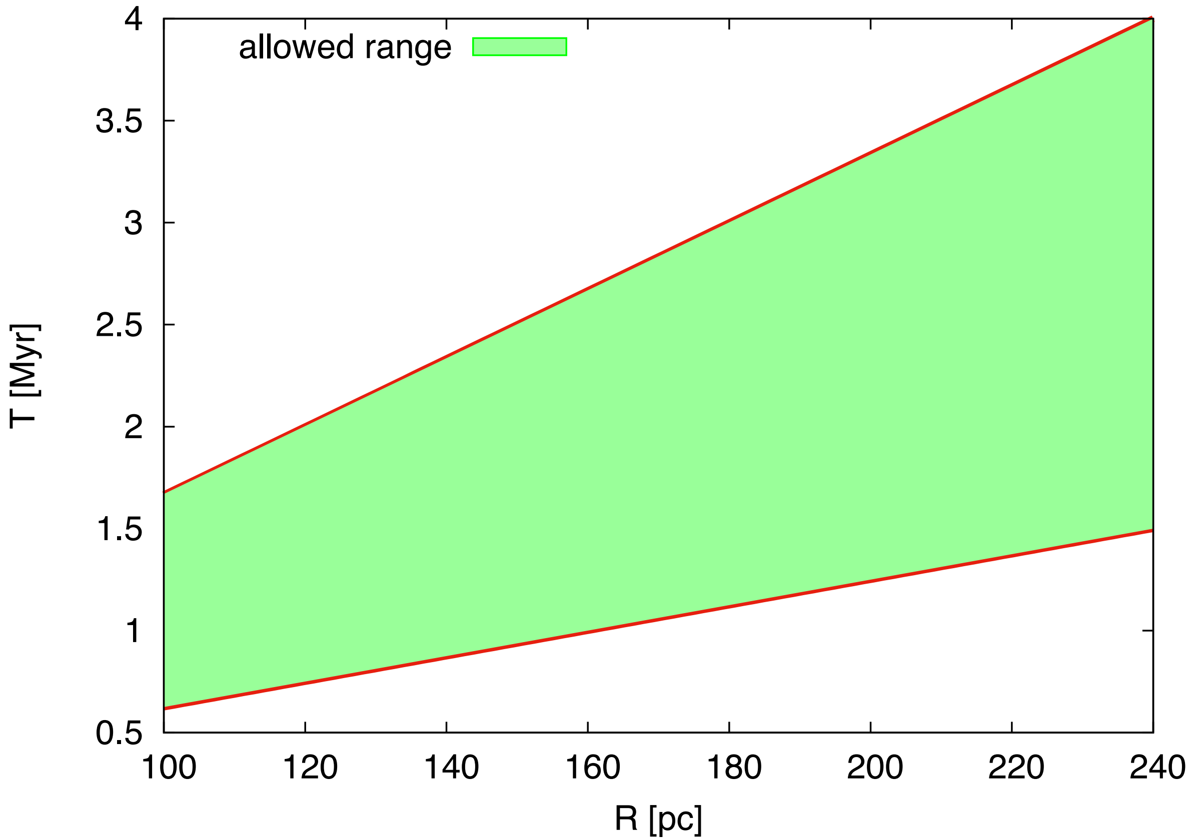
Anisotropy and flux from 2 Myr SN



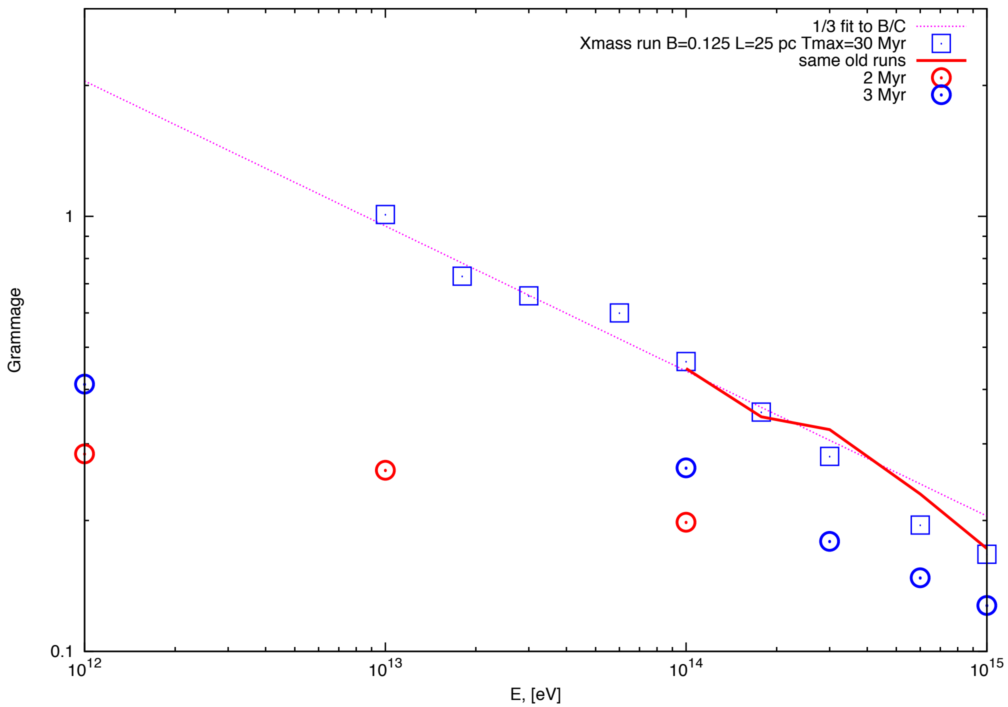
A=3/2 R/T

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

Anisotropy and parameters of SN



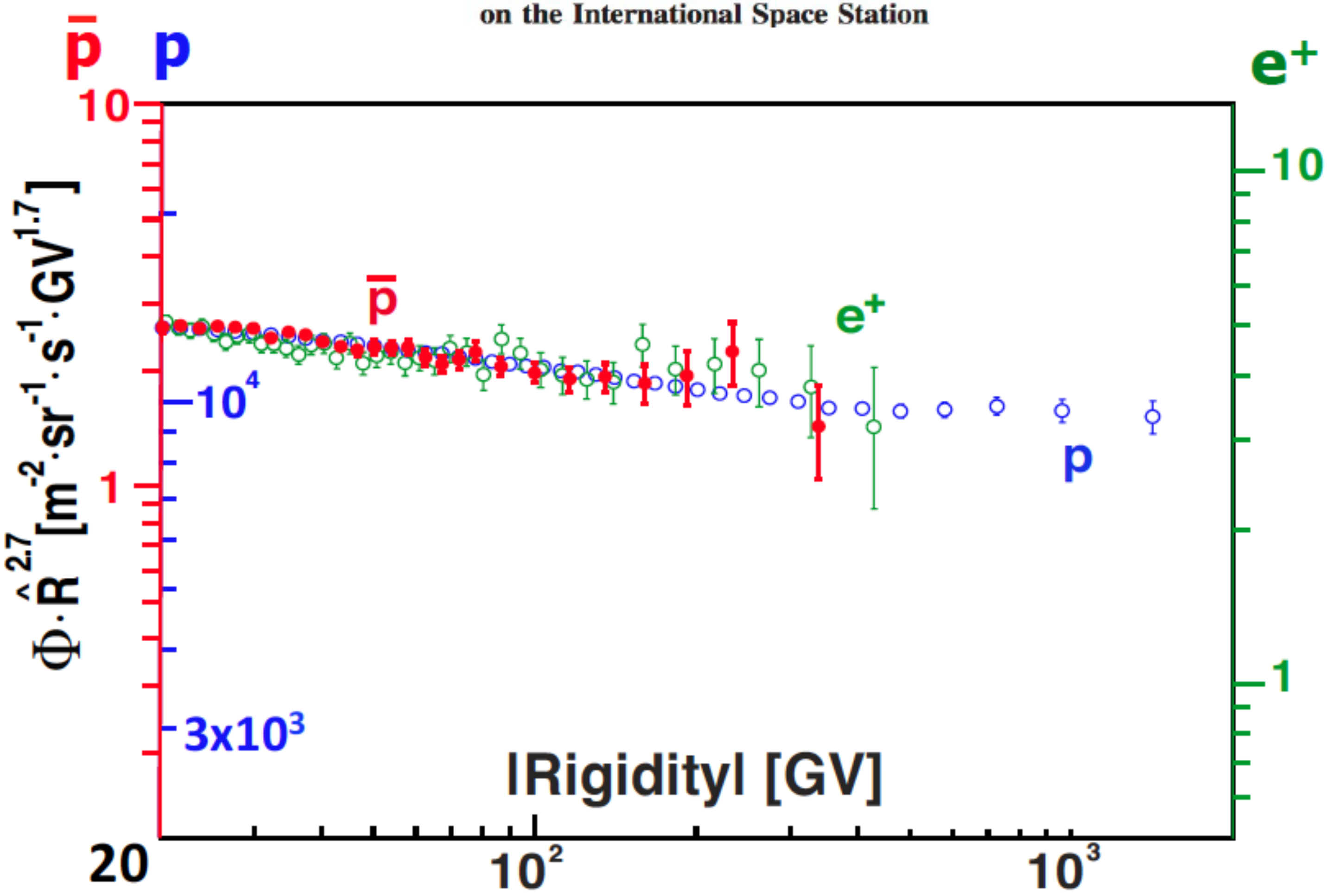
Grammage to create secondaries



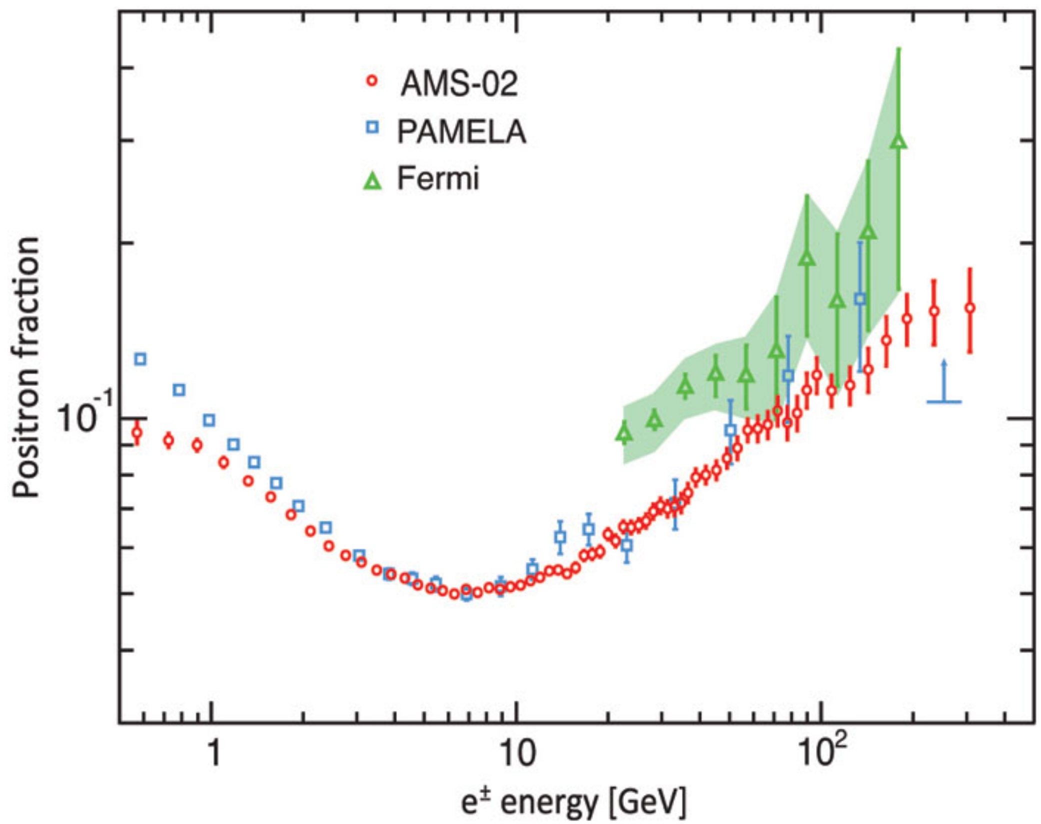
The antiproton flux compared to other particle fluxes

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

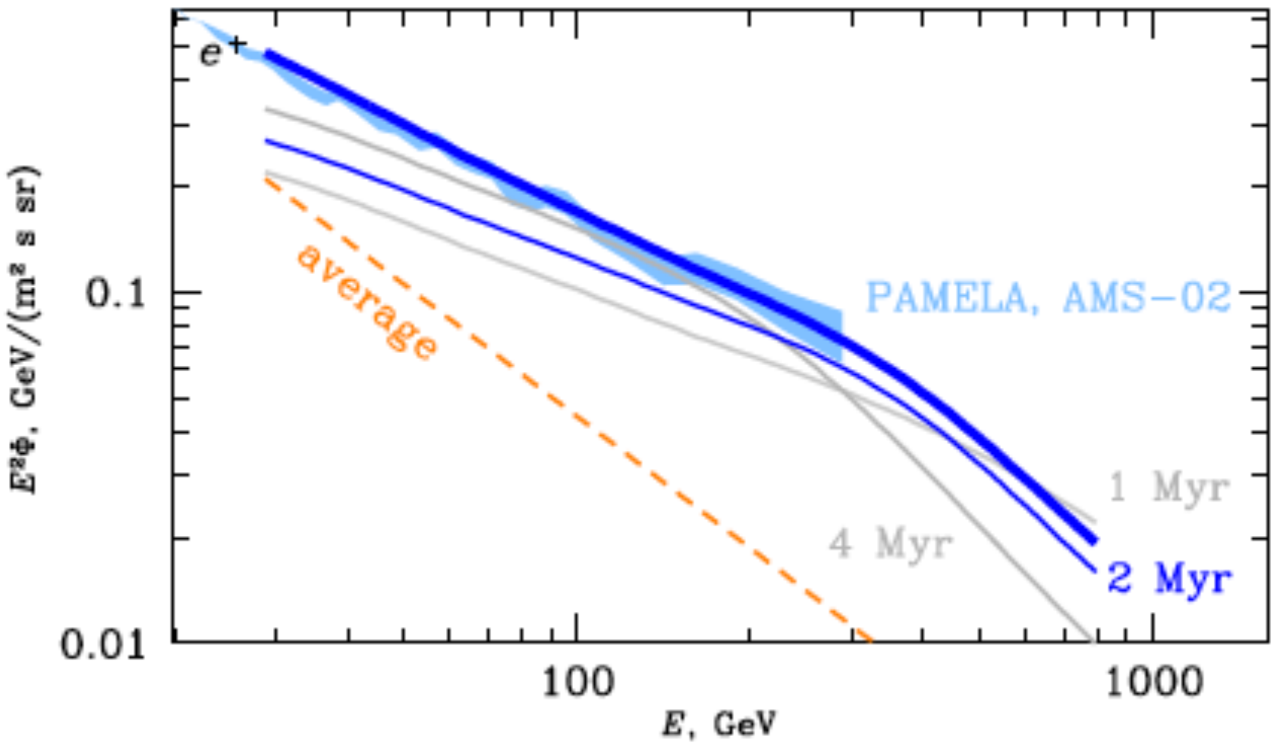
Antiproton Flux, Antiproton-to-Proton Flux Ratio, and Properties of Elementary Particle Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station



Positron to (electron + positron) ratio

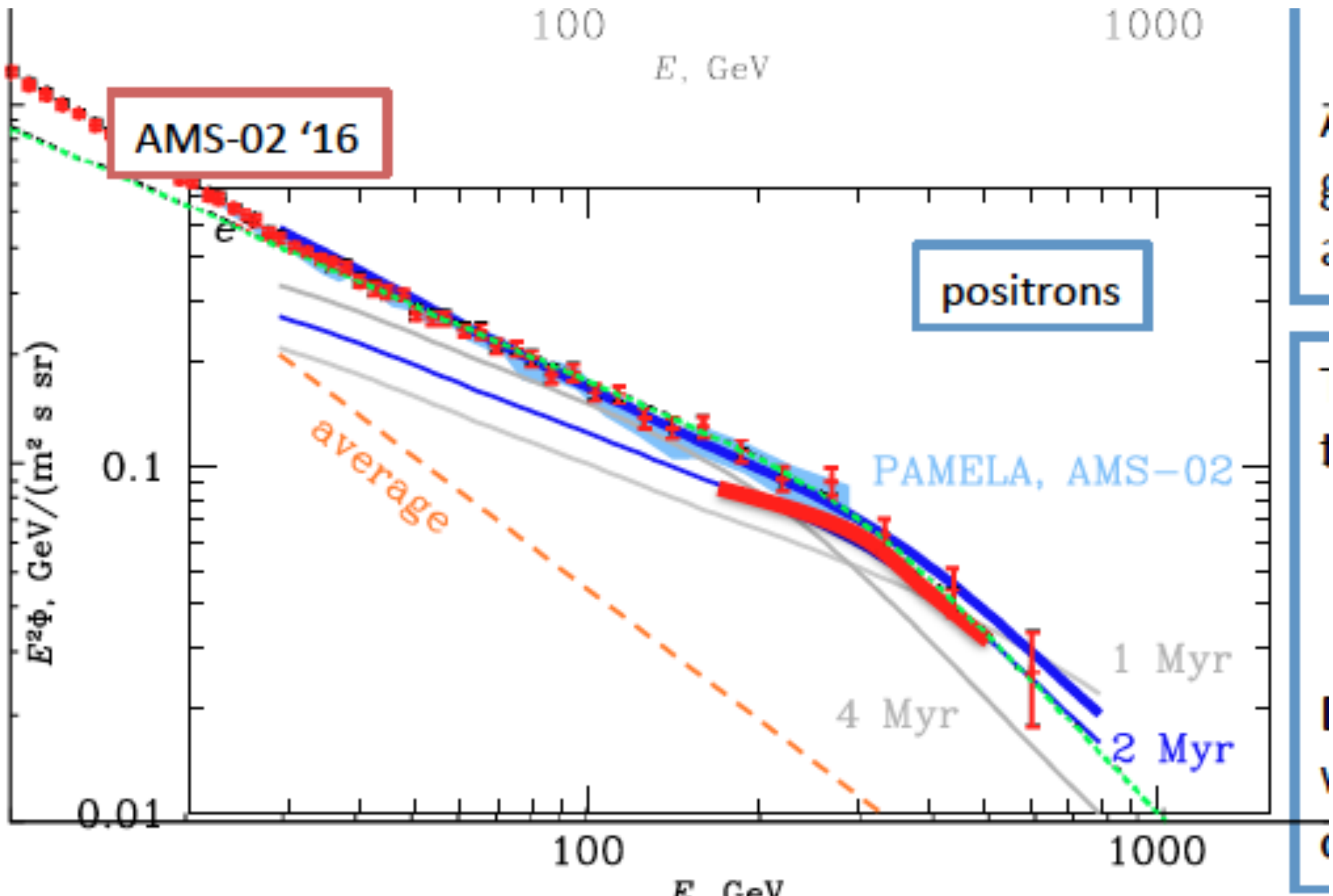


Positron flux PAMELA/AMS-II



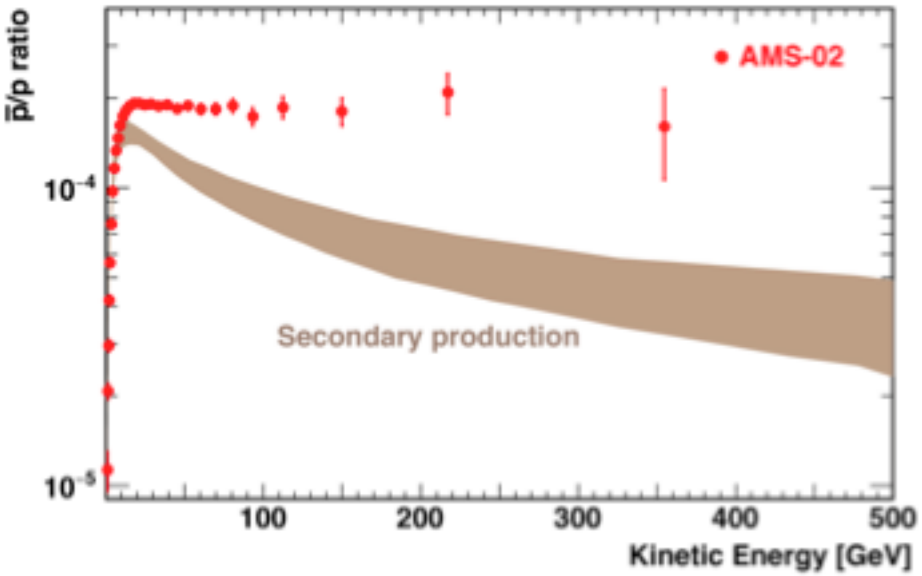
M.Kachelriess, A. Neronov and D.Semikoz, arXiv:1504.06472

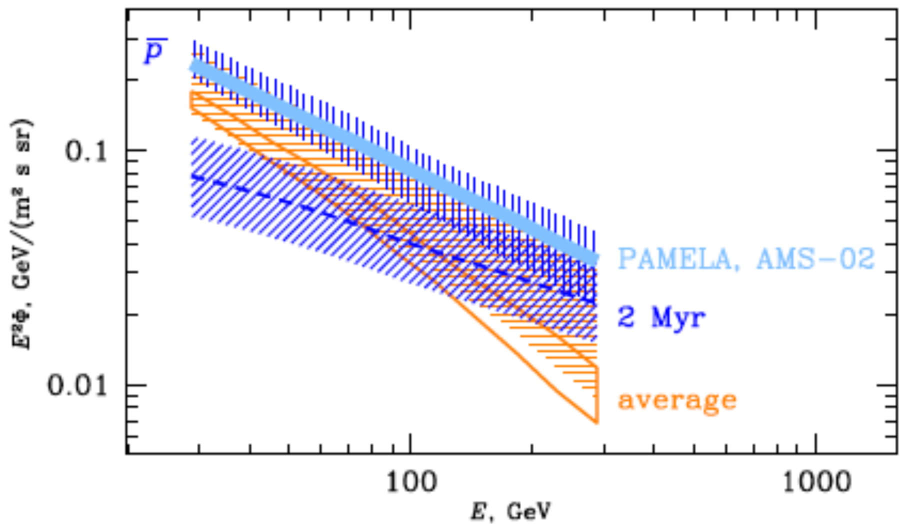
Positron flux PAMELA/AMS-II



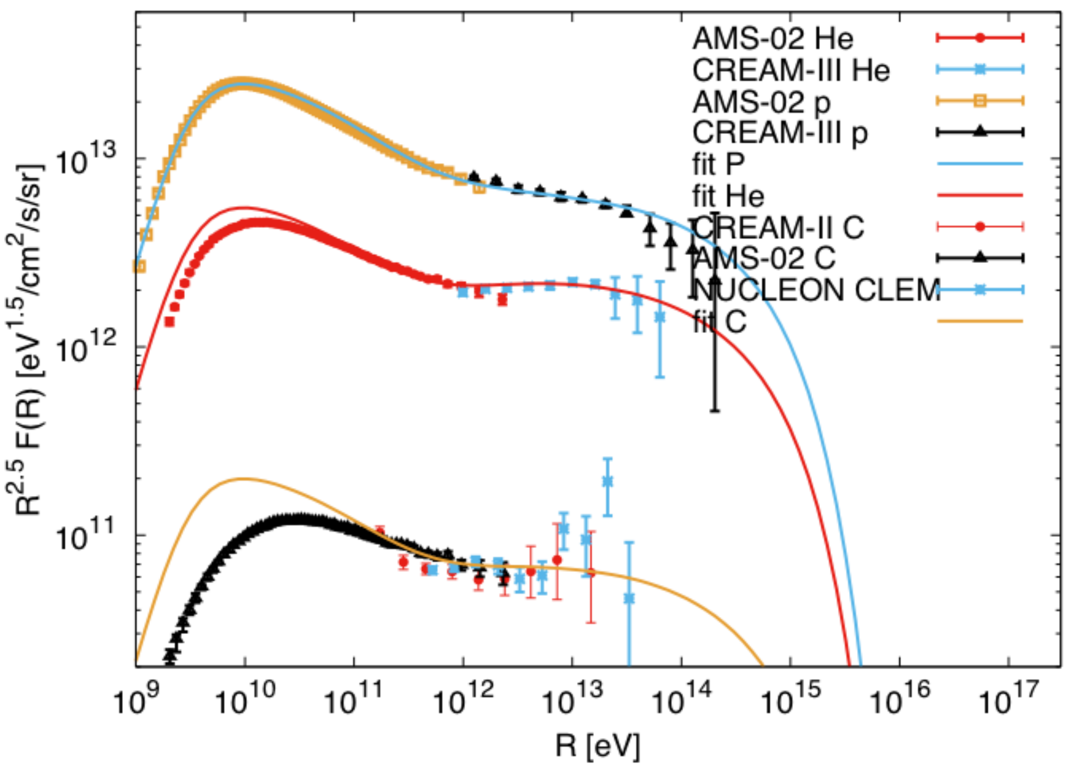
Kachelriess et al. '15

Antriprotons



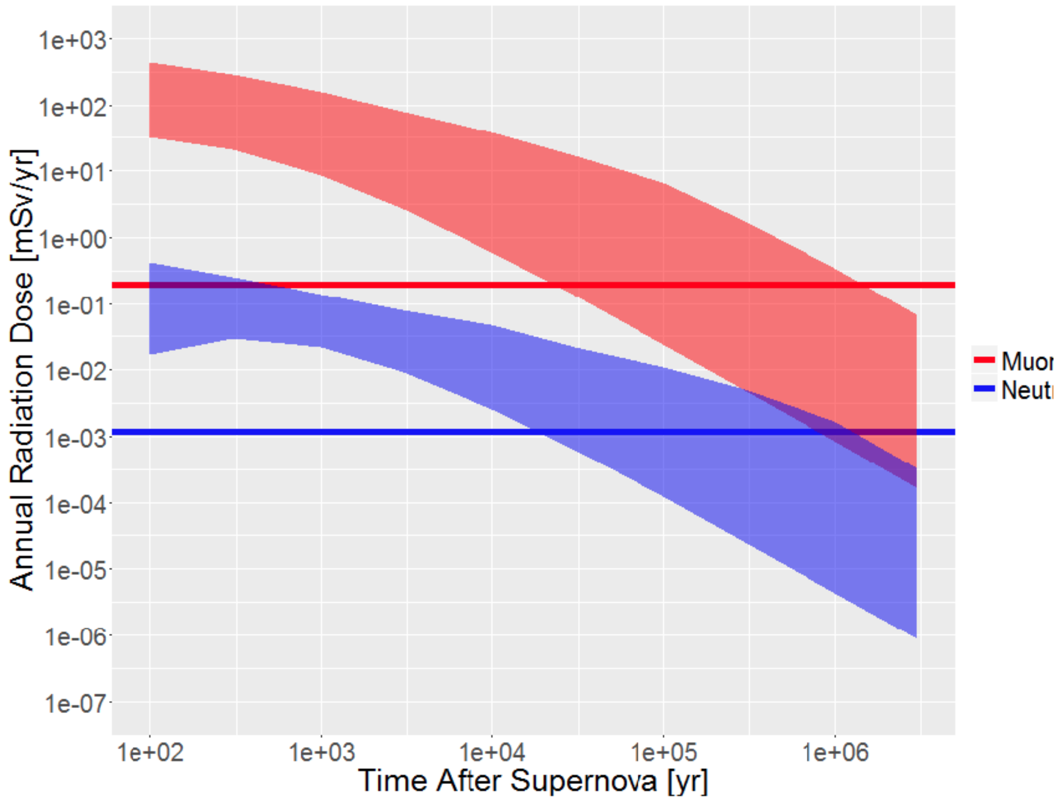


Nuclei



Ratio of nuclei fluxes at TeV energies differs from one at GeV
2 Myr SN solve problem (M.Kachelriess, A.Neronov and D.S. 2017)

Radiation at Earth from local SN



Melott et al 1702.0436

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*