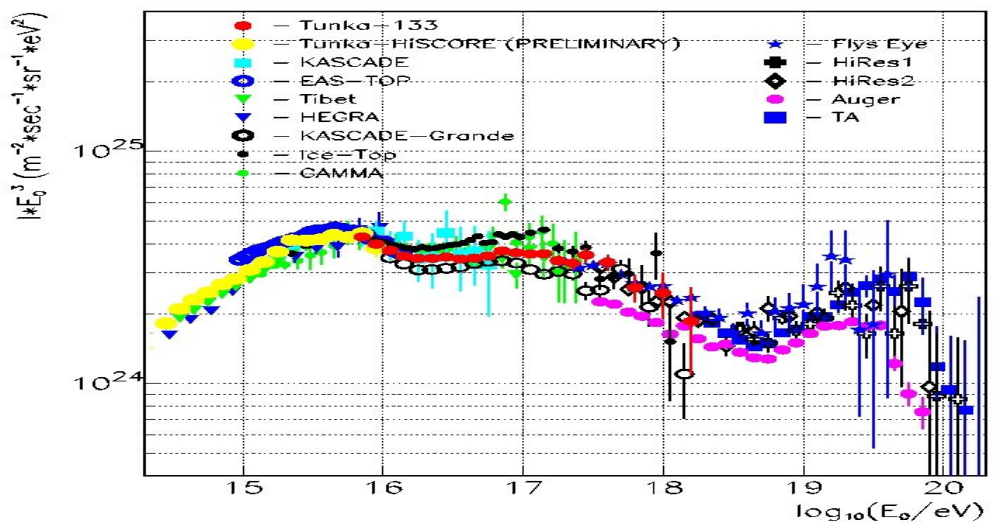
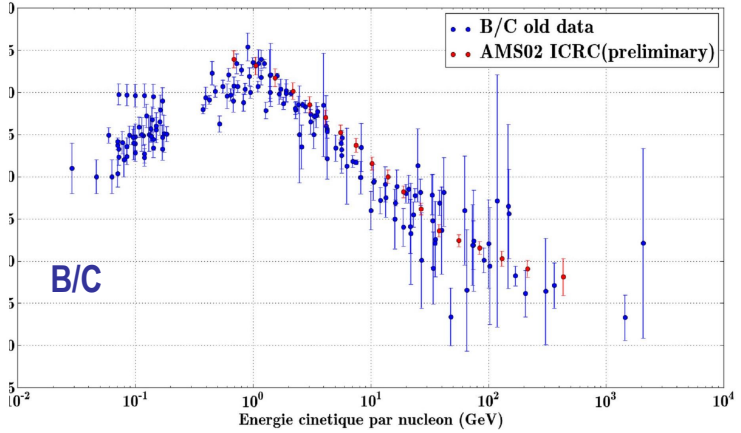
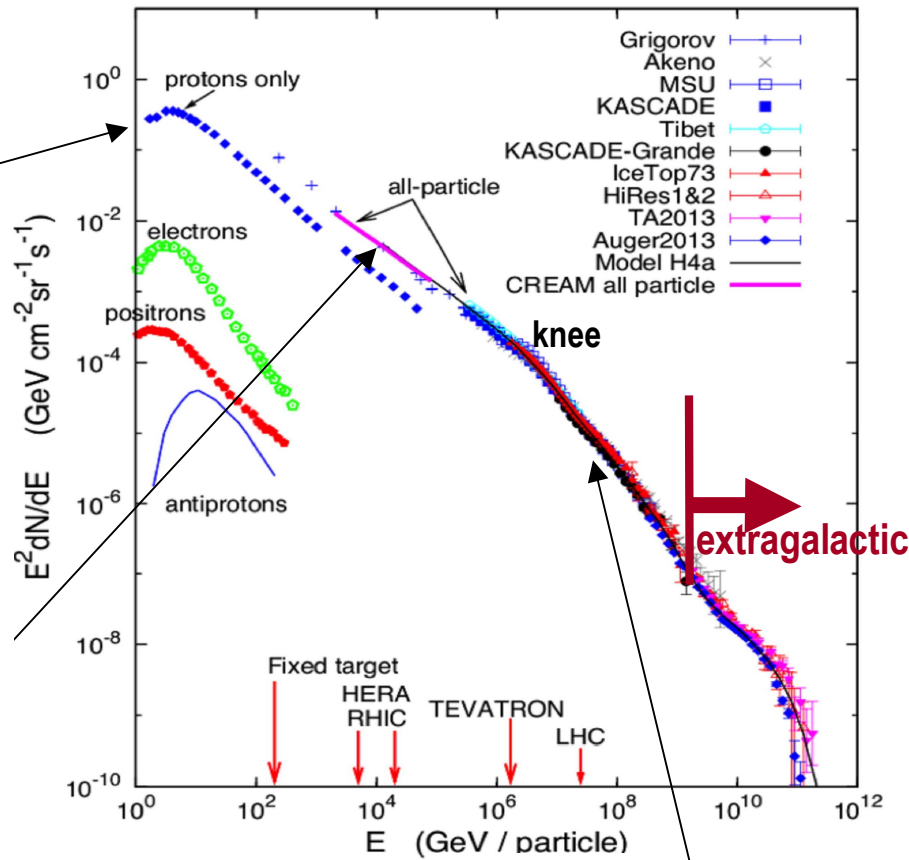
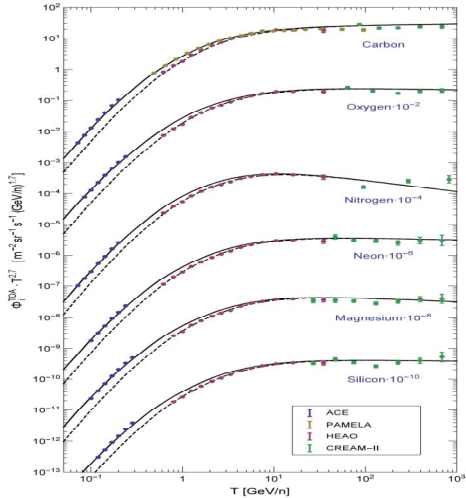
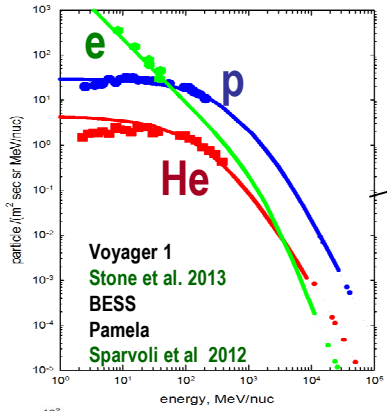


# Origin of cosmic rays: modern status

Vladimir Ptuskin

IZMIRAN

ISVHECRI 2016



# $^{60}\text{Fe}$ nucleosynthesis-clock isotope in Galactic cosmic rays

beta-decay primary  $t_{1/2} = 2.6 \cdot 10^6 \text{ yr}$   
primary cosmic-ray clock

ACE - CRIS instrument  
(Si solid-state detectors)

17 yr of data collection at 195 - 500 MeV/n

$3.55 \cdot 10^5$  Fe nuclei  $15 \cdot ^{60}\text{Fe}$  nuclei

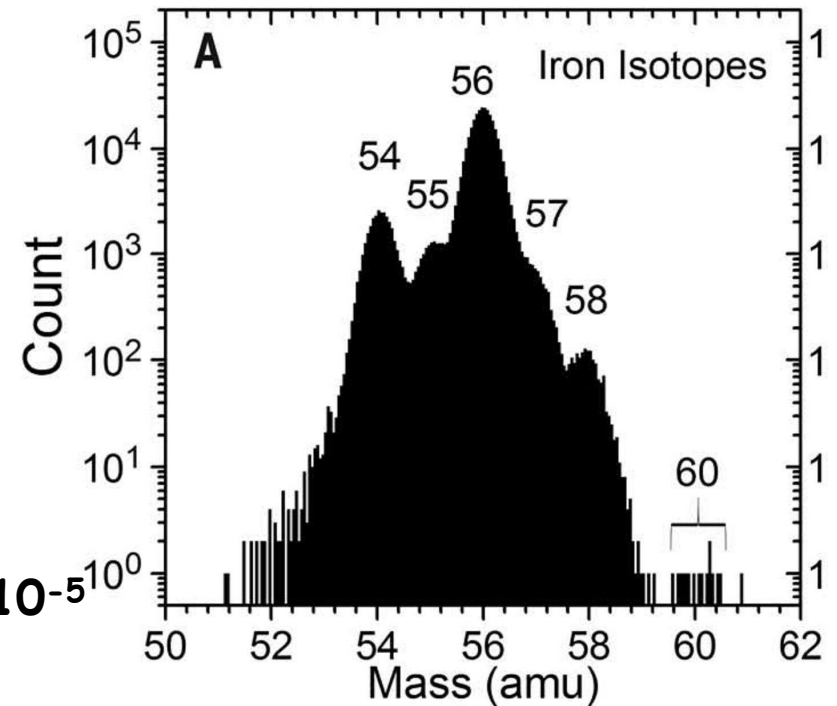
average source ratio  $^{60}\text{Fe}/^{56}\text{Fe} = (7.5 \pm 2.9) \cdot 10^{-5}$   
ratio ejected by massive star  $\sim 4 \cdot 10^{-4}$

time between nucleosynthesis and acceleration:

$$10^5 \text{ yr} < T < 2 \cdot 10^6 \text{ yr}$$

distance to the source (SNR)  $< 600 \text{ pc}$

Binns et al 2016

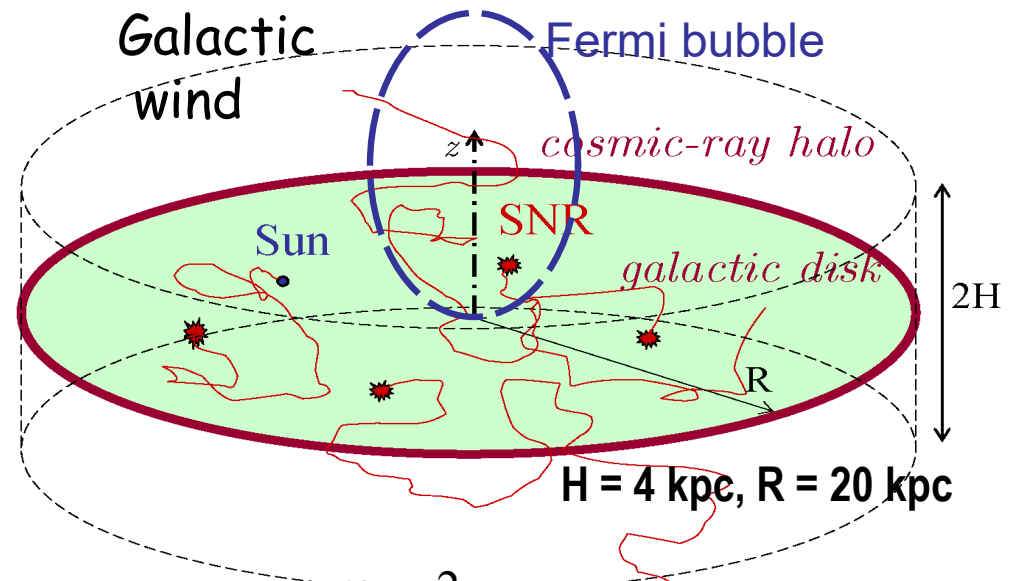


$^{59}\text{Ni}$

$^{60}\text{Fe}$

# basic Galactic model of cosmic-ray origin: acceleration in SNR and pulsars + diffusion in interstellar magnetic fields

Ginzburg 1953, Ginzburg & Syrovatsky 1963, Berezhko & Krymsky 1988, Berezhinsky et al. 1990



$$D \approx 3 \times 10^{28} \text{ cm}^2/\text{s}, \text{ at } 1 \text{ GeV}/n$$

$$D \propto (p/Z)^a, \quad a = 0.3 \dots 0.5, \quad > 1 \text{ GeV}/n$$

$$\text{resonant scattering } r_g = 1/k_p$$

$$L_{\text{cr}} \approx 10^{41} \text{ erg/s}, \quad Q_{\text{cr}} \propto (p/Z)^{\gamma_s},$$

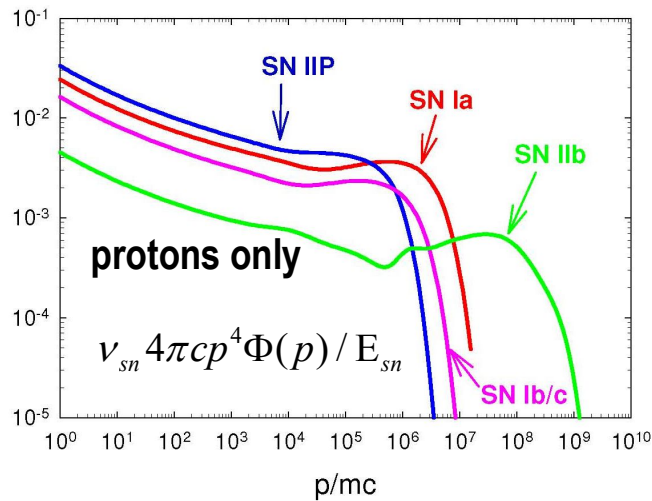
$$\gamma_s = 2.7 - a = 2.2 \dots 2.4, \quad > 1 \text{ GeV}/n$$

numerical modeling: GALPROP

Strong & Moskalenko 1998, Strong et al 2007

# calculated spectrum of Galactic cosmic rays

Ptuskin, Zirakashvili, Seo 2010

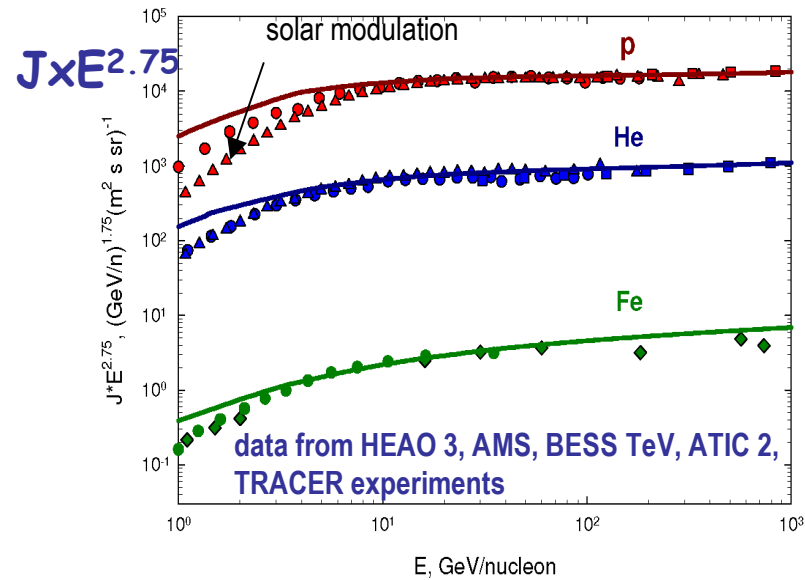


hydrodynamic eqs. +  $P_{cr}$ ;  
diffusion-convection transport eq. for CR with Alfvénic drift;  
«knee» is formed at the beginning of Sedov stage

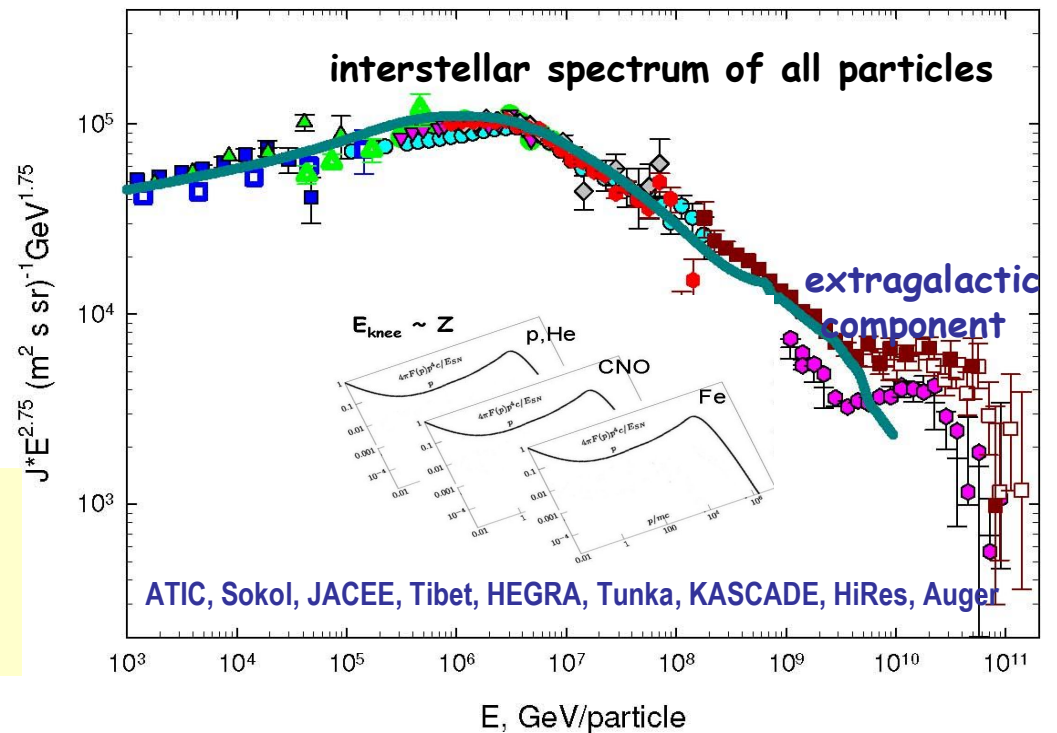
$$E_{knee} / Z \approx 1 \times 10^{15} W_{sn,51} n^{1/6} M_{ej}^{2/3} \text{ eV},$$

$$E_{knee} / Z \approx 8 \times 10^{15} W_{sn,51} \left( \dot{M}_{51} / u_{w,6} \right)^{1/2} M_{ej} \text{ eV}$$

assuming Bohm diffusion  $D = v r_g / 3$



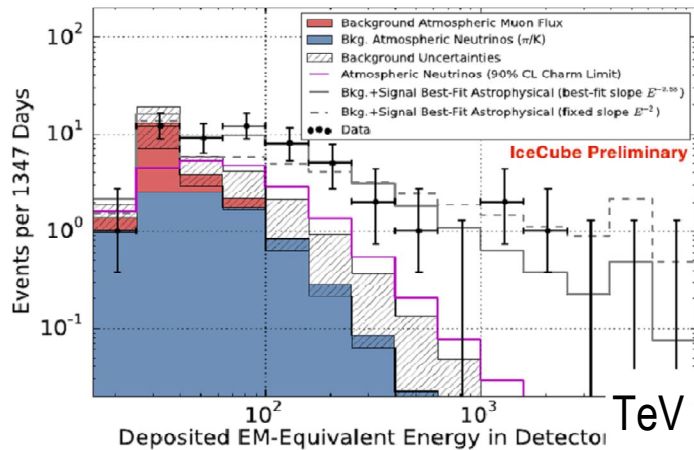
$$D_{ism} \propto \left( \frac{\text{pc}}{Ze} \right)^{0.54}$$



# high energy neutrinos of cosmic origin

**1 km<sup>3</sup> IceCube neutrino detector at South Pole: registration of Cherenkov light produced in ice by charged secondary particles**

$$E_{\nu}^2 \left( \frac{dN}{dE_{\nu}} \right) = (0.84 \pm 0.3) \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$



**~ WB bound;  
no significant clustering found;  
consistent with isotropy**

**Aartsen et al. 2013, 2014, 2015**

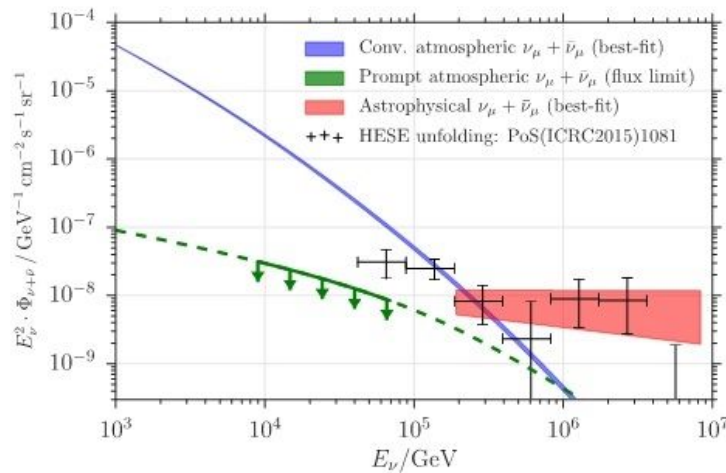
**54 (= 40+14) events at 30 TeV - 2 PeV in 2009 - 2014**

**↑  
track events**

**- complimentary measurement: interaction vertex can be outside the instrumental volume**

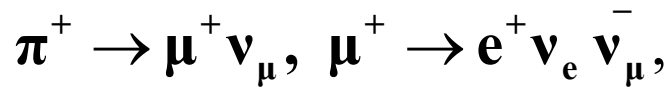
**Aartsen et al. 2016**

**29 events at 200 TeV - 5 PeV in 2009 - 2015**



# spectra of protons and pp neutrinos produced in SNR IIn during 30 years via interactions and decay chains

Zirakashvili & Ptuskin 2016



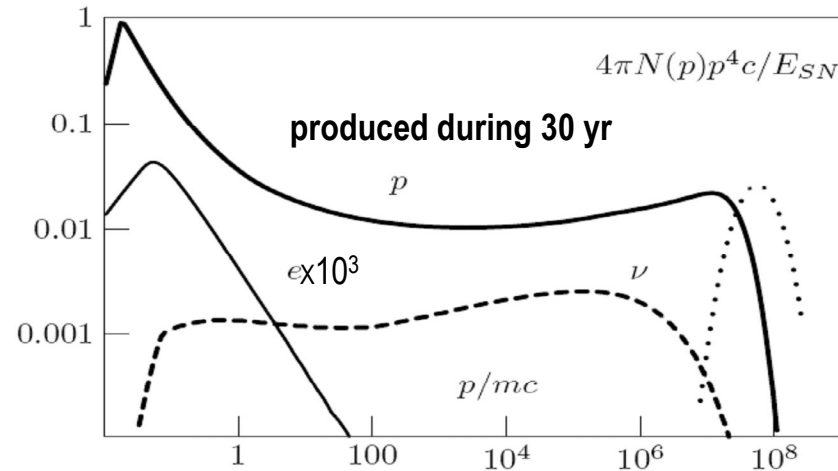
$$E_\nu \approx 0.05 \times E_p$$

$E_{SN} = 10^{52}$  erg,  $M_{ej} = 10 M_{Sun}$ ,  $k = 9$ ,  
presupernova wind mass loss

$$dM/dt = 10^{-2} M_{Sun}/yr$$

stellar wind velocity  $u_w = 100$  km/s,

$$T_w = 10^4 K$$



30% of  $W_{sn}$  go to cosmic rays

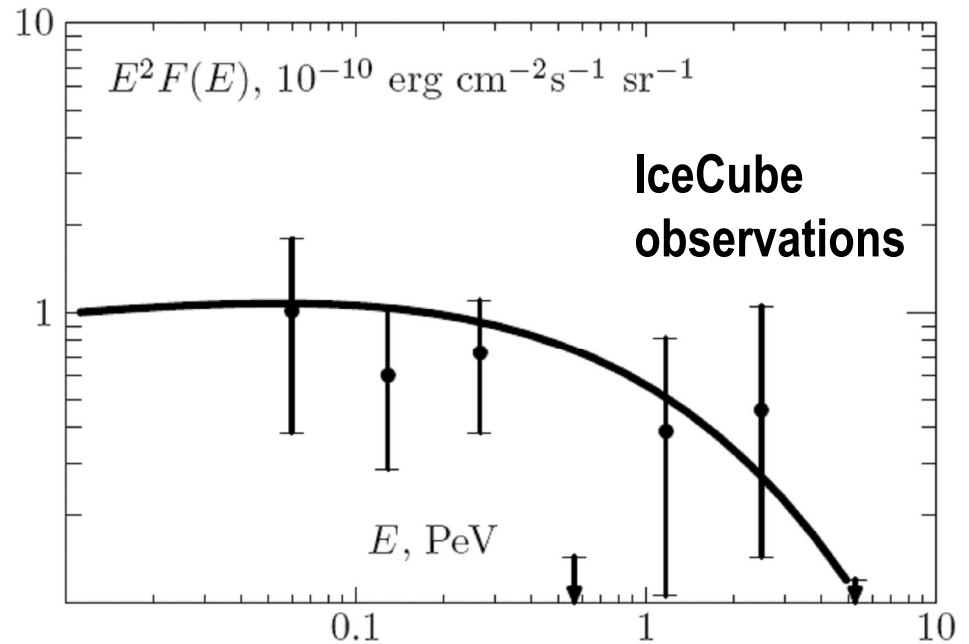
$E_{knee} \sim 80$  PeV

## neutrino flux produced by SN IIn in the Universe

SN IIn rate  $10^{-6} (1+z)^{3.3} \text{ Mpc}^{-3} \text{ yr}$

$z_{max} < 1$ ;  $\sim (1+z)^0$ ,  $1 < z < 5$

$\sim 1\%$  of all core collapse SNs in the Universe



## Correlations of IIn SNe and IceCube neutrinos

only: ~ 2 IceCube events are expected to be associated with known Type IIn SN at  $z < 0.1$ ;  
14 of 54 are track events with angular resolution  $< \sim 1$  degree  
(the rest  $< \sim 15$  degrees)

track event #47 from the 1<sup>st</sup> list:

1.35 degree from SNIIn 2005bx;  $z = 0.03$ ,

$$M_{\dot{}} = 0.037 M_{\odot}/\text{yr}, u_w = 813 \text{ km/s}$$

{expect 0.25 tracks within 1.35 degree direction to known 200 SNIIn}

track event #11 from the 2nd list:

0.3 degree from SNIIn 2005jq;  $z = 0.23$ ,

age at detection 5.3 yr

{probability of coincidence = 0.02}

## anomalies in cosmic ray energy spectra below the knee

deviations from the plain power laws at  $10$  to  $10^5$   $\text{Gev}/n$ :

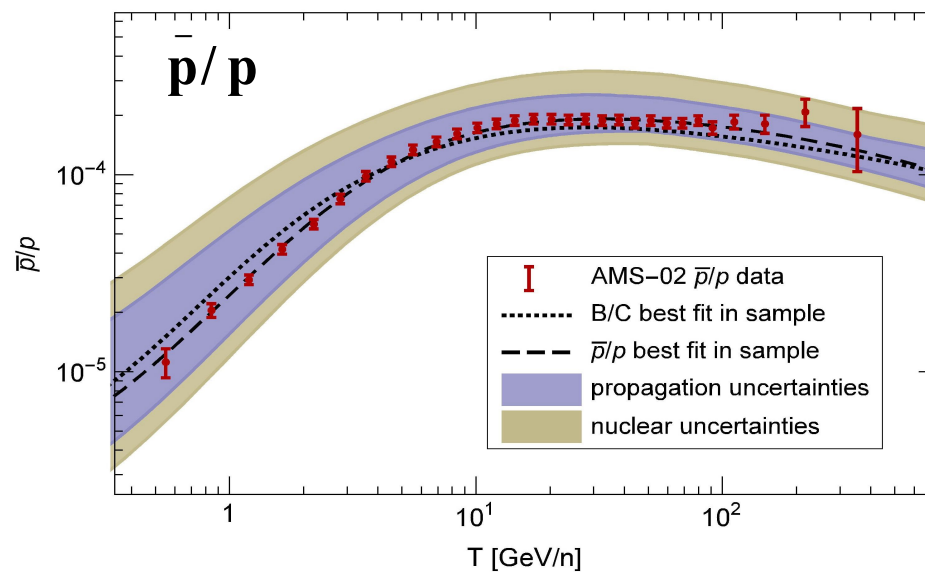
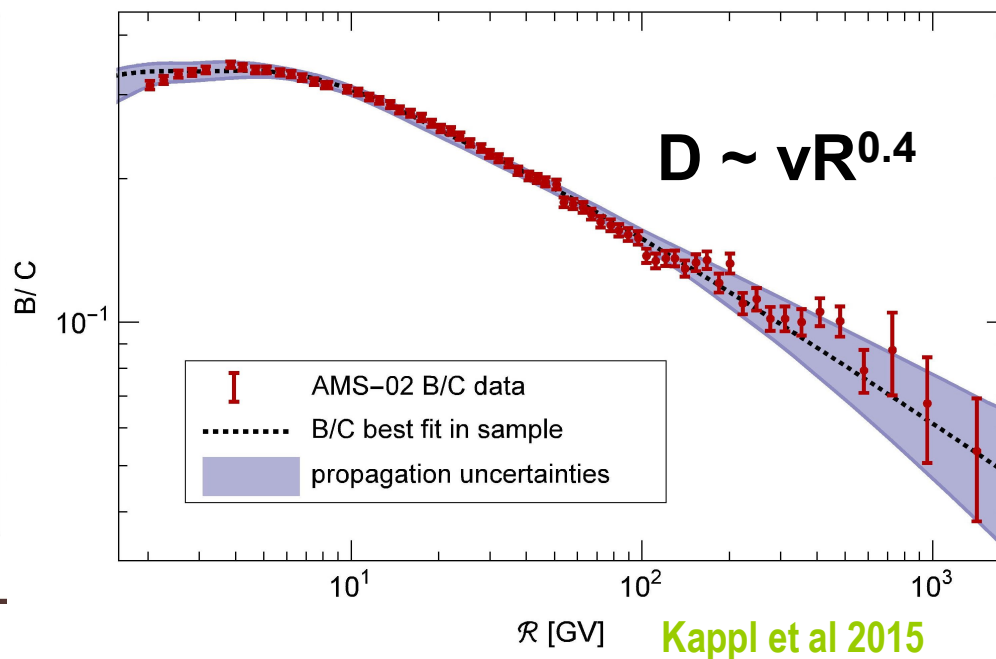
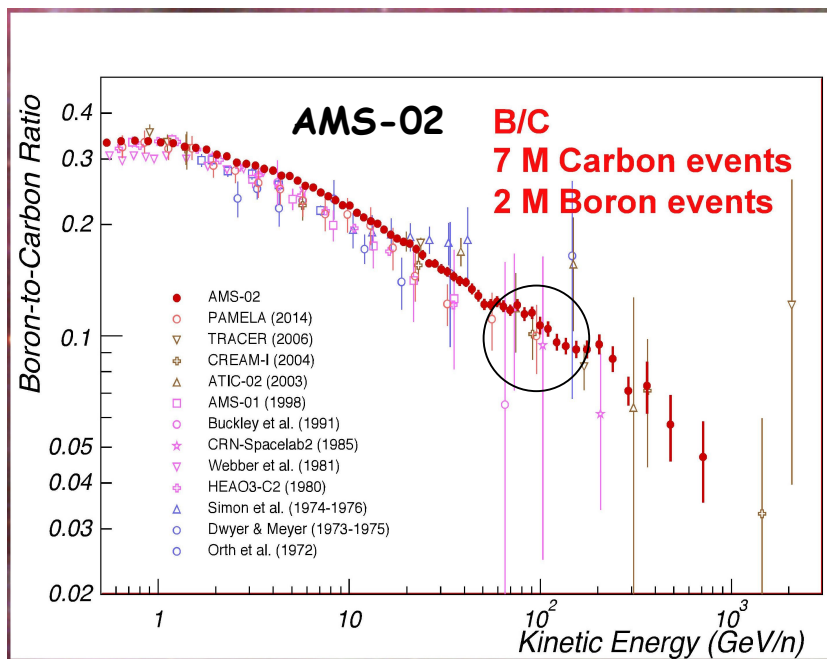
ATIC-2 (Panov et al. 2009),

CREAM (Yoon et al 2011),

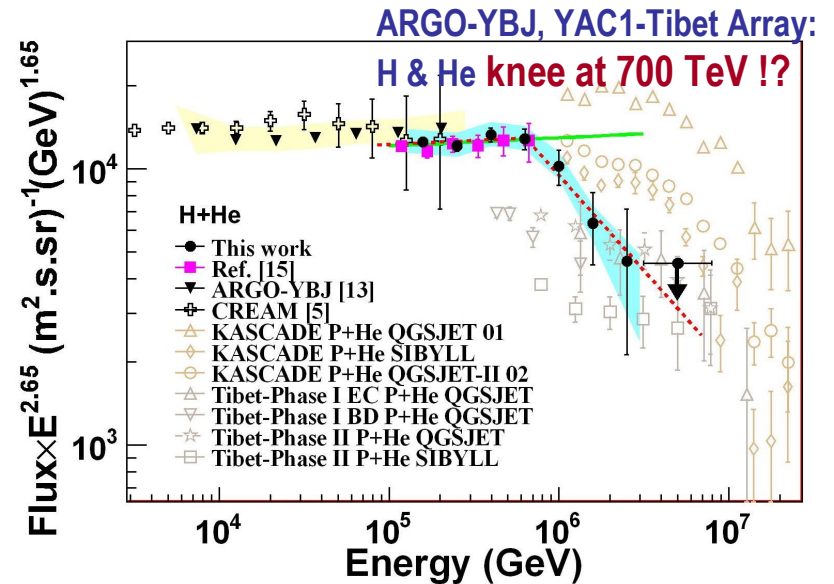
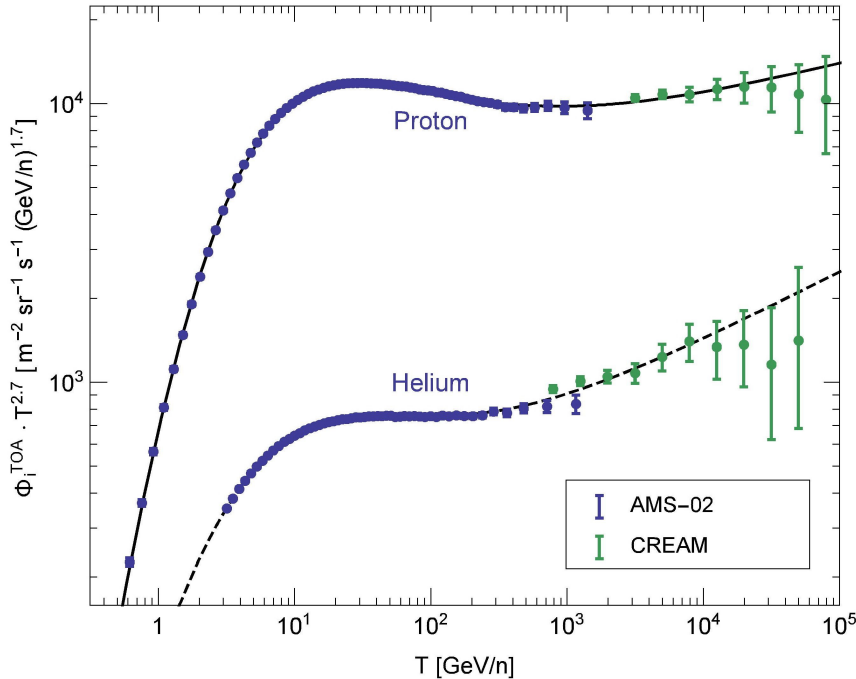
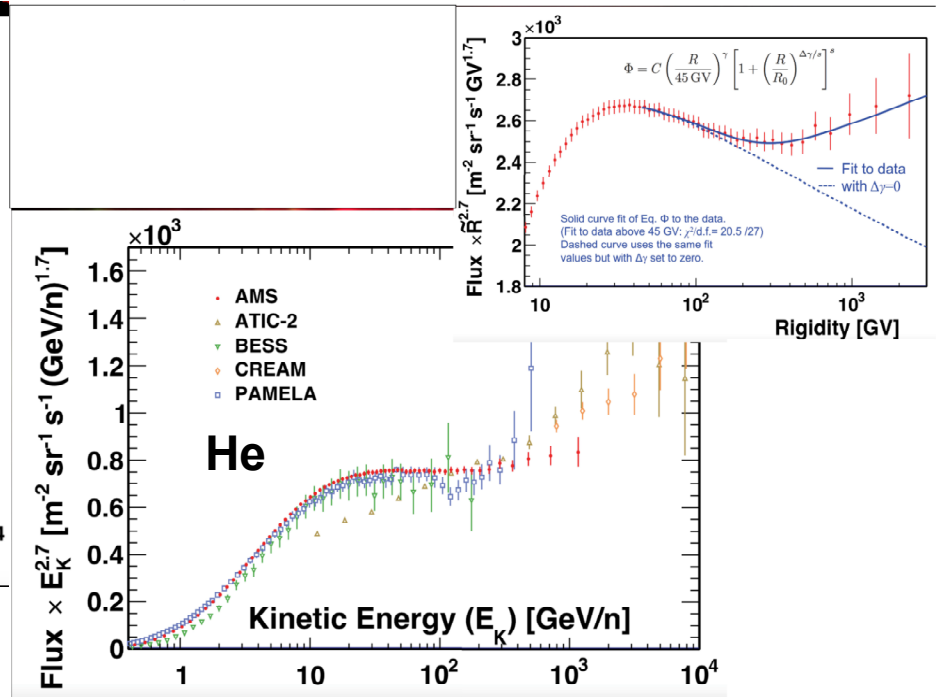
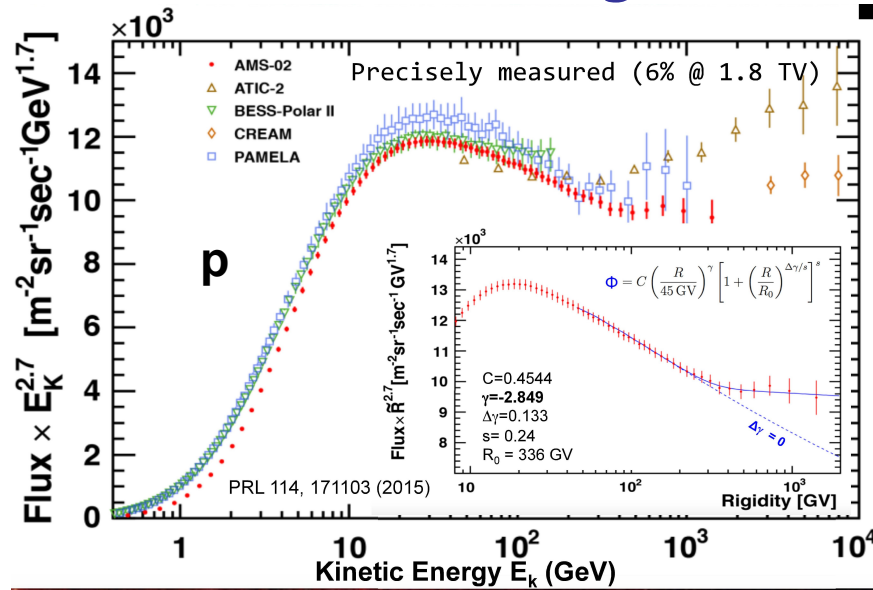
PAMELA (Adriani et al. 2011),

AMS-02 (Aguilar et al 2015), ...

# secondary nuclei



# hardening of H & He spectra above ~ 230 GV



# some suggested explanations of features in H & He spectra:

hardening above 230 GV

spectrum produced by superposition of sources Vladimirov et al 2012, Zatsepin & Sokolskaya 2006;

reacceleration by SNR shocks VP, Zirakashvili, Seo 2011, Thoundam & Hoerandal 2015;

effect of local sources Erlykin & Wolfendale 2011, Bernard et al 2013, Liu et al 2015;

streaming instability below 200 GV Blasi, Amato. 2012;

different turbulence in halo and disk Tomassetti 2012.

spectra of p and He are different

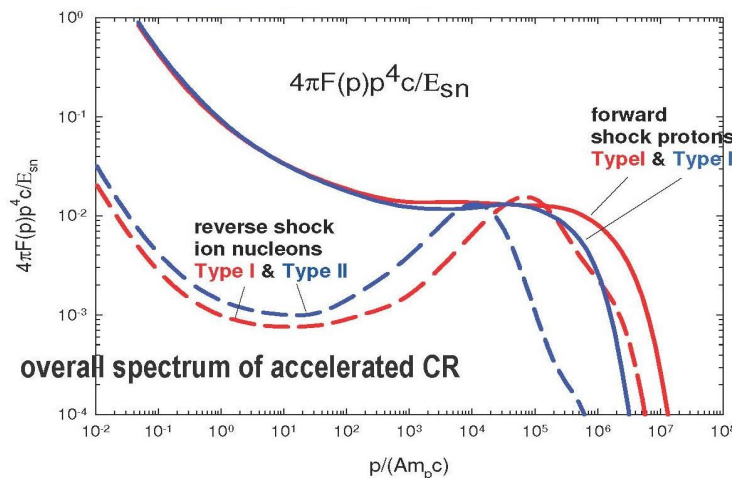
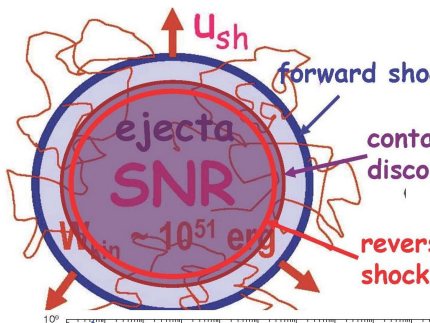
shock goes through material enriched in He:

bubble Ohira & Ioka 2011 or variable (ionized) He/p concentration Drury 2011;

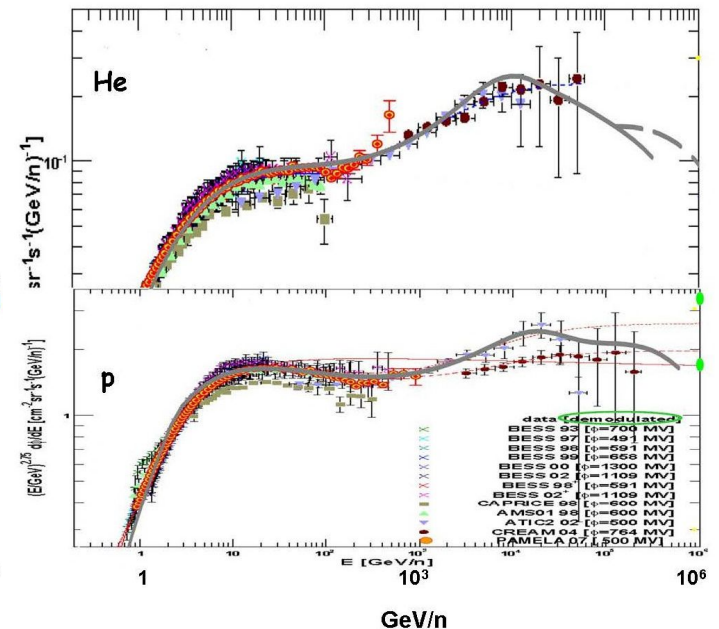
p, He injection for varying  $M_A$  Malkov et al 2012.

possible explanation of both features:

concave spectrum and contribution of reversed SNR shock VP, Zirakashvili, Seo 2013

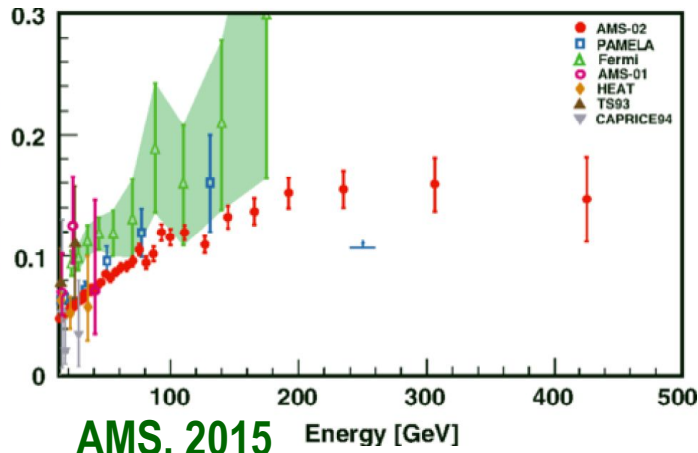
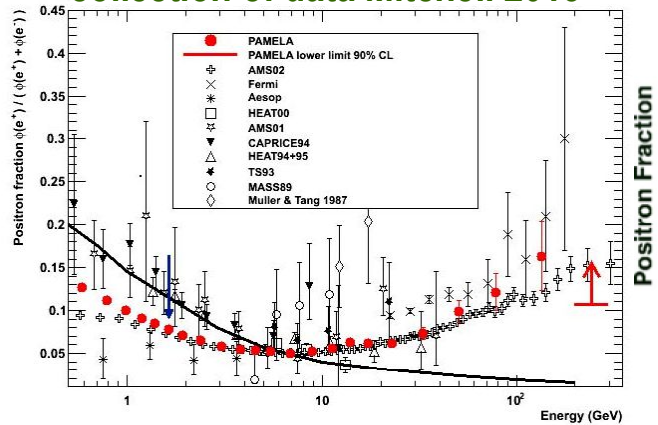


Jx E<sup>2.7</sup>

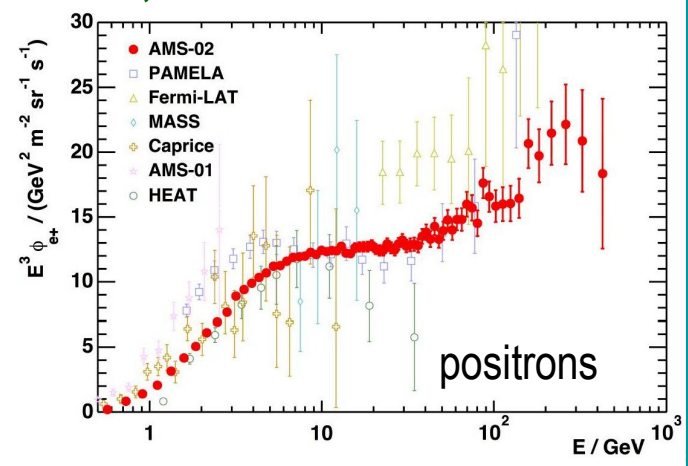
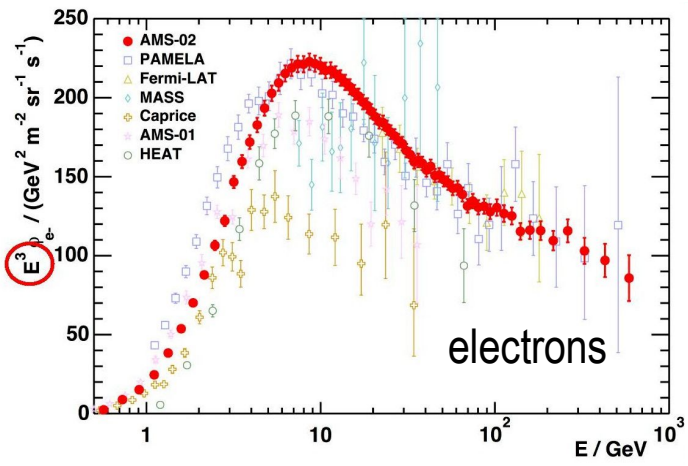


# positrons in cosmic rays

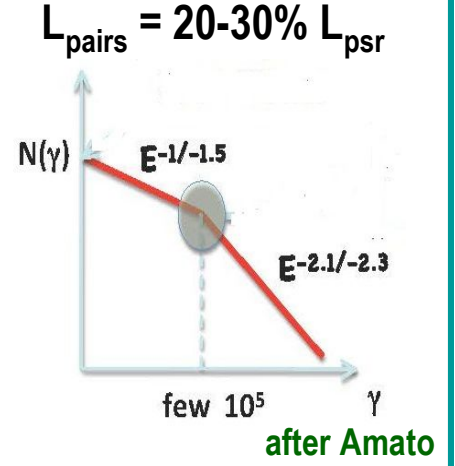
## collection of data Mitchell 2013



## AMS, 2015



## anti-matter factory



- **pulsar/PWN origin** Harding, Ramaty 1987, Aharonian et al. 1995, Hooper et al. 2008, Malyshev et al. 2009, Blasi, Amato 2011, Di Mauro et al. 2014
- **reverse shock in radioactive ejecta** Ellison et al 1990, Zirakashvili, Aharonian 2011
- **annihilation and decay of dark matter** Tylka 1989, Fan et al 2011

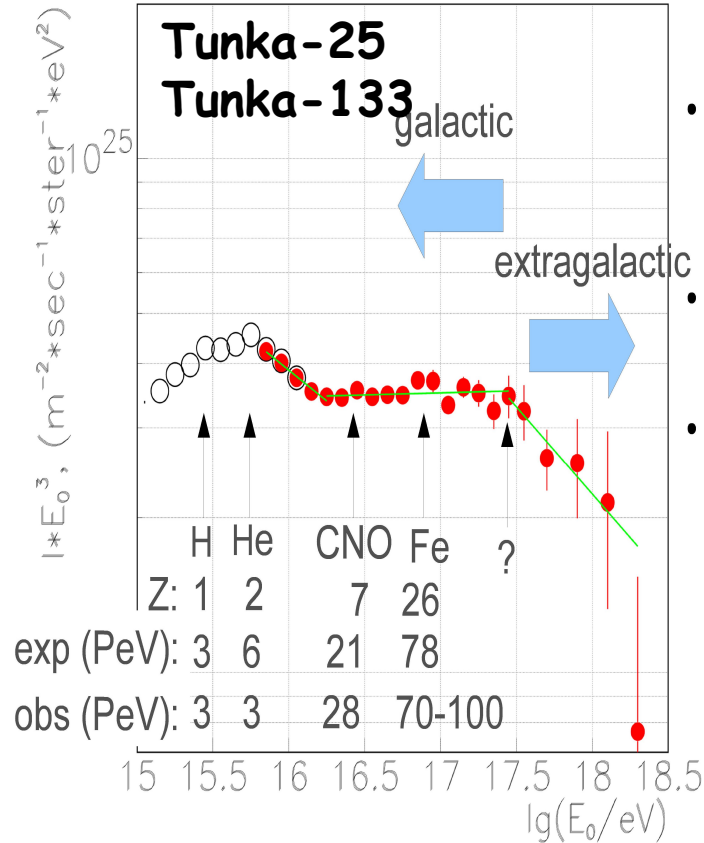
# structure above the knee and transition to extragalactic component

knee at 3 PeV (light primaries),

hardening at 20 PeV (medium component),

2<sup>nd</sup> knee at 300 PeV

Prosin et al 2013, Epimakhov et al 2015



the classical view:

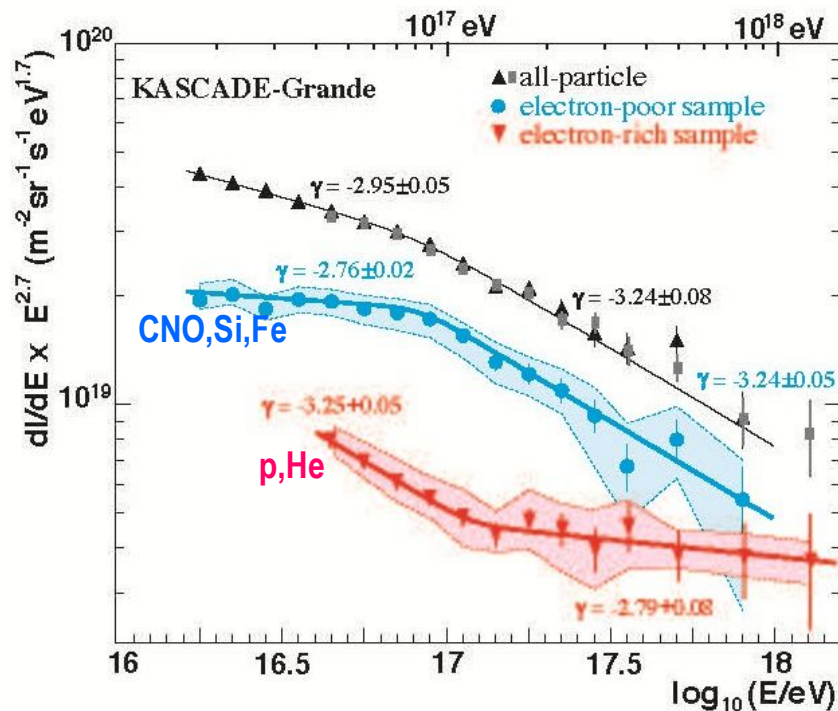
- rigidity dependent cut-offs of different nuclei groups ( $E_c \sim Z$ )
- the composite knee – hydrogen and helium
- the 2<sup>nd</sup> knee – acceleration limit of the Galaxy

Sveshnikova et al 2014:

composition at 1PeV: H 17%, He 46%, CNO 8%, Fe 16%

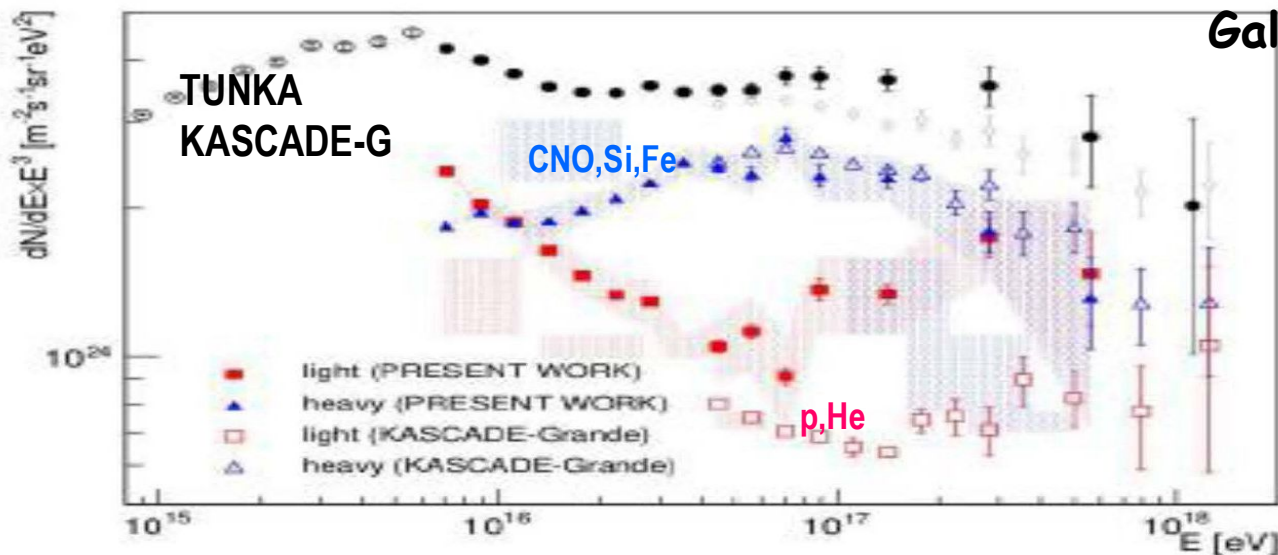
+ EG component H 75%, He 25% as in Kotera & Lemoine 2008

$J \times E^{2.7}$



Iron knee at  
 $8 \times 10^{16} \text{ eV} = 26 \times 3 \times 10^{15} \text{ eV}$

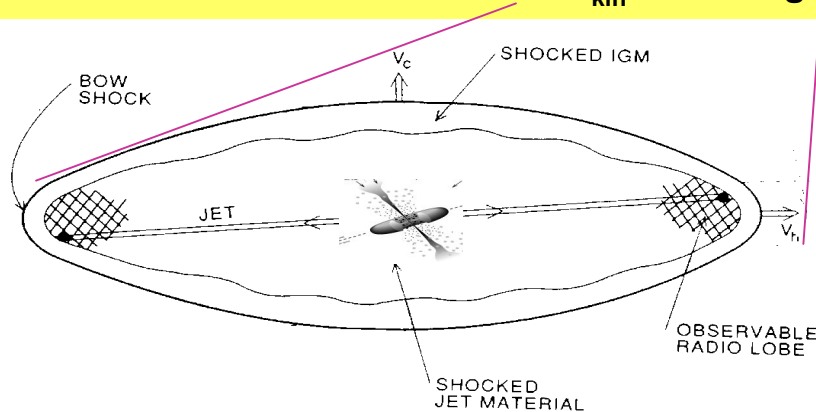
light ankle at  $1.2 \times 10^{17} \text{ eV}$   
 - transition to EG component  
 or onset of a new high energy  
 Galactic source population



# extragalactic sources of cosmic rays

energy release in units  $10^{40}$  erg/(s Mpc<sup>3</sup>)

| needed in CR<br>at $E > 10^{19.5}$ eV | SN                        | AGN jets   | GRB                          | newly born<br>fast pulsars<br>( $< 5$ ms) | accretion on<br>galaxy clusters |
|---------------------------------------|---------------------------|--|------------------------------|---|---------------------------------|
| $3 \cdot 10^{-4}$ (Auger)             | $3 \cdot 10^{-1}$<br>kin. | 3<br>& $6 \cdot 10^{-2}$ for<br>$L_{\text{kin}} > 10^{44}$ erg/s | $3 \cdot 10^{-4}$<br>X/gamma | $10^{-3}$<br>rotation                     | 10<br>strong shocks             |
| $8 \cdot 10^{-3}$ for $E > 10^9$ eV   |                           |  |                              |   |                                 |



Schematic diagram of overpressured cocoons around jets (Begelman & Cioffi 1989).

**AGN jets**

$$E_{\text{max}} \approx 10^{20} \times Z \times \beta^{1/2} \times \left( L_{\text{jet}} / 10^{45} \text{ erg / s} \right)^{1/2} \text{ eV}$$

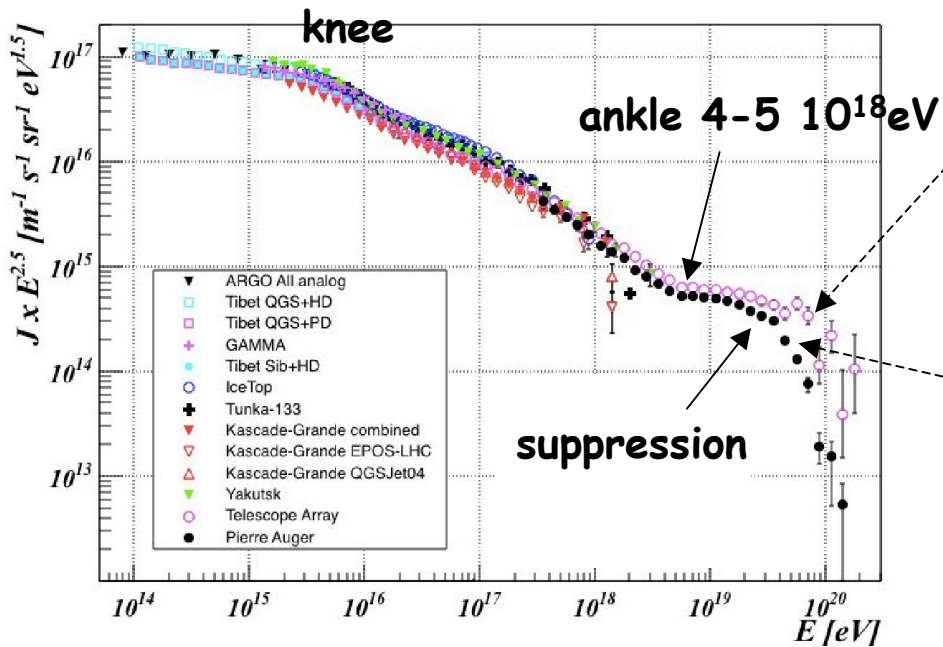
Lovelace 1976, Biermann & Strittmatter 1987, Norman et al 1995, Lemoine & Waxman 2009

**fast new born  
pulsars**

$$E_{\text{max}} \approx 10^{19} \times Z \times \left( \Omega / 10^4 \text{ sec} \right)^2 \text{ eV}$$

$B = 10^{12} \dots 10^{13} \text{ G}$

Gunn & Ostriker 1969, Berezhinsky et al. 1990, Arons 2003, Blasi et al 2000, Fang et al. 2013



## TA+HiRes

- light composition
- "hot spot" anisotropy

if protons dominates:

source spectrum

$\sim E^{-2}$ ,  $E_{\text{max}} \sim 10^{21}$  eV;

GZK suppression

## Auger

- transition to heavy elements above  $10^{19}$  eV
- anisotropy - correlation with matter distribution

source composition is highly enriched in heavy nuclei;

source spectrum is more hard

than  $E^{-1}$ ,  $E_{\text{max}} \sim 5 \times 10^{18} Z$  eV

# Conclusions

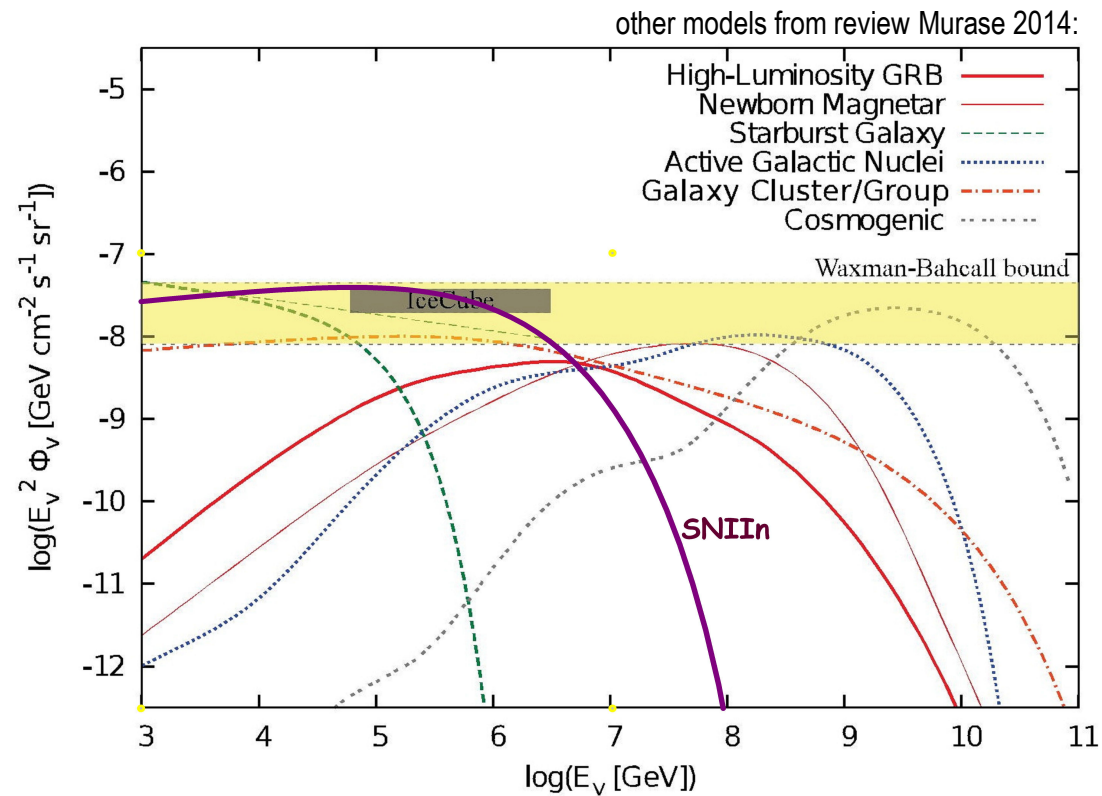
Cosmic ray origin scenario where supernova remnants serve as principle accelerators of cosmic rays in the Galaxy is strongly confirmed by numerical simulations of diffusive shock acceleration. PWN may be responsible for observed flux of cosmic ray positrons.

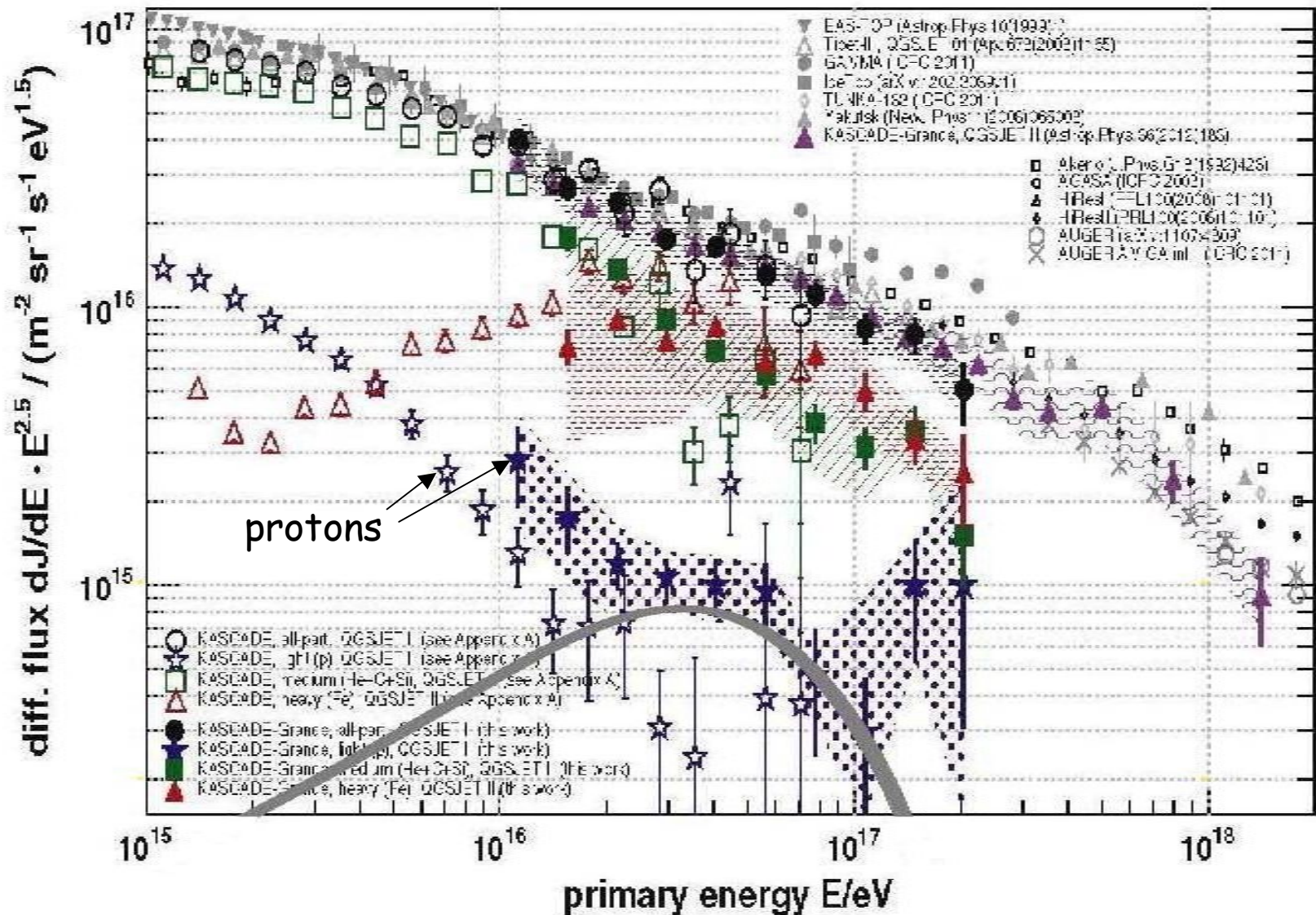
Diffusion provides reasonably good description of cosmic ray propagation in the Galaxy even under simple assumptions on cosmic ray transport coefficients and geometry of propagation region (e.g. as loaded in GALPROP code).

High precision measurements confirm anomalies in cosmic ray spectra of Hydrogen and Helium that require further theoretical work. The antiproton data are compatible with pure secondary origin but allow DM annihilation contribution above  $\sim 100$  GeV.

Eliminating the uncertainties with energy spectrum and composition is necessary for understanding of cosmic ray origin at the highest energies.

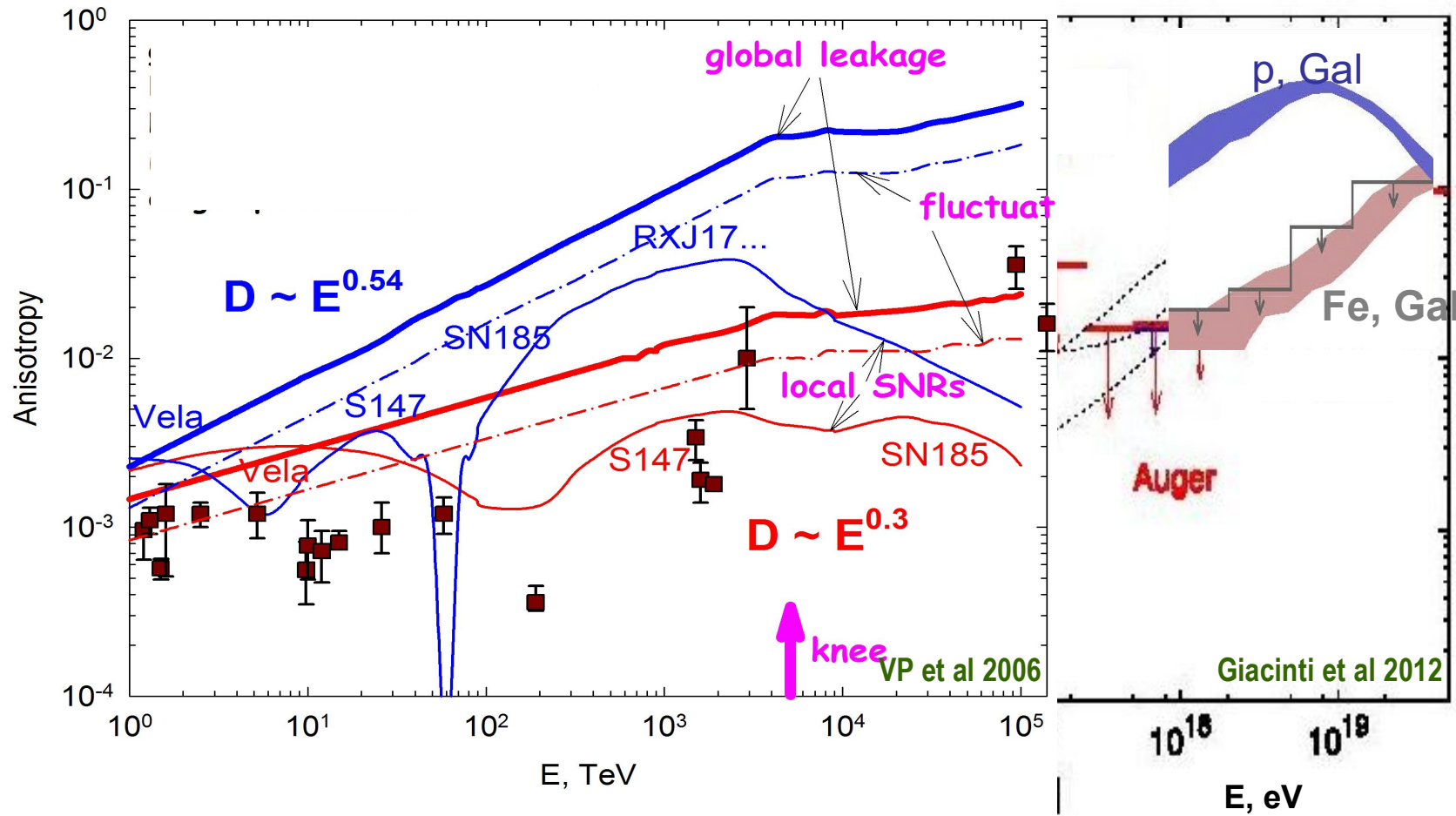
Neutrino production of accelerated protons in extragalactic SNIIn supernova remnants may explain the flux of high energy astrophysical neutrinos observed in IceCube experiment.



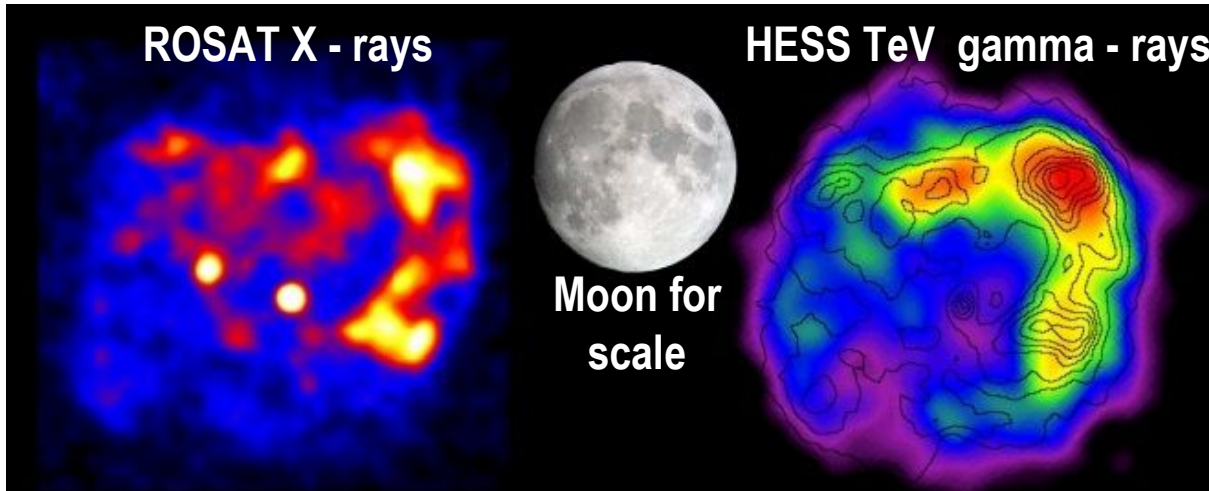


solid line - calculated extragalactic proton background produced by SNIIn (without possible magnetic horizon effect);  
 data on cosmic ray protons and nuclei from [Apel et al 2013](#)

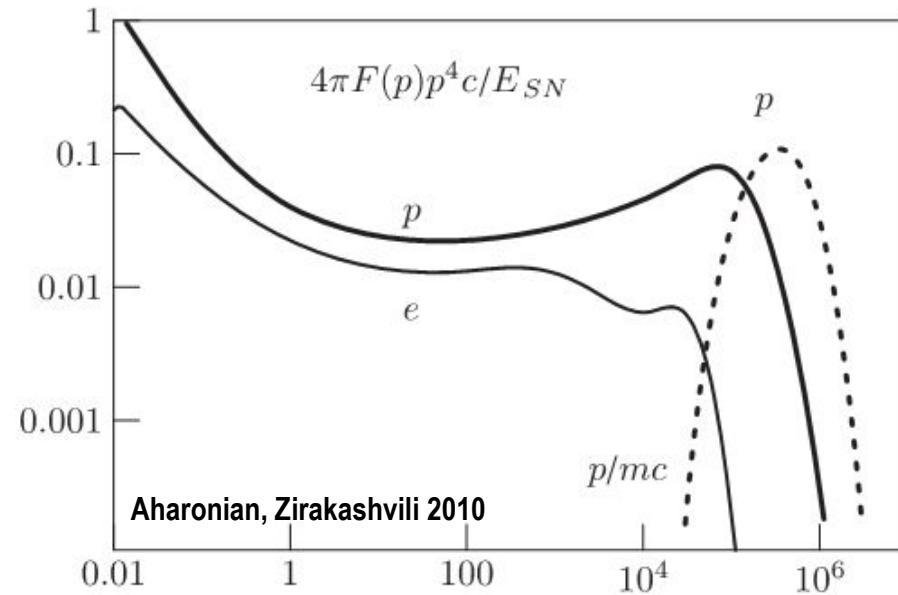
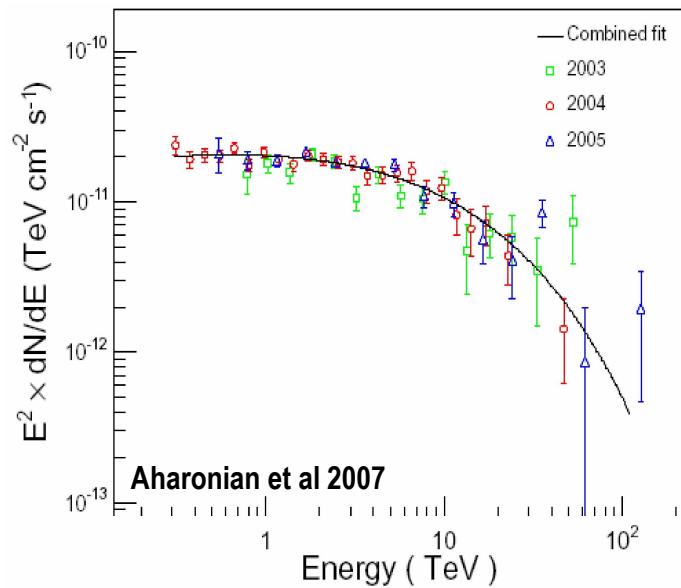
# cosmic ray anisotropy, equatorial dipole amplitude



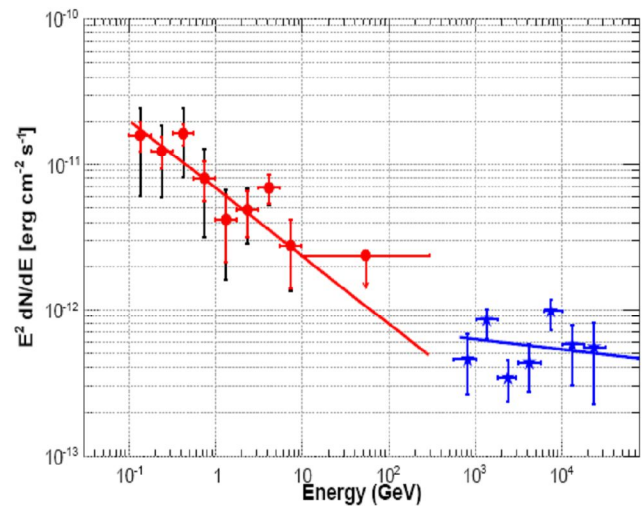
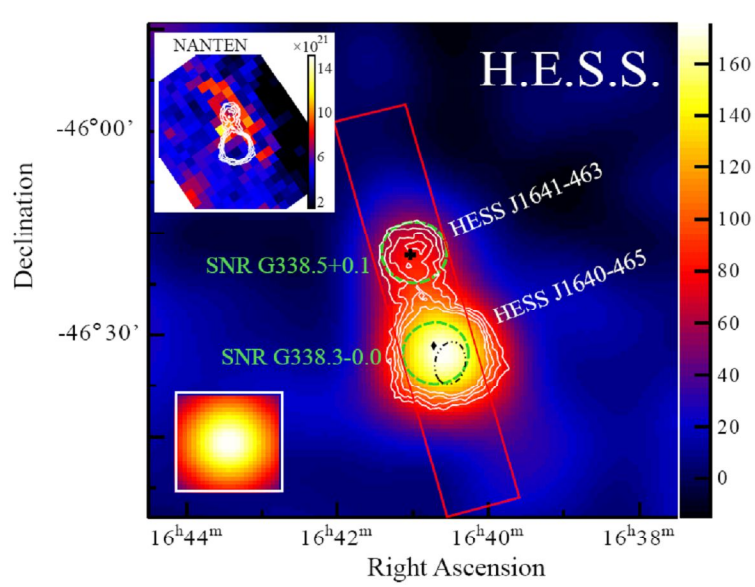
Gombosi et al. 1975, Linsley & Watson 1977, Lloyd-Evans 1982, Kifune et al. 1986, Lee & Ng 1987, Bird et al. 1989, Nagashima et al. 1989, Andreev et al. 1991, Cutler & Groom 1991, Fenton et al. 1991, Mori et al. 1995, Aglietta et al. 1996, Efimov et al. 1997, Munakata et al. 1999, Ambrosio et al. 2003



RX J1713.7-3946,  
1600 yr, 1 kpc



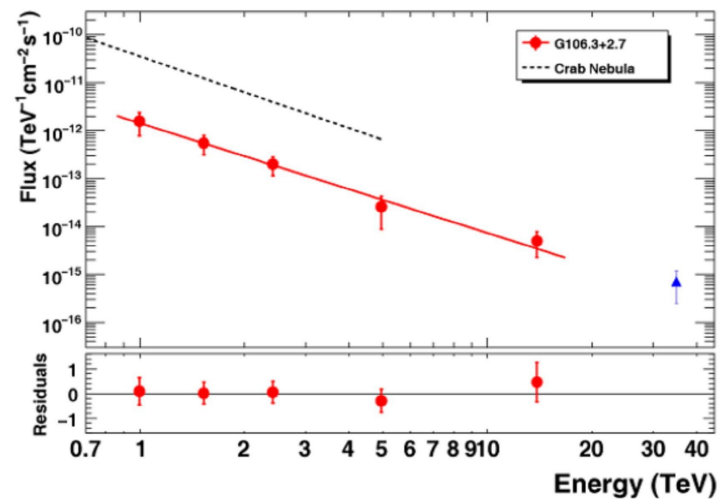
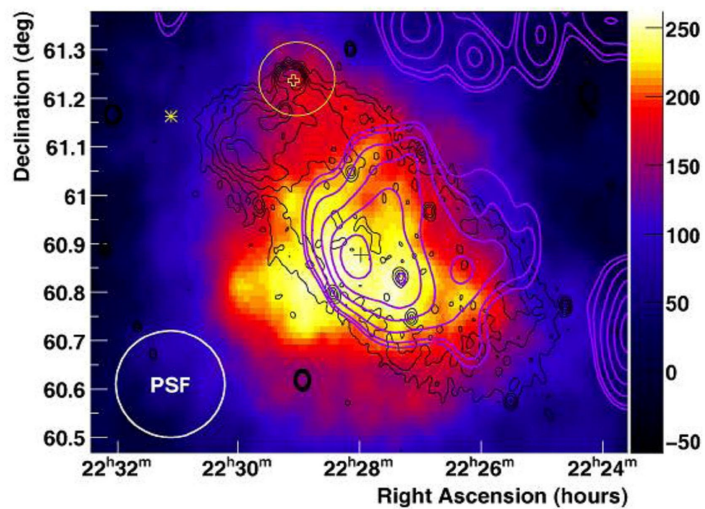
Spatially integrated spectra of accelerated protons and electrons (multiplied by 5000) at  $t = 1620$  yr. The runaway particles, which have left the remnant is shown by dashed line.



Abramowski et al. 2014, Lemoine-Goumard et al. 2014

## SNR G106.3+2.7 / PSR J2229+6114

$d = 800 \text{ pc}, t = 10^4 \text{ yr}$



VERITAS + MILAGRO