# GALACTIC COSMIC RAYS: PROGRESS and PROBLEMS

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- **Galactic Cosmic Ray Standard Model (GCR SM)**
- **PAMELA and Fermi LAT anomalies**
- **Transition from Galactic to extragalactic CR**
- **Extensions of GCR SM**

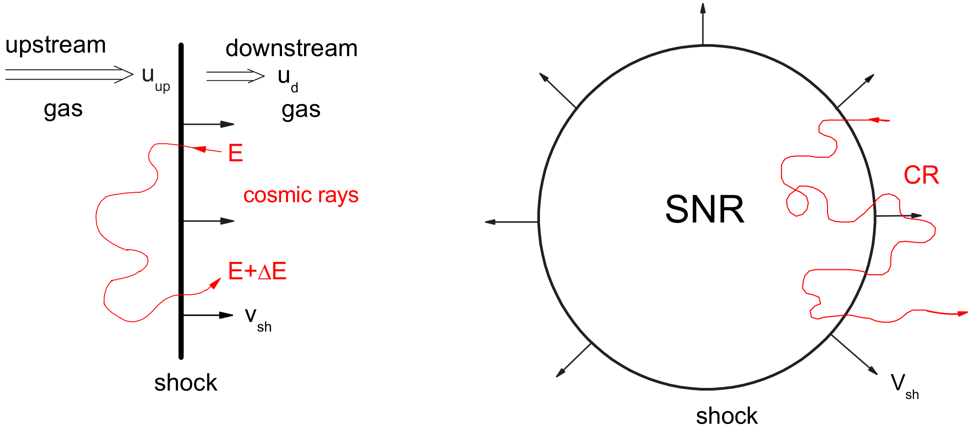
# STANDARD MODEL for GALACTIC CRs

- **sources:** **SN remnants.**
- **acceleration:** **diffusive shock acceleration.**
- **propagation:** **diffusion.**

Ginzburg 1951, Ginzburg and Syrovatskii 1960.

# DIFFUSIVE SHOCK ACCELERATION

$$\frac{\partial f(\vec{x},t)}{\partial t} = \nabla(D\nabla f) - \vec{v}\nabla f + \frac{1}{3}(\vec{\Delta}\vec{v})p\frac{\partial f}{\partial p} + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial f}{\partial p}\right] + Q_{\rm inj}(\vec{x},\vec{p},t).$$




energy gain at each crossing $\Delta E/E \sim v_{\rm sh}/c$, spectrum $N(E)dE \sim E^{-2}dE$.
$E_{\rm max}$ from: $t_{\rm acc} \leq t_{\rm diff}$, where $t_{\rm acc} \sim D/v_{\rm sh}^2$ and $t_{\rm diff} \sim R_{\rm sh}^2/D$.
For Bohm diffusion $D_B \sim r_L c$: $\mathbf{E_{max} \sim (v_{sh}/c)R_{sh}B}$, $E_{\rm max}$ is too low.
With SNR parametrs $v_{\rm sh} \sim 5\times 10^8$ cm/s, $R_{\rm sh} \sim 10^{19}$ cm and $B \sim 3\ \mu$G :

$$\mathbf{E_{max} \sim 2\times 10^{14}\ Z\ (B/3\mu G)\ \ eV}$$

(first by Cesarsky and Laggage 1981).

## DIFFUSIVE SHOCK ACCELERATION: PROGRESS

- **$E_{max}$ :**
  **Acceleration to the highest energies occurs at the beginning of Sedov phase. Non-linear amplification of turbulent magnetic field in the shock precursor due to streaming instability of CR produces magnetic field with strength $\delta B \sim B \sim 10^{-4}$ G (Bell and Lucek).**

$$E_{max} = 4 \times 10^{15} Z \frac{B}{10^{-4}G} \left( \frac{W_{51}}{n_g/cm^3} \right)^{2/5} \text{ eV}$$

$$E_p^{max} = 4 \times 10^{15} B_{-4} \text{ eV}, \qquad E_{Fe}^{max} = 1 \times 10^{17} B_{-4} \text{ eV}$$

- **spectrum:**
  **At fixed SNR age the spectrum of escaped particles is close to $\delta$-function. but time-averaged spectrum is $\propto E^{-2}$ or flatter at highest energies (Ptuskin, Zirakashvili 2006).**

## PROPAGATION IN THE GALAXY

**Diffusive propagation equation for a single source:**

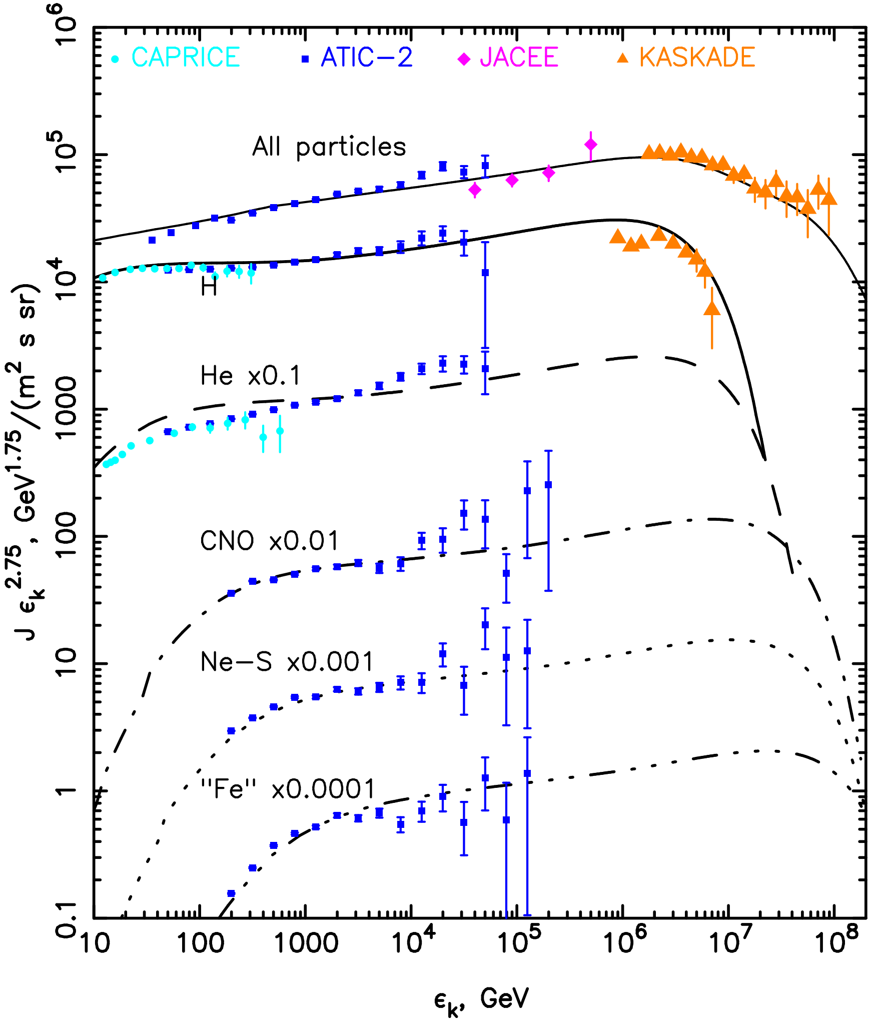
$$\frac{\partial f(x,t)}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial f}{\partial x}\right) - \frac{\partial}{\partial x}(uf) + \frac{1}{3}\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^3\frac{\partial u}{\partial x}f\right) - \frac{f}{\tau_A} -$$

$$-\frac{1}{p^2}\ \frac{\partial}{\partial p}\ \left[b(p)\ \frac{\partial f}{\partial p}\right]\ + \frac{1}{p^2}\ \frac{\partial}{\partial p}\left[p^2\ D_{pp}\ \frac{\partial f}{\partial p}\right]\ + Q(\Gamma)\ \delta^3(x - x_g),$$

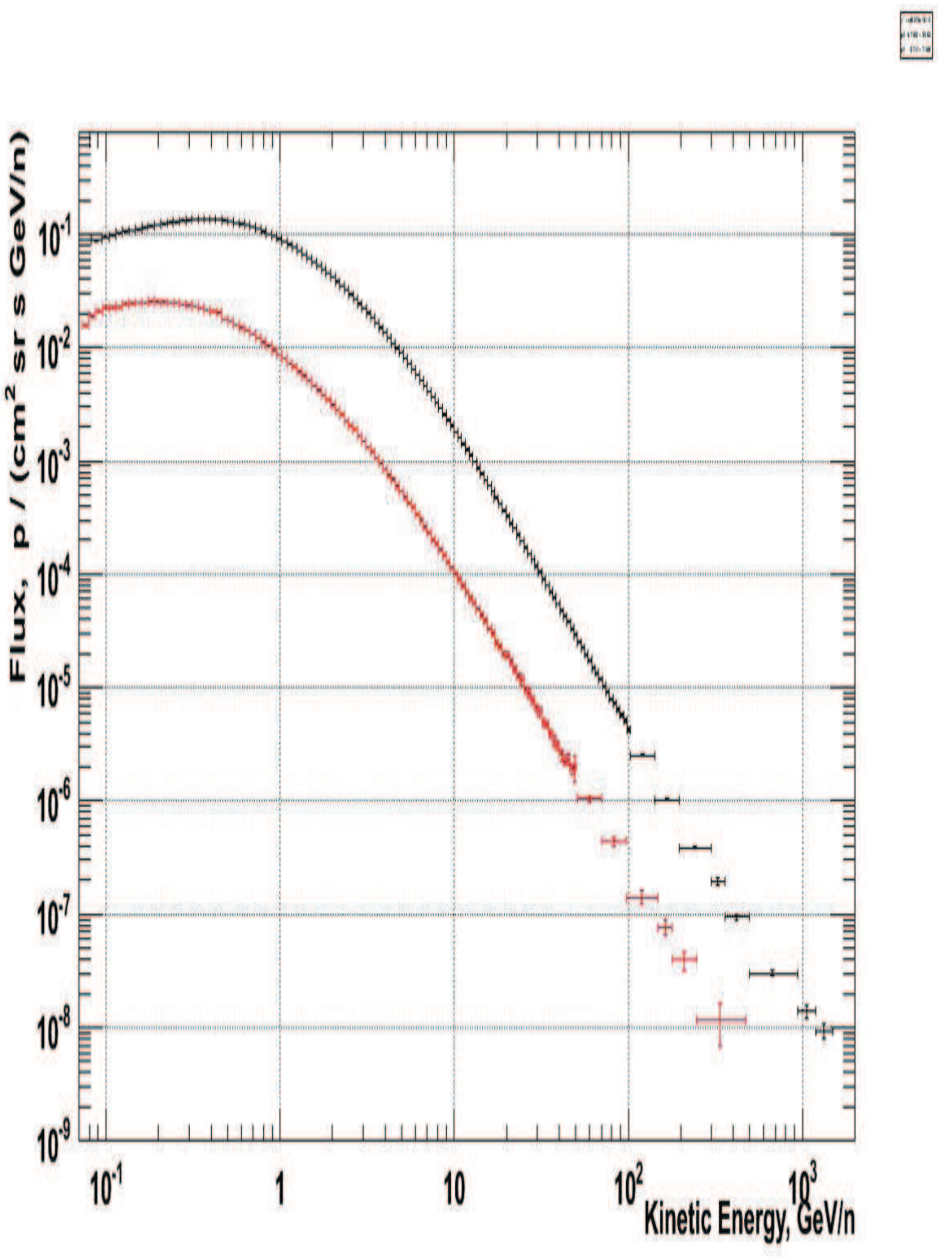
where $Q(\Gamma) = \frac{(\gamma_g - 2)L_0}{Am_N}\Gamma^{-\gamma_g}, b(p) = dp/dt,\ \Gamma$ is Lorentz factor.

# SM : GALACTIC SPECTRA AND KNEES

## Berezhko and Völk 2007

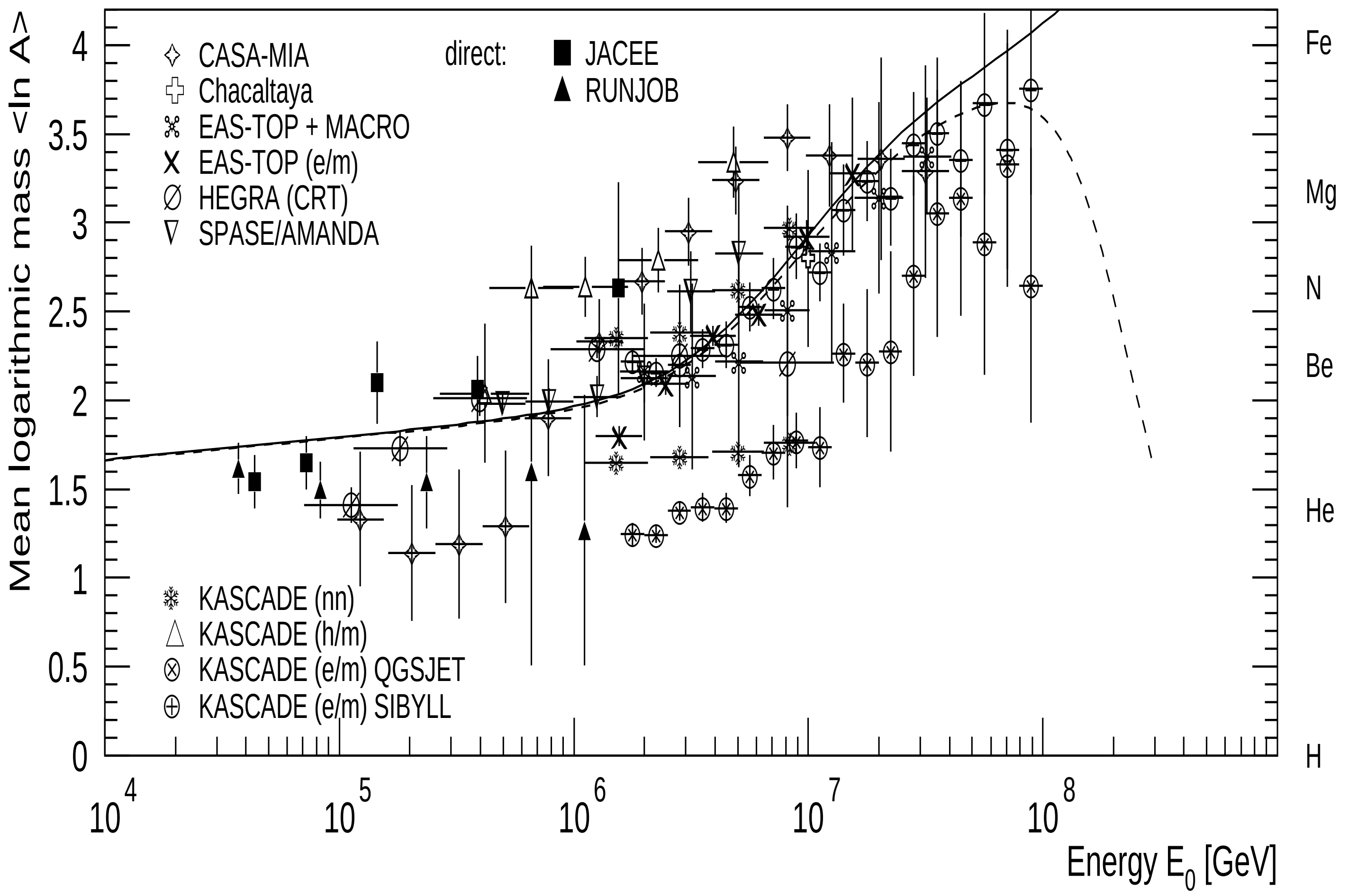


# PAMELA AND FLATNESS OF HELIUM SPECTRUM



# MASS COMPOSITION VS ENERGY

Compilation of Hörandel 2005




**SM** agrees with **EAS-TOP** and **KASCADE**

# SPECTRA: QUALITATIVE ESTIMATES

$$\mathbf{D(E) \propto E^{\mu}}$$

with $\mu = \mathbf{1/3}$ (Kolmogorov), $\mu = \mathbf{1/2}$ (Kraichnan), $\mu = \mathbf{0}$ (shock waves).

## Protons and primary nuclei (p)

generation: $Q_p(E) \propto E^{-\gamma_g}, \;\; \tau_{\rm esc} \propto D^{-1}(E) \propto E^{-\mu}$

$$\mathbf{n_p(E) \sim Q_p(E) \tau_{esc}(E) \propto E^{-(\gamma_g+\mu)}}$$

**observed:** $\gamma_g + \mu = 2.7$, **acceleration:** $\gamma_g = 2$, hence $\mu = \mathbf{0.7}$.

## High energy positrons ($\mathbf{p + p \rightarrow \pi^+ \rightarrow e^+}$)

generation: $Q_{e^+}(E) \sim n_p(E)\, \sigma\, n_{\rm gas}\, c \;\propto E^{-(\gamma_g+\mu)}$

$$n_{e^+}(E) \sim Q_{e^+}(E)\, \tau_{\rm loss} \;\propto E^{-(\gamma_g+\mu+1)}$$

## High energy primary electrons

$$Q_e(E) \propto E^{-\gamma_g}, \;\; n_e(E) \sim Q_e(E)\, \tau_{\rm loss}(E) \propto E^{-(\gamma_g+1)}.$$

## $\mathbf{e^+/e^-}$ ratio

$n_{e^+}/n_{e^-} \propto E^{-\mu}$ in contrast to PAMELA.

# ANISOTROPY

$$\delta(E) \sim \frac{J(E)}{n(E)c} \sim \frac{\mathbf{D(E)}}{c}\frac{1}{n}\frac{\partial n}{\partial r} \propto E^{\mu}, \quad \mu = 0.7.$$

At high energy the predicted anisotropy is too high.

**Observavations:**

$10^{11} - 10^{13}$ eV, amplitude $\sim 3 \times 10^{-4}$, phase $\sim$ (0 - 4) hr

**EAS-TOP,** ApJ, 470, 501, 1996 and ApJ, 692, L130, 2009 :

$1 \times 10^{14}$ eV, amplitude $= (2.6 \pm 0.8) \times 10^{-4}$, phase $= (0.4 \pm 1.2)$ hr

$4 \times 10^{14}$ eV, amplitude $= (6.4 \pm 2.5) \times 10^{-4}$, phase $= (13.6 \pm 1.5)$ hr

# INCOMPLETENESS and PROBLEMS of GCR SM

## Acceleration and sources

- **Injection for shock acceleration.**
- **Alternative acceleration/sources (subdominant).**
- **Inhomogeneous distribution of sources.**

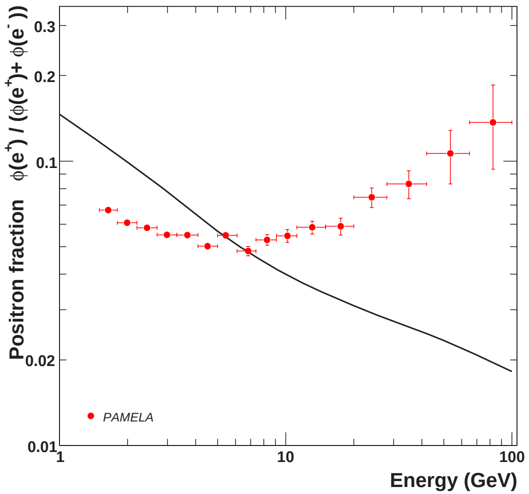
## Propagation

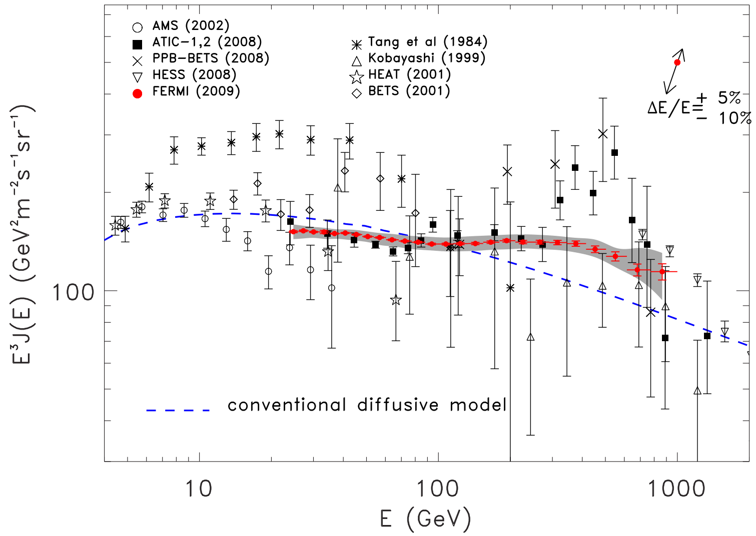
- **Magnetic field is not reliably known.**
- **Breaking of diffusive regime at highest energies.**
- **Reacceleration uncertainties.**

## Problems of GCR Standard Model

- **Flatness of He spectrum (but PAMELA !)**
- **Large $\mu$ ($\mu = 0.7$).**
- **Anisotropy $\delta(E) \propto D(E) \propto E^{\mu}$ is too large at high energy.**
- **No observed pp-produced gamma and neutrino radiations from SNR.**

# PAMELA and FERMI LAT




## Possible explanations

- Parameter uncertainties in SM: Delahaye et al. (Torino-Annecy) 0809.5268
- $e^+e^-$ from pulsars: Büshing et al., Ap.J. L678, 39, 2008.
- DM annihilation: Cirolli et al., 0809.2409.

# CONSERVATIVE (GCR SM) EXPLANATIONS
# OF PAMELA and FERMI ANOMALIES

# Positron excess in GCR SM

P. Blasi, PRL 103, 051104, 2009

**Production of positrons due to $pp \to \pi^+ \to e^+$ in the region of acceleration.**

$$Q_{e^+}(E) = \int dE' n_p(E', x) \frac{d\sigma(E', E)}{dE'} n_g(x) c$$

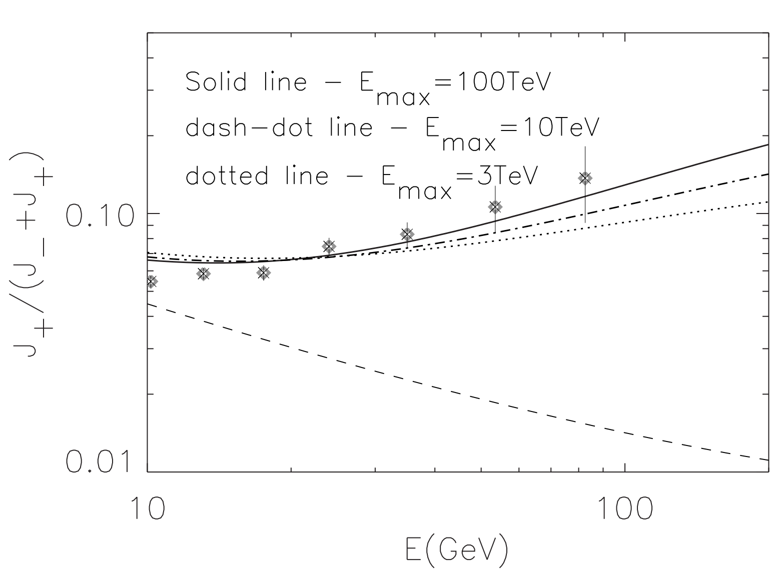
**Acceleration of injected positrons** ($f_{e^+}(x) \equiv f(x)$).

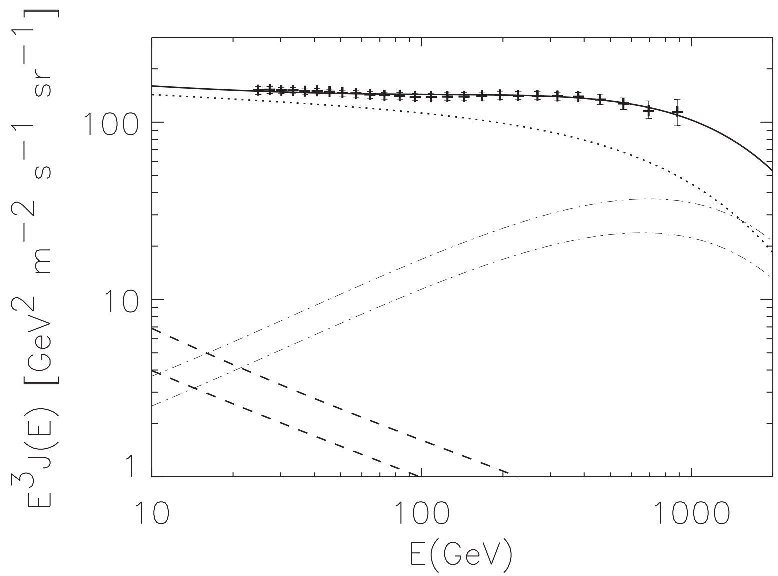
$$D\frac{\partial^2 f}{\partial x^2} - v\frac{\partial f}{\partial x} + \frac{1}{3}\frac{dv}{dx}p\frac{\partial f}{\partial p} + Q_{e^+}(p, x) = 0.$$

$$D(E) = D_0 E^\mu, \quad \mu = 0.6, \quad E_{\max} = 100 \text{ TeV}$$

- $\mu = 0.6$ is a problem.
- $E_{\max} = 100$ TeV is too high for old SNRs

## P. Blasi, PRL 103, 051104, 2009 Results




PAMELA: $e^+/(e^+ + e^-)$ ratio Fermi LAT: $(e^+ + e^-)$ flux.

**Similar effects with ratio increase**

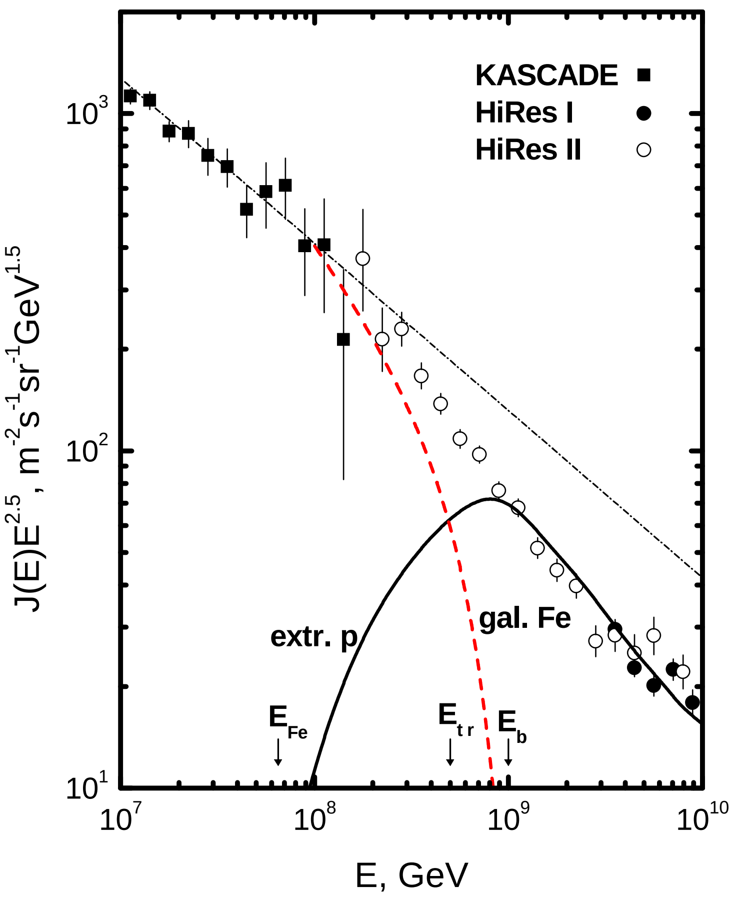
**secondary/primary nuclei :** Mertsch, Sarkar 2009, Ti/Fe observed in ATIC-2.

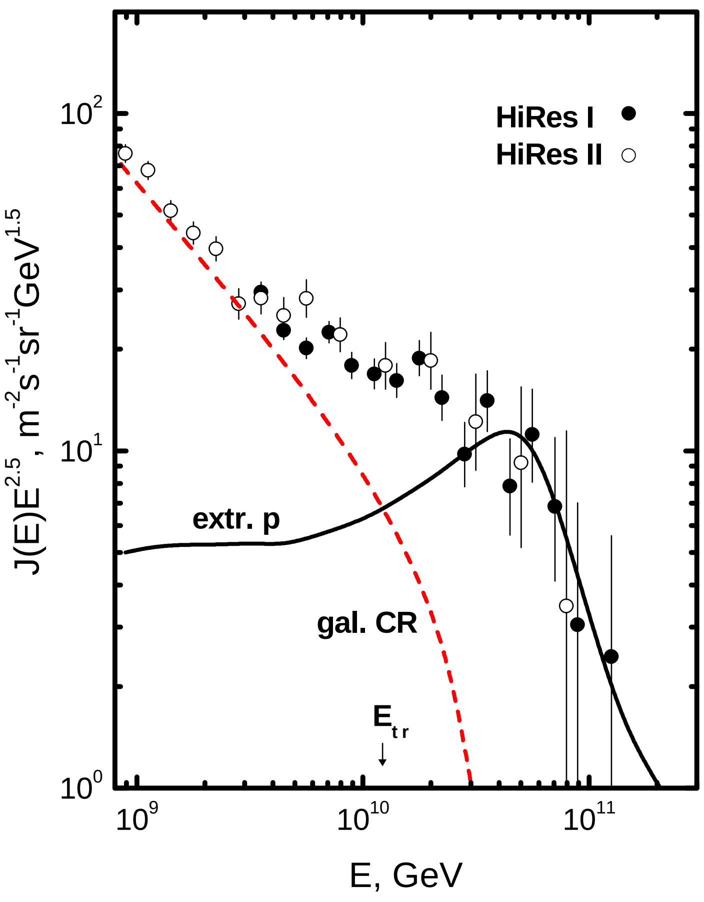
$\bar{p}/p$**-ratio:** Blasi, Serpico 2009, predicted.

# TRANSITION FROM GALACTIC TO EXTRAGALACTIC CR

**In the dip model transition occurs at $E_{\rm tr} < E_b = 1 \times 10^{18}$ eV, i.e. at second knee. This transition agrees perfectly with the standard galactic model.**

**In the ankle model transition occurs at $E_a = 4 \times 10^{18}$ eV and the galactic flux at this energy is half of the total in contradiction with standard galactic model.**

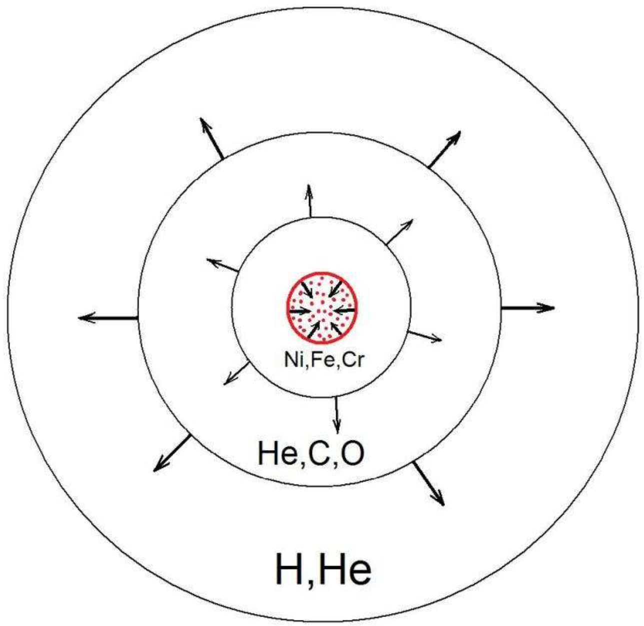


# EXTENSIONS OF GCR SM

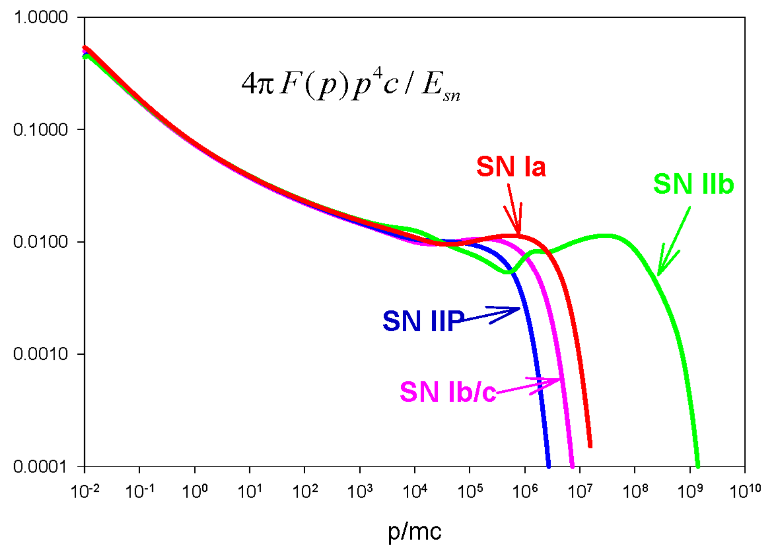
# PARTICLES WITH $E > 10^{18}$ eV FROM SNRs

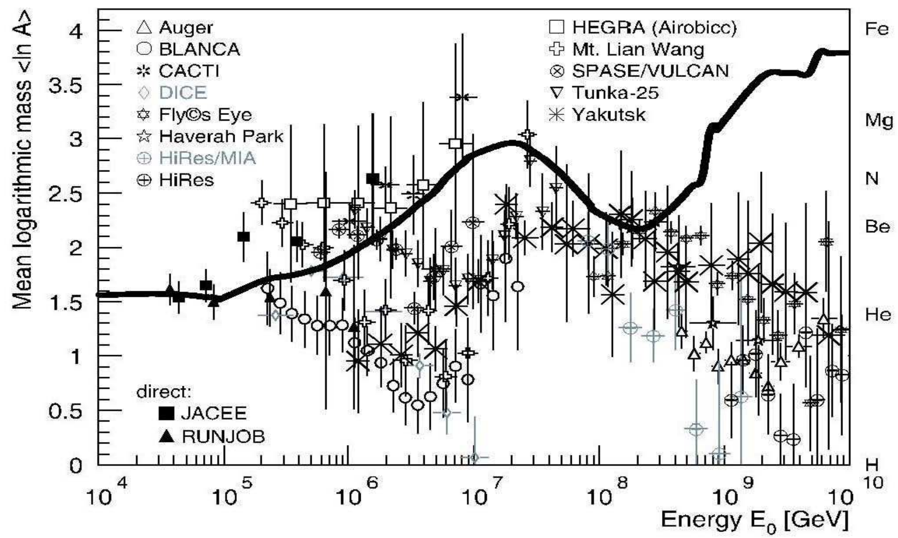
**Ptuskin, Zirakashvili, Seo 2010**




**Progenitor of SNII is red supergiant.**
**Evolution: core contraction and stellar wind.**
**SN explosion into space with stellar wind.**
**SN shock with $E_{\max}$ at Sedov stage.**
**Sedov phase starts in inner shell.**
**4 groups of SNRs: Ia, Ibc, IIP and IIb.**

# ENERGY SPECTRA and MASS COMPOSITION



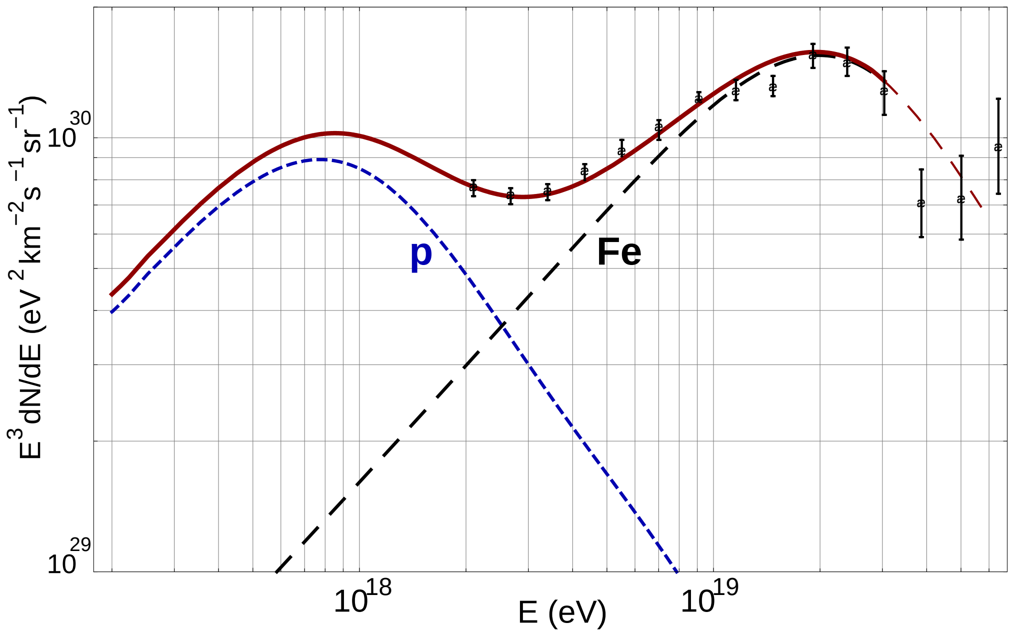




**Source spectra for protons**

**Mass composition of diffuse flux**

# UHECR from GRBs in Milky Way

## Calvez, Kusenko, Nagataki PRL 105.091101, 2010




- **GRBs are distributed in MW with random space location and with rate $\nu_{\rm GRB} \sim 10^{-5}$ yr$^{-1}$.**
- **CR production $\propto E^{-2.3}$ with 90% protons and 10% Fe.**
- **Particles propagate diffusively.**

**(also Dermer and Holmes 2005)**

# CONCLUSIONS

- **GCR SM, based on the diffuse shock acceleration in SNRs and diffusive propagation in the Galaxy, describes well the basic observations: knees, spectra, secondary/primary ratio etc. However, the SM is incomplete and meets some problems.**

- **The problems include: (i) flatness of He spectrum (however, PAMELA !), (ii) large $\mu = 0.7$, (iii) too large anisotropy predicted at high energy, and (iv) non-observation of hadronic gamma-rays and neutrinos from SNRs.**

- **Recently, GCR SM has been questioned by PAMELA and Fermi anomalies. Now it is understood that they can be solved within framework of SM, and tested by measuring $\bar{p}/p$ ratio and secondary/primary nuclei ratio in future experiments at $E \gtrsim 1$ TeV. The other solutions, e.g. pulsars or DM, can provide subdominant effects.**

- **The transition from galactic to extragalactic CRs in the dip model fits well the GCR SM. The ankle model needs the extended GCR SM**