# Hypernova and Gamma-ray Burst Remnants as TeV Unidentified Sources

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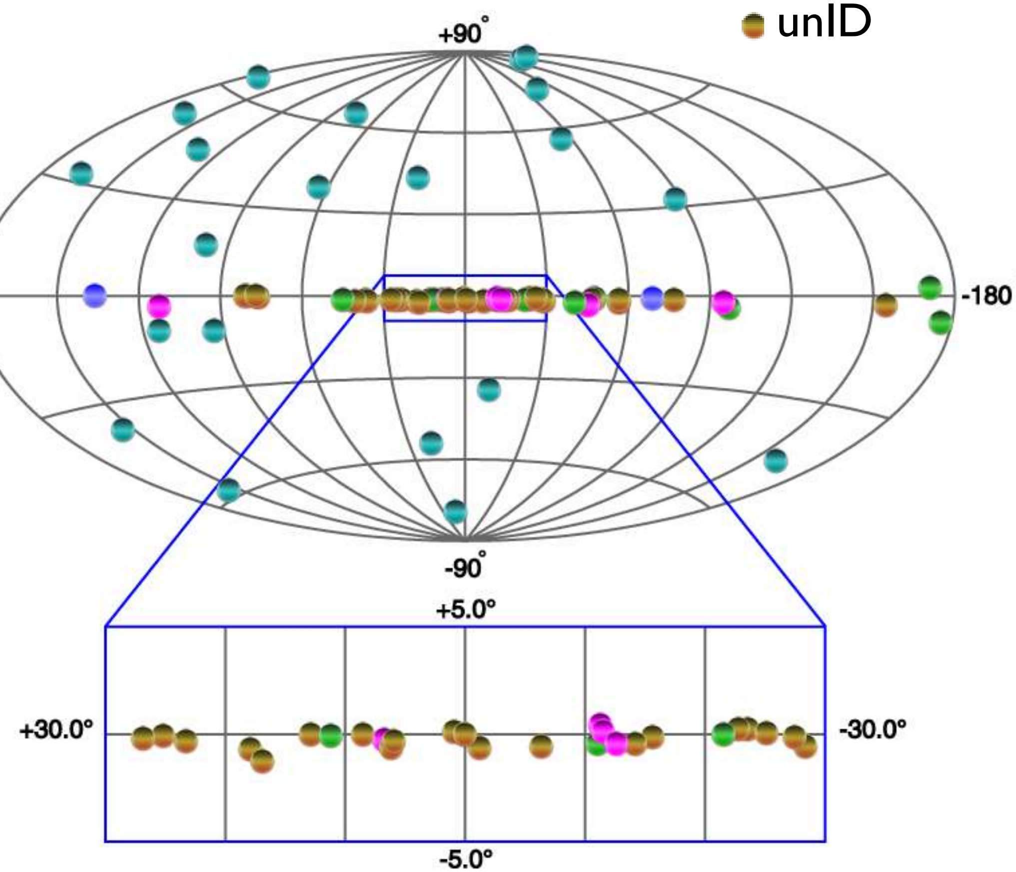
# TeV unIDs

1. So far $N_{unID}$ ~10-30 TeV unIDs have been observed.
2. They generally lie close to the Galactic plane, suggesting a Galactic origin.
3. They are extended, $\Delta\Omega$~0.05-0.3°.
4. The flux is $\varepsilon_\gamma F_{\varepsilon_\gamma}$ ~$10^{-12}$-$10^{-11}$ erg $s^{-1}cm^{-2}$ at $\varepsilon_\gamma$ ~0.2TeV.
5. They have a power-law spectrum with index of 2.1-2.5.
6. Some TeV unIDs have strong upper limits in X-rays with a TeV to X-ray flux ratio of $F_{TeV}/F_X$ >~50 from Suzaku (Matsumoto et al. 2007; Bamba et al. 2007) and in radio with $F_{TeV}/F_{radio}$~$10^3$ (Atoyan et al. 2006; Tian et al. 2008).

# Energetics of TeV unIDs

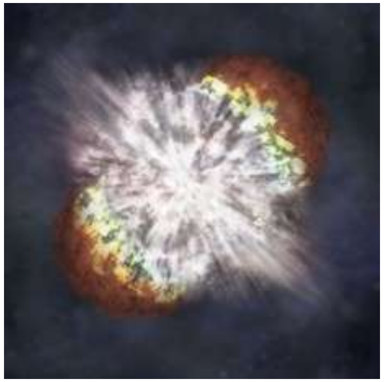
- Cosmic-ray accelerators as possible origin: ex. Supernova remnants (SNRs)
- Required galactic energy budget
  $4\pi d^2\ \varepsilon_\gamma F_{\varepsilon_\gamma}\ N_{\mathrm{unID}}$
  $\sim 10^{34\text{-}35}(d/10\mathrm{kpc})^2$ erg s$^{-1}$
- Supernovae
  $10^{50}$erg / 100yr
  $\sim 10^{41}$erg s$^{-1}$
- TeV unIDs are a rarer type of source!




http://tevcat.uchicago.edu/

# Hypernovae and low-luminosity GRBs

- Long GRBs – rare SNe with relativistic jets, expected to leave GRB remnants
- Hypernovae (~100 $E_{SN}$), sometimes associated with GRBs, occur more frequently than GRBs.
  - Ex. SN1998bw/GRB980425, SN2003dh/GRB030329, SN2003lw/GRB031203
  - Rate is even higher if we are missing GRB-unassociated HN (ex. SN1996ef)
- Low-luminosity GRBs with slower or semi-relativistic jets may be a large fraction of SNe.
  - Ex. GRB980425/SN1998bw, GRB060218/SN2006aj



*Hypernova: the origin of the most dangerous gamma-ray bursts?*

# Models

1. $\pi^0$ decay model
   - pp interaction by accelerated CRs
2. $\beta$ decay model
   - $\beta$ decay of the neutron component of the CR outflow accelerated by the jets followed by inverse Compton scattering
3. Radio-isotope (RI) decay model **New!**
   - Lorentz-boosted MeV decay gamma-rays of accelerated RI

# Hypernova shocks – $\pi^0$ decay model

- $\pi^0$ from *pp* interaction between ISM and CRs accelerated by SN/HN shocks
  - Leptonic models may predict too much synchrotron emission.
- Flux scaled from SN case

$$\varepsilon_\gamma F_{\varepsilon_\gamma} \sim 10^{-12}\ \zeta_{-1} E_{51} n d_{10\mathrm{kpc}}^{-2}\ \mathrm{erg\ s^{-1} cm^{-2}}$$

$\zeta_{-1} = (\zeta / 0.1)$: fraction of CR energy per log interval, $n$: ISM density ($\mathrm{cm^{-3}}$), $E_{51} = E_{CR}/10^{51}$erg, $d_{10\mathrm{kpc}}$=d/10kpc

- Time independent – sources could be old: $t_{age} \sim 10^5$yr
  - Electrons lost their energy until now.

*Hypernova remnant candidate W49B*

# $\pi^0$ decay model

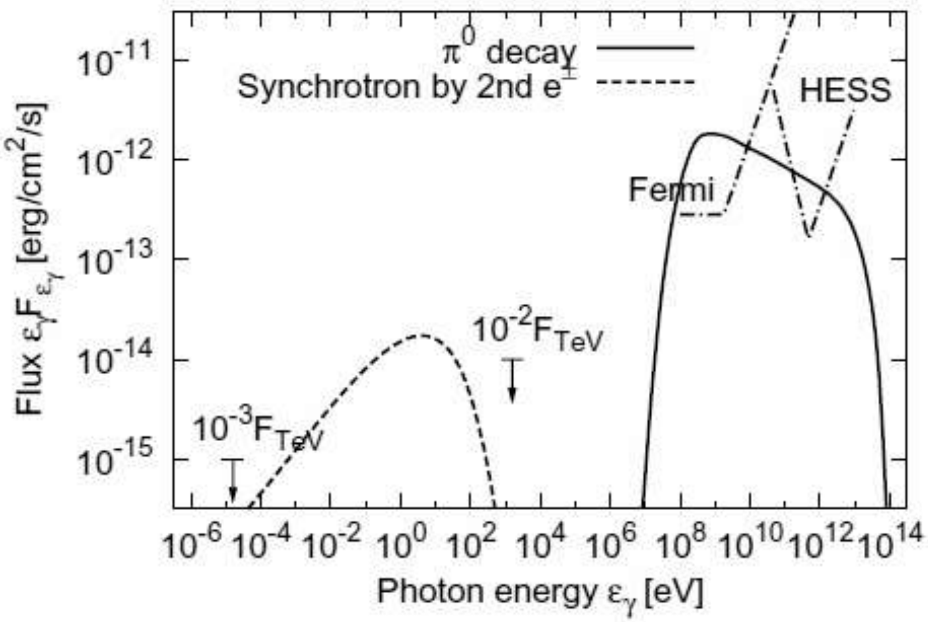



FIG. 1.— Flux from the $\pi^0$ decay via *pp* interactions between the ISM and CRs accelerated by the hypernova shocks, compared with the Fermi and HESS sensitivities. We assume a remnant of age $t_{\rm age} = 10^5$ yr at $d = 10$ kpc with a CR energy $E = 3 \times 10^{51}$ erg and the CR spectral index $p = 2.2$ in the energy range $m_p c^2 < \varepsilon_p < 10^5 m_p c^2$. We also show the synchrotron emission from $\pi^0$ decay positrons and electrons for $B = 3\mu$G, compared with the observational upper limits for an X-ray to TeV flux ratio of $10^{-2}$ and a radio to TeV flux ratio of $10^{-3}$. We use a code of Kamae et al. (2006) for calculating *pp* interactions.

# Observed number of HN remnants

- Flux sensitivity to an extended source (radius $r$)

  $F_{\varepsilon_\gamma}^{\text{extended}} = F_{\varepsilon_\gamma}^{\text{point}}(r/d\theta_{\text{cut}})$

  $\therefore F_{\varepsilon_\gamma}^{\text{point}}(r/d\theta_{\text{cut}}) < F_{\varepsilon_\gamma} \propto E\, n\, d^{-2}$
- Max. distance to a source: $d_{\max} \propto E\, n\, r^{-1}$
- Observable volume in Galactic disk: $V \propto d_{\max}^2 \propto E^2 n^2 r^{-2} \propto E^{8/5} n^{12/5}$, where $r \propto E^{1/5} n^{-1/5} t_{\text{age}}^{2/5}$
- Observed number of HN remnants (note $E_{\text{HNR}} \sim 10 E_{\text{SNR}}$)

$$\frac{N_{HNR}^{obs}}{N_{SNR}^{obs}} \sim \frac{R_{HNR} V_{HNR}}{R_{HNR} V_{HNR}} \sim \frac{10^{-4}\,\text{yr}^{-1} \cdot 10^{8/5}}{10^{-2}\,\text{yr}^{-1} \cdot 1^{8/5}} \sim 0.4$$

- Angular size of old ($10^5$yr) HN remnants:

  $r/d \sim 30\text{pc}/d \sim 0.2°(d/10\text{kpc})^{-1}$
  - Cf. SNR $r/d \sim 2°(d/1\text{kpc})^{-1}$ ($\rightarrow$ more extended SNRs?)
- Density around HN could be larger for star forming regions (but they may be runaway massive stars with no enhancement).

# GRB jets – β decay model

- A fraction of SNe/hypernovae is associated with long GRB and their jets.
- (Time-delayed) β decay of the neutron component of the CR outflow accelerated by the jets followed by inverse Compton scattering. [W49B case: Ioka et al. 2004, ApJ / MM 23-AUG-2004]
- Jet-like emission would appear outside of the SNR, since β decay can occur outside the remnant.
- Old (~$10^5$yr) jet remnants could be TeV unID sources (electrons go down since $t_{cool}$~$10^5$yr).
- Expected total number is 0.1-1 for a Galactic GRB rate of ~$10^{-5}$-$10^{-6}$ yr $^{-1}$.
- Optimistic rate consistent with the late-time radio observations is ~$10^{-4}$ yr $^{-1}$ (~10% of the SN Ibc rate), yielding a total number of ~10, because a larger fraction of SNe may have lower-luminosity (LL) jets that were not identified.

# β decay model

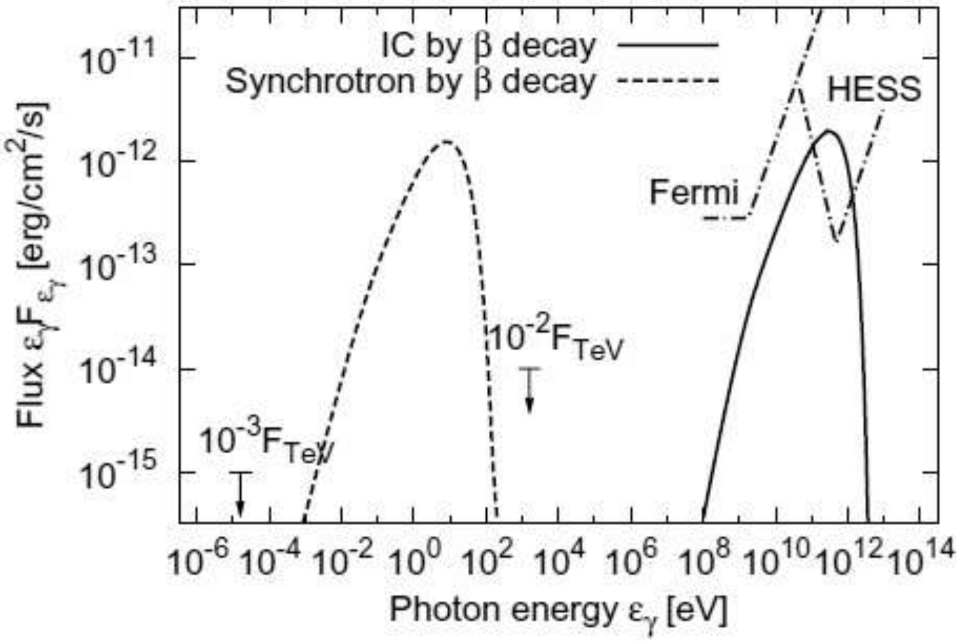



FIG. 2.— Flux from the IC scattering of CMB photons by the $\beta$ decay electrons via the CR neutron component in the GRB jets, compared with the Fermi and HESS sensitivities. We assume a remnant of age $t_{\rm age} = 10^5$ yr at $d = 10$ kpc with a CR energy $E = 3 \times 10^{51}$ erg [i.e., an old remnant version of Model (I) in Ioka et al. (2004)] and a CR Lorentz factor $10^6 < \gamma_n < 10^9$. We also show the synchrotron emission from $\beta$ decay electrons for $B = 3\mu$G, compared with observational upper limits for an X-ray to TeV flux ratio of $10^{-2}$ and a radio to TeV flux ratio of $10^{-3}$.

# GRB jets – radio-isotope (RI) decay model

- Features
  - Composition of jet is unknown - $^{56}$Ni, $^{56}$Co?
  - HN/SN shock→explosive nucleosynthesis→$^{56}$Ni production →accretion and ejection by central engine
  - Photodisintegration
    - Suppressed in LL jets (temperature < ~MeV)
    - Reproduced in a cooling wind if disintegrated [MacFadyen 2003]
  - GRB-associated HN may be $^{56}$Ni-rich [Maeda&Nomoto 2002]
- RI Decay

$$^{56}\mathrm{Co}^* \rightarrow {}^{56}\mathrm{Co} + \gamma \ (\sim 2\mathrm{MeV})$$
$$^{56}\mathrm{Co} + e^- \rightarrow {}^{56}\mathrm{Fe}^* + \nu_e \ [\tau_{\mathrm{Co}} \ln 2 = 77.2 \ \mathrm{d}]$$
$$^{56}\mathrm{Fe}^* \rightarrow {}^{56}\mathrm{Fe} + \gamma(\sim 2\mathrm{MeV})$$

  - If nuclei are fully ionized,

$$^{56}\mathrm{Co} \rightarrow {}^{56}\mathrm{Fe}^* + e^+ + \nu_e \ [\tau_{i\mathrm{Co}} \sim 5\tau_{\mathrm{Co}}] \ [\mathrm{Cf.}\ \tau_{i\mathrm{Ni}} \ln 2 = 3\times 10^4 \mathrm{yr}]$$
$$^{56}\mathrm{Fe}^* \rightarrow {}^{56}\mathrm{Fe} + \gamma(\varepsilon_{\mathrm{RI}} \sim 2\mathrm{MeV})$$

  - In expanding jet: $^{56}$Ni → $^{56}$Co → $^{56}$Fe can start

# RI decay model – cont.

- $^{56}$Co flux by shock (Lorentz factor $\Gamma$) acceleration
  - Shock radius < Co decay length: $r<ct_{Co}\ \ln 2\ \beta\Gamma$
  - Shock radius > Ni decay length: $r>ct_{Ni}\ \ln 2\ \beta\Gamma$
  - Jet energy $E_j=(4\pi/3)r^3nm_pc^2\ \beta^2\Gamma^2\ \therefore 2E_{j,51}{}^{1/5}n^{-1/5}<\beta\Gamma<8E_{j,51}{}^{1/5}n^{-1/5}$
  - Observed mean lifetime: $t_\gamma=\gamma t_{iCo}\sim 10^5\mathrm{yr}\ \gamma_5$
    - $t_{iCo}=5t_{Co}$ : lifetime of ionized $^{56}$Co
  - Observed boosted gamma-ray energy: $\varepsilon_\gamma=\gamma\varepsilon_{RI}\sim 0.2\mathrm{TeV}\ \gamma_5$
  - The ratio of gamma-ray energy to the $^{56}$Co CR energy: $f=\varepsilon_\gamma/56m_pc^2\sim 4\times10^{-5}$
  - Gamma-ray flux: $\varepsilon_\gamma F_{\varepsilon_\gamma}=f\zeta E/(4\pi d^2t_\gamma)\sim 10^{-12}\mathrm{erg\ s^{-1}cm^{-2}}\ \zeta_{-1}E_{51}/(\gamma_5\, d_{3kpc}{}^2)$
- Rate
  - The total source number is 0.1-1 for a Galactic GRB rate of $10^{-5}$-$10^{-6}$ $\mathrm{yr^{-1}}$, while the most optimistic number is ~10 for a rate consistent with the late-time radio observations $10^{-4}\ \mathrm{yr^{-1}}$ (~10% of SN Ibc rate)
  - We can detect a fraction $(3\mathrm{kpc}/10\mathrm{kpc})^2\sim 0.1$ of these sources.

# RI decay model – cont.

- Maximum energy
  - The shocked $^{56}Co$ is accelerated to a power-law spectrum
  - $dN_{Co} \propto \varepsilon_{Co}^{-p} d\varepsilon_{Co}$ for $\varepsilon_{Co} < \varepsilon_{Co,max}$. The maximum energy can be $\varepsilon_{Co,max} \sim 3 \times 10^{17}$ eV (e.g., Murase et al. 2008), which provides $\varepsilon_{\gamma,max} \sim f \times (3 \times 10^{17} \mathrm{eV}) \sim 10$ TeV decay gamma-ray.
  - The Larmor radius of $^{56}Co$ CRs is $4(\varepsilon_{Co}/10^{17}\mathrm{eV}) B_{-6}^{-1}$ pc  
    $\rightarrow$ isotropic emission of decay gamma-rays
- Energy spectrum

$$\varepsilon_\gamma F_{\varepsilon_\gamma} = \varepsilon_\gamma^{-p+1} \exp(-\varepsilon_p / \varepsilon_\gamma)$$

$$\varepsilon_p = \varepsilon_{IR} (t/t_{iCo}) \sim 0.2\mathrm{TeV}(t/10^5\mathrm{yr})$$

- Softer than parent CRs, because low-energy CRs decay: $(d/dt)\exp(-t/\gamma t_{iCo}) \propto \varepsilon_\gamma^{-1} \exp(-\varepsilon_p / \varepsilon_\gamma)$
- HESS unID: $E^{-2.1\sim2.5} \rightarrow p = 1.1\text{-}1.5$… non-linear effect? (It could be related to $E \sim E_{jet}$)

# Radio-isotope decay model

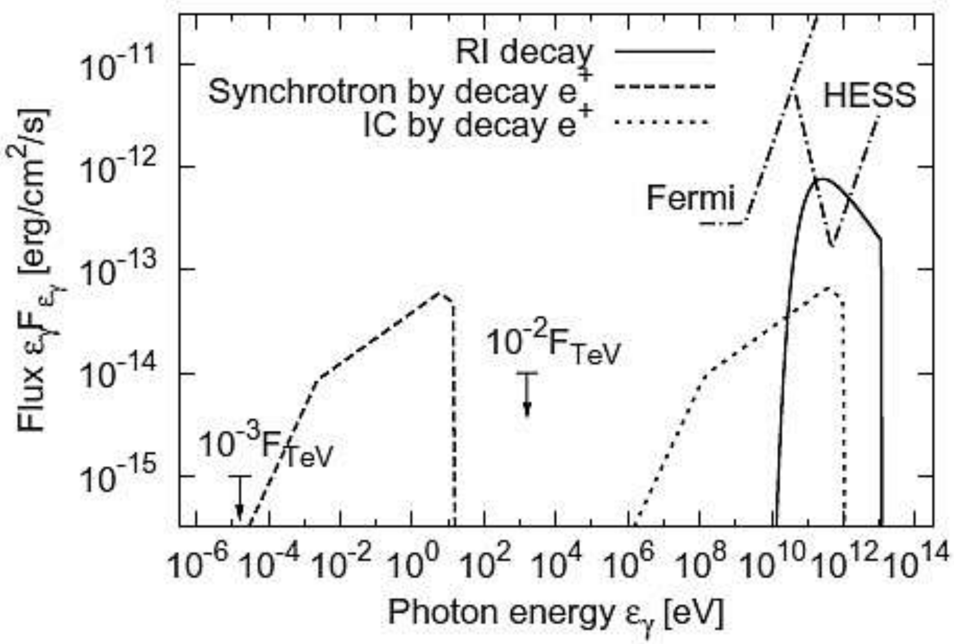



FIG. 3.— Flux of the decay gamma-rays from accelerated RI $^{56}$Co CRs in equations (10), (15) and (16), compared with the Fermi and HESS sensitivities. We assume a remnant of age $t_{\rm age} = 10^5$ yr at $d = 3$ kpc with a CR energy $E = 3 \times 10^{51}$ erg and spectral index $p = 1.5$. We also show the synchrotron and IC emission from decay positrons given by equation (11) for $B = 3\mu$G and the cosmic microwave background, compared with observational upper limits for an X-ray to TeV flux ratio of $10^{-2}$ and a radio to TeV flux ratio of $10^{-3}$.

# RI decay model - IC/Synchrotron

- IC/Synch from decay positrons
  - $dN_e = \varepsilon_e^{-p} d\varepsilon_e$ for $\Gamma m_e c^2 < \varepsilon_e < \varepsilon_p$
  - $dN_e = \varepsilon_e^{-p-1} d\varepsilon_e$ for $\varepsilon_p < \varepsilon_e < \varepsilon_{max}$
  - Synchrotron $\nu^{lyn} = qB\, \varepsilon_e^{2}/2\, m_e^{3} c^5 \sim 10^{-4} B_{-6}\, (\varepsilon_e /0.1\mathrm{TeV})^2$
  - IC (with CMB) $\nu^{IC} \sim 9\, \varepsilon_{CMB} (\varepsilon_e / m_e c^2)^{2} \sim 10^8 (\varepsilon_e /0.1\mathrm{TeV})^2$
  - Cooling time $t_c = 3 m_e^{2} c^3 / 4 \sigma_T \varepsilon_e U \sim 10^7 (\varepsilon_e/0.1\mathrm{TeV}) U_{-12}^{-1}$ yr $> t_\gamma$ for $\varepsilon_e < \varepsilon_{max} \sim 10\mathrm{TeV}$ ($U$: energy density of $B$ and CMB) $\rightarrow$ Luminosity suppressed by $t_\gamma / t_c \sim 10^{-2} (t_\gamma / 10^5 \mathrm{yr}) \varepsilon_e / 0.1\mathrm{TeV}) U_{-12}$
  - ~eV photons by decay positrons come from an extended region where optical background dominates.

# Discussion

- Model discrimination: gamma-ray morphology
  - $\pi^0$ decay : shell structure
    - GeV emission if p=2.1-2.4 continues down to GeV
  - $\beta$ decay : elongated structure
    - Low GeV emission
  - RI decay : center-filled structure
    - Low GeV emission, but young remnants could be bright if $\varepsilon_p$~20GeV (t/$10^4$yr)
- Neutrinos
  - $\pi^\pm$ decay $\nu$'s in $\pi^0$ decay model, no $\nu$'s in $\beta$ decay model, $^{56}Co \rightarrow {}^{56}Fe^* + e^+ + \nu_e$ in RI decay model, but fluxes are low.
- CRs above knee could be produced mainly by extragalactic and/or Galactic GRBs/HNe. Increasingly heavy composition may indicate acceleration by jets as in RI decay model.
- GRB remnants may be also responsible for CR positron/electron excess reported by PAMELA/ATIC/PPB-BETS [Ioka 2008].