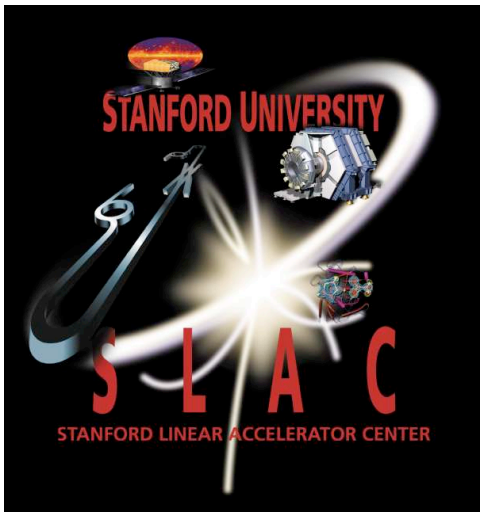
Particle Acceleration in SNR

Hiroyasu Tajima
Stanford Linear Accelerator Center
Kavli Institute for Particle Astrophysics and Cosmology



Outline

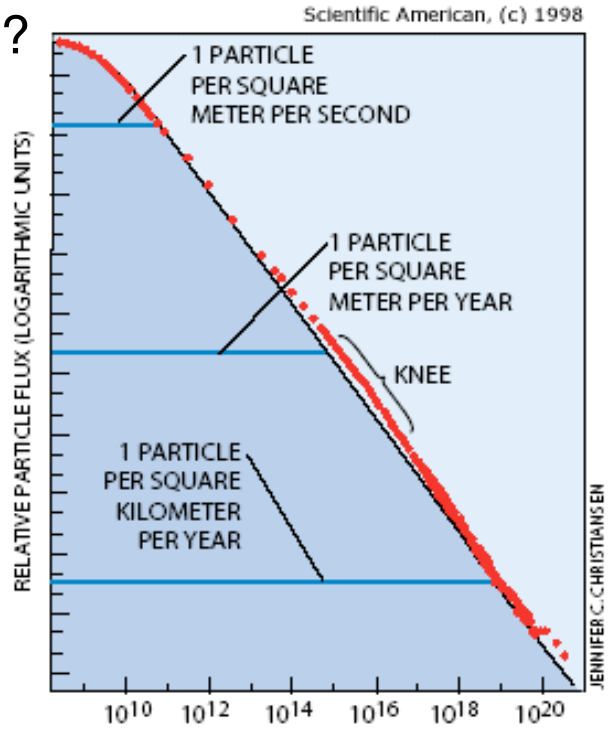
- **Introduction.**
- **Science.**
- **GLAST analysis.**

KIPAC

March 23, 2006
GLAST lunch

Cosmic Rays

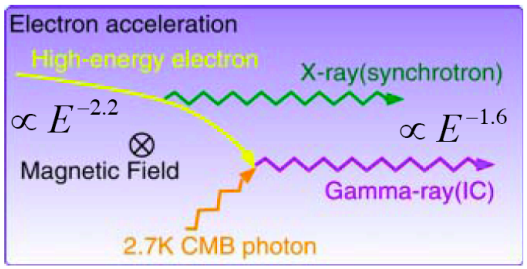
- **Origin of cosmic ray protons?**
  - **Particle accelerator in the Universe?**
  - **Many evidences for electron acceleration.**
    - Electron is efficient gamma-ray emitter.
      - Synchrotron radiation, Compton scattering.
  - **No smoking gun for proton acceleration found.**
    - Why so hard to find proton acceleration?
      - Nuclear interaction.
    - How to distinguish gamma-ray from proton origin?
      - Spectrum.
      - Angular distribution.

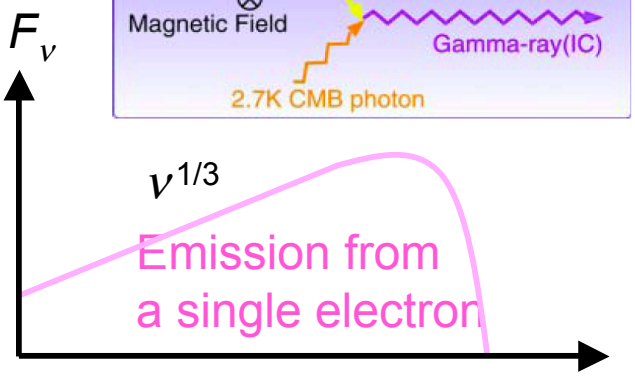


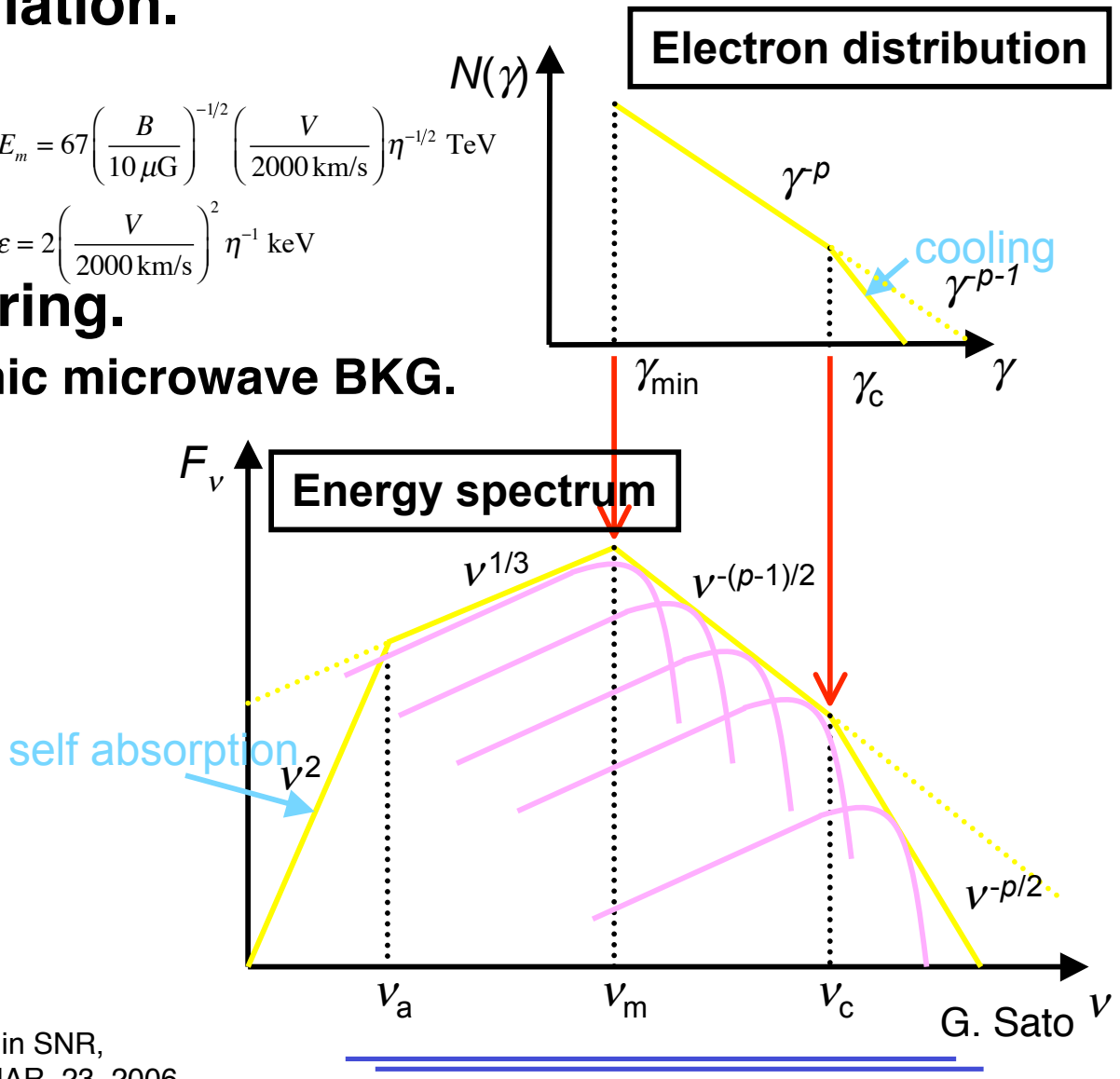
Gamma-ray Emission from Electrons

- **Synchrotron radiation.**
  - $E^{-p} \Rightarrow \epsilon^{-(p-1)/2}$
  - **Polarization.**
  - **Cut off energy:** $\varepsilon = 2\left(\frac{V}{2000\,\mathrm{km/s}}\right)^2 \eta^{-1}\ \mathrm{keV}$
- **Compton Scattering.**
  - **Up-scatter cosmic microwave BKG.**
  - $E^{-p} \Rightarrow \epsilon^{-(p-1)/2}$

$$E_m = 67\left(\frac{B}{10\,\mu\mathrm{G}}\right)^{-1/2}\left(\frac{V}{2000\,\mathrm{km/s}}\right)\eta^{-1/2}\ \mathrm{TeV}$$



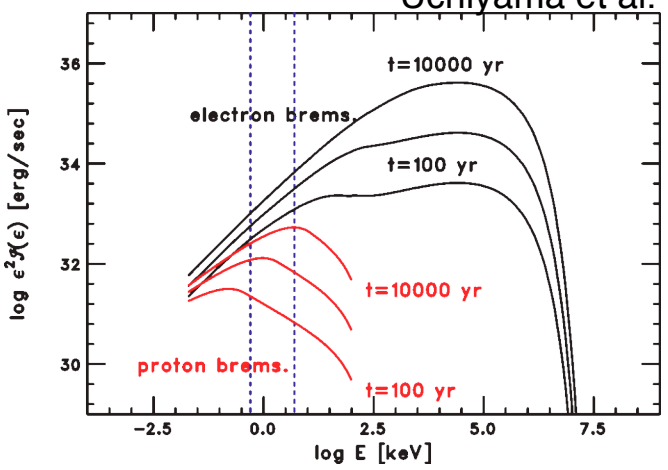


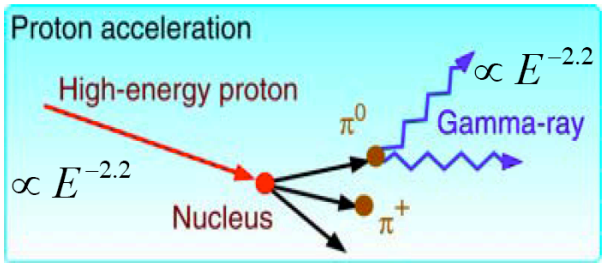


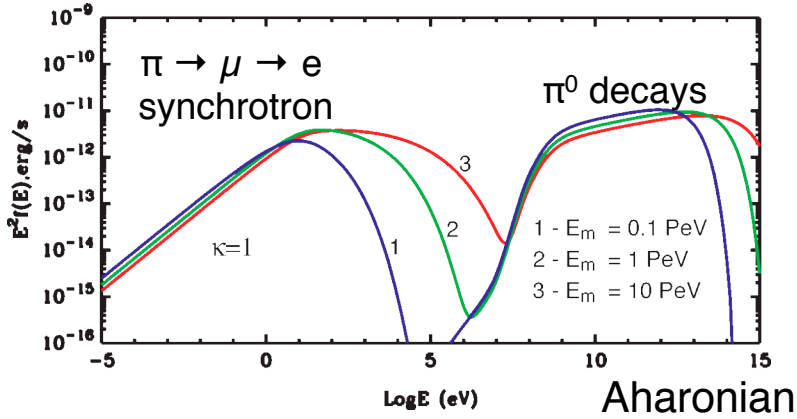
Gamma-ray Emission from Hadrons

- **Interaction with matters.**
  - **Bremsstrahlung.**
    - $E < E_{cou}$: ϵ^{-1} (independent of parent energy spectrum).
    - $E > E_{cou}$: $E^{-p} \Rightarrow \epsilon^{-p}$ (no change).
    - E_{cou}: $230\left(\frac{n}{10\,\mathrm{cm}^{-3}}\right)\left(\frac{\tau_{age}}{1000\,\mathrm{yr}}\right)\mathrm{keV}$
    - $\epsilon_{cou}(p) = m_e/m_p E_{cou}$, $\epsilon_{cou}(e) = E_{cou}$.
  - **π^0 decays.**
    - $E^{-p} \Rightarrow \epsilon^{-p}$ (no change).
  - **$\pi^{\pm} \rightarrow \mu^{\pm} \rightarrow e^{\pm}$**
    - Synchrotron, Compton

Uchiyama et al.





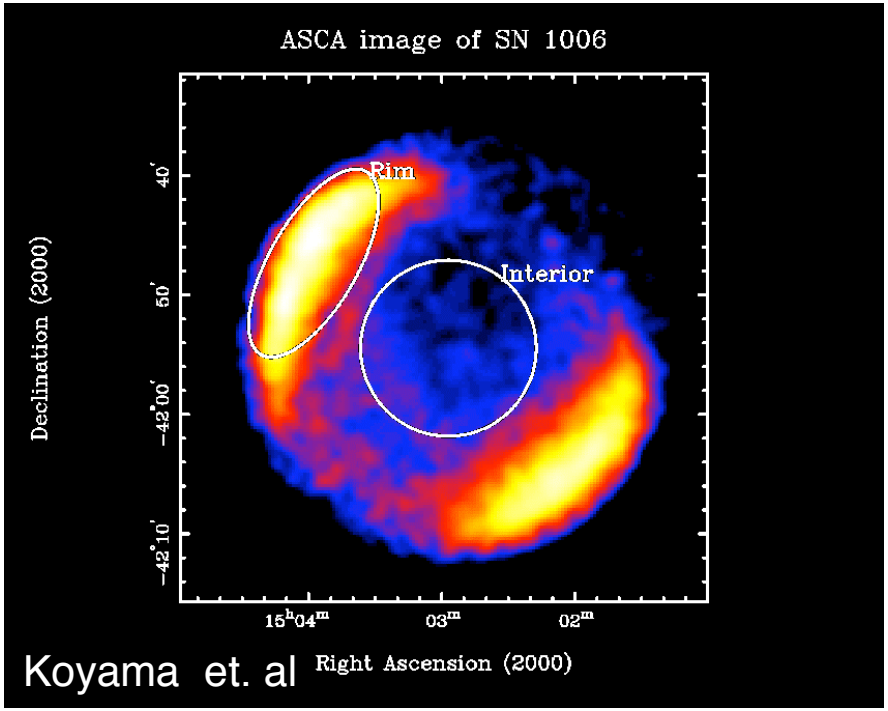


Aharonian

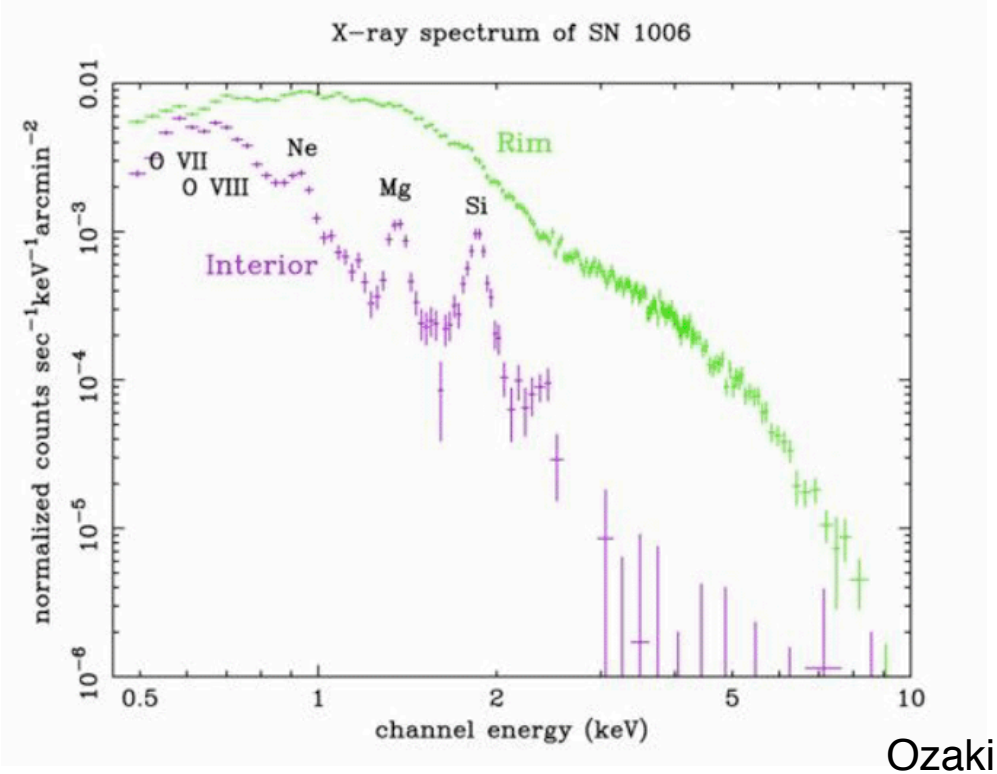
Particle Acceleration in SNR,
H. Tajima GLAST lunch, MAR. 23, 2006

Particle Acceleration in SNR

- **Young shell-type supernova: SN1006.**
  - **Power law spectrum from rim is best described by synchrotron emission by ultra-relativistic electrons.**
  - **First evidence of particles accelerated to > 10^{14} eV.**



Koyama et. al

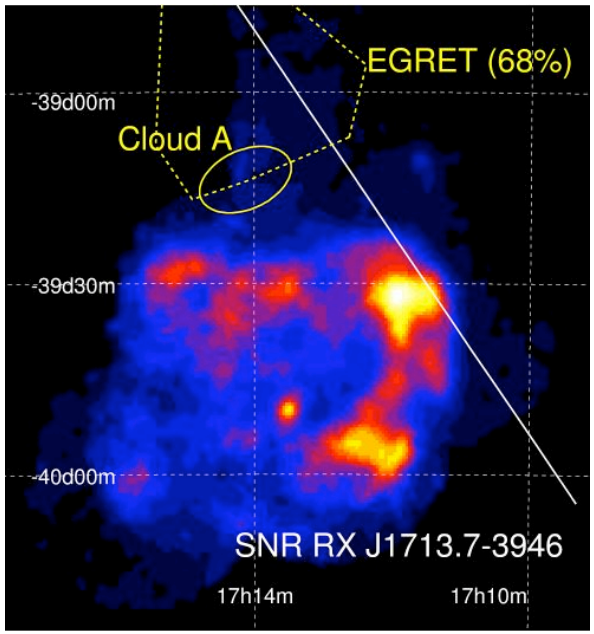


Ozaki

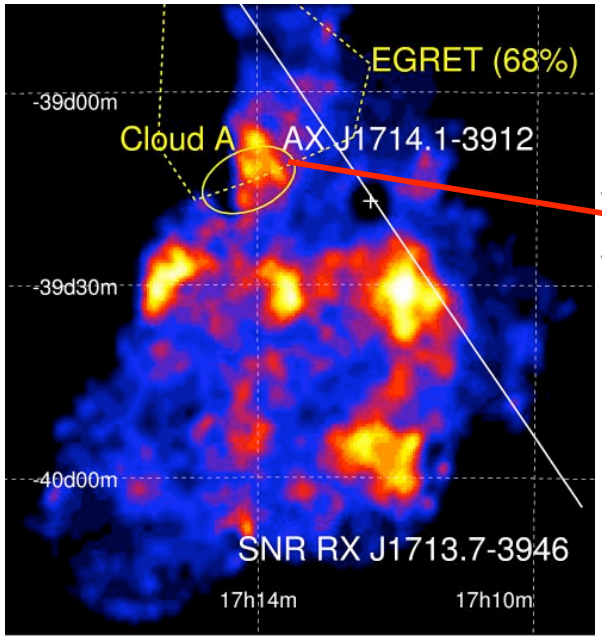
Proton Bremsstrahlung in SNR

- **Evidence of proton bremsstrahlung in AX J1714-3912.**
  - **Spectrum is inconsistent with synchrotron model.**
    - Power law index, no energy cut off
  - **Upper limits from CMPTEL and EGRET rule out electron bremsstrahlung.**
  - **Cloud A is 6 kpc away, not connected with RX J1713-3946**

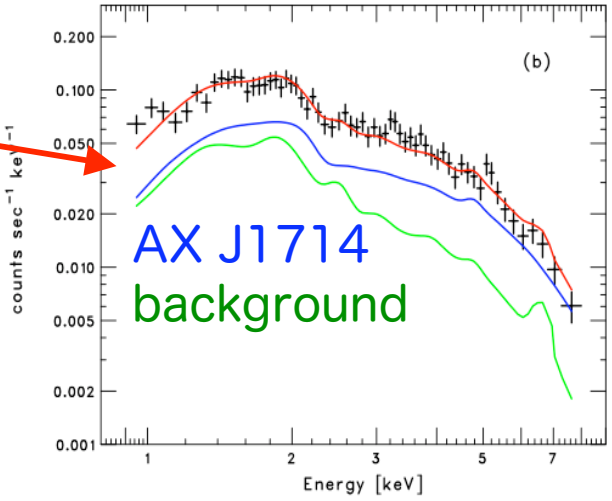
ASCA 1-3 keV



ASCA 5-10 keV



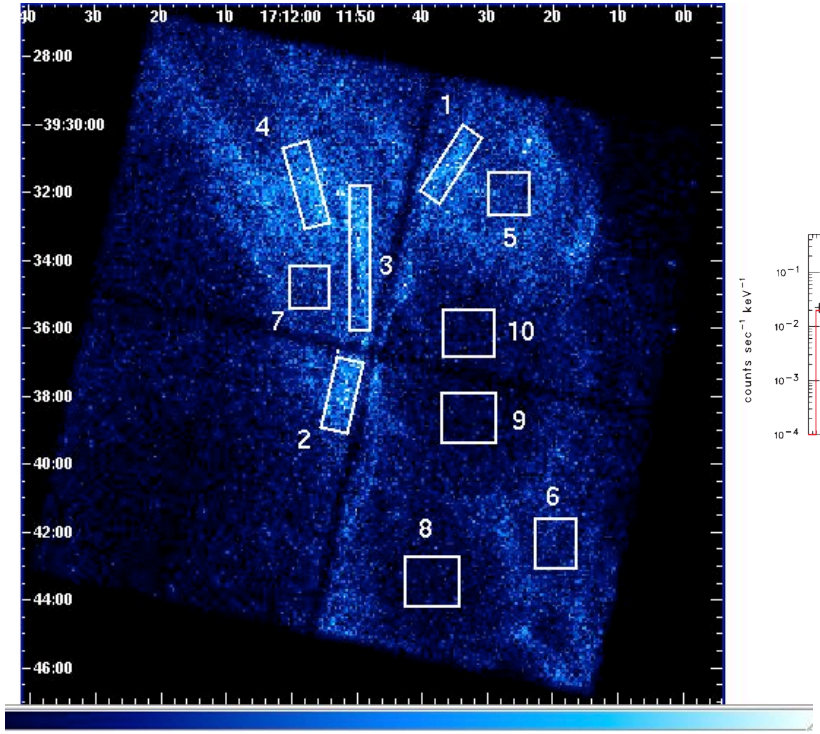
Uchiyama et al. 2002



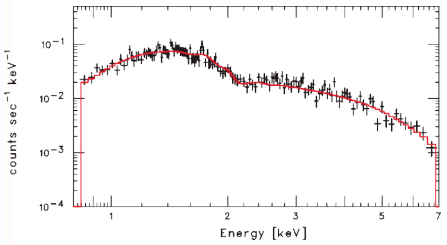
X-ray spectrum (0.8-8 keV)

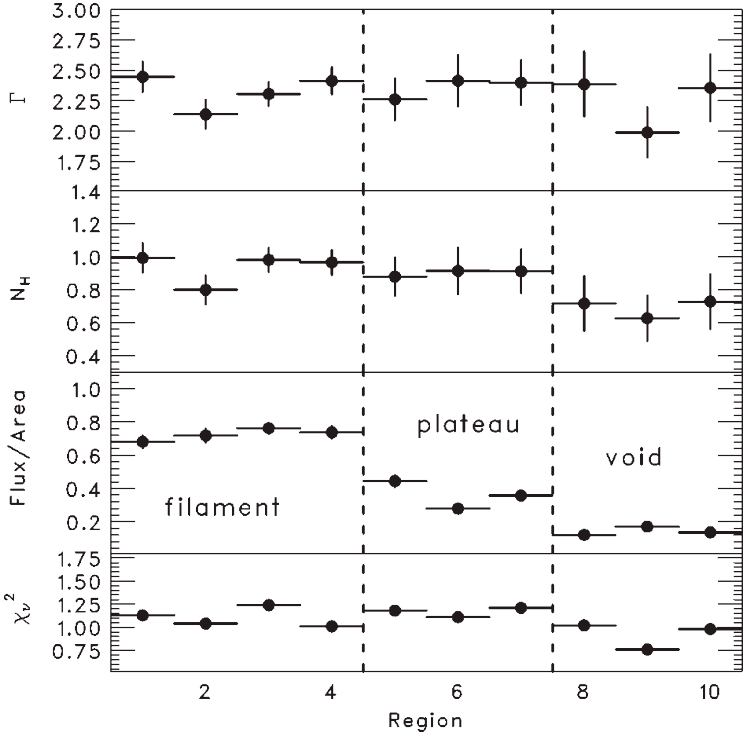
Issues with Electron Acceleration

- **Chandra observation of RX J1713-3946.**
  - **Similar spectrum independent of luminosity.**
  - **Energy cut off higher than electron acceleration model.**
    - Separate zones for acceleration and X-ray emission?
    - More efficient particle acceleration than standard DSA?
      - Non-linear shock acceleration models.



X ray spectrum
0.8-7 keV



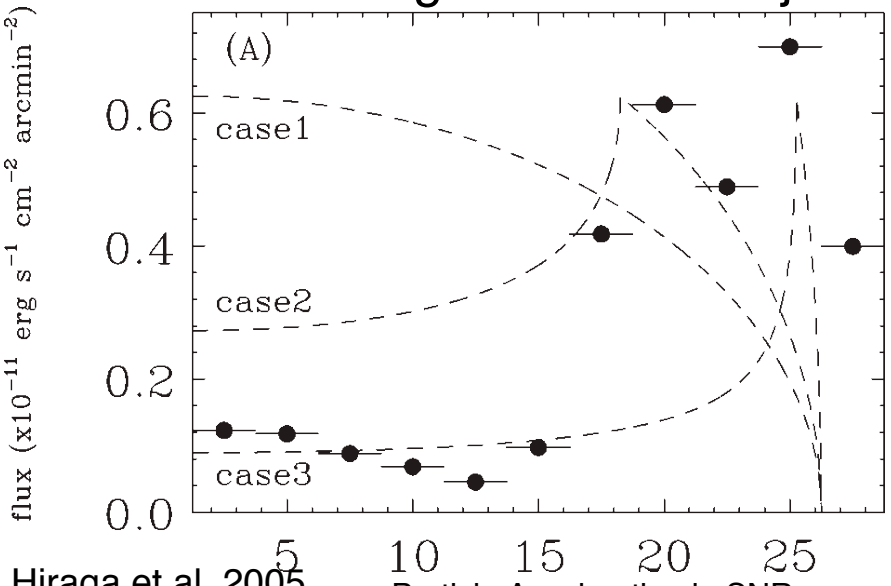


Uchiyama et al. 2003

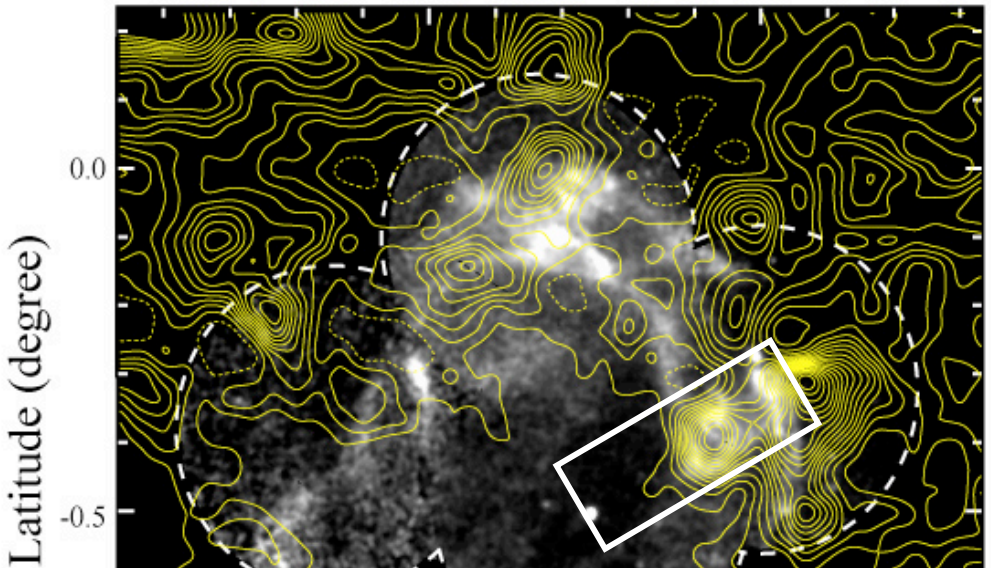
Interaction with Molecular Cloud

- **XMM Observation of RX J1713-3946.**
  - **Photon index is uniform around 2.1–2.5.**
    - Same emission mechanism responsible for X-radiation.
  - **Radial profile exclude spherical radiation.**
  - **N_H in rim is higher than interior by 3–4 x 10^{21} cm^{-2}**
    - Consistent with NANTEN observation of X-ray bright part
      - $N_H \sim 3 \times 10^{21}$ cm^{-2}.
    - Higher electron injection rate in the rim?

Moriguchi et al. 2005



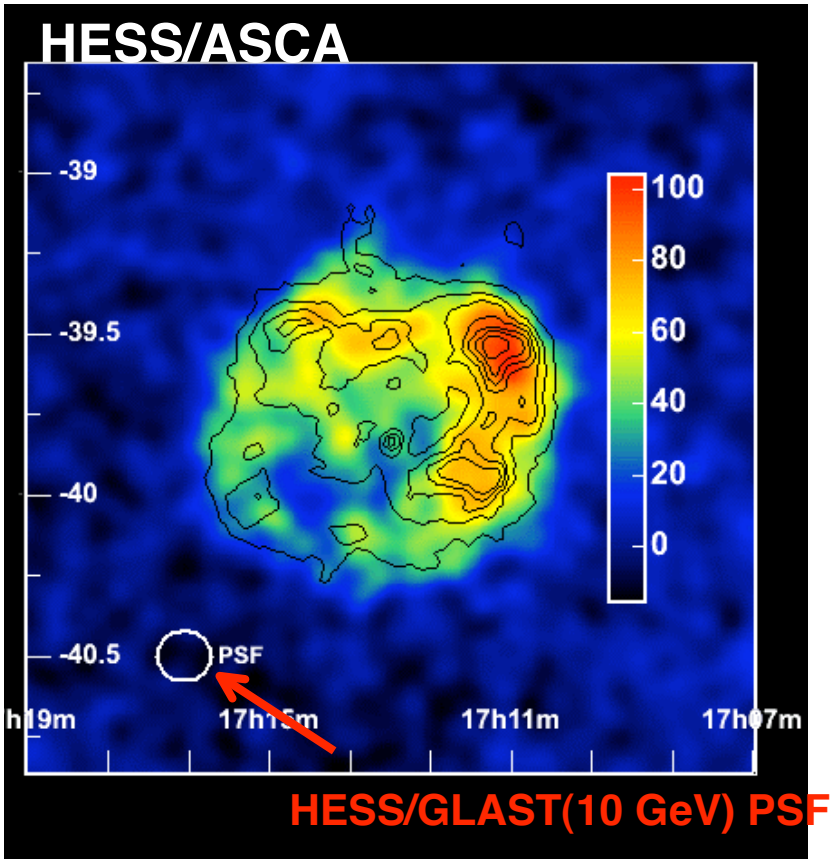
Hiraga et al. 2005



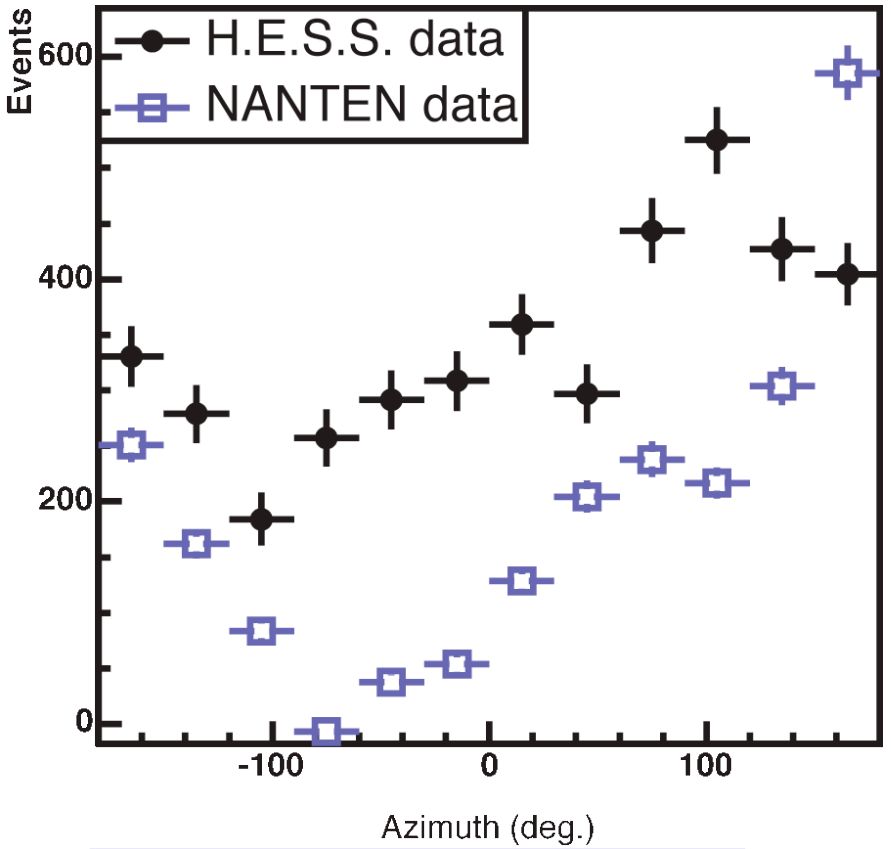
TeV Gamma-ray from SNR

- **HESS observation of RX J1713-3946**
  - **Evidence for particle acceleration > 100 TeV.**
  - **Azimuth profile does not match very well with NANTEN.**
    - Detailed 3D analysis required for better understanding.

Funk



Aharonian et al. 2005

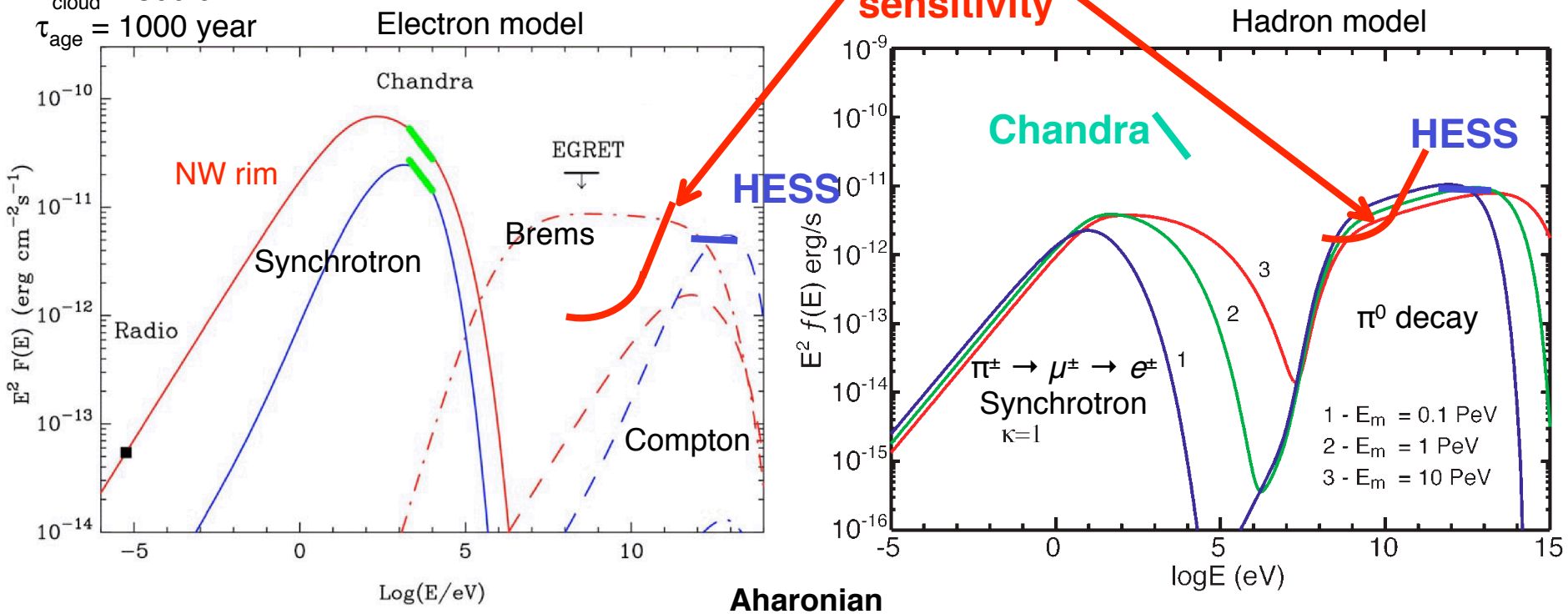


Particle Acceleration in SNR,
H. Tajima GLAST lunch, MAR. 23, 2006

SNR Broad Band Energy Distribution

- **Electron and proton give different spectra.**
  - **2-zone electron model.**
  - **Both models are not quit right.**
    - Harder proton spectrum (Γ~1.5) can raise synchrotron intensity in hadron model.

B_{int} = 5 μG
B_{rim} = 20 μG
n_{int} = 1 cm^{-3}
n_{cloud} = 300 cm^{-3}
τ_{age} = 1000 year



Aharonian

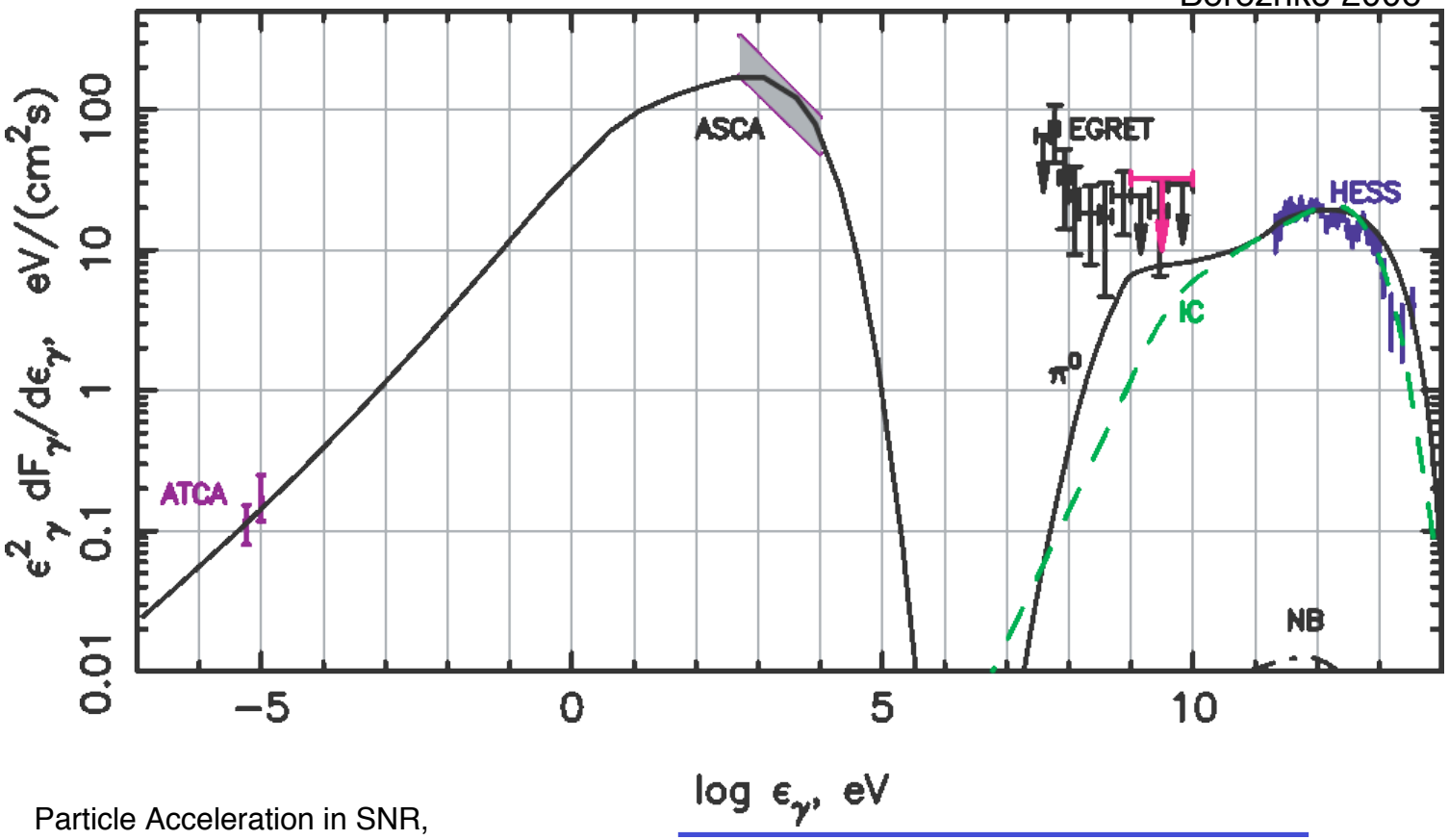
Particle Acceleration in SNR,
H. Tajima GLAST lunch, MAR. 23, 2006

Non-Linear Shock Acceleration Model

- **Feedback from accelerating cosmic rays.**
  - **Field amplification of plasma.**
  - **Efficient cosmic ray acceleration.**

B_d = 126 μG
K_{ep} = 10^{-4}
E_{SN} = 1.8 x10^{51} erg
τ_{age} = 1600 year

Berezhko 2006

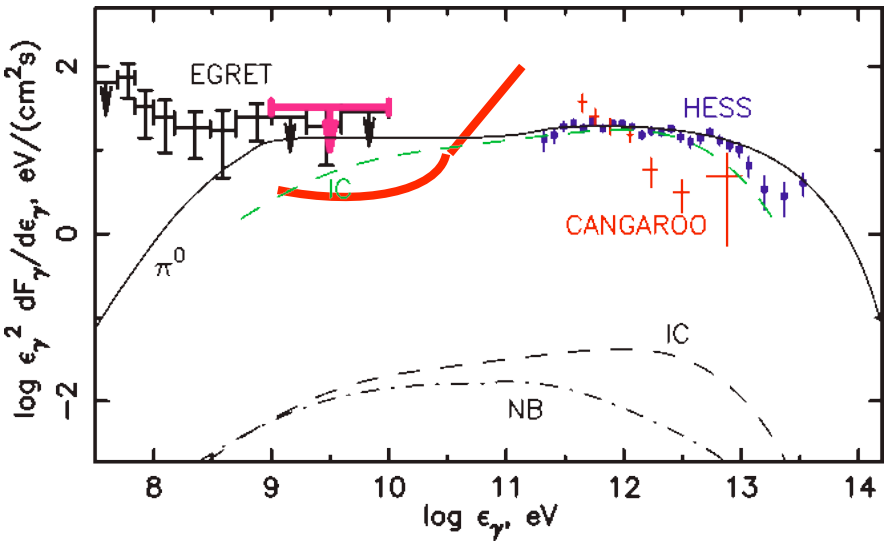


Particle Acceleration in SNR,
H. Tajima GLAST lunch, MAR. 23, 2006

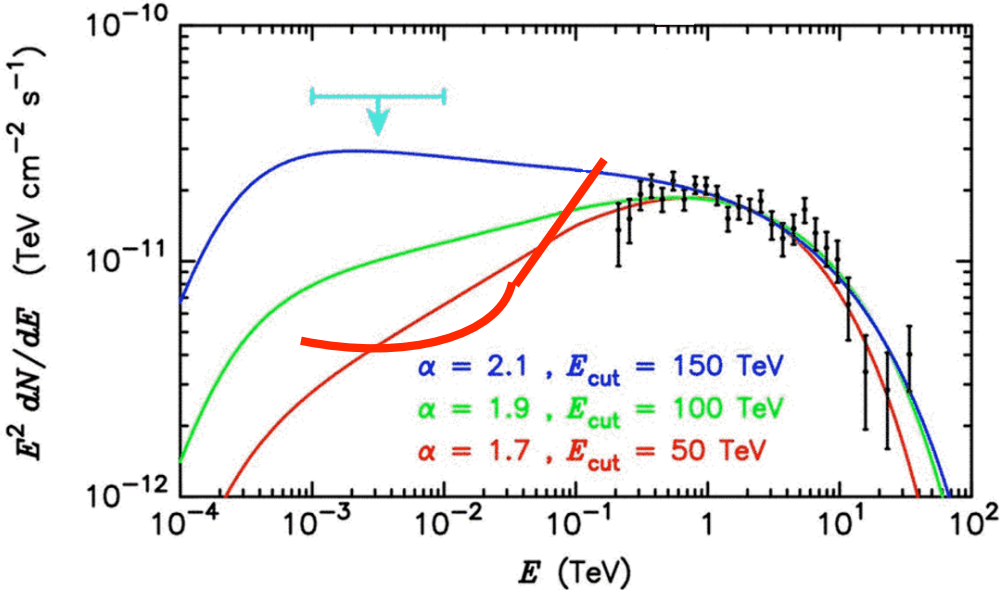
GLAST Observation of RX J1713-3946

- **Differentiate electron and proton models.**
  - **π^0 spectrum below 1 GeV is constrained by π^0 production and decay kinematics.**
    - Independent of acceleration model.
  - **π^0 spectrum above 1 GeV constrains proton spectrum.**
    - $\Gamma_\gamma \approx \Gamma_p$

Berezhko 2006



Aharonian 2006



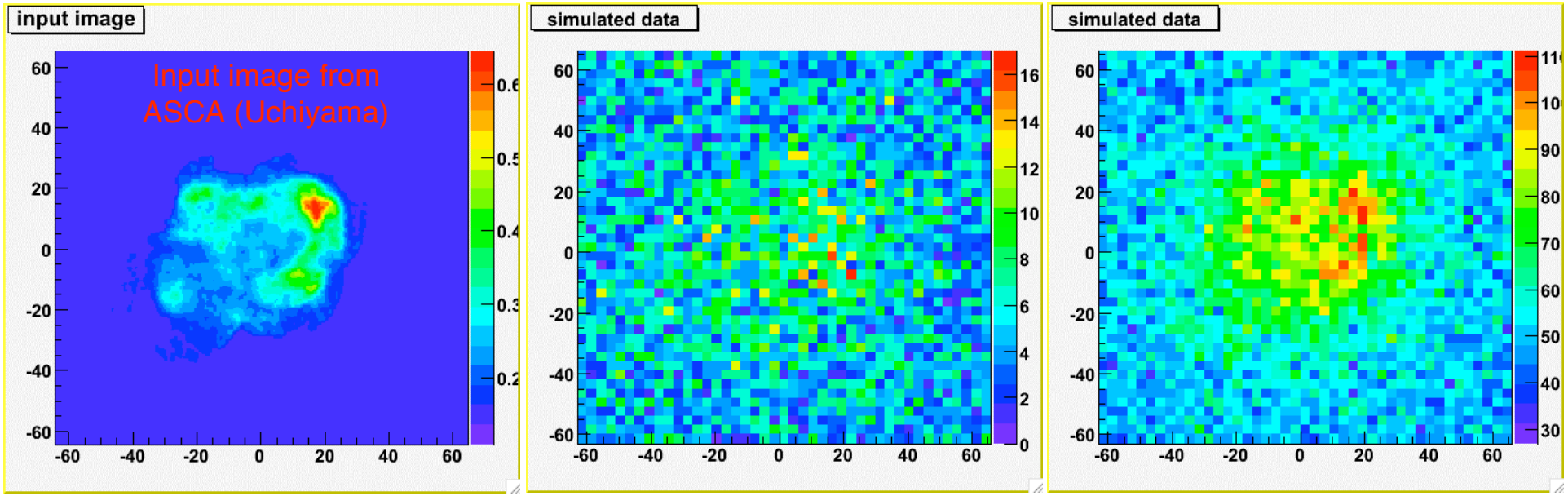
Particle Acceleration in SNR,
H. Tajima GLAST lunch, MAR. 23, 2006

GLAST Analysis of Extended Source

- **Poor GLAST PSF make it difficult to resolve RX J1713-3946.**
  - **Maximum likelihood fit cannot be used without a model.**
  - **Image deconvolution required.**

GLAST 10^7 s observation
@ 10^{-12} erg/cm^2/s
E > 1GeV, PSF = 25'

GLAST 10^8 s observation
@ 10^{-12} erg/cm^2/s
E > 1GeV, PSF = 25'



Iterative Deconvolution Algorithm

- **Richardson-Lucy**

$$\psi_j^{r+1} = \psi_j^r \sum_i \tilde{\phi}_i \frac{P_{ij}}{\sum_k P_{ik}\psi_k^{r-1}}$$

ψ_j^r : deconvolved image

$\tilde{\phi}_i$: observed image

P_{ij} : PSF kernel

  - **ψ: normalized, non-negative.**
  - **Can be used for event-by-event data with varying PSF.**

$$\psi_j^{r+1} = \frac{1}{N}\psi_j^r \sum_n \frac{P_j(n)}{\sum_k P_k(n)\psi_k^{r-1}}$$

- **Adaptive Maximum Entropy Method**

$$\psi_j^{r+1} = \psi_j^r \left[\sum_i \tilde{\phi}_i \frac{P_{ij}}{\sum_k P_{ik}\psi_k^{r-1}} - \alpha\left(\ln\frac{\psi_j^r}{\chi_j} - \sum_k \psi_k^r \ln\frac{\psi_k^r}{\chi_k} \right) \right]$$

$\chi_i = \sum_k \Pi_{ik}\psi_k$

(adaptive "default" image)

  - **Suppress local maximum/minimum due to noise by applying entropic penalty.**

- **Two Channel Decomposition Method**

$$\psi = \psi_{PS} + \psi_{DF}$$

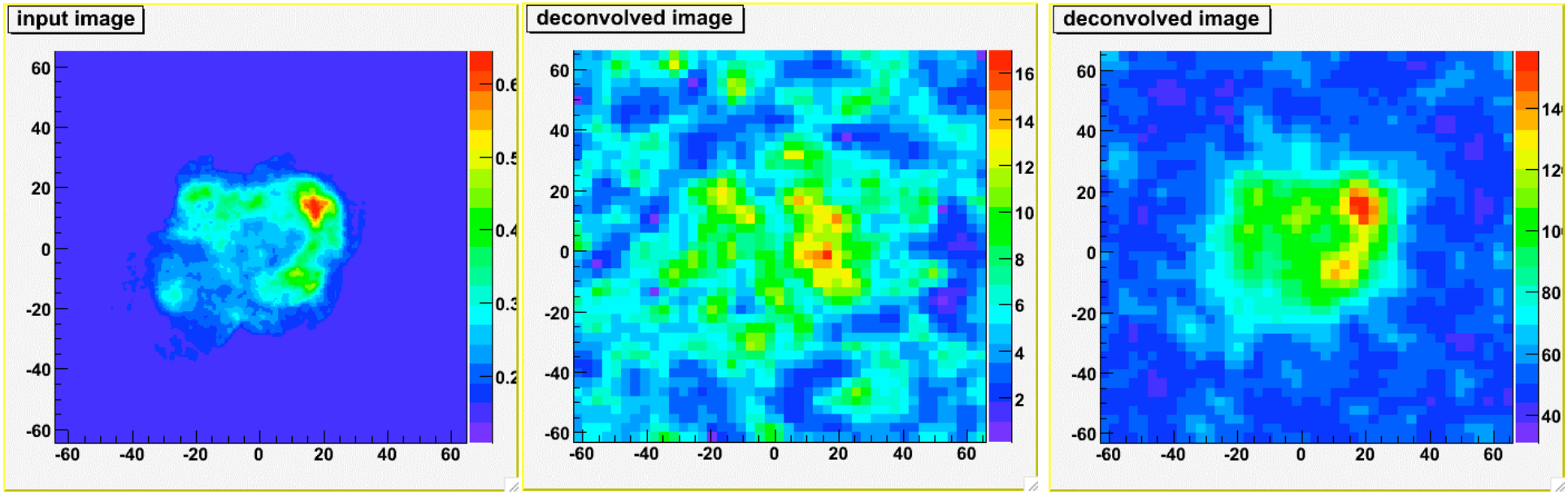
  - **Avoid entropic penalty for known point sources.**

Deconvolved Image

- **Deconvolved image gives better representation of input image.**
  - **NW rim clearly stands out.**
  - **Poor image at low statistics.**
    - Deconvolution can not fix statistical fluctuation.

GLAST 10^7 s observation
@ 10^{-12} erg/cm^2/s
E > 1GeV, PSF = 25'

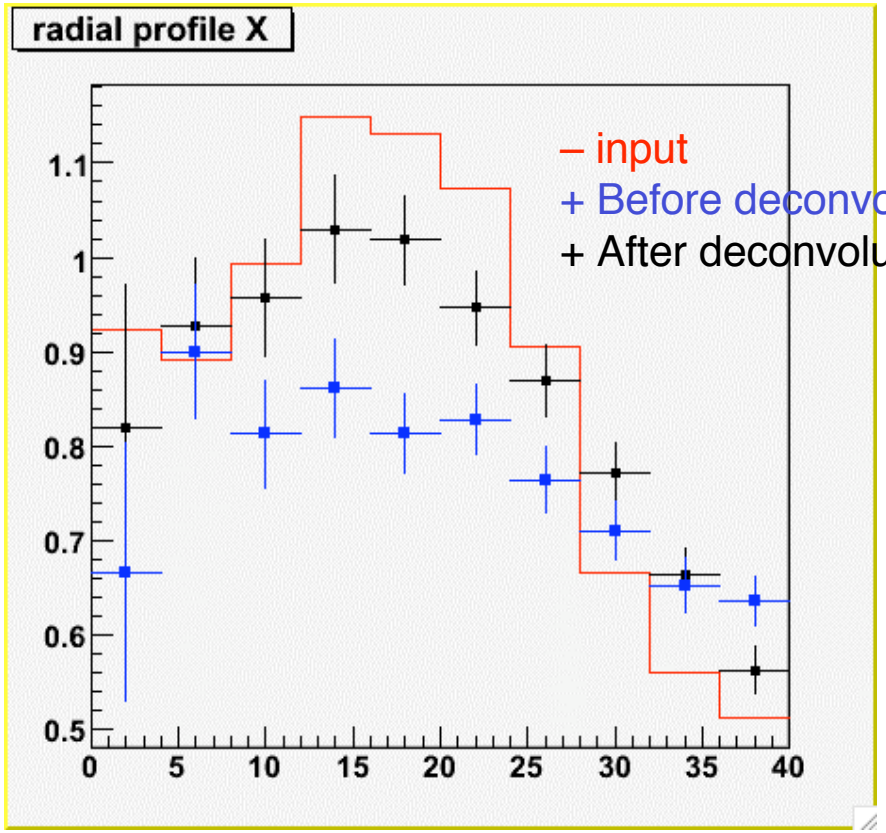
GLAST 10^8 s observation
@ 10^{-12} erg/cm^2/s
E > 1GeV, PSF = 25'



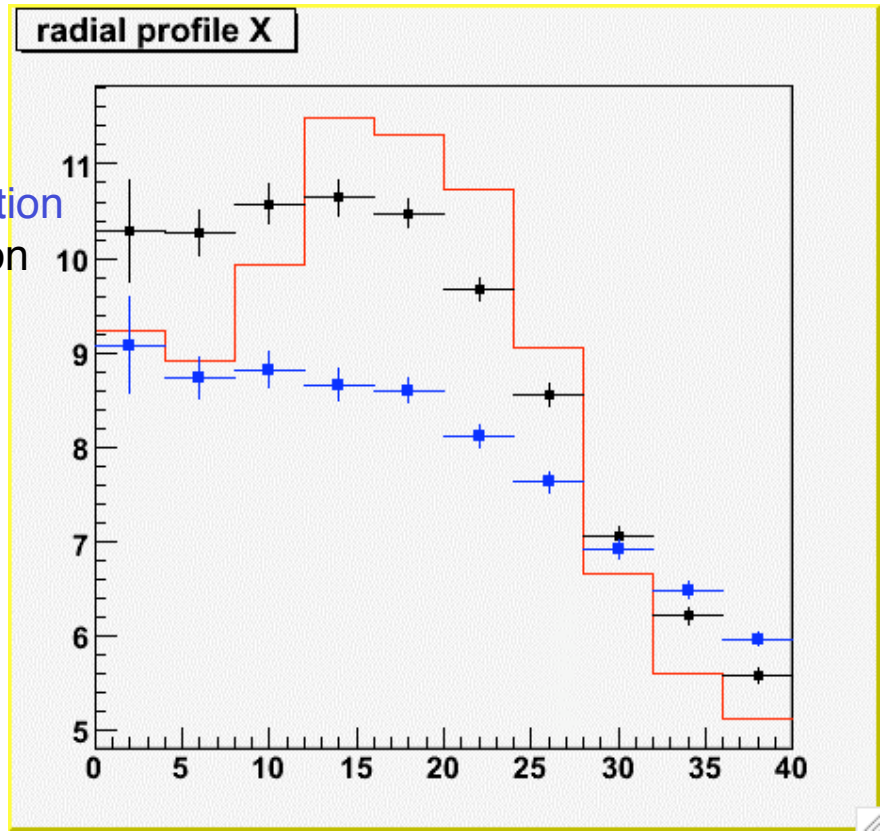
Deconvolved Radial Profile

- **Radial profile is much improved after deconvolution.**

GLAST 10^7 s observation



GLAST 10^8 s observation



Summary

- **GLAST will give conclusive proof on the origin of gamma-rays from RX J1713-3946.**
  - **In conjunction with X-ray and TeV measurements.**
  - **Measure parent proton spectrum.**
- **Image deconvolution is a key to study extended sources.**
  - **R-L method is promising.**
  - **Future improvements.**
    - Energy dependent PSF.
    - Event by event PSF.