Particle Acceleration in Galaxy Clusters

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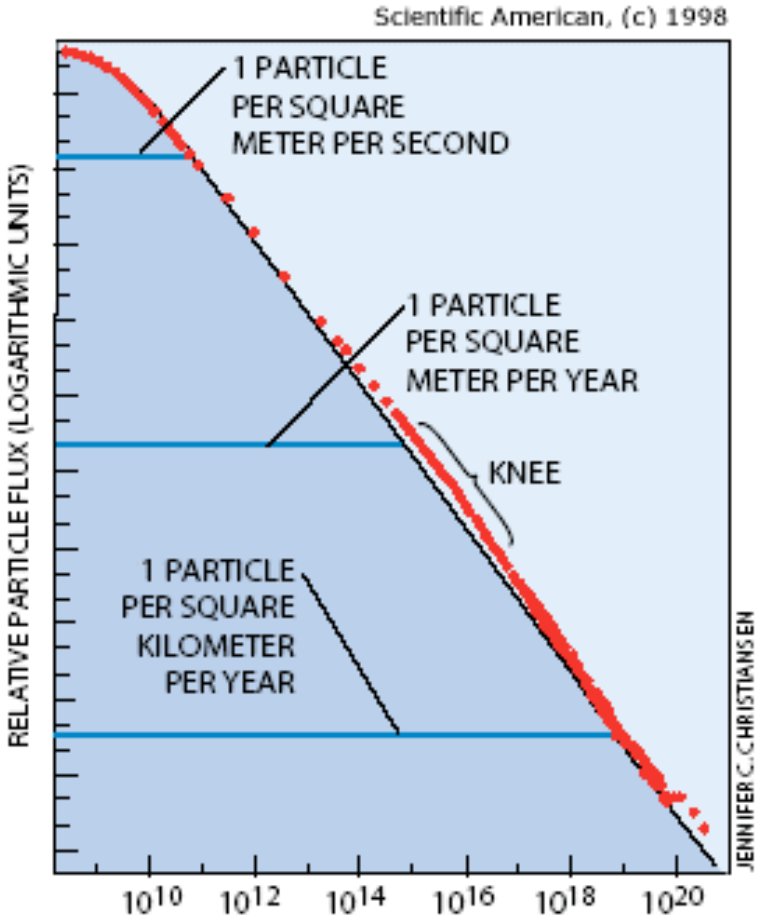
Outline

- **Introduction.**
- **Science.**
- **EGRET analysis.**

October 26, 2006
GLAST lunch

Cosmic Particle Accelerators

- **Origin of cosmic ray protons?**
  - **Galactic SNRs (Supernova Remnants) are considered as the best candidates for cosmic-rays below "Knee".**
    - Only circumstantial evidence
      - Diffusive shock acceleration. (Blanford&Eichler 1977)
      - CR energy sum consistent with SNR kinetic energy. (Ginzburg&Syrovatskii 1964)
    - No observational evidence for hadronic acceleration.
  - **Cosmic-rays above "Knee" are considered extragalactic.**
    - Gamma-ray bursts (GRB).
    - Active Galactic Nuclei.
    - Galaxy clusters.



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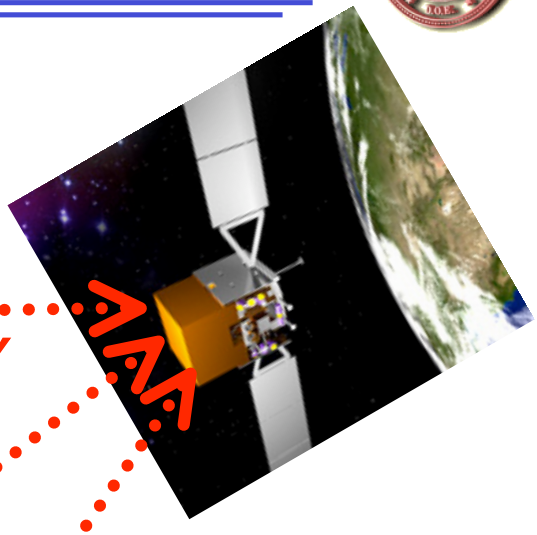
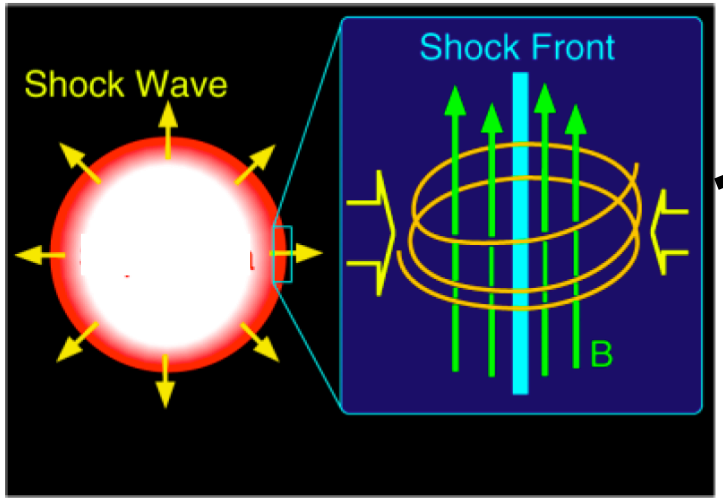
Hadronic Cosmic-ray Interactions





γ (CMB)

γ (Cosmic Microwave Background)

e^+e^-

Compton scattering

γ

p

π^0

γ (CMB)

$\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$

p

p (Inter stellar medium)

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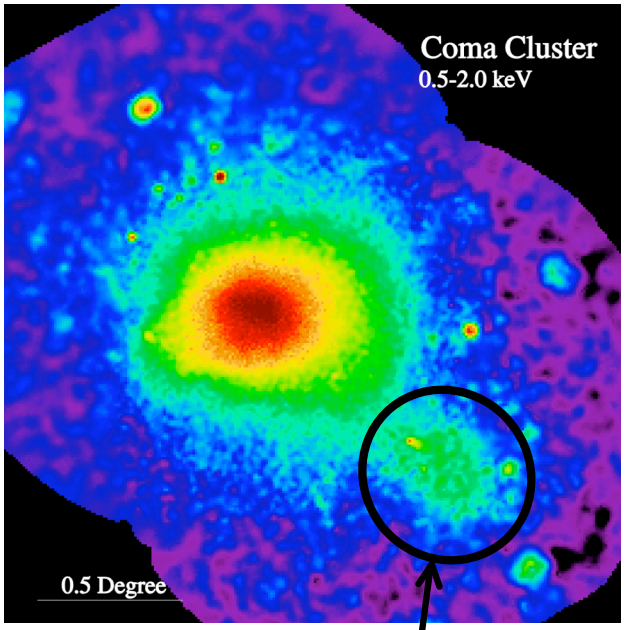
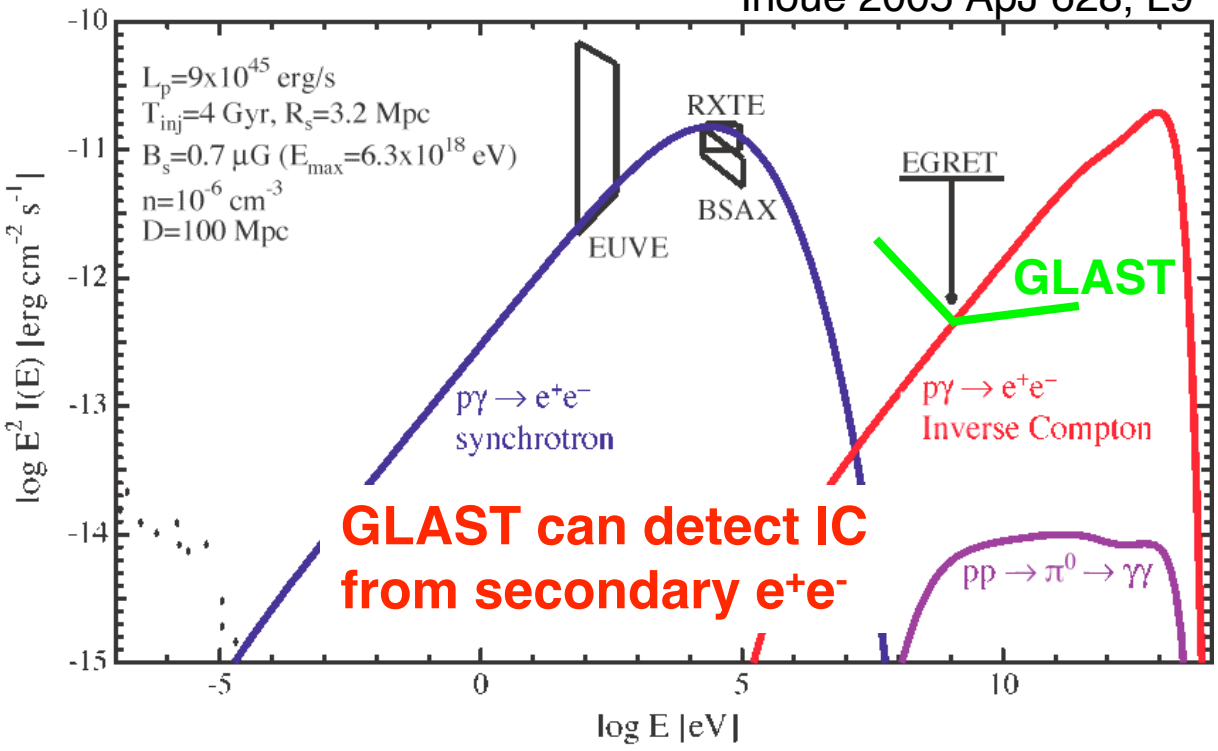
γ-rays from Merging Galaxy Cluster

- **Strong shock due minor merger of galaxy clusters.**
  - **Model parameters are tuned to be consistent with existing measurements.**
  - **Particle acceleration up to 10^{19} eV. (Origin of UHE-CR?)**
  - **Secondary e^+e^- following proton interaction with CMB photon are dominant origin of gamma-rays.**



merging galaxy group

Inoue 2005 ApJ 628, L9



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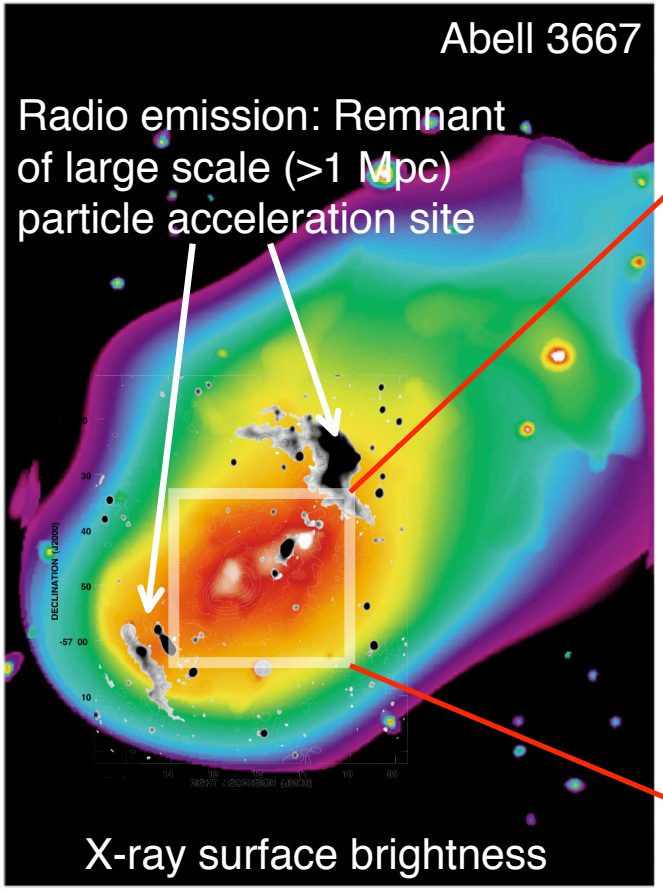
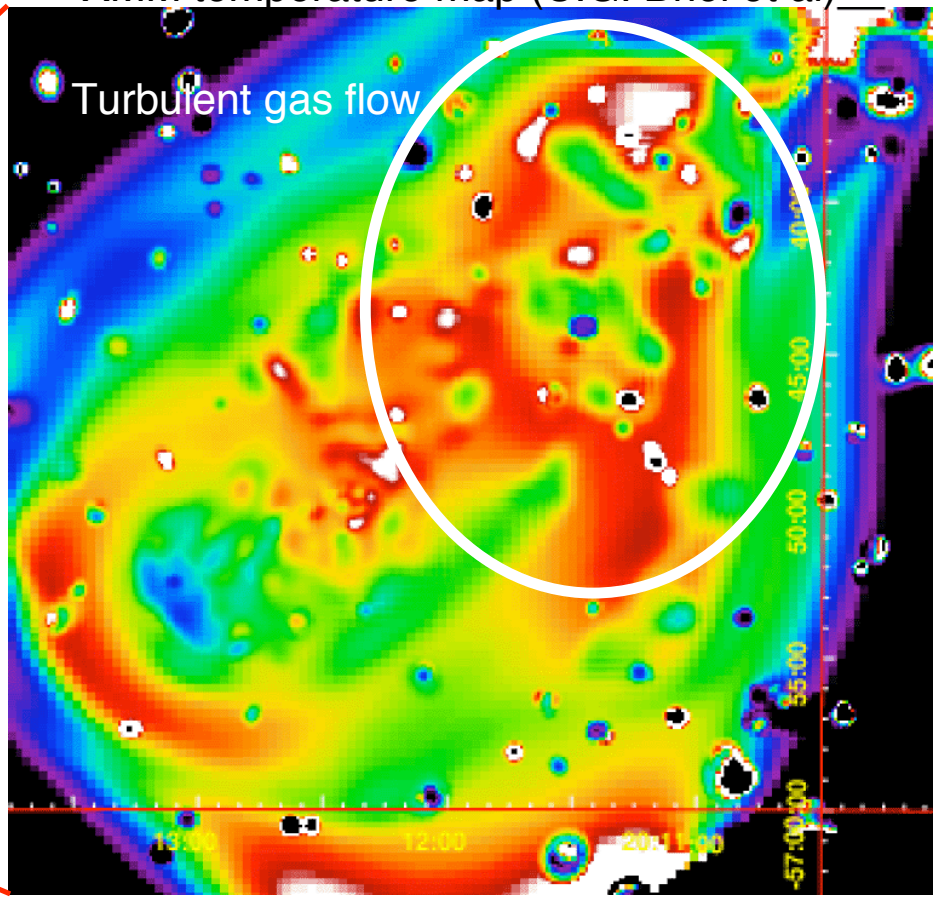
Merging Galaxy Clusters

- **Large scale shock by merging galaxy clusters.**
  - **Origin of Ultra High Energy Cosmic-ray (UHECR)?**

ROSAT März 2003



XMM temperature map (U.G. Briel et al)



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Electron Acceleration in Merging GC

- **Actively merging galaxy clusters can be good electron accelerators.**
  - **Electrons lose their energy very efficiently by gamma-ray emissions.**
  - **Constant acceleration necessary to keep it going.**
  - **Maximum electron energy**
    - Shock acceleration time
      = cooling time by Compton scattering

$$t_{\rm acc} \approx \frac{r_{\rm L} c}{V_s^2} = \frac{\gamma_e m_e c}{e B V_s^2} = 1.6\times10^{-4}\,\frac{\gamma_e}{(B/1\mu{\rm G})(V_s/1000\,{\rm km/s})^2}$$

$$t_{\rm IC} = \frac{\gamma_e m_e c^2}{(4/3) c \sigma_{\rm T} U_{\rm CMB} \gamma_e^2} = 2.3\times10^{12}/\gamma_e (1+z)^4$$

$$\gamma_{e,\max} = 1.2\times10^{8}\sqrt{B/1\mu{\rm G}}\,(V_s/1000\,{\rm km/s})/(1+z)^2$$

$r_{\rm L}$: Larmor radius
V_s: shock velocity

Gamma-ray Flux from Merging GC

- **Observed gamma-ray flux within shock propagation time.**

$$\frac{dF}{d\varepsilon_\gamma} = \frac{(1+z)}{4\pi d_L^2 t_{\rm shock}} \frac{dN_\gamma}{d\varepsilon_\gamma}$$

- **Spectrum normalization**

$$\int d\gamma_e m_e c^2 \gamma_e \frac{dN_e}{d\gamma_e} = \xi_e E_{\rm baryon}, \quad \xi_e \approx 0.05$$

- **Number of EGRET detectable gamma-ray clusters**

$$N(>F) = \int dz \int_{M(z,F)}^{\infty} dM \frac{dV}{dz} R_{\rm form}(M,z) t_{\rm shock}$$

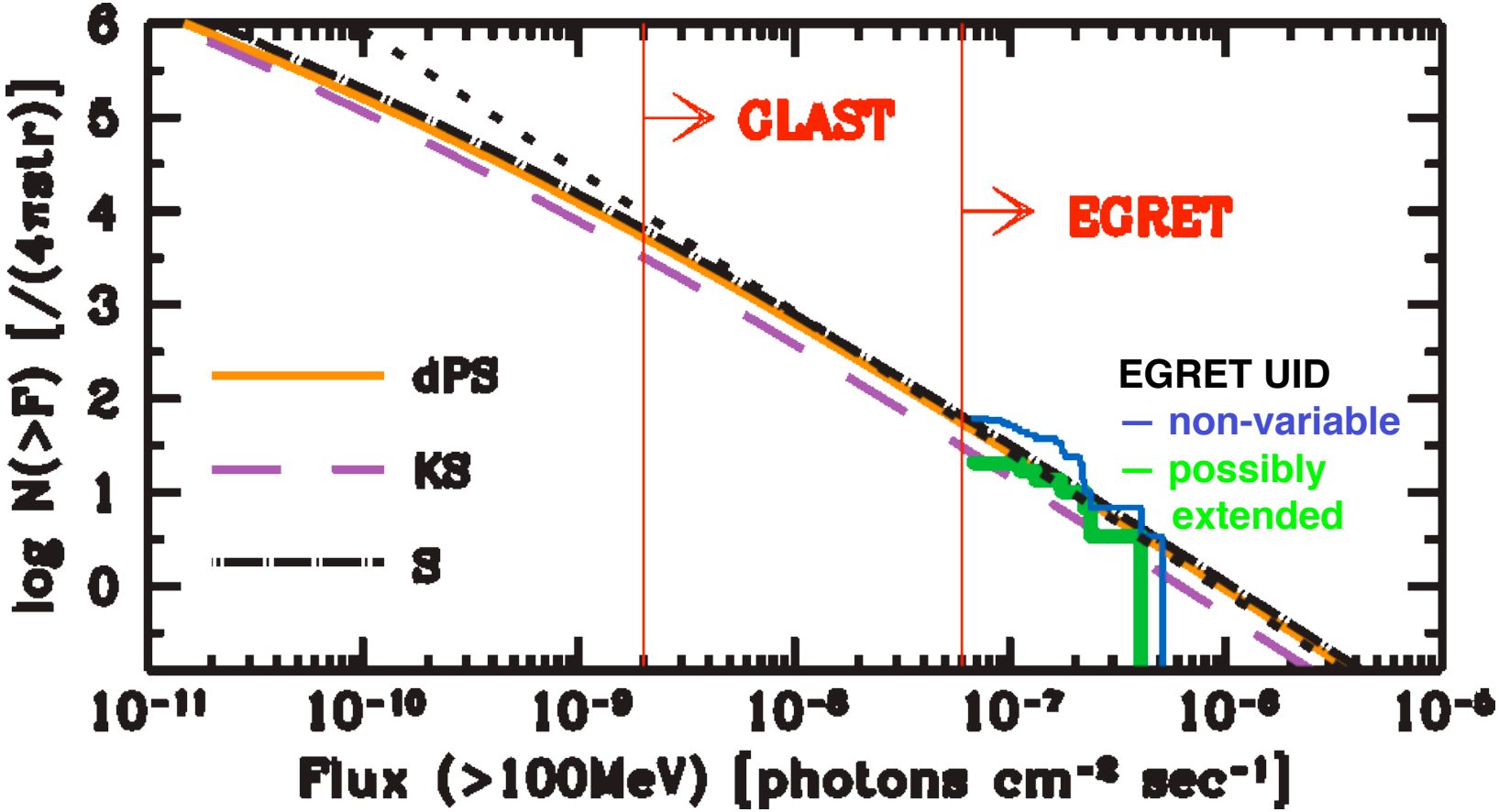
$$t_{\rm shock} \approx 1.5/(1+z)^{3/2}\ {\rm Gyr} \ >> t_{\rm IC} = 2.1/(1+z)^4 \sqrt{\varepsilon_\gamma/{\rm GeV}}\ {\rm Myr}$$

Shock propagation time

for ε_γ > MeV

EGRET Detectable Galaxy Clusters

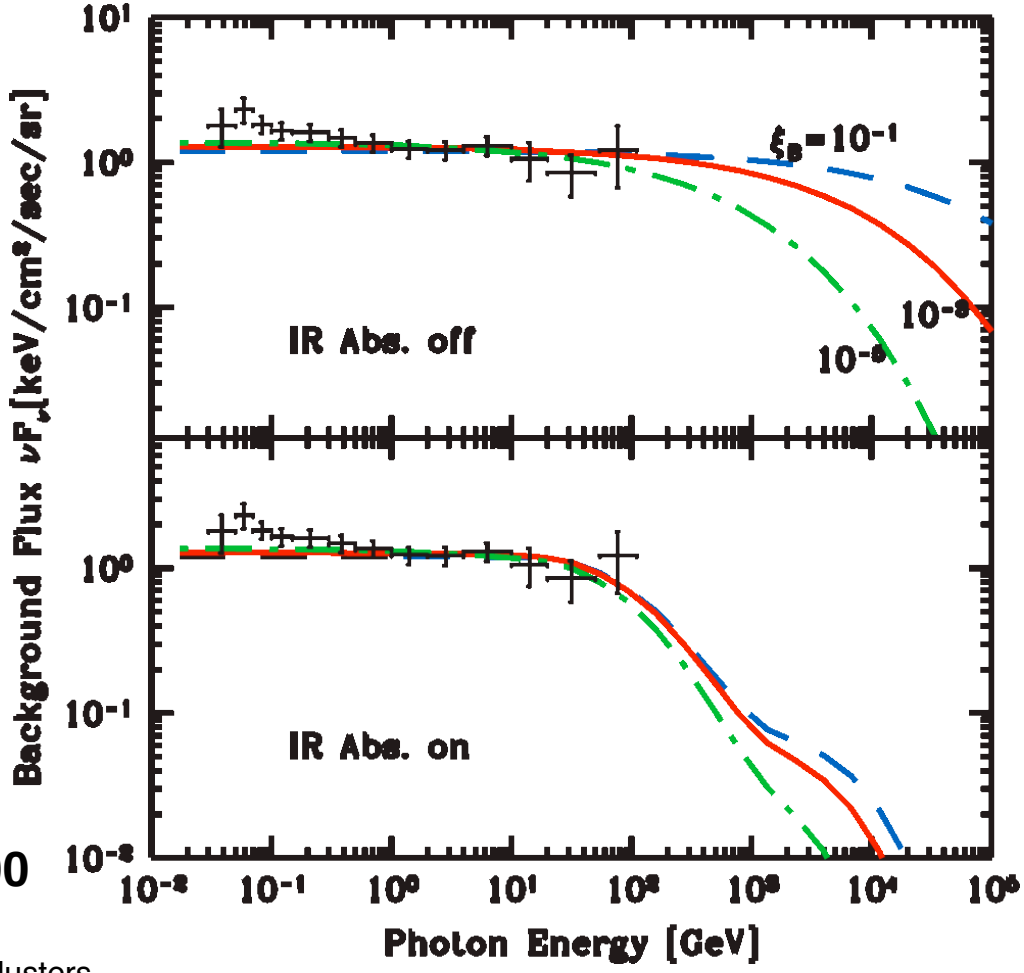
- **Expected logN-logF and EGRET UID population**
  - **GLAST may find thousands of them.**



Totani&Kitayama 00

Origin of Extragalactic γ-ray BG?

- **Extragalactic gamma-ray BG observed by EGRET can be explained by gamma-ray clusters.**



Totani&Kitayama 00

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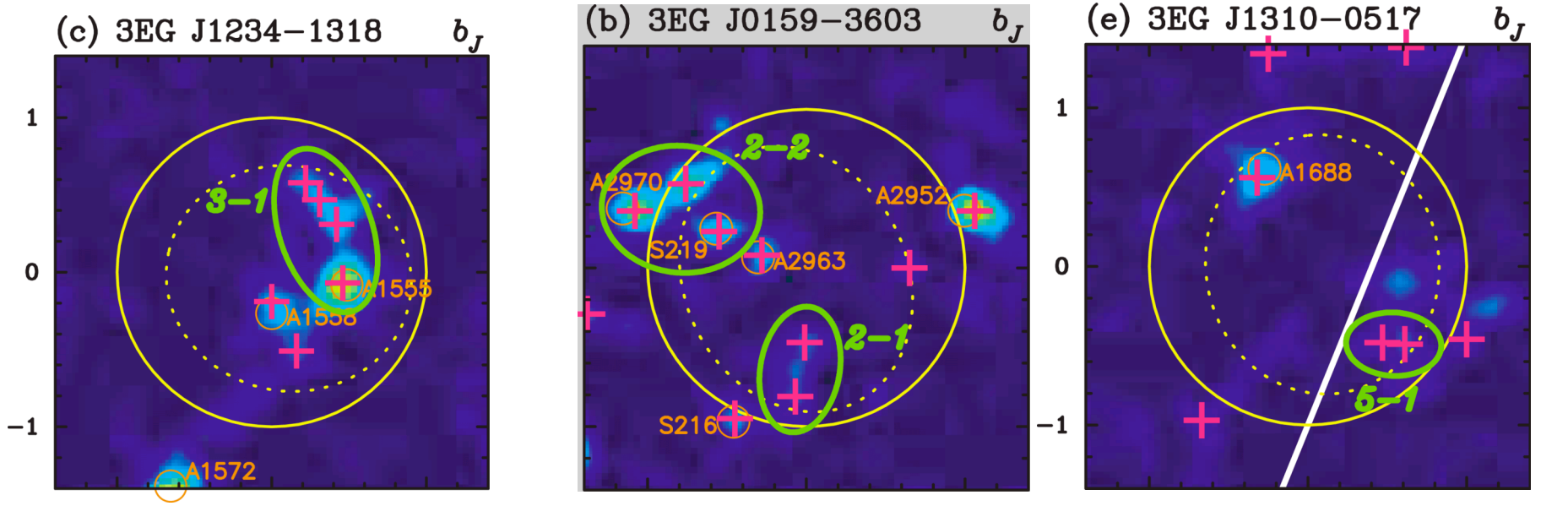
Why not detected in other bands?

- **X-ray (ROSAT limit: ~4x10^{-12} ergs/cm^2/s)**
  - **IC flux expected in X-ray band: ~1.6x10^{-11} ergs/cm^2/s**
  - **However, X-ray from this class of clusters are more extended than ordinary clusters.**
    - CXB confusion raises the detection limit.
    - Deep Suzaku observation would give stringent constraints on this model.
  - **Not enough time to heat up the gas.**
- **Optical**
  - **Merging clusters are harder to identify by eye since they are more extended than the stabilized ones.**
- **Radio**
  - **Synchrotron is too dim due to low *B*.**

Association with Cluster Pairs/Groups

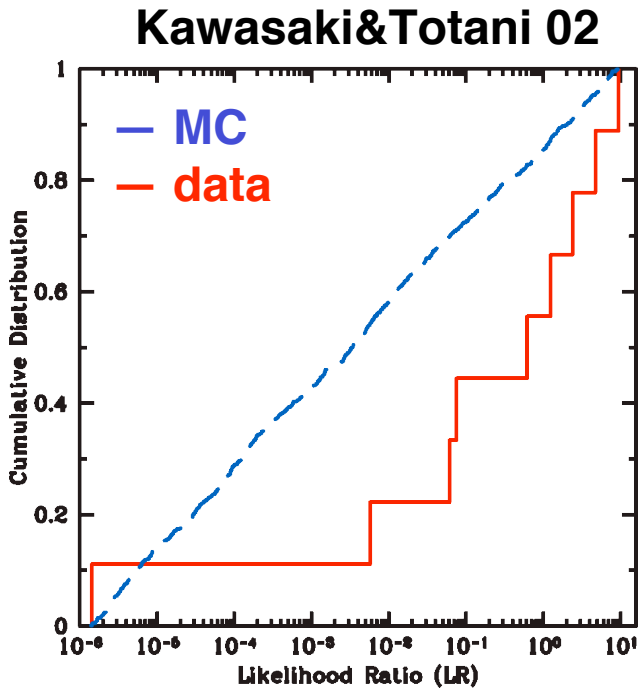
- **Automated cluster-finding technique based on maximum likelihood method.**
  - **Several associations of CPG (cluster pairs/groups) with EGRET nonvariable UID sources with $|b|>45^{o}$(Gehrels 00).**



Kawasaki&Totani 02

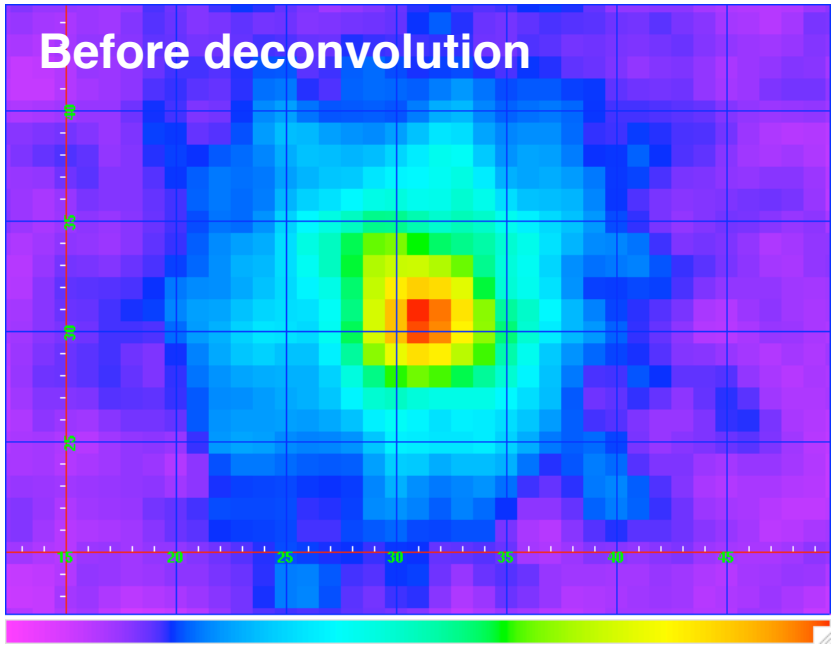
Statistical Significance of Association

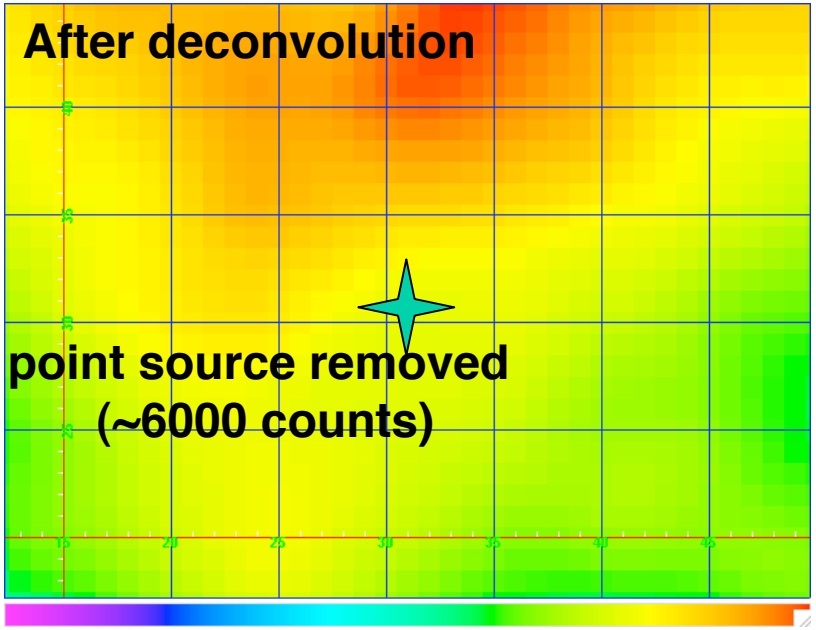
- **5 out of 7 EGRET nonvariable UID sources are associated with CPGs within 1º radius.**
  - **If random, 1.5 CPGs expected. Observed 6 CPG is 3.7σ effect.**
  - **Association with single clusters is consistent with random, i.e. 1.1σ.**
- **Mean Closest Separation: 0.84º**
  - **1.84±0.39o if random. 2.6σ effect.**
- **Likelihood ratio: dp(r:ID)/dp(r:c)**
  - **KS test gives 2.3% chance probability**
- **However,**
  - **Two sources are variable, another two sources are questionable (Reimer 03, Tompkins 99, Torres 01).**
  - **AGN contamination?**



Reanalysis of EGRET data

- **Image deconvolution with event-by-event PSF.**
  - **See my talk at DC2 closeout for details.**
  - **Incorporated wavelet filtering to reduce the effect of Poisson noise. (thanks to Stefano).**
  - **Energy dependent EGRET PSF (thanks to Jim).**
  - **Test with Crab, PSF looks OK.**





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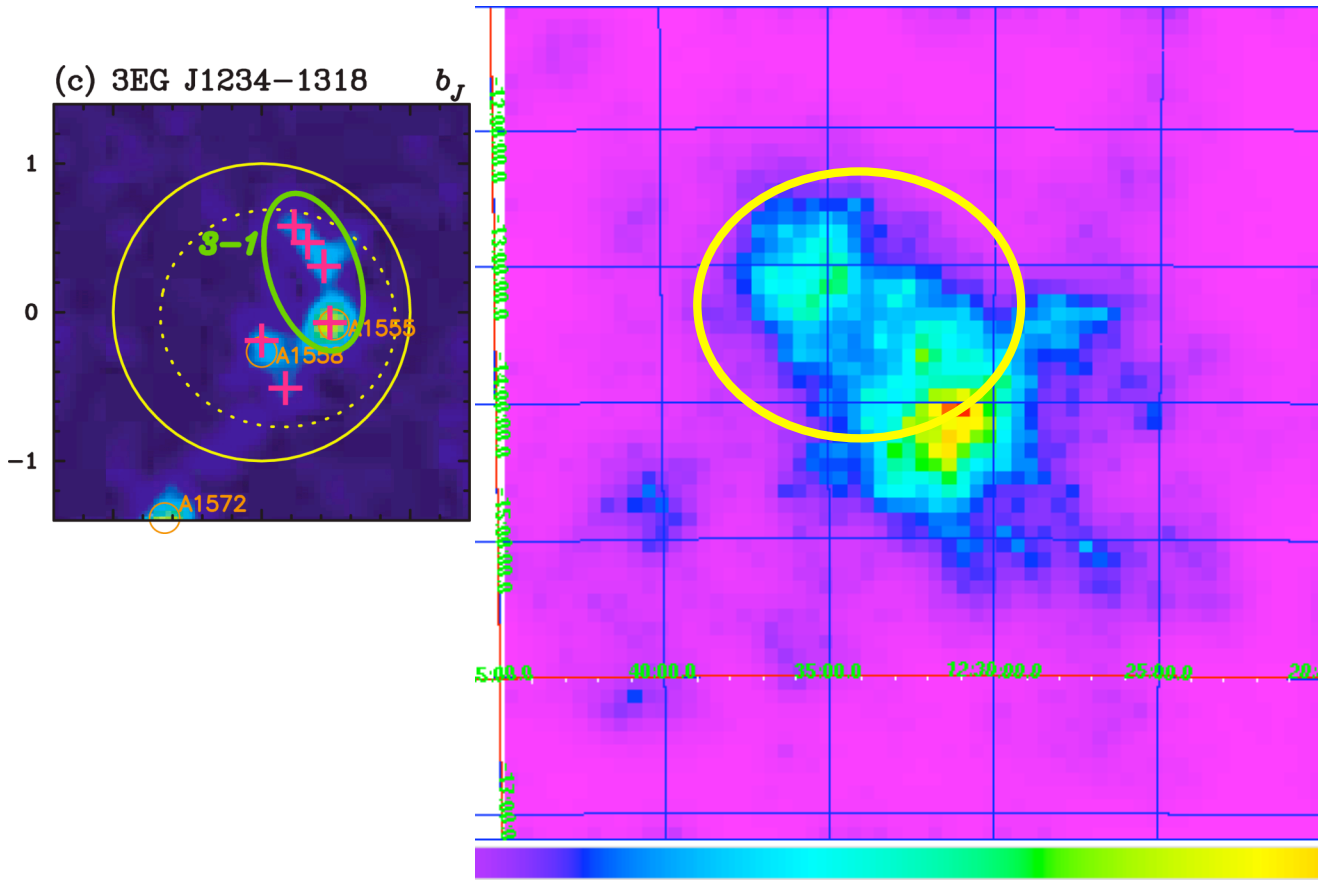
Deconvolved 3EG J1234-1318

- **Image deconvolution favors extended source.**
  - **Rejects point source hypothesis at (184.7,-14.1).**
  - **Need further studies to make statistical significance.**



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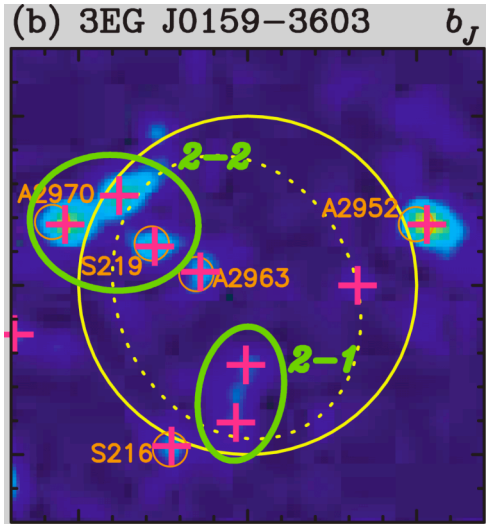
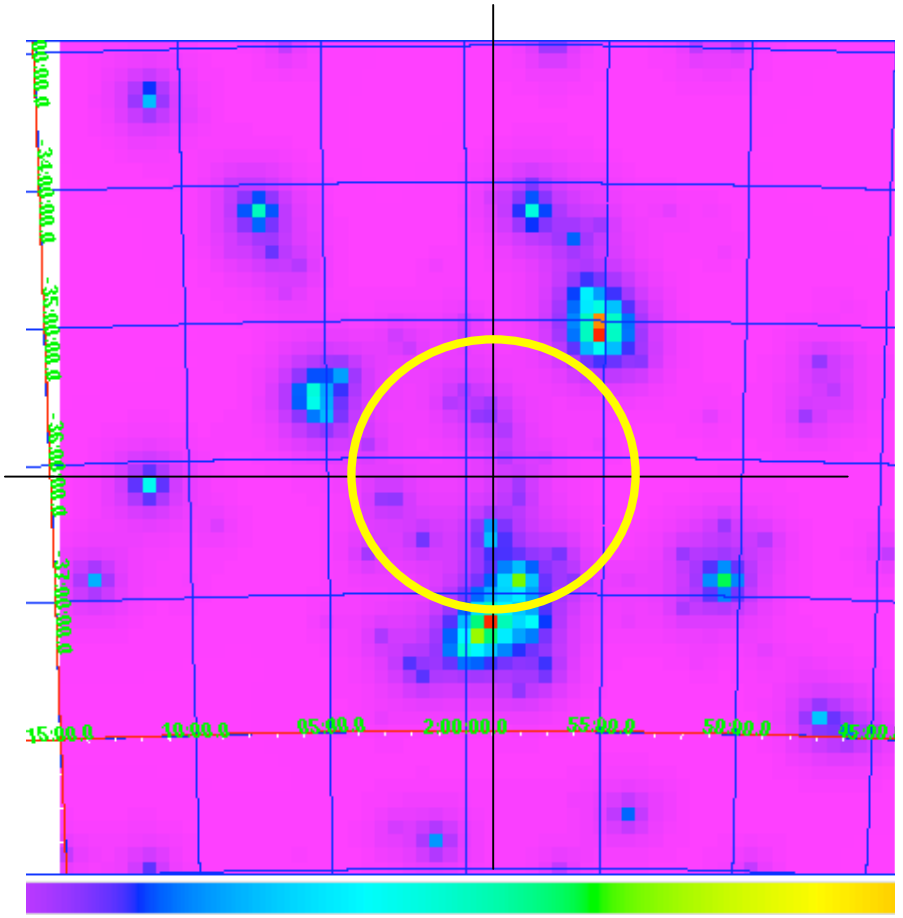
Deconvolved 3EG J0159-1318

- **I just got this picture at 11:55AM today…**





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