銀河団における超高エネルギー物理過程

井上 進 (国立天文台)

標準的な階層的構造形成の描像では、銀河団の周りに強い降着衝撃波が普遍的に存在するはずである。そこでは陽子が10^{18}-10^{19} eVの超高エネルギーまで加速されうるが、その際、マイクロ波背景放射との相互作用で生成された２次的電子・陽電子対はシンクロトロン硬Ｘ線放射と逆コンプトンTeVガンマ線放射を引き起こす。この放射は各々Suzaku、NeXT等の衛星、及びHESS、CANGAROO III等のチェレンコフ望遠鏡により、近傍の銀河団での検出が充分期待でき、降着衝撃波の空間分布や銀河団外縁部での磁場等について重要な情報をもたらすはずである (**Inoue, Aharonian & Sugiyama 2005**)。これの検証を目指し、HESSによるいくつかの近傍の銀河団の観測計画 (**Inoue, Gabici, Aharonian & Rowell, HESS proposal accepted**) が進行中であり、「すざく」による観測案も申請中である (**Inoue et al., Suzaku proposal submitted**)。また、同様の降着衝撃波で、電荷の大きい鉄などの重イオンが加速されれば、10^{20} eVに至る最高エネルギー宇宙線源の有力な候補になりうる。構造形成シミュレーションに基づく現実的な銀河間磁場の分布や、高エネルギー原子核伝播中に起きる反応過程の詳細な数値計算を用いてこの可能性を調べた結果、現在の宇宙線観測をおおよそ矛盾なく説明できることがわかった。さらに、予想される特徴的なスペクトル・到来方向分布・組成は、将来的にAuger、Telescope Array、EUSO等の実験により検証可能である (**Inoue, Sigl, Armengaud ¥& Miniati, in prep.**)。

銀河団における超高エネルギー物理過程

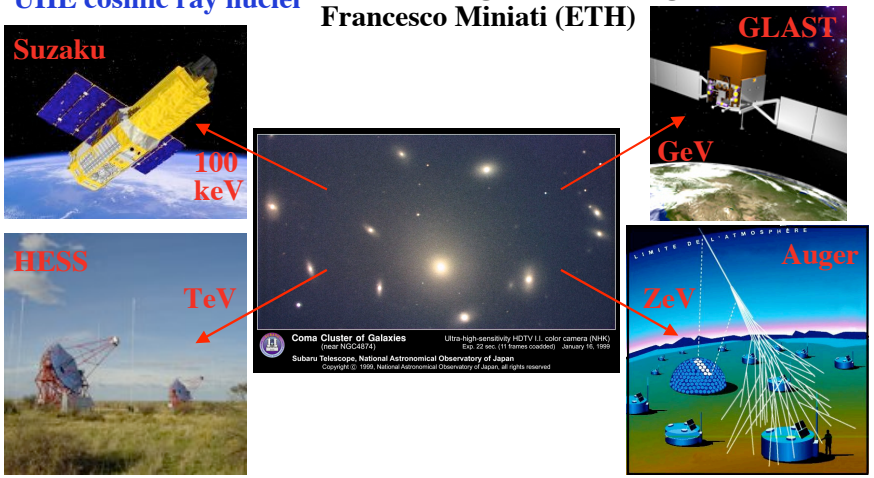
井上 進 (国立天文台)

UHE proton induced hard X-rays & γ-rays

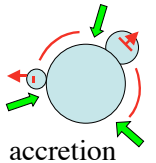
UHE cosmic ray nuclei

w. Felix Aharonian (MPIK), 杉山直 (国立天文台)

w. Günter Sigl, Eric Armengaud (IAP)
Francesco Miniati (ETH)

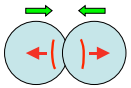


cluster accretion shocks



accretion
(minor merger)

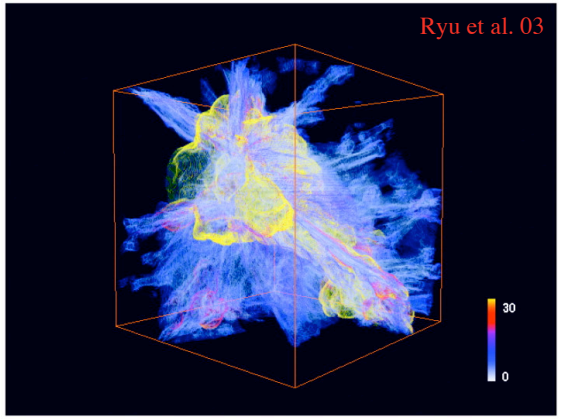
strong (high $\mathcal{M}$) shock
-> high injection,
hard spectra



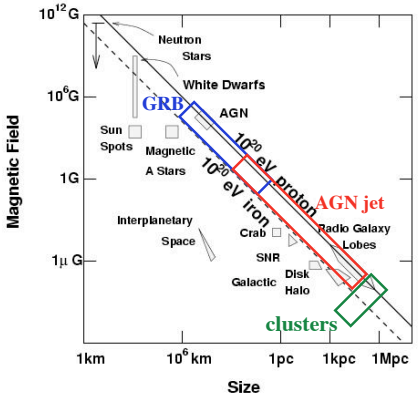
(major) merger

weak (low $\mathcal{M}$) shock
-> low injection,
soft spectra

crucial for nonthermal high energy phenomena



UHECRs from cluster accretion shocks?



Norman, Achterberg & Melrose ‘95
Kang, Ryu & Jones 96
Kang, Rachen & Biermann 97

energetic requirements

UHECR@10^{20} eV
u_{CR} ~10^{-20} erg cm^{-3}
τ_{CR} ~0.3(1) Gyr for p (Fe)
P_{CR} ~3x10^{37} erg s^{-1}Mpc^{-3}

massive clusters (~10^{15} $M_\odot$)

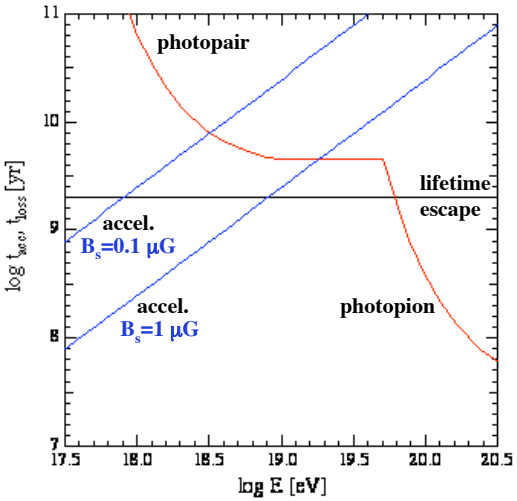
$L_{cluster}$~10^{46} erg/s
$n_{cluster}$~10^{-6} Mpc^{-3}
$P_{cluster}$~~10^{40} erg s^{-1}Mpc^{-3}

energetically plausible, but proton E_{max} insufficient

UHE proton-induced pair emission from cluster accretion shocks

Inoue, Aharonian & Sugiyama 2005 ApJ 628, L9

max p energy accel. vs CMB losses, lifetime



e.g. Coma-like cluster
M=2x10^{15} $M_\odot$(T=8.3 keV)
WMAP cosmo. parameters

shock radius, velocity, etc.

R_s~3.2 Mpc
V_s~2200 km/s
$B_{s,eq}$~ 6 μG

Bohm limit shock accel.

$t_{acc}=(20/3)\ \eta\ r_g c/V_s^2$

SNR observations η~1
e.g. Völk et al. 05

shock lifetime

t_s~2 Gyr < t_{adiab}~6 Gyr

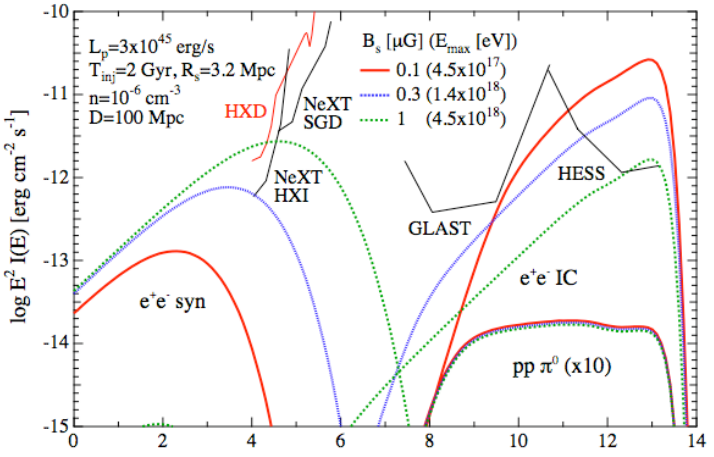
E_{max}~10^{18}-10^{19} eV
photopair important

emitted flux & detectability

Coma-like cluster at D=100 Mpc

sensitivities for 1 deg^2 extended source

> TeV absorption by IRB, CMB



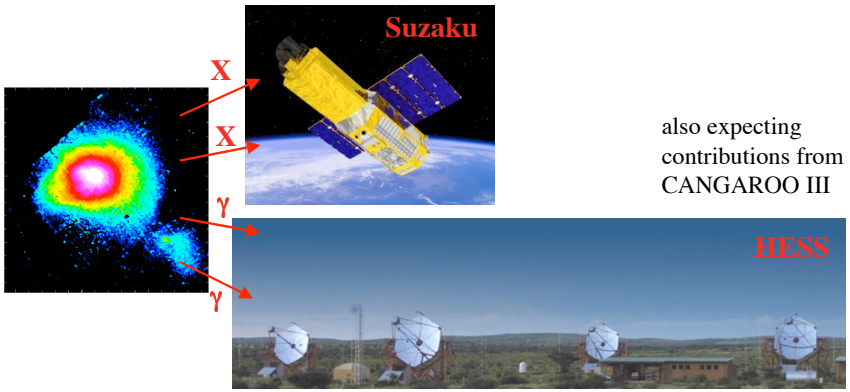
- large radiative efficiency from protons
- hard (Γ~-1.5) spectrum + rollover
- sensitive to B

<-> primary IC, pp π^0 (Γ~-2)

TeV γ-ray and hard X-ray observations of clusters

coming very soon!!!

- Inoue, Gabici, Aharonian & Rowell, HESS proposal, accepted
- Inoue, Nakazawa, Fukazawa et al., Suzaku proposal, submitted



also expecting
contributions from
CANGAROO III

nuclei from cluster accretion shocks as UHECRs

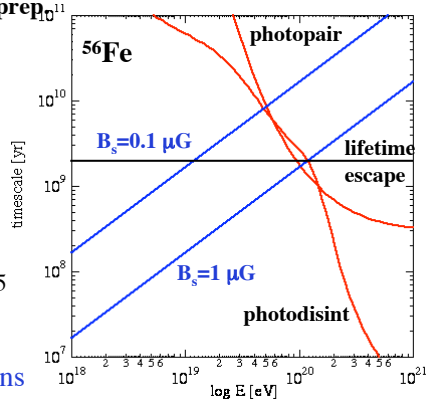
Inoue, Sigl, Armengaud & Miniati, in prep

maximum E for heavy nuclei

photopair+photopion CMB
photodisint FIRB+CMB

if B_s~1 μG
$E_{Fe,\ max}$>~10^{20} eV
photopair important

B_s~1 μG Johnston-Hollitt & Ekers '05

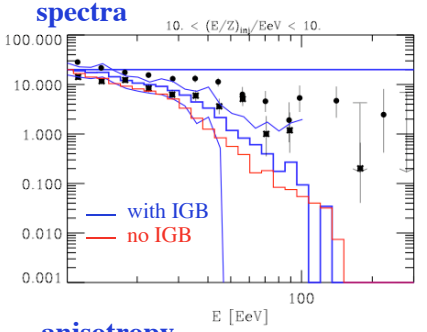


UHE nuclei propagation calculations

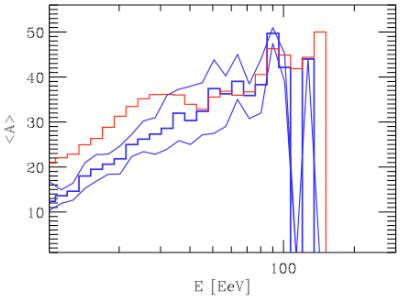
- realistic IGB models based on cosmological simulations
- source density ~10^{-6} Mpc^{-3} ∝ baryon density
- $E_{max}(Z)$ from t_{acc} vs. t_{loss}, t_{life}
- Galactic CR-like source composition (n_{Fe}/n_p~0.05)
- interactions in CMB+FIRB, deflections in IGB including all secondary nuclei

UHE nuclei from clusters: results

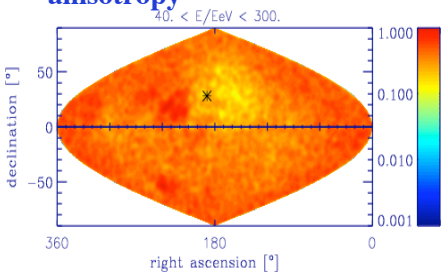
spectra



composition

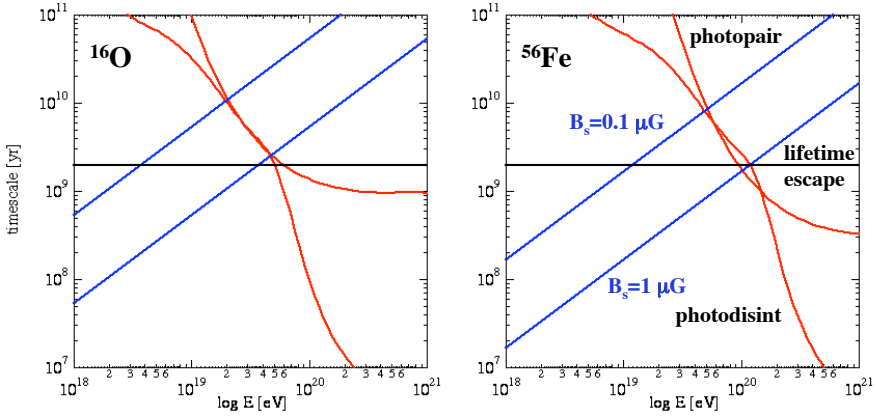


anisotropy



spectra, anisotropy, composition
- consistent with
  current HiRes but not AGASA…
- predictions:
  - "GZK" cutoff $>10^{20}$ eV
  - heavy dominant $>10^{19}$ eV
  - one or few extended source(s)
    $>4\times10^{19}$eV

UHE nuclei induced pairs



photopair important
additional hard X-ray and γ-ray emission, broader spectra
direct proof of nuclei acceleration in cluster accretion shocks

summary UHE processes in cluster accretion shocks

UHE p-induced emission
- acceleration to E~10^{18}-10^{19}eV
- efficient secondary pair emission
  -> hard X sync. Suzaku, NeXT (imaging), …
  -> TeV IC HESS, CANG.III, other current IACTs
- important probe of UHE p acceleration, B in cluster outskirts, …

stay tuned for upcoming HESS & Suzaku observations!

UHECR nuclei
- Fe acceleration to E~10^{20}eV plausible if B~1 μG
- UHECR flux and spectra consistent if n_{Fe}/n_p~0.05 at source
- predictions for Auger, TA, EUSO:
  - spectra: cutoff >~10^{20} eV
  - composition: p dominant ~<10^{19} eV, Fe dominant >~10^{20} eV
  - anisotropy: a few extended sources >~4×10^{19} eV
- additional hard X/TeV from pairs HESS, Suzaku, …