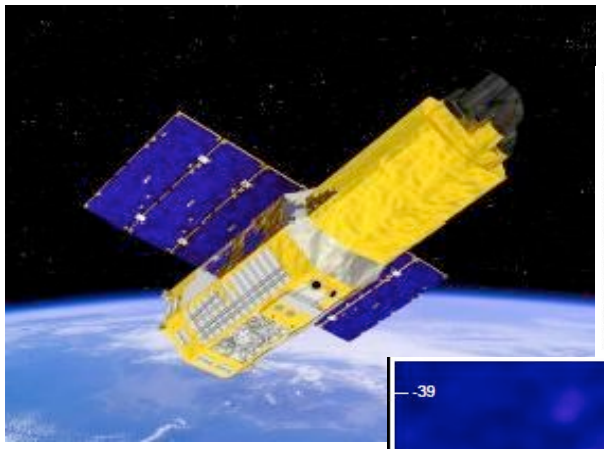
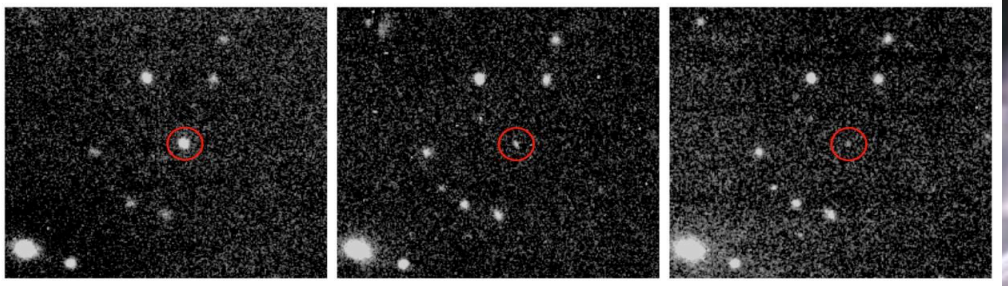
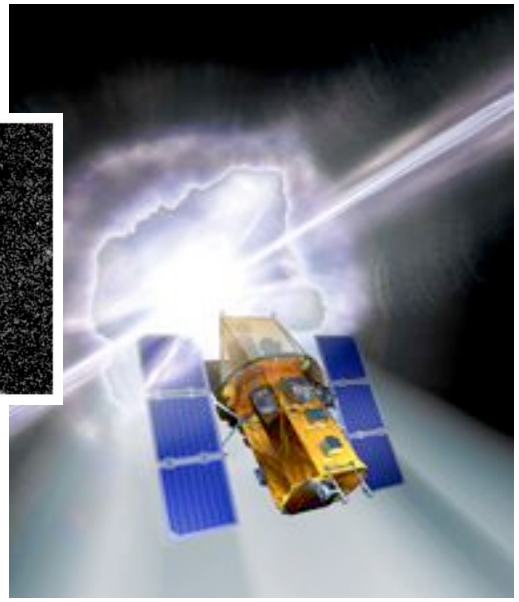
高エネルギー天文学宇宙物理学の進歩と展望

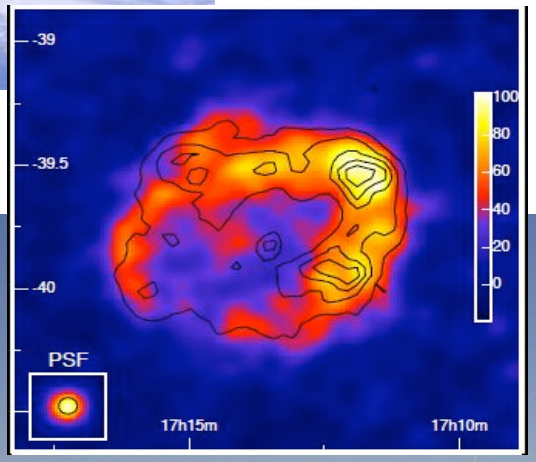
「超熱的宇宙」　“The superthermal universe”

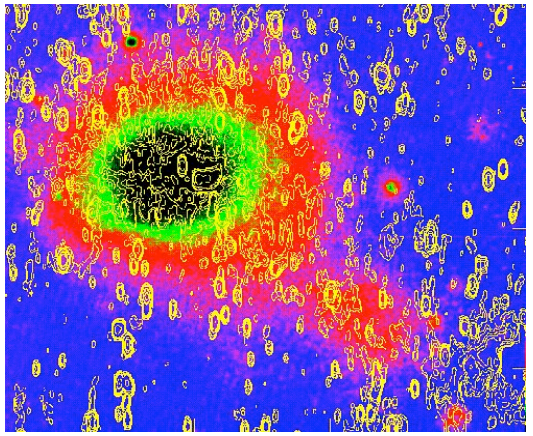
井上 進（国立天文台）

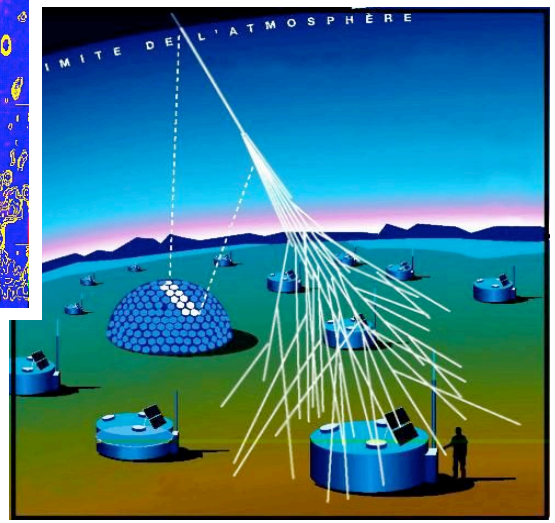












selected topics

1. The origin of cosmic rays

Galactic CRs, SNR X+γ-rays, ultra high energy CRs

2. Gamma-ray mysteries

new & unidentified TeV sources

3. The nature of GRBs

SWIFT progress: short GRBs, L correlations, lots of confusion, …

4. High energy cosmology

high-z GRBs, blazars

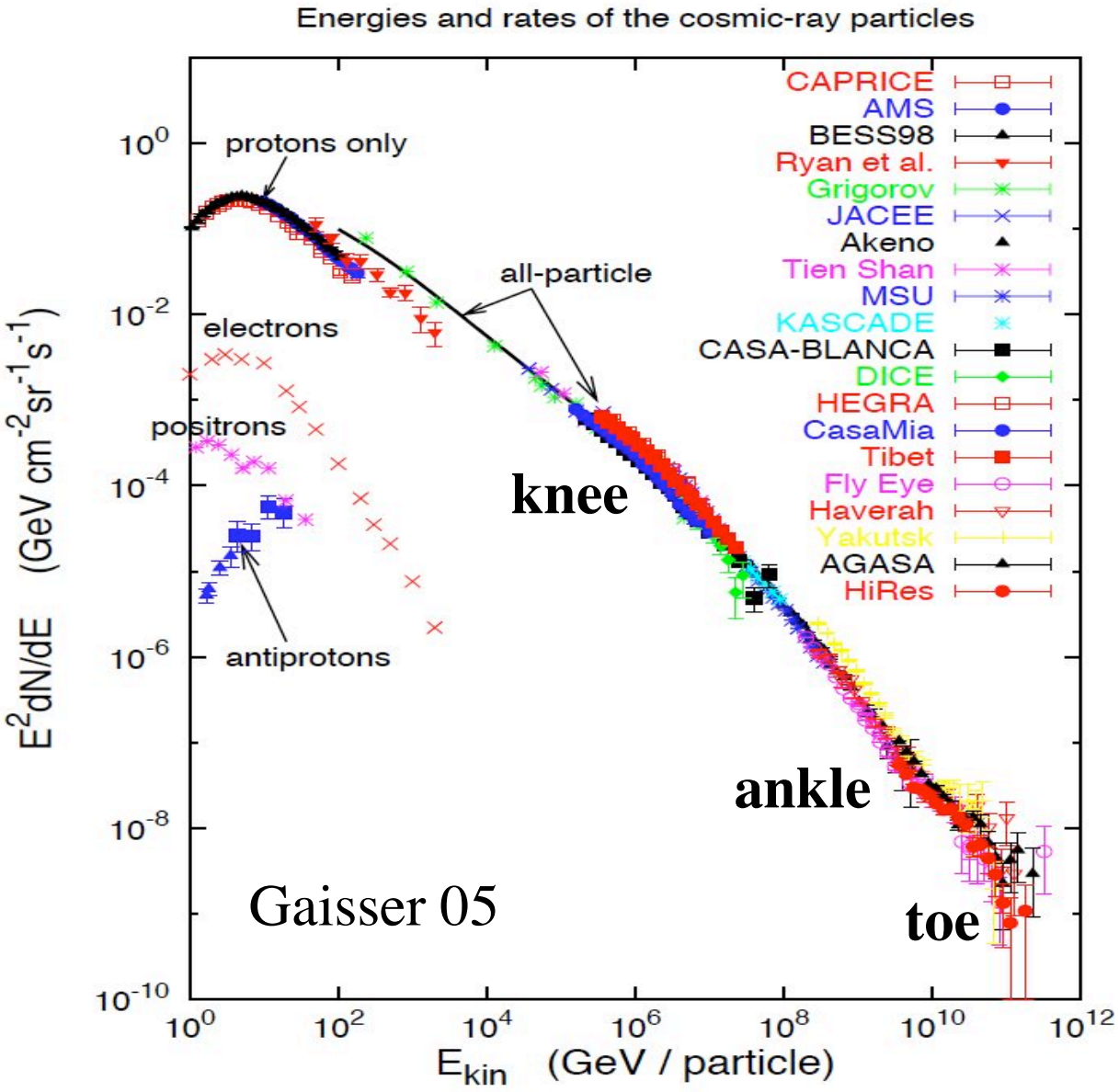
5. Large-scale high energy astrophysics

HE processes in galaxies, clusters, …
role of CRs in star/galaxy/cluster formation, …

extremely rapid progress, great surprises & expectations
ever growing impact on other fields (large-scale universe)

1. The origin of cosmic rays

observed CR spectrum: great power-law in the sky



up to knee ($<10^{15\text{-}16}$ eV)

Galactic SNRs?

$L_{GCR} \sim 10^{41}$ erg/s

$\sim 0.1 \times E_{SN}/t_{SN}$

BUT

simple theory: $E_{max} < 10^{14}$eV?

no direct evidence for protons

knee-ankle ($10^{15\text{-}16}$-10^{18} eV)

Galactic? no new source?

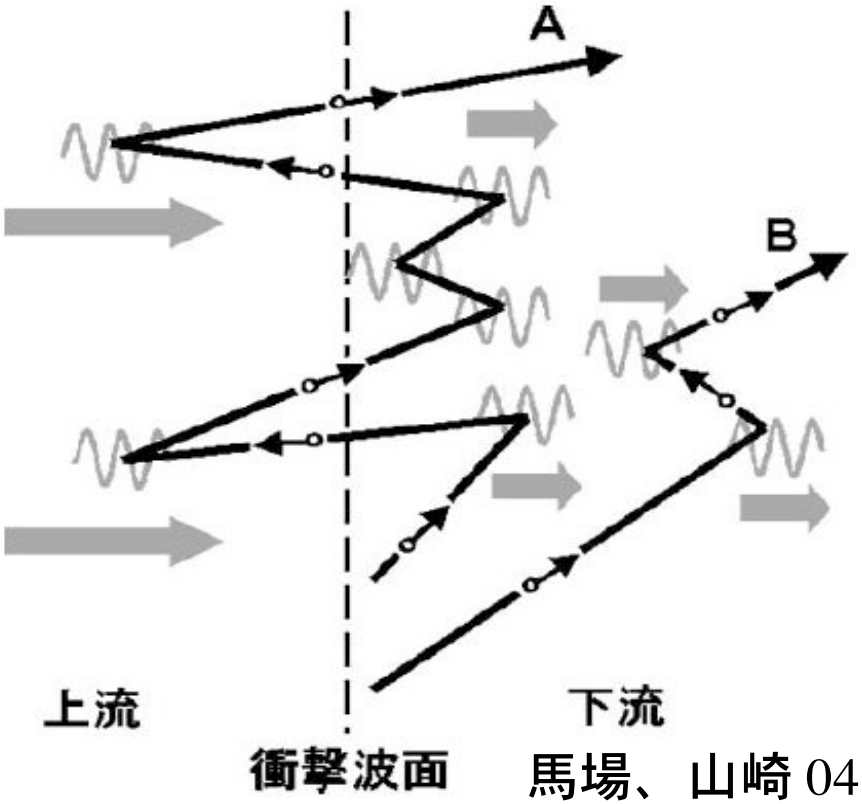
above ankle ($>10^{18}$ eV)

extragalactic: AGNs?

GRBs?

???

shock acceleration



馬場、山崎 04

- power-law spectrum
  $dN/dE \sim \propto E^{-2}$ for strong shock
- very efficient
  up to ~50% of kinetic energy

basic emission processes

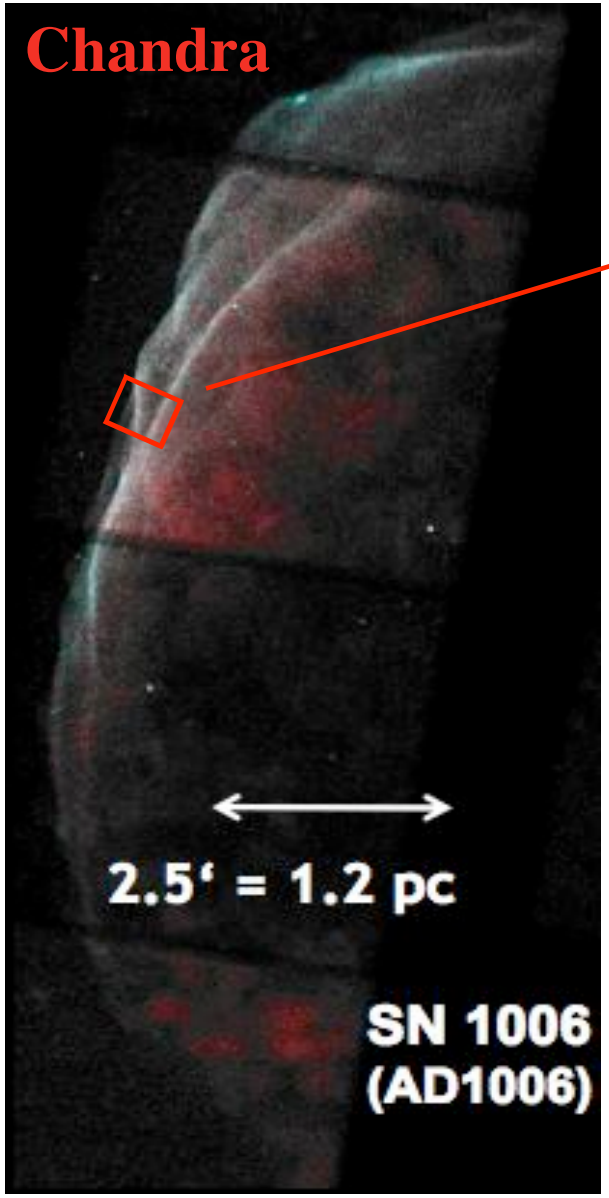
synchrotron $e^- + B \rightarrow e^- + \gamma$

inverse Compton $e^- + \gamma \rightarrow e^- + \gamma$

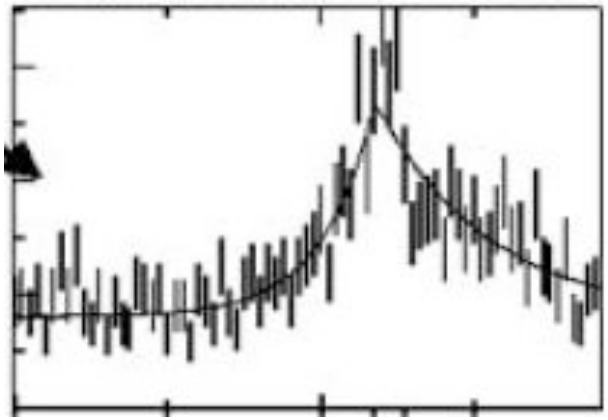
p-p pi0 $p_{CR} + p_{gas} \rightarrow \pi^0, \pi^{+-}$ $\pi^0 \rightarrow 2\gamma$

$\pi^{+-} \rightarrow e^{+-} 3\nu$

SNRs: X-rays in high resolution



Bamba+ 03



shock surfaces ~ very thin filaments
→ B~ few 100 μG

CR B amplification?

Lucek Bell 00, Bell 04

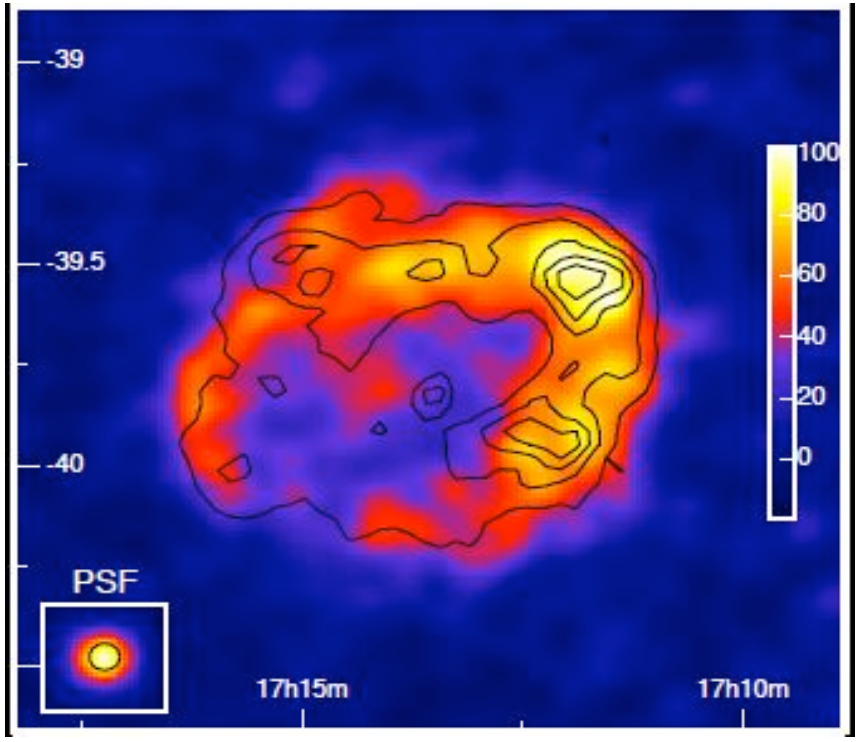
acceleration up to E_{knee}!

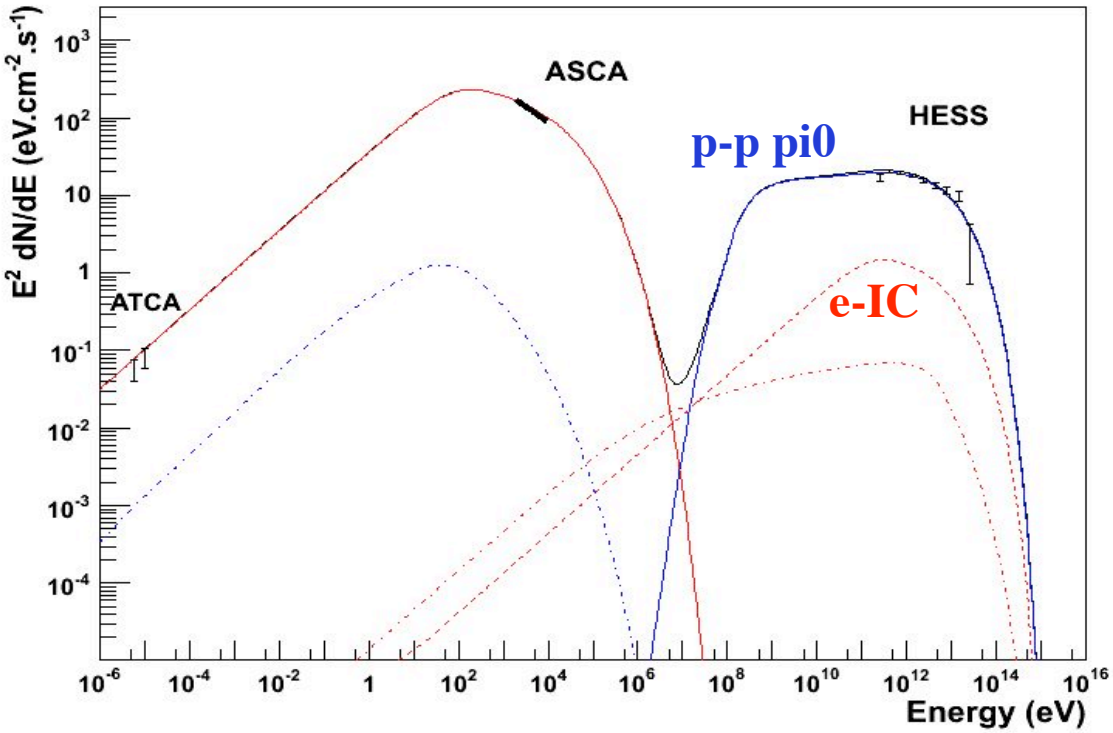
SNRs: TeV gamma-ray image!

Aharonian+ 04 Nat., 05, 06

RX J1713.7-3946

(discovered by **CANGAROO** Enomoto+ 02)





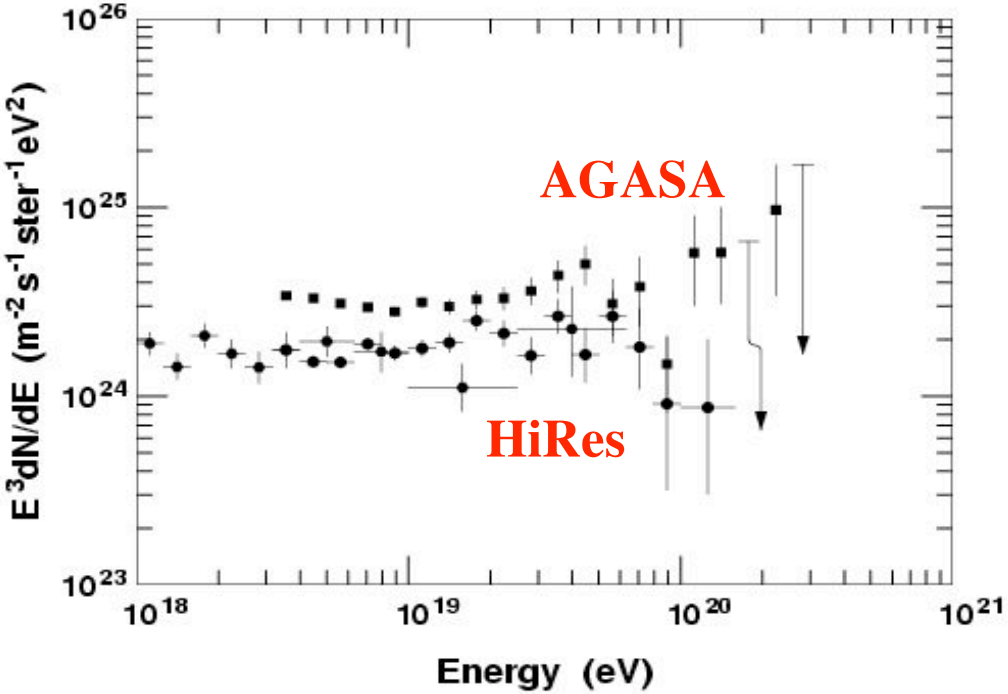
p-p pi0 likely (+some e-IC?)

E_{max}~100 TeV< E_{knee}
later/other SNRs up to E_{knee}?

ν source?

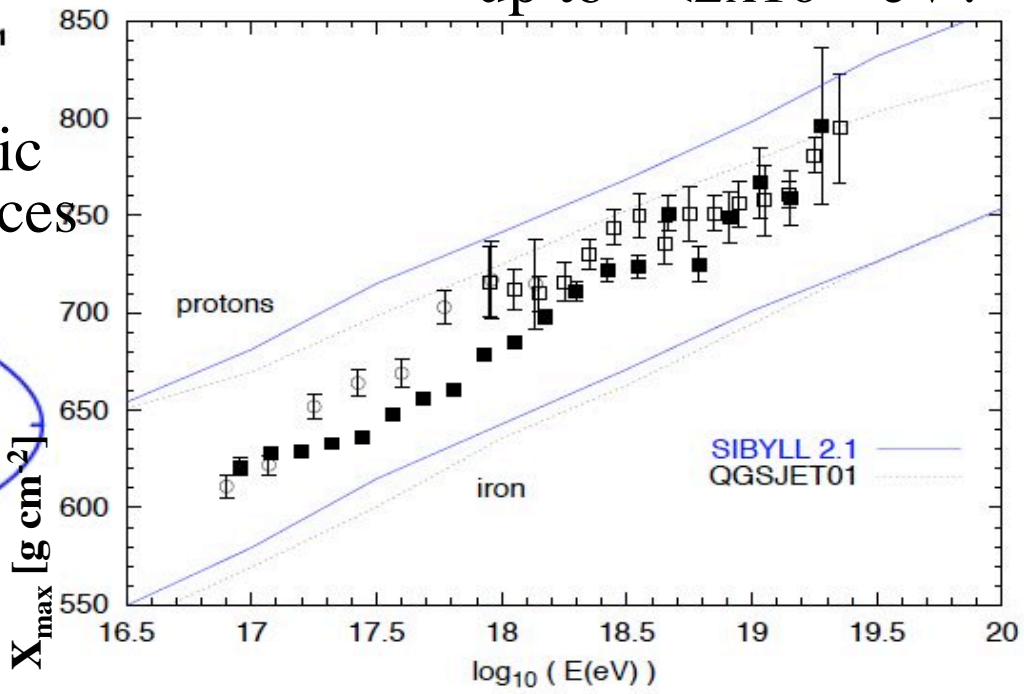
UHECRs: observations

spectrum at least up to 10^{20} eV

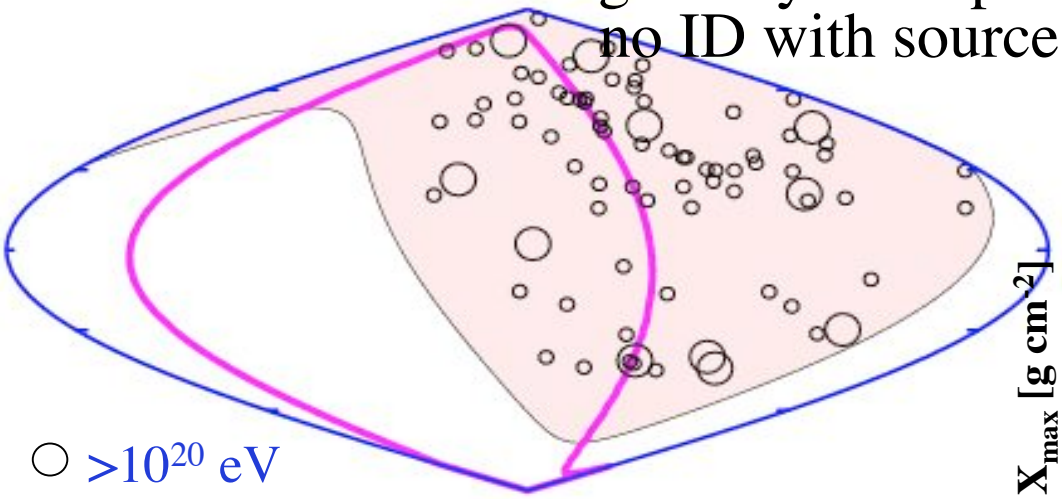


E_{max}~3x10^{20} eV
~50J ~ kinetic E
of 100km/h fastball

composition light dominant
up to ~<2x10^{19} eV?



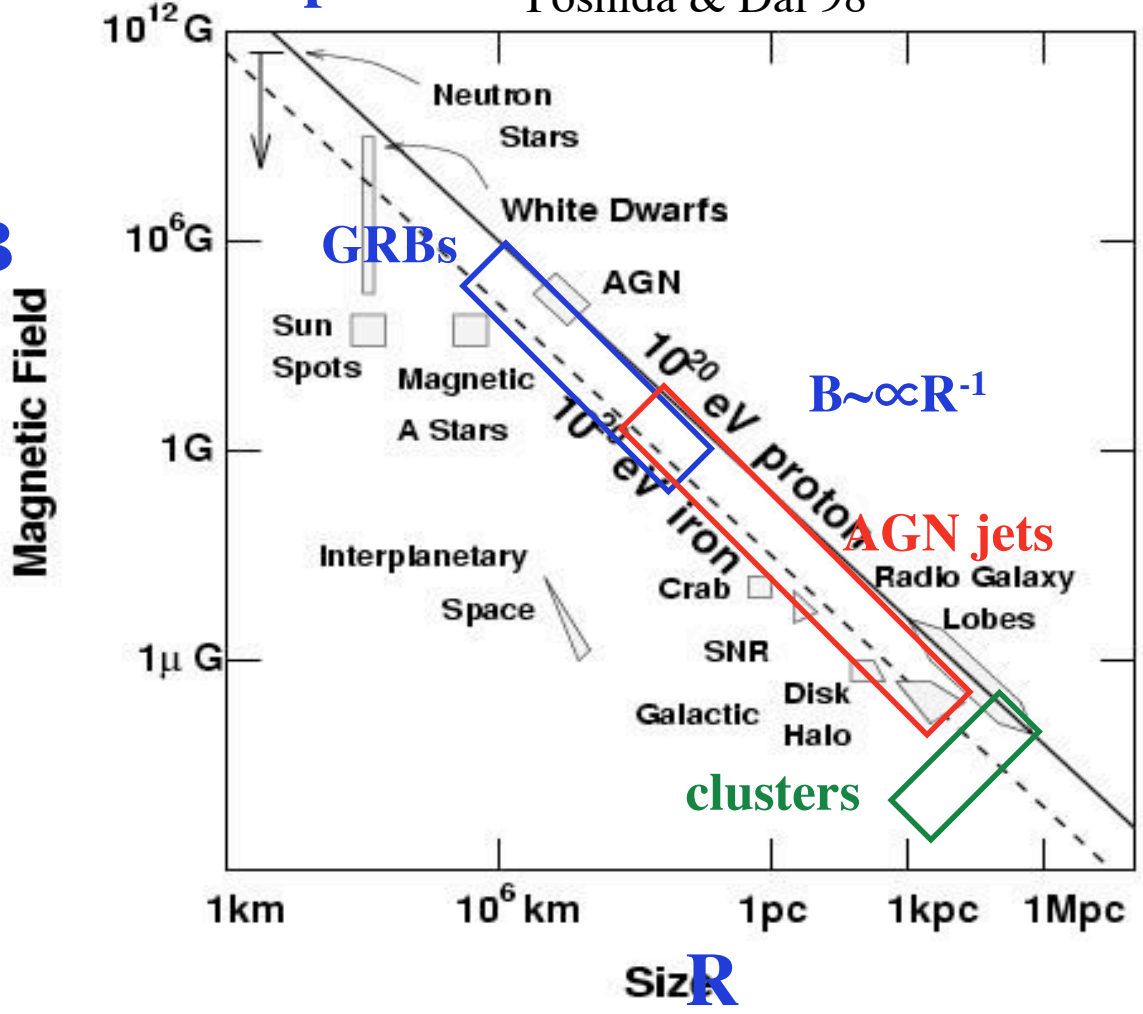
arrival directions globally isotropic
no ID with sources



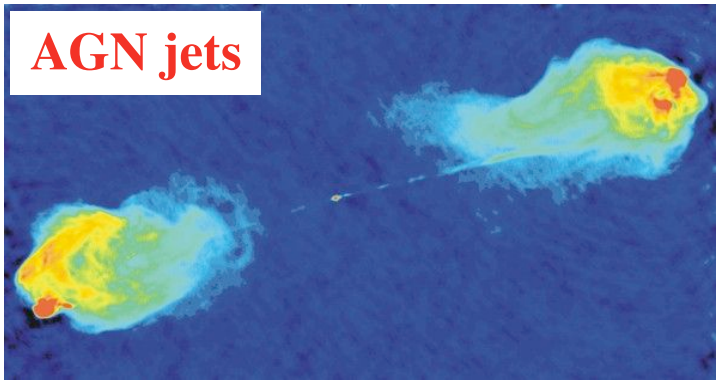
○ >10^{20} eV

UHECR sources?

"Hillas plot" adapted from Yoshida & Dai 98

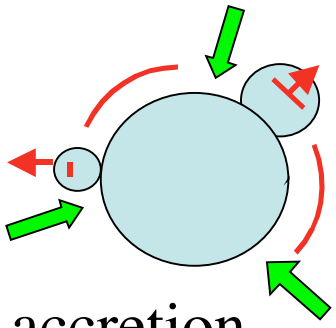


$$E \leqq Ze\,B\,R\,(v/c)$$



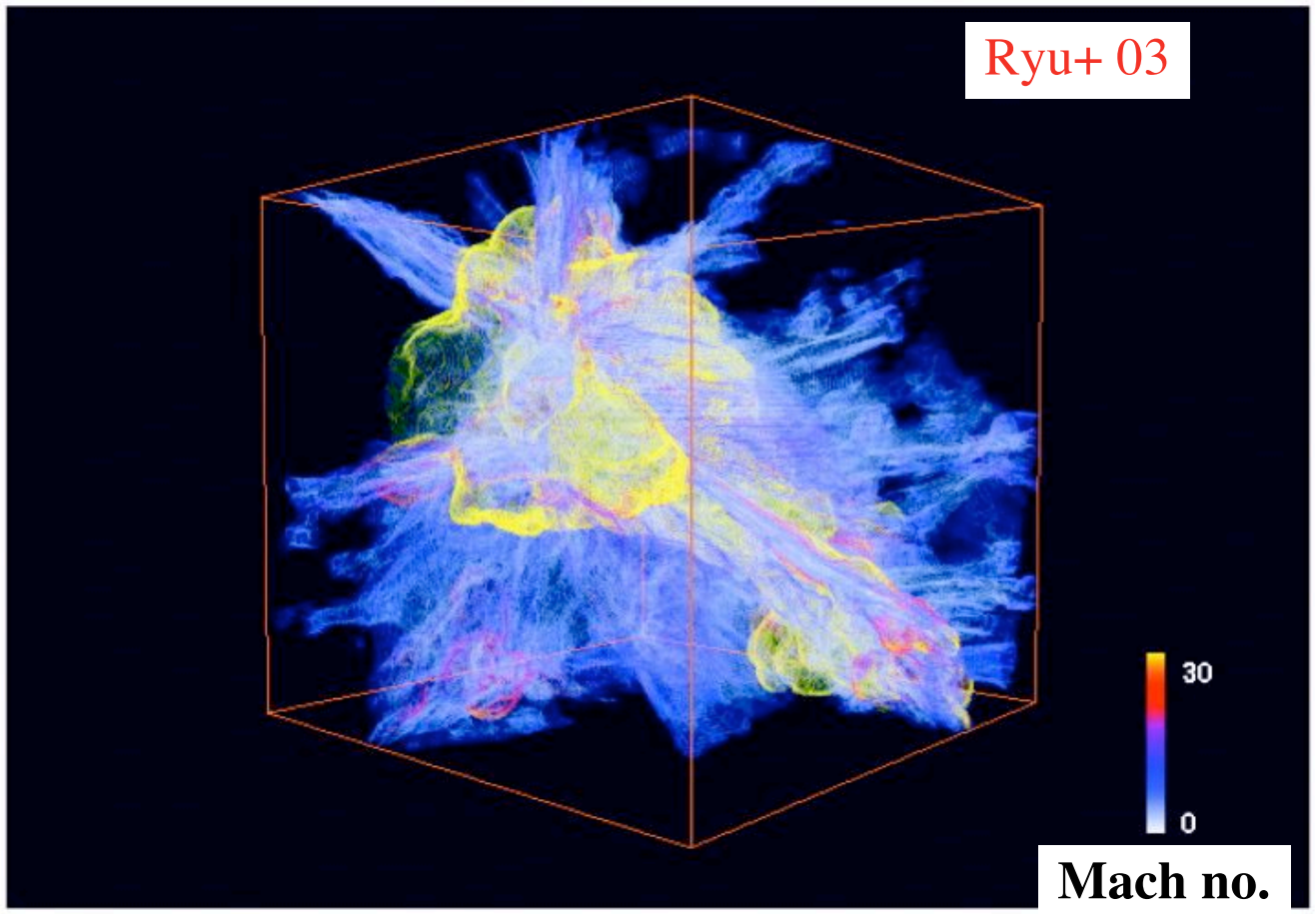
something else???

cluster accretion shocks



accretion
(minor merger)

strong shocks

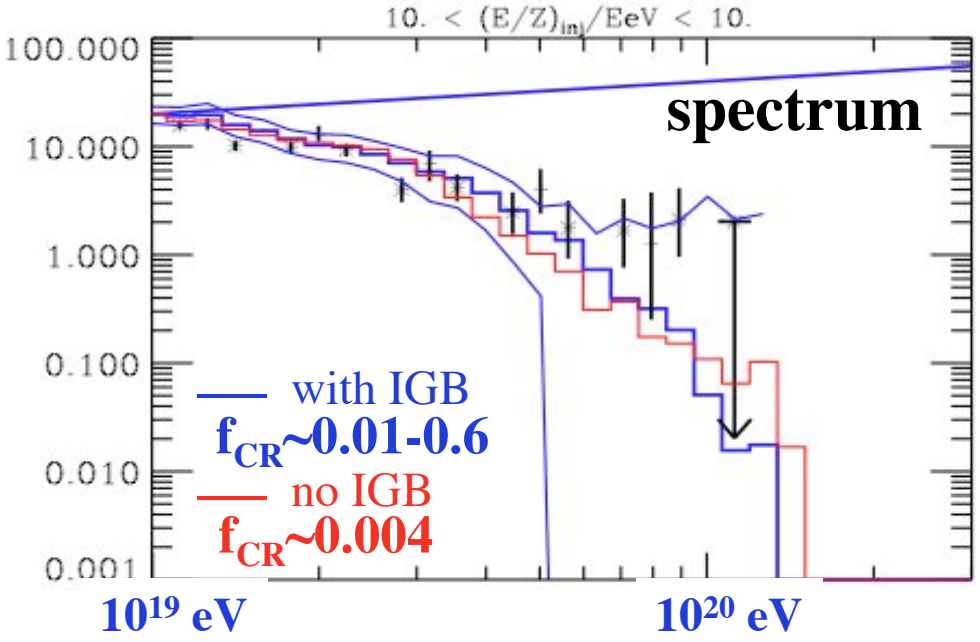


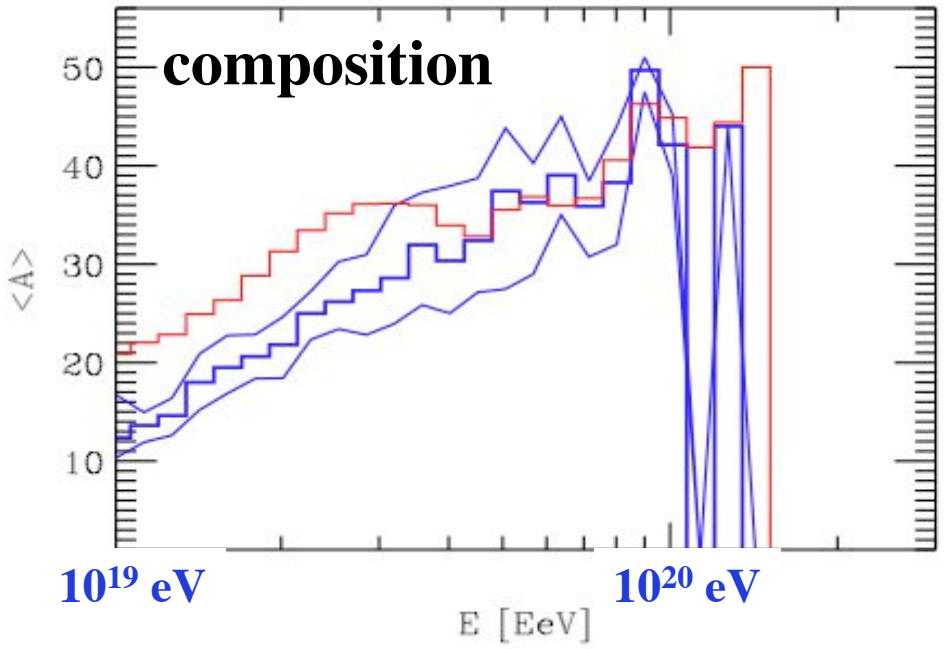
protons $E_{p,\,max} \sim 10^{18}$-10^{19} eV Kang, Rachen, Biermann 97

HOWEVER

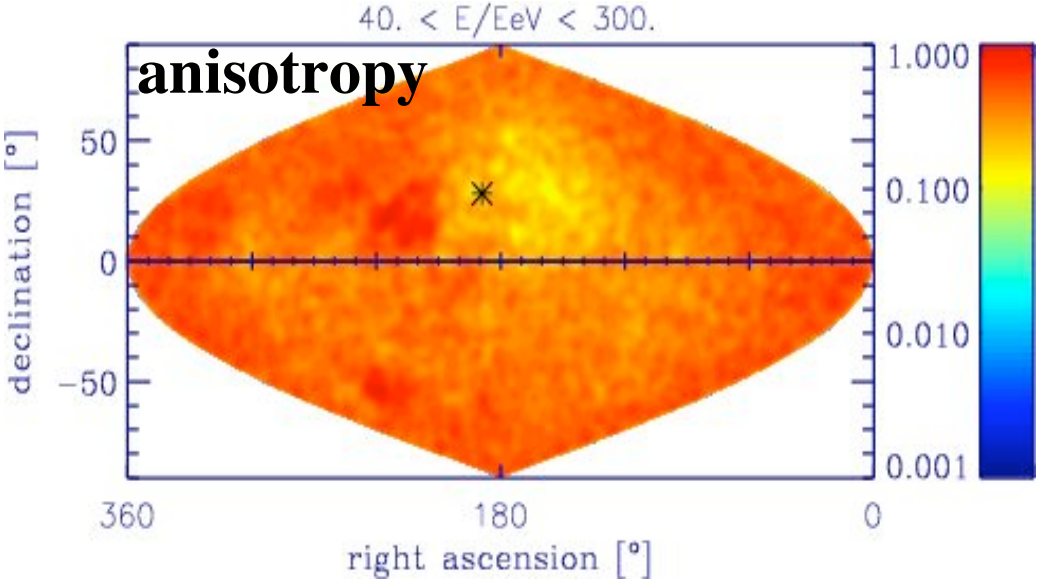
Fe nuclei (Z=26) $E_{Fe,\,max} > \sim 10^{20}$ eV if $B_s \sim 1$ μG

UHECRs as nuclei from clusters





SI, Sigl, Miniati, Armengaud
PRL, submitted
(astro-ph/0701167)



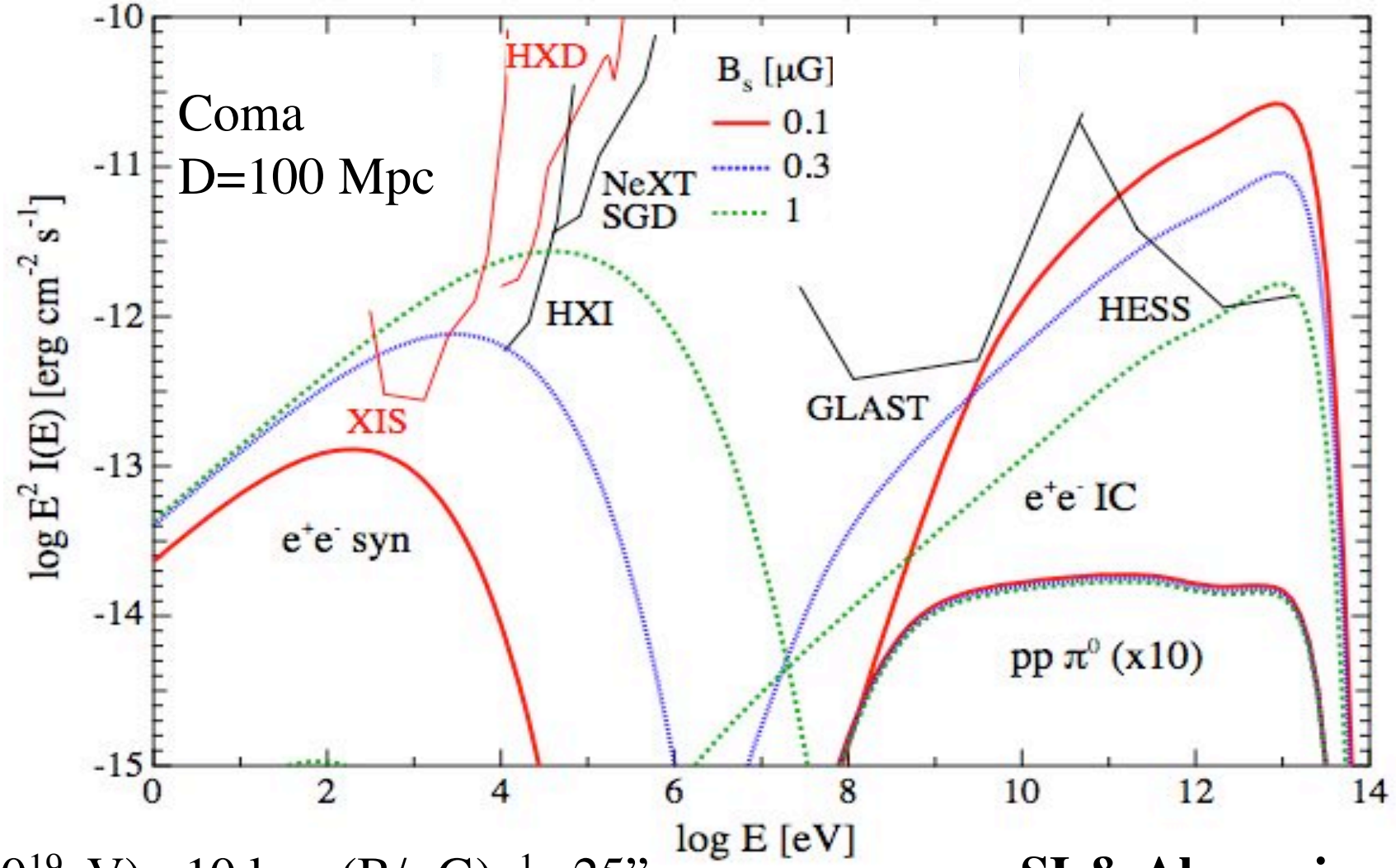
consistent with current data
(including AGASA?)

clear predictions for
Auger, Telescope Array, EUSO

UHE proton-induced hard X+γ emission from clusters

$p(10^{19}eV) + \gamma_{CMB} \rightarrow p + e^+e^- (10^{16}eV)$ **SI, Aharonian, Sugiyama 05**

$e^+e^- + B(\sim\mu G) \rightarrow$ keV, $e^+e^- + \gamma_{CMB} \rightarrow$ TeV



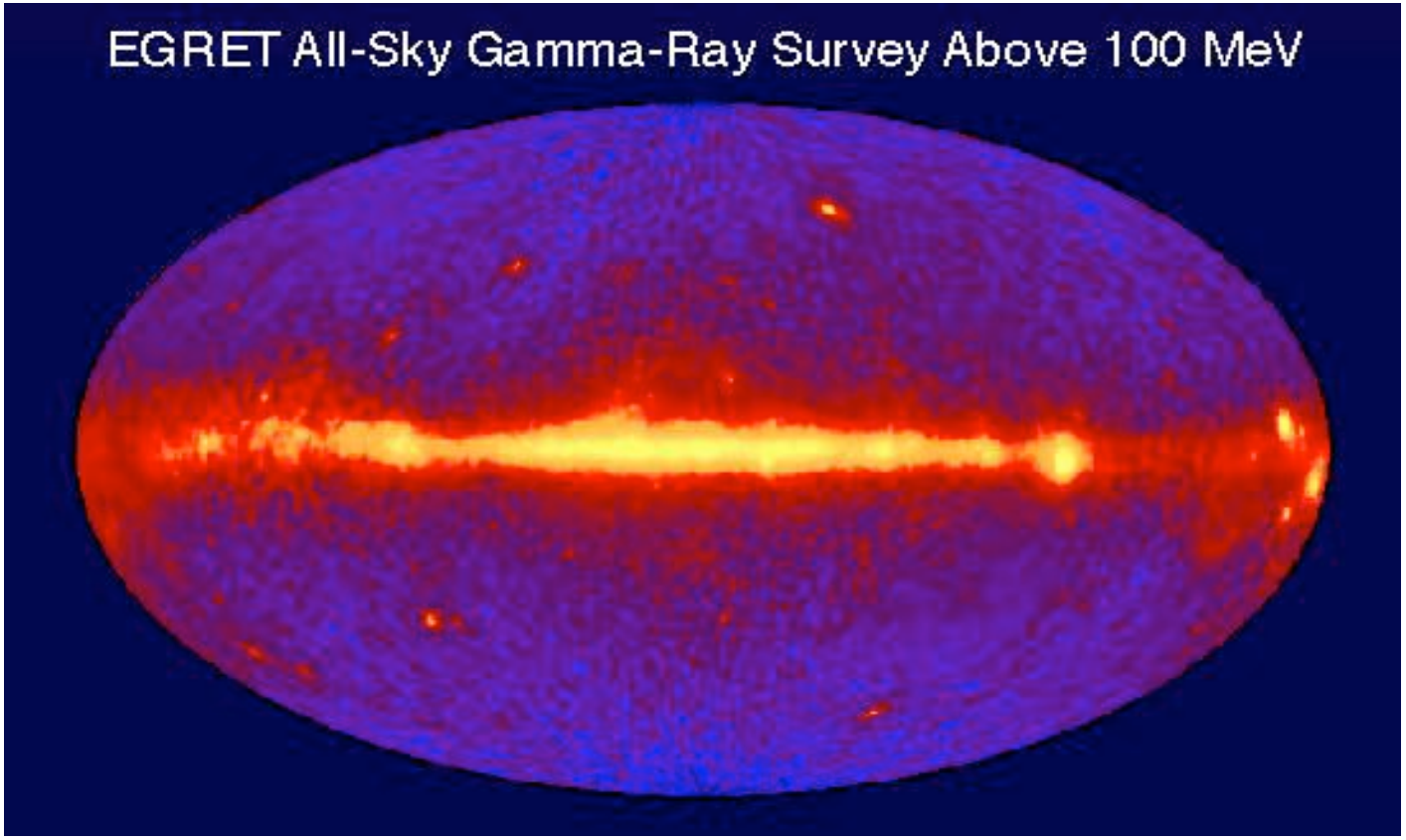
$R_g(10^{19}eV) \sim 10 \text{ kpc } (B/\mu G)^{-1} \sim 25''$

X-ray imaging of UHE proton acceleration

SI & Aharonian in prep.

2. Gamma-ray mysteries

GeV gamma-ray sky



Galactic: pulsars+nebulae, background

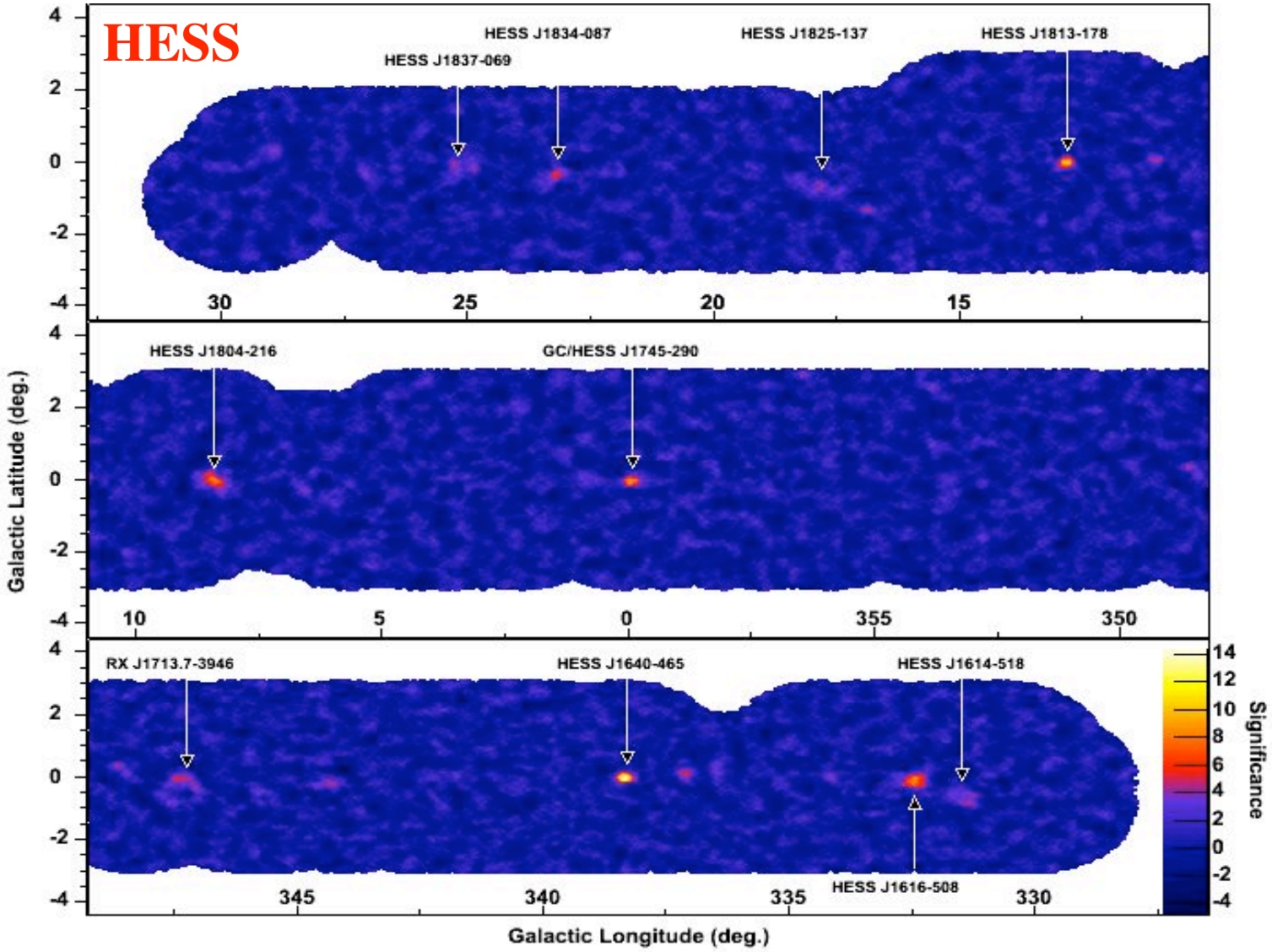
unidentified (SNRs? binaries?)

extragalactic: blazars, GRBs

unidentified, background

TeV Galactic plane survey

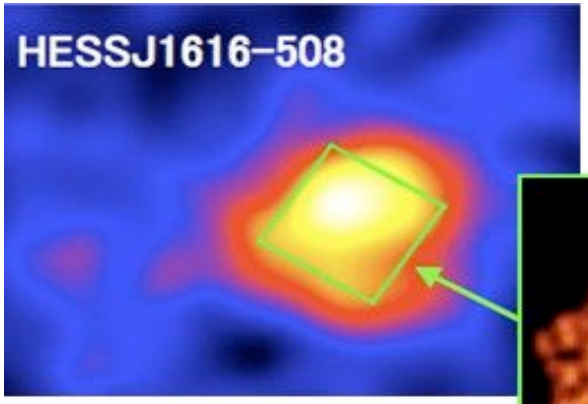
Aharonian+ 05 Sci., 06



2(+2?) SNRs
5(+2?) pulsar nebulae
3 X-ray binaries
1 Gal. Center

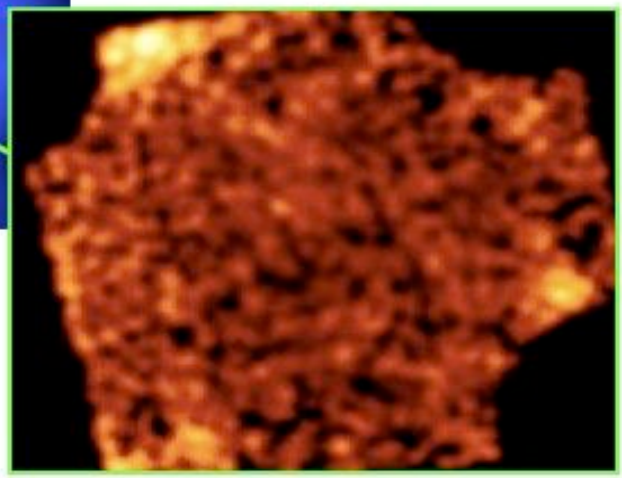
8 unidentified!

TeV unID sources: dark accelerators!



HESS

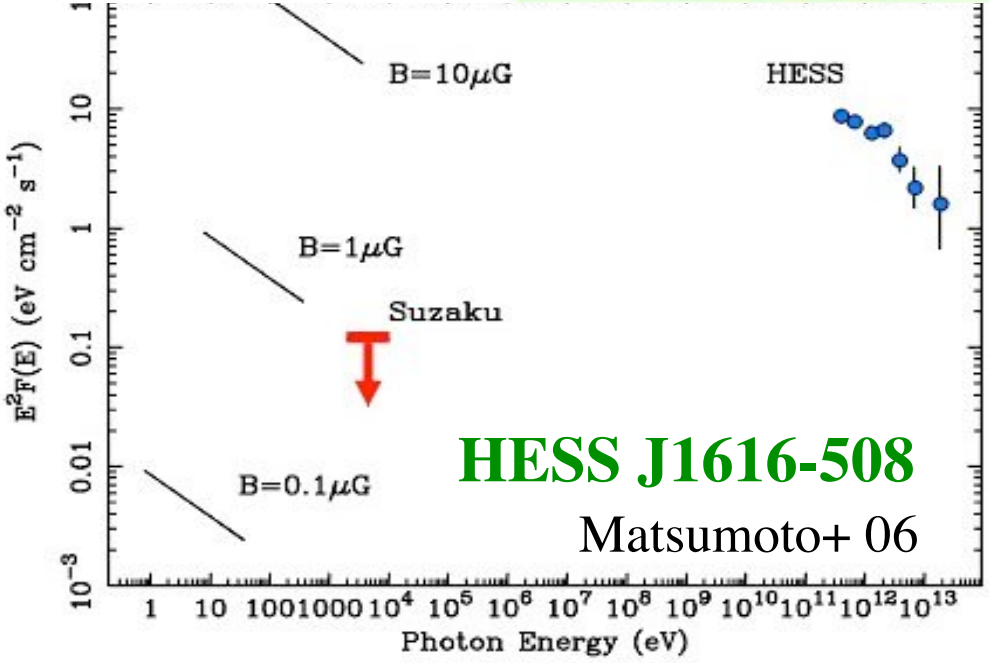
Suzaku



possibilities

- OB stellar winds+CRs
- old SNRs
- GRB remnants
- photoexcitation of CR nuclei
- dark matter

???



HESS J1616-508

Matsumoto+ 06

protons, hard spectra

→ true sources of Galactic CRs??

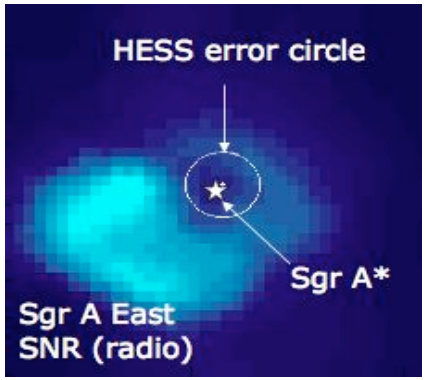
other TeV discoveries

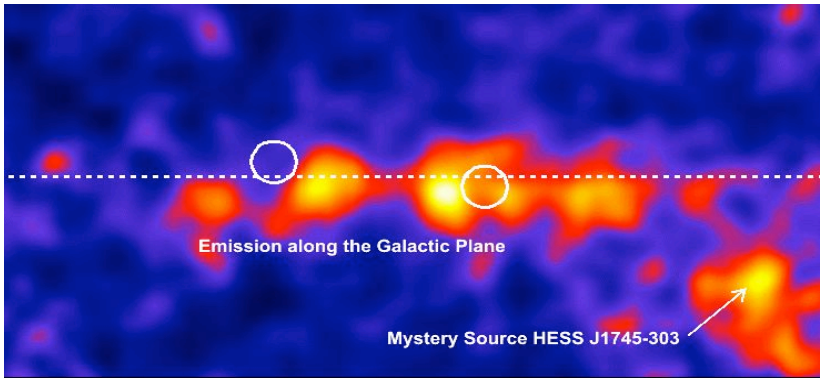
mostly HESS, also MAGIC

Galactic Center A+ 04, 06

origin?

dark matter ruled out





Galactic plane A+ 06 Nat.

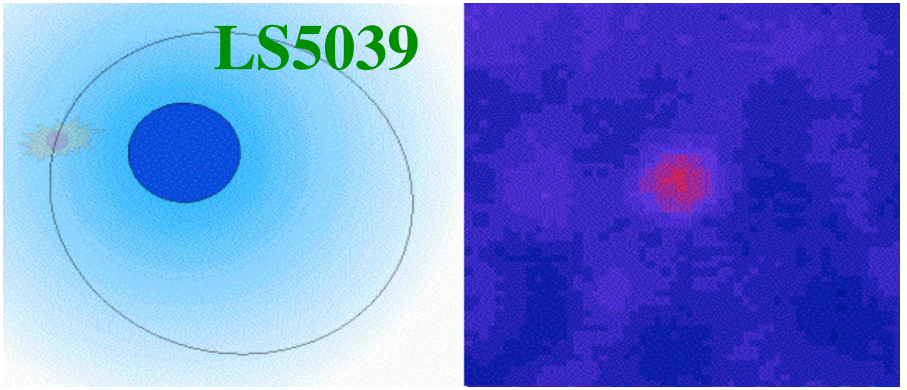
CR spectral variations

γ-ray binaries (microquasars) A+ 05 Sci., 06
Albert+ 06 Sci.

orbital modulation, pair absorption

BH (microblazar) or NS (wind nebulae)?

ν source?



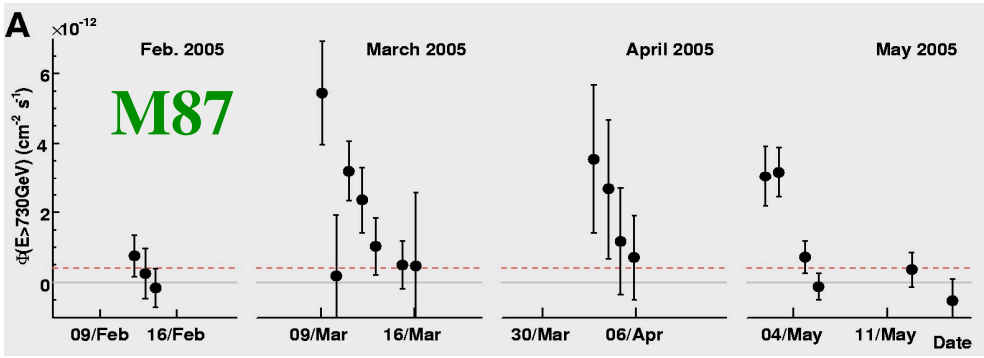
radio galaxy A+ 06 Sci.

surprisingly fast variability

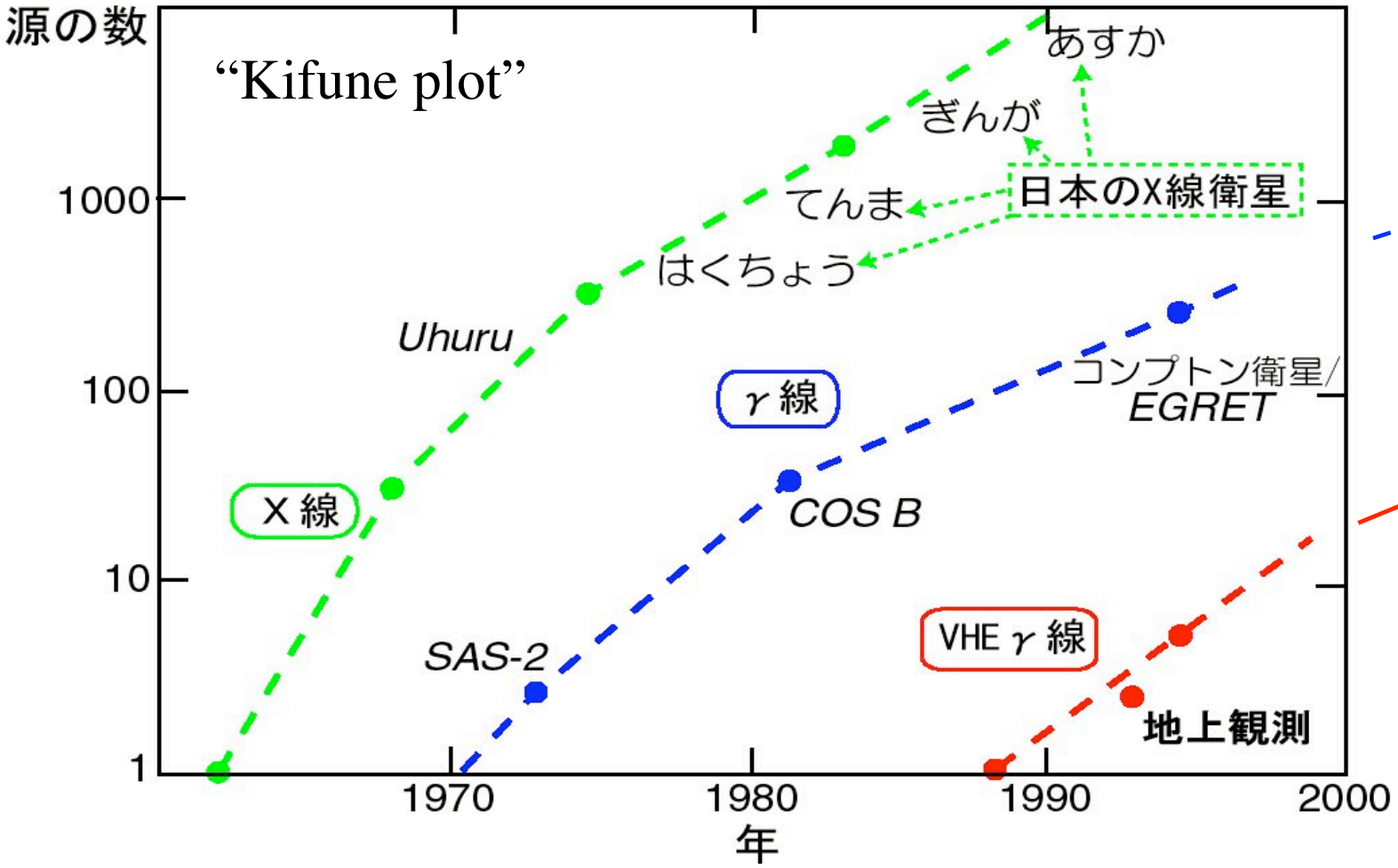
→ emission site few R_s?

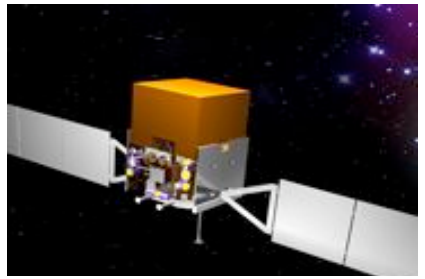
stellar winds A+ 07

p-p pi0 or e-IC?



progress forecast for high energy astronomy





? GLAST

HESS (II)

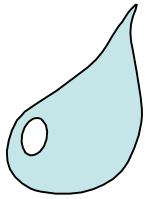
MAGIC (II)
CANG. III
VERITAS

20XX ?
UHECR?
neutrino?

http://www.mpi-hd.mpg.de/hfm/HESS/HESS.html

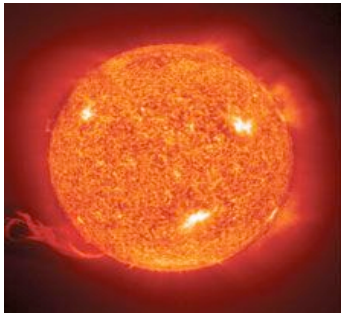
3. The nature of gamma-ray bursts

$$E=mc^2$$



=

原子爆弾



太陽
~10^{33}g

=

GRB
~10^{52}erg

太陽が一生かけて出すエネルギーを数秒で放出

GRBは宇宙一明るい謎の天体

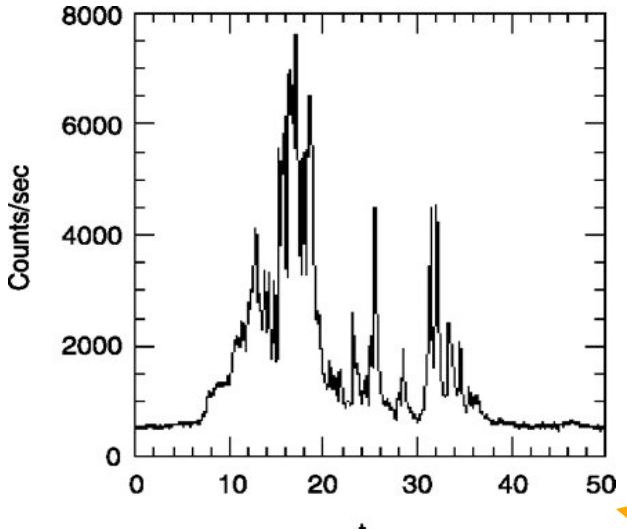
井岡氏より

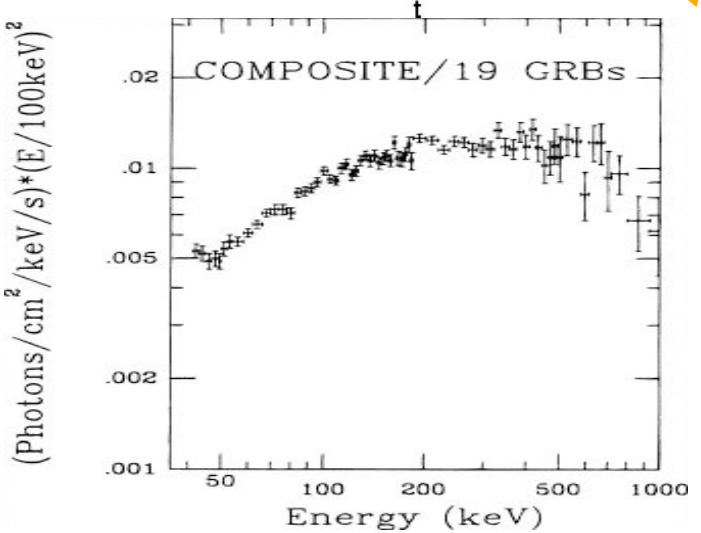
GRBs: emission properties

luminous $L_\gamma \sim 10^{52}$-$10^{54}\, f_\Omega$ erg/s (collimation $f_\Omega \sim 0.001$-0.01?)

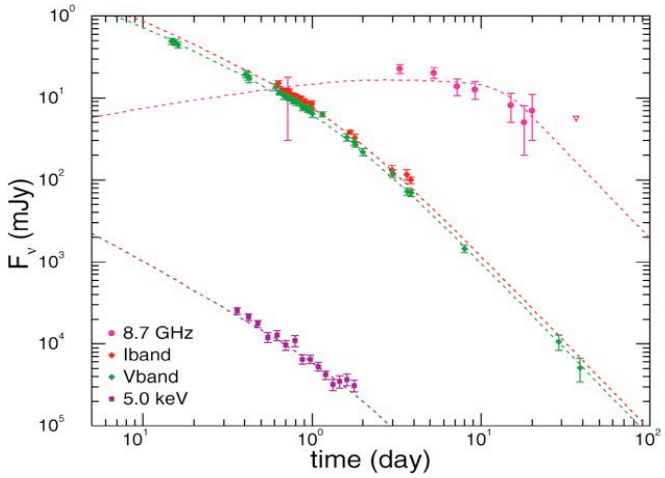
broadband radio-GeV γ-rays

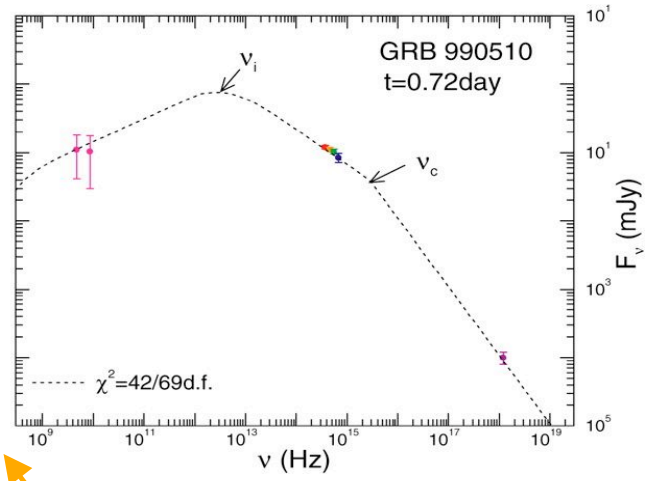
prompt emission





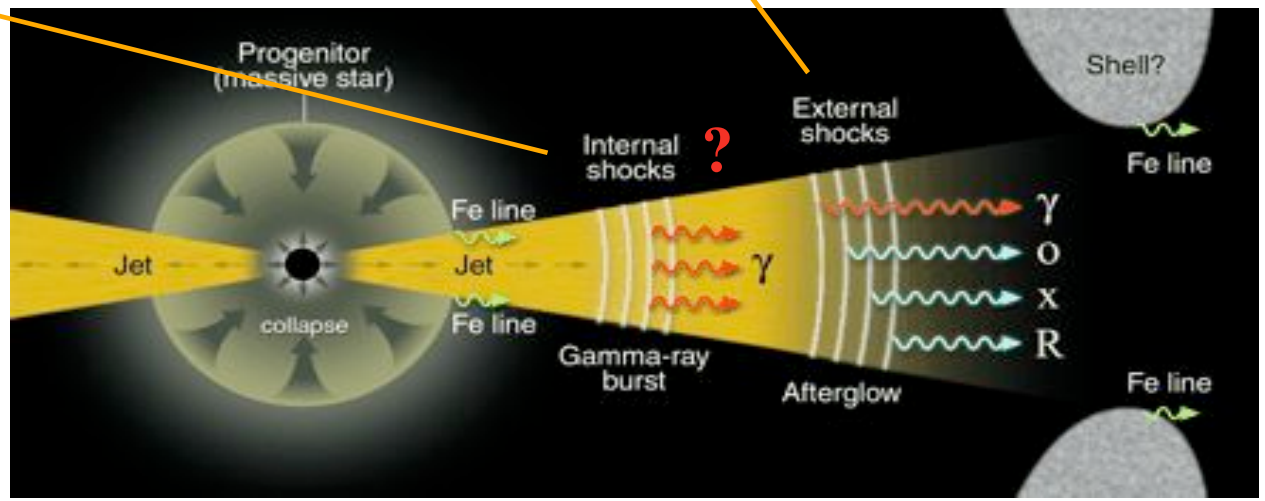
afterglow emission





internal shock?

external shock



Meszaros 01,02

GRB global properties

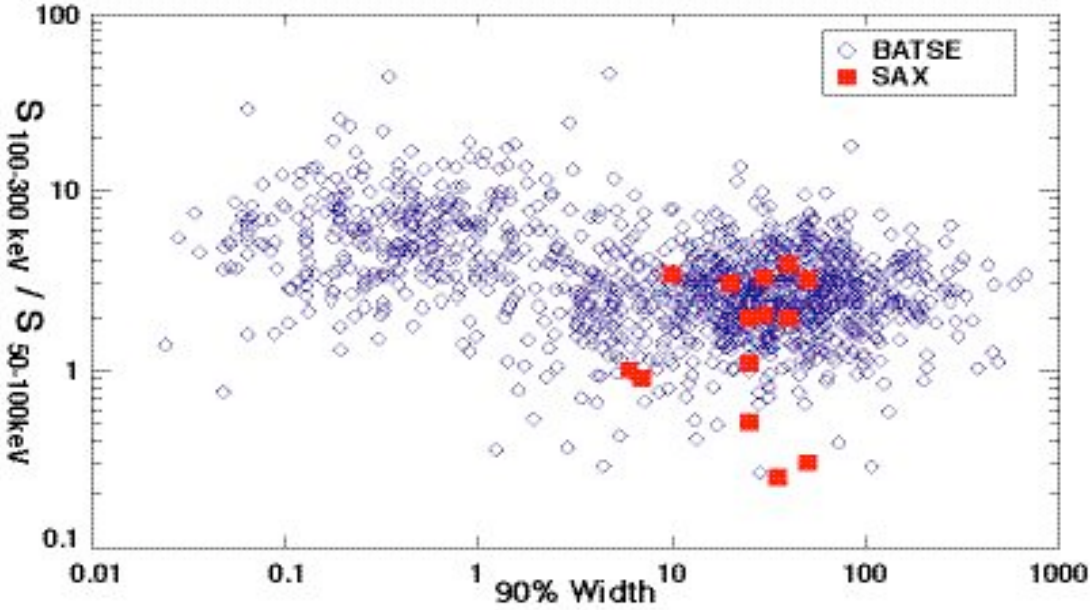
high-z ~0.2-6.3

event rate (z=0)~10^{-7} f_{Ω}^{-1} /yr/gal

~0.001-0.01 xSN?

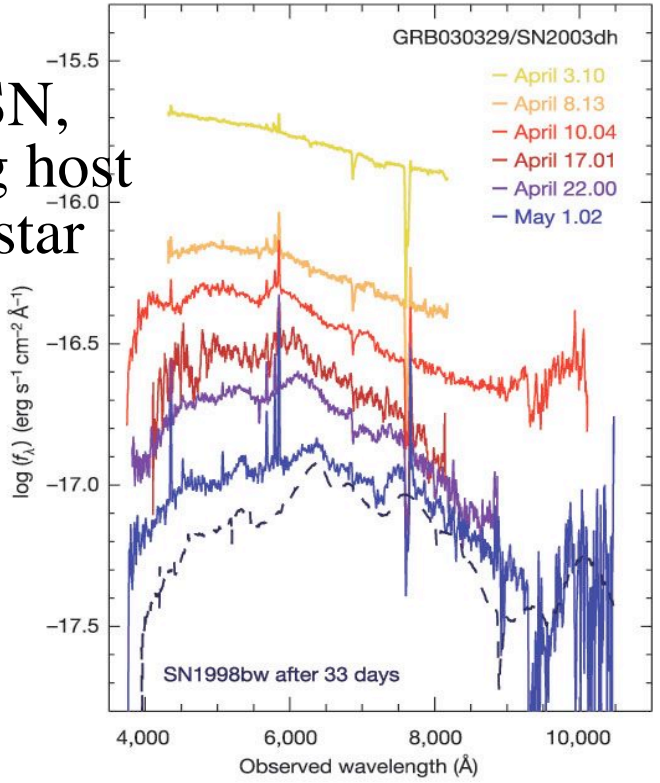
long-soft/short-hard dichotomy

otherwise very diverse



pre-SWIFT view of (long) GRBs

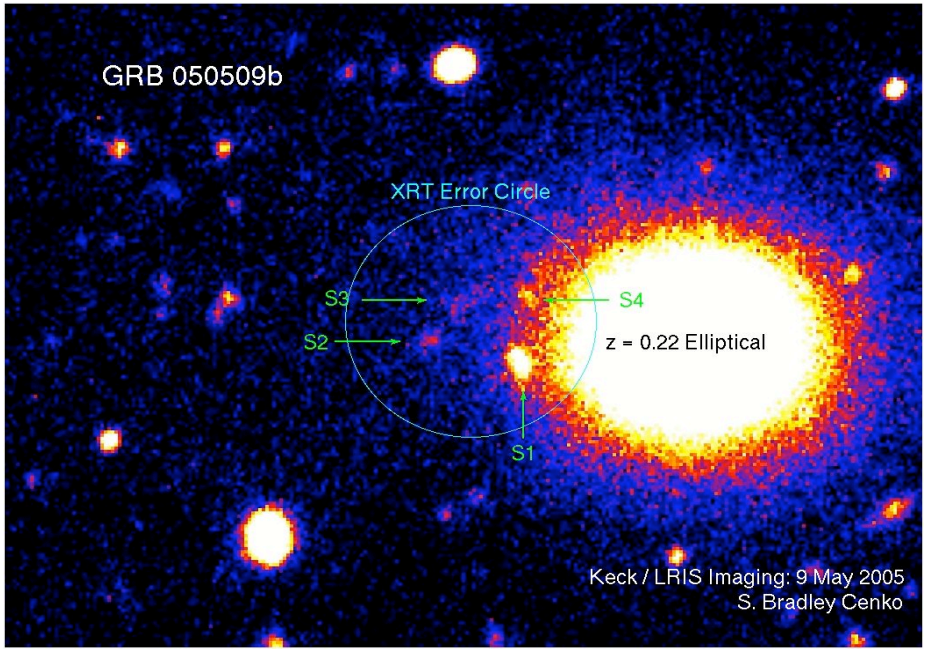
coincident SN, star-forming host → massive star collapse



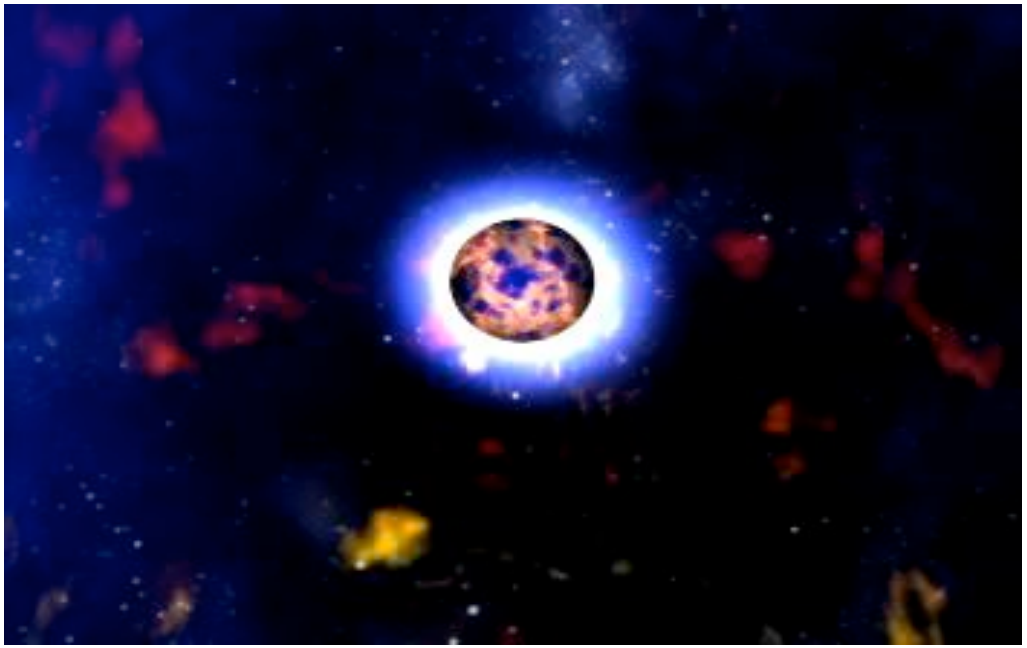
short GRBs with SWIFT

for at least some:
elliptical host
z<<1, low L
no SN
low surrounding n

→ **compact binary mergers**
gravitational wave connection



Gehrels+ 05 Nat.
Fox+ 05 Nat.
Berger+ 05 Nat.
etc.



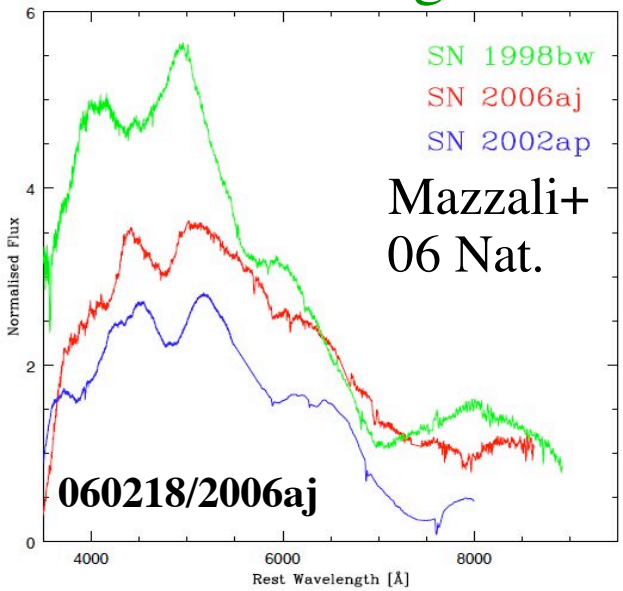
BUT

high-z short GRBs

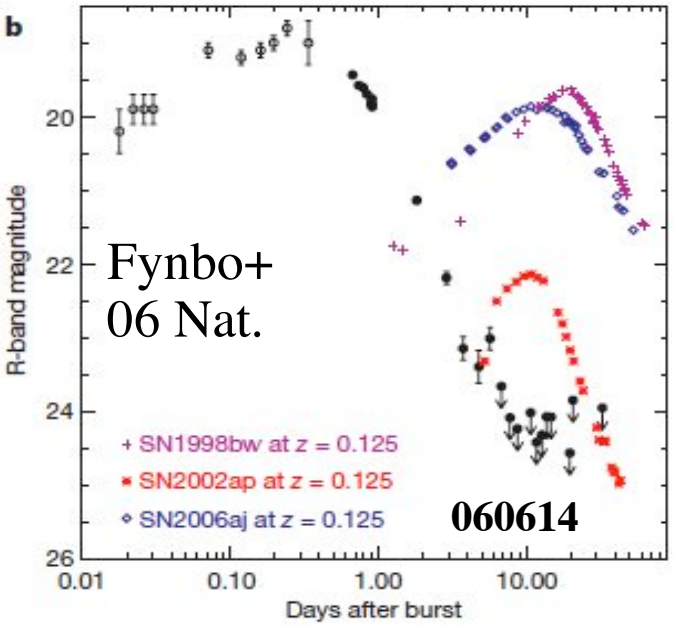
long short GRBs

surprises (chaos) with SWIFT

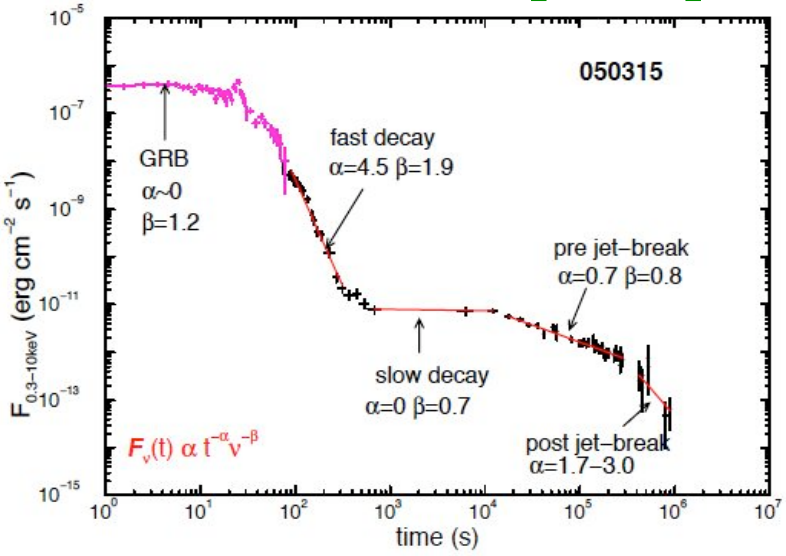
NS-SN GRB magnetar?



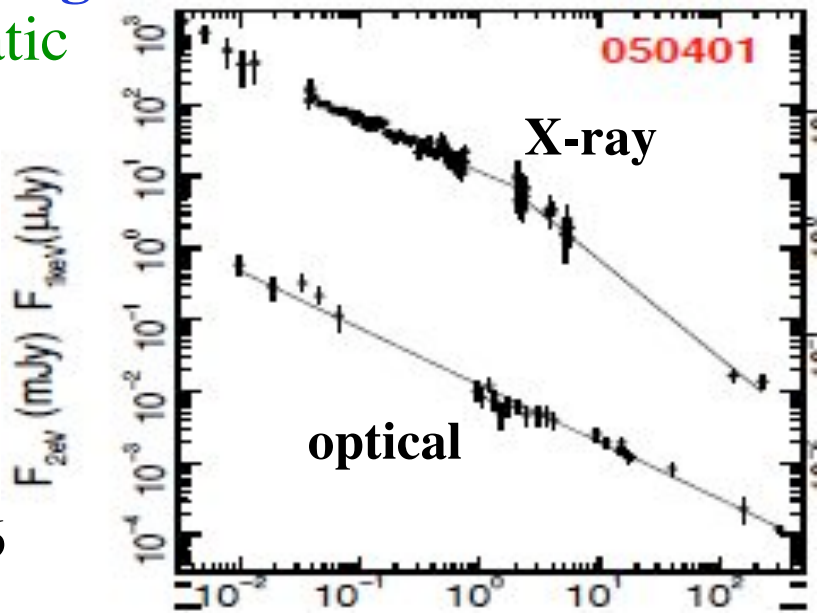
SN-less GRB dark hypernovae?



early afterglow steep-flat phase



late afterglow chromatic breaks



Panaitescu 06

GRBs in the SWIFT era: what is clear?

- **(some) short GRBs different from long GRBs**

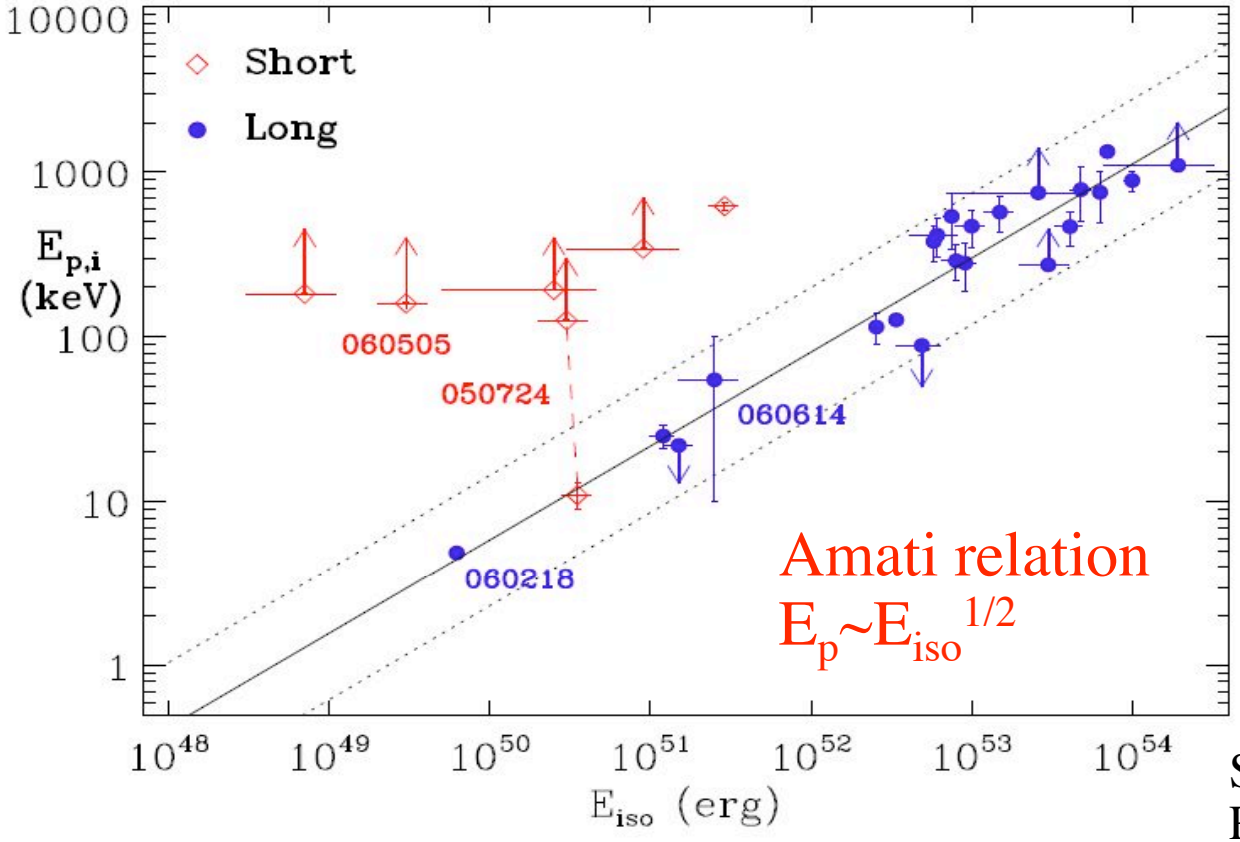
- **GRBs not as simple as once thought**
  (high-z/long short GRBs, NS-SN GRBs, SN-less GRBs,
  early steep-flat decay, chromatic breaks…)

- **GRBs promising as high-z probes**

GRB prompt emission: unsolved mystery

luminosity correlations (=distance indicators)

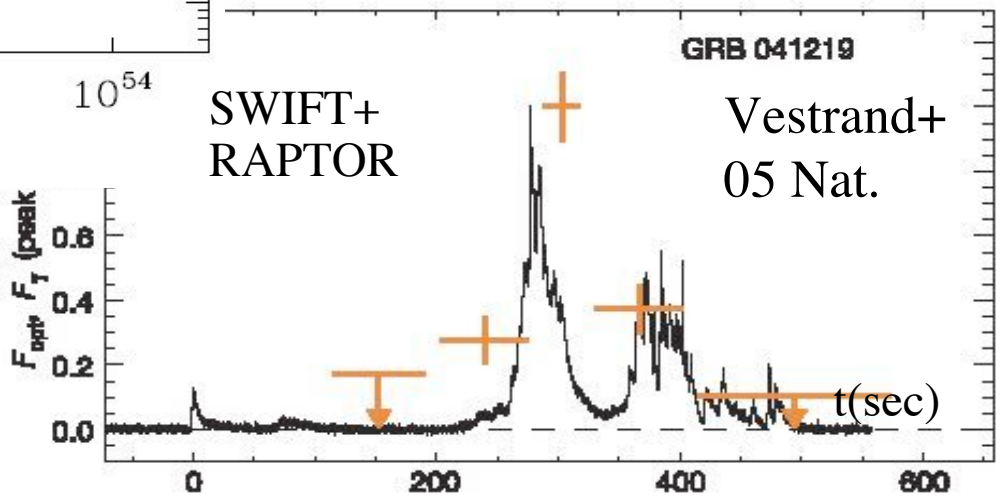
energy dissipation?
emission process?



cannot be explained easily with "standard" internal shock sync.

also crucial for cosmology

optical emission

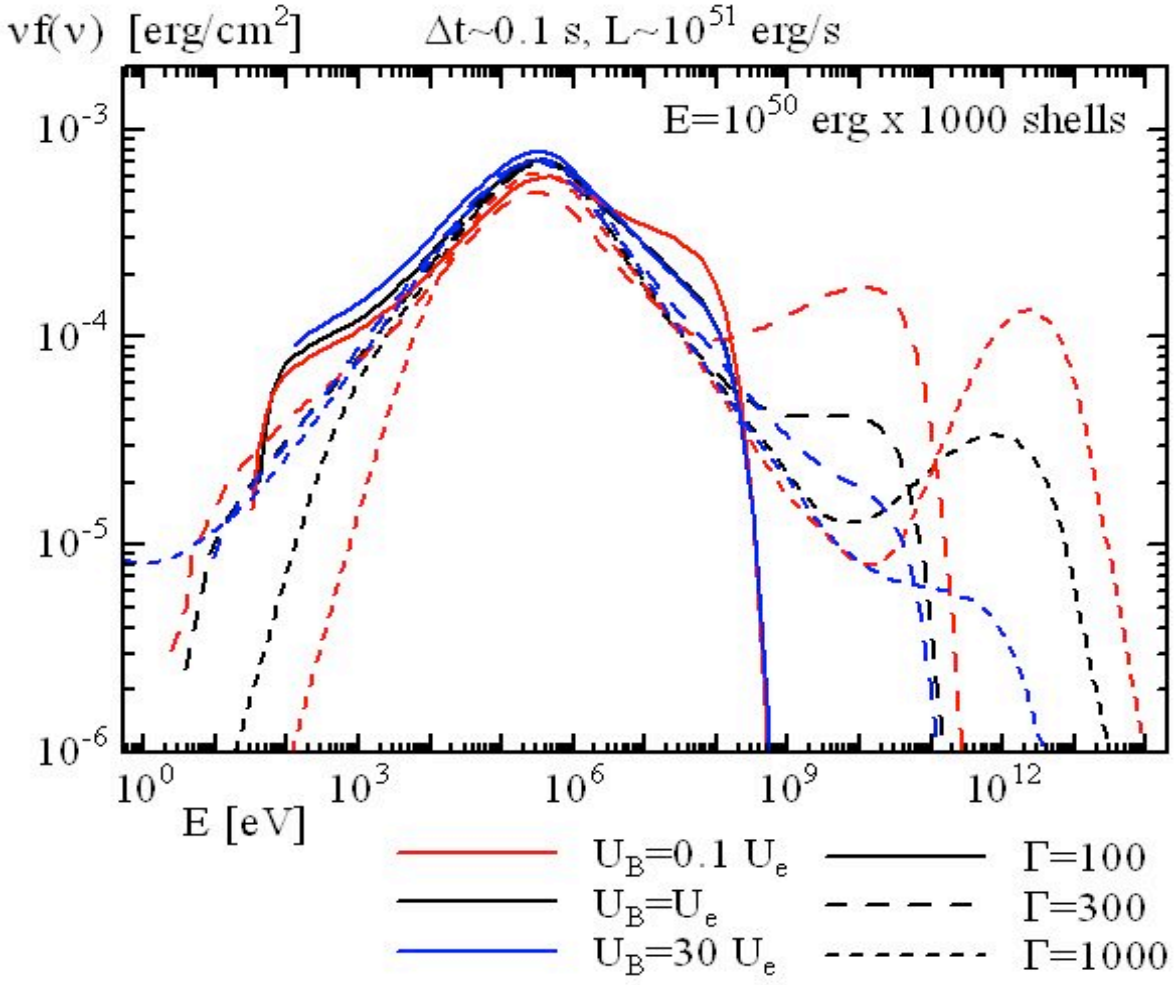


need broadband observations!

GeV-TeV, IR, radio, neutrino…

prompt GeV-TeV: expectations

Asano & SI, in prep.

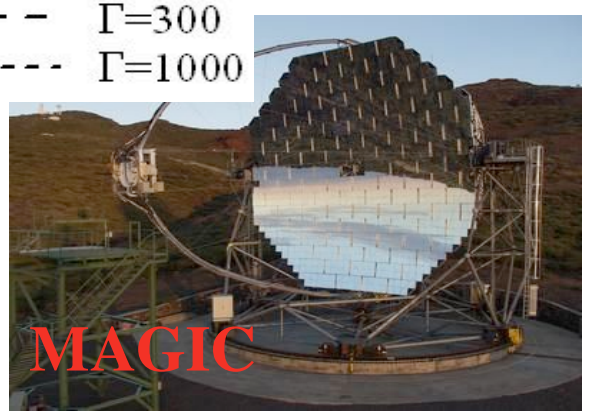


models with hadronic processes, pair cascading

determine Γ, B

test UHECR accel.

ν production



4. high energy cosmology (probing the universe at HE)

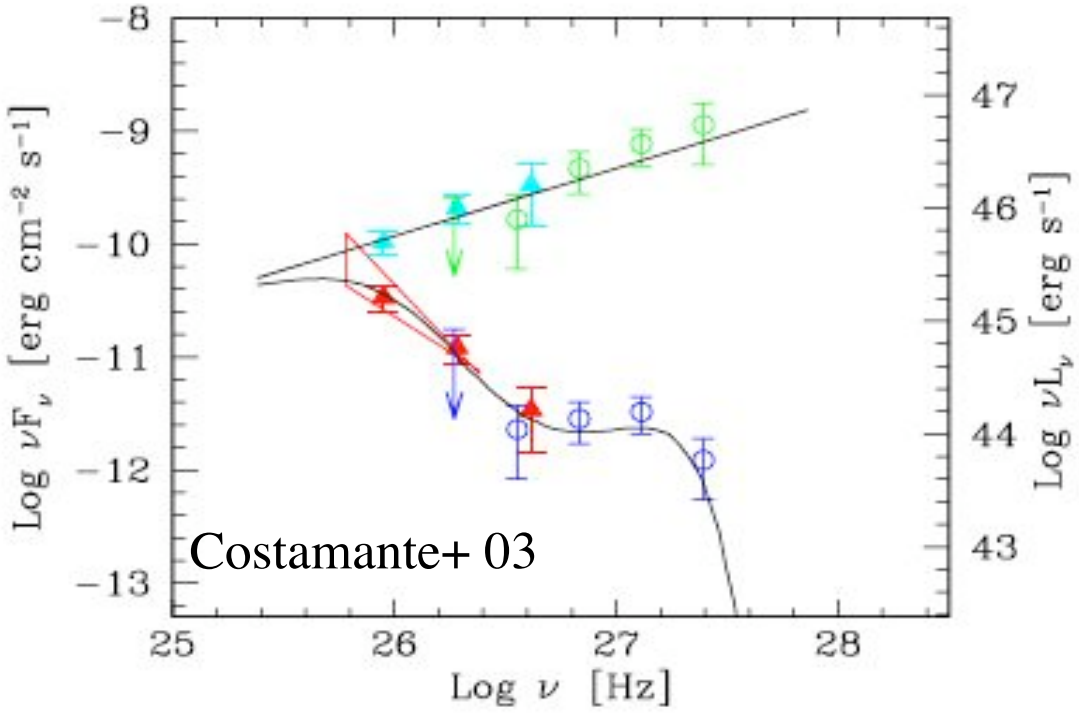
gamma-ray "absorption": probe of diffuse radiation fields

$\gamma + \gamma \rightarrow e^+ + e^-$

E ε

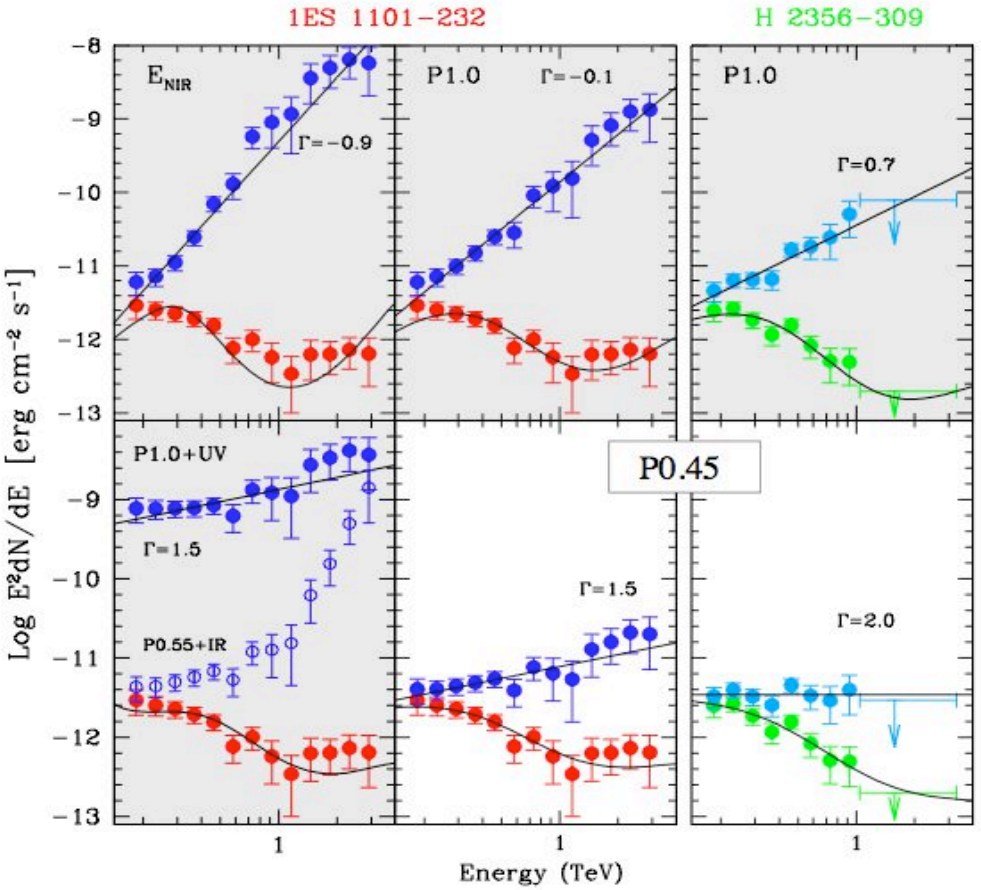
e.g. TeV + 1eV (IR)

100 GeV + 10 eV (UV)

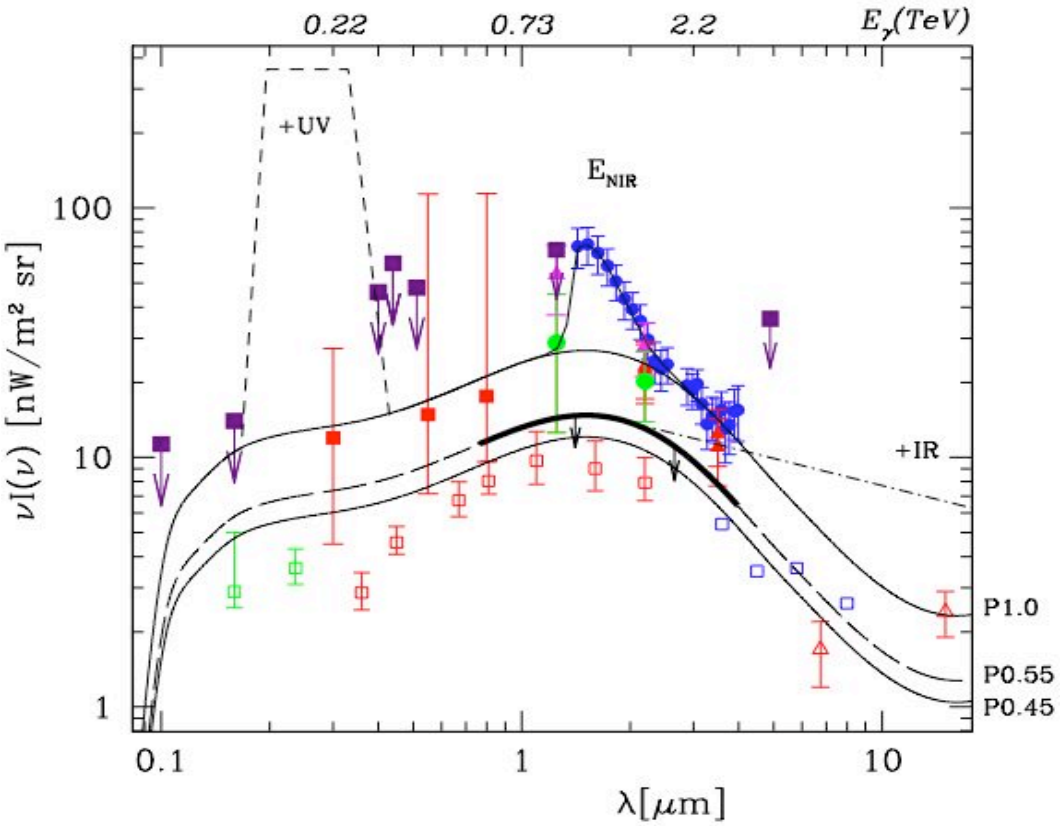


probing local IR background with gamma-ray absorption

γ-ray absorption in blazars at z=0.165, 0.186 (highest to date)



Aharonian+ 06 Nat.

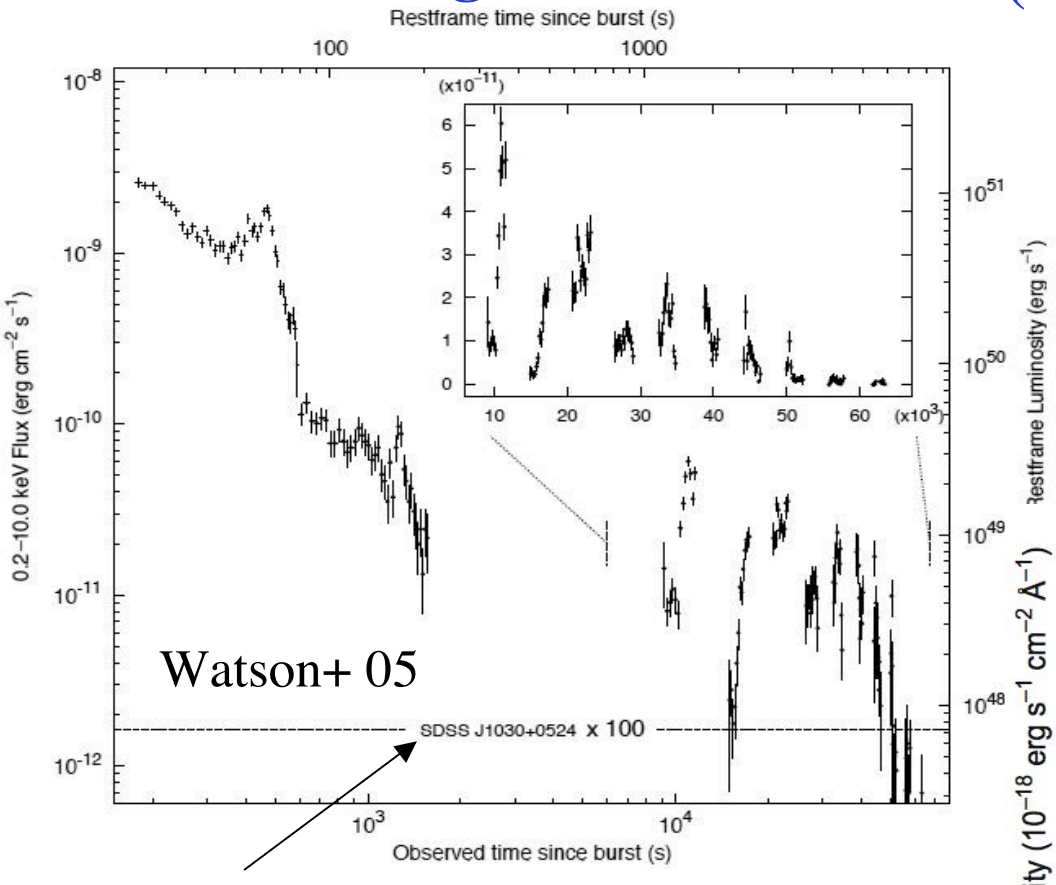


- **strongly rules out NIR peak**
- **probably little "missing light"**

no strong Pop III <-> Matsumoto+ Kashlinsky+

GRB050904 z=6.295!!!

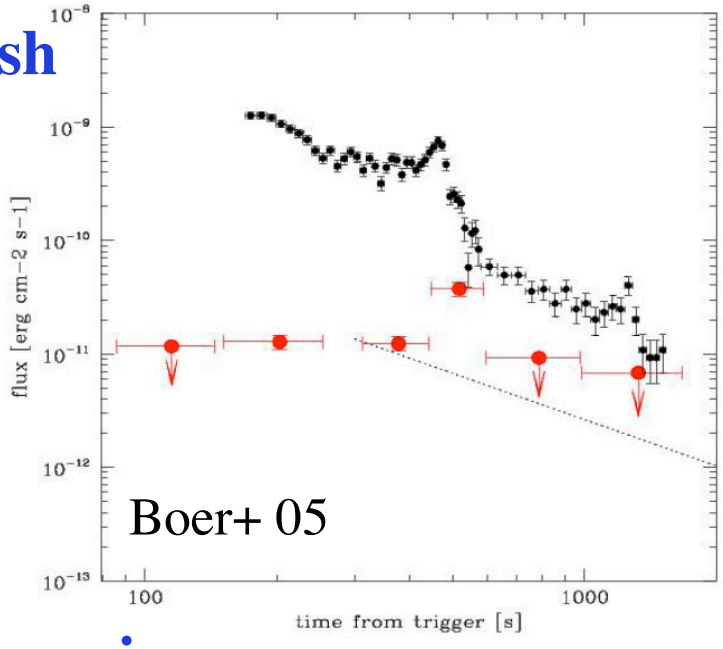
SWIFT/XRT light curve



Watson+ 05

100x flux of quasar at same z

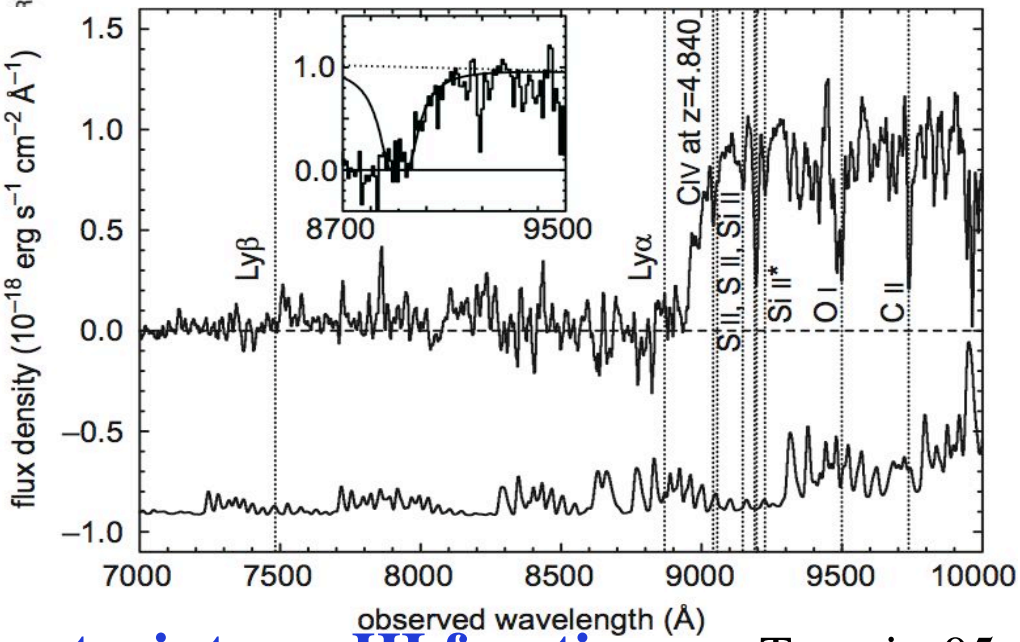
optical flash TAROT (25cm!)



Boer+ 05

Subaru spectroscopic z

Kawai+ 05 Nat.

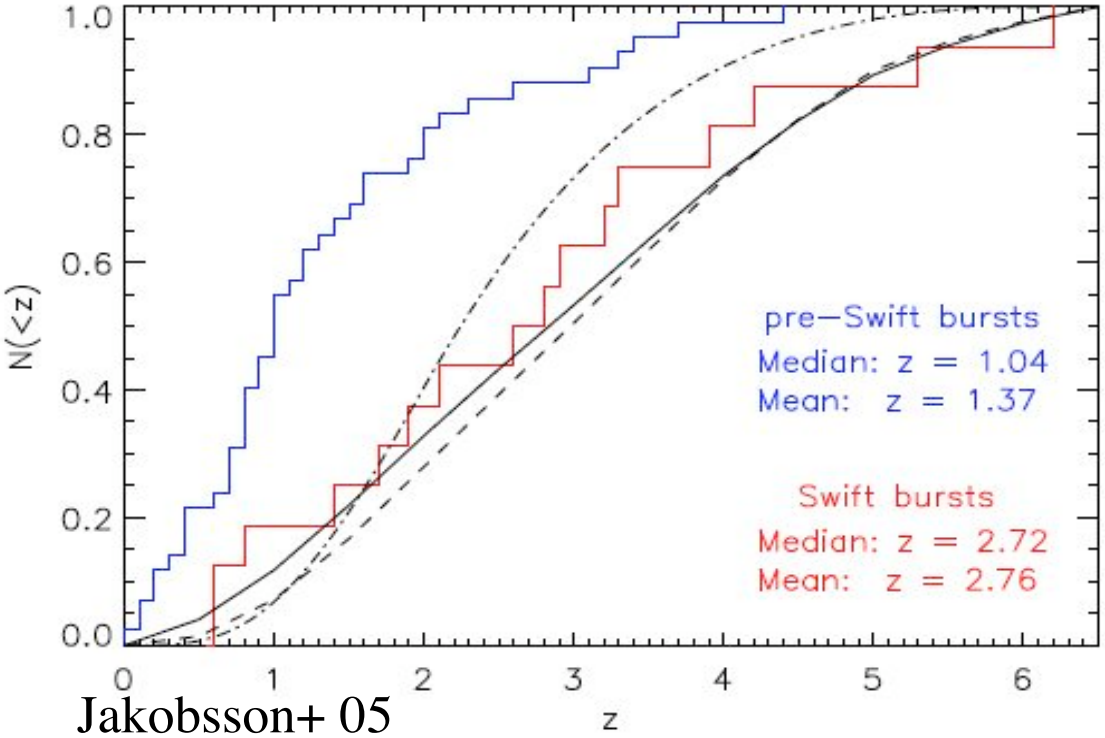


new constraints on HI fraction

Totani+ 05

GRBs at very high z: expectations

observed z-distribution of SWIFT bursts



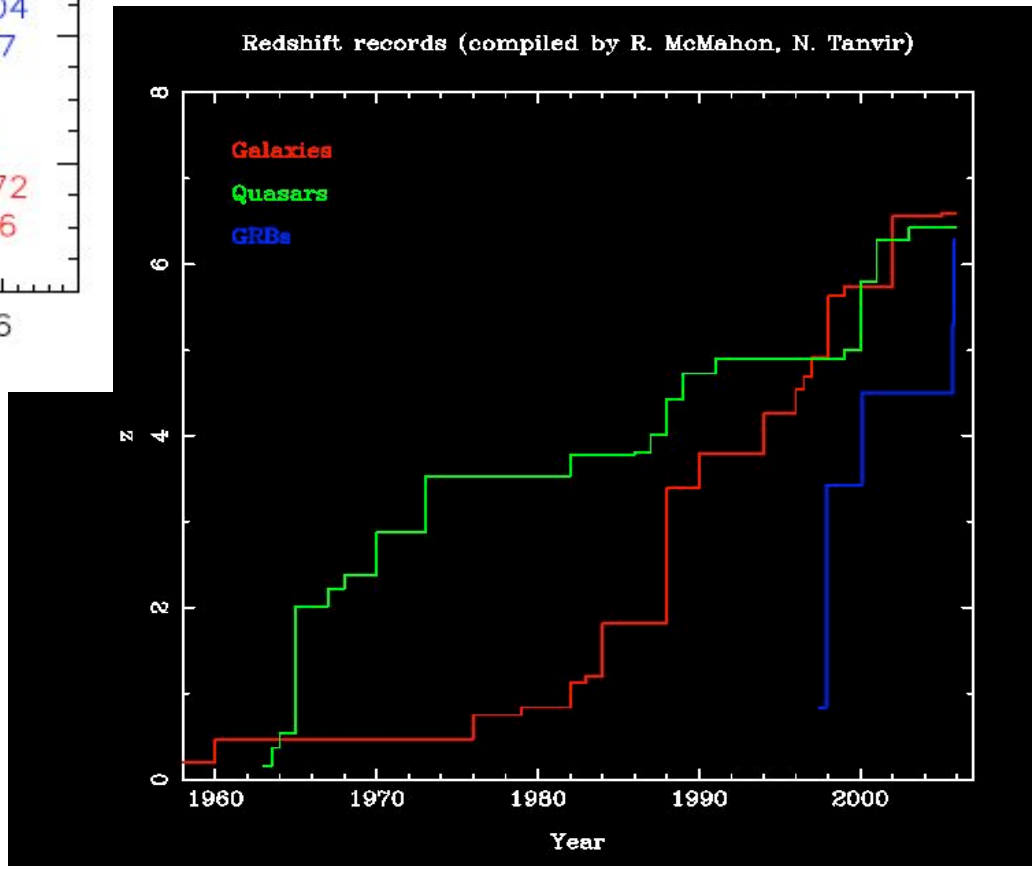
Jakobsson+ 05

- **mean z=2.8**
- **fraction at z>5 7-40%**

Bromm & Loeb 02, 05

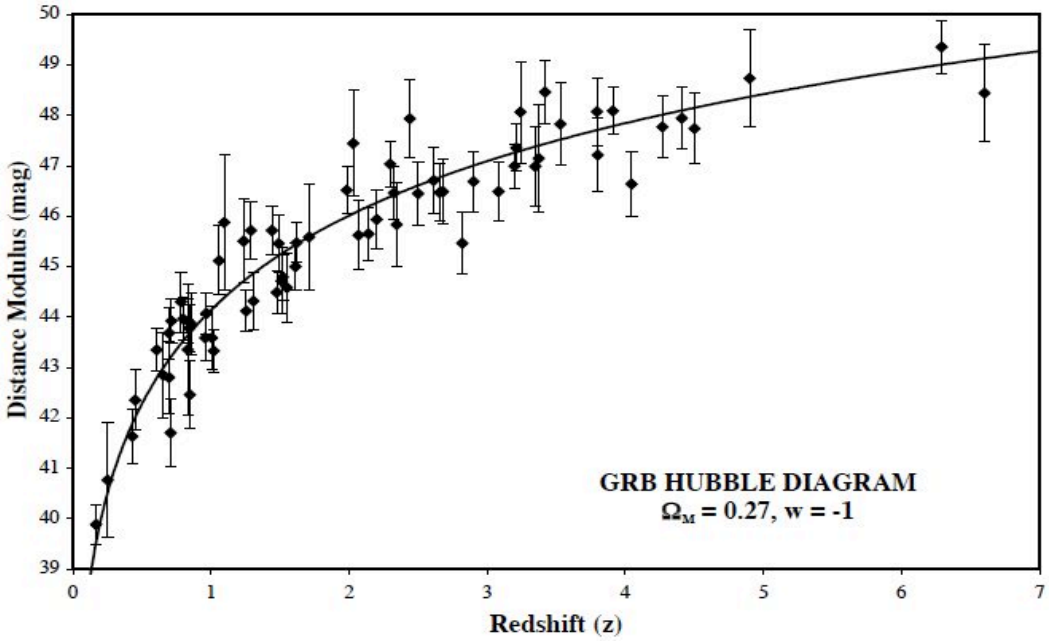
- **model predictions rate(z>10)~1-10/yr?**

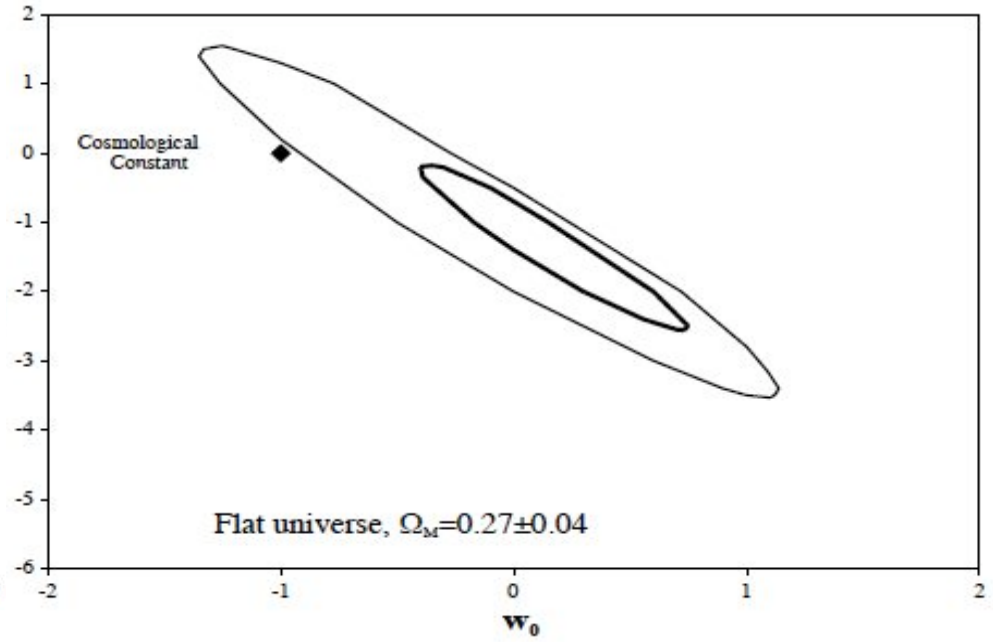
history of record redshifts



GRBs as dark energy probe?

e.g. Schaefer astro-ph/0612285





problems with distance indicators:

1. unclear selection effects

2. no physical basis!

⇔ SNIa

GRBs as star formation rate indicators

GRBs as signposts for high-z (low metal.) galaxies

GRBs as broadband beacons: probing the dark ages

GeV: UV background from pair absorption

SI, Salvaterra, Choudhury, Schneider, Ciardi, Ferrara, in prep.

GeV: weak intergalactic B field from delayed secondary emission

Ichiki, Takahashi, SI, in prep.

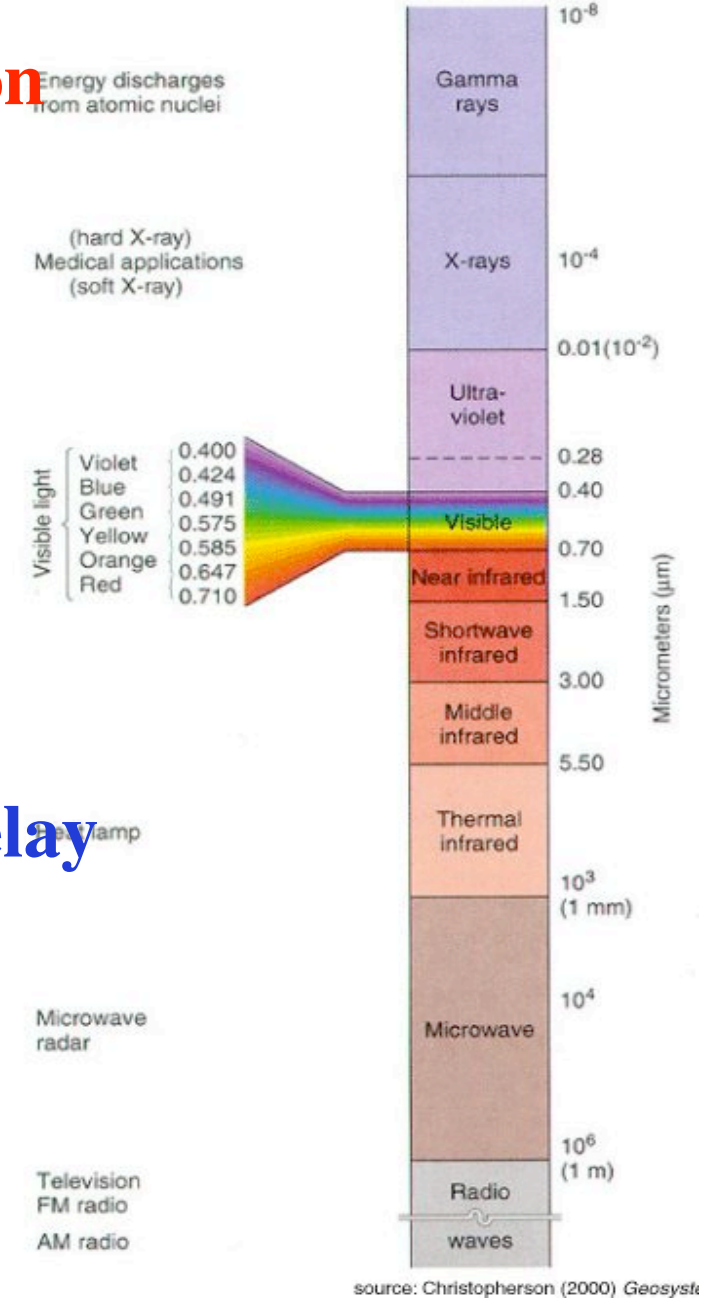
radio-submm: star-forming gas from atomic/molecular absorption lines

SI, Omukai, Ciardi 06

LF radio: ionized IGM from dispersion delay

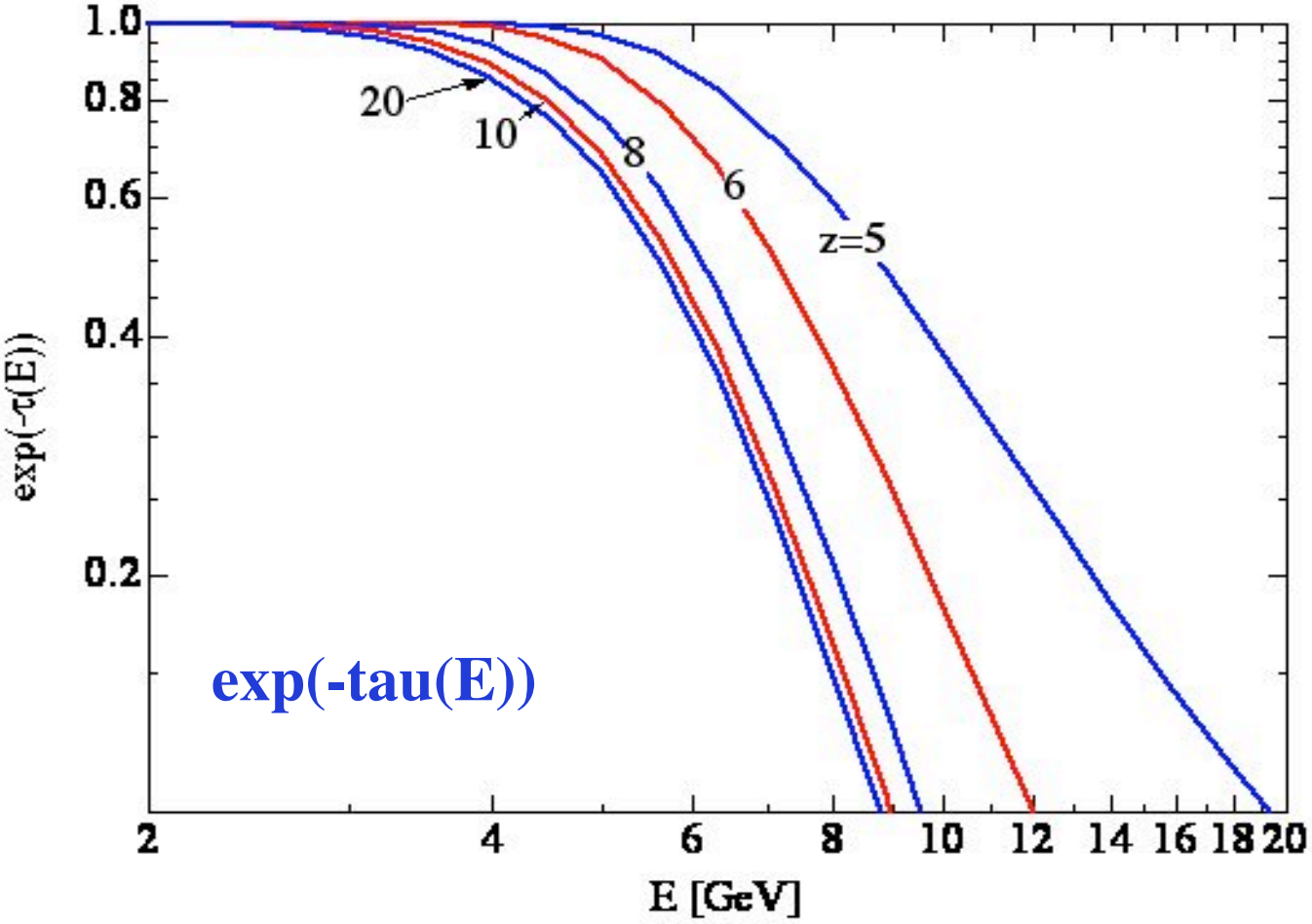
SI04, Ioka 03

others
NIR: IGM HI from Lyα damping wing
metal evolution from absorption lines
X: WHIM from absorption lines
radio: HI from 21cm absorption
…



probing high-z UV background with pair absorption

SI, Salvaterra, Choudhury, Schneider, Ciardi, Ferrara, in prep.



GRB GeV

bright GRBs
z~<10 with GLAST
typical GRBs
z>~30 with 5@5

high-z UV model

Choudhury & Ferrara 05, 06

consistent with
WMAP3, x_{HI}, HUDF NIR…

significant opt. depth from z~5-8 at several GeV
→ important info on UV at reionization epoch
but not much effect above z~8

GLAST

dark matter

If GLAST sees, discovery of the century!

If GLAST doesn't see, no problem for anyone (including those who say it will).

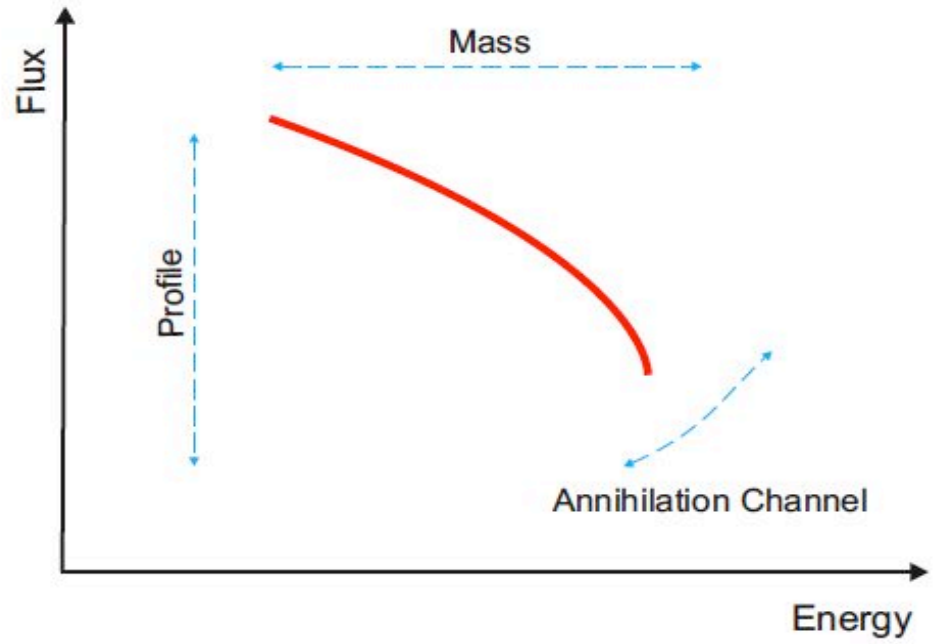


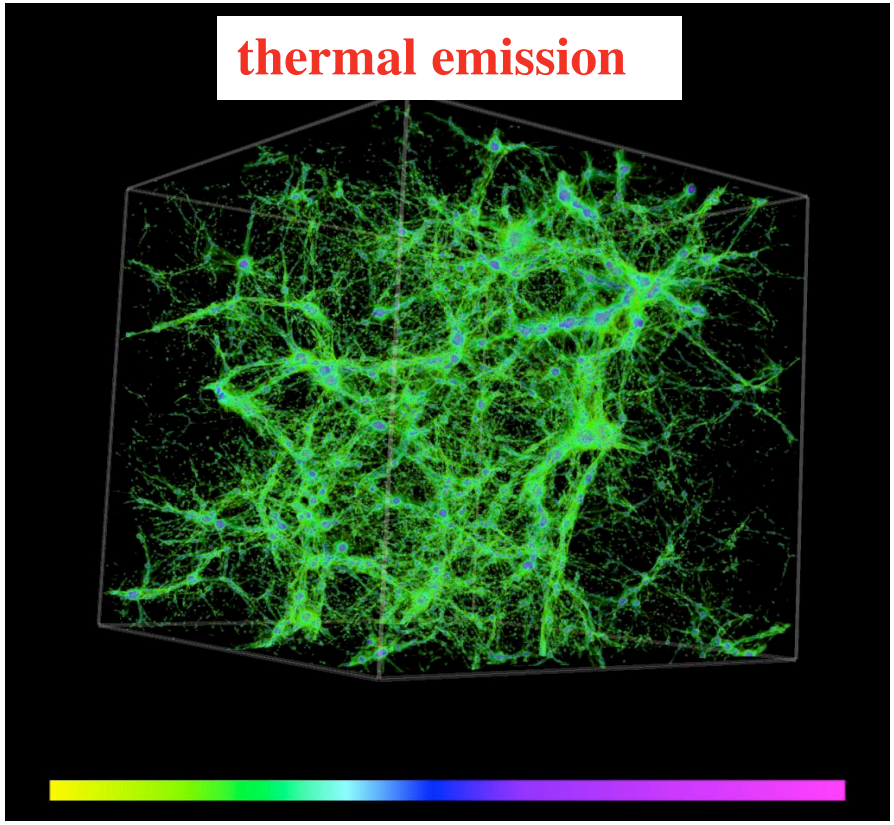
Fig. 1 The problem with indirect searches: the lack of constraints on the mass scale, the profile and the leading annihilation channel, leads to uncertainties on the energy scale and on the spectrum normalization and shape respectively.

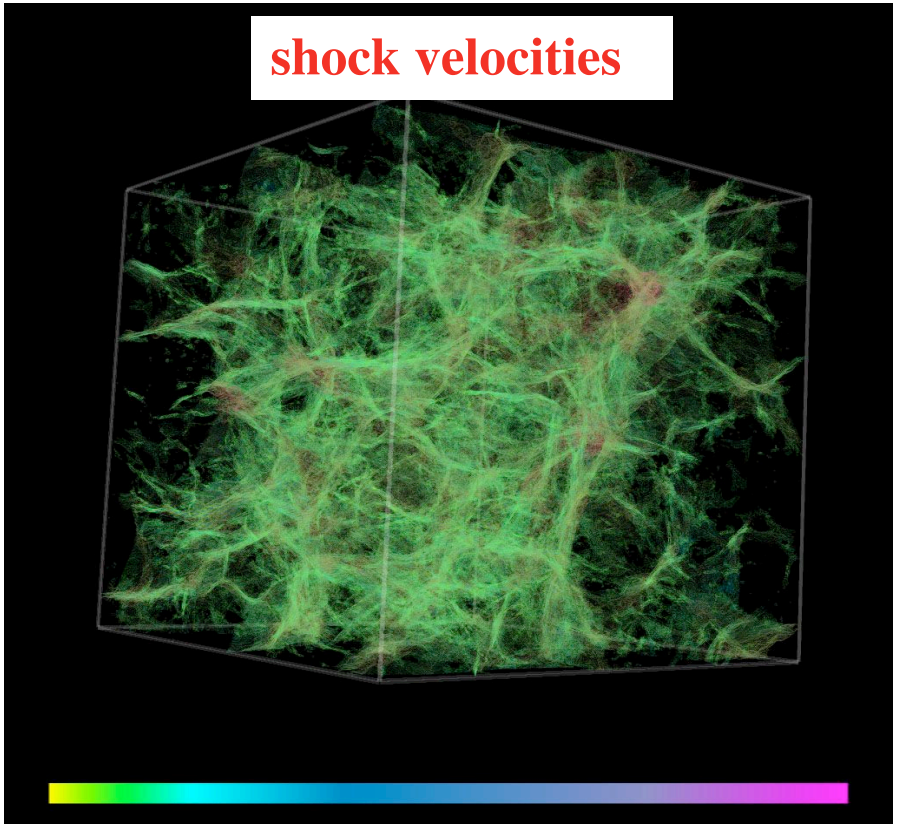
Bertone 06

5. large-scale high energy astrophysics

large scale structure formation (SF) shocks

formation of galaxies, groups, clusters...
= hierarchical, dark matter-driven mergers and accretion
→ shock formation → gas heating **+** particle acceleration
→ nonthermal radiation

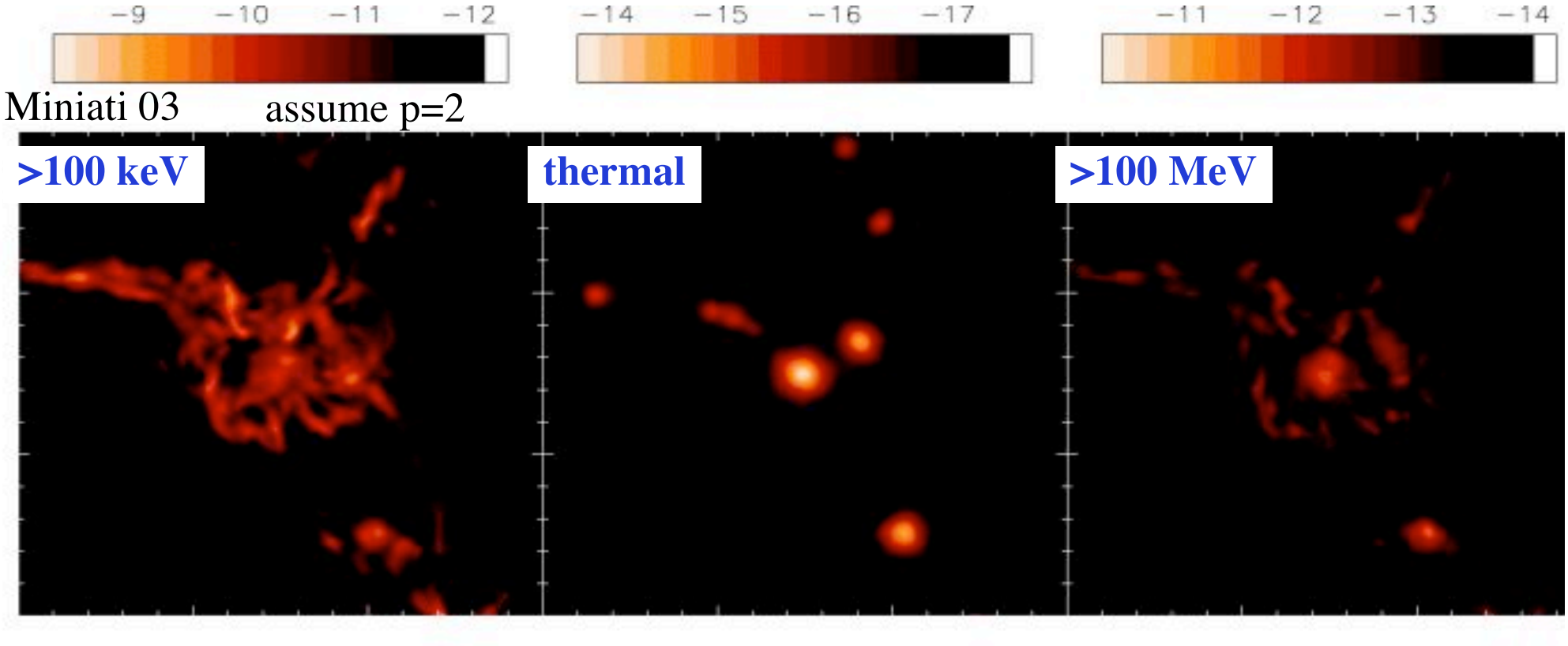




cosmological hydro simulations by Ryu+ 03

expected high energy emission from clusters

- primary electron IC — traces shock — $t_{IC} << t_{shock}$ — e.g. Waxman & Loeb 00, Totani & Kitayama 00
- LE proton p+p->π_0 — traces gas — $t_{loss}, t_{conf} >> t_H$ — e.g. Völk+ 96, Berezinsky+ 97

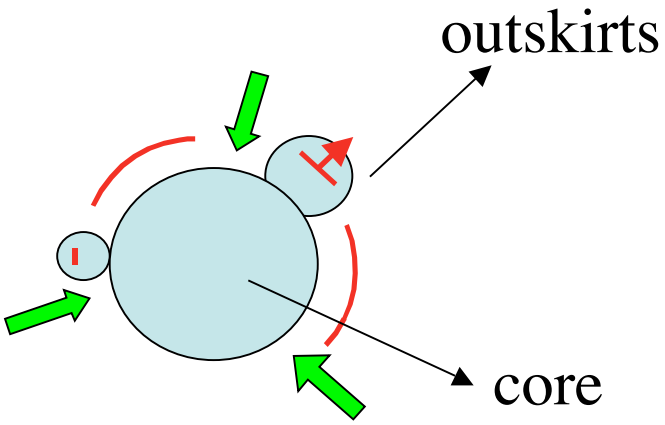


+ • **UHE proton-induced pair syn.+IC** — **SI, Aharonian, Sugiyama 05**

gamma-rays from clusters: expectations

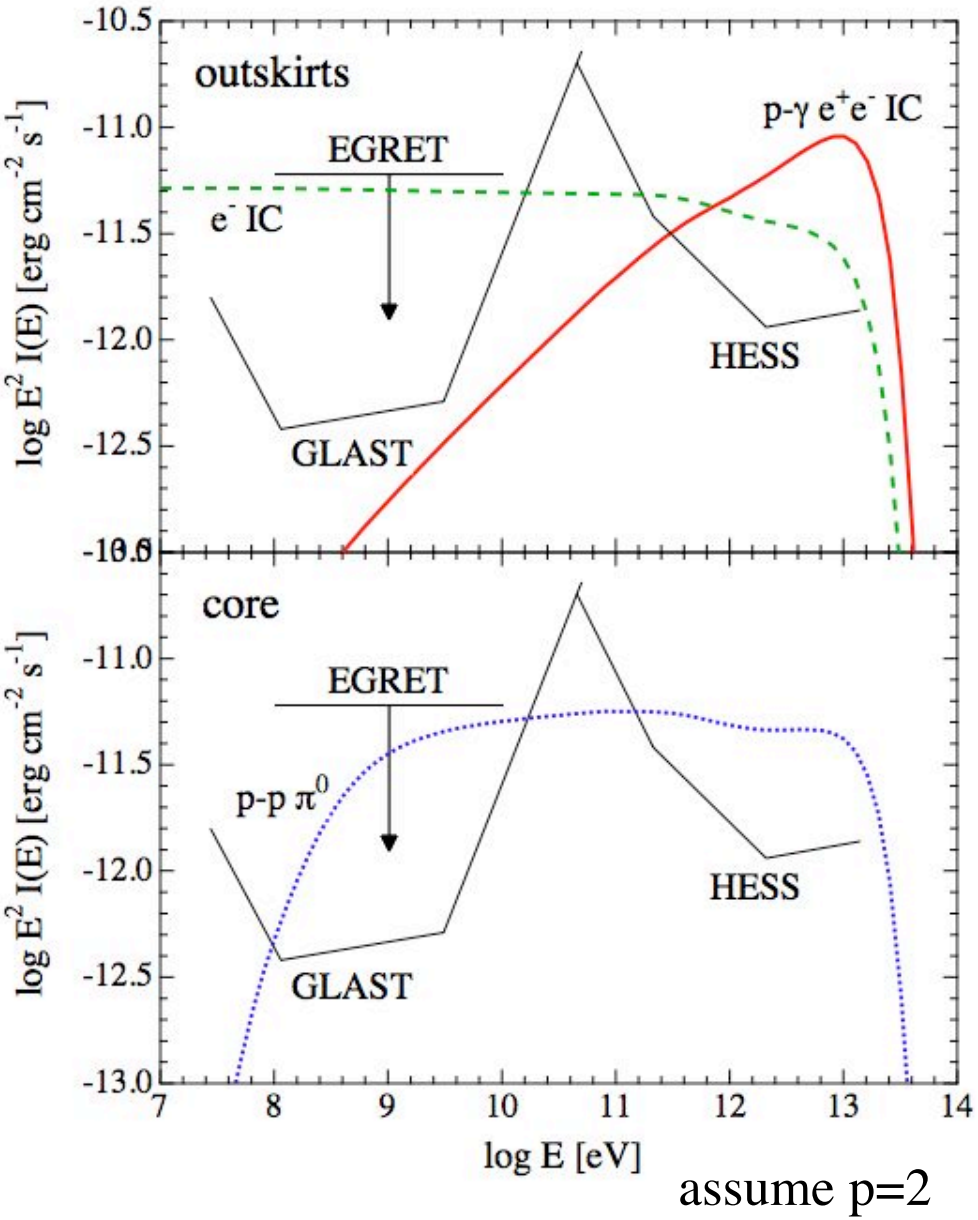
SI, Gabici, Aharonian, Rowell

HESS proposal, accepted



different processes should dominate at different energy, location

assume ξ_e=0.01

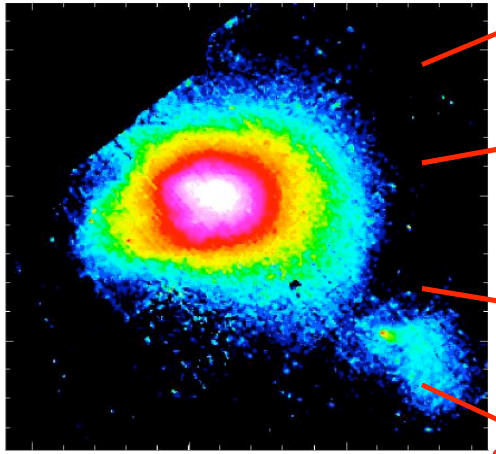


assume p=2

ongoing/future observations of clusters

TeV **SI, Gabici, Aharonian, Rowell,** HESS proposal
observations under way!

hard X **Nakazawa+**, Suzaku observations of A3667
SI, Nakazawa, Fukazawa+, Suzaku AO-2 proposal, submitted

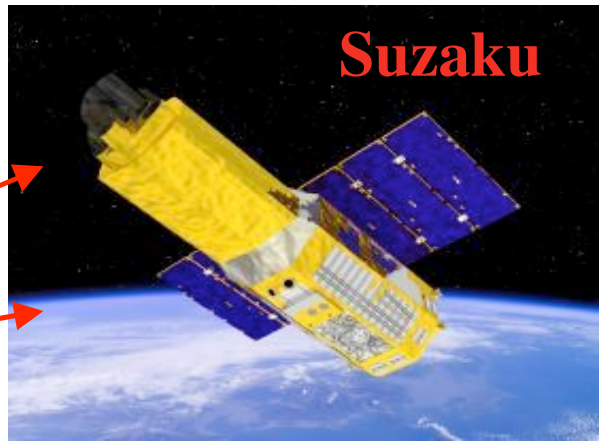


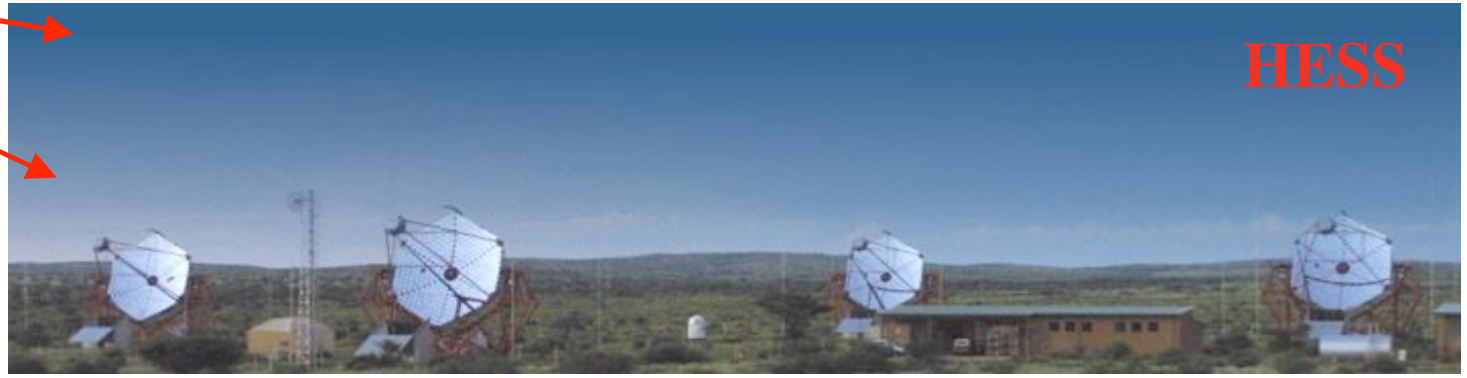
X

X

γ

γ





GeV GLAST

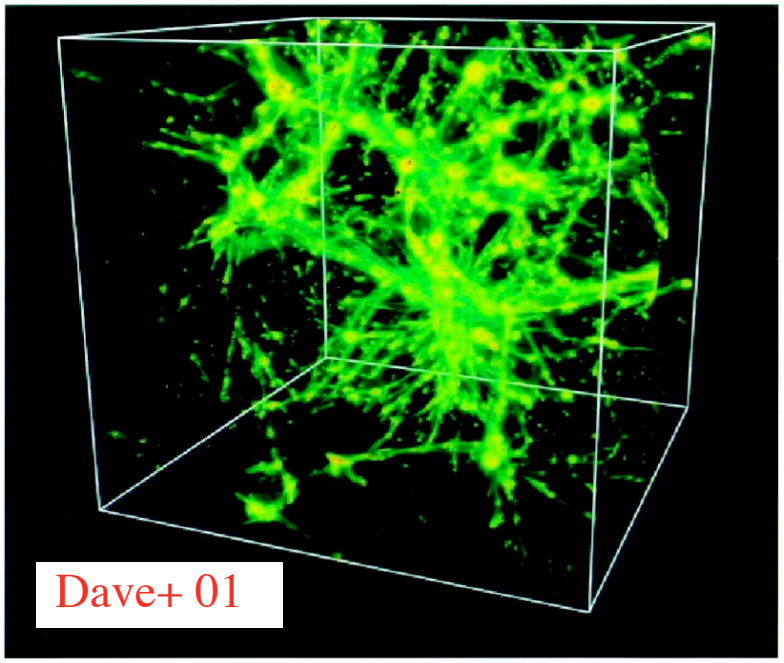
hard X imaging NeXT

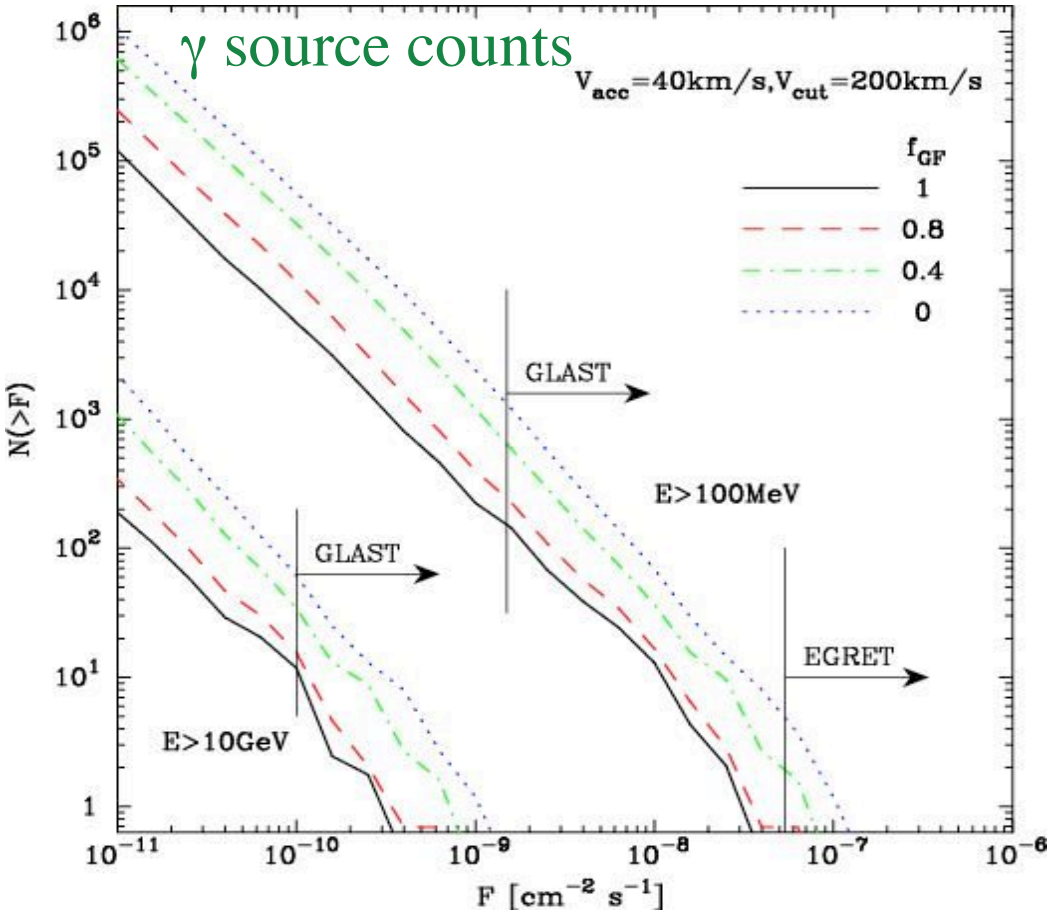
probing structure formation with gamma-rays: warm-hot IGM (missing baryons)

SI & Nagashima, in prep.
(see also astro-ph/0502338)

SF shocks → **WHIM** **DIOS**

$e^- + \gamma_{CMB} \rightarrow e^- + \gamma$ **GLAST**





baryon condensation into stars
-> shock suppression affects
γ-ray source statistics,
contribution to γ background

important constraint on WHIM,
complementary to thermal lines

LiBeB archaeology: CR activity in the early Galaxy

light element production by CRs

p, α + C,N,O → ^{7}Li, ^{6}Li , Be, B + …

α + α → ^{7}Li, ^{6}Li + …

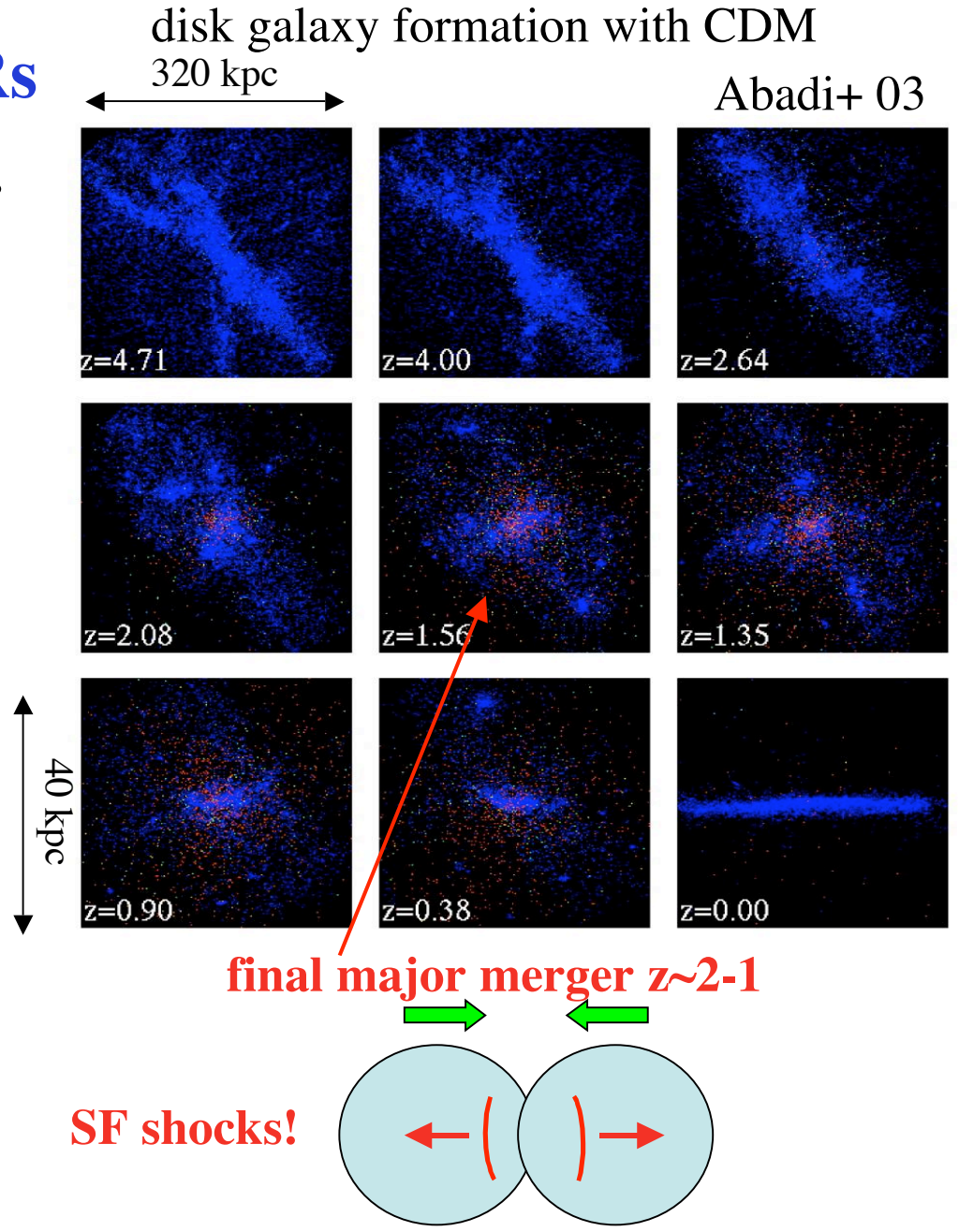
LiBeB in metal-poor halo stars
= fossil record of past CR activity

SF shocks in the early Galaxy

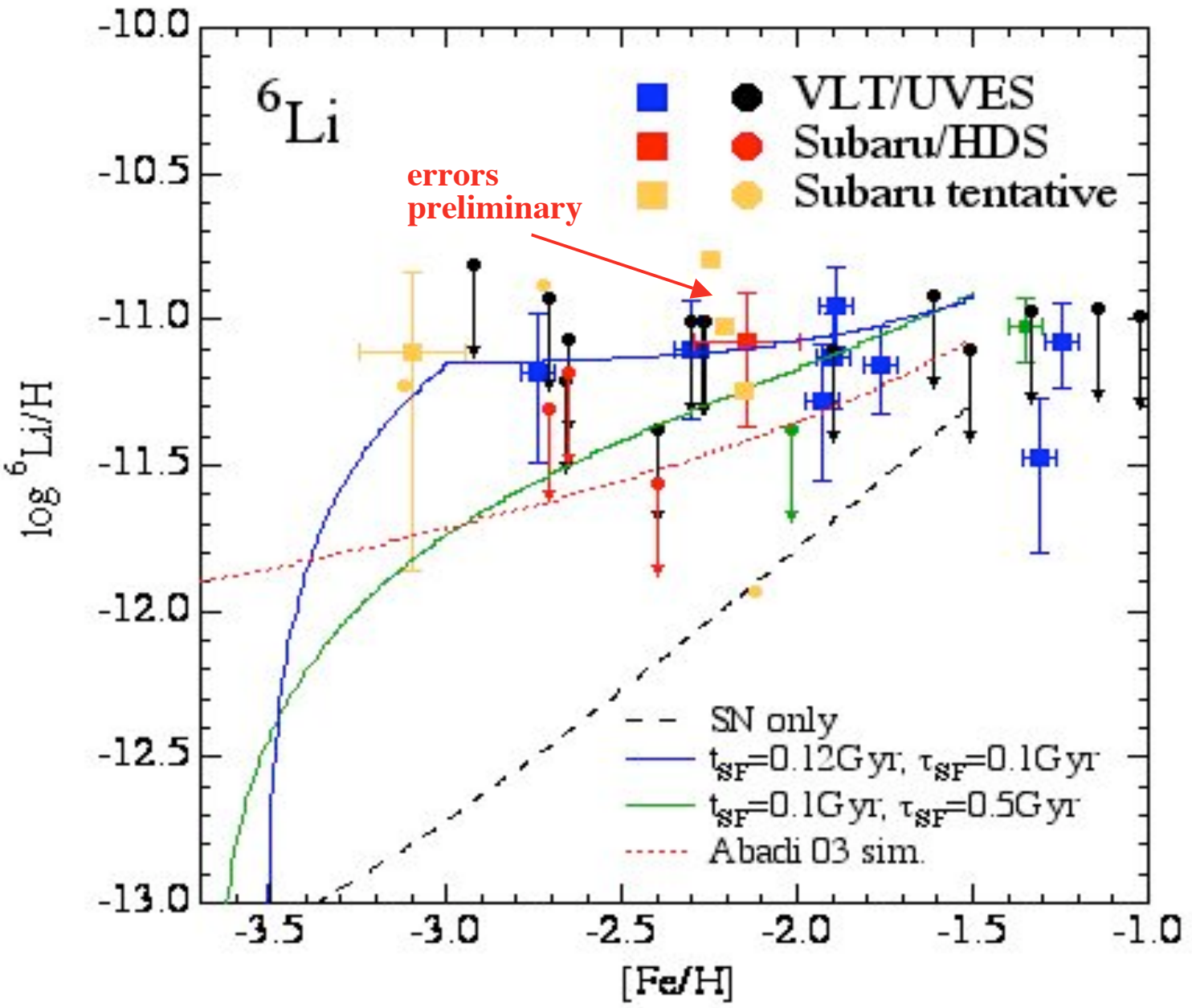
no ejection of fresh CNO, Fe
⇔ SN CRs
^{7}Li dominated by BBN

key element: ^{6}Li

Suzuki & SI 02



Subaru observations of ^{6}Li in metal-poor halo stars



Aoki, SI+ in prep.

total 5.5 nights
very challenging!

high ^{6}Li/Fe in some stars at very low Fe/H!

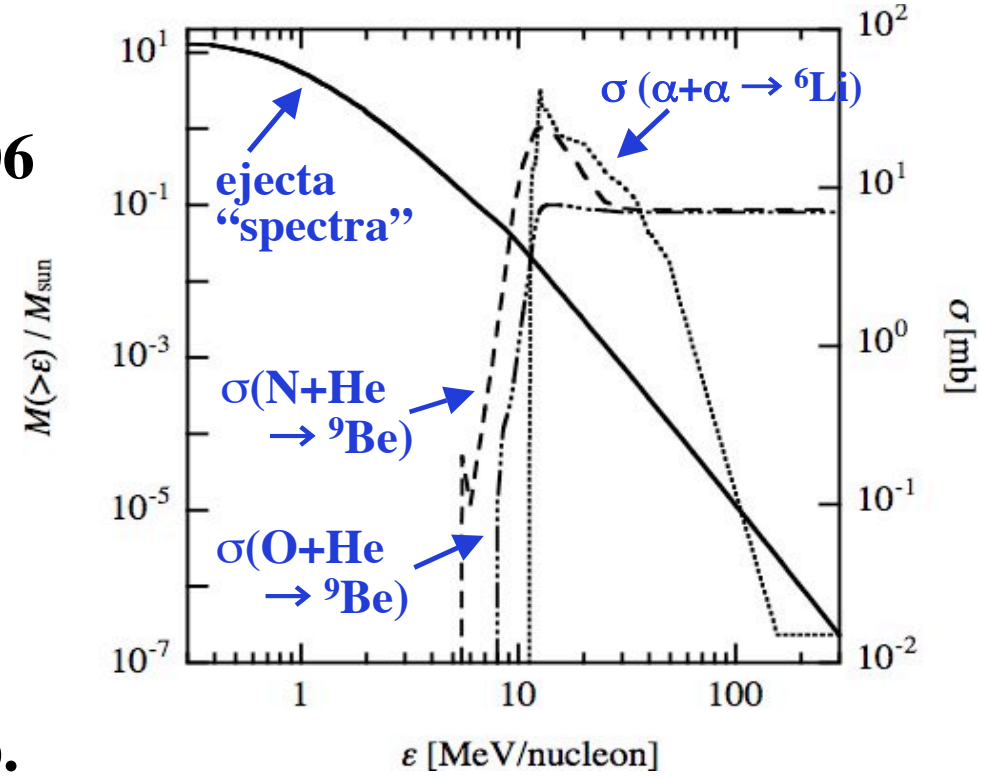
but also upper limits → intrinsic dispersion

SF CRs:
need large delay between SF and star formation

nonstandard supernova origin for ^{6}Li?

energetic SNIbc

Nakamura, SI, Wanajo, Shigeyama 06



Pop III SNe (vs SF CRs)

SI, Rollinde, Vangioni, Olive, in prep.

CR feedback on structure formation?

feedback during galaxy formation

SN, AGN, UV… **CR?**

Ostriker 06
effects not included in current simulations:
- **cosmic rays**
- magnetic fields
- dust

CRs compared to thermal gas

- more compressible, more buoyant $p \propto \rho^{4/3}$
- less cooling
- more diffusive

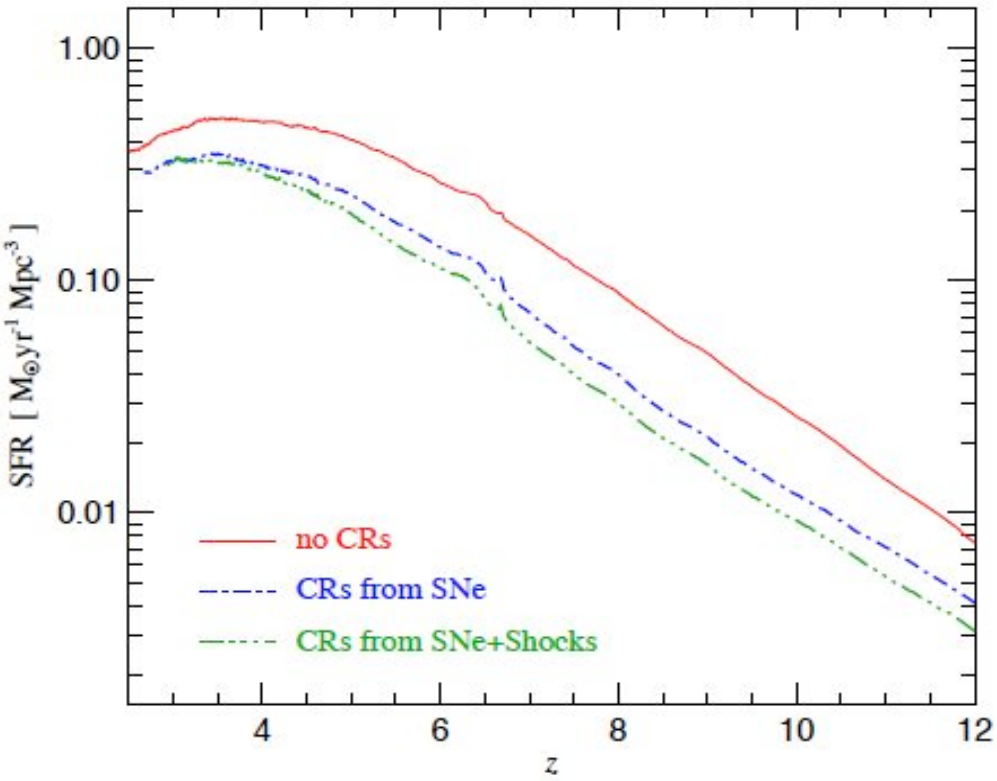
potential effects

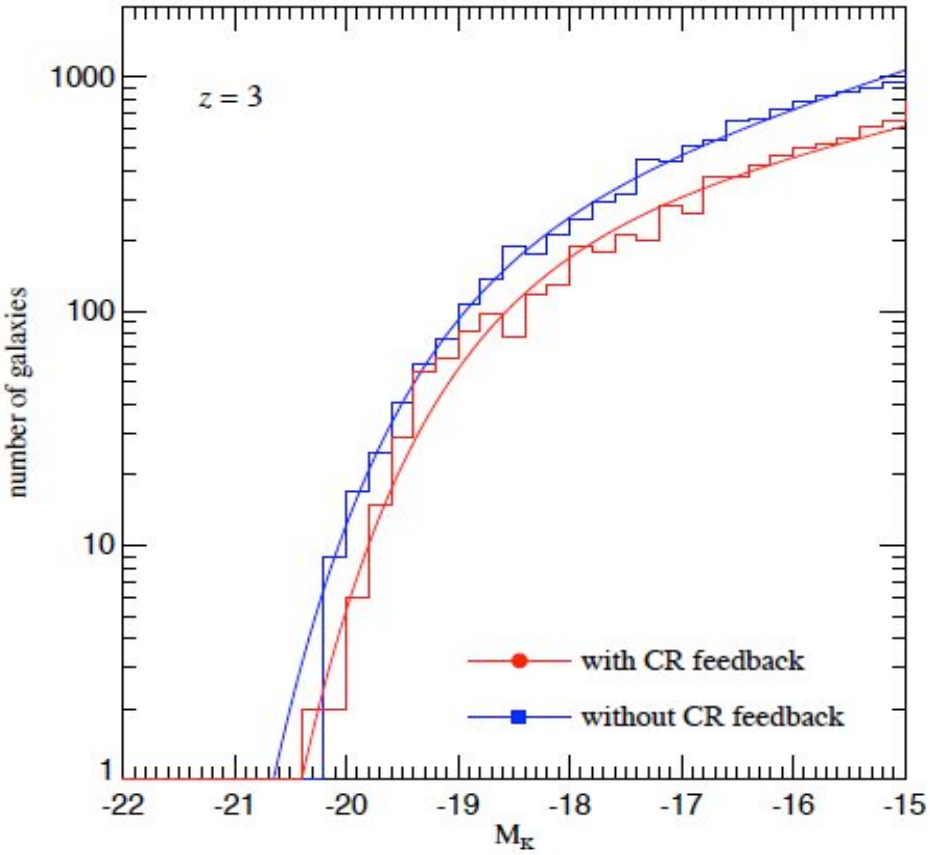
- pressure (support, displacement)
- heating

- B amplification?
- nonthermal emission
- LiBeB production

CR feedback in simulations of galaxy formation

Ensslin+ 06, Jubelgas+ 06





significant suppression of star formation in small galaxies M~<10^{10} M_{sol}

,, at high z

(slightly) flatter faint end slope of galaxy LF

solve angular momentum problem?

BUT formulation may be oversimplified

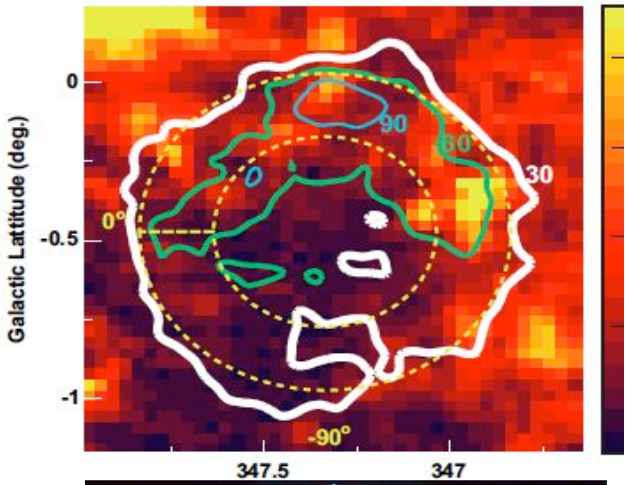
(no momentum conserv. for CRs!)

other potential roles of CRs

star formation near SNRs

enhanced CR ionization?

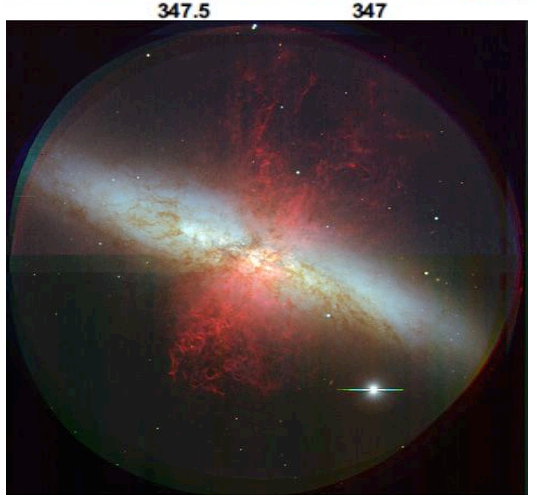
→ less ambipolar diffusion & core collapse?
more disk MRI & accretion rate? Fatuzzo+ 06



galactic winds (starburst galaxies)

crucial for galaxy evolution (feedback, metal ejection)
but wind mechanism unknown

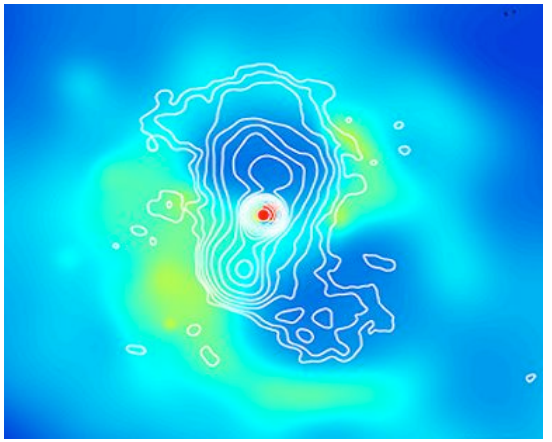
thermal? radiative? ⇔ CR-driven? Socrates+ 06



cluster cool cores ("cooling flows")

requires distributed, fine-tuned heating (by AGNs?)

CR heating?
nonequil. excitation by CRs?



まとめ：高エネルギー天文学と超熱的宇宙

長年の謎の解決
相次ぐ新しい発見と驚き
更なる進歩への高い期待

高エネ(ガンマ線)天文学：
　辺境 → 宇宙の理解に不可欠
高エネ天体・現象：
　げてもの → 宇宙で本質的な役割

過去の歴史は次々に塗り替えられ、
新しい歴史が今まさに作られ続けている！