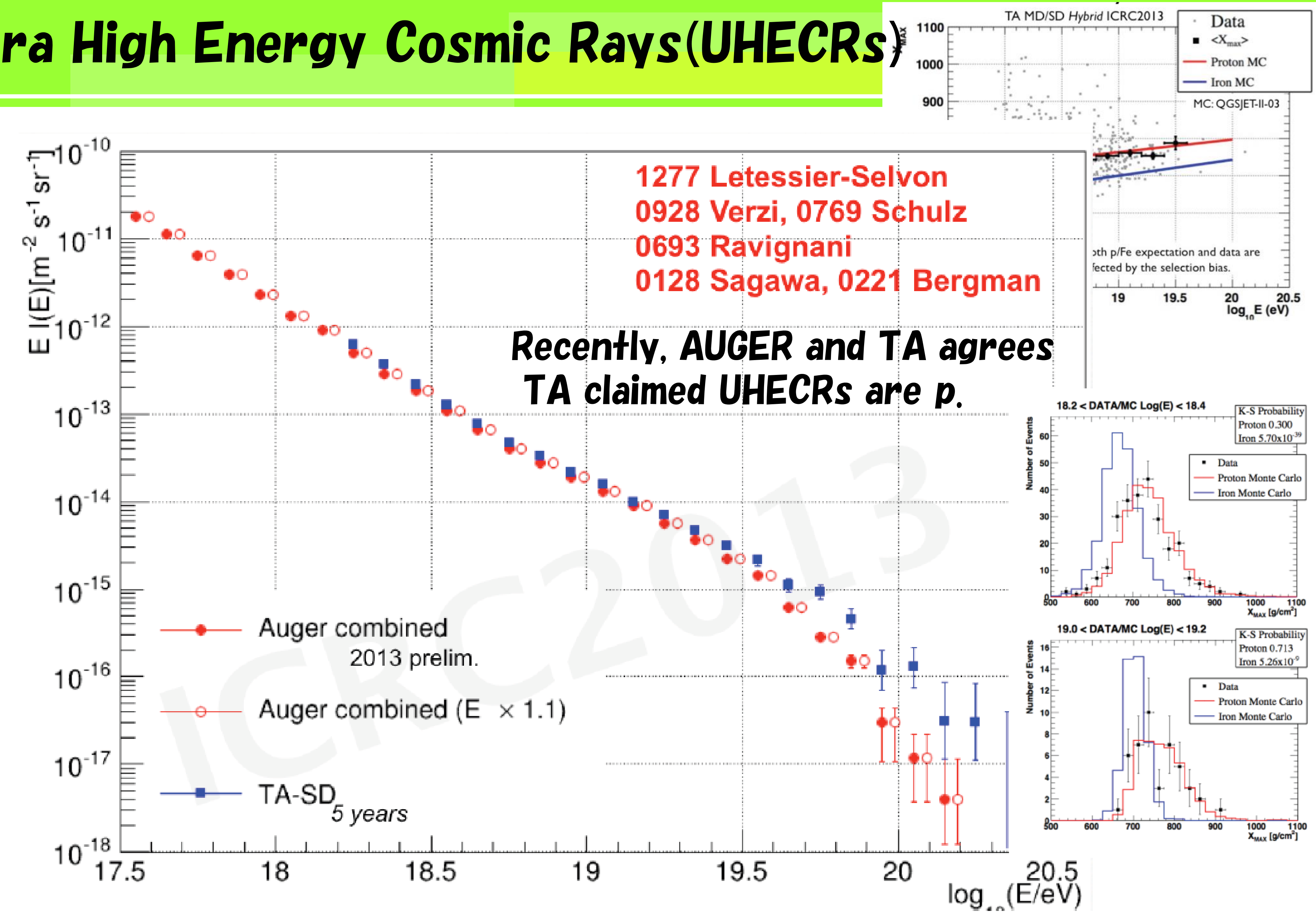
UHECRs, Neutrinos, and GRBs

Katsuaki Asano
(ICRR, Tokyo)

Ultra High Energy Cosmic Rays(UHECRs)

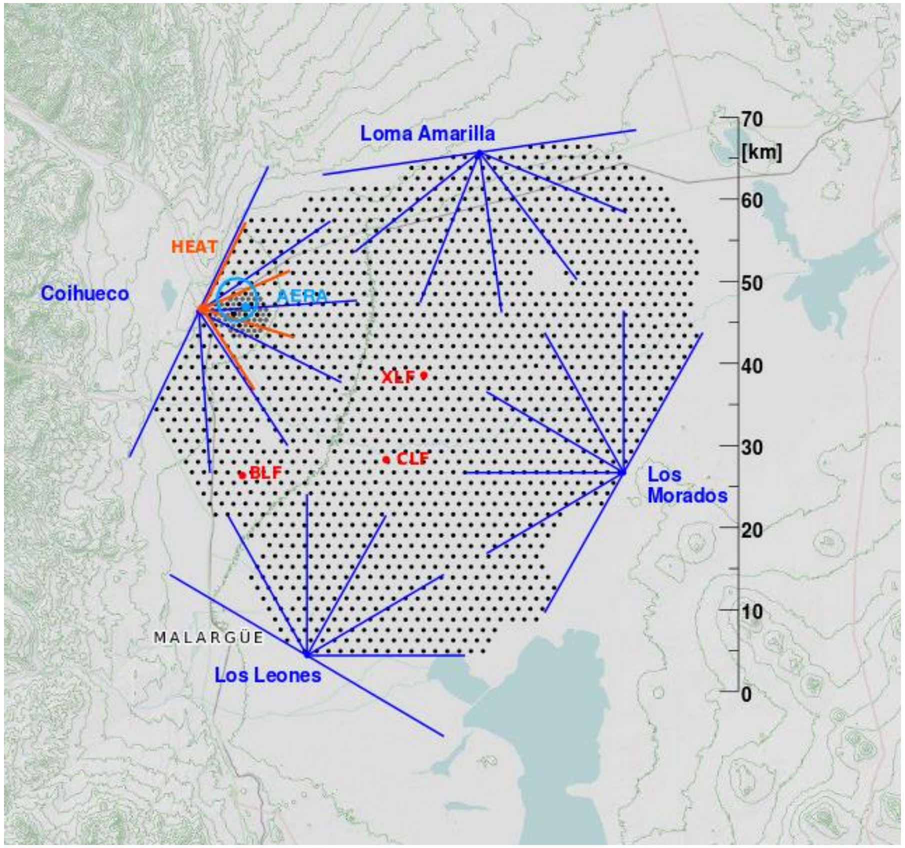


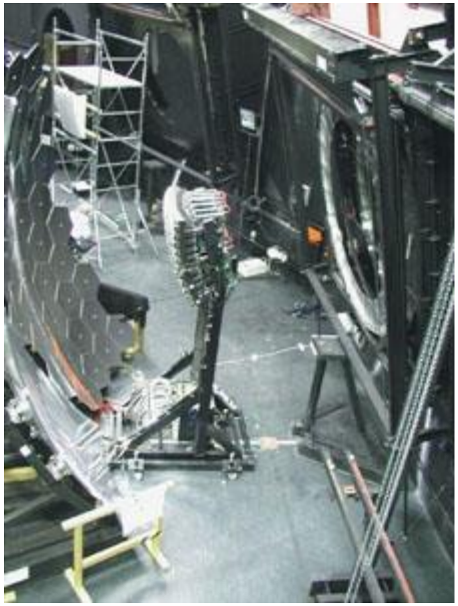
1277 Letessier-Selvon
0928 Verzi, 0769 Schulz
0693 Ravignani
0128 Sagawa, 0221 Bergman

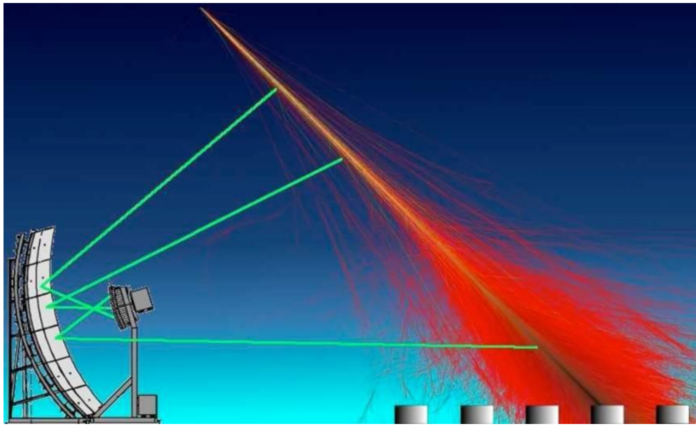
Recently, AUGER and TA agrees
TA claimed UHECRs are p.

Pierre AUGER

Argentina

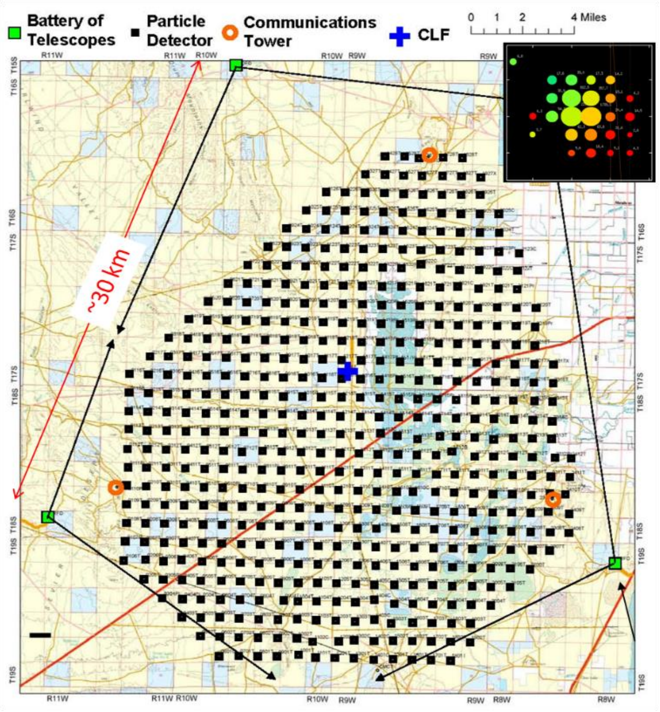






Telescope Array (TA)

Utah, USA

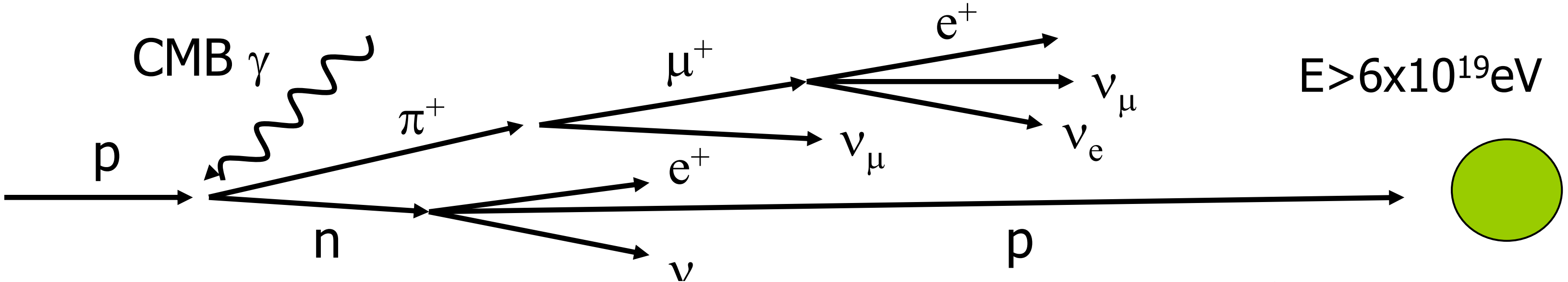


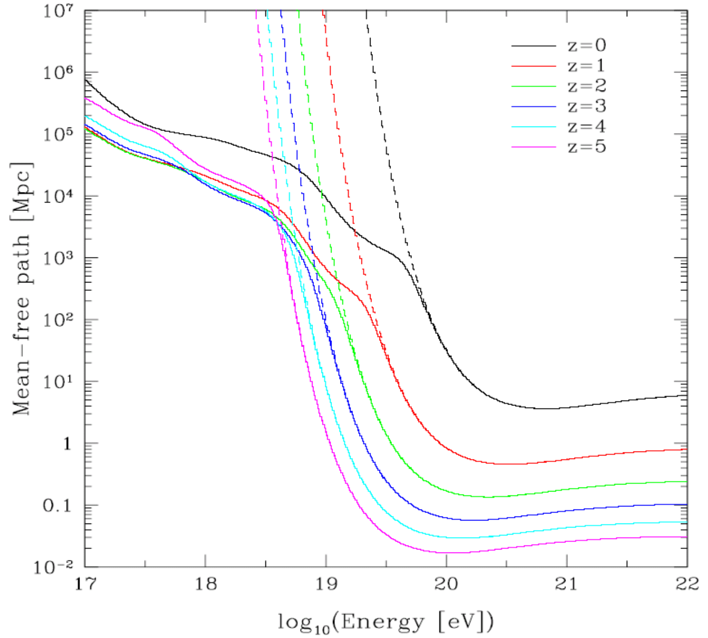
UHECRs

- Production Rate ~ $5\text{x}10^{43}$ erg/Mpc^3/yr
  - Note: Core collapse SN ~10^{47} erg/Mpc^3/yr
- Source Candidates: AGN, GRB, Galaxy Cluster etc. within 100 Mpc
- Composition: Proton? Fe?
- Anisotropy: If UHECRs are p, we can expect.
  - Excess near Cen A? TA Hot spot?
- Production Mechanism: (Relativistic) Shock? DC Acceleration? Stochastic Acceleration?
- Can we see secondary particles? (Gamma-ray, Neutrino)

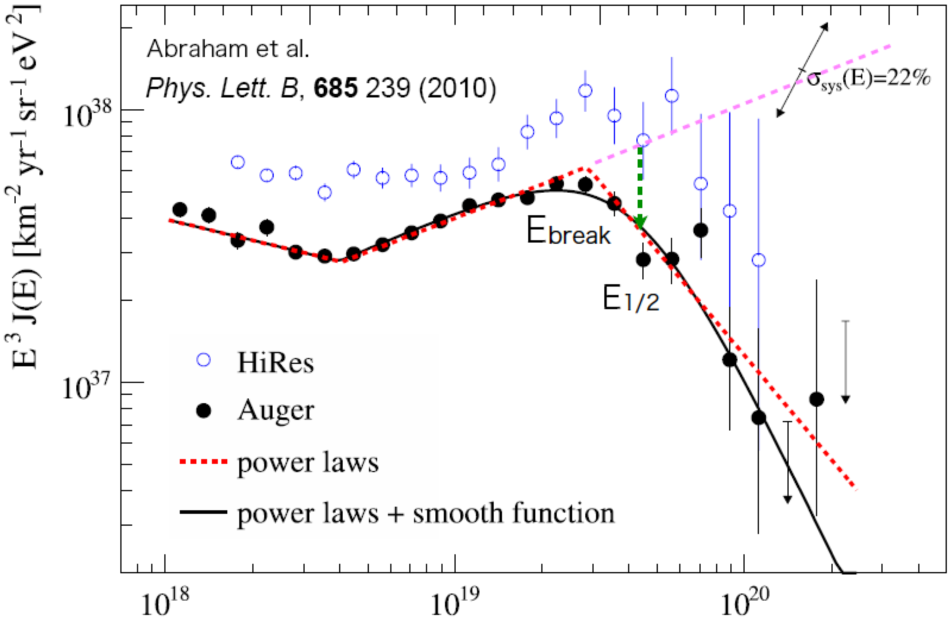
GZK Mechanism

Cosmic Rays of >10^{20}eV cannot propagate beyond100Mpc



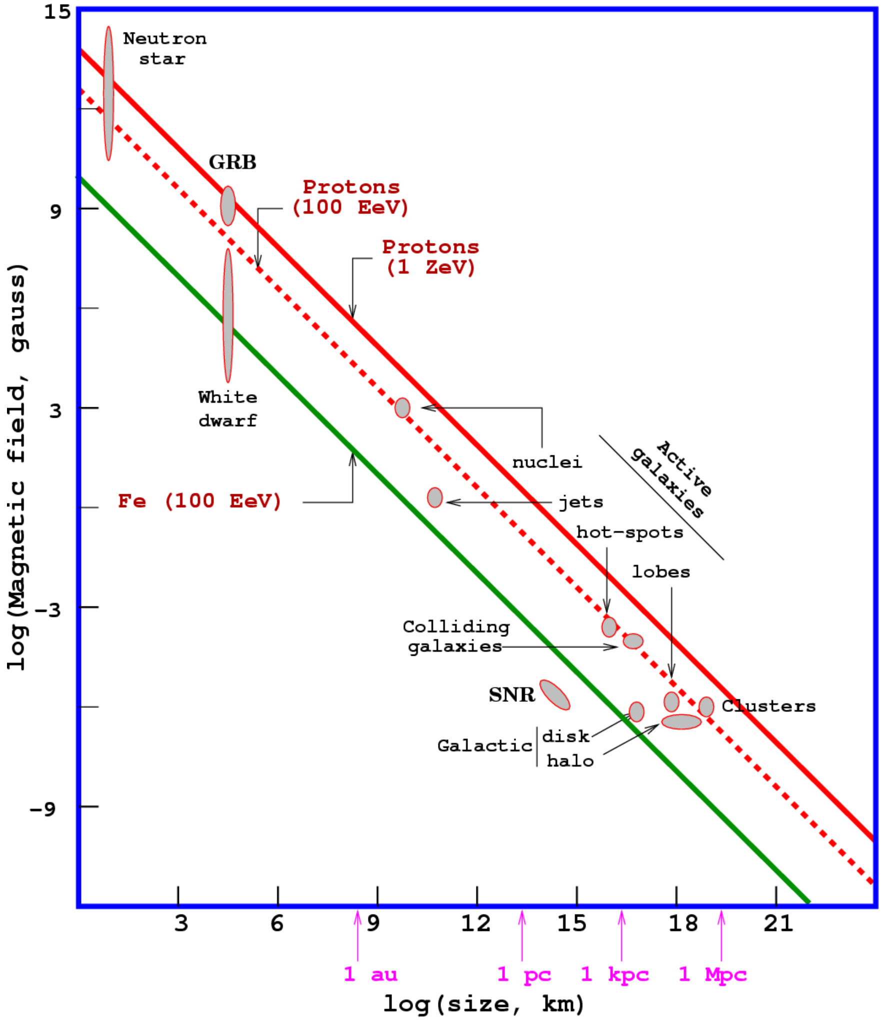


(Takami et al. 2007)



Source Candidates

Hillas-plot
(candidate sites for E=100 EeV and E=1 ZeV)



$E_{max} \sim ZBL$ (Fermi)

$E_{max} \sim ZBL\Gamma$ (Ultra-relativistic shocks-GRB)

To confine particles in the source,
$r_{gyro} <$ source size.

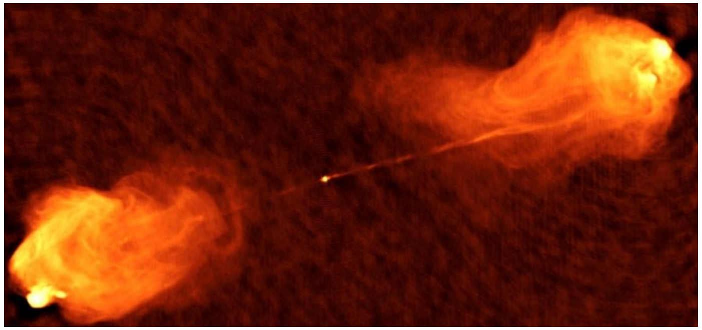
$$\varepsilon < ZeBL$$

Source Size

Magnetic field

p: Z=1, Fe: Z=26

Shock at AGN hot spot



Required conditions in shock acceleration

$$t_{acc} < t_{dyn} < t_{cool}$$

t_{cool} **Cooling Timescale, For protons, pion production may be the main cooling process. For electrons, synchrotron cooling is crucial.**

t_{dyn} **Dynamical Timescale, ∼shock propagation timescale. In the optimistic case, it is almost equal to the escape timescale.**

$$t_{acc} \sim \xi \frac{r_{gyro}}{c} = \xi \frac{\varepsilon}{ZeB} \propto \varepsilon$$

Bohm Limit: $\xi = 1$

At the maximum energy

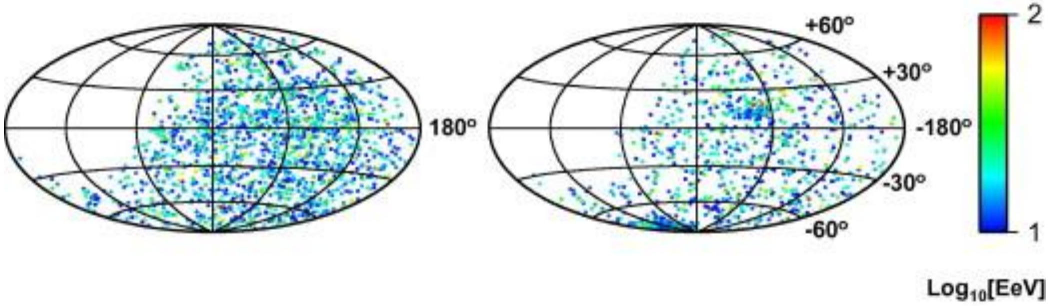
$$t_{acc} \sim t_{dyn}$$

If $t_{dyn} = \frac{L}{c}$

The Bohm Limit is equivalent to the Hillas condition.

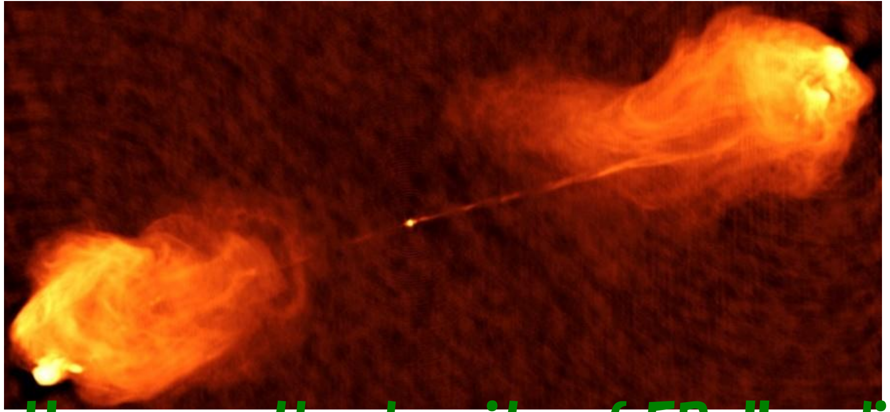
Required source densities

Takami & Sato 2009



An anisotropy analysis resulted in the source density:

$$\geq 10^{-4}\ \mathrm{Mpc}^{-3}$$



However, the density of FR-II radio galaxies is… $\sim 3\times 10^{-8}\ \mathrm{Mpc}^{-3}$

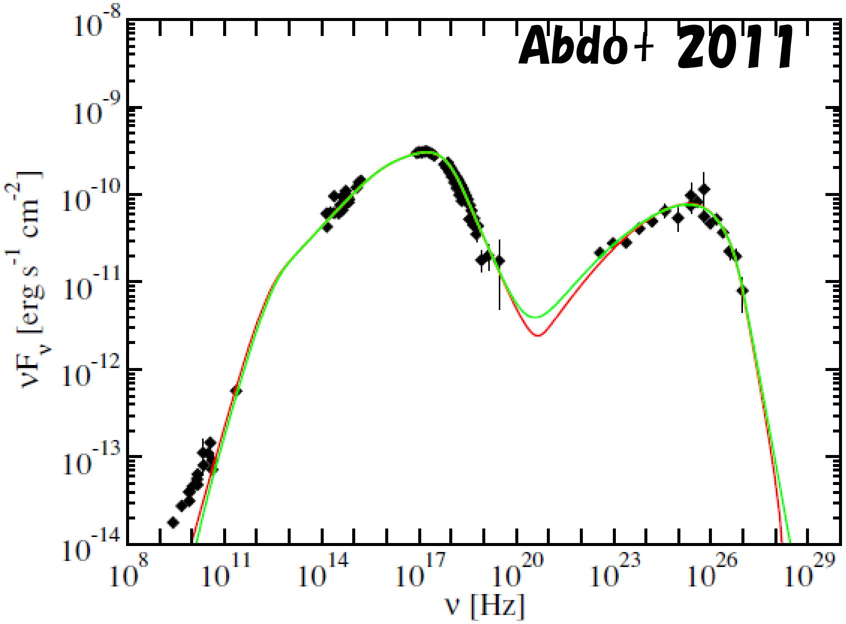
Hillas condition implies

$E < eBr\beta$, $B^2/8\pi = L_B/4\pi r^2\Gamma^2\beta c$

→ Required magnetic luminosity

$L_B \equiv \varepsilon_B L > 10^{45.5}$ erg/s $\Gamma^2\ \beta^{-1}$

Blazar Mrk 421:

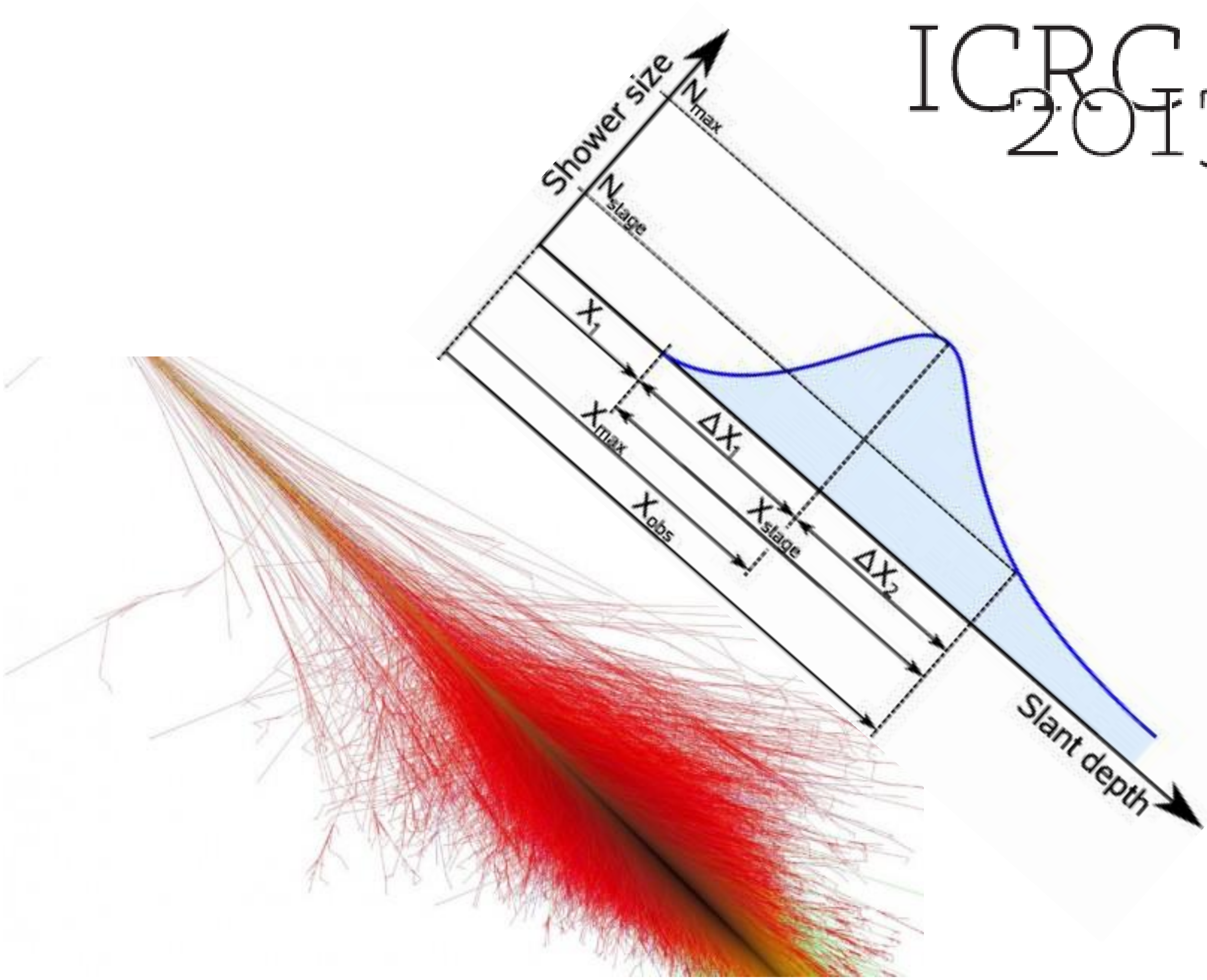


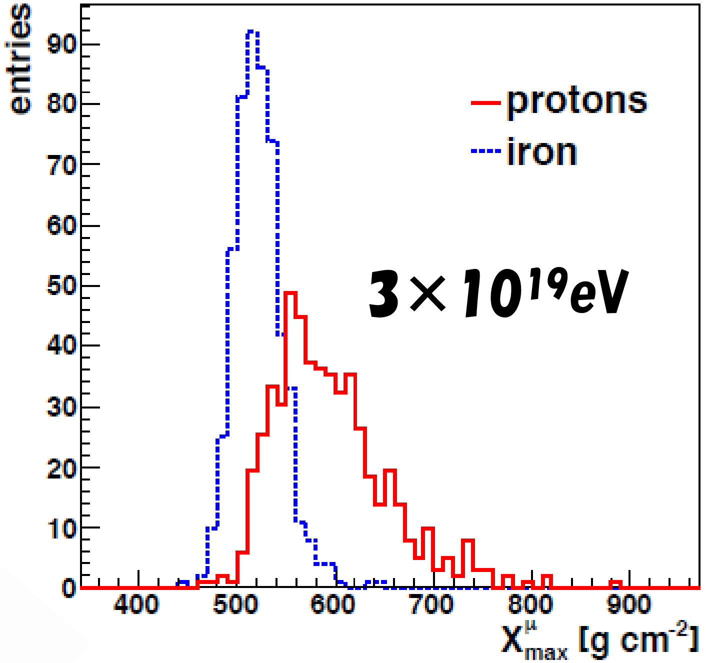
The maximum energy of electrons is far below the Bohm Limit.

Inoue & Takahara 1996

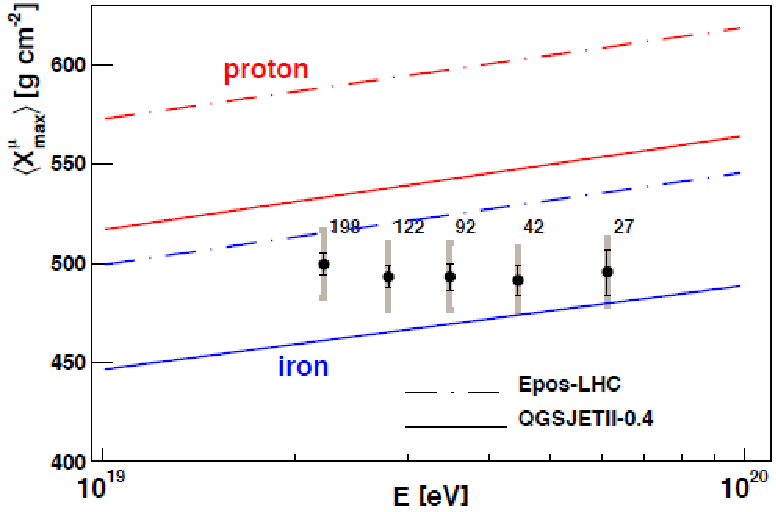
X_{max}

ICRC 2013



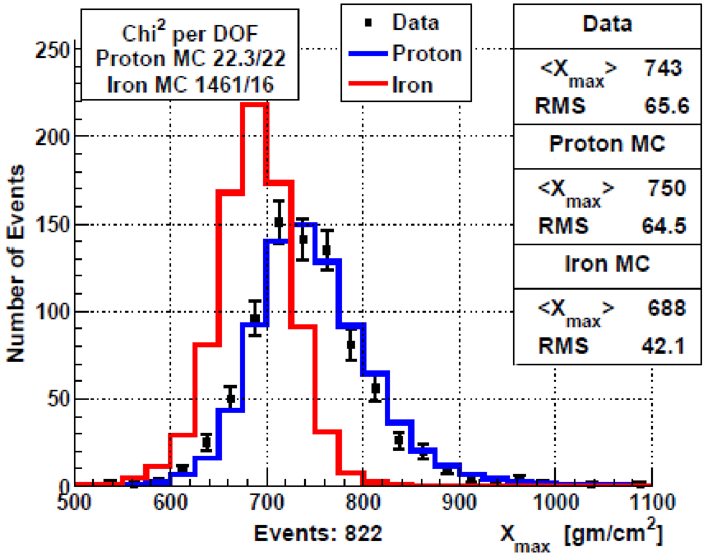


3×10^{19}eV

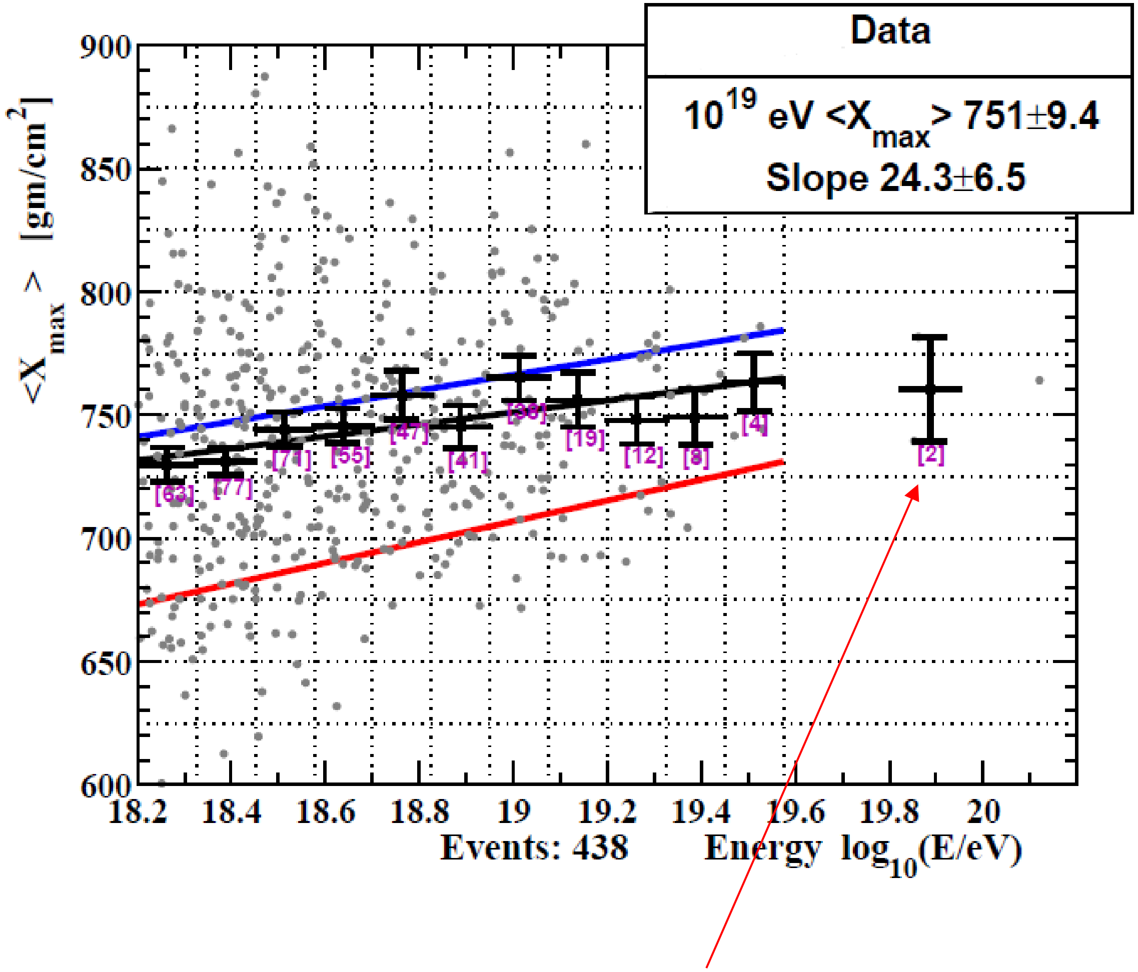


Composition in TA results

arXiv: 1408.1726



$\varepsilon > 10^{18.2}$ **eV**

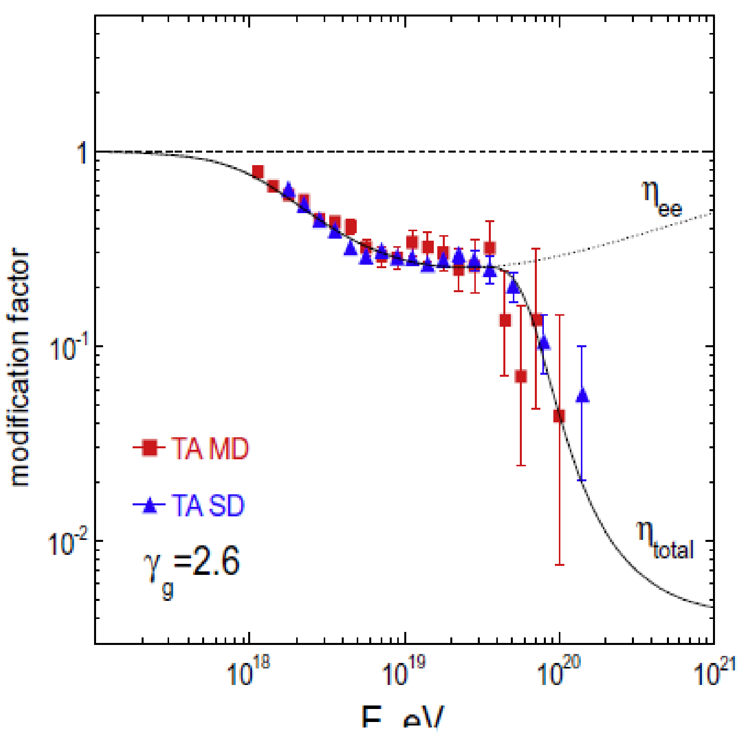


Iron?

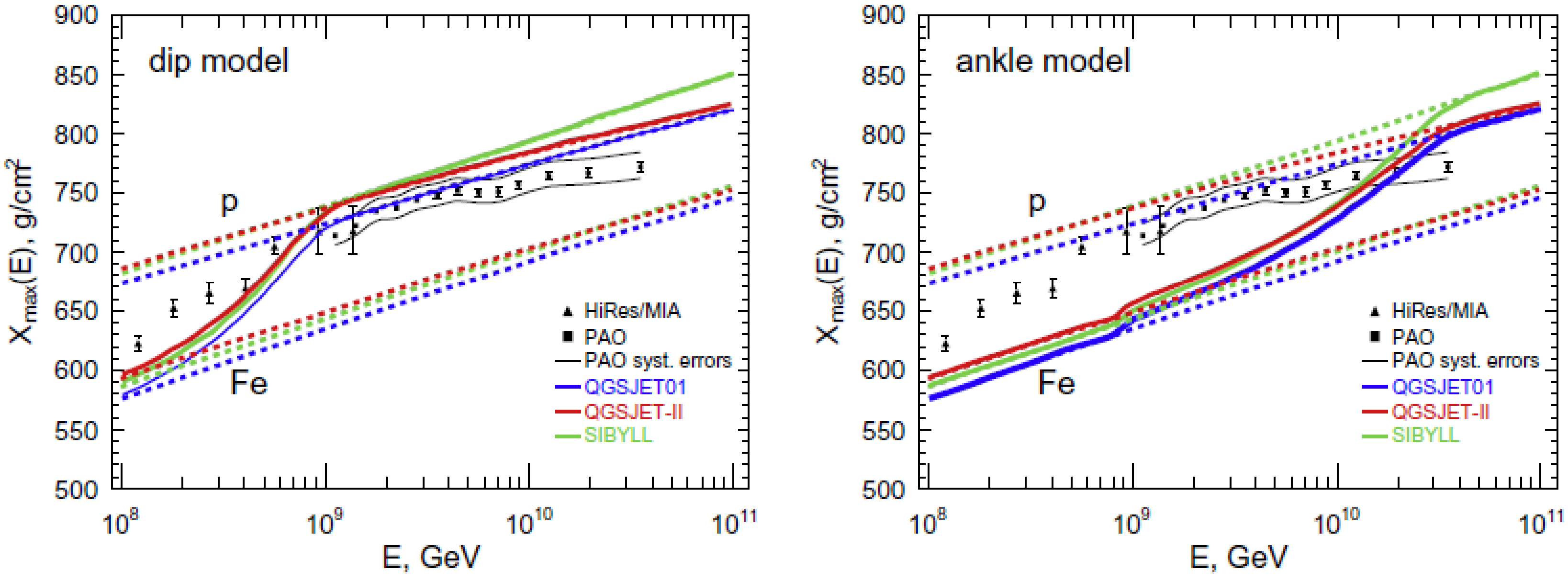
Dip and Ankle Models

Heavy nuclei have been in the spotlight, while the dip model (proton model) agrees with the spectrum and Xmax.

$$p + \mathrm{CMB}\,\gamma \rightarrow p + e^{+} + e^{-}$$

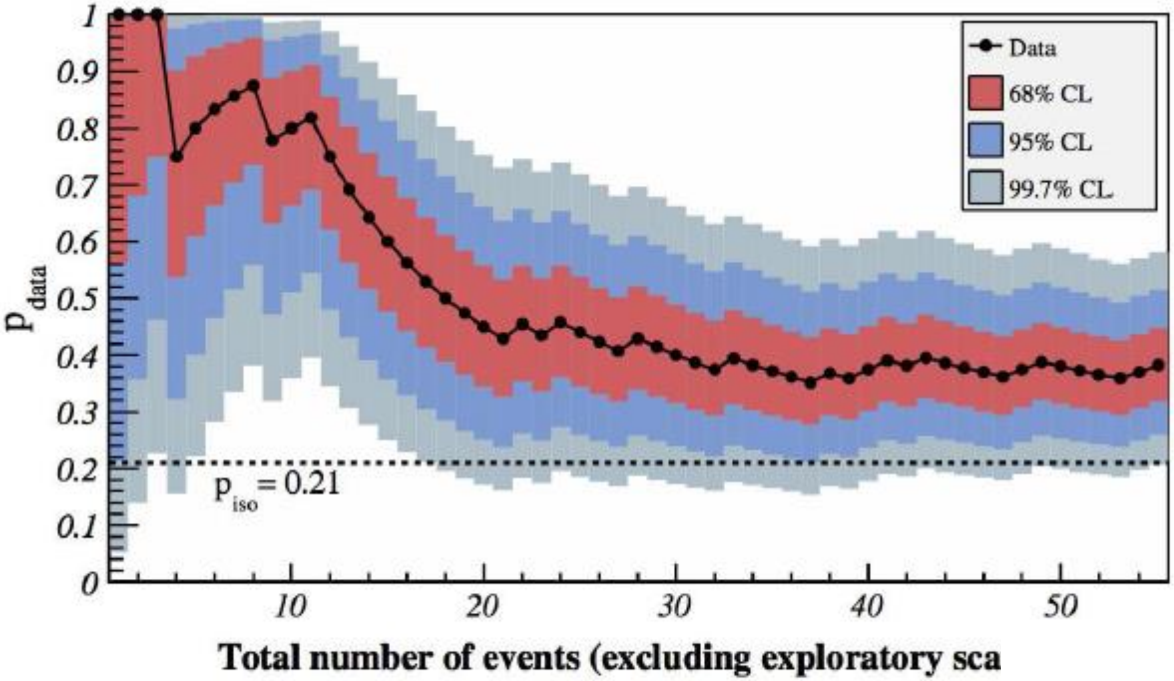


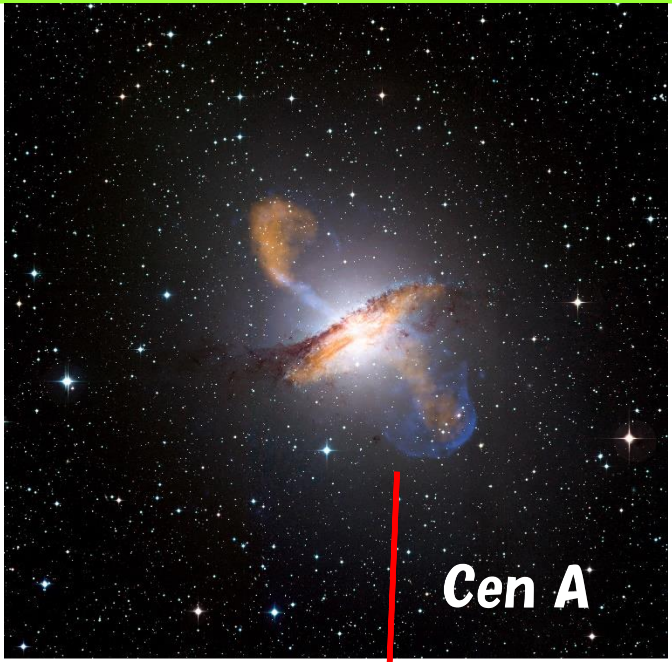
Aloisio, Berezinsky, Gazizov 2012

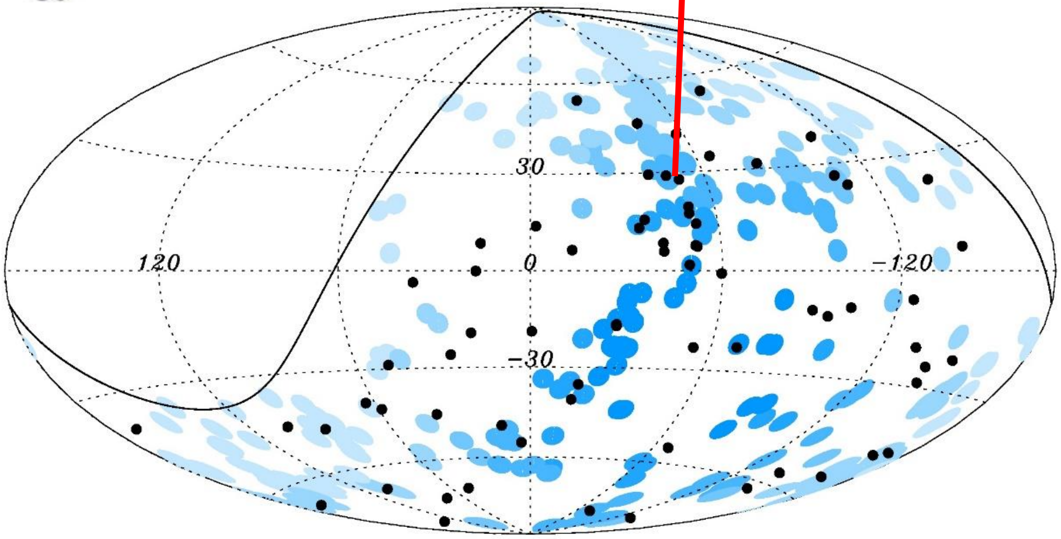


Anisotropy in AUGER

Events correlate with AGNs





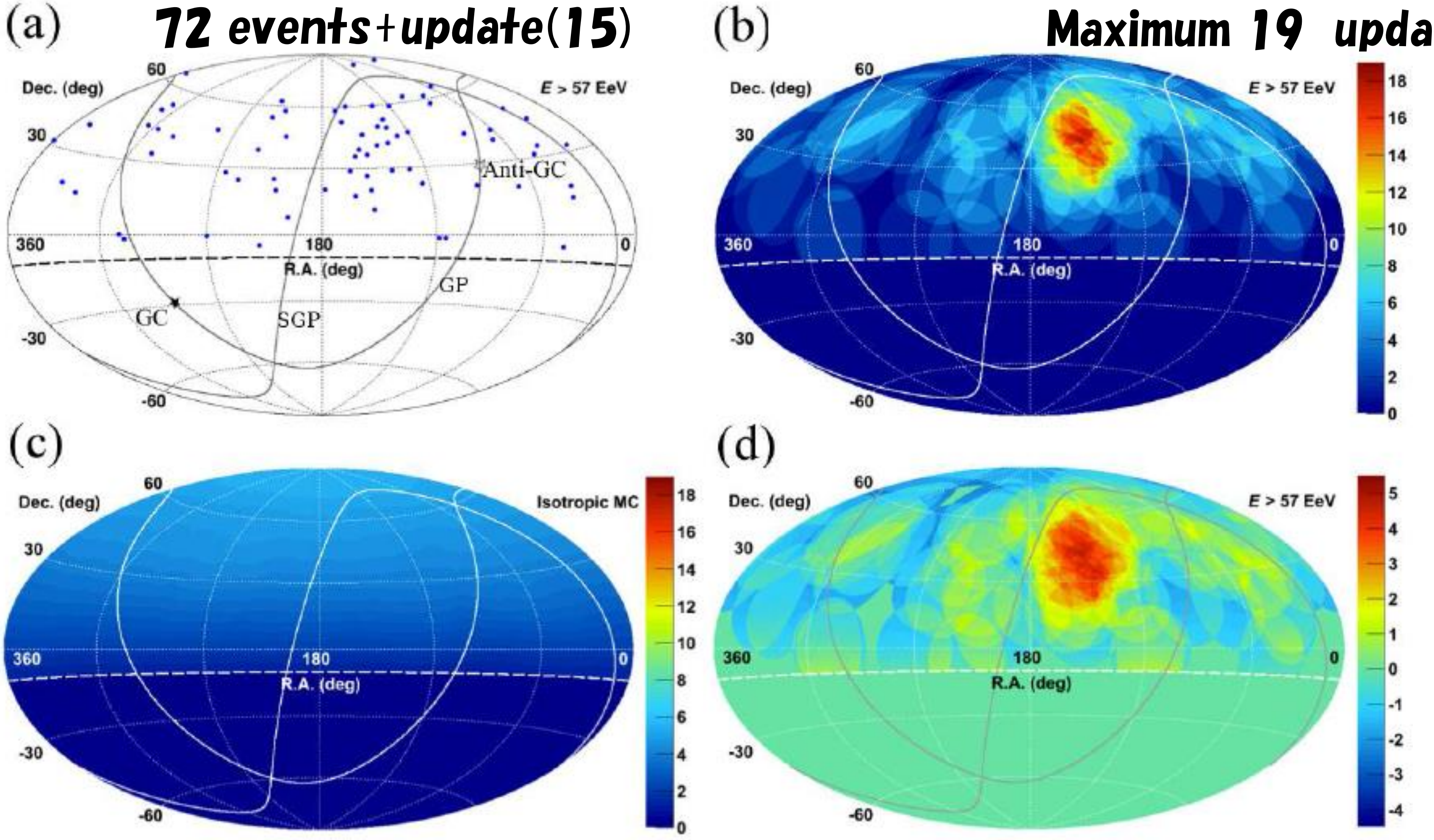


Anisotropy in TA

Abbasi+ 2014

Events in 20° -circle
Average: 5.5,
Maximum 19 update 23(5.5σ)

72 events+update(15)

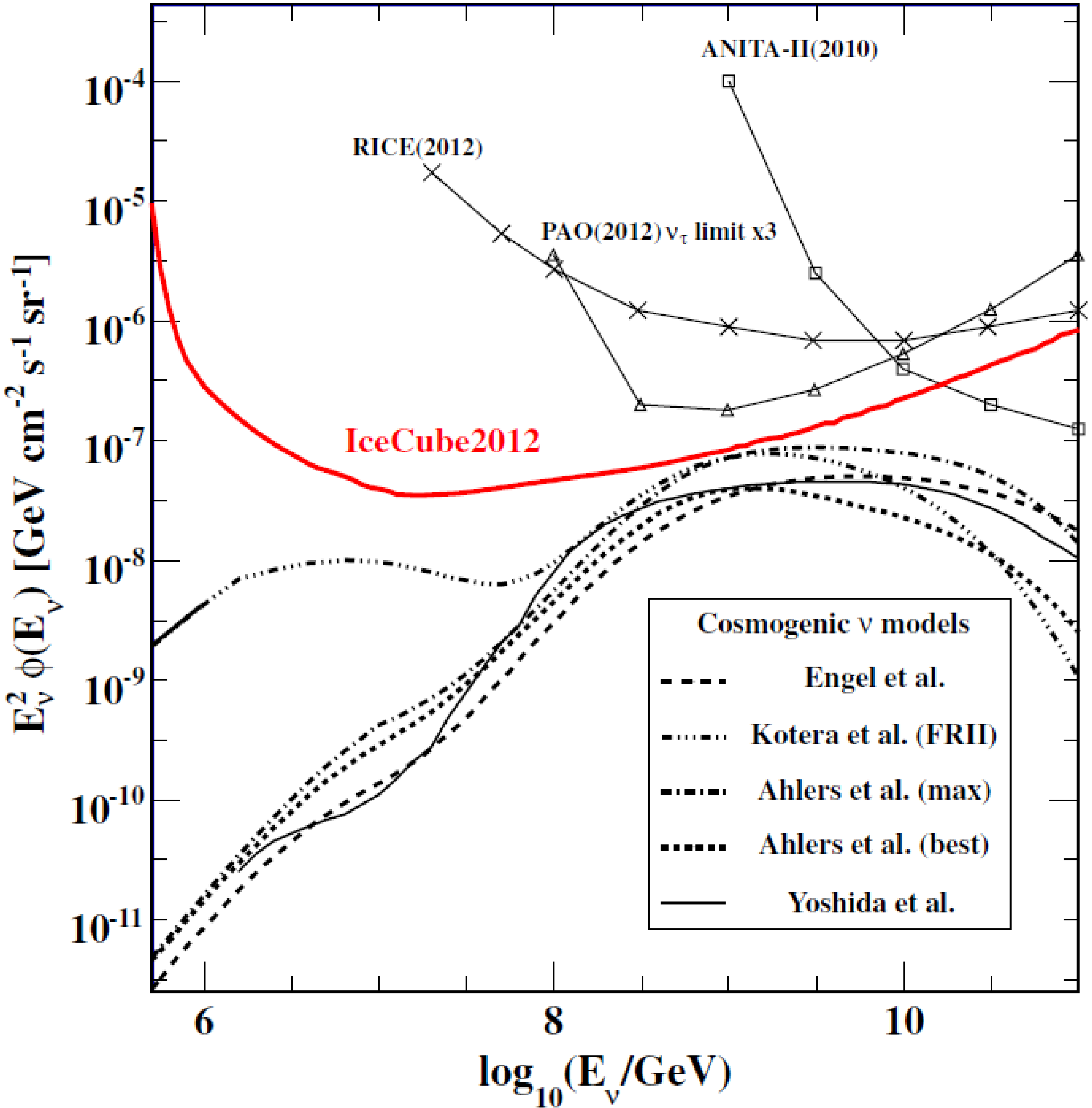


Ursa Major
Mrk 421
M82, M81
M106

4σ Results

Cosmogenic Neutrinos

Neutrino can come from beyond 100Mpc.
Strong UHECR source evolution
→high neutrino flux



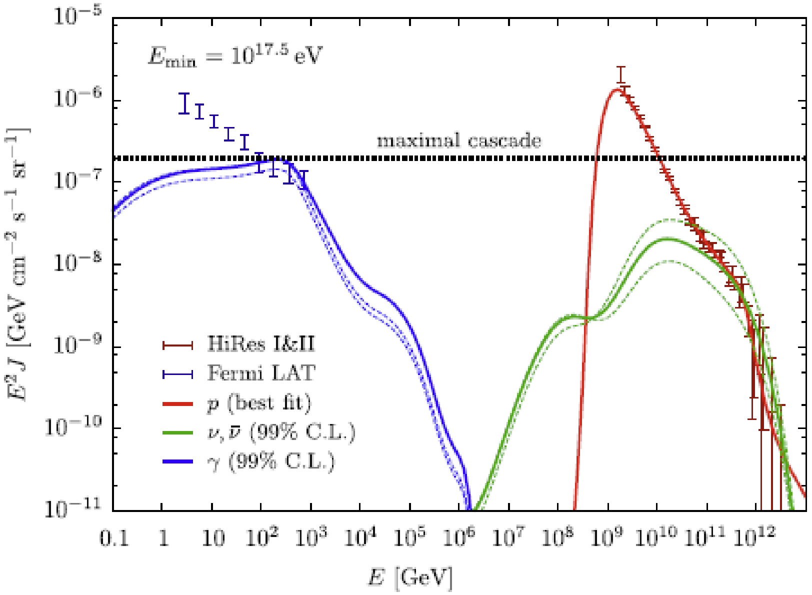
Aartsen+ 2013

In Ahlers+

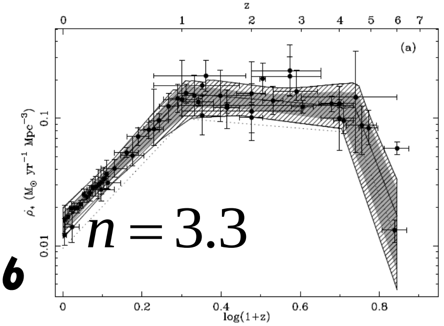
$$\mathcal{L}_p(z,E) = \mathcal{H}(z)\mathcal{L}_p(0,E)$$

$$\mathcal{H}(z) \equiv (1+z)^n\Theta(z_{\max}-z)$$

$z_{\max}=2$ $n=4.6$



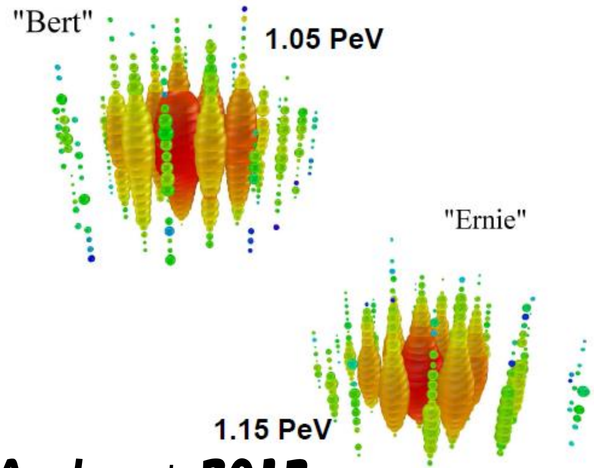
c.f. SFR
Hopkins & Beacom 2006



$n=3.3$

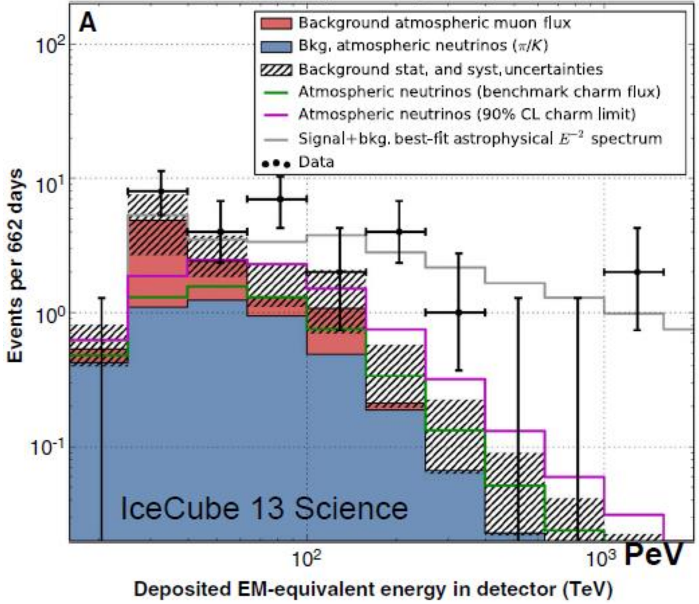
PeV neutrinos detected with IceCube

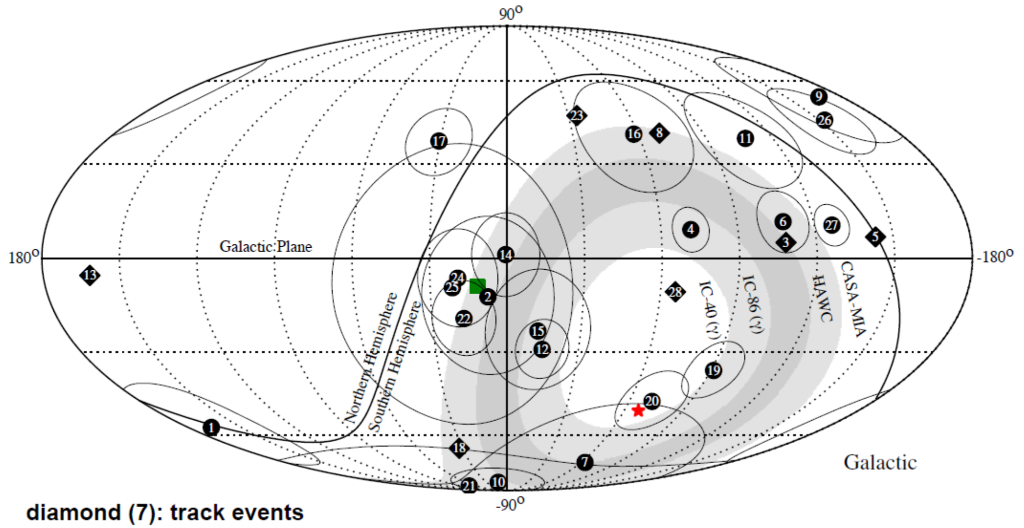
First detection of PeV events (~3σ)



Aartsen+ 2013

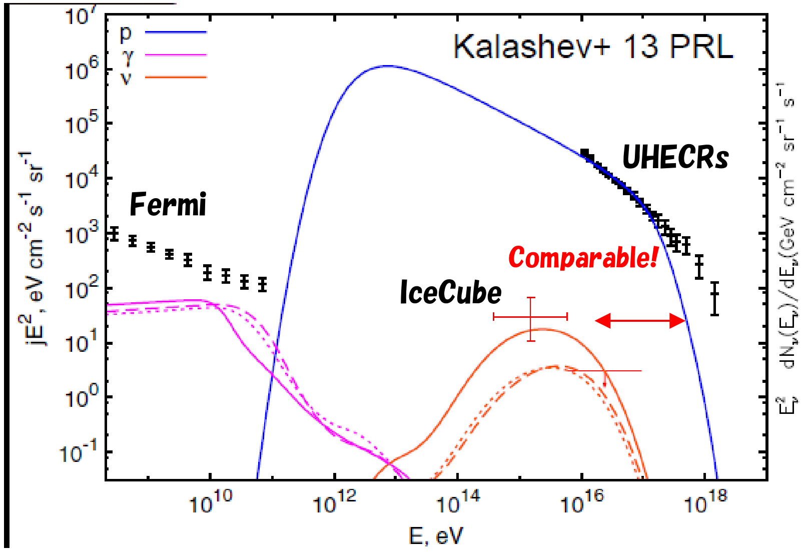
Follow-up analysis (~4σ)





diamond (7): track events
circle (21): shower event

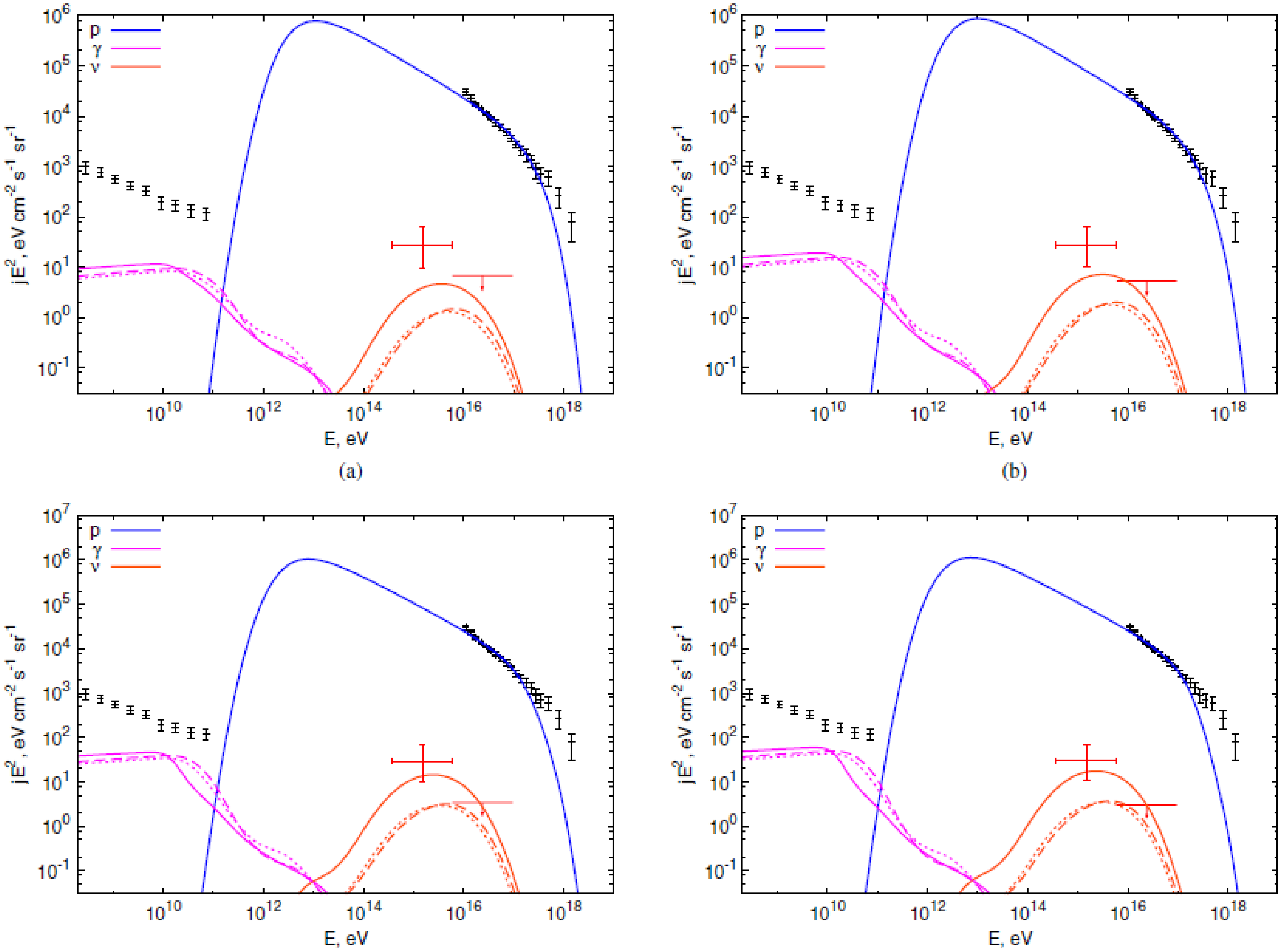
Ahlers & KM 13; complied from IceCube 13 Science



See also Ioka & Murase 2014

CRs and PeV neutrinos

If all high-energy CRs are extra galacitic, …



(a) (b) (c) (d)

CRs are all proton?

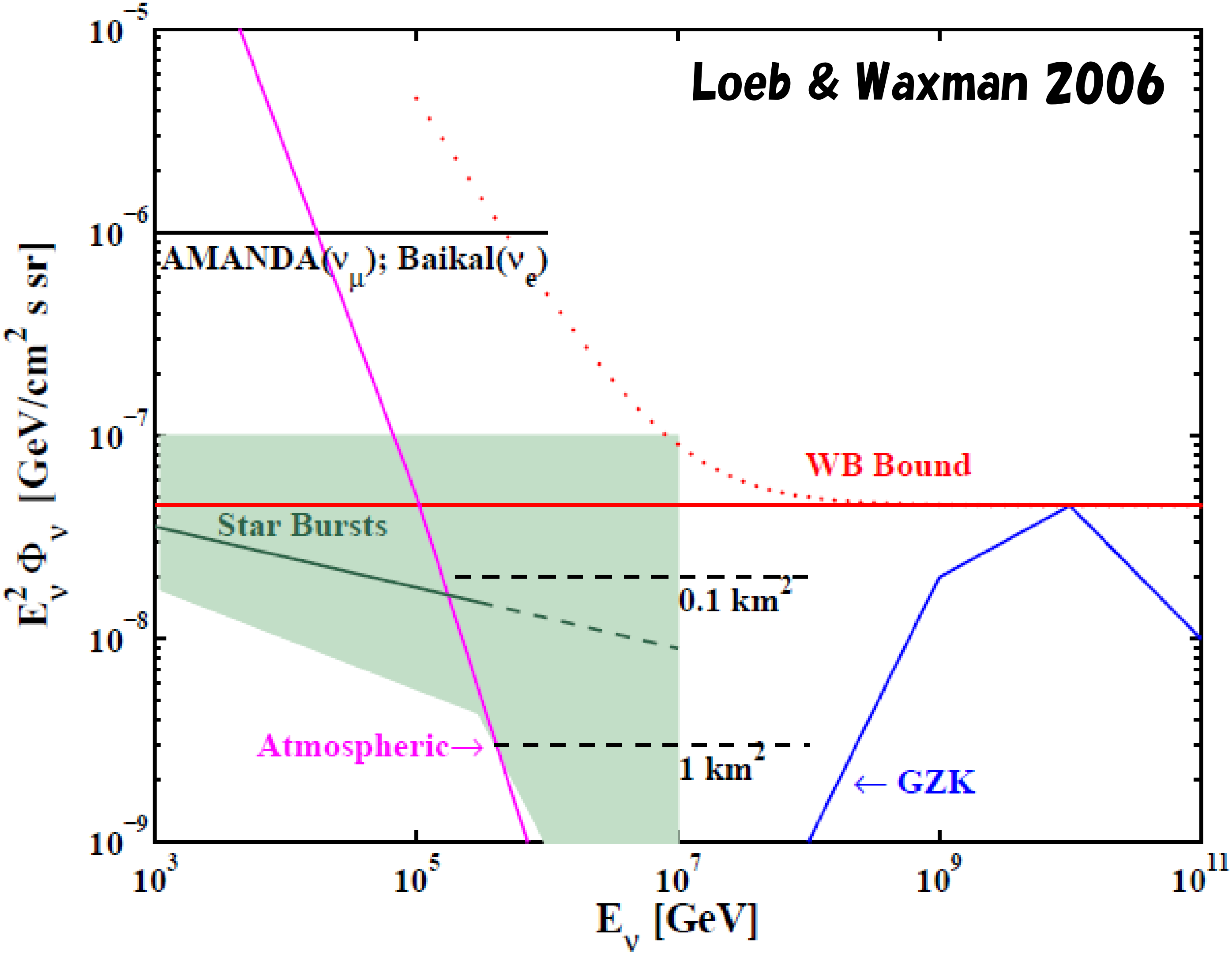
$$\rho(z) = \begin{cases} (1+z)^m, & 0 < z < z_1 \\ (1+z_1)^m, & z_1 < z < z_2 \\ (1+z_1)^m 10^{k(z-z_2)}, & z > z_2. \end{cases}$$

TABLE I. Evolution parameters for AGN with different values of the x-ray power L_x inferred from observational data [32] are shown in the upper part of the table. The required power per unit volume W_p of cosmic rays with energies $E_p > 10^{13}$ eV was calculated under the assumption that an average AGN is described by one of these evolution models.

L_x, erg/s	$10^{42.5}$	$10^{43.5}$	$10^{44.5}$	$10^{45.5}$
m	4.0 ± 0.7	3.4 ± 0.5	5.0 ± 0.2	7.1 ± 1.0
z_1	0.7	1.2	1.7	1.7
z_2	0.7	1.2	2.7	2.7
k	-0.32	-0.32	-0.43	-0.43
W_p, 10^{40}(erg/s Mpc^3)	7.0	6.0	1.3	0.22

Kalashev, Kusenko, Essey 2013

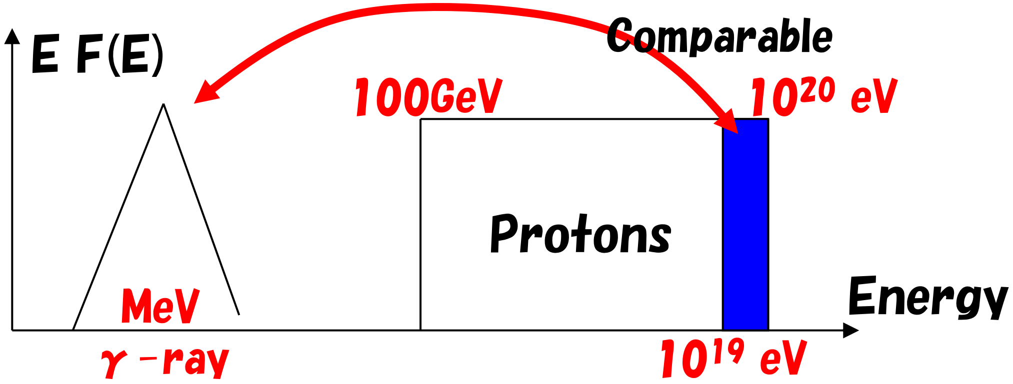
Neutrinos from starburst galaxies



UHECRs and GRBs

See Waxman arXiv:1010.5007

We need **5x10^{43} ergs/Mpc^3/yr** above 10^{19} eV as the local production rate of UHECRs. This is close to the local release rate of gamma-rays from GRBs!



- The integrated proton energy should be 10-30 times the gamma-ray energy.
- But, the gamma-ray energy per burst is huge; the isotropic energy is 10^{52}-10^{55} erg.

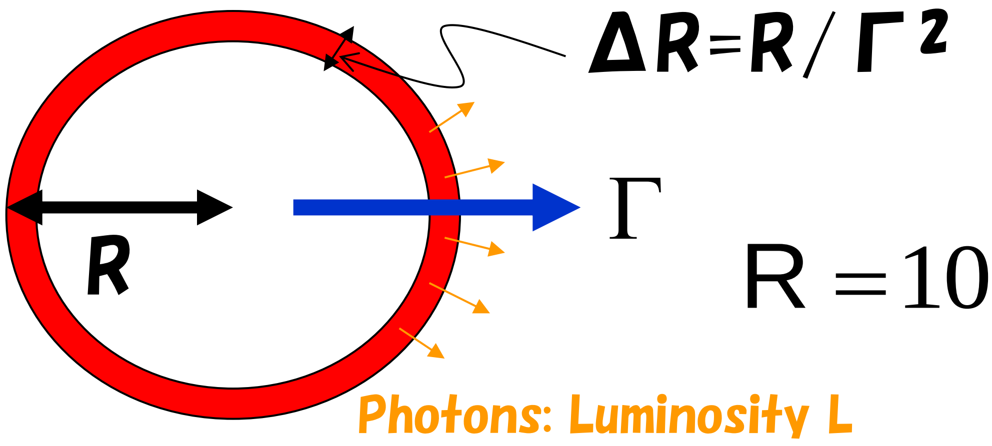
$$E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}} = 3.0\times 10^{43}\,{\rm ergs\,Mpc^{-3}\,yr^{-1}}\left(\frac{\xi_{\rm acc}}{10}\right)\left(\frac{20}{R}\right) \times \left(\frac{E_\gamma^{\rm iso}}{3\times 10^{53}\,{\rm ergs}}\right)\left(\frac{\rho_{\rm HL}(0)}{0.2\,{\rm Gpc^{-3}\,yr^{-1}}}\right) \quad @10^{19}{\rm eV}$$

$$\xi_{acc} \equiv U_p / U_e \approx U_p / U_\gamma$$

$$R \equiv \ln(E_{\rm CR}^{\rm max} / E_{\rm CR}^{\rm min})$$

Murase, Ioka, Nagataki, Nakamura 2008

Physical Condition in a Shell



$$R = 10^{14}\,\text{cm}, \Gamma = 300, L = 10^{52}\ \text{erg/s}$$

In the comoving frame

Energy Density: $U = \frac{L}{4\pi c R^2 \Gamma^2} \approx 3\times 10^{7}\ \text{erg/cc}$

Magnetic Field: $B \approx \sqrt{0.1\times 8\pi U} \approx 8600\,\text{G}$

Time Scales

Let us consider a proton of 10^{19}eV

In the comoving frame,

$$\gamma = \frac{10^{19}\mathrm{eV}}{\Gamma m_p c^2} \approx 3.6\times 10^7$$

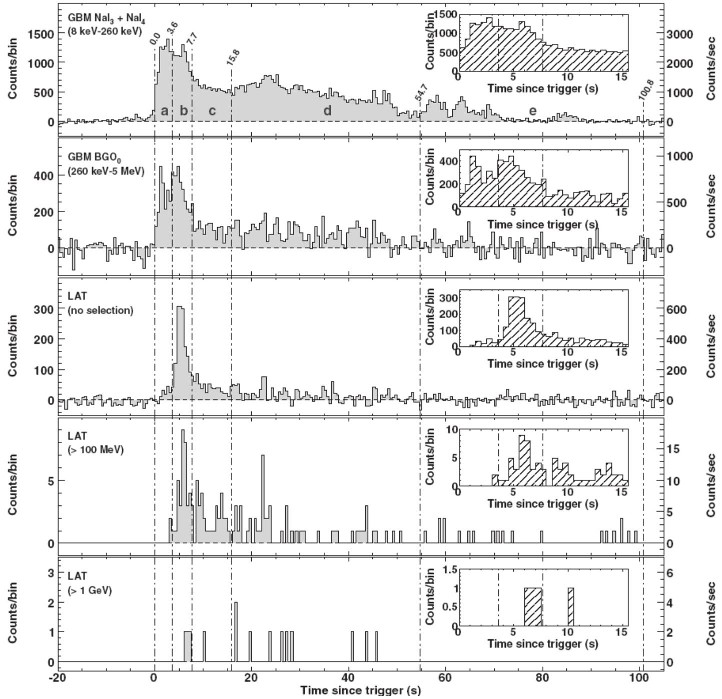
Acceleration Time Scale: $\approx \frac{R_L}{c} = \frac{\gamma m_p c^2}{eBc} \approx 0.4\,\mathrm{sec}$

Dynamical Time Scale: $R/\Gamma c \approx 11\,\mathrm{sec}$

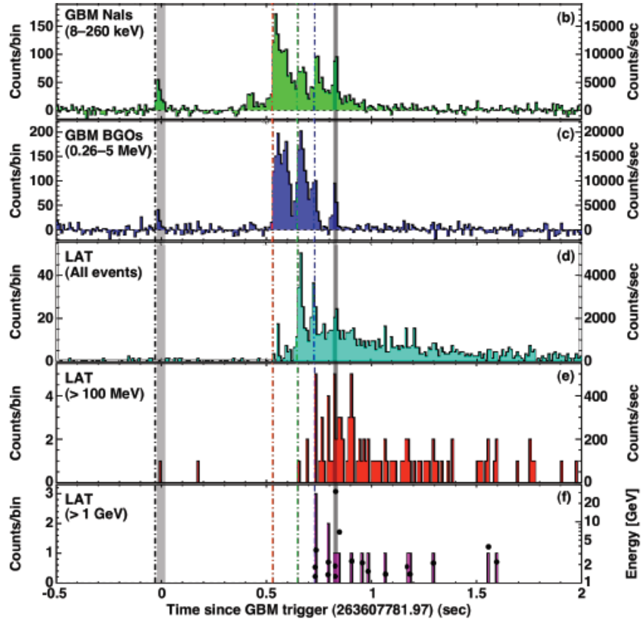
Cooling Time Scale: $\frac{6\pi m_p^3 c}{\sigma_T m_e^2 B^2 \gamma} \approx 1800\,\mathrm{sec}$

Fermi Results for GRBs

Delayed Onsets in GeV

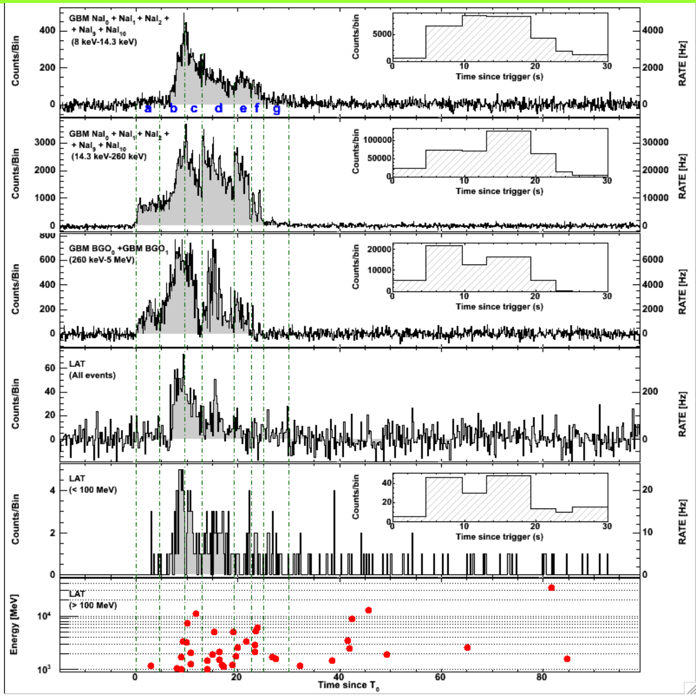


GRB 080916C Abdo+ 2009

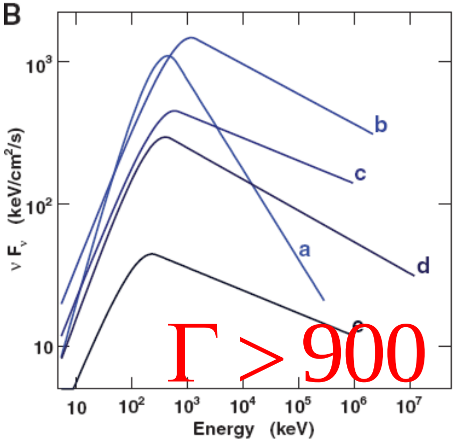


Short GRB 090510

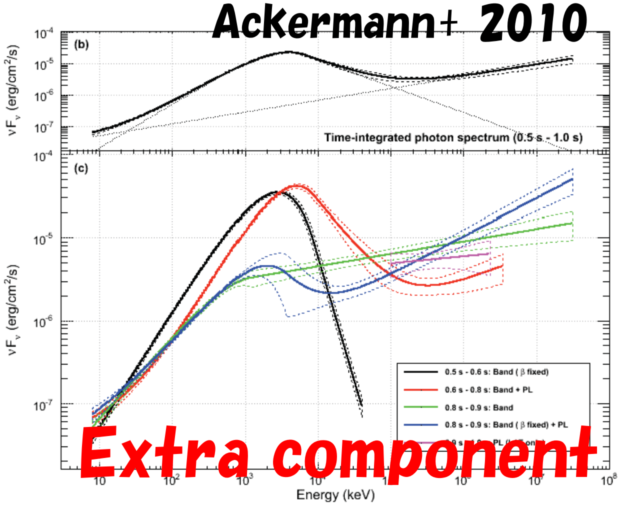
Ackermann+ 2010



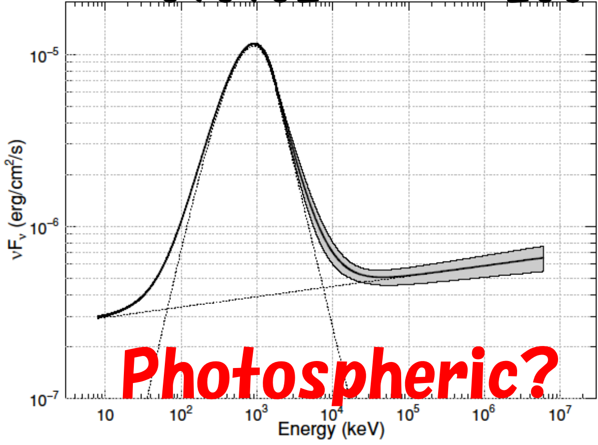
GRB 090902B Abdo+ 2009



$\Gamma > 900$



Extra component



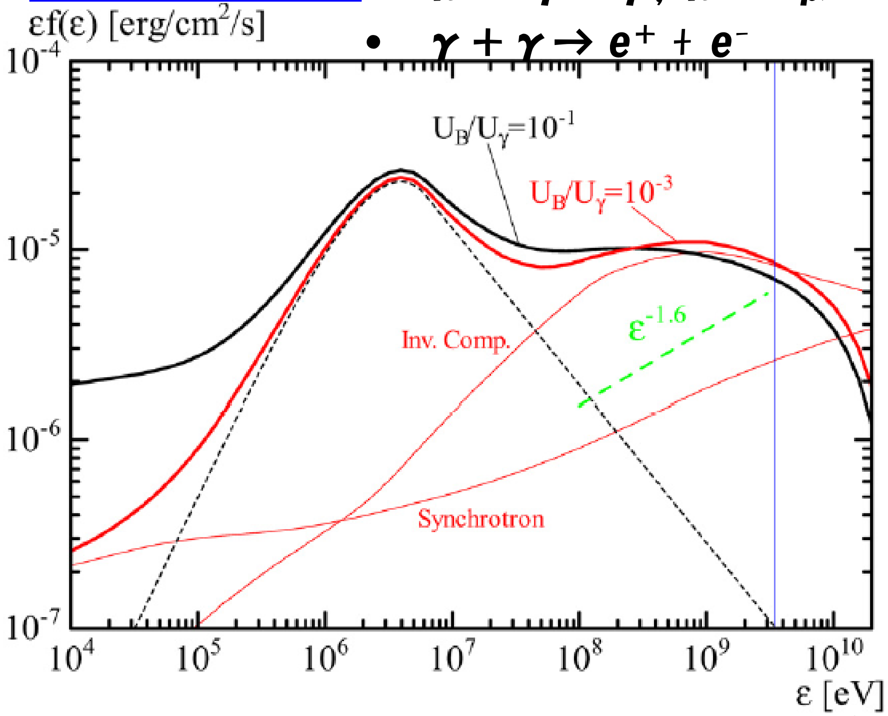
Photospheric?

Photon signature of proton acceleration

- $p+\gamma \rightarrow p(n)+\pi^0(\pi^+)$
- $p+\gamma \rightarrow p+ e^+ + e^-$
- $\pi^0 \rightarrow \gamma+\gamma,\ \pi^+ \rightarrow \mu^+ + \nu_\mu$
- $\gamma+\gamma \rightarrow e^+ + e^-$

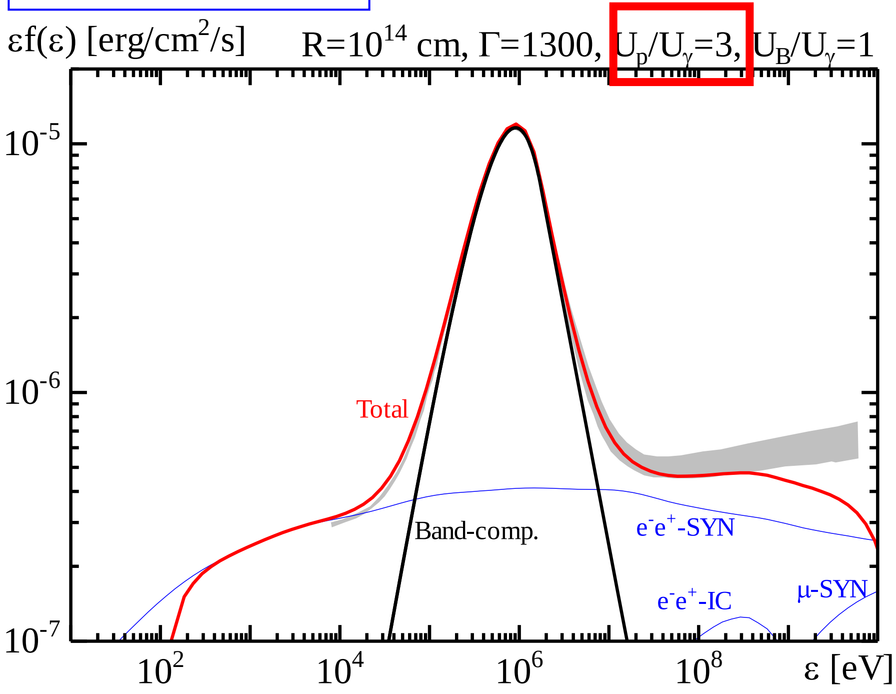
See Vietri 1997; Dermer & Atoyan 2006 etc.

GRB 090510



Asano, Guiriec & Meszaros 2009

GRB 090902B



Asano, Inoue and Meszaros 2010

Weak magnetic field ->
enhance SSC component,
but low cascade efficiency

$$U_B / U_\gamma = 10^{-3}$$

$$\boxed{L_p / L_\gamma = 200}$$

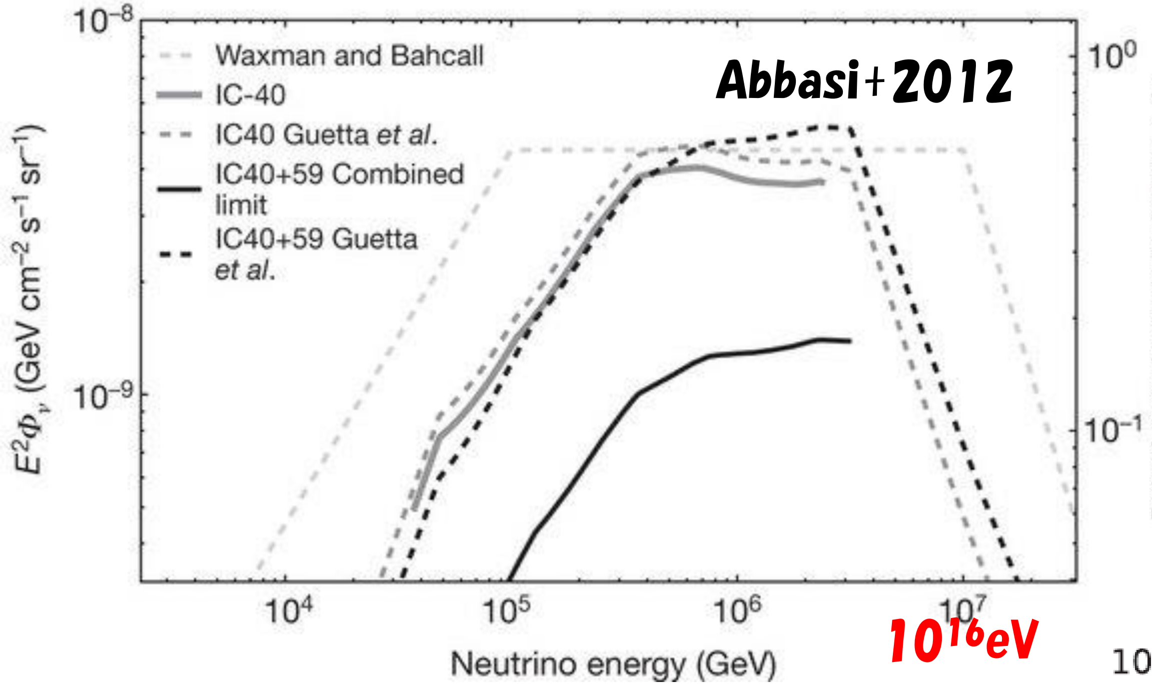
Do not need SSC

⇒ strong B

⇒ high cascade efficiency

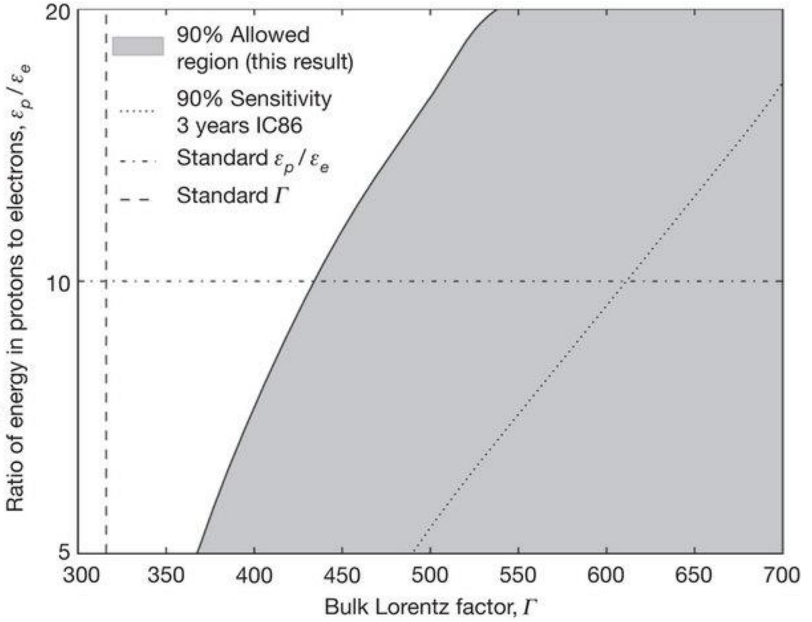
⇒ Energies of protons and photons are comparable.

No Neutrino detection from GRBs

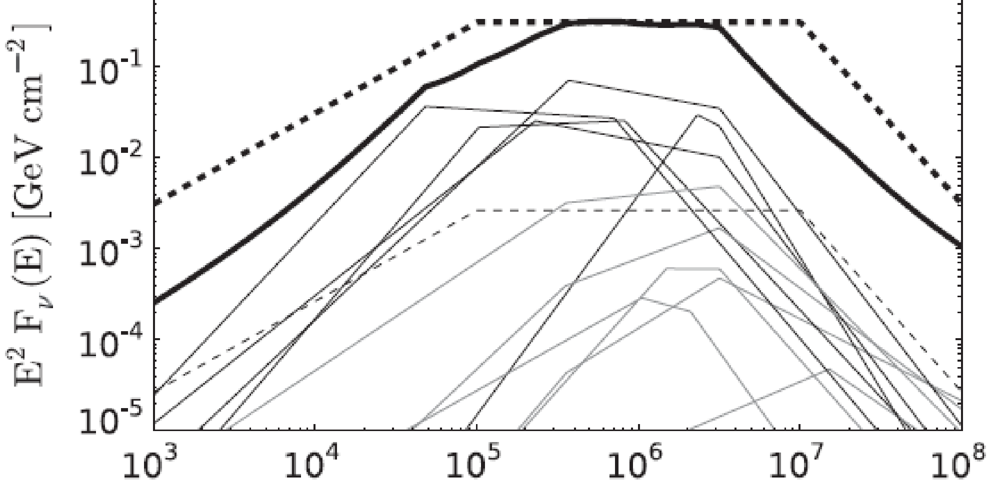


Abbasi+2012

10^{16}eV

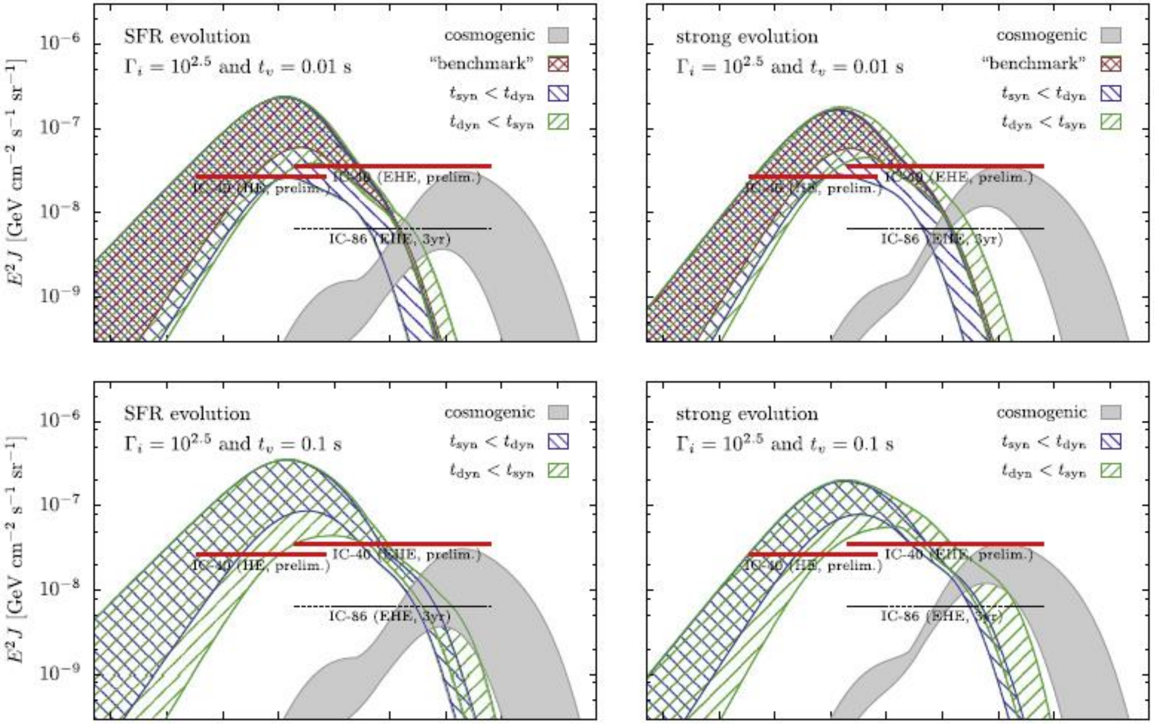


- **"Benchmark" = Γ = 300, δt = 10ms, $L_p/L_\gamma = 10$**

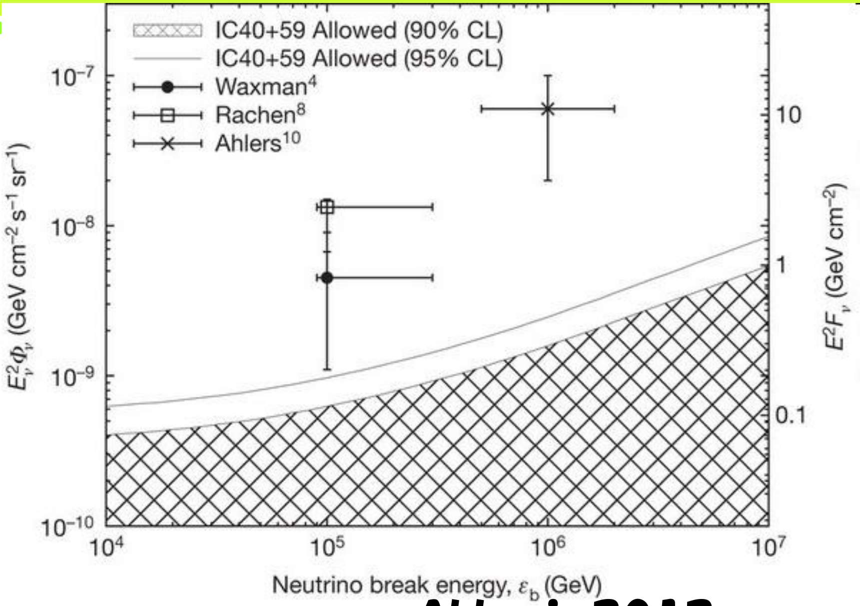


Abbasi+2011

UHECR-GRB Scenario

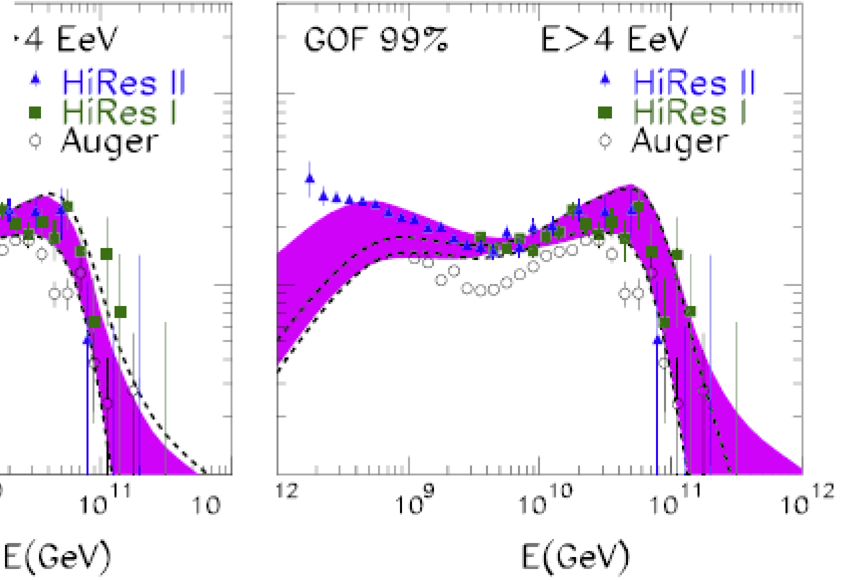


Ahlers+ 2011



Abbasi+2012

GRB scenario is rejected?

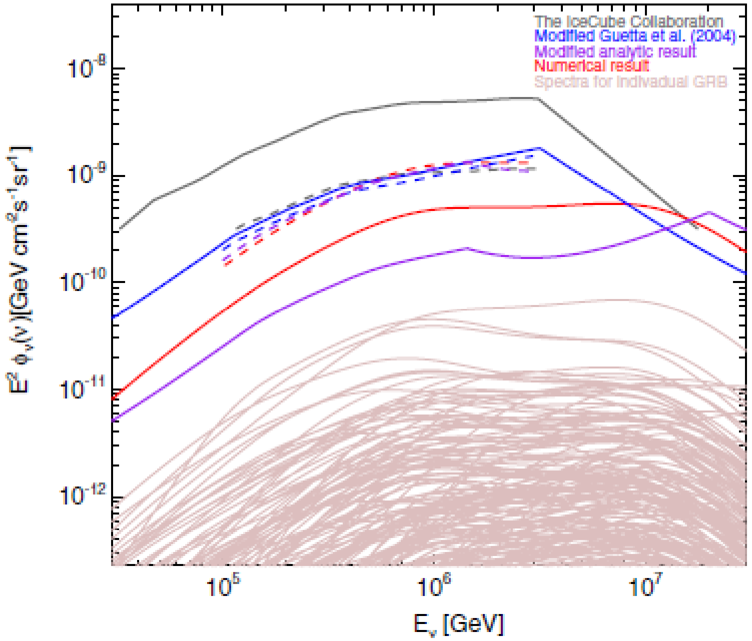


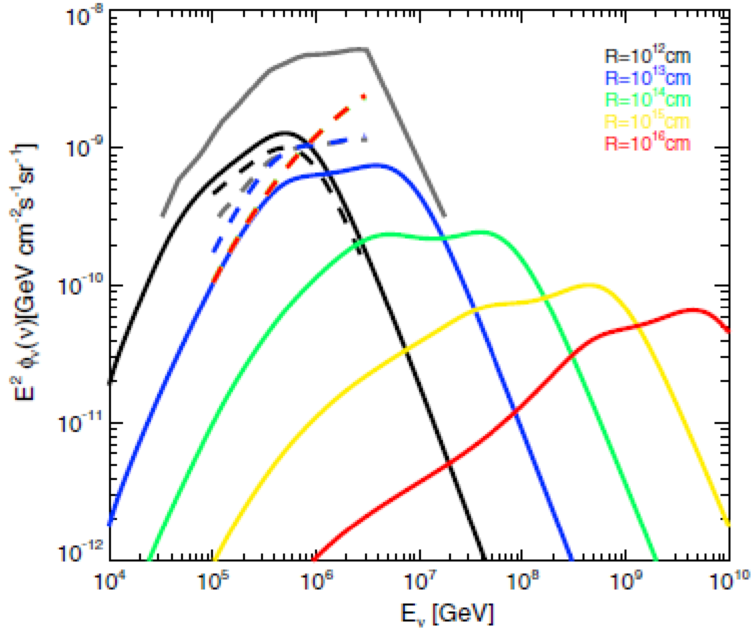
"Benchmark" Case

The Astrophysical Journal, 752:29 (10pp), 2012 June 10
doi:10.1088/0004-637X/752/1

ICECUBE NONDETECTION OF GAMMA-RAY BURSTS: CONSTRAINTS ON THE FIREBALL PROPERTIES

Hao-Ning He[1,2,3], Ruo-Yu Liu[1,2], Xiang-Yu Wang[1,2], Shigehiro Nagataki[3], Kohta Murase[4], and Zi-Gao Dai[1,2]





The benchmark case (Γ =300, f_p=10, 10ms) is OK.

PHYSICAL REVIEW D 85, 027301 (2012)

See also, Note on the normalization of predicted gamma-ray burst neutrino flux

Zhuo Li

Neutrino non-detection from a very bright GRB

THE ASTROPHYSICAL JOURNAL LETTERS, 772:L4 (5pp), 2013 July 20
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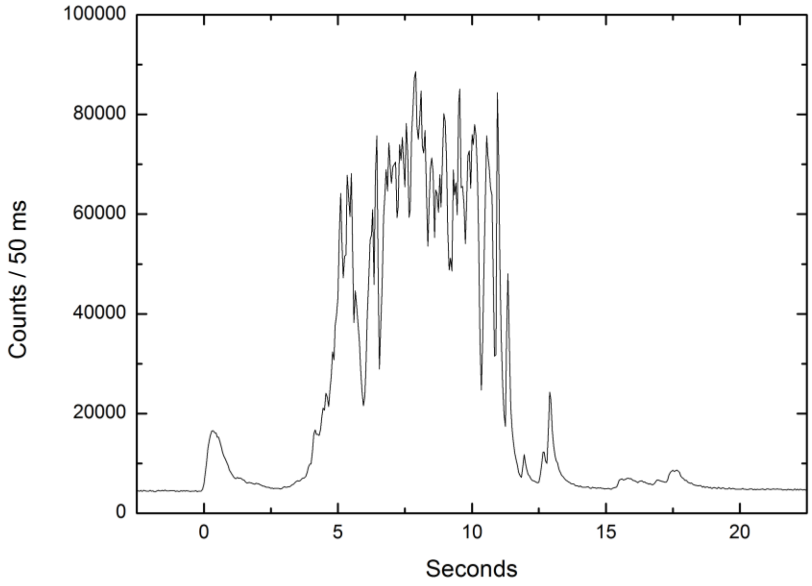
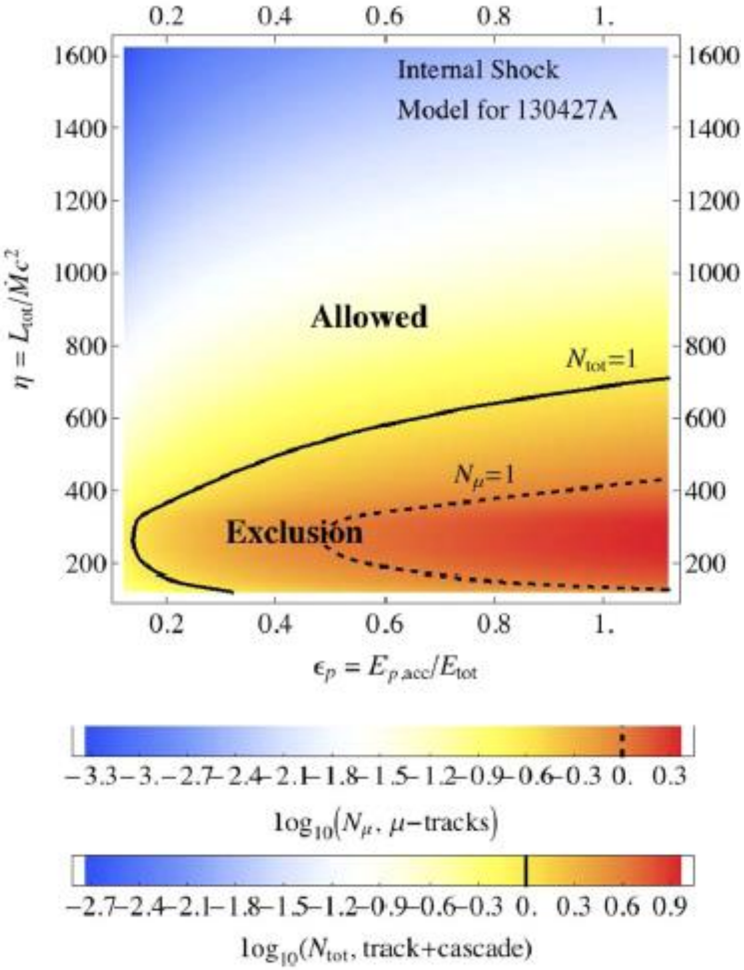
GRB 130427A



$z=0.34$
$\sim 10^{-3}$erg/cm^2

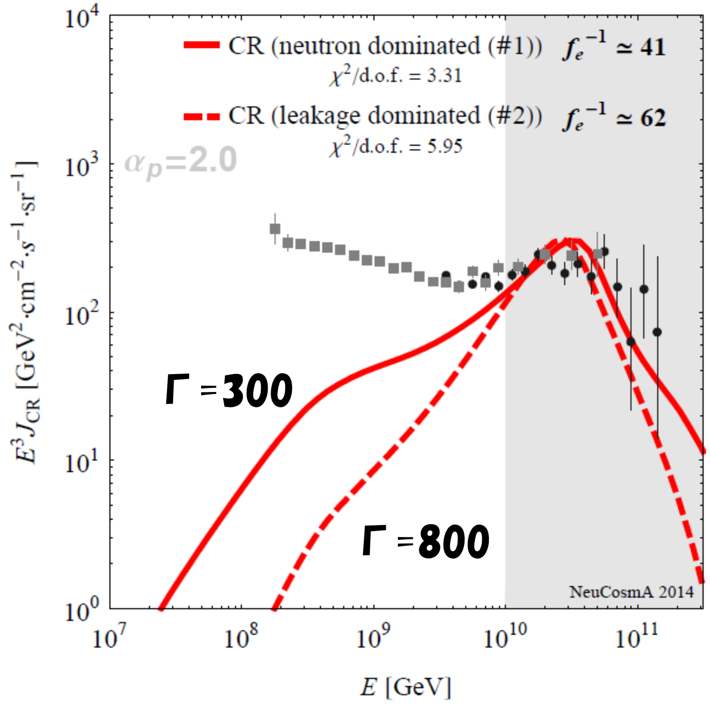
ON THE NEUTRINO NON-DETECTION OF GRB 130427A

SHAN GAO, KAZUMI KASHIYAMA, AND PETER MÉSZÁROS

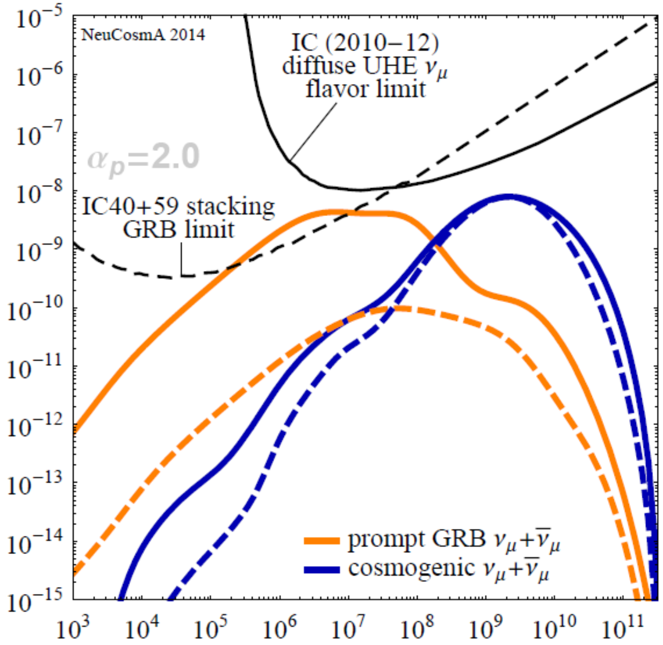


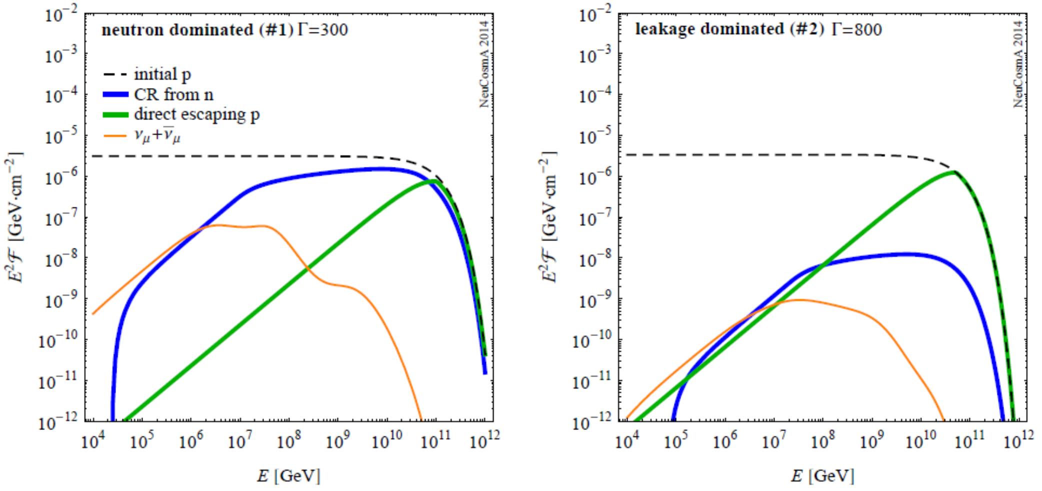
If GRB rate=Star Formation Rate

Baerwald+ 2014



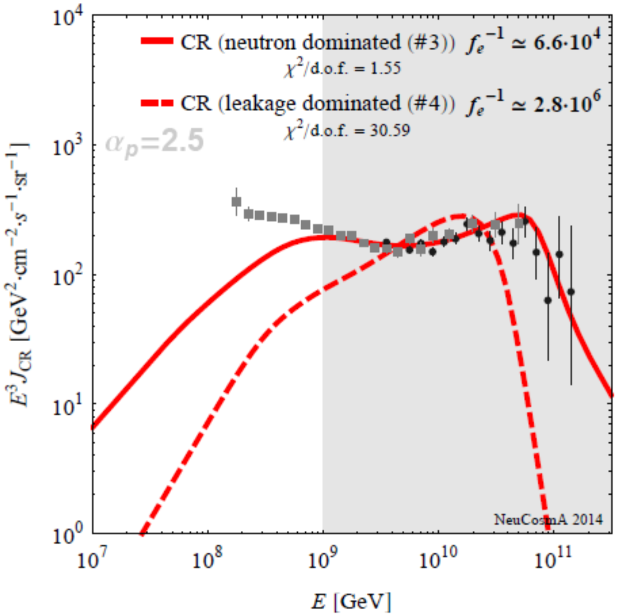
Hopkins & Beacom star formation rate

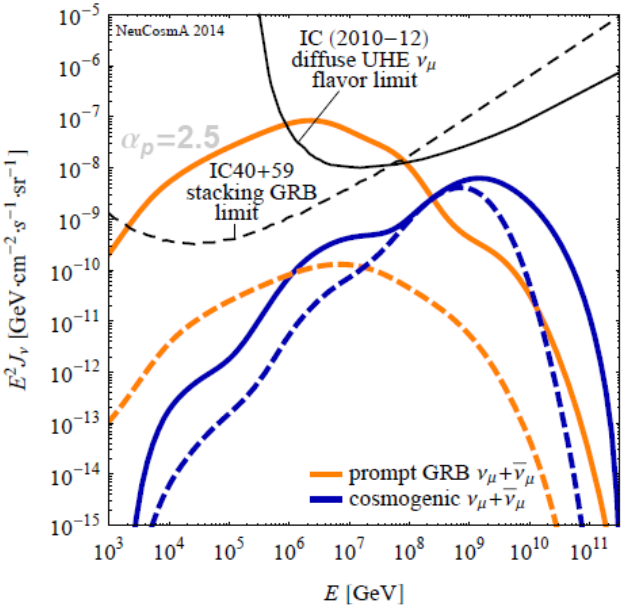


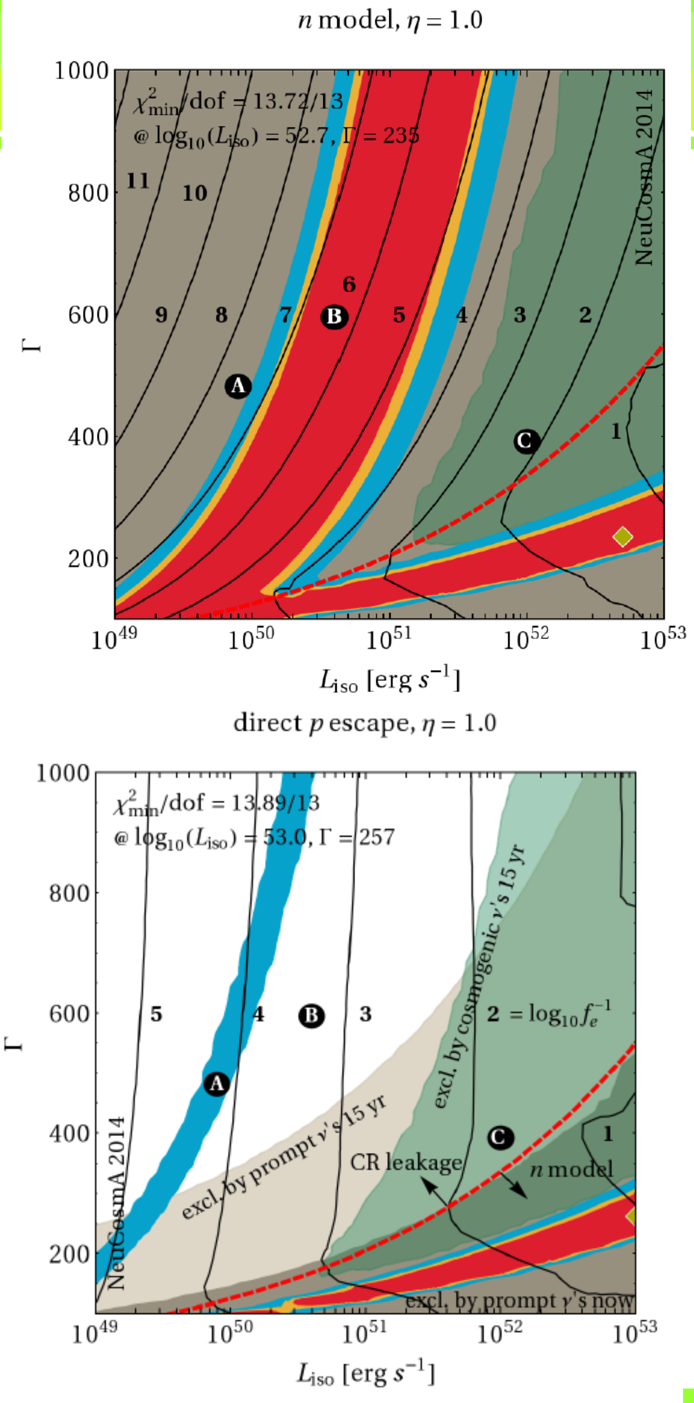


Cont.

Dip model…





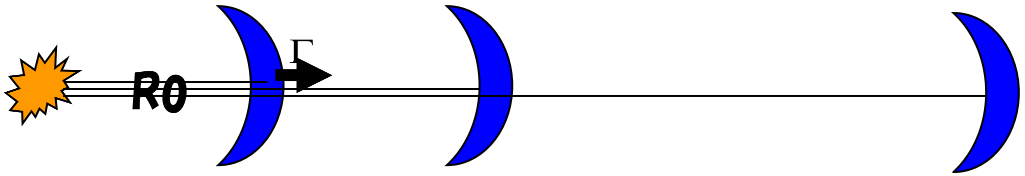


The dip model requires a huge baryon load.

The ankle model seems still OK.

Time-dependent calculation

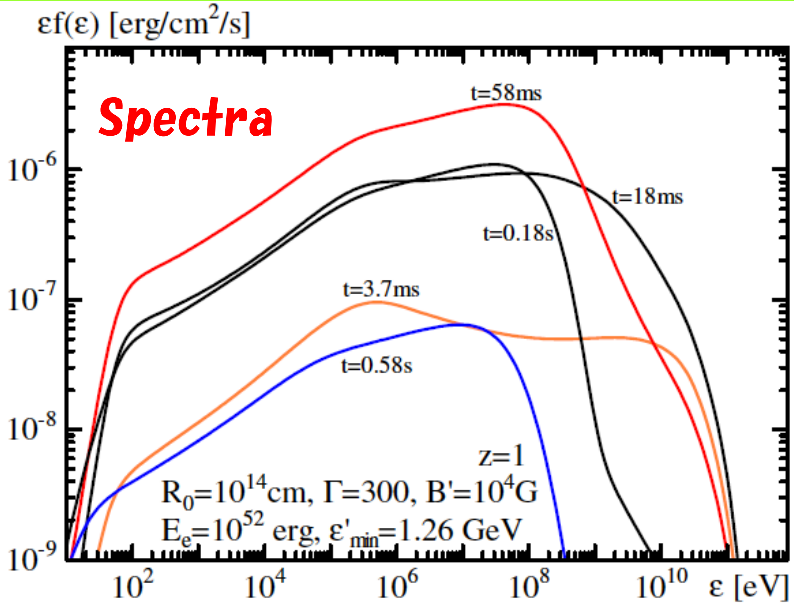
Asano & Meszaros 2011 & 2012

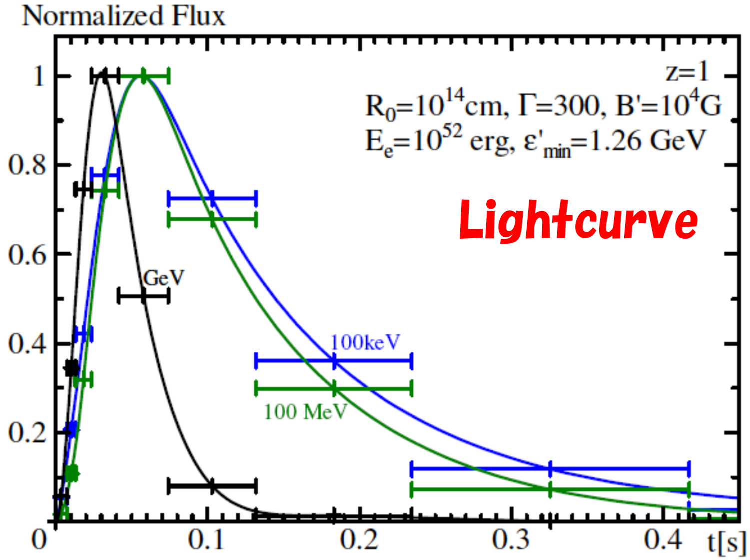


One-zone approximation in a shell

- Relativistically expanding shell (from $R=R_0$)
- Synchrotron
- Inverse Compton (Thomson scat – Klein-Nishina regime)
- Synchrotron self-absorption
- Electron-positron pair creation
- Adiabatic cooling
- Photon escape
- Lagrangian scheme in energy space
- $p(n)+\gamma \rightarrow p(n)+\pi^0(\pi^+)$
- $p(n)+p \rightarrow p(n)+p+\pi^0(\pi^+)$
- $p+\gamma \rightarrow p+e^+ + e^-$
- $\pi^0 \rightarrow \gamma+\gamma,\ \pi^+ \rightarrow \mu^+ + \nu_\mu$
- $\mu^+ \rightarrow e^+ + \nu_\mu + \nu_e$
- Synchrotron from p, π^+, μ^+
- Inverse Compton from p, π^+, μ^+

See also Pe'er & Waxman 2005, Pe'er 2008, Belmont+ 2008, Vurm & Poutanen 2009, Bosnjak+ 2009, Daigne+ 2011

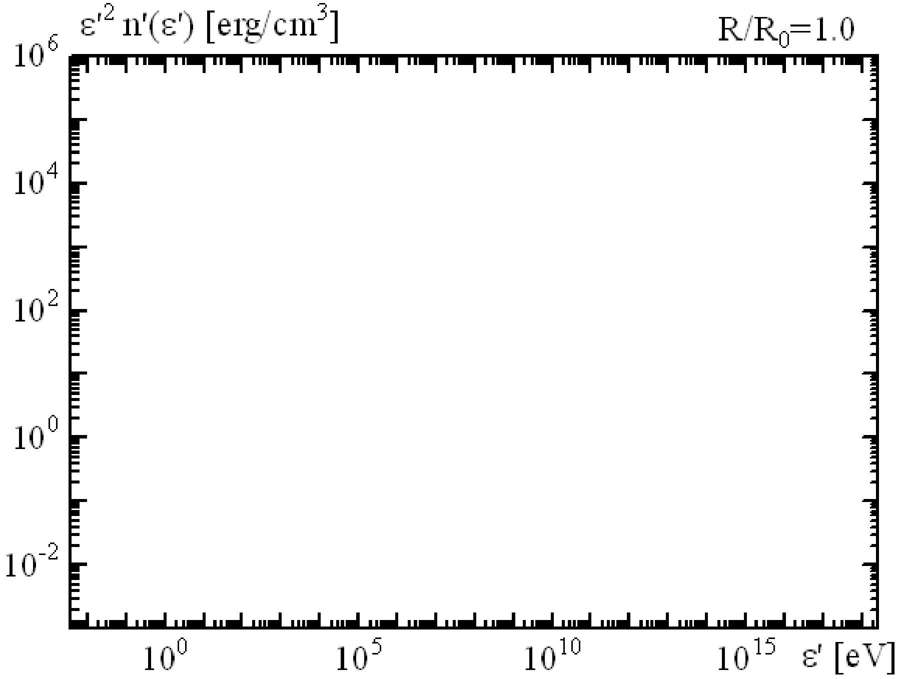




Usual internal shock model

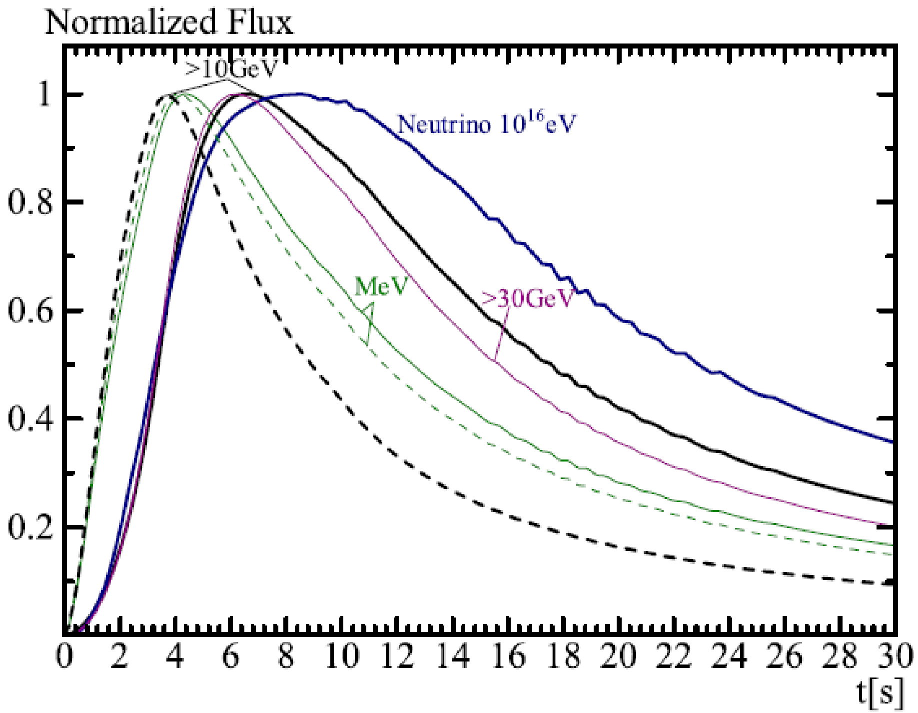
Time-Dependent Simulation

In this method, the photon and neutrino spectra are consistent!
(Remind that the top-down UHECR model is rejected
by the absence of the secondary particles)



Asano & Meszaros 2012

$R_0 = 10^{15}$ cm, $\Gamma = 800$,
$Ee = 10^{52}$ erg, $Ep = 10^{53}$ erg,
$U_B/Ue = 0.1$ ($B \propto 1/R$)
$\varepsilon'_{min} = 1.4$ GeV



Broad and delayed light curve
in GeV-TeV range.
→ Hadronic signature

Constraints

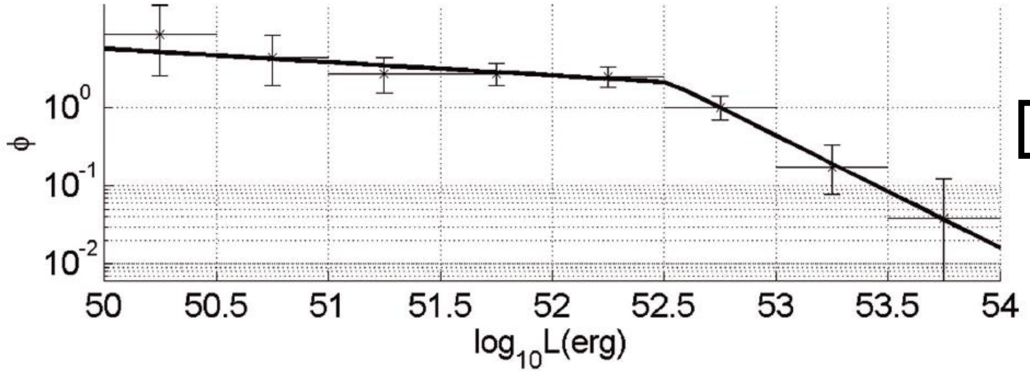
- Luminosity Function
- Evolution of GRB rate
- Shock Radius ⇔ Variability Timescale ($\delta t \sim R/\Gamma^2/c$)
- Photon Spectrum (ε_p-L_p relation)
- Pulse Number per burst (E_p-L_p relation + δt)

Free Parameters

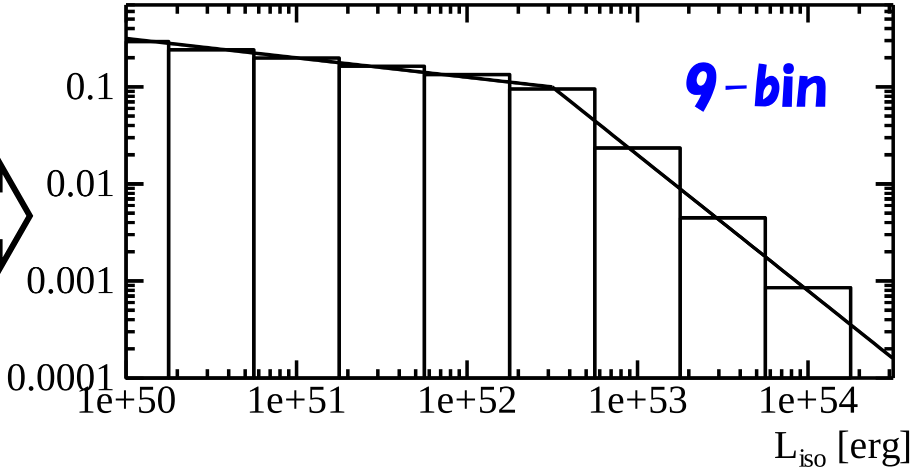
- Magnetic Field (L_B/L_γ)
- Amount of Protons (L_p/L_γ)
- Bulk Lorentz Factor

Revisiting the classical model

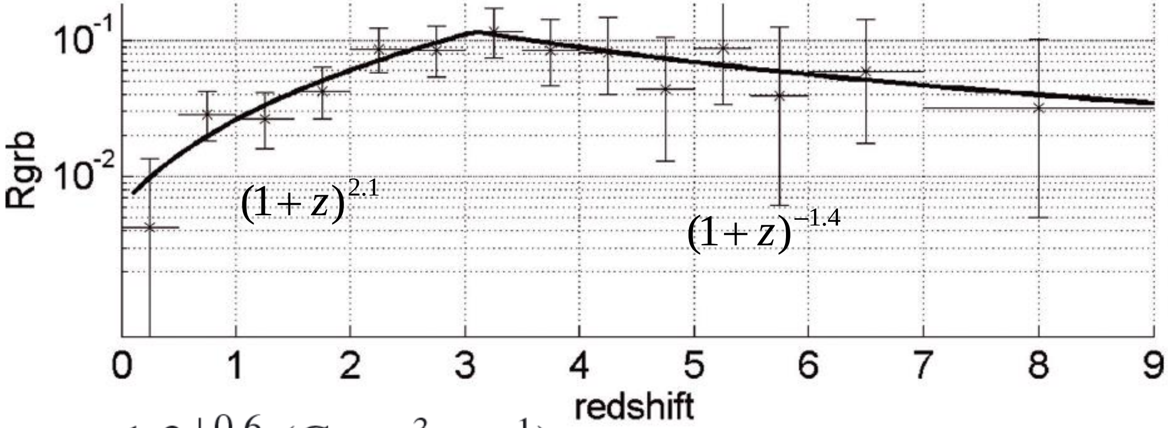
Luminosity function



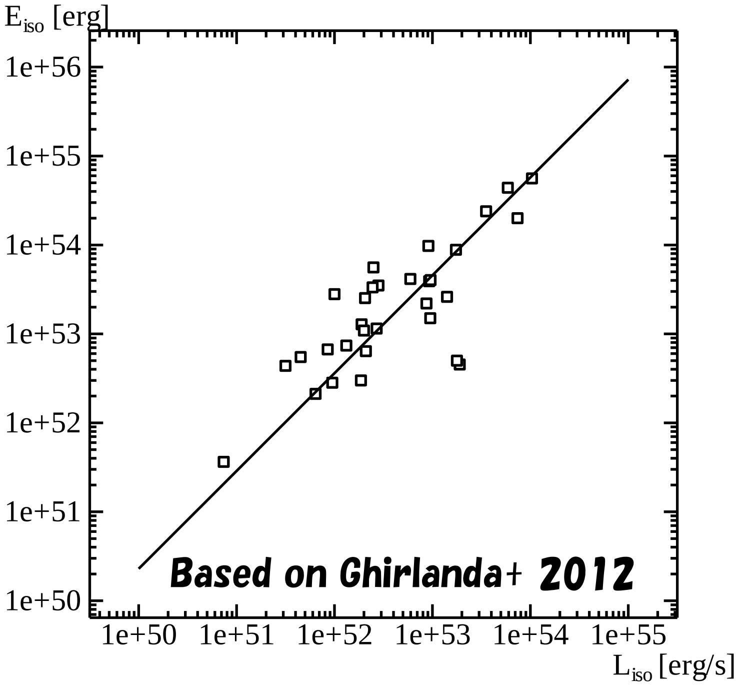
Wanderman & Piran 2010



Redshift distribution



$\rho_0 \simeq 1.3^{+0.6}_{-0.7}$ (Gpc^{-3} yr^{-1})



Based on Ghirlanda+ 2012

+ Yonetoku relation

Variability Timescale

Arimoto, Kawai, Asano+ 2010

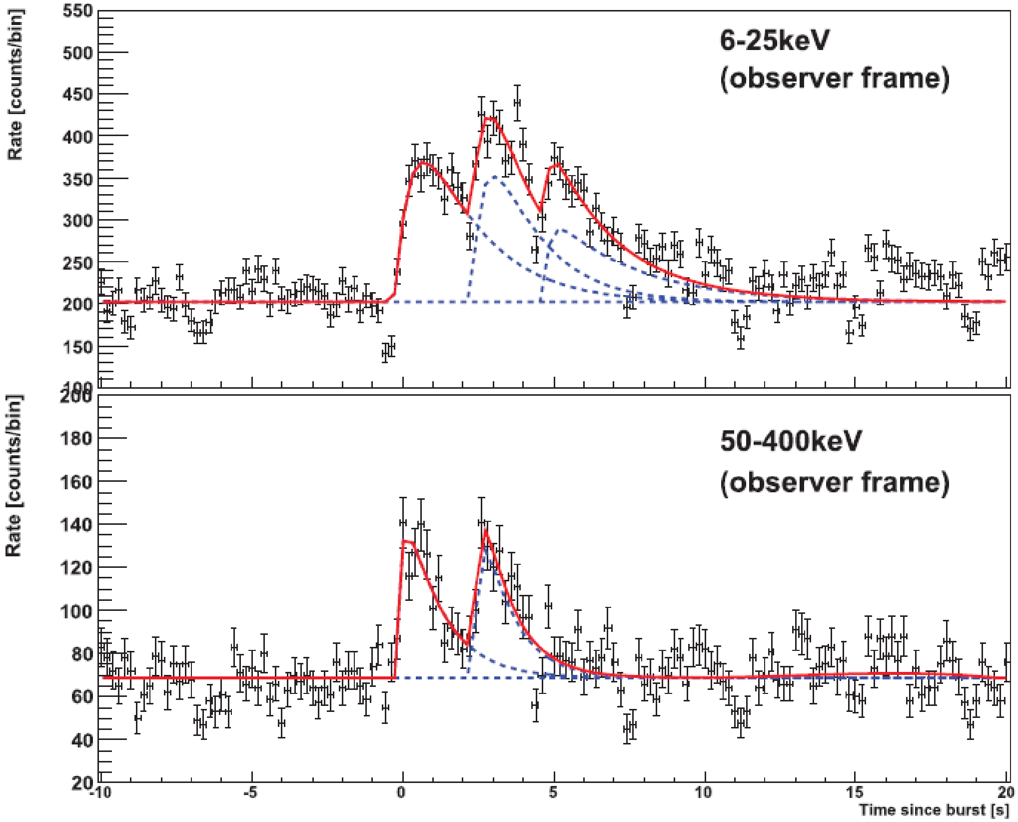
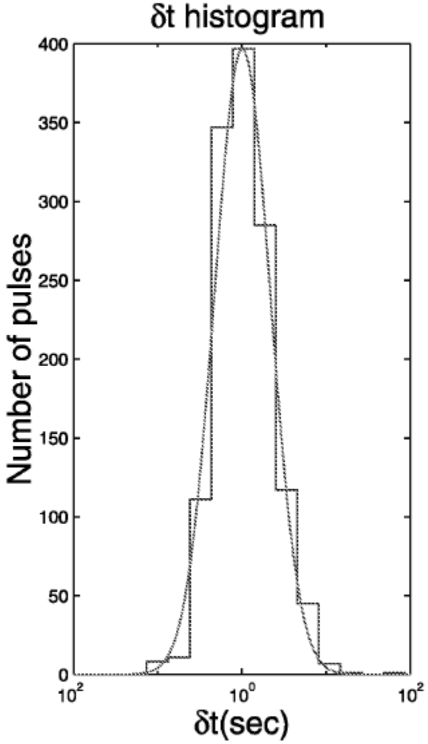


Fig. 2. Pulse fit for GRB 050408 in the 6–25 keV and 50–400 keV bands in the observer's frame.

HETE-2

Pulse timescale

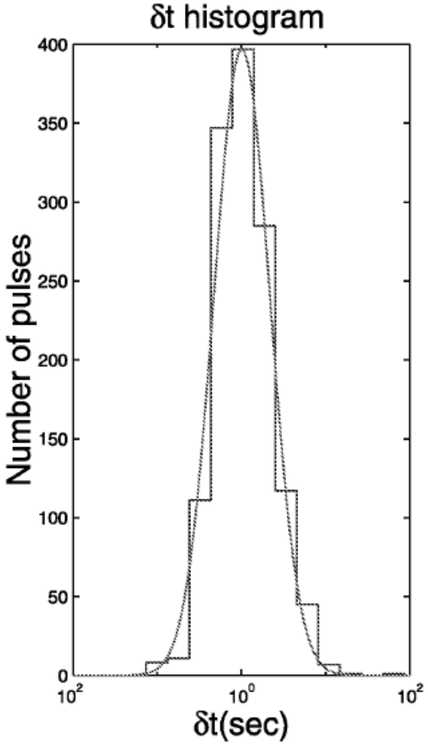


Nakar & Piran 2002
Log-normal: $\sigma = 0.77$

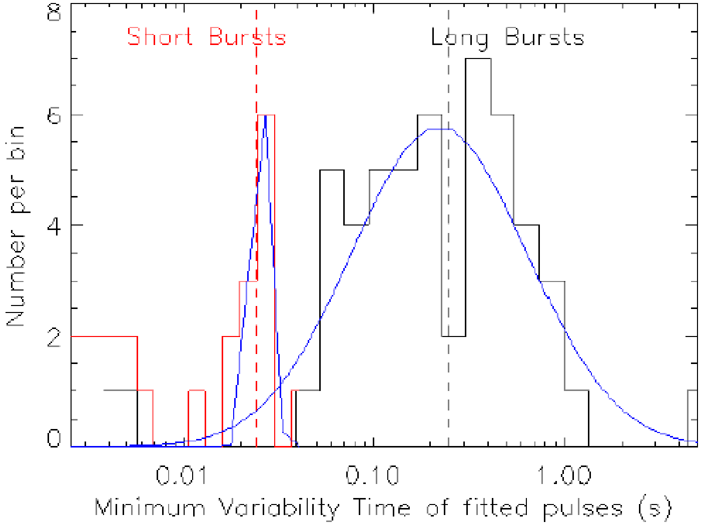
The universality of the variability timescale ＝10ms is not established.

Revisiting the classical model

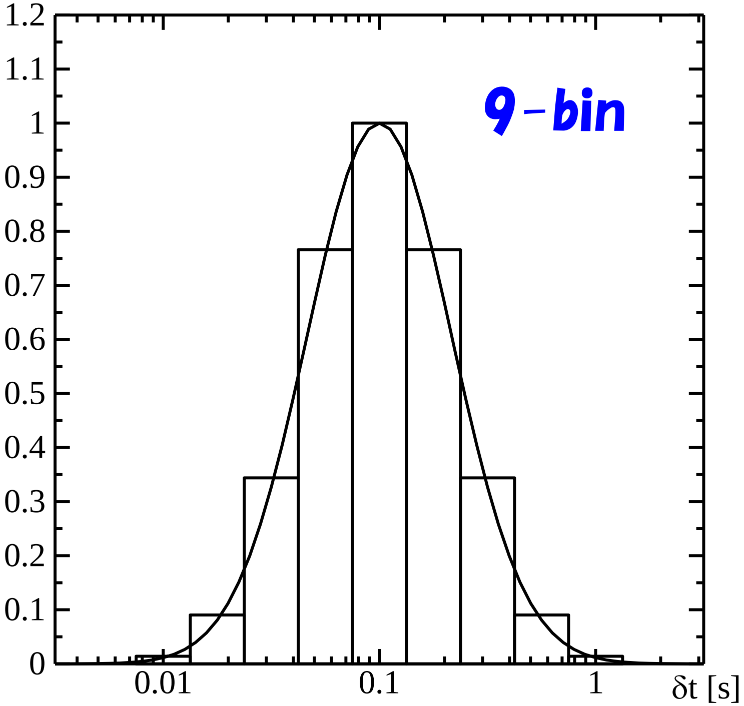
Pulse timescale



Nakar & Piran 2002
Log-normal: σ =0.77



Bhat 2013



Emission radius

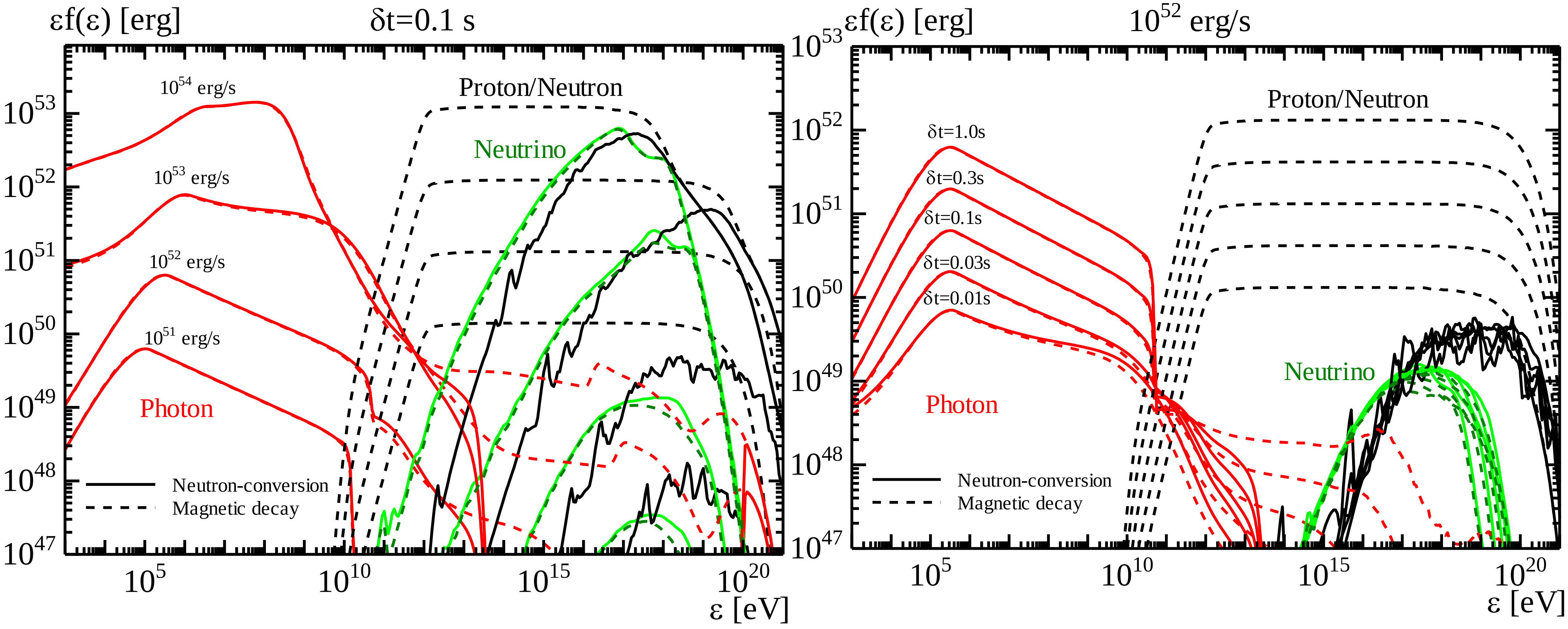
$$R \sim c\delta t\Gamma^2$$

Time-dependent simulation

$$\frac{L_p}{L_\gamma}=10, \frac{L_B}{L_\gamma}=0.1$$

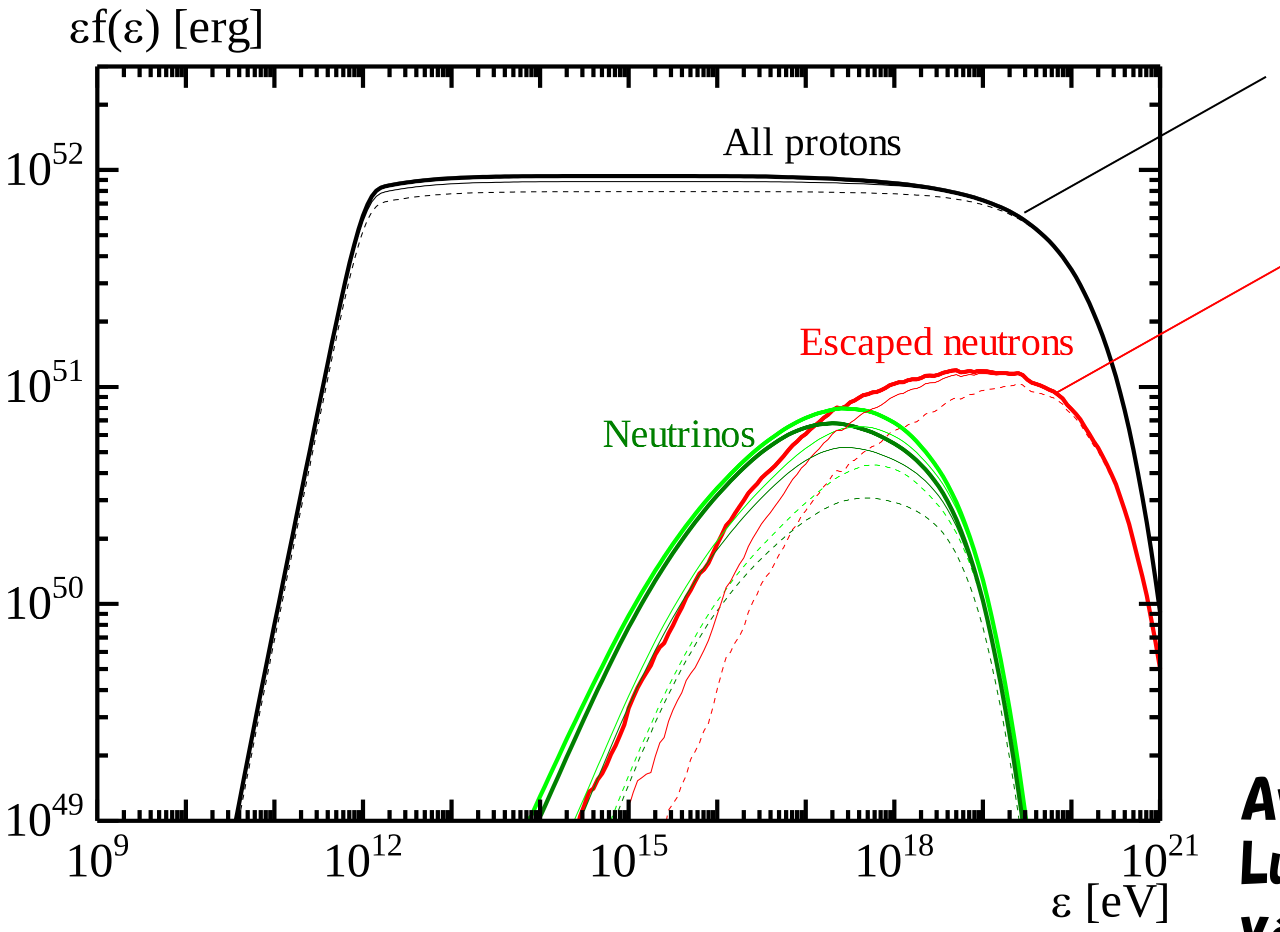
$$\Gamma=300$$

Spectra from one pulse



Numerical code: Asano & Meszaros 2012

Average spectra from a GRB

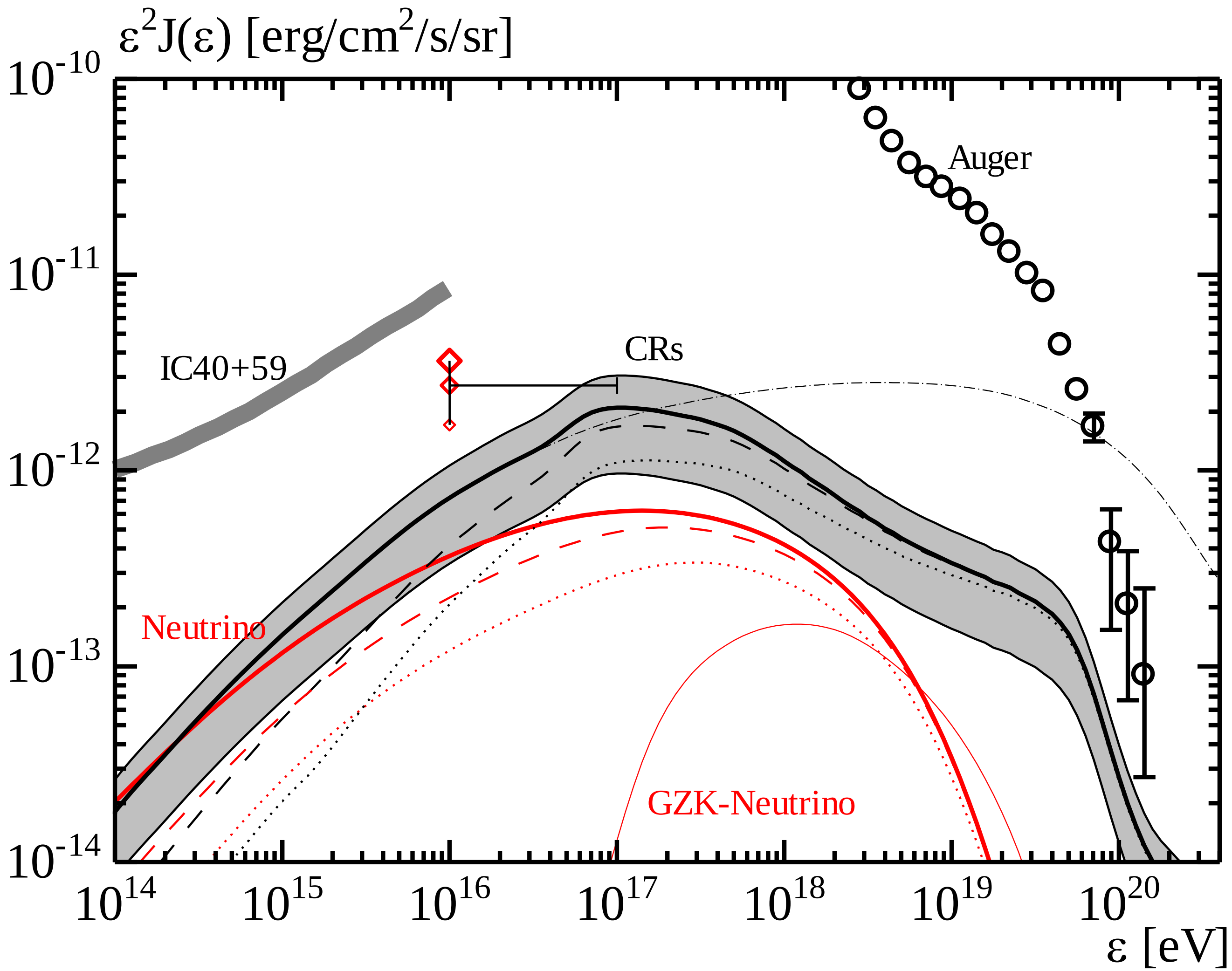


Optimistic case for UHECR production.

Pessimistic case

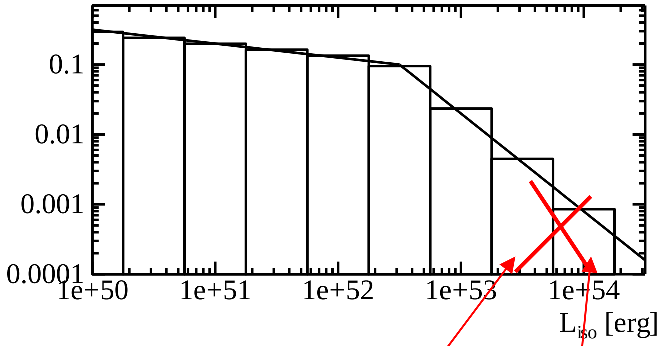
Average over Luminosity and variability timescale

Neutron-conversion model



$$\frac{L_p}{L_\gamma} = 10, \ \frac{L_B}{L_\gamma} = 0.1$$

$$\Gamma = 300$$

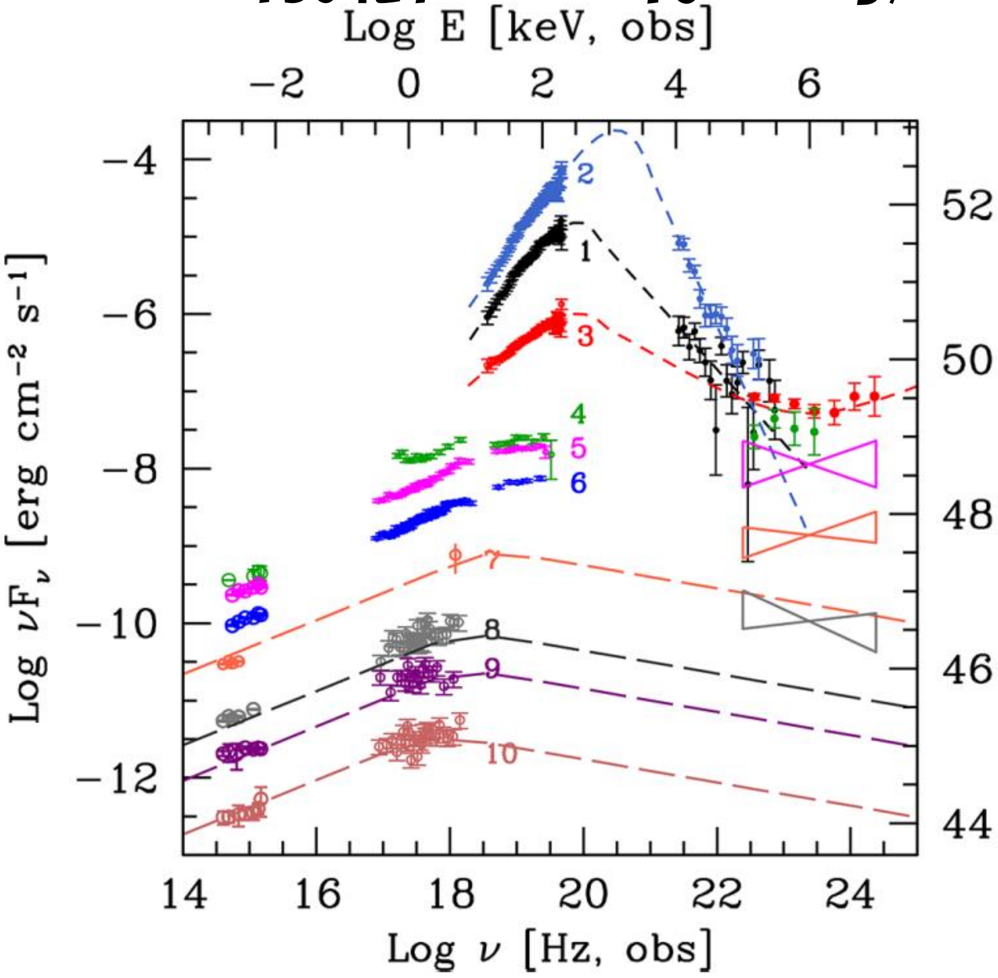


0.4%

0.09%

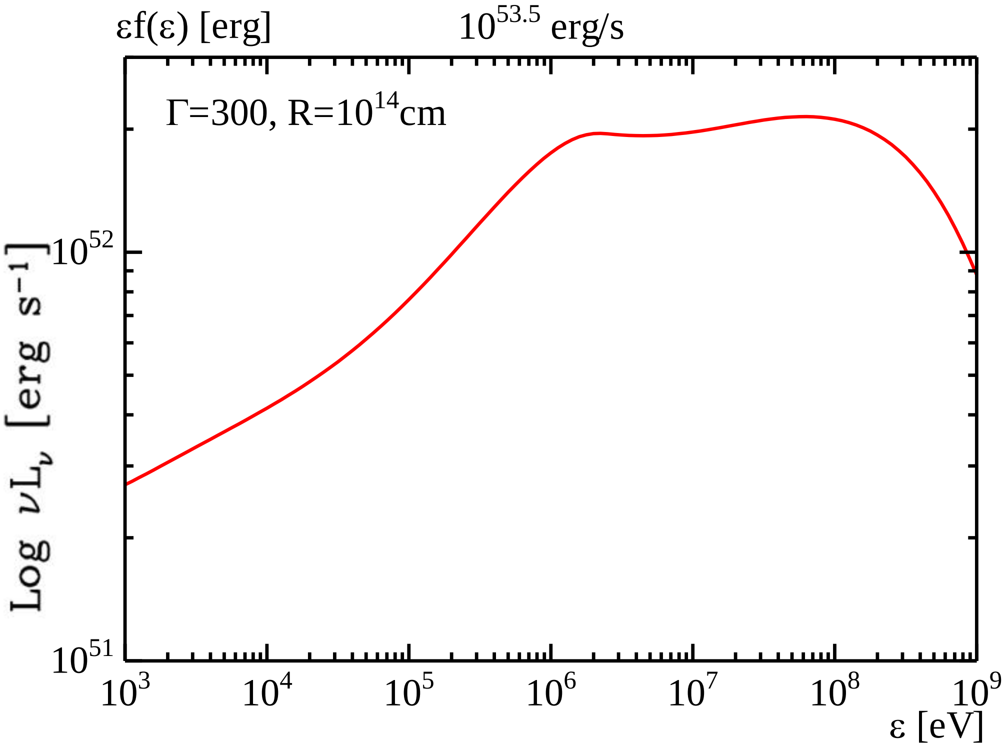
Bright GRBs are inconsistent with the benchmark

GRB 130427A $L \sim 10^{53.5}$ erg/s



Maselli+ 2013

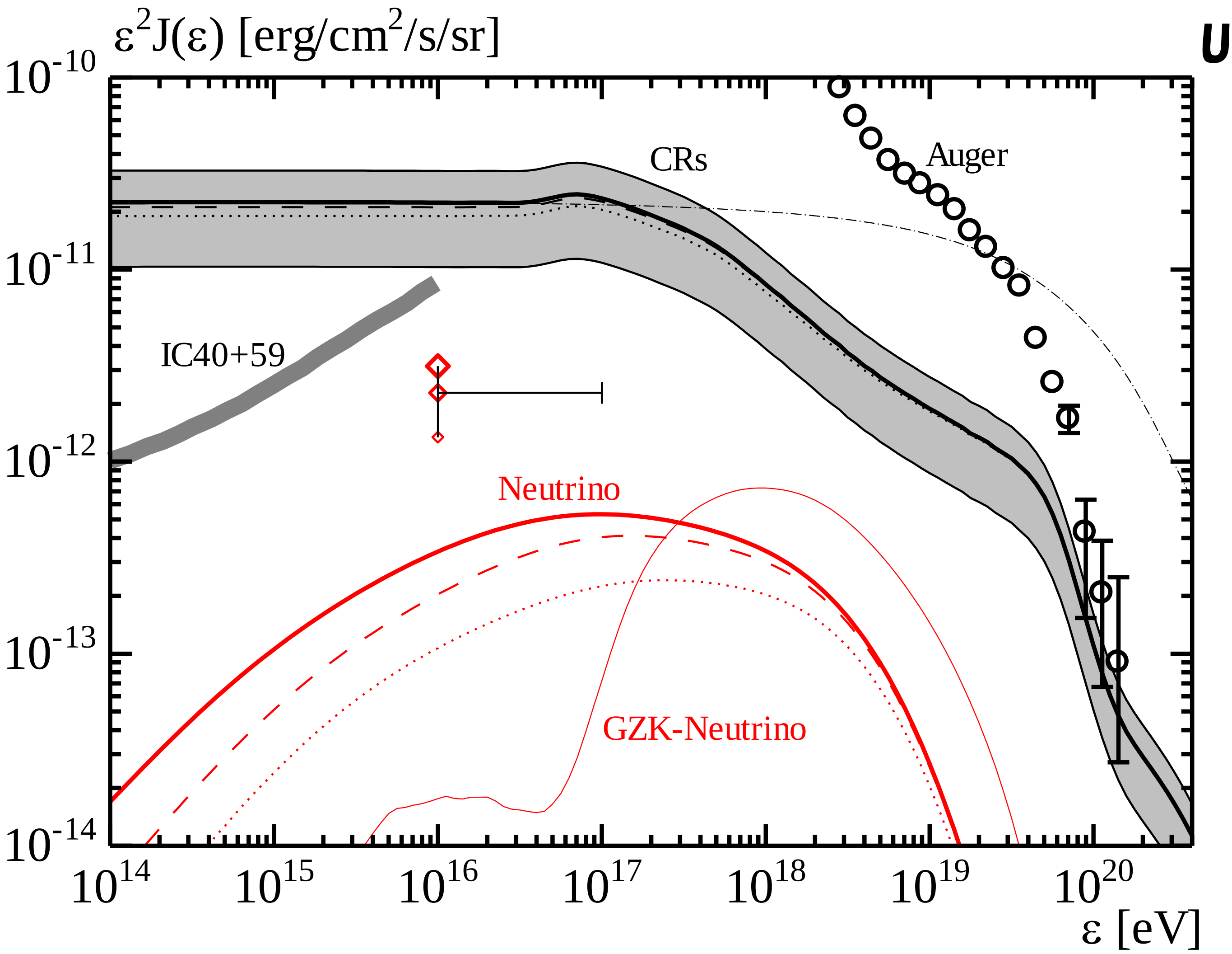
Model calculation



Cascade emission dominates!

→ High Γ, or low Lp

Optimistic model

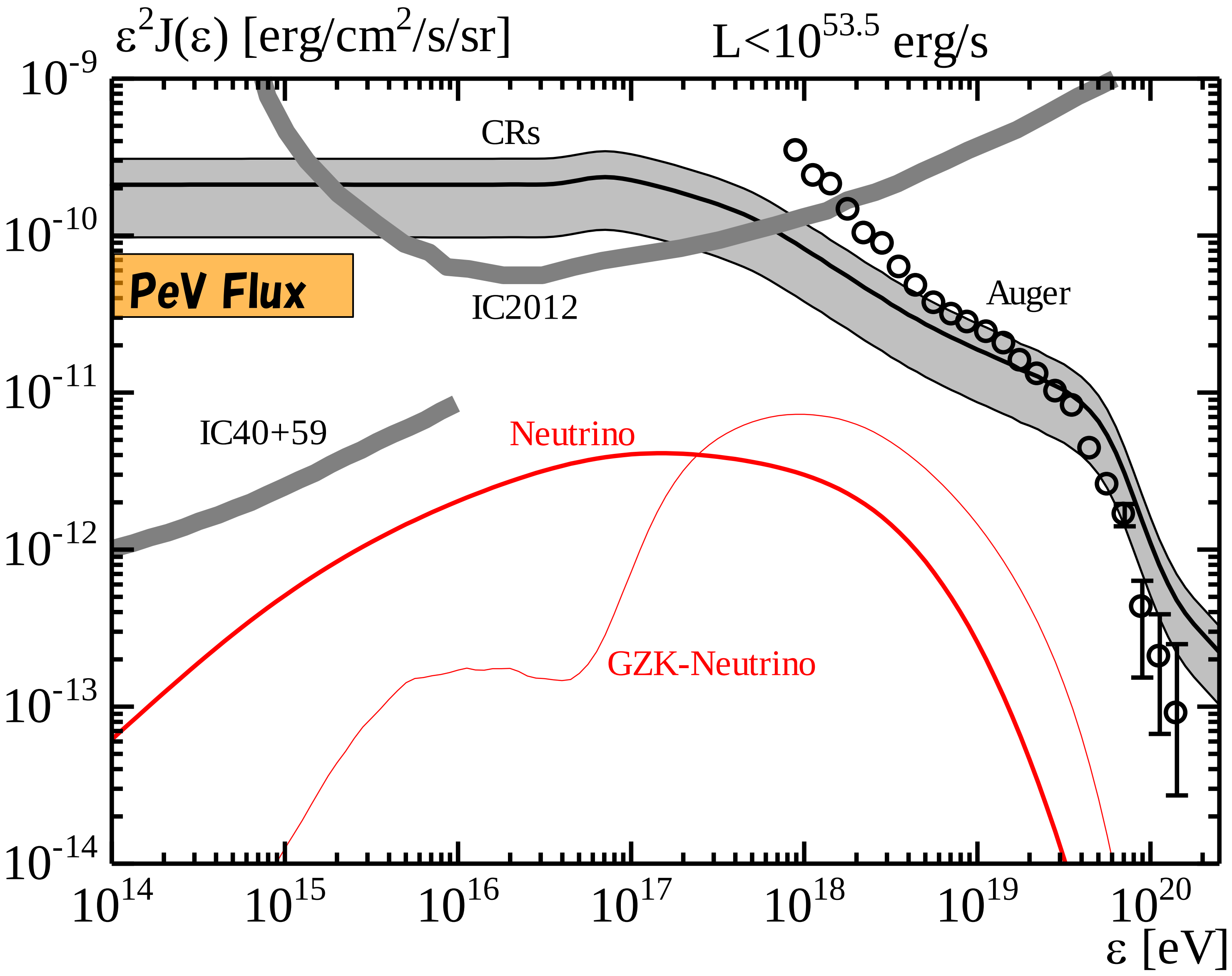


UHECR escaping from $R=3R_0$

$$\frac{L_p}{L_\gamma}=10,\ \frac{L_B}{L_\gamma}=0.1$$

$$\Gamma = 300$$

Further 10times CR Loading



Ankle model with optimistic CR escape

Just assuming enhancement of CR production rate.

Not verified the consistency with the secondary gamma-ray signals.

Summary

- IceCube constrained only neutrinos from a small fraction of GRBs (bright end).
- Most of such GRBs are not likely the source of UHECRs.
- Highest energy UHECRs can be originated from GRBs, but it is not straightforward to agree with the flux at 10^{19}eV (ankle).
- The energy budget allows more protons for usual GRBs.
- Higher Γ for brighter GRBs? This further suppresses the neutrino flux.

予備スライド