Cosmic Accelerators, III:

Ultra-High Energy Cosmic Ray & Neutrino Sources

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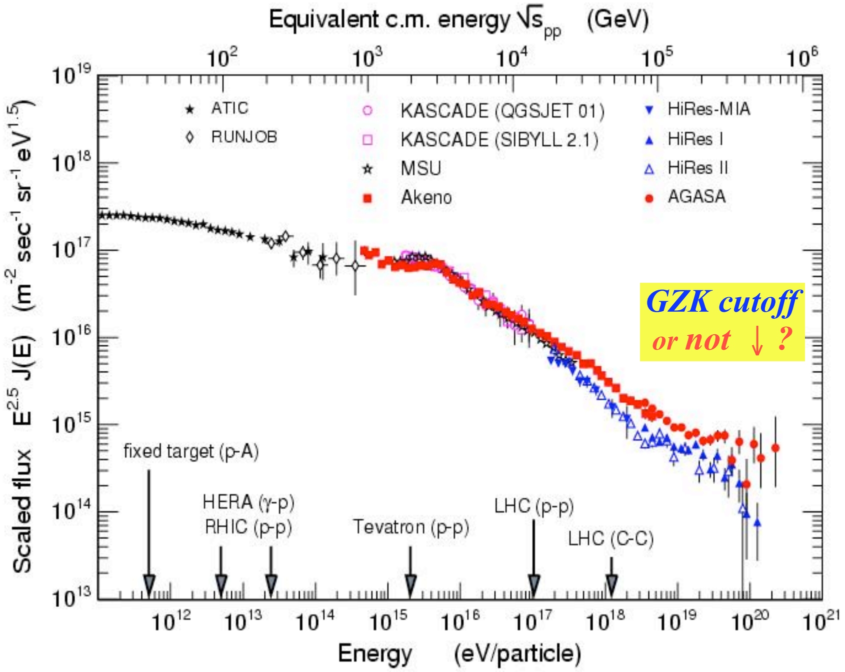
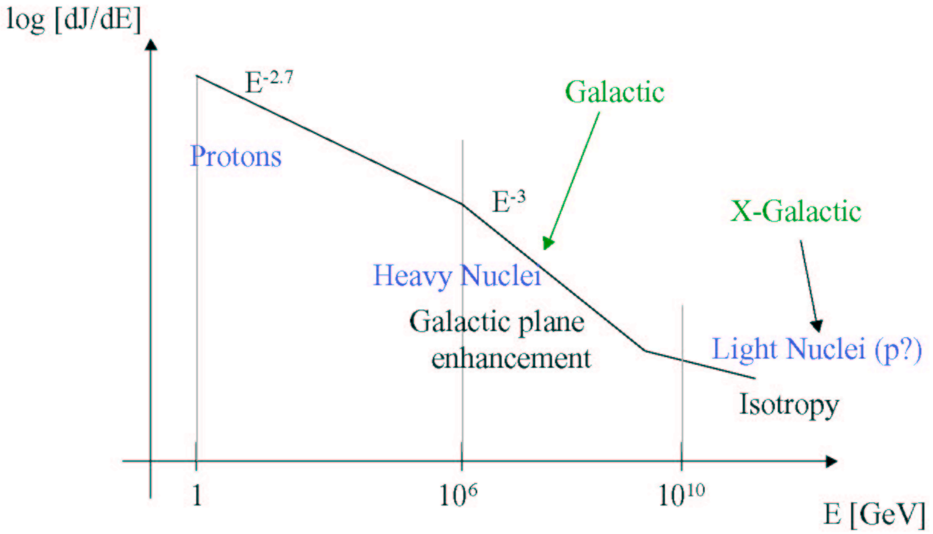
SLAC 2010 Summer School

CR spectrum *(Pre-Auger)*

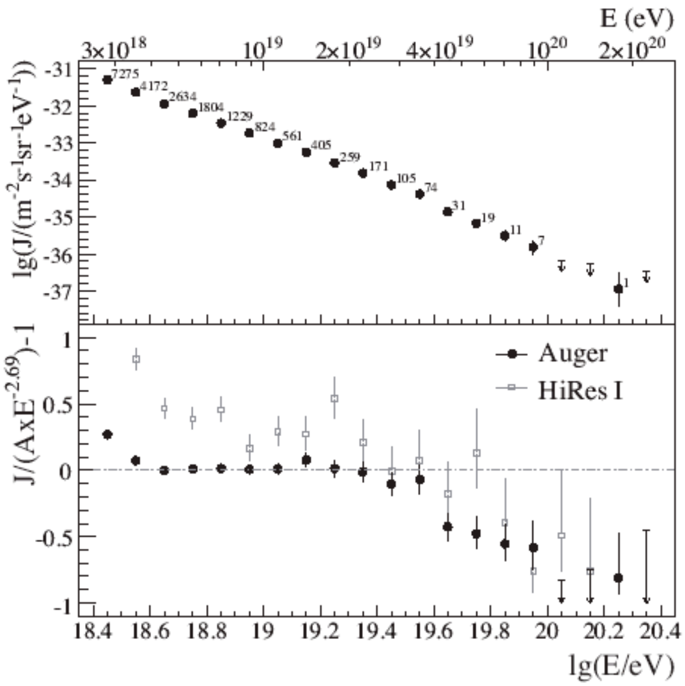


GZK cutoff
or not ↓ *?*

Cosmic ray flux and Composition



$U_{cr}(1GeV)=1\ eV/cm^3$

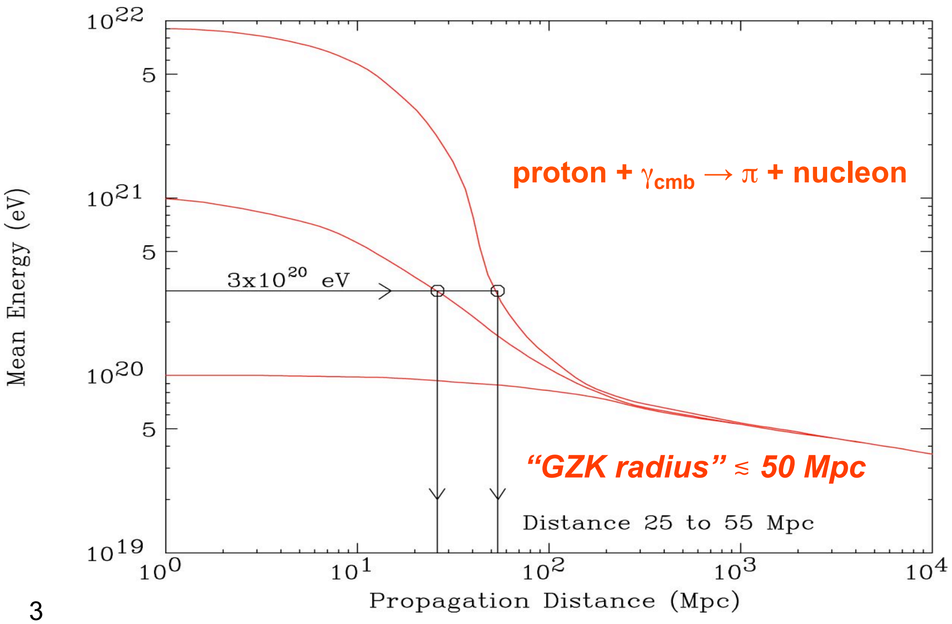


Auger : spectrum

(≳2008)

Cut-off: YES !

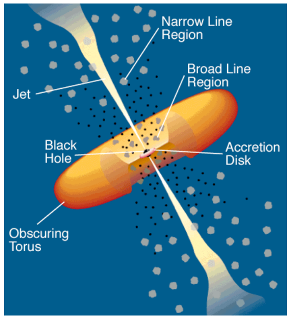
How far do they come from?



proton + $\gamma_{cmb} \rightarrow \pi$ + nucleon

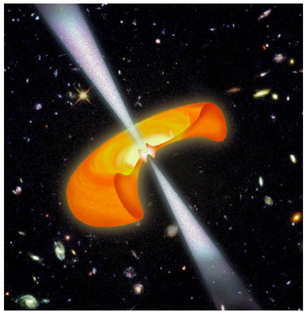
"GZK radius" $\lesssim$ 50 Mpc

Likely Egal UHECR/NU Sources:

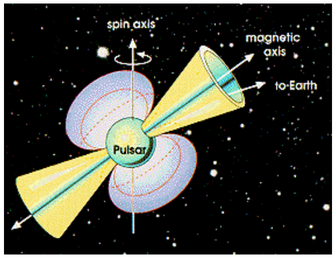


AGN

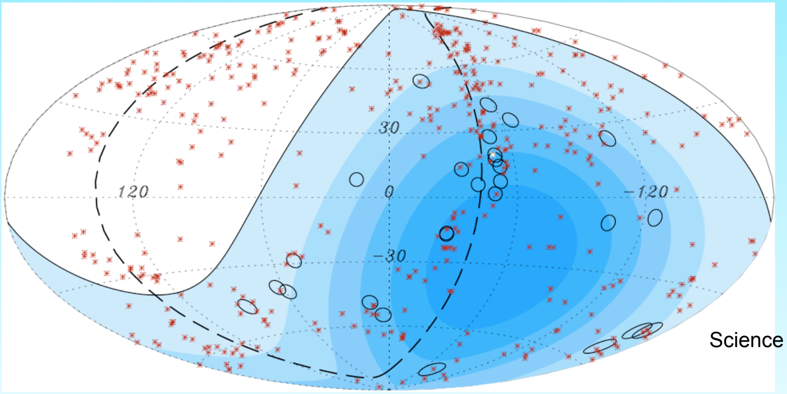
GRB



MGR



AUGER :
UHECR spatial correlations with AGN/LSS



Science Nov 2007

- Dashed line: supergalactic equator
- Circles (proton): Events E>4.5x10^{19} eV
- Crosses: Veron-Cety catalog AGNs

Auger spatial correlation

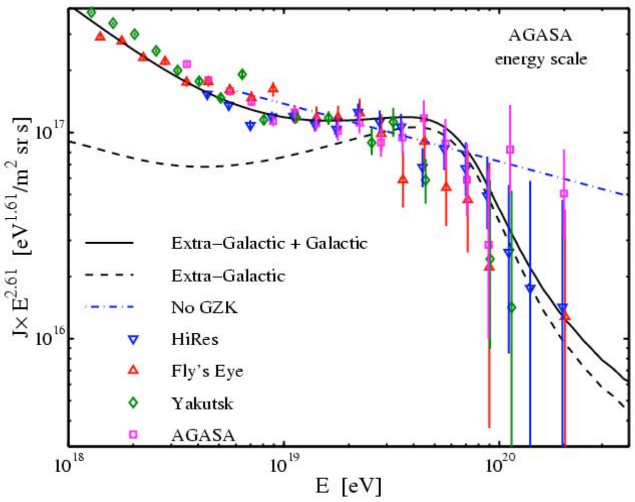
Science, 07

- Found 3σ corr. with V.C. AGNs within 3.5 deg inside 75 Mpc, for 28 events E>4.5x10^{19} eV
- The above correlation suggest protons
- But not sure it is AGNs - could be corr. w. underlying LSS
- Kashti-Waxman confirm correl. with LSS at >98% CL .
- If heavy: many more gals. inside each event's larger angular spread.
- ***But: AGN significance now (09) weakened to 1.7 σ***

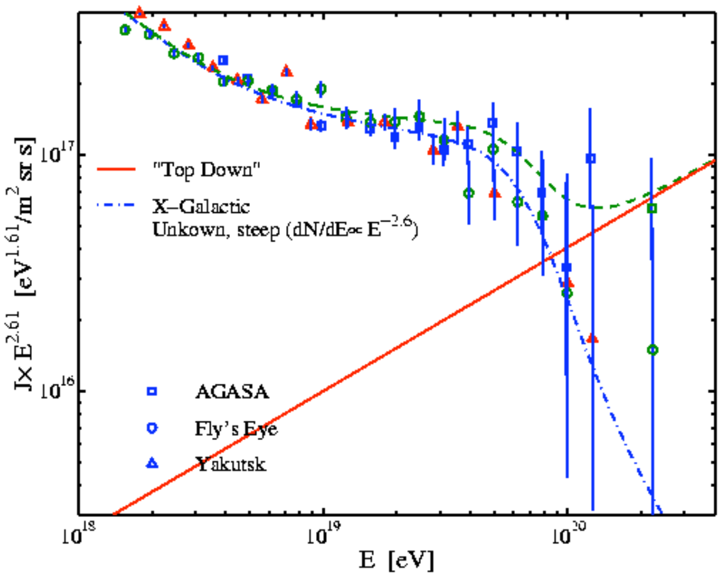
→ ***Could be sources in galaxies - GRB ? HNs? MGRs?***
Or other, less extreme and more common galaxies?

UHECR spectrum vs. Extragal. (GRB, or other Ap.) model

Waxman 06

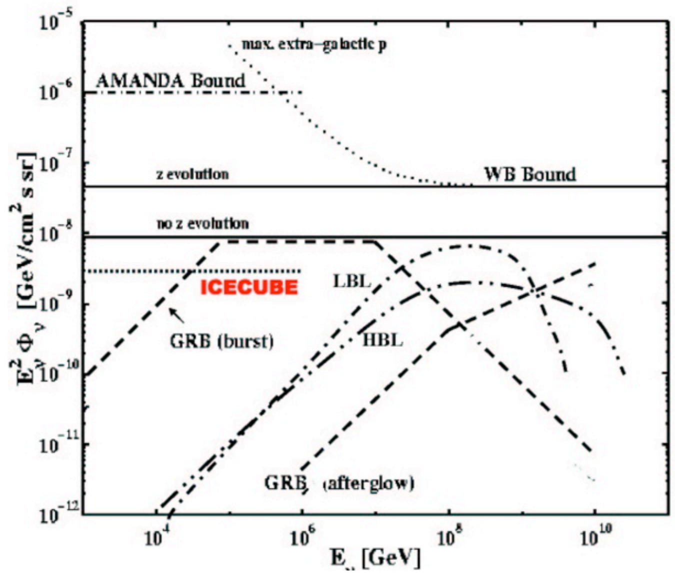


Exotic vs. Astrophysical sources



Waxman-Bahcall (MPR) nu-bound

(limit where all CR protons interact, lead to a ν_μ)



↙ WB assumes max. effic'y of

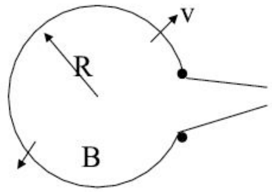
$p,\gamma \rightarrow \pi^\pm$

$\rightarrow \mu^\pm, \nu_\mu$

$\rightarrow e^\pm, \nu_e, \nu_\mu$

← For comparison: some ap. source ν diffuse flux predictions

CR : acceleration ?



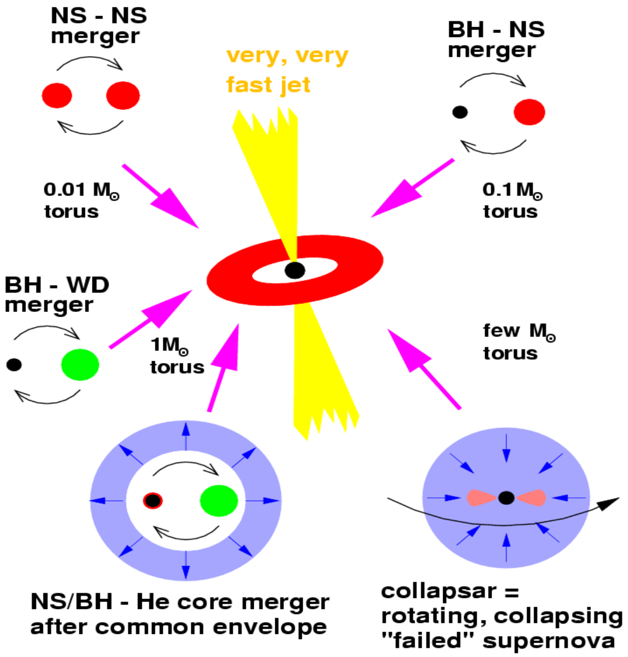
$$V = \frac{1}{c}\dot{\Phi} \sim \frac{1}{c}\frac{BR^2}{R/\mathrm{v}} = \beta\, BR$$

$$\rightarrow \varepsilon_p < \beta e B R$$

$$\Rightarrow L > 4\pi R^2 \frac{B^2}{8\pi} v > \frac{1}{2\beta}\left(\frac{\varepsilon_p}{e}\right)^2 c$$

$$\boxed{\Rightarrow L > 2\frac{\Gamma^2}{\beta}\varepsilon_{p,20}^2 \times 10^{45}\mathrm{erg/s}}$$

GRB:→ Hyperaccreting Black Holes (*via PNS?*)

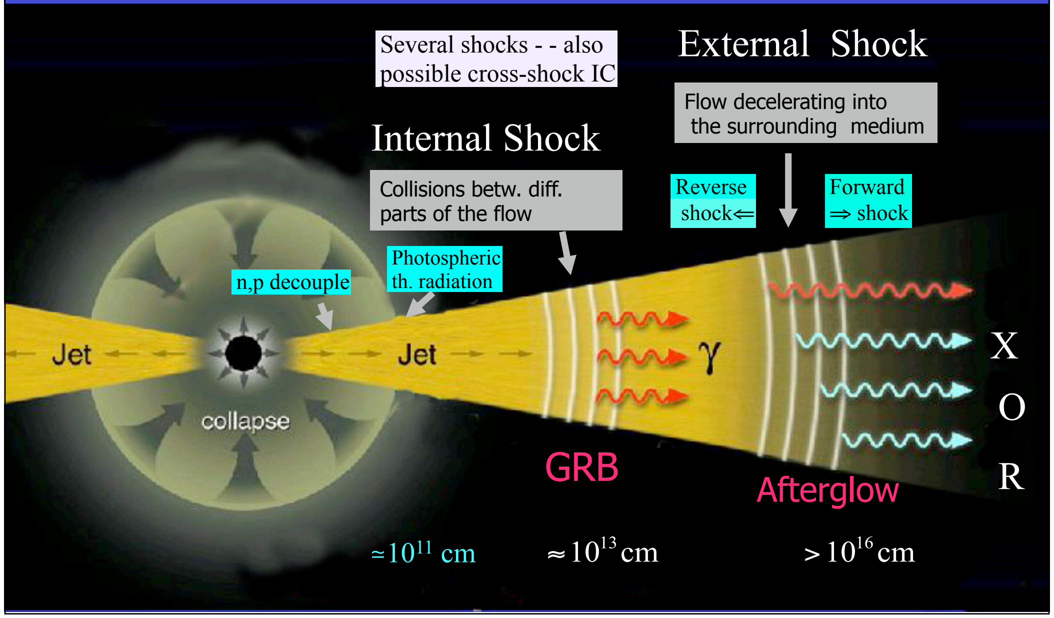


M. Ruffert, H.-Th. Janka, 1998

short

long

Fireball Model of GRBs



Several shocks - - also possible cross-shock IC

External Shock

Flow decelerating into the surrounding medium

Internal Shock

Collisions betw. diff. parts of the flow

Reverse shock⇐

Forward ⇒ shock

n,p decouple

Photospheric th. radiation

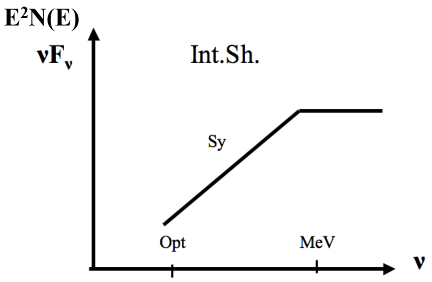
$\simeq 10^{11}$ cm

$\approx 10^{13}$ cm

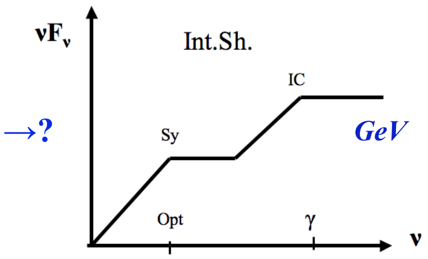
$> 10^{16}$ cm

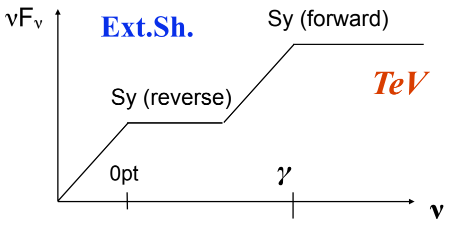
Standard GRB shock γ-ray components :

shock Fermi acc. of e^- → synchrotron and inv.Compton



Or →?





- **GRB 990123** ⟶ bright (9th mag) **prompt opt. transient** (Akerlof etal 99) .
  – 1st 10 min: decay steeper than forw.sh.
- →Interpreted as **reverse shock** .....
- .... *But is it?*

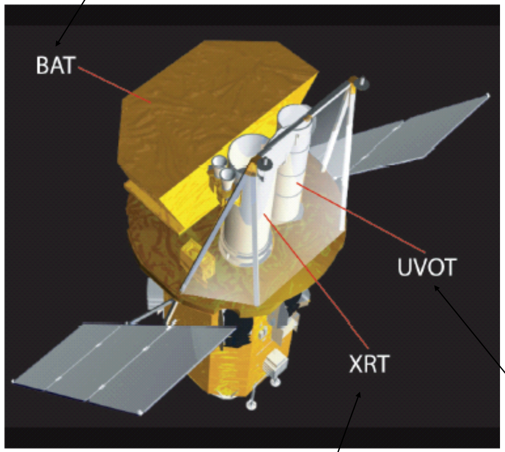
UHE CRs & ν , γ from GRB

$p\gamma$, $pp \longrightarrow$ UHE ν , γ

- If protons present in (baryonic) jet → p^+ Fermi accelerated (as are e^-)
- $p,\gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}, \nu_{\mu} \rightarrow e^{\pm}, \nu_e, \nu_{\mu}$ (**Δ**-res.: $E_p E_\gamma \sim 0.3$ GeV^2 in jet frame)
- → $E\nu_{,br} \sim 10^{14}$ eV for MeV γs (int. shock)
- → $E\nu_{,br} \sim 10^{18}$ eV for 100 eV γs (ext. rev. sh.) **: ICECUBE**
- $\rightarrow \pi^0 \rightarrow 2\gamma \rightarrow$ γγ cascade **: GLAST, ACTs..**
- Test hadronic content of jets (are they pure MHD/$e^{\pm}$, or baryonic …?)
- Also (if dense): $p,\gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}, \nu_{\mu} \rightarrow e^{\pm}, \nu_e, \nu_{\mu}$
- Test acceleration physics (injection effic., ε_e, ε_B..)
- Test scattering length (magnetic inhomog. scale?..or non-Fermi?..)
- Test shock radius: γγ cascade cut-off:
- $E_\gamma \sim$ GeV (internal shock) ; $E_\gamma \sim$ TeV (ext shock/IGM)
- ⟶ photon cut-off: diagnostic for int. vs. ext-rev shock

BAT: Energy Range: 15-150kev
FoV: 2.0 sr
Burst Detection Rate: 100 bursts/yr

SWIFT



Three instruments

Gamma-ray, X-ray and optical/UV

Slew time: 20-70 s !

>95% of triggers yield XRT det
>50% triggers yield UVOT det.

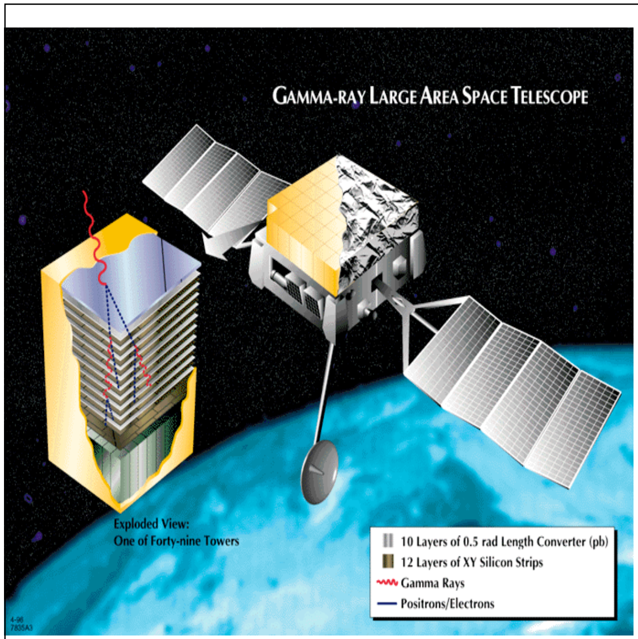
UVOT: Wavelength Range: 170-650nm

XRT: Energy Range: 0.2-10 keV

Launched Nov 04

Mission Operations Center: @ PSU
(Bristol Res. Park)

Fermi



Also on Fermi : **GBM** **(~BATSE range) ;**
12 NaI: 10keV-3 MeV; 2 BGO: 150 keV-30 MeV

- Launched June 11 2008
- **LAT**: Pair-conv.modules + calorimeter
- 20 MeV-300 GeV,

  $\Delta E/E \sim 10\% @ 1$ GeV
- FoV = 2.5 sr (2xEgret), ang.res. $\theta \sim 30'' - 5'$ (10GeV)
- Sensit. $\sim 2.10^{-9}$ ph/cm^2/s

  (2 yr; > 50xEgret)
- GBM: FoV 4π, 10keV-30MeV
- 2.5 ton , 518 W
- expect det/loc ~60 GRB/yr; simult. w. Swift : 30/yr

GRB 080916c

Abdo et al. (the Fermi collaboration), 2009 Science

A bright ***LONG*** burst :

1) All spectra approximate Band functions : same mechanism?

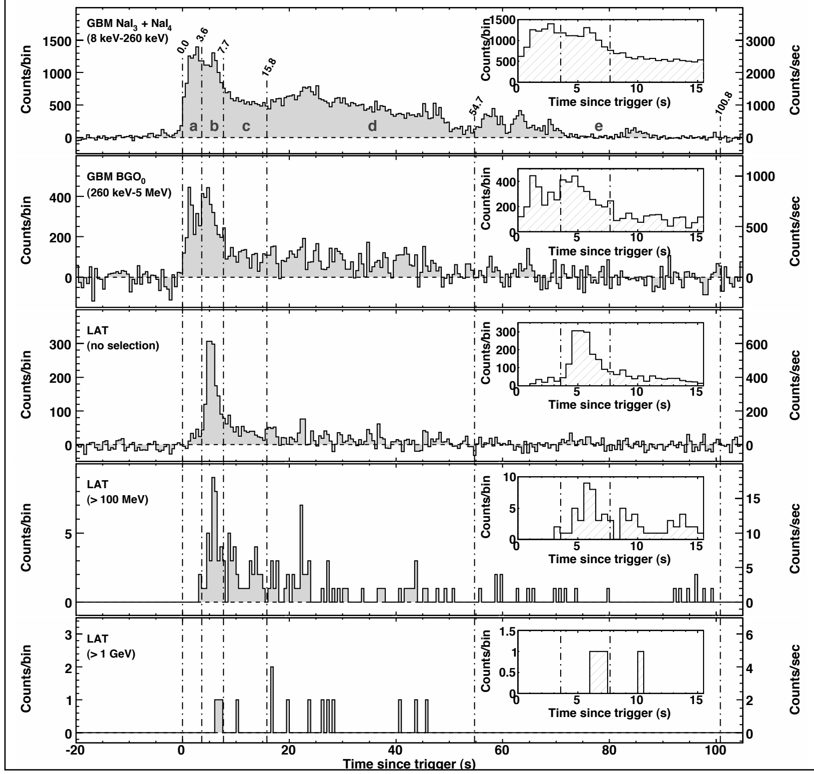
- Could be Synchrotron. No obvious cutoff or a softening → $\Gamma \gtrsim 100$; expect also SSC , but this could be > TeV, not observed
- Since no statistically significant higher energy component above Band, the latter must have either E $\gtrsim$TeV or $Y \sim \varepsilon_e/\varepsilon_B \lesssim 0.1$

2) GeV only in 2nd pulse or later, vs. MeV (1st pulse) - Why ?

- Could originate in different region, e.g. a 2nd set of internal shocks, with ≠ parameters or physics (possible)
- Or radiation from one set of shells up-scattered by another set of shells ? (but no expected delay between 2nd LAT & GBM)

GRB 080916c

Abdo, A. and Fermi coll., 09, Sci. 323:1688

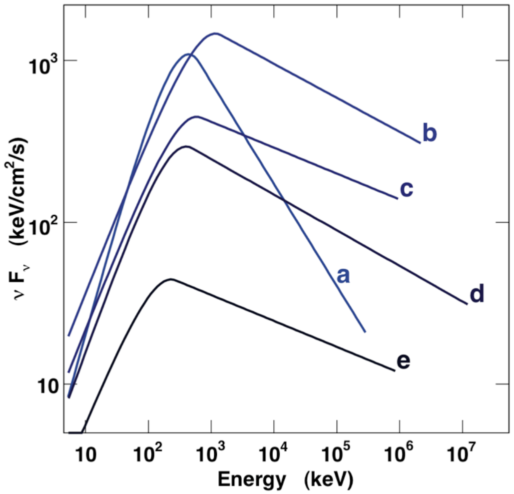


Light-curve
E↓

Notice :
GeV photons
←“lag”
behind MeV!

GRB 080916C

Spectrum



- "Band" fits (joint GBM/LAT) for ***all*** the different time intervals
- Soft-to-hard, to "sort-of-soft-peak-but-hard-slope" afterglow
- No evidence for ***2nd*** component

Mészáros

GRB 080916c

(the Fermi collaboration, 2009)

3) GeV only in 2nd pulse or later, vs. MeV (1st pulse) - Why ?

•***Hadronic?*** (the burning question)... natural delay since extra time for cascade to develop & expect HE photons

but :

•***Leptonic*** models (synchrotron + inverse Compton) also possible ....

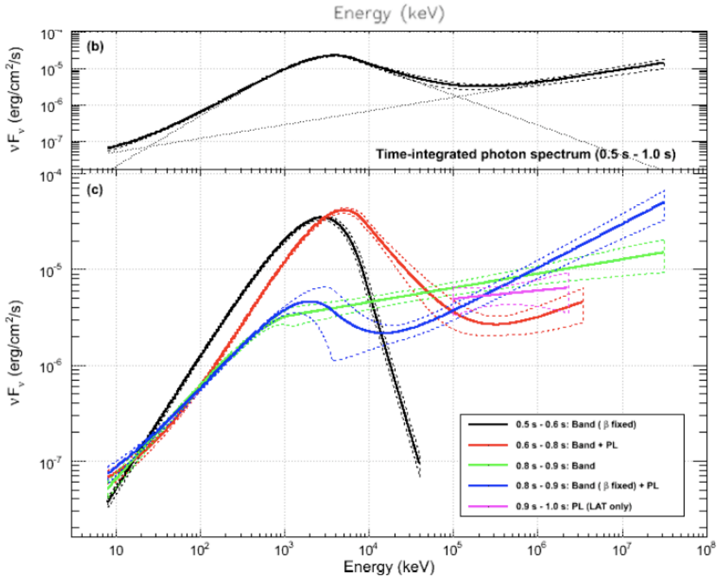
→***more analysis needed to test hadronic model and/or constrain variants of leptonic model***

Future Fermi+Swift+ground observations will tell

GRB 090510

- Fermi LAT/GBM identified ***SHORT*** burst
- Shows (sim. to long bursts) time ***LAG*** between soft 1st pulse and hard 2nd pulse
- This shows an ***EXTRA*** spectral component, besides usual Band component (first clear!)
- ***Hadronic?*** Maybe...

GRB 090510



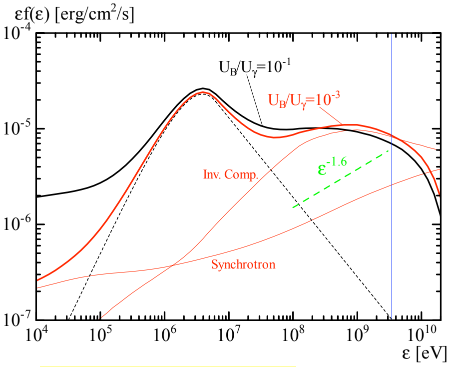
Spectrum:
clear 2nd
comp (5σ)

Abdo, et al. 09
(LAT/GBM coll.)
Nature, subm.
arXiv/0908.1832

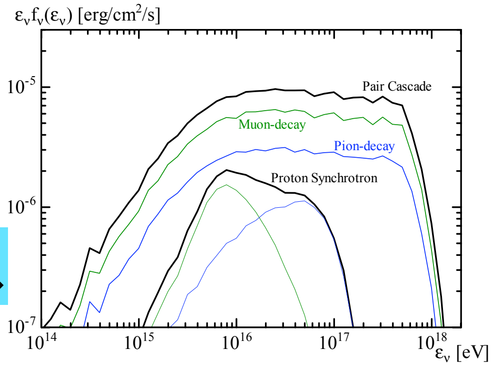
Hadronic model: ***090510***

Asano, Guierec, Mészáros, 09
(in prep.)

Secondaries from
photomeson cascades ✔
(but: need $L_{p,iso}$~10^{55} erg/s !)



Secondary
photons ↑



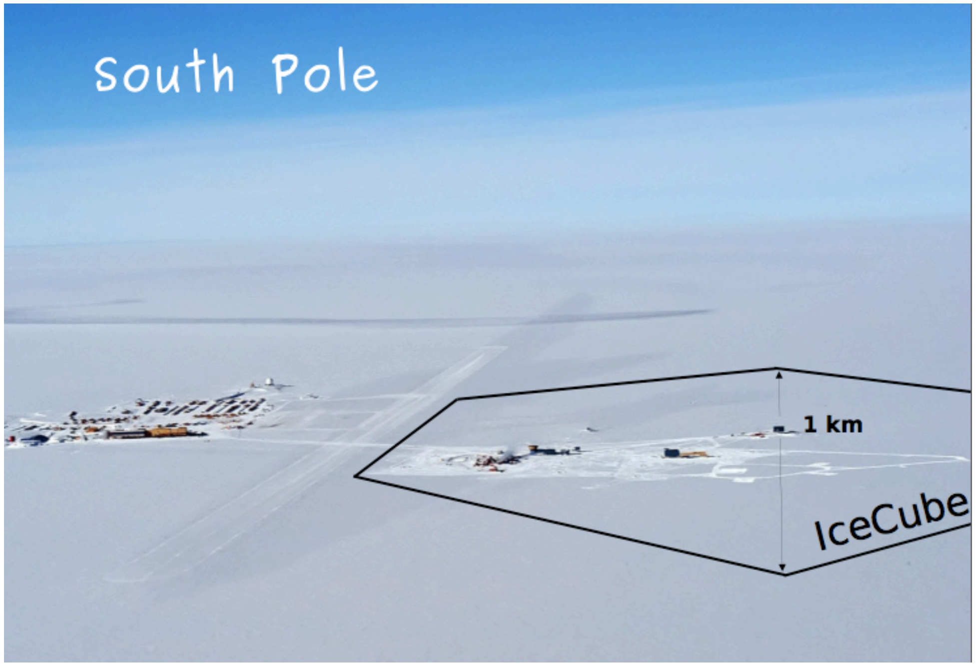
Secondary
neutrinos →

(not detectable, for this burst!)

UHE neutrinos from GRB

- Need baryon-loaded relativistic outflow
- Need to accelerate protons (as well as e^-)
- Need target photons or nuclei with $\tau \gtrsim 1$ (generally within GRB itself or environment)
- Need $E_{rel,p} \gtrsim$ 10-20 $E_{rel,e}$
- Might hope to detect individual GRB if nearby ($z \lesssim 0.15$), or else cumul. background
- If detected, can identify hadronic γ in GRB?

ICECUBE



IceCube (2010)

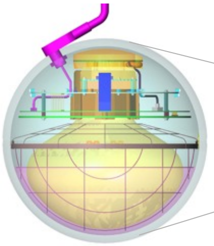
5160 DOMs on 86 strings

160 tank ice-Cherenkov surface air shower array (IceTop) – see talk by T. Gaisser

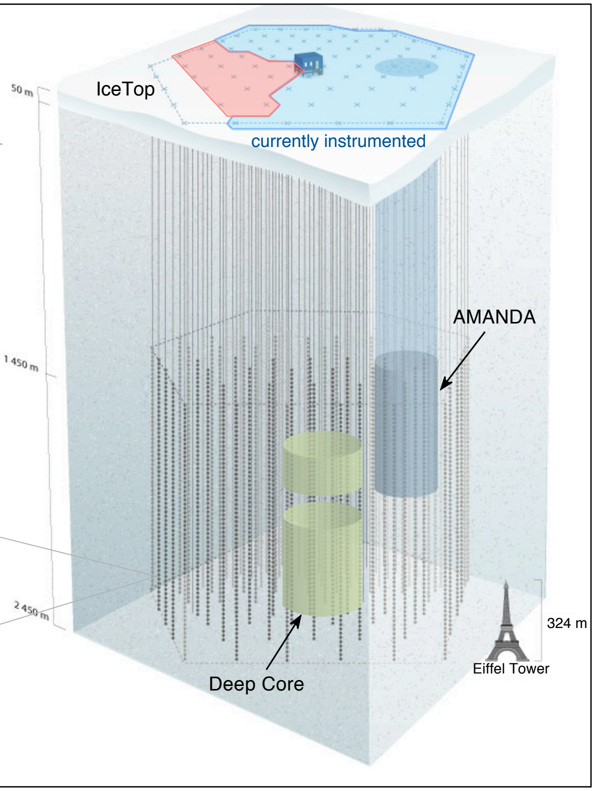
Includes DeepCore infill array (sensitivity to lower energies)

79 strings deployed to date in 6 construction seasons

(79/86 complete)

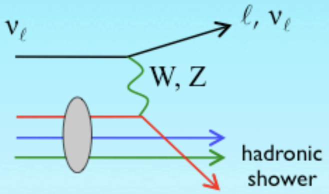


Digital Optical Module (DOM)

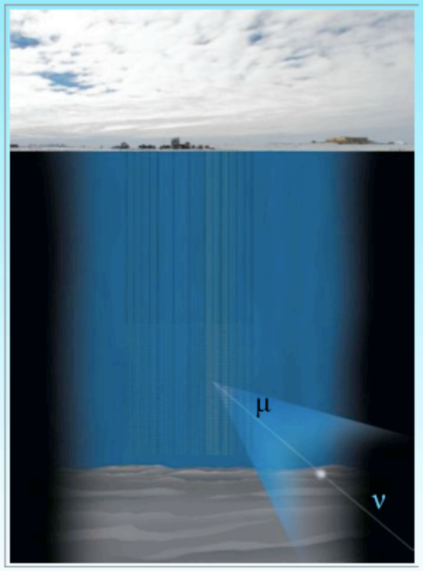


Neutrino Telescopes

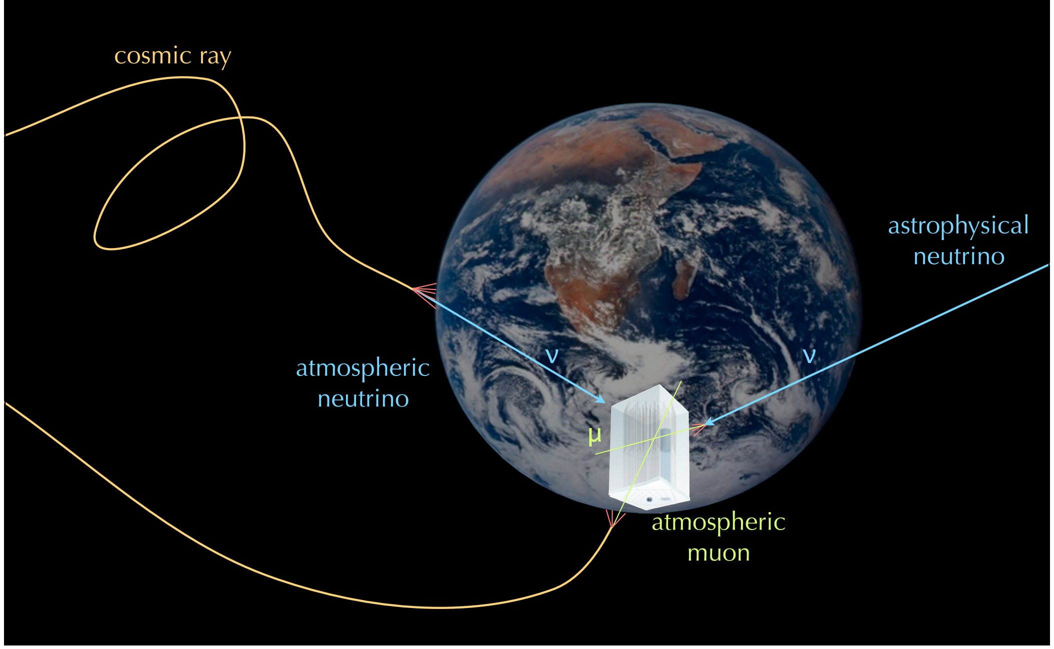
- Neutrinos interact in or near the detector



  - $\mathcal{O}$(km) muons from ν_μ (CC)
  - $\mathcal{O}$(10 m) particle cascades from ν_e, low energy ν_τ, and NC interactions
  - Cherenkov radiation detected by optical sensors

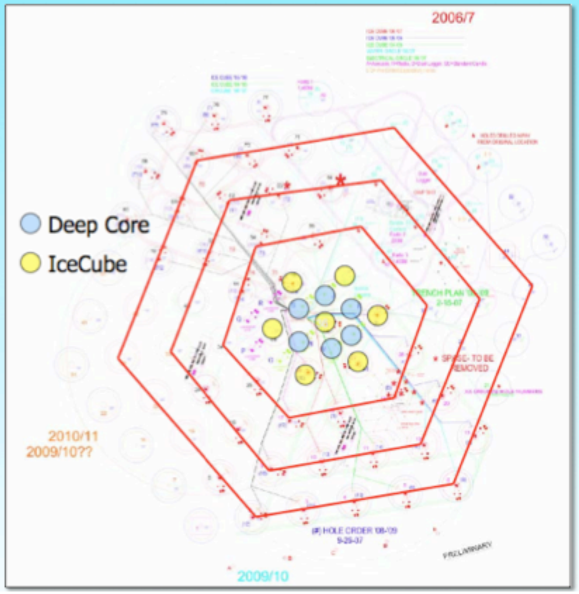


Signals and Backgrounds



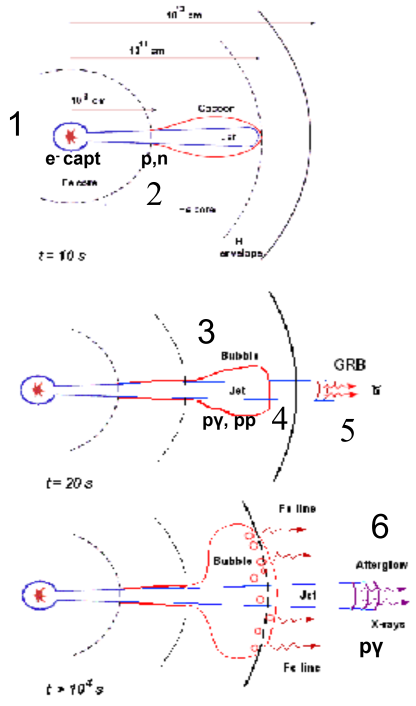
IceCube Deep Core

- Extend IceCube sensitivity to neutrinos with energies below a few hundred GeV
  - Six strings with 60 high-QE PMTs each
  - Use very clear ice at bottom of IceCube (λ_{att} ~ 40-50 m, cf. 20 m)
  - IceCube active veto
    - Reduce cosmic ray muons to atm. ν level (factor 10^{-6})



UHE ν in GRB

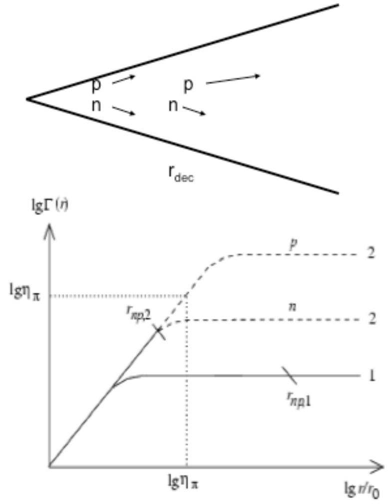
Various collapsar GRB ν-sites



- 1) at collapse, similarly to supernova core collapse, make GW + **thermal ν (MeV)**
- 2) If jet outflow is baryonic, have p,n
- → p,n relative drift, **pp/pn** collisions
- → inelastic nuclear collisions
- → **VHE ν *(GeV)***
- 3 Int. shocks while jet is inside star, accel. protons → **pγ, pp/pn** collisions → **UHE ν *(TeV)***
- 4) internal shocks below jet photosphere, accel. protons → **pγ, pp/pn** collisions → **UHE ν *(TeV)***
- 5) Internal shocks outside star accel. protons
- → pγ collisions → **UHE ν *(100 TeV)***
- 6) ← External rev. shock: → pγ → **EeV ν (10^{18} eV)**

“Hadronic” GRB Fireballs:

Thermal p,n decoupling → VHE ν, γ

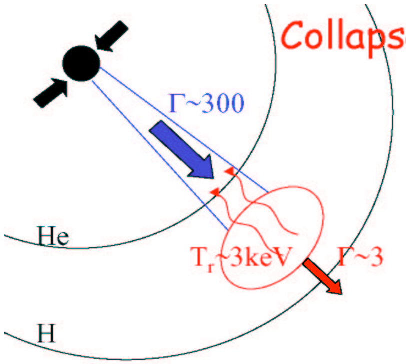


Bahcall & Meszaros 2000

- Radiation pressure acts on e^-, with p^+ coming along (charge neutrality)
- The n scatter inelastically with p^+
- The p,n initially expand together, while $t_{pn} < t_{exp}$ (p,n inelastic)
- When $t_{pn} \sim t_{exp}$ → p,n decouple
- At same time, $v_{rel} \geq 0.5c$ → p,n becomes inelastic → π^+
- Decoupling important when $\Gamma \geq 400$, resulting in $\Gamma_p > \Gamma_n$
- Decay → ν, of $E_\nu \geq 30$-40 GeV
- **Motivation for DEEP-CORE !**

While jet is inside progenitor:

Collapsar GRB ν's



$$\frac{\varepsilon_p}{\Gamma}\Gamma\varepsilon_\gamma \geq 0.3\,\mathrm{GeV}^2$$

$$\Rightarrow \quad \varepsilon_p \geq 100\,\mathrm{TeV}$$

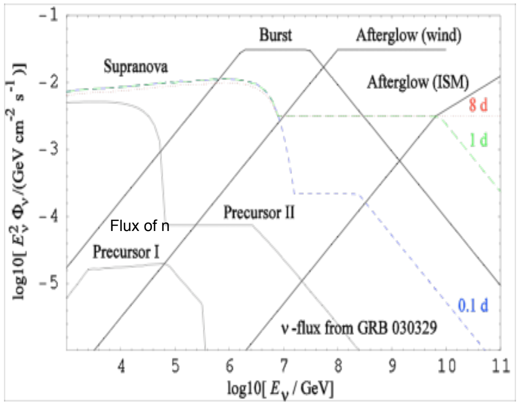
- $\varepsilon_\nu \geq 10^{12.5}$ eV

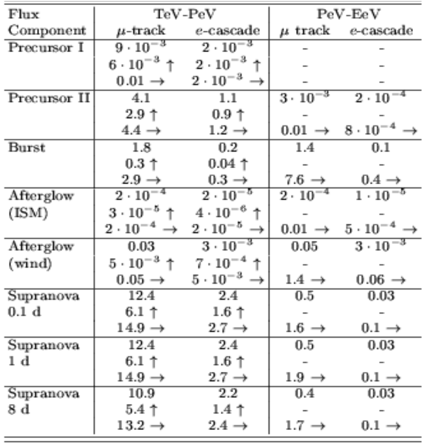
  $N_{\nu\to\mu} \approx 0.2\,/\,\mathrm{km}^2/\mathrm{Collapse}$ (10^3 GRBs/yr)
- Both "Chocked" and "successful" jets

Meszaros & Waxman 01

GRB 030329: precursor (& pre-SN shell?) with ICECUBE

Burst of Lγ~10^{51} erg/s, E_{SN} ~$10^{52.5}$ erg, @ z~0.17, θ~68°



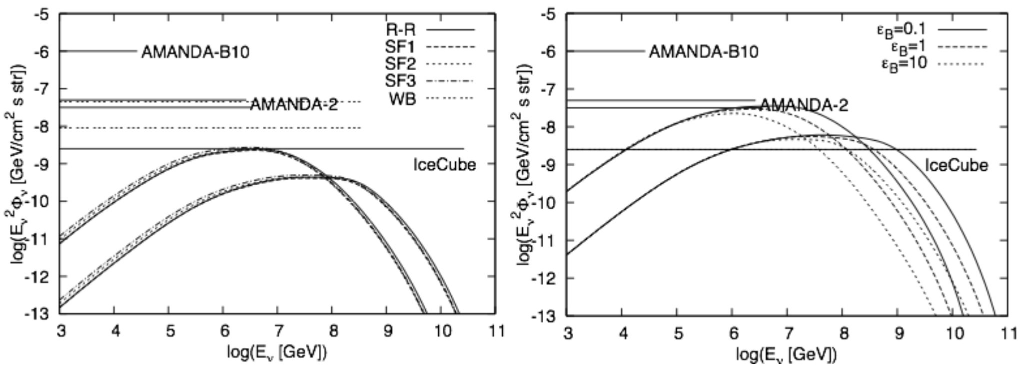


Flux Component	TeV-PeV μ-track	TeV-PeV e-cascade	PeV-EeV μ track	PeV-EeV e-cascade
Precursor I	$9 \cdot 10^{-3}$ $6 \cdot 10^{-3}$ ↑ 0.01 →	$2 \cdot 10^{-3}$ $2 \cdot 10^{-3}$ ↑ $2 \cdot 10^{-3}$ →	- - -	- - -
Precursor II	4.1 2.9 ↑ 4.4 →	1.1 0.9 ↑ 1.2 →	$3 \cdot 10^{-3}$ - 0.01 →	$2 \cdot 10^{-4}$ - $8 \cdot 10^{-4}$ →
Burst	1.8 0.3 ↑ 2.9 →	0.2 0.04 ↑ 0.3 →	1.4 - 7.6 →	0.1 - 0.4 →
Afterglow (ISM)	$2 \cdot 10^{-4}$ $3 \cdot 10^{-5}$ ↑ $2 \cdot 10^{-4}$ →	$2 \cdot 10^{-5}$ $4 \cdot 10^{-6}$ ↑ $2 \cdot 10^{-5}$ →	$2 \cdot 10^{-4}$ - 0.01 →	$1 \cdot 10^{-5}$ - $5 \cdot 10^{-4}$ →
Afterglow (wind)	0.03 $5 \cdot 10^{-3}$ ↑ 0.05 →	$3 \cdot 10^{-3}$ $7 \cdot 10^{-4}$ ↑ $5 \cdot 10^{-3}$ →	0.05 - 1.4 →	$3 \cdot 10^{-3}$ - 0.06 →
Supranova 0.1 d	12.4 6.1 ↑ 14.9 →	2.4 1.6 ↑ 2.7 →	0.5 - 1.6 →	0.03 - 0.1 →
Supranova 1 d	12.4 6.1 ↑ 14.9 →	2.4 1.6 ↑ 2.7 →	0.5 - 1.9 →	0.03 - 0.1 →
Supranova 8 d	10.9 5.4 ↑ 13.2 →	2.2 1.4 ↑ 2.4 →	0.4 - 1.7 →	0.03 - 0.1 →

Razzaque, Mészáros, Waxman 03 PRD 69, 23001

Internal shock ν's, contemp. with γ's

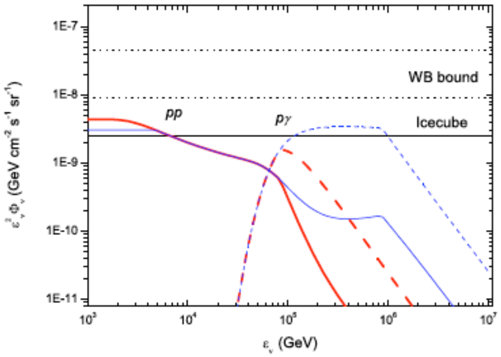
Detailed ν_μ diffuse flux incl. cooling, using GEANT4 sim., integrate up to z=7, U_p/U_γ=10 (left) ; z=20, U_p/U_γ=100 (right)



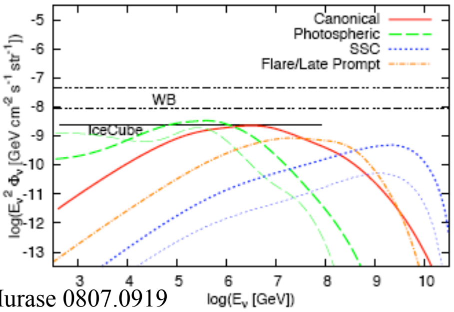
Asano 05, ApJ 623:967; Murase & Nagataki 06, PRD 73:3002

GRB ‘Photospheric’ Neutrinos

- GRB relativistic outflows have a Thomson scattering $\tau_T \sim 1$ “photosphere” , below which photons are quasi-thermal
- Shocks and dissipation can occur below photosphere.
- Acceleration of protons occurs, followed by pp and pγ interactions → neutrinos
- Gas and photon target density higher than in shocks further out.
- Characteristics resemble precursor neutrino bursts, but contemporan. with prompt gamma-rays

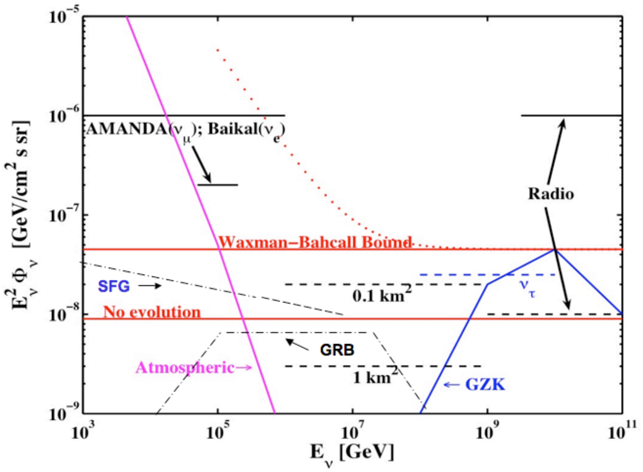


Wang, Dai 0807.0290



Murase 0807.0919

ν spectrum from pγ in internal & external shocks in GRB & SFG



- Shocks accelerate p^+ (as well as the e^- which produce γ_{MeV})
- **Δ**-res.: $E'_p E'\gamma \sim 0.3 GeV^2$ in comoving frame, in lab:

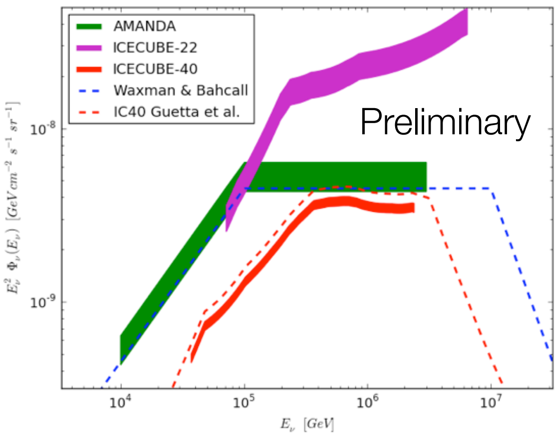
  → $E_p \geq 3x10^6 \Gamma_2^2$ GeV

  → $E_\nu \geq 1.5x10^2 \Gamma_2^2$ TeV
- Internal shock p,γ_{MeV}

  → ~100 TeV νs
- External shock p,γ_{UV}

  → ~ 0.1-1 EeV νs
- Diff. flux: detect in km^3

GRB Search with IceCube 40-String Data

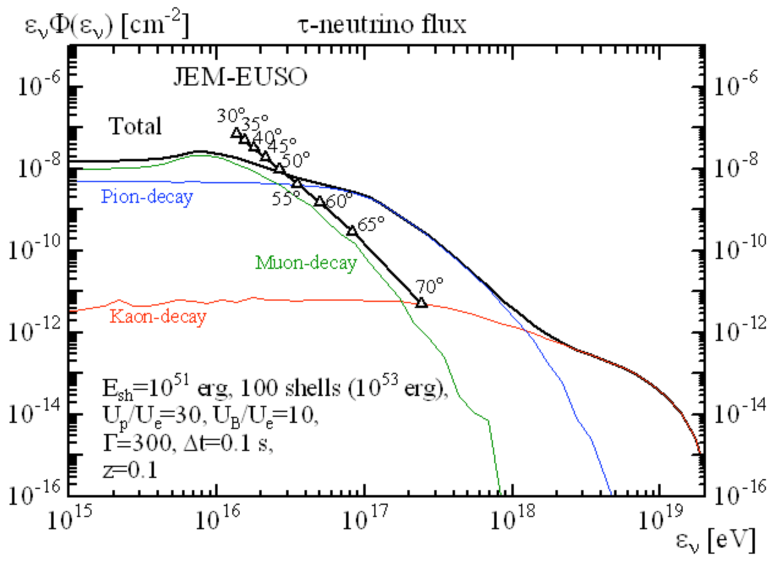


117 Northern hemisphere GRBs from 2008 (40-string) data run

Preliminary 90% CL upper limit is 81% of predicted Guetta-like neutrino flux

- One year with 40 strings provides better sensitivity than the full seven year AMANDA-II data set

EHE ν's



Neutrino fluxes;
Asano et al, 09,
arXiv:0908.0392

JEM-EUSO sens.:
M. Teshima, MPI

- Crucial parameter for neutrino (and CR) flux is U_p/E_e .
- Note that ν's from pion decay are good targets too (not just muon decay)
- For typical values $U_p/E_e \sim 30$ needed to make GRB "interesting" UHECR sources, the neutrino flux might be detectable from ***individual*** GRB sources at ***z~0.1*** with JEM-EUSO (K. Asano et al, 2008, in prep.)

GZK CR Sources

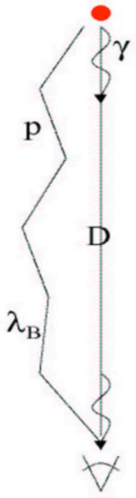
- Sources: GRB ✓ ; AGN.... #?
- Rate: R_{GRB} (z=0)~ 0.5 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

  $\sim 0.5\ 10^{-3}\ (D/100\ \mathrm{Mpc})^{-3}\ \mathrm{yr}^{-1}$
- But, arrival time dispersion:

  $t_{\mathrm{dis}} \sim 10^{7}\mathrm{yr}\ (B/10^{-8}\ \mathrm{G})^{2}\ (\lambda_{B}/1\ \mathrm{Mpc})$

  $(D/100\mathrm{MPC})^{2}\ (E_{p}/10^{20}\ \mathrm{eV})^{-2}$
- $N_{\mathrm{GRB}}(E>E_{p},\ D<D_{\mathrm{GZK}}) \sim R.\ t_{\mathrm{disp}}$

  $\sim 10^{4}\ B_{-8}^{2}\ \lambda_{B,0}\ D_{100}^{2}\ E_{p20}^{2}$
- GZK event rate: ~ 1 $/\mathrm{Km}^{2}$ /100 yr ✓



[Waxman 95, 2005]

CR Flux & spectrum - GRB

Protons

Electrons

- Particle spectrum:
- γ spectrum

$$dn_p / d\varepsilon_p \propto \varepsilon_p^{-2} \quad \longleftarrow \quad dn_e / d\varepsilon_e \propto \varepsilon_e^{-2}$$

[Waxman 95]

- p energy production:
- γ energy production

$$\varepsilon_p^2 \frac{d\dot{n}_p}{d\varepsilon_p} \sim 10^{44} \frac{\mathrm{erg}}{\mathrm{Mpc}^3\mathrm{yr}} \quad \longleftarrow \quad \varepsilon_e^2 \frac{d\dot{n}_e}{d\varepsilon_e} = \frac{30}{\mathrm{Gpc}^3\mathrm{yr}} \times 10^{51}\mathrm{erg} = 0.3 \times 10^{44} \frac{\mathrm{erg}}{\mathrm{Mpc}^3\mathrm{yr}}$$

Afterglow ⟶ **z distribution**

[Frail et al. 01
Schmidt 01]

$$\varepsilon_e^2 \frac{dn_e}{d\varepsilon_e} = \frac{0.5}{\mathrm{Gpc}^3\mathrm{yr}} \times 500 \times 0.5 \cdot 10^{51}\mathrm{erg} = 1.3 \times 10^{44} \frac{\mathrm{erg}}{\mathrm{Mpc}^3\mathrm{yr}}$$

What about Magnetars ?

Isolated neutron stars where the main source of energy is the magnetic field

[***most*** observed NS have $B = 10^9 - 10^{12}$ G and are powered by accretion, rotational energy, residual internal heat]

BUT:

In ***Magnetars*** the “external” field: $B = 10^{14} - 10^{15}$ G

internal field: $B > 10^{15}$ G

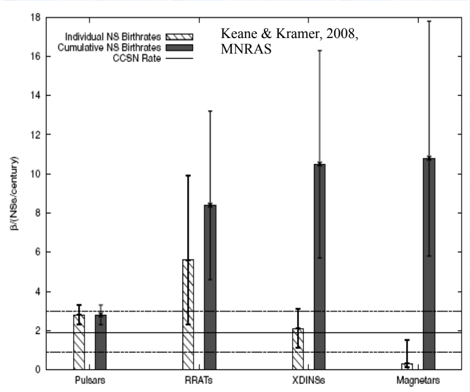
See review: Mereghetti 2008, A&A Rev. 15, 225

Magnetar birthrate

~ a few every 10^4 years per galaxy

large uncertainties:

- small statistics (~10 persistent sources)
- uncertain lifetimes (~10^4 yrs ?),
- number and duty cycle of transient magnetars



Keane & Kramer, 2008, MNRAS

Birthrate of radio PSR and core collapse SN (1-3 / century) already in reasonable agreement → no much room for other populations of NS

Magnetars ~ 0.1-0.3 / century i.e. up to ~10% of radio PSRs

See also:
Gill & Heyl 2007, MNRAS 381,52 (~0.22 / century + transients)
Muno et al. 2008, ApJ 680, 639 (~0.3 – 6 / century)

A different magnetar signature :

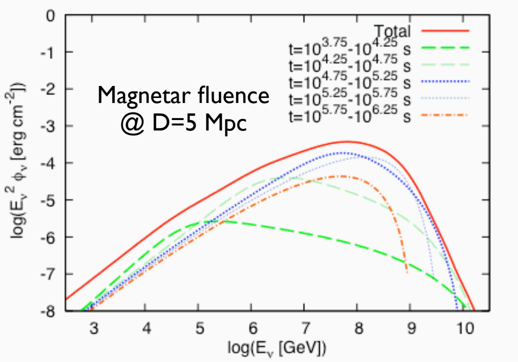
Magnetar birth ν-alert?

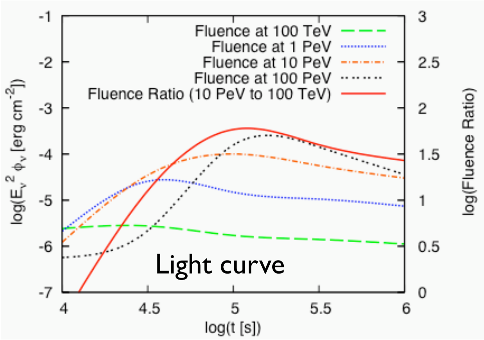
Murase, Mészáros & Zhang, PRD '09, PRD 79, 103001

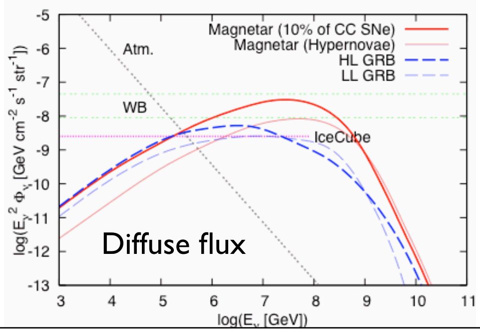
- Magnetar fields ($B \sim 10^{14}$-10^{15} G) may result from turbulent dynamo when born with fast (ms) rotation
- A fraction ≲0.1 of CC SNe may result in magnetars
- In PNS wind, wake-field acceleration can lead to UHECR energies $E(t) \lesssim 10^{20}$ eV $Z\, \eta_{-1}\, \mu_{33}^{-1}\, t_4^{-1}$
- Surrounding ejecta provides cold proton targets for $pp \rightarrow \pi^{\pm} \rightarrow \nu$
- ν-fluence during time t_{int} first increases (strong initial π/μ cooling), then decreases (with the proton flux)

Magnetar birth ν-alert

Murase, Mészáros & Zhang 09,
PRD 79, 103001



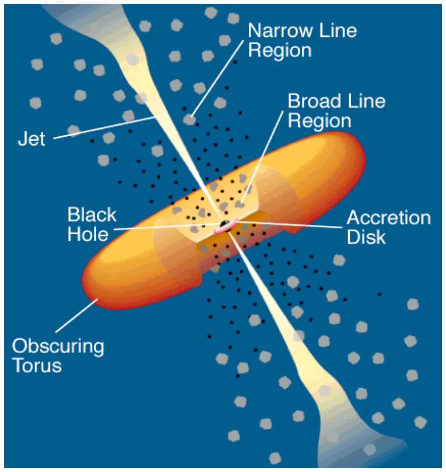




- Can signal birth of magnetar
- Test UHECR acc. in magnetar

-BUT: Not an explanation for Auger, because a) UHECR flux not sufficient, and b) UHECR spectrum not like Auger obs.

AGN as UHE γ (CR, ν) sources



- Big brother of GRB: massive BH (10^7-10^8 M_{sun}) fed by

  an accretion disk → jet –
- But, jet $\Gamma_{j,agn}$ ~ 10-30

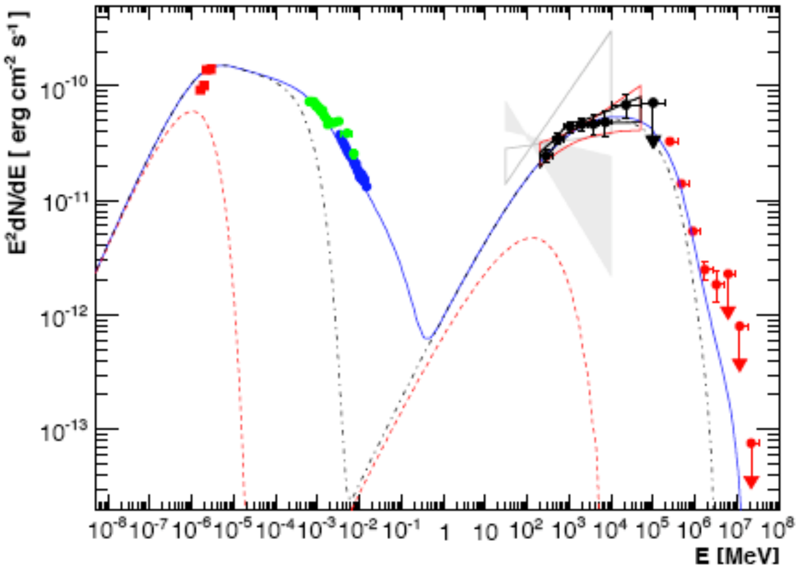
  (while $\Gamma_{j,grb}$ ~ 10^2 - 10^3)
- UV photons from disk; in addition, line clouds provide extra photons

  (+back-scatter)
- Typical ("leptonic") model:

  SSC (sync-self-compton);
  SEC(sync-exter.compton)

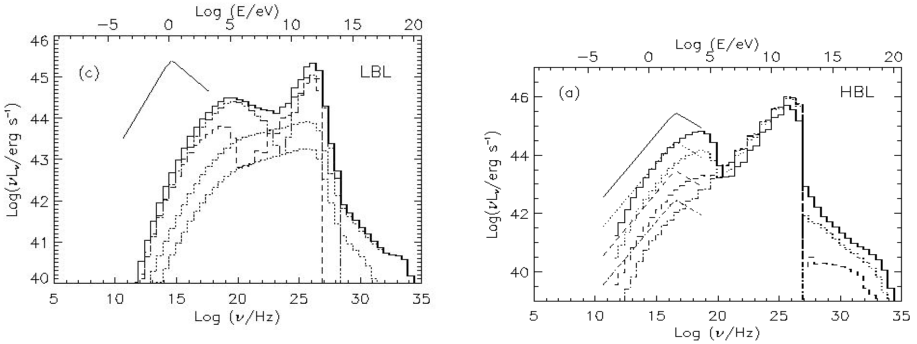
HESS + Fermi : PKS 2155

γ-spectrum



Radio-loud hadronic Blazar models

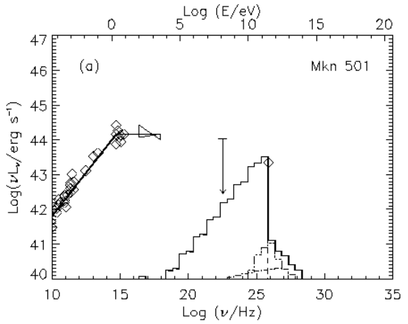
(PSB-proton synchrotron blazar - γ-ray spectrum from cascades)

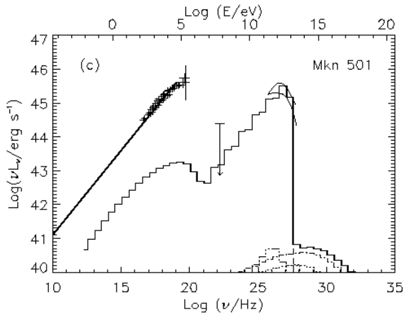


- Full : synchrotron γ SED (target photons)
- Dash: p-sync. casc.; Dash-3 dot: $\mu^{\pm}$-sync. casc; Dots: π^0 casc; Dash-dot: $\pi^{\pm}$ casc

(Muecke, et al, Apph, astro-ph/0206164)

Mrk 501 : protypical HBL





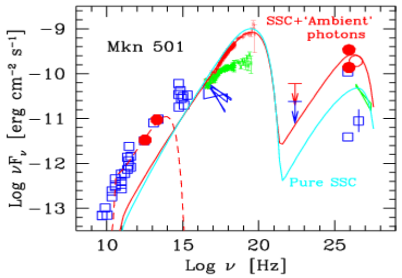
- a) - PSB: Quiet state γ
- b) - PSB: Flare state γ

  - e-sync g targets + p-sync g + p,g casacdes, pm casacdes & sync (Muecke et al, a-ph/0206164)

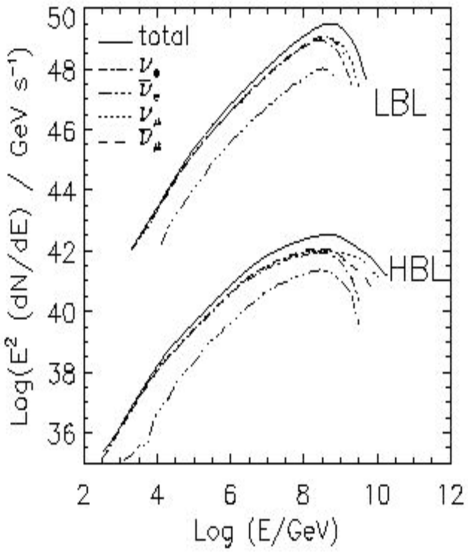
- c) → LEP:Flare state γ

→ e-sync g + e-Inv. Compton scatt (Ghisellini et al, e.g.

A&A 386, 833 (2002) etc – “standard” astrophysical. picture



UHE ν spectra of indiv. AGN: SPB



- Generic neutrino spectra in LBL, HBL from p,γ interact. with softer/harder target synchrotron spectra
- “Internal” synchrotron low hump assumed + proton sync contrib. to high hump
- “External+internal” target photons yields alternative models

[Muecke et al 02]

Are RL AGN the UHECR sources?

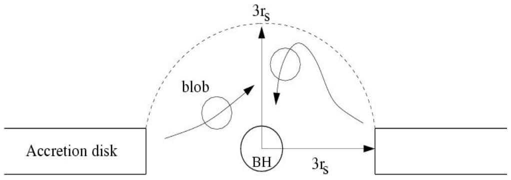
- **Correlation betw. highest energy cosmic rays and the nearby active galactic nuclei detected by Fermi**
- Rodrigo S. Nemmen, **arXiv:1007.5317v1**
- Analyze correlation of positions of gamma-ray sources in the Fermi Large Area Telescope First Source Catalog (1FGL) and the First LAT Active Galactic Nuclei (AGN) Catalog (1LAC) with the arrival directions of UHECRs observed with the Pierre Auger Observatory.
- When selecting the 1LAC AGNs closer than 200 Mpc, find strong association (5.4 sigma) between their positions and the directions of UHECRs on a ~17 degree angular scale; the probability of this being due to an isotropic flux of cosmic rays is 5x10^{-8}.
- There is also a 5 sigma correlation with nearby 1LAC sources on a 6.5 degree scale.
  They identify 7 gamma-ray loud AGNs associated with UHECRs within ~17 degrees:
  Cen A, NGC 4945, ESO 323-G77, 4C+04.77, NGC 1218, RX J0008.0+1450 and NGC 253.
- They interpret these results as providing additional support to the hypothesis of the origin of UHECRs in nearby extragalactic objects. As the angular scales of the correlations are large, possibility that intervening magnetic fields considerably deflect the trajectories
- (And large angle suggests heavy element composition, though not as heavy as Fe).

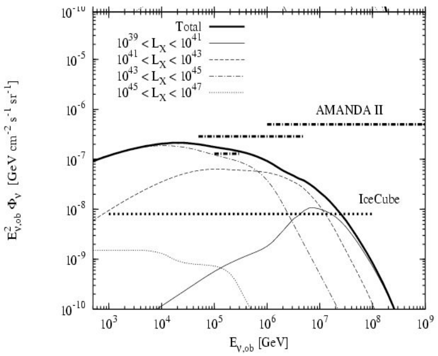
Or, alternatively: RQ AGNs

Pe'er, Murase, Mészáros, 2010, PRD in press (arXiv:0911.1776)

- Could be that culprits are radio-quiet **(RQ) AGNs**
- Enough of them inside GZK radius
- Evidence for small jets in RQ AGNs
- Evidence for heavy CR composition (X_{max}-E)
- Can accelerate **heavy elements** to right energies
- Can survive photo-dissociation
- Heavy elements have larger Larmor radii
- Correlation with matter (gal) distribution is good.

RQ (core) AGN ν-emission





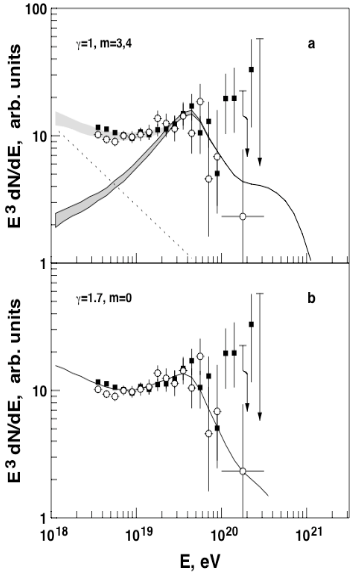
- AGN are powered by accretion on massive (10^6-10^8 M_{sun}) BHs
- 90% of AGNs are radio-quiet (no jets), core X-ray
- Core emission model: aborted jet → cloud collisions →shocks → p accel. → pγ → π^+ → ν
- **← Diffuse flux: already constrained by AMANDA**
- π^0 → GeV γ (soft photon density too high for TeV γ)

Alvarez-Muñiz & Mészáros, 2004, PRD 70, 123001

What about $E_\nu \gtrsim 10^{19}$ eV ?

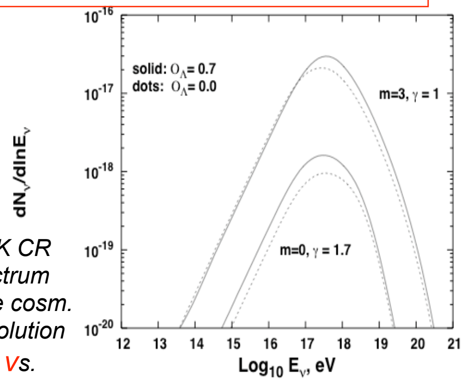
from GZK CRs *to* GZK νs

2 ≠CR models
↓ **same GZK** CR fit

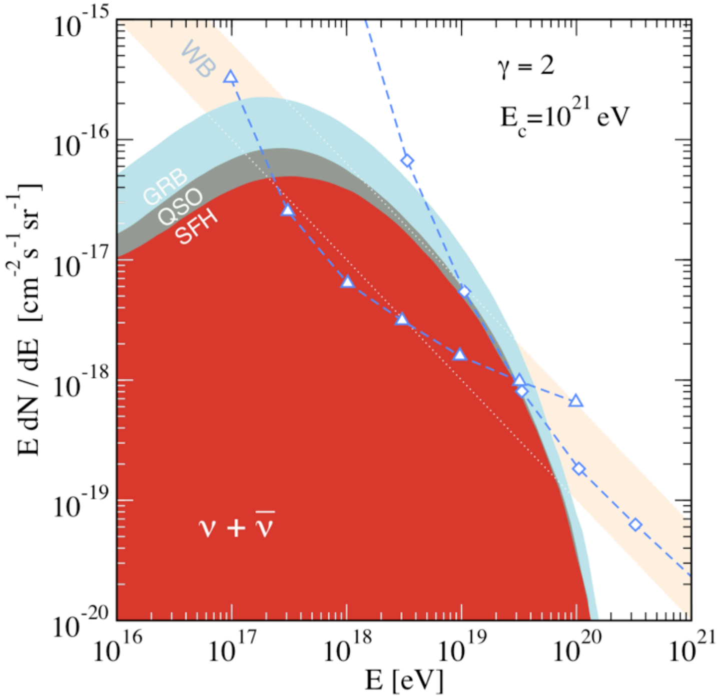


But … lead to ≠ *GZK ν flux* ↓

Can infer GZK CR injection spectrum and/or source cosm. luminosity evolution via their GZK νs.



Seckel & Stanev astroph/050244



GRB GZK cosmogenic neutrinos

Yuksel & Kistler 07
PRD 75:083004

If GRB make the GZK UHECR, then:

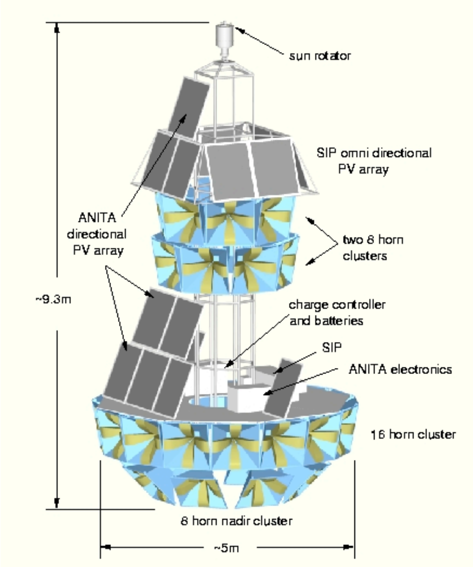
ν flux dep. on

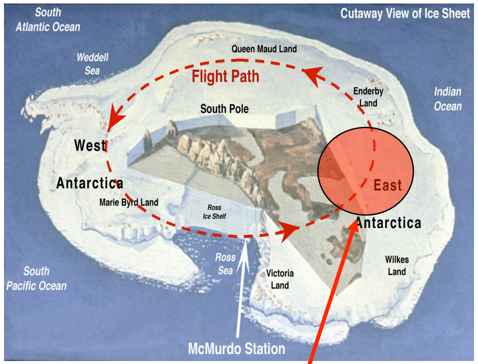
GRB rate vs. z
(from z>> R_{GZK})

Potential of Cosmogenic νs for CR Composition

- If CRs have large fraction of heavies, depending on source distance, photodissociation opt. depth could be $<1 \rightarrow$ only some of them break up into p,n
- Implies smaller fraction contributes to π^+ and cosmogenic ν production (Anchordoqui et al 06)
- Cosmogenic ν flux vs. CR flux may help resolve discrepancy between Auger X_{max} data and apparent correlation with AGN suggesting protons

ANtarctic **I**mpulsive **T**ransient **A**ntenna

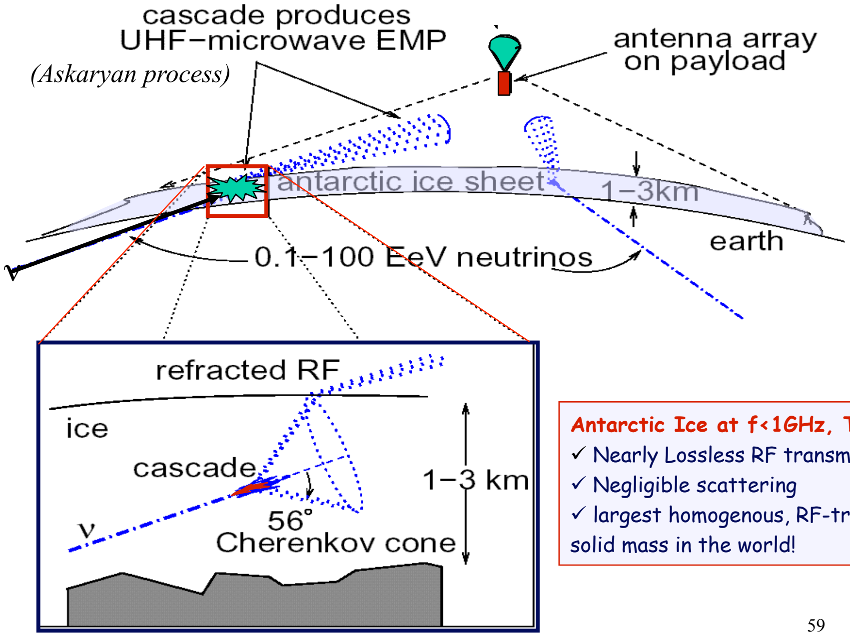




600 km radius,
1.1 million km^2

- Launched & flown 30 days in early 07 - results being analyzed

ANITA



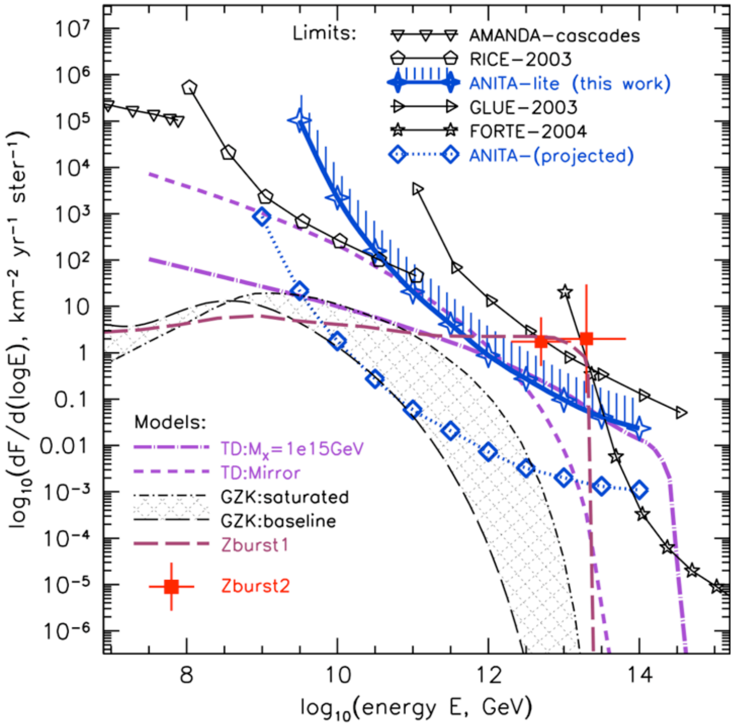
Antarctic Ice at f<1GHz, T<-30C

✓ Nearly Lossless RF transmission

✓ Negligible scattering

✓ largest homogenous, RF-transmissive solid mass in the world!

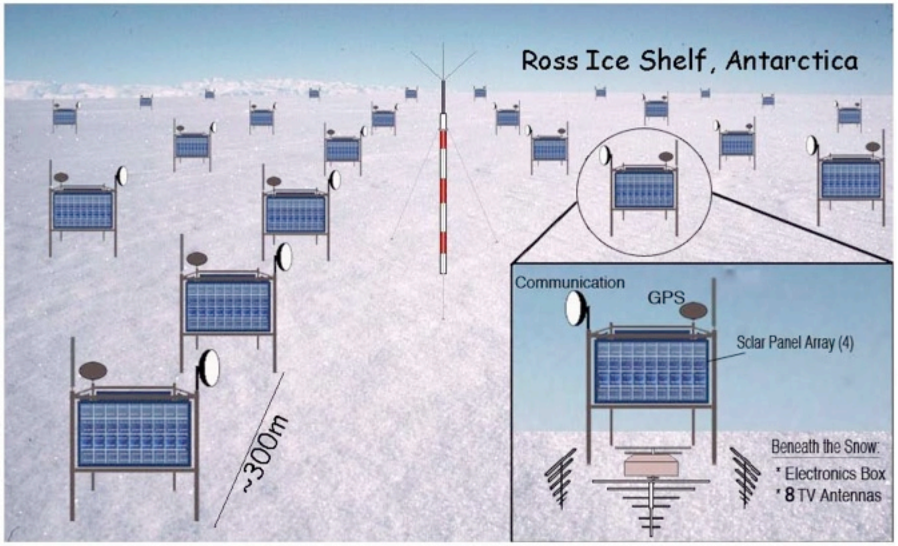
ANITA GZK limits



Barwick et al,
PRL 96:171101

ARIANNA Concept

100 x 100 station array, ~1/2 Teraton

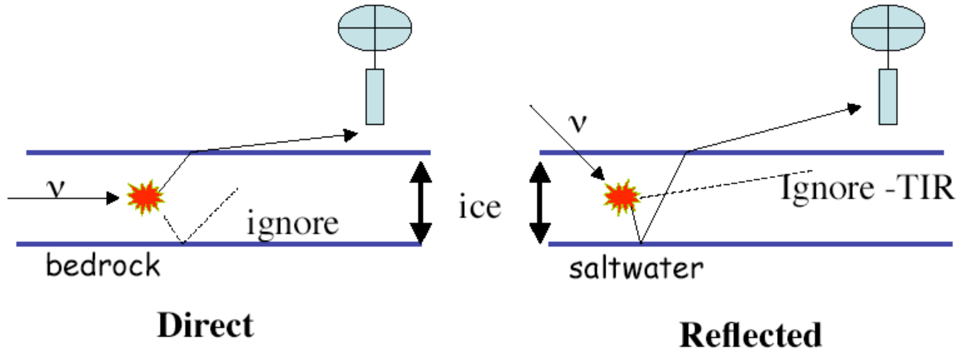


100x100 stations under the snow,
sep. 300 m, pointed downwards ↗

Barwick 07

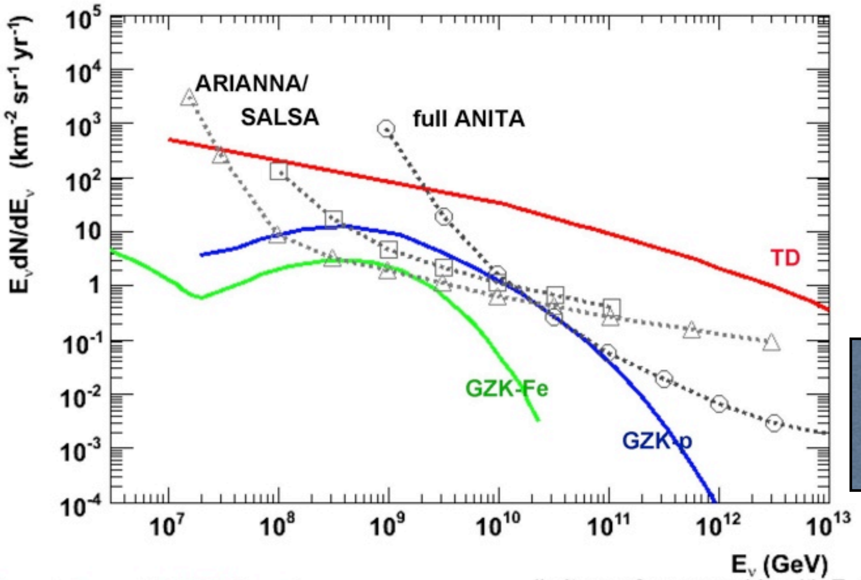
Arianna concept

Reflected and Direct Events



Threshold: 3×10^{17} eV , 2π sky coverage - Expect 40 (down) GZK ν/yr, Δθ~1 deg, point sensitivity $E^2 dN/dE \sim 3\times10^{-9}$ GeV/cm^2/s after 1 year

Reaching GZK sensitivity
& Lowering the Theshold



limits are for energy bin with E_{hi}/E_{lo}=e

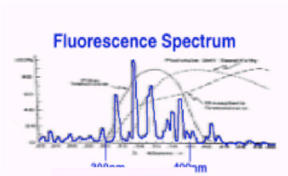
Events! even if UHECR are Iron

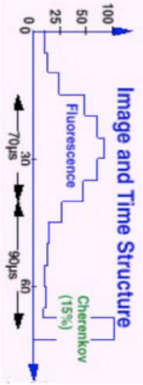
LOFAR : Low Frequency Array

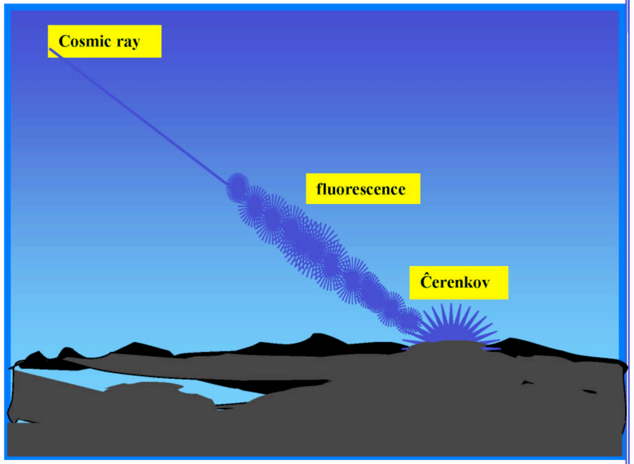
LOPES LOFAR prototype, Karlsruhe

Text

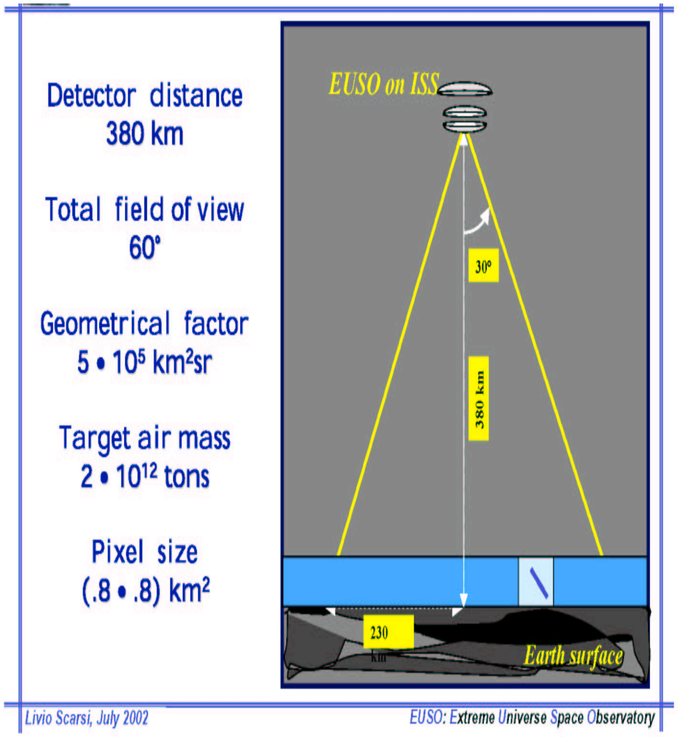
EUSO Approach







JEM EUSO



Detector distance
380 km

Total field of view
60°

Geometrical factor
$5 \bullet 10^5$ km^{2}sr

Target air mass
$2 \bullet 10^{12}$ tons

Pixel size
$(.8 \bullet .8)$ km^2

Livio Scarsi, July 2002

EUSO: Extreme Universe Space Observatory

- ISS project, orig. ESA/NASA/RSA/JAXA; precursor for **OWL** (free-flyer)
- $5.10^{19} – 10^{21}$ eV EECRs, EENUs
- Monocular 2.5m Fresnel lens, measure EAS via atmos. fluor. emiss
- Thresh: 3.10^{19} eV; Effic. @ 10^{20} eV : 300-1000 event/yr
- Orig. launch: 2012, but shuttle?
- **Current plan: JEM/JAXA, 2013 unmanned vehicle**

Conclusions

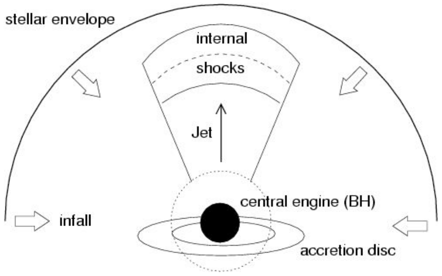
- Particle astrophysics is a rising young field; many major new facilities will ensure continued rapid growth. Great synergistic opportunities.
- Will learn much about GRB, AGN in GeV range; many with good photon statistics to 0.1-0.2 TeV; even more so for SNR
- Unidentified TeV/EGRET sources may yield surprises
- Will constrain particle acceleration / shock parameters, compactness of emission region (dimension, mag.field,.)
- TeV γ detection: mainly from few/nearby GRB, but many AGN, SNR
- UHECR : chemical composition, angular correl.: sources?
- UHE ν will allow test of proton content of jets, proton injection fraction, test shock acceleration physics, magn. field
- If UHE ν NOT detected in GRB, AGN → jets are Poynting dominated!
- Probe ν interactions at ~ TeV CM energies
- GW detection will test DNS, BHNS merger model & confirm GR
- Constraints on stellar birth and death, star formation rates at high redshifts (first structures?)

Conclusions

- The sources of UHECR (and potentially of UHENU) are still unknown
- Will learn much about best candidates (GRB, AGN, MGR) from GeV and TeV photon observations; many with good photon statistics
- Will constrain particle acceleration / shock parameters, compactness of emission region (dimension, mag.field,.)
- UHECR : chemical composition, angular correl.: sources?
- UHE ν will allow test of proton content of jets, proton injection fraction, test shock acceleration physics, magn. field
- If UHE ν NOT detected in GRB, AGN → jets are Poynting dominated!
- Probe ν interactions at ~ TeV CM energies
- Constraints on stellar birth & death rates @ high-z, first structures?
- Cosmogenic nus: probe CR origins, sources

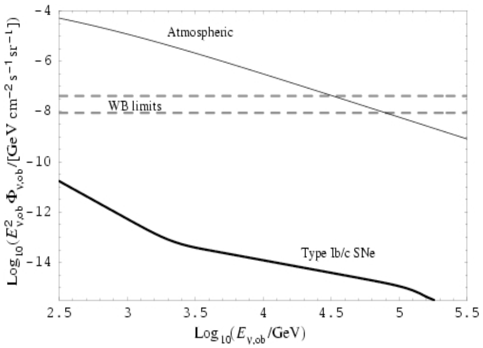
Back-up slides

Semi-relat. (“slow”) jets in core-collapse SN?



- Maybe all core coll. (II or Ib/c) SN resemble (watered-down) GRB?
- Evidence for asymmetric expansion of c.c. (Ib/c) SNR:
  - asymmetric remnants
  - optical polarization
  - jets may help eject envelope
- → slow jets Γ~ few ?

Core collapse SN : slow jets?



Spectrum and diffuse flux ↑

Razzaque, Mészáros, Waxman, 2004, PRL 93, 181101

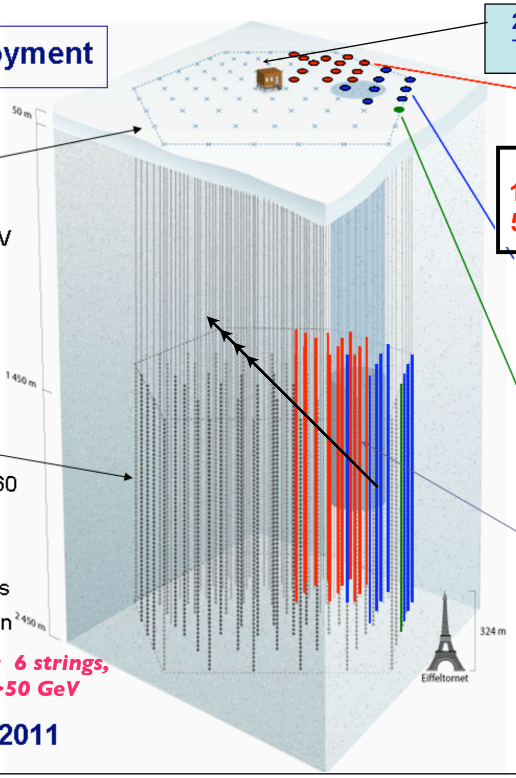
Ando & Beacom, 2005, PRL 95, 1103

- Maybe all core coll. (or Ib/c) SN resemble (watered-down) GRB?
- Evidence for asymmetric expansion of c.c. (Ib/c) SNR: slow jets Γ~ few ?
- If so, accel protons while jet inside star, $p\gamma \rightarrow \pi, \mu \rightarrow \nu$ (TeV)
- **Diffuse flux:** ***negligible,***
- *but*
- ***individual SN*** in nearby (2-3 Mpc) gals, e.g. M82, NGC253, **detectable** (if have slow jets),

  at a rate ~ 1 SN/5 yr,
  fluence ~2 up-muons/SN

  (hypernova: 1/50 yr, 20 up-μ),
  negligible background, in km^3 detectors - **ICECUBE**

IceCube Deployment



2008-2009: 21 strings,
Total: ***59 strings (73%)***

2006-2007:
13 strings deployed

22 strings
1320 digital modules
52 surface detectors

2005-2006: 8 strings

2004-2005 : 1 string

First data in 2005
first upgoing muon:
July 18, 2005

AMANDA
19 strings
677 modules

IceTop
Air shower detector
Threshold ~ 300 TeV

InIce
planned 80 strings of 60
optical modules each

17 m between modules
125 m string separation

Deep Core: 6 strings,
threshold >50 GeV

Completion by 2011

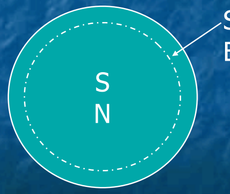
Origin of 10^{19}-10^{21} eV UHECR: may be GRB - but what about 10^{16}-10^{19} eV?

Radio, x-ray & gamma-ray observations of SN1998bw/GRB980425

- sub-energetic GRB—GRB980425: E~1e48 erg (d=38 Mpc)
- Radio afterglow modeling: E>1e49 erg,   \Gamma~1-2
- X-ray afterglow: E~5e49 erg, \beta=0.8

Mildly relativistic ejecta component

E_SN=3-5e52 erg
V=0.1c



SN shock acceleration in the Envelope?

Tan et al. 01
Woosley et al. 99

Other SN/GRB w. semi-relativistic ejecta: →

- SN2003lw/GRB031203
- SN2006aj/GRB060218

The maximum energy of accelerated particles

1) Type Ib/c hypernovae expanding into the stellar wind of Wolf-Rayet star
2) equipartition magnetic field B, both upstream and downstream

$$B^2/8\pi = 2\epsilon_B \rho_w(R) c^2 \beta^2$$

$$\rho_w(R) \propto R^{-2}$$

Maximum energy:

Hillas

Bell & Lucek

01

$$\varepsilon_{\rm max} \simeq ZeBR\beta = 4\times 10^{18} Z \times \epsilon_{B,-1}^{1/2} \left(\frac{v}{10^{10}{\rm cms^{-1}}}\right)^2 \left(\frac{\dot{M}}{3\times10^{-5}{\rm M_\odot yr^{-1}}}\right)^{1/2} v_{w,3}^{-1/2} {\rm eV}$$

Protons can be accelerated to ~10^{19} eV
Heavy nuclei can be accelerated to ~Z*10^{19}eV

Flux level--- energetics

Kinetic energy generation rate:

$$\dot{\epsilon}_k(z=0) = R_{\rm HN} E_{k,\rm HN}$$
$$= 2.5 \times 10^{46} \left(\frac{R_{\rm HN}}{500{\rm Gpc^{-3} yr^{-1}}}\right) {\rm erg\ Mpc^{-3}\ yr^{-1}}$$

Compare w. normal GRBs

	Hypernova (v=0.1c)	Normal GRBs
Rate (z=0)	~500 $\rm Gpc^{-3}\,yr^{-1}$	~1 $\rm Gpc^{-3}\,yr^{-1}$
kineticenergy	3-5e52 erg	1e53-1e54erg

The required rate :

$$R_{\rm HN} = 750 Z^{-1.2} (f_z/3)^{-1} {\rm Gpc^{-3} yr^{-1}}$$

Normal Ib/c SN rate:

$$\sim 2 - 5 \times 10^4\ {\rm Gpc^{-3} yr^{-1}}$$

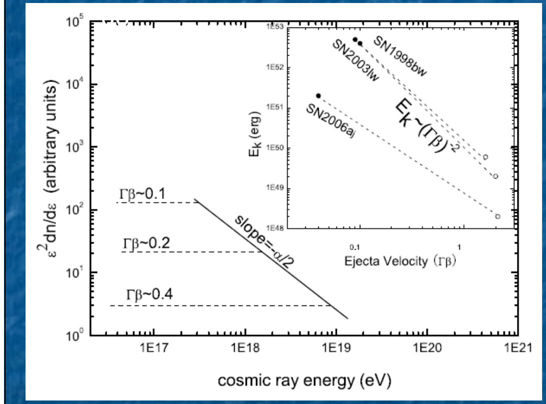
sub-energetic GRB rate:

$$100 - 1800\ {\rm Gpc^{-3} yr^{-1}}$$

Soderberg et al.

Energy distribution with velocity

Data from Soderberg et al.



Wang, Razzaque, Meszaros, Dai 07

- Normal SN $E_k \propto (\Gamma\beta)^{-5}$

  Very steep distribution -> negligible contribution to high-energy CRs

  Berezhko & Volk 04

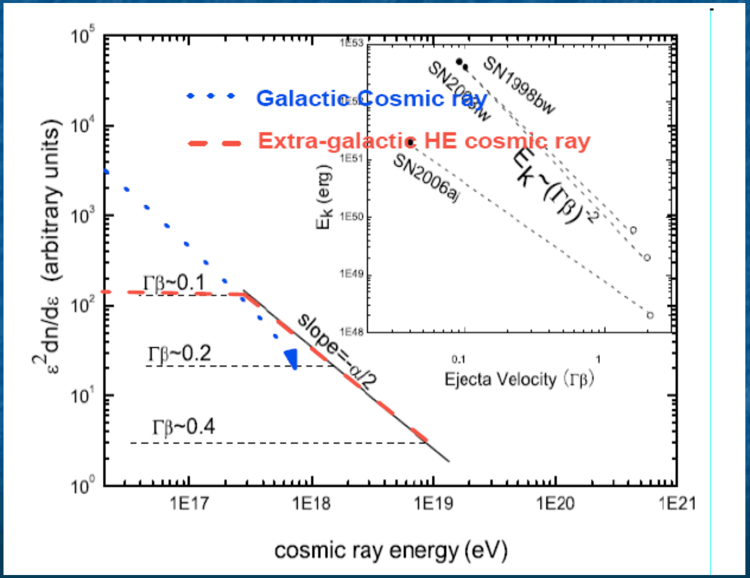
- Semi-relativistic hypernova: high velocity ejecta with significant energy is essential

  $E_k \sim (\Gamma\beta)^{-2}$

⇨ CR spectrum: $\varepsilon^2 (dN/d\varepsilon) \propto \varepsilon^{-\alpha/2}$

$\alpha \sim 2$

Transition from GCRs to EGCRs



GRB 080319B

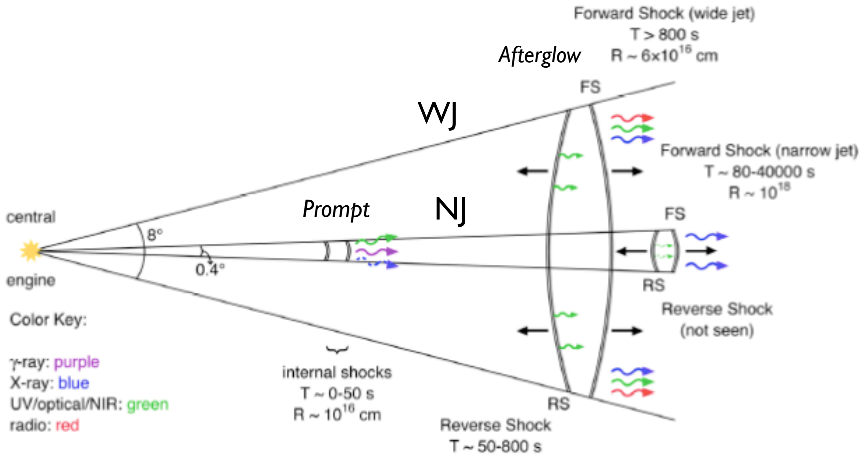


Figure 4 | Schematic of Two-Component Jet Model. Summary diagram showing spectral and temporal elements of our two-component jet model. The prompt γ-ray emission is due to the internal shocks in the narrow jet, and the afterglow is a result of the forward and reverse shocks from both the narrow and wide jets. The reverse shock from the narrow jet is too faint to detect compared to the bright wide jet reverse shock and the prompt emission. If X-ray observations had begun earlier, we would have detected X-ray emission during the prompt

Mészáros

LIV limits GRB 080916C

Fermi collaboration (Abdo et al), 2009, Sci. subm.

1st and 2nd order (n=1,2) energy dependent pulse time dispersion
in effective field theory formulation of LIV effects, where

leading order deviation is $E^2 - p^2 - m^2 \approx \pm E^2 (E/E_{QG})^n$

$$\Delta t = \frac{(1+n)}{2H_0} \frac{E_h^n - E_l^n}{(M_{\mathrm{QG},n}c^2)^n} \int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}} dz' \,,$$

Conservative lower limit on E_{QG} , taking E_h/t ($E_h/t^{1/2}$) with t=pulse time since trigger

$$\begin{aligned} M_{\mathrm{QG},1} &> (1.50 \pm 0.20) \times 10^{18} \left(\frac{E_h}{13.22^{+0.70}_{-1.54}\ \mathrm{GeV}} \right) \left(\frac{t}{16.54\ \mathrm{s}} \right)^{-1} \mathrm{GeV}/c^2 \,, \\ M_{\mathrm{QG},2} &> (9.42 \pm 1.21) \times 10^{9} \left(\frac{E_h}{13.22^{+0.70}_{-1.54}\ \mathrm{GeV}} \right) \left(\frac{t}{16.54\ \mathrm{s}} \right)^{-1/2} \mathrm{GeV}/c^2 \,. \end{aligned}$$

These are the most stringent limits to-date via dispersion

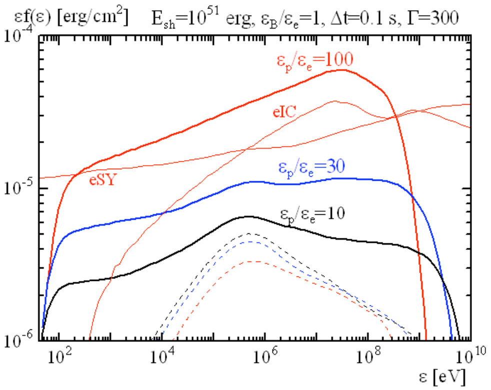
Potential GZK Neutrino Detectors

Detector or Experiment	Effective GZK threshold energy(1) EeV	Effective GZK Geometric volume(2) km^3	target density gm/cm^3	Effective interaction mass km^3 w.e.	Effective neutrino target area(3) km^2	Accept-ance solid angle(4) ster	GZK neutrino Aperture km^2 ster	actual or projected livetime/yr sec/yr	GZK neutrino rate (minimum) (5) events per calendar yr	GZK neutrino rate (maximum) events per calendar yr
Active or completed:										
AGASA(6)	0.3	1000	1.00E-03	1.0	7.44E-04	2	1.49E-03	3.00E+07	2.4E-02	1.2E-01
AMANDA(7)	0.1	4.0	0.9	3.6	1.80E-03	1	1.80E-03	3.00E+07	4.2E-02	2.1E-01
GLUE(8)	300	100000	2	200,000	1.79E+03	0.01	17.89	2.00E+05	2.8E-04	1.4E-03
Fly's Eye(9)	1	500	6.00E-04	0.30	3.44E-04	2	6.88E-04	3.00E+06	6.0E-04	3.0E-03
HiRes(10)	1	8500	6.00E-04	5.1	5.85E-03	2	1.17E-02	2.00E+06	6.8E-03	3.4E-02
EAS-TOP(11)	0.3	30	6.00E-04	0.018	1.34E-05	2	2.68E-05	1.00E+07	7.8E-05	3.9E-04
RICE(12)	0.3	1.0	0.9	0.9	6.69E-04	6	4.02E-03	3.00E+06	6.5E-03	3.3E-02
In construction or advanced planning:										
Auger(13)	1	15000	8.00E-04	12	1.38E-02	3	4.13E-02	3.00E+07	0.36	1.80
ANTARES/NEMO	0.3	30	1.00E+00	30	2.23E-02	0.6	1.34E-02	3.00E+07	0.22	1.09
EUSO(14)	100	1000000	1.00E-03	1,000	6.02E+00	2	12.04	3.00E+06	0.031	0.15
IceCube(15)	0.3	60	0.9	54	4.02E-02	0.6	2.41E-02	3.00E+07	0.64	3.21
ANITA(17)	3	600000	0.9	540,000	9.20E+02	0.01	9.20	1.81E+06	1.75	8.74
Telescope Array	1	30000	1.00E-03	30	3.44E-02	2	6.88E-02	2.00E+06	0.040	0.20
Proposed, pre-proposal, or conceptual										
OWL(16)	100	5.80E+06	1.00E-03	5,800	3.49E+01	1.0	36.13	3.00E+06	0.09	0.46
SALSA(18)	0.3	15	2.2	33	2.45E-02	7	0.17	3.00E+07	2.80	14.0
SuperRICE(19)	3	100	0.9	90	1.53E-01	6	0.92	3.00E+07	2.89	14.5

Hadronic GRB:

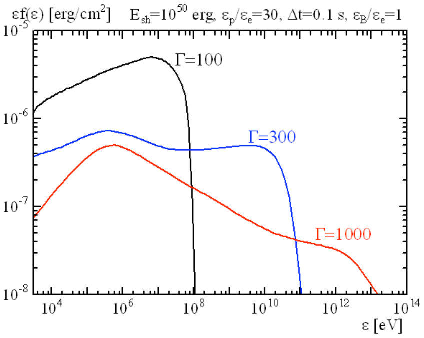
easier to look for secondary *photons*

from p,γ interactions



Asano, Inoue & Mészáros
ApJ in press, arXiv:0807.0951

If GRB are UHECR sources, may need $\varepsilon_p/\varepsilon_e \gtrsim 10$ → tends to give identifiable "hadronic" photon peak



Diagnostic for
↑: high $\varepsilon_p/\varepsilon_p$
←: high bulk Γ
→ : high $\varepsilon_B/\varepsilon_e$