The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
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International Atomic Energy Agency

2036-18

International Workshop: Quantum Chromodynamics from Colliders to Super-High Energy Cosmic Rays

25 - 29 May 2009

Gamma-Ray Bursts: GeV/TeV photon emission & UHECR/UHEV/GW

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Gamma-Ray Bursts :

GeV/TeV photon emission
and
UHECR/UHEV/GW

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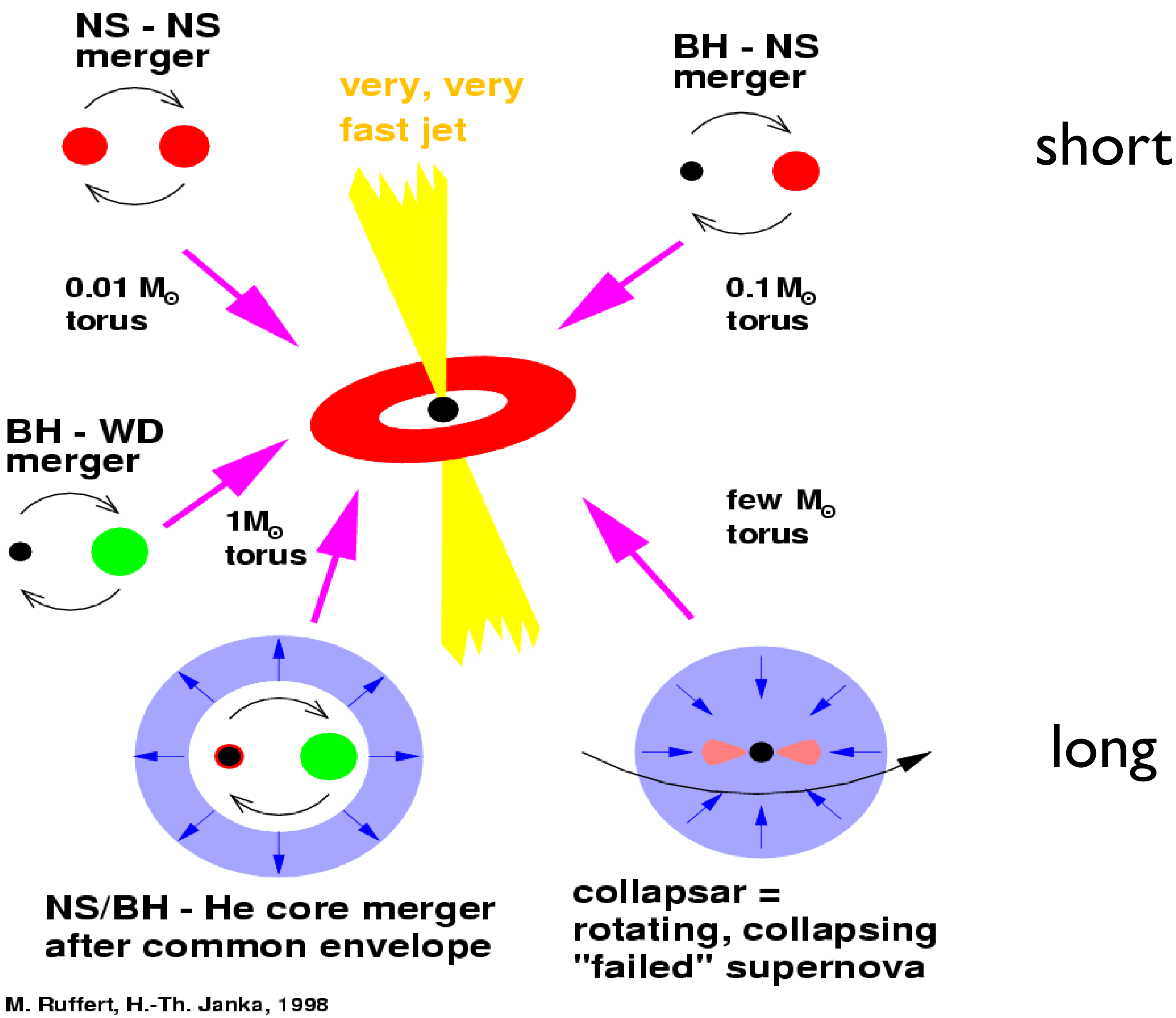
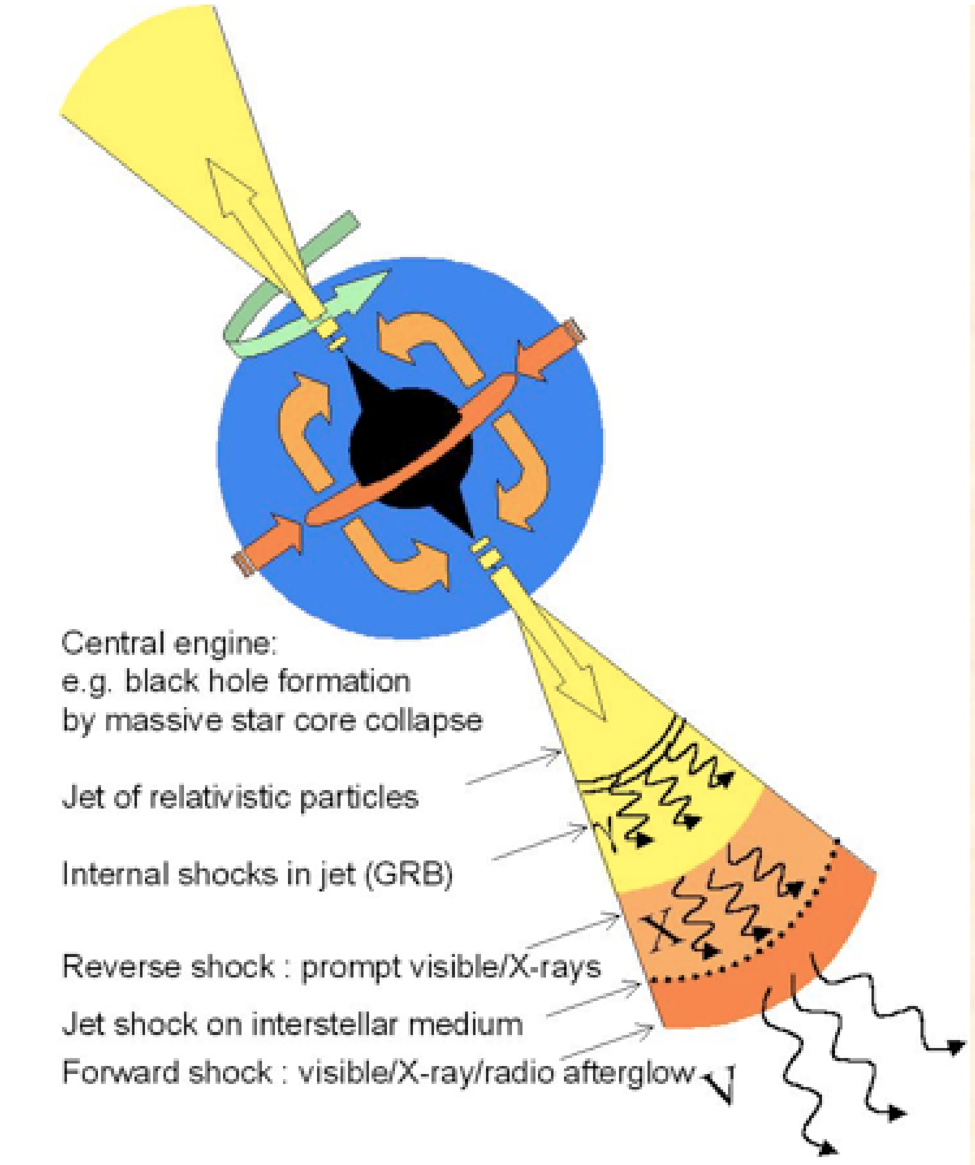
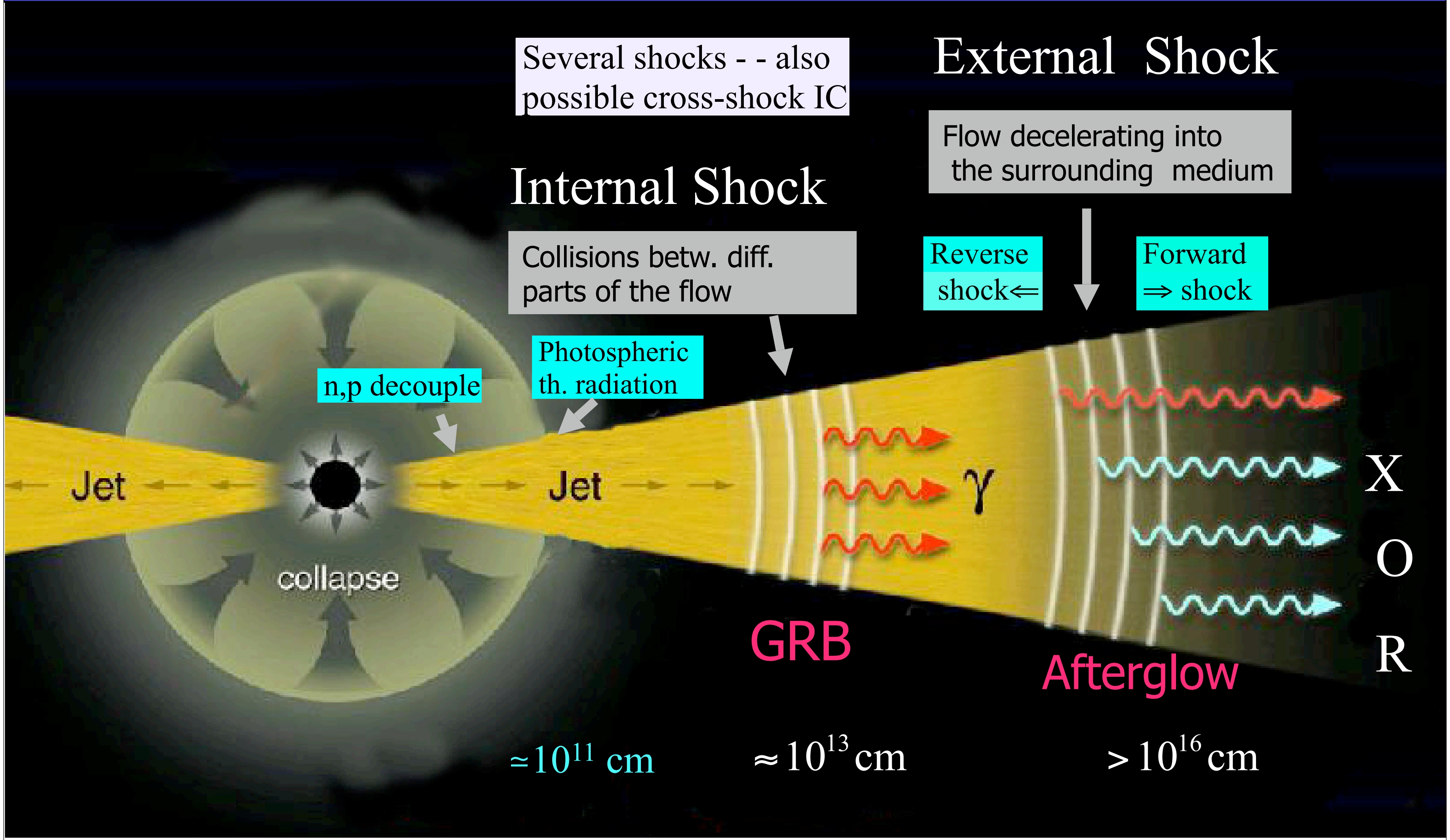
GRB:→ Hyperaccreting Black Holes (*via PNS?*)



GRB paradigm

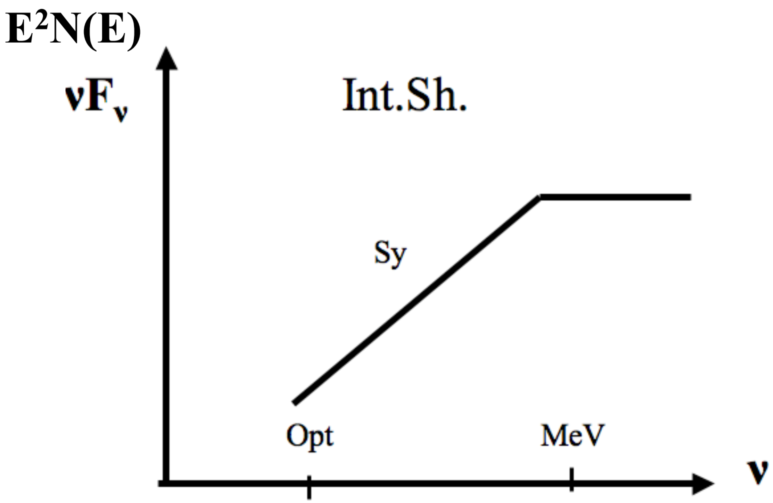


Fireball Model of GRBs

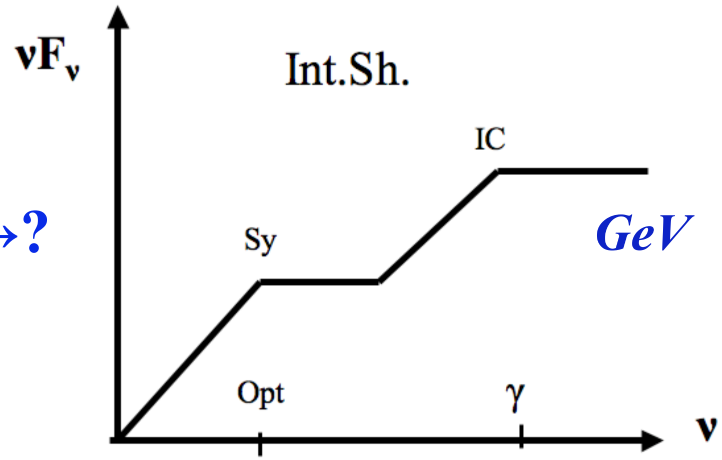


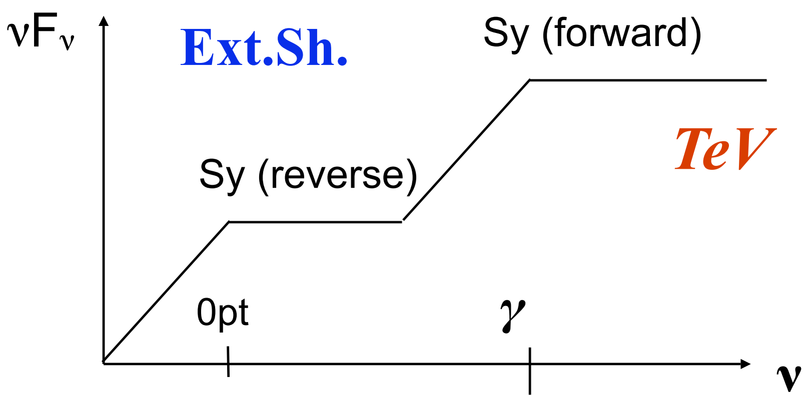
Standard shock γ-ray components :

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



Or →?





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

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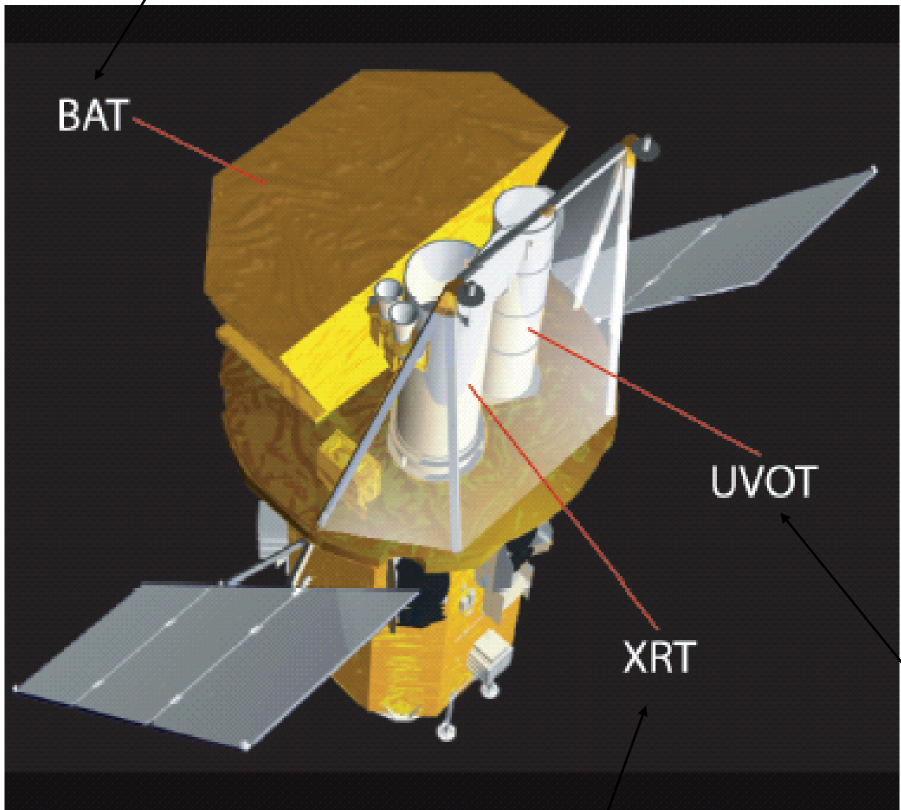
BAT: Energy Range: 15-150kev
FoV: 2.0 sr
Burst Detection Rate: 100 bursts/yr

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.

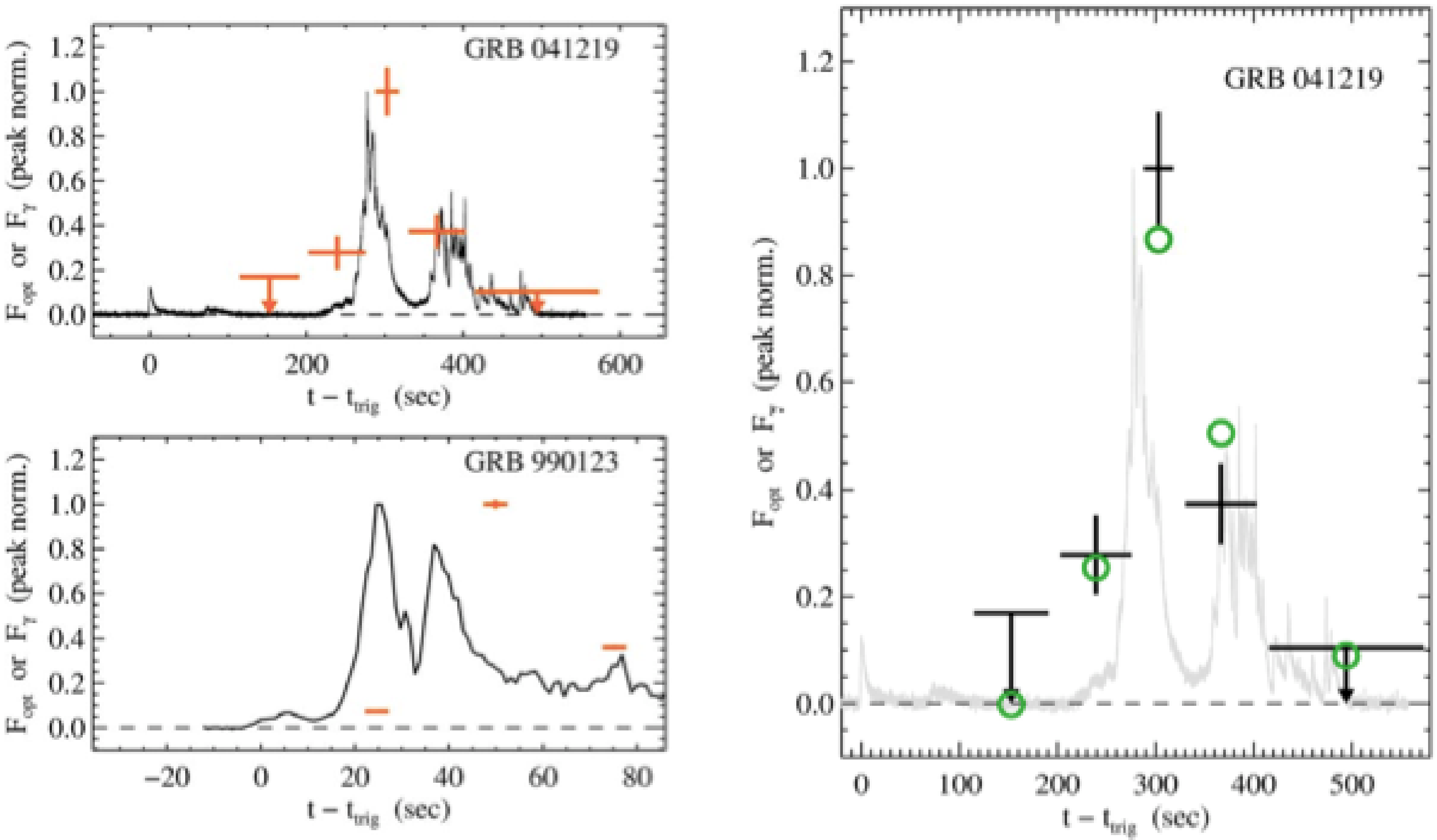
UVOT: Wavelength Range: 170-650nm

XRT: Energy Range: 0.2-10 keV

Launched Nov 04

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

But: prompt γ,opt. related?



Sometimes same origin, sometime not ? (Vestrand et al, 06)

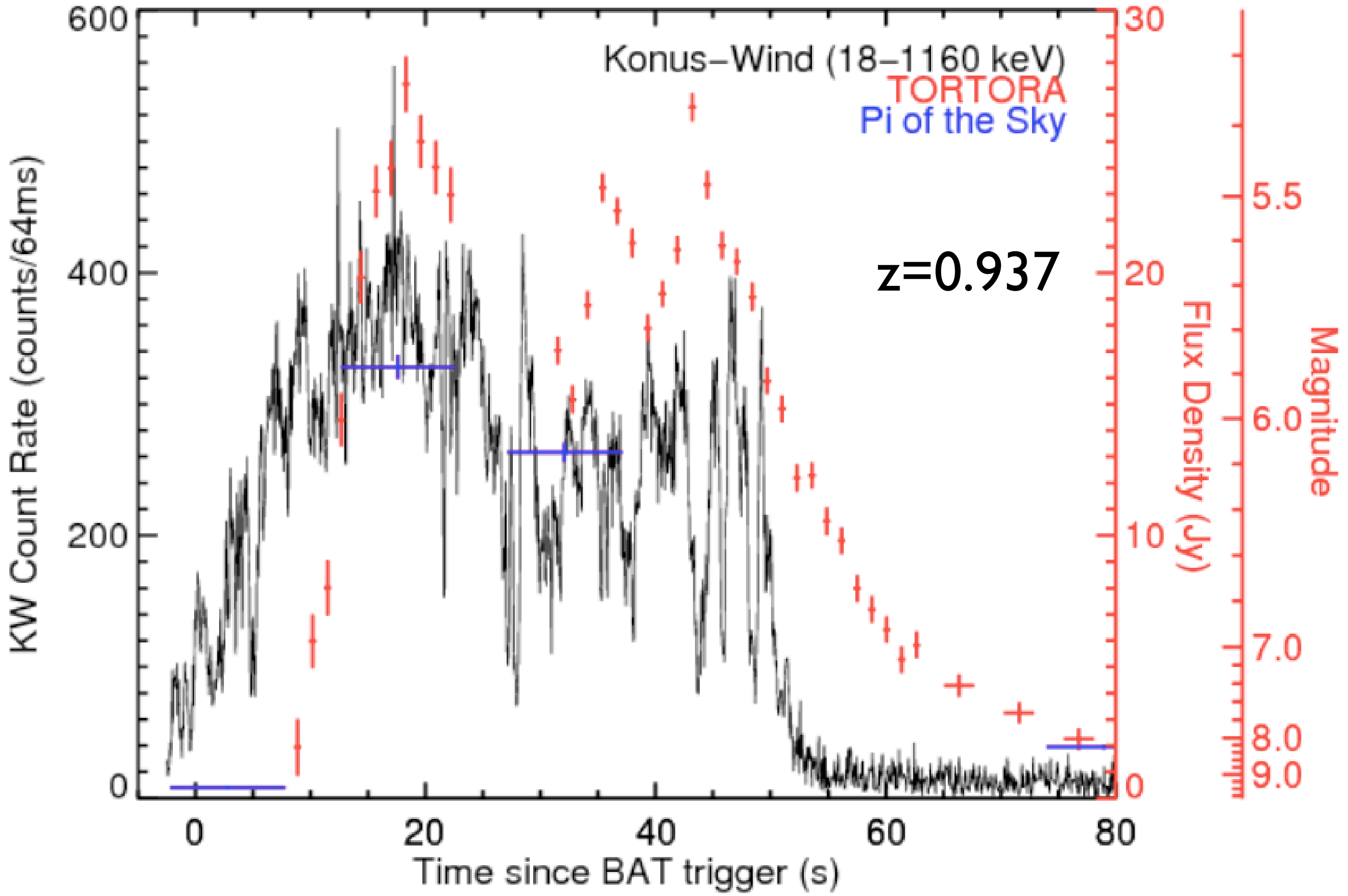


Figure 1 | Prompt Emission Light Curve. The Konus-Wind background-subtracted γ-ray lightcurve (black), shown relative to the *Swift* BAT trigger time, T_0. Optical data from "Pi of the sky" (blue) and TORTORA (red) are superimposed for comparison. The optical emission begins within seconds of the onset of the burst. The TORTORA data have a gap during the slew of the REM telescope to this field, but show 3 sub-peaks in the optical brightness, reaching a peak brightness of 5.3 magnitudes (white). The γ-ray light curve has multiple short peaks; these are not well correlated with the optical peaks in detail (cf. ref 25), but the optical pulses may be broader and peak somewhat later than the γ-ray pulses, if the optical is slightly below the synchrotron self-absorption frequency, which may account for the lack of detailed correlation. The optical flash, however, begins and ends at approximately the same times as the prompt γ-ray emission, providing strong evidence that both originate at the same site. See

GRB 080319B

A prompt "naked eye" optical GRB

Racusin et al, 08 Nature 455:183

γ, opt prompt l.c. appear similar → same emission region, e.g. "internal" shock; but rad. mechanism?

Interpret prompt as:

i) optical synchrotron
ii) 0.1-1 MeV IC (SSC)
(and)
iii) predict 2nd order IC @ ~100 GeV

(there are also differing opinions)

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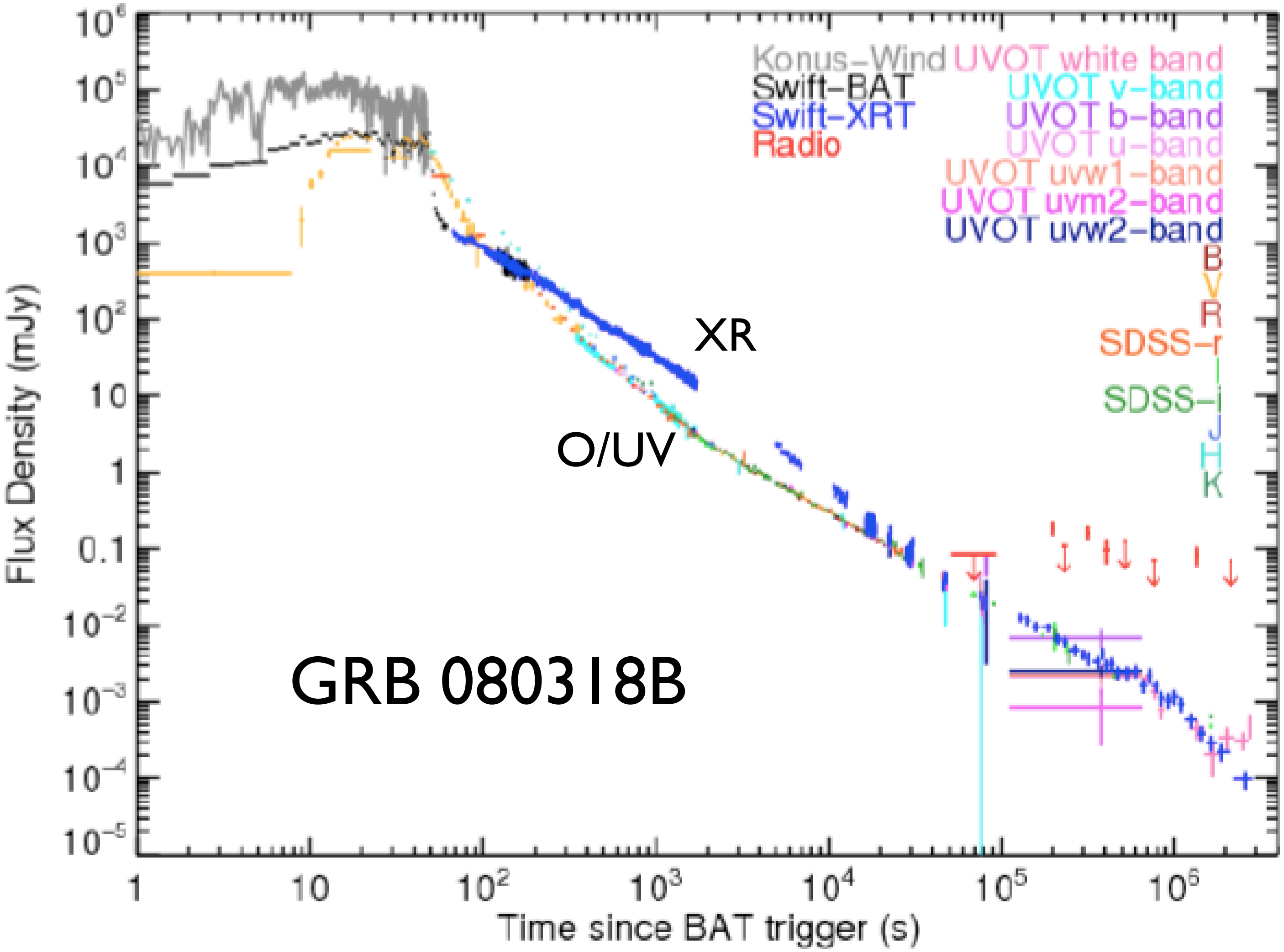
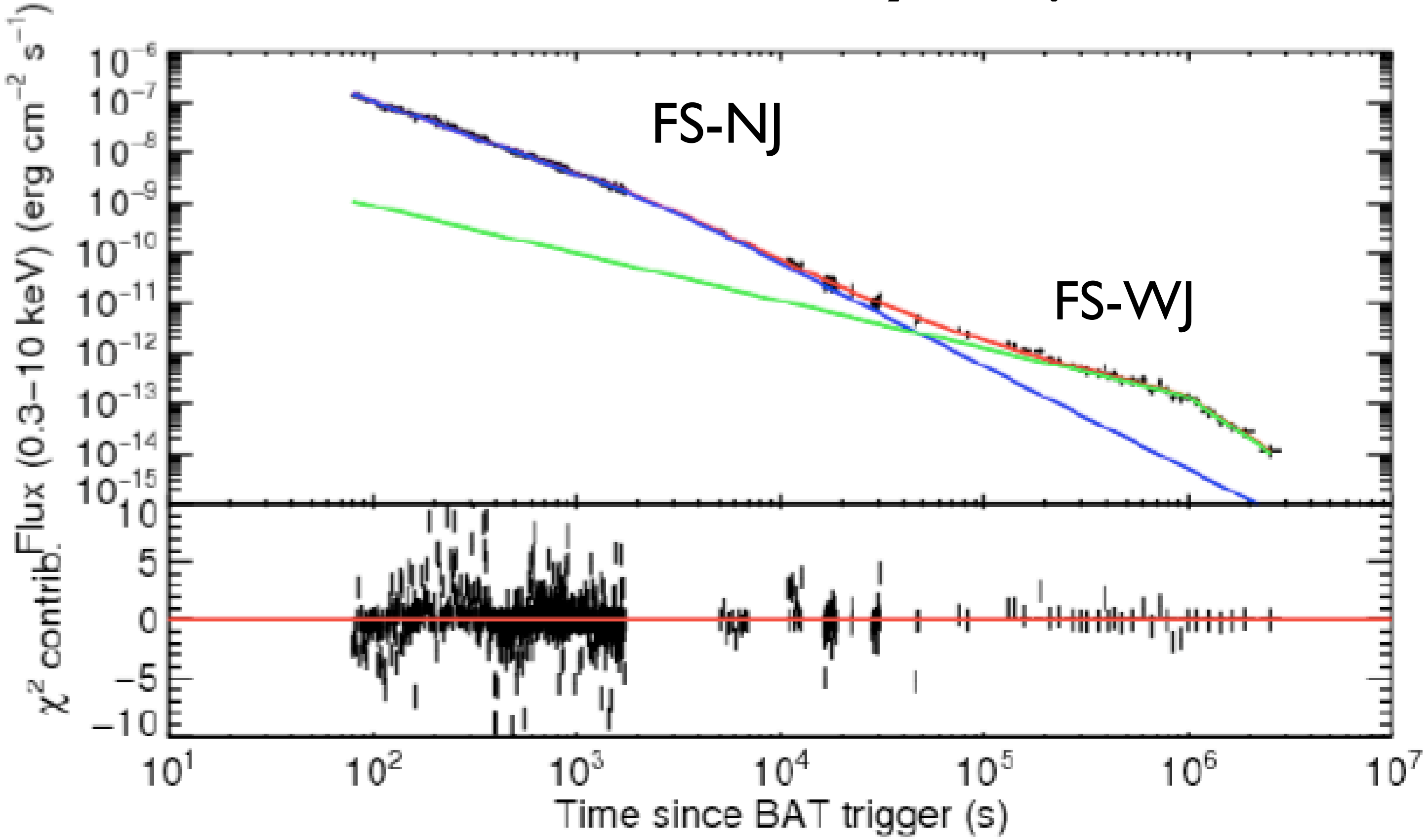


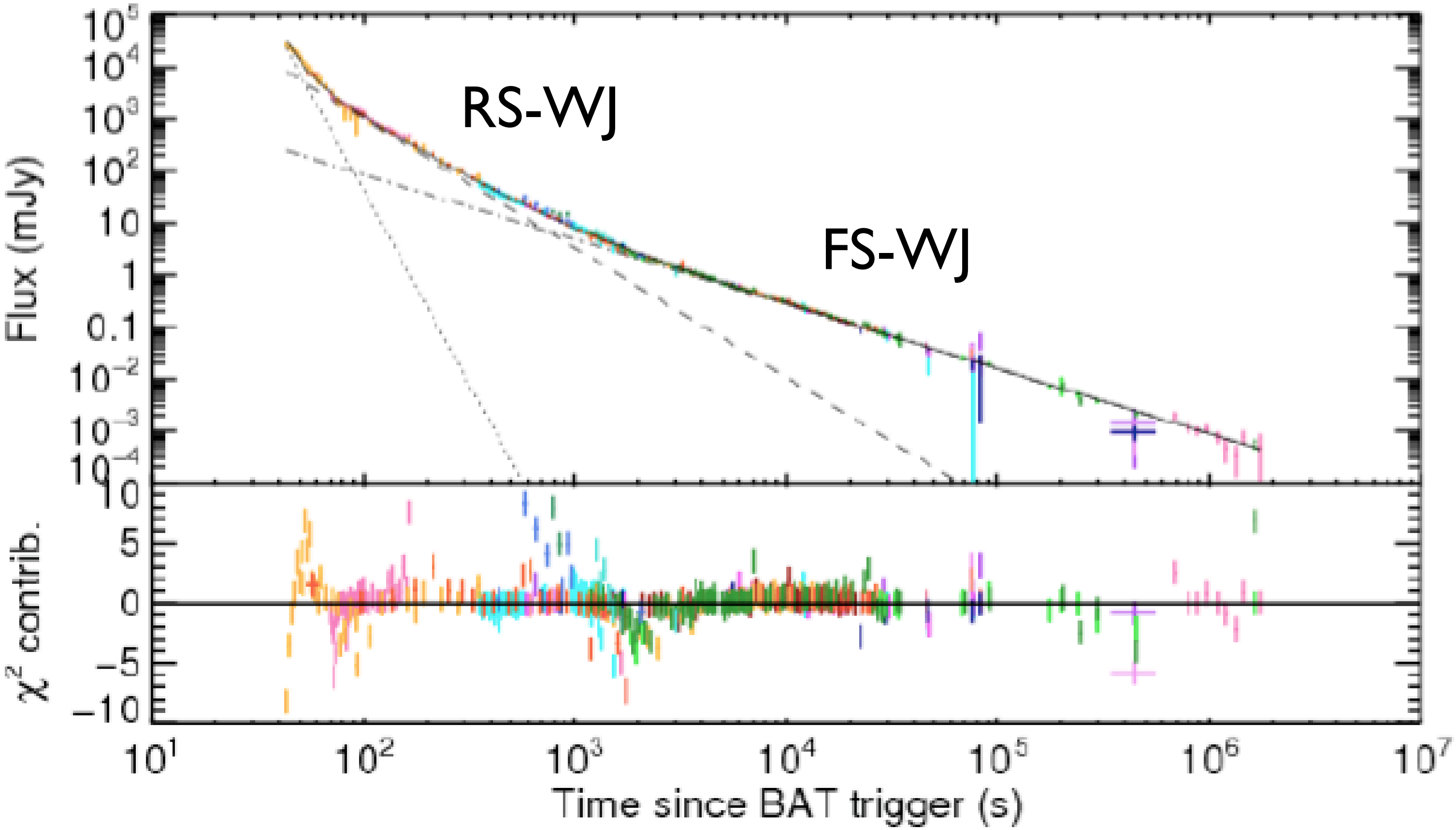
Figure 2 | Composite Light Curve. Broadband light curve of GRB 080319B, including radio, NIR, optical, UV, X-ray and γ-ray flux densities. The UV/optical/NIR data are normalized to the UVOT v-band in the interval between T_0+500 s and T_0+500 ks. The *Swift*-BAT data are extrapolated down into the XRT bandpass (0.3-10 keV) for direct comparison with the XRT data. The combined X-ray and BAT data are scaled up by a factor of 45, and the Konus-Wind data are scaled up by a factor of 10^4 for comparison with the optical flux densities. This figure

080319B X-Ray 2-jet fit



Supplementary Figure 7 | Two-Component Jet Model fit to X-ray Afterglow. The X-ray afterglow is best described by the superposition of two broken power-laws, which is consistent with the narrow and wide jets of a two-component jet expanding into a stratified wind environment. The narrow jet dominates the first ~40 ks of the afterglow as indicated by the blue line, which shows the fit to the narrow jet component. After the narrow jet break decays, the wide jet dominates as indicated by the green line fit to late afterglow. The red line shows the superposition of both components and the overall fit to the X-ray light curve.

080319B optical 2-jet fit



Supplementary Figure 6 | Three-Spectral Component Fit to the Decaying Optical Transient Following the peak of the prompt optical flash, the optical transient light curve displays three distinct components that dominate in the intervals t<50s, 50s<t<800s, and t>800s. The initial decay of the bright optical flash is a power-law with α_1=6.5±0.9 (dotted line). This is superimposed on a power-law with decay index α_2=2.49±0.09 (dashed line) that dominates in the middle time interval and a third power-law with α_3=1.25±0.02 (dot-dashed line)

GRB 080319B

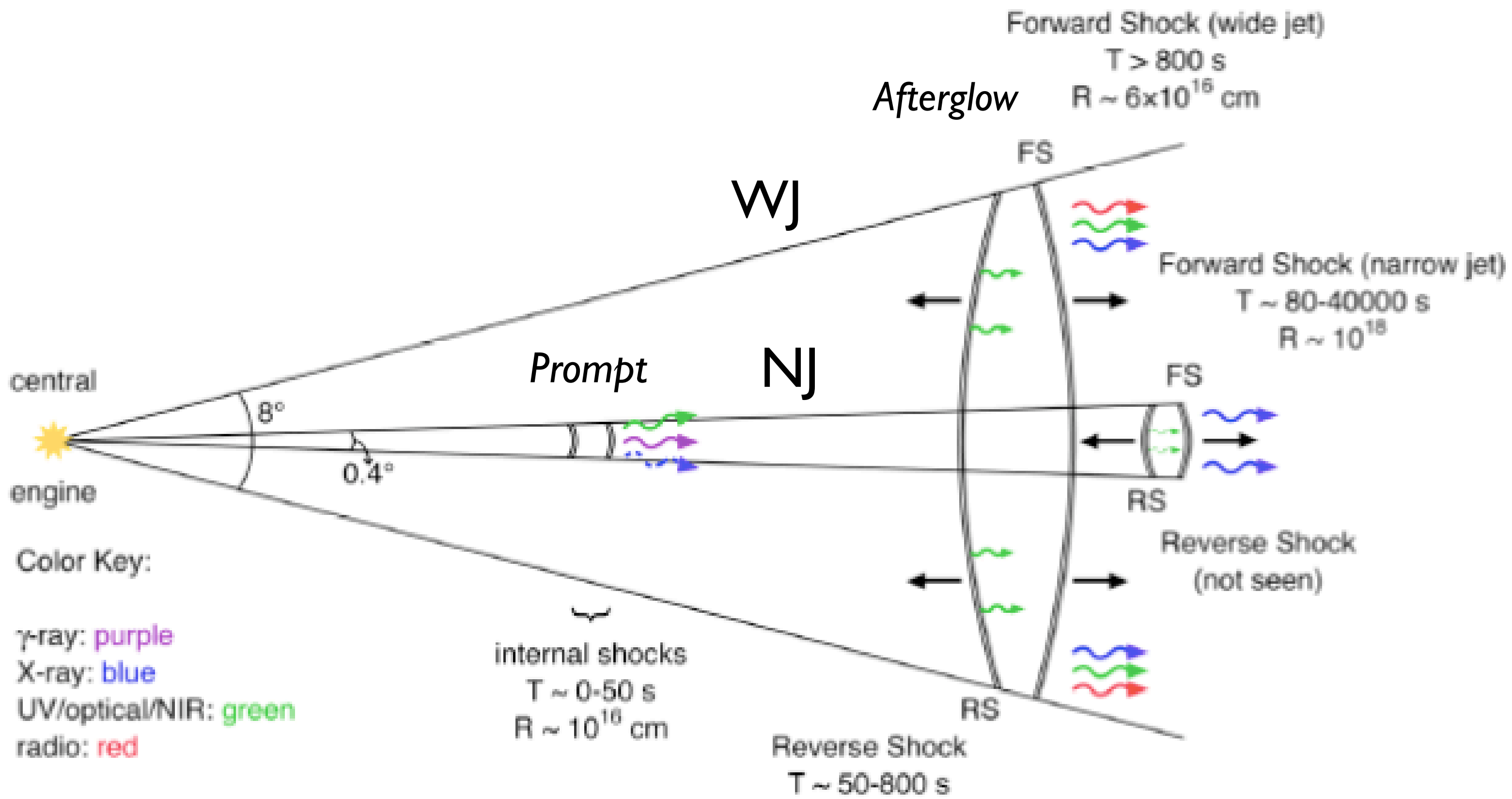
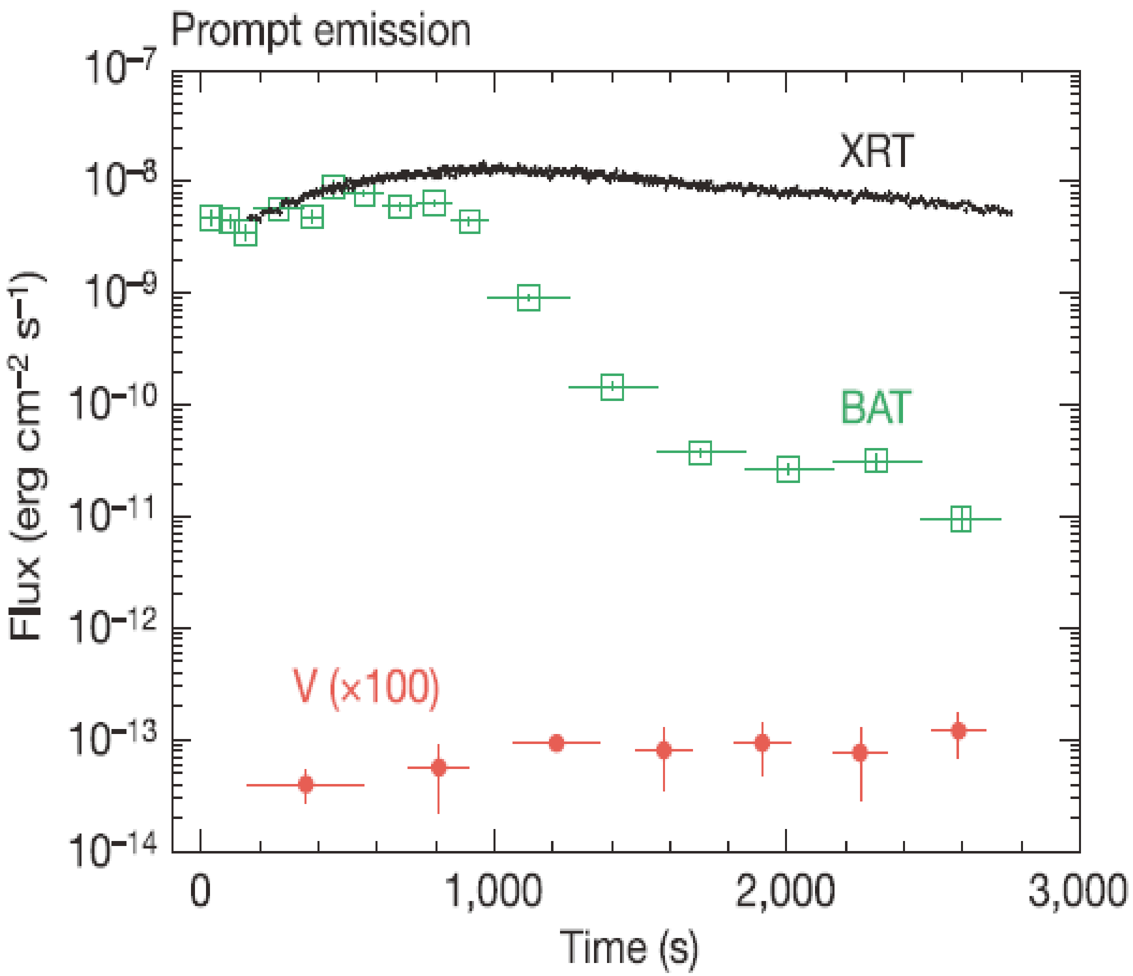


Figure 4 | Schematic of Two-Component Jet Model. Summary diagram showing spectral and temporal elements of our two-component jet model. The prompt γ-ray emission is due to the internal shocks in the narrow jet, and the afterglow is a result of the forward and reverse shocks from both the narrow and wide 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

A different prompt: GRB060218/SN2006aj

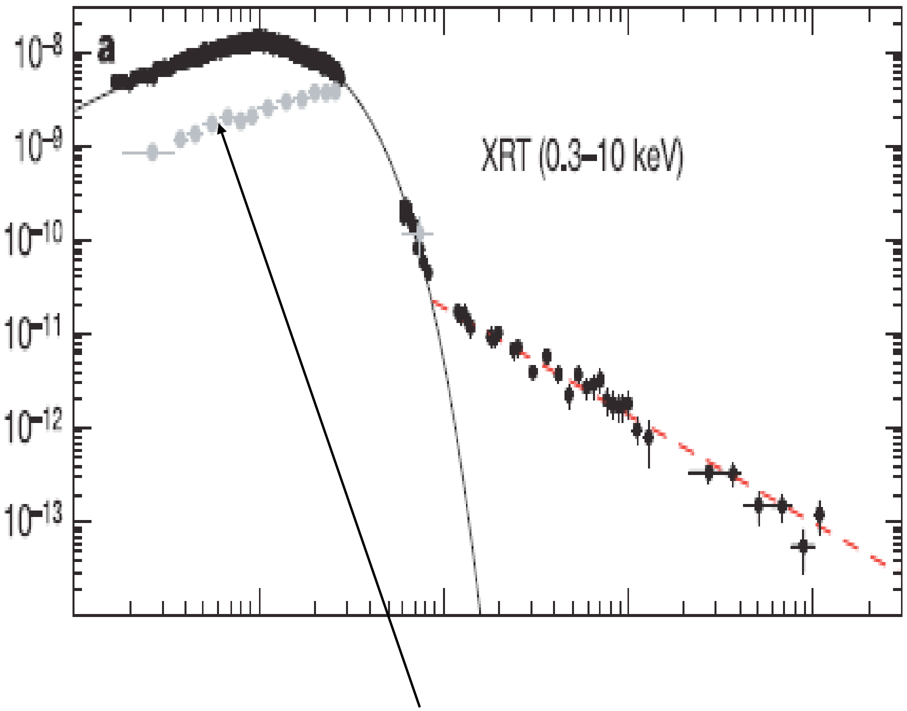
There may be more to "prompt" emission than high Γ shocks !



- An unusually long, smooth burst, T_{90}~2100±100 s
- Low luminosity, low energy : E_{iso}~6x10^{49} erg
- z=0.033, 2nd nearest GRB (138 Mpc)
- GRB/XRF

Campana et al. 2006

A 'prompt' X-ray BB component !



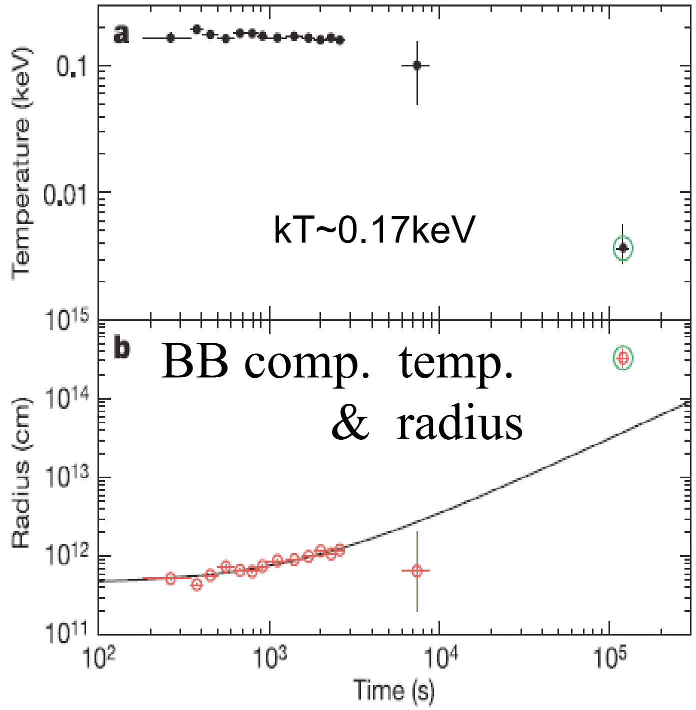


Figure 3 | Evolution of the soft thermal component temperature and radius. a, Evolution of the temperature of the soft thermal component. The

Contribution of a fitted **black-body component** (20%) to the 0.3-10KeV flux:

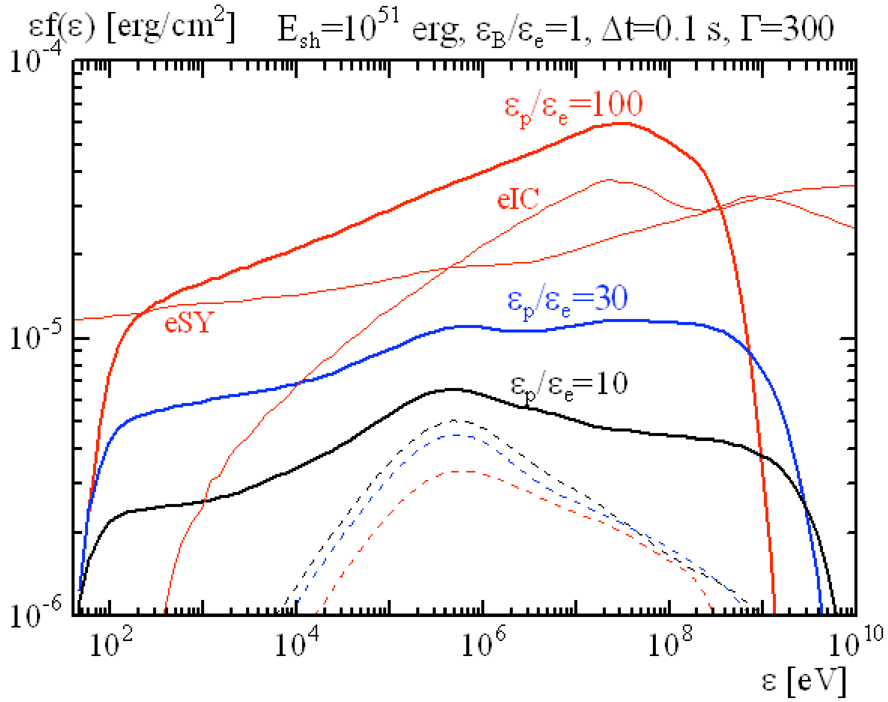
BB Interpreted as **break-out** of an **anisotropic**, ***semi-relativistic, radiation-mediated*** **shock** from Thomson optically thick ***stellar wind***

(Campana et al 06, Nature 442:1006; Waxman, Mészáros & Campana, 07, ApJ 667:351)

UHE CRs & ν , γ from GRB

pγ, pp $\longrightarrow$ UHE ν , γ

- If protons present in (baryonic) jet $\rightarrow$ 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.: $E_p E_\gamma \sim 0.3\ \mathrm{GeV}^2$ in jet frame)
- $\rightarrow E\nu_{,br} \sim 10^{14}$ eV for MeV γs (int. shock)
- $\rightarrow E\nu_{,br} \sim 10^{18}$ eV for 100 eV γs (ext. rev. sh.) : ICECUBE
- $\rightarrow \pi^0 \rightarrow 2\gamma \rightarrow$ $\gamma\gamma$ 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: $\gamma\gamma$ cascade cut-off:
- $E_\gamma \sim$ GeV (internal shock) ; $E_\gamma \sim$ TeV (ext shock/IGM)
- $\longrightarrow$ photon cut-off: diagnostic for int. vs. ext-rev shock



Hadronic GRB:

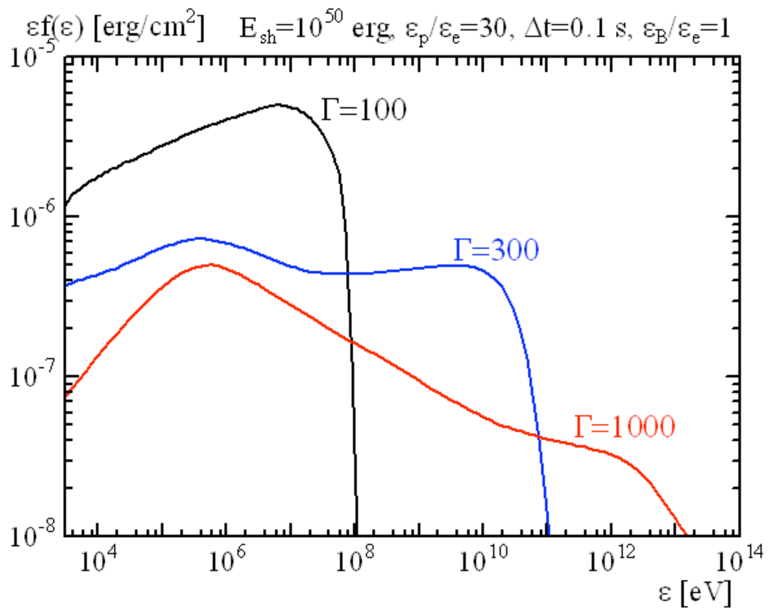
easier to look for

photons from p,γ

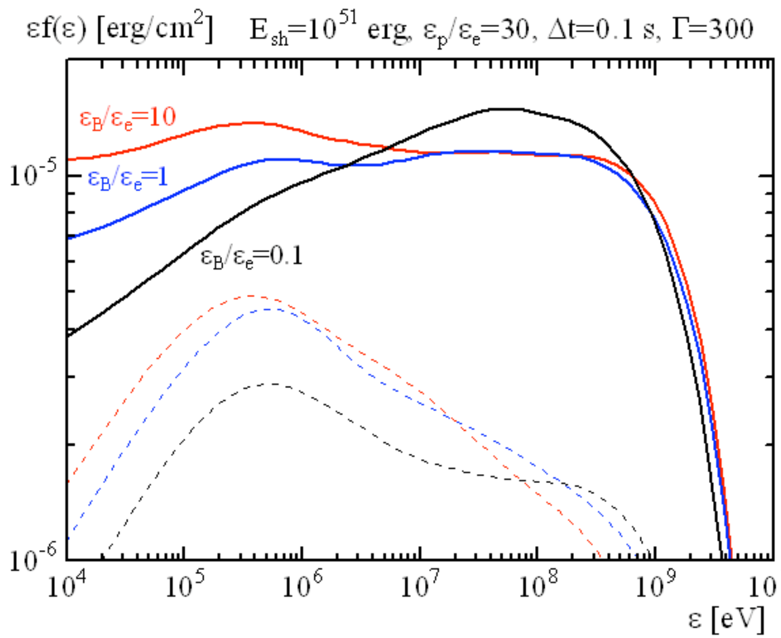
interactions

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

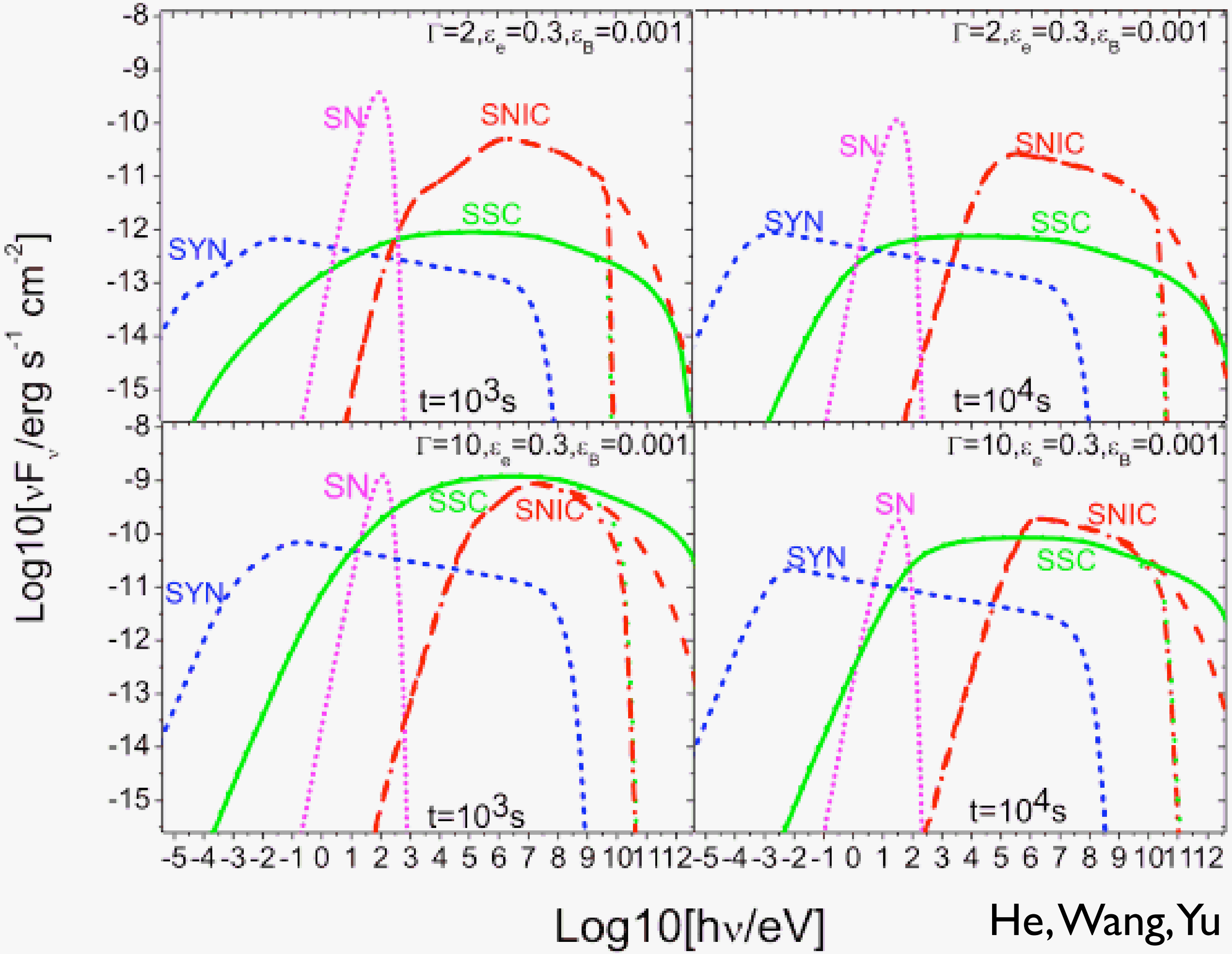


Diagnostic for
↑: high $\varepsilon_p/\varepsilon_p$
←: high bulk Γ
→ : high $\varepsilon_B/\varepsilon_e$



LL GRB : GeV-TeV γs

arising from leptonic sy-IC origin

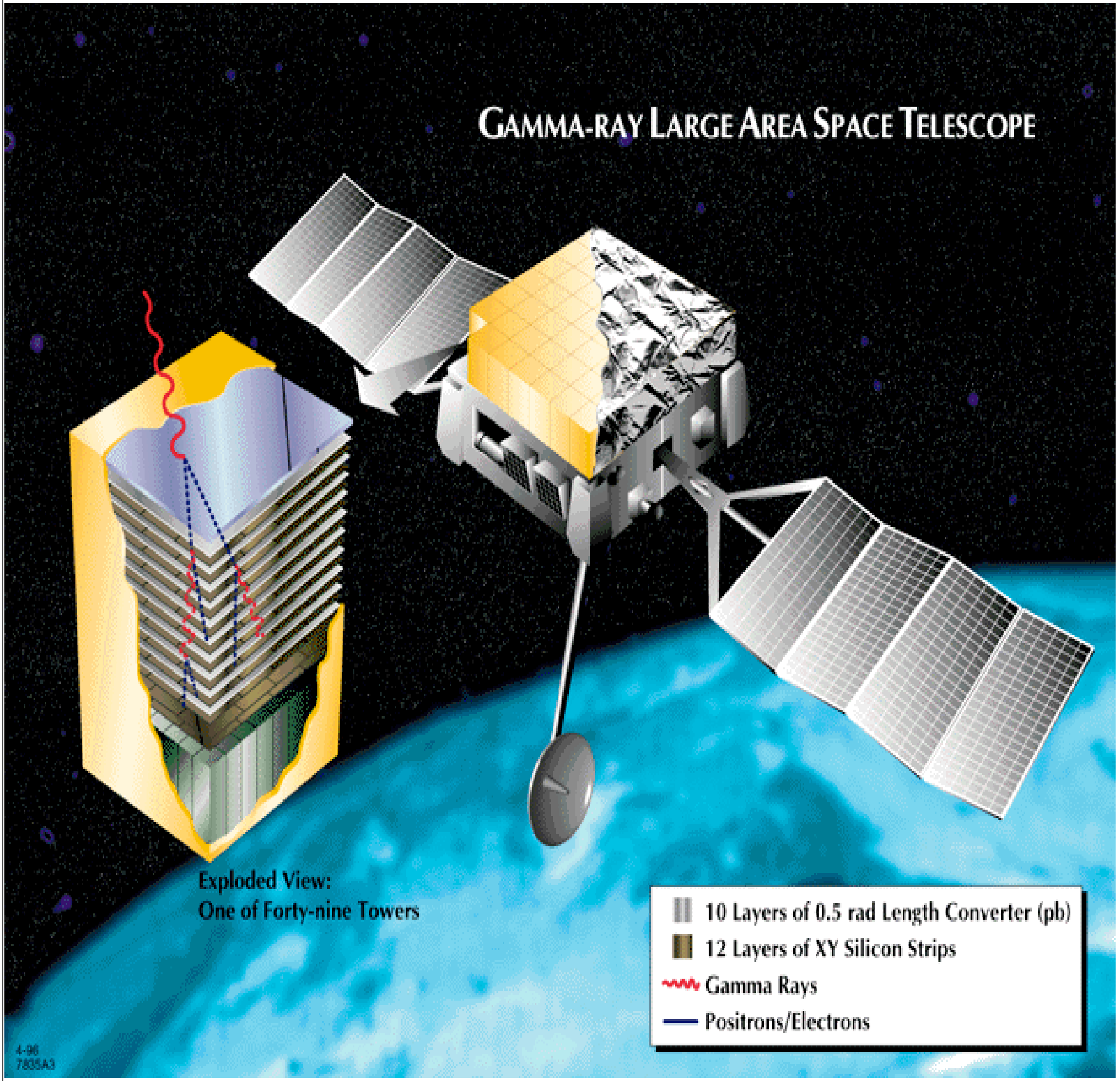


2 sources of hot IC e^- :
shocks- a: Γ~2, b: Γ~10
a) rel. jet in SS stage
b) semirelat. outflow

and

2 sources of seed photons:
a) synchrotron (SSC)
b) SN UV (SN IC) ,
incl. early th. & late RI

He, Wang, Yu & Mészáros 09



Fermi

- Launched June 11 2008
- **LAT**: Pair-conv.modules + calorimeter
- 20 MeV-300 GeV,
  ΔE/E~10%@1 GeV
- FoV = 2.5 sr (2xEgret), ang.res. θ~30"-5' (10GeV)
- Sensit. ~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

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

FERMI
GRB 080916C

First ***high quality*** burst
seen in both ***GBM + LAT***,
with light curve and spectrum over 6 dex

(on behalf of Fermi collaboration)

GRB 080916c

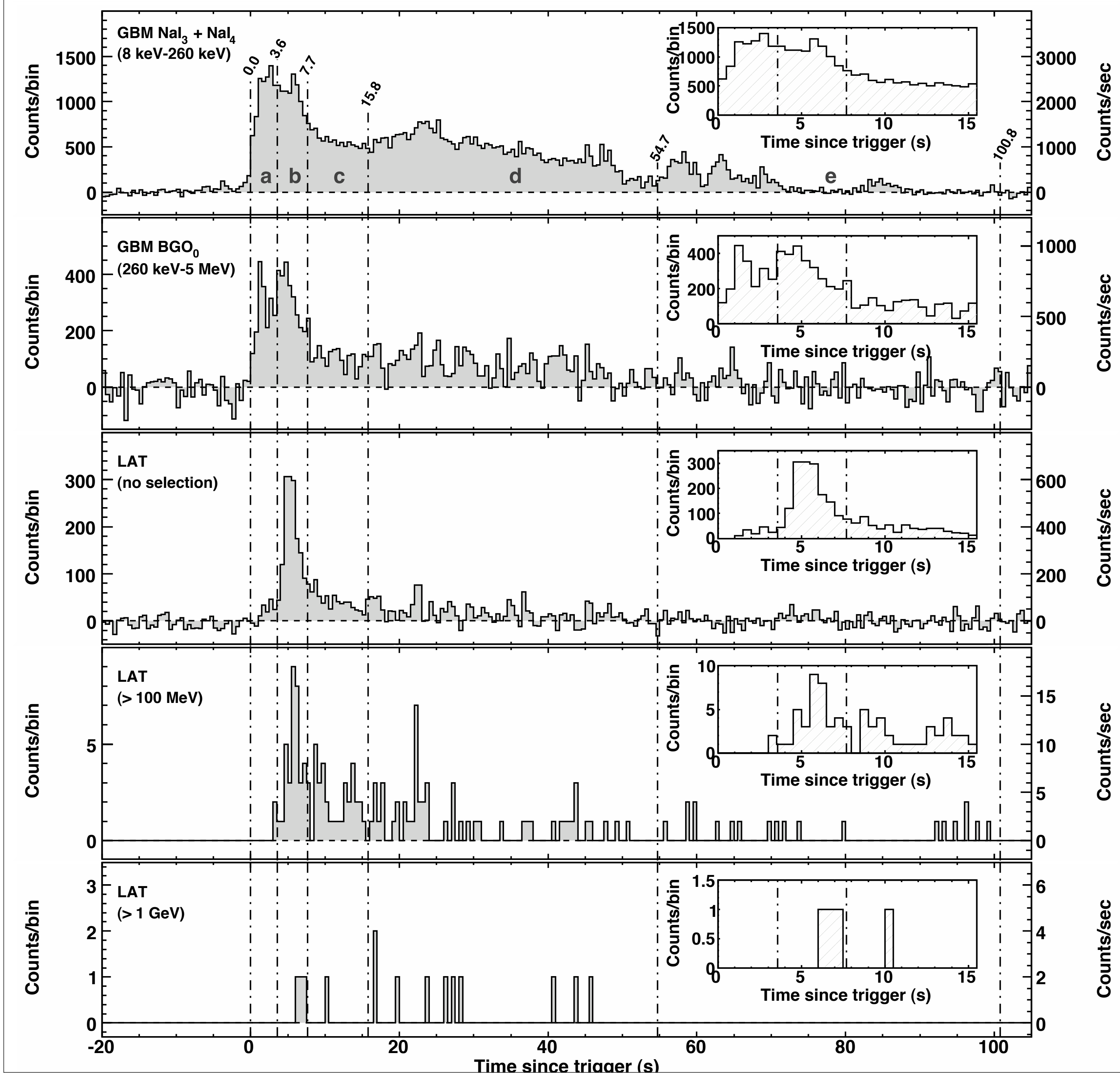
(the Fermi collaboration, 2009)

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 upscattered 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!

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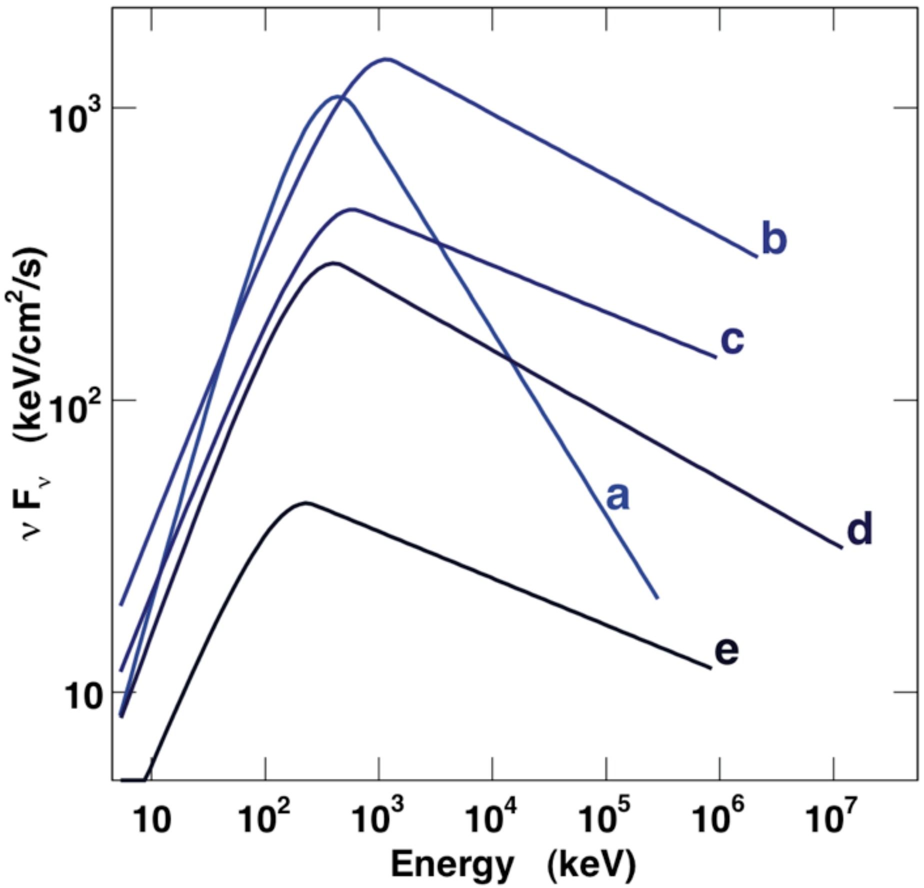
GRB 080916C

Spectrum



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

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GRB 080916c

(the Fermi collaboration, 2009)

3) Other delayed / extended GeV mechanisms:

•***Hadronic?*** (the burning question)... natural delay since extra time for cascade to develop - ***but :*** expect hard to soft time evolution & distinct sp. component - not seen)

• ***Temporally extended GeV*** (between 200-1400s have only LAT, no GBM emission): is this GeV due to the ***afterglow?*** e.g. late arrival of SSC, as argued already for 940217, etc.
- ***but :*** do not see gap or spectral hardening/new HE comp.
- Consistent w. 2nd pulse: could be ***all*** GeV is Sy. afterglow ?

Upshot:

more analysis needed to test hadronic model and/or constrain variant of leptonic model

Future Fermi+Swift+ground observations will tell

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

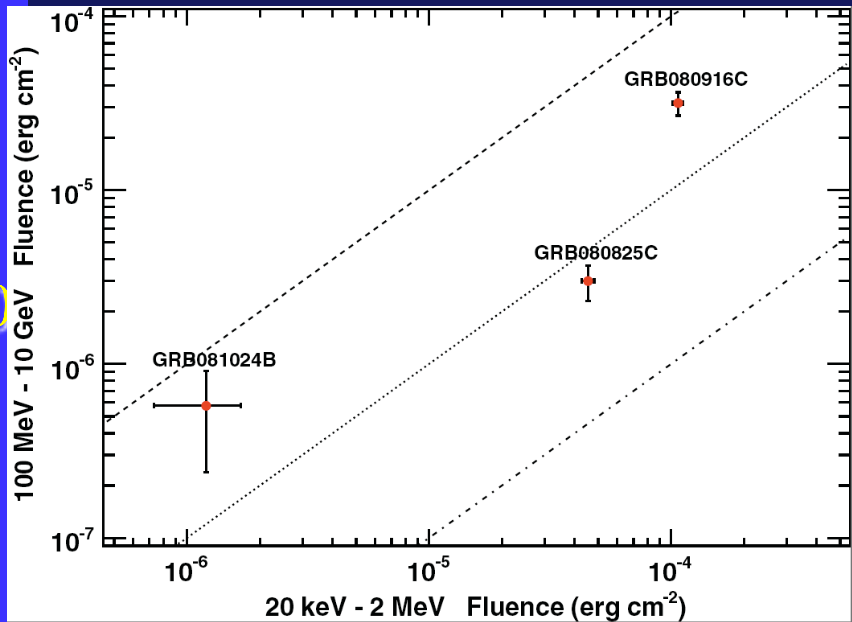
$$M_{\mathrm{QG},1} > (1.50 \pm 0.20) \times 10^{18} \left(\frac{E_h}{13.22^{+0.70}_{-1.54}\ \mathrm{GeV}}\right)\left(\frac{t}{16.54\ \mathrm{s}}\right)^{-1} \mathrm{GeV}/c^2 \,,$$

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

These are the most stringent limits to-date via dispersion

Fermi GRB detections:

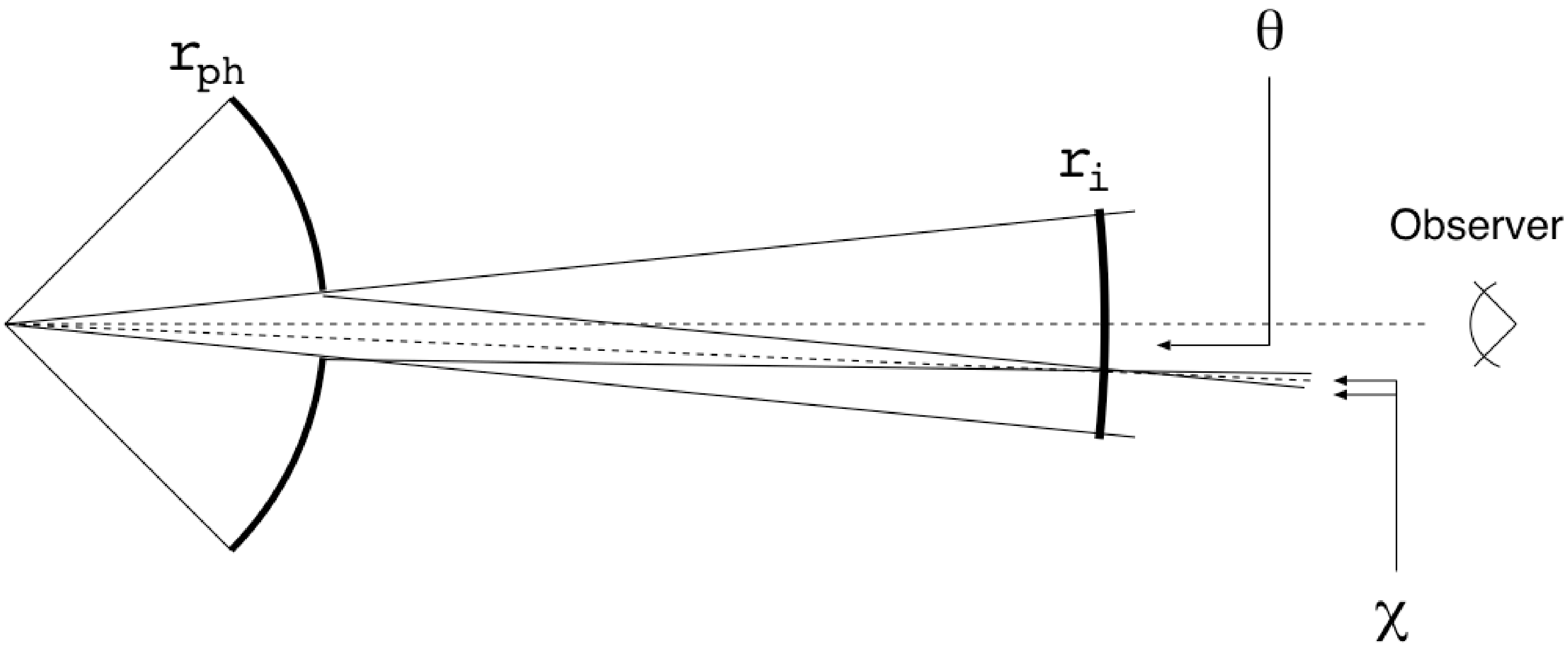
- **GBM:**
  - 160 GRBs so far (18% are short)
  - Detection rate: ~200-250 GRB/yr
  - A fair fraction are in LAT FoV
  - Automated repoint enabled
- **LAT detections**: (7 in 1st 9 months)
  - GRB080825C: >10 events above 100 MeV
  - GRB080916C: >10 events above 1 GeV and >140 events above 100 MeV
  - GRB081024B: first short GRB with >1 GeV emission
  - 7 + 2 more possible detections



From: Horst 09, Granot 09 & GBM/LAT coll

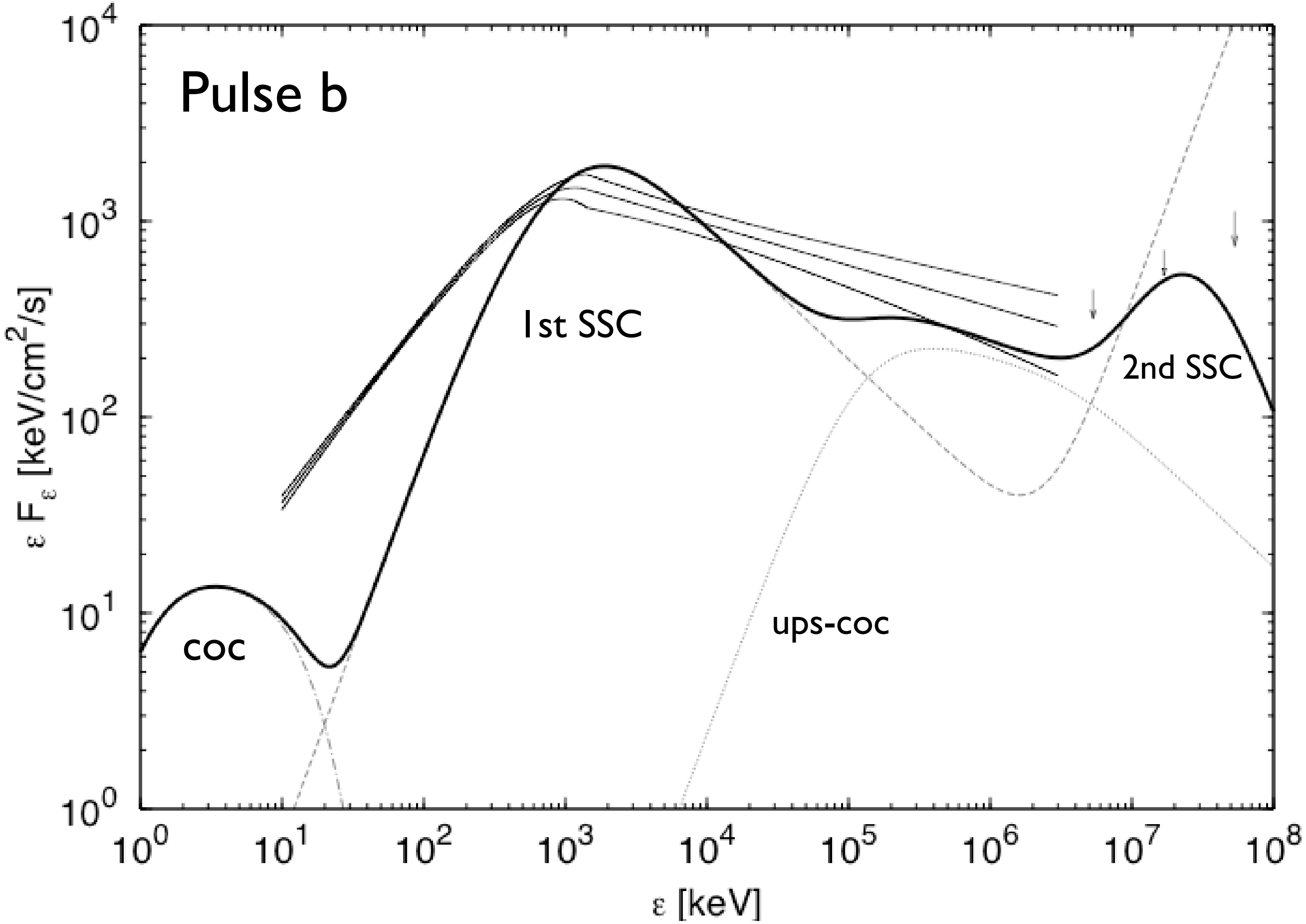
A cocoon upscattering model of GRB lags, e.g. GRB 080916C

Toma, Wu & Mészáros, arXiv:0905.1697



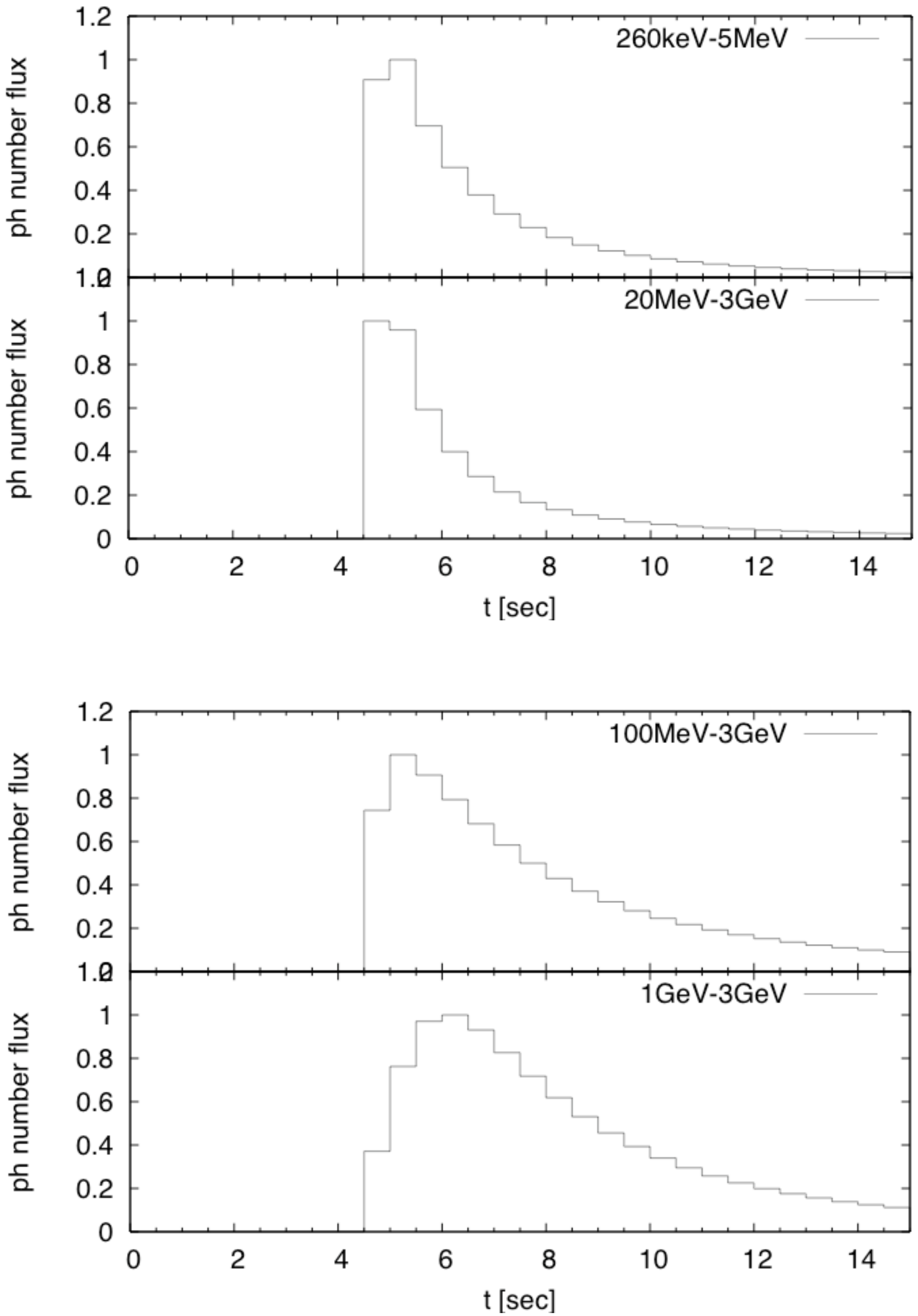
- Assume jet emits synchrotron in optical, 1st ord SSC in MeV
- Cocoon emits soft XR, jet upscatters to ~0.3 GeV; time lag ~3s

Cocoon + jet IS



- L_{55}=1.1, Γ_3=0.93, Δt_j=2.3 s, γ_m=400, γ_c=390, τ_T=3.5x10^{-4}, , ε_B=10-5, ε_e=0.4

Data: courtesy of Fermi GBM/LAT coll.



Photon time lags

- photon arrival time in different energy bands
- GeV band: delayed 2-3 s, due to geometry (source photons come from high latitude cocoon)

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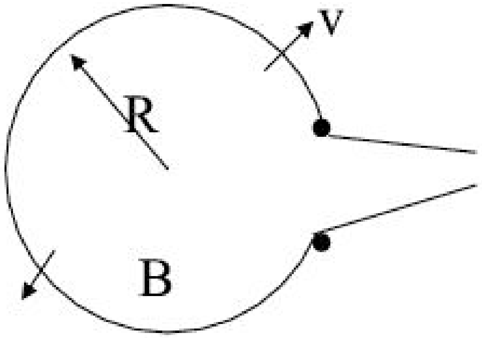
UHECR : acceleration ?



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

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

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

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

⇒ GRB,

AGN?

(only strongest AGN qualify !)

Auger spatial correlation

Science, 07

- Find 3σ corr. with V.C. AGNs within 3.5 deg inside 75 Mpc, for 28 events E>4.5x10^{19} eV ***(but now ~2σ)***
- The above correlation suggest protons
- But cannot say positively it is AGNs - could be correl. with underlying LSS
- Kashti-Waxman confirm correl. with LSS at >98% confidence level, via two-pt corr., ang. power spectr. and predicted-observed coincid.
- If heavy mix: many more gals. inside each event's larger angular spread.

→ ***Could be sources in galaxies - GRB ?***

CR Flux & spectrum - GRB

Protons

- Particle spectrum:

$$dn_p / d\varepsilon_p \propto \varepsilon_p^{-2}$$

- p energy production:

$$\varepsilon_p^2 \frac{d\dot{n}_p}{d\varepsilon_p} \sim 10^{44} \frac{\text{erg}}{\text{Mpc}^3\text{yr}}$$

Electrons

- γ spectrum

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

[Waxman 95]

- γ energy production

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

Afterglow $\longrightarrow$ z distribution

[Frail et al. 01
Schmidt 01]

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

GZK CR Sources

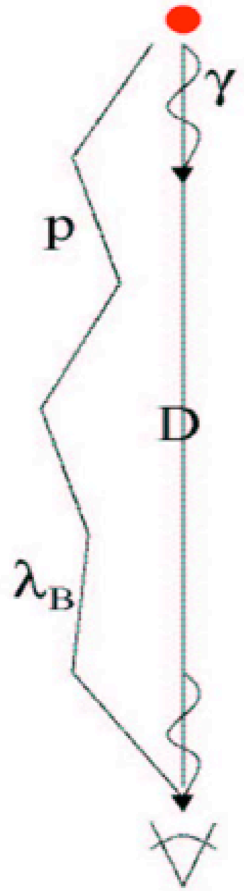
- Sources: GRB ✓; AGN.... #?
- Rate: R_{GRB} (z=0)~ 0.5 Gpc^{-3} yr^{-1}

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

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

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

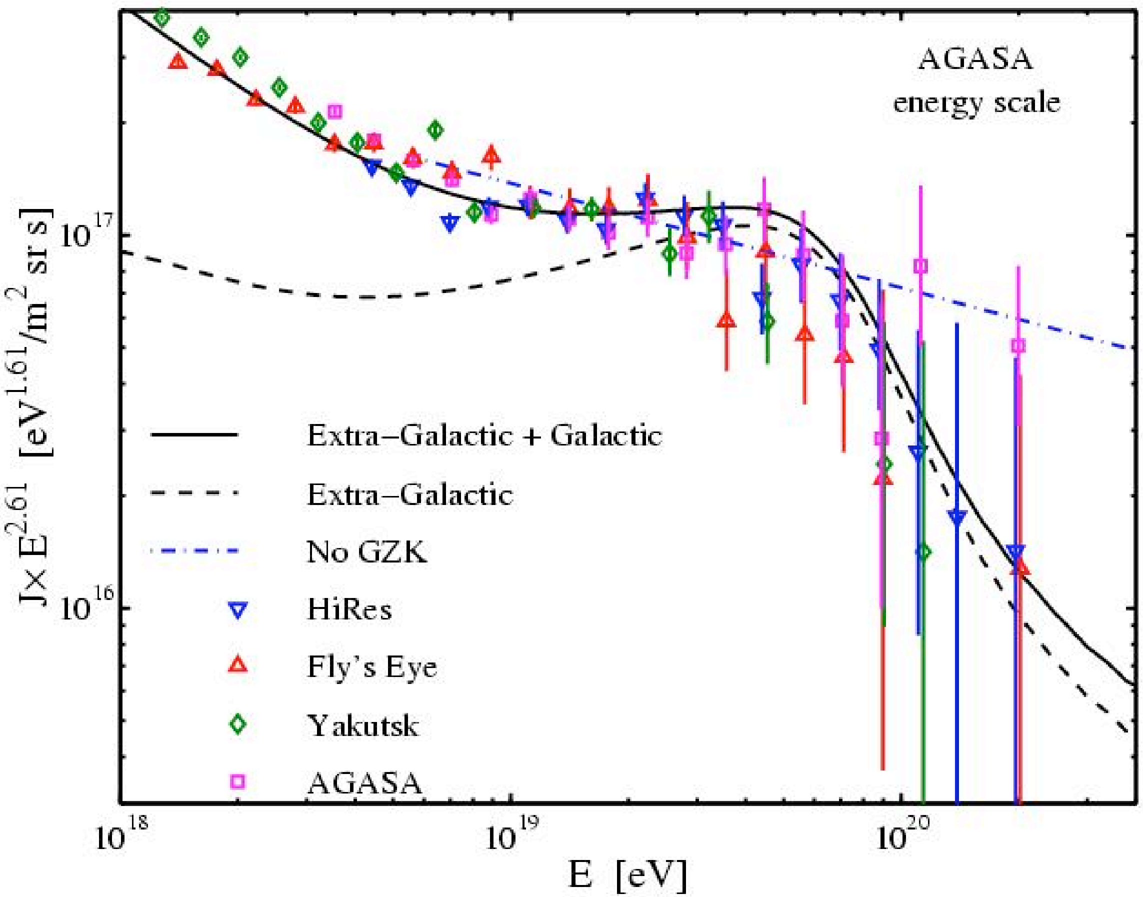
  $\sim 10^4\ B_{-8}^2\ \lambda_{B,0}\ D_{100}^2\ E_{p20}^2$
- GZK event rate: ~ 1 $/Km^2$ /100 yr ✓



[Waxman 95, 2005]

UHECR data vs. GRB model

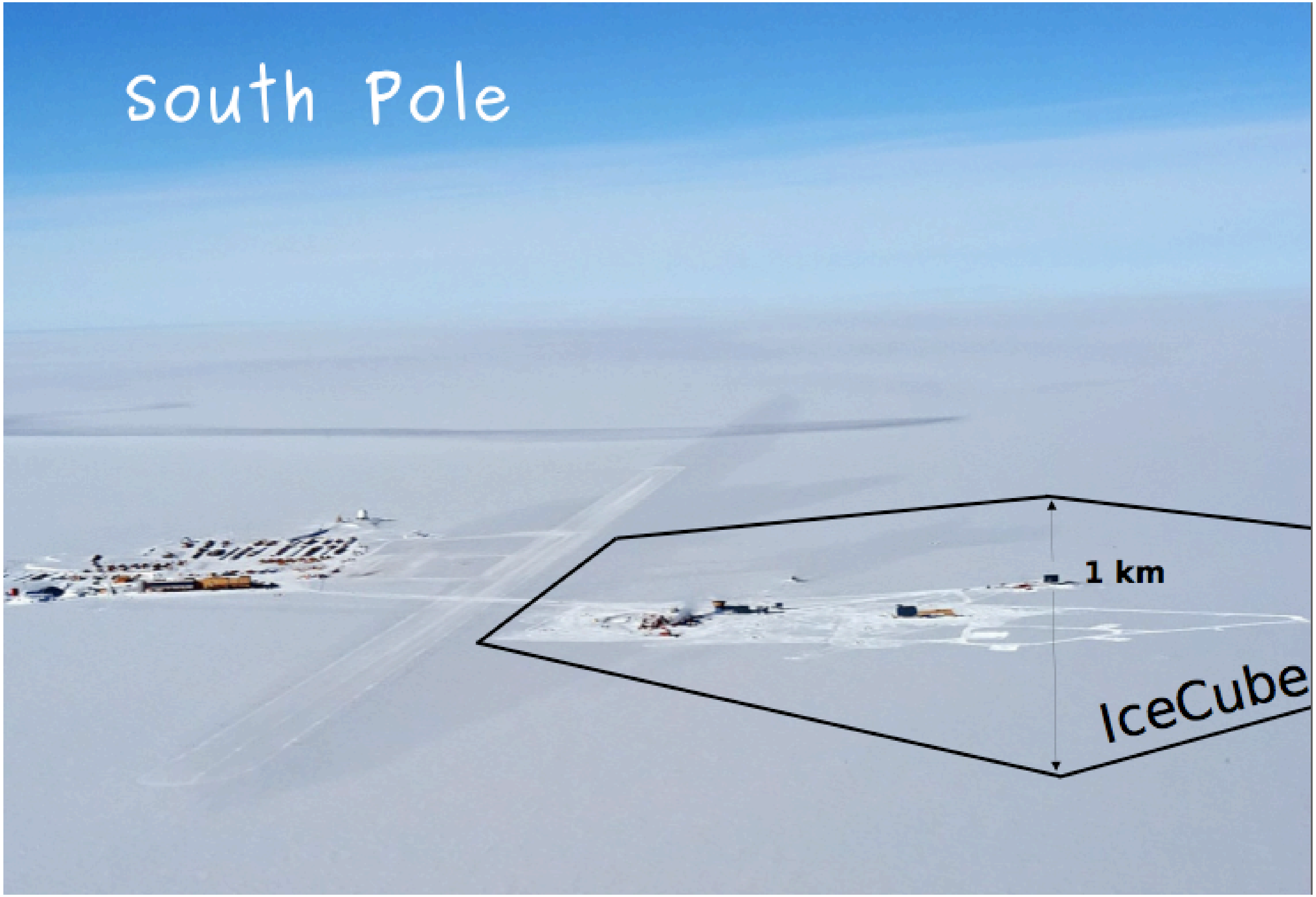
Waxman 06



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

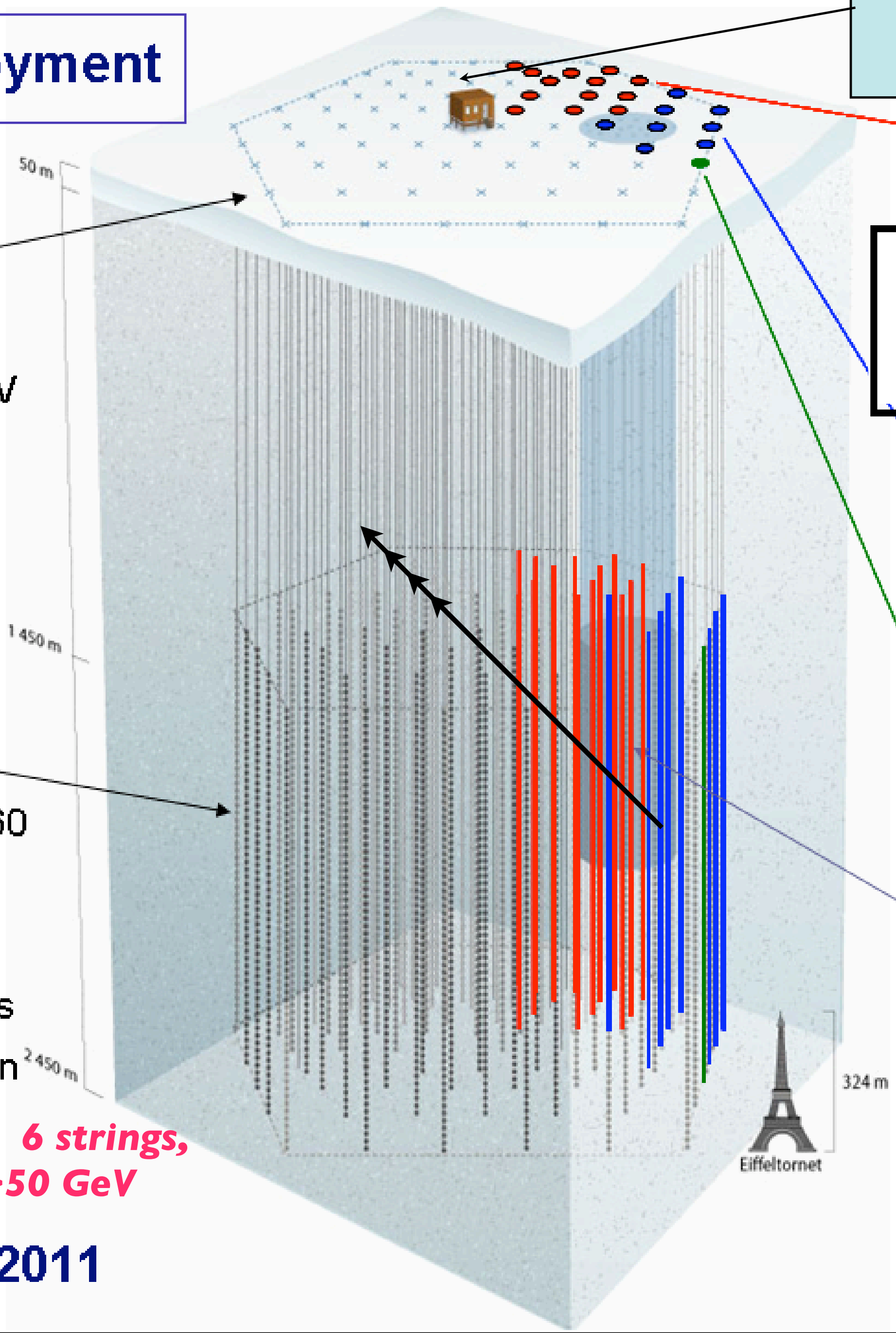


IceCube Deployment

IceTop

Air shower detector

Threshold ~ 300 TeV



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

InIce

planned 80 strings of 60 optical modules each

17 m between modules

125 m string separation

Deep Core: 6 strings, threshold >50 GeV

AMANDA

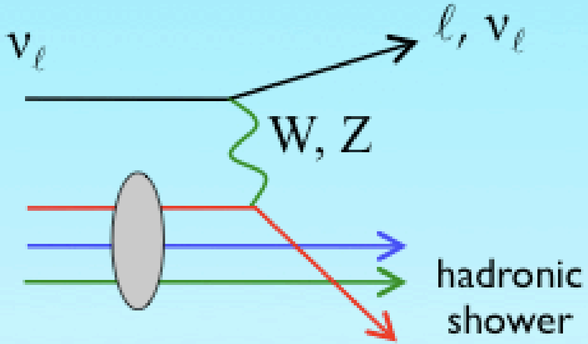
19 strings

677 modules

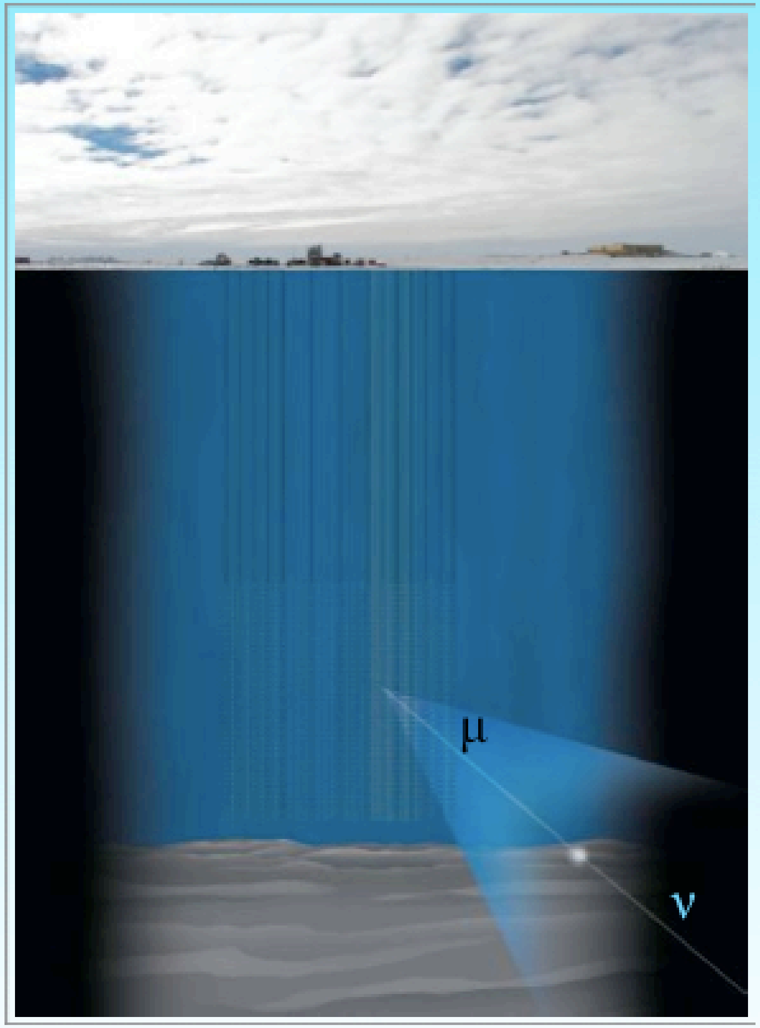
Completion by 2011

Neutrino Telescopes

- Neutrinos interact in or near the detector

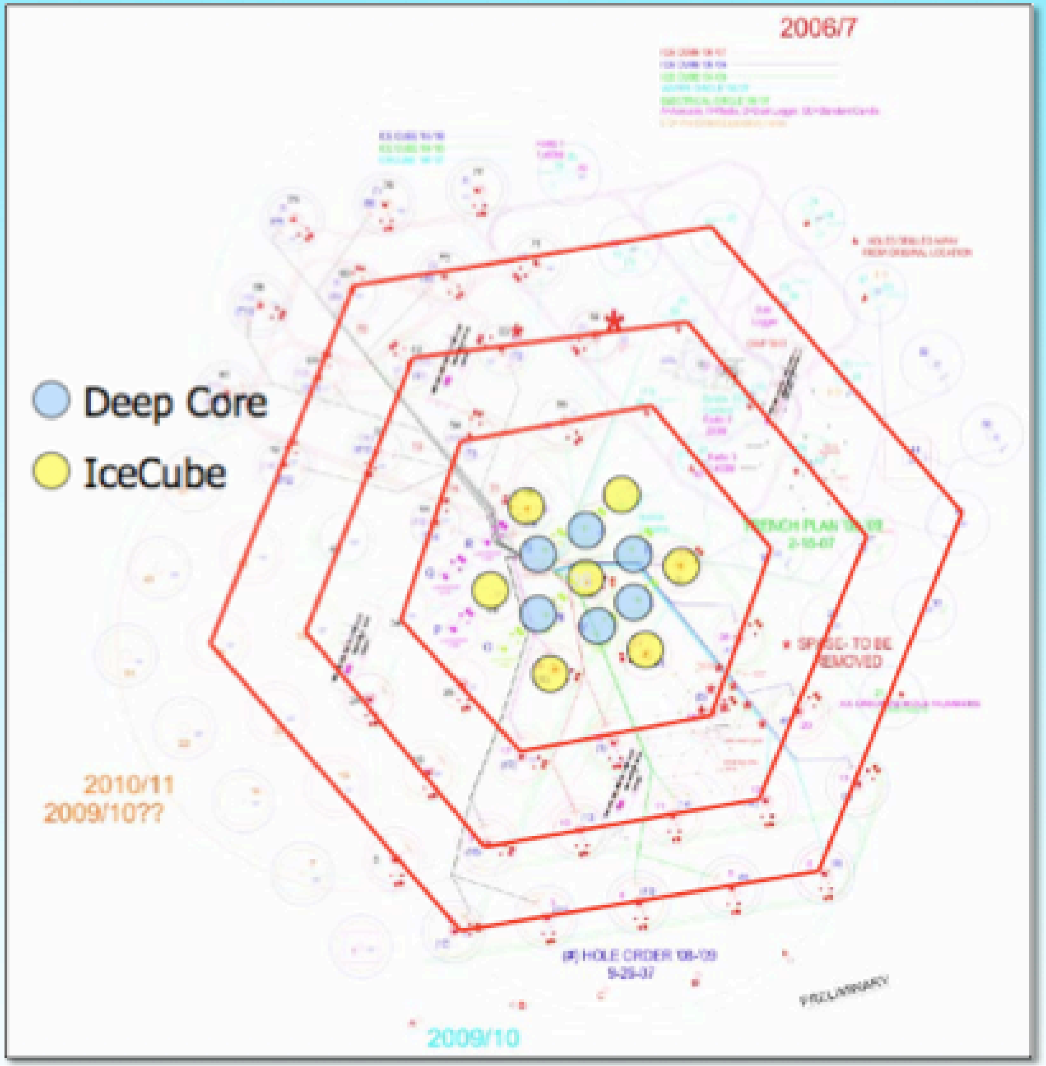


  - $\mathcal{O}$(km) muons from ν_μ (CC)
  - $\mathcal{O}$(10 m) particle cascades from ν_e, low energy ν_τ, and NC interactions
  - Cherenkov radiation detected by optical sensors



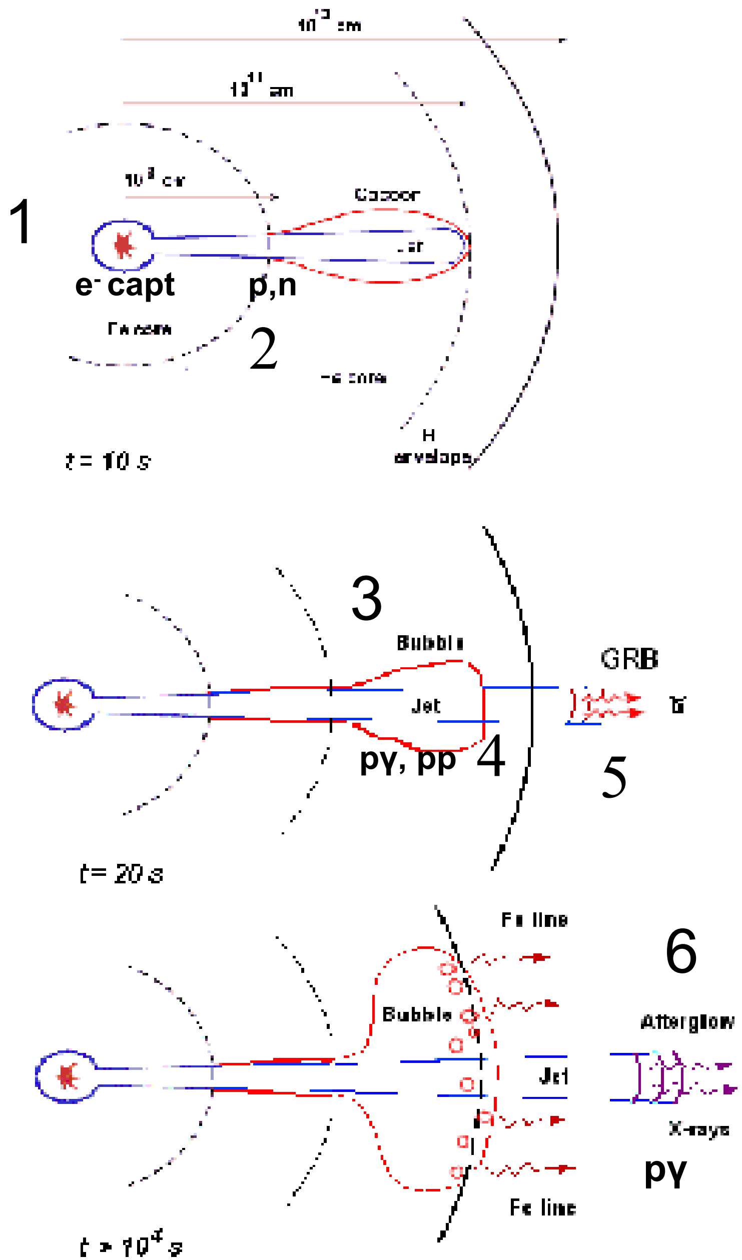
IceCube Deep Core

- 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

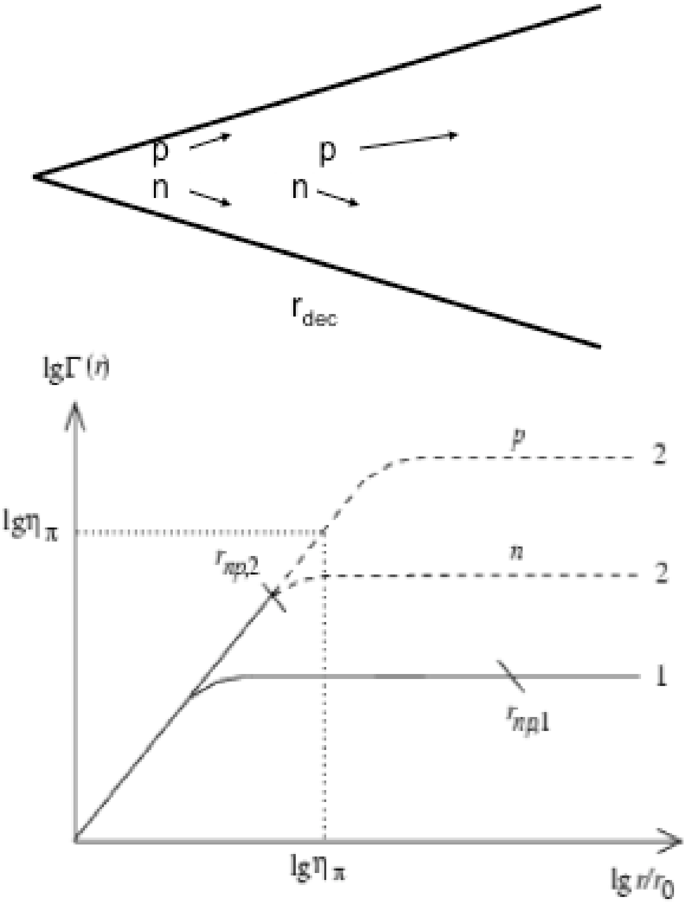
Various collapsar GRB ν-sites



- 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:

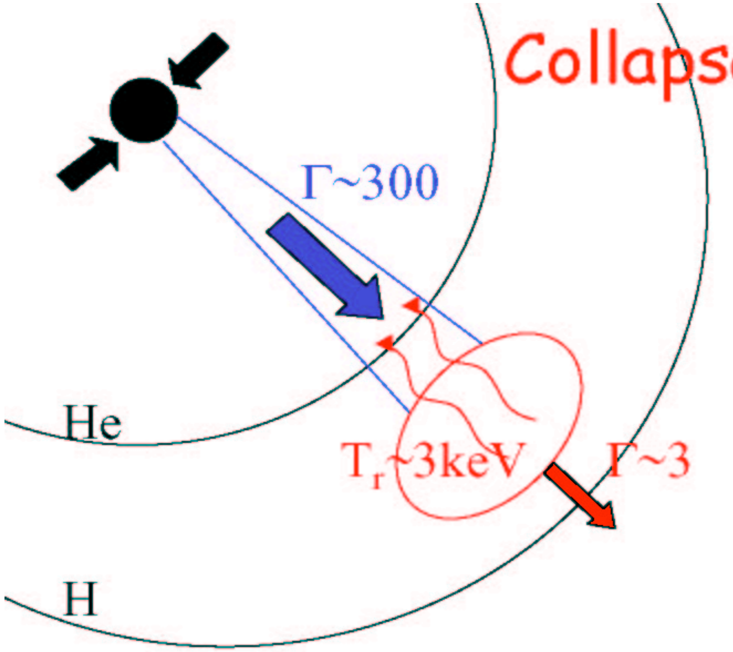
Thermal p,n decoupling → VHE ν, γ



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:



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

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

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

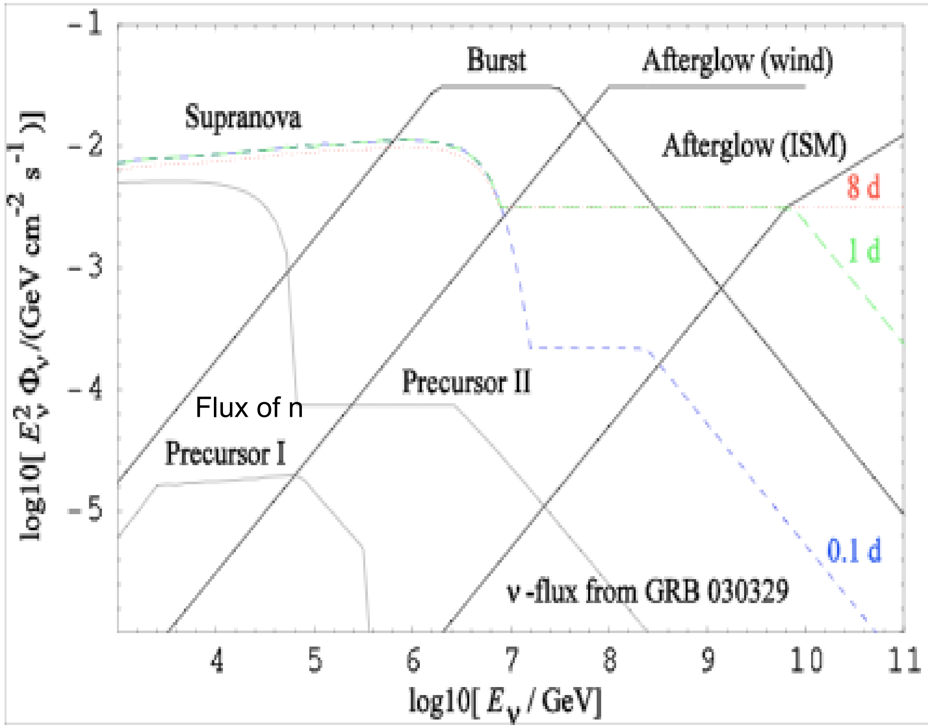
  $N_{\nu\to\mu} \approx 0.2\,/\,\mathrm{km}^2/\mathrm{Collapse}$ (10^3 GRBs/yr)

- Both "Chocked" and "successful" jets

Meszaros & Waxman 01

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

Burst of $L\gamma \sim 10^{51}$ erg/s, $E_{SN} \sim 10^{52.5}$ erg, @ $z \sim 0.17$, $\theta \sim 68^o$

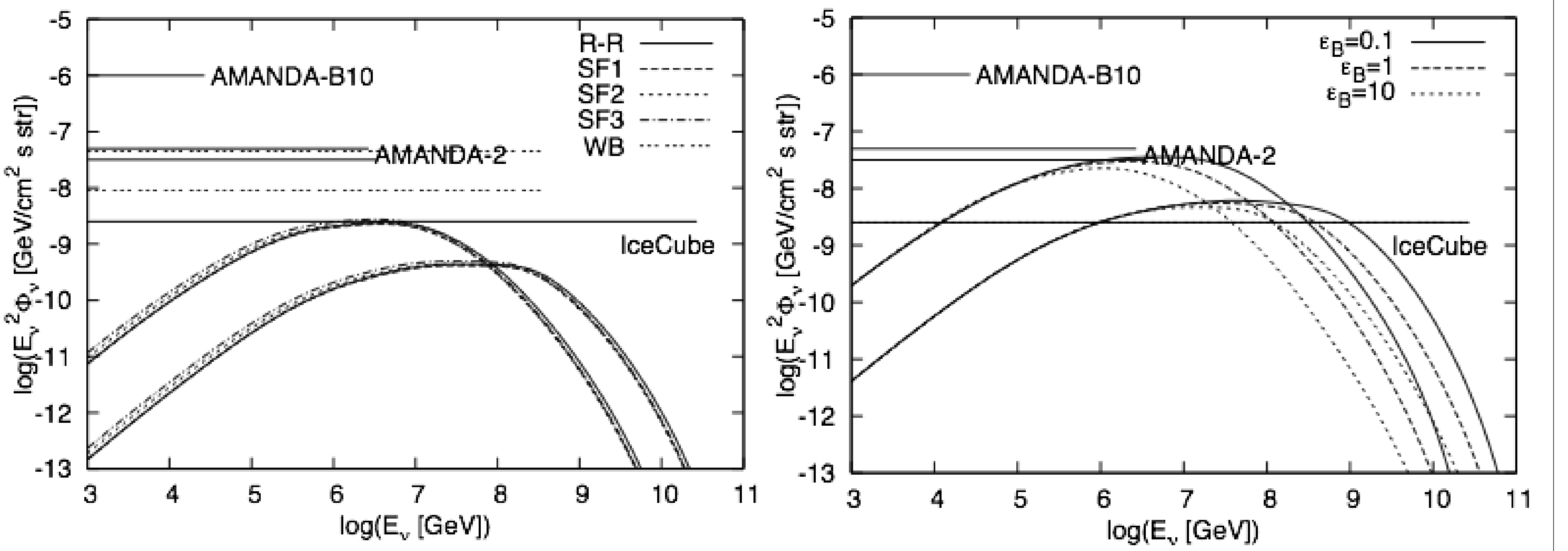


Flux Component	TeV-PeV μ-track	TeV-PeV e-cascade	PeV-EeV μ track	PeV-EeV e-cascade
Precursor I	$9 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	-	-
	$6 \cdot 10^{-3} \uparrow$	$2 \cdot 10^{-3} \uparrow$	-	-
	$0.01 \rightarrow$	$2 \cdot 10^{-3} \rightarrow$	-	-
Precursor II	4.1	1.1	$3 \cdot 10^{-3}$	$2 \cdot 10^{-4}$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

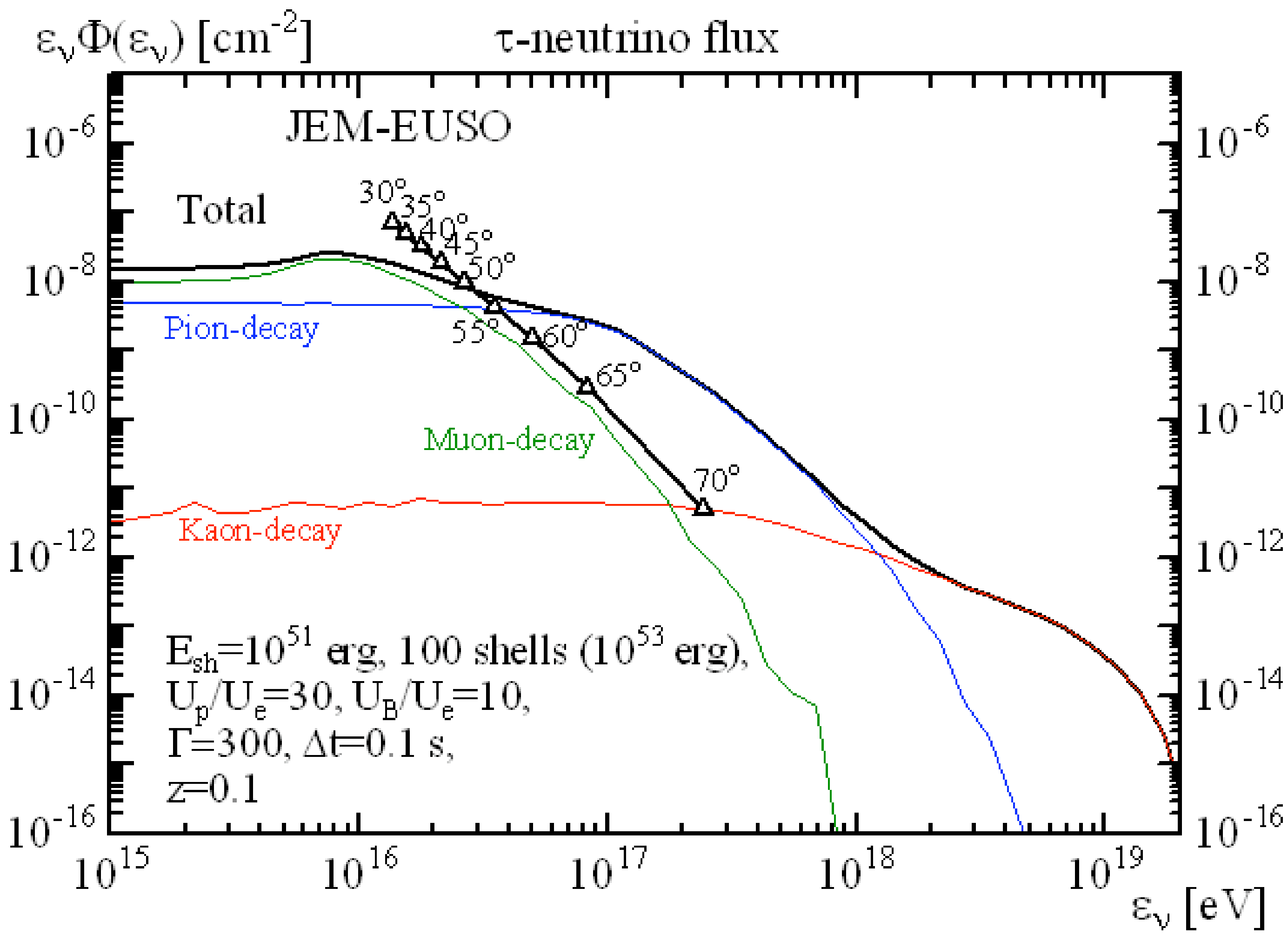
Razzaque, Mészáros, Waxman 03 PRD 69, 23001

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



EHE ν's

Neutrino fluxes; Asano et al, 2008, in prep.

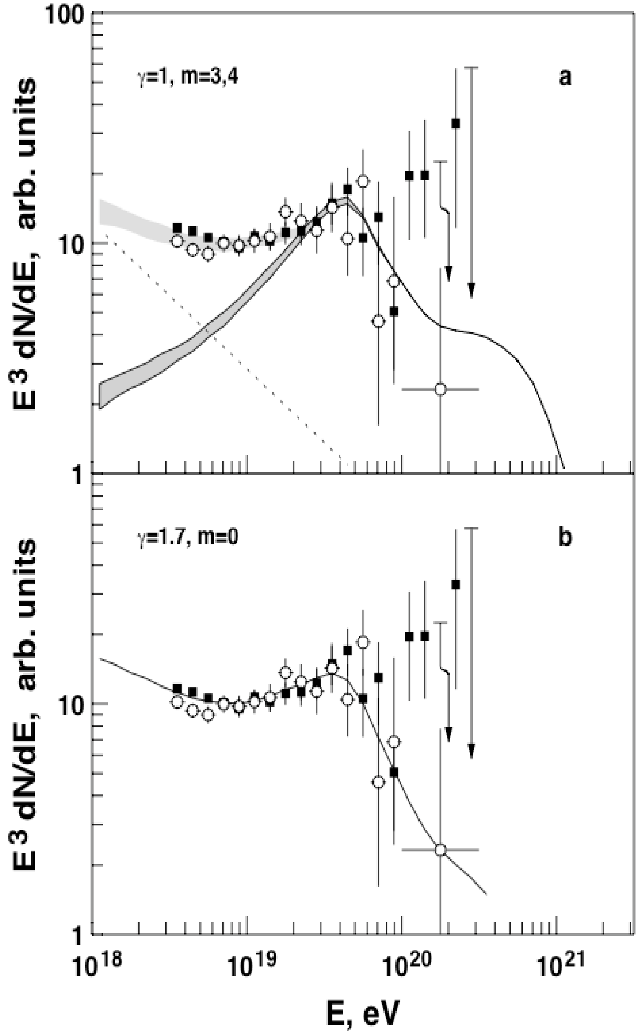
(JEM-EUSO sens.: M. Teshima, MPI)

- 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.)

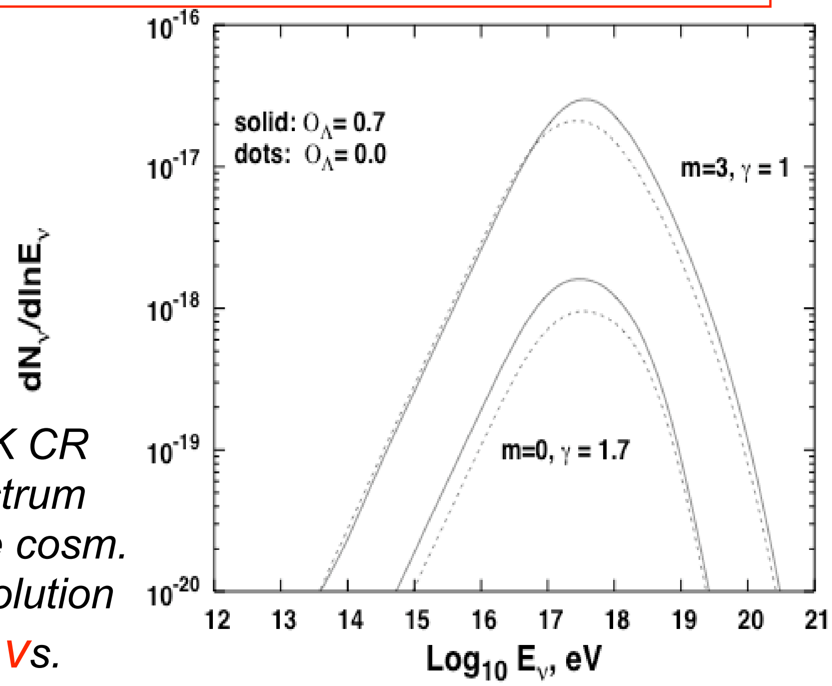
What about $E_\nu \gtrsim 10^{19}$ eV ?

2 ≠CR models
↓ **same GZK** CR fit

from **GZK CRs**
to **GZK νs**



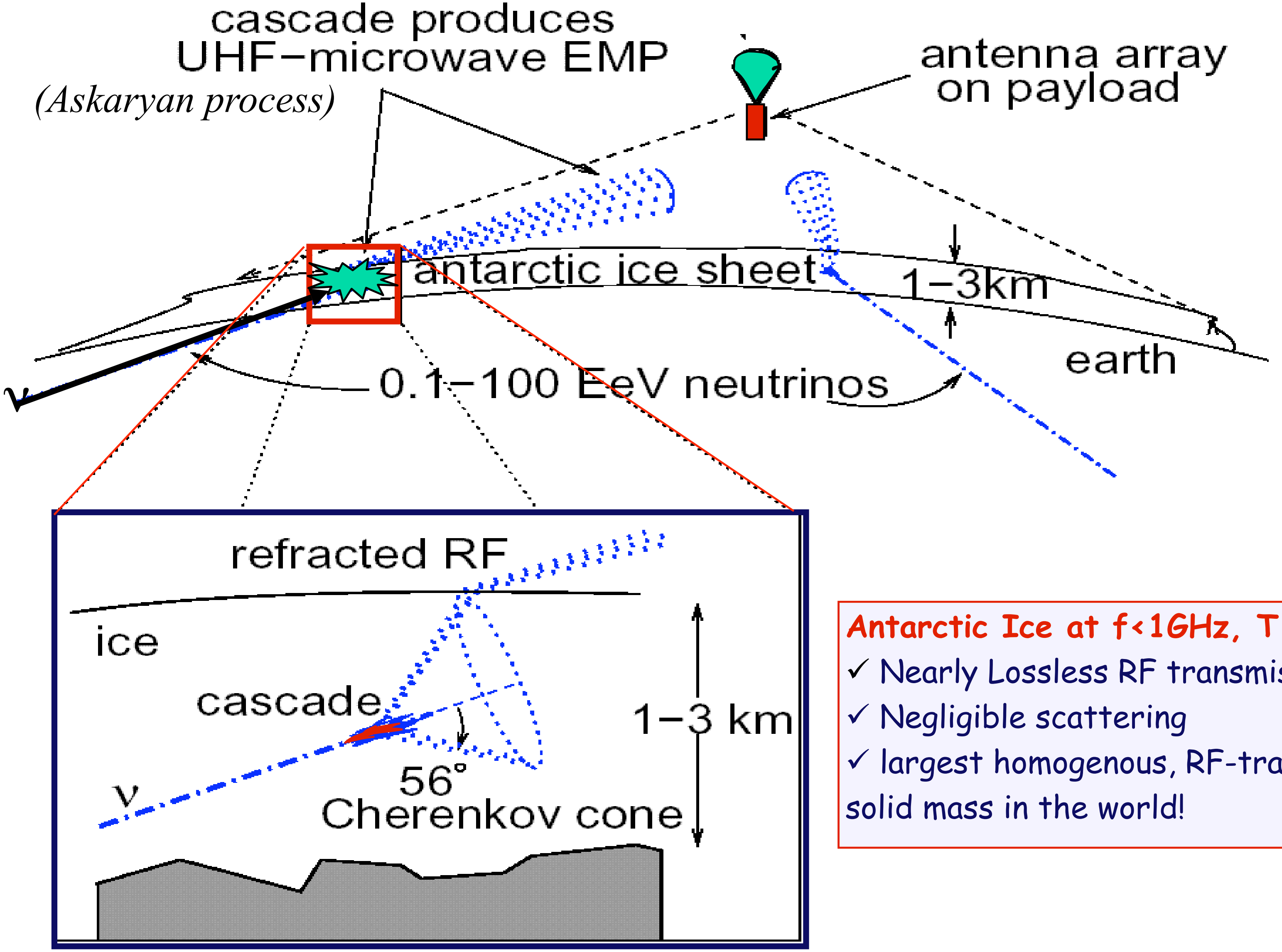
But … lead to ≠ *GZK ν flux* ↓



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

Seckel & Stanev astroph/050244

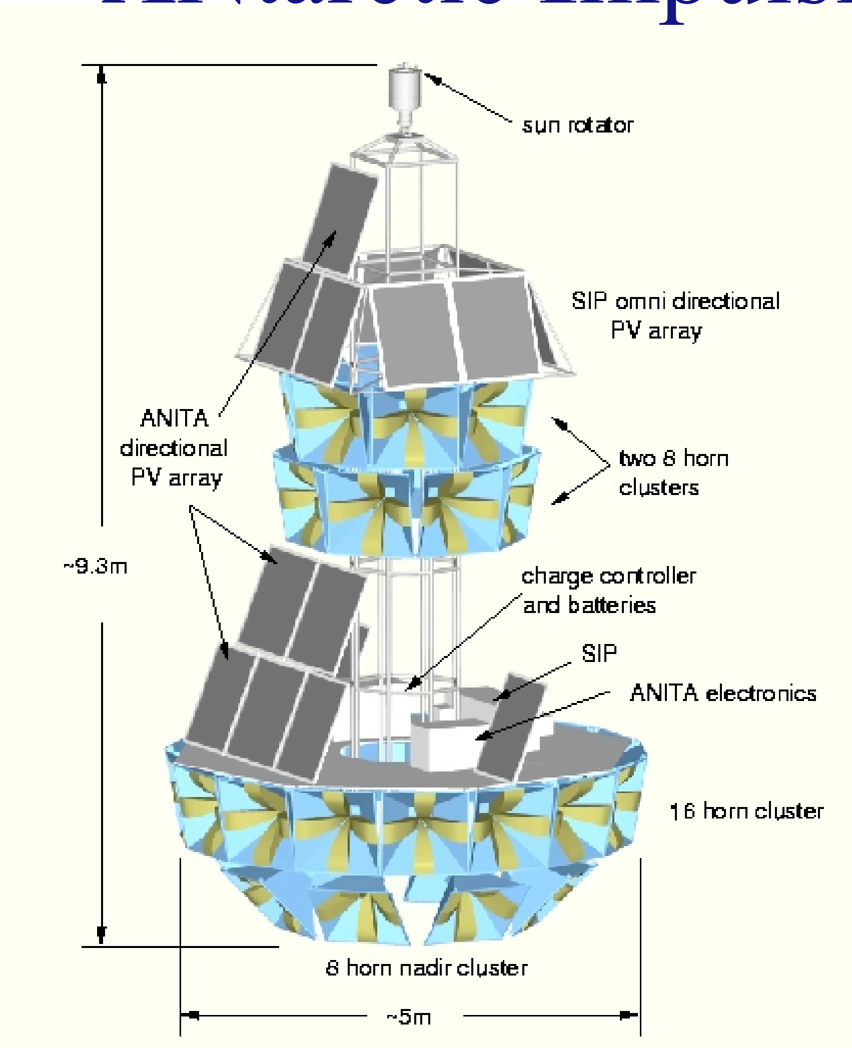
Cosmogenic ν : ANITA

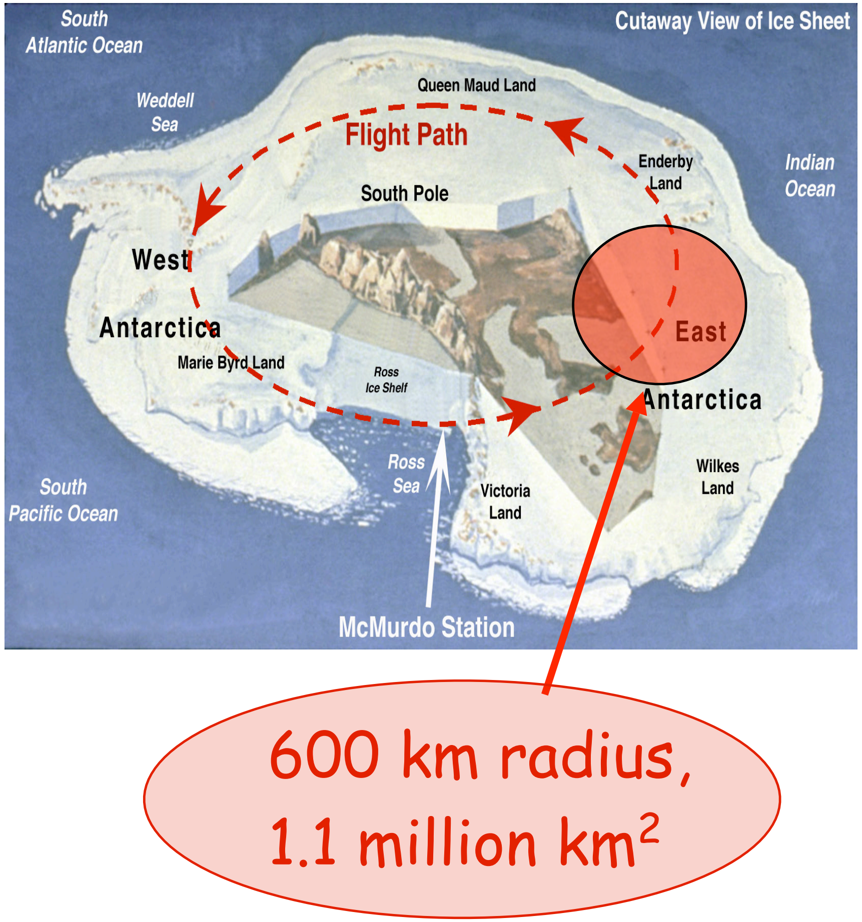


Antarctic Ice at f<1GHz, T<-30C

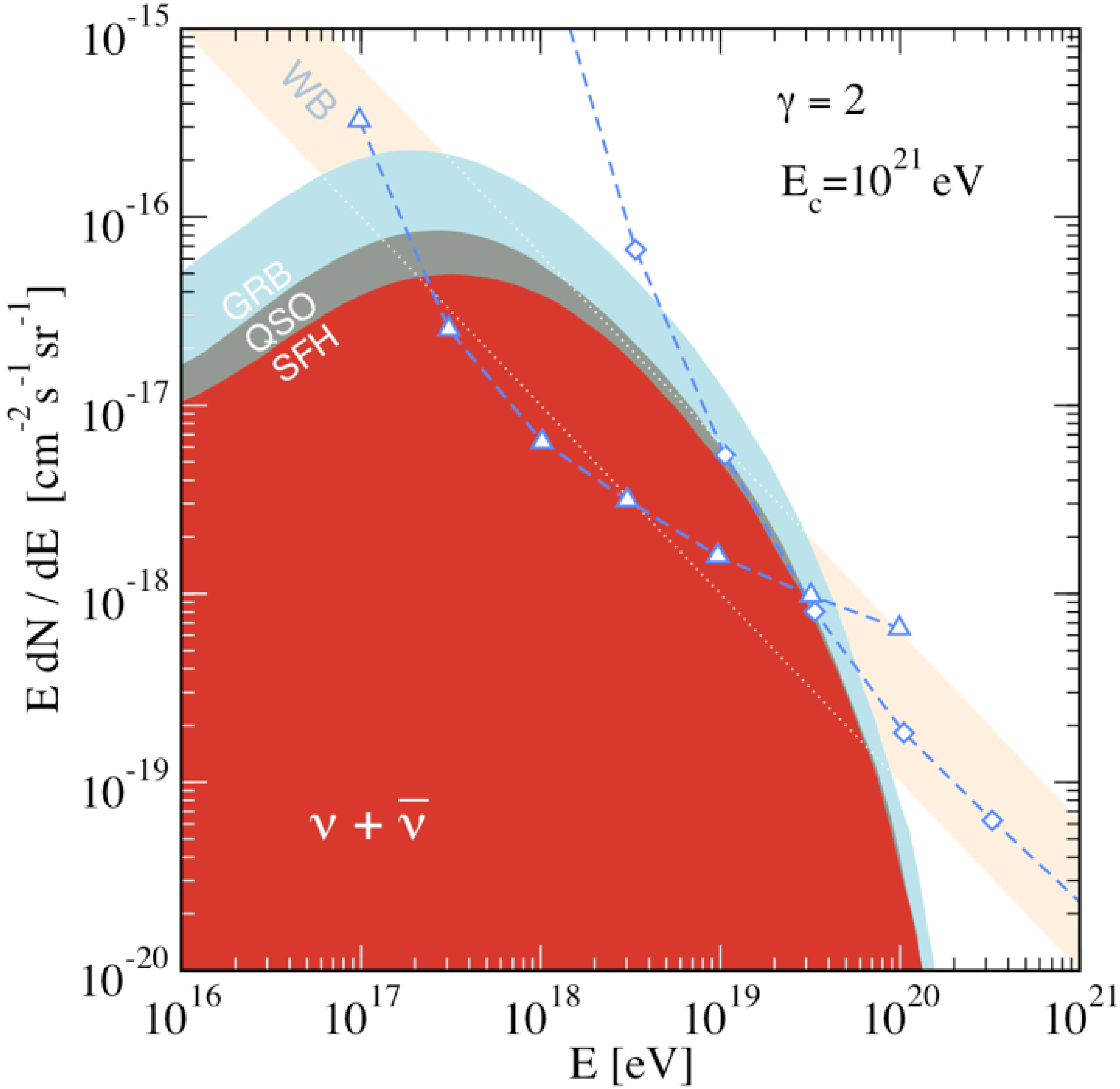
- ✓ Nearly Lossless RF transmission
- ✓ Negligible scattering
- ✓ largest homogenous, RF-transmissive solid mass in the world!

ANtarctic Impulsive Transient Antenna





- Launched & flown 30 days in early 07



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})

Another magnetar signature?

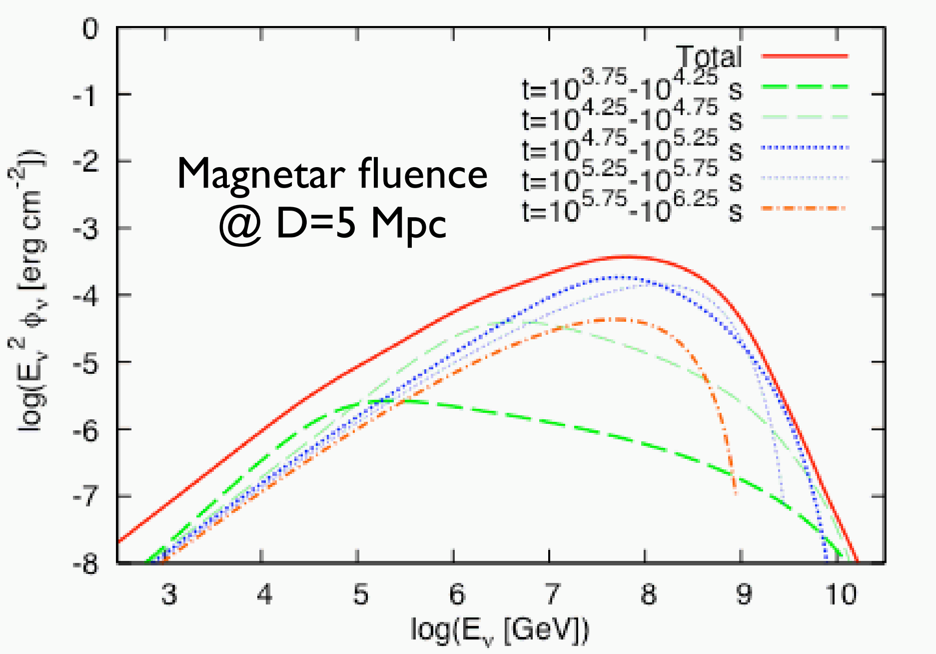
Magnetar birth ν-alert

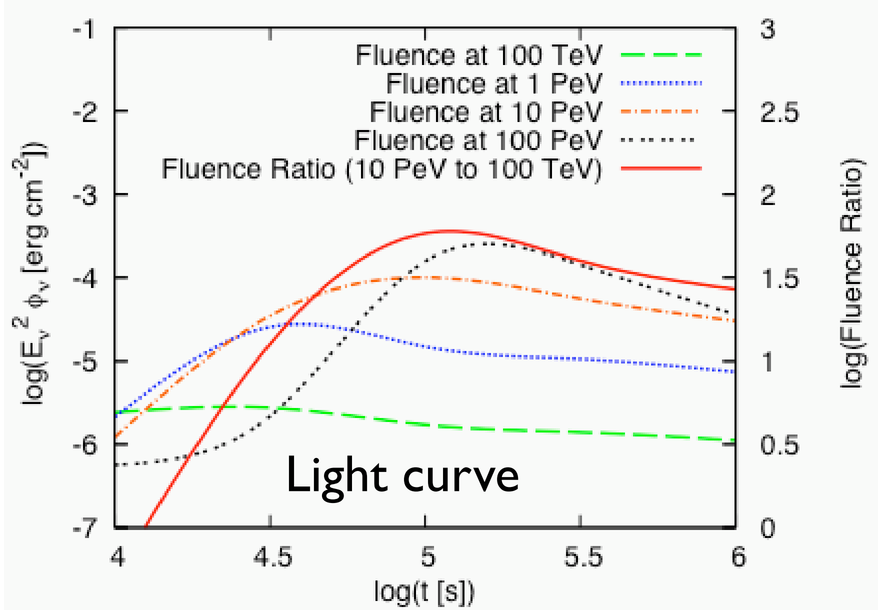
Murase, Mészáros & Zhang, PRD in press; arXiv: 0904.2509

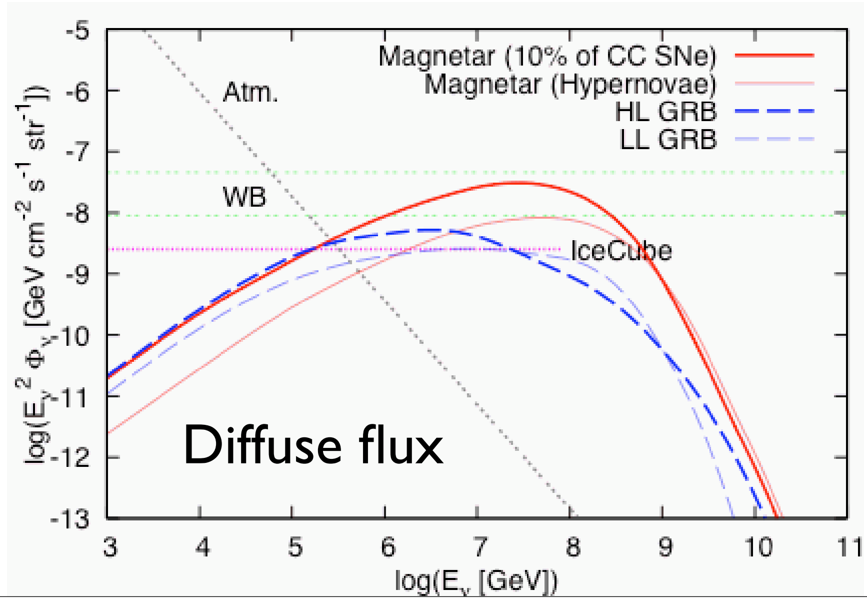
- Magnetars ($B \sim 10^{14}$-10^{15} G) may result from turbulent dynamo when born with fast (ms) rotation
- A fraction $\lesssim 0.1$ of CC SNe may result in magnetars
- In PNS wind, wake-field acceleration can lead to UHECR energies $E(t) \lesssim 10^{20}$ eV $Z\, \eta_{-1}\, \mu_{33}^{-1}\, t_4^{-1}$
- 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







- 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.

LIGO

•¬Hanford (WA) site,
+ Livingstone (LA)
• 4 km Michelson interf., vacuum laser refl.
• Sci. runs started in 2002

VIRGO→

• Italian/French: @ Cascina, Pisa →
• 2x3 km arms laser interf.
• Sci. runs (2 wks) already started

- Science goals: test GR +
- Compact bin. inspiral (dns,dbh,nsbh)
- GRB, core-coll. SN, NS r-mode osc.
- Stochastic GW backgr (inflation)
- *Also : Geo-600, TAMA*

Simple astrophysical GRB GW model:

either bin.merger or collapsar:

⇒ as if blobs orbiting

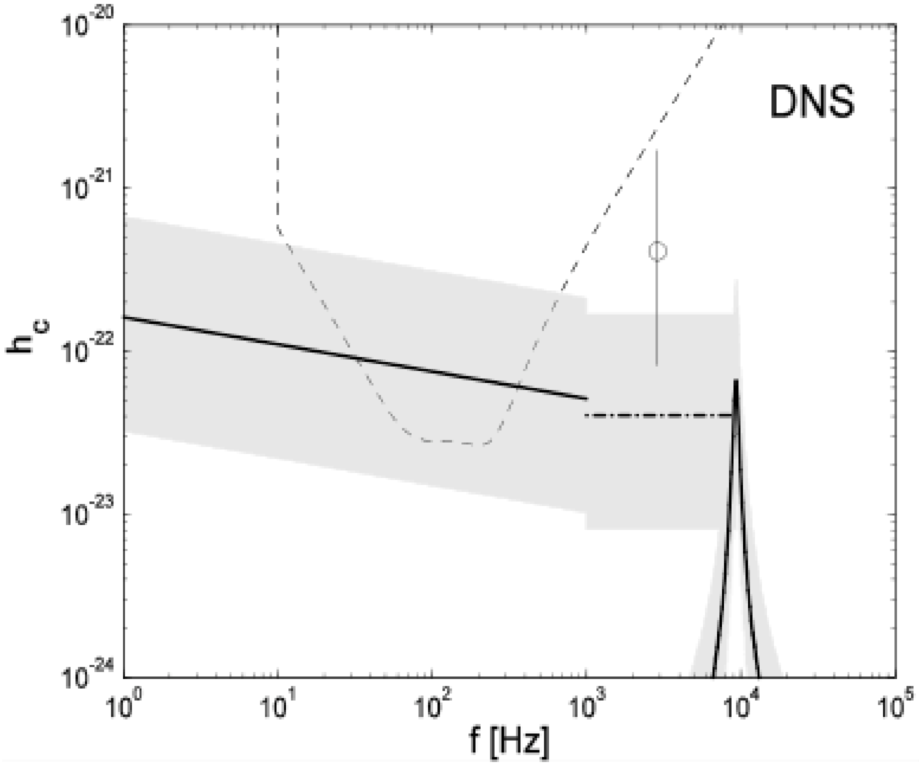
(fast rot. → instab. → blobs → merge ;

or: double NS, NS/BH: blobs → merge)

3 Usual Phases of Rotating Collapse

- In-spiral (binaries, or core blobs)
- Merger - central condensation + disk, subject to instabilities (again blobs?)
- Ring-down

GRB Progenitor GW Signals: DNS



Dashed: LIGO II sensitivity

Double neutron star

Charact. Strain h_c

D (avg) =220 Mpc,

$m_1=m_2=1.4\ M_\odot$

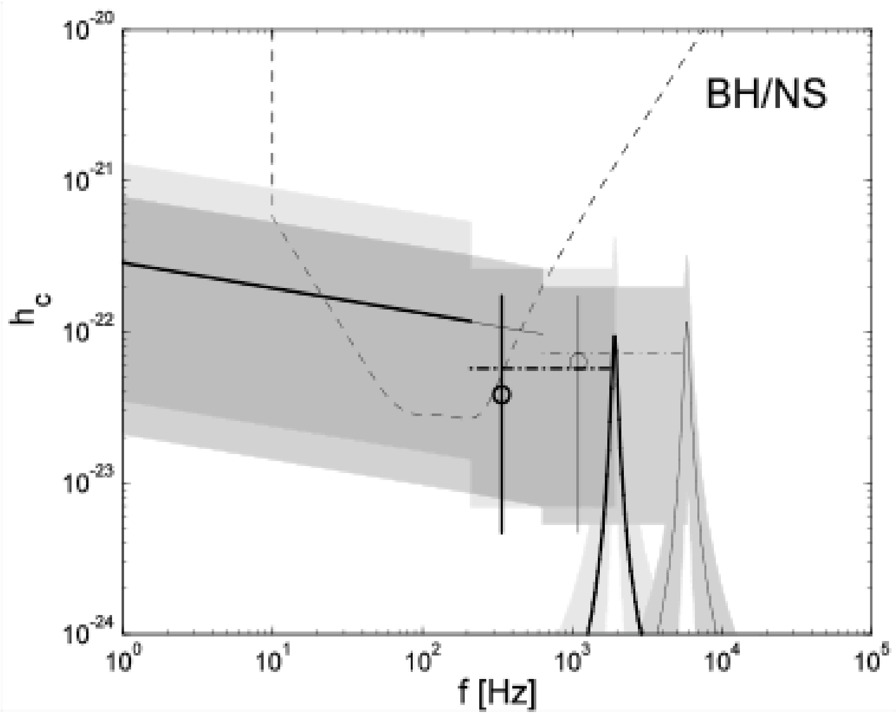
a=0.98, $e_m=0.05$,

$m=m'=2.8\ M_\odot$, N=10,

$e_r=0.01$

Solid: inspiral; Dot-dash: merger;
Circle (bar inst); Spike: ring-down);
Shaded region: rate/distance uncertainty

GRB Progenitor GW Signals: BHNS



Solid: inspiral; Dot-dash: merger; circle (bar inst); spike: ring-down); shaded region: rate/dist uncertainty
Dashed: LIGO II noise $[f\, S_h(f)]^{1/2}$

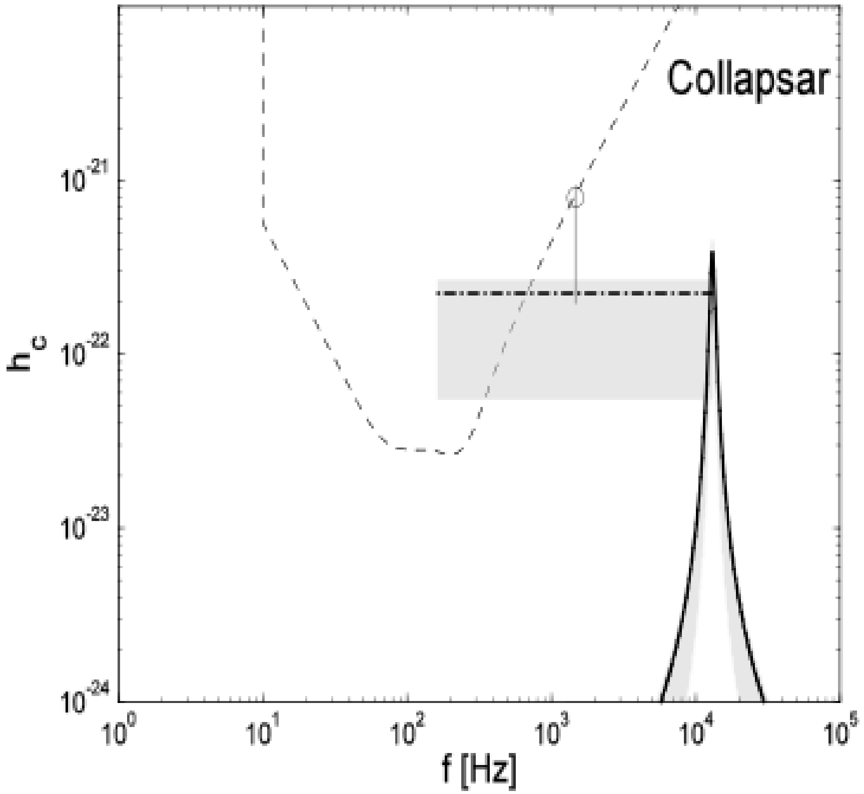
Black hole-neutron star

thin: =170Mpc,
m_1=3.0 $M_\odot$, m_2=1.4 $M_\odot$,
m=0.5 $M_\odot$, m'=4 $M_\odot$

thick: d=280Mpc,
m_1=12 $M_\odot$, m_2=1.4 $M_\odot$
m=0.5 $M_\odot$, m'=13 $M_\odot$;

Both: a=0.98, e_m=0.05,
N=10, e_r =0.01

GRB Progenitor GW Signals: Collapsar



Collapsar w. core breakup, bar inst.

(optimistic numbers!)

d=270 Mpc,
$m_1=m_2=1\ M_\odot$, a=0.98,
e_m =0.05,
merge at $r=10^7$ cm;
$m=1\ M_\odot$, $m'= 3\ M_\odot$,
N=10, e_r =0.01

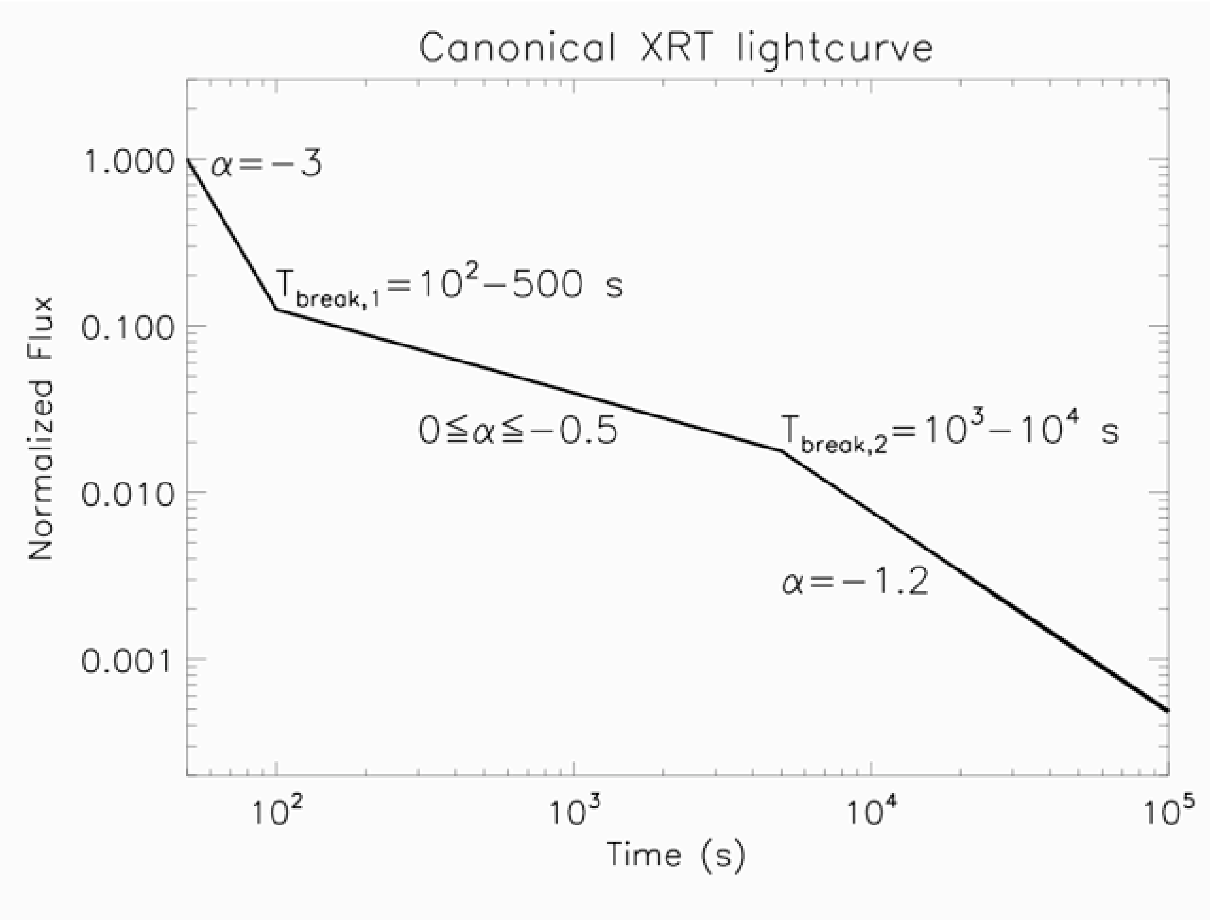
Dashed: LIGO II noise $[f\, S_h(f)]^{1/2}$

Kobayashi & Mészáros 02, ApJ 589, 861

Solid: inspiral; dot-dash: merger;
circle :bar inst; spike: ring-down);
shaded : rate/dist uncertainty

GW-GRB in the Swift Era:

A temporary magnetar phase in GRB ?



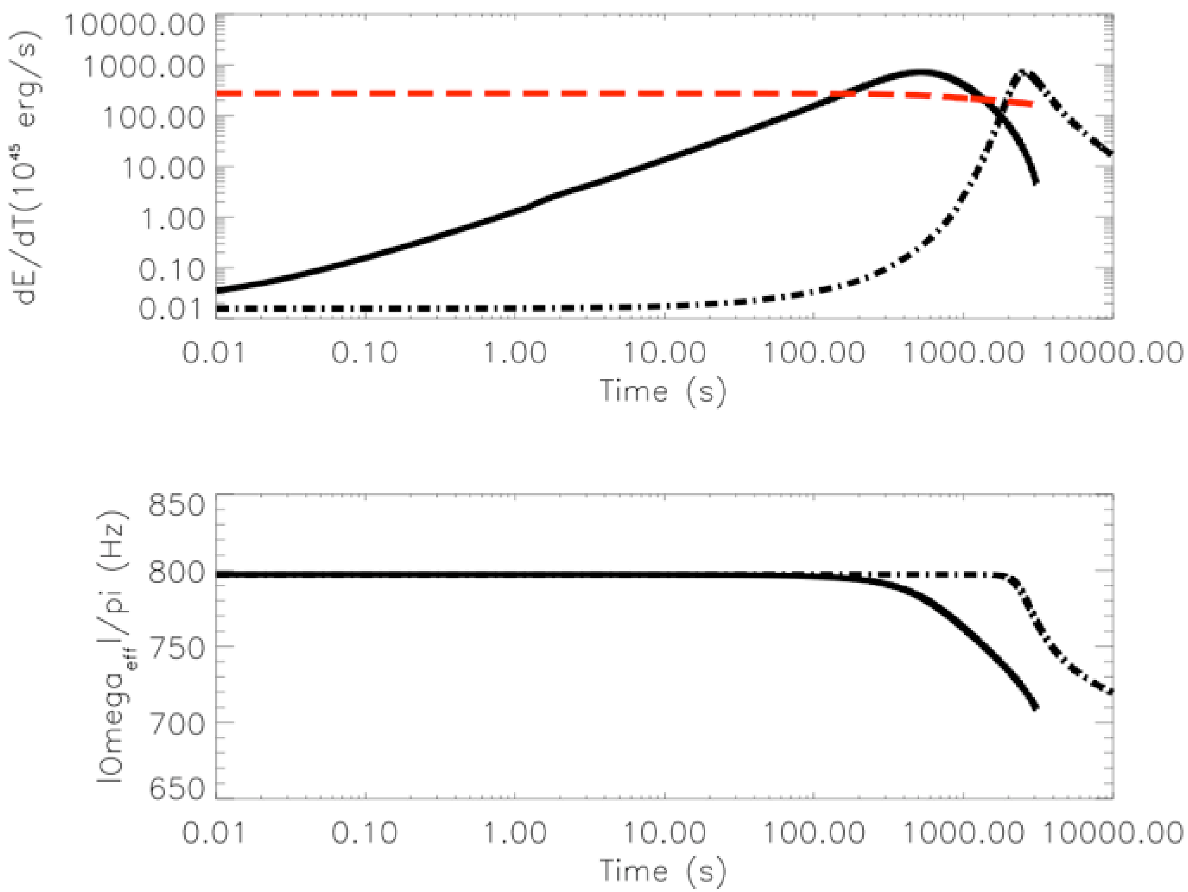
- It is one of the explanations for Swift X-ray plateaus (→energy injection)
- If so, magnetar must be fast rotating (collapsar paradigm)
- Fast rotation → bar instability?
- If so → GW emiss.

A. Corsi & P. Meszaros 09

GW + EM dipole losses

Bar instability → rotating ellipsoid

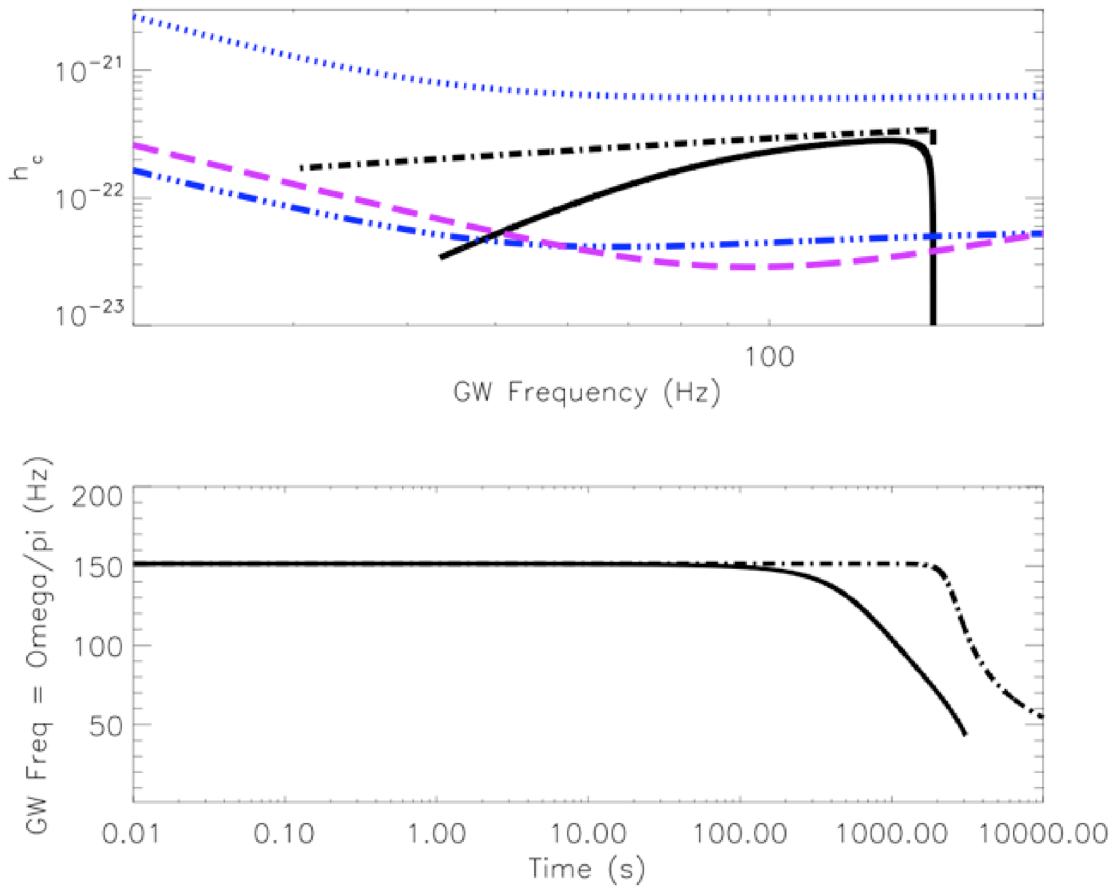
GW: with pattern Ω - EM: from frozen-in surface field



- Upper:
- Red: EM dipole energy losses ;
- Dot-dash: GW losses without EM loss term
- Solid black: GW losses with EM loss term
- Lower:
- Surface fluid effective angular velocity Ω_{eff}/π, where $\Omega_{eff} = \Omega - \Lambda$ (pattern minus peculiar) along a Riemann seq. (e.g. Lai-Shapiro)

Corsi & Mészáros

GW & EM loss effects



Upper: GW amplitude h_c @ d=100 Mpc, for:

- Black-solid: GW+EM
- Black-dash-dot: GW only
- Blue-dot: Virgo nom.
- Purple dash: adv. LIGO/Virgo
- Blue solid: Virgo adv.(bin)

Lower:
GW signal freq., for:

Black-solid: GW + EM losses
Black-dash: GW losses (only)

Corsi & Meszaros 09

Conclusions

- Will learn much from coordinated O/IR/MeV/GeV photon observations
- Will learn even more from coordinated photon + GW and/or neutrino observations
- GW: reveal role of binaries (short) or instabilities (long) in GRB mechanism: real nature of the central engine?
- Nus: reveal role of protons in GRB, whether outflow is MHD or hadronic, and whether GRB are source of some (all?) UHECR