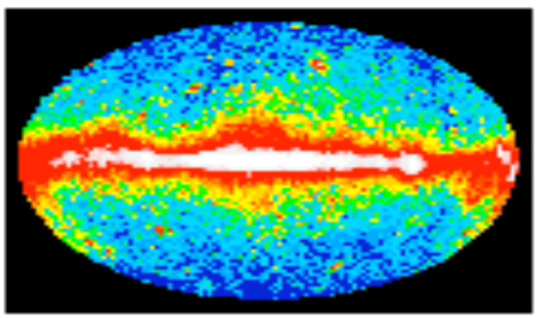
Gamma-Ray Bursts

Recent Results and Ultra-high Energy Perspectives

Peter Mészáros

Pennsylvania State University

For a few seconds, a GRB dominates the gamma-ray brightness of the entire Universe



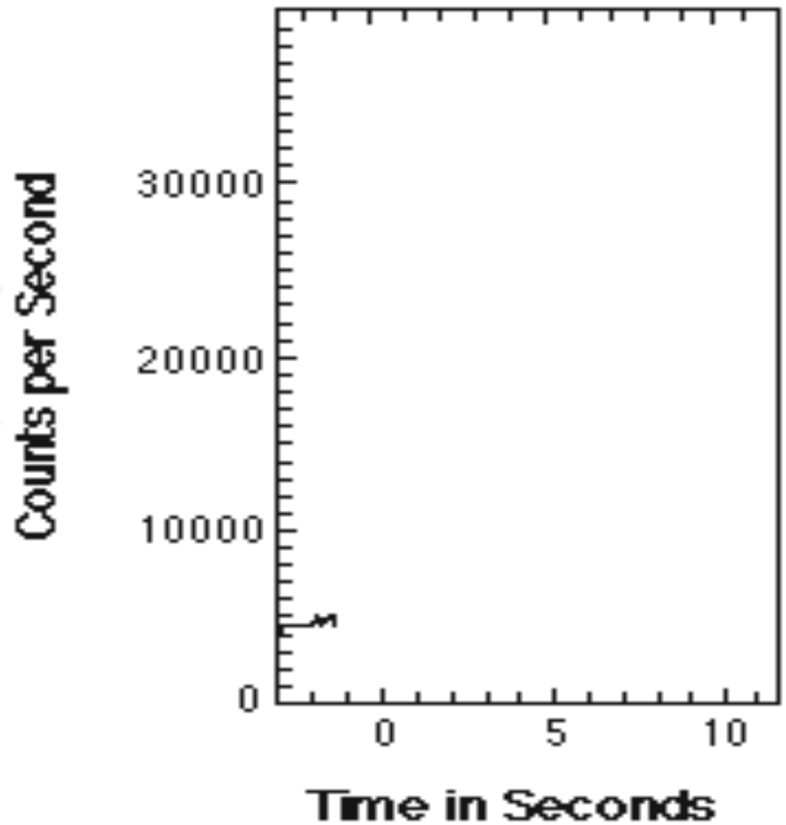


Fig. Credit: Tyce DeYoung

GRB: *basic numbers*

- Rate: ~ 1/day inside a Hubble radius
- Distance: $0.1 \leq z \leq$ **6.3 !** → **D ~ 10^{28} cm**
- Fluence: $F = \int flux.dt \sim 10^{-4} - 10^{-7}$ erg/cm^2

  ~ **1 ph/cm^2** (γ-rays !)

- Energy output: $10^{53} (\Omega/4\pi) D^2_{28.5} F_{-5}$ erg

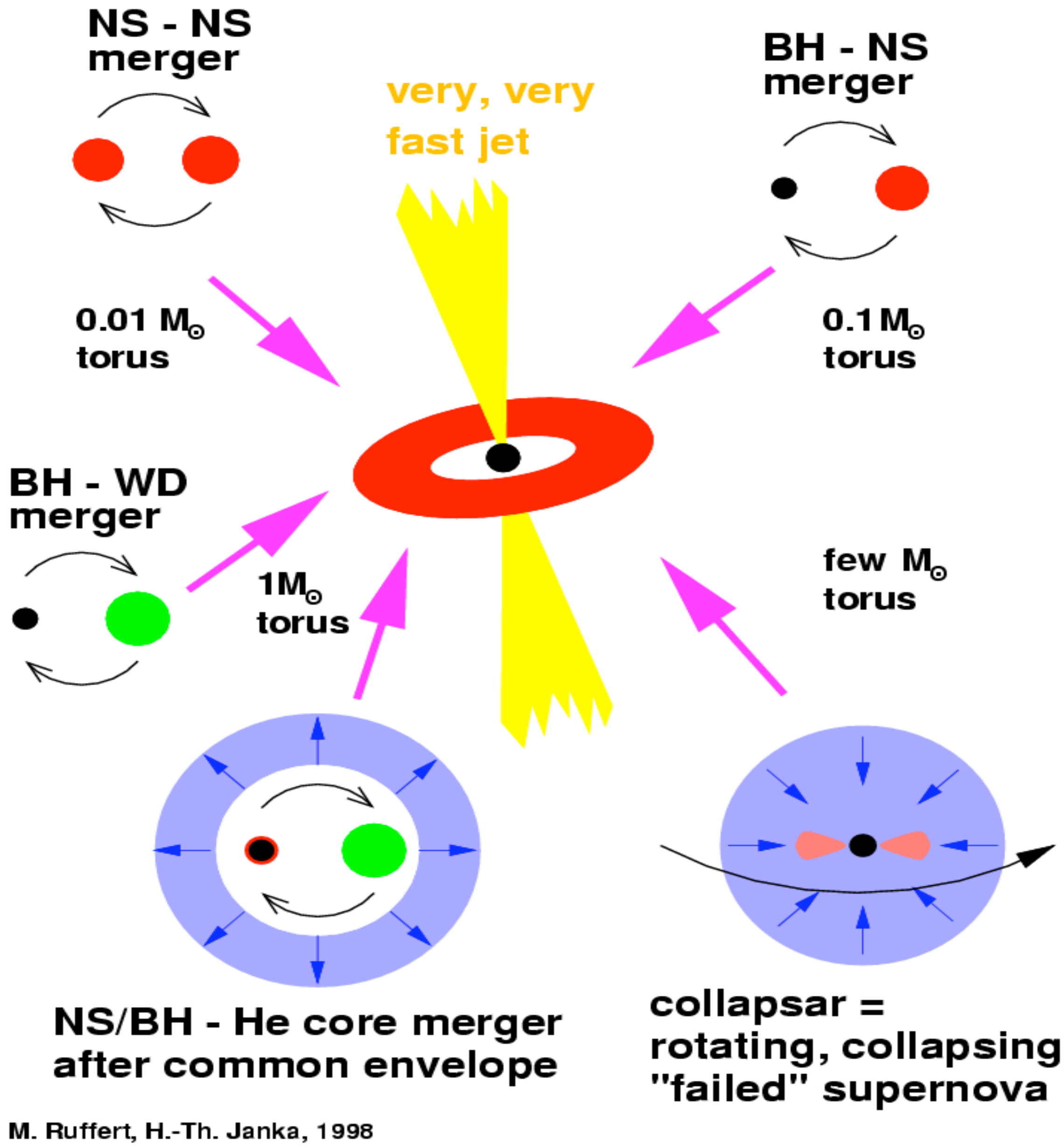
  jet: **$\Omega \sim 10^{-2}$** – 10^{-1} → $E_{\gamma,tot} \sim$ **10^{51} erg**

  $E_{\gamma,tot} \sim L_\Theta \times 10^{10}$ year ~ L_{gal} x 1 year

- Rate(GRB) ~ $10^{-6}(2\pi/\Omega)$ /yr/gal → **1/day (z<3)**

whereas Rate [SN] ~ $1O^{-2}$/yr/gal, or 10^7 /yr ~ 1/s (z δ3)

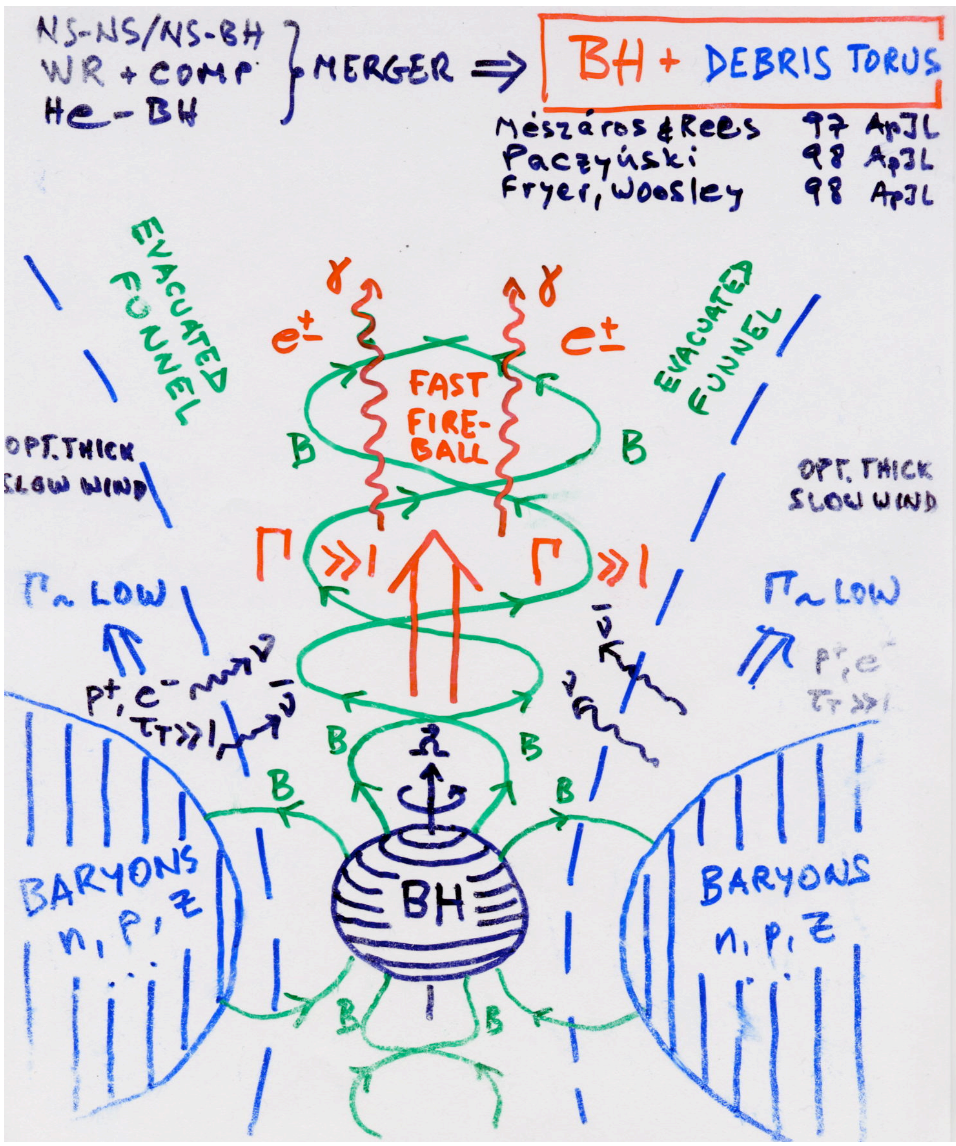
GRB: → Hyperaccreting Black Holes (current paradigm)



Short
(t_γ δ 2 s)

Long
(t_γ τ 2 s)

BH + accr. Torus ➡ *Jet*



- Both collapsar or merger → BH+accr.torus→fireball
- Massive rot. star: sideways pressure confines/channel outflow ⟶ **fireball** **Jet**
- Nuclear density hot torus → can have **νν→e±** **jet**
- Hot infall →convective dynamo → B~10^{15} G, twisted (thread BH?)

⟶**Alfvénic** or e$^{\pm}$pγ **jet**

- (Note: magnetar might do similar)

Explosion $\longrightarrow$ FIREBALL

- $E_\gamma \; \tau \; 10^{51} \; \Omega_{-2} \; D^2_{28.5} \; F_{-5}$ erg
- $R_0 \sim c\, t_0 \sim 10^7 \, t_{-3}$ cm

  $\Rightarrow$ Huge energy in very small volume
- $\tau_{\gamma\gamma} \sim (E_\gamma / R^3{}_0 m_e c^2)\sigma_T R_0 >> 1$

  $\rightarrow$ Fireball: $e^\pm,\gamma,p$ relativistic gas
- $L_\gamma \sim E_\gamma / t_0 >> L_{Edd} \rightarrow$ expanding ($v \sim c$) fireball

  (Cavallo & Rees, 1978 MN 183:359)
- Observe $E_\gamma > 10$ GeV …but

  $\gamma\gamma \rightarrow e^\pm$, degrade 10 GeV $\rightarrow$0.5 MeV?

  $E\gamma \; Et > 2(m_e c^2)^2/(1-\cos\Theta) \sim 4(m_e c^2)^2/\Theta^2$

  $\Rightarrow$ Ultrarelativistic flow $\rightarrow \Gamma \; \tau \; \Theta^{-1} \sim 10^2$

  (Fenimore etal 93; Baring & Harding 94)

Relativistic Outflows

- Energy-impulse tensor : $\mathbf{T_{ik} = w\, u_i\, u_k + p\, g_{ik}}$,
  $\mathbf{u^i}$: 4-velocity, $\mathbf{g_{ik}}$= metric, $g_{11}=g_{22}=g_{33}=-g_{00}=1$, others 0;
  ultra-rel. enthalpy: $w = 4p \propto n^{4/3}$, w, p, n : in comoving-frame
- 1-D motion : $u^i=(\gamma,u,0,0)$, where $\mathbf{u = \Gamma\, (v/c)}$,
  v = 3-velocity, **A**= outflow channel cross section :
- Impulse flux — **$Q=(w\, u^2 + p)\, A$**
  energy flux — **$L= wu\, \Gamma\, c\, A$**
  particle number flux — **$J= n\, u\, A$**
- Isentropic : **L, J constant** →

  $w\, \Gamma / n$ = constant (relativistic Bernoulli equation);
  for ultra-rel. equ. of state $p \propto n^{4/3}$, and cross section $A \propto r^2$

→ **$n \propto 1 / r^2\, \Gamma$** comoving density drops
→ **$\Gamma \propto r$** "bulk" Lorentz factor initially grows with **r**.

JET MOVIE

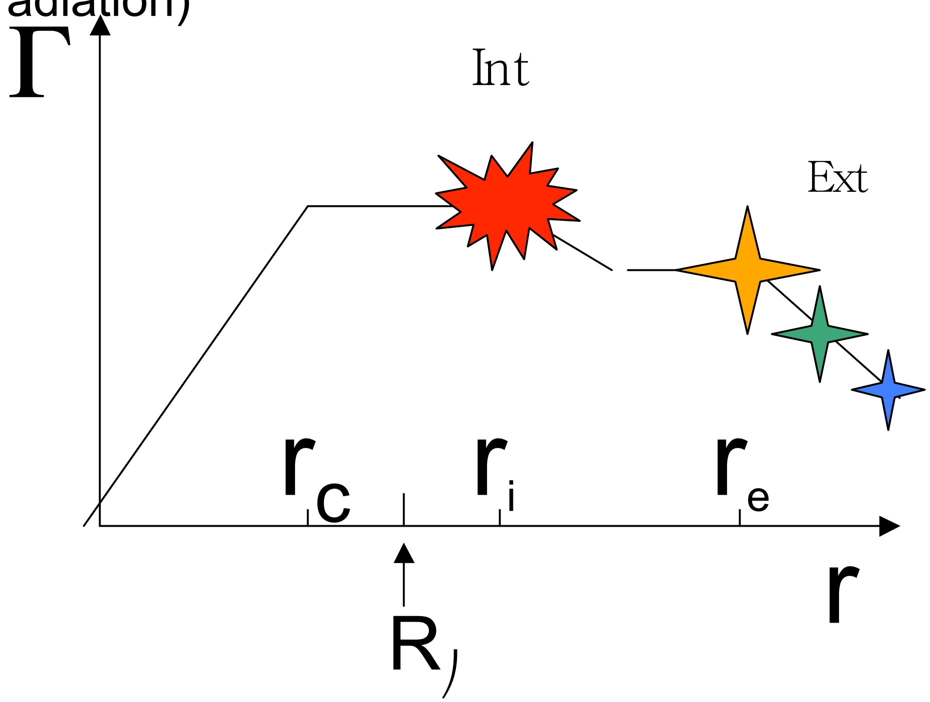
Mészáros, qcd05

Non-thermal γs: *Internal & External Shocks*

in optically thin medium outside progenitor:

→ **SHORT & LONG-TERM BEHAVIOR**

Shocks solve radiative inefficiency problem (reconvert bulk kin. en. into random en. → radiation)



- Lorentz factor Γ first grows $\Gamma \propto r$, then saturates, $\Gamma \propto$ constant, until …
- **Outside** the star, after jet is opt. thin: Internal shocks: $r_i \sim 10^{12}$cm

  →**γ-rays** (burst, t~sec)
- Externals shocks start at $r_e \sim 10^{16}$cm, progressively weaken as it decelerates

PREDICTION :

- External **forward** shock spectrum **softens** in time:

  X-ray, optical, radio …

  →**long fading afterglow !**

  (t ~ min, hr, day, month)
- External **reverse** shock (less relativistic): **Optical → quick fading** (t ~ mins)

  (Mészáros & Rees 1997 ApJ 476,232)

Shock formation

- Collisionless shocks (gas too rare)
- "Internal" shock waves: where ?

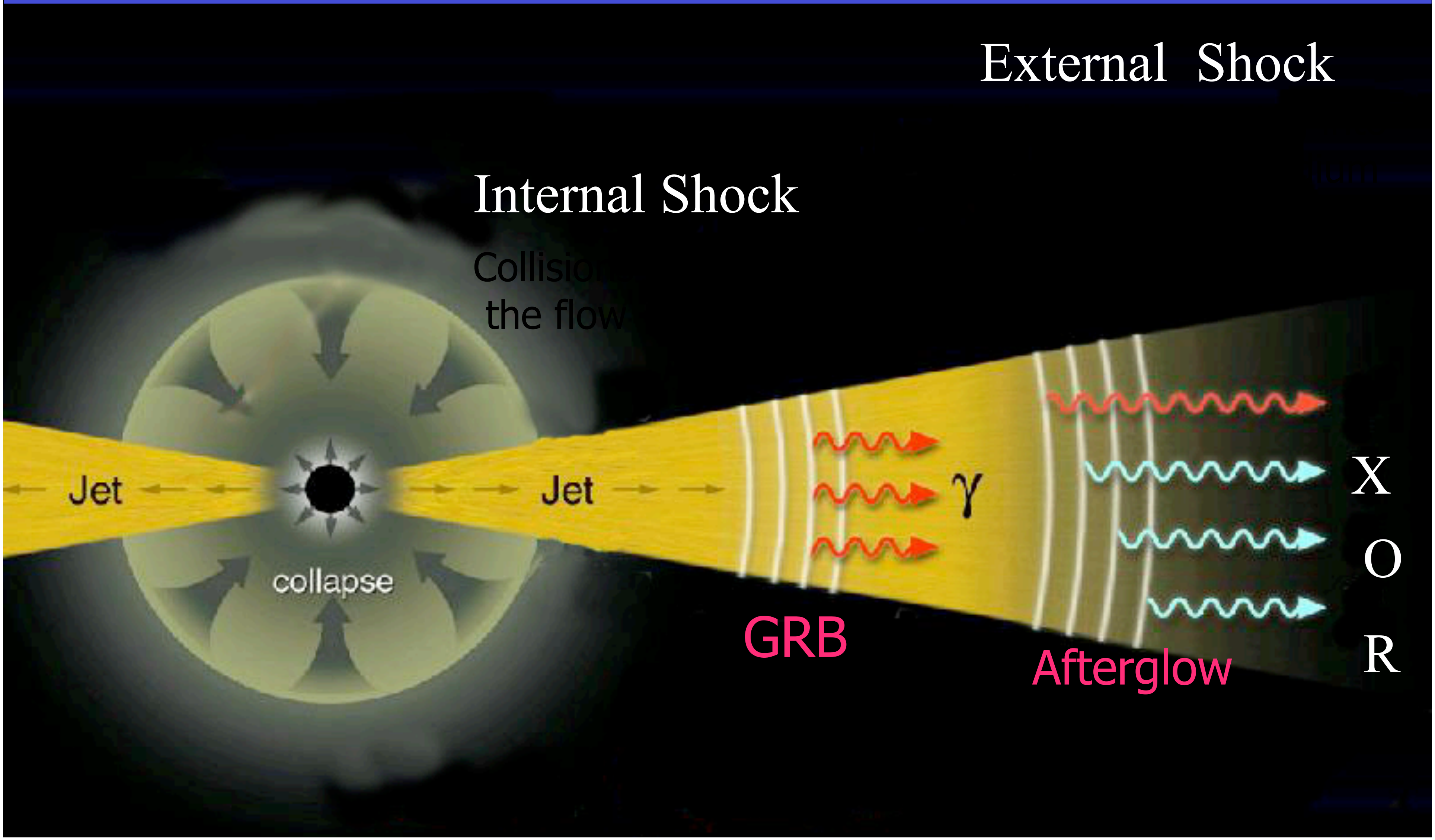
If two gas shells ejected with $\Delta\Gamma=\Gamma_1-\Gamma_2\sim\Gamma$, starting at time intervals $\Delta t \sim t_v$,, they collide at r_{is} ,

$r_{is} \sim 2\, c\, \Delta t\, \Gamma^2 \sim 2\, c\, t_v\, \Gamma^2 \sim 6.1O^{11}\, t_{-3}\, \Gamma_2^{\,2}$ cm
(internal shock)

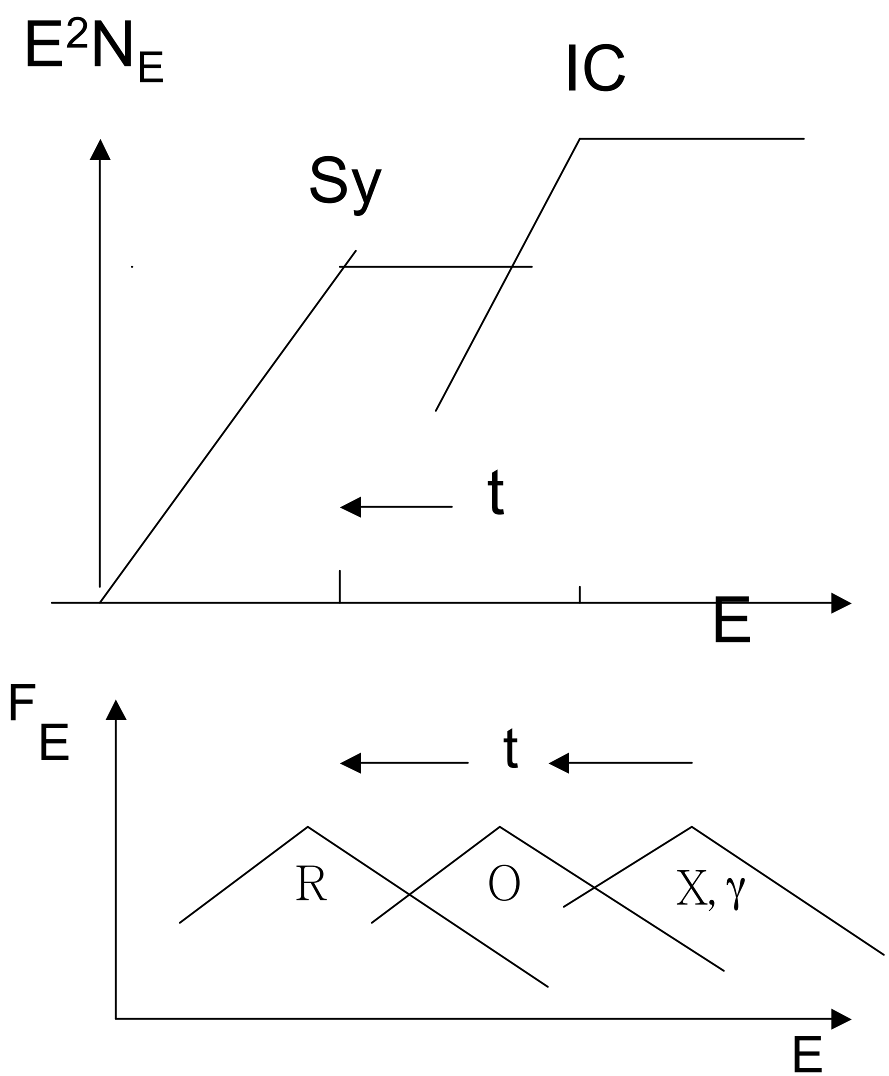
- "External shock": merged ejected shells coast out to r_{es}, where they have swept up enough enough external matter to slow down, $E=(4\pi/3)r_{es}^{\;3}\, n_{ext}\, m_p\, c^2\, \Gamma^2$,

$r_{es}\sim (3E/4\pi n_{ext} m_p c^2)^{1/3}\Gamma^{-2/3} \sim 3.1O^{16}(E_{51}/n_O)^{1/3}\Gamma_2^{\,-2/3}$ cm
(external shock)

Fireball Model: long GRBs

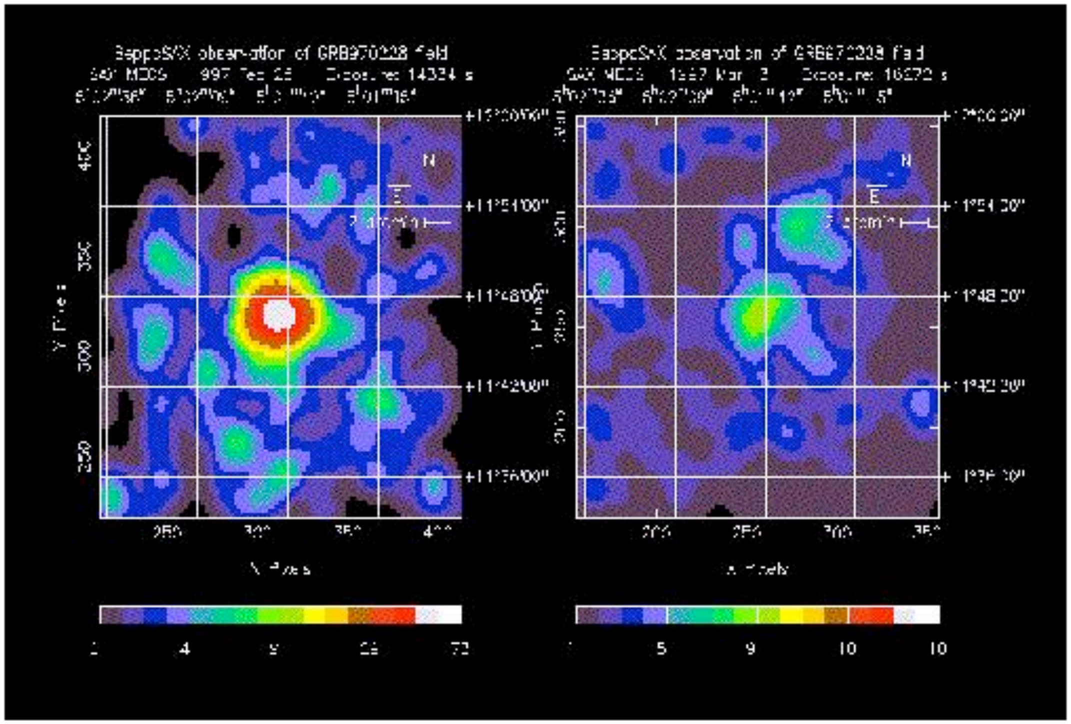


Shock Particle & Photon Spectrum



- **Non-thermal** power law of relativistic electrons, accelerated by Fermi mechanism
- → Non-thermal photon spectrum, both in internal and external shocks, due to
- **Synchrotron**, peak at ~200 keV , in 10^2-10^4 G field
- **Inv. Compton**, peak ~ GeV
- Sy peak location, ratio Sy/IC dep. on $\mathbf{B_{sh}}$, $\boldsymbol{\gamma_{e,m}}$
- Peak **softens** with time
- Ratio Sy/IC **decr** w. time

GRB 970228 : **BeppoSAX**
Discovery of an **afterglow**



Feb 28 March 3

F_x ~3E-12 erg.cm2/keV/s , decr. By 1/20

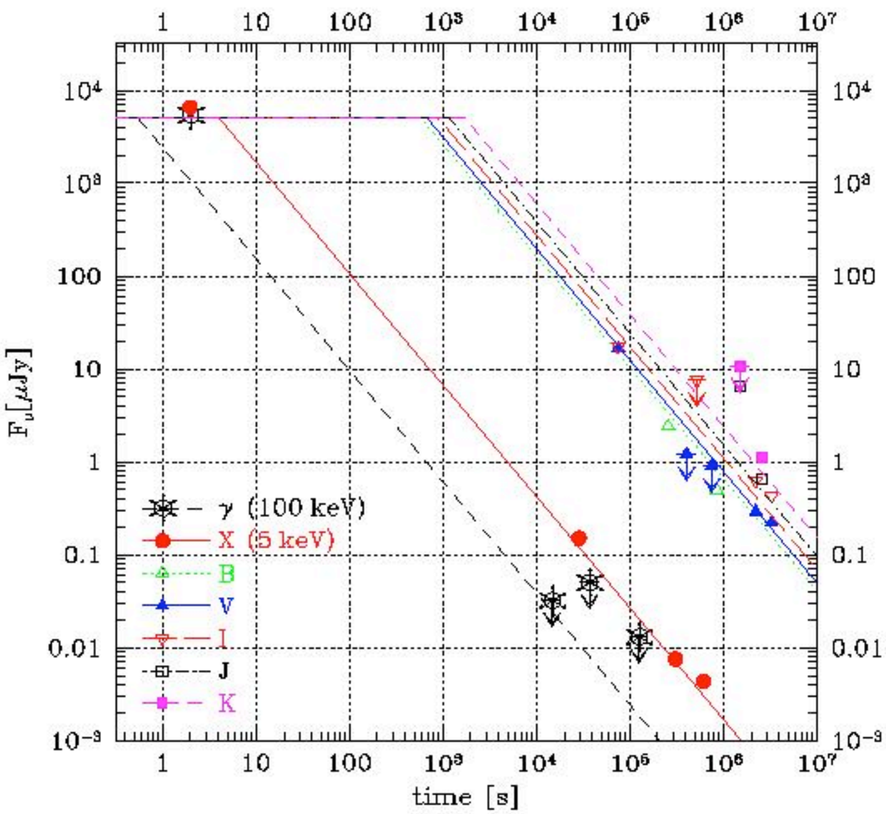
(Costa et al 1997, Nature 387:783)

- X-ray location:2-3 arcmin →raster
- →optical (arcsec) & radio location
- Can identify host galaxy, redshift

→ located at cosmological dist.

→ **NEW ERA!**

GRB afterglow blast wave model



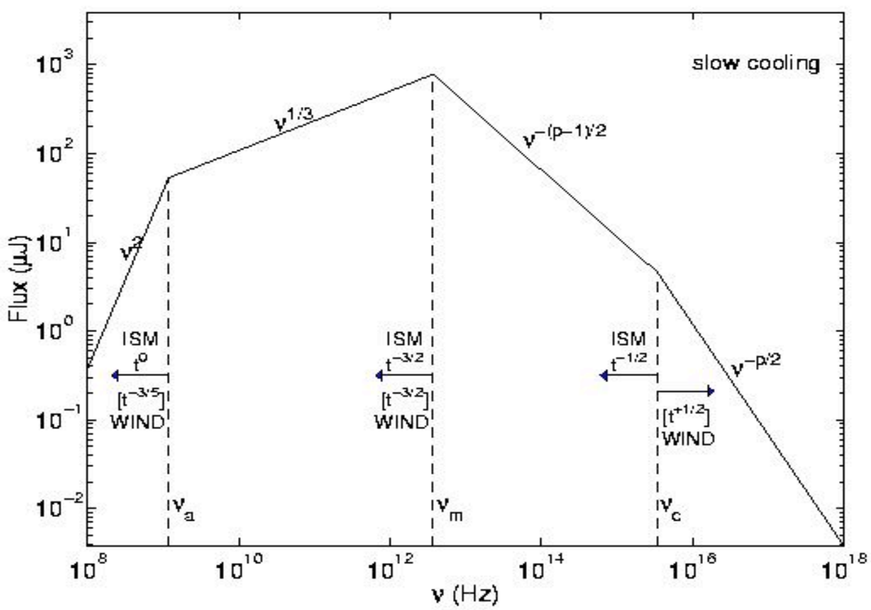
GRB 970228 as blast wave:

Wijers, Rees & Mészárosl 97 MNRAS 288:L51 fit to

Mészáros, Rees 97 ApJ 476:232 model

- Simplest case: adiabatic forward shock synchrotron rad'n from shock-accel. non-thermal e^-
- $F(\nu,t) \propto \nu^{-\beta}\, t^{-\alpha}$
- $\alpha = (3/2)\,\beta$
- Parameters E_0, ε_e, ε_B, ($\beta=(p-1)/2$)

Snapshot Afterglow Fits



Sari, Piran, Narayan '98 ApJ(Let) 497:L17)

Break frequency decreases in time (at rate dep. on whether ext medium homog. or wind (e.g. $\rho \propto r^{-2}$)

- Simplest case: $t_{cool}(\gamma_m) > t_{exp}$, where $N(\gamma) \propto \gamma^p$ for $\gamma > \gamma_m$ (i.e. $\gamma_{c(ool)} > \gamma_m$)
- 3 breaks: $\nu_{a(bs)}$, ν_m, ν_c
- $F_\nu \propto \nu^2$ $(\nu^{5/2})$; $\nu < \nu_a$;

  $\propto \nu^{1/3}$; $\nu_a < \nu < \nu_m$;

  $\propto \nu^{-(p-1)/2}$; $\nu_m < \nu < \nu_c$

  $\propto \nu^{-p/2}$; $\nu > \nu_c$

(Mészáros, Rees & Wijers '98 ApJ499:301)

Collapsar & SN connection

GRB030329/SN2003dh

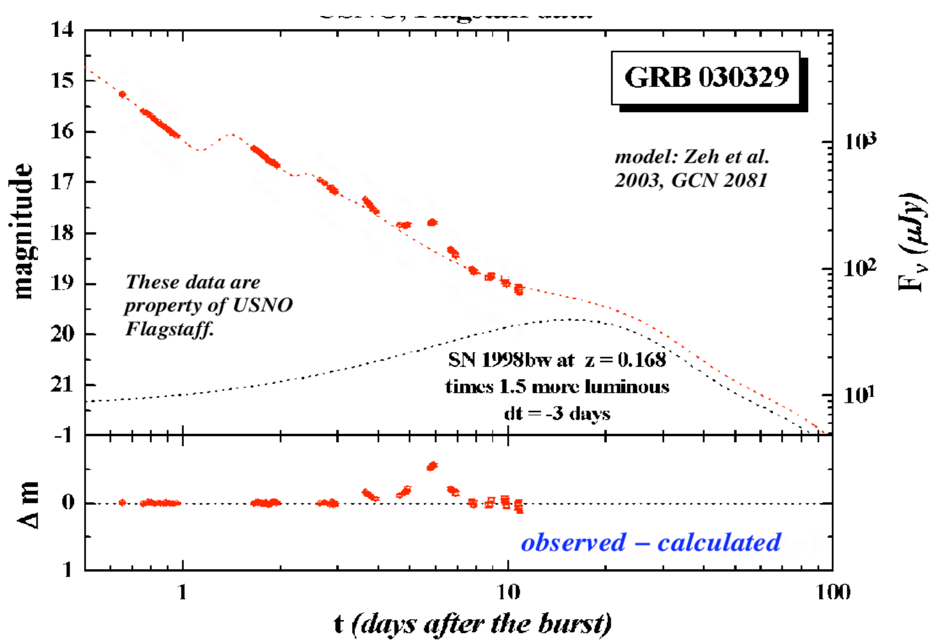
Credit: Derek Fox & NASA ↓

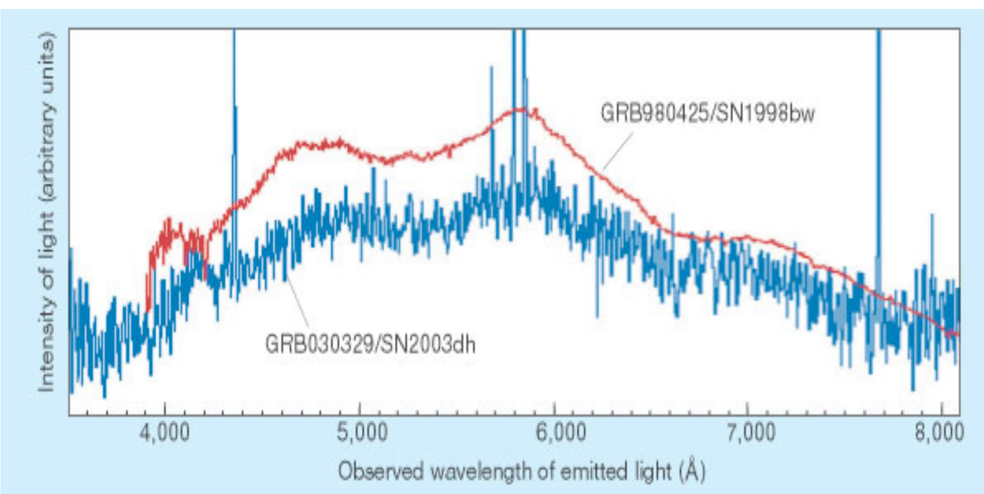
- Core collapse of star w. M~30 M_{sun}
  → BH + disk (if fast rot.core)
  → jet (MHD? baryonic? high Γ,
  + SNR envelope eject (?)
- 3D hydro simulations (Newtonian SR) show that baryonic jet w. high Γ can be formed/escape
- SNR: not seen *numerically* yet (**but:** several previous observ. suggestions, e.g. late l.c. hump + reddening) ;

… and more recently …

Collapsar & SN : does one imply the other ?

GRB 030329 ⇔ SN 2003dh : Yes !

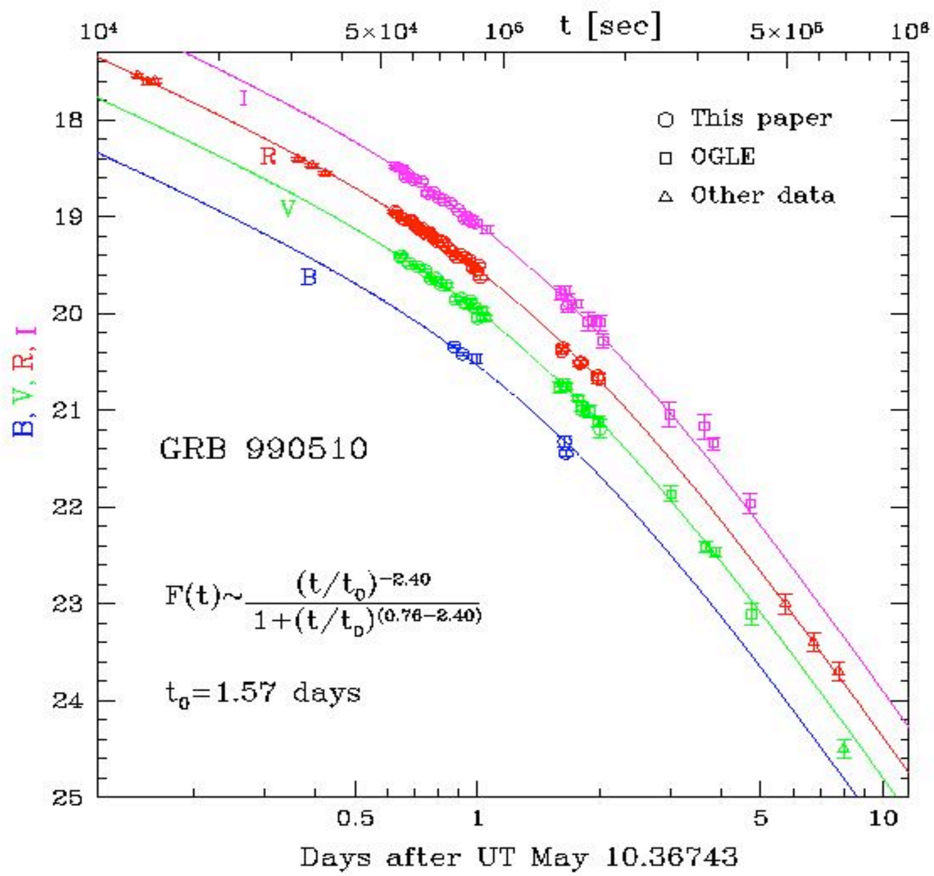




- 2nd Nearest "unequivocal" cosmological GRB: **z=0.17**
- **GRB-SN association: "strong"**
- Fluence:10^{-4} erg cm^{-2} , among highest in BATSE, but Δt_γ~30s, nearby; $E_{\gamma,iso}$~$10^{50.5}$erg: ~typical,
- $E_{SN2003dh,iso}$ ~$10^{52.3}$ erg ~ $E_{SN1998bw,iso}$ (↔grb980425) $v_{sn,ej}$ ~0.1c (→ "hypernova")
- GRB-SN imultaneous? at most: < 2 days off-set (from opt. lightcurve) (i.e. not a "supra-nova")
- But: might be 2-stage (<2 day delay))- NS-BH collapse ? → ν predictions may test this !

(other: GRB031203/SN2003lw, z=0.1055, aph/0403608)

Light curve break: Jet Edge Effects

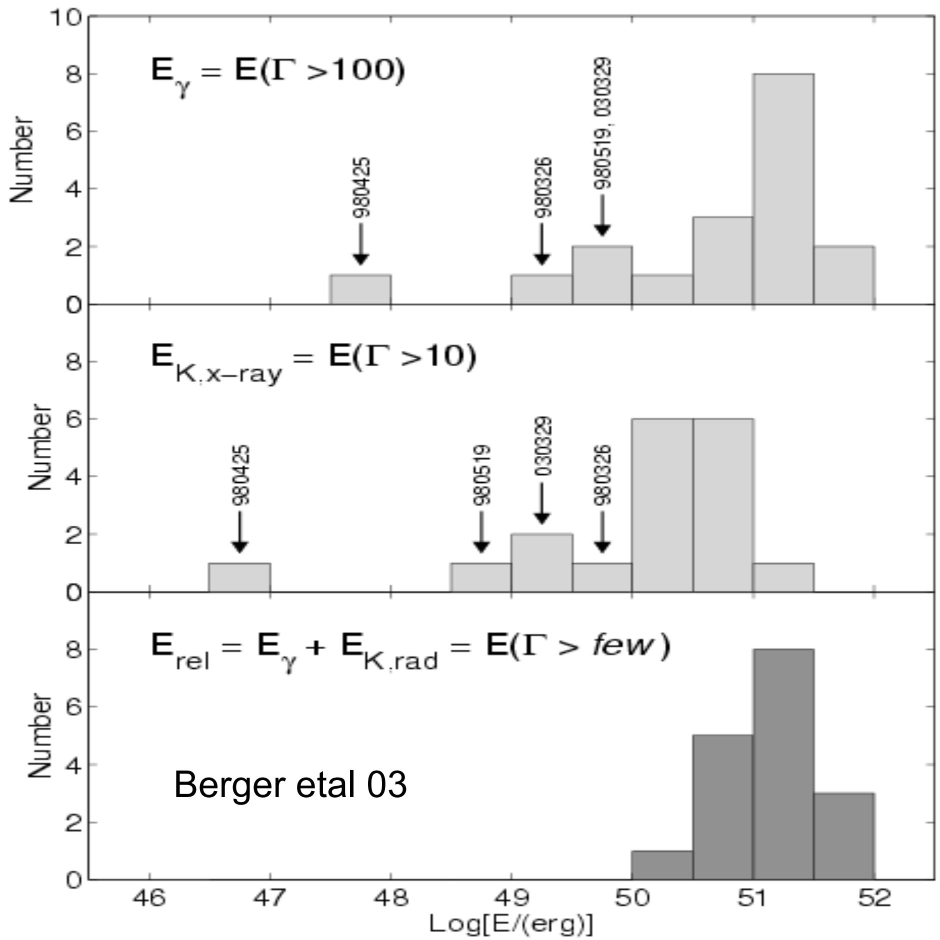


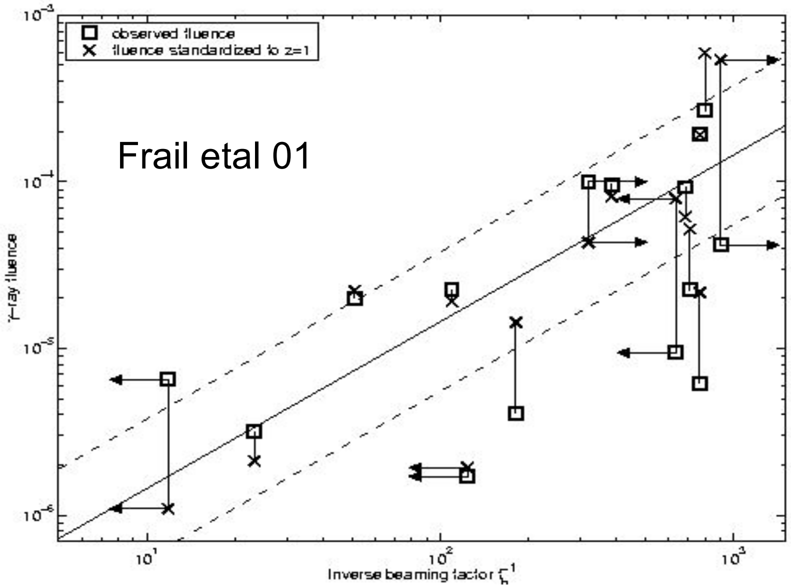
- Monochromatic break in light curve time power law
- expect $\Gamma \propto t^{-3/8}$, as long as $\theta_{light\ cone} \sim \Gamma^{-1} < \theta_{jet}$, (spherical approx is valid)
- "see" jet edge at $\Gamma \sim \theta_{jet}^{-1}$
- Before edge, $F_\nu \propto (r/\Gamma)^2 . I_\nu$
- After edge, $F_\nu \propto (r\theta_{jet})^2 . I_\nu$,

  $\rightarrow F_\nu$ steeper by $\Gamma^2 \propto t^{-3/4}$
- After edge, also side exp.

$\rightarrow$ further steepen $F_\nu \propto t^{-p}$

Jet Collimation & Energetics





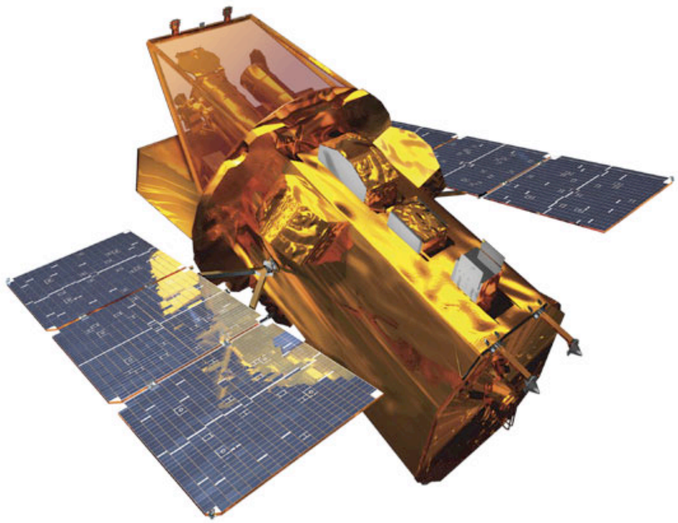
- ↑Jet opening angle inv. corr. w. $L_{\gamma(iso)}$
- ← $L_{\gamma(corr)}$ **~ const.**
- **GRB030329:** evidence for 2-comp. jet:

  $\theta_\gamma \sim 5^o < \theta_{radio} \sim 17^o$
- **→ $E_{total} = E_\gamma + E_{kin}$ ~ const.**

(→ quasi-standard candle)

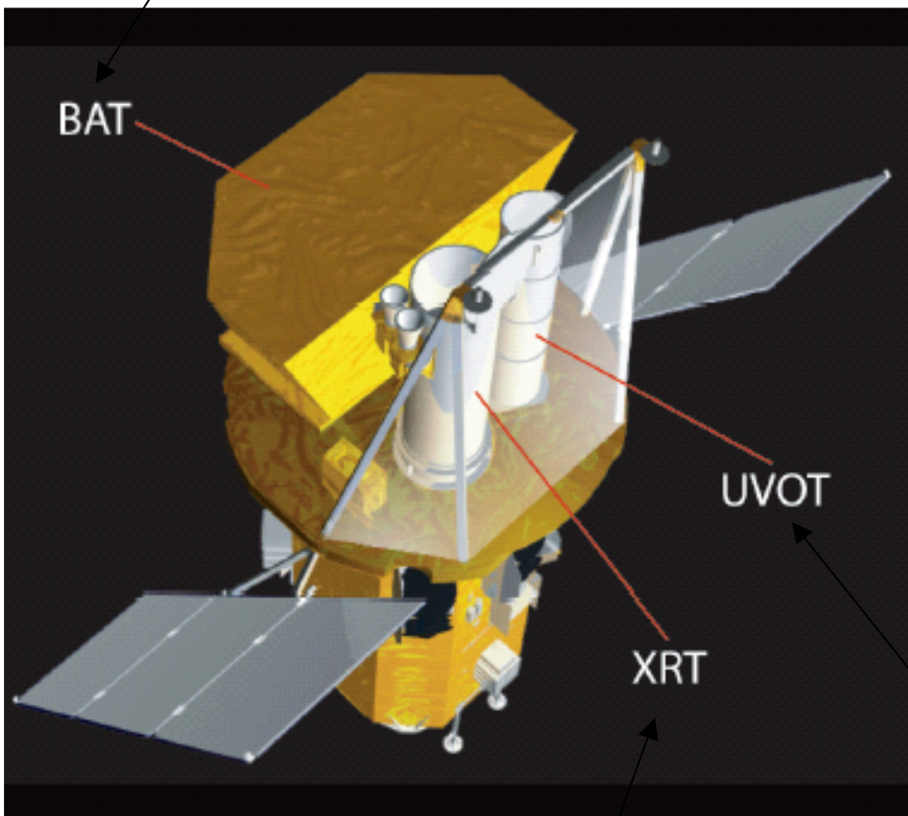
SWIFT

Blasted off on 11/20/2004



Mészáros, qcd05

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



Three instruments

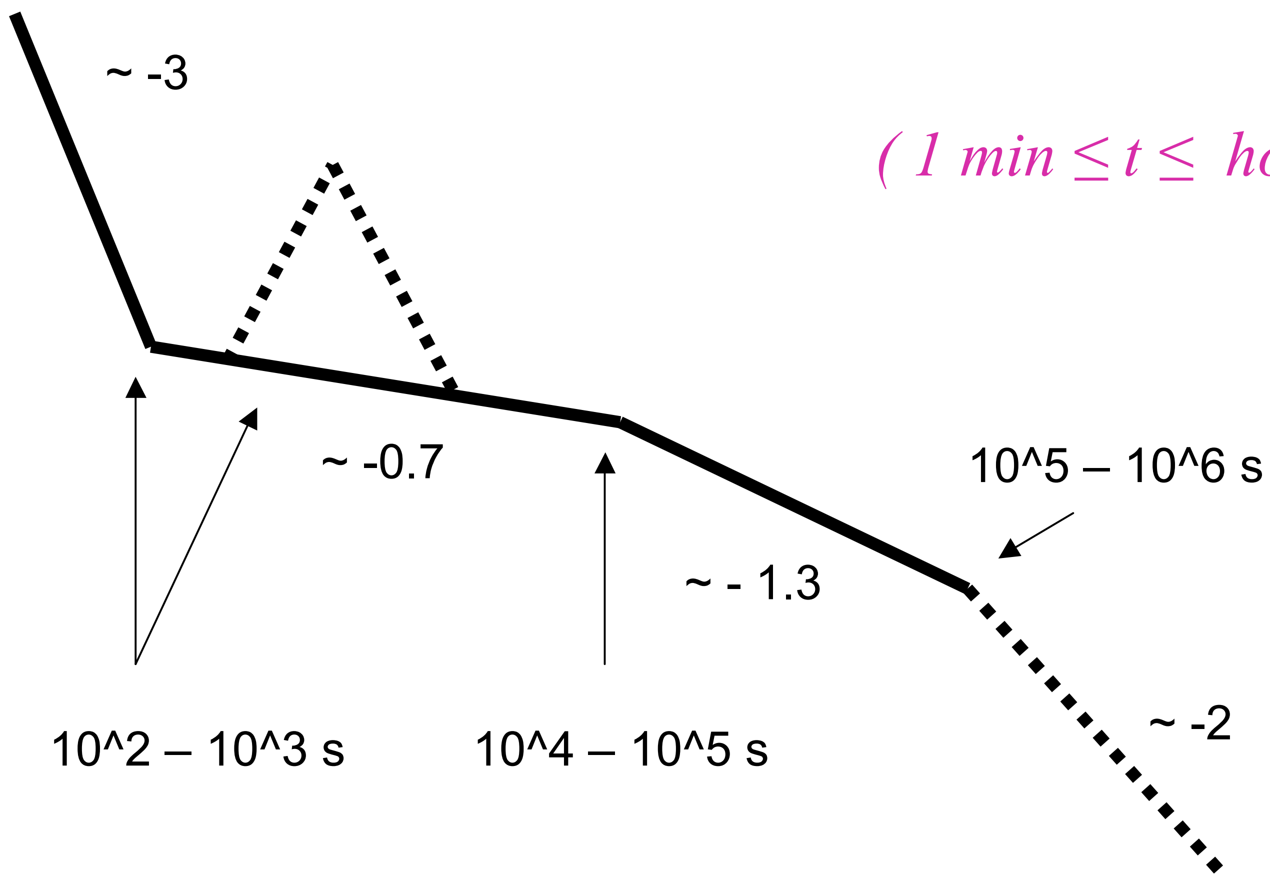
Gamma-ray, X-ray and optical/UV

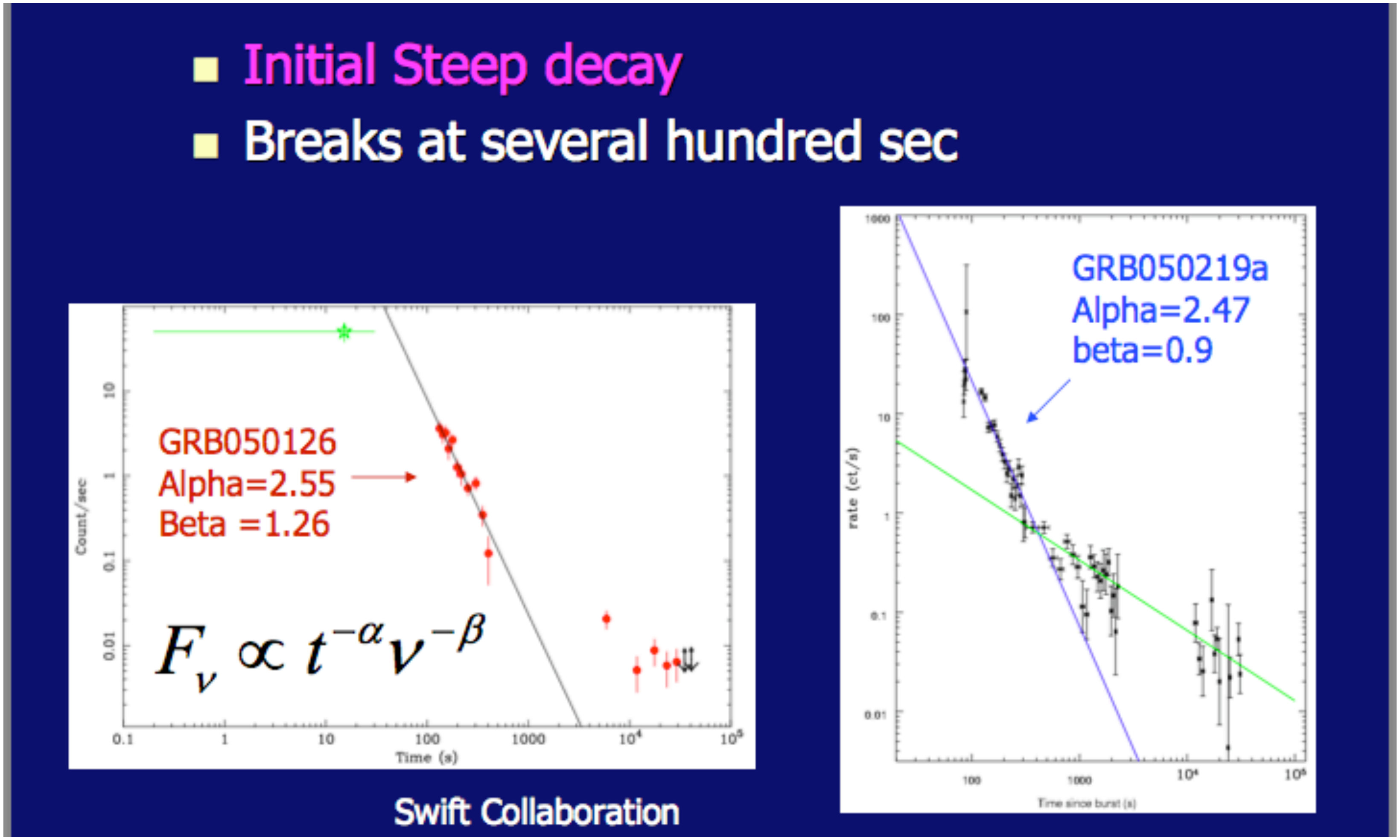
Slew time: 20-70 s !

UVOT: Wavelength Range: 170-650nm

XRT: Energy Range: 0.2-10 keV

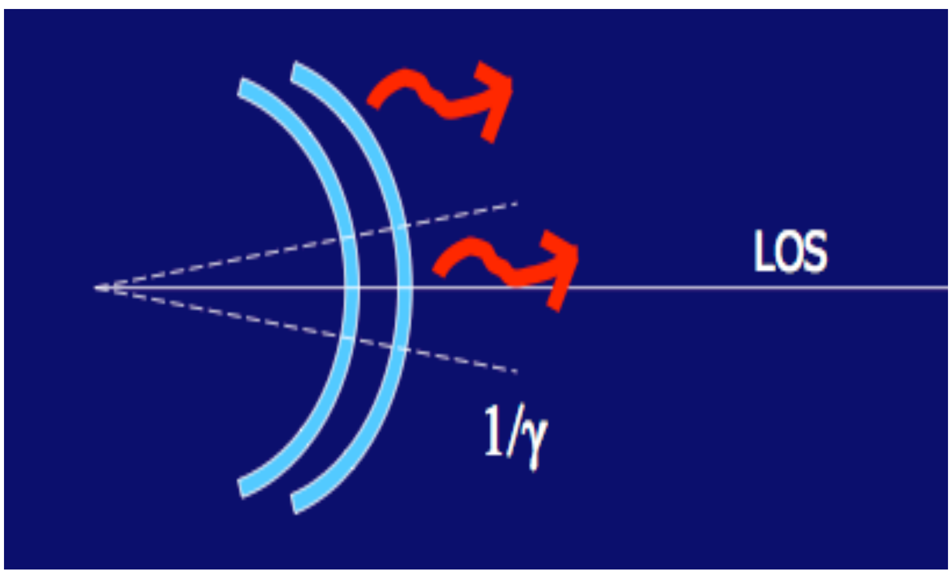
New features seen by Swift : A Generic X-ray Lightcurve?





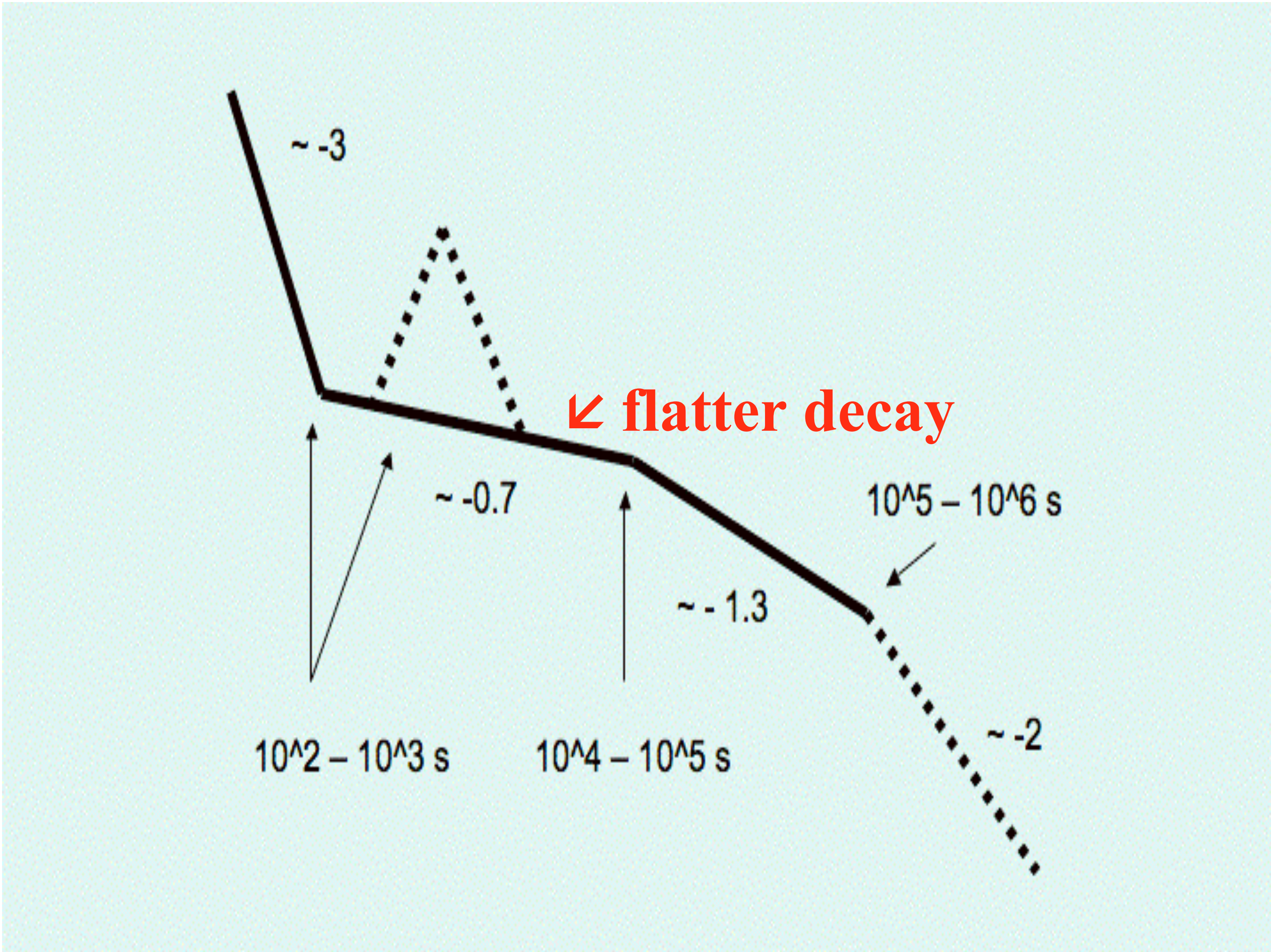
- Small angle jet break? (patchy jet?)
- Thermal cocoon expansion?
- Photospheric emission?
- High latitude emission ("curvature effect")?

Initial rapid decay: **High latitude emission**

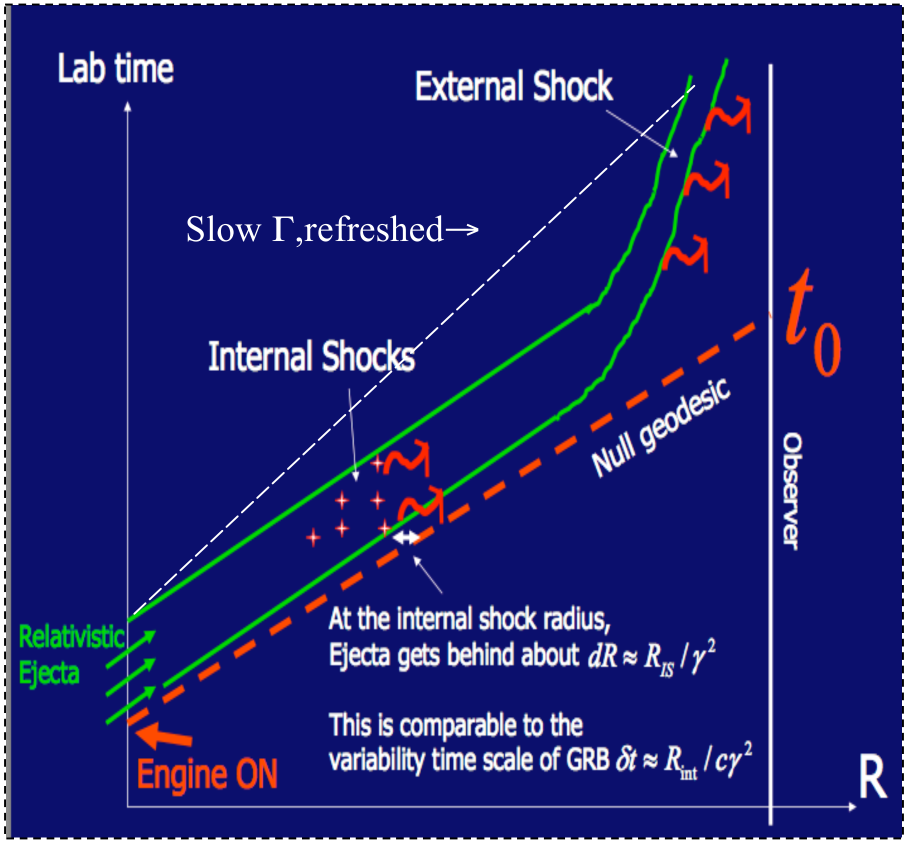


- Might be patchy shell (mini- jet break) - but α-β relation does not generally fit (where $F_\nu \sim t^{-\alpha} \nu^{-\beta}$)
- More likely : drop is due to **tail end of GRB** (high latitude emission) : rad'n from angles $\boldsymbol{\theta > \Gamma^{-1}}$ arrives at time $\mathbf{t \sim R\theta^2/2c}$ later than from θ~0, and is softer by $D \sim t^{-1}$; expect

$\alpha = 2 + \beta$, ~ OK



Mészáros, qcd05



Flatter decay ($0.2 \leq \alpha \leq 1$)

- Probably due to "refreshed shocks",

due ***either*** to:

- ***Long*** duration ejection

($t \sim t_{flat}$) ; ***or***

- ***Short*** ejection ($t \sim t_\gamma$), but with range of Γ, e.g. $M(\Gamma) \sim \Gamma^{-s}$, $E(\Gamma) \sim \Gamma^{-s+1}$,

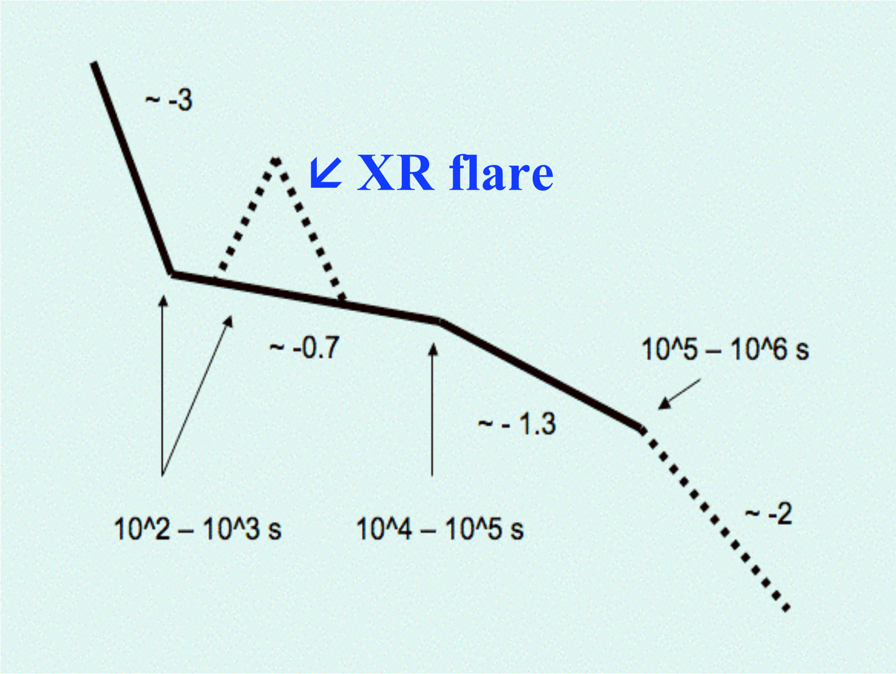
for $\rho \sim r^{-g}$ ext. medium :

FS: $\alpha=[-4-4s+g+sg+\beta(24-7g+sg)]/[2(7+s-2g)]$

RS: $\alpha=[8-4s-3g+sg+\beta(12-3g+sg)]/[2(7+s-2g)]$

Rees+PM, 98 ApJ 496, L1 ; Sari +PM, 00, ApJ 535, L33 ; Zhang +PM 01, ApJ 552, L35

XR Flares in GRB late XR l.c.



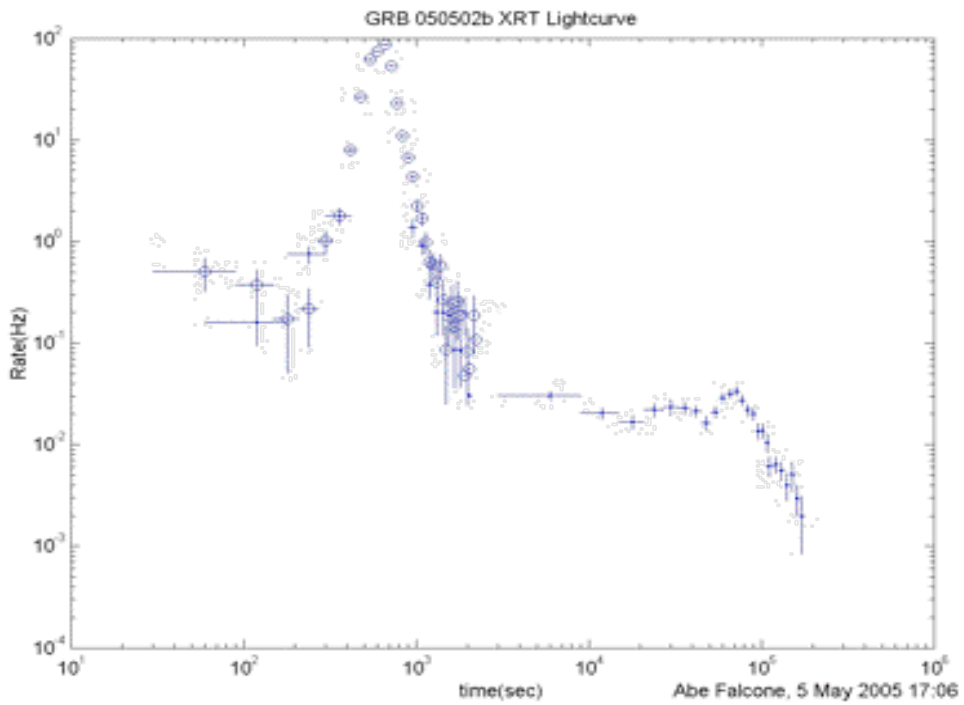
Could be due to:

- Refreshed shocks
- IC from reverse shock
- External density bumps
- 2- or multiple comp. jet
- Continued ctrl. engine activity
- ….
- Main constraints: very (to extremely) sharp rise and decline ($t^{\pm 3} \longleftrightarrow t^{\pm 6}$)

Continued central engine activity?

e.g.:

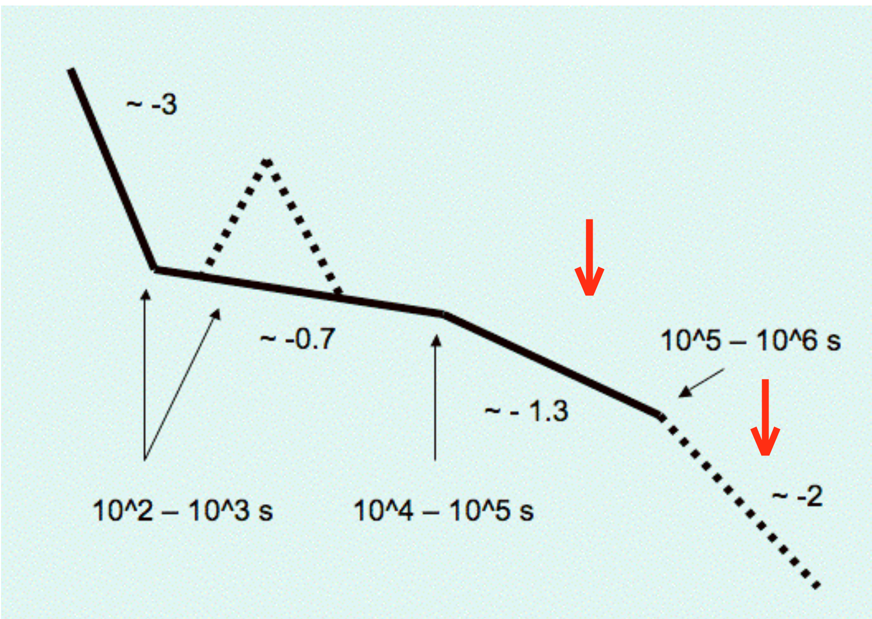
Late Internal Shocks



- Rapid falling rules out density bump, refreshed shocks & two-component models
- A factor of 500 re-brightening is difficult for the SSC model
- The central engine is active again hundreds of seconds later!
- Implications for XRFs.

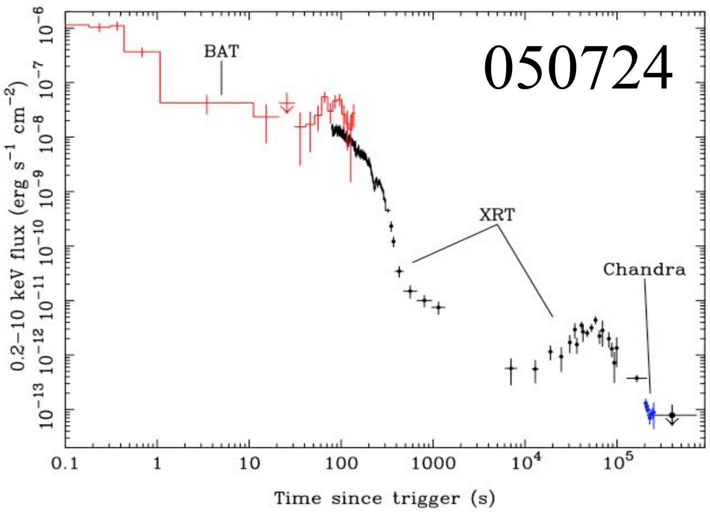
Burrows et al., 2005
Zhang et al. 2005

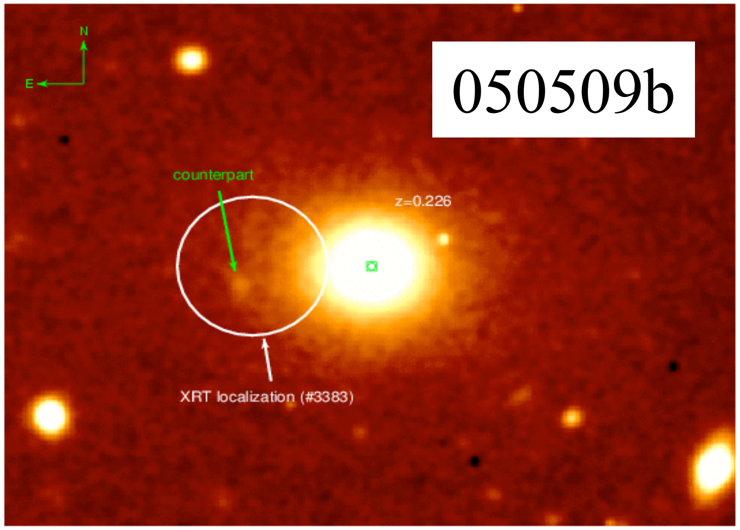
Final two XR l.c. sections:
business as usual (almost)?



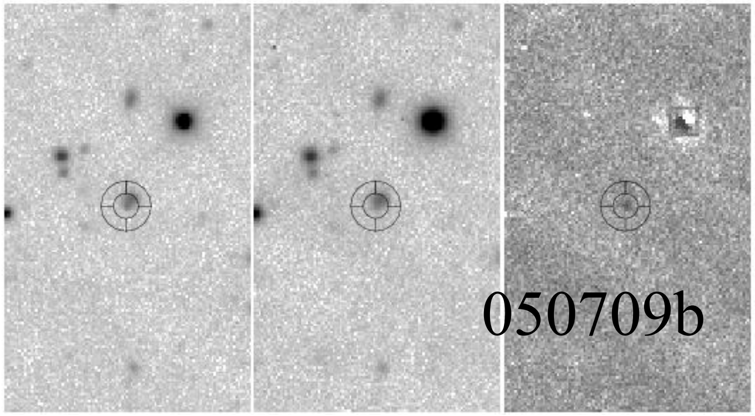
- Next moderate decay α~-1.1 to -1.5: "usual" forward shock decay
- Final steep decay α~-2 to -3 : "usual" jet break, α~(p-1)/2 to -p

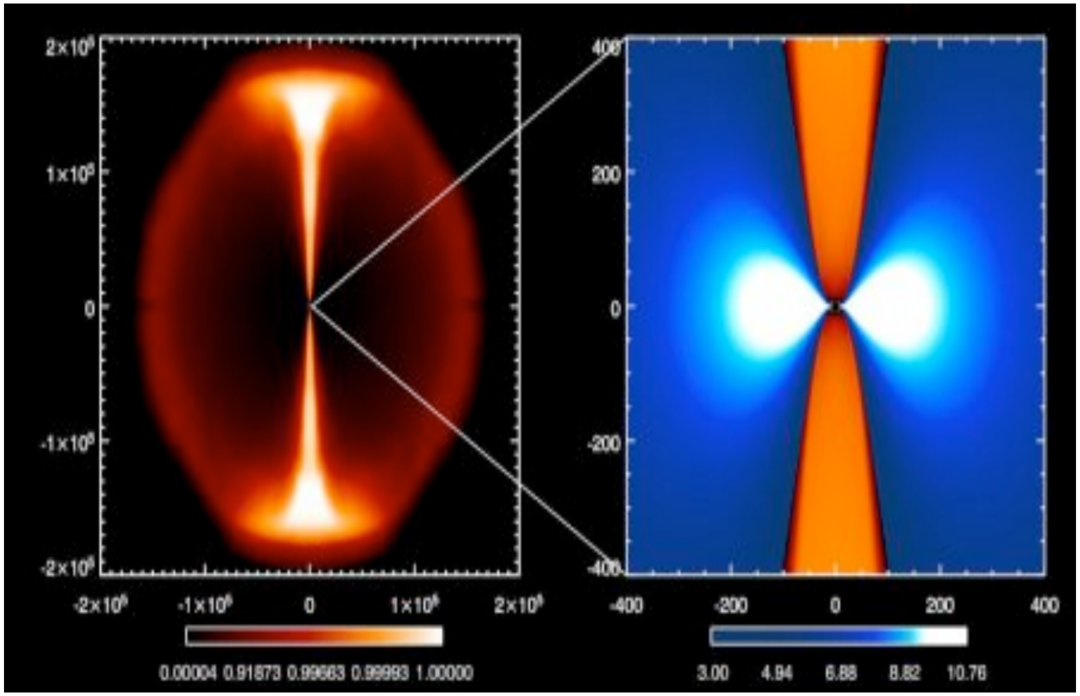
Short Bursts





- Hosts: **E , Irr , SFR**
  (compat. W. NS merg,
  but: some SGR, other?)
- Redshift : < 0.1 to > 0.7
- XR, OT, RT: yes (mostly)
- XR l.c.: similar to long bursts?
  (XR bumps too- late engine?)

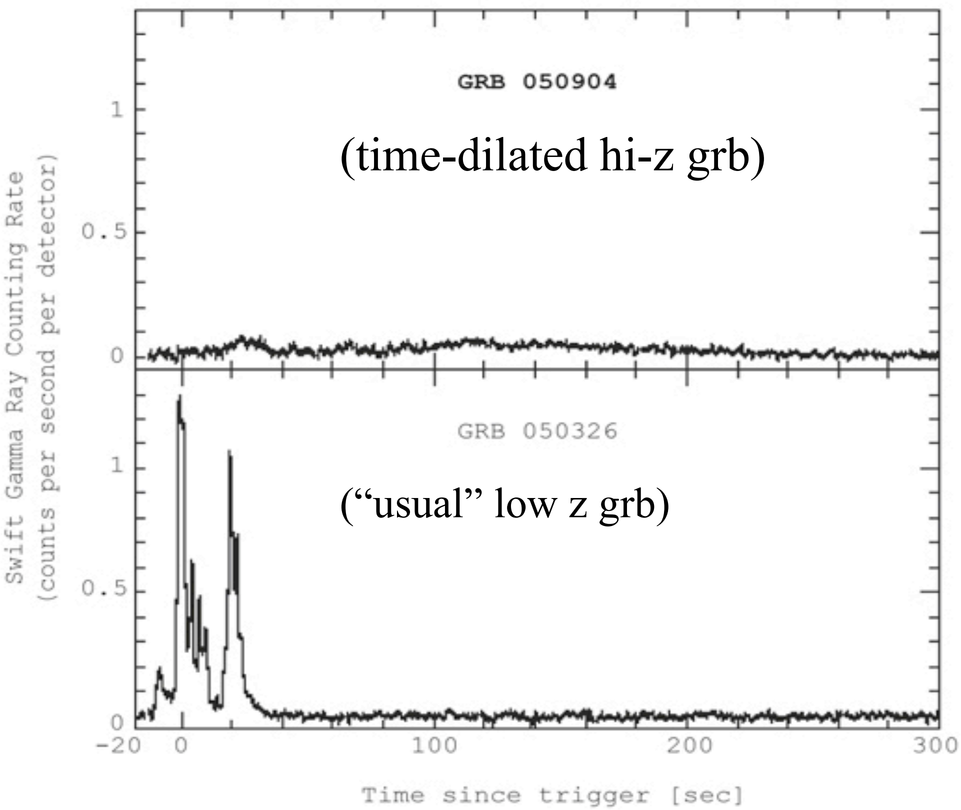




Short burst paradigm:

***NS-NS*, or *NS-BH* merger**

- ***NS-NS merger movie***
- ***NS-BH merger movie***



Time decay of OT, t →

Most distant

long burst from Swift

(z=6.29):

GRB050904

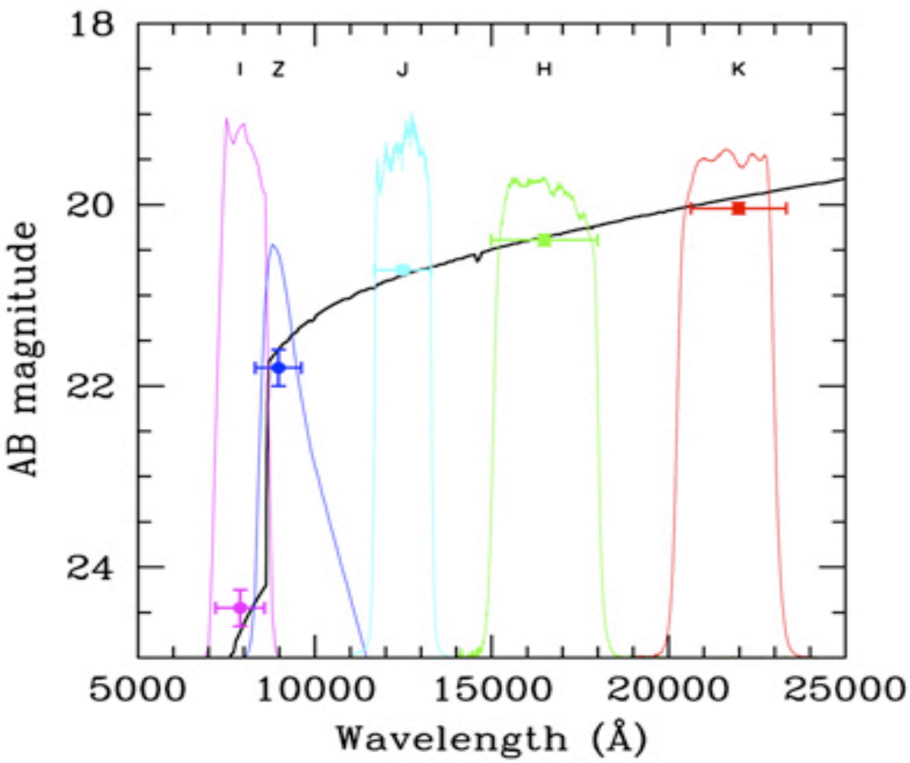
- Discovered/localized by **Swift**

  BAT, XRT, UVOT

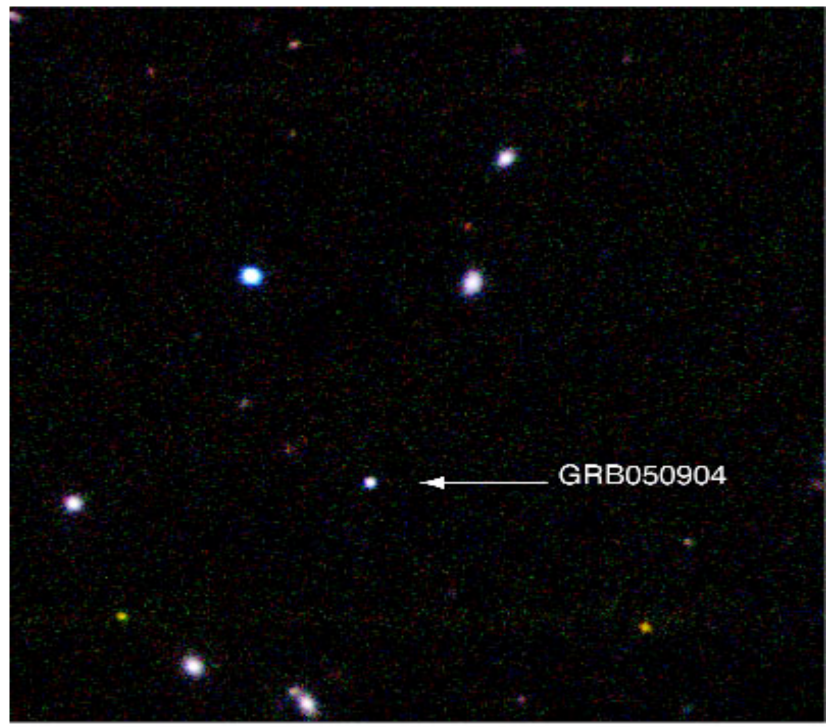
- Prompt robotic ground I,R band **TAROT, P60** upper limits, detection J=17 mag **FUN/SOAR**

  →photometric z>6

GRB 050904

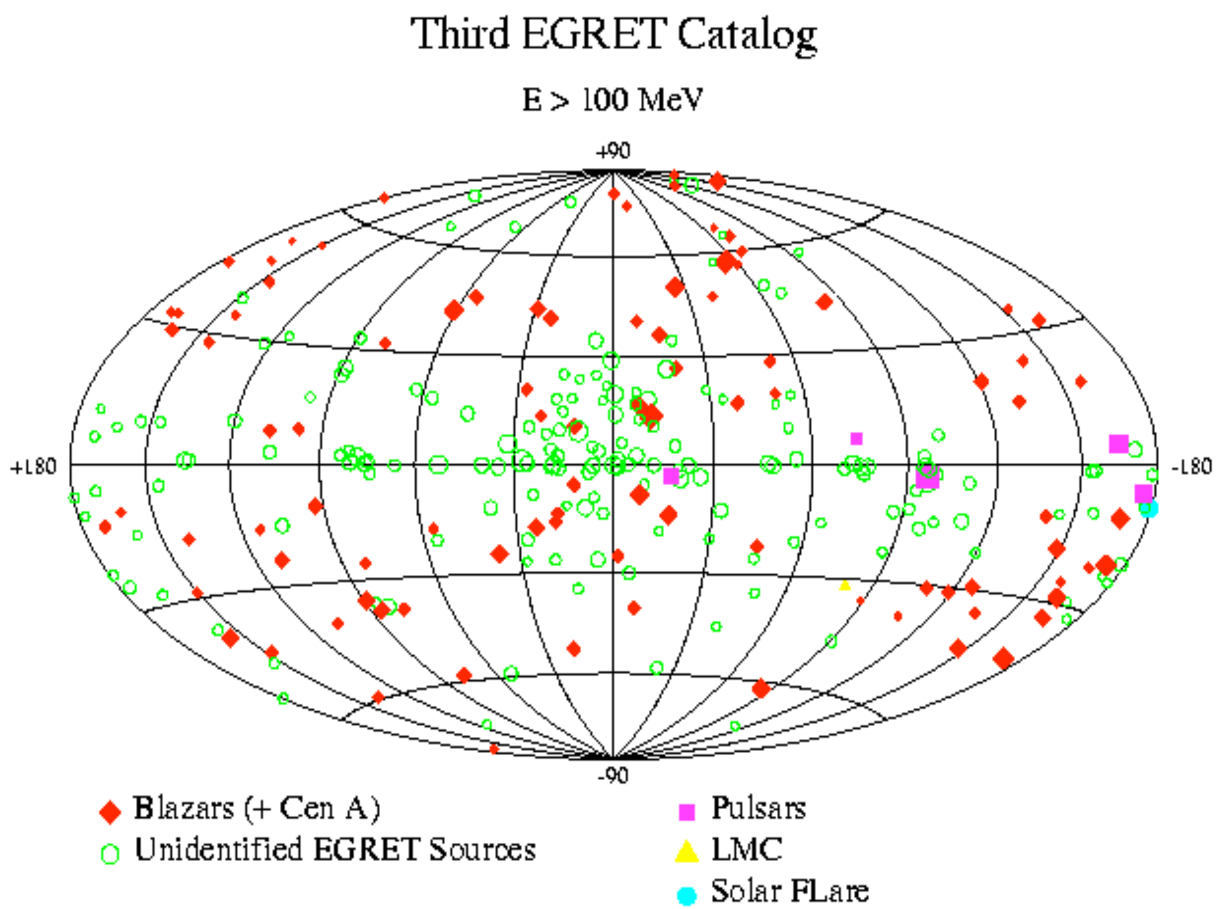


“photometric” z>6 : Ly α(1210 A) abs. cut-off



The Distant Gamma-Ray Burst GRB050904
(ISAAC/VLT)

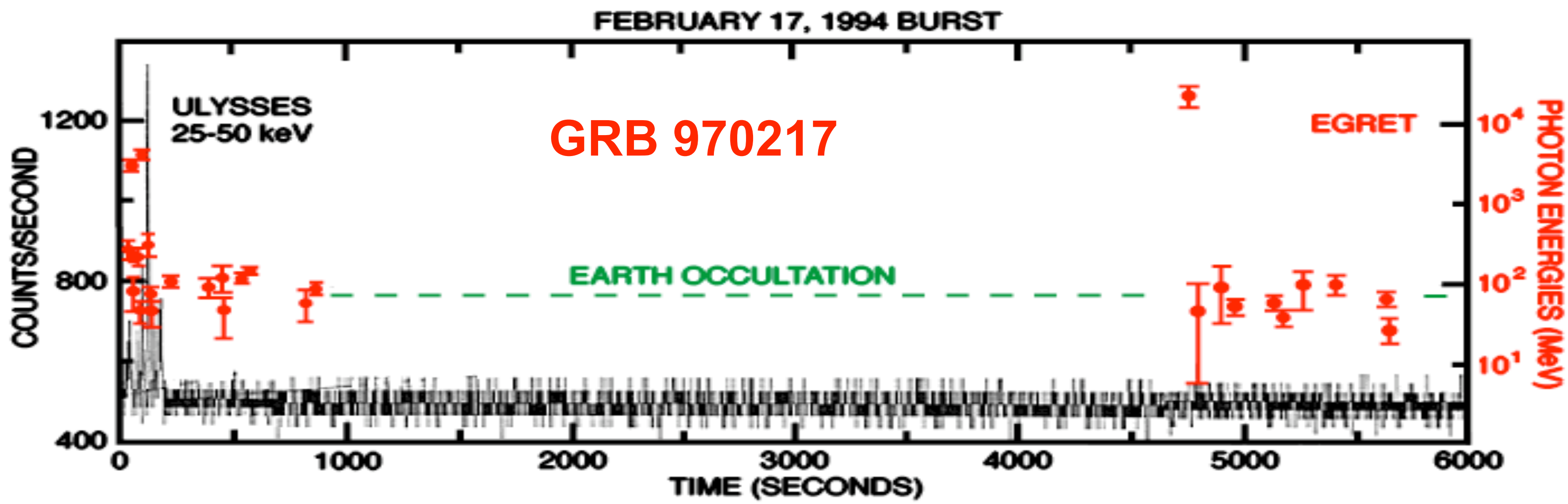
and ... ***Subaru*** 8.2m telescope spectrum, 3.2 days later: **z=6.29 !**

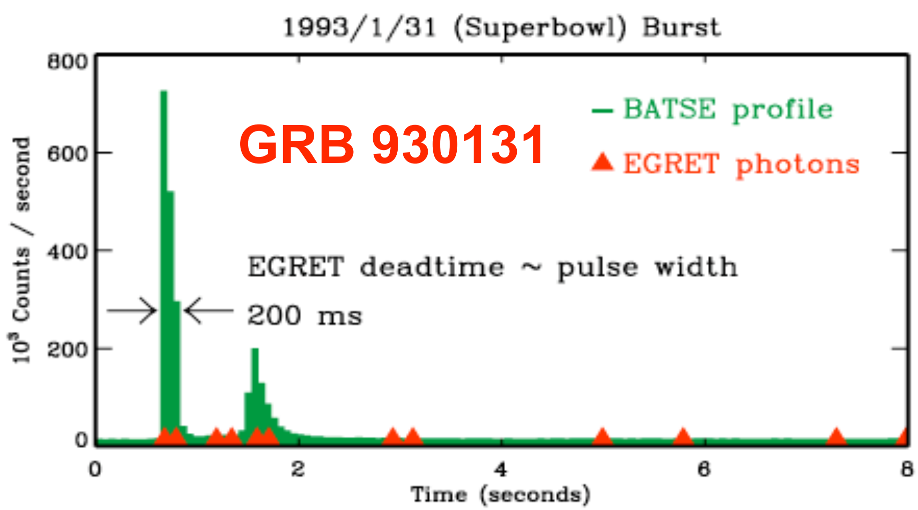


GeV γ
emission from
GRB,
PSR,
SNR,
other galactic, extragalactic
&un-id sources

- **GeV: space obs. (SAS-2, HEAO-A4, Kvant….)**
- **EGRET** spark chamber: 5 GRB, 6 PSR & 60 blazars @δ10GeV
- + ~25 other **Unidentified** **EGRET** γ-ray sources

Two EGRET spark chamber GeV Bursts





- >10 GeV photon flux can last for τ 1 hr,

  start with MeV trigger
- Energy Fluence

  $F_{0.1\text{-}10\ \mathrm{GeV}} \sim F_{0.1\text{-}10\ \mathrm{MeV}}$

Mészáros, qcd05

Simplest "delayed" GeV γ mech.

- GeV emission seen, start ~ same time as MeV trigger, but lasting ~ 1 hr:

  → could be

  a) **internal** shock synchrotron

  → normal duration **MeV** to ~GeV

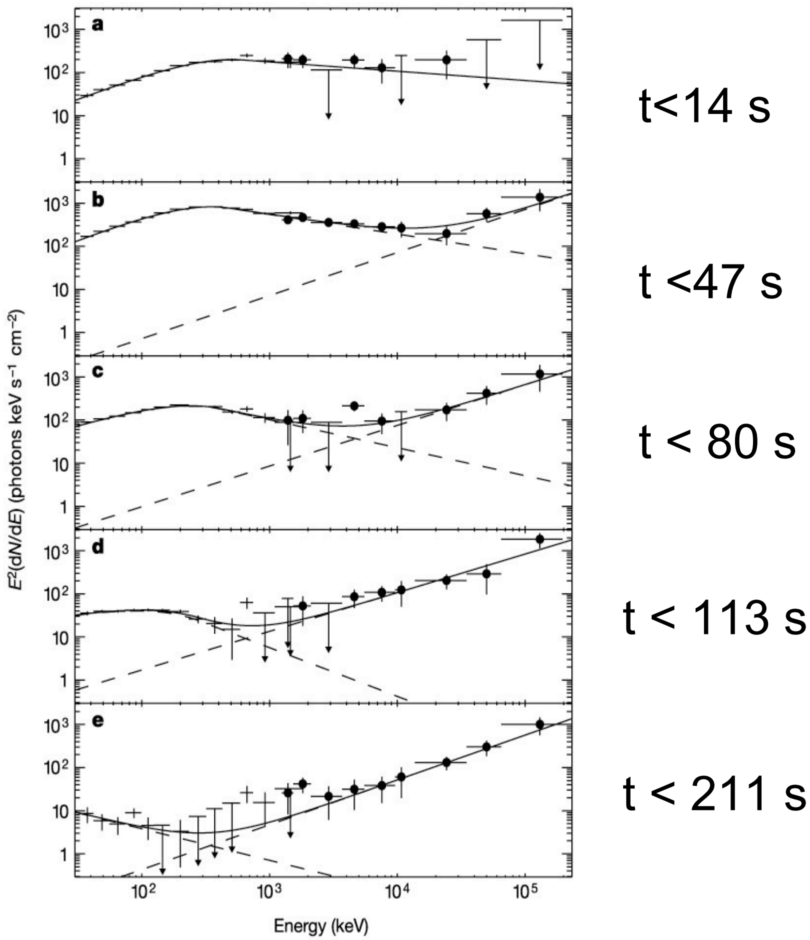
  b) **external** shock (moder. Γ, low n_{ext})

  IC → ~ **GeV** to TeV, lasts ~mins-hr

(Meszaros & Rees 1994 MNRAS 269, L41)

- Other possib (Katz 94) : proton impact on bin. comp.* pp → γ

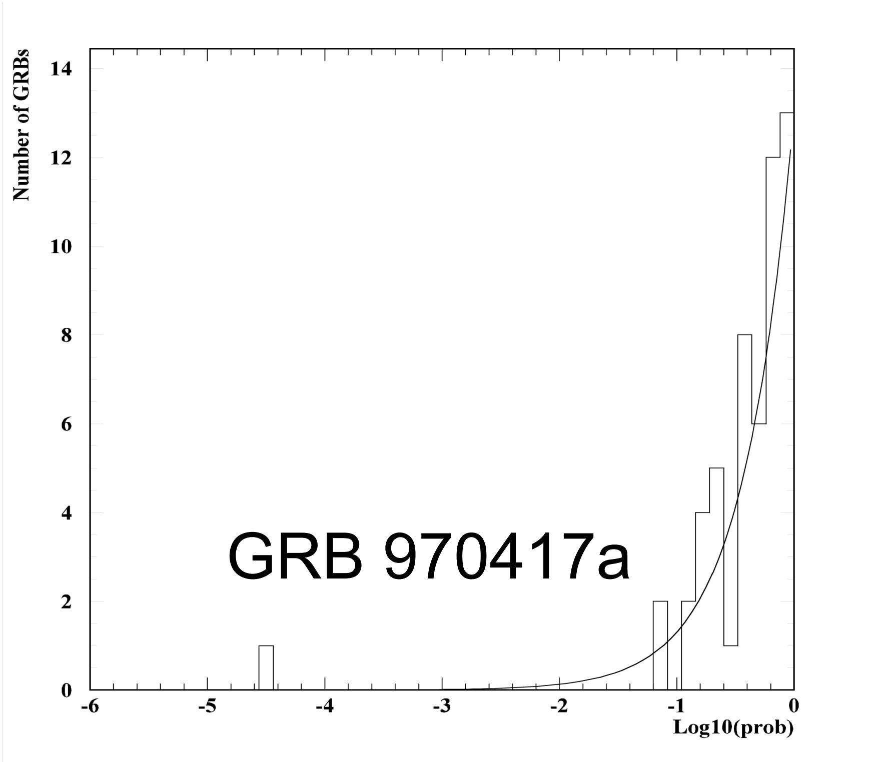
GRB 941017 : pγ signature?

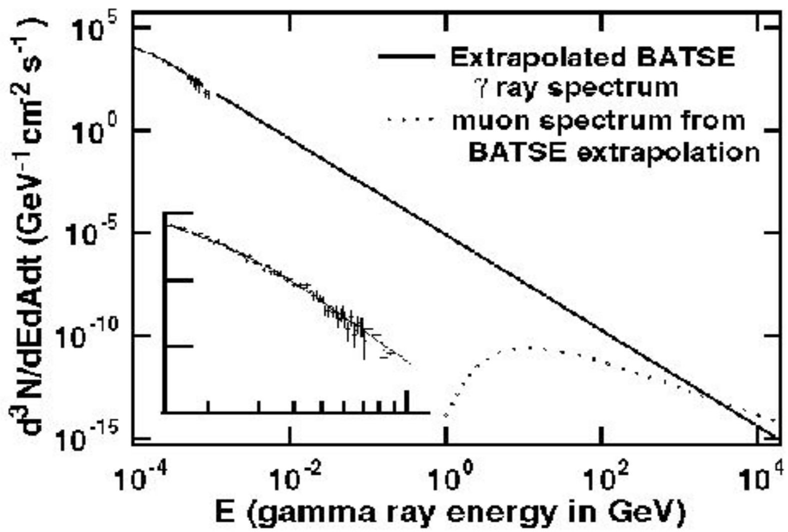


Gonzalez, Dingus et al, 03, Nature 424, 749

- Hard **(10-200 MeV)** comp. in EGRET TASC calorimeter **not** compatible w. BATSE MeV fit (but in 26 other bursts a single BATSE/TASC fit works well)
- Hard comp. more prominent in time → **pγ signature?** might explain delay, hardness

- **Alternative: could be IC**, in regime where IC sp is harder than sync PL ; e.g. scatt. of lower energy synch. asymptote; or observe IC region where electrons with a range of energies scatter off a range of photon energies (Granot,Guetta, astroph/0309231)

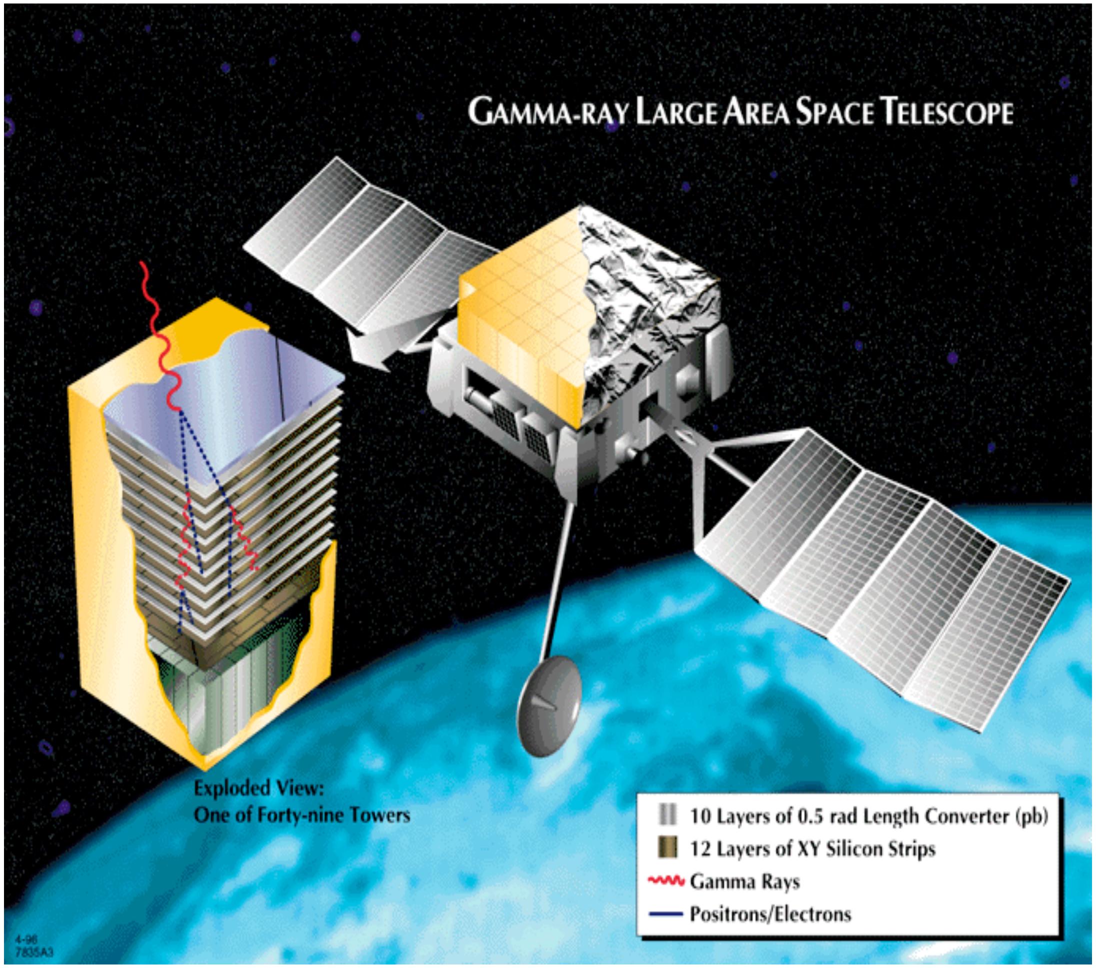




TeV γ Detection Status

- **Milagrito** :Tentative (**3σ**) TeV detection ; $\Phi_{TeV} \sim 10\ \Phi_{MeV}$; but, no z (abs? dδ100 Mpc?)
  Atkins etal, 00, ApJL..
- **Tibet** array: superpose 50-60 ≠ bursts in time-coincid. w. MeV: joint TeV det. significance 6**σ ?**
  (Amenomori et al AA '96)
- **GRAND**: GRB 971110 TeV reported at **2.7σ**
  (Poirier et al PRD 03, aph/0004379)

GLAST : LAT (Stanford +)



Also on GLAST: GBM (next slide)

- LAT: launch exp ’06, Delta II, 2-300 GRB/2yr
- Pair-conv.mod+calor.
- 20 MeV-300 GeV, ΔE/Eδ10%@1 GeV
- fov=2.5 sr (2xEgret), θ ~30”-5’ (10 GeV)
- Sens τ2.10^{-9}ph/cm^{2}/s (2 yr; > 50xEgret)
- 2.5 ton, 518 W

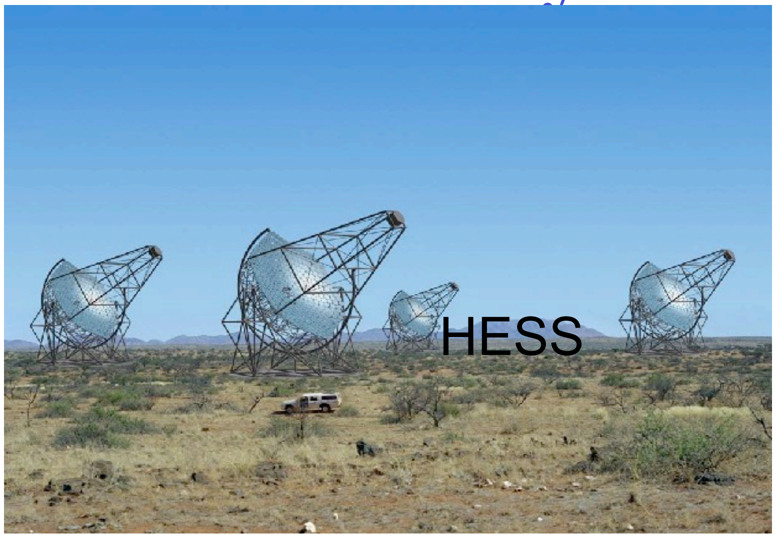
GeV-TeV γ experiments underway

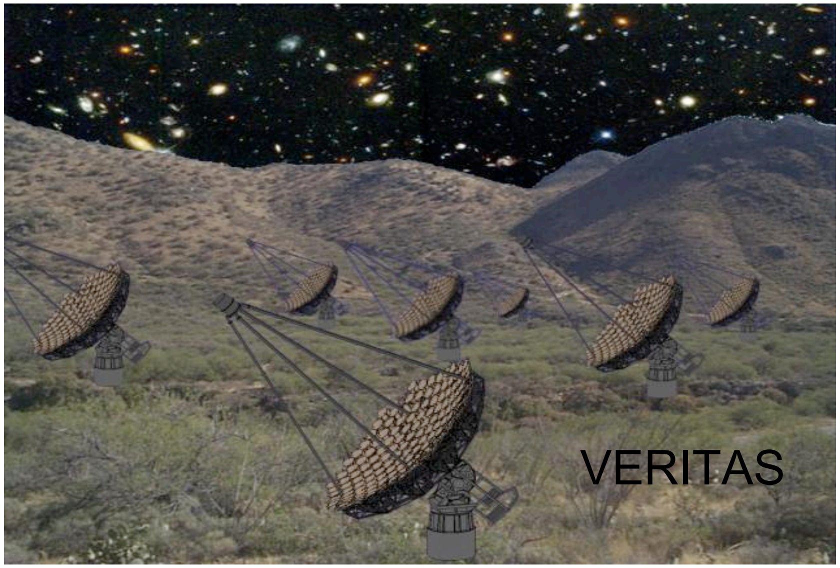
Cherenkov Telescopes

← Water

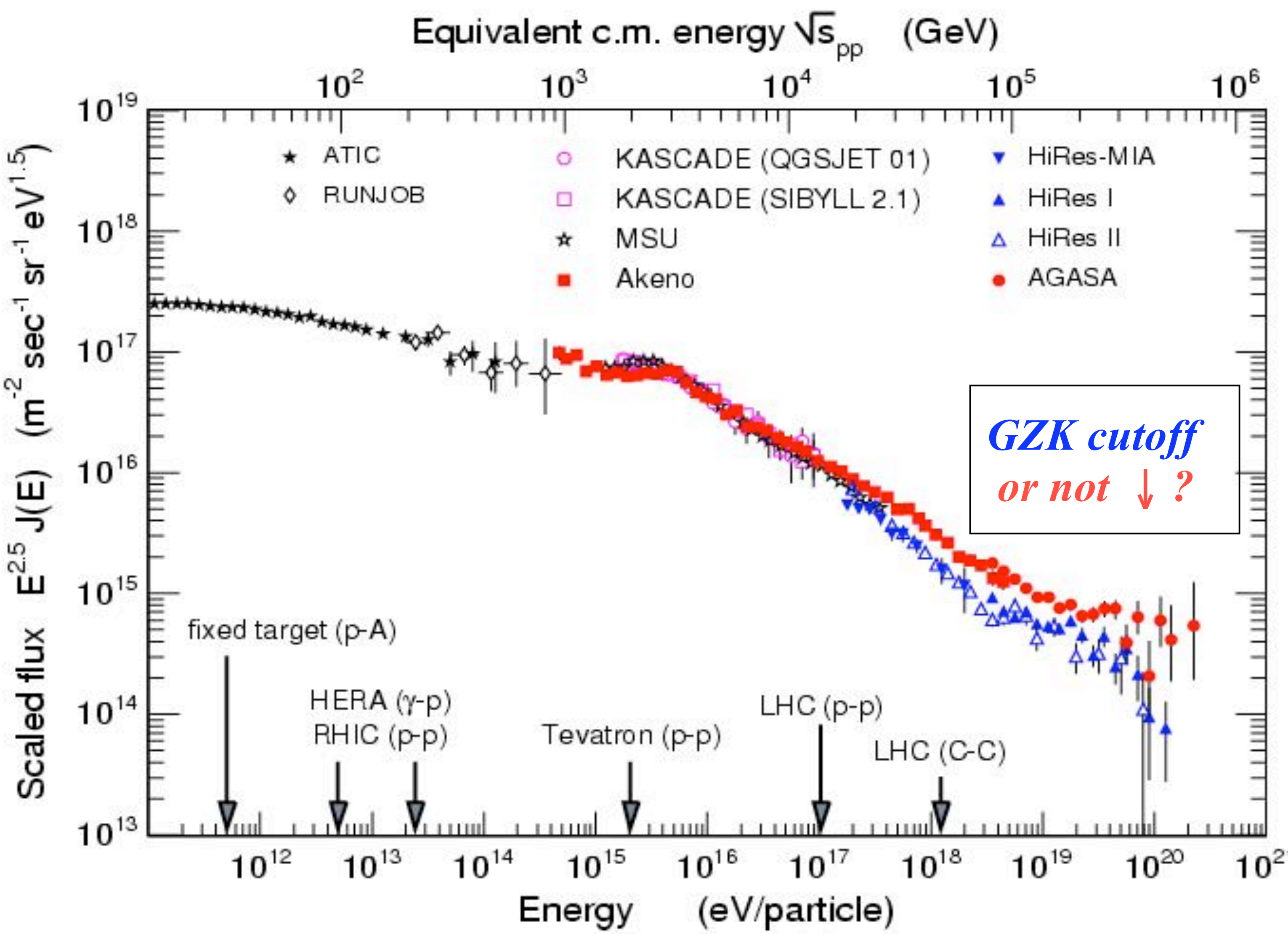
Air →

↓ ↓



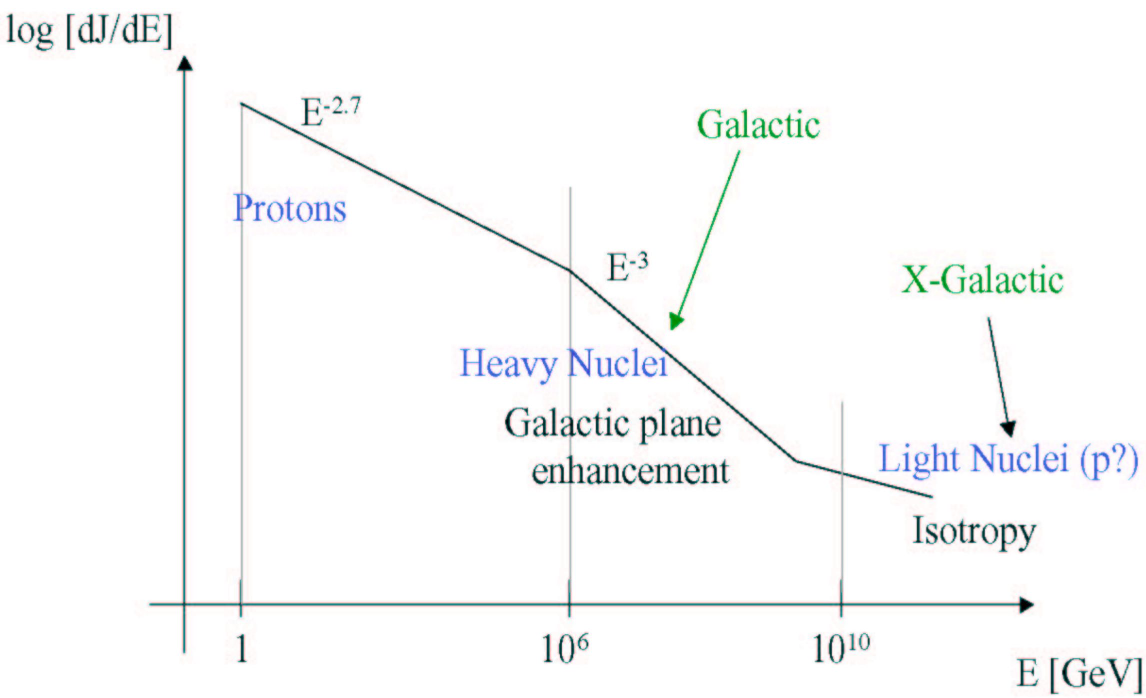


CR spectrum



Mészáros, qcd05

Cosmic ray flux and Composition



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

[Blandford & Eichler, Phys. Rep. 87; Axford, ApJS 94; Nagano & Watson, Rev. Mod. Phys. 00] [Slides: Waxman 04]

Acceleration to 10^{21}eV?

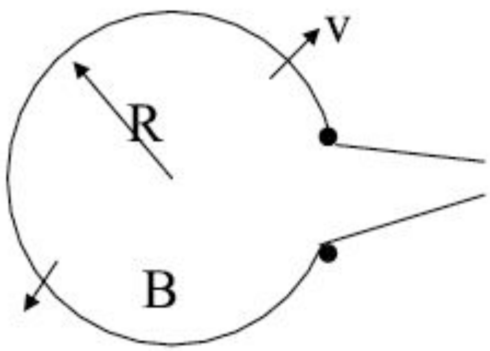
~10^2 Joules

~ 0.01 M_{GUT}

dense regions with exceptional gravitational force creating relativistic flows of charged particles, e.g.

- **Active galactic nuclei (AGN), blazars**
- **Gamma Ray Bursts**

CR acceleration



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

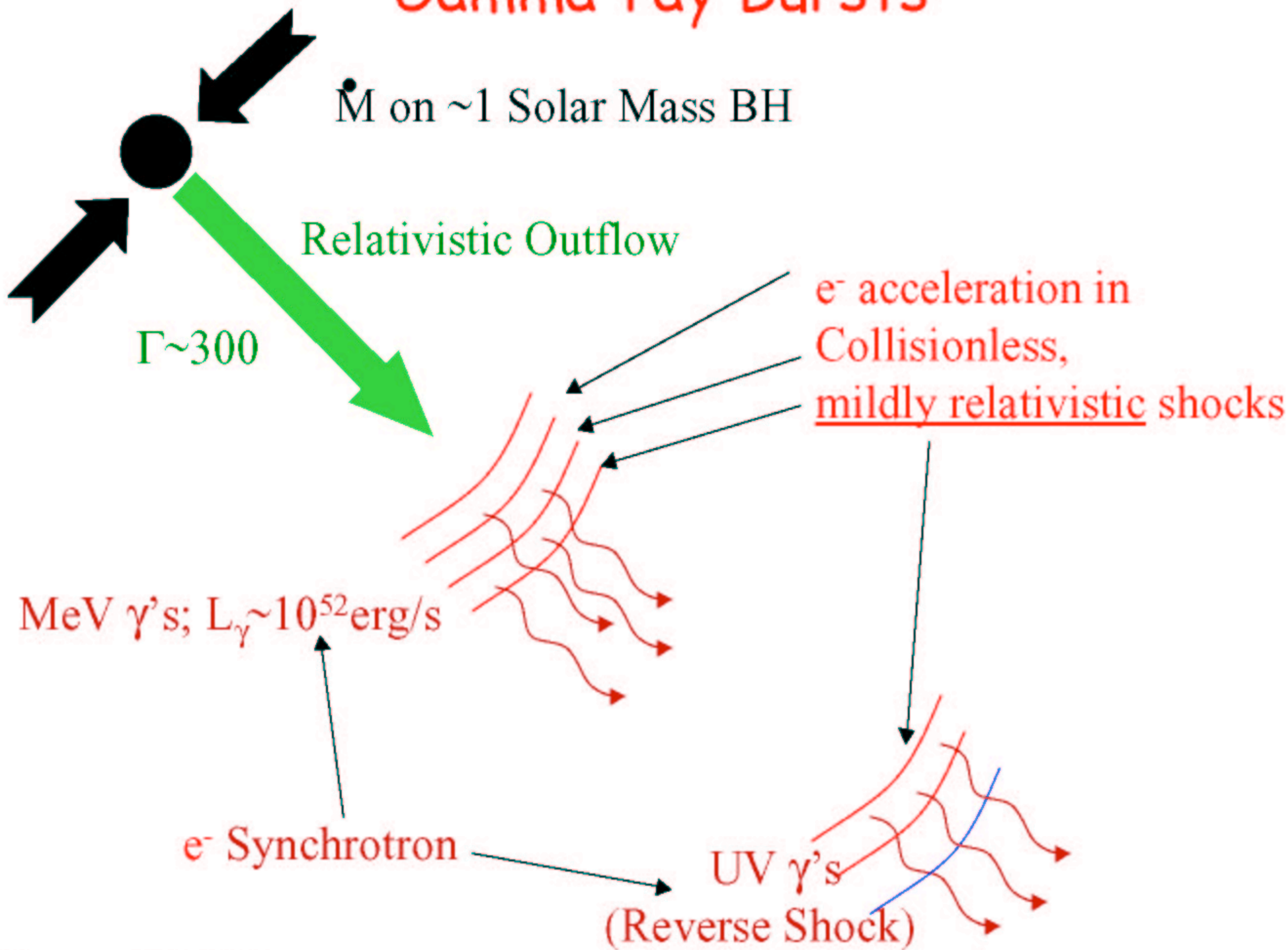
$$\rightarrow \varepsilon_p < \beta e B R$$

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

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

Mészáros, qcd05

Gamma-ray Bursts



[Meszaros, ARA&A 02]

p^+/e^- acceleration in GRB

Protons

- Acceleration:

$$u_B / u_e > 0.02\, \varepsilon^2_{p,20} L^{-1}_{\gamma,52}$$

- Energy loss:

$$\Gamma > 10^2\, \varepsilon^{3/4}_{p,20}$$

Electrons

- MeV γ's, efficiency:

$$u_B / u_e \approx u_e / u_{\rm Internal} > 0.1$$

- Pair production:

$$\Gamma > 10^{2.5}$$

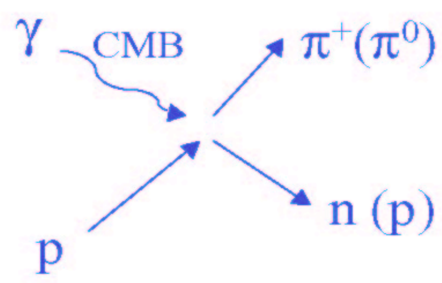
[Waxman 95]

Afterglow ⟶ z distribution

$$L_\gamma \approx 10^{51}\,{\rm erg/s} \;\rightarrow\; 10^{52}\,{\rm erg/s}$$

[Frail et al 00]

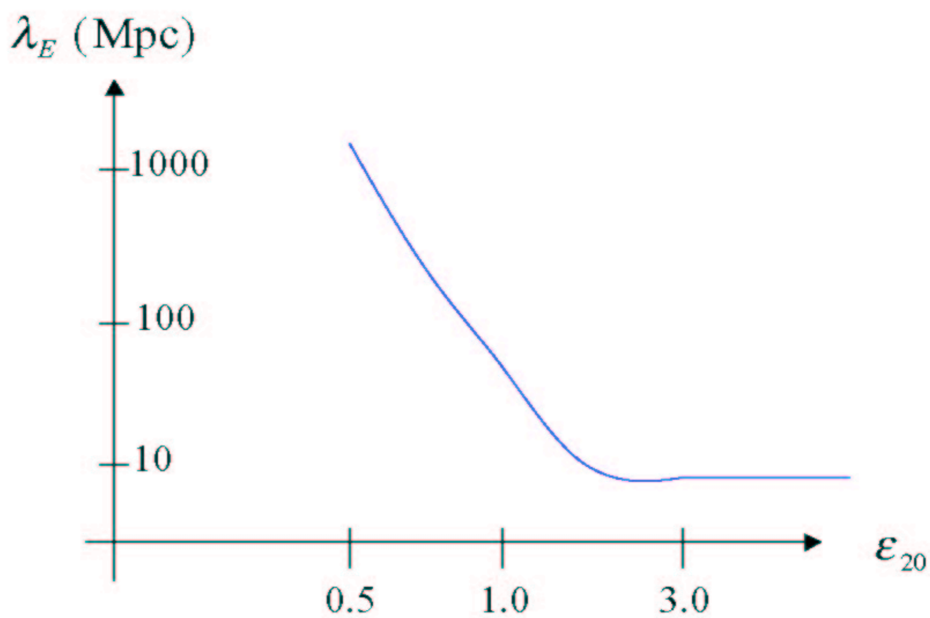
Propagation - GZK radius



$$\varepsilon_\gamma > \frac{m_\pi m_p}{\varepsilon_p} \sim 10^{-3}\varepsilon_{20}^{-1}\ \mathrm{eV} \Rightarrow \quad n_\gamma \sim \frac{400}{\mathrm{cm}^3}\exp\left[1-\frac{3}{\varepsilon_{20}}\right]$$

$$\lambda_E \sim \frac{m_p}{m_\pi}\frac{1}{n_\gamma \sigma_{\gamma p}}$$

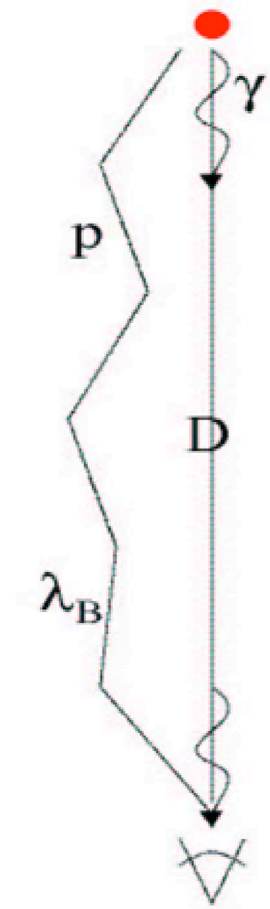
$$\sim 11\exp\left[\frac{3}{\varepsilon_{20}}-1\right] \quad \mathrm{Mpc}$$



[Greisen 66;
Zatsepin & Kuzmin 66]

GZK 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}~3 10^7yr (B/10^{-9} G)^2 (λ_B/10 Mpc)
  (D/100MPC)^2 (E_p/10^{20} eV)$^{-2}$
- N_{GRB}(>E_p, <D) ~ R. t_{disp}
  ~10^4 $B_{-9}^{\ 2}$ λ_{B10} $D_{100}^{\ 2}$ $E_{p20}^{\ 2}$
- GZK event rate: ~ 1 /Km^2 /100 yr) ✓



[Waxman 95]

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

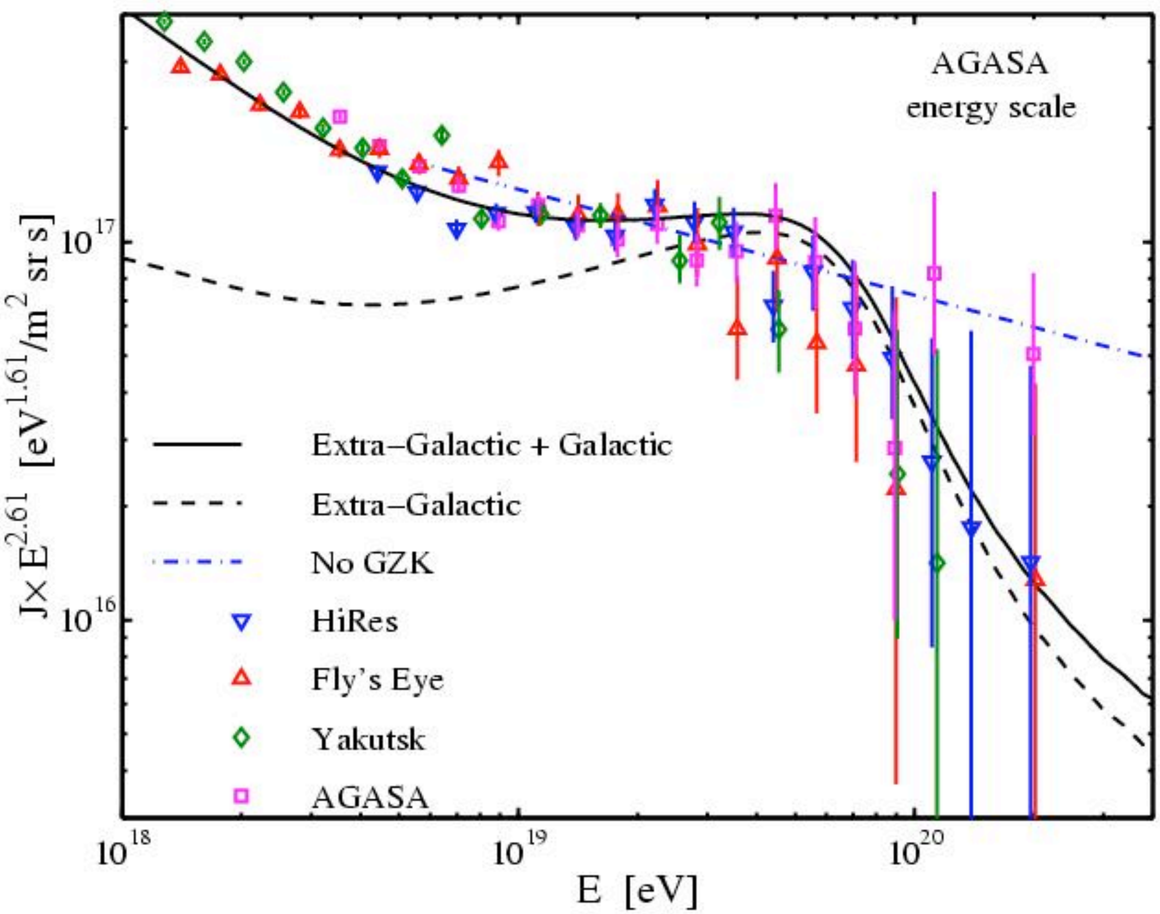
$$\longleftarrow \quad \varepsilon_e^2 \frac{d\dot{n}_e}{d\varepsilon_e} = \frac{30}{\text{Gpc}^3\text{yr}} \times 10^{51}\text{erg} = 0.3 \times 10^{44} \frac{\text{erg}}{\text{Mpc}^3\text{yr}}$$

Afterglow $\longrightarrow$ z distribution

[Frail et al. 01
Schmidt 01]

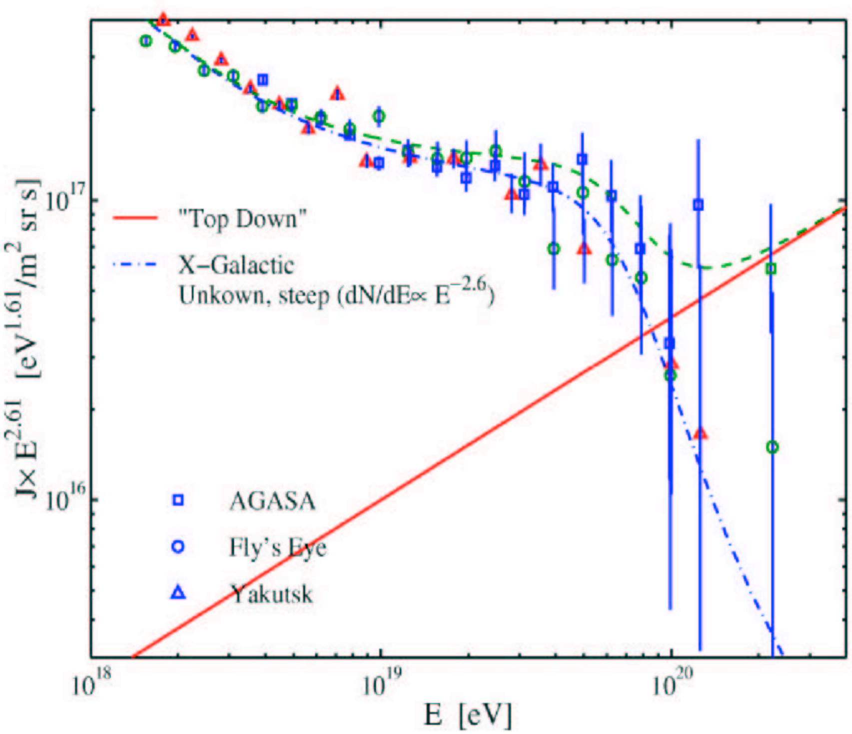
$$\varepsilon_e^2 \frac{dn_e}{d\varepsilon_e} = \frac{0.5}{\text{Gpc}^3\text{yr}} \times 500 \times 0.5 \cdot 10^{51}\text{erg} = 1.3 \times 10^{44} \frac{\text{erg}}{\text{Mpc}^3\text{yr}}$$

CR data vs. model



[slide: Waxman 05]

"Top Down" Contribution?



Mészáros, qcd05

$p,\gamma \rightarrow$ 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.: $E_p E_\gamma \sim 0.3$ 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.) $\rightarrow$ **ICECUBE**
- $\rightarrow \pi^0 \rightarrow 2\gamma \rightarrow$ $\gamma\gamma$ cascade $\rightarrow$ **GLAST, ACTs..**

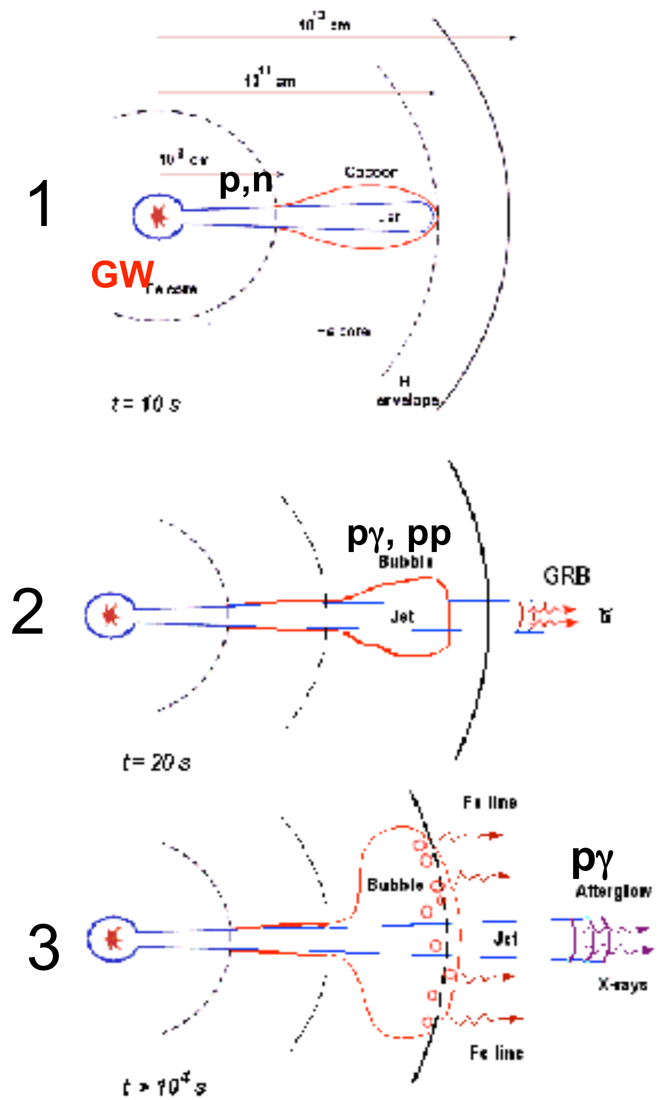
(Waxman-Bahcall 1997;99; Boettcher-Dermer 1998; 00;)

- Test hadronic content of jets (are they pure MHD/$e^\pm$, or baryonic …?)
- 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:

  $\varepsilon_\gamma <$ GeV (internal shock) ; $\varepsilon_\gamma <$ TeV (ext shock/IGM)

  Different $\gamma\gamma$ cut-off due to $\neq$ compactness param. ($\tau_{\gamma\gamma}$, R_{sh})

$\longrightarrow$ **photon cut-off: diagnostic for int. vs. ext-rev shock**



UHE ν (&γ) in GRB

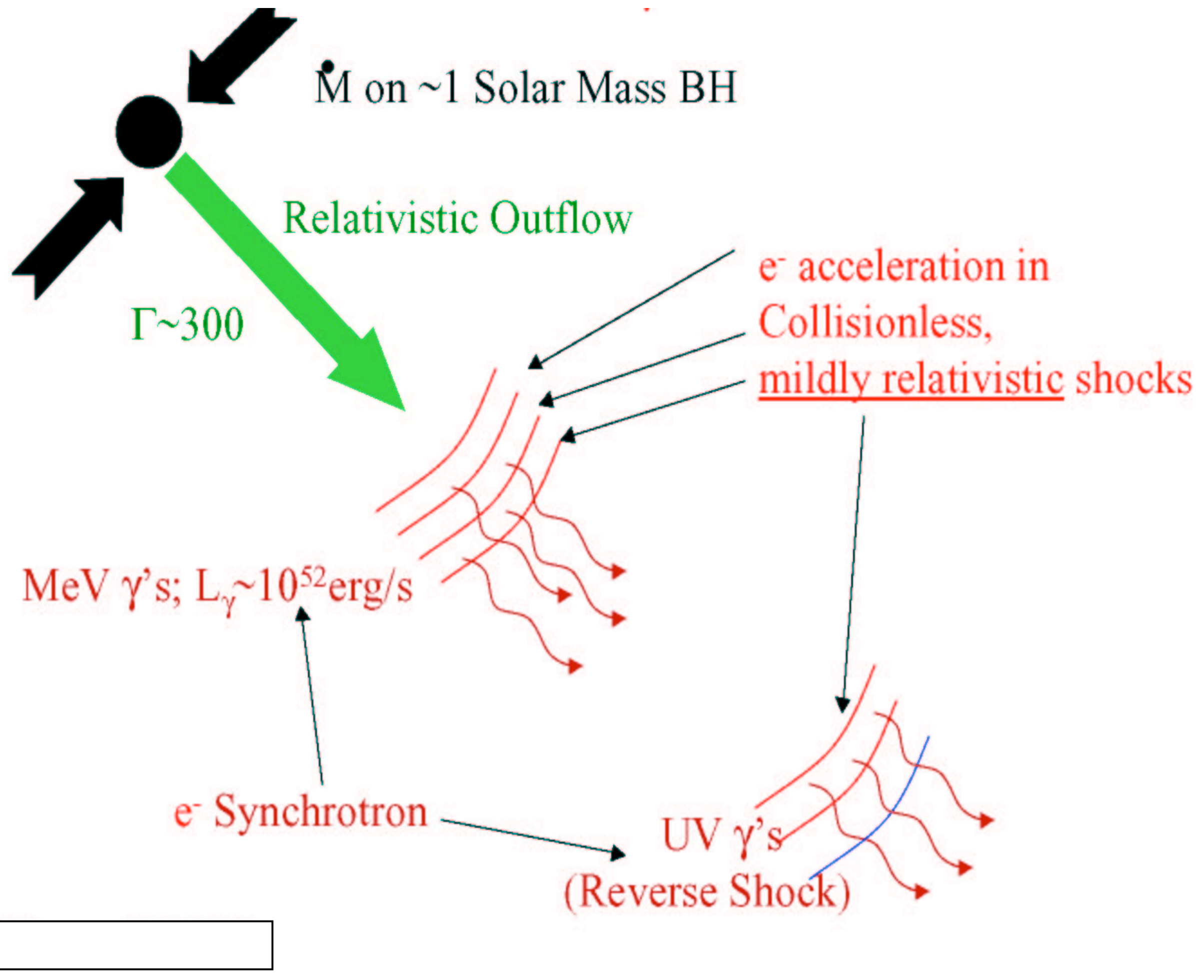
4 possible collapsar-jet sites

- 0) at collapse, make GW + thermal νs
- 1) If jet outflow is baryonic, have p,n
  → p,n relative drift, **pp/pn** collisions
  → inelastic nuclear collisions
  → **VHEν *(GeV)***
- 2) Shocks while jet is inside / can accel. protons → **pγ, pp/pn** collisions
  → **UHEν *(TeV)***
- 3) Shocks outside / accel. protons
  → **pγ** collisions (+pp/pn - if supranova)
  → **UHECR , UHEν, UHEγ**
  (~10^{20} , 10^{14}-10^{18}, ~10^{9} eV)
- 4) ***If*** external beam dump (bin.comp., SNR..)
  → **pγ, pp** of jet protons on shell targets
  → **UHEν (> *TeV*)**

Mészáros, qcd05

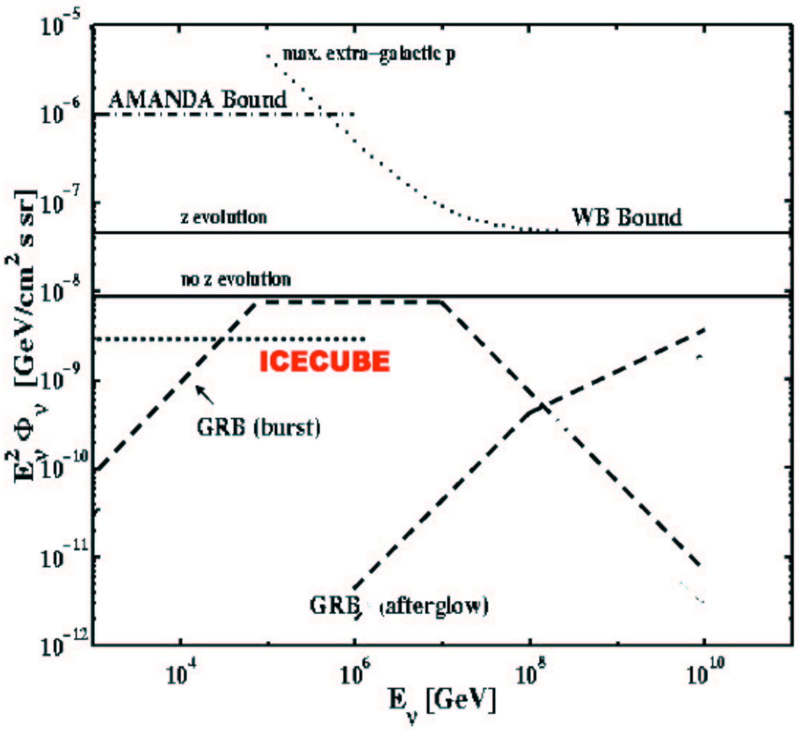
GRB: internal & external shocks

(outside progenitor star)



Mészáros, qcd05

ν from pγ in internal & external shocks in GRB



Waxman, Bahcall 97 PRL

- Shocks accel p^+ as well as e^- → p PL
- **Δ**-res.: $E'_p\,E'_\gamma \sim 0.3\,\mathrm{GeV}^2$ in comoving frame, in lab:

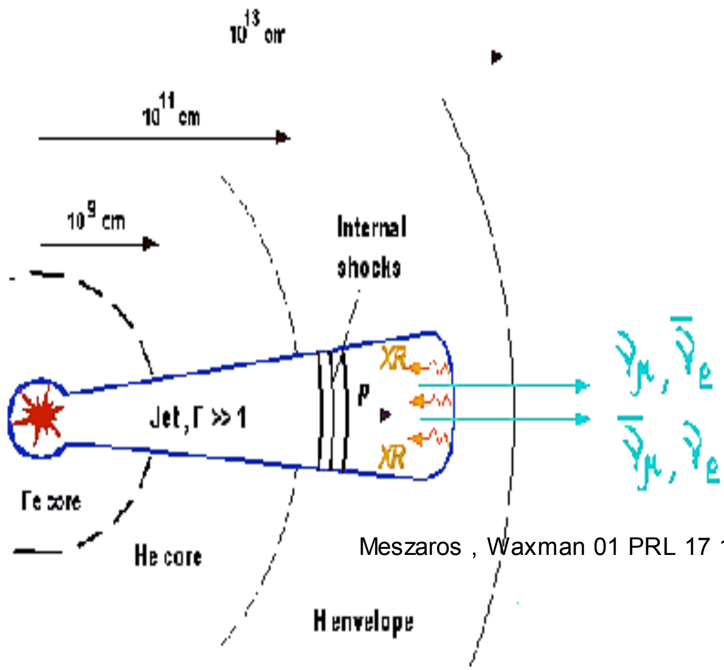
→ $E_p \geq 3\mathrm{x}10^6\,\Gamma_2^{\,2}$ GeV

→ $E_\nu \geq 1.5\mathrm{x}10^2\,\Gamma_2^{\,2}$ TeV

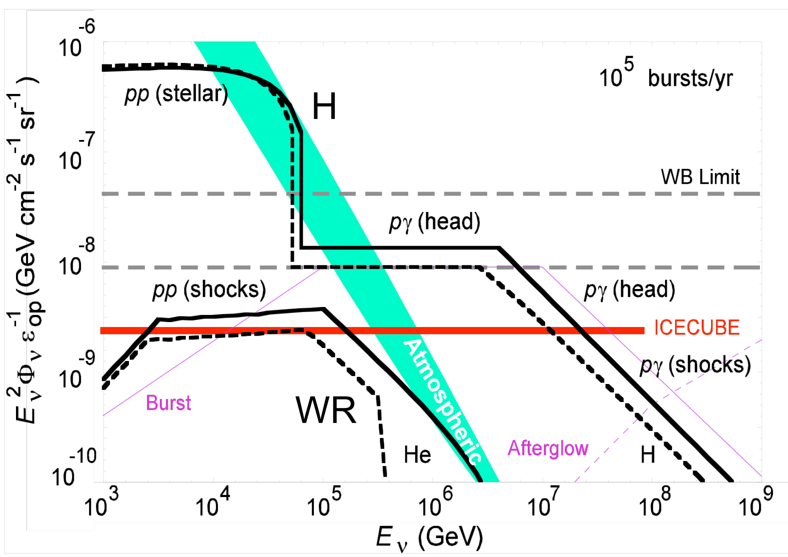
- Internal shock $p\gamma_{MeV}$ → ~100 TeV νs
- External shock $p\gamma_{UV}$ → ~ 0.1-1 EeV ν
- Diffuse flux: det. w. km^3

(2) Jet inside star:

GRB ν,γ Precursor



Meszaros , Waxman 01 PRL 17 1102



Razzaque, PM, EW 03 PRD 68, 3OO1)

- Jet propagating through progenitor, *BEFORE* emerging from stellar envelope, can have int. shocks which accel. p^+ → pγ on unobserved X-rays , → $\pi^\pm$, ν pp, pn on stellar envelope → $\pi^\pm$, ν

  E_ν~ few TeV neutrino precursor
- If progenitor has R_J~10^{12} cm (BSG) → Rate($\nu_{\mu\,,\,TeV}$) prec > Rate($\nu_{\mu\,,\,100\,TeV}$)int.shock (easier to detect in ICECUBE)
- but, if WR, R_J~10^{11} cm → Rate($\nu_{\mu\,,\,TeV}$) prec < Rate($\nu_{\mu\,,\,100\,TeV}$) int.shock → test progen. size (e.g. @ high z : popIII?)
- At jet break-out: → photon flashes

  (Ramirez-Ruiz, McFadyen, Lazzati 02; Waxman, Mészáros 02)

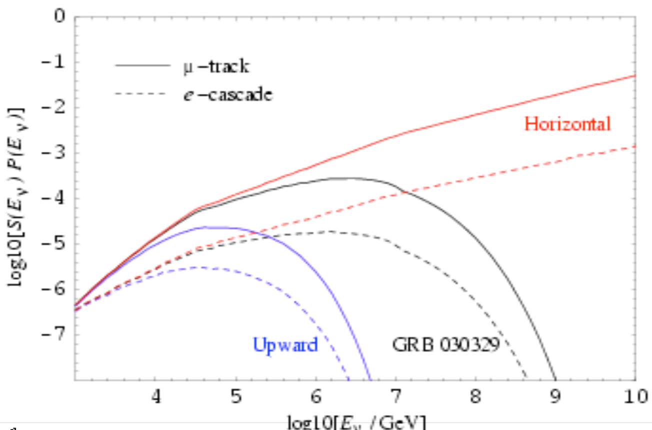
  i) thermal keV γ flash

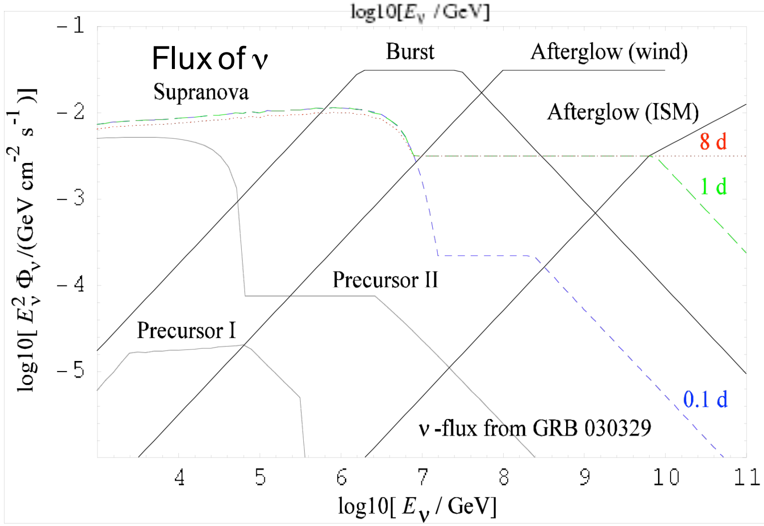
  ii) non-therm.10-100 MeV γ (IC upscatt of XR) → precursors (δ few sec.) of "usual" MeV γ
- Blue: ν- spectrum: E_ν ~ 100 TeV, p,γ→ π,μ,ν from shocks outside star

GRB 030329: SN shell & precursor with ICECUBE

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

Prob.of ν interaction

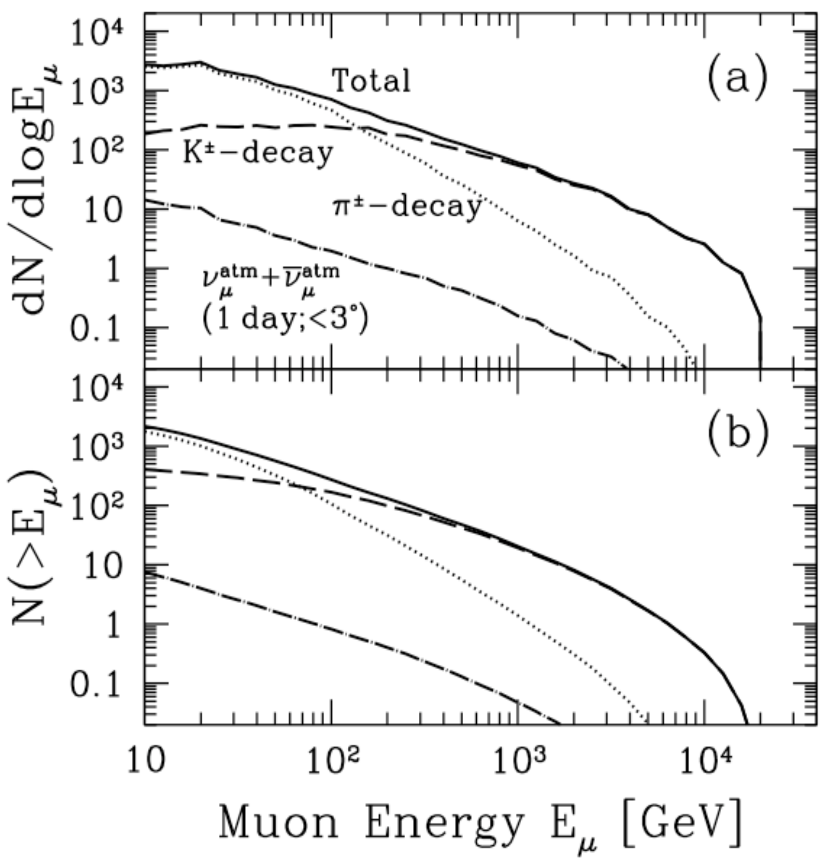




Flux Component	TeV-PeV μ-track	TeV-PeV e-cascade	PeV-EeV μ track	PeV-EeV e-cascade
Precursor I	$9 \cdot 10^{-3}$	$2 \cdot 10^{-3}$	-	-
	$6 \cdot 10^{-3} \uparrow$	$2 \cdot 10^{-3} \uparrow$	-	-
	$0.01 \rightarrow$	$2 \cdot 10^{-3} \rightarrow$	-	-
Precursor II	4.1	1.1	$3 \cdot 10^{-3}$	$2 \cdot 10^{-4}$
	$2.9 \uparrow$	$0.9 \uparrow$	-	-
	$4.4 \rightarrow$	$1.2 \rightarrow$	$0.01 \rightarrow$	$8 \cdot 10^{-4} \rightarrow$
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

Core collapse SN : slow jets?



Razzaque, Mészáros, Waxman '04, PRL 93, 181101;
(err: '05, PRL 94, 9903)
Ando, Beacom (Kaons from pp - astro-ph/0502521)

- 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, pγ→πμ→ ν_μ (*TeV*)
- **Diffuse flux: might be interesting**

  (if 100% SNII make jets),

  but, more interestingly:
- **individual SN** in nearby (2-3 Mpc) gals, e.g. M82, NGC253,

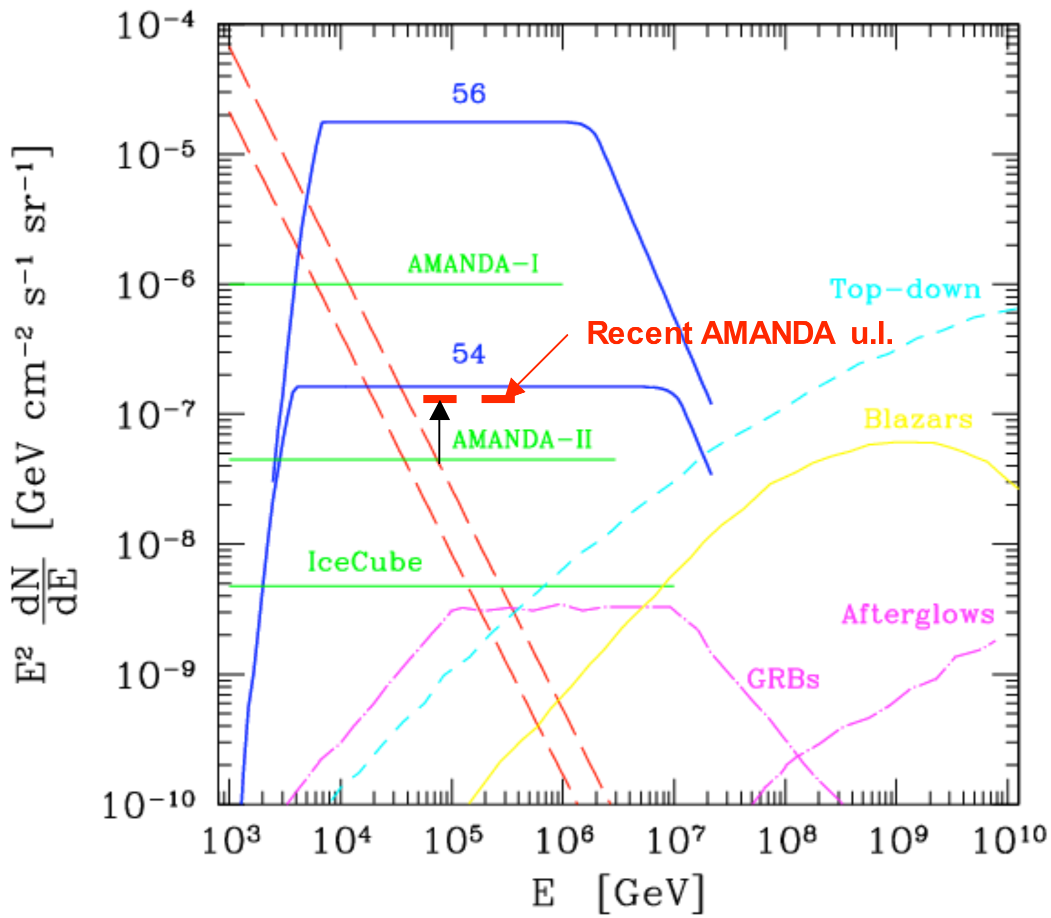
  → ***detectable*** (if have slow jets),

  at a rate ~ 1 SN/few yr,

  fluence ~ 100 up-muons/SN,

  negligible background, in km^3 detectors - **ICECUBE, KM3NeT**

Diffuse UHE ν from pop.III



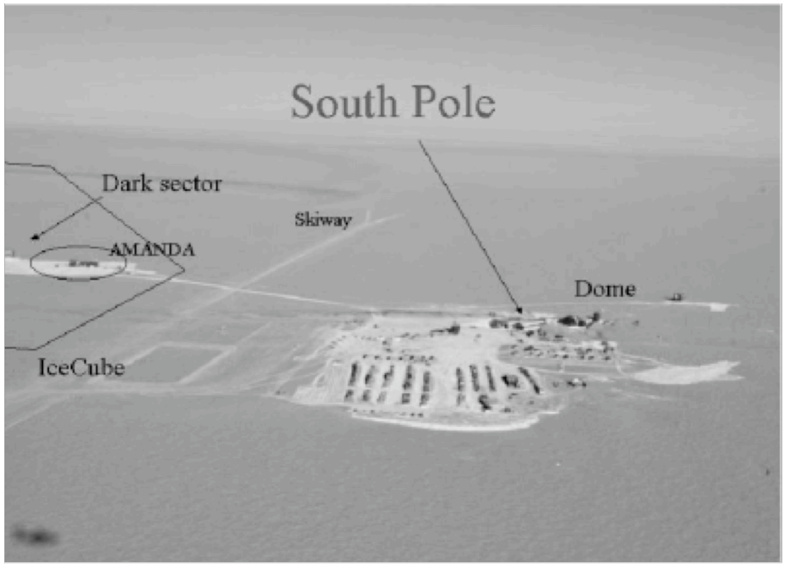
- At z~5-30(?) pop.III , M~ 30-300 M$_\odot$, core coll →BH+ accr.
- Buried jets→pγ→ ν_μ , → ν-bursts (but: dep. on stellar rot.rate)
- E_{iso}~10^{54}-10^{56} (?) erg (dep. on BH mass, dM/dt)
- Detect high z star formation, primordial IMF
- **Recent (8/04) :** can constrain w. **AMANDA** latest results:

→ E_{iso}~10^{56} erg only for ≤1%,

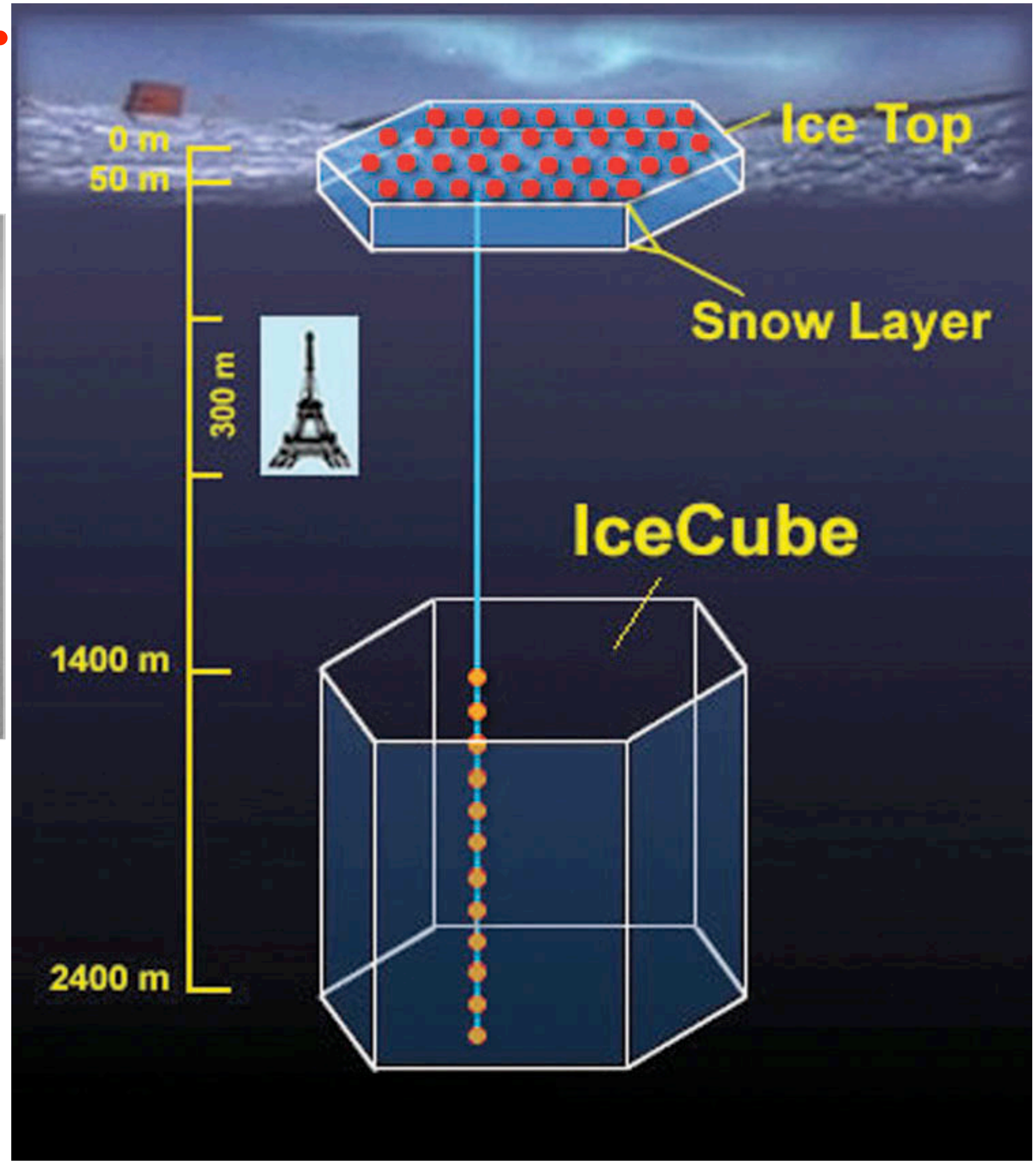
→ E_{iso}≥10^{54} erg for ≤ 50% !

Schneider, Guetta, Ferrara aph/0201342

ICECUBE: km^3

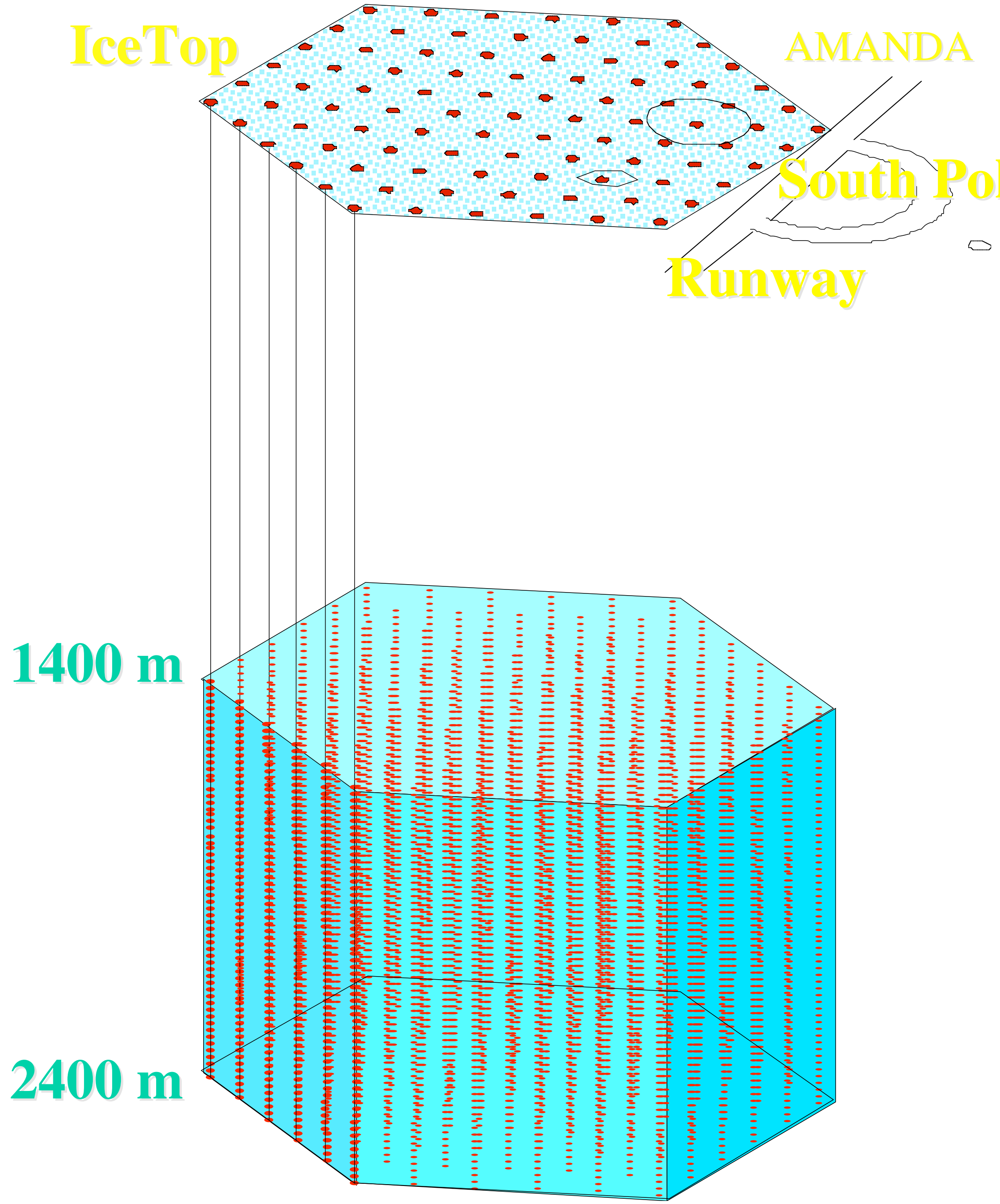


- Extension of Amanda
  0.05 km^3 → km^3=1Gton
- Amanda gave proof of concept, useful science results.
- IceCube funding in place, 1st new string beyond Amanda already installed.
- Completion by 2010



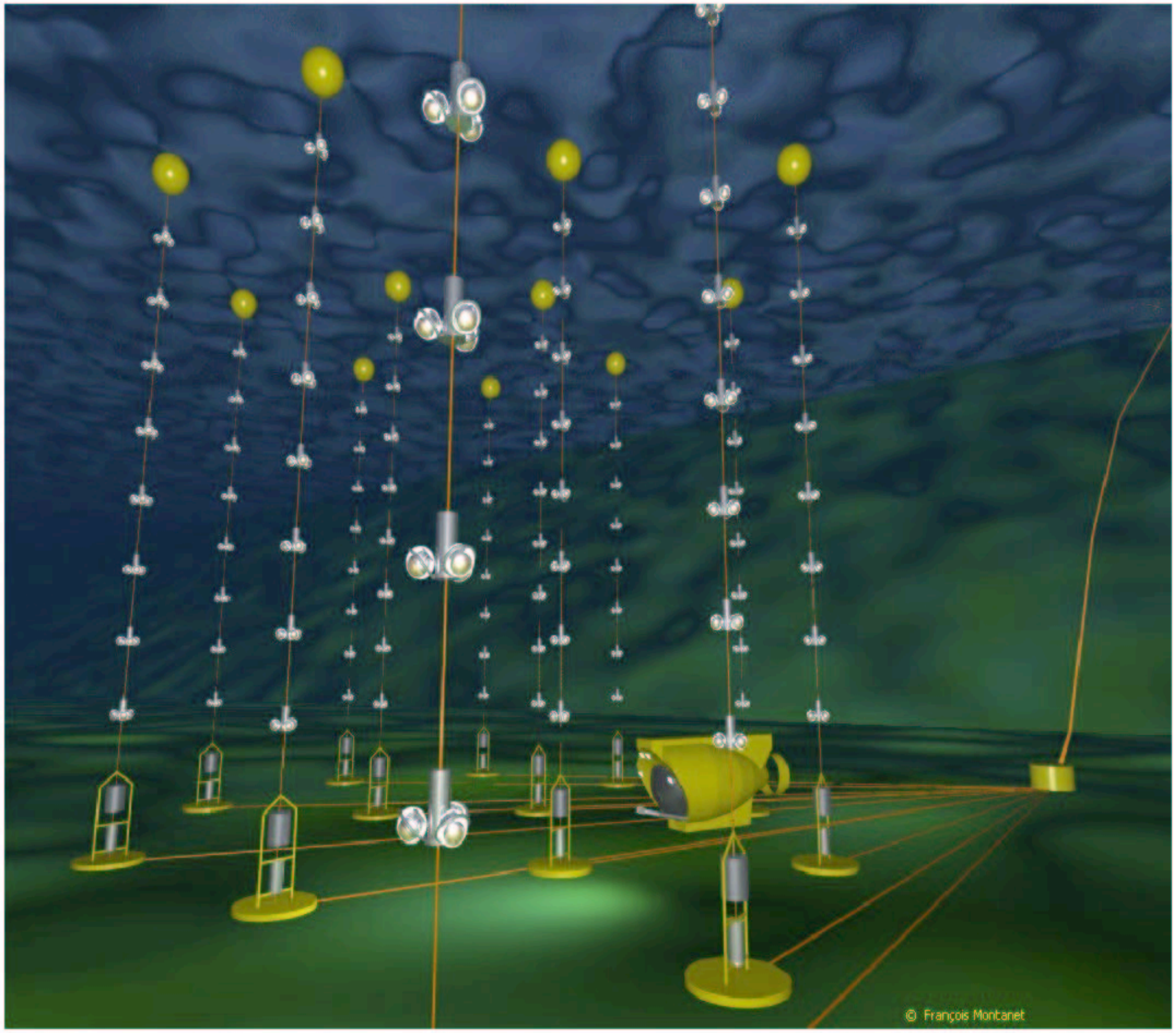
IceCube

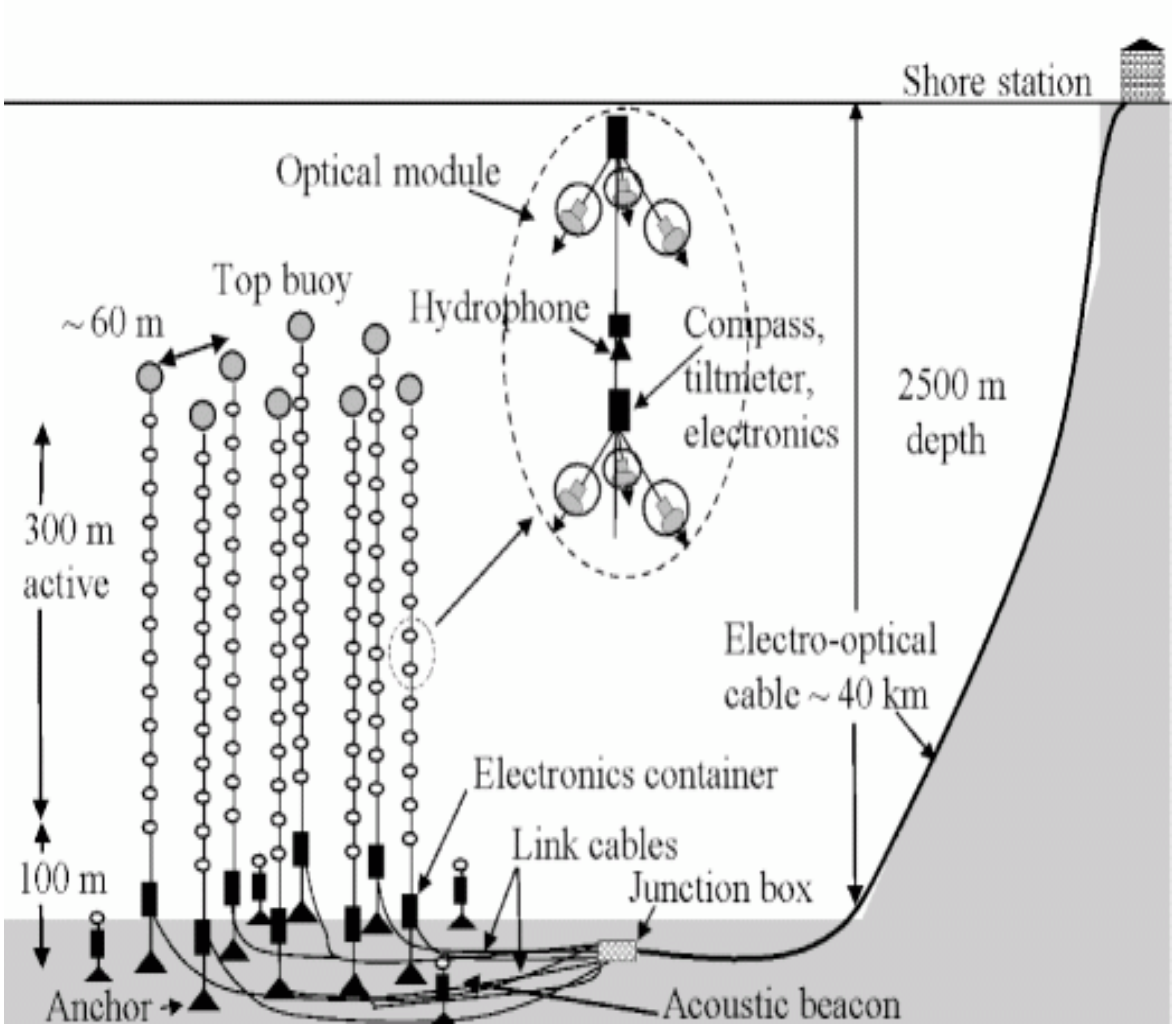
- **80 Strings**
- **4800 PMT**
- **Instrumented volume: 1 km3 (1 Gton)**
- **IceCube is designed to detect neutrinos of all flavors at energies from 10^7 eV (SN) to 10^{20} eV**



Mészáros, qcd05

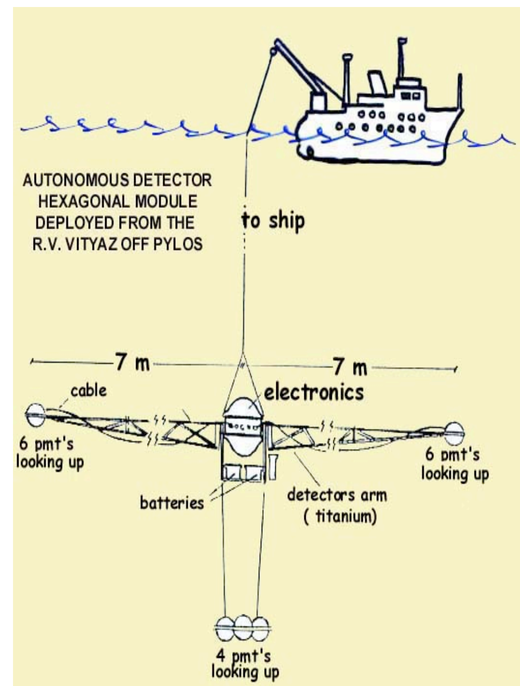
The Mediterranean ANTARES experiment



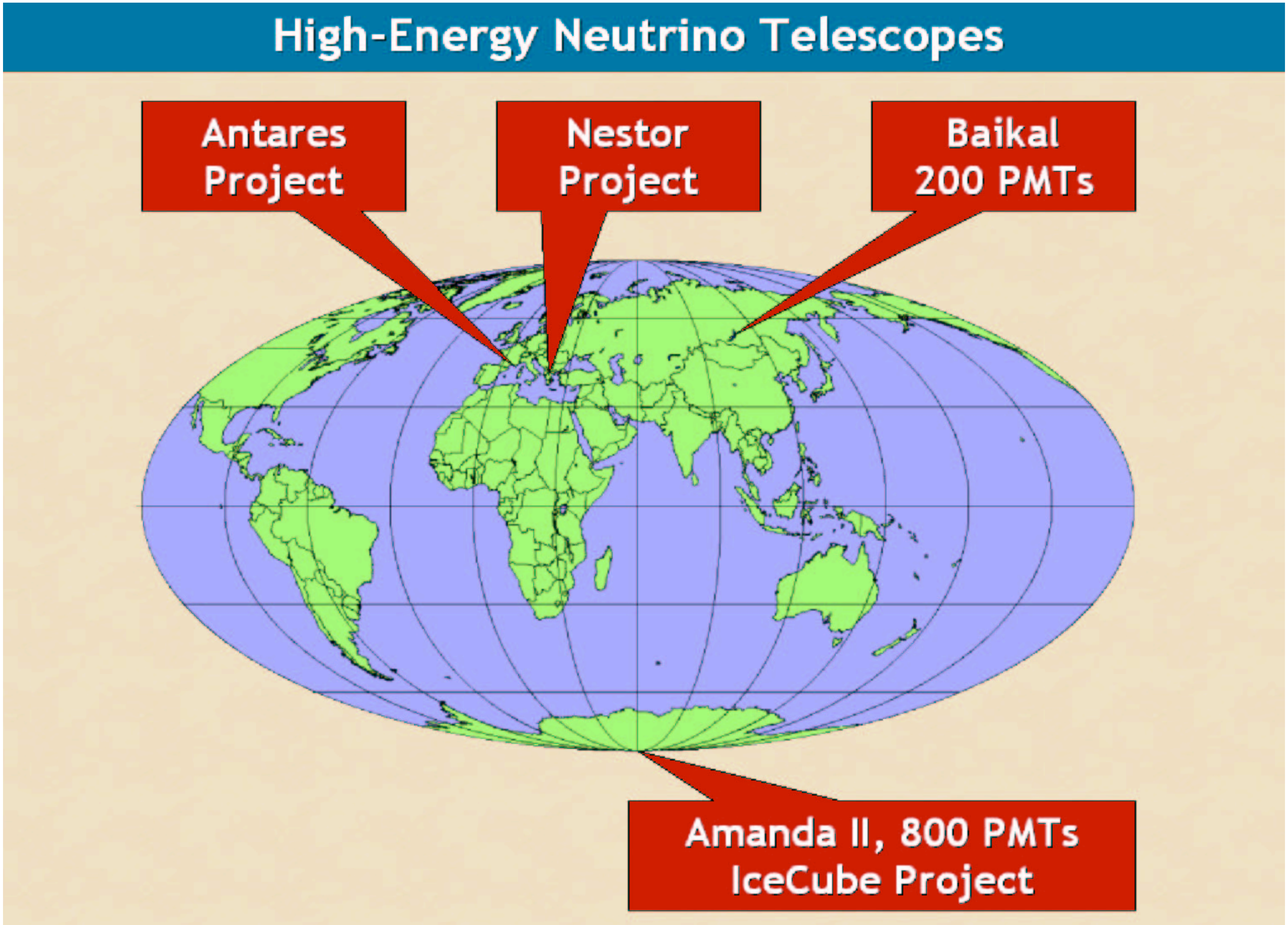


KM3NeT

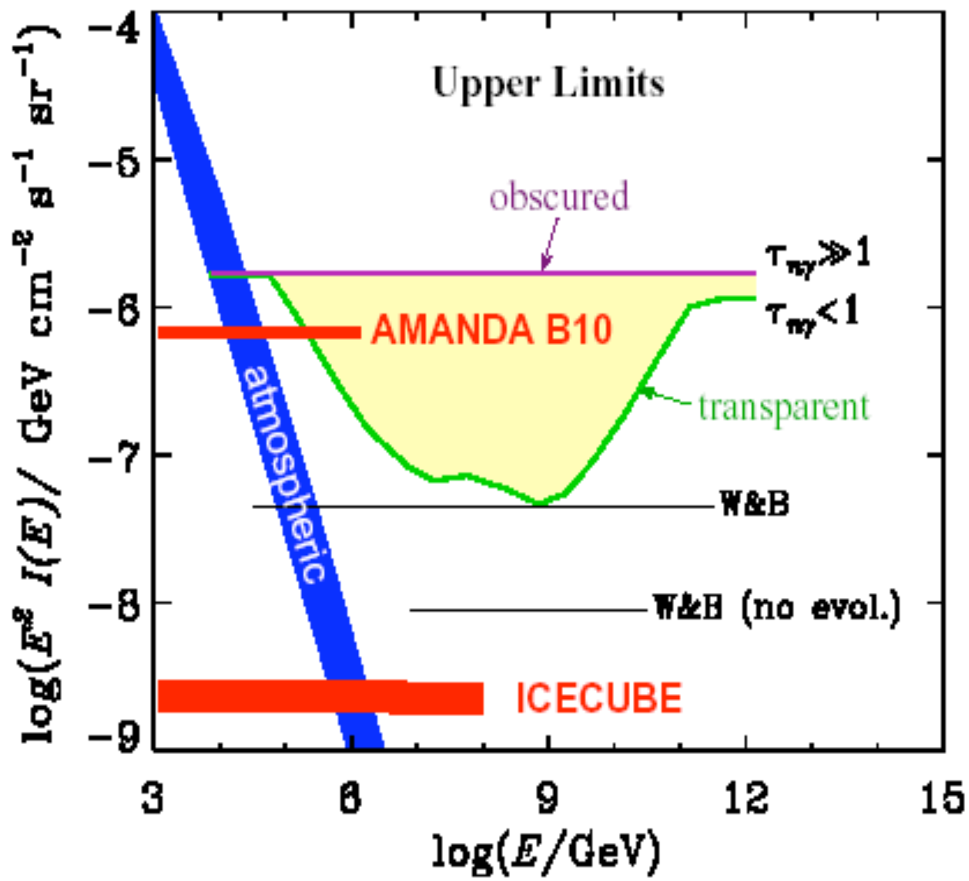
- EU collaboration
- Site :Mediterranean Sea
- based on: **NESTOR, NEMO, ANTARES**



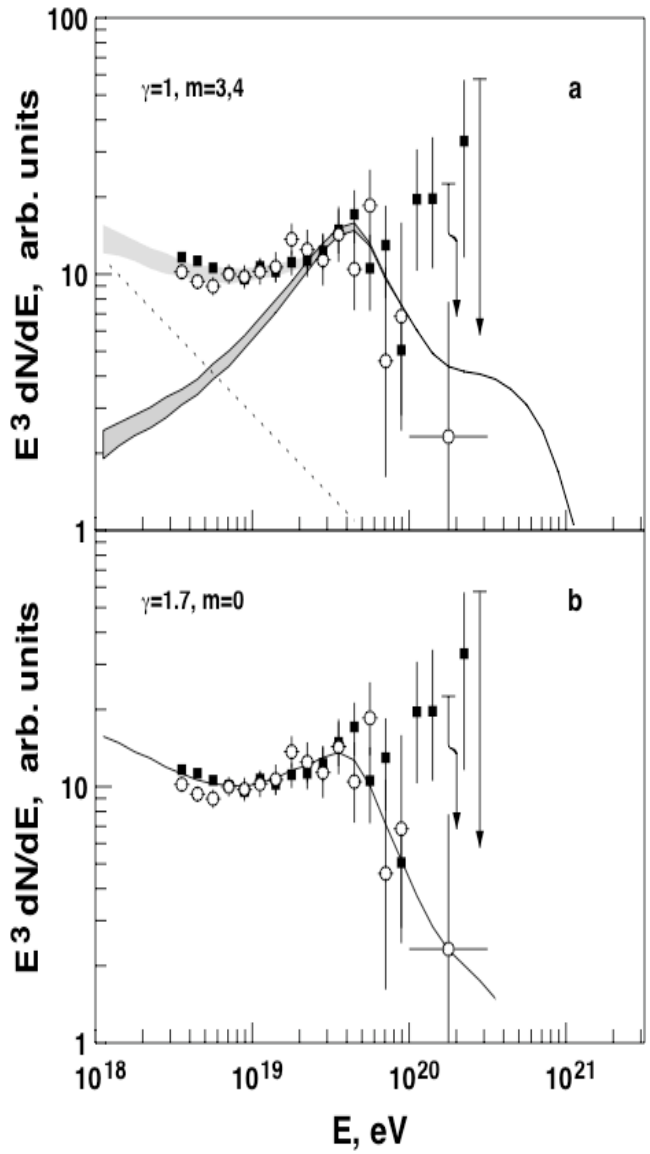
- Km^3 water Cherenkov detector
- Deployment approx. 2010
- Complement ICECUBE: $\lambda_{sc,abs}$~(100,10) H_20, $\lambda_{sc,abs}$~(20,100) Ice
- Northern site: at lower E , complementary sky coverage


High-Energy Neutrino Telescopes
Antares Project
Nestor Project
Baikal 200 PMTs
Amanda II, 800 PMTs IceCube Project

Diffuse UHE ν : CR bound and sensitivity, bckg

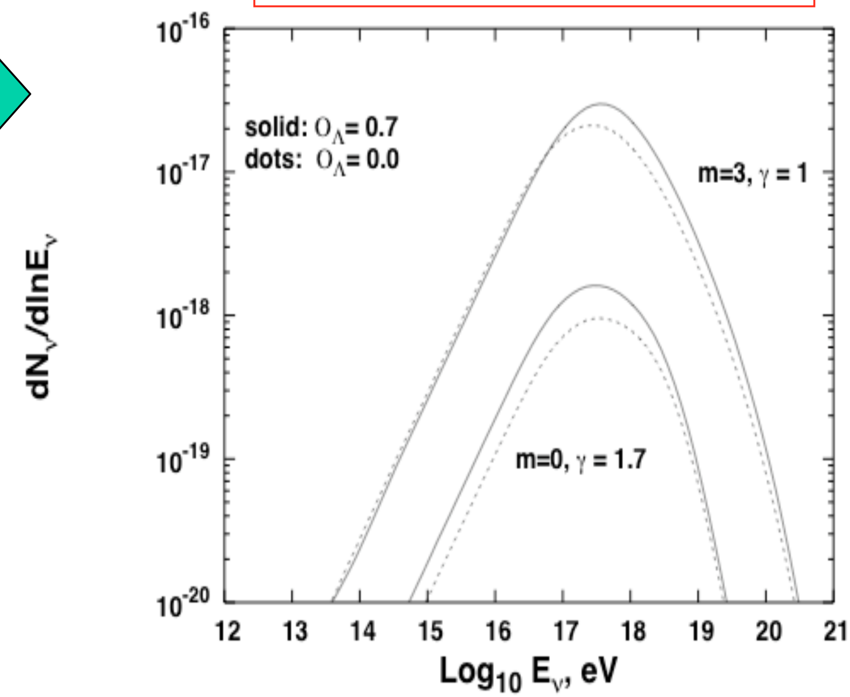


2 ≠ CR models → same GZK fit



from GZK CRs *to* GZK νs

→ ≠ GZK ν flux



Seckel & Stanev astroph/050244

Towards a GZK ν detector

Standard model GZK: Φ_ν: <1 per km^2 per day

Only 1 in 500 interact in ice

[slides courtesy: Silvestri & Saltzberg]

Both **AMANDA-II** or **IceCube** may expect to see 1 event every 2 years in its fiducial volume—
requires astronomical level of patience!

QUESTION:

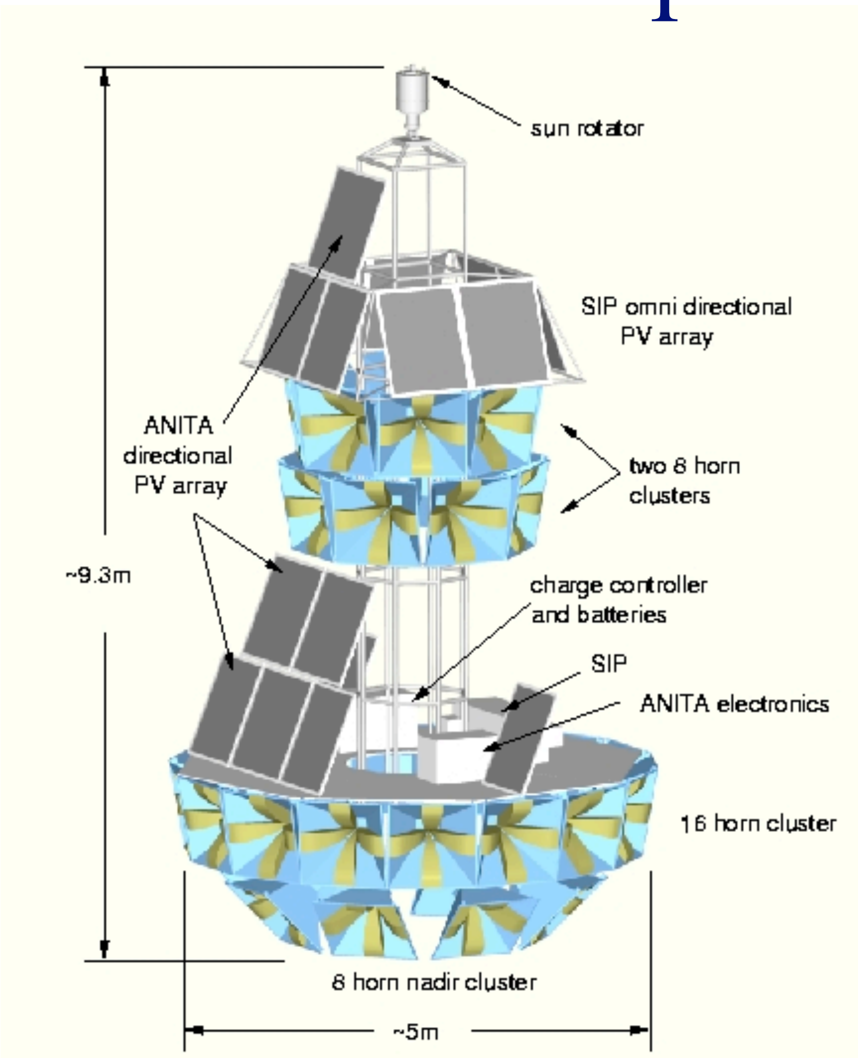
How to get the ~100-1000 km^3 sr yr exposures needed to detect GZK neutrinos at an acceptable rate?

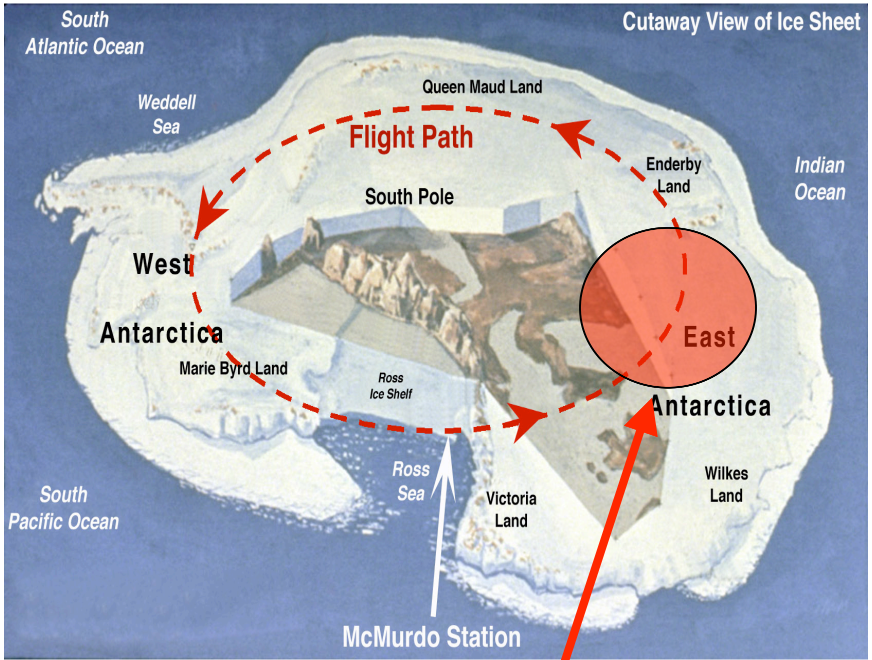
ANSWER

Askaryan process: coherent **radio** Cherenkov emission:

- EM cascades produce a charge asymmetry ➔ radio pulse
- Process is coherent ➔ Quadratic rise of power with cascade energy
- Neutrinos can shower in radio-transparent media:
  - air, ice, rock salt, etc.
  - ➔RF economy of scale very competitive for giant detectors

ANtarctic Impulsive Transient Antenna

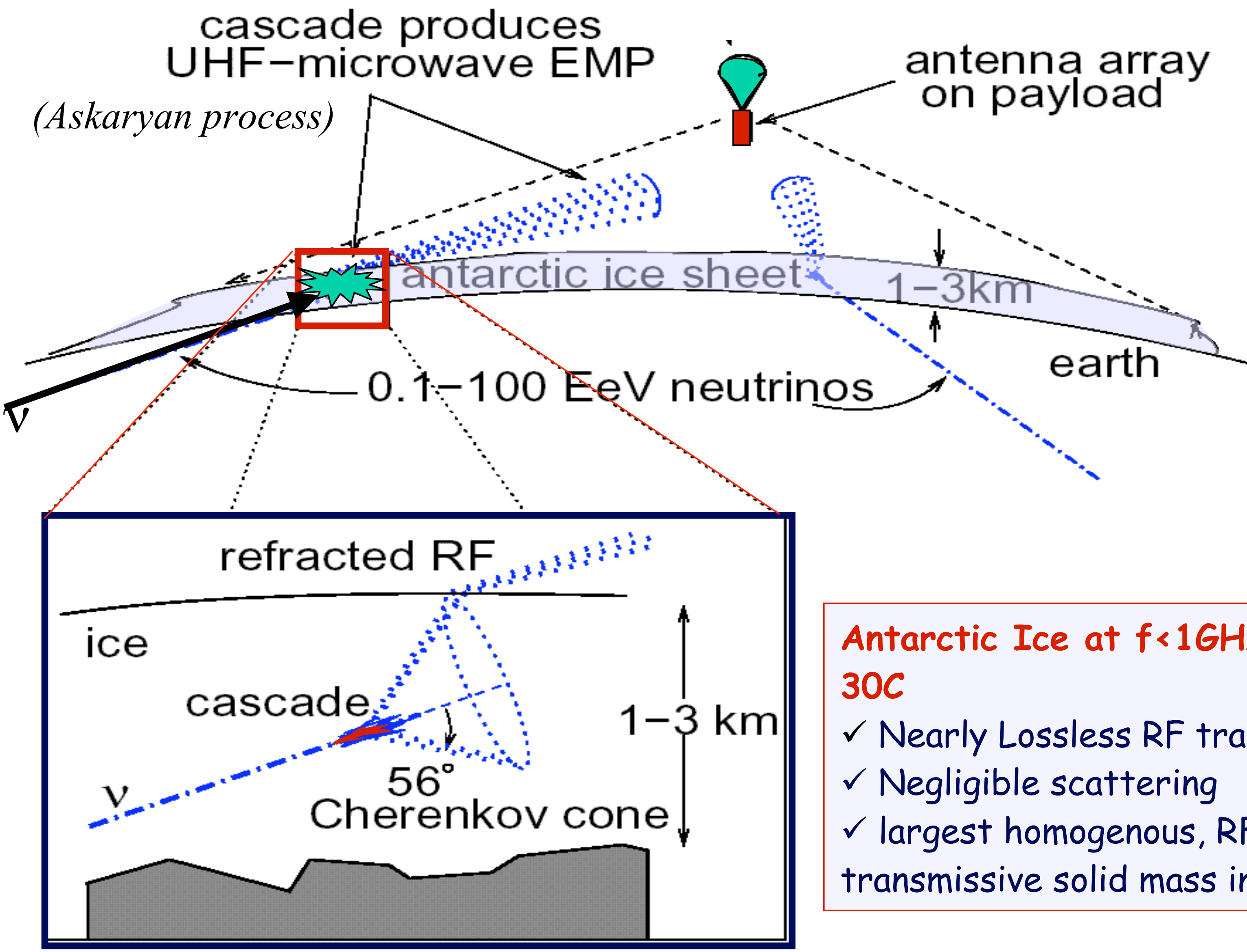




600 km radius,
1.1 million km^2

- NASA funding started 2003 for full launch in 2006
- ANITA-lite succesfully launched & tested Dec 2003

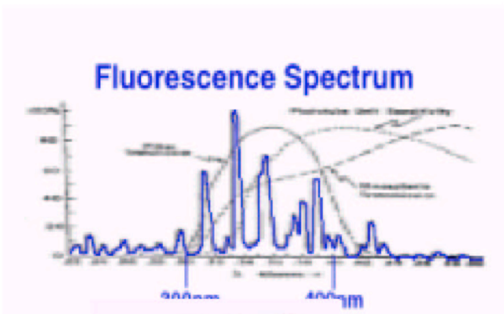
ANITA concept

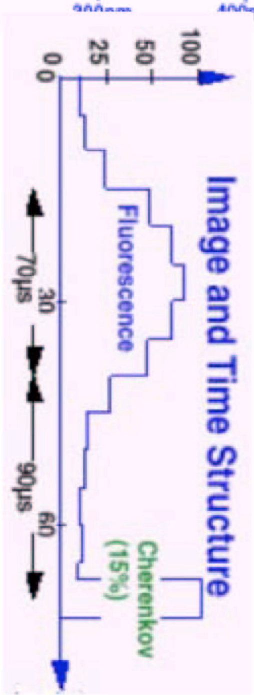


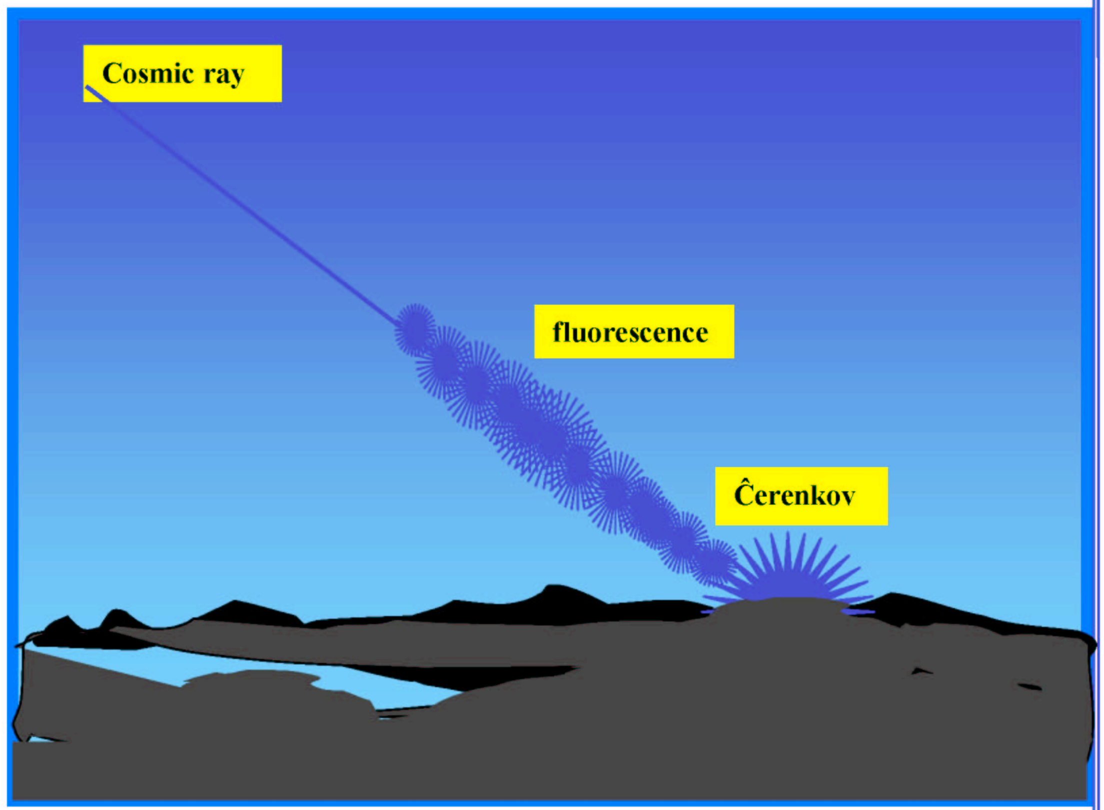
Antarctic Ice at f<1GHz, T<-30C

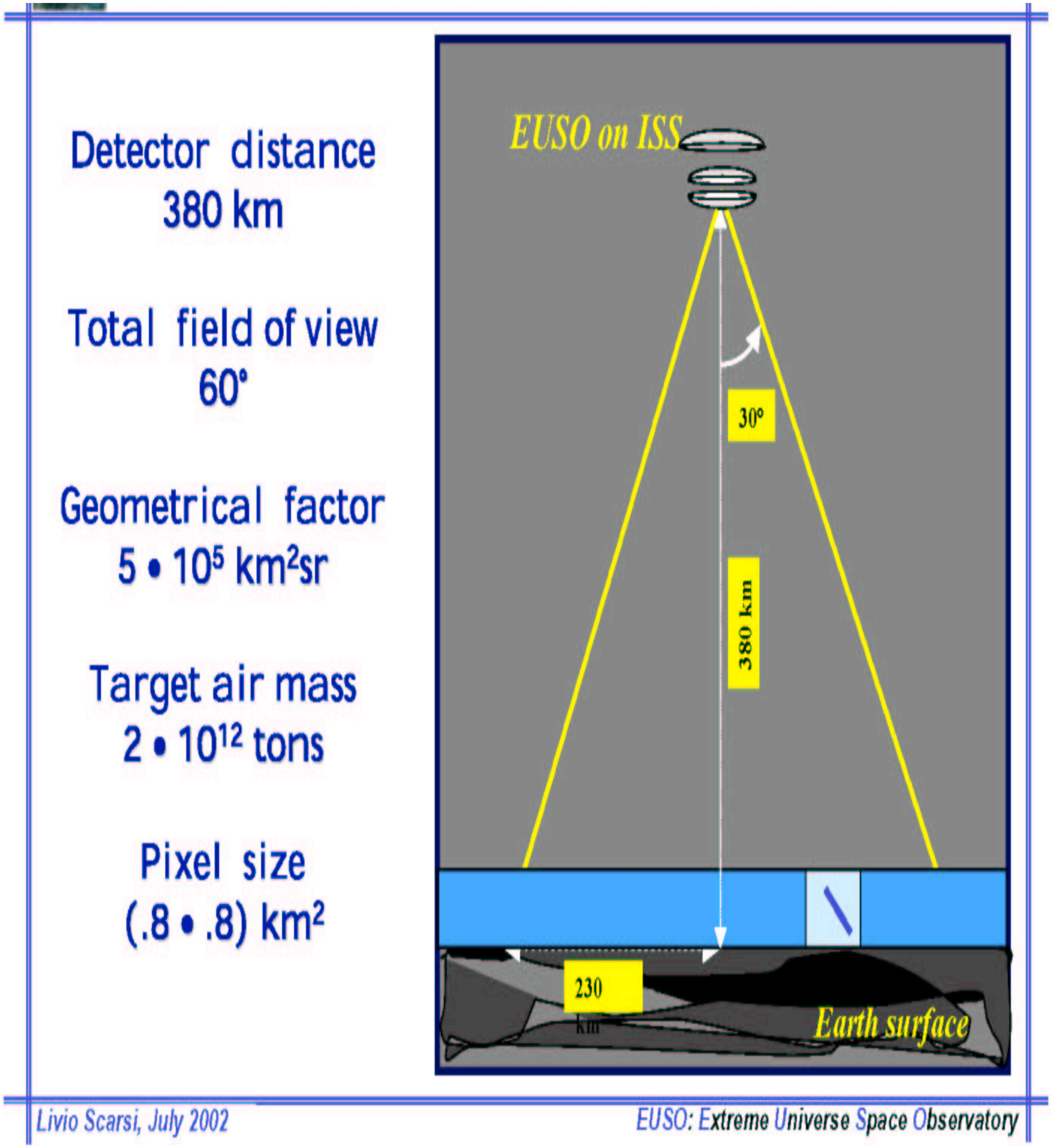
✓ Nearly Lossless RF transmission
✓ Negligible scattering
✓ largest homogenous, RF-transmissive solid mass in the world!

EUSO Approach





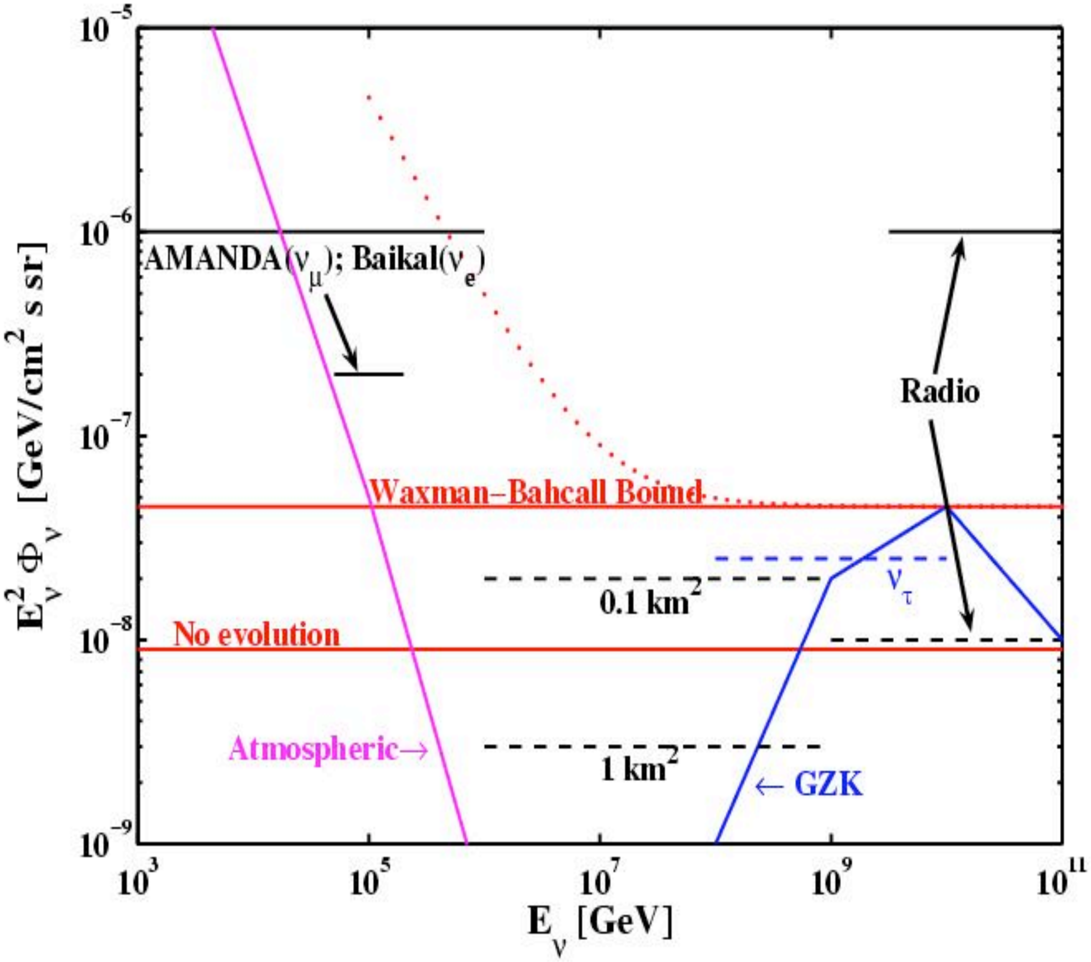




EUSO

- ISS project ESA/NASA/RSA/JSA; precursor for **OWL** (free-flyer)
- $5.10^{19} - 10^{21}$ eV EECRs, EENUs
- Monocular 2.5m Fresnel lens, measure EAS through atm. fluor
- Thresh: 3.10^{19} eV; Effic. @ 10^{20} eV : 300-1000 event/yr
- Launch: 2010-12,
  but: shuttle ?
- Possibly: JSA unmanned shuttle

CR & ν bounds



Mészáros, qcd05

Summary & Prospects

- GRB, XXR, XRF may form a continuum; jet geometry unknown, but unlikely to be very narrow
- Polarization (O, γ?) will provide important clues
- X-ray lines may serve as very high z (<15) distance gauge
- GRB continuum (if present) detectable to z <30
- UHE **γ,ν** will test proton/MHD content of jets, shock accel.physics, magnetic field generation, turbulence
- Probe hadron/EM interactions at ~ TeV-PeV energies
- Investigate stellar evolution & death, star formation rates and large scale structure at redshifts of first objects
- Test strong field gravity, ultrahigh mass/energy densities