Gamma-Ray Bursts

and

GLAST

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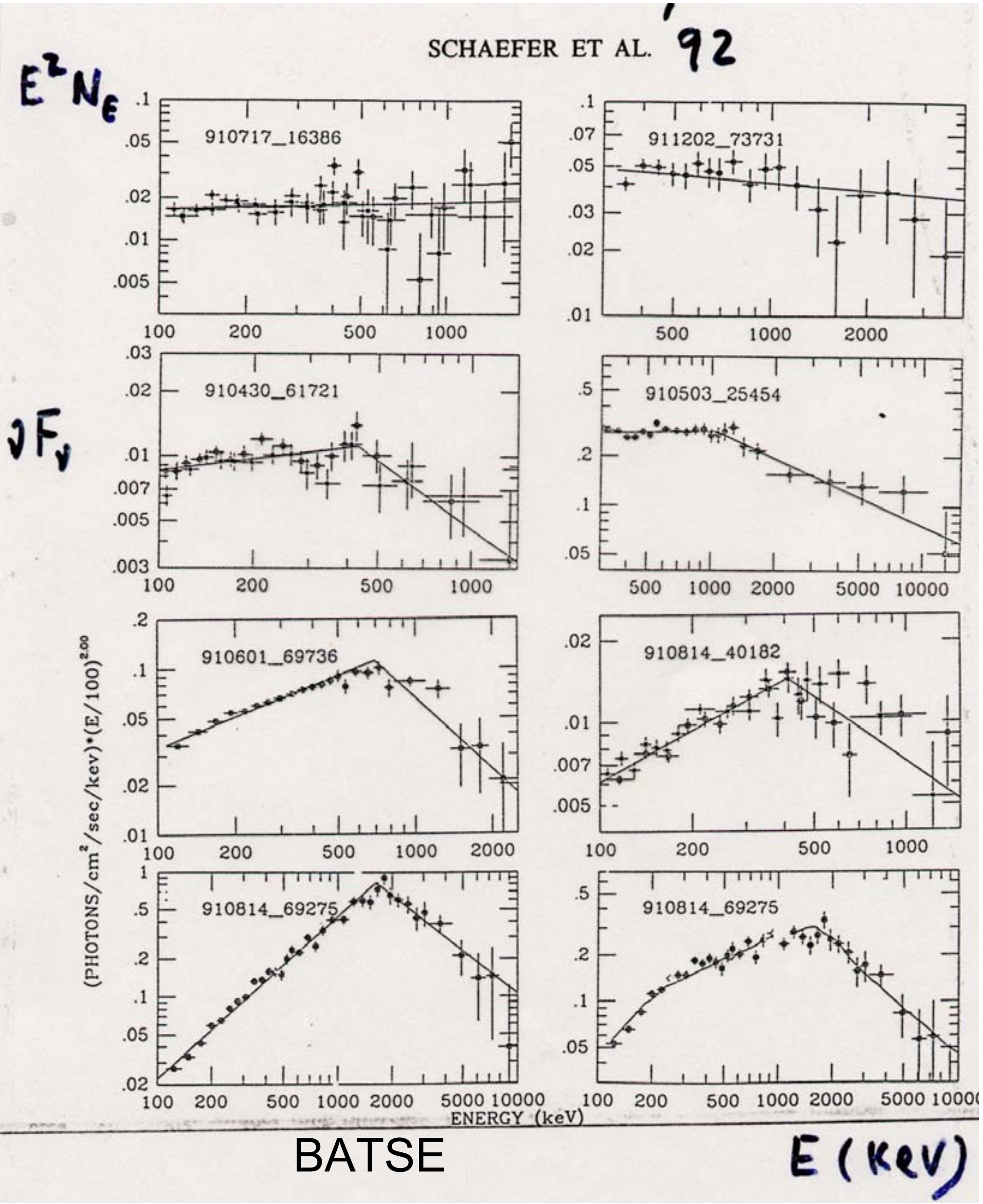
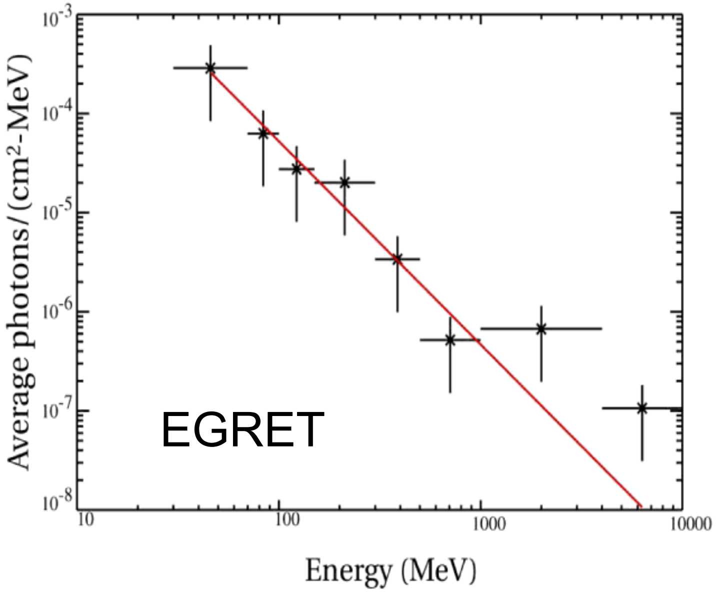
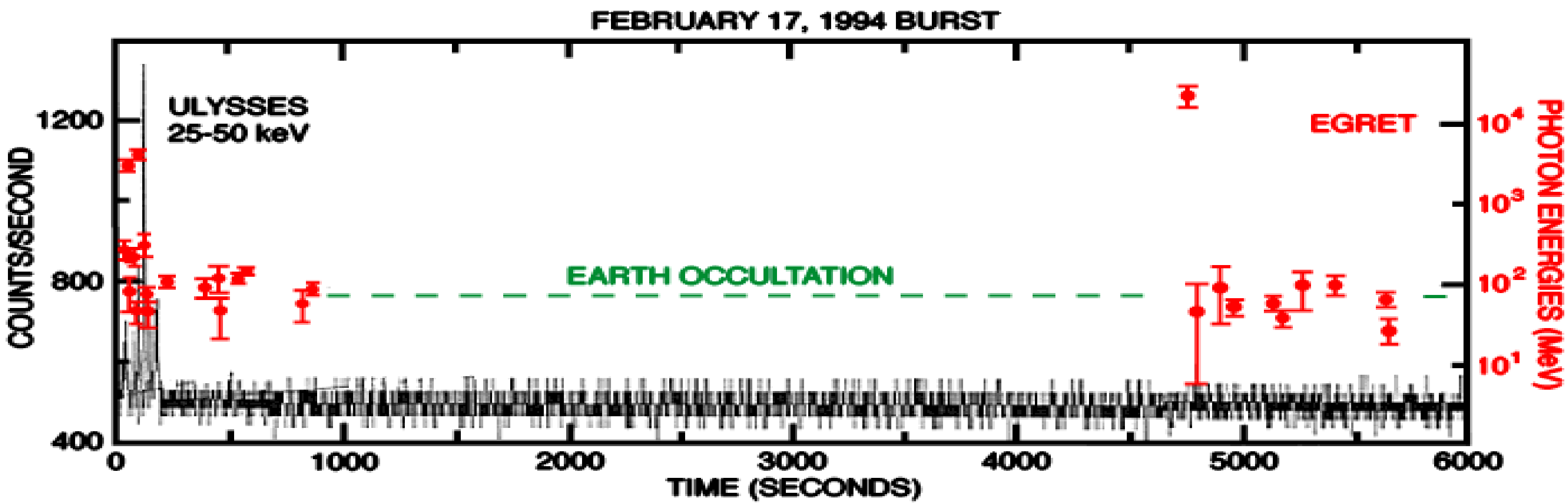
GRB Spectra

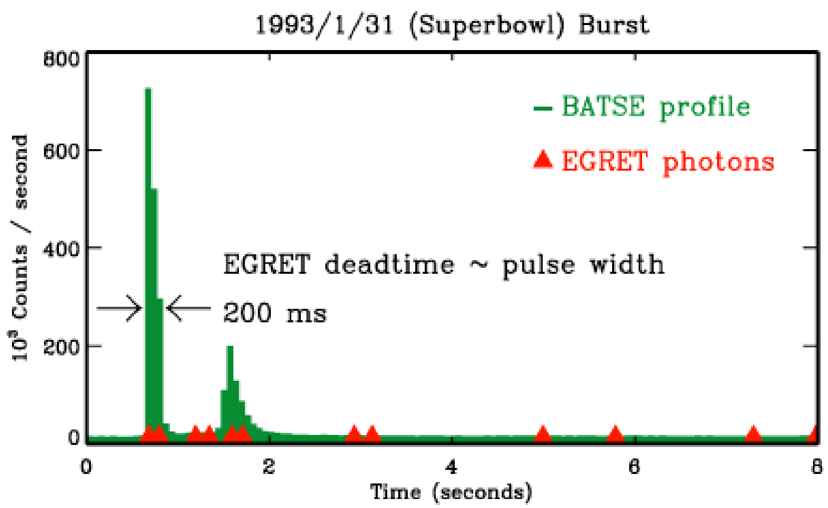




- Spectra are non-thermal (broken PL)
- E_{pk} ~ 0.3 MeV, most energy above it
- Flux extends **>10 GeV** in some GRB

Two EGRET Bursts





- >10 GeV photons can last for > 1 hr,

  start w. MeV trigger
- Considerable energy

  at 100 MeV-10 GeV

GRB: basic numbers

- Distance: $0.35 \lesssim z \lesssim 4.5$ $\rightarrow D \sim 10^{28}$ cm
- Fluence: $F = \int flux.dt$ $\sim 10^{-4} - 10^{-7}$ erg/cm^2

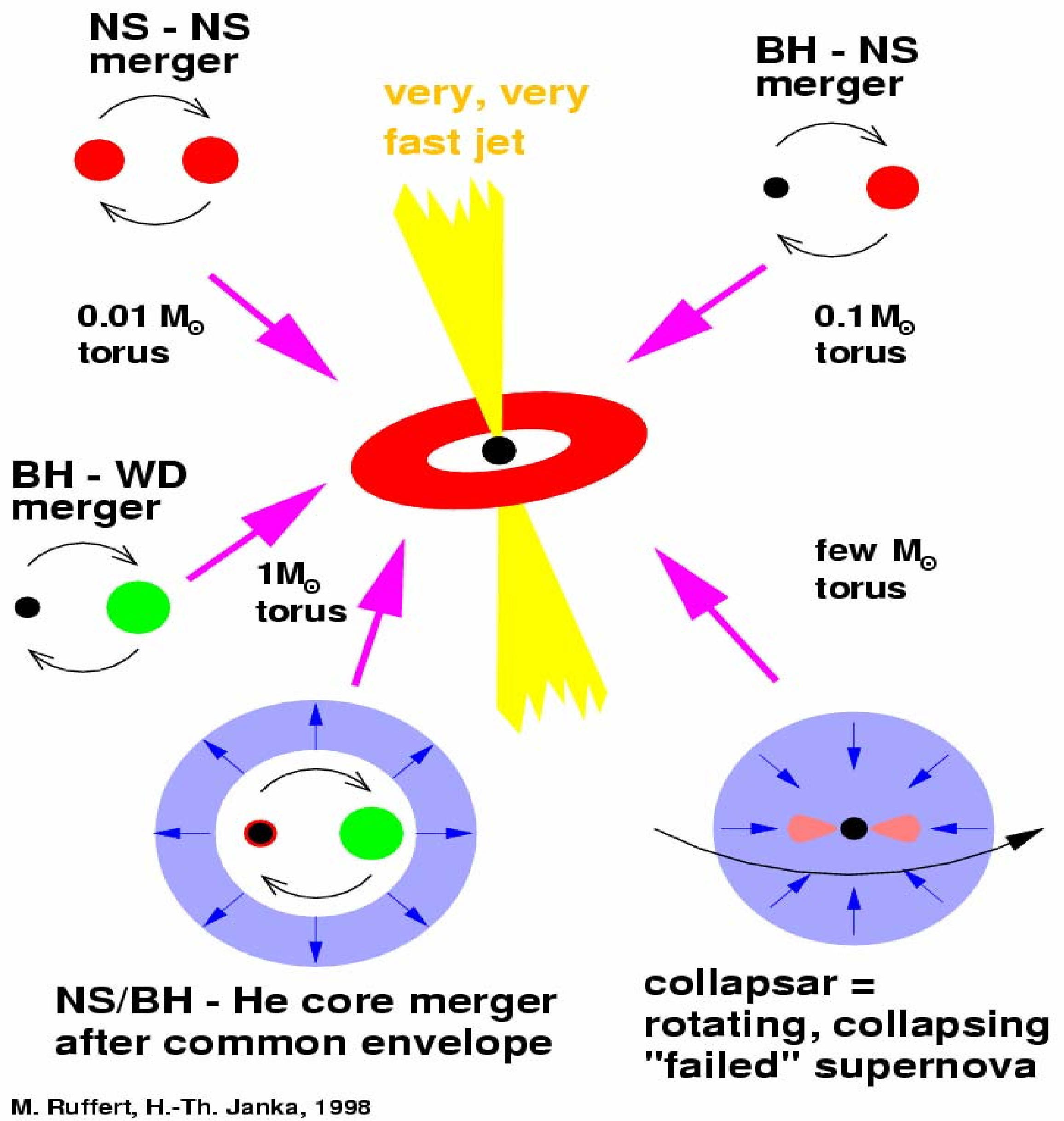
  ~ 1 ph/cm^2
- Energy output: $10^{53} (\Omega/4\pi) D^2_{28.5} F_{-5}$ erg

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

  $E_{\gamma,tot} \sim L_{\odot} \times 10^{10}$ year $\sim L_{gal} \times 1$ year
- Rate(GRB) ~ 1/day $\rightarrow 10^{-6}(\Omega/2\pi)^{-1}$ /yr/gal

  (whereas Rate(SN) ~ 10^7 /yr ~ 1/s at $z \lesssim 1$)

Hyperaccreting Black Holes



Short

Long

Explosion ⟶ FIREBALL

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

⟶ 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

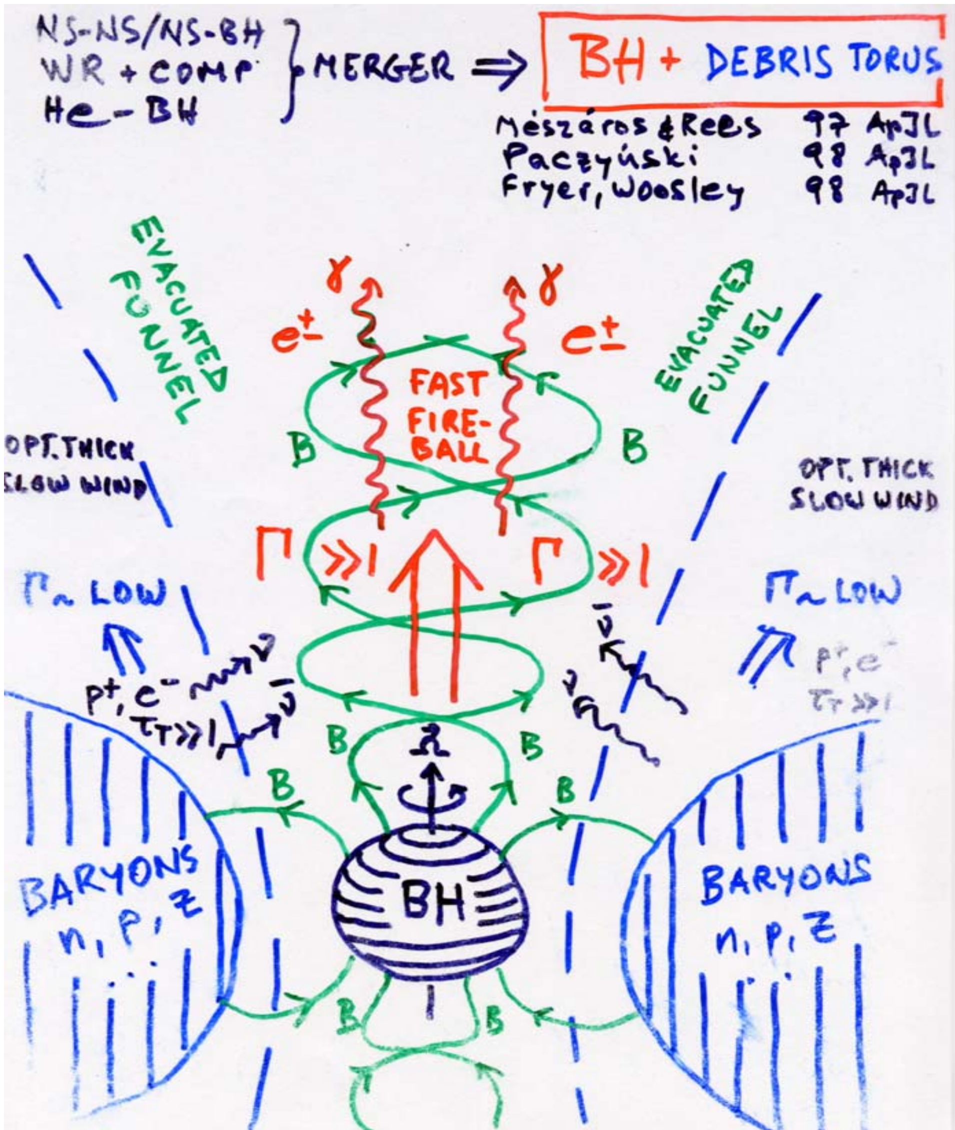
$\gamma\gamma \rightarrow e^\pm$, degrade 10 GeV $\rightarrow$0.5 MeV?

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

⟶ Ultrarelativistic flow $\rightarrow \Gamma \gtrsim \Theta^{-1} \sim 10^2$

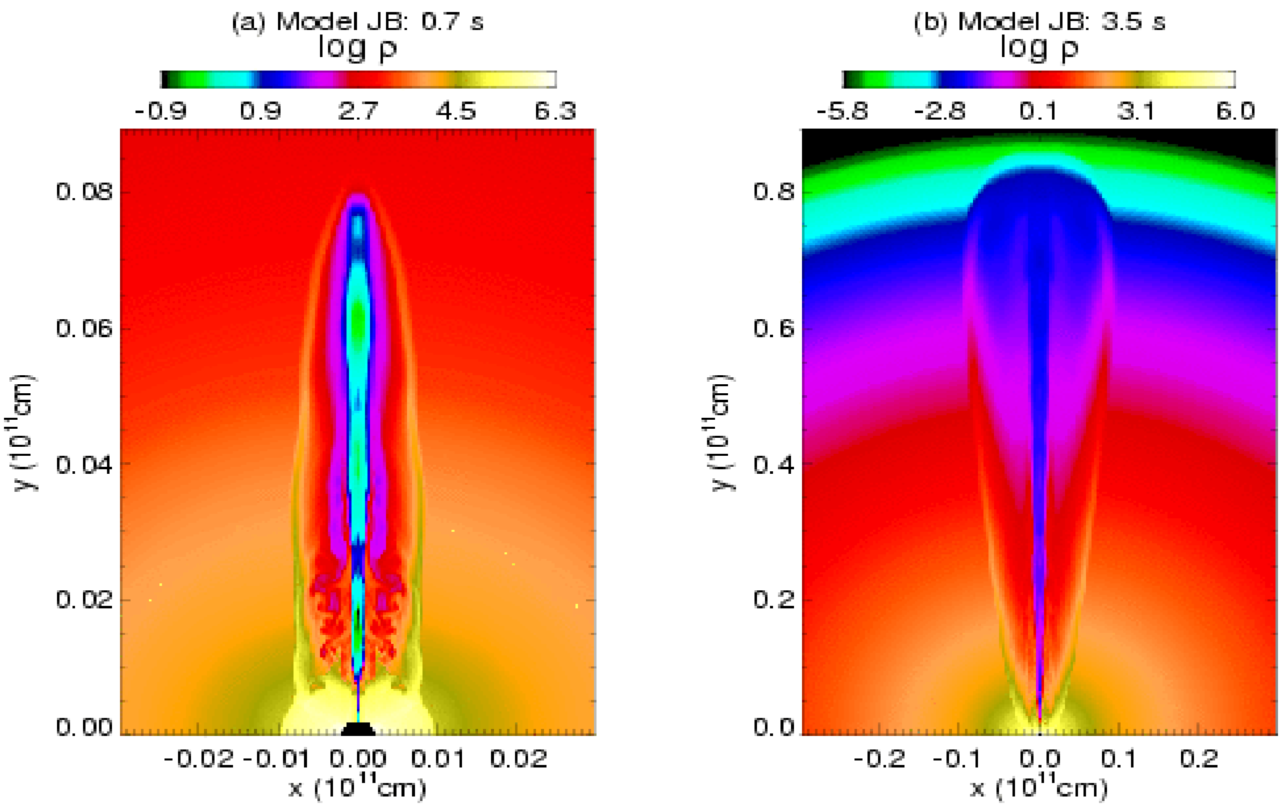
(Fenimore etal 93; Baring & Harding 94)

BH + accr. Torus → Jet



- Collapsar or merger →BH+accr.torus
- Nuclear density hot torus → $\nu\nu$→$e^{\pm}$
- Hot infall →conv.
- Dynamo → B~10^{15} G, twisted (thread BH?)
- →Alfvénic or $e^{\pm}p\gamma$ jet
- (Note: magnetar might do similar)

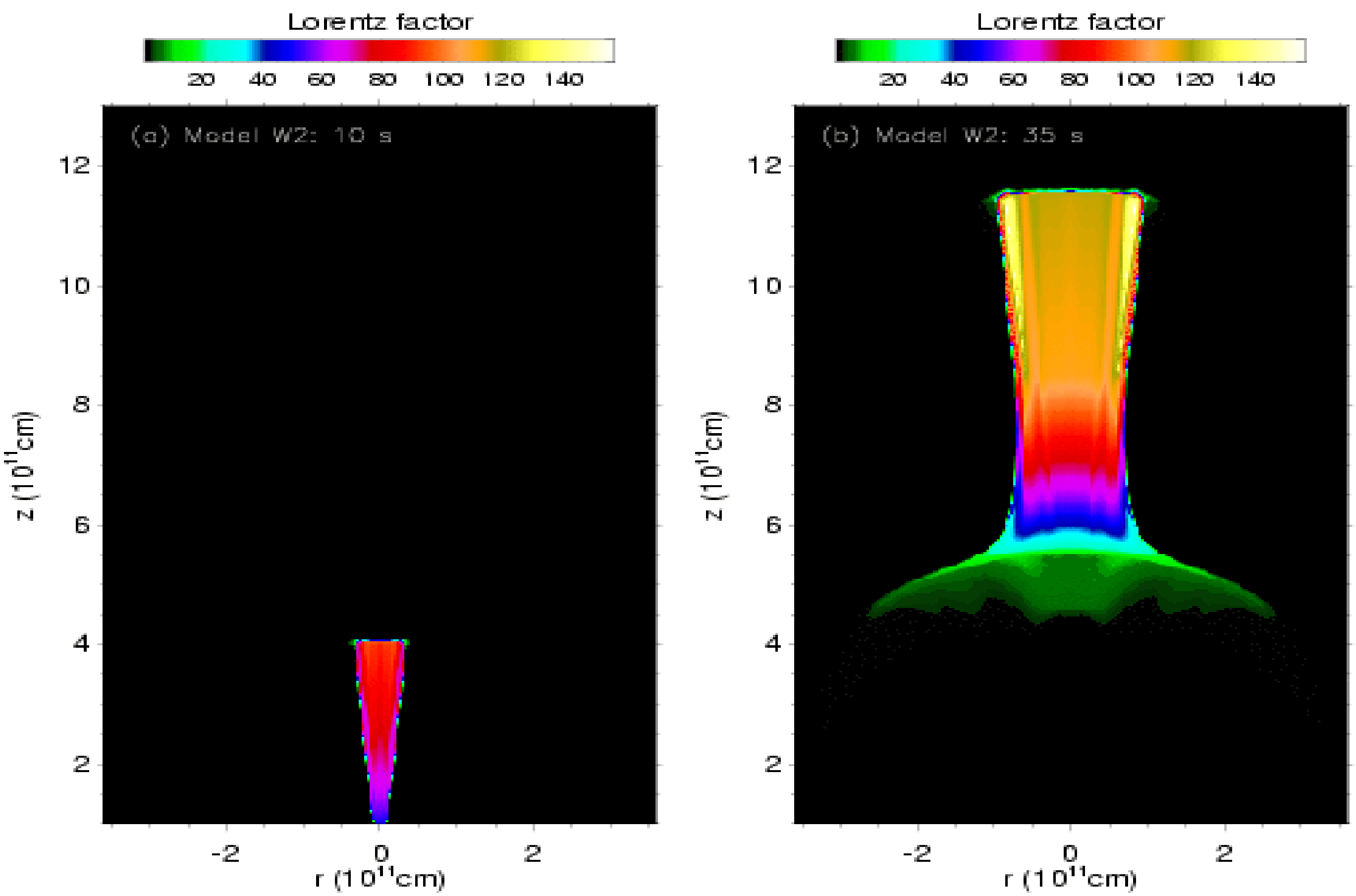
Jet emergence from star



Zhang, et al astro-ph/0207436

- Num.simulations: (Aloy et al 00 ; Zhang, Woosley, McFadyen 02)
- So far: 2D, SR; jet first $v_h \lesssim c$, then $v_h \rightarrow c$ as analytical calc's indicated $\rightarrow$ OK
- KH instab: variable power output, Γ
- Prelim. (num.) concl.: jets emerge only from stars of $R_\star \lesssim 10^{11}$cm; but larger stars not calculated num'ly;
- analyt. est. indicate larger radii may be possible (Meszaros, Rees 02, ApJ 556, L37)

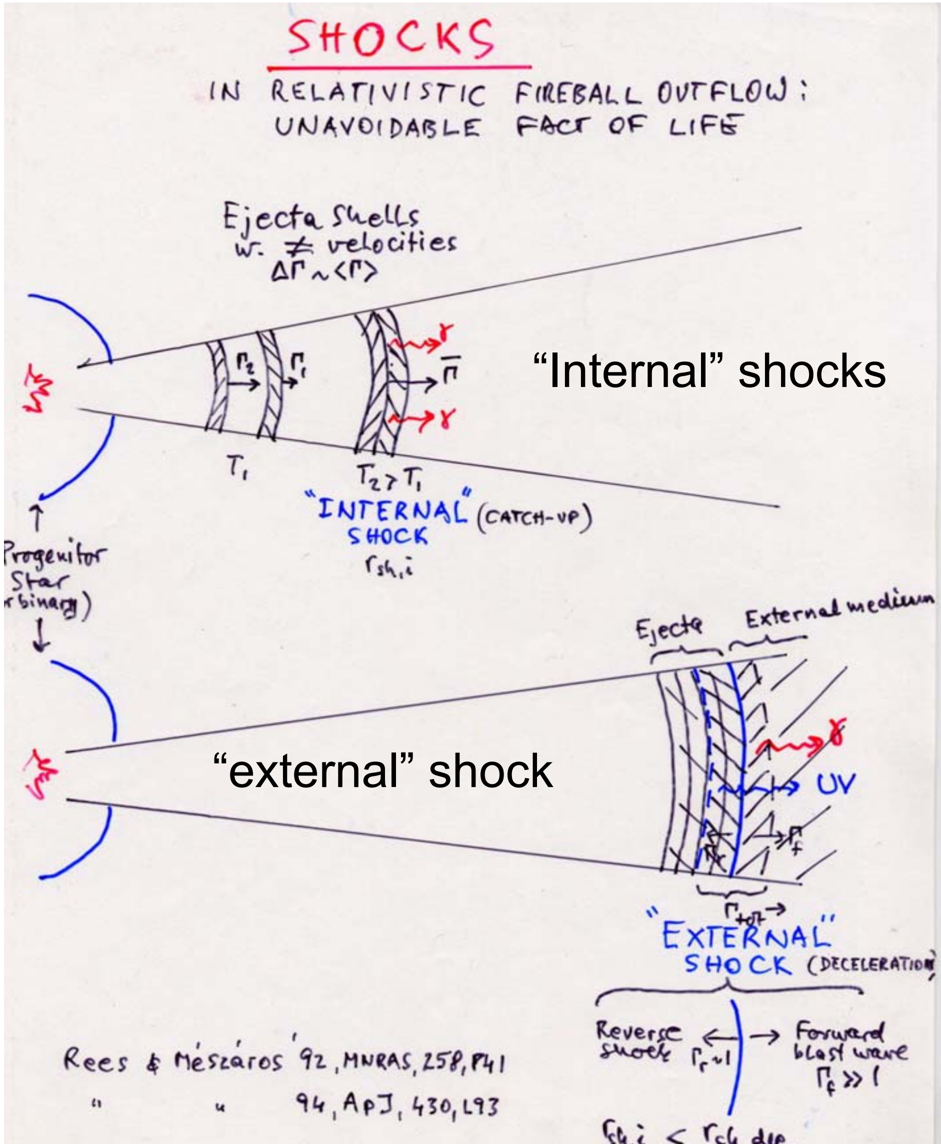
Jet Emergence through stellar wind



- Jet emerge into stellar wind $\rho \propto r^{-2}$;
- details dep on various assumed parameters, but..
- Jet emerge with $\Gamma_f \sim 150$, decr. w. angle $\rightarrow$ OK

Zhang, et al astro-ph/0207436

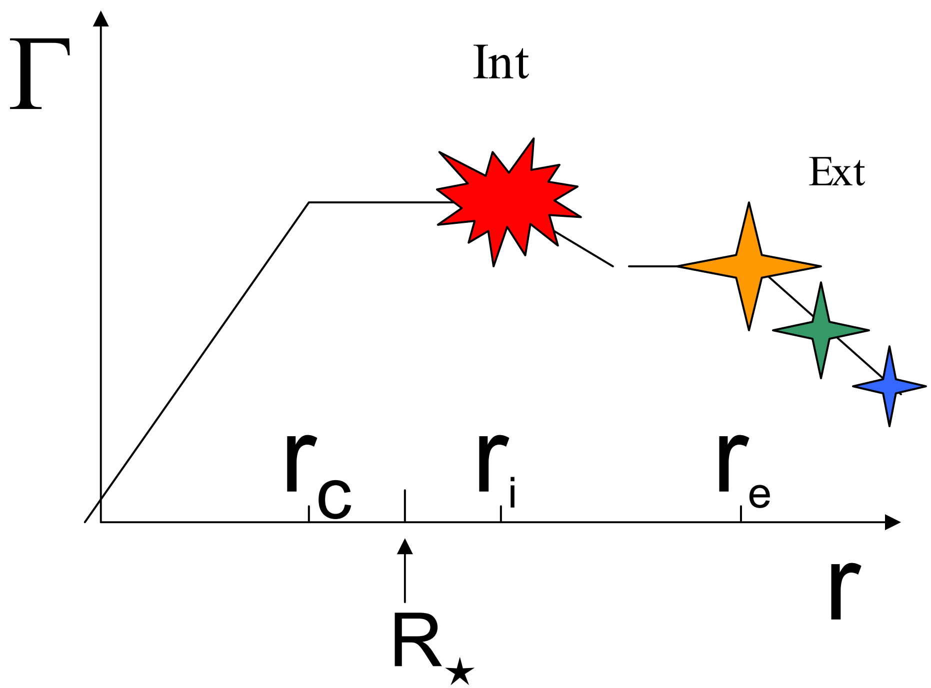
Shocks in Fireball Outflow



- Shocks expected in any unsteady supersonic outflow (esp. in a non-vacuum environment)
- Internal shocks: fast shells catch up slower shells (unsteady flow)
- External Shock: flow slows down as plows into external medium
- NOTE: “ext.” termination shock & internal shocks might be expected also while jet is still inside star

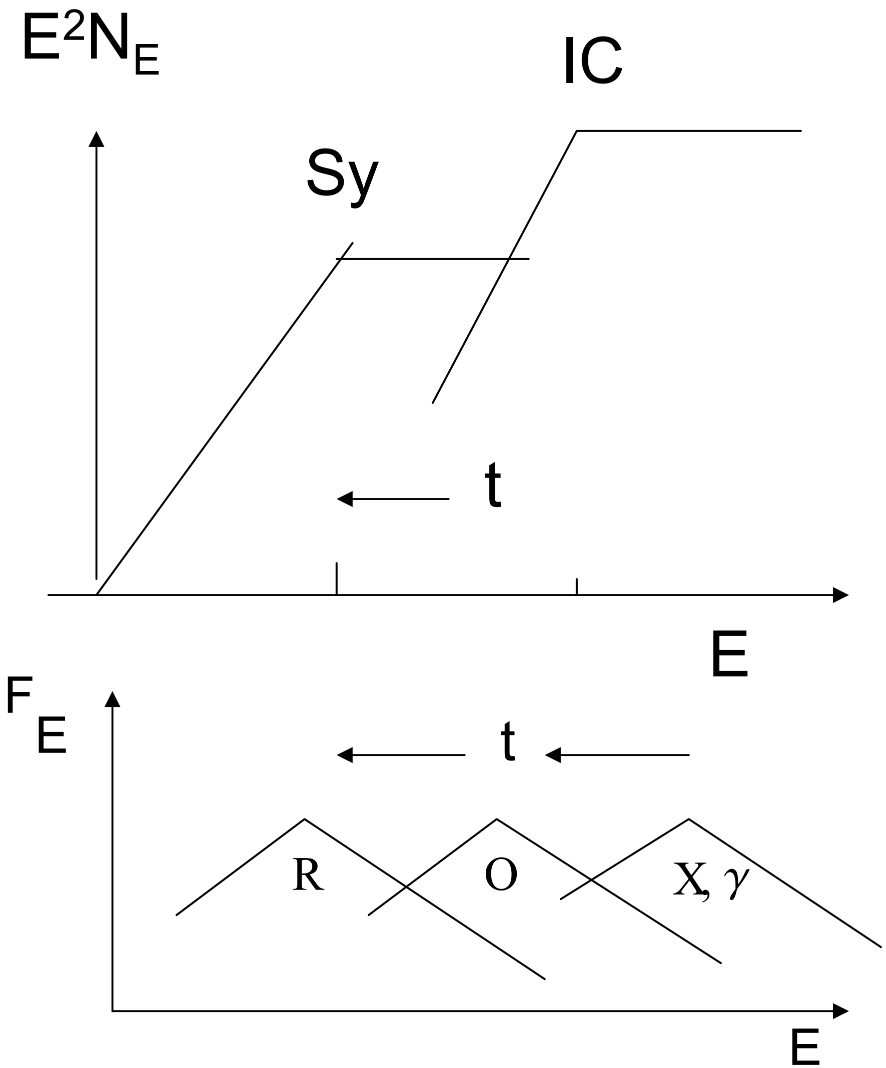
Internal & External Shocks

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



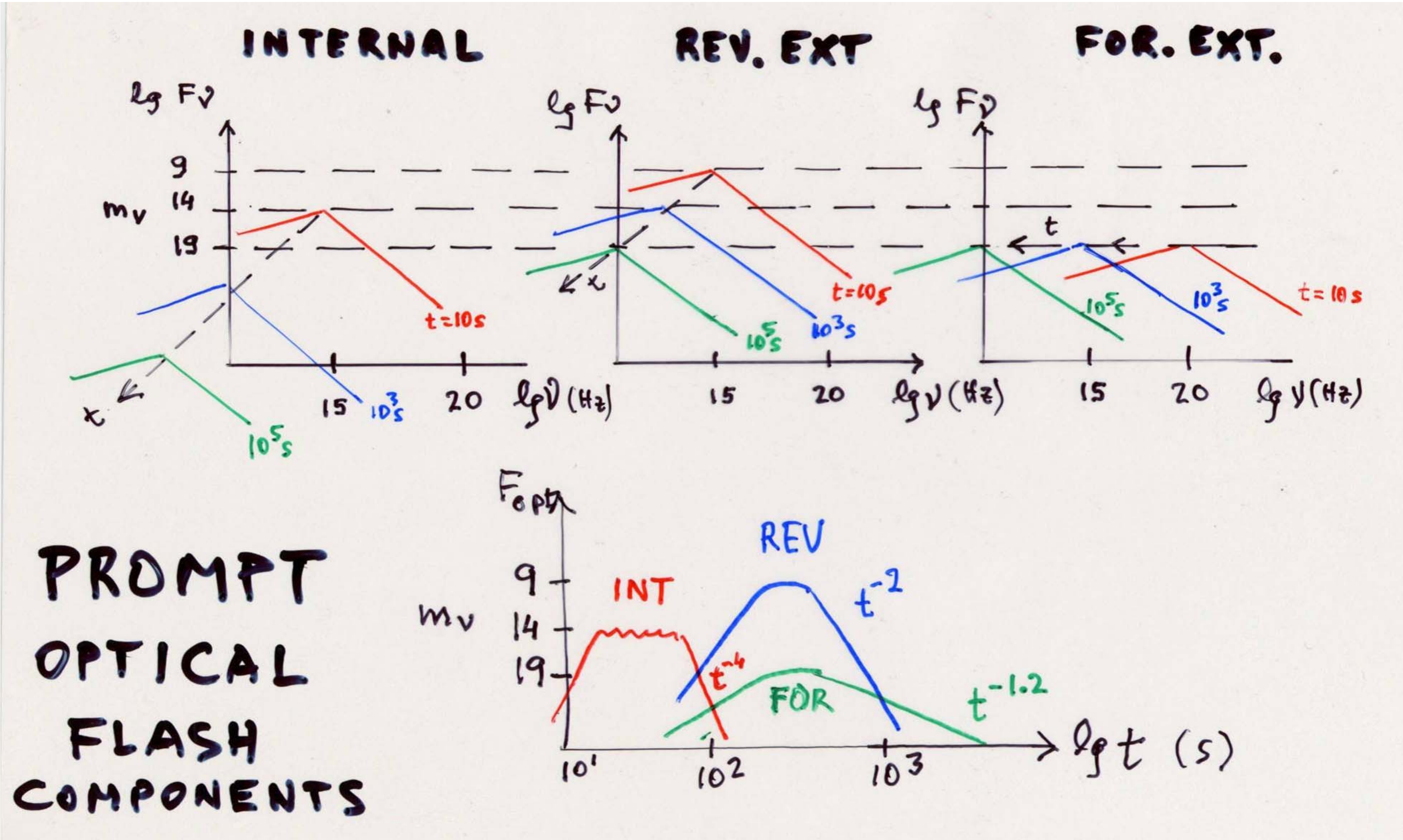
- Lorentz factor Γ first grows $\Gamma \propto r$, then coasts $\Gamma \propto$constant, until …
- **Outside** the star, after jet is opt. thin: Internal shocks: $r_i \sim 10^{12}$cm
  →**γ-rays** (burst, t~sec)
- Externals shocks start at $r_e \sim 10^{16}$cm, progressively weaken as it decelerates
- 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)

Shock Photon Spectrum



- Non-thermal power law spectrum, both in int. and ext. shocks, due to
- Synchrotron, peak at ~200 keV (or ~ eV?)
- Inv. Compton, peak ~ GeV (or ~200 keV ?
- Sy peak location, ratio Sy/IC dep. on B_{sh} , $\gamma_{e,m}$
- Peak softens with time
- Ratio Sy/IC decr w. time

Prompt & Late Spectral Evolution



Mészáros & Rees '97, ApJ 476, 232 ; '99 MNRAS 306, L39

EGRET GeV Bursts

- GeV emission, starting ~ with MeV trigger, but lasting $\gtrsim$ 1 hr:

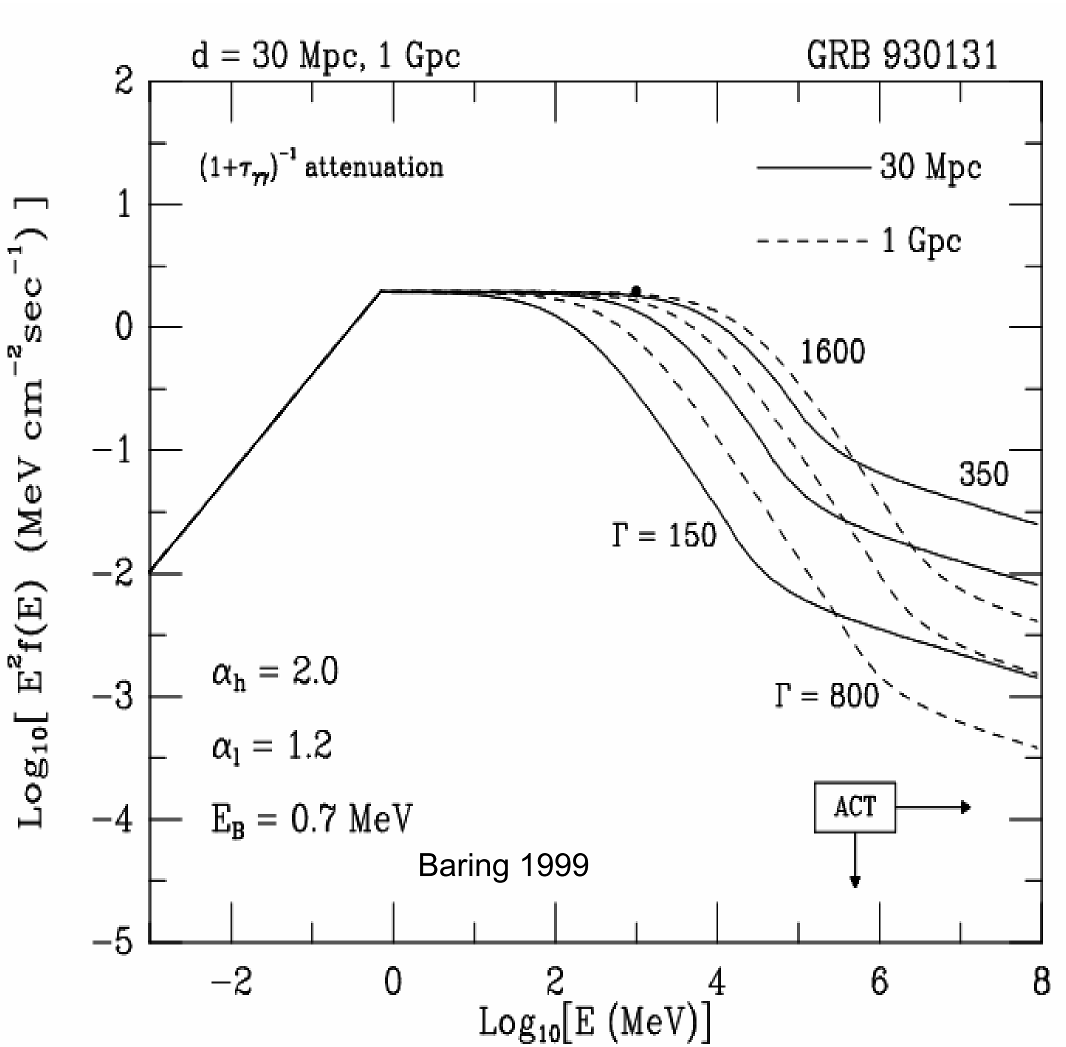
  $\rightarrow$ could be

  a) normal duration MeV synchrotron internal shock,

  b) followed by long-lasting GeV I.C. external shock (moderate Γ, low n_{ext})

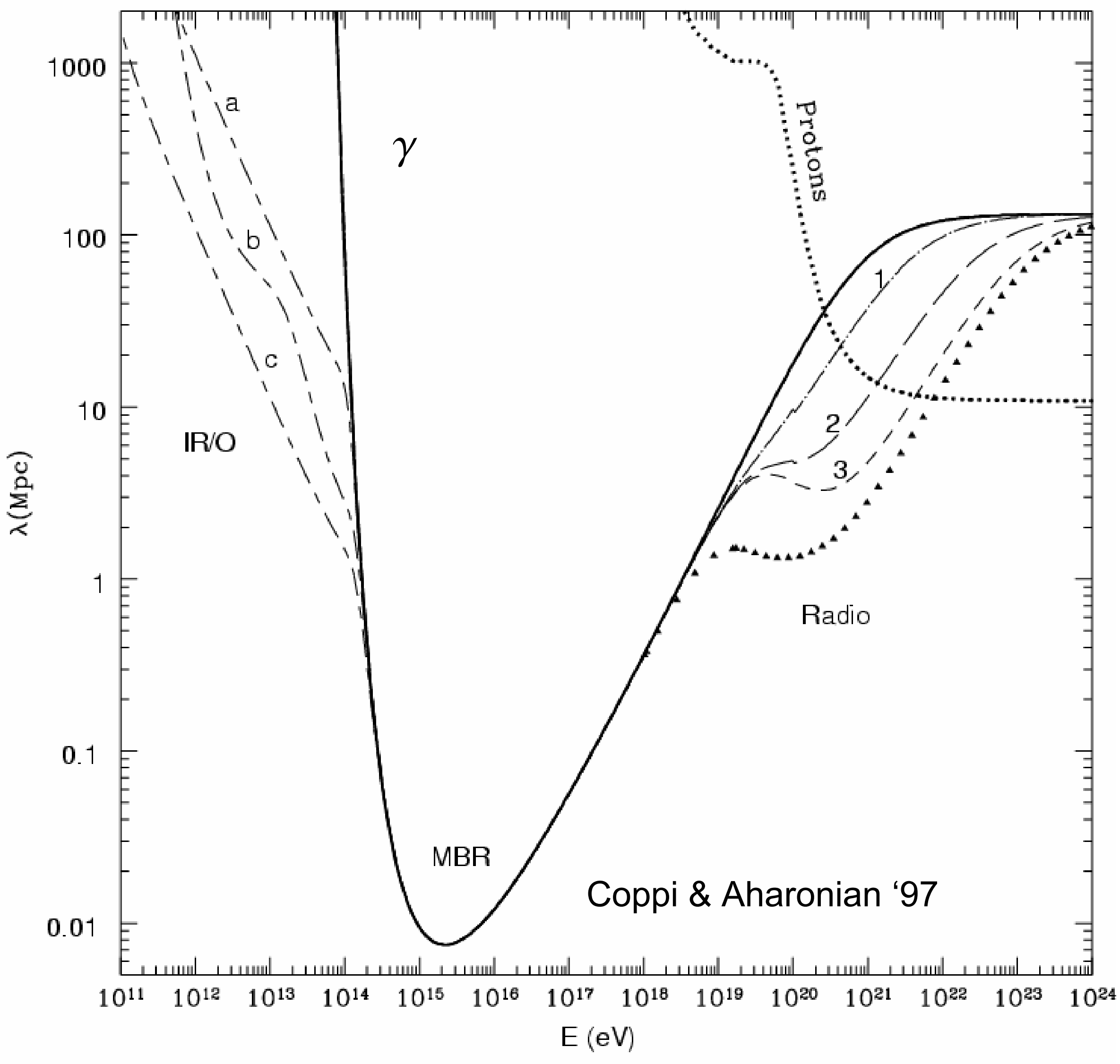
(Meszaros & Rees 1994)

GeV-TeV photons from GRB



- Internal shocks: $\gamma\gamma \rightarrow e^{\pm}$, $\tau_{\gamma\gamma} \geq 1$ @ $E_\gamma \gtrsim \Gamma^2_{300}$ GeV
  $\rightarrow$ pair cutoff in spectr
  $\Longrightarrow$ get info about r $_{sh}$ (compactness, $\tau_{\gamma\gamma}$)
- In ext.shock, $\tau_{\gamma\gamma} \leq 1$ on GRB target γ;
- test if shock is int. or ext;
  test bulk Lorentz factor, shock accel efficiency, magnetic field in shock (max. $e^{\pm}$ energy? $\rightarrow$size of accel region)

$\gamma\gamma$ Opacity of the Universe



- In ext.shock, $\tau_{\gamma\gamma}\leq 1$ for >TeV on GRB target γ, but
- In Universe, $\tau_{\gamma\gamma}\geq 1$ for >TeV on IR bkg γ (D$\lesssim$100Mpc) →test IR bkg spectral density,
- constrain early star formation rate &

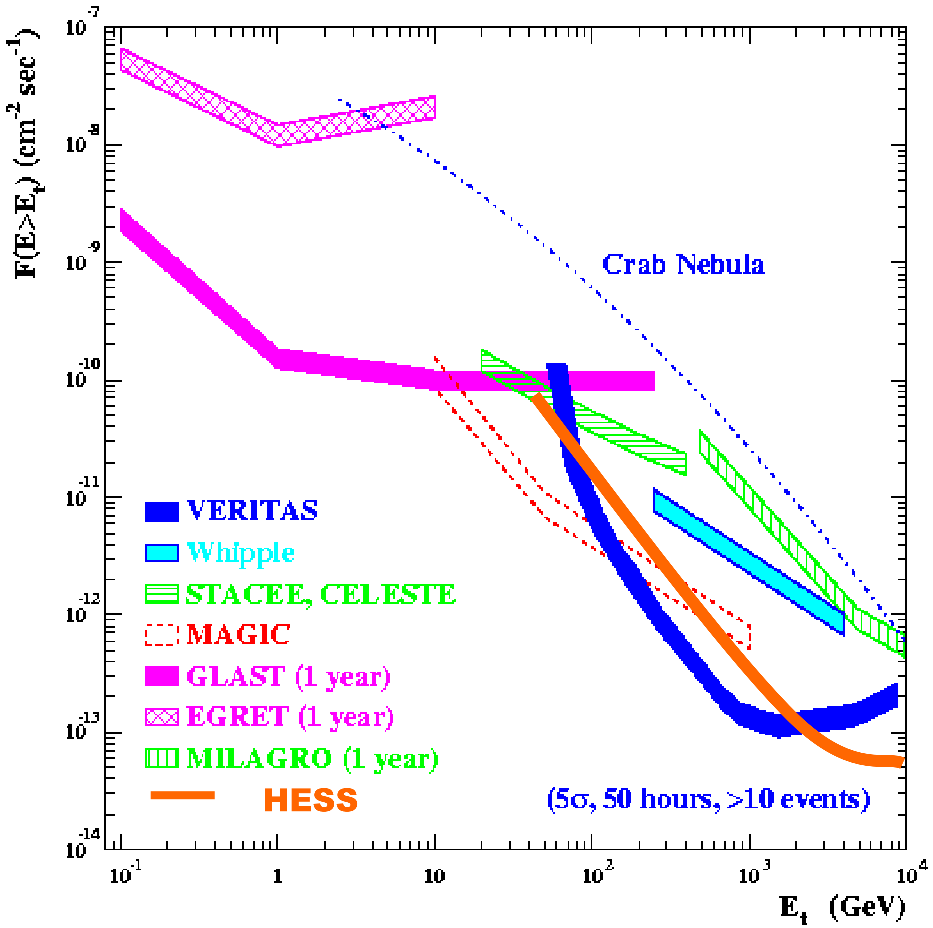
  z-distr of SFR, LSS, cosmology

GeV-TeV γ 's (etc): MILAGRO

- Football stadium sized x 2m deep Cherenkov water detector @ LANL
- Smaller prototype Milagrito has been up 3-4 yrs
- Report tentative (<3σ) detection of TeV γ-rays from a GRB (Atkins et al 2000)

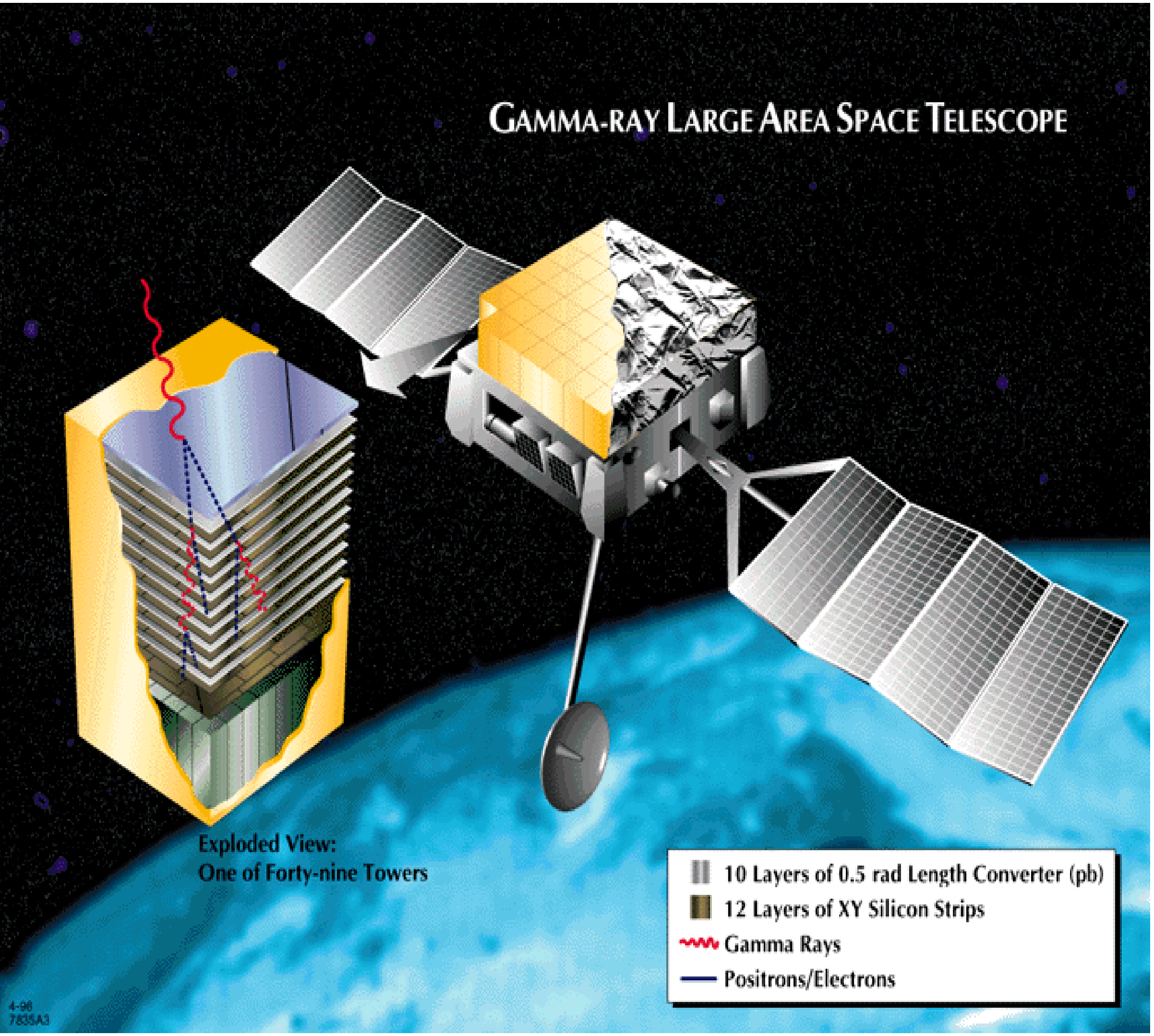
GeV-TeV γ's: Air shower Cherenkov telescopes underway

Point Source Sensitivities



- **MAGIC**: La Palma (Munich)
  Monoc. 1x17m, >30 GeV, ‘01
- **HESS**: Namibia (Heidelberg)
  Stereo 4x12m, > 50 GeV, ’02
- **CANGAROO**-III: Austral(Tokyo)
  Stereo 4x10m, >50 GeV, ’03
- **VERITAS**: Arizona (SAO)
  Stereo 7x10m, >50 GeV, ’05
- **STACEE**: Sandia (UCLA/Chic)
  solar tower, 20-300GeV, ’01
- **MILAGR(ITO)O**, LANL, NM
  water, > 20 GeV, A~5.10^7 cm^2
- **GLAST** (LAT): space (Stanford)
  Silicon, 20 MeV-300 GeV, ‘06

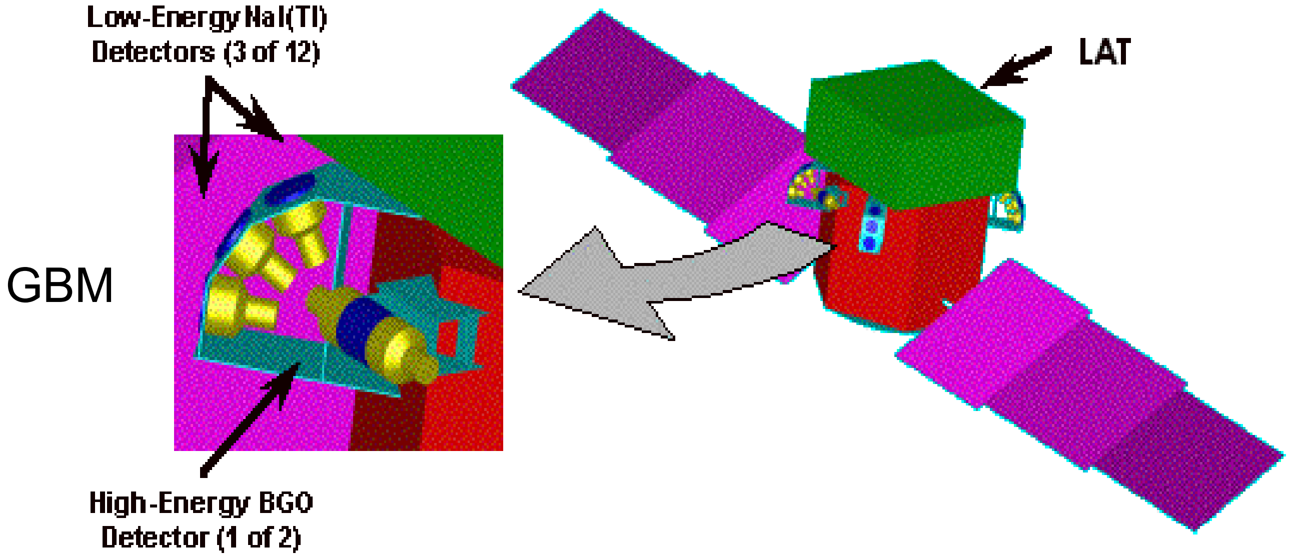
GLAST : LAT (Stanford, SLAC,…)



- Launch exp '06, Delta II, 2-300 GRB/2yr
- Pair-conv.mod+calor.
- 20 MeV-300 GeV, $\Delta E/E \lesssim 10\%$@1 GeV
- fov=2.5 sr (2xEgret), θ~30"-5' (10 GeV)
- Sens $\gtrsim 2.10^{-9}$ph/cm^2/s (2 yr; $\simeq$ 50xEgret)
- 2.5 ton, 518 W

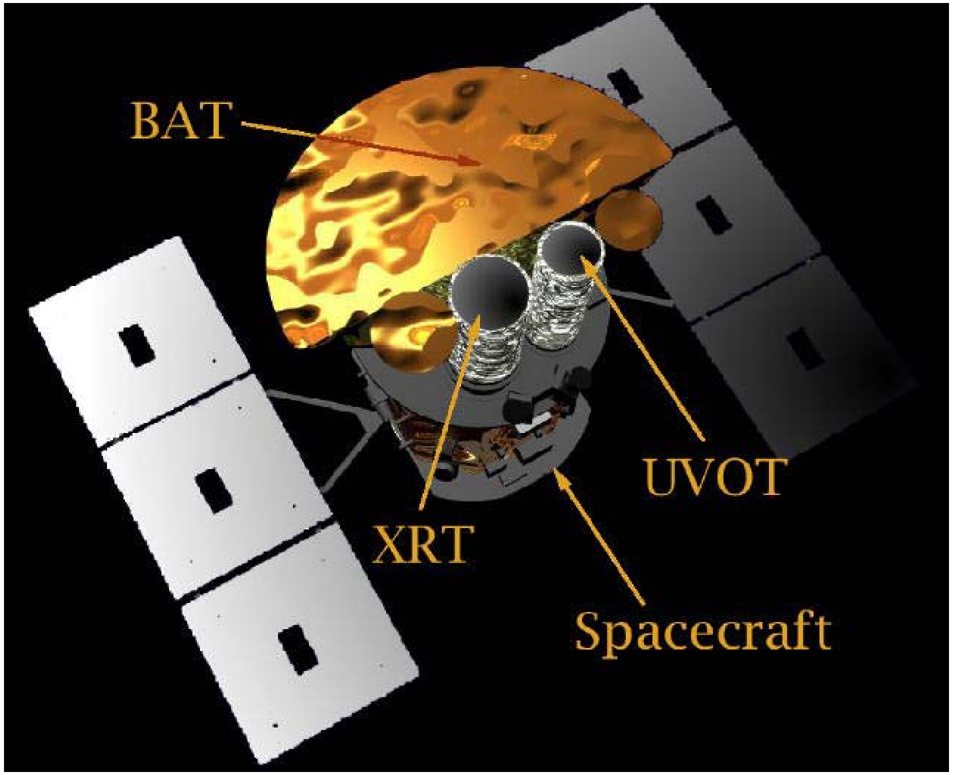
Also on GLAST: GBM (next slide)

GLAST - GBM (NASA-MSFC)



- 12 NaI scint.det (5 keV-1 MeV) →trigger & location
- 2 BGO (Bismuth Germanate) scint.det. (150 keV-30 MeV)
- At upper energy end overlap with LAT;
  NaI+BGO ~ similar charact. as BATSE lad+sd
  (but wider en.range & smaller area)

Swift



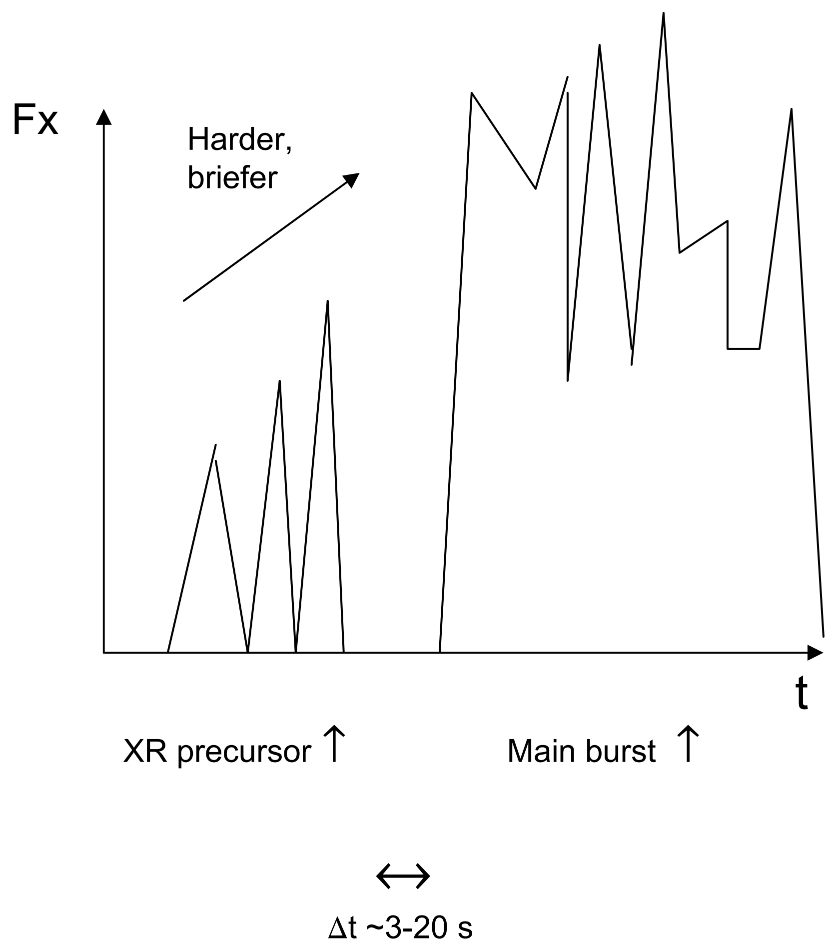
- Exp. Launch Sept ’03
- Goddard, Penn State, Leicester, Milan, MSSL, Rome collab.
- BAT: 10-150 keV CdZnT, θ~1-4’ posit’n
- XRT: 0.2-10 keV CCD, θ~1” res./positn
- UVOT: 170-650 nm,θ~0.5”,

Expect ~250-300 GRB/yr localized & followed up in gamma/XR/Opt

Swift (cont.)

- BAT: coded mask CdZnT det., 5x BATSE sensitivity, spectra R~20 (10-150keV) , FOV 2 sr
  position (θ~1-4') to ground in ~5 s
- XRT: CCD det θ~0.3-2.5" pos (in 25-70s), FOV 23'x23', F_E ~2.10^{-14} erg/cm^2/keV/s (in 10^4 s), spectra (0.2-10keV) R~20
- UVOT: fov 17'x17' f/13, 30cm, $m_v \lesssim 21$(10s), gratings: sp R~300-600 $m_v \lesssim 17$, 6 color photom. redshifts $1.5 \lesssim z \lesssim 4(5)$ $m_v \lesssim 24$ (10^3s)

Collapsar XR Precursor

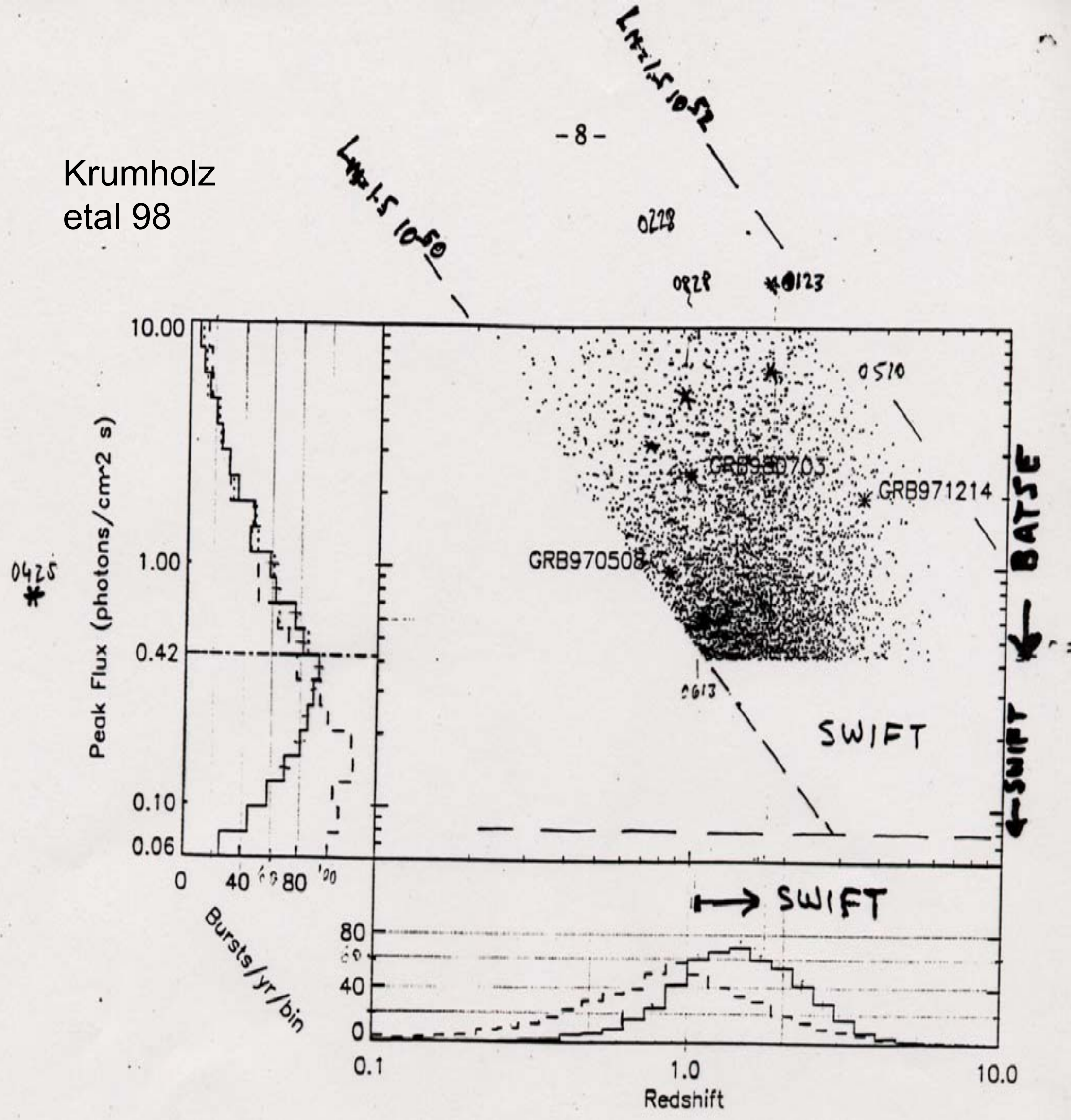


Waxman, Meszaros astro-ph/0206392

- Collapsar: H (r=$10^{12.5}$ cm),
  He(r=10^{11} cm),
  CO(r=10^{10} cm)
- "Cork" expelled in jet breakout has ~3 shock/raref episodes →XR pulses
- Shocks get briefer & harder
- Flux & per. charact of model H (blue SG): may detect; He, CO dwarfs: difficult
- Precursor-main: 3-20 s del

GRB redshift dependence

Krumholz etal 98

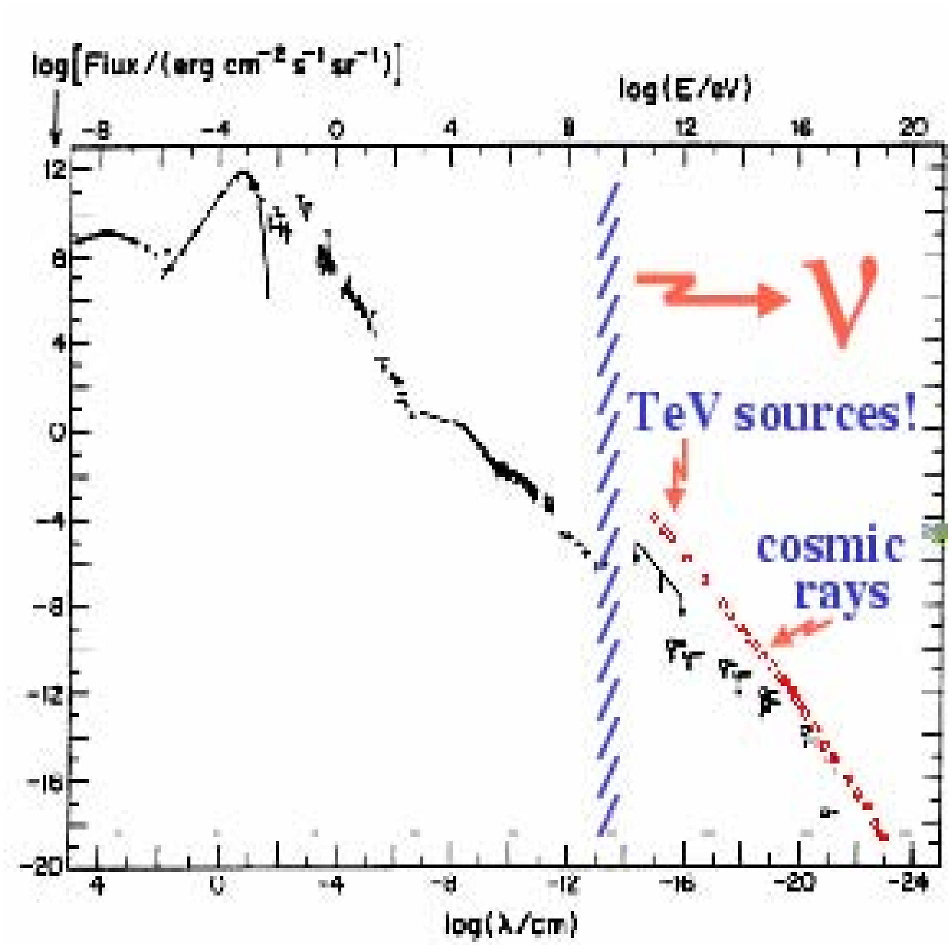


- Solid: GRB rate ∝ star formation rate; dashed: rate ~comov. const.
- **Swift:** expect 250-300

  GRB det/yr, 4x times fainter than BATSE
- If bursts at z≳10-15, can detect them ;but distance ID difficult.

Solid:grb foll. star form rate, dashed: grb const.com.dens.

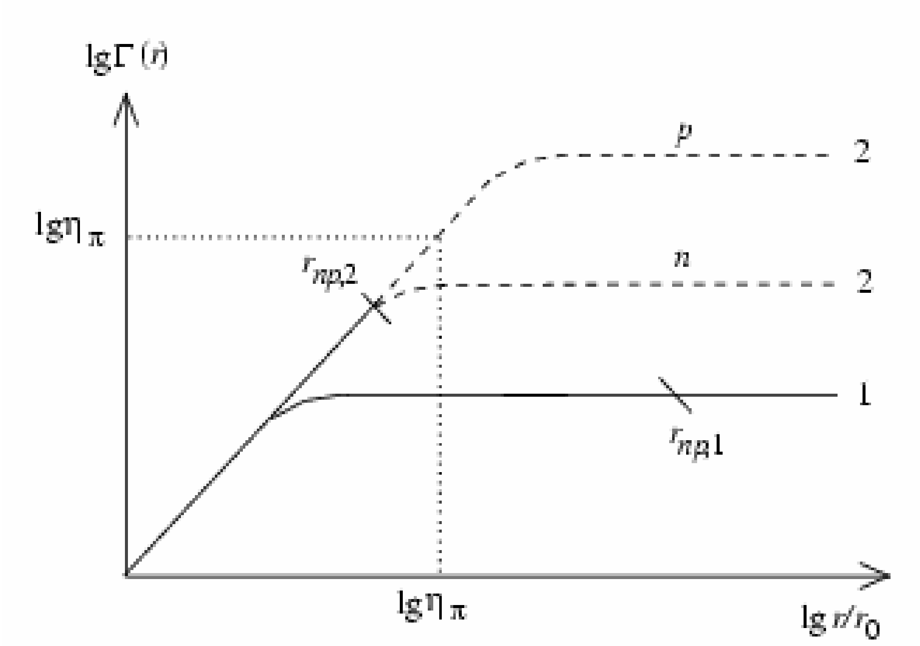
CR's & ν's : sub-TeV to ZeV?



↑ (Halzen, Cooper 02)

- Universe opaque to γ $\epsilon_\gamma \gtrsim 10^{12}$ eV=TeV due to $\gamma\gamma \rightarrow e^\pm$ on IR bkg
- U. also opaque to p at $\epsilon_p \gtrsim 10^{20}$ eV=0.1 ZeV due to $p\gamma \rightarrow \pi^+$ +… on CMB
- Also p of $\epsilon_p \lesssim 10^{19}$ eV lose direction info (B_{gal})
- ν only high-energy messenger from high z pointing back at source !

Proton-Neutron Component



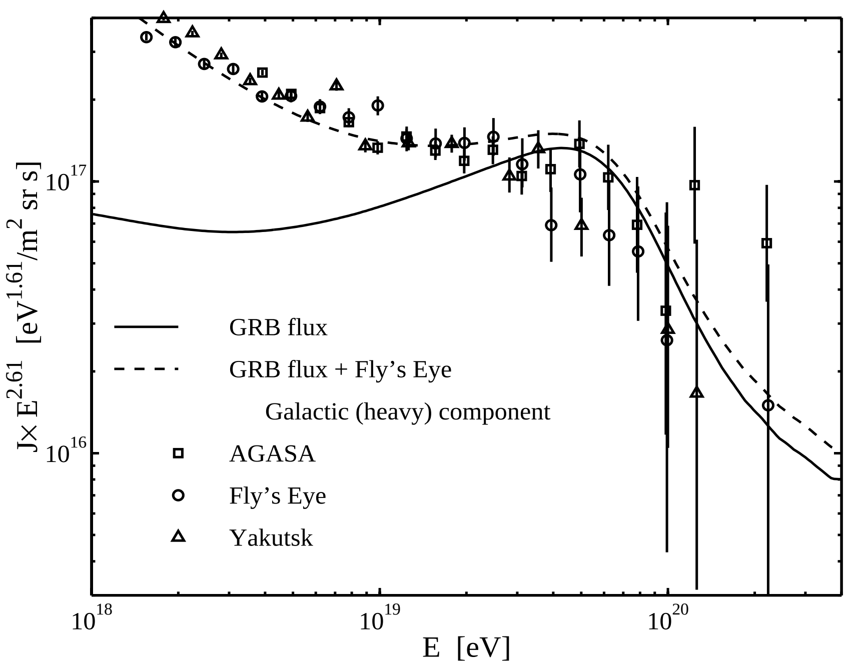
(Bahcall & Meszaros 2000 PRL 85:1362)

- p-n expand together while $t_{pn} > t_{exp}$ (rad. pressure acts on p)
- p-n decouple ($v_{rel} \to c$) when $t_{pn} \gtrsim t_{exp}$ ($\tau_{pn} \sim 1$), and $\sigma_{pn} \to$ inelastic f. $\Gamma \gtrsim \Gamma_{\pi} \sim 400$

(Derishev etal 99; Bahcall,Meszaros 00; Fuller etal 00)

- $pn \to \pi^{\pm} \to \mu^{\pm}, \nu_{\mu} \to e^{\pm}, \nu_e, \nu_{\mu}$
  $\to \pi^0 \to 2\gamma$
- ICECUBE: $\epsilon_{\nu\mu} \sim$ 5-10 GeV , at $z \sim 1$, $R_{\nu} \sim 7$/yr from all GRB, in coinc.w.γ (if PMT density large enough)
- **GLAST**: $\epsilon_{\gamma} \sim 10$ GeV, $z \sim 0.1$

Proton Acceleration in GRB



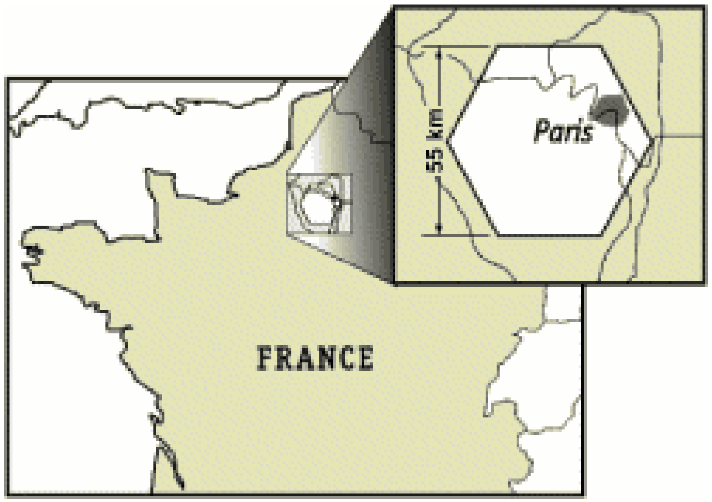
(Waxman, Neutrino 2000, hep-ph/0009152)

- Internal & extern.(rev) shocks mildy relativ'c $\rightarrow$spectrum $N(E) \propto E^{-2}$
- Can reach $E \sim 10^{20}$ eV (for $\xi_B \xi_e \gtrsim 0.02$, $\Gamma \gtrsim 130$)
- CR energy input at10^{20}eV $dE/dt dV \sim 10^{44} \zeta \, erg/Mpc^3/yr$ where $\zeta \sim 0.5 - 3$ (z-evol.)
- Entire >10^{20}eV CR flux from GRB? yes/no/possib

(Waxman NucPhS 87:345'00; Stecker APPh 14:207 '00)

Pierre Auger

Ultra-high energy cosmic ray observatory



- NSF project, south : (Argentina) partly complete – north:planned
- Planned area 3,000 km^2 , sensitive to CR energies $>10^{20}$ eV (GZK lim)
- 1600 ground particle detectors, 11,000 liters ea., 1.5 km apart, ea.
- In addition, several air fluorescence telescopes
- Also: tau-neutrinos (horiz.l showers- Earth-skimming & through Andes)

UHE ν's from pγ collisions

- Internal shocks$\rightarrow E_p > 10^{16}$eV coll.w.$E_\gamma \sim$MeV

  $dN_\gamma/dE \propto E^{-\beta}$, $\beta \sim 1,2$

  $\Longrightarrow p\gamma \rightarrow \pi^\pm \rightarrow \mu^\pm, \nu_\mu \rightarrow e^\pm, \nu_e, \nu_\mu$ (Δ-res.)
- $\Longrightarrow E_\nu \sim 5.10^{14}$ eV Γ_{300} $(E_\gamma/1\mathrm{MeV})^{-1}$,

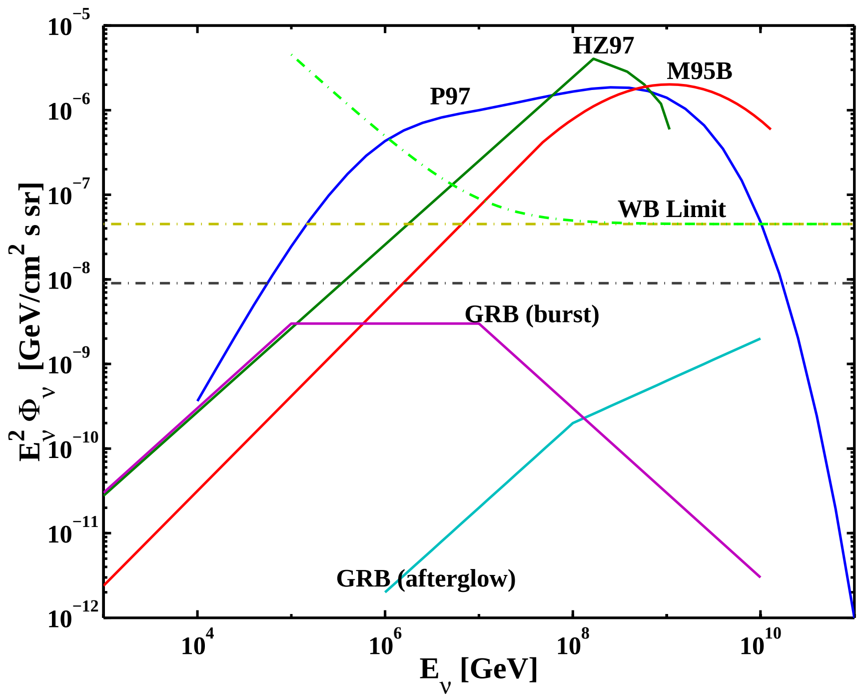
  $E^2\nu\Phi_\nu \approx 10^{-9}$ $(E\nu/E\nu_b)$ GeV/cm^2 s sr

  (Waxman, Bahcall 97; Rachen, Meszaros 98)
- Ext. shock $E_p > 10^{19}$eV, $E_\gamma \sim 10$eV,

  $\Longrightarrow E_\nu \sim 5.10^{17}$-$10^{19}$ eV, (Waxman,Bahcall 00, Vietri 98)

  $E^2\nu\Phi_\nu \approx 10^{-10}$ $(E_\nu/10^{17}\mathrm{eV})^\beta$ GeV/cm^2 s sr
- $\Rightarrow$ detect w. **ICECUBE** (& test shock acc)
- $p\gamma \rightarrow \pi^0 \rightarrow 2\gamma$, $E\gamma \sim 0.1$-1 GeV $\rightarrow$ **GLAST**

UHE ν Fluxes Expected



$E^2\Phi_\nu$ power/decade UHE ν from GRB int.shock & afterglow, and var. AGN jet models, with the Waxman-Bahcall 98 and MPR 99 CR limits

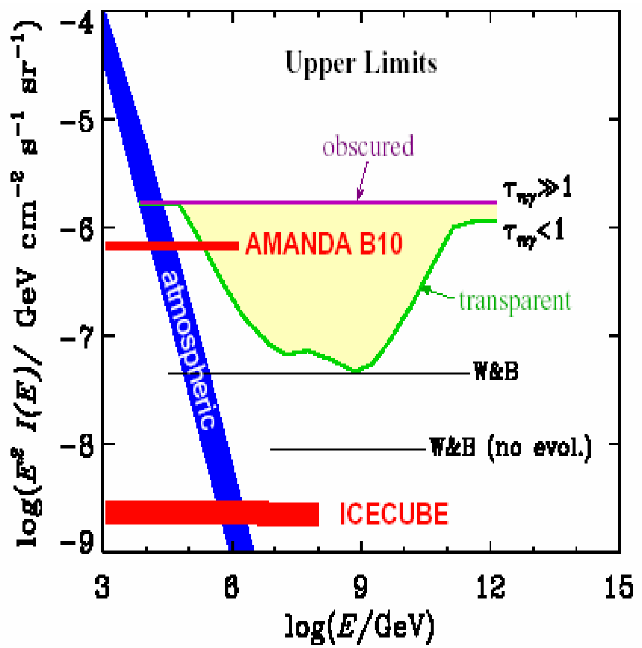
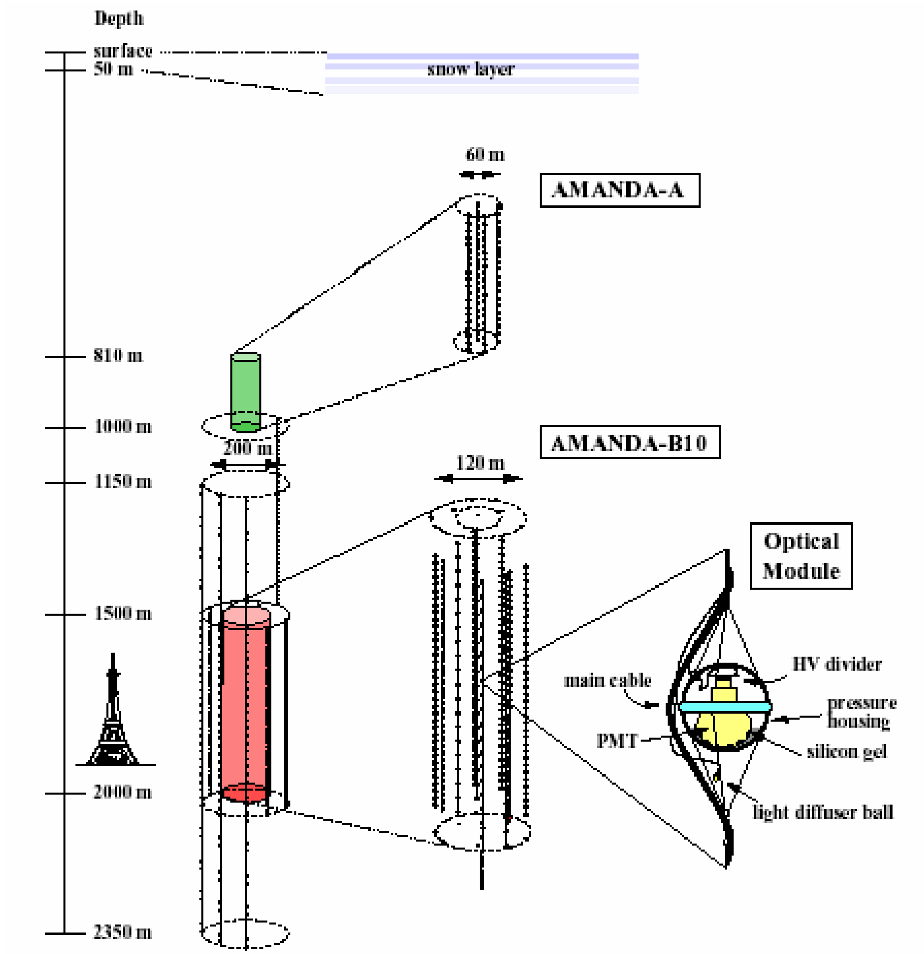


FIG. 6: The neutrino flux from compact astrophysical accelerators. Shown is the range of possible neutrino fluxes associated with the the highest energy cosmic rays. The lower line, labeled "transparent", represents a source where each cosmic ray interacts only once before escaping the object. The upper line, labeled "obscured", represents an ideal neutrino source where all cosmic rays escape in the form of neutrons. Also shown is the ability of AMANDA and IceCube to test these models.

(Halzen & Hooper PhysRep 02)

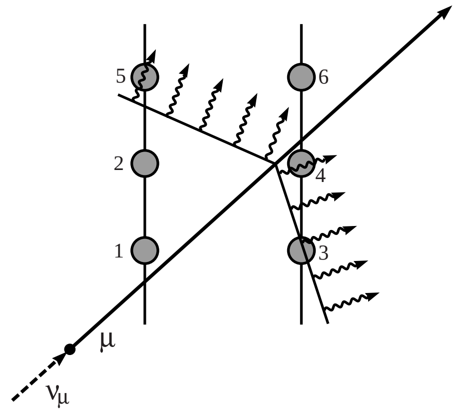
AMANDA : Antartic Muon and Neutrino Detector

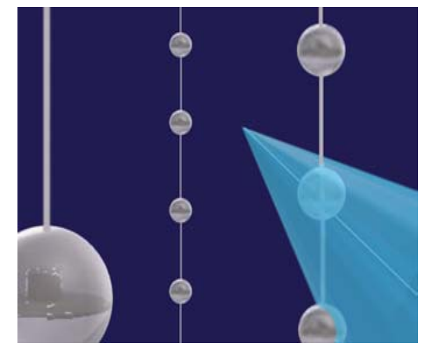


AMANDA as of 2000
Eiffel Tower as comparison
(true scaling)

zoomed in on
AMANDA-A (top)
AMANDA-B10 (bottom)

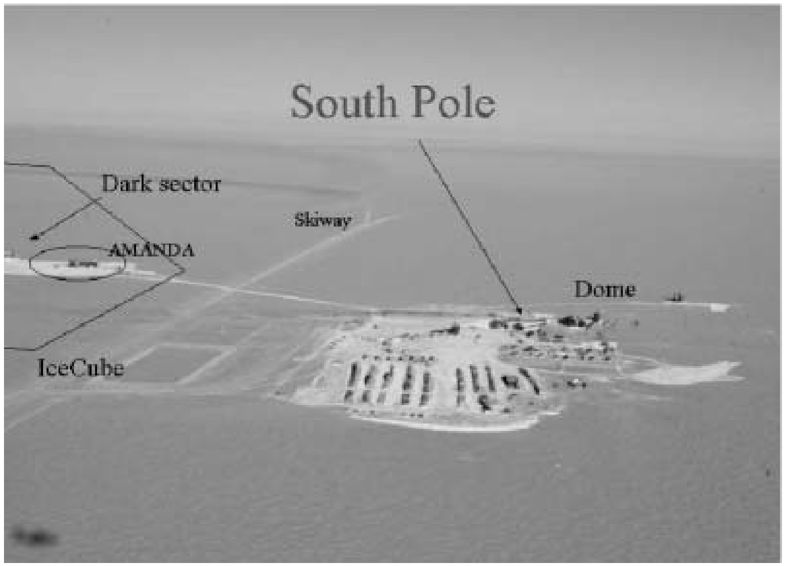
zoomed in on one
optical module (OM)



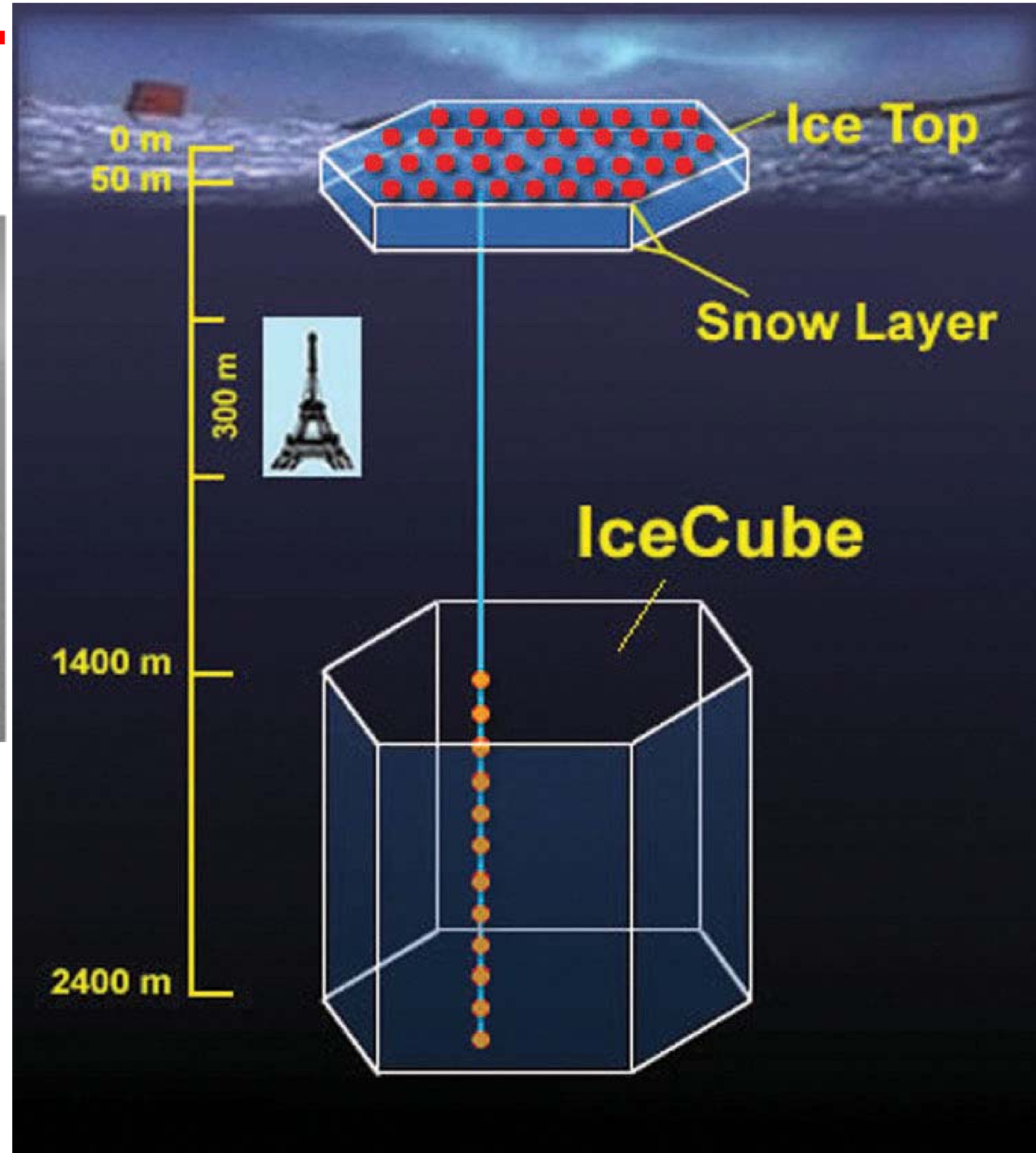


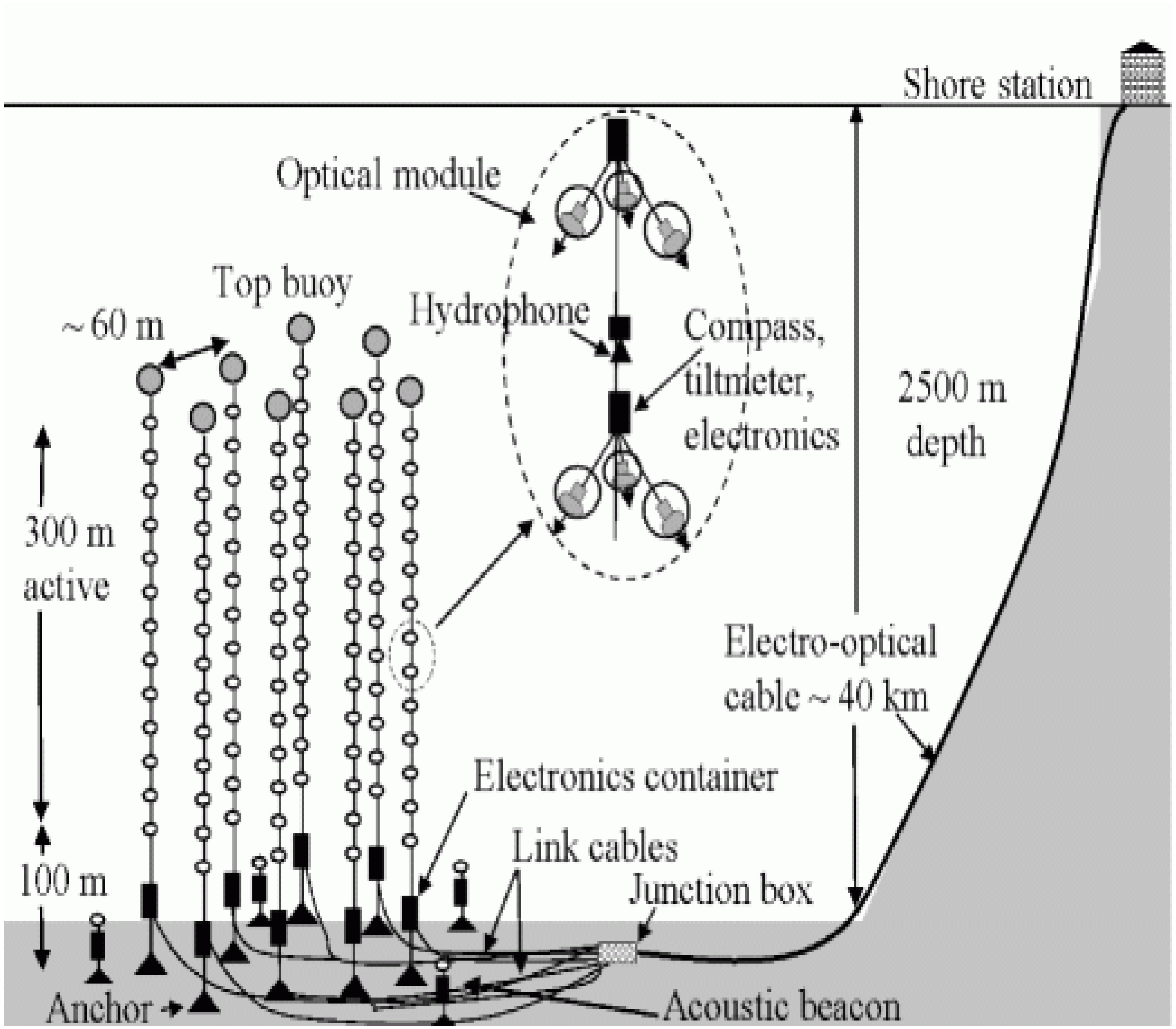
- Upward muons from ν
  $\nu^{\mu} \to \pi^{\pm} \to \mu^{\pm}$
- Cherenkov light: collective EM radiation in polarized medium (“sonic boom” from rel. muons v_μ>c/n)
- PMT strings 1.1.km under ice, current vol. 0.15 km^3

ICECUBE: km^3



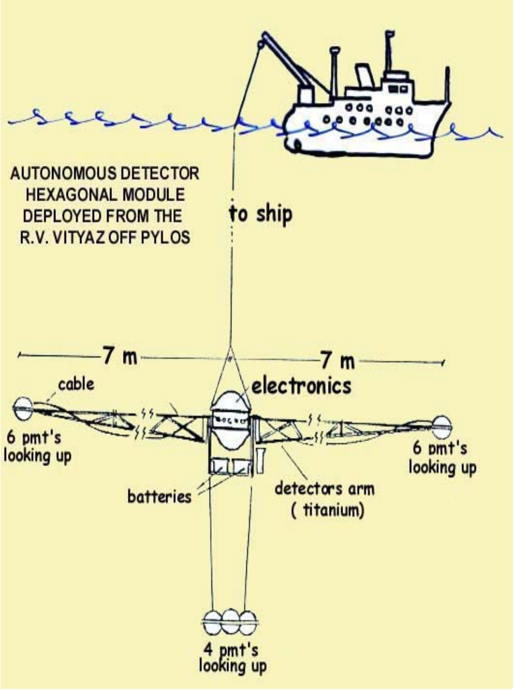
- Extension of Amanda
  0.15 $km^3 \rightarrow km^3$=1Gton
- Initial funds for 2002 √
- 80 strings , 4800 PMTs (ice)
  + air shower surface array
- Design for det.all flavor ν's , from 10^7 eV (SN) to 10^{20} eV





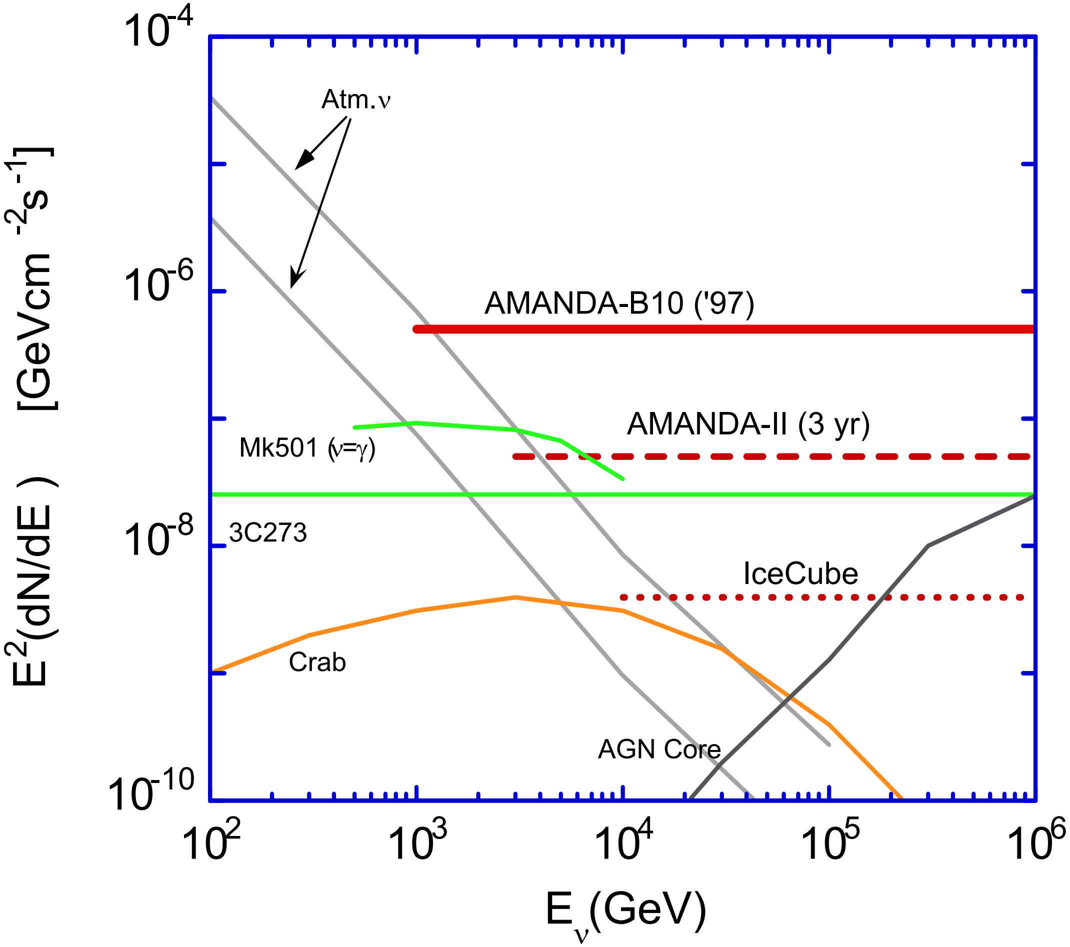
←Antares

- French/Italian/UK.. collaboration
- Site off Toulon
- Other: **NESTOR** ↓ Greek/German/Russian



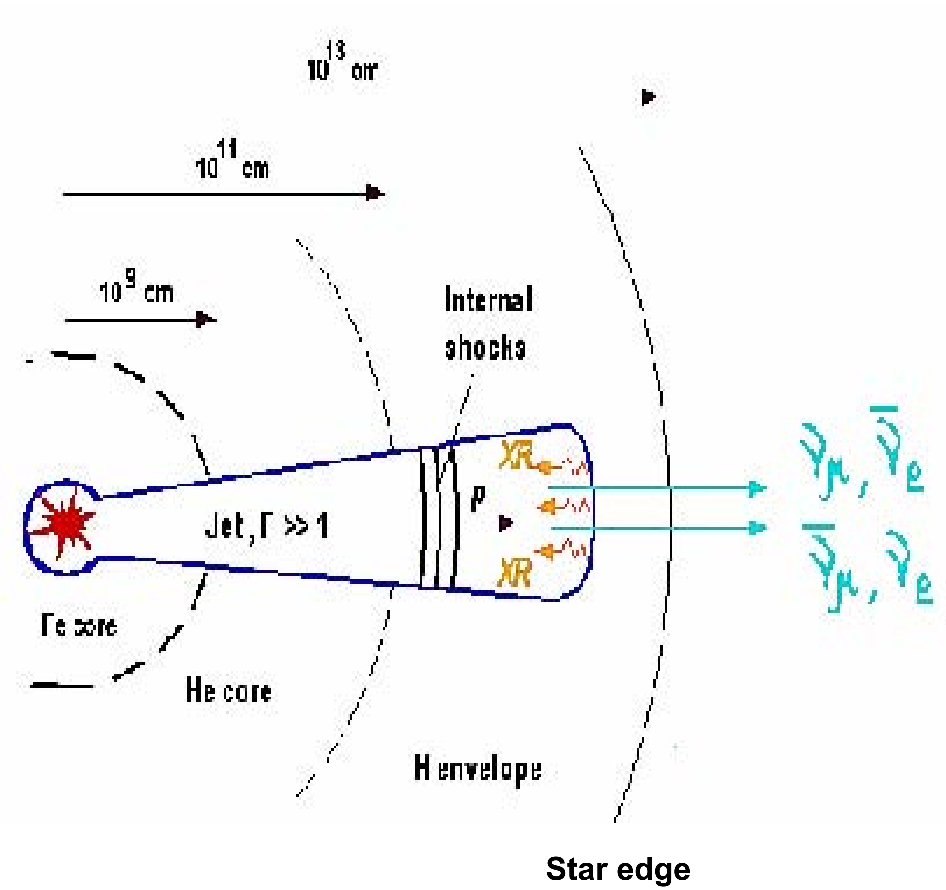
- Km^3 water Cherenkov detector
- Deployment approx. 2010
- Complement ICECUBE: $\lambda_{sc,abs}$~(100,10) H_20, $\lambda_{sc,abs}$~(20,100) Ice
- Northern site: at lower E complementary sky coverage

Point Source Sensitivities



Icecube collaboration

TeV ν from bursting & choked GRB



- Jet in massive collapsar has "external" (termination) shock and **internal** shocks , even **while inside the star**
- Int. shocks accel. protons to $E_p > 10^5$ GeV, which collide with thermal X-rays in jet cavity
- → **E$\nu \gtrsim$2(2/1+z) TeV**

$F_\nu \approx 10^{-5}\ E_{53}/D_{28}^2$ erg/cm^2

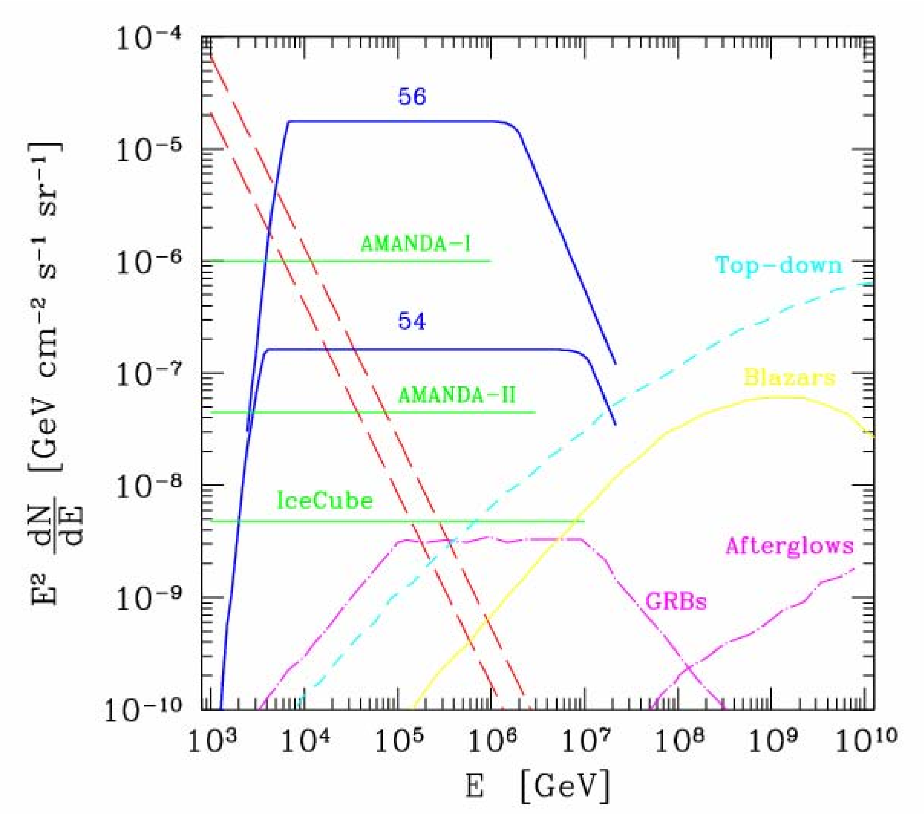
$N\mu \sim 0.2$ /km^2 (avg., 10^5 /yr)

~ 10 /km^2 (rare, ~ 3 /yr)

- ν-precursor in γ-bright GRB, and $\pi^0 \rightarrow 2\gamma$ det. @ low z w. **GLAST**
- ν- burst in γ-dark (choked) GRB → new "EM unseen" source! (e.g. pop. III ★ ?)

Mészáros, Waxman 01 PRL 87:171102

Diffuse UHE ν from pop.III collapse



Schneider, Guetta, Ferrara aph/0201342

- At z~5-30(?) pop.III , M~ 30-300 $M_\odot$, E_{iso}~10^{54}-10^{56}(?) erg
- Buried jets→pγ→ν_μ , → ν-bursts, **AMANDA/ICECUBE**
- "low-z" GRB, AGN etc
- π^0 →2γ , det. w. **GLAST**
- Detect highest z ⋆form'n, get primordial IMF,

Summary

- GRB detected and extensively studied from radio to 10 GeV (so far)
- Working model (relat. fireball + shocks) has withstood tests; will it continue to?
- Progress being made on central engine, progenitor
- Significant potential as cosmological tool
- Working on GeV-TeV EM signature → **new window**
- TeV-EeV neutrino signals: **new window**
- Gravitational wave signals: **new window**
- ⇨ **New surprises are expected !**