Gravitational Waves from GRB

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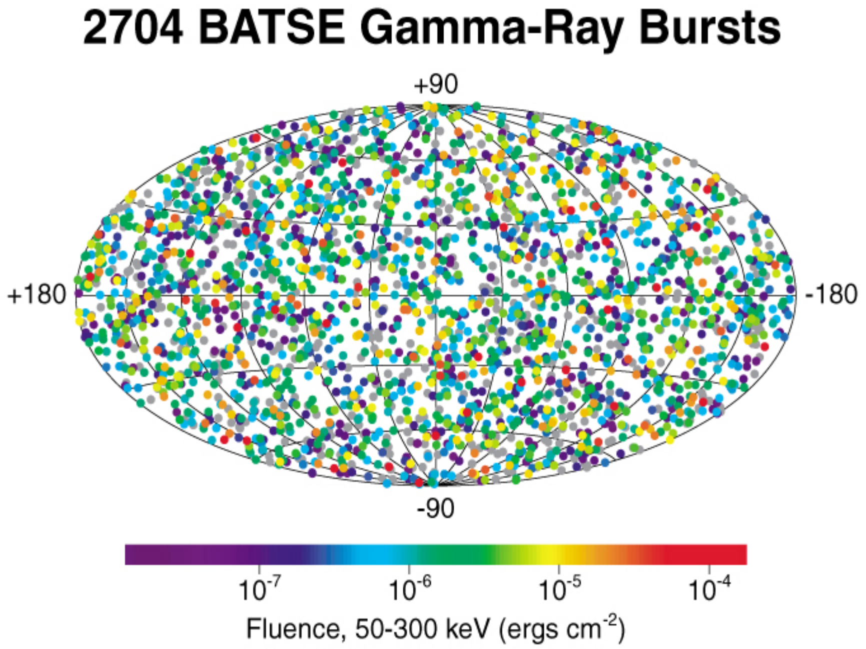
GRB Sky & Temporal Distrib.



2704 BATSE Gamma-Ray Bursts

- Cosmological distrib. (isotr.) ~3500 bursts
- Out to $z \gtrsim 4.5$ (20?)
- ~ 1/day @ $z \lesssim$ few
- ~ 2/3 “long” (t_γ >2s)

→ massive coll/SN?

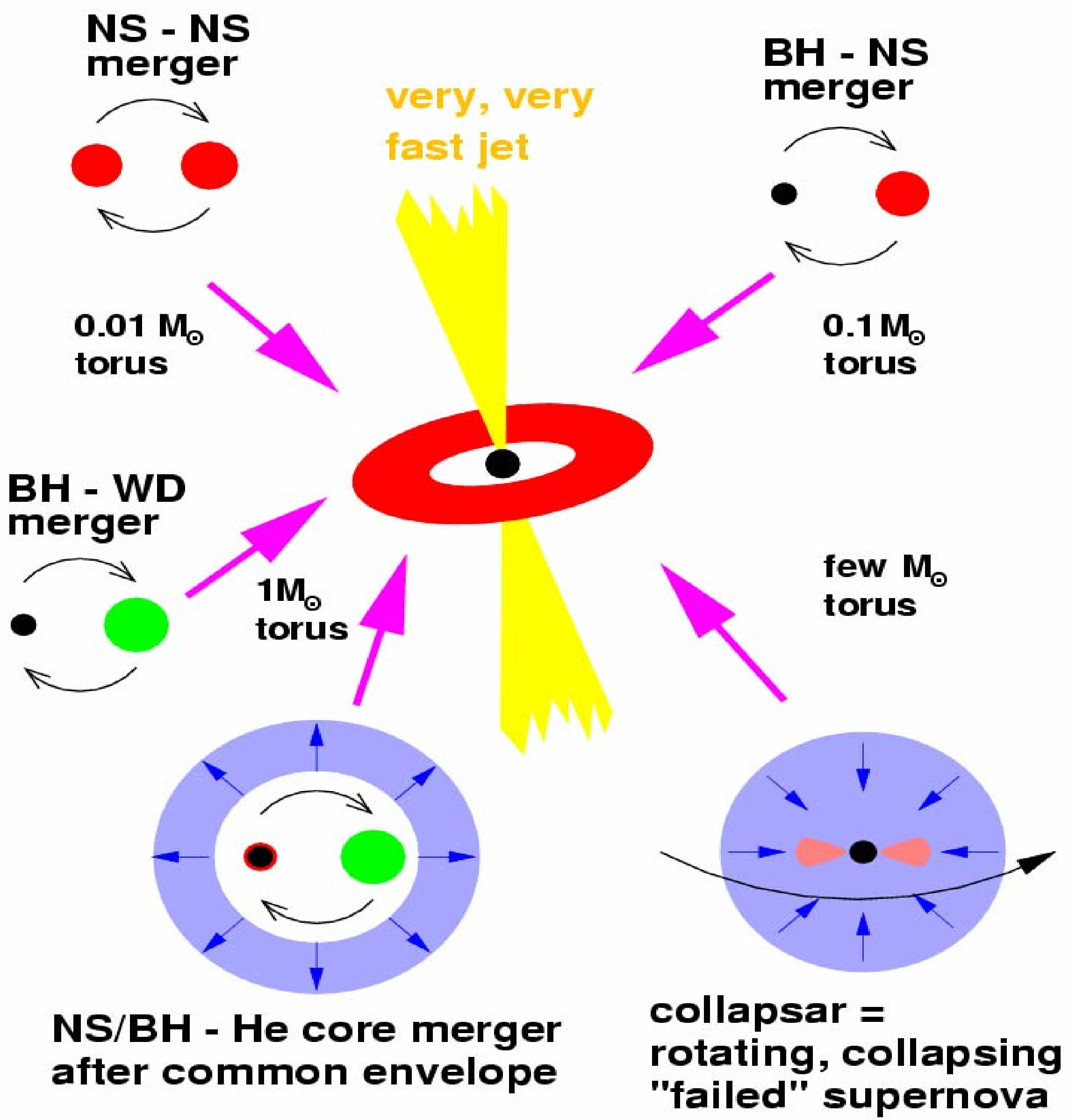
~50 afterglows well-id’d & localized in γ,X,O,R, measured redshift;
massive ★ progenitor ~confirmed

- ~ 1/3 “short” (t_γ <2s)

→ NS mergers/mag?

No afterglows so far, no ID,
only rough (deg) localization-
progenitor speculative.

GRB:→ Hyperaccreting Black Holes (leading paradigm)



NS - NS merger

0.01 $M_\odot$ torus

very, very fast jet

BH - NS merger

0.1 $M_\odot$ torus

BH - WD merger

1 $M_\odot$ torus

few $M_\odot$ torus

NS/BH - He core merger after common envelope

collapsar = rotating, collapsing "failed" supernova

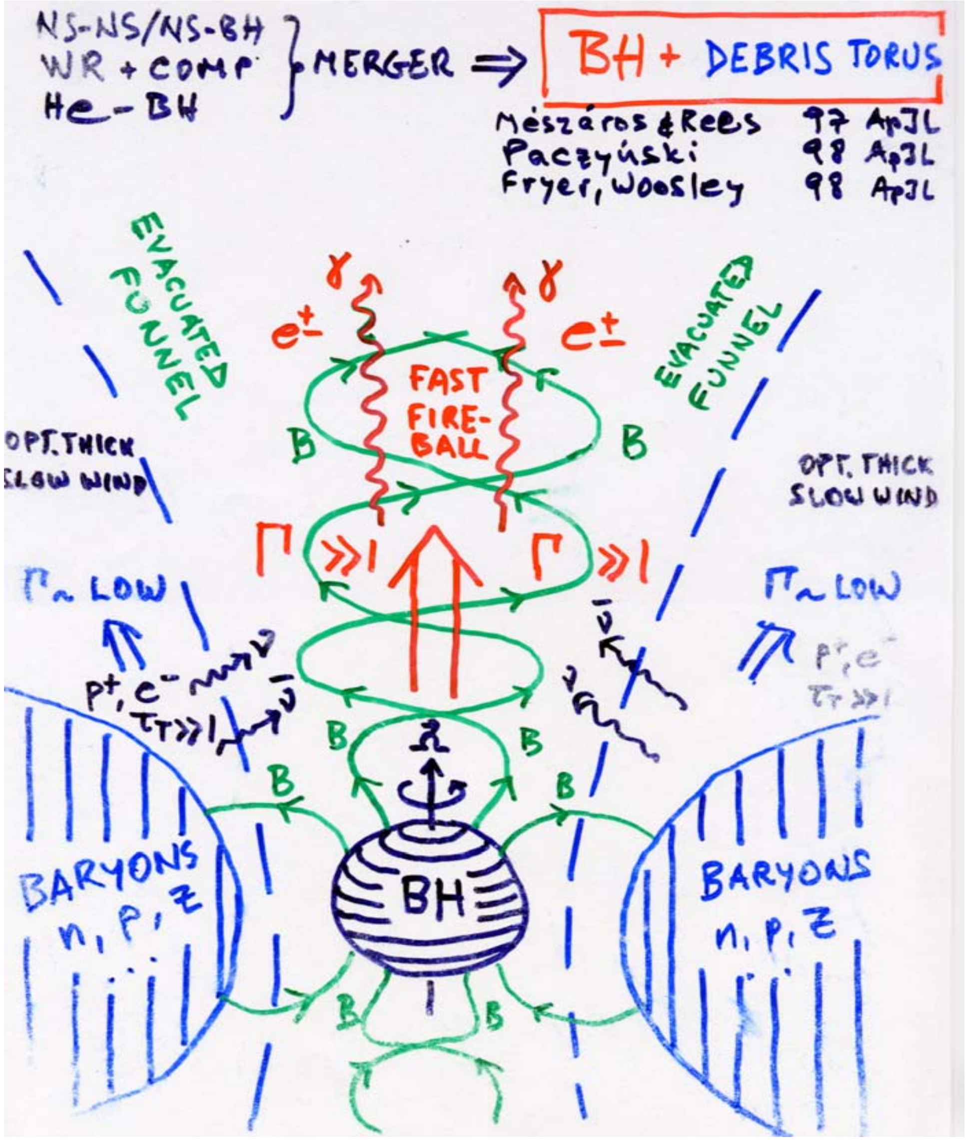
M. Ruffert, H.-Th. Janka, 1998

Short

Long

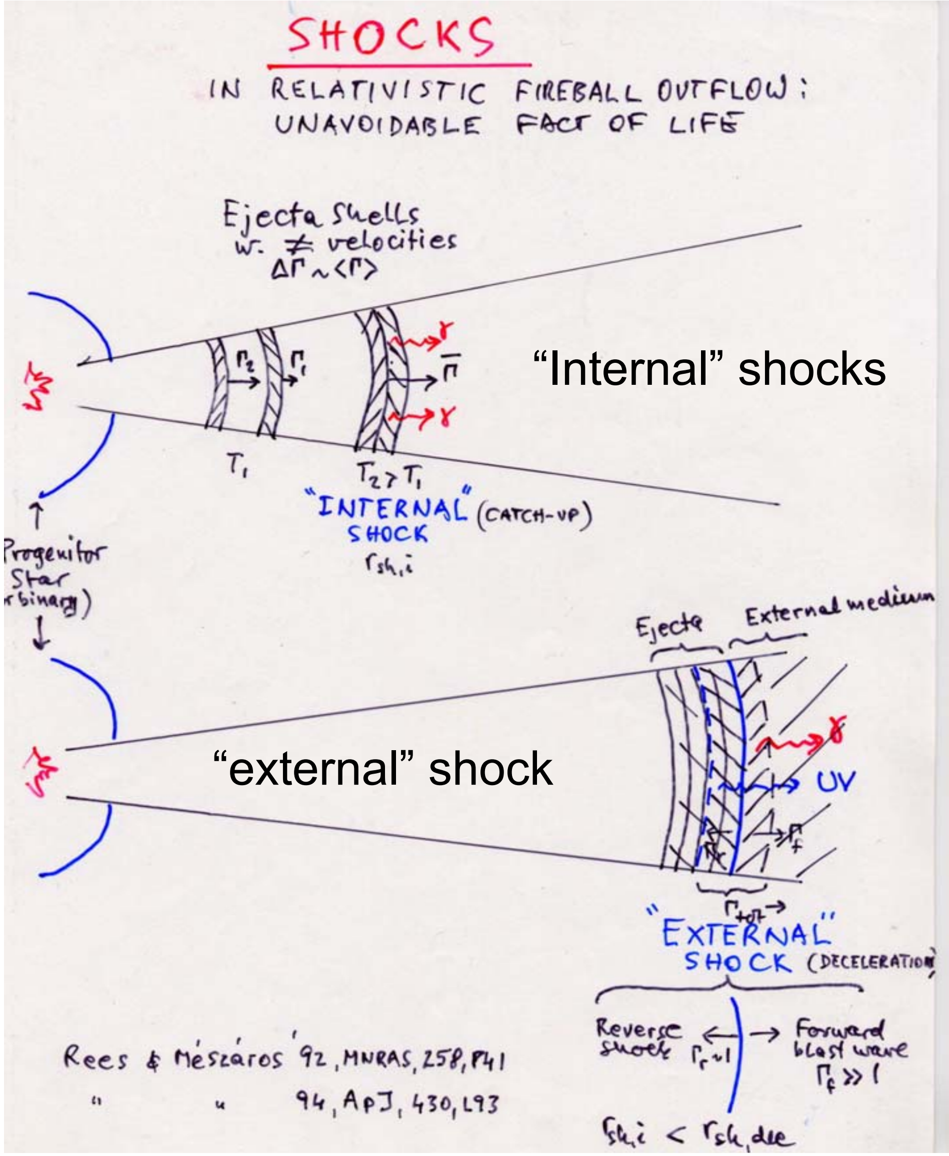
(Alternative :
both long & short
are collapsars,
w. ≠ accr times
(v.Putten/Ostriker)

BH + accr. Torus ➡ Jet



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

γ-rays: Shocks in Fireball/Jet



SHOCKS

IN RELATIVISTIC FIREBALL OUTFLOW: UNAVOIDABLE FACT OF LIFE

"Internal" shocks

"external" shock

Rees & Mészáros '92, MNRAS, 258, P41
" " '94, ApJ, 430, L93

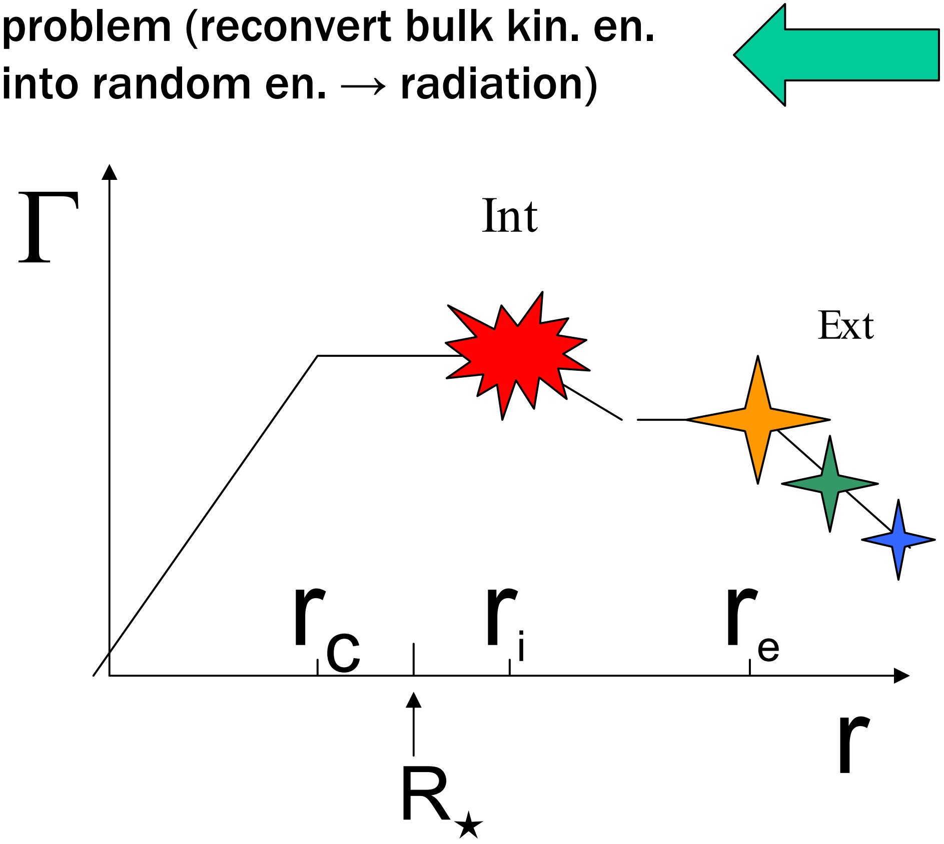
- **Shocks** expected in any unsteady supersonic outflow (esp. in a non-vacuum environment)
- **Internal** shocks: fast shells catch up slower shells (unsteady flow)
- **External** Shock: flow slows down as plows into external medium
- NOTE: "external" and "internal" shocks might be expected both while jet is inside star, as well as after it is outside. Former: γs do not escape; latter: they do.

Internal & External Shocks

in the optically thin medium outside progenitor:

LONG-TERM BEHAVIOR?

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

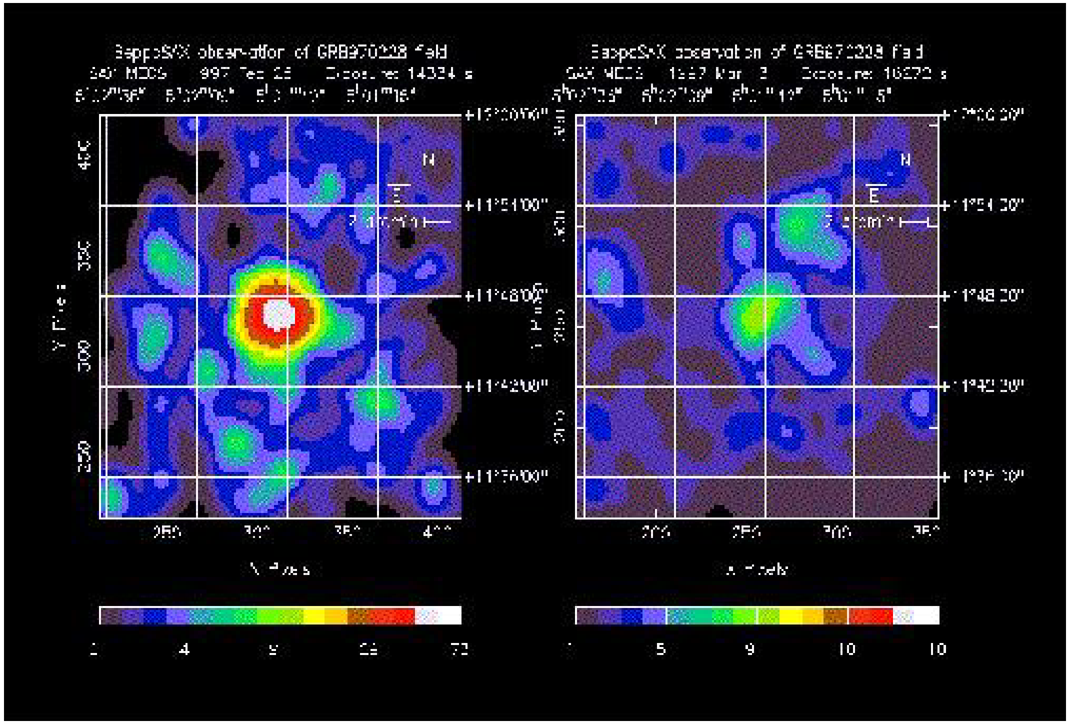


- Lorentz factor Γ first grows $\Gamma \propto r$, then coasts $\Gamma \propto$ constant, until …
- **Outside** the star, after jet is opt. thin: Internal shocks: $r_i \sim 10^{12}$cm
  →**γ-rays** (burst, t~sec)
- Externals shocks start at $r_e \sim 10^{16}$cm, progressively weaken as it decelerates

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)
  (Meszaros & Rees 1997 ApJ 476,232)

GRB970228 afterglow: Discovery by Beppo-SAX



Feb 28

March 3

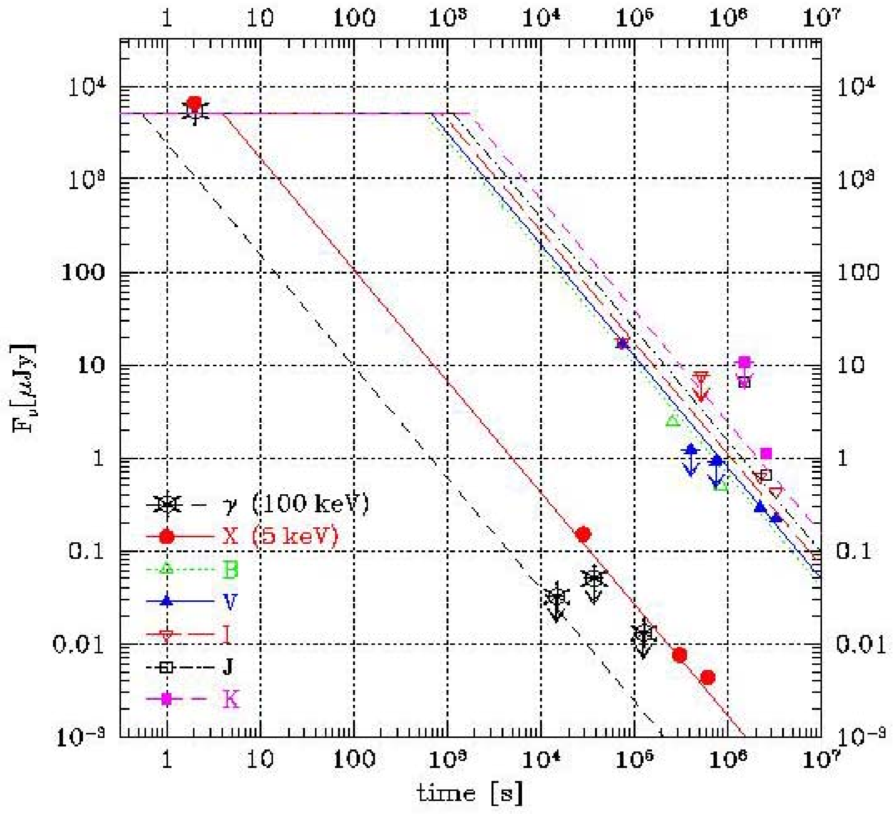
- X-ray location:2-3 arcmin →raster
- →optical (arcsec) & radio location
- Can identify host galaxy, redshift

➡ located at cosmological dist.

F_x ~3E-12 erg.cm2/keV/s , decrease by 1/20 in 8 hrs

(Costa et al 1997, Nature 387:783)

GRB afterglow blast wave model



GRB 970228 as blast wave:

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

Mészáros, Rees 97 ApJ 476:232 model

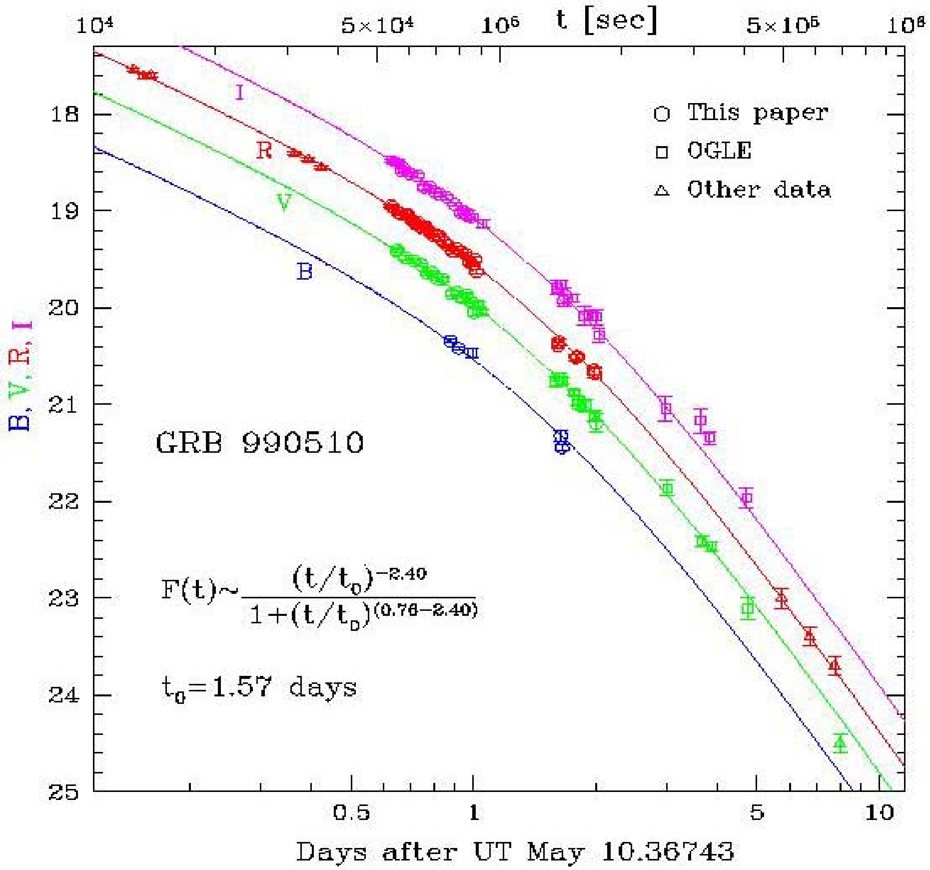
- Simplest case: adiabatic forward shock synchrotron rad’n from shock-accel. non-thermal e^-
- $F(\nu,t) \propto \nu^{-\beta} t^{-\alpha}$
- $\alpha = (3/2)\,\beta$
- Parameters E_0, ϵ_e, ϵ_B, (β=(p-1)/2)

Ultra-relativistic, collimated jets: ?

- 3-D num. hydro simulations (Aloy et al 00 ; Zhang, Woosley, McFadyen 02; Zhang, Woosley03)
- So far: Newt.SR, no MHD; jet first $v_h \lesssim c$, then $v_h \to c$ as in analyt. calc's → OK
- Γ up to 150 → OK
- KH instab: variable power output, var Γ
- Prelim (num) concl.: jets emerge only from $R_\star \lesssim 10^{11}$cm; (but larger stars not calculated num'ly);
- analyt. est. indicate larger stellar radii are possible (Meszaros, Rees 02, ApJ 556, L37)

W. Zhang & Woosley 03 ↑

Evidence for (collimated) Jets



- $\Gamma \propto t^{-3/8}$, but as long as $\theta_{casual} \sim \Gamma^{-1} < \theta_{jet}$, spherical expansion is good approx
- "see" jet edge at $\Gamma \sim \theta_{jet}^{-1}$
- Before, $F_\nu \propto (r/\Gamma)^2 . I_\nu$
- After, $F_\nu \propto (r\theta_{jet})^2 . I_\nu$,

  steeper by $\Gamma^2 \propto t^{-3/4}$
- After $\Gamma < \theta_{jet}^{-1}$ also can start sideways expansion,

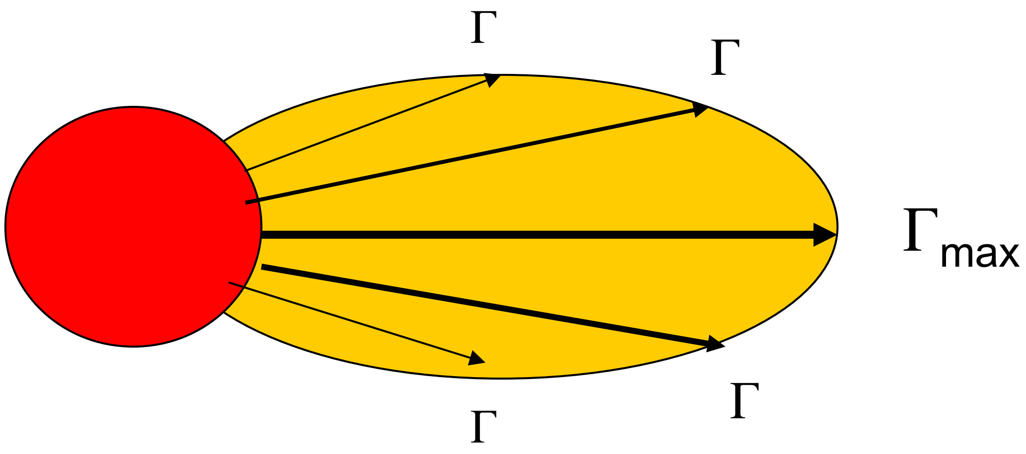
  → further steepen $F_\nu \propto t^{-p}$

Collimation vs. type

- **Long bursts**: “collapsars”, massive stellar envelope provides transverse pressure for collimation.
  All jets so far are long bursts (but obs. select.);
  on avg long bursts brighter than short ones,
  log N-log S departs more from Euclidean

- **Short bursts**: could be (?) DNS mergers;
  no stellar envelope to collimate jet;
  on avg. are slightly fainter than long bursts,
  log N-log S closer to Euclidean
  → consistent with less collimation

“Shaped” jets



(Rossi, Lazzati& Rees ’02; Zhang & Mészáros ’02)

- Jets unlikely to be top-hats
- $L(\theta)$ $[\Gamma(\theta)?] \propto \theta^{-2}$ “universal” beam also fits jet data
- At high θ expect softer radiation

→ “XRF”s?,

“Orphan” afterglow?

Collapsar & SN :

does one imply the other ?

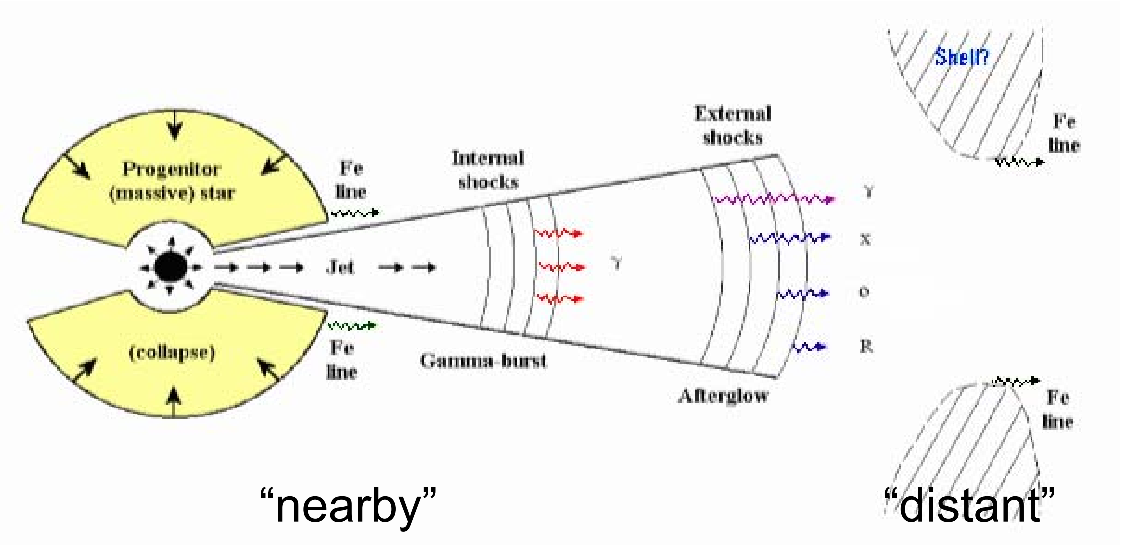
- Core collapse of star w. $M \gtrsim 30\ M_\odot$
  → BH + disk (if fast rot.core)
  → jet (MHD? baryonic? high Γ,
  + SNR envelope eject (?)
- 3D hydro simulations (Newtonian SR) show that baryonic jet with high Γ can be formed & escape
- SNR: not seen numerically yet, **but** observational suggestions, e.g. late l.c. hump + reddening- and :
- GRB 030329: det. SN ~time coincid.!

Collapsar & SN (ANIMATION!)

Credit: Derek Fox

& NASA ↓

XR lines: Collapsar Jet or SN Shell



- “Nearby” model : Collapsar w., e.g. decaying jet($\gtrsim$dy),e.g from fall -back BH accretion, or magnetar
- Timescale: intrinsic, $R \sim 10^{13}$ cm
- $L_x \sim 10^{47}$ erg/s, $\propto t^{-1.3-1.5}$, $n \sim 10^{18}$/cc,
- $\xi \sim 10^3 \rightarrow$ **Fe Kα,** $L_{Fe} \sim 10^{45}$ erg/s
- Need $M_{Fe} \sim 10^{-5}\ M_\odot$ -solar or enrich. OK

(Rees & Mészáros 00, ApJ 545:L73)

- “Distant” model: pre-supernova shell (“supranova”), or gas from companion star?
- Timescale: geom., $r \sim 10^{15}$-10^{16} cm, $t \sim (r/c)(1-\cos\theta) \sim$dy
- Need $M_{Fe} \sim 0.1$-$1\ M_\odot$, 10-10^2 x solar
- 70 day for Ni→Fe?

(Piro etal 00, Sci.290:955;
Vietri etal 01, ApJ 550:L43)

GRB Progenitor Rates & Min. Distances for 1 event/year

	Rate (avg)	Rate-rge	Dist (avg)	Dist-range
	$\mathrm{Myr^{-1}gal^{-1}}$	$\mathrm{Myr^{-1}gal^{-1}}$	Mpc	Mpc
DNS	1.2	0.01-80.	220	53-1100
BH-NS a	2.6	0.001-50	170	62-2300
BH-NS b	0.55	0.001-50	280	62-2300
BH-WD	0.15	0.0001-1	430	230-4900
BH-He	14	0.1-50	95	62-490
Collapsar	630	10-1000	27	23-110

(Data from Fryer etal, 99, ApJ 526,152; Belczynski etal, 02, ApJ 571,394)

Simple parametrized astrophysical GRB GW model: Shiho Kobayashi & P.M.

In-spiral phase

- Inspiral of m_1, m_2 (binaries):

  $h_c(f) = f\,|\hat{h}(f)|$: characteristic strain

  $<\rho^2> = 4 \int (|\hat{h}|^2/S_h)\,df = (2/5\pi^2 d^2) \int df\,(1/f^2 S_h)(dE/df)$

  $dE/df = [(\pi G)^{2/3}/3]\,\mathcal{M}^{5/3} f^{-1/3}$: energy spectrum,

  $\mathcal{M} = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$: chirp mass [Flanagan, Hughes 99]

- → $h_c(f) \sim (1/\pi d)[(G/10c^3)(dE/df)]^{1/2}$

  $\sim 1.4\ 10^{-21}(d/10\mathrm{Mpc})^{-1}(\mathcal{M}/M_\odot)^{5/6}(f/100\mathrm{Hz})^{-1/6}$

Merger

- binary, or coll. blob in-spiral ends (for DNS/BH-WD-He) at $f_i \sim 10^3\ (M/2.8M_\odot)^{-1}$Hz / $0.1(M/M_\odot)^{1/2}\ (l/10^9\text{cm})^{-3/2}$ Hz
- Merger ends (quasi-normal ring l=m=2 starts) at $f_q \sim F(a)\ c^3/2\pi\ GM \sim 32\ F(a)\ (M/M_\odot)^{-1}$ kHz ; [$F(a)=1-0.63(1-a)^{3/10}$]
- En. Radiated: $E_m = \epsilon_m\ (4\mu/M)^2\ Mc^2$; [$\epsilon_m \sim 5\%$, $\mu=m_1m_2/M$]
- $dE/df \sim E_m\ /(f_q - f_i\ ) \sim E_m\ /f_q$ (asume simple flat spectrum)
- $h_c\ (f) \sim (1/\pi d)[(G/10\ c^3)(dE/df)]^{1/2}$ $\sim 2\ .7\ .10^{-22}\ F(a)^{-1/2}\ (\epsilon_m\ /0.05)^{1/2}(4\mu/M)(M/M_\odot\ )(d/10\text{Mpc})^{-1}$

(e.g. Lai & Wiseman 96; Khanna etal 99; Flanagan & Hughes 98)

Bar / Dynamical Instabilities

- Bar mass m, length 2r, around BH mass m',

  rot. freq. $\omega = (Gm'/r^3)^{1/2}$
- Disk: dynamical instab. → blob, mass m $\sim \alpha M_\odot$ around BH mass $\sim 3\text{-}10\ M_\odot$
- Both → similar expression ,

  $h = (32/45)^{1/2} (G/c^4)(mr^2\, \omega^2/d)$

  $h_c \sim N^{1/2}\, h$ [N : # of cycles of approx. coherence ~10]

  $\sim 2.10^{-21} (N/10)^{1/2} (mm'/M_\odot{}^2)(d/10\mathrm{Mpc})^{-1} (r/10^6\ \mathrm{cm})^{-1}$

(e.g. Fryer, Holz & Hughes 02)

Ring-down

- Deformed BH → damped oscillations,

  slowest mode: l=m=2 (also pref. excited)
- Spectrum peaks at $f_q \sim 32\, F(a)(M/M_\odot)^{-1}$ kHz,

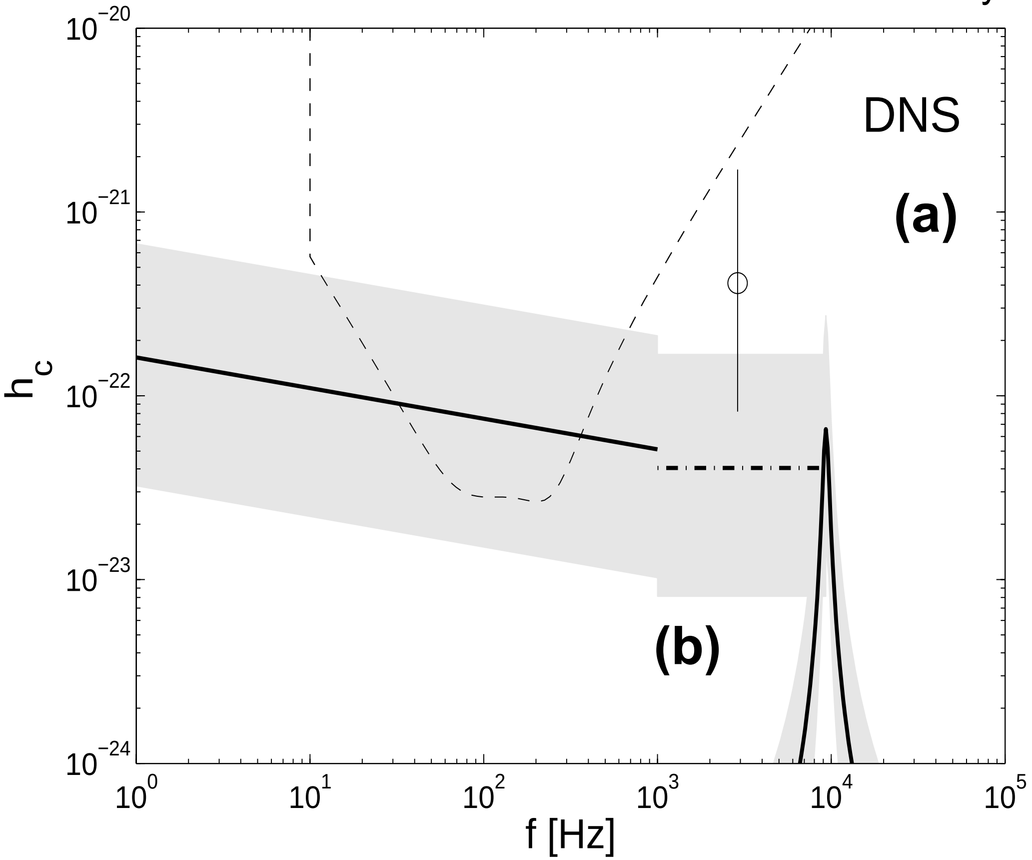
  width $\Delta f \sim \tau^{-1} \sim \pi\, f_q / Q(a)$; [$Q(a)=2(1-a)^{-9/20}$]
- $dE/df \sim (E_r\, f^2 / 4\, \pi^4\, f_q^2\, \tau^3\,)$.

  $.\{[(f-f_q)^2 + (2\pi\tau)^{-2}]^{-2} + [(f+f_q)^2 + (2\pi\tau)^{-2}]^{-2}\}$

  (where $E_r = \epsilon_r\, (4\, \mu/M)^2\, Mc^2$, assumed $\epsilon_r = 0.01$ rad. en.)
- $h_c \sim 2.\ 10^{-21}\, (\epsilon_r / 0.01)^2 (Q/14F)^{1/2} (\mu/M_\odot)(d/10\mathrm{Mpc})^{-1}$

GRB Progenitor GW Signals: DNS

Kobayashi & Mészáros 03, ApJ(a-ph/0210211)



Double neutron star

Charact. Strain h_c

D (avg) =220 Mpc,

$m_1=m_2=1.4\ M_\odot$,

$a=0.98$, $\epsilon_m=0.05$,

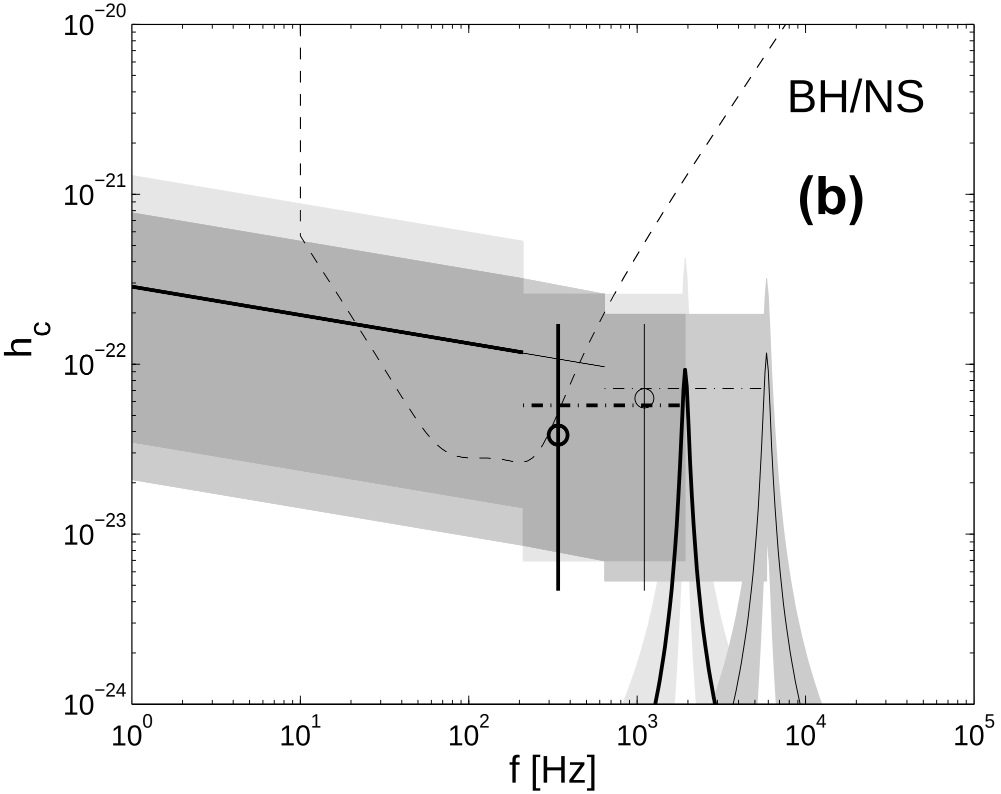
$m=m'=2.8\ M_\odot$, $N=10$,

$\epsilon_r=0.01$

Dashed: LIGO II sensitivity

Solid: inspiral; Dot-dash: merger;
circle (bar inst); spike ring-down);
shaded region: rate/distance uncertainty

GRB Progenitor GW Signals: BHNS

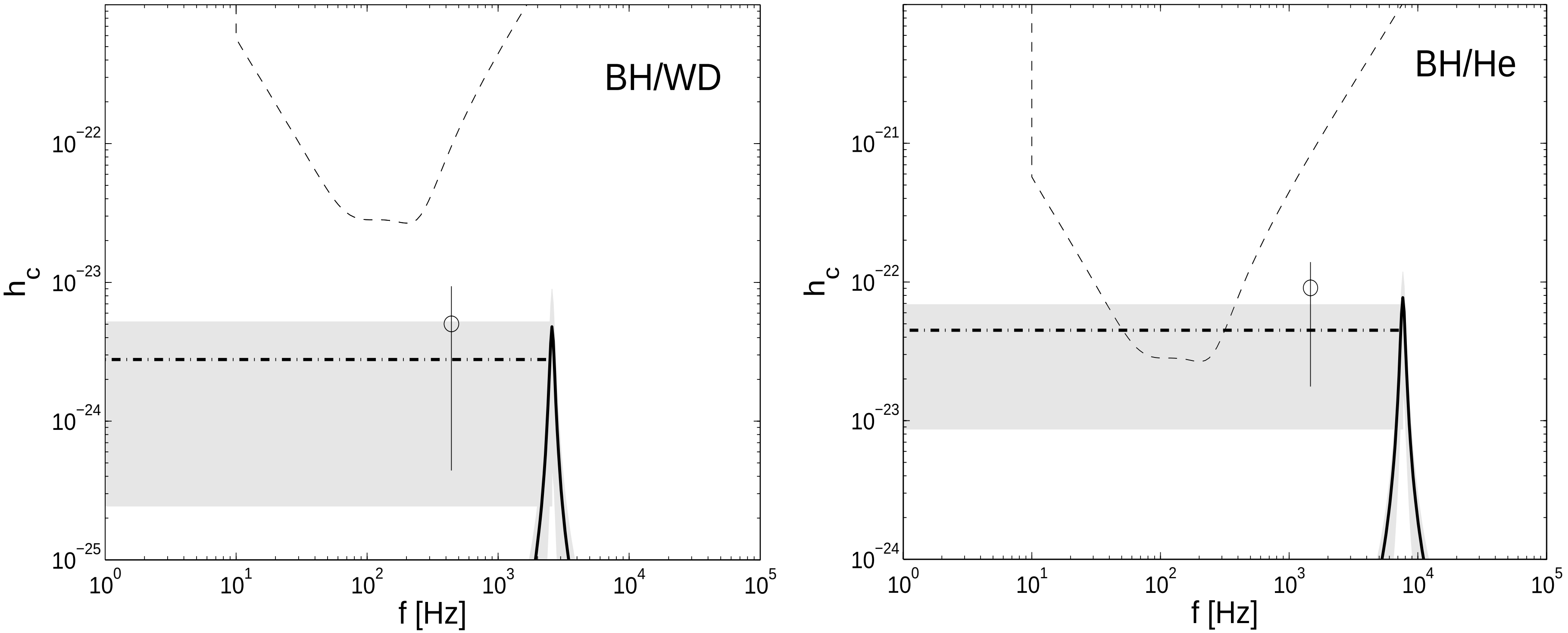


- Solid: inspiral; Dot-dash: merger; circle (bar inst); spike ring-down); shaded region: rate/dist uncertainty Dashed: LIGO II noise $[f\,S_h(f)]^{1/2}$

Black hole-neutron star

thin: d=170Mpc,
$m_1=3.0M_\odot$, $m_2=1.4\,M_\odot$, ,
$m=0.5\,M_\odot$, $m'=4\,M_\odot$
thick: d=280Mpc,
$m_1=12\,M_\odot$, $m_2=1.4\,M_\odot$,
$m=0.5\,M_\odot$, $m'=13\,M_\odot$;
Both: $a=0.98$, $\epsilon_m=0.05$,
$N=10$, $\epsilon_r=0.01$

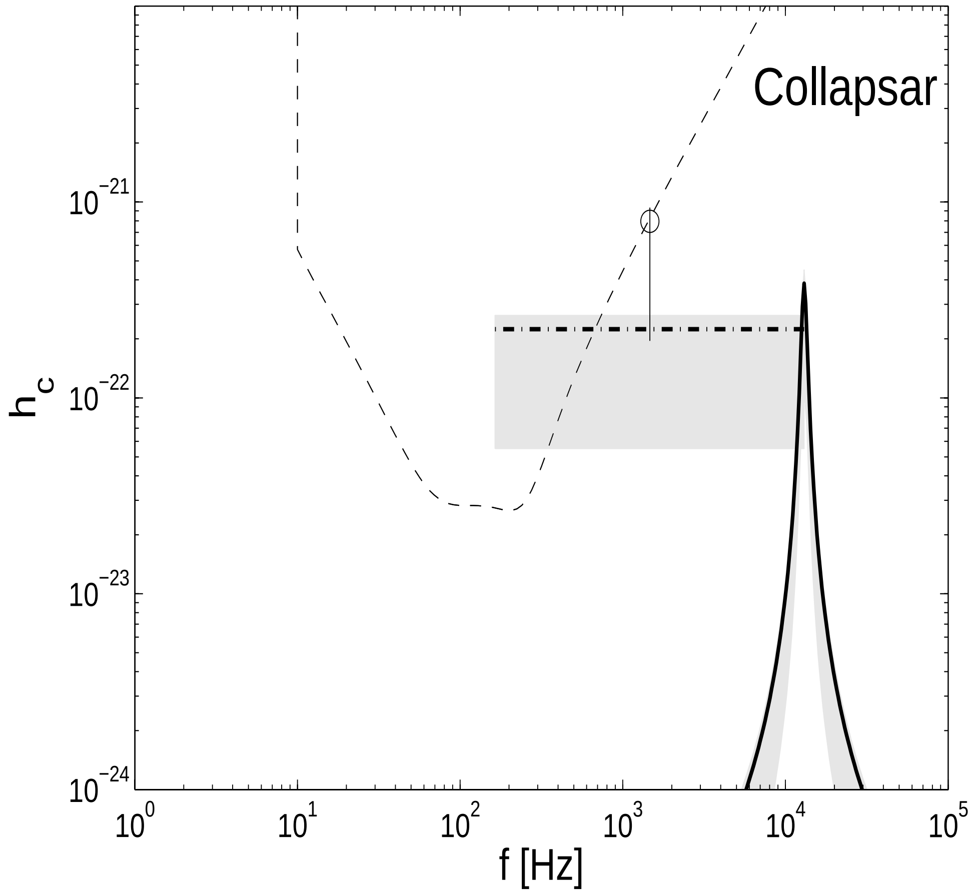
Unpromising GRB/GW signals: **BH/WD,He**



- **BH-WD**: d=430 Mpc, m_1=10, m_2=0.1, a=0.98, ϵ_m=0.05; m=0.1, m'=10, N=10, ϵ_r=0.01
- **BH-He**: d=95 Mpc, m_1=3, m_2=0.4, a=0.98, ϵ_m=0.05; m=0.4, m'=3, N=10, ϵ_r=0.01

GRB Progenitor GW Signals: Collapsar

Kobayashi & Mészáros 03, ApJ(a-ph/0210211)



Collapsar w. core breakup, bar inst.

(optimistic numbers!)

d=270 Mpc,

$m_1=m_2=1\ M_\odot$, a=0.98,

$\epsilon_m=0.05$,

merge at $r=10^7$ cm;

$m=1\ M_\odot$, $m'=3\ M_\odot$,

$N=10$, $\epsilon_r=0.01$

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

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

Detectability :

Binary progenitors: upper limits, in one year LIGO II

- **BH-NS**, **NS-NS**: waveform templates
  → matched filtering, esp. for in-spiral;
  S/N : $\rho = [\, 4 \int \{\hat{h}(f)|^2 / S_h(f)\} \, df \,]^{1/2} \gtrsim 5$
  (where S_h (f): noise power of detector)
- $\rho_{\mathrm{DNS,insp}} \sim$
  $7.5 \; (1.5,30) \; (\mathcal{M}/1.2 M_\odot)^{5/6} \, (R/1.2 \; \mathrm{Myr}^{-1} \, g^{-1})^{1/3}$
- $\rho_{\mathrm{BHNS,insp}}^{\mathrm{(case\ a)}} \sim$
  $13 \; (0.9,35) \; (\mathcal{M}/1.8 M_\odot)^{5/6} \, (R/2.6 \; \mathrm{Myr}^{-1} \, g^{-1})^{1/3}$

$\rho_{\mathrm{BHNS,insp}}^{\mathrm{(case\ b)}} \sim$
$12 \; (1.5,54) \; (\mathcal{M}/3.2 \; M_\odot)^{5/6} \, (R/0.55 \; \mathrm{Myr}^{-1} \, g^{-1})^{1/3}$

Detectability :

Collapsars: upper limits, in one year LIGO II:

- No templates (e.g. merger, ring-down):
  → use cross correlation of 2 det. output

[Finn et al, 99 ; Finn, Krishna & Sutton, astro-ph/0304228]

- s_i (t)= h_i(t + n_i(t); n_i(t) =detector noise;
  [spatial coincidence made through arrival time correction];
  signal weighted cross correlation : [G: filter function]
  $X_{on} \sim \int df \int df' \, \delta_T(f-f') \, \hat{s}_1^*(f) \, \hat{s}_2 (f') \, \hat{G}(f')$
  noise fluctuation cross correlation : [T= gw-γ lag] :
  σ_{off} = avg $[(n_1,n_2)^2]^{1/2} \sim C \, [(T/4) \int df / S^2 (|f|)]^{1/2}$
  S/N : $\rho = X_{on} / \sigma_{off} \gtrsim 5$
- $\rho_{\mathbf{Coll,merg}}$ ~ **3** $(\epsilon_m/0.05)$ (F[a]]/0.8) $(T/10\ s)^{-1/2}$
  . $(\mu / 0.5\ M_\odot)^2 \, (R/630\ Myr^{-1}\ gal^{-1})^{2/3}$

[Kobayashi & Mészáros 03, ApJ in press (astro-ph/0210211]

GW Polarization

Kobayashi & Mészáros 03, ApJL 585, L89

- $h^{TT} \propto [\, \nabla\nabla\, Y^{22}\,]^{TT}$ (transv. traceless comp.)

  $h_+ \propto (1+\cos^2 \alpha)$, $h_x \propto 2 \cos\alpha$,

  $h_i = \mathrm{Re}\{ A_i \exp[-i\omega t] \}$,

  where for l=m=2 mode $A_+ \propto (1+\cos^2 \theta)$, $A_x \propto 2i \cos \theta$

  (α: angle resp. ang. mom; θ: viewing angle)

Pol. Tensor $\rho_{ab} = \langle A_a A_b^* \rangle / \langle |A_+|^2 + |A_x|^2 \rangle =$

$$= (1/2) \begin{pmatrix} 1+\xi_3 & \xi_1 - i\xi_2 \\ \xi_1 + i\xi_2 & 1-\xi_3 \end{pmatrix}$$

$\xi_1 = 0$, $\xi_2 = f(\theta)$ → circular polarization,

$\xi_3 = 2(1-\cos\theta)^2 (1+\cos\theta)^2 / [(1-\cos\theta)^4 + (1+\cos\theta)^4] \equiv P$ → lin. polariz.

$P \sim 10^{-2} (\theta / 30^{\circ})^4$ → degree of lin. polarization of GW

(while **$L_\gamma \propto \theta^{-2}$** → γ-ray lum. of long GRB (collapsar?))

Polarization Detectability

- Need 2 detectors with non-paralell arms
- At least S/N $\rho \geq P^{-1}$ to detect linear pol. deg. P ;
  (from num. sim. → need $\rho = 10\ P^{-1}$)
- Collapsar: $\rho \sim 16\ (d/100\ \mathrm{Mpc})^{-1}$

→ optimal orientation, P=1% if $d_{max} < 3.5$ Mpc

- But, 10^3 grb/yr at <3 Gpc →$<d_{min}> \sim 300$ Mpc
- LIGO II sensit'y @ $f_0 \sim 150$Hz :
  $[f_0\ S(f_0\ )]^{1/2} \sim 3.10^{-23}\ \mathrm{Hz}^{-1}$, and $d_{max} \propto S_0^{-1/2}$;
  → **if future** detector with $[f_0\ S(f_0\ )]^{1/2} \sim 3.10^{-25}\ \mathrm{Hz}^{-1}$
  → may detect **P~1%** in **1 year**

Kobayashi & Mészáros 03, ApJL 585, L89

Some potential GW-EM correlations in GRB

- DNS/BHNS: good GW source, but weaker (less collimated) GRB
  - expect “short” (<2 s) GRB, no (or weak) afterglow (?)
- Collapsar: weaker GW source, but strong and “long” (>2 s) GRB, with many EM afterglows observed
- GW for both may be detectable w. LIGO II (Kobayashi & Mészáros, ApJ (a-ph/0210211)
- non-aligned jet obs. at $\Gamma \sim \theta_j^{-1}$, and $\Gamma \propto t^{-1/2}$

  → afterglow peaks at time $t_p \propto \theta^2$ after GW → $P \propto t_p^2$
- XRFs: may be misaligned jets, →preceded by GW,

  XR softness $\propto t_p^{1/2}$ (Kobayashi & Meszaros 03 ApJL 585, L89)
- Collapsar: BH of $\neq$ ang. rot. rate “a” have $\neq$ polar accr. rates,

  and $\neq$ polar infall turnaround times (“explosion”), ⟶ predict $\neq$ delays between GW and GRB as function of stellar mass & BH rotation rate a (e.g. for $M_* = 40\ M_\odot$, $t_{del} \sim 50, 60, 10^4$s for a=0.95, 0.75, 0

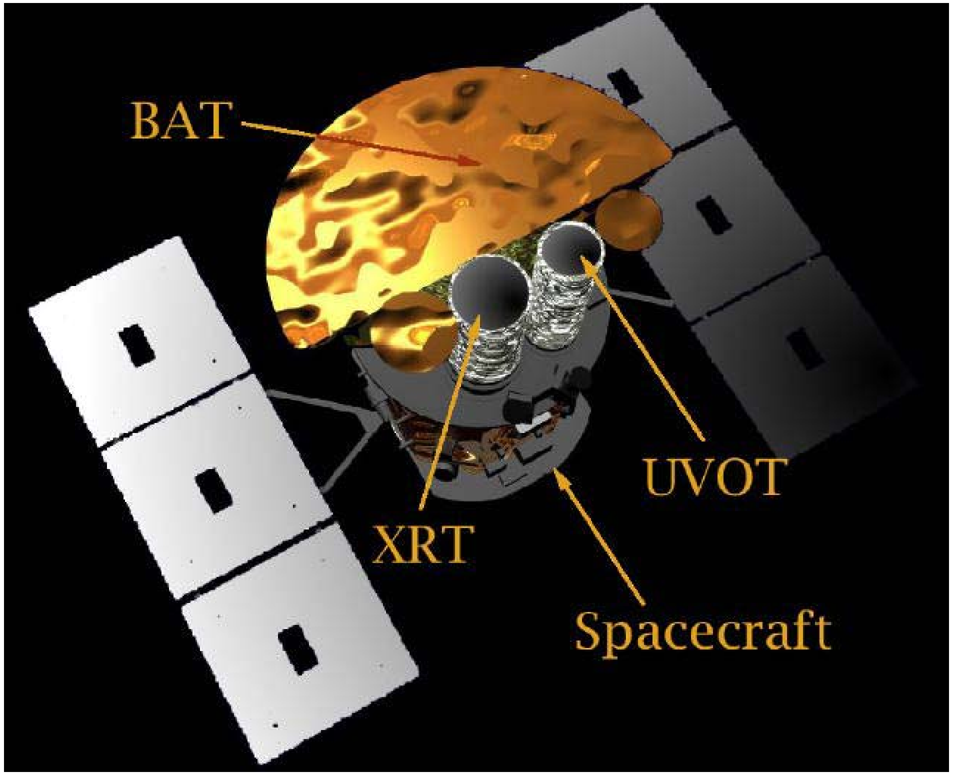
  (Fryer & Mészáros 03 ApJL, a-ph/0303334)

HETE-2 & SWIFT

Credit: HETE-2 & NASA ↓

- **HETE-2** is now working
  (~ 1-2 bursts/month) , ~ deg positions transm. to ground robotic opt. cam.
  → 2 prompt flashes 1-10 min. after trig.
- **SWIFT** : launch December 03;
- Expect 200-300 bursts/year
- Fast-slewing ($\lesssim$minute) for on-board XR & Opt follow-up,
- Transmit ~deg positions in 5-10 sec, arc-sec position in $\lesssim$5 min

Swift



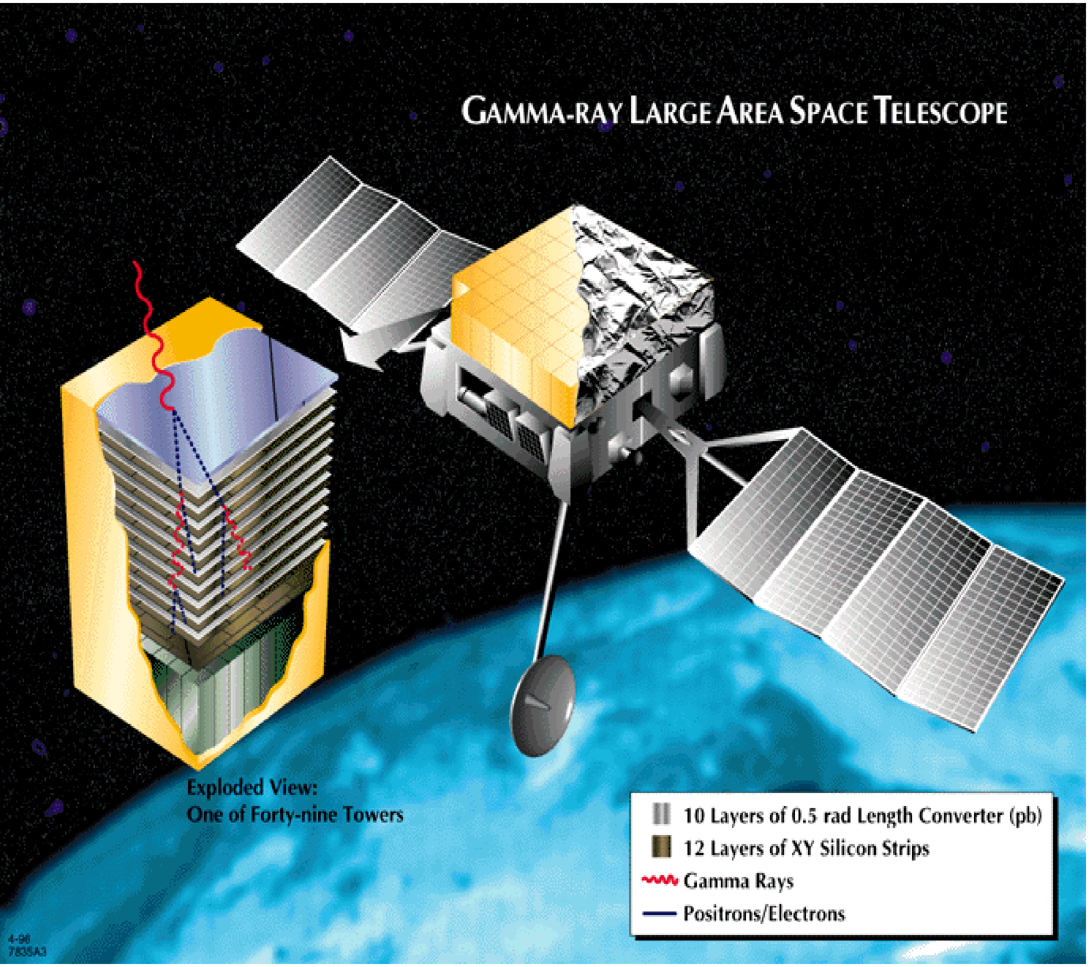
Expect ~250-300 GRB/yr localized & followed up in gamma/XR/Opt

- Sched Launch Dec 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”,

Swift (cont.)

- BAT: coded mask CdZnT det., 5x BATSE sensitivity, spectra R~20 (10-150keV) , FOV 2 sr, quick position (θ~1-4’) to ground in ~5 s
- XRT: CCD detector mosaic, imaging+spectra; fine position θ~0.3-2.5” in 25-70s ; FOV: 23’x23’, flux sensitivity $F_E \sim 2.10^{-14}$ 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: spectral resolution R~300-600 $m_v \lesssim 17$, 6 color photom redshifts $1.5 \lesssim z \lesssim 4(5)$ $m_v \lesssim 24$ (10^3s)

GLAST : LAT (Stanford + int.coll.)



- LAT: 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)

UHE ν

from p,γ in γ-detected GRBs

- Relativistic jet expands beyond stellar debris, where it is optically thin
- "Internal" N.R. shocks in jet accelerate p,e to relativistic power law (Fermi: index -2)
- e,B $\rightarrow \gamma$ (MeV, broken power law), and

$p,\gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}, \nu_{\mu} \rightarrow e^{\pm}, \nu_e, \nu_{\mu}$ (Δ-res.)

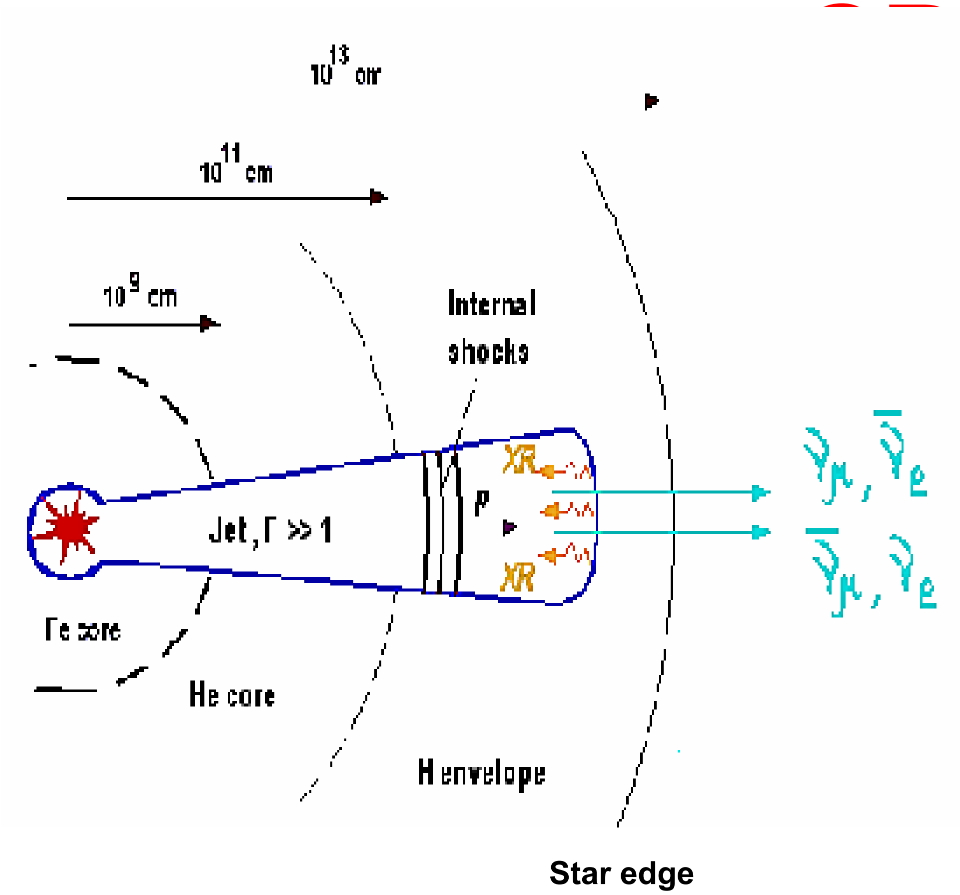
$E_{\nu} \sim 5.10^{14}$ eV $\Gamma_{300} (E_{\gamma}/1\mathrm{MeV})^{-1}$ (~100 TeV)

Flux: $E_{\nu}^2\, dN/dE_{\nu} \sim 10^{-8} (E\nu/E\nu_b)$ GeV/cm^2 s sr

(Waxman & Bahcall 1997)

Mészáros gw03

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)

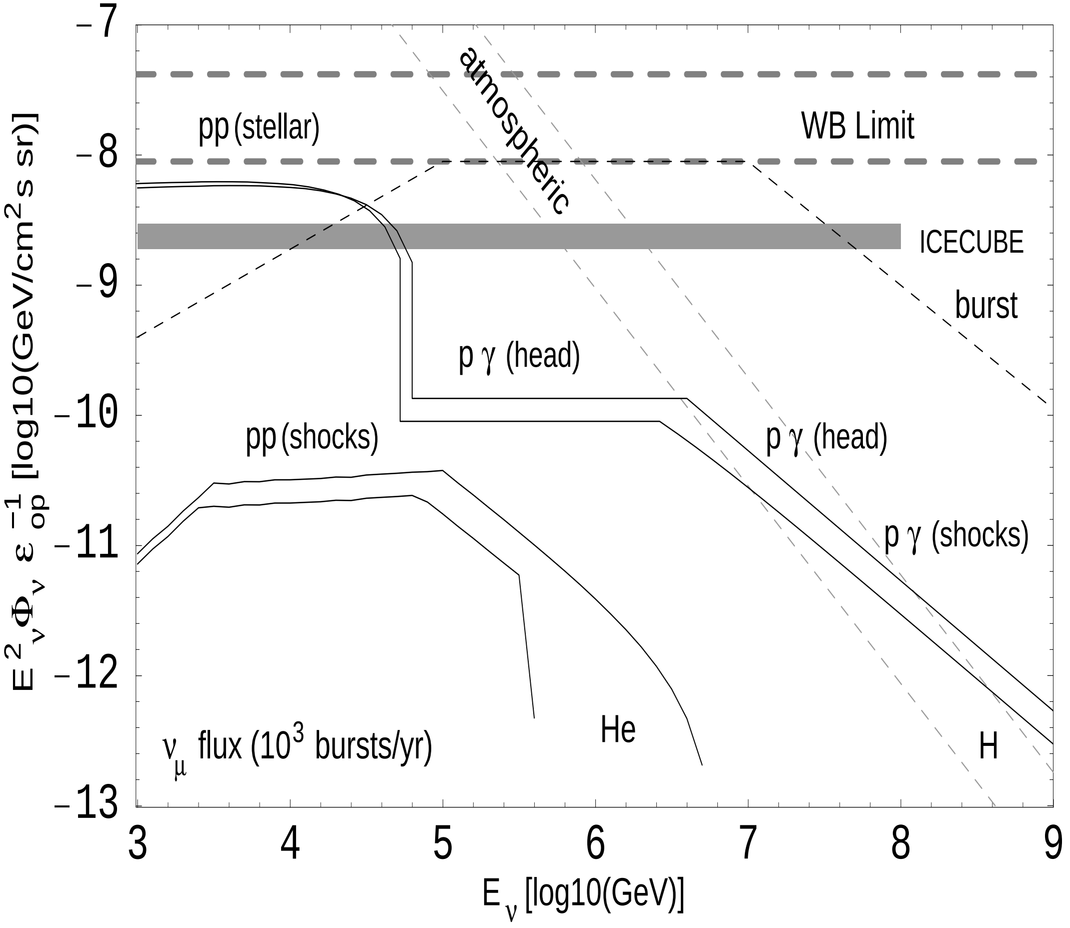
- ν-precursor in γ-bright GRB, or
- ν- burst in γ-dark (choked) GRB

→ new "EM unseen" source!

(e.g. pop. III ★ ?)

Mészáros, Waxman 2001 PRL 87:171102

Successful & Choked GRB UHE ν



Razzaque, Meszaros & Waxman, astro-ph/0303505)

- ⟵ “**Successful” bursts**, diffuse ν-flux before jet emerges (later see γ-rays too)
- **Upper** curves (logR=12.5cm):
  (H) He core + H env star
- **Lower** curves (logR=11 cm):
  (He) He core (no H env) star
- Contributions: a) pγ from int. shocks; b) pγ at the jet head (at higher E’s); c) pp and pn from accel. jet protons with p,n in shocks and in stellar envelope (at lower E’s:domin. by multipion decays

- **Choked bursts** (where jet never emerges): no γ-rays, but diff. ν-flux $\lesssim$**x100 higher**

GRB w. pre-supernova shell ?

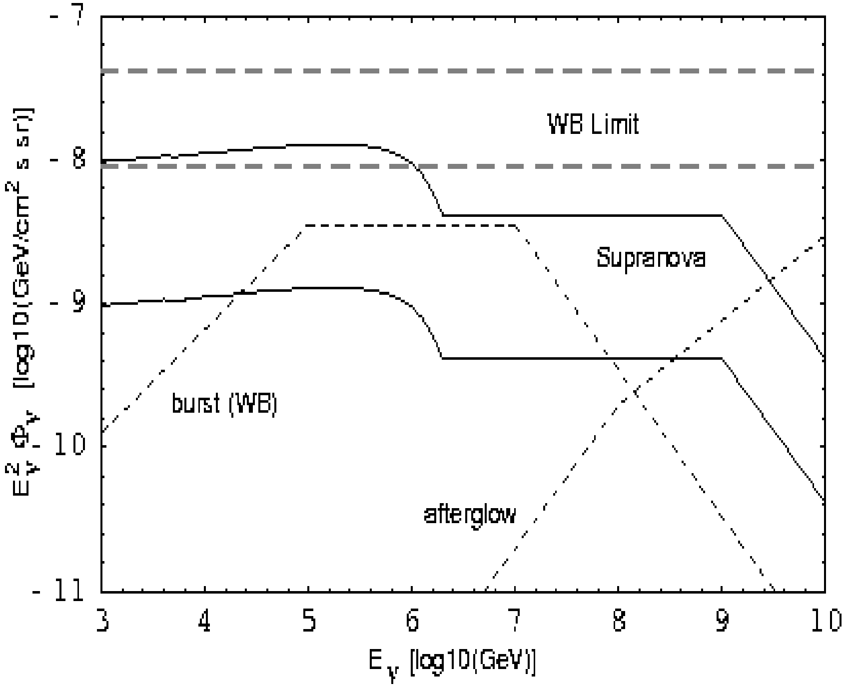
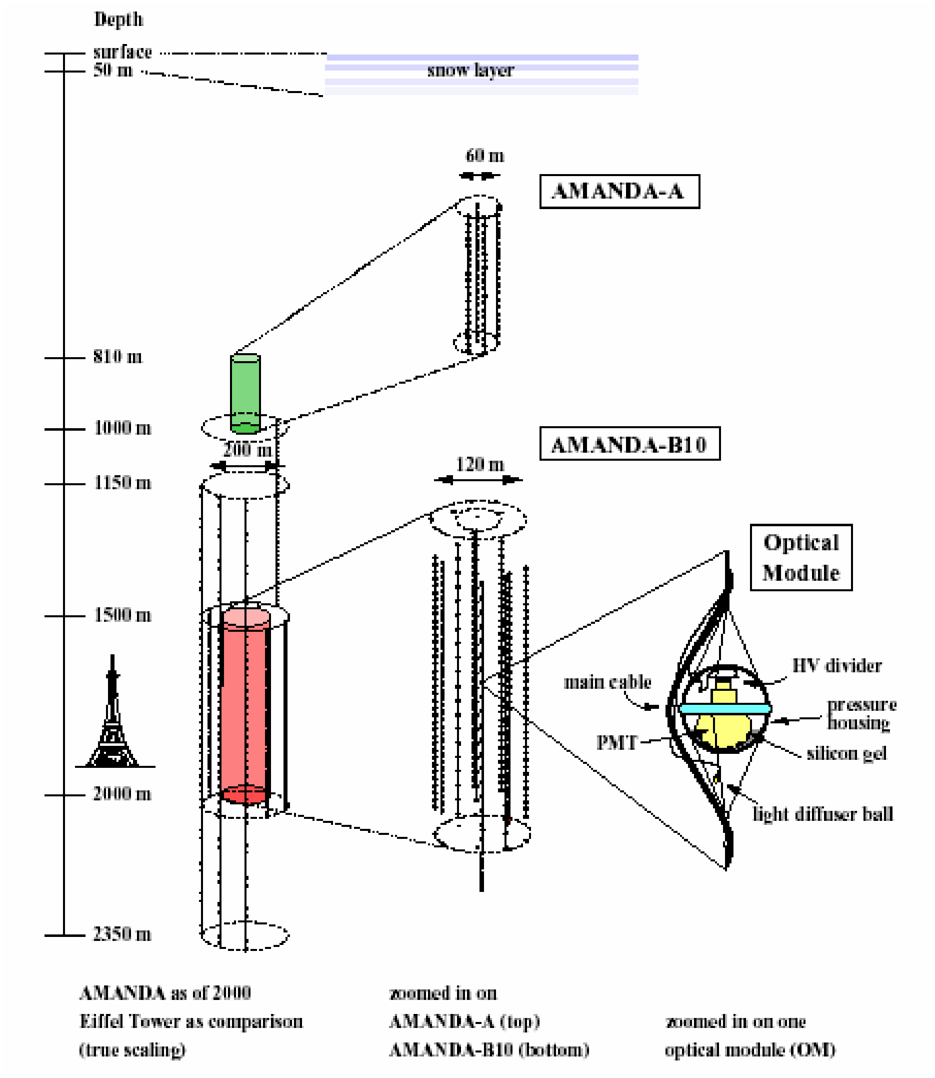


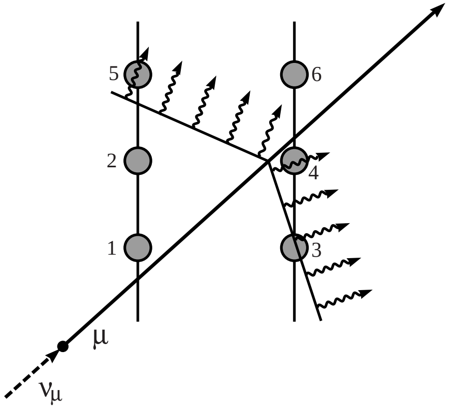
Fig. 1.— Diffuse neutrino flux ($E_\nu^2\Phi_\nu = E_\nu^2 dN/dE_\nu$) from post-supernova (supra-nova) models of GRBs (solid curves), assuming that all GRBs have an SNR shell (top curve) or 10% of all GRBs have an SNR shell (bottom curve). Long dashed straight lines correspond to the Waxman-Bahcall cosmic-ray limit, short short dashed curves are the diffuse ν flux from GRB internal shocks and afterglows.

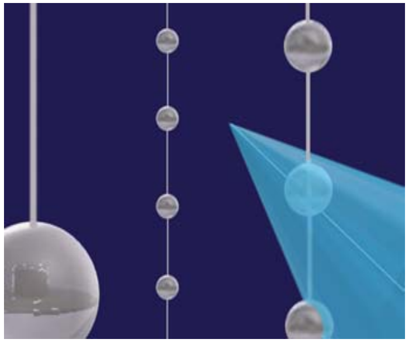
Razzaque, Meszaros, Waxman, PRL in press, astro-ph/0212536

- GRB may be assoc. w. supernova-like events
 → SNR shell;
- But: simult., or precursor SN? ("supranova" hypothesis
- If precursor SN, the SNR shell is ideal target (beam dump) for p accel in same shocks that produce γ-rays
- Below $p\gamma(\Delta$-res) thr. have pp, above have $p\gamma \rightarrow \pi\mu e\nu$
- Distinctive ν-spectrum, break energy dep. on age of SNR
- Extend to harder energies than $p\gamma$ from usual internal (γ)shock

AMANDA : Antartic Muon and Neutrino Detector



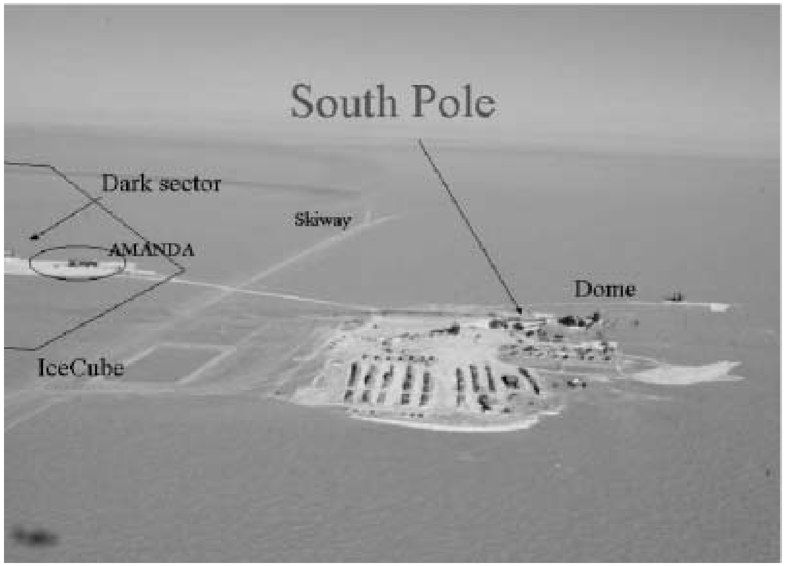




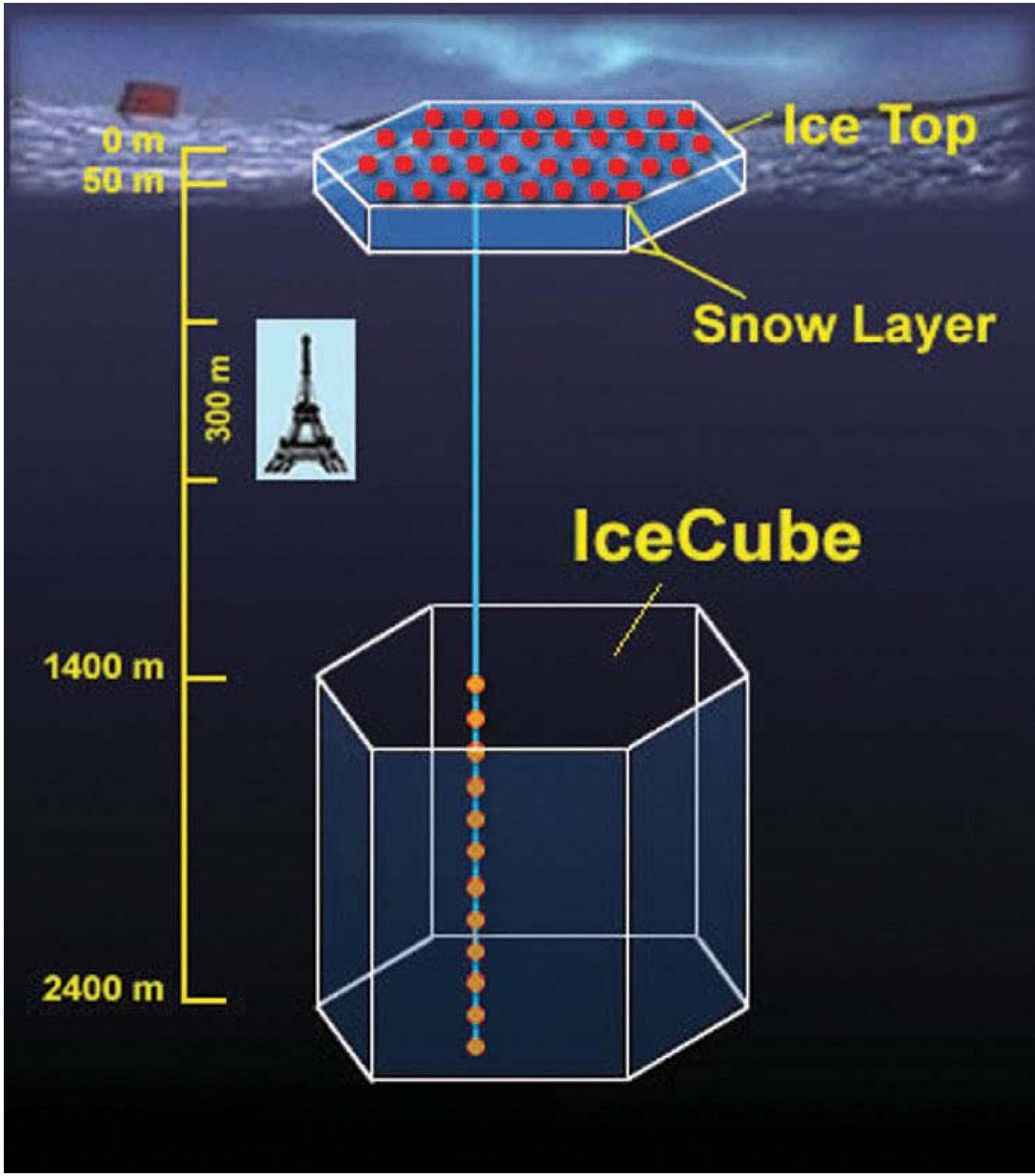
- Upward muons from ν
  $\nu^{\mu} \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}$
- Cherenkov light: collective EM radiation in polarized medium ("sonic boom" from rel. muons $v_{\mu} > c/n$)
- PMT strings 1.1.km under ice, current vol. 0.1 km^3

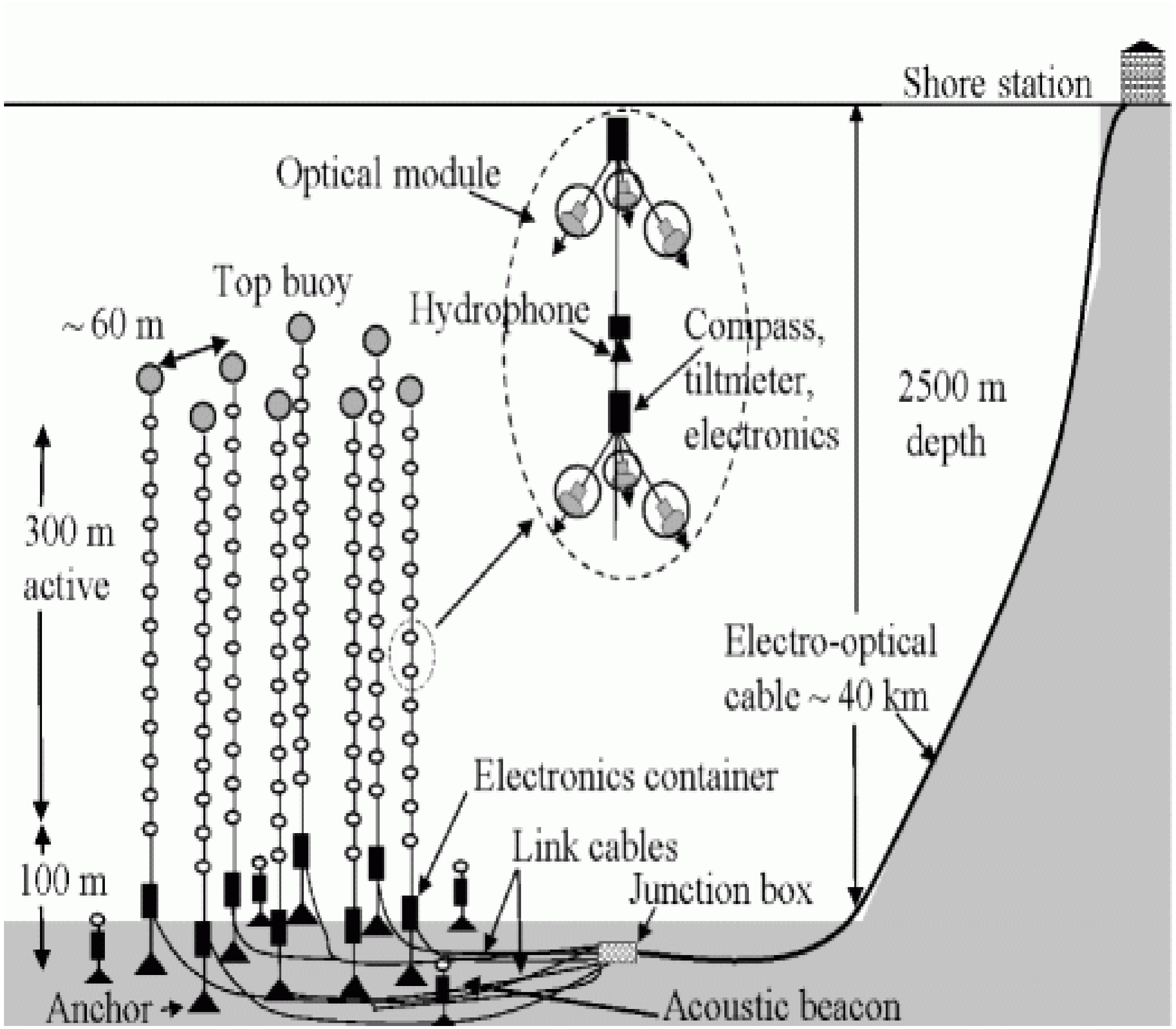
ICECUBE:

km^3



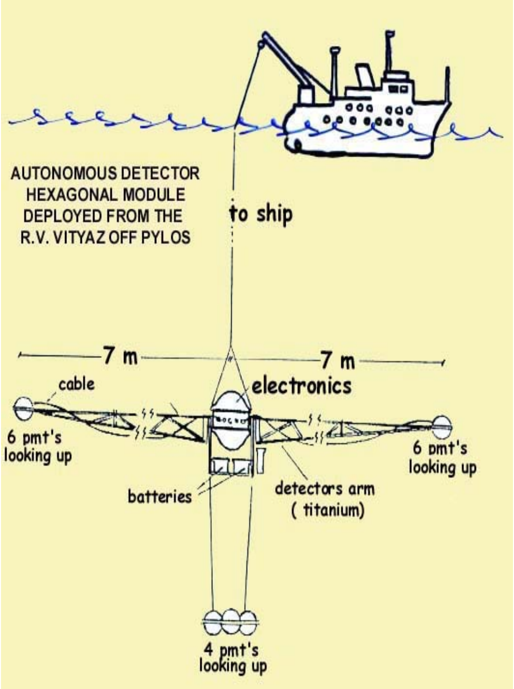
- Extension of Amanda
  0.15 km^3 → km^3=1Gton
- Initial funds for 2002 √
- 80 strings , 4800 PMTs (ice)
  + air shower surface array
- Design for det.all flavor ν's , from 10^7 eV (SN) to 10^{20} eV





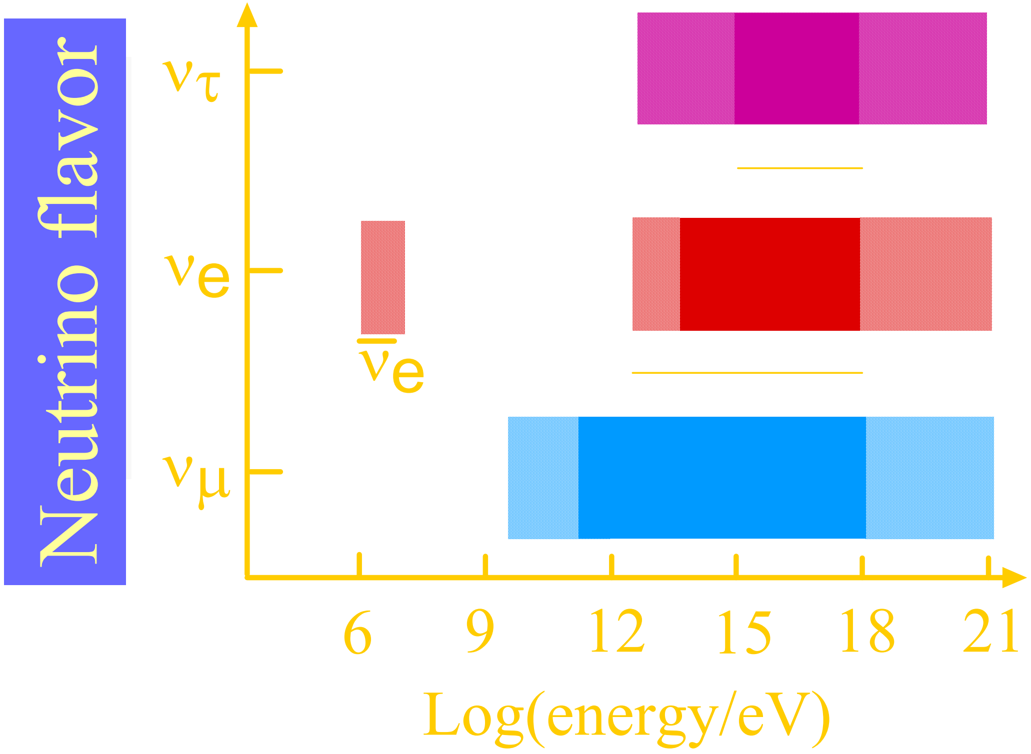
⟵Antares

- 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

Neutrino ID, energy & angle

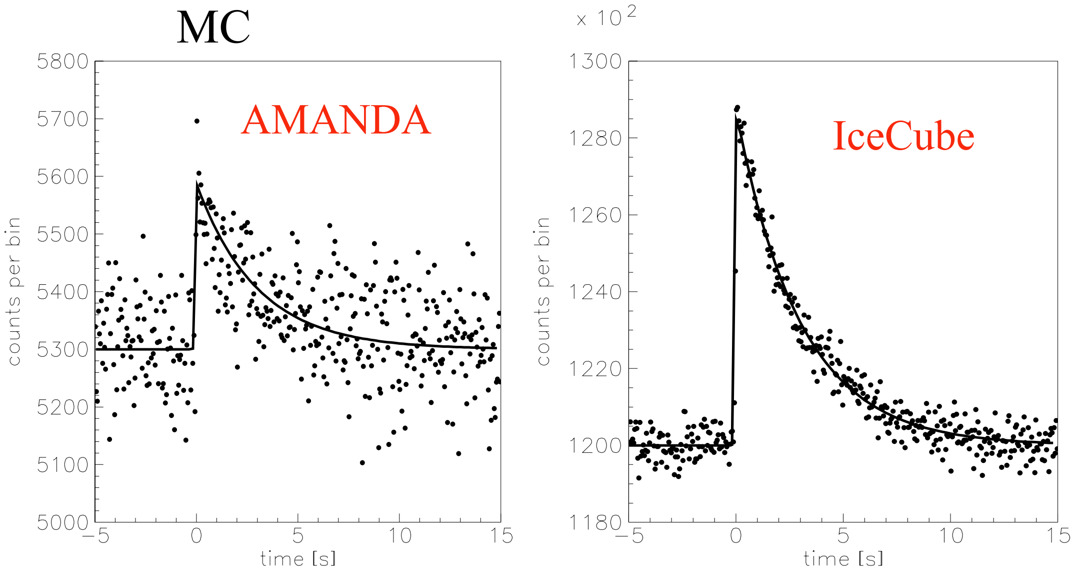


- **Filled area: particle id, direction, energy**
- **Shaded area: energy only**

ICECUBE collaboration

Supernova Detection

- $\nu_e + p \longrightarrow n + e^+$
  (10-40 MeV)
- Low PMT noise (<500Hz) increase due to the positrons
- AMANDA/IceCube records noise on the PMTs over 0.5 sec and summing up total rate over 10 sec intervals.
- Detectors to be connected to Supernova Early Warning System



- Amanda B-10: 60% of Milky Way
- Amanda A-II : 95% " " "
- ICECUBE: up to LMC

SUMMARY

- GRB are frequent events, with rich EM phenomenology, good timing & position
- Fairly well understood afterglow theory, but crucial central engine/progenitor questions remain unresolved
- GW signatures of GRB may be detectable, are potentially useful discriminants of progenitor candidates
- ν signatures may be detectable, in coincidence with both EM and GW signals