Gravitational Waves from GRB

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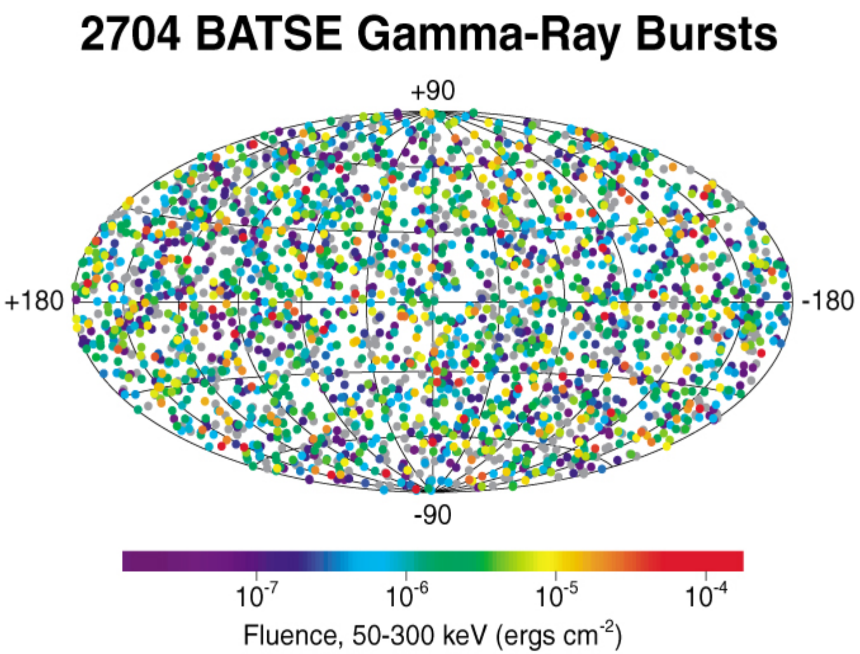
GRB Sky & Temporal Distrib.



- 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?

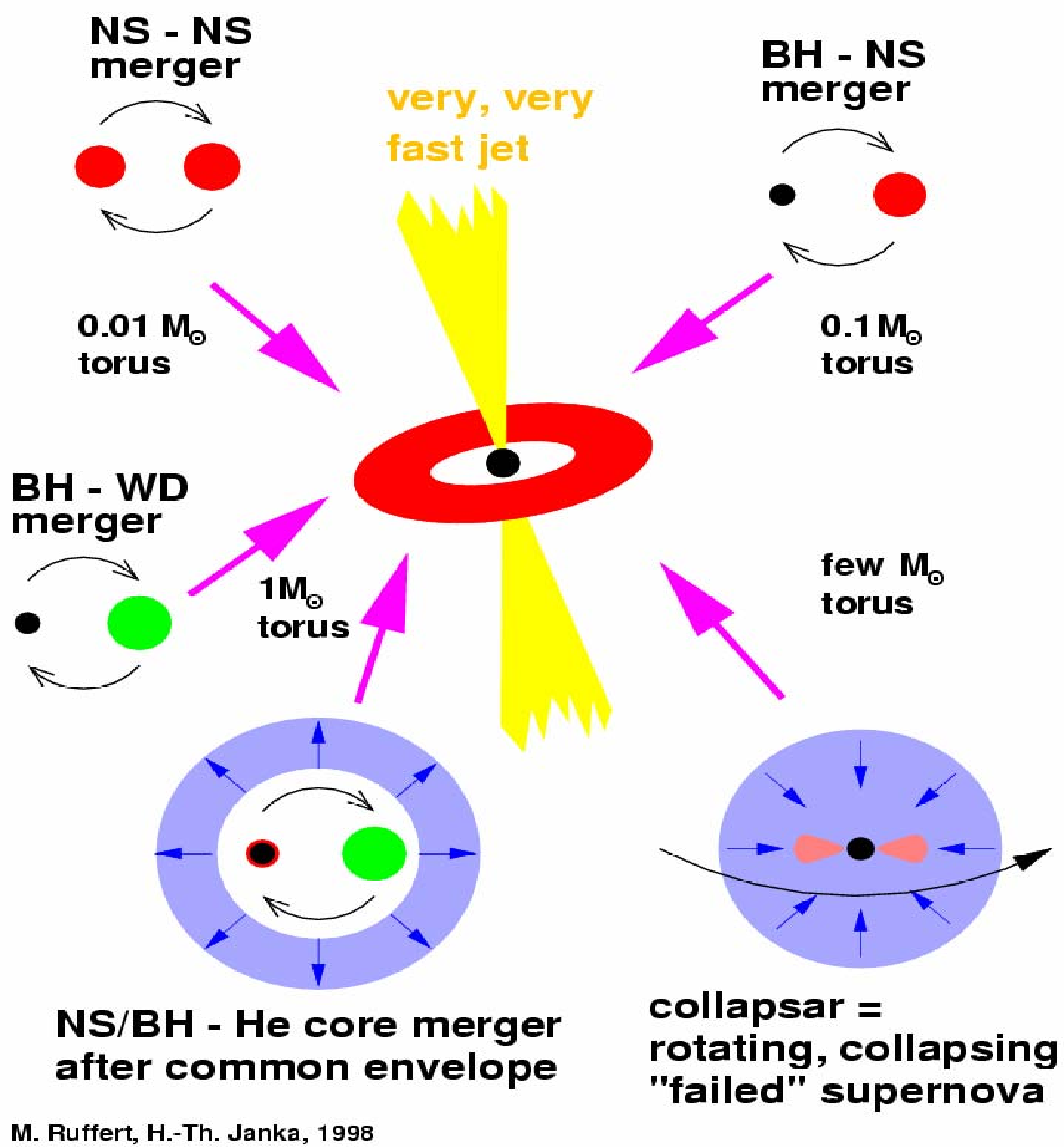
~50 afterglows well-id’d & localized in γ,X,O,R, measured redshift; massive ⋆ progenitor ~confirmed

- ~ 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)



Short

Long

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

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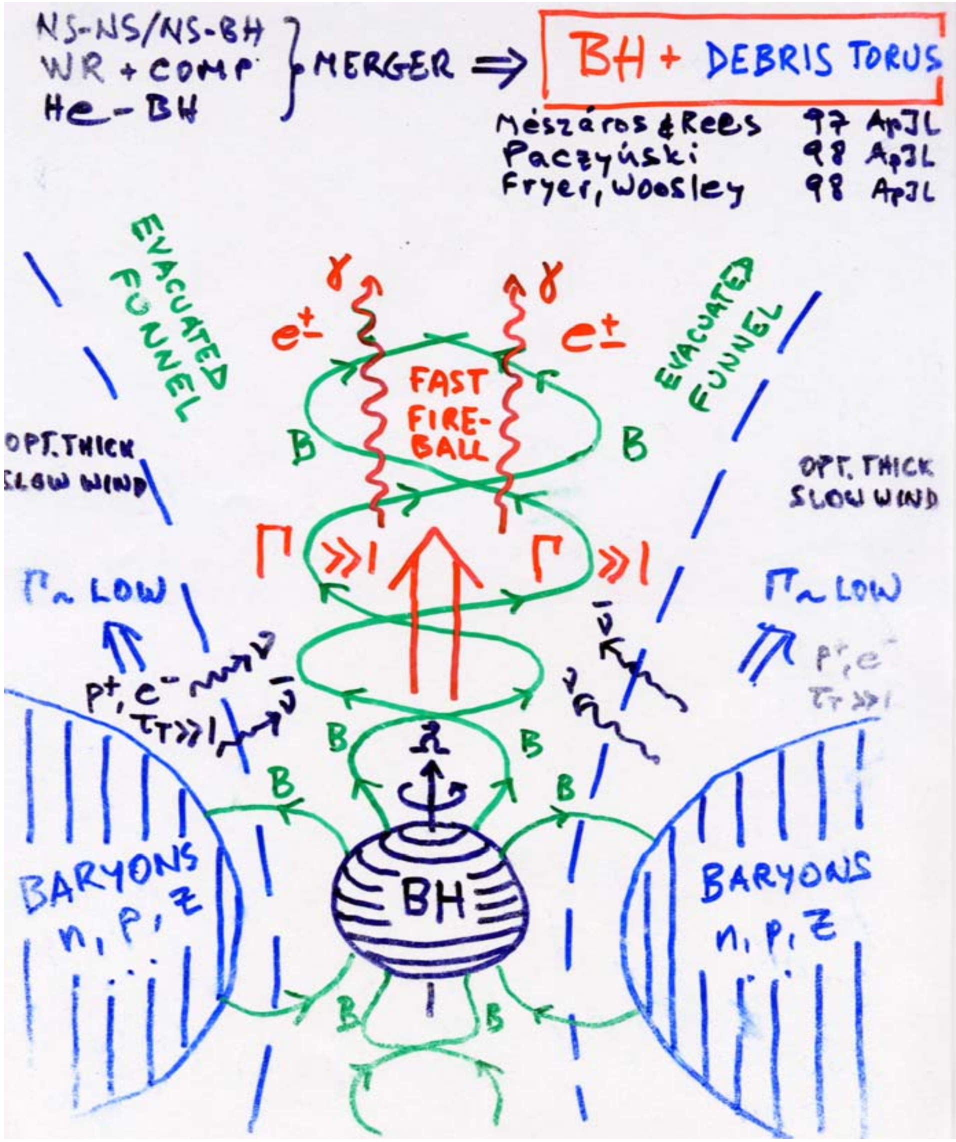
BH + accr. Torus ⇨ Jet



- 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$^{\pm}$pγjet
- (Note: magnetar might do similar)

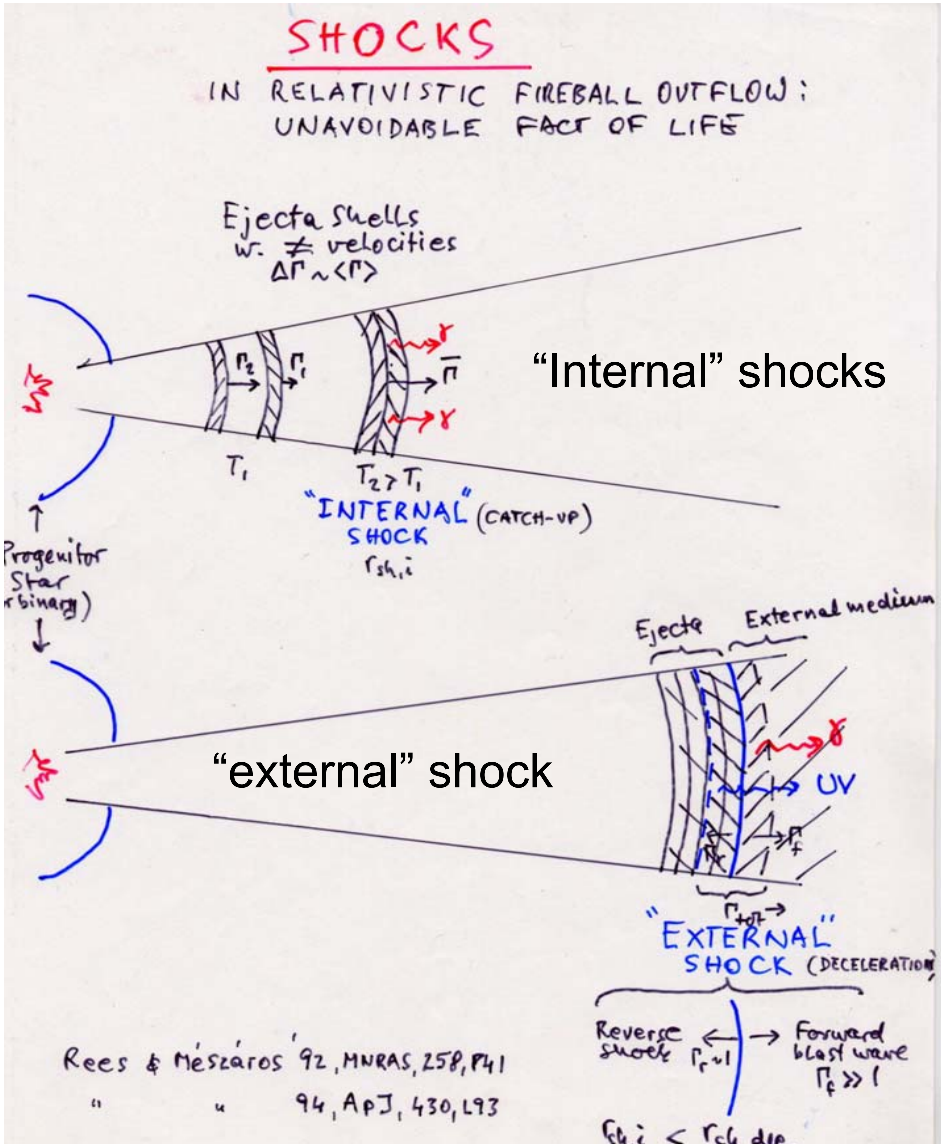
Mészáros gw03

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 $\to$ OK
- Γ up to 150 $\to$ 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)

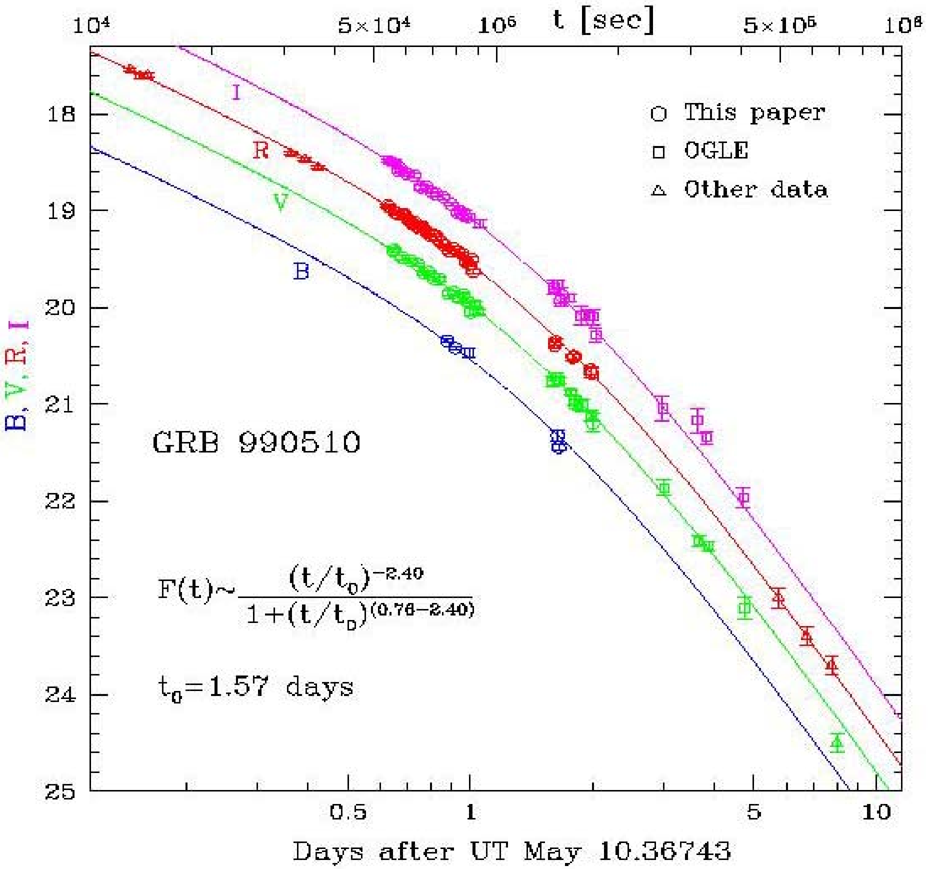
W. Zhang & Woosley 03 ↑

γ-rays: Shocks in Fireball/Jet



- **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.

Evidence for (collimated) Jets



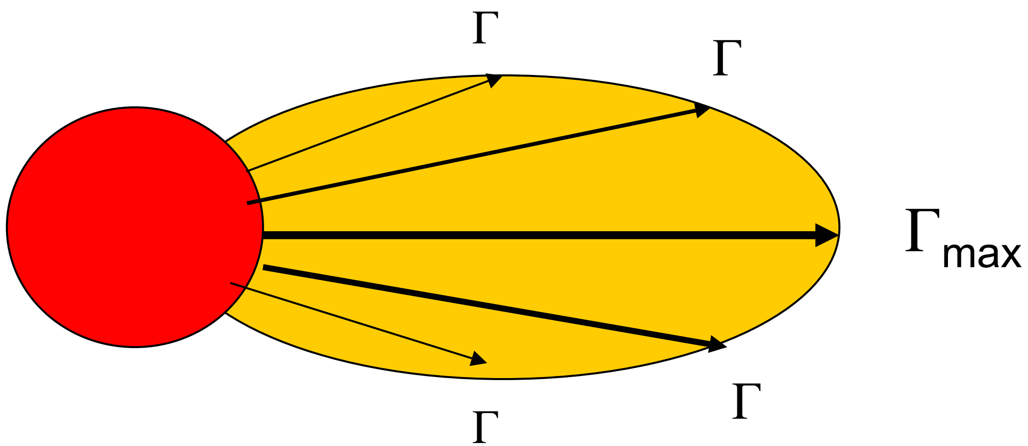
- $\Gamma \propto t^{-3/8}$, but as long as $\theta_{casual} \sim \Gamma^{-1} < \theta_{jet}$, spherical expansion is good approx
- "see" jet edge at $\Gamma \sim \theta_{jet}^{-1}$
- Before, $F_\nu \propto (r/\Gamma)^2 . I_\nu$
- After, $F_\nu \propto (r\theta_{jet})^2 . I_\nu$,
  steeper by $\Gamma^2 \propto t^{-3/4}$
- After $\Gamma < \theta_{jet}^{-1}$ also can start sideways expansion,
  $\rightarrow$ 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
  $\rightarrow$ consistent with less collimation

"Shaped" jets



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

- Jets unlikely to be top-hats
- L(θ) [$\Gamma(\theta)$?] $\propto \theta^{-2}$

  "universal" beam also fits jet data
- At high θ expect softer radiation

  → "XRF"s?,

  "Orphan" afterglow?

GRB Progenitor Rates & Distances for 1 event/year

	Rate (avg)	Rate-rge	Dist (avg)	Dist-range
	$Myr^{-1}gal^{-1}$	$Myr^{-1}gal^{-1}$	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

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

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

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

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

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

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: $E_m = \epsilon_m\ (4\mu/M)^2\ Mc^2$; [$\epsilon_m \sim 5\%$, $\mu = m_1 m_2/M$]
- $dE/df \sim E_m\ /(f_q - f_i\ ) \sim E_m\ /f_q$ (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 ~3-10 $M_\odot$
- 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]

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

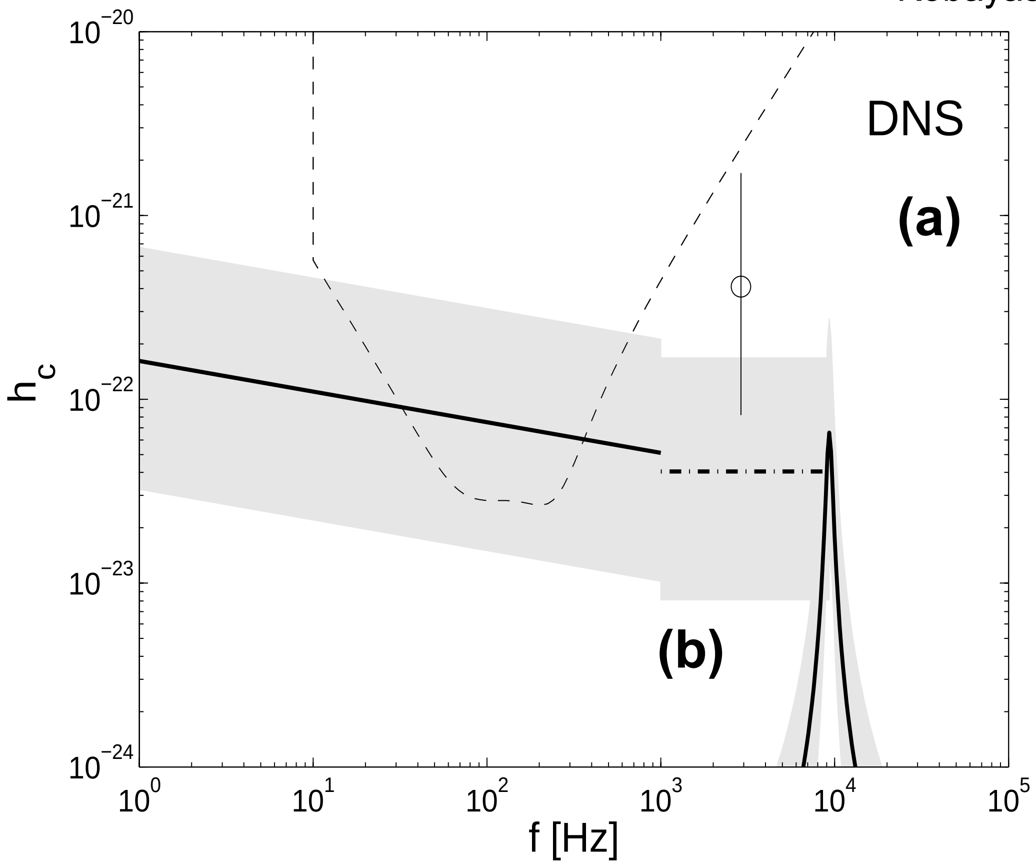
(e.g. Fryer, Holz & Hughes 02)

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.)
- $h_c \sim 2.\ 10^{-21}\, (\epsilon_r\, /0.01)^2 (Q/14F)^{1/2} (\mu/M_\odot)(d/10Mpc)^{-1}$

GRB Progenitor GW Signals: DNS

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



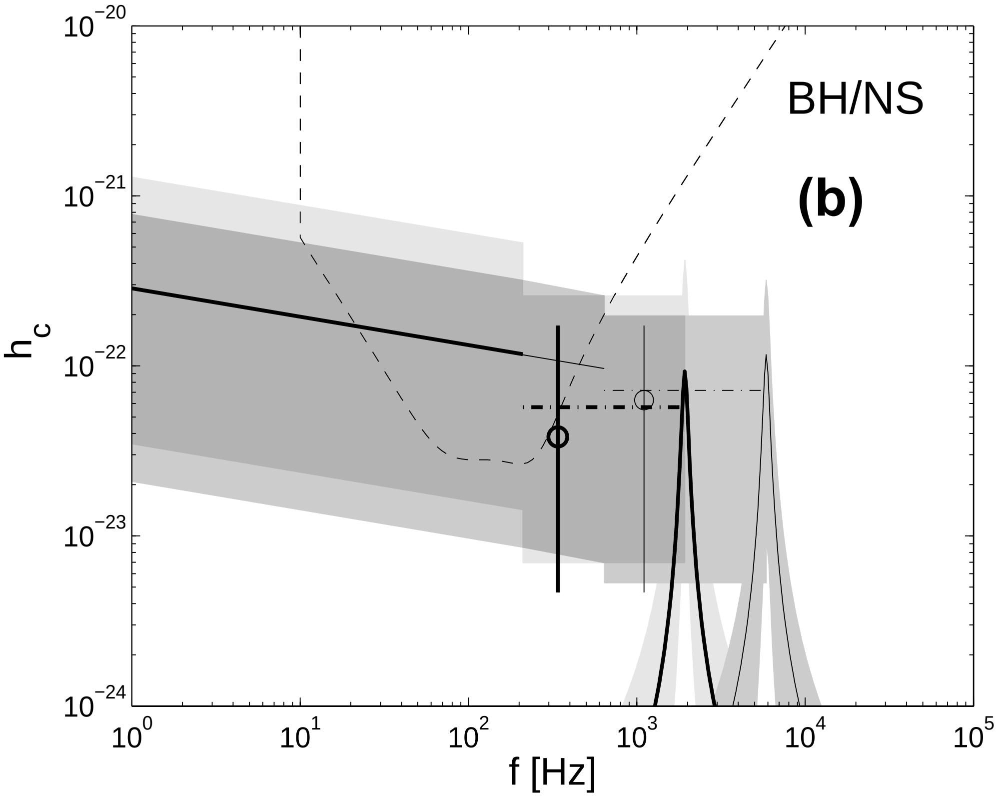
Double neutron star

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

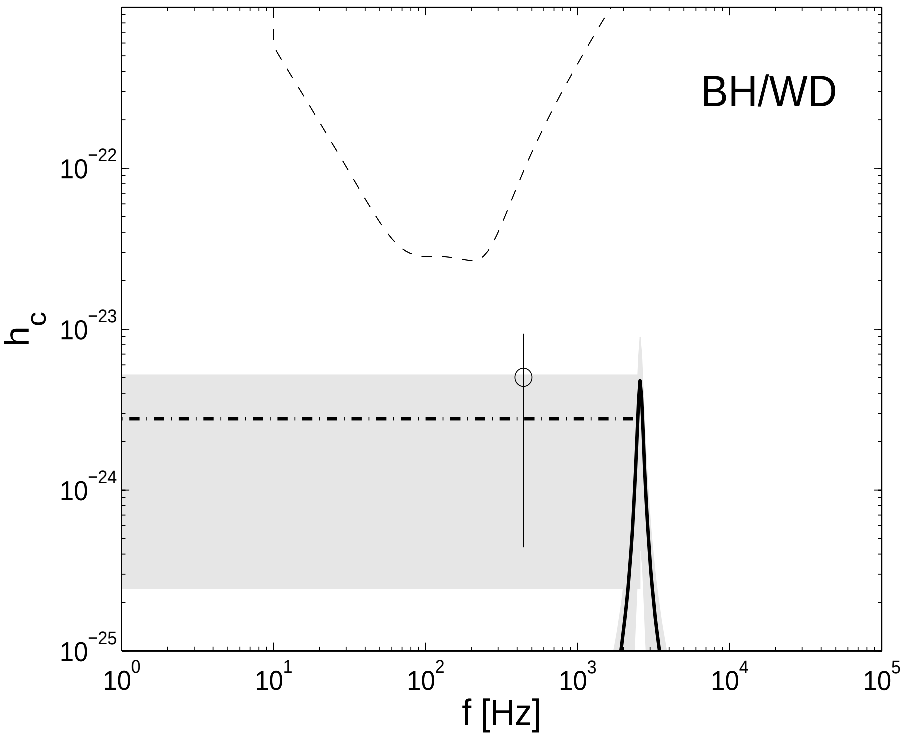


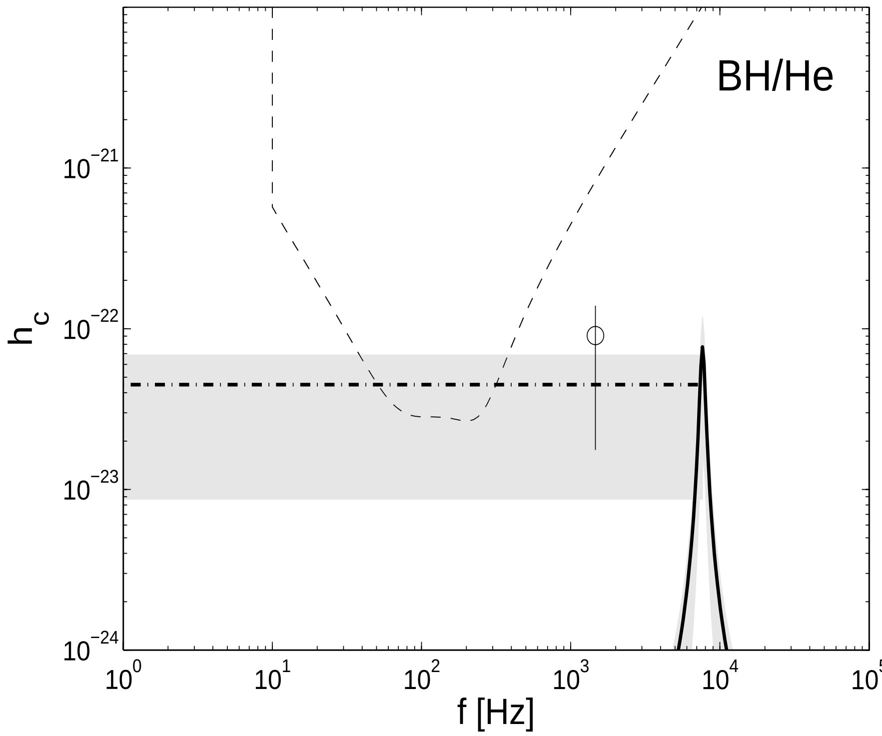
•Solid: inspiral; Dot-dash: merger; circle (bar inst); spike ring-down); shaded region: rate/dist uncertainty Dashed: LIGO II noise $[f S_h(f)]^{1/2}$

Black hole-neutron star

thin: d=170Mpc,
m_1=3.0$M_\odot$, 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, ϵ_m=0.05,
N=10, ϵ_r =0.01

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

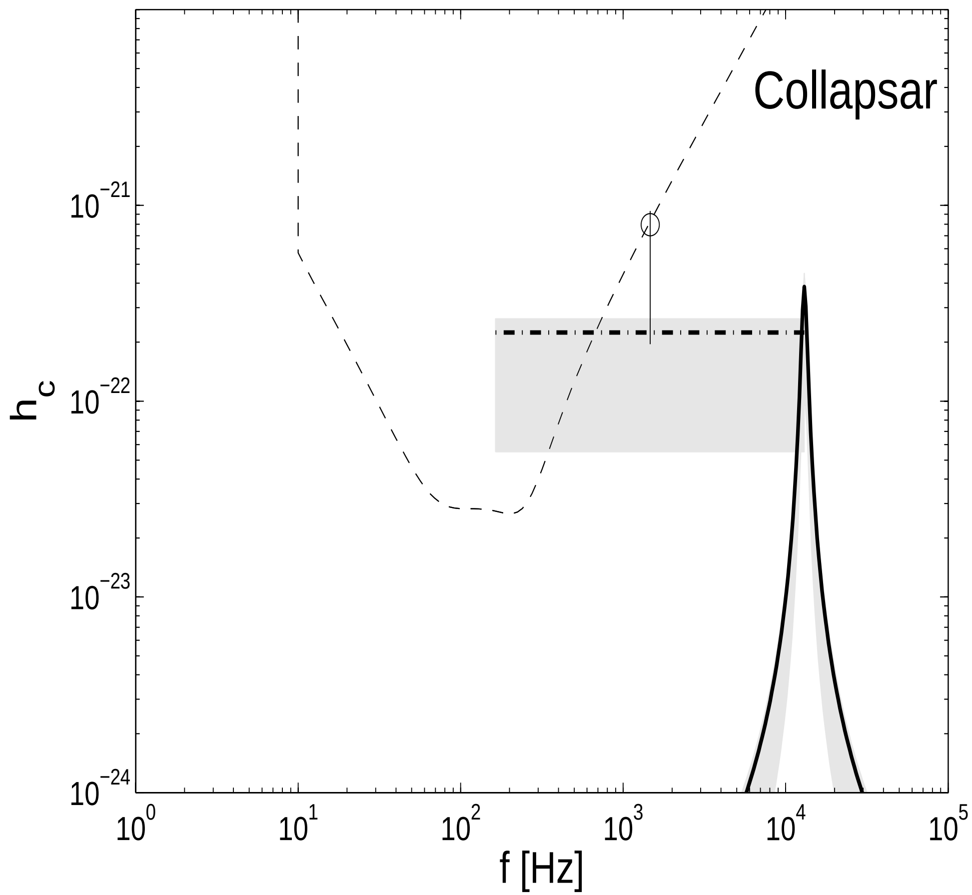




- **BH-WD**: d=430 Mpc, m_1=10, m_2=0.1, a=0.98, ϵ_m=0.05; m=0.1, m'=10, N=10, ϵ_r=0.01
- **BH-He**: d=95 Mpc, m_1=3, m_2=0.4, a=0.98, ϵ_m=0.05; m=0.4, m'=3, N=10, ϵ_r=0.01

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,
ϵ_m =0.05,
merge at r=10^7 cm;
m=1 $M_\odot$, m'= 3 $M_\odot$,
N=10, ϵ_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)
- $\rho_{\mathbf{DNS,insp}}$ ~
  $7.5\ (1.5,30)\ (\mathcal{M}/1.2M_\odot)^{5/6}\ (R/1.2\ \mathrm{Myr}^{-1}\ \mathrm{g}^{-1})^{1/3}$
- $\rho_{\mathbf{BHNS,insp}}$ **(case a)** ~
  $13\ (0.9,35)\ (\mathcal{M}/1.8M_\odot)^{5/6}\ (R/2.6\ \mathrm{Myr}^{-1}\ \mathrm{g}^{-1})^{1/3}$

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

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] :

  $\sigma_{off} = \text{avg}\ [(n_1,n_2)^2\ ]^{1/2} \sim C\ [(T/4) \int df\ /S^2\ (|f|)\ ]^{1/2}$

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

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

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

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

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

(while **$L_\gamma \propto \theta^{-2}$** $\rightarrow$ 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 →$<d_{min}>$~300 Mpc
- LIGO II sensit'y @ f_0~150Hz :
  $[f_0\ S(f_0\ )]^{1/2} \sim 3.10^{-23}\ \mathrm{Hz}^{-1}$, 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 GW-EM connections 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 $\Gamma \propto t^{-1/2}$
  $\rightarrow$ afterglow peaks at time $t_p \propto \theta^2$ after GW $\rightarrow$ P $\propto t_p^2$
- XRFs: may be misaligned jets, $\rightarrow$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"), $\longrightarrow$ 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)