Astrophysical implications of external triggers, GRB030329 in particular

External Triggers subgroup

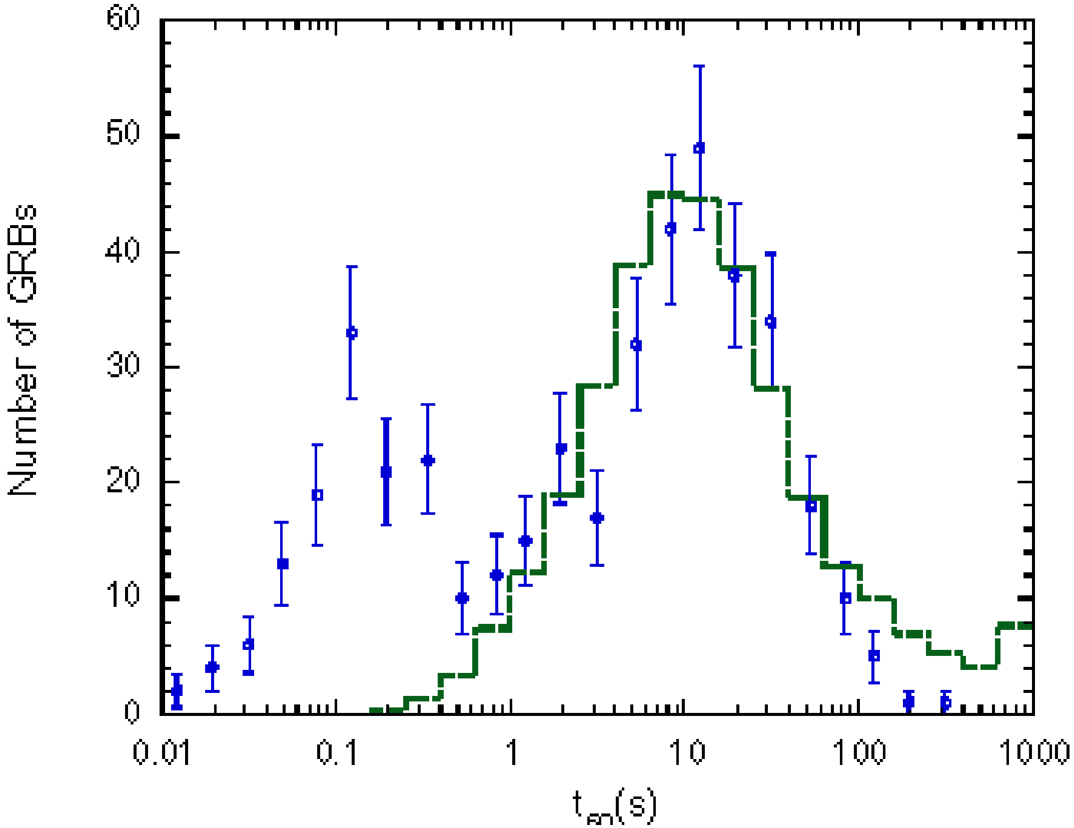
- GRB astrophysics is still very uncertain
- Associated GW emission: even more uncertain

⇒ Interpret our observations in the simplest terms

- Easy to re-cast in terms of specific models
- Provides some astrophysical context which is readily interpretable

Probable: The GRB field will need GW observations to fully understand GRB progenitor astrophysics

Short and Long GRBs…



BATSE data

Prejudices:

- Long GRBs are Collapsars (2 events)
- Short GRBs are compact inspirals

Burst categories associated with GRBs

1. Short (~1ms) GW bursts
   - SN-like core bounces, including collapsars (the long-GRB SM)
     - Plausible for GRB030329
   - The astrophysical modeling can serve only as a guide of signal *character*, not to be taken literally
   - Gaussians, sine-gaussians
   - ZM or DFM or ?

⇒ Main focus of current analyses in ExtTrig group

2. Must also consider longer duration, sinusoid-like bursts:
   - Interesting core dynamics: bar-instabilities, core fragmentation
   - Large ang. mom., lumpy, accretion torus (van Putten)

     The most specific model (and potentially prolific GW producer)
   - Binary inspirals (the "leading" candidates for short GRBs)

Determining an astrophysically relevant limit

- Trigger inputs:
  - event position on sky (assume a point with errors here)
  - event time to <1s
  - distance (z) if known from afterglow measurements
- Assume a waveform h(t) and polarization
  - A “surrogate” waveform (G or SG, for example), or a modeled waveform (e.g. ZM)
  - Can specify polarization, if predicted. (Assume unpol. for now.)
- Inject series of such waveforms into pipeline → upper limit

Relate observed h(t) to GW Energy…

$$P_{GW} \propto \left| \frac{dh(t)}{dt} \right|^2$$

$$E_{GW} = \left(\frac{2\pi^2 c^3}{G} \right) d^2 \int_0^\infty f^2 |\tilde{h}(f)|^2 df$$

for an observation (or limit) made at a luminosity distance *d* from a source.

- For example, consider an upper limit corresponding to a gaussian signal (h_O, σ) with a specified polarization and orientation, then:

$$E_{GW} = \left(\frac{\sqrt{\pi}\, c^3}{8G} \right) \left(\frac{d^2 h_o^2}{\sigma} \right)$$

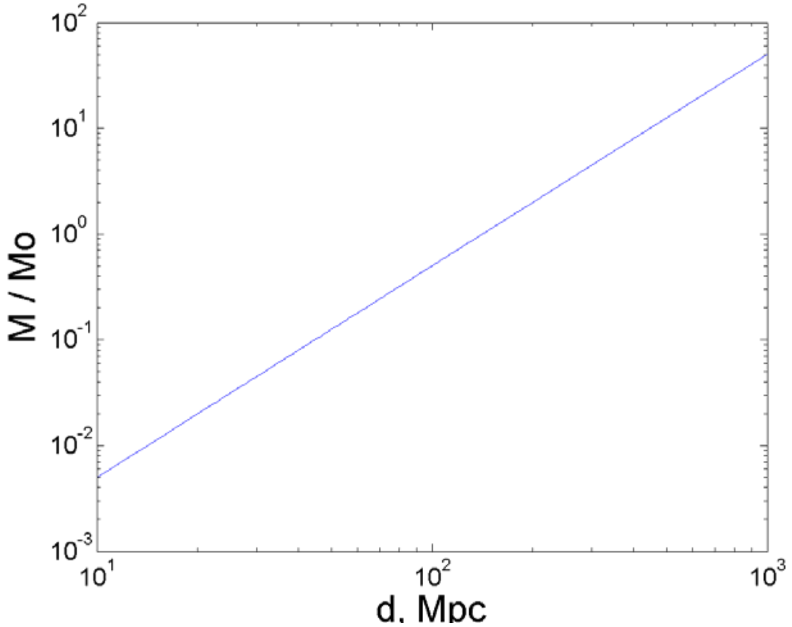
a) Assume there exists some mechanism which converts non-spherical mass into GW:

$$\text{Set } E_{GW} = M_{\text{ns}} c^2$$

$$M_{\text{ns}} = 0.5 M_{\odot} \left(\frac{1\text{ms}}{\sigma}\right) \left(\frac{h_o}{10^{-20}}\right)^2 \left(\frac{d}{100\text{Mpc}}\right)^2$$

- Minimal astrophysical assumptions
  - Isotropic GW emission
  - Short, core-collapse-like bursts

- Note: For d=100 Mpc, the GRB rate is about 1/yr for a GRB beaming angle of 2°



b) If we can assume a GRB is associated with a truly SN-like core collapse, then we *might* estimate GW energy based on SN calculations.

E.g., assuming axisymmetry, a max. efficiency is $\varepsilon \sim 7\times 10^{-4}$, then

$$E_{GW} = \epsilon M_{\text{axi}} c^2$$

$$M_{\text{axi}} = 7 M_\odot \left(\frac{1\text{ms}}{\sigma}\right) \left(\frac{h_o}{10^{-20}}\right)^2 \left(\frac{d}{10\text{Mpc}}\right)^2 \left(\frac{7\times 10^{-4}}{\epsilon}\right)$$

- 1.4 M_O at this efficiency ⇒ d=5 Mpc
- 1.4 M_O and d=10Mpc ⇒ ε = 0.4 %

Waveforms…

- Surrogates
  - Gaussian: $$E_{GW} = \left(\frac{\sqrt{\pi}\,c^3}{8G}\right)\left(\frac{d^2 h_\circ^2}{\sigma}\right)$$
  - Sine-gaussian: $$E_{GW} = \left(\frac{\sqrt{\pi}\,c^3}{16G}\right)\left(\frac{d^2 h_\circ^2}{\sigma}\right)\left(1 - e^{-4\pi^2 f_\circ^2 \sigma^2}\right)$$
- For waveforms such as ZM or DFM:
  - Determine h_peak and $\int f^2 h(f)^2\, df$ for each waveform whose hrss corresponds to the observed limit
  - Form distribution of derived M_ns, etc
- For putative long duration waveforms, the limits improve for comparable strain amplitudes… this work in progress.

Idea is to include these calculations as standard part of injection/analysis pipeline; implement as a Matlab script, for example

GRB030329

H1-H2 only ⇒ antenna attenuation factor 0.37 (assuming unpolarized)

$d \approx z(c/H_o)(1 + z/4)$, for $\Omega=1$

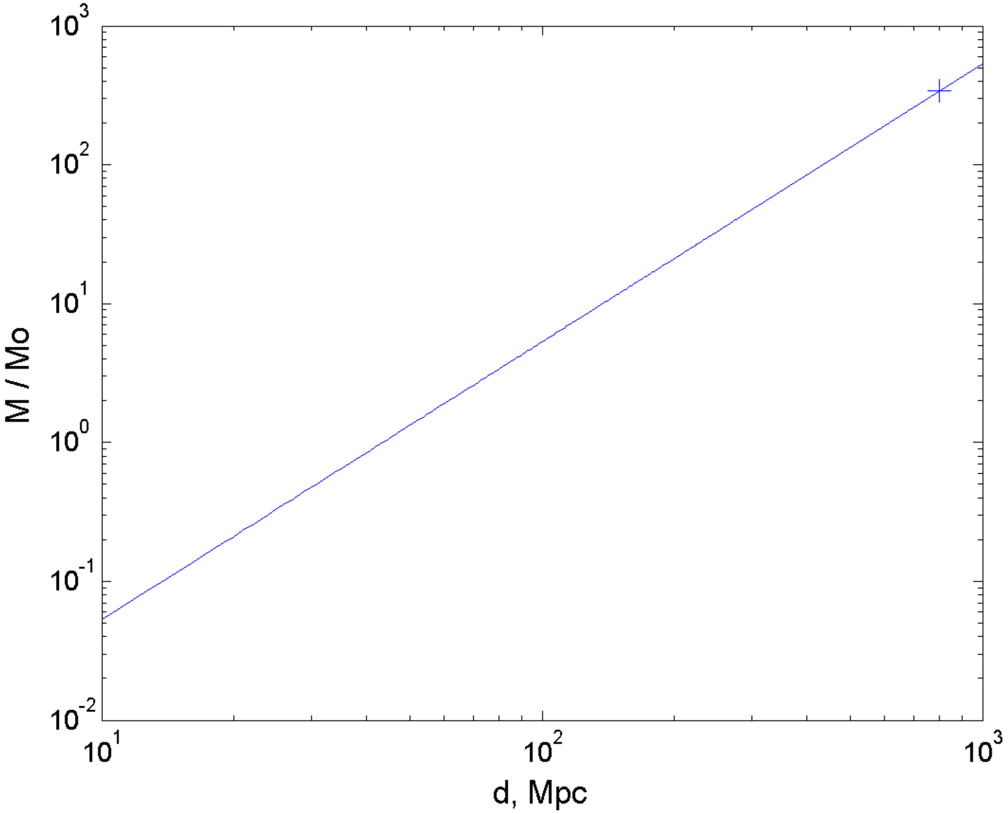
$z=0.1685 \Rightarrow d=800\text{Mpc}$, for $H_o=66$ km/s/Mpc

Using sine-gaussian limit for Q=8.9, f=250 Hz, 90% eff:

$h_O = 6.8\times10^{-20}$

$\Rightarrow$M_ns = 2.0 M_O $(d/100\text{Mpc})^2$

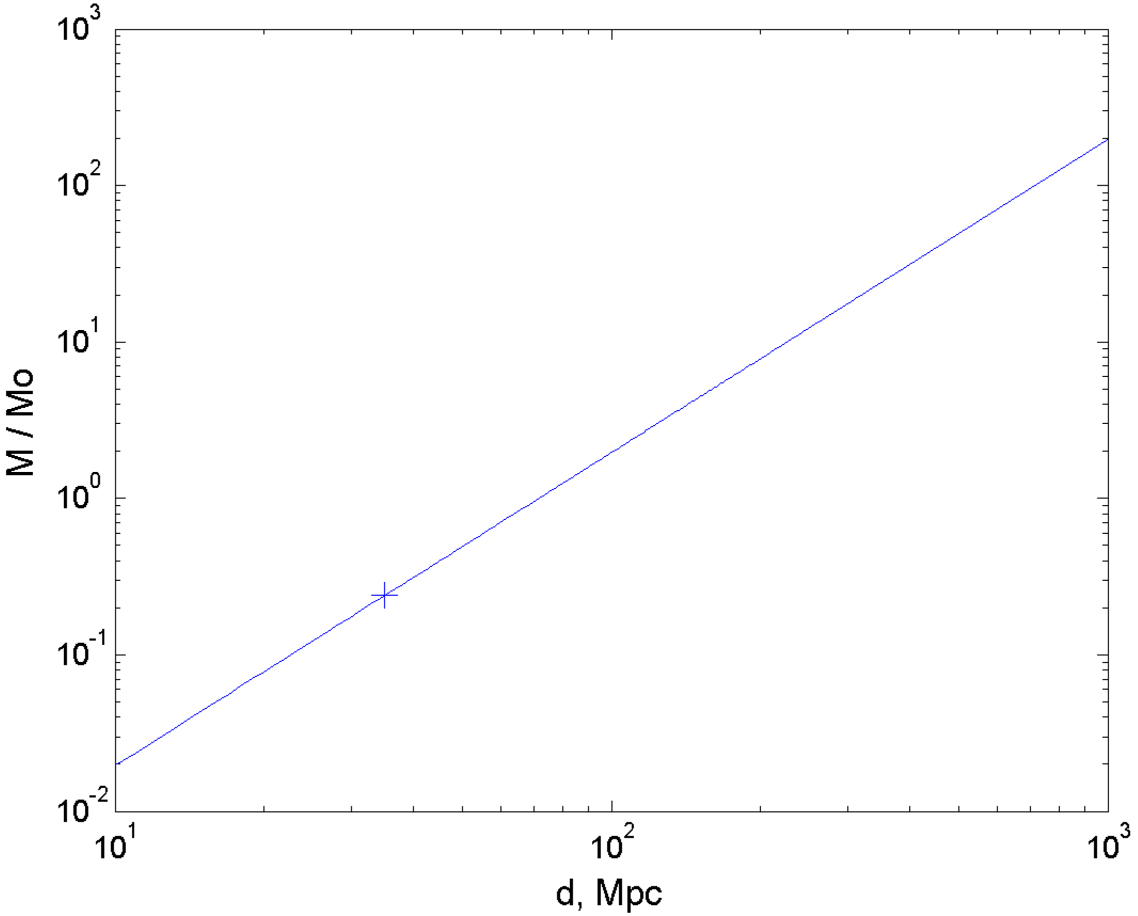
$\approx 125\ M_O\ (1 / 0.37) = 340\ M_O$



Prospects example

- GRB980425: d=35Mpc, assuming GRB030329 H1-H2 sensitivity and optimal orientation:

M_ns = 0.24 M_O



Astrophysical Models Considered

1. *Collapsars ("standard" GRB progenitor model) –*

   Collapse of massive (>$20M_{\odot}$), rapidly rotating (,non-H) star to a black hole; star shell is blown off ("hypernova"); accretion inflow produces relativistic (γ~200) outflow ("fireball") which gets beamed by interaction with asymmetric shell, producing photons ⇒ GRB.

   Time scales for collapse and accretion-jet are both ~1 ms.

   Δ derives from v<c for jet between core and r ~ 10^{12} m ⇒ < 200 ms.

   T depends…

a) GWB due to SN-like core collapse (use DFM as guide)

   Expect *T* to be small; how does it "scale" from type-II SN ?? (100 ms)

b) Core collapse ⇒ bar instability (*under review*)

   ~sinusoid, *f* ~ 0.1-1 kHz; How many cycles?? (100-1000,10000?)

c) Core collapse ⇒ fragmentation (guesses in literature)

d) Unstable torus (van Putten, et al.) – large GW power

   Modulated sinusoid, *f* ~ 0.2-1.2 kHz; *T* ~ GRB duration

Astrophysical Models (contd.)

2. *Cannonball GRB model –*

   Progenitors are ordinary core-collapse SNe. Infall of stellar shell remnant onto core ⇒ highly relativistic ($\gamma \sim 10^3$) “cannonball” pair ⇒ highly beamed GRB

   $\Delta \sim 1$ s (requires clarification)

   T and waveforms: use DFM

3. GW emission from the relativistic jet (fireball/cannonball) itself

   Produces “burst with memory”;

   requires further study

   $$h = \left(\frac{G}{c^2} \right) \frac{4\gamma m}{d}$$

4. Binary inspirals

   BH formation; accretion disk ⇒ GRBs.

   Leading candidates for short (<2 s) duration GRBs.

   Not clear that triggers are helpful… is there a study?

   No current plans to pursue this explicitly.

Parameters Summary

Model*	Δ (s)	T (s)	wf type	wf parameters range
1-a	$[0,0.2](1+z)$	$0.1(1+z)$	G and SG	The DFM suite
1-b	$[0,0.2](1+z)$	$[0.01,1](1+z)$	SG	$100 < f_0 < 1000$ Hz; σ : 10–100 cycles
1-c	$[0,0.2](1+z)$	$[0.01,1](1+z)$	chirp (SG) ?	see discussion
1-d	$[0,0.2](1+z)$	$[10,100](1+z)$ $\propto$ GRB duration	SG	$200 < f_0 < 1200$ Hz; $10 < \sigma < 100$ s
2	$[1,100]$	$0.01(1+z)$	G and SG	The DFM suite
3	$[1,100]$	~ 0.01 ?	?	see discussion
4	0 ?	$[0,10]$?	chirp	Leave to Inspiral Group ?

1-a Collapsar, “SN-like” core collapse

1-b Collapsar, with core bar instability

1-c Collapsar, with core fragmentation

1-d Collapsar, with unstable torus (van Putten)

2 Cannonball

3 GW from the GRB jets

4 Binary inspiral

wf waveform

z redshift

G gaussian (σ)

SG sine gaussian (σ, f_0)