Gravitational-Wave Burst Detection: Sources

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What are GW Bursts?

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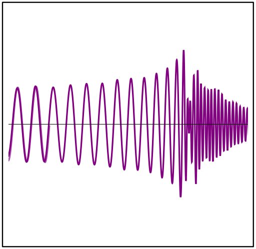
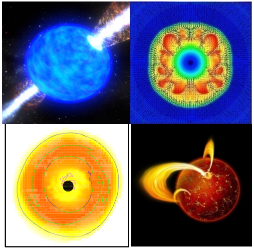
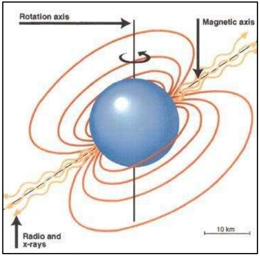
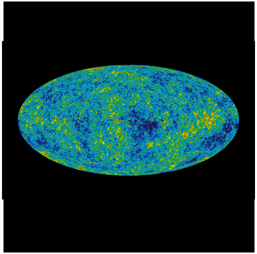
transient		
continuous		

What are GW Bursts?

In Principle

Any *transient* GW signal; i.e, one with duration in the detector's sensitive band that is much smaller than the observation time.

- Examples: compact binary coalescences, supernovae, long gamma-ray bursts, flaring magnetars, glitching pulsars, perturbed neutron stars / black holes, cosmic strings, micro-quasars . . .
- LIGO, Virgo: typically < 1 s (excluding CBCs), but some signals up to O(100) s or possibly more.

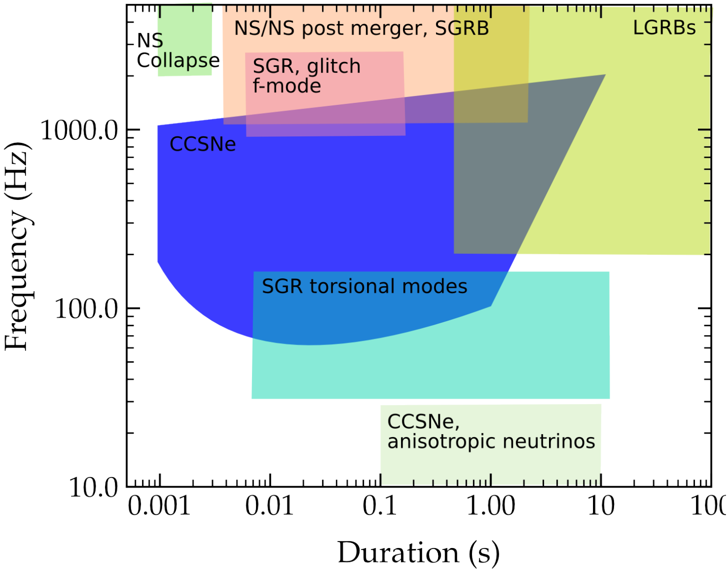
What are GW Bursts?

In Practice

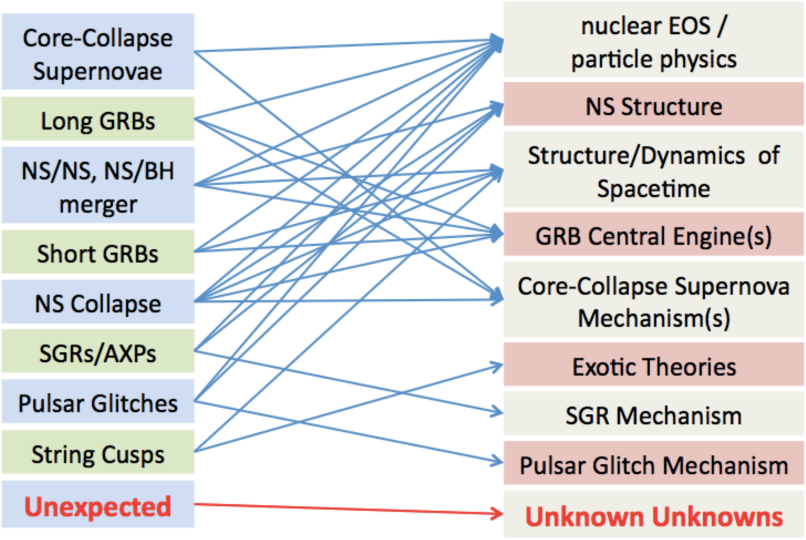
By convention, “bursts” are transients for which the GW waveform is not known or is too complicated to allow for a templated search.

- includes: supernovae, long gamma-ray bursts, highly eccentric binary mergers, . . .
- excludes: binary inspirals (but not necessarily mergers), cosmic strings, . . .
- Frequency content does not generally scale with $1/\tau$.
- Associated with energetic, transient astrophysical phenomenon – sources also observable in EM/neutrinos.

Burst Sources (slide by C. Ott)



Burst Science (slide by C. Ott)



Outline of this Lecture

- Definitions & motivations.
- Burst detectability.
- Sources:
  - bursting magnetars
  - long gamma-ray bursts & engine-driven supernovae

Notes on Burst Detectability

Signal-to-noise ratio

- Even though we don't use matched filters, the matched-filter signal-to-noise ratio (SNR) is still the natural measure of burst detectability (next lecture):

$$\rho^2 = 2\int_{-\infty}^{\infty} df\, \frac{|F_+\tilde{h}_+(f) + F_\times \tilde{h}_\times(f)|^2}{S(f)} \,. \qquad (1)$$

- Here $S(f)$ is the one-sided noise power spectrum, defined by

$$\langle n^*(f) n(f') \rangle = \frac{1}{2}\delta(f - f') S(f) \,. \qquad (2)$$

- When $h(t)$ is not known we can still estimate ρ from the energy E_{GW} emitted in GWs.

Root-sum-square amplitude

- A standard signal measure for burst searches is the root-sum-square amplitude:

$$h_{\mathrm{rss}}^2 = \int_{-\infty}^{\infty} dt \left[h_+^2(t) + h_\times^2(t) \right] \tag{3}$$

$$= 2\int_0^{\infty} df \left[|\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2 \right] . \tag{4}$$

- This has the same units as the noise spectrum, so we can use it to estimate the SNR. E.g., for unpolarised narrowband GWs we have

$$\rho^2 \simeq [F_+^2 + F_\times^2] \frac{h_{\mathrm{rss}}^2}{S(f)} . \tag{5}$$

RSS and Energy

- We can relate h_{rss} to the energy emitted in GWs, E_{GW}, using the flux (energy per unit area per unit time):

$$
\begin{aligned}
F_{\mathrm{GW}} &= \frac{c^3}{16\pi G}\langle \dot{h}_+^2(t) + \dot{h}_\times^2(t)\rangle && (6)\\
&= \frac{\pi c^3}{4G}\frac{1}{T}\int_{-\infty}^{\infty} df\, f^2 \left(|\tilde{h}_+(f)|^2 + |\tilde{h}_\times(f)|^2\right) . && (7)
\end{aligned}
$$

- For a narrowband signal & isotropic emission this gives

$$
\begin{aligned}
E_{\mathrm{GW}} &= 4\pi r^2\, T\, F_{\mathrm{GW}} && (8)\\
&= \frac{\pi^2 c^3}{G} r^2 f_0^2 h_{\mathrm{rss}}^2 . && (9)
\end{aligned}
$$

SNR and Energy

- Combining eqns (5) and (9) relates SNR to energy:

$$\rho^2 = [F_+^2 + F_\times^2] \frac{G}{\pi^2 c^3} \frac{E_{\rm GW}}{S(f_0) r^2 f_0^2} \,. \tag{10}$$

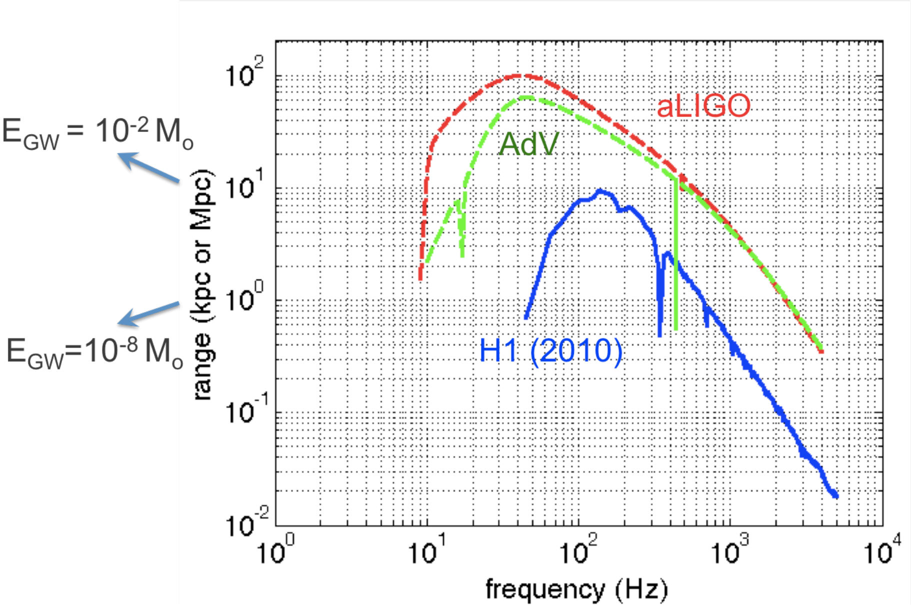
- Averaging over angles (sky direction, source orientation) gives average range for detection with $\rho \geq \rho_0$:

$$\mathcal{R}_{\rm eff} \simeq \left(\frac{G}{2\pi^2 c^3} \frac{E_{\rm GW}}{S(f_0) f_0^2 \rho_{\rm det}^2} \right)^{1/2} \,. \tag{11}$$

- For a homogeneous isotropic population of sources of rate density $\dot{\mathcal{N}}$, the detection rate is

$$\dot{N} = \frac{4}{3} \pi \mathcal{R}_{\rm eff}^3 \dot{\mathcal{N}} \,. \tag{12}$$

Burst Range for SNR > 20 (Sutton 2013)



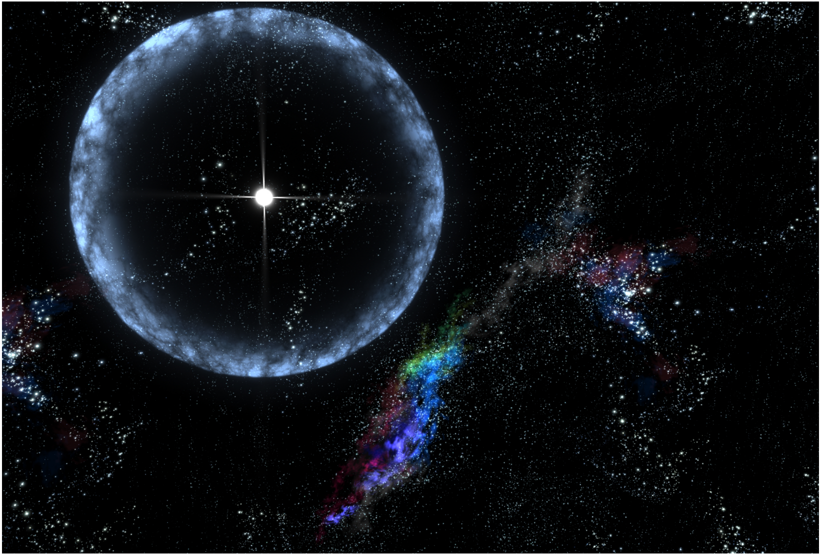
Burst Sources

Magnetar Giant Flares

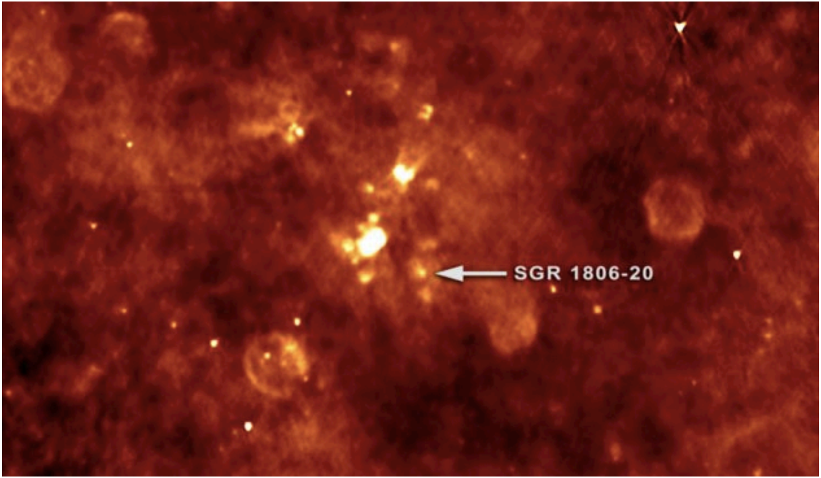
Soft-gamma repeaters (SGRs) and anomalous X-ray pulsars: pulsars with few-second periods (Mereghetti 2008).

- Thought to be magnetars - isolated neutron stars with enormous B fields (10^{15} G).
- Exhibit repetitive outbursts in X-rays and γ-rays lasting $\sim 0.1\,\mathrm{s}$ with luminosities up $\sim 10^{42}\,\mathrm{erg\,s^{-1}}$.
- A few (SGR 0526$-$66, SGR 1900$+$14, SGR 1806$-$20) have shown rare ($< 0.1\,\mathrm{yr}^{-1}\,\mathrm{gal}^{-1}$) hard-spectrum giant flares with luminosities of up to $10^{47}\,\mathrm{erg\,s^{-1}}$. Possible causes:
  - Magnetic stresses fracturing the magnetar crust and leading to a large-scale rearrangement of the internal field (Thompson & Duncan 1995)
  - Large-scale rearrangement of the magnetospheric field due to magnetic reconnection (Lyutikov 2006, Gill & Heyl 2010).

Magnetar Giant Flares



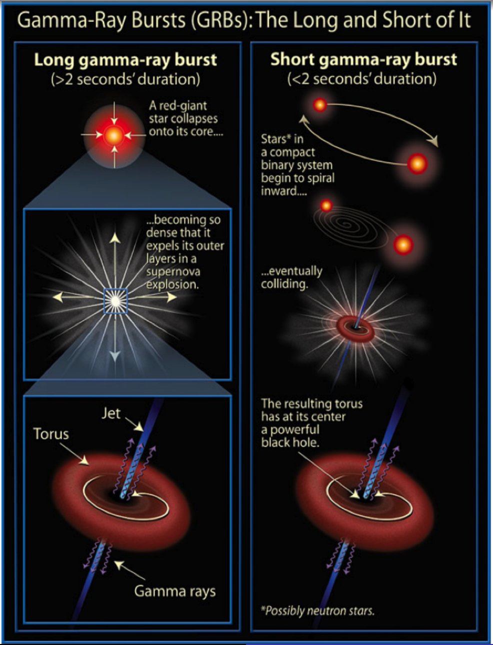
Magnetar Giant Flares



Giant Flares & GW Emission

- Giant flares may excite nonradial pulsational modes with kHz-frequencies in the magnetar (de Freitas Pacheco 1998).
- Theoretical upper limits on E_{GW} based on the energy reservoir associated with a change in the magnetic potential energy of the magnetar (Ioka 2001, Corsi & Owen 2011).
  - Crust-cracking: $10^{47} - 10^{48}$ erg ($10^{-7}\,M_{\odot}c^2$ to $10^{-6}\,M_{\odot}c^2$) with conventional matter ($10^{48} - 10^{50}$ erg with exotic quark and/or baryon-meson matter).
  - Magnetic rearrangement: $10^{45} - 10^{48}$ erg ($10^{-9}\,M_{\odot}c^2$ to $10^{-6}\,M_{\odot}c^2$)
  - Can be probed by Advanced LIGO/Virgo for a Galactic source.
- Studies of pulsational mode excitation suggest weaker emission that may not be detectable (Levin & van Hoven 2011, Zink et al. 2012).

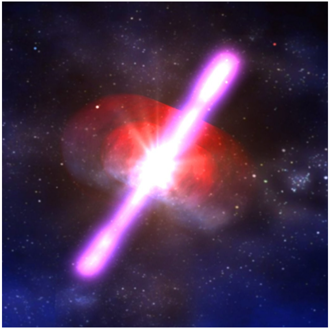
Gamma-Ray Bursts



Long Gamma-Ray Bursts

- Flashes of γ rays observed $\sim$1/day, isotropically distributed over the sky, from cosmological distances.
- Long-duration[1] GRBs ($T_{90} \gtrsim 2\,\mathrm{s}$ are associated with the collapse of massive stars.

- Long GRBs are strongly beamed, and likely have jets with Lorentz factors $\Gamma \gtrsim 100$ and isotropic equivalent luminosities of $10^{51}\,\mathrm{erg\,s^{-1}}$ to $10^{53}\,\mathrm{erg\,s^{-1}}$.
- Central engine of long GRBs is thought to be either a *collapsar* (a black hole with an accretion disk (Woosley 1993) or a *millisecond magnetar* (Metzger et al. 2011).



[1] T_{90} is the time over which 90% of the γ counts are detected.

Engine-Driven Supernovae

- Core-collapse supernovae associated with GRBs are highly energetic type Ic-bl events.
  - "Ic" = compact hydrogen/helium poor progenitor star
  - "-bl" = broad line $\rightarrow$ have relativistically Doppler-broadened spectral features.
- Type Ic-bl events also occur without an associated GRB, and are frequently identified as *engine-driven CCSNe* that exhibit luminous radio emission (Soderberg et al. 2006).
- All likely driven by a central engine that launches a collimated bipolar jet-like outflow.
  - The duration of the central engine's operation determines if the jet can leave the progenitor star and make a GRB.
  - If it fails to emerge, the GRB is "choked" and a more isotropic energetic CCSN explosion is likely to result.
  - Relativistic shock breakout through the stellar surface could produce low-luminosity GRBs (Bromberg et al. 2011).
  - GW emission processes of engine-driven CCSNe are likely very similar to long GRBs.

Scenarios for GWs from Long GRBs: I

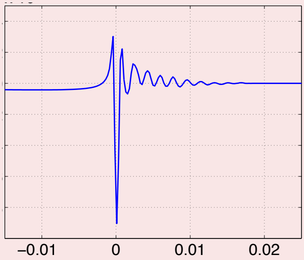
Dynamical Fragmentation (extreme)

- The collapsing extremely rapidly differentially spinning stellar core fragments into a coalescing system of two protoneutron stars (Davies et al. 2002).
- May be unlikely given model predictions for the rotational configuration of GRB progenitor stars.
- Very strong GW emission: $E_{\mathrm{GW}} \sim 10^{-2}\,M_\odot c^2$ to $10^{-1}\,M_\odot c^2$ in the $50\,\mathrm{Hz}$ to $1000\,\mathrm{Hz}$ frequency band.
- Advanced detectors could observe out to $\sim 100\,\mathrm{Mpc}$.

Scenarios for GWs from Long GRBs: II

Core bounce (robust)

- Initial collapse leads to rapidly rotating protoneutron star.
- Core bounce produces a linearly-polarized GW signal with $E_{\mathrm{GW}} \sim 10^{-8}\,M_\odot c^2$ to $10^{-7}\,M_\odot c^2$ between $100\,\mathrm{Hz}$ and $1000\,\mathrm{Hz}$ (Ott et al. 2012).
- Detectable only for Galactic events.
- Same emission for "ordinary" core-collapse supernovae.



Scenarios for GWs from Long GRBs: III

Rotational Instabilities (moderate)

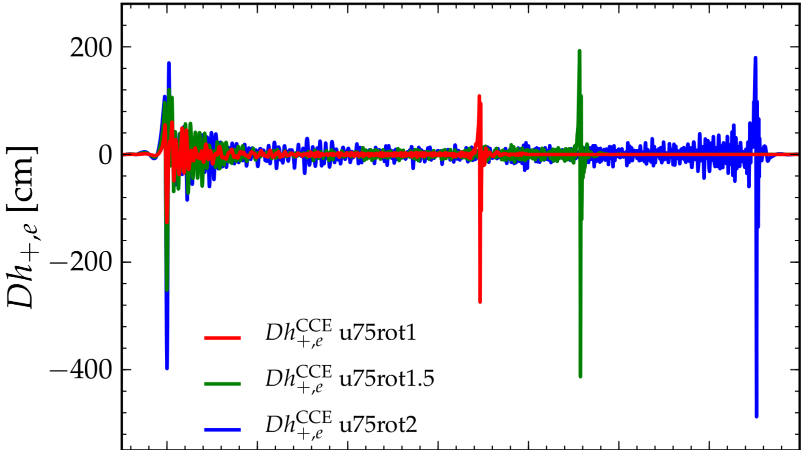
- The new-born protoneutron star may be spinning near breakup speed.
- This can induce rotational instabilities that induce ellipsoidal deformations of the protoneutron star, leading to strong, quasi-periodic, elliptically-polarized GW emission (Fryer & New 2011).
- Typical GW strain: $1.4\,M_\odot$ and radius of $12\,\mathrm{km}$, spinning with a period of $1\,\mathrm{ms}$ may be $h \sim \mathrm{few} \times 10^{-22}$ at $10\,\mathrm{Mpc}$. If the deformation lasted for $100\,\mathrm{ms}$, $E_{\mathrm{GW}} \sim 10^{-1}\,M_\odot c^2$ would be emitted at $2000\,\mathrm{Hz}$.
- Detectable to $\sim$ few Mpc (Local Group).

Scenarios for GWs from Long GRBs: IV

Collapse to Black Hole (robust)

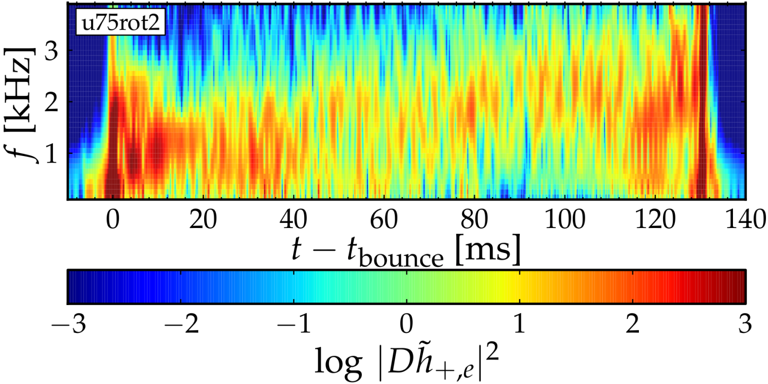
- Collapsar scenario: accretion causes protoneutron star to collapse to a spinning black hole.
- Collapse and ringdown of the newborn black hole leads to a GW burst at $\mathrm{few} \times 10^2\,\mathrm{Hz}$ to $\mathrm{few} \times 10^3\,\mathrm{Hz}$ with $h \sim 10^{-20}$ at $10\,\mathrm{kpc}$ and $E_{\mathrm{GW}} \sim 10^{-7}\,M_{\odot}c^2$. (Ott et al. 2011).
- Detectable only for a Galactic source.

Scenarios for GWs from Long GRBs: IV



(Ott et al. 2011)

Scenarios for GWs from Long GRBs: IV



(Ott et al. 2011)

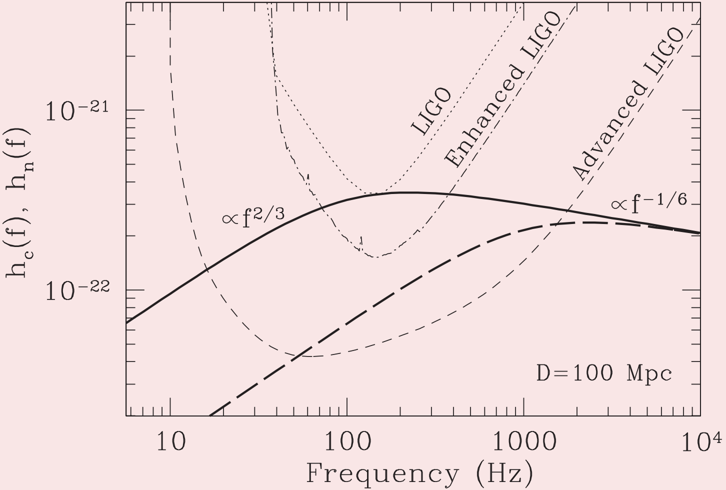
Scenarios for GWs from Long GRBs: V

Accretion Torus Fragmentation (moderate)

- The outer regions of the accretion disk are inefficiently cooled and form a thick torus.
- Gravitational instability may lead to fragmentation of the torus overdense regions that condense to neutron-star-like objects and then inspiral into the central black hole (Piro & Pfahl 2007).
- $1M_\odot$ fragment and a $8M_\odot$ central black hole, this would yield $E_{\mathrm{GW}} \sim 10^{-3}\,M_\odot c^2$ to $10^{-2}\,M_\odot c^2$ in the most sensitive band of LIGO-Virgo.
- Detectable to $\sim 100\,\mathrm{Mpc}$.

Scenarios for GWs from Long GRBs: V

Accretion Torus Fragmentation (Piro & Pfahl 2007)



Scenarios for GWs from Long GRBs: VI

Papaloizou-Pringle instability (moderate)

- The accretion torus may be unstable to the Papaloizou-Pringle instability or to co-rotation instabilities (Papaloizou & Pringle 1984).
- E_{GW} of order $10^{-2}\,M_\odot c^2$ to $10^{-1}\,M_\odot c^2$ and GW frequencies of $100\,\mathrm{Hz}$ to $200\,\mathrm{Hz}$ for a $m = 1$–dominated non-axisymmetric disk instability in a disk around a $10\,M_\odot$ black hole (Kiuchi et al. 2011).
- Detectable to $\sim 100\,\mathrm{Mpc}$.

Scenarios for GWs from Long GRBs: VII

Suspended Accretion (extreme)

- Low-order turbulence powered by black-hole spindown may emit strong GWs. (van Putten et al. 2004).
- Produces an anti-chirp GW. (Most of the emission occurs near the innermost stable orbit, which moves out in radius as the black hole is spun down.)
- Simple estimates suggest GW frequencies in the $100\,\mathrm{Hz}$ to $1000\,\mathrm{Hz}$ band.
- Depending on the initial black hole spin, E_{GW} could be of order $0.1\,M_{\odot}c^2$.
- Detectable to $\sim 100\,\mathrm{Mpc}$.

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