Gravitational Waves and Gamma-Ray Bursts

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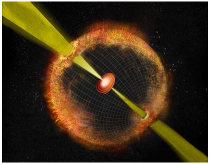
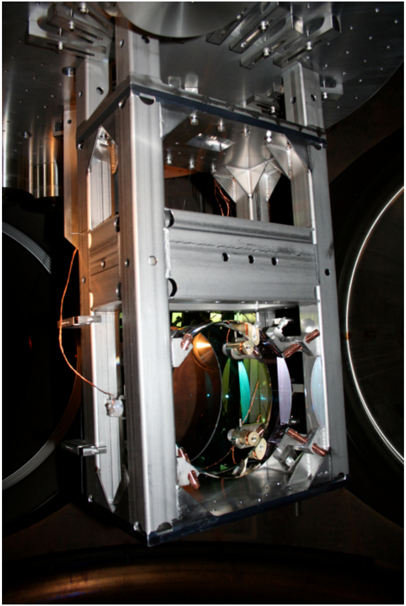
for the LIGO and Virgo collaborations

LAPP/IN2P3 - Annecy





GR → Gravitational Waves

- Gravitational Waves (GW) → usually seen as linear limit of GR

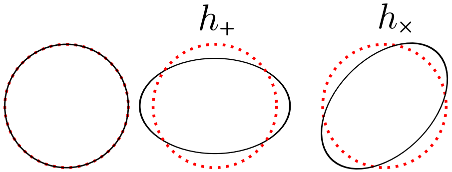
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, \quad h_{\mu\nu} \ll 1 \quad \eta_{\mu\nu}\text{– flat metric}$$

$$\text{Einstein's equations} \Rightarrow \Box h_{\mu\nu} = 0$$

- Waves propagating at speed of light
- 2 transverse polarizations

$$h_{\mu\nu} = h_+ A_{\mu\nu} + h_\times B_{\mu\nu}$$

- Effect on free test masses

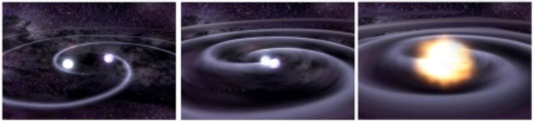


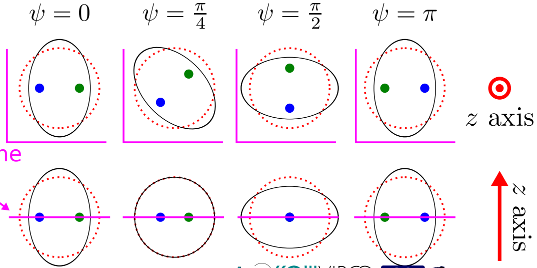
Gravitational sources – quadrupolar approximation

Approximation: far field + slow moving source

- Dominant source: mass distribution quadrupolar moment

$$h_{jk}^{TT} = \underbrace{\frac{2G}{rc^4}}_{\text{1/distance}} \underbrace{P_{jkmn}}_{\text{projection}} \underbrace{\ddot{I}^{mn}\left(t - \frac{r}{c}\right)}_{\text{quadrupolar moment}}$$





circular polarization
$h_+ = \pm i h_\times$

linear polarization
$h_+ \neq 0, \quad h_\times = 0$

Gravitational wave source: luminosity

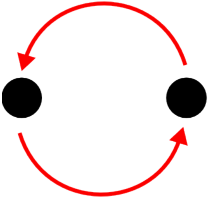
Luminosity (radiated power) in GW

$$\mathcal{L}_{\mathrm{GW}} = \frac{G}{5c^5}\langle \dddot{I}_{\mu\nu}\dddot{I}^{\mu\nu}\rangle = \frac{c^5}{G}\underbrace{\epsilon^2}_{\text{asymmetric}}\underbrace{\left(\frac{R_s}{R}\right)^2}_{\text{compact}}\underbrace{\left(\frac{v}{c}\right)^6}_{\text{relativistic}}$$

- Good sources are:
  - asymmetric $\rightarrow \epsilon = \frac{I_{xx}-I_{yy}}{I_{zz}} \sim 1$
  - compact $\rightarrow$ size R is near the Schwartzschild radius R_s
  - relativistic $v \sim c$
- Example of terrestrial production
  - 10 ton steel bar $\rightarrow$ not compact
  - rotating at 50 Hz, size 1 m $\rightarrow$ non relativistic
  - $\Rightarrow$ GW amplitude $h \sim 10^{-35}$, flux $\sim 10^{-31}\,\mathrm{W\,m^{-2}}$

$\Rightarrow$ Astrophysical sources
  - neutron star merger at 10 Mpc $\rightarrow$ (volume covers a few dozen galaxies)
  - GW amplitude $h \sim 10^{-21}$, flux $\sim 10^{-3}\,\mathrm{W\,m^{-2}}$ $\rightarrow$ possible
- NB: Earth radius $\times\ 10^{-21} \sim$ atomic nucleus radius

Indirect observation of GWs

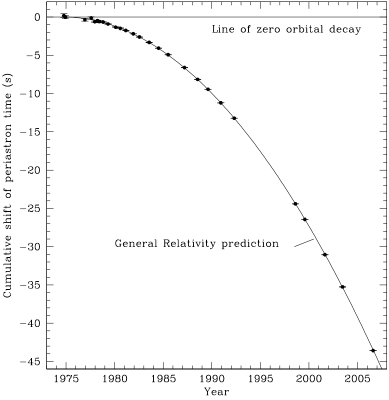


- Neutron star binary $\rightarrow \mathcal{L}_{GW}$

$\Rightarrow$ Energy loss of the binary neutron star system

- Orbital period measured through Doppler effects on radio pulses
- Follows GR with $\sim 10^{-3}$ precision

binary pulsar PSR1913+16

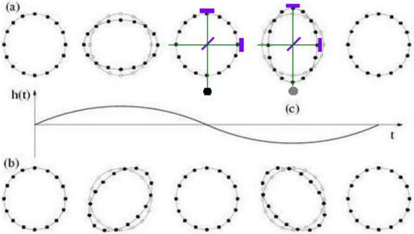


Hulse-Taylor Nobel Prize 1993

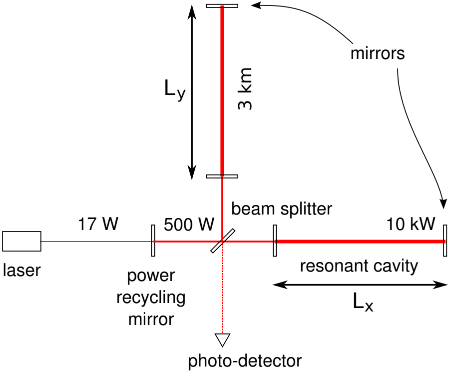
Observation of primordial GW imprint in the CMB with BICEP?

Direct observation principles

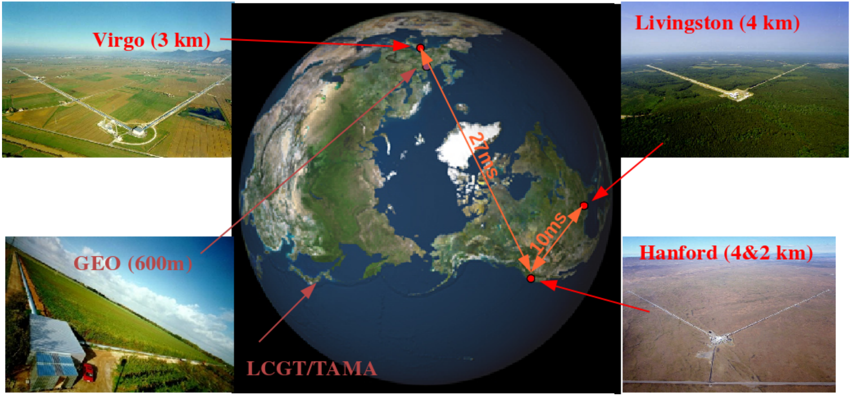
Look at the relative variation of two orthogonal lengths
⇒ Michelson interferometer



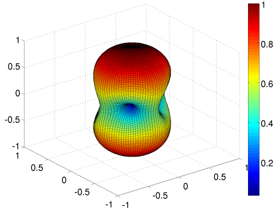
basic optical layout of a GW detector



- Suspended mirrors (horizontally free masses)

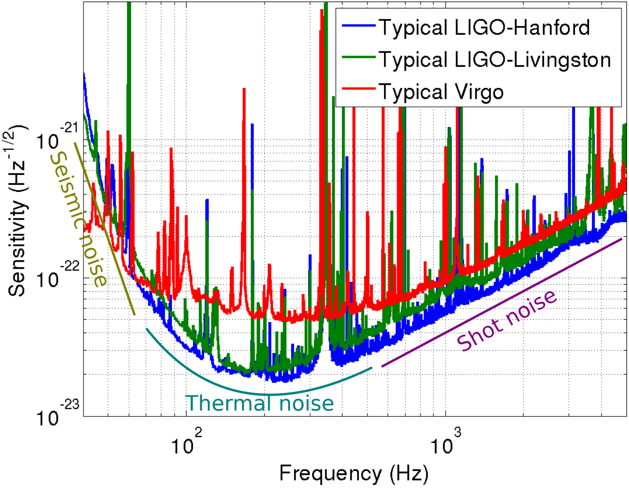


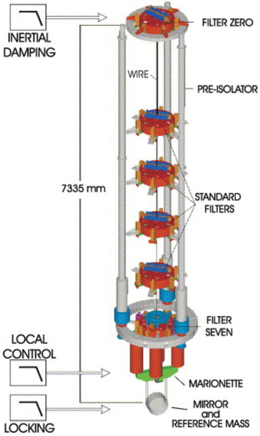
- GW same everywhere but propagation delayed
  $\Rightarrow$ Reject spurious non-Gaussian glitches
- 3 omnidirectional detectors
  $\rightarrow$ sky localization by triangulation



antenna response

A network of detectors – 2009/2010





- Most sensitive for GW in [50, 500] Hz band
  (Abadie et al., 2012c)

Gamma-ray burst models

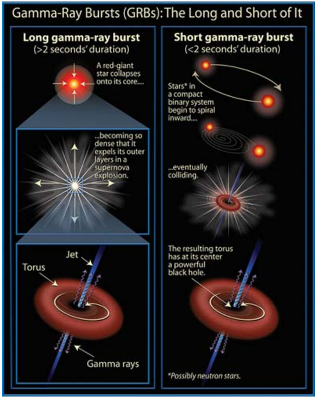
- Long GRBs

⇒ Massive rapidly spinning star collapse and explosion

- Short GRBs

⇒ Coalescence of a neutron star and a compact object

- Both cases: asymmetric, compact, relativistic ⇒ good GW source
- typical GRB distance $\sim 10\,\text{Gpc}$

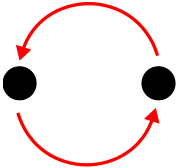


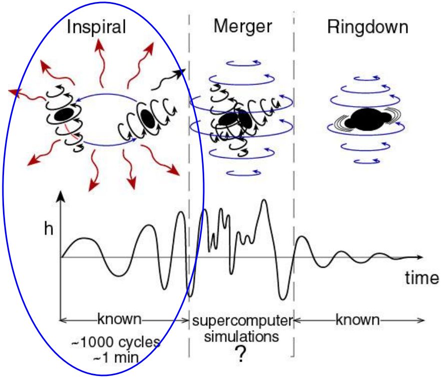
Potential lessons from GW-GRB detection

- Confirm the binary coalescence model for short GRBs
- Constraints on the jet opening angle
- Precise measurement of GW speed, $\Delta v/c \sim 10^{-16}$
- Measure of Hubble's constant independent of cosmic ladder
- ...

GW emission - coalescence scenario

- Binary system of two compact objects (NSNS or NSBH)





- Lose energy by GW radiation
- GW emission enters sensitive band ($\gtrsim 50\,\mathrm{Hz}$) $< 50\,\mathrm{s}$ before coalescence
- NS needs to be disrupted $\rightarrow M_{BH} < 20\,M_{\odot}$ (Duez, 2009)
  $\rightarrow$ negligible GW S/N at merger, ringdown

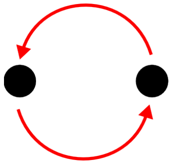
GW emission - coalescence scenario

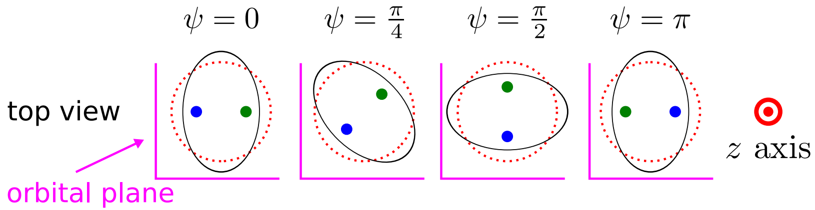
- GRB central engine formed in $\lesssim 1\,\mathrm{s}$
- γ-ray emission delayed by $\lesssim T_{90} \sim 2\,\mathrm{s}$

$\Rightarrow$ coalescence time $[-5, 1]\,\mathrm{s}$ prior to GRB observation

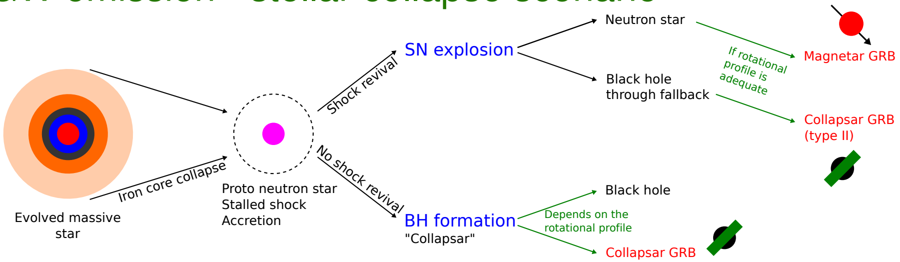
- GRB observed $\longrightarrow$ rotation axis points at observer

$\Rightarrow$ GW well known and circularly polarized
up to inclination of 60° $\longrightarrow$ loose constraint
(jet opening angle $\lesssim$ 30°)





GW emission - stellar collapse scenario



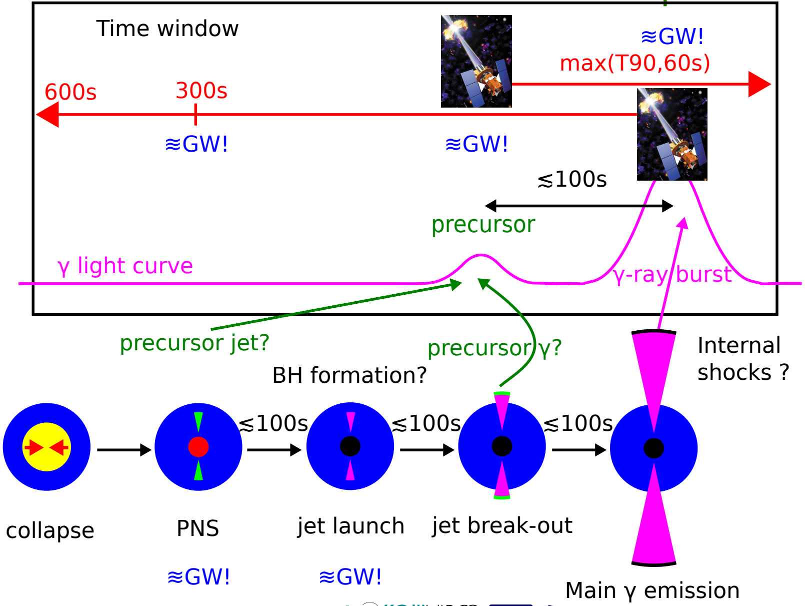
- Magnetar central engine / Proto neutron star
  - bar mode instability in the star (Shibata et al., 2003)
  - neutron star core fragmentation (Davies et al., 2002; Kobayashi and Mészáros, 2003)
- Black hole and accretion disk
  - Disk fragmentation (Piro and Pfahl, 2007)
  - Disk precession (Romero et al., 2010)

$\Rightarrow$ circular polarization along rotation axis

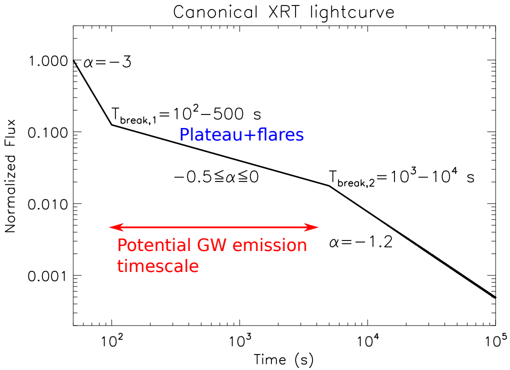
$\Rightarrow$ Emitted GW energy $\lesssim 10^{-2}\, M_\odot c^2$ (10^{52} erg)

- Other emission mechanism but no prospects for extra-galactic reach
  - Out of frequency band (Neutrino, normal modes, ...)
  - Too small amplitude (Core bounce, SASI, ...)

GW vs GRB time of arrival - stellar collapse



Long time scale emission



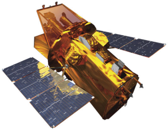
- Plateau and flares in GRB afterglows
- Long lived EM emission from the central engine (Rowlinson et al., 2013)
- Long lived GW emission $\sim 10^3$ s?
  - Secular bar mode instability in neutron star (Corsi and Mészáros, 2009)
  - Fallback accretion on neutron star (Piro and Thrane, 2012)

$\Rightarrow$ Long $\sim 10^3$ s poorly modeled transients

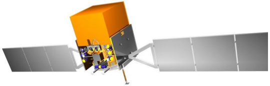
- Methods are in developments (Aasi et al., 2013)

Comprehensive data sample – (Aasi et al., 2014)

- 2005 – 2010 → 2 years of data
- Network of four GW detectors
  - LIGO Hanford 1 and 2
  - LIGO Livingston
  - Virgo, Italy



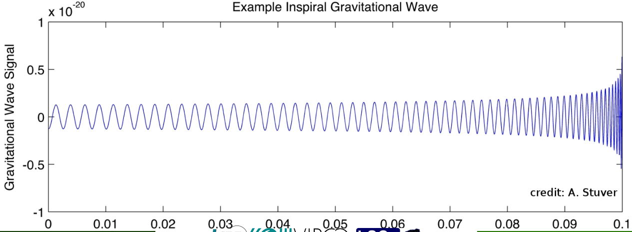
- GRBs observed by γ-ray satellites
  Gamma-ray burst Coordinates Network
  + Inter Planetary Network



- 508 GRBs with good data from at least two GW detectors
- includes 69 “short” GRBs – lenient classification
  - $T_{90} < 4\,\mathrm{s}$
  - or short spike at light curve start (extended emission sGRB)
  - Completeness more important than purity

Two complementary searches – (Aasi et al., 2014)

- Broad in scope – covers most possibilities
  - "burst" searching method – any signal shapes
  - Limited to $60 - 500\,\mathrm{Hz}$ band, $\lesssim 1\,\mathrm{s}$ duration
  - Assumes circular polarization
  - Loose time coincidence between γ-rays and GW $T_{\mathrm{GW}} - T_{\gamma} \in [-600, \max(T_{90}, 60)]\,\mathrm{s}$
- Focused on short GRBs – binary coalesence
  - Inspiral waveform templates, NS-NS and NS-BH
  - Tight time coincidence between γ-rays and GW inspiral end time $T_{\mathrm{GW,\ coalescene}} - T_{\gamma} \in [-5, 1]\,\mathrm{s}$
  - More sensitive to inspiral signals by factor ~ 2
- Both combine data coherently from ≥ 2 detectors

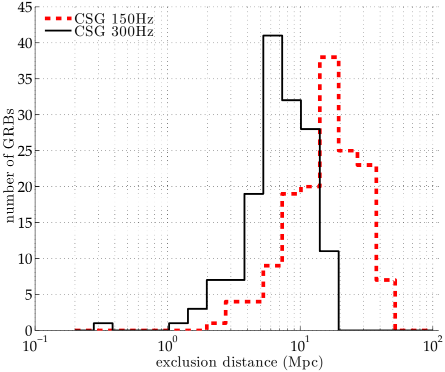


GW non detection consequences

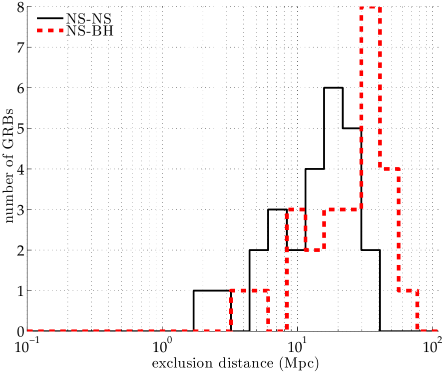
GRB progenitor distance exclusion

2009-2010 GCN sample

Unmodeled GW bursts with $E_{GW} = 10^{-2}\, M_\odot\, c^2$



Binary system coalescence



	burst 150Hz	burst 300Hz	NS-NS	NS-BH
median (Mpc)	17	7	16	28

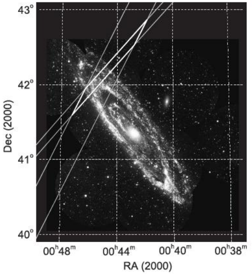
(Abadie et al., 2012b)

GRB070201 / GRB051103

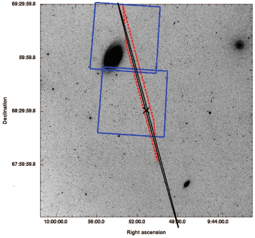
Significant previous non detections

- Short GRBs,
  - GRB070201 sky location overlap with M31, (Andromeda 770 kpc)
  - GRB051103 sky location overlap with M81 ($\sim$ 3.6 Mpc)
- no GW found
  - $\Rightarrow$ Binary coalescence in M31 excluded at >99% confidence level (Abbott et al., 2008)
  - $\Rightarrow$ Binary coalescence in M81 excluded at 98% confidence level (Abadie et al., 2012a)
- Compatible with
  - Neutron star quake in M31/M81 (Soft gamma-repeater)
  - Coalescence in galaxy behind M31/M81

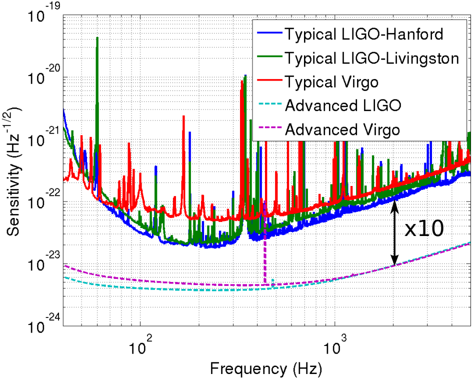
GRB070201 error box (Mazets et al., 2008)



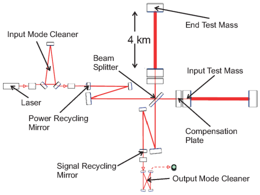
GRB051103 error box (Hurley et al., 2010)



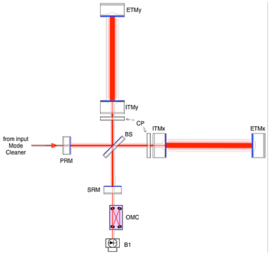
Network of “Advanced” detectors (talk by C. Pankow)



Advanced LIGO



Advanced Virgo

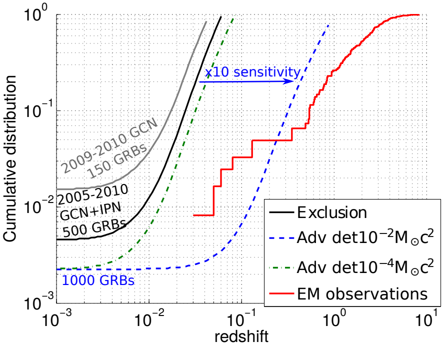


- 3 Advanced LIGO / Advanced Virgo → 2015
- factor ∼ 10 improvement in sensitivity
- factor ∼ 10^3 improvement in volume within reach
- Reaching design sensitivity will take a few years

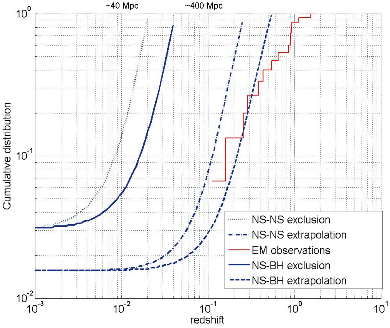
- KAGRA (LCGT, Japan) started construction → 5 detectors ∼ 2020

Expectations & Prospects (Aasi et al., 2014)

Unmodeled GW bursts



Binary coalescence



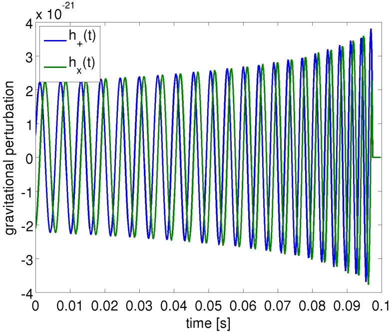
- Prospects for advanced detectors
  - Don't miss nearby GRB $\rightarrow$ full sky/time coverage
  - $\times$10 sensitivity
    $\times$2 number of GRBs $\Leftarrow$ γ-ray satellite coverage crucial
  - long GRBs, possible if optimistic GW emission
  - short GRBs, quite possible, especially if significant NS-BH fraction
    expect $\sim$ 1 detection per year

Measuring Hubble's constant with GWs

All potential GWs sources $z \lesssim 0.1$: $H_0 = c\frac{z}{D_L}$

$$\begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix} = \underbrace{\frac{A(t;\,(1+z)\mathcal{M})}{D_L}}_{\text{enveloppe}} \underbrace{\begin{bmatrix} (1+\cos^2\iota)\cos(\Psi(t;\,(1+z)\mathcal{M})) \\ 2\cos\iota\sin(\Psi(t;\,(1+z)\mathcal{M})) \end{bmatrix}}_{\text{polarized oscillations}}$$

- $A/\Psi(t;\,(1+z)\mathcal{M})$ - GW shape sets absolute amplitude of the waveform
- D_L - luminosity distance
  $\Rightarrow$ Measure D_L from GW amplitude
- ι - binary inclination angle - degenerate with luminosity distance (polarization is hard to measure)
- z - redshift - degenerate with the mass of the binary



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Several approaches

⇒ Measure D_L from GW amplitude

Measuring Hubble's constant with GWs

$$\begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix} = \frac{A(t; (1+z)\mathcal{M})}{D_L} \begin{bmatrix} (1+\cos^2\iota)\cos(\Psi(t); (1+z)\mathcal{M}) \\ 2\cos\iota\sin(\Psi(t); (1+z)\mathcal{M}) \end{bmatrix}$$

Several approaches

⇒ Measure D_L from GW amplitude

- Combine GW and GRB observation (Nissanke et al., 2010)
  - redshift given by EM observations
  - γ-ray observation means binary close to face-on
    → helps breaking the D_L vs inclination degeneracy

Measuring Hubble's constant with GWs

$$\begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix} = \frac{A(t; (1+z)\mathcal{M})}{D_L} \begin{bmatrix} (1+\cos^2\iota)\cos(\Psi(t); (1+z)\mathcal{M}) \\ 2\cos\iota\sin(\Psi(t); (1+z)\mathcal{M}) \end{bmatrix}$$

Several approaches

⇒ Measure D_L from GW amplitude

- Combine GW and GRB observation (Nissanke et al., 2010)
- Use GW information alone - Assume $\mathcal{M}$ (Taylor et al., 2012)
  - Assume $\mathcal{M}$ known - binary neutron star system
    → Measure redshift from GW shape
  - Dozens of events per year
    → helps breaking the D_L vs inclination degeneracy

Measuring Hubble's constant with GWs

$$\begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix} = \frac{A(t; (1+z)\mathcal{M})}{D_L} \begin{bmatrix} (1+\cos^2\iota)\cos(\Psi(t); (1+z)\mathcal{M}) \\ 2\cos\iota \sin(\Psi(t); (1+z)\mathcal{M}) \end{bmatrix}$$

Several approaches

⇒ Measure D_L from GW amplitude

- Combine GW and GRB observation (Nissanke et al., 2010)
- Use GW information alone - Assume $\mathcal{M}$ (Taylor et al., 2012)
- Combine GW and galaxy catalogs (Del Pozzo, 2012)
  - Measure redshift statistically from catalog
    → All potential host within large 3D wedge of the universe
  - Dozens of events per year
    → helps breaking the D_L vs inclination degeneracy

Measuring Hubble's constant with GWs

$$\begin{bmatrix} h_+(t) \\ h_\times(t) \end{bmatrix} = \frac{A(t; (1+z)\mathcal{M})}{D_L} \begin{bmatrix} (1+\cos^2\iota)\cos(\Psi(t); (1+z)\mathcal{M}) \\ 2\cos\iota\sin(\Psi(t); (1+z)\mathcal{M}) \end{bmatrix}$$

Several approaches

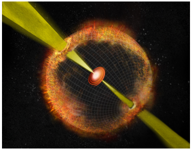
⇒ Measure D_L from GW amplitude

- Combine GW and GRB observation (Nissanke et al., 2010)
- Use GW information alone - Assume $\mathcal{M}$ (Taylor et al., 2012)
- Combine GW and galaxy catalogs (Del Pozzo, 2012)
- In all cases $\sim$ 10% precision on H_0
- Measurement independent of cosmic ladder

Summary

- Long and short GRBs progenitors may produce large amounts of GWs
- Some relevant exclusions: GRB070201, GRB051103
- Good prospects for first detection with advanced detectors $\gtrsim$ 2015
- Joint GW-γ observation will determine the nature of GRB progenitors
- Full sky γ-ray coverage essential in 2015-2020

Swift/BAT	10% of sky
SVOM/GRM	20% of sky
Fermi/GBM	60% of sky
IPN	most of the sky?



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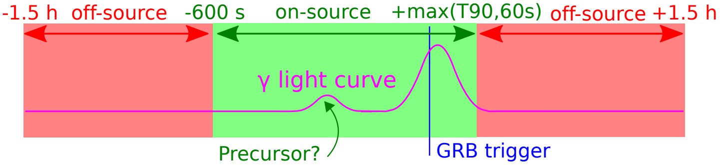
GRB triggered GW burst search



- Known position and time
  - Reduced time → reduced background
  - Position → simplify coherent network analysis
    - time delays between detectors constrained by sky location box
    - ∼ 20% sensitivity improvement (Wąs et al., 2012)

⇒ Better sensitivity by a factor ∼ 2 wrt to all-sky/all-time search

- On-source data
  - Search for potential GW events
- Off-source data, time slides
  - Measurement of event background distribution
- Repeated independently for each GRB