Prospects with Advanced Gravitational Wave detectors

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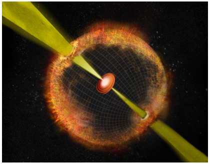
YITP



Outline

LIGO/Virgo

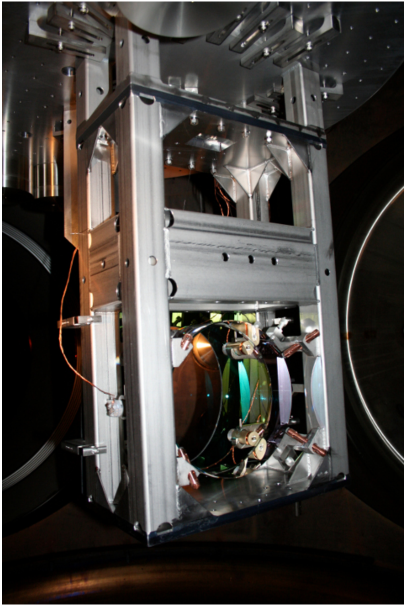
Detectors

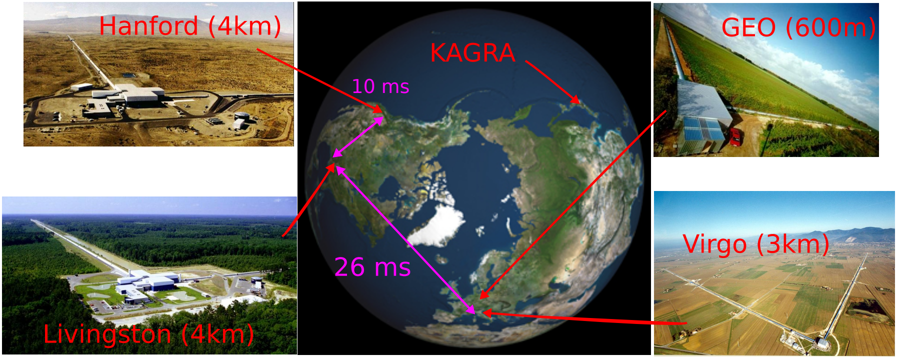
Result highlights

Gamma-ray bursts

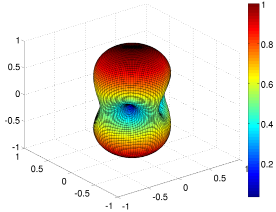
Supernovae

Summary



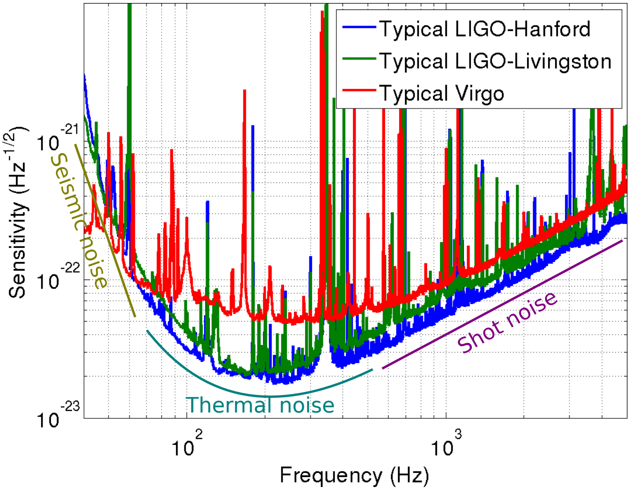


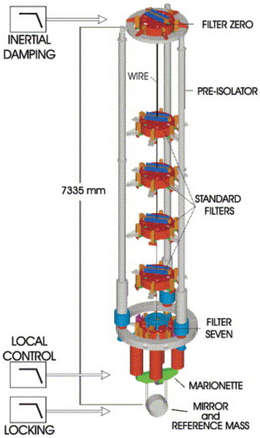
- GW same everywhere but propagation delayed
  ⇒ Reject spurious non-Gaussian glitches
- 3 omnidirectional detectors
  → sky localization by triangulation



antenna response

A network of detectors – 2009/2010



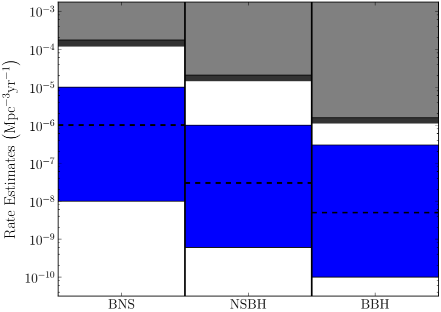


- Most sensitive for GW in [50, 500] Hz band

(Abadie et al., 2012e)

What have we not seen?

Results - binary coalescence



- Search for coalescence of binary neutron star and/or black hole (Abadie et al., 2012d)
- 2005-2010 upper limits 2 orders of magnitude above expectation
- advanced detectors $\rightarrow \times 10^3$ increase in sensitive volume
- 40 yr^{-1} detections expected (Abadie et al., 2010)
  - Large errors on astrophysical predictions: 0.4 – 400 yr^{-1}
  - Based on binary pulsars observation / population synthesis

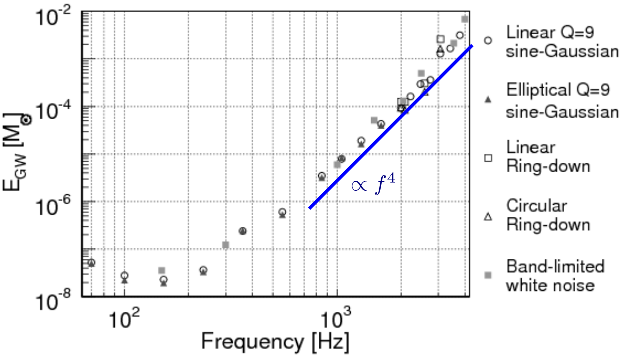
Results - isolated neutron stars

- Young pulsars (neutron stars)
  - Crab (SN 1054)
  - Vela (SN $\sim 10^4$ yr ago)
  - ...

  spin frequency is precisely observed in radio
- The rotation period is decreasing
  $\longrightarrow$ loss of rotational energy
- less than 1% of Crab energy loss is due to GW emission (Aasi et al., 2013a)
- less than 10% of Vela energy loss is due to GW emission (Aasi et al., 2013a)
- Without any radio observation the limits on energy loss higher by $\sim 10^2 - 10^3$ (Abadie et al., 2011)

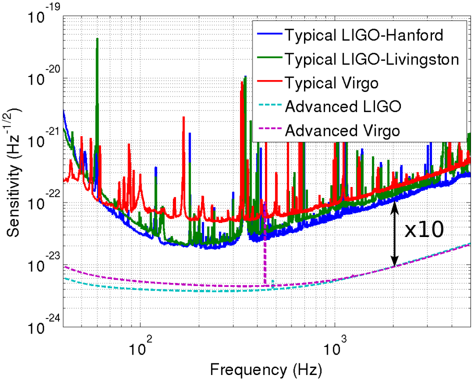
$\Rightarrow$ EM observation enhance GW searches sensitivity

Results - unmodeled GW bursts

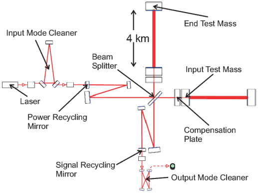


- Search for generic bursts of GWs (2009-2010) (Abadie et al., 2012a)
  - Binary mergers
  - Stellar collapse
  - ...
- Sensitivity in terms of E_{GW} emitted at 10 kpc

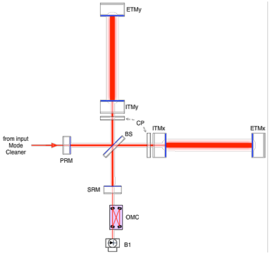
Network of “Advanced” detectors



Advanced LIGO



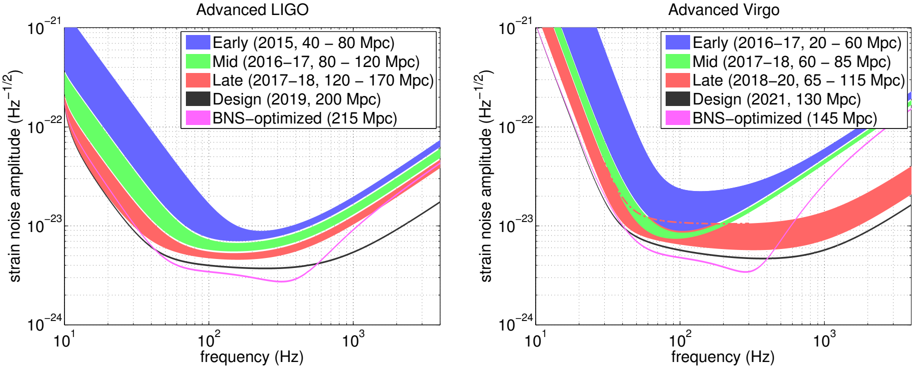
Advanced Virgo



- 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 construction underway → 5 detectors ∼ 2020

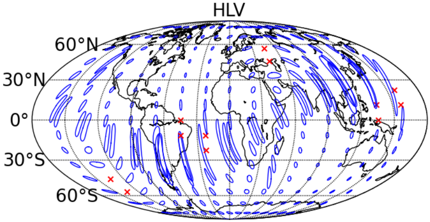
Reaching design will take time



- Best guesses

(Aasi et al., 2013b)

A fourth detector site helps with sky localization



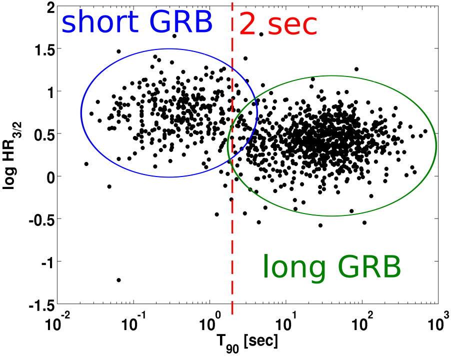
- Third Advanced LIGO detector planned in India 2020-2022

(Aasi et al., 2013b)

Gamma-ray bursts

Gamma-ray bursts

- Observational definition → a burst of γ-rays (10 keV – 1 MeV)
- Discovered in the 70's by nuclear bomb test surveillance satellites



BATSE 4B catalog

- T_{90} - duration of 90% of photon counts ($\sim$ 15 – 300 keV)
- Two observational populations:
  - short-hard GRBs $T_{90} \lesssim 2\,\mathrm{s}$ spectrum peaks at higher energy
  - long-soft GRBs $T_{90} \gtrsim 2\,\mathrm{s}$ spectrum peaks at lower energy

Gamma-ray burst models

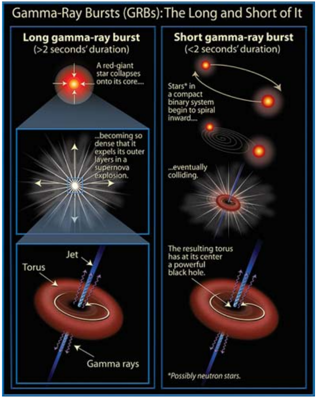
- Long GRBs

⇒ 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 ~ 10 Gpc



Potential lessons from GW-GRB detection

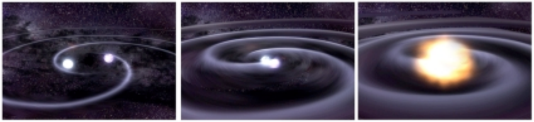
- Confirm the binary coalescence model for short GRBs
- Learn more about central engine of long GRBs
  - black hole or magnetar?
- Precise measurement of GW speed, $\Delta v/c \sim 10^{-16}$
- Measure of Hubble's constant independent of cosmic ladder

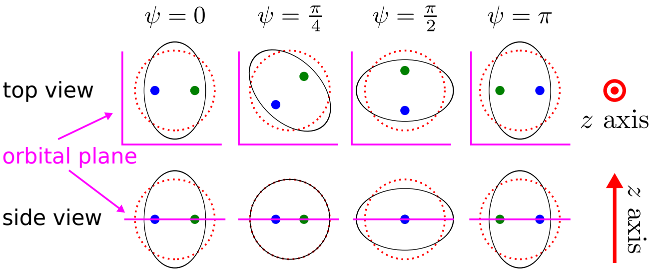
Gravitational sources – quadrupolar approximation

Approximation: far field + slow moving source

- Dominant source: mass distribution quadrupolar moment

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



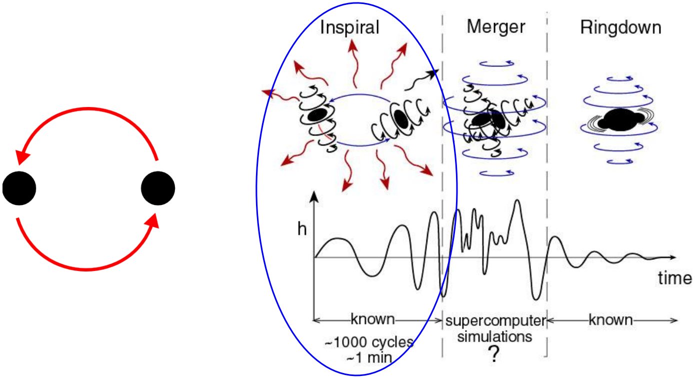


circular polarization
$h_+ = \pm i h_\times$

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

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 $\rightarrow M_{\mathrm{BH}} < 20\,\mathrm{M}_{\odot}$ (Duez, 2009)
  $\rightarrow$ negligible GW S/N at merger, ringdown

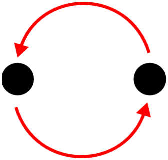
GW emission - coalescence scenario

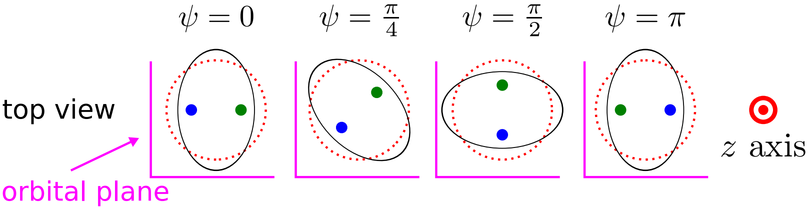
- GRB central engine formed in $\lesssim 1\,\mathrm{s}$
- γ-ray emission delayed by $\lesssim T_{90} \sim 2\,\mathrm{s}$

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

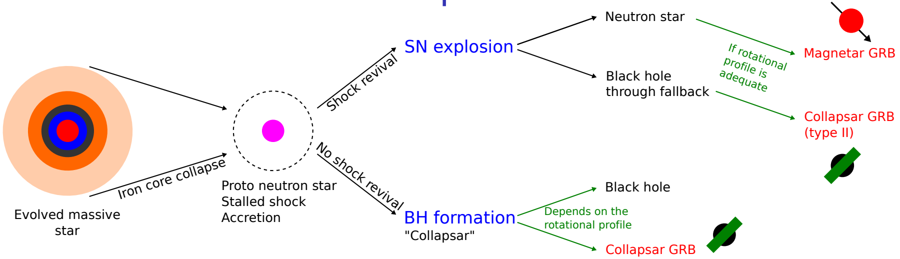
- GRB observed → rotation axis points at observer

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





GW emission - stellar collapse scenario



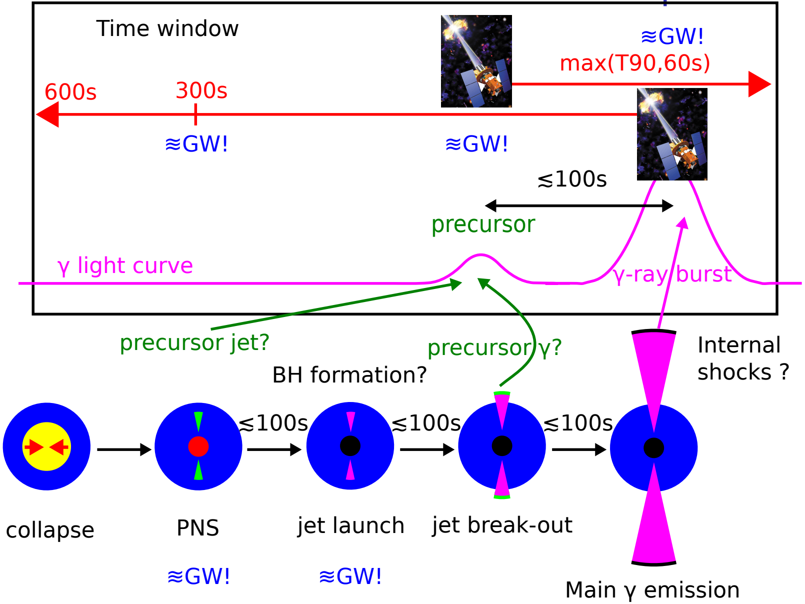
- Magnetar central engine / Proto neutron star
  - bar mode instability in the star (Shibata et al., 2003)
  - neutron star core fragmentation (Davies et al., 2002; Kobayashi and Mészáros, 2003)
- Black hole and accretion disk
  - Disk fragmentation (Piro and Pfahl, 2007)
  - Disk precession (Romero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

⇒ circular polarization along rotation axis

⇒ Emitted GW energy $\lesssim 10^{-2}\,M_\odot c^2$

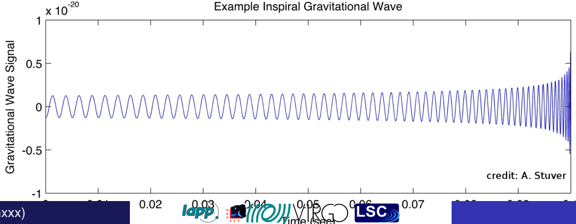
- Other emission mechanism but no prospects for extra-galactic reach
  - Out of frequency band (Neutrino, normal modes, ...)
  - Too small amplitude (Core bounce, SASI, ...)

GW vs GRB time of arrival - stellar collapse



Two complementary searches – (Abadie et al., 2012c)

- 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 $T_{\mathrm{GW}} - T_\gamma \in [-600, \max(T_{90}, 60)]\,\mathrm{s}$
  - More sensitive than blind search by factor ~ 2
- 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

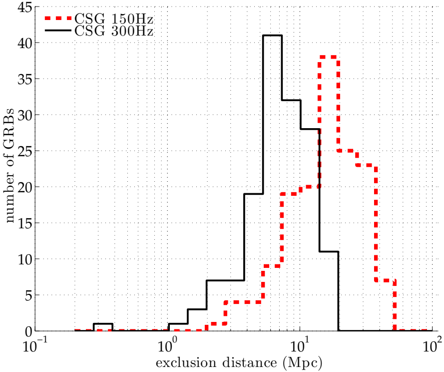


credit: A. Stuver

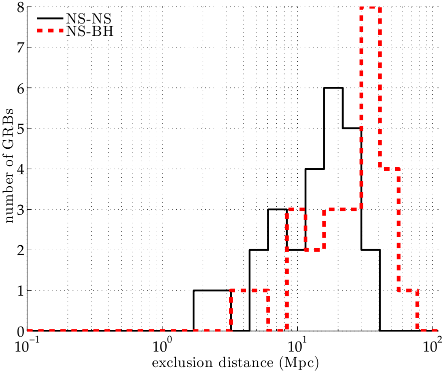
2009-2010, GW non detection consequences

GRB progenitor distance exclusion

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



Binary system coalescence



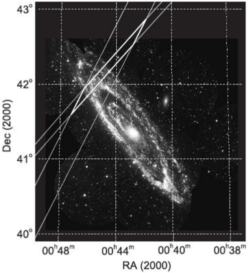
	burst 150Hz	burst 300Hz	NS-NS	NS-BH
median (Mpc)	17	7	16	28

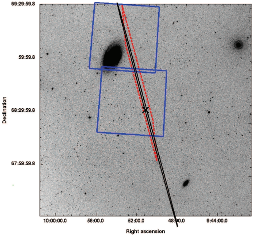
(Abadie et al., 2012c)

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
  - ⇒ Binary coalescence in M31 excluded at >99% confidence level (Abbott et al., 2008)
  - ⇒ Binary coalescence in M81 excluded at 98% confidence level (Abadie et al., 2012b)
- Compatible with
  - Neutron star quake in M31/M81 (Soft gamma-repeater)
  - Coalescence in galaxy behind M31/M81

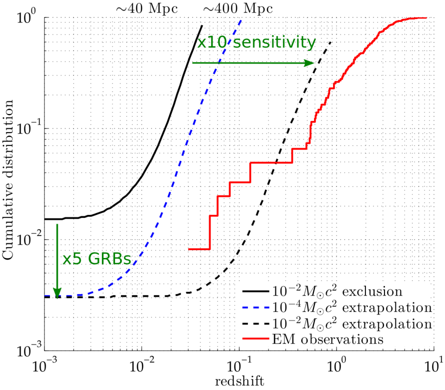

GRB070201 error box (Mazets et al., 2008)


GRB051103 error box (Hurley et al., 2010)

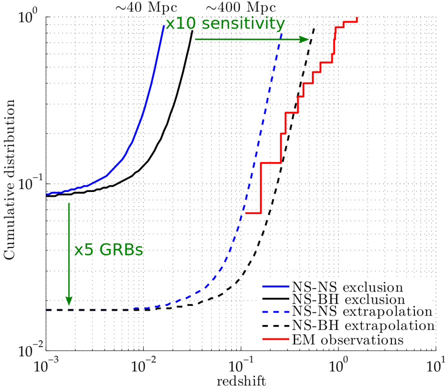
Expectations & Prospects

- 2009-2010 results

Unmodeled GW bursts



Binary coalescence

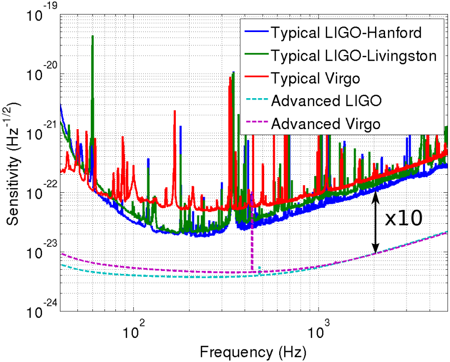


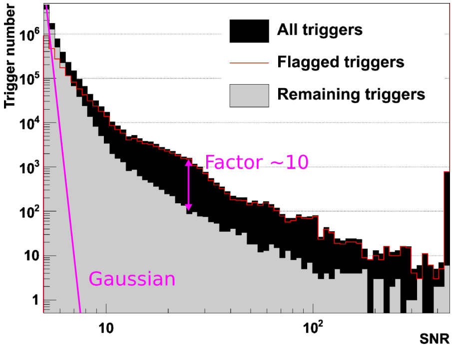
- Prospects for advanced detectors (Abadie et al., 2012c)
  - ×10 sensitivity, ×5 number of GRBs $\Leftarrow$ γ-ray satellite coverage
  - long GRBs, possible if optimistic GW emission
  - short GRBs, quite possible, especially if significant NS-BH fraction

Supernovae prospects

rule of thumb for GW sensitivity

GW sensitivity



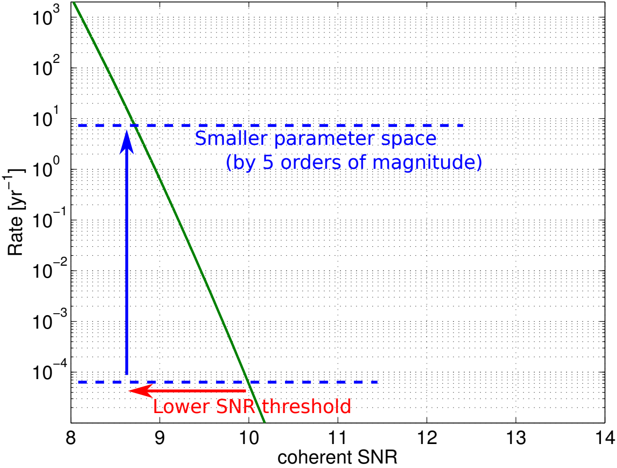


$$\text{smallest observable GW amplitude} \propto S(f) \times \text{S/N}_{\text{threshold}}$$

- Astrophysical triggers, GW models, etc ... changes search parameter space

⇒ $\text{S/N}_{\text{threshold}}$ depends on the search hypothesis

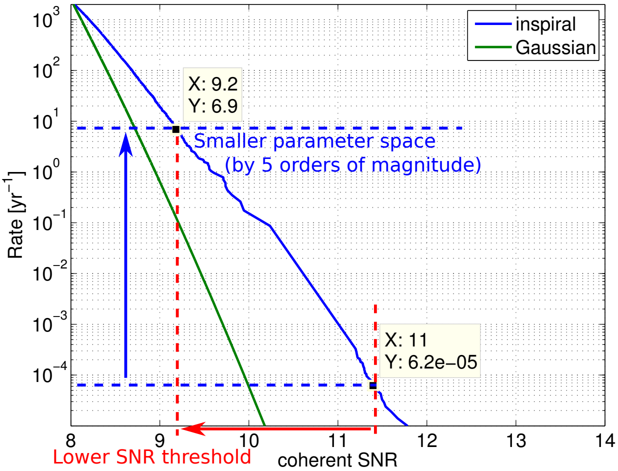
Triggered search in Gaussian noise



Localization in time: $\frac{\text{few minutes}}{\text{few months}} \sim 10^{-5}$

⇒ Improves sensitivity by 15%, 50% in volume

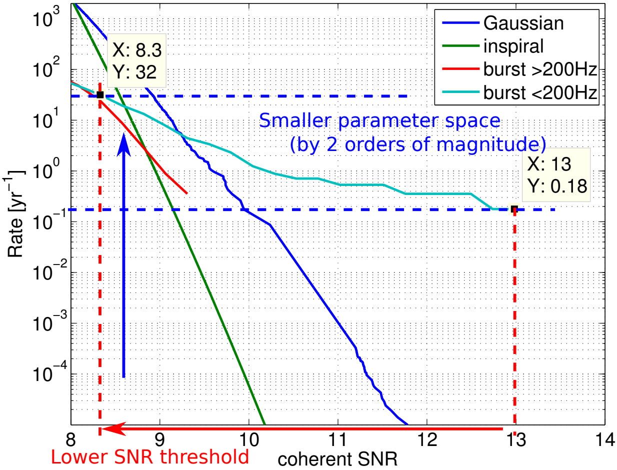
Well cleaned real noise (inspiral + χ^2 test) (Aasi et al., 2013b)



Localization in time: $\frac{\text{few minutes}}{\text{few months}} \sim 10^{-5} \sim$ short GRB case

$\Rightarrow$ Improves sensitivity by 20%, 70% in volume

Real data, no GW model (Aasi et al., 2013b)



Localization in time: $\frac{\text{1 day}}{\text{few months}} \sim 10^{-2} \sim$ long GRB case

$\Rightarrow$ Improves sensitivity by 60%, factor 4 in volume

Rule of thumb for GW detectability (Sutton, 2013)

- GW amplitude (rss – root-sum-square)

$$h_{\text{rss}} = \sqrt{\int_{-\infty}^{\infty} [h_+^2(t) + h_\times^2(t)]\mathrm{d}t}$$

- Energetics for signal at frequency f_0

$$E_{\text{GW}} = \underbrace{\alpha}_{\text{emission geometrics}} \frac{\pi^2 c^3}{G} r^2 f_0^2 h_{\text{rss}}^2$$

- Signal to Noise Ratio

$$\rho^2 = \underbrace{\Theta^2}_{\text{antenna geometrics}} \frac{h_{\text{rss}}^2}{S(f_0)^2}$$

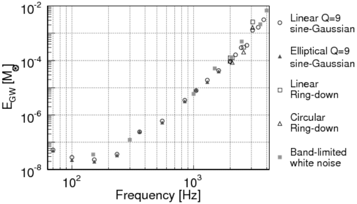
- Volume where S/N above threshold ρ_{det}

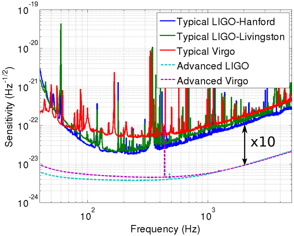
$$\mathcal{R} \simeq \left(\frac{G}{2\pi^2 c^3}\right)^{1/2} \frac{\sqrt{E_{\text{GW}}}}{S(f_0) f_0 \rho_{\text{det}}}$$

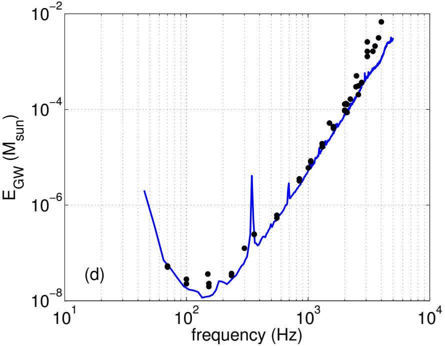
- Almost independent of emission polarization

Value of ρ_{det} in practice (Sutton, 2013)

$$\mathcal{R} \simeq \left(\frac{G}{2\pi^2 c^3}\right)^{1/2} \frac{\sqrt{E_{\text{GW}}}}{S(f_0)\, f_0\, \rho_{\text{det}}}$$

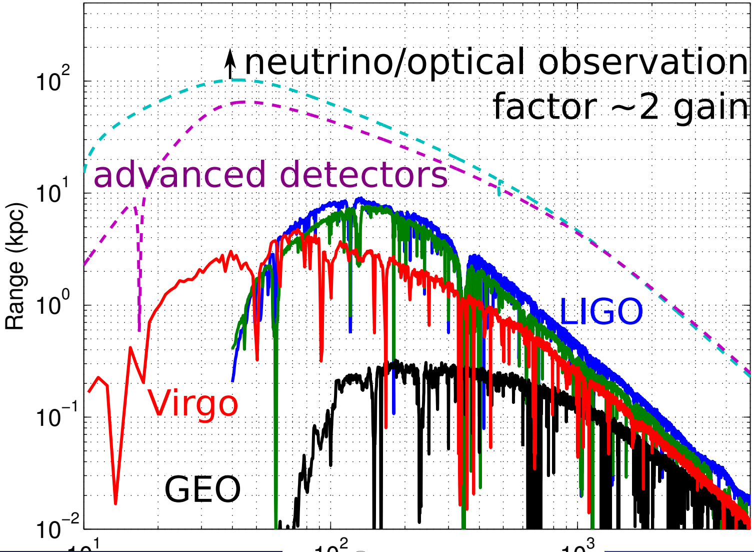






$\Rightarrow \rho_{\text{det}} \simeq 20$

Range frequency dependence, $E_{GW} = 10^{-8} M_{\odot} c^2 \simeq 10^{46} erg$



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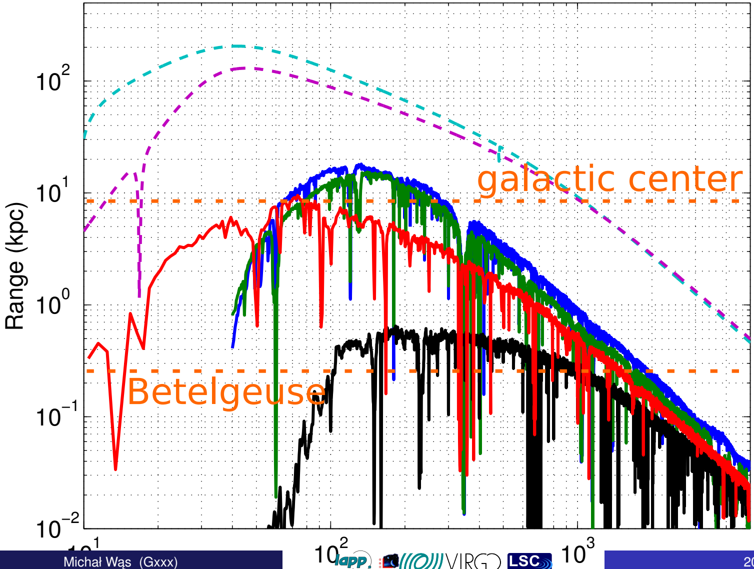

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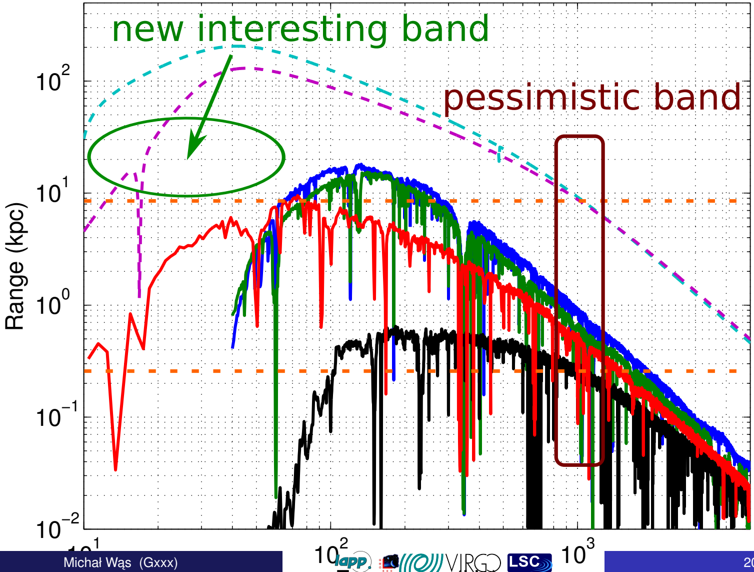
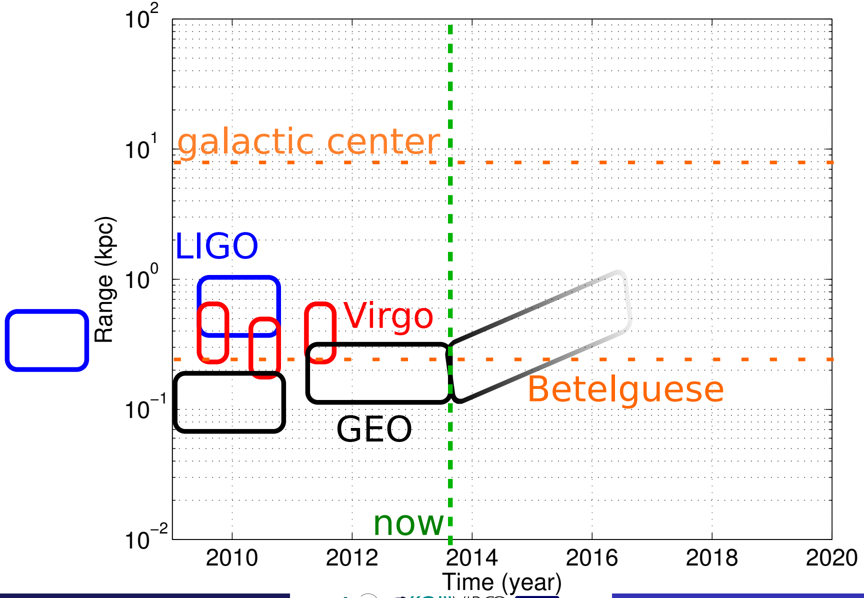
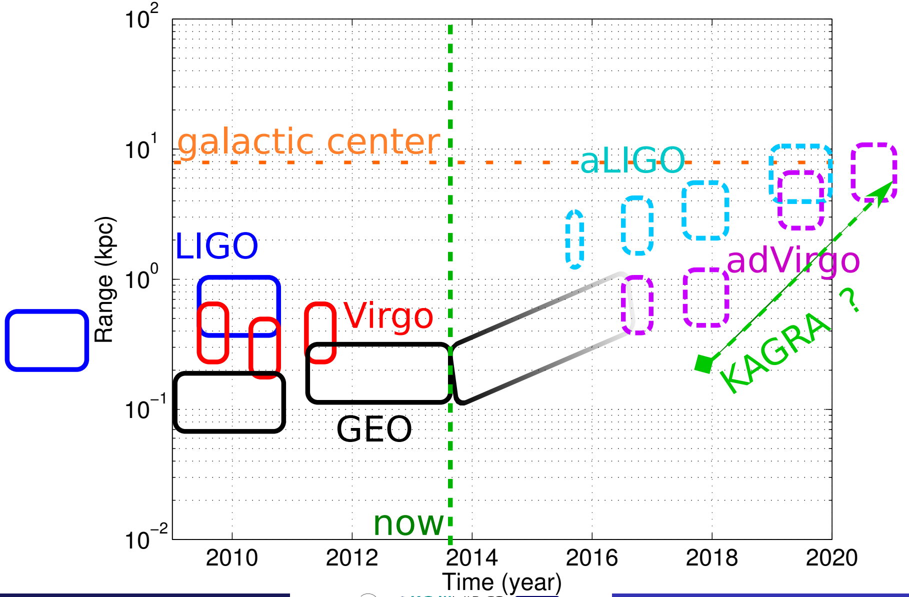


pessimistic SN range (1 kHz) – history

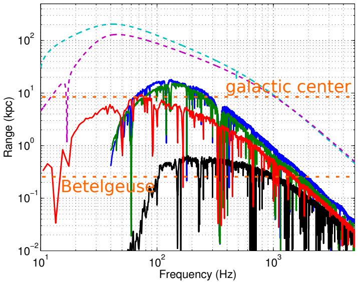


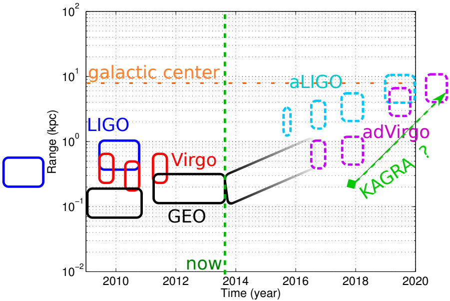
pessimistic SN range (1 kHz) – future (Aasi et al., 2013b)



Summary

- Good prospects for first detection with advanced detectors $\gtrsim$ 2015
  - Binary coalescences
  - Gamma-ray bursts
  - Pulsars
  - Galactic supernova





- Is $E_{\mathrm{GW}} \sim 10^{-8}\,\mathrm{M}_\odot c^2 \simeq 10^{46}$ erg a good rule of thumb?
- Are energetics flat with frequency?
  Higher GW emission efficiency at high frequency?

Be careful with energy plots

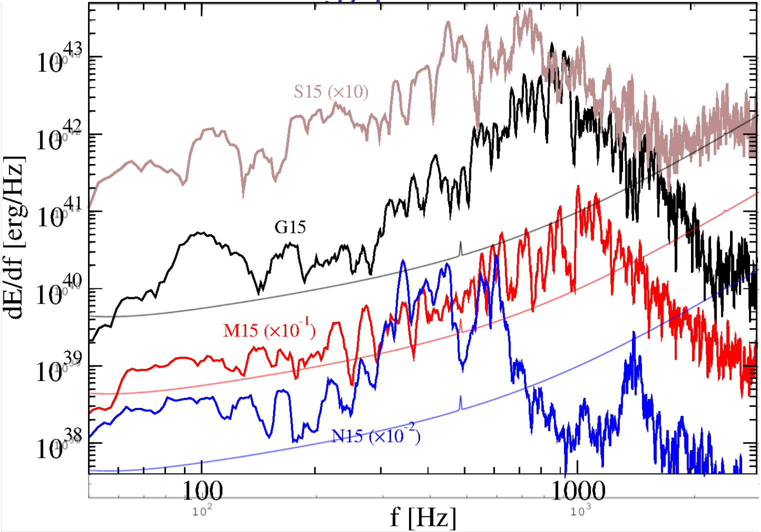
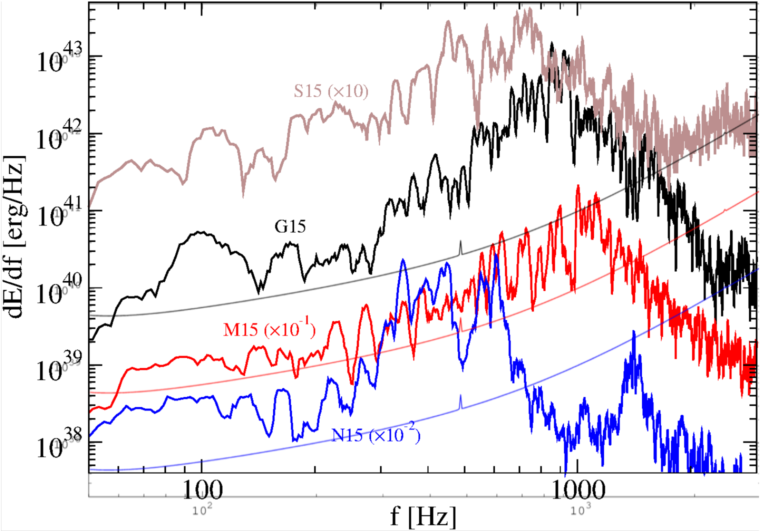


Figure 8 of Müller et al. (2013), with aLIGO sensitivity at 10 kpc
Caveat: stappled plot last night

Low and high frequency as important



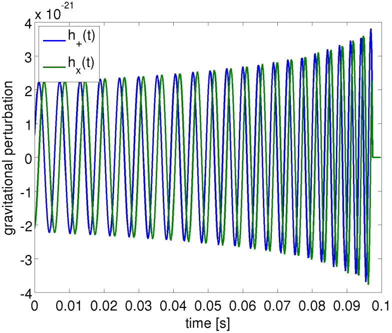
Müller et al. (2013)

Measuring Hubble's constant with GWs

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

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

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



Measuring Hubble's constant with GWs

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

Several approaches

- Combine GW and GRB observation (Nissanke et al., 2010)
  - redshift given by EM observations
  - GW shape yields absolute amplitude
    → Measure D_L from GW amplitude
  - γ-ray observation means binary close to face-on
    → helps breaking the D_L vs inclination degeneracy
- Use GW information alone (Taylor et al., 2012)
  - Assume $\mathcal{M}$ known - binary neutron star system
    → Measure redshift from GW shape
  - GW shape yields absolute amplitude
    → Measure D_L from GW amplitude
  - Dozens of events per year
    → helps breaking the D_L vs inclination degeneracy
- In both cases $\sim$ 10% precision on H_0
- Measurement independent of cosmic ladder

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