LIGO/Virgo/GEO/KAGRA science

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9th LISA symposium @ BnF-Paris
May 24th 2012

Outline

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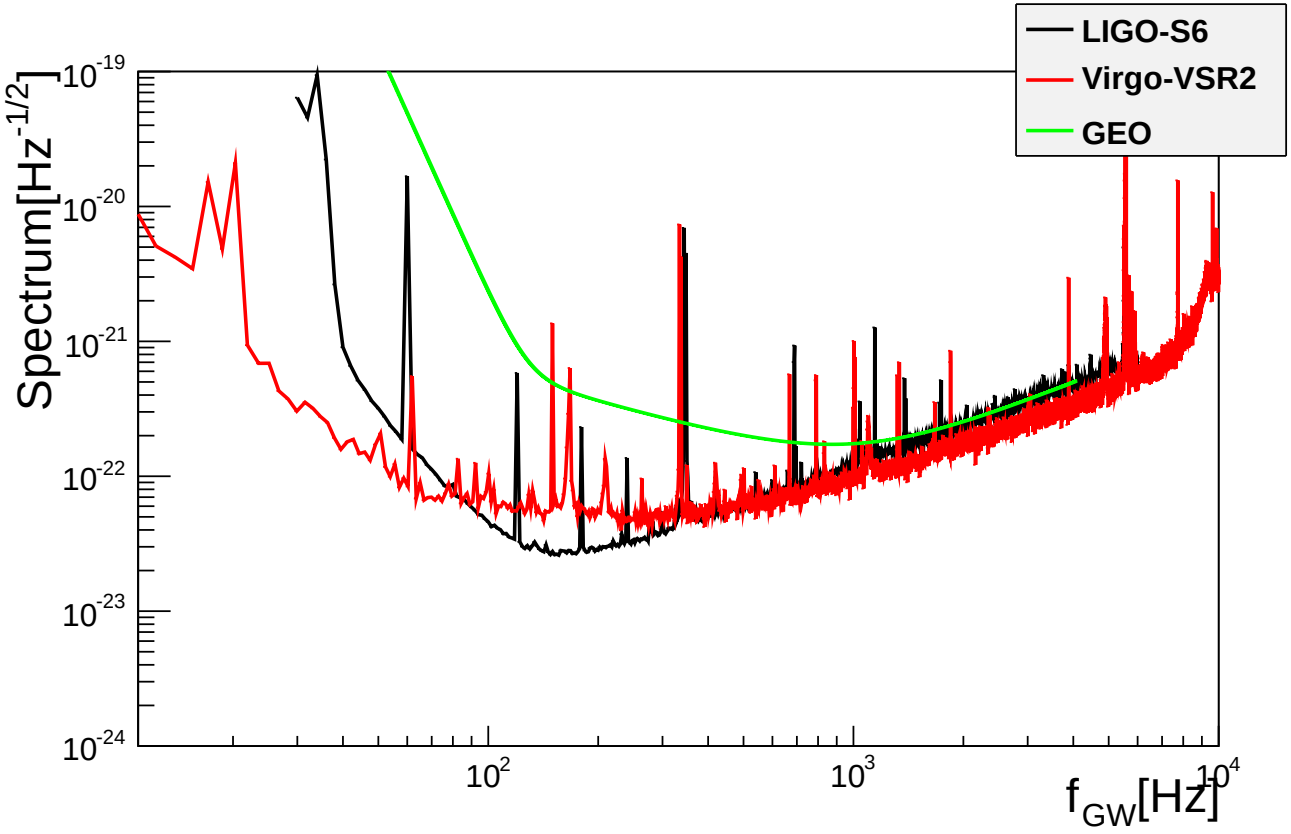
The 2 LIGO's and Virgo ended their joint science runs on

October 20th 2010



LIGO Hanford

LIGO Livingston

Virgo

GEO

LIGO Hanford

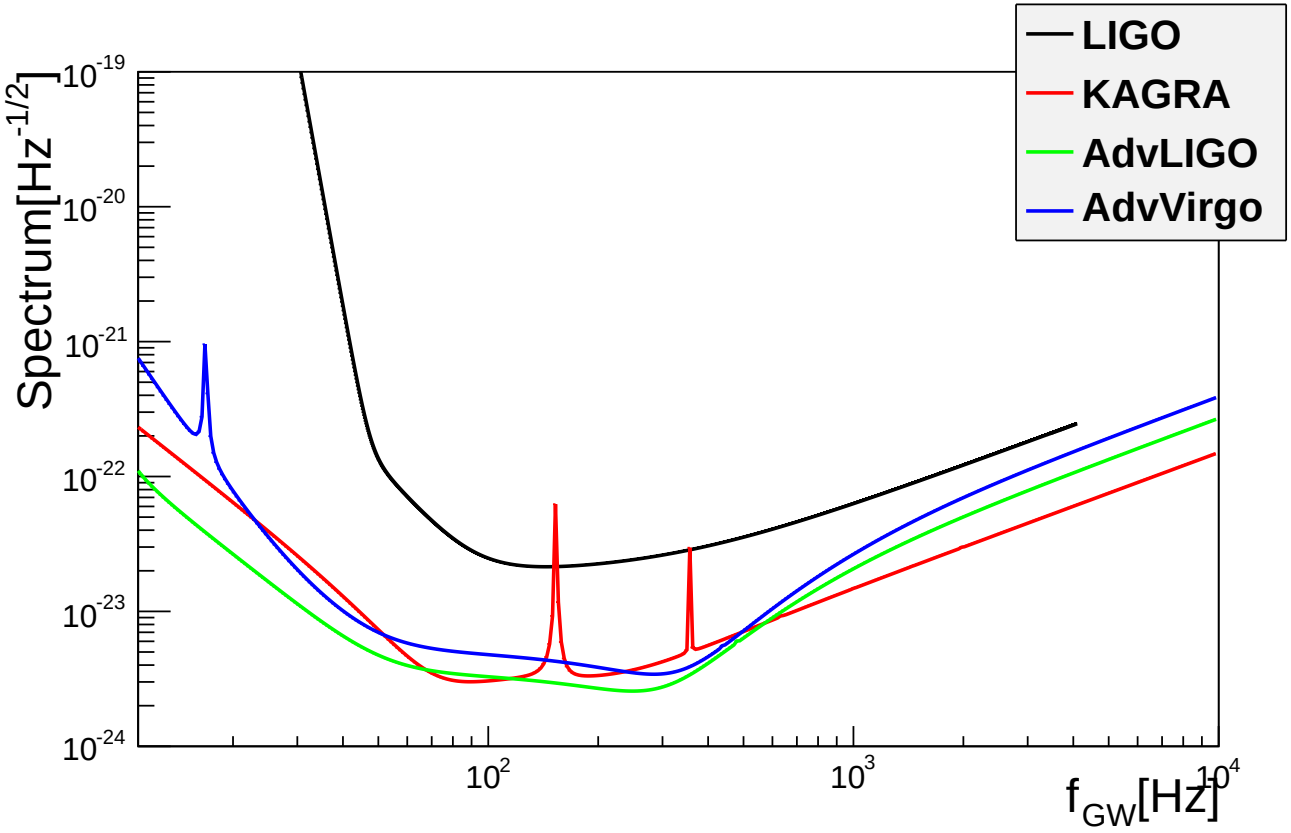
LIGO Livingston

Virgo

GEO

KAGRA

Advanced detector sensitivities



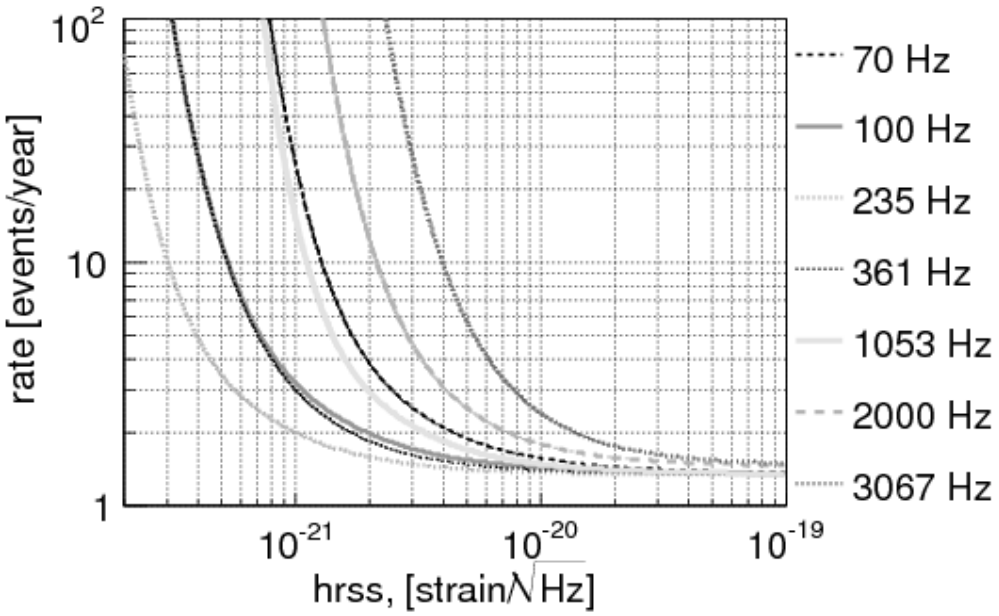
Science run for LIGO/Virgo due to restart by the end of 2014
KAGRA due to join in 2017

Burst signals

- Supernovae and collapsing stars: typical amplitude

$$h \sim 10^{-21} \left(\frac{E_{GW}}{10^{-7} m_{\odot}} \right) \left(\frac{1\text{msec}}{T} \right)^{1/2} \left(\frac{1\text{kHz}}{f} \right) \left(\frac{50\text{kpc}}{D} \right)$$

Limits for signals centered at different freq's



1.7 yr of data, LIGO/Virgo arXiv:1202.2788

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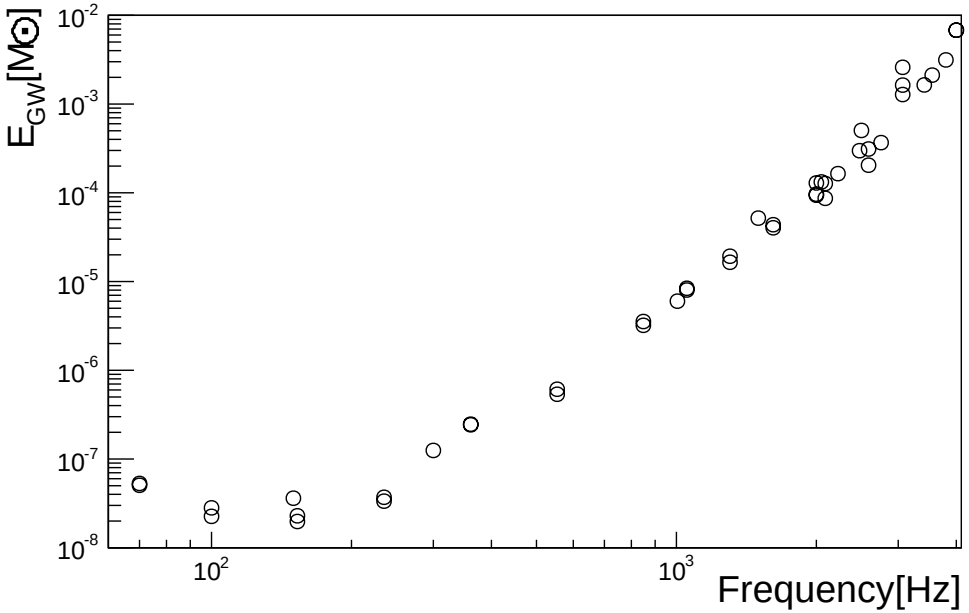
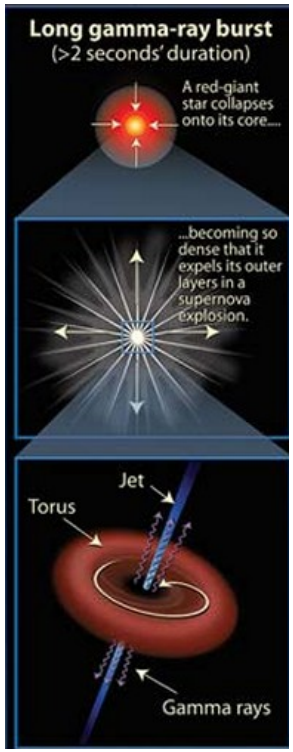
Typical E_{GW} for D=50kpc signals centered at different freq's

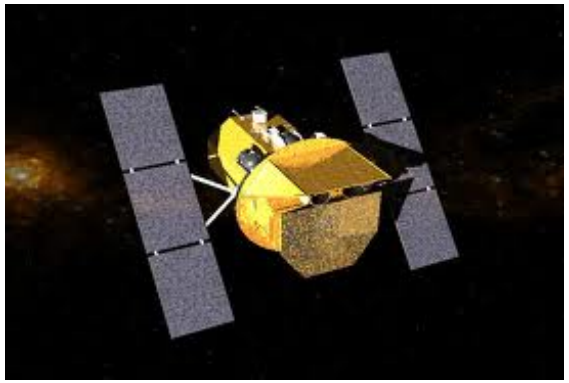


1.7 yr of data, LIGO/Virgo arXiv:1202.2788

Triggered searches: Gamma Ray Bursts

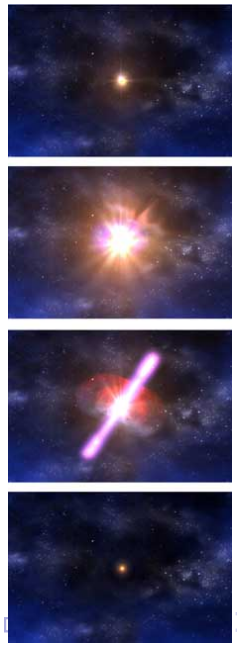
Long ($\gtrsim$2 secs) associated with core-collapse SuperNovae





Swift, Fermi, MAXI, SuperAGILE, INTEGRAL, IPN

Short ($\lesssim$1 sec) $\sim$ binary inspiral



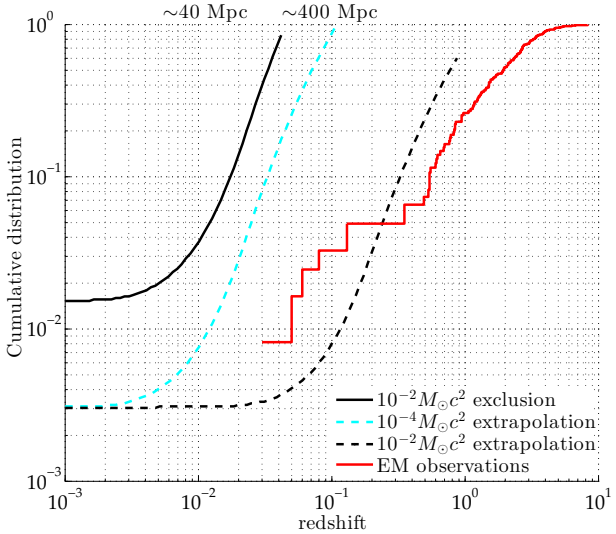
Both may produce GW & EM radiation

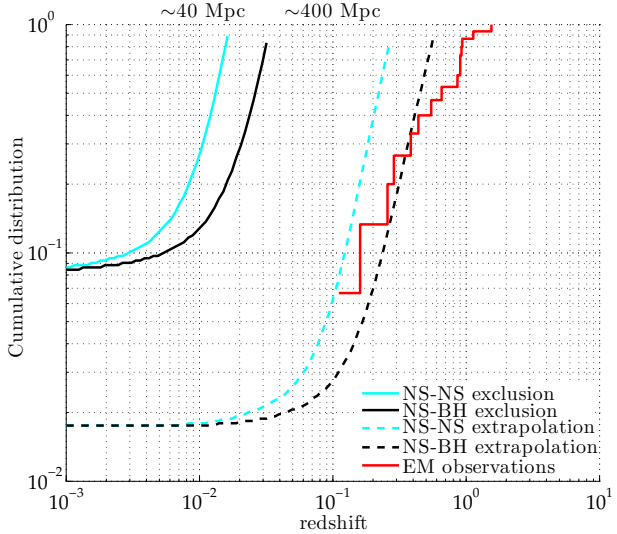
Coincidence with Gamma Ray Bursts

Search in a $-600 \div +60$ sec window around the GRB event

- 150 analyzed via an un-modeled burst search excluded within $D_{burst} \sim 17$ Mpc$(E_{GW}/10^{-2}M_{\odot})^{1/2}$ for signals at 150 Hz
- 24 analyzed via matched filtering with coalescing binary signals
  $D_{NS-NS} \sim 17$ Mpc $\quad M_{NS} \sim 1.4 \pm 0.2$
  $D_{BH-NS} \sim 29$ Mpc $\quad M_{NS} \sim 1.4 \pm 0.4 \quad M_{BH} \sim 10 \pm 6$

Distance cumulative distibutions:





Looks promising for Adv-LIGO/Virgo (LIGO/Virgo et al. arXiv:1205.2216)

GRB & follow-up

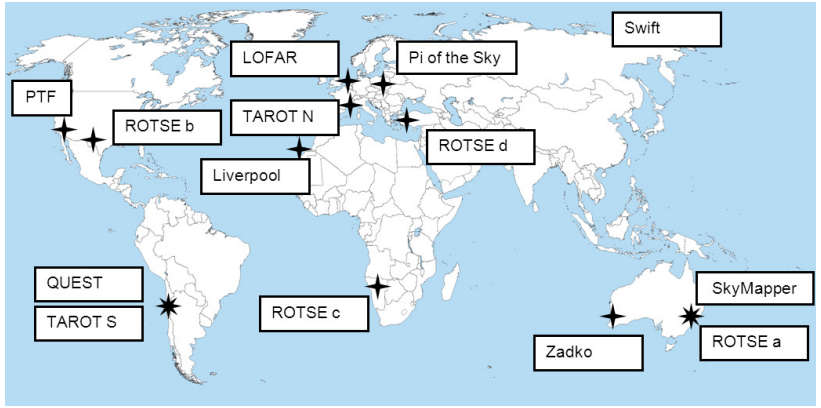
GRB 05113 found in M31 @ $D = 3.5$ Mpc
dedicated analysis excluded binary coalescence origin

LIGO arXiv:1201.4413

Rapid detection GW-triggers
follow-up image analysis

↓

joint GW-EM detection
GW-triggers will be followed-up in the radio, optical and X bands with $O(30')$ latency



LIGO/Virgo A&A 2012, LIGO/Virgo/Swift arXiv:1205.1124

Triggered searches: neutrinos

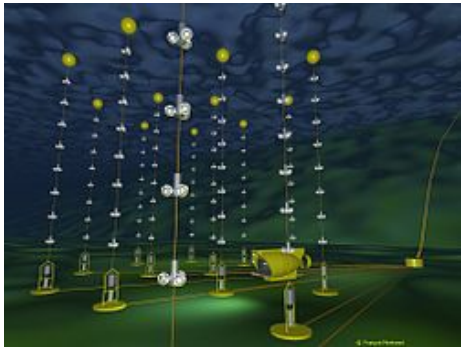
GW search in coincidence with
High Energy Neutrinos $\gtrsim 100$GeV
Possible sources:
long GRB, supernovae, cosmic strings...
No significant trigger in $T_{obs} \simeq 100$ days

$$\rho_{GW-HEN} \lesssim 10^{-3}\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}\left(\frac{E_{GW}}{10^{-2}M_{\odot}}\right)^{-3/2}$$

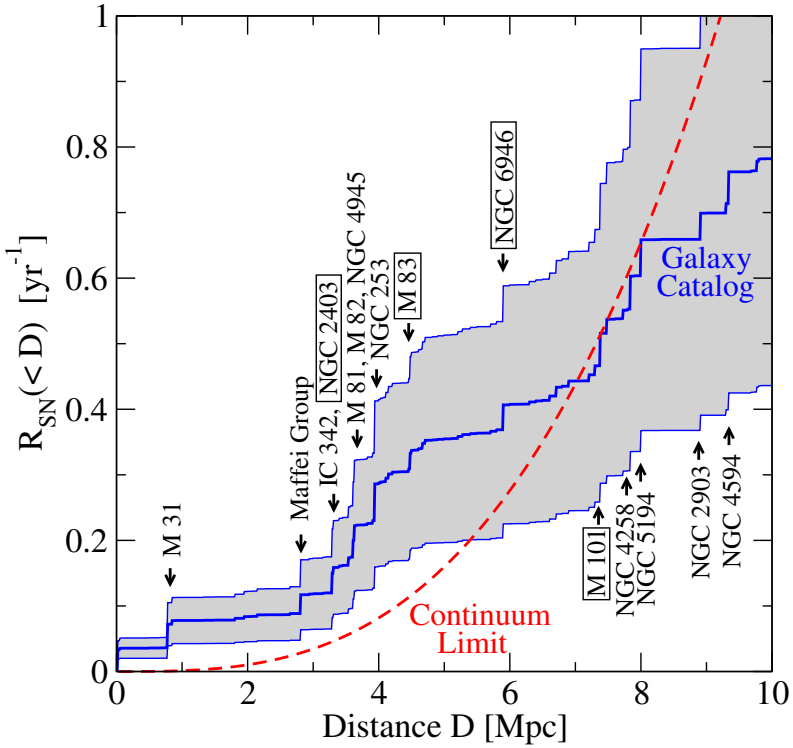
LIGO/Virgo/ANTARES arXiv:1205.3018

158ν-events (Feb-Sep 2007) from

ANTARES ($\pm$496sec win.)



Expected SuperNova rate



Ando et al. PRL 2006

External triggered search: magnetars

GW-search in coincidence with 1217 soft GRB's from 5 Soft Gamma Repeaters and 1 Anomalous X-ray Pulsar associated with magnetars @ 2 < D/kPc < 15 (4 sec win.)

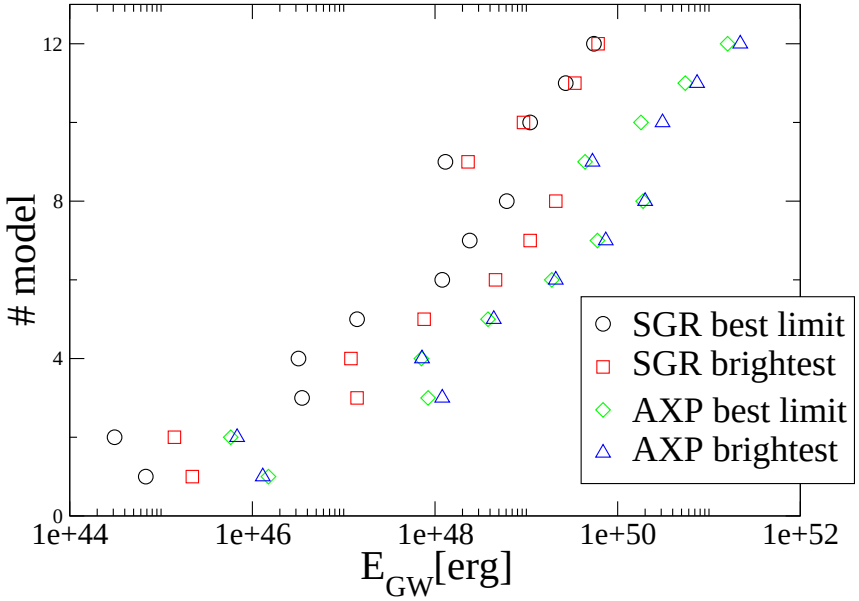
Energy upper limits for

2 magnetars

12 different waveforms

$L_{\odot} \simeq 4 \cdot 10^{33}$erg/s

$M_{\odot} \sim 10^{54}$ erg



LIGO/Virgo AJ 2011

Asymmetric rotating neutron star

- Pulsar asymmetry $\epsilon \rightarrow h \sim \epsilon (Rf)^2 M/D$

$$L_{GW} = f^6 M^2 R^4 \epsilon^2 \rightarrow t_{SD} \sim \frac{M(Rf)^2}{L_{GW}} = f^{-1} \left(\frac{M}{R}\right)^{-1} \frac{1}{\epsilon f^3}$$

If all the spin-down is due to GW emission

$\epsilon \simeq 7 \cdot 10^{-3}$	$\epsilon_{GW} < 1.4 \cdot 10^{-4}$	Crab
$\epsilon \simeq 1.2 \cdot 10^{-3}$	$\epsilon_{GW} < 5 \cdot 10^{-4}$	Vela

Beating the spin-down limit!

LIGO/Virgo APJ 2010

- Best upper limit $h_{ul} \sim 10^{-24}$ @ 150Hz

LIGO/Virgo APJ 2010, 2011, PRD 2012

- Upper limit on GW's emitted by Vela pulsar glitch
  $h_{ul} < 10^{-20}$ $E_{GW} < 10^{45}$ erg

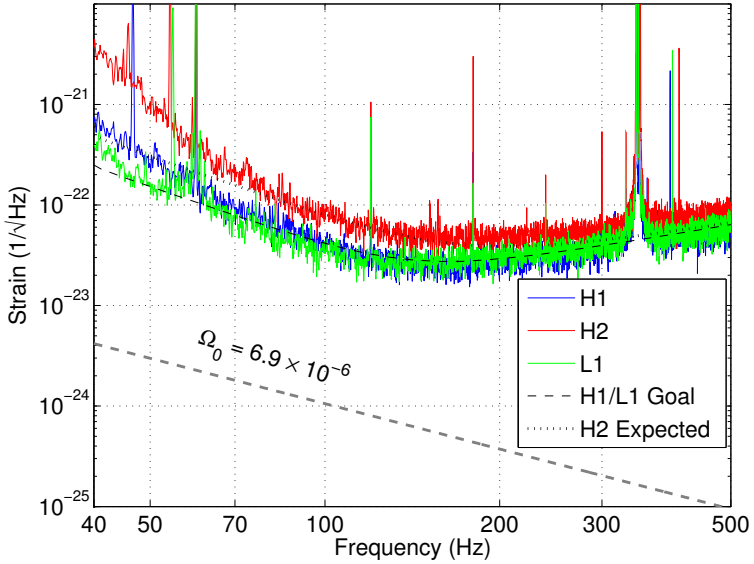
LIGO PRD 2011

Stochastic background

$$\Omega_{GW} = \frac{f}{\rho_c}\frac{d\rho_{GW}}{df} \qquad S_h(f) = \frac{3H_0^2}{4\pi^2}\frac{\Omega_{GW}}{f^3}$$

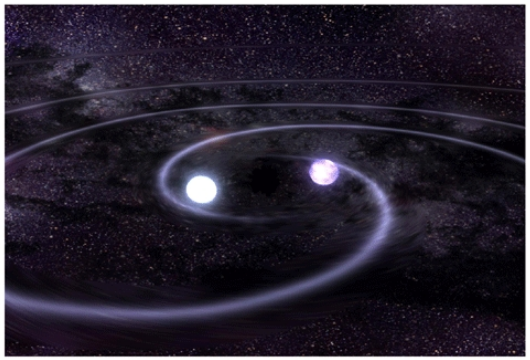
$$SNR^4 = 2T\int_0^\infty df\,\gamma^2(f)\frac{S_h^2(f)}{S_{n_1}(f)S_{n_2}(f)}$$

Bound on stochastic GW's between 50 and 150 Hz

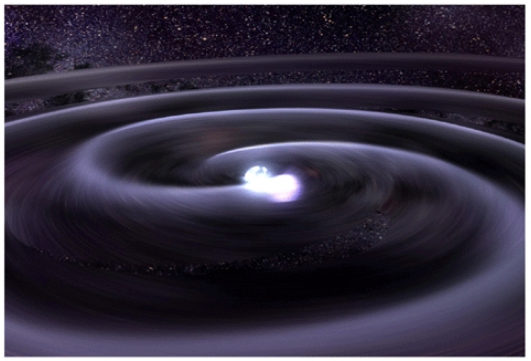


LIGO/Virgo Nature 2009

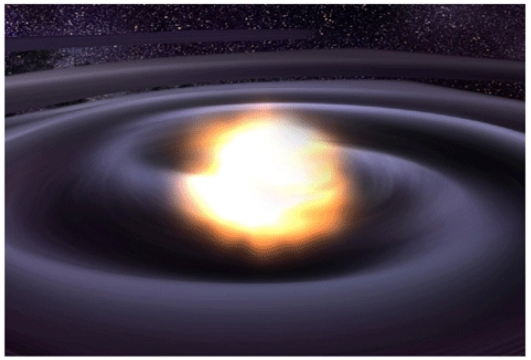
Compact binary coalescences



Inspiral phase
post-Newtonian
approximation: v/c

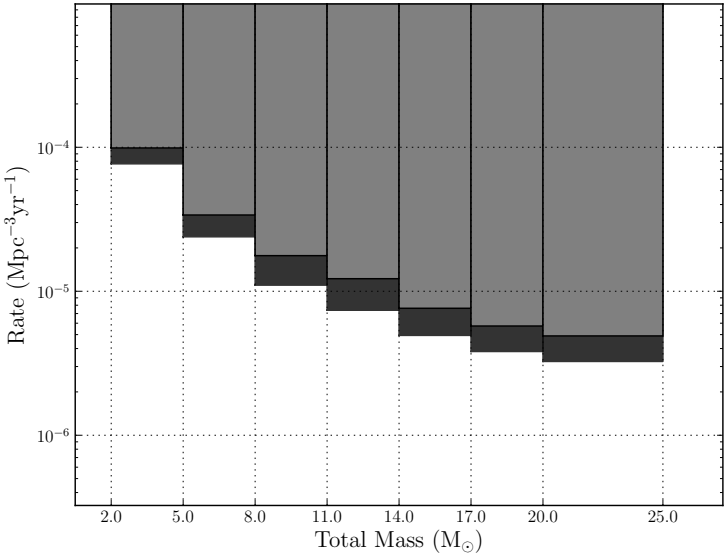


Merger: fully
non-perturbative



Ring-down:
Perturbed
Kerr Black Hole

Accurate source modeling allows match-filtering



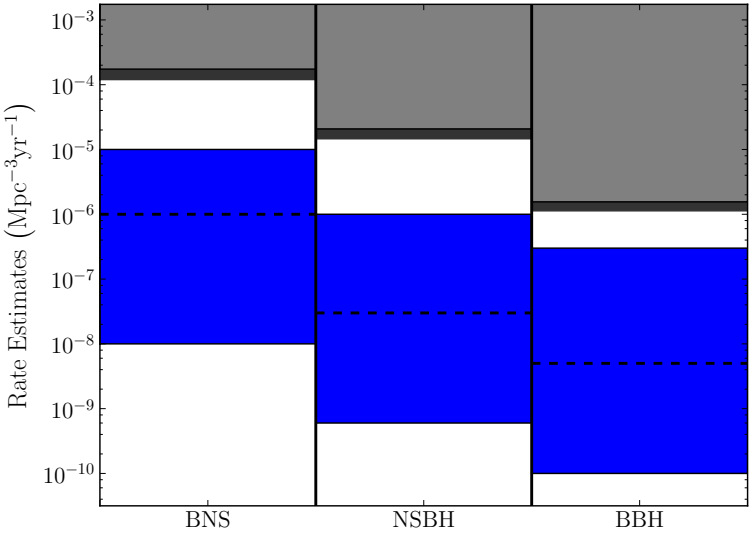
Low mass (<25$M_\odot$) binary (inspiral)

Upper limit from previous runs

improved by the 7/2009-10/2010 run

Combined upper limit from old and new runs compared with astrophysical estimates

LIGO/Virgo PRD 2012



Upper limits for high mass systems

- For high masses $25 < M/M_\odot < 100$ also merger and ring-down are in band and necessary to have complete analytic description of coalescence waveform
  Observative bound on coalescence rate
  $R_c < 2$ Mpc^{-3} Myr^{-1}

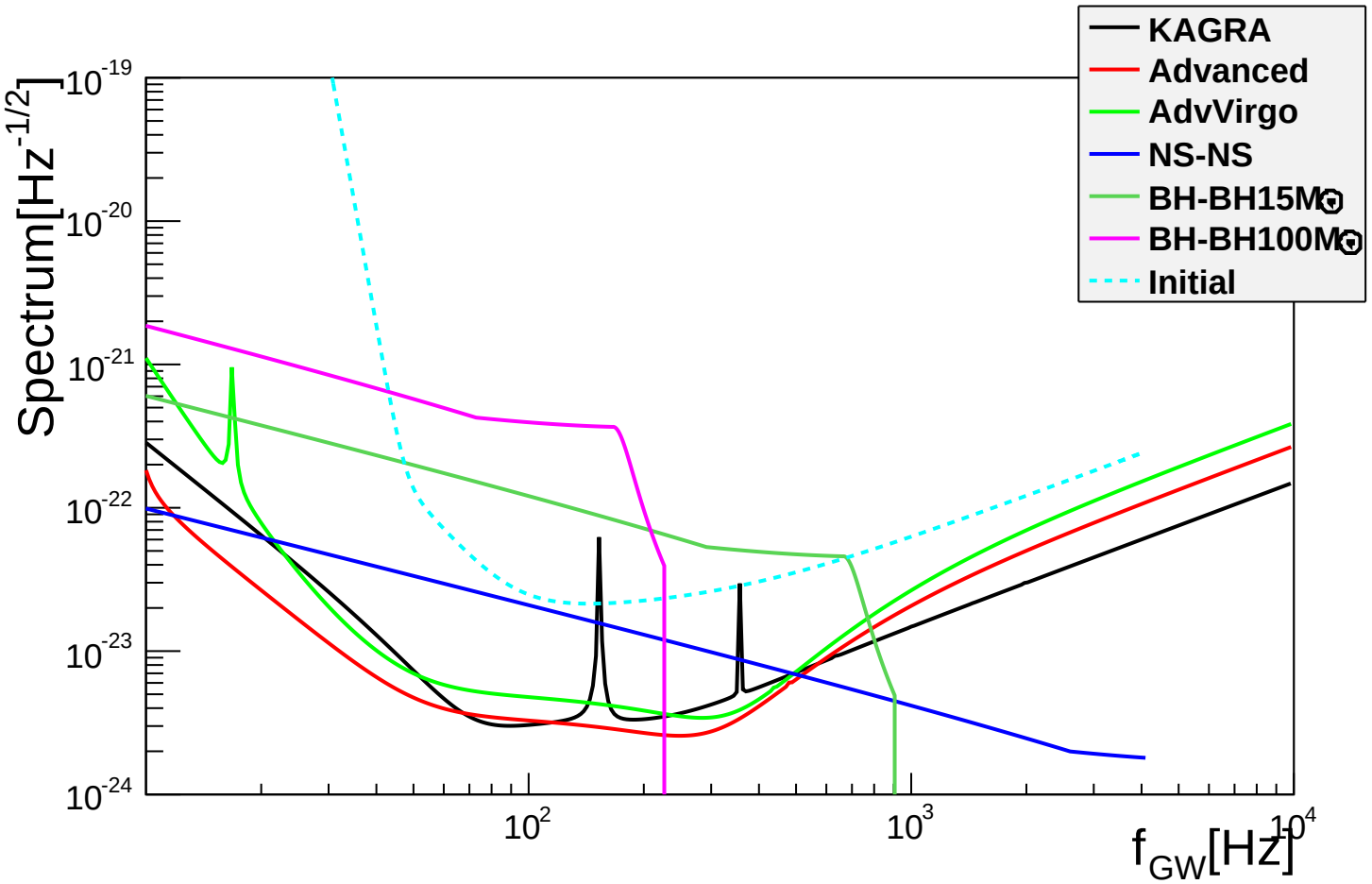
  LIGO/Virgo PRD 2011

- For higher masses $100 < M/M_\odot < 500$ signals are burst-like:
  Best upper limit for equal mass system with $M \sim 170 M_\odot$:
  Merger Rate $R_m < 0.13$ Mpc^{-3} Myr^{-1}

  LIGO/Virgo arXiv:1201.5999

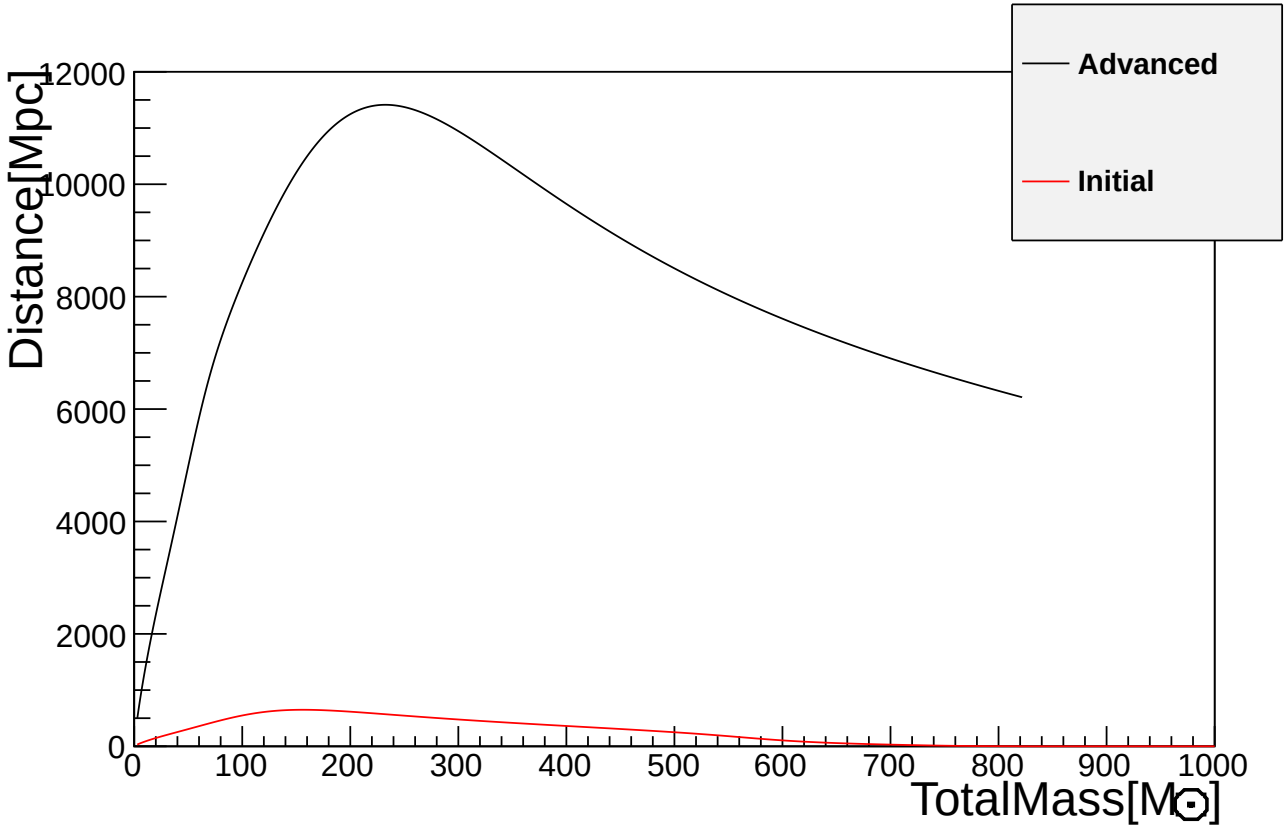
Outline

Advanced detectors



Sensitivity vs. signals @ 200Mpc w. optimal orientation

Distance reach for compact binary coalescence



Observational rate estimates

LIGO/Virgo Advanced Observatories will detect

($SNR = 8$, optimal orientation)

	NS-NS	10 $M_\odot$ BH-BH
Distance (Mpc)	450Mpc	1GPc
Rates $\mathrm{MWEG}^{-1}\mathrm{Myear}^{-1}$	$1 \div 10^3$	$4 \cdot 10^{-2} \div 100$

$$N = 0.011 \times \frac{4}{3}\pi \left(\frac{D_H/\mathrm{Mpc}}{2.26}\right)^3 \mathrm{MWEG}$$

Realistic case:

$$R_{NS-NS} \sim 40\mathrm{yr}^{-1} \qquad R_{BH-BH} \sim 10^2\mathrm{yr}^{-1}$$

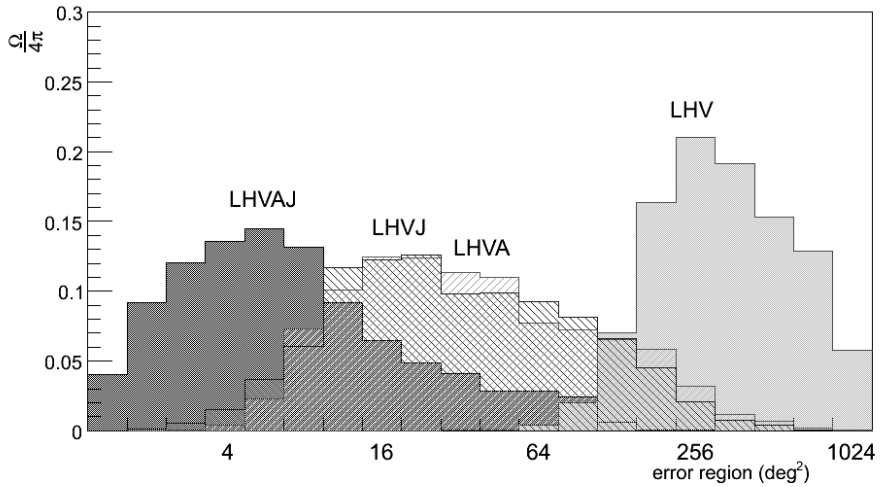
for LIGO/Virgo at design sensitivity

LIGO/Virgo CQG 2010

Advanced LIGO/Virgo goals

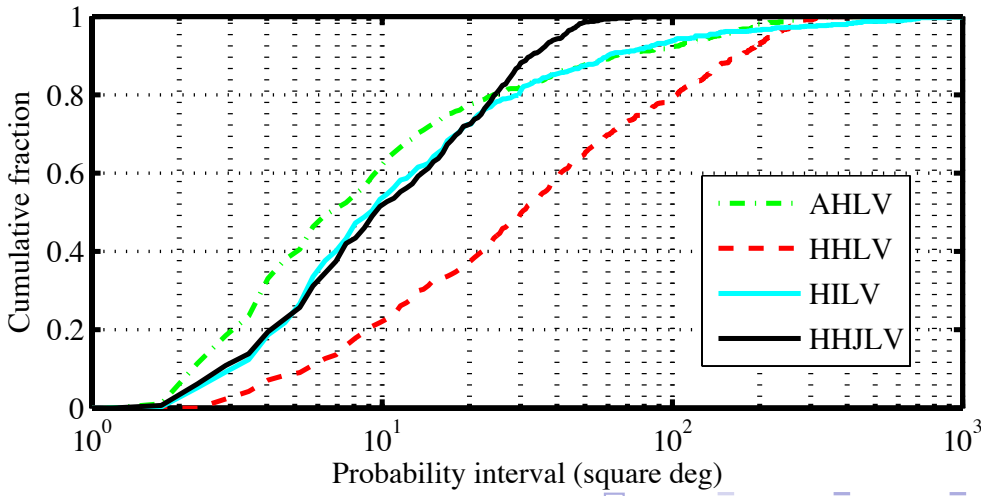
- Make first "direct" detection of GW's from neutron stars and/or black holes
- Probe $1 \div$ few $100\,M_\odot$ black holes
- Measure rate of binary coalescences
- Measure pulsar parameters
- Possible probe of neutron star interior/nuclear matter at high density
- Verify association between short GRB's and GW's
- Combine EM and GW detection
- Make strong tests of GR
- Use coalescing binaries as standard sirens for cosmology

Detector number and location affects source sky position reconstruction
Sky fraction of reconstructed source position vs. error region size



Burst-like injections
excess noise analysis
Klimenko et al. PRD 2012

Inspiral waveform injections and analysis
$5 < SNR < 35$
Veitch et al. arXiv:1201.1195



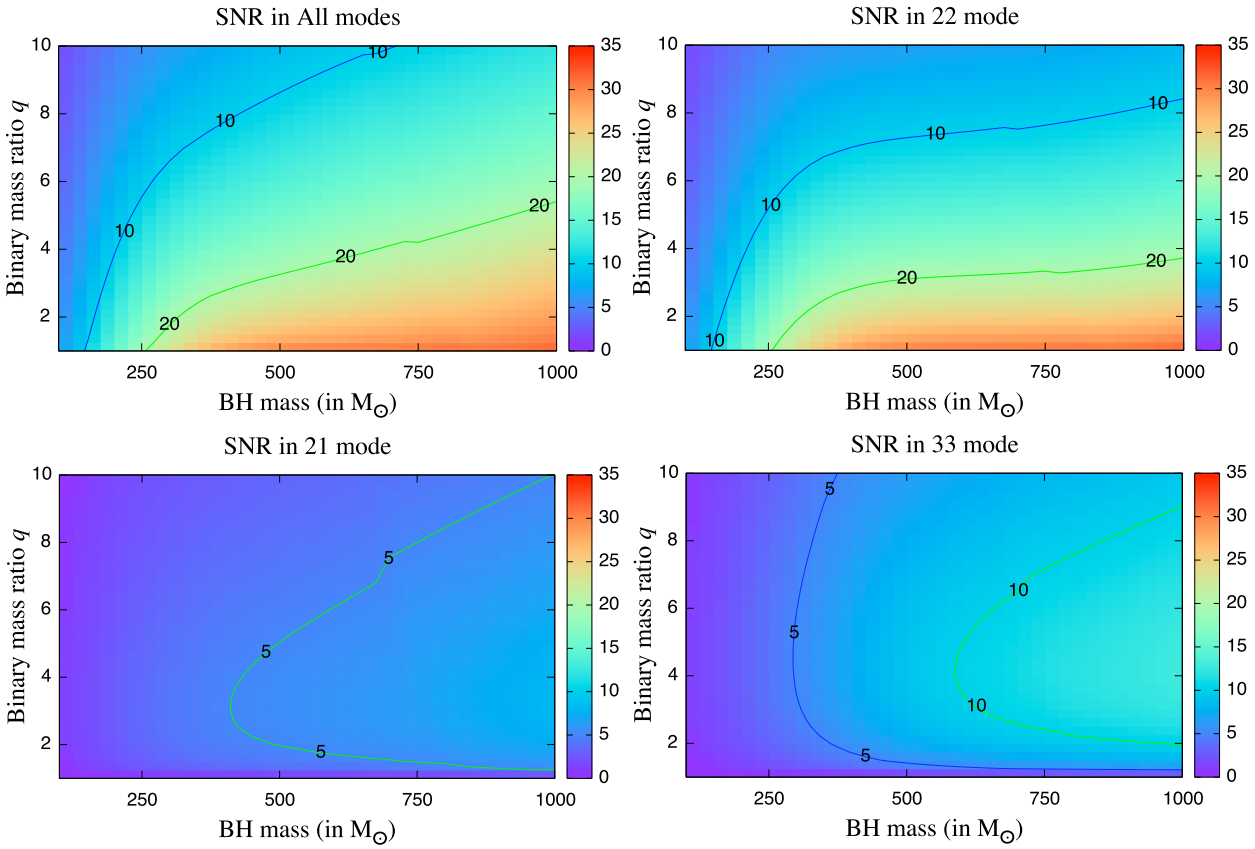
More detectors help

- Larger baseline improves localization
- Positions orthogonal to the detectors' plane are better recovered
- Large (future) survey telescopes like LSST can scan a $10^o \times 10^o$ sky patch in 30 minutes
- A fourth detector with giving a longer base-line improves drastically the localization

Possibility of an additional detector in INDIA

Fundamental Gravity

- Black hole ring-down modes depend on mass and spin: test of the no-hair theorem are hard with AdvLIGO/Virgo



source @ 1Gpc, Kamaretsos et al. PRD 2011

Fundamental Gravity

- Strong field test of gravity: present observations constrain conservative gravity at first post-Newtonian (PN) order and disspative effects at leading order in binary pulsar where $v/c \sim 10^{-3}$
  GW detectors' output is sensitive to phase $\phi(t)$ and its PN corrections

$$\phi(t) = \phi_N \left(1 + \#v^2(t) + \ldots + \#v^6(t) + \ldots\right)$$

  In principle at least 3PN order is necessary for match-filtering

  See Salvatore Vitale poster and N. Yunes talk on Friday

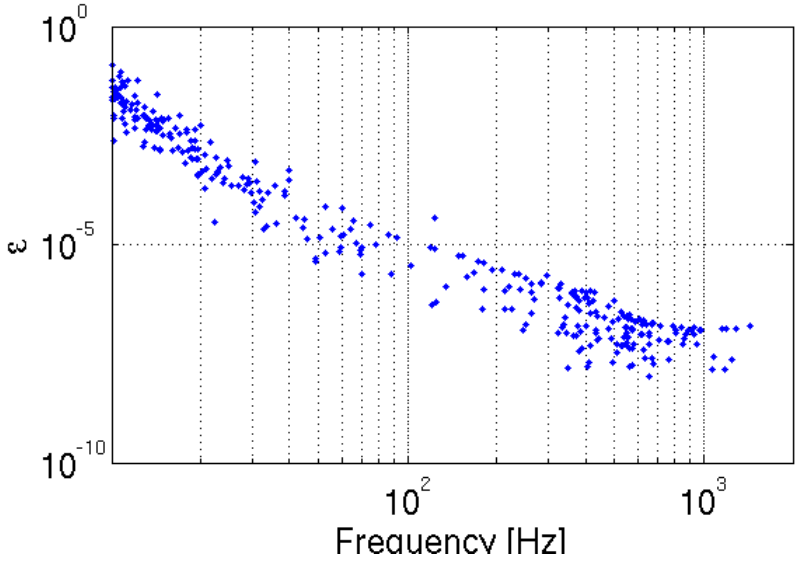
- Learn about neutrino mass by coincidence with EM events

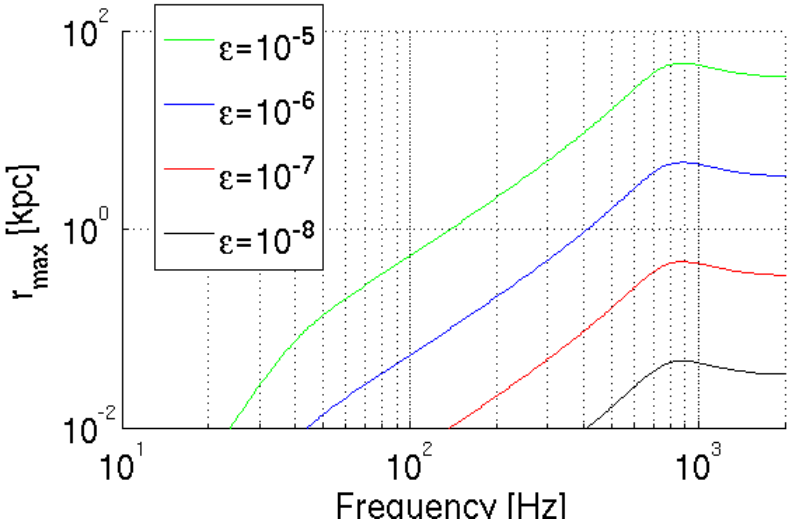
Astrophysics goals

- Direct detection of pulsars, binary neutron stars and black holes
- Rate of coalescences in the mass range $< \mathrm{few}100\, M_\odot$
- Ellipticity of neutron stars
- Learning about magnetars and pulsar glitches
- Neutron stars and nuclear matter and high density
- Supernovae (not granted)

Periodic signals in the Advanced detectors

Minimum detectable ellipticity for known pulsars

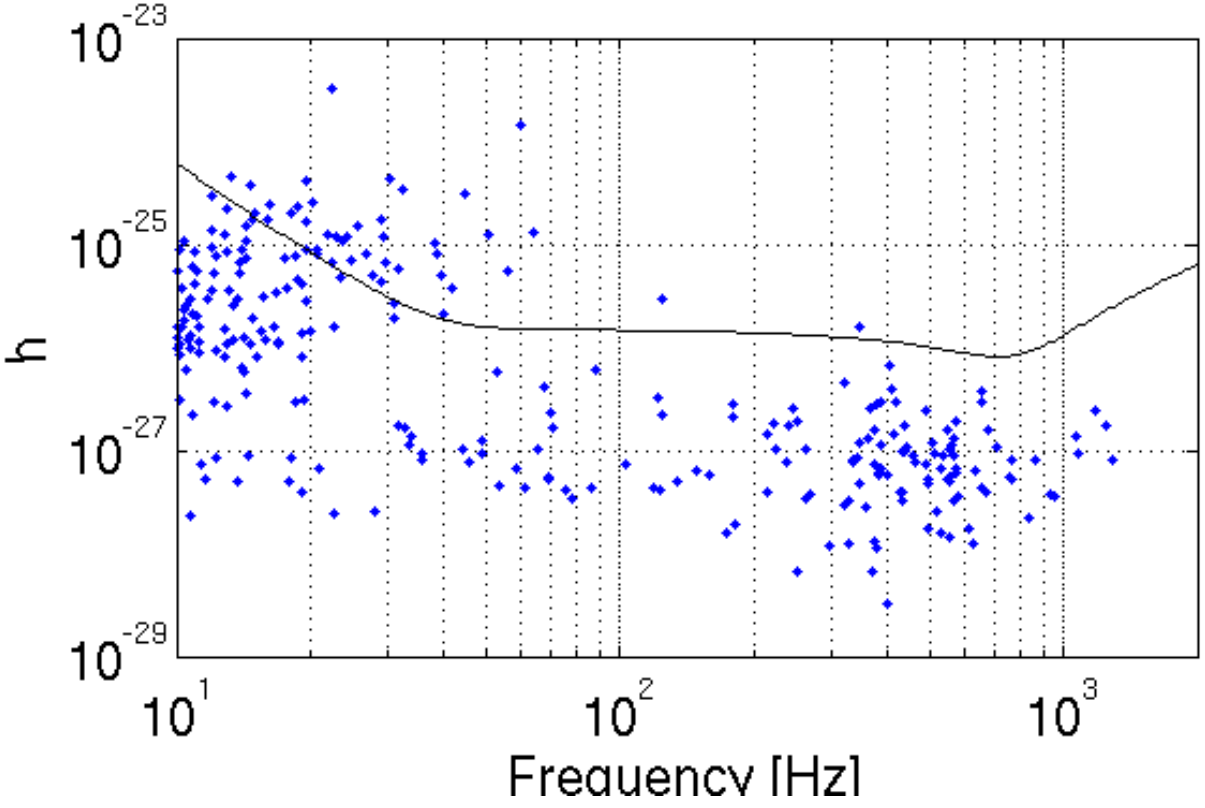




Distance reach
Target: galactic sources

C. Palomba

Integrated sensitivity (T_{obs}=1yr) for known pulsars vs. spin-down limit

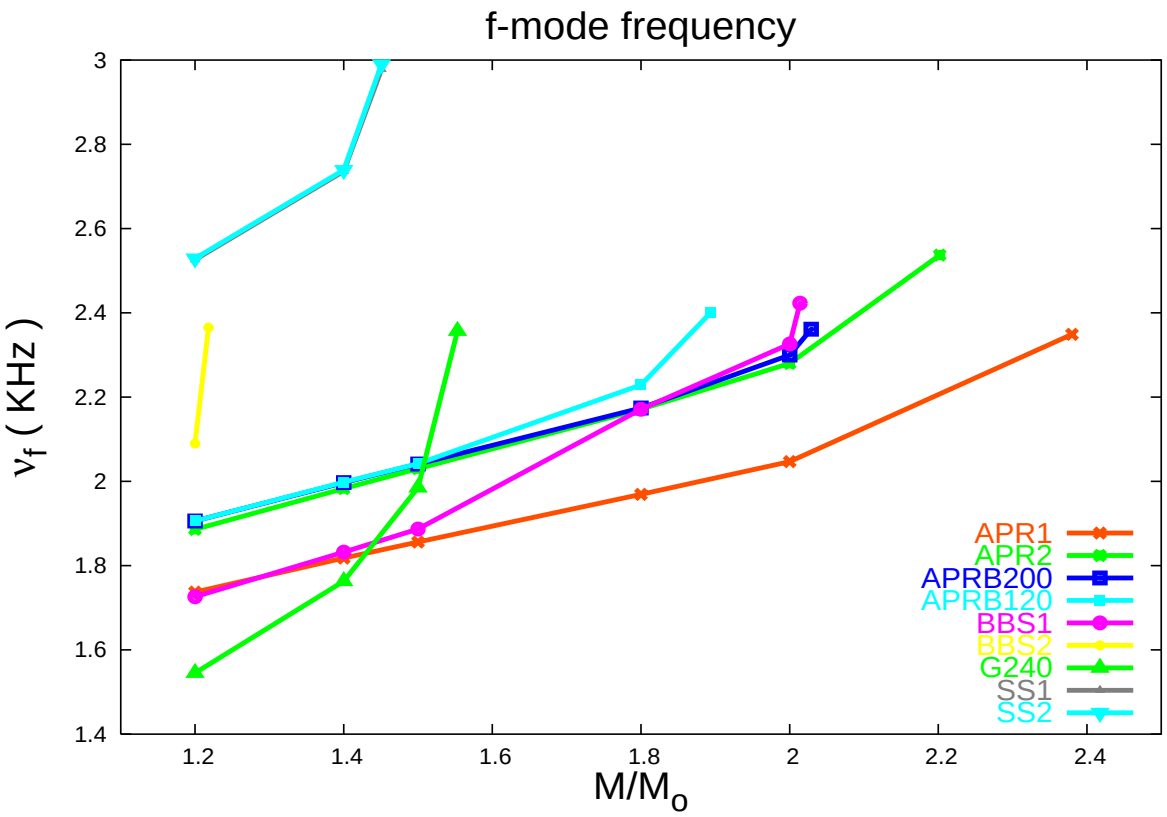


C. Palomba

Probing neutron star interior

Glitches (magnetars) may cause oscillations of the core → GW

Normal modes freq. vs. Mass for various eq.'s of state



Benhar, Ferrari and Gualtieri, 2004

Measuring the Hubble constant H_0

Coalescing binary systems are standard sirens:

$$h(t) = \frac{G_N \eta M^{5/3} f^{2/3}}{D} \cos\left[\phi(t)\right]$$

In cosmological settings source and observer clocks tick differently:

$$dt_o = (1+z)dt_s \qquad f_o(1+z) = f_s$$

$$h(t_o) = \frac{G_N \eta f_o^{2/3} M^{5/3} (1+z)^{2/3}}{a(t_o) D} \qquad \cos\left[\phi(t_s(t_o))\right]$$

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$$\phi\left(t_s/M\right) = \phi\left(t_o/\mathcal{M}\right) \qquad \mathcal{M} \equiv (1+z)M$$

Schutz, Nature '86

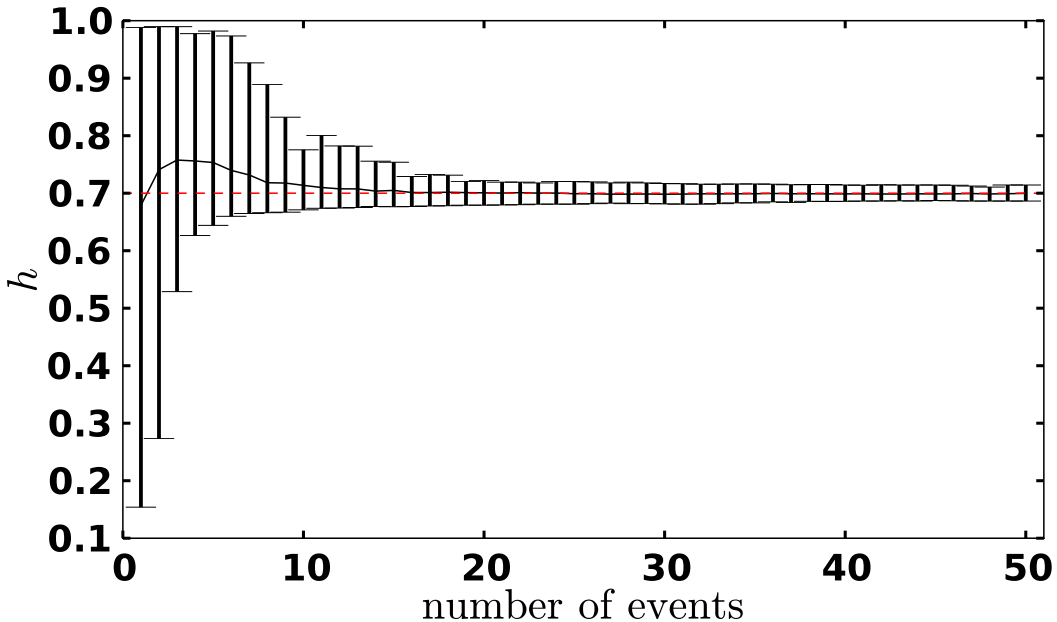
Determining $H_0 \equiv h\, H_{100}$

Hubble law: $z = H_0\, D_L$

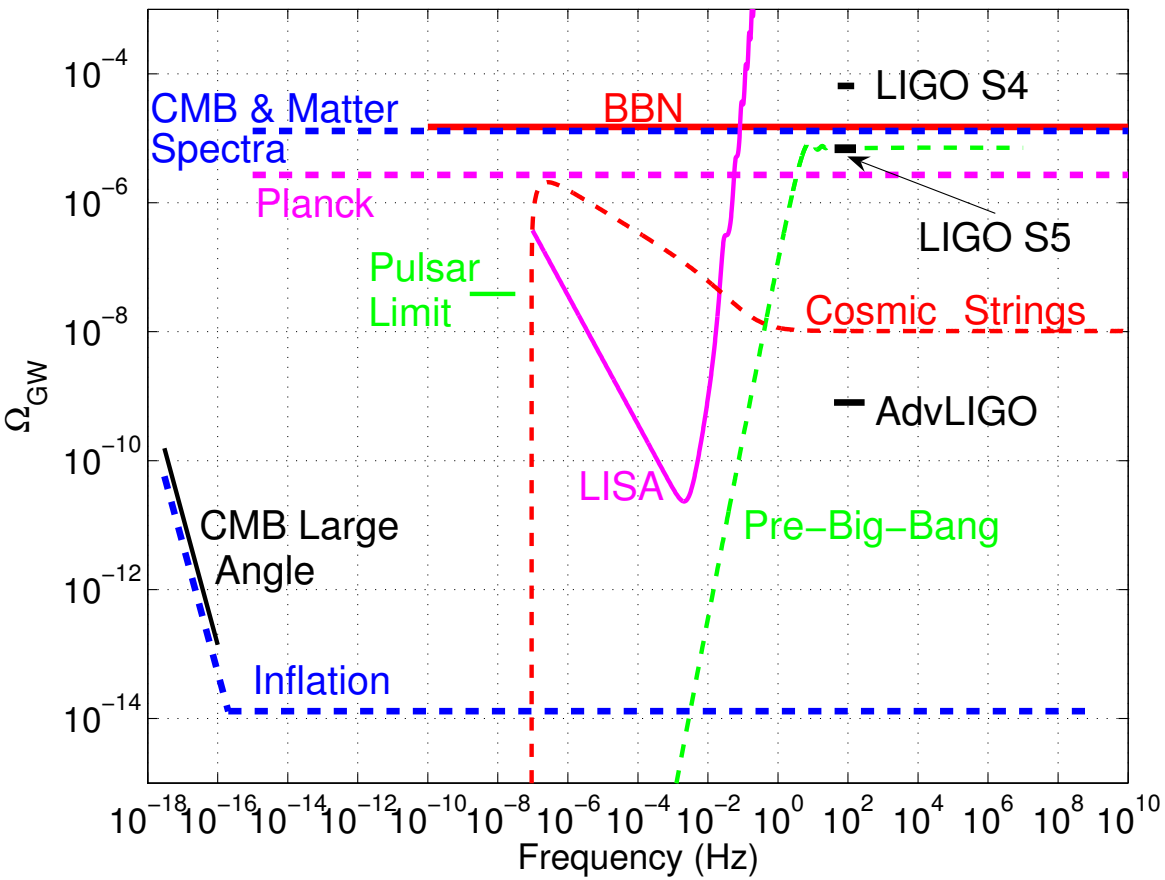
D_L can be measured, z degenerate with M, however if

- the source in the sky has been localized (α, δ)
- GW sources are in the galaxy catalog with known red-shift

$$P(z, D_L|c_i) = \int d\mathcal{M}\, d\vec{\theta}\, d\alpha\, d\delta\, P(D_L\mathcal{M}, \vec{\theta}, \alpha, \delta|c_i)\pi(z, |\alpha, \delta)$$



$m_1, m_2 \subset (1, 15) M_\odot$
$D_L < 450$ Mpc
$(z \lesssim 0.1)$
W. Del Pozzo, arXiv:1108.1317



LIGO/Virgo Nature 2009

No compelling case for stochastic GW detection, unless some exotic sources jumps in

Outline

Outlook

- A new class of astrophysical objects will become visible:
  detection of solar mass black holes
  neutron star interiors
  origin of GRB's
  combined electromagnetic and gravitational detections
- Fundamental physics:
  test GR in the genuinely strong regime
  eq. of state of supra-nuclear matter
  independent constraint/measurement of neutrino mass
- Cosmology:
  Hubble law (equation of state of dark energy)

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- unknown unknowns...