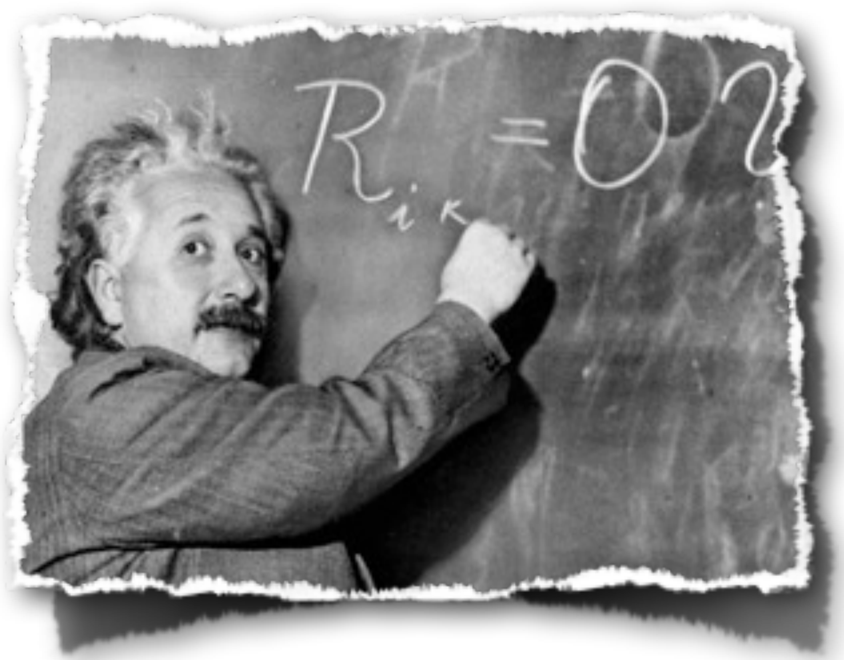
Gravitational-wave- physics and astronomy: Status and prospects

P. Ajith International Centre for Theoretical Sciences, TIFR, Bangalore

27th IAGRG Meeting Srinagar (Garhwal) 9 March 2013

Towards the first direct detection of gravitational waves

- **Theory** The existence of gravitational waves (GWs) is a well-established prediction of GR.



Towards the first direct detection of gravitational waves

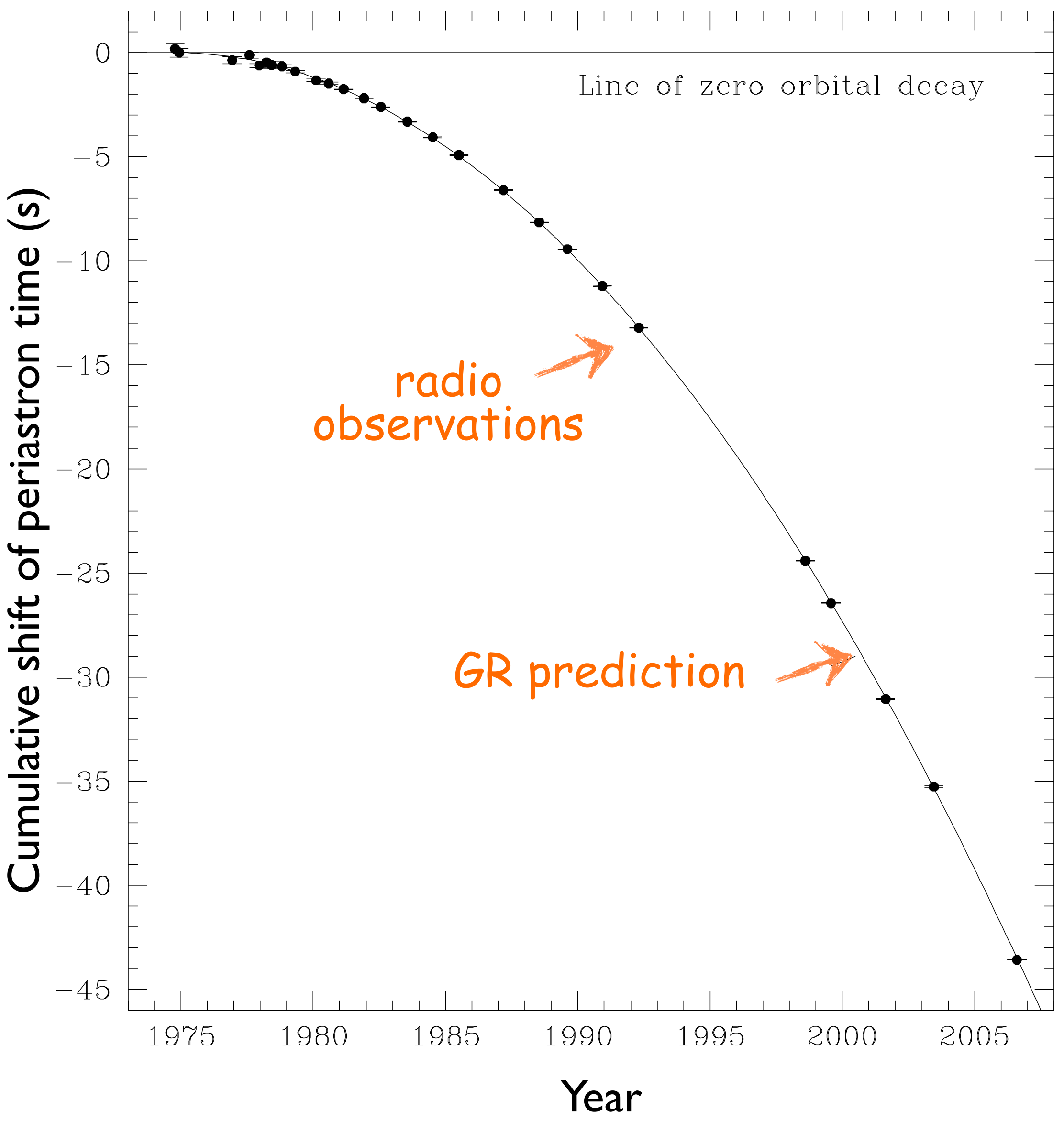
- **Theory** The existence of gravitational waves (GWs) is a well-established prediction of GR.
- **Observational evidence** Radio observations of several binary pulsars provide unequivocal evidence supporting the existence of GWs.

observed decay of the orbital period

GR prediction (quadrupole formula)

$$\dot{P}_b = (0.997 \pm 0.002)\, \dot{P}_b^{\mathrm{GR}}$$

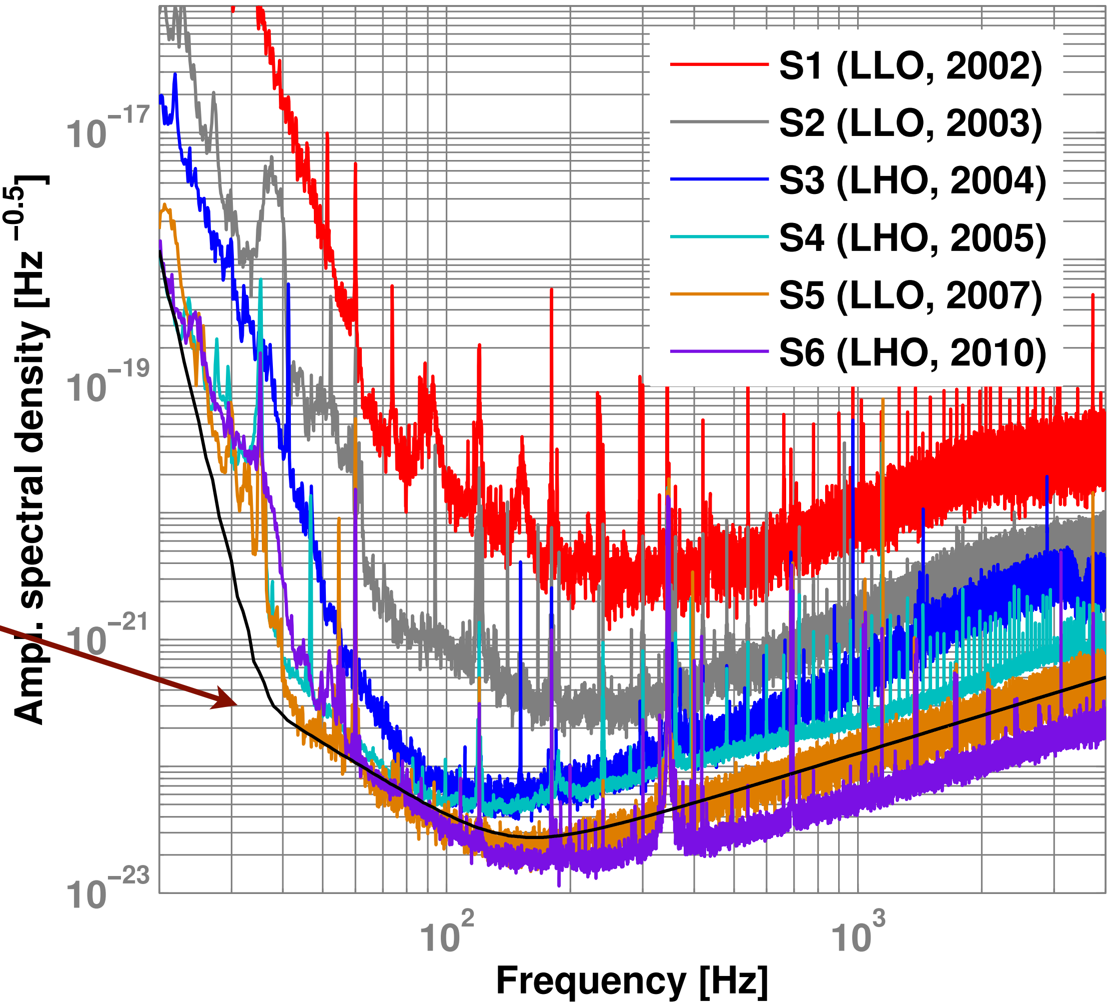
[Weisberg et al (2010)]



36 years of radio observations of the binary pulsar PSR B1913+16 (Hulse-Taylor binary) ➞ Decay of the orbital period agrees precisely with GR prediction, due to GW emission.

Towards the first direct detection of gravitational waves

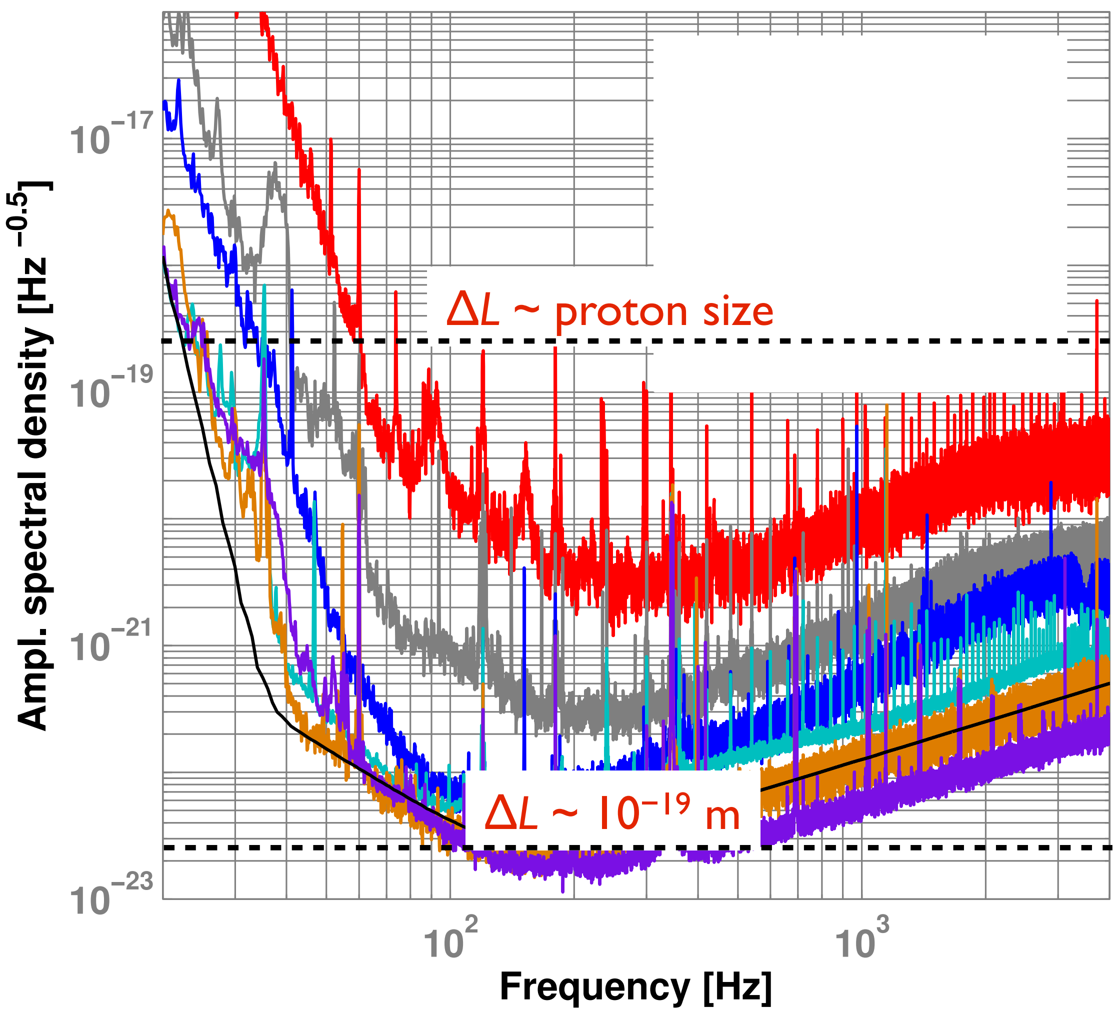
- **Theory** The existence of gravitational waves (GWs) is a well-established prediction of GR.
- **Observational evidence** Radio observations of several binary pulsars provide unequivocal evidence supporting the existence of GWs.
- **Detection techniques** KM scale interferometric GW detectors have achieved design sensitivity & conducted several data-taking runs.



Progression of the sensitivity of LIGO detectors over the last decade.

Towards the first direct detection of gravitational waves

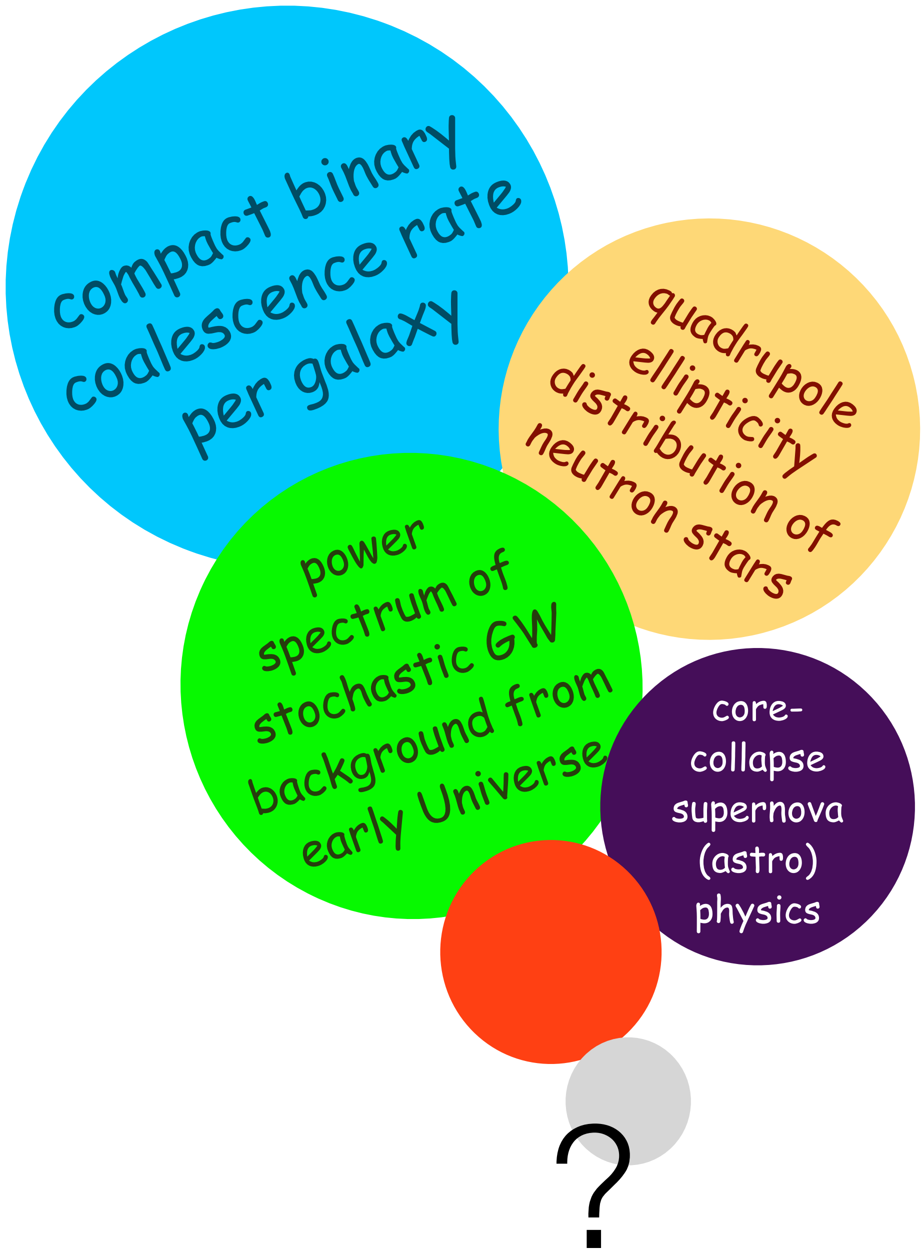
- **Theory** The existence of gravitational waves (GWs) is a well-established prediction of GR.
- **Observational evidence** Radio observations of several binary pulsars provide unequivocal evidence supporting the existence of GWs.
- **Detection techniques** KM scale interferometric GW detectors have achieved design sensitivity & conducted several data-taking runs.



Progression of the sensitivity of LIGO detectors over the last decade.

Towards the first direct detection of gravitational waves

- **Theory** The existence of gravitational waves (GWs) is a well-established prediction of GR.
- **Observational evidence** Radio observations of several binary pulsars provide unequivocal evidence supporting the existence of GWs.
- **Detection techniques** KM scale interferometric GW detectors have achieved design sensitivity & conducted several data-taking runs.
- **GW event rates** No direct detection so far! Almost all uncertainty resides in the astrophysics.
  - Considerable reduction of uncertainty on various fronts by recent astronomical observations & theoretical work.

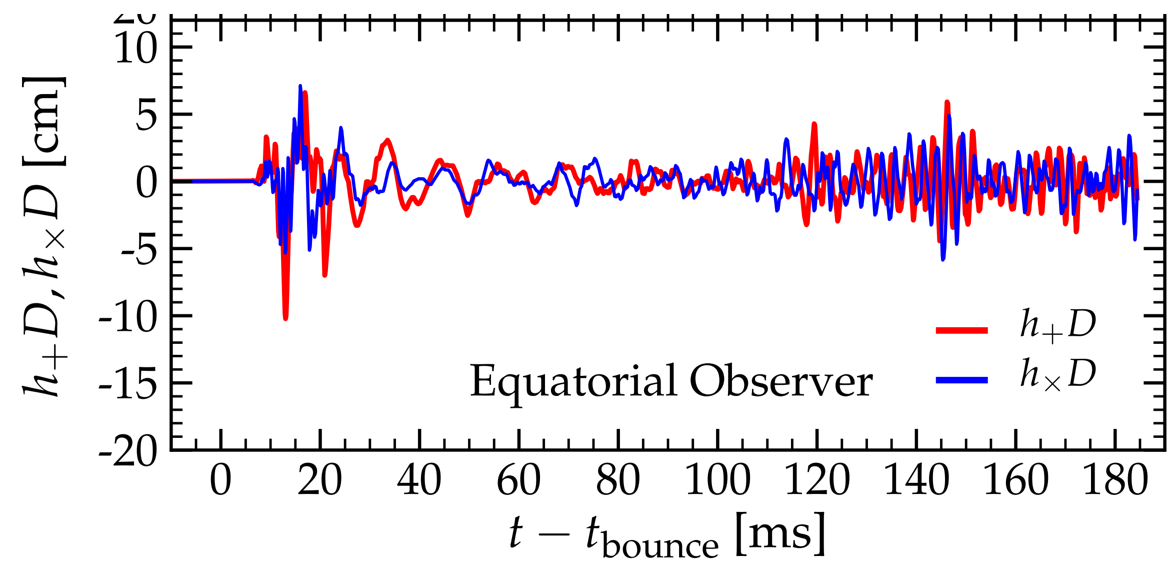


Expected sources of gravitational waves

- **Burst sources** Collapse of massive stellar cores can produce a burst of GWs.

leaves behind
a compact object
(black hole or neutron star)

[Ott et al (2012)]

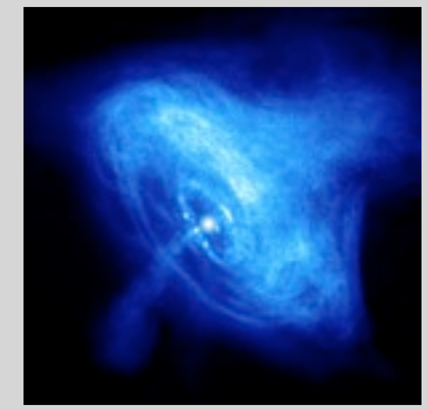


may also produce a
supernova/long GRB

$$E_{\mathrm{GW}} = 10^{-12} - 10^{-4}\ M_\odot\, c^2$$

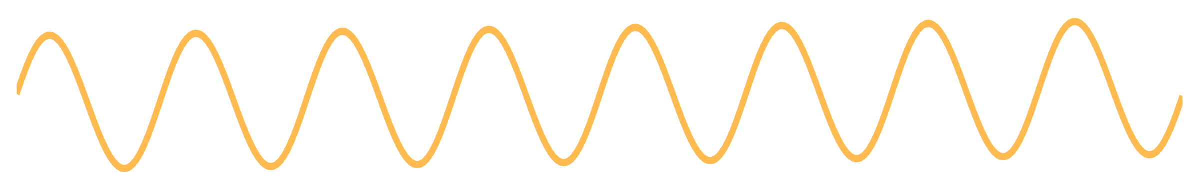
Expected sources of gravitational waves

- **Burst sources** Collapse of massive stellar cores can produce a burst of GWs
- **Continuous sources** Spinning neutron stars with non-axisymmetric deformations.



some of the NSs are observed as pulsars (e.g. Crab)

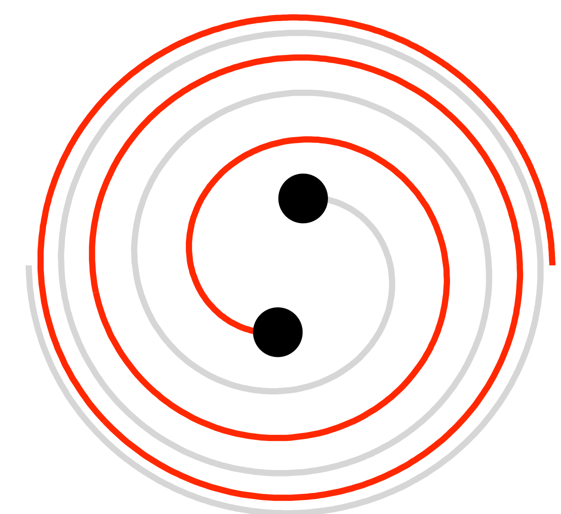
$h(t)$



will get Doppler modulated by the motion and spin or the earth.

Expected sources of gravitational waves

- **Burst sources** Collapse of massive stellar cores can produce a burst of GWs
- **Continuous sources** Spinning neutron stars with non-axisymmetric deformations.
- **Compact binary coalescences** driven by GW emission.



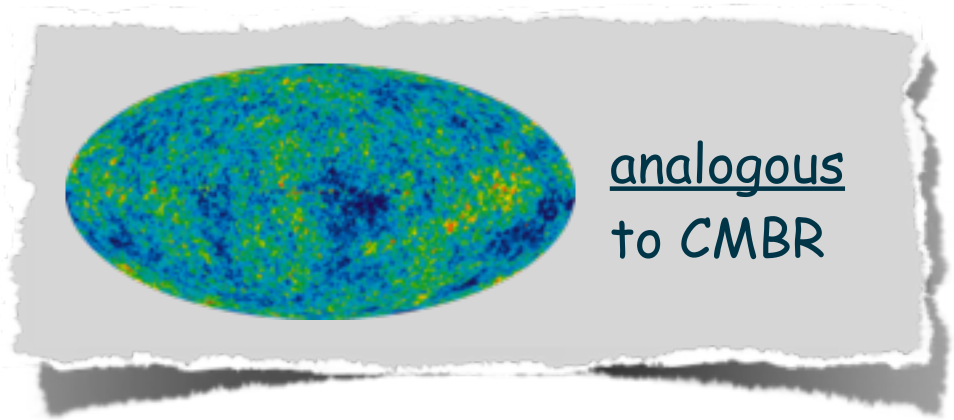
$$E_{\rm GW} \simeq 0.01 - 0.15\ Mc^2$$

$h(t)$

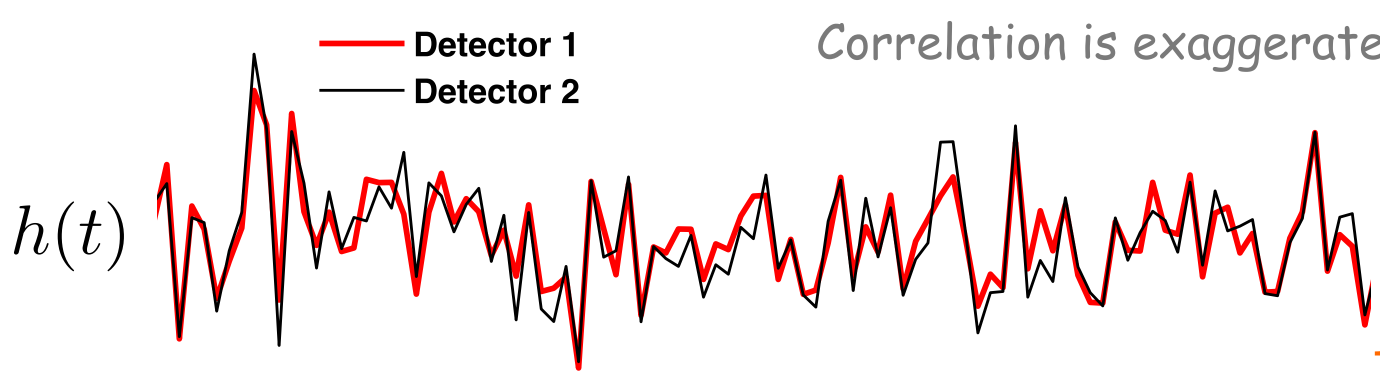
merger (involving NS) might also produce a short GRB

Expected sources of gravitational waves

- **Burst sources** Collapse of massive stellar cores can produce a burst of GWs
- **Continuous sources** Spinning neutron stars with non-axisymmetric deformations.
- **Compact binary coalescences** driven by GW emission.
- **Stochastic GW background** Produced by superposition of a number of astrophysical sources or by energetic processes in the Early Universe.



Correlation is exaggerated



Detection prospects of compact binaries **By 2G detectors**

[Abadie et al (2010)]

DETECTORS	SOURCES	MEAN DETECTION RATE
Initial detectors	NS-NS Binaries NS-BH Binaries BH-BH Binaries	0.02 / yr 0.004 / yr 0.007 / yr
Advanced detectors	NS-NS Binaries NS-BH Binaries BH-BH Binaries	40 / yr 10 / yr 20 / yr

Note: Large uncertainties (three orders of magnitude)

Detection prospects of other sources **By 2G detectors**

- **Core-collapse supernovae** According to the current simulations, GW signals are detectable only from SNe in near Universe (< 1 Mpc). Rate: $\sim$ 1/100 to 1/20 years.

Detection prospects of other sources **By 2G detectors**

- **Core-collapse supernovae** According to the current simulations, GW signals are detectable only from SNe in near Universe (< 1 Mpc). Rate: ~ 1/100 to 1/20 years.

- **Spinning neutron stars** Unlikely to detect GWs from the 2000 known pulsars. However, an estimated 10^9 neutron stars exist in our galaxy!

[Pitkin (2011)]

ELLIPTICITY ϵ: $(I_{xx} - I_{yy})/ I_{zz}$	10^{-5}	10^{-6}	10^{-7}	10^{-8}
If GW power = spin-down power:	8	5	4	1
If GW power = 50% spin-down power:	5	3	3	1
If GW power < 10% spin-down power:	~0	~0	~0	~0

Note: Distribution of ellipticity & GW power unknown. Current upper limit from LIGO on the GW emission from Crab pulsar: GW power < 2% spin-down power.

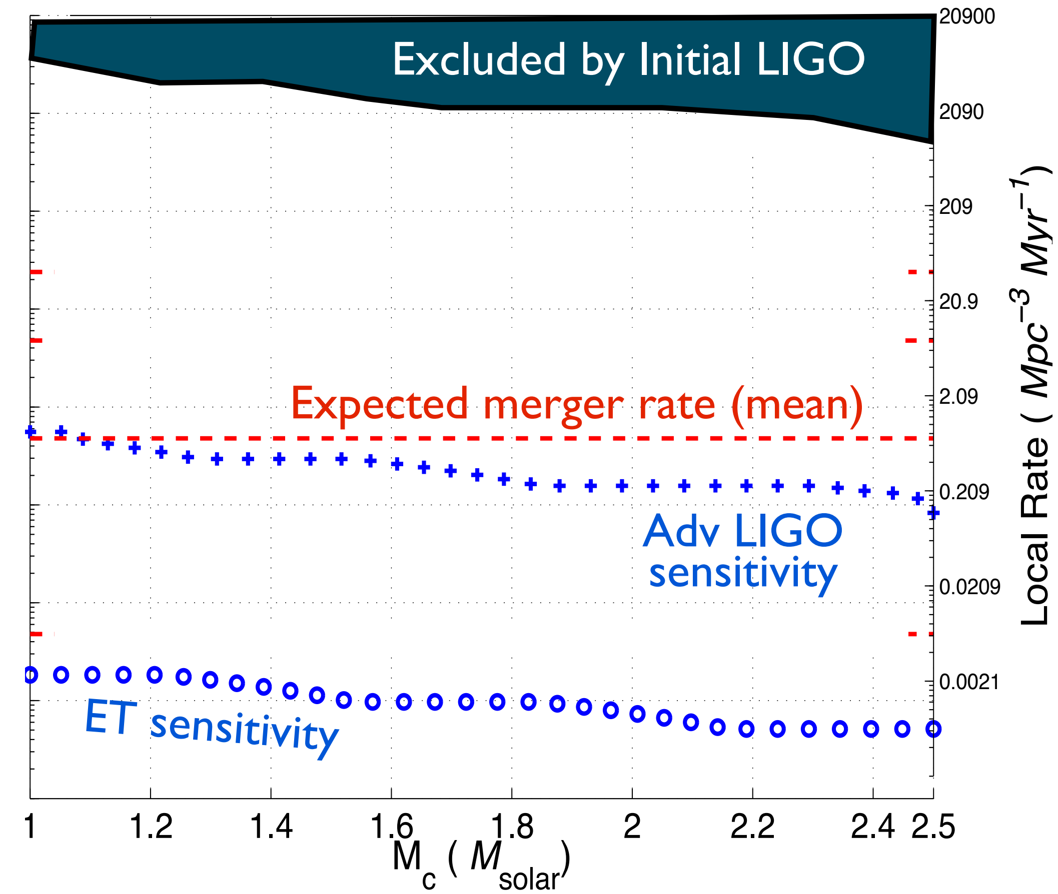
Detection prospects of other sources **By 2G detectors**

- **Core-collapse supernovae** According to the current simulations, GW signals are detectable only from SNe in near Universe (< 1 Mpc). Rate: ~ 1/100 to 1/20 years.

- **Spinning neutron stars** Unlikely to detect GWs from the 2000 known pulsars. However, an estimated 10^9 neutron stars exist in our galaxy!

- **Astrophysical GW background** Astrophysical background from CBCs might be detectable if the actual event rates are ~ predicted mean rates.

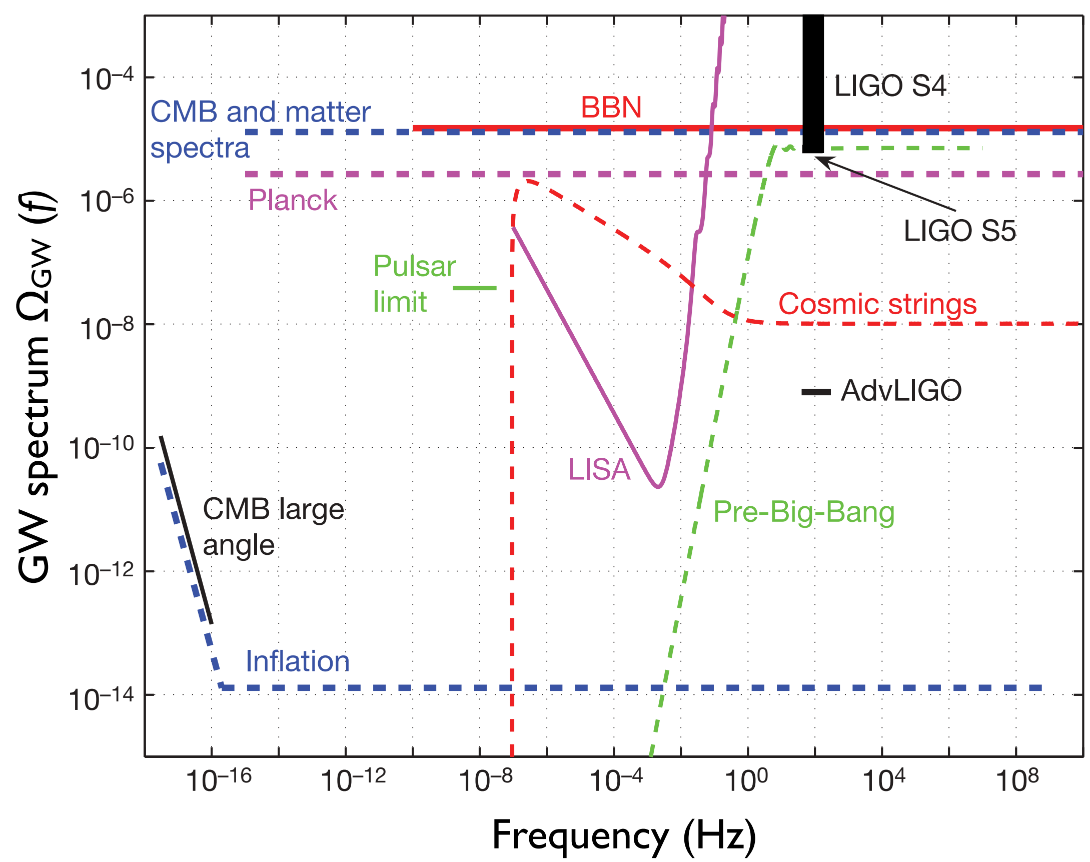
[Wu et al (2011)]



Detection prospects of other sources **By 2G detectors**

- **Core-collapse supernovae** According to the current simulations, GW signals are detectable only from SNe in near Universe (< 1 Mpc). Rate: ~ 1/100 to 1/20 years.
- **Spinning neutron stars** Unlikely to detect GWs from the 2000 known pulsars. However, an estimated 10^9 neutron stars exist in our galaxy!
- **Astrophysical GW background** Astrophysical background from CBCs might be detectable if the actual event rates are ~ predicted mean rates.
- **Cosmological GW background** GW spectrum predicted by std inflation is too weak. Upper limits can constrain a number of (more exotic) models.

[LIGO & Virgo 2009]

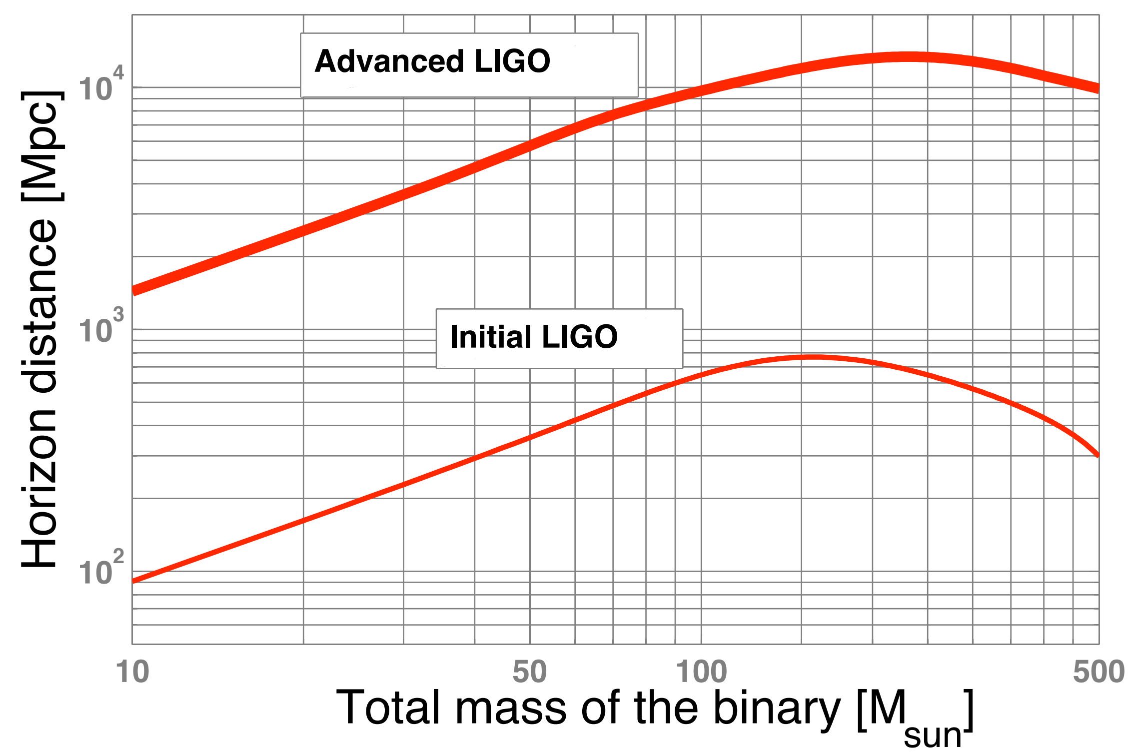


Predictions of the stochastic GW background by various models, and current/expected upper limits.

Status of the experimental effort

- Initial LIGO detectors achieved design sensitivity in 2007. Conducted two (~year-long) science runs with sensitivity ≥ design sensitivity.
  - Non-detection of GWs is consistent with the astrophysical understanding of the event rates.
- Detectors are being upgraded now. 2G detectors will be operational in a few years, and are expected to reach their design sensitivity within this decade.
  - Exciting possibility of **LIGO India**!

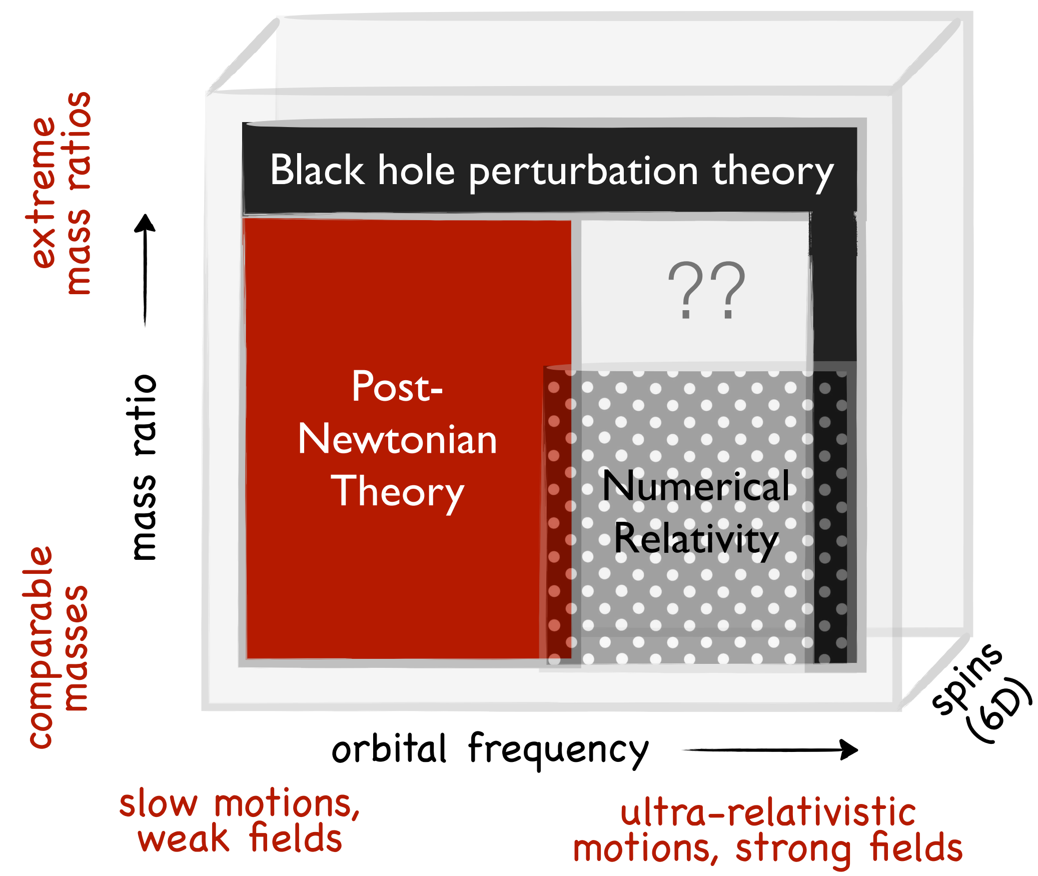
[Ajith et al (2008)]



Distance to which optimally-oriented compact binaries (equal-mass) can be observed with an SNR of 8.

Status of the theoretical work

- **Binary black holes** Dramatic progress in analytical- & numerical relativity in recent years.
    - Binary black-hole problem is essentially "solved". Current work on computing high-accurate waveforms, extending the parameter space, developing semi-analytical descriptions of the coalescence by combining NR & AR, applying these in GW searches...

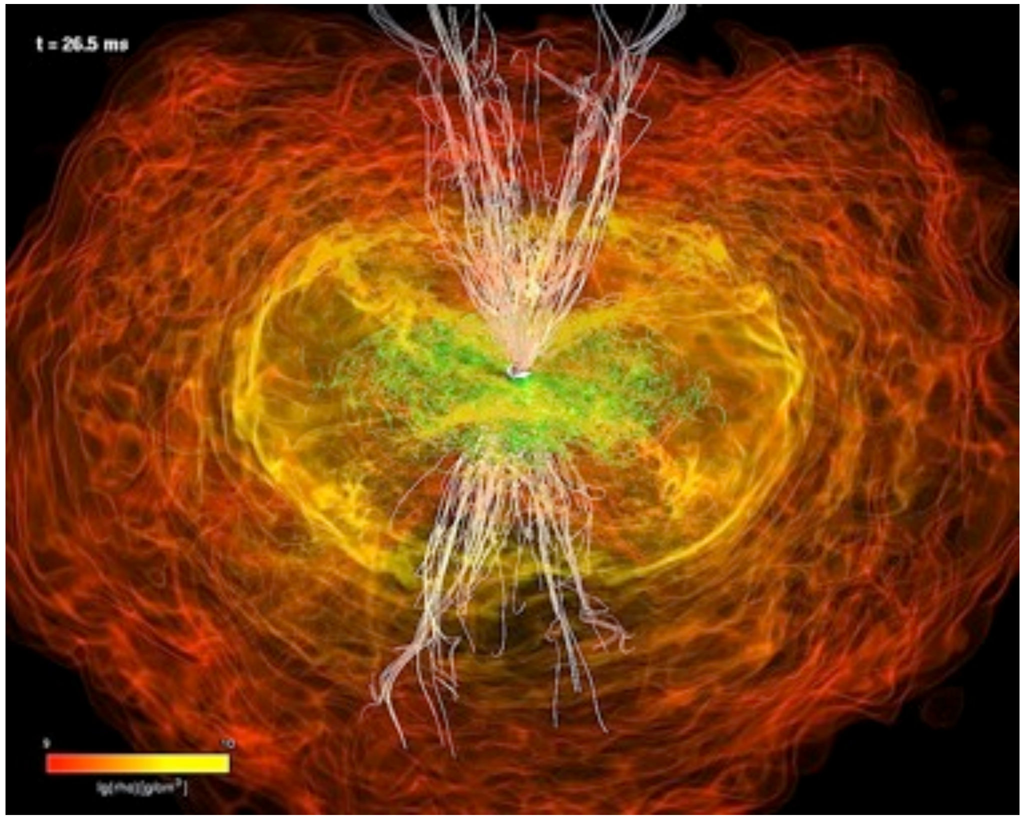


Interplay of analytical and numerical relativity in binary black-hole problem.

Status of the theoretical work

- **Binary black holes** Dramatic progress in analytical- & numerical relativity in recent years.
- **Binaries involving neutron stars** In addition to GR, effect of nuclear matter, magnetic fields etc. have to be considered.
    - First simulations including realistic EoS, magnetic fields etc. Some exploration of the EoS parameter space. Preliminary evidence that magnetized BNS mergers able to launch jets → sGRB central engine.

[Rezzolla et al (2011)]

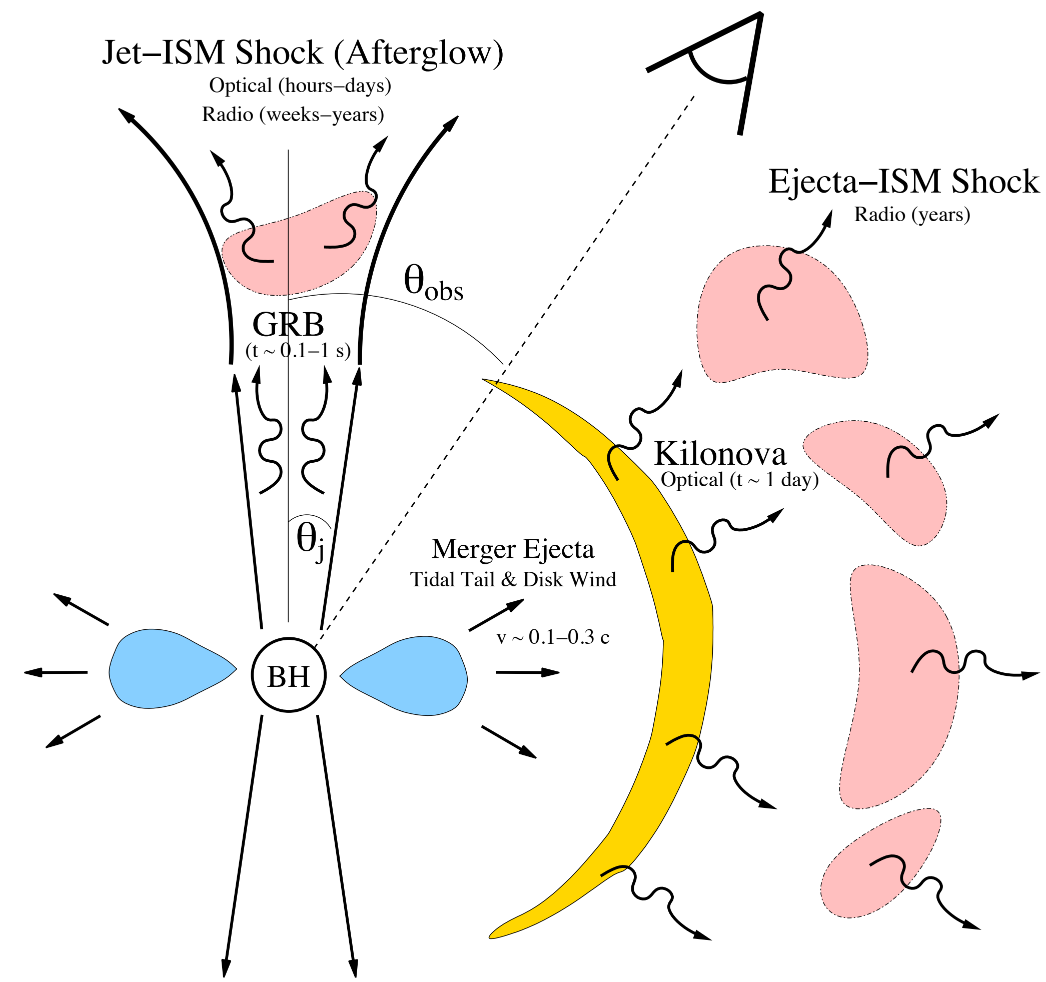


Numerical simulation of the merger of NS-NS binary. Magnetic fields can support GRB jets.

Status of the theoretical work

- **Binary black holes** Dramatic progress in analytical- & numerical relativity in recent years.
- **Binaries involving neutron stars** In addition to GR, effect of nuclear matter, magnetic fields etc. have to be considered.
    - **Modelling & observation of EM counterparts** Systematic exploration of the EM counterparts of CBC, towards better understanding of the false-association rates, preparation for low-latency followup of GW candidates.

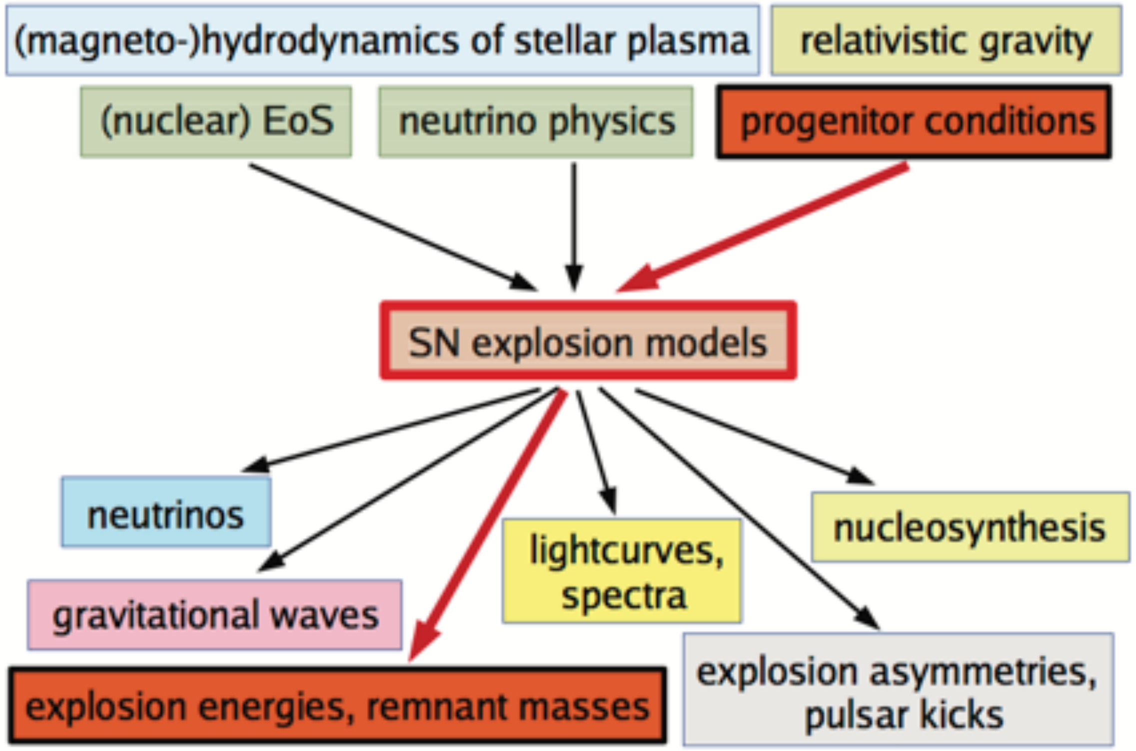
[Metzger & Berger (2011)]



Status of the theoretical work

- **Binary black holes** Dramatic progress in analytical- & numerical relativity in recent years.
- **Binaries involving neutron stars** In addition to GR, effect of nuclear matter, magnetic fields etc. have to be considered.
- **Core-collapse SNe** First 3D GR simulations with sophisticated treatment of the neutrino physics. Debate is still ongoing as to the exact nature of the SN explosion mechanism.

[Janka et al (2012)]



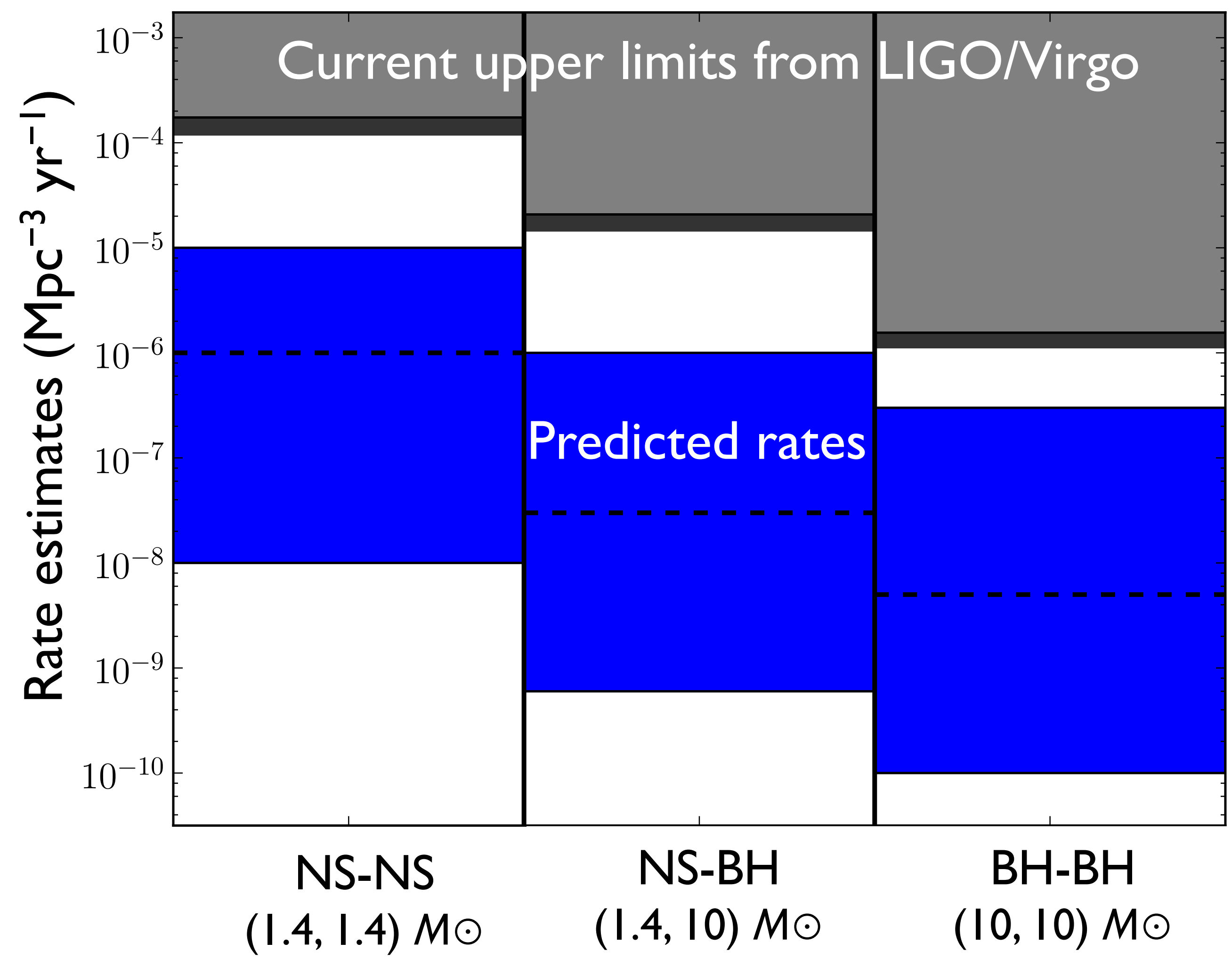
Physics, Astrophysics and Cosmology from GW observations

What can we expect in the next 5-10 years?

Astrophysics using GW observations

- **Constrain models of compact binary formation & evolution** Even with no detections!

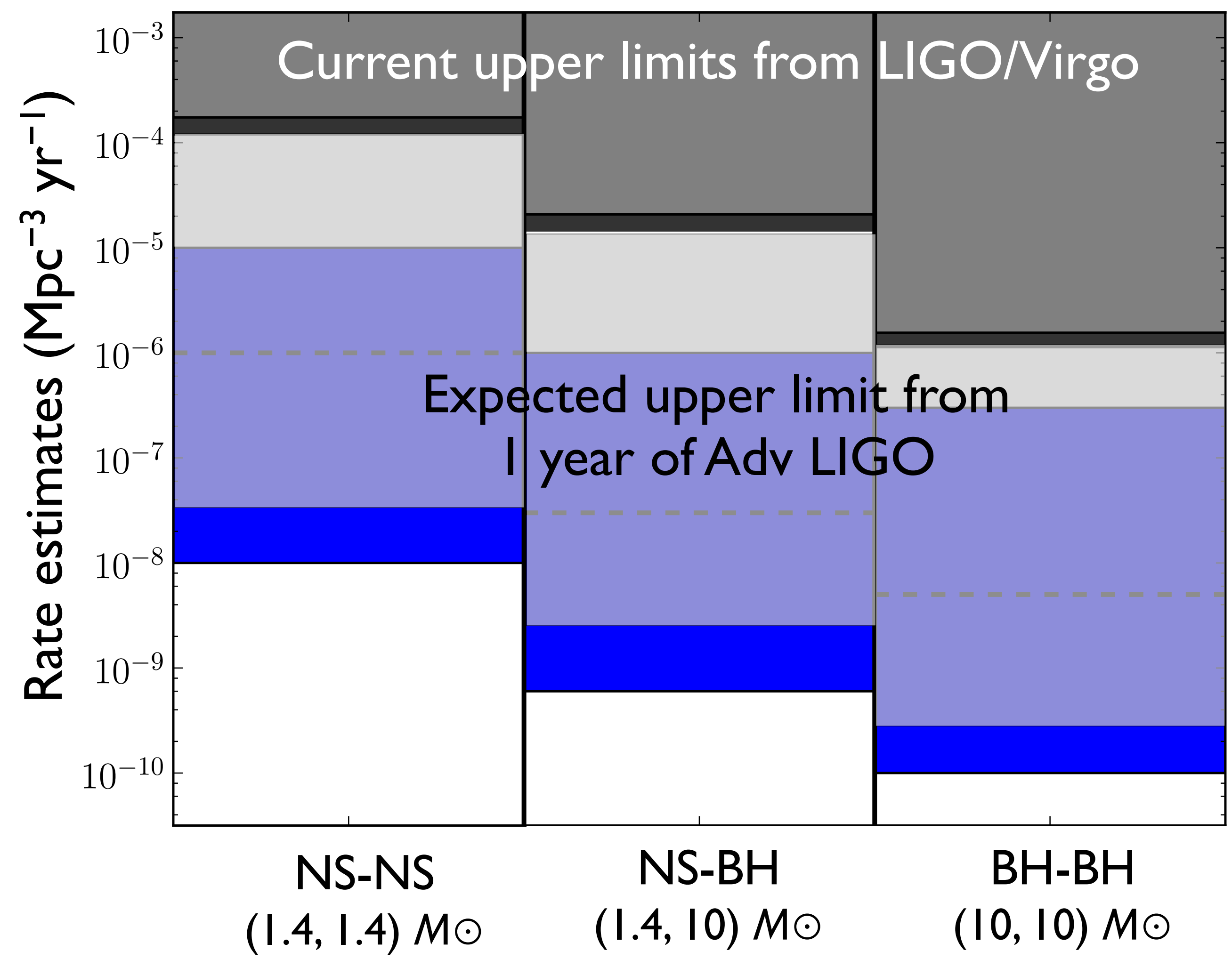
[Abadie et al (2012)]



Astrophysics using GW observations

- **Constrain models of compact binary formation & evolution** Even with no detections!

[Abadie et al (2012)]



Astrophysics using GW observations

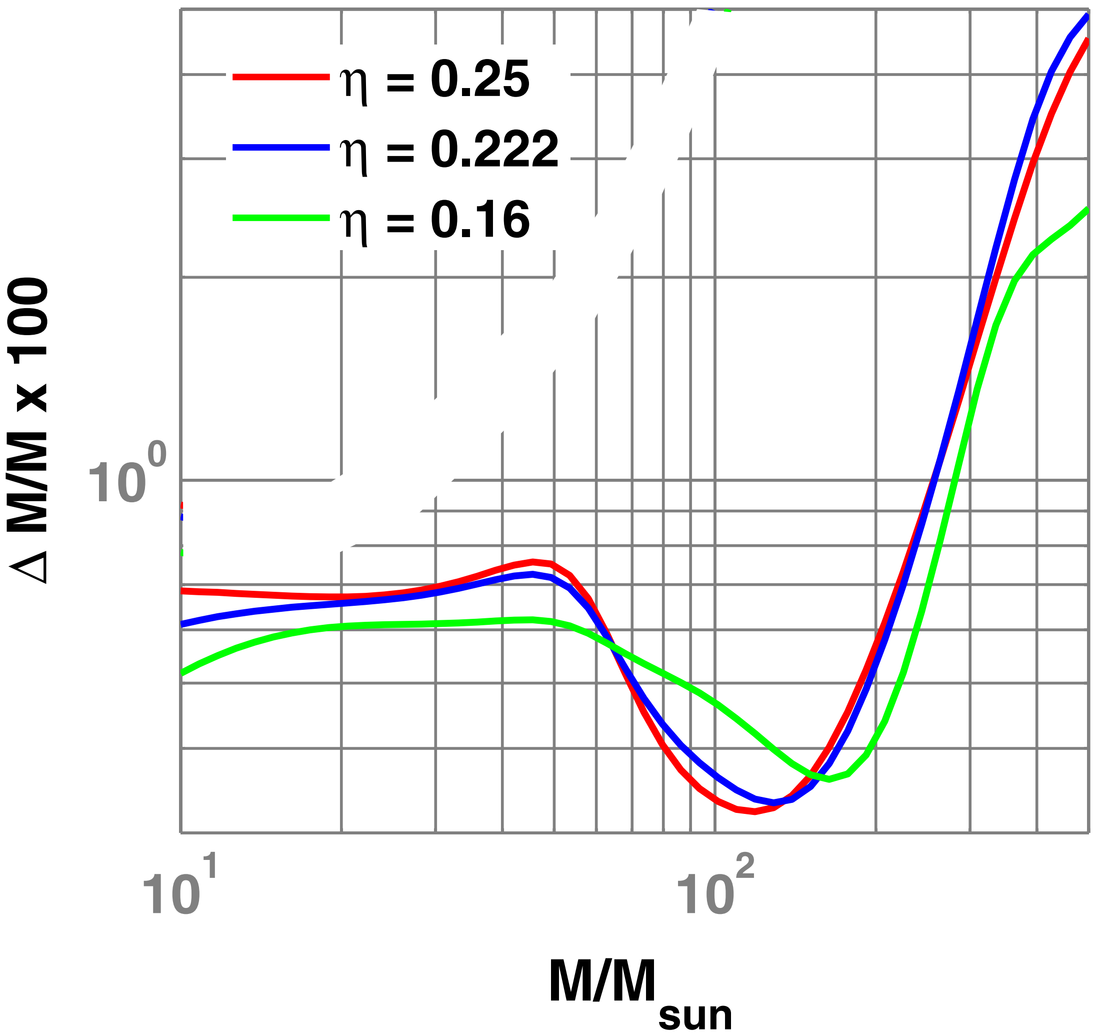
- **Constrain models of compact binary formation & evolution** Even with no detections!

- **First detection of BH-BH and NS-BH binaries** A new population of astronomical sources. Great potential for tests of GR, astrophysics & cosmology.

Astrophysics using GW observations

- **Constrain models of compact binary formation & evolution** Even with no detections!
- **First detection of BH-BH and NS-BH binaries** A new population of astronomical sources. Great potential for tests of GR, astrophysics & cosmology.
- **First direct measurements of BH masses and spins** Sources are very well understood (unlike in EM astronomy), GW signal encodes direct information of the masses & spins.

[Ajith & Bose (2009)]

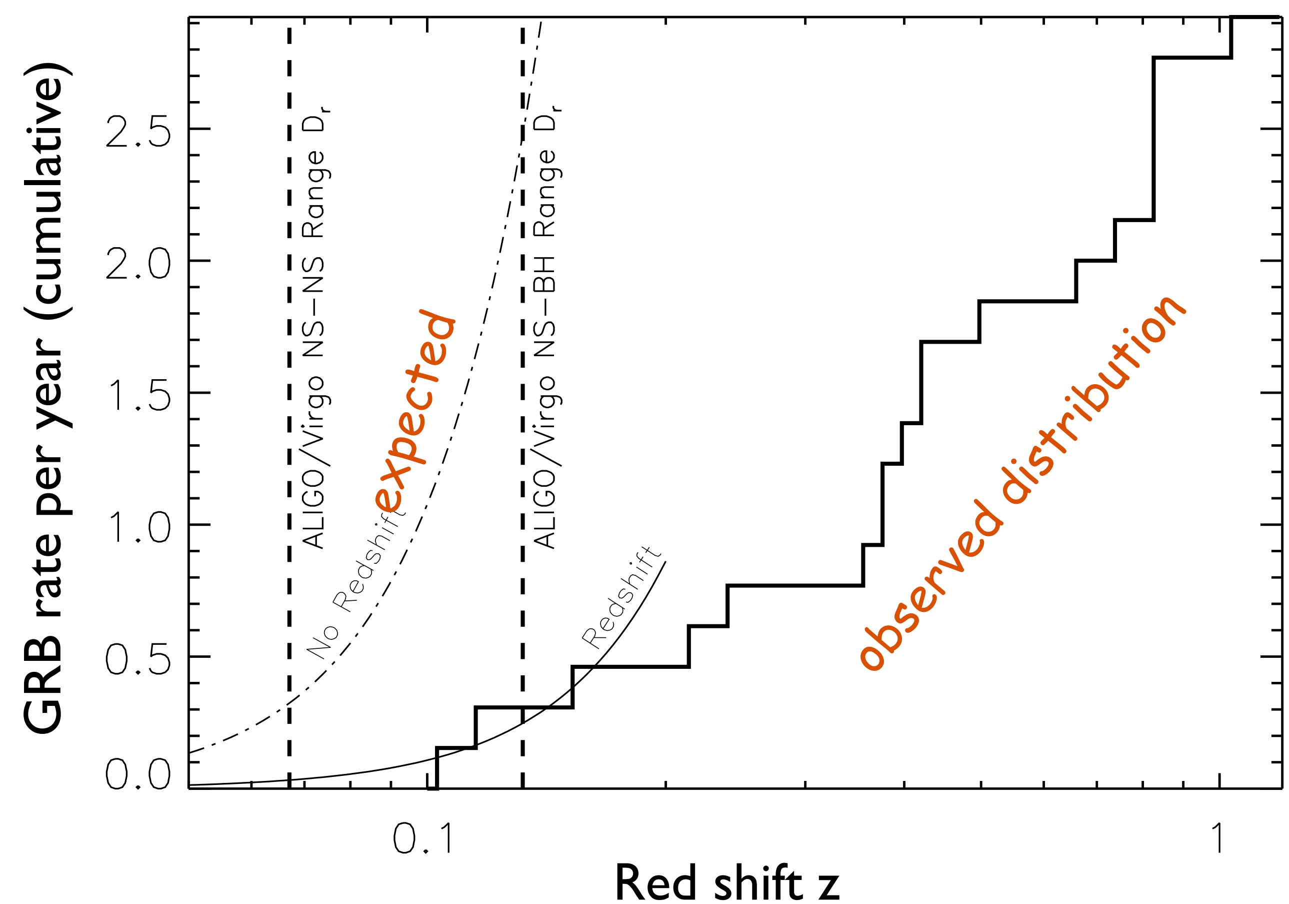


1-σ error in measuring the total mass of BBHs located at 1 Gpc (Adv LIGO)

Astrophysics using GW observations

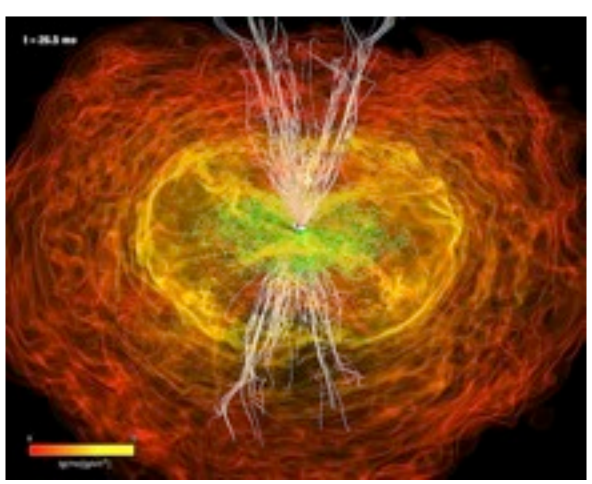
- **Test sGRB-GW association** Short-hard GRBs are <u>hypothesized</u> to be powered by compact-binary mergers. One unique coincident GRB-GW observation will shed light on this.

[Metzger & Berger (2011)]



Observed & expected distribution of SGRBs (Swift)

[Rezzolla et al (2011)]



Astrophysics using GW observations

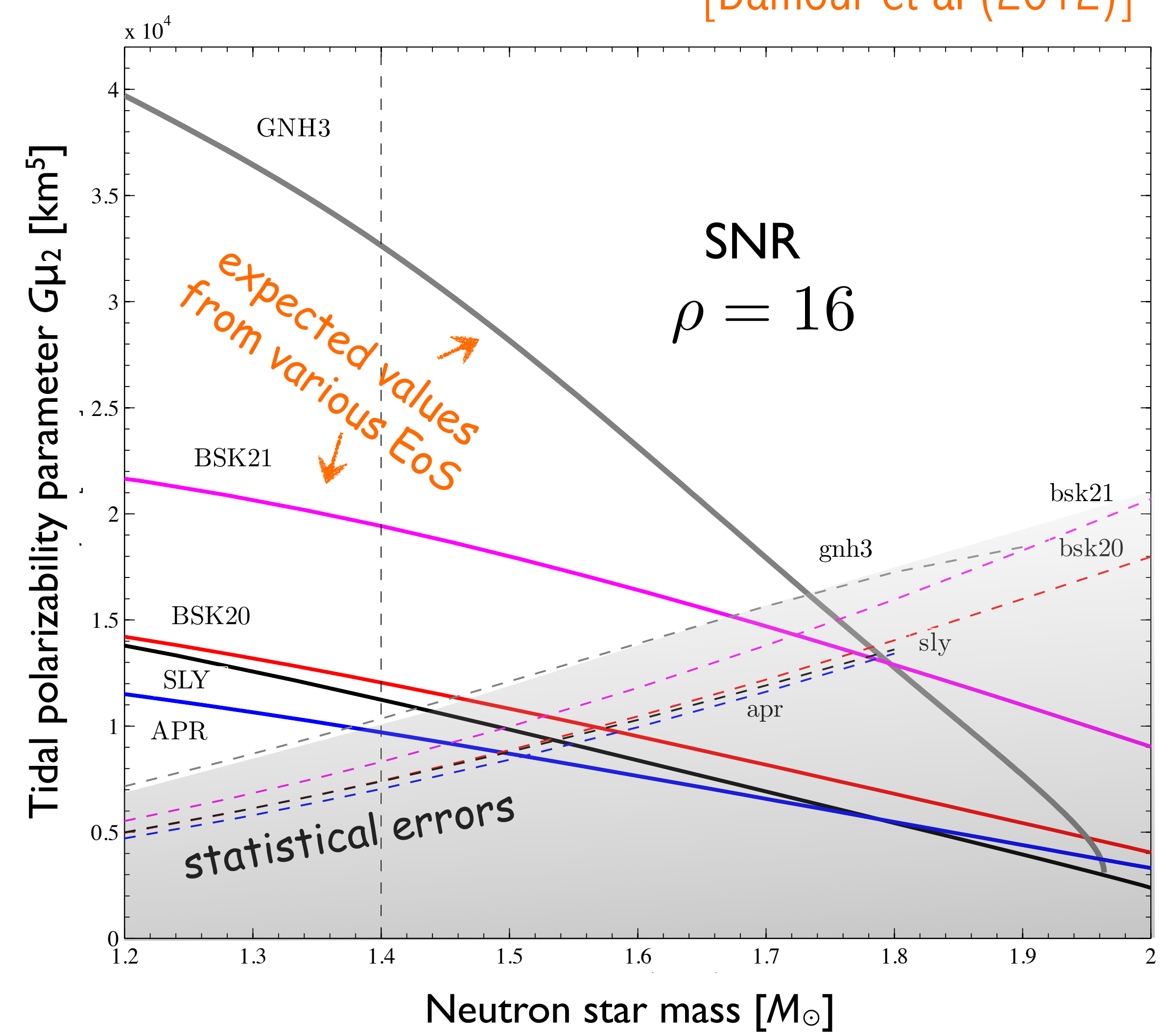
- **Test sGRB-GW association** Short-hard GRBs are hypothesized to be powered by compact-binary mergers. One unique coincident GRB-GW observation will shed light on this.

- **EoS of neutron stars** BNS/NSBH inspiral signals contain information of the NS EoS (through tidal deformation).

  - Need "fairly loud events" (SNR ≃ 16) in Adv LIGO (expectation: ~6 per year).

  - Merger/ring-down part expected to have clearer signature. NR simulations are getting mature to explore this. E.g. [Lackey et al (2011)]

[Damour et al (2012)]



In the unshaded region, the tidal deformation can be measured in Adv LIGO.

Tests of GR using GW observations

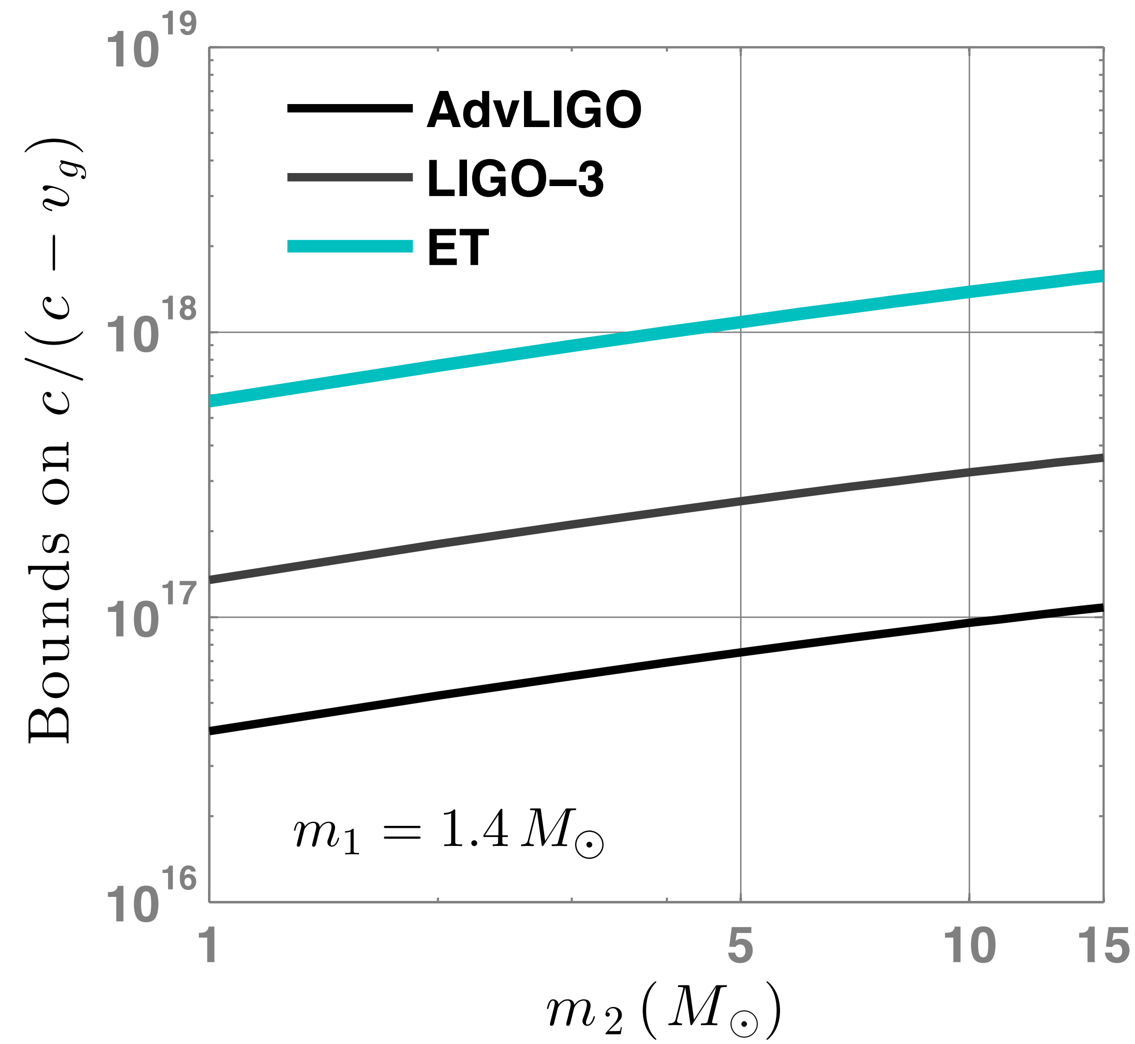
- **Speed of GWs** Time-delay between GW and EM (γ-ray) signals from SGRBs can constrain the speed of GWs [Will 1998].

distance to the source

$$\frac{c}{c - v_g} = \frac{D}{c\,\Delta t}$$

speed of GWs (v_g= c in GR)

observed time-difference btwn the GW & EM signals (after subtracting the time-delay in emission, measurement errors etc.)



From the coincident GW+EM observation (Δt = 1sec) of <u>one</u> SGRB, powered by NSBH merger (located at the horizon distance).

Tests of GR using GW observations

- **Speed of GWs** Time-delay between GW and EM (γ-ray) signals from SGRBs can constrain the speed of GWs [Will 1998].
- **Mass of the graviton** A bound on v_g implies a bound on the graviton-mass [Will 1998].

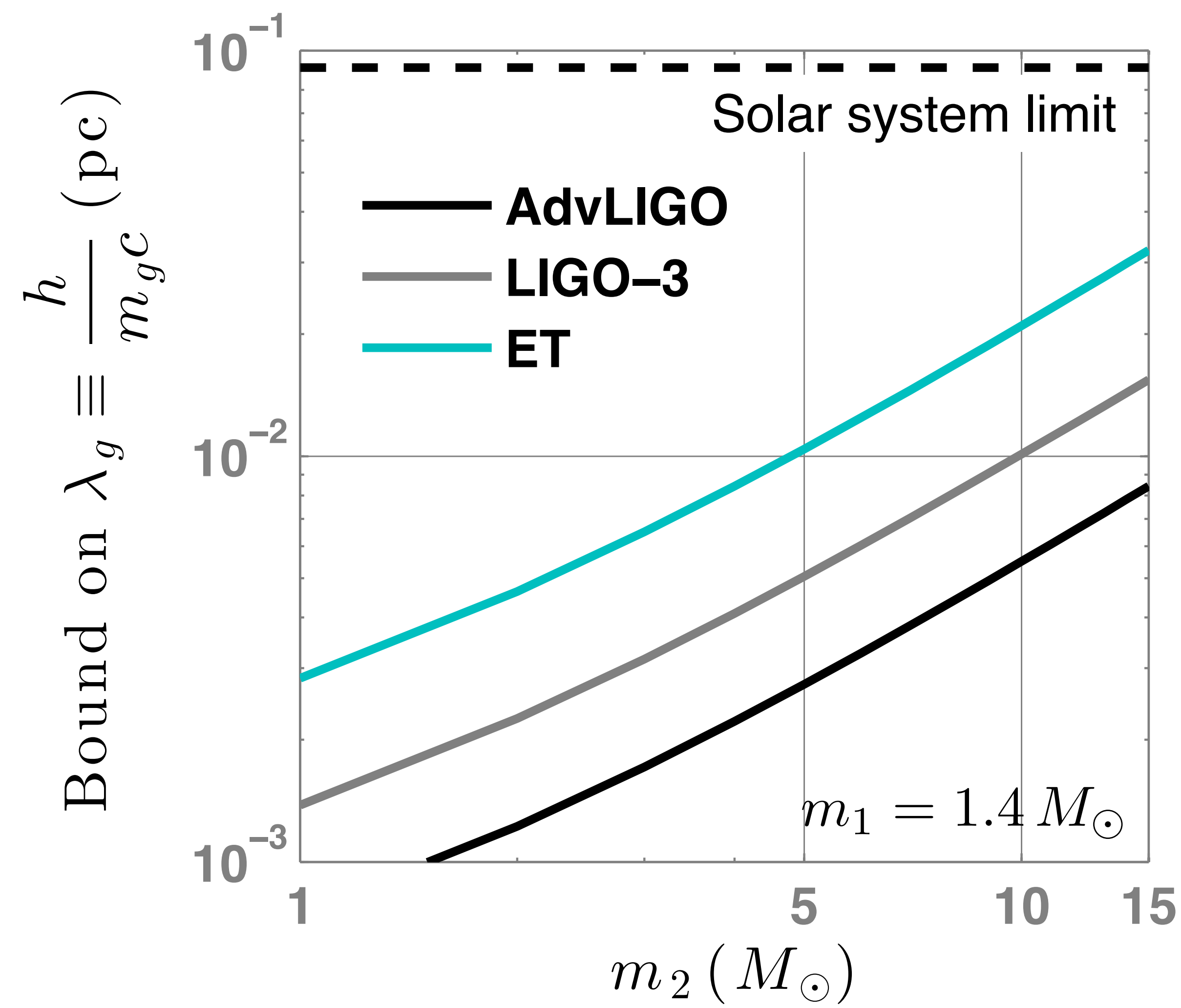
Dispersion relation

$$v_g^2/c^2 = 1 - m_g^2\, c^4/E_g^2$$

speed of GWs (v_g= c in GR)

rest mass of the graviton (m_g= 0 in GR)

energy of the graviton



From the coincident GW+EM observation (Δt = 1sec) of *one* SGRB, powered by NSBH merger (located at the horizon distance).

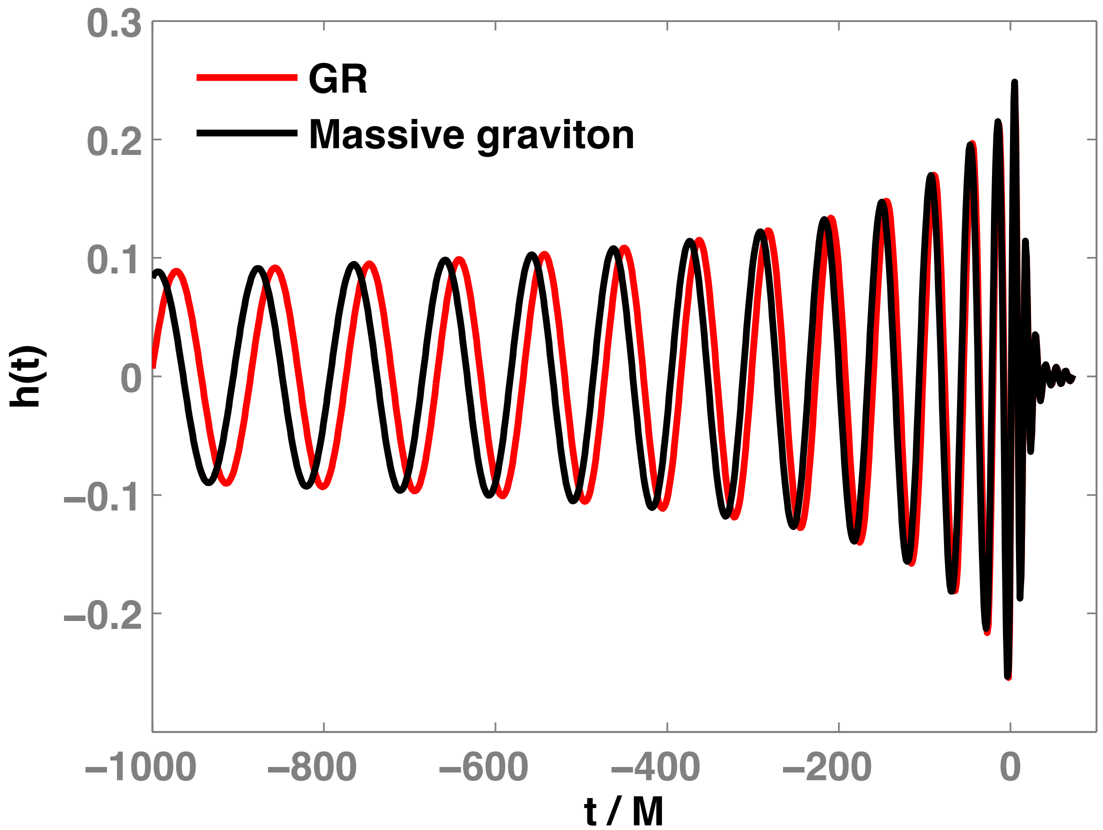
Tests of GR using GW observations

- **Speed of GWs** Time-delay between GW and EM (γ-ray) signals from SGRBs can constrain the speed of GWs [Will 1998].

- **Mass of the graviton** A bound on v_g implies a bound on the graviton-mass [Will 1998].
  - GW observations of CBCs can constrain the mass of graviton without relying on an EM counterpart.

hf_GW

$$v_g^2/c^2 = 1 - m_g^2 c^4/E_g^2$$

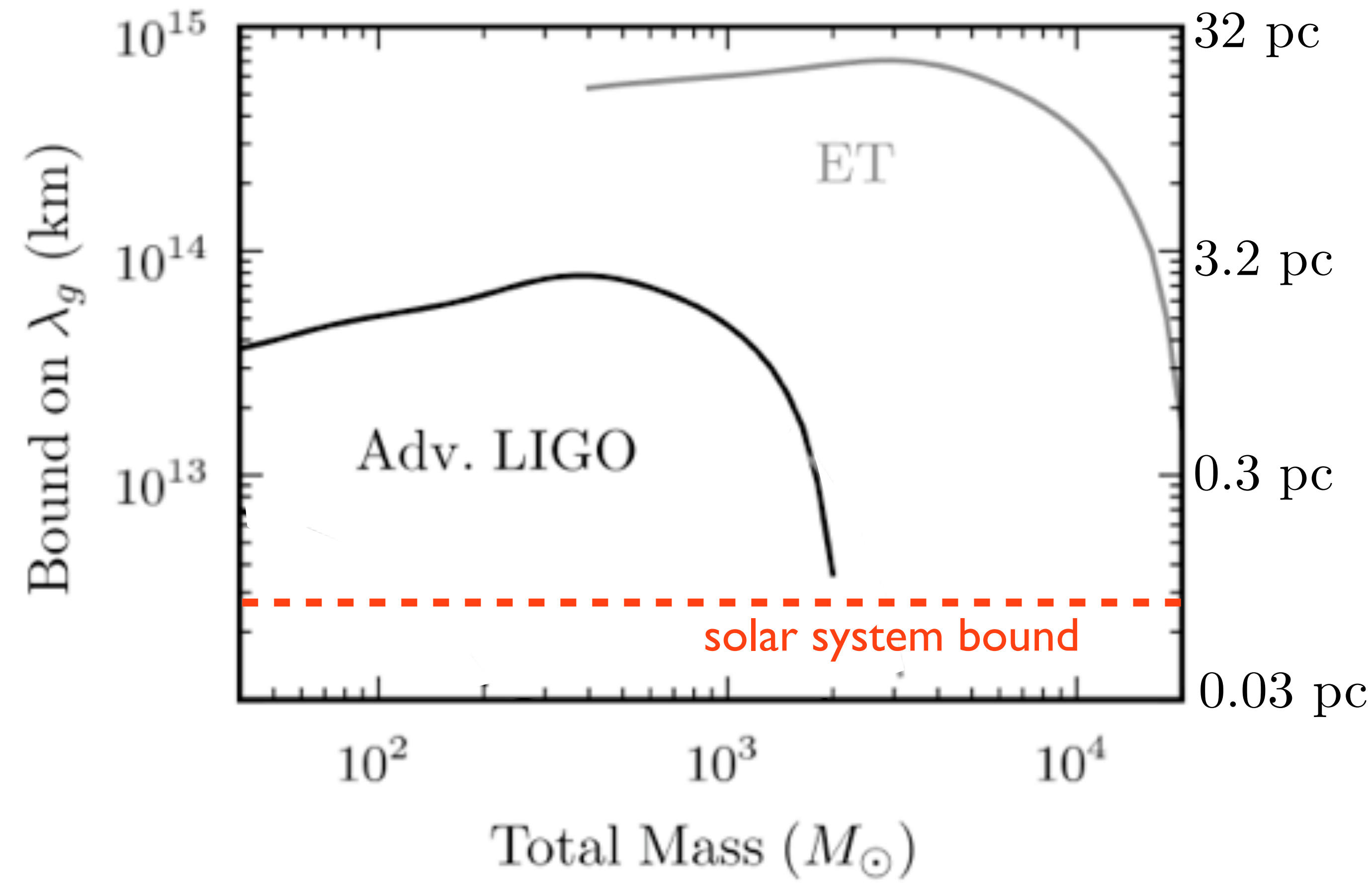


Different frequency components travel with different speeds → characteristic deformation in the observed signal!

Tests of GR using GW observations

- **Speed of GWs** Time-delay between GW and EM (γ-ray) signals from SGRBs can constrain the speed of GWs [Will 1998].
- **Mass of the graviton** A bound on v_g implies a bound on the graviton-mass [Will 1998].
    - GW observations of CBCs can constrain the mass of graviton without relying on an EM counterpart.

[Keppel & Ajith (2010)]

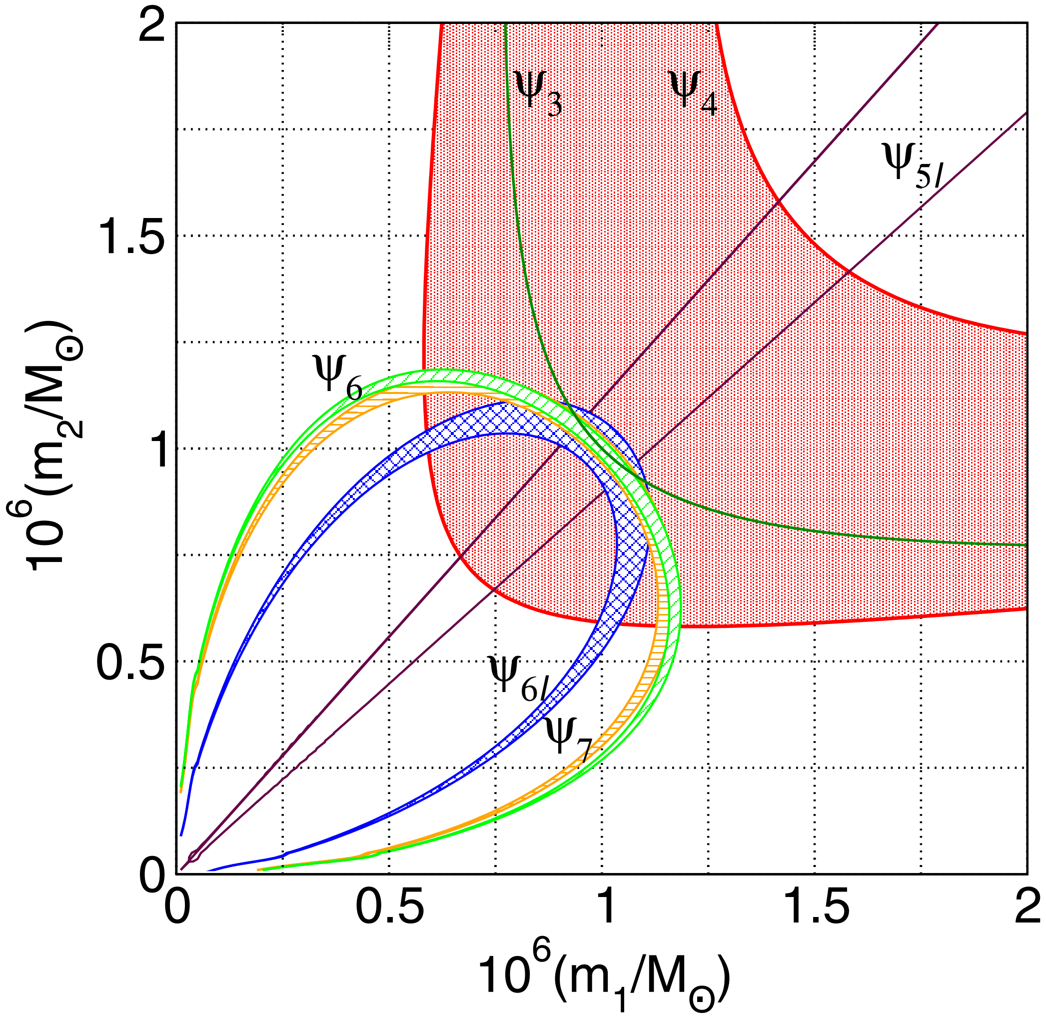


Expected bounds on the Compton wavelength of the graviton from BBH observations by future detectors. (d_L = 1 Gpc)

Tests of GR using GW observations

- **Speed of GWs** Time-delay between GW and EM (γ-ray) signals from SGRBs can constrain the speed of GWs [Will 1998].
- **Mass of the graviton** A bound on v_g implies a bound on the graviton-mass [Will 1998].
- **Testing PN theory** by independently estimating the PN parameters [Arun et al 2006].
  - Two parameters constrain the masses; estimation of more parameters provide consistency tests (analogous to binary pulsar tests).

[Arun et al (2006)]



Shaded regions show the values of m_1 & m_2 that give the observed values of the PN parameters. If the theory is correct, all curves should intersect in a single point.

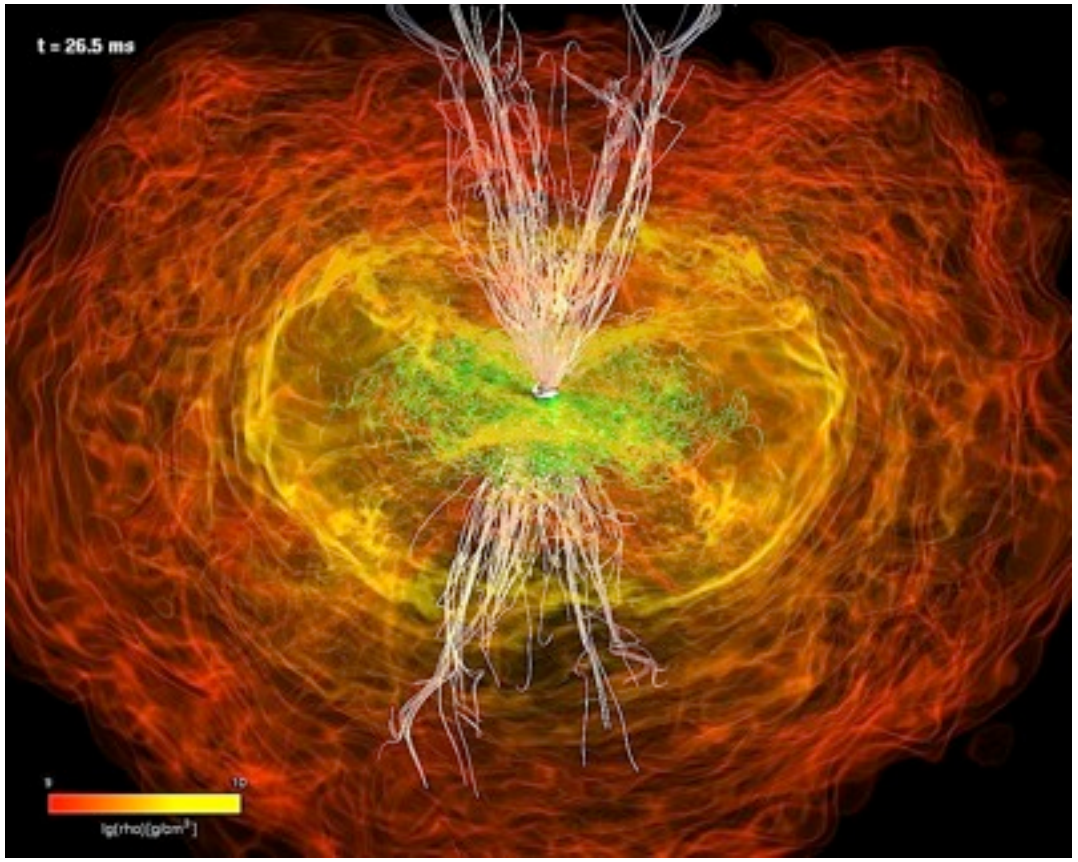
Tests of GR using GW observations

- **Speed of GWs** Time-delay between GW and EM (γ-ray) signals from SGRBs can constrain the speed of GWs [Will 1998].
- **Mass of the graviton** A bound on v_g implies a bound on the graviton-mass [Will 1998].
- **Testing PN theory** by independently estimating the PN parameters [Arun et al 2006].
- **More general tests: PPE framework** Generalize the (GR) GW signal by introducing extra parameters that are motivated by alternative theories; estimate them [Yunes & Pretorius 2009].

Cosmology using GW observations

- **CBCs are standard sirens** Self calibrating sources → cosmic expansion rate. [Schutz (1986)]

[Rezzolla et al (2011)]



Numerical simulation of the merger of NS-NS binary. Magnetic fields can support GRB jets.

GWs

absolute determination of the luminosity distance

EM counterpart

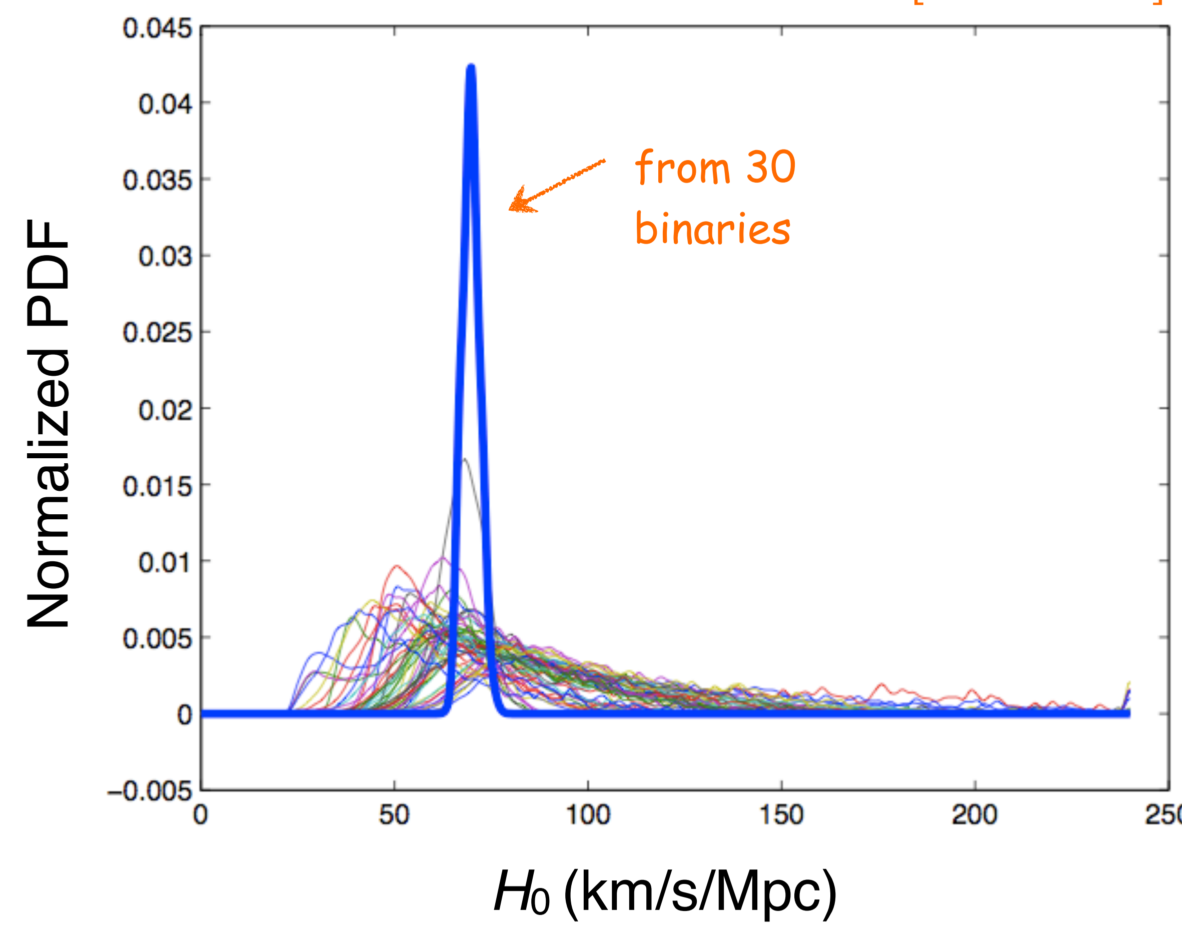
e.g. GRB afterglow → red-shift information

Cosmology using GW observations

- **CBCs are standard sirens** Self calibrating sources → cosmic expansion rate. [Schutz (1986)]
    - **2G network** Modest measurement of H_0. [Nissanke et al (2010)]
    - **3G network** more interesting measurements (comparable to other dark energy missions). [Zhao et al (2011)]

Note: very different systematics!

[S. Nissanke]

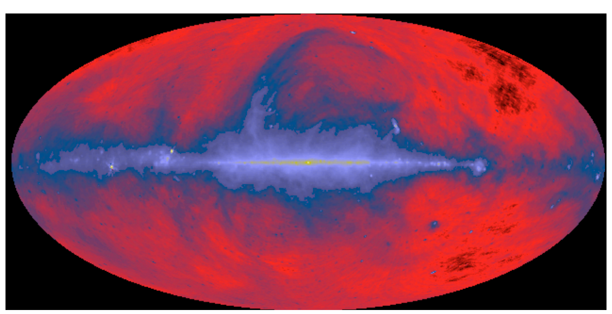


Expected errors on H_0 : 13% (4 detections), 5%(15 detections), 3.4% (30 detections). Using LIGO-Virgo-KAGRA-India network.

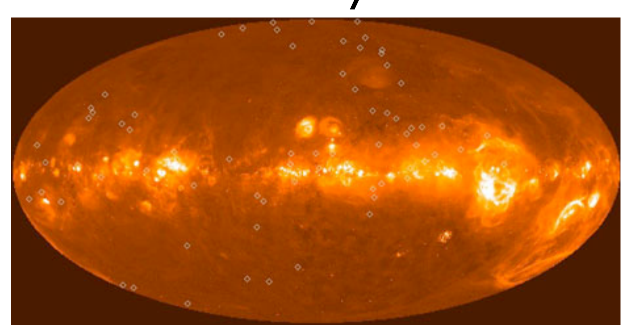
Summary

- Significant progress in the experimental efforts for the first direct detection of GWs, as well as in the theoretical work in the modeling of relativistic astrophysical phenomena producing GW signals & their multi-messenger counterparts.
- First detections very likely happen over the next few years with the advent of 2G detectors.
- Once detected, GWs will open up a new observational window to the Universe. Can expect similar explosion in the astrophysics knowledge with the advent of radio, x-ray or gamma-ray astronomies.

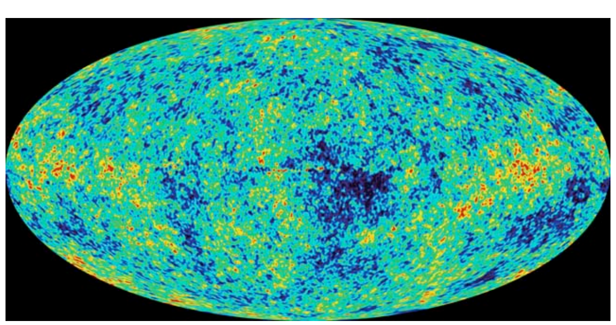
Radio



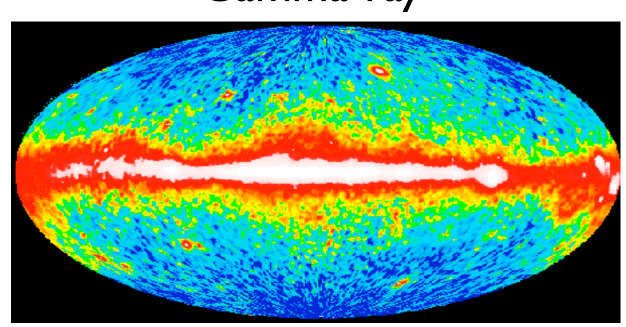
X-ray

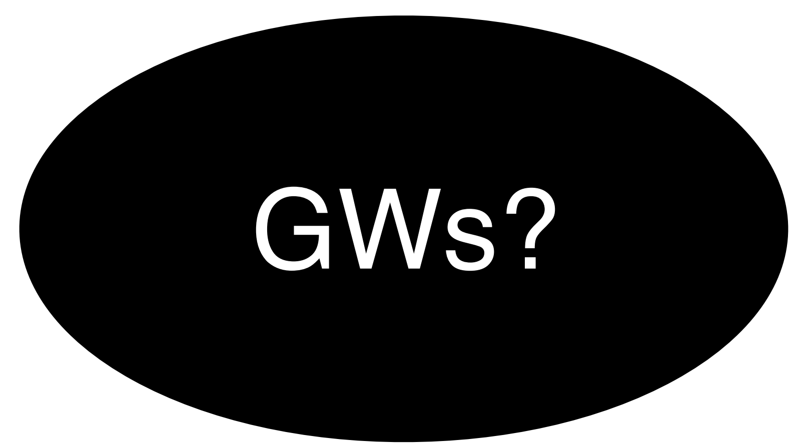


Microwave

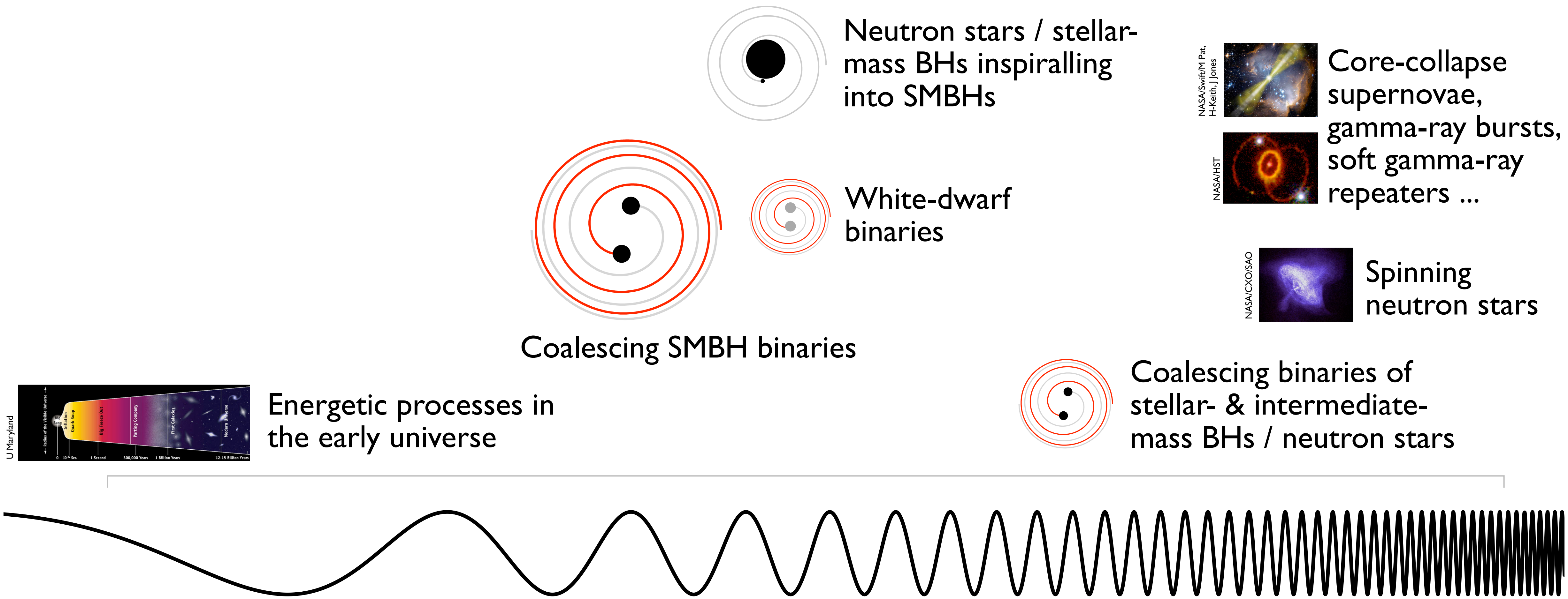


Gamma-ray





The gravitational-wave spectrum



Frequency	10^{-16} Hz	$10^{-9} - 10^{-6}$ Hz	$10^{-5} - 10^{-1}$ Hz	$10^{-1} - 1$ Hz	$1 - 10^{4}$ Hz
Wavelength	10^{21} km	$10^{14} - 10^{11}$ km	$10^{10} - 10^{6}$ km	$10^{6} - 10^{5}$ km	$10^{5} - 10$ km
Detection	CMB Polarization	Pulsar timing	eLISA/NGO	BBO/DECIGO	LIGO/Virgo/KAGRA/ET