The gravitational-wave window to the Universe

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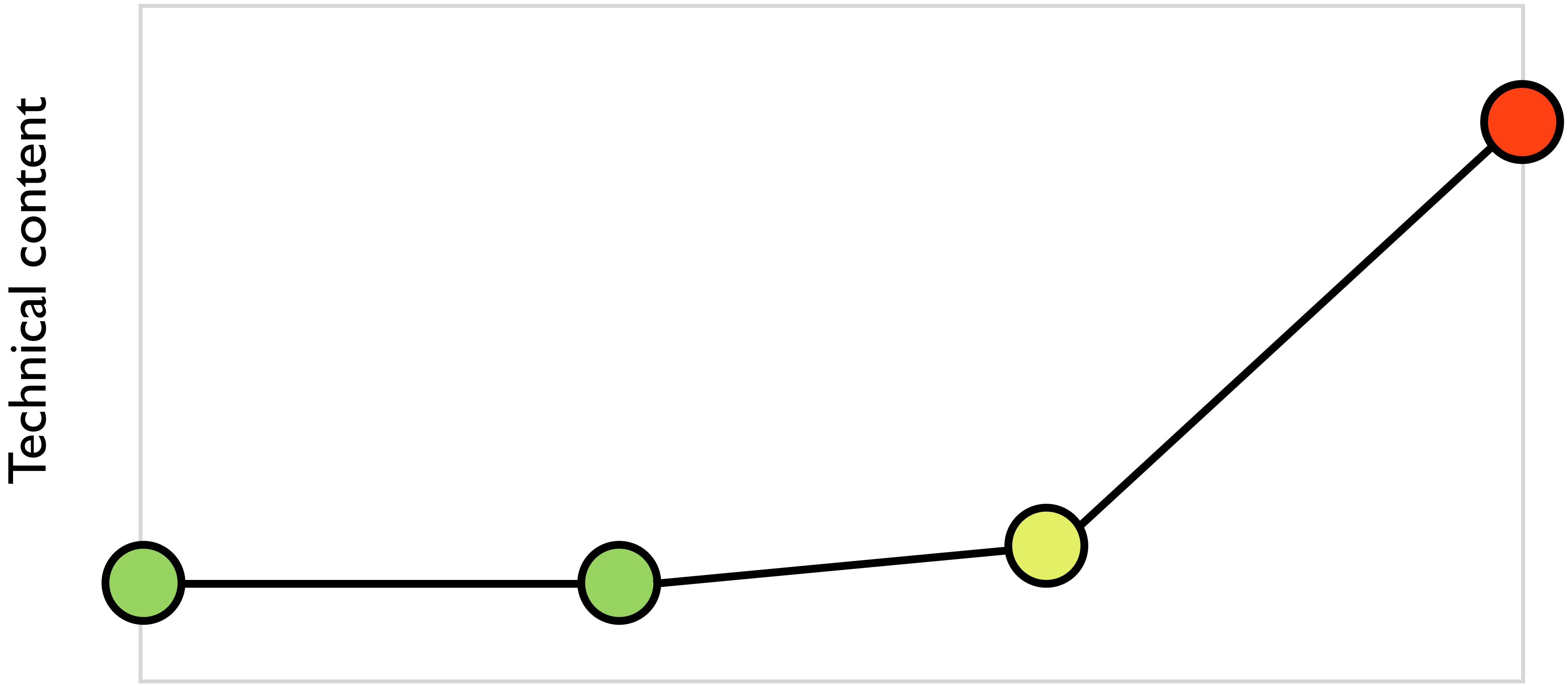
ICTS Colloquium 11 June 2012

Overview of the talk

GWs, sources of GWs	Observational evidence of GWs	GW detection, current status	Expected results in the next 5-10 years

Overview of the talk



GWs,
sources of GWs

Observational
evidence of GWs

GW detection,
current status

Expected results
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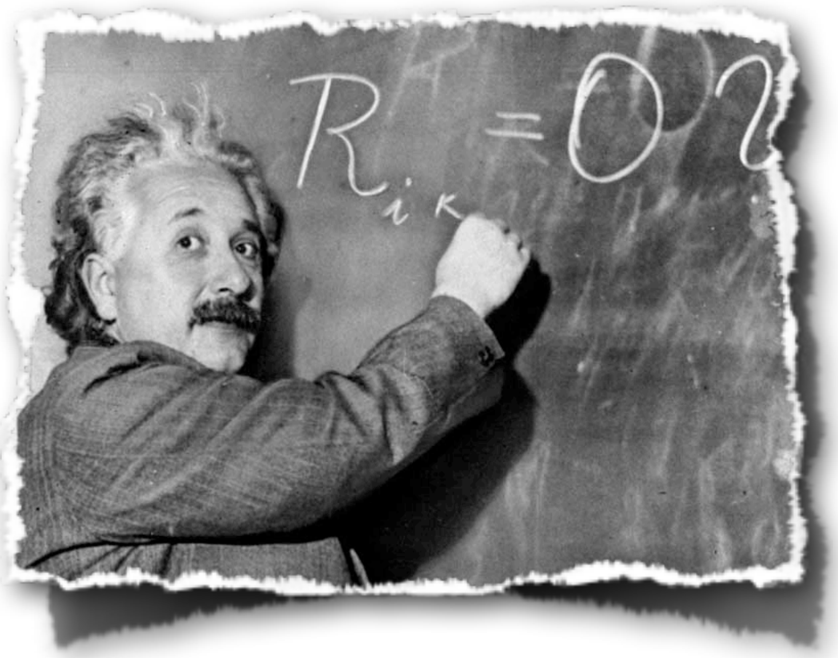
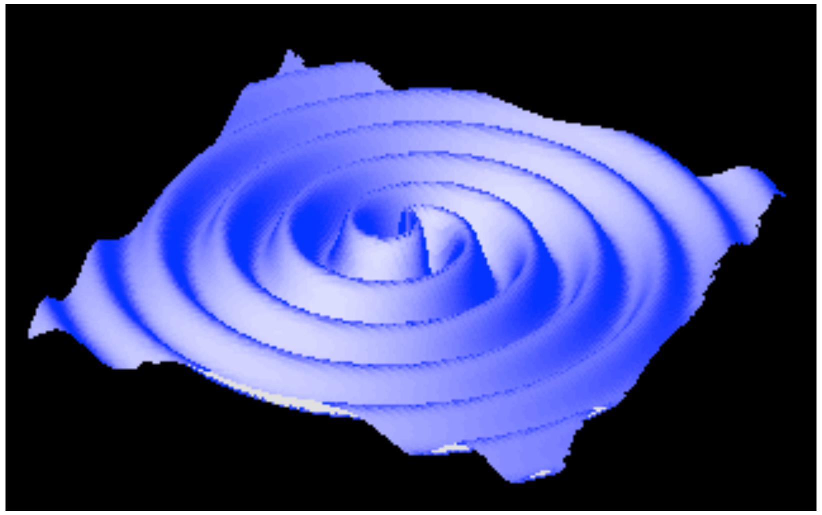
Gravitational waves

- The existence of gravitational waves (GWs) is one of the most intriguing predictions of General Relativity.
- GWs are freely propagating oscillations in the geometry of spacetime — ripples in the fabric of spacetime.





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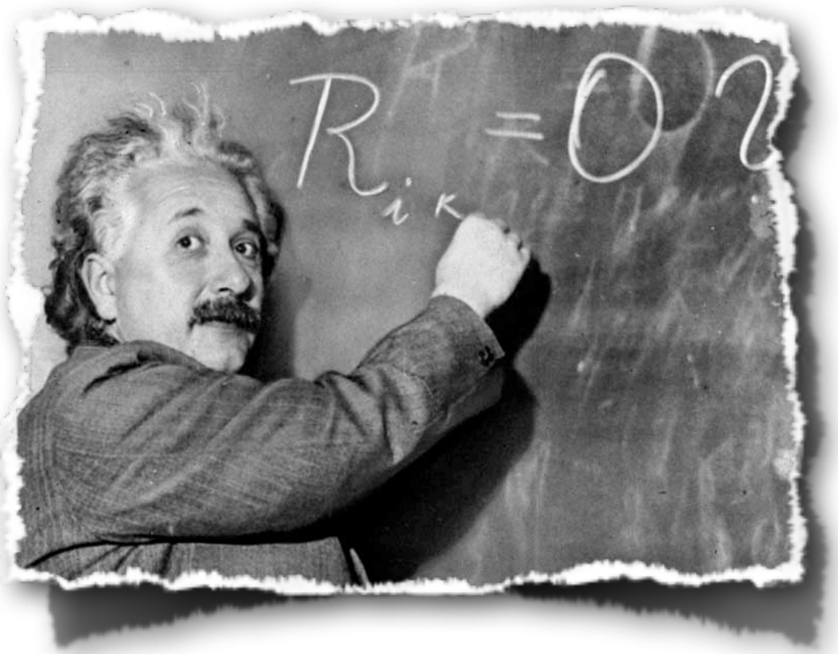
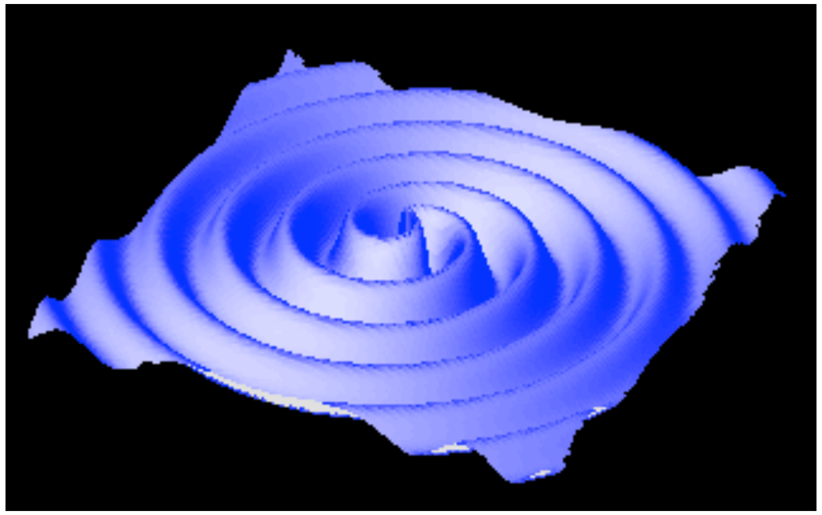
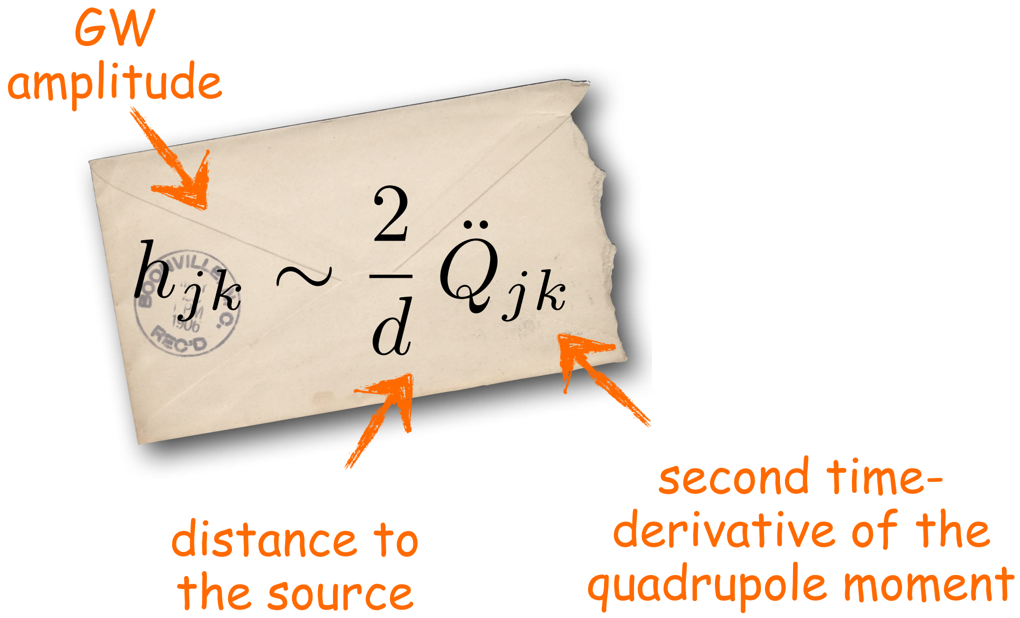


accelerating charges (dipole moment) → electromagnetic waves

accelerating masses (quadrupole moment) → gravitational waves



Expected sources of gravitational waves

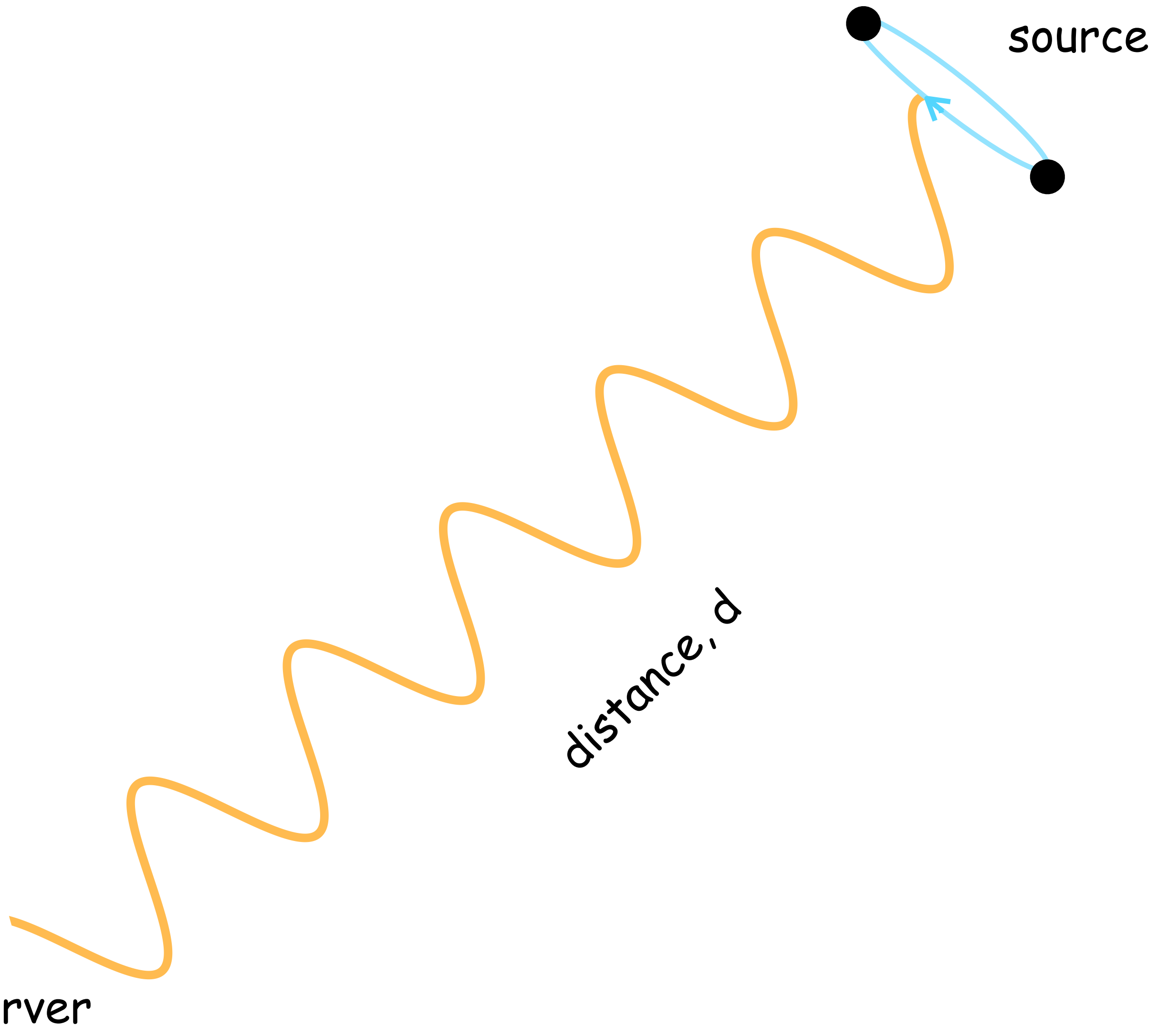


GW amplitude

$$h_{jk} \sim \frac{2}{d}\ddot{Q}_{jk}$$

distance to the source

second time-derivative of the quadrupole moment



$$g_{jk} \simeq \eta_{jk} + h_{jk}$$

Expected sources of gravitational waves

reduced-
mass of the
source

"compactness"
of the source

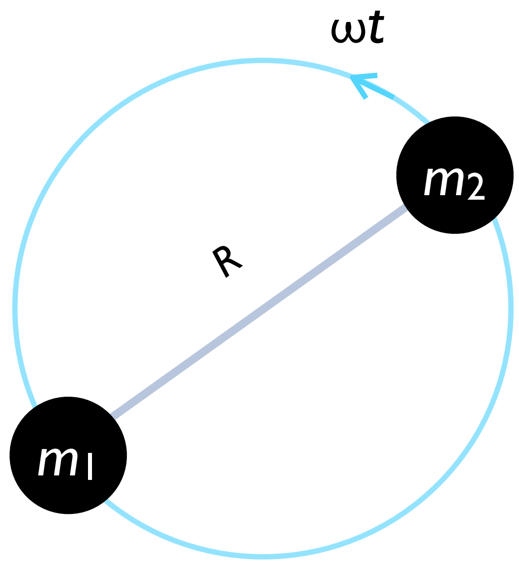
frequency of
the source

$$h_{jk} \sim \frac{2}{d}\,\ddot{Q}_{jk} \quad \sim \left(\frac{G}{c^4}\right)\frac{4\mu}{d}\left(\frac{M}{R}\right)\cos 2\,\omega t$$

10^{-45}!

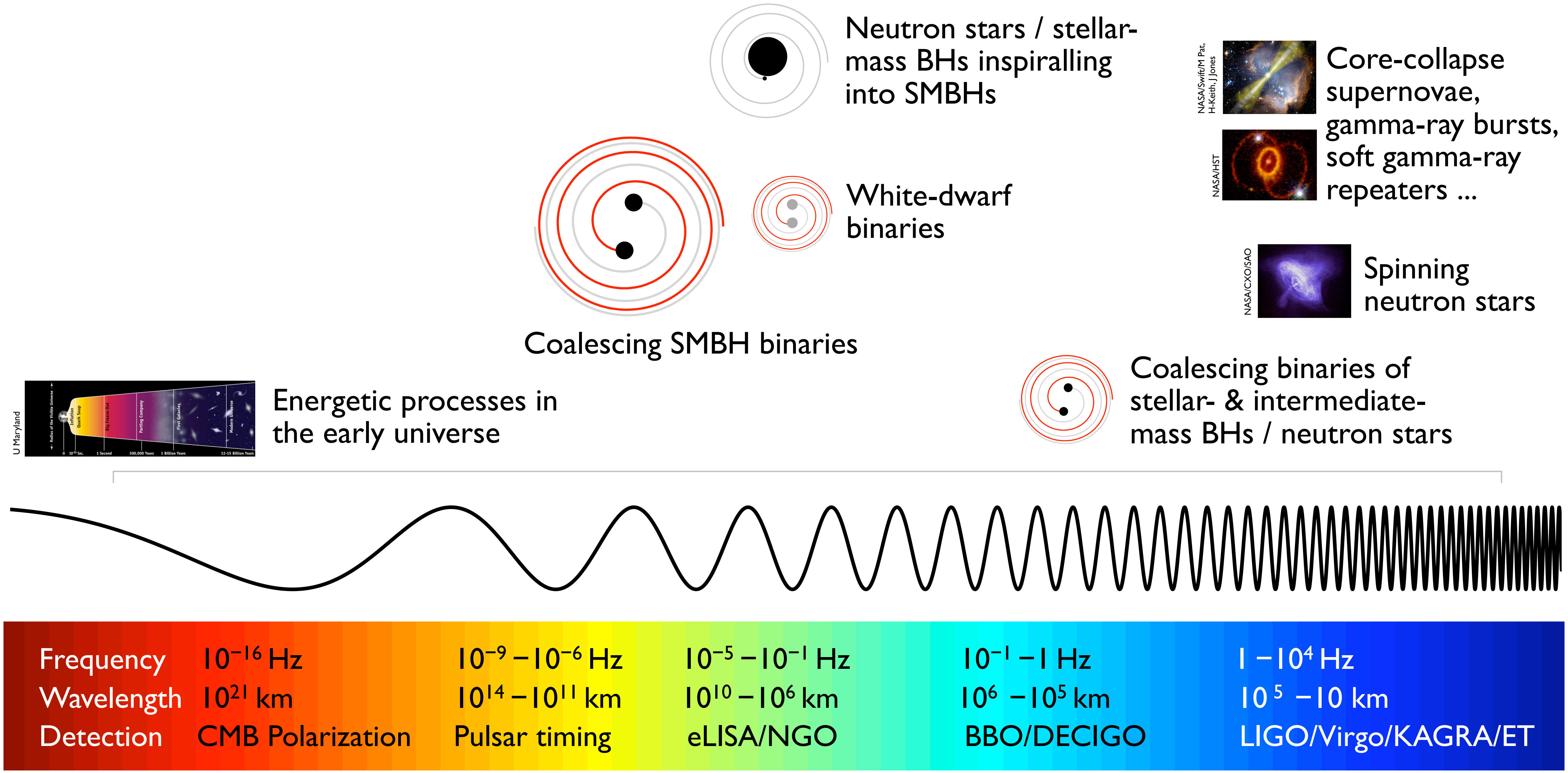
Keplerian v^2

Most promising sources are **relativistic** phenomena involving **massive** and **compact** objects



$M = m_1 + m_2$

Expected sources of gravitational waves



Neutron stars / stellar-mass BHs inspiralling into SMBHs

Core-collapse supernovae, gamma-ray bursts, soft gamma-ray repeaters ...

NASA/Swift/M Pat, H-Keith, J Jones

NASA/HST

White-dwarf binaries

Spinning neutron stars

NASA/CXO/SAO

Coalescing SMBH binaries

Energetic processes in the early universe

U Maryland

Coalescing binaries of stellar- & intermediate-mass BHs / neutron stars

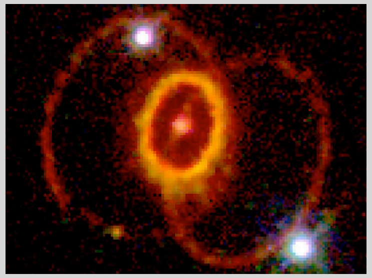
Frequency	10^{-16} Hz	$10^{-9} - 10^{-6}$ Hz	$10^{-5} - 10^{-1}$ Hz	$10^{-1} - 1$ Hz	$1 - 10^{4}$ Hz
Wavelength	10^{21} km	$10^{14} - 10^{11}$ km	$10^{10} - 10^{6}$ km	$10^{6} - 10^{5}$ km	$10^{5} - 10$ km
Detection	CMB Polarization	Pulsar timing	eLISA/NGO	BBO/DECIGO	LIGO/Virgo/KAGRA/ET

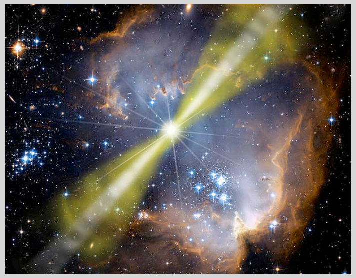
Expected sources of gravitational waves

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

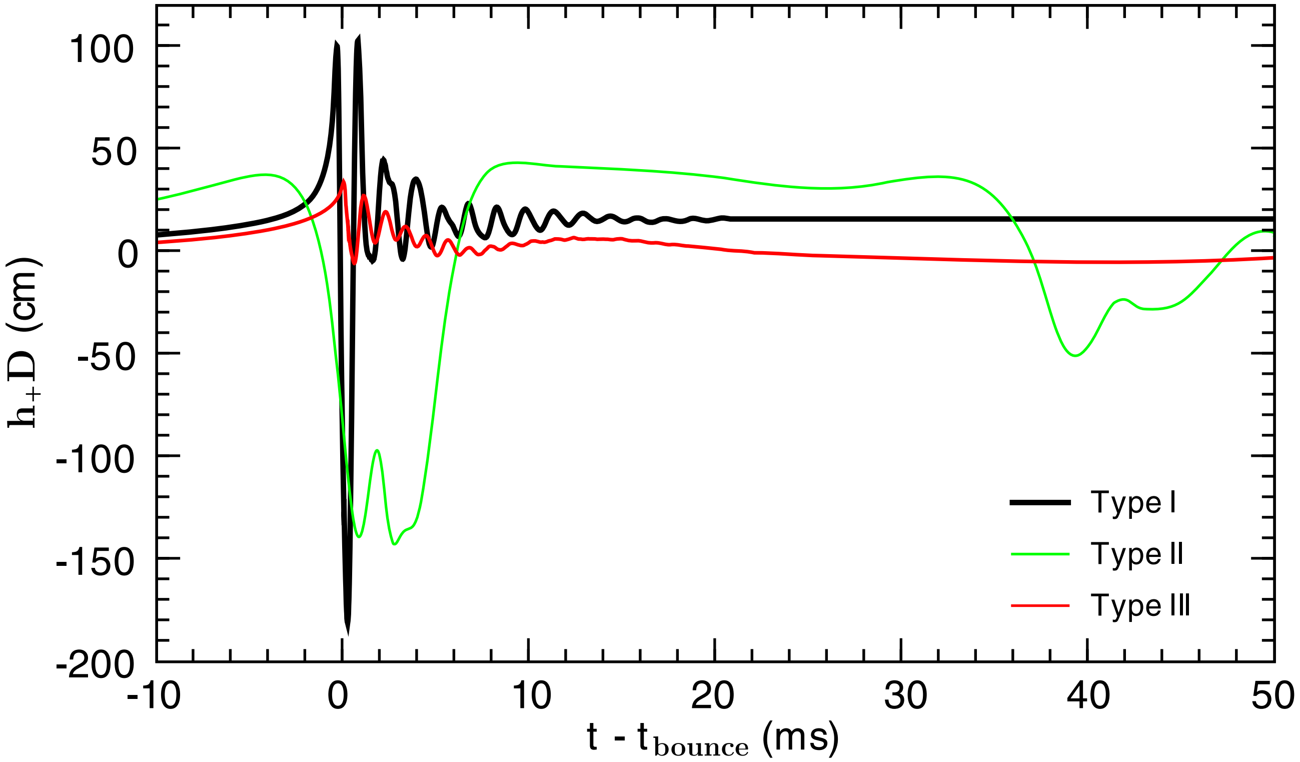
leaves behind
a compact object
(black hole or neutron star)

may also produce a
supernova/long GRB





[Dimmelmeier et al (2002)]

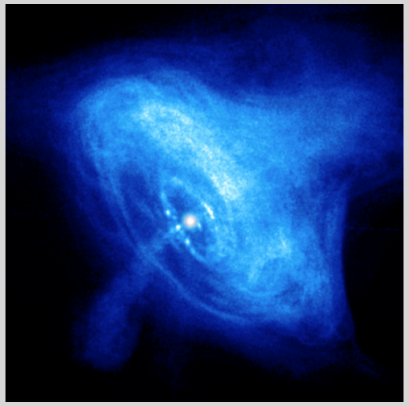


$$E_{\rm GW} = 10^{-12} - 10^{-4}\ M_\odot\, c^2$$

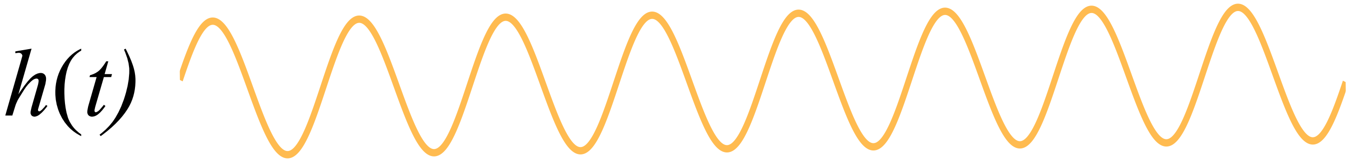
Expected sources of gravitational waves

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

Asymmetric collapse can leave the newly born neutron star highly spinning.



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

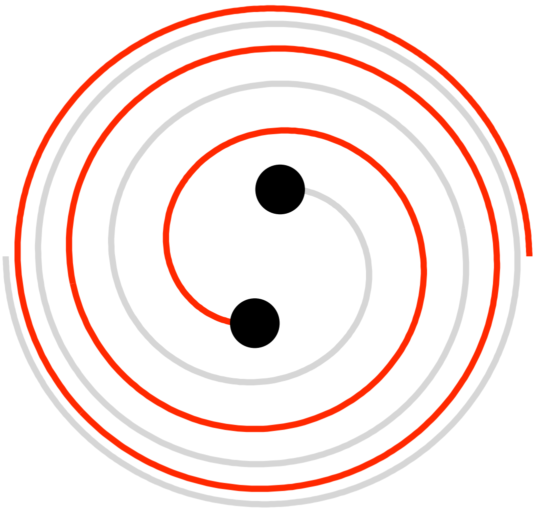


will get Doppler modulated by the motion and spin or the earth.

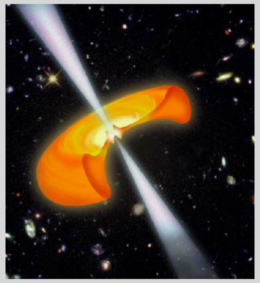
Expected sources of gravitational waves

[Seminar Tomorrow]

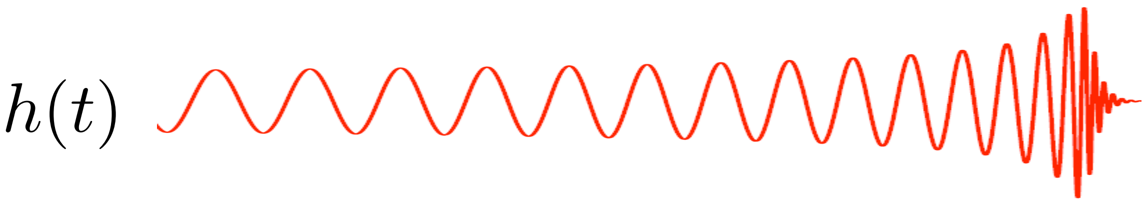
- **Burst sources** Collapse of massive stellar cores can produce a burst of GWs
- **Continuous sources** Spinning neutron stars with non-axisymmetric deformations.
- **Compact binary coalescences** driven by GW emission.



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

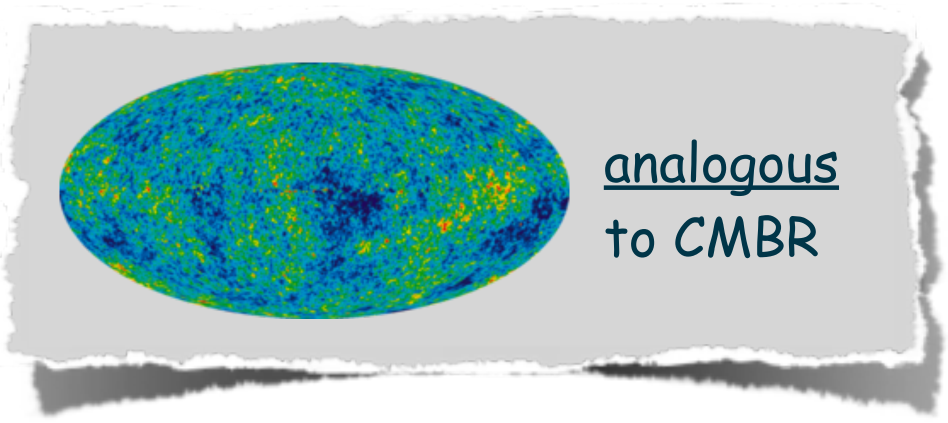


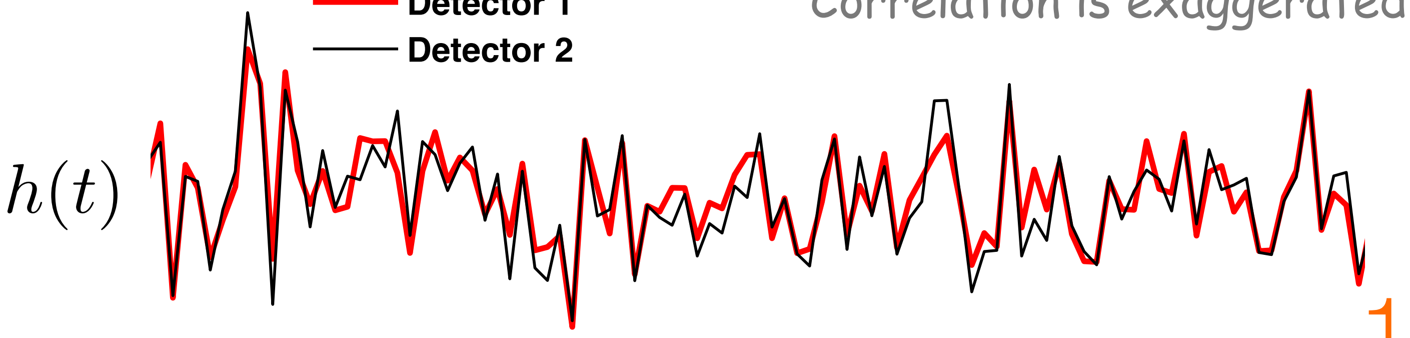
merger (involving NS) might also produce a short GRB



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.

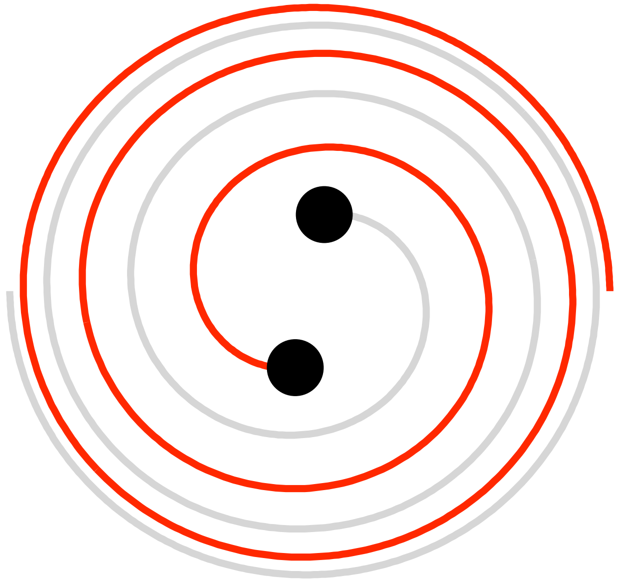




Correlation is exaggerated

Observational evidence for the existence of GWs

- Binary neutron stars lose their orbital energy by GW emission and starts to “inspiral”.



Observational evidence for the existence of GWs

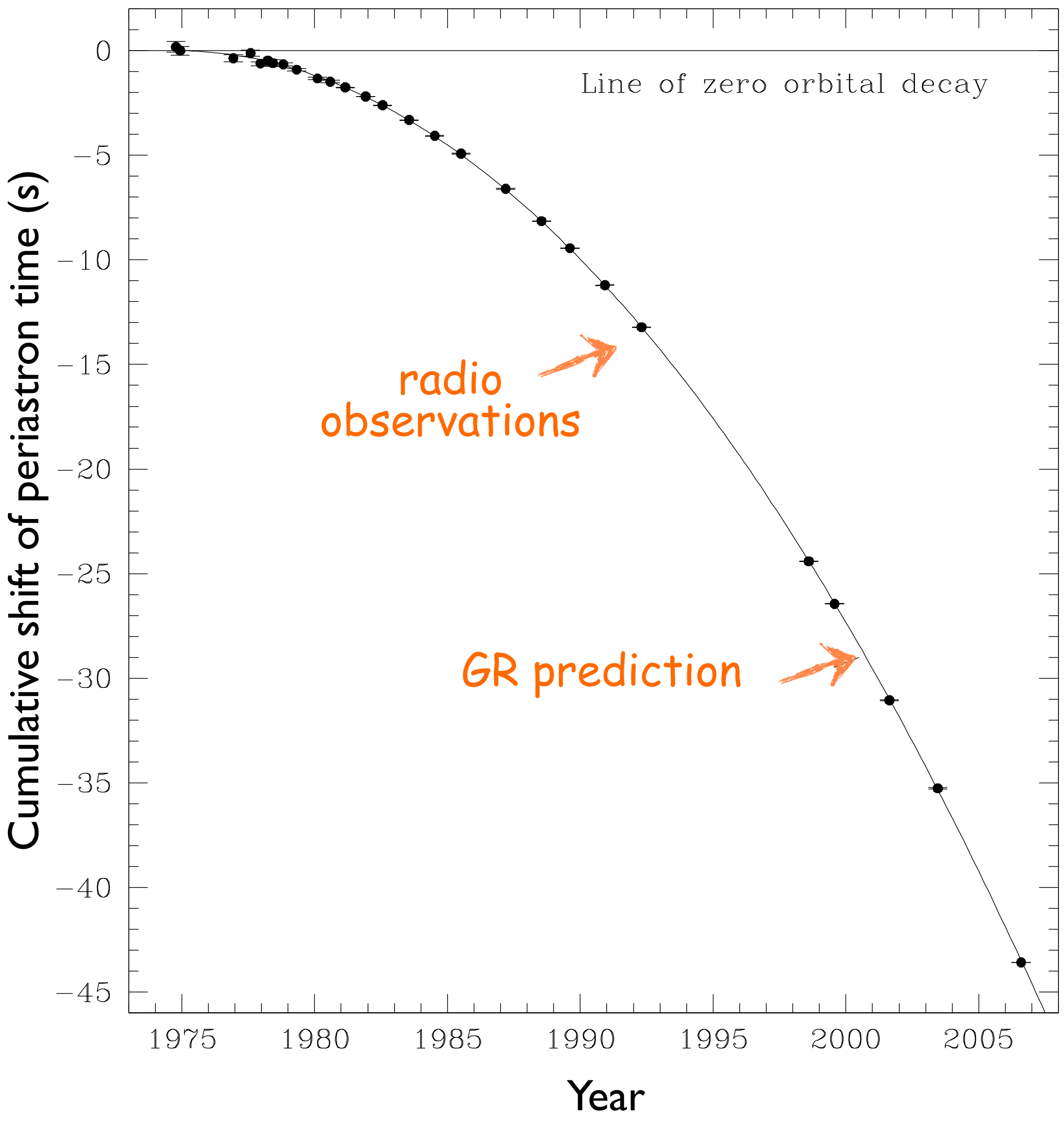
- Binary neutron stars lose their orbital energy by GW emission and starts to “inspiral”.
- 36 years of radio observations of the binary pulsar PSR B1913+16 → Decay of the orbital period agrees precisely with GR prediction.

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)]

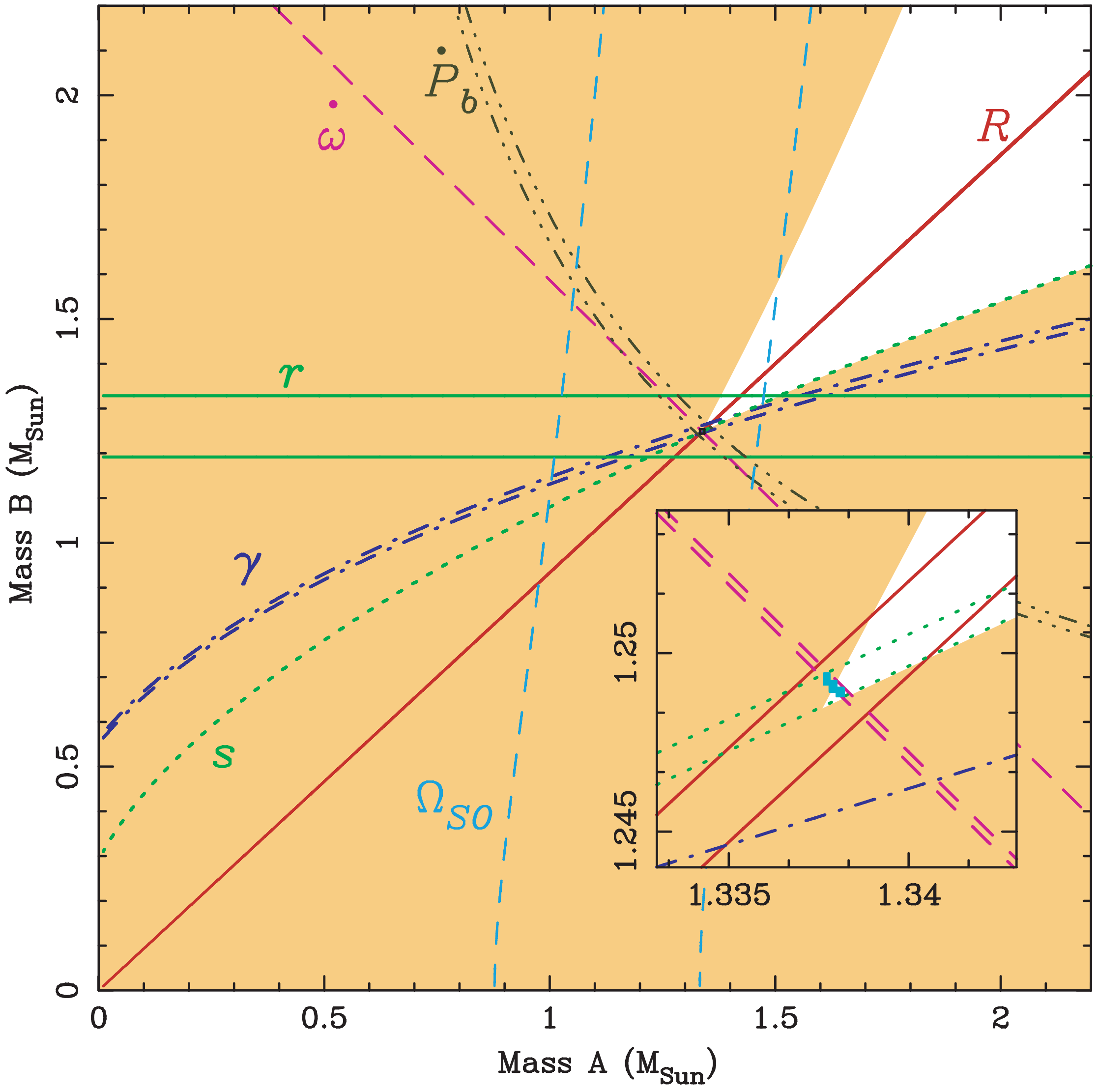


Observational evidence for the existence of GWs

- Binary neutron stars lose their orbital energy by GW emission and starts to “inspiral”.
- 36 years of radio observations of the binary pulsar PSR B1913+16 ➞ Decay of the orbital period agrees precisely with GR prediction.
- More binaries discovered later (including a double pulsar) ➞ further confirmation.

$$\dot{P}_b = (1.003 \pm 0.014)\,\dot{P}_b^{\mathrm{GR}}$$

[Kramer & Wex (2009)]

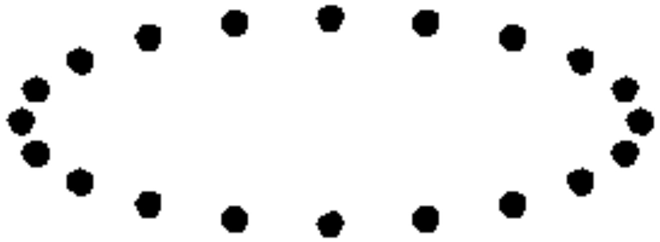


Constraints on “Post-Keplerian” parameters from PSR J0737-3039

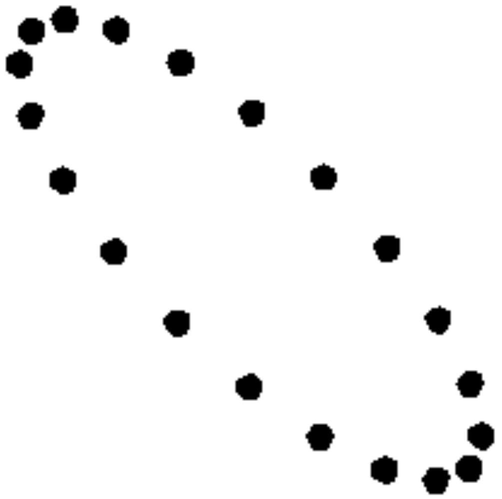
Detection of GWs: Laser interferometers

- **GWs distort the spacetime geometry:** stretch and squeeze orthogonal (transverse) directions.

"plus" polarization



"cross" polarization



GWs are passing perpendicular to the screen

Detection of GWs: Laser interferometers

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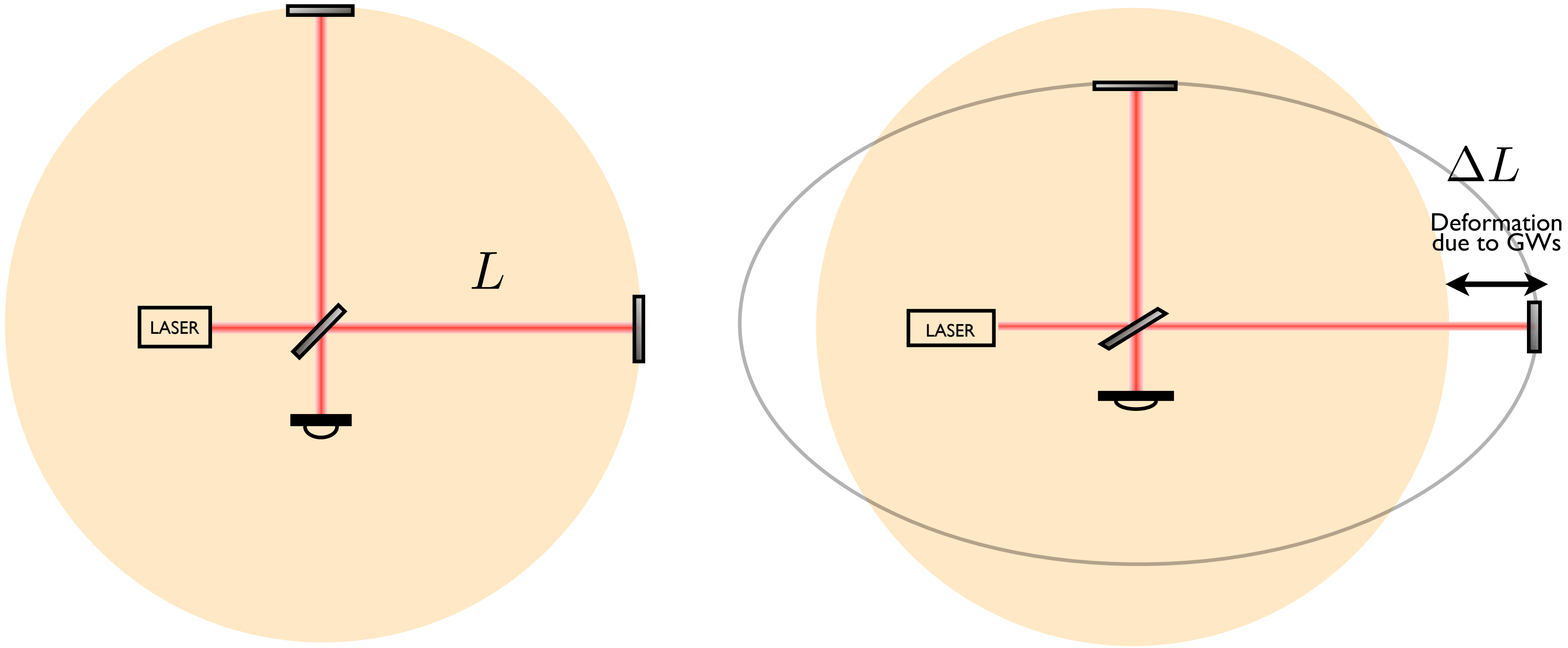


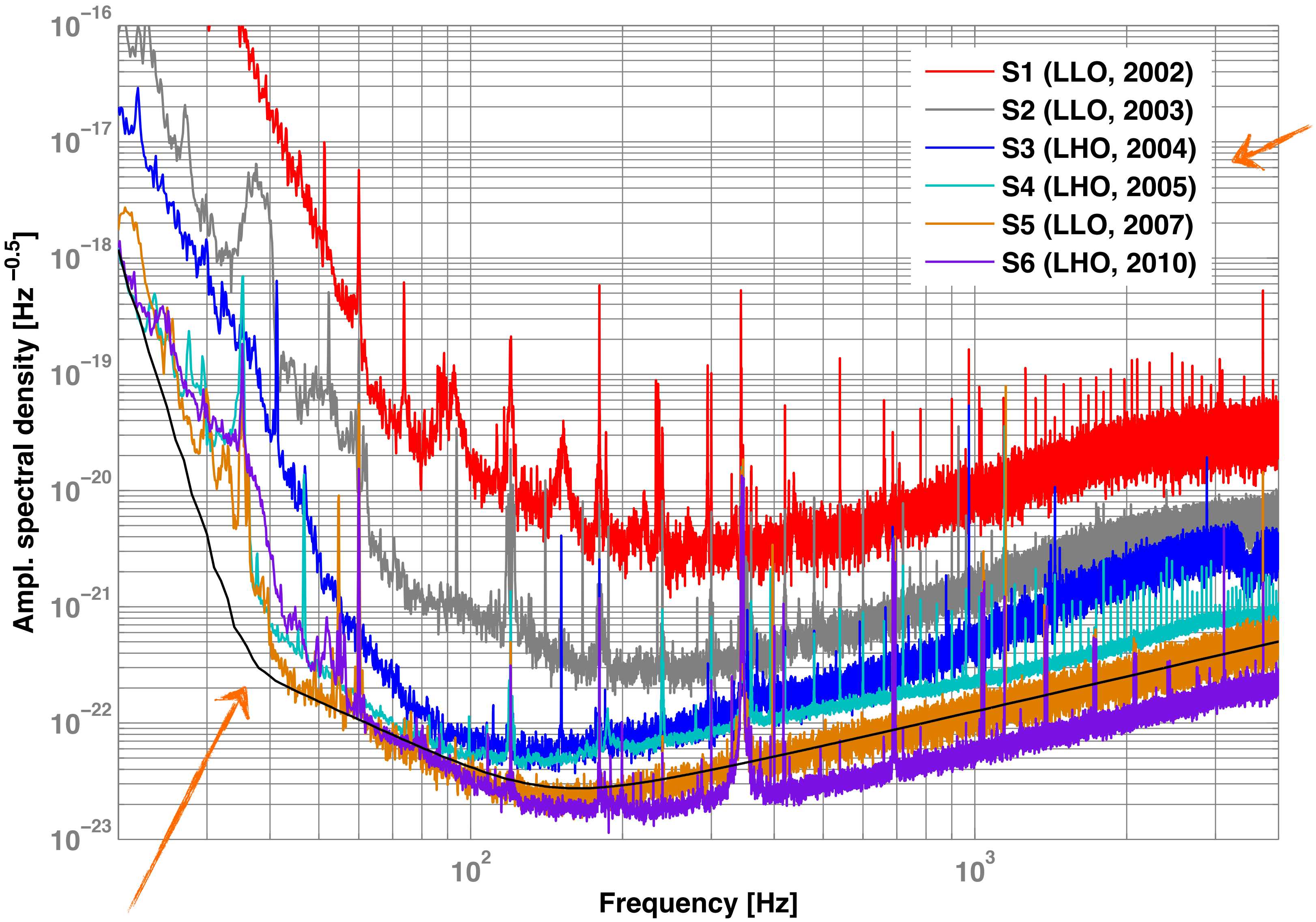
GW strain

Expected distortions are tiny: $h = \dfrac{\Delta L}{L} \sim 10^{-21}$ (BNS inspiral at 20 Mpc)

Required displacement sensitivity of interferometers ($L \sim 1$ km) $10^{-18}\,\mathrm{m}$ (1/1000 size of nucleus)

The experimental challenge

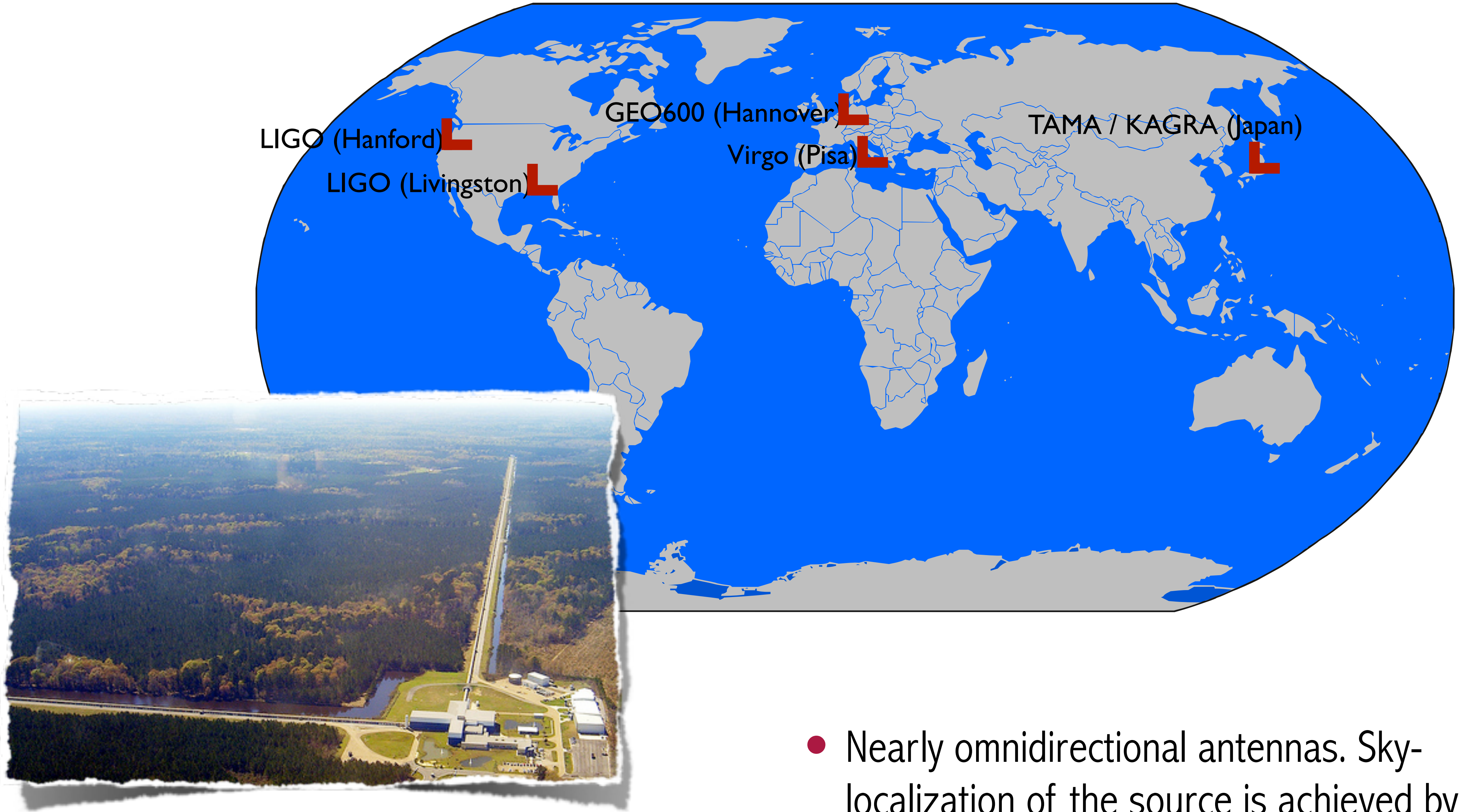
- Initial LIGO detectors achieved their design sensitivity in 2007.



science data taking runs

design sensitivity

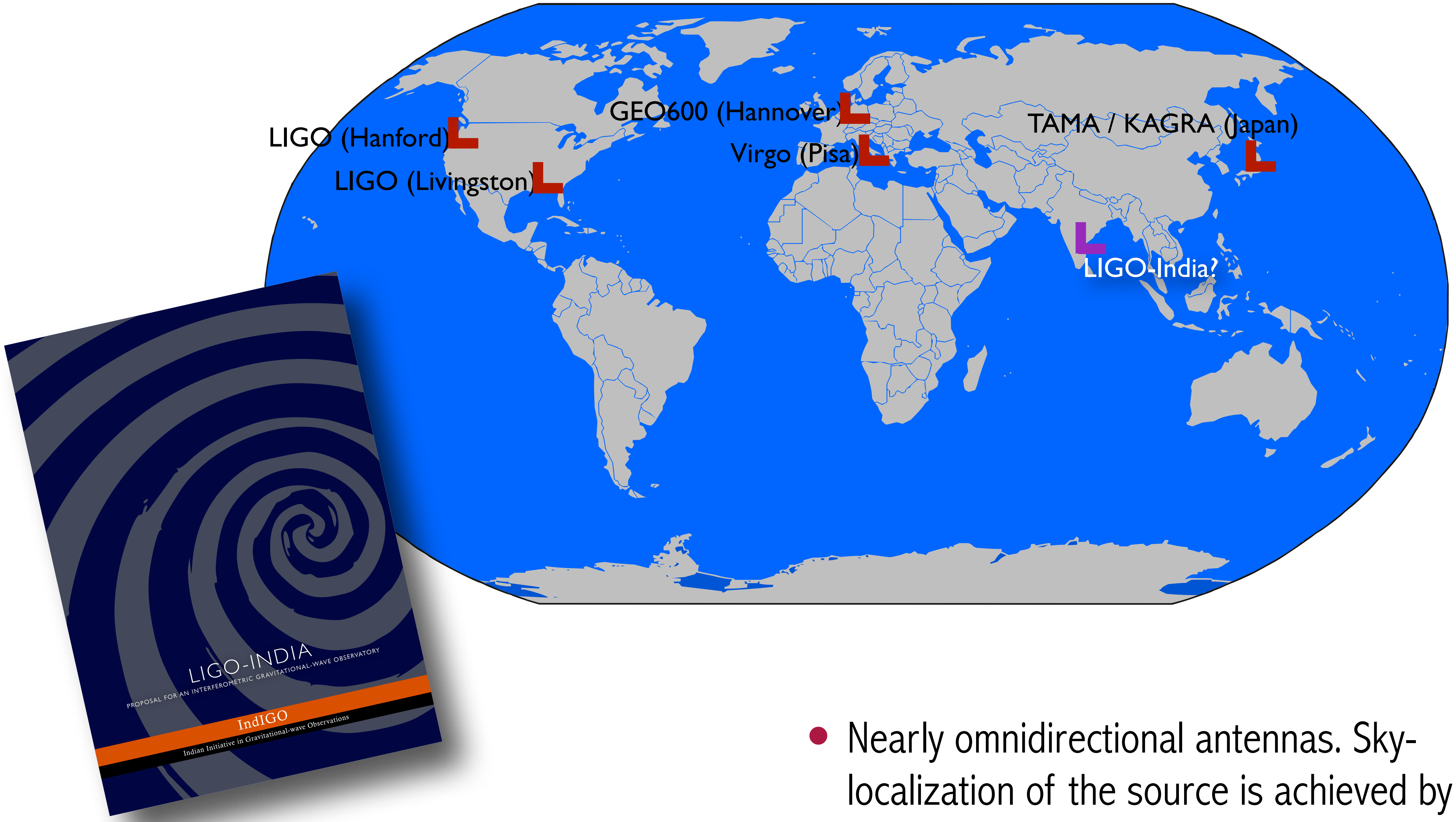
Worldwide network of GW observatories



LIGO (Livingston)

- Nearly omnidirectional antennas. Sky-localization of the source is achieved by “aperture synthesis”.

Worldwide network of GW observatories



LIGO-INDIA

PROPOSAL FOR AN INTERFEROMETRIC GRAVITATIONAL-WAVE OBSERVATORY

IndIGO

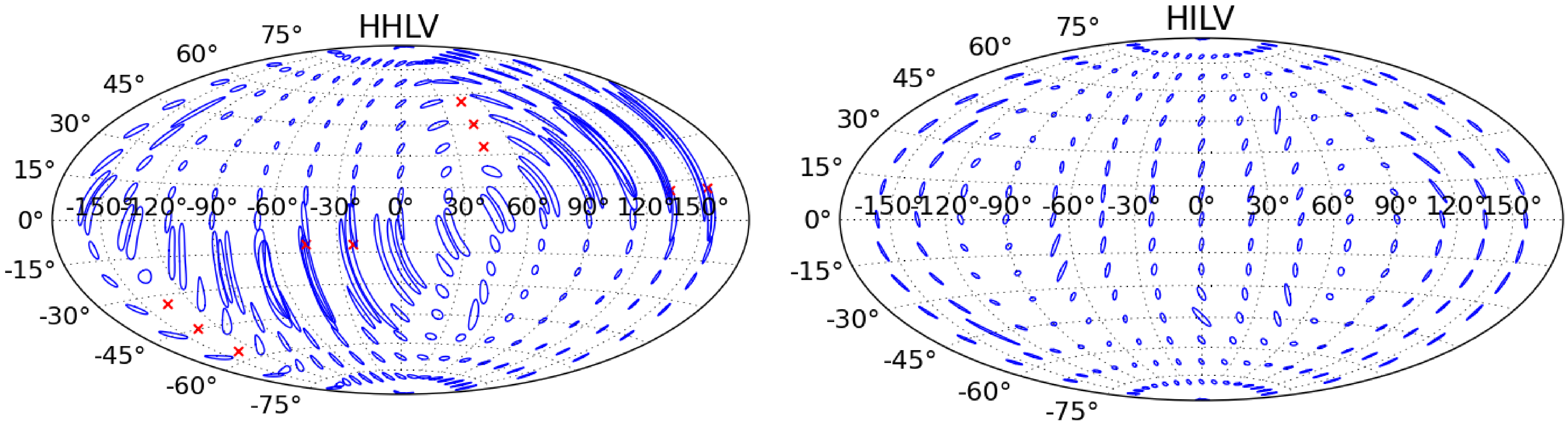
Indian Initiative in Gravitational-wave Observations

http://www.gw-indigo.org/ligo-india

- Nearly omnidirectional antennas. Sky-localization of the source is achieved by "aperture synthesis".

LIGO-India

- **LIGO-India** ⇒ significant improvement in angular resolution, sky coverage & duty cycle of the network.



[Fairhurst (2012)]

sky localization: imperative for multi-messenger astronomy

angular resolution ∝ baseline of the network

The data analysis challenge

- Signals are rare, weak, and buried in the noise.
  Need sophisticated data analysis techniques.

similar challenge as in searches for dark
matter particles, high-energy neutrinos etc.

but several GW sources can be accurately
modeled by analytical/numerical GR.

The data analysis challenge

- Signals are rare, weak, and buried in the noise. Need sophisticated data analysis techniques.

Matched filter

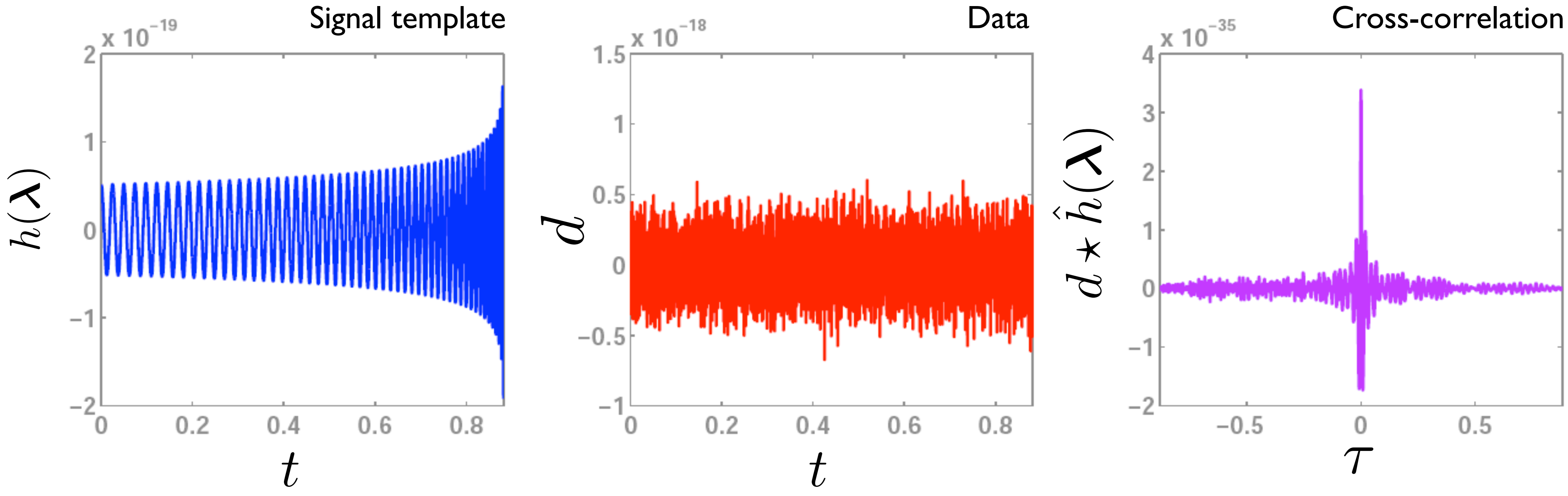
$$\rho \equiv \max_{\boldsymbol{\lambda}} \left[d \star \hat{h}(\boldsymbol{\lambda}) \right]$$

SNR

data

signal template

source parameters



The data analysis challenge

- Signals are rare, weak, and buried in the noise.
  Need sophisticated data analysis techniques.

$$\rho \equiv \max_{\boldsymbol{\lambda}} \left[d \star \hat{h}(\boldsymbol{\lambda}) \right]$$

source parameters

for many searches, exploration of the full parameter space is computationally limited.

e.g. search for unknown pulsars, coalescing compact binaries with significant spins etc.

Solutions:

- **Unknown pulsars:** Volunteer computing [Einstein@Home project]
- **Spinning compact binaries:** Find “approximate descriptions” of the source and hence reduce the dimensionality of the parameter space [Seminar Tomorrow]

The data analysis challenge

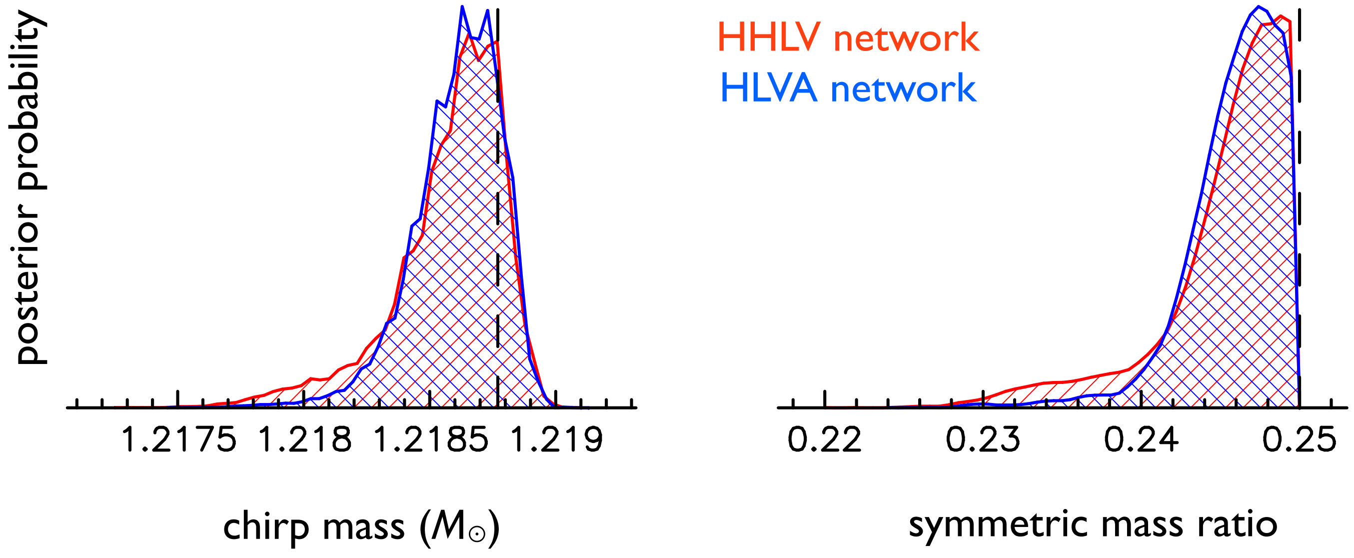
- Signals are rare, weak, and buried in the noise. Need sophisticated data analysis techniques.
- Posterior distribution of the source parameters can be estimated by Bayesian inference.

prior distribution of parameter λ

$$p(\boldsymbol{\lambda}|d) \propto p^0(\boldsymbol{\lambda})\,\mathcal{L}(d|\boldsymbol{\lambda})$$

posterior distribution of λ, given data d

likelihood of d, given λ

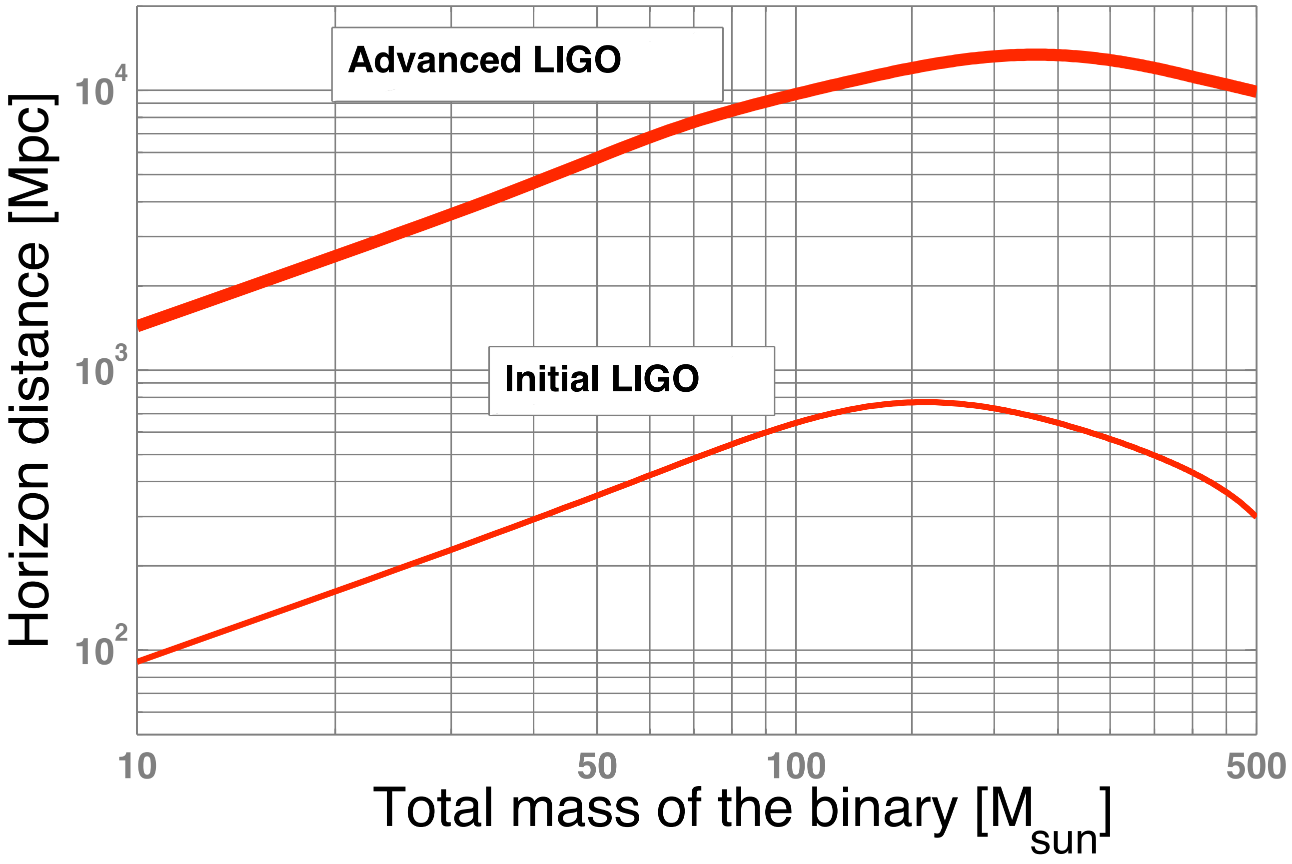


[Veitch et al (2012)]

Status of gravitational-wave detection

- No detection of GWs so far. The non-detection is consistent with the astrophysical expectations.
    - Several interesting upper limits on GW emission [www.ligo.org].
- Detectors are being upgraded to their "advanced" configurations (10x improvement in sensitivity). Expected operation by ~2015.

[Ajith et al (2008)]



GW detectors are amplitude detectors

10x increase in the sensitivity → 1000x improvement in the event rates.

Expected detction rates

[Abadie et al (2010)]

DETECTORS	SOURCES	EXPECTED (MEAN) DETECTION RATE
Initial detectors	NS-NS Binaries	1 per 50 years
	NS-BH Binaries	1 per 250 years
	BH-BH Binaries	1 per 140 years
Advanced detectors	NS-NS Binaries	40 per year
	NS-BH Binaries	10 per year
	BH-BH Binaries	20 per year

Note: Large uncertainties.
Actual rates could be an order of magnitude lower or higher!

Physics, Astrophysics and Cosmology from GW observations

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

Physics, Astrophysics and Cosmology from GW observations

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

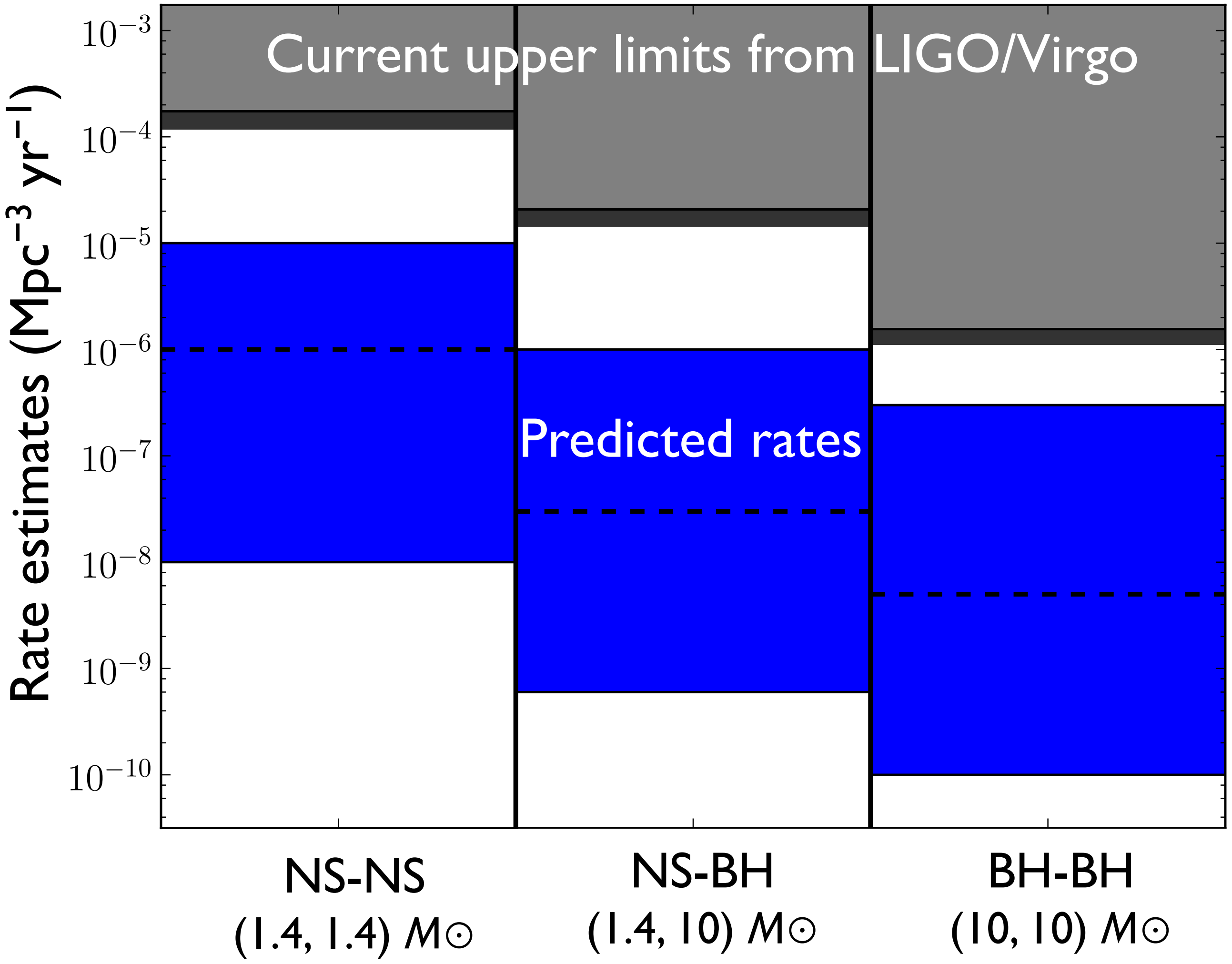
GWs and EMWs carry qualitatively different information

- GWs are produced by coherent bulk motions of massive sources.
- EMWs are produced by incoherent motions of a large number of small sources.

Astrophysics using GW observations

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

[Abadie et al (2012)]



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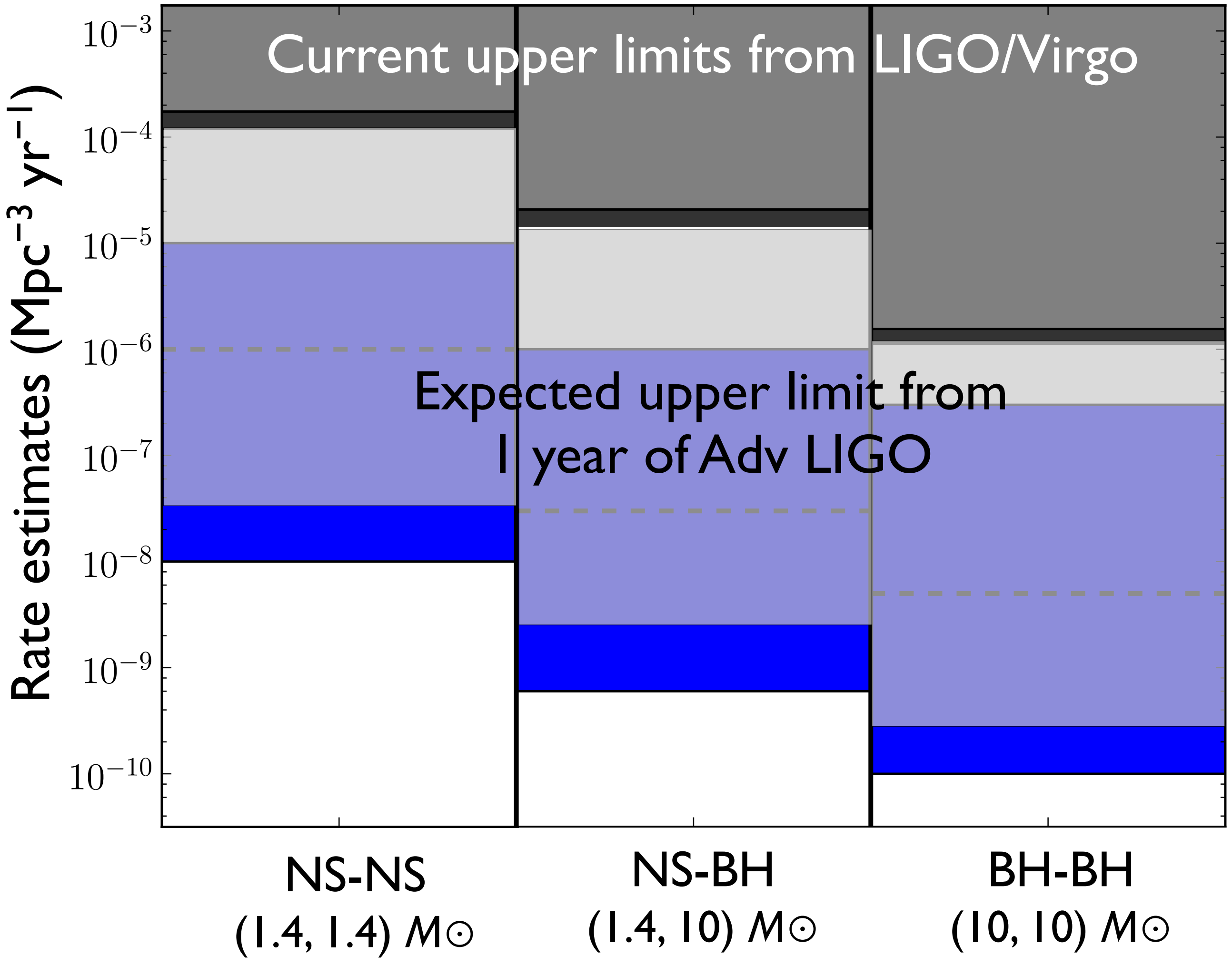

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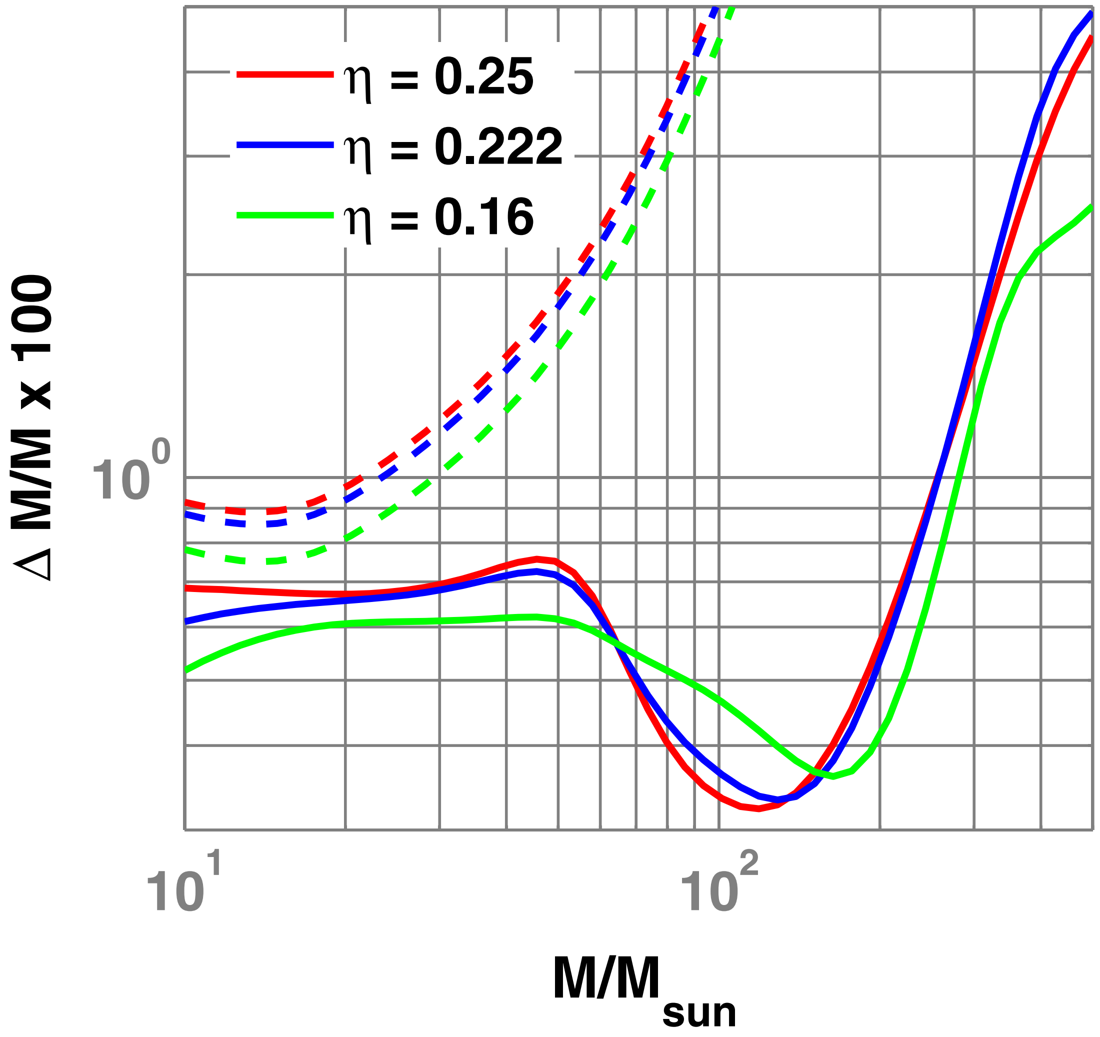
- **First detection of BH-BH and NS-BH binaries** A new population of astronomical sources. Great potential for tests of GR, astrophysics & cosmology.

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)]

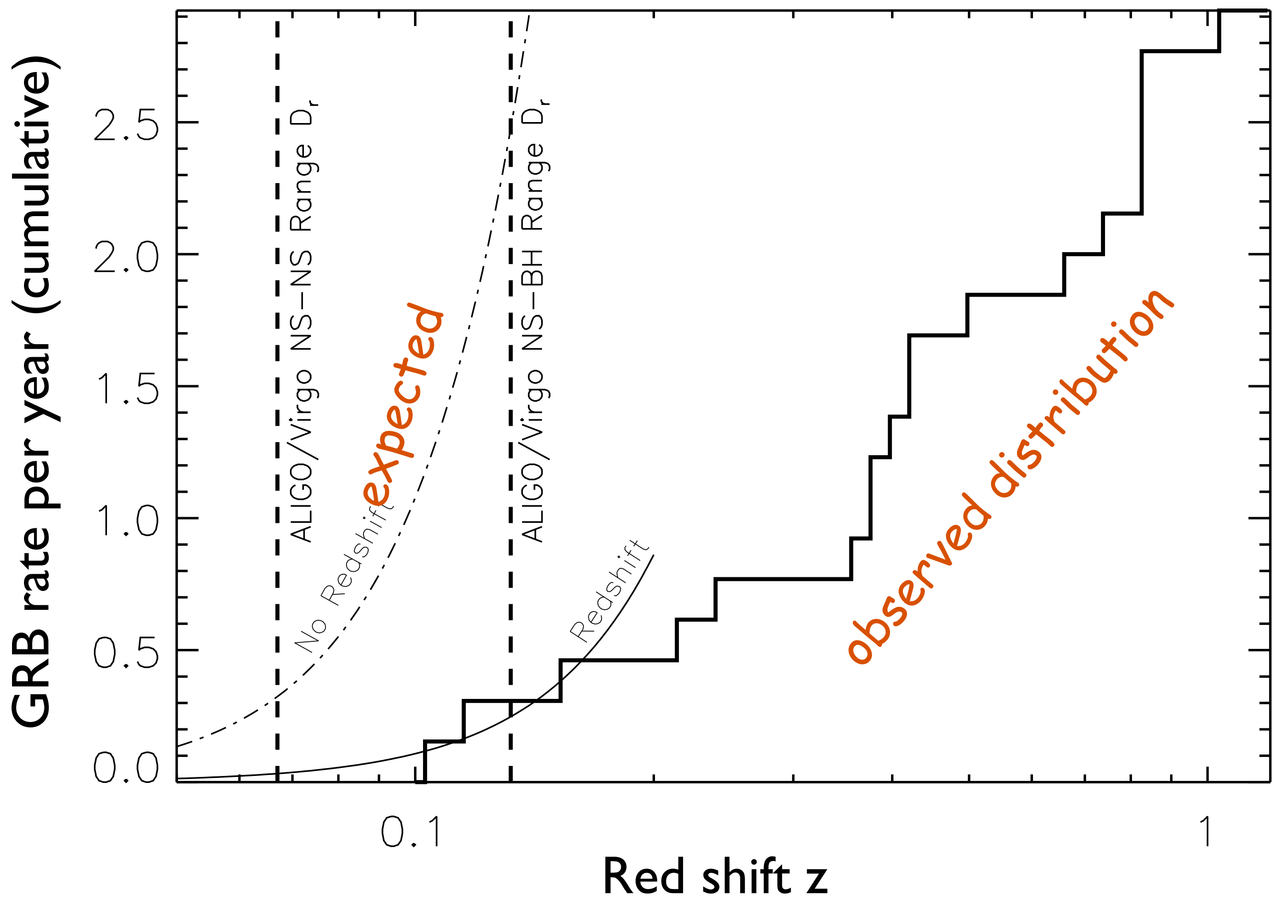


1-σ error in measuring the total mass of BBHs located at 1 Gpc (Adv LIGO)

Astrophysics using GW observations

- **Test sGRB-GW association** Short-hard GRBs are hypothesized to be powered by compact-binary mergers. One unique coincident GRB-GW observation will shed light on this.
  - Only 2/19 of the observed SGRBs are localized to z ≲ 0.2. BUT, only 1/3 of the observed GRBs has enabled z determination!

[Metzger & Berger (2011)]

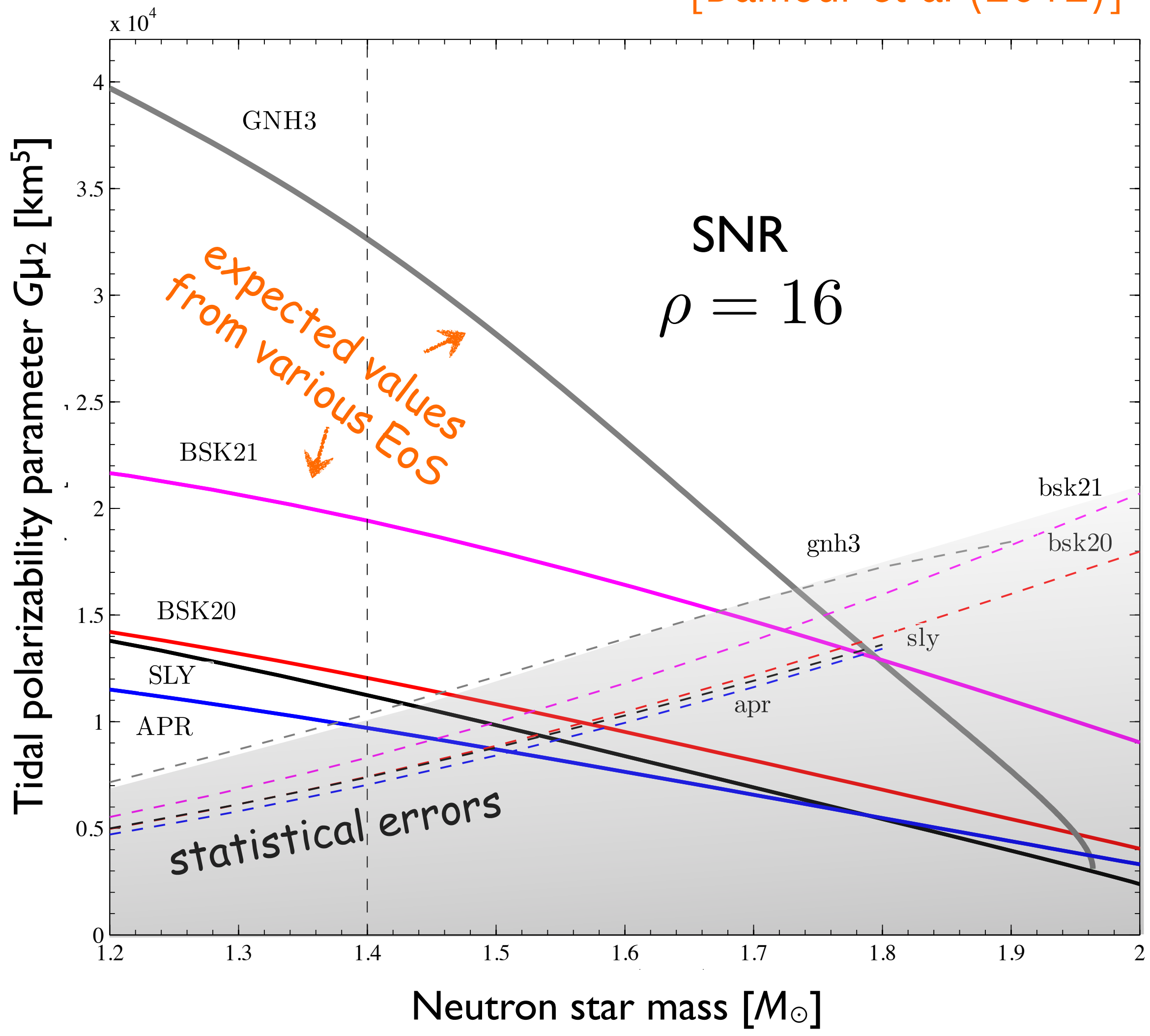


Observed & expected distribution of SGRBs (Swift)

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: ~5 BNS & 1 NSBH events 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. 3G detectors will make very accurate measurements.

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].

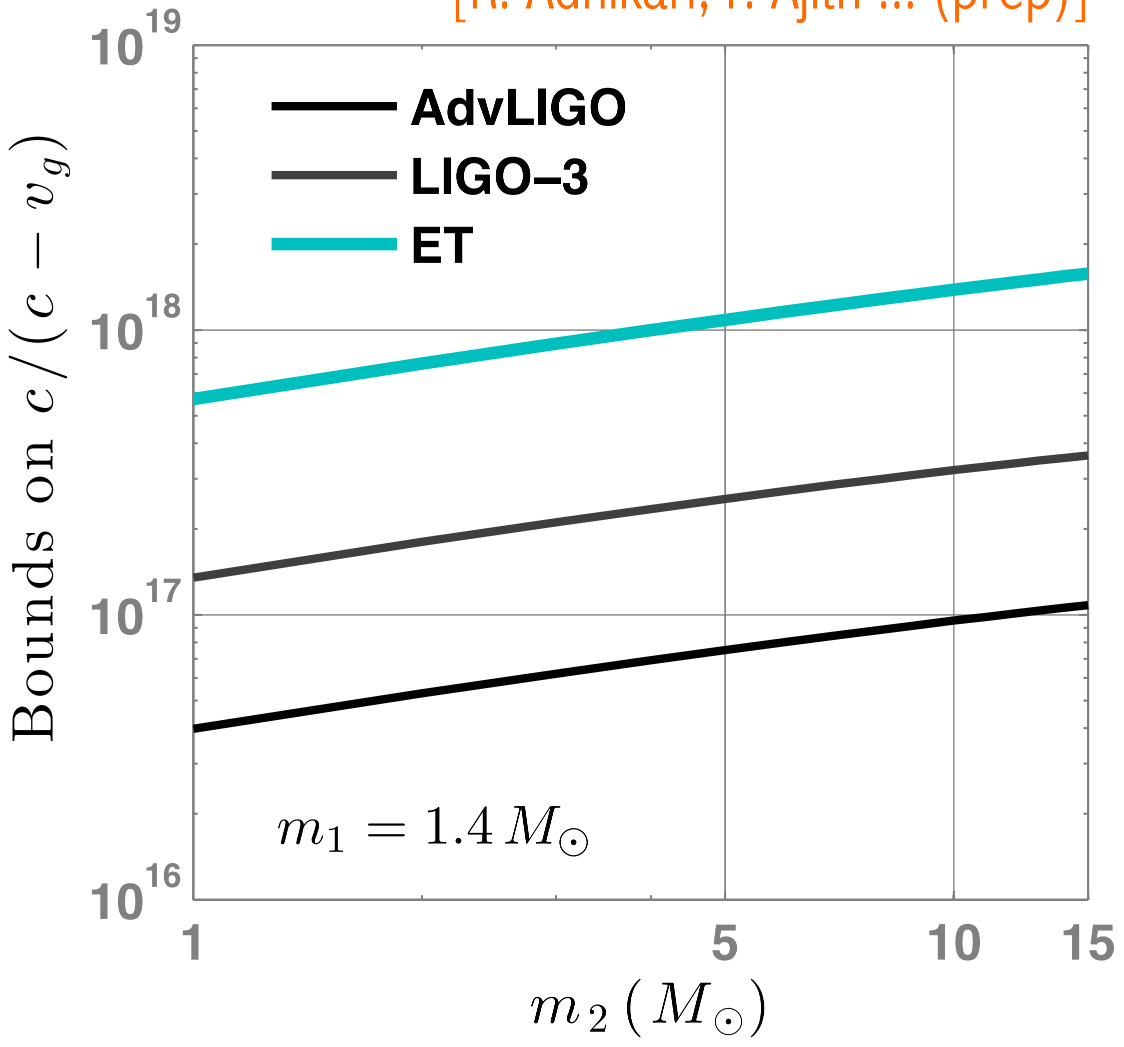
distance to the source

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

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.)

[R. Adhikari, P. Ajith ... (prep)]



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

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- **Mass of the graviton** A bound on v_g implies a bound on the graviton-mass [Will 1998].

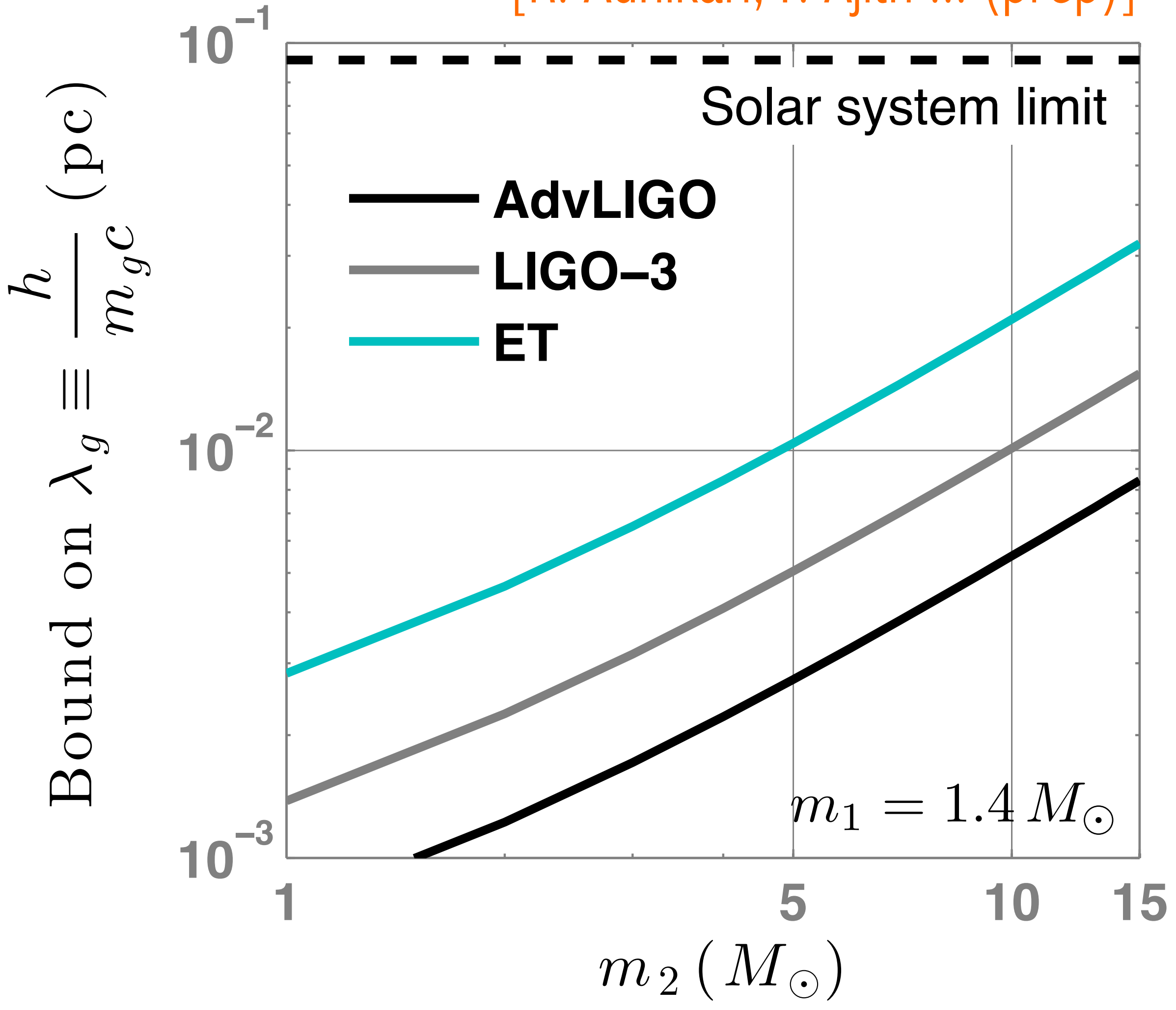
Dispersion relation

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

speed of GWs
(v_g= c in GR)

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

energy of
the graviton


[R. Adhikari, P. Ajith ... (prep)]

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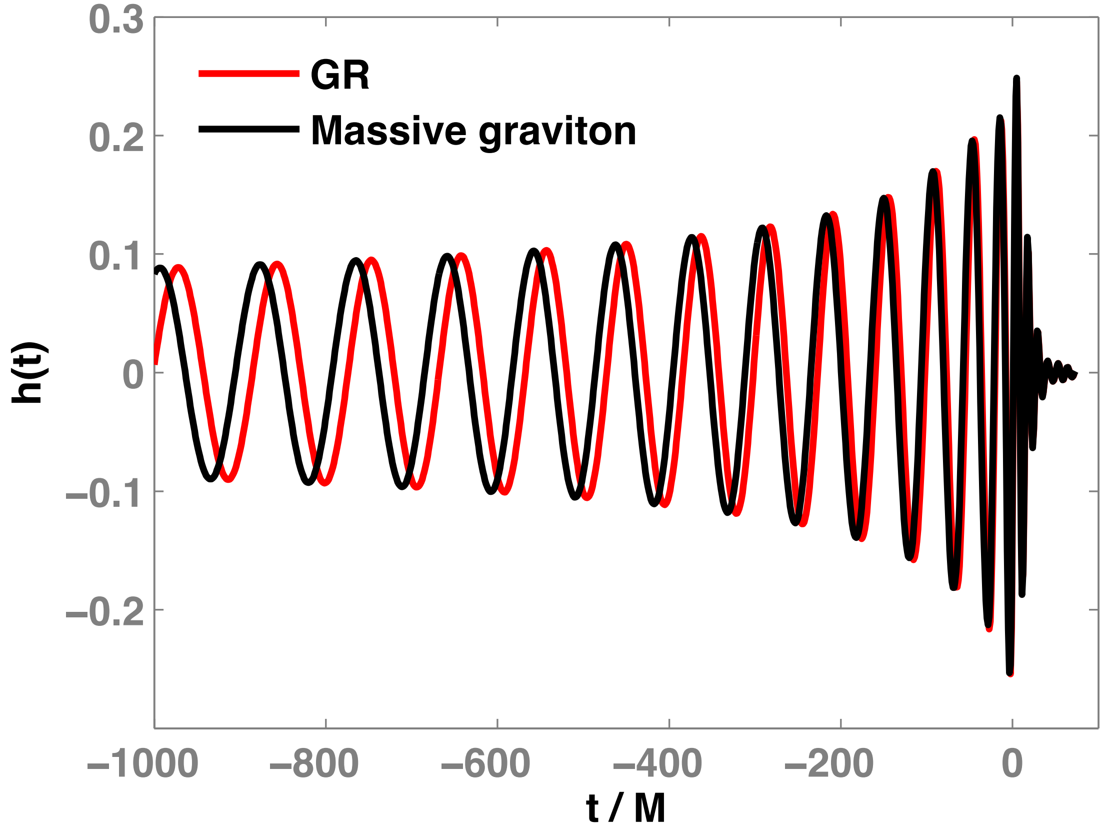
- **Mass of the graviton** A bound on v_g implies a bound on the graviton-mass [Will 1998].
  - GW observations of CBCs can constrain the mass of graviton without relying on an EM counterpart.

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

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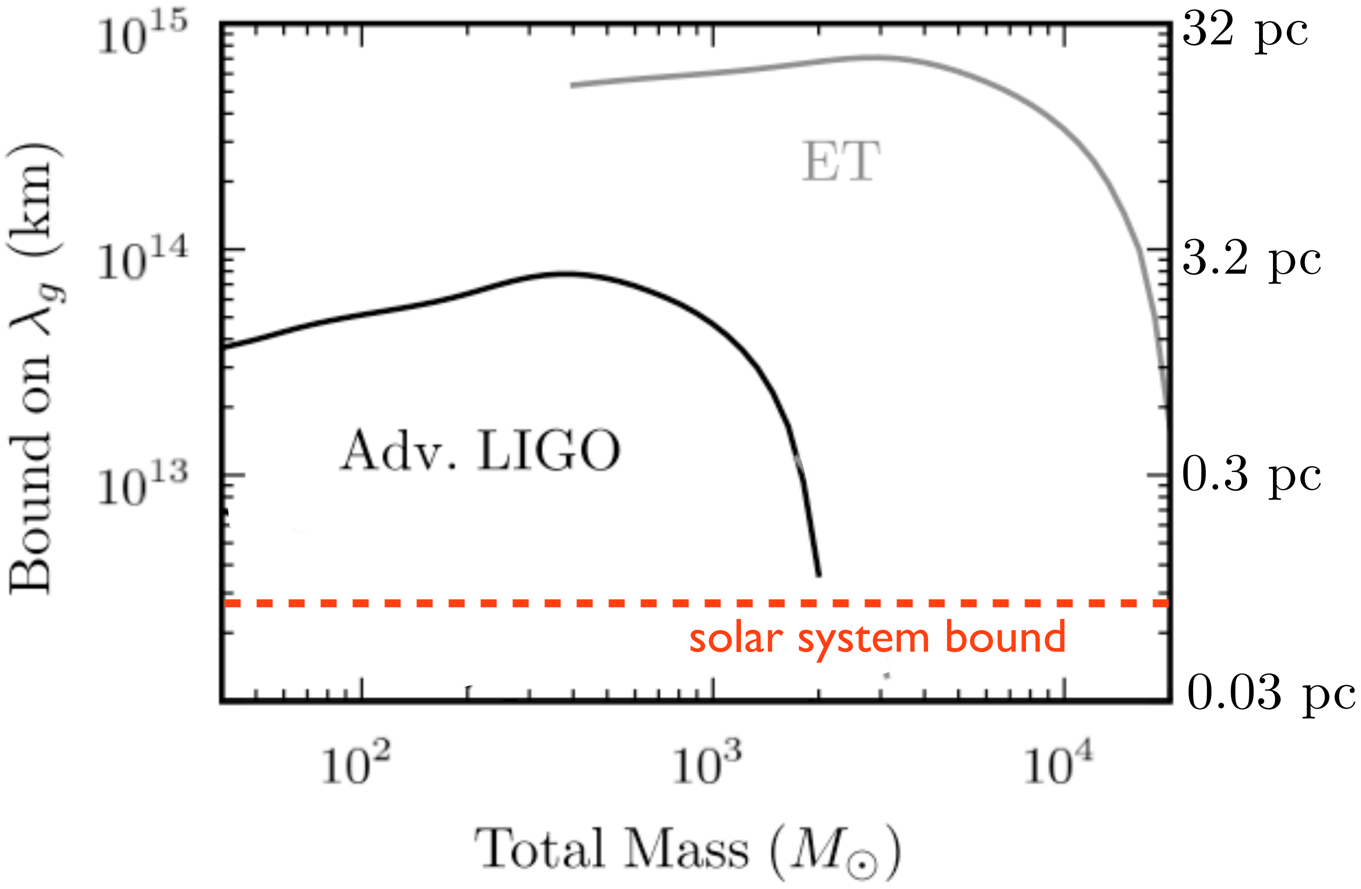
    - GW observations of CBCs can constrain the mass of graviton without relying on an EM counterpart.

[Keppel & Ajith (2010)]

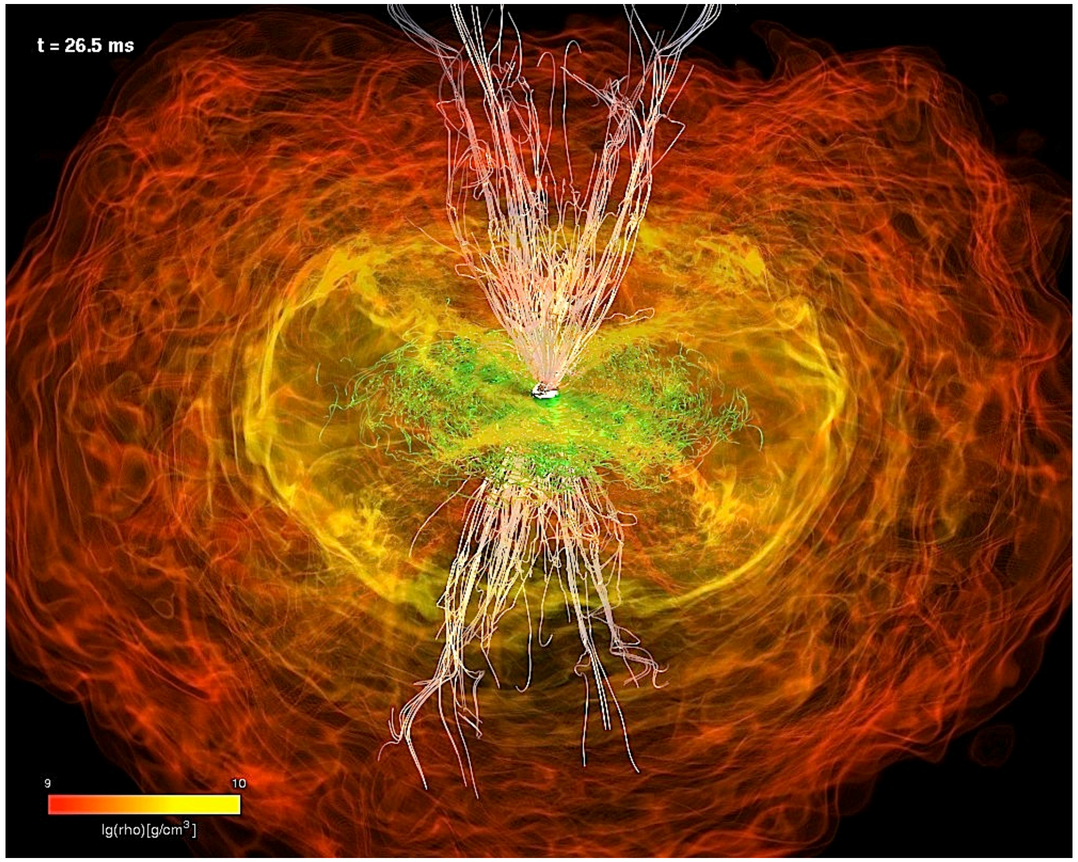


Expected bounds on the Compton wavelength of the graviton from BBH observations by future detectors. (d_L = 1 Gpc)

Cosmology using GW observations

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

[Rezzolla et al (2011)]



GWs

absolute determination of the luminosity distance

EM counterpart

e.g. GRB afterglow → red-shift information

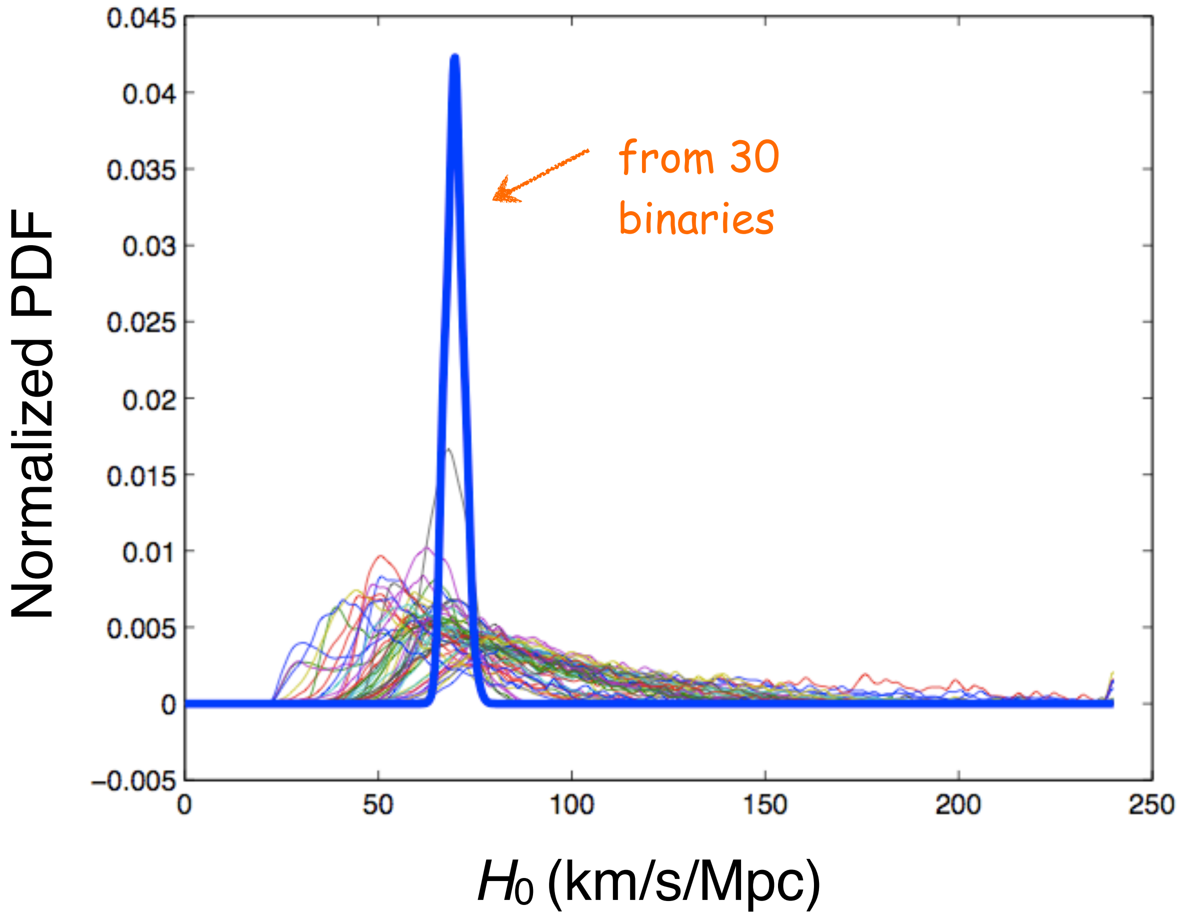
Numerical simulation of the merger of NS-BH binary. Magnetic fields can support GRB jets.

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 detectors: more interesting measurements (comparable to other dark energy missions). [Zhao et al (2011)]

Note: very different systematics!

[S. Nissanke]

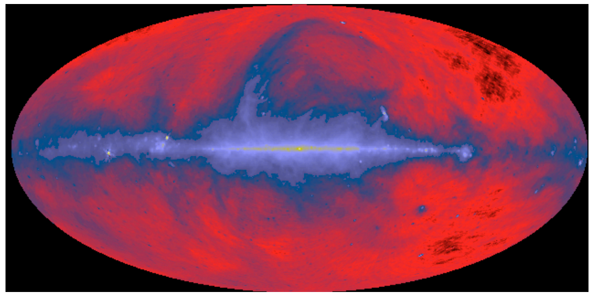


Expected errors on H_0 : 13% (4 detections), 5%(15 detections), 3.4% (30 detections). Using LIGO-Virgo-KAGRA-India network.

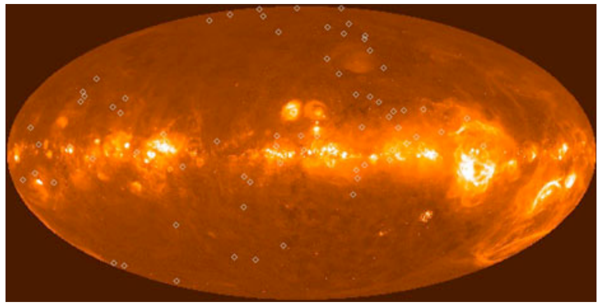
Summary

- Significant progress in the experimental efforts for the first direct detection of GWs. First detections very likely happen over the next 5 years with the advent of the second-generation 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.
- Possibility of LIGO-India is exciting! Significant benefits for GW astronomy. Great potential for the Indian community to be a major player in the field before the big explosion!

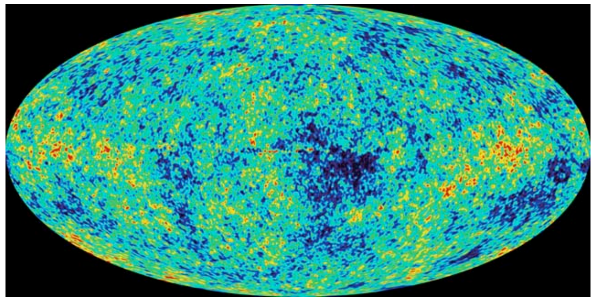
Radio



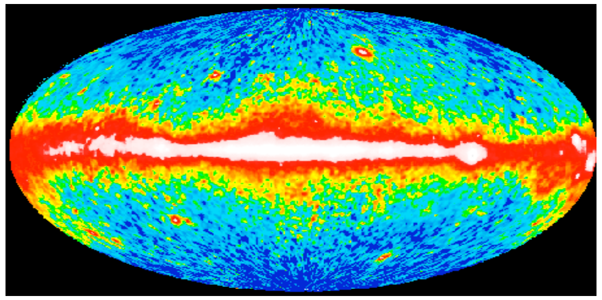
X-ray



Microwave



Gamma-ray



GWs?