Fundamental physics, astronomy and cosmology from gravitational-wave observations

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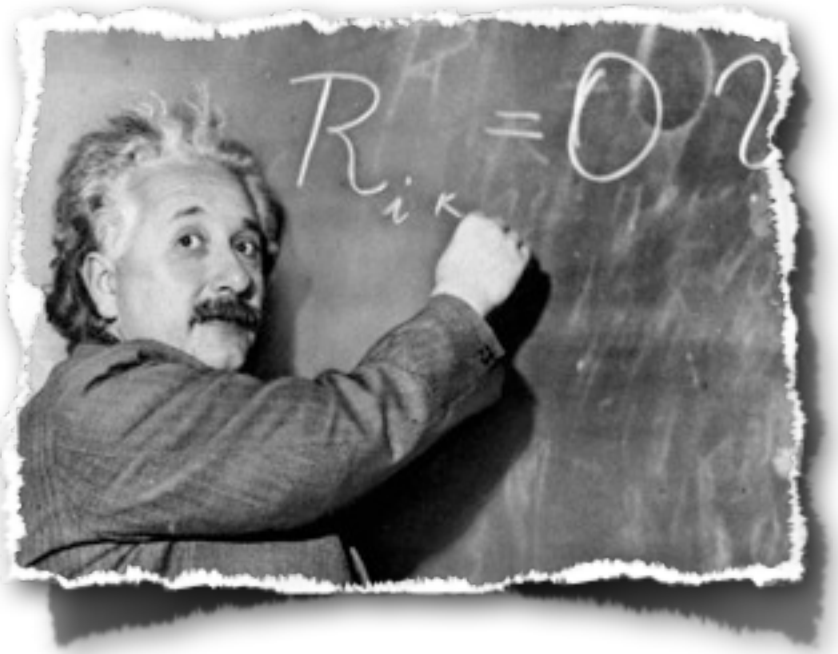
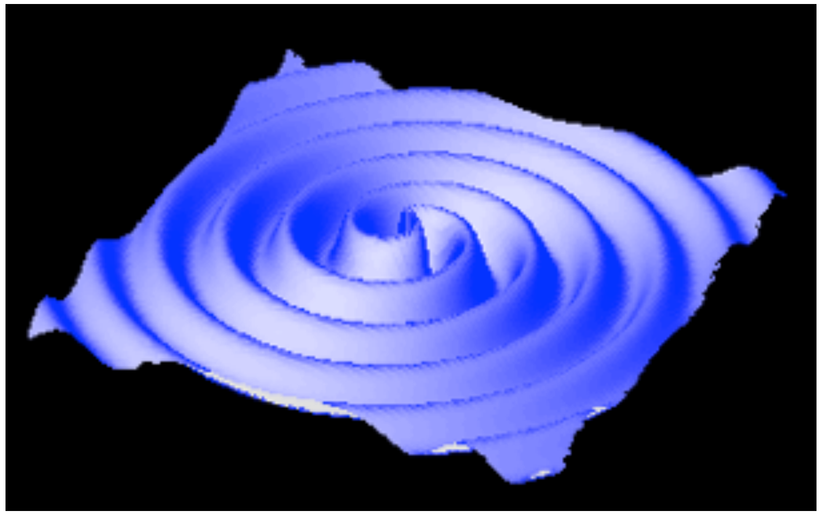
Saha Theory Workshop Saha Institute Kolkata 29 Jan 2015

Gravitational waves

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





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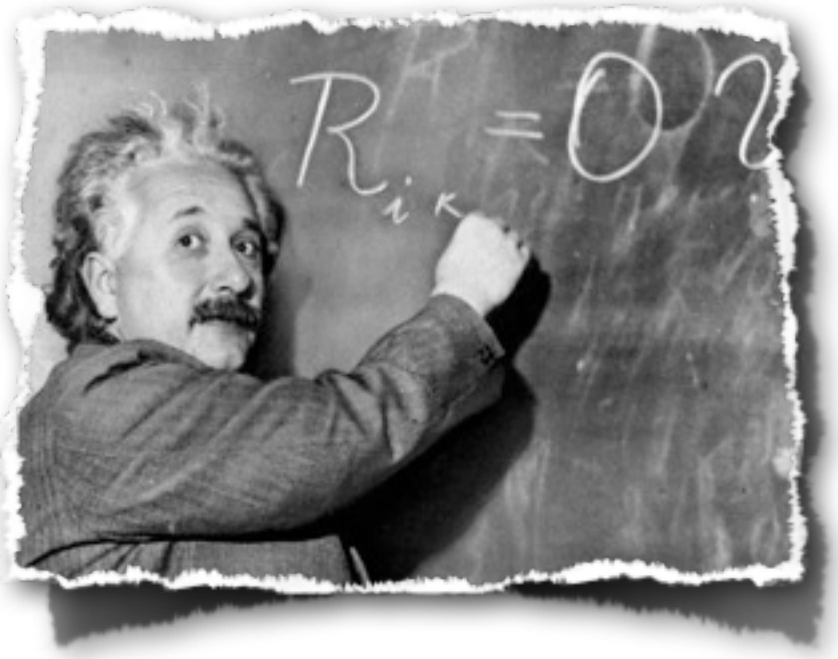
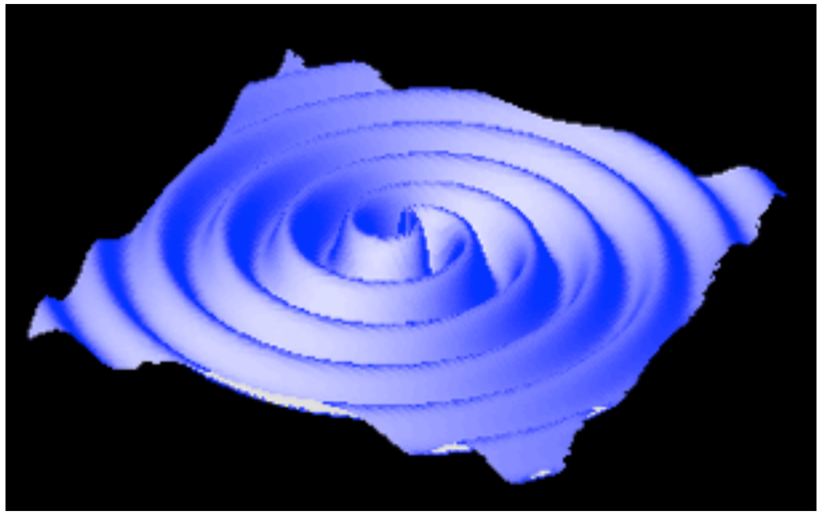


accelerating charges (time-varying dipole moment) → electromagnetic waves

accelerating masses (time-varying quadrupole moment) → gravitational waves



Observational evidence of gravitational waves

- A direct detection of GWs is yet to be made. But indirect evidence comes from the observations of binary pulsars.
- 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.

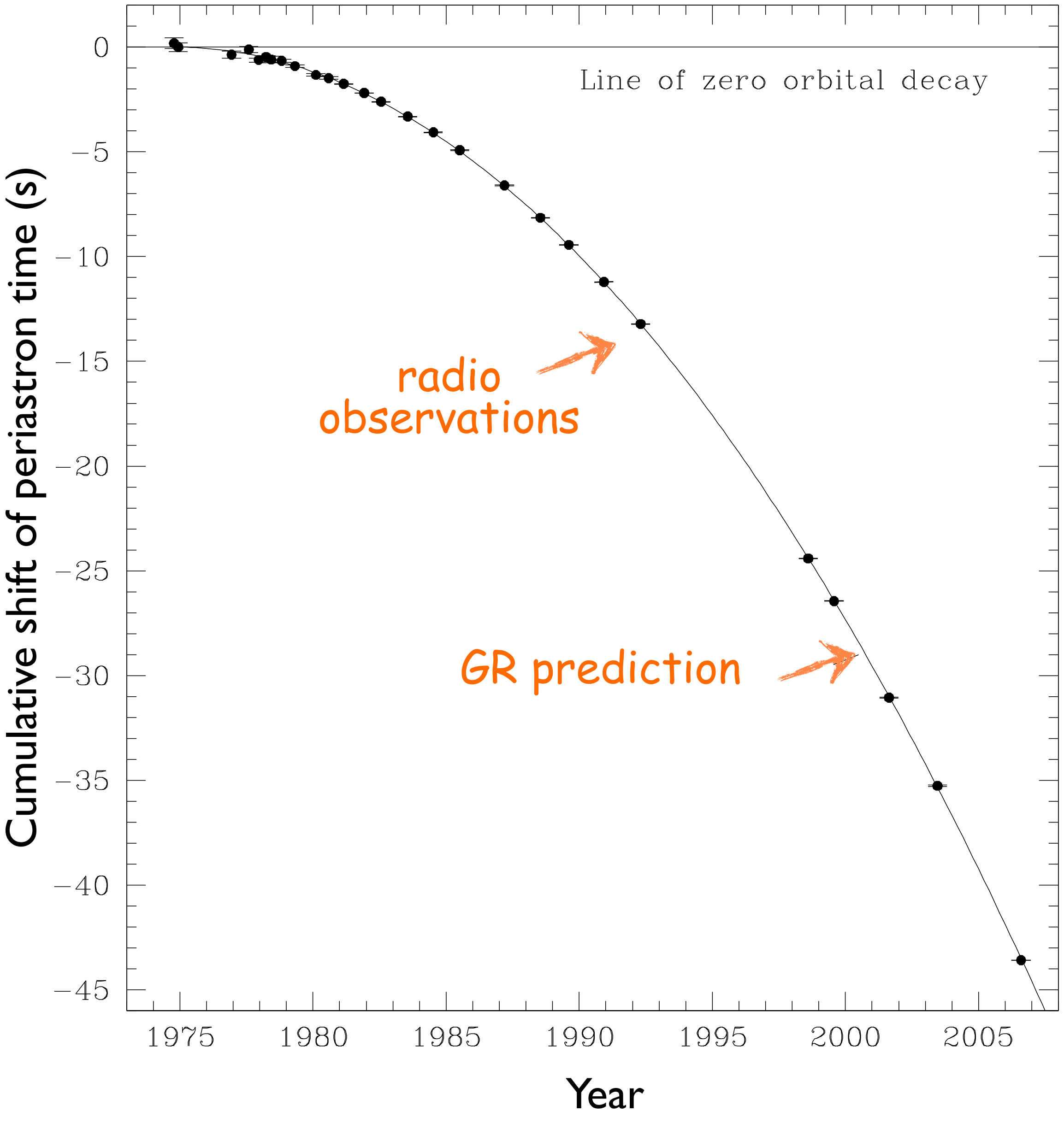
observed decay of the orbital period

GR prediction

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

Eventually the two stars will coalesce, but that will take another 100 million years!

[Weisberg et al (2010)]



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R. A. Hulse and J. H. Taylor.

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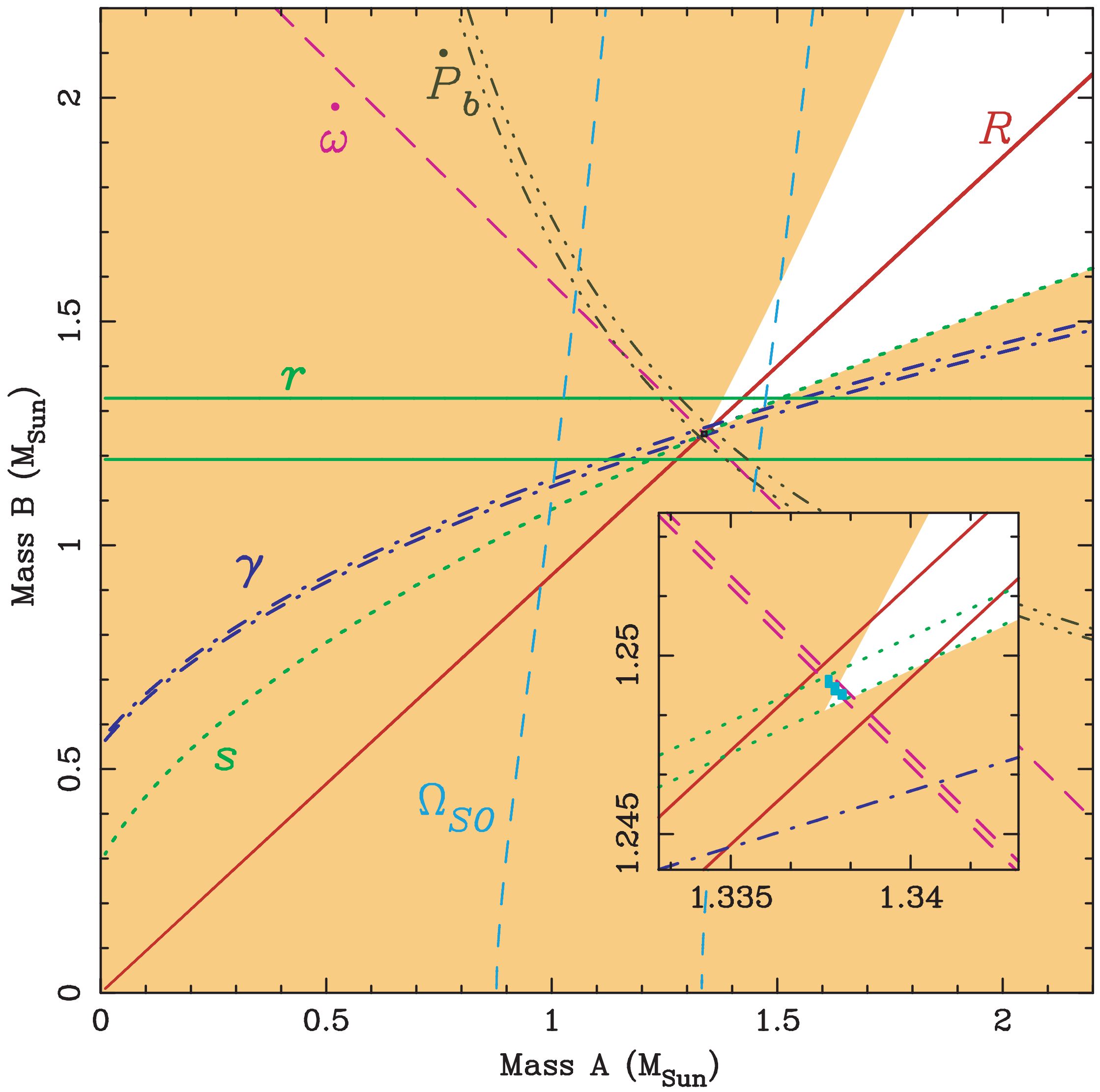
- Binary neutron stars lose their orbital energy by GW emission and starts to “inspiral”.

- 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

Direct detection of gravitational waves

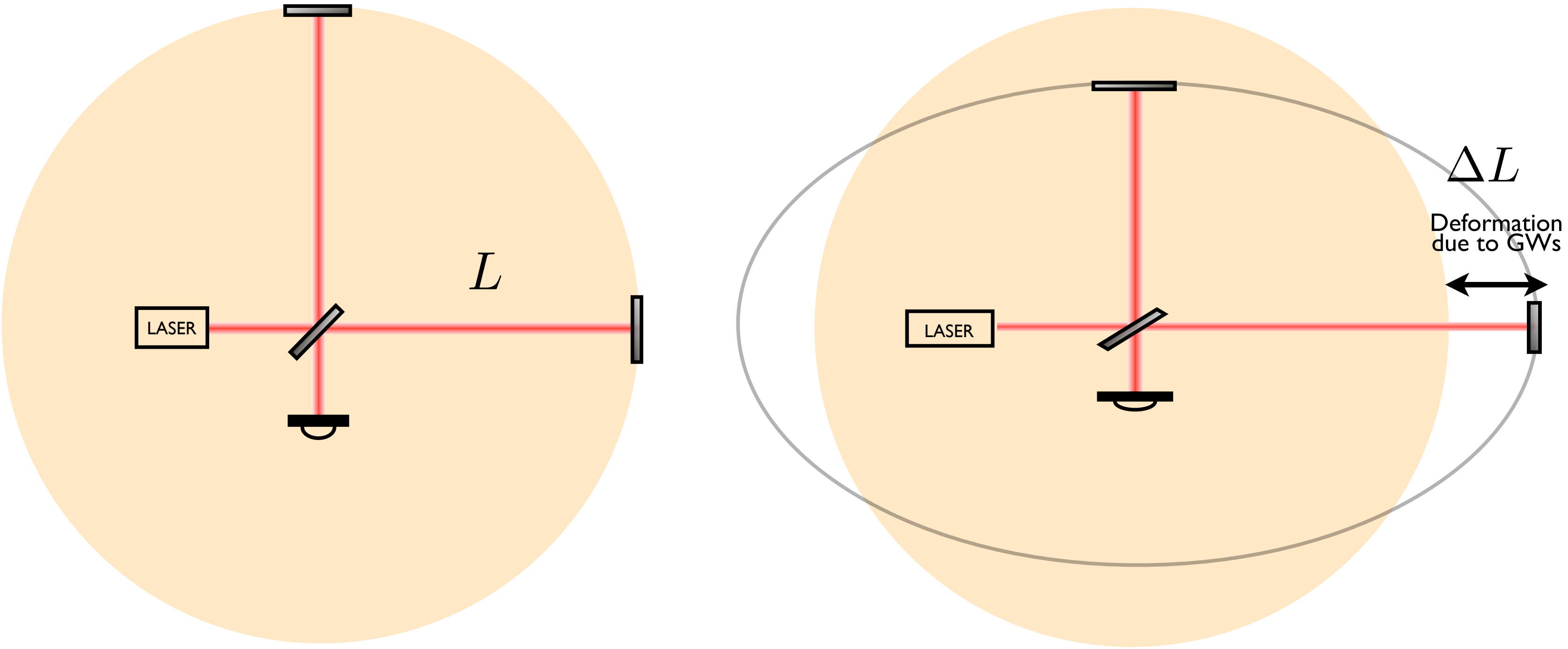
- When GWs pass through earth, they change the geometry of the spacetime.
- These changes can be detected with the help of laser interferometers.

Effect of GWs on a ring of test particles

"x" polarisation "+" polarisation

Direct detection of gravitational waves

- **Experimental challenge** Expected distortions are tiny!



GW strain

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

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

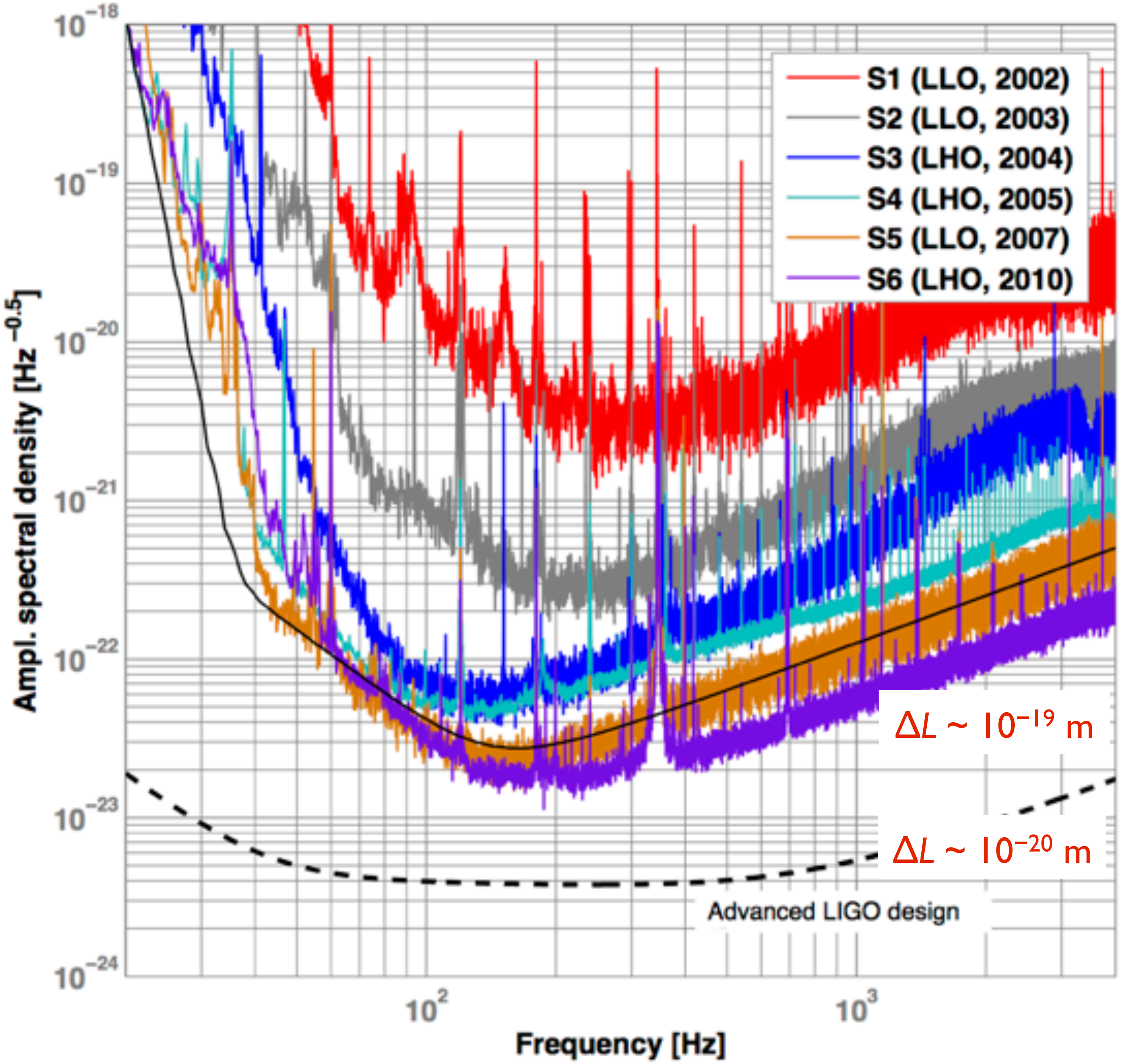
Direct detection of gravitational waves

- A worldwide network of ground-based detectors has started an exciting search for GWs.

LIGO Observatories in Hanford and Livingston, USA

Laser Interferometric GW detectors

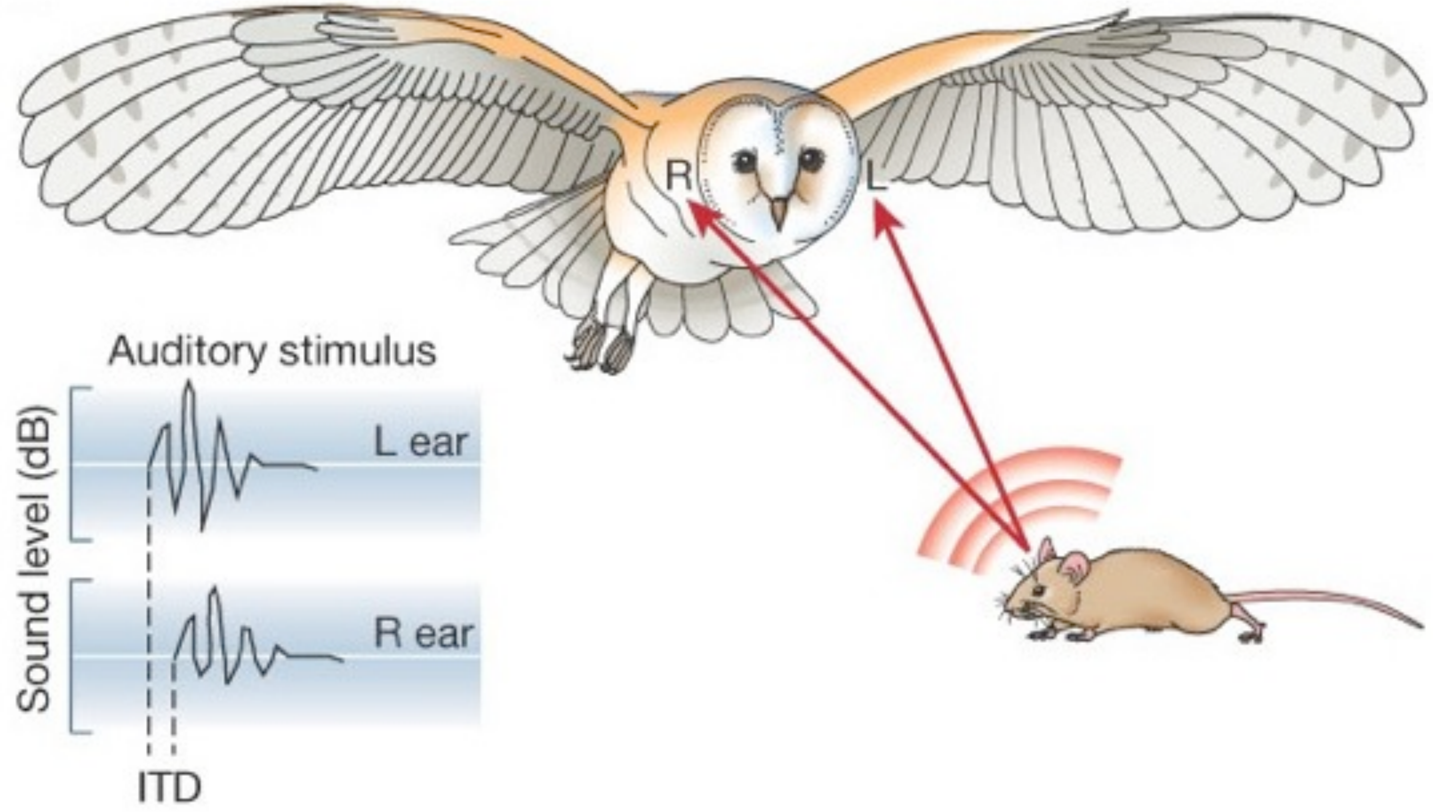
- Initial LIGO detectors achieved their design sensitivity in 2007. Advanced LIGO detectors will start operating in 2015. Expected to achieve design sensitivity by 2018.



$\Delta L \sim 10^{-19}$ m

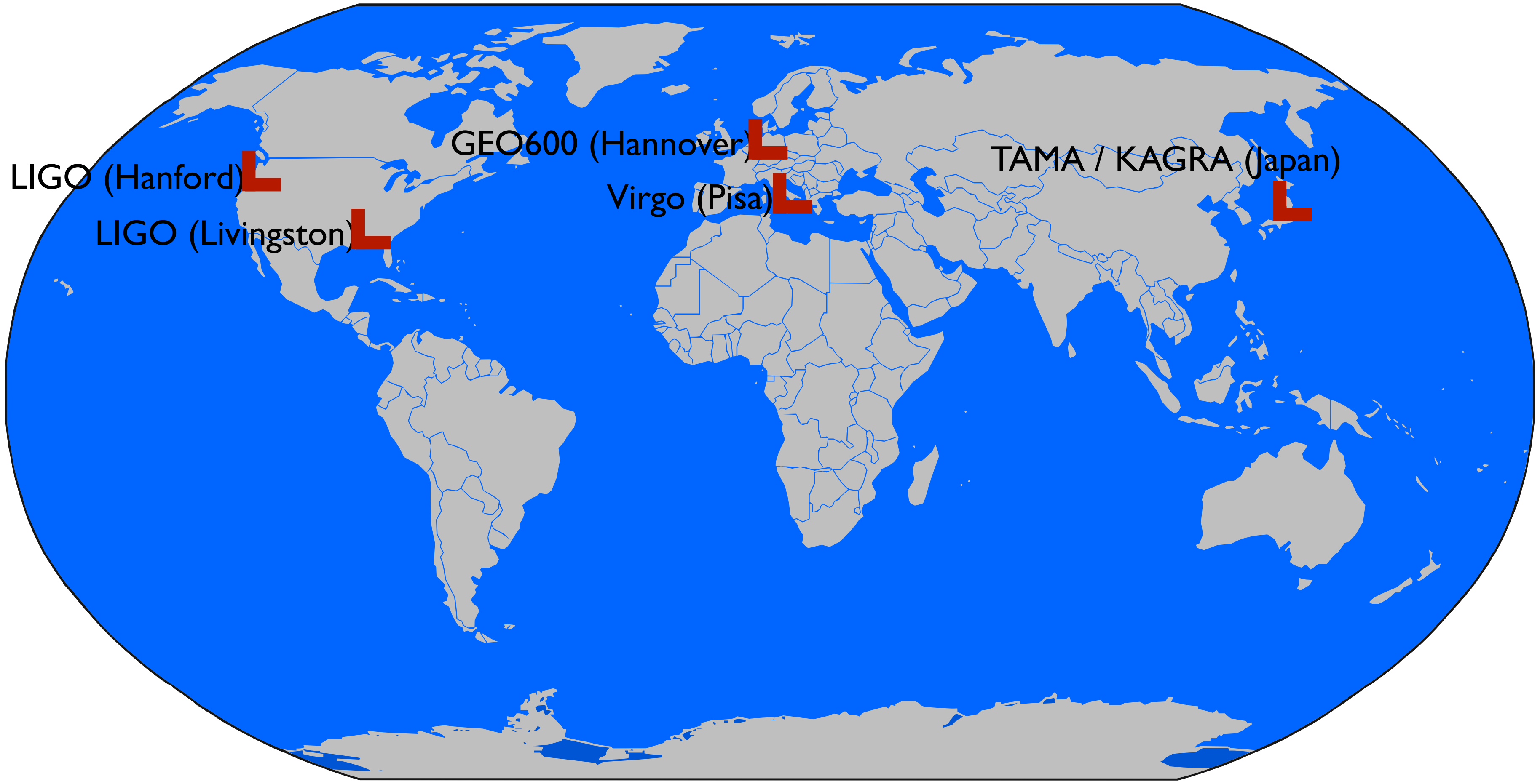
$\Delta L \sim 10^{-20}$ m

GW astronomy requires a worldwide network of observatories

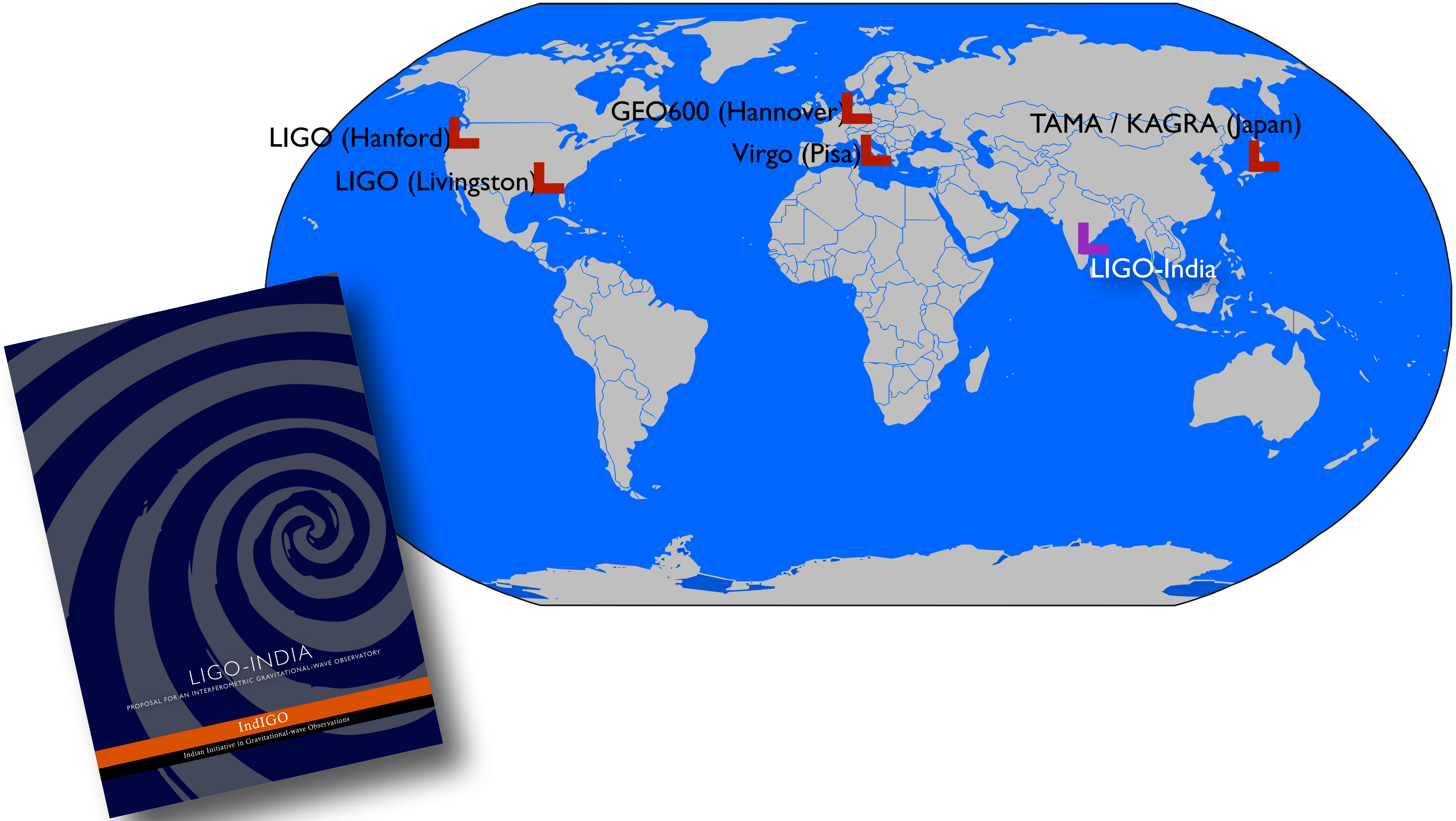


- Interferometric GW detectors are nearly omnidirectional antennas. Sky-localization of the source is achieved by combining data from multiple, geographically separated detectors.

GW astronomy requires a worldwide network of observatories



GW astronomy requires a worldwide network of observatories



LIGO-INDIA
PROPOSAL FOR AN INTERFEROMETRIC GRAVITATIONAL-WAVE OBSERVATORY
IndIGO
Indian Initiative in Gravitational-wave Observations

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

LIGO-India

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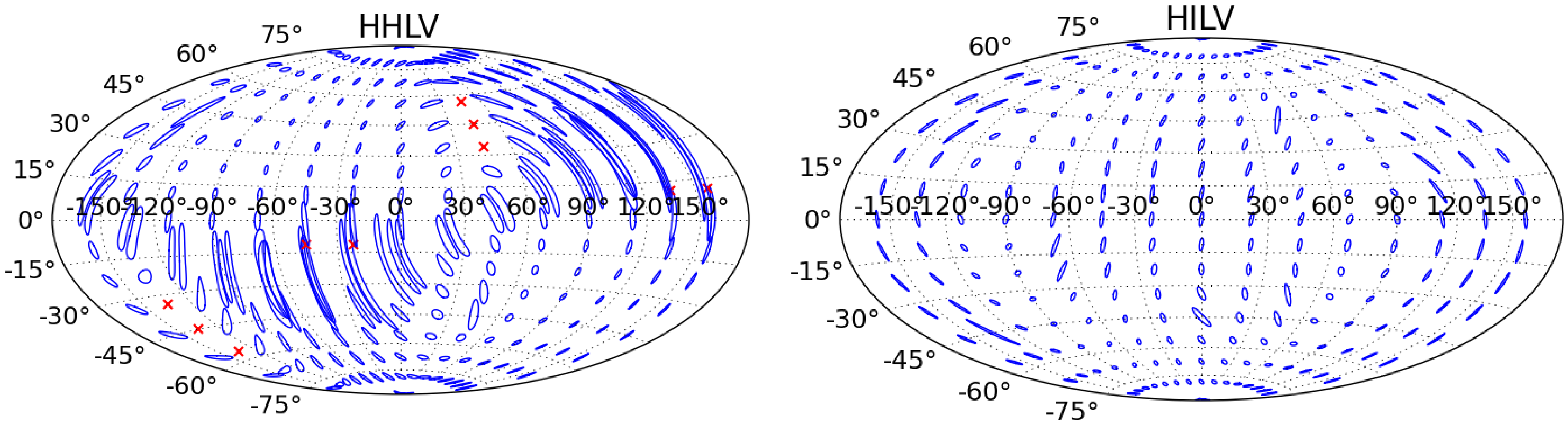
- Ongoing proposal to re-locate the third Advanced LIGO detector to India.
    - LIGO to provide interferometer components (laser, suspensions, optics, control systems, software). India to provide site, vacuum system, infrastructure and human resources.
- Will be jointly operated by the Indian nodal institutions (IUCAA, IPR, RRCAT) and LIGO Lab (USA).
- US National Science Board approved the change in scope of the Adv LIGO project. Pending approval from the Indian government as a national mega project.

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

Expected detection rates

GW detectors are amplitude detectors (unlike telescopes).
10x improvement in the sensitivity ⇒ 1000x increase in the event rates!

[Abadie et al (2010)]

DETECTORS	SOURCES	EXPECTED DETECTION RATE
Initial detectors	NS-NS Binaries NS-BH Binaries BH-BH Binaries	1 per 50 years (mean) 1 per 250 years (mean) 1 per 140 years (mean)
Advanced detectors	**NS-NS Binaries** **NS-BH Binaries** **BH-BH Binaries**	**0.4 – 400 per year** **0.2 – 200 per year** **0.4 – 1000 per year**

Note: Large uncertainties in the astrophysical estimates. However,
even the most pessimistic estimates suggest that detection is within reach!

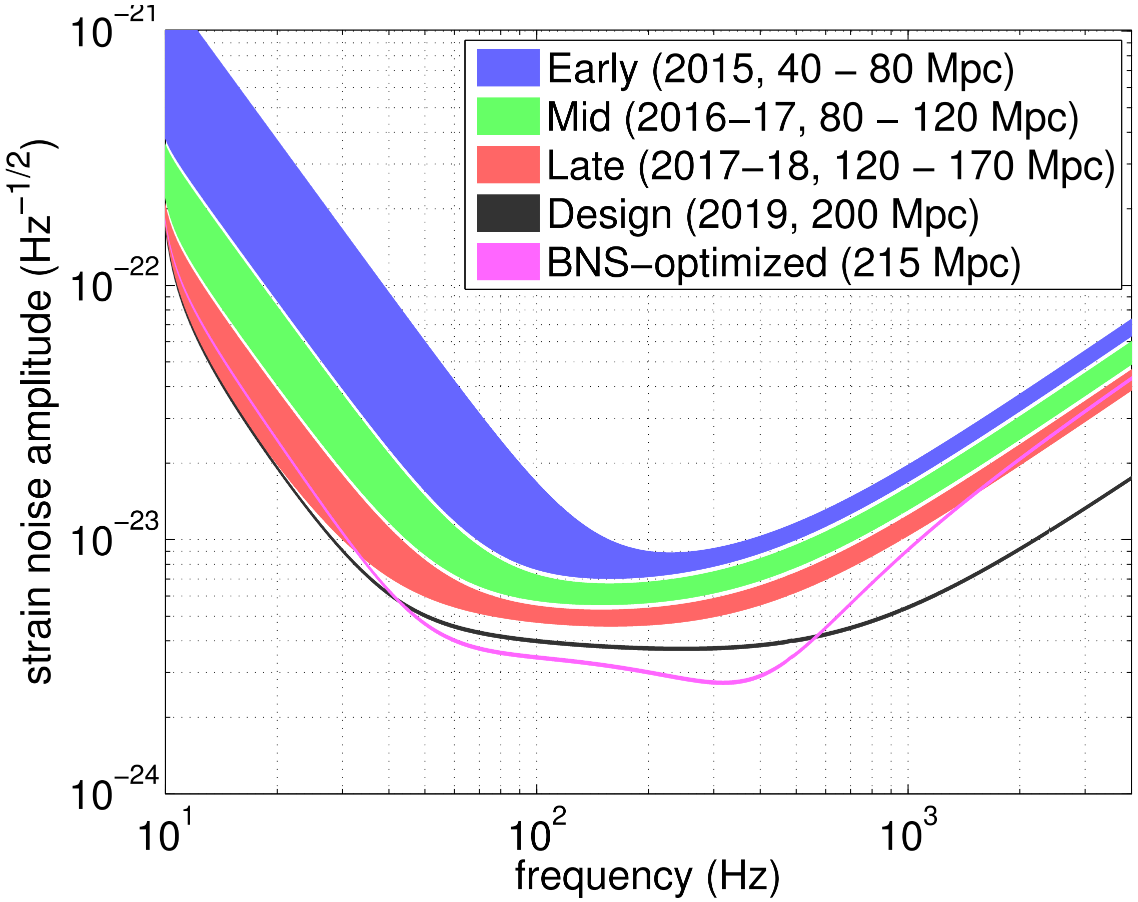
When do we expect the first detections?

- Difficult to make accurate predictions due to the uncertainties in the astrophysical event rates and challenges in the commissioning.

- **Plausible observing scenarios**

Epoch	Plausible BNS detections	% BNS localized within 5 [20] deg
2015	0.0004 — 3	
2016-17	0.006 — 20	
2017-18	0.04 — 100	1 — 2 [10 —12]
2019+	0.2 — 200	3 — 8 [8 —28]
2022+ (India)	0.4 — 400	17 [48]

[Aasi et al, arXiv:1304.0670]



Physics, Astrophysics and Cosmology from GW observations

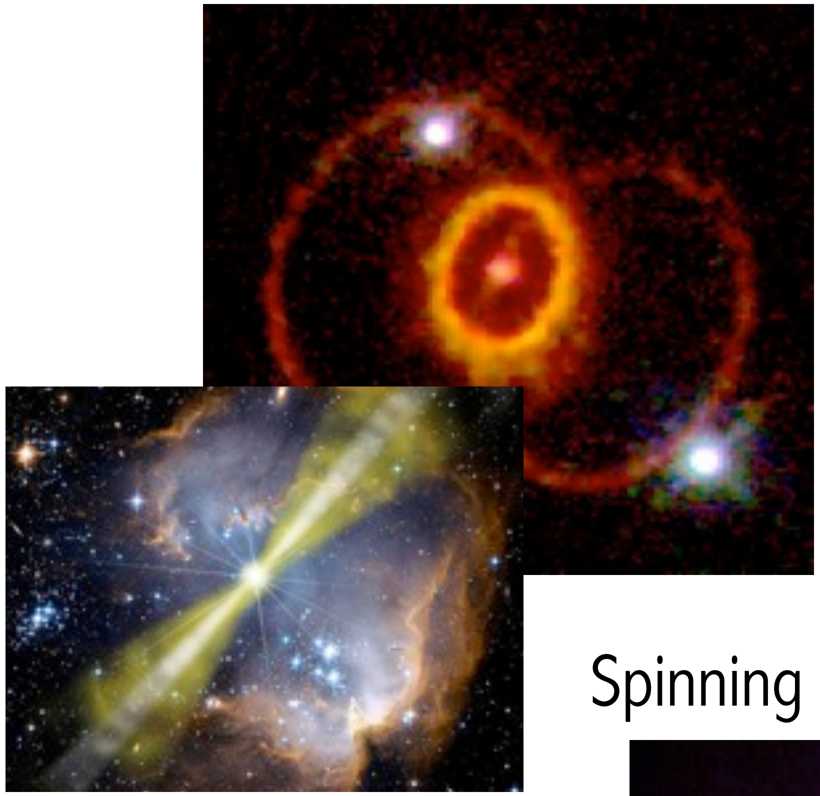
What can we expect in the next 5-10 years?

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.

GW astronomy: Sources and science

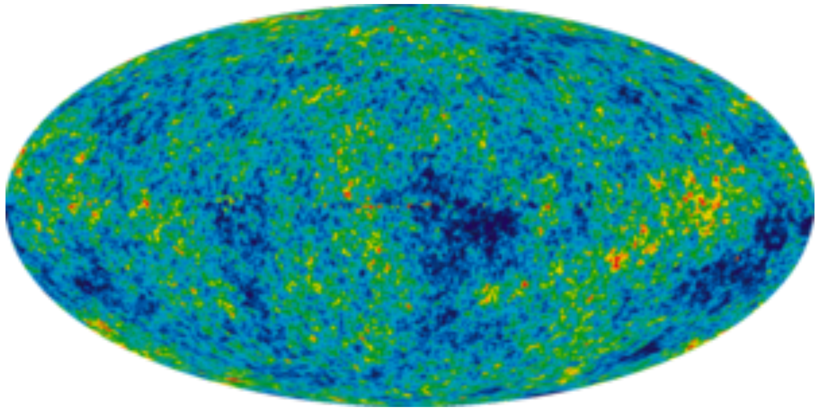
Core-collapse and supernova



Coalescing compact binaries

Spinning neutron stars

Stochastic GW background



Extracting information from GW observations

- For sources such as CBCs, spinning neutron stars, etc., expected signals are well-modelled in GR. Weak signals buried in the noise can be detected by cross-correlating the data with “banks” of (millions of) theoretical templates.

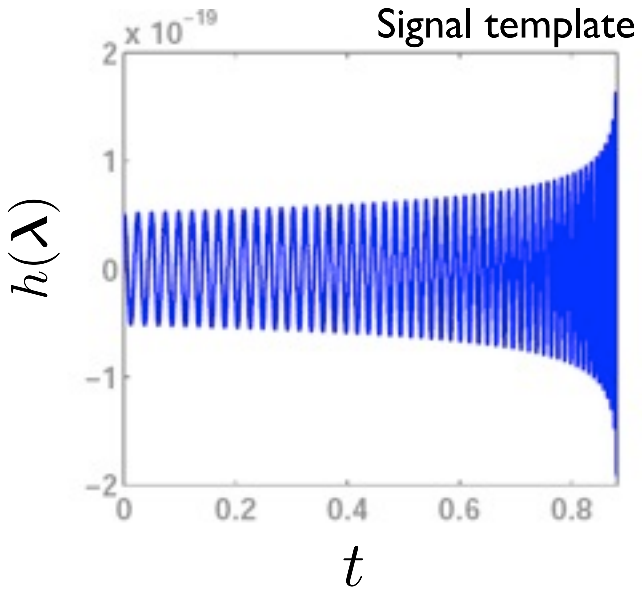
$$\rho \equiv \max_{\boldsymbol{\lambda}} \left[d \star \hat{h}(\boldsymbol{\lambda}) \right]$$

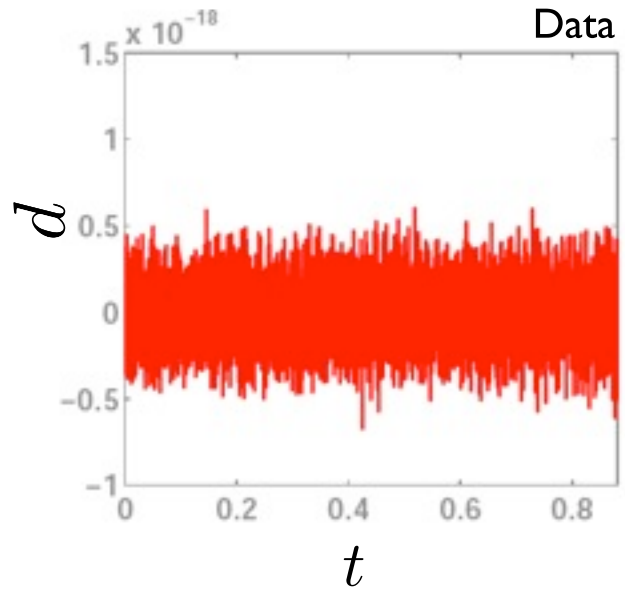
SNR

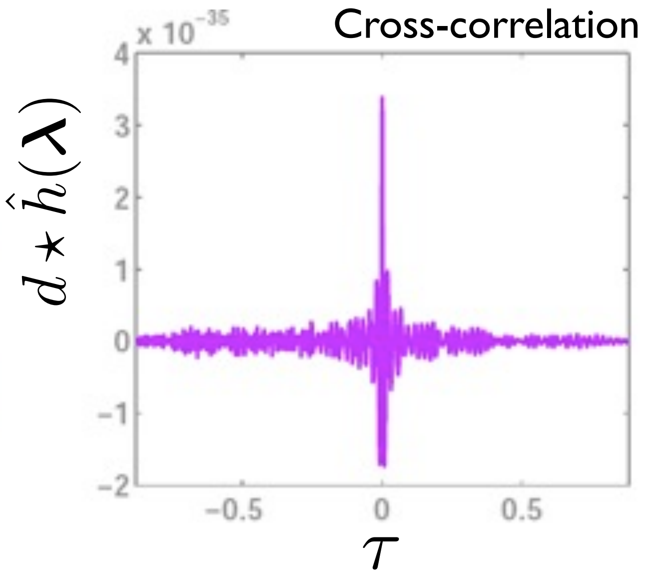
data

signal template

source parameters


Signal template


Data


Cross-correlation

Extracting information from GW observations

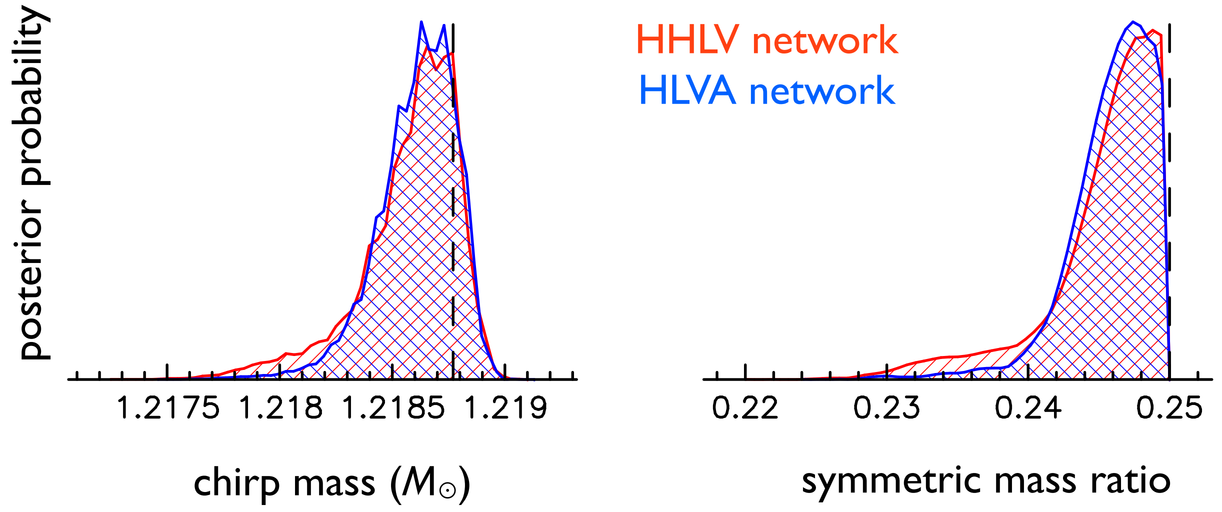
- Posterior distribution of the source parameters can be estimated by Bayesian inference.

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

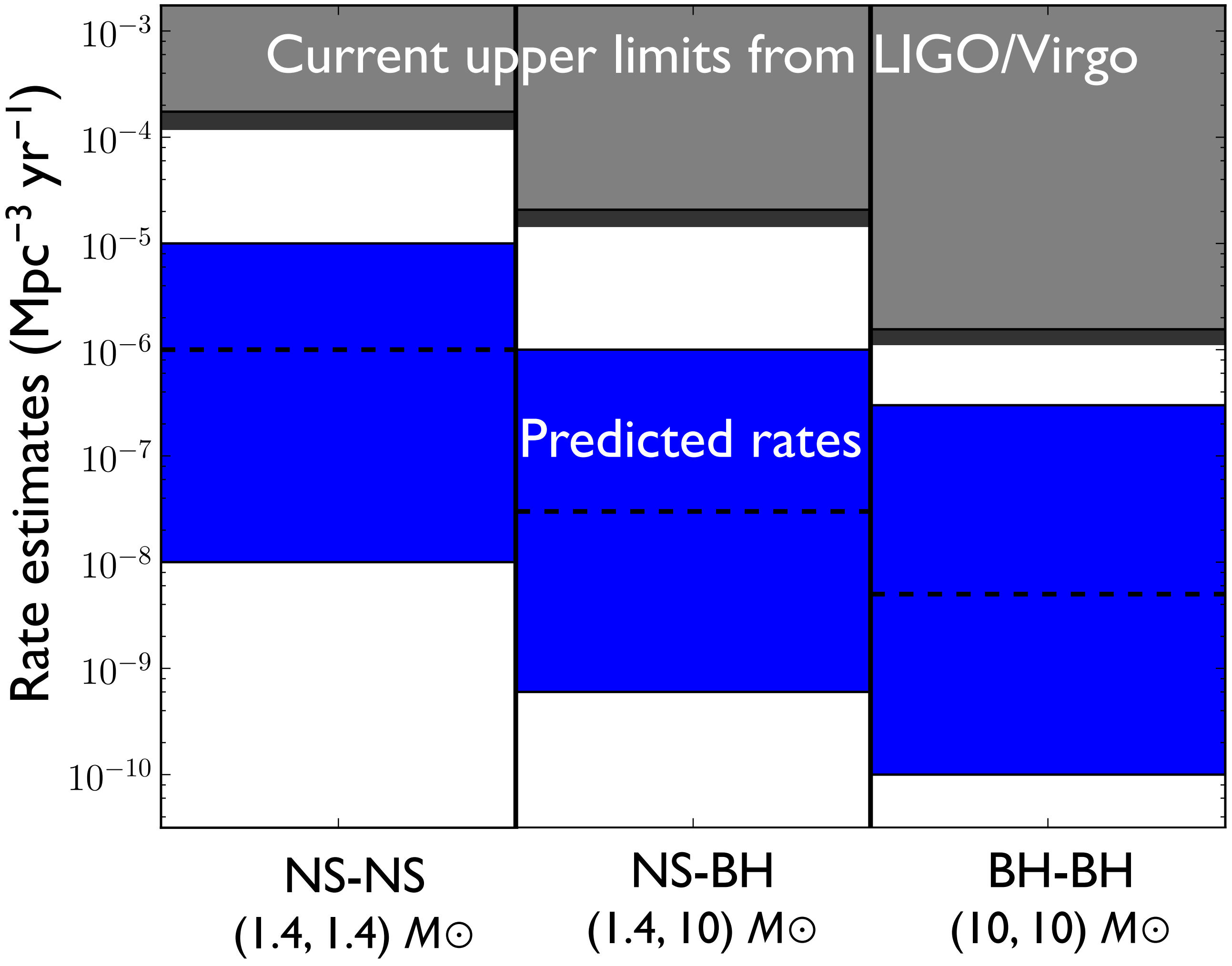


[Veitch et al (2012)]

Astrophysics using GW observations

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

[Abadie et al (2012)]



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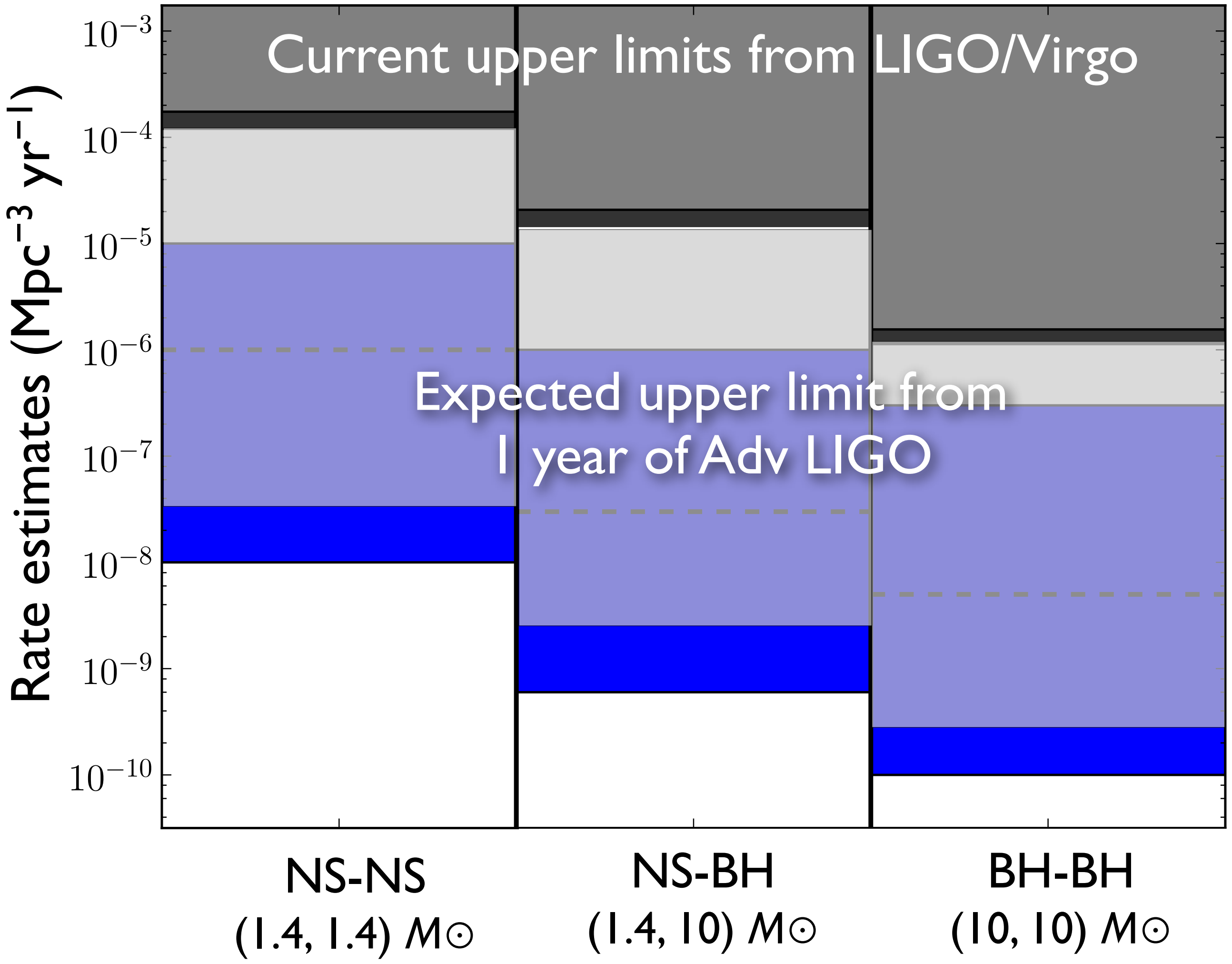
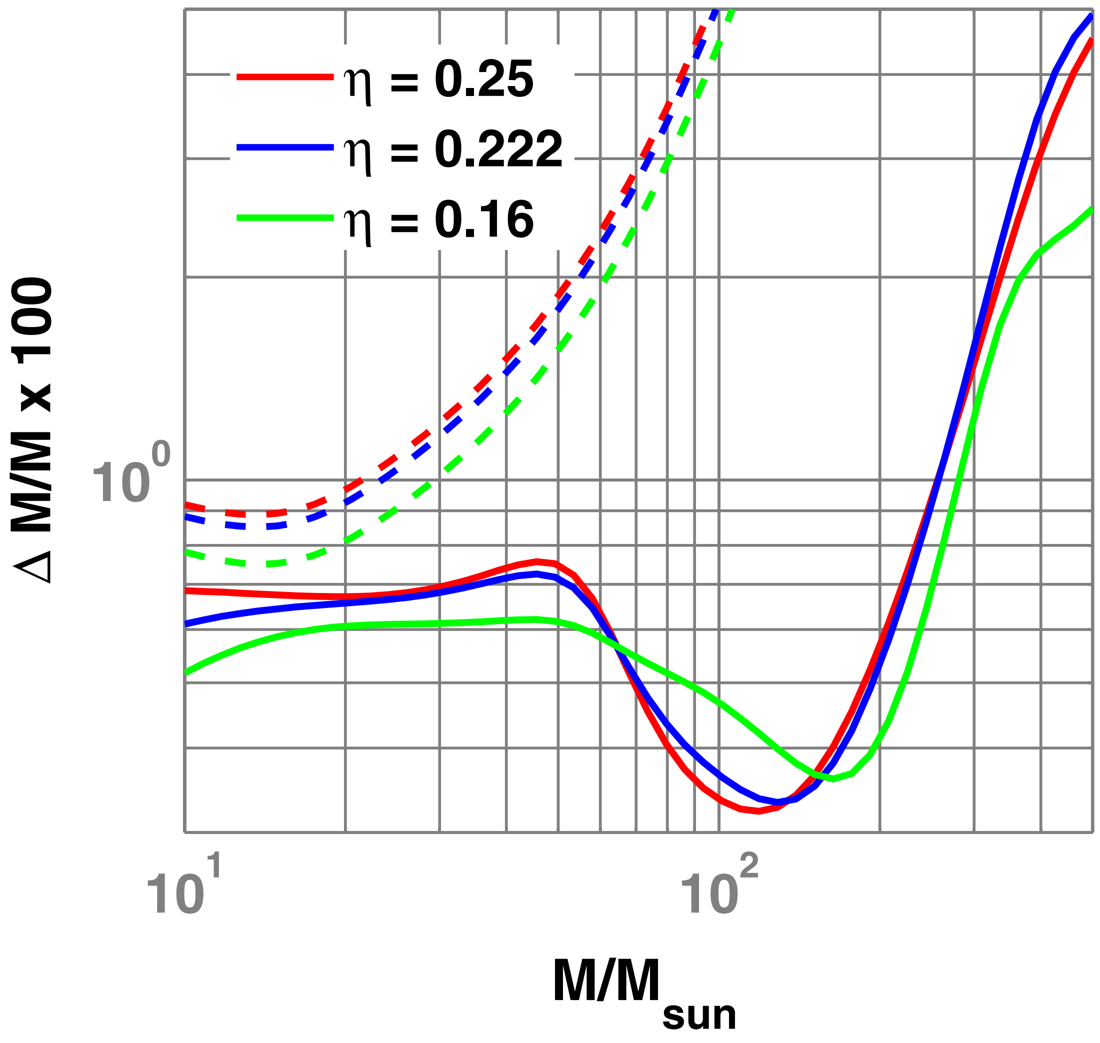


Astrophysics using GW observations

- **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)]

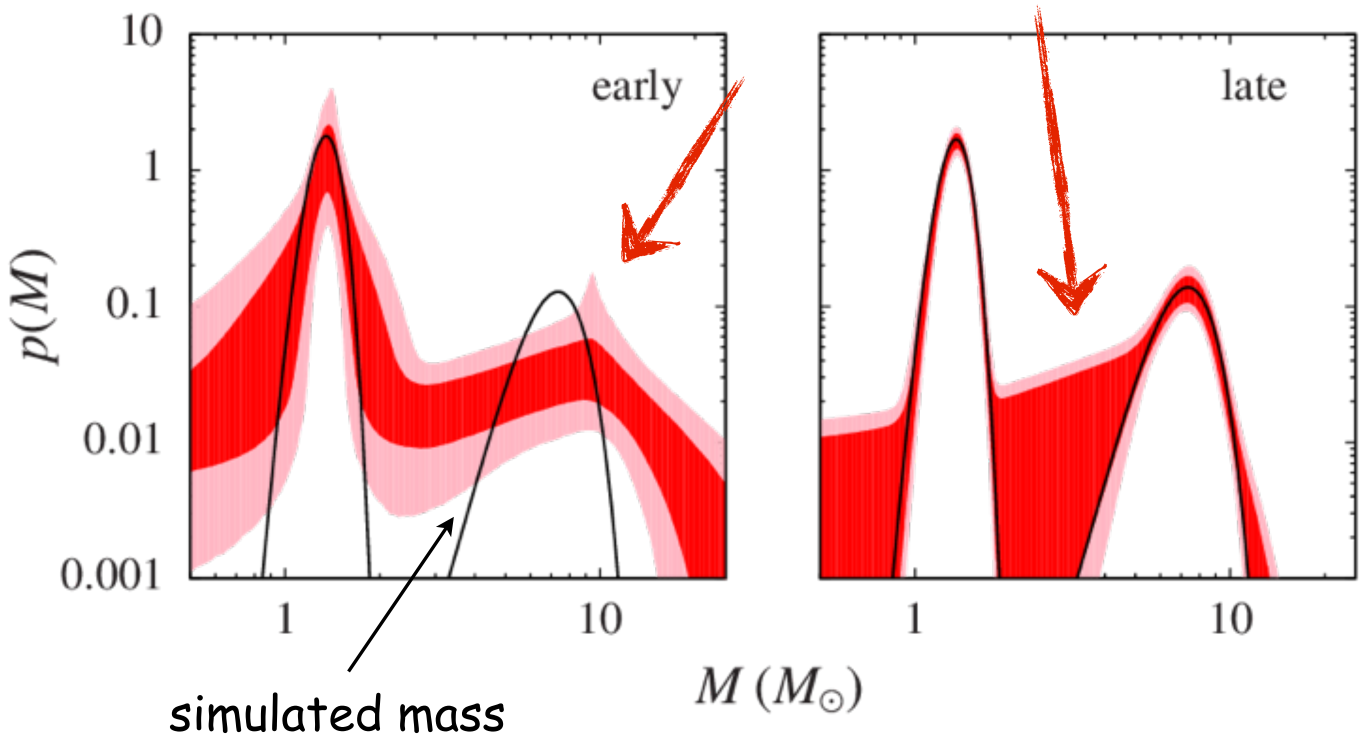


1-σ error in measuring the total mass of BBHs located at 1 Gpc (Adv LIGO)

Astrophysics using GW observations

- **Measuring the mass function of black holes and neutron stars** by combining multiple observations of compact binary coalescences.

reconstructed mass function from 1 year of Adv LIGO observation



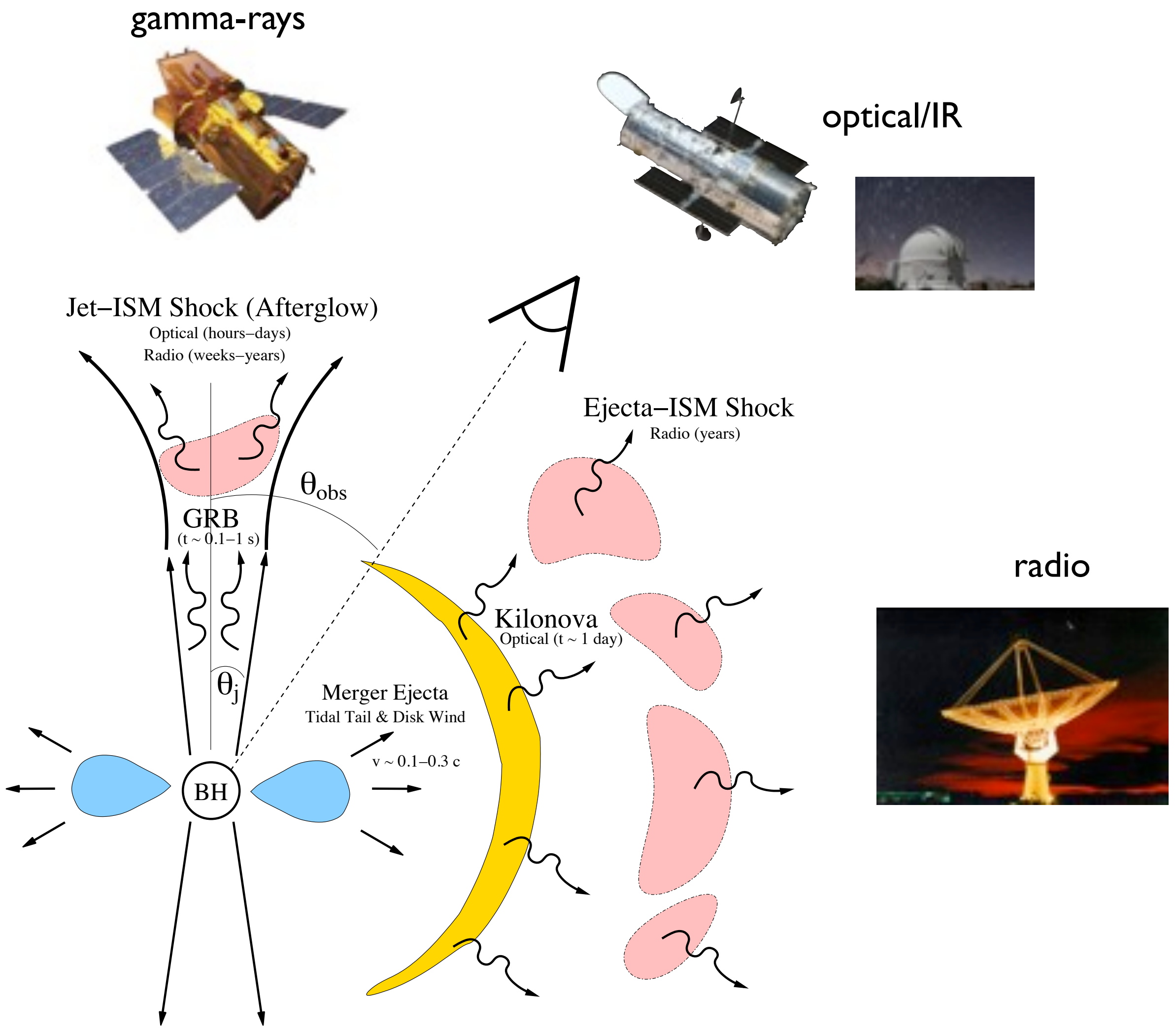
simulated mass function

[Messenger, Del Pozzo, Veitch, in Prep]

Astrophysics using GW observations

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

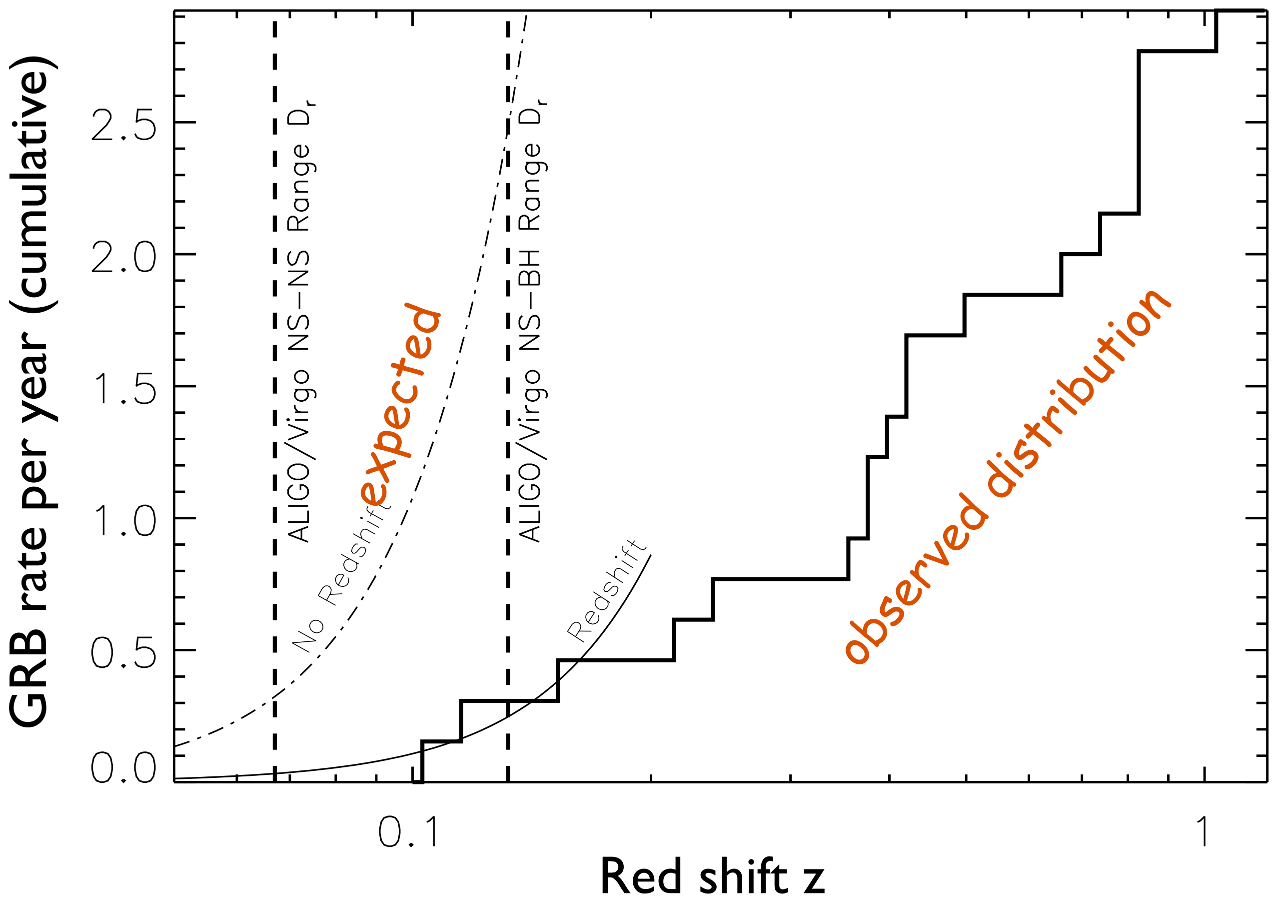
[Metzger & Berger (2011)]



Astrophysics using GW observations

- **SGRB central engines** 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)]

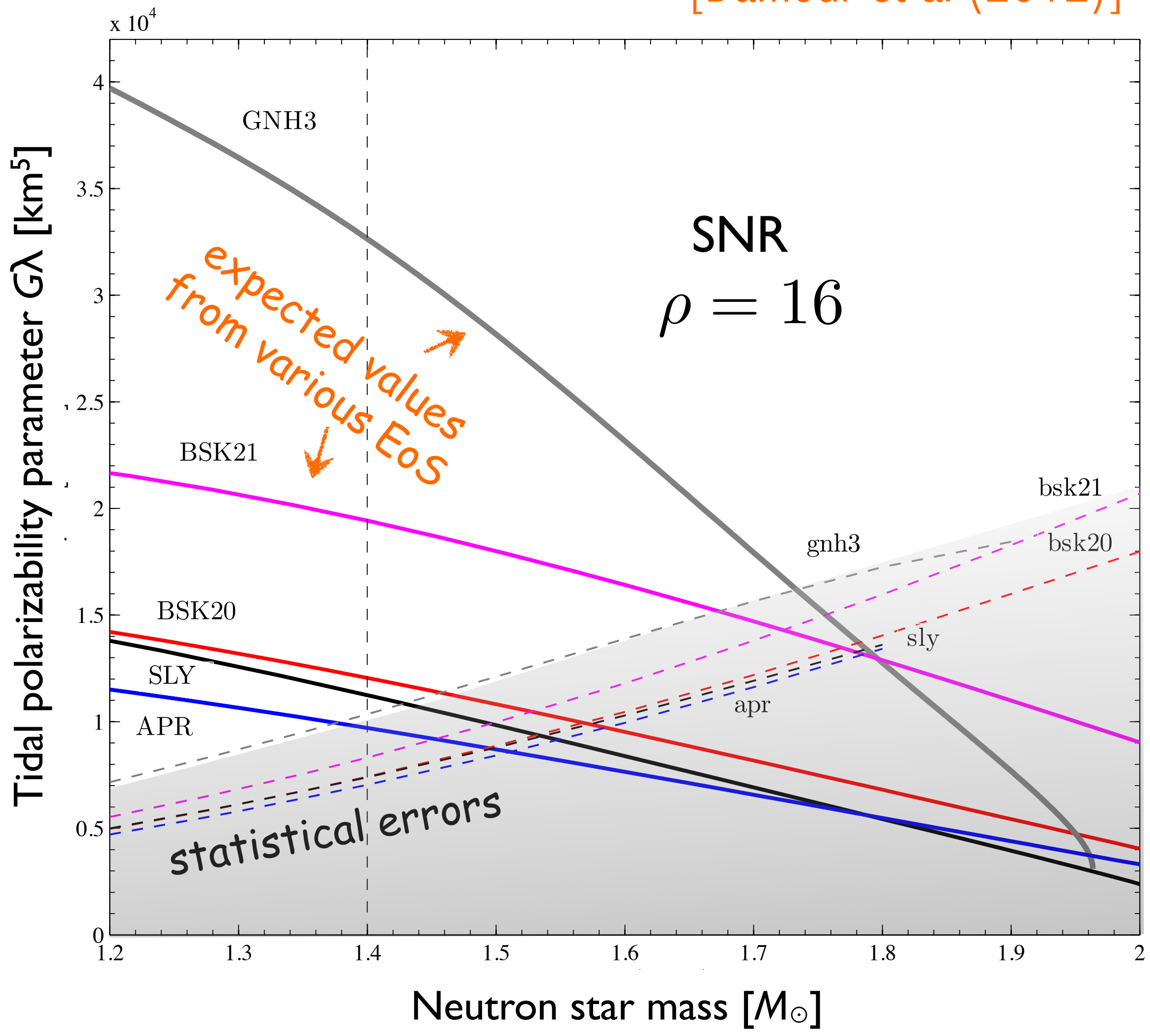


Observed & expected distribution of SGRBs (Swift)

Astrophysics using GW observations

- **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).

[Damour et al (2012)]

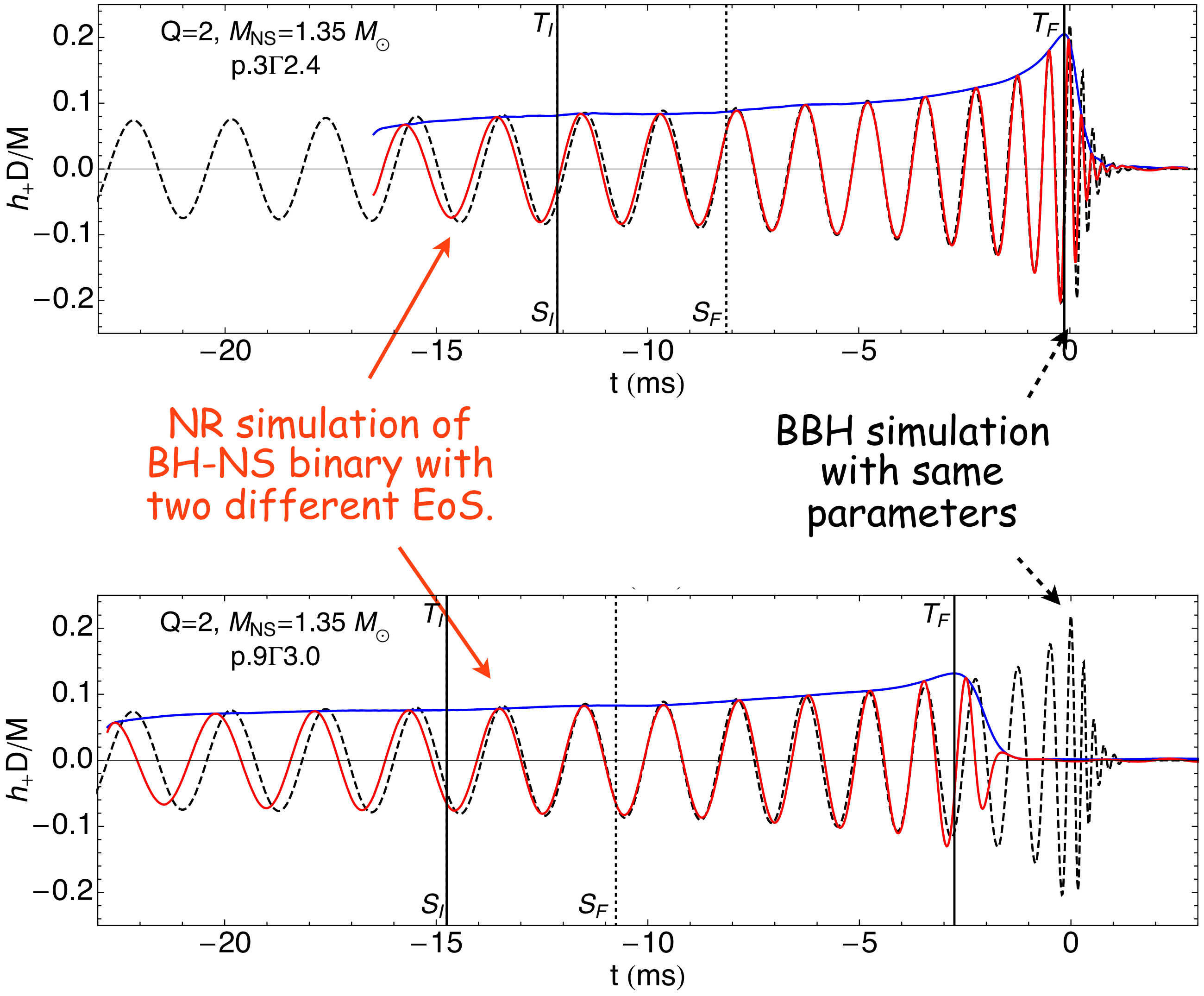


In the unshaded region, the tidal deformation can be measured in Adv LIGO. 3G detectors will make very accurate measurements.

Astrophysics using GW observations

- **EoS of neutron stars** BNS/NSBH inspiral signals contain information of the NS EoS (through tidal deformation).
  - Merger/ring-down part expected to have clearer signature. NR simulations are getting mature to explore this.

[Lackey et al (2011)]



NR simulation of BH-NS binary with two different EoS.

BBH simulation with same parameters

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].

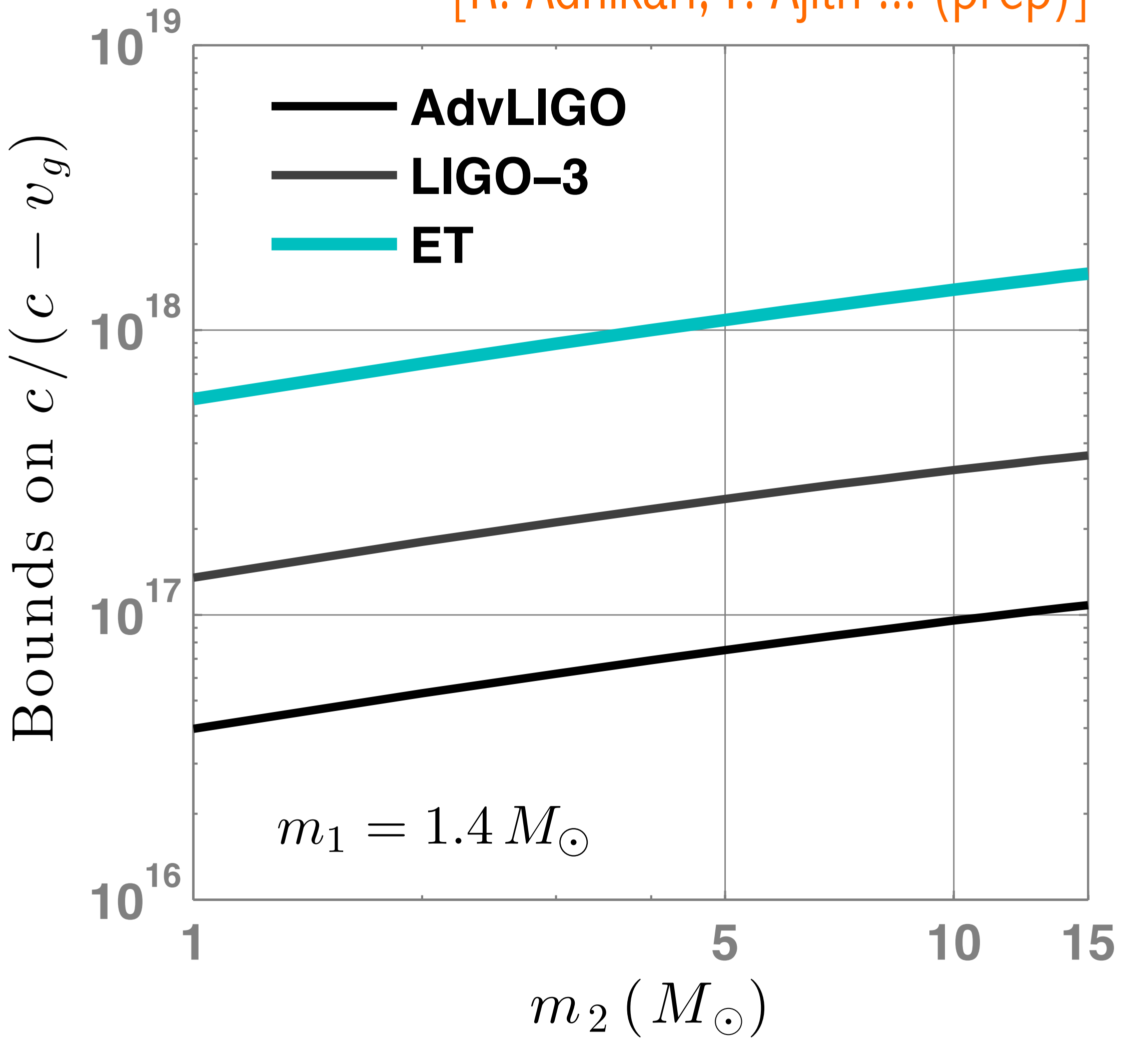
distance to the source

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

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 <u>one</u> SGRB, powered by NSBH merger (located at the horizon distance).

Tests of GR using GW observations

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

Dispersion relation

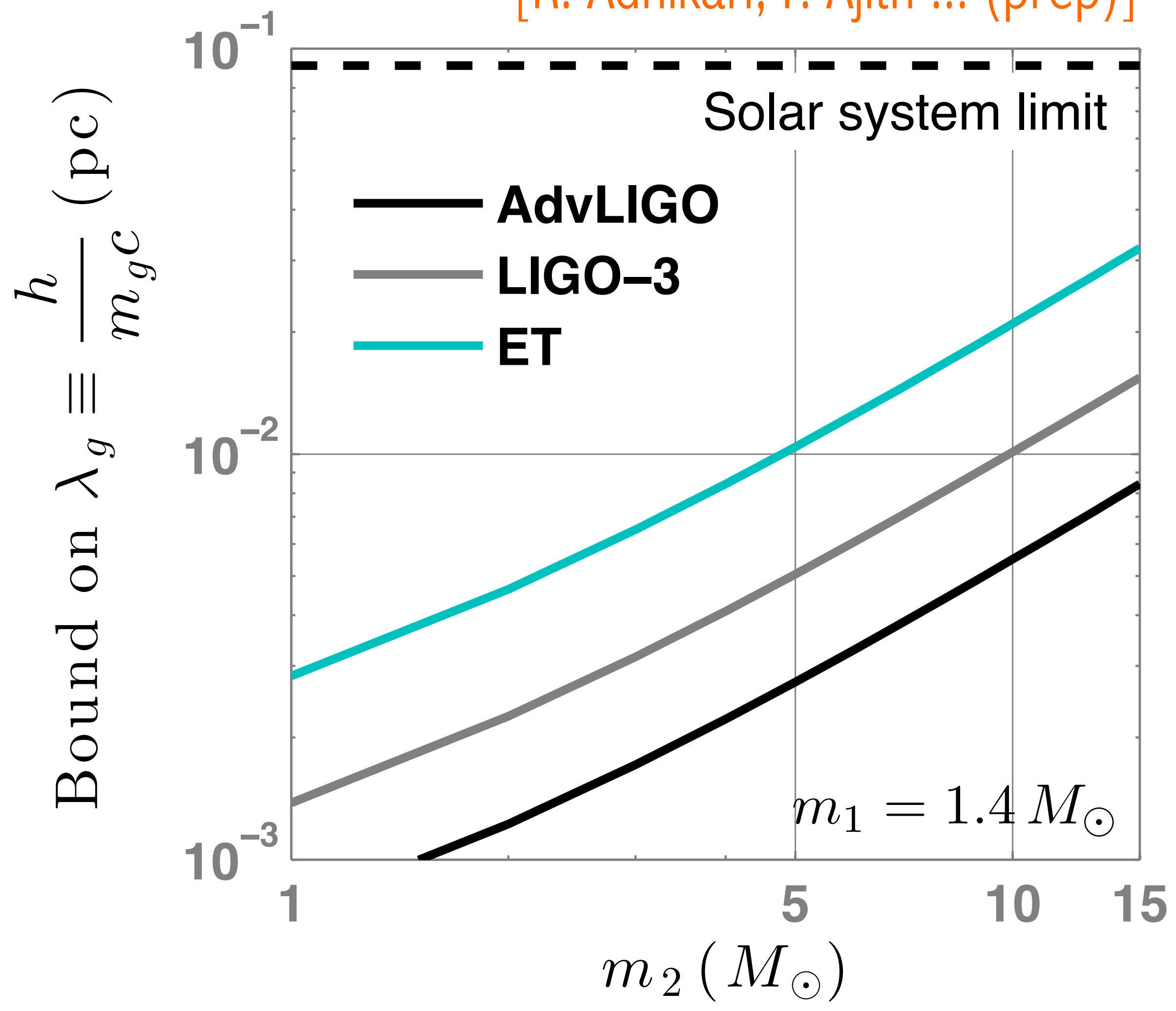
$$v_g^2/c^2 = 1 - m_g^2\, c^4/E_g^2$$

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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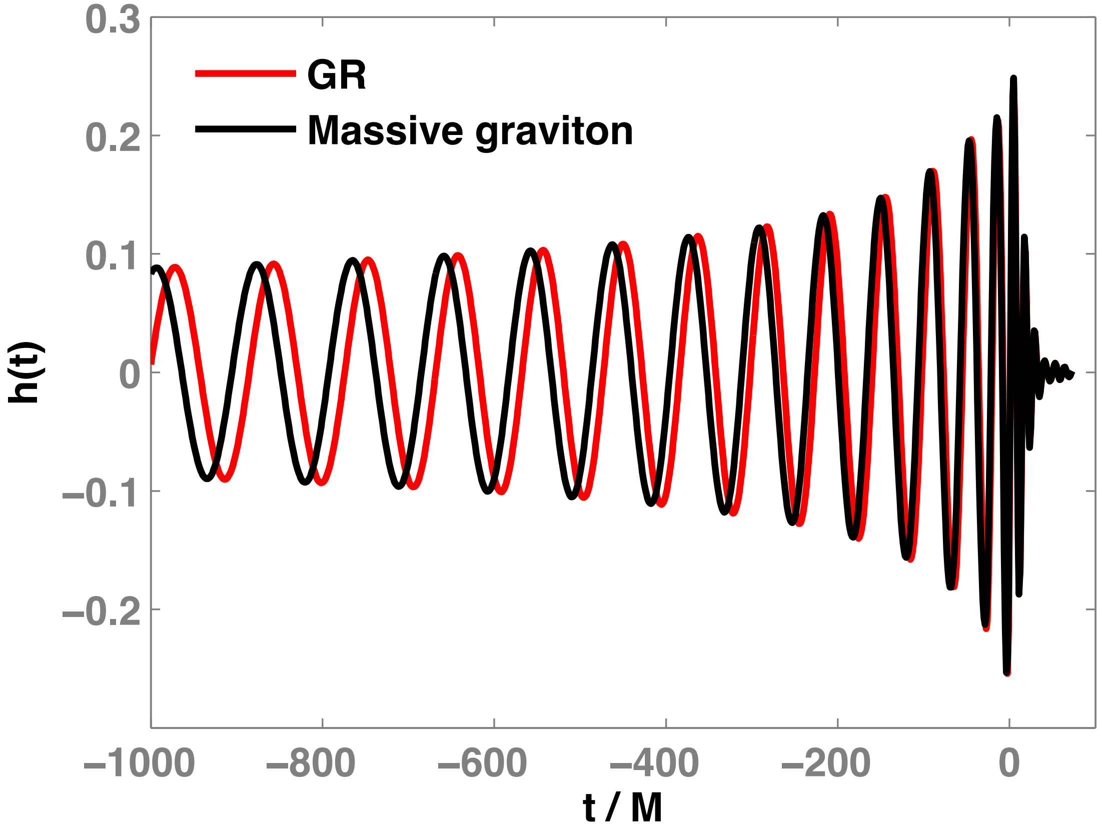
Tests of GR using GW observations

- **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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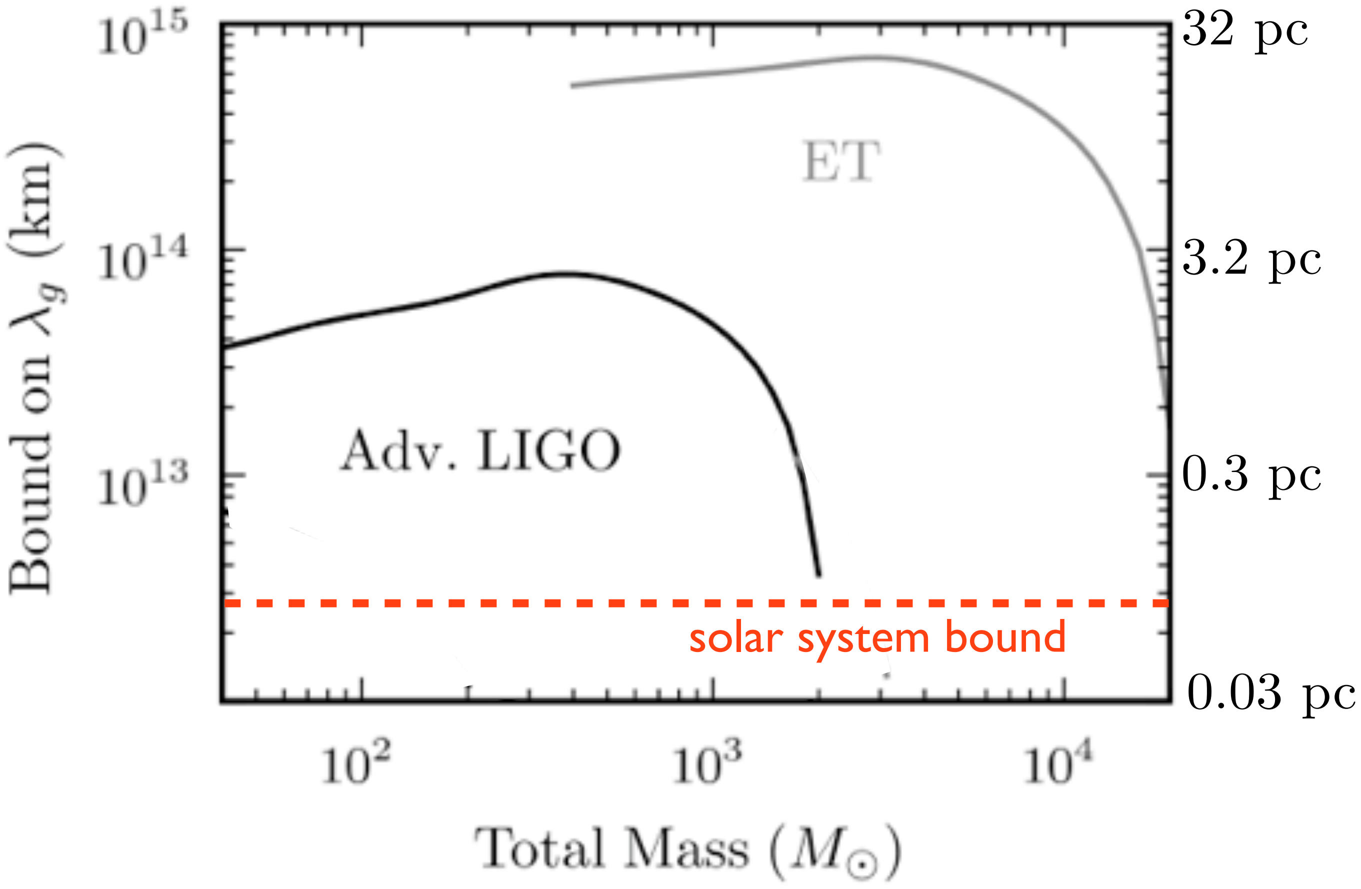
[Keppel & Ajith (2010)]

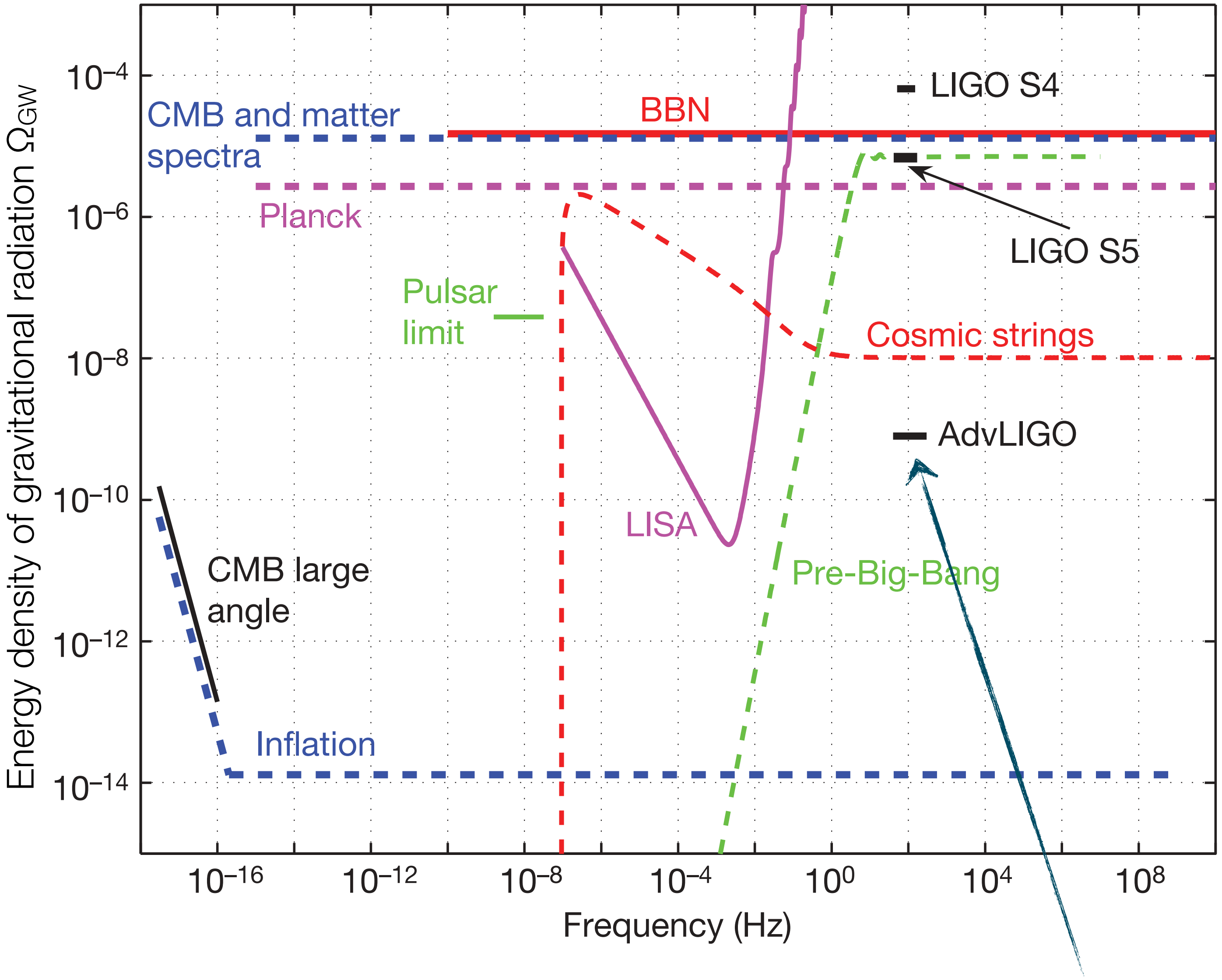


Expected bounds on the Compton wavelength of the graviton from BBH observations by future detectors. (d_L = 1 Gpc)

Early Universe Cosmology

- Stochastic GW spectrum predicted by std. inflationary cosmology is too low to be detected by Advanced LIGO. However, the upper limits will constrain more exotic models.

[LIGO & Virgo Collaboration 2009]

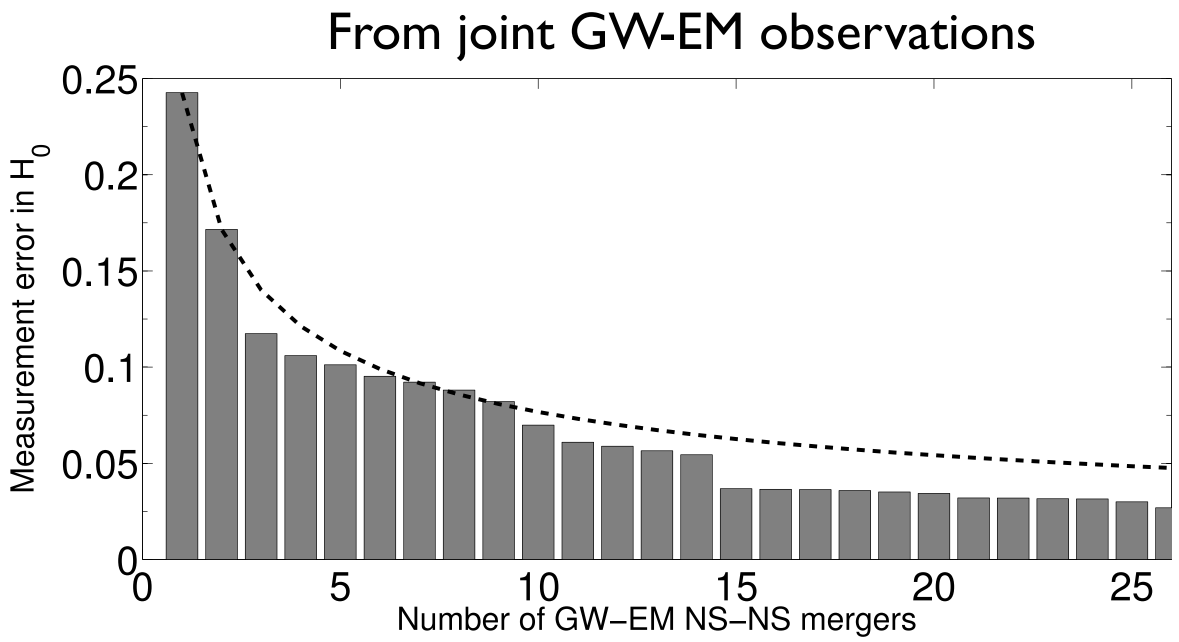


expected upper limit
from Adv LIGO

Expansion history of the Universe

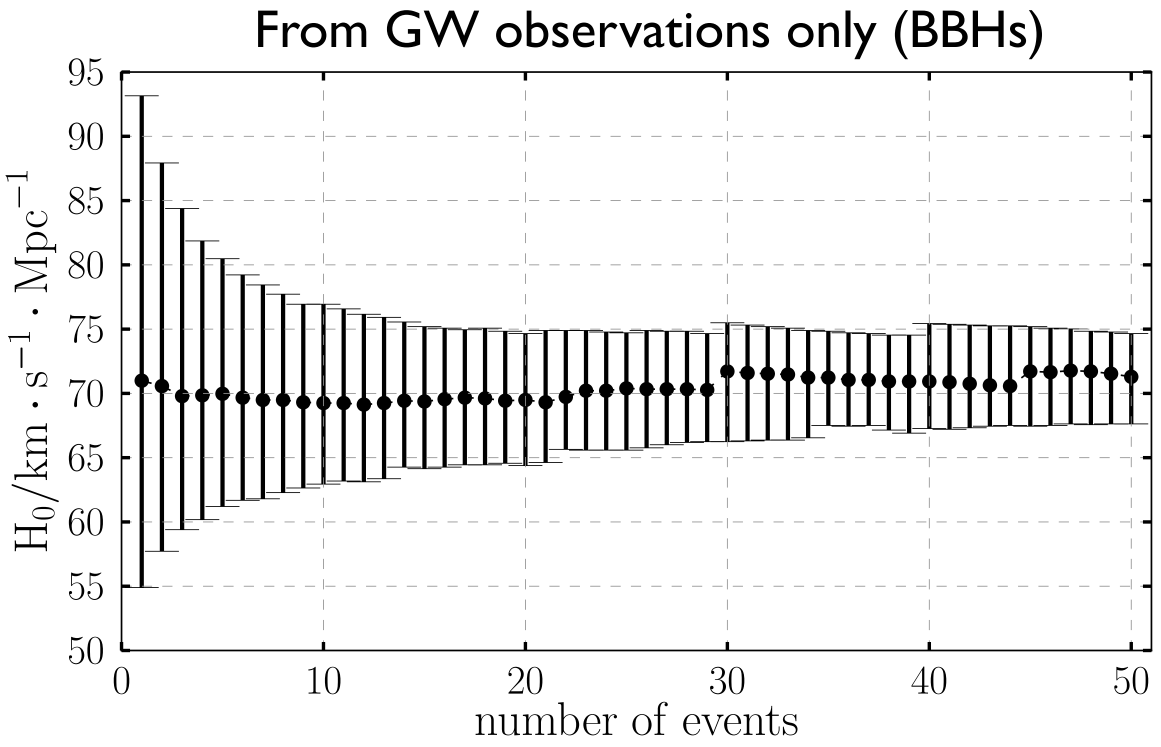
- **CBCs are standard sirens** Self calibrating sources → cosmic expansion rate. [Schutz (1986)]
    - 2G network: modest measurement of H_0. [Nissanke et al (2013), Del Pozzo (2011)]
    - 3G detectors: more interesting measurements (comparable to other dark energy missions). [Zhao et al (2011)]

Note: very different systematics!



From joint GW-EM observations

[Nissanke et al (2013)]



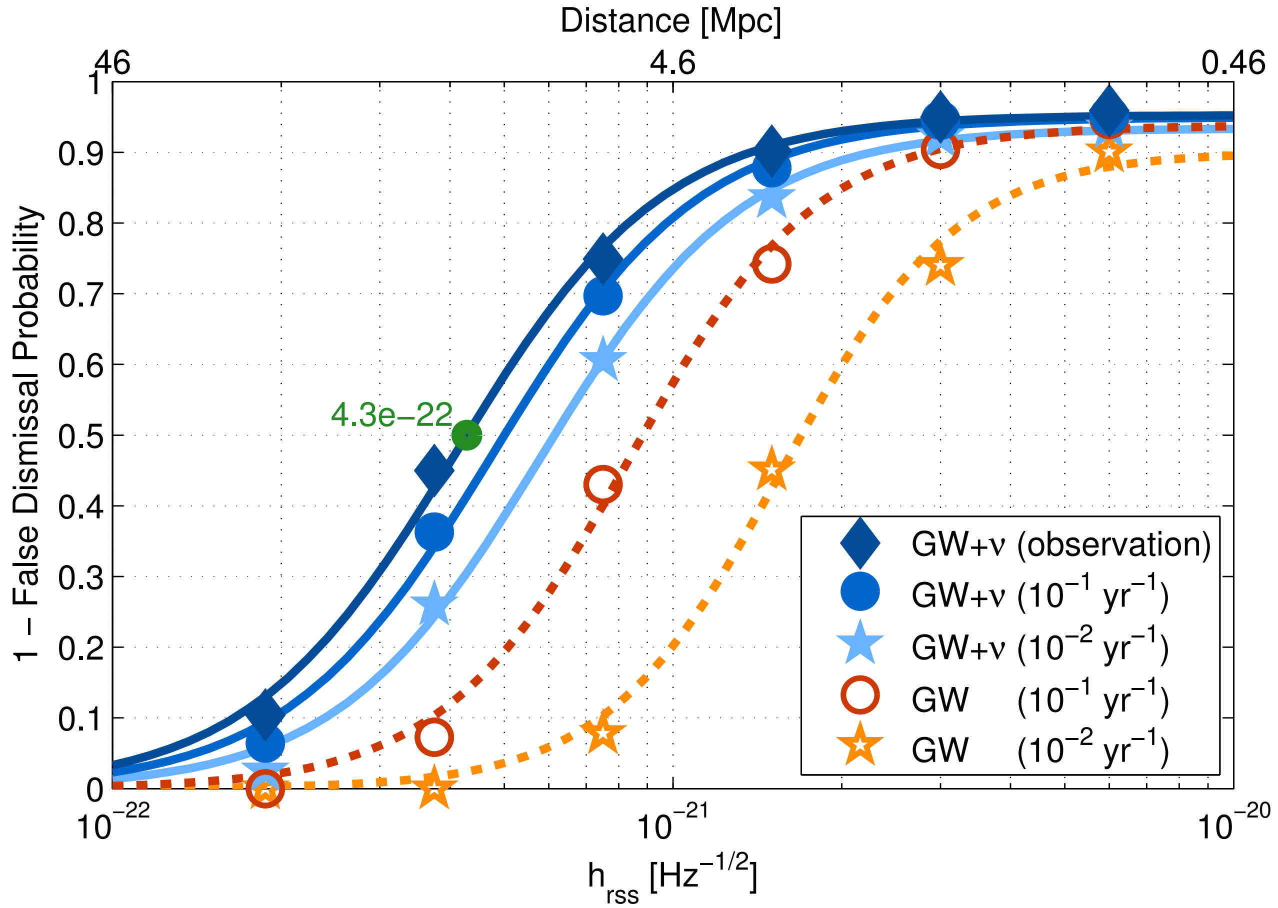
From GW observations only (BBHs)

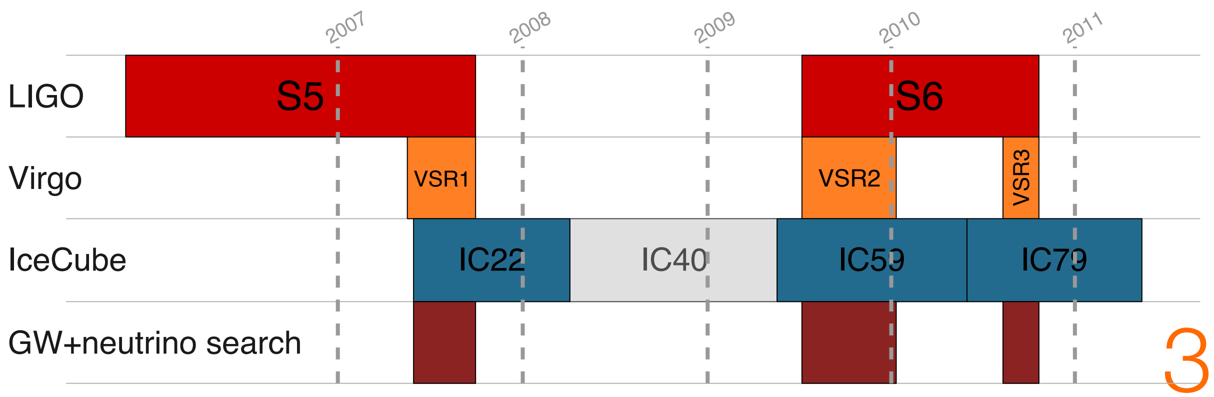
[Del Pozzo (2011)]

Joint searches with HE neutrinos: Searching for the exotica!

- IceCube has detected several high-energy neutrinos -- believed to be of astrophysical origin.
  - Several joint searches between LIGO-Virgo and neutrino detectors (IceCube, ANTARES) performed in the past.
  - No detections. Expected joint detection rates for realistic sources (GRBs, SGRs, etc.) small.
  - However, there are may be unknown unknowns!

[IceCube + LIGO-Virgo collaborations, 2014]



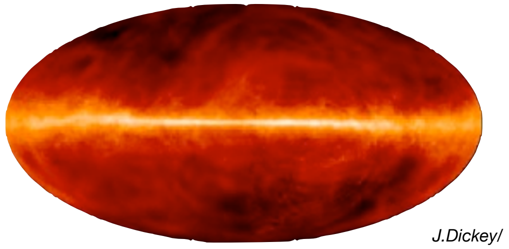


Summary

- First direct detection of GWs expected in the next few years by second-generation interferometric detectors.
- Once detected, GW observations will open a new, unique window for astronomy. Complementing, corroborating and perhaps challenging the information gained from EM/astroparticle observations.
- **LIGO India**: Great opportunity for the Indian scientific community to be a major player in a research frontier anticipating big discoveries!

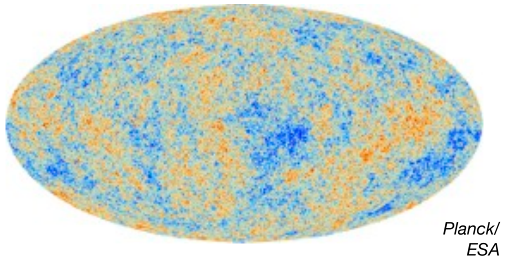
Observational windows to the Universe

Radio (21 cm)



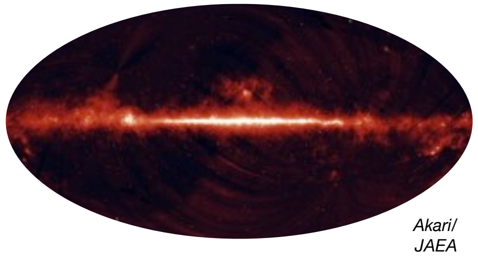
J.Dickey/
NASA SkyView

Microwave (CMB)

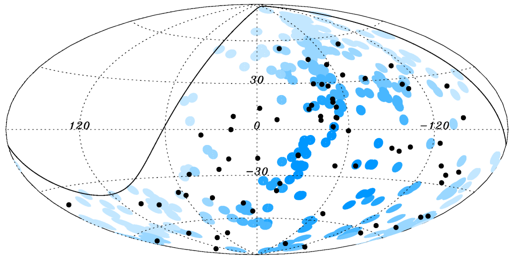


Planck/
ESA

Infrared (9 µm)



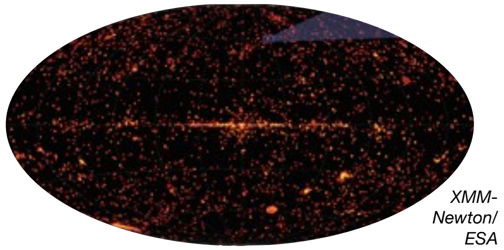
Akari/
JAEA



Optical

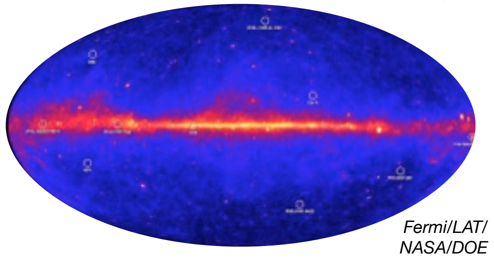
Axel
Mellinger

x-ray

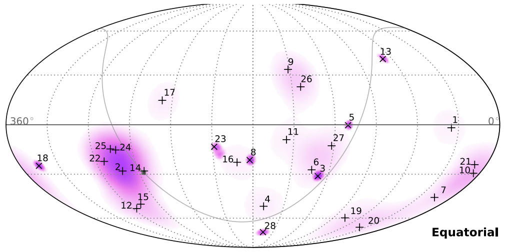


XMM-
Newton/
ESA

Gamma ray (GeV)

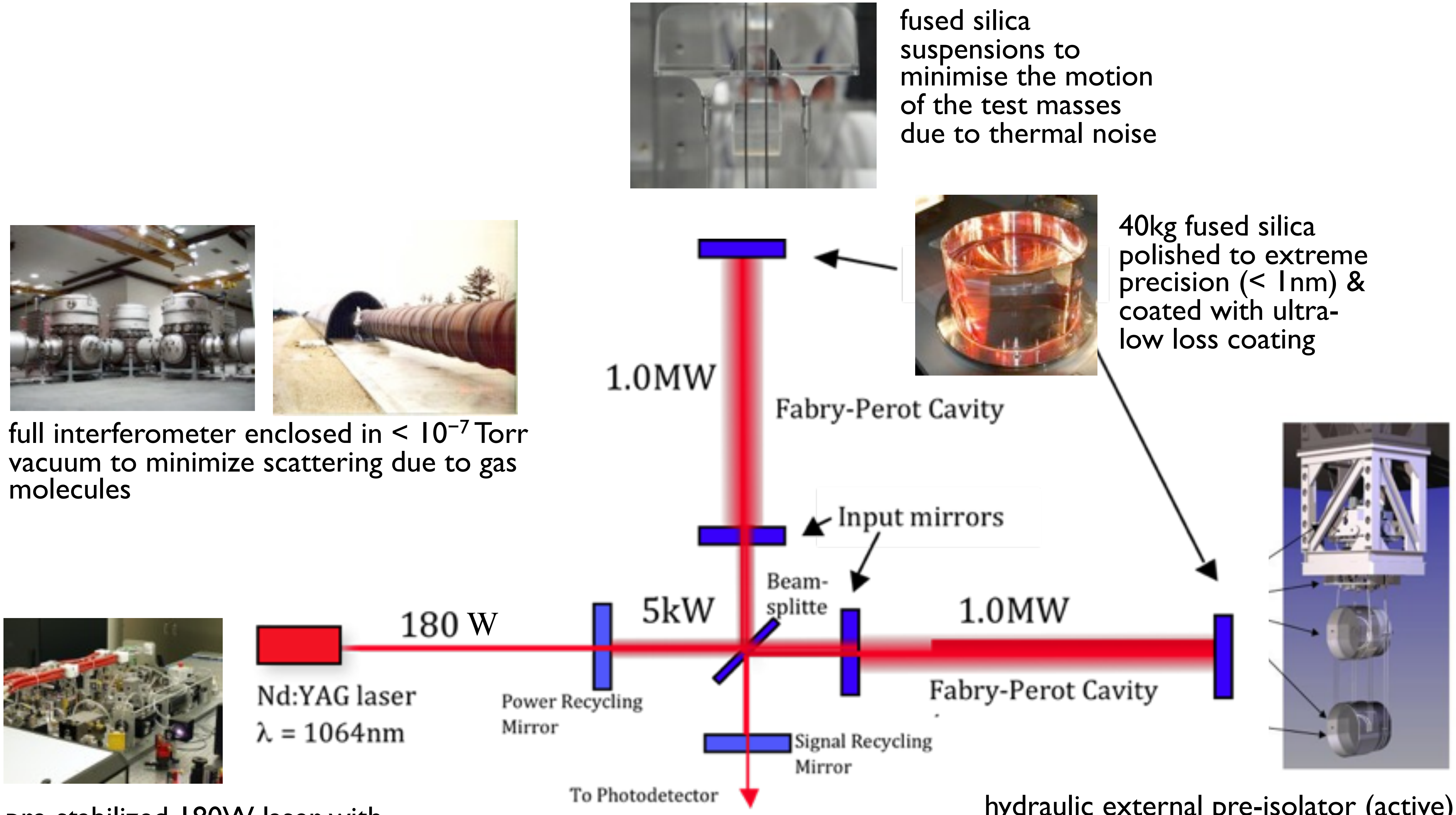


Fermi/LAT/
NASA/DOE



GW sky?

Advanced LIGO



fused silica suspensions to minimise the motion of the test masses due to thermal noise

40kg fused silica polished to extreme precision (< 1nm) & coated with ultra-low loss coating

full interferometer enclosed in $< 10^{-7}$ Torr vacuum to minimize scattering due to gas molecules

pre-stabilized 180W laser with intensity stability $10^{-9}/\sqrt{\text{Hz}}$ & frequency stability 10^{-7} Hz/$\sqrt{\text{Hz}}$.

hydraulic external pre-isolator (active) + 4 level suspensions (passive) to minimize seismic coupling