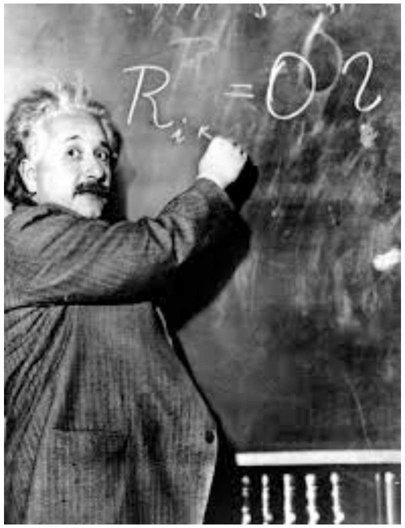
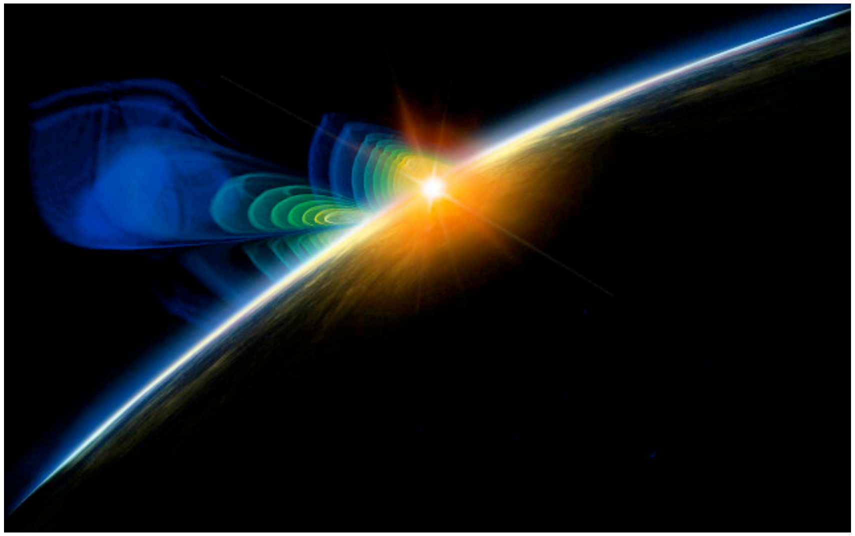
Einstein's GR @ 100: LIGO-enabled Science



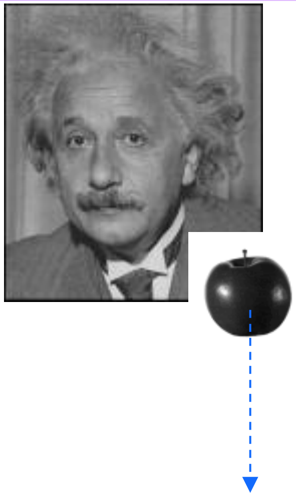
Gabriela González,
Louisiana State University

Advanced LIGO Dedication
LIGO Hanford Observatory, May 19, 2015

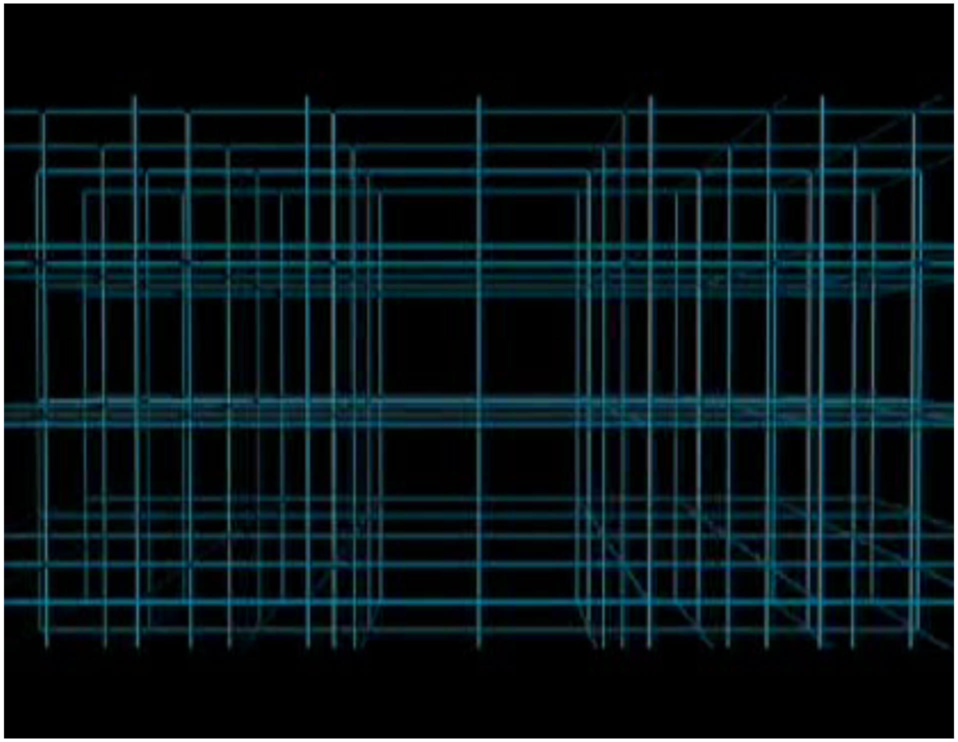


LIGO-G1500655

Einstein’s gravitation

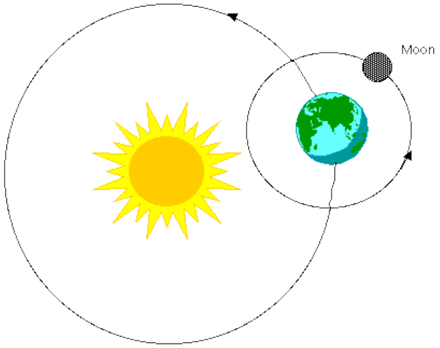


No “instantaneous gravitational force”
When masses move, they wrinkle the space time fabric, making other masses move.



Credit: AMNH

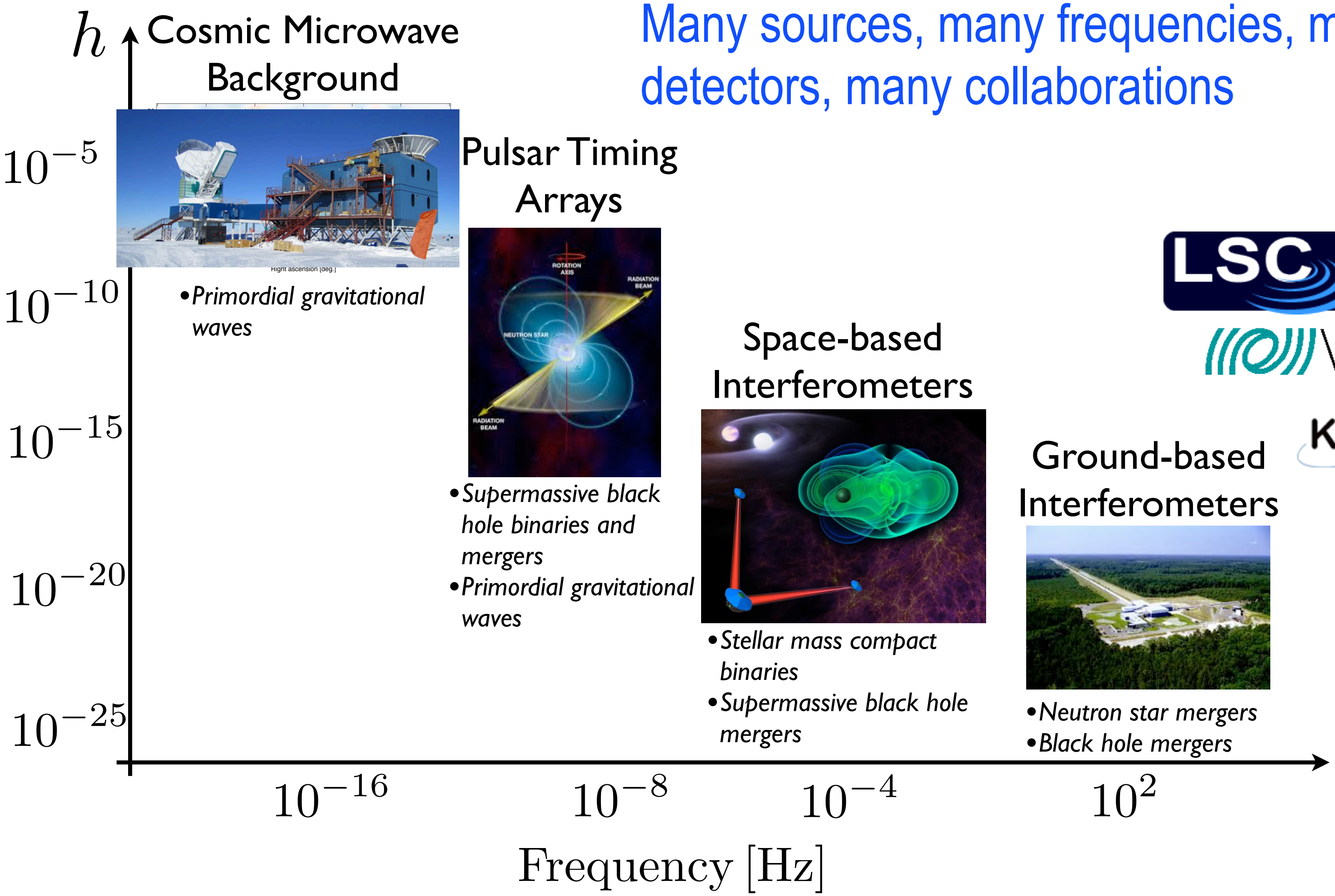
Explains just as well as Newton’s why apples fall and planetary motion…



.. but it also predicts gravitational waves traveling away from moving masses!

GW landscape

Many sources, many frequencies, many detectors, many collaborations



Cosmic Microwave Background

- *Primordial gravitational waves*

Pulsar Timing Arrays

- *Supermassive black hole binaries and mergers*
- *Primordial gravitational waves*

Space-based Interferometers

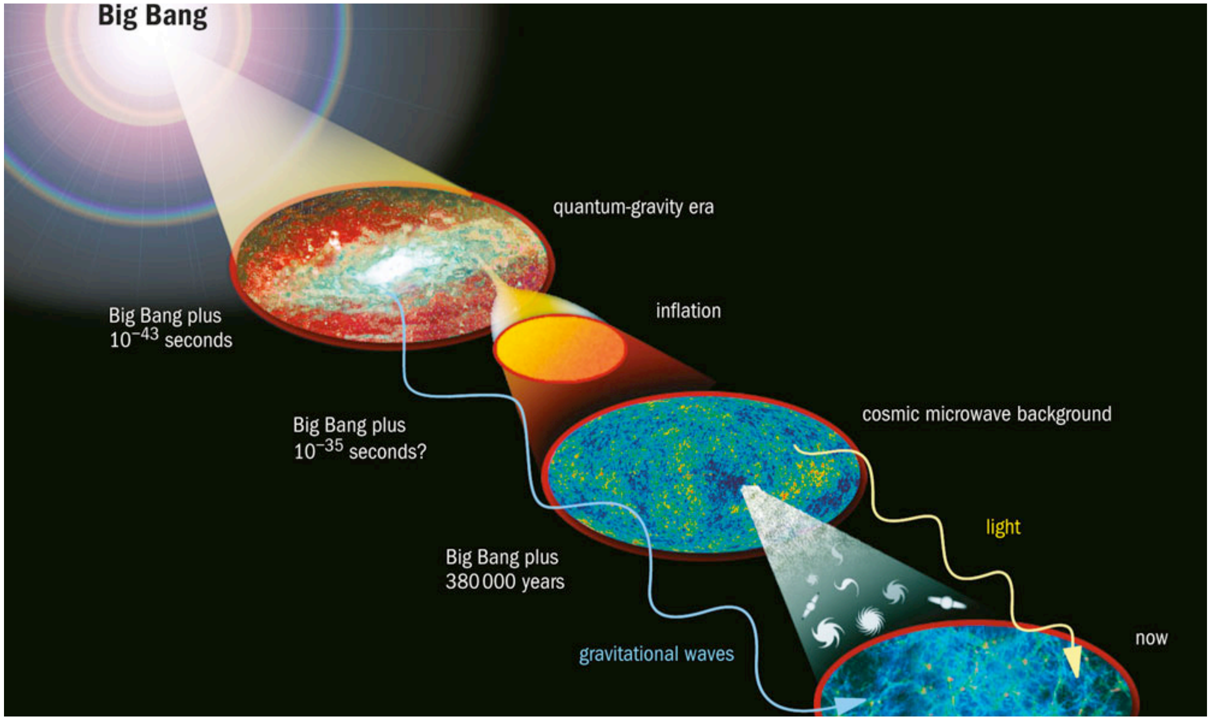
- *Stellar mass compact binaries*
- *Supermassive black hole mergers*

Ground-based Interferometers

- *Neutron star mergers*
- *Black hole mergers*

Credit: Nanograv/Bicep2

GWs from a stochastic background



(Courtesy: NASA)

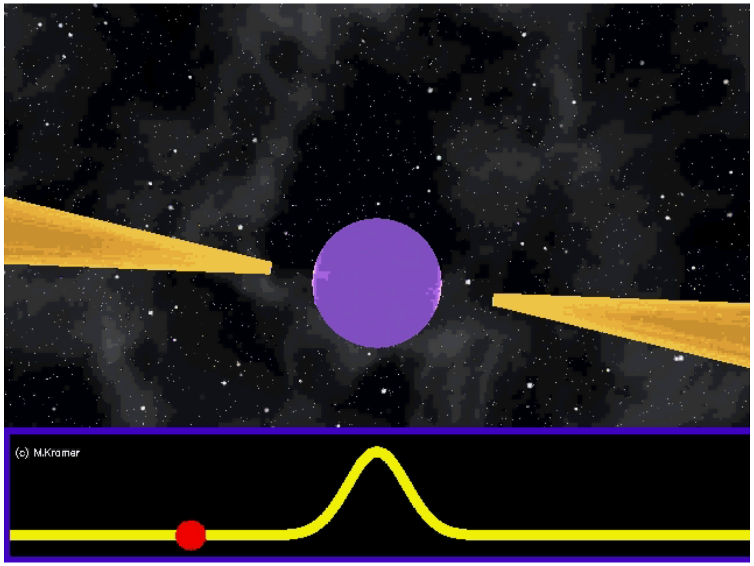
We have learned much about the early history of the Universe from observation of the “cosmic microwave background” (and using Einstein’s theory) – but there is also a “gravitational wave background” from even earlier times.

GWs from Supernova explosions

Credit: NASA

SN explosions generated by the collapse of a star under its own gravity give birth to neutron stars and black holes with mass close to the Sun's, but with the size of a city.
If the explosion is not perfectly symmetric, and happens in our Galaxy or very nearby, we may detect the gravitational waves produced with LIGO.

GWs from rotating stars

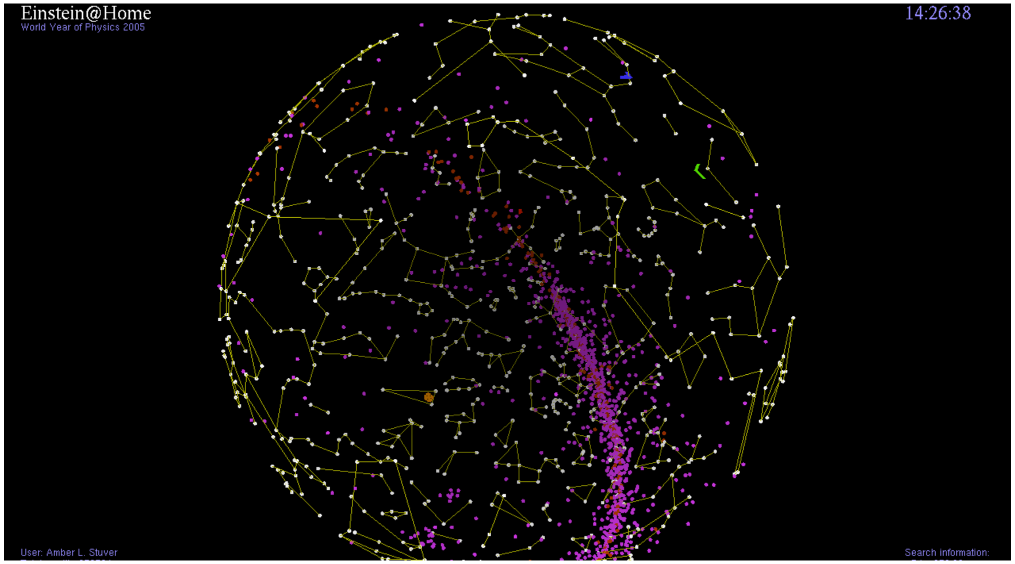


Credit: M. Kramer

Crab pulsar and nebula
Credit: NASA/CXC/ASU/J. Hester et al.

Neutron stars are born rapidly spinning, emitting electromagnetic beams: they are “pulsars”. Eventually, electromagnetic power is exhausted, and older neutron stars do not pulsate. Pulsars are very precise clocks – rivaling atomic clocks. “Pulsar timing” will allow detection of gravitational waves with parsec scale wavelengths and periods of years.
The structure of the interior of neutron stars, or “equation of state”, is not well known, and is something we can learn about from gravitational waves.

Neutron stars



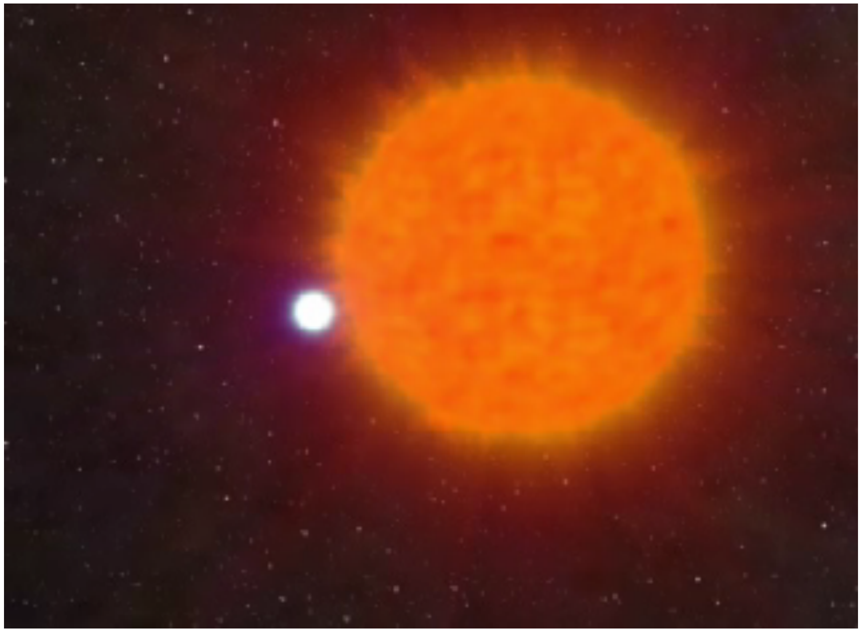
User: Amber L. Stuver

Search information:

Neutron stars emit gravitational waves themselves, with an amplitude proportional to their non-spherical shape and twice their rotation frequency – but neutron stars are *very* smooth!

There are about 2,000 pulsars observed in our galaxy, but there are about 100 million neutron stars in the Milky way.

Neutron stars in Binary systems

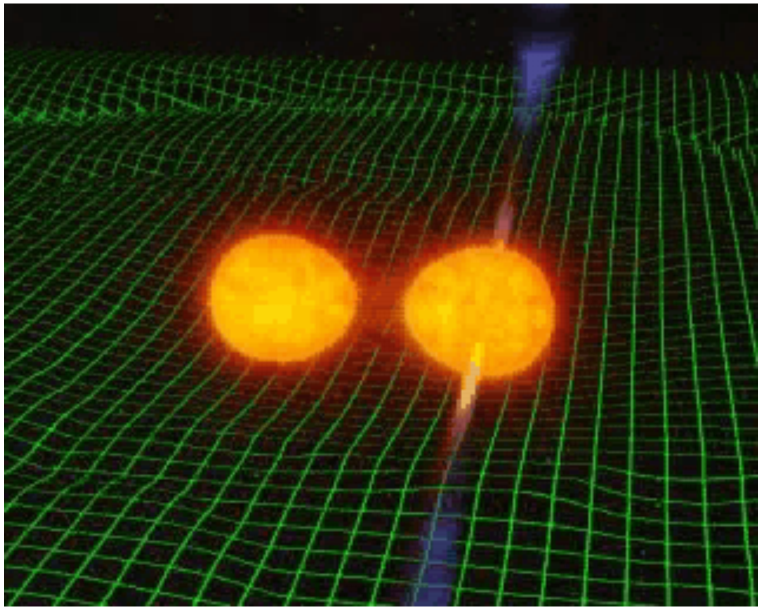


Credit: John Rowe animations

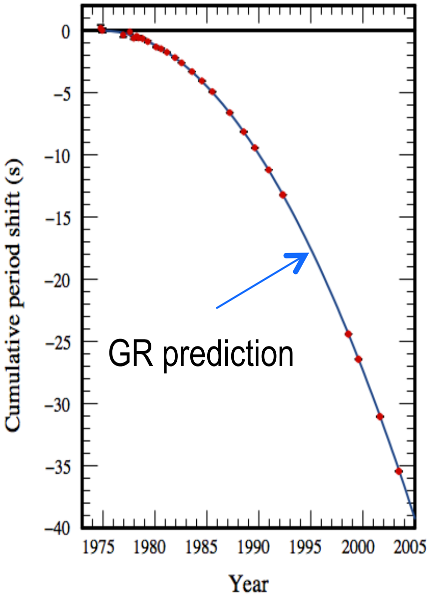
About 5% of neutron stars are part of a binary system, eventually forming a binary system with two neutron stars, or a neutron star and a black hole.

GWs from binary systems

Hulse,
Taylor
Nobel Prize
1993



Credit: [John Rowe animations]()



Weisberg, Nice & Taylor, 2010
(Courtesy Joel Weisberg)

Binary systems of compact objects as neutron stars and black holes lose energy to gravitational waves, orbiting closer and closer until merging into a larger black hole. The amplitude and frequency of the gravitational wave before the merger is “easy” to calculate using Einstein’s theory – this is likely to be the bread-and-butter of Advanced LIGO when it begins detecting astrophysical signals.

GR theory and waveforms

"Post Newtonian expansion"

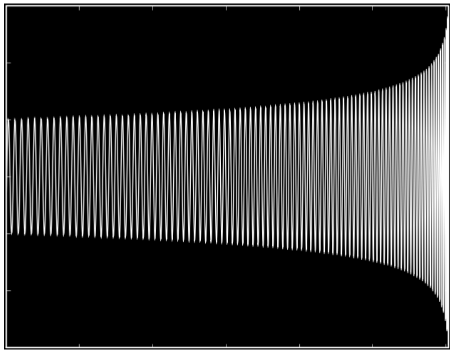
1 PN

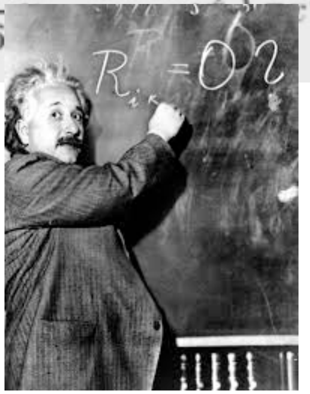
1.5 PN

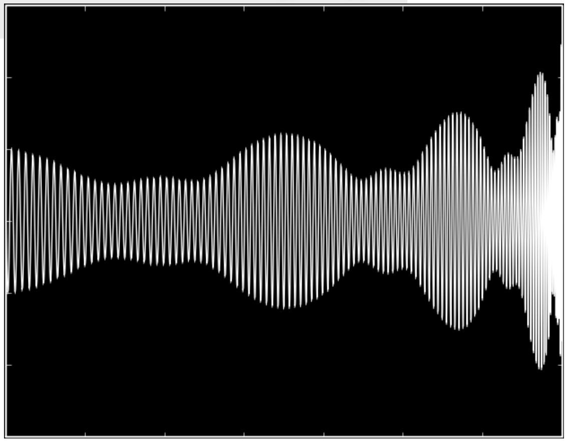
$$\phi = -\frac{x^{-5/2}}{32\nu}\left\{1 + \left(\frac{3715}{1008} + \frac{55}{12}\nu\right)x - 10\pi x^{3/2} + \left(\frac{15293365}{1016064} + \frac{27145}{1008}\nu + \frac{3085}{144}\nu^2\right)x^2 + \left(\frac{38645}{1344} - \frac{65}{16}\nu\right)\pi x^{5/2}\ln\left(\frac{x}{x_0}\right) + \left[\frac{12348611926451}{18776862720} - \frac{160}{3}\pi^2 - \frac{1712}{21}\gamma_E - \frac{856}{21}\ln(16x) + \left(-\frac{15737765635}{12192768} + \frac{2255}{48}\pi^2\right)\nu + \frac{76055}{6912}\nu^2 - \frac{127825}{5184}\nu^3\right]x^3 + \left(\frac{77096675}{2032128} + \frac{378515}{12096} \quad 74045 \quad {}^2\right) \quad {}^{7/2} + \mathcal{O}\left(\frac{1}{c^8}\right)\right\}, \qquad (318)$$

$$x \equiv \left(\frac{Gm\Omega}{c^3}\right)^{2/3} = \mathcal{O}\left(\frac{1}{c^2}\right).$$

Expansion parameter

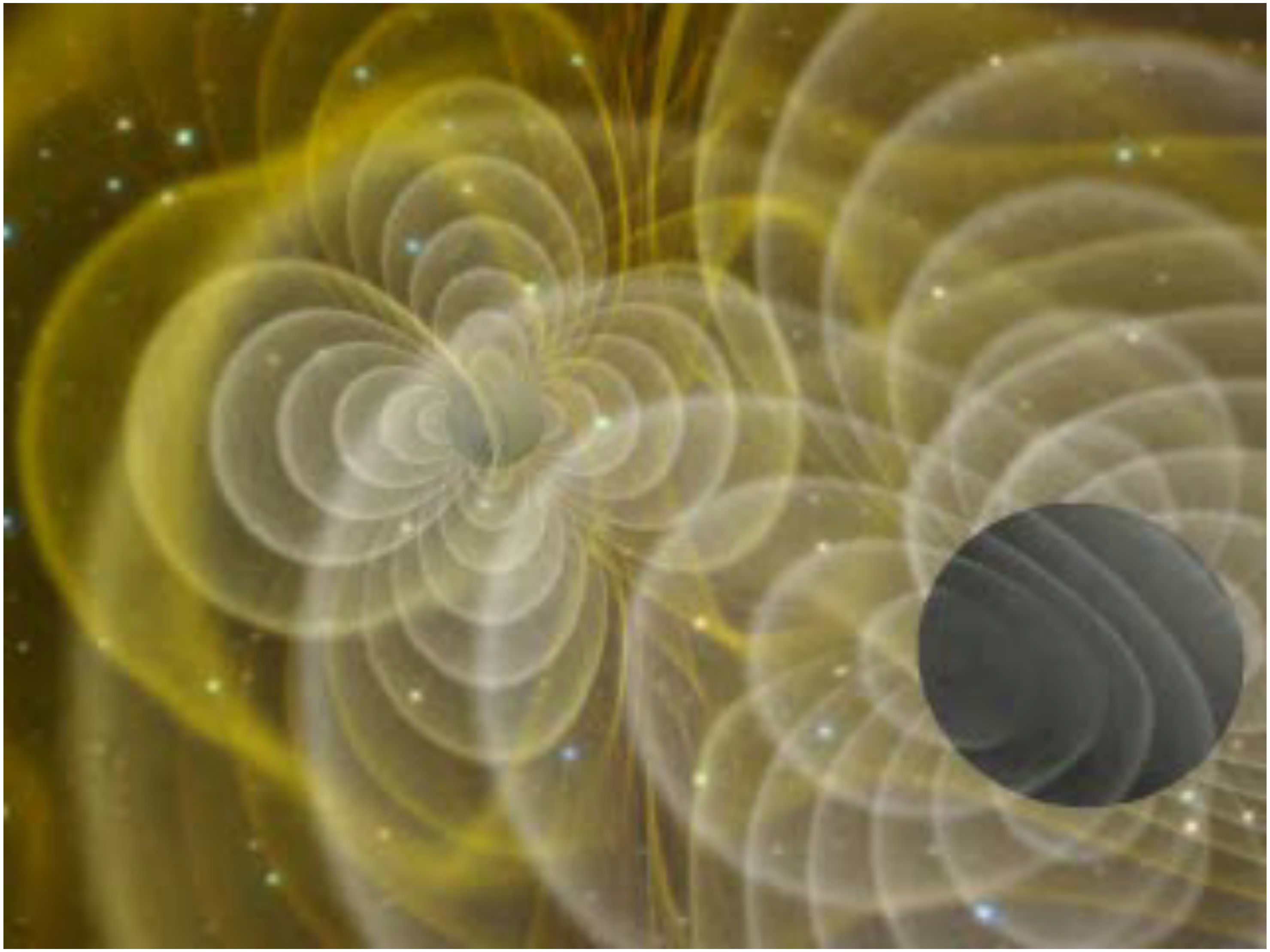






Living Rev. Relativity, 17 (2014), 2

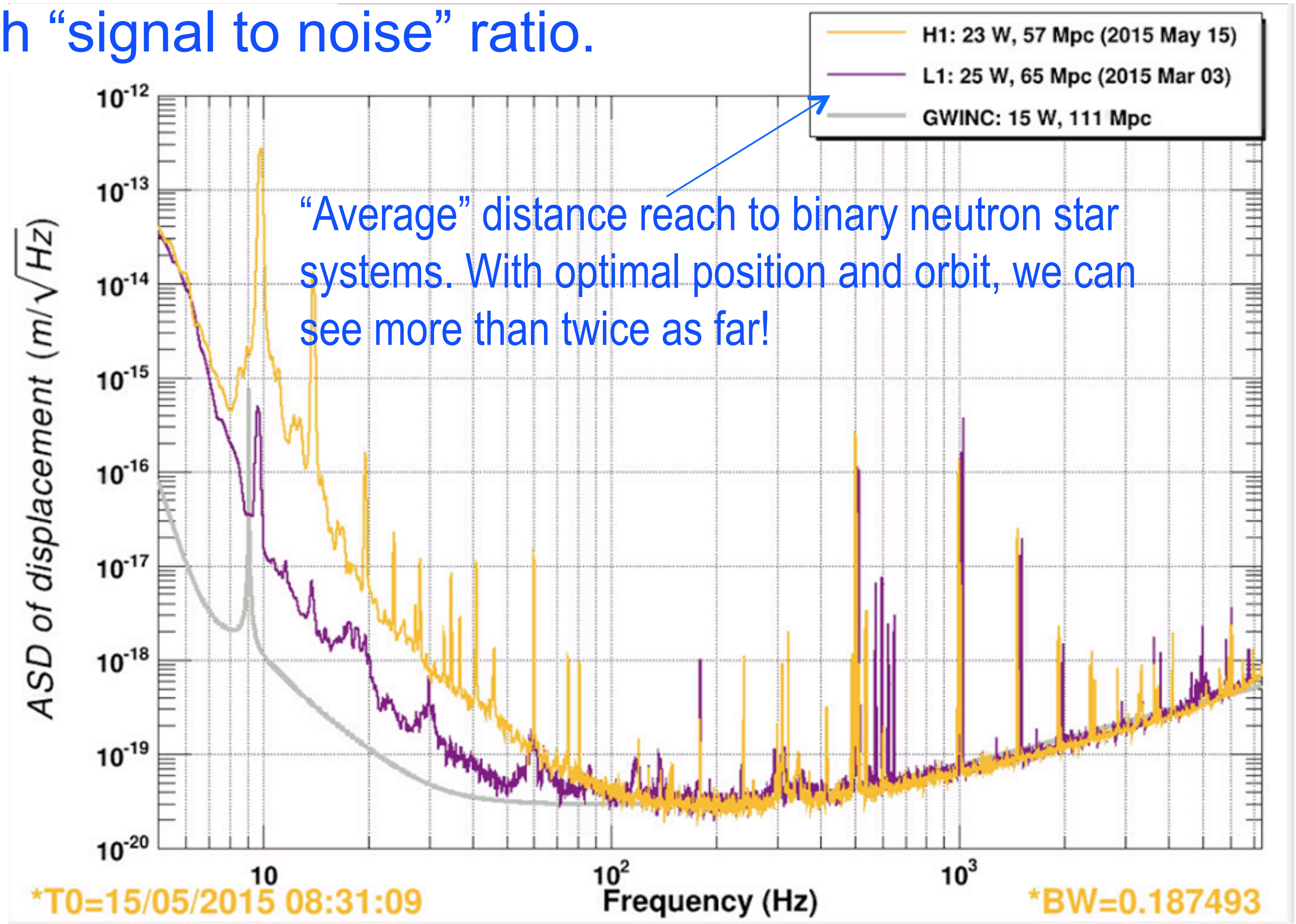
Einstein's GR on computers



Credit: Henze, NASA

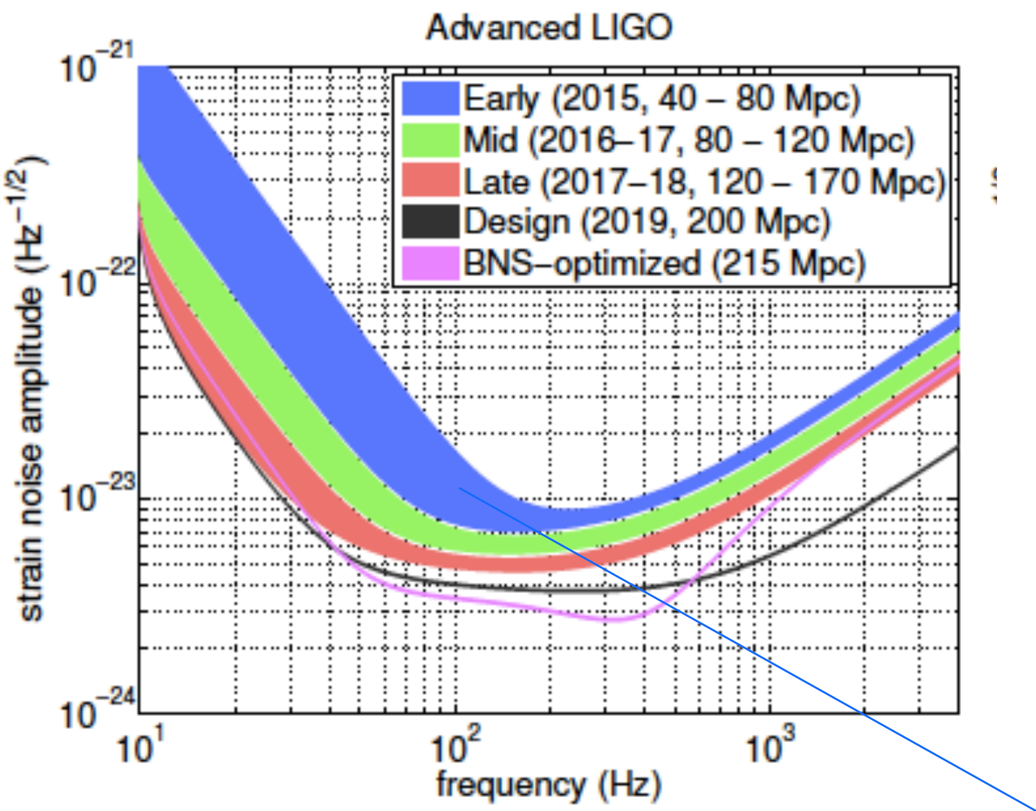
How far can we see?

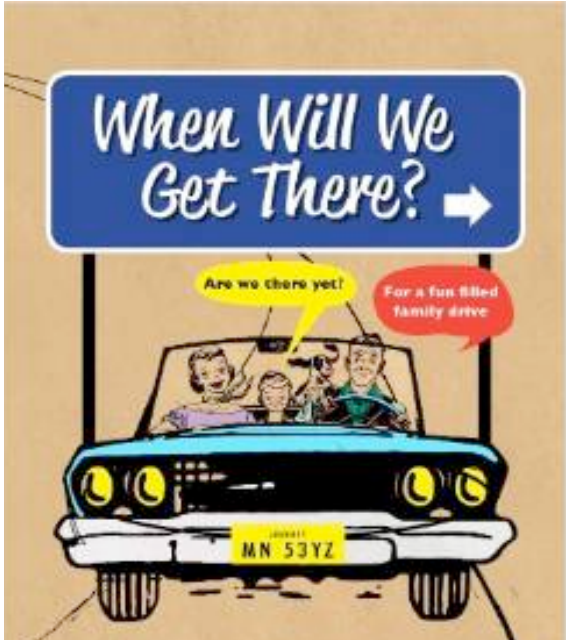
Using known waveforms for binary systems, given the “noise” in a detector we can calculate how far we can detect signals with enough “signal to noise” ratio.



“Average” distance reach to binary neutron star systems. With optimal position and orbit, we can see more than twice as far!

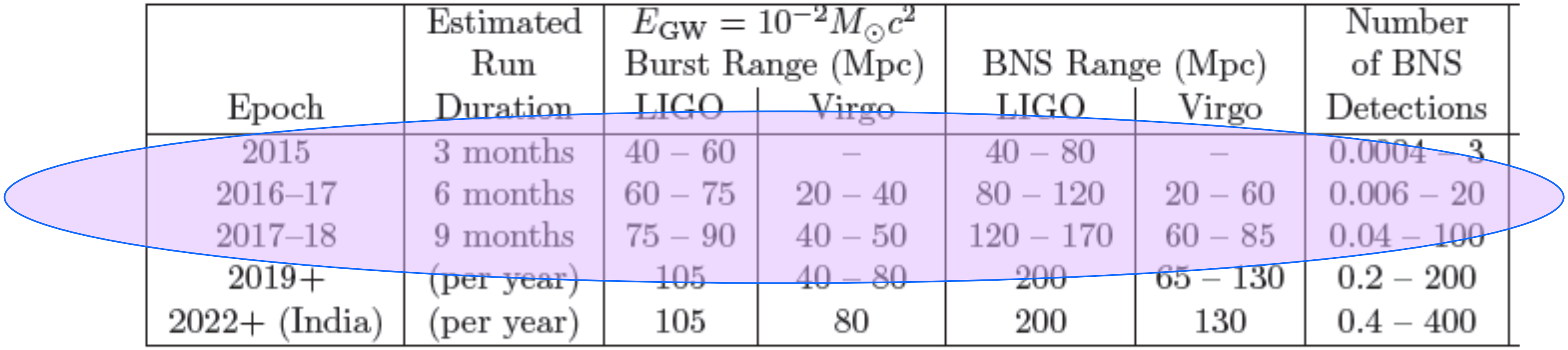
When will we detect GWs?





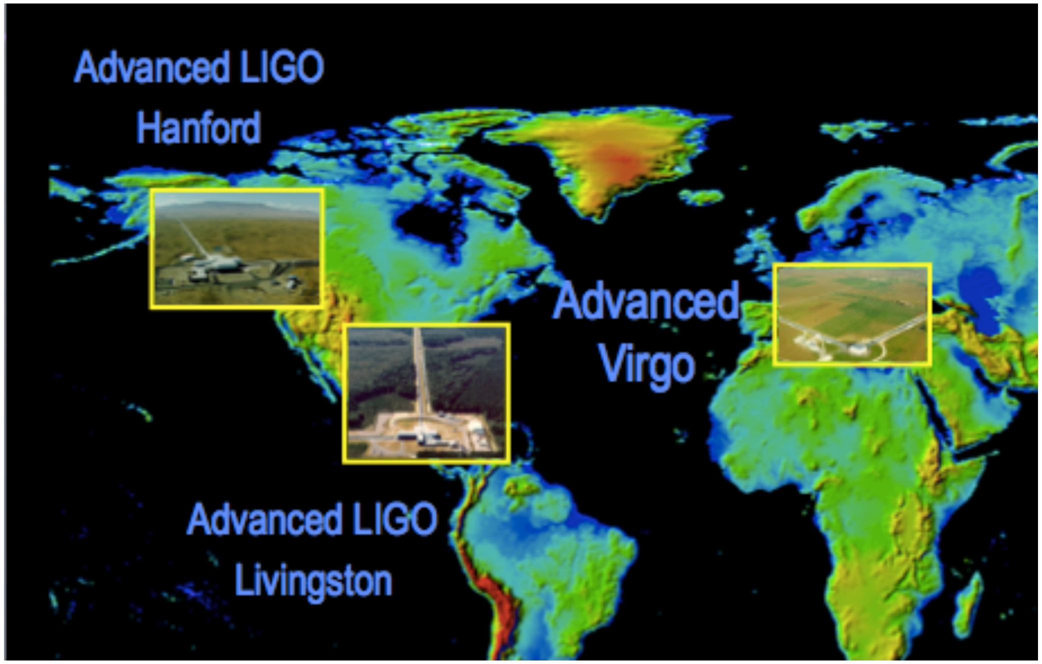
Already here!

We’ll have GWs soon



Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) Virgo	BNS Range (Mpc) LIGO	BNS Range (Mpc) Virgo	Number of BNS Detections
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200
2022+ (India)	(per year)	105	80	200	130	0.4 – 400

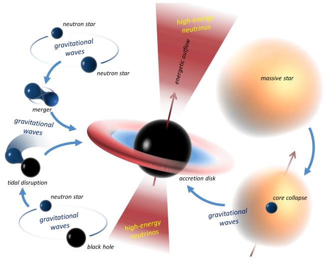
arXiv:1304.0670

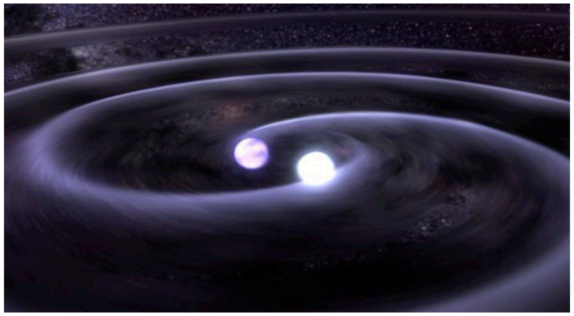


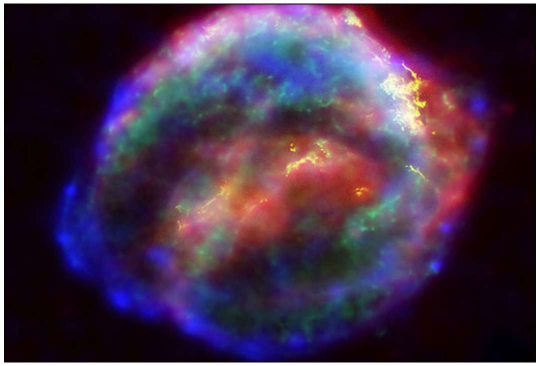
But that’s only the beginning…

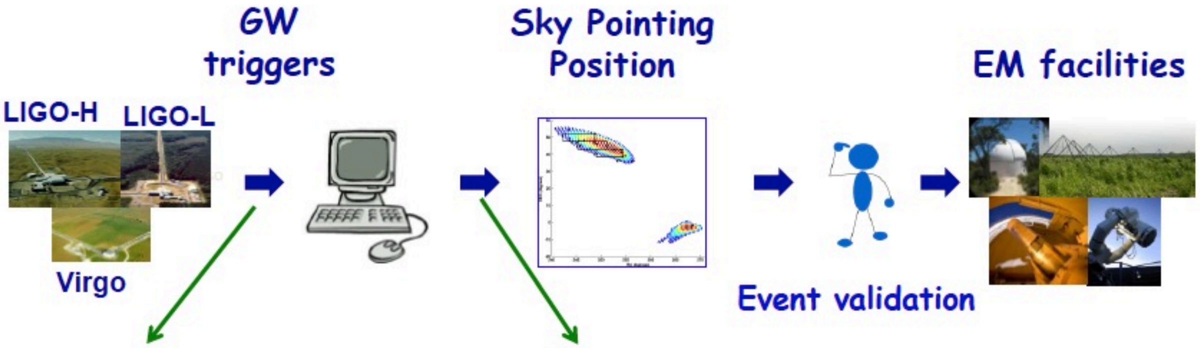
- Science with GWs will need more than the first few detections:
  - Astrophysics will need EM counterparts : multi-messenger astronomy.
  - Source localization and more uptime will need a world-wide gravitational network with several detectors.
  - Testing GR will need large signal-to-noise ratio detections, and comparison with numerical relativity simulations.
  - Equation of state of neutron stars information will arise from detectors’ sensitivity at ~kHz frequencies of the binary merger.
  - Population studies will need large statistics.

Multi-messenger astronomy









GW triggers

LIGO-H

LIGO-L

Virgo

Sky Pointing Position

Event validation

EM facilities

"Search Algorithms" to identify the GW-triggers

"Software" to identify GW-trigger for the EM follow-up:

- select statistically significant triggers wrt background
- determine telescope pointing

GW detectors follow HE, EM signals

Knowledge of transients from electromagnetic telescopes or satellites (GRBs) or neutrino detectors can be followed up in the GW data with more prior information.

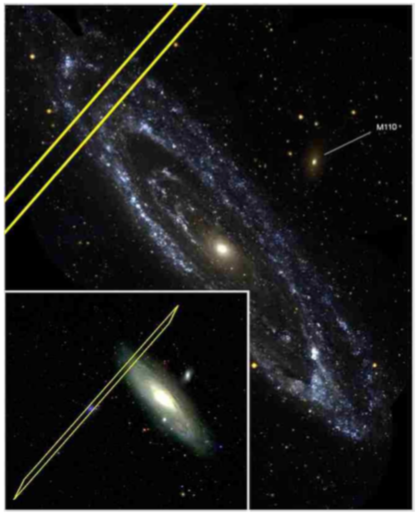
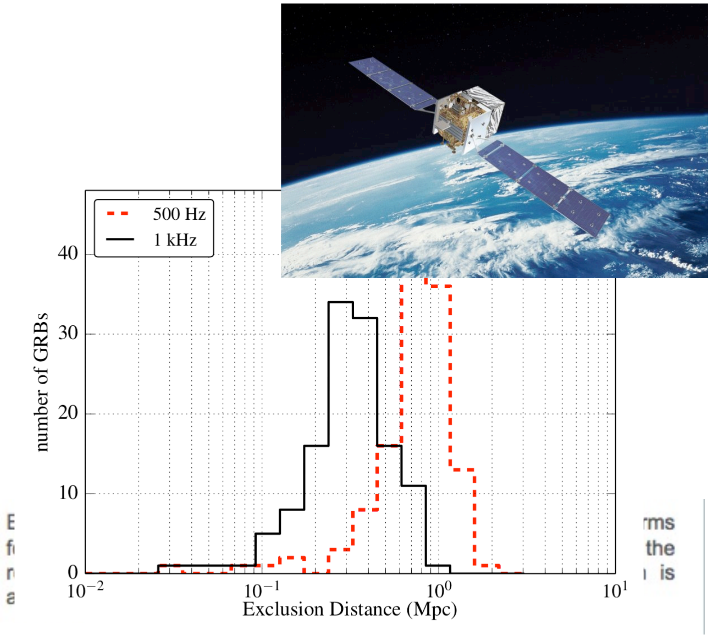


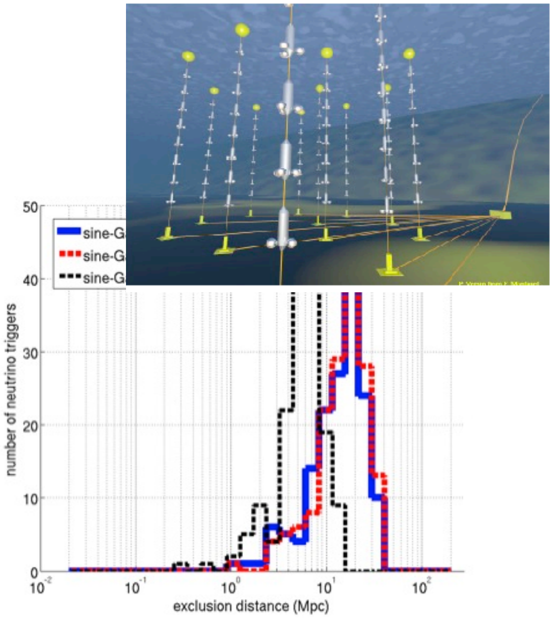
FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (Adelman-McCarthy et al. 2006; SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et al. 2005).

GRB070201
Astrophys. J. **681** (2008) 1419



Follow up of 129 GRBs

PRD 89 (2014), 122004



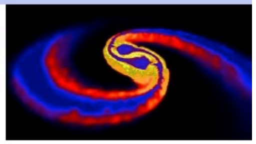
Joint search with Antares

JCAP **1306** (2013) 008

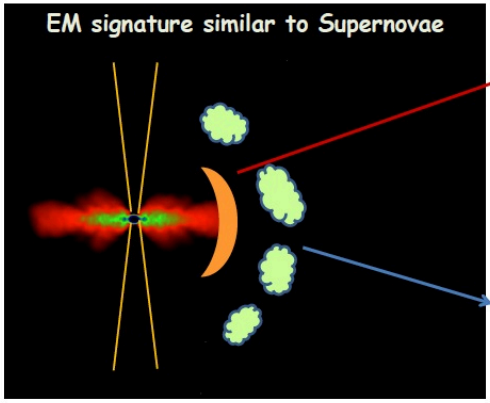
Known multi-messengers

Kilonovae

Significant **mass (0.01-0.1 m_o)** is **dynamically ejected** during **NS-NS NS-BH mergers** at **sub-relativistic velocity (0.1-0.2 c)**



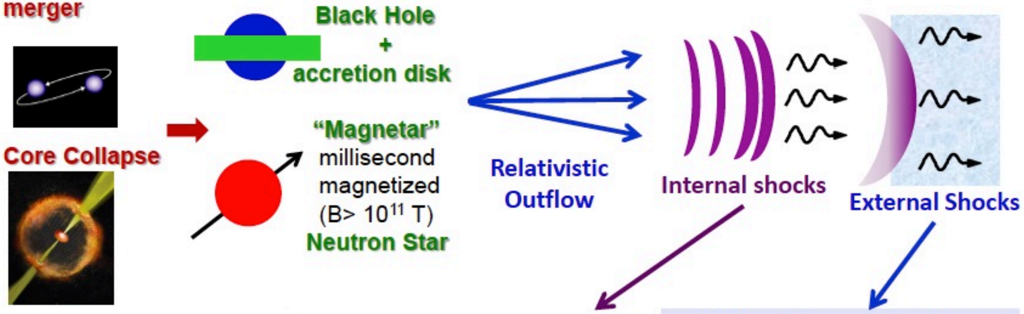
(Piran et al. 2013, MNRAS, 430; Rosswog et al. 2013 , MNRAS, 430)



Macronova – Kilonova
short lived IR-UV signal (days) powered by the radioactive decay of heavy elements synthesized in the ejected outflow **Kulkarni 2005, astro-ph0510256; Li & Paczynski 1998,ApJL, 507 Metzger et al. 2010, MNRAS, 406; Piran et al. 2013, MNRAS, 430**

RADIO REMNANT
long lasting radio signals (years) produced by interaction of ejected sub-relativistic outflow with surrounding matter **Piran et al. 2013, MNRAS, 430**

GRBs emission - Fireball Model



Cataclysmic event

NS-NS NS-BH merger

Core Collapse

Central engine

Black Hole + accretion disk

"Magnetar" millisecond magnetized (B> 10^{11} T) **Neutron Star**

Relativistic Outflow

Internal shocks

External Shocks

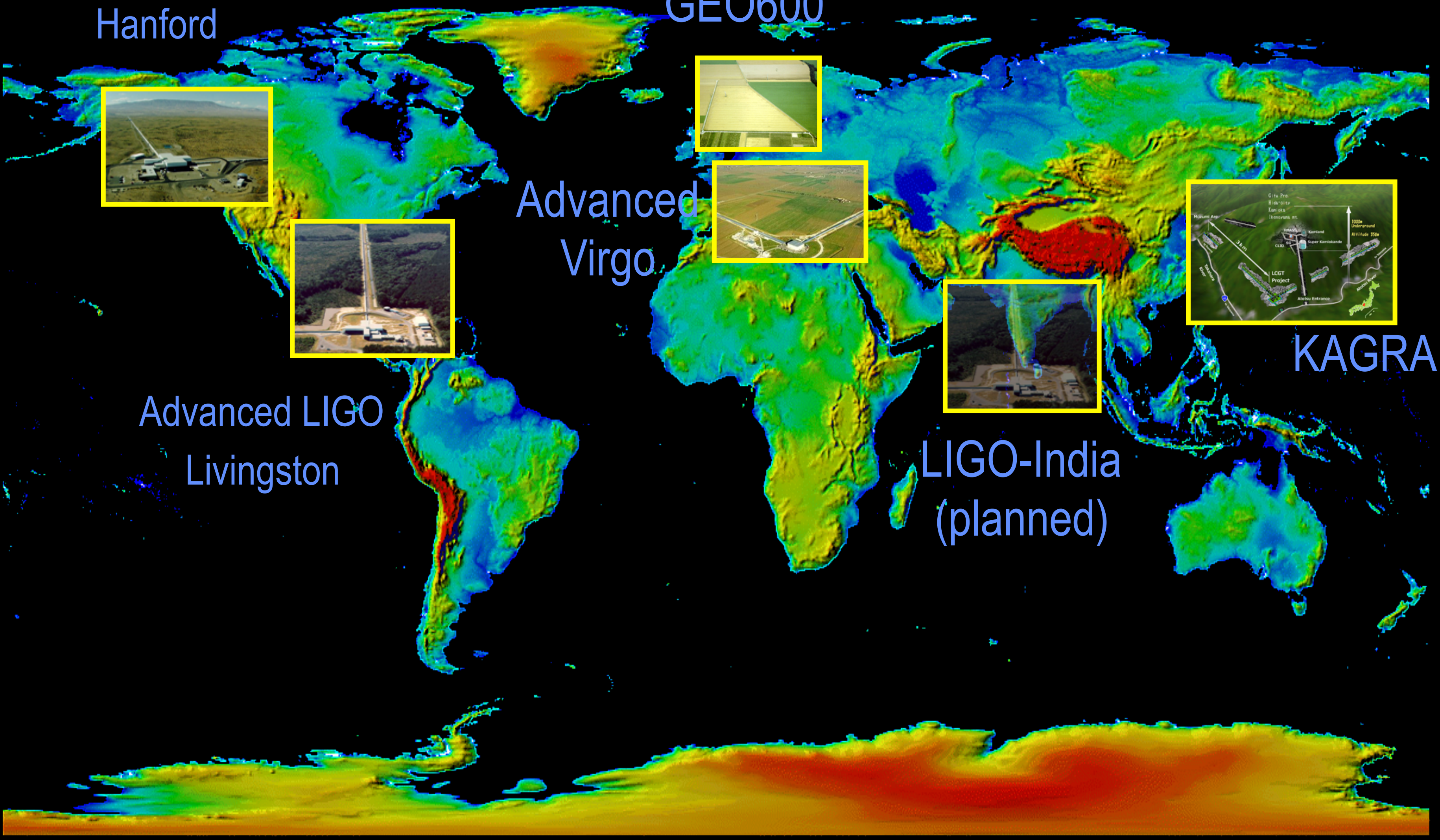
Prompt emission

γ-ray - within seconds

Afterglow emission

Optical, X-ray, radio - hours, days, months

The GW Detector Network~2022



Advanced LIGO
Hanford

GEO600

Advanced
Virgo

KAGRA

Advanced LIGO
Livingston

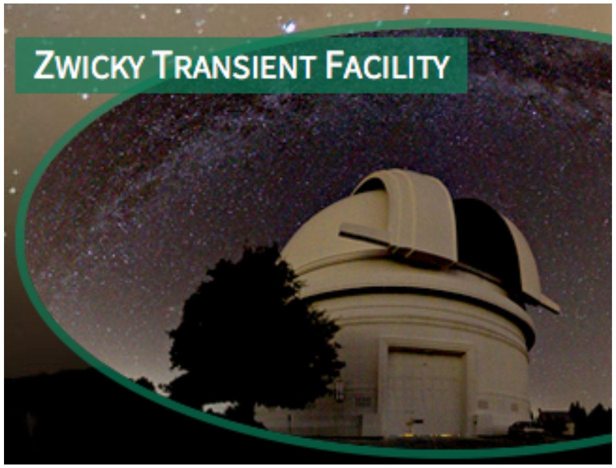
LIGO-India
(planned)

Some of our partners – ready to observe!

More than 70 astronomy agreements with partners for 2015-18

THE DARK ENERGY SURVEY

SAAO
South African Astronomical Observatory



CRTS *Catalina Real-Time Transient Survey*

TAROT

Télescopes à Action Rapide pour les Objets Transitoires

INAF ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

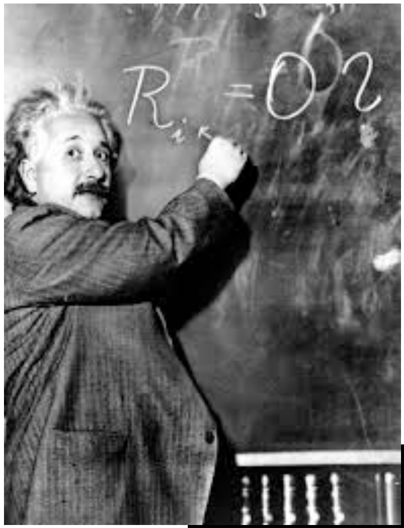
Exciting near future observations

LSST received its federal construction start in 2014 and will achieve engineering first light five years after that. Full science operations for the ten-year survey will begin two years after engineering first light.

What 0.5deg^2 will look like with LSST:

Deep Lens Survey / UC Davis / NOAO

GR@100 and LIGO



Einstein would be very happy visiting LIGO today, and would not doubt we are at the dawn of gravitational wave astrophysics.