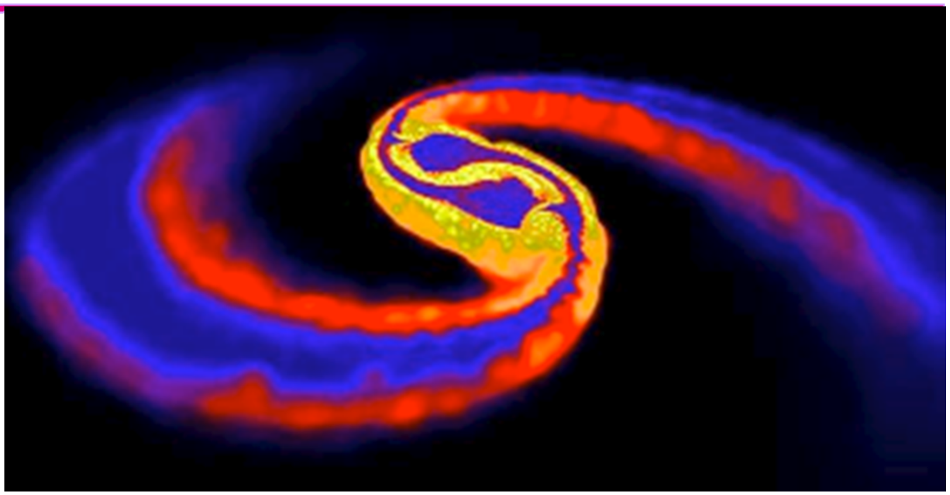
Exploring the Universe with Gravitational Waves

- Gravitational waves
- Global network of GW detectors
- Source localization
- Advanced LIGO
- Astrophysical sources
- Opening the GW sky

No discovery to report here!



"Merging Neutron Stars" (Price & Rosswog)

Fig. 1.1 – LIGO detector with 4 km arms at Livingston, Louisiana

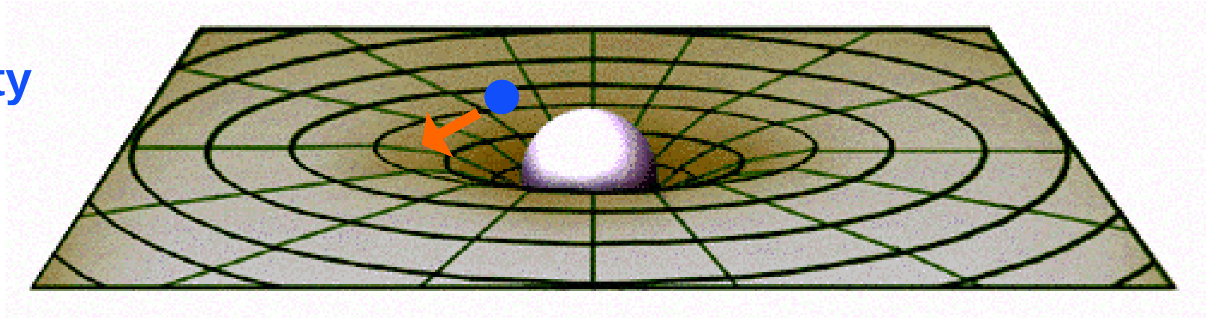
Fig. 1.2 – Virgo Detector, with 3 km arms, at Cascina, near Pisa

Alan Weinstein, Caltech
for the LIGO Scientific Collaboration

LIGO-G1300642
Lepton-Photon, SF, 24-29 June 2013

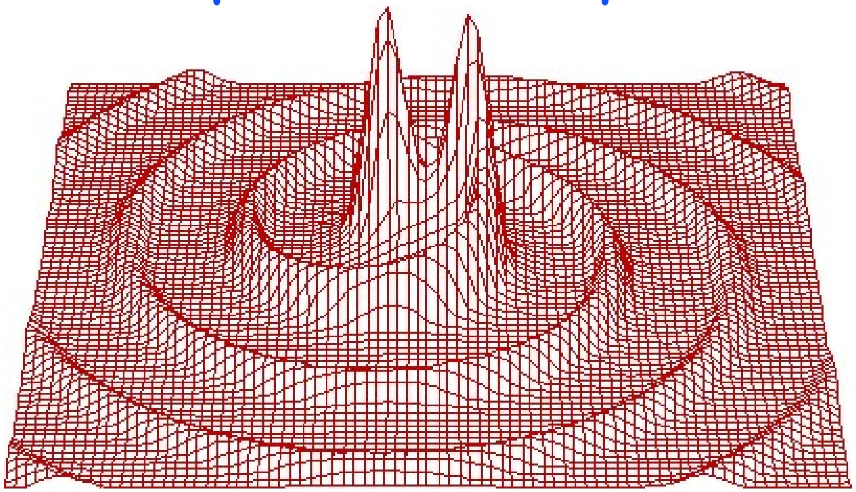
Gravitational Waves

Static gravitational fields are described in General Relativity as a curvature or warpage of space-time, changing the distance between space-time events.



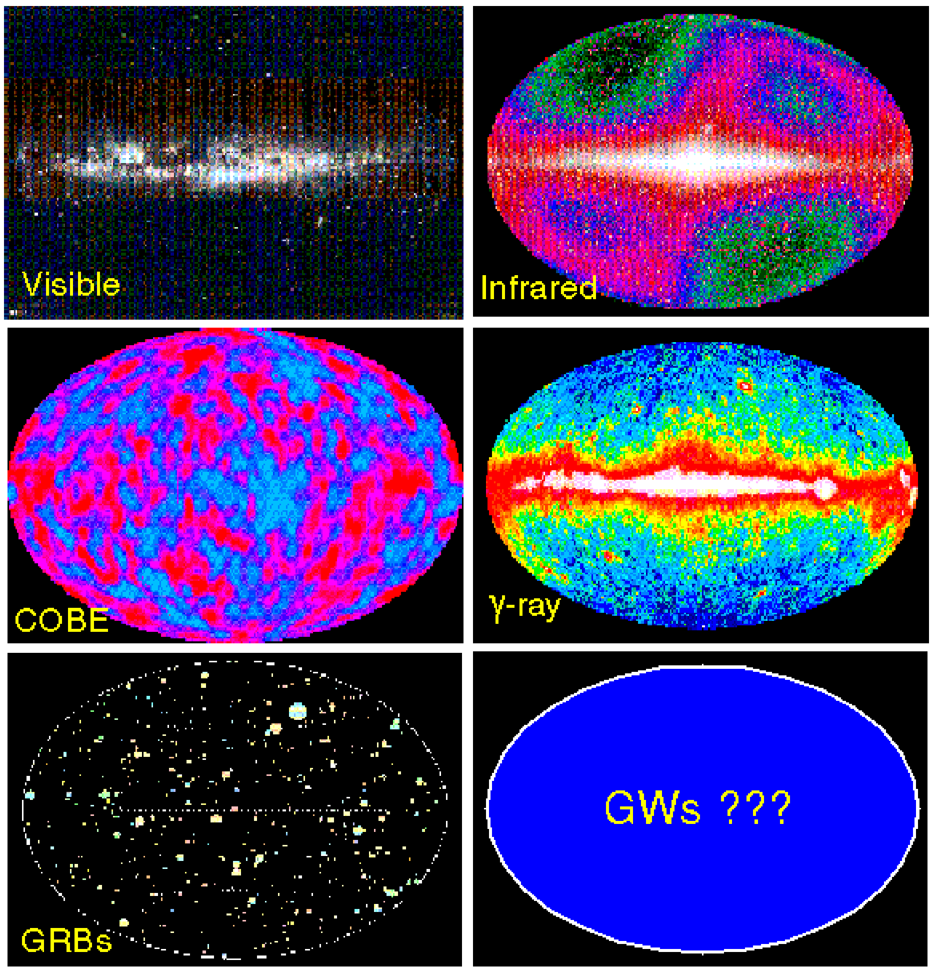
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

Shortest straight-line path of a nearby test-mass is a ~Keplerian orbit.



If the source is moving (at speeds close to c), *eg,* because it's orbiting a companion, the "news" of the changing gravitational field propagates outward as gravitational radiation – a wave of spacetime curvature

A NEW WINDOW ON THE UNIVERSE



The history of Astronomy: new bands of the EM spectrum opened → major discoveries!

GWs aren't just a new band, they're a new spectrum, with very different and complementary properties to EM waves.

- Vibrations *of* space-time, not *in* space-time
- Emitted by coherent motion of huge masses moving at near light-speed; not vibrations of electrons in atoms
- Can't be absorbed, scattered, or shielded.

GW astronomy is a totally new, unique window on the universe

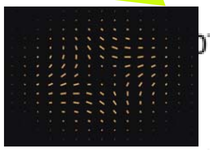
Frequency range of GW Astronomy

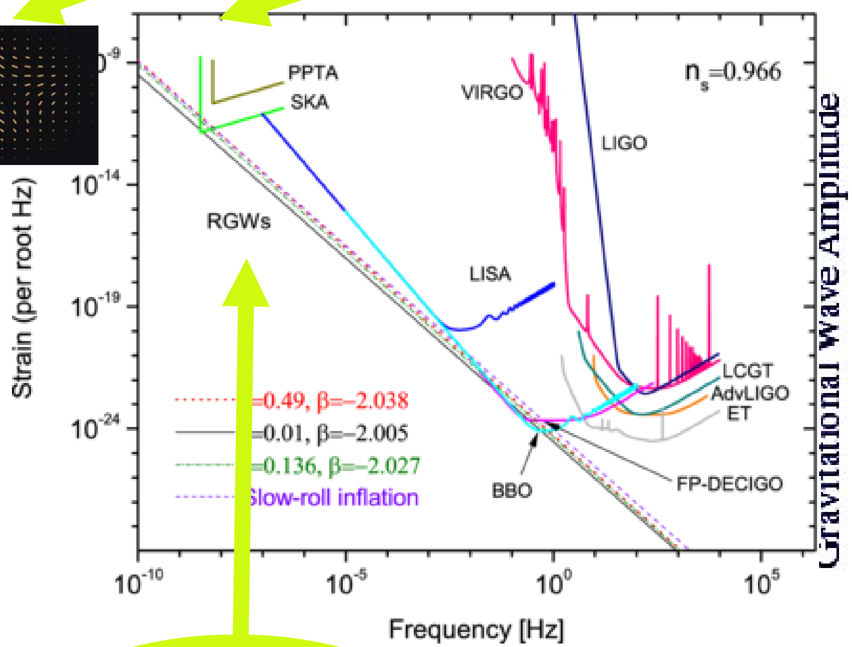
CMB B-pol

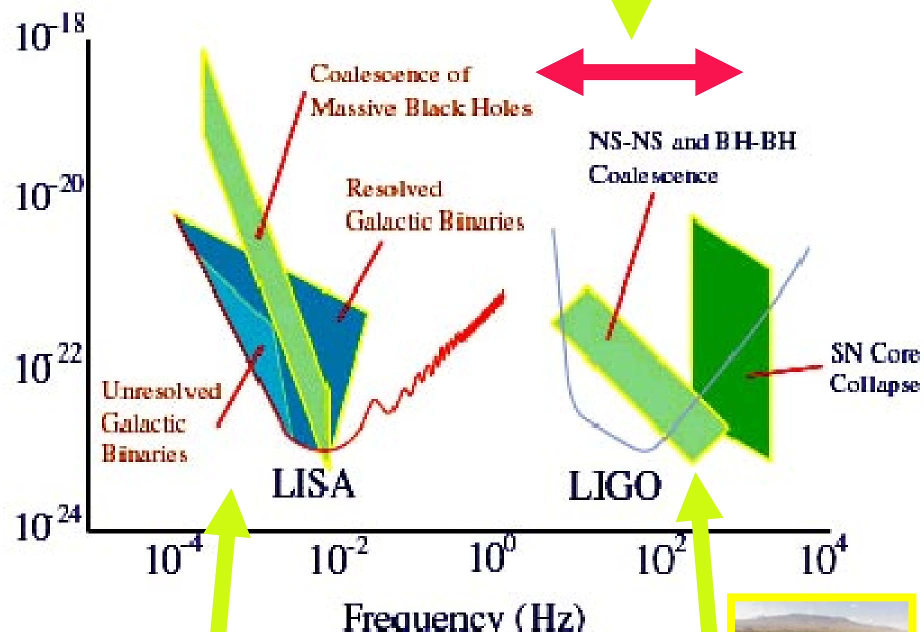
nHz

Audio band

Figure 5 from Minglei Tong 2012 Class. Quantum Grav. 29 155006

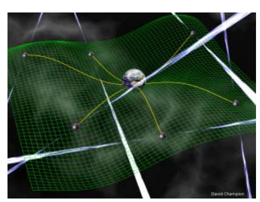






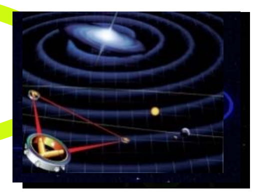
Pulsar timing

http://www.ipta4gw.org/



Space

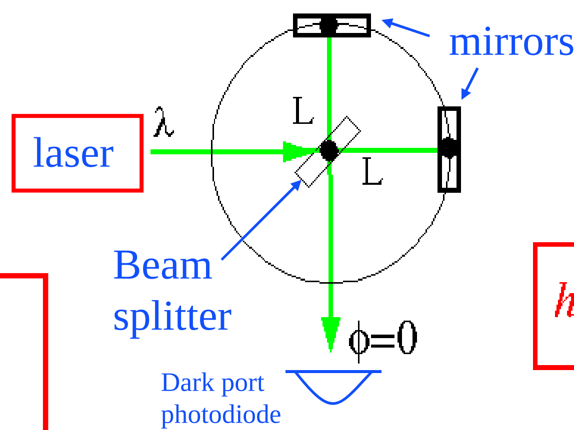
www.elisa-ngo.org/

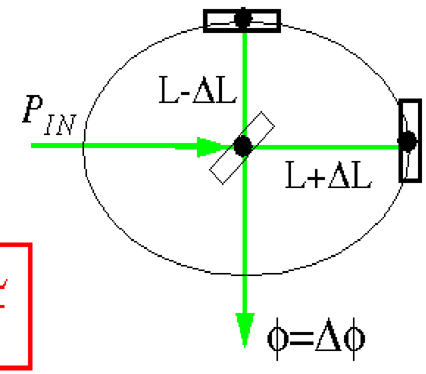


Terrestrial

Interferometric detection of GWs

GW acts on freely falling masses:



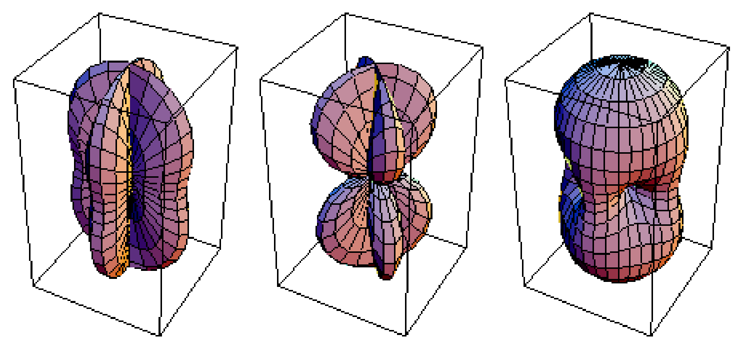


$$h = \frac{\Delta L}{L}$$

For fixed ability to measure ΔL, make L as big as possible!

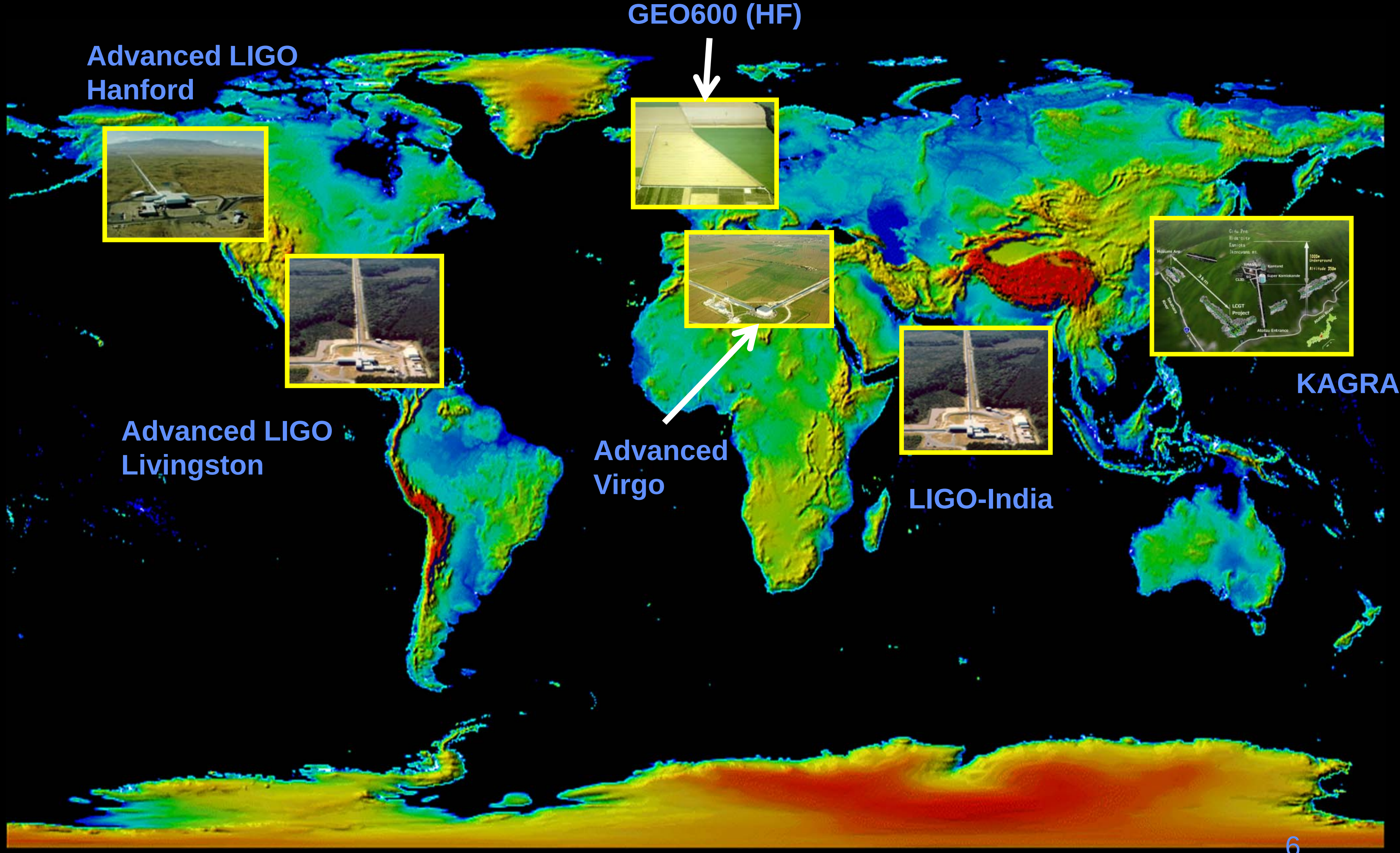
$$P_{out} = P_{in} \sin^2(2k\Delta L)$$

Antenna pattern:
(not very directional!)



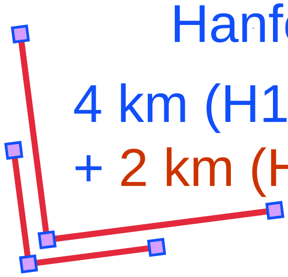
+ polarization × polarization unpolarized

The Advanced GW Detector Network



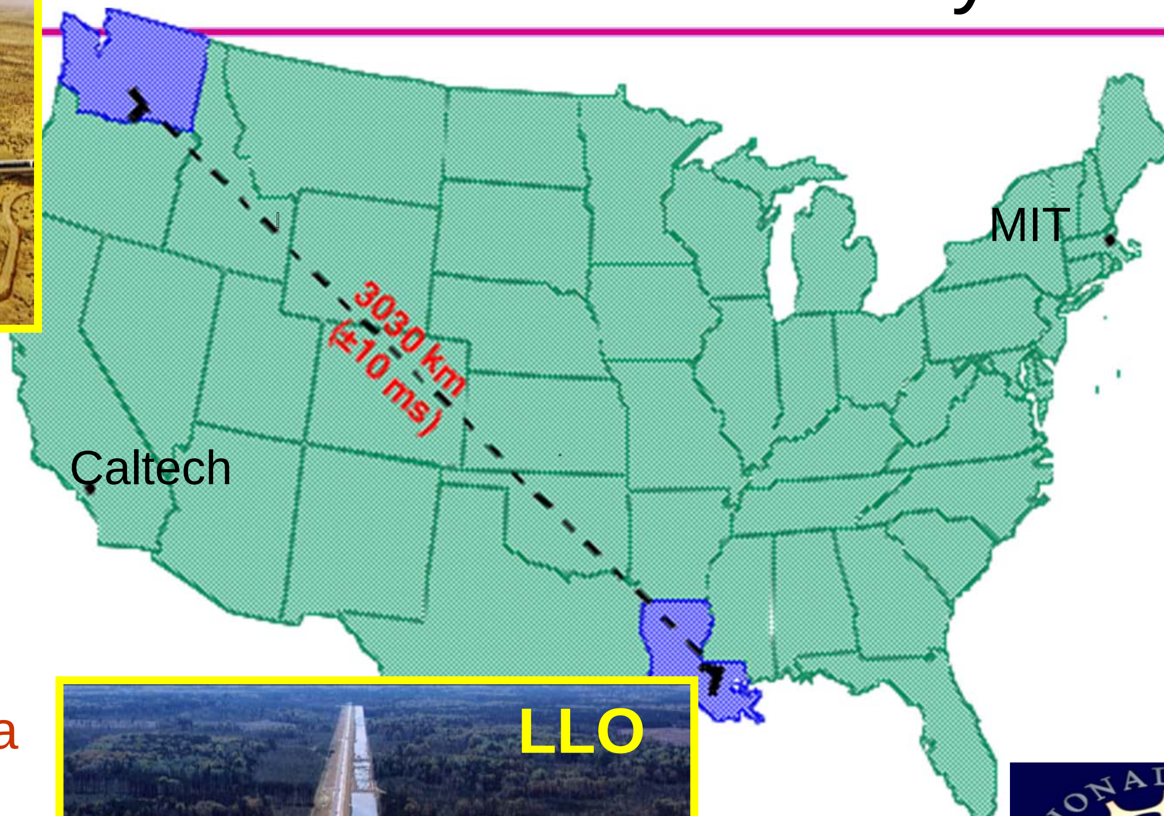
LIGO: Laser Interferometer Gravitational-wave Observatory

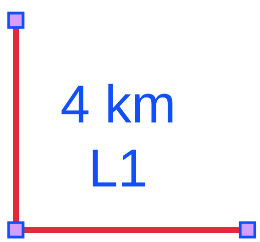
Hanford, WA



4 km (H1)
+ 2 km (H2), c.2010

Plan for ~2015:
aLIGO 4km H2 to India





4 km
L1

Livingston, LA

LIGO Scientific Collaboration

LIGO

LSC

University of Maryland 1856

Michigan

University of Strathclyde

ACIGA

Loyola University New Orleans

Montana State University

University of Washington

University of Glasgow

Syracuse University Founded AD 1870

Trinity University

San José State University

University of Wisconsin UW Milwaukee

ANU The Australian National University

Università degli Studi del Sannio

LSU

UTB TSC

The University of Western Australia

1754

NASA Goddard Space Flight Center

Moscow State University

California Institute of Technology 1891

Northwestern University

Rochester Institute of Technology R·I·T 1829

Andrews University

The University of Adelaide Australia

Massachusetts Institute of Technology

Southeastern Louisiana University

University of Massachusetts Amherst 1863

Embry-Riddle Aeronautical University

University of Southampton

PennState 1855

Carleton College Northfield, Minn. A.D. 1866

GEO 600

Cardiff University

Universitat de les Illes Balears

Washington State University

UF University of Florida

The University of Mississippi

Charles Sturt University

University of Rochester

NAOJ

University of Minnesota

Southern University Agricultural & Mechanical College

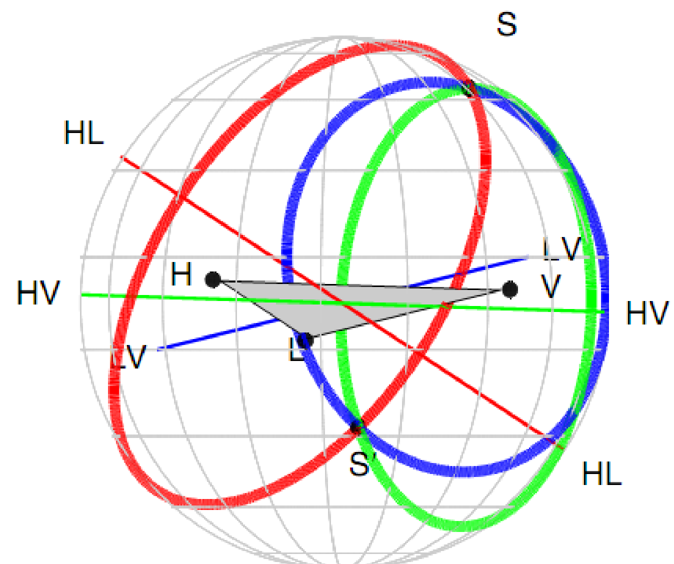
Hobart and William Smith Colleges

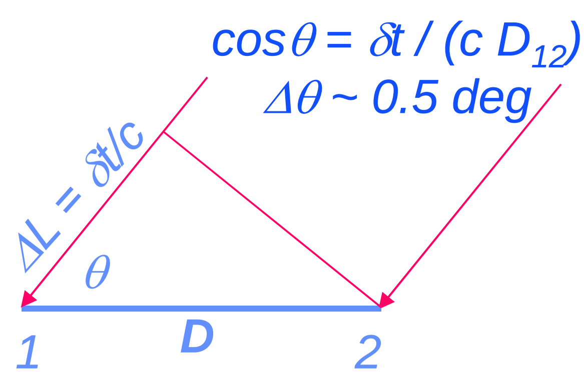
Science & Technology Facilities Council Rutherford Appleton Laboratory

Universität Hannover

Event Localization With An Array of GW Interferometers

- Gravitational-wave astronomy is *greatly* enhanced by having a multiplicity of interferometers distributed over the globe.
  - » GW interferometry, ‘Aperture synthesis’
- Advantages include:
  - » Source localization *in near real time*
  - » Enhanced network sky coverage
  - » Maximum time coverage – a fraction of the detectors are‘always listening’
  - » Detection confidence - coincidence
  - » Source parameter estimation
  - » Polarization resolution

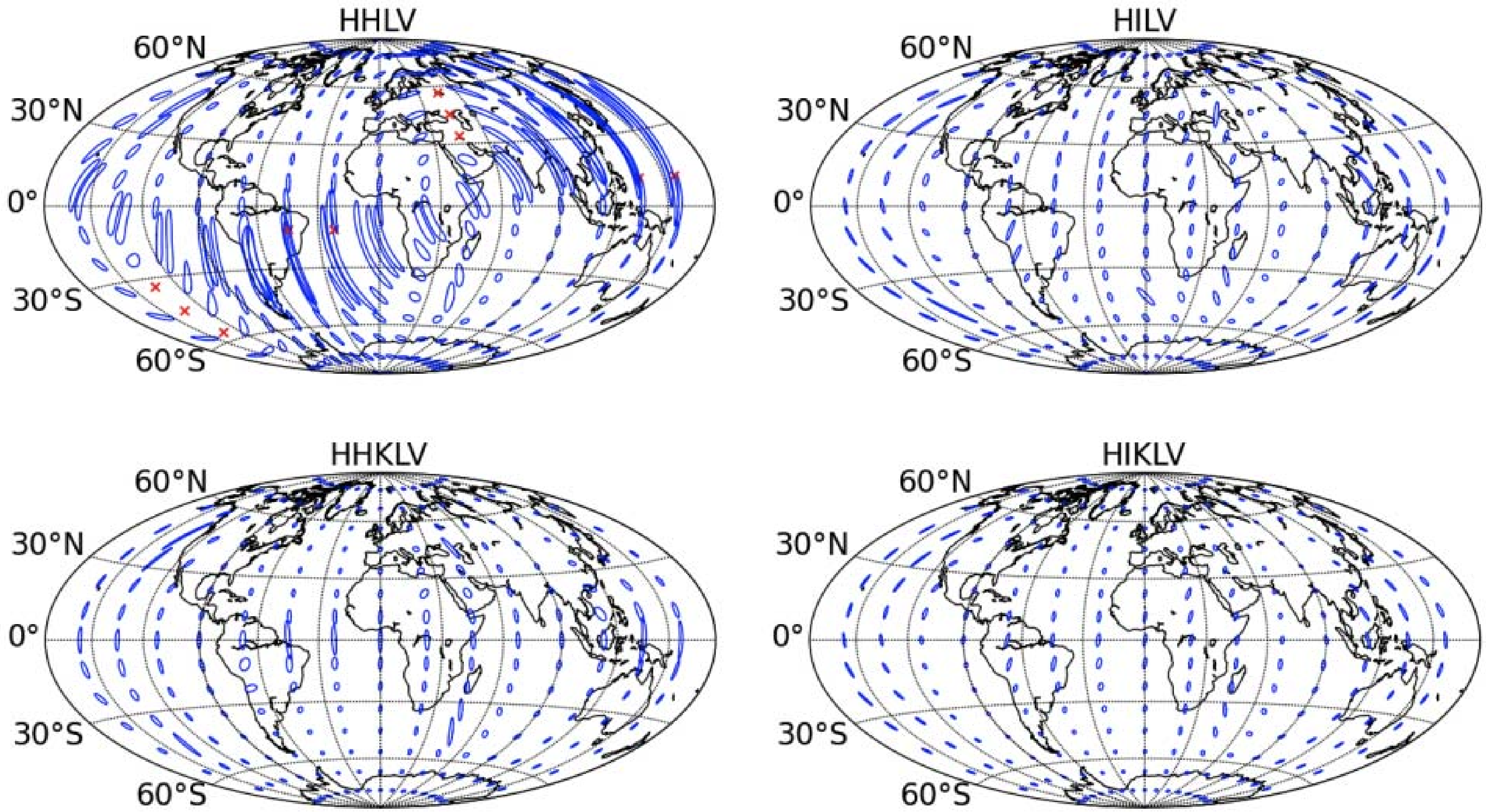




Source localization with LIGO-India

Determination of source sky position: NS-NS binary inspirals @ 160 Mpc

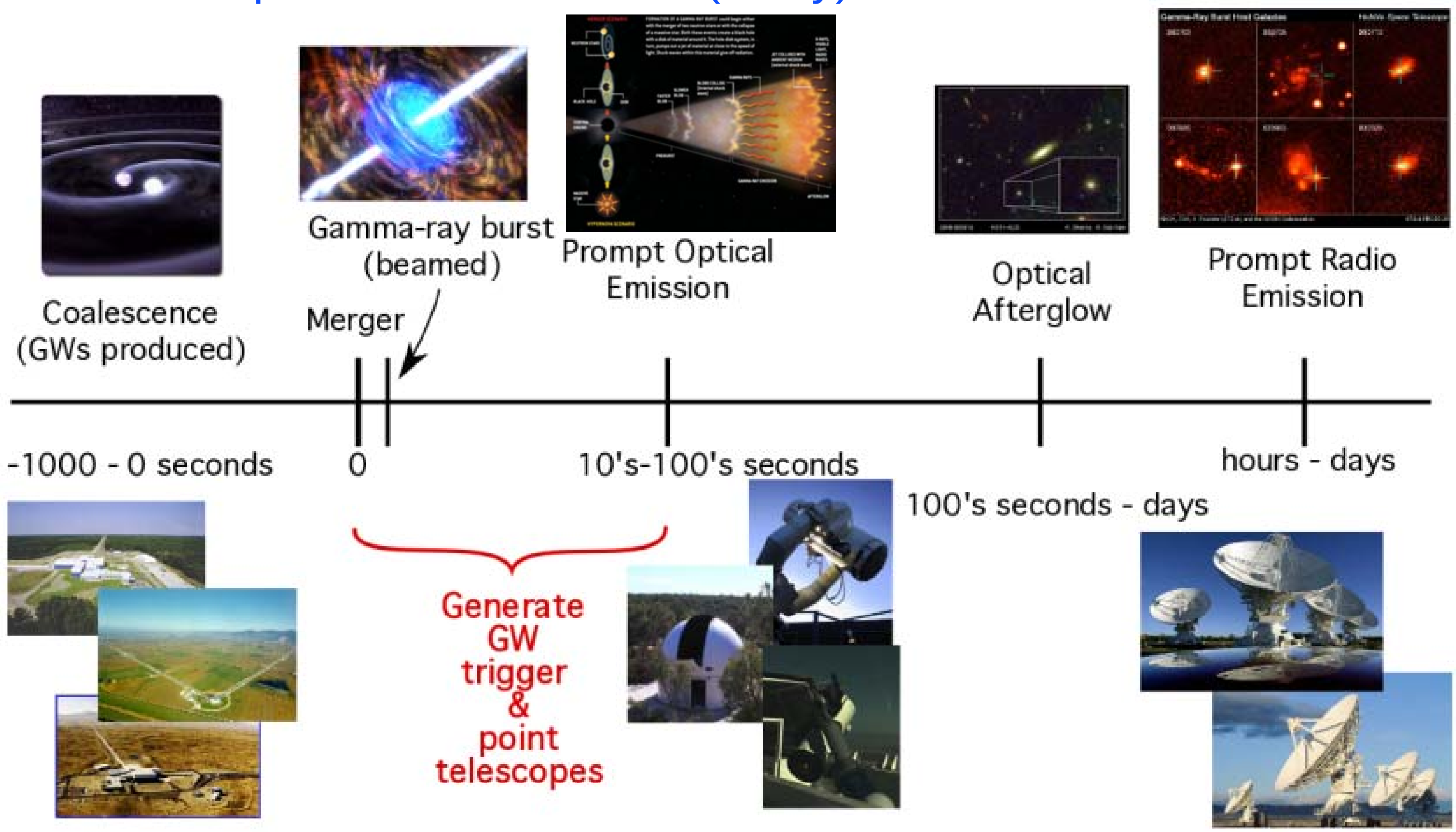
Without LIGO-India **With LIGO-India**



S. Fairhurst (2012); LSC - arXiv:1304.0670v1(2013)

Low-latency identification of transients for rapid (< ~100s) followup

EM counterparts to GW sources (if any) are short-lived and faint



Call for partnerships with EM, ν observers: http://www.ligo.org/science/GWEMalerts.php

EM and GW Multi-messenger Astronomy

Light Curve & Spectrum:

» Precise sky location
» Host galaxy
» Gas environment
» Progenitor star
» EM energetics
» Red shift

Gravitational Waves:

» Bulk motion dynamics
» Binary parameters
» Direct probe of central engine
» Progenitor mass
» GW energetics
» Luminosity distance

more complete picture of progenitor physics

Combining these observations will also
- increase detection confidence,
- allow a measurement of the local Hubble constant.

Initial, Enhanced, and Advanced LIGO schedule

now

2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015

S5 data run

e-LIGO installation and commissioning

S6 data run

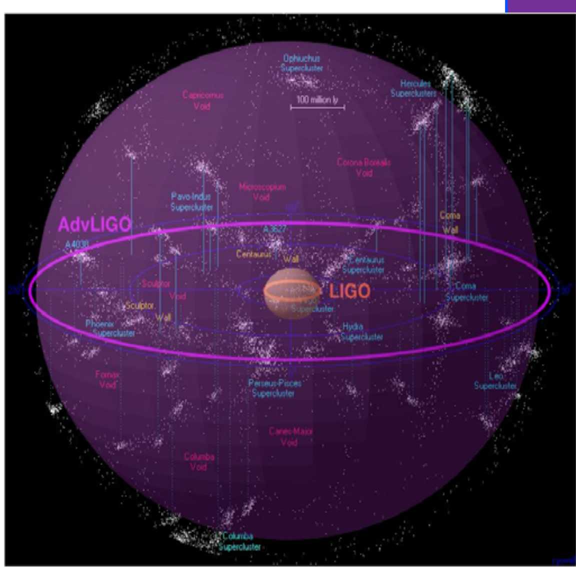
Dark period

S6 data analysis & preparations for Advanced LIGO commissioning and open data

Advanced LIGO Project

Adv LIGO Installation begins

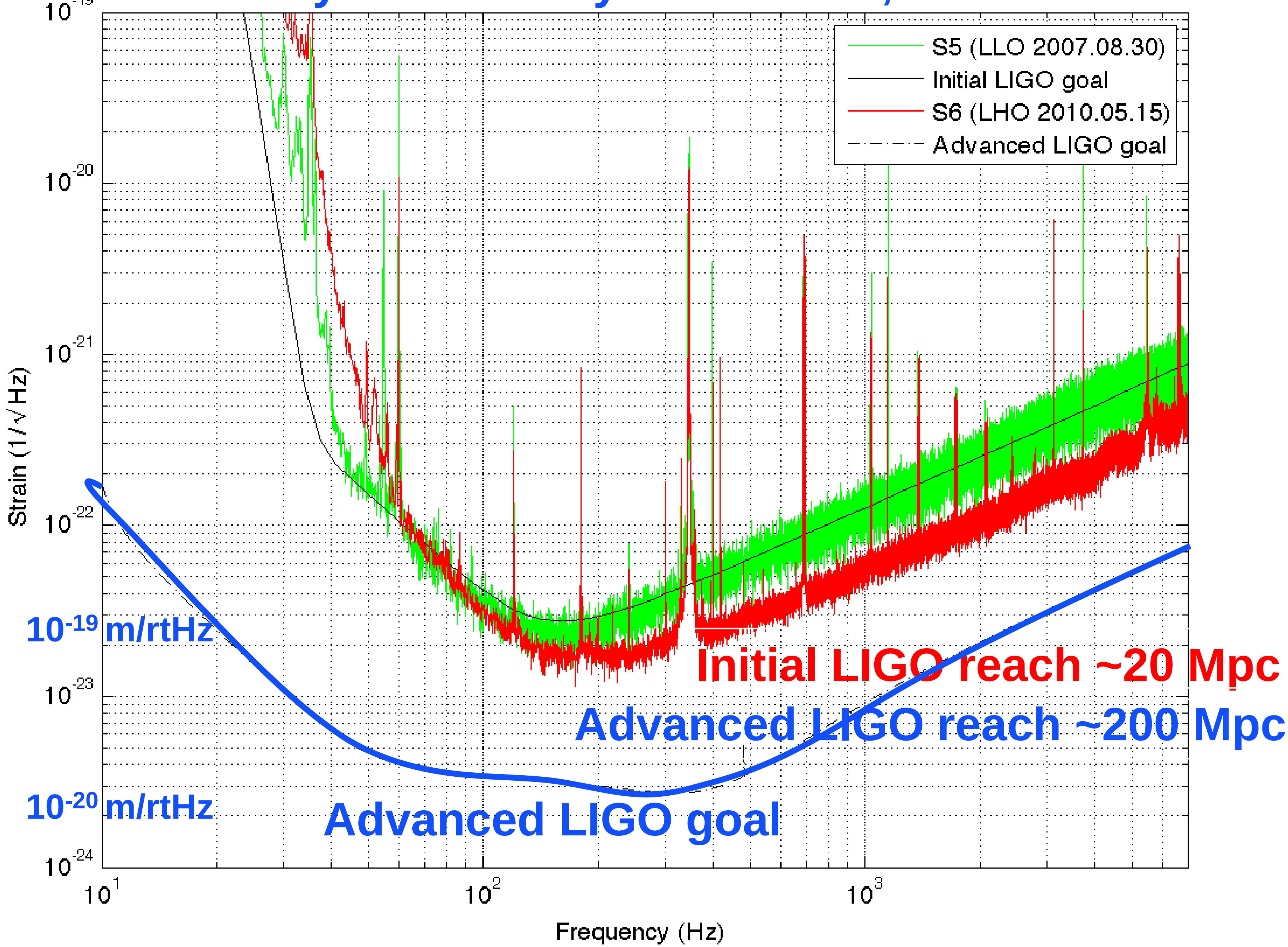
Commissioning & initial data With Advanced LIGO

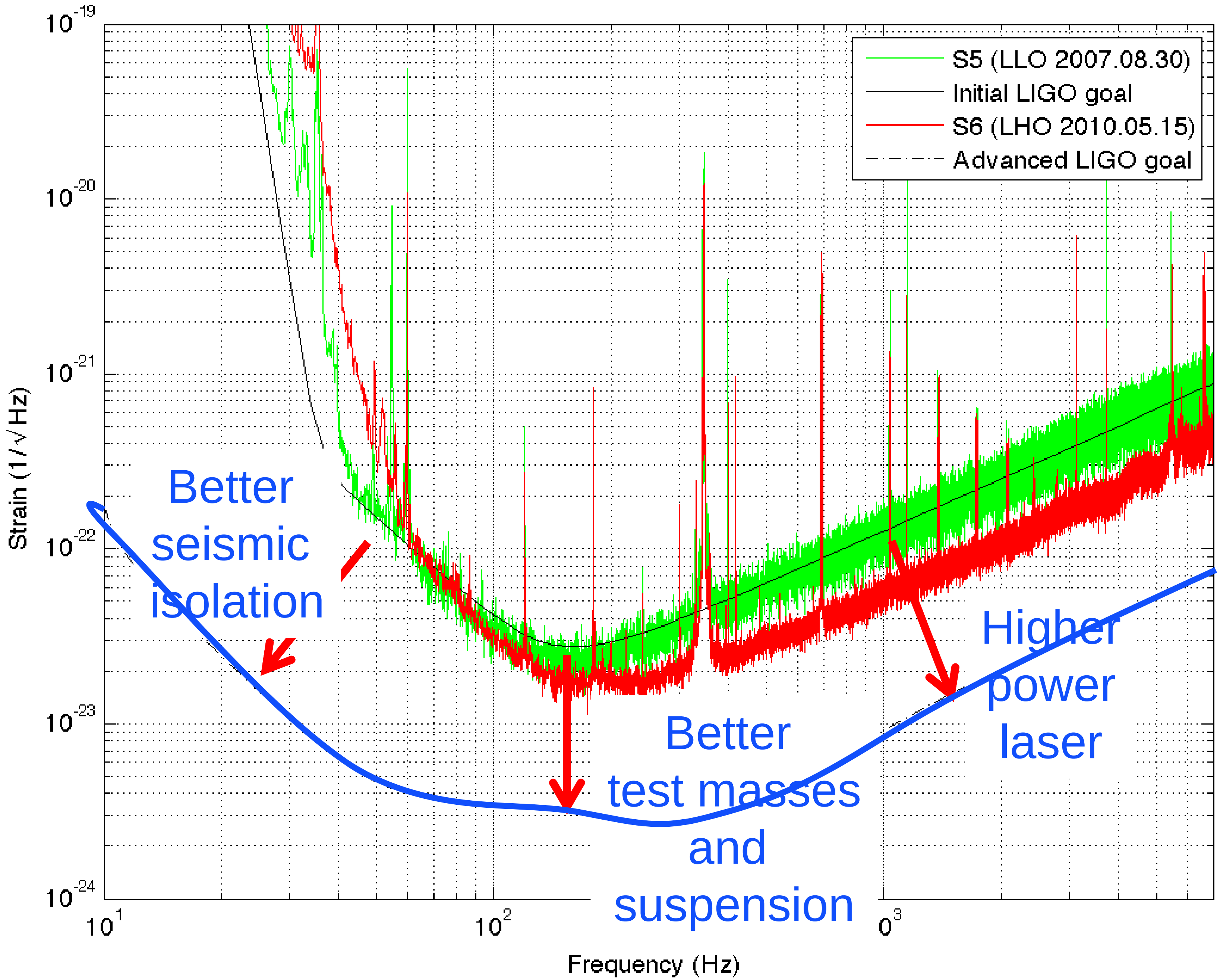


Improve amplitude sensitivity by a factor of 10x, and…

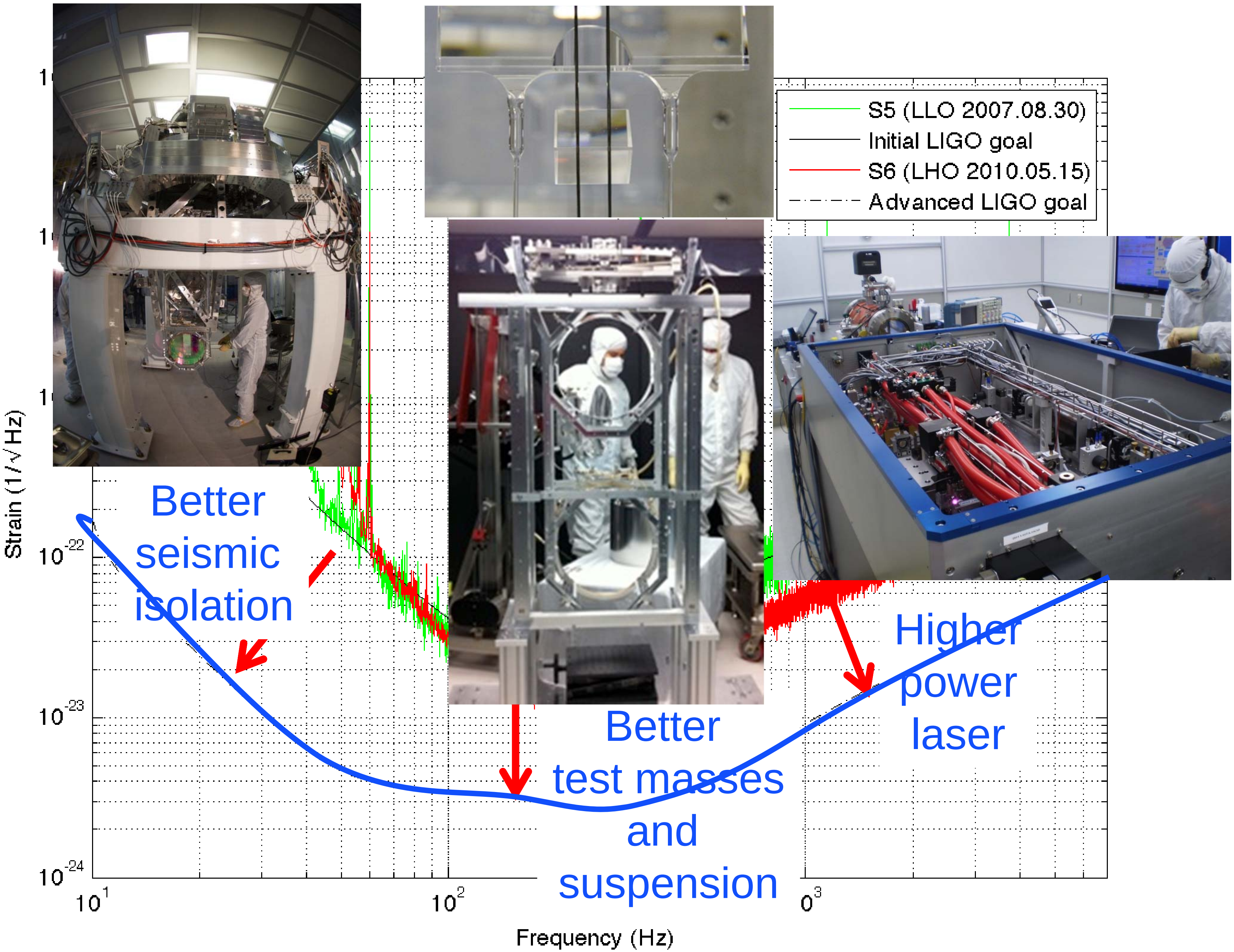
⇒ Number of sources goes up 1000x!

Strain sensitivity achieved by Initial LIGO, Enhanced LIGO

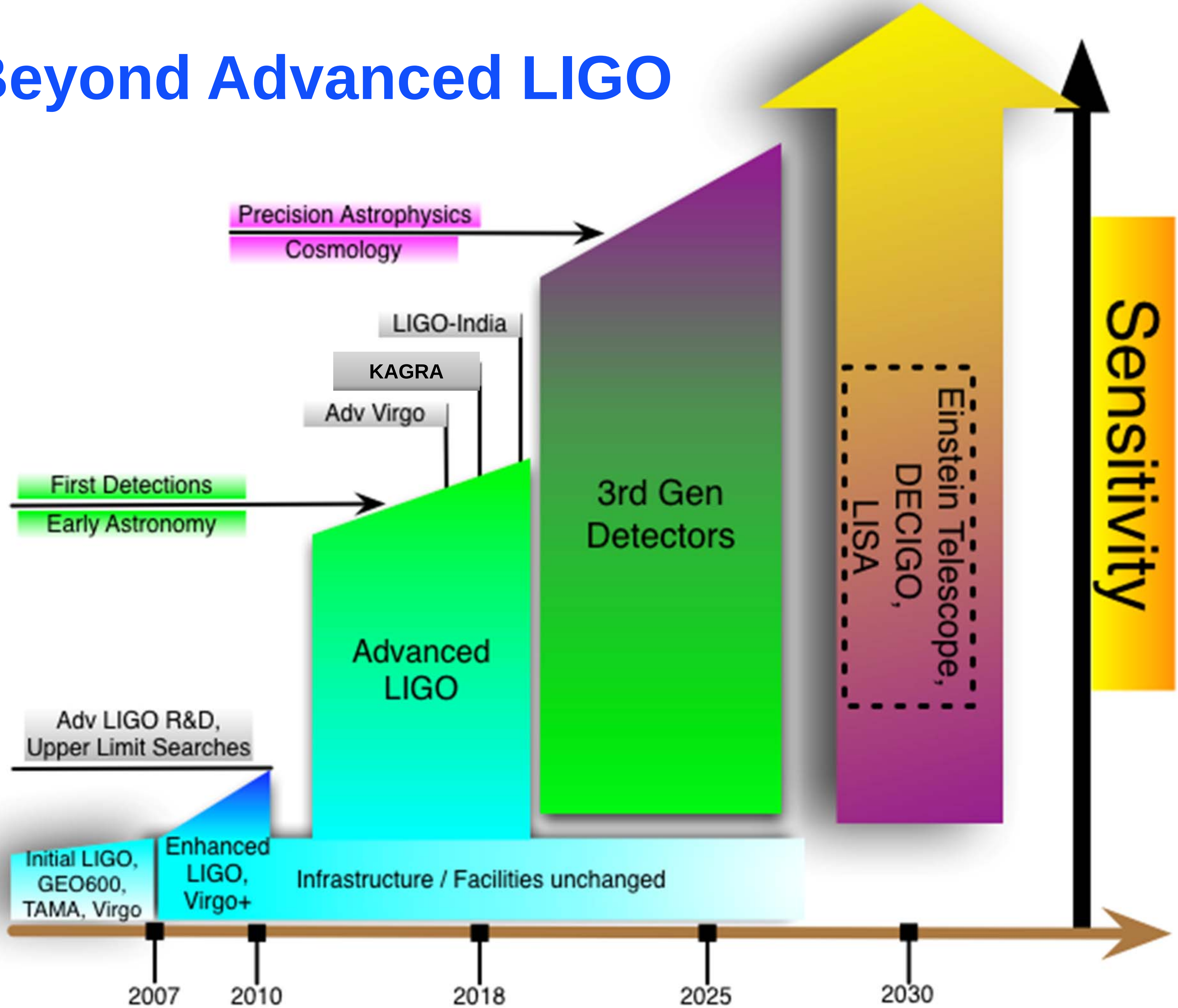




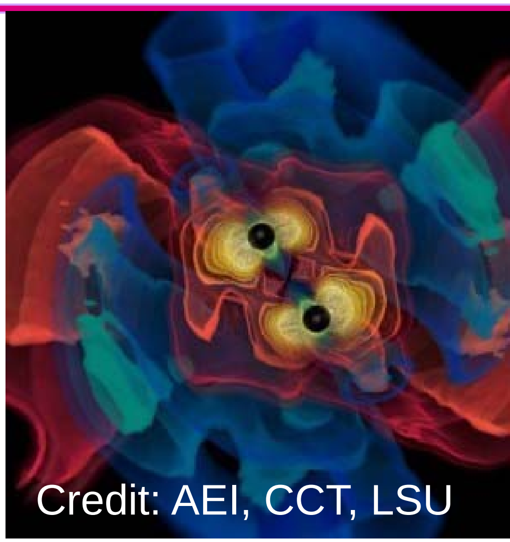
S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
Frequency (Hz)
Better seismic isolation
Better test masses and suspension
Higher power laser


S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
Frequency (Hz)
10^-22
10^-23
10^-24
10^1
10^2
0^3
Better seismic isolation
Better test masses and suspension
Higher power laser

Beyond Advanced LIGO



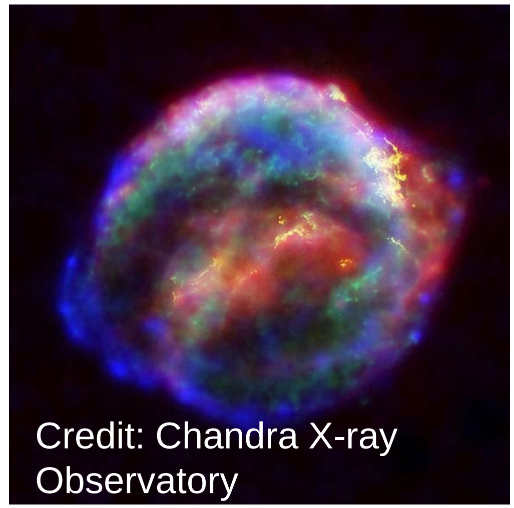
LIGO GW sources for ground-based detectors: The most energetic processes in the universe



<u>Coalescing Compact Binary Systems</u>: Neutron Star-NS, Black Hole-NS, BH-BH

- Strong emitters, well-modeled,

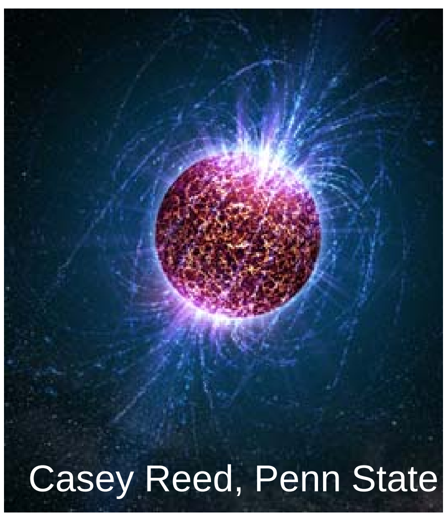
- (effectively) transient



<u>Asymmetric Core Collapse Supernovae</u>

- Weak emitters, not well-modeled (‘bursts’), transient

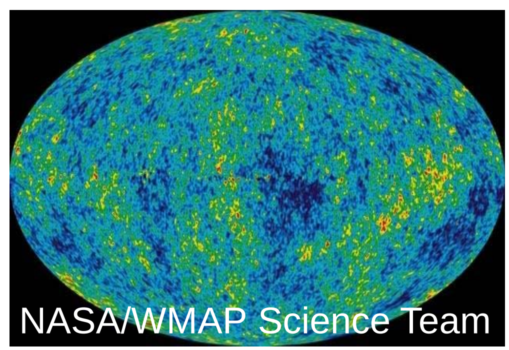
- Cosmic strings, soft gamma repeaters, pulsar glitches also in ‘burst’ class



<u>Spinning neutron stars</u>

- (effectively) monotonic waveform

- Long duration



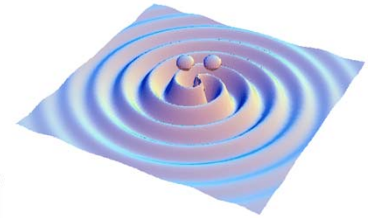
<u>Cosmic Gravitational-wave Background</u>

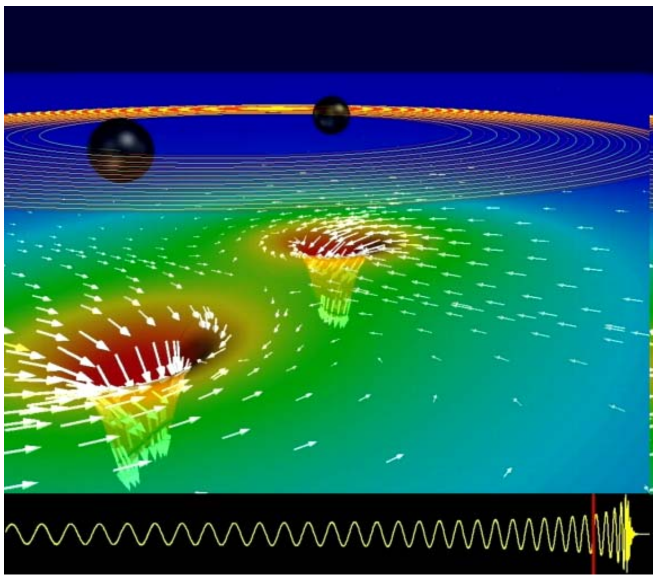
- Residue of the Big Bang, long duration

- Long duration, stochastic background

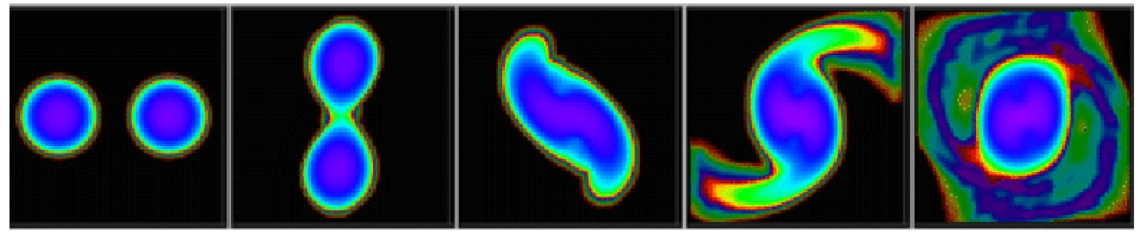
LIGO

GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)





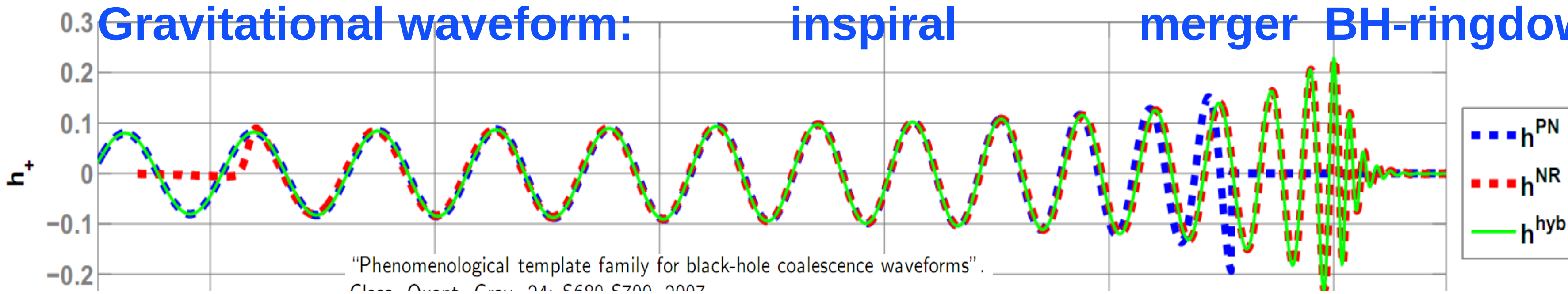
• Neutron star – neutron star (Centrella et al.)



Tidal disruption of neutron star

A unique and powerful laboratory to study strong-field, highly dynamical gravity and the structure of nuclear matter in the most extreme conditions

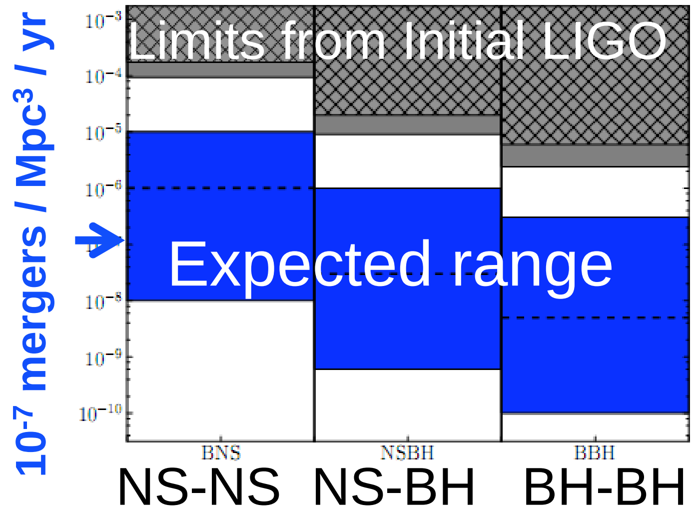
Gravitational waveform: inspiral merger BH-ringdown



Waveform carries lots of information about binary masses, orbit, merger

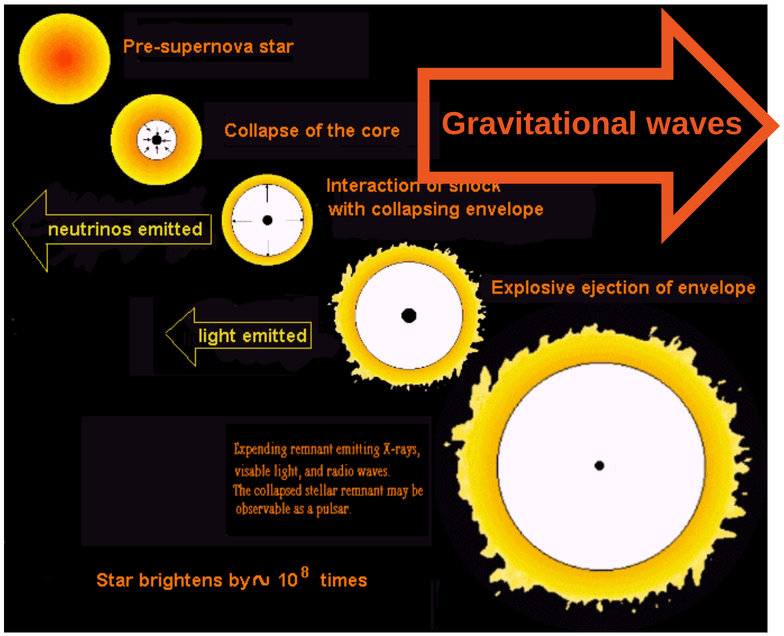
Expected ranges of binary merger rates

- Estimates of astrophysical event rate (mergers / Mpc^3 / yr) from known NS-NS close binaries in our galaxy, and population synthesis models.
    - LVC, Class. Quant. Grav. 27 (2010) 173001
- Detection range in Mpc (SNR = 8 in one detector, averaged over source sky location and orientation) based on aLIGO Mode 1b noise model (P=125 W, T_{SRM}=20%, F_{SRM}=0°)

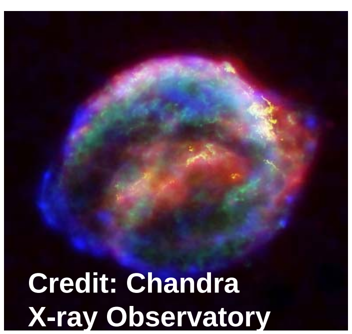


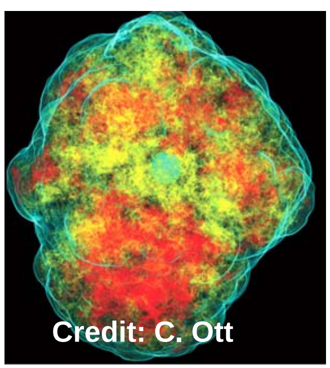
System	Masses (M_{sun})	Range (Mpc)	Low rate est. (yr^{-1})	Realistic rate (yr^{-1})	High rate est. (yr^{-1})
NS-NS	1.4/1.4	200	0.4	40	400
NS-BH	1.4/10	410	10	300	
BH-BH	10/10	970	20	1000	

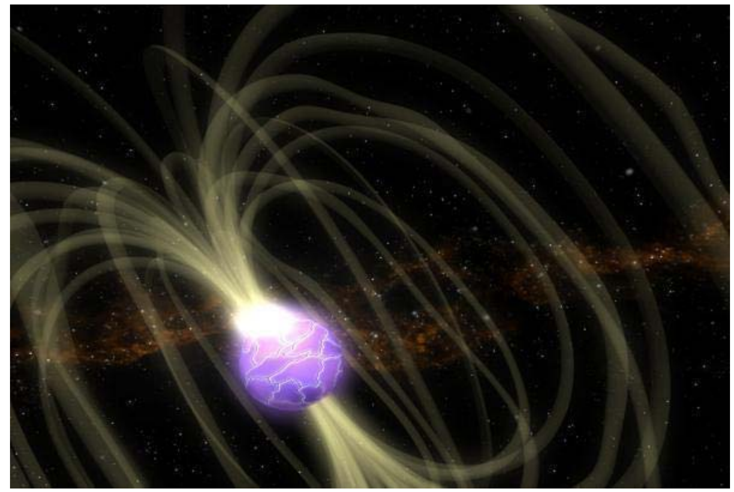
Unmodeled, short-duration (<~ 1 s) GW Bursts



Core collapse supernova

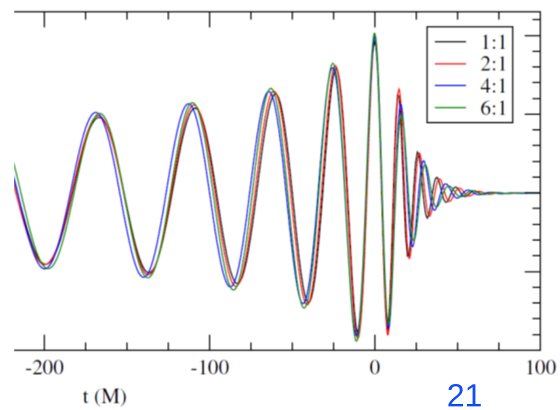






Magnetar flares / storms

High-mass binary merger and ringdown



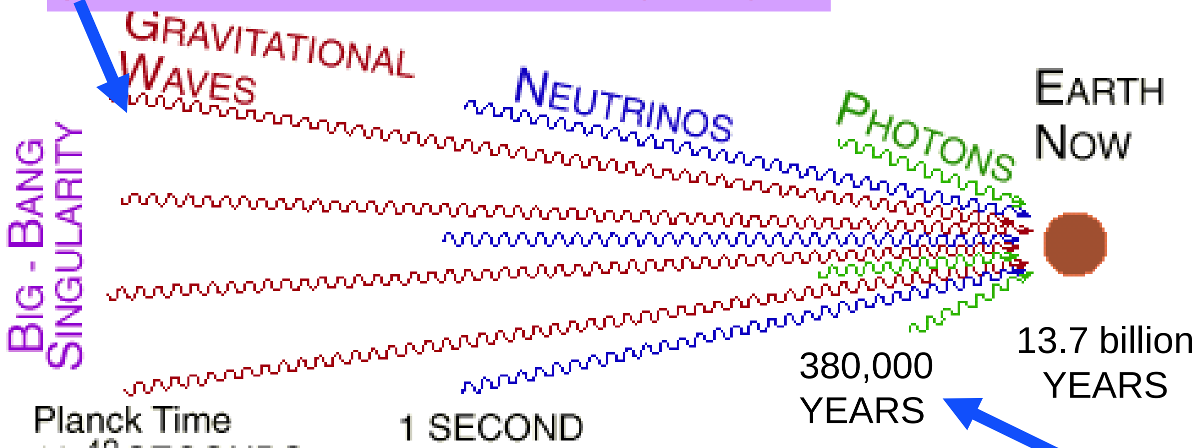
Gravitational waves from Big Bang

Waves now in the LIGO band were produced 10^{-22} sec after the big bang

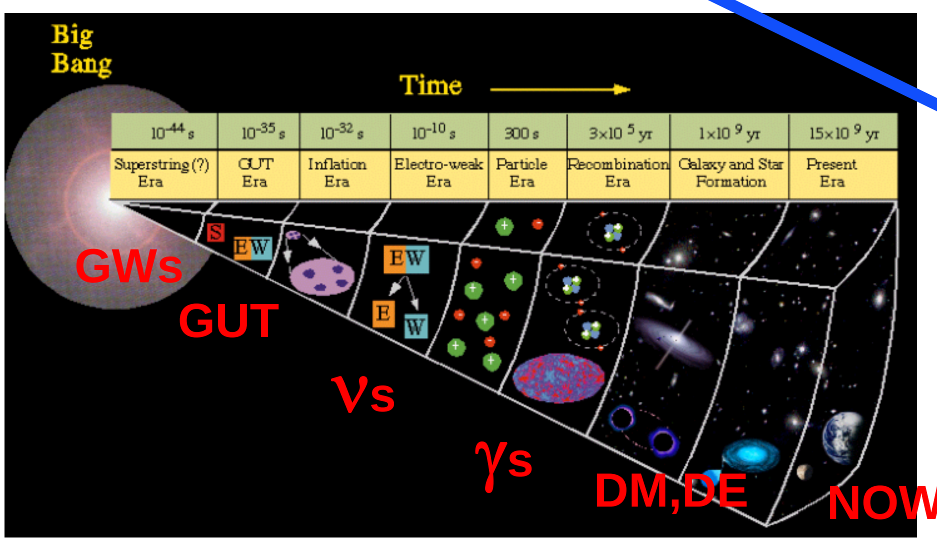
$$\Omega_{GW}(f) = \frac{1}{\rho_c}\,\frac{d\rho_{GW}(f)}{d\ln f}$$

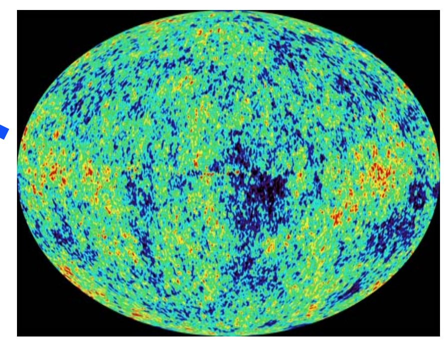
$$\rho_{GW} = \frac{c^2}{32\pi G} < \dot{h}_{ab}\,\dot{h}^{ab} >$$

$$h(f) = 6.3 \times 10^{-22}\,\sqrt{\Omega_{GW}(f)}\left(\frac{100\text{ Hz}}{f}\right)^{3/2}\text{Hz}^{-1/2}$$



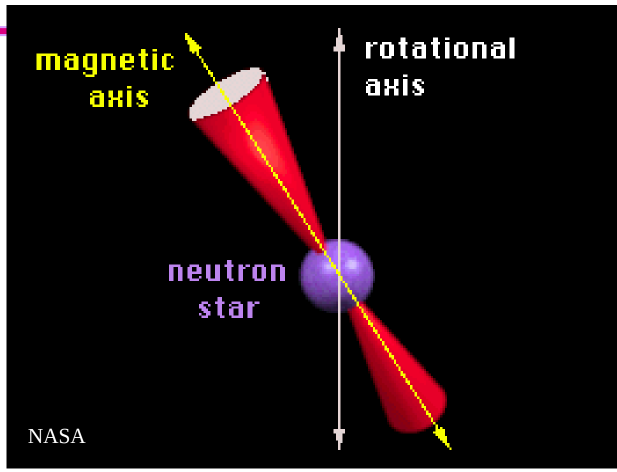
Planck Time
10^{-43} SECONDS
Singularity creates Space & Time of our universe



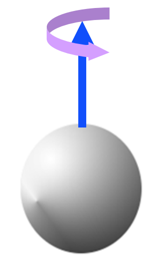


cosmic microwave background -- WMAP 2003

Pulsars and continuous wave sources

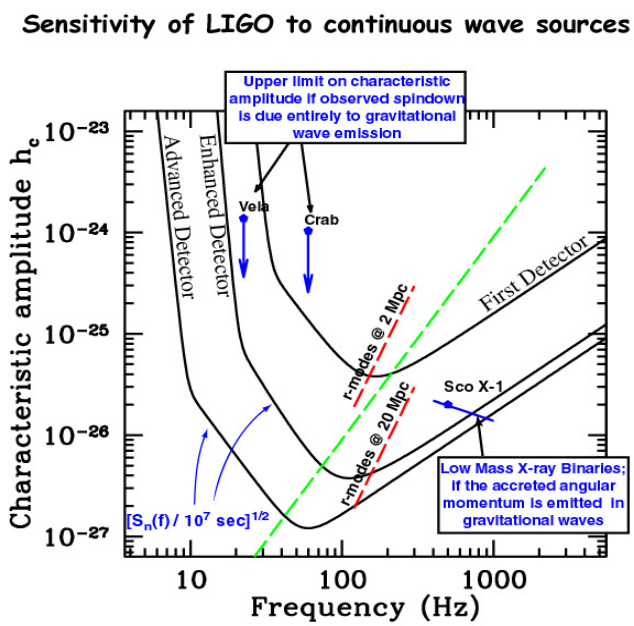


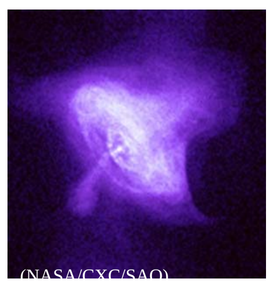
- **Pulsars in our galaxy**
  - »non axisymmetric: 10-4 < ε < 10-6
  - »science: EOS; precession; interiors
  - »“R-mode” instabilities
  - »narrow band searches best

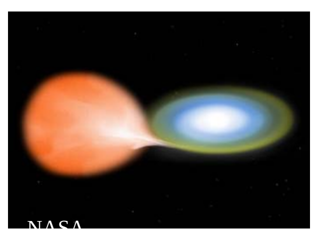


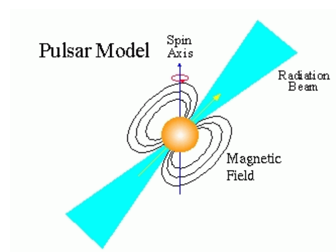
$$h = \frac{4\pi^2 G}{c^4} \frac{I f_{GW}^2}{d} \varepsilon$$

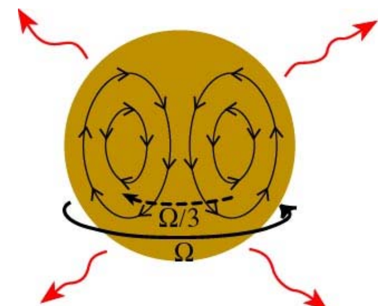
$$f_{GW} = 2\, f_{ROT}$$





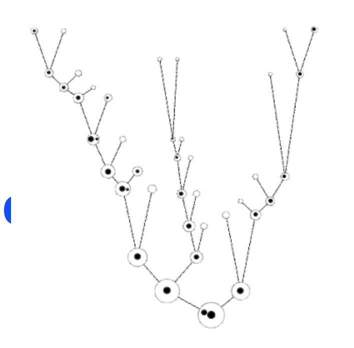






Astrophysical science with binary mergers

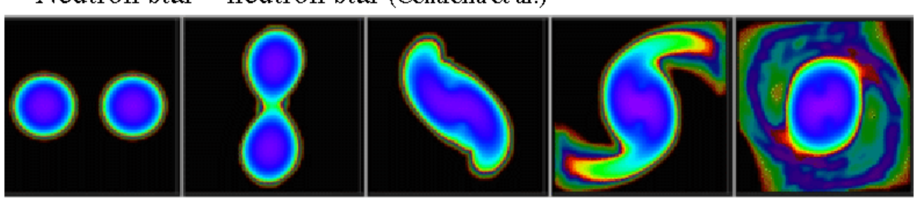
- **Merger rates as function of mass, mass ratio, spin**
  - » **Establish existence of black hole binaries**
  - » **Neutron star mass distribution**
  - » **Black hole number, mass, spin and location distribution**
  - » **Search for intermediate-mass black holes**
- **Inform / constrain astrophysical source distribution mod**
  - » **Extract population synthesis model parameters.**
  - » **Binary formation and evolution history**
  - » **Explore hierarchical merger scenarios**

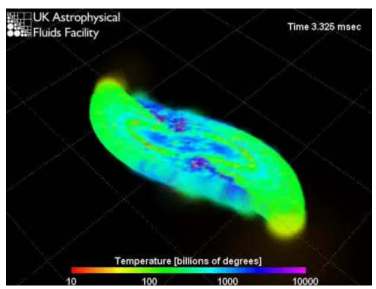


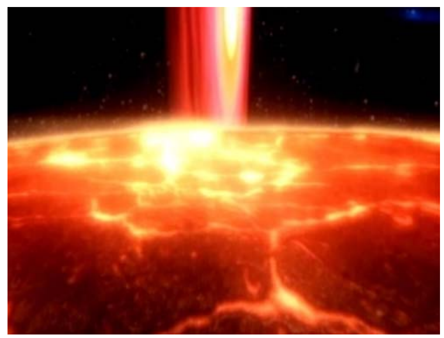
ciera.northwestern.edu/rasio

- **Study matter effects in waveform: tidal disruption, NS EOS.**

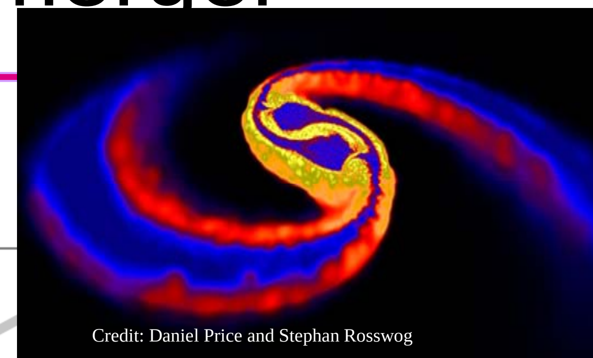
• Neutron star – neutron star (Centrella et al.)

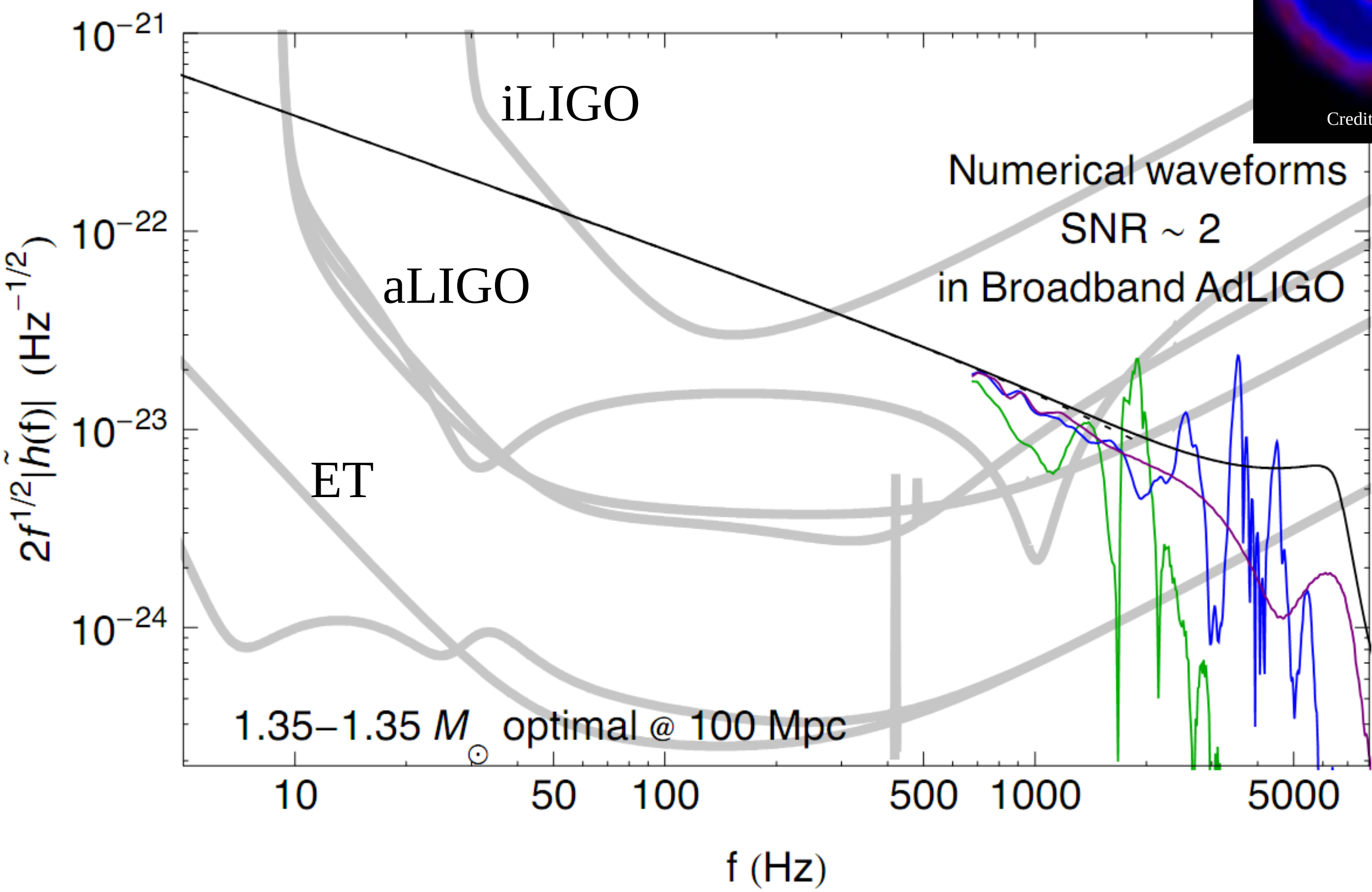






Effects of tidal disruption of neutron stars near merger

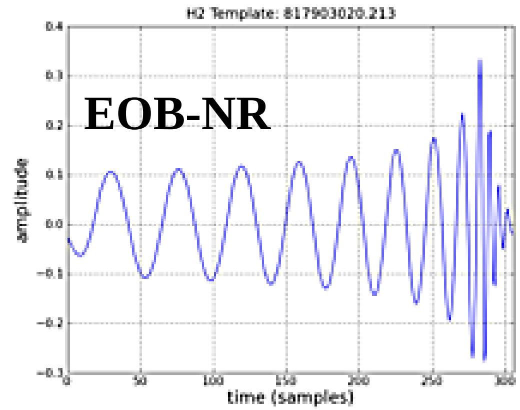




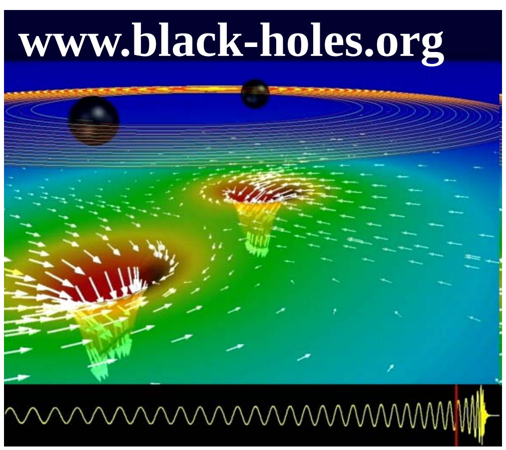
Testing General Relativity in the strong-field, dynamical regime

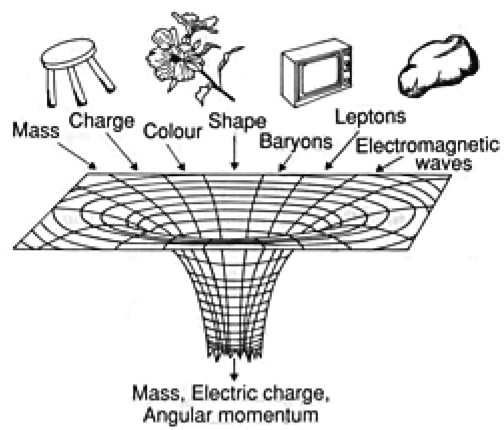
- **Test post-Newtonian expansion of inspiral phase.**

$$\Psi(f) \equiv 2\pi f t_0 + \varphi_0 + \frac{3}{128\eta v^5}\left(1 + \sum_{k=2}^{7} v^k \psi_k\right).$$



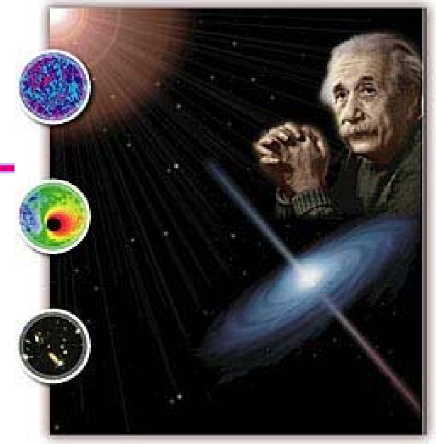
- **Test Numerical Relativity waveform prediction for merger phase.**
- **Test association of inspiral and ringdown phases: BH perturbation theory, no-hair theorem.**





nonlocal.com/hbar/blackholes.html

Testing beyond-GR



- Constrain beyond-GR parameters (Will, 2006)
- Directly measure speed of gravitational waves, constrain (or measure) the mass of the graviton.
- Constrain (or measure) longitudinal or other polarizations.
- Constrain (or measure) parity-violating effects in wave generation/propagation (Yunes et al, 2010).
- Constrain "parameterized post-Einsteinian framework" (Yunes & Pretorius, 2009)
- Test specifically for scalar-tensor and other alternative-gravity theories

Summary

- An int'l network of ground-based GW detectors is taking shape.
- iLIGO's science run (S5) at design sensitivity completed in 2007
- eLIGO's science run (S6) at enhanced sensitivity completed in 2010
  - » No detections to report
  - » LIGO searches producing some interesting upper limits
- Advanced LIGO construction is in progress, on time and budget; commissioning and first observations in ~2014-15
  - » Sensitivity/range will be increased by a factor of 10-15
  - » We expect to found the field of GW astrophysics with advanced detectors
- VIRGO, KAGRA, GEO-HF, will be online around ~2015-2016
- Detections, and the exploration of the universe with GWs, will begin over the next decade!

… Fin …

We look forward to the coming advanced detector era:

- **the discovery and exploration of the GW sky;**
- **unique tests of General Relativity in the strong-field, highly non-linear and dynamical regime;**
- **joint observations and discoveries with EM and neutrino telescopes;**
- **and a rich new branch of astrophysics.**

But most of all, we look forward to …

the unexpected!