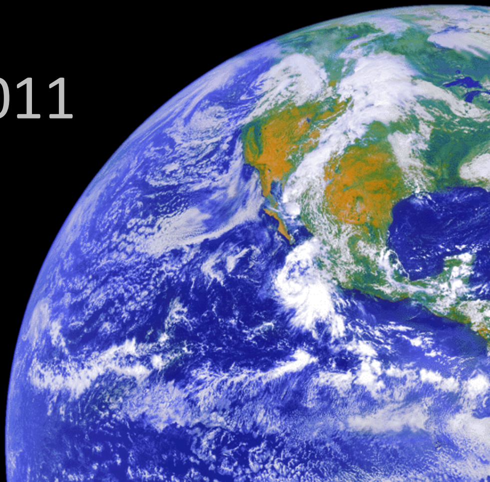
Gravitational Wave Astronomy and Astrophysics: A Status Report

Peter Shawhan (U. of Maryland)
for the LIGO Scientific Collaboration
and Virgo Collaboration

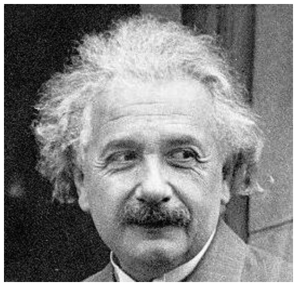
SESAPS Meeting — Roanoke, Oct. 22, 2011

LIGO-G1100895-v2



GOES-8 image produced by M. Jentoft-Nilsen, F. Hasler, D. Chesters (NASA/Goddard) and T. Nielsen (Univ. of Hawaii)

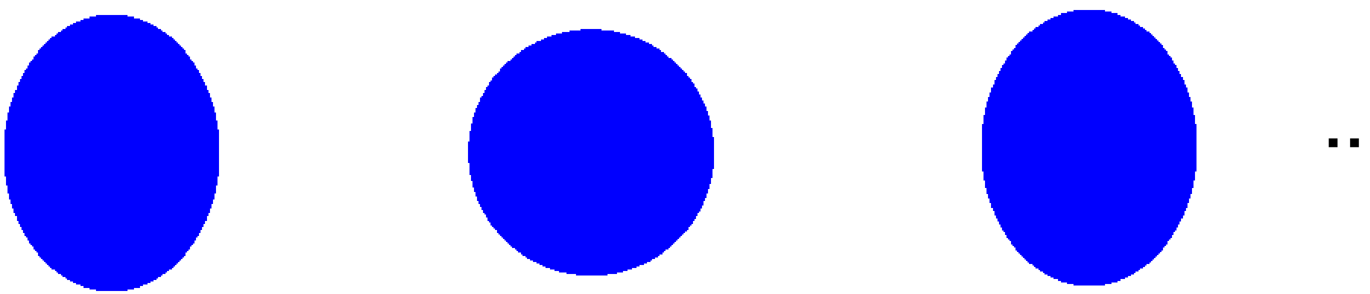
Gravitational Waves



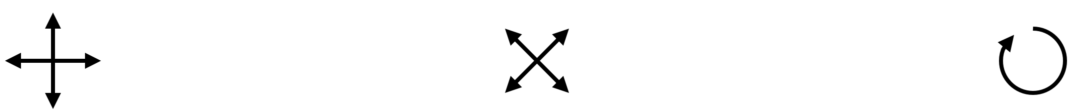
The Einstein field equations of GR have wave solutions !

- ► Emitted by a rapidly changing configuration of mass
- ► Travel away from the source at the speed of light
- ► Change the effective distance between inertial points — i.e. the spacetime metric — transverse to the direction of travel

Looking at a fixed place in space while time moves forward, the waves alternately *stretch* and *shrink* the space



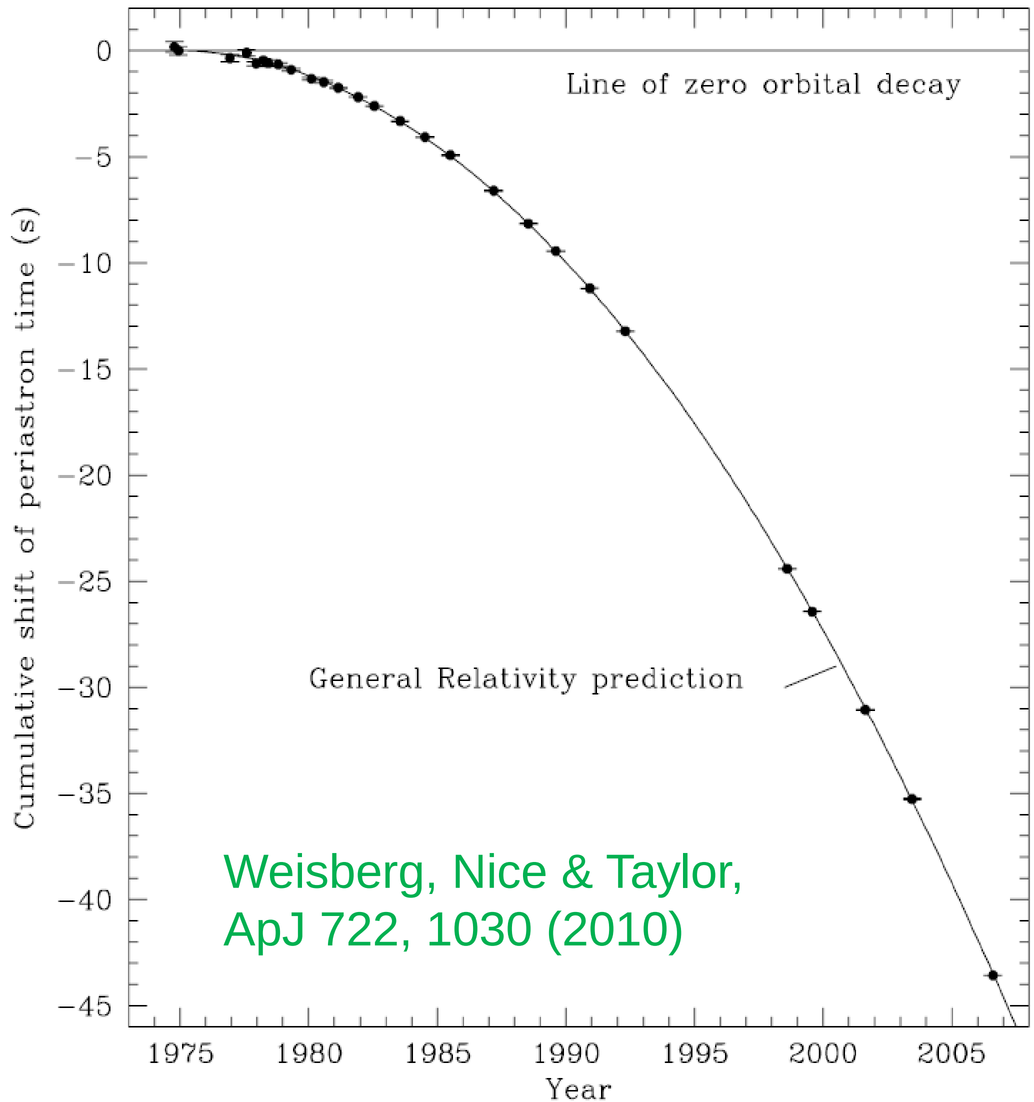
"Plus" polarization   "Cross" polarization   Circular polarization



Do Gravitational Waves *Really* Exist?

Long-term radio observations of the Hulse-Taylor binary pulsar B1913+16 have yielded neutron star masses (1.44 and 1.39 $M_\odot$) and orbital parameters

System shows very gradual orbital decay – just as general relativity predicts !
⇒ Very strong indirect evidence for gravitational radiation



Weisberg, Nice & Taylor, ApJ 722, 1030 (2010)

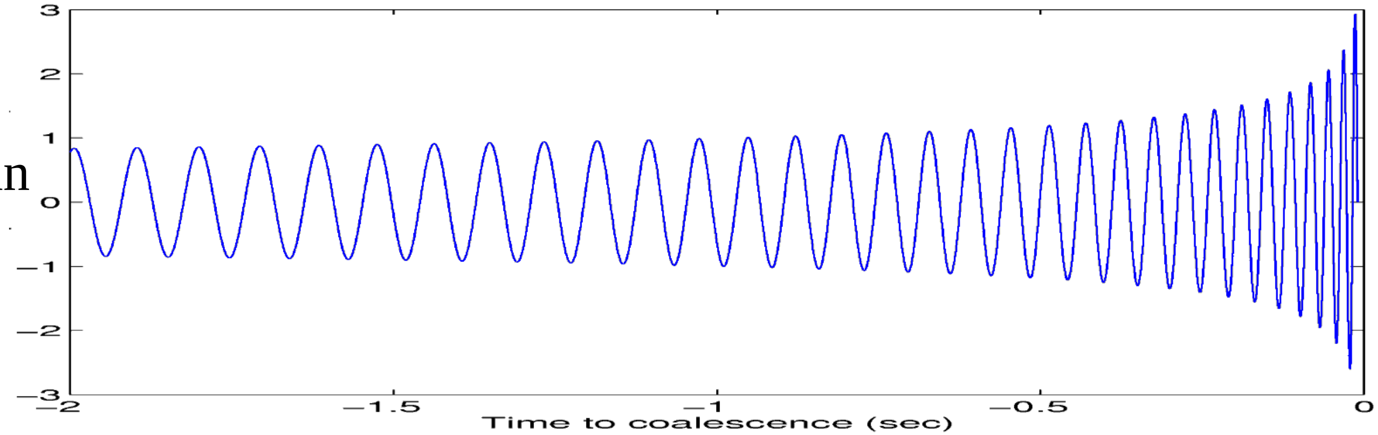
The Fate of B1913+16

Gravitational waves carry away energy and angular momentum

Orbit will continue to decay—“inspiral”—over the next ~300 million years, until…

GW strain

h(t)



The neutron stars will merge !

And possibly collapse to form a black hole

The Promise and the Challenge

Gravitational radiation is a unique messenger

- Emission pattern is broad, not beamed
- Not scattered or attenuated by matter
- Carries information about the core engine of astrophysical events
- Details of waveform reflect the astrophysics of the source and the fundamental theory of gravity

Events which produce gravitational waves are rare (per galaxy)

Strain amplitude is inversely proportional to distance from source

→ Have to be able to search a large volume of space

→ Have to be able to detect very weak signals

Typical strain amplitude at Earth: $h \sim 10^{-21}$!

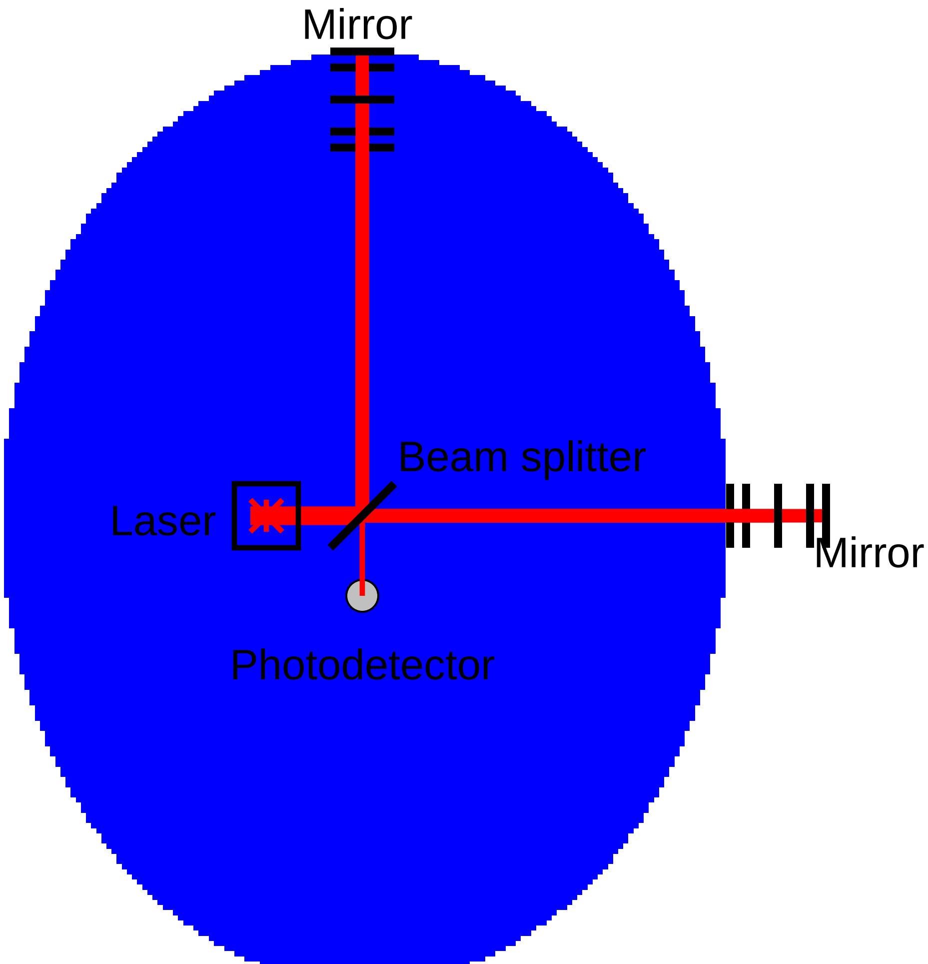
Gravitational waves have not been directly detected – yet

Gravitational Wave Detectors

Laser Interferometers as GW Detectors

Variations on basic Michelson design, with two long arms

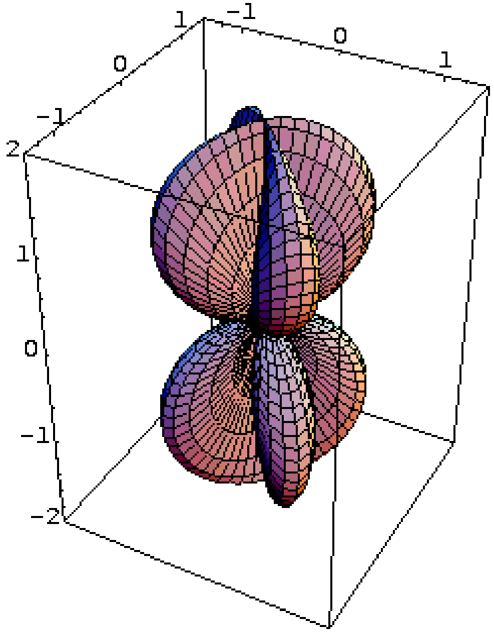
Measure *difference* in arm lengths to a fraction of a wavelength



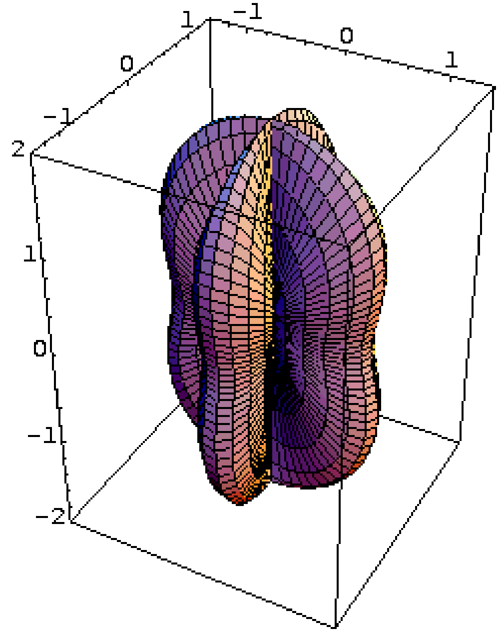
Antenna Pattern of a Laser Interferometer

Directional sensitivity depends on polarization of waves

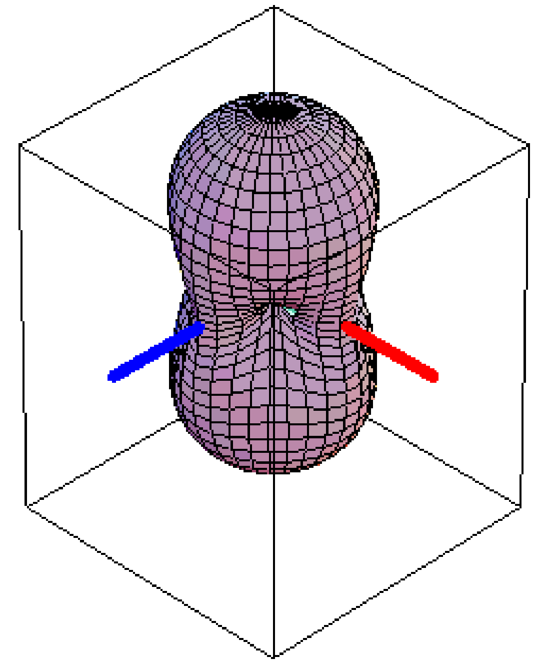
"×" polarization



"+" polarization



RMS sensitivity



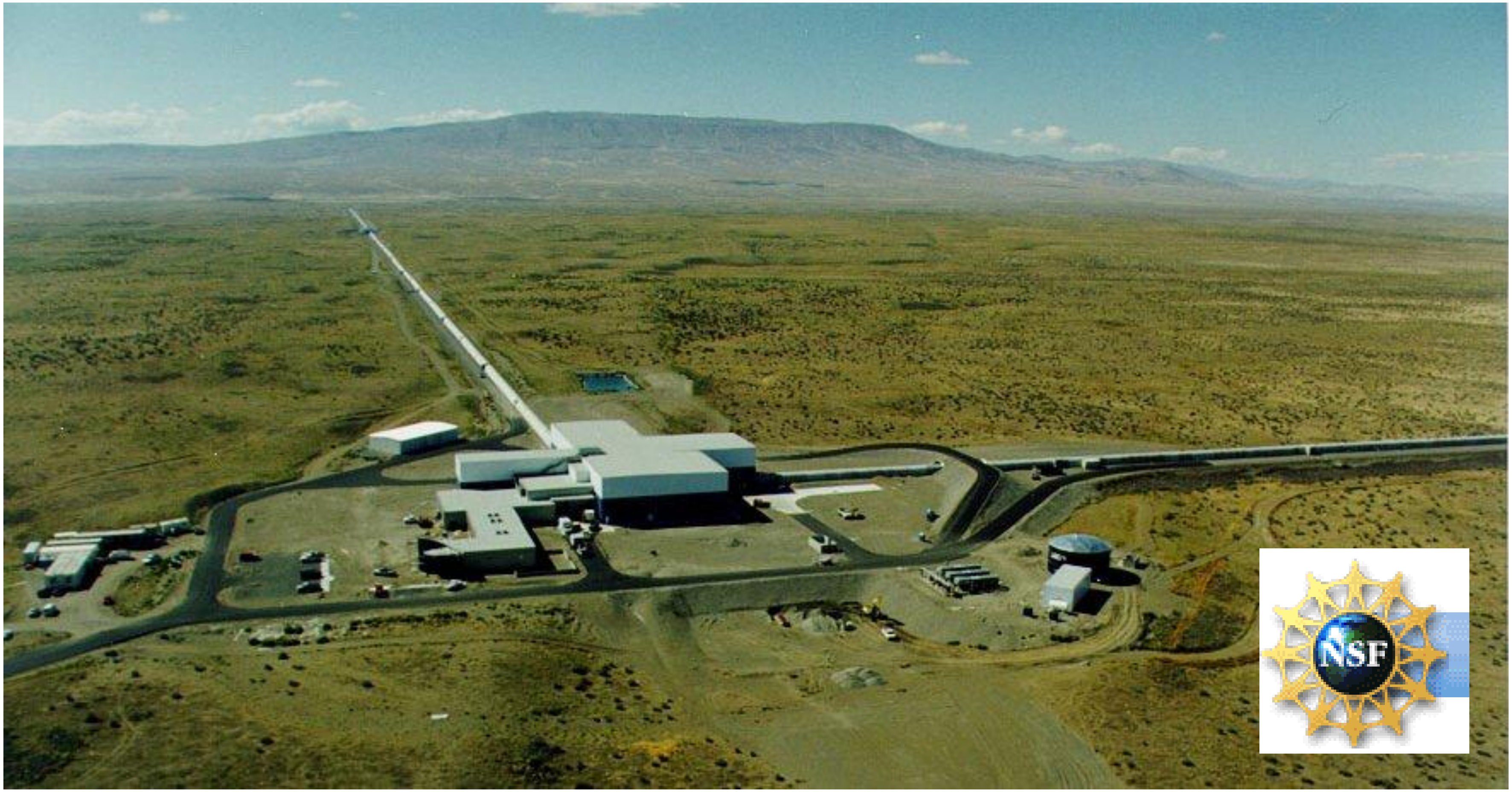
A broad antenna pattern

⇒ **More like a radio receiver than a telescope**

LIGO:
Laser Interferometer Gravitational-wave Observatory

LIGO Hanford Observatory

Located on DOE Hanford Nuclear Reservation north of Richland, Washington



Two completely independent interferometers coexist in the beam tubes

LIGO Livingston Observatory

Located in a rural area of Livingston Parish east of Baton Rouge, Louisiana

One interferometer with 4 km arms

Virgo Observatory

European Grav. Wave Observatory

Located near Pisa, Italy

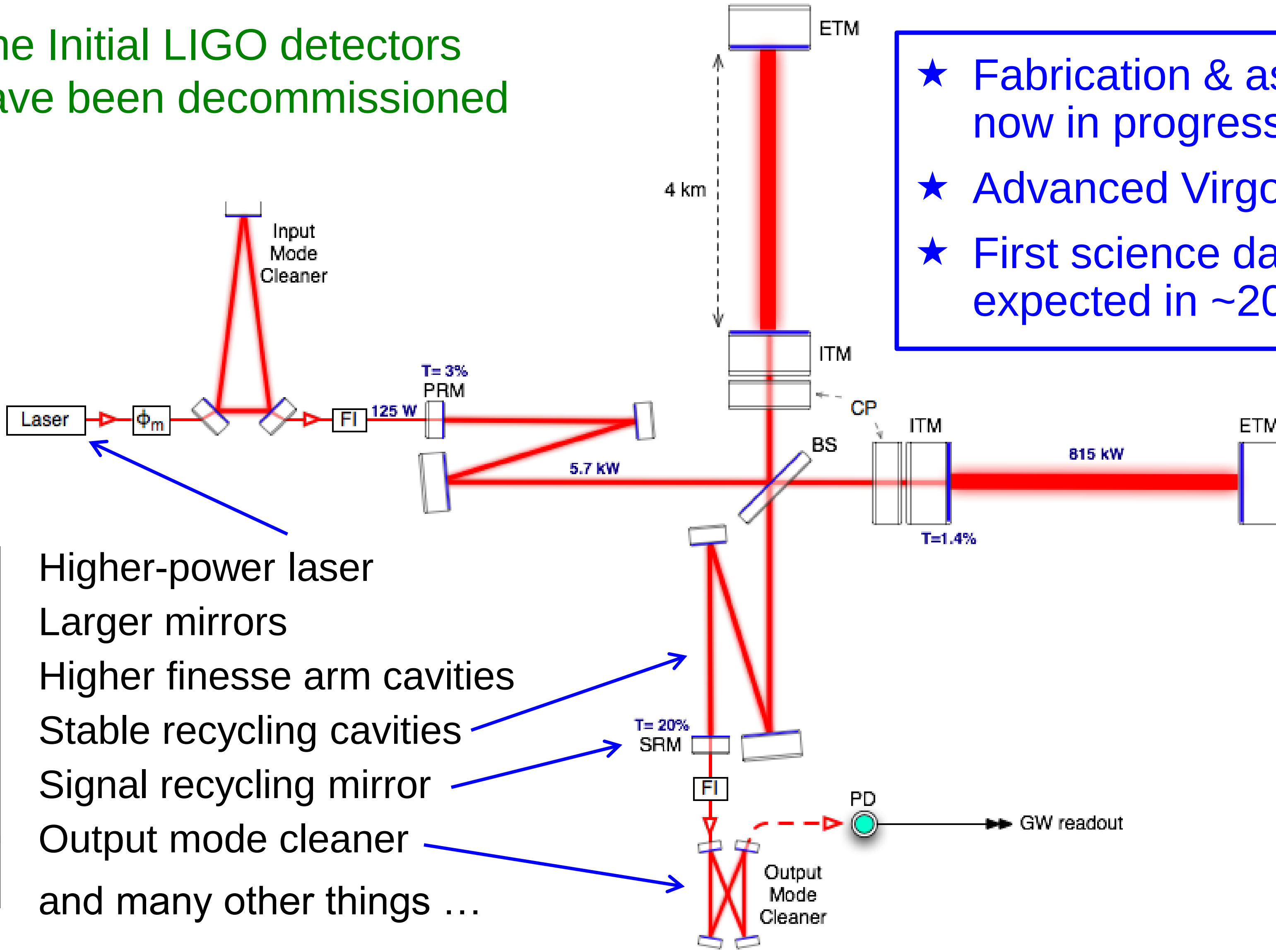
One interferometer with 3 km arms

★ **LIGO and Virgo are separate collaborations, but work together**

Advanced LIGO Optical Layout

The Initial LIGO detectors have been decommissioned

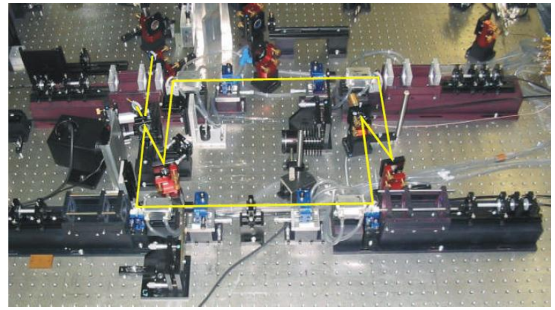
- ★ Fabrication & assembly now in progress !
- ★ Advanced Virgo too
- ★ First science data expected in ~2015



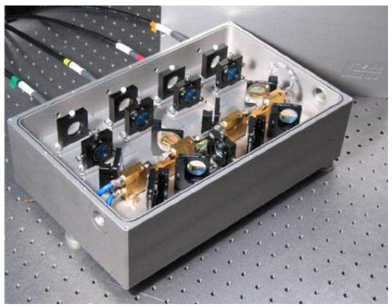
Improvements

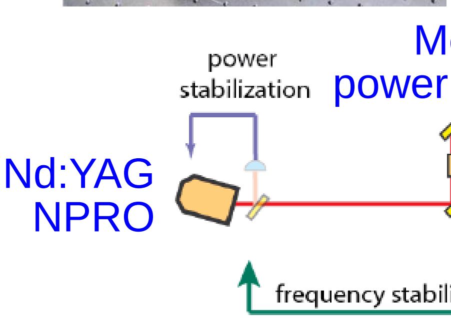
- Higher-power laser
- Larger mirrors
- Higher finesse arm cavities
- Stable recycling cavities
- Signal recycling mirror
- Output mode cleaner
- and many other things …

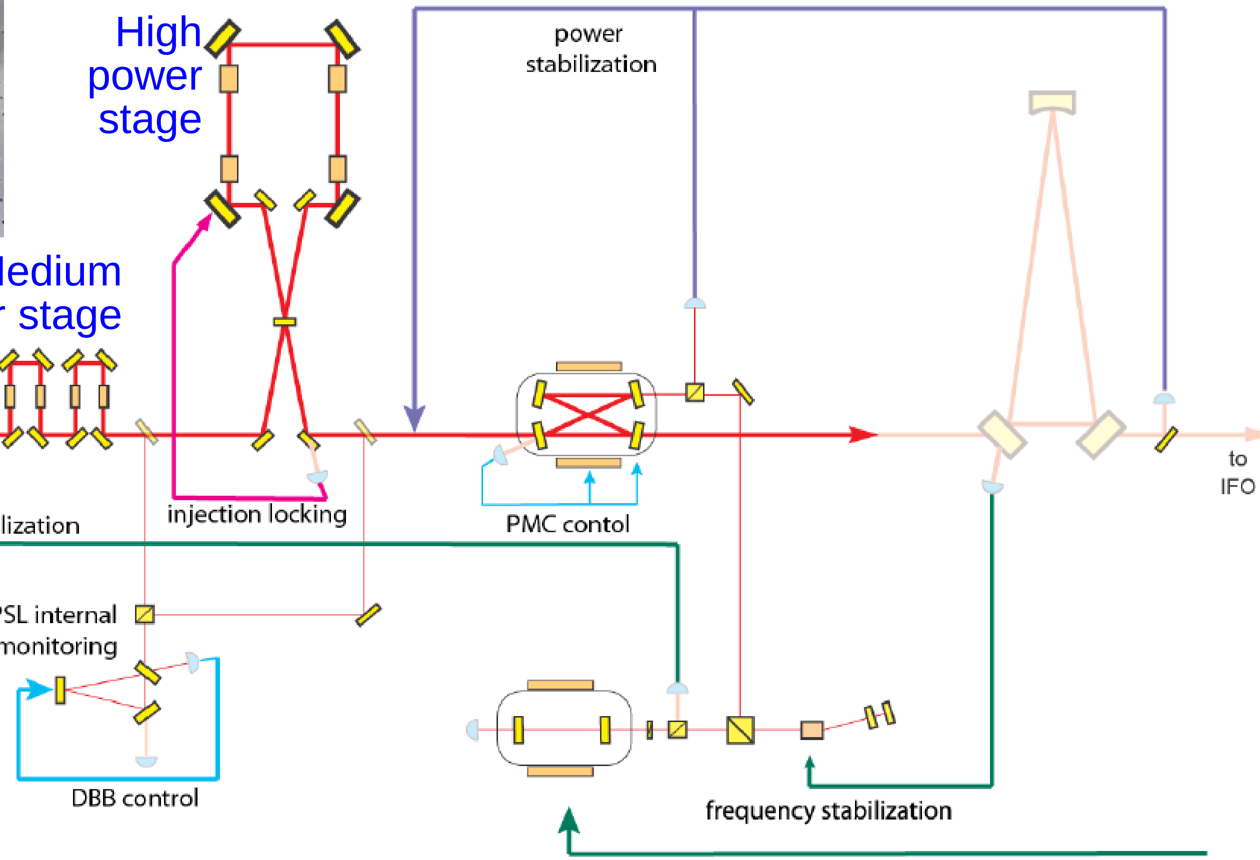
Advanced LIGO Pre-Stabilized Laser

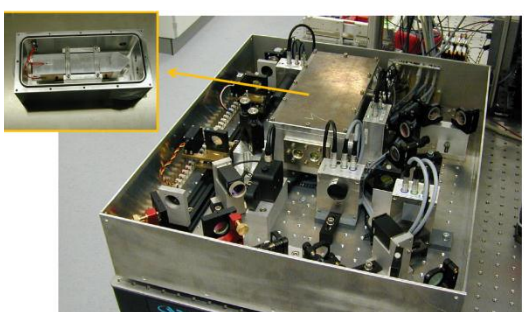


Output to interferometer: 125 W







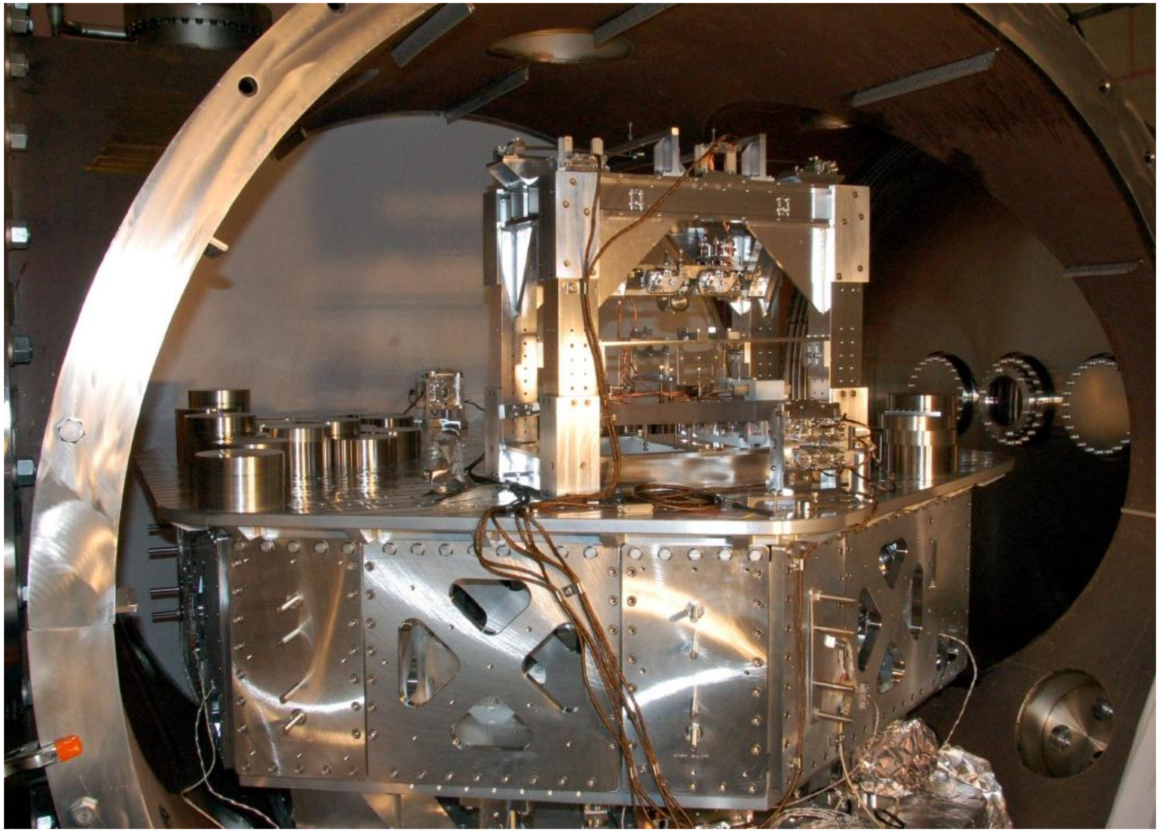


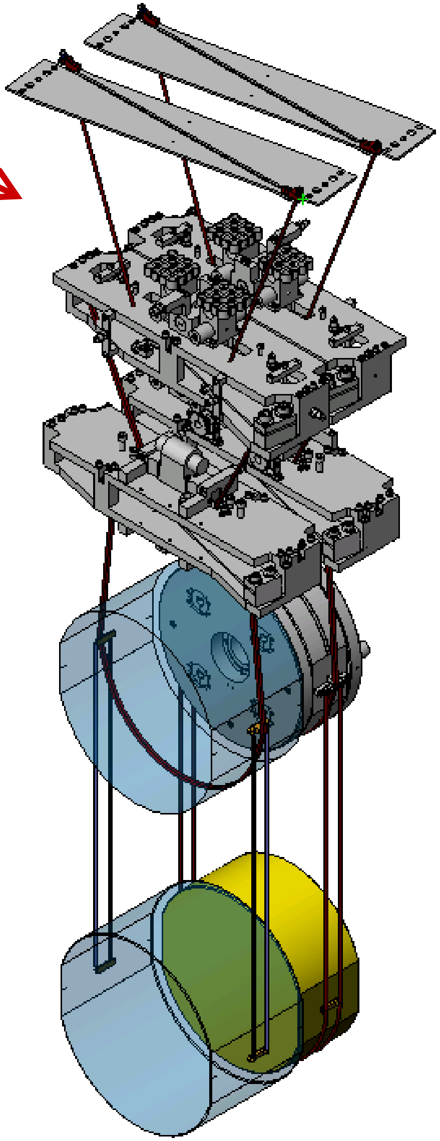
Advanced LIGO Vibration Isolation

Multiple-pendulum mirror suspensions

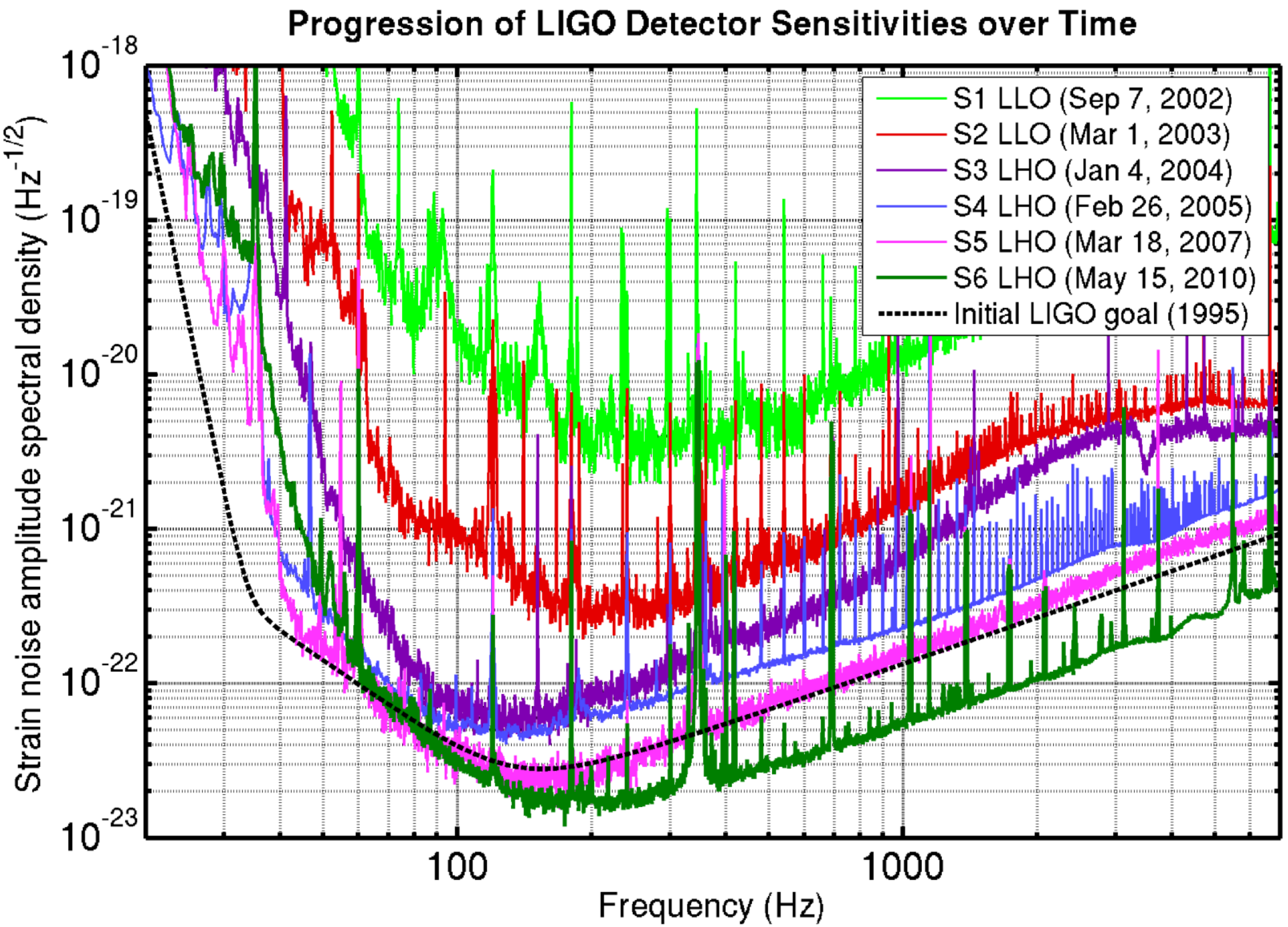
Active vibration isolation stages

Good suppression above ~0.1 Hz

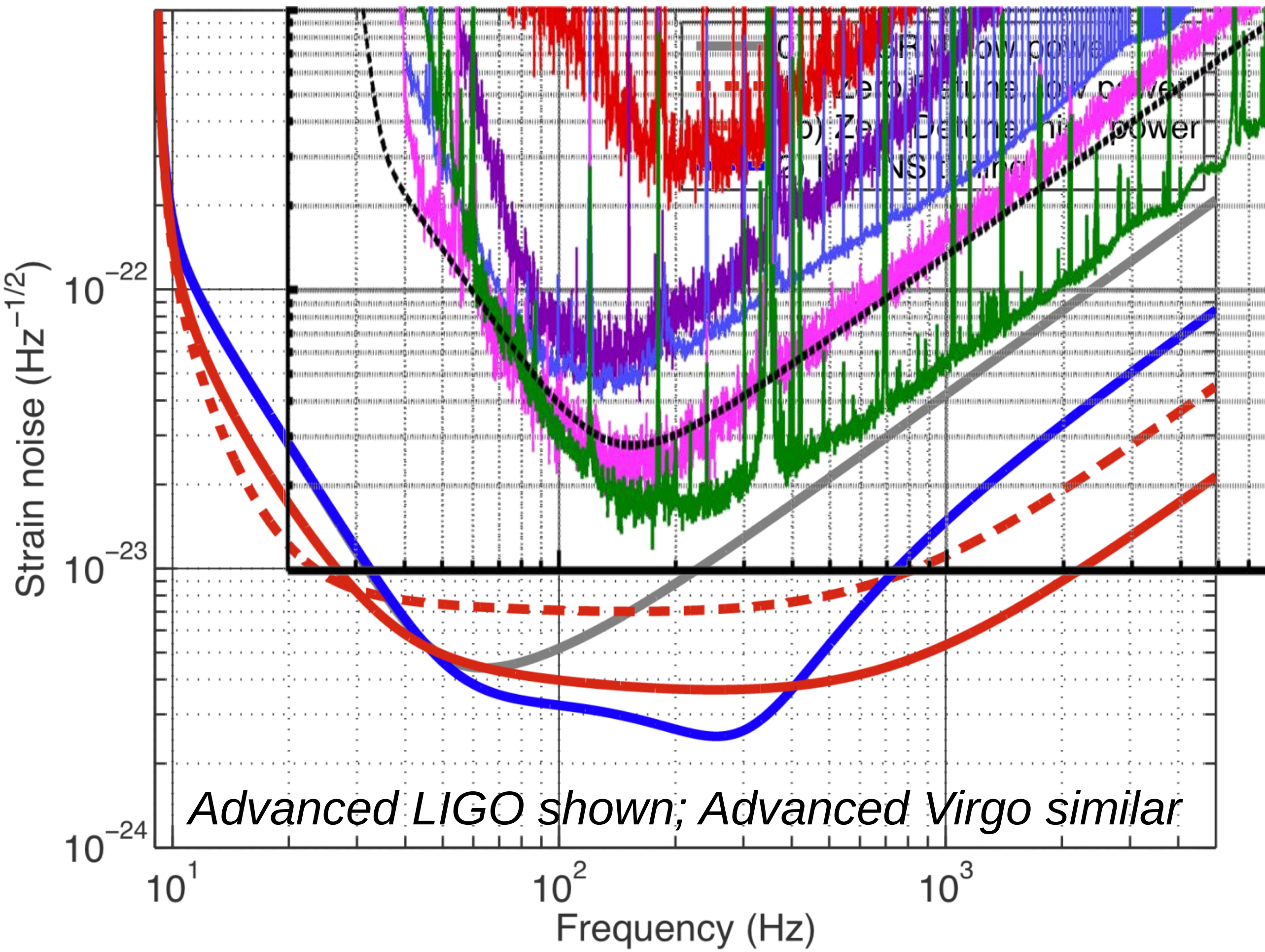




LIGO Noise vs. Frequency – So Far



Projected Noise Spectra



Orientation-averaged detection range for binary inspirals

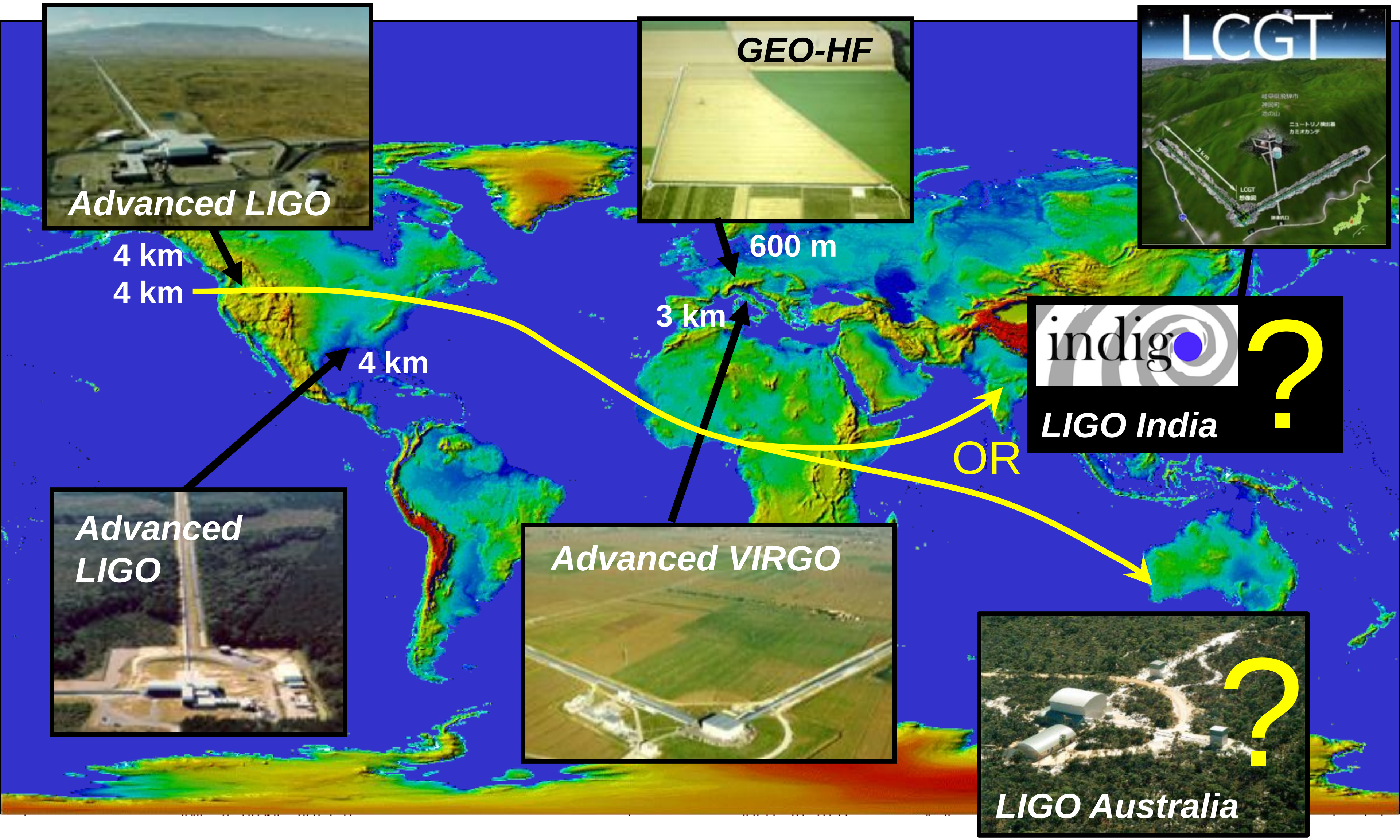
case	NS-NS	BH-BH (30 $M_{\odot}$)
No SRM	150 Mpc	1.60 Gpc
0-det low P	145 Mpc	1.65 Gpc
0-det high P	190 Mpc	1.85 Gpc
NS-NS tuned	200 Mpc	1.65 Gpc

Best guess: will detect dozens per year

Factor of ~10 better amplitude sensitivity than initial detectors

→ Factor of ~1000 greater volume of space

Advanced GW Detector Network, Circa 2015–17



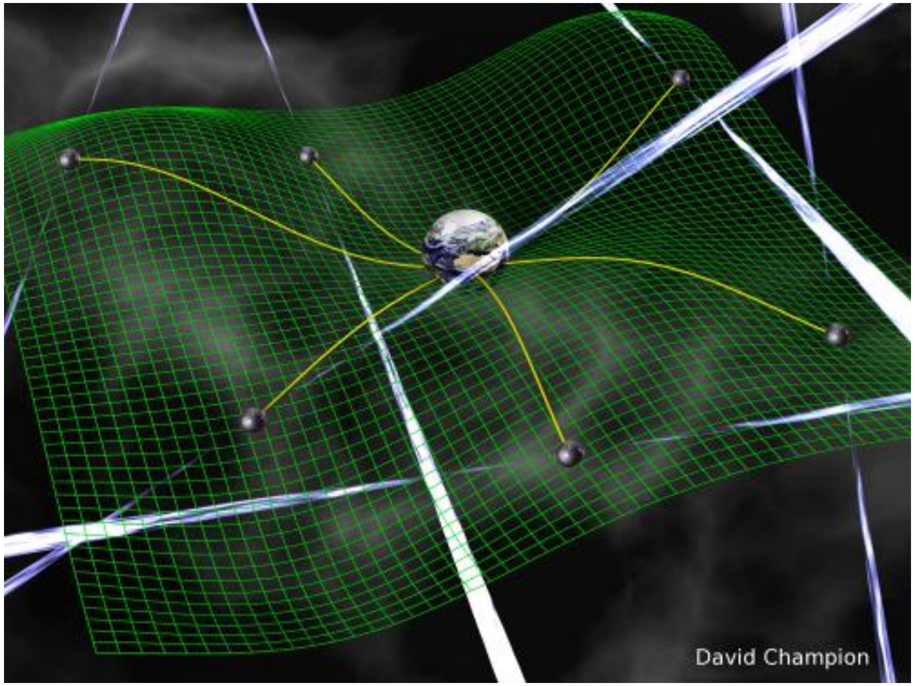
Detecting GWs with Pulsar Timing

Pulse arrival time at Earth is shifted by gravitational wave

Look for correlated time variations among millisecond pulsars with strong, narrow pulse profiles

Three established projects:

- NANOGrav
- European Pulsar Timing Array
- Parkes Pulsar Timing Array



Now collaborating as the International Pulsar Timing Array consortium – http://www.ipta4gw.org/

Searching for very low frequency GWs in timing residuals

- Related to frequency and total span of pulsar observations
- Periods from ~1 month to ~30 years

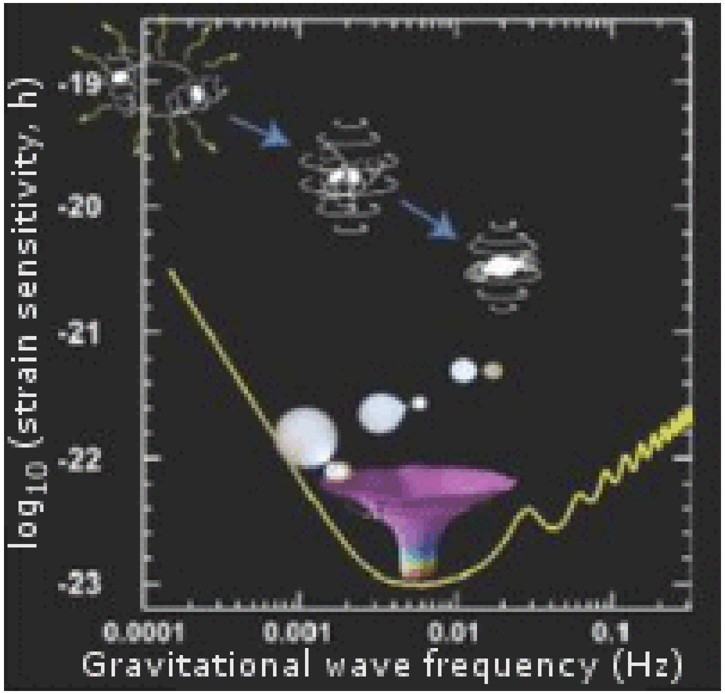
Space-Based GW Detectors

By going into space, we can:

- Completely avoid seismic noise
- Make the arms millions of km long

Science targets are at low frequencies, below ~0.1 Hz

- Supermassive black hole mergers
- Extreme-mass-ratio inspirals
- Galactic binaries
- Stochastic GW signals



LISA abandoned this year as a joint ESA-NASA mission

- Europeans strongly considering down-scoped "eLISA" mission proposal
- NASA soliciting the development of new mission concepts
- Stay tuned…

Gravitational Wave Astrophysics, and Some Search Results So Far

Binary Inspiral Searches

Latest published results from LIGO+Virgo

[Abadie et al., PRD 82, 102001 (2010)]

Search using matched filtering

No inspiral signals detected

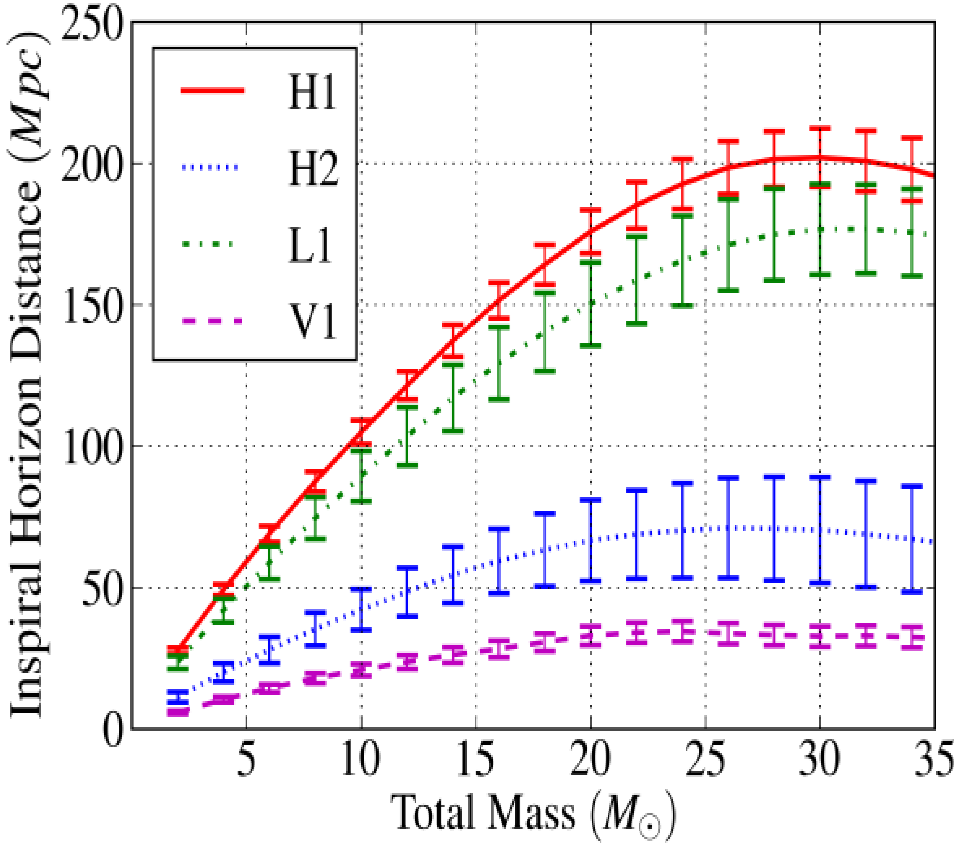
90% confidence limits on coalescence rates:

For binary neutron stars:
0.0087 per year per "L_{10}"
(**0.015** per year in a galaxy like the Milky Way)

Also rate limits for binary black holes, BH-NS systems

Not yet confronting expected range of merger rates

How far away could we hear?



Looking Forward to Info from Inspirals

Time evolution of GW amplitude and frequency from a compact binary system depend on the properties of the binary system

From a single inspiral, can determine (at least in principle)**:**

- Masses of the components
- Black hole spin(s)
- Orientation of the orbit
- Location in the sky

From a sample of many inspirals, can determine:

- Abundance of compact binary systems
- Distribution of masses and spins in binaries
- Spatial distribution — host galaxy types, etc.

Tracing the Expansion of the Universe

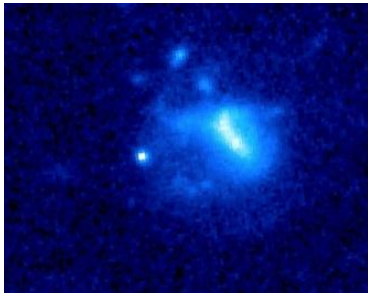
GR predicts the *absolute* luminosity of a binary inspiral+merger → detection of a signal measures the luminosity distance directly

So a compact binary is a "standard siren"

Precision depends on signal strength, ability to disentangle orbit orientation

Identifying an optical counterpart provides redshift

Like:

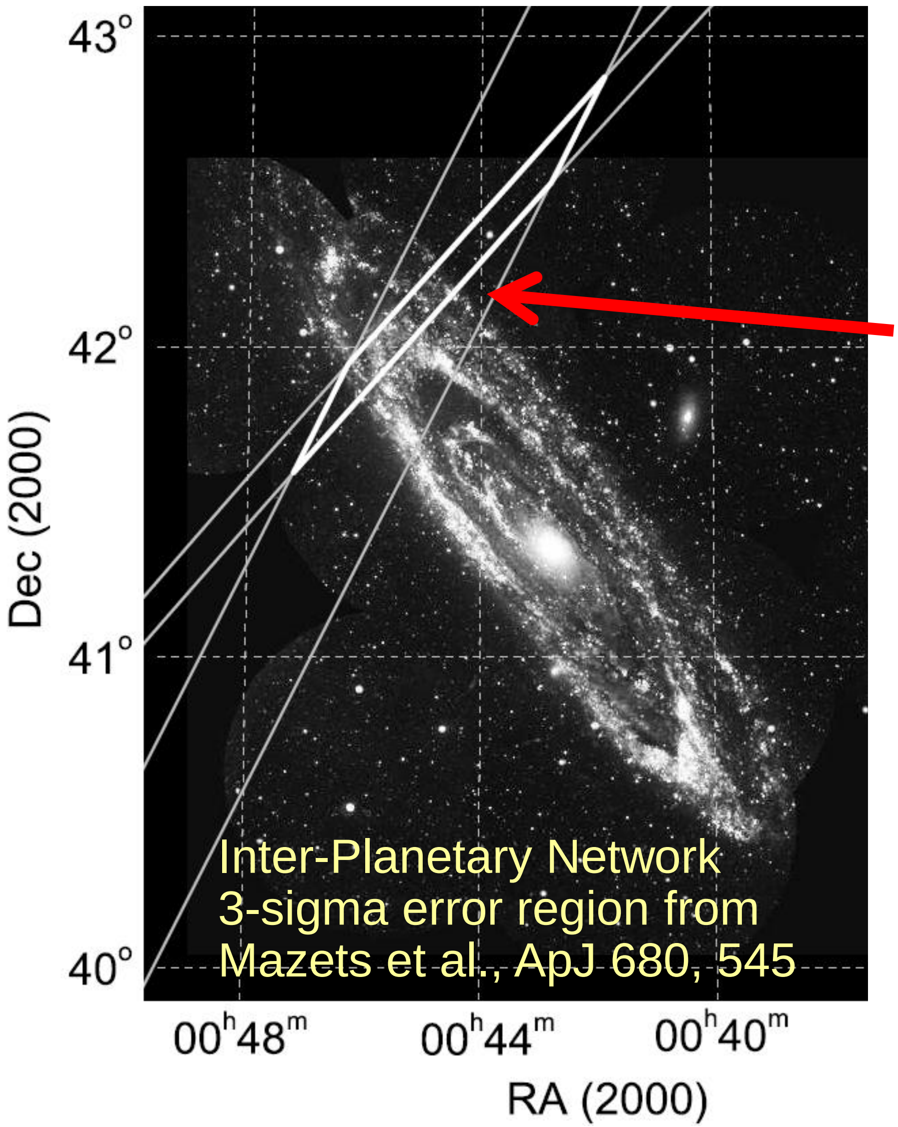


Optical afterglow of GRB 050709
Hubble image 5.6 days after initial gamma-ray burst
(Credit: Derek Fox / Penn State University)

With a sample of events, can trace out distance-redshift relation

e.g. measure cosmological *w* parameter

GRB 070201



Short, hard gamma-ray burst

Leading model for short GRBs: binary merger involving a neutron star

Position was consistent with being in M31 (Andromeda galaxy)

Both LIGO Hanford detectors were operating

Searched for inspiral & burst signals

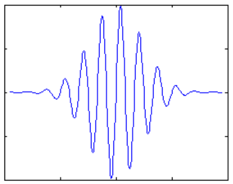
Result from LIGO data analysis:
No plausible GW signal found; therefore very unlikely to be from a binary merger in M31

[Abadie et al., PRD 82, 102001 (2010)]

All-Sky GW Burst Searches

LIGO+Virgo Search for any transient signal in the data

with frequency content in the range 64-6000 Hz and duration up to 1 sec



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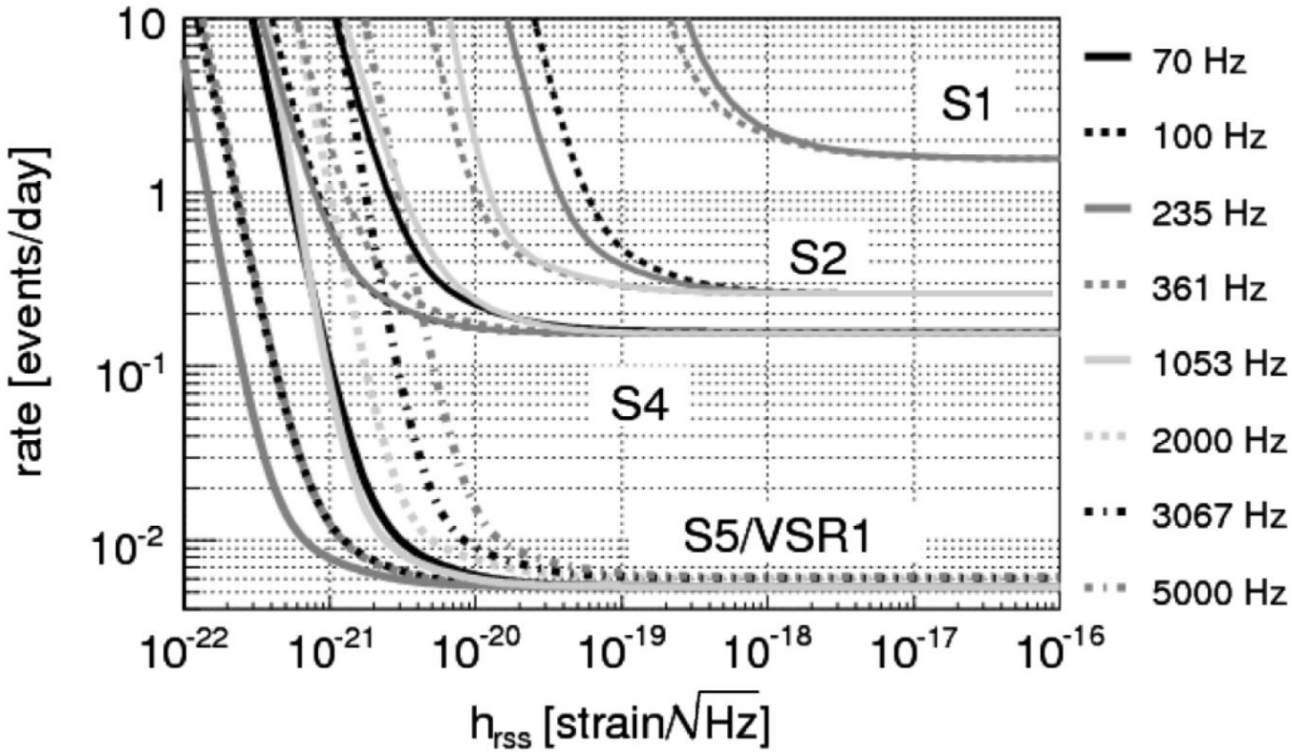


Abadie et al., PRD 81, 102001 (2010)

GW energy sensitivity for a 153 Hz burst:

~2 x 10^{-8} $M_{\odot}c^2$ at 10 kpc , ~0.05 $M_{\odot}c^2$ at 16 Mpc

One Goal: Probe Supernova Dynamics

Core-Collapse Supernovae (type Ib/c and type II) occur frequently and liberate up to

Bill Saxton, NRAO/AUI/NSF

~10^{53} erg

~1% as EM radiation

- Optical
- Radio
- X-ray
- Gamma ray

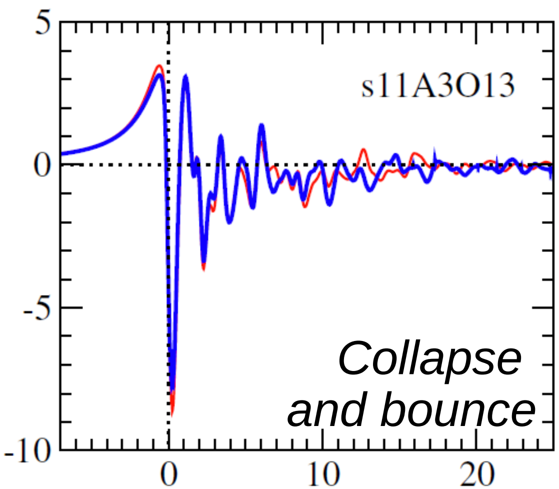
~99% as neutrinos

- Low-energy
- High-energy??

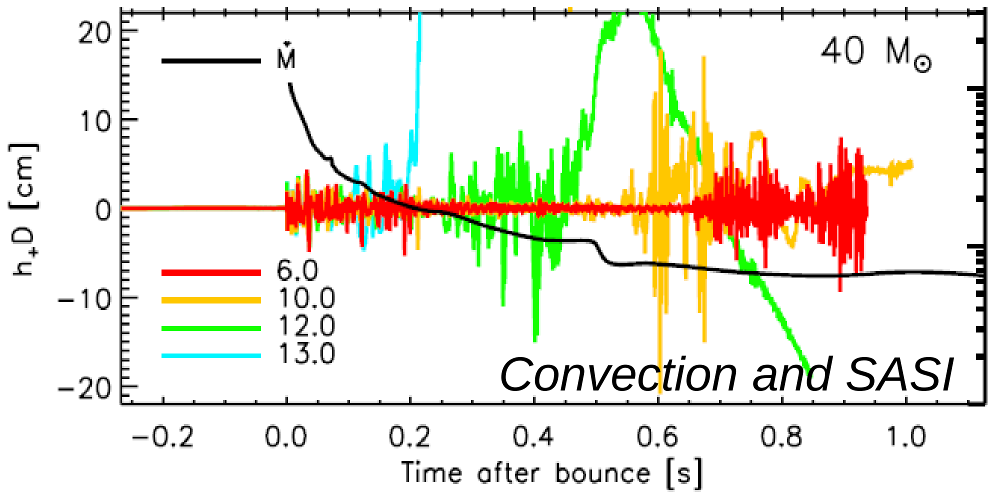
??? as gravitational waves

- Depends on mass flows in and around the core

What SN Waveforms Can We Expect?



Dimmelmeier et al., PRD 78 (2008)



Murphy, Ott & Burrows, ApJ 707 (2009)

Mechanism	Waveform	Polarization
Collapse and bounce	spike	linear
Rotational instabilities	quasiperiodic	circular
Convection	broadband	mixed
Standing Accretion Shock Instability	broadband	mixed
Proto-neutron star *g*-modes	quasiperiodic	linear

…

→ Detecting (or not detecting) a GW signal can tell us what is driving supernova explosions

Search for GWs from the Crab Pulsar

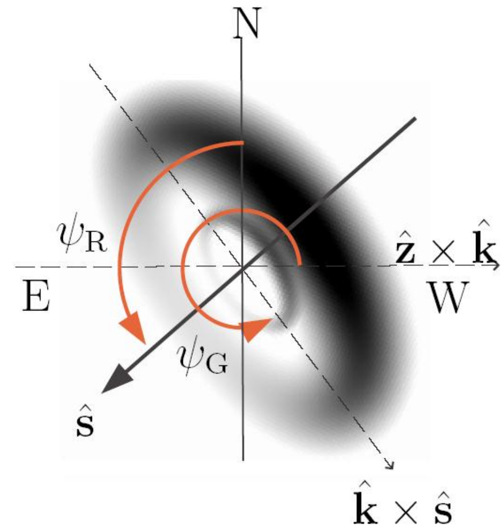
The Crab pulsar spin rate is slowing down – why?

Search for a continuous-wave signal, demodulating detector motion

X-ray observations tell us the orientation of the spin axis

Chandra image

Model



No GW signal detected

[Abbott et al., ApJ 713, 671 (2010)]

Upper limit on GW strain amplitude: $h_0 < 2 \times 10^{-25}$

Implies that GW emission accounts for ≤ 2% of total spin-down power

Results from LIGO S5 data analysis

Searched for isotropic stochastic signal with power-law spectrum

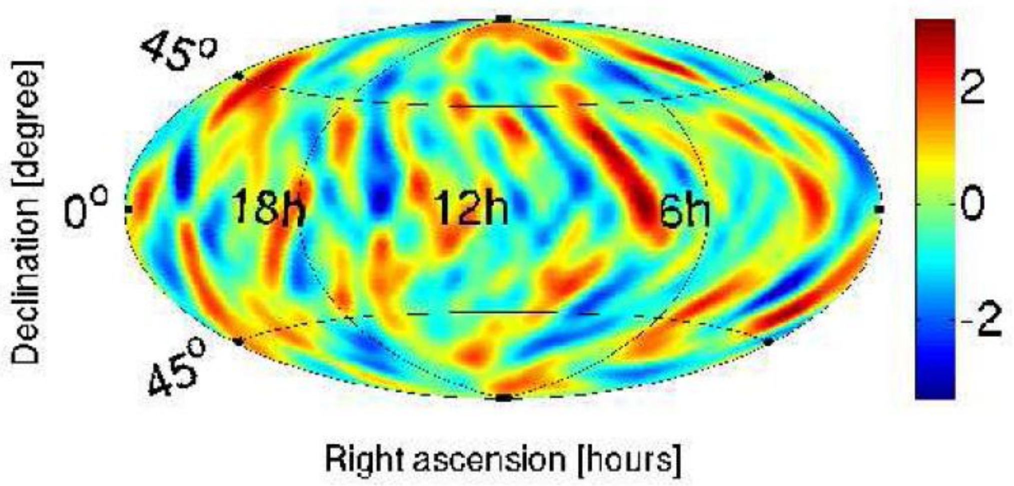
For flat spectrum, set upper limit on energy density in gravitational waves:

$\Omega_0 < 6.9 \times 10^{-6}$ [LSC+Virgo, Nature 460, 990 (2009)]

Just below the indirect limits from Big Bang Nucleosynthesis and CMB

Starts to constrain cosmic (super)string and "pre-Big-Bang" models

Also, directional upper limits on anisotropic signals:



[Abadie et al., arXiv:1109.1809]

Searches for Stochastic GWs 2

Pulsar timing search for isotropic stochastic background of GWs

Jenet et al., ApJ 653, 1571 (2006)

Analysis used 7 pulsars over time spans of at least a few years

Placed limits on energy density of stochastic GW background

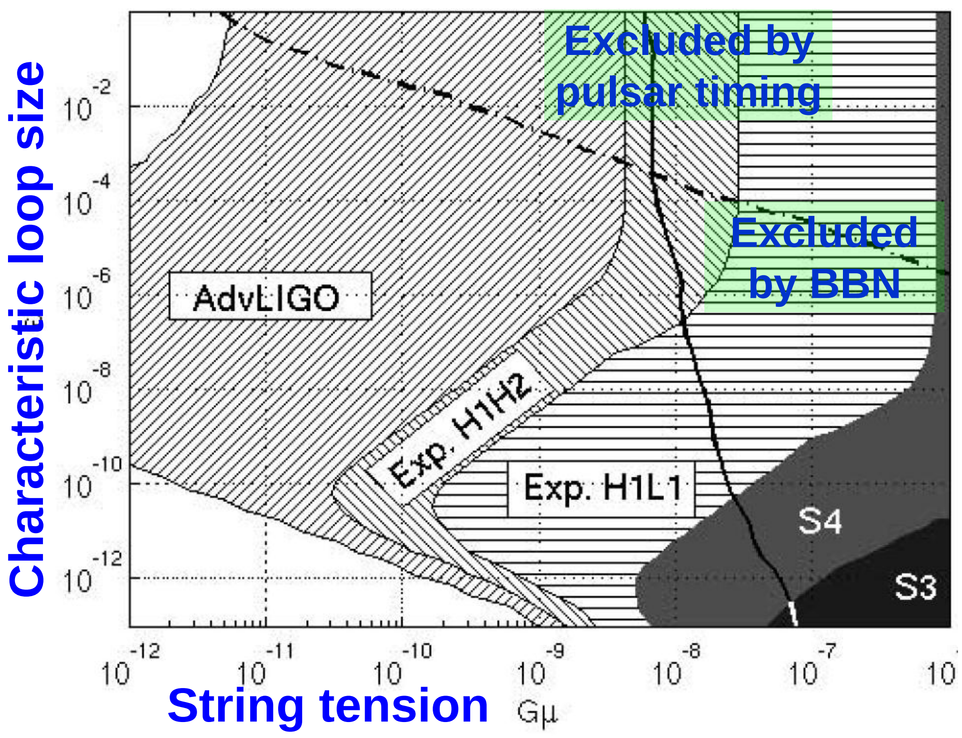
Derived limits on:

Mergers of supermassive binary black hole systems at high redshift

Relic gravitational waves
Cosmic superstrings

Complementary to LIGO search results

Probe different regions of parameter space



Connecting with Astrophysical Events

Multi-messenger astronomy !

Benefits: confirm event candidate, pin down location, correlate data

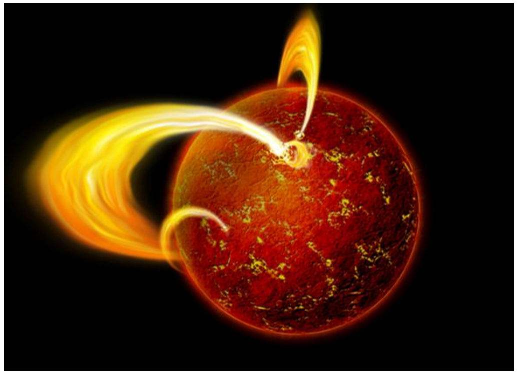
★ **Searches triggered by electromagnetic or particle detections**

Gamma-ray bursts (GRBs)

Soft gamma repeaters (SGRs) / magnetars

Vela pulsar timing glitch

High energy neutrinos



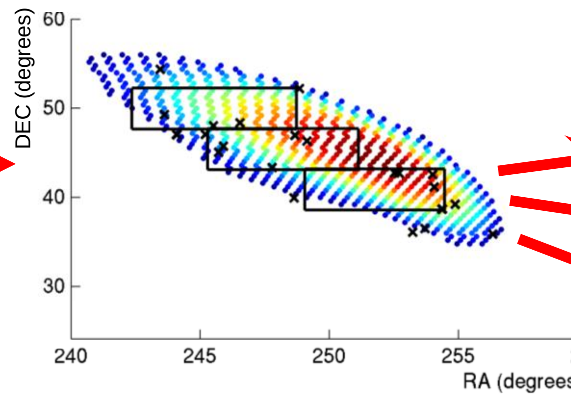
★ **Low-latency electromagnetic follow-up observations**

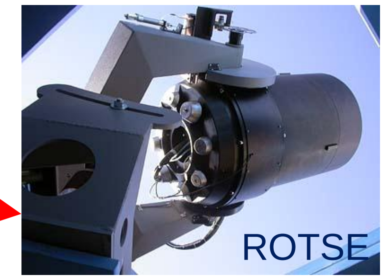
Analyze GW data quickly, identify candidates, send alerts to optical, X-ray and radio telescopes

Try to catch an EM transient that otherwise would be missed

First Implementation of Low-Latency EM Follow-Ups: 2009–2010

Analyze GW data, select candidates





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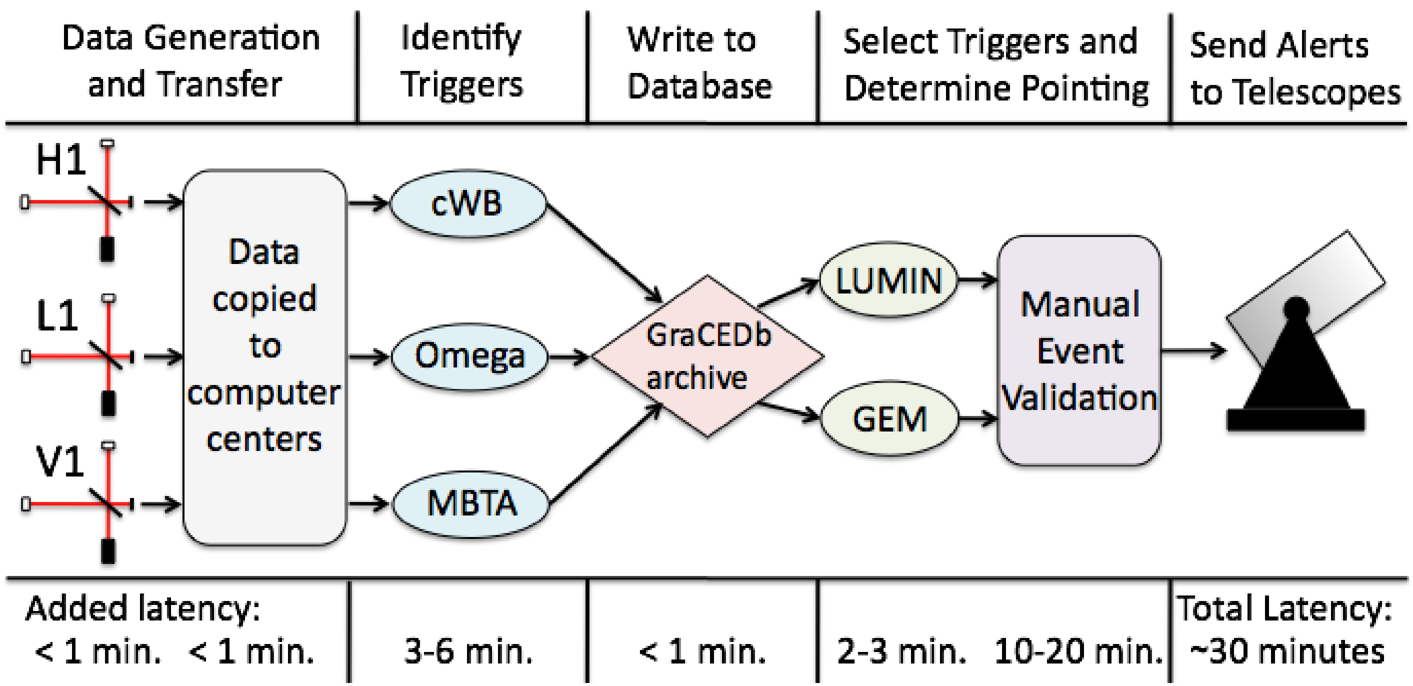

Described in Abadie et al. arXiv: 1109.3498

Summary

Gravitational wave observing has begun

- Initial interferometric detectors operated successfully for a number of years
- Many results published — upper limits and astrophysical interpretations
- Within one order of magnitude (amplitude) of detecting signals !
- EM follow-up observations were a novel feature of the 2009–10 run

Currently upgrading to Advanced LIGO and Advanced Virgo

- Will resume science running in ~2015
- LCGT will join the network a bit later

Other detectors

- Pulsar timing arrays – improving now
- Space-based detectors
- Concepts for future underground detectors