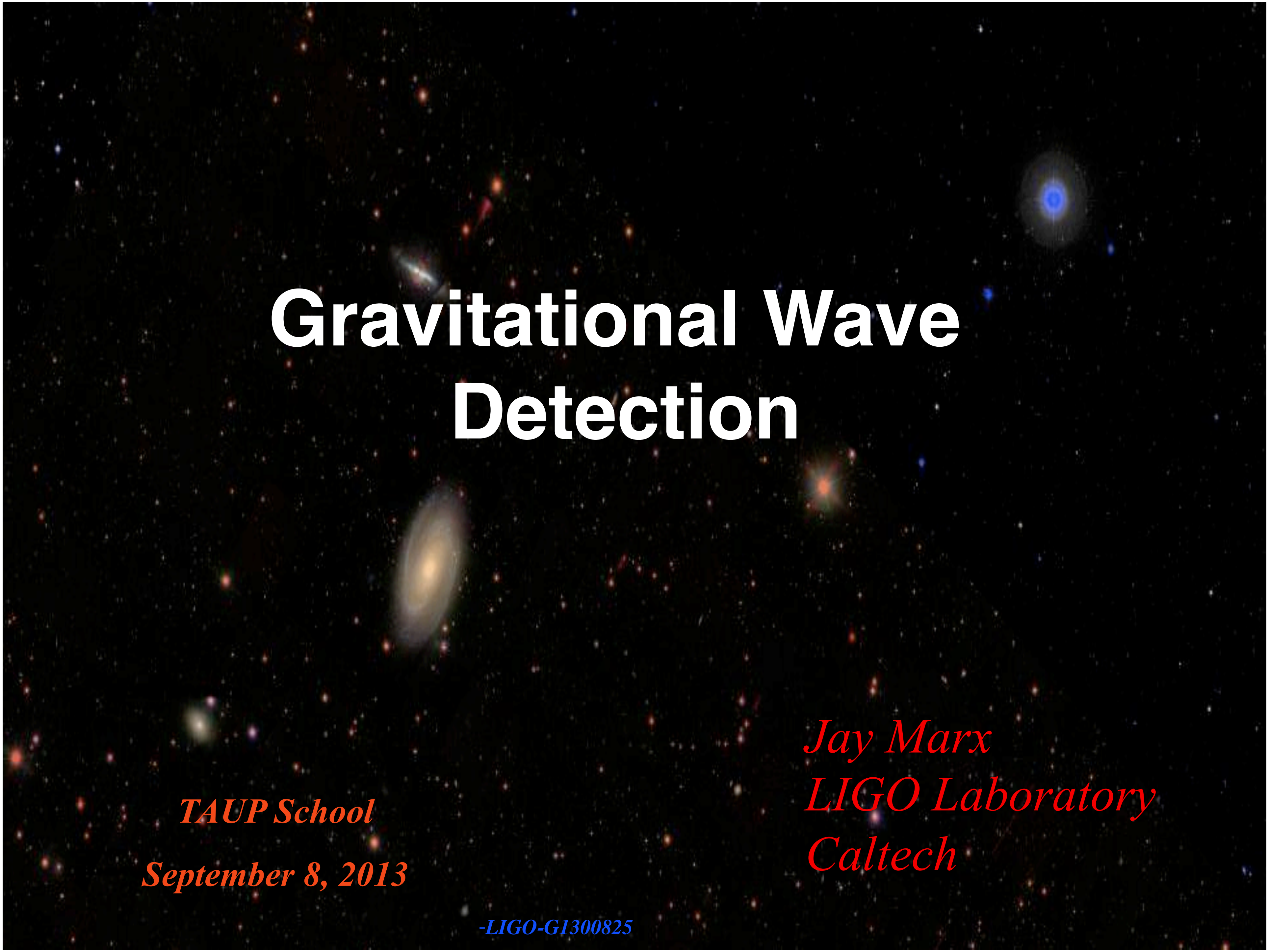


Gravitational Wave Detection

Jay Marx
LIGO Laboratory
Caltech

TAUP School

September 8, 2013

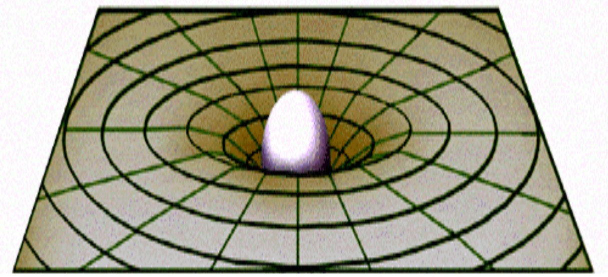
-LIGO-G1300825

Topics

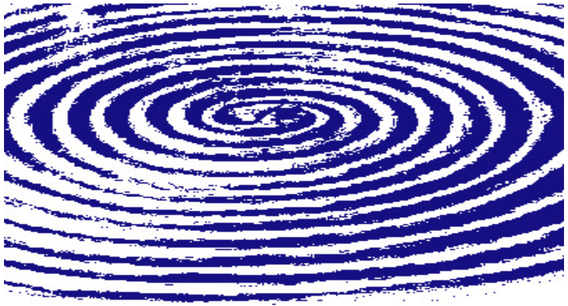
- ***About gravitational waves***
  - *Characteristics of GWs*
  - *Astrophysical sources of GWs*
  - *Are GWs detectable???, how**?***
- ***GW interferometry-- LIGO***
- ***The global GW interferometer network***
  - *LIGO, VIRGO, KAGRA, –status and plans*
- ***Gravitational wave astronomy– a new window on the universe***
- ***Other approaches***
  - *Space-based interferometry*
  - *Pulsar timing*
  - *CMB B-polarization*

Gravitational waves

- General Relativity- The fabric of space-time is dynamic
  - Mass causes fabric to warp and in some circumstances to ripple

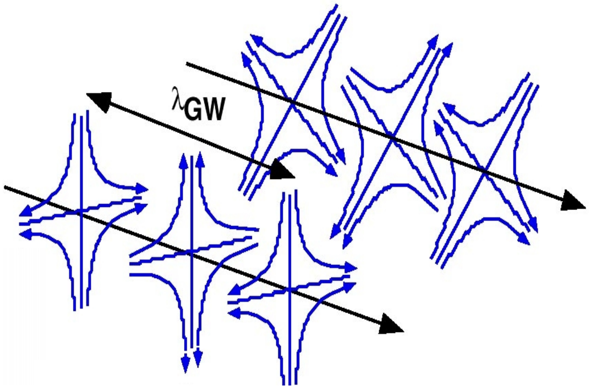


- GWs are ripples in the fabric of space-time that propagate at light-speed

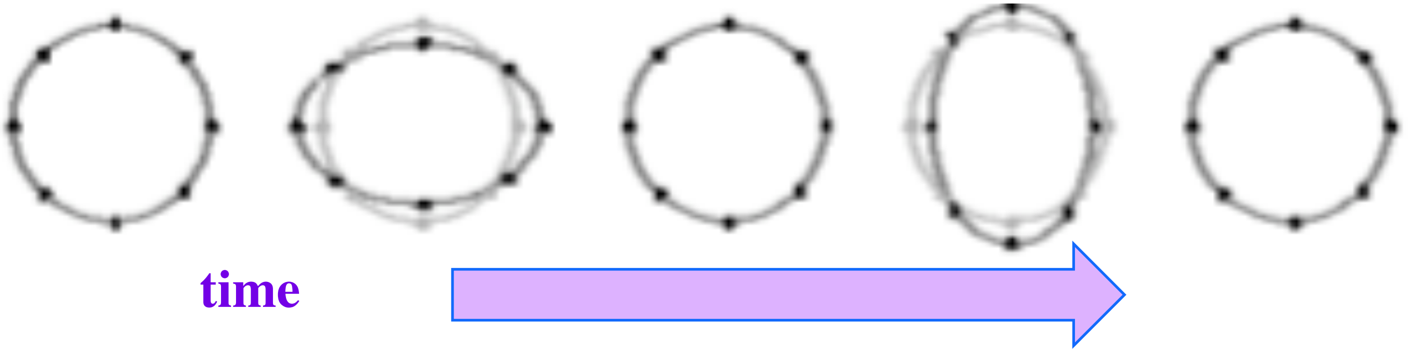


Gravitational waves

- Because GR is a tensor theory GWs are transverse, quadrupole waves with 2 polarizations (45° to each other).

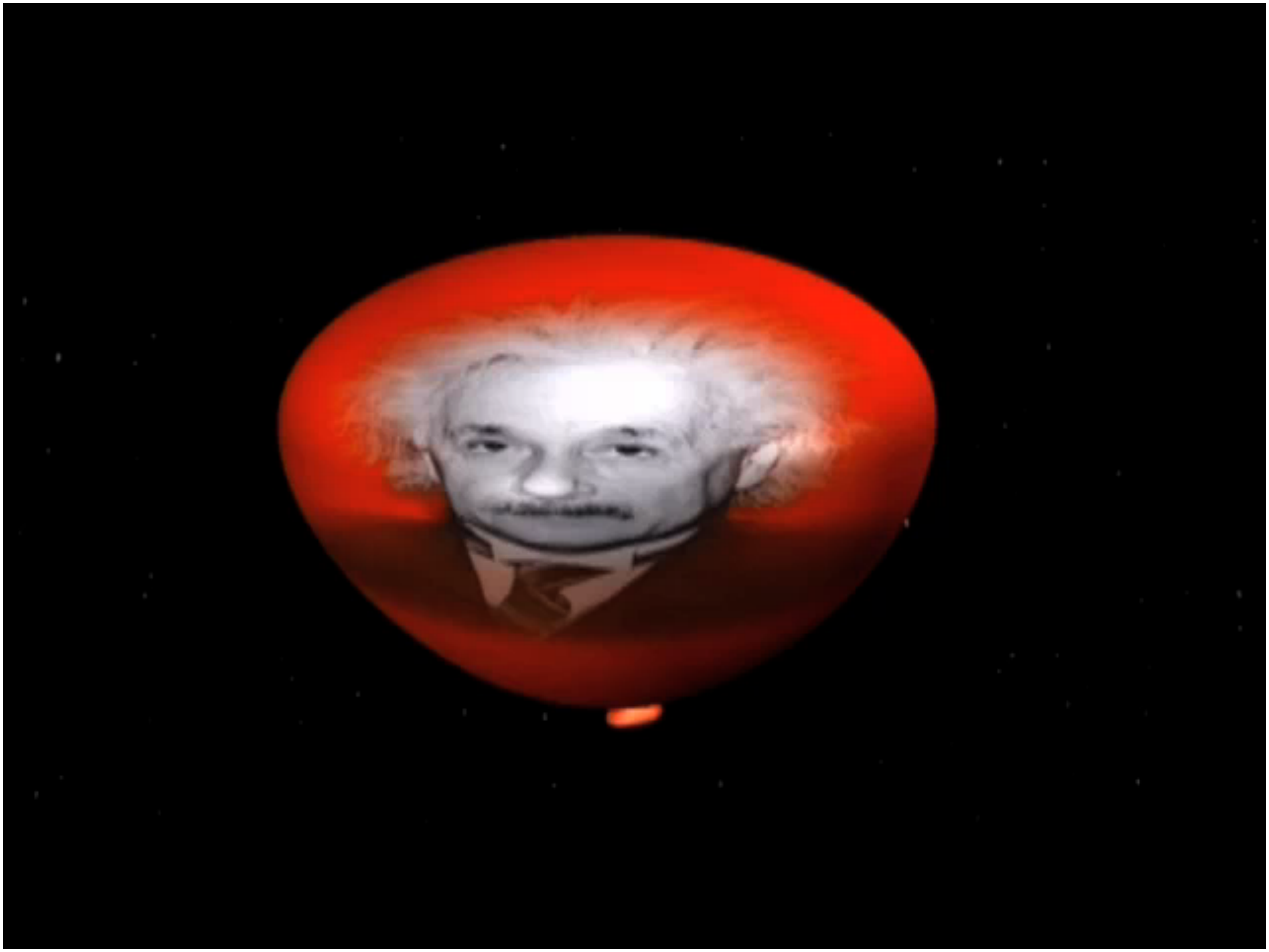


- ***Gravitational waves stretch/squeeze space and everything in it transverse to direction of propagation. The key to detecting them.***



- ***GW's are emitted by accelerating aspherical mass distributions--***
  - ***i.e. an accelerating quadrupole moment***

A GW traveling into the screen



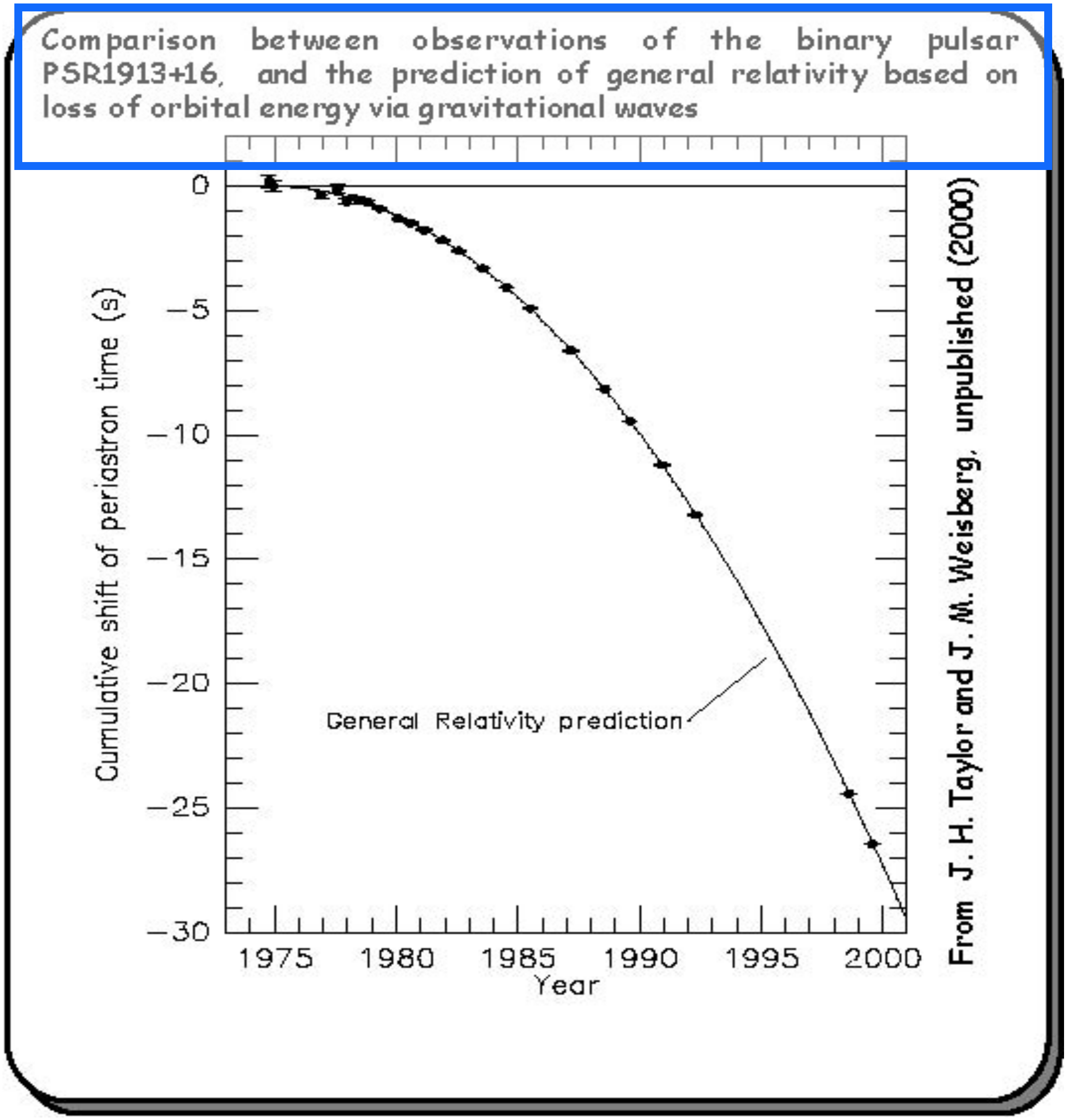
“Indirect” evidence for gravitational waves

Joseph H.Taylor Jr

Russel A. Hulse

Discovered and Studied Pulsar System PSR 1913 + 16 with Radio Telescope

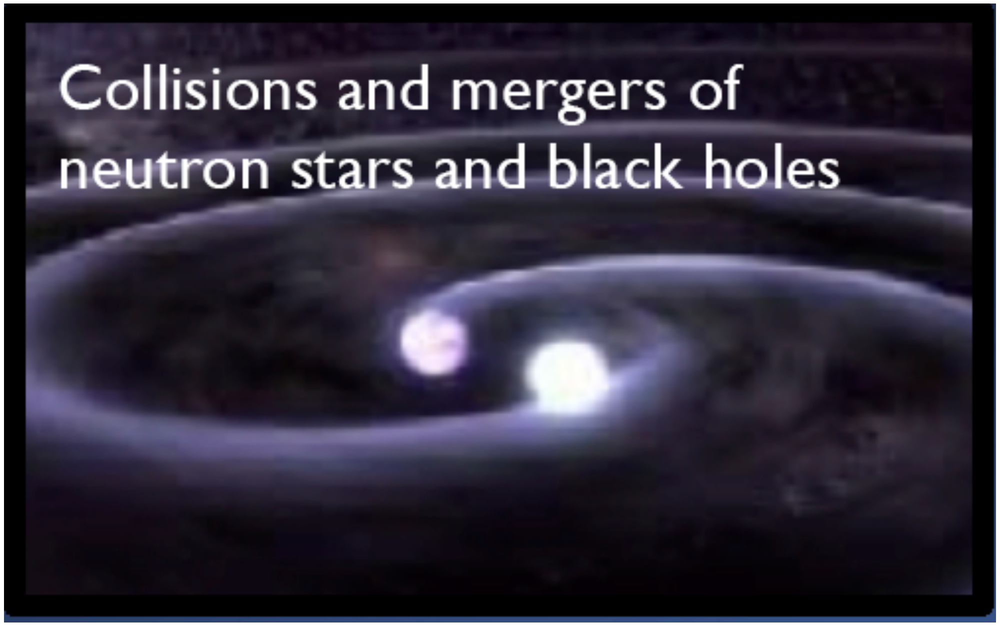
Won 1993 Nobel Prize

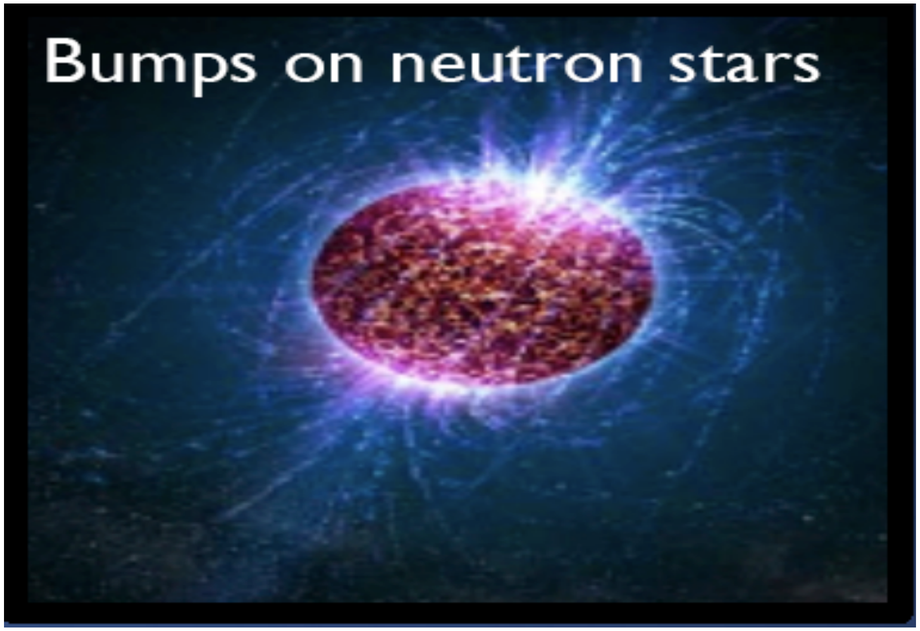


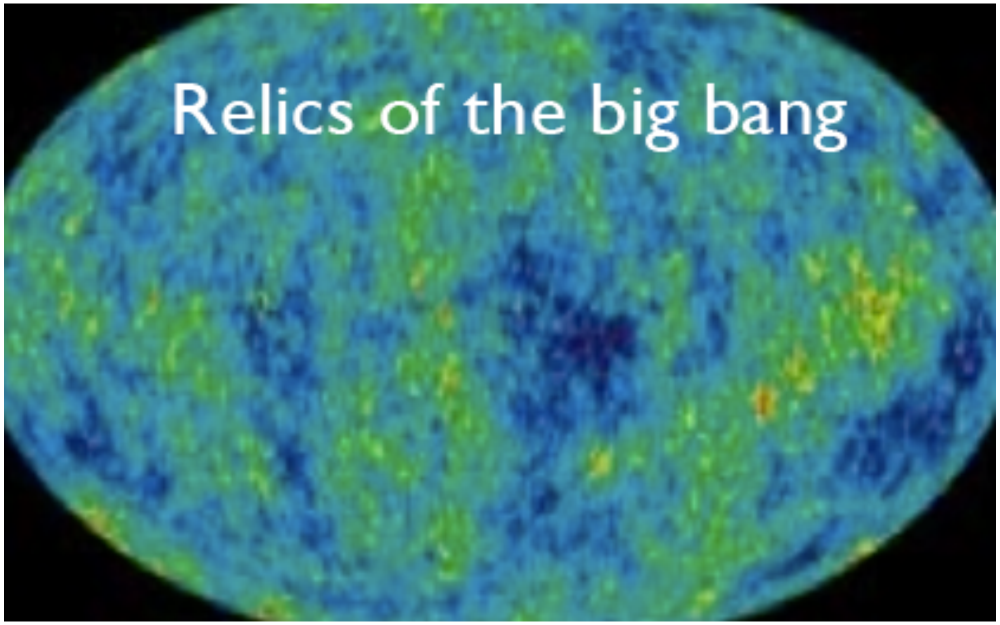
Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

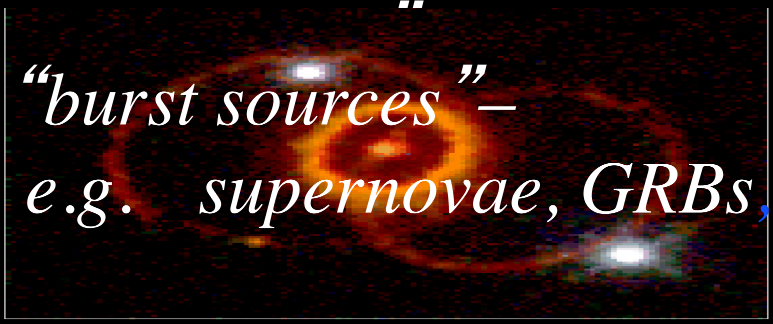
From J. H. Taylor and J. M. Weisberg, unpublished (2000)

GWs--ripples in space-time from some of natures most violent events


Collisions and mergers of neutron stars and black holes

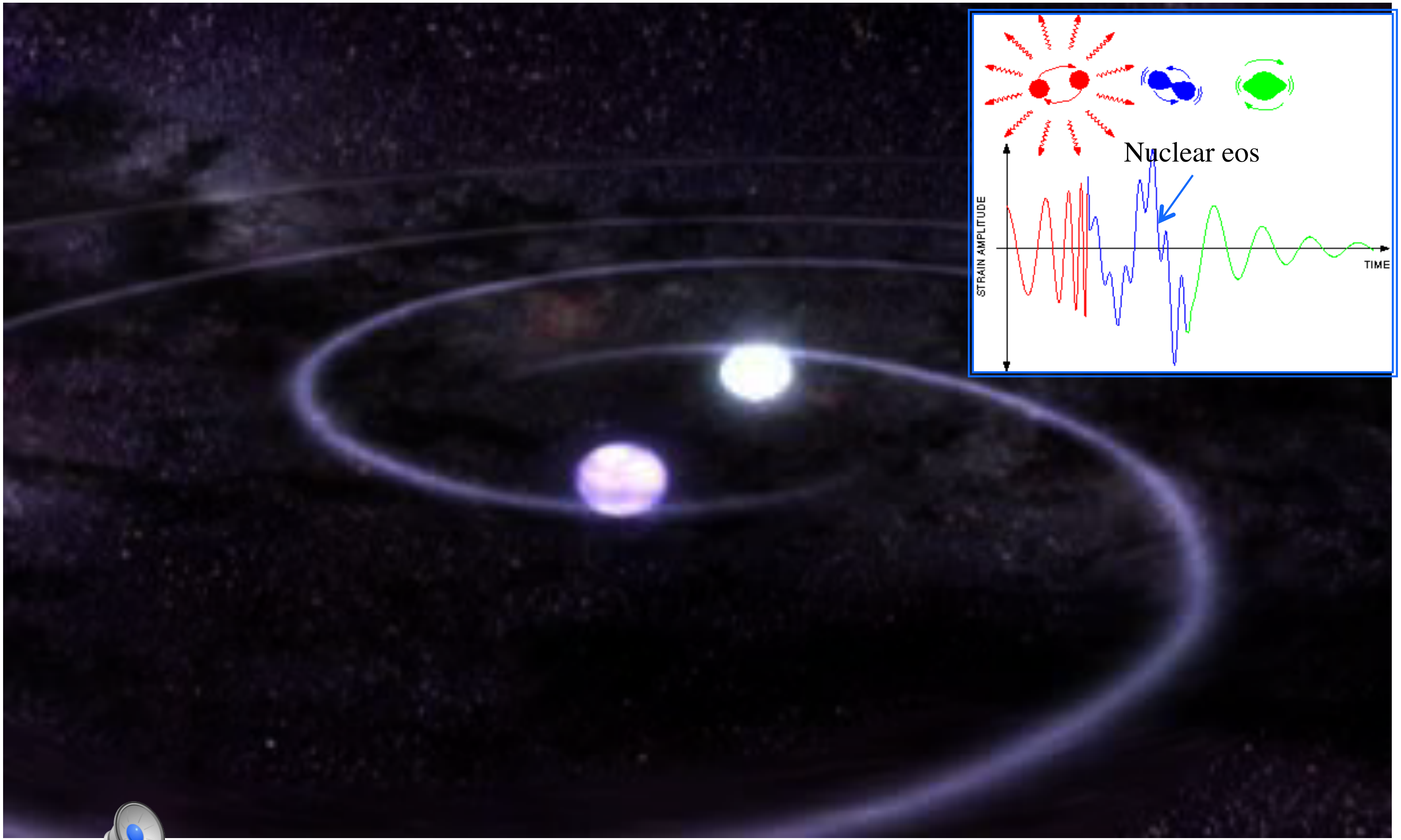

Bumps on neutron stars


Relics of the big bang


"burst sources"– *e.g. supernovae, GRBs*,

and unknown/unexpected sources

GWs from NS-NS inspiral & merger



GWs carry very different information about source than EM radiation

- **EM radiation emitted by moving electric charges**
  - » Emitted from small regions, with short wavelength
  - » Carries information about small portion of astronomical source (that's why can image source with EM)
  - » Can be absorbed/distorted in transit by intervening matter
- **GWs emitted due to motion of overall mass of entire system**
  - » GWs have wavelengths comparable to size of system
  - » Convey information about the motion of large-scale mass distributions- gives a "picture" of the dynamics of an astronomical system
  - » Gravity is weak so GWs travel ~unimpeded from source

Amplitude of Gravitational Waves

e.g. from merging neutron stars

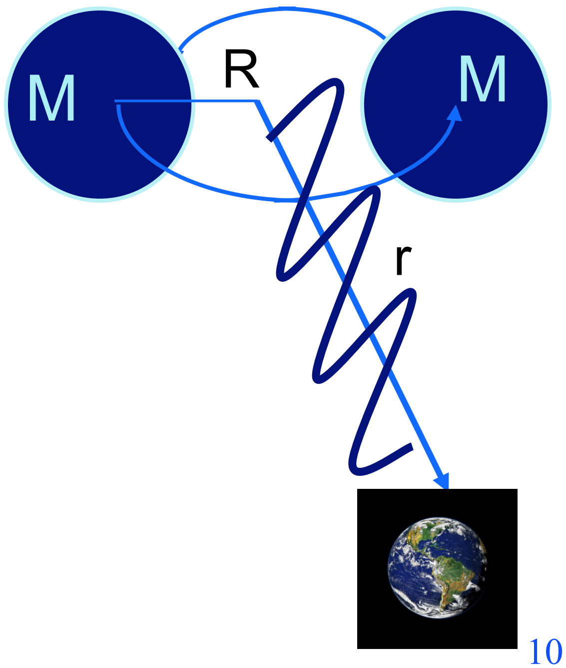
~ 50 million light years away

- Gravitational wave strain (strain $h = \Delta L/L$)

"h" is relative stretch/squeeze of fabric of space over a distance L due to a passing gravitational wave

Einstein-- $$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \Rightarrow h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r}$$

for this example $h \sim 10^{-21}$



If the distance to the nearest stars is stretched by a factor of 10^{-21} this corresponds to width of a human hair

The tiny size of the effect of a GW sets the challenge for detecting them

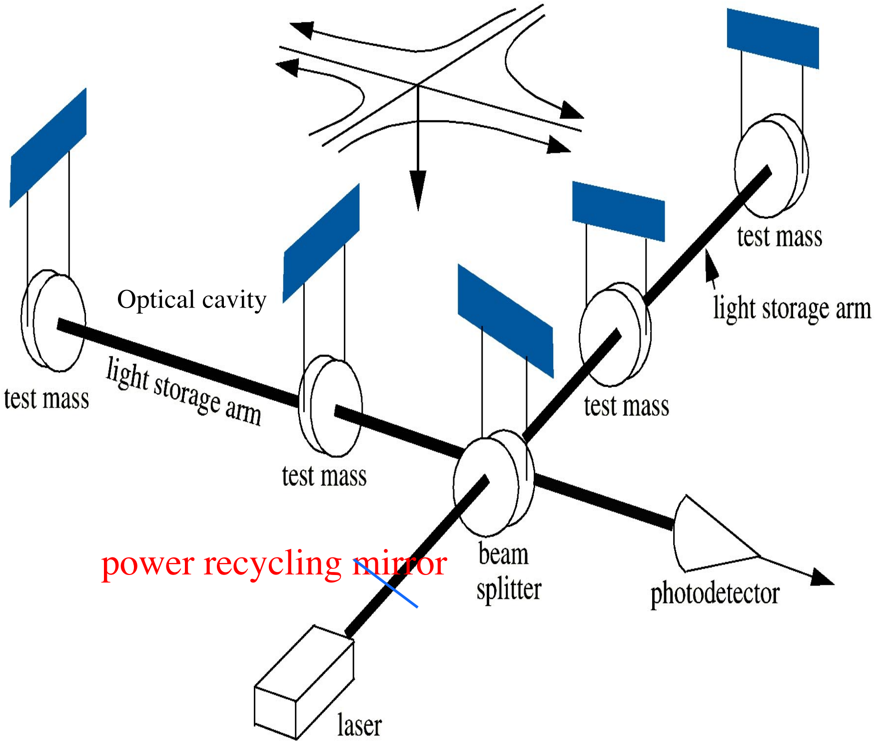
Detecting GWs with Precision Interferometry

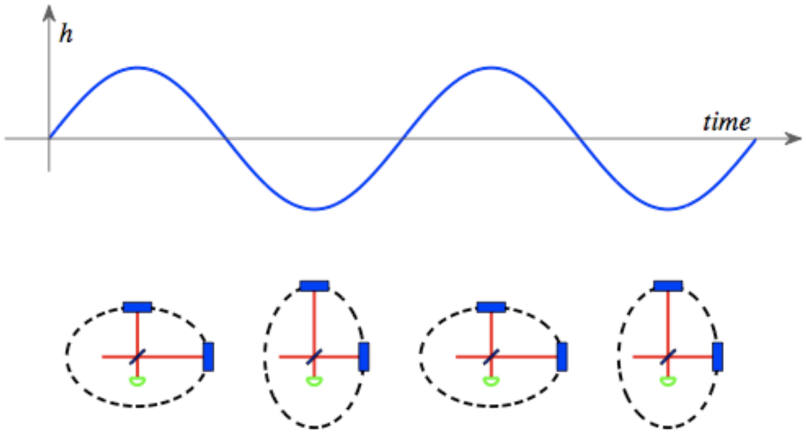
- Suspended mirrors in L-shaped configuration act as markers of points in the fabric of space/time

- A passing gravitational wave alternately stretches (compresses) space-time thus changing the relative separation of the mirrors in each arm.

- Optical interferometery is used to measure relative separation between mirrors in each arm

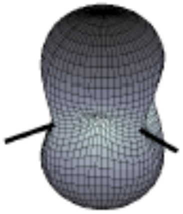
The wavelength of light (~1 millionth of a meter) is the yardstick to measure mirror separation



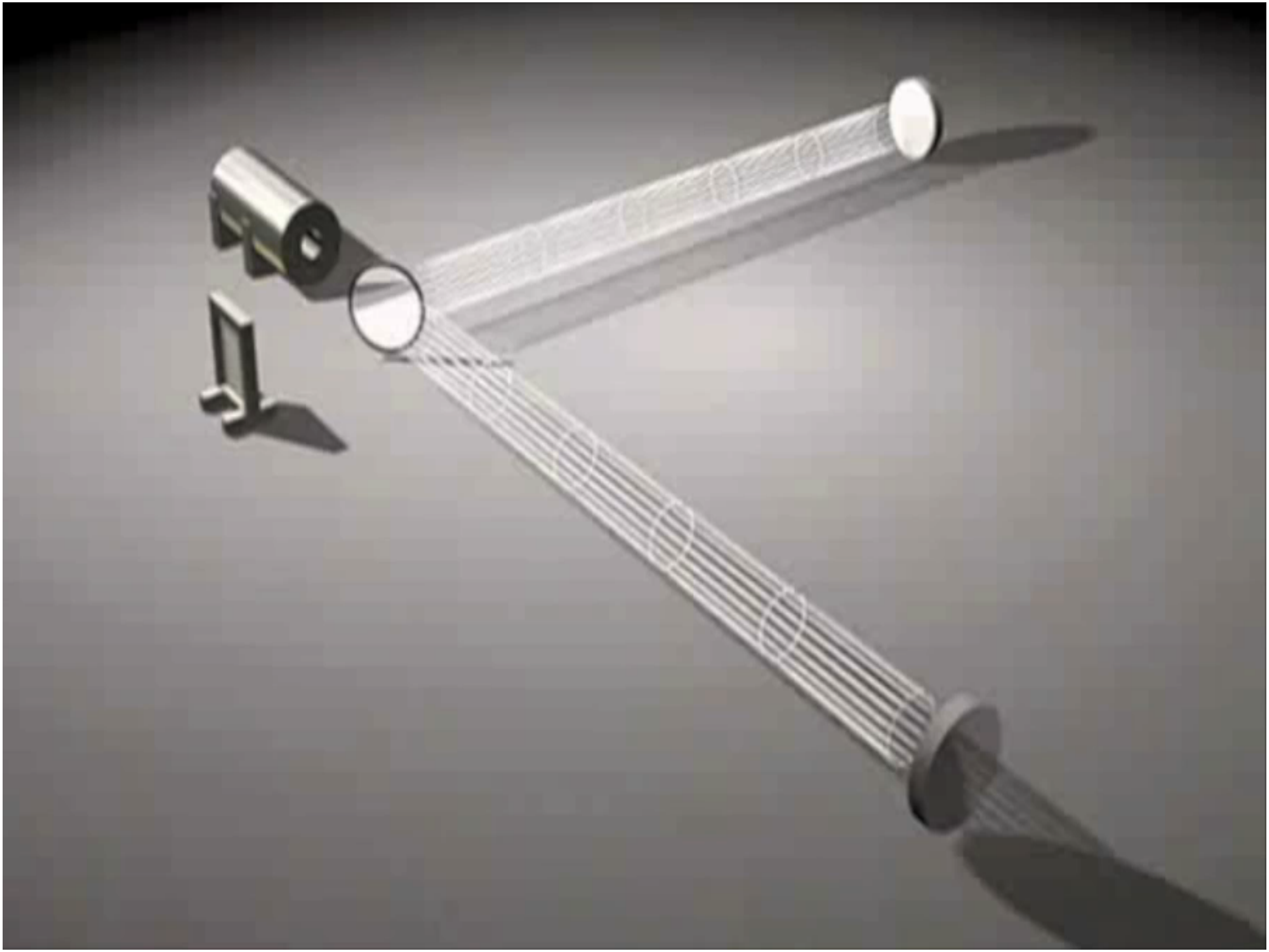


Interferometer GW detectors-- sensitivity

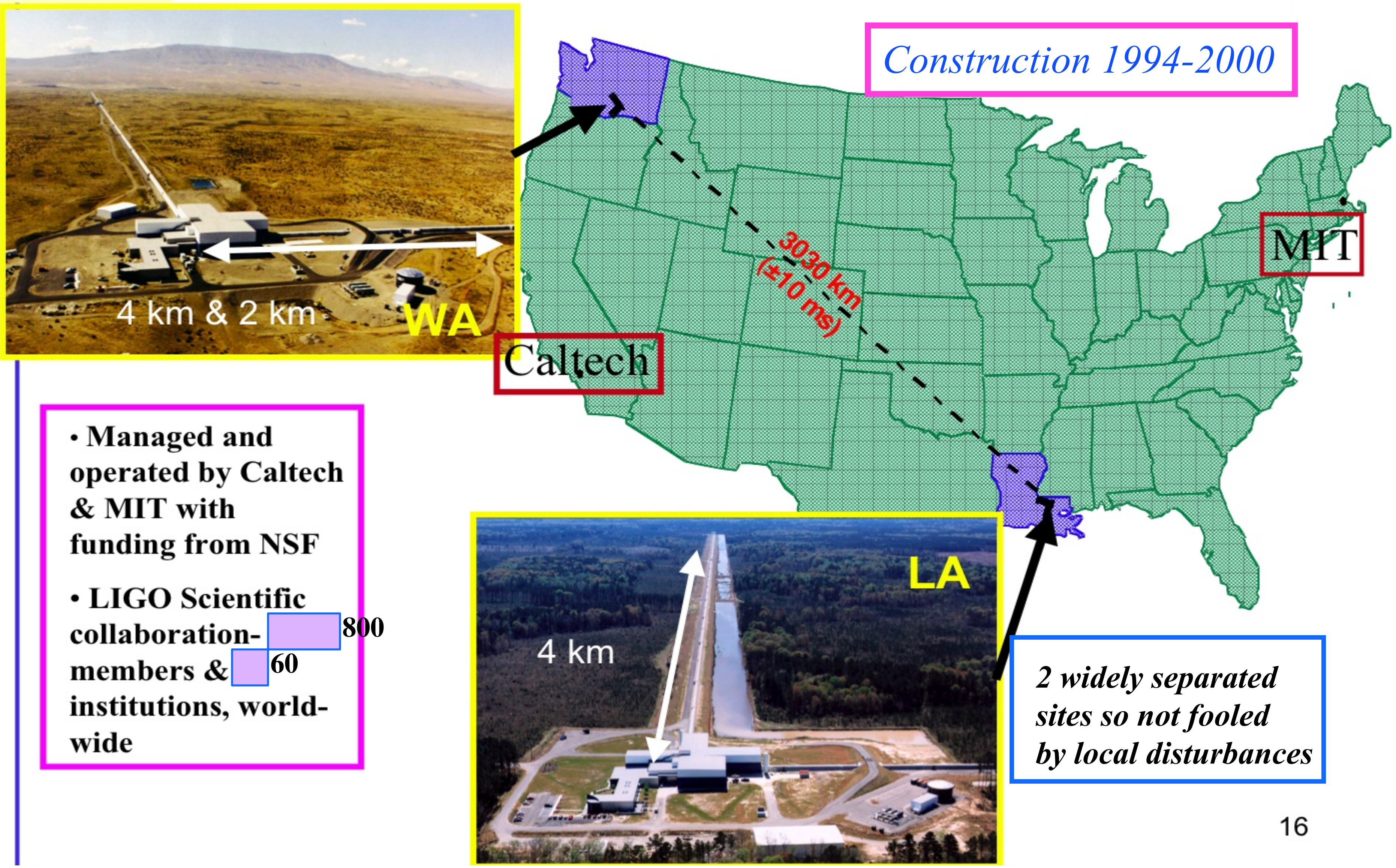
- Interferometry is sensitive to the amplitude of passing gravitational waves
  - » Signal diminishes as 1/r from source (not $1/r^2$)
- The directional sensitivity of a GW interferometer is somewhat isotropic (actually peanut shaped)
  - » The detector is sensitive to GWs from all directions.



- So the volume from which GWs of a given strength can be detected depends ~on the cube of the detector sensitivity.
- If sources are uniformly distributed the number of sources that can be detected also depends ~on the cube of the detector sensitivity.
  - » Major gains come with relatively small improvements in sensitivity



LIGO Laser Interferometer Gravitational-wave Observatory



Construction 1994-2000

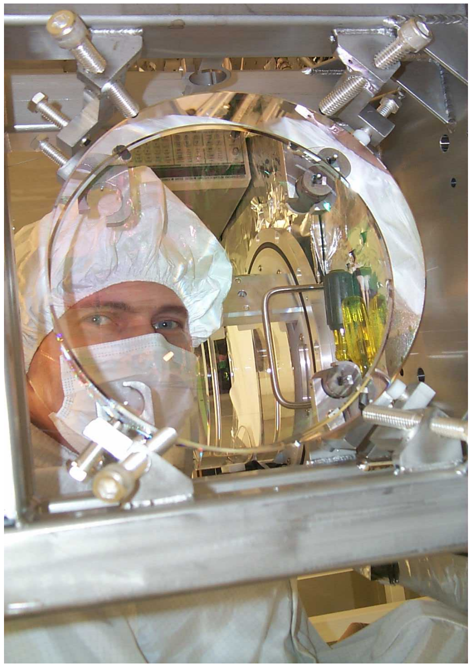
- **Managed and operated by Caltech & MIT with funding from NSF**
- **LIGO Scientific collaboration- 800 members & 60 institutions, world-wide**

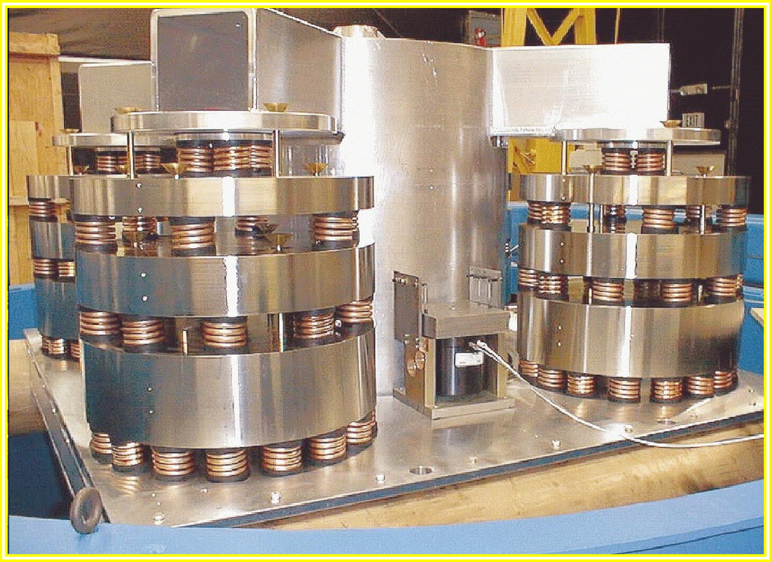
2 widely separated sites so not fooled by local disturbances

Hanford
Washington

Livingston
Louisiana

Some initial LIGO hardware





The experimental challenge for LIGO

Remember $h = 10^{-21}$**?** $h = \Delta L / L$

The strain from a GW from a neutron star pair merging 50 million light years away

For *LIGO the length of the arms of the interferometer is* L= 4 km

So if $h=10^{-21}$***, with arm length of*** $L=4$ ***km***
the effect of the GW is to change the distance between mirrors by:

$\boxed{\Delta L \sim 4 \times 10^{-18}}$ ***meters!!!***

What makes building a GW detector so hard?

The challenge: measure the relative distance of mirrors in 4 km interferometers arms to accuracy ~10^{-18} m;

~ 1/1000 the size of a proton!!!!

- With 1 micron (10^{-6} m) light need to measure interference fringes to ~10^{-12}
- So must have intense laser and understand and control anything that can jiggle the mirrors, noise and other effects that could mimic gravitational waves at the 10^{-18} m scale in kilometer-scale instruments

Is it even possible to reach the needed sensitivity?

Intrinsic resolution of interferometers- how accurately can a fringe be split?

It's counting statistics-- sqrt of number of photons during measurement. If enough laser power it can be done (e.g. 10 W)

- *10^{21} photons/second at beam splitter where interference occurs*
- *Measurement time ~10^{-2} seconds (at 100 Hz)*
- *Effective arm length 4 km (L) * average number passes for each photon (Fabry-Parot arm cavities--- b~50)*

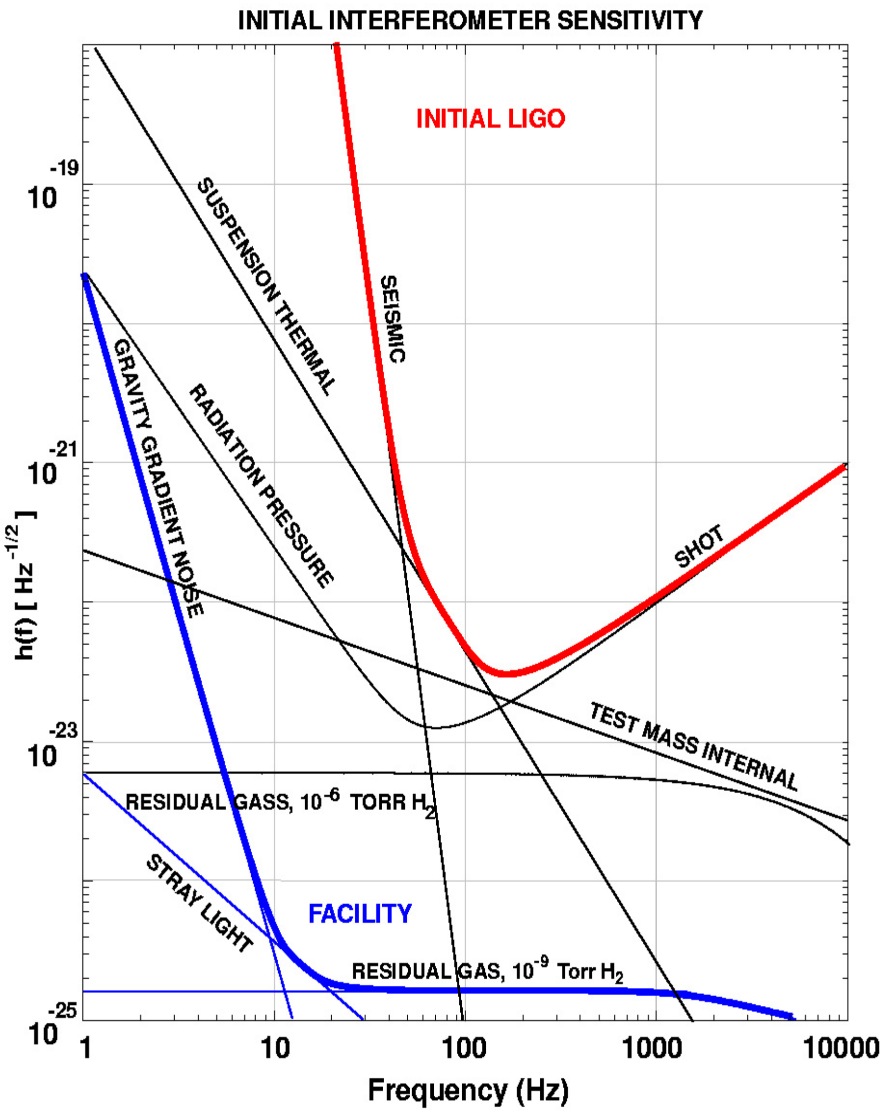
$$h = \frac{x}{} \sim \frac{\lambda}{h\;Lb\sqrt{\dot{N}\tau}}$$

← *1 x 10^{-6} cm*

$h = 6x10^{-22}$ at 100 Hz

But with adequate sensitivity still need to deal with noise

Major noise sources must be under control



~40 Hz to few kHz

- Displacement Noise
  - Seismic motion (limit at low frequencies)
    - Ground motion from natural and anthropogenic sources
  - Thermal Noise (limit at mid-frequencies)
    - vibrations due to finite temperature
  - Radiation Pressure
- Sensing Noise (limit at high frequency)
  - Photon Shot Noise
    - quantum fluctuations in the number of photons detected
- Facilities limits
  - Residual Gas (scattering)
- Inherent limit on ground
  - Gravity gradient noise
- Technical noise-
  - laser, control, electronics, etc

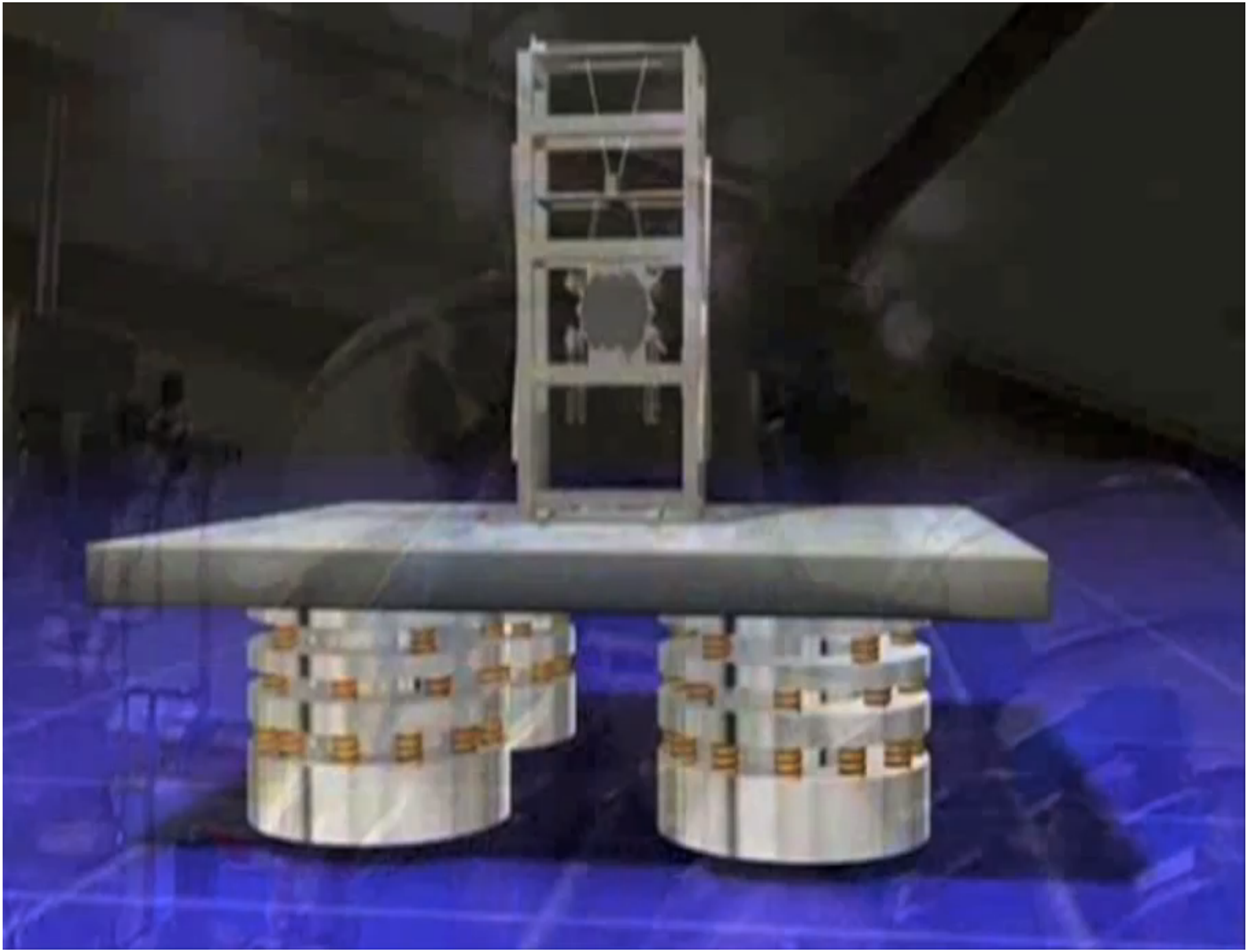
How to suppress noise- some examples

- Ground motion (Seismic noise) limits low frequencies
  - Multiple layers of “shock absorbers”
  - Pendulum suspensions
  - Sense ground motion & feed forward

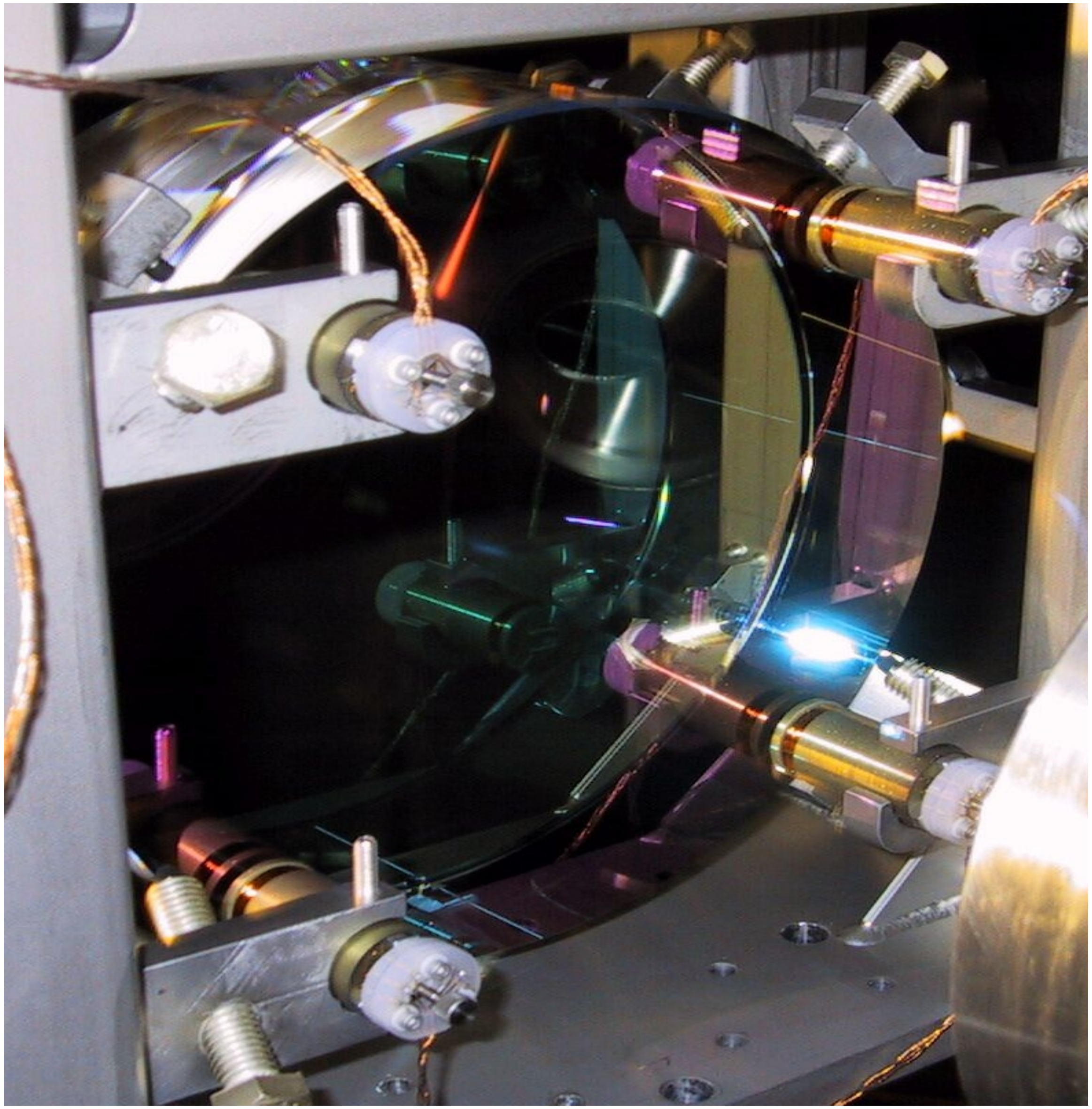
- Finite temperature of equipment (thermal noise) limits middle frequencies
  - Large optics to spread out heat from intense drive laser
  - High Q optics to gather thermal noise to frequencies away from observing frequency band
  - Thermal compensation (e.g. ring laser to restore shape of heated optics)

- Quantum nature of light (Shot Noise fluctuations) limits high frequencies
  - High laser power reduces fluctuations but more thermal effects

- Many levels of sensors and feedback to stabilize optical system



Mirror and control actuators



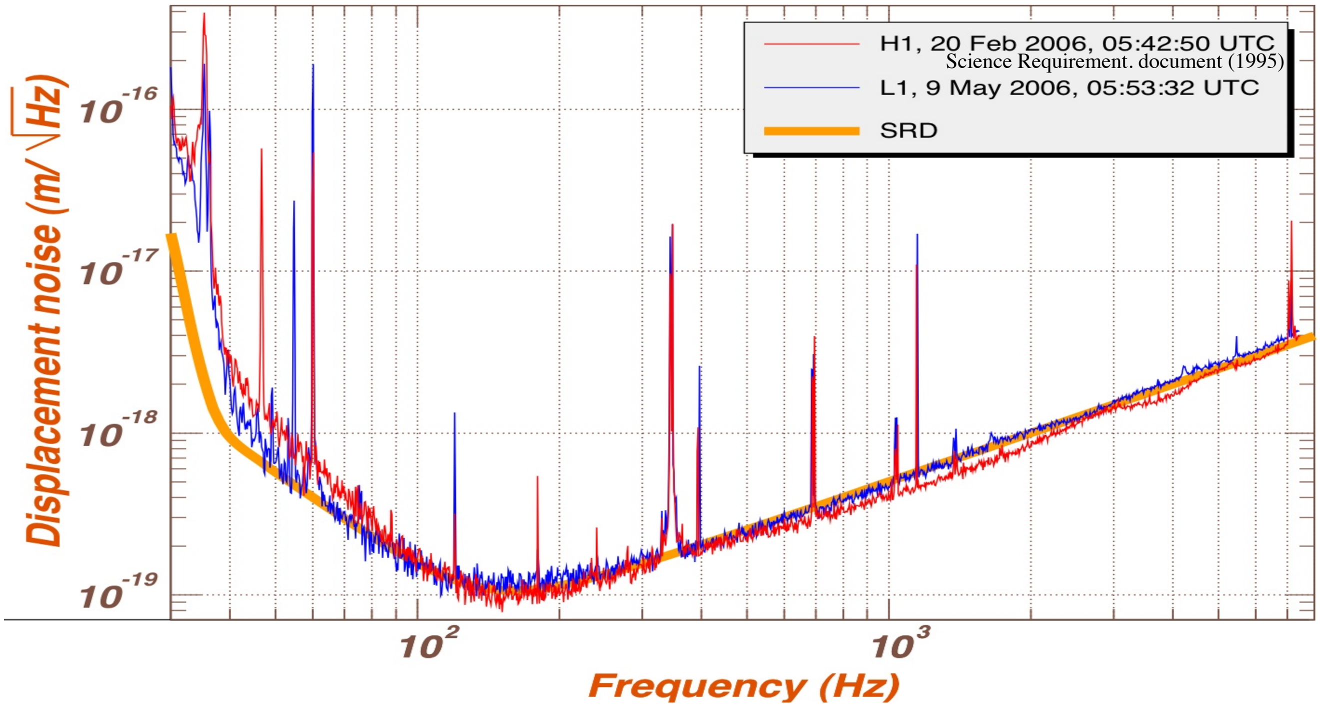
How to avoid being fooled by false signal

- **Monitor everything that can fake a GW signal**
  - Ground motion (with seismometers)
  - Line voltage
  - Acoustic noise (mircophones)
  - Magnetic fields
  - Etc.
- **Require *at least* 2 independent signals**
  - e.g. 2 inteferometers, 2000 miles apart
  - Interferometer + external trigger (e.g. optical supernova)
- Many other checks of reality of a signal—

  e.g blind signal injections

LIGO– reaching design sensitivity

- **In 2005 after 5 years of intense effort the predicted sensitivity was reached--LIGO could measure 10^{-18}m**
- **LIGO was ready to begin the serious search for GWs**



LIGO's evolution after reaching design sensitivity

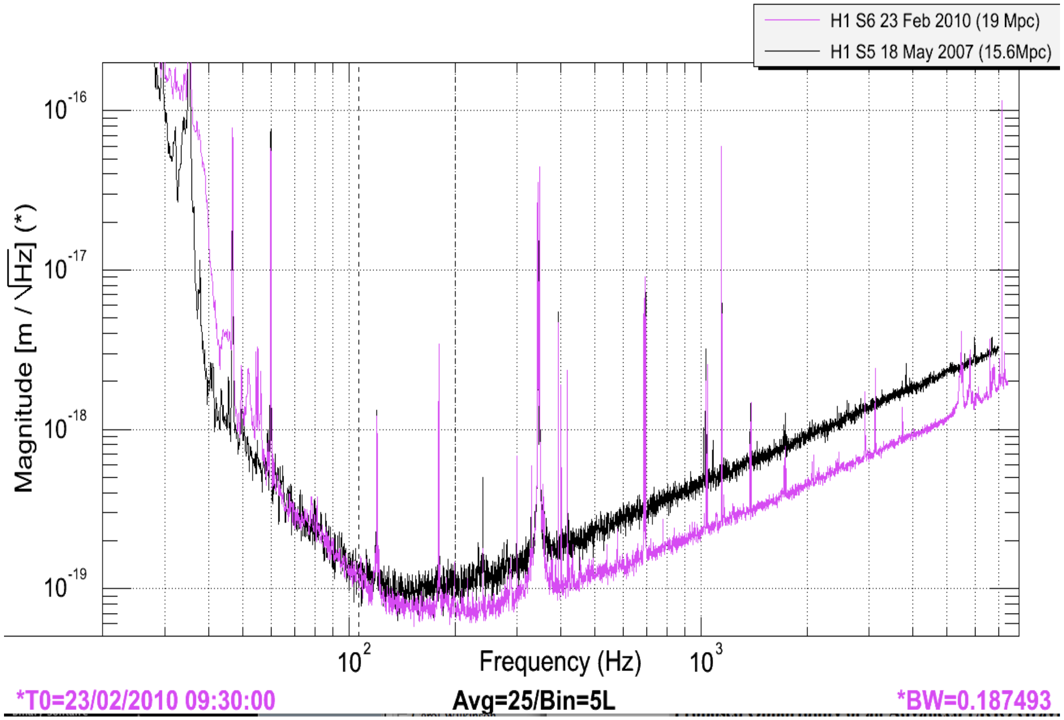
- **Initial phase- search for gravitational waves**
  - » **November 2005 to October 2007**
    - –Successful 2 year long science run at design sensitivity
    - –Hundreds of galaxies in range of LIGO
    - –Would see merging neutron star binaries as far as 100 million light-years from earth

- –Data analyzed, science results published

LIGO's evolution after reaching design sensitivity

» **Enhanced LIGO**

- **July 2009 - October 2010 (S6 science run)**
  - Key technical step towards Advanced LIGO- new readout, higher laser power (35 W), real Advanced LIGO hardware field tested.
  - Gave improved sensitivity over previous run



Data analysis

Data analysis by the LIGO Scientific collaboration is organized into four types of search analyses:

1. Binary coalescences ("inspiraling" NS-NS, BH-BH or NS-BH pairs)

   - Signal shape matched to well-modeled chirped waveforms

2. Transients sources with unmodeled waveforms ("bursts ")

   - High S/N in coincidence with external trigger or between LIGO sites

3. Continuous wave sources ("GW pulsars")-

   - GW signal phased to known pulsar ephemeris after Doppler correction

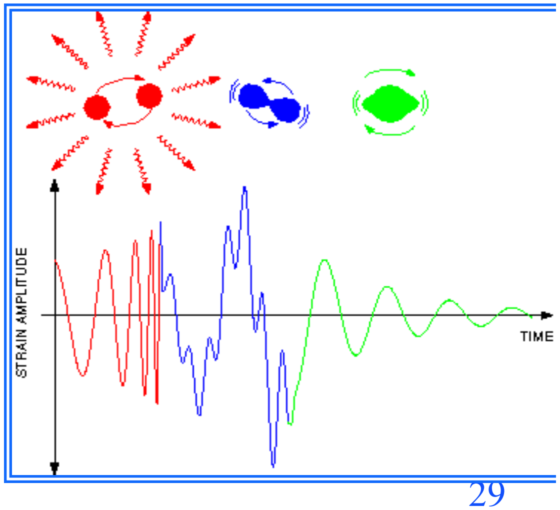
4. Stochastic gravitational wave background (cosmological & astrophysical foregrounds)

   - Stochastic signal correlated between multiple interferometers

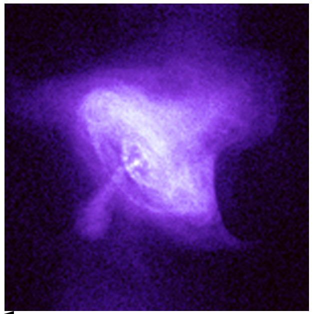
Sample of science results from 1st Gen detectors

LIGO, Virgo, GEO, TAMA

- **No GW observed with --- not unexpected -- odds ~ few % with best 1st generation detector sensitivity (LIGO)**
- **Data sets scientifically meaningful upper limits on numbers or strength of cosmic sources**
- e.g. Binary neutron stars or black holes coalescing
  - » In Milky Way sized galaxy
    - – NS-NS merger happens less often than about once every 50 years
    - – for 5.0 M_o BH-BH merger happens less often than about once every 250 years



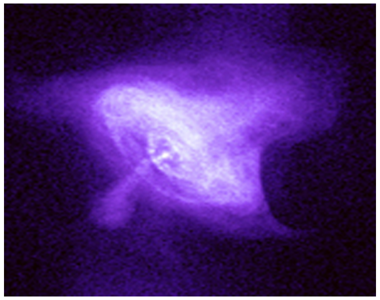
Some science results



- Pulsars
  - » Looked for GW signal from ~100 known pulsars
    - – Only get GW emission if source is aspherical

      - Results--pulsars are very spherical
      - Limits on pulsar ellipticity $< 10^{-6}$
        - » means if bump on 10 km (city sized) pulsar it is <1 cm

Crab pulsar spindown limit

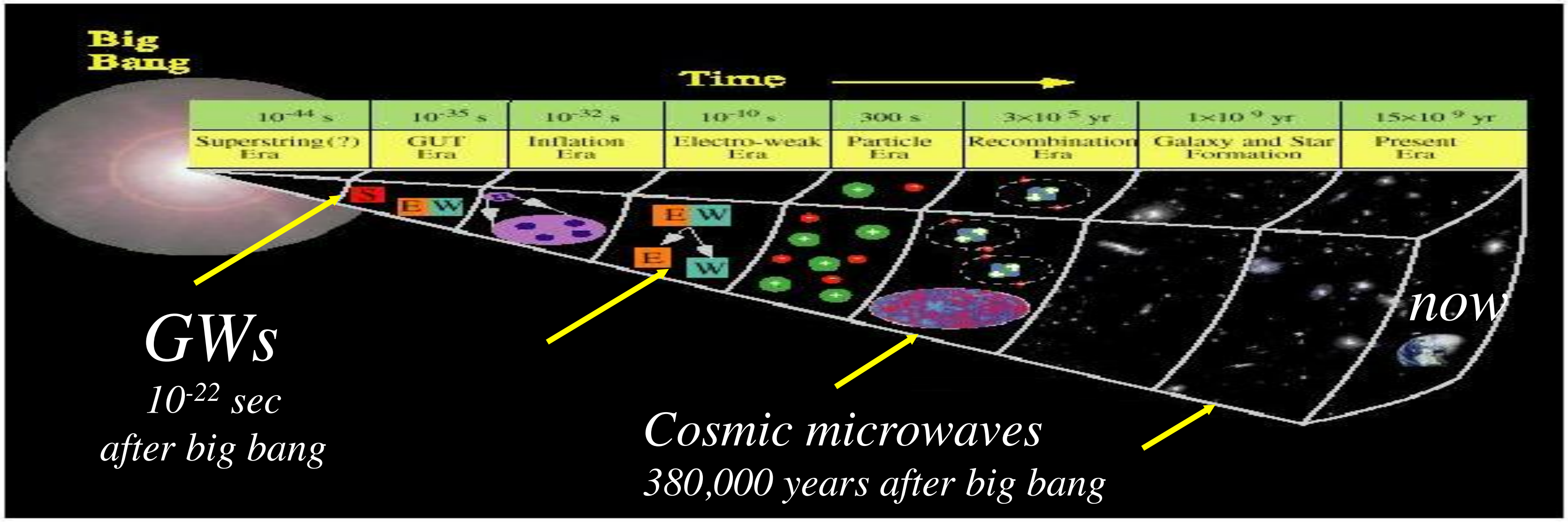


- Remnant of supernova explosion
  - In our galaxy, ~6500 light years distant
  - Neutron star spinning at ~30 Hz
- Slows down by ~38 ns per day due to emission of energy
- How much of energy loss is into gravitational waves?
- Result from LIGO data--

  Less than few % of energy loss in spin-down goes into GWs

Search GW signal from big bang

- Only possible way to “see” all the way back to the big bang
- Big bang should have produced GWs that fill all of space



GWs

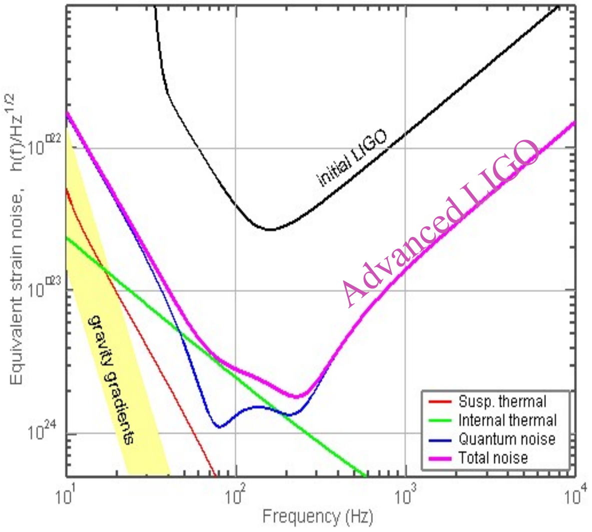
10^{-22} sec after big bang

Cosmic microwaves

380,000 years after big bang

- Results -- GWs from the big bang make up less than 1/100,000 of the energy density in the universe in ~20--~1000 Hz band

Next generation–e.g. Advanced LIGO



- Project to improve sensitivity by 10
  - Sensitive to sources 10x further away
  - **Number of extragalactic sources in range increased by $(10)^3$=1000**

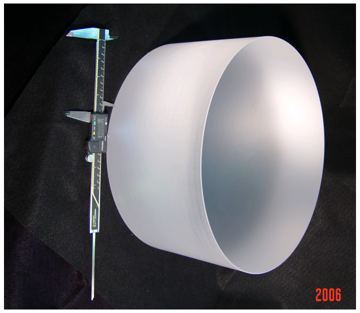
Expect to observe GWs at few/week to few/month rate

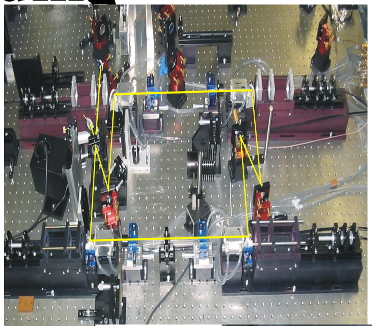
1 day of observing with Advanced LIGO
equivalent to more than 1 year of initial LIGO

- Began project in April 2008; funded by NSF ($205M); UK, Germany, Australia
  - About 90% complete; construction finished in 2015
  - 3 new instruments- 1 at Louisiana site, 1 at Hanford site, 1 at possible 3rd site (India?)

Advanced LIGO- improvements from initial LIGO

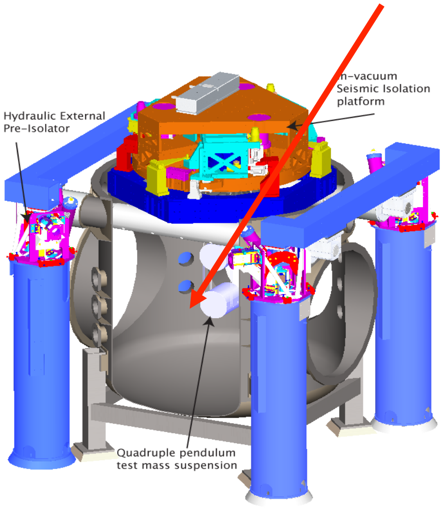
- **Keep initial LIGO “infrastructure” and sites**
  - » Vacuum system (4 km arms), building, roads, etc.
- **Improved technical components including---**

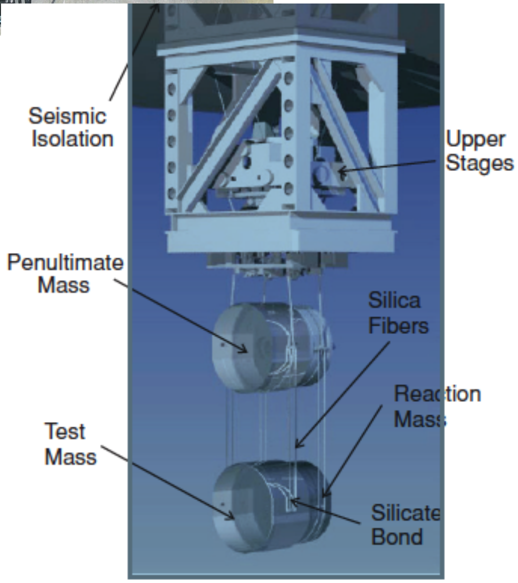




- >10x higher power laser
- Larger, better mirrors

  (to handle increased thermal load)
- Better thermal compensation
- Better isolation of optics from vibrations

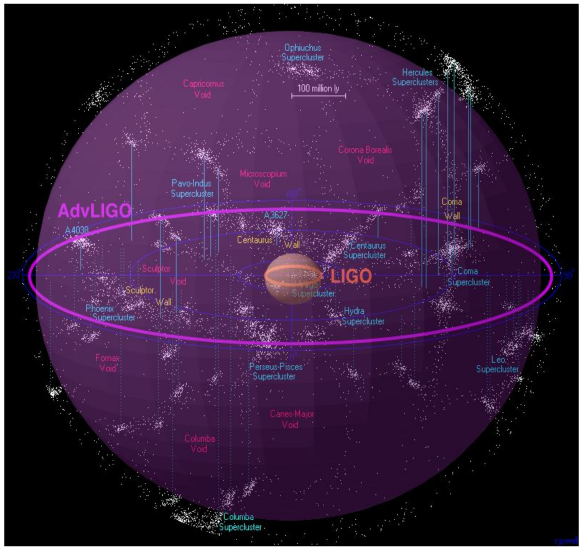




How far will Advanced LIGO “see”

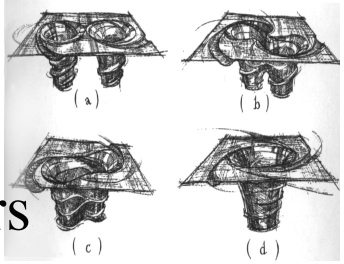
- **Merging neutron star binaries:**

  * Initial LIGO: ~100 million light years
  * Advanced LIGO: ~1000 million light years
  hundreds of thousand of galaxies in range



- **Merging black hole binaries:**

  * Initial LIGO: Up to 10 M_o, at ~600 million light years
  * Advanced LIGO: Up to 50 M_o in most of the universe



When will gravitational waves be discovered??

- First finish Adv. LIGO/Virgo construction, then learning curve to reach design sensitivity
- Hopefully by 2016 or 2107 when Advanced LIGO and Virgo can "observe" 1000 more galaxies than with initial LIGO and Virgo.
- Expected signal rate ~1/week to 1/month

Then the era of gravitational wave astronomy will begin

GW astronomy needs a global partnership between GW instruments around the world and other telescopes

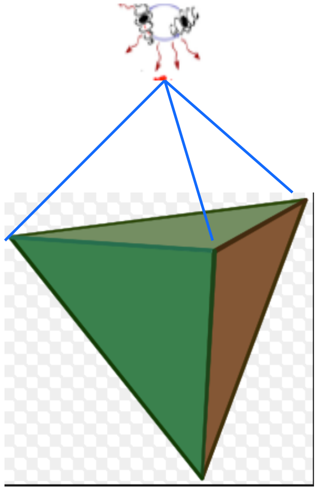
- **Need an earth-spanning GW instrument to pinpoint direction of GW sources over the whole sky**

- This will permit optical, x-ray, radio telescopes to do follow-up observations of sources of GWs

“We see a GW; point your telescope there; what do you see?”

Towards a global GW "telescope"

- **Source location on sky by time-of-arrival triangulation between instruments separated by *continental distances-***
  - » Pointing accuracy poor in-plane of 3 instruments

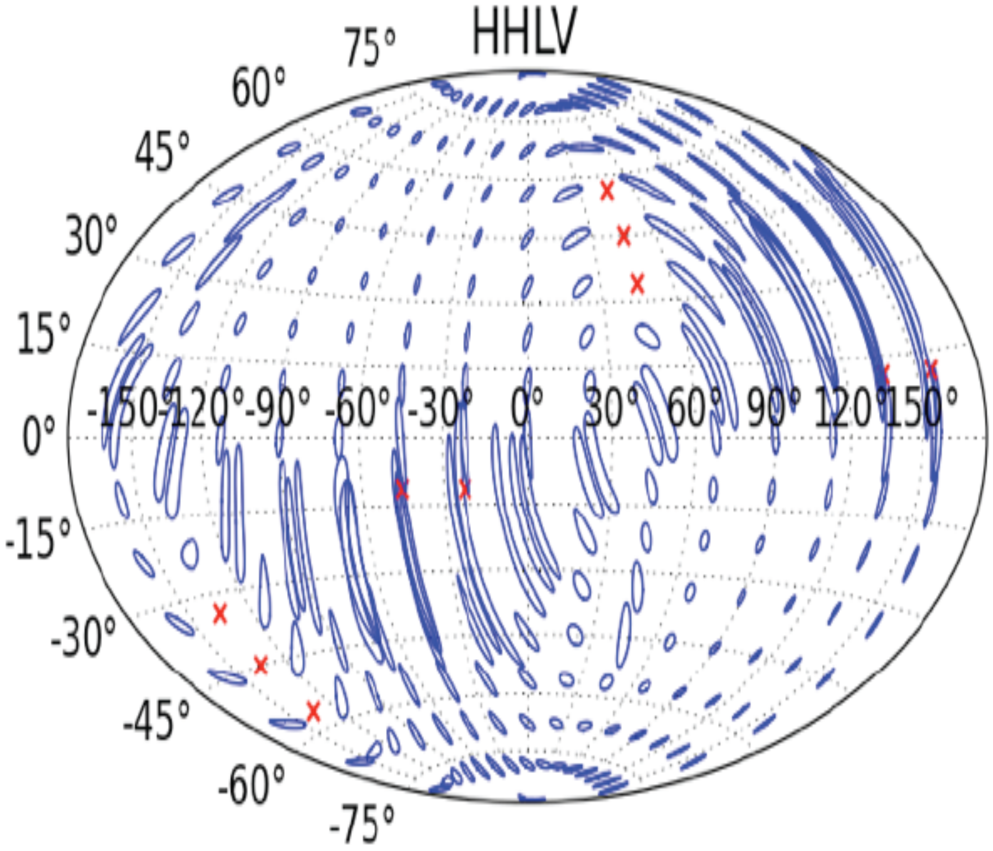


- **Goal**- global tetrahedron of instruments so can triangulate in all directions
- **Also determine**
  - » Source polarization from several projections
  - » More accurate waveform determination
- **The future global array**--
  - » **Northern plane-- US**- Adv. LIGO; **Europe**- Adv. Virgo; **Japan**- KAGRA;
  - » **Southern site–** hopefully LIGO-India

The future for ground-based GW interferometers– next 10 years

- Advanced LIGO will be operating in ~2015; hopefully with good sensitivity in 2016.
- Advanced Virgo (3 km arms, near PISA, Italy; Italian, French, Polish, Hungarian collaboration) is being built on same time-scale as Adv. LIGO and will achieve comparable sensitivity.
- The Japanese GW community is building KAGRA, a 3 km *cryogenic underground* interferometer in the Kamioka mine. Hopefully observing by the end of this decade.
- The Indian community is seeking funding for a third Advanced LIGO site in India. LIGO-India could be operating early in the next decade.

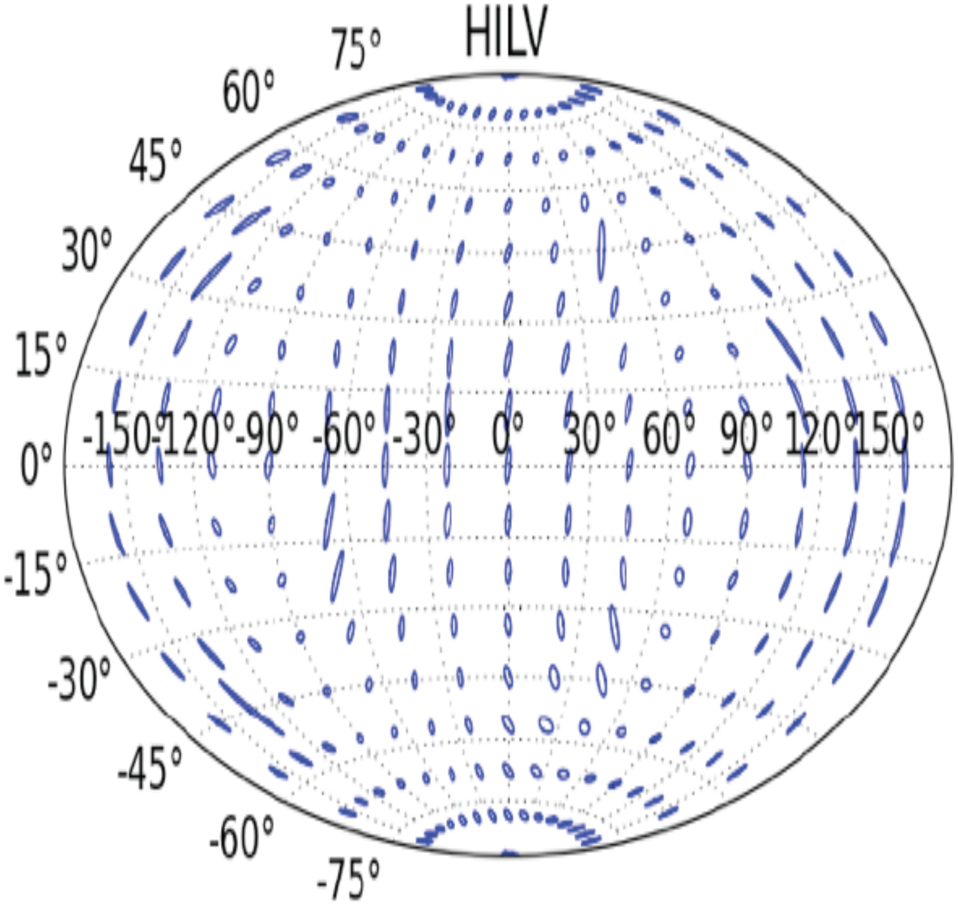
Pointing accuracy– LIGO and Virgo only



Fairhurst 2011

Red crosses denote regions where the network has blind spots

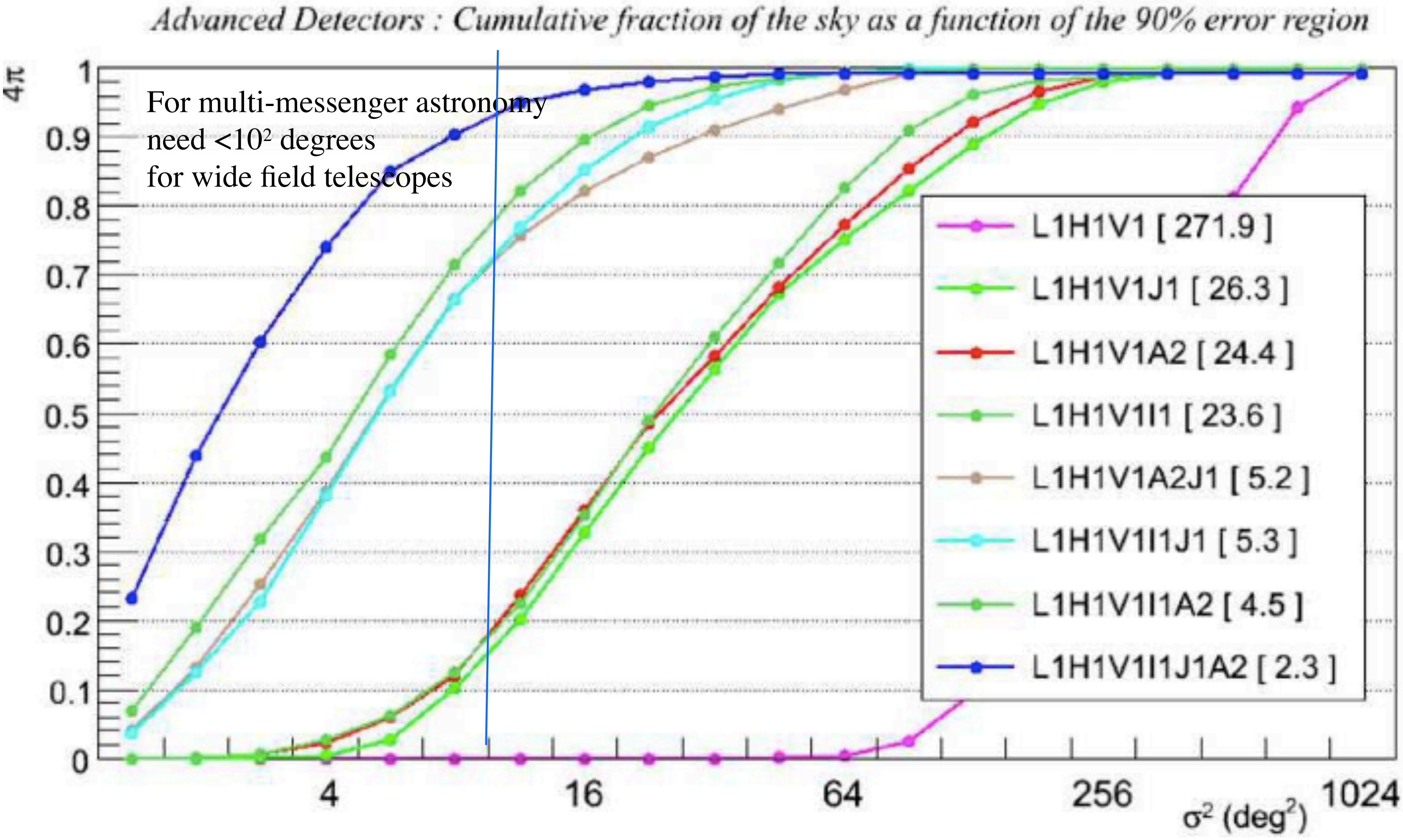
Pointing accuracy- LIGO, VIRGO, India



Even better with KAGRA

Fairhurst 2011

Similar Result for Burst Sources



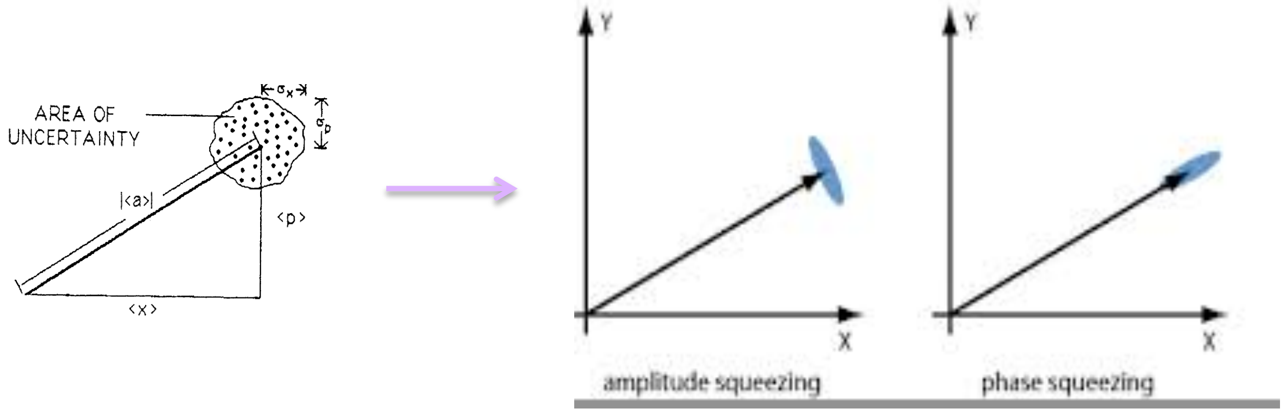
For multi-messenger astronomy need <10^2 degrees for wide field telescopes

Example science from global GW telescope

- Multi-messenger astronomy– correlate signals seen in GW with observations in EM (optical, radio, x-ray, gamma), neutrinos to characterize sources of GWs; e.g.
  - » Are short gamma ray bursts NS-NS mergers?
  - » Use merging NS-NS as standard sirens for dark energy measurement—
    - – NS-NS GW emission strength well-calculated
    - – Observed GW strength + polarization (orientation of binary) gives distance
    - – Optical observation gives redshift of host galaxy
- In merger phase of neutron state pairs, shape of GW signal is related to nuclear equation of state

Likely upgrade to Adv. detectors- squeezed light

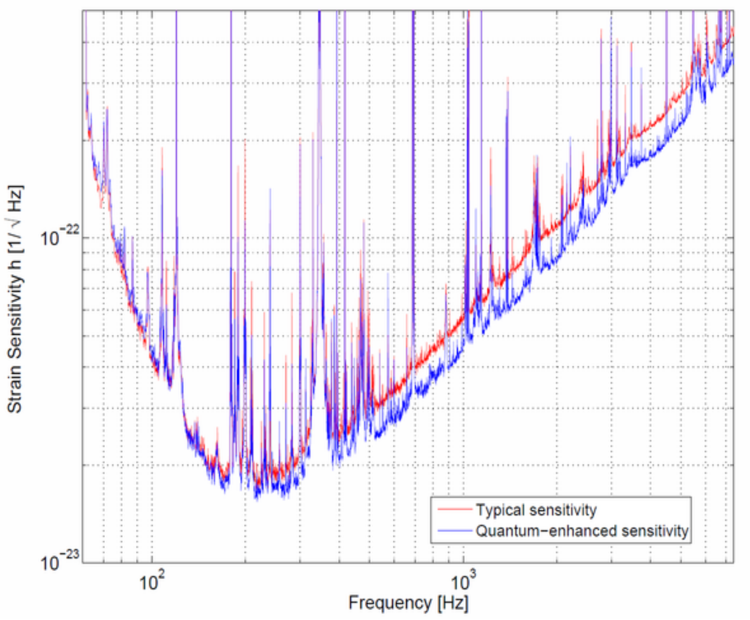
- Goal---improve sensitivity give big payoff
  - » extragalactic range improves as sensitivity^3
    - – factor 2 improvement gives 8 times number sources in range
- How--trade-off amplitude and phase quantum fluctuations (noise) within uncertainty principle constraint– uses complicated optical techniques



Likely upgrade to Adv. detectors- squeezed light

- Demo squeezer used in GEO and full LIGO interferometer—
  - Results (LIGO)--- ~2db improved sensitivity in shot noise region

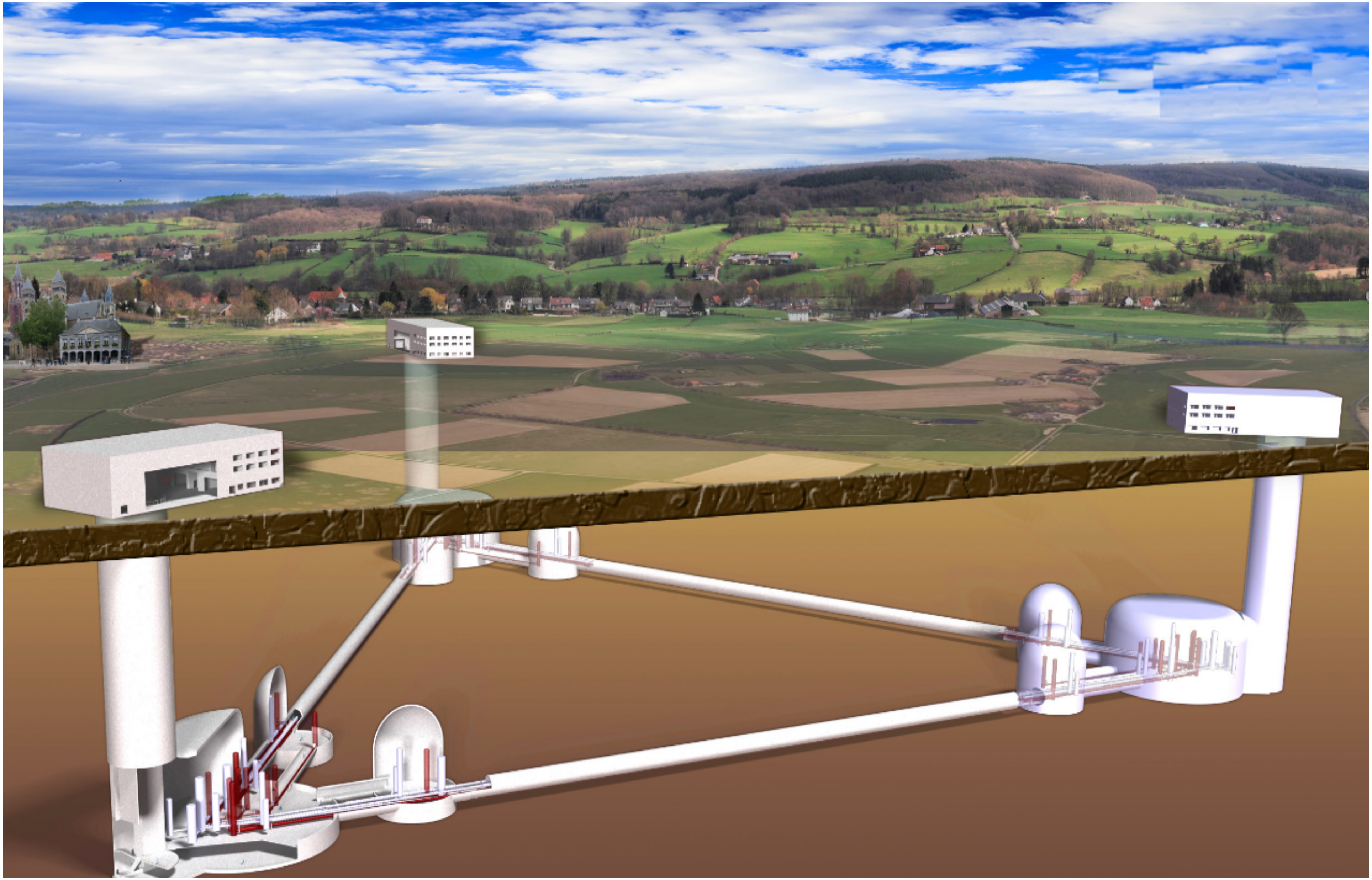
- Carefully engineered squeezer could improve sensitivity by ~factor of 2.
  - Will likely be installed in LIGO and other detectors in perhaps 3-5 years.



Next huge step—underground interferometer

- To reduce seismic noise and gravity gradient noise
- Allows bandwidth extended from ~10 Hz to ~1 Hz
  - More pulsars, higher mass merging binaries, more sensitive to primordial GWs,……..
- Improve sensitivity ~10 over Adv. LIGO, VIRGO, KAGRA
- European design study for Einstein Telescope
  - 3 interferometers, each tuned/optimized to different band
  - 100-200 meters underground with 10 km long arms
  - Cost ~1B$ scale
  - Hopefully observation of GWs triggers construction funding so ET is observing sometime in the 2020’s

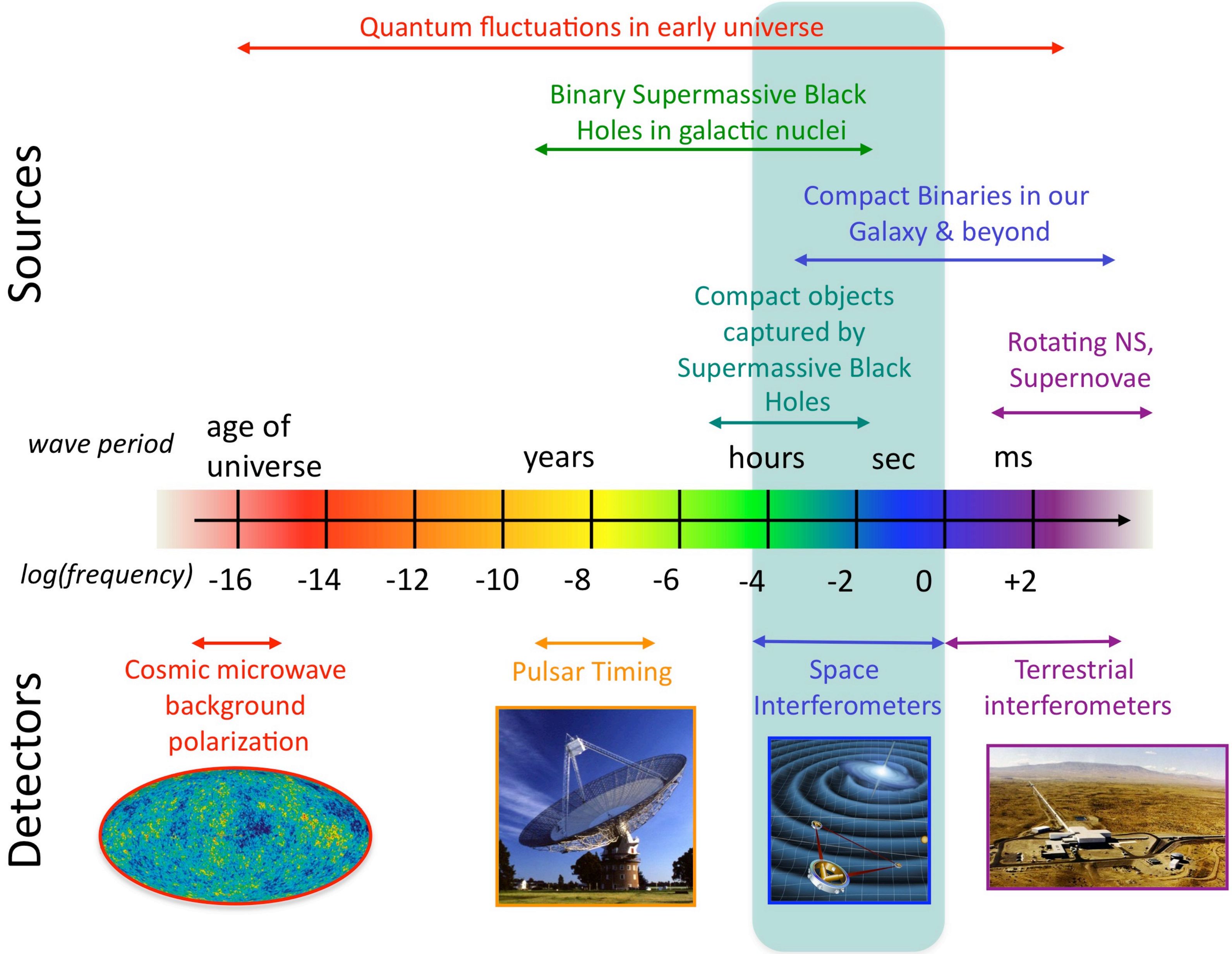
Einstein Telescope concept



Observing in the ~Hertz to ~kHertz band these ground-based interferometers we expect to learn about some of the must energetic events in the universe (e.g. colliding black holes) and discover new objects and phenomena “out there”

What about other frequencies and techniques?

The Gravitational Wave Spectrum



Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

Rotating NS, Supernovae

wave period age of universe years hours sec ms

log(frequency) -16 -14 -12 -10 -8 -6 -4 -2 0 +2

Detectors

Cosmic microwave background polarization

Pulsar Timing

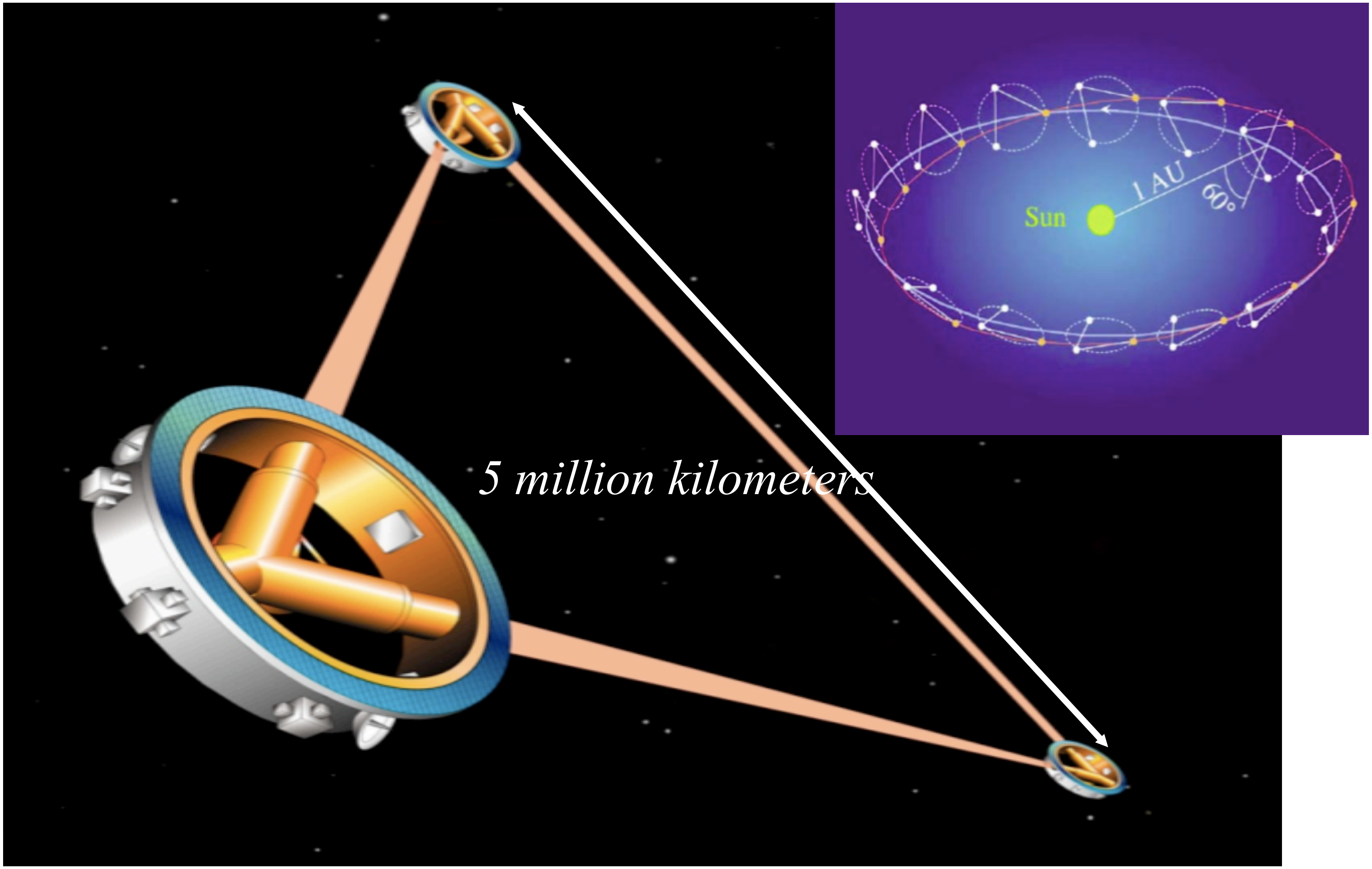
Space Interferometers

Terrestrial interferometers

Other approaches to detecting GW sources that emit at other frequencies

- **Interferometers in space–** at TAUP- J. Livas talk on 9/11
  - » e.g. merging massive black holes (millions x M_o)
  - » GWs from early universe
    - – ~10^{-1} to 10^{-4} Hertz frequency range
- **Pulsar timing--** at TAUP- Sarah Burke Spolaor talk on 9/11
  - » e.g. even more massive merging black holes (billions x M_o)
  - » GWs from early universe
    - – ~10^{-6} to 10^{-9} Hertz frequency range
- **Polarization of the CMB radiation**
  - » GWs from early universe
  - » Below ~10^{-13} Hertz frequency range

LISA- hopefully launched early next decade by ESA



Pulsar timing

- Pulsars form a system of very stable galactic clocks
- Intervening GWs will distort pulse arrival time at earth by ~10s of ns
- Since distances are thousands of light-years, pulsar timing is sensitive to very long wavelength GWs
- Detection will require achieving required timing accuracy and monitoring of ~20-50 pulsars for several years. Could happen in the next few years
- An international consortium (IPTA) is using radio telescopes around the globe

Polarization of the CMB

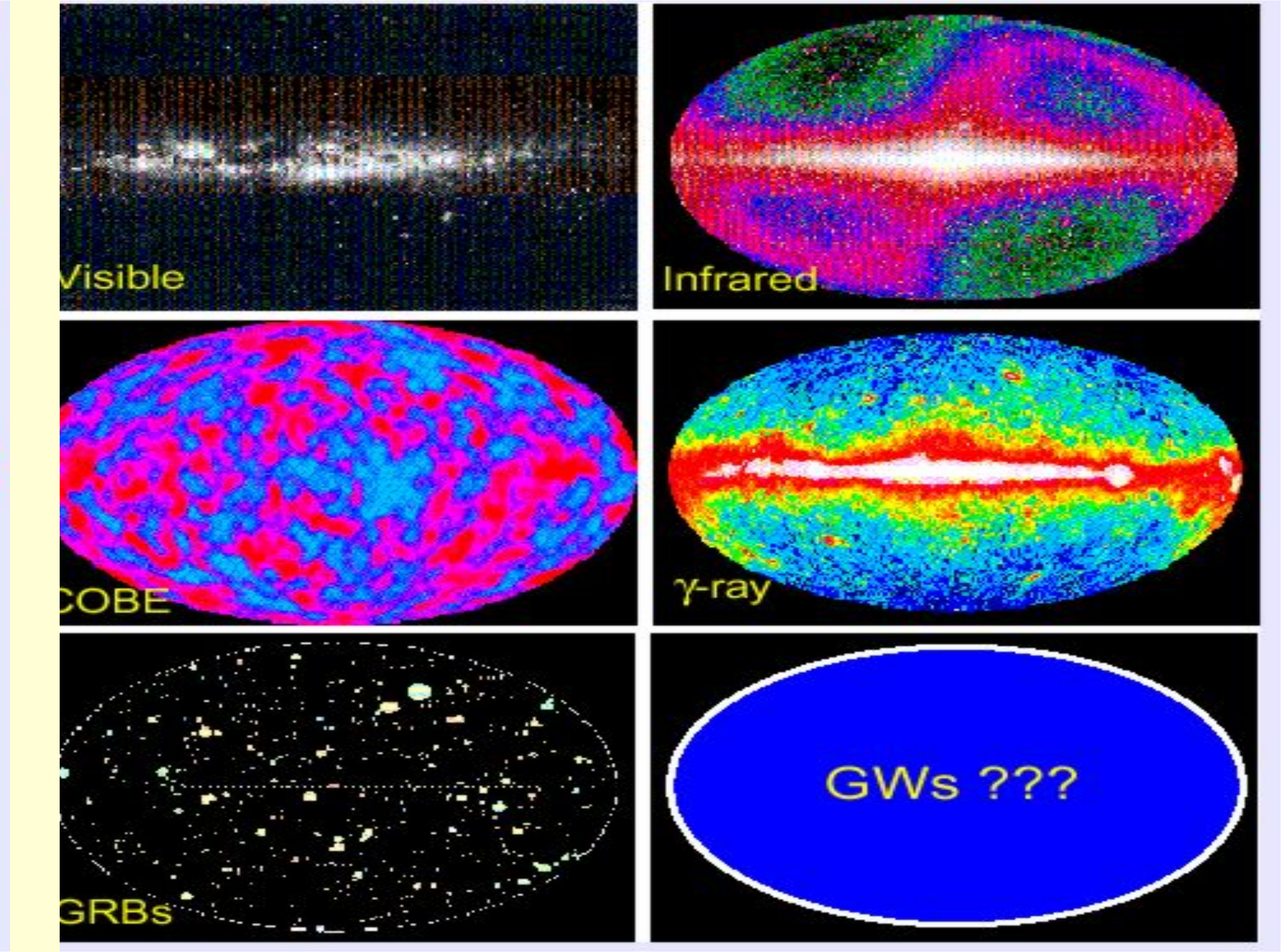
- Inflation predicts the existence of primordial gravitational waves on cosmological length scales.

- The search for primordial B-mode (curl component) polarization of the CMB provides an important opportunity to detect the imprint of these gravitational waves. The effect is extremely subtle– about 10^{-7} of the CMB temperature

- Recently B-mod polarization has been detected by the South Pole Telescope. But the majority of B-mode is produced by the effect of gravitational lensing on E-mode polarized radiation and other effects.

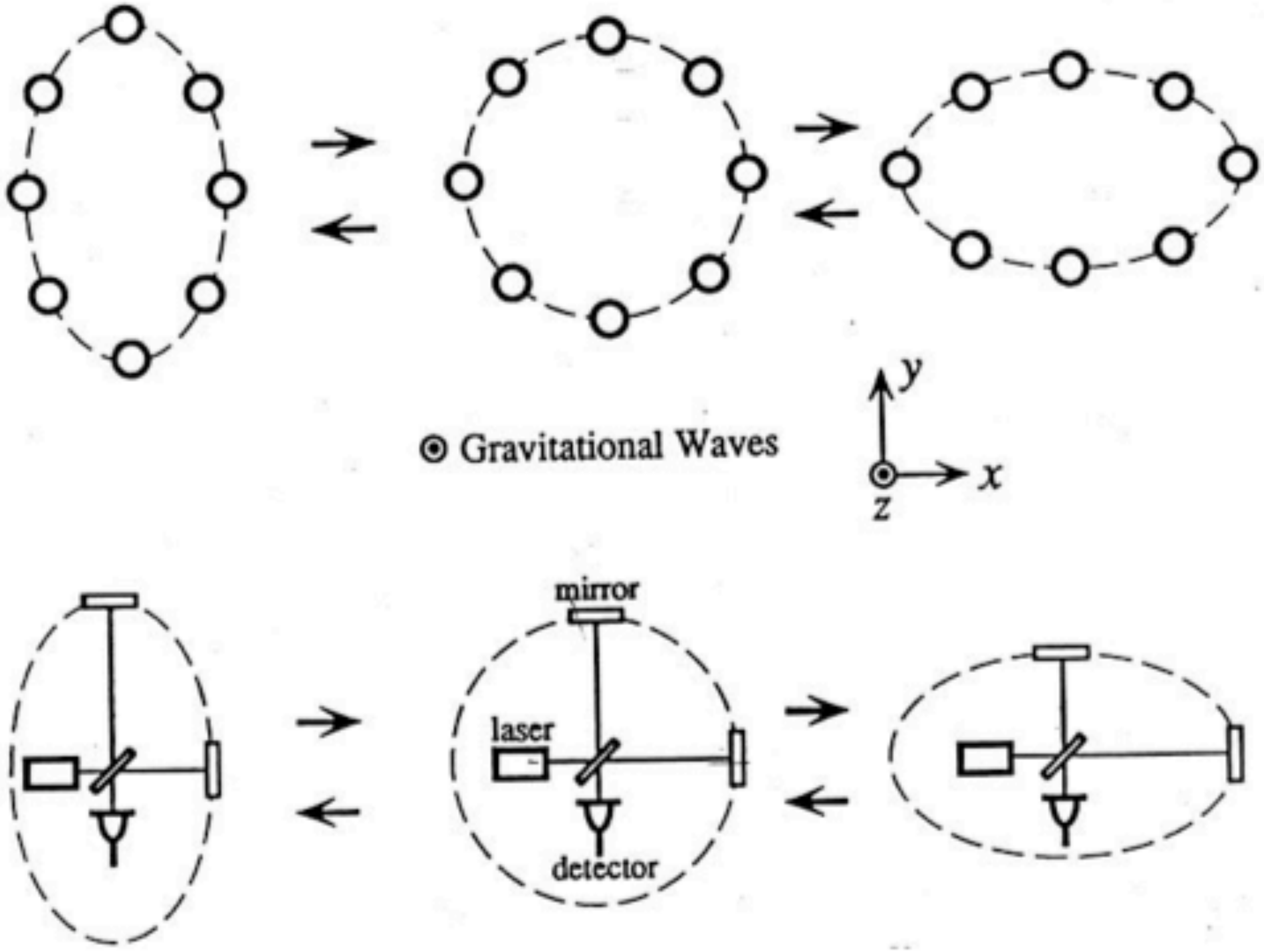
- Primordial GWs may be observed in the future if the non-GW effects can be understood with enough precision and subtracted from the overall B-mode polarization.

Observation of GWs across a broad spectrum will give a new view of the heavens, new and deeper insights into nature

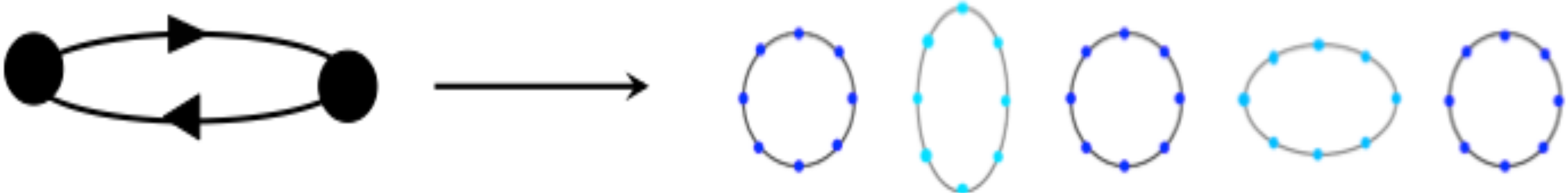


Backup slides

Gravitational waves can be seen with an instrument sensitive to changes in length



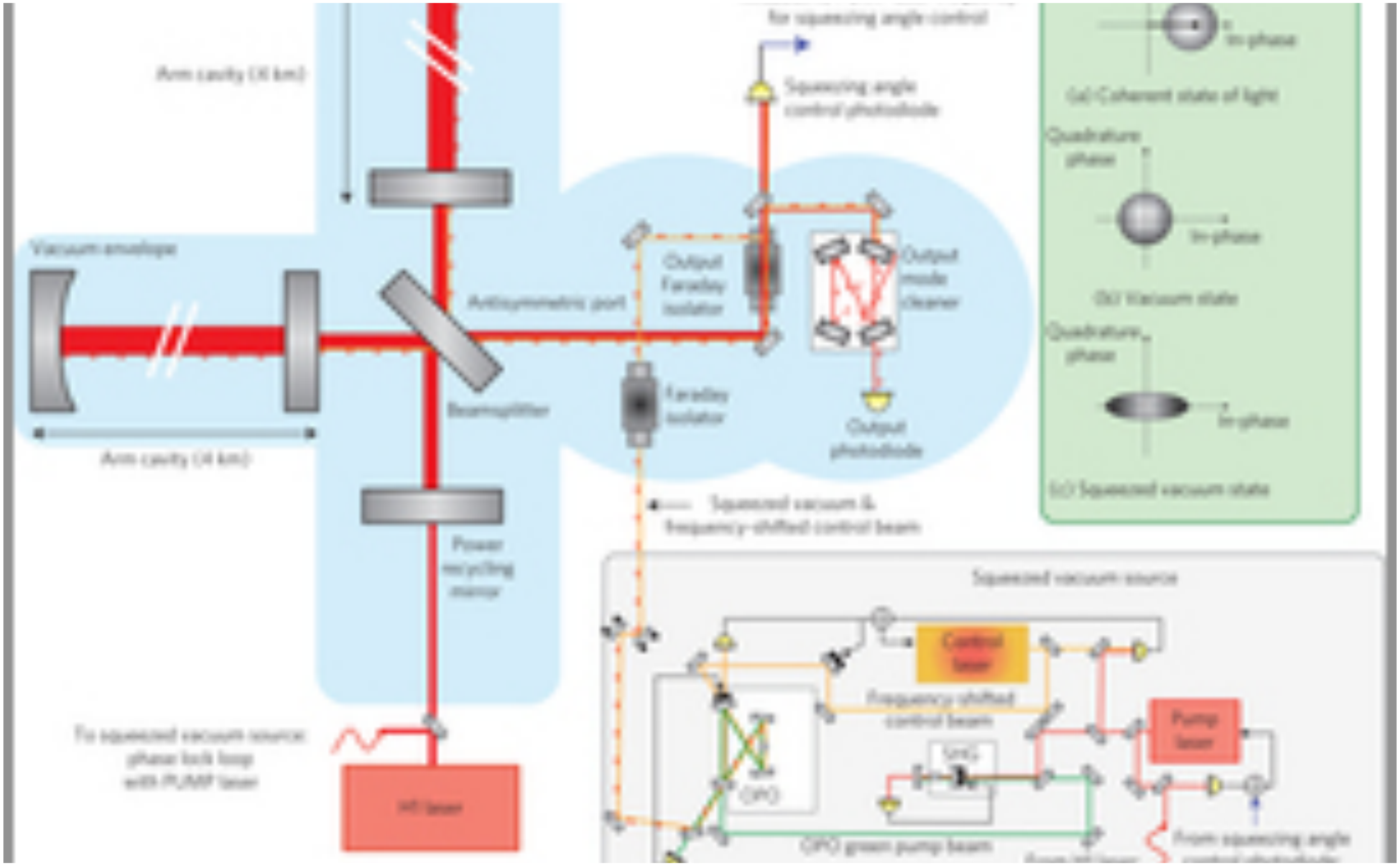
- Most sources will be elliptically polarized
  - » Need complete polarization information to extract distances, energies, other details of sources
- L-detectors are polarization selective
  - » Completely insensitive to one linear polarization
- Must have a three dimensional array of detectors to extract maximum science



Gravitational wave astronomy

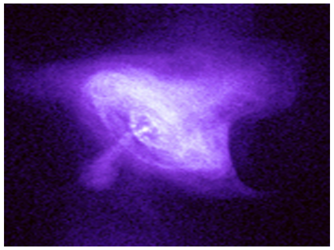
---a new window on the Universe---

Squeezed light demo for LIGO

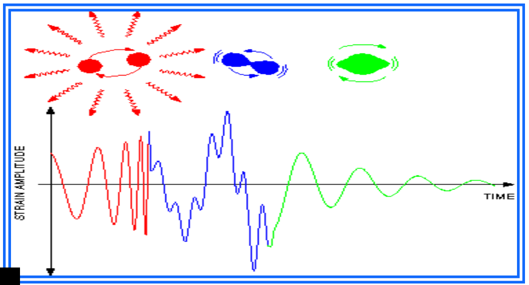


Some cosmic sources of GWs

- **Pulsars**---spinning neutron stars

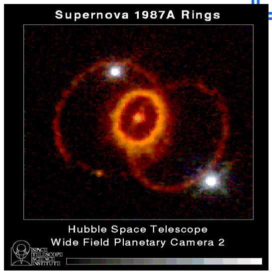


- **Merging neutron star and black hole binaries** in distant galaxies

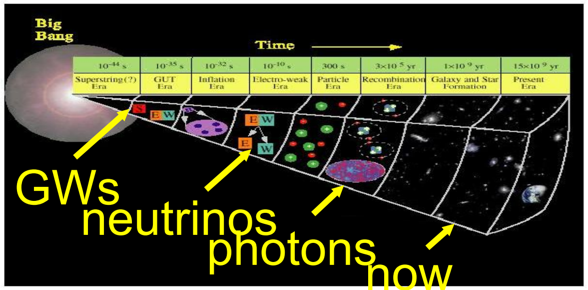


Information is encoded

- **Huge explosions** --examples
  - **Supernovae**--collapsing core of massive stars
  - **Gamma ray bursts**



- The **big bang**, **cosmic strings** and other phenomena from the early universe



- **The Unexpected-** **?**

  new instruments see new phenomena!

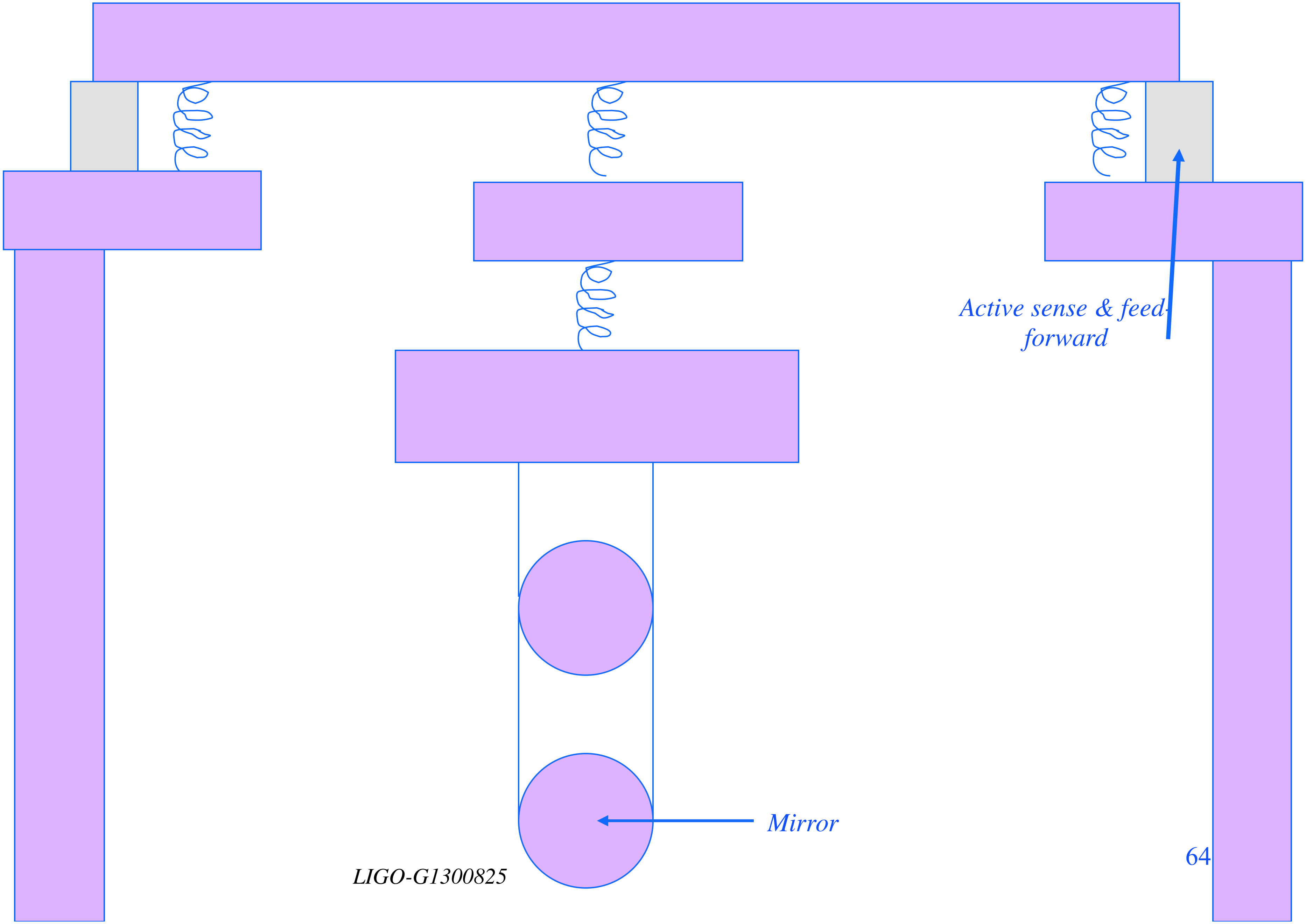
By the end of this decade we hope to have a world-spanning GW telescope

- Advanced LIGO and Advanced Virgo should be on the air in 2015-16
  - Hopefully 1st observation of GWs in 2016 or 2017
- KAGRA (Japan) will be online late in this decade and LIGO-India soon thereafter
- The advanced instruments will give our 1st view of the gravitational wave sky with enough pointing accuracy to enable follow-up observations with optical, x-ray, radio, gamma ray and neutrino telescopes

LIGO-India

- **Idea- Use components from one of the two Advanced LIGO detectors that was to be installed at Hanford to assemble a detector in infrastructure provided by India**
  - Science benefit “no-brainer”
  - Idea took hold; National Science Foundation approved
- Indian GW community has been part of LIGO for years
  - Participating in Adv. LIGO installation/commissioning
- LIGO-India in Indian government’s five year plan–funding approval expected in next few months
- If it happens, LIGO-India will operate as a third LIGO site early in the next decade

LIGO seismic isolation concept



Active sense & feed-forward

Mirror