Title: Exploring the Warped Side of the Universe

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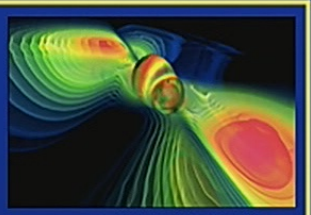
Abstract: Some of the most violent events in the Universe are accompanied by spectacular warpages of space-time that travel to us in the form of gravitational waves. Gravitational waves were predicted by Einstein's theory of general relativity over a century ago, but scientists have not yet detected them directly. Learn about how we search for these tiny space-time ripples and decode the unique information they carry about mysterious events in space as far back in time as the first moments after the Big Bang.



Exploring the Warped Side of the Universe

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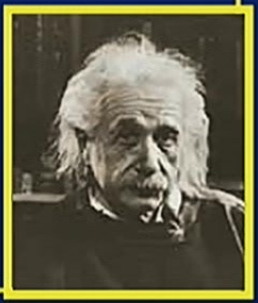
Convergence @ Perimeter Institute
June 2015

LIGO

Einstein's legacies

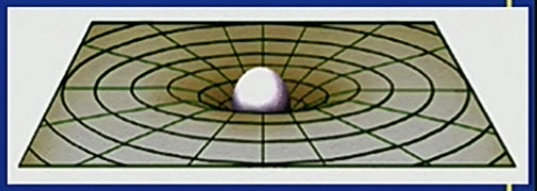
- Gravitational wave astrophysics is about to take off (within this decade)
- A number of search techniques maturing

- A new generation of terrestrial gravitational wave detectors are coming online now
- They are the most sensitive detectors ever operated → 10^{-19} m
- Quantum uncertainty imposes a fundamental limit to the detector sensitivity
- Ironically, Einstein struggled with both ideas



Gravitational waves (GWs)

- Prediction of Einstein's General Relativity (1916)
- Ripples of the space-time fabric
- GWs stretch and squeeze the space transverse to direction of propagation
- Emitted by accelerating massive objects
  - Neutron stars & black holes
  - Orbits, explosions, collisions
  - Deformation of rotating stars
  - The Big Bang
  - The unknown



$$h_{GW} = \frac{\Delta L}{L}$$

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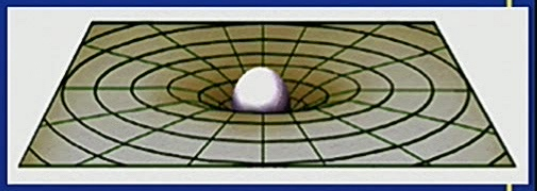

$$h_{GW} = \frac{\Delta L}{L}$$

$$h_{GW} \sim 10^{-21}$$

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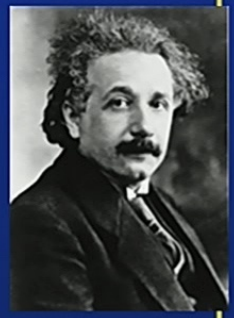
A bit of history

- Gravitational radiation was first introduced by Einstein in 1916 in his seminal paper on General Relativity
- In a subsequent paper in 1918 Einstein gave the first correct formulation of gravitational waves



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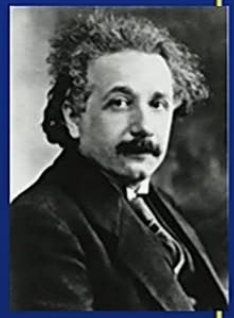

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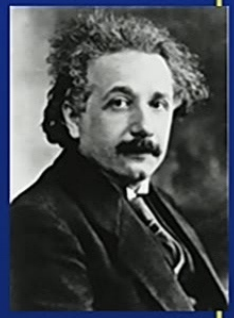

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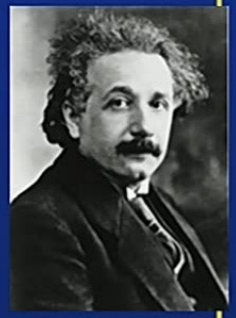
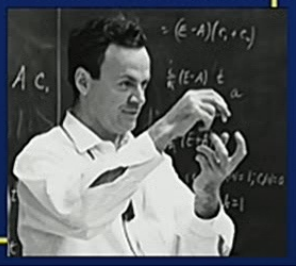
- Doubts and controversy finally subside after 1957



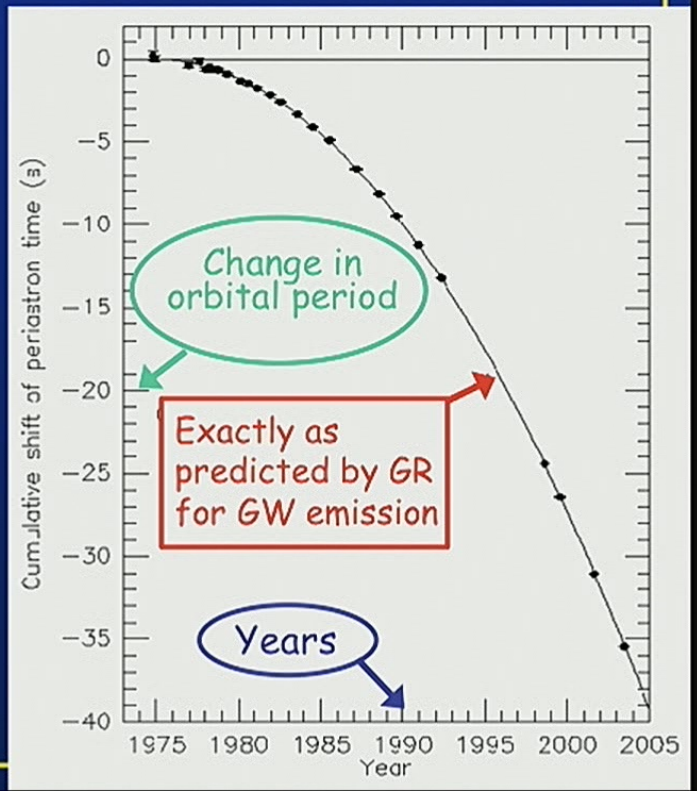


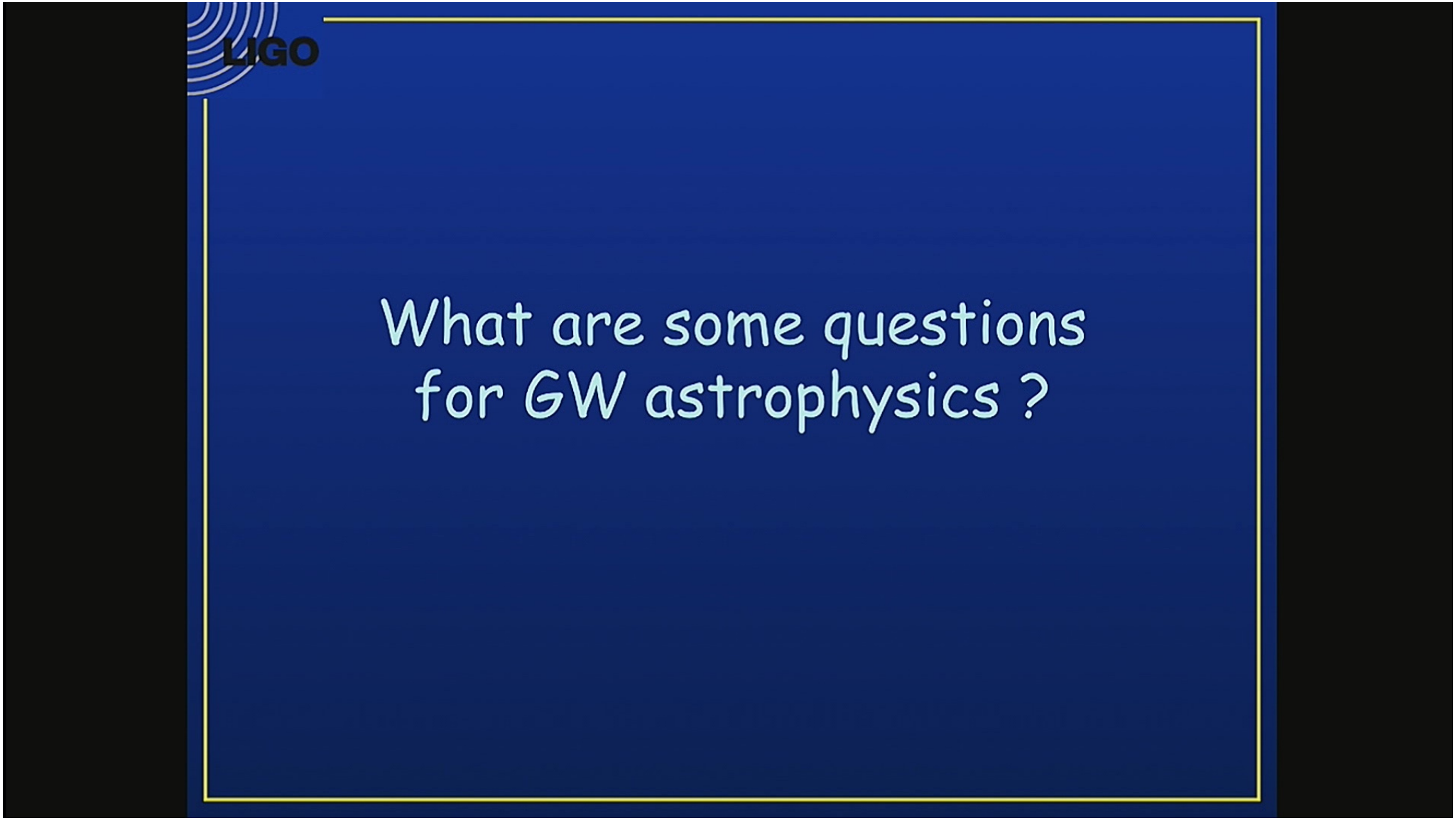
The evidence, at last

Hulse & Taylor's Binary Neutron Star System
(discovered in 1974, Nobel prize in 1993)

PSR 1913 + 16

- Two neutron stars orbiting each other at 0.0015c
- One is a pulsar with its lighthouse beam pointed toward us
- Emit GWs and lose energy
- Measured change in orbital period due to GW emission

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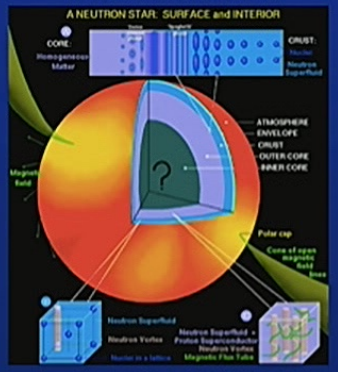
What are some questions
for GW astrophysics ?

Some big questions

- Neutron stars
  - What is the equation of state?
  - What is the maximum mass?
  - What is the structure?
  - What is the population?

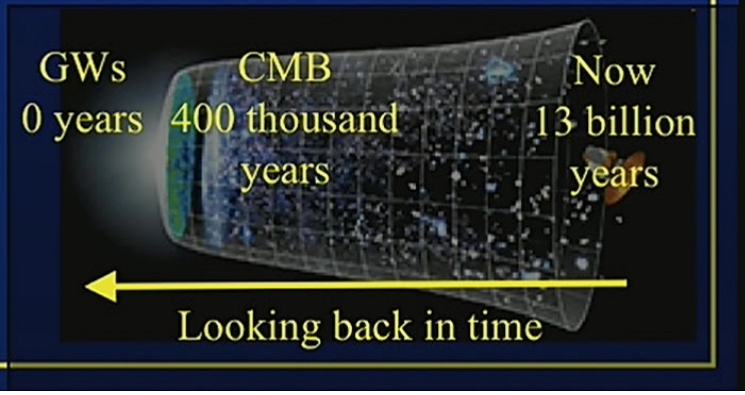


- Black holes
  - What is the population of BH with different masses?
  - Do they exist in binaries?
  - How do they form? How do they die?
  - How does Nature grow supermassive BH?
  - Are they characterized only by mass and spin?
  - Can we map BH spacetimes?

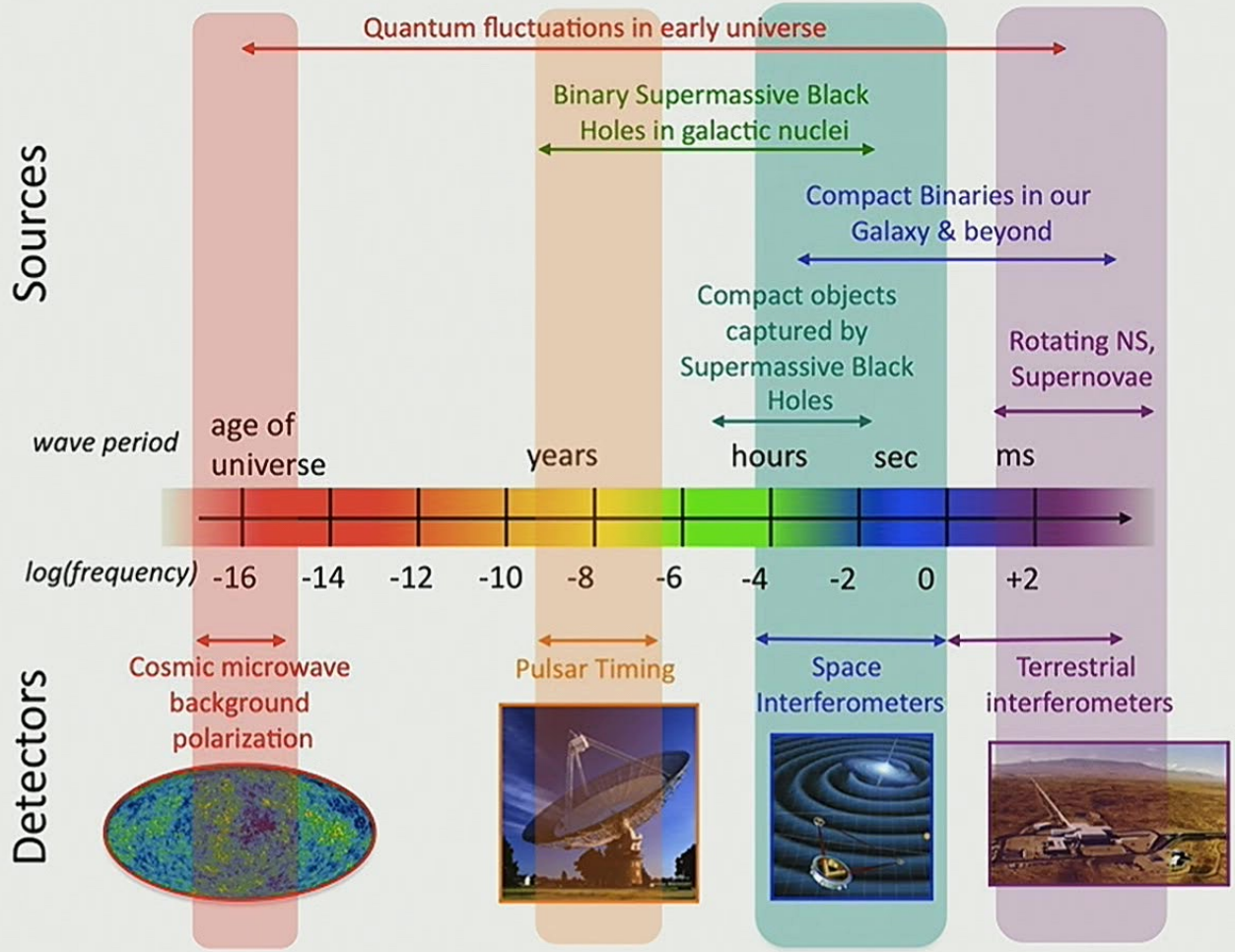
Some big and hard questions

- Core collapse supernovae
  - What are the explosion mechanisms?
  - What is the structure and dynamics of the progenitor star?
  - What is going on deep in the core?

- Primordial GW background
  - What processes existed in the very early Universe?
  - What can we learn about inflation, phase transitions, cosmic strings?



The Gravitational Wave Spectrum



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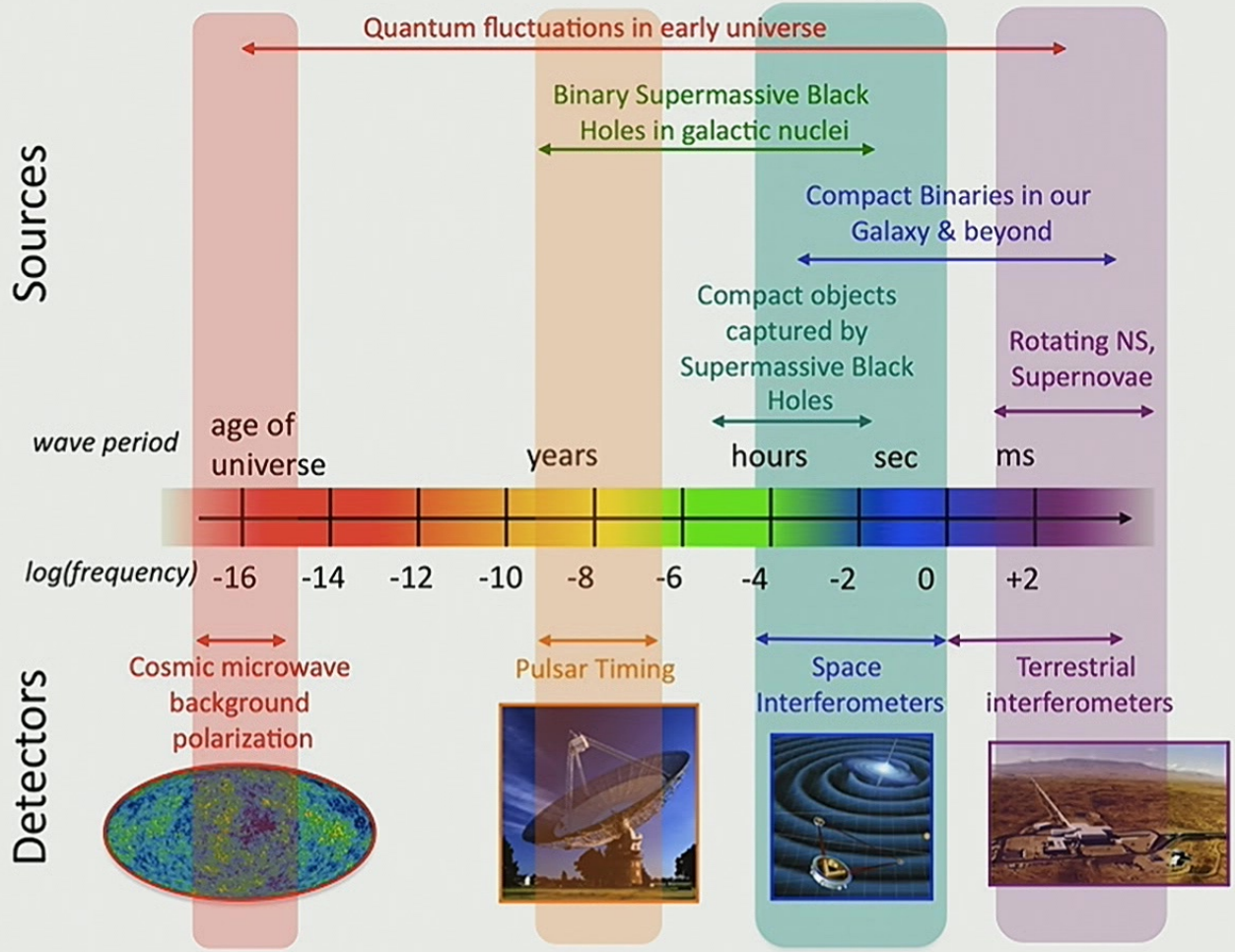

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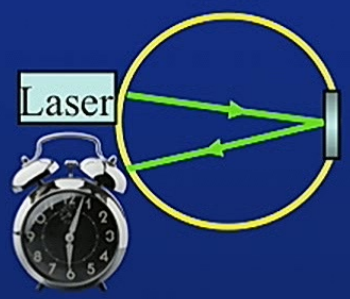
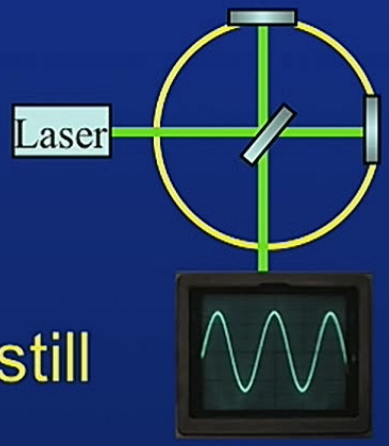
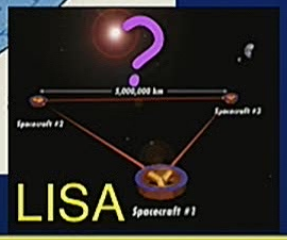
Simple concept, challenging implementation



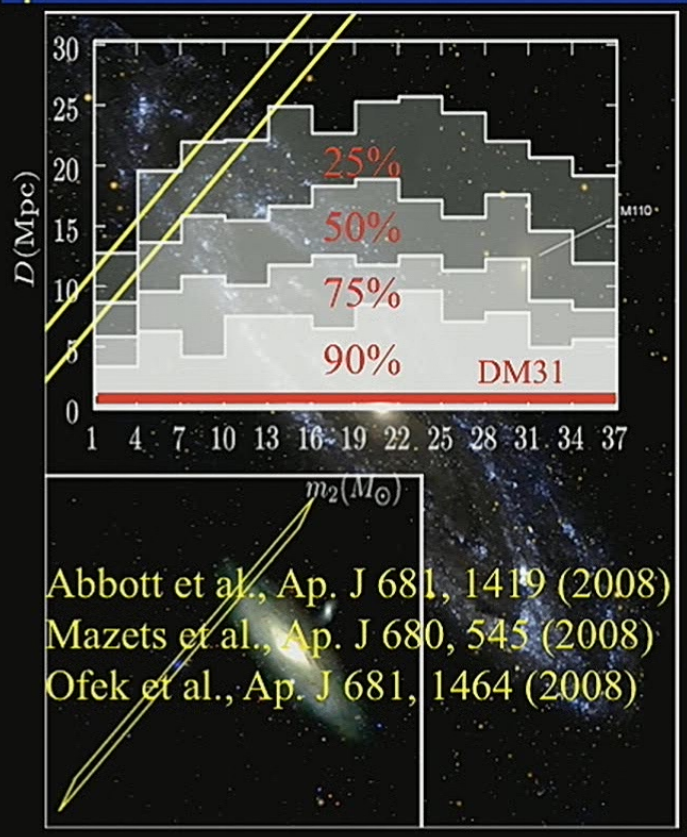


- Make mirrors that are very still
  - Vibration isolation and thermal fluctuation control
- Probe the mirror positions using laser light
  - Ultra-high precision optical measurement
  - Manipulate quantum fluctuations of the light

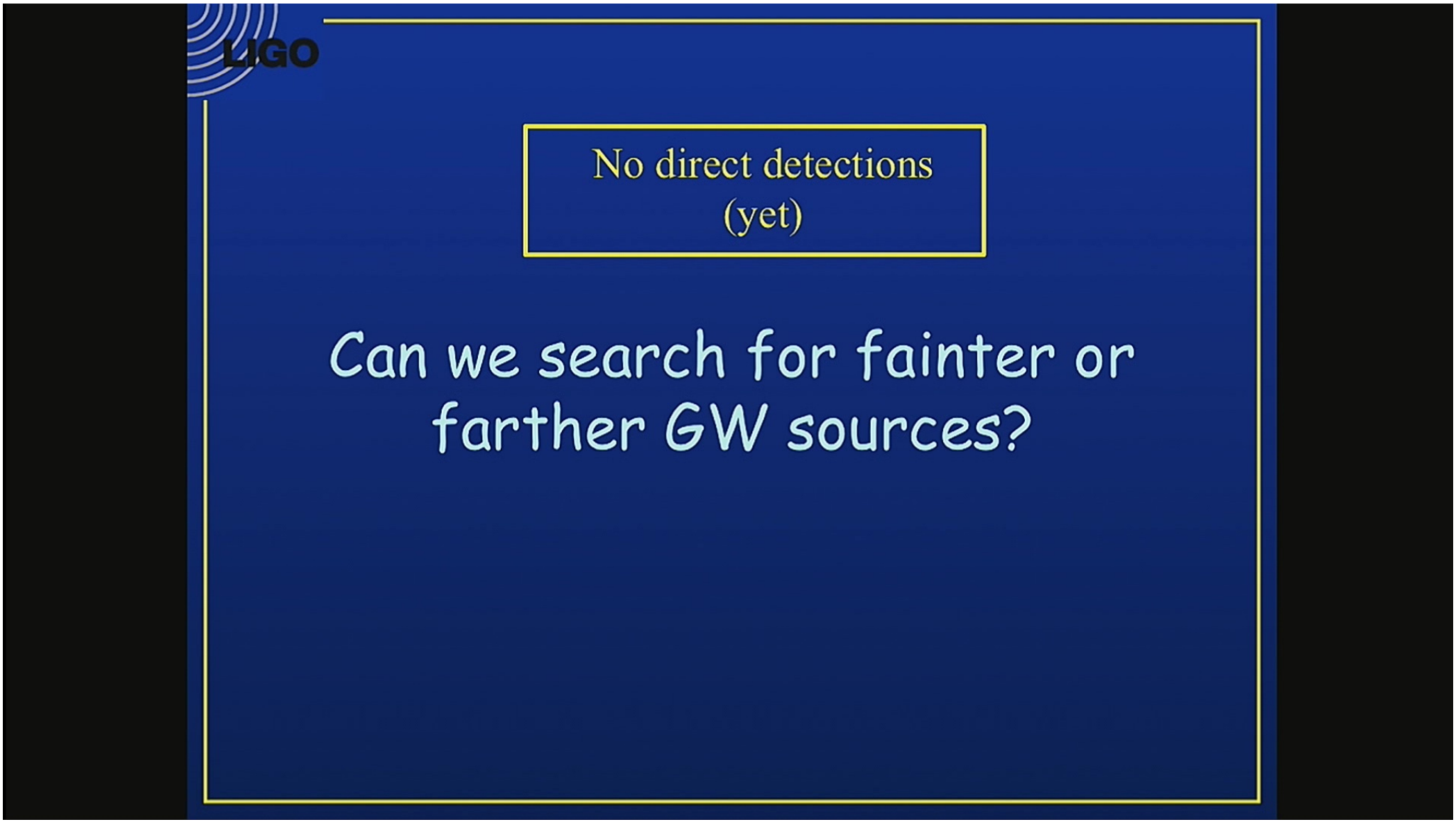
Global network of detectors



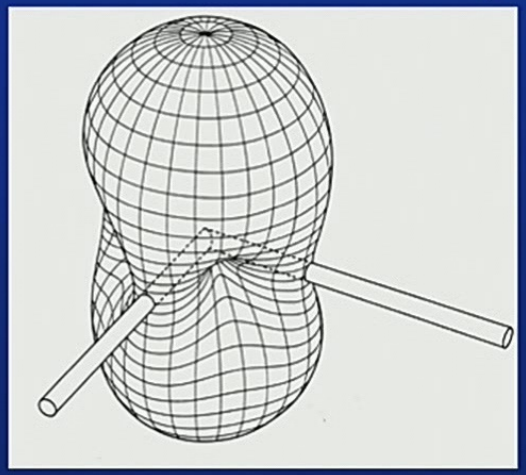
The search for GRB070201

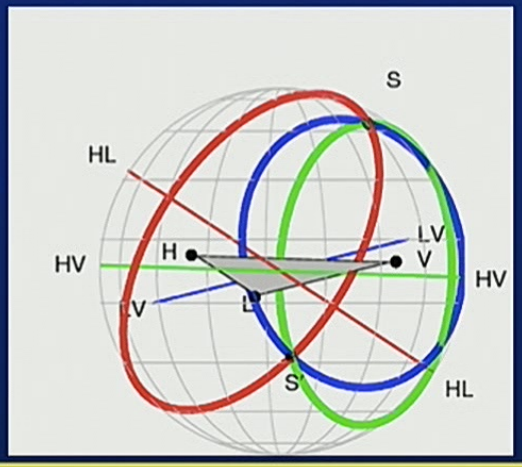


- GRB 070201
  - Very luminous short duration, hard gamma-ray burst
  - Detected by Swift, Integral, others
  - Consistent with being in M31
  - Leading model for short GRBs: binary merger involving a neutron star
- Looked for a GW signal in LIGO
  - **No plausible GW signal found**
  - **Can say with >99% confidence that GRB070201 was NOT caused by a compact binary star merger in M31**
- Conclusion: it was most likely a Soft Gamma Repeater giant flare in M31


LIGO
No direct detections
(yet)
Can we search for fainter or
farther GW sources?

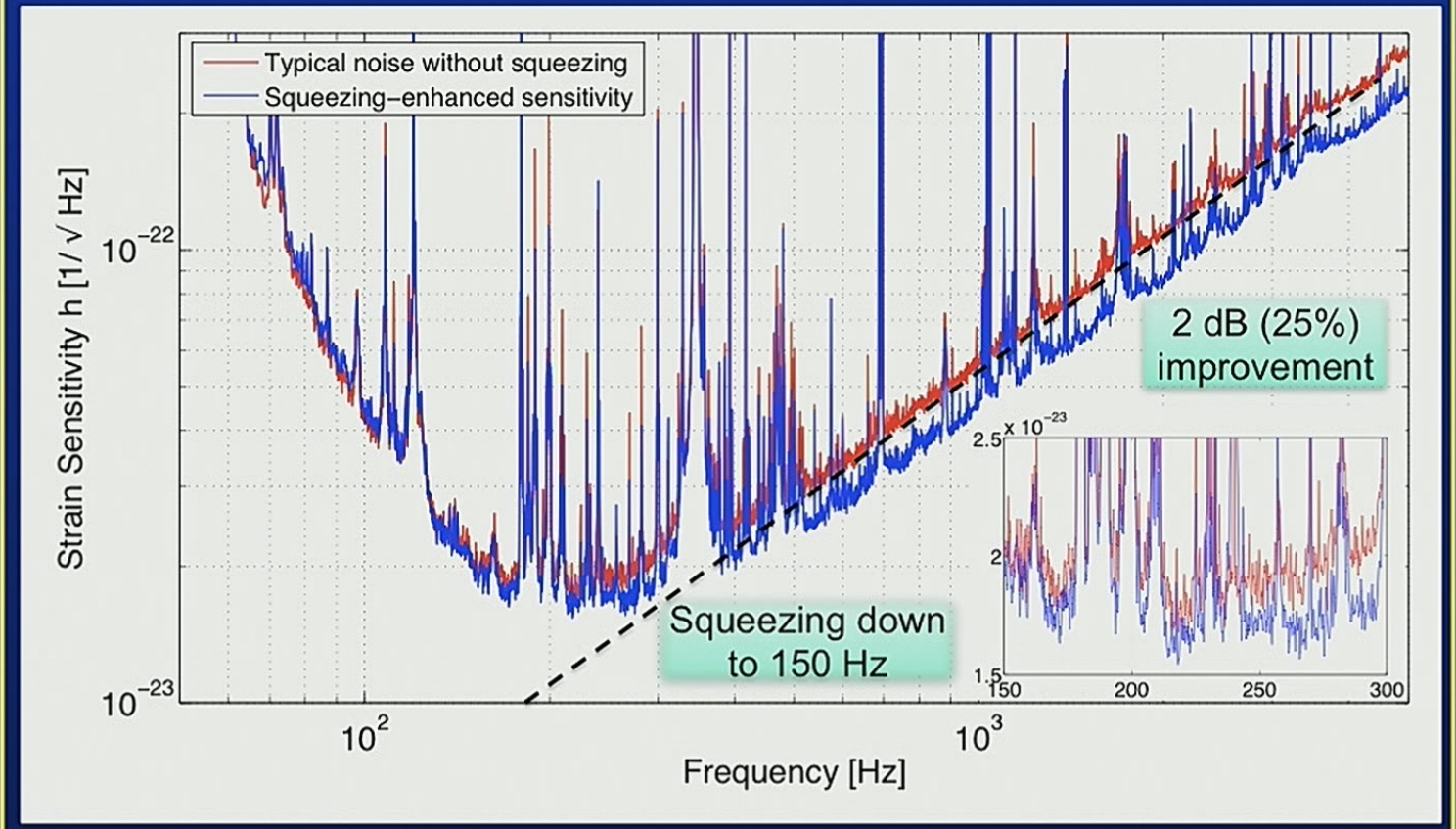
Why a global network?





- Angular response is pure quadrupole
  - Nearly omni-directional
  - Earth transparent to GW
- Pinpoint sources in sky by triangulation
  - Localization depends strongly on SNR and number of detectors
- Large duty factor (fraction of time the network has high sensitivity)
  - Need five sites to get 4 detectors operational ~85% of the time

Sub-quantum LIGO



LIGO Scientific Collaboration, Nature Photonics (2013)

The Dawn of GW Astrophysics

Planck + SPT + ACT + Spider
- Multi-wavelength
- Foreground dust

Nanograv + EPTA + PPTA
- Better timing precision
- More sources

Space detectors
- Resurrected

LIGO + VIRGO + KAGRA
- Improve sensitivity
- Better theory and data analysis
- Sky localization and EM follow-up

10^{-16} Hz 10^{-9} Hz 10^{-4} Hz 10^{0} Hz 10^{3} Hz