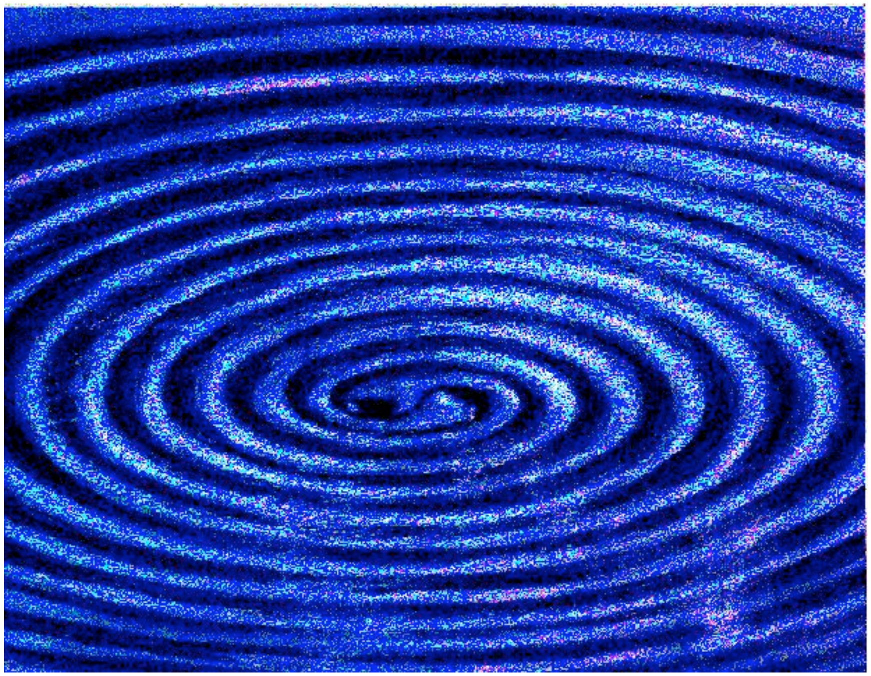
The Physics of Interferometric Gravitational Wave Observatories



Riccardo DeSalvo

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LIGO-G070862-00-R

Summary

- Using Long baseline interferometers such as LIGO, Virgo, GEO600 and TAMA GW observatories are poised to detect gravitational waves within the next decade.
- The underlying physical principles of these detectors will be discussed
- Some current upper limits will be presented.
- A variety of possibilities for a future generation of ground based interferometers will be discussed.

General Relativity: “a theorist’s Paradise, but an experimentalist’s Hell”

C. Misner, K. S. Thorne and J.A Wheeler, ***Gravitation*** p. 1131 (1973)

AIP Emilio Segrè Visual Archives

- gravitational waves
- Convincing observational evidence for their existence not available until ~70 years after initial prediction (Binary Pulsar)
- After 90 years, direct detection still eludes us
- We may have a direct detection before the 100th anniversary of their prediction

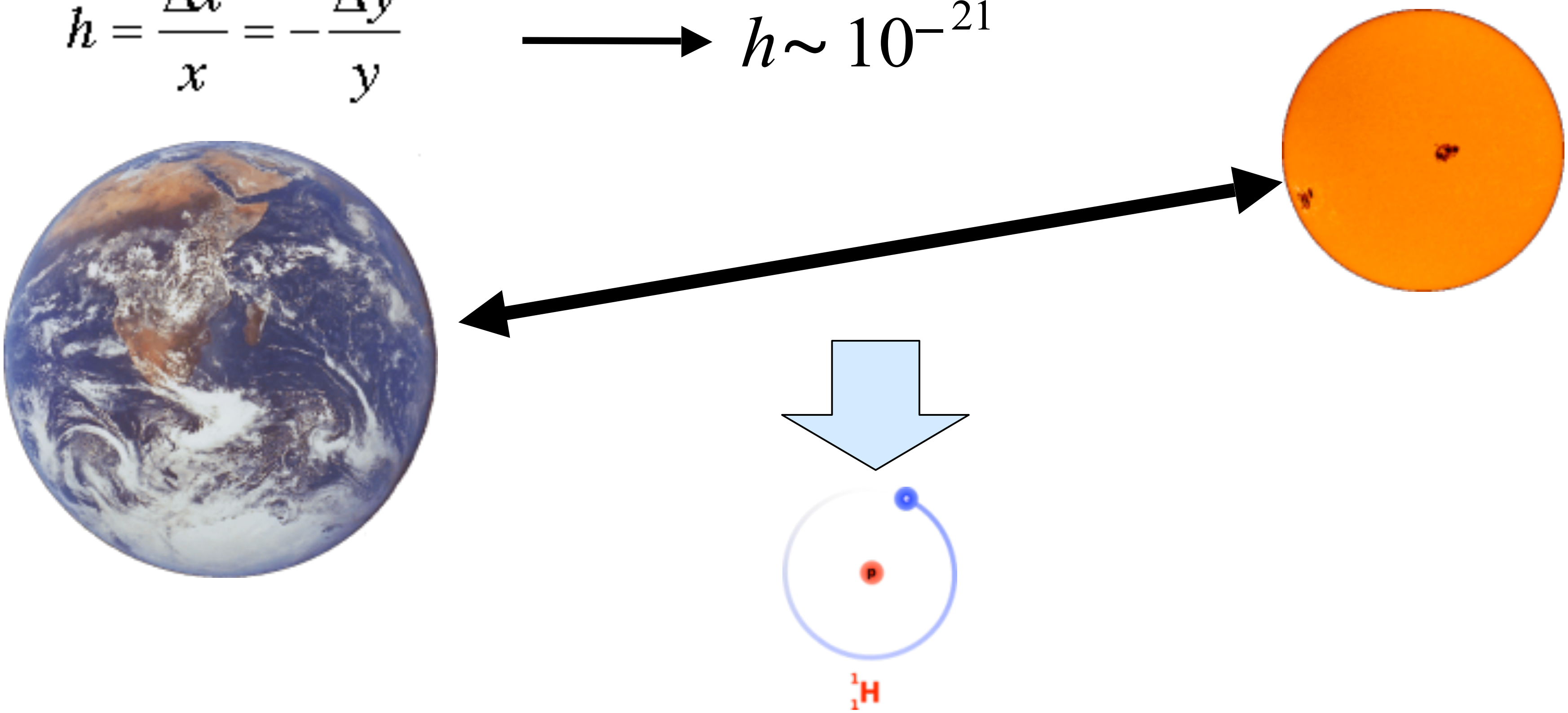
If this is hell,

Who needs Paradise?

Effect of GW is extremely weak

Typical Event: 1.4 M NS- NS binary inspiral in Virgo cluster (@15Mpc)

$$h = \frac{\Delta x}{x} = -\frac{\Delta y}{y} \longrightarrow h \sim 10^{-21}$$



Change by the diameter of a hydrogen atom

Indirect evidence of gravitational radiation


Hulse


Taylor

Radio pulsar B1913+16

Periodic modulation

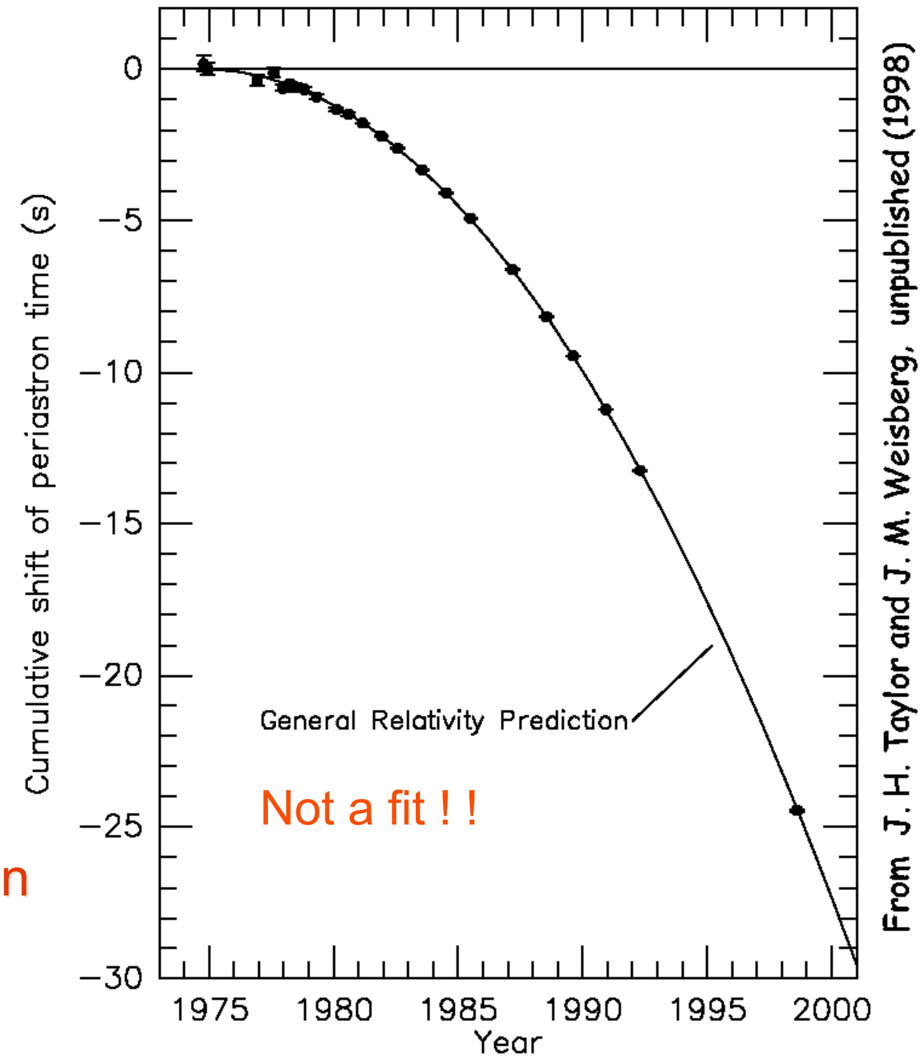
→ Binary neutron star

GW emission

→ Orbital decay

Perfect matching with the GR prediction

Nobel Prize in Physics, 1993



GW Sources Lurking in the Dark

Two body merging systems

- Neutron star – Neutron star
- Black hole – Neutron star
- Black hole – Black hole

Single frequency sources

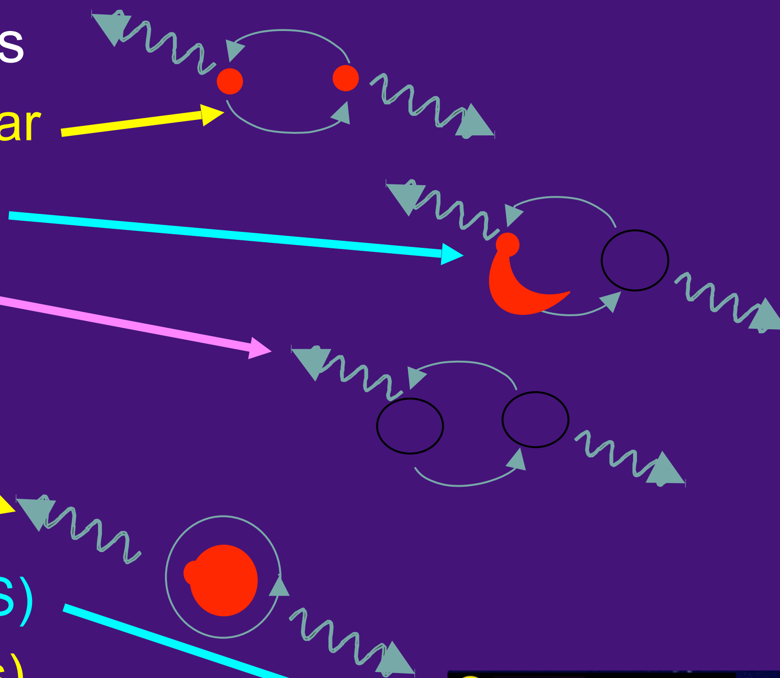
- Rotating pulsars

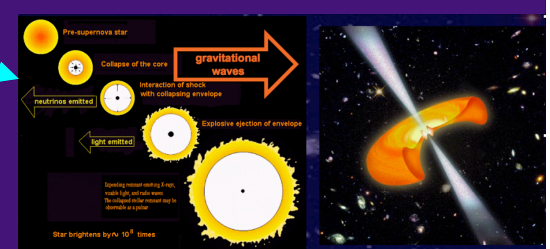
"Burst" sources

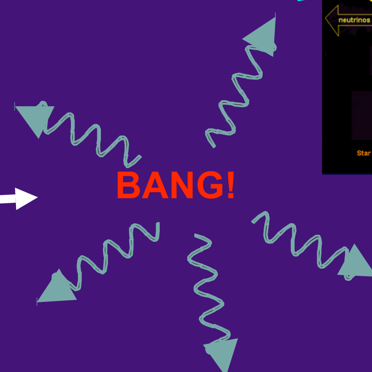
- Supernovae (escaping NS)
- Gamma ray bursts (GRBs)
- ?????

the Big Bang

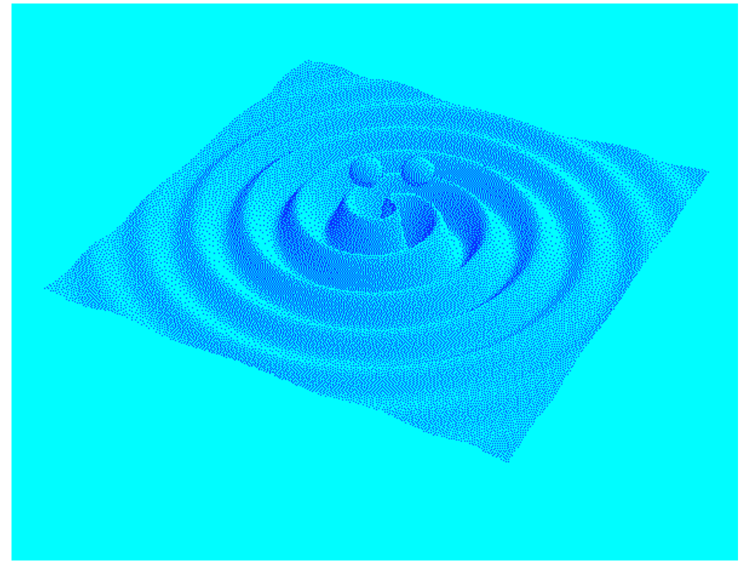
- Stochastic background
- Cosmic Strings







A NEW WINDOW ON THE UNIVERSE

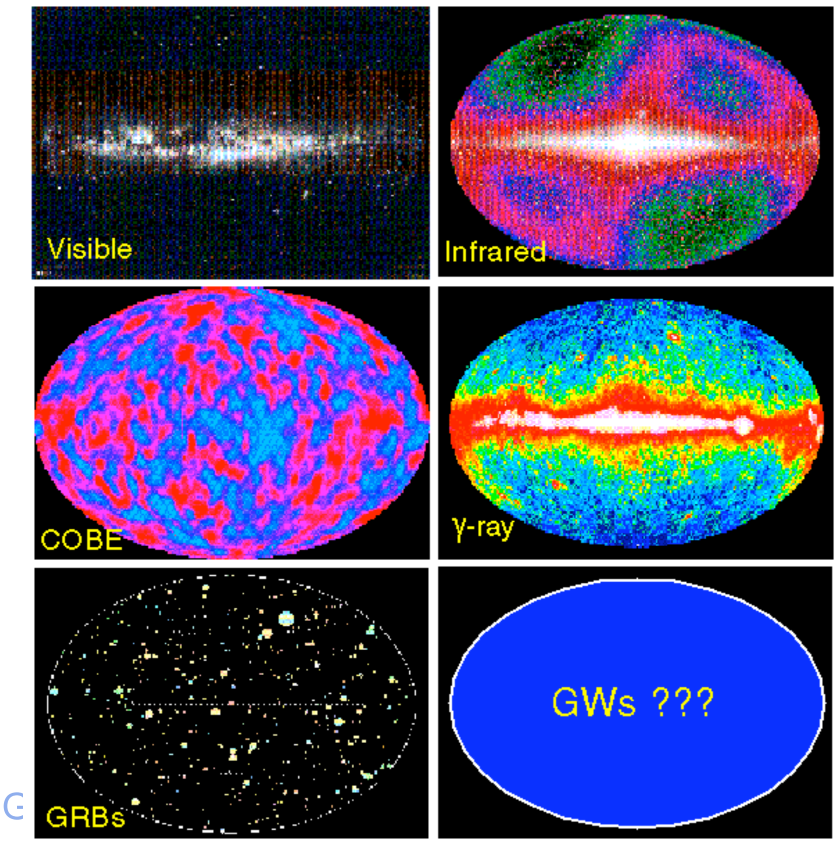


Electro-Magnetic Wave Observations

New wavelength ⟶ Discoveries

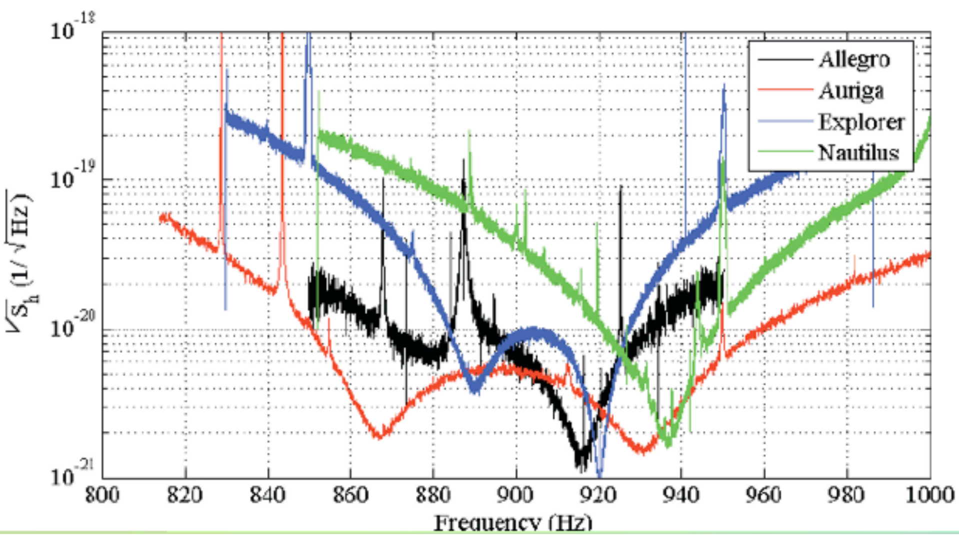
Gravitational Waves: Totally New (not even EMW)

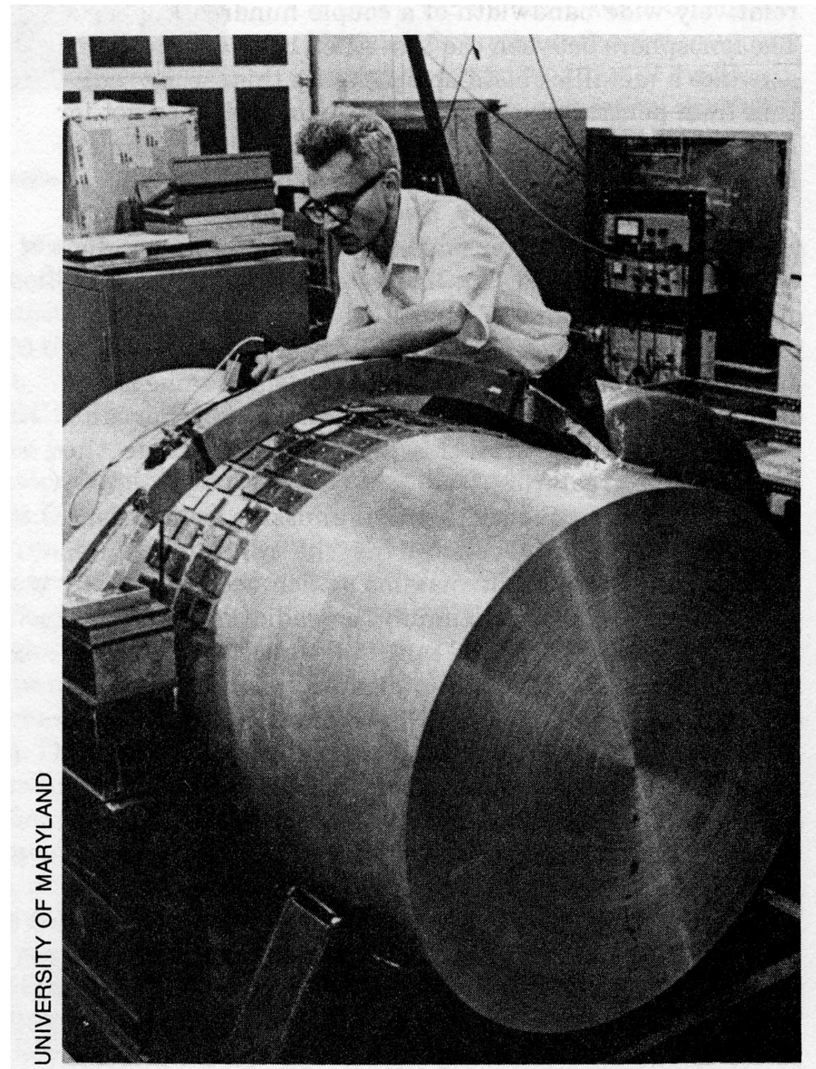
EM	GW
Motion of charged particles	Coherent motion of huge masses
Wavelength < source size (imageable)	Wavelength > source size (no image)
Absorbed, scattered, by matter	Almost no absorp-tion, scattering
10MHz and up	10kHz and down



First attempts
Resonant Bar Detectors

- First ground-based detectors—the beginning of GW detection
  - Joseph Weber 1960's
- Bandwidth limited to the bar resonances

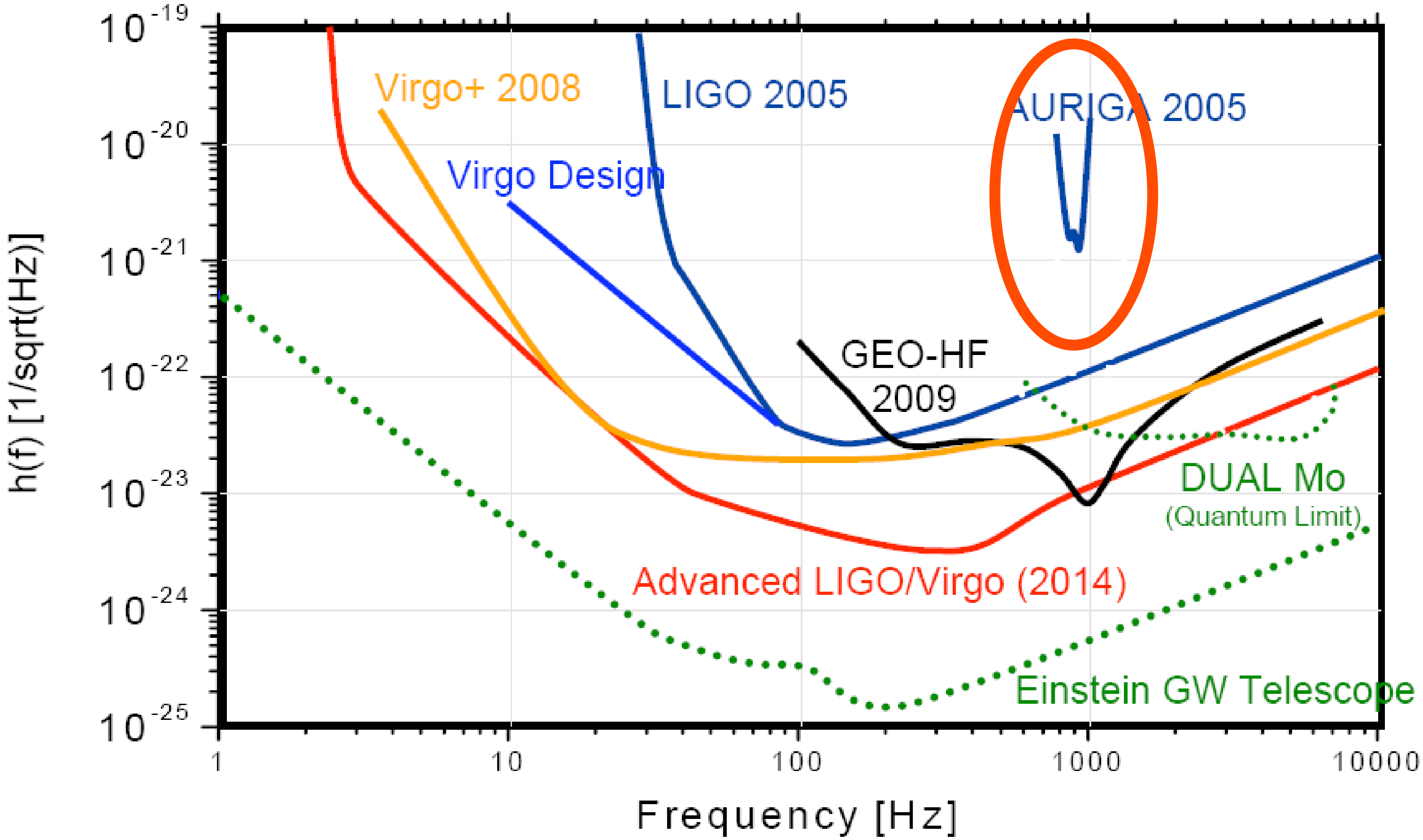




Joe Weber

Ground-based Gravitational Wave Detection:Now and Future

Limitations of the Bar detectors

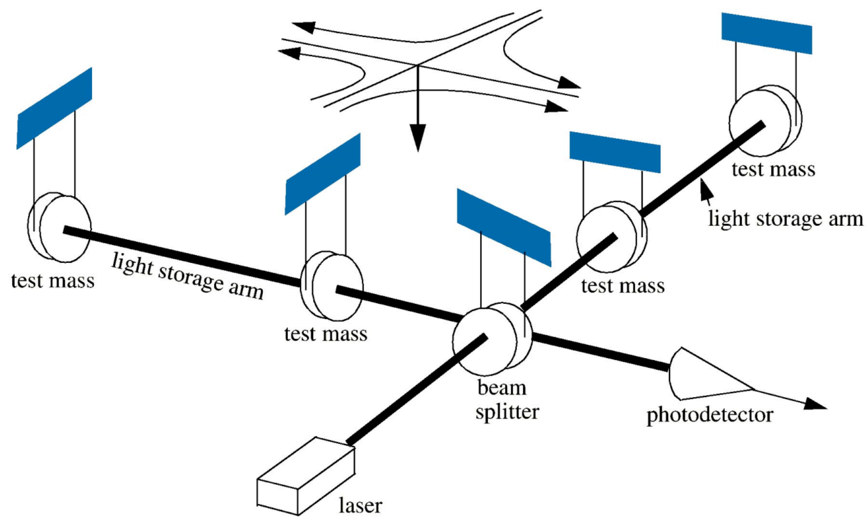


Harald Lück for the European Gravitational-Wave Community

Detecting GWs with Interferometry

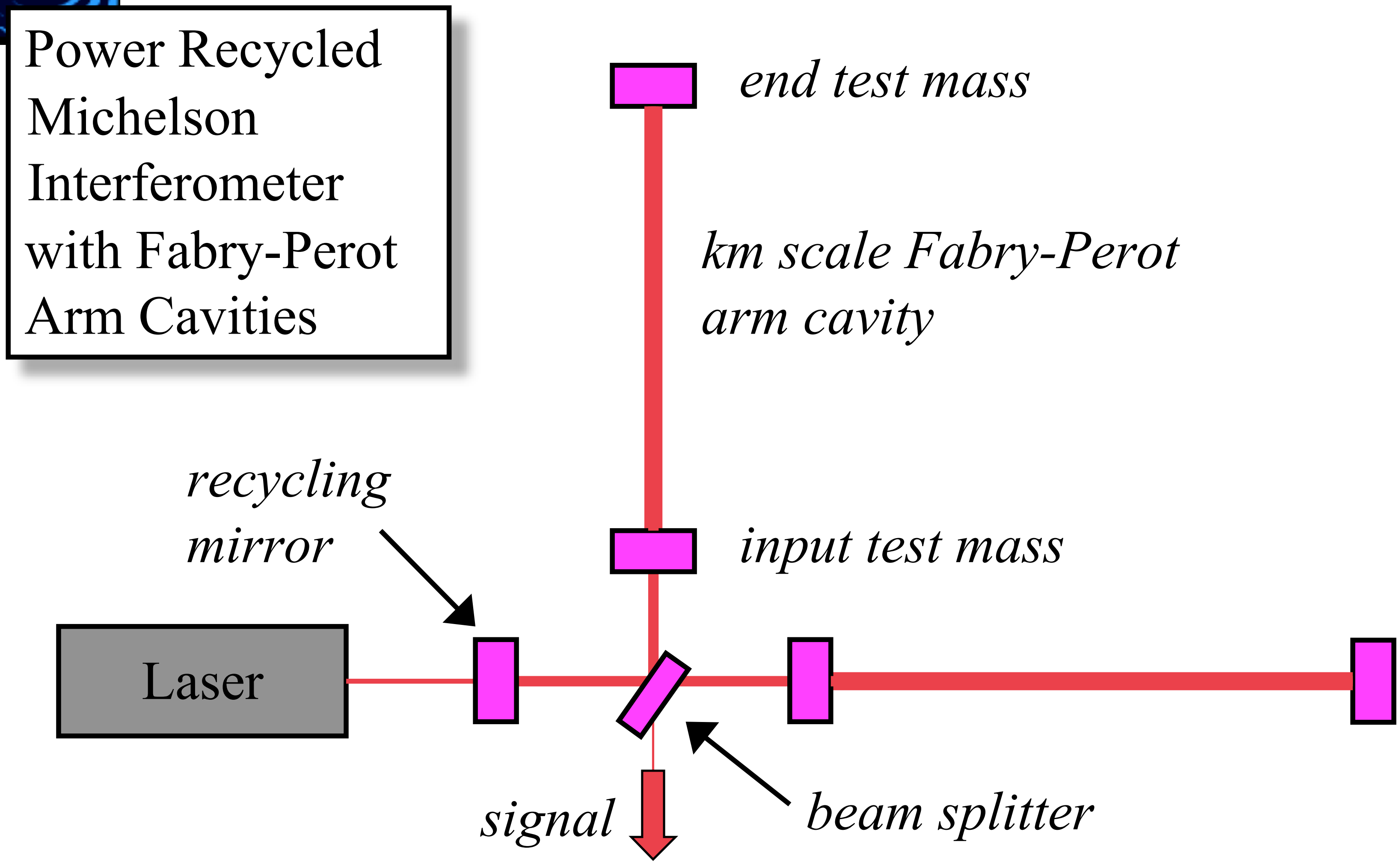
$$h = \Delta L / L$$

Suspended mirrors act as "free-falling" test masses (in horizontal plane) for frequencies f >> f_{pend}



Terrestrial detector
For $h \sim 10^{-22} - 10^{-21}$
L ~ 4 km (LIGO)
$\Delta L \sim 10^{-18}$ m

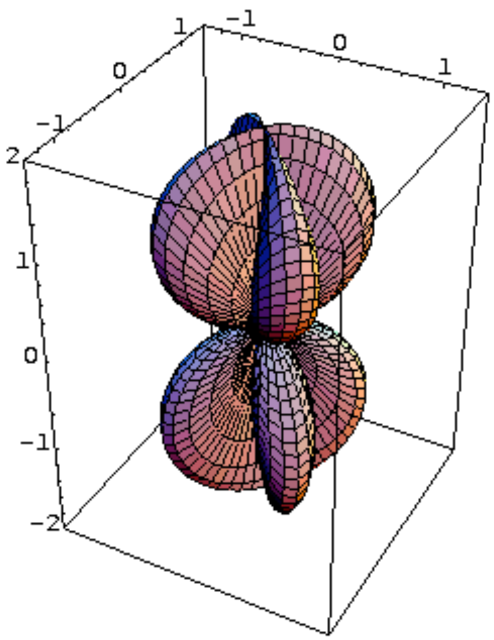
Typical Optical Configuration



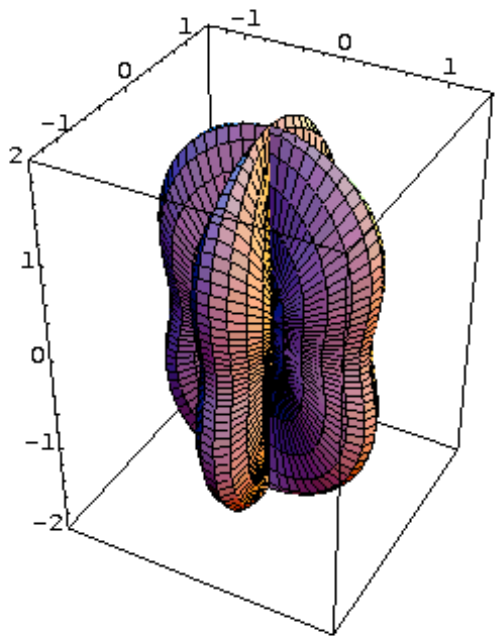
An interferometer is not a telescope

- Sensitivity depends on propagation direction, polarization

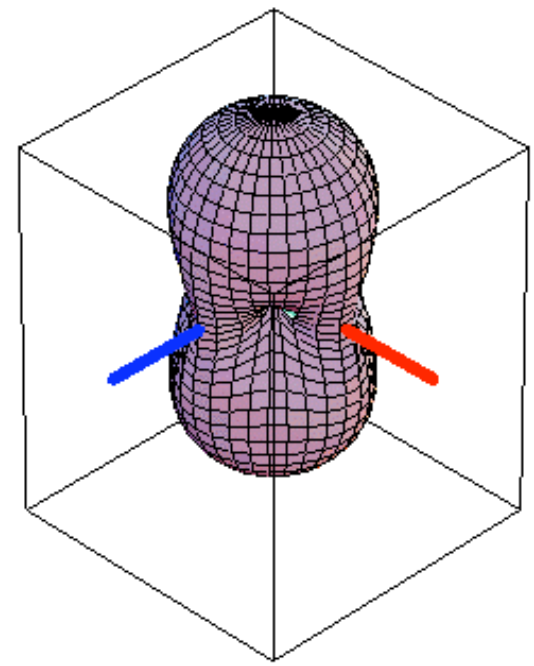
“×” polarization



“+” polarization

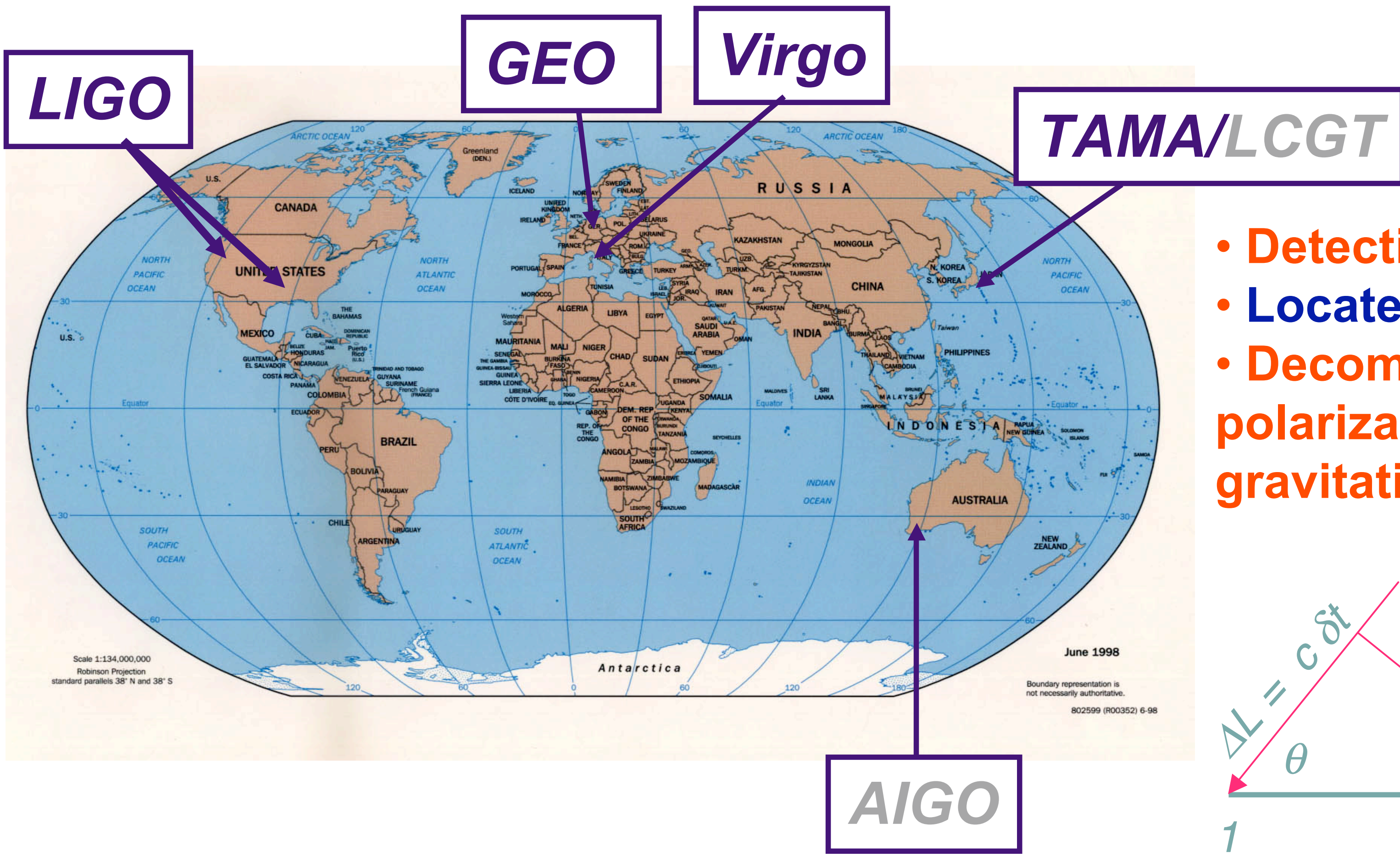


RMS sensitivity

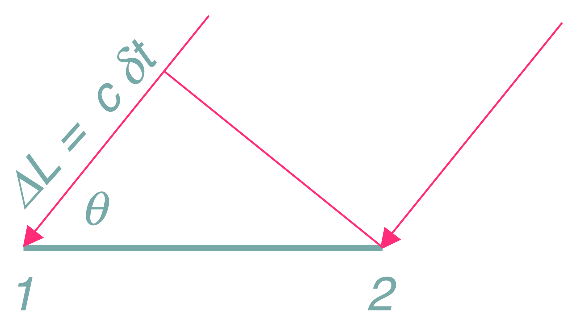


- Really a microphone!

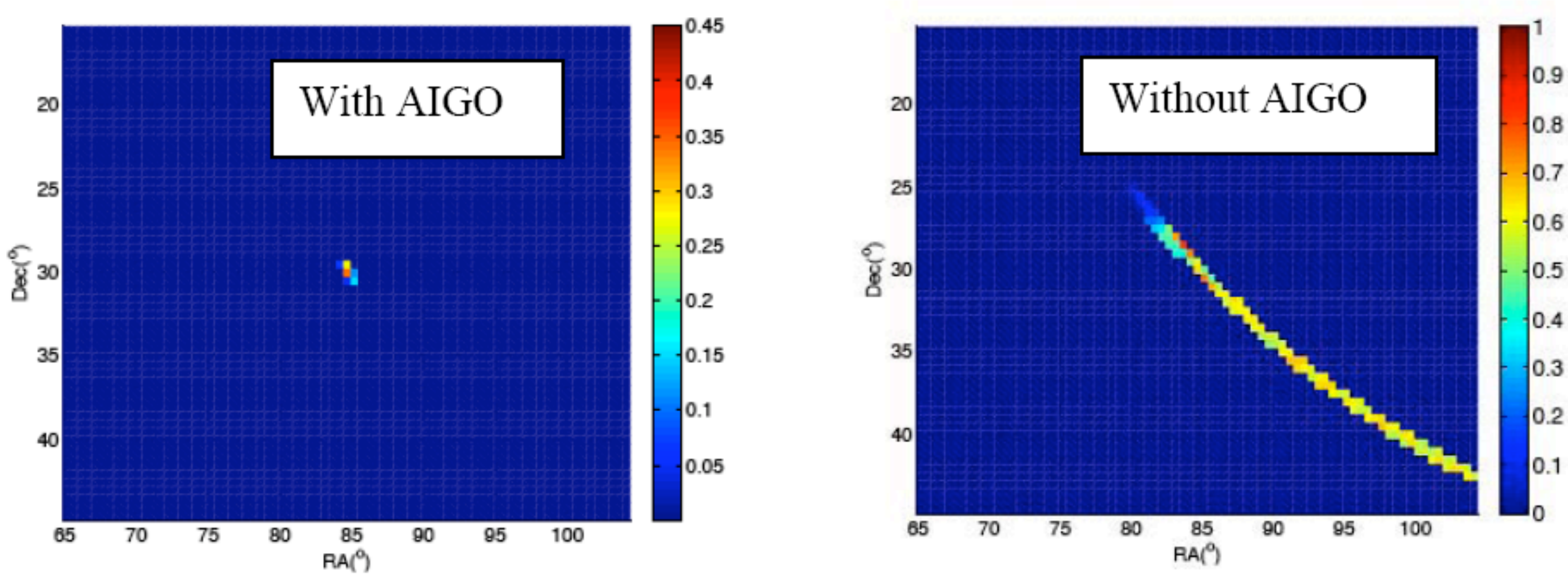
A Global Network of Gravitational Wave Interferometers necessary to point at the stars



- Detection confidence
- Locate sources
- Decompose the polarization of gravitational waves

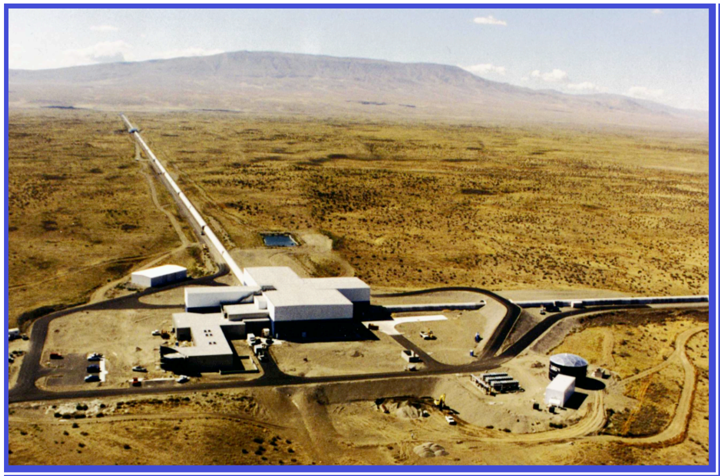


Importance of a network



- **Improvement of position sensitivity of present Network (Virgo-LIGO-GEO) with the addition of a Southern advanced GW interferometer**
- **It would provide strong science benefits e.g. host galaxy localization**

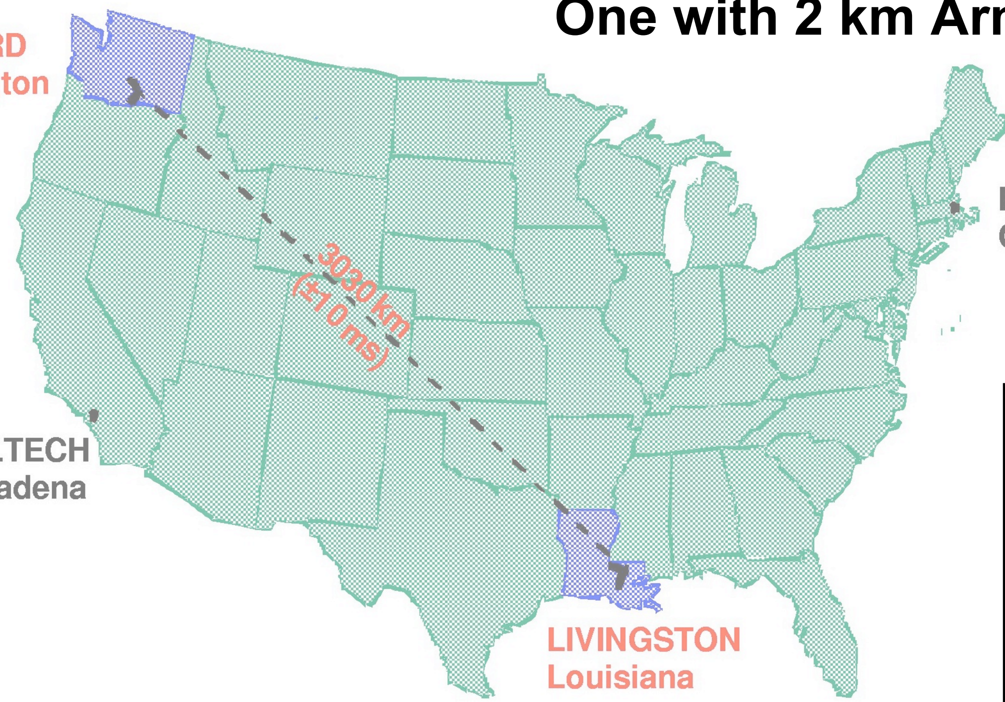
David Coward and David Blair



LIGO

(Laser Interferometer Gravitational-wave Observatory)

Hanford
One interferometer with 4 km Arms,
One with 2 km Arms



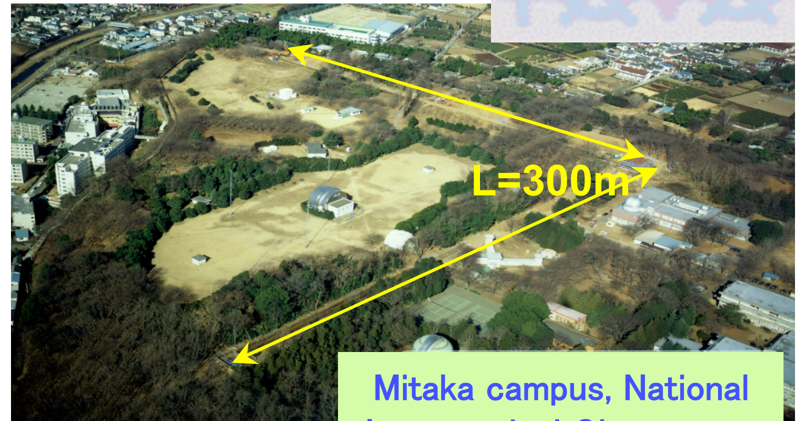
Livingston
One interferometer with 4 km Arms

Virgo

One interferometer with 3 km arms, located near Pisa

GEO600, TAMA, AIGO, LCGT

GEO 600 m arms,
located near Hannover
Germany



TAMA 300 m Fabry Perot arms,
located in Mitaka, near Tokyo

LCGT (proposal only)
3000 m Fabry Perot arms,
to be located in Kamioka mine
Japan

AIGO
80 m interferometer test facility
8km x8 km site 70 km N of Perth

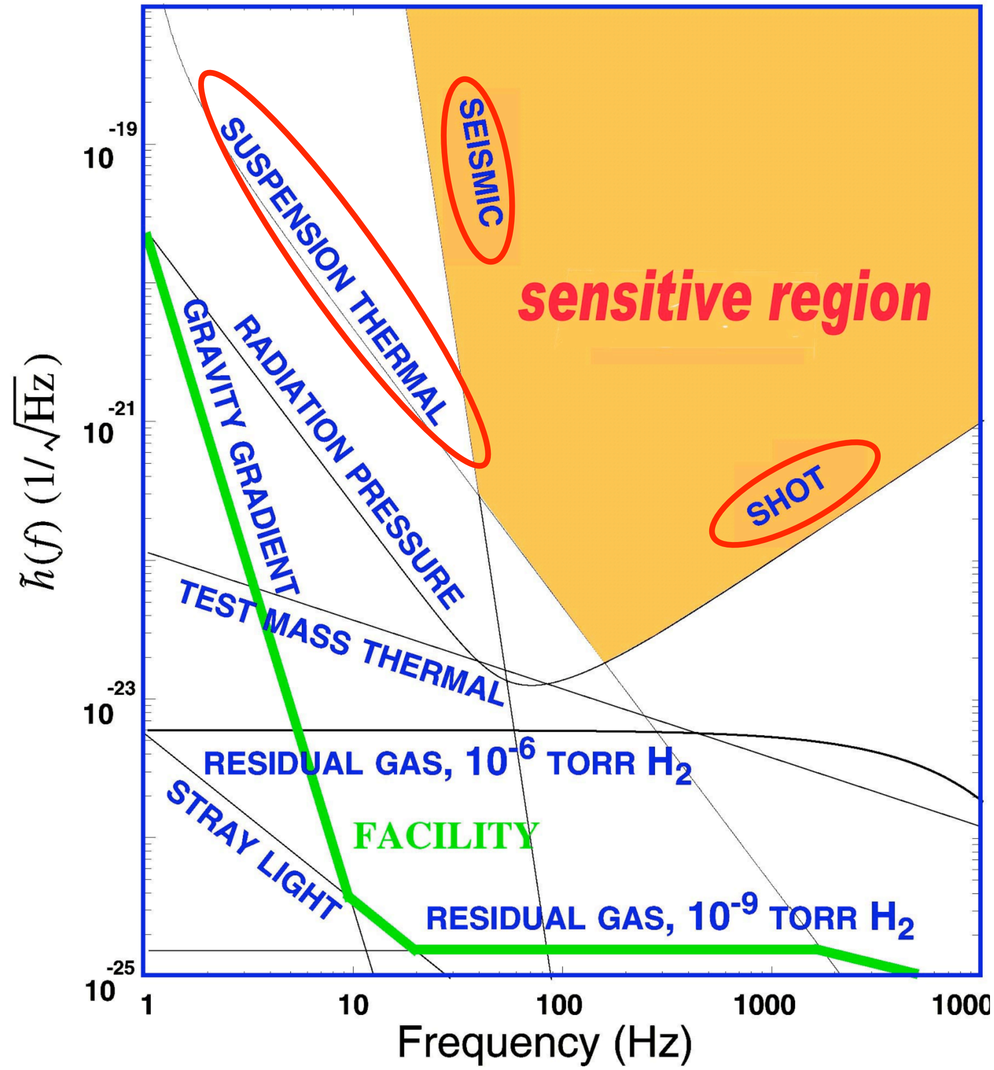
Sensitivity limitations

- fundamental noise sources

- Shot noise
- Mirror thermal noise
- Suspension thermal noise
- Newtonian noise/gravity gradi
  - (fluctuation of verticality of g!)

- But also technical noises

- Seismic noise
- Control noise



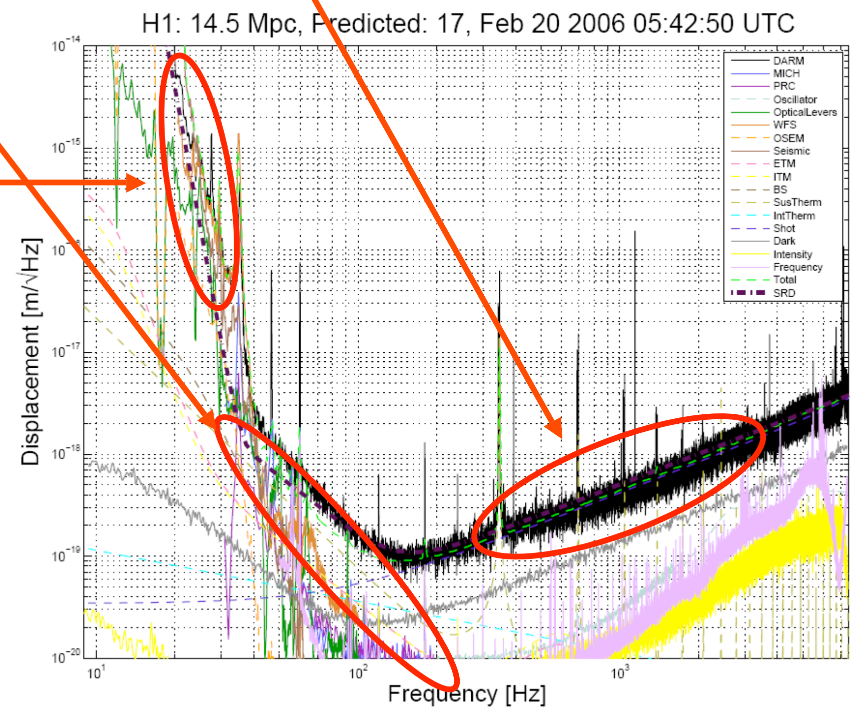
Sensitivity limitations

- All fundamental noise sources in advanced detectors

- Shot noise
- Mirror thermal noise
- Suspension thermal noise
- Newtonian noise
  - (fluctuation of verticality of g!)

- But also technical noises

- Seismic noise
- Control noise



Thermal Noise

Thermal vibration of the molecules of mirror / suspension material

Fluctuation Dissipation Theorem

Mechanical loss ⟷ Connection to the heat bath → Thermal fluctuation of mirror surface

High mechanical quality mirror substrate / coating materials

Low mechanical loss suspension fibers
Fused silica fibers with silica bonding

Fused silica mirror

Other challenges for mirrors

Large mirror (40kg):
- large beam size (average out thermal fluctuations)
- Small radiation pressure noise

Precision manufacturing/metrology:
- Large radius of curvature
- Smooth polishing (<0.1nm RMS micro roughness)

Optical Absorption:
- Optical loss < 0.5 ppm/cm
- Thermal lensing compensation system

Thermal Noise

Thermal vibration of the molecules of mirror / suspension material

Fluctuation Dissipation Theorem

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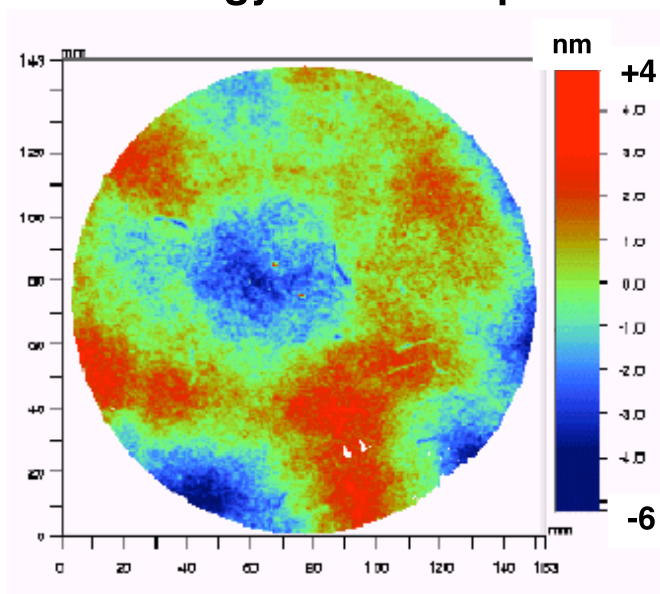
High mechanical quality mirror substrate / coating materials

Low mechanical loss suspension fibers
Fused silica fibers with silica bonding

Fused silica mirror

Metrology: Phase Maps



Reject Mirror!

Error ±5nm

Other challenges for mirrors

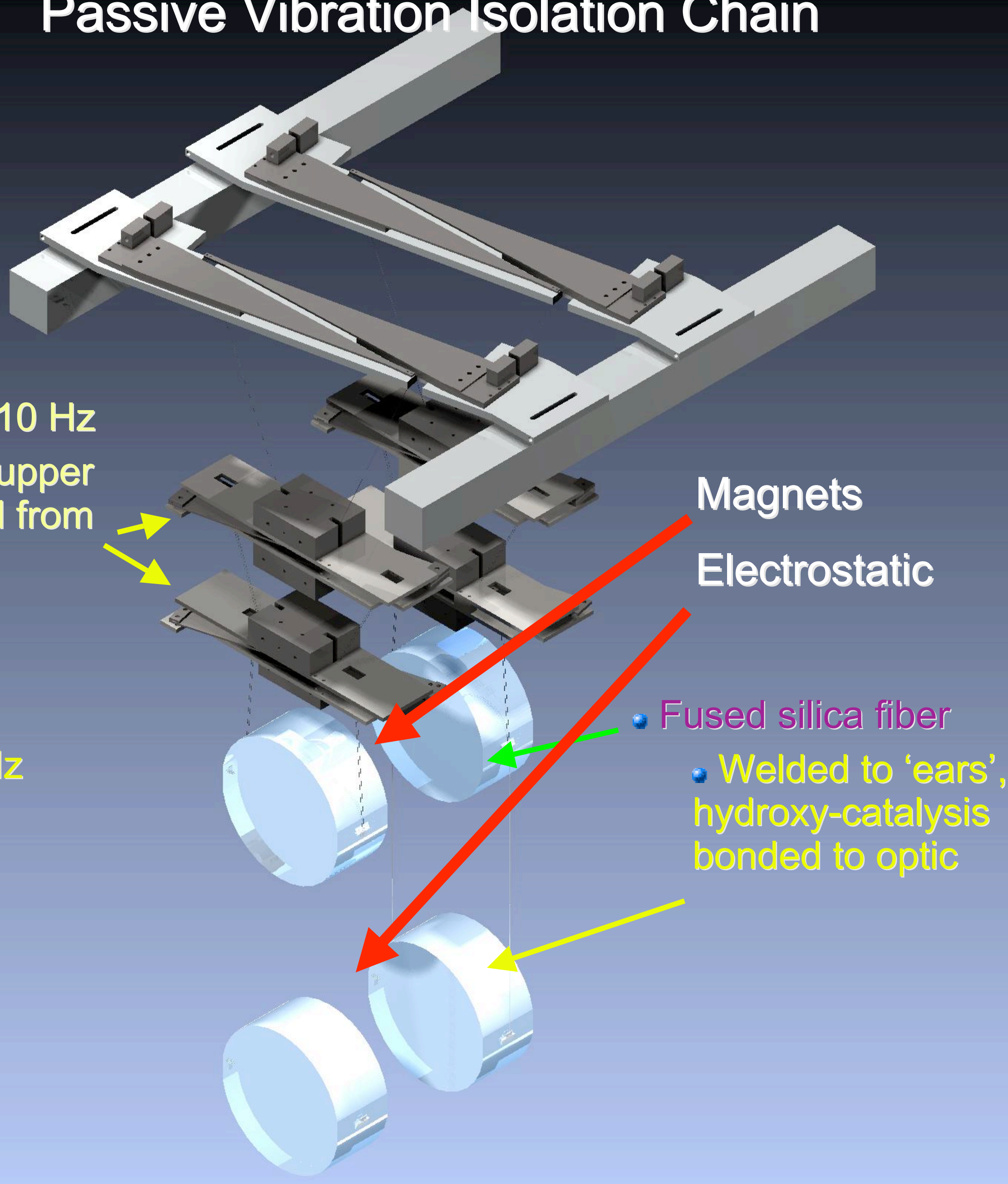
Large mirror (40kg):
- large beam size (average out thermal fluctuations)
- Small radiation pressure noise

Precision manufacturing/metrology:
- Large radius of curvature
- Smooth polishing (<0.1nm RMS micro roughness)

Optical Absorption:
- Optical loss < 0.5 ppm/cm,   <0.25 ppm/pass
- Thermal lensing compensation system

Passive Vibration Isolation Chain

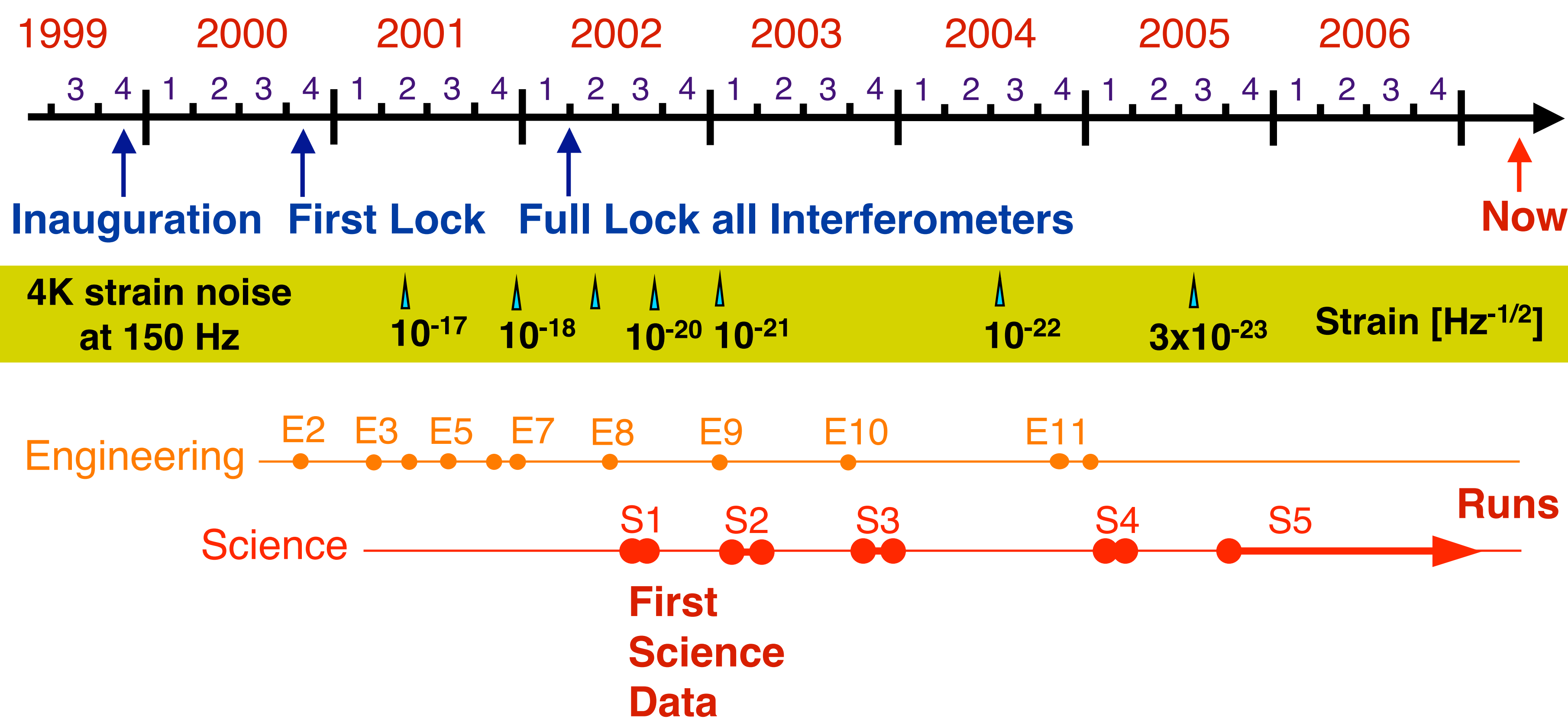
- Quadruple pendulum:
  - » ~10^7 attenuation @10 Hz
  - » Controls applied to upper layers; noise filtered from test masses
- Seismic isolation and suspension together:
  - » 10^{-19} m/rtHz at 10 Hz



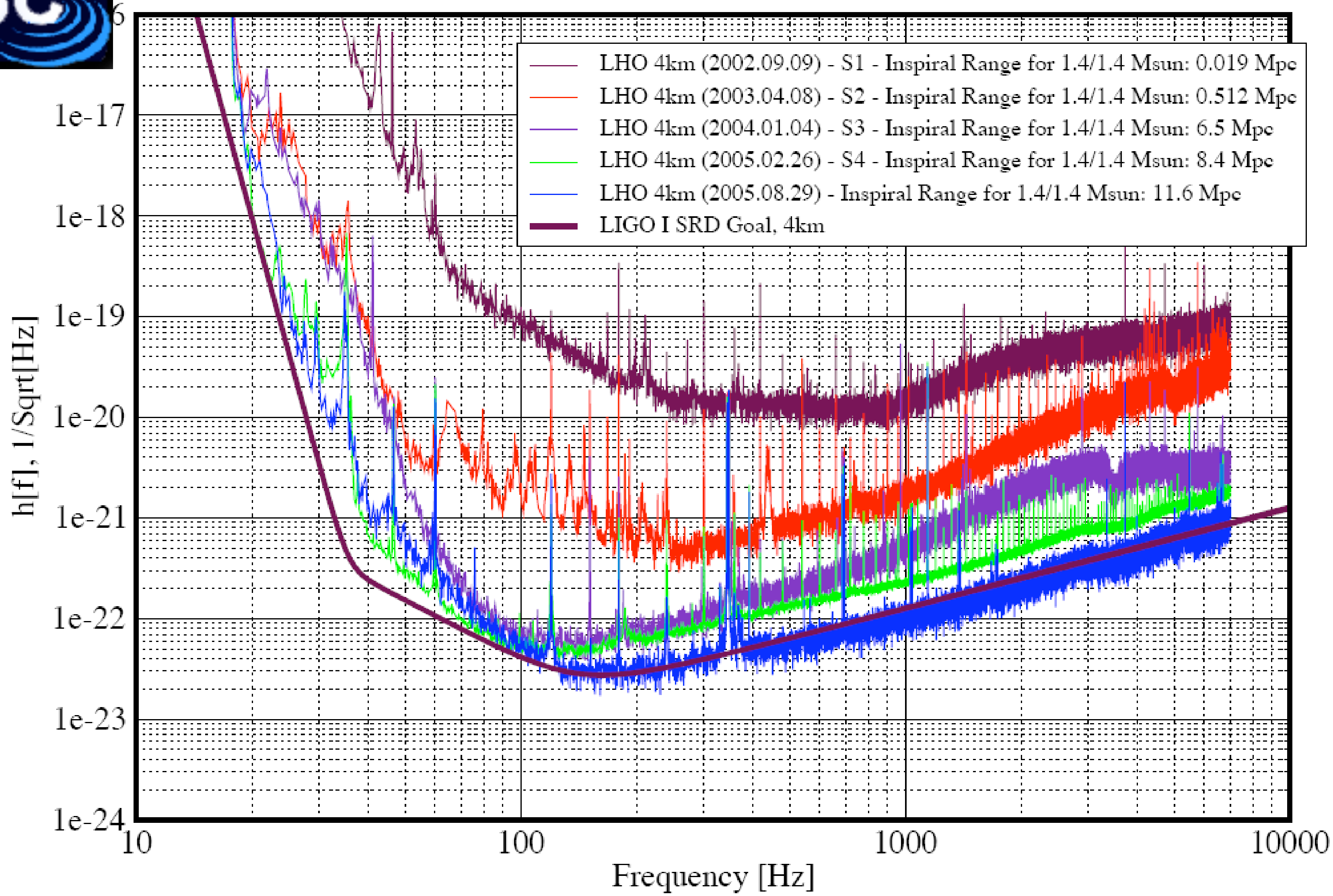
Complex instruments

- Complex to build
- Very complex to commission and tune

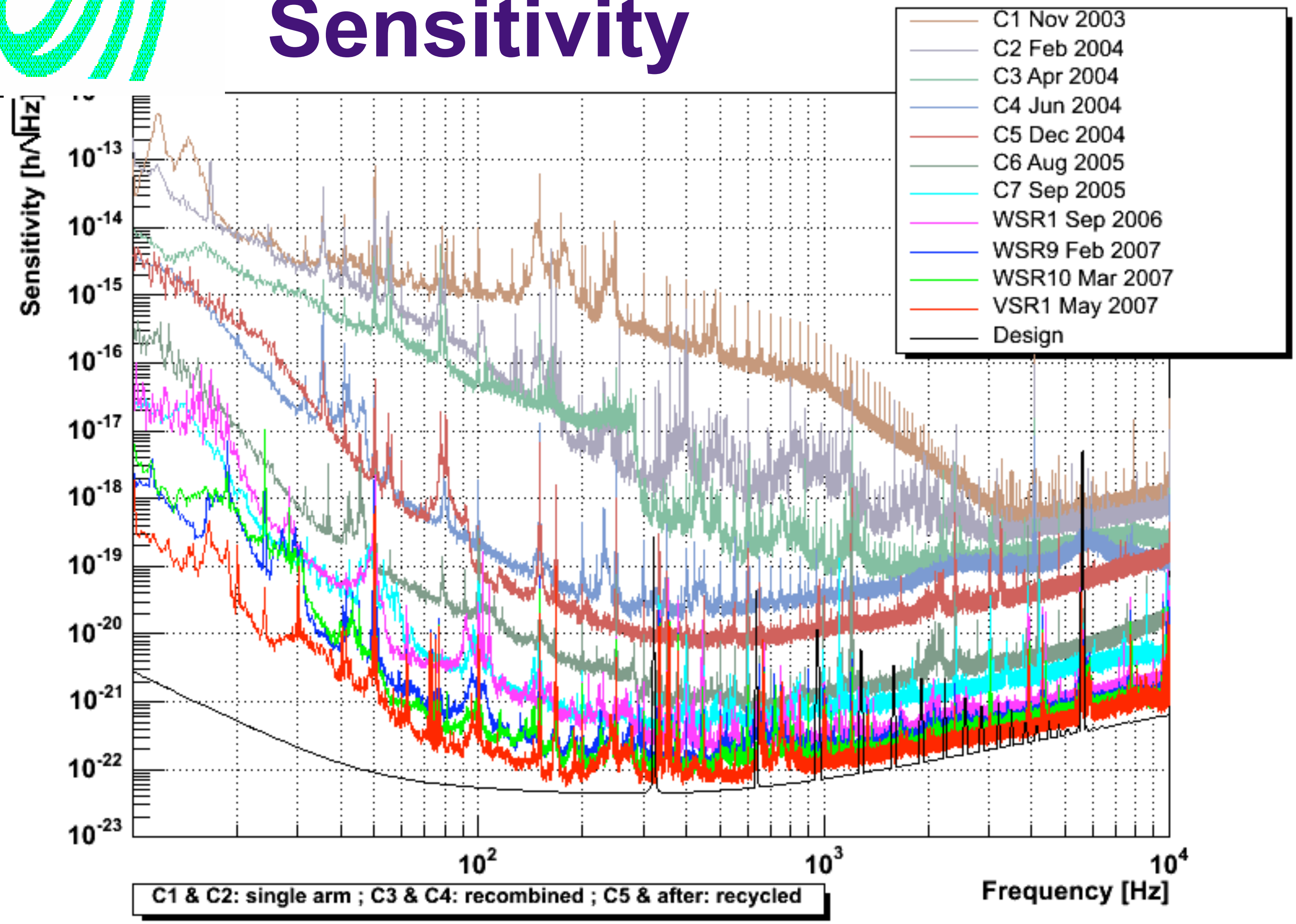
LIGO History



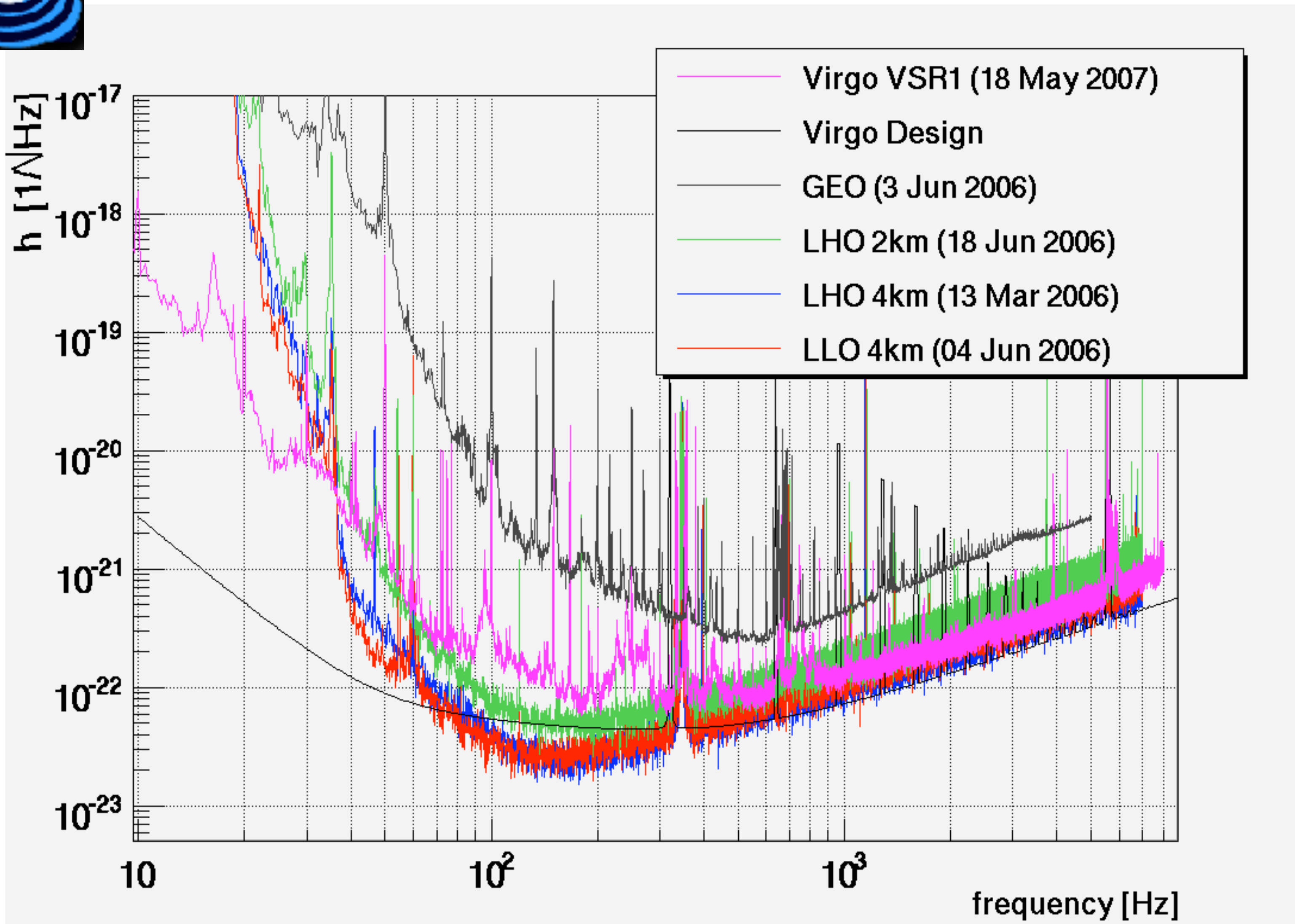
Progress of LIGO Sensitivity



Progress of Virgo Sensitivity

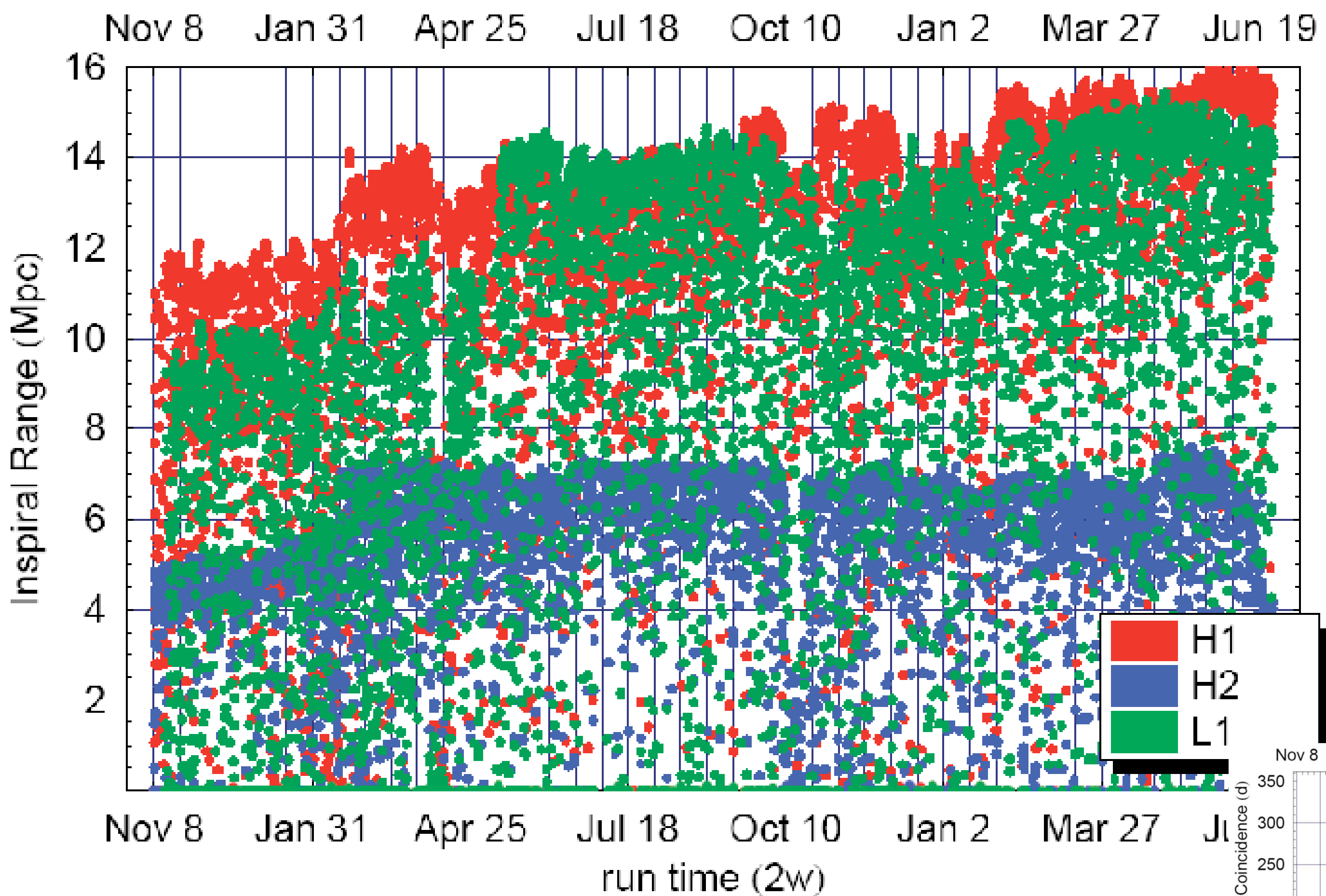


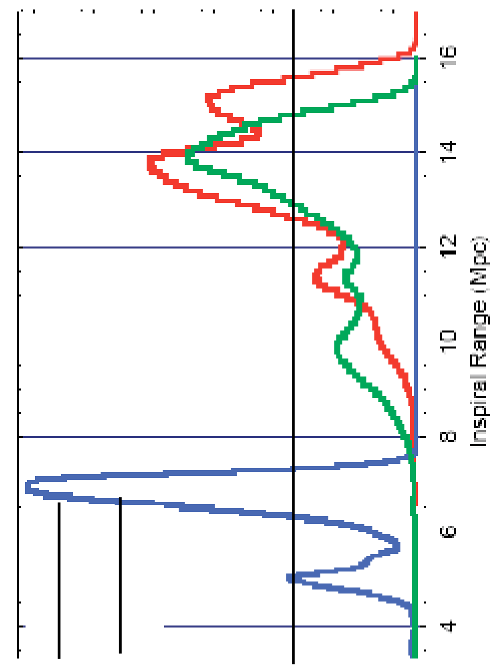
Present Network Sensitivity

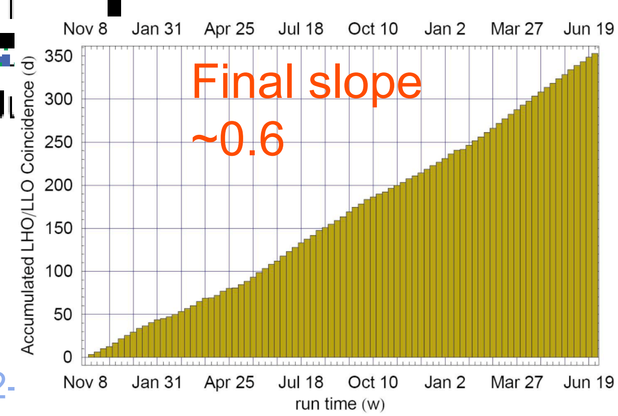


- Observatories need to Observe
  - Sensitivity / Covered Reach
  - Duty factor

Duty Factor for S5

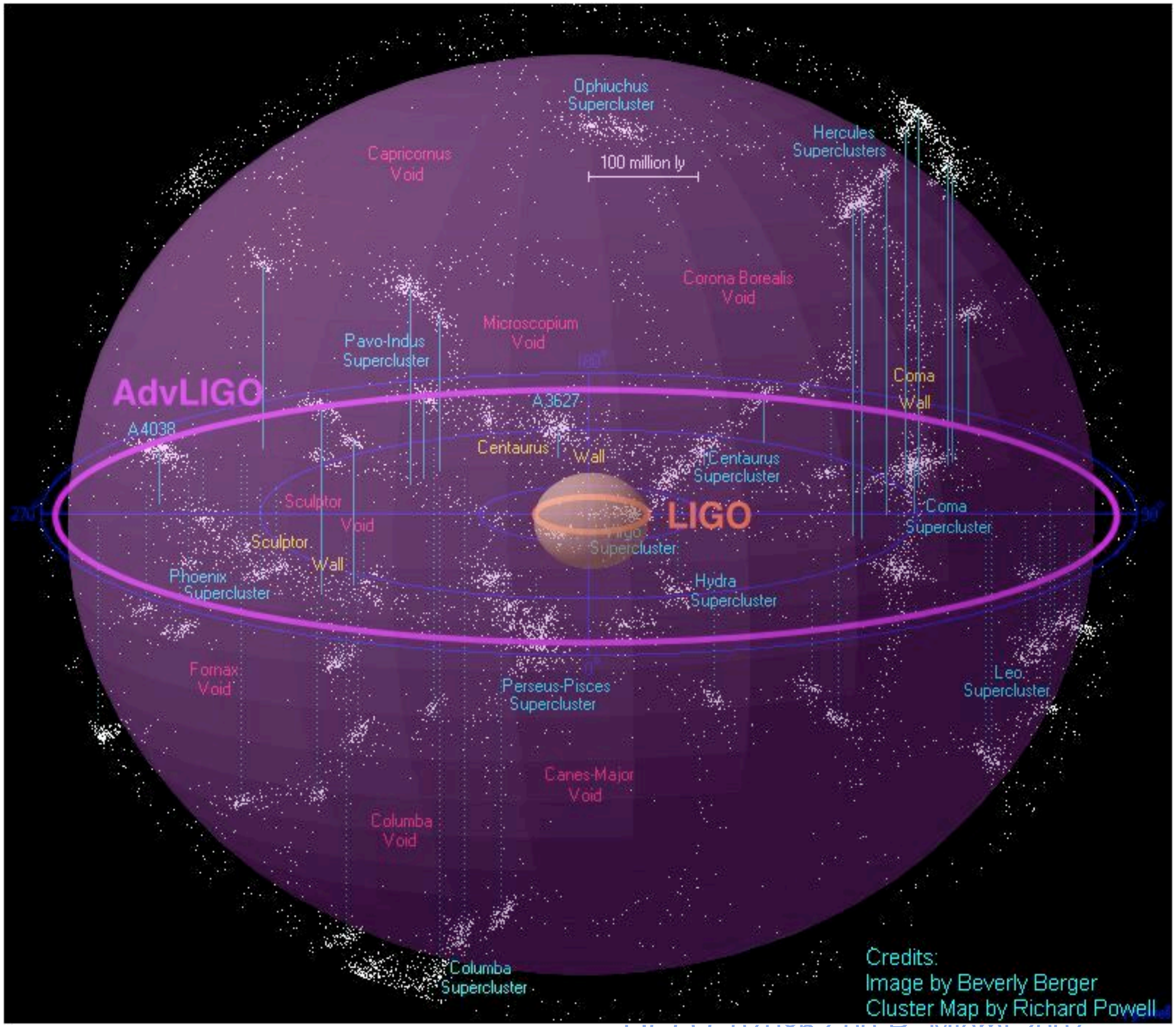






Final duty cycle ~0.85

Astrophysical Reach of Advanced LIGO

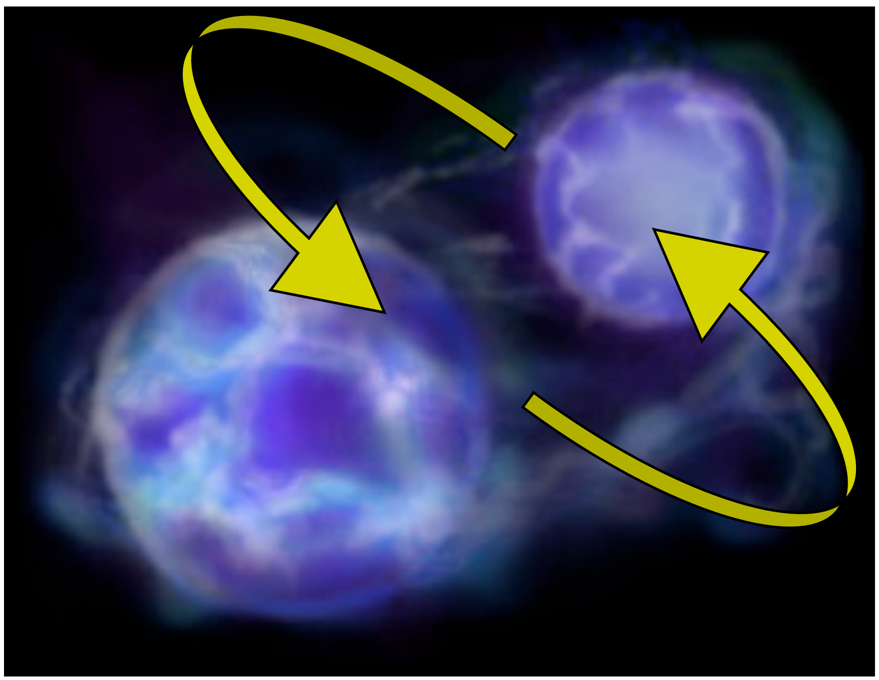


Have we detected a gravitational wave yet?

- No, not yet.
- When will we detect a gravitational wave?
- "Predictions are difficult, especially about the future" (Yogi Berra)
- Nonetheless…
  - Enhanced LIGO
    - 2009-2010
    - Most probable event rate is 1 per 6 years for NS/NS inspirals
  - Advanced LIGO
    - 2015-beyond
    - Rates are much better
- In the meantime, we set upper limits on rates from various sources

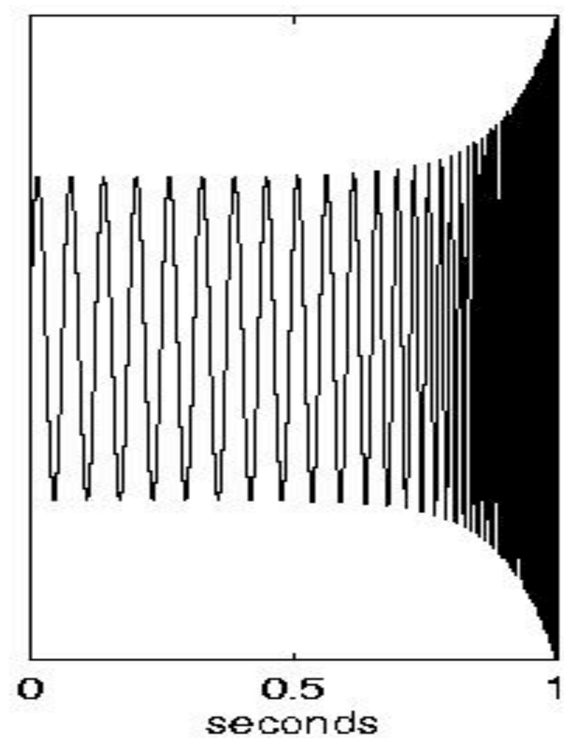
Some recent results from LIGO

Neutron-star binary systems



Credit: Jillian Bornak

Frequency Chirp



Credit:
http://www.srl.caltech.edu/lisa/graphics/master.html

Inspirals

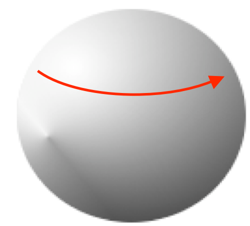
- Nothing to show so far

  - Expected probability with current sensitivity
    ~ few percent / per year

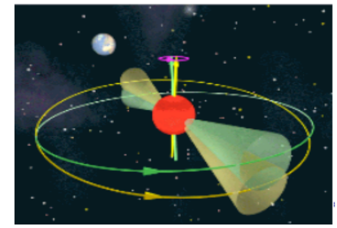
  - Wait for advanced detectors

Status of pulsar GW searches

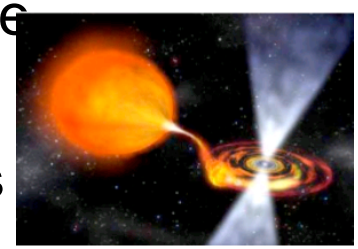
- Rapidly spinning neutron stars provide a potential source of continuous gravitational waves
- To emit gravitational waves they must have some degree of non-axisymmetry
    - Triaxial deformation due to elastic stresses or magnetic fields
    - Free precession about axis
    - Fluid modes e.g. r-modes
- Size of distortions can reveal information about the neutron star equation of state



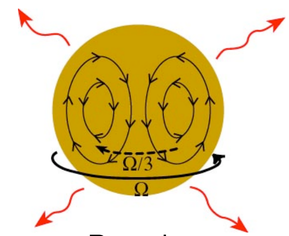
"Mountain" on neutron star



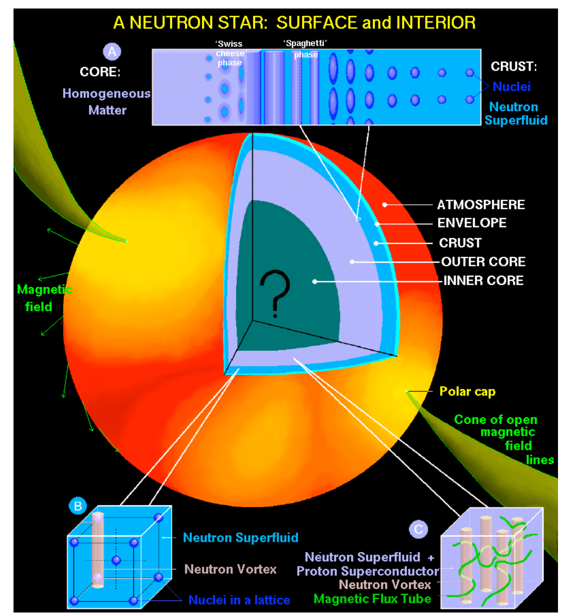
Wobbling neutron star



Accreting neutron star

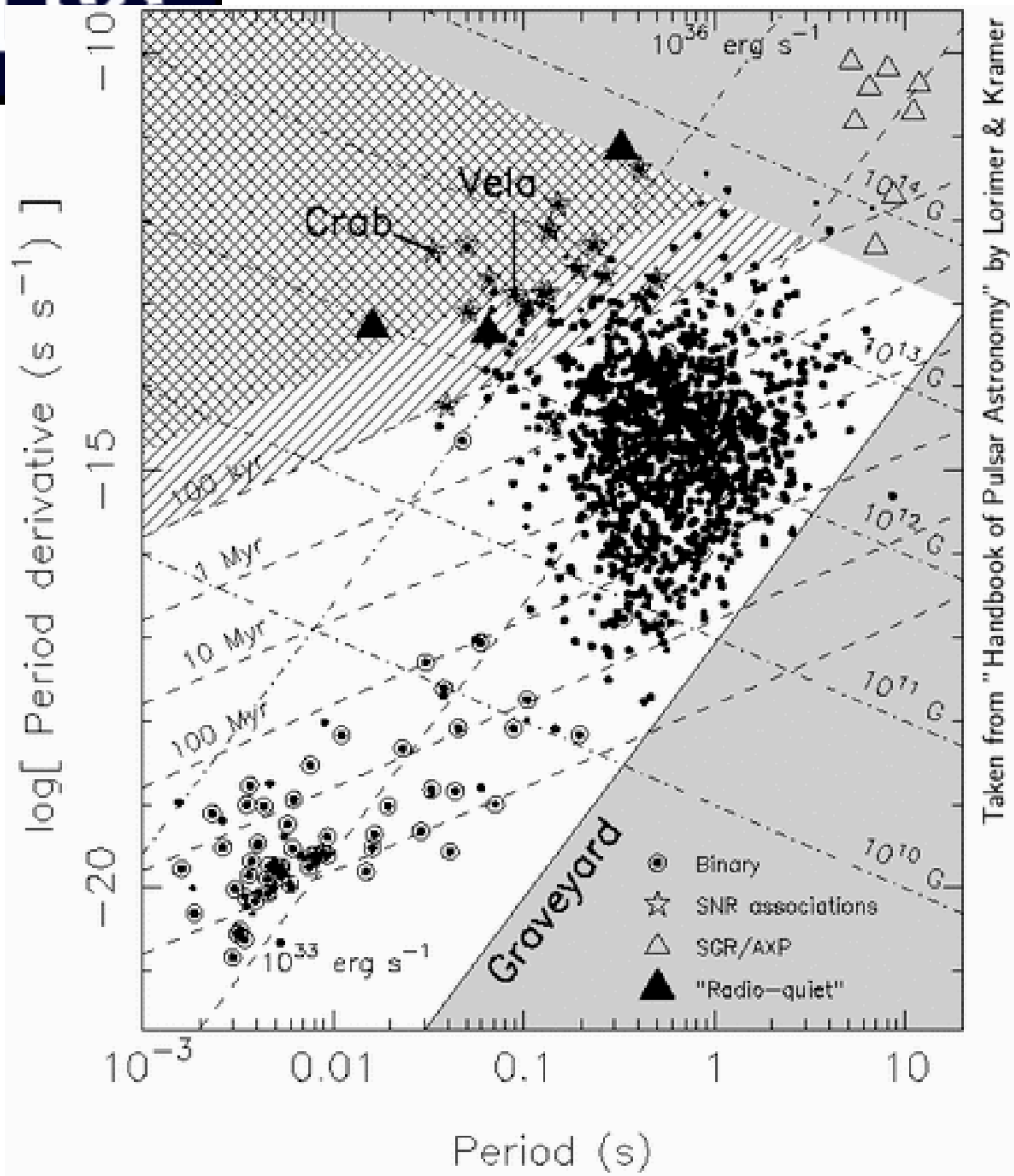


R-modes



www.astroscu.unam.mx/neutrones/NS-Picture/NStar/NStar_IS.gif

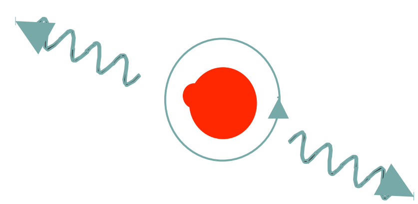
Pulsar Search



Rapidly rotating neutron stars
Emitting radio waves

Many more lurking in the dark

May emit GW if elliptic
or have mountains



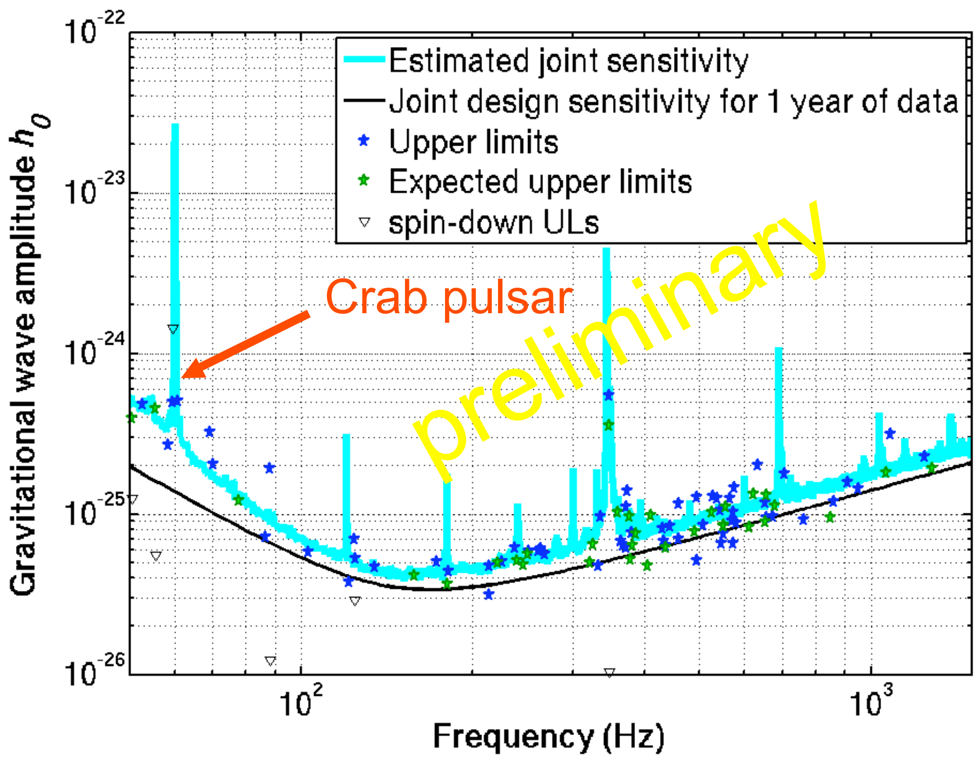
I_{zz}:Principal moment of inertia

ϵ :Equatorial ellipticity

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{\epsilon I_{zz} \nu^2}{r}$$

Searches for Periodic Signals from Known Radio/X-ray Pulsars

- Use demodulation, correcting for motion of detector
  - Doppler frequency shift, amplitude modulation from antenna pattern
- S5 *preliminary* results (using first 13 months of data):
  - 97 Pulsars scanned
  - Placed limits on strain h_0 and equatorial ellipticity ε
  - ► ε limits as low as $\sim 10^{-7}$
  - Crab pulsar: LIGO limit on GW emission is now below upper limit inferred from spindown rate



Beating the Spin Down Upper Limit for the Crab Pulsar

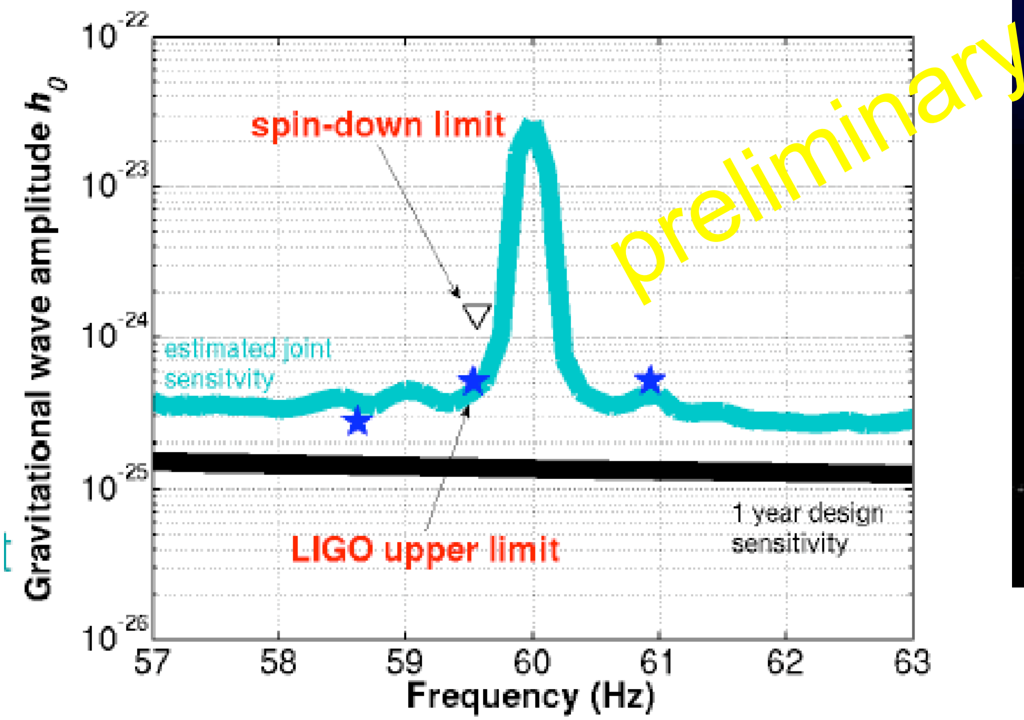
Assume energy dissipation is solely due to GW emission.

$$h_0^{\text{spin down}} = \left(\frac{5}{2} \frac{G I_{zz} \dot{\nu}}{c^3 r^2 \nu} \right)^{\frac{1}{2}} \qquad h_0 < 1.4 \times 10^{-24}$$

Current upper limit from LIGO S5 data (up to Aug. 23 2006)

$$\epsilon < 2.6 \times 10^{-4}, h_0 < 5.0 \times 10^{-25}$$

Beat the spin down limit by a factor of 2.9



Short Duration GRBs

Oct. 6, 2005

Fox, et al., Nature 437, 845 (2005)

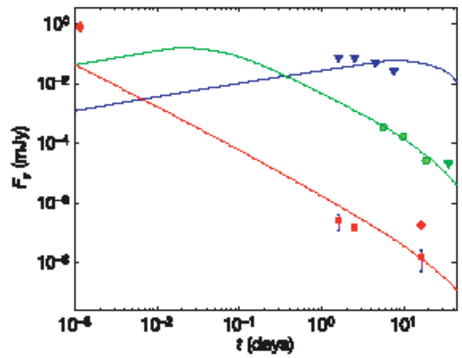


Figure 3 | Observations of the GRB 050709 afterglow and illustrative models. The X-ray (red), optical (green) and radio (blue) data taken from

Gehrels, et al., Nature 437, 851 (2005)

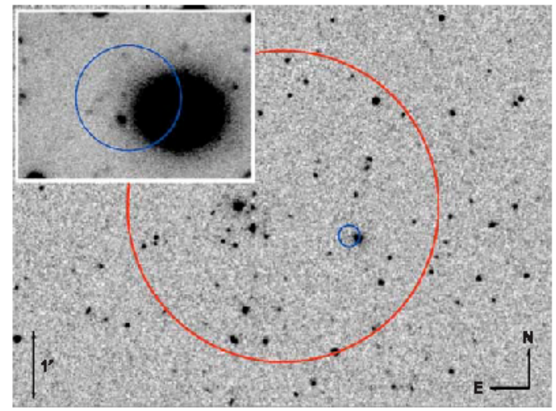


Figure 1 | Optical images of the region of GRB 050509B showing the association with a large elliptical galaxy. The Digitized Sky Survey image.

"There may be more than one origin of short GRBs, but this particular short event has a high probability of being unrelated to star formation and of being caused by a binary merger."

"In all respects, the emerging picture of SHB properties is consistent with an origin in the coalescence events of neutron star–neutron star or neutron star–black hole binary systems."

GRB070201

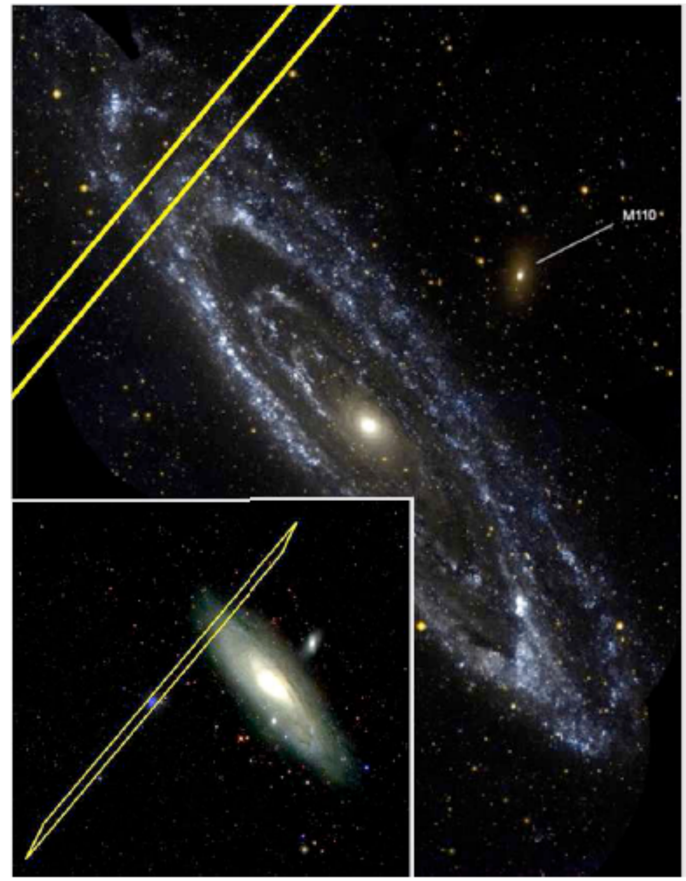
A short (0.5 s) hard gamma-ray burst (Feb. 1st 2007)
Detected by Konus-Wind, INTEGRAL, Swift, MESSENGER

$E_{iso} \sim 10^{45}$ ergs
if at M31 distance
(more similar to SGR energy than GRB energy)

The error box for the source location overlaps with the spiral arms of M31

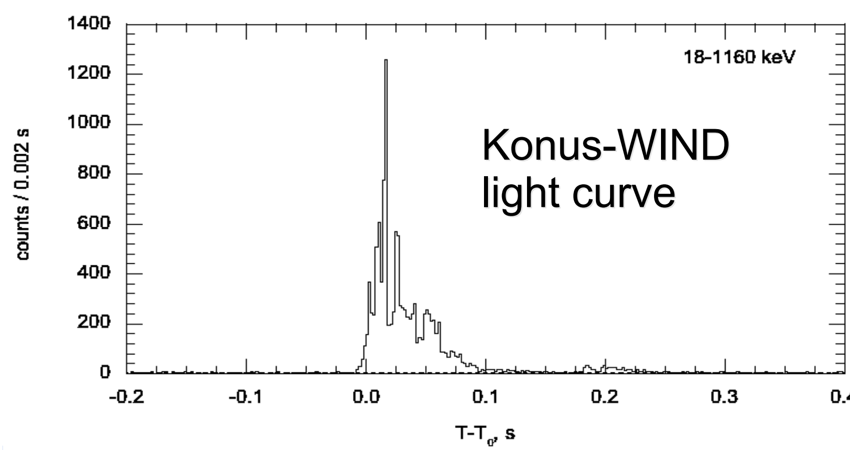
Short GRB progenitors: possibly NS/NS mergers

→ Emit strong gravitational waves



What can we do with this event ?

- In the case of a detection:
  - Confirmation of a progenitor (e.g. coalescing binary system)
  - GW observation could determine the distance to the GRB
- No-detection:
  - Exclude progenitor in mass-distance region
  - With EM measured distance to hypothetical GRB, could exclude binary progenitor of various masses
  - Possible statements on progenitor models
  - Bound the GW energy emitted by a source at M31

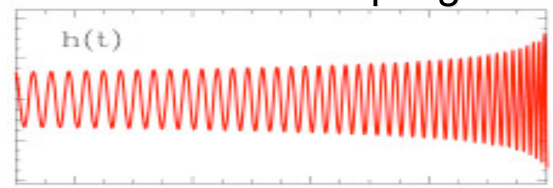


GRB070201, two methods

Search for compact binary inspiral signals

- Matched filtering with Waveform: (Post Newtonian approximation)
- Mass parameters unknown

Chirp signal



$$1\,M_{\odot} < m_1 < 3.0\,M_{\odot} \quad 1.0\,M_{\odot} < m_2\, 40.0\,M_{\odot}$$

No plausible gravitational waves identified

Compact binary progenitor at M31 is excluded at > 99% confidence level
Compact binary progenitor up to 3.5Mpc away is excluded at 90% confidence level

Burst signal search

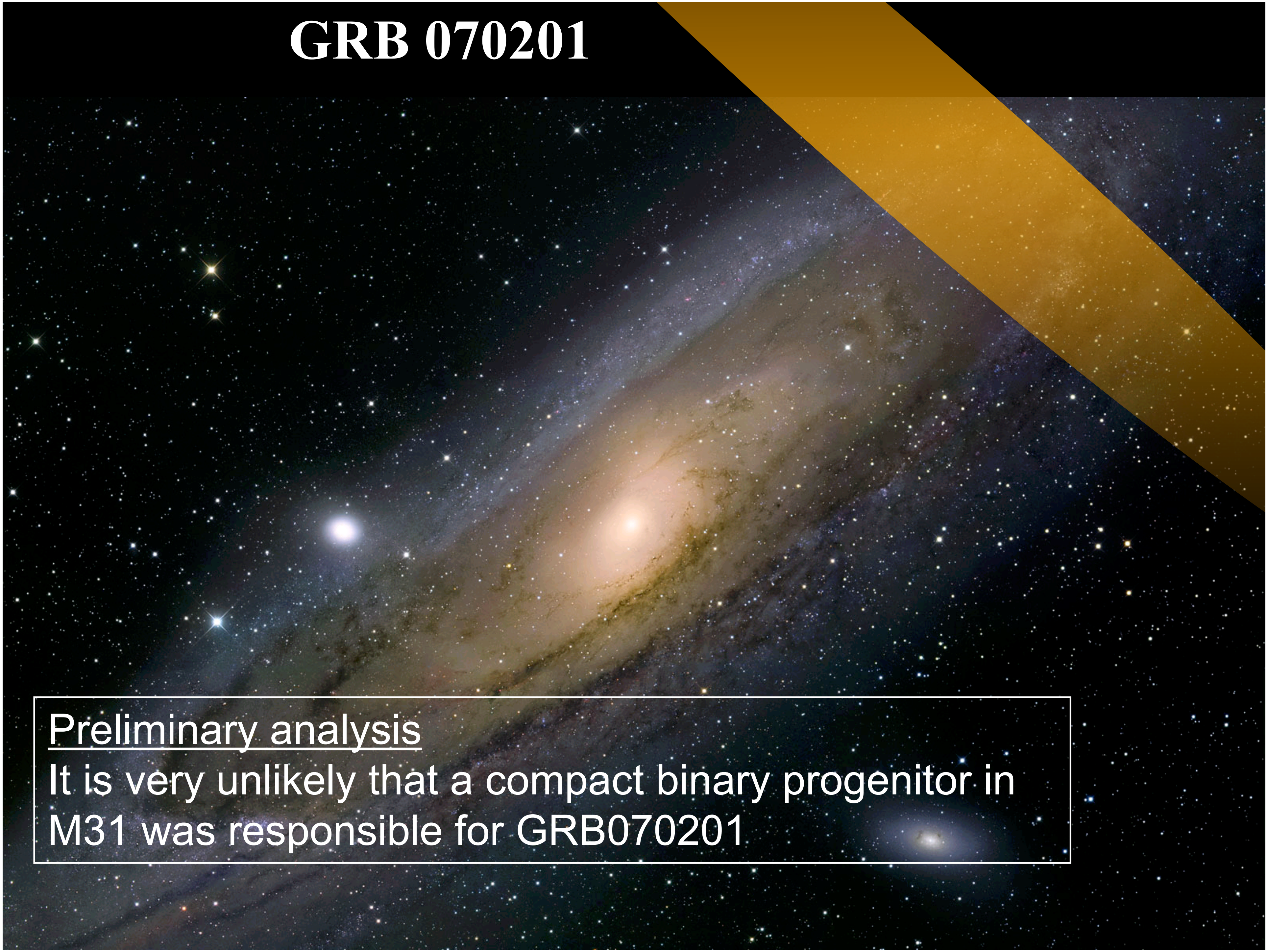
- Wide bandwidth correlation based burst signal search (40 – 2000Hz)
- Upper limit: $h_{RSS}^{90\%} = 1.25 \times 10^{-21}\, 1/\sqrt{\mathrm{Hz}}$ within a ~100ms period peaked at 150Hz
- Corresponding energy:

$$E_{ISO} < 4.4 \times 10^{-4} M_{\odot} c^2 (7.9 \times 10^{50}\,\mathrm{ergs})$$

- assuming the distance of M31

A Joint Search for Gravitational Wave Bursts with AURIGA and LIGO
arXiv:0710.0497v1 [gr-qc]

GRB 070201

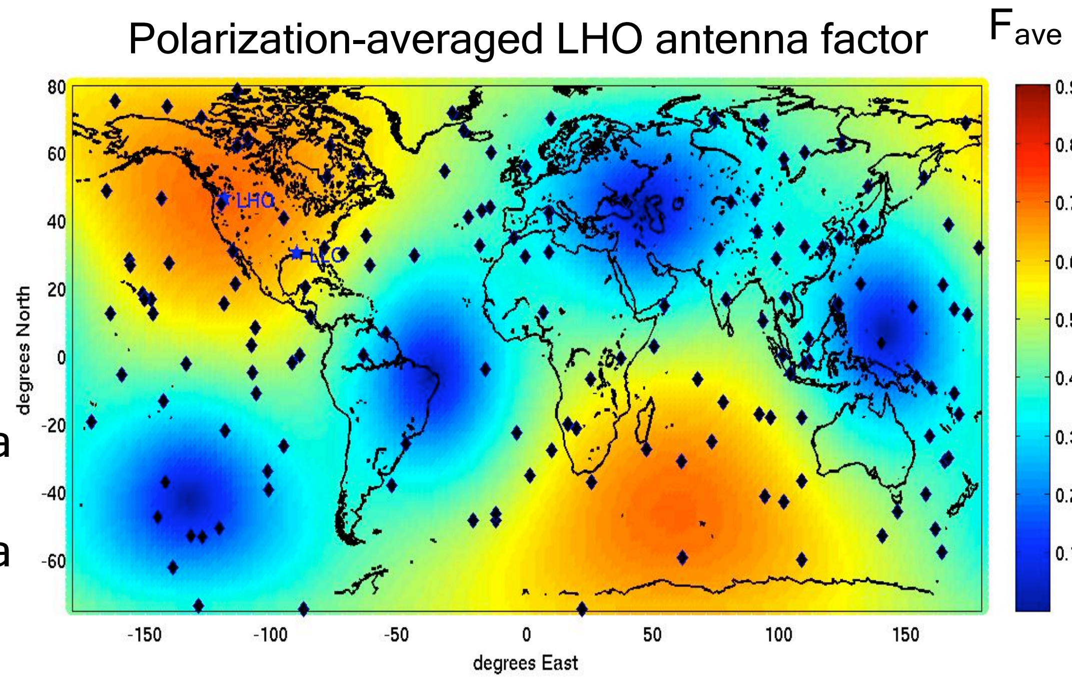


Preliminary analysis

It is very unlikely that a compact binary progenitor in M31 was responsible for GRB070201

GRB triggers from GCN for the LIGO S5 run

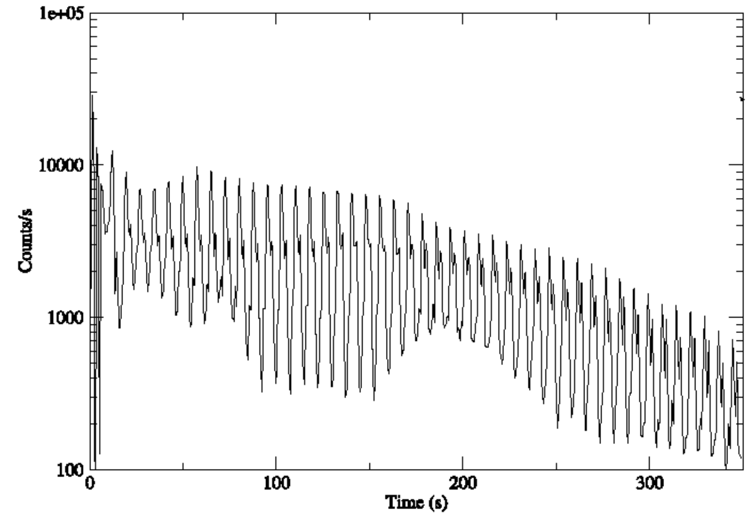
- 157 GRB triggers from November 4, 2005 to March 31, 2007
  - ~70% with double-IFO coincidence LIGO data
  - ~40% with triple-IFO coincidence LIGO data
  - ~25% with redshift
  - ~10% short-duration GRBs
  - all but two have position information



LIGO sensitivity depends on GRB position

SGR1806-20 Hyper Flare

Soft Gamma-ray Repeater 1806-20: Hyper Flare on December 24 2004



T.Strohmayer and A.Watts, *ApJ* **653** L594 (2006)

- Quasi Periodic Oscillation(QPO) observed in X-ray tail
- Possible connection with excitations of neutron star's mechanical oscillation modes

LIGO status at the moment:
Post-S3, pre-S4
Only Hanford 4km was in operation

Search method:
Look for excess power at the event time in the QPO frequency range (several frequencies, time intervals)

No significant deviation from the background noise found.
The best upper limit: $4.5\times10^{-22}\,1/\sqrt{\mathrm{Hz}}$
(92.5Hz QPO observed from 150-260sec after the start of the flare)

Corresponding GW energy:
(assuming isotropic emission)

$$7.7\times10^{46}\,\mathrm{erg}=4.3\times10^{-8}\,M_{\odot}c^{2}$$

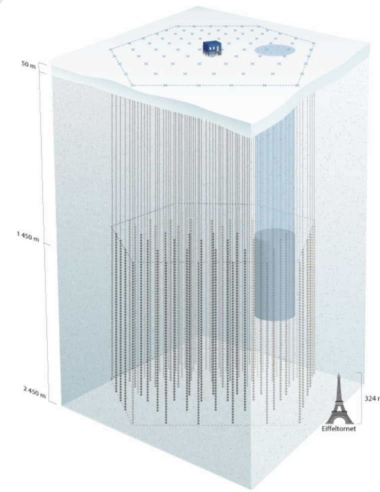
Comparable to the electromagnetically radiated energy

The best GW upper limit on this type of source.
First multiple-frequency asteroseismology using a GW detector

Details published in B. Abbott et al., *Phys. Rev. D* **76**, 062003 (2007)

Example of Study of Coincidence Analysis with IceCube

Burst GW search: Overwhelming number of noise events
Can be reduced with coincidences
IceCube: a neutrino detector at the south pole

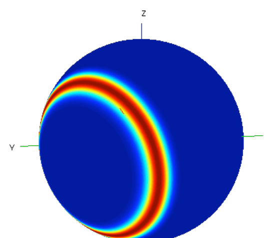


Search for astrophysical events emitting GW and high-energy neutrino bursts simultaneously.

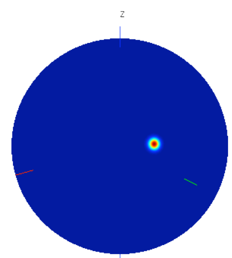
Coincident analysis between independent detectors
→ Reject most background events

Two-stage coincidence

- Event time coincidence
(within a certain time window)
- Spatial coincidence
(evaluated by an unbinned maximum likelihood method)

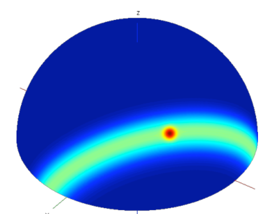


LIGO event



IceCube event

→



Overlap event

Monte Carlo simulations

Simulated LIGO S5 and IceCube 9-string events

False Alarm Rate [events/year] = $\frac{1}{435}\left(\frac{p}{1\%}\right)\left(\frac{T_w}{1\,\mathrm{sec}}\right)$

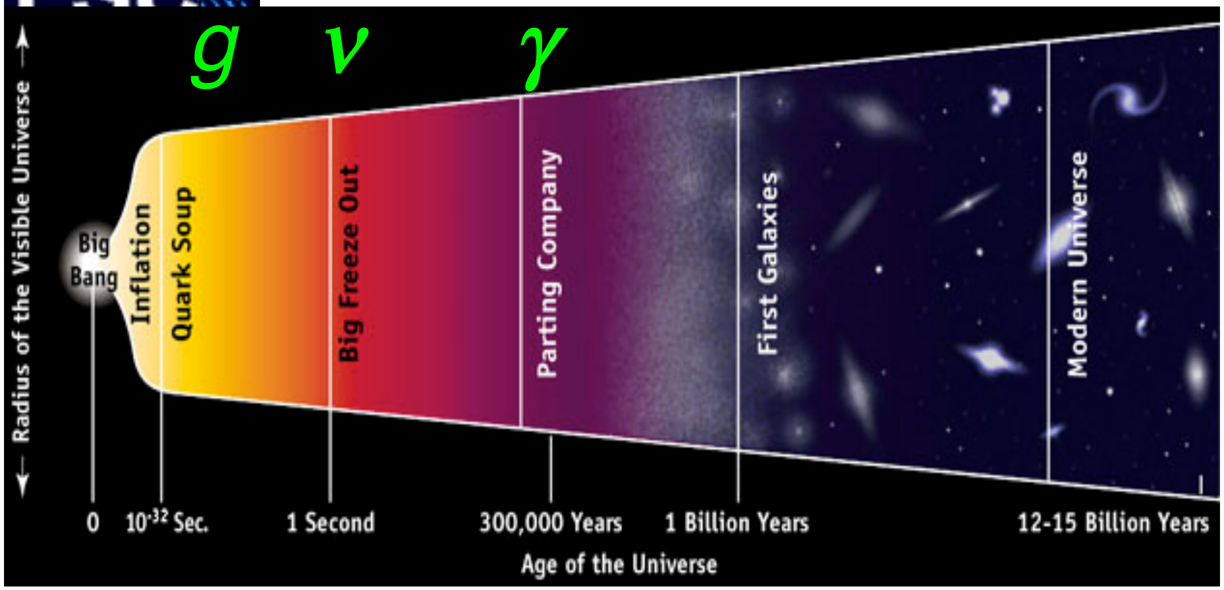
T_w : Time Window
p : p-value

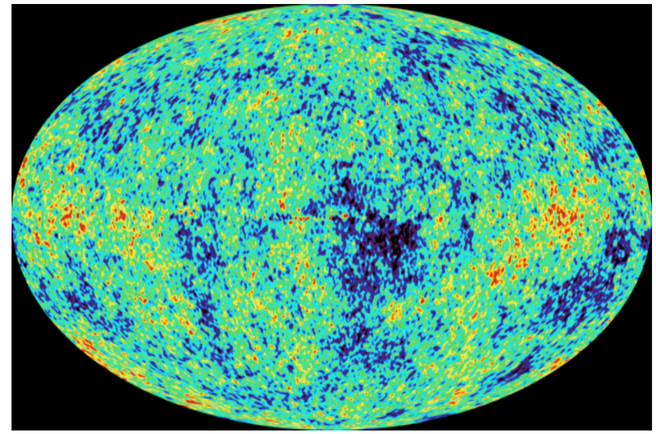
Better than the SNEWS standard

We can relax the event trigger threshold → better sensitivity

Note: Above are not real data analysis results. This is a proposal of a method.

Gravitational waves from a stochastic background





Analog from cosmic microwave background -- WMAP 2003

GWs can probe the very early universe

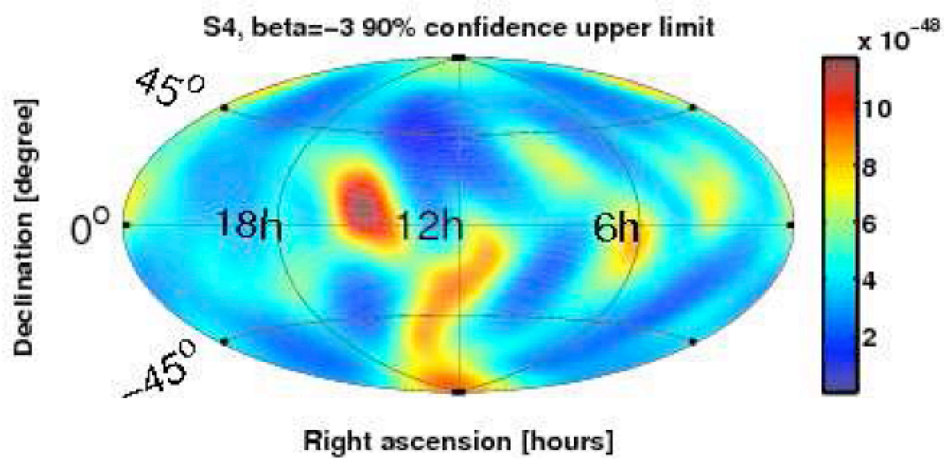
- Detect by cross-correlating interferometer outputs in pairs: Hanford - Livingston, Hanford - Hanford
- Good sensitivity requires:
  - $\lambda_{GW} \geq 2D$ (detector baseline)
  - $f \leq 40\ Hz$ for LIGO pair over 3000 km baseline
- Initial LIGO limiting sensitivity (1 year search): $\Omega_{GW} < 10^{-6}$

$$\int_0^\infty d\ln f\,\Omega_{gw}(f) = \frac{\rho_{gw}}{\rho_{critical}}$$

The integral of $[1/f \cdot \Omega_{GW}(f)]$ over all frequencies corresponds to the fractional energy density in gravitational waves in the Universe

Searches for a Stochastic Signal

- Weak, random gravitational waves could be bathing the Earth
  - Left over from the early universe, analogous to CMBR ;
    or from many overlapping signals from astrophysical objects
  - Assume spectrum is constant in time
- Search by cross-correlating data streams
- S4 result *[A.p. J. 659, **918 (2007)**]*
  - Searched for isotropic stochastic signal with power-law spectrum
  - For flat spectrum, set upper limit on energy density in gravitational waves:
  - $\Omega_0 < 6.5 \times 10^{-5}$
- Or look for anisotropic signal:
  [A.p.J., 659:918–930 (2007)]
- S5 analysis in progress

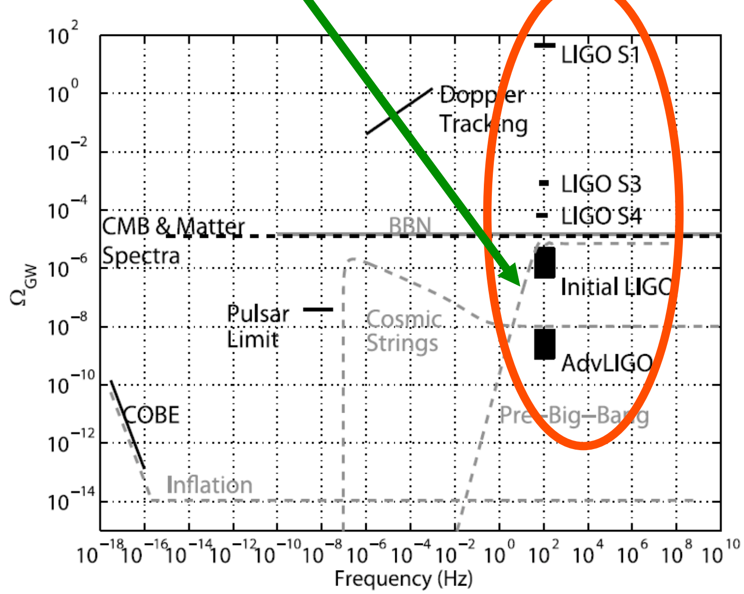


S3, S4 results

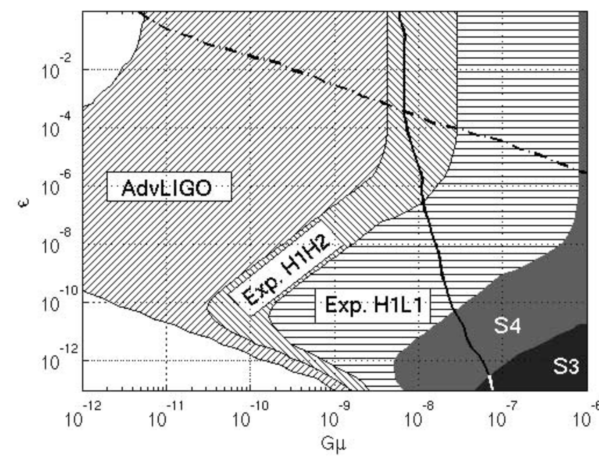
B. Abbott *et al.*, *Astrophys. J.* **659**:918-930, 2007

Comparison with other experiments and theoretical models

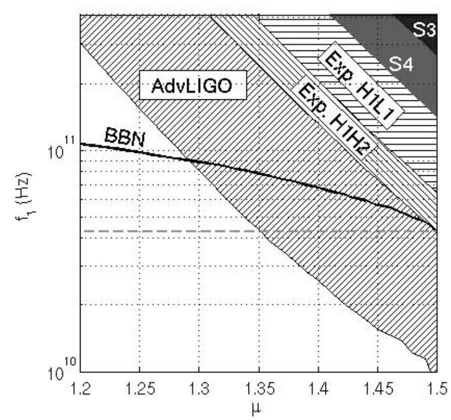
S5 data shall beat the big bang nucleosynthesis bound.



Cosmic string model excluded parameter space

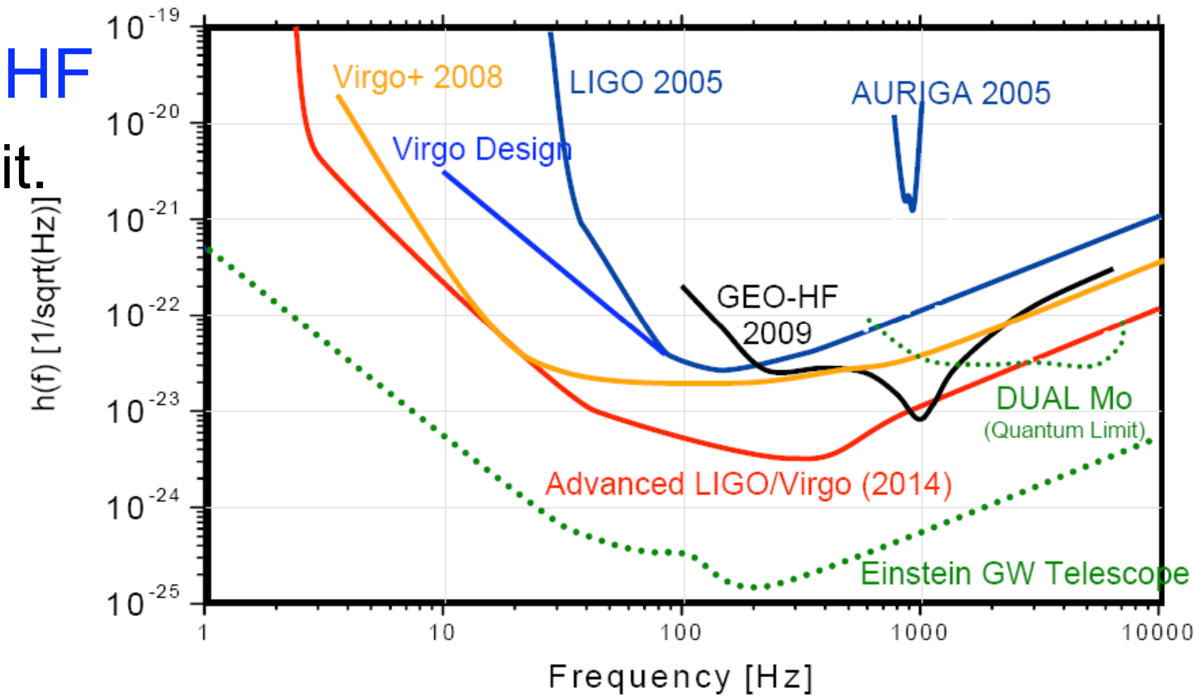


pre-big bang excluded parameter space



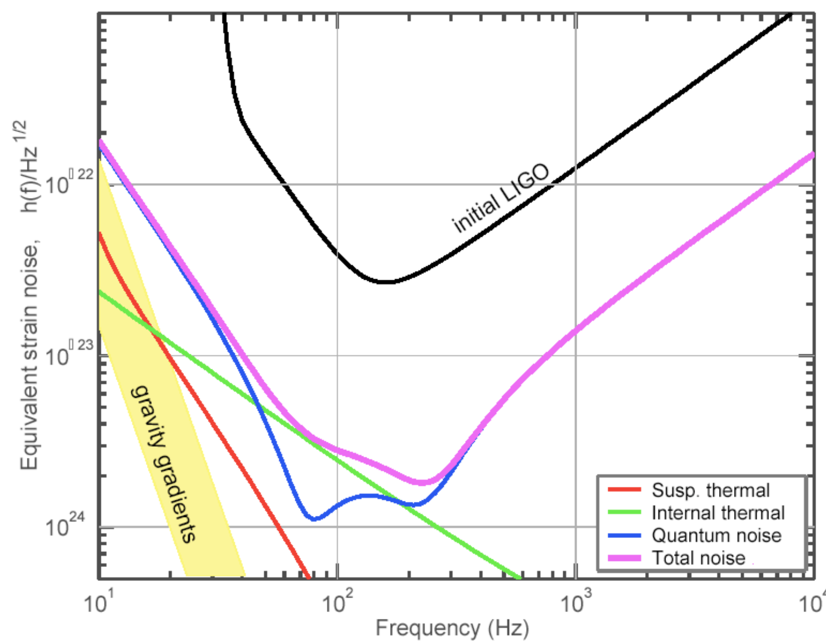
Where do we go from here?

- Advanced Virgo/LIGO sensitivity limited by:
  - thermal noise below
    - 1 MW light to match thermal noise with optical resolution
  - radiation pressure at LF
  - shot noise at HF
    - Quantum limit.



Where do we go from here?

- Little margin to reduce Thermal Noise
- Longer length to increase strain sensitivity
  - 30 km proposed for Einstein GW Telescope
- Heavier mirrors to widen the Quantum limit "V"



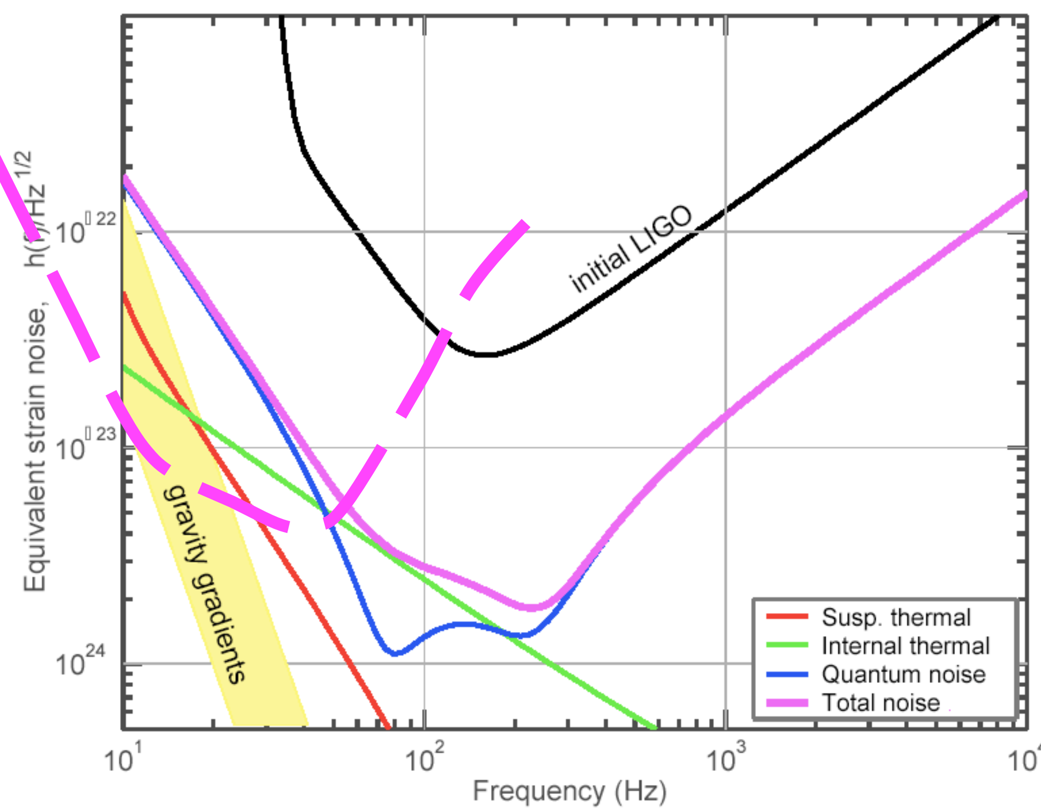
Where do we go from here?

- Bigger black holes generate stronger signals
- Visible at larger distances
- Bigger Black holes merge at lower Frequency than Advanced Virgo/LIGO sensitivity band
  - Basically the maximum frequency is limited by speed of light orbit around diameter of event horizon

Where do we go from here?

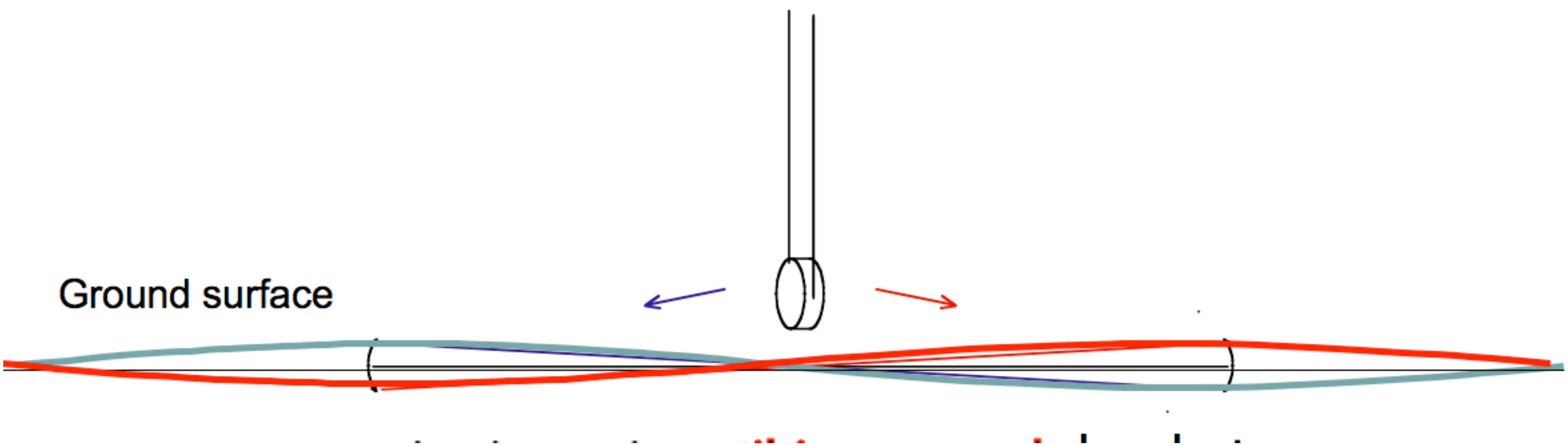
- Multiple parallel interferometers to widen the sensitivity band
- Lower power in the interferometer lowers the Radiation Pressure wall

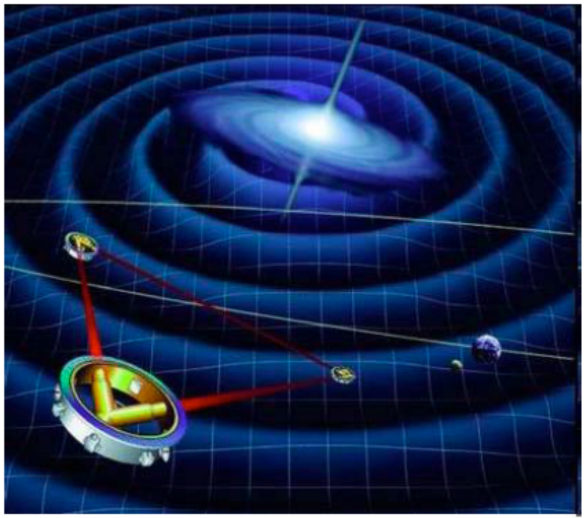
- Fluctuations of verticali of g at low frequency on Earth's surface overwhelm GW signal
  - Newtonian Noise/ Gravity Gradient



Causes of NN on the surface

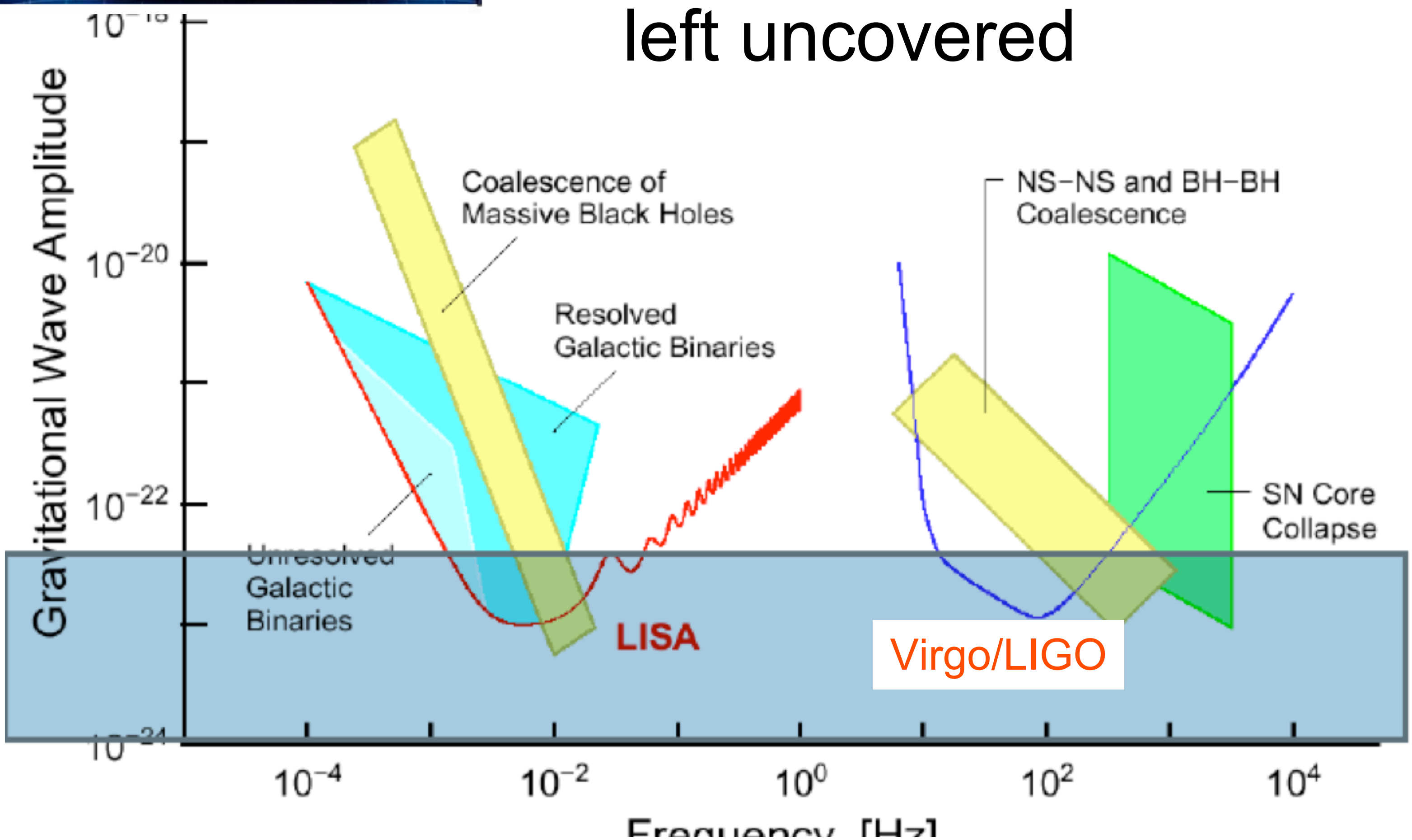
- The dominant term of NN is the rock-to-air interface movement





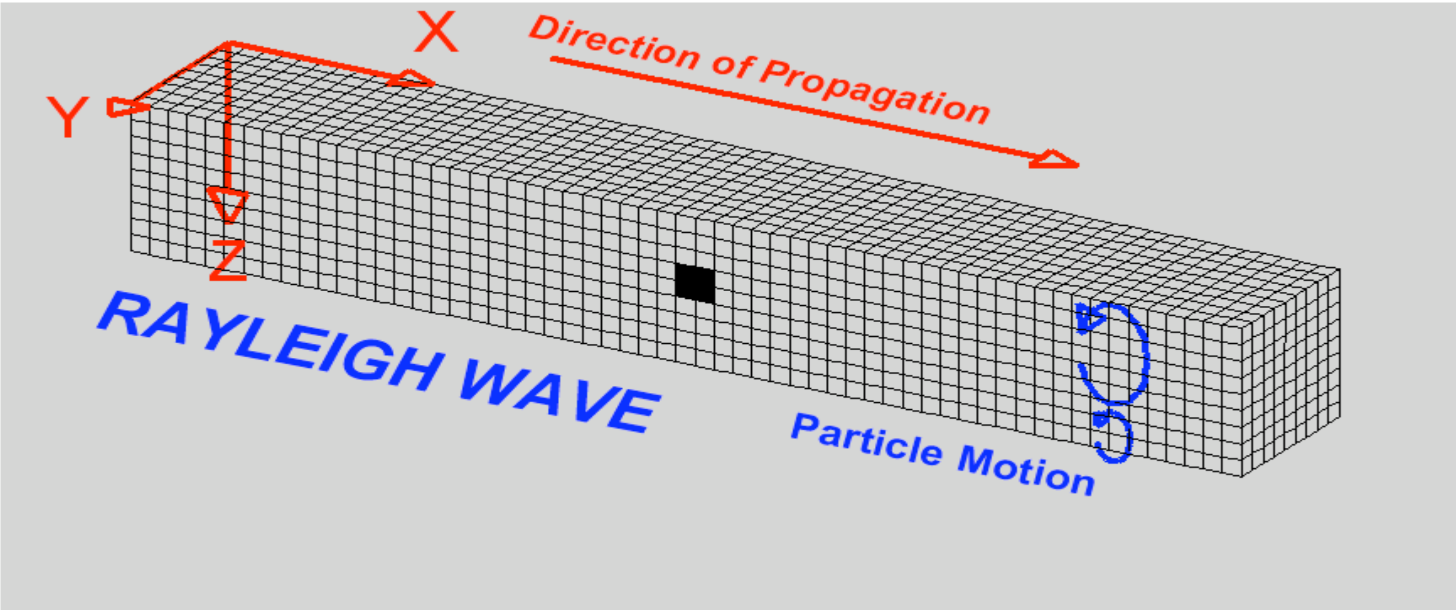
Going to space?

- Too much frequency band left uncovered

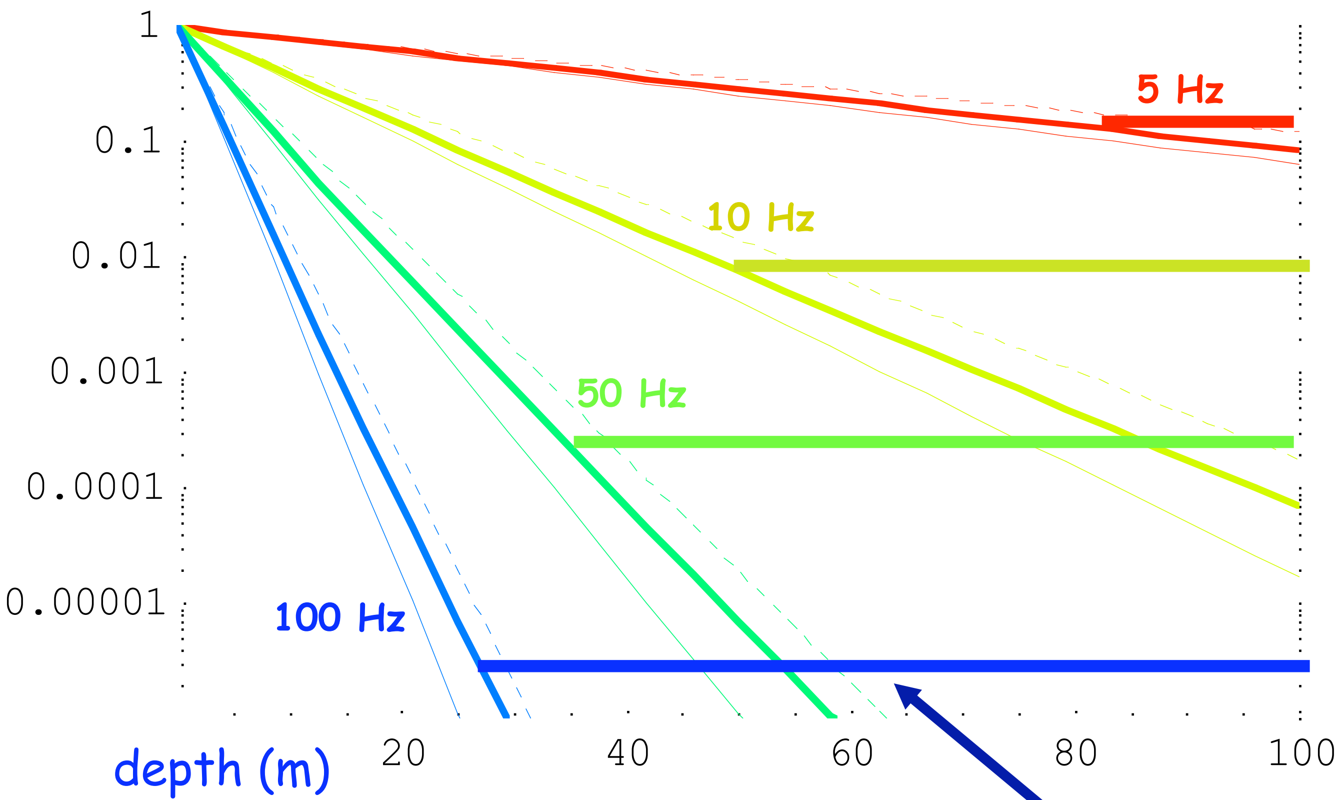


Going underground: Newtonian noise reduction

- Surface waves are probably the most important excitations for GGN
  - A simple fact: surface waves die off exponentially with depth



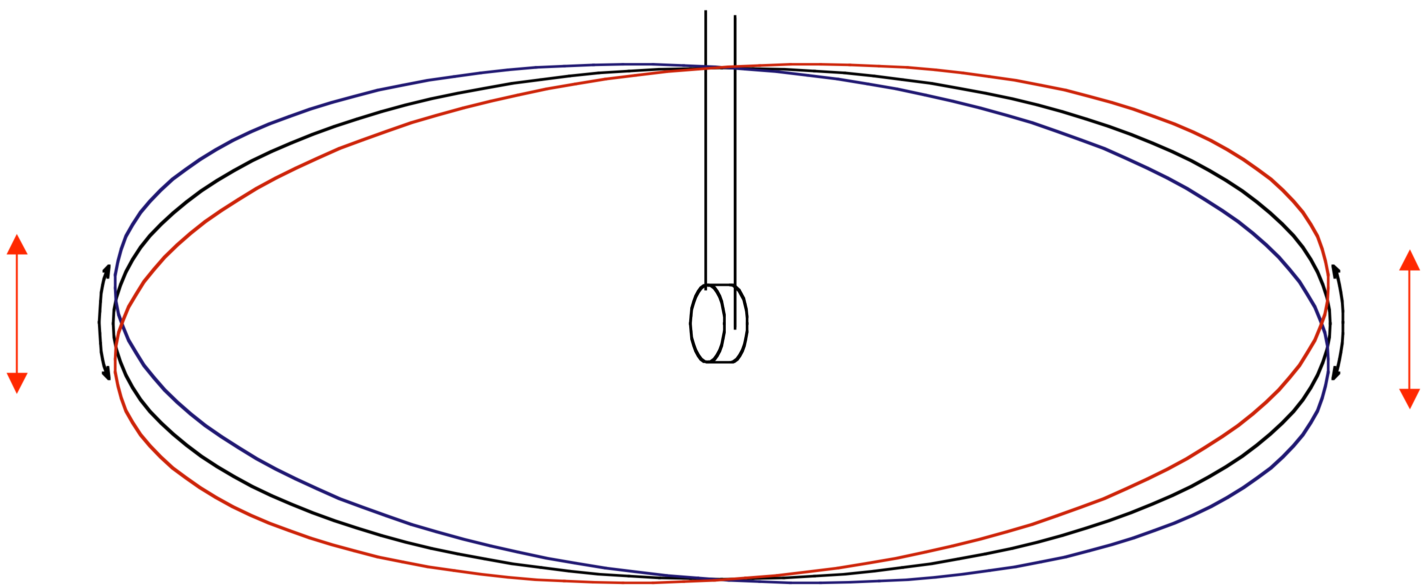
Newtonian Noise vs. depth
(uniform density/stiffness approx.)



Volume waves contributions will not share this fast decay

NN reduction

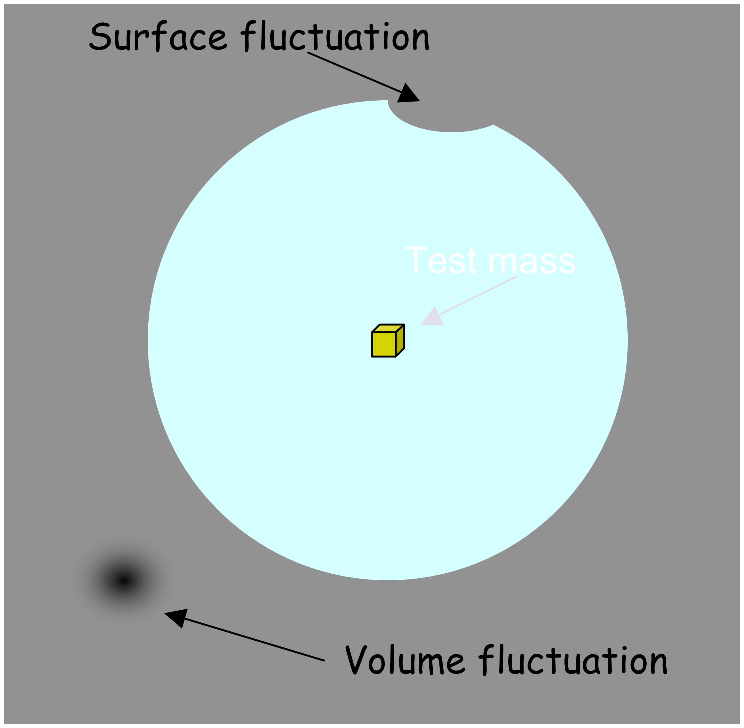
- A test mass placed at the center of a spherical Cavern is insensitive to the effects of ground tilting



a tilting symmetrical cavern leads to
NO fluctuating attraction force

A rough model for an underground cavity

$$\vec{u}_{l,m} = \vec{\nabla}\xi_{l,m} + \vec{\nabla} \times (\vec{x} \times \vec{\nabla})\eta_{l,m} + (\vec{x} \times \vec{\nabla})\tau_{l,m}$$



Bulk contribution to GGN:

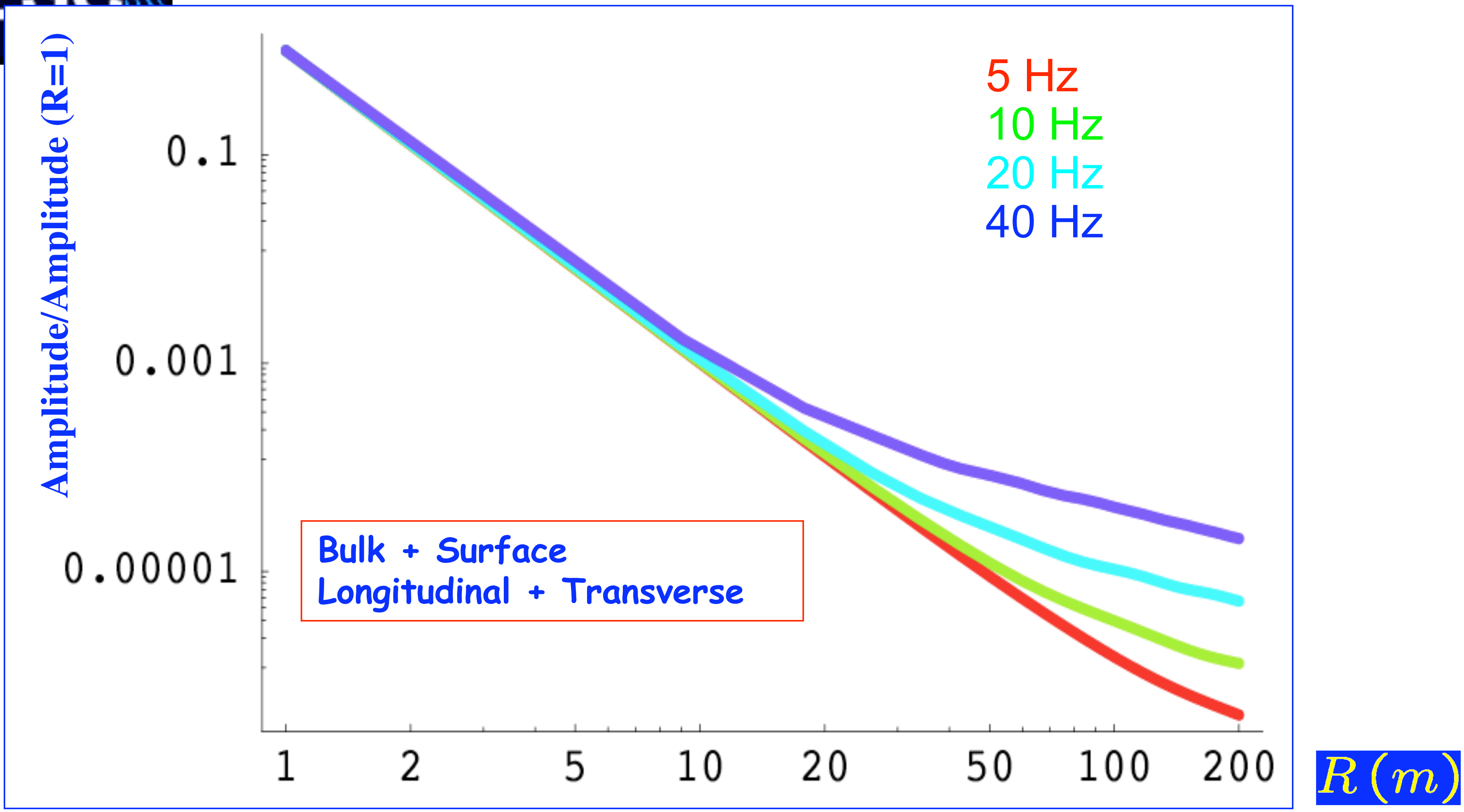
$$\vec{a}_{l,m} = -G\rho \int \vec{\nabla} \cdot \vec{u}_{l,m} \frac{\vec{r}}{r^3} dV$$

Surface contribution to GGN:

$$\vec{a}_{l,m} = -G\rho \int \vec{R} \cdot \vec{u}_{l,m} \frac{\vec{R}}{R^2} d\Omega$$

- Only "dipole" contribution $\sim Y_{1m}(\theta, \phi)$ to bulk GGN (cavity displacements)
- Both transverse & longitudinal contributions to surface GGN
- Toroidal modes: transverse, no surface motion, no Newtonian

R dependence: final result



Good reduction with a reasonable cavity's size.

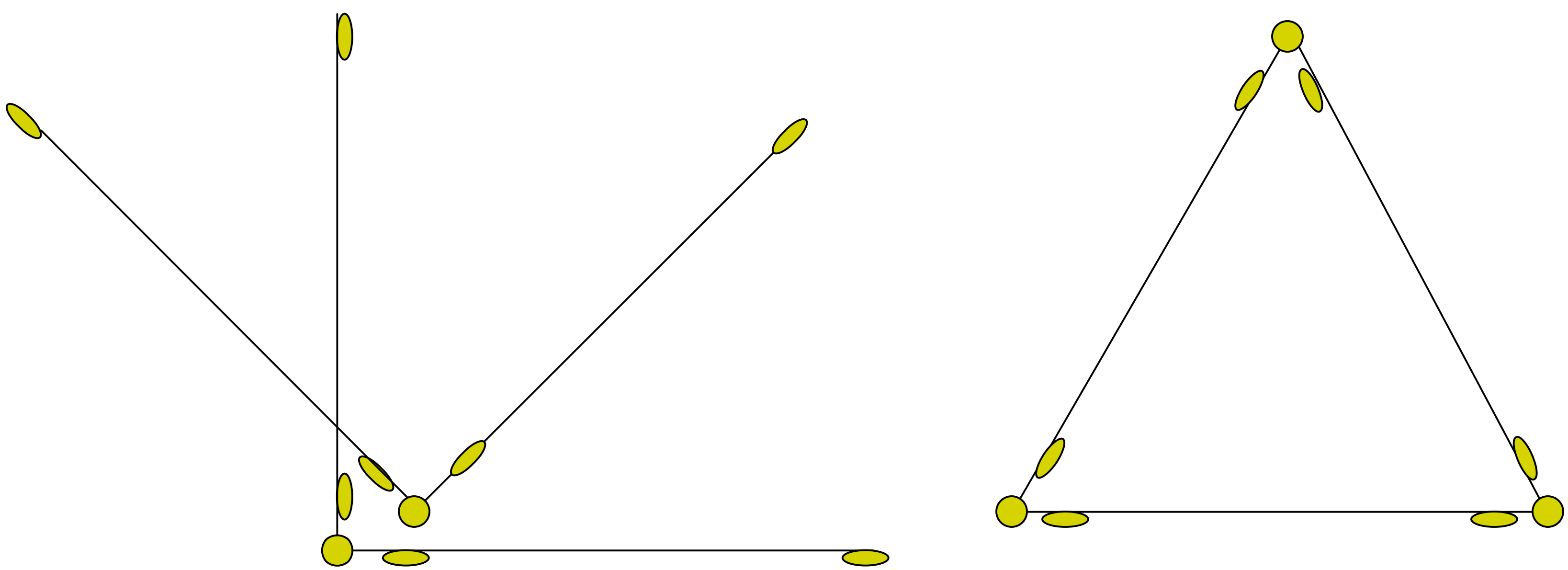
Low frequency perspectives

- Going underground (100<1000m) one can explore GW at lower frequencies (~1 Hz)

- At lower frequency lower optical power requirements

- Possible use of cryogenics to reduce thermal noise

Crossed Interferometers or triangular interferometers to cover both polarizations



The Gravitational Wave Universe

?

Stay tuned…

Acknowledgments

- Members of the LIGO Scientific Collaboration
- National Science Foundation

More Information

- http://www.ligo.caltech.edu; www.ligo.org;

http://www.physics2005.org/events/einsteinathome/index.html

References

- Web of Science, search under Abbott et al., or LIGO SCI COLLABORATION