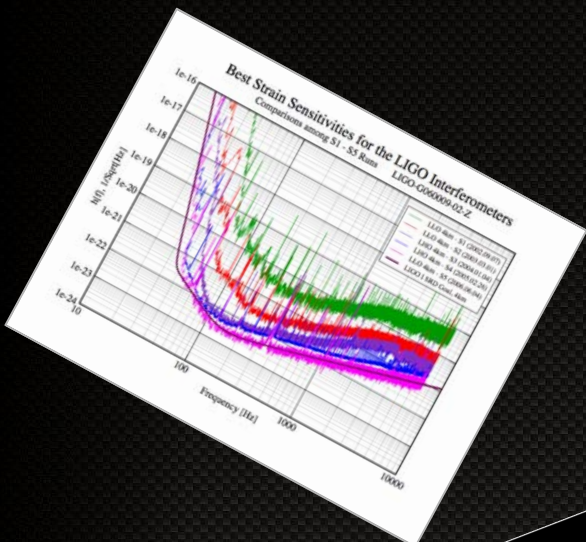
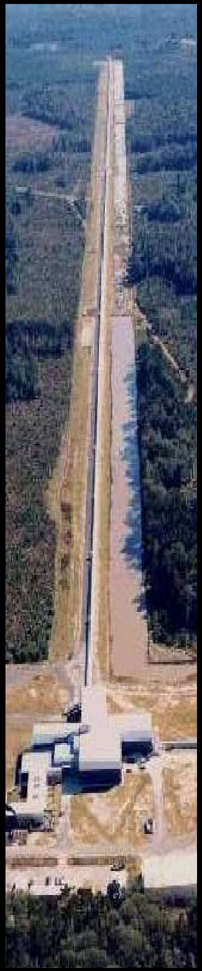
Astrophysics Results to Future Measurements with Gravitational-wave Observatories



Szabolcs Márka
for the LIGO Scientific Collaboration

PennState, University Park, PA, 2008

Overview



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2. What are we searching for ?
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   SGRs? GRBs? Pulsars? Cosmic background?
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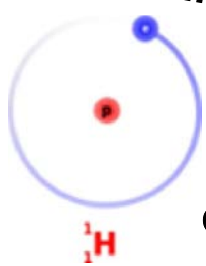
Gravitational waves can carry unique information about black holes, neutron stars, supernovae, the early evolution of the universe, and gravity itself…

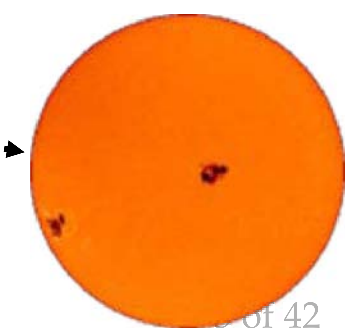
However, they are either extremely weak or extremely rare…

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

0.000000000000000000001



Changes by the ~ diameter of a hydrogen atom !

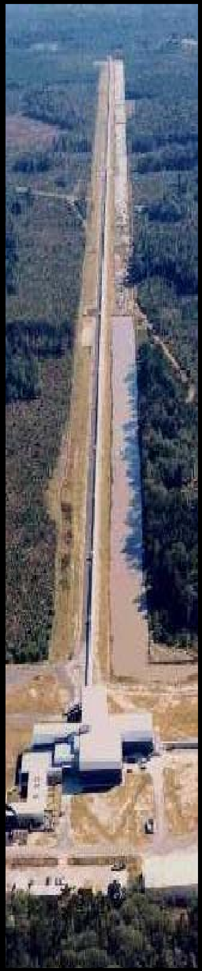


Some of the Ultimate Goals for the Observation of GWs

- **Tests of Relativity**
  - Wave propagation speed (delays in arrival time of bursts)
  - Characterization of the radiation field (polarization of radiation of CW sources)
  - Detailed tests of General Relativity (chirp waveforms)
  - Black holes & strong-field gravity (merger, ringdown of excited BH)

- **Gravitational Wave Astronomy (observation, populations, properties):**
  - Compact binary inspirals
  - Gravitational waves and gamma ray burst associations
  - Black hole formation
  - Supernovae
  - Newly formed neutron stars - spin down in the first year
  - Pulsars and rapidly rotating neutron stars
  - Stochastic background

Overview



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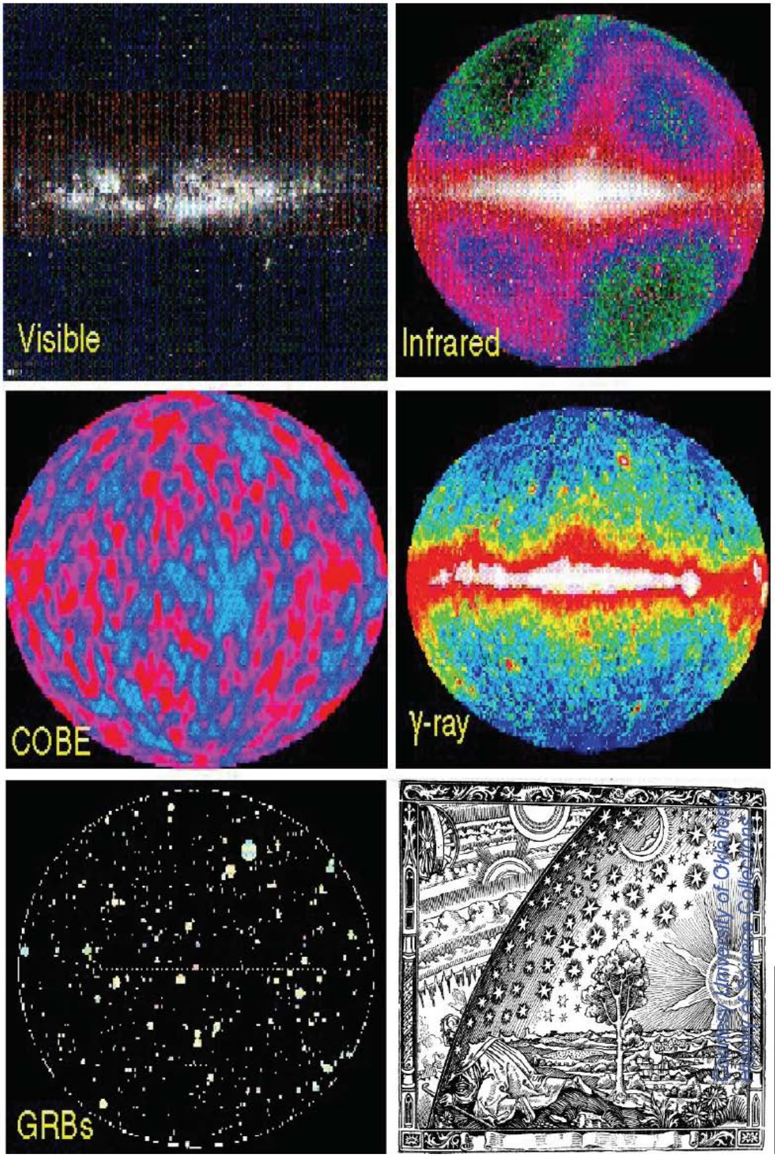
New Window on the Universe

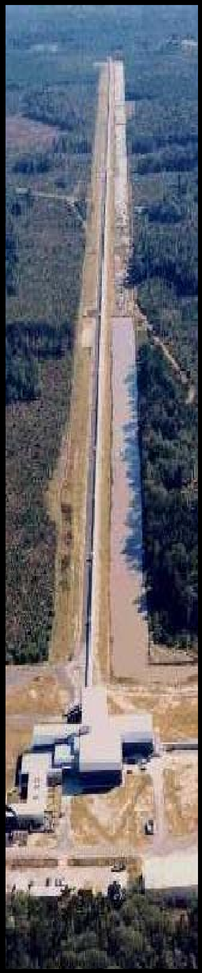


Foreseen sources:

- **Supernovae / GRBs:** *"bursts"*
  - » burst like signals
  - » coincidence with electromagnetic or neutrino detections
- **Compact binary inspiral:** *"chirps"*
  - » Waveforms are described
  - » search technique: matched templates
- **Pulsars:** *"periodic"*
  - » search for observed neutron stars
  - » all sky search (computing challenge)
- **Cosmological Signals** *"stochastic"*
  - » Shows up as correlated noise in different detectors

POSSIBILITY FOR THE UNEXPECTED IS VERY REAL!

Overview



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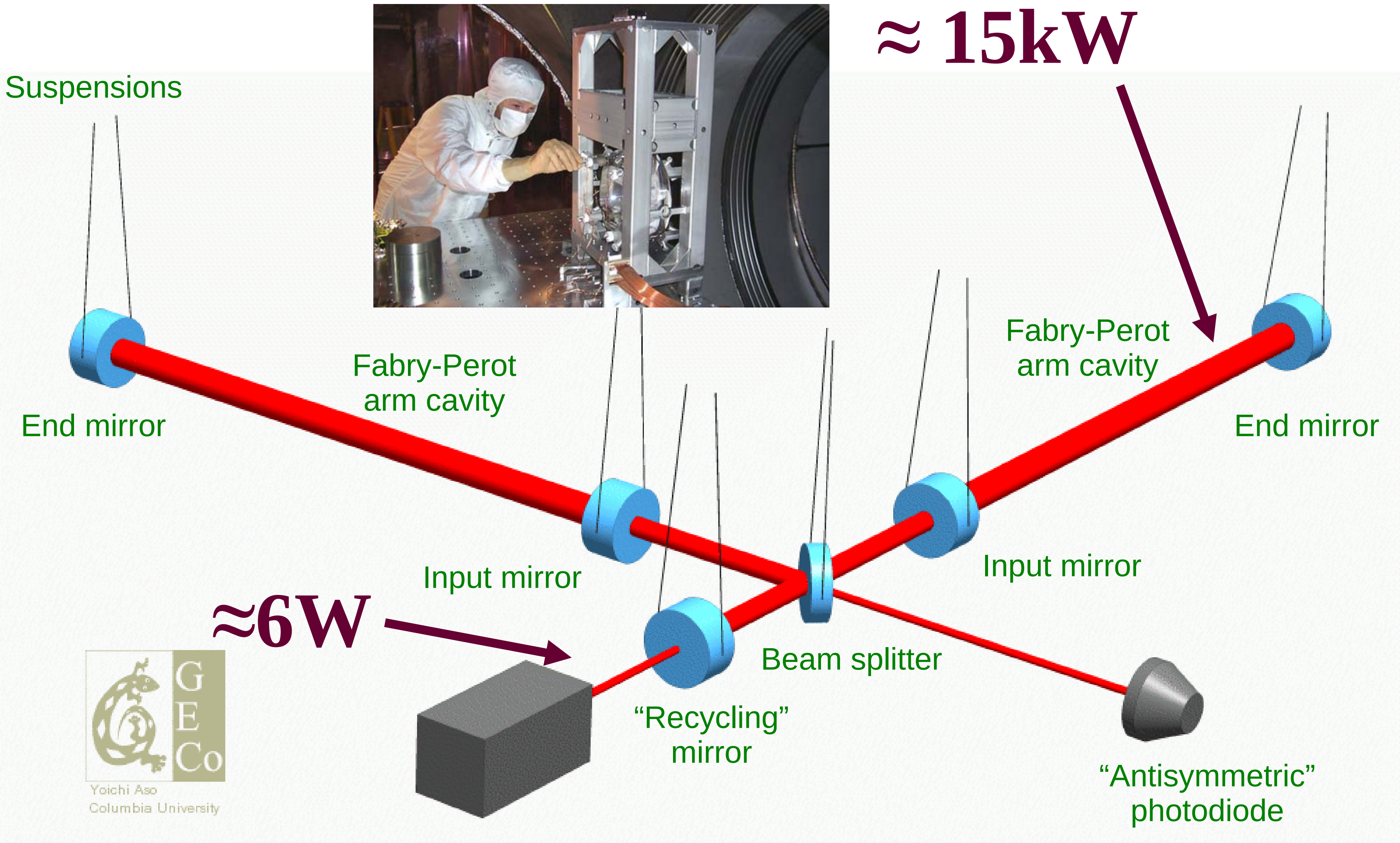
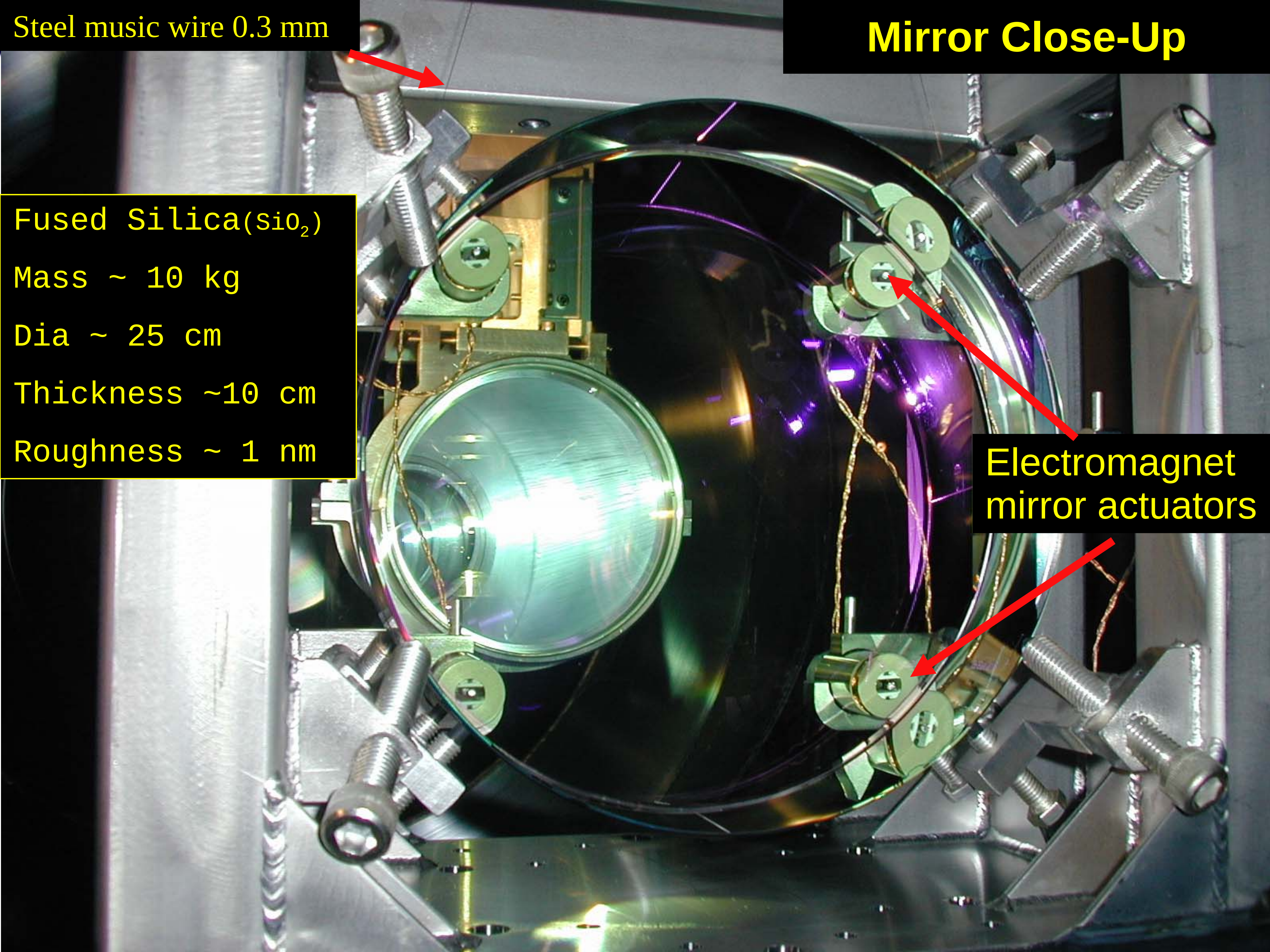
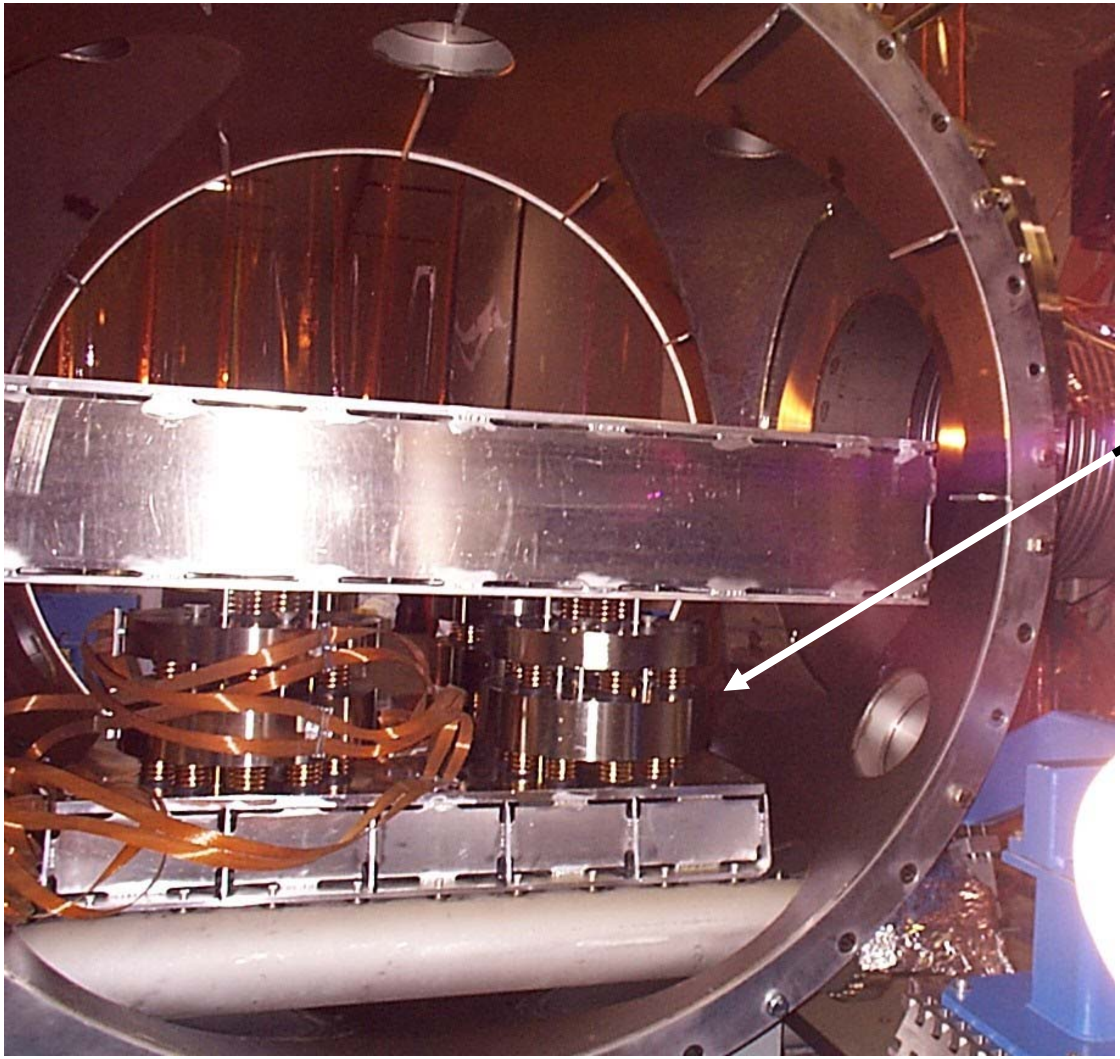
Optical Layout (not to scale)




Steel music wire 0.3 mm
Mirror Close-Up
Fused Silica(SiO_2)
Mass ~ 10 kg
Dia ~ 25 cm
Thickness ~10 cm
Roughness ~ 1 nm
Electromagnet mirror actuators

A Mirror *in situ*

Vibration Isolation



Optical tables are supported on "stacks" of weights & damped springs

Wire suspension used for mirrors provides additional isolation

Active isolation now being added at Livingston

Vacuum System

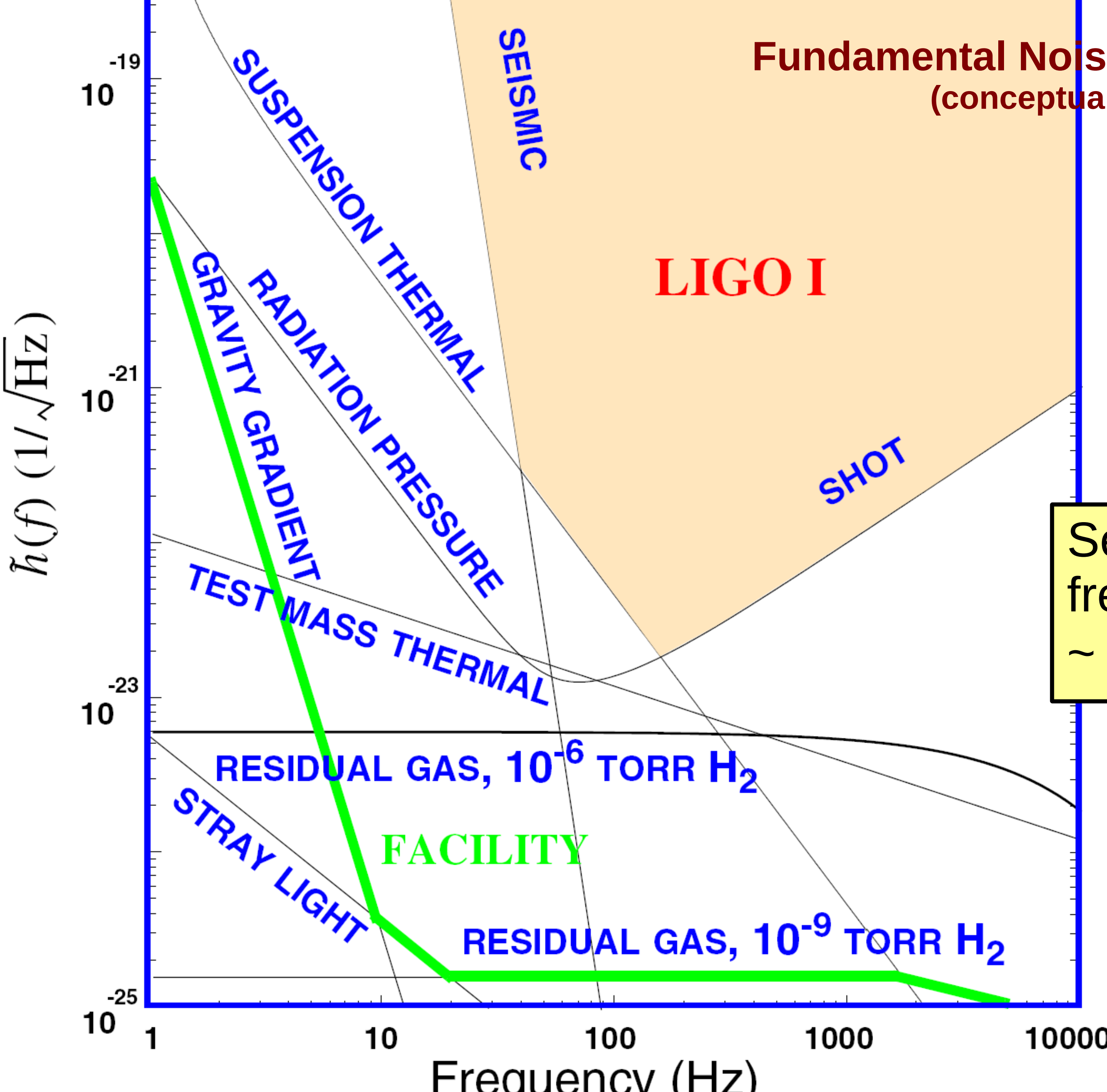
LIGO Observatories

2 km

4 km

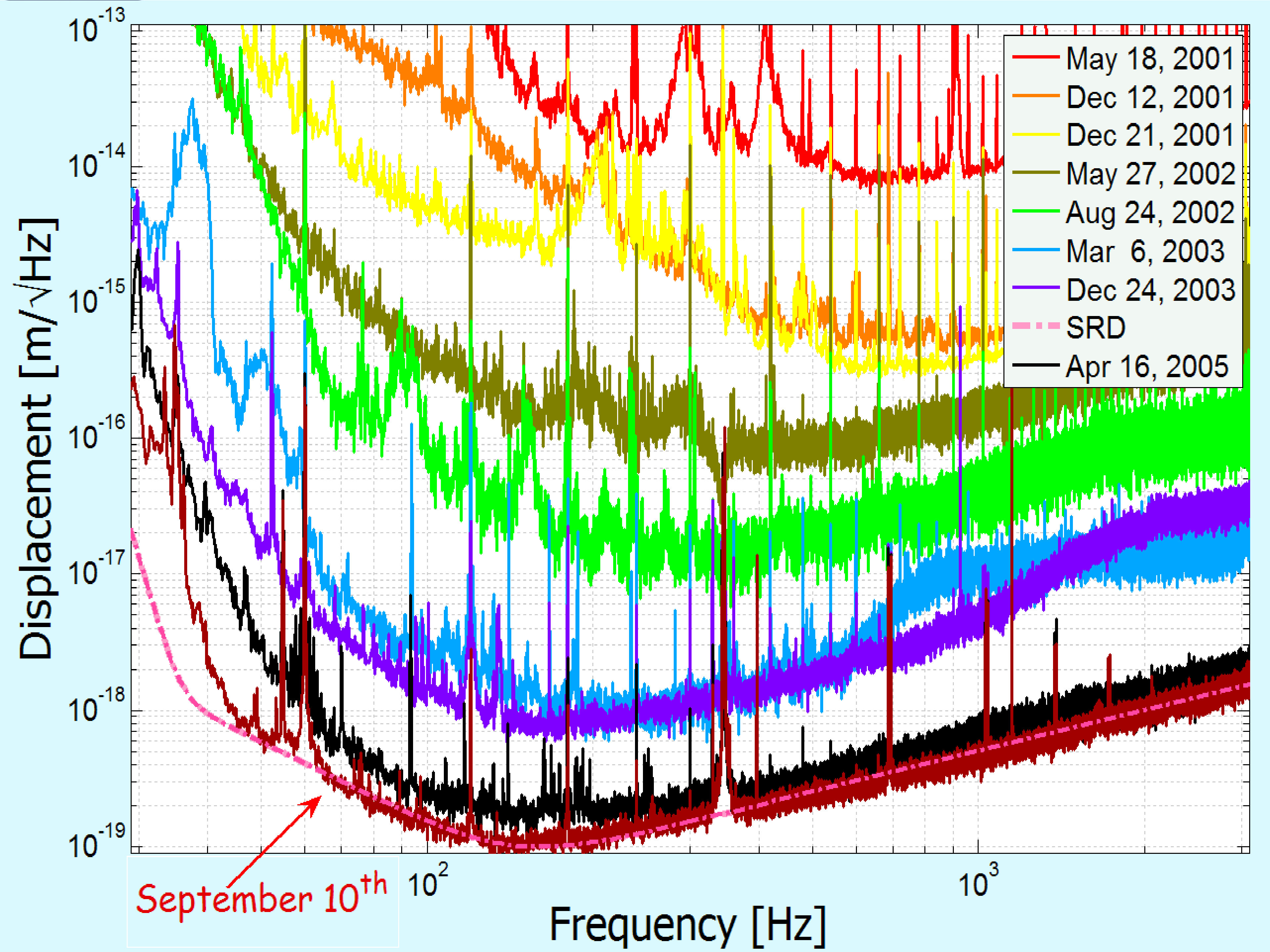
4 km

Fundamental Noise Sources
(conceptual)



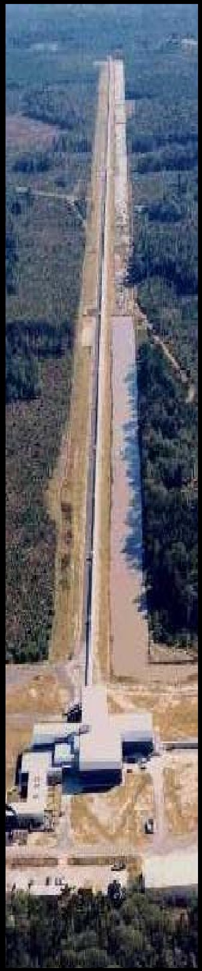
Sensitive frequency range: ~ 40 – 2000 Hz

- If detector is not perfectly tuned, other noise sources can easily dominate !



May 18, 2001
Dec 12, 2001
Dec 21, 2001
May 27, 2002
Aug 24, 2002
Mar 6, 2003
Dec 24, 2003
SRD
Apr 16, 2005
Displacement [m/√Hz]
Frequency [Hz]
September 10th

Overview



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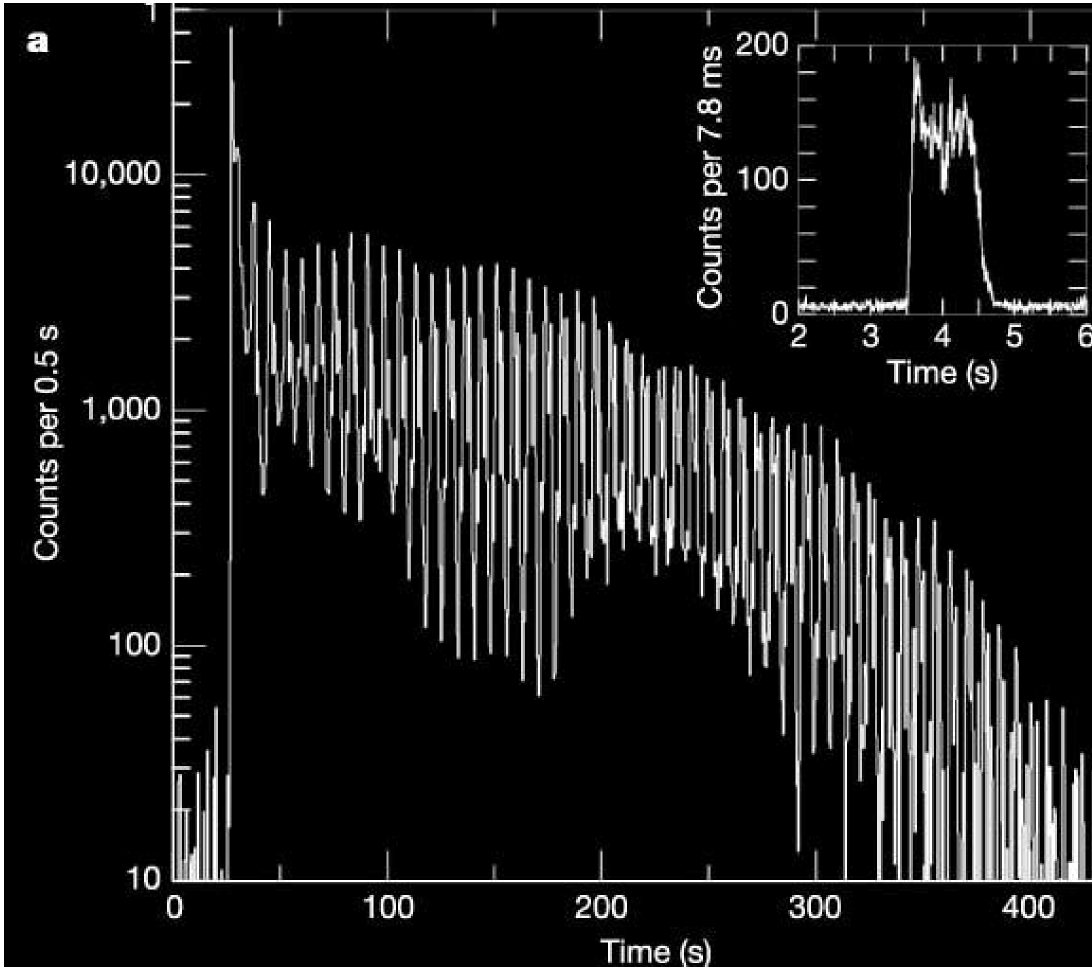
SGR 1806 Hyperflare

The SGR 1806-20 Hyper Flare of December 27, 2004

RHESSI X-ray light curve (20 -100 keV)

- Soft Gamma-ray Repeater SGR 1806-20 emits a record flare
- Distance [6 - 15] kpc
- Energy ~10^{46} erg
- Pulsating tail lasting six minutes



- High Frequency QPOs (Israel et al. 2005, Watts & Strohmayer 2006)
  - » RXTE and RHESSI
  - » SGR 1900+14
- Plausibly mechanically driven

Objective:

Measure GW radiation associated with periods and frequency of observations

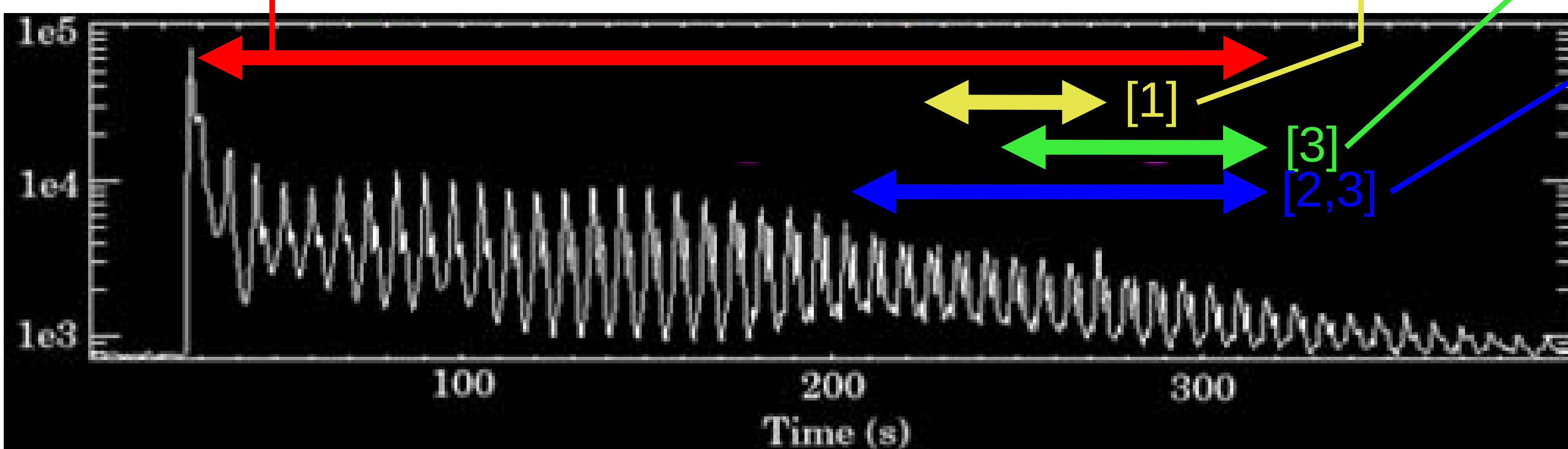
- No significant departure from background
  - no GW detection

$h^{90\%}_{rss\text{-}det}$ = 4.53 x 10^{-22} strain/rHz

$h^{90\%}_{rss\text{-}det}$ = 4.67 x 10^{-22} strain/rHz

$h^{90\%}_{rss\text{-}det}$ = 7.19 x 10^{-22} strain/rHz

$h^{90\%}_{rss\text{-}det}$ = 9.50 x 10^{-22} strain/rHz

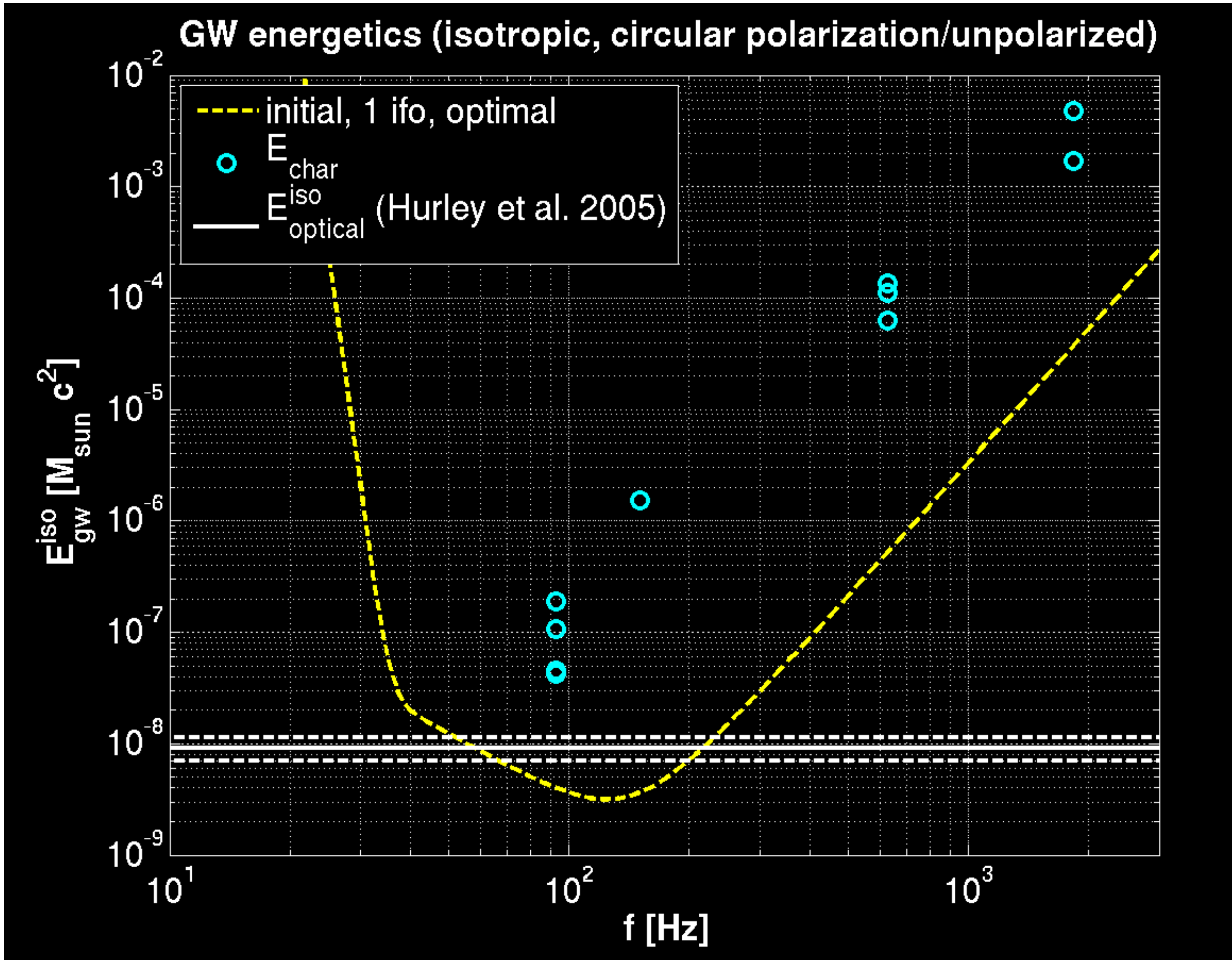


[1] G.Israel et al, *ApJ* **628** L53 (2005)
[2] A.Watts and T.Strohmayer, *ApJ* **637** L117 (2006)
[3] T.Strohmayer and A.Watts, *ApJ* **653** L594 (2006)

Gravitational Wave Energetics – SGR1806-20 Hyperflare

- For the 92.5Hz QPO observation (150s-260s)
  - » **$E^{iso,90\%} = 4.3 \times 10^{-8}\ M_{sun}c^2$**

- This energy is comparable to the energy released by the flare in the electromagnetic spectrum



- Assuming
  - » Isotropic emission
  - » Equal amount of power in both polarization (circular/unpolarized)
- $E^{iso,\ 90\%}$ is a characteristic energy radiated in the duration and frequency band we searched

GRB 070201 and M31

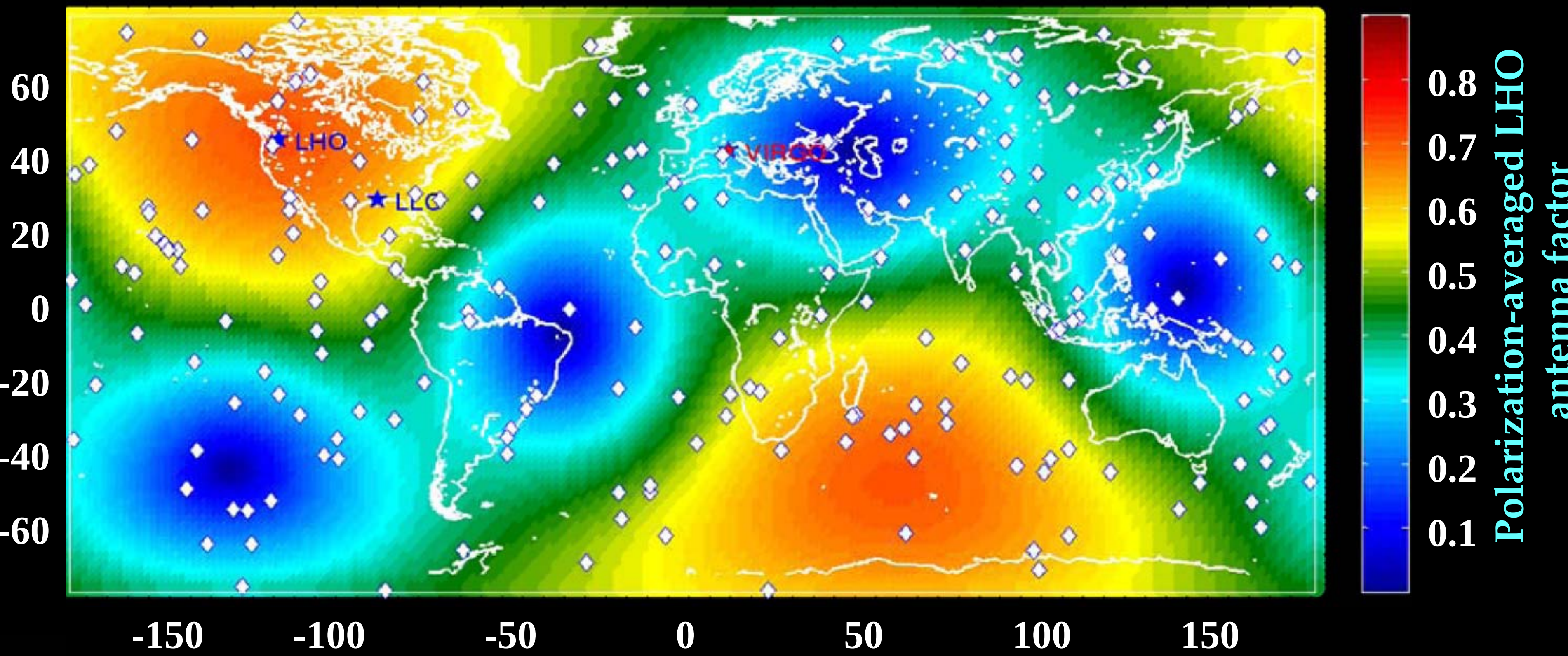
Astrophysical Event Triggered Searches

- » Gamma-ray transients (GRBs, SGRs)
- » Optical transients
- » Neutrino events
- » …

  - ➢ Correlation in time
  - ➢ Correlation in direction
  - ➢ Information on the source properties
  - ➢ …

- ✓ Confident detection of GWs (eventually).
- ✓ Better background rejection ⇒ Higher sensitivity to GWs.
- ✓ More information about the source/engine.
- ⚠ ✓ Even upper limits can have interesting implications. ⚠

213 GRB triggers from Nov 4 2005 to Sept 30 2007

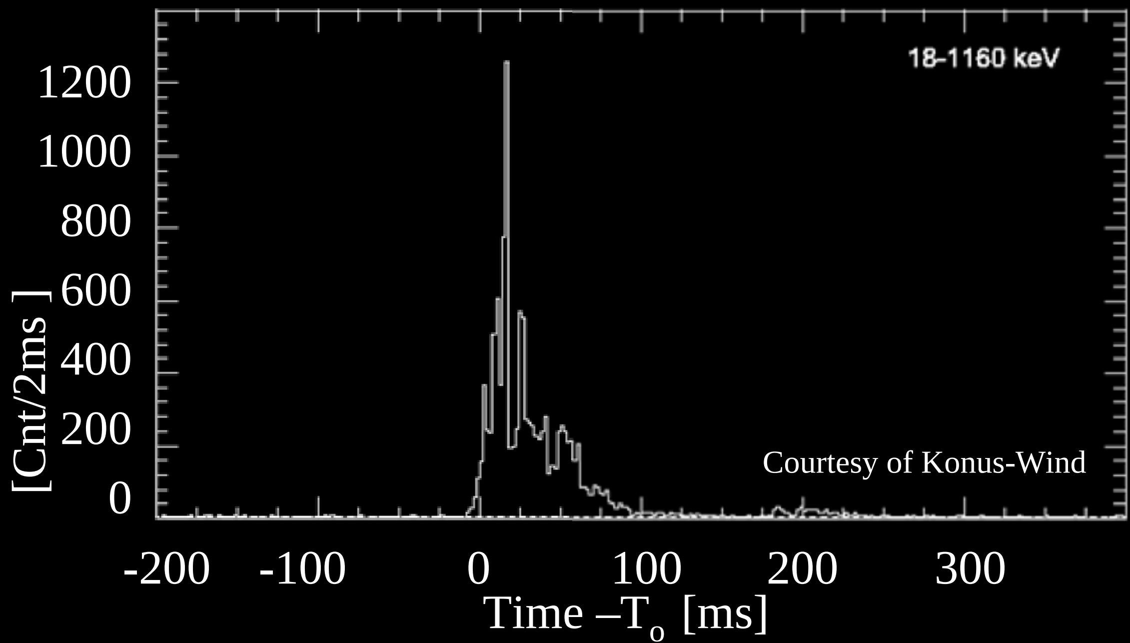


– GRB triggers **(mostly from Swift, IPN, INTEGRAL, HETE-2)**

- **~70% with double-IFO coincidence LIGO data**
- **~40% with triple-IFO coincidence LIGO data**
- **~25% with measured redshift**
- **~15% short-duration GRBs**

EM Observations - GRB 070201

Detected by Konus-Wind, INTEGRAL, Swift, MESSENGER



Described as an

"intense short hard GRB" **(GCN 6088)**

Duration ~0.15 seconds,

followed by a weaker, softer pulse with duration ~0.08 seconds

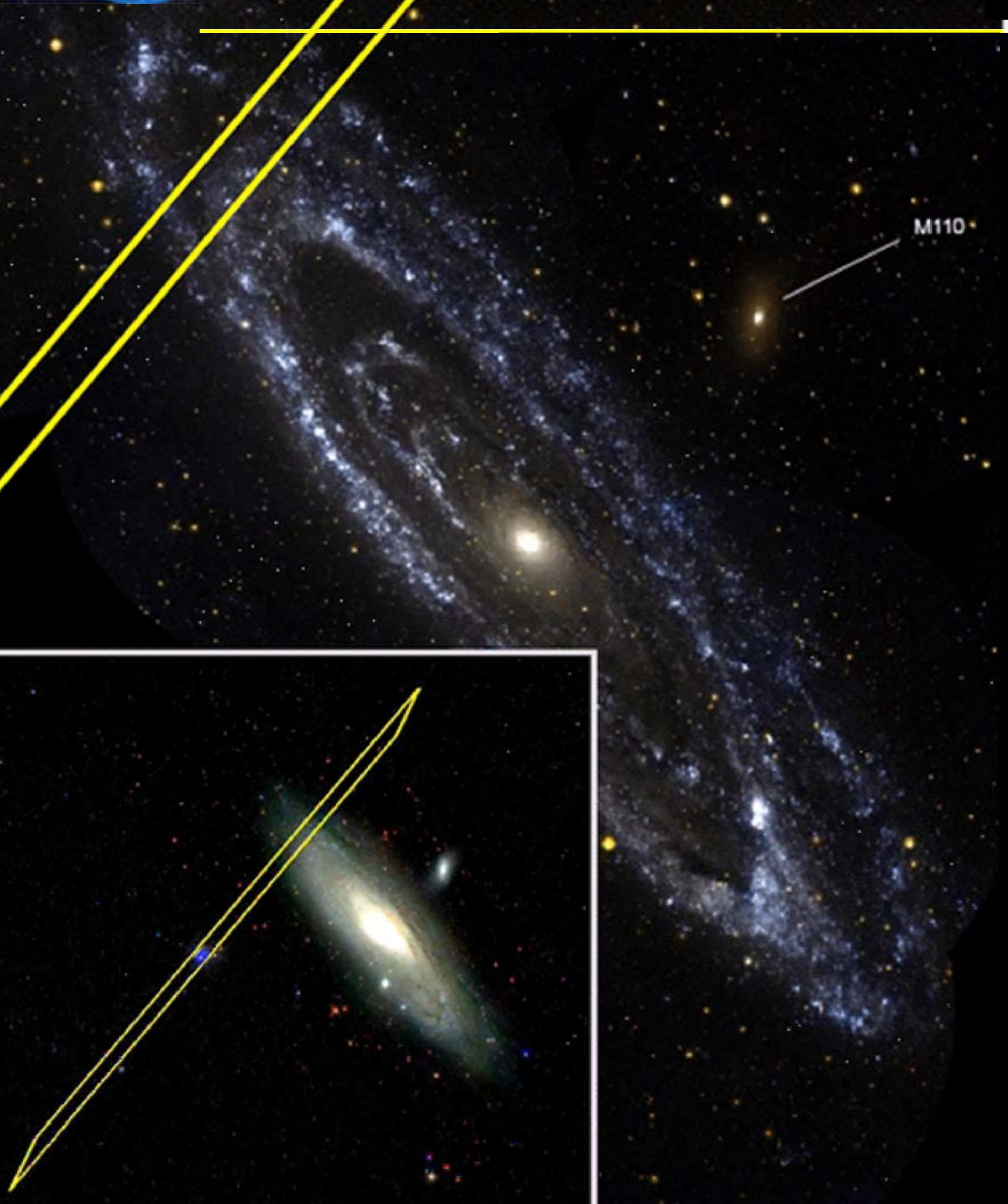
R.A. = 11.089 deg,
Dec = 42.308 deg

Antenna responses of LIGO Hanford:

$$F_{RMS} = \sqrt{F_+^2 + F_\times^2} / \sqrt{2} = 0.304$$

$$h(t) = F_+(\theta, \phi, \psi) h_+(t) + F_\times(\theta, \phi, \psi) h_\times(t)$$

GRB 070201 – Sky Location



R.A. = 11.089 deg,
Dec = 42.308 deg

$D_{M31} \approx 770$ kpc

Possible progenitors for short GRBs:

- **NS/NS or NS/BH mergers**
  Emits strong gravitational waves

- **SGR**
  May emit GW but weaker

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

LSC

Implications

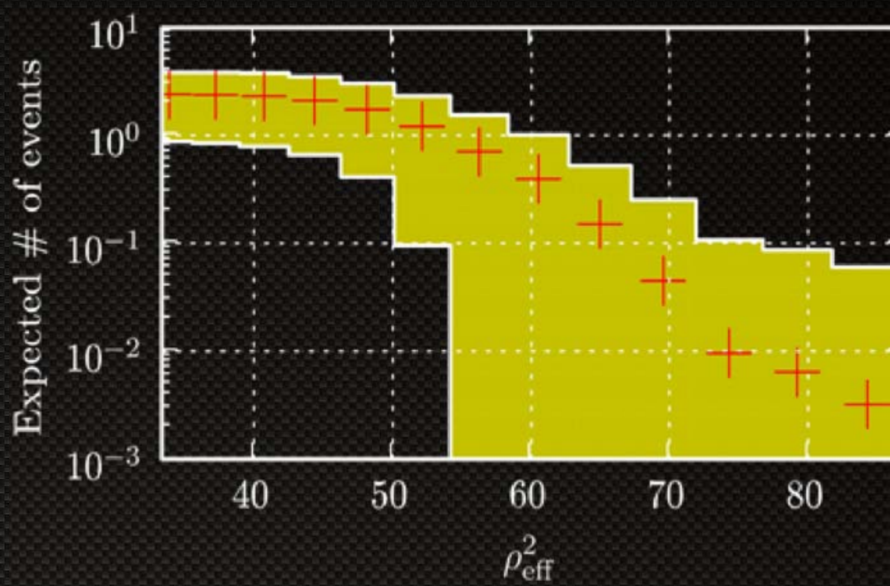
- **In case of a detection:**
  - » Confirmation of a progenitor (e.g. coalescing binary system)
  - » GW observation could determine the distance to the GRB

- **In case of non-detection:**
  - Exclude progenitor/model in mass-distance region
  - Assumed M31 distance to hypothetical GRB ⇒

    exclude binary progenitor
  - Bound the GW energy emitted by a source in M31
  - …

Background:

Compact Binary Inspiral Search

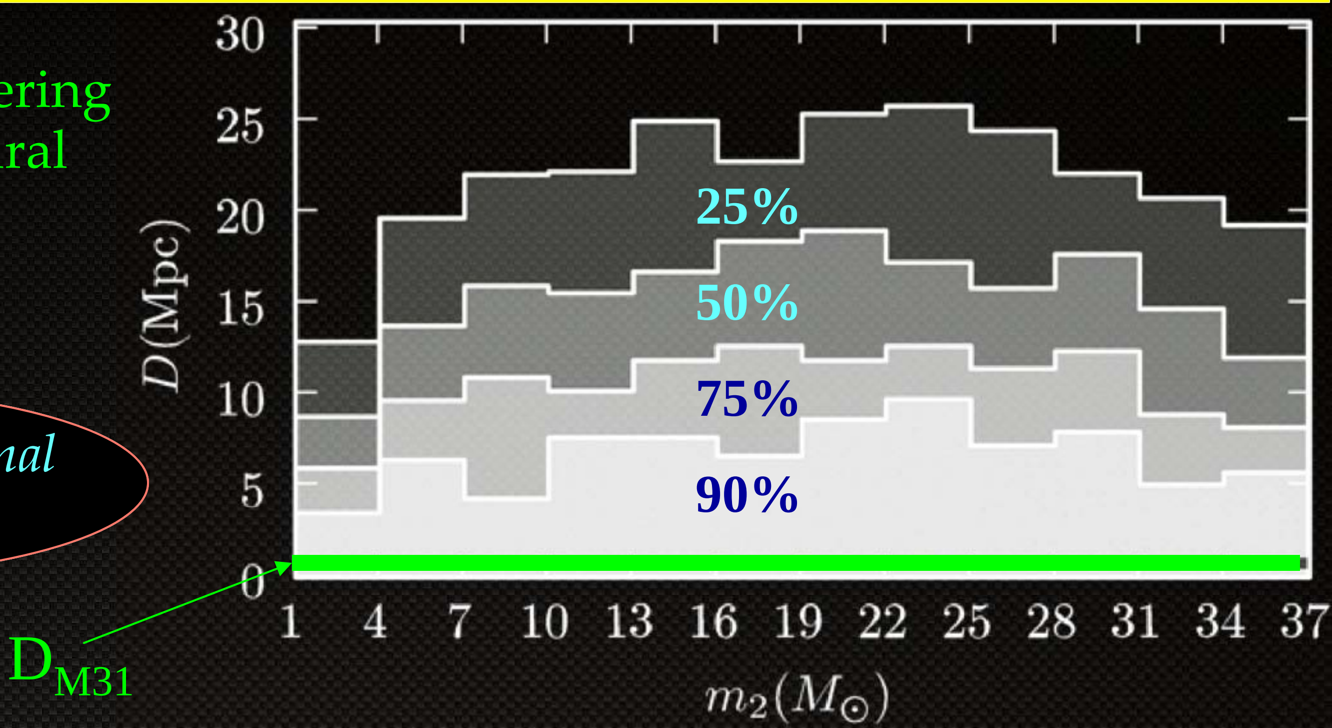


A cumulative histogram of the expected number of background triggers in 180 s based on the analysis of the off source times (+)

Results: Model Based Compact Binary Inspiral Search

Exercise matched filtering techniques for inspiral waveform search

No plausible gravitational waves identified



Exclude compact binary progenitor with masses

$1\ M_\odot < m_1 < 3\ M_\odot$ and $1\ M_\odot < m_2 < 40\ M_\odot$ with $D < 3.5$ Mpc away at 90% CL

Exclude any compact binary progenitor in our simulation space

at the distance of M31 at > 99% confidence level

Results: Model *Independent* Compact Binary Inspiral Search

Excess Power type search

No plausible gravitational waves identified

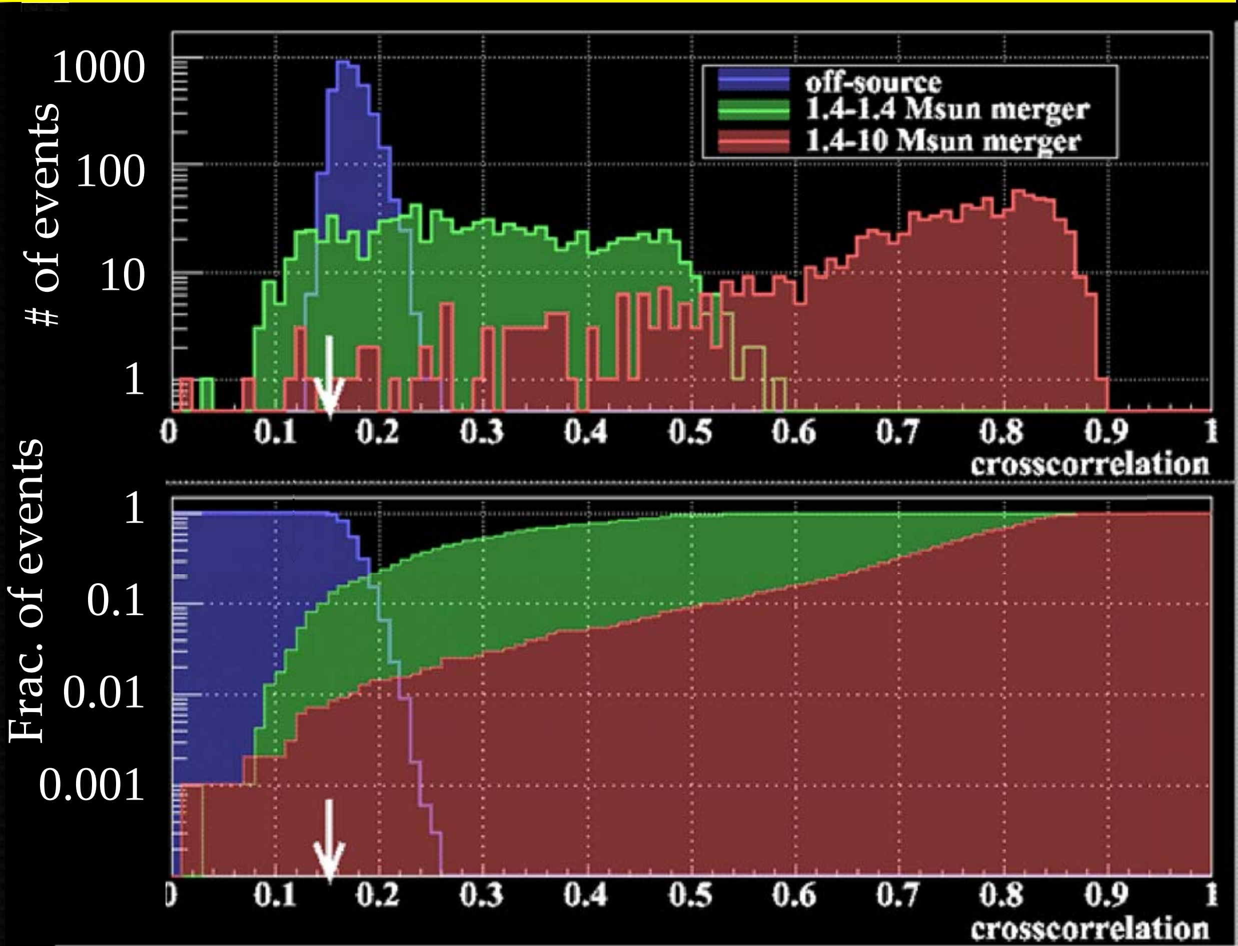
Injected simulated waveforms

- **NS-NS inspirals (1.4-1.4 $M_\odot$)**

and

- **NS-BH inspirals (1.4-10 $M_\odot$)**

at nominal M31 distance



Efficiency > 0.878, 1.4 - 1.4 $M_\odot$

Efficiency > 0.989, 1.4 - 10 $M_\odot$

These results give an independent way to reject hypothesis of a compact binary progenitor in M31

Soft Gamma-ray Repeater in M31 ?

SGR: highly magnetized neutron star;
can have giant flares (rare)
(arXiv:0712.1502)

- **Giant flare from an SGR:**
  - **a hypothesized explanation for 070201 burst**
- **Energy release in gamma rays consistent with SGR model**
  - **Measured gamma-ray fluence = 2 x 10^{-5} ergs/cm^2 (Konus-Wind)**
- **Corresponding gamma-ray energy, assuming isotropic emission, with source at D = 770 kpc (M31):**

$$E_{\gamma,\mathrm{iso}} = \phi \times 4\pi D^2 \approx 10^{45} \text{ ergs}$$

- **SGR models predict energy release in GW to be no more than ~10^{46} ergs**

Model independent burst search result

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$$E_{\gamma,\mathrm{iso}} = \phi \times 4\pi D^2 \approx 10^{45} \text{ ergs}$$

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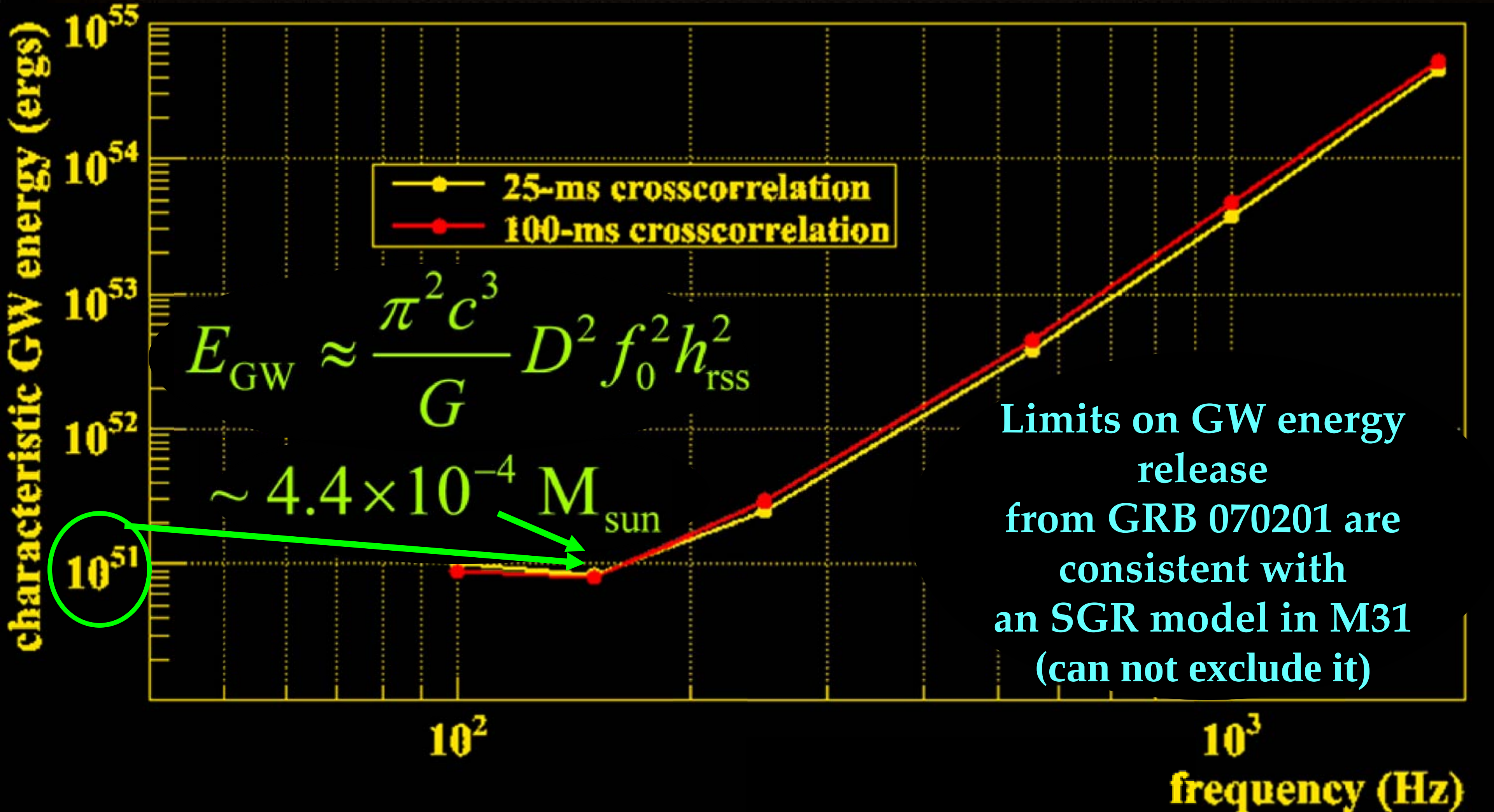

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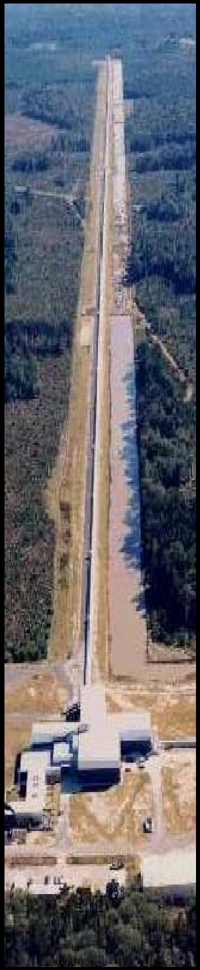

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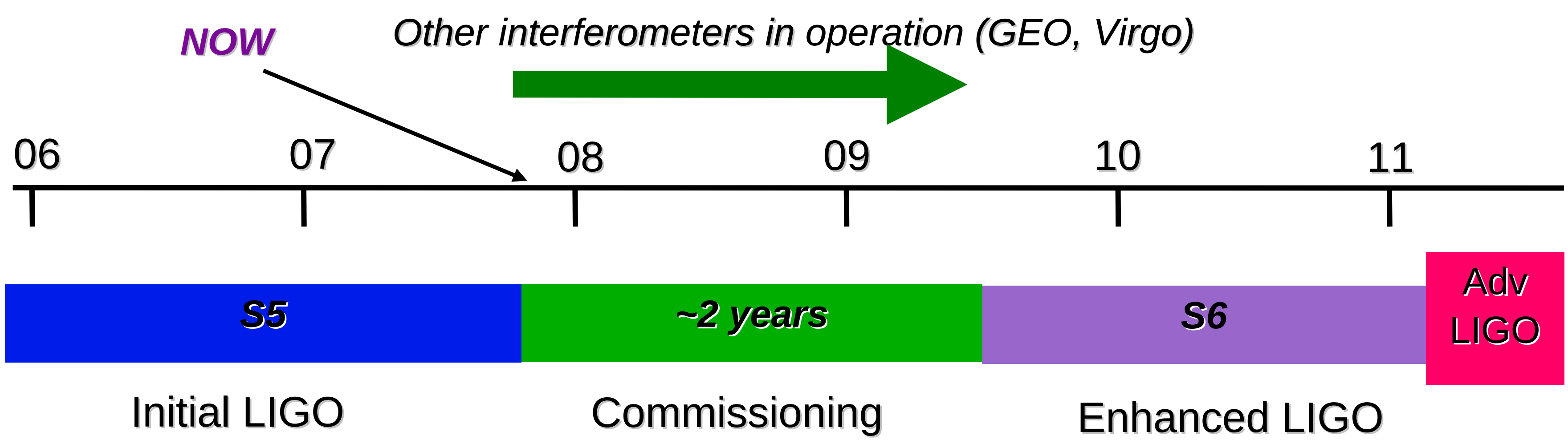
Advanced LIGO

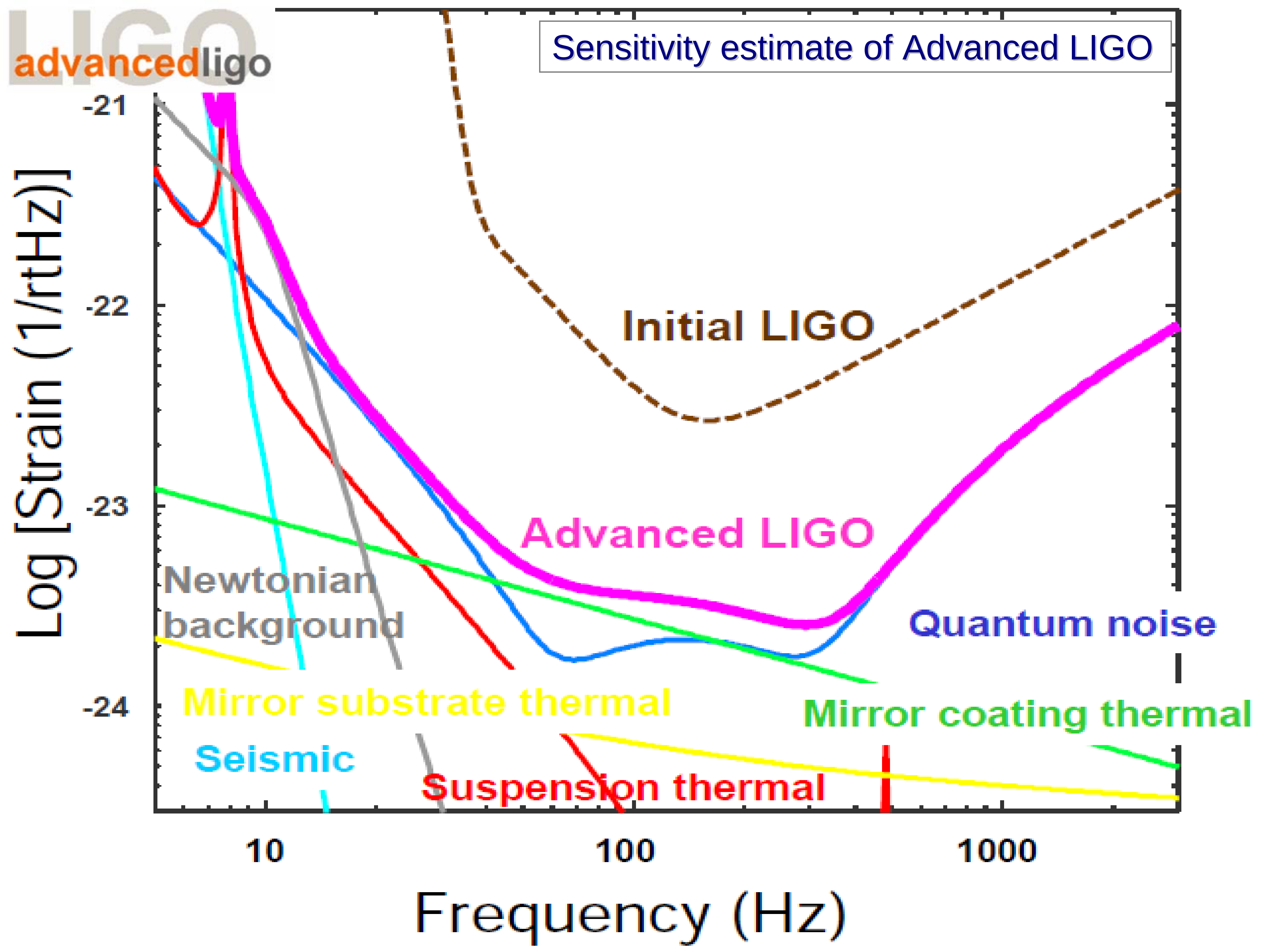
- **Major upgrade of LIGO interferometers**
- **A factor of > × few improvement in strain sensitivity: > × few^3 in detectable volume**
- **1 day of AdvLIGO observation ≈ 1 year of current LIGO observation**
- **Detect gravitational waves regularly**
- **Installation : planed to start in 2011, Observation: start in 2014**

Before Advanced LIGO

- Enhanced LIGO: a factor of 2 improvement from the current LIGO
- Installation and commissioning has just started (2 years)
- S6: 1 year of triple coincidence data with improved sensitivities

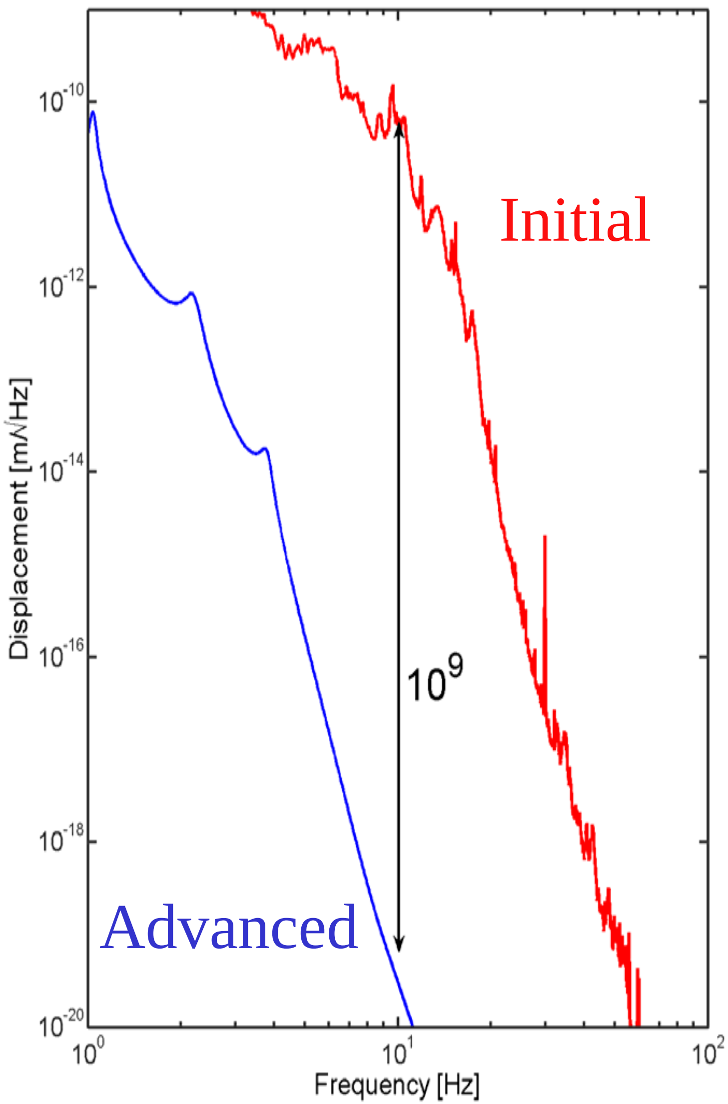
Time-line




advancedligo
Sensitivity estimate of Advanced LIGO
Log [Strain (1/rtHz)]
-21
-22
-23
-24
Initial LIGO
Advanced LIGO
Newtonian background
Quantum noise
Mirror substrate thermal
Mirror coating thermal
Seismic
Suspension thermal
10
100
1000
Frequency (Hz)

What is advanced in Advanced LIGO ?

- Seismic noise
  - » Active isolation system
  - » Mirrors suspended as fourth (!!) stage of quadruple pendulums
- Thermal noise
  - » Suspension ➔ fused silica fibers
  - » Test mass ➔ more massive; better coatings
- Optical noise
  - » Laser power ➔ increase to ~200 W
  - » Optimize interferometer response ➔ signal recycling

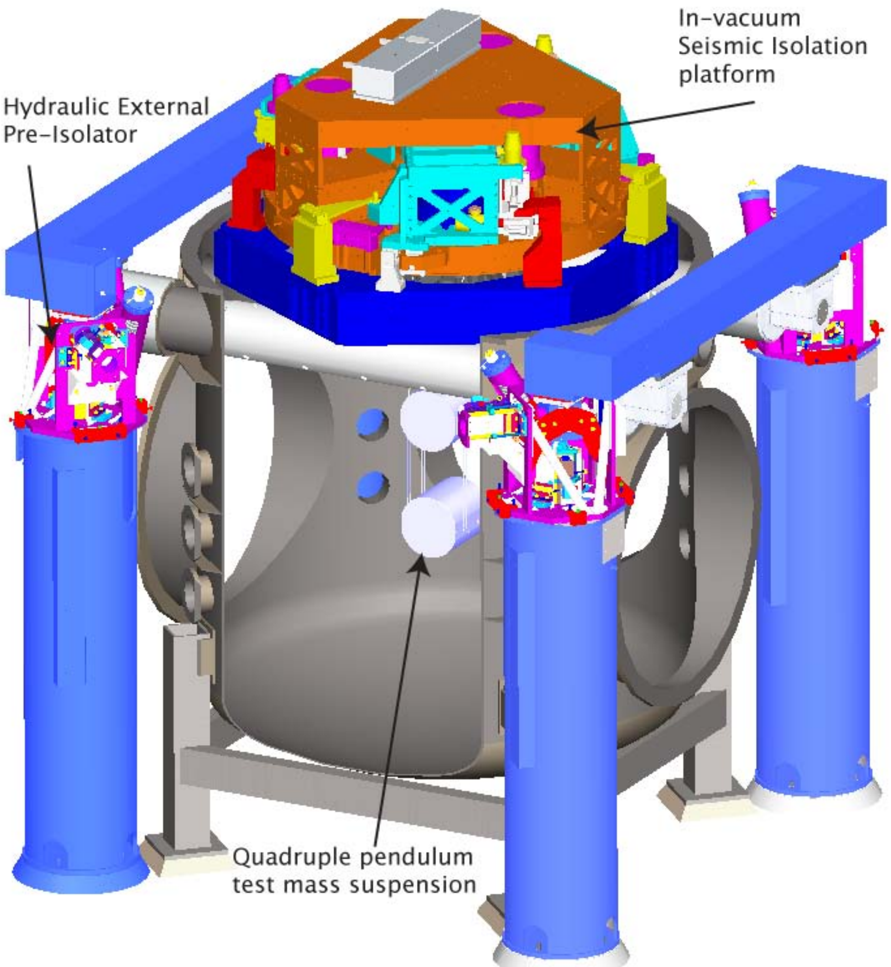


Subsystem and Parameters	Advanced LIGO Reference Design	Initial LIGO Implementation
Comparison With initial LIGO Top Level Parameters		
Observatory instrument lengths; LHO = Hanford, LLO = Livingston	LHO: 4km, 4km; LLO: 4km	LHO: 4km, 2km; LLO; 4km
Anticipated Minimum Instrument Strain Noise [rms, 100 Hz band]	$< 4 \times 10^{-23}$	4×10^{-22}
Displacement sensitivity at 150 Hz	$\sim 1 \times 10^{-20}$ m/√Hz	$\sim 1 \times 10^{-19}$ m/√Hz
Fabry-Perot Arm Length	4000 m	4000 m
Vacuum Level in Beam Tube, Vacuum Chambers	$<10^{-7}$ torr	$<10^{-7}$ torr
Laser Wavelength	1064 nm	1064 nm
Optical Power at Laser Output	180 W	10 W
Optical Power at Interferometer Input	125 W	6 W
Optical power on Test Masses	800 kW	15 kW
Input Mirror Transmission	0.5%	3%
End Mirror Transmission	5-10 ppm	5-10 ppm
Arm Cavity Beam size (1/e^2 intensity radius)	6 cm	4 cm
Light Storage Time in Arms	5.0 ms	0.84 ms
Test Masses	Fused Silica, 40 kg	Fused Silica, 11 kg
Mirror Diameter	34 cm	25 cm
Suspension fibers	Fused Silica ribbons	Steel Wires
Seismic/Suspension Isolation System	3 stage active, 4 stage passive	Passive, 5 stage
Seismic/Suspension System Horizontal Attenuation	$\geq 10^{-10}$ (10 Hz)	$\geq 10^{-9}$ (100 Hz)

Seismic Isolation

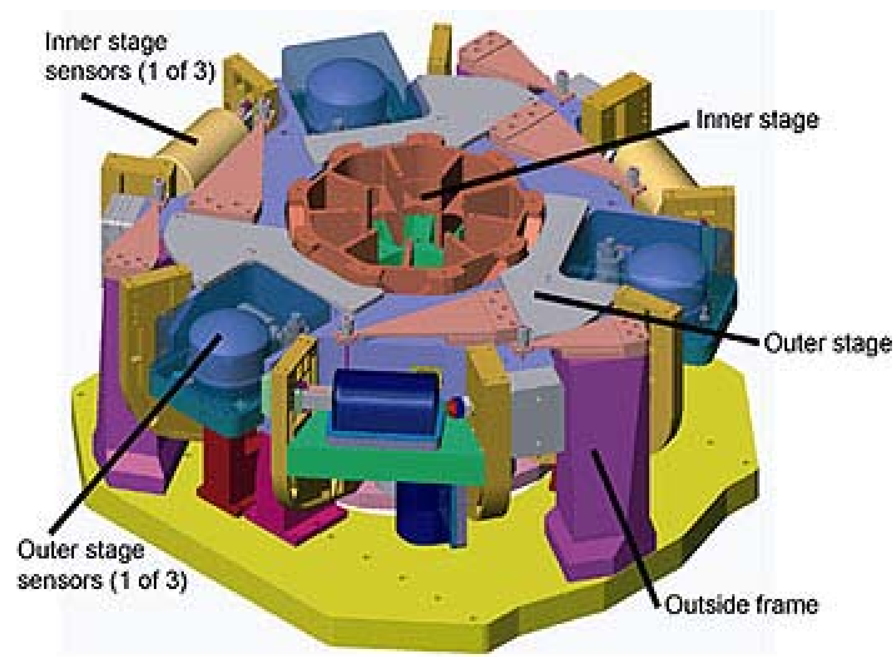
Required for: Seismic noise reduction, Stable operation

Combination of active and passive isolation stages.



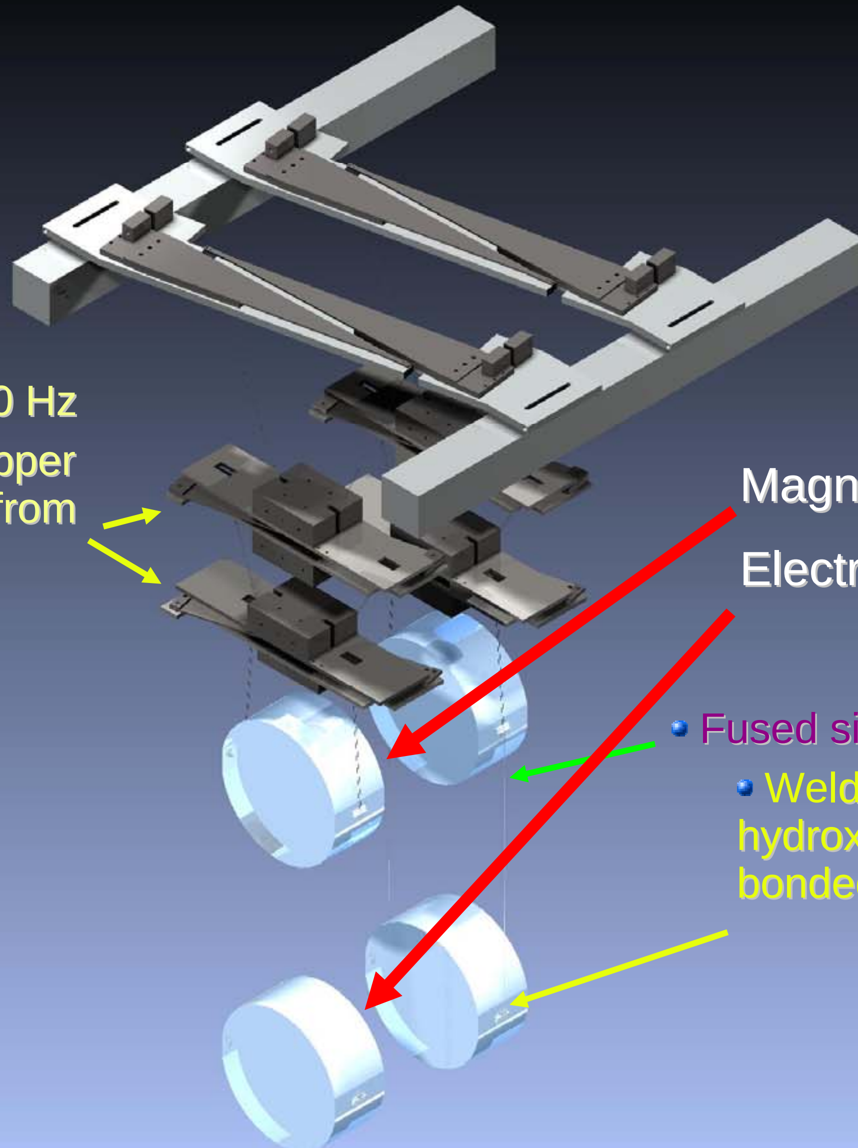
Active system requirement
x3000 attenuation @ 10Hz

Internal Active Isolation Platform



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



- Fused silica fiber
  - Welded to 'ears', hydroxy-catalysis bonded to optic

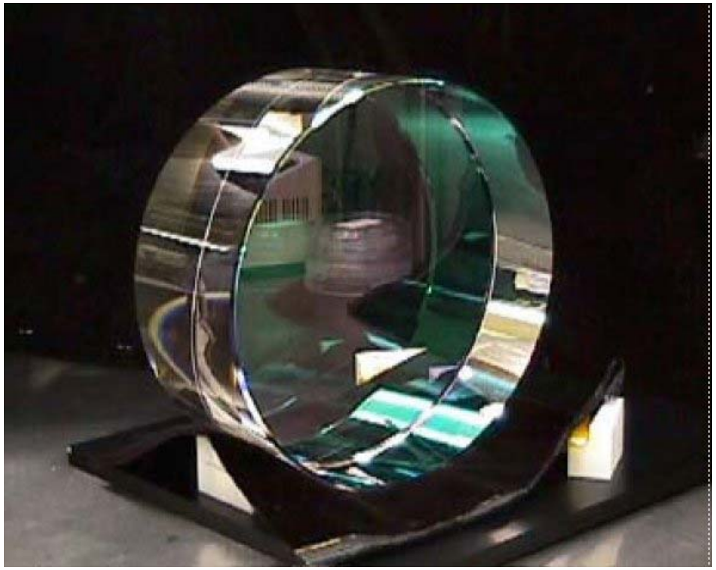
Thermal Noise

Thermal vibration of the molecules of mirror / suspension material

High mechanical quality mirror substrate / coating materials

Low mechanical loss suspension fibers
Fused silica fibers with silica bonding

Fused silica mirror



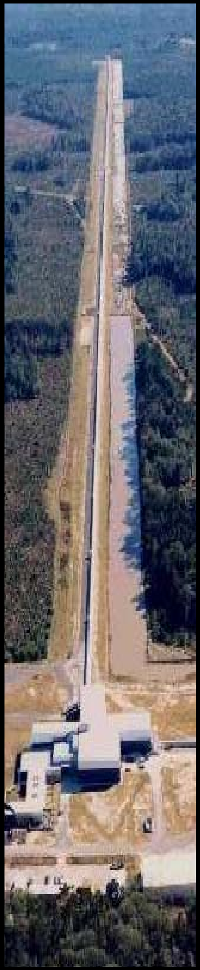
Other challenges for mirrors

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

Overview



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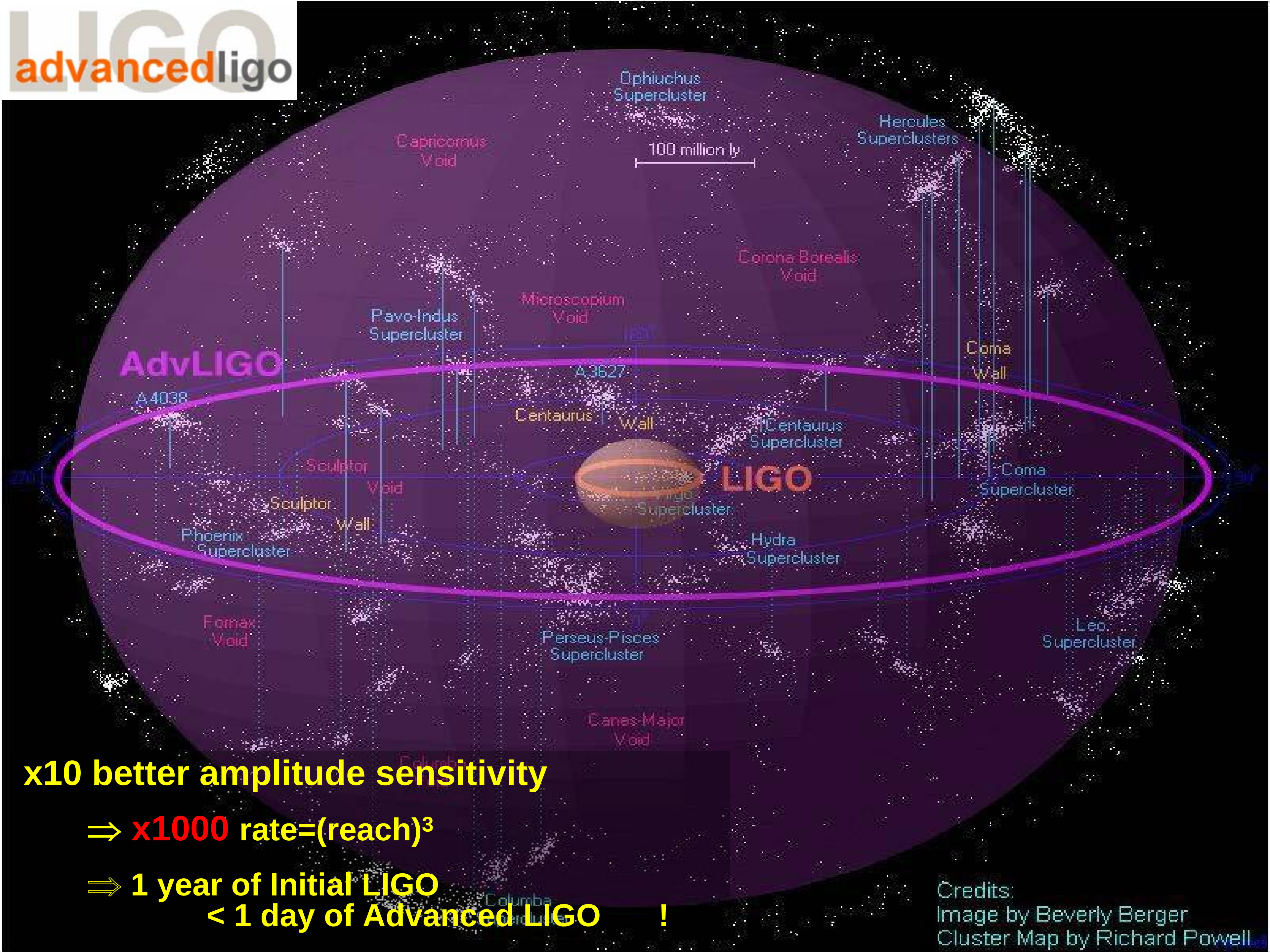

x10 better amplitude sensitivity

⇒ **x1000 rate=(reach)^3**

⇒ **1 year of Initial LIGO < 1 day of Advanced LIGO !**

Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

1. B. Kocsis, M.E. Gaspar, S. Marka, "Detection Rate Estimates of Gravity-waves Emitted During Parabolic Encounters of Stellar Black Holes in Globular Clusters", Astrophys.J.648:411-429,2006

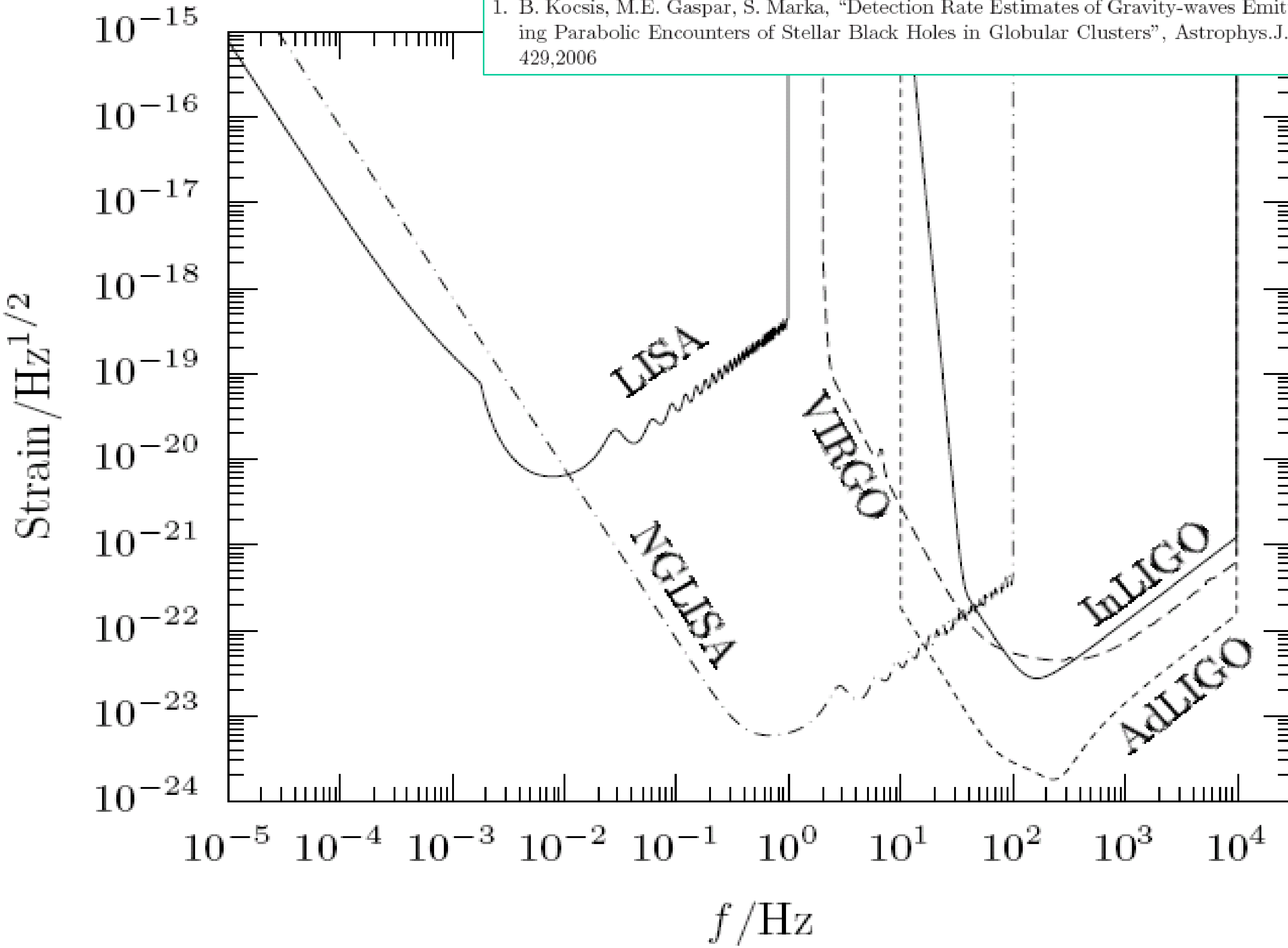

FIG. 1.— Goal sensitivity curves for interferometric GW detector facilities: InLIGO, VIRGO, AdLIGO, *LISA*, and *NGLISA*.

This is great exploratory science !

- There is a bold effort underway to get a new view of the universe
  - »- Initial LIGO has reached its design sensitivity
    - – S5 accomplished : more than 1 year of data collected
    - – Several astrophysically interesting results are out
      - Crab pulsar upper limit
      - Stochastic background
      - SGR1806-20
      - GRB070201
      - And others to come…
- Active data sharing collaboration with VIRGO
- Advanced LIGO should see sources… excitement is high!

We are grateful to:

Acknowledgments

- Members of the LIGO Laboratory, members of the
LIGO Science Collaboration, National Science Foundation

LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronom
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravit

- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

LIGO Scientific Collaboration Demographic Makeup

- There are **563** people in the LSC (including undergraduates)
- Number of colleges, universities, and research institutions in the LSC: **55**

*Hispanic, African American, Native American, US-based institutions only

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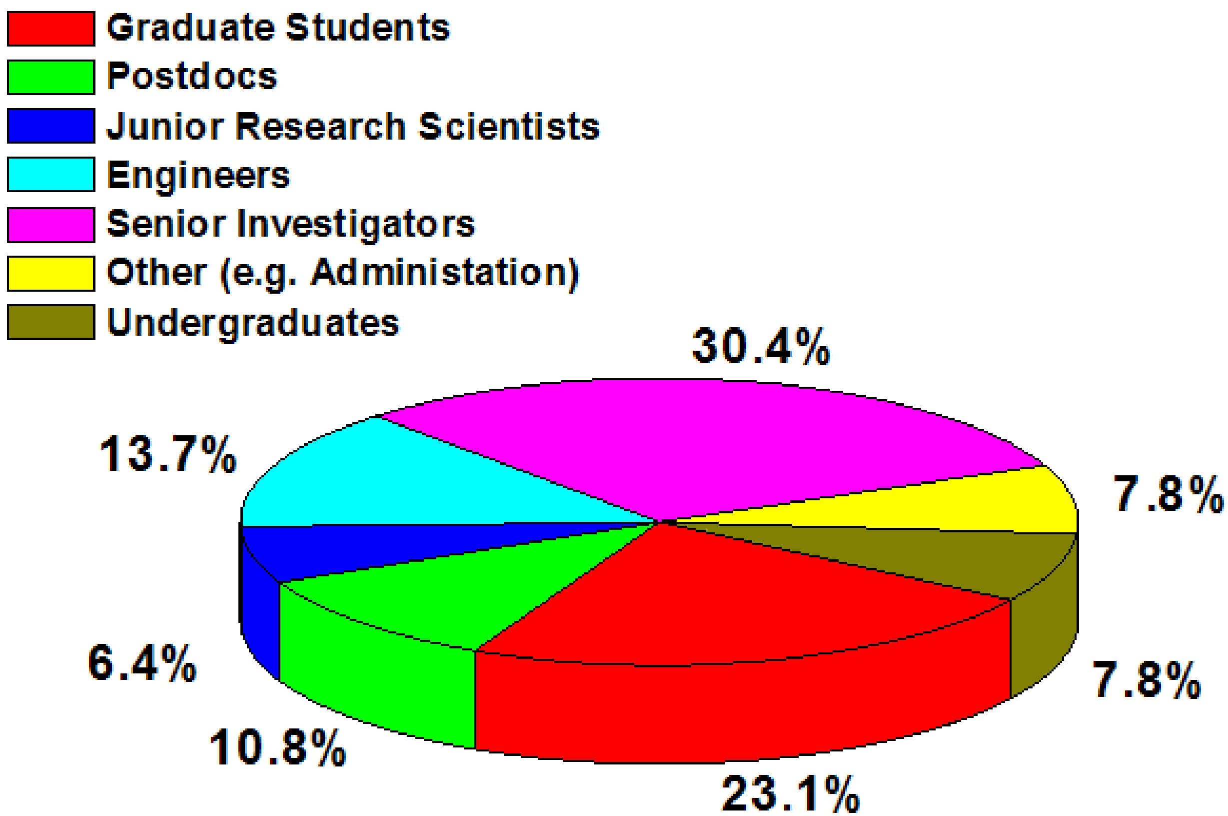
- M



LIGO Scientific Collaboration Geographic Makeup by State

The LSC has members from **16** states:

Arizona, California, Florida, Illinois, Louisiana, Maryland, Massachusetts, Michigan, Minnesota, Montana, New York, Oregon, Pennsylvania, Texas, Washington, Wisconsin

LIGO Scientific Collaboration Geographic Makeup by Country

The LSC has members from **11** countries:

» USA, Australia, Germany, India, Italy, Japan, Hungary, Poland, Spain, Russia, UK

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