The LIGO gravitational wave observatories:
Recent results and future plans

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- on behalf of the LIGO Science Collaboration -

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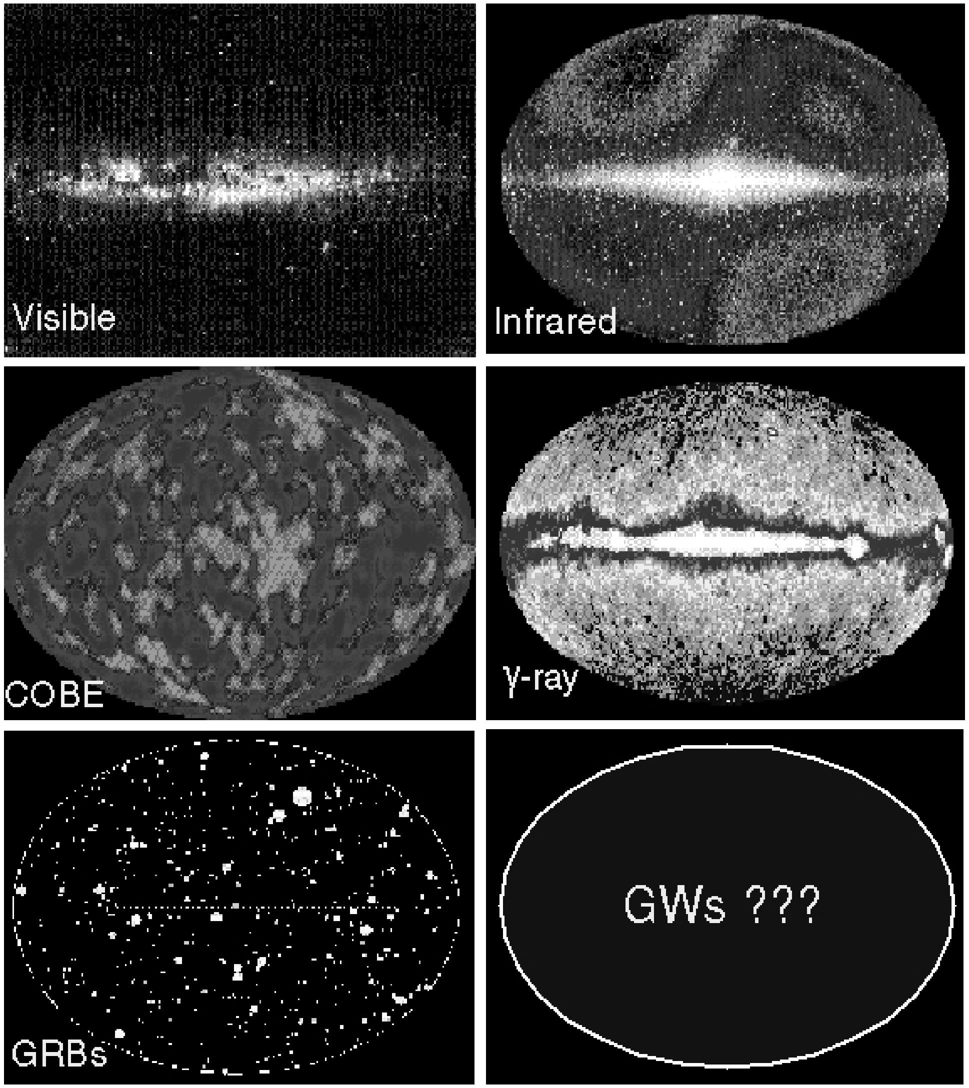
Gravitational Wave Astronomy
A new window on the universe



GRAVITATIONAL WAVES PROVIDE A NEW AND UNIQUE VIEW OF THE DYNAMICS OF THE UNIVERSE.

EXPECTED SOURCES:

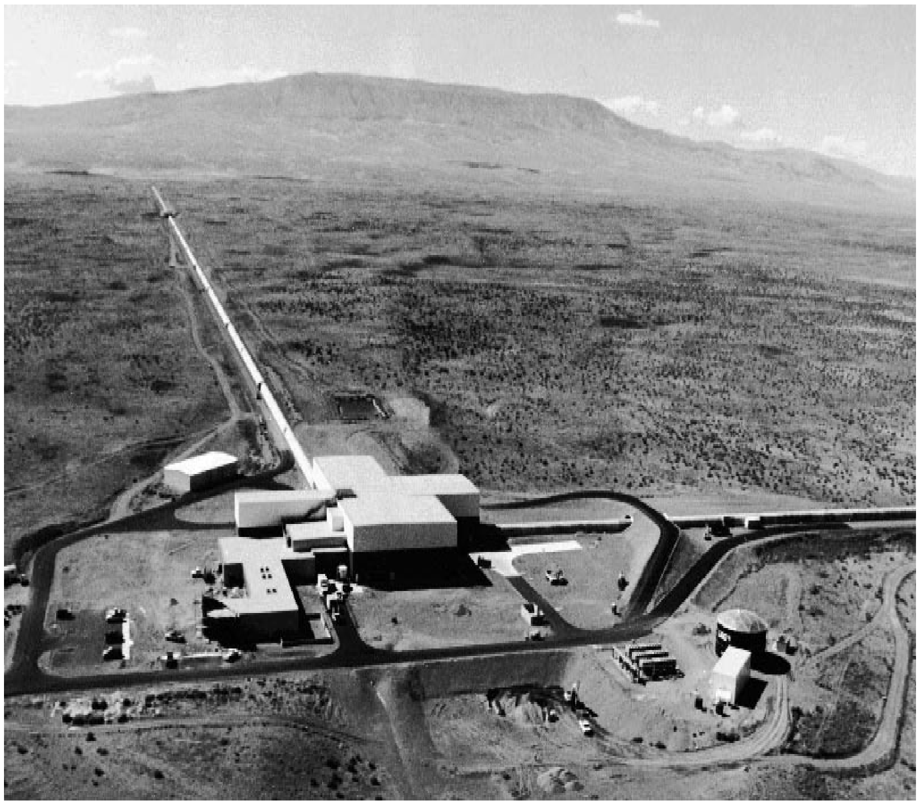
- **BURST & TRANSIENT SOURCES - *SUPERNOVAE***
- **COMPACT BINARY SYSTEMS -**
- ***INSPIRALS***
- **ROTATING COMPACT STARS -**
- ***GRAVITATIONAL WAVE PULSARS***
- **STOCHASTIC GRAVITATIONAL WAVE BACKGROUND**

POSSIBILITY FOR THE UNEXPECTED IS VERY REAL!

Laser Interferometer Gravitational-wave Observatory (LIGO)

Hanford WA

Observatories:
LIGO Hanford, LIGO Livingston



LIGO Hanford Observatory (LHO)
26 km north of Richland WA

2 Interferometers, one 4 km and one 2 km, in same vacuum envelope

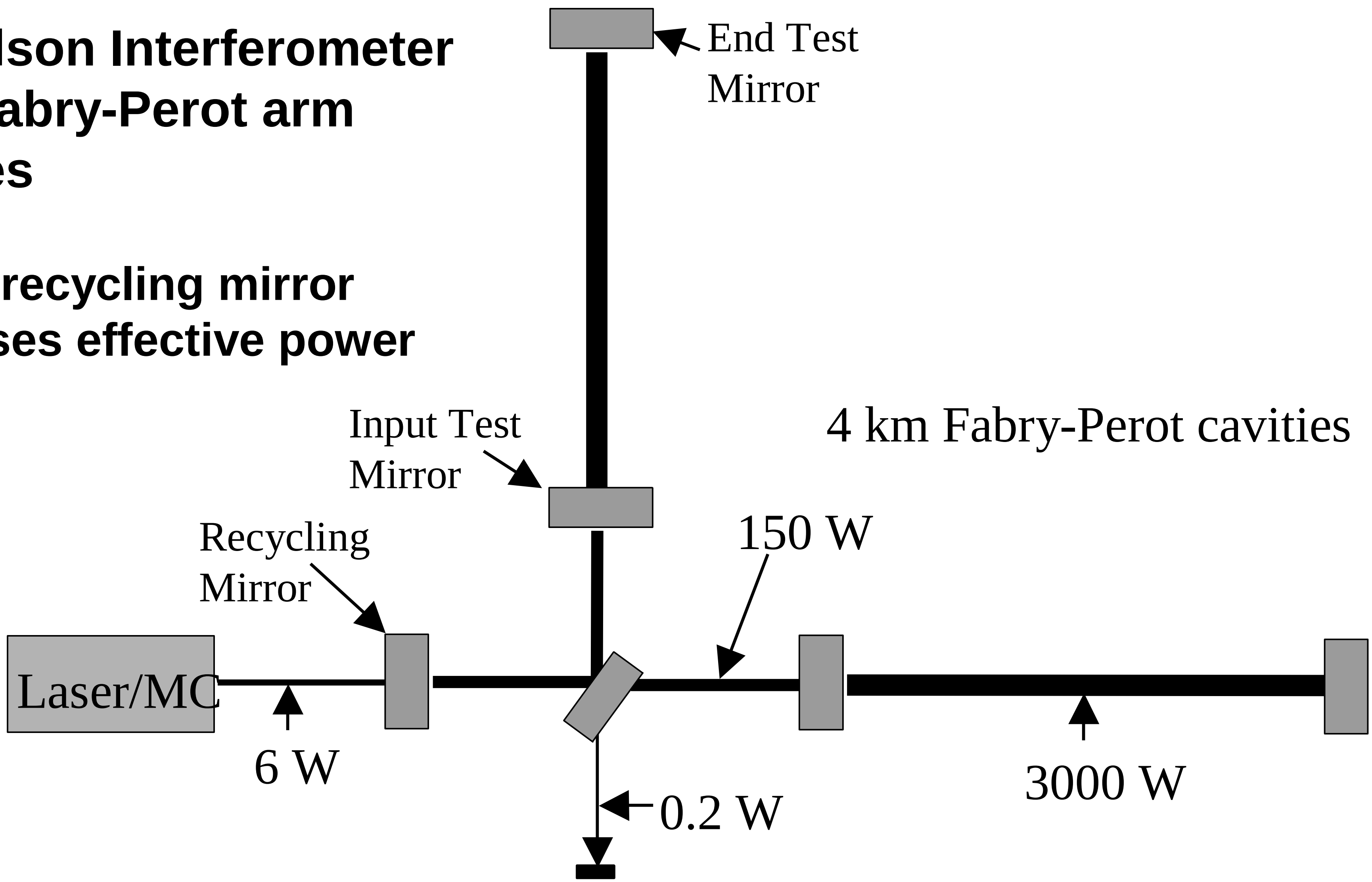
LIGO Livingston Observatory (LLO)
24 km east of Baton Rouge LA

Single 4 km Interferometer

LIGO Interferometer Optical Configuration

ichelson Interferometer ith Fabry-Perot arm avities

ower recycling mirror ncreases effective power



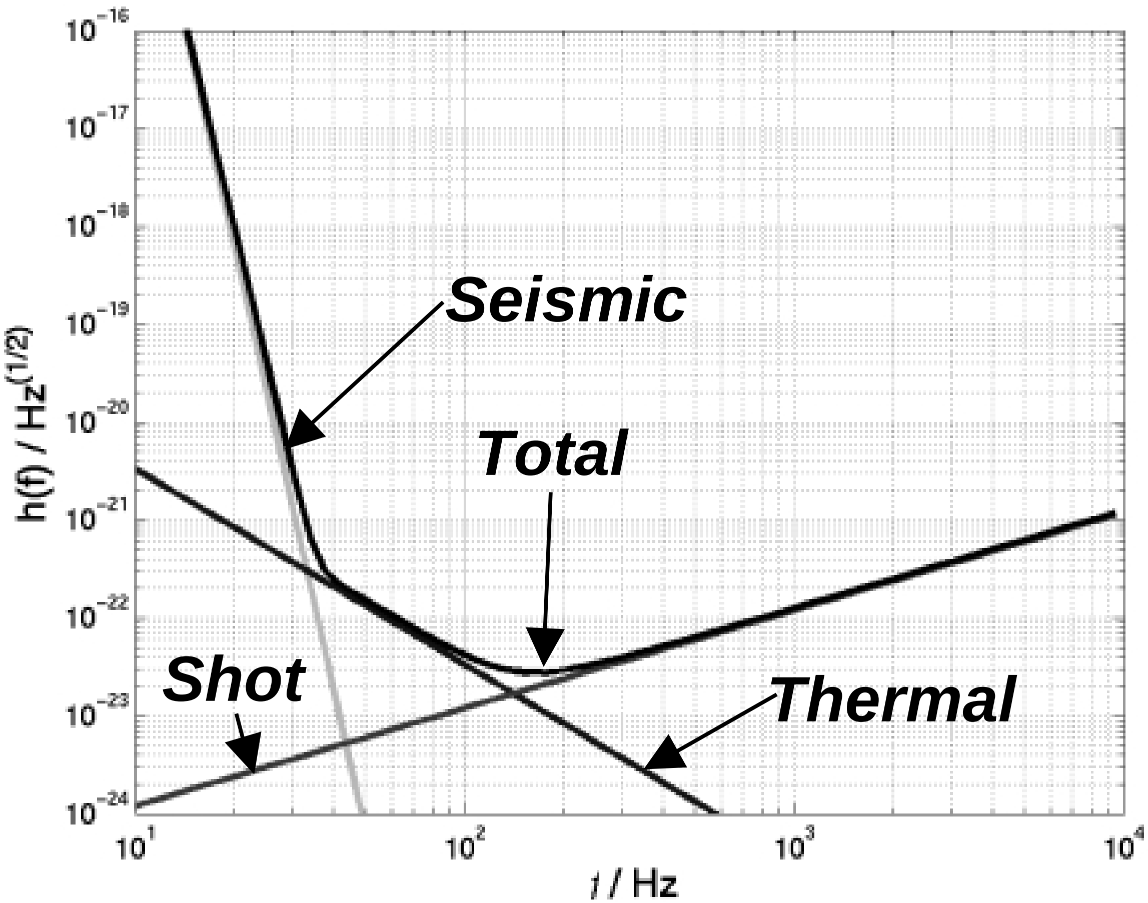
Design Sensitivity for LIGO 4 km Interferometer

Peak Sensitivity ~ 3 10^{-23} / $Hz^{1/2}$ @ 150 Hz

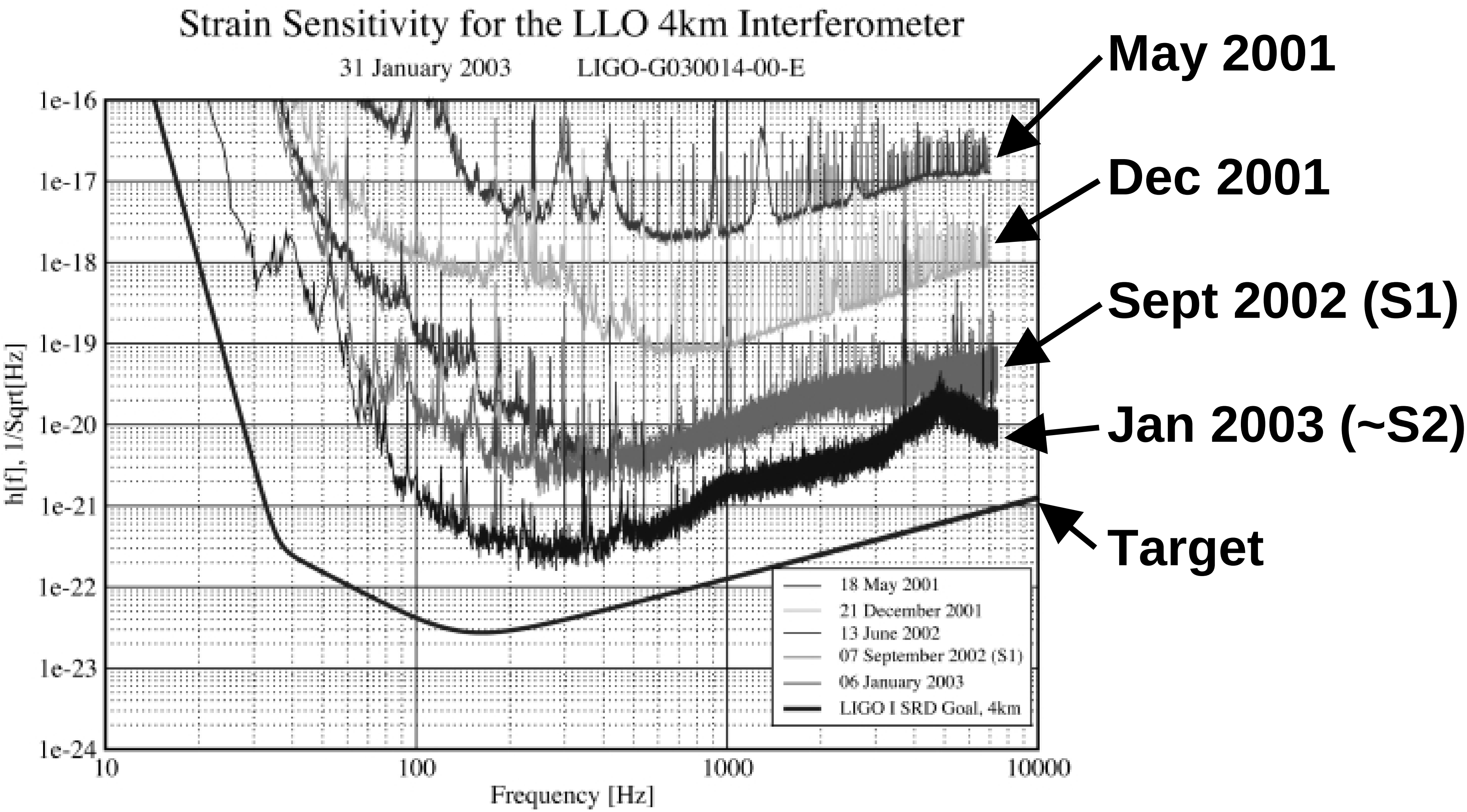
Low Frequencies
f < 40 Hz
Seismic noise from ground

Middle Frequencies
40 Hz < f < 150 Hz
Thermal noise from mirror suspensions

High Frequencies
f > 150 Hz
Shot noise from laser

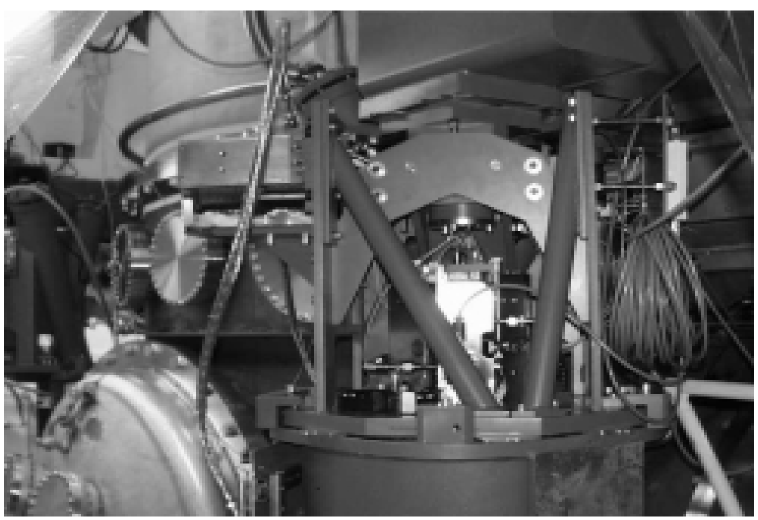


LIGO Livingston Strain Sensitivity

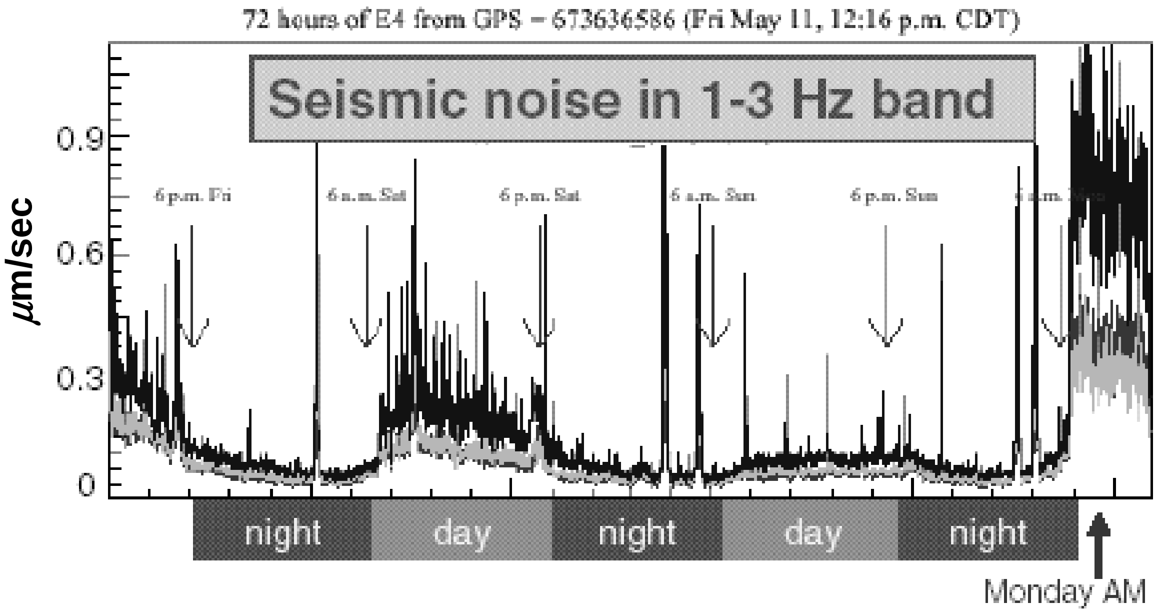


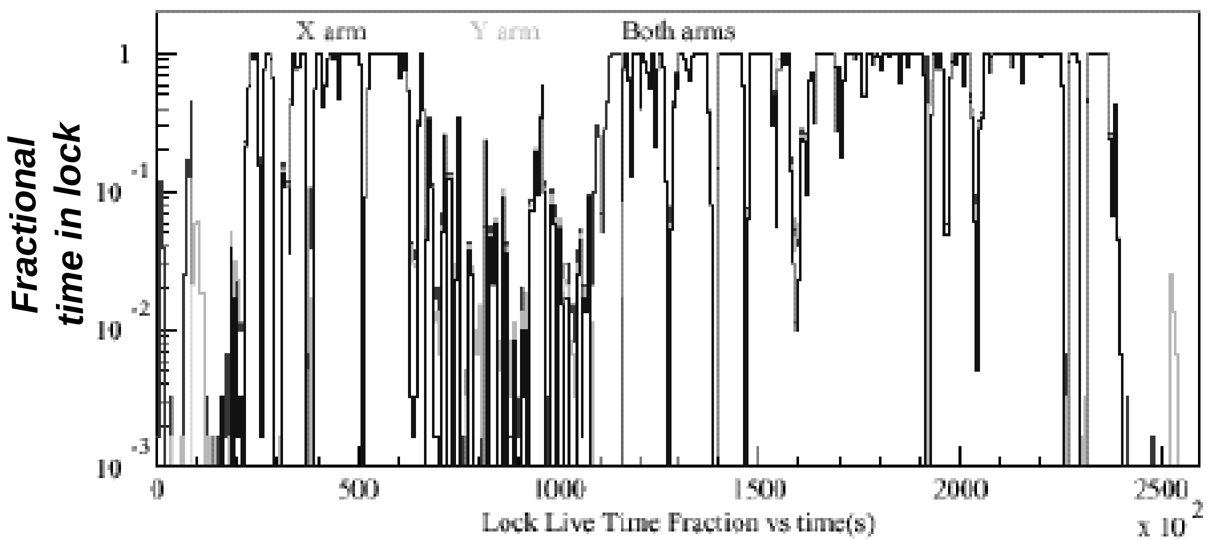
Seismic Noise at Livingston

- ***Seismic noise at Livingston site large during day***
- ***Nearby logging and other anthropogenic sources***
- ***Very difficult to lock during day***
- ***Hydraulic pre-isolators to be installed to reduce down time***



Hydraulic Pre-isolator





Source Categories
Determined by characteristics

Unmodeled bursts - Supernova, γ - ray bursts, ...

No templates available

Look for excess power in frequency-time space, amplitude changes, rise times

Binary mass inspirals - Neutron stars, black holes

Use matched template technique

Requires input from numerical relativists, astrophysicists, and others

Periodic sources - Pulsars, rotating compact stars

Use template for continuous wave

Can integrate data to increase signal-to-noise ratio

Stochastic background - Remnant of big bang, collections of weak sources, ...

Need to cross correlate pairs of detectors

Collaboration among detectors, interferometers, bars, spheres, ...

Upper Limits on Burst Sources

Able to exclude gravitational wave bursts of peak strength ***h*** above rate ***r***

Burst model --

» 1 ms long Gaussian

» Other burst models examined

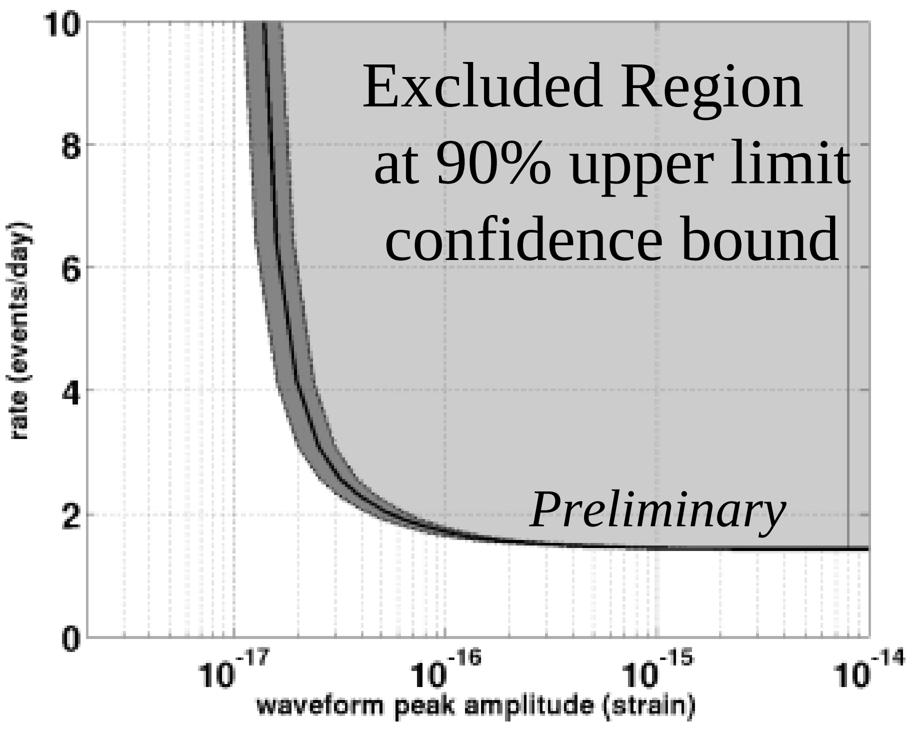
» Linear polarization with random orientation

» Arriving from random directions

Generate event candidates from two trigger algorithms (TF clusters, SLOPE)

» No vetoes used

» Coincidence between detectors required



RELIMINARY S1 Search results:

1.6 events/day (50% efficiency point is at h~3x10^{-17}).

Upper limit in *rate* constrained by observation time:

» S1: 17d - **this result**

» IGEC - 90d (2X coinc.), 260d (3X coinc.)

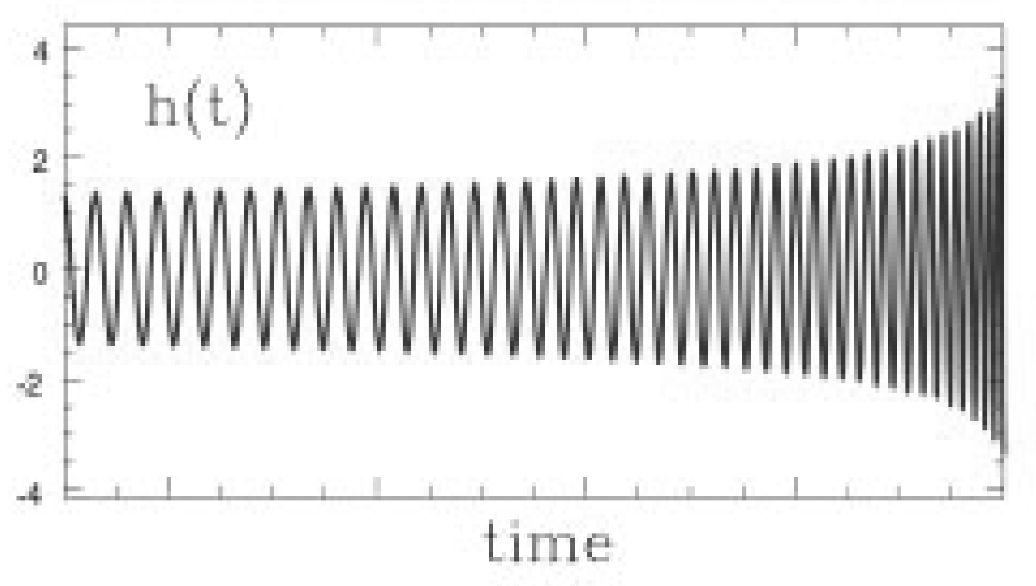
» Astone - 90d

Upper limits work in close collaboration with GEO600

Upper Limits on Inspiraling Binaries

Source targets:

- Compact neutron star binaries undergoing orbital decay and coalescence, (1-3 M_{sun})
- Masses, positions, orbital parameters, distances: unknown
- MACHO binaries (0.5-1 M_{sun}) search under way



S1 range included Milky Way (our Galaxy) and LMC and SMC

Search method

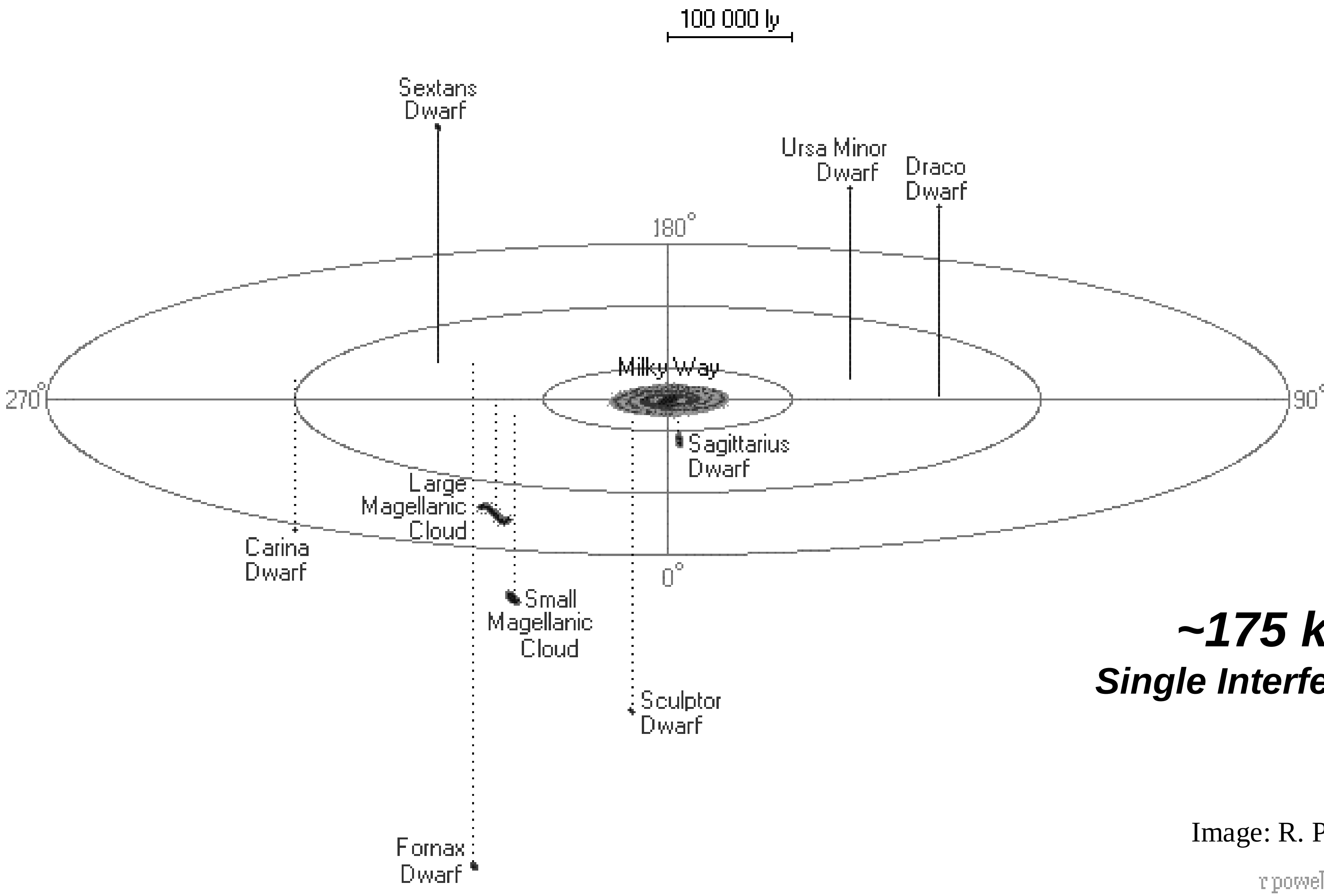
- Template based matched filtering

S1 results

No event candidates found in coincidence

90% confidence upper limit: **inspiral rate < 170/year** per Milky-way equivalent galaxy, in the (m1, m2) range of 1 to 3 solar masses.

Range for neutron star inspirals during S1

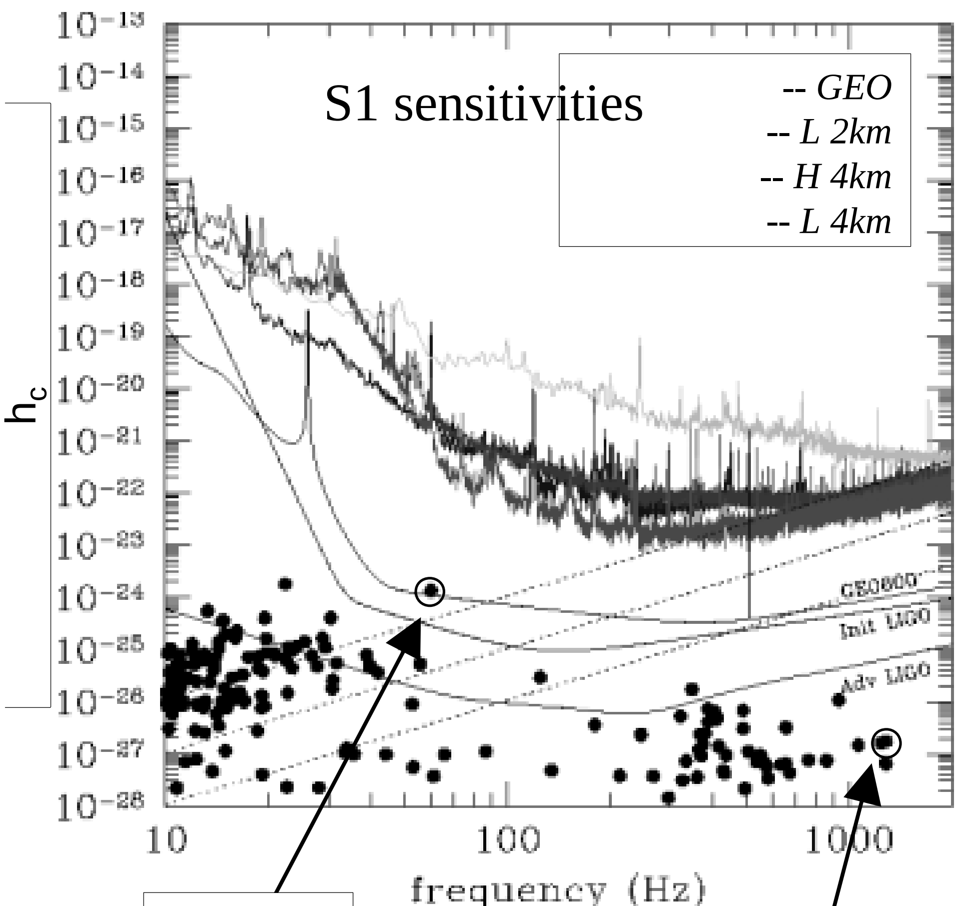


~175 kpc

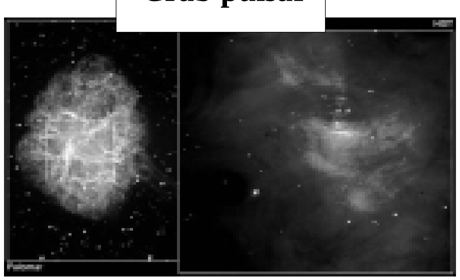
Single Interferometer

Image: R. Powell

Upper Limits on Periodic Sources



Crab pulsar



PSR J1939+2134
P = 0.00155781 s
f_{GW} = *1283.86 Hz*
D = 3.6 kpc

» **Source:** PSR J1939+2134 (fastest known rotating neutron star) located 3.6 kpc from us.

- **Frequency of source:** known
- **Rate of spindown:** known
- **Sky coordinates (α, δ) of source:** known
- **Amplitude h_0:** unknown (spindown: $h_0 < 10^{-27}$)
- **Orientation ι:** unknown
- **Phase, polarization φ, ψ:** unknown

» **Two search methods**

- **Time domain - optimal for detection**
- **Frequency domain - sets Bayesian upper limit**

» **S1 results**

- **$h_o<1.4\times10^{-22}$** (from Livingston)
- Constrains **ellipticity** $\varepsilon < 2.7\times10^{-4}$

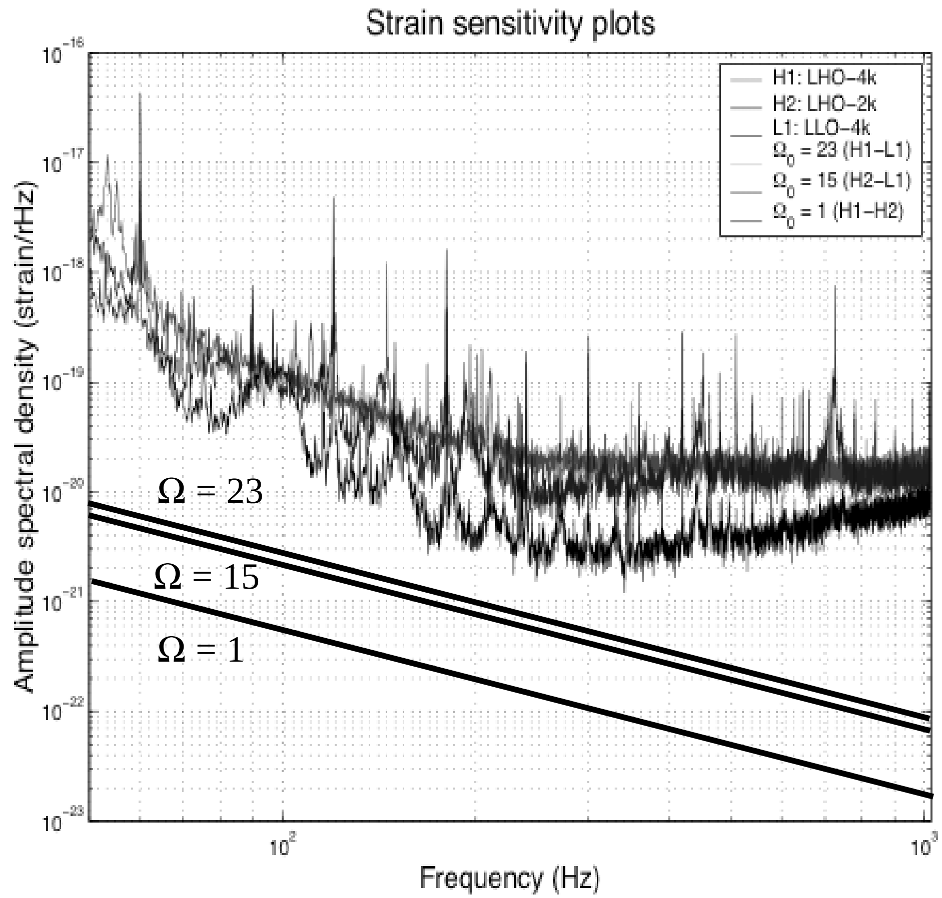
Upper Limits on Stochastic Background

Sources

•Early universe sources (inflation, cosmic strings, etc) produce very weak, non-thermal unpolarized, isotropic, incoherent background spectrum

•Contemporary sources (unresolved SN & inspiral sources) produce power-law spectrum

•Indirect constraint from nucleosynthesis on fractional energy density $\Omega_{GW}(f) < 10^{-5}$



- **S1 search results:**

  H1-H2 cross-correlation contaminated by environmental noise ($\Omega_{GW} < 0$)

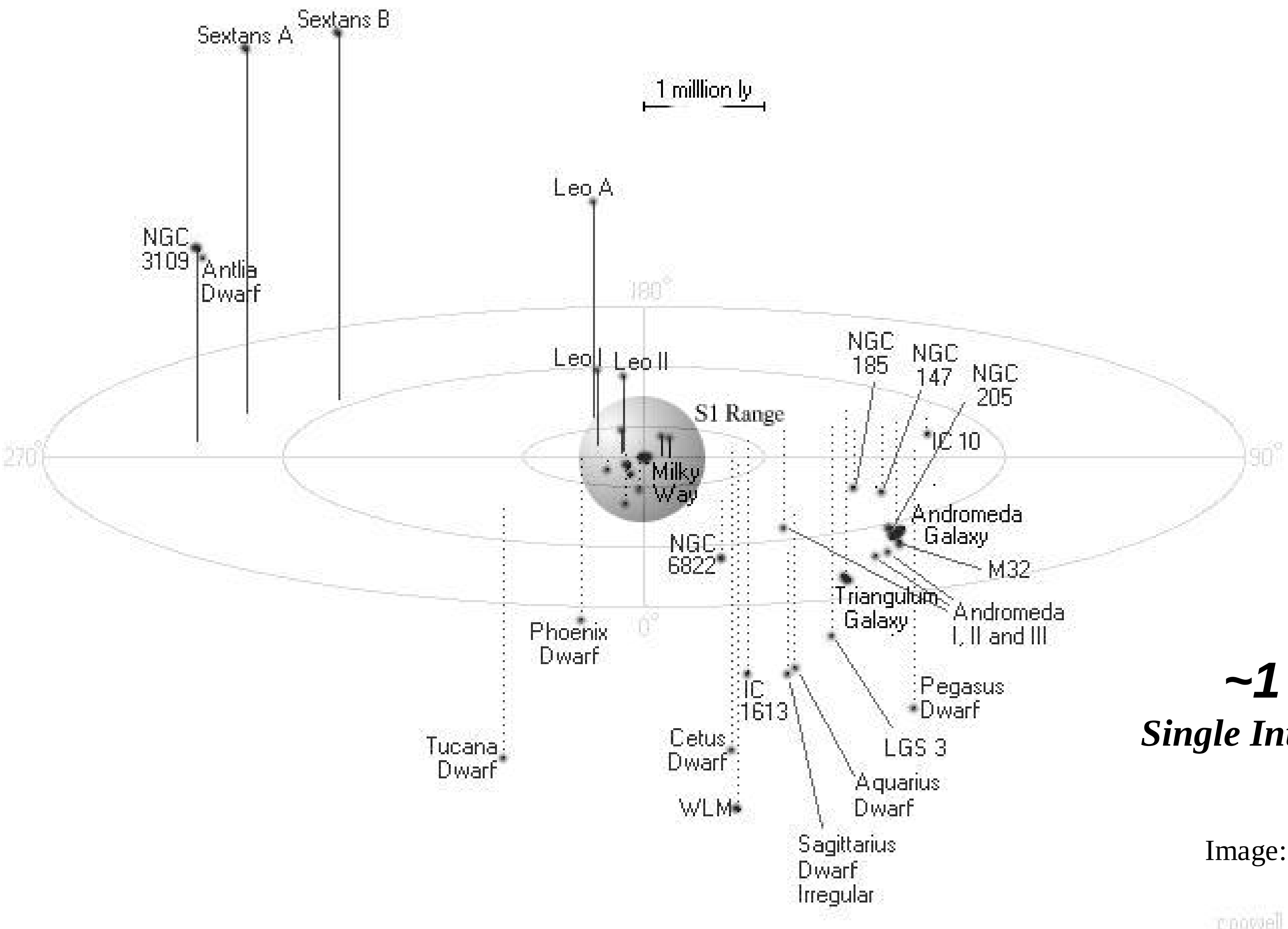
  Limit from H2-L1 (with 90% confidence): **Ω_{GW} (40Hz - 314 Hz) < 23 ± 4.6**

  Best limit from direct measurements

Future Science Runs

- S2 run from February 2003 - April 2003
  - » Eight weeks of data collected
  - » Coincidence with GEO and TAMA
- Sensitivity improved over S1
  - » 1 Mpc Neutron star inspiral range at Livingston
- Further analysis of data in progress
  - » Black hole inspirals, neutron stars source in Andromeda
  - » Templates for black hole ringdowns and supernova
  - » Burst correlations with γ-ray bursts, Type II Supernova
  - » More pulsars in periodic search including Crab
  - » Look for stochastic correlations with ALLEGRO
- S3 data run scheduled for fall 2003
- Seismic retrofit at Livingston to follow S3

Range for neutron star inspirals during S2

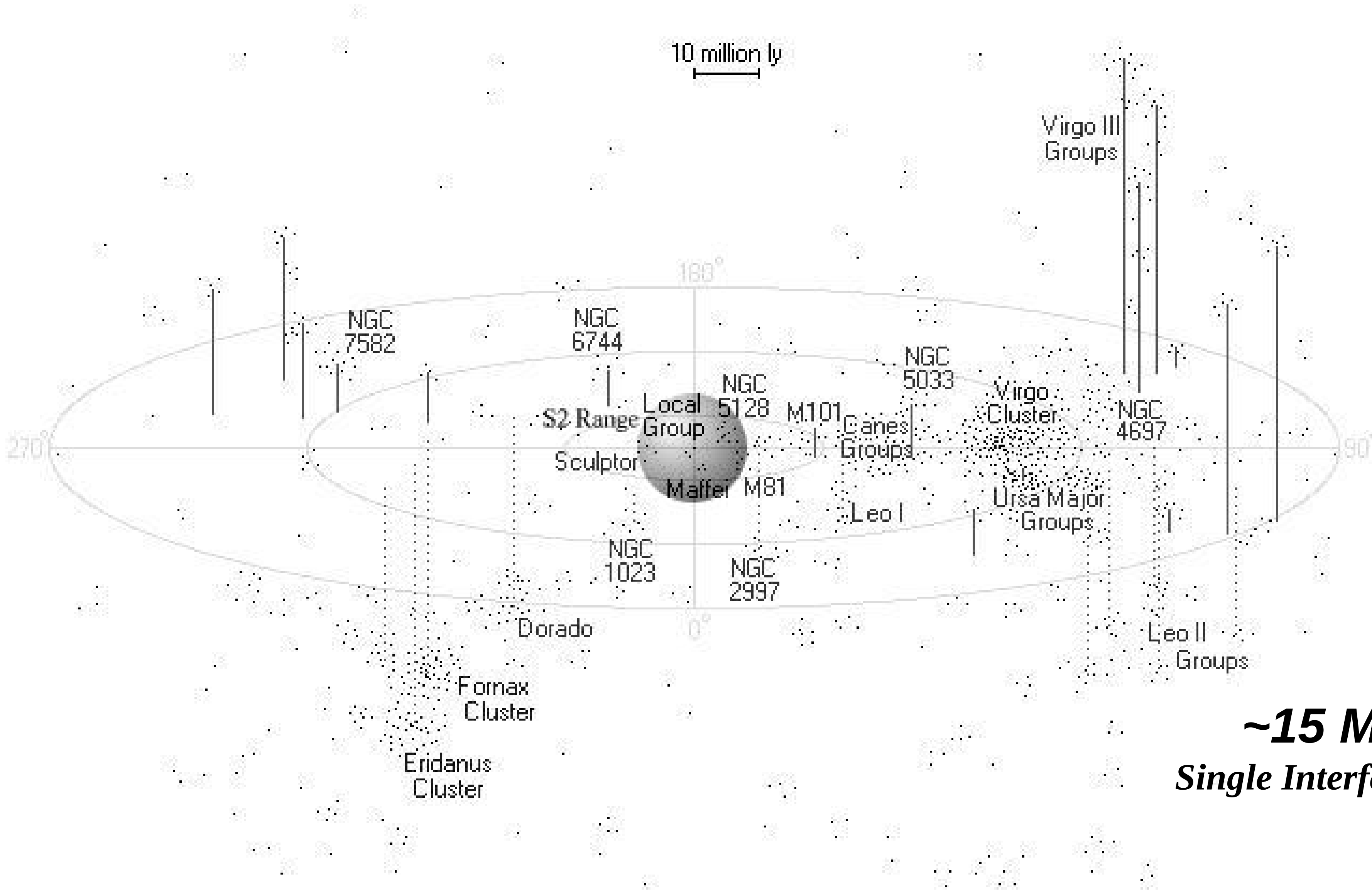


~1 Mpc

Single Interferometer

Image: R. Powell

Range for neutron star inspirals at design sensitivity

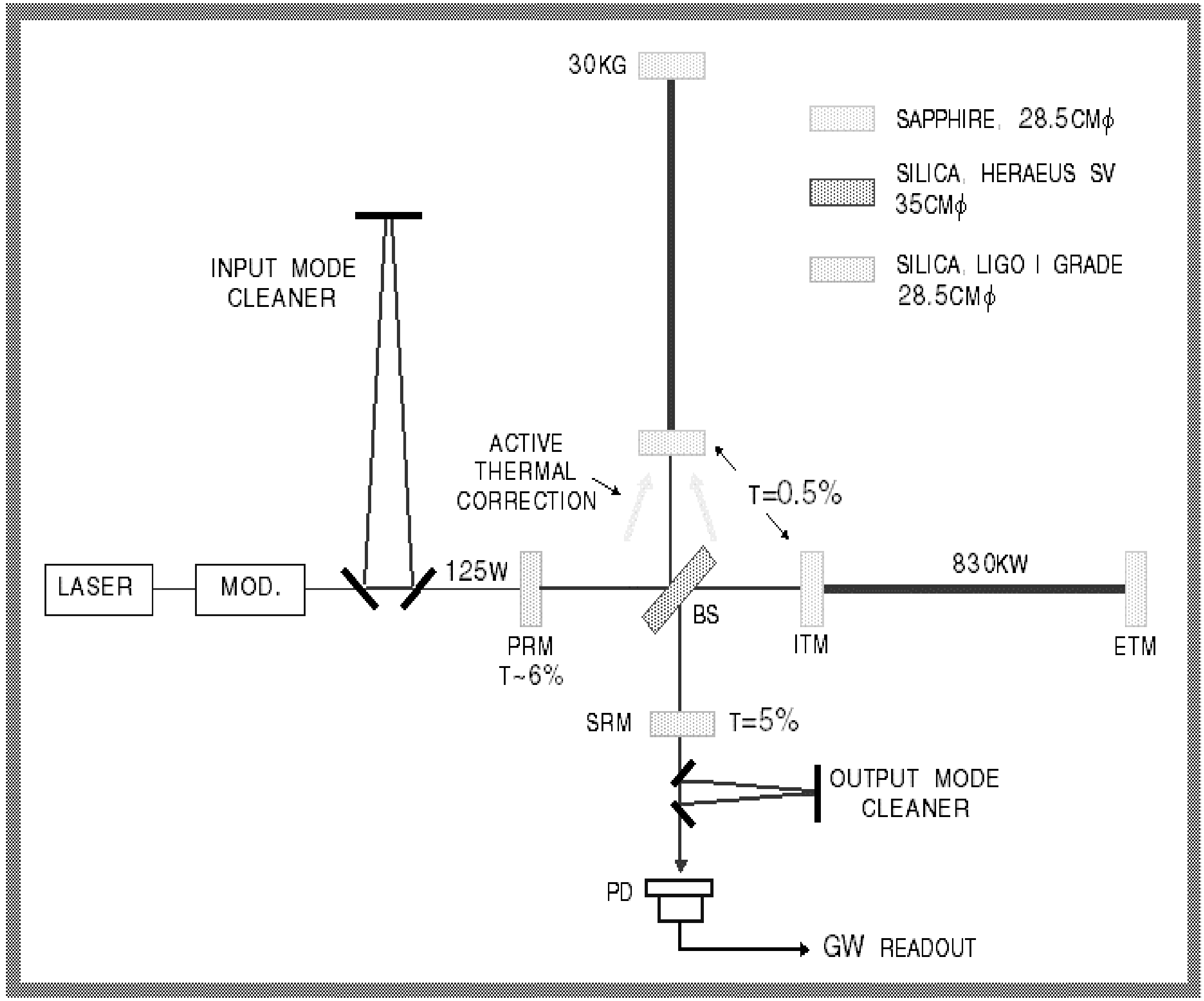


~15 Mpc

Single Interferometer

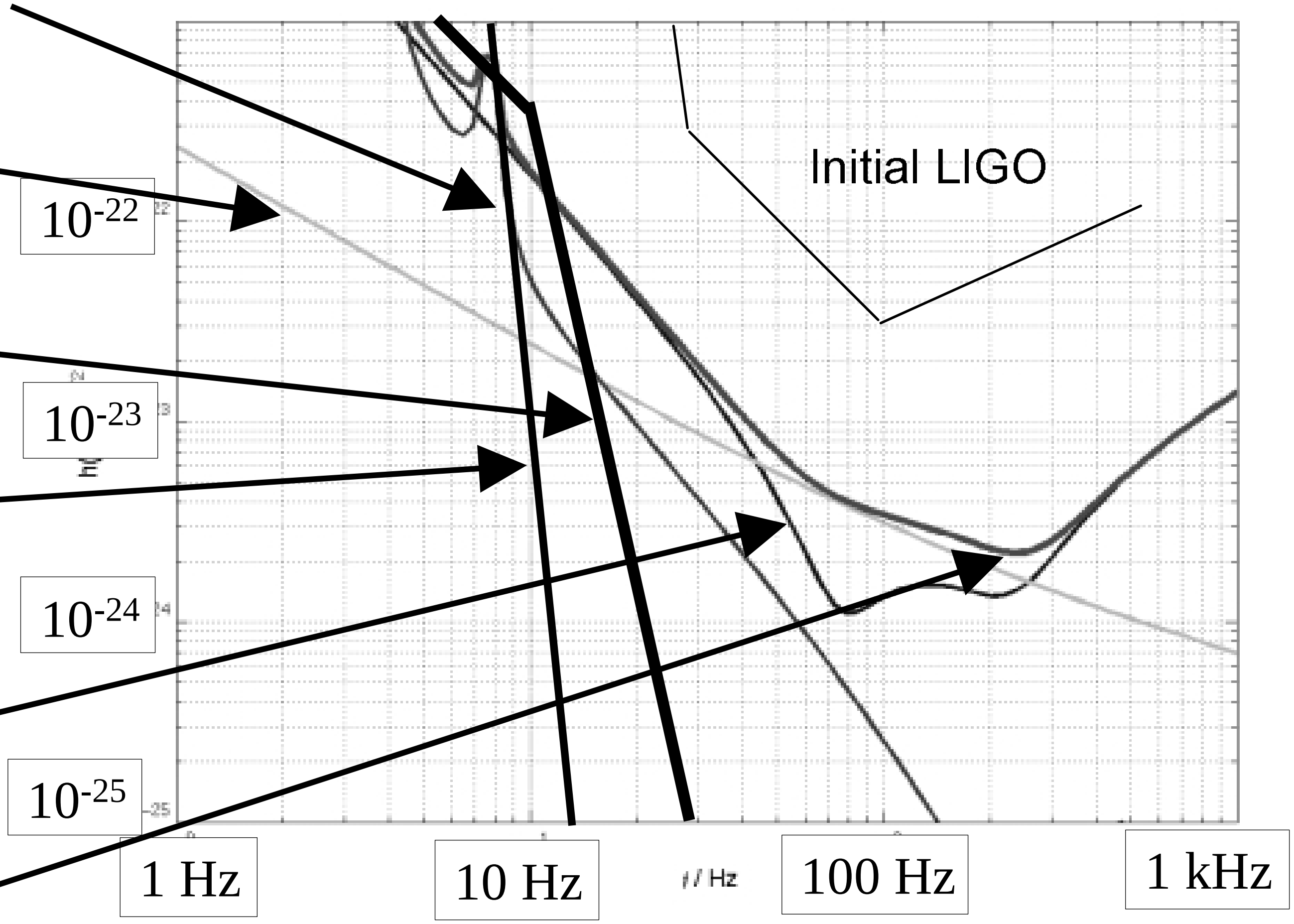
Advanced LIGO configuration

- ***Higher laser power reduces shot noise but requires thermal correction***
- ***Sapphire optics and improved coatings reduces internal mode thermal noise***
- ***Improved seismic isolation allows for sensitivity down to 10 Hz***
- ***Signal recycling mirror allows for flexible sensitivity curve***

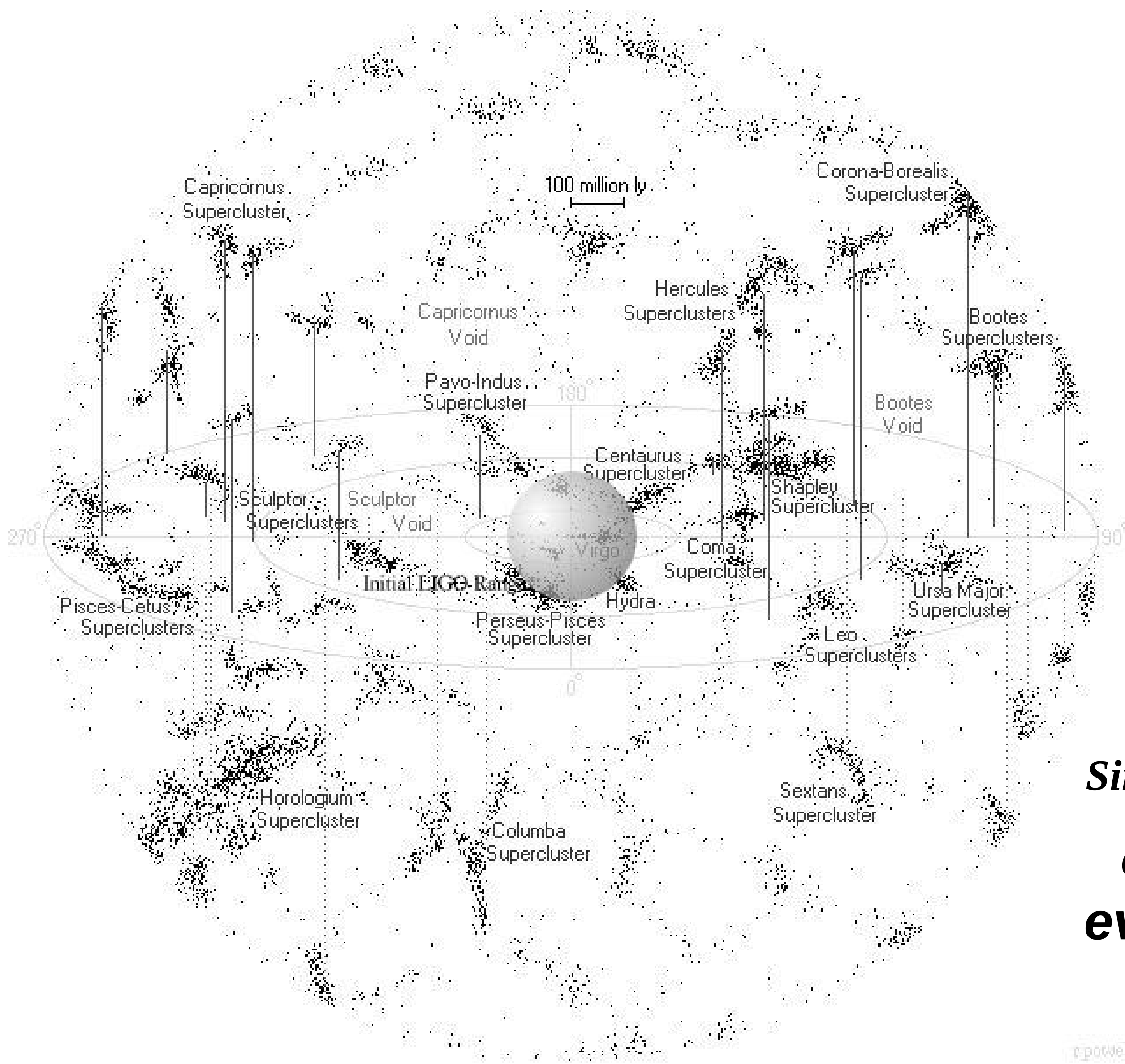


Advanced LIGO sensitivity

- Suspension thermal noise
- Internal thermal noise
- Newtonian background, estimate for LIGO sites
- Seismic cutoff at 10 Hz
- Unified quantum noise dominates at most frequencies for full power, broadband tuning
- Total noise



Range for neutron star inspirals at Advanced LIGO sensitivity



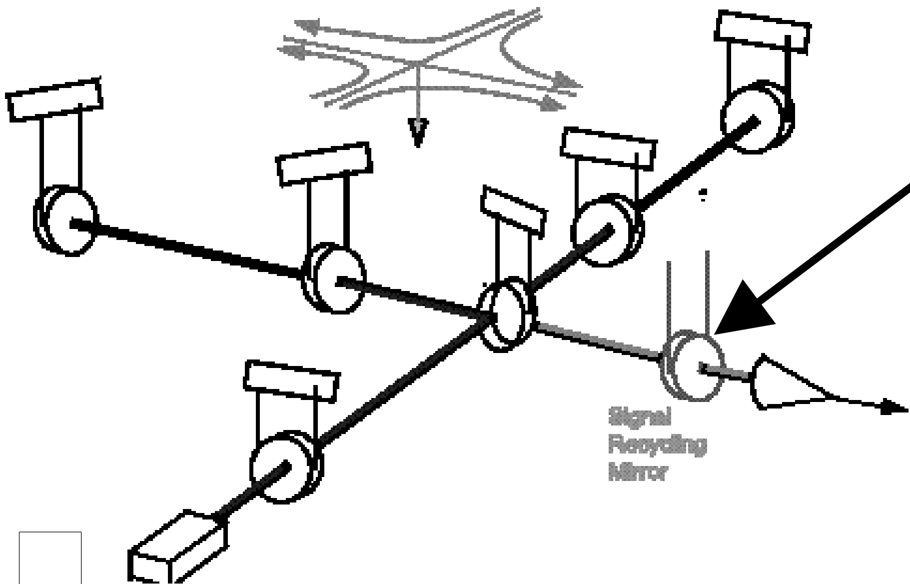
~200 Mpc

Single Interferometer

expect a few events per year

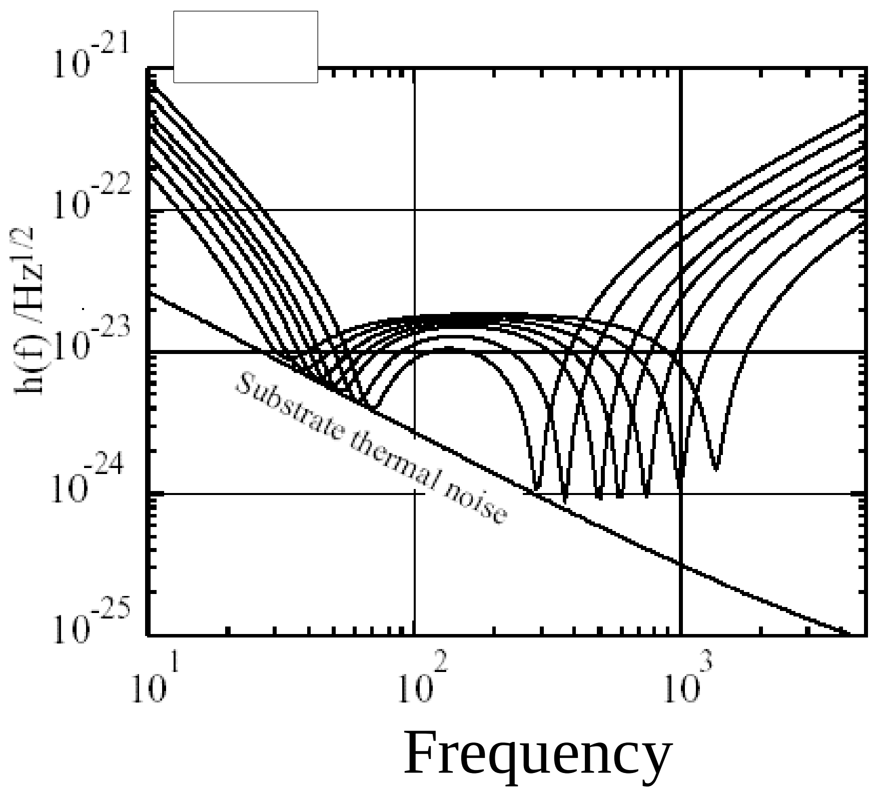
Image: R. Powell

Tunability of Advanced LIGO



- Extra mirror at output port
- Signal recycling allows for different sensitivity curves
- Small changes in mirror position change frequency response

- Can optimize for broadband response or narrowband at a chosen frequency
- Can be tuned against technical constrainst, e.g. thermal noise
- Can be tuned for particular astrophysical source



Timeline

- Initial LIGO Observation 2002 - 2006
  - » 1+ year observation at design sensitivity
  - » Significant networked observation with GEO, LIGO, TAMA, bars, etc
- R&D program to develop technologies 1998 - 2005
  - » Conceptual design developed by LSC in 1998
  - » Cooperative Agreement carries R&D to Final Design, 2005
- Proposal submitted in Feb 2003 for fabrication, installation
- Long-lead purchases planned for 2004
  - » Sapphire Test Mass material, seismic isolation fabrication
  - » Prepare a stock of equipment for minimum downtime, rapid installation
  - » Gain experience with installation and commissioning at MIT with LASTI
- Start installation in 2007
  - » Baseline is a staged installation, Livingston and then Hanford Observatories
- Start coincident observations in 2009

Conclusion

LIGO is taking scientifically interesting data

» S1 run basis for upper limits on gravitational wave sources

» S2 data at unprecedented sensitivities

Commissioning of interferometers closing in on goal

» About an order of magnitude from design sensitivity in some bands

» Seismic retrofit at Livingston will address duty cycle

Advanced LIGO proposed

» Research into new technologies ongoing

» Plan to be operational in 2009

Collaboration expanding

» Analysis of data by many groups in LIGO Science Collaboration

» Coincident running of multiple detectors across the globe

» International team designing and building Advanced LIGO

LIGO Science Collaboration

- Scientific impetus, expertise, and development throughout the LIGO Scientific Collaboration (LSC)
  - Remarkable synergy, critical mass (400+ persons, 100+ graduate students, 40+ institutions)
  - International support and significant material participation
  - Especially strong coupling with German-UK GEO group, capital partnership
- Advanced LIGO design, R&D, and fabrication spread among participants
  - LIGO Laboratory leads, coordinates, takes responsibility for Observatories
- Continuing strong support from the NSF at all levels of effort theory, R&D, operation of the Laboratory
- International network growing: VIRGO (Italy-France), GEO-600 (Germany-UK), TAMA (Japan), ACIGA (Australia)