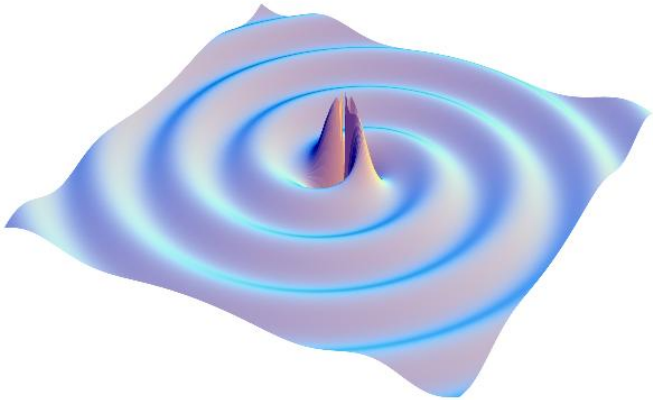
The Present Gravitational Wave Detection Effort



Keith Riles
University of Michigan

LIGO Scientific Collaboration

International Conference on Topics in Astroparticle and Underground Physics

Rome – July 1, 2009

LIGO-G0900597-v1

What <u>are</u> Gravitational Waves?

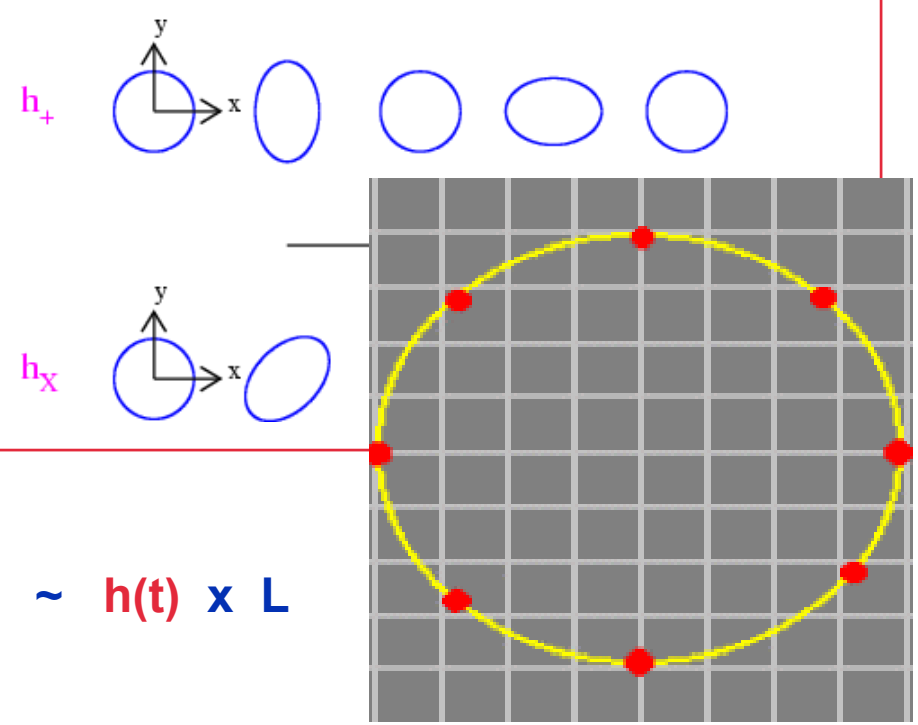
- **Gravitational Waves = "Ripples in space-time"**
- **Perturbation propagation similar to light (obeys same wave equation!)**
  - Propagation speed = c
  - Two transverse polarizations - <u>quadrupolar</u>: + and x

Example:

Ring of test masses

responding to wave

propagating along z



Amplitude parameterized by (tiny)

dimensionless strain h: $\Delta L \sim h(t) \times L$

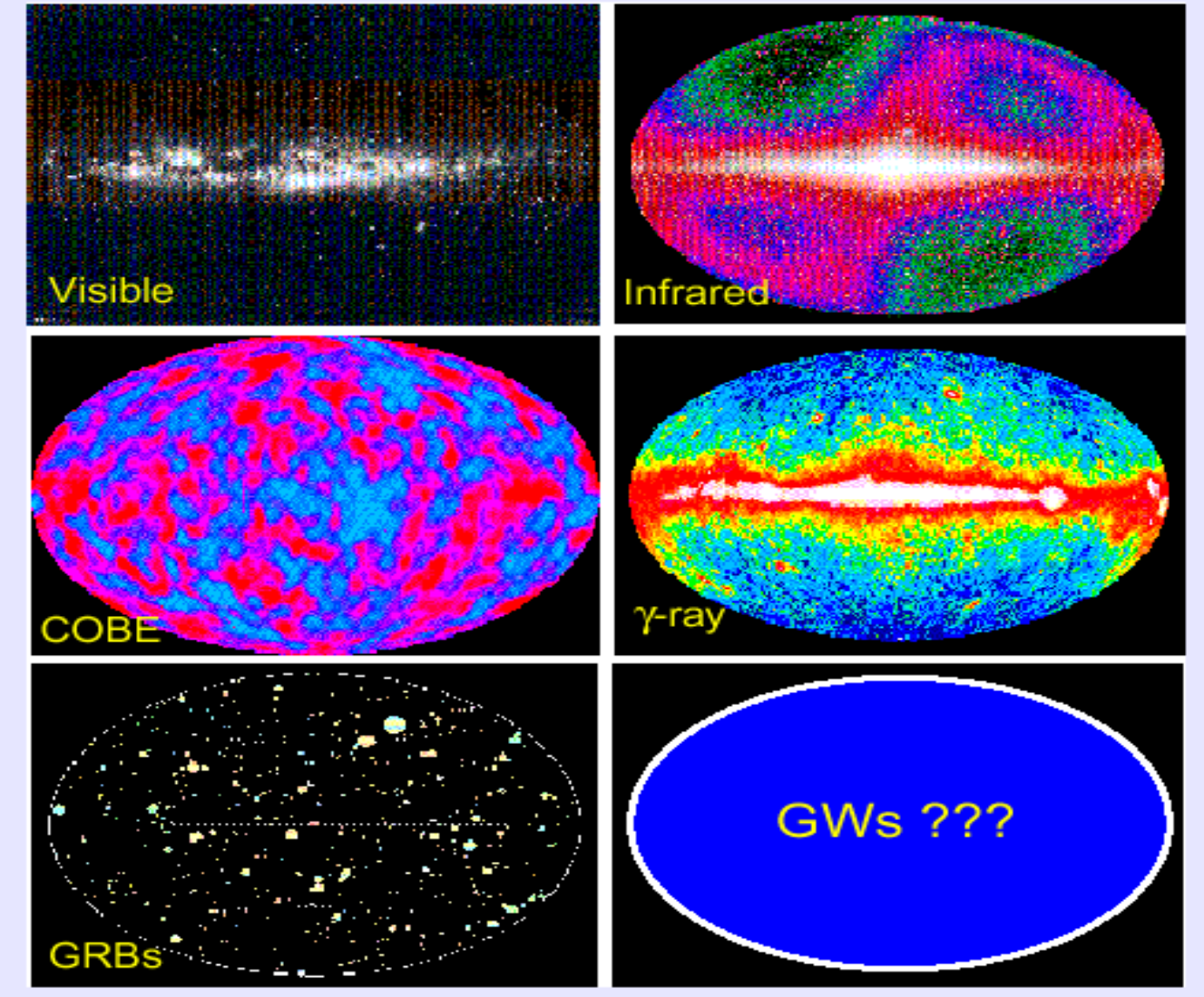
Why look for Gravitational Radiation?

- Because it's there! (presumably)

- Test General Relativity:
  - Quadrupolar radiation? Travels at speed of light?
  - Unique probe of strong-field gravity

- Gain different view of Universe:
  - Sources cannot be obscured by dust / stellar envelopes
  - Detectable sources some of the most interesting, least understood in the Universe
  - Opens up entirely new non-electromagnetic spectrum

What might the sky look like?



What makes Gravitational Waves?

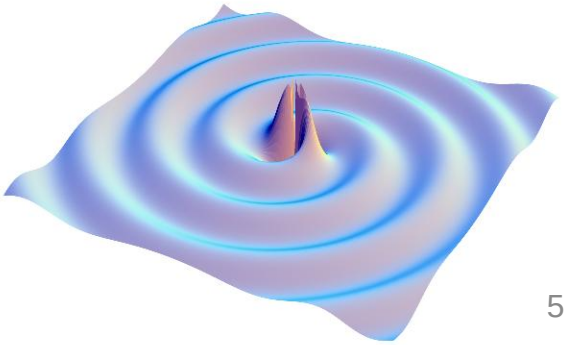
- Radiation generated by quadrupolar mass movements:

$$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2}{dt^2}(I_{\mu\nu})$$

(with $I_{\mu\nu}$ = quadrupole tensor, r = source distance)

- Example: Pair of 1.4 M_{solar} neutron stars in circular orbit of radius 20 km (imminent coalescence) at orbital frequency 400 Hz gives 800 Hz radiation of amplitude:

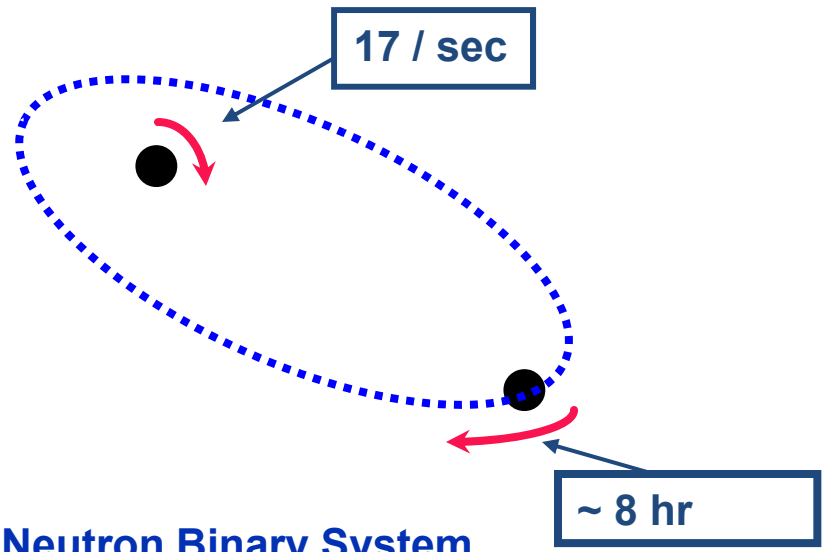
$$h \approx \frac{10^{-21}}{(r/15\mathrm{Mpc})}$$



Strong Indirect Evidence:
Binary Orbit Decay

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



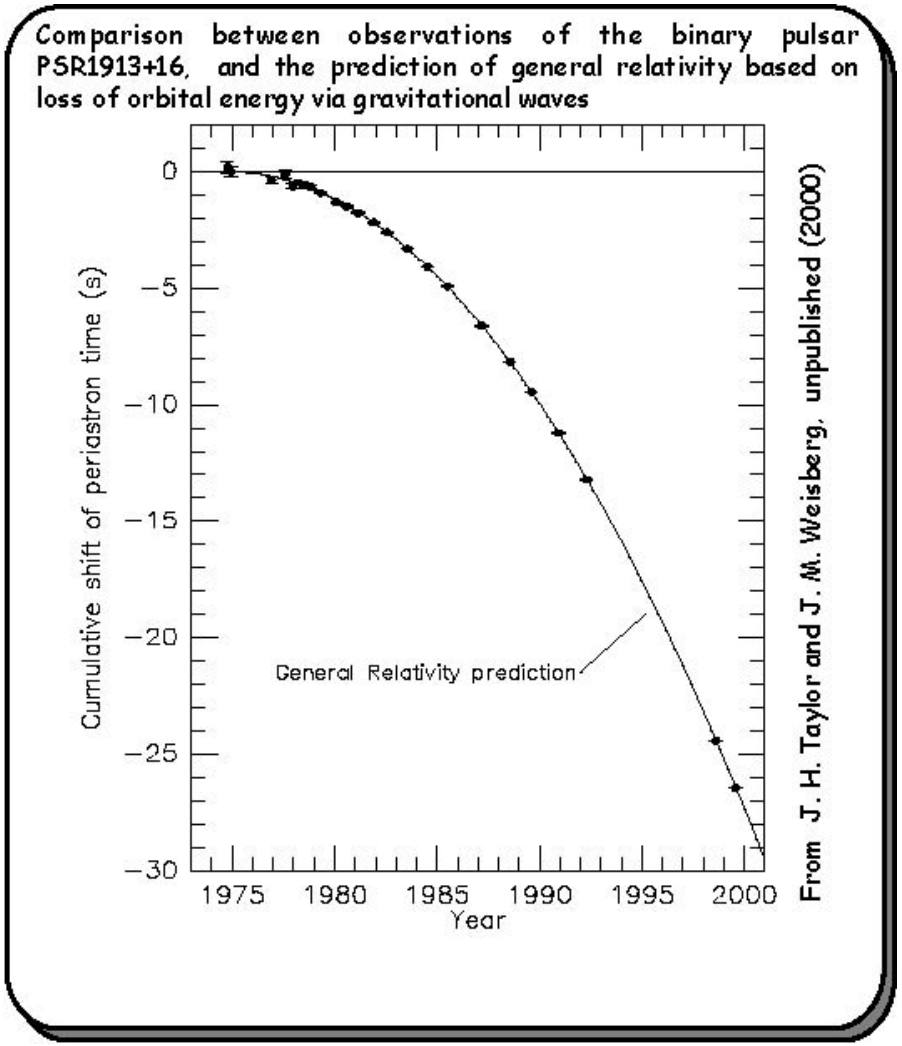
Neutron Binary System

- separated by 10^6 miles
- $m_1 = 1.44 m_\odot$; $m_2 = 1.39 m_\odot$; $\varepsilon = 0.617$

Prediction from general relativity

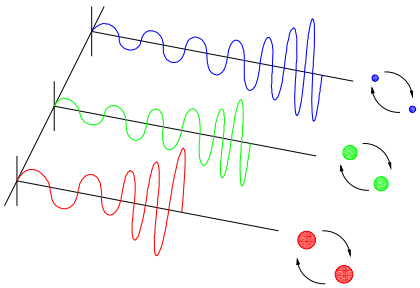
- spiral in by 3 mm/orbit
- rate of change orbital period

Emission of gravitational waves

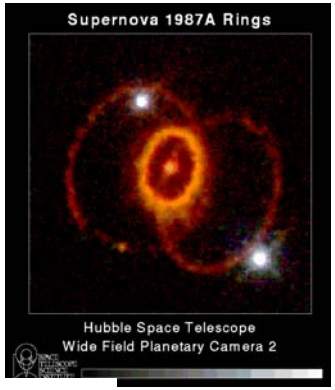


What makes Gravitational Waves?

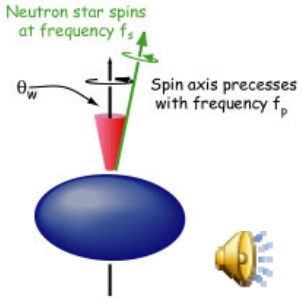
- **Compact binary inspiral:** *"chirps"*
  - NS-NS waveforms are well described
  - Recent progress on BH-BH waveforms



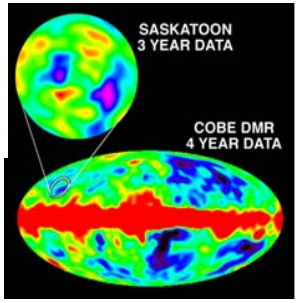
- **Supernovae / GRBs:** *"bursts"*
  - burst signals in coincidence with signals in electromagnetic radiation / neutrinos
  - all-sky untriggered searches too



- **Pulsars in our galaxy:** *"periodic"*
  - search for observed neutron stars
  - all-sky search (computing challenge)

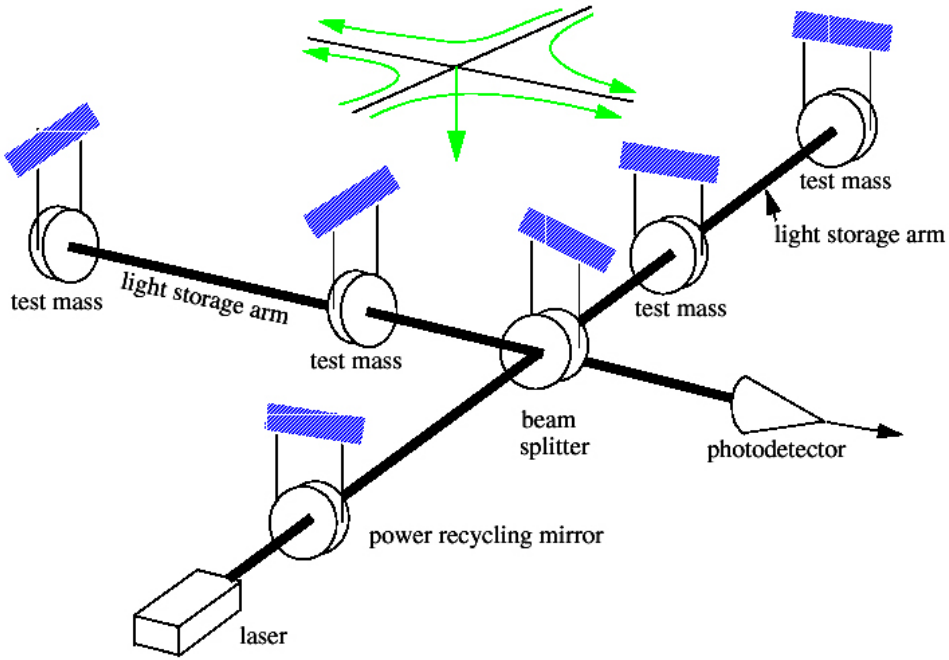


- **Cosmological Signals** *"stochastic background"*



Gravitational Wave Detection

- Suspended Interferometers
  - Suspended mirrors in “free-fall”
  - Michelson IFO is “natural” GW detector
  - Broad-band response (~10 Hz to few kHz)
  - Waveform information (e.g., chirp reconstruction)



The Global Interferometer Network

The three (two) LIGO, Virgo and GEO interferometers are part of a Global Network.

Multiple signal detections will increase detection confidence and provide better precision on source locations and wave polarizations

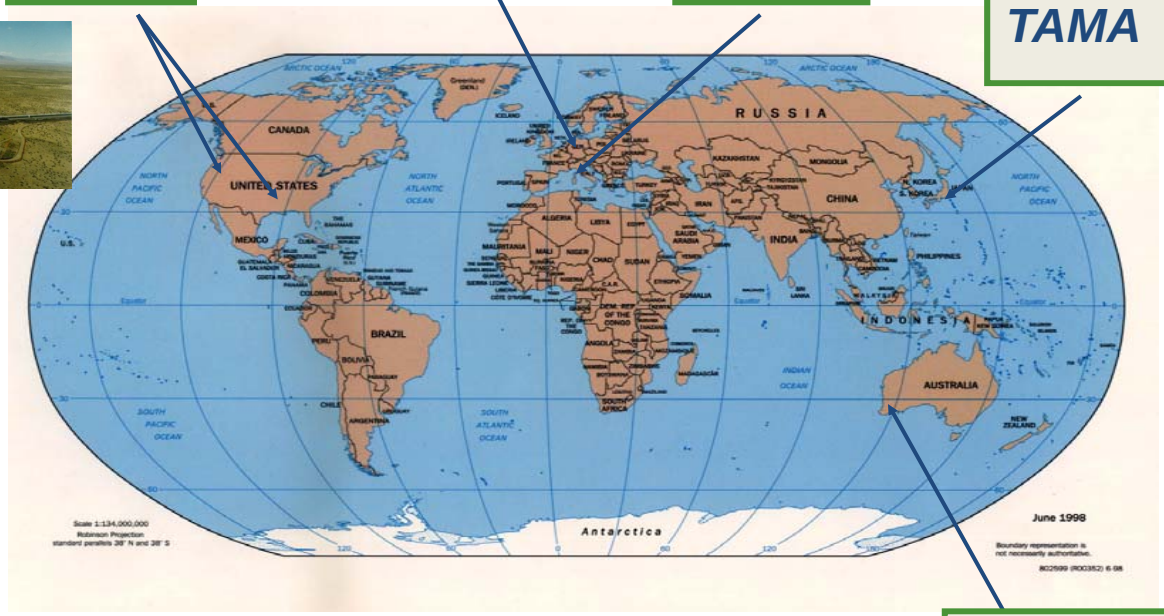
L1

G1

V1

H1, H2

T1



Major Interferometers world-wide

LIGO Livingston, Louisiana & Hanford, Washington	2 x 4000-m (1 x 2000-m)	Completed 2-year data run at design sensitivity – "enhancement" finishing
VIRGO Near Pisa, Italy	1 x 3000-m	Took ~4 months coincident data with LIGO – approaching design sensitivity
GEO Near Hannover, Germany	1 x 600-m	Took data during L-V downtime, about to undergo upgrade
TAMA Tokyo, Japan	1 x 300-m	Used for R&D aimed at future underground detector

Data Runs

Have carried out a series of Engineering Runs (LIGO E1–E14, Virgo WSR 1-13) and Science Runs (LIGO S1--S5, Virgo VSR1) interspersed with commissioning

S1 run:

17 days (Aug / Sept 2002) – Rough but good practice

S2 run:

59 days (Feb—April 2003) – Many good results

S3 run:

70 days (Oct 2003 – Jan 2004) -- Ragged

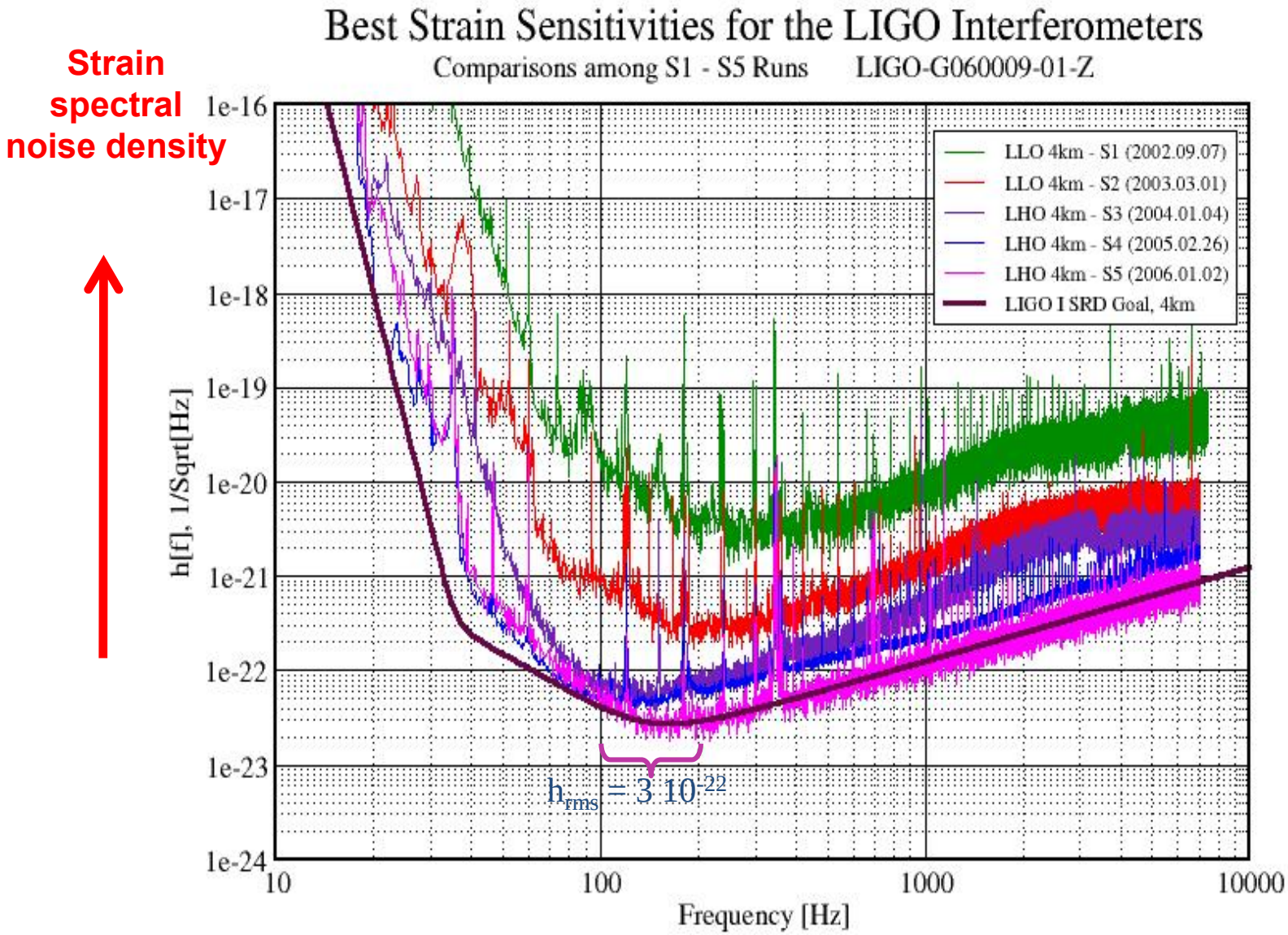
S4 run:

30 days (Feb—March 2005) – Another good run

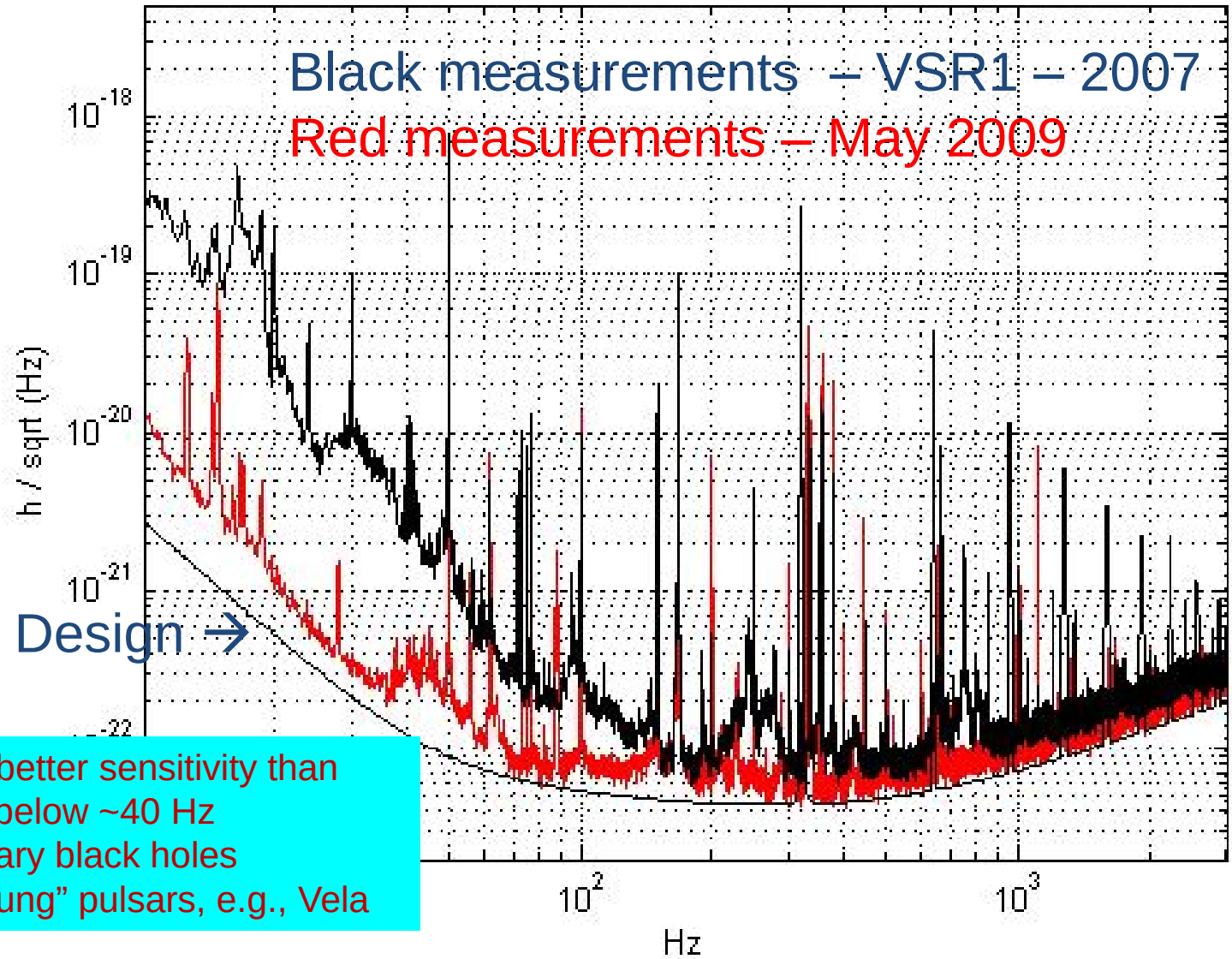
S5 run: (VSR1 for Virgo)

23 months (Nov 2005 – Sept 2007) – At design sensitivity – focus of today

LIGO S1 → S5 Sensitivities

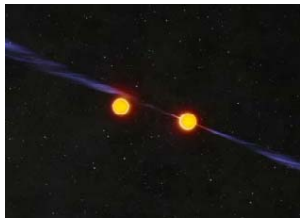


Virgo Sensitivities



Much better sensitivity than LIGO below ~40 Hz
→ Binary black holes
→ "Young" pulsars, e.g., Vela

Search for binary systems

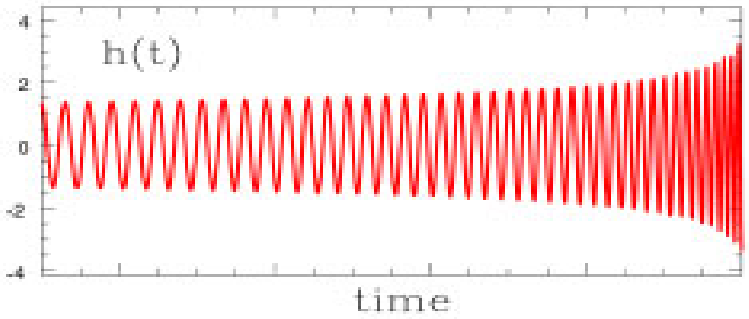


John Rowe, CSIRO

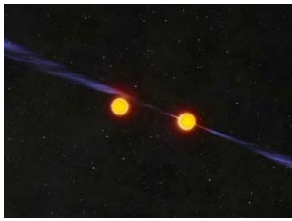
Use calculated templates for inspiral phase ("chirp") with optimal filtering.

Search for systems with different masses:

- **Binary neutron stars (~1-3 solar masses):**
  ~15 sec templates, 1400 Hz end freq
- **Binary black holes (< ~30 solar masses):**
  shorter templates, lower end freq
- **Primordial black holes (<1 solar mass):**
  longer templates, higher end freq

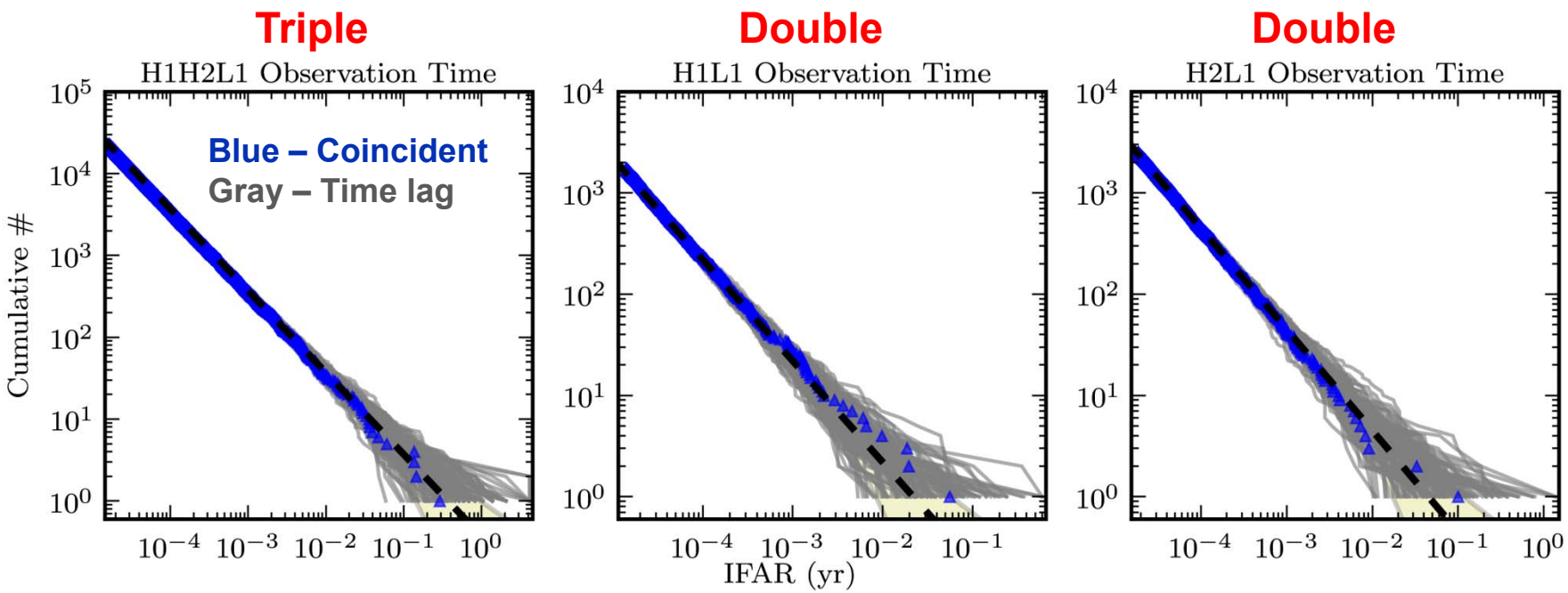


Searching for binaries



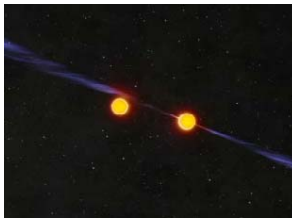
John Rowe, CSIRO

- Use two or more detectors: search for double or triple *coincident* "triggers"
- Can infer masses and "effective" distance.
- Estimate <u>inverse false alarm probability</u> of resulting candidates: detection?



S5 Year 1 Search for "Low-Mass" Inspirals

Searching for binaries



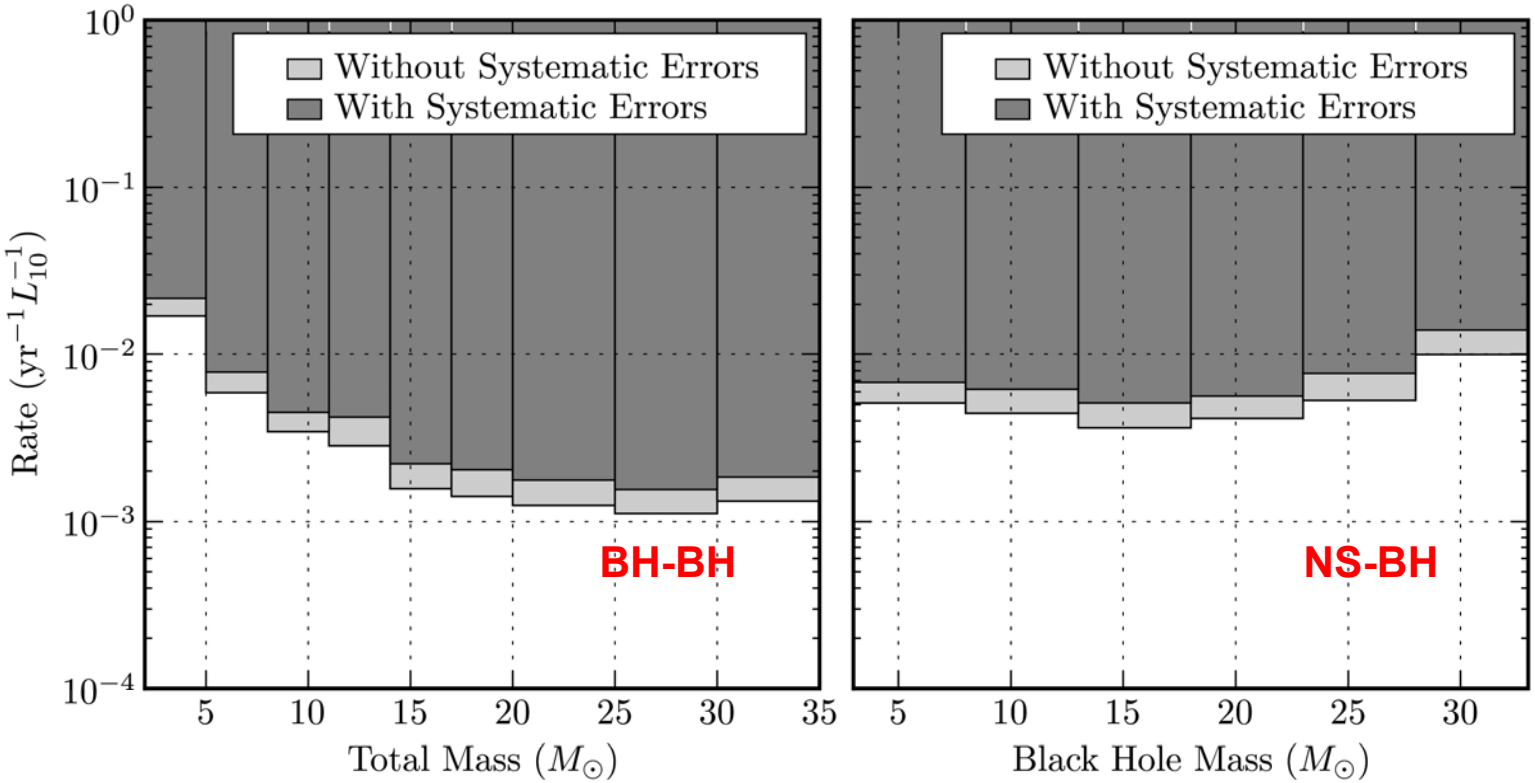
John Rowe, CSIRO

- No evidence of excess
- Use detection efficiency and surveyed galaxies

  → Set upper limit vs stellar mass

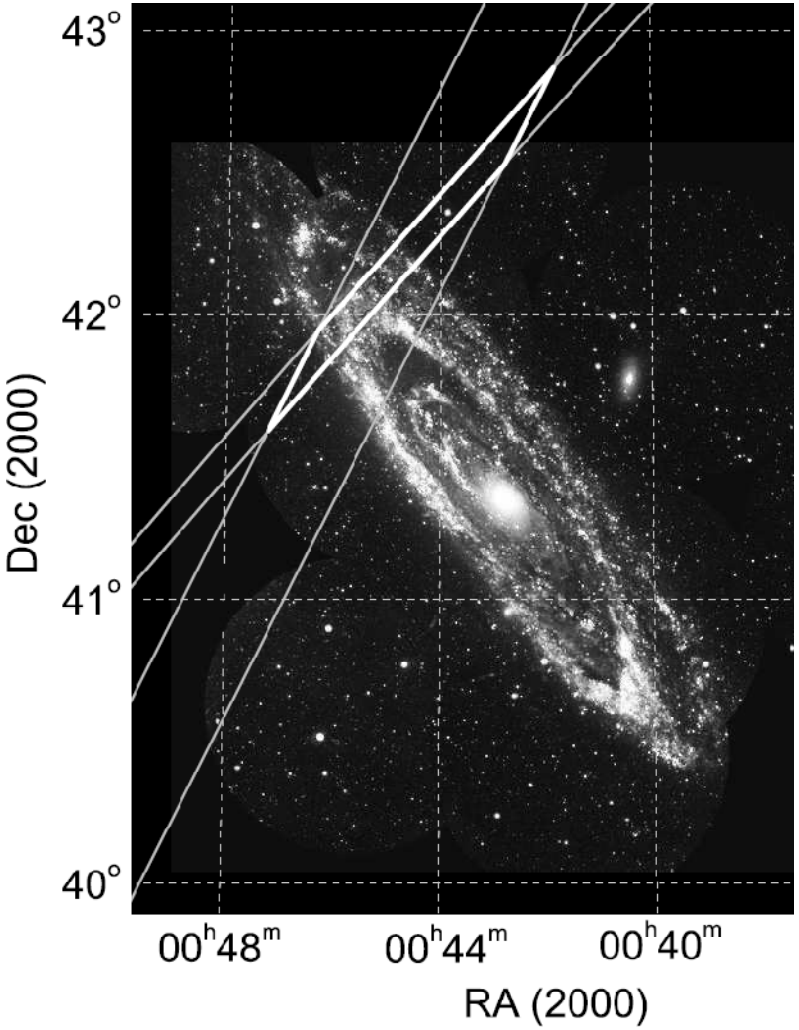
Phys. Rev. D 79 (2009) 122001

$L_{10} = 10^{10} \times$ blue solar luminosity
Milky Way = 1.7 L_{10}



Searching for bursts

GRB 070201



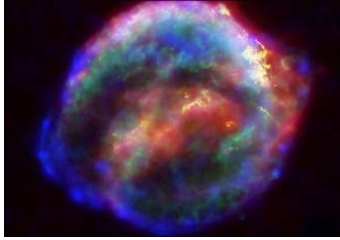
IPN 3-sigma error region from Mazets et al., ApJ 680, 545

- **Short, hard gamma-ray burst**
  - **A leading model for short GRBs: binary merger involving a neutron star**
- **Position (from IPN) consistent with being in M31 (Andromeda)**
- **LIGO H1 and H2 were operating**
- **Result from (several) LIGO searches: No plausible GW signal found; therefore very unlikely to be from a binary merger in M31**

Ap. J. 681 (2008) 1419

→ **Likely was SGR giant flare in M31**

Searching for bursts (untriggered)

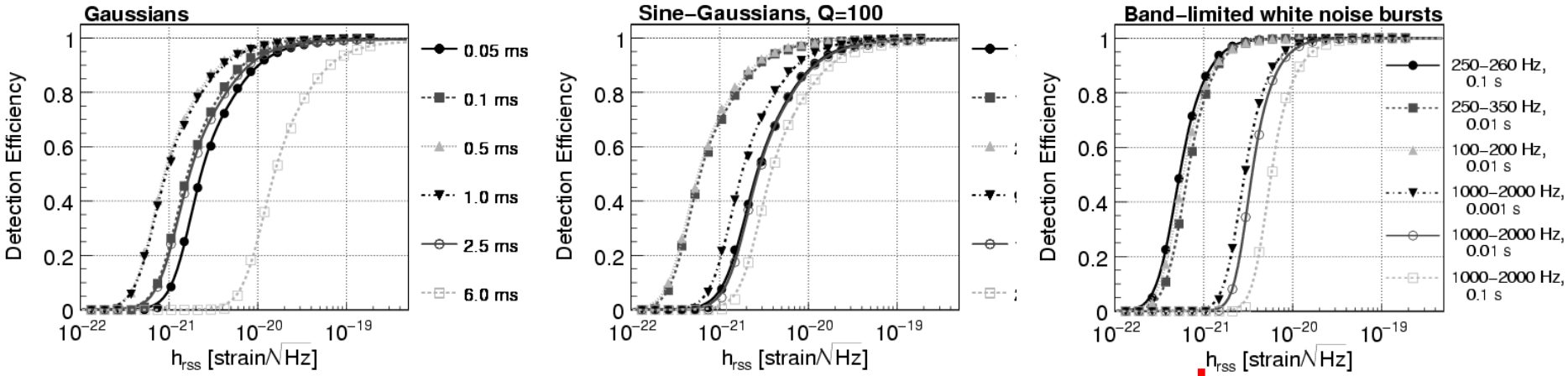


- Search for double or triple coincident triggers (three algorithms)
- Check waveform consistency among interferometers – apply vetoes
- Set a threshold for detection for low false alarm probability
- Evaluate efficiency for <u>variety of simple waveforms</u>

Parameterize strength in terms of "root sum square of h" : h_{RSS}

$$(h_{RSS})^2 = \int_{-\infty}^{+\infty} (|h_+(t)|^2 + |h_\times(t)|^2)\,dt$$

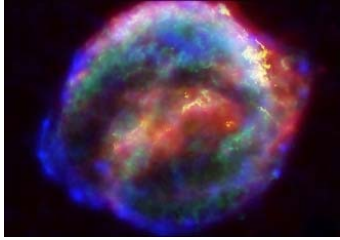
Sampling of efficiency curves:



h_{RSS}

S5 Year 1 Search for Untriggered Bursts

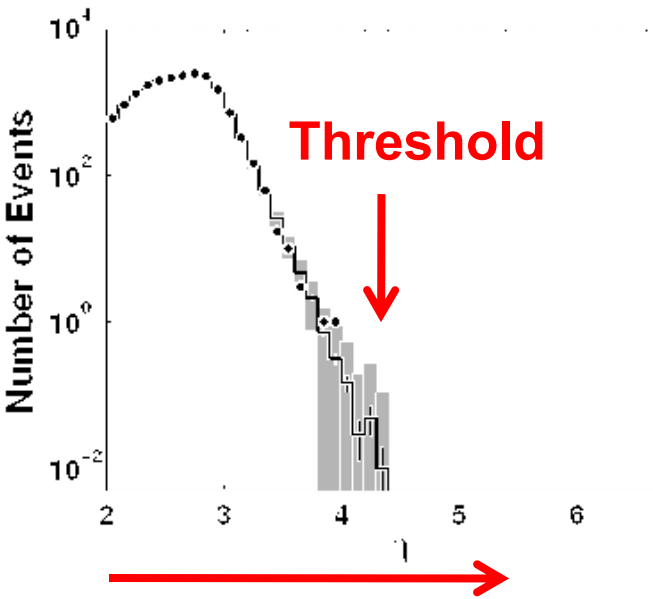
Searching for bursts (untriggered)

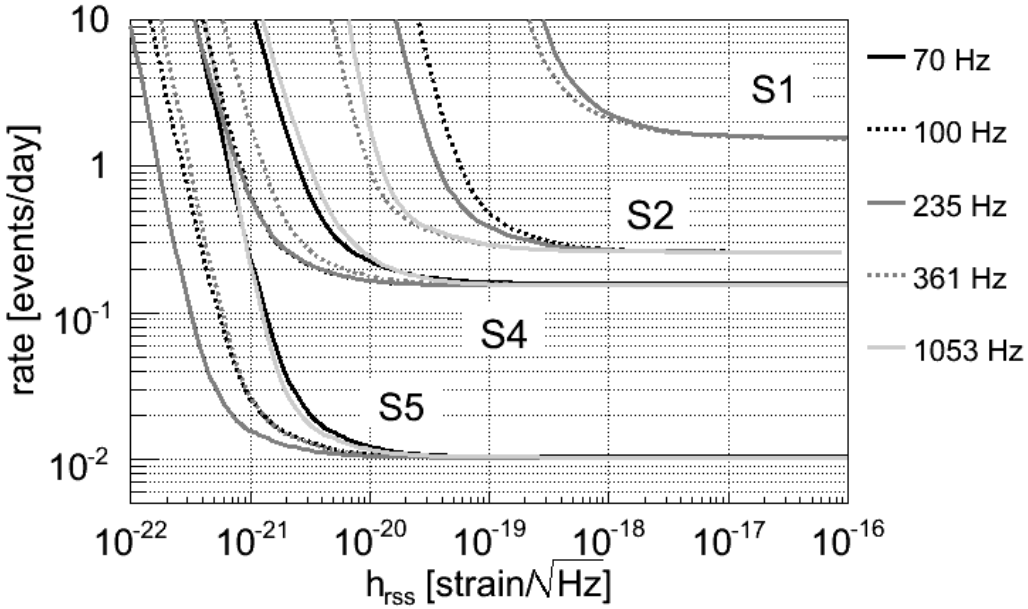


Detected triggers and expected background for one algorithm (Coherent WaveBurst – wavelet-based) for triple-coincident triggers with $f_{central}$ > 200 Hz

No candidates found above threshold in any of the searches

→ Set upper limits on rate vs h_{RSS}



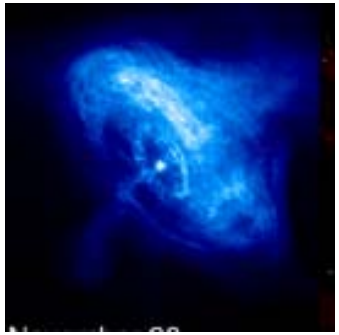


arXiv:0905.0020 (May 2009)

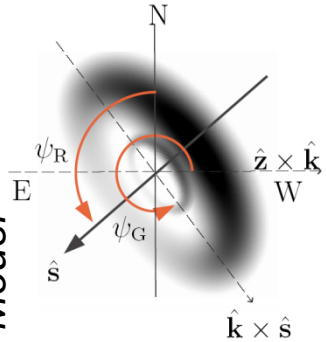
Searching for continuous waves

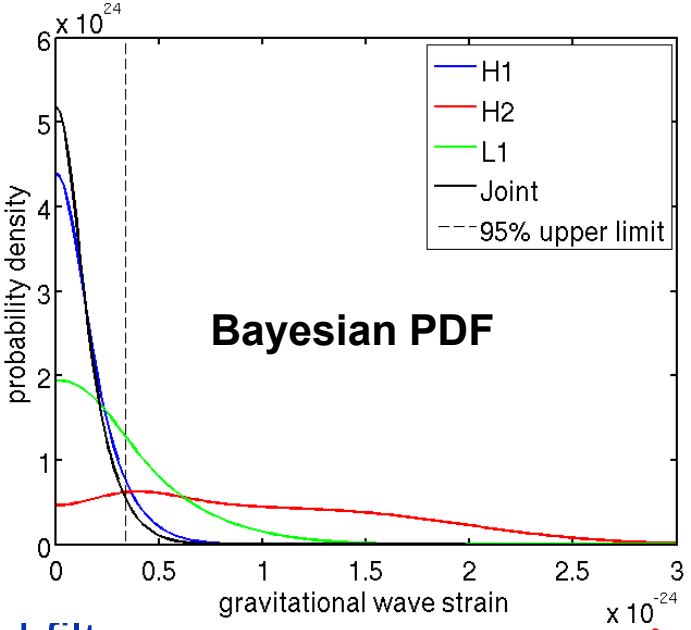
Crab Pulsar

Chandra image



Model





Use coherent, 9-month, time-domain matched filter

Strain amplitude h_0

Upper limits on GW strain amplitude h_0

Single-template, uniform prior: **3.4** **10^{-25}**

Single-template, restricted prior: **2.7** **10^{-25}** →

Multi-template, uniform prior: **1.7** **10^{-24}**

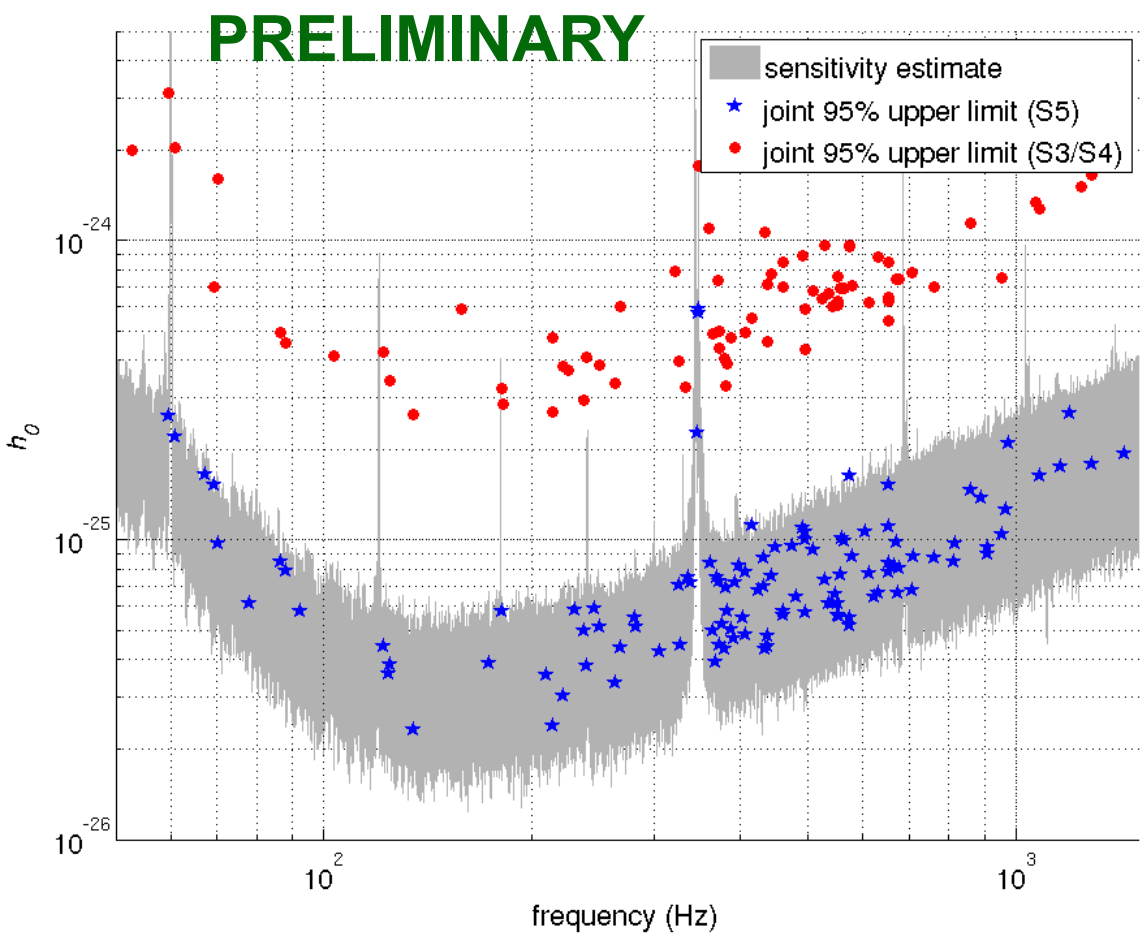
Multi-template, restricted prior: **1.3** **10^{-24}**

Implies that GW emission accounts for ≤ 4% of total spin-down power

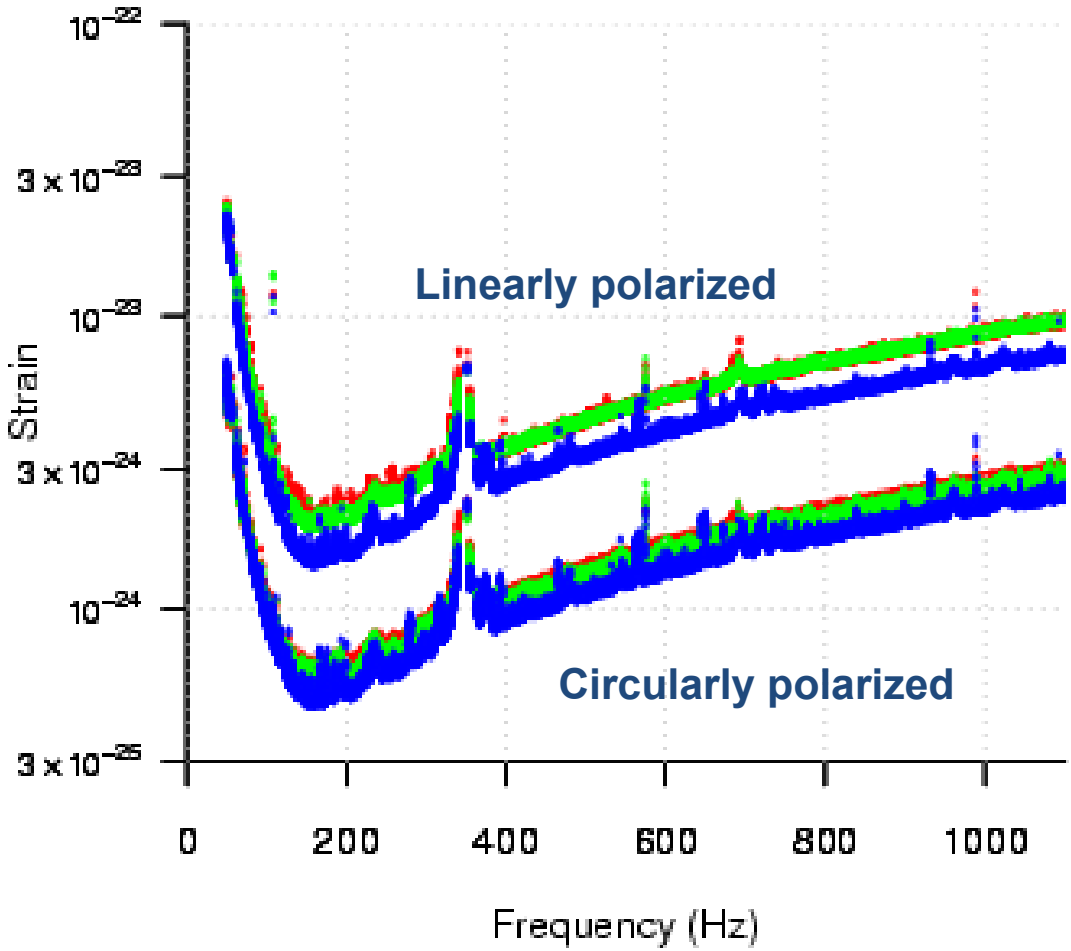
Ap. J. Lett **683 (2008) 45**

Searching for continuous waves

Same matched-filter algorithm applied to 116 known pulsars over 23 months of S5



Searching for continuous waves



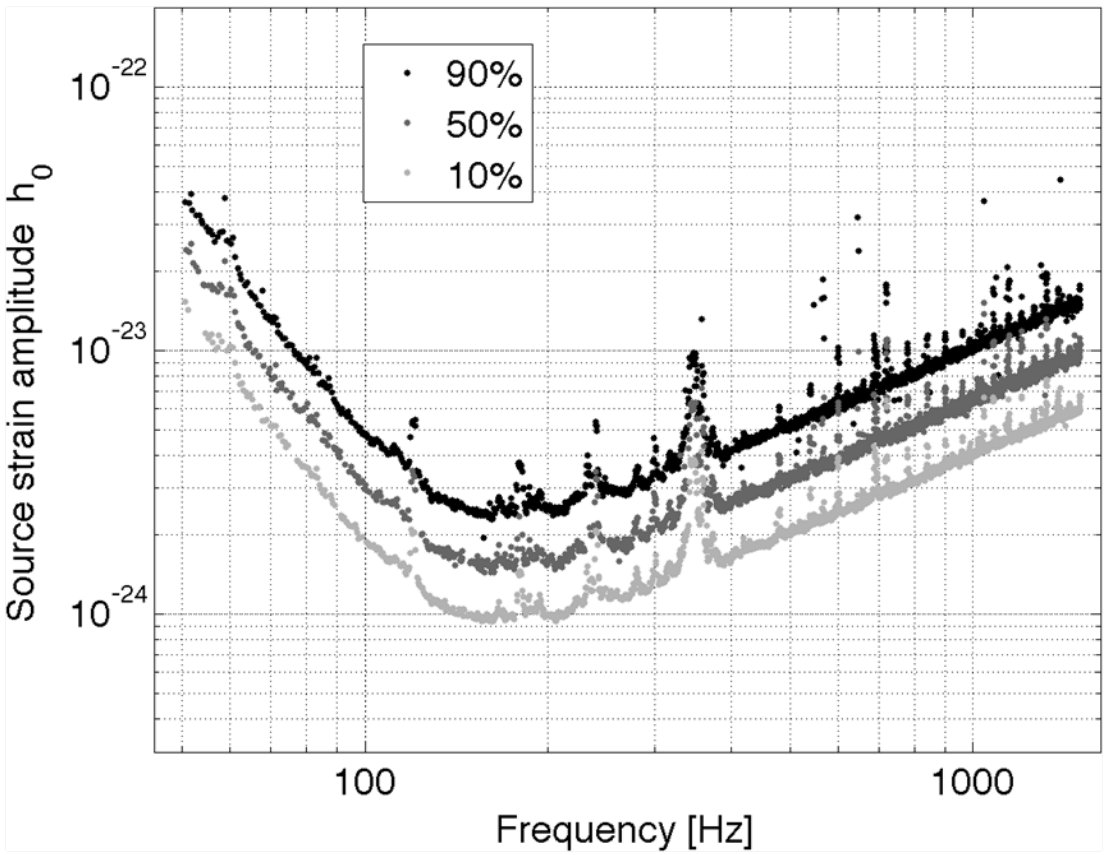
Phys. Rev. Lett. 102 (2009) 111102

All-sky search for unknown isolated neutron stars

Semi-coherent, stacks of 30-minute, demodulated power spectra

("PowerFlux")

Searching for continuous waves



All-sky search for unknown isolated neutron stars

Coincidence among multiple 30-hour coherent searches

(Einstein@Home)

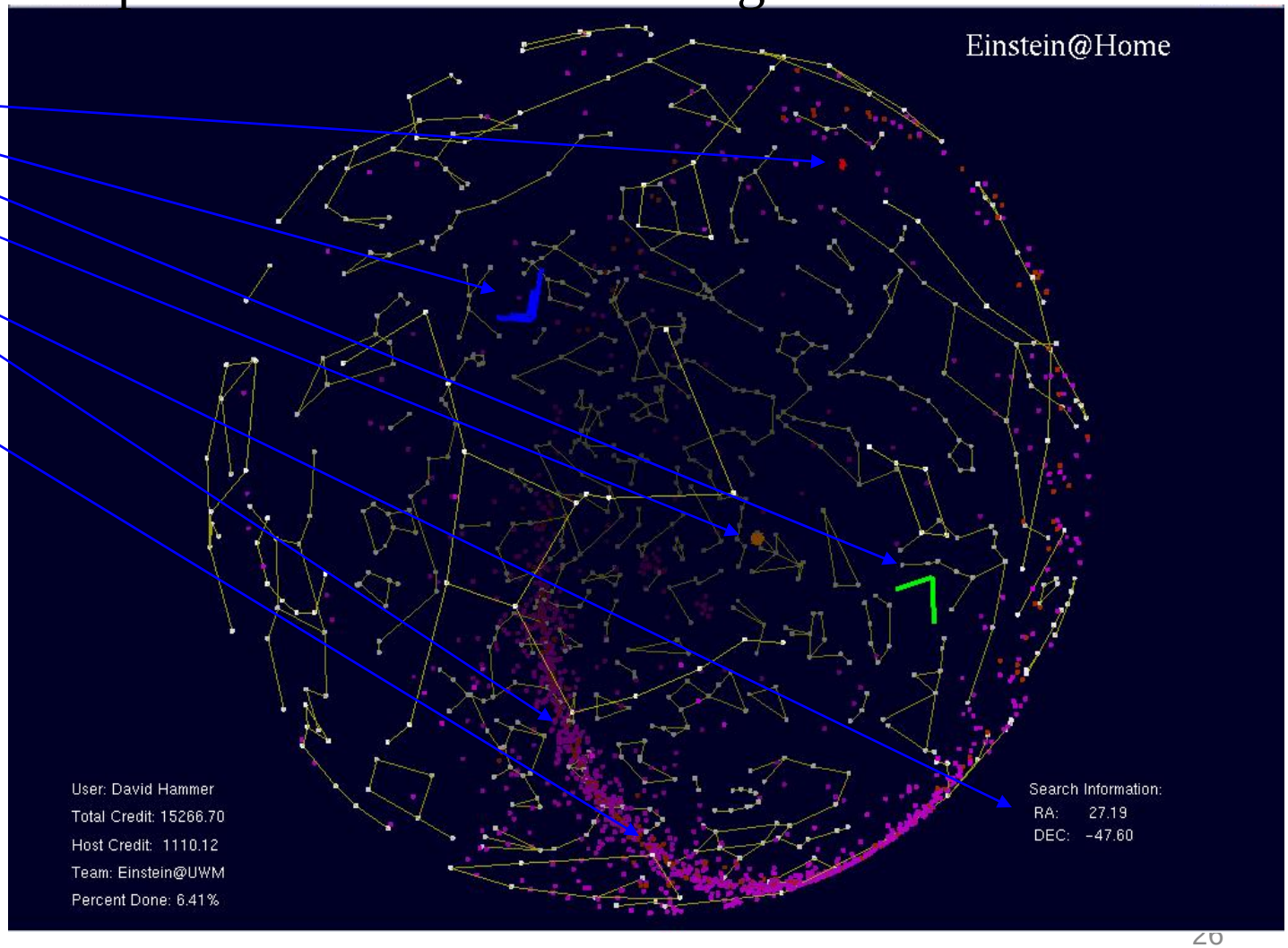
arXiv:0905.1705 (May 2009)

EINSTEIN@HOME

Catch a Wave From Space

http://www.einsteinathome.org/

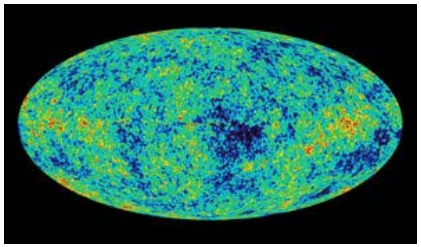
- GEO-600 Hannover
- LIGO Hanford
- LIGO Livingston
- Current search point
- Current search coordinates
- Known pulsars
- Known supernovae remnants



Improved (hierarchical) algorithm now running

Your computer can help too!

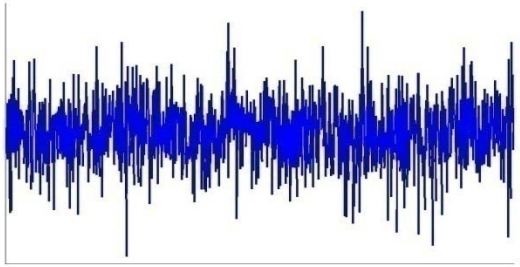
Searching for a stochastic background



NASA, WMAP

- **A primordial isotropic GW stochastic background is predicted by most cosmological theories.**
- **Given an energy density spectrum $\Omega_{gw}(f)$, there is a strain power spectrum:**

$$\Omega_{GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{GW}(f)}{d\ln f}$$

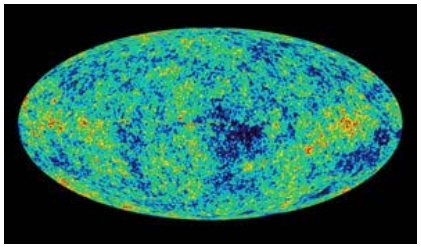


$$S_{\rm gw}(f) = \frac{3H_0^2}{10\pi^2} f^{-3}\Omega_{\rm gw}(f)$$

$$h(f) = S_{\rm gw}^{1/2}(f) = 5.6\times10^{-22}\, h_{100}\sqrt{\Omega_0}\left(\frac{100\text{Hz}}{f}\right)^{3/2} \text{Hz}^{1/2}$$

- **The signal can be searched from <u>cross-correla*tions*</u> *in different pairs of detectors: L1-H1 and H1-H2*.**
- **The farther the detectors, the lower the frequencies that can be searched.**

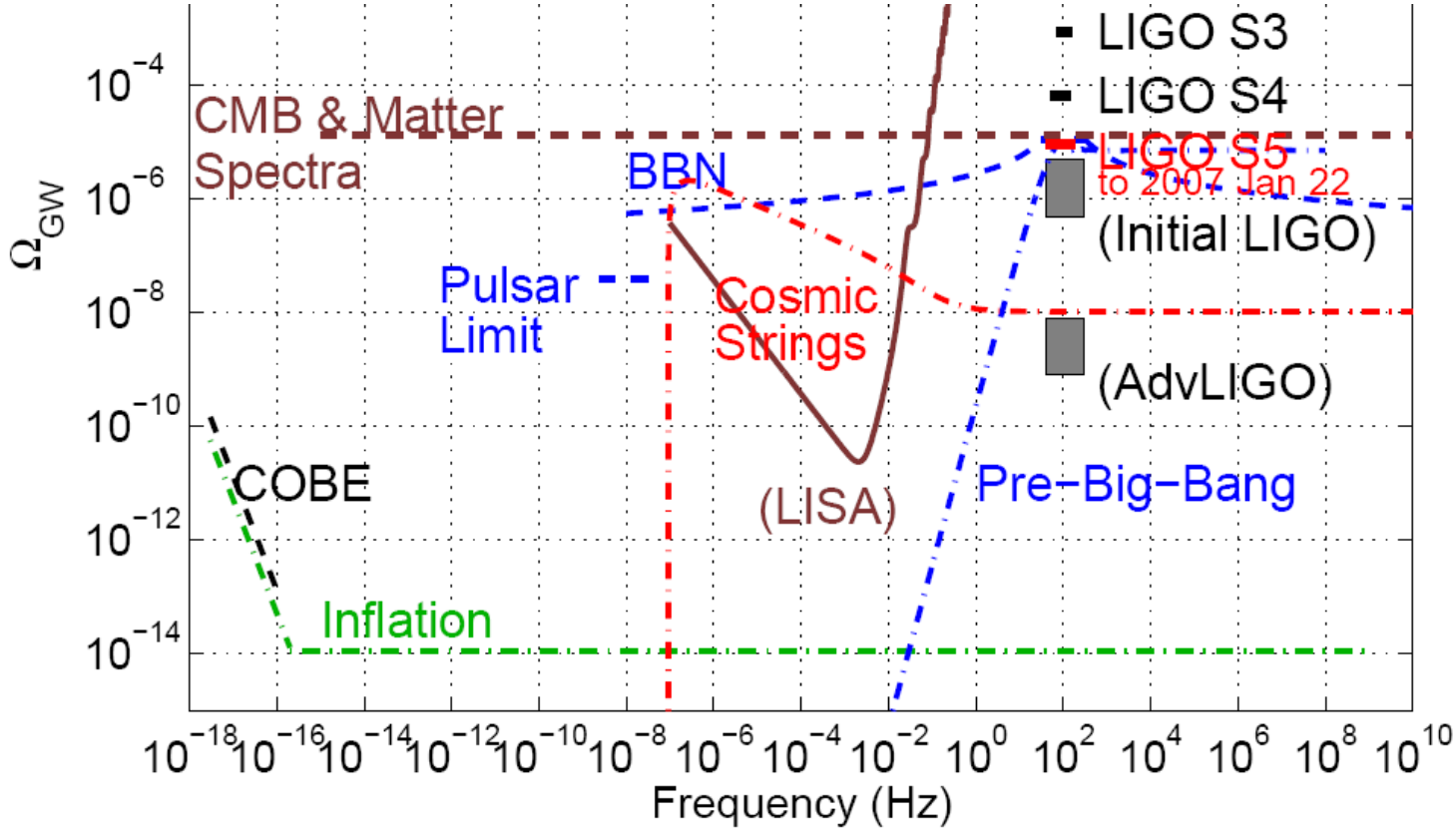
Searching for a stochastic background



NASA, WMAP

Early-S5 H1-L1 Bayesian 90% UL:

$$\Omega_{90\%} = 9.0 \times 10^{-6} \text{ (42-177 Hz)}$$



Other S5 Searches (released)

Search for Gravitational Wave Bursts from Soft Gamma Repeaters
Phys Rev Lett 101 (2008) 211102

Search for High Frequency Gravitational Wave Bursts in the First Calendar Year of LIGO's Fifth Science Run
arXiv:0904.4910

Stacked Search for Gravitational Waves from the 2006 SGR 1900+14 Storm
arXiv:0905.0005

Search for Gravitational Waves from Low Mass Compact Binary Coalescence in 186 Days of LIGO's fifth Science Run
arXiv:0905.3710

Other S5 (S6) Searches Underway (planned)

Inspirals:

High-mass, spinning black holes
Year 2, joint LIGO-Virgo
Ringdowns
GRBs

Bursts:

Year 2, Joint LIGO-Virgo
GRBs

Continuous wave:

Full-S5 all-sky searches (semi-coherent, Einstein@Home)
Directed searches (Cassiopeia A, globular clusters, galactic center, SN1987A)
"Transient CW" sources
All-sky binary

Stochastic:

Full-S5 isotropic – imminent
Directed (anisotropic)
H1-H2
High-frequency (37 kHz – LIGO arm free spectral range)

Looking Ahead

Both LIGO and Virgo underwent significant upgrades since last science run:

Initial LIGO → "Enhanced LIGO"

Initial Virgo → "Virgo +"

Data taking resumes <u>next week</u>, but with significant commissioning breaks scheduled to fix noise sources that sustained running reveals

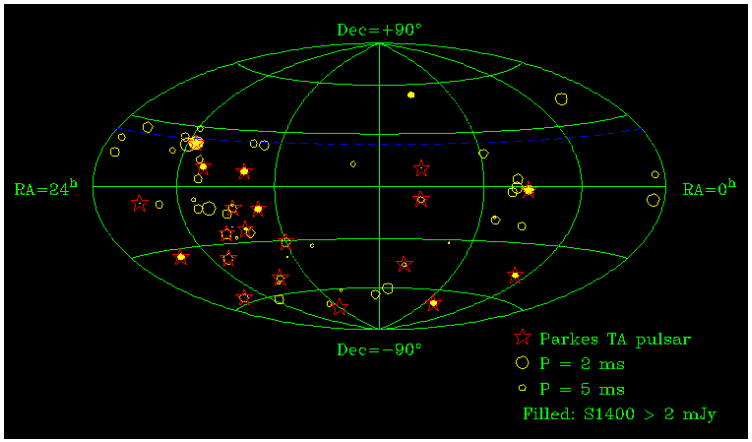
→ Running/commissioning strategy worked very well for LIGO in S5

→ Aiming at up to factor of two improvement in strain sensitivity
(most feasible for higher frequencies)

Shutdown for installation of Advanced LIGO and Virgo – early 2011
(see presentation by G. Losurdo)

Searching for very-low-frequency stochastic gravity waves – Pulsar Timing Arrays

By precisely monitoring the timings of an array of many millisecond pulsars in different directions, radio astronomers hope to detect direct evidence of stochastic gravitational waves



→ Look for quadrupolar pattern in solar system timing residuals

Several groups:

Parkes Pulsar Timing Array (Australia)
European Pulsar Timing Array (U.K., France, Netherlands, Italy)
Nano-Grav (USA)

→ Aiming to improve upon existing limit: $\Omega(\mathrm{nHz}) < 10^{-8}$

Eventual followup with proposed Square Kilometer Array (SKA)
→ Aiming to reach $\Omega(\mathrm{nHz}) < 10^{-13}$

Summary

Bottom line:

No GW signal detected yet ☹

But

- **Not all S5 / VSR1 searches completed**
- **Upcoming S6 / VSR2 searches should be more sensitive**
- **Advanced LIGO / Virgo promise major sensitivity improvements with orders of magnitude increase in expected event rates**

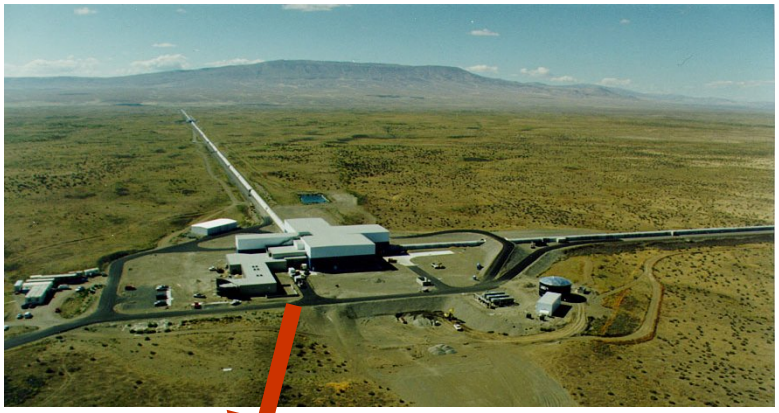
And

- **Radio pulsars may provide alternative first glimpse of the elusive graviton**

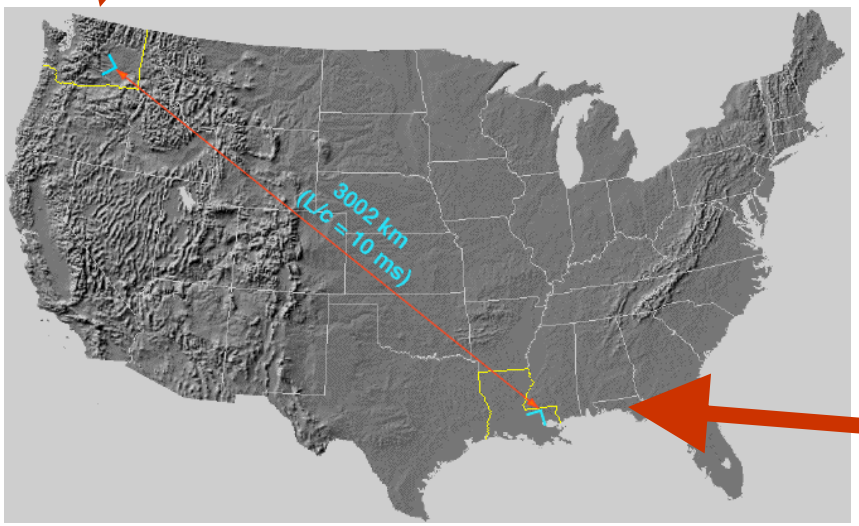
Extra Slides

LIGO Observatories

Hanford



Observation of nearly simultaneous signals 3000 km apart rules out terrestrial artifacts



Livingston

Virgo

Have begun collaborating with Virgo colleagues (Italy/France)

Took data in coincidence for last ~4 months of latest science run

Data exchange and joint analysis underway

Will coordinate closely on detector upgrades and future data taking

3-km Michelson Interferometer just outside Pisa, Italy

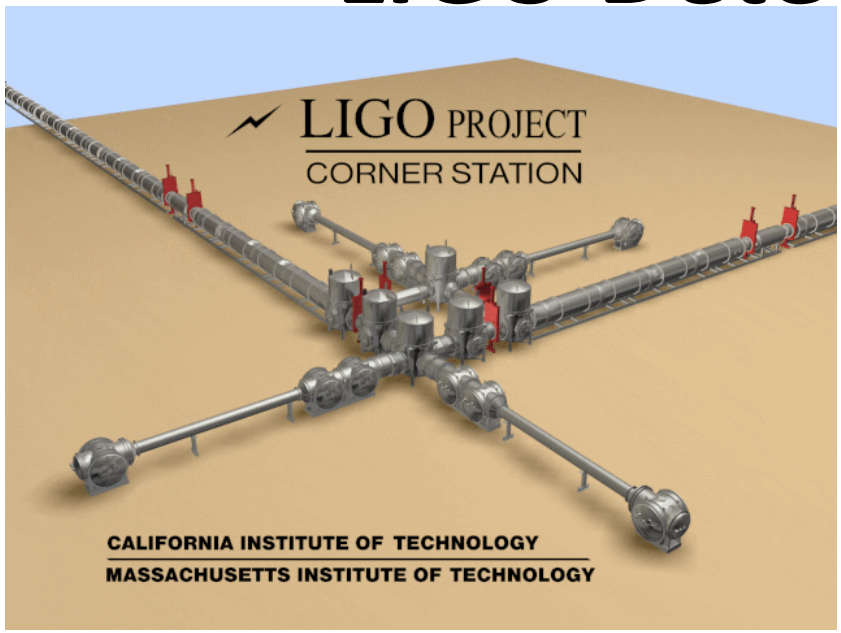
GEO600

Work closely with the GEO600 Experiment (Germany / UK / Spain)

- **Arrange coincidence data runs when commissioning schedules permit**
- **GEO members are full members of the LIGO Scientific Collaboration**
- **Data exchange and strong collaboration in analysis now routine**
- **Major partners in proposed Advanced LIGO upgrade**

600-meter Michelson Interferometer just outside Hannover, Germany

LIGO Detector Facilities



- Stainless-steel tubes

  (1.24 m diameter, ~10^{-8} torr)
- Gate valves for optics isolation
- Protected by concrete enclosure

Vacuum System

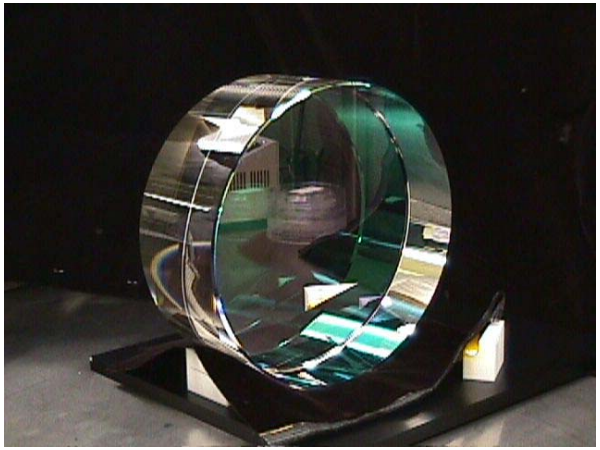
LIGO Detector Facilities

LASER

- Infrared (1064 nm, 10-W) Nd-YAG laser from Lightwave (now commercial product!)
- Elaborate intensity & frequency stabilization system, including feedback from main interferometer

Optics

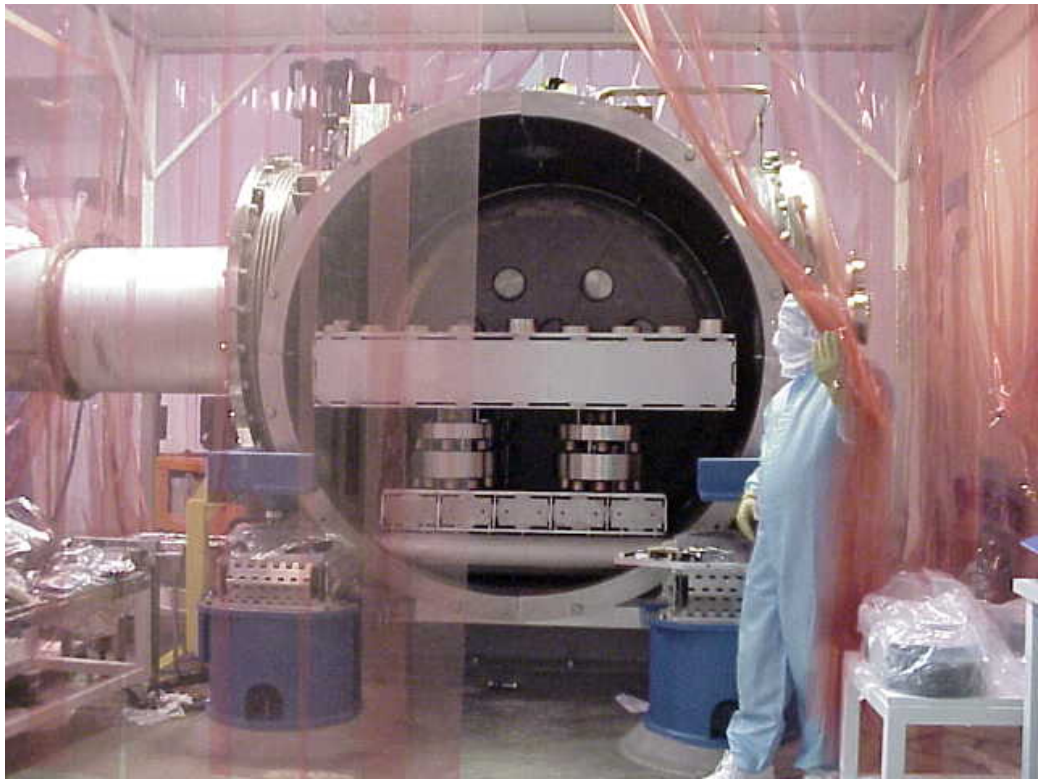
- Fused silica (high-Q, low-absorption, 1 nm surface rms, 25-cm diameter)
- Suspended by single steel wire
- Actuation of alignment / position via magnets & coils

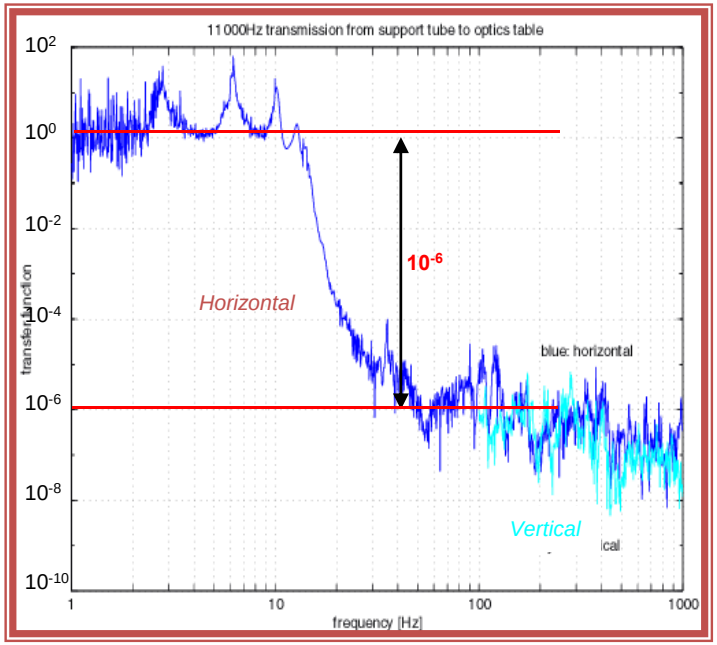


LIGO Detector Facilities

Seismic Isolation

- **Multi-stage (mass & springs) optical table support gives 10^6 suppression**
- **Pendulum suspension gives additional $1 / f^2$ suppression above ~1 Hz**



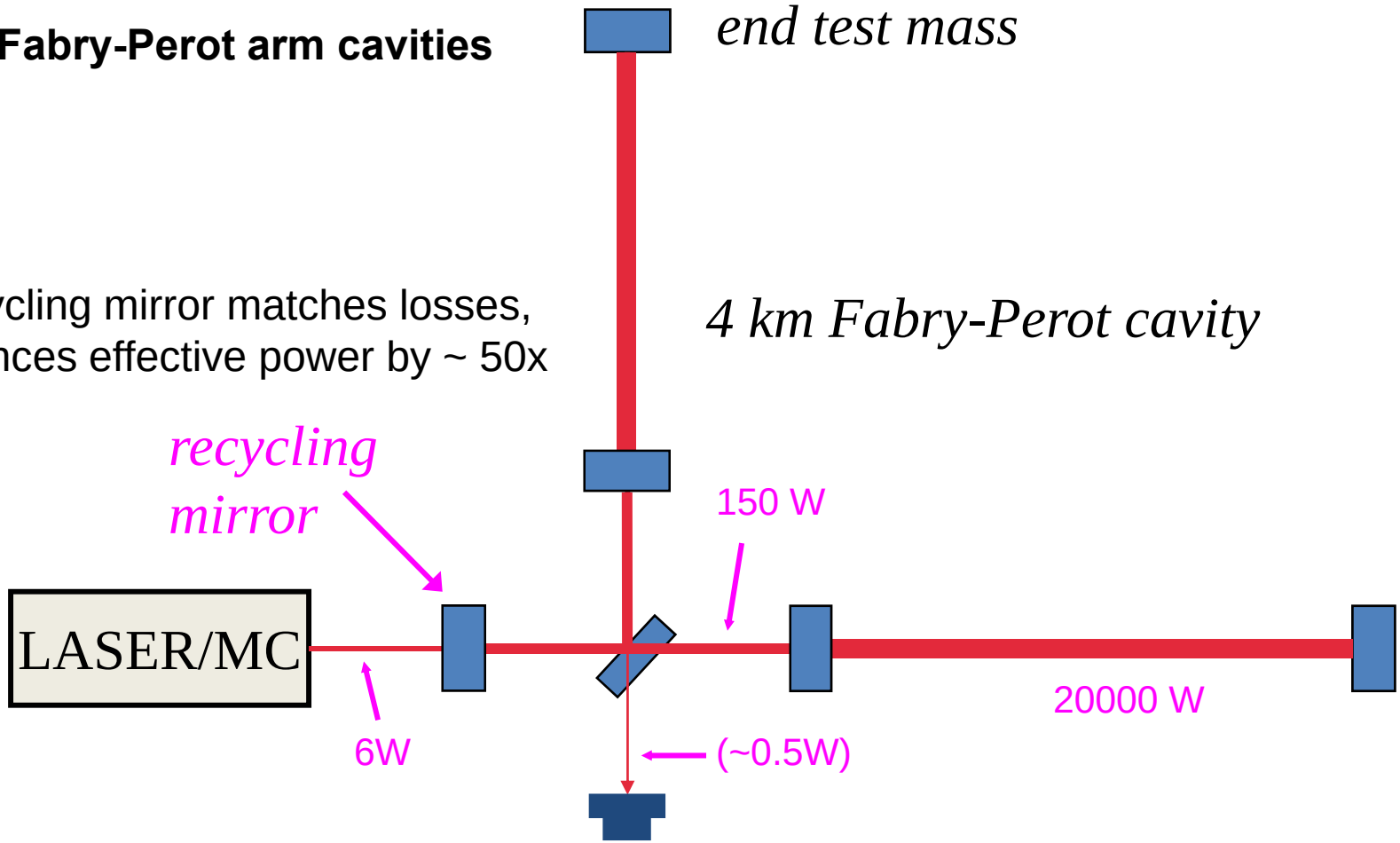


LIGO Interferometer Optical Scheme

Michelson interferometer

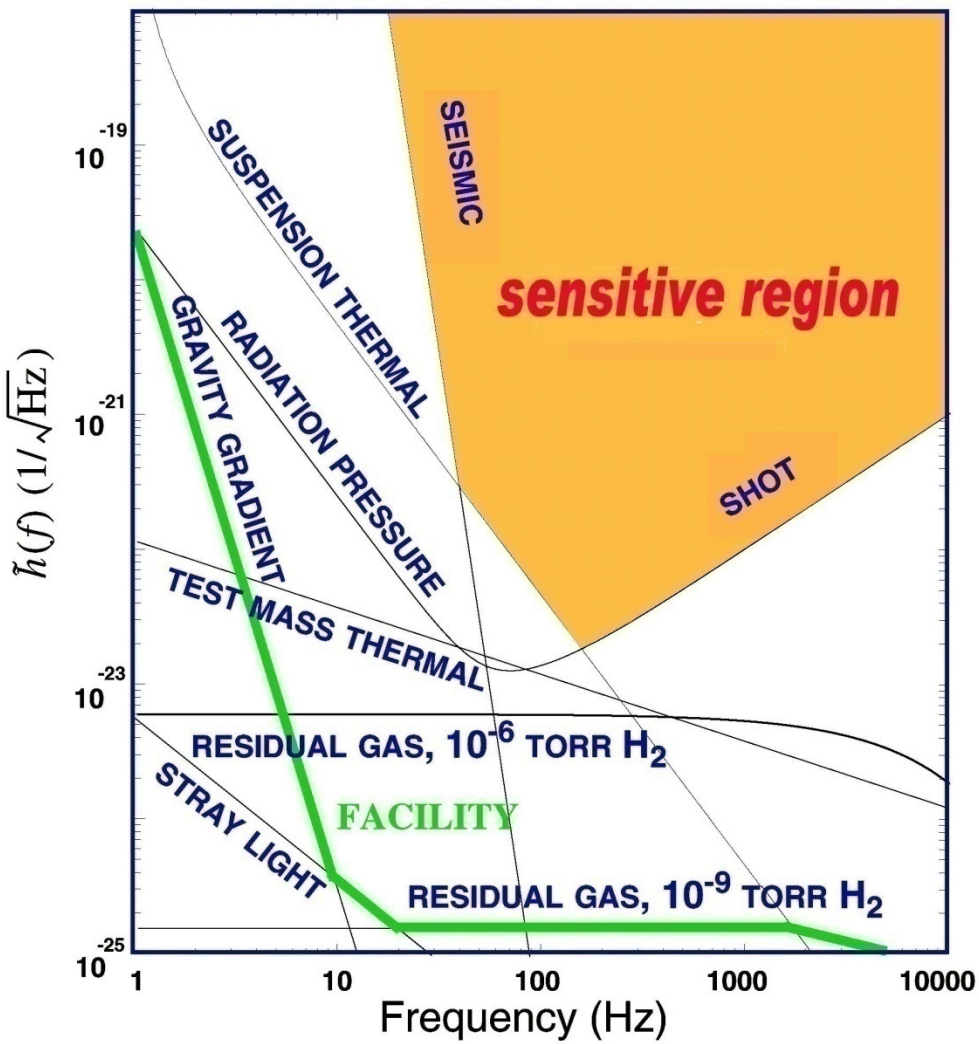
With Fabry-Perot arm cavities

•Recycling mirror matches losses, enhances effective power by ~ 50x



What Limits the Sensitivity of the Interferometers?

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels



Best design sensitivity:

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

“Locking” the Interferometer

Sensing gravitational waves requires sustained resonance in the Fabry-Perot arms and in the recycling cavity

→ Need to maintain half-integer # of laser wavelengths between mirrors

→ Feedback control servo uses error signals from imposed RF sidebands

→ Four primary coupled degrees of freedom to control

→ Highly non-linear system with 5-6 orders of magnitude in light intensity

Also need to control mirror rotation (“pitch” & “yaw”)

→ Ten more DOF’s (but less coupled)

And need to stabilize laser (intensity & frequency), keep the beam pointed, damp out seismic noise, correct for tides, etc.,…