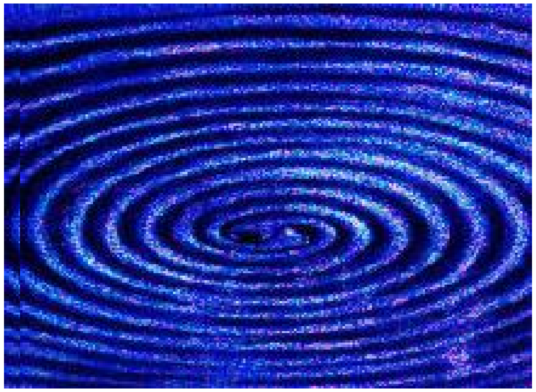


LIGO: The Search for the Gravitational Wave Sky

- status, physics, results, prospects

Ray Frey, University of Oregon

for the

LIGO Scientific Collaboration

C2CR07, Granlibakken

- Introduction (brief)
- Current status
- Observational results, selected
- Prospects: enhanced and Advanced LIGO; toward a worldwide network of GW observatories

No detections can be reported (yet).

LIGO-G070027-00-Z

Laser Interferometer Gravitational-wave Observatory

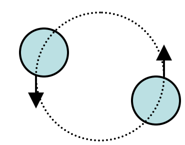
- **Managed and operated by Caltech & MIT with funding from NSF**
- **Ground breaking 1995**
- **1st interferometer lock 2000**
- **LIGO Scientific collaboration: 45 institutions, world-wide**

G070027-00

Required GW Sensitivity

- GW emission requires time varying quadrupole moment of mass distribution
- Strain estimate (h = δL/ L) :

$$h \sim \left(\frac{GM}{c^2}\right)\left(\frac{v^2}{c^2}\right)\frac{1}{r}$$

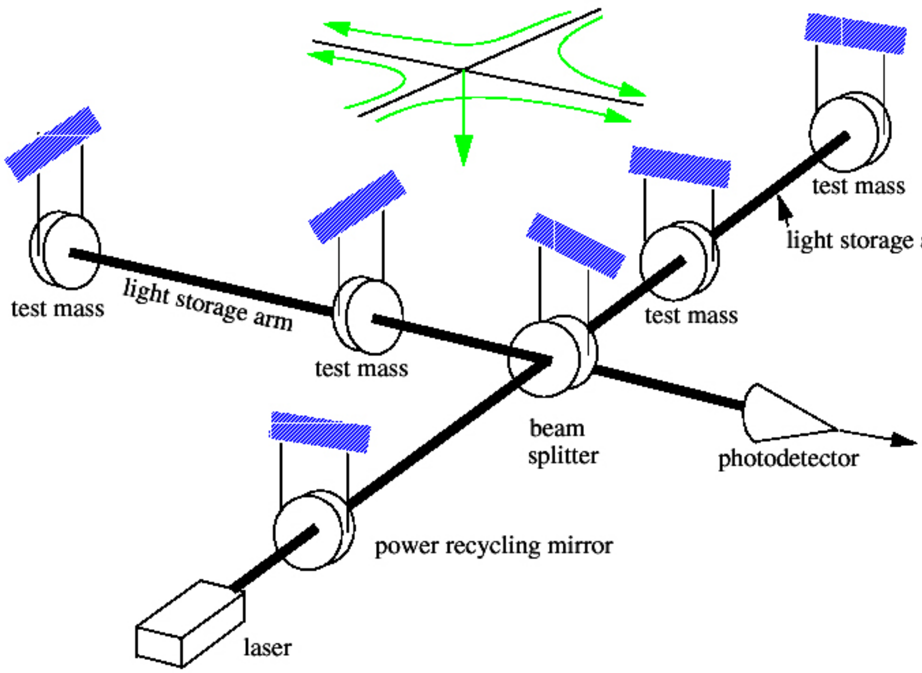


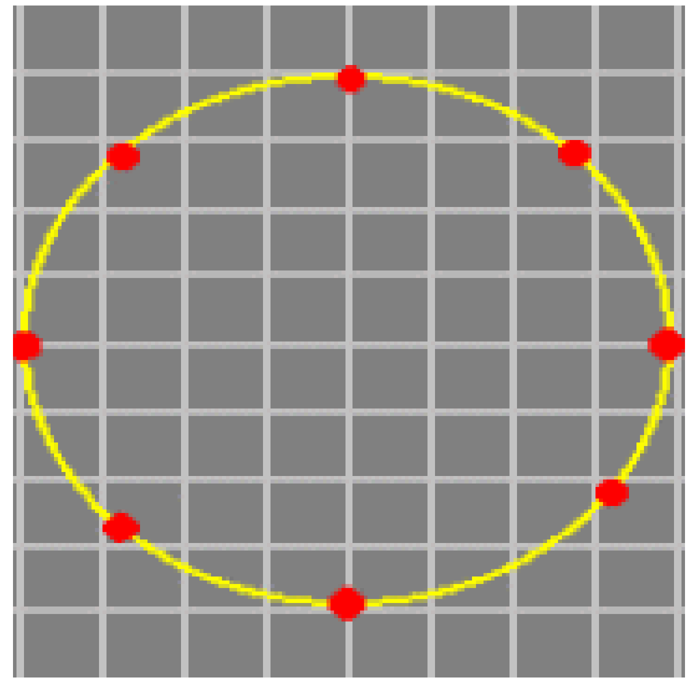
For $1M_\odot \Rightarrow R_s = 2GM_\odot/c^2 = 3$ km

If $v \approx c$, then at $r = 15$ Mpc:

$$h \sim 3 \times 10^{-21}$$

GW Interferometer Principle

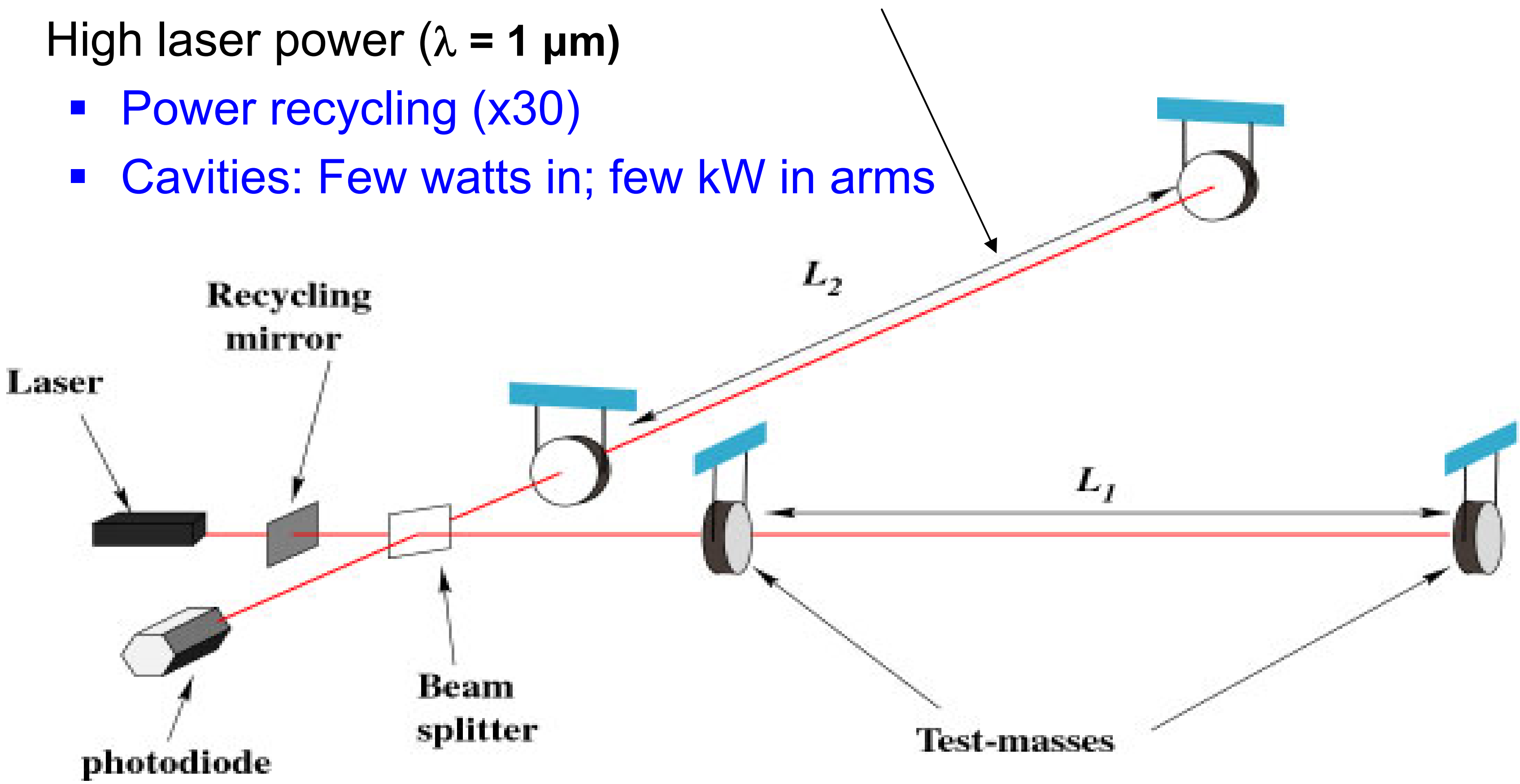




GW strain: $h = \delta L / L$

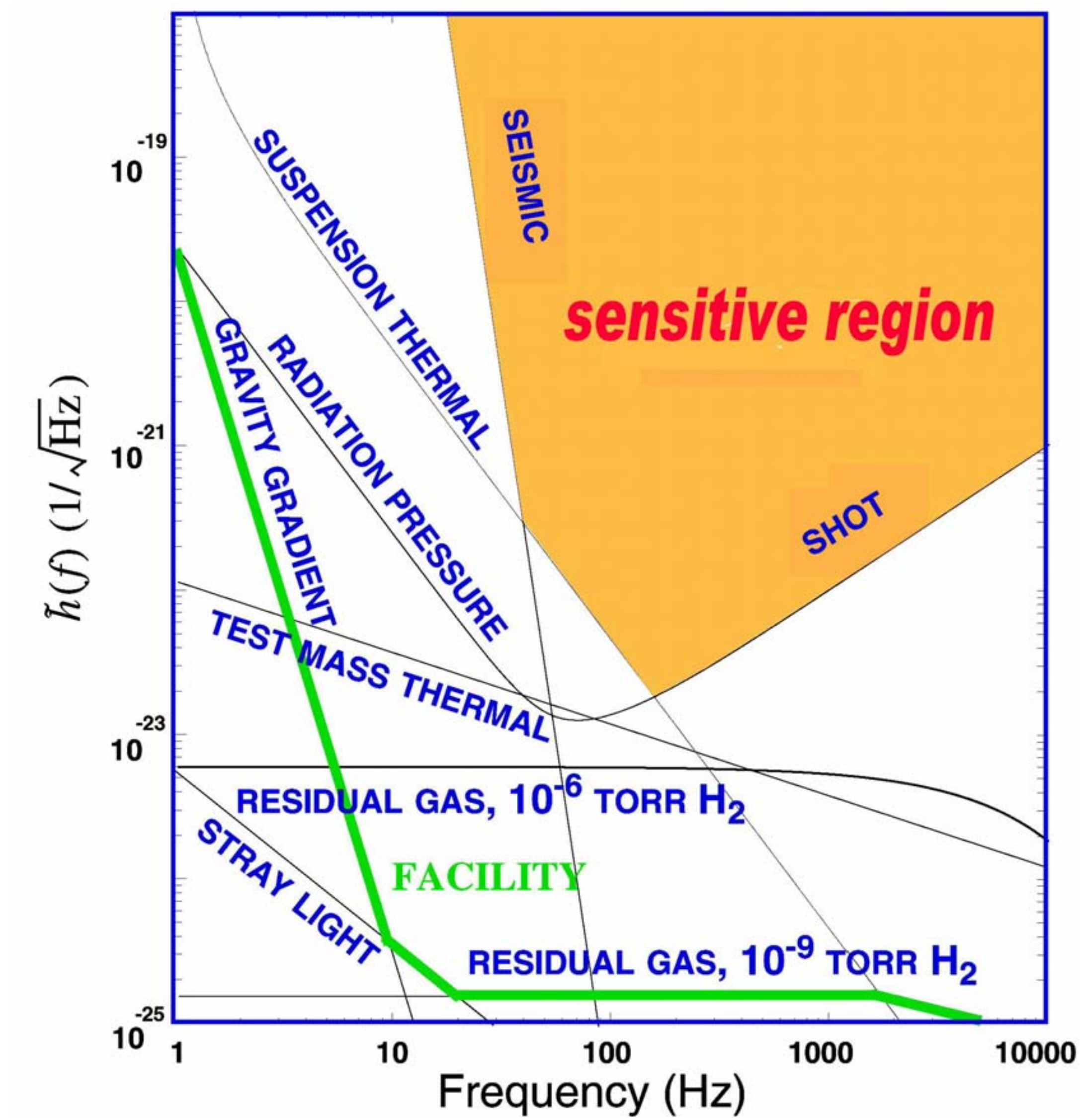
Interferometer parameters

- Long baseline 4 km ($h = \delta L / L$) - **For $h \approx 10^{-21}$, $L \approx 1$ km, then $\delta L \approx 10^{-18}$ m**
  - $\Rightarrow$ $\delta\Phi \approx 10^{-9}$ rad required phase sensitivity
- Fabry-Perot Cavity storage time ~1 ms (~100 bounces)
- High laser power (λ **= 1 μm)**
  - Power recycling (x30)
  - Cavities: Few watts in; few kW in arms

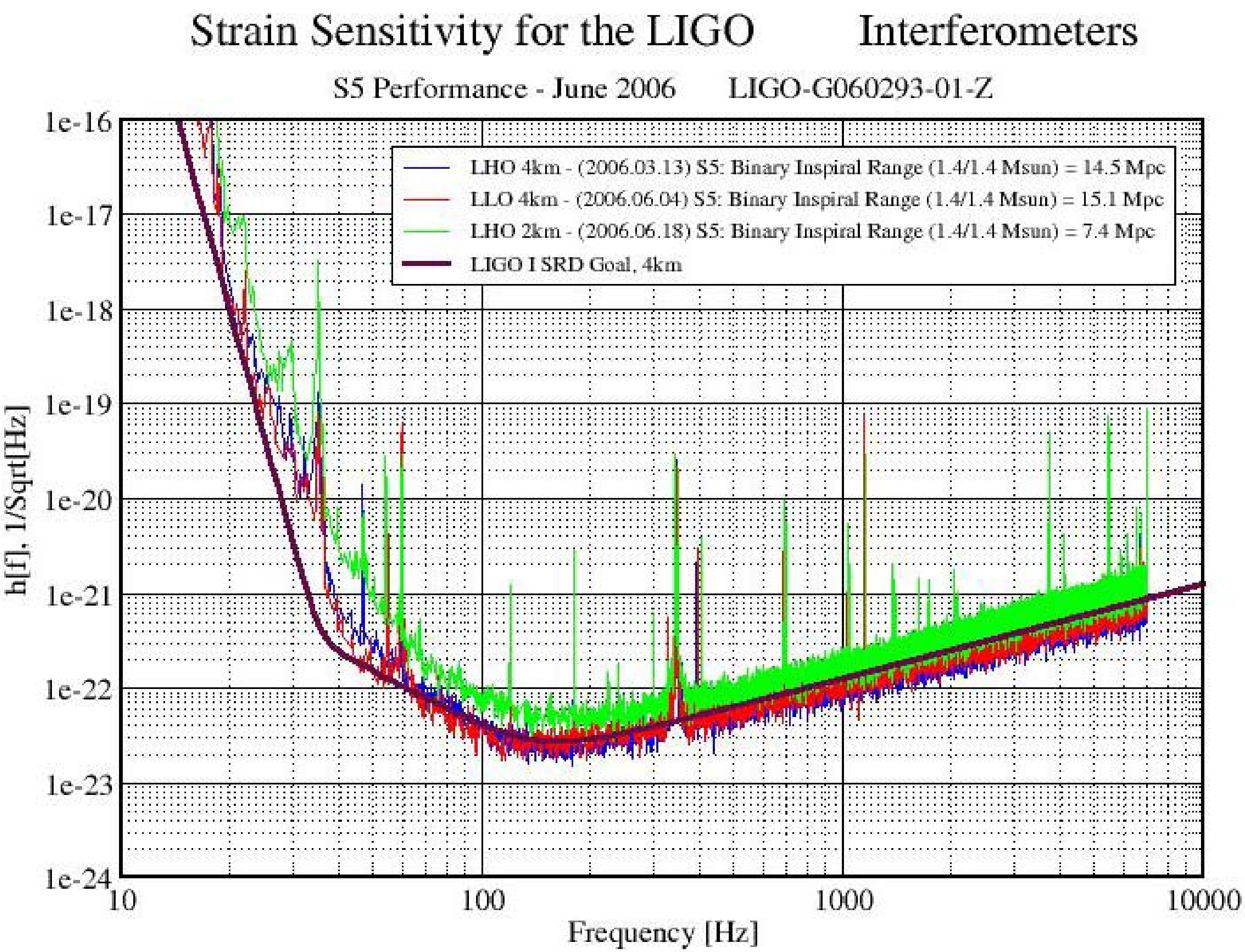


What Limits Sensitivity of the Interferometers?

- Seismic noise & vibration limit at low frequencies
- Thermal noise of suspensions and test masses
- Quantum nature of light (Shot Noise) limits at high frequencies
- Limitations of facilities much lower

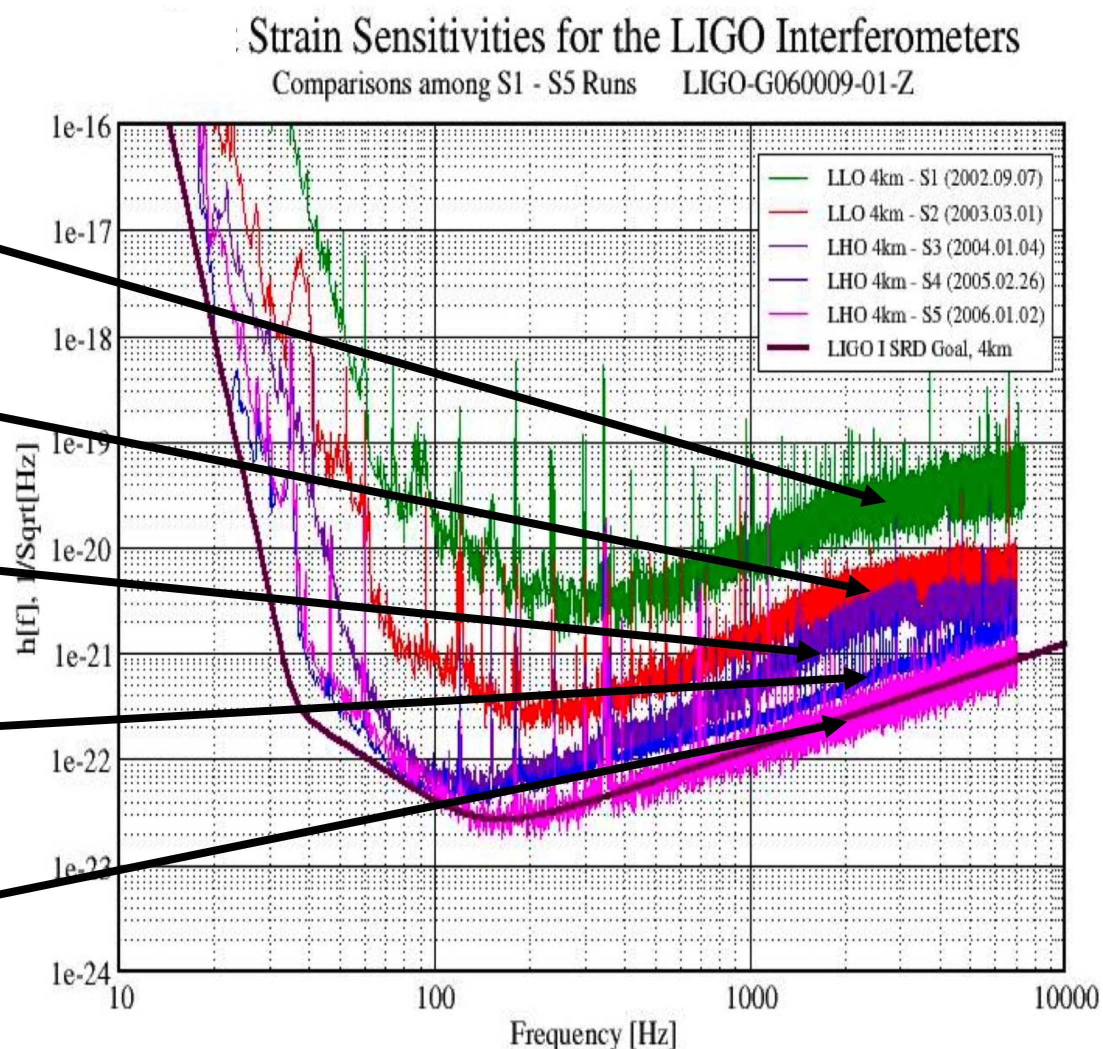


S5 Science Run: LIGO at Design Sensitivity

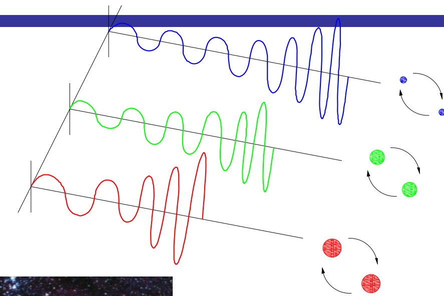


Science runs and sensitivity

Run	# days
S1 Sept ‘02	17
S2 Feb 03-Apr 03	59
S3 Nov 03-Jan 04	70
S4 Feb- March 05	30
S5 Nov 05 -- ?	ongoing

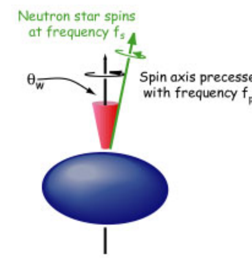


Astrophysical Signal Types



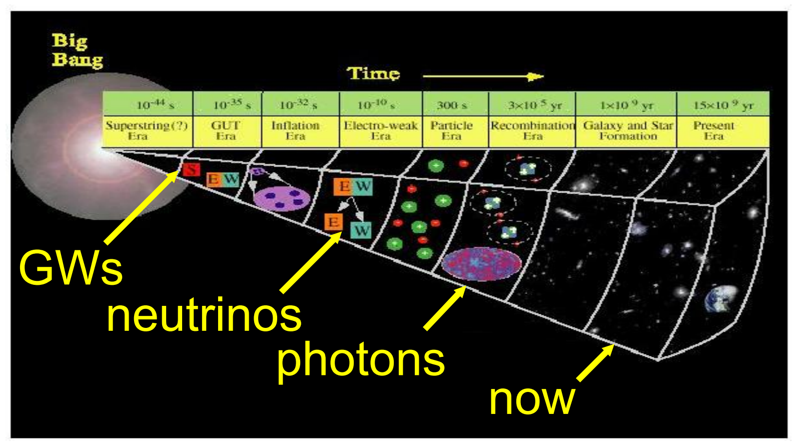
- Compact binary inspiral: *"chirps"*
  - NS-NS, BH-BH waveforms are well described
  - search technique: matched templates

- Supernovae / GRBs: *"bursts"*
  - "unmodelled" search
  - triggered searches



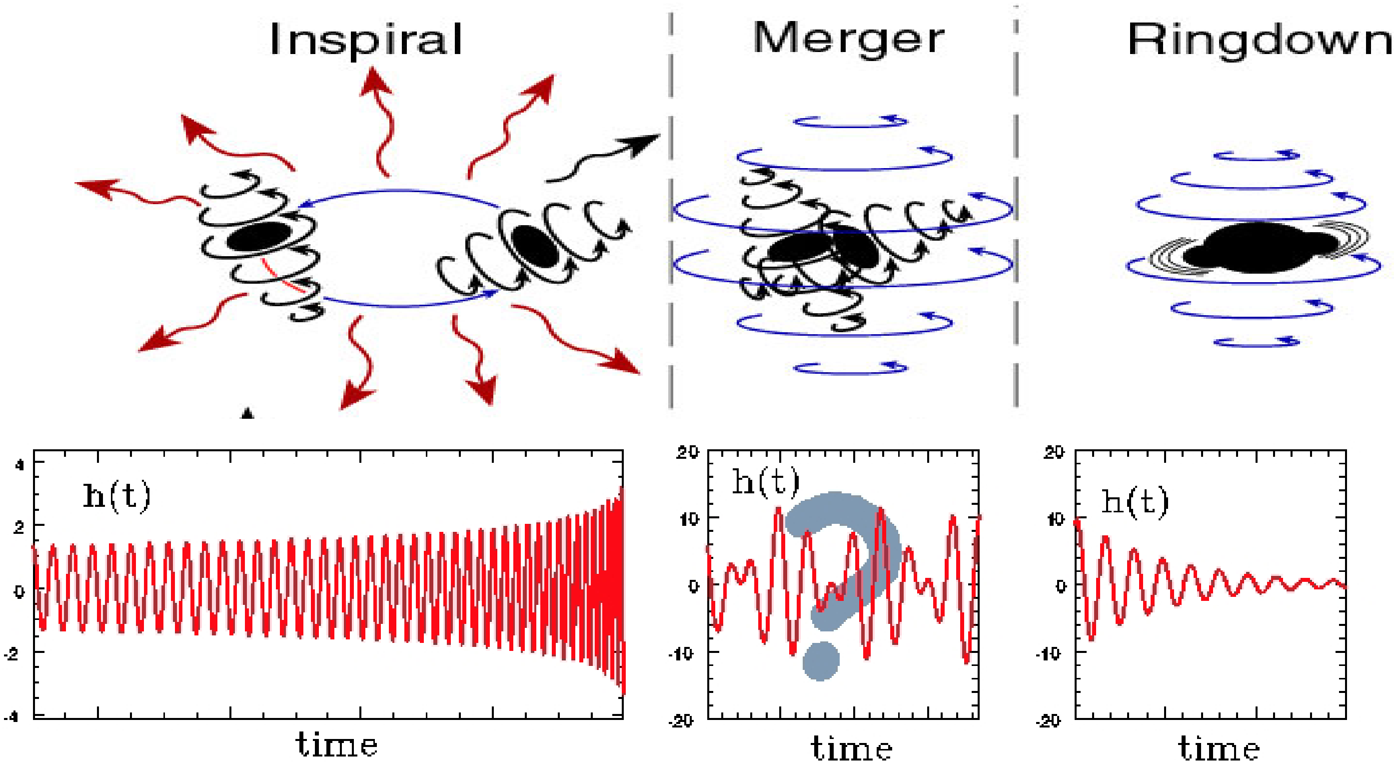
- Pulsars in our galaxy: *"periodic"*
  - observe known neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)
  - Low-mass X-ray binaries

- Cosmological *"stochastic background"*

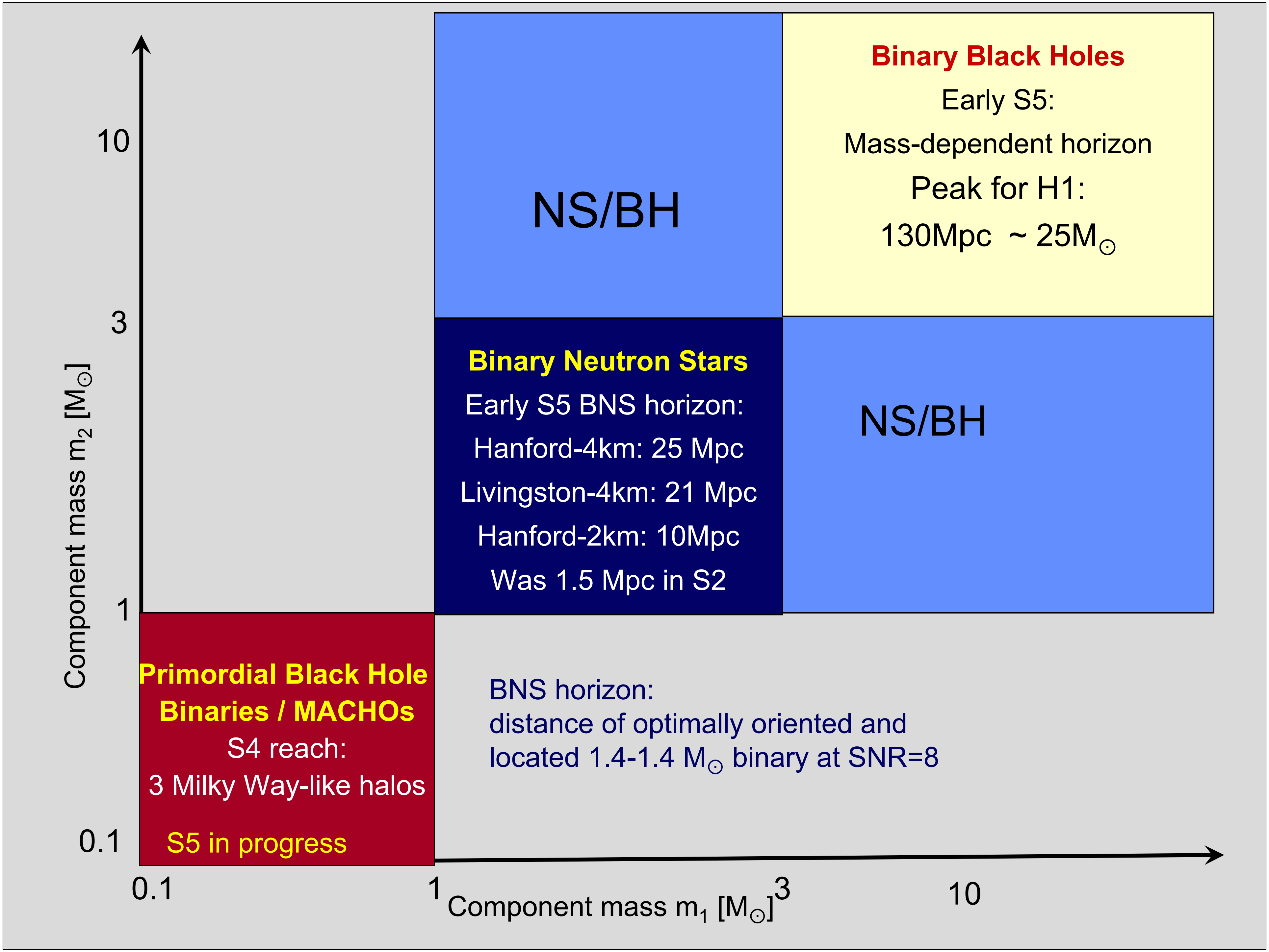


Coalescing Compact Binaries

NS-NS, BH-BH, (BH-NS) binary systems



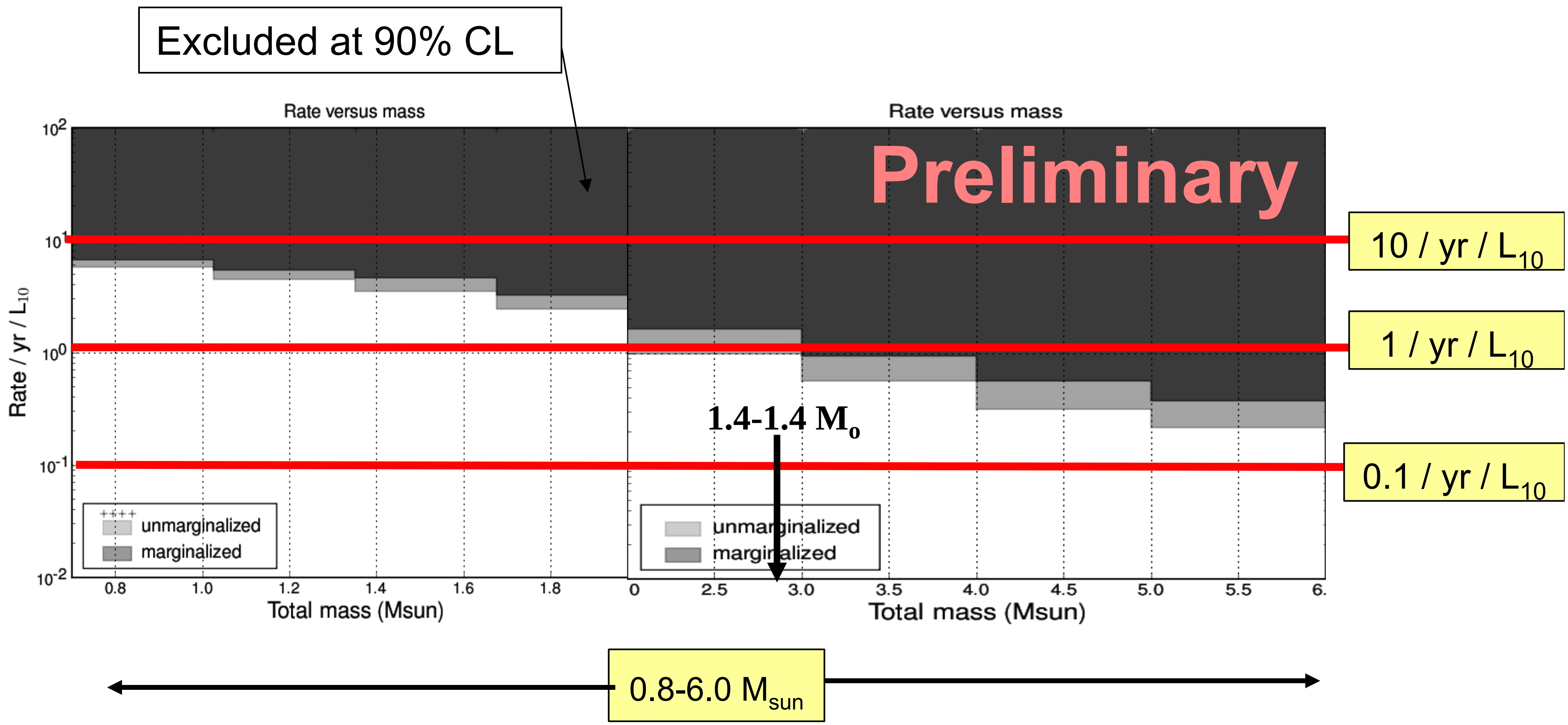
Matched filter | Template-less | Matched filter



Binary Black Holes
Early S5:
Mass-dependent horizon
Peak for H1:
130Mpc ~ 25M⊙
NS/BH
Binary Neutron Stars
Early S5 BNS horizon:
Hanford-4km: 25 Mpc
Livingston-4km: 21 Mpc
Hanford-2km: 10Mpc
Was 1.5 Mpc in S2
NS/BH
Primordial Black Hole Binaries / MACHOs
S4 reach:
3 Milky Way-like halos
S5 in progress
BNS horizon:
distance of optimally oriented and located 1.4-1.4 M⊙ binary at SNR=8
Component mass m2 [M⊙]
Component mass m1 [M⊙]
10
3
1
0.1
0.1
1
3
10

S4 upper limits-compact binary coalescence

Rate/year/L_{10} vs. binary total mass ($L_{10} = 10^{10}$ L_{sun} (1 Milky Way = 1.7 L_{10})

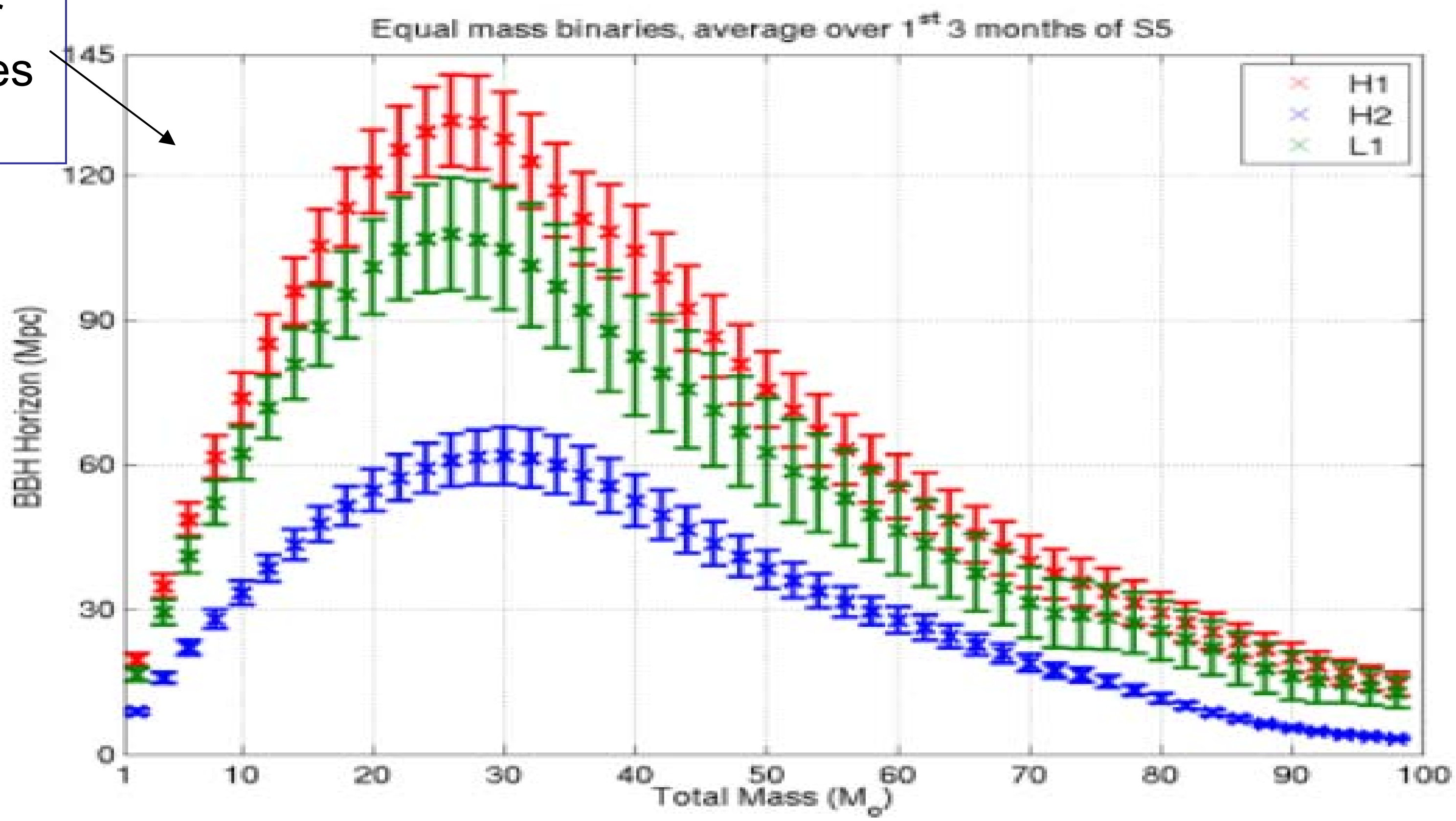


S5 search for compact binary signals

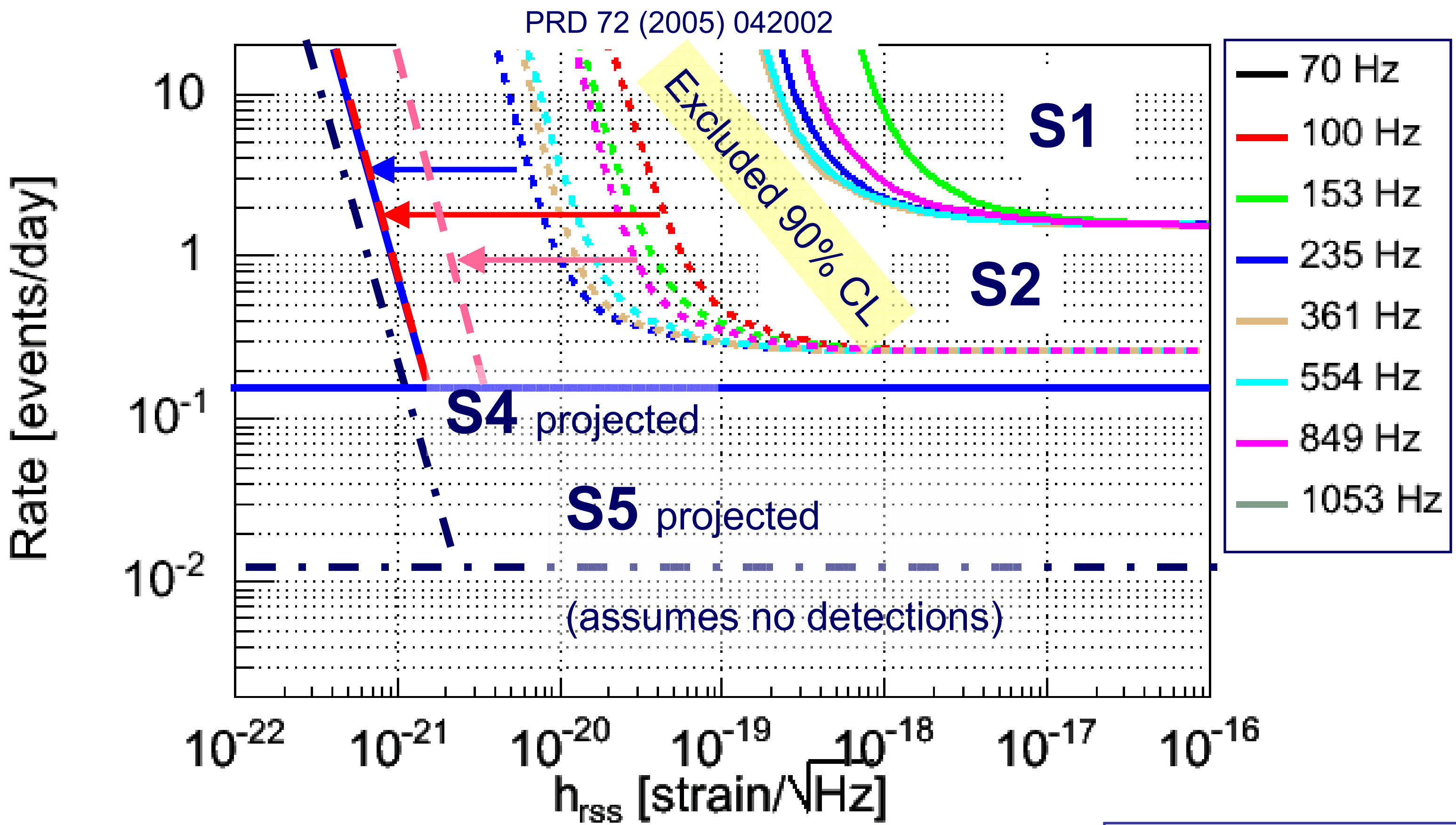
- 3 months of data analyzed- no signals seen
- For 1.4-1.4 M_o binaries, ~ 200 MWEGs in range
- For 5-5 M_o binaries, ~ 1000 MWEGs in range

Inspiral horizon for equal mass binaries vs. total mass

(horizon=range at peak of antenna pattern; ~2.3 x antenna pattern average)



Burst Search (All-sky) Results and Prospects

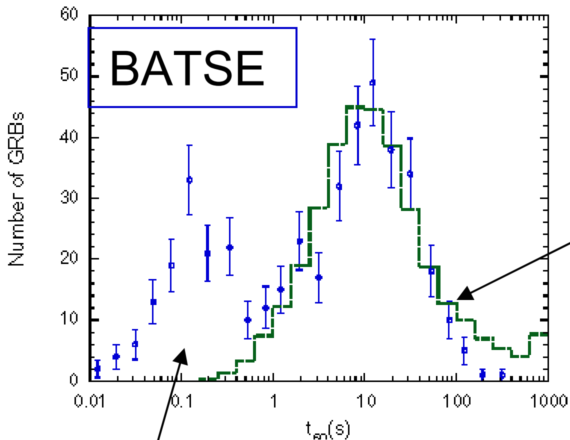


S5 sensitivity:

$E_{GW} > 1\ M_{\odot}c^2$ at 75Mpc

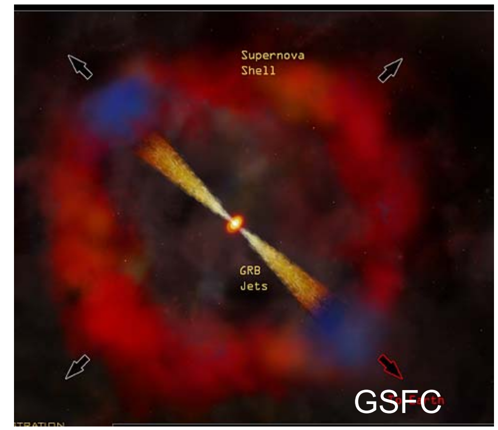
$E_{GW} > 0.05\ M_{\odot}c^2$ at 15Mpc

Gravitational Radiation and Gamma-ray Bursts



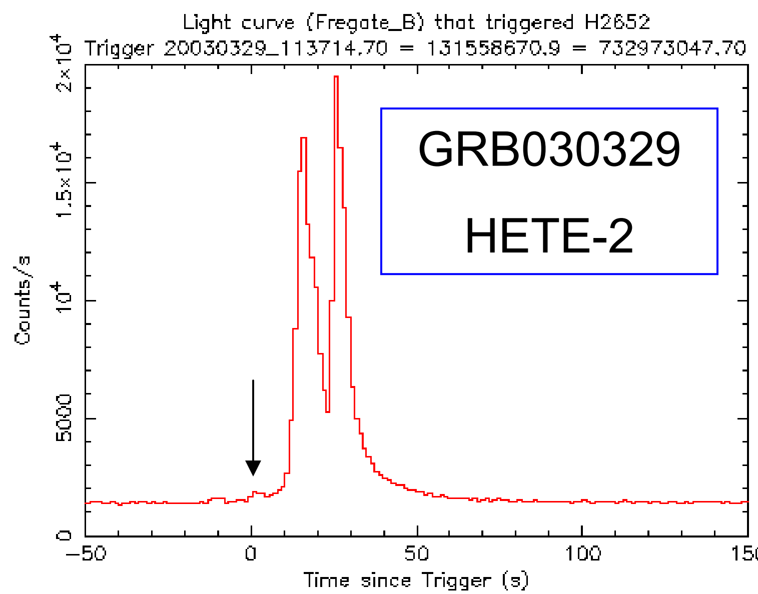
Long-duration GRBs

- Stronger afterglows → z
- SNe or "hypernovae"
- mean z ≈ 2.5



Short-duration GRBs

- Until 2005, no measured z's → enter **Swift**
- Now: a few z's → "compact binary mergers"

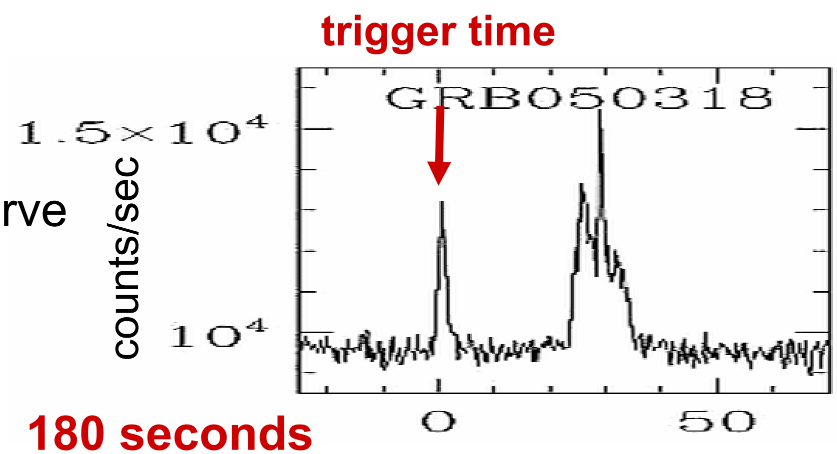


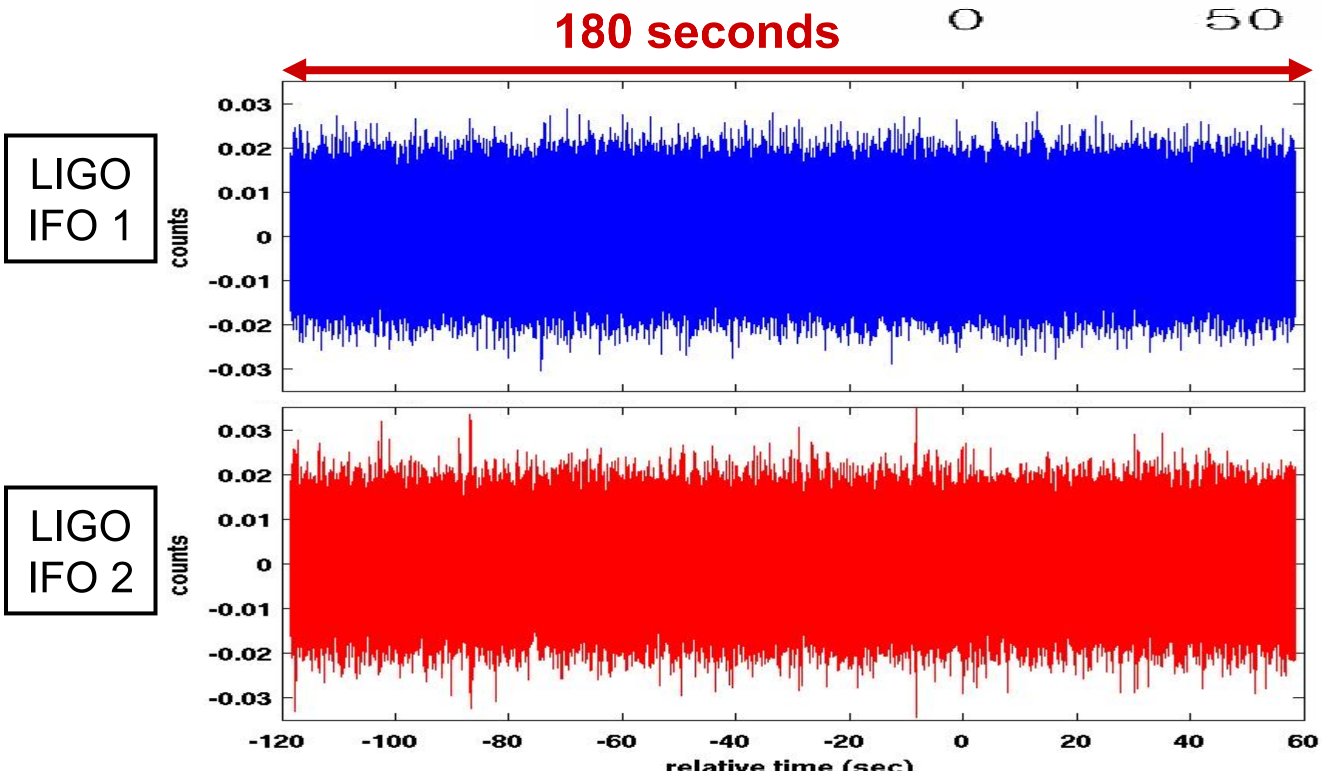
Oct 6, 2005

- mergers are efficient GW radiators
- much smaller z's (mean ≈ 0.4)

Search Method: GWs associated with GRBs

sample GRB lightcurve
(Swift)





use 180-second LIGO *on-source* data surrounding GRB trigger

↓

crosscorrelate output of two IFOs over ≤100 ms

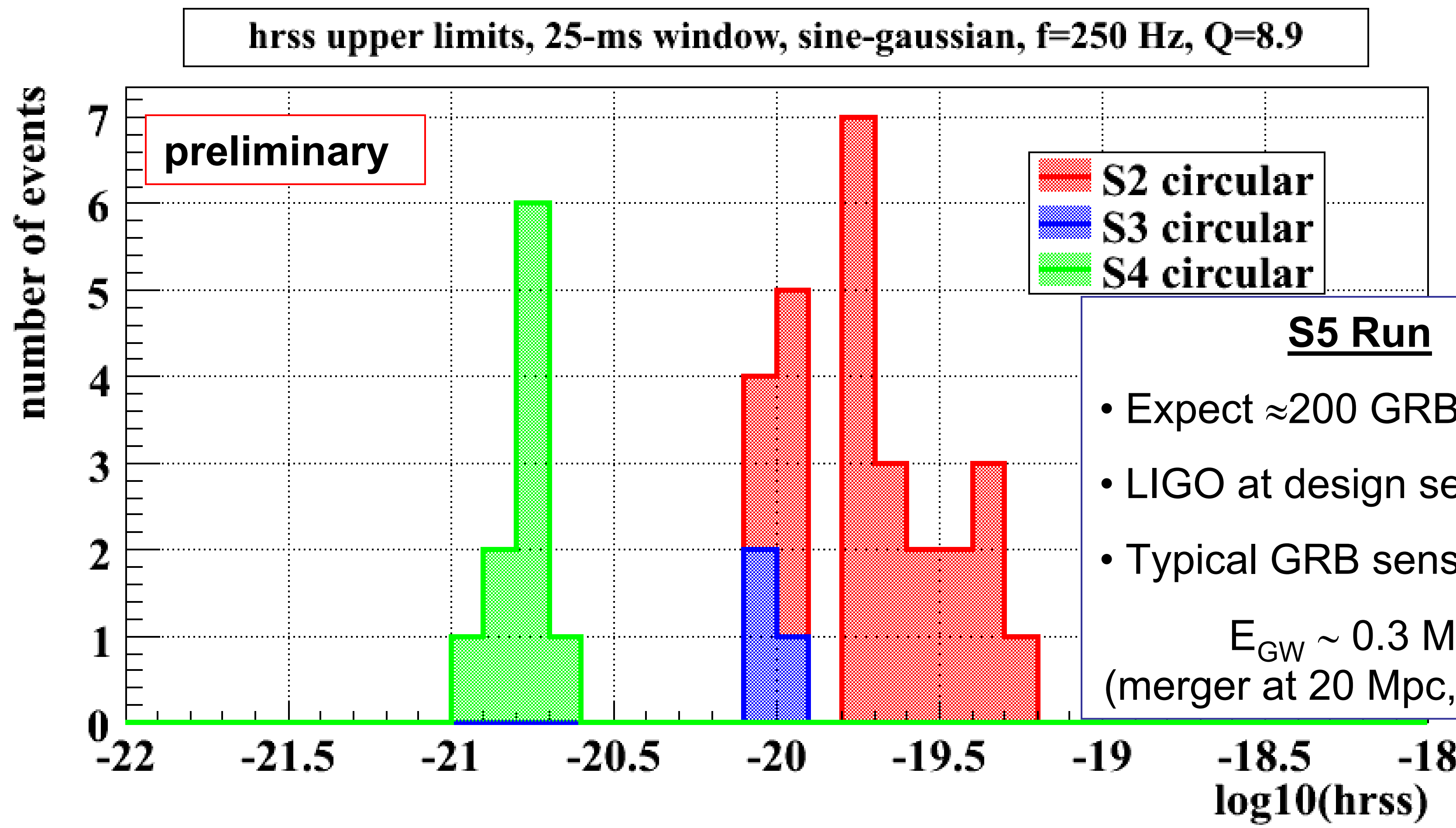
↓

look for largest on-source crosscorrelation and compare to nearby off-source segments

GRB-GW Results

No significant detections in S2, S3, S4 ⇒ strain (h_{rss}) limits

to be submitted to PRD



S5 Run

- Expect ≈200 GRBs
- LIGO at design sens.
- Typical GRB sensitivity:

$E_{GW} \sim 0.3\ M_{\odot}\ c^2$
(merger at 20 Mpc,250 Hz)

Search for known pulsars - preliminary

95% upper limits for 97 pulsars using ~10 months of the S5 run

For 32 of the pulsars we give the *expected* sensitivity upper limit (red stars) due to uncertainties in the pulsar parameters .

Pulsar timings provided by the Jodrell Bank pulsar group

Lowest GW strain upper limit:

PSR J1802-2124

(f_{gw} = 158.1 Hz, r = 3.3 kpc)

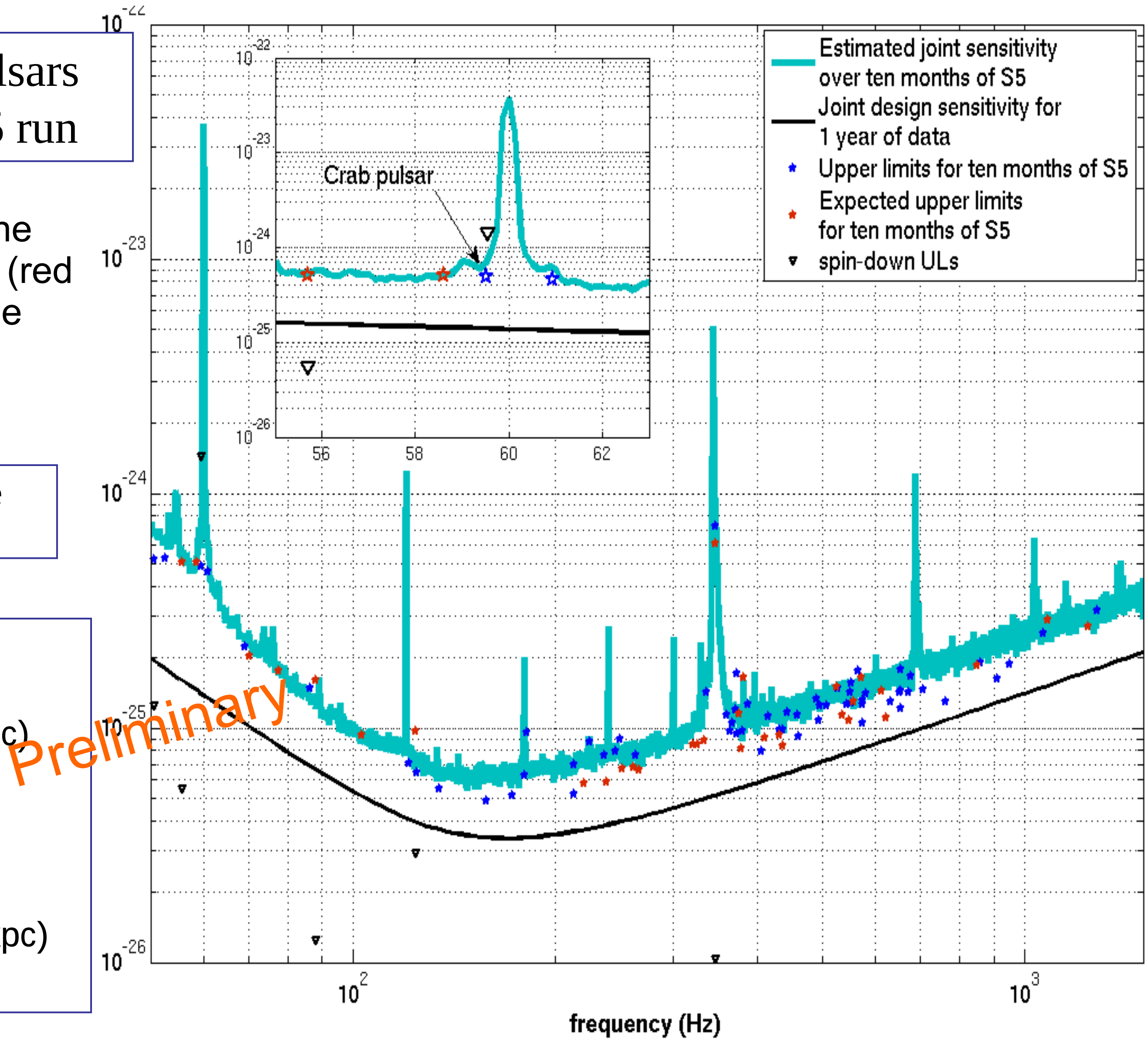
$\mathbf{h_0 < 4.9\times10^{-26}}$

Lowest ellipticity upper limit:

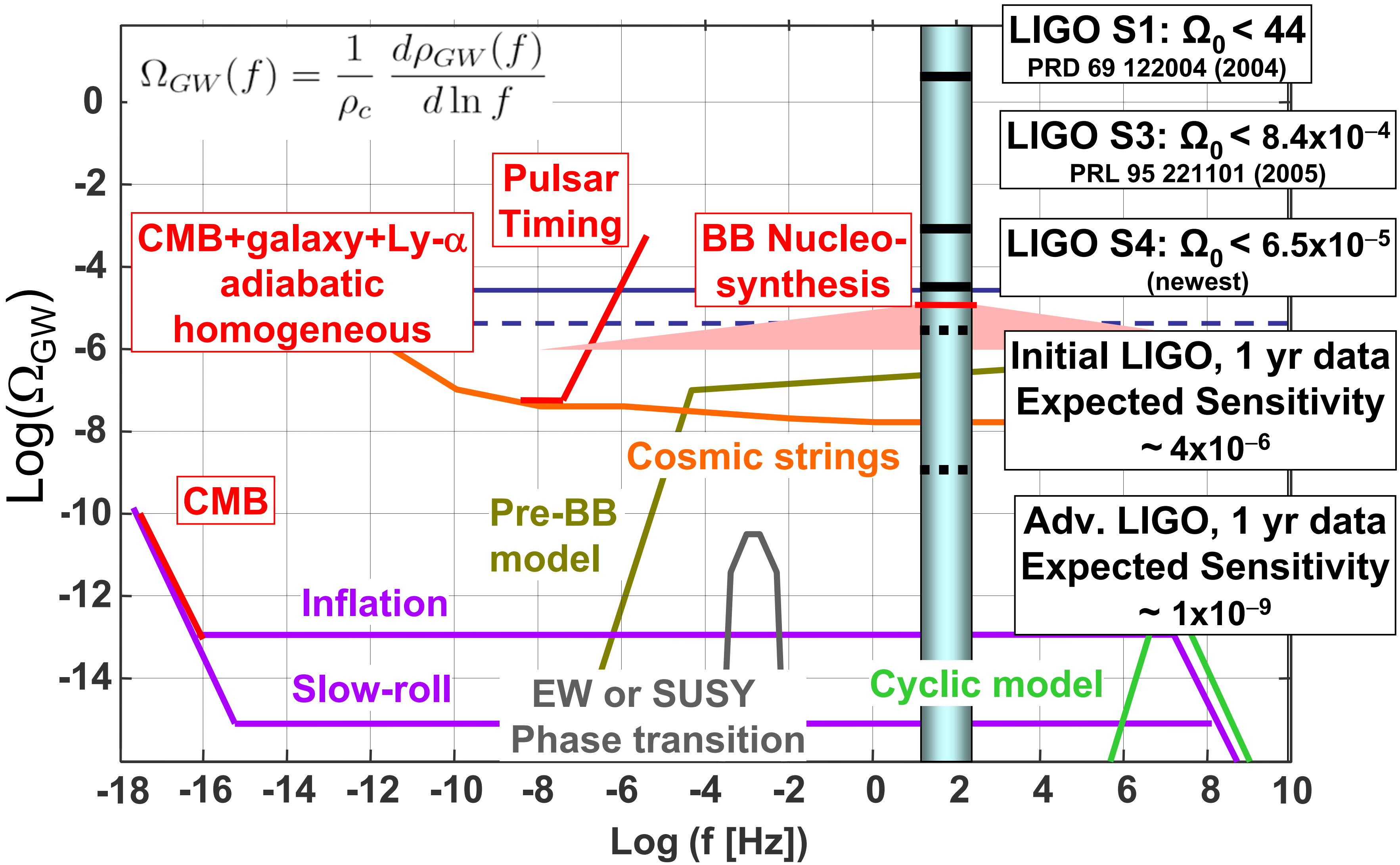
PSR J2124-3358

(f_{gw} = 405.6 Hz, r = 0.25 kpc)

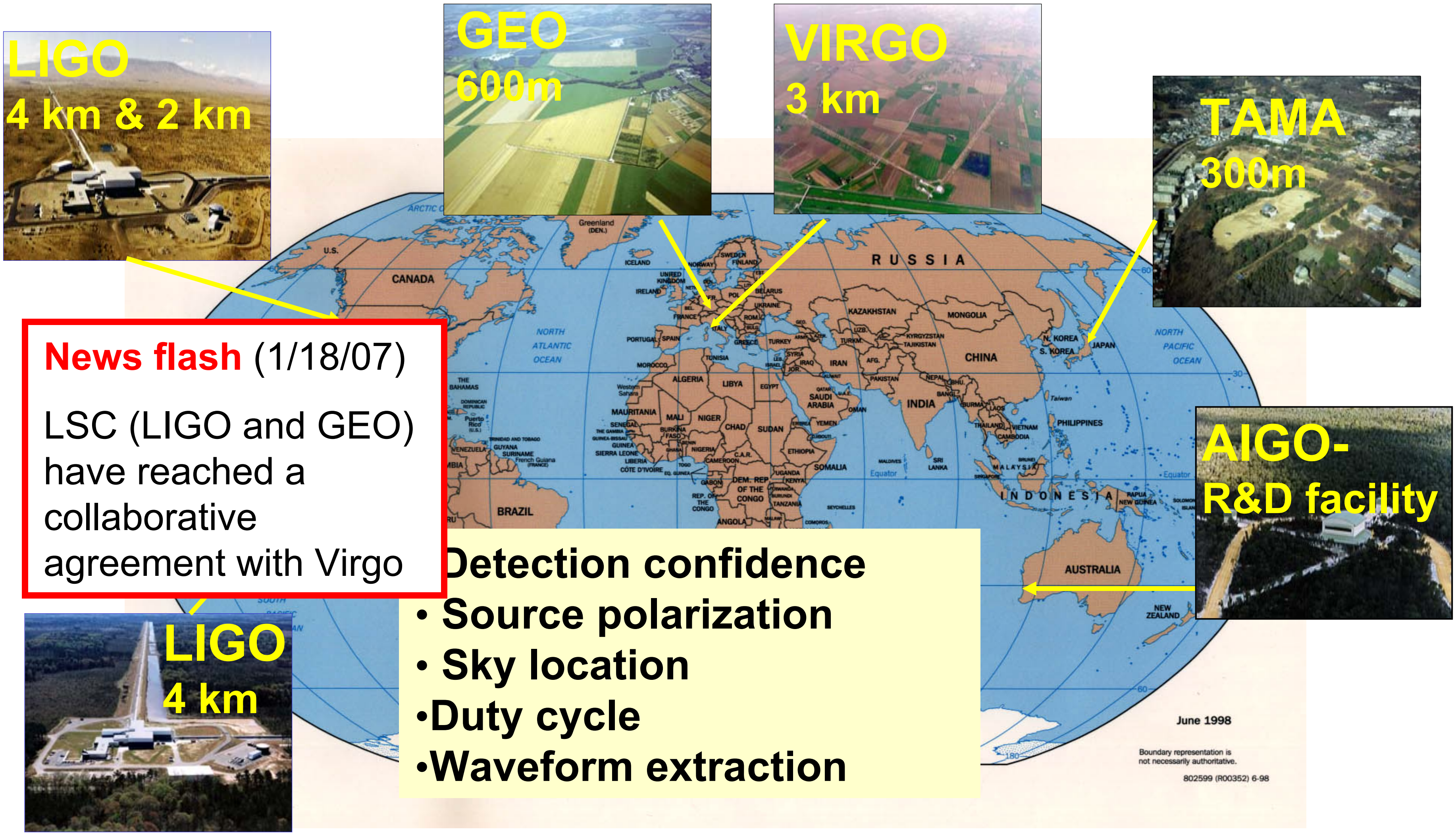
$\boldsymbol{\varepsilon < 1.1\times10^{-7}}$



Relic GWs: Results and Prospects



Global network of interferometers



News flash (1/18/07)

LSC (LIGO and GEO) have reached a collaborative agreement with Virgo

- **Detection confidence**
- **Source polarization**
- **Sky location**
- **Duty cycle**
- **Waveform extraction**

The Future: Enhanced and Advanced LIGO

S5 Run ← → | S6 ← → | S7 ←

2006	2007	2008	2009	2010	2011	2012	2013	2014

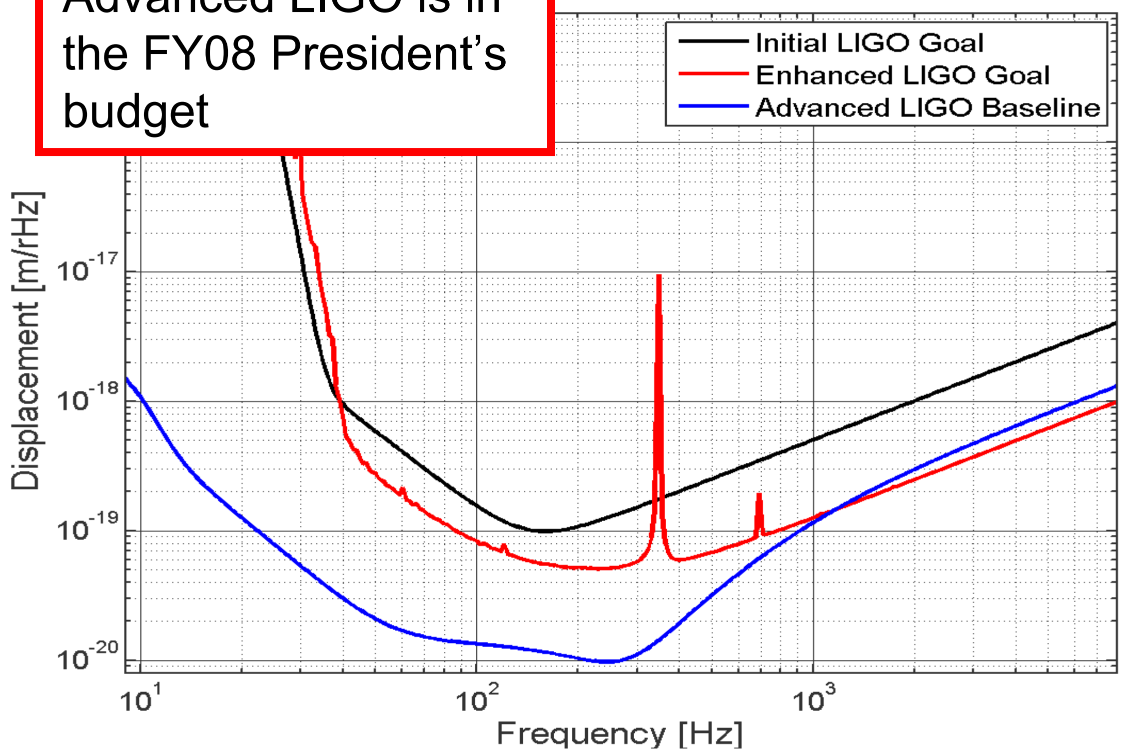
LIGO | ***enhanced* LIGO**

Advanced LIGO

build hardware | installation | science

News flash:

Advanced LIGO is in the FY08 President's budget



Enhanced LIGO (S6)

- readout noise; laser power
- Commission AdLIGO readout with real IFOs
- reduce AdLIGO startup time

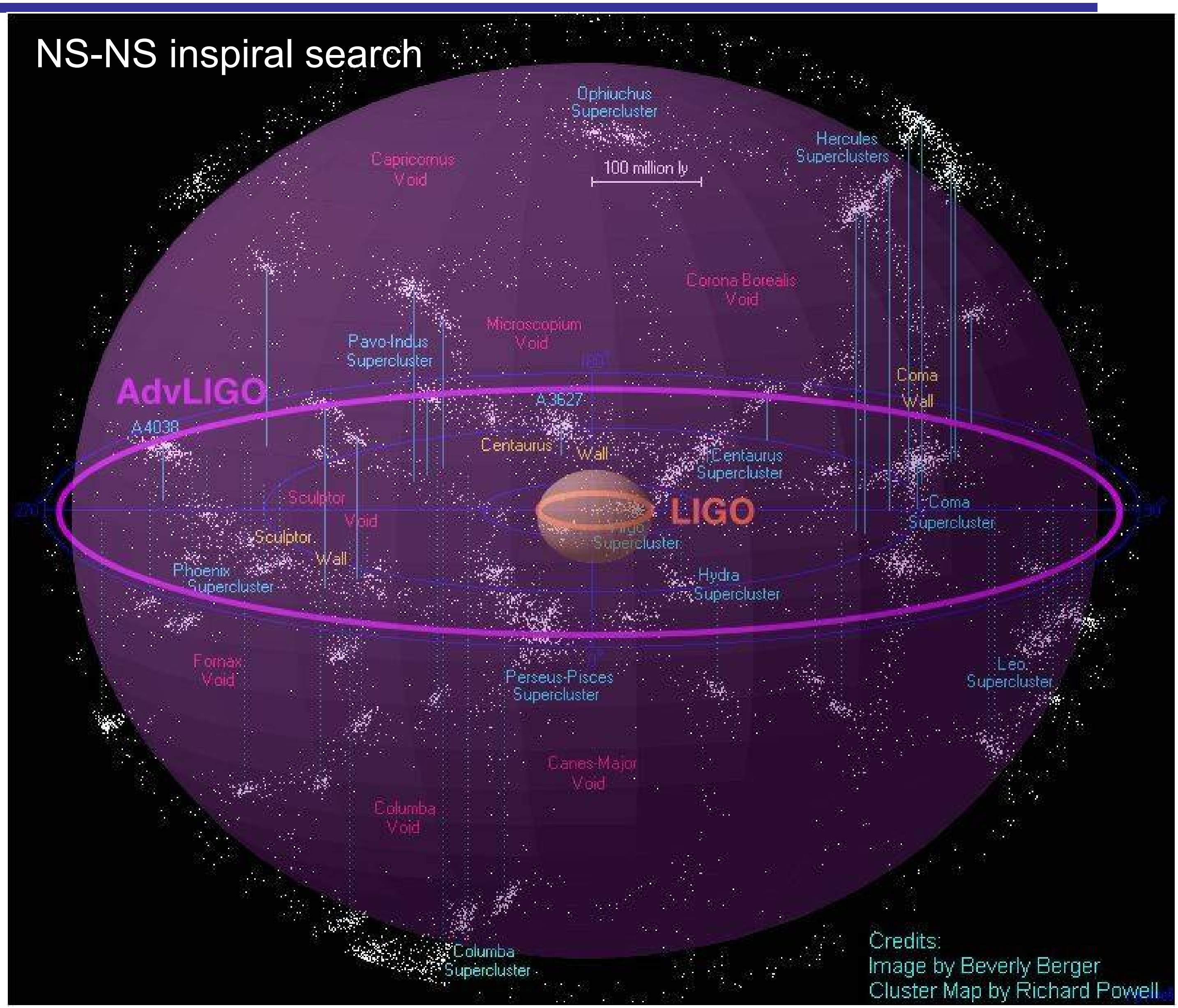
Advanced LIGO

- Major upgrades: optics, lasers, suspensions, ...
- $\times$10 better sensitivity

Advanced LIGO reach (example)

NS-NS sources $\sim$(h sensitivity)$^{2.7}$

h sensitivity will improve by $\approx$10, with improved bandwidth



Observational Publications

Bursts

- All-sky untriggered searches:
  - S1 - PRD **69**, 102001 (2004)
  - S2 - PRD **72**, 062001 (2005) ; LIGO+TAMA - PRD **72**, 122004 (2005)
  - S3 - CQG **23**, S29-S39 (2006)
  - S4 - to be submitted 3/07
- GRB-GW searches:
  - GRB030329 – PRD **72**, 042002 (2005) ;
  - S2,S3,S4 – to be submitted to PRD 3/07
- Search for quasi-periodic GWs from SGR 1806-20 following record gamma-ray flare of Dec 27, 2004 - to be submitted 3/07
- Cosmic (super-)string GW search (S5) – in preparation

Stochastic

- S1 - PRD **69**, 122004 (2004)
- S3 - PRL **95**, 221101 (2005)
- S4 – submitted to ApJ

Projects and Publications (contd)

Pulsars

- Searches: S1 - PRD **69**, 082004 (2004) ;
- S2 known pulsar search - PRL **94**, 181103 (2005)
- S2 coherent search – submitted to PRD
- S2 Hough transform search - PRD **72**, 102004 (2005)
- S3/S4 known pulsar search – to be submitted 3/07

Inspirals/coalescences

- NS-NS searches:
    - S1 - PRD **69**, 122001 (2004)
    - S2 - PRD **72**, 082001 (2005)
    - S3/S4 – in preparation
- S2 MACHO search - PRD **72**, 082002 (2005)
- S2 LIGO+ TAMA - PRD **73**, 102002 (2006)
- S2 BH-BH search - PRD **73**, 062001 (2006)

Summary

- LIGO is now a powerful scientific instrument with “reasonable” sensitivity to astrophysical GW sources
  - Analysis groups and methods have reached a mature level with a good publication record
- Now it is up to nature...

- The scientific collaboration (LSC) is strong and prospects are excellent for advancing GW science through the next decade
  - Advanced LIGO is on track
  - Future ground-based GW science will be based on a global network of sensitive interferometers (LIGO, GEO, Virgo, ...)