Gravitational Wave Astronomy from the Ground and Space

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Outline

Review results from ***most sensitive*** data&searches
from ground-based GW observations:

- * what searches have been performed
- * if no detection what quantities are constrained by
  these null observations
- * a priori expectations/
  astrophysical significance of the constraints
- * prospects for *upcoming* improvements

LISA

- * brief mention

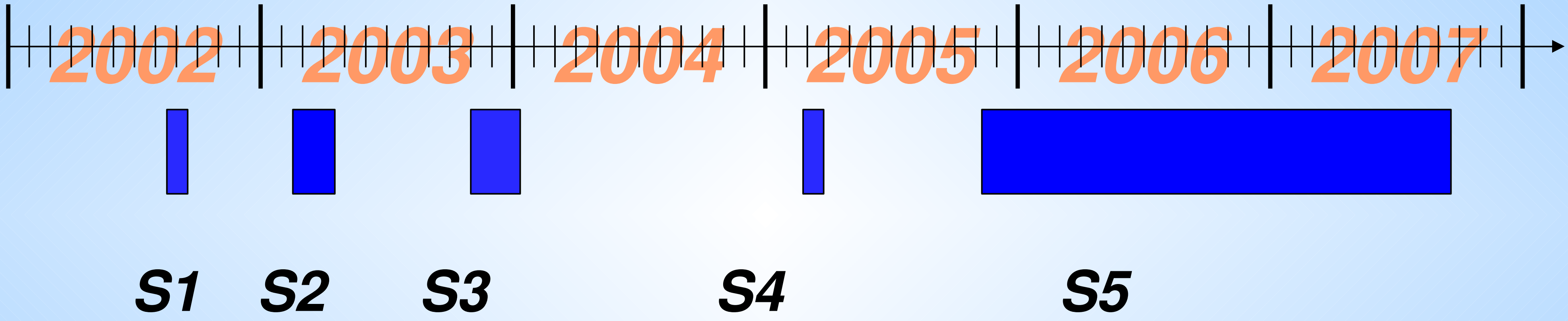
Conclusions

Disclaimer

Review results from ***most sensitive*** data&searches from ground-based GW observations:

will *not* attempt to describe *all searches* ever done or in project nor to mention *all detectors* taking data or under design.

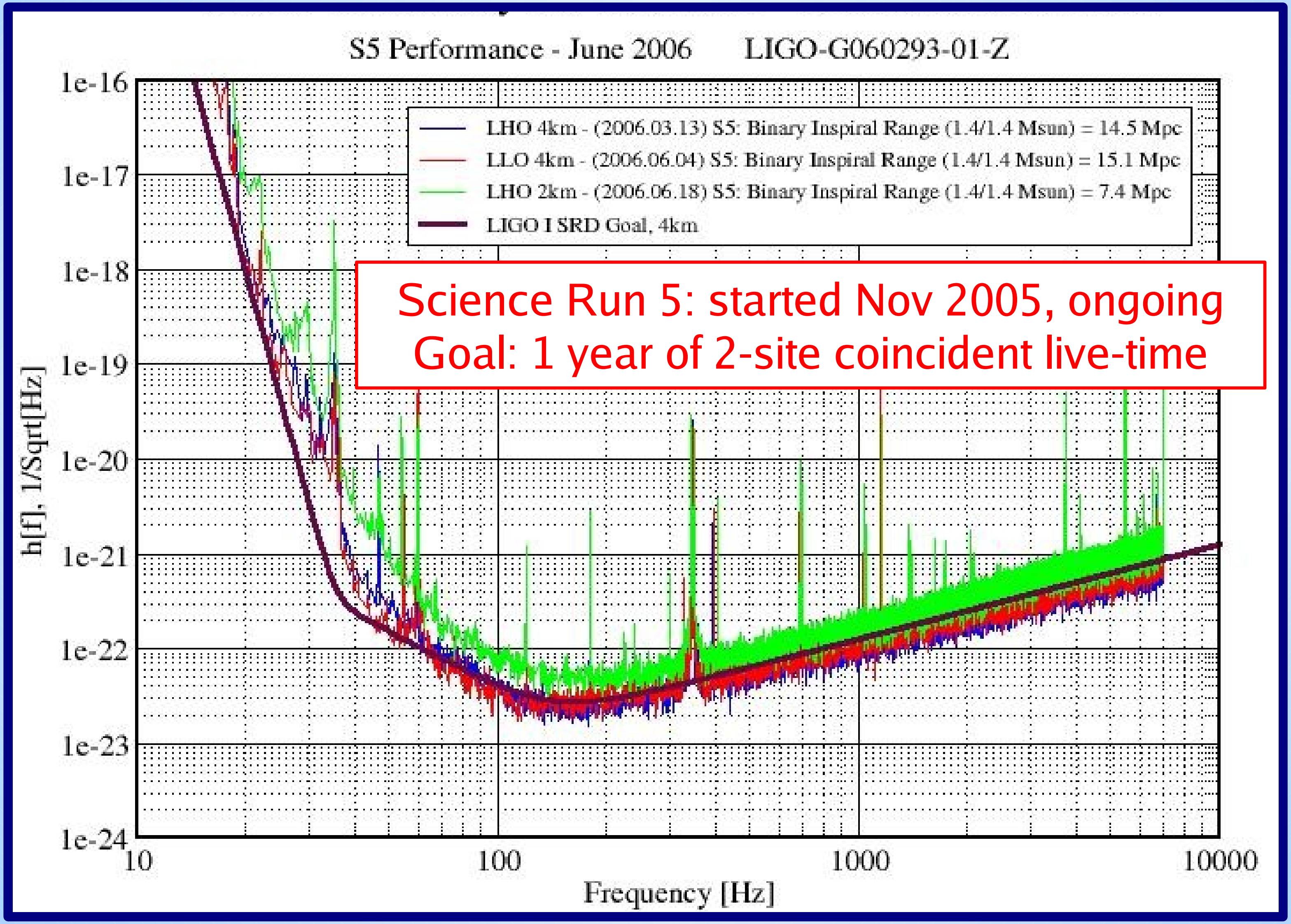
LIGO is nearing completion of its 5th science run (S5)



Duty factors:

		(so far)			
H1	59 %	74 %	69 %	80 %	73 %
H2	73 %	58 %	63 %	81 %	77 %
L1	43 %	37 %	22 %	74 %	62 %

5th Science Run of LIGO



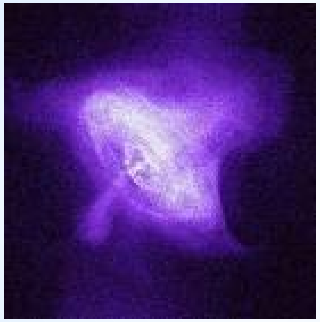
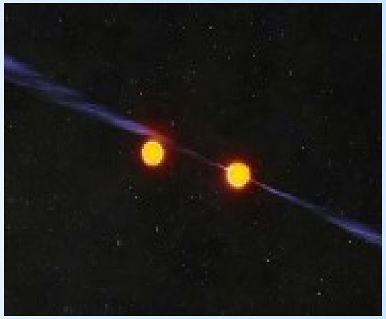
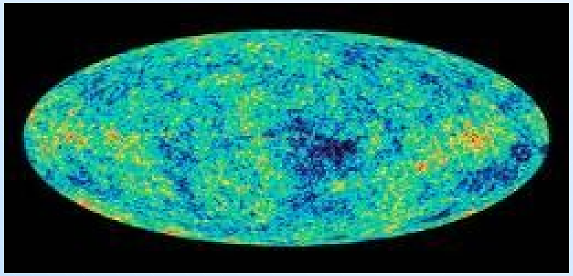
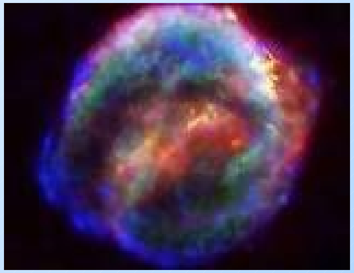
Science Run 5: started Nov 2005, ongoing
Goal: 1 year of 2-site coincident live-time

LIGO's window

In the sensitive band of current ground-based detectors one could detect signals in four categories:

- from inspiraling compact objects
- bursts , typically arising from catastrophic events
- continuous quasi-periodic waves
- stochastic background of gravitational radiation

This scheme largely reflects different analysis techniques

	Long duration	Short duration
Matched filter	 Pulsars	 Compact Binary Inspirals
Template-less methods	 Stochastic Background	 Bursts

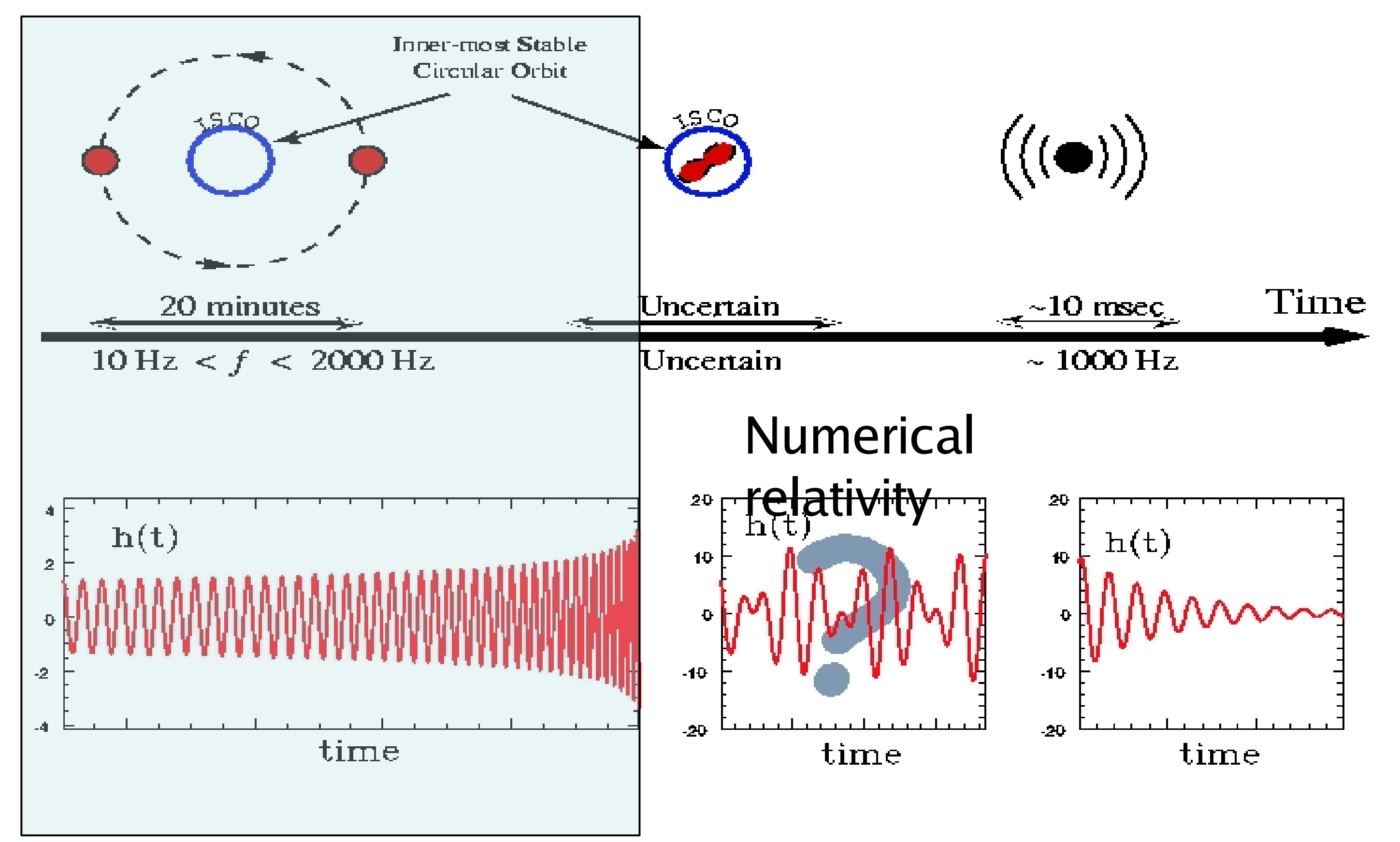
Credit:NASA/CXC/ASU/J. Hester et al.;

[redacted]

Signals from inspiraling compact objects are considered to be the most promising source for ground based detectors

Let's start from these.

Waveform reasonably well modeled and can be used to look for systems up to $\sim 80\ M_{sun}$.



Numerical relativity

Searches for signals from coalescences of compact objects

Most recent *released* result on inspiral searches from the LIGO Scientific Collaboration analyzed S3 and S4 data, together (arXiv:**gr-qc/0704:3368**)

No plausible gravitational wave event was found.

Talk by C. **Robinson for the LSC**: An upper limit on the rate of compact binary coalescences in the component mass range 0.35-80M_{sun}. In all cases the upper limit (in the range 0.1-10 yrs^{-1} L_{10}^{-1}) is still quite far from the theoretical predictions.

Astrophysical predictions:

- Merger rates are expressed as events per unit time per unit galaxy

- BNS merger rates inferred[p91,nps91] from 4 known binary systems suggest ranges[kk04,k04] of

$$10\text{-}170 \text{ X } 10^{-6} \text{ yrs}^{-1} \quad L_{10}^{-1}$$

with $L_{10}^{-1} = 10^{10} L_{B,sun}$ and $L_{B,sun} = 2.16 \text{ X } 10^{33}$ erg/s

- BBH/BHNS merger rates are much less certain and merger rates lie in the range[s05,s06]

BBH: $0.1 - 15 \text{ X } 10^{-6} \text{ yrs}^{-1} \quad L_{10}^{-1}$

BHNS: $0.15 - 10 \text{ X } 10^{-6}$ yrs -1 L_{10}^{-1}

p91: Phinney,ApJ 380,L17,(1991)
nps91: Narayan,Piran,Shemi, ApJ 379,17,(1991)
kk04: Kalogera et al, ApJ Letters 614, L137 (2004)
k04: Kalogera et al, ApJ 601, L179 (2004)
s05: O'Shaugenessy et al, ApJ 633, 1076, (2005)
s06: O'Shaugenessy et al, astro-ph/0610076

What does 10-170 X 10^{-6} yrs $^{-1}$ L_{10}^{-1} translate into, for expected detection rate ?

- $\mathcal{R}$ = 10-170 X 10^{-6} yrs $^{-1}$ L_{10}^{-1} : number of events per “galaxy” per megayr

R = $\mathcal{R}$ X C X T detection rate

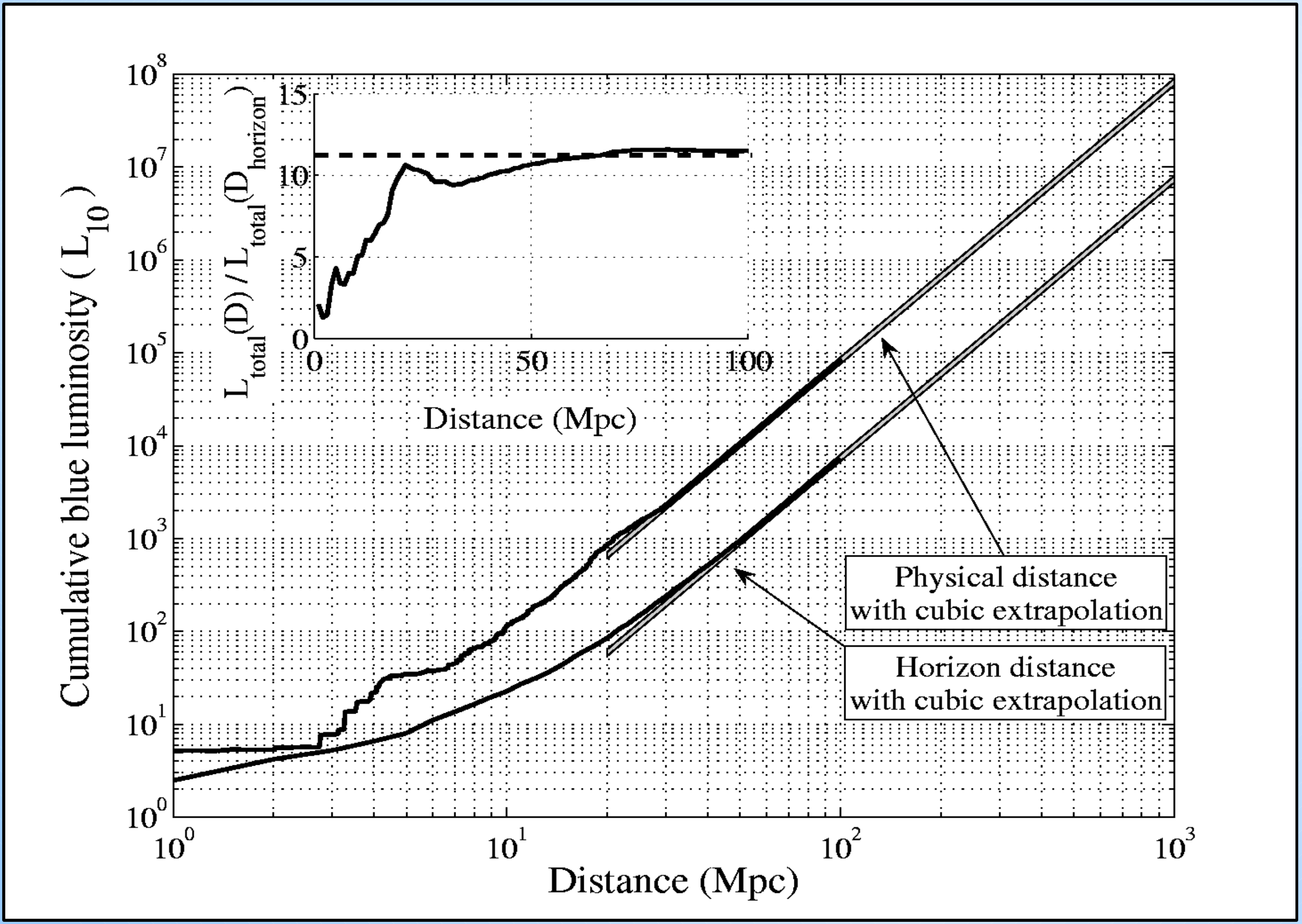
X C: number of “galaxies” the search can see L_{10}^{-1}

X T: observation time of search

- C = C(D_H) D_H : horizon distance of a search: maximum distance at which a signal may still be detected

Cumulative luminosity function

Catalog of galaxies has been developed and cumulative luminosity $C(D_H)$ computed as a function of the distance *(Kopparapu et al, arXiv:0706.1283v1)*



Horizon distance of a search: maximum distance at which a signal may still be detected.

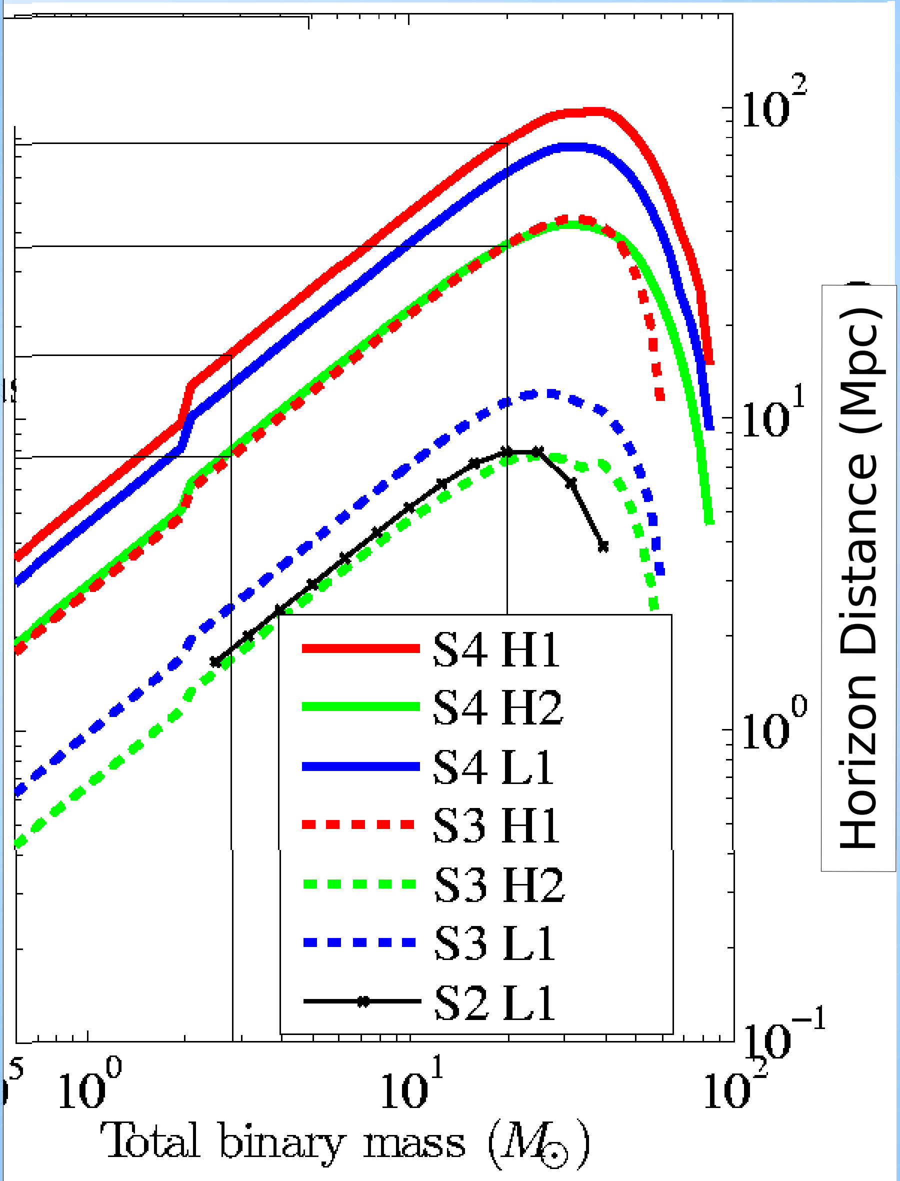
The horizon distance

(for data that has been analyzed)

distance at which an optimally oriented and located binary would produce a signal with an SNR=8.

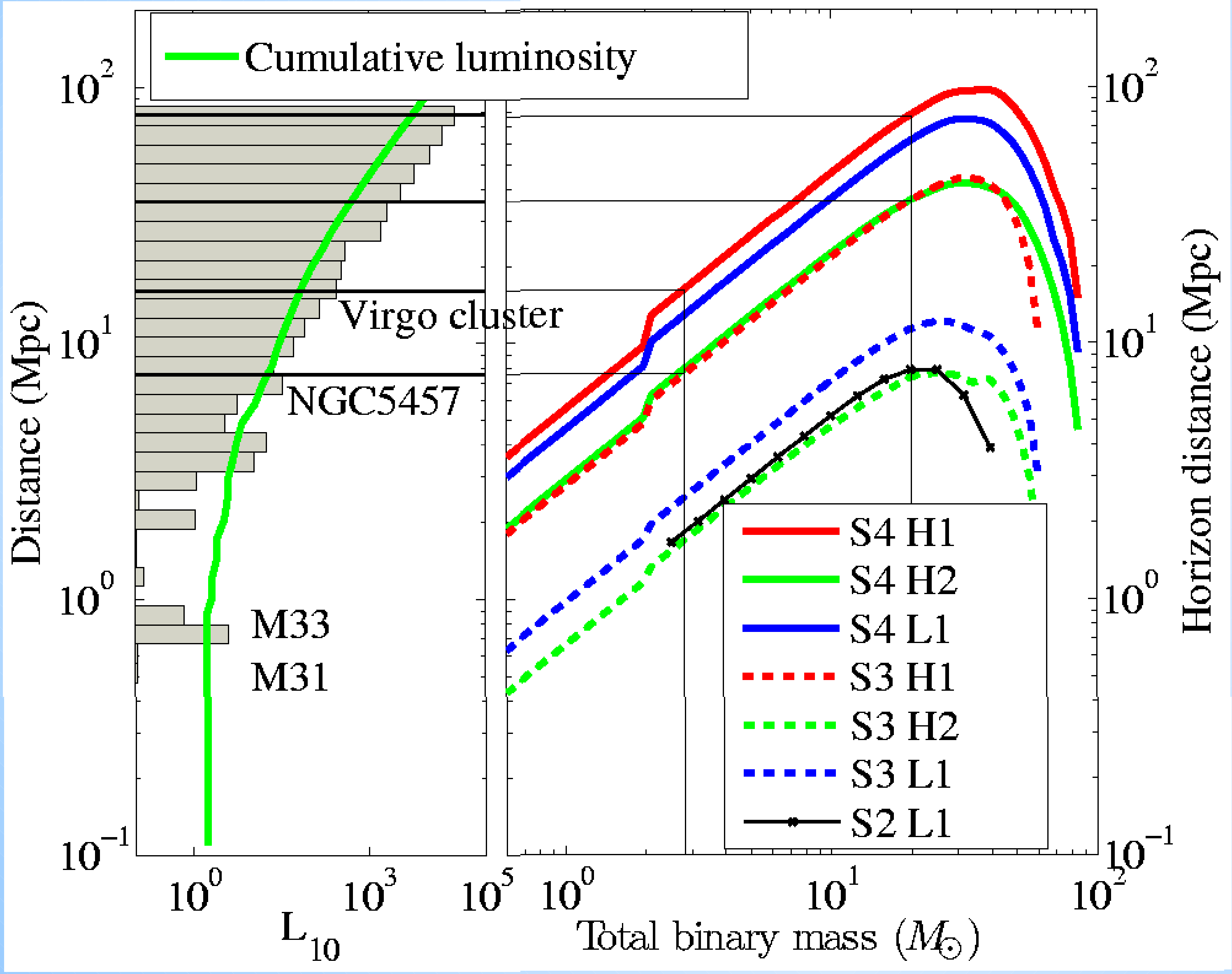
For H1 during S4:

D_H = 5.7Mpc for 0.5-0.5 M_{sun} systems
D_H = 16.1Mpc for 1.4-1.4 M_{sun} systems
D_H = 77Mpc for 10-10 M_{sun} systems



LSC, S3-S4 inspiral search, arXiv/0704:3368,Talk by C. **Robinson for the LSC**

… for S4 these translate in expected rates of



LSC, S3-S4 inspiral search, arXiv/0704:3368

≈ 1/(2000yrs)-
-1/100(yrs)
for BNS,
with DH ~ 16Mpc

≈ 1/(1000yr)-
-1/(10yrs)
for BBH,
with DH ~ 100Mpc

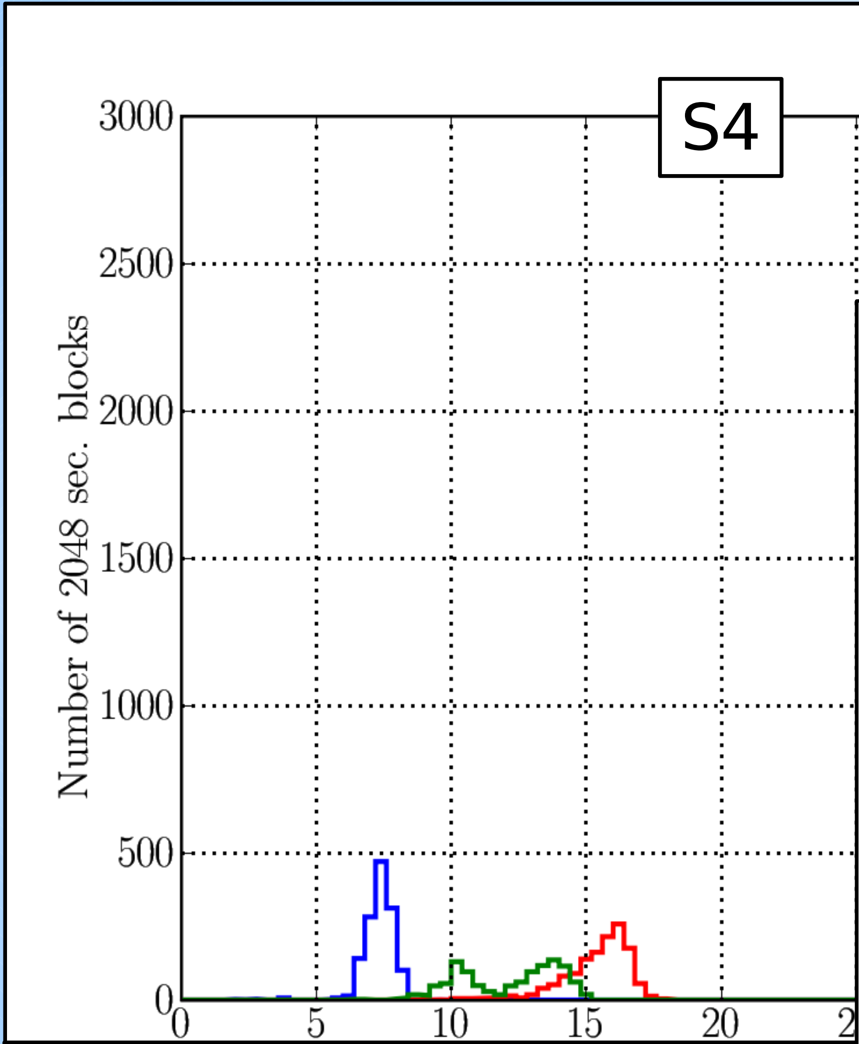
Not so great

ENHANCED:
≈ 1/(60yrs)-1/3yr
for BNS,
with DH ~ 60Mpc

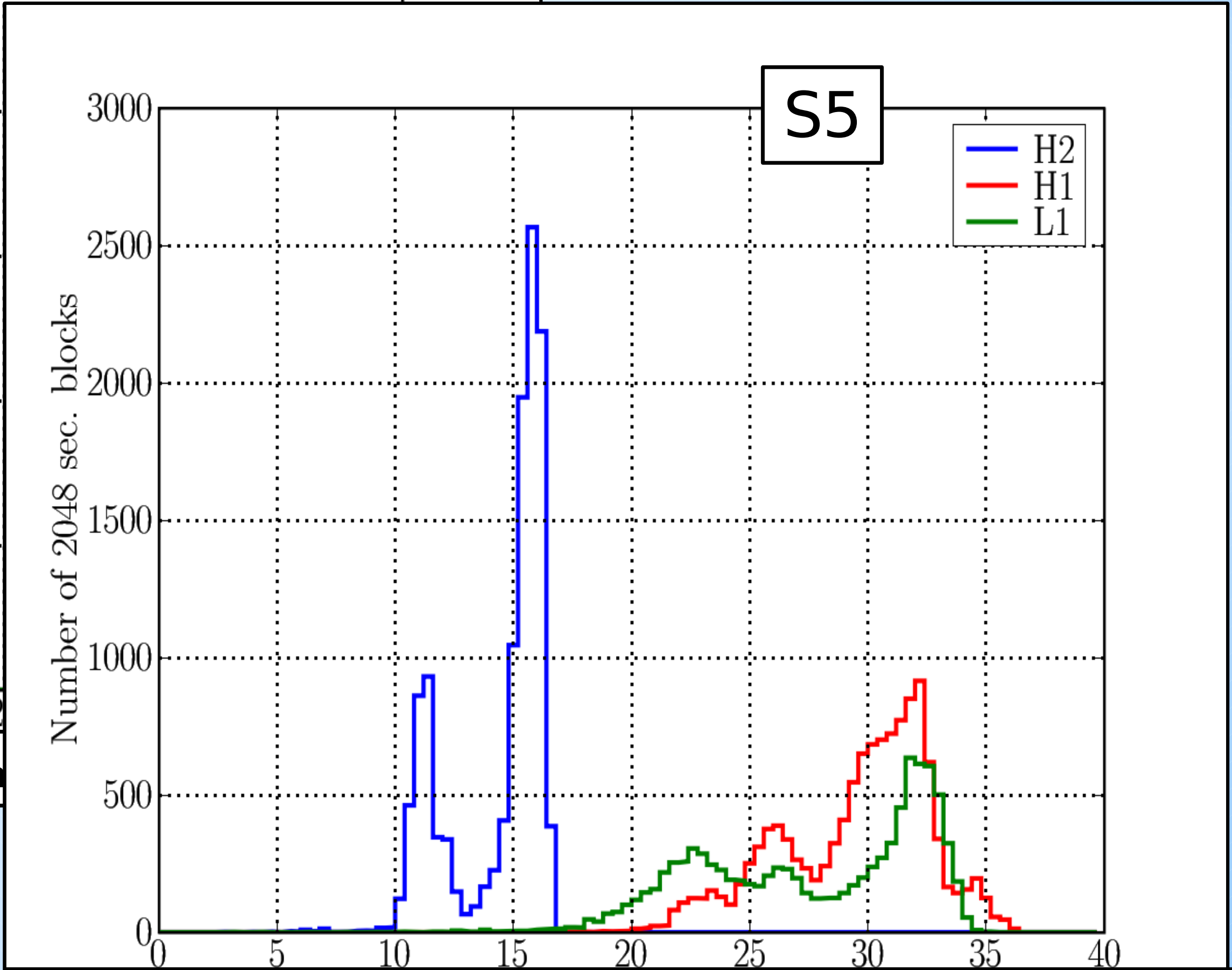
ADVANCED:
≈ 7-400/yr
for BNS,
with DH ~ 450Mpc

S5 reach

D. Keppel for the LSC, APS 07 meeting

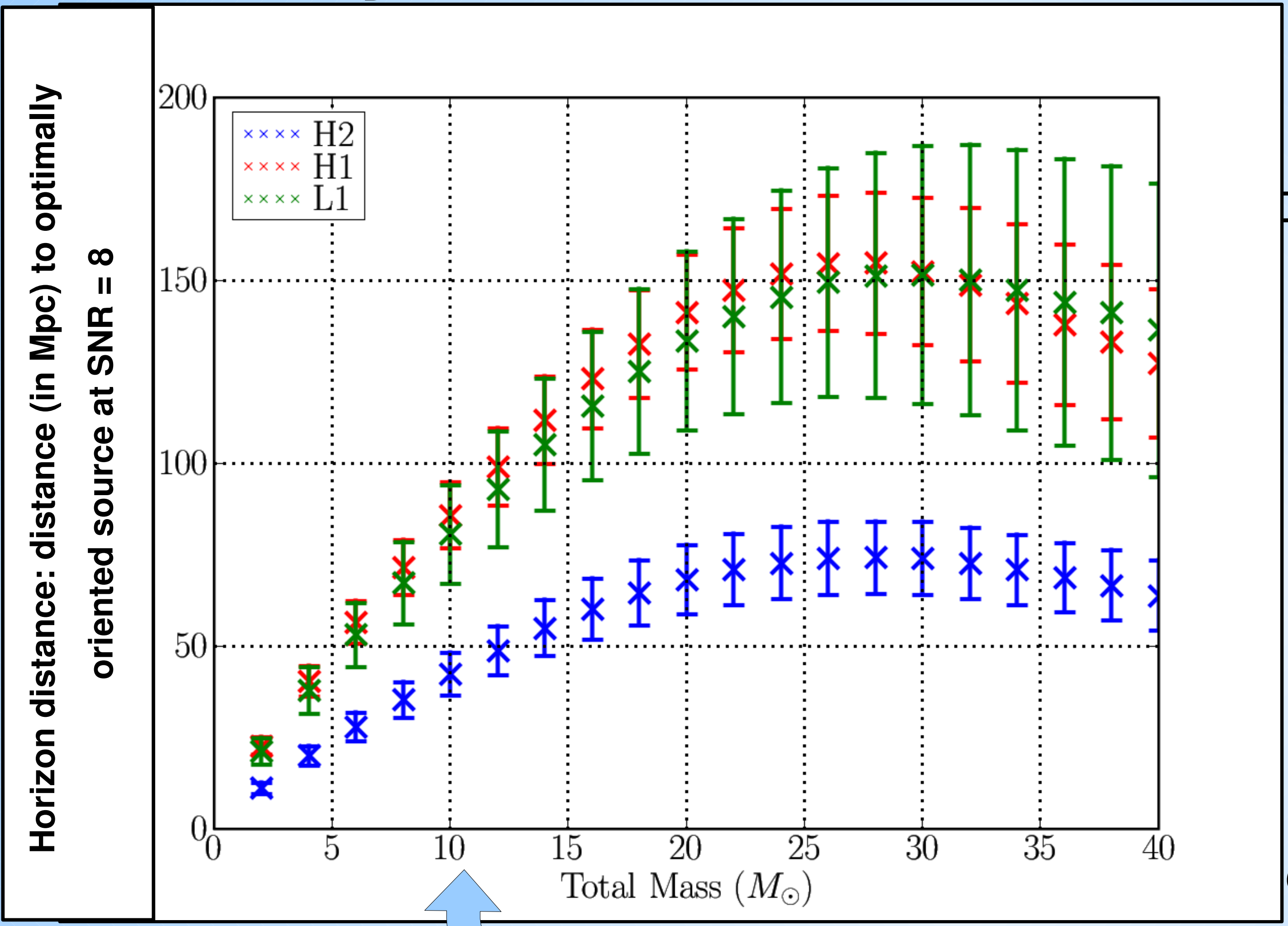


Distance to optimally oriented 1.4,1.4 solar m



Distance to optimally oriented 1.4,1.4 solar mass BNS at SNR = 8

First year of S5, estimated rates



D. Keppel for the LSC, APS 07 meeting

Reach of the search

+ Observation time of the search

+ Blue luminosity versus Distance Curve

+ Global astrophysical rate estimate

⬇

Estimate of the rate for the search

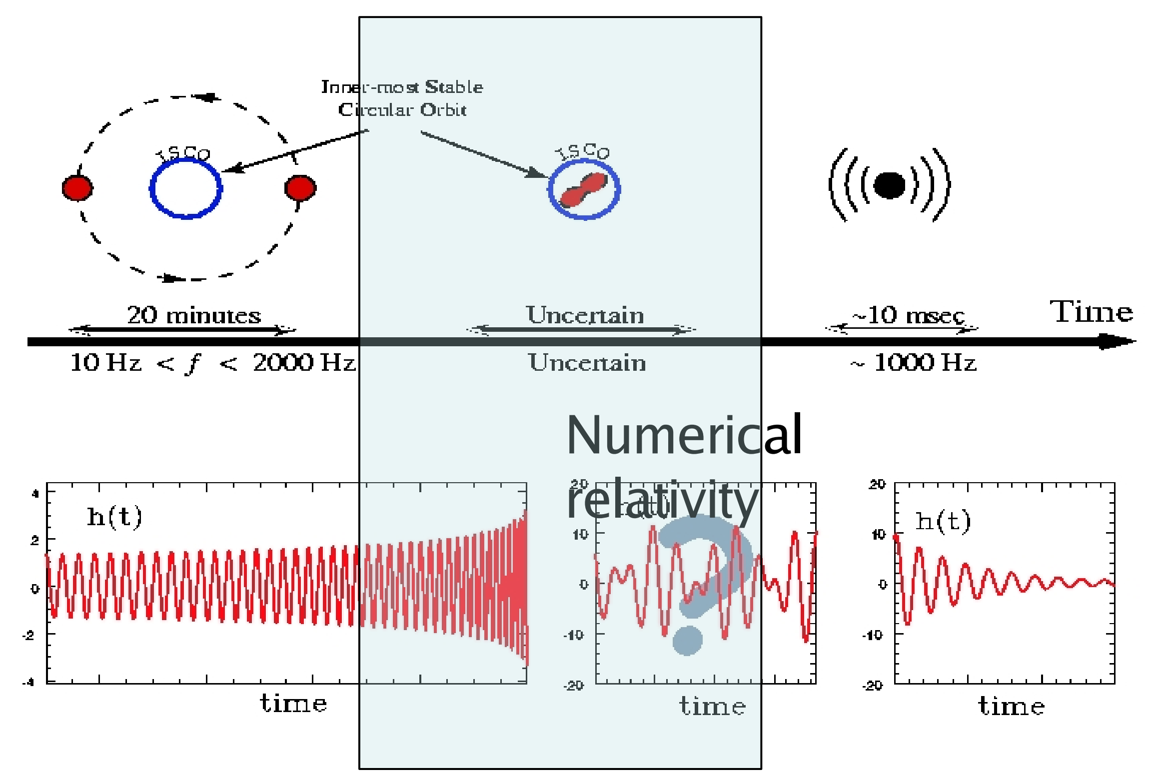
First year of S5, estimated rates

Component masses (M_{sun})	1.4,1.4	5,5	10,10
Cumulative blue luminosity of search, C [L_{10}]	200	2400	11000
Tobs [yr]	0.77		
Astrophysical Rate per unit Tobs and C [yr L_{10}]$^{-1}$	10-170X10^{-6}	0.15-10X10^{-6}	
Expected detection rate for the search [yr]$^{-1}$	1/[650-40]	1/[4000-50]	1/[800-10]

Other blind searches: for GW bursts

All inspirals of compact objects

- -all inspirals of compact objects
- - Supernovae core-collapse
- - Black hole normal modes
- - Neutron star instabilities
- - Cosmic string cusps and kinks
- - The unexpected!



Numerical relativity

What we know about th

- Catastrophic astrophysical events will plausibly be accompanied by short GW signals
- Exact waveforms are not or poorly modeled
- Durations from few millisecond to x100 millisecond durations with enough power in the instruments sensitive band (100-few Khz)-
- aimed to the all-sky, all-times blind search for the unknown using minimal assumption on the source and waveform morphology

Analysis scheme

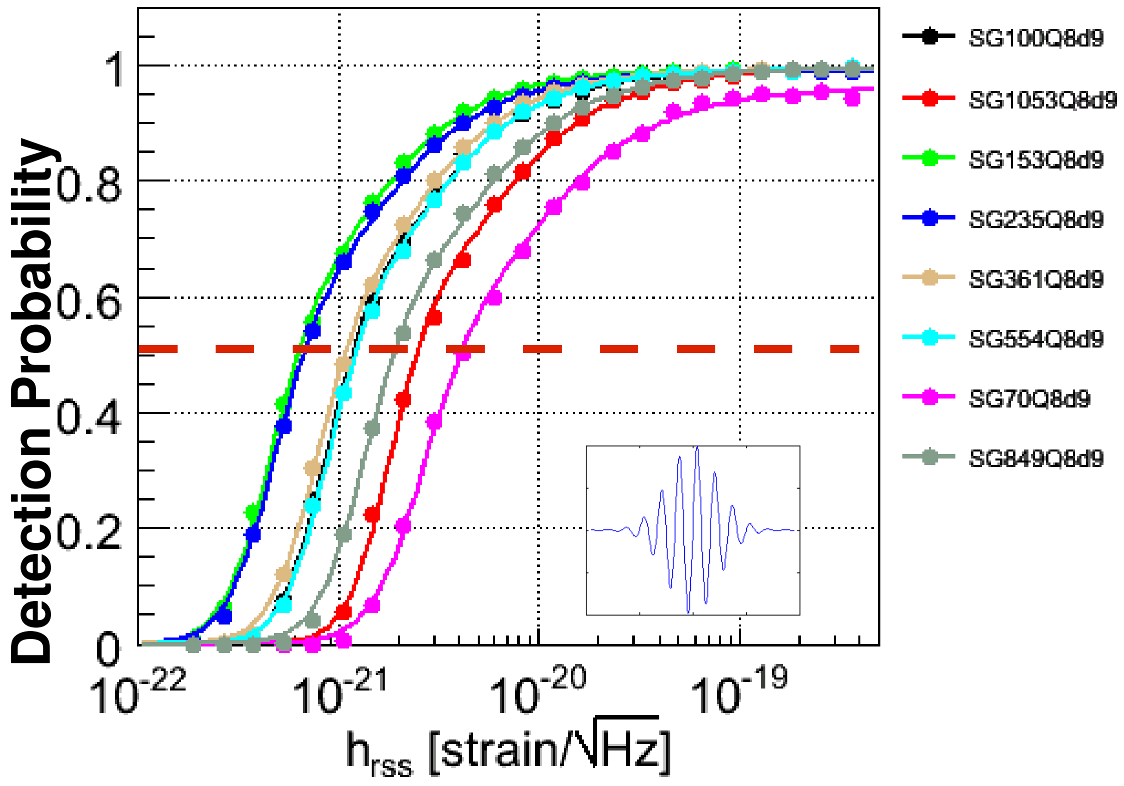
same as in arXiv:0704.0943 [gr-qc]

- Less sensitive than optimal matched filtering techniques that assume good a priori knowledge of the waveform.
- Non coherent hierarchical combination of data from detectors and complementary techniques to reduce false alarm.
- Coherent follow-up (see Yakushin’s talk).

S5 Detection Efficiency

(first 5 months of S5)

Putative waveform are injected and pipeline efficiency is measured



$$h_{\rm rss} \equiv \sqrt{\int \left(|h_+(t)|^2 + |h_\times(t)|^2\right) dt}$$

Instantaneous energy flux:

$$\frac{\mathrm{d}^2 E_{\rm GW}}{\mathrm{d}A\,\mathrm{d}t} = \frac{1}{16\pi}\frac{c^3}{G}\left\langle (\dot{h}_+)^2 + (\dot{h}_\times)^2 \right\rangle$$

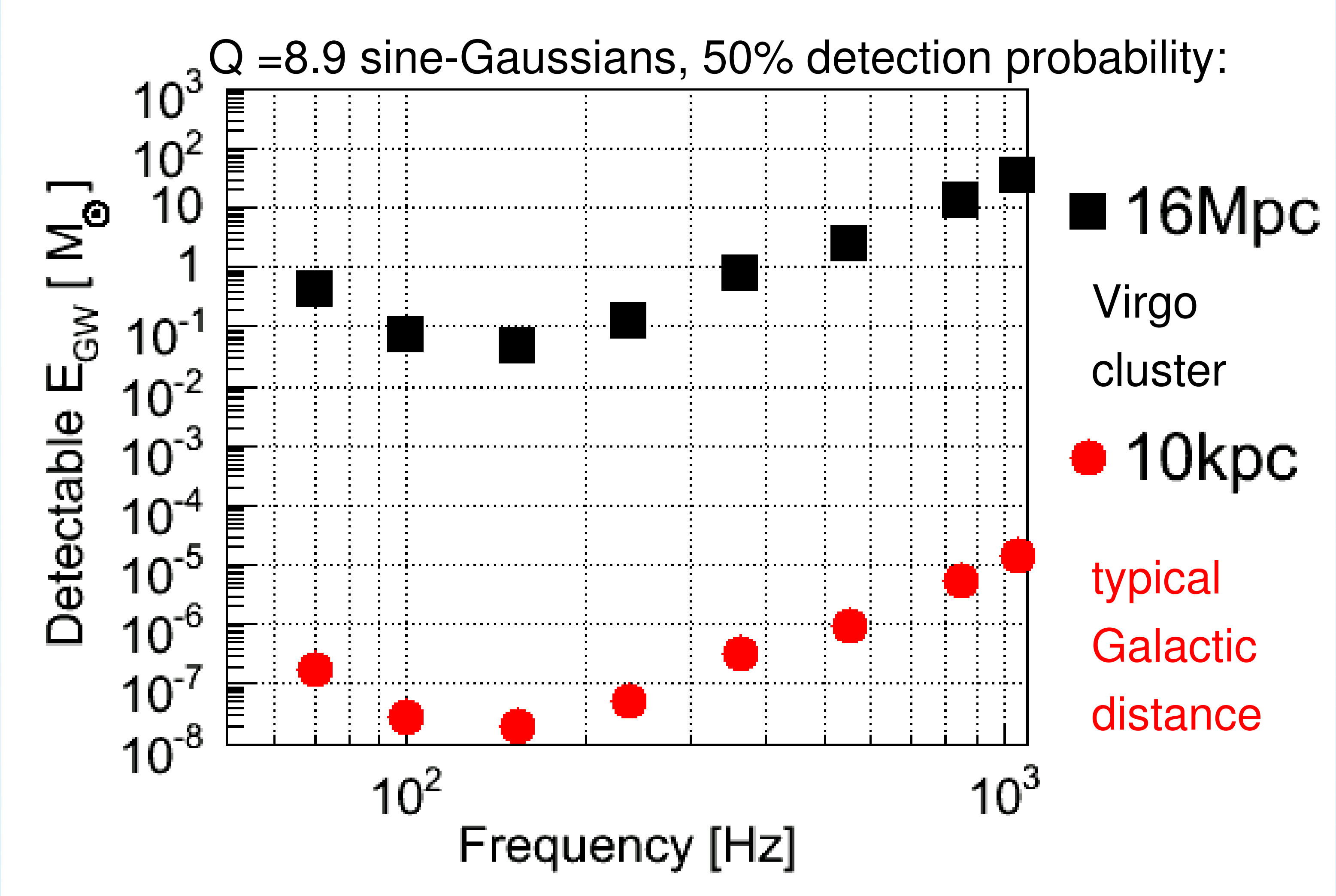
Assume isotropic emission to get rough estimates

For a sine-Gaussian with *Q*>>1 and frequency *f*$_0$:

$$\overset{\textbf{50\%}}{E_{\rm GW}} = \frac{r^2 c^3}{4G}(2\pi f_0)^2 h_{\rm rss}^{2\,\textbf{50\%}}$$

Cadonati for the LSC, APS 07, G070209-03

Detection Efficiency / Range


Q =8.9 sine-Gaussians, 50% detection probability:

Cadonati for the LSC, APS 07, G070209-03

For a 153 Hz, *Q* =8.9 sine-Gaussian, the S5 search can see with 50% probability:

~ 2 × 10^{-8} M c^2 at 10 kpc (typical Galactic distance)

~ 0.05 M c^2 at 16 Mpc (Virgo cluster)

Emission predictions and S5 reaches

- Recent ***core-collapse supernova*** simulations (Ottl et al, PRD Lett. 96 (2006)):
11 M_{sun} progenitor, S5 reach is ≈ **400pc**.
25 M_{sun} model was found to emit more, yielding a reach of ≈ **15kpc**.

Merging BBHs (Baker et al, PRD 93,(2006))), radiate up to $0.03M_{tot}\ c^{-2}$ in Gws.
If m1=m2=10, then f ~ 750Hz, which yields a reach of ≈ 3Mpc.
If **m1=m2=50 M_{sun}** then f ~ 150Hz and reach ≈ **120Mpc**.

BBH merger rates:

$$0.1\text{- } 15 \text{ X } 10^{-6}\ \mathrm{yrs}^{-1}\ L_{10}^{-1} \rightarrow 1/[3000\text{-}7]\mathrm{yrs}$$

Estimate of reach for various models following [1] and rescaling for S5-to-S4 sensitivity
[1] arXiv:0704.0943v1 [gr-qc], LSC, burst searches in S4 data

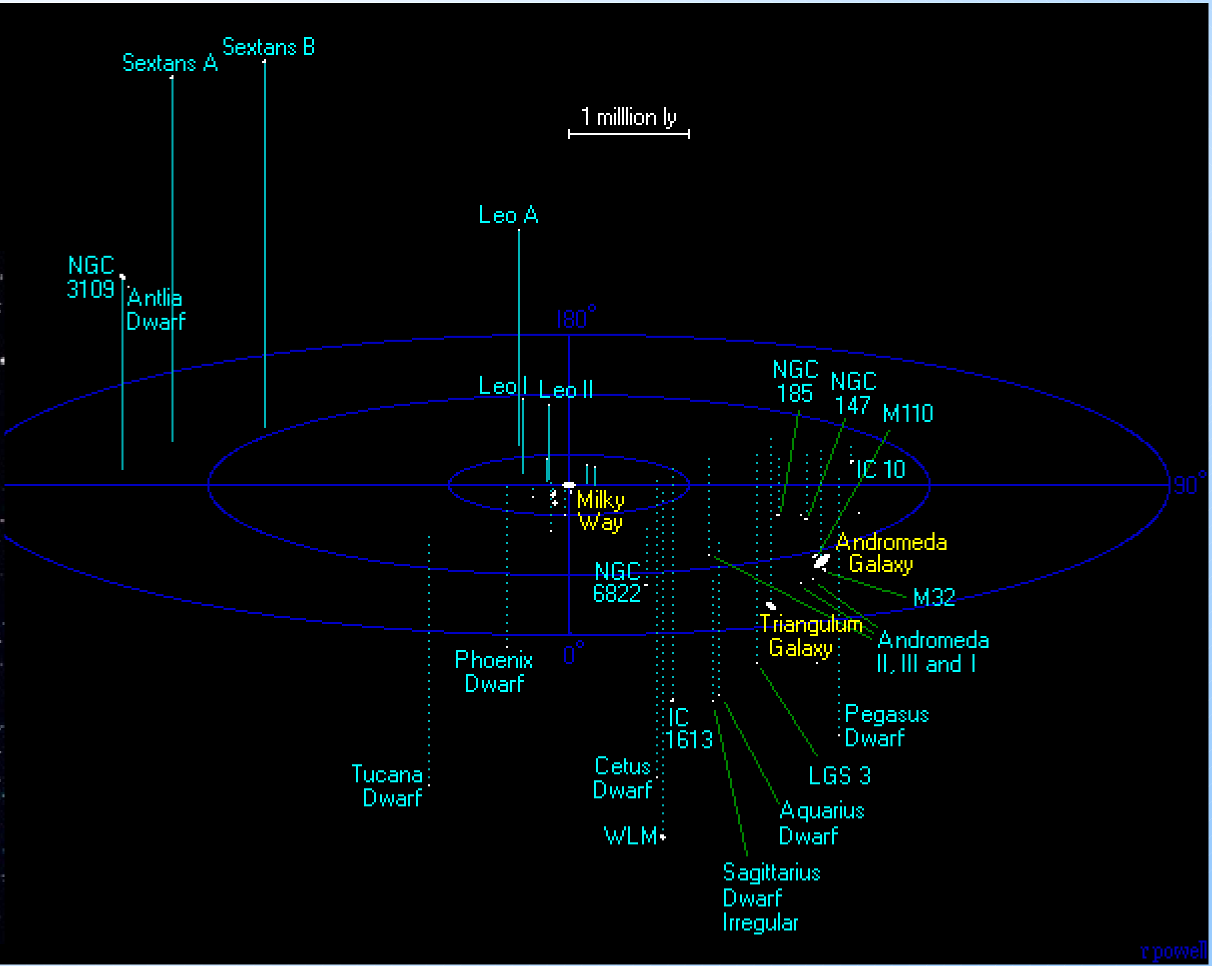
Searches triggered by em observations

GRB070201

detected by Konus-Wind,
INTEGRAL, Swift, MESSENGER

- Described as an “intense short hard GRB”
- a = 11.089 deg, d = 42.308 deg, error = 0.325 sq. deg, center is 1.1 deg from center of M31 (800kpc) and includes its spiral arms
- $E_{iso} \sim 10^{45}$ ergs if at M31 distance
- Hanford detectors were taking data

Credit: The Electronic Universe Project



Short GRBs and GRB070201

Most likely short GRBs are associated with the NS-NS or NS-BH merger.
They are the em counterpart of strong gravitational wave signals.

Simultaneous detection of GRB and a GW event would
- firm evidence that hard GRBs do indeed stem from compact binary mergers
- provide insight into merger physics
- measure cosmological parameters (luminosity distance from GWs, red shift from em)

A non-detection of GRB070201 would

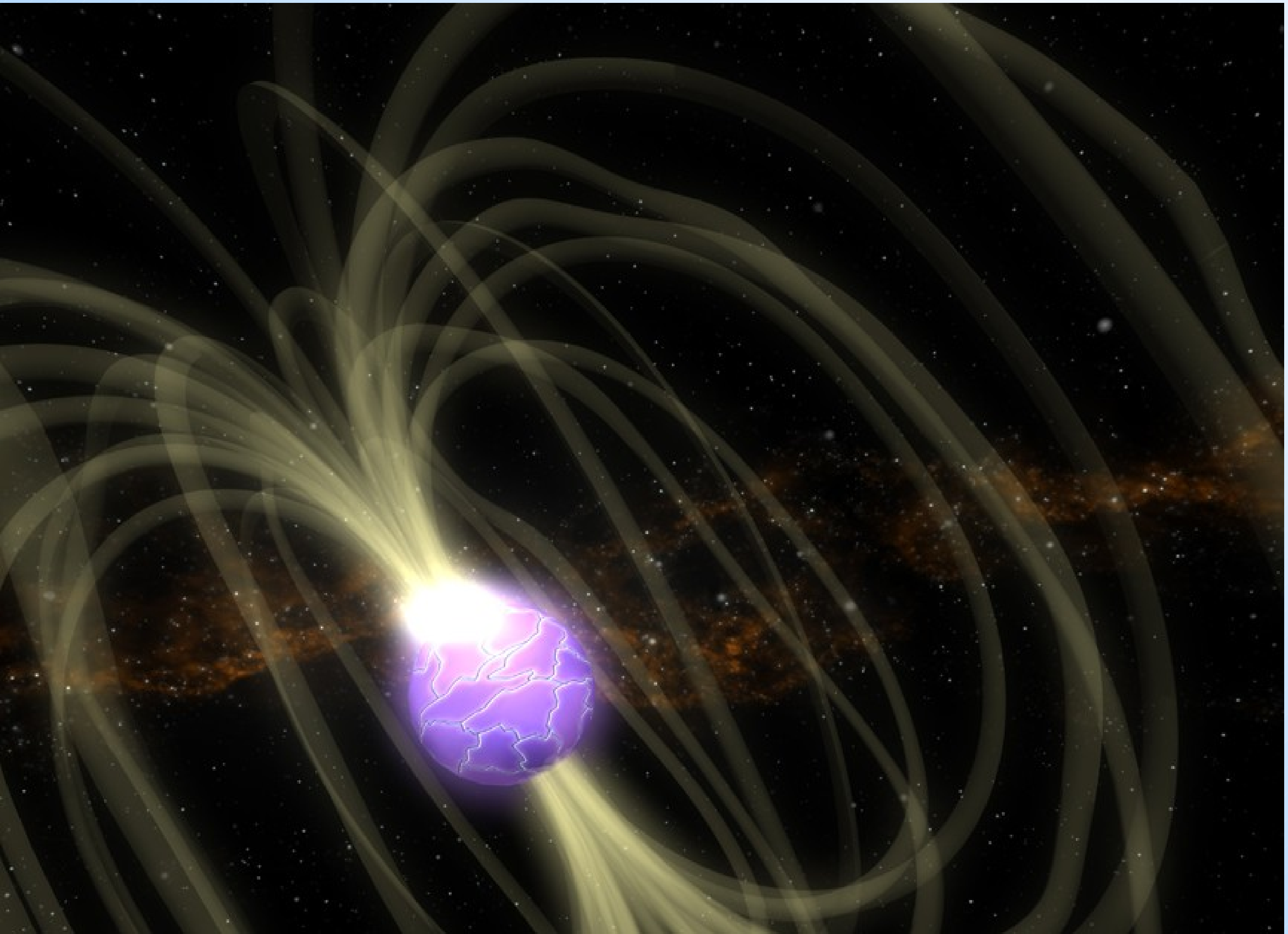
- Exclude progenitor in mass-distance region
  - Bound the GW energy emitted by a source M31

Preliminary results of this triggered search today in S. Marka's talk on behalf of the LSC

Triggered searches SGR1806-20 hyperflare 27 Dec 04

LSC, astro-ph/0703419v2 and S. Marka's talk

Artist conception, credit: NASA



- H1 in astrowatch
- Galactic neutron star SGR 1806-20 emits a record flare
- Distance ≈ 10kpc [6-15kpc]
- Energy ~10^{46} erg
- X-ray pulsating tail lasting six minutes
- These QPO oscillations are in 300-2000Hz range *(Israel et al. 2005, Watts & Strohmayer 2006)*, LIGO's sensitive band
- May be explained as due to a magnetar starquake
- QPOs might be driven by star's seismic modes
- GW could be associated with these modes
- FRMS=0.174

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

- A number of papers have come out that, based on different magnetar models, attempt to explain the observed QPO structure.

- GW observations could help rule out some of these models
  - Which modes emit GWs
  - Where does the energy come from/star model
- GW search: no significant deviation from off-source sample was observed
- **90% upper limits on GW at detector were placed for emission at all QPOs. Most stringent for the 92.5Hz QPO: $h_{rss}^{90\%}=4.53\times10^{-22}$ which corresponds to an isotropic emission of 7.67×10^{46} erg, 4.29×10^{-8} M_{sun}.**

-This energetics range starting to probe interesting range, because

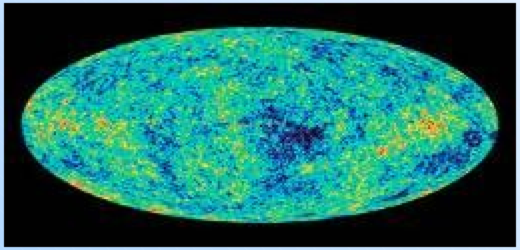
i) it is same order as (isotropic) em energy emitted

ii) for a normal star max elastic energy in crust is 10^{44} erg

iii) with sensitivity improvements of 2 the energies probed will be in the lower 10^{46} erg, and with advanced LIGO at lower frequency ranges of a few 10^{43} erg become accessible.

Long-lived signals

Stochastic background



Periodic Signals

Stochastic background

- S4 data

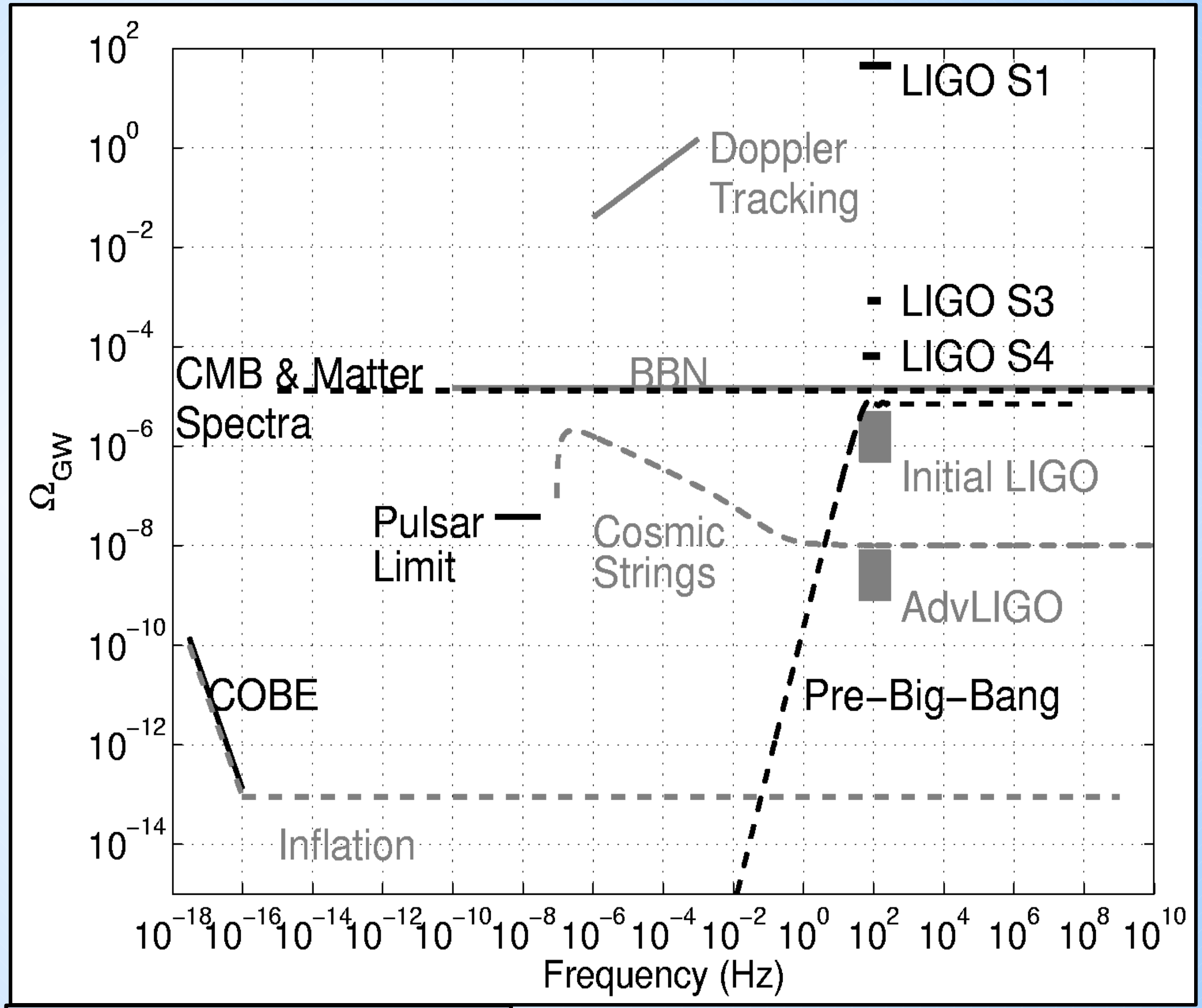
- no detection

- for flat spectrum upper limit on GW energy density is:

$\Omega_{GW} < 6.5 \times 10^{-5}$

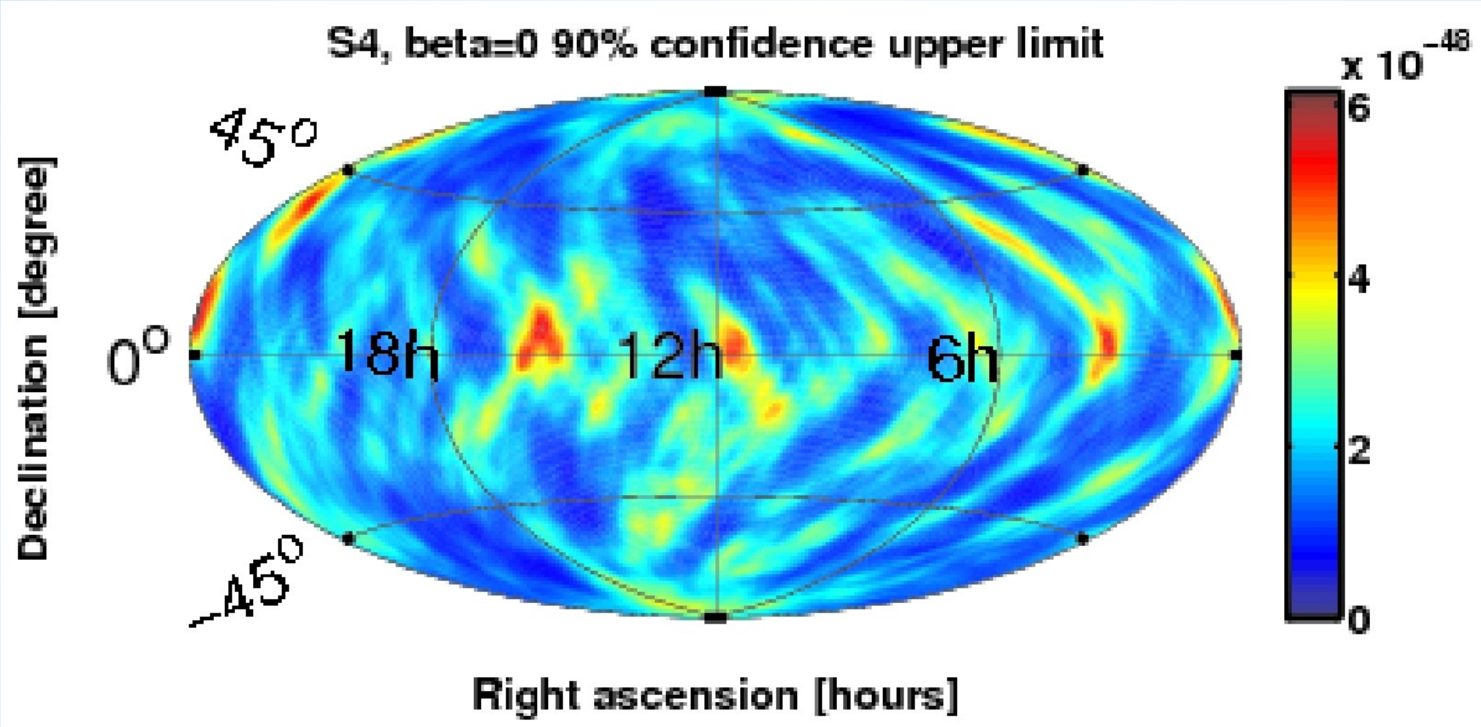
best UL to date, but still above Big Bang Nucleosynthesis constraint

(may, however, constrain cosmic string models.)



LSC, ApJ 659 (2007)

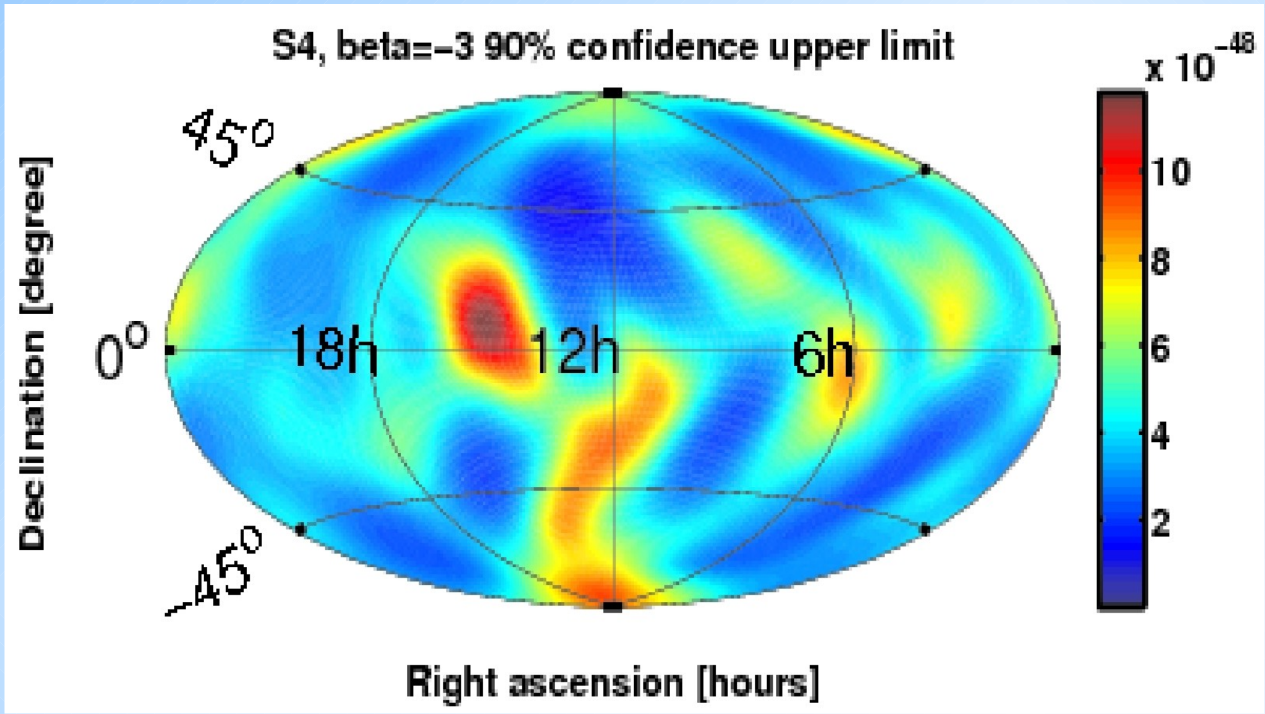
Point sources (S4)



Upper limits on flat strain power spectrum, H_0 in the [50-1800] Hz: 8.5 - 61 x 10^{-49} Hz^{-1}

Compare with estimated contribution from all LMXBs within 15Mpc ≈
10^{-55} Hz^{-1}(100Hz/f)(100Hz/Δf)

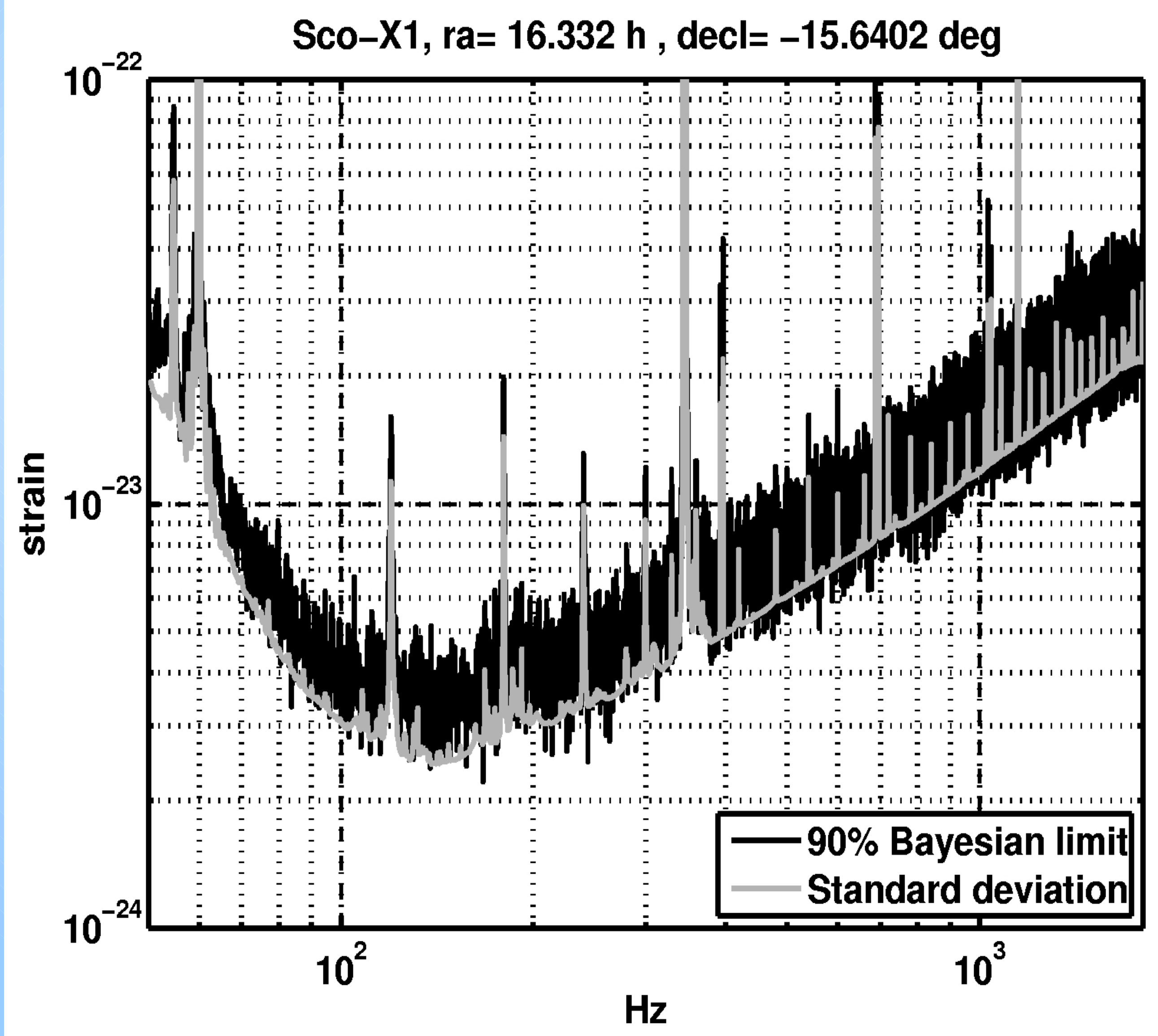
Point sources



Upper limits on H(f) in the [50-1800] Hz band for -3 power SB spectrum:
1.2 - 12 x 10^{-48} Hz^{-1}

Point source: Sco-X1

Accretion-driven neutron star. If GW emission balances the torque, the GW luminosity can be estimated from the X-ray luminosity



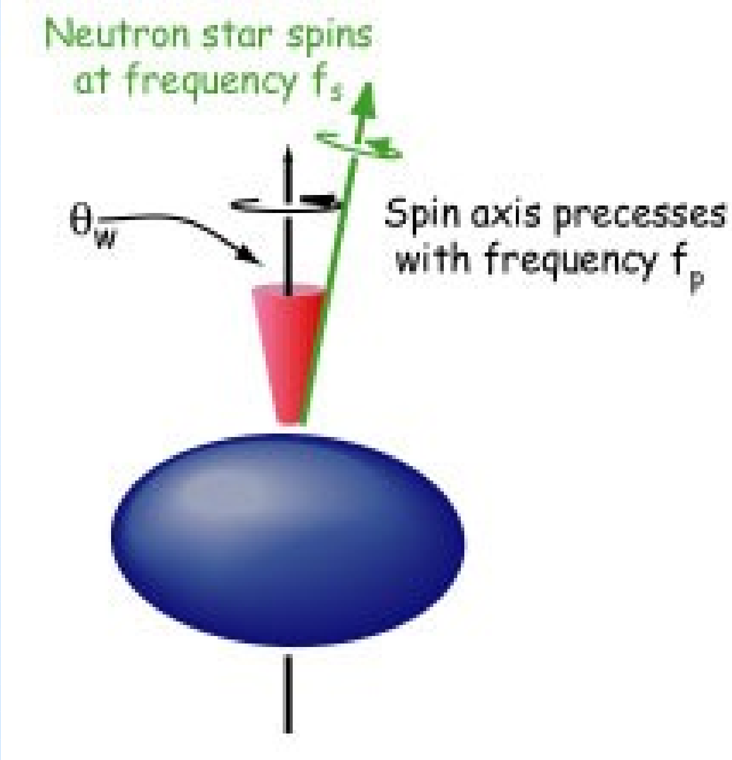
Upper limits on $h_{rms} \approx$ 3.4×10^{-24} (f/200Hz) f>200Hz in each 0.25Hz bin

$h_{rms} / h^{LX}_{rms} \approx 100\ (f/200Hz)^{2/3}$ f>200Hz

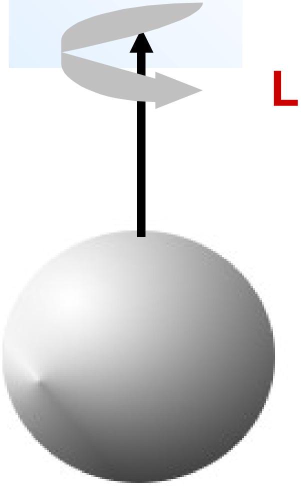
Continuous GW signals

Continuous GW signals

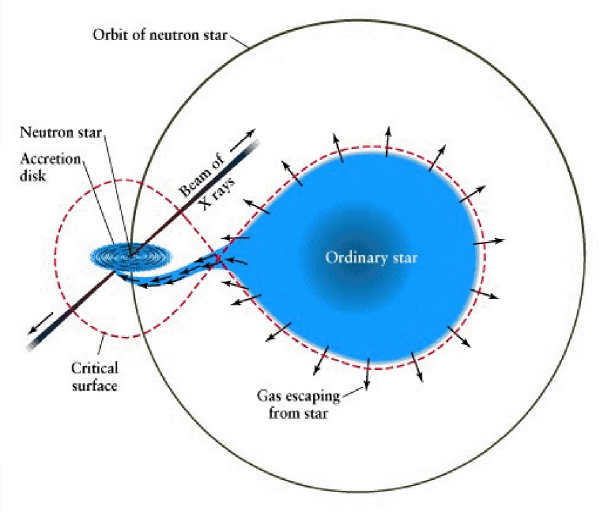
- Pulsars (spinning neutron stars) are known to exist!
- Emit gravitational waves if they are non-axisymmetric:



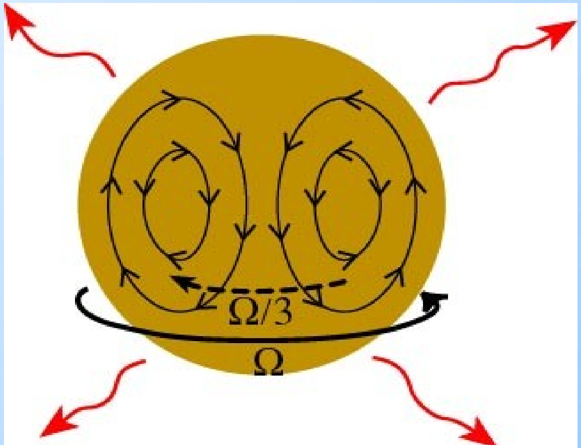
Wobbling Neutron Star



Bumpy Neutron Star

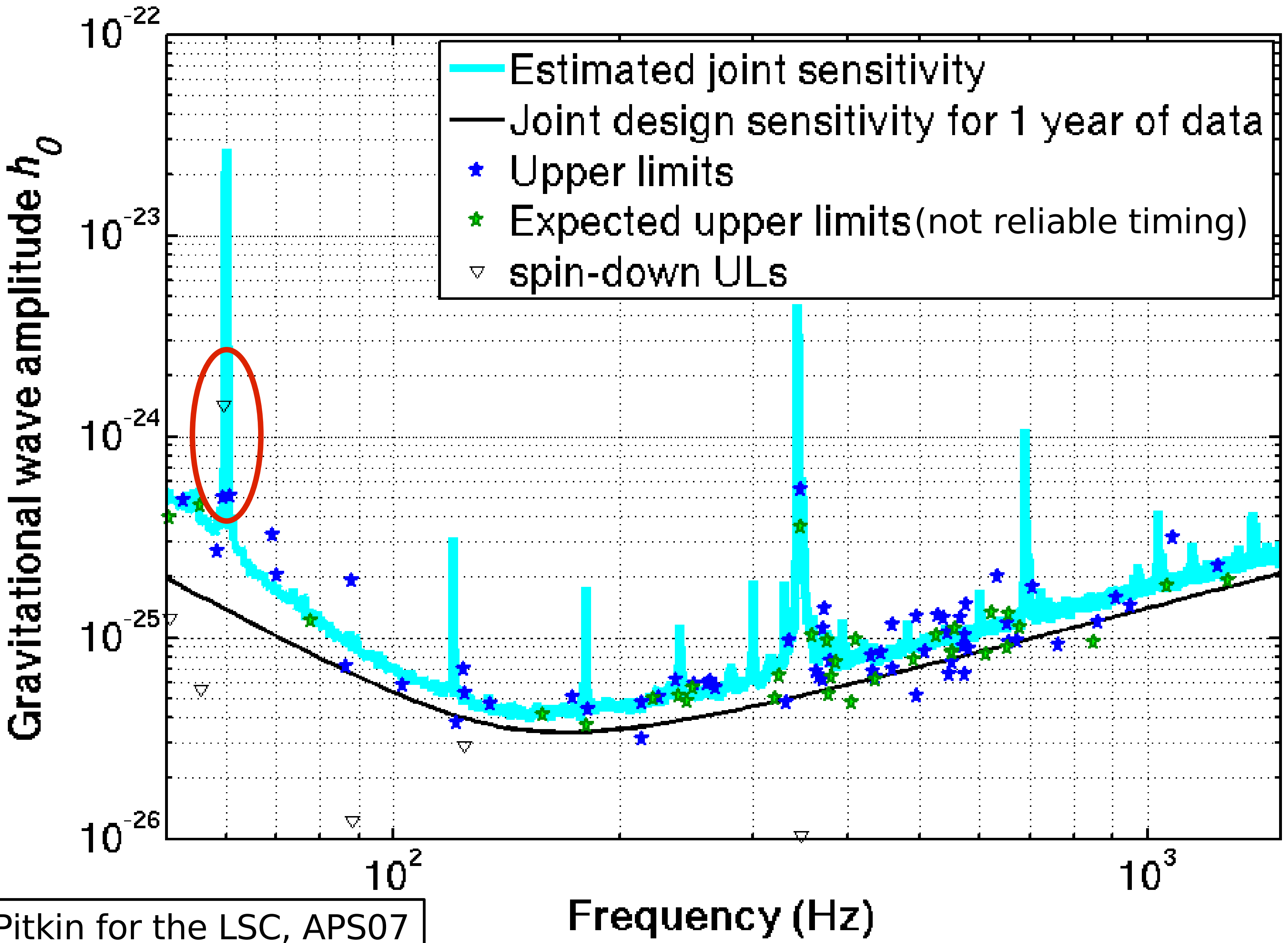


Low Mass X-Ray Binaries



Young Neutron Stars

Known pulsars, preliminary S5



Pitkin for the LSC, APS07

Known pulsars, preliminary S5

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{\epsilon I f^2}{d}$$

known

fiducial value

Joint 95% upper limits from first ~13 months of S5 using H1, H2 and L1 (97 pulsars)

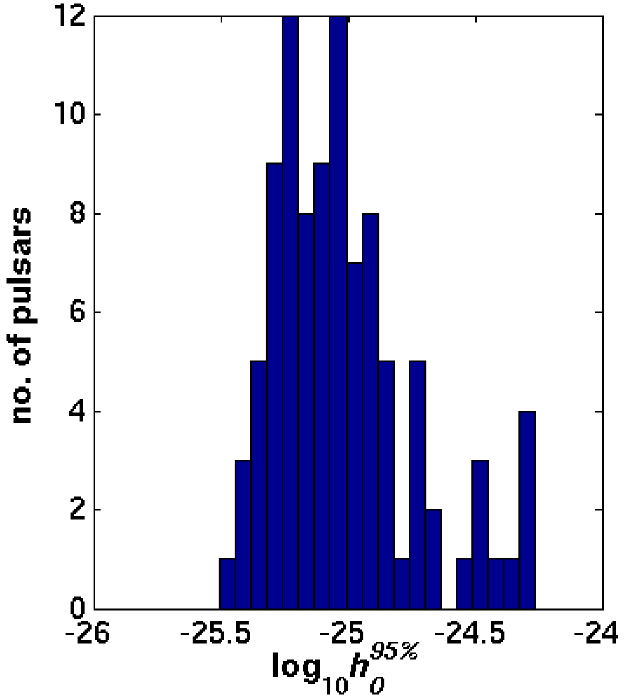
Lowest h_0 upper limit:

PSR J1623-2631 (ν_{gw} = 180.6 Hz, r = 2.2 kpc) $h_{0\_min} = 3.4\times10^{-26}$

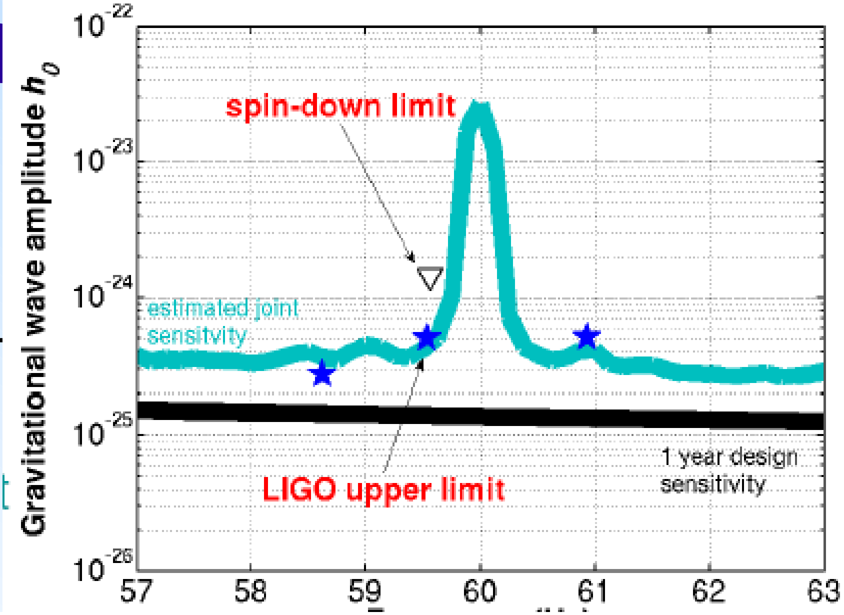
Lowest ellipticity upper limit:

PSR J2124-3358 (ν_{gw} = 405.6Hz, r = 0.25 kpc) $\varepsilon = 7.3\times10^{-8}$

Due to pulsar glitches the Crab pulsar result uses data up to the glitch on 23 Aug 2006, and the PSR J0537-6910 result uses only three months of data between two glitches on 5th May and 4th Aug 2006



Crab pulsar prelim



$h_{0\ spin\text{-}down} = 1.4\text{x}10^{-24}$

$h_{0\ S5\ first\ year} = 5\ \ \text{x}10^{-25}$

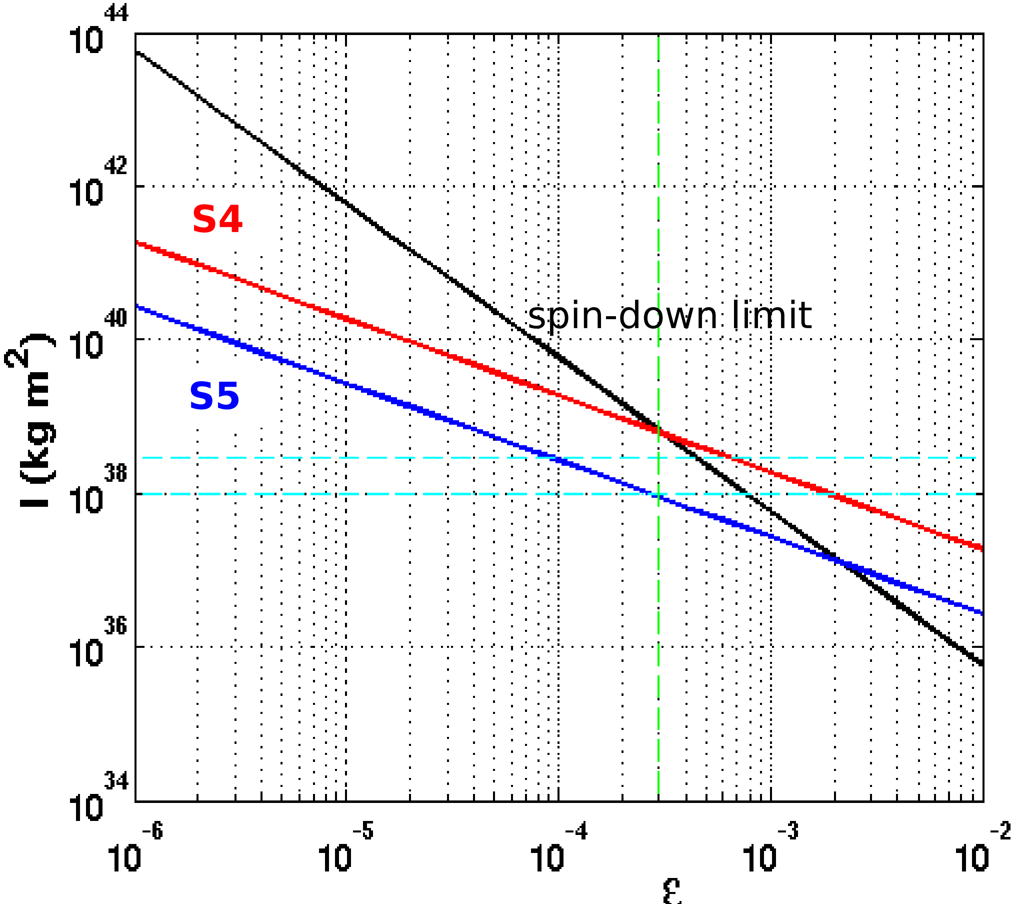
at fiducial I = 1

However, we know that not all energy goes into GWs: [1] estimates

But I could be higher than the fiducial value. No definitive observational evidence but a number of theoretical investigations* suggest:

I = 1-3 x 10^{38} (kg m^2)

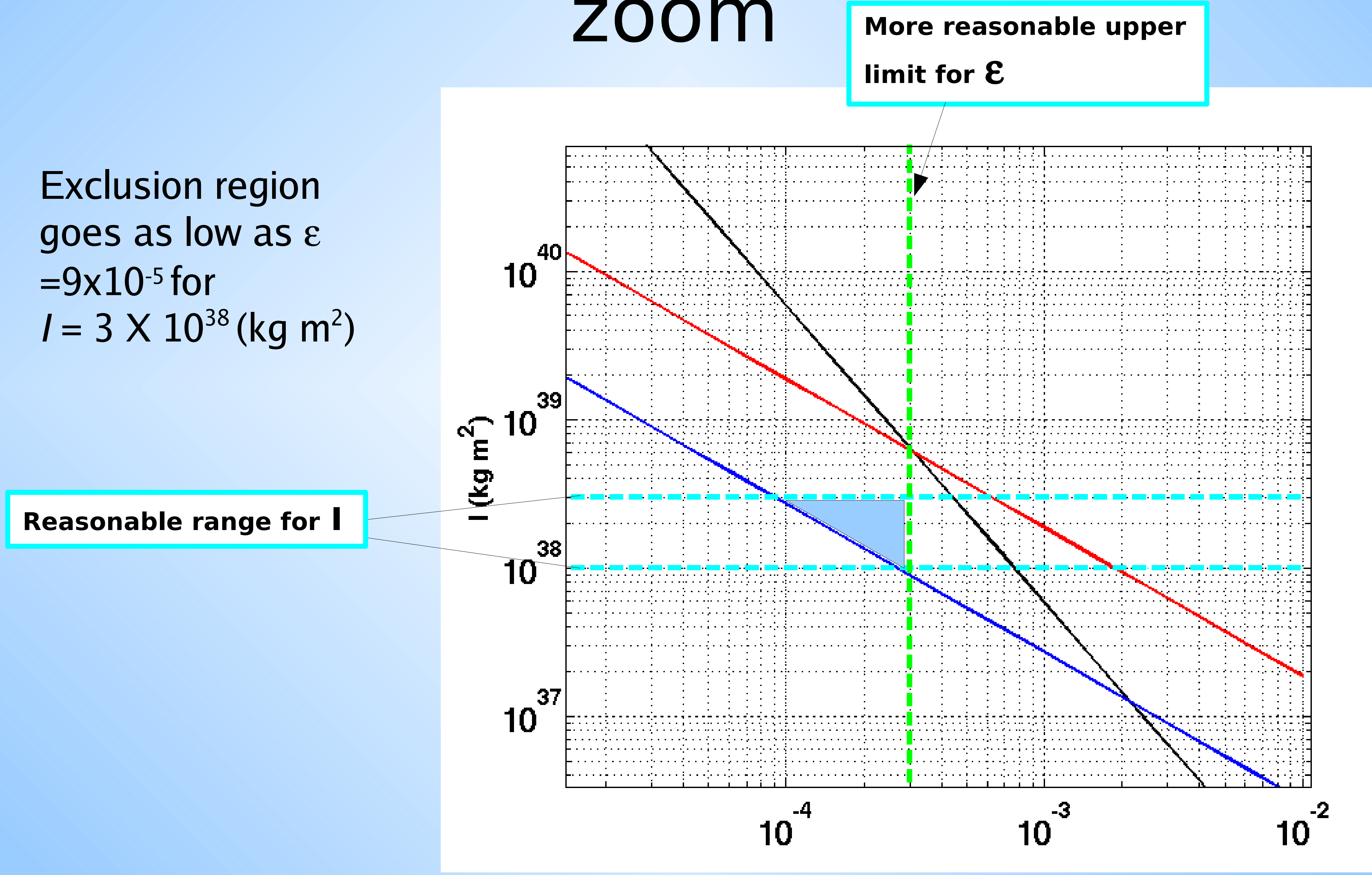
Upper limit on h_0 can be recast as exclusion area on $I\varepsilon$ plane:



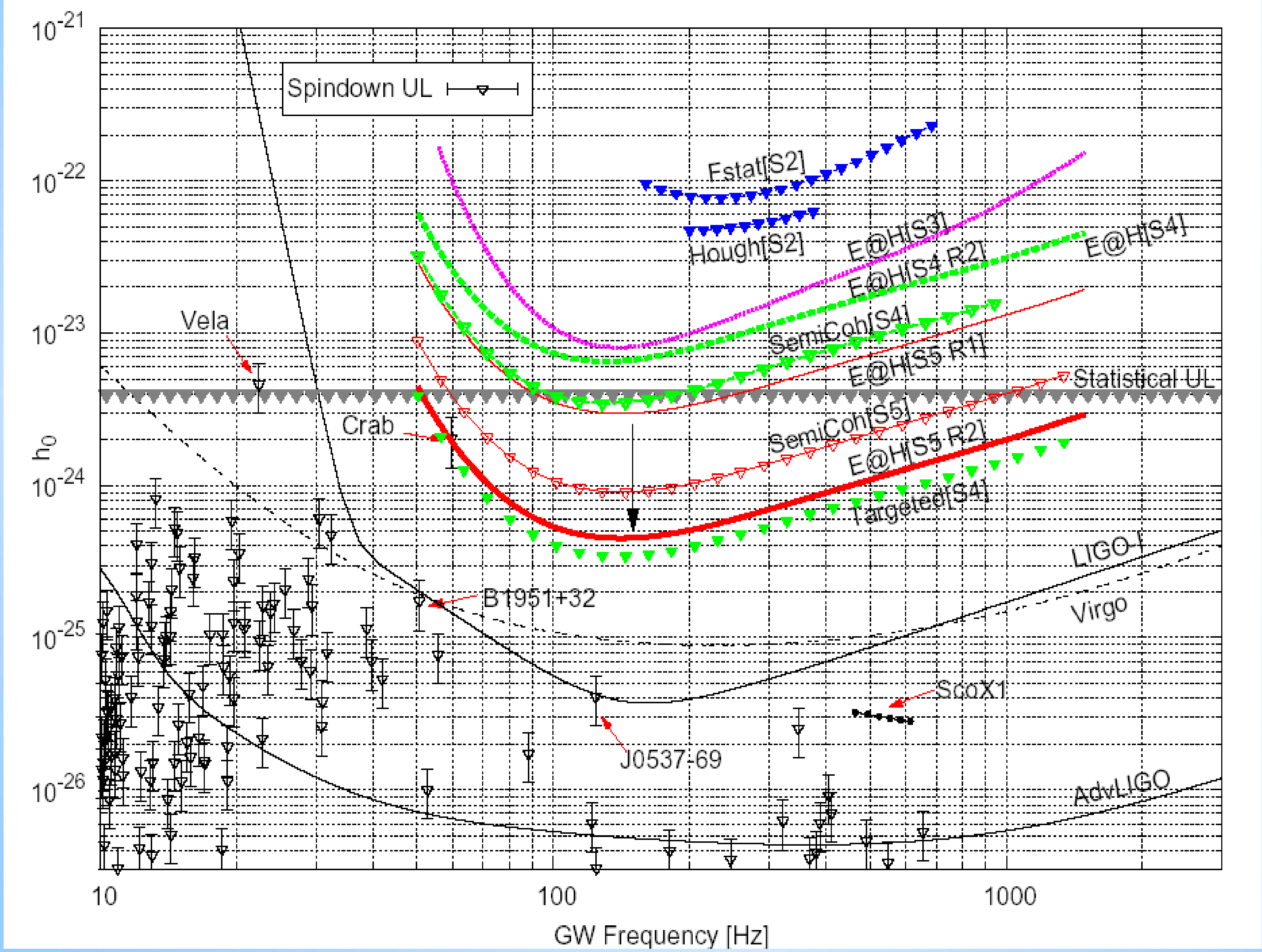
[1]: Palomba, AA, (354) (2000)

zoom

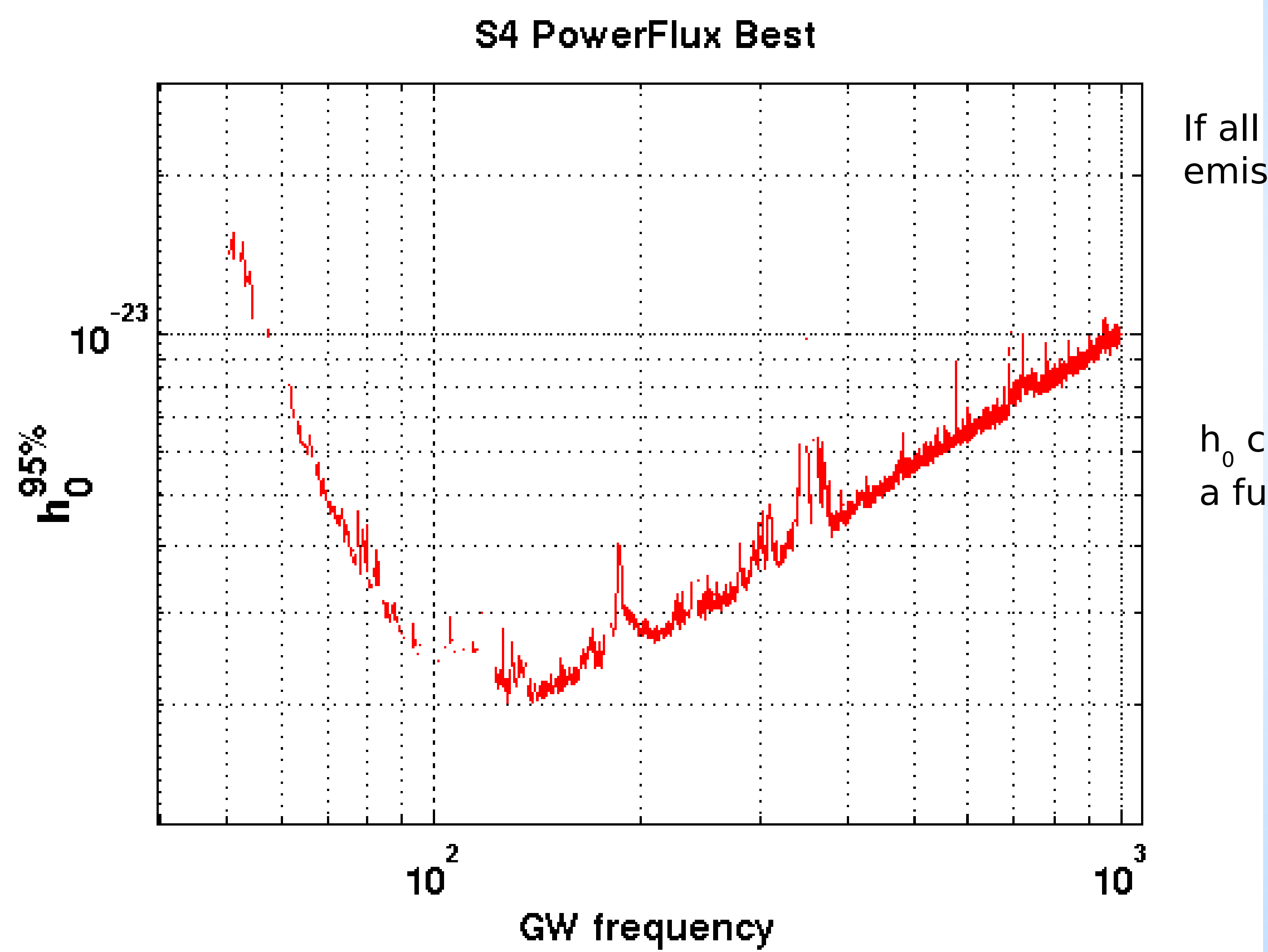
Exclusion region goes as low as ε =9×10^{-5} for
I = 3 X 10^{38} (kg m^2)



Blind(er) searches



Blind searches: expressing results



$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I f^2}{d} \varepsilon$$

If all spindown is due to GW emission (for I=1e38kgm^2):

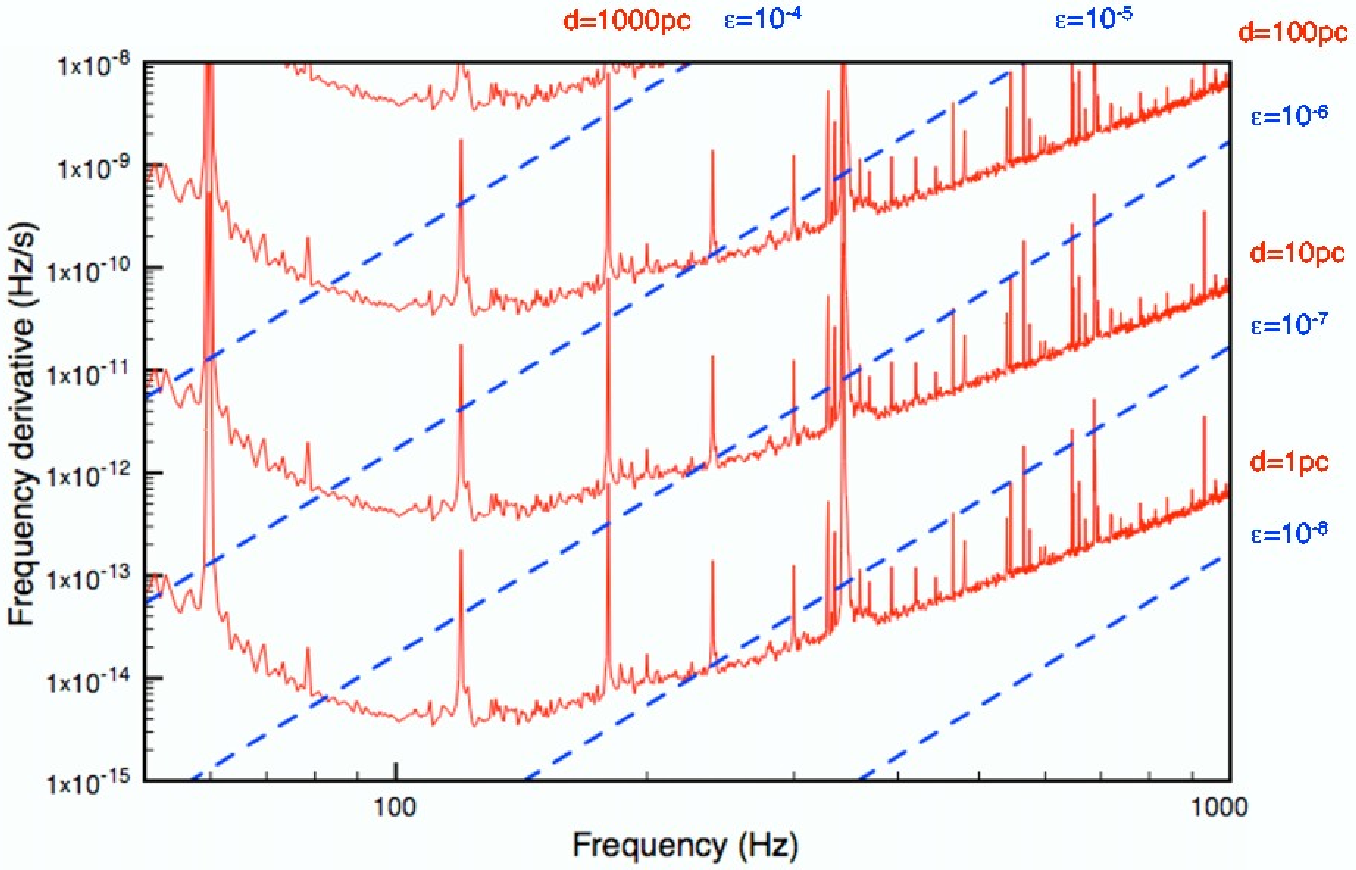
$$\varepsilon^2 = 7.6 \times 10^5 \frac{\dot{f}}{f^5}$$

h_0 can be expressed as a function of only f, fdot, and d.

Expressing the reach of search from UL values.

Contour plots of distance at which one of the fast-scan **S4 searches** could detect a source with a given f and fdot.

These are NOT typical S5 numbers. Deepest searches are expected to reach ~1kpc for $\varepsilon=10^{-5}$.



Wide-band and spindown searches. Overview by G. Mendell.

LISA

LISA will do gravitational wave astronomy

- LISA will observe from 0.1 mHz to about 0.1 Hz
- What astronomical systems have time-scales of seconds to hours?
  - Black holes of mass M have dynamics up to f_{max}~1 mHz $(M/10^6 M\ )^{-1}$
  - Binary systems have orbital frequencies in this range if the stars are compact: white dwarfs, neutron stars, or stellar black holes
  - There are random backgrounds due to binaries, black holes, and any primordial sources of GWs
  - Exotic systems, such as cosmic strings, may radiate in this band.
- Besides doing astronomy, LISA will do fundamental physics:
  - Study black holes in great detail, testing general relativity: BH uniqueness, Hawking area theorem, cosmic censorship
  - Measure the Hubble rate as a function of time to high *z:* track dark energy evolution.

The data analysis

- Different data analysis problem with respect to ground-based detectors:
Searches for various signals are not independent

EMRI signals require search over very large parameter space-> hierarchical method has to be developed

WD-WD binary confusion noise

Signal extraction and parameter estimation has to be done iteratively, from strongest sources to weaker ones

- Mock LISA Data Challenge: 2nd challenge just completed.
  - Focuses efforts of community.
  - Has leveraged existing techniques from ground based detectors

Short-period binaries

- Above 0.1mHz: several “verification” binaries
  - 0.1-2mHz resolvable galactic binaries
    - Should be possible to remove them from the data
    - And for some fraction of them determine distribution of parameters
- Below 0.2mHz: non resolvable -> confusion noise
  - WD/WD Distribution propoerties

Merger of SMBH

- 10^4-10^7 M_{sun} : very loud, should be able to see merger waveform and compare with simulations. Non-linear effects of gravity. Perhaps rare.
- 10^3-10^5 M_{sun} : less rare, will not see merger phase.

Captures of compact objects by MBH

- mapping of space-time around MBH
- Census of the BHs
- There may be strong background if SMBH at early times grew by I/EMRI capture

Collapse of supermassive stars

- To form SMBHs in galactic nuclei

Stochastic background

- Not so great

GW astronomy......

...we're getting there. GW observations are *starting* to contribute astrophysical information.

If GW were observed now no cherished belief would be challenged.

If GW are not observed by advanced ground-based detectors and LISA, cherished beliefs will be questioned.

.... in the mean time.... stay tuned!

"Are we there yet?" cartn from http://media.bestprices.com/

The End