Una breve rassegna di alcuni recenti risultati di LIGO

M.Alessandra Papa

Max Planck Inst. f. Gravitationsphysik and
Univ. of Wisconsin- Milwaukee

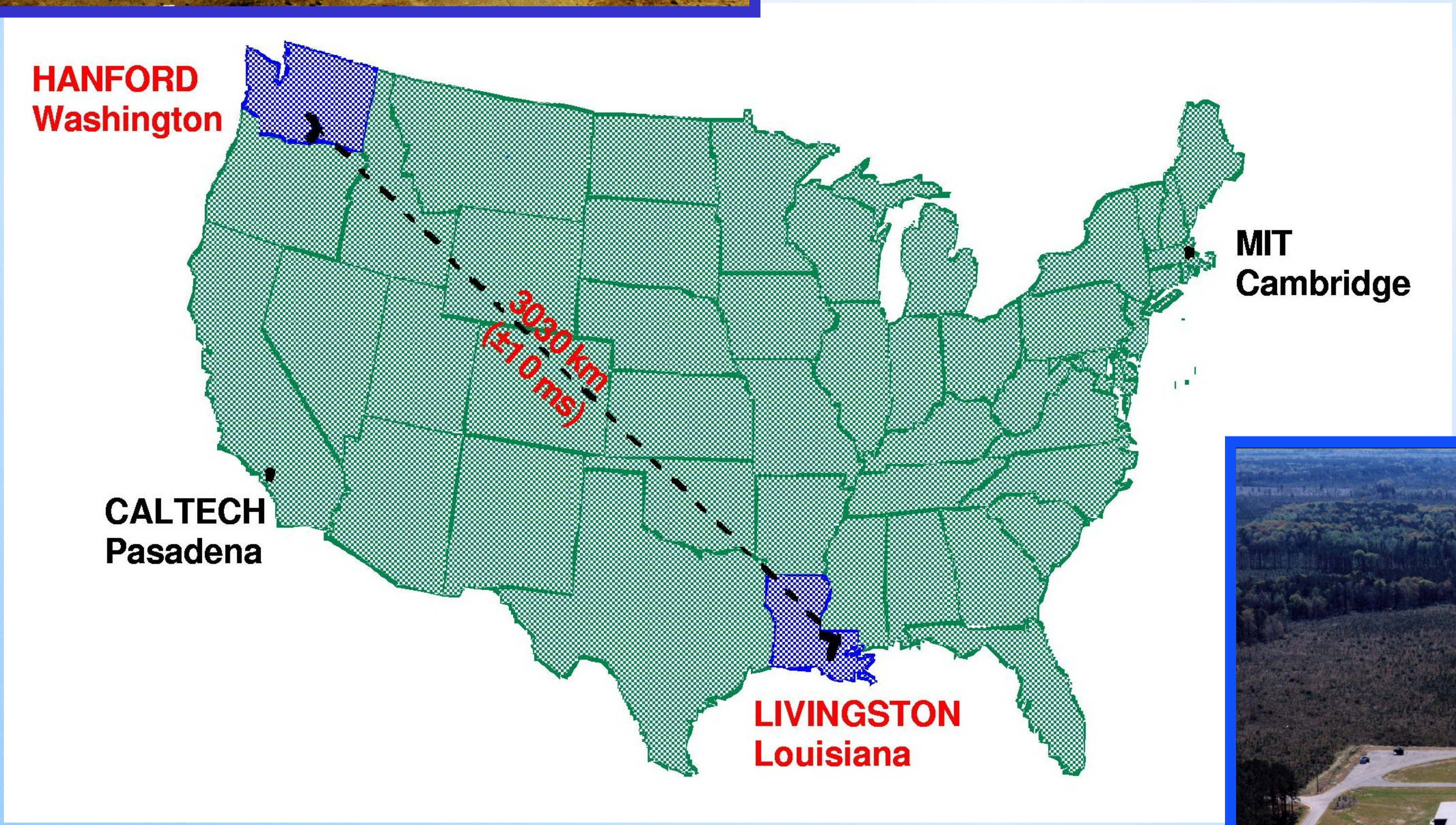
Simposio in onore di Gianvittorio Pallottino,
Febbraio 2008, Univ. di Roma ``La Sapienza''

LIGO DCC: G080057-00-Z

LIGO

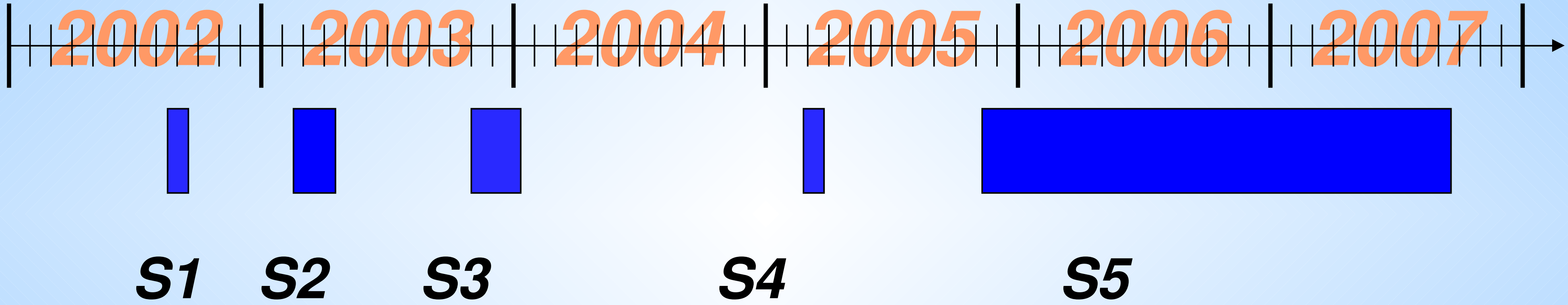
(Laser Interferometer Gravitational-wave Observatory)

One interferometer with 4 km arms, one with 2 km arms

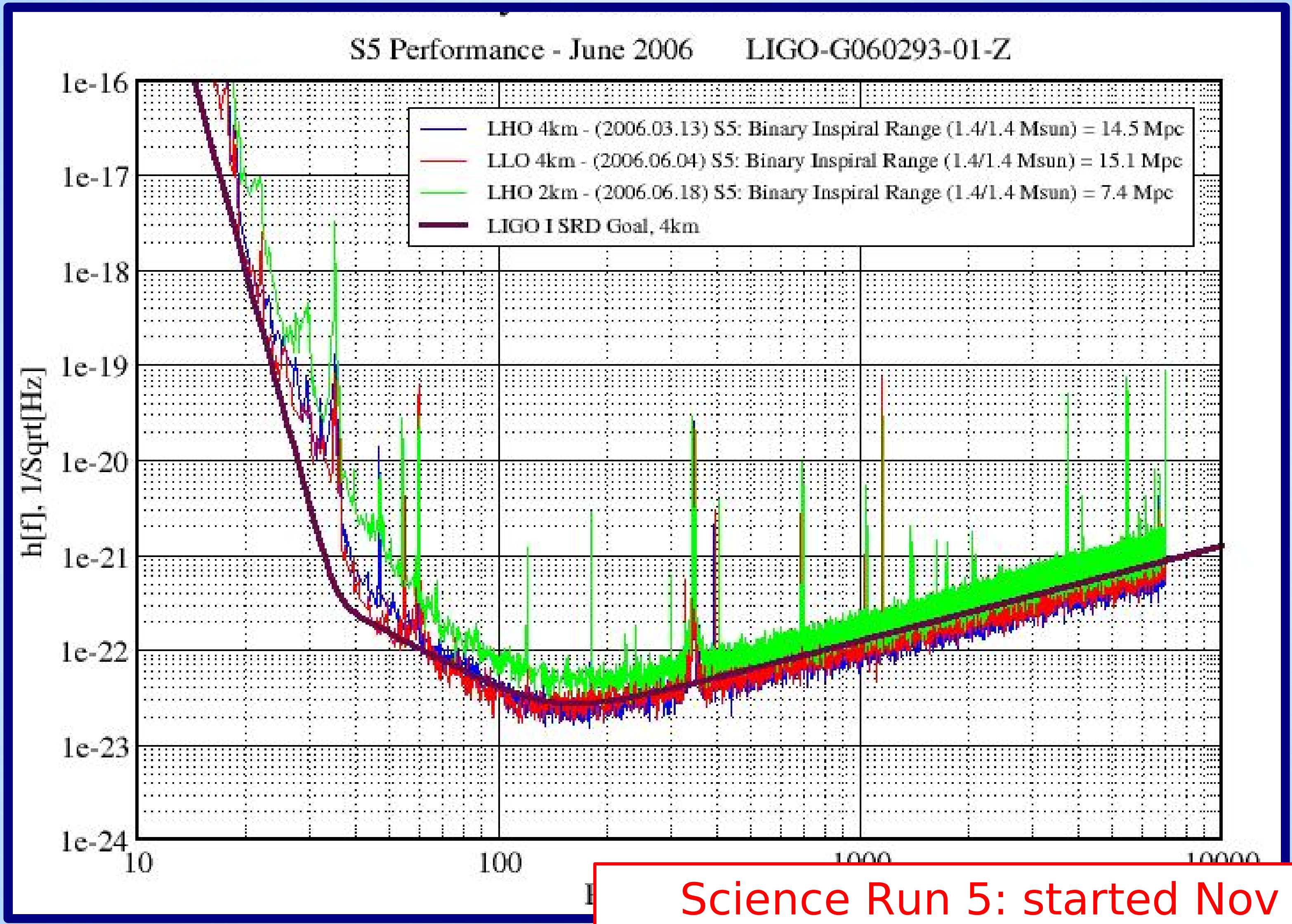


One interferometer with 4 km arms

LIGO has completed its 5th science run (S5)



5th Science Run of LIGO



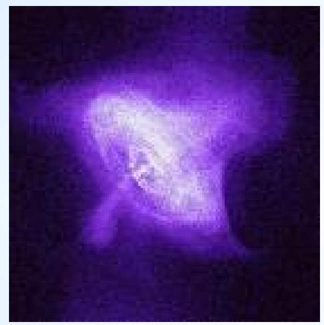
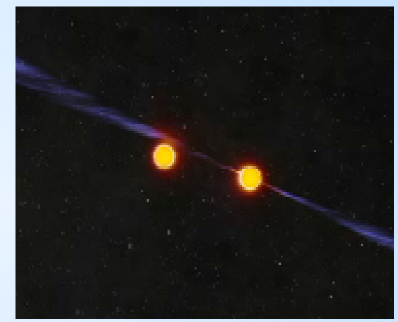
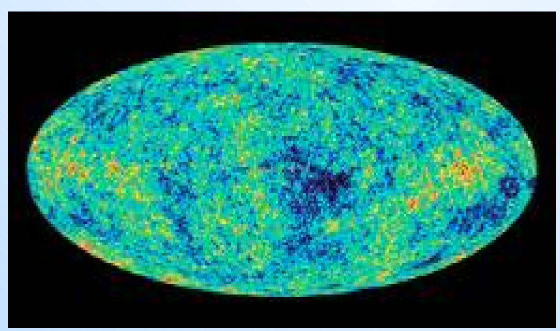
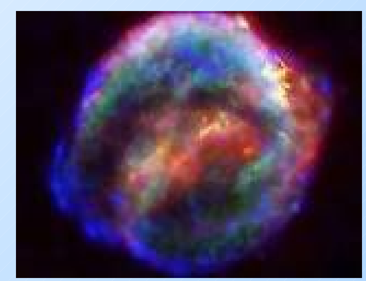
Science Run 5: started Nov 2005, lasted ~ 2 years.
Goal: 1 year of 2-site coincident live-time

LIGO's window

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

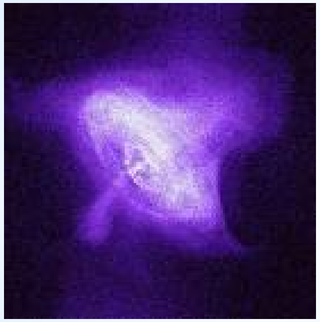
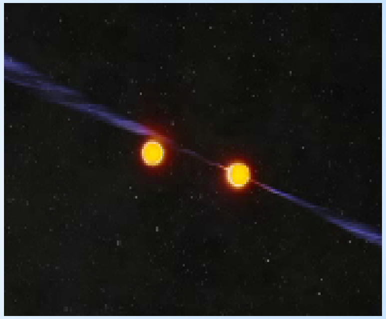
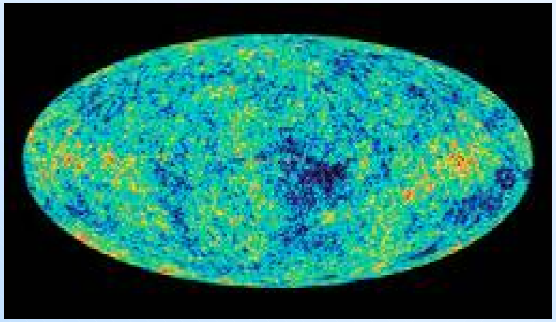
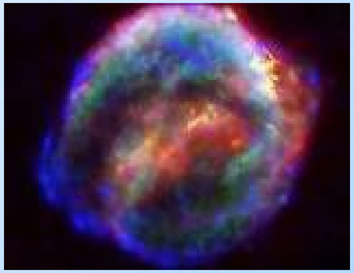
- from inspiraling compact objects
- bursts , typically arising from catastrophic events
- continuous quasi-periodic waves
- stochastic background of gravitational radiation

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.;

This scheme largely reflects different analysis techniques

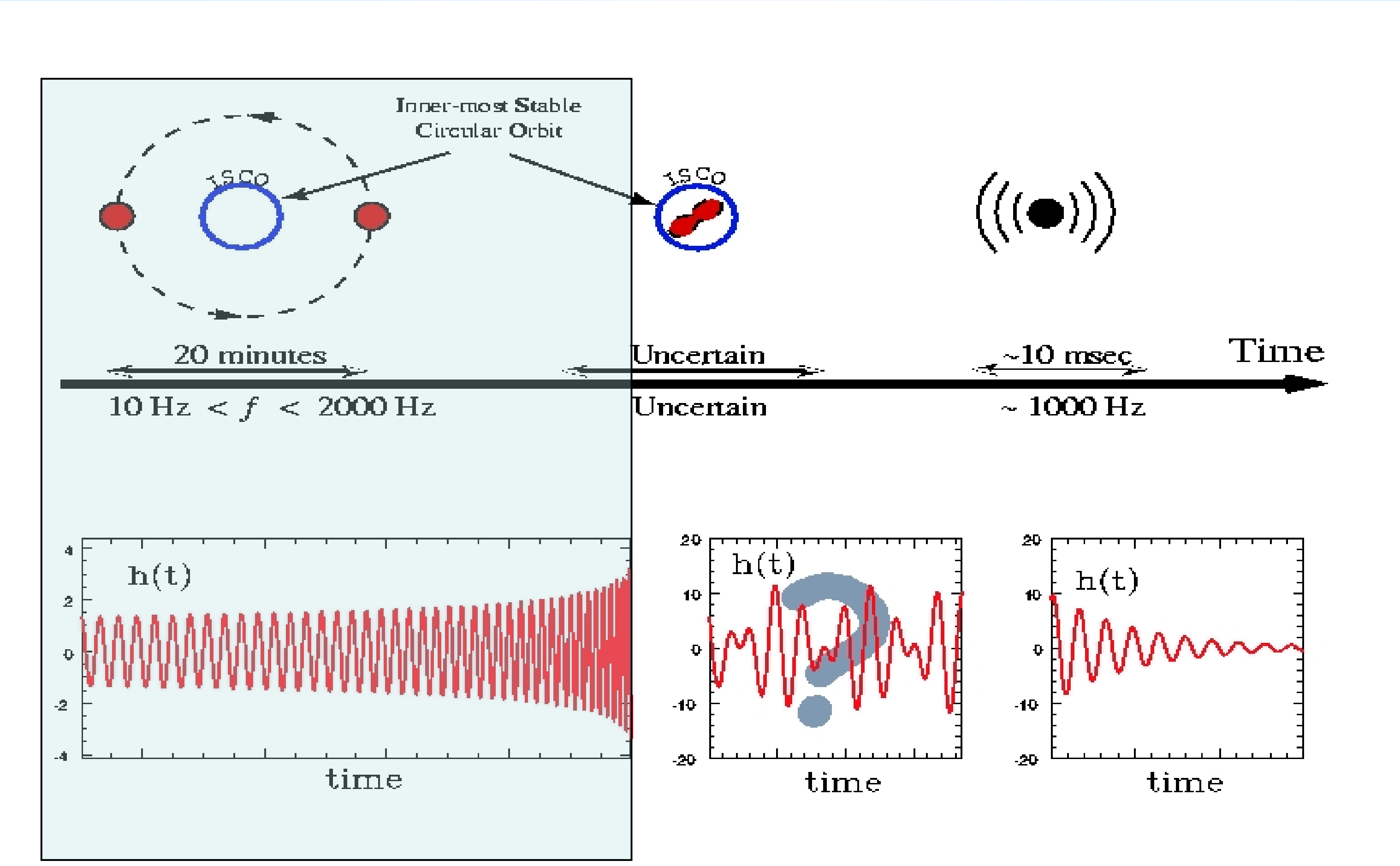
	Long duration	Short duration
Matched filter	 Pulsars	 Compact binary inspirals
Template-less methods	 Stochastic Background	 Bursts

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

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

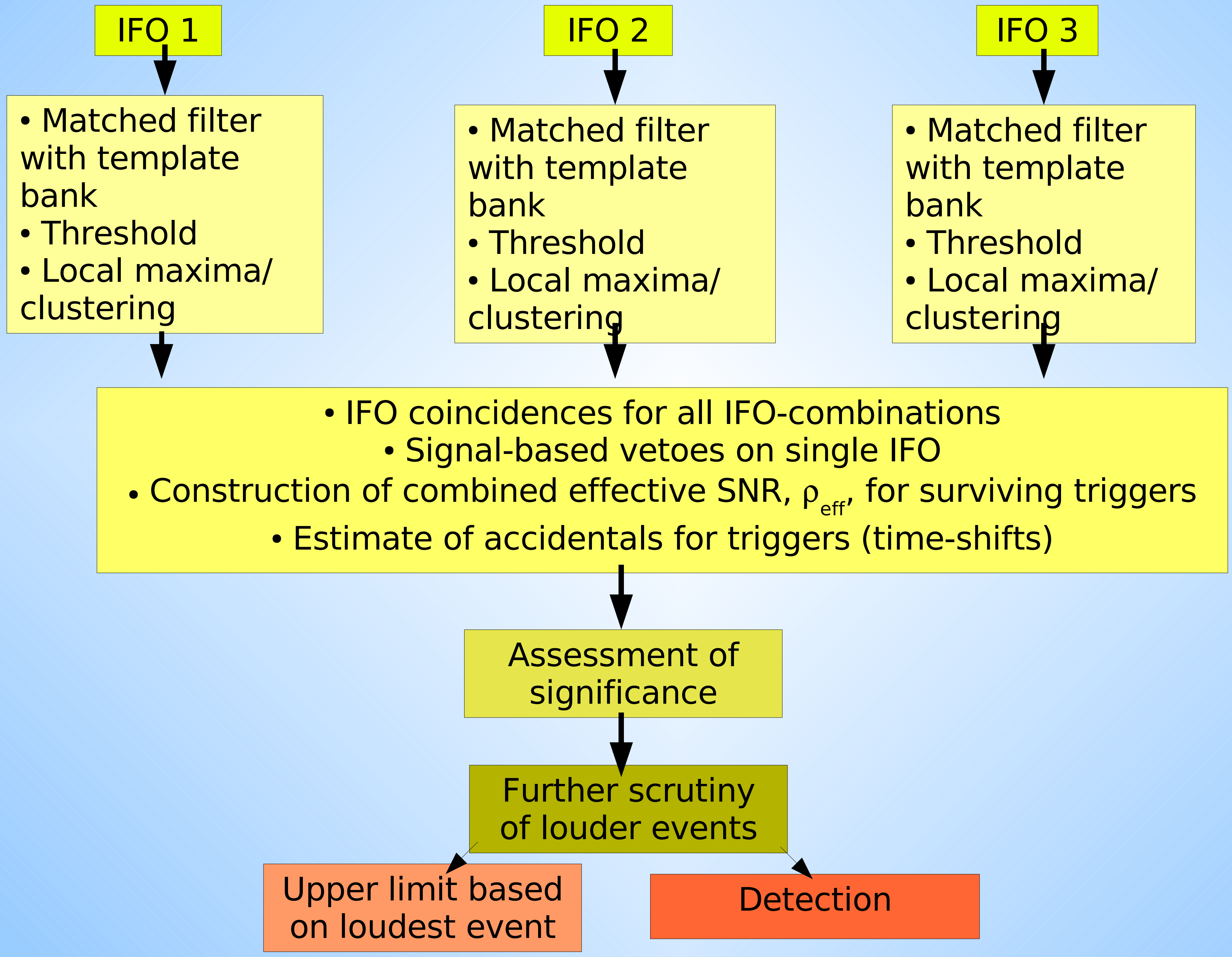
Let's start from these.

Expected signal



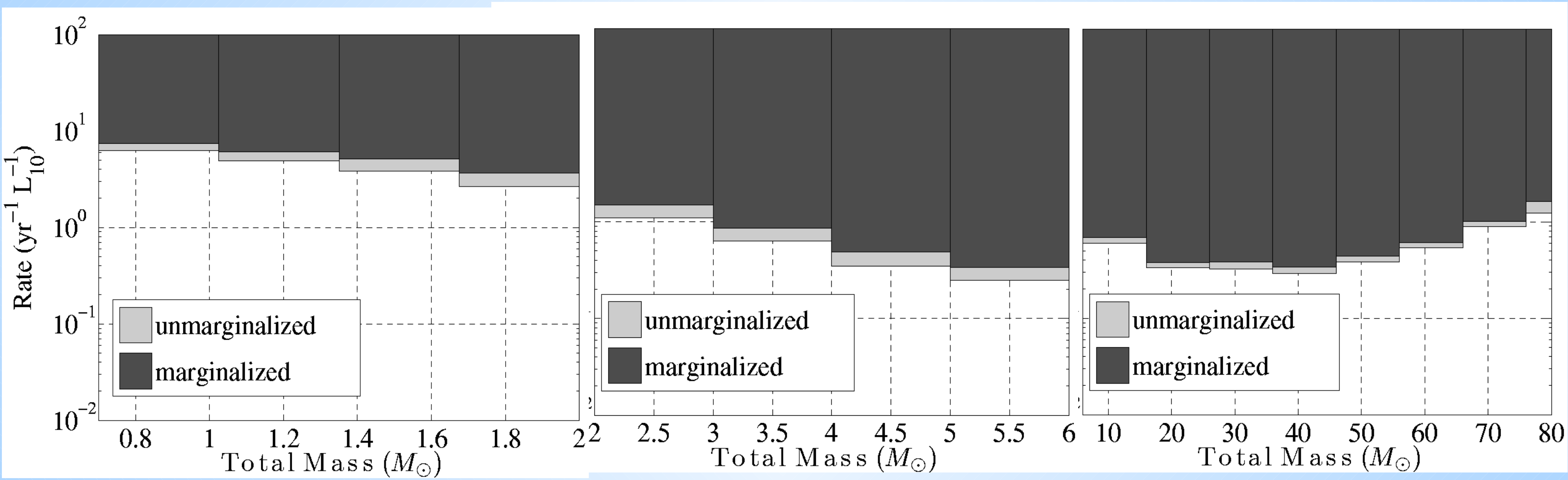
- In the LIGO band we can in principle observe inspirals from binaries with total mass < 200Msol
- How well we can predict all these waveforms is another matter
- Post Newtonian waveforms accurately model evolution across the entire LIGO band for systems with total mass smaller than 3Msol

Compact binaries search pipeline schematics



S4 Upper limit results

LSC, arXiv:0704.3368, submitted to PRD



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

$$10\text{-}170 \times 10^{-6}\ \mathrm{yrs}^{-1}\ \ L_{10}^{-1}$$

with $L_{10} = 10^{10}\ L_{B,sun}$ and $L_{B,sun} = 2.16 \times 10^{33}$ erg/s

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

BBH: $0.1 - 15 \times 10^{-6}\ \mathrm{yrs}^{-1}\ \ L_{10}^{-1}$

BHNS: $0.15 - 10 \times 10^{-6}$ 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 for a search ?

- $\mathcal{R}$ = 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

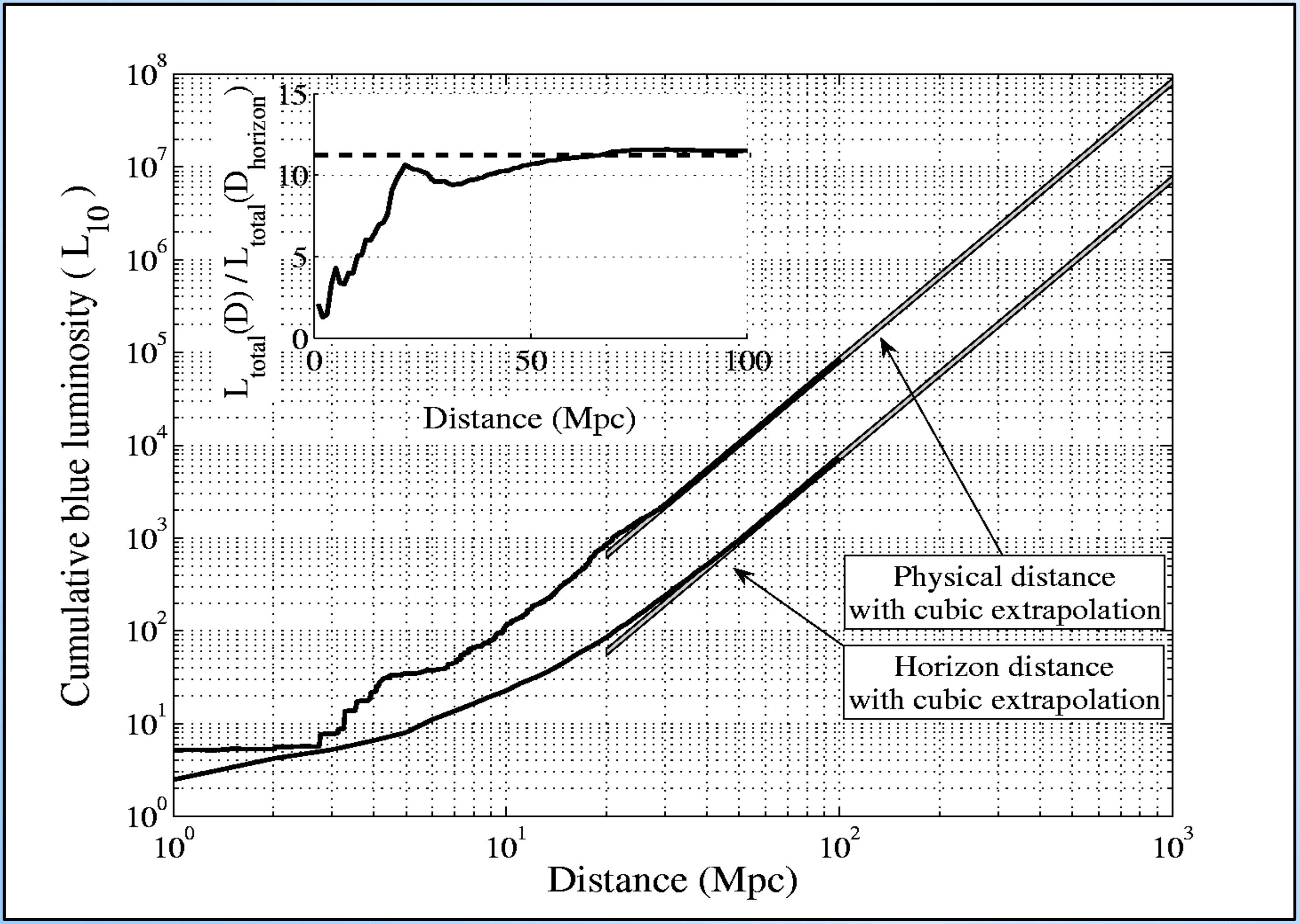
X C: number of "galaxies" the search can see L_{10}

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.

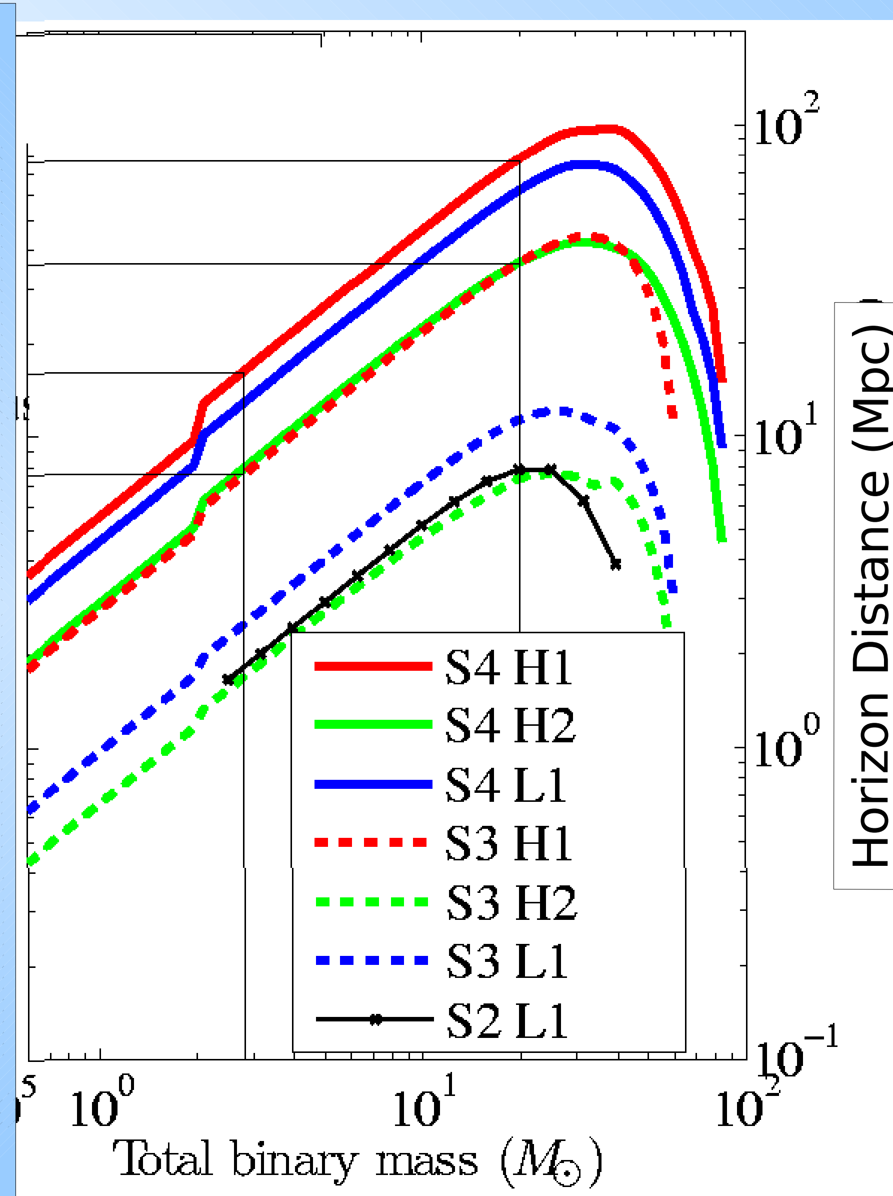
The horizon distance

(for data that has been analyzed)

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

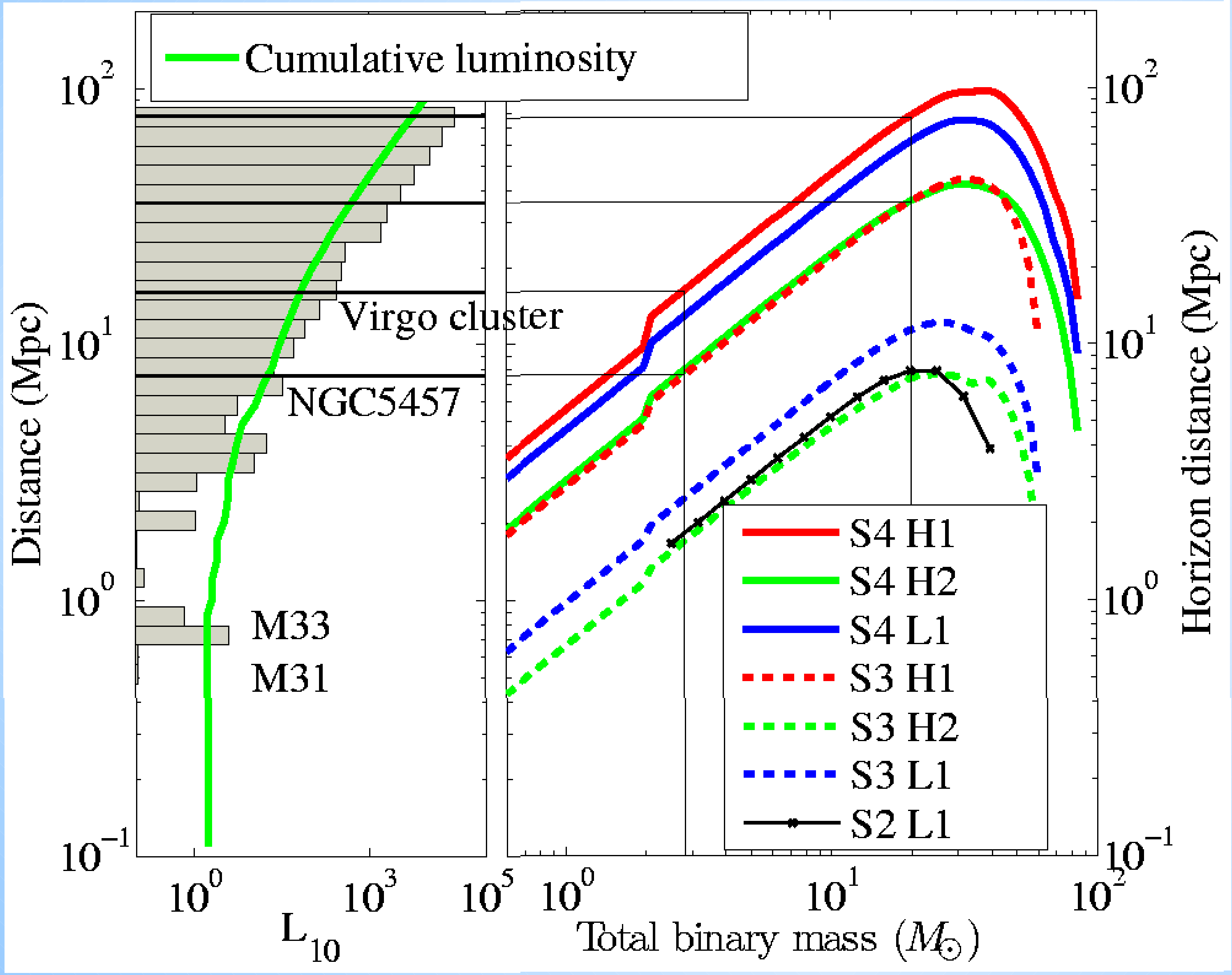
For H1 during S4:

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 A. sengupta

... for S4 these translate in expected rates of



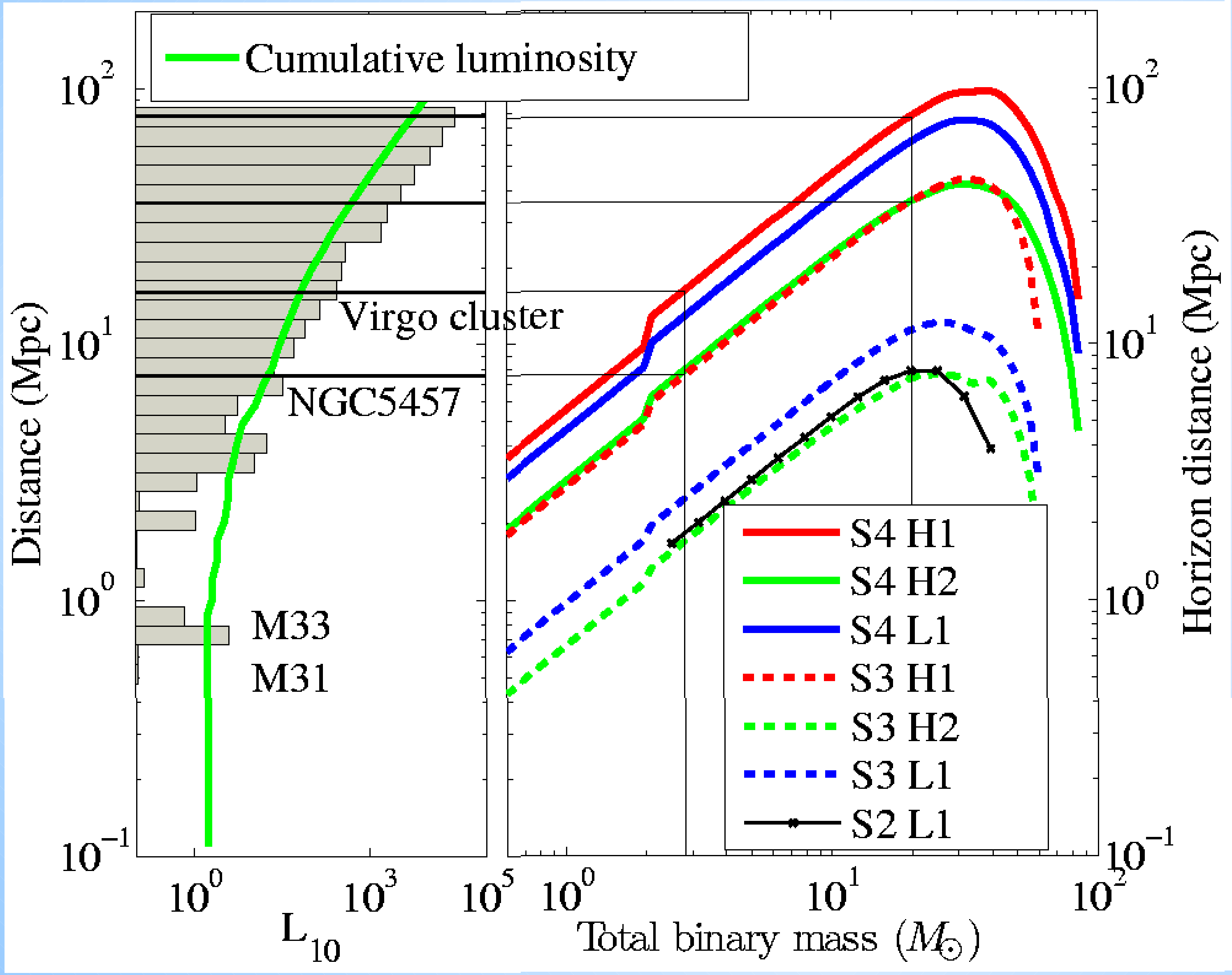
≈ 1/(2000yrs)- -1/100(yrs) for BNS, with DH ~ 16Mpc

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

Not so great

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

... for our next detectors

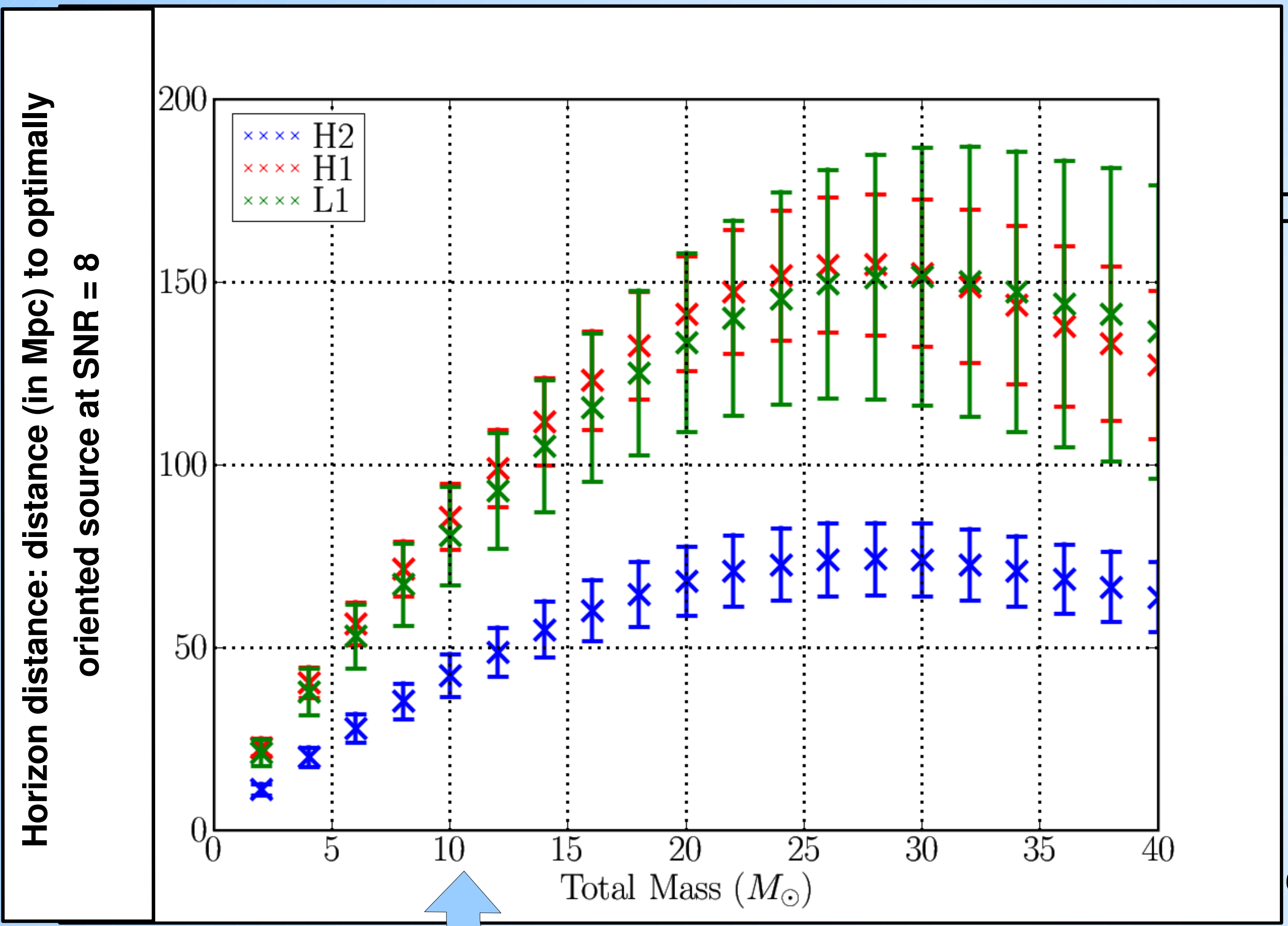


ENHANCED (2009):
≈ 1/(60yrs)-1/3yr
for BNS,
with DH ~ 60Mpc

ADVANCED (2014):
≈ 7-400/yr
for BNS,
with DH ~ 450Mpc

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

S5 sensitivity: estimated rates



D. Keppel for the LSC, APS 07 meeting

Reach of the search

\+ Blue luminosity versus Distance Curve

\+ Global astrophysical rate estimate

1 event / 400-25 yrs 1.4-1.4 Mso
1 event / 2700-20 yrs 5-5 Msol
1 event / 450 – 3 yrs 10-10 Msol

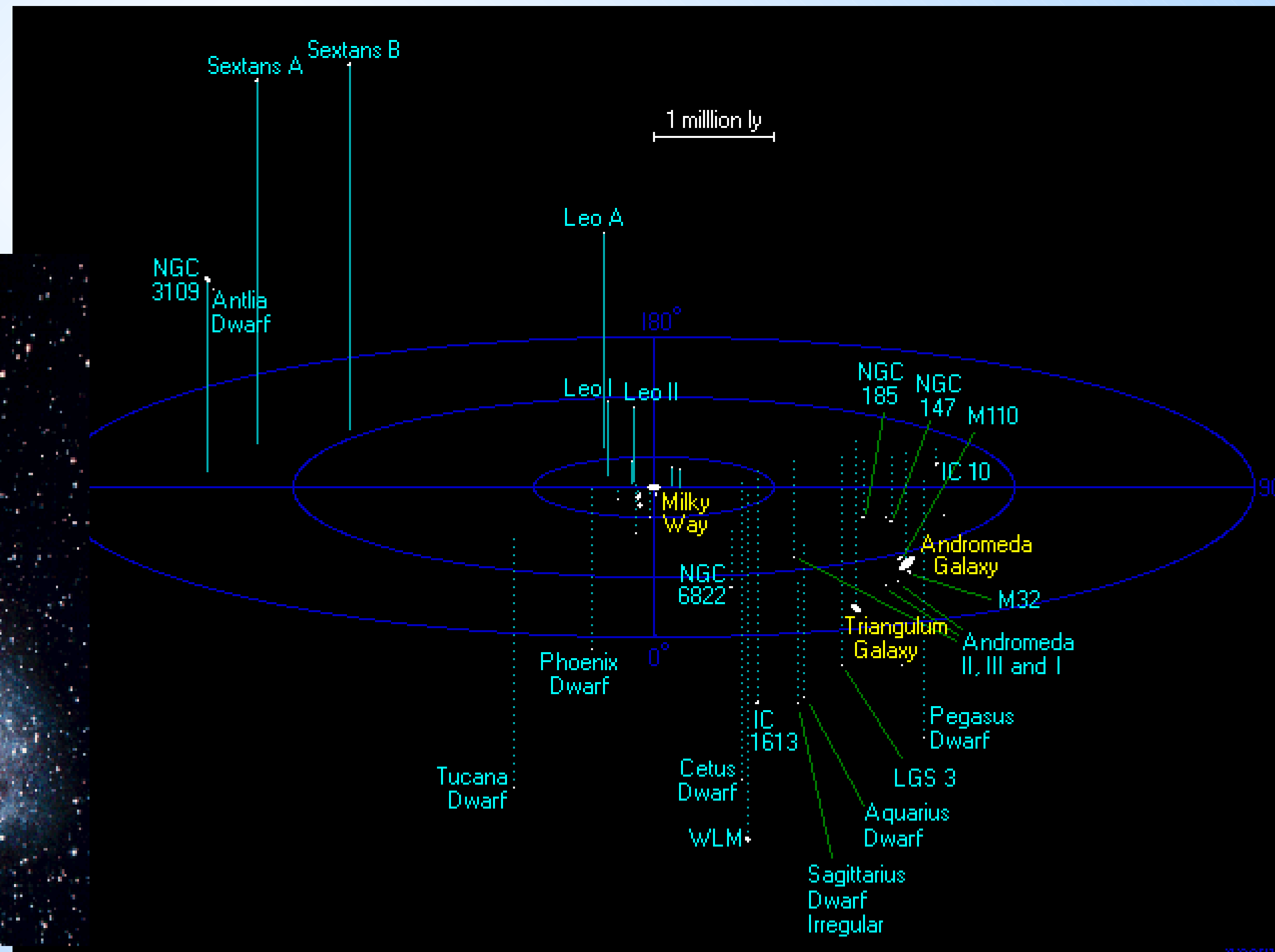
Searches triggered by em observations

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} ~ 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

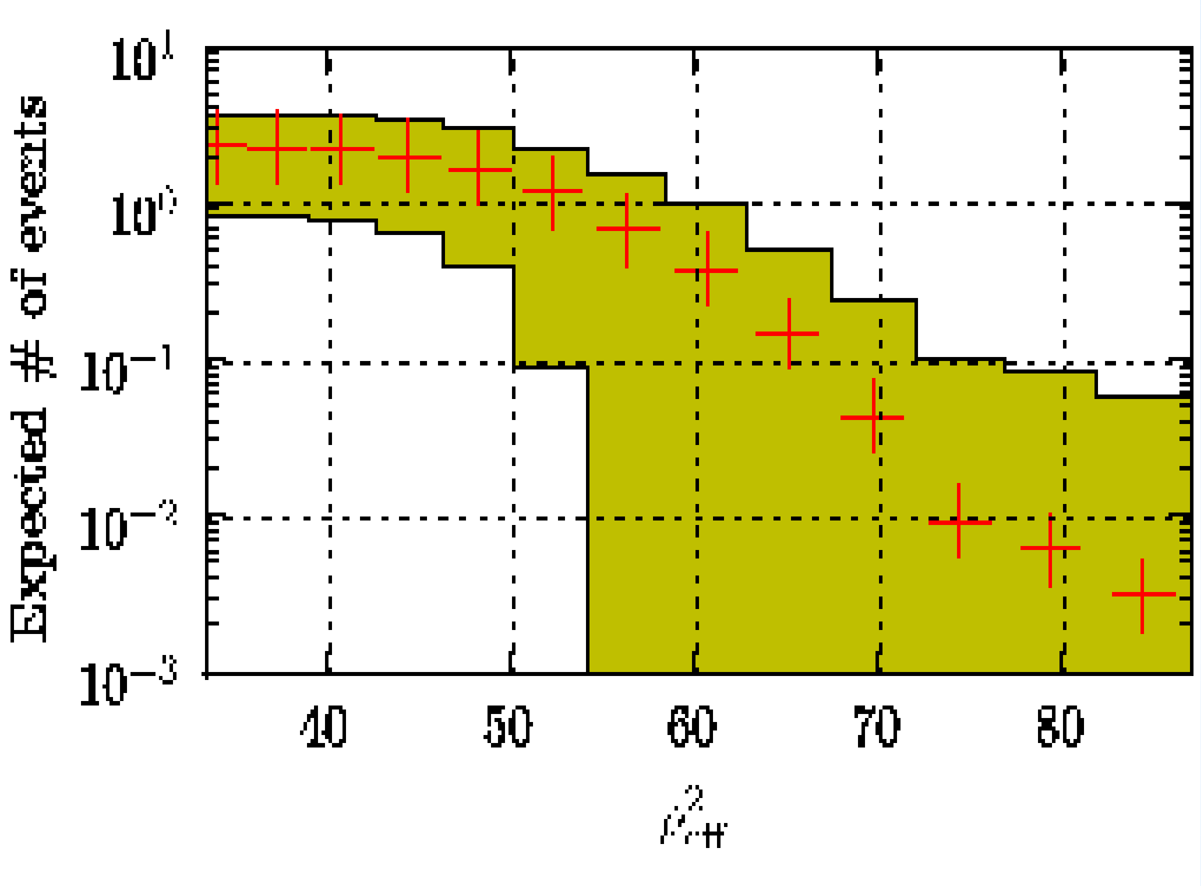
- Exclude progenitor in mass-distance regio

- Bound the GW energy emitted by a source M31

GW observations
arXiv:0711.1163v2, submitted to ApJ Lett

- **Search for signal from compact binary**
  - » standard matched filter pipeline applied to 180s around GRB time
  - » $1M_{sol} < m1 < 3M_{sol}$ and $1M_{sol} < m2 < 40\ M_{sol}$
- **Search for unmodeled burst**
  - » cross-correlation of data streams, within 180s of GRB time
  - » cross-correlation windows: 25ms and 100ms

Inspiral search results



- **mean rate of background coincidences: 2.4 (per 180s segment)**
- **found: ZERO**

We then evaluate the probability of a null result given a progenitor with certain parameters at a given distance:

$$p[0|h(t;m_2,D)] = \int p(\vec{\mu})\; p[0|h(t;m_2,D,\vec{\mu})]\; d\vec{\mu}$$

$$\vec{\mu}=(m_1,\vec{s}_1,\vec{s}_2,\iota,\phi_0,t_0)$$

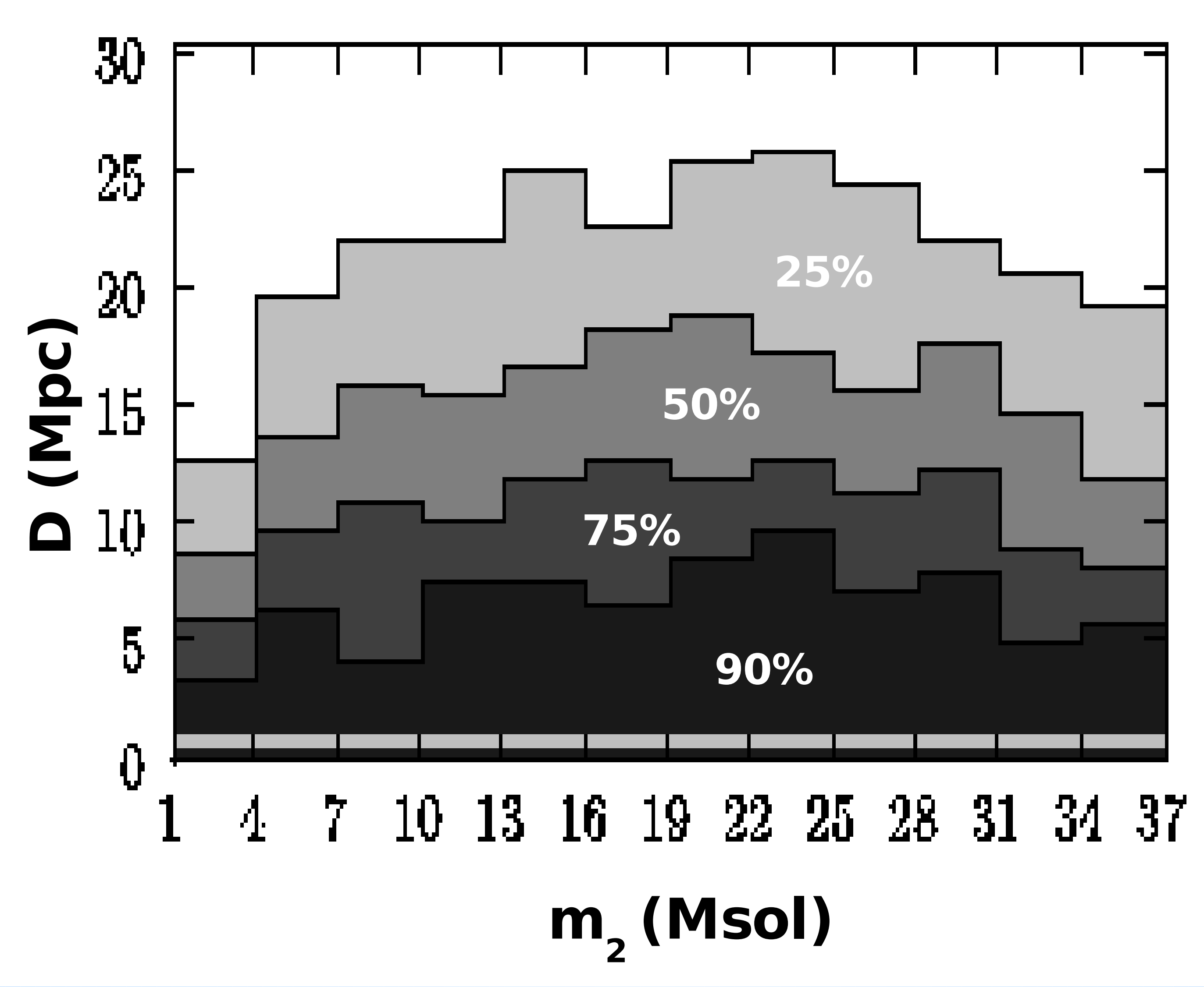
Inspiral search results

- uniform priors were used on m_1, t_0, ϕ_0
- priors on $\iota, \vec{s}_1, \vec{s}_2$:
  - $0 \leqslant \frac{a}{M} \leqslant 0.75$ for neutron stars
  - $0 \leqslant \frac{a}{M} \leqslant 0.98$ for black holes
  - spin directions uniformly distributed on sphere
  - $-1 \leqslant \cos(\iota) \leqslant 1$ uniformly distributed

$$\frac{a}{M} = \frac{cS}{GM^2}$$

S: spin angular momentum.

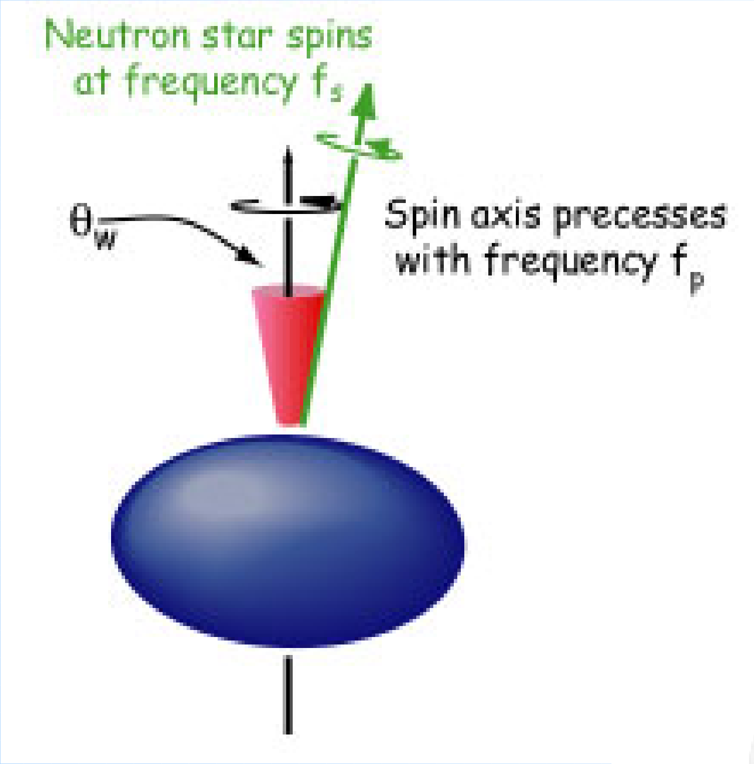
Inspiral search results: exclusion regions



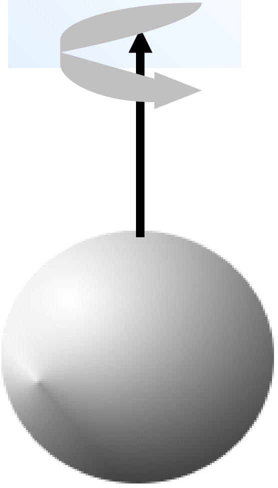
Continuous GW signals

Continuous GW signals

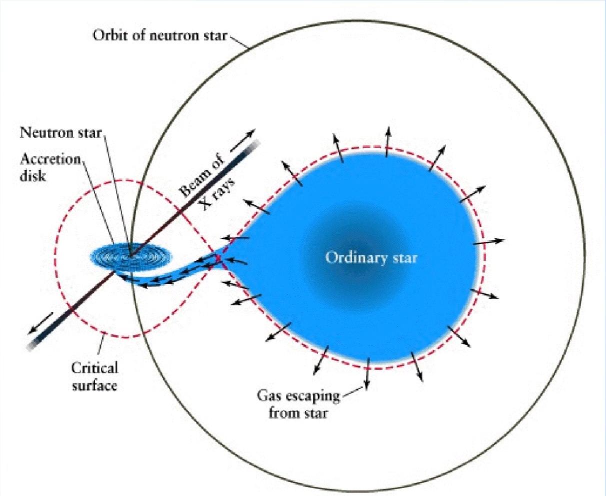
– Pulsars (spinning neutron stars) are known to exist!
– Emit gravitational waves if they are non-axisymmetric:



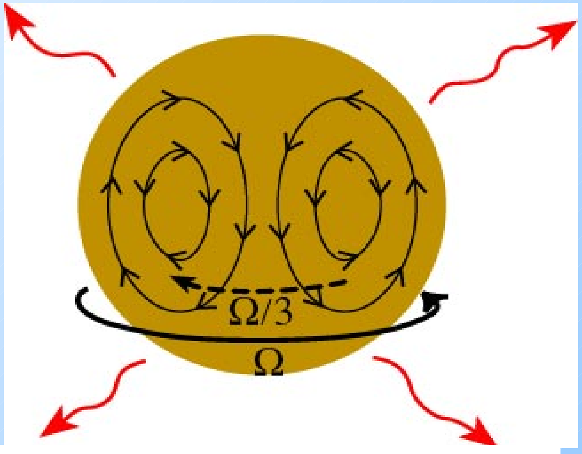
Wobbling Neutron Star



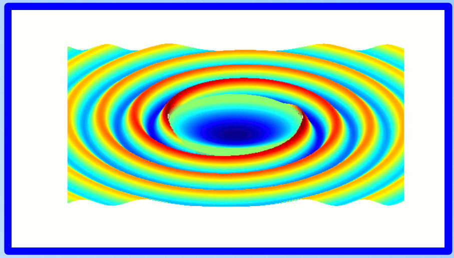
Bumpy Neutron Star



Low Mass X-Ray Binaries



Young Neutron Stars



Searches

1. **Known pulsars (radio & x-ray) (e.g., Crab pulsar)**

   Position & frequency evolution known (including derivatives, timing noise, glitches, orbit)

2. **Unknown neutron stars**

   Nothing known, search over sky position, frequency & its derivatives.

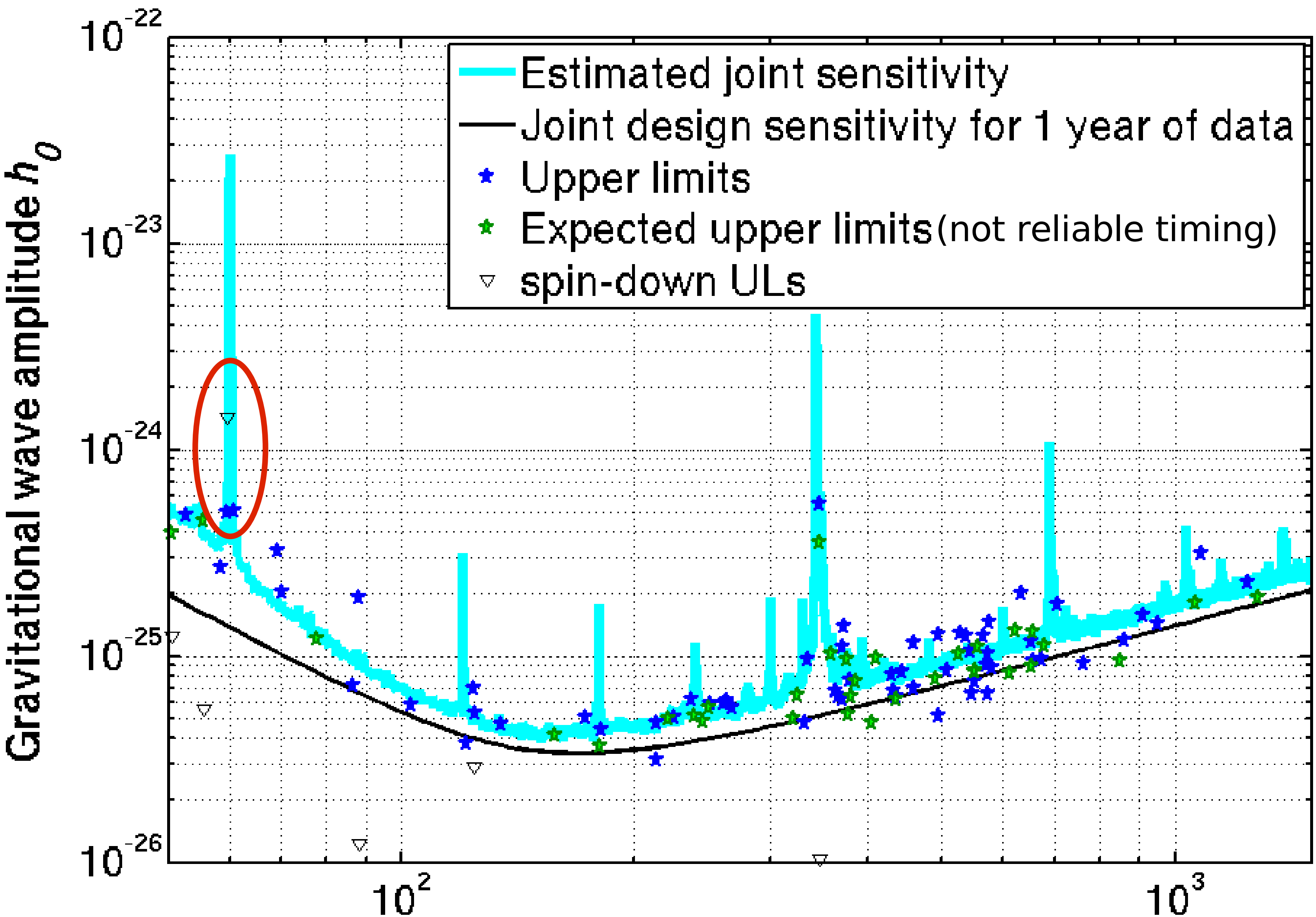
3. **Accreting neutron stars & LMXBs (e.g., Sco-X1)**

   Position known; some need search over freq. & orbit.

4. **Targeted sky position: galactic center, globular clusters, isolated non-pulsing neutron stars (e.g., Cas A)**

   Search over frequency & derivatives.

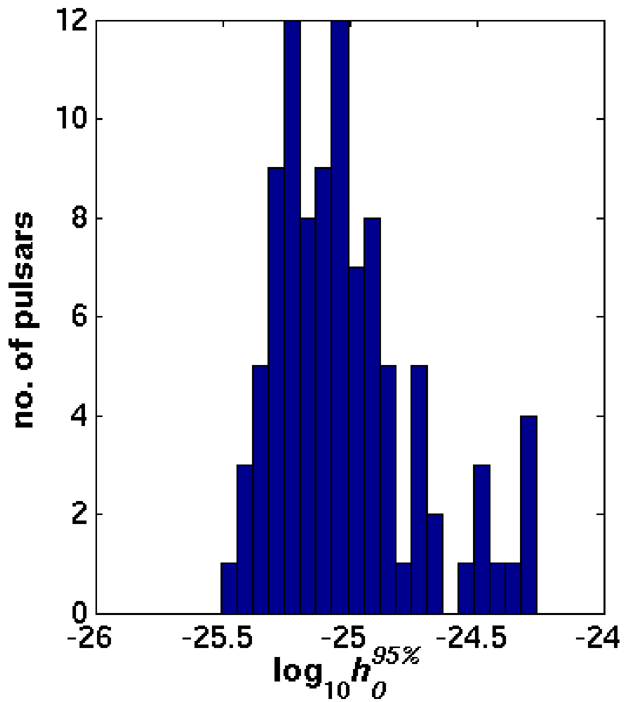
Known pulsars, preliminary S5



Pitkin for the LSC, APS07

Known pulsars, preliminary S5

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)

$h_{0\_min} = 3.4 \times 10^{-26}$

Known pulsars, preliminary S5

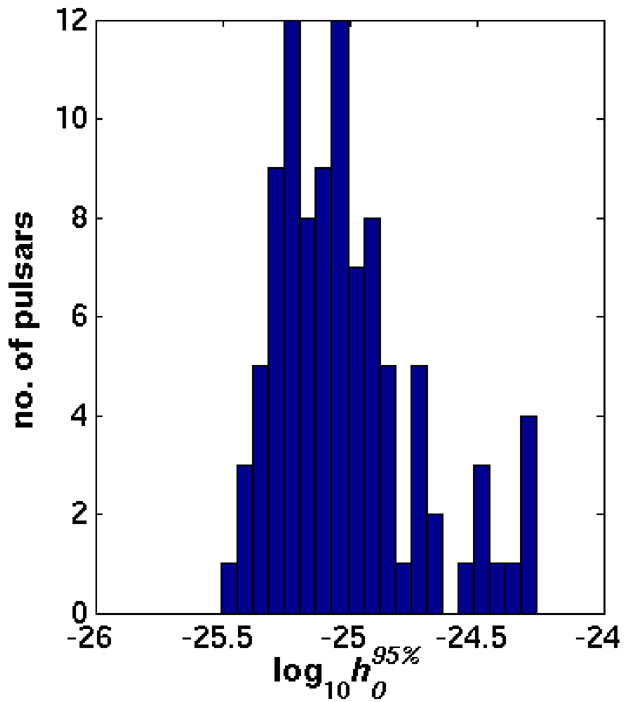
$$h_0 = \frac{16\pi^2 G}{c^4} \frac{\epsilon I f^2}{d}$$

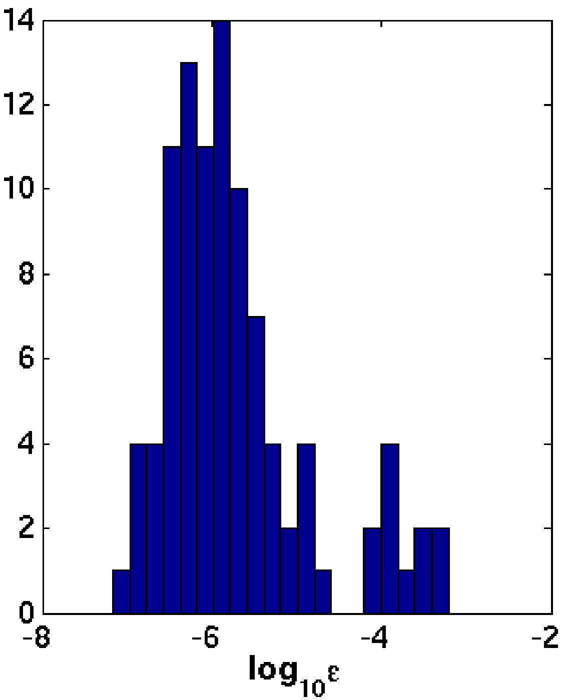
known

fiducial value

Lowest ellipticity upper limit:

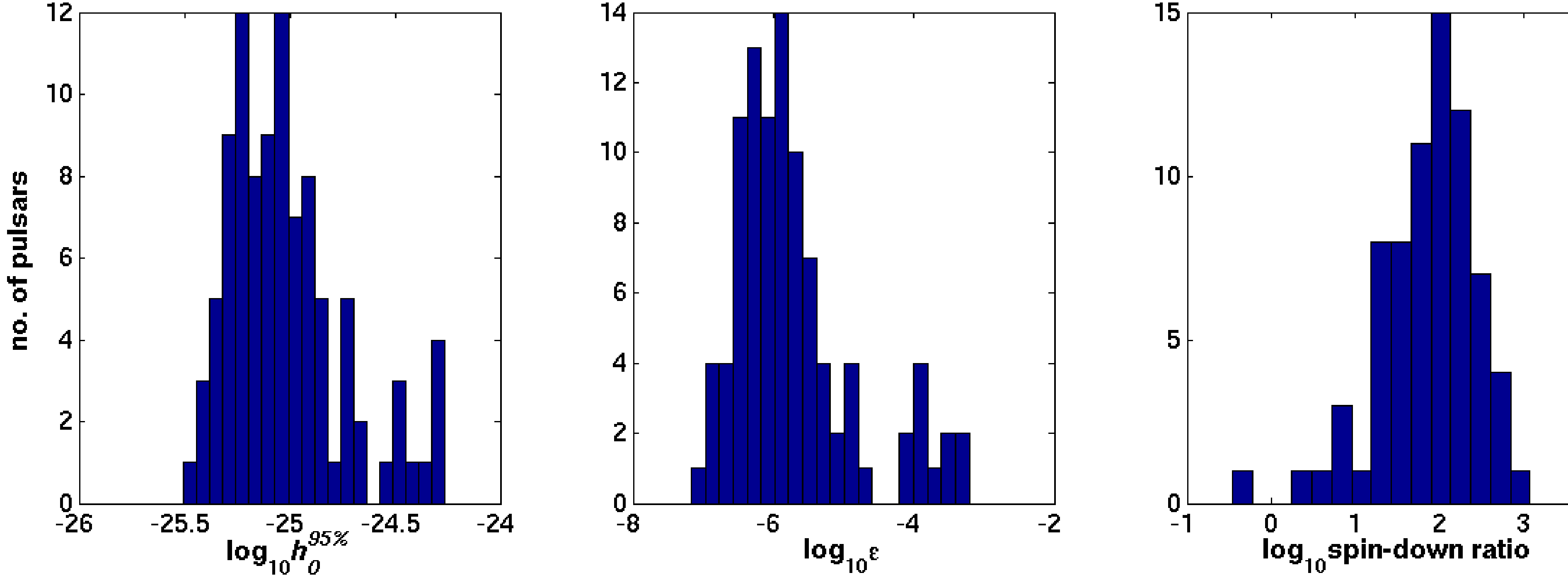
PSR J2124-3358 (ν_{gw} = 405.6Hz, r = 0.25 kpc) $\varepsilon = 7.3\mathrm{x}10^{-8}$





Known pulsars, preliminary S5

If all rotational kinetic energy were carried away by GWs, then: $$h_0^{spin-down} = \sqrt{\frac{5G}{2c^3}\frac{I\dot{f}}{d^2 f}}$$



Pitkin for the LSC, APS07

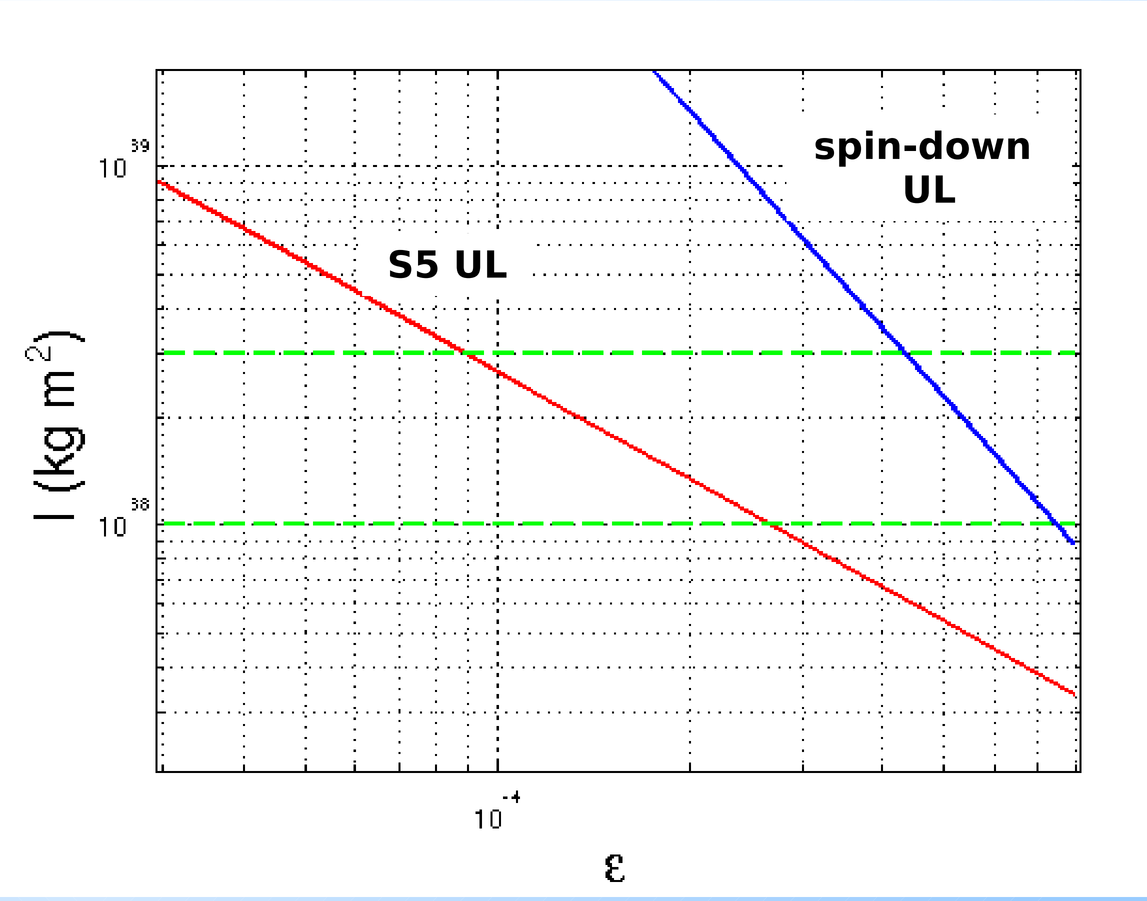
Known pulsars, preliminary S5

$h_{0\ spin\text{-}down} = 1.4 \times 10^{-24}$
$h_{0\ S5\ first\ year} = 5 \times 10^{-25}$ at fiducial $I = 10^{38}$ kgm^2

$-\ \varepsilon_{spin\text{-}down} = 7.3 \times 10^{-4}$
$-\ \varepsilon_{S5\ first\ year} = 2.6 \times 10^{-4}$
less than 13% power is carried away by Gws. Energy budget cannot exclude this GW emission.

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:



The main problem

- the most promising searches are the ones for objects that we do *not* know about
- very large parameter space: entire sky, hundreds of Hz, wide fdot range
- one gains in sensitivity by increasing the observation time
- for coherent searches (the most sensitive) the gain in resolution is very fast with increasing observation time
- the computational cost soon (very few days) becomes unmanageable
- have to resort to hierarchical techniques, using non-coherent methods as well

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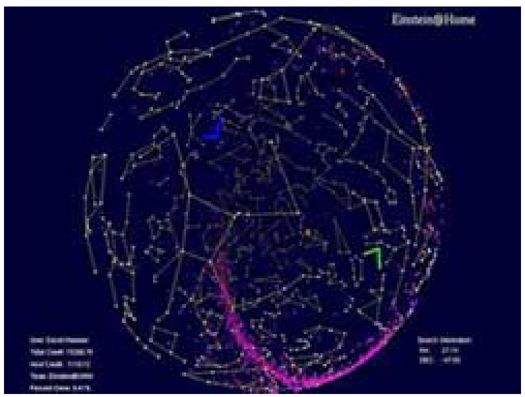

Einstein@Home screensaver

According to Albert Einstein, we live in a universe full of gravitational waves. He suggested that the movements of heavy objects, such as black holes and dense stars, create waves that change space and time. We have a chance to detect these waves, but we need your help to do it!

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APS physics

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GW astronomy now ...

...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