Gravitational Wave Data Analysis

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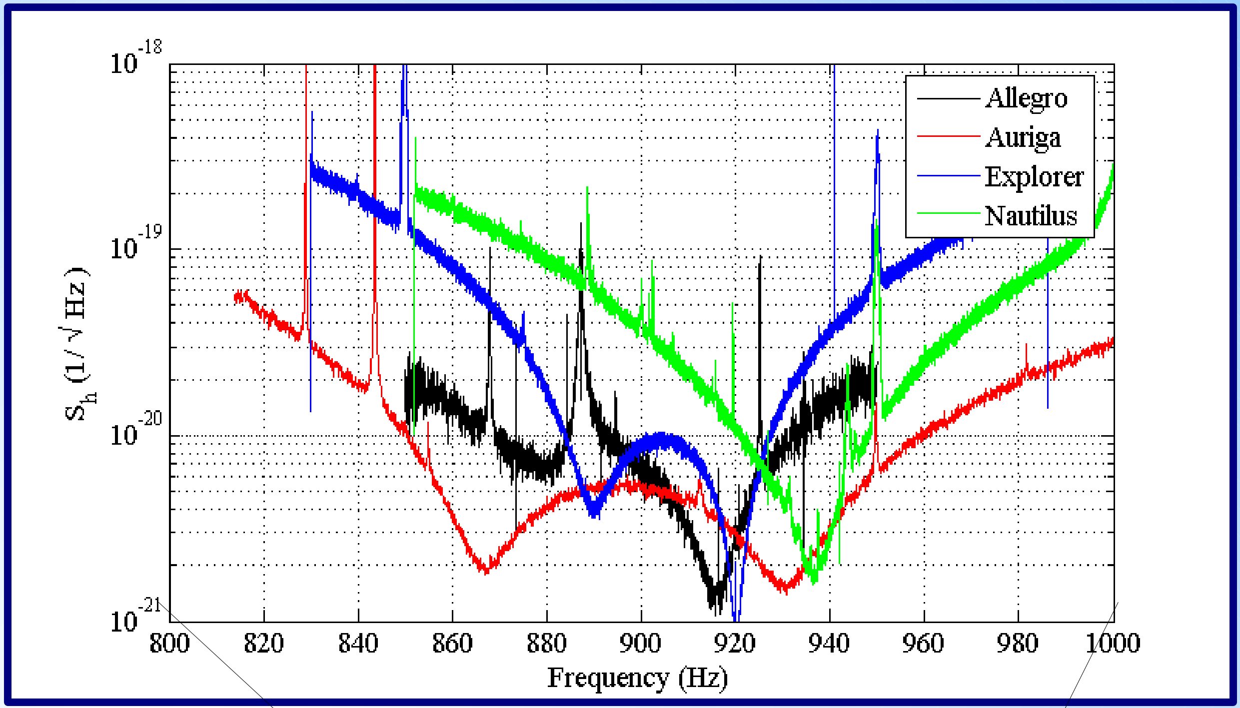
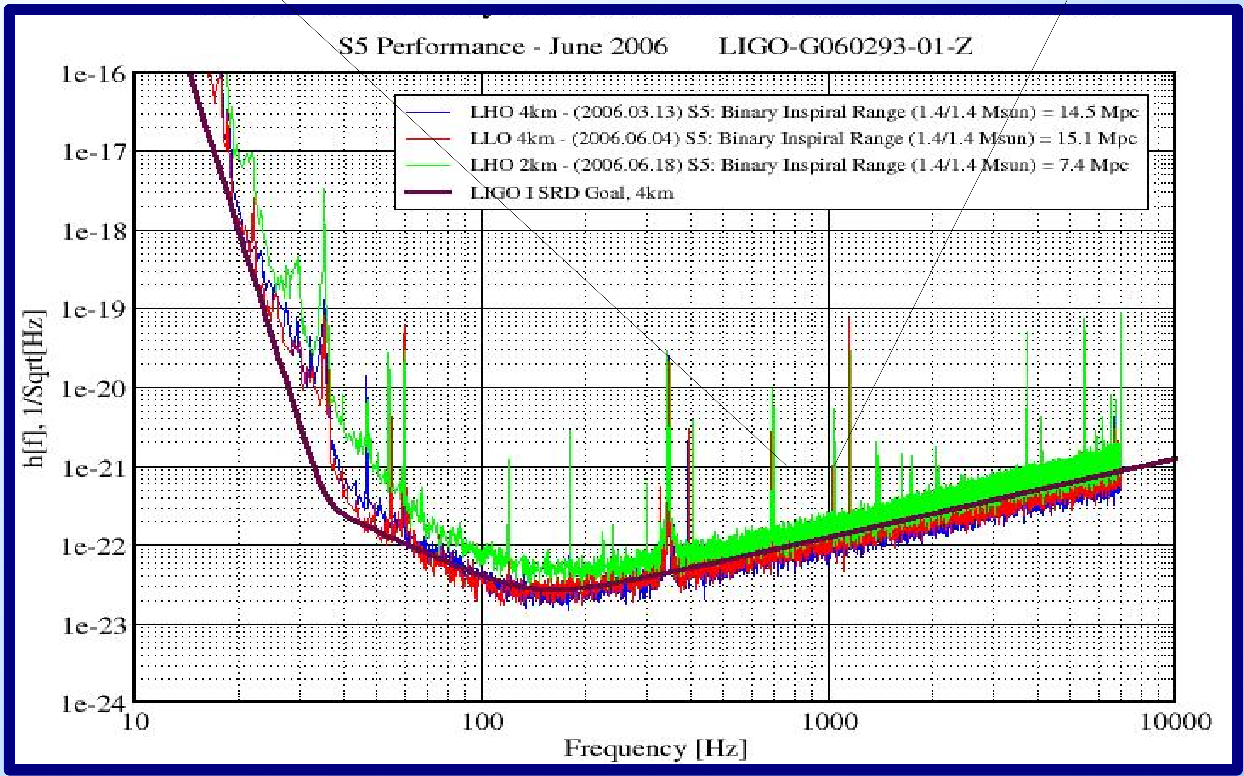
ICGC Conference 2007, December Pune

Gravitational wave data analysis

* legacy from bar detectors



* interferometric detectors

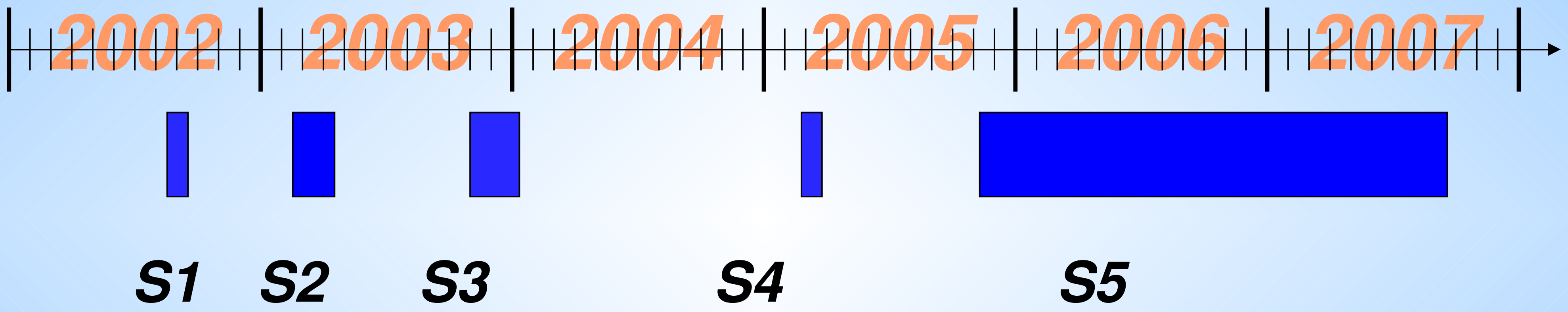


Outline

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

* outline of analysis method
* what quantities are constrained by null observations
* a priori expectations/
  astrophysical significance of the constraints
* prospects for improvements

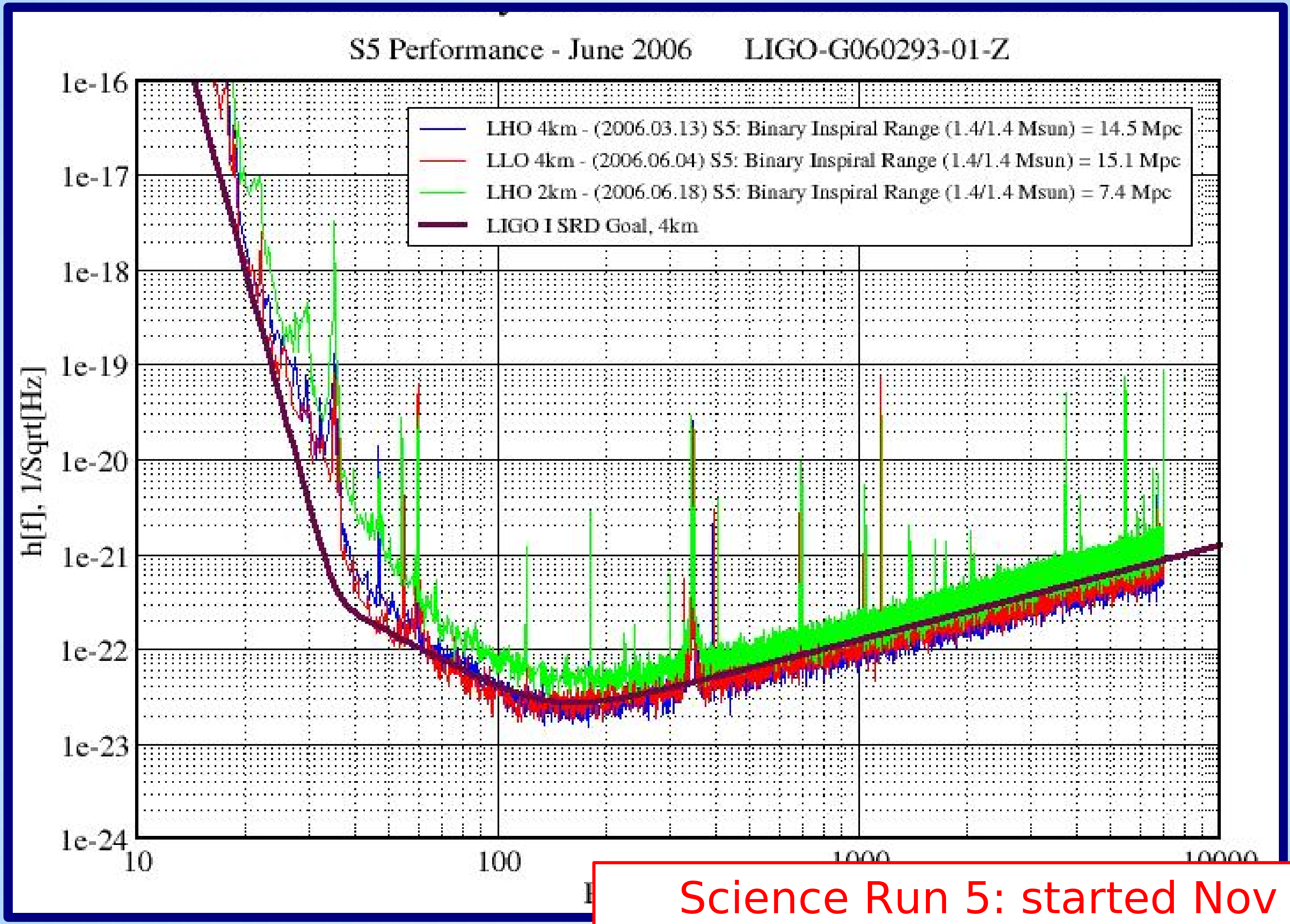
LIGO has completed its 5th science run (S5)



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



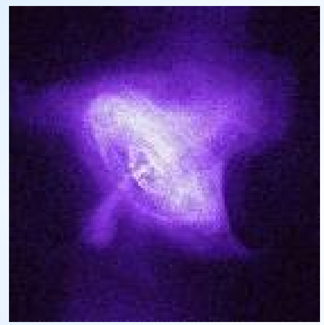
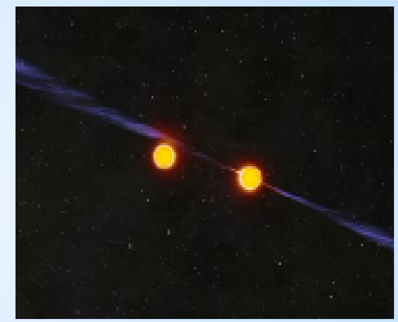
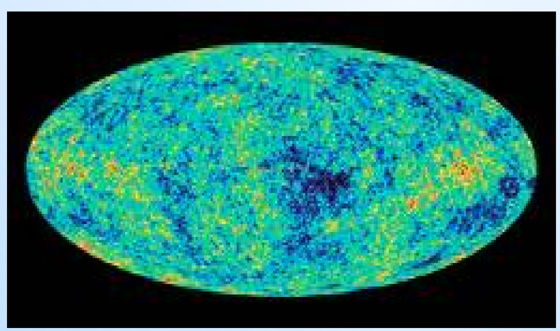
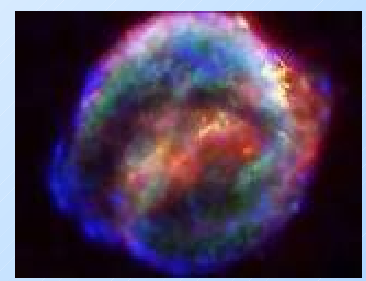
Science Run 5: started Nov 2005, lasted ~ 2 years.
Goal: 1 year of 2-site coincident live-time

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

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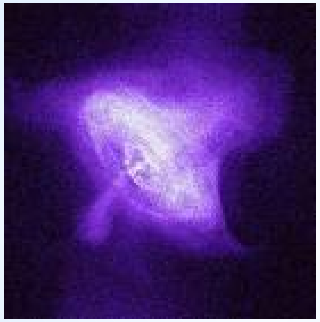
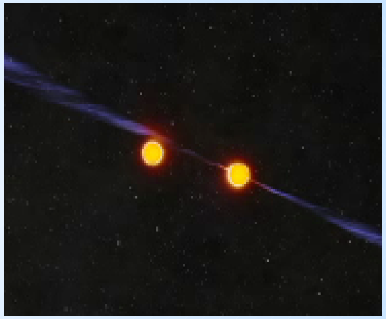
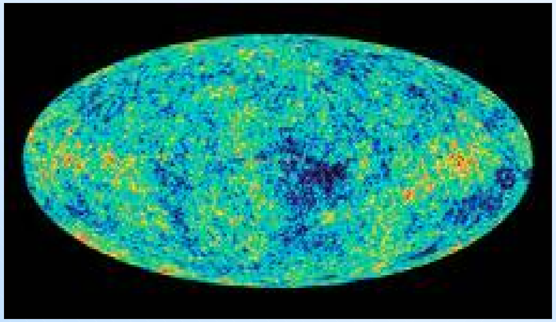
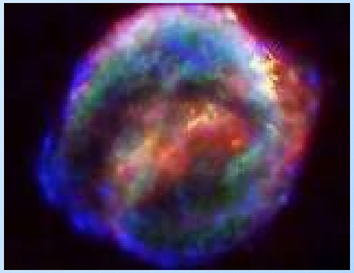
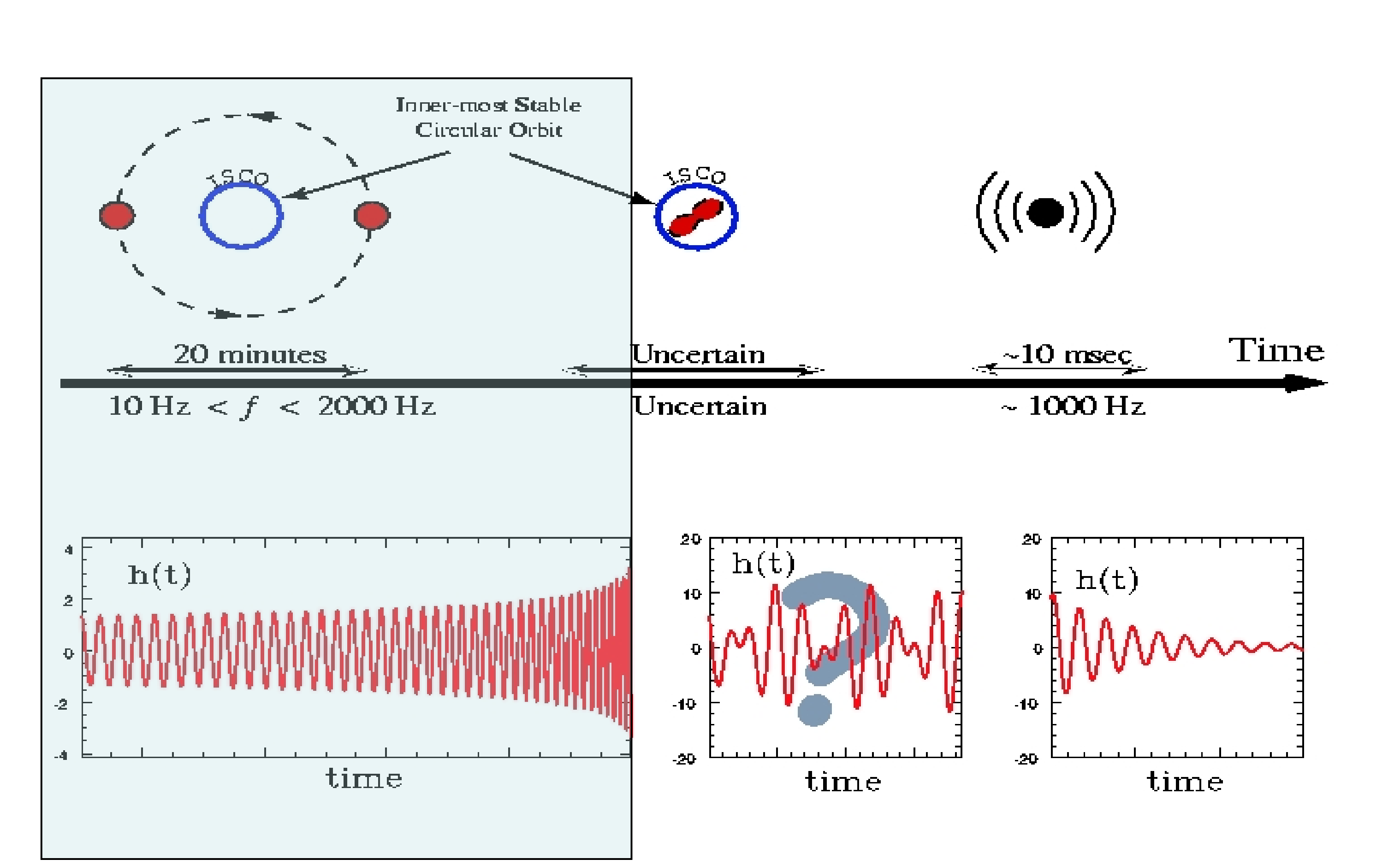
Matched filter	 Pulsars	 Compact binary inspirals
Template-less methods	 Stochastic Background	 Bursts

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

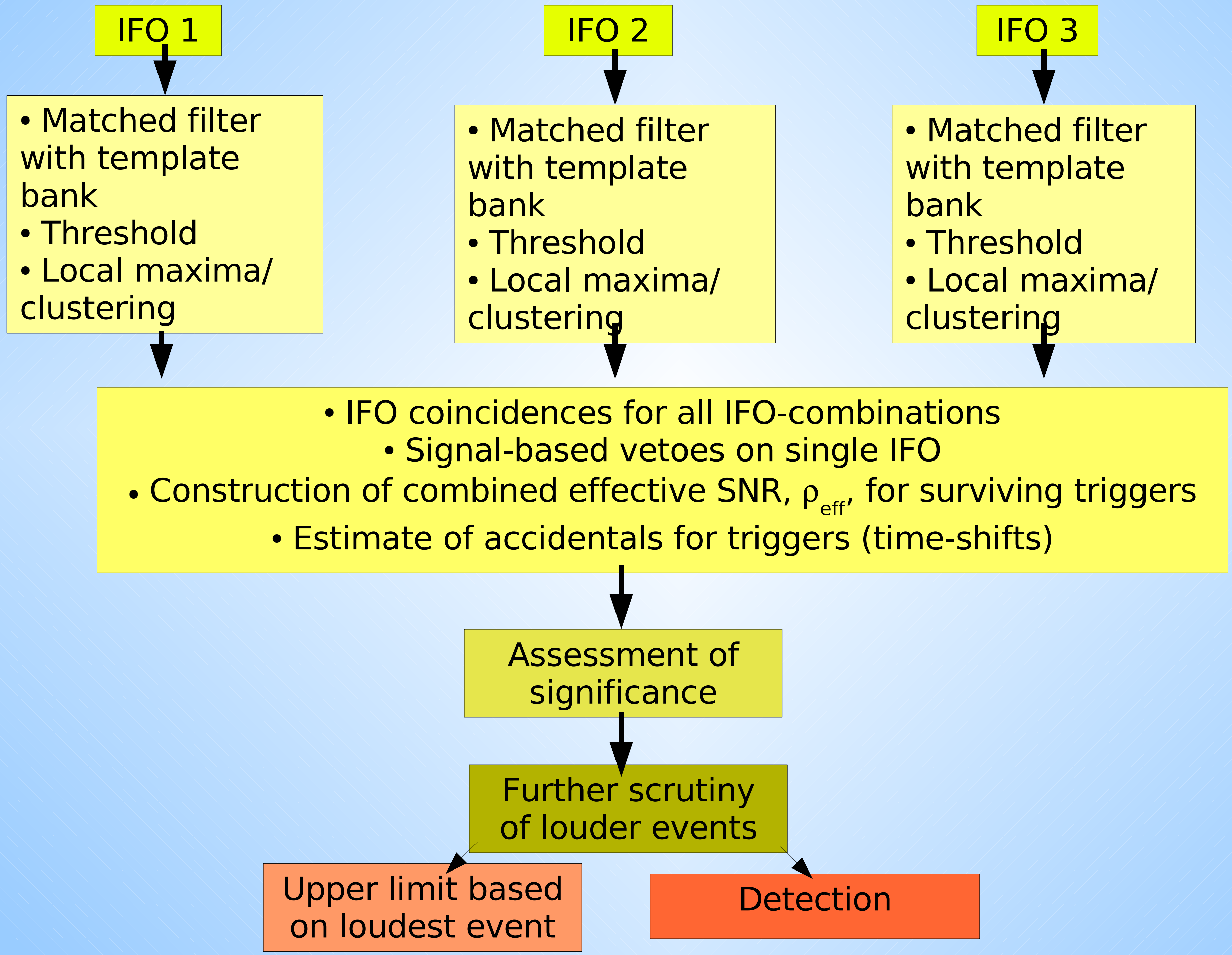
Let's start from these.

Expected signal



- In the LIGO band we can 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 for systems with total mass smaller than 3Msol

Compact binaries search pipeline schematics

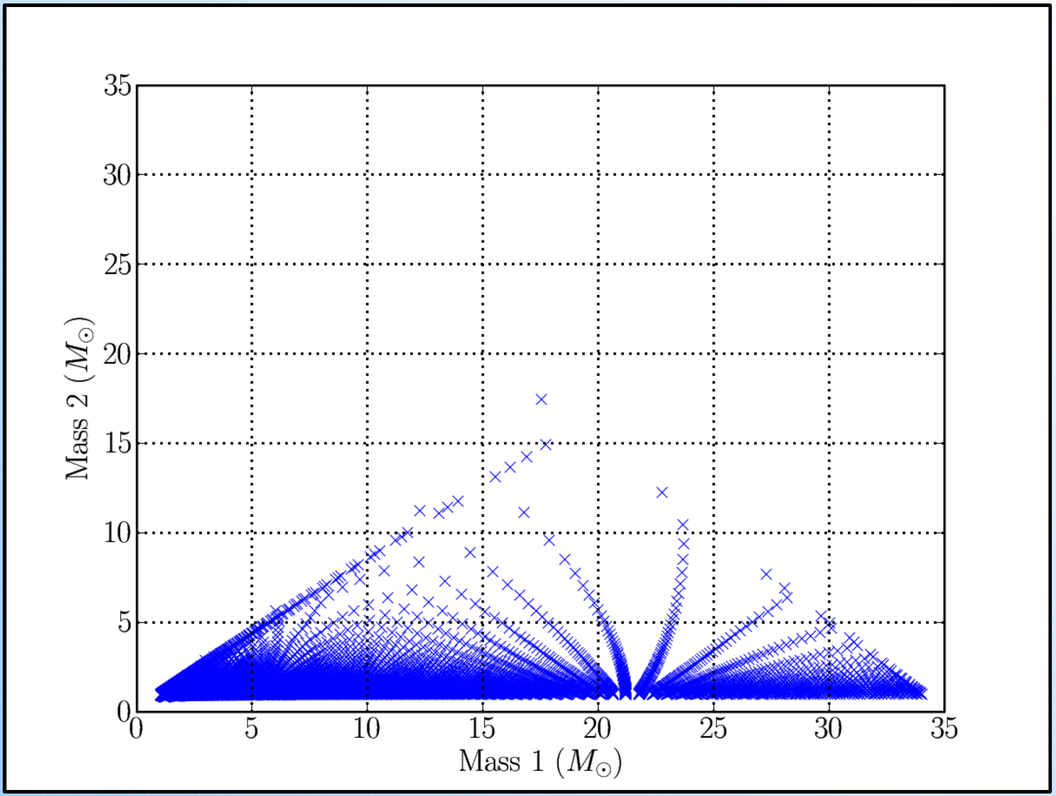


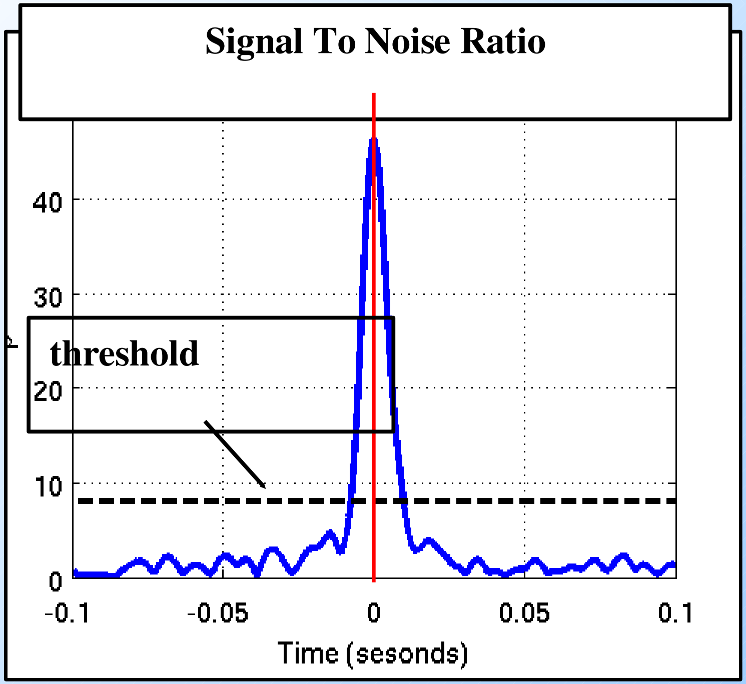
search pipeline schematics

IFO 1 → • Matched filter with template bank • Threshold • Local maxima/ clustering

IFO 2 → • Matched filter with template bank • Threshold • Local maxima/ clustering

IFO 3 → • Matched filter with template bank • Threshold • Local maxima/ clustering





search pipeline schematics

IFO 1

- Matched filter with template bank
- Threshold
- Local maxima/ clustering

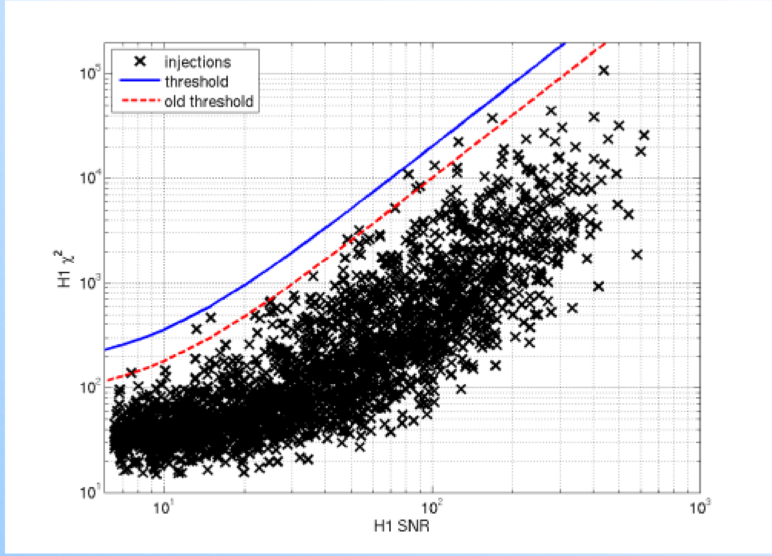
IFO 2

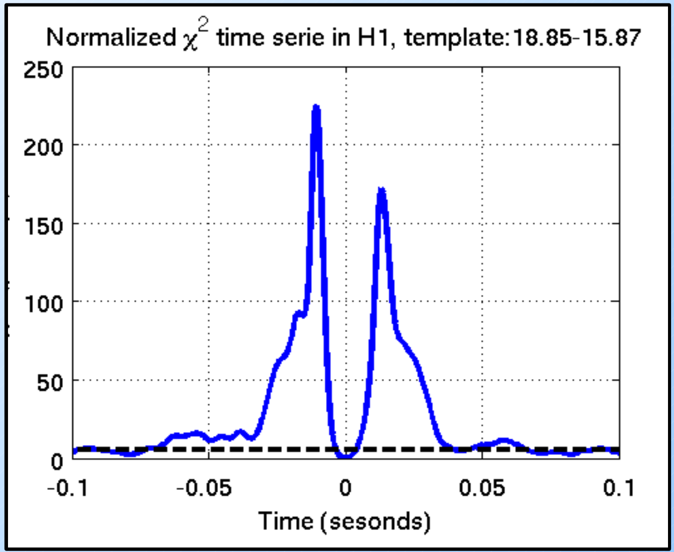
- Matched filter with template bank
- Threshold
- Local maxima/ clustering

IFO 3

- Matched filter with template bank
- Threshold
- Local maxima/ clustering

- IFO coincidences for all IFO-combinations
- Signal-based vetoes on single IFO
- Construction of combined effective SNR, ρ_{eff}, for surviving triggers
- Estimate of accidentals for triggers (time-shifts)





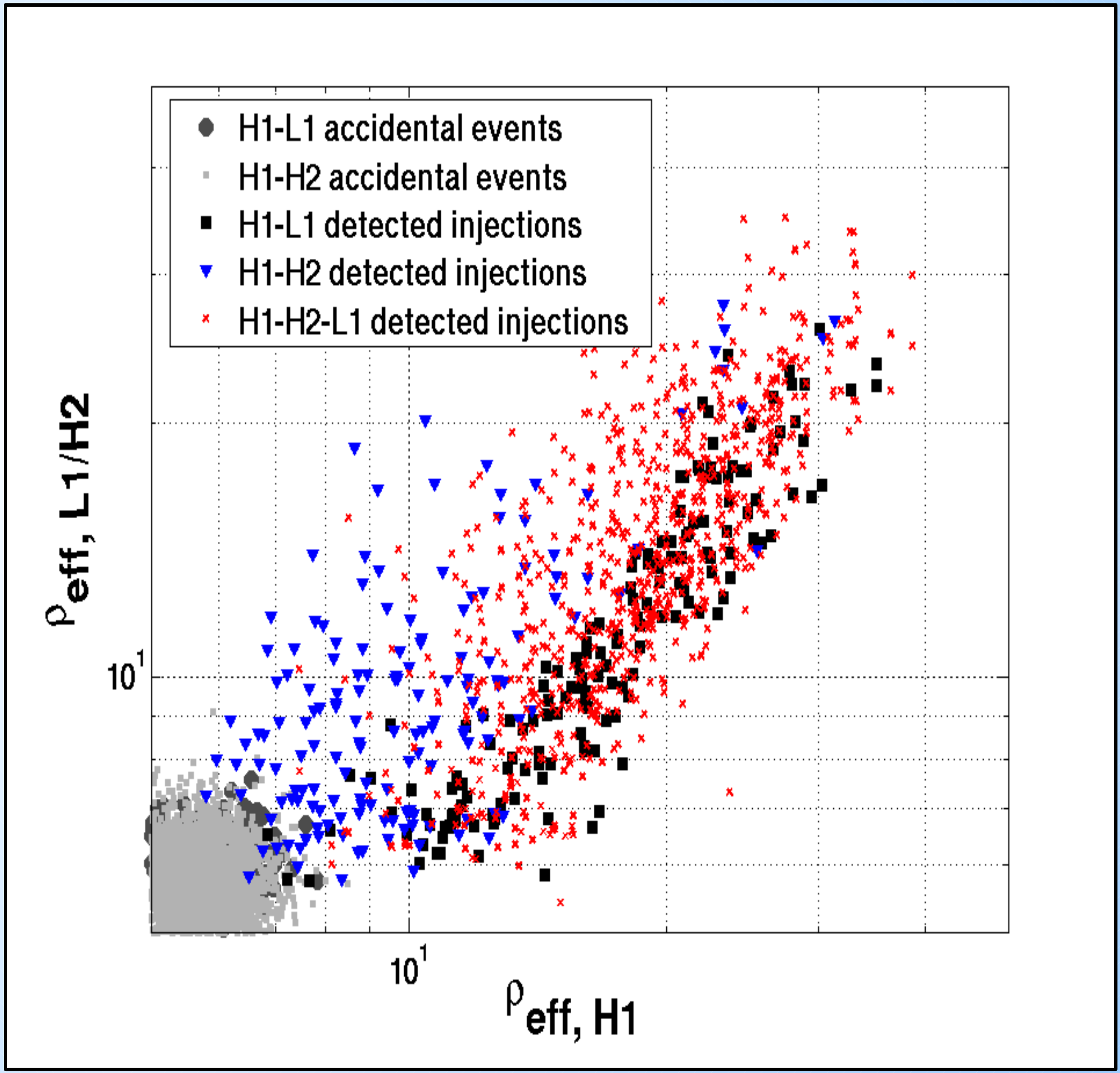
Search pipeline schematics injections and accidentals

$$\rho_{\mathrm{eff}}^2 = \frac{\rho^2}{\sqrt{\left(\frac{\chi^2}{\mathrm{DoF}}\right)\left(1+\frac{\rho^2}{250}\right)}}$$

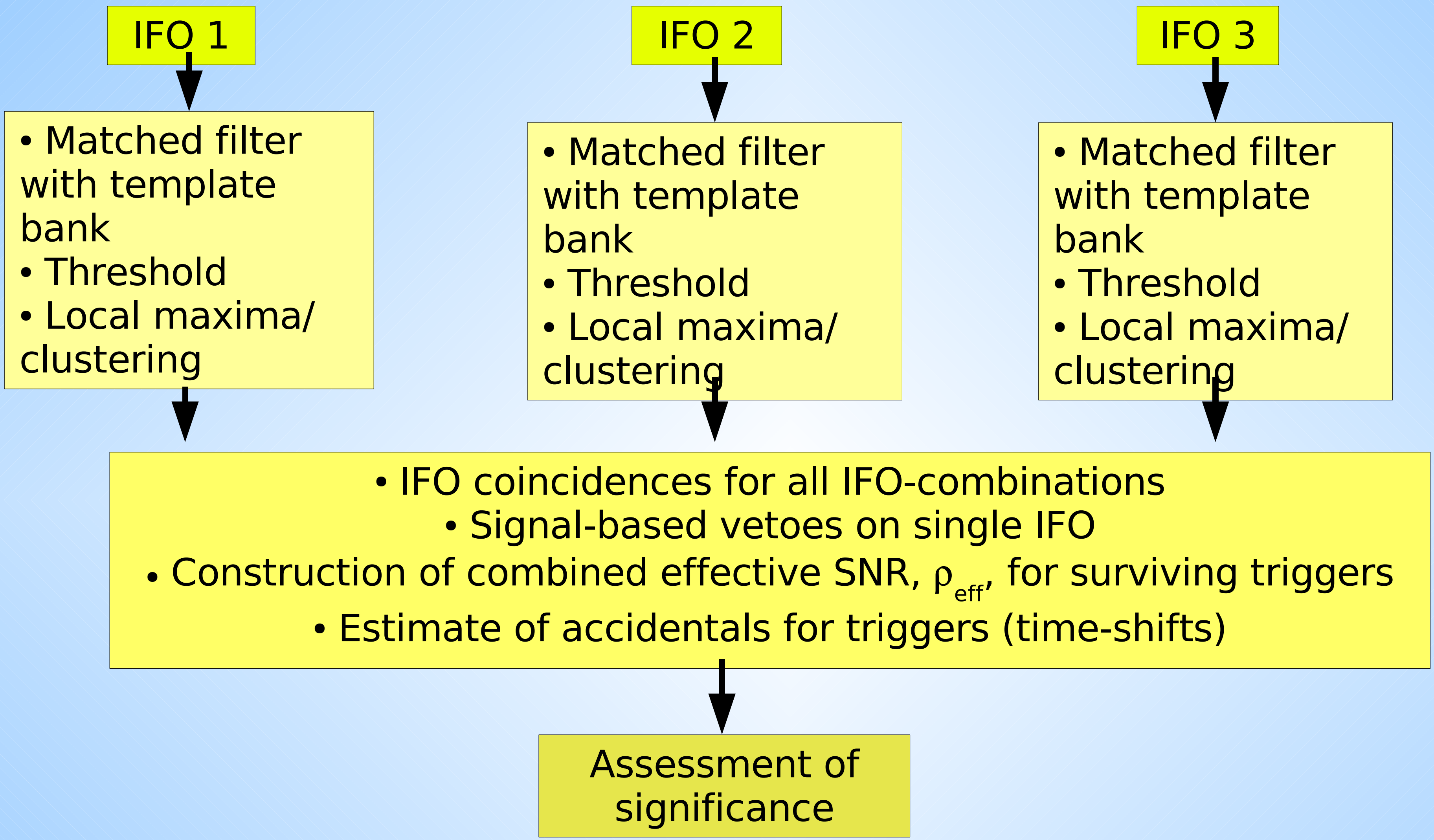
$$\rho_c^2 = \sum_i \rho_{eff,i}^2$$

1-Injections: can be used to tune the search parameters such as coincidence windows to be sure not to miss any real GW event.

2-Background estimation: the time stamps of the data is time-shift the data from the different detectors so as to estimate the accidental rate of triggers. Each search used 100 time-shifts.

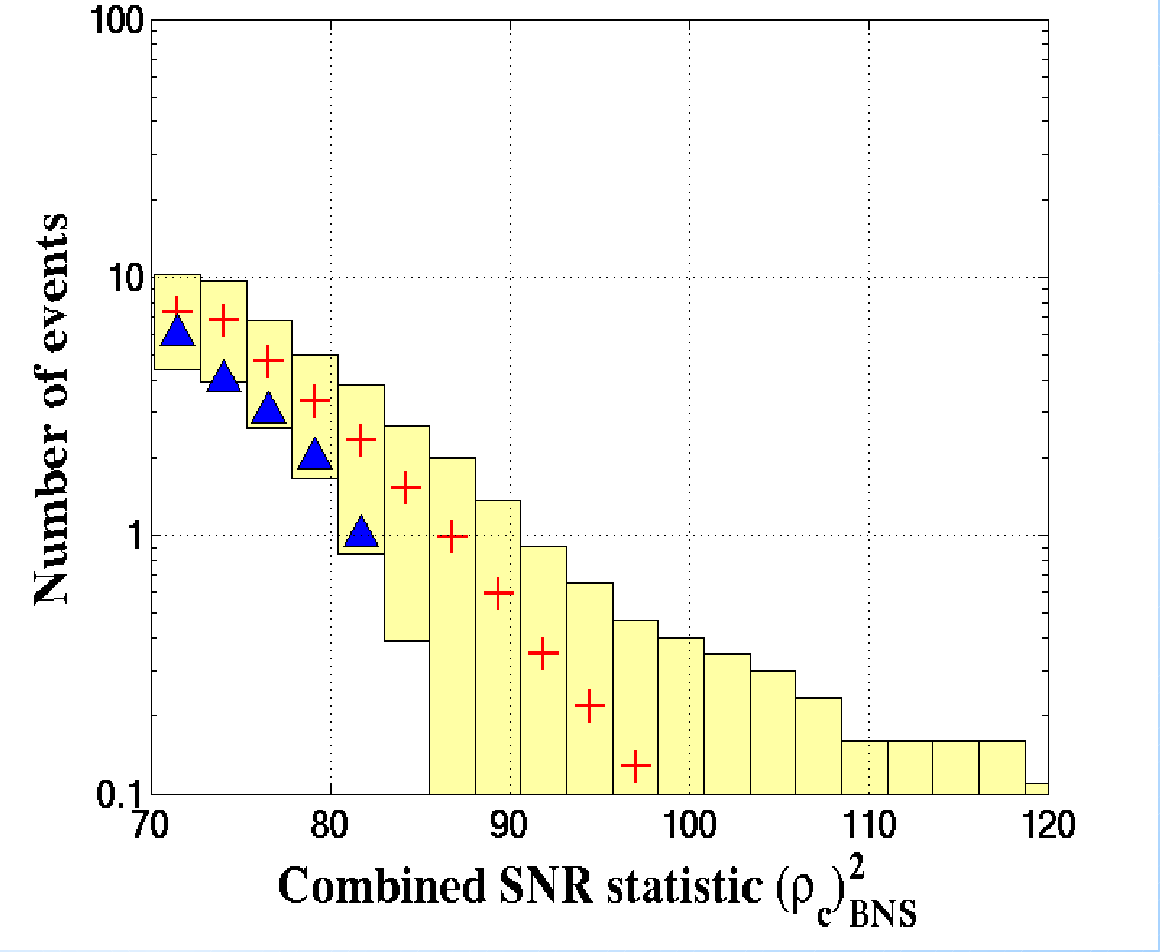


search pipeline schematics



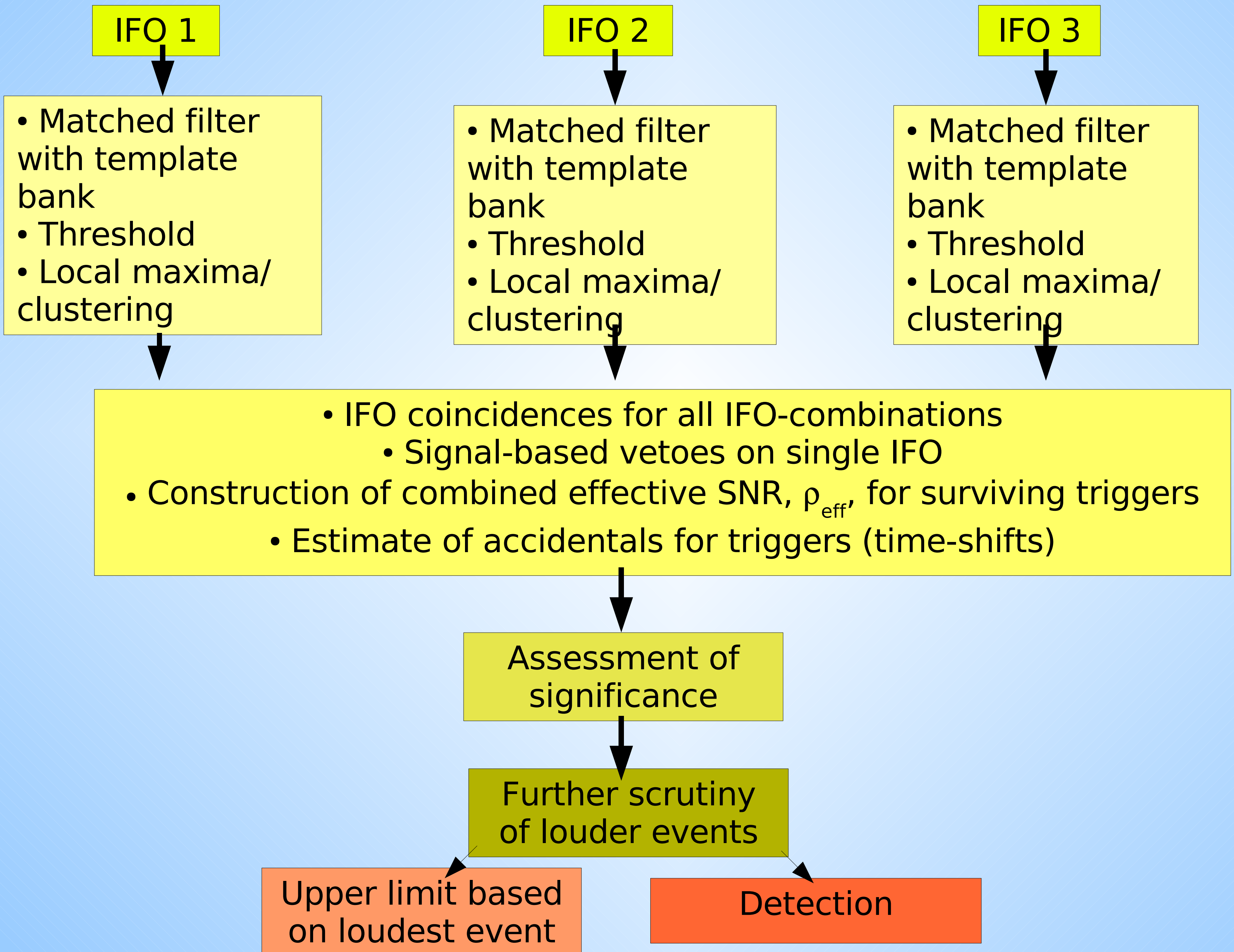
Assessment of significance

The analysis produces a list of coincident triggers. These triggers need to be compared with a background estimate for the same quantities. Which is obtained with the time-shifts.



If an in-time coincidence trigger is above the estimated background, then it is a candidate event, and needs follow-ups.

search pipeline schematics



Follow-up studies at the end of the automated pipeline

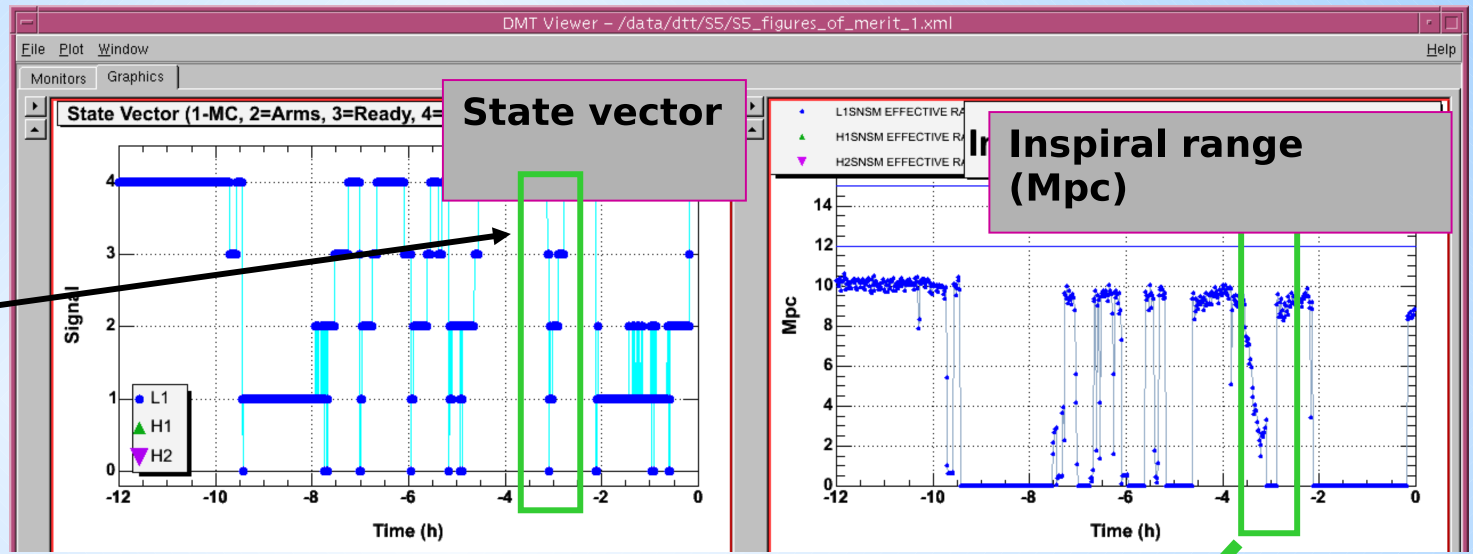
- Statistical significance of the candidate
- Status of the interferometers
- Check for environmental or instrumental causes
- Candidate appearance
- Check the consistency of the candidate estimated parameters
- Check for data integrity
- Check for detection robustness (ex: versus calibration uncertainties)
- Application of coherent network analysis pipelines
- Check ringdown and burst results
- Check for coincidence with searches external to our GW searches: other E/M or particle detectors…

Status of the interferometers

Ex: Status of the L1 detector at the time of the background trigger

⇒ **Check figure of merits (state vector, inspiral range, …)**

Figures of merit posted in the elog



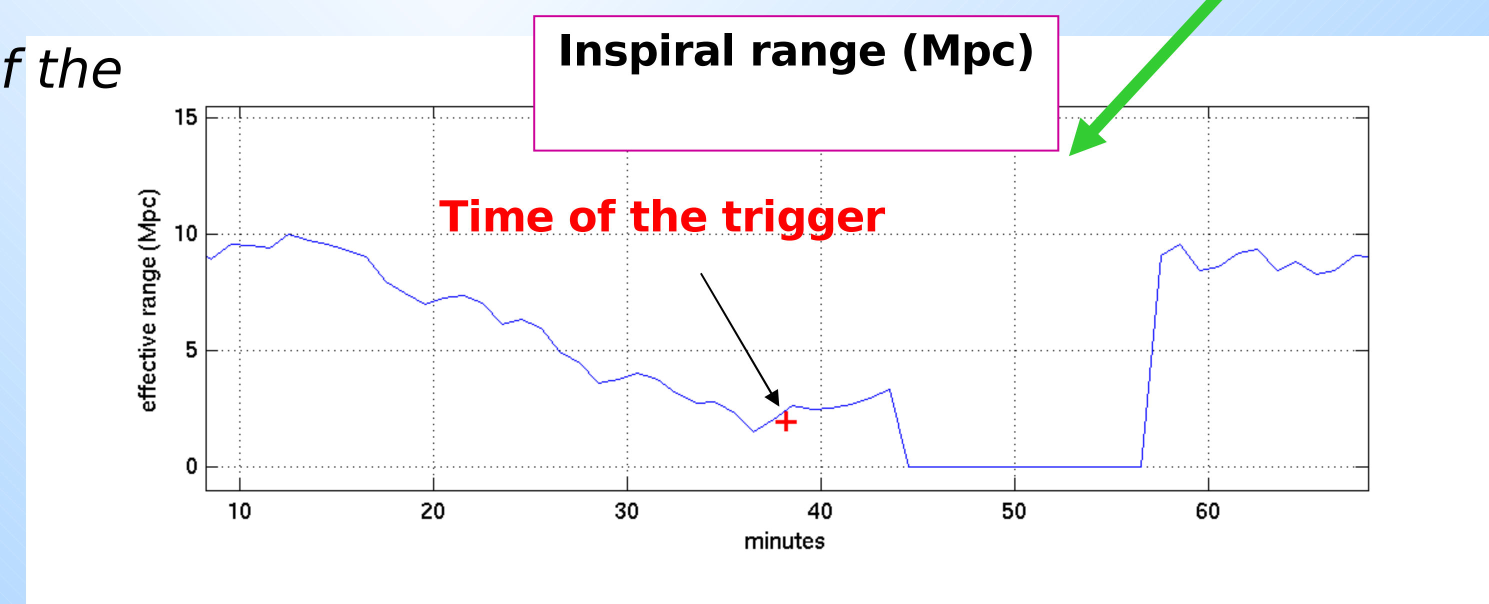
State vector:

Flag indicating ifo in science mode

Inspiral Range:

(averaged horizon of the inspiral search for a 1.4/1.4 solar mass system)

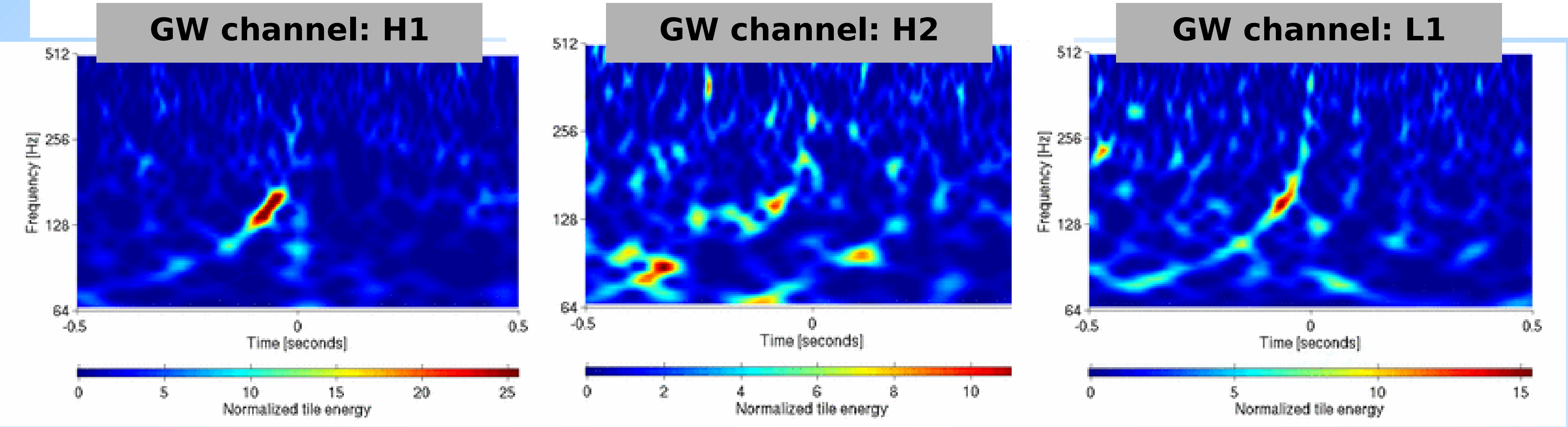
⇒ Candidate happens while L1 inspiral range is dropping



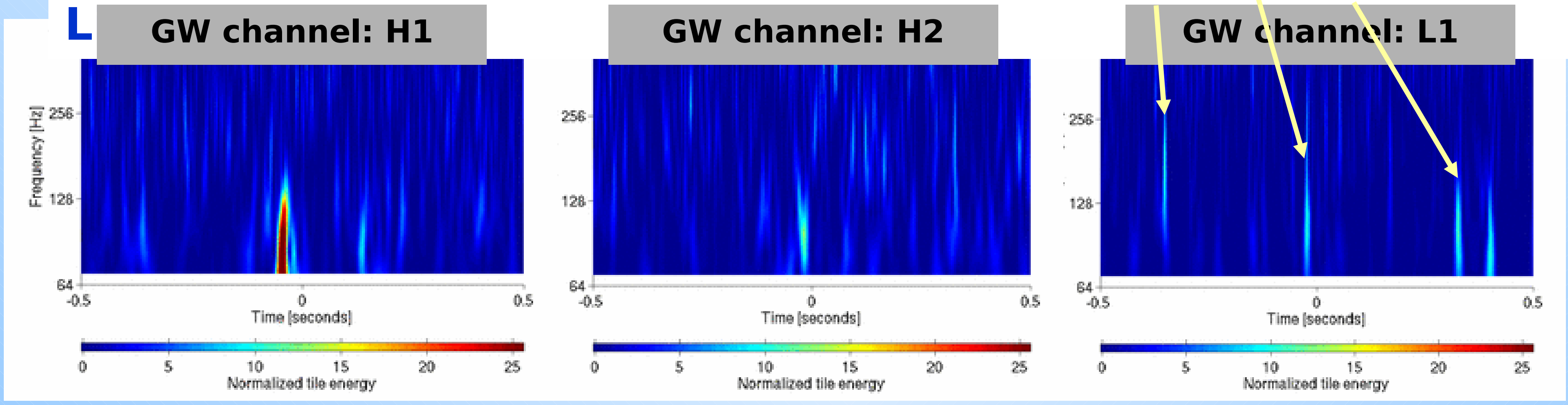
Candidate appearance

⇒ **Check time series, and time-frequency spectrograms of the candidate**

Ex: Inspiral hardware injection: Chirp visible in H1 and L1



Ex: Background trigger (time slide) → multiple transients at L

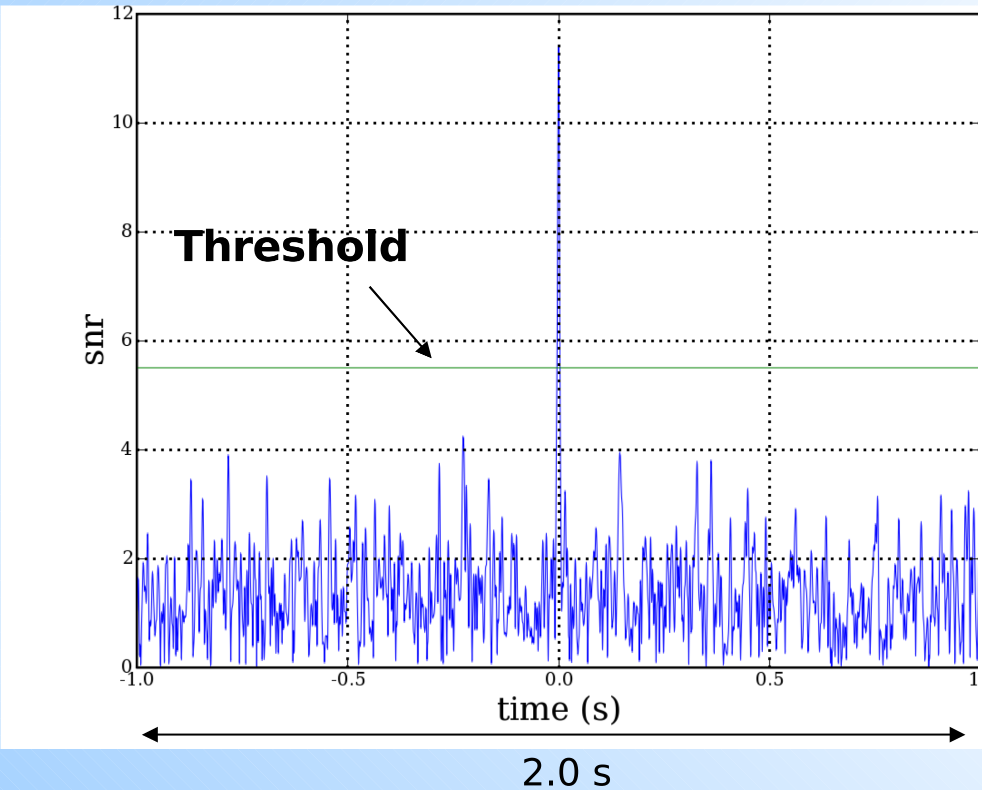


Candidate appearance

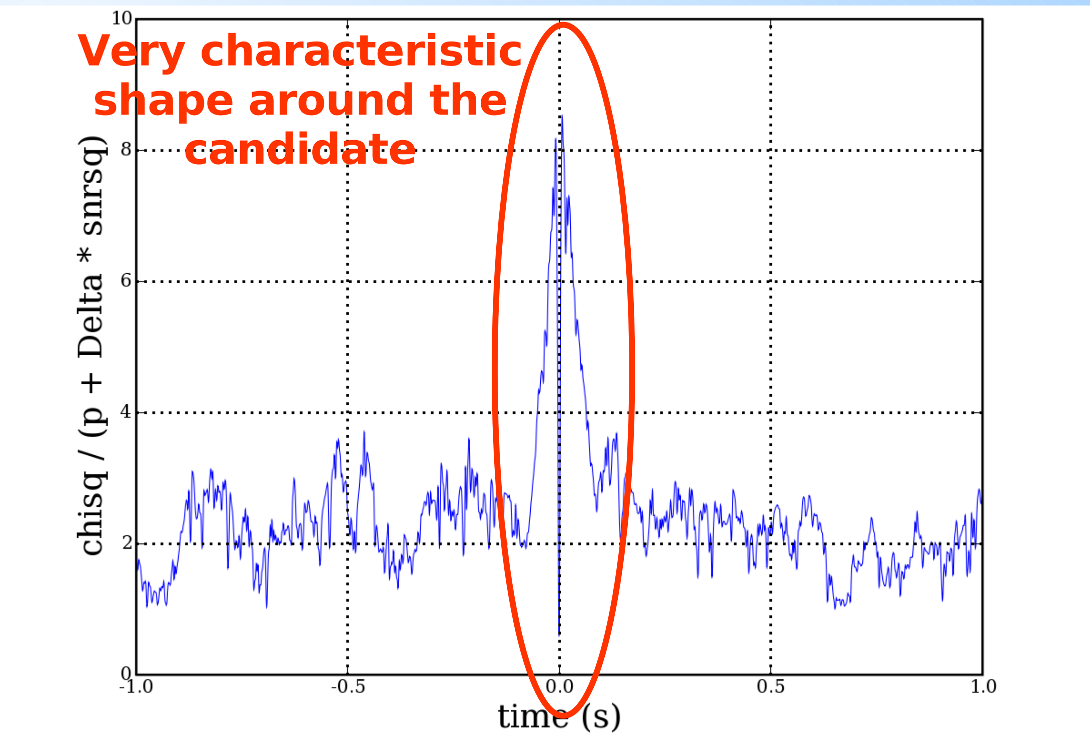
⇒ **Check SNR and CHISQ time series after match filtering the data**

Ex: Inspiral hardware injection, L1 trigger

SNR time series



χ^2 time series

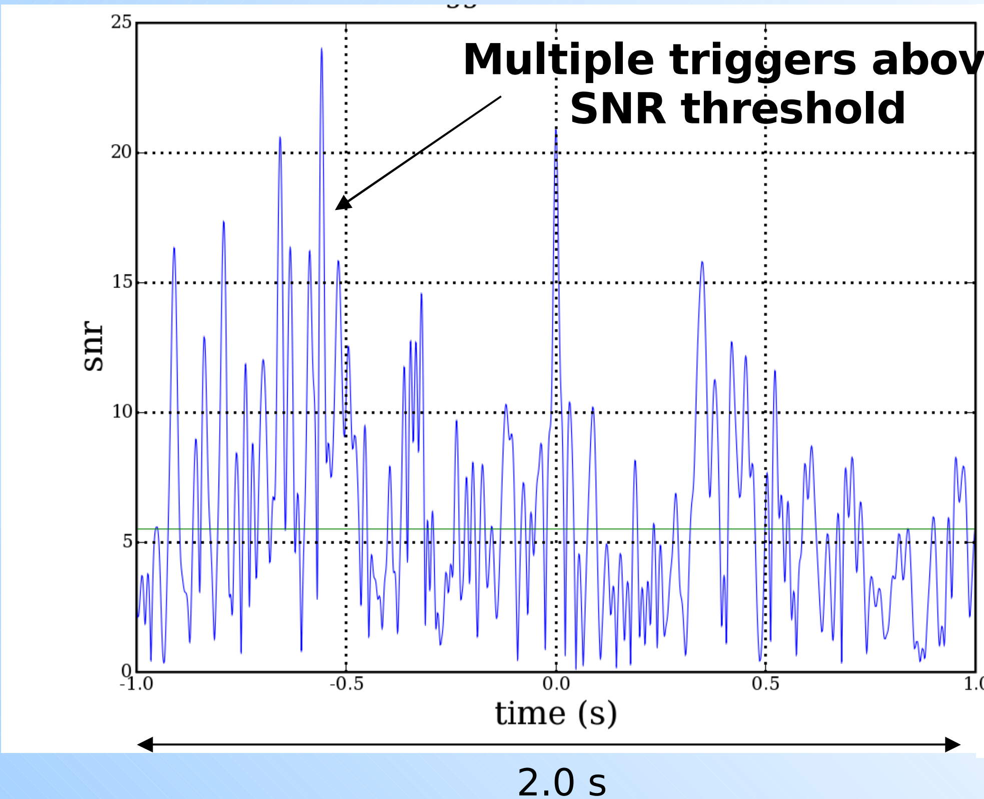


Candidate appearance

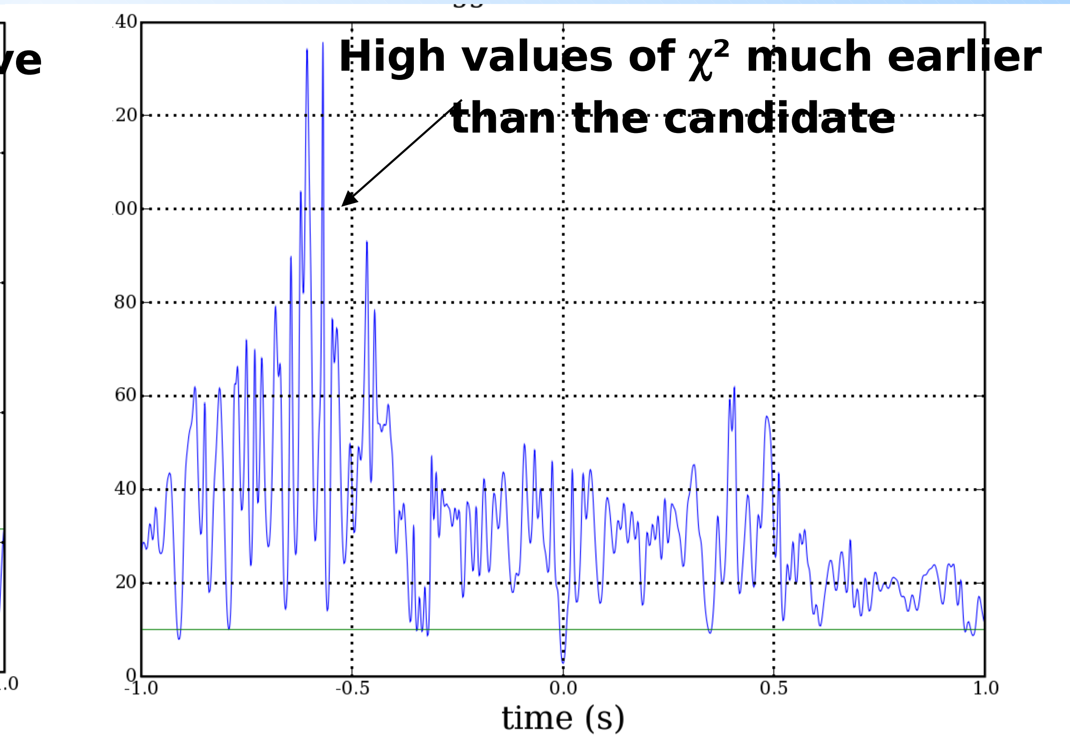
⇒ **Check SNR and CHISQ time series after match filtering the data**

Ex: Background trigger in L1

SNR time series



χ^2 time series



⇒ **Both time series show a very noisy period.**

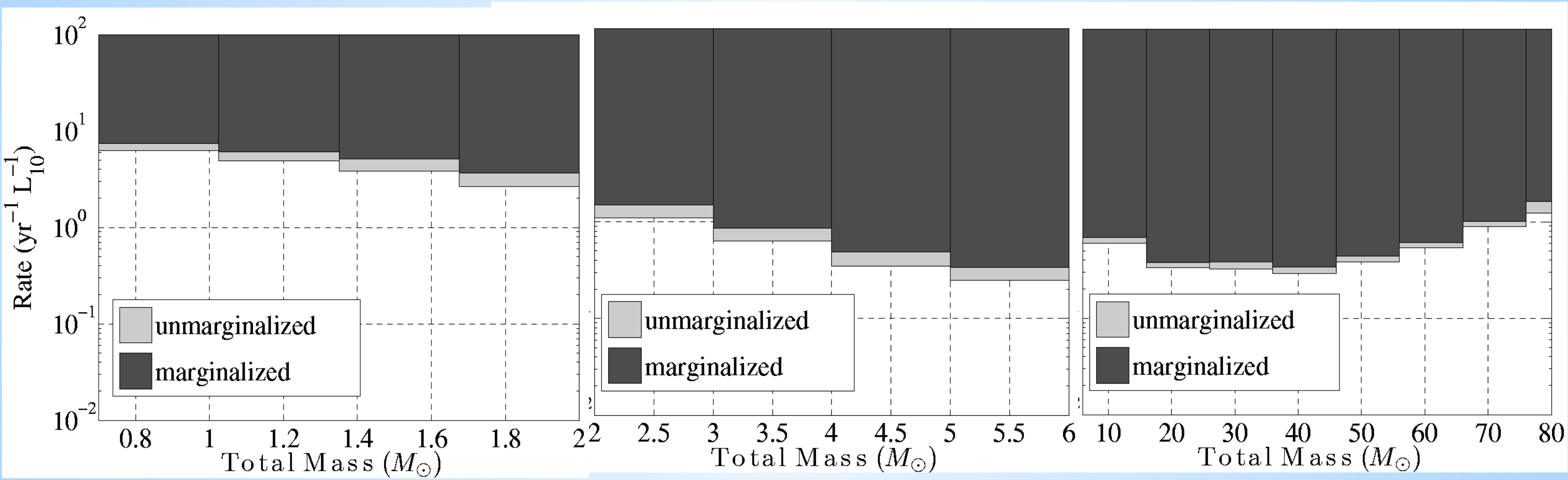
⇒ **Thus this candidate cannot be defended**

S4 Upper limit results

LSC, arXiv:0704.3368, submitted to PRD

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

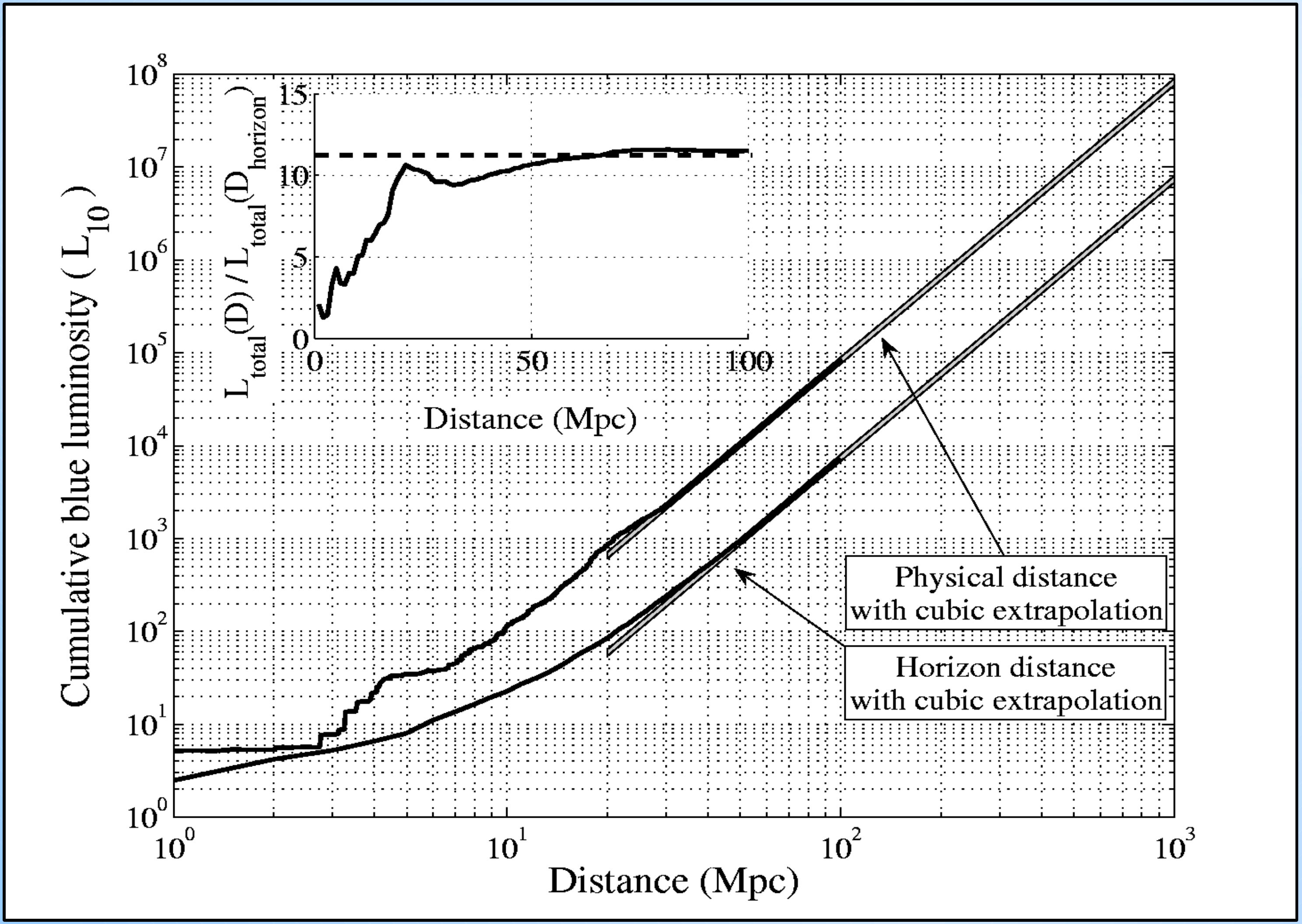
X C: number of “galaxies” the search can see L_{10}

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.

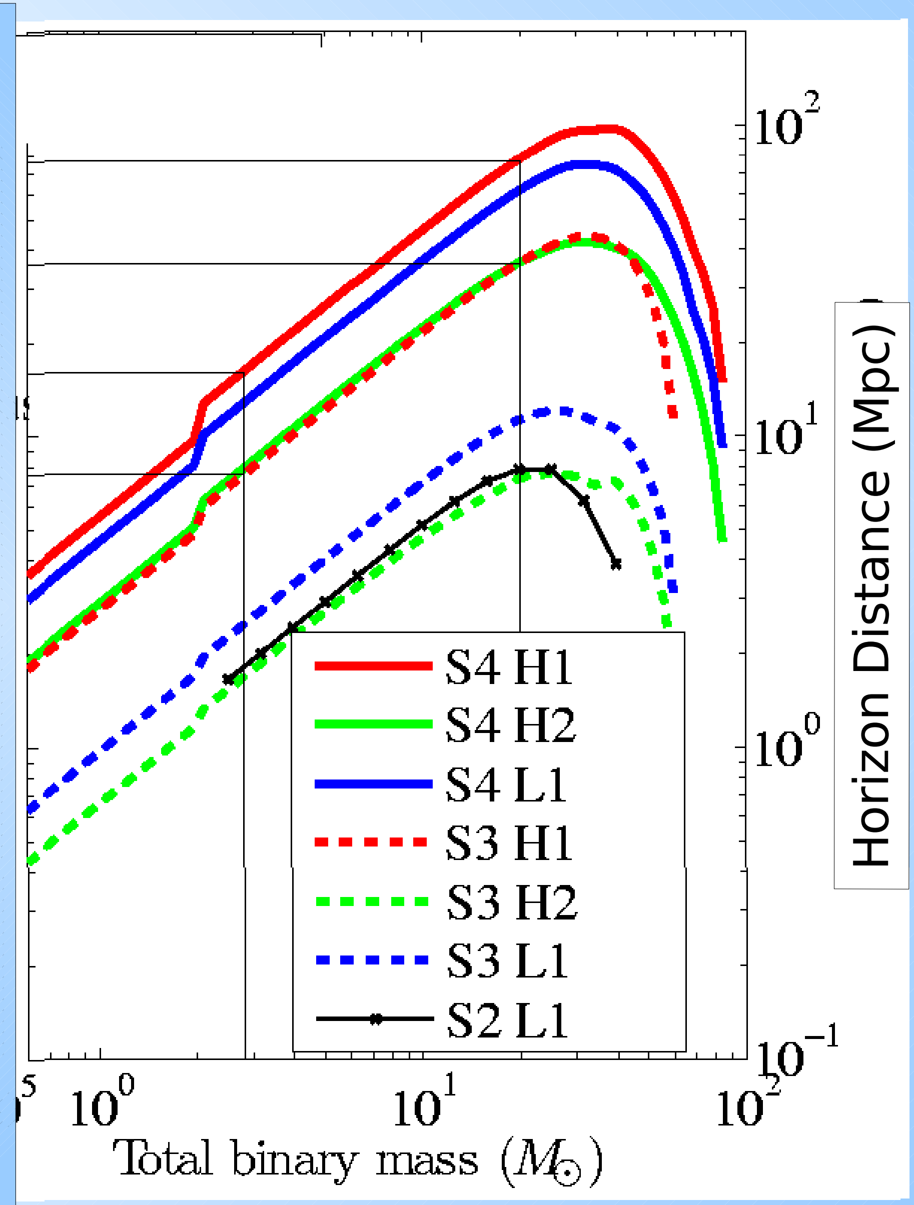
The horizon distance

(for data that has been analyzed)

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

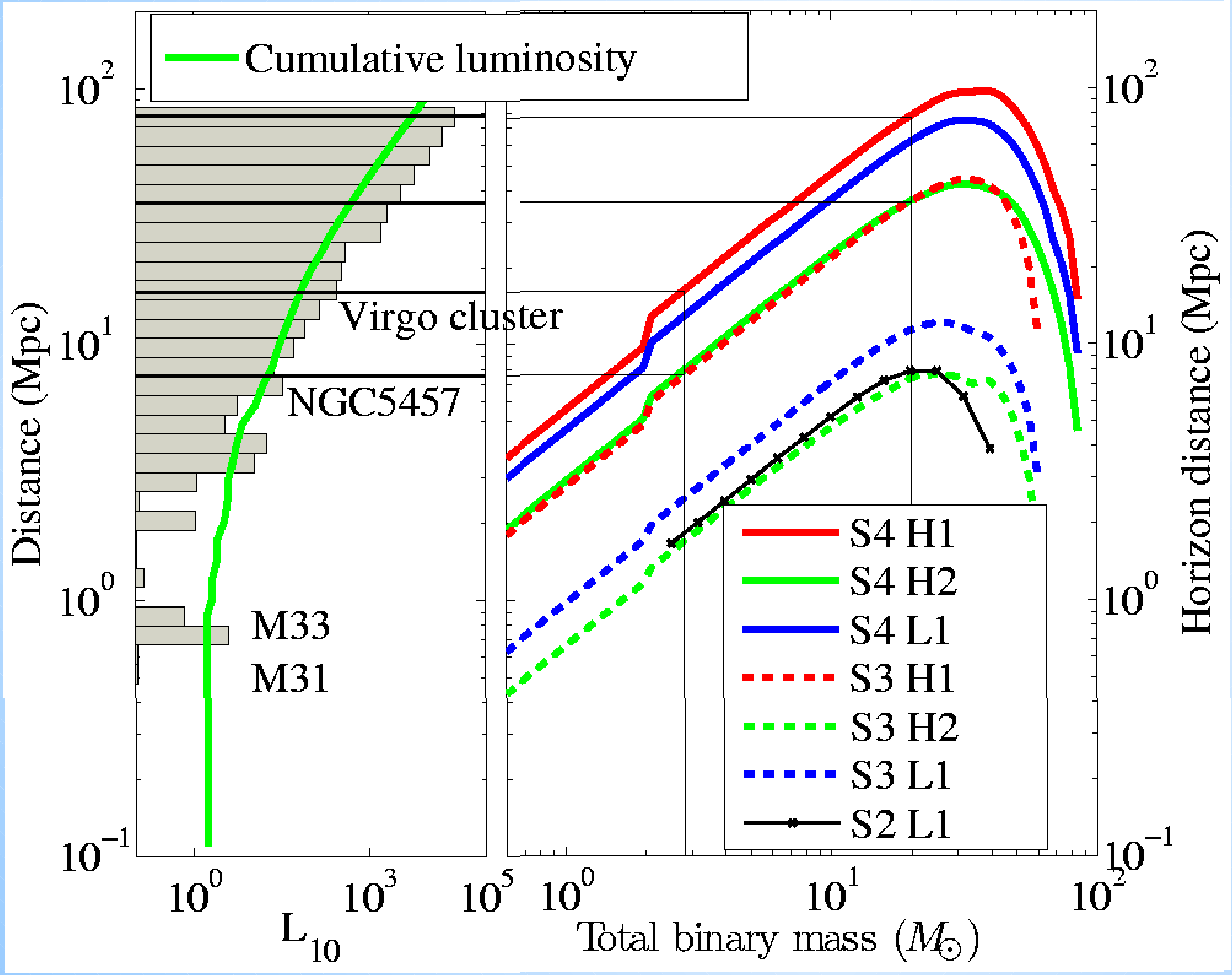
For H1 during S4:

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



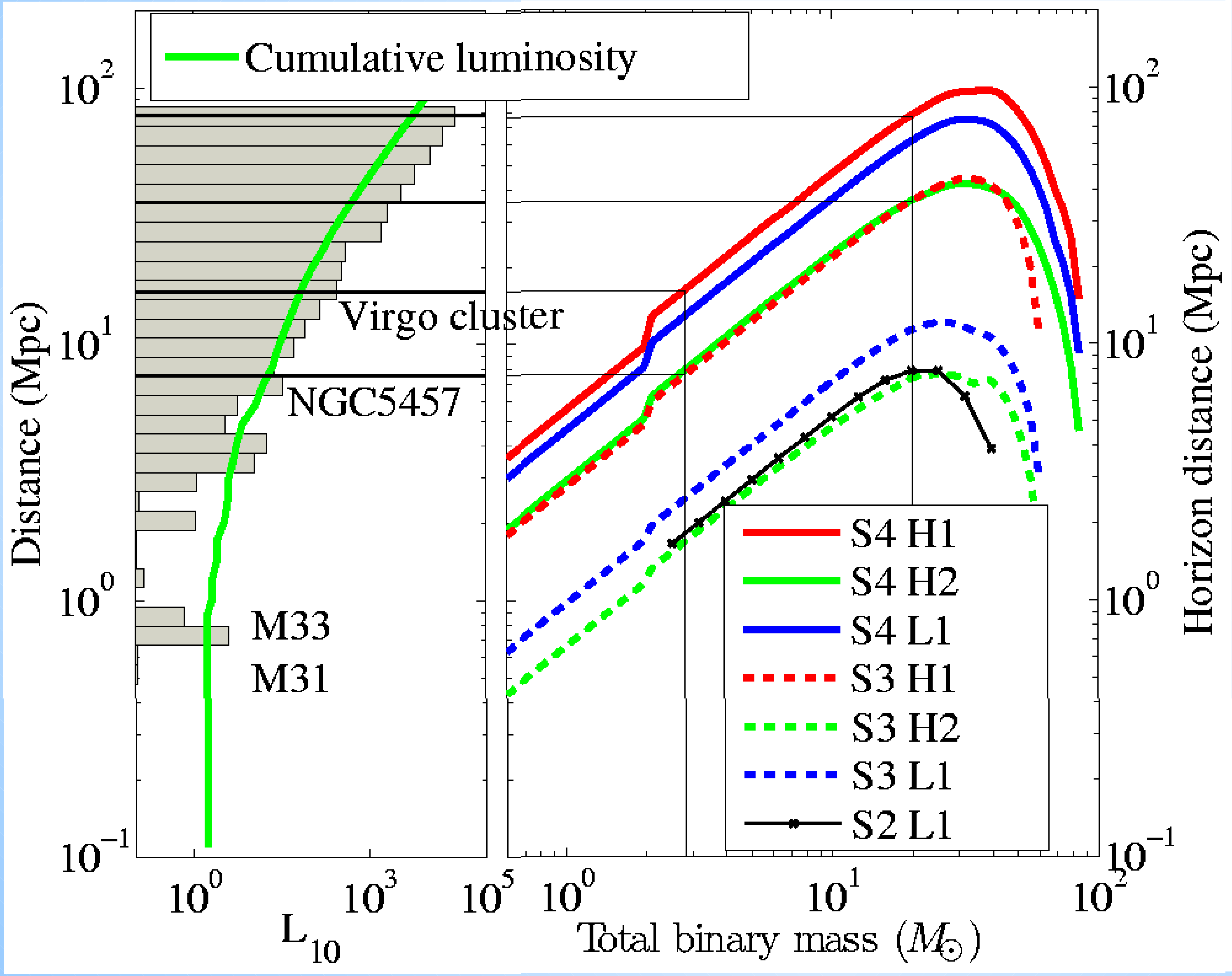
≈ 1/(2000yrs)- -1/100(yrs) for BNS, with DH ~ 16Mpc

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

Not so great

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

... for our next detectors

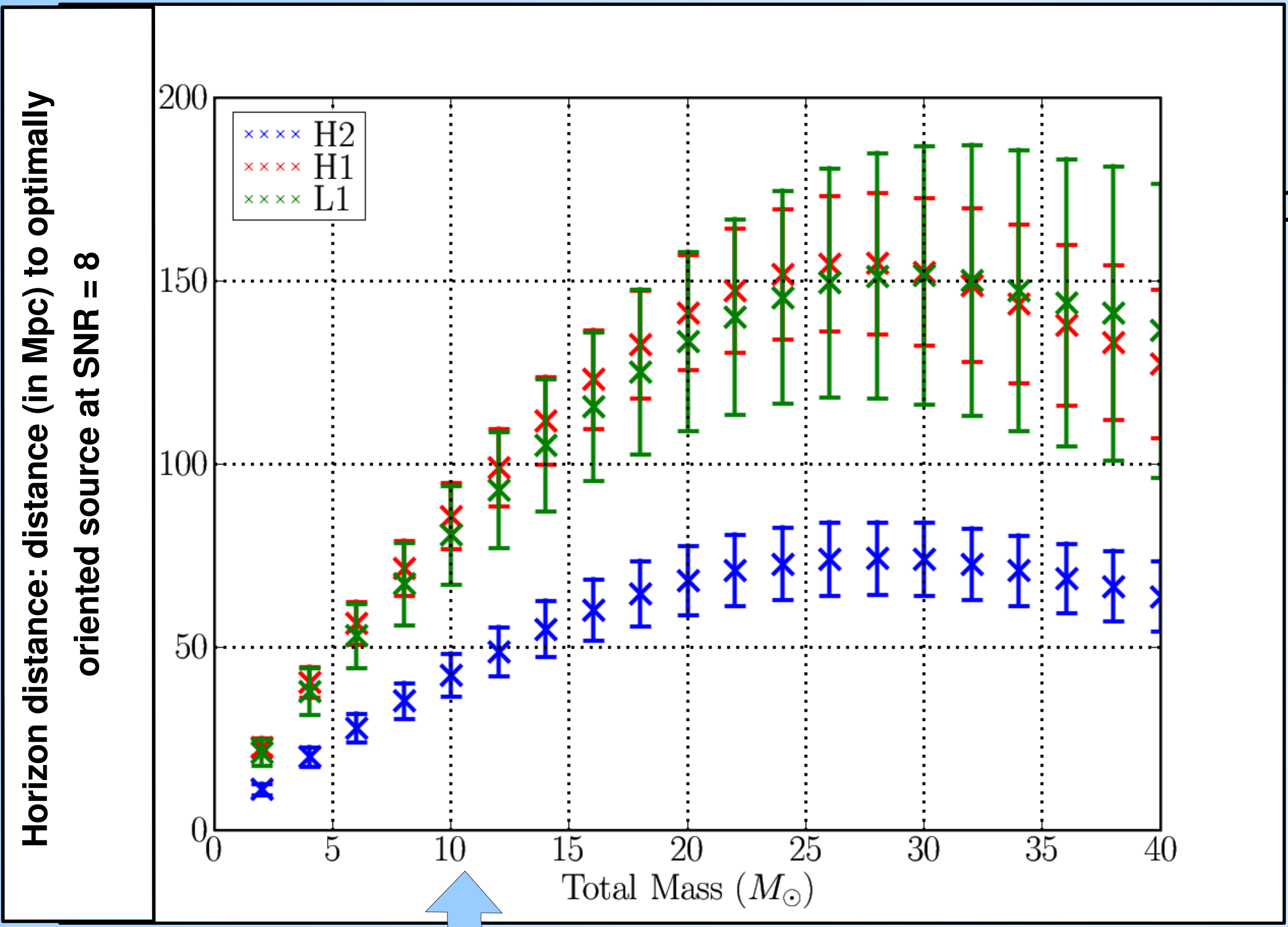


ENHANCED (2009):
≈ 1/(60yrs)-1/3yr
for BNS,
with DH ~ 60Mpc

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

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

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

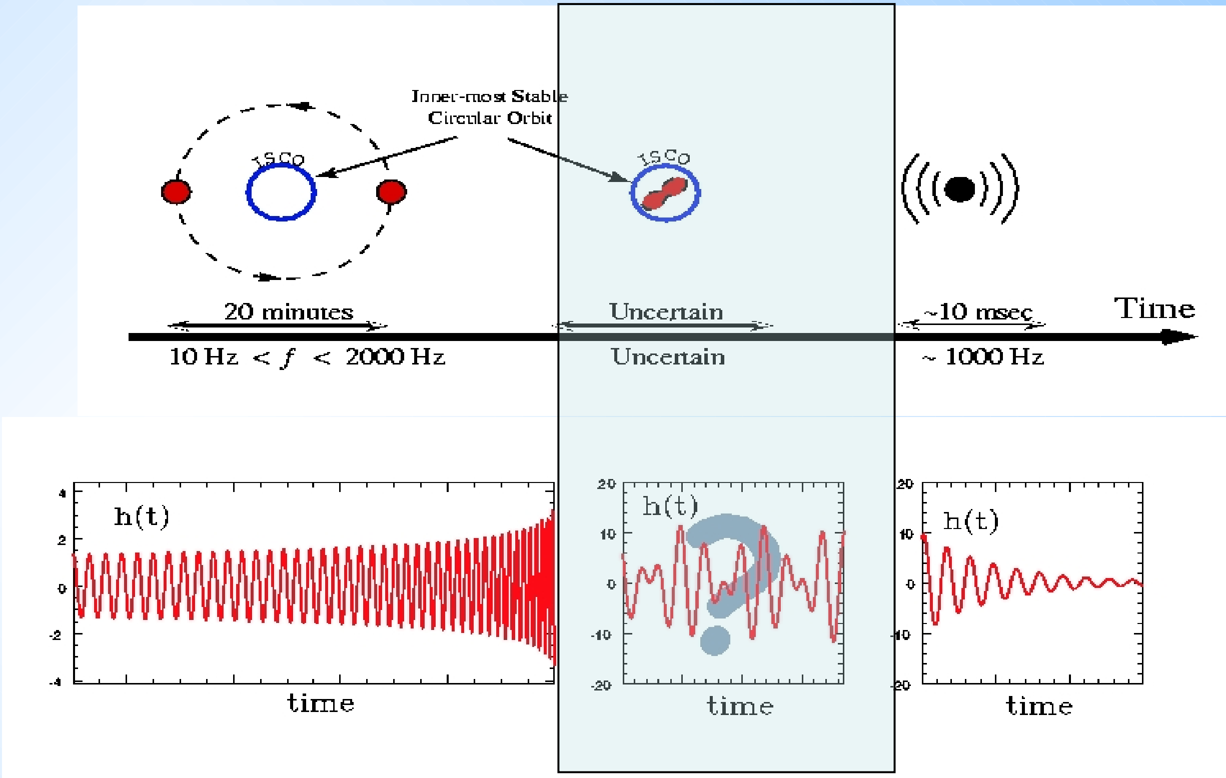
First year of S5, estimated rates

Component masses (M_{sun})	1.4,1.4	5,5	10,10
Cumulative blue luminosity of search, C [L_{10}]	200	2400	11000
Tob s [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
- - Neutron star instabilities
- - Cosmic string cusps and kinks
- - The unexpected!



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

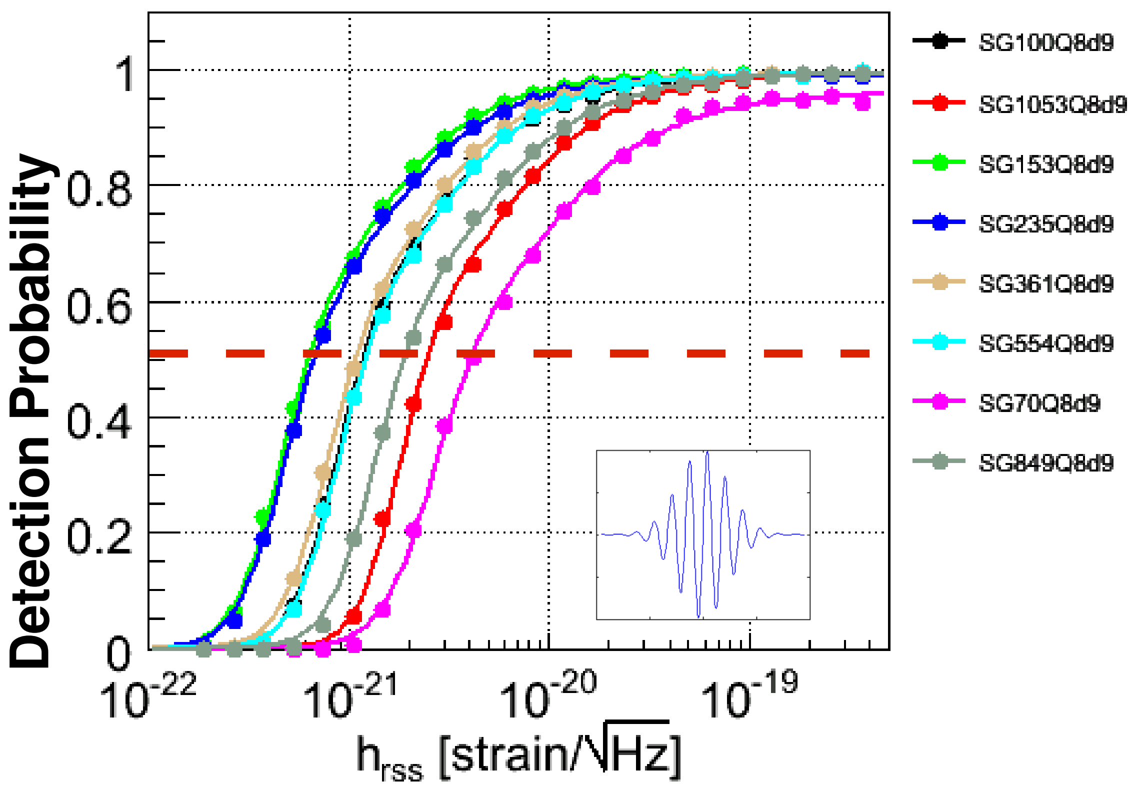
same as in arXiv:0704.0943 [gr-qc]

CQG 24, 5343-5369 (2007)

- 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

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

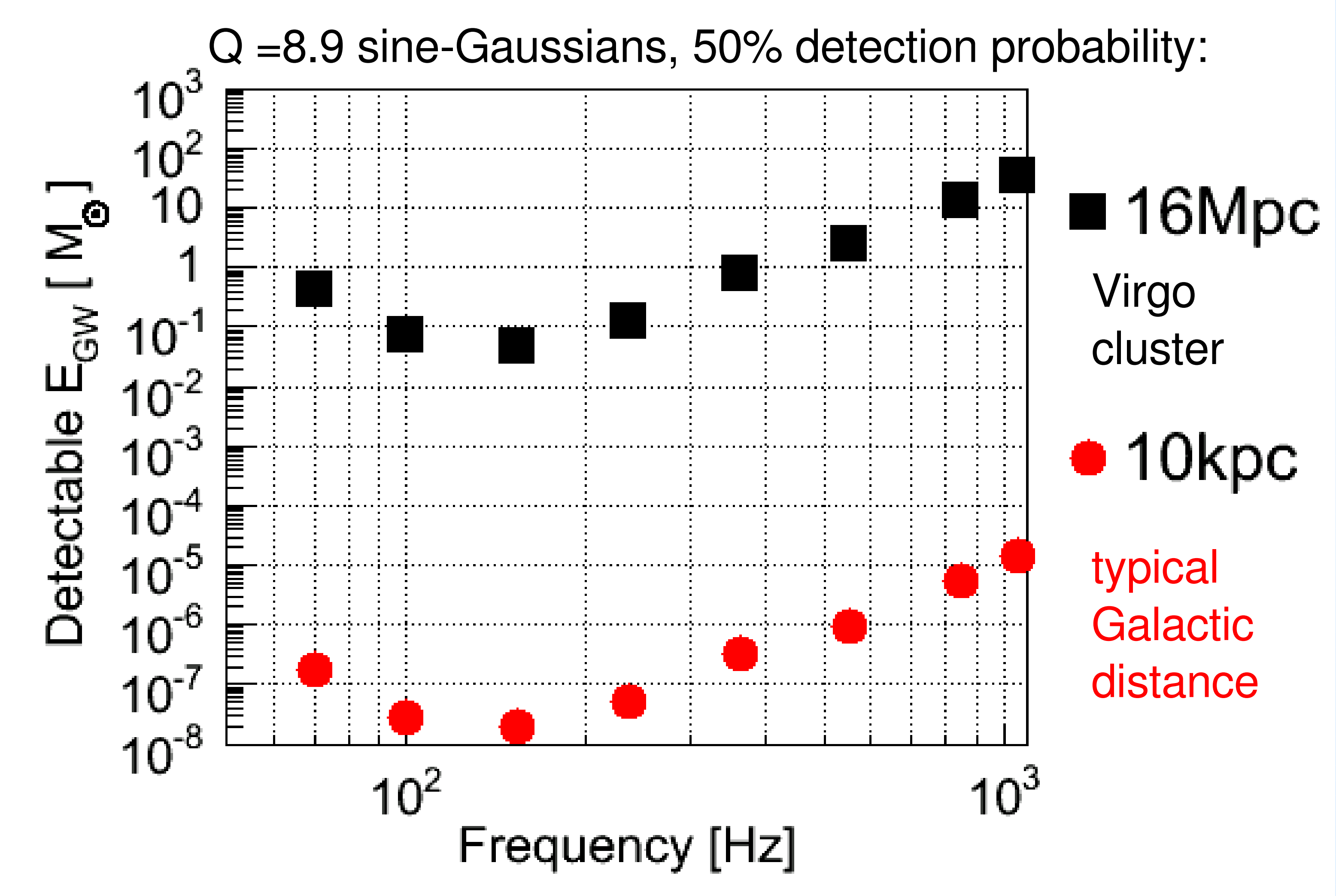
For a sine-Gaussian with Q>>1 and frequency f_0 :

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

Cadonati for the LSC, APS 07, G070209-03

Detection Efficiency / Range

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} $M_\odot c^2$ at 10 kpc (typical Galactic distance)

~ 0.05 $M_\odot c^2$ at 16 Mpc (Virgo cluster)

Emission predictions and S5 reaches

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

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

BBH merger rates:

$0.1\text{-}15 \times 10^{-6}\ \text{yrs}^{-1}\ L_{10}^{-1}$ → 1/[3000-7]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

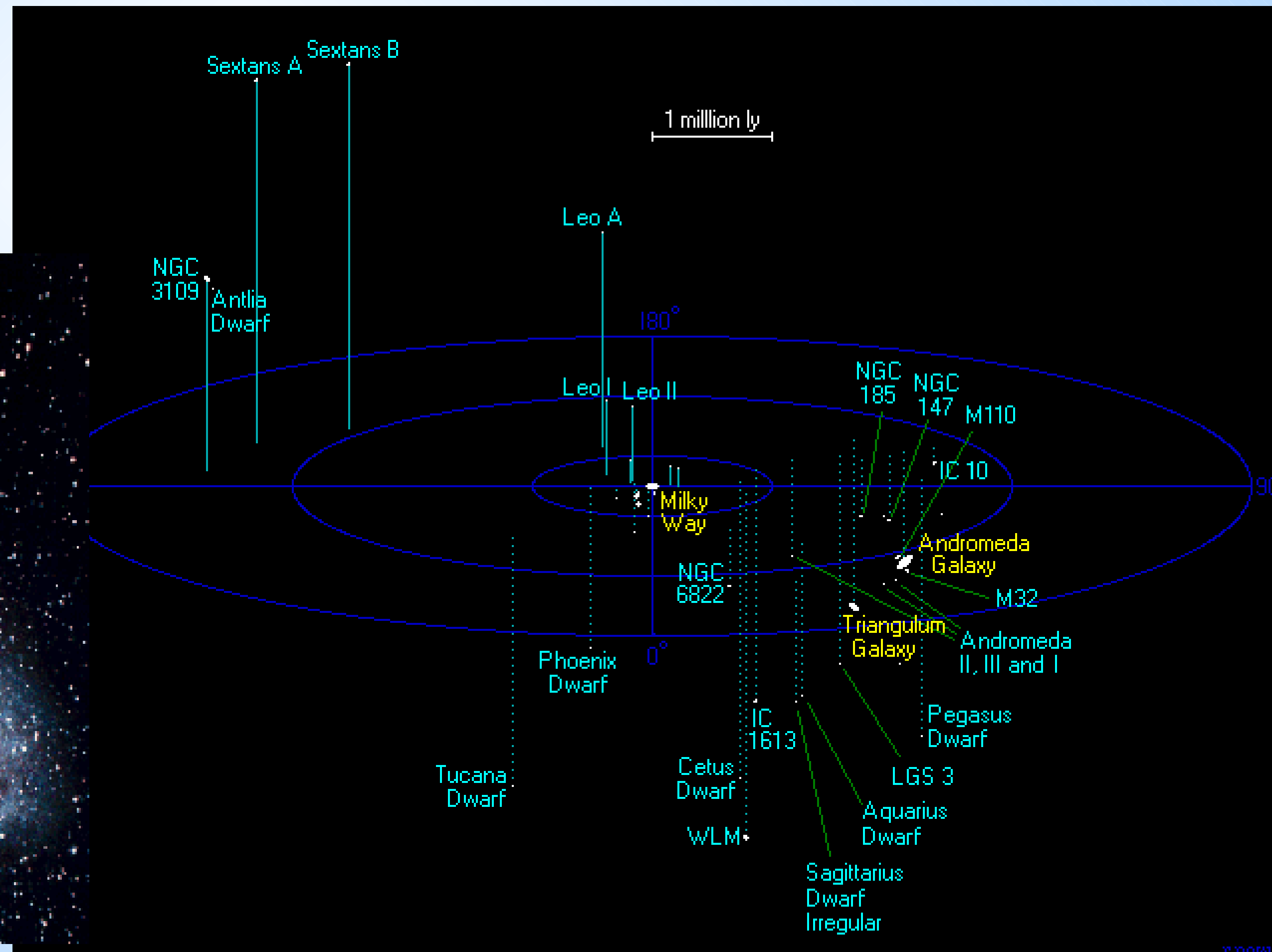
Searches triggered by em observations

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 regio

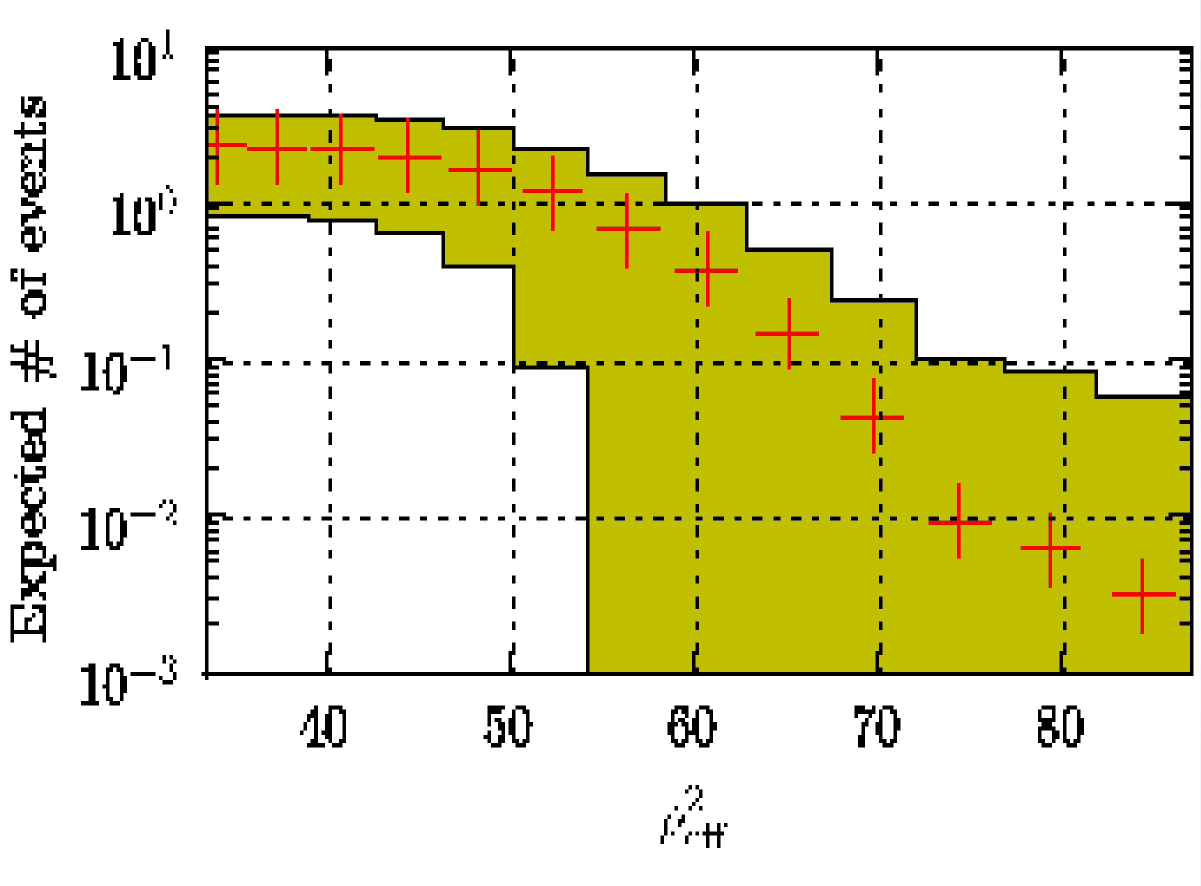
- Bound the GW energy emitted by a source M31

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**

upper limit:

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

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

Inspiral search results

- uniform priors were used on m_1, t_0, ϕ_0

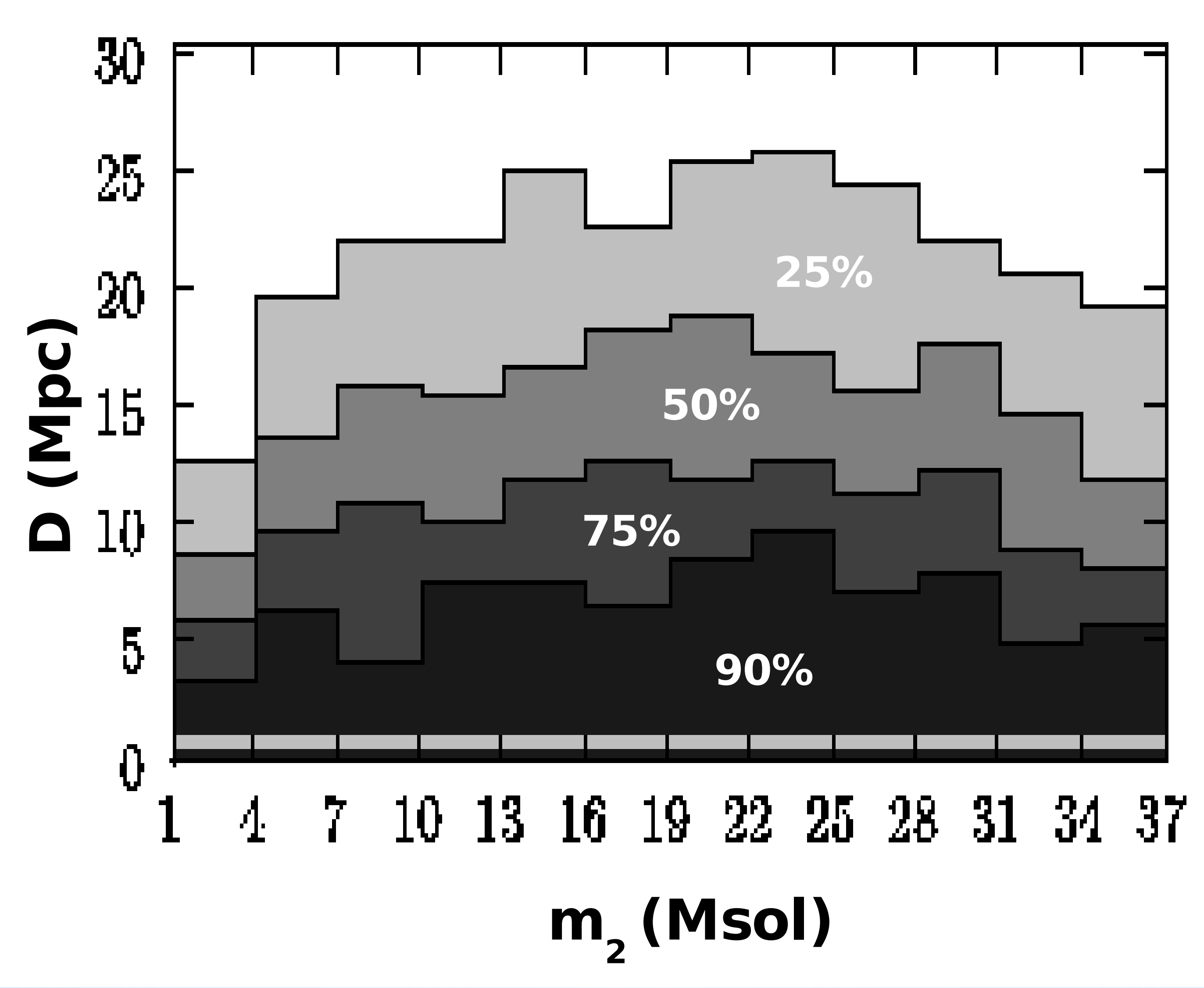
- priors on $\iota, \vec{s}_1, \vec{s}_2$:

  - $0 \leqslant \frac{a}{M} \leqslant 0.75$ 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

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

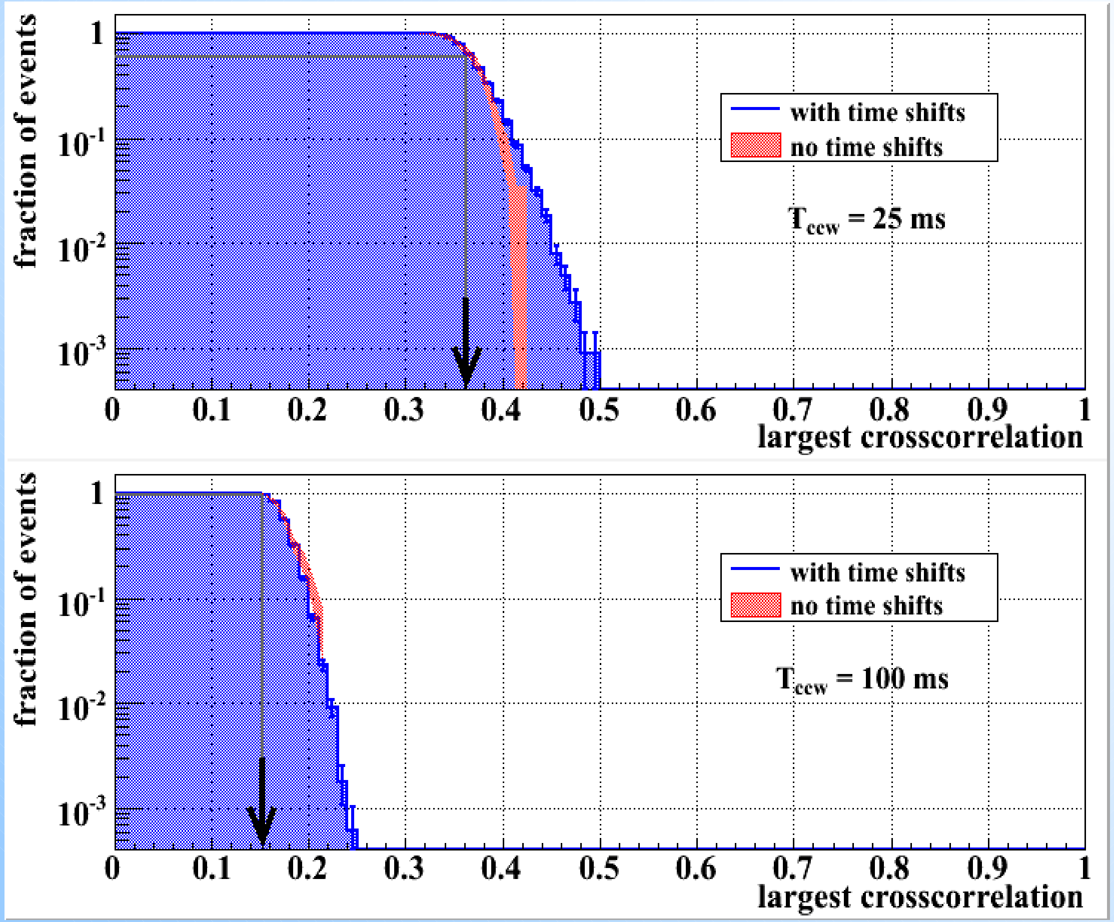
S: spin angular momentum.

Inspiral search results: exclusion regions



Burst search results

- cross-correlation (cc) of data streams, within 180s of GRB time
- cc windows: 25ms and 100ms
- largest cc: 0.36 (25ms) and 0.15 (100ms)
- false alarm probability of on-source largest crosscorrelation is estimated using these distributions:

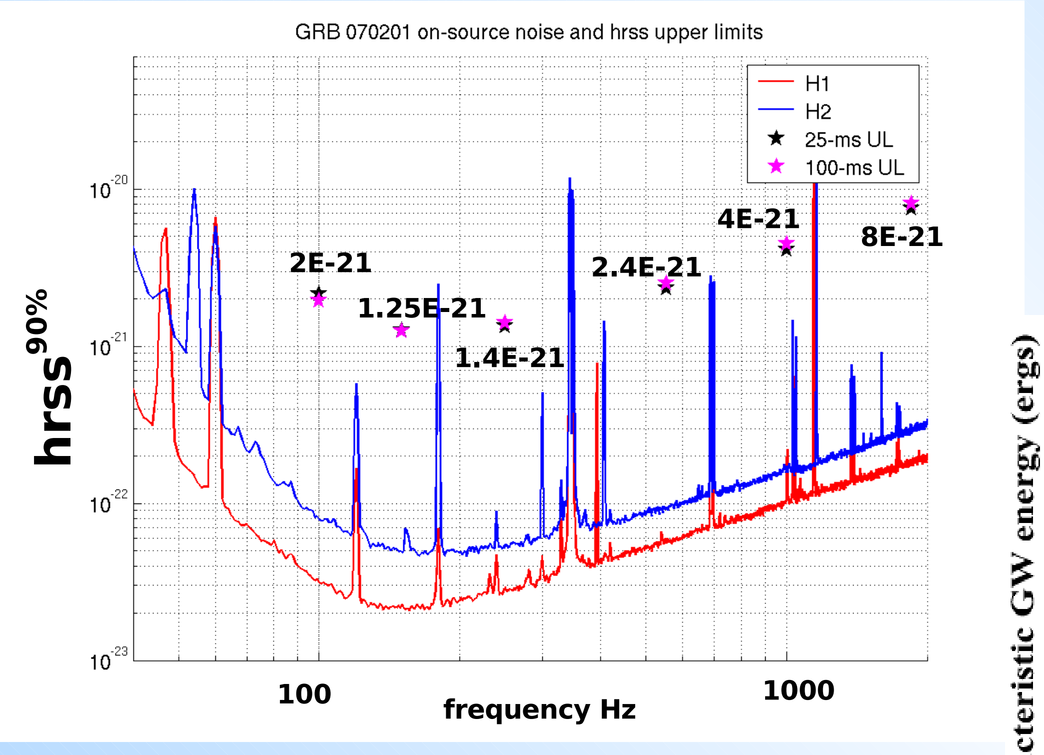


p = 0.58 for 25-ms cc
p = 0.96 for 100-ms cc

➔consistent with null hypothesis

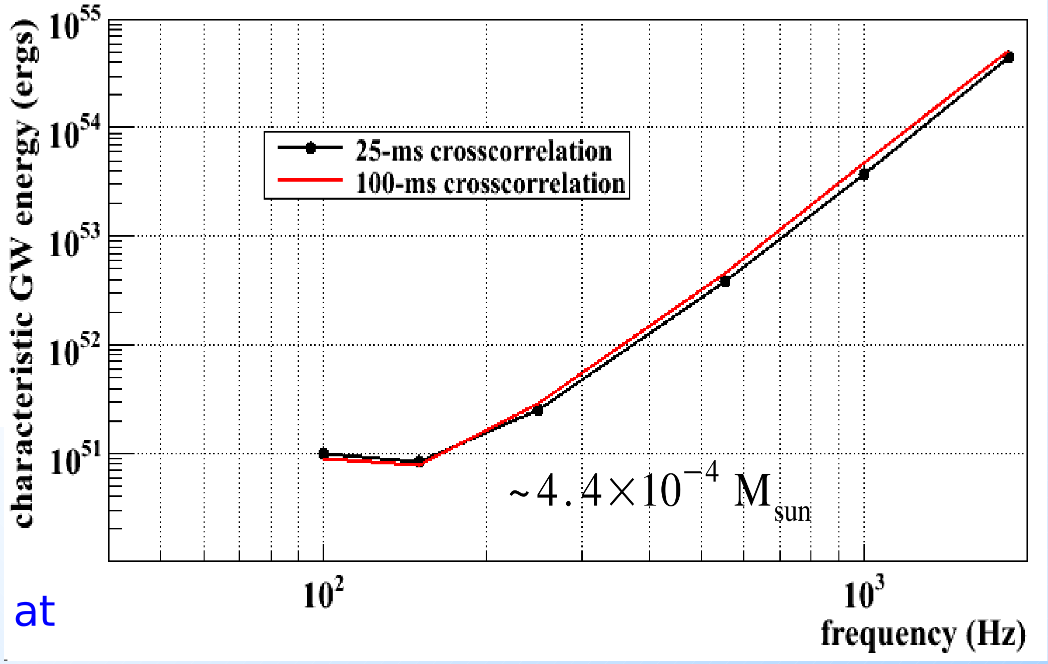
90% confidence upper limits on hrss

Q = 8.9, circularly polarized sine-gaussians



Corresponding GW energy, assuming isotropic emission, with source at D = 770 kpc:

$$E_{GW} \approx \frac{\pi^2 c^3}{G} D^2 f_0^2 h_{rss}^2$$



- measured gamma-ray fluence = 1.6 x 10^{-5} ergs/cm^2 (Konus-Wind)
- corresponding energy release in gamma-rays at M31,

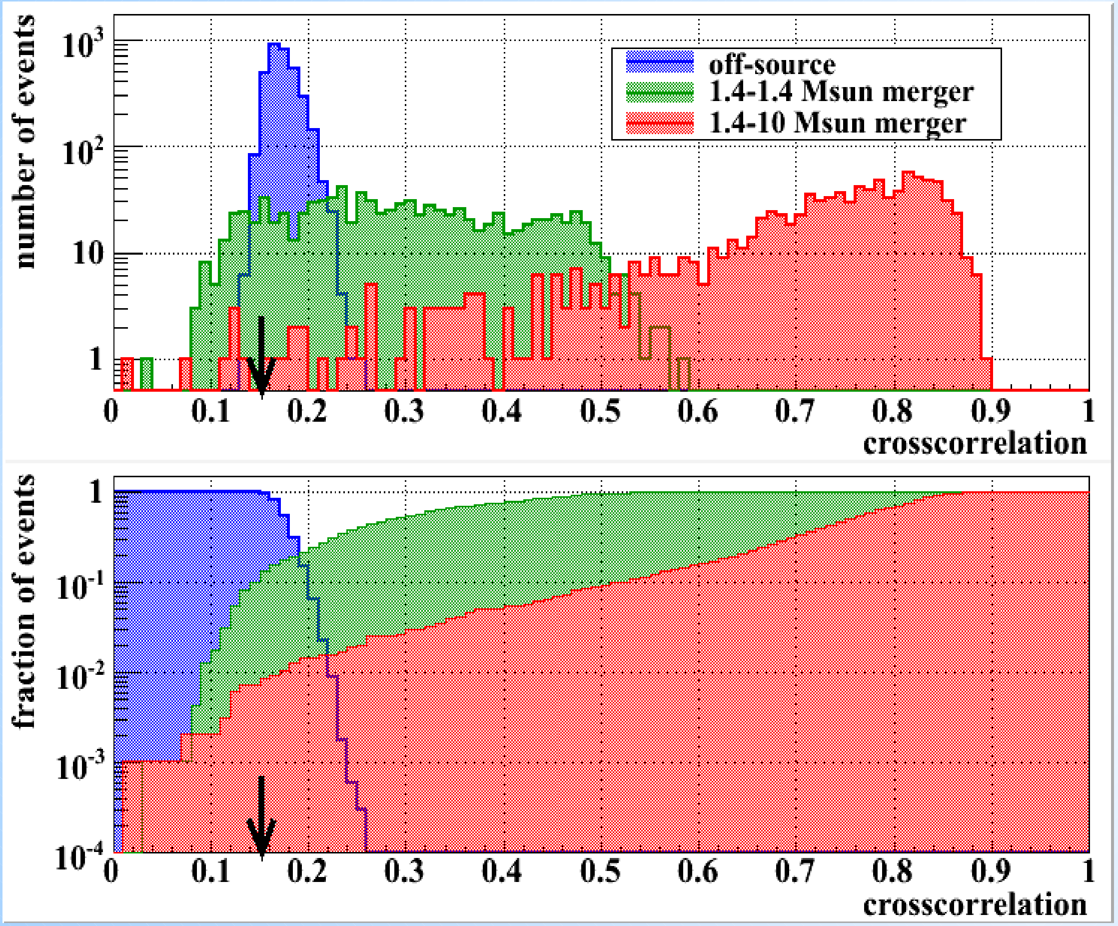
$$E_{\gamma,\mathrm{iso}} = \varphi \times 4\pi D^2 \approx 10^{45} \text{ ergs}$$

➔ orders of magnitude smaller than LIGO limit on energy release in GW for GRB 070201

- SGR models predict energy release in GW to be no more than ~10^{46} ergs

LIGO limits on GW energy release from GRB 070201 do not exclude SGR models in M31

sensitivity of the burst search to inspirals



- injected into on-source segment simulated NS-NS inspirals (1.4-1.4 Msun), and NS-BH inspirals (1.4-10 Msun)
- inclination angles of binary plane were isotropically distributed
- simulations did not include merger phase of coalescence
- measured fraction of events which had crosscorrelations larger than the on-source largest crosscorrelation
- **at 90% confidence,**

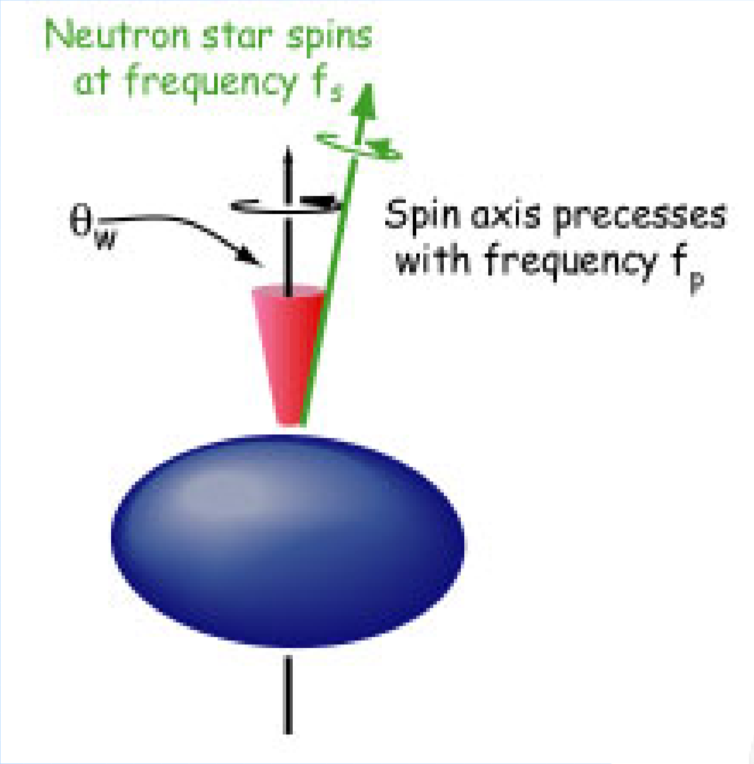
efficiency > 0.878, 1.4-1.4 Msun
efficiency > 0.989, 1.4-10 Msun

These results give an independent way to reject hypothesis of a compact binary progenitor in M31

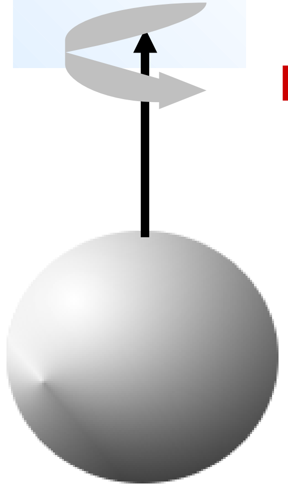
Continuous GW signals

Continuous GW signals

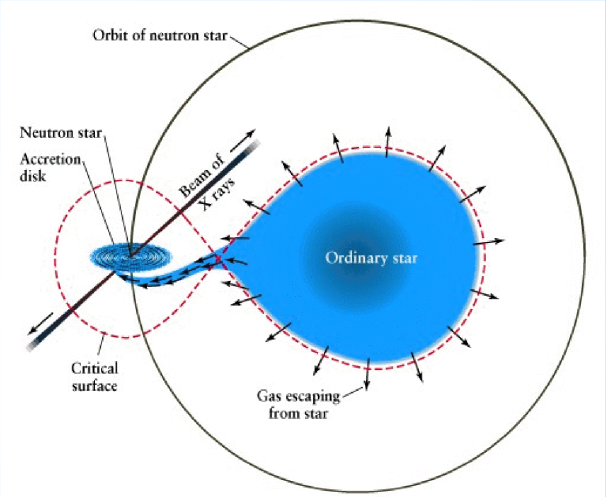
– Pulsars (spinning neutron stars) are known to exist!
– Emit gravitational waves if they are non-axisymmetric:



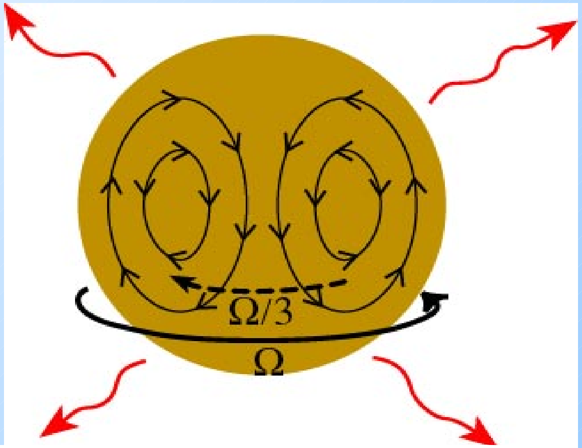
Wobbling Neutron Star



Bumpy Neutron Star

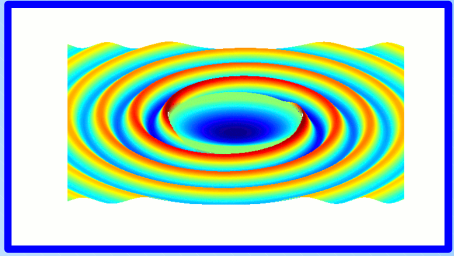


Low Mass X-Ray Binaries



Young Neutron Stars

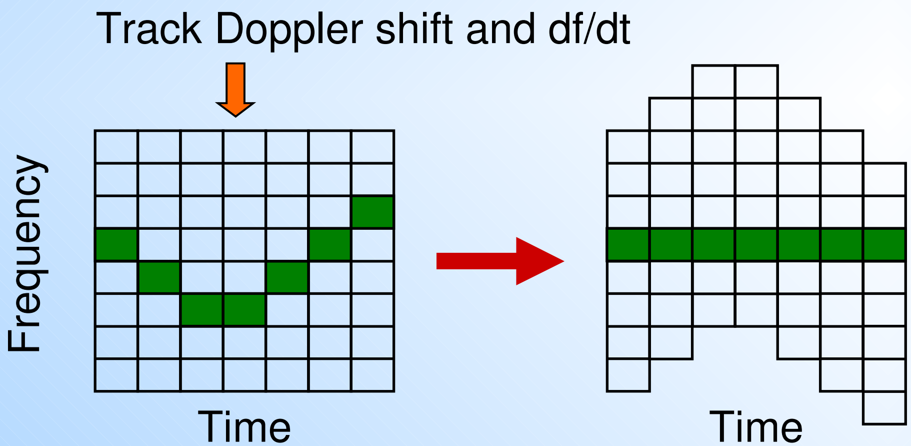
Searches



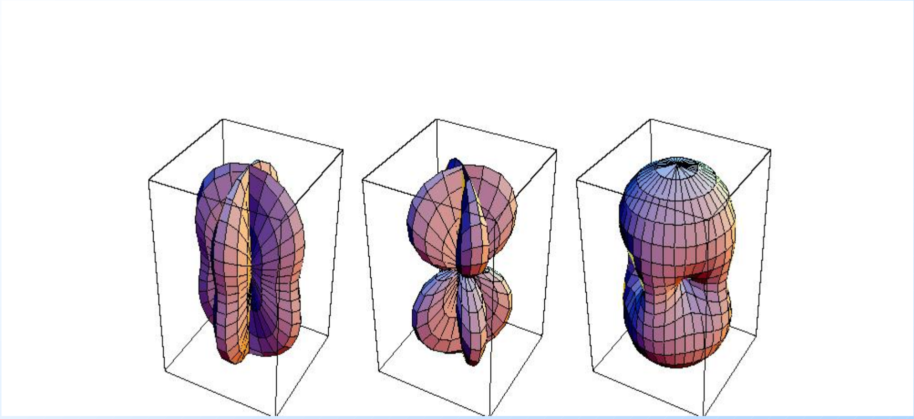
1. **Known pulsars (radio & x-ray) (e.g., Crab pulsar)**
   - Position & frequency evolution known (including derivatives, timing noise, glitches, orbit).
2. **Unknown neutron stars**
   - Nothing known, search over sky position, frequency & its derivatives.
3. **Accreting neutron stars & LMXBs (e.g., 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.

Methods

- Semicoherent Methods
  - StackSlide: add the power
  - Hough: add weighted 1 or 0
  - PowerFlux: add weighted power

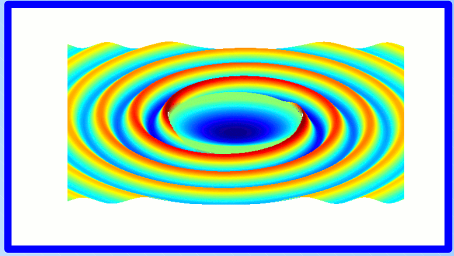


- Coherent Methods
  - Bayesian + Param. Estimation
  - Maximum Likelihood & Matched Filtering



- Weights depend on both noise and antenna patterns:
- Methods can include multi-detector data and coincidence steps.
- Hierarchical Methods: combine the above to maximize sensitivity.

Searches



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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.

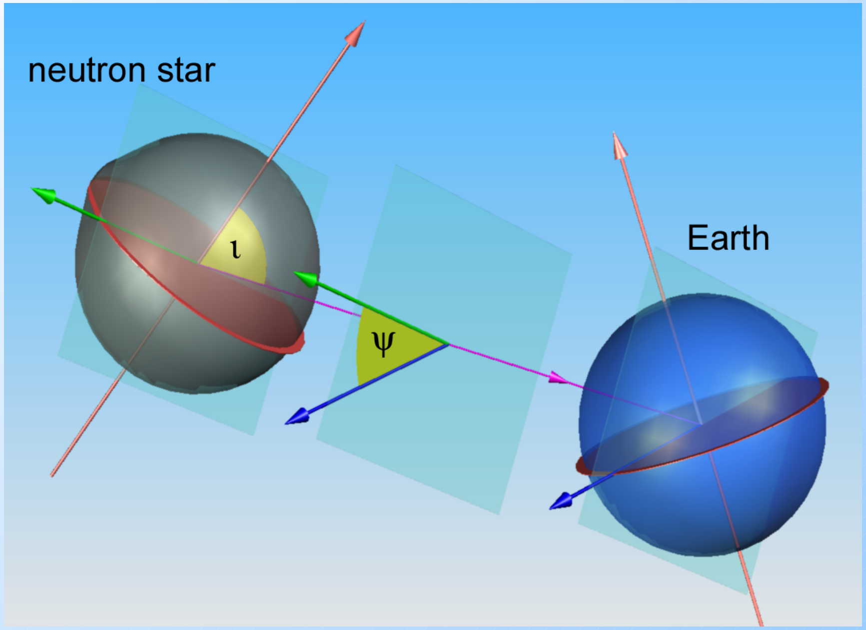
Signal model

- The GW signal can be modelled as

$$h(t) = \frac{1}{2}F_{+}(t;\psi)h_0(1+\cos^2\iota)\cos 2\Psi(t) + F_{\times}(t;\psi)h_0\cos\iota\sin 2\Psi(t)$$

- The unknown parameters are
  - h_0 - amplitude of the gravitational wave signal
  - ψ - polarization angle of signal; embedded in $F_{x,+}$
  - ι - inclination angle of the pulsar
  - ϕ_0 - initial phase of pulsar $\Phi(0)$

- In the targeted searches we currently only look for signals at twice the rotation frequency of the pulsars
- For blind searches the location in the sky and the source's frequency evolution are unknown.



Known pulsars

• A **Bayesian** approach: the **joint posterior distribution of the probability of our unknown parameters**, using priors on $h_0, \cos\iota$, ψ and φ_0 **is computed:**

$$p\left(a\middle|\left\{B_k\right\}\right) \propto p\left(a\right) \cdot p\left(\left\{B_k\right\}\middle|a\right)$$

posterior

prior

likelihood

Known pulsars

• The *likelihood* that the data are consistent with a given set of model parameters, is proportional to exp($-\chi^2/2$), where

$$\chi^2(a) = \sum_k \left| \frac{B_k - y(t_k; a)}{\sigma_k} \right|^2$$

• B_k are the heterodyned, downsampled and Doppler-corrected. The $y(t_k)$ is the signal. The sum is only over valid data, so dropouts and gaps are dealt with simply.

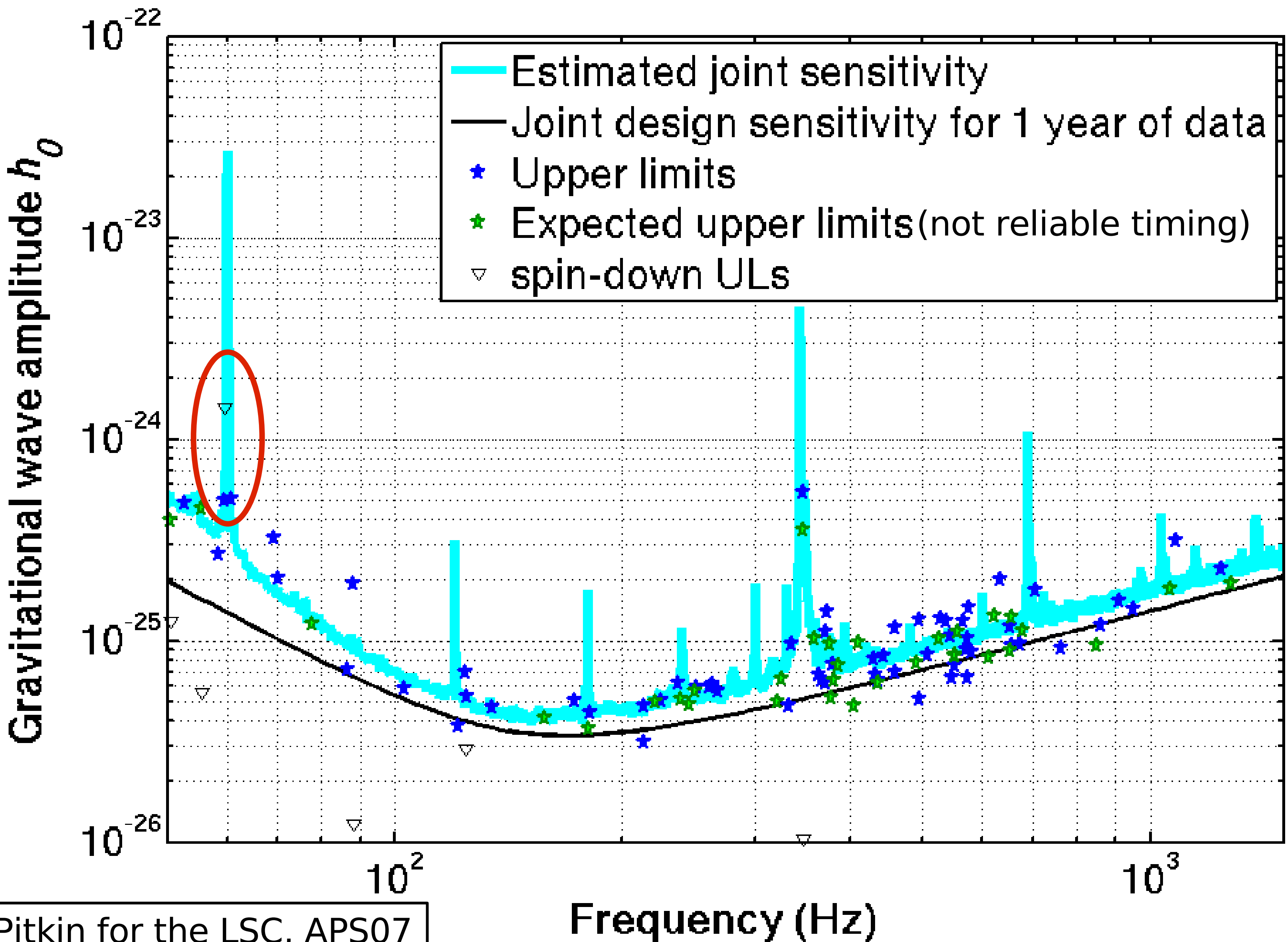
• Finally we marginalize over the unknown parameters to leave the posterior distribution for the probability of h_0:

$$p(h_0 | \{B_k\}) \propto \iiint e^{-\chi^2/2} d\varphi_0 \, d\psi \, d\cos\iota$$

• The 95% confidence upper limit:

$$0.95 = \int_0^{h_{95}} p(h_0 | \{B_k\}) \, dh_0$$

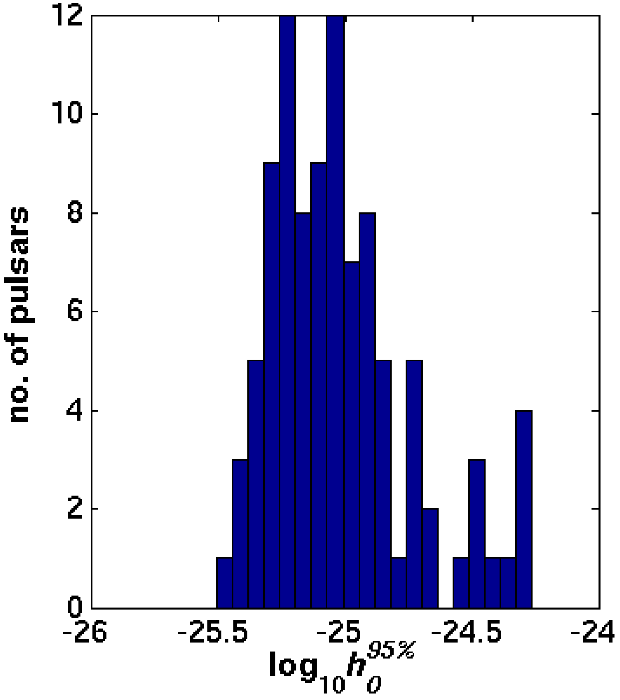
Known pulsars, preliminary S5



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} = 3.4x10^{-26}

Pitkin for the LSC, APS07

Known pulsars, preliminary S5

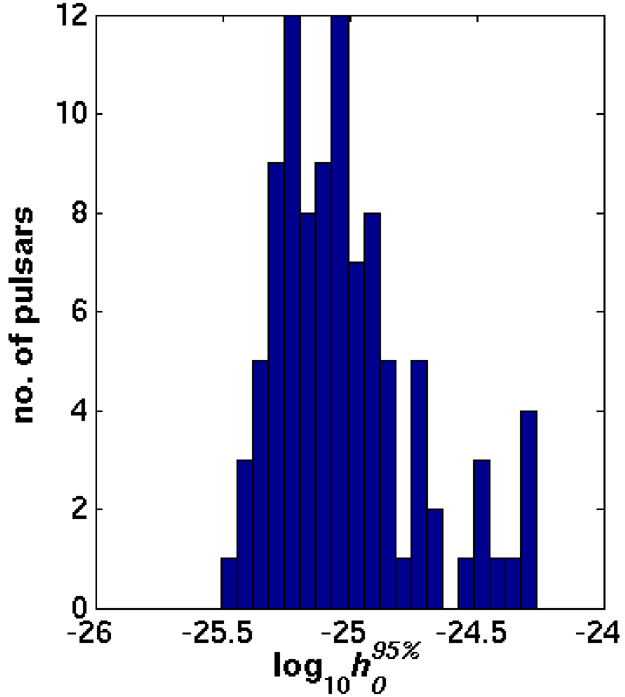
$$h_0 = \frac{16\pi^2 G}{c^4} \frac{\epsilon I f^2}{d}$$

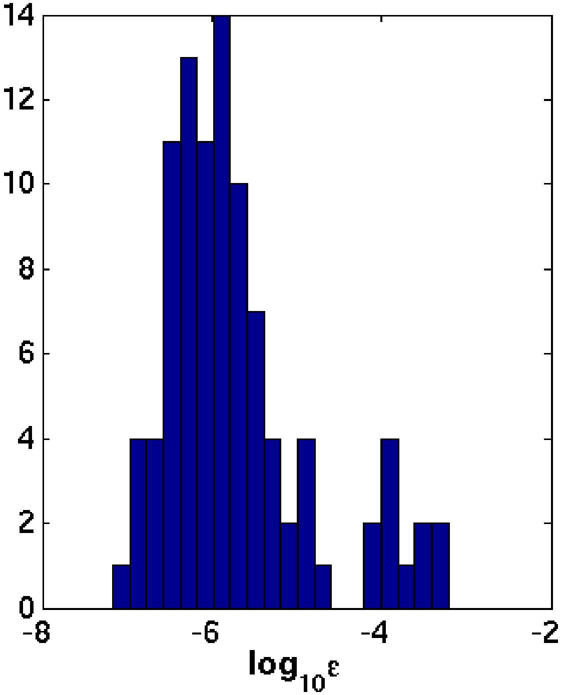
known

fiducial value

Lowest ellipticity upper limit:

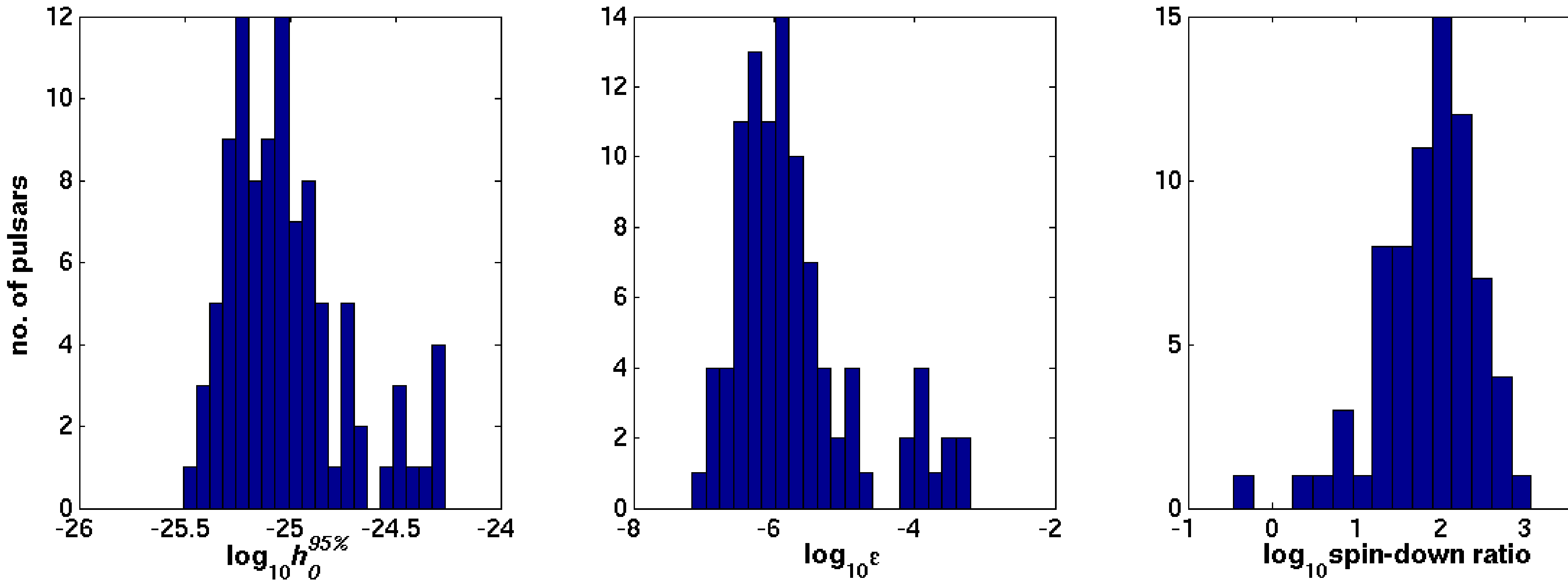
PSR J2124-3358 (ν_{gw} = 405.6Hz, r = 0.25 kpc) $\varepsilon = 7.3\mathrm{x}10^{-8}$





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

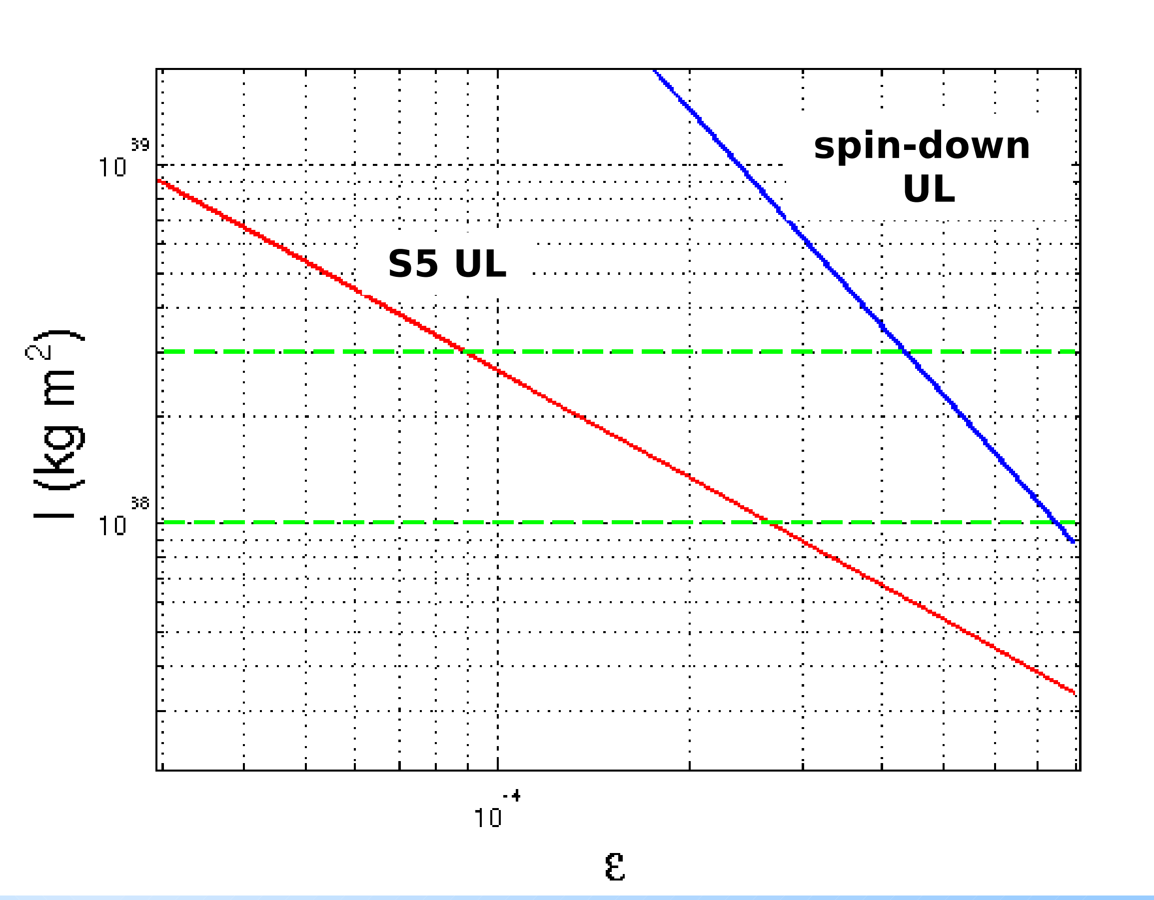
$h_{0\ spin\text{-}down}$ = 1.4x10^{-24}
$h_{0\ S5\ first\ year}$ = 5 x10^{-25}

at fiducial I = 10^{38}kgm^2

$-\ \varepsilon_{spin\text{-}down}$ = 7.3x10^{-4}
$-\ \varepsilon_{S5\ first\ year}$ = 2.6 x10^{-4}
less than 13% power is carried away by GWs

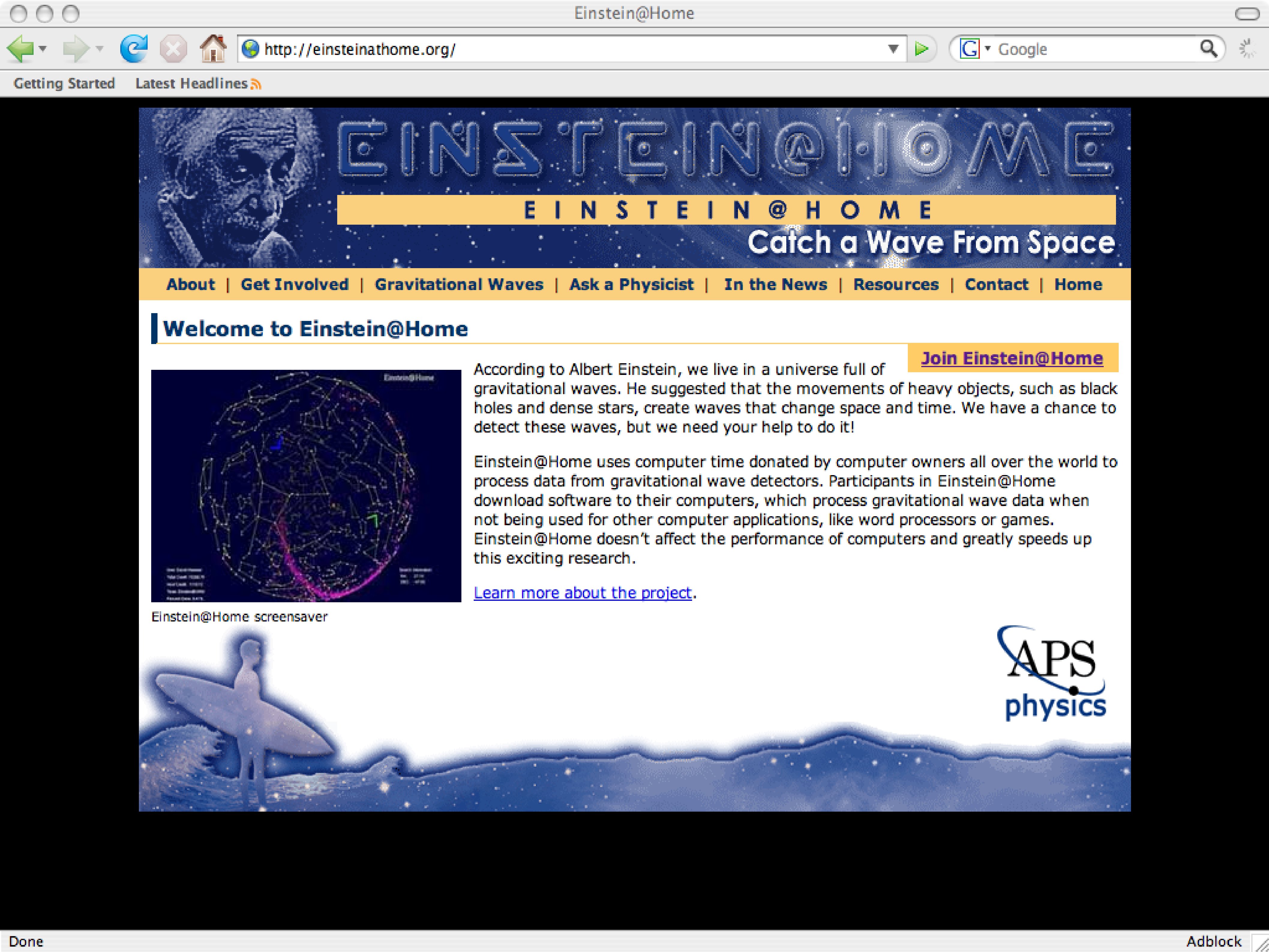
But I could be higher than the fiducial value. No definitive observational evidence but a number of theoretical investigations* suggest:
I = 1-3 x 10^{38} (kg m^2)

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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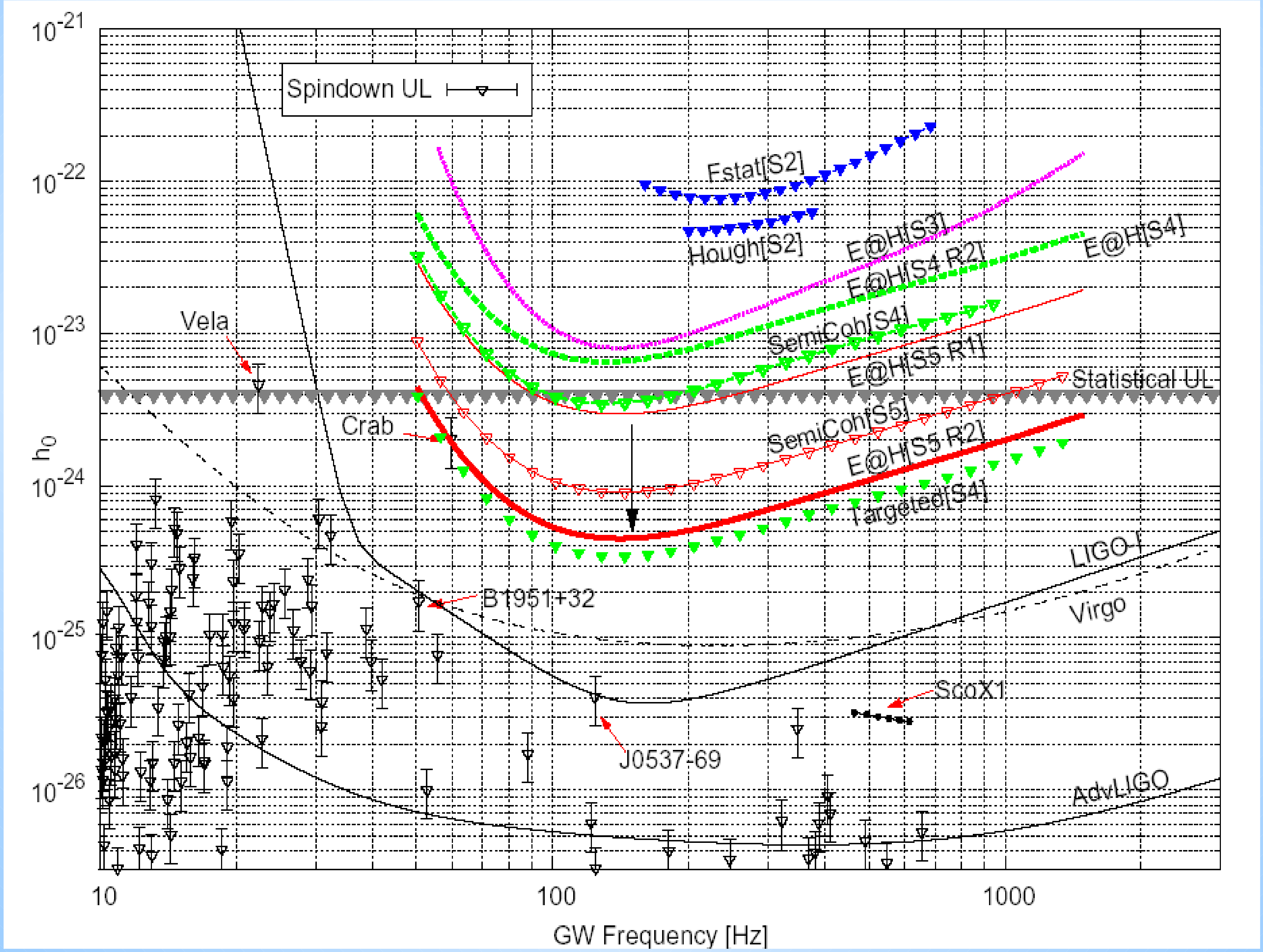
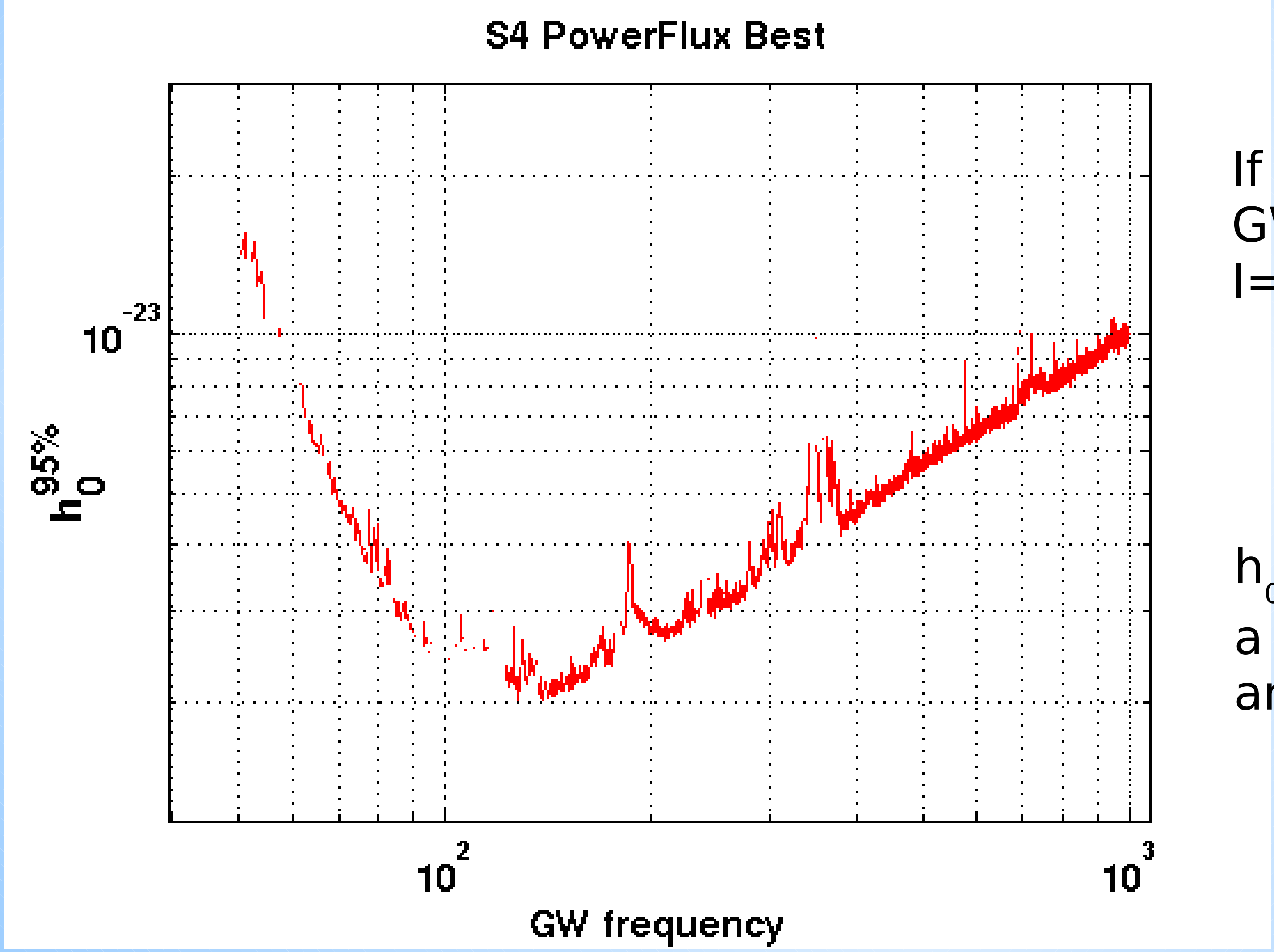
Some results on wide-parameter space searches

Some results on wide-parameter space 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 $I = 1e38 kgm^2$):

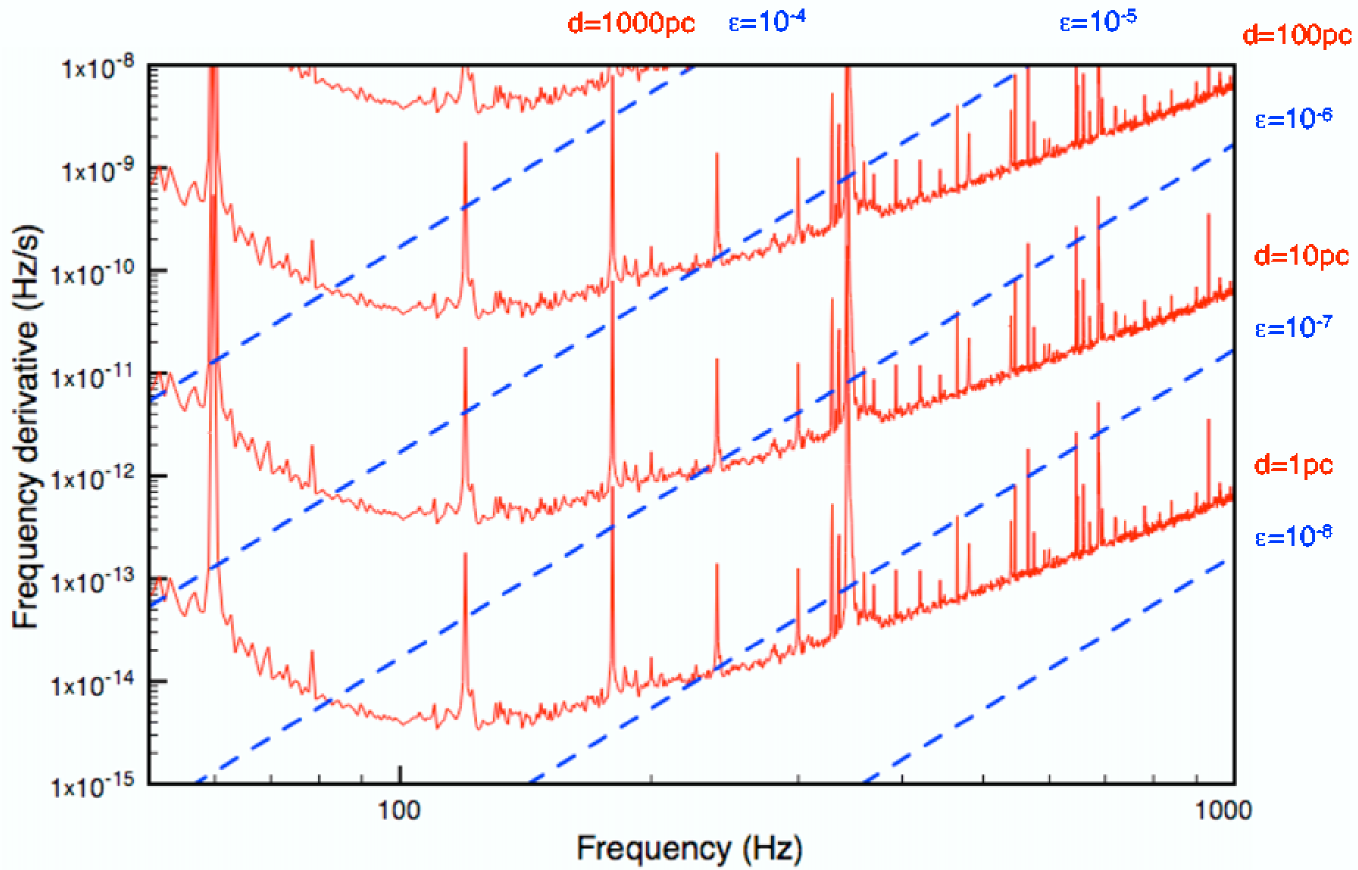
$$\varepsilon^2 = 7.6 \times 10^5 \frac{\dot{f}}{f^5}$$

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

Expressing the reach of search from UL values.

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

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



….so what to take away from all this?

- GW data analysis is still a relatively young endevour
- plenty of areas where more work is needed
  - data analysis
    - mature pipelines
    - beyond detection to parameter estimation
    - truly integrated network analysis
  - at the interface with astronomy
    - to better target our searches
    - to better interpret our results
  - at the interface with relativity
    - to construct accurate waveforms
    - or to extract from numerical simulations relevant features
  - at the interface large scale computing
    - to farm out computationally-intensive searches
    - to produce significant online-triggers
    - to handle the data set across different institutions
    - maintain and control a large and distributed software-base

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