Panning for Gravitational Gold: Status and Prospects for the Search of Gravitational Wave Events in the LIGO Data Stream

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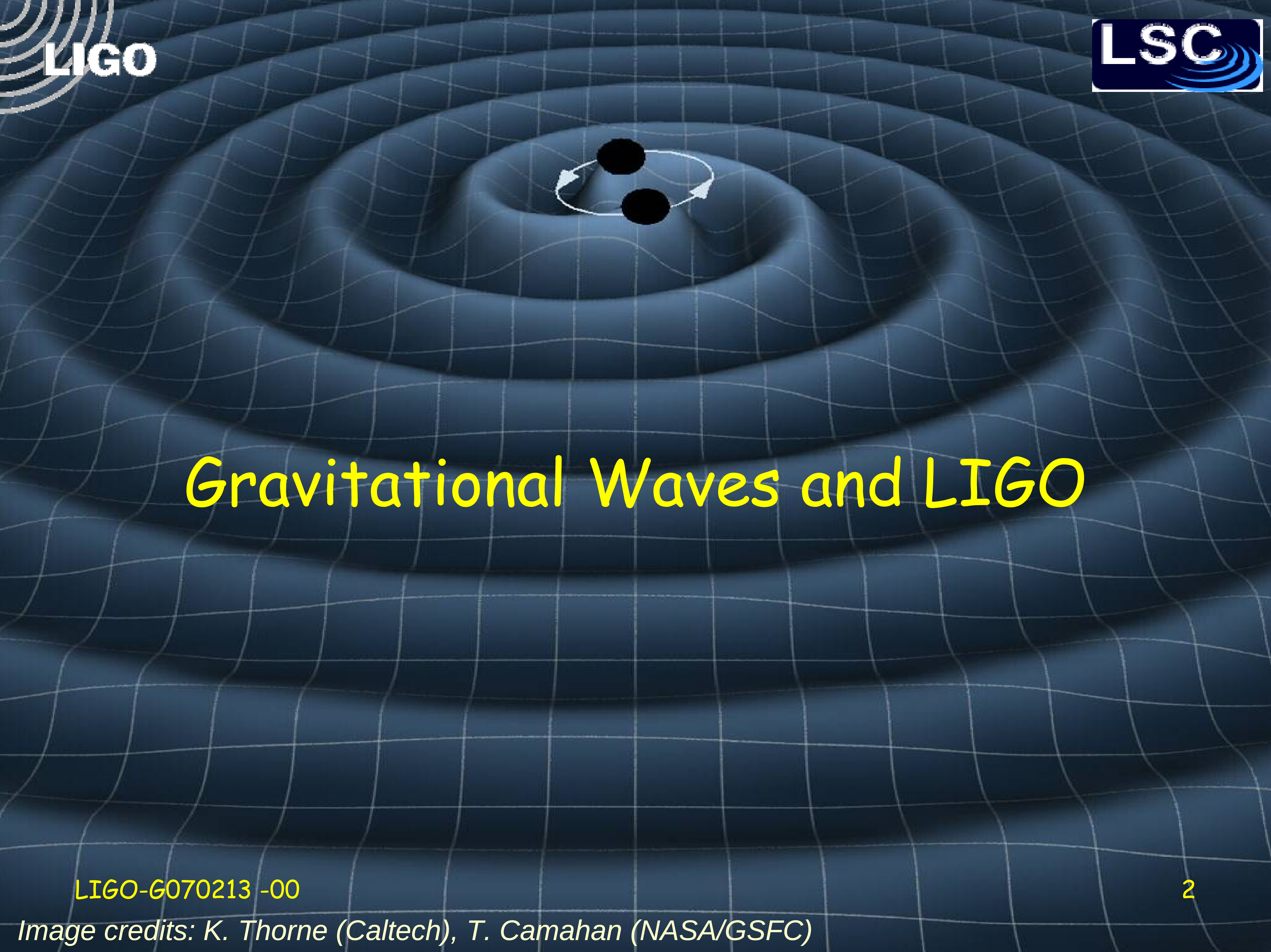
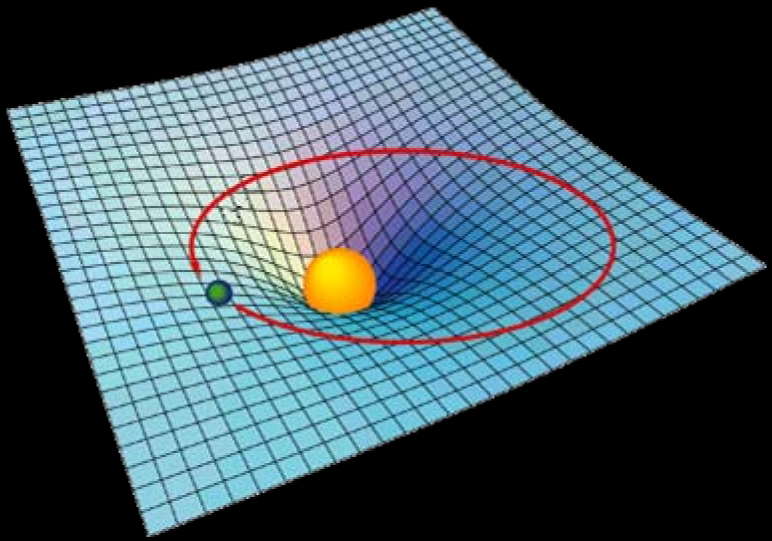


Gravitational Waves and LIGO

Image credits: K. Thorne (Caltech), T. Camahan (NASA/GSFC)

Einstein's Vision: General Relativity (1916)



Gravity is not a force,
but a property of space-time

"Mass tells space-time how to curve,
and space-time tells mass how to move."
John Archibald Wheeler

Einstein's Equations:

When matter moves, or changes its configuration, its gravitational field changes. This change propagates outward as a *ripple in the curvature of space-time*: a gravitational wave.

GWs are Hard to Find: Space-Time is Stiff!

Einstein's equations are similar to equations of elasticity: T = ($c^4/8\pi G$) h

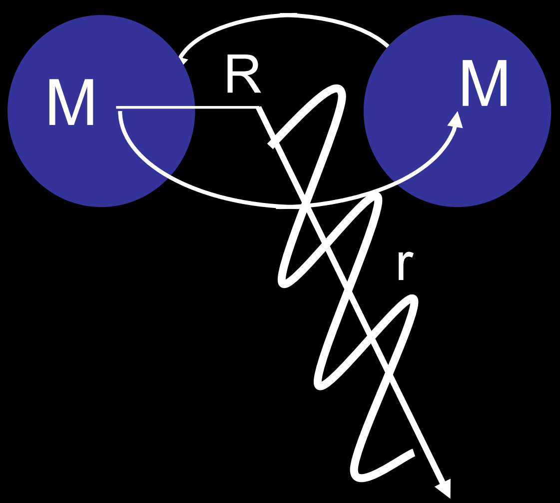
$c^4/8\pi G \sim 10^{42}$N is the space-time "stiffness" (energy density/unit curvature)

The wave can carry huge energy with miniscule amplitude: $h \sim (G/c^4)(E/r)$

For colliding $1.4M_\odot$ neutron stars in the Virgo Cluster:

$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \Rightarrow h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$

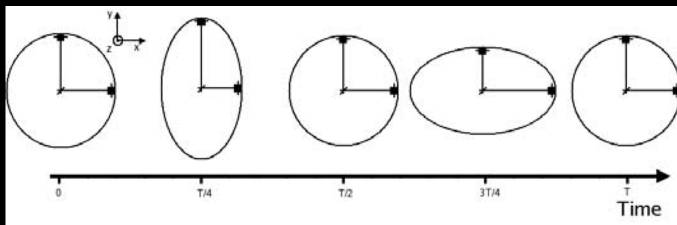
I =quadrupole mass distribution of source



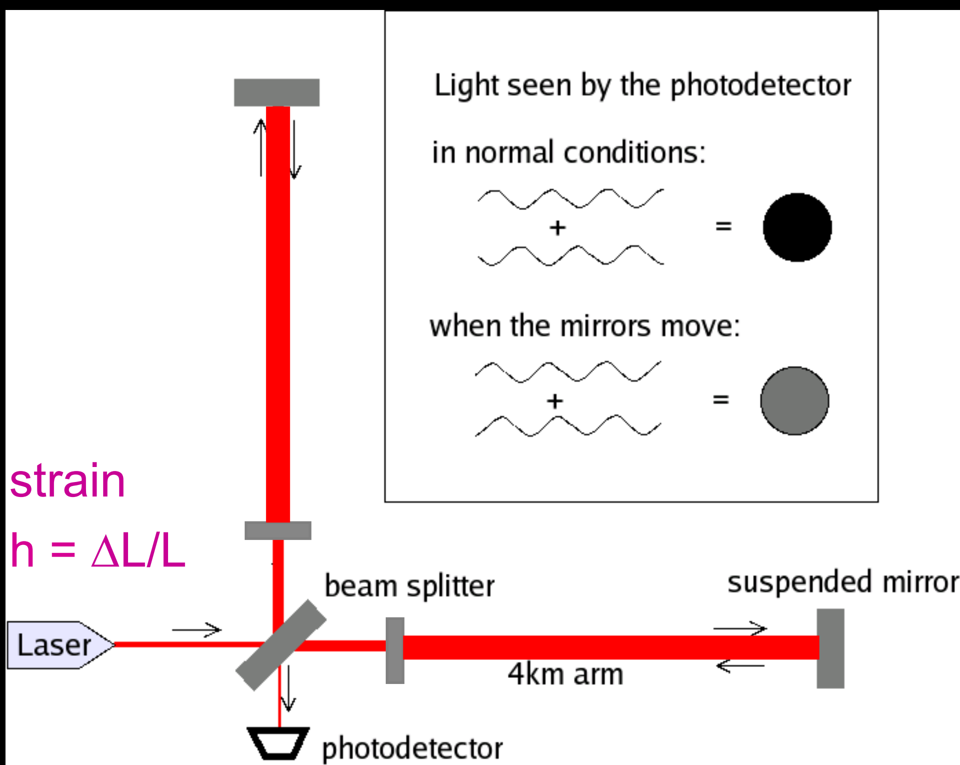
$M \approx 10^{30}$ kg
$R \approx 20$ km
$F \approx 400$ Hz
$r \approx 10^{23}$ m

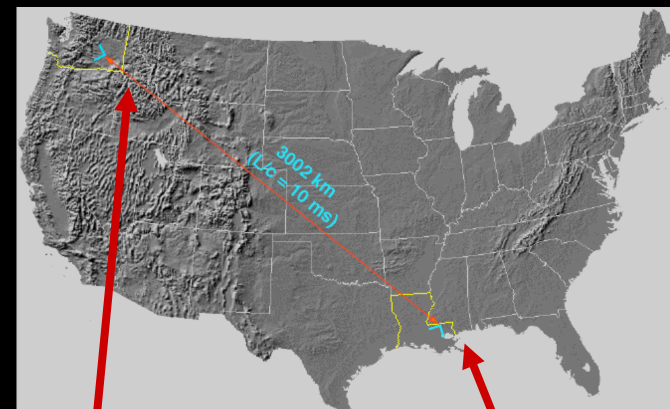
$h \sim 10^{-21}$

The LIGO Observatory



Initial goal: measure difference in length to one part in 10^{21}, or 10^{-18} m

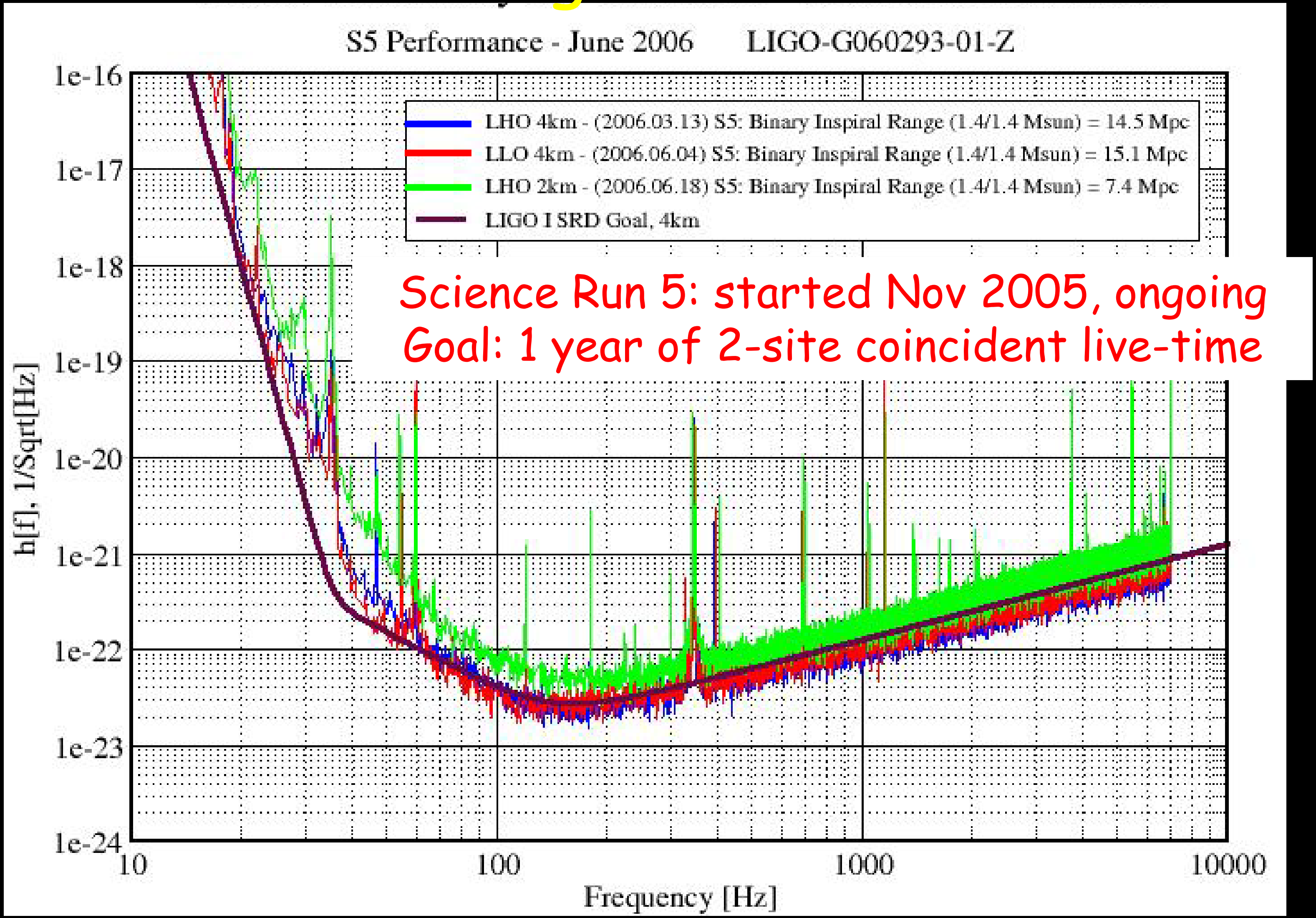




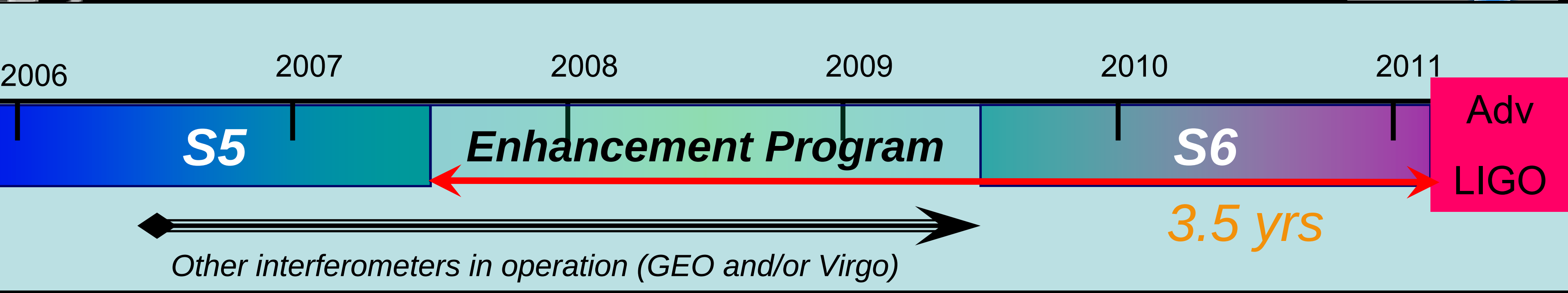
Hanford Observatory
4 km and 2 km interferometers
H1 and H2

Livingston Observatory
4 km interferometer
L1

LIGO Conquers its Experimental Challenges in S5



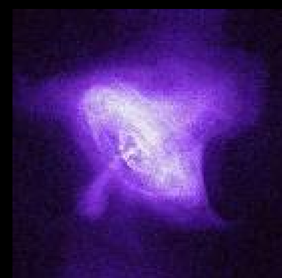
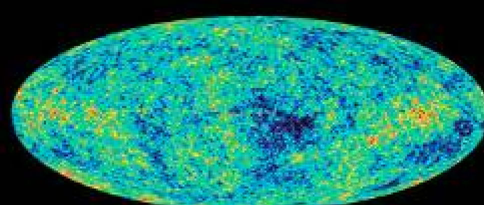
The Path Ahead



- The first science run of LIGO *at design sensitivity* is in progress
  - Hundreds of galaxies now in range for 1.4 $M_{\odot}$ neutron star binary coalescences
- Enhancement program
  - In 2009 ~8 times more galaxies in range
- Advanced LIGO
  - Construction start expected in FY08
  - 1000 times more galaxies in range
  - Expect ~1 signal/day - 1/week in ~2014

The science from the first 3 hours of Advanced LIGO should be comparable to 1 year of initial LIGO

Sources And Methods

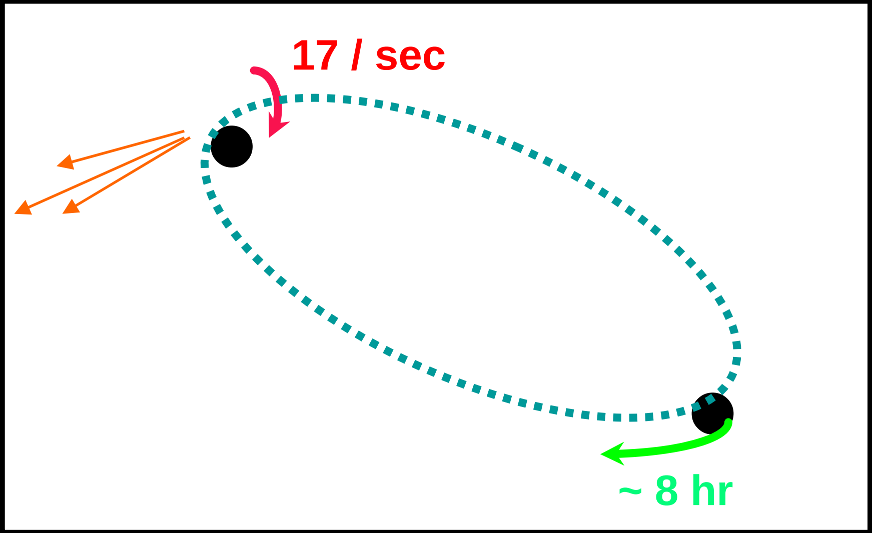
	Long duration	Short duration
Matched filter	 Pulsars	 Compact Binary Inspirals
Template-less methods	 Stochastic Background	 Bursts

Searching with some knowledge of what to look for

Image Courtesy: Library of Congress

Binary Systems

We know gravitational waves emitted from ***compact binary systems*** exist:



PSR1913+16 Hulse-Taylor

Neutron Star Binary System

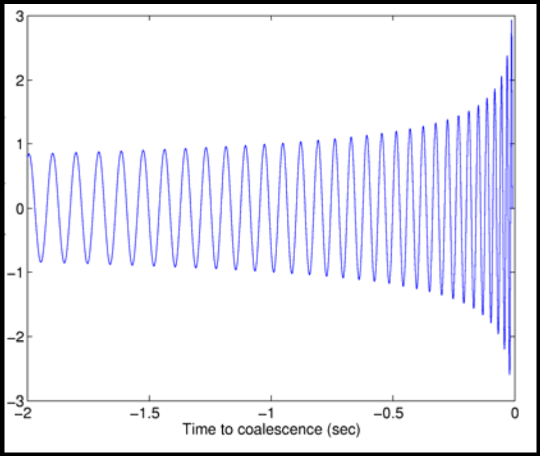
- separated by 10^6 miles
- $m_1 = 1.4M_\odot$ $m_2 = 1.36M_\odot$

Exact match to general relativity

- spiral in by 3 mm/orbit
- shortening of orbital period

- Gravitational waves carry away energy and angular momentum. Orbit will continue to decay
- In ~300 million years, the "inspiral" will accelerate, and the neutron stars coalesce
- Gravitational wave emission will be strongest near the end

h(t)

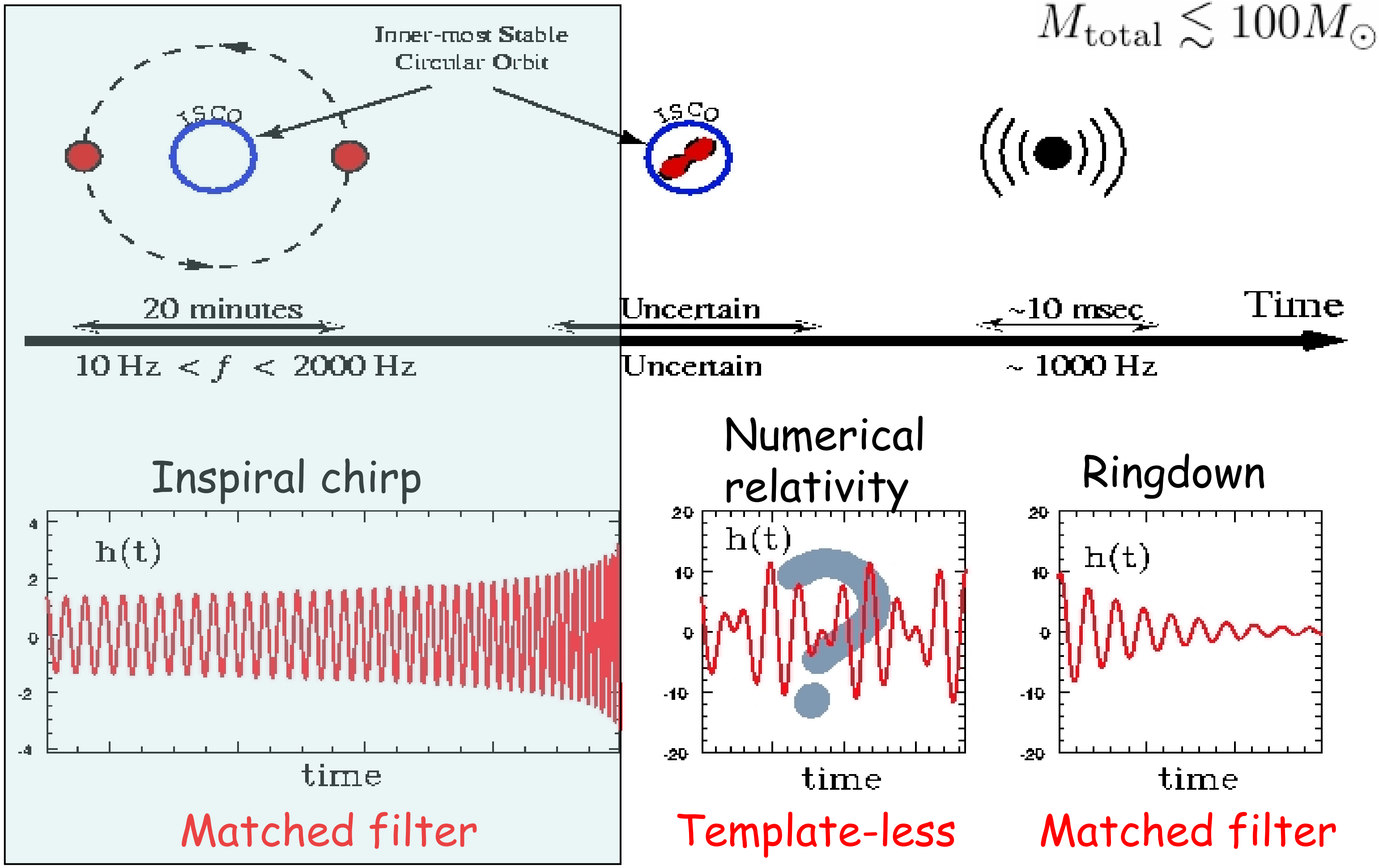


LIGO

Evolution of Binary System

LIGO is sensitive to inspirals containing neutron stars and black holes

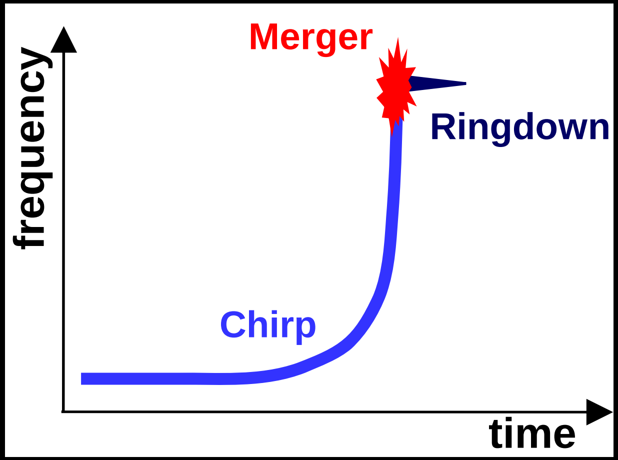
$M_{\rm total} \lesssim 100 M_\odot$



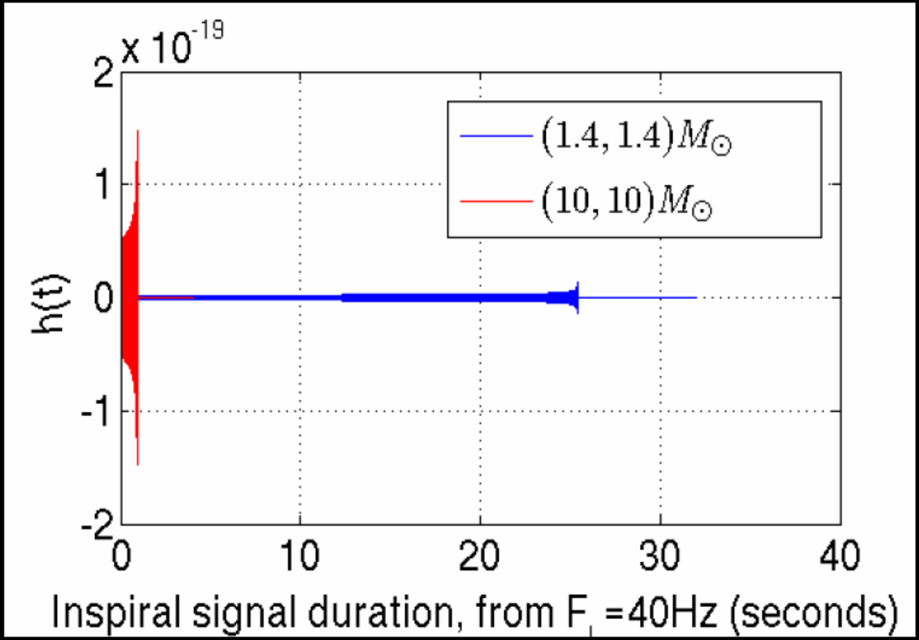
Inspiral Chirp

$$h(t) = \frac{1Mpc}{D_{\rm eff}} \left[h_c(t) \cos\Phi + h_s(t) \sin\Phi\right]$$

2 polarizations



- Amplitude and duration only depend on the masses m_1 and m_2 and the lower cutoff frequency.
- Neglect spin for now
- $D_{\rm eff}$ effective distance, depends on the physical distance r and on orientation of the binary system; $D_{\rm eff}>r$



Matched Filtering

FFT Data

Template, generated in frequency domain in stationary phase approximation

$$z(t) = 4 \int_0^\infty \frac{\tilde{s}(f)\ \tilde{h}^*(f)}{S_n(f)}\ e^{2\pi i f t}\ df$$

$$\tilde{h}_c^I(f) = -i\tilde{h}_s^I(f)$$

One-sided noise power spectral density

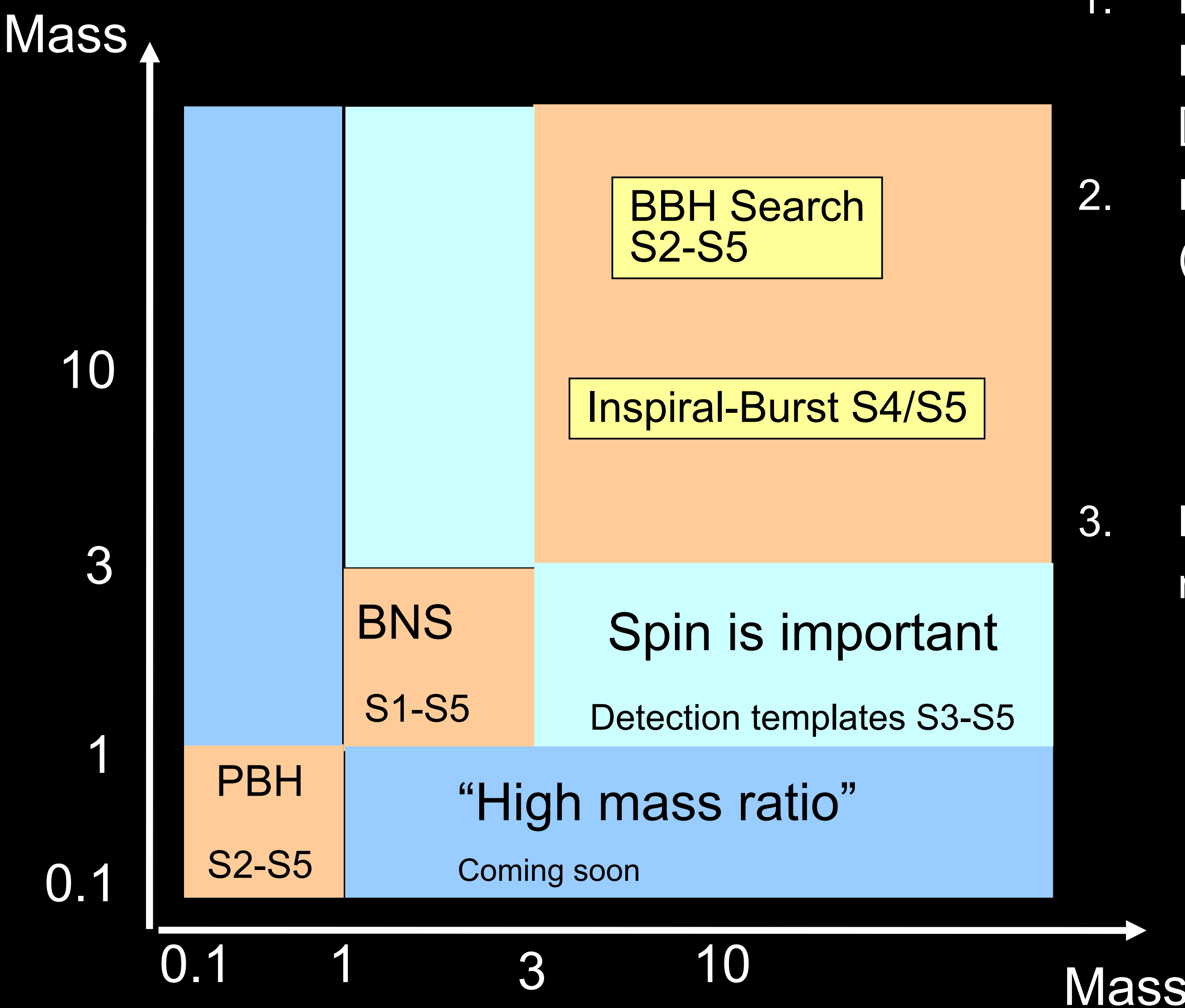
SNR: $$\rho(t) = \frac{|z(t)|}{\sigma}$$

$$\sigma^2 = \frac{1}{2}\langle |z(0)|^2 \rangle = 4 \int_0^\infty \frac{|\tilde{h}_c^I(f)|^2}{S_n(f)} df$$

To search for signals in a mass region of interest, we lay a grid of templates so that loss in SNR between signal in space and nearest template is no greater than ~ 3%

Look for maximum of $\rho(t)$ above threshold ➔ trigger

Binary Mass Plane



1. Primordial Black Hole Binaries (PBH): m_1, m_2 in [0.35-1] $M_\odot$
2. Neutron Star Binaries (BNS): m_1, m_2 in [1-3] $M_\odot$
   accurate waveforms from Post-Newtonian approximation
3. Black Hole Binaries (BBH): m_1, m_2 in [3-80] $M_\odot$

   waveforms not accurately known, phenomenological templates

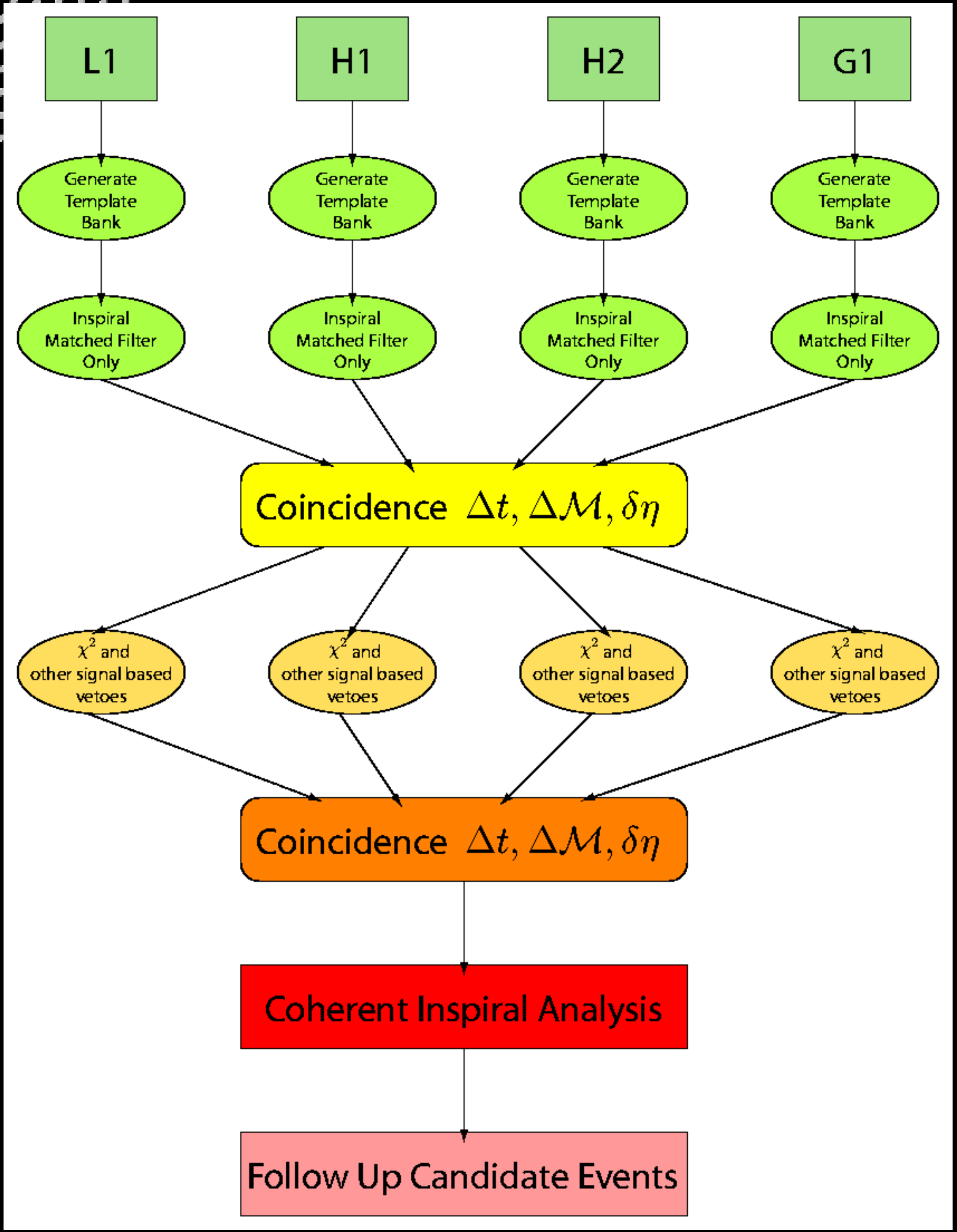
Expected Rate

- Neutron star binaries ~ 1/30y – 1/3y with Initial LIGO band, range
  - Mass distribution from population synthesis simulations
  - Spatial distribution following blue light luminosity?

  } Not certain

- Primordial binary black holes in the galactic halo <8/kyr
  - Can make a reasonable spatial model
  - Don't know mass distribution

- BH+BH and BH+NS binaries - predicted rate is highly uncertain, estimated mean rate ~1/y
  - Don't have a handle on mass and spatial distributions



Coincidence Analysis

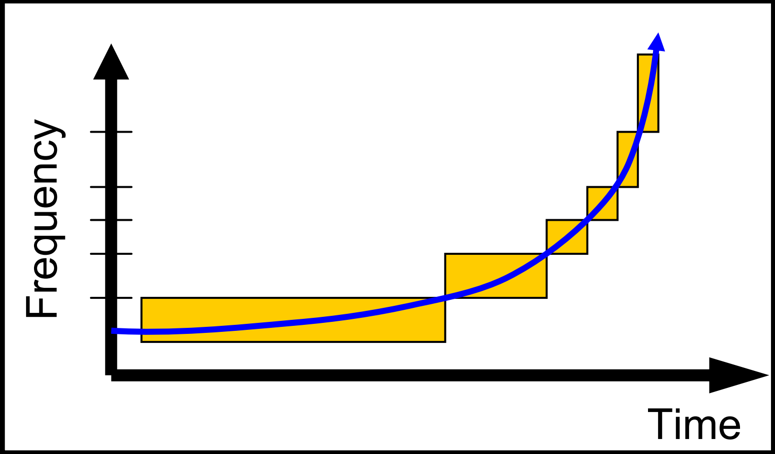
Single-detector SNR is not enough to establish confidence in an event.

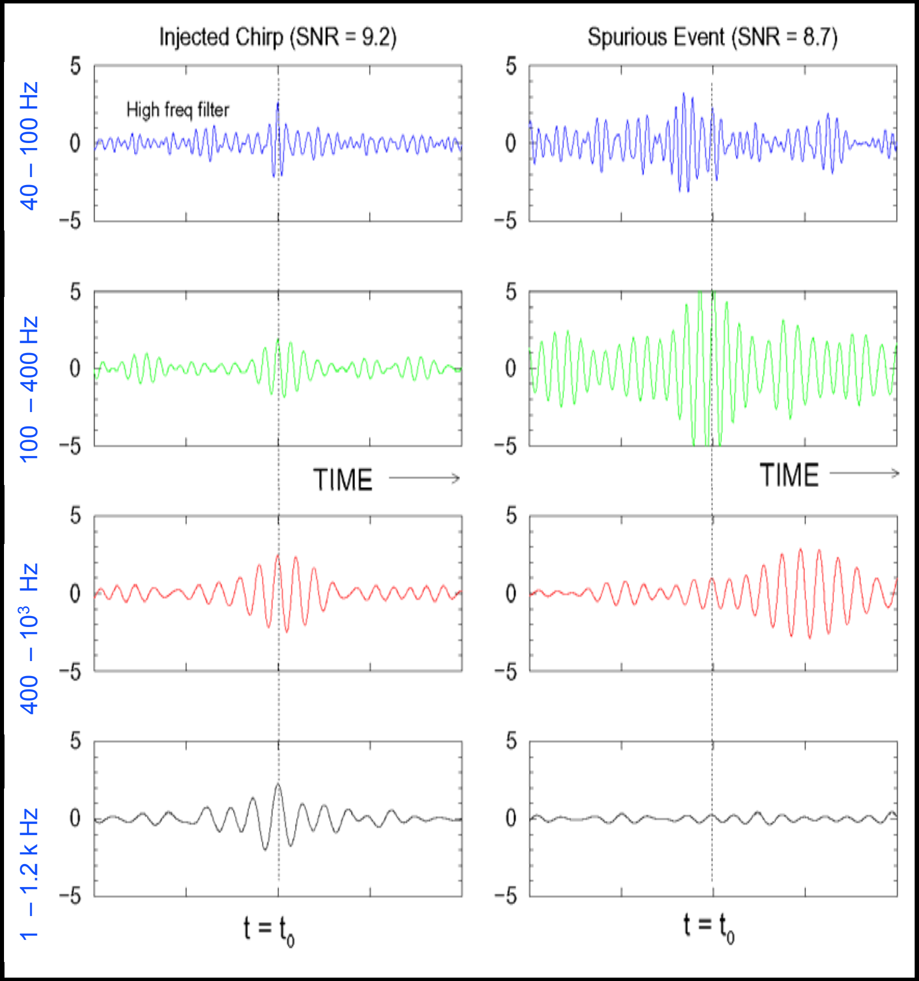
Require coincident detection in at least two detectors:

- Mass -- particularly chirp mass
- End time -- also used for estimation of sky location
- Distance -- only important for co-located Hanford instruments

Signal Based χ^2

To discriminate from noise events, divide template into p bands, compute $z_l(t)$ in each band. This is done only for the lower masses, NOT for BBH.





$$\chi^2(t) = p\sum_{l=1}^{p} \| z_l(t) - z(t)/p \|^2$$

$$\xi*^2 = \frac{\chi^2}{p(1+\delta^2\rho^2)}$$

Account for template mismatch δ=0.03

Discriminating Signal from Noise

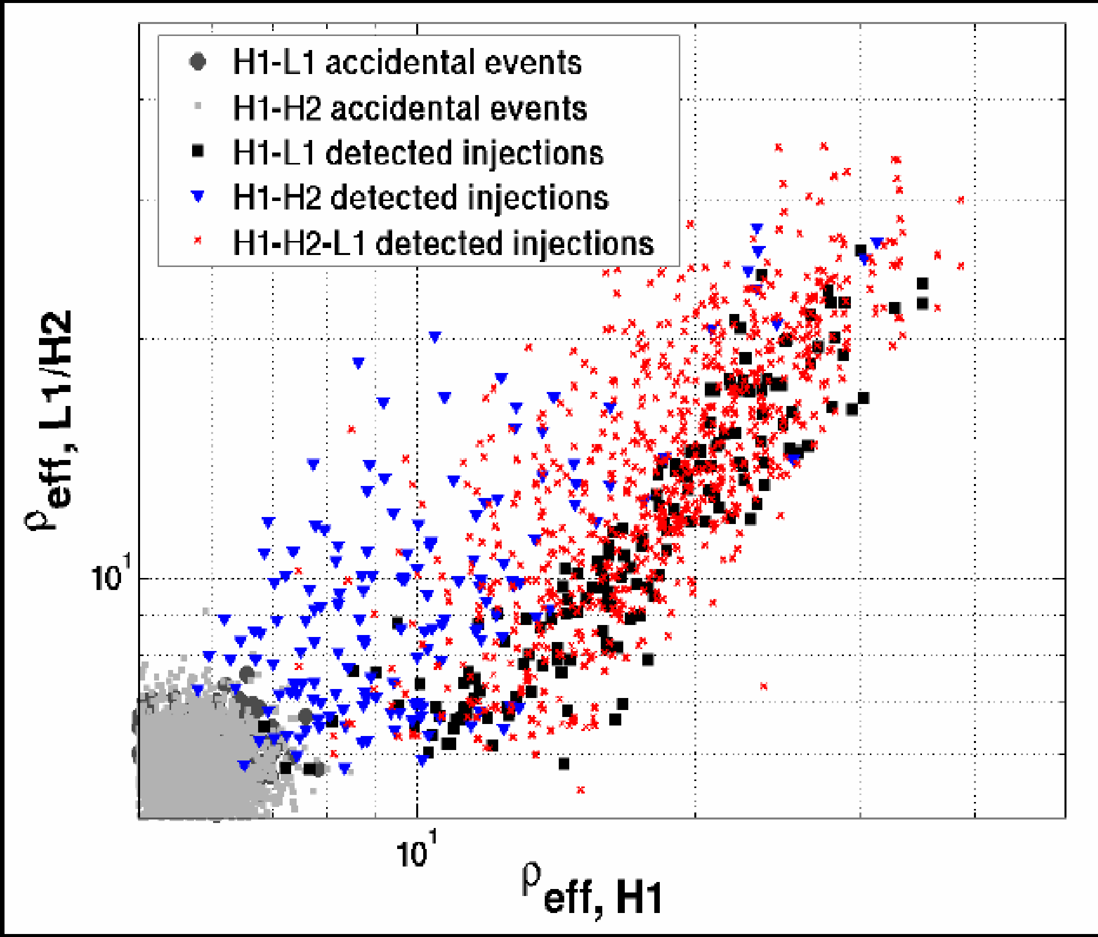
Simulated signal "injection" for efficiency estimate

100 time-slides for background estimate

For BNS and PBH: effective SNR

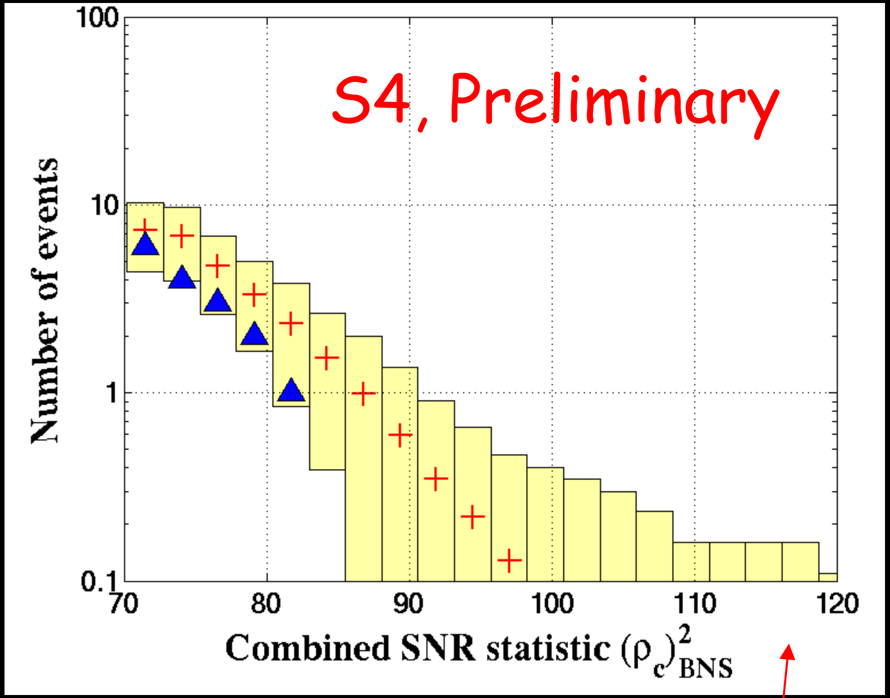
$$\rho^2_{\text{effective}} = \rho^2 \Bigg/ \sqrt{\left(\frac{\chi^2}{2p-2}\right)\left(1+\frac{\rho^2}{250}\right)}$$

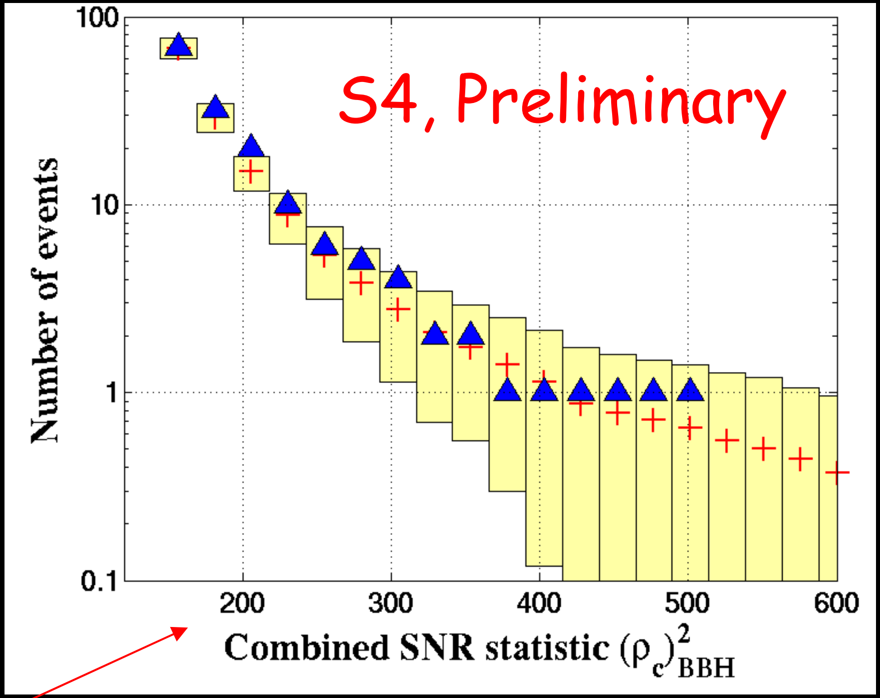
For BBH, use SNR ρ



Ref: LIGO-G060630-00

Comparing Coincidences with Background





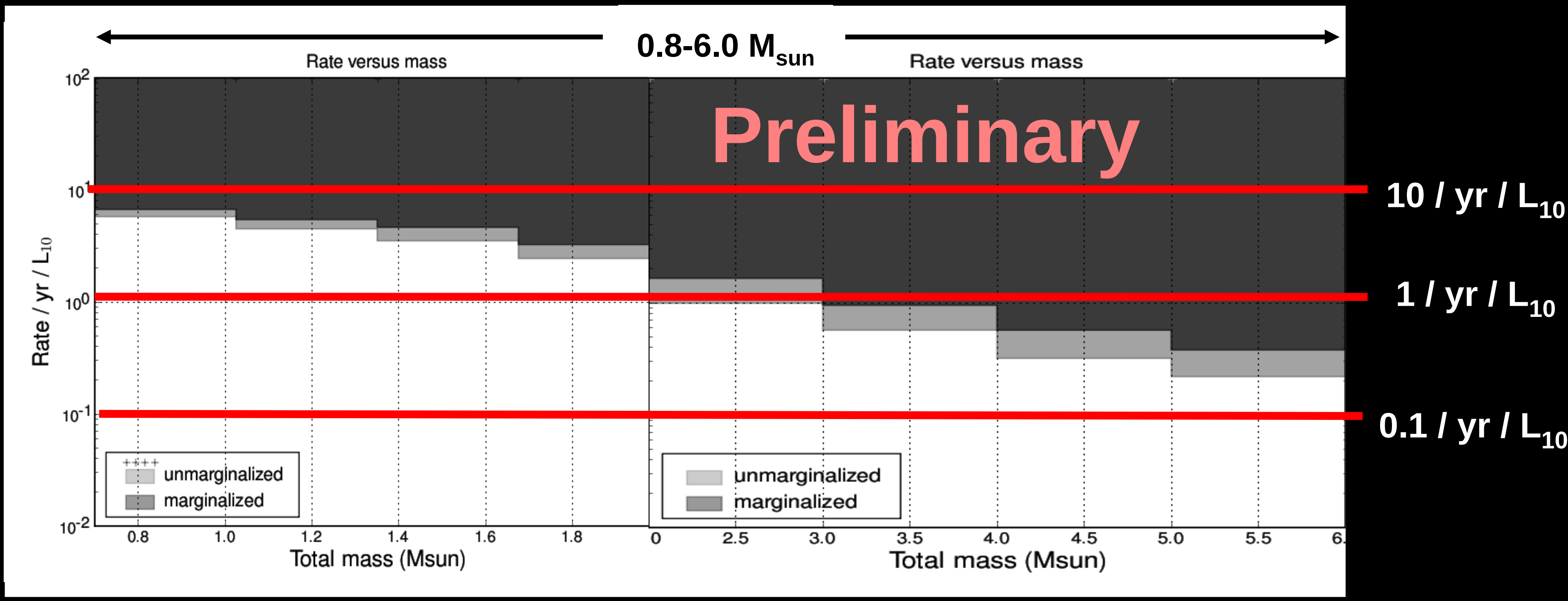
Similar plot for PBH

Combined effective SNR square-sum over detectors

Ref: LIGO-G070086-00

No detections through the first 3 months of S5

Current upper limits from the S4 run, for PBH and BNS (total mass: 0.8-6 $M_{\odot}$)



Rate/year/L_{10} vs. binary total mass

$L_{10} = 10^{10} L_{sun,B}$ (1 Milky Way = 1.7 L_{10})

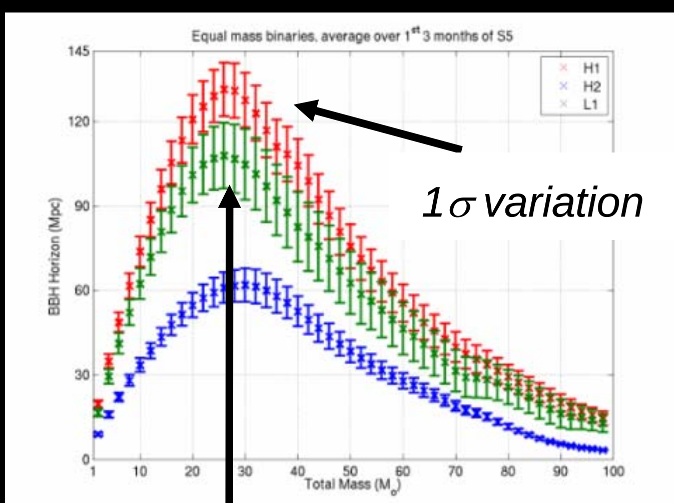
The dark region is excluded at 90% CL

Horizon in S5

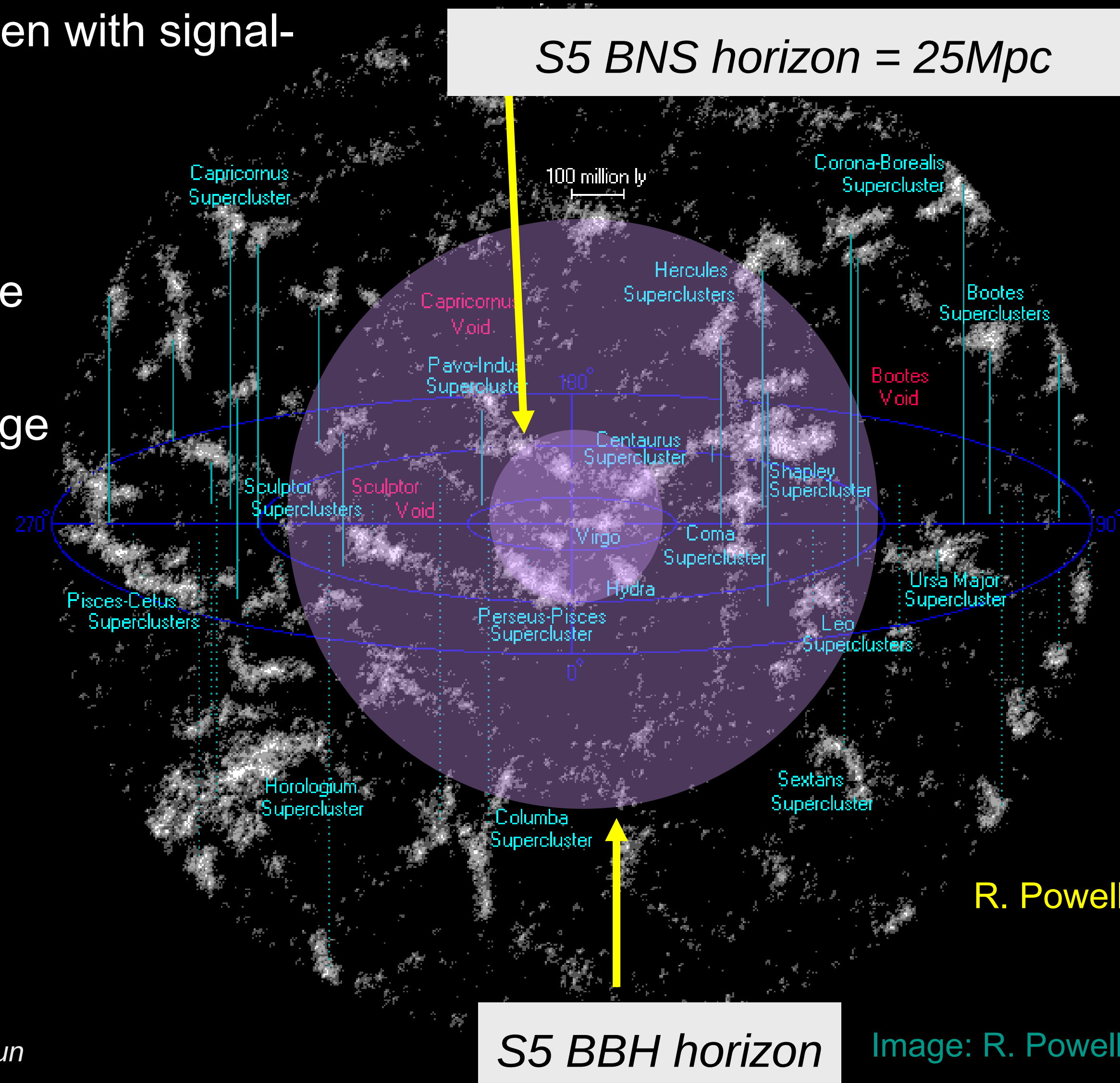
distance at which an optimally oriented and located binary system can be seen with signal-to-noise ratio $\rho=8$

For 1.4-1.4 M_o binaries:
~ 200 MWEGs in range

For 5-5 M_o binaries:
~ 1000 MWEGs in range

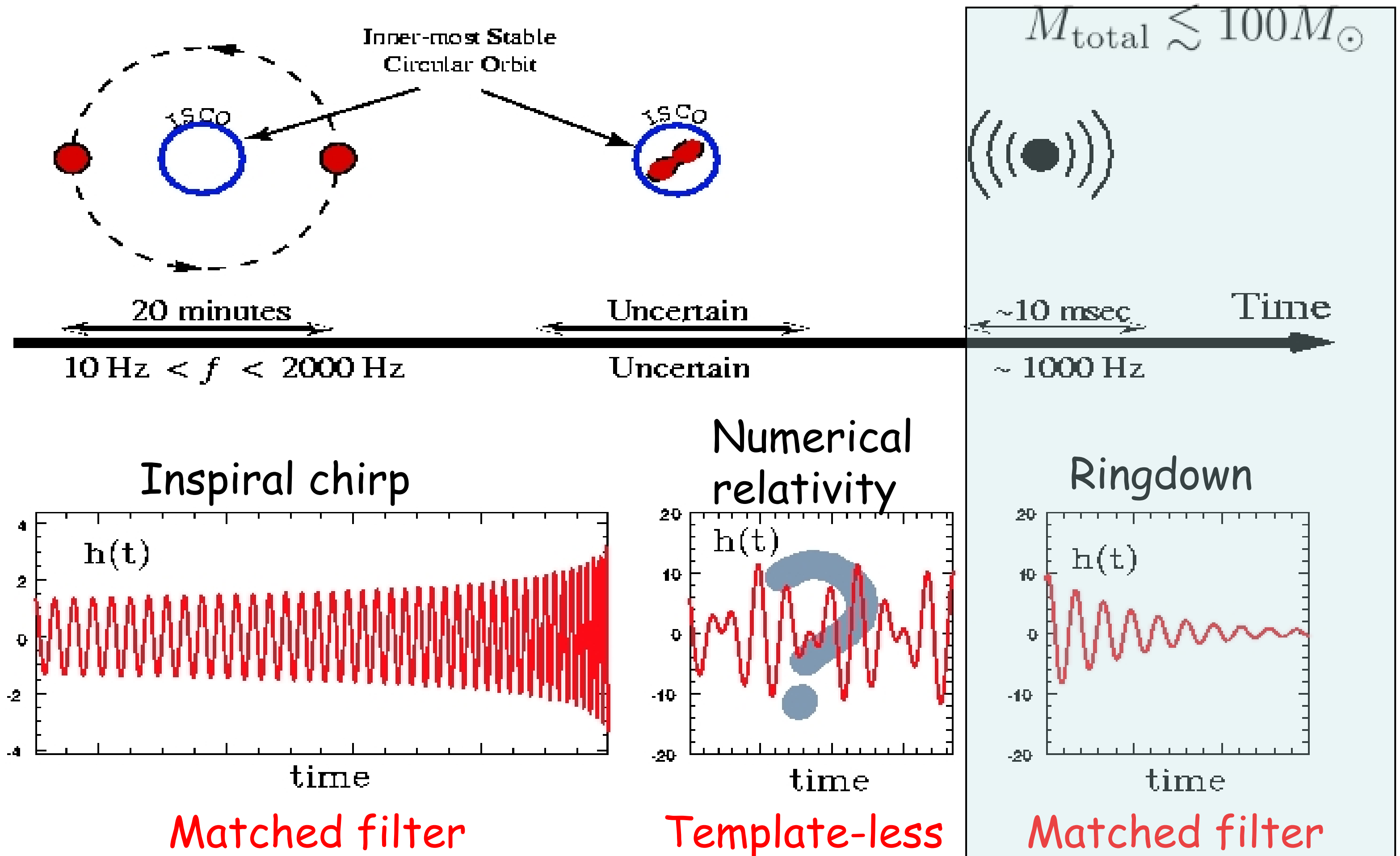


Peak 130Mpc at total mass ~ 25M_{sun}



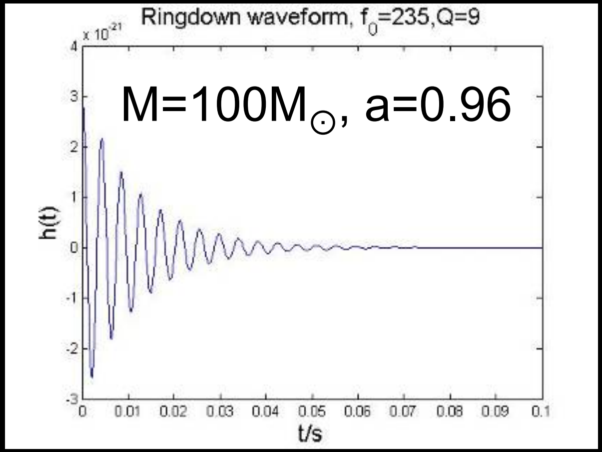
Evolution of Binary System

LIGO is sensitive to inspirals containing neutron stars and black holes



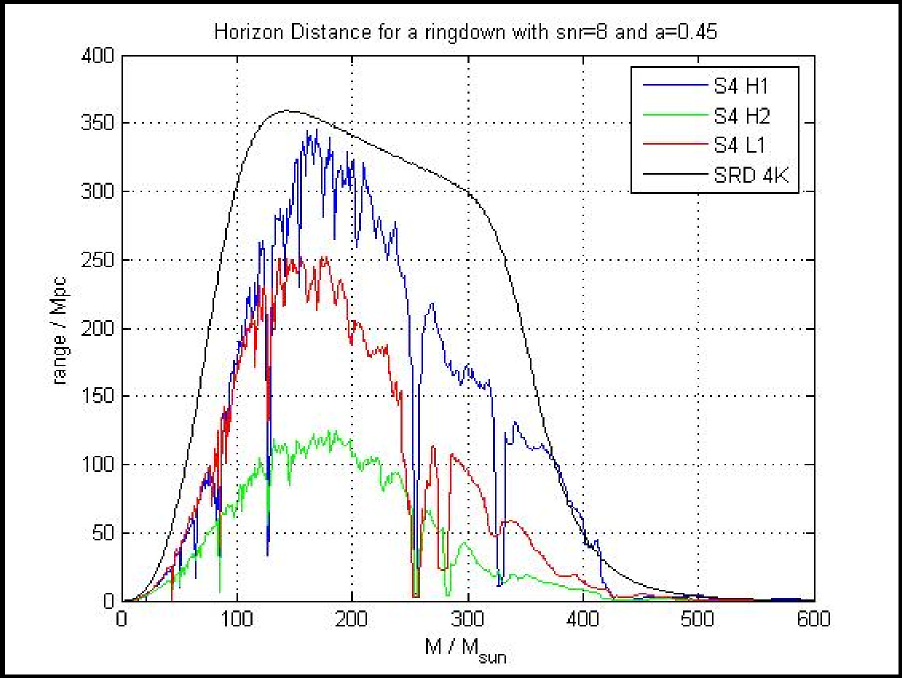
Ringdown Waveforms

- If final product of inspiral is perturbed black hole, it will settle down to a Kerr black hole by quasinormal ringdown
- Waveforms are well modeled by black hole perturbation theory



Assumed mass fraction emitted as GW's ε = 1%

Ongoing search for ringdown waveform with a multi-interferometer pipeline similar to inspiral



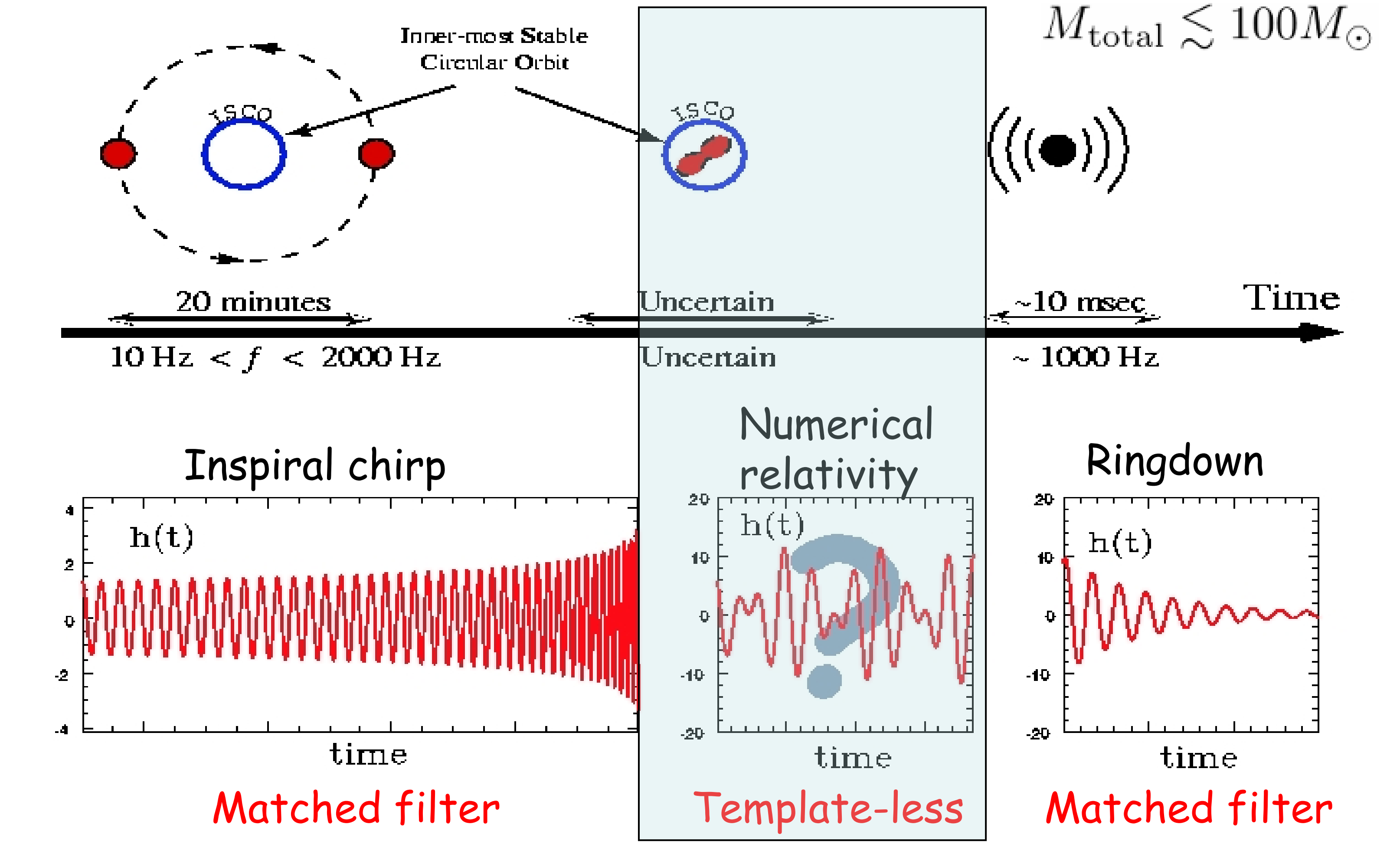
LIGO-G070213 -00

It gets harder if we do NOT know what to look for, but that's where the excitement is…

Image Courtesy: Library of Congress

Evolution of Binary System

LIGO is sensitive to inspirals containing neutron stars and black holes



Gravitational Wave Bursts

Bursts: any non-inspiral, gravitational-wave transients for which we have no exact waveform or close approximation.

GWB sources are typically not well understood, involving complicated (and interesting!) physics.

They are more difficult to detect, but the scientific payoff from GWB detections could be very high.

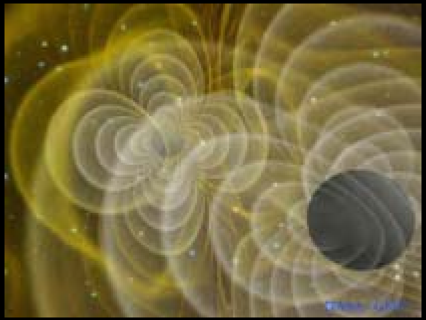
SN1987A

Supernovae:

- GWs are emitted if there are asymmetries in the core collapse.
- Galactic rate: 1/50y
- Virgo cluster rate: 3/y

Black Hole / Black Hole coalescence:

- chirp at low frequency, short time in LIGO band
- uncertainties on templates
- matched filter not as effective as with neutron star binaries, makes sense looking for the merger
- no prediction on rate
- waveforms: recent progress in numerical relativity



NASA/GSFC

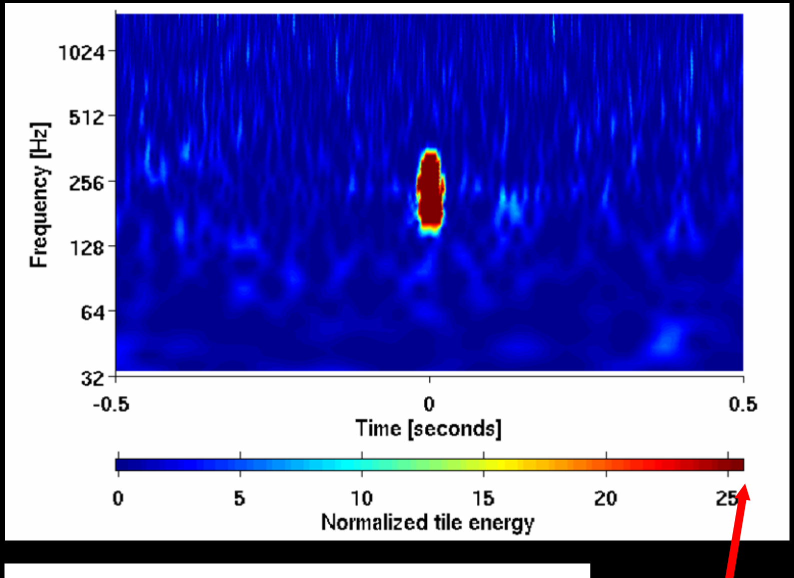
Other Examples:

- Instabilities in nascent neutron stars
- Kinks and cusps in cosmic strings

Excess Power Detection

All-sky, all-time search for transient increase in power in some time-frequency region, with minimal assumptions on the signal:

- Duration: 1 to 100 ms
  - characteristic time scale for stellar mass objects
- Frequency: 60 to 2,000 Hz
  - Determined by detector's sensitivity
- Many different implementations
  - Fourier modes, wavelets, sine-Gaussians
  - Multiple time/frequency resolutions
  - Provide redundancy and robustness



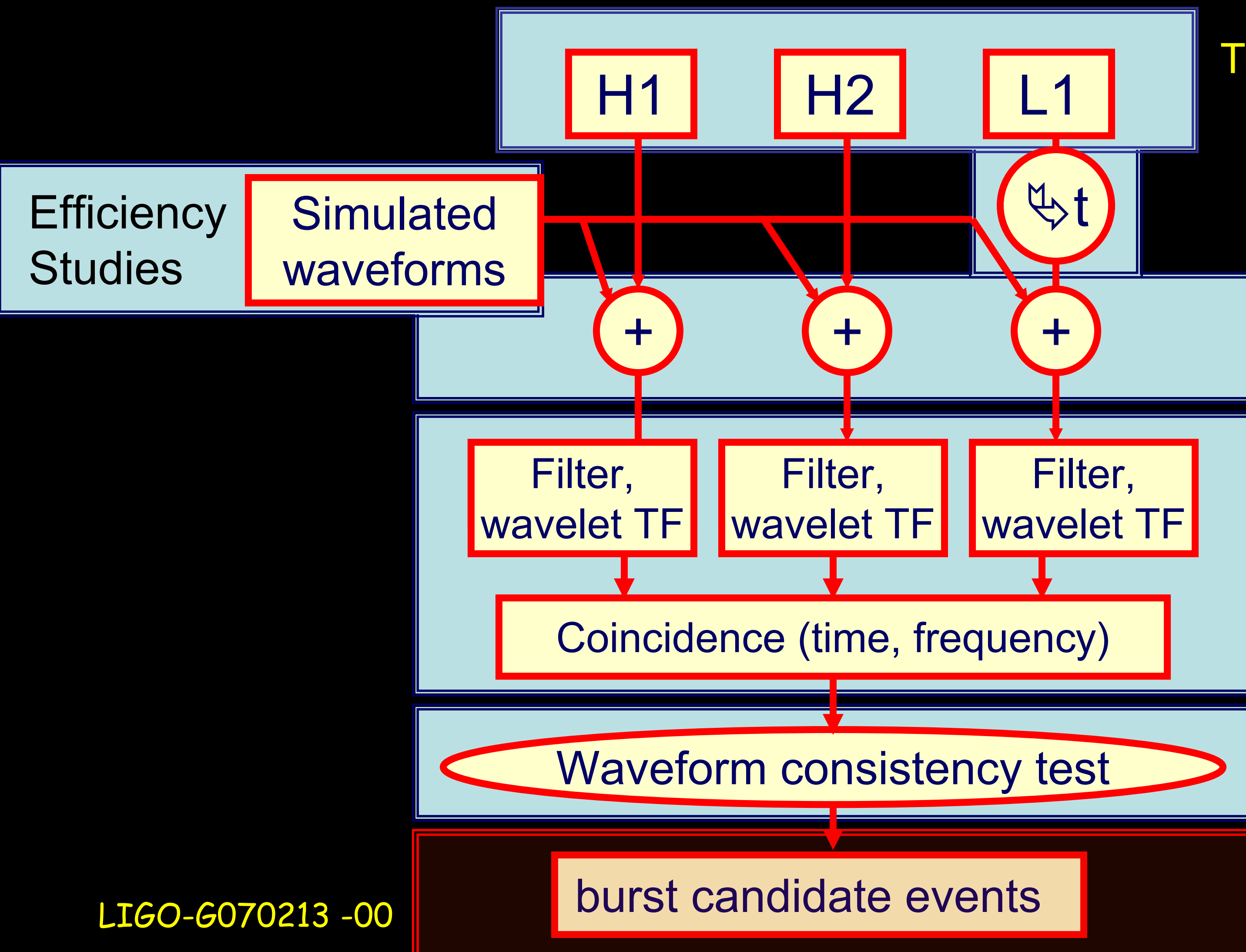
$$h_{rss} = \sqrt{\int_0^\infty |h(t)|^2 dt} = \sqrt{\int_{-\infty}^\infty |\tilde{h}(f)|^2 df}$$

h_{rss} is a template-less measure of the transient's amplitude

The tricky part: discriminating signal from detector noise

- veto known artifacts
- coincidence between detectors

Burst All-Sky Pipeline



Threefold Coincidence

Time Slides

WaveBurst
Event Trigger
Generator
Zg threshold

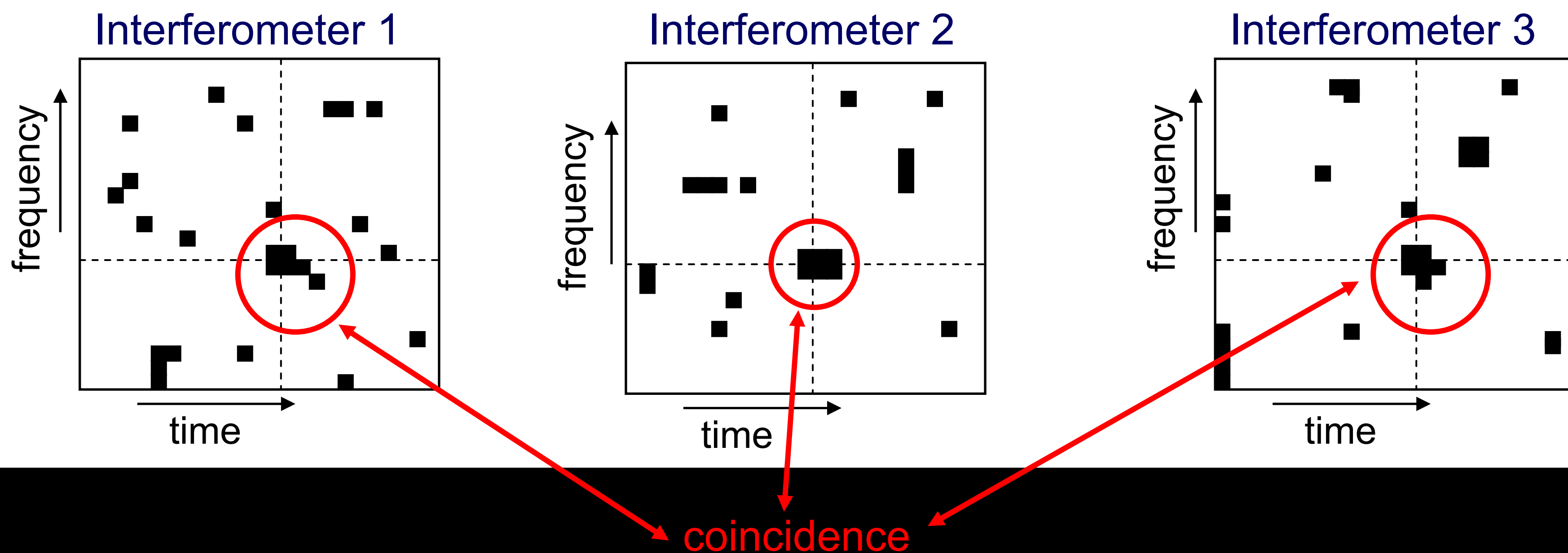
CorrPower
r-statistic test
Γ threshold

WaveBurst

Excess power in wavelet time-frequency plane.

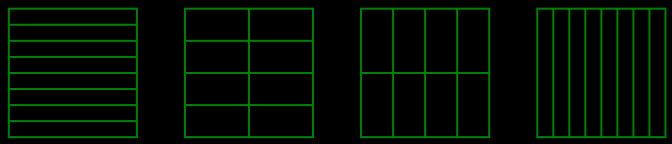
Ref: Class. Quantum Grav. 21 (2004) S1819

10% black pixel probability



Current implementation:

Wavelet decomposition from 64–2048 Hz
with 6 different resolutions from
1/16 sec × 8 Hz to 1/512 sec × 256 Hz

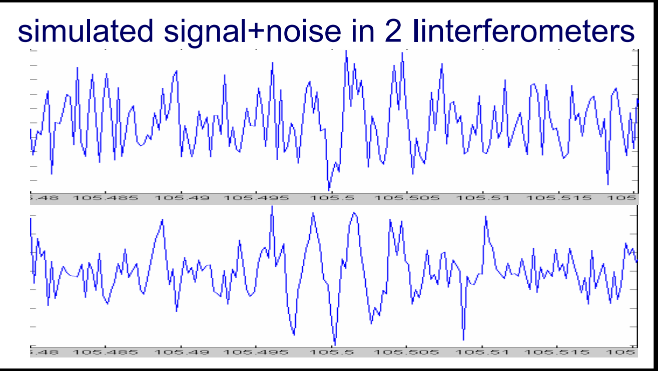


WaveBurst outputs coincident events with their significance in each of the three interferometers.
Parameter estimation: time, duration, frequency, signal amplitude at Earth

Threshold on combined significance of the triple coincident event (Z_g)

The *r*-statistic Waveform Consistency Test

Ref: *Class. Quantum Grav. 21 S1695-S1703*



we cannot match-filter to a waveform, but we can match waveforms from different interferometers

Process pairs of interferometers (whitened data, 64-2000Hz) and compute the normalize linear cross-correlation (*r*-statistic).

The signal duration is unknown → test different integration windows (20, 50, 100 ms)

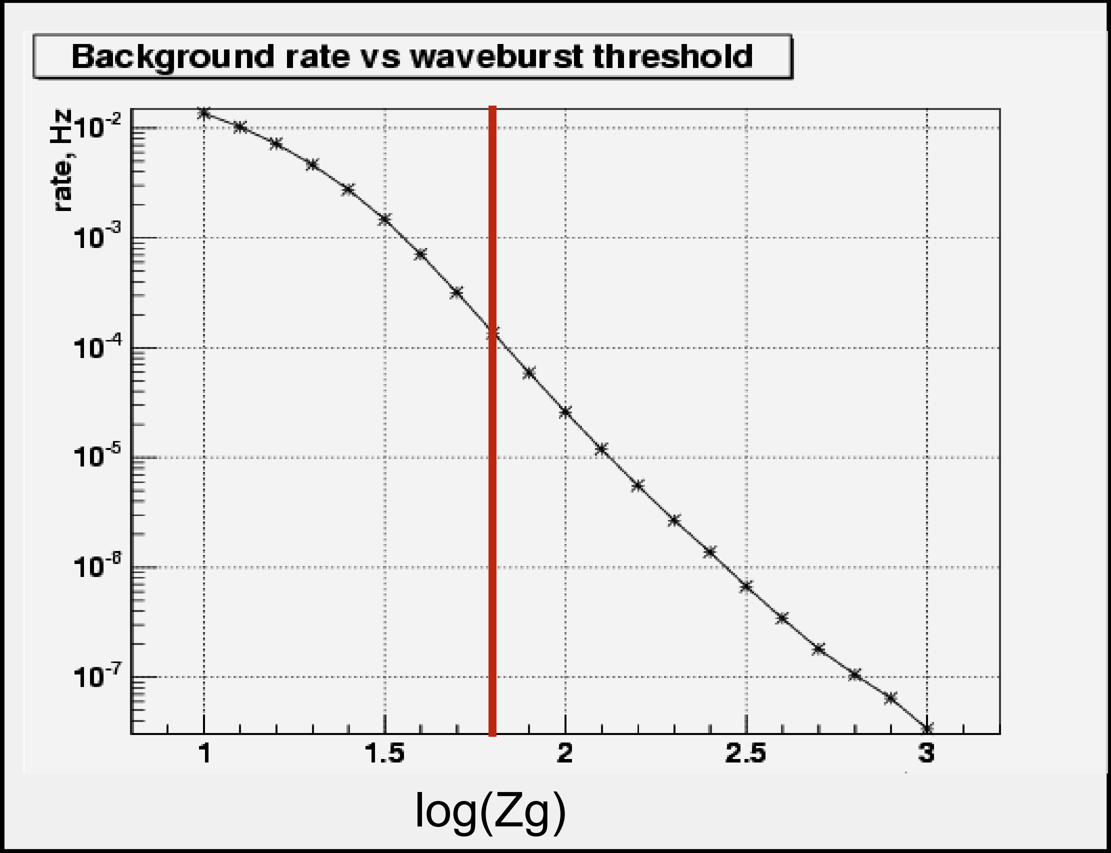
The incident GW direction is unknown → allow time delay (Δt) between the two data series 11ms H1-L1 and H2-L1 ; 1ms H1-H2

Find maximum correlation over window lengths and time shifts and the significance of the null-hypothesis test

Calculate overall significance statistic Γ by combining the 3 pairs

$$\Gamma = \max(\Gamma^{L1H1} + \Gamma^{L1H2} + \Gamma^{H1H2})/3$$

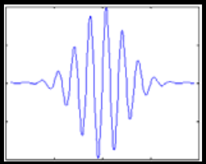
Selection Criteria

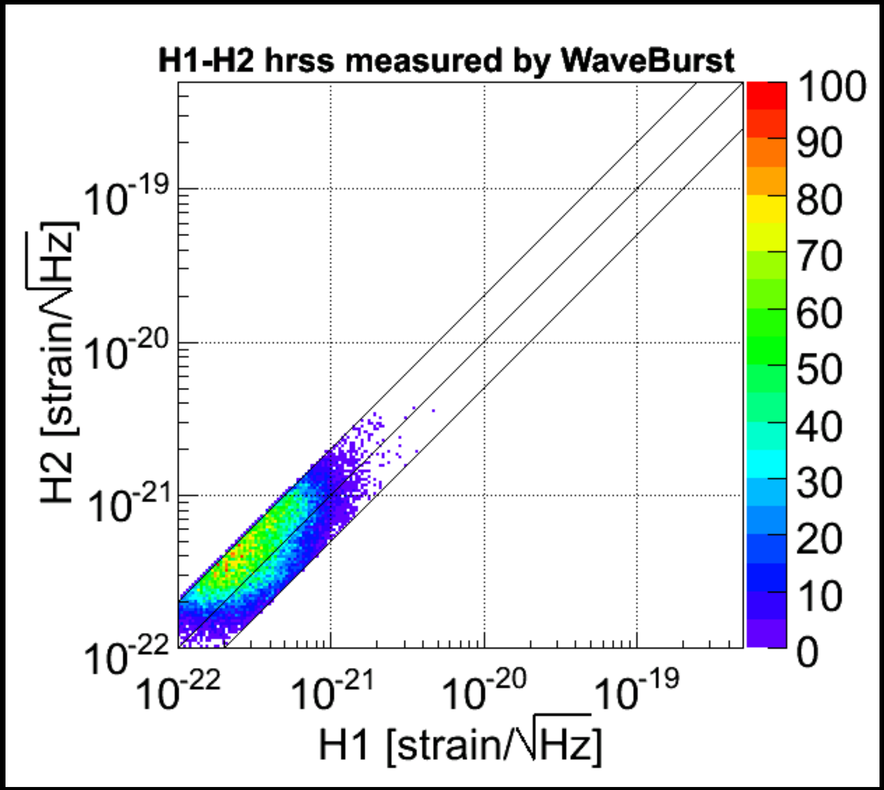


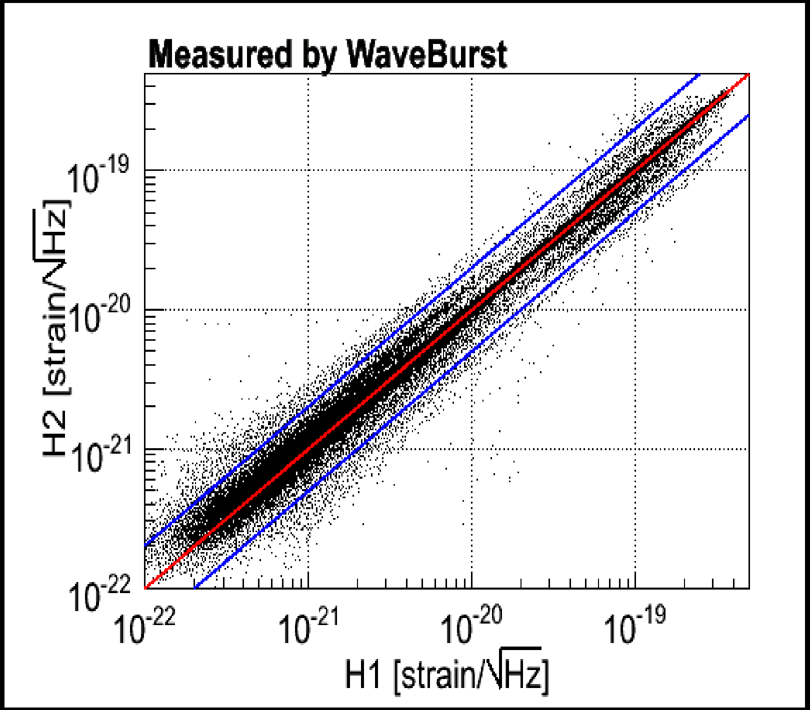
- Frequency: 64-1600 Hz
- Zg ≥ 6.0
- Data Quality Cuts
- Analysis Cuts: H1-H2, H1-L1, frequency-dependent threshold

H1-H2 Consistency Checks

Simulations:
Sine-Gaussians Q=8.9,3

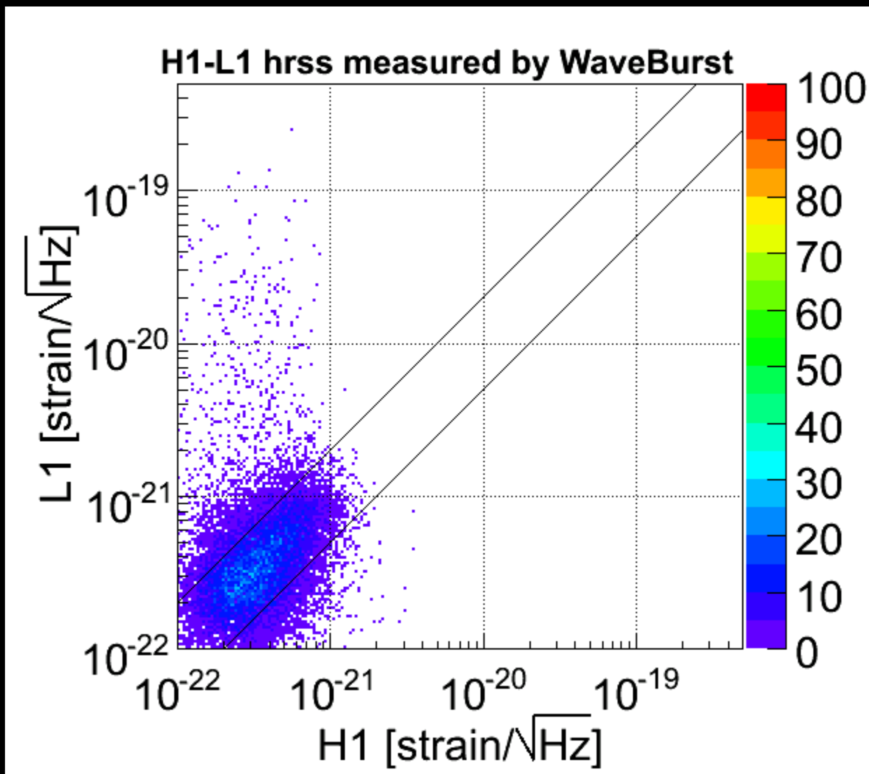






- Estimated amplitudes must agree within a factor of two.
- Signals must be positively correlated

L1-H1 Checks



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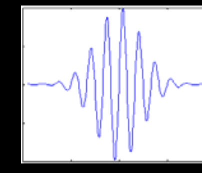
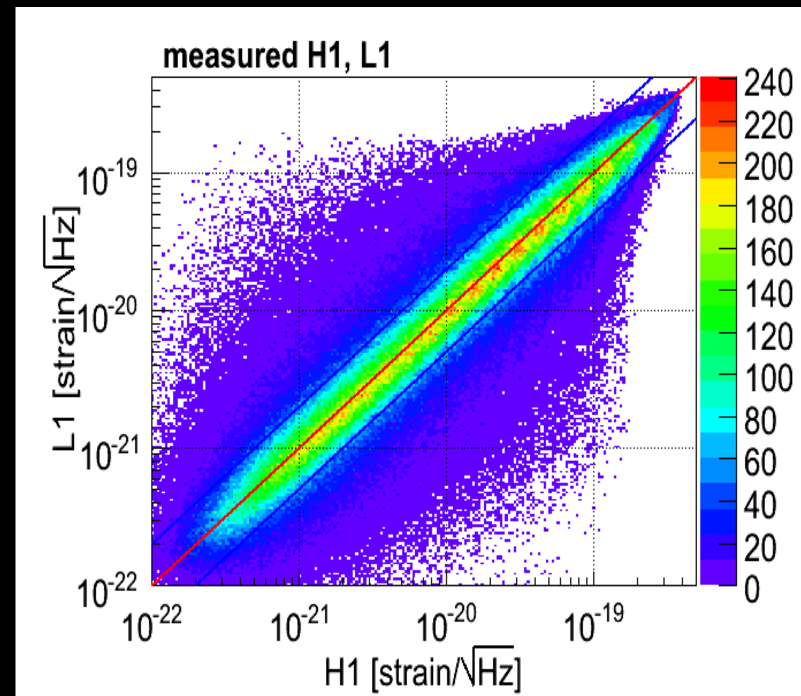




Require $\Gamma_{H1L1} > 3$
(less than 0.1% probability to get the measured linear cross-correlation from uncorrelated noise at L1 and H1)

Data Quality Veto Strategy

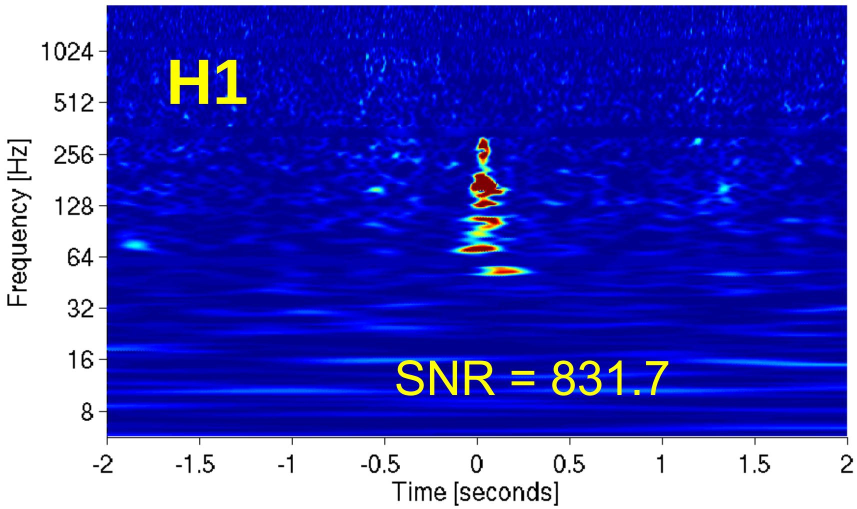
Cited examples are for the S5 Burst search.
Very similar choices in Inspiral search, with some subleties in the Cat 1-2 distinction

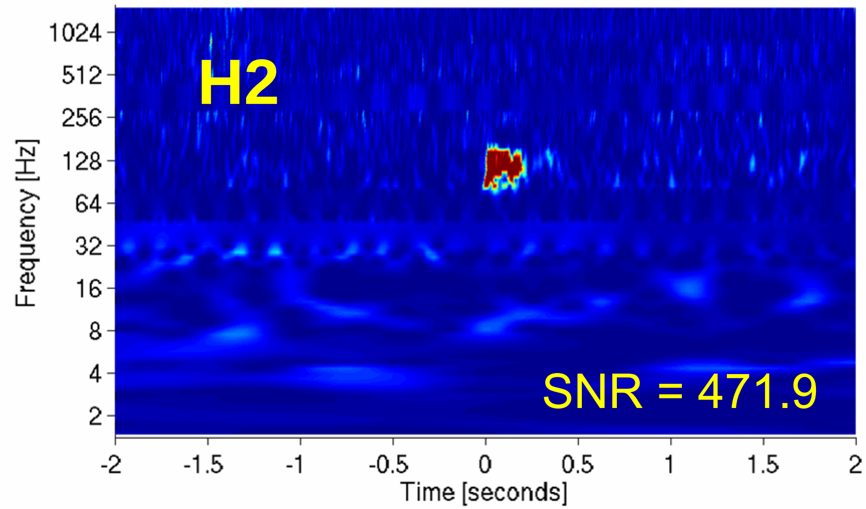
Category 1	Inspiral: data not worth analyzing Burst: Minimal data quality vetoes, for the selection of data segments to be analyzed *(e.g. calibration problems, test injections, photodiode saturations)*
Category 2	"Unconditional" post-processing vetoes: data is unreliable and there is an established one-on-one correlation with loud transients. *(e.g. saturations in the alignment control system, glitches in the power main)*
Category 3	"Conditional" post-processing vetoes, for upper limit: statistical correlation to loud transients. We still look for detection candidates at those times, exerting caution when establishing detection confidence. *(e.g. train/seismic flags, 1 minute pre-lockloss, "dips" of light stored in the arm cavities)*
Category 4	Advisory flags: no clear evidence of correlation to loud transients, but if we find a detection candidate at these time, we need to exert caution *(e.g. high wind and certain data validation issues)*

In addition: event-by-event veto based on correlated glitching on auxiliary channels

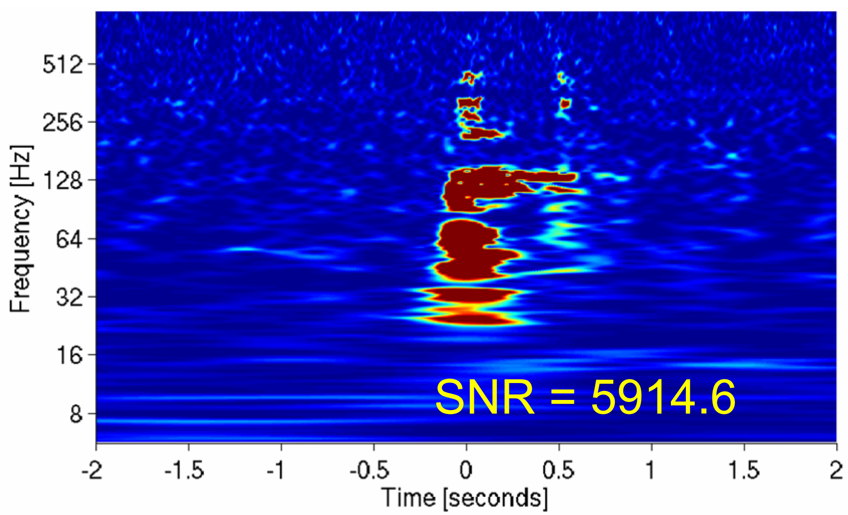
Ref: LIGO-G060628-00

An example of local seismic disturbances



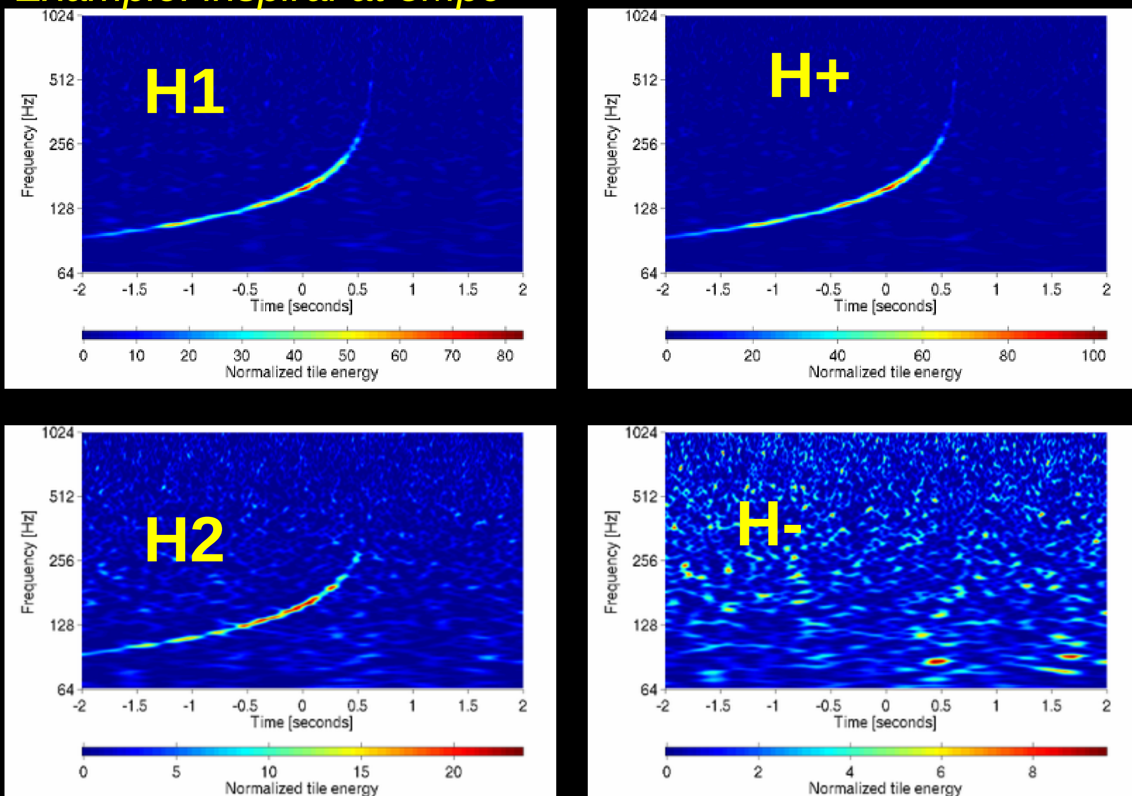


H0:PEM-ISCT4_ACCZ



Soon-To-Be-Implemented: H1-H2 Null-Stream Veto

Example: inspiral at 5Mpc



H+ The optimal linear combination that maximizes the signal to noise ratio of potential signals.

$$H_+ = \left(\frac{1}{S_1} + \frac{1}{S_2}\right)^{-1} \left(\frac{H_1}{S_1} + \frac{H_2}{S_2}\right)$$

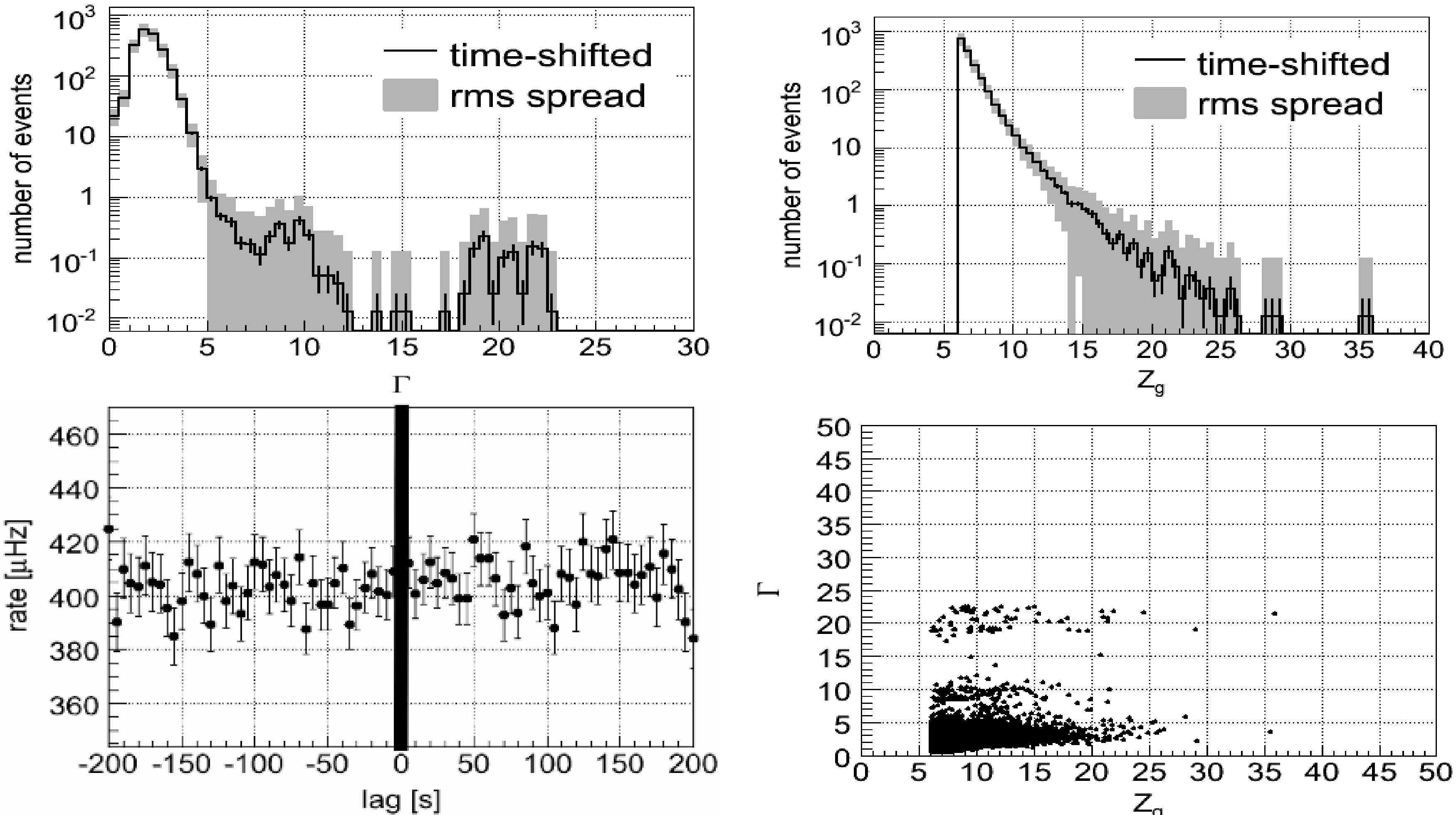
H- The null stream, which should be consistent with noise in the case of a true gravitational-wave

$$H_- = H_1 - H_2$$

This null-stream formalism can be generalized to an arbitrary network of interferometers, for source localization

First 5 months of S5: Before Analysis and DQ Cuts

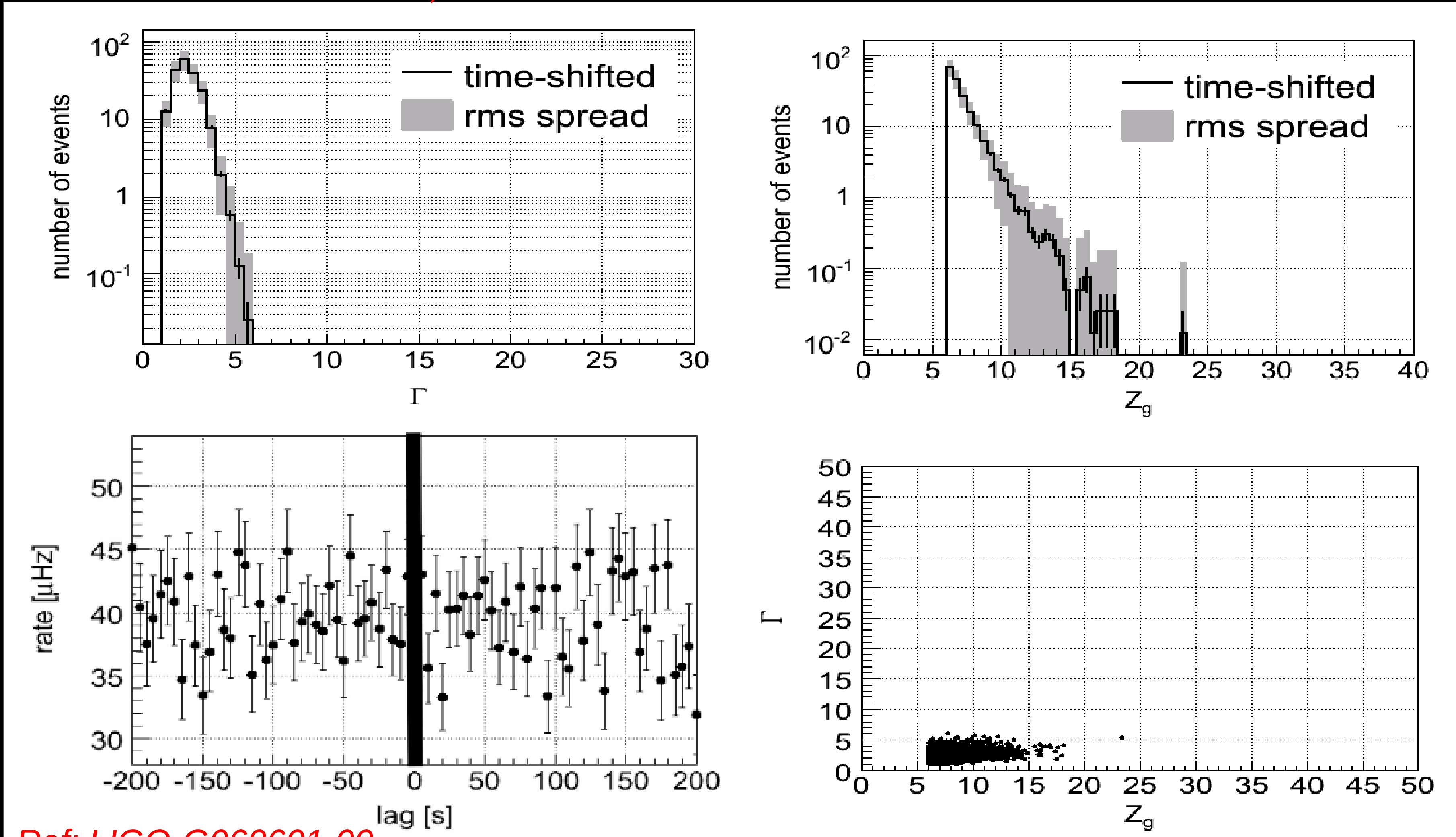
Accidental coincidences, from 100 LHO-LLO time-slides



Ref: LIGO-G060601-00

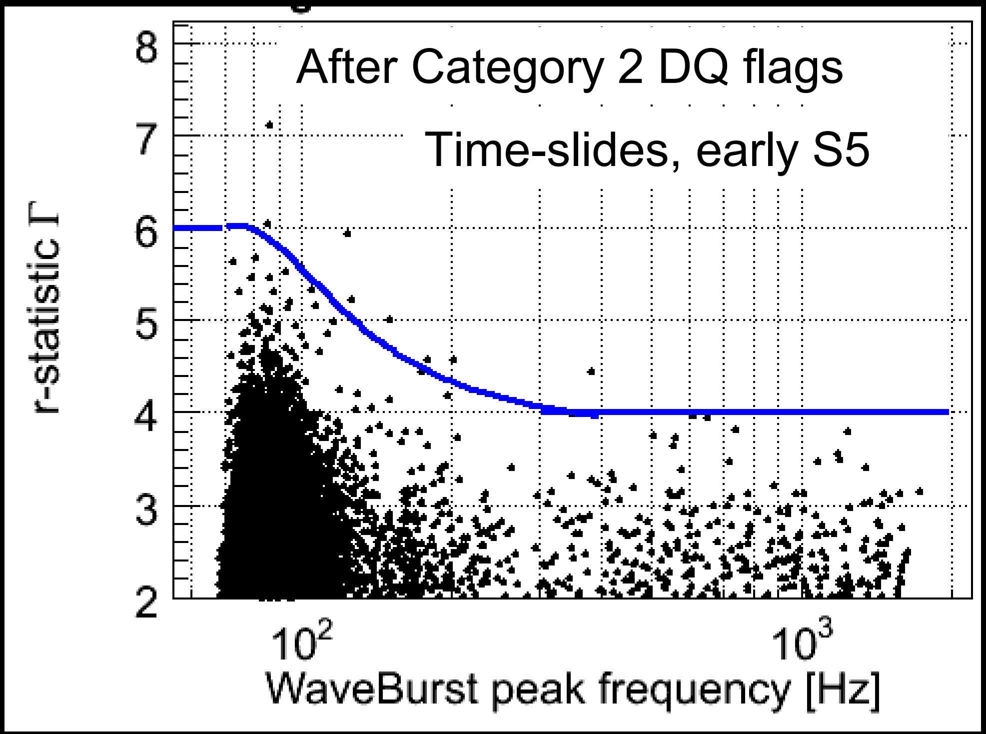
First 5 months of S5: After Analysis and DQ Cuts

Accidental coincidences, from 100 LHO-LLO time-slides



Ref: LIGO-G060601-00

S5: Frequency-dependent Threshold



Ref: LIGO-G060601-00

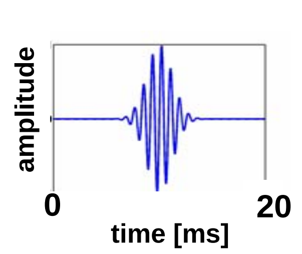
Empirically chosen, frequency-dependent threshold
~1/(f-64Hz) in 100-300Hz,
4 at high frequency,
6 at low frequency

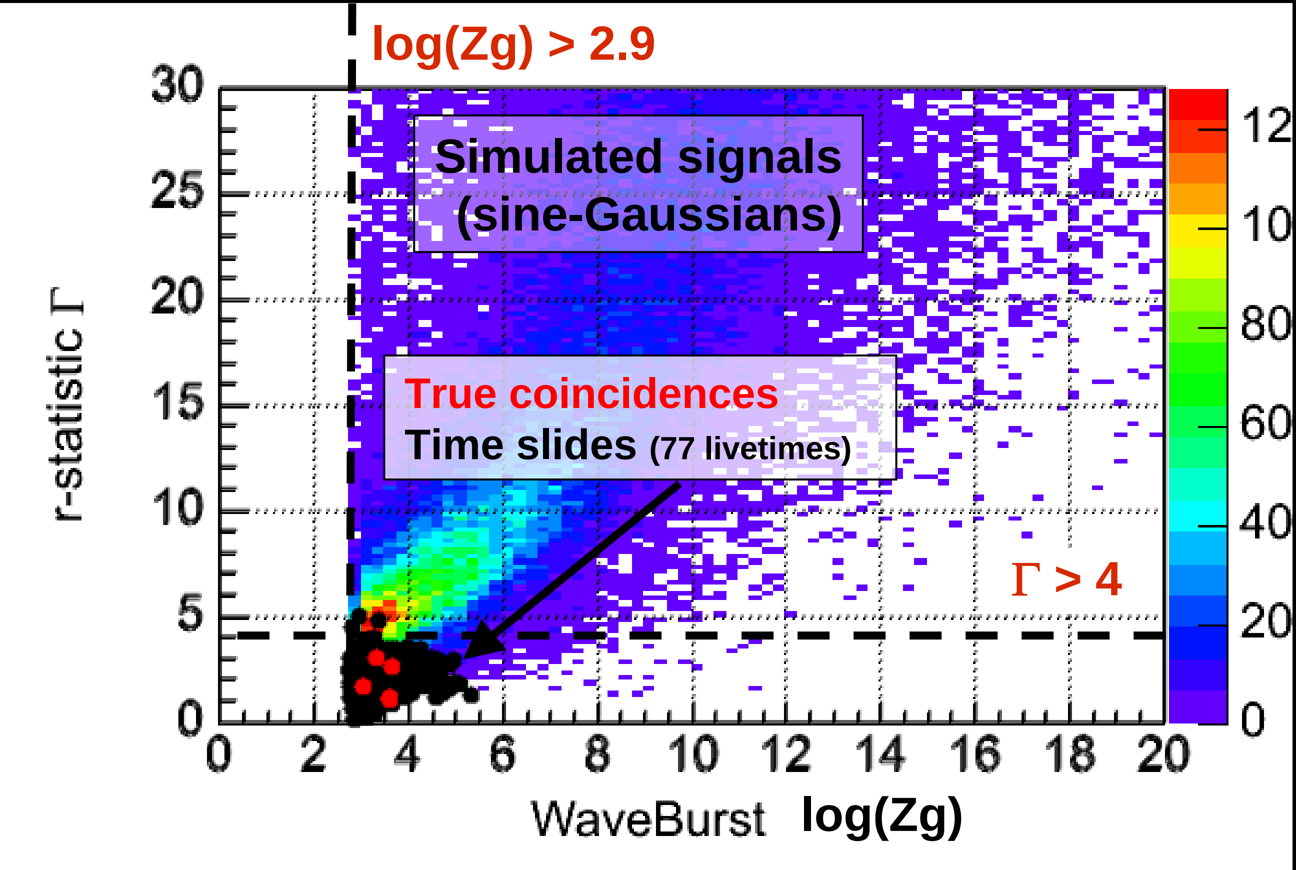
Target rate of accidentals:
<< 1 per analysis period

Expected: 0.06 in early S5, 0.4/year

…we are still completing the S5 analysis, so let's look at S4 results…

Upper Limit From S4 Analysis





Blind analysis:

thresholds chosen on a set of 100 time-slides (different from those used for background estimation)

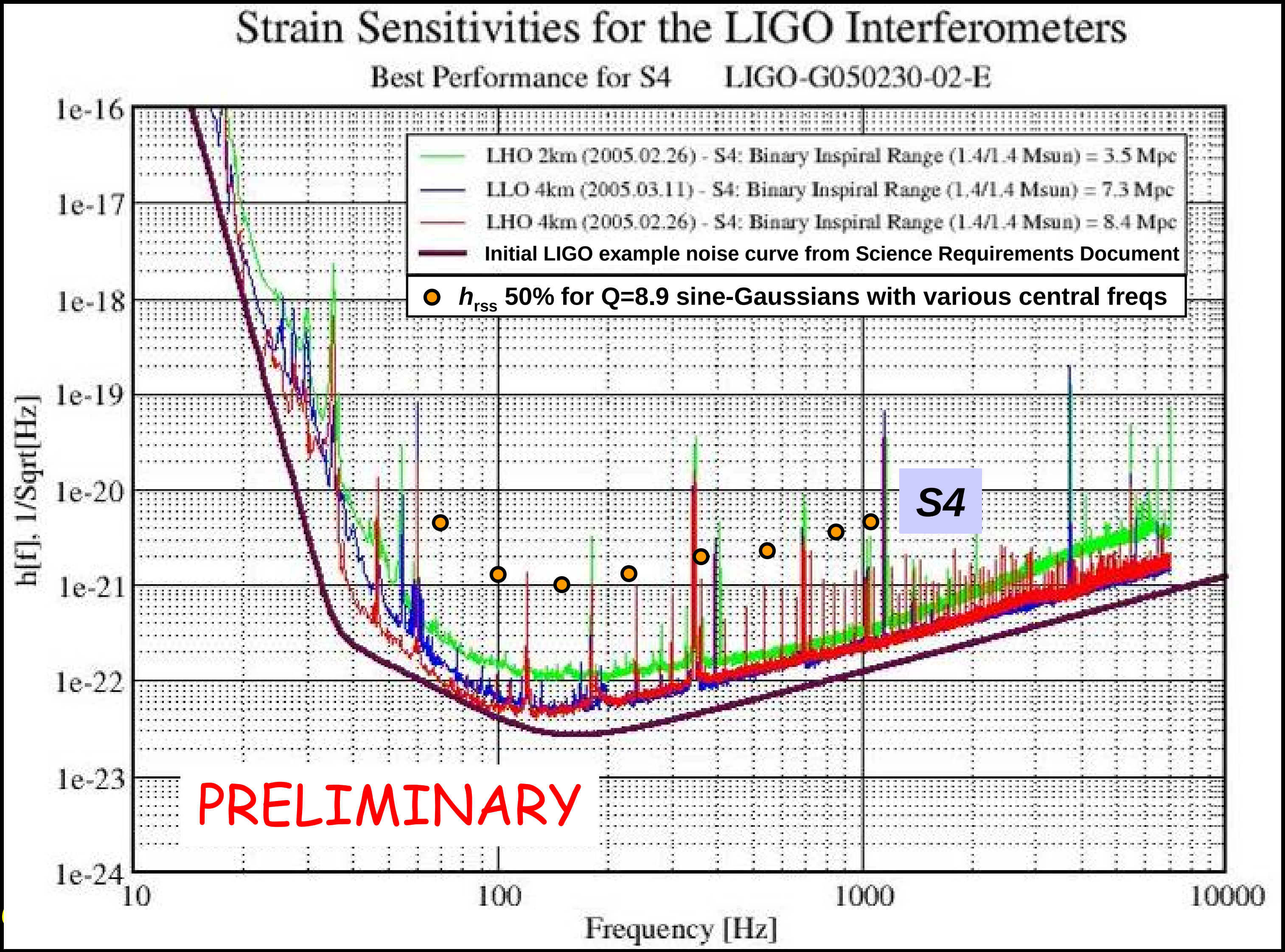
Expected 0.04 events

Frequentist one-sided upper limit (90% C.L.) based on zero events passing all cuts in S5: $R_{90\%}$ = 2.303 / 15.53 days = 0.15 /day

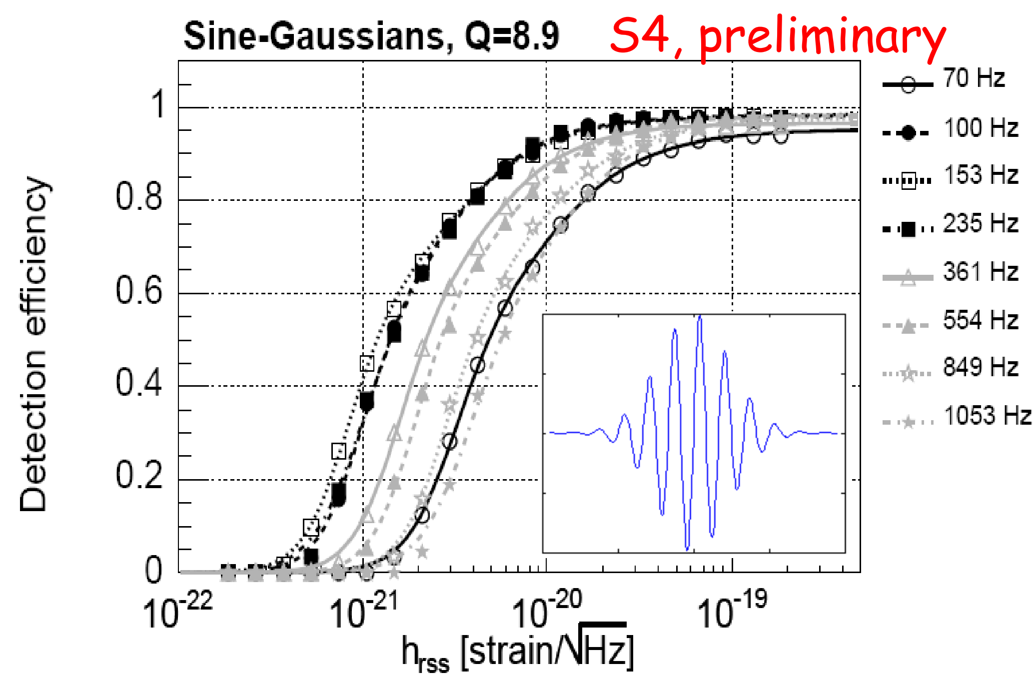
LIGO-G070213 -00

PRELIMINARY

S4 Sensitivity



Detection Efficiency / Range



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

Instantaneous energy flux:

$$\frac{d^2 E_{\rm GW}}{dA\, dt} = \frac{1}{16\pi} \frac{c^3}{G} < (\dot{h}_+)^2 + (\dot{h}_\times)^2 >$$

Assume isotropic emission to get rough estimates

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

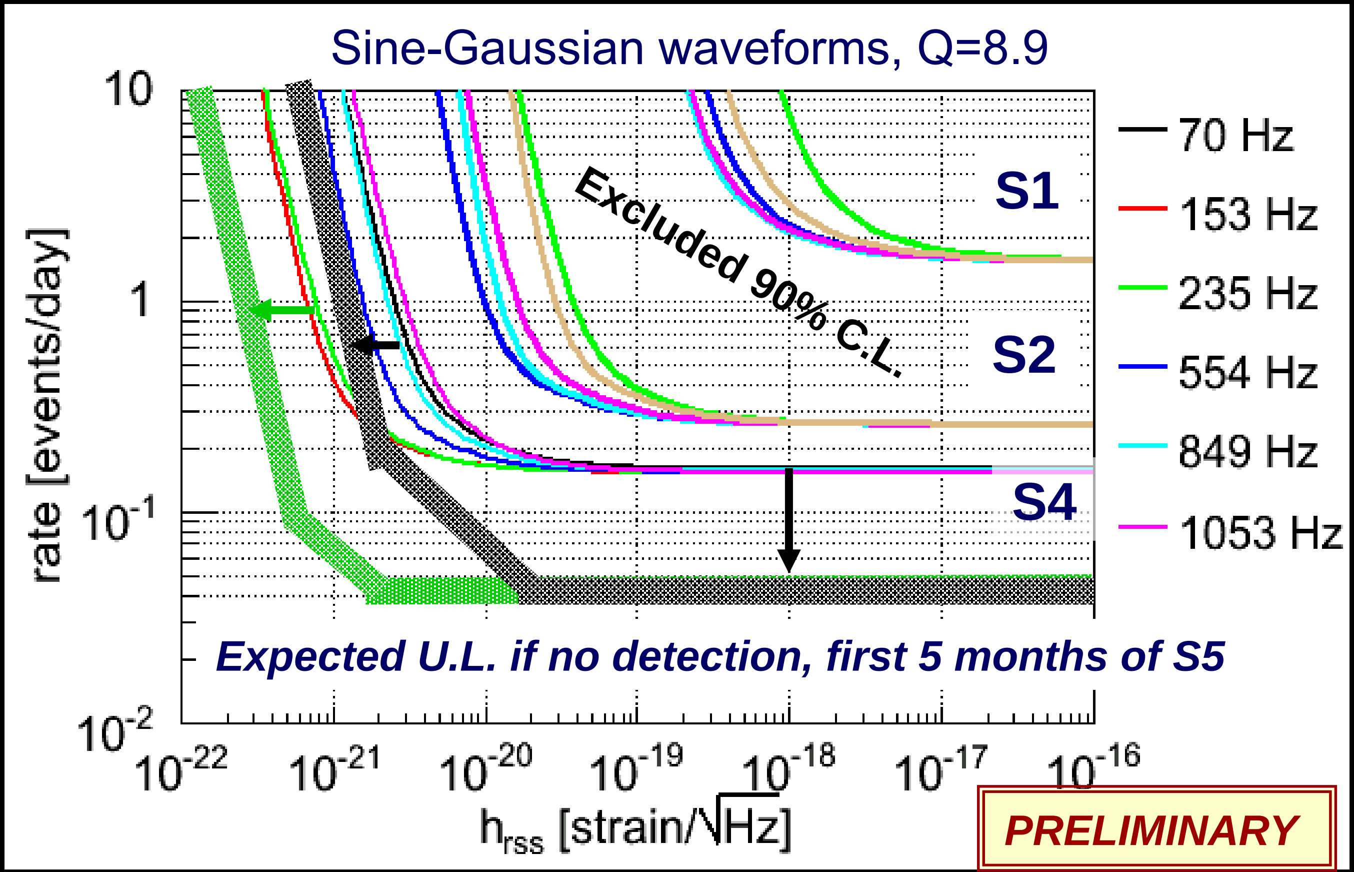
$$E_{\rm GW} = \frac{r^2 c^3}{4G} (2\pi f_0)^2 h_{\rm rss}^2$$

For a 153 Hz, Q =8.9 sine-Gaussian, the S4 search can see:

~ $8 \times 10^{-8}\ M_\odot c^2$ at 10 kpc (typical Galactic distance)

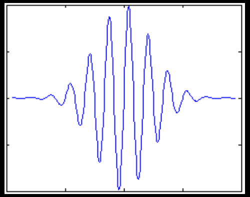
~ $0.2\ M_\odot c^2$ at 16 Mpc (Virgo cluster)

"Interpreted" Upper Limit



Lower rate limits from longer observation times

Lower amplitude limits from lower detector noise



$$R(h_{rss}) = \frac{\eta}{\varepsilon(h_{rss}) \times T}$$

η = upper limit on event number

T= live time

$\varepsilon(h_{rss})$ = detection efficiency

A similar upper limit curve for each simulated template (Gaussian, black-hole mergers, supernovae…)

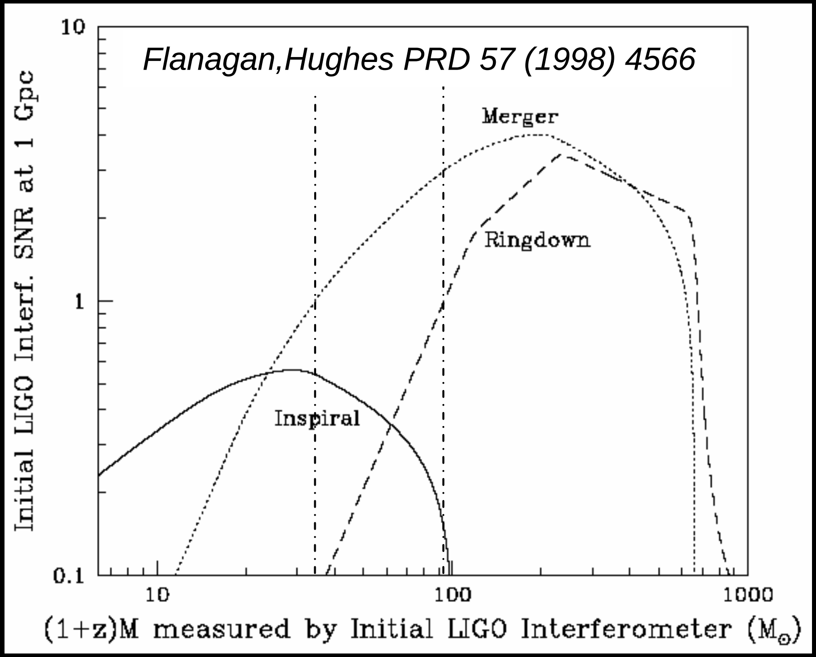
Ref: LIGO-G060601-00

Prospects

Image Courtesy: Library of Congress

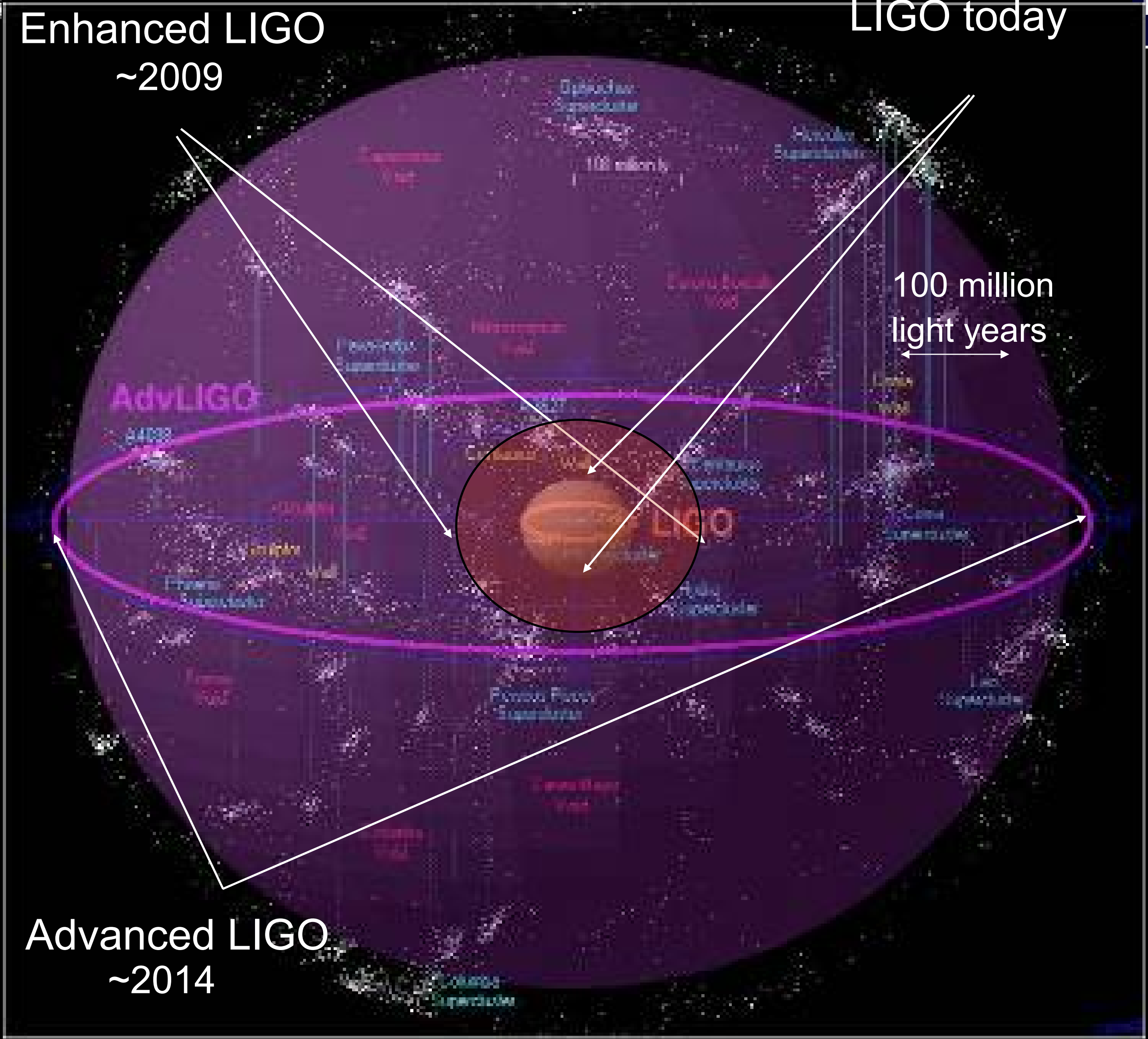
- Analysis of S5 data is in full swing
  New results soon…

- Inspiral-Burst-Ringdown followup, with input from Numerical Relativity



- Fully coherent network searches (world-wide interferometer network): source localization and waveform reconstruction

- Null-stream veto implementation
- Coincidence with GRBs


LIGO
LSC
Enhanced LIGO
~2009
LIGO today
100 million
light years
AdvLIGO
LIGO
Advanced LIGO
~2014