Status and Recent Results from the LIGO Experiment

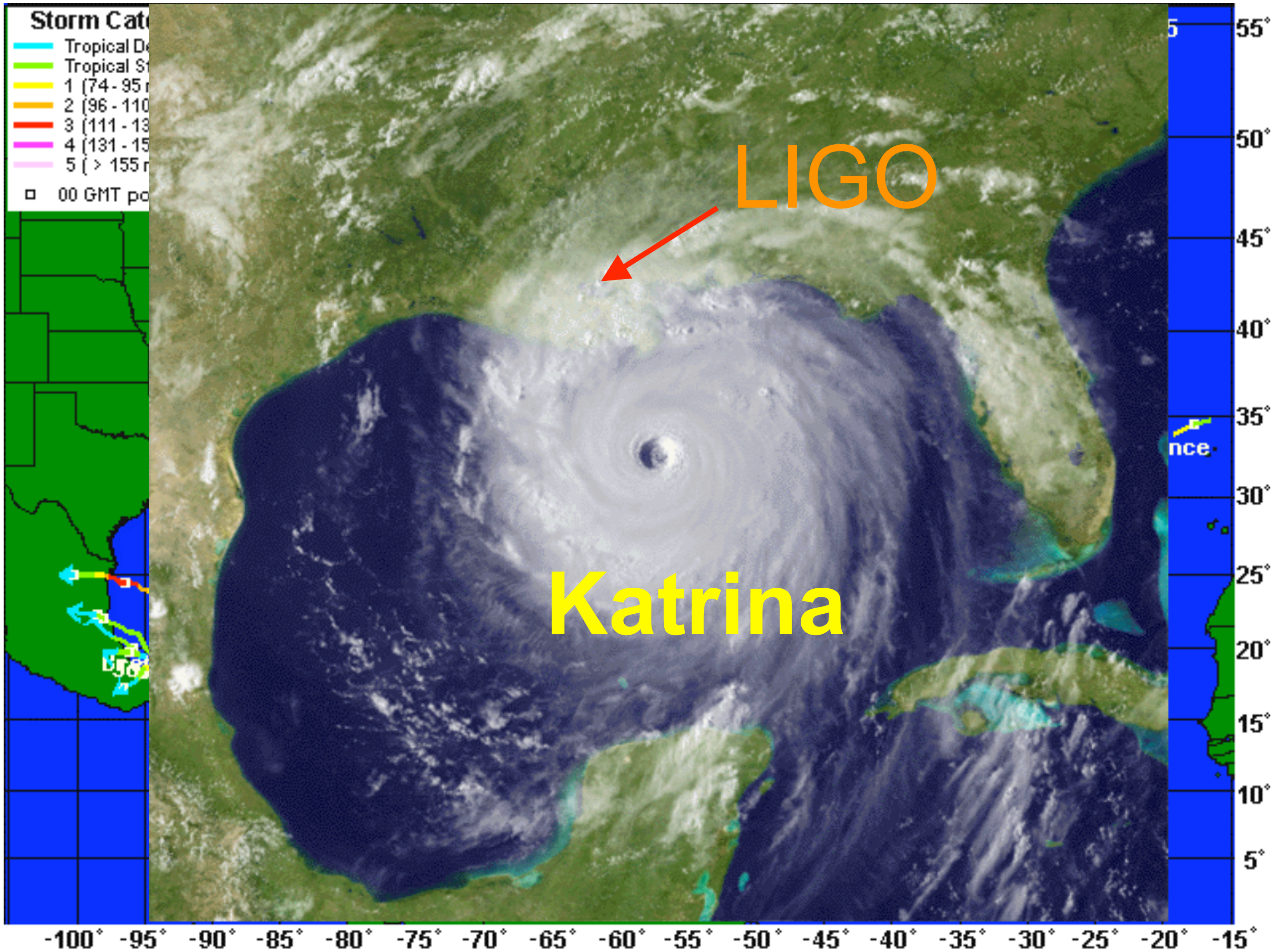
Brian O'Reilly

California Institute of Technology

LIGO Livingston Observatory

Vanderbilt University Physics Department Colloquium

Summer 2005



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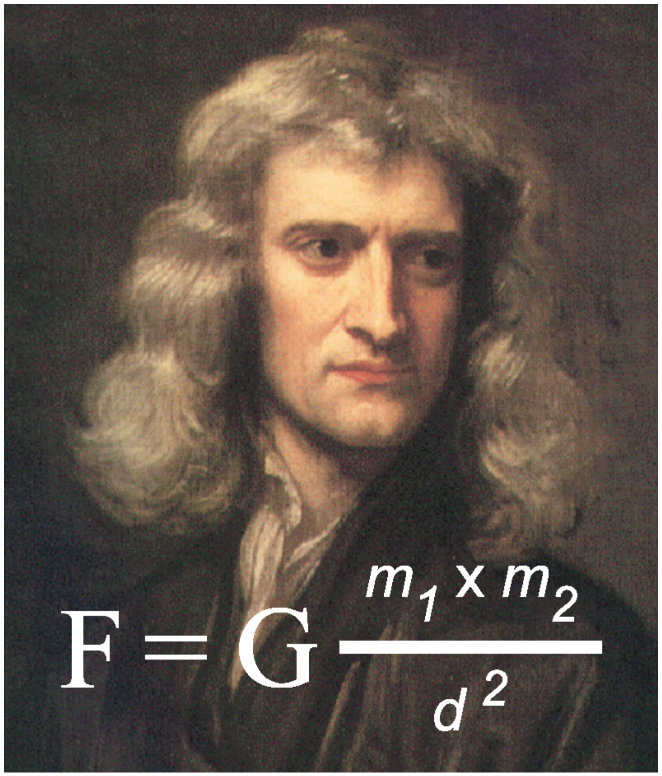
Outline

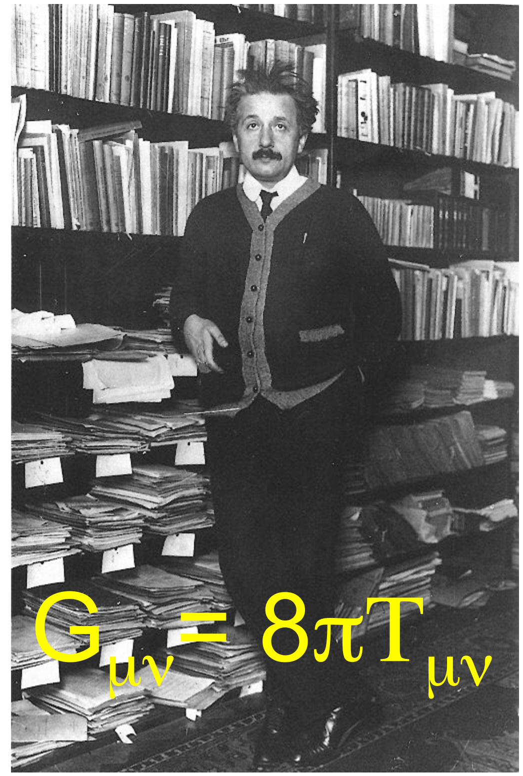
- What is Gravity.
- GW Interferometers.
- Performance.
- Gravitational Wave Sources.
- Searches using the S2 data.
- Advanced LIGO and Outlook for the future.

What is Gravity?



Newton

Action at a distance



Einstein

Gravitational Radiation traveling at the speed of light

What are Gravitational Waves?

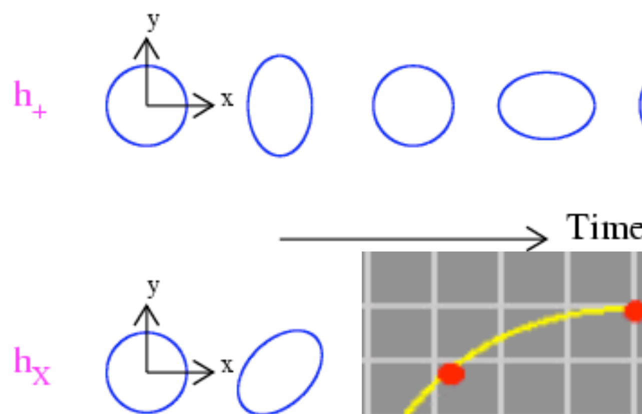
- Gravitational Waves = "Ripples in space-time"
- Two transverse polarizations - quadrupolar: + and x

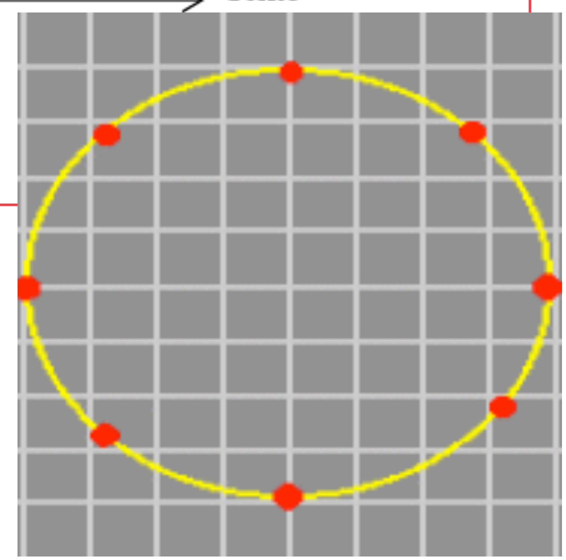
Example:

Ring of test masses

responding to wave

propagating along z





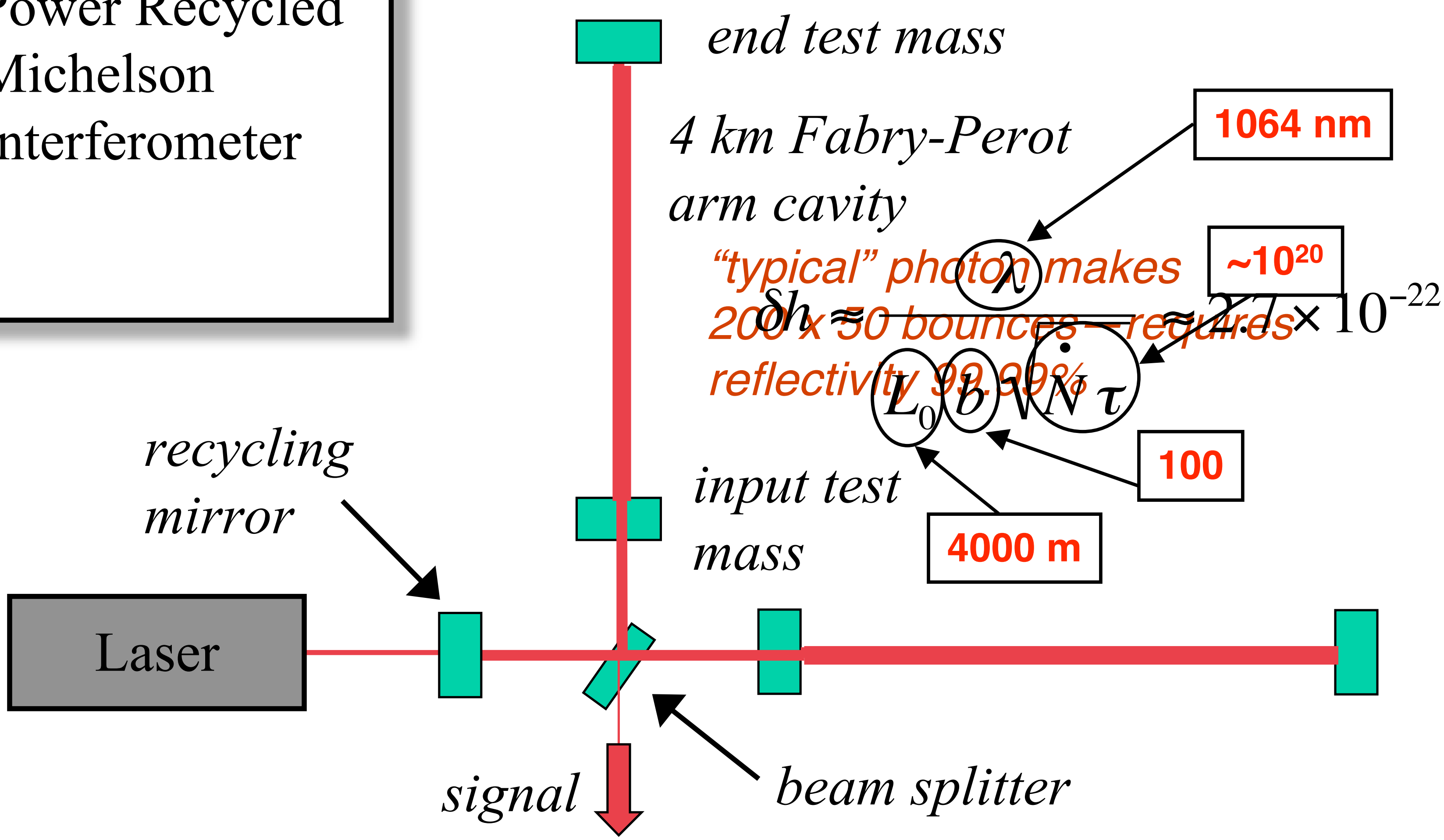
Amplitude parameterized by

dimensionless strain h: $\Delta L \sim h(t) \times L$

Need to measure strain of ~ 10^{-22}-10^{-23}

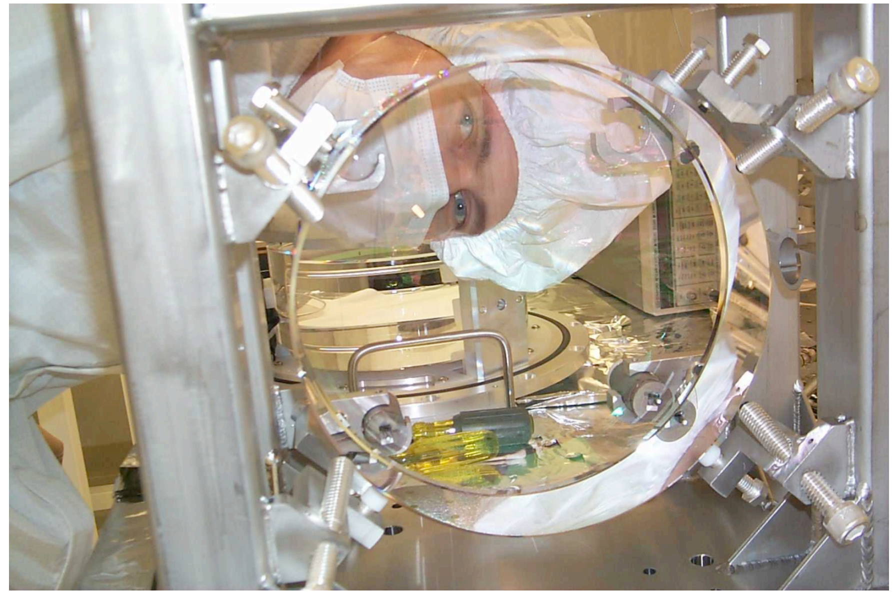
Optical Configuration

Power Recycled Michelson Interferometer

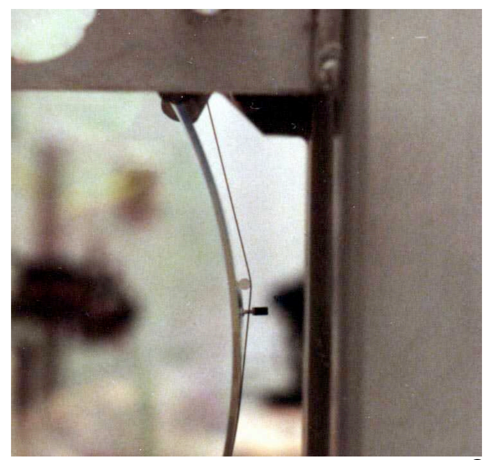


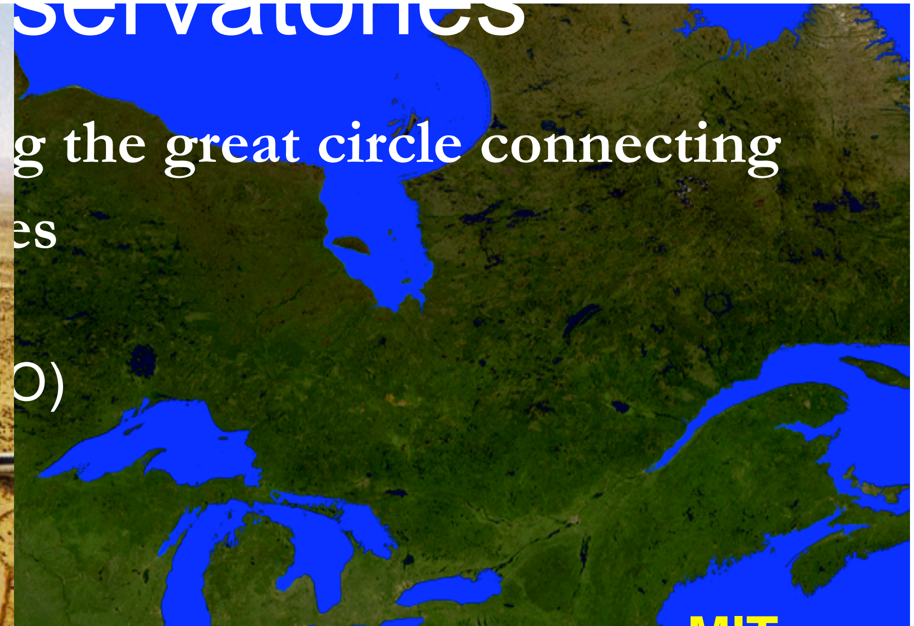
Vacuum "Envelope"

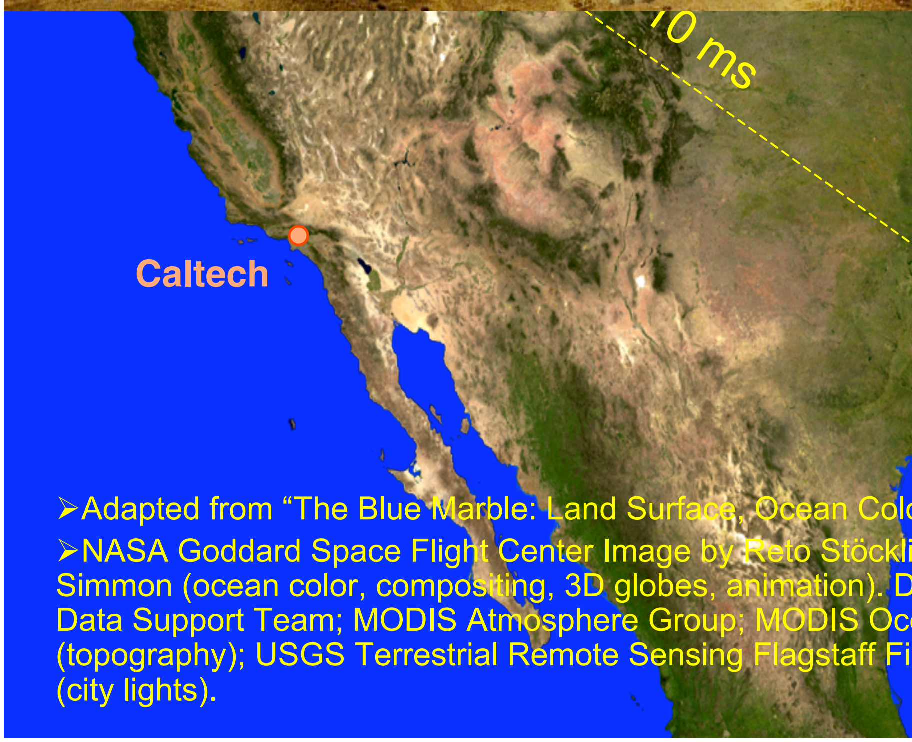
Optic Suspension



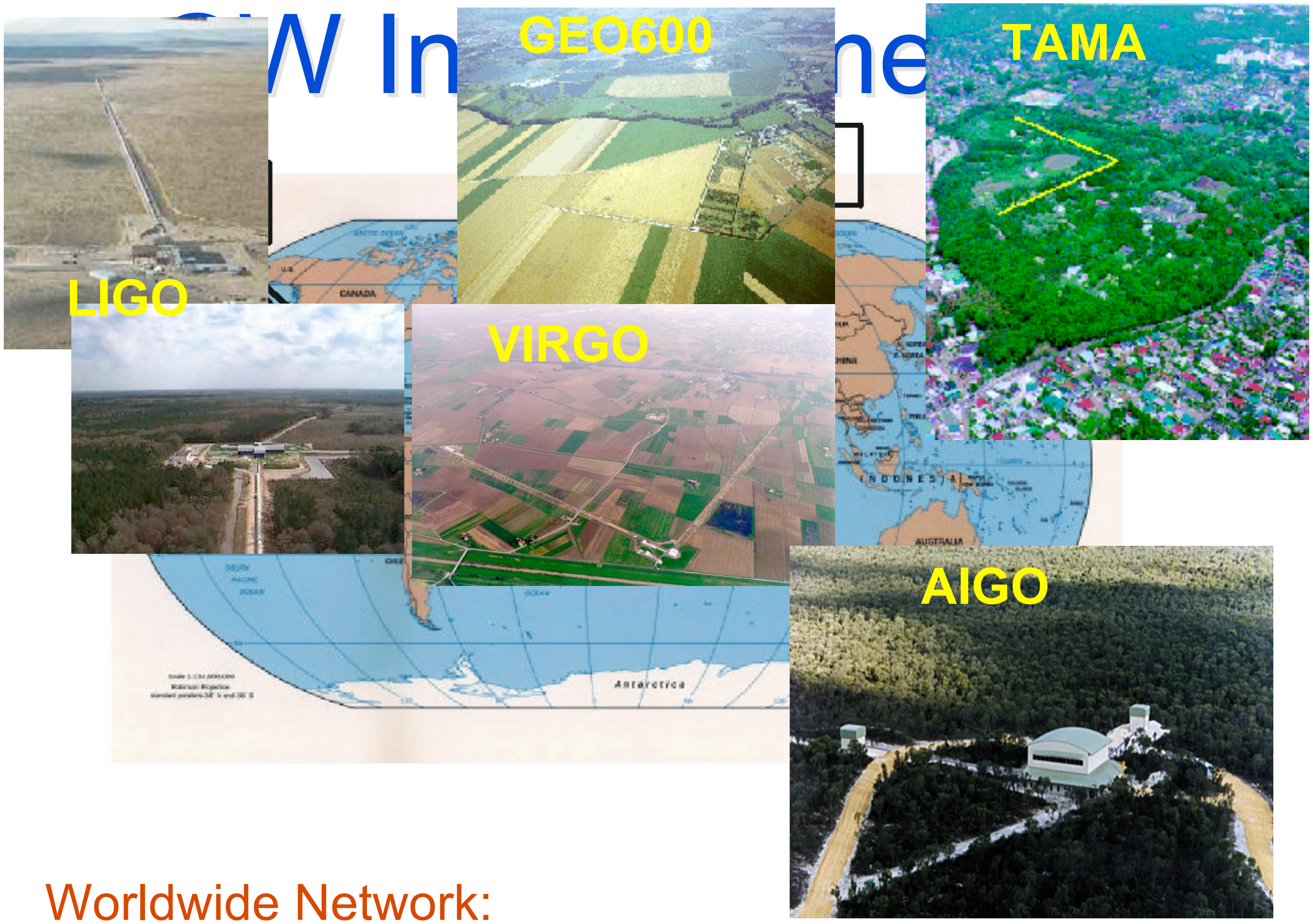
- Magnets and coils control position and angle of mirrors
- Suspension provides $1/f^2$ attenuation above the pendulum resonance ~0.75 Hz.
- Suspension is critical to controlling thermal noise.







➢Adapted from "The Blue Marble: Land Surface, Ocean Colo
➢NASA Goddard Space Flight Center Image by Reto Stöckli
Simmon (ocean color, compositing, 3D globes, animation). D
Data Support Team; MODIS Atmosphere Group; MODIS Oce
(topography); USGS Terrestrial Remote Sensing Flagstaff Fi
(city lights).



- Worldwide Network:
  - We are already working with TAMA and GEO and beginning to work with VIRGO.

Designed Noise Budget

Seismic:
Ground noise spectrum

$h(f) \propto f^{-2}$

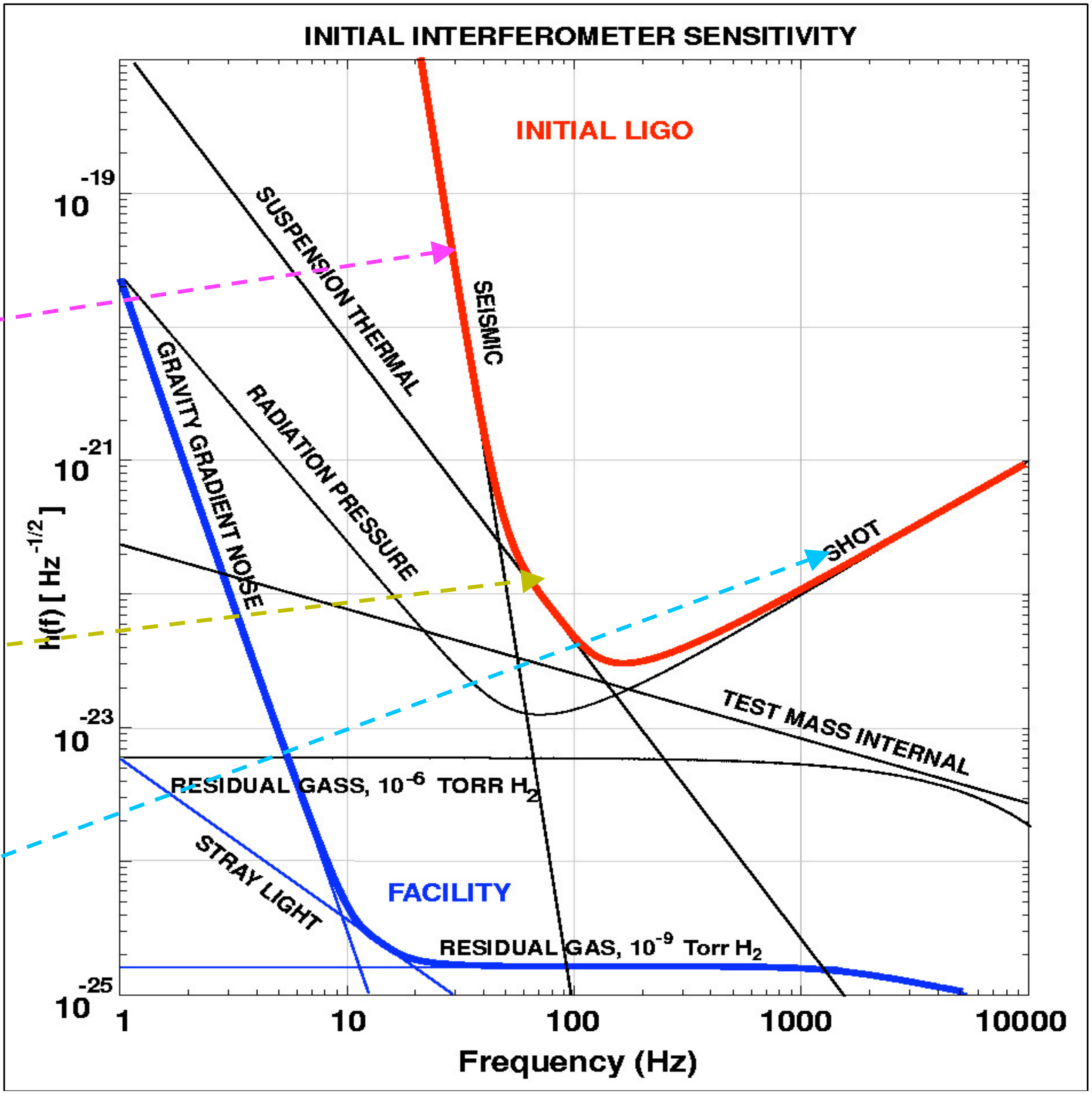
filtered by an isolation stack and a ~1 Hz pendulum

Suspension Thermal:
Viscously damped pendulum

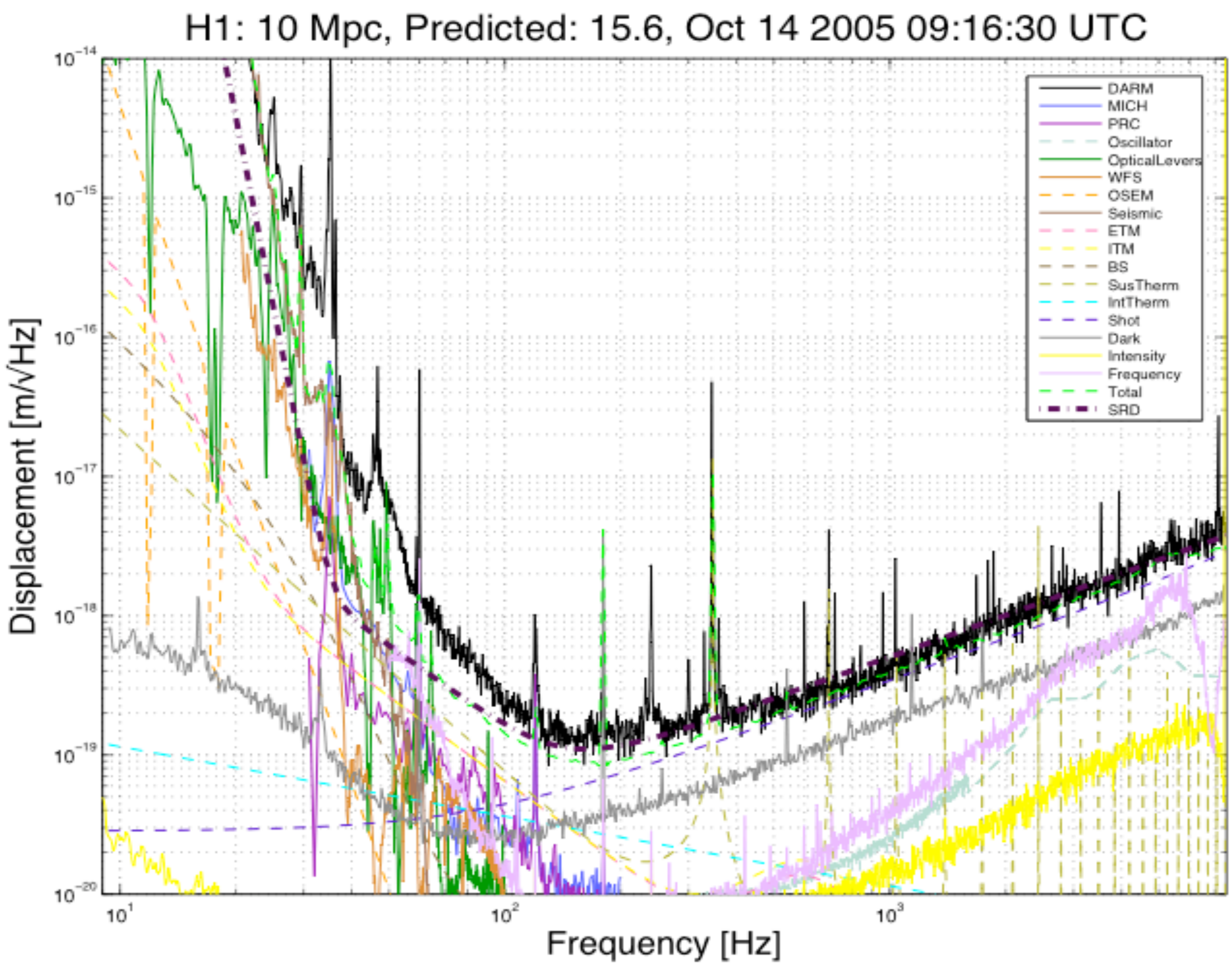
$h(f) \propto f^{-2}$

Shot Noise:
Photon Counting Statistics

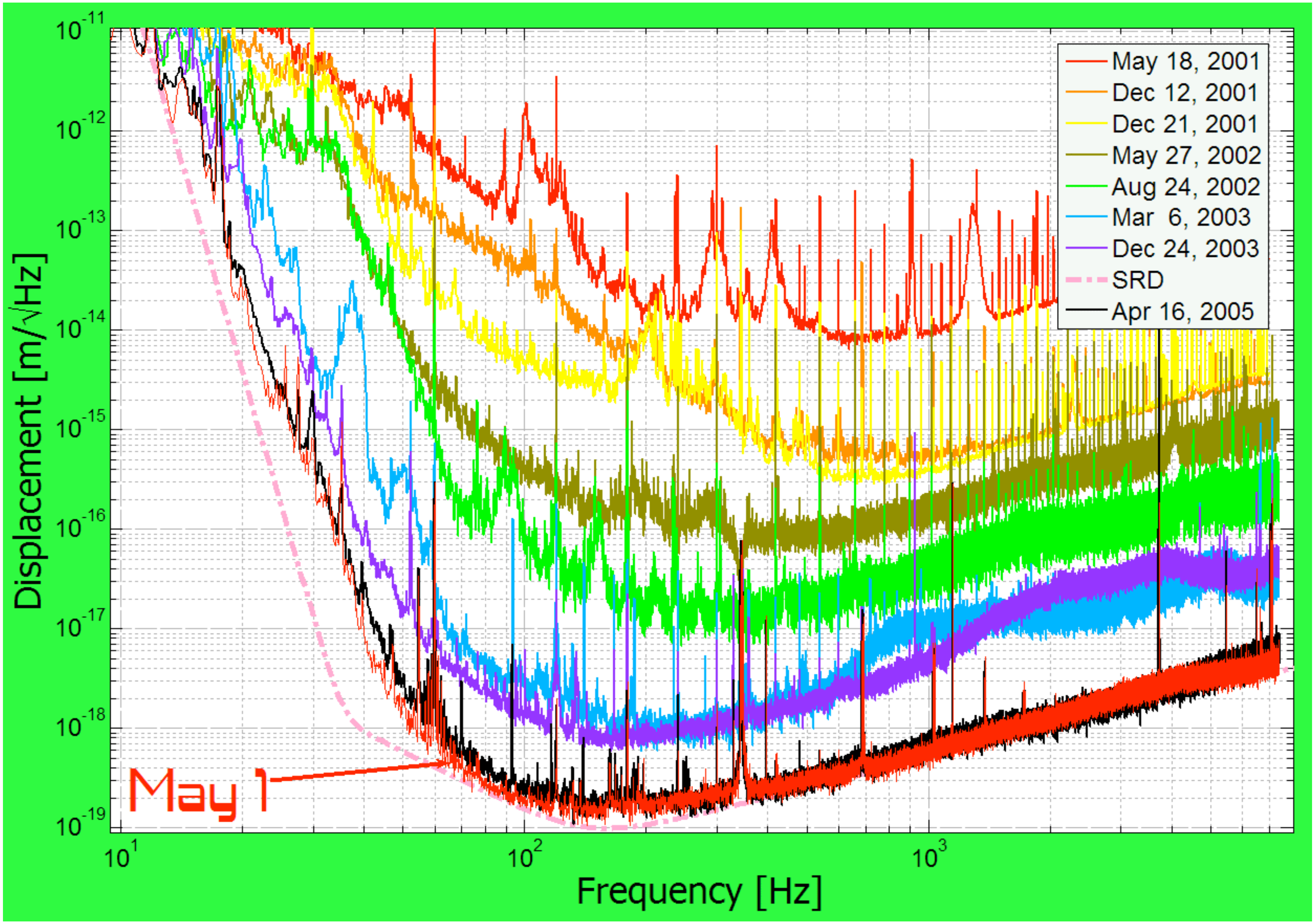
$h(f) \propto f^{-1}$

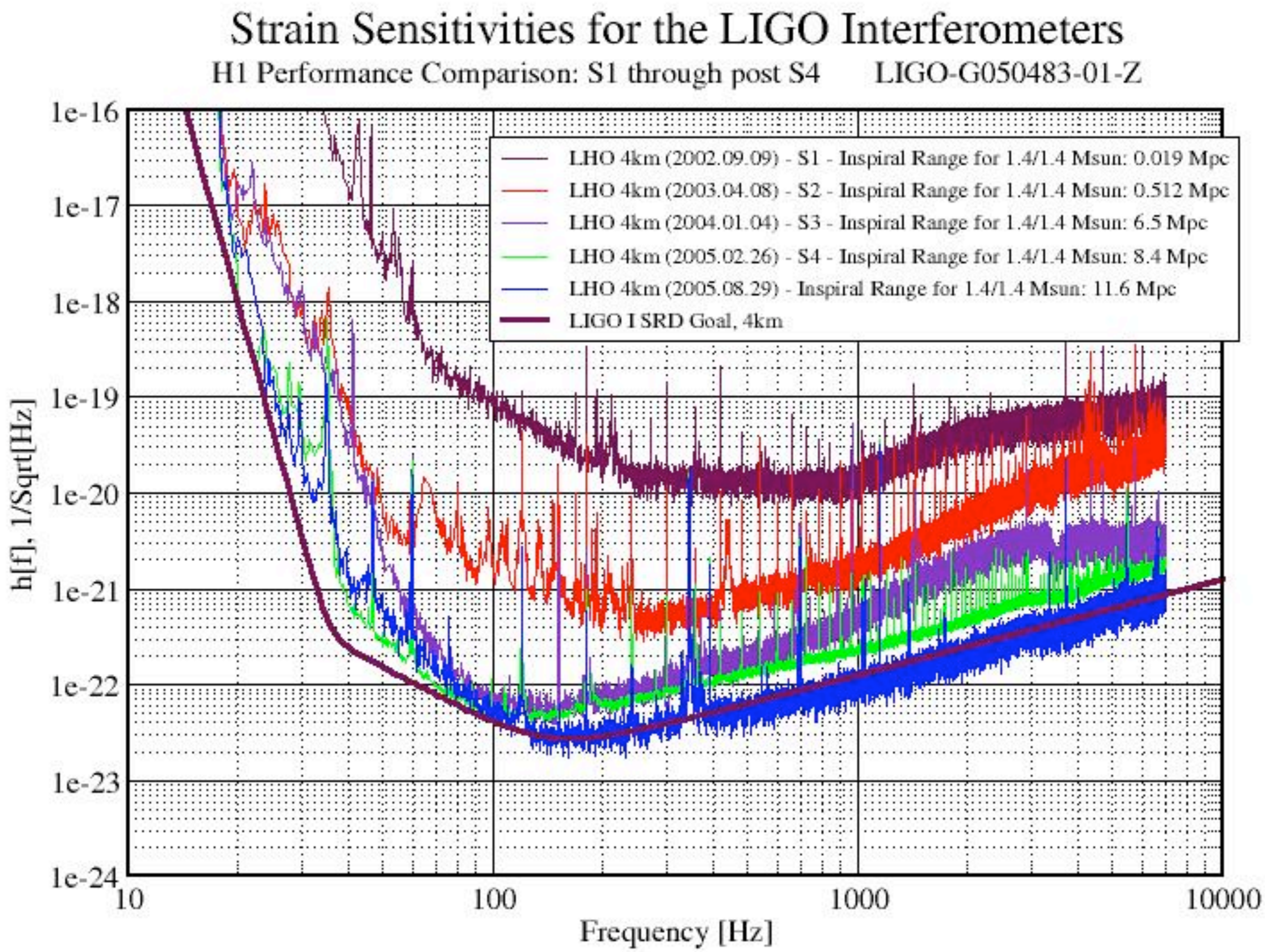


Actual Noise Budget



Louisiana Interferometer

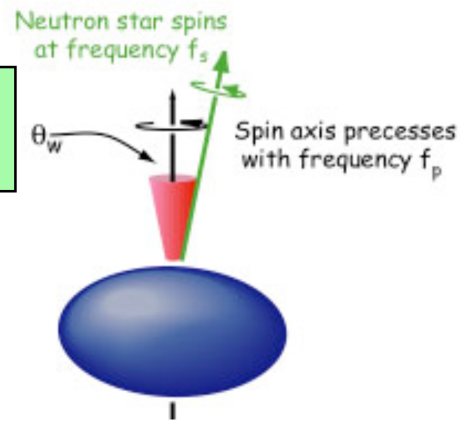




Strain Sensitivities for the LIGO Interferometers
H1 Performance Comparison: S1 through post S4
LIGO-G050483-01-Z
LHO 4km (2002.09.09) - S1 - Inspiral Range for 1.4/1.4 Msun: 0.019 Mpc
LHO 4km (2003.04.08) - S2 - Inspiral Range for 1.4/1.4 Msun: 0.512 Mpc
LHO 4km (2004.01.04) - S3 - Inspiral Range for 1.4/1.4 Msun: 6.5 Mpc
LHO 4km (2005.02.26) - S4 - Inspiral Range for 1.4/1.4 Msun: 8.4 Mpc
LHO 4km (2005.08.29) - Inspiral Range for 1.4/1.4 Msun: 11.6 Mpc
LIGO I SRD Goal, 4km
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]

Gravitational Wave Sources

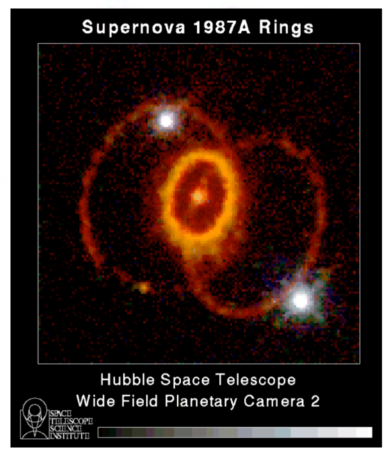
Spinning or wobbling neutron stars



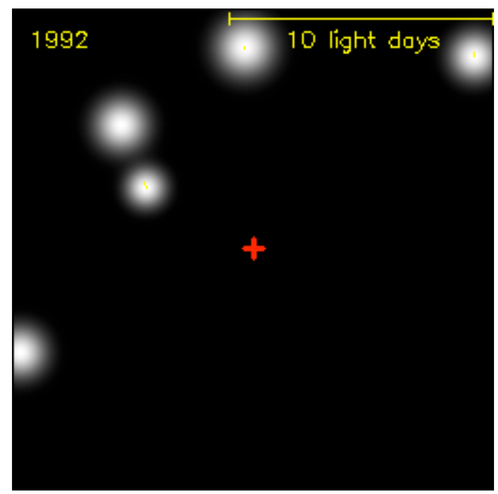
matter

Massive Star

Giant Phases



Infrared and sub-millimeter Astronomy Group at MPE



Grav

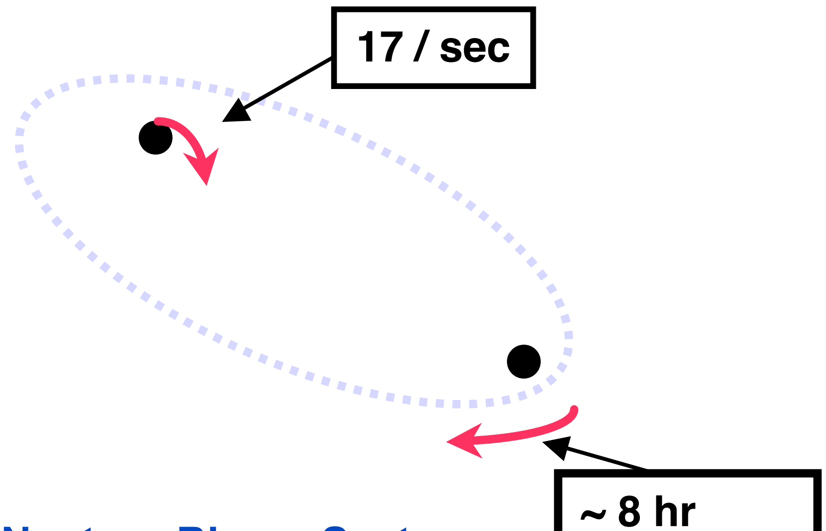
Compress into small space

GRB, Ringdowns

Strong Evidence: Orbital Decay

Neutron Binary System – Hulse & Taylor

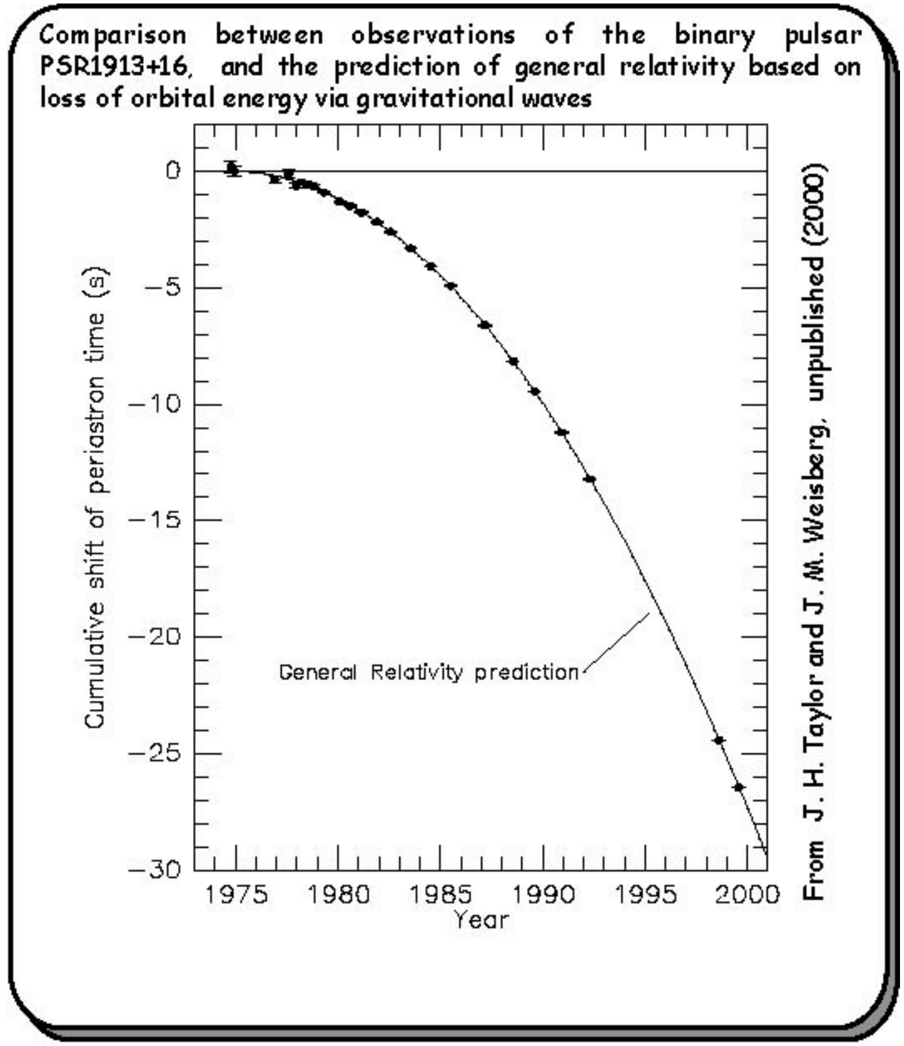
PSR 1913 + 16 -- Timing of pulsars



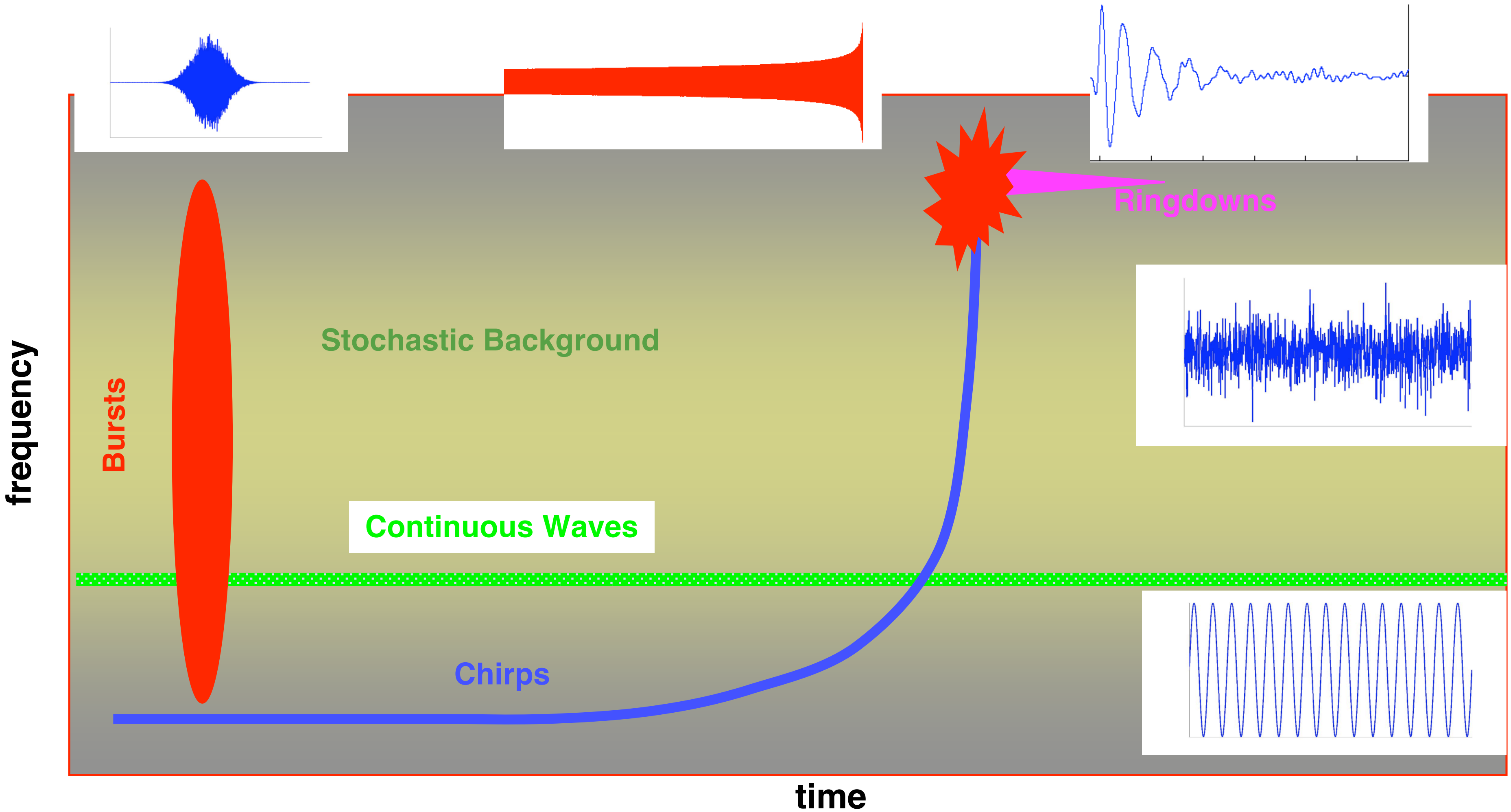
Neutron Binary System
- **separated by 10^6 miles**
- **$m_1 = 1.44 m_\odot$; $m_2 = 1.39 m_\odot$; $\varepsilon = 0.617$**

Prediction from general relativity
- **spiral in by 3 mm/orbit**
- **rate of change orbital period**

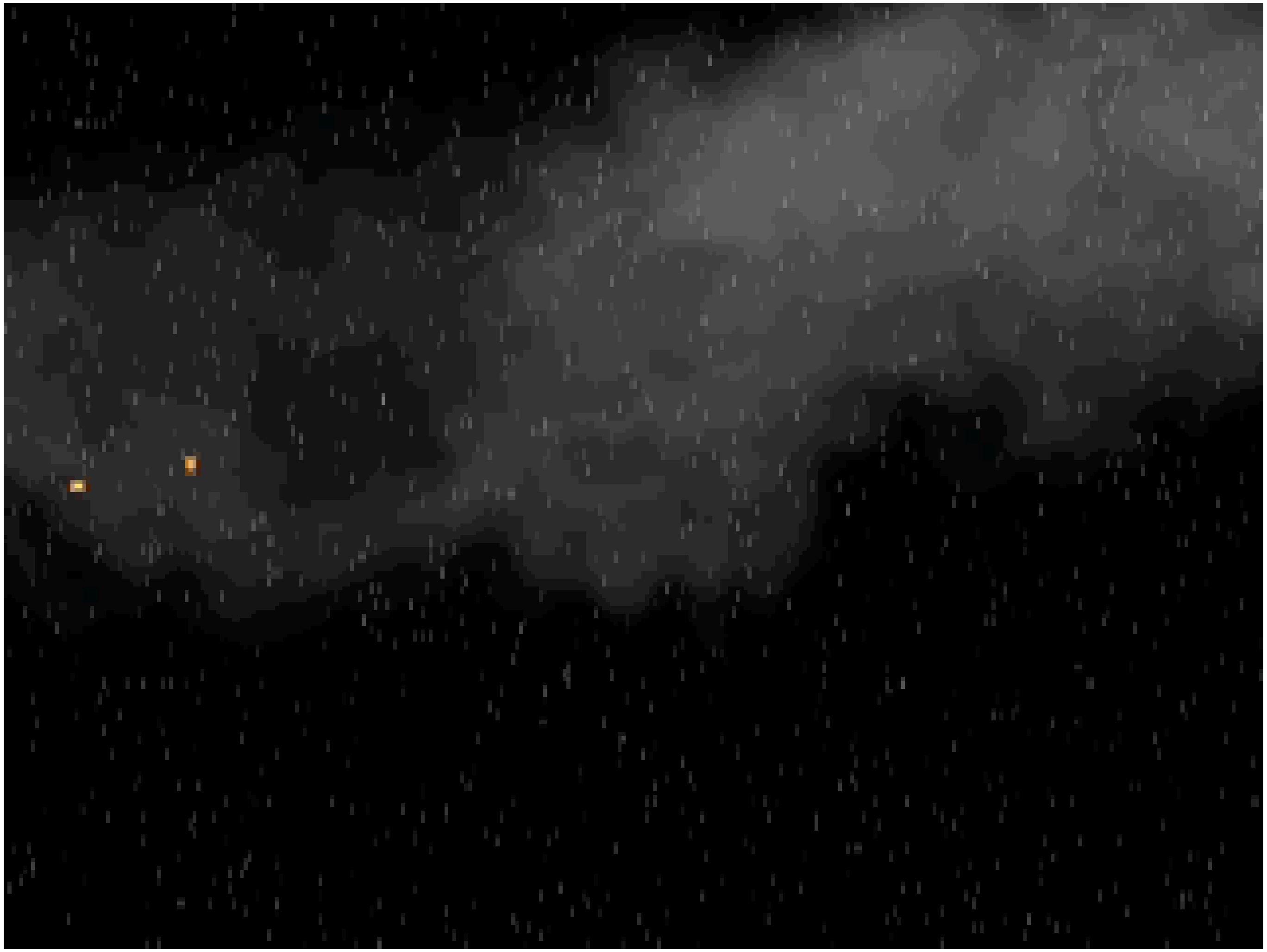
Emission of gravitational waves



Search Targets



“Chirps”



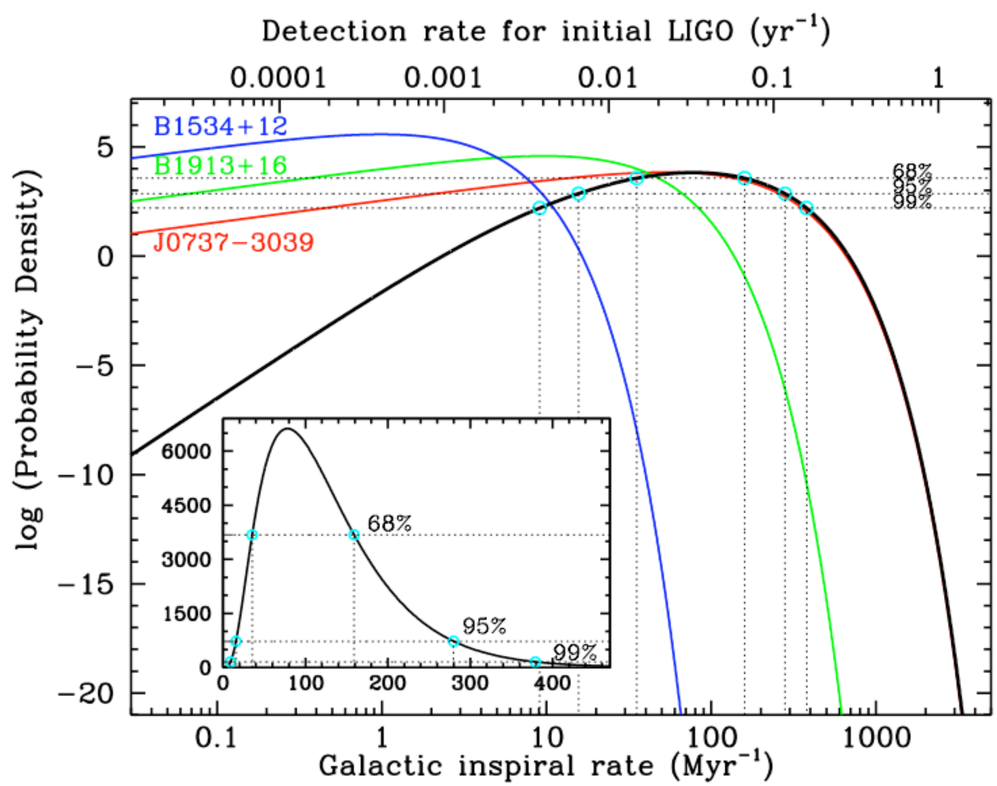
The LIGO Scientific Collaboration

- Approximately 500 members
- 35 Institutions plus the LIGO laboratory.
- International participation from Australia, Germany, India, Japan, Russia, Spain and the U.K.
- Consists of technical and data analysis groups tasked with detector characterization, Advanced LIGO R&D and the search for Gravitational Waves.

BNS Rate Predictions

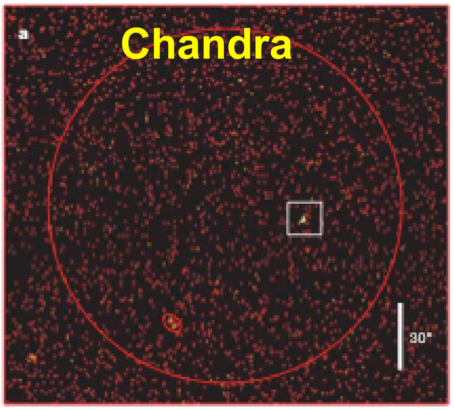
- Initial LIGO (20 Mpc):
  - Peak: 35/(10^3 yr)
  - 95% CL: 10-120/(10^3 yr)
- Advanced LIGO (350 Mpc)
  - Peak: 175 event/yr
  - 95% CL: 35-630 events/yr
- But small statistics, based on three known relativistic binaries.

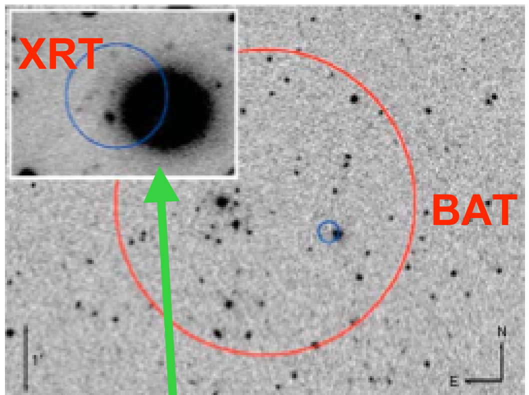
V. Kalogera et al.

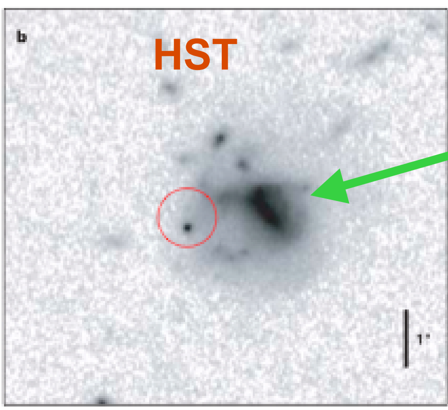


Short GRBs

GRB050709 **GRB050509B**

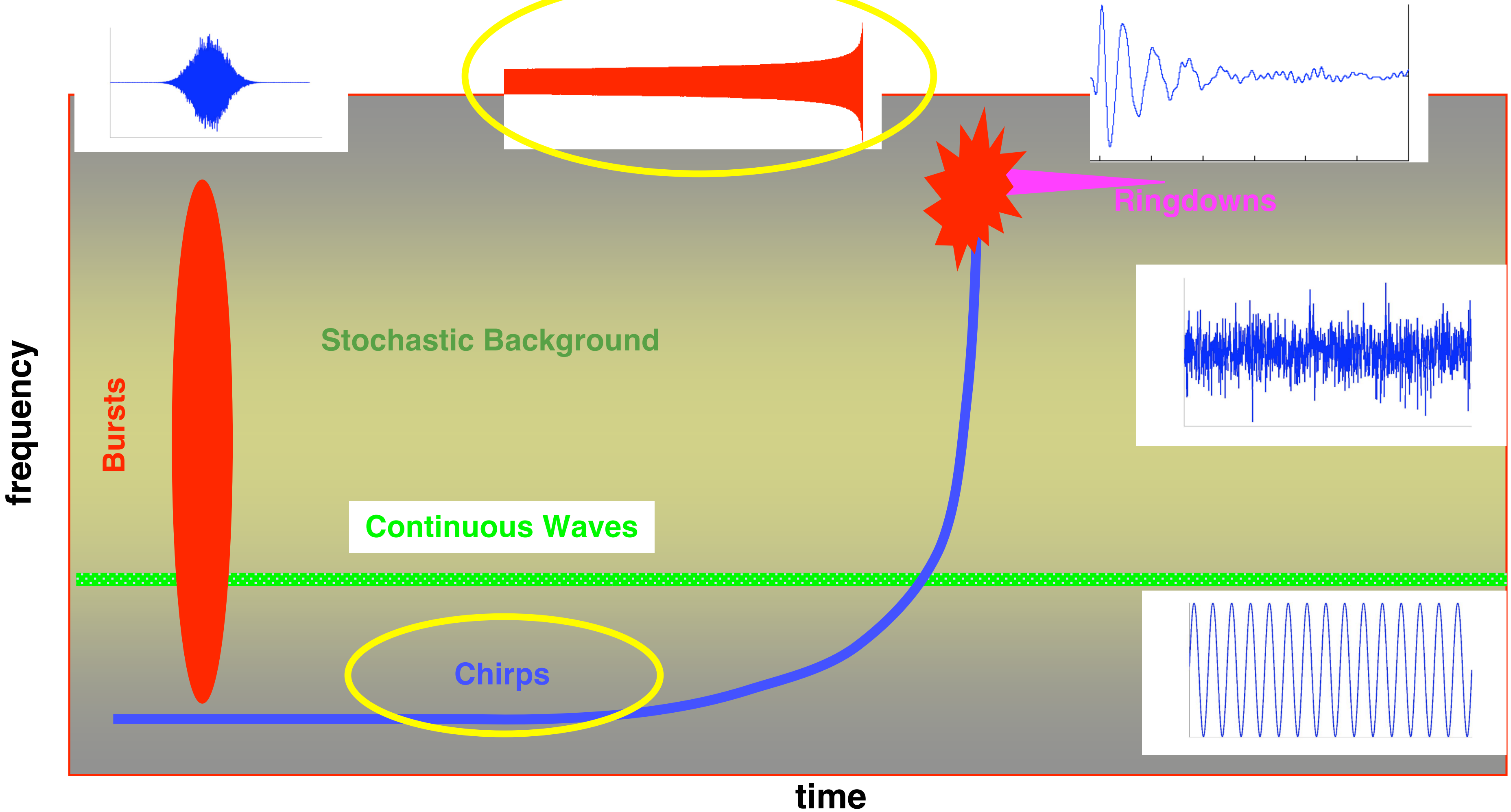




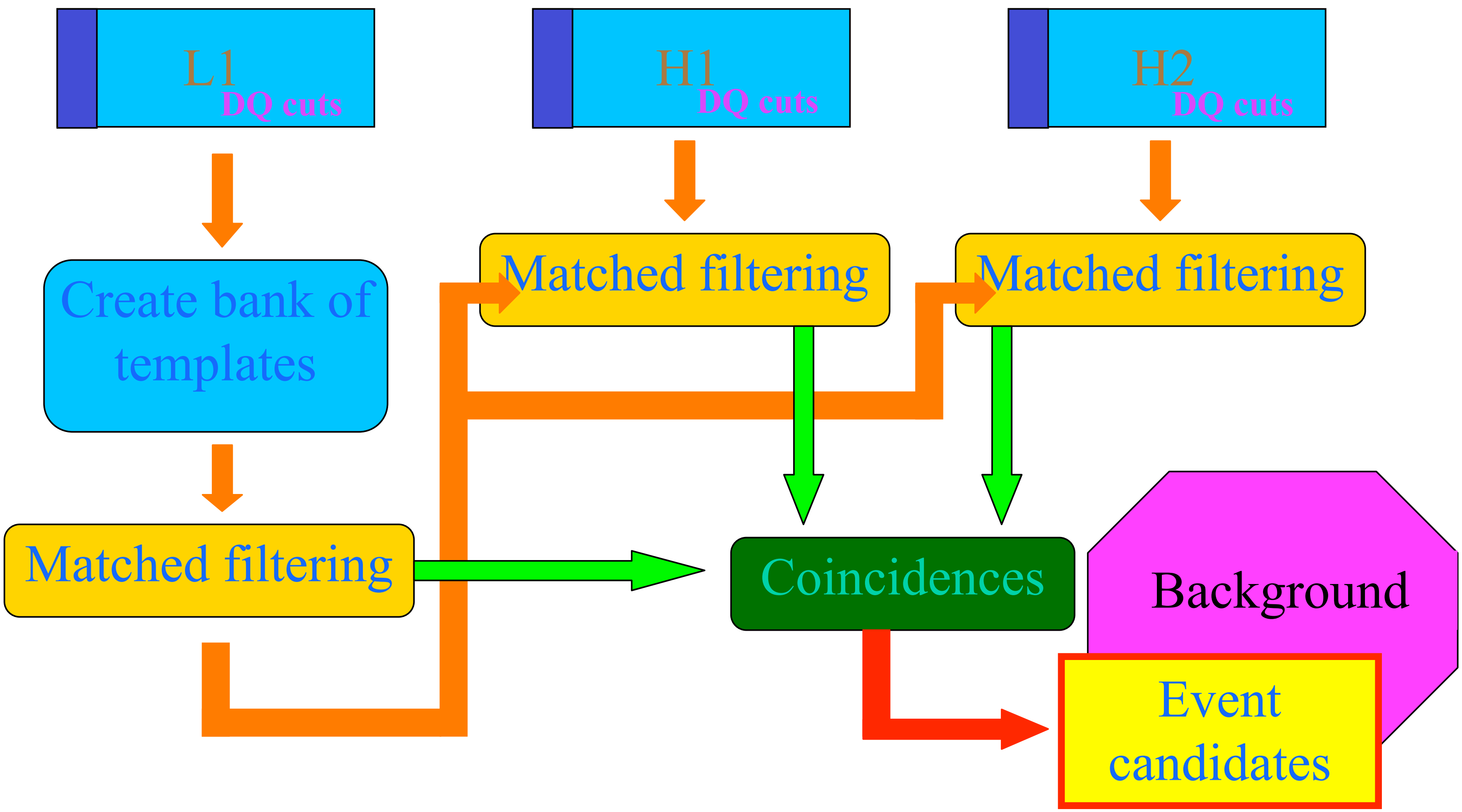


- 050509B Associated with non-star forming elliptical galaxy.
- 050709 Associated with younger star-forming galaxy.
- No evidence of associated supernovae.
- Two other events GRB050724 and GRB050813 have similar redshifts and peak luminosities.
- Perhaps arising from NS-NS or NS-BH merger?
- Ramifications for LIGO as yet unclear.

Search Targets

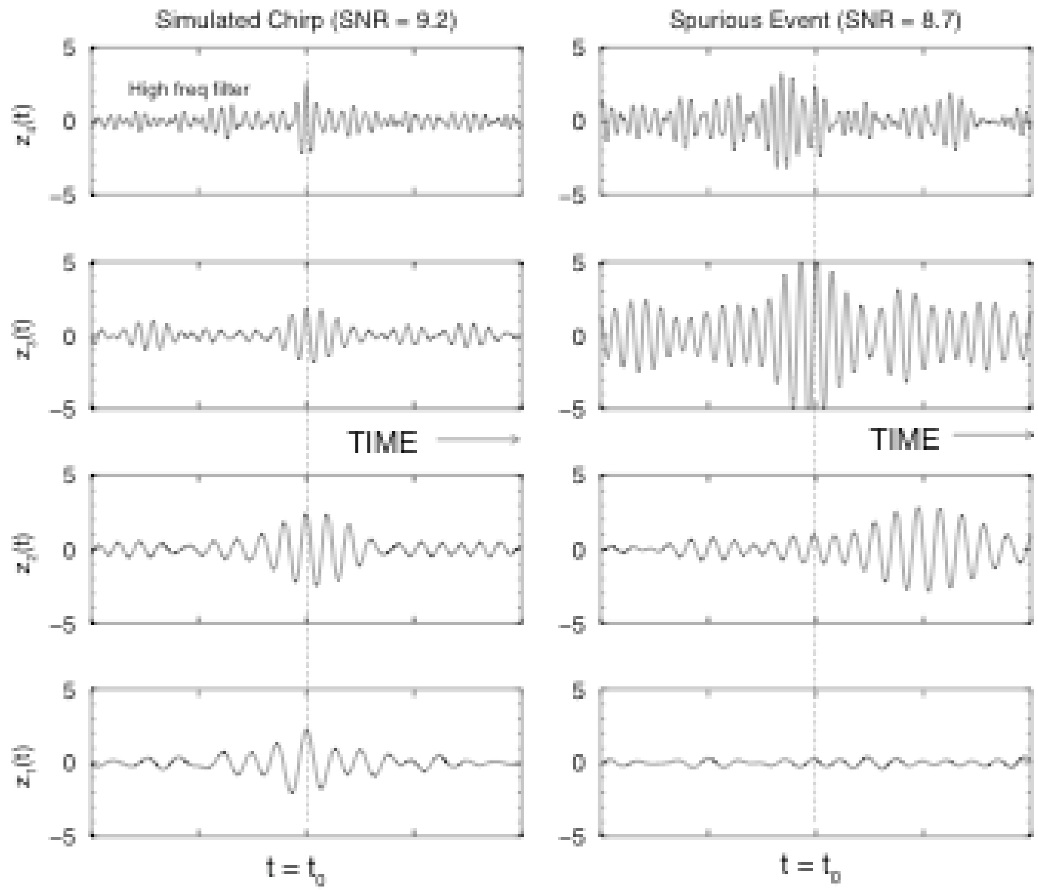


Inspiral Pipeline (simplified)



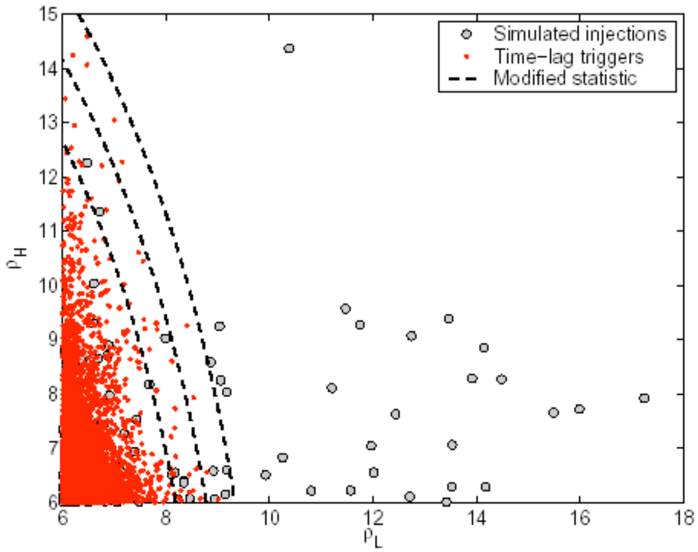
χ^2 Test

- Divide template into *p* frequency bands, each of which contributes *1/p* to the total SNR.
- Construct χ^2 statistic comparing the magnitude and phase of SNR accumulated in each band to the expected amount.
- In S2 used *p = 15*
- χ^2 threshold determined from playground data.



B. Allen, Phys Rev. D**71**, 062001 (2005)

S2 BNS search



False alarm coincident triggers, and simulated injections

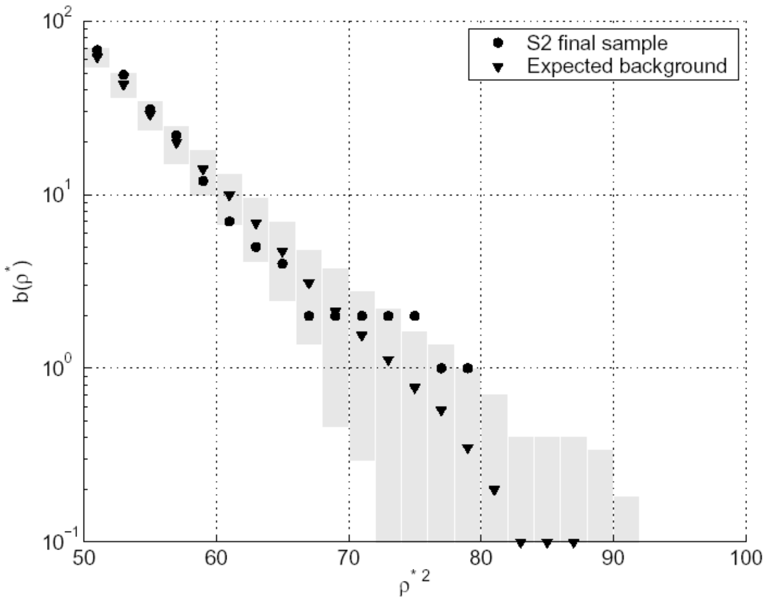


FIG. 8: The number of triggers per S2 above combined SNR ρ^*.

- Used a combined SNR:

$$\sqrt{{\rho_L}^2 + \frac{{\rho_H}^2}{4}}$$

- Modified clustering technique, instead of using max SNR, used *best-fit clustering:*

$$\frac{\chi_H^2}{p + \delta^2 \rho_H^2} + \frac{\chi_L^2}{p + \delta^2 \rho_L^2}$$

S2 Result

- Loudest event statistic:

$$R < R_{90\%} = \frac{2.303 + \ln P_b}{T N_G(\rho_{max})}$$

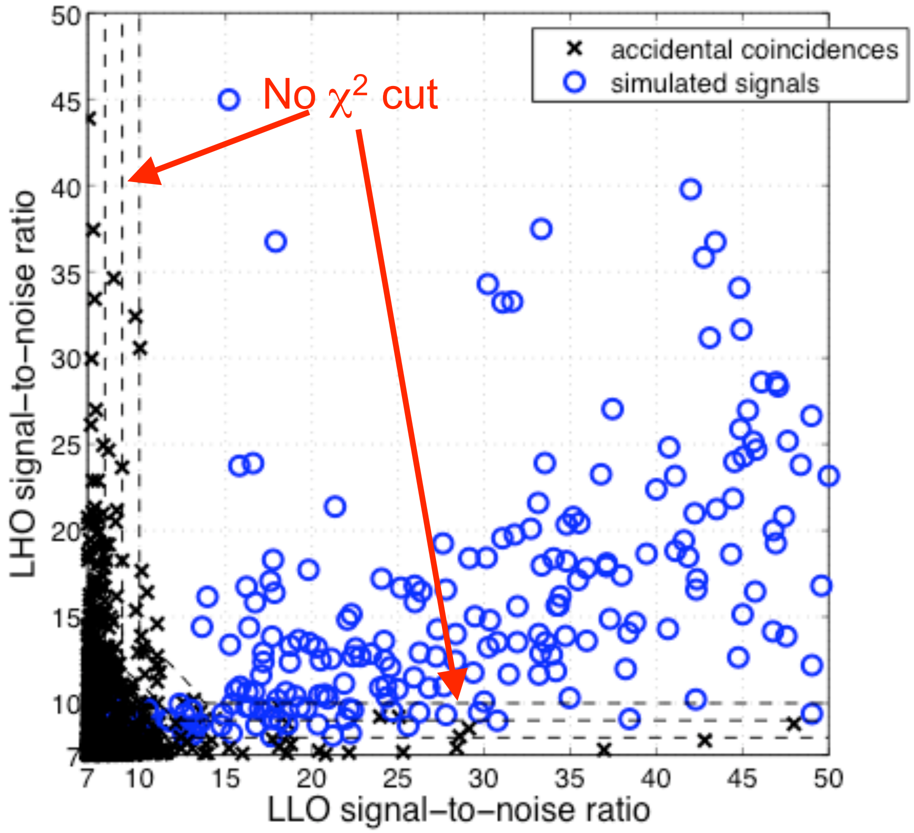
- A frequentist upper limit. ρ_{max} is the maximum observed SNR, P_b is the probability that all background triggers have SNR < ρ^*, conservatively taken = 1, T is the total observation time (339 h) and $N_G(\rho_{max})$ is the total number of MWEG to which the search is sensitive.

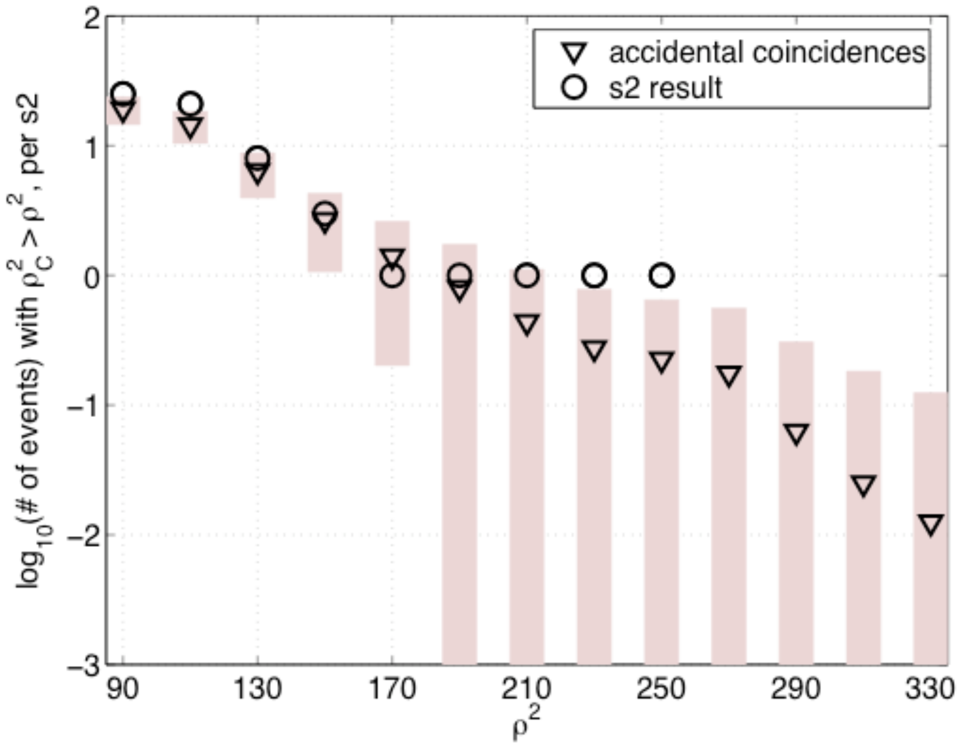
$$R_{90\%} = 47\ y^{-1}\ MWEG^{-1}$$

S2 BBH Search

- Component mass 3-20 M_{sol}
  - f of ISCO: 733 - 110 Hz
  - Time in detection band: 0.607 - 0.013 seconds
  - χ^2 test is not effective
- Use phenomenological family of waveforms
  - A. Buonanno, Y. Chen and M. Vallisneri, Phys. Rev. D **67**,024016 (2003)
  - Good match with models, efficient at recovering injections.
  - Not good for parameter estimation.
  - Restricting template bank can lead to atypical waveforms.
    - On average 958 templates per 2048 s of L1 data.

S2 BBH Results

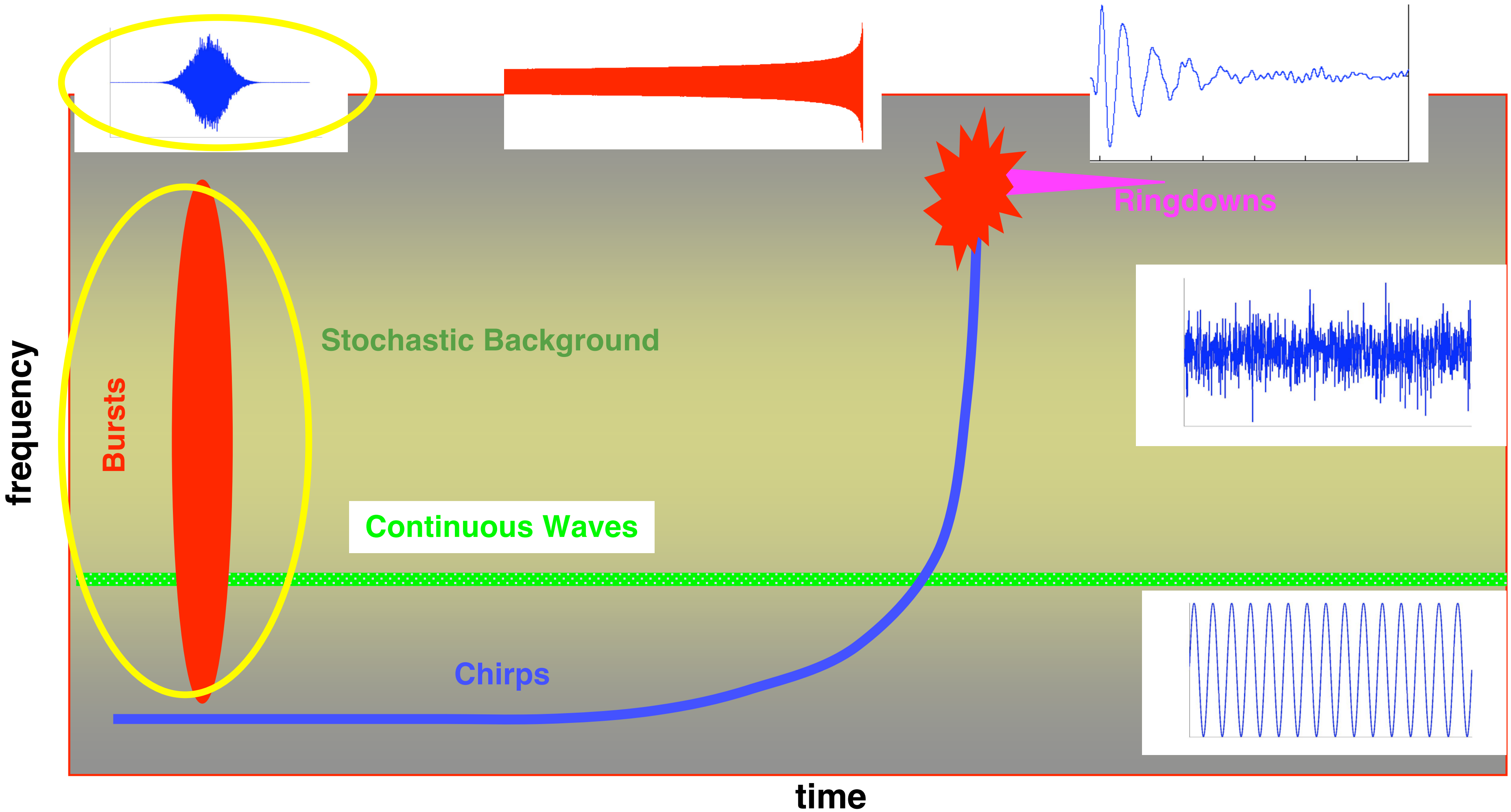




$$\rho_C = \min\{\sqrt{\rho^2{}_L + \rho^2{}_H}, 2\rho^2{}_H - 3, 2\rho^2{}_L - 3\}$$

$R_{90\%}$ = 35 y^{-1} $MWEG^{-1}$

Search Targets



Burst Search

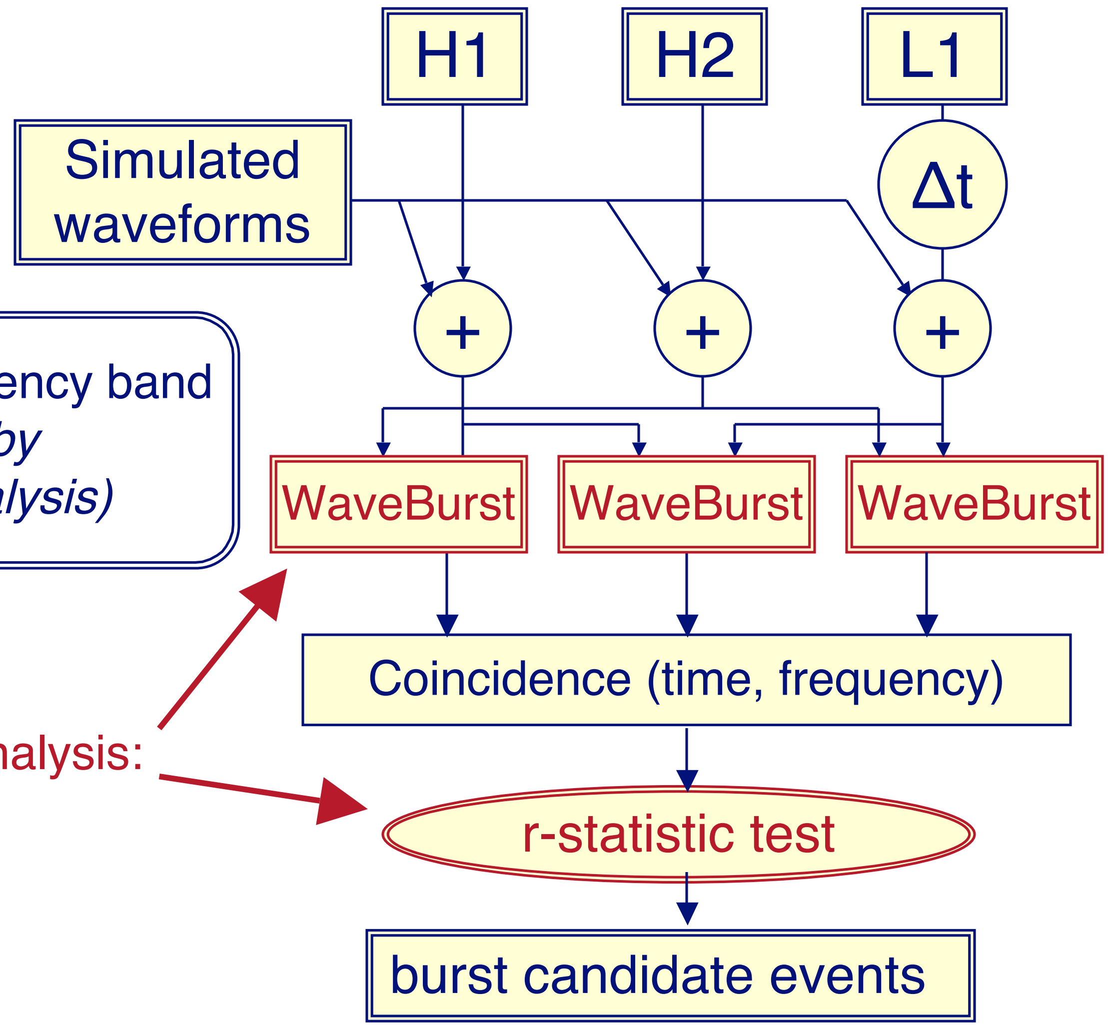
- Threefold coincidence for reduction of accidentals
- A “blind” search tuned on a playground, O(10%) of full data
- Determine background by forming time-delayed coincidences
- Measure detector and algorithm response via software and hardware injections
  - Establish efficiency as function of signal strength
  - Quantify accuracy of burst parameter estimation
  - Use ad hoc or astrophysically motivated waveforms

S2 Burst Analysis Pipeline

The search uses all three LIGO interferometers (H1, H2, L1)

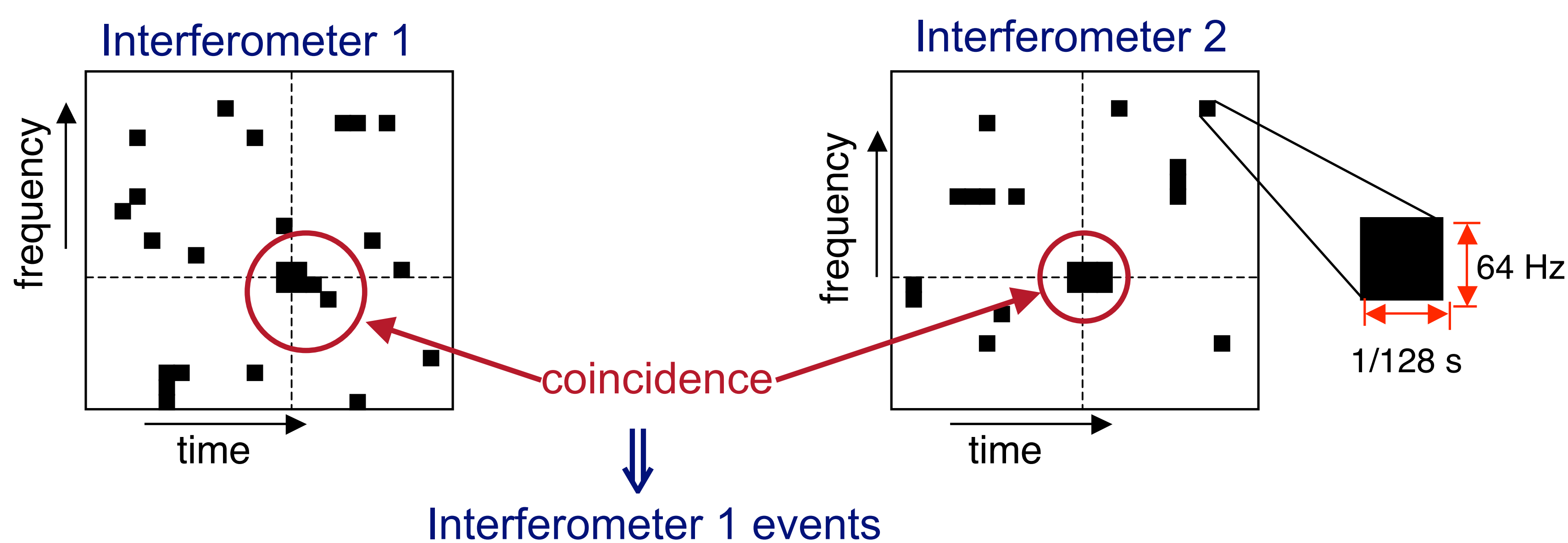
Search in 100-1100 Hz frequency band
(higher frequencies covered by LIGO-TAMA coincidence analysis)

Novelties since the S1 analysis:



WaveBurst: Candidate Events Generation

- Excess power in wavelet time-frequency plane.
  - Black pixels



Repeat on 3 pairs, to obtain events from 3 interferometers and their significance..

Threshold on combined significance of triple coincidence events.

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

r-statistic Waveform Consistency Test

Process **pairs** of interferometers (whitened data, 100-2000 Hz)

What is the probability that the 2 data sequences are un-correlated ?

r-statistic:

$$r_k = \frac{\sum_i (x_i - \bar{x})(y_{i+k} - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_{i+k} - \bar{y})^2}}$$

Significance of null-hypothesis:

$$S = \mathrm{erfc}\left(\sqrt{r^2 \frac{N}{2}}\right)$$

The incident GW direction is unknown
→ allow time delay (Δt) between the two data series

$$C_M = \max_{\Delta t}\left(-\log_{10} S(\Delta t)\right)$$

Combine IFO pairs and search possible signal duration to maximize the final statistic Γ

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

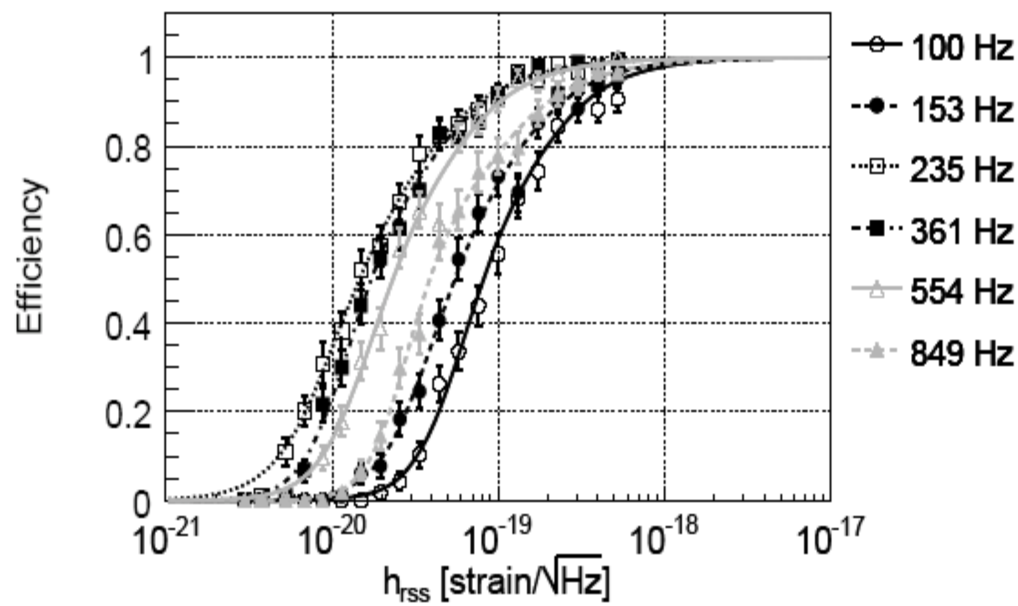
Ref. *Class. Quantum Grav. 21 S1695-S1703*

Detection Efficiency Studies

- Measure test waveform efficiencies vs. signal strength $h_{rss} = \sqrt{\int |h(t)|^2 \, dt}$
  - Sine-Gaussians, Gaussians
  - core collapse supernovae from three models (ZM,DFM,OBLW)
  - BBH merger (and ringdown) waveforms (Lazarus project)

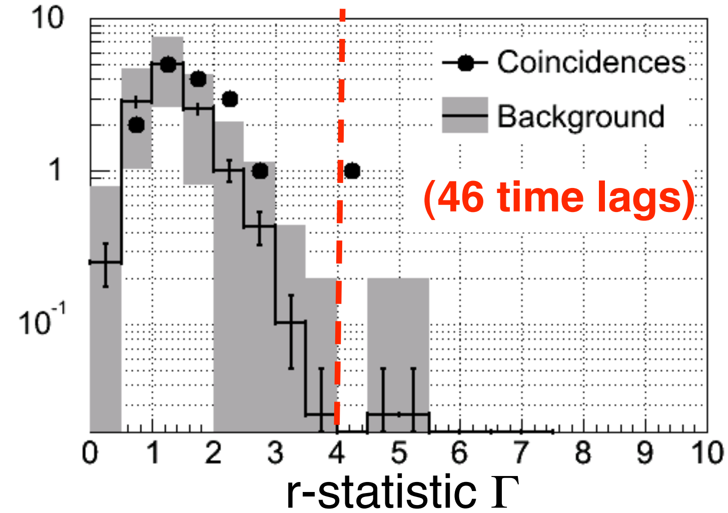
- Source sky coordinates and polarizations were taken randomly; fixed inclination taken for SN,BBH
- Software injections: signals added to digitized interferometer output
- Hardware injections: signals added to length servo signal

Q=8.9 sine-Gaussian Efficiencies

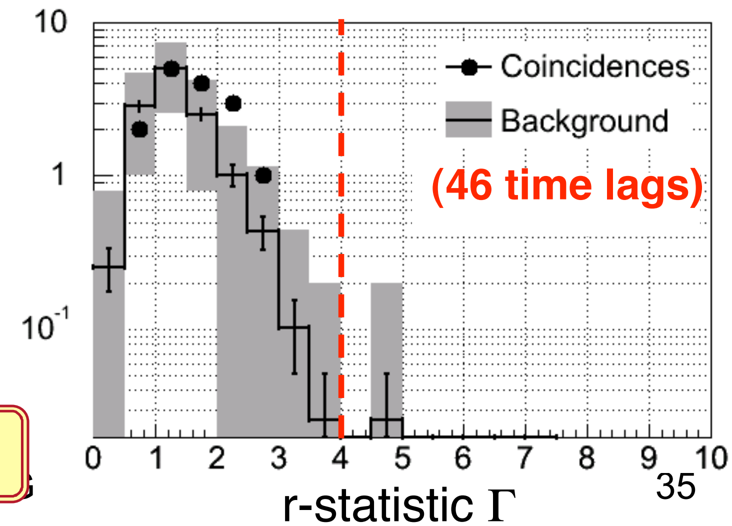


Upper Limit on Rate of Detectable Bursts

- The blind procedure gives one candidate
  - Event immediately found to be correlated with airplane over-flight at Hanford.
  - Acoustic noise detected in microphones and known couplings account for Hanford burst triggers (solved before the S3 run)
- Background estimate is 0.05

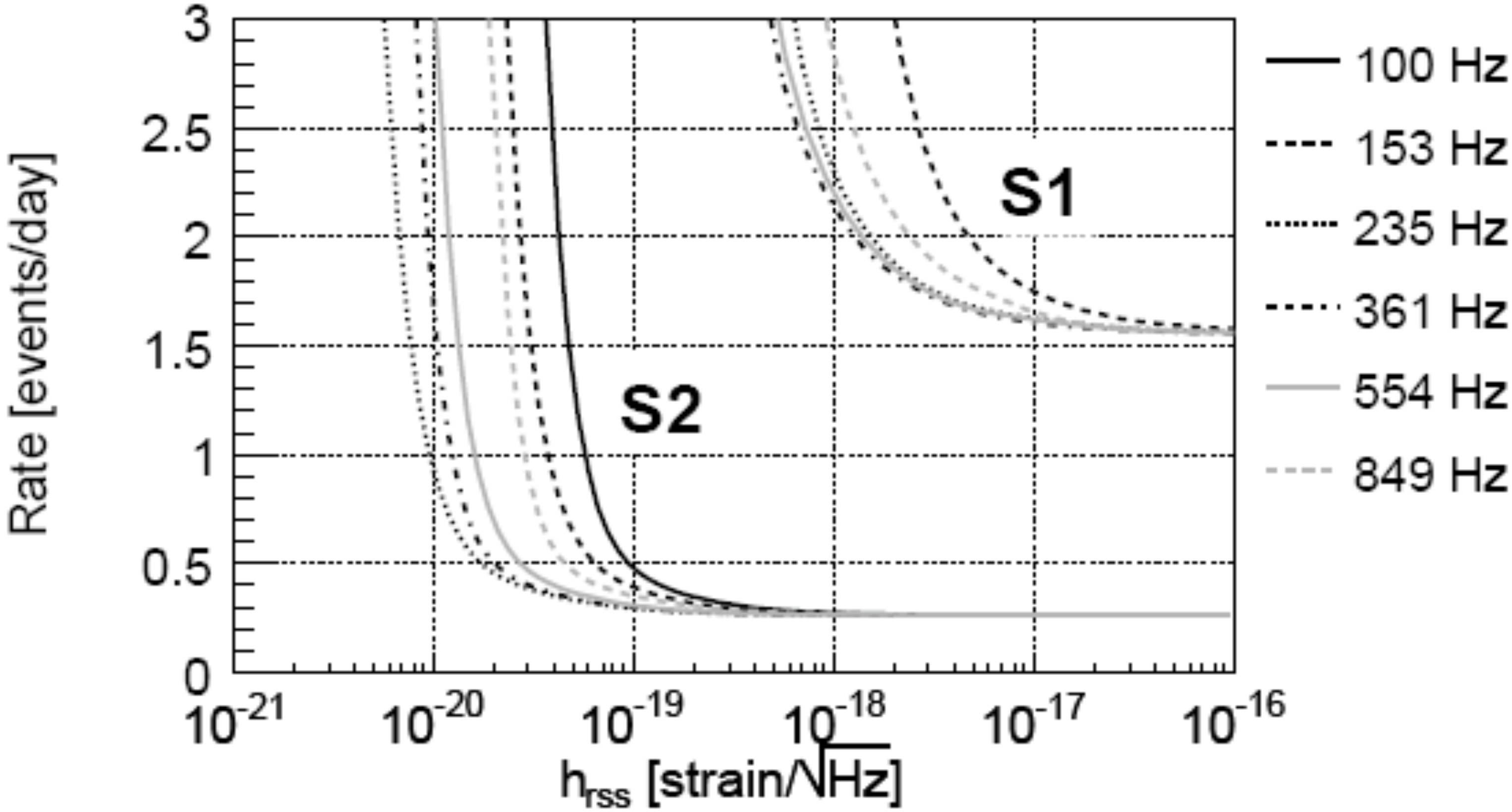


- Introducing a post-facto acoustic veto
  - power in 62-100 Hz band in PSL table microphone
- Background estimate is 0.025
- 90% CL upper limit is 2.6 events
  - Account for modified coverage due to introduction of post-facto veto



Rate upper limit = 0.26/day (1.6/day in S1)

Interpreted results: rate-strength curves

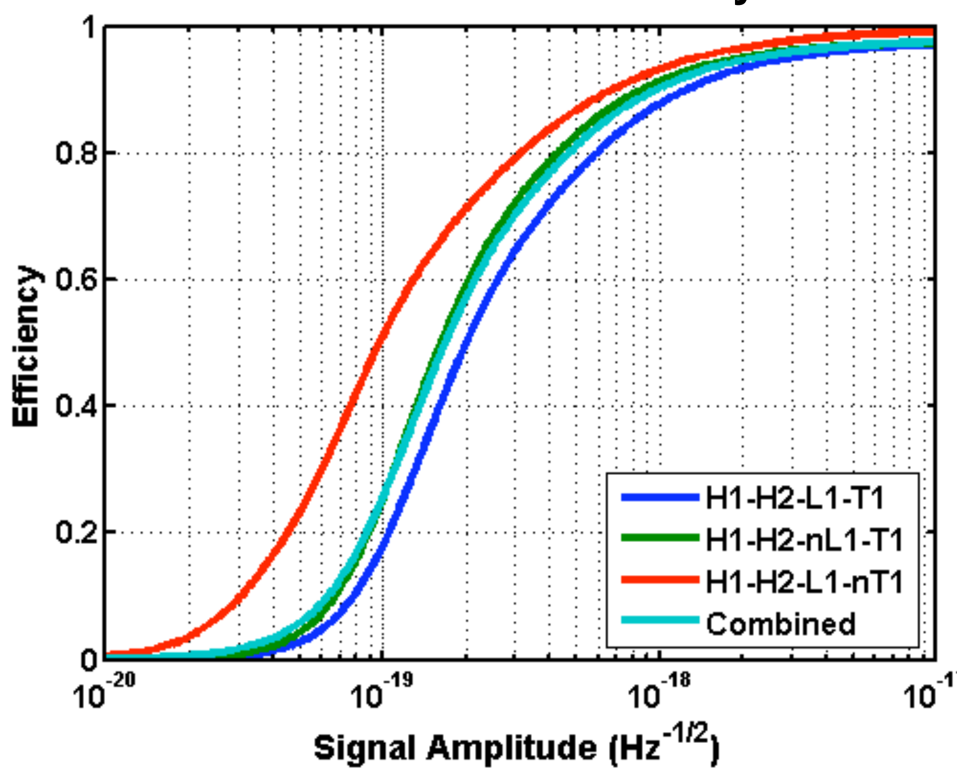


- S2 search detects less than 0.26 events/day at the 90% conf. level
- Divide by the efficiency curve for a particular waveform to get rate vs strength exclusion region

LIGO-TAMA search

- LIGO - TAMA S2/DT8 joint burst search
  - High-frequency search uses the minimum of noise envelope: [700,2000]Hz
  - Complementary to the LIGO-only S2 search [100,1100]Hz
  - Uses similar overall methodology
- Maximize observation time
  - 19.7 days of x3/x4 coincidence observation
  - 6.9 days of x4 coincidence observation
- No gravitational wave bursts found corresponding to a 90% upper limit of 0.12 events/day
- Sine-Gaussian simulations (with sky & polarization averaging) indicate a 50% detection efficiency at 2x10^{-19} $Hz^{-1/2}$

Detection efficiency



S1 Physics Papers

- *First Upper Limits from LIGO on GW Bursts,* B. Abbott et al. (LSC), Phys. Rev. D **69** (2004) 102001
- *Setting Upper Limits on the Strength of Periodic GW from PSR J1939 + 2134 Using the First Science Data from the GEO600 and LIGO Detectors,* B. Abbott et al. (LSC), Phys. Rev. D **69** (2004) 082004
- *Analysis of LIGO Data for GW from Binary Neutron Stars*, B. Abbott et al. (LSC), Phys. Rev. D **69** (2004) 122001
- *Analysis of LIGO Data for Stochastic GW,* B. Abbott et al. (LSC), Phys. Rev. D **69** (2004) 122004

S2 Physics Papers

- *A Search for Gravitational Waves Associated with the Gamma Ray Burst GRB030329 Using the LIGO Detectors,* B. Abbott et al. (LSC), Phys. Rev. D 72, 042002 (2005)
- *Upper Limits on Gravitational Wave Bursts in LIGO's Second Science Run,* B. Abbott et al. (LSC), Phys. Rev. D 72, 062001 (2005)
- *Upper Limits from the LIGO and TAMA Detectors on the Rate of Gravitational-Wave Bursts,* B. Abbott et al. (LSC), Submitted to Phys. Rev. D

S2 Physics Papers cont.

- *Search for gravitational waves from galactic and extra-galactic binary neutron stars,* B. Abbott et al. (LSC), To appear in Phys. Rev. D
- *Search for Gravitational Waves from Primordial Black Hole Binary Coalescences in the Galactic Halo,* B. Abbott et al. (LSC), To appear in Phys. Rev. D
- *Search for gravitational waves from binary black hole inspirals in LIGO data,* B. Abbott et al. (LSC), Submitted to Phys. Rev. D
- *Joint Search for Gravitational Waves from Inspiralling Neutron Star Binaries in LIGO and TAMA300 data,* in progress

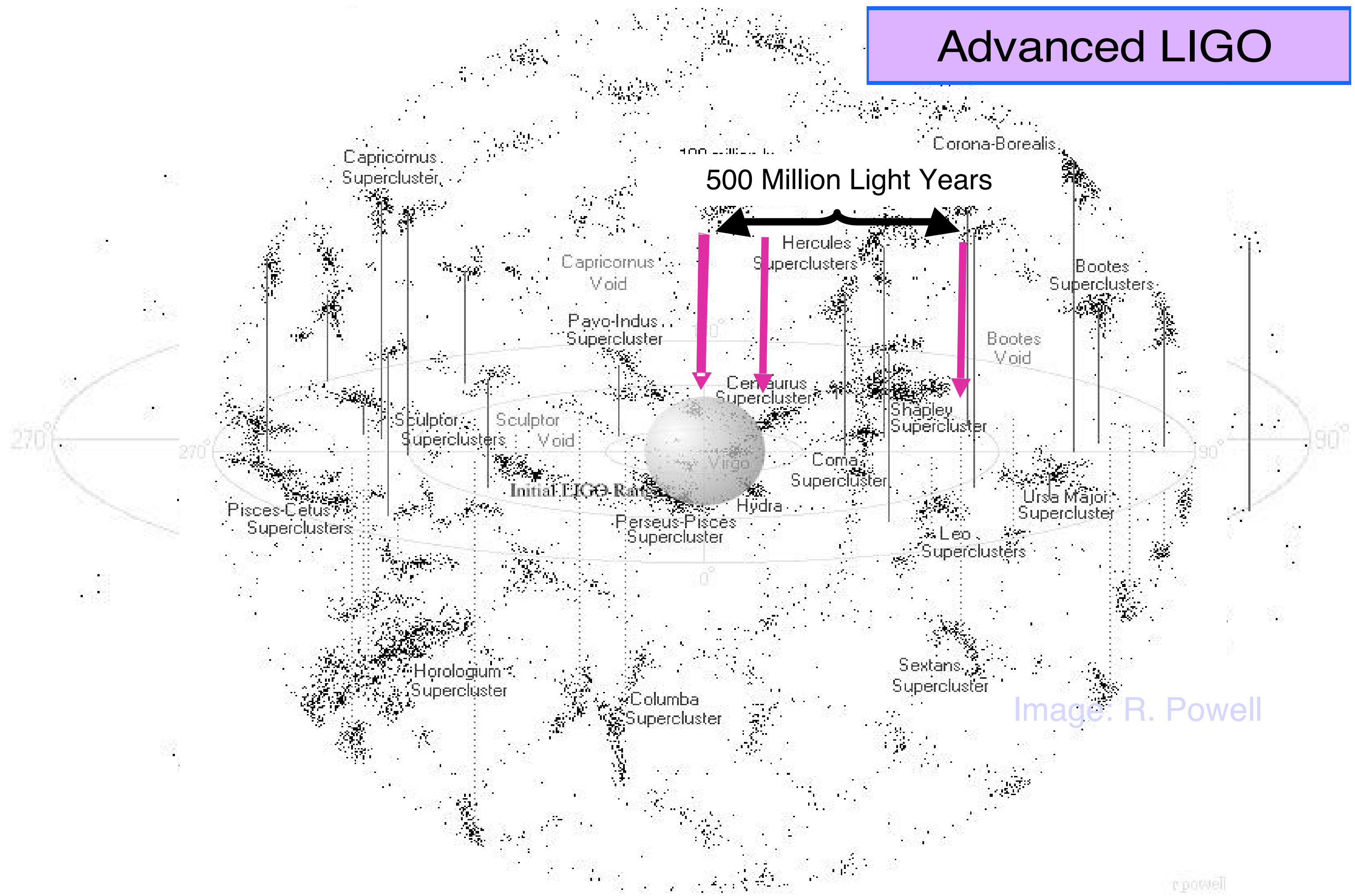
S2 Physics Papers cont.

- *Limits on gravitational wave emission from selected pulsars using LIGO data,* B. Abbott et al. (LSC), Phys. Rev. Lett. 94, 181103 (2005)
- *First all-sky upper limits from LIGO on the strength of periodic gravitational waves using the Hough transform,* B. Abbott et al. (LSC), Submitted to Phys. Rev. D

S3 Physics Papers

- *Upper Limits on a Stochastic Background of Gravitational Waves,* B. Abbott et al. (LSC), To appear in Phys. Rev. Lett.

LIGO to Advanced LIGO

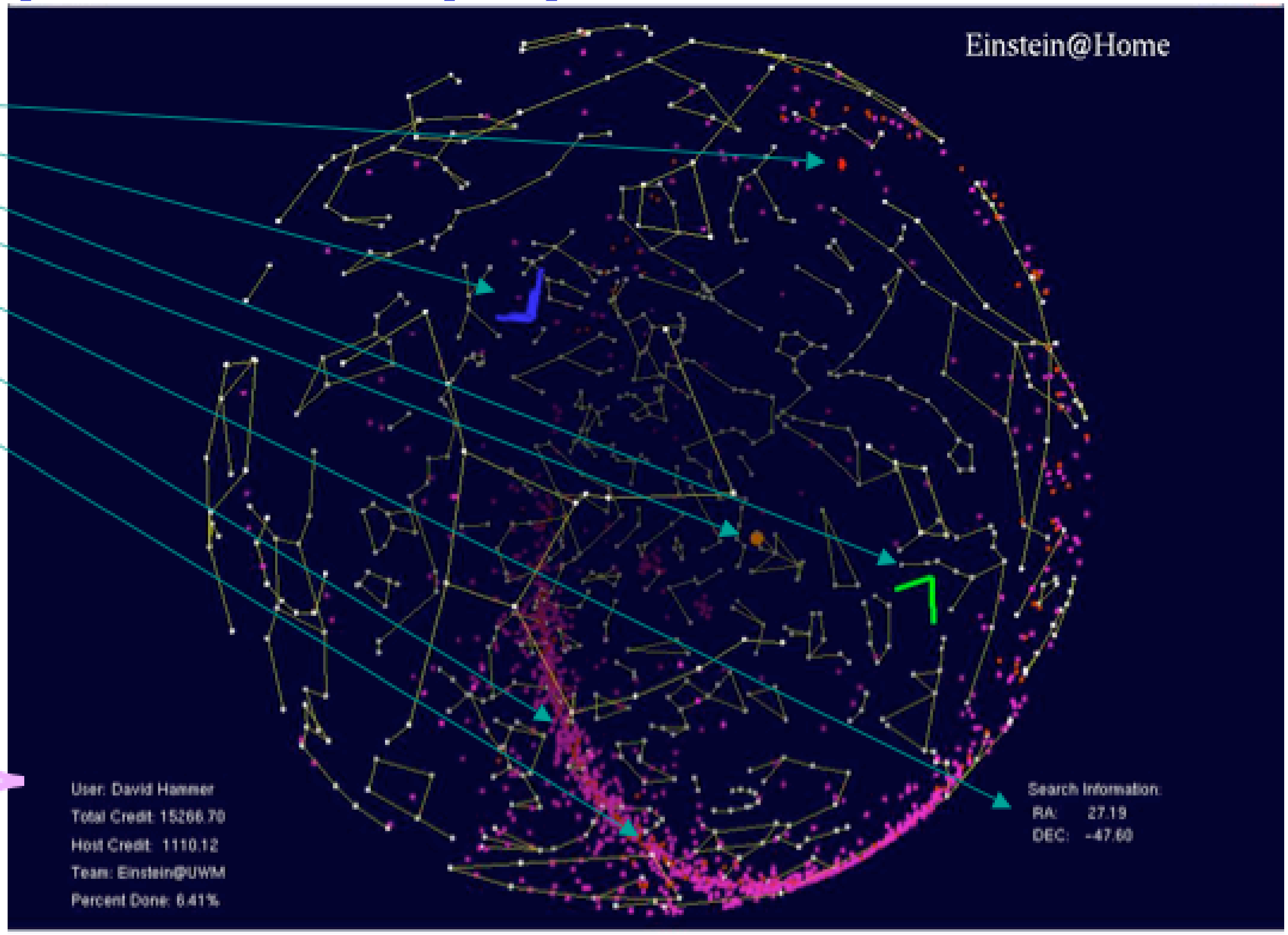


Outlook

- The fifth science run is scheduled to begin next month.
- Plan to run for ~1 yr with a range of > 10 Mpc in each 4 km interferometer, > 4 Mpc in 2 km interferometer.
- Expect preliminary results by Summer '06
- How can you help?

http://einstein.phys.uwm.edu/

- GEO-600 Hannover
- LIGO Hanford
- LIGO Livingston
- Current search point
- Current search coordinates
- Known pulsars
- Known supernovae remenants



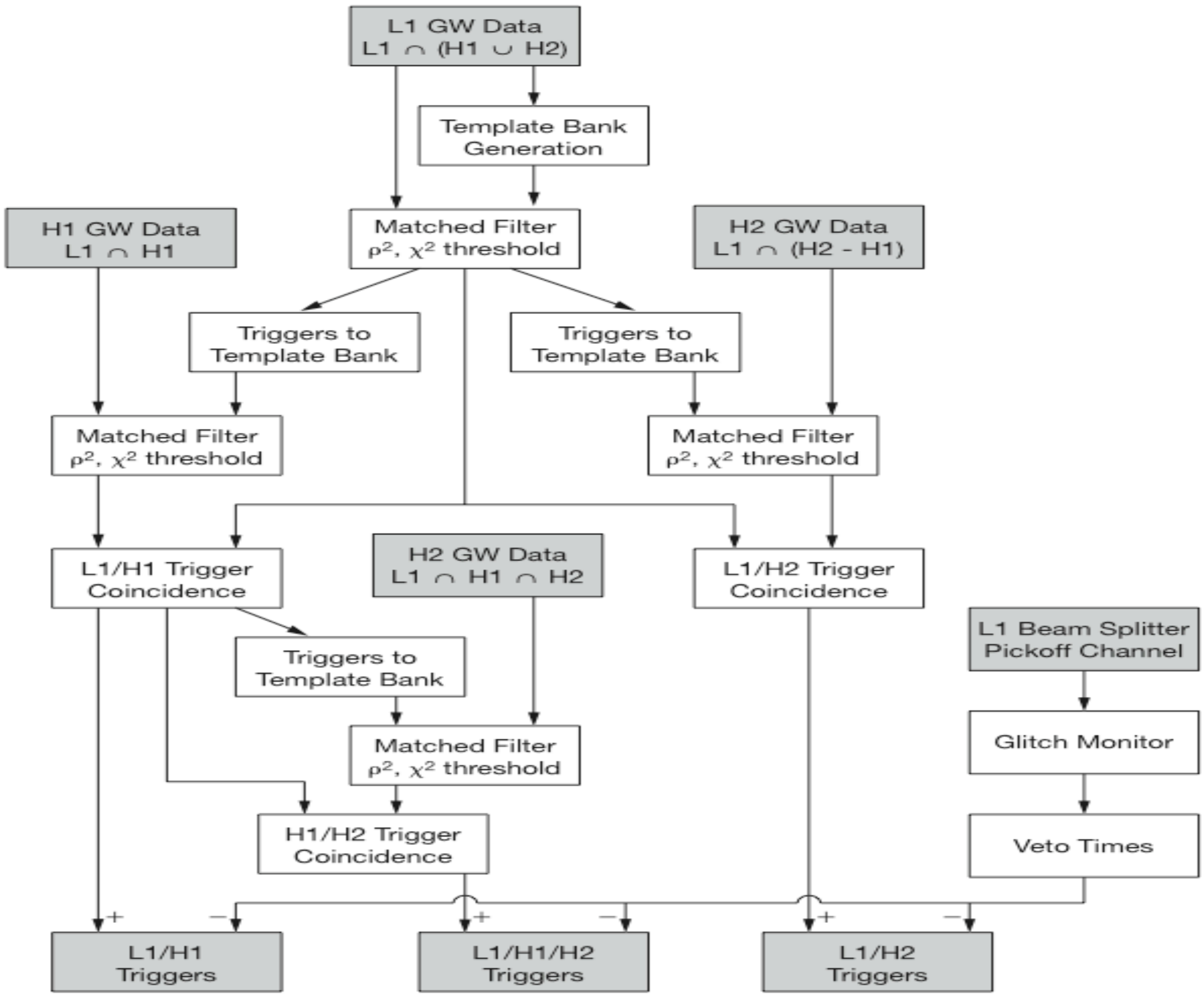
- User name
- User's total credits
- Machine's total credits
- Team name
- Current work % complete

Now: S3 all-sky search.

Next: S4 data, best 40 hours.

Answer Slides

S2 BNS Analysis Pipeline



BCV Waveform

$$h(f) = f^{-7/6}(1 - \alpha f^{2/3})\theta(f_{cut} - f)\exp[i(\phi_0 + 2\pi t_0 f + \psi_0 f^{-5/3} + \psi_3 f^{-2/3})]$$