# Gravitational Wave Astronomy III

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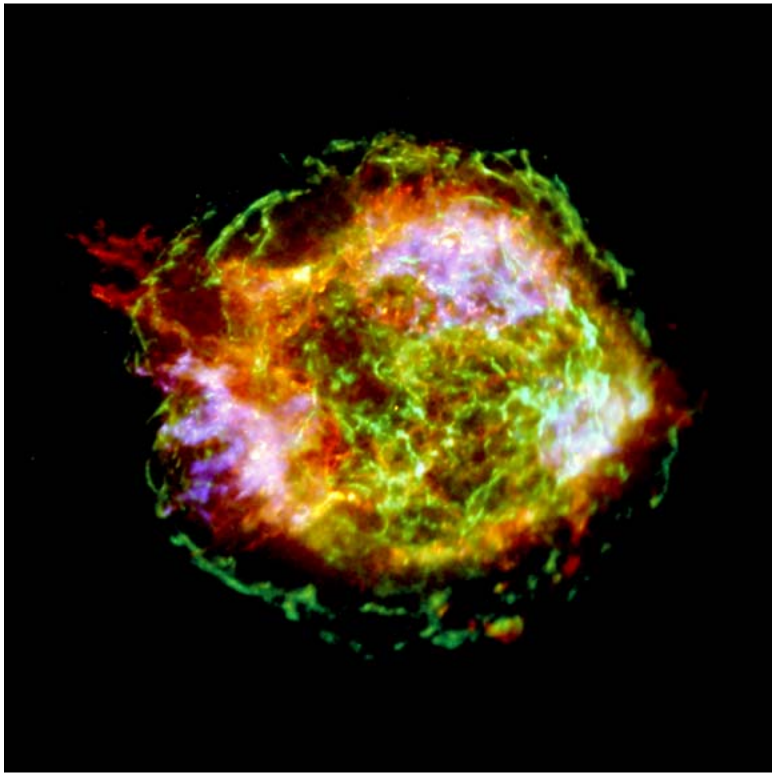
*on behalf of the LIGO Scientific Collaboration*
*http://www.ligo.org*

CERN
Oct 16-18, 2006

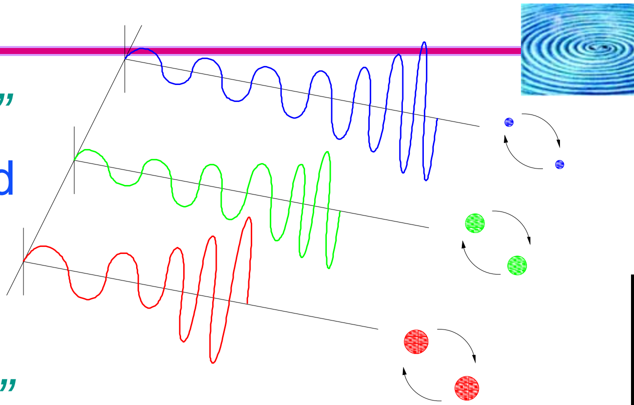


**Supernova remnant Cas A**
**Credit: NASA/CXC/GSFC/U. Hwang et al.**

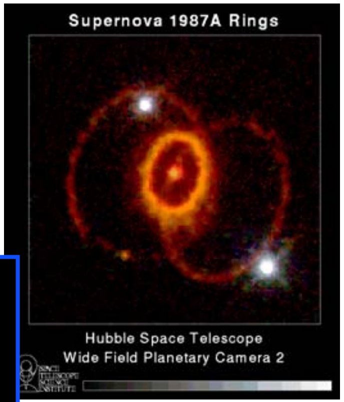
# Overview

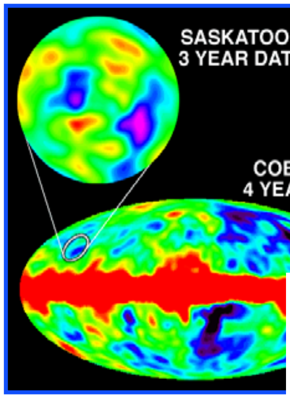
- Day 1 : Introduction. Sources. Detectors.
  - » An introduction to gravitational wave astronomy
  - » What are gravitational waves
  - » Sources
  - » Brief survey of detectors: bars, ground-based interferometers (each with one or two highlights), LISA
- Day 2 : Ground-based interferometry
  - » Interferometric detectors
    - – LIGO, GEO, Virgo
  - » Some topics in commissioning: the path to design sensitivity
  - » Science mode running with LIGO, GEO and TAMA
- Day 3 : Data analysis.  Future detectors.
  - » Search methods
  - » Analyses from science runs for inspiral, burst, stochastic and continuous wave sources
  - » Advanced LIGO, Advanced Virgo

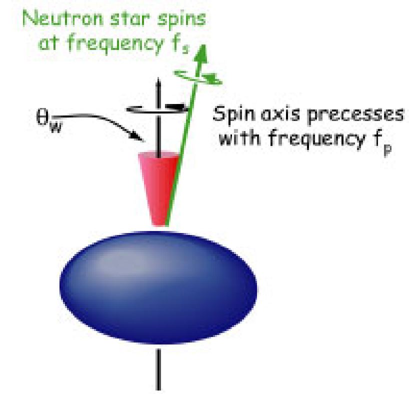
# What makes gravitational waves?



- Compact binary inspiral: *“chirps”*
    - » NS-NS waveforms are well described
    - » BH-BH need better waveforms
- Supernovae / GRBs: *“bursts”*
    - » burst signals in coincidence with signals in electromagnetic radiation / neutrinos
    - » all-sky untriggered searches too
- Cosmological Signal: *“stochastic background”*
- Pulsars in our galaxy: *“continuous waves”*
    - » search for observed neutron stars
    - » all-sky search (computing challenge)



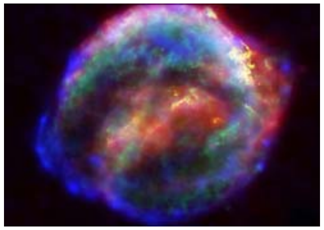
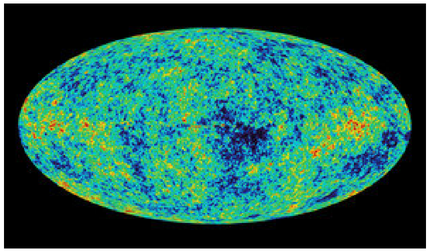
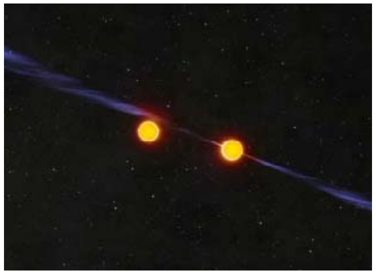
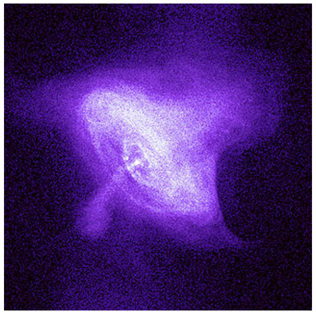




# Signal duration and template

| | Short duration | Long duration |
|---|---|---|
| no matched filter | Burst search | Stochastic search |
| matched filter | Inspiral search | CW search |

# Signal duration and template

| | Short duration | Long duration |
|---|---|---|
| no<br>Both IGEC2 bars and LSC results |  |  |
| matched filter |  |  |

G.F. Prodi, INFN
IGEC2 collab.

# First results by IGEC2

6 month of data of **AURIGA-EXPLORER-NAUTILUS**

**May 20 - Nov 15, 2005**

IGEC2 was the only gw observatory in operation

**search for transient gw signals**

to **identify single candidates** with high confidence :

triple coincidences

false alarm rate of 1 per century

wider target signals than IGEC1

**no candidates found**

G.F. Prodi, INFN
IGEC2 collab.

# IGEC2 search for bursts

perform only **ONE composite search** made by
the **OR among** the following **data selections:**

- SNR > 4.95 for AU, EX and NA
  0.396 false alarm /century
  targets signals peaked on EX-NA sweet spots
- SNR > 7.00 for AU, SNR>4.25 for EX and NA
  0.572 false alarm /century
  targets signals barely detectable by EX and NA
- common absolute thresholds IGEC1-style:
  thresholds 1.3, 1.4, 1.5, ..., 3.0 x $10^{-21}$/Hz
  0.134 false alarm /century
  targets $\delta$-like signals

**130 days** of net simultaneous observation time by the three INFN resonant bar detectors

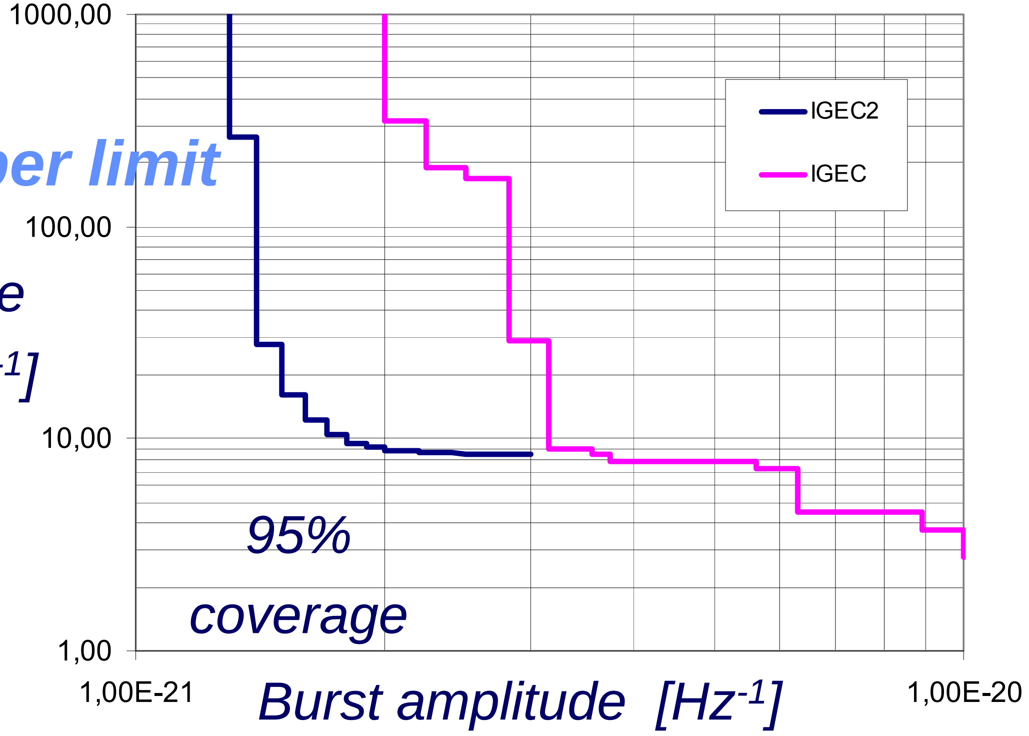
G.F. Prodi, INFN
IGEC2 collab.

# IGEC2 Results

- At last, we “opened the box” on Sept. 25 after exchanging the secret time shifts ☺ …no candidates were found.…the usual upper limit…☹
- Comparison with the upper limits given by the IGEC 1997-2000 observations is possible using a **subset** of the current analysis:

the IGEC1-style search

targeting δ-like signals



# S2 untriggered burst search

- bursts less than 1s, in band 100-1100Hz
- 9.98d of data analyzed
- Event triggers generated on triple-coincidence data, followed up by “r-statistic” waveform consistency test
- Background set by similar analysis with time-shifted data
- Set limit on rate of detectable gravitational wave bursts
- Test efficiency of pipeline to detect particular waveforms: both ad hoc (gaussian, sine-gaussian) and astrophysically-motivated waveforms (core-collapse and binary black hole) applied
- Set rate vs strength exclusion regions for these waveforms

# S2 untriggered burst search

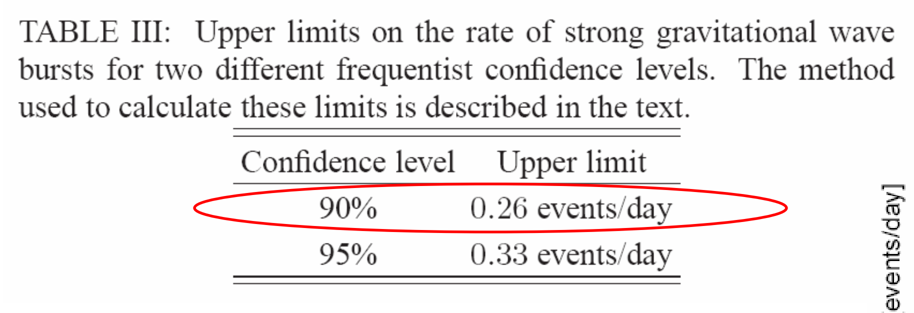
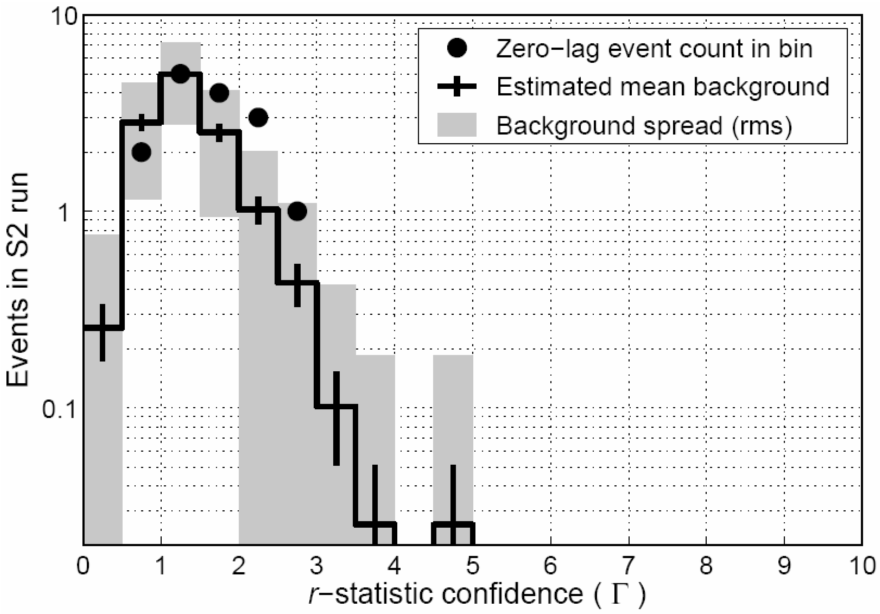
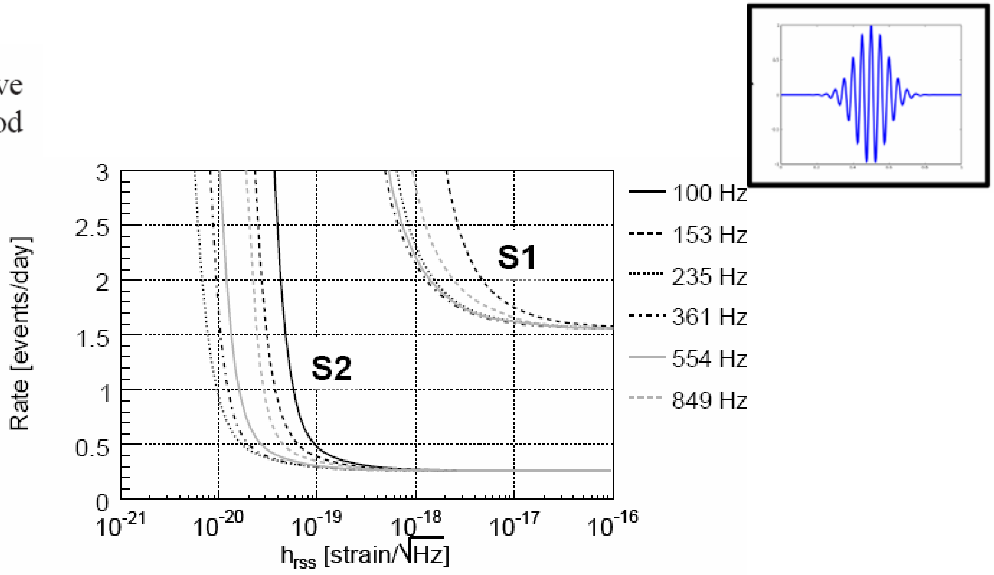
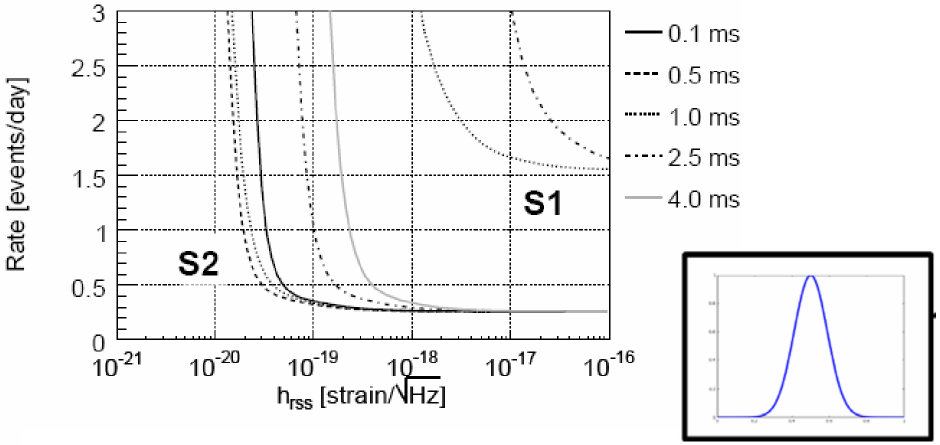


TABLE III: Upper limits on the rate of strong gravitational wave bursts for two different frequentist confidence levels. The method used to calculate these limits is described in the text.

| Confidence level | Upper limit |
|---|---|
| 90% | 0.26 events/day |
| 95% | 0.33 events/day |



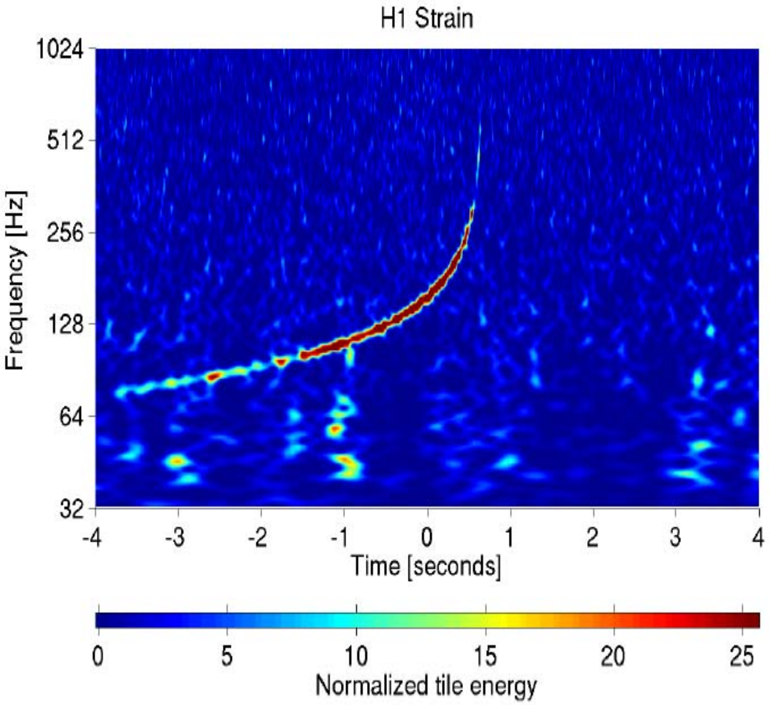




# Bursts: excess power detection

- Now consider later runs, S3-S5
- Look for transient increase in power in some time-frequency region:
  - » Minimal assumptions about 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

Simulated binary inspiral signal in S5 data



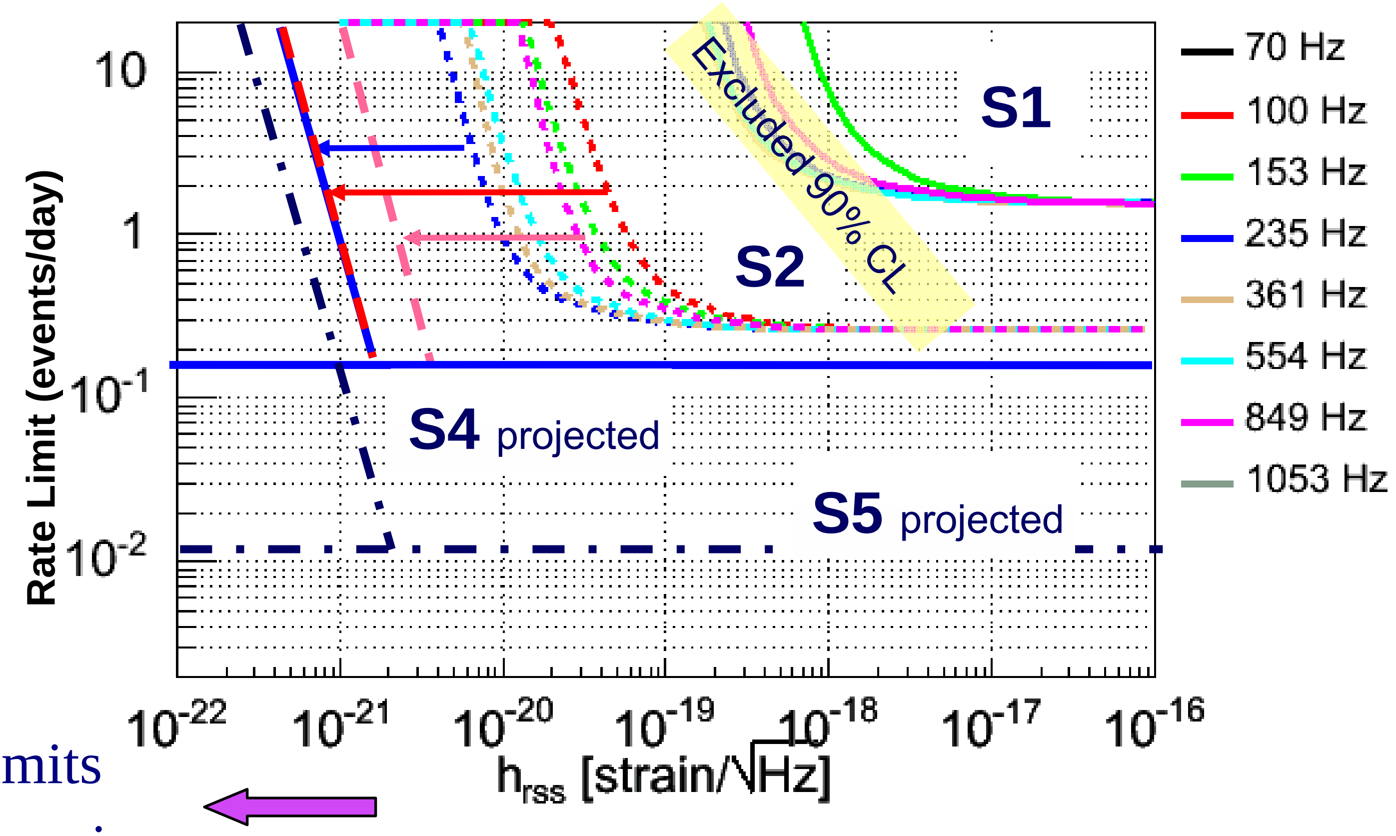
# Consistency Checks

- Require time and frequency coincidence in three LIGO detectors.
- Follow up coincidences with:
  - » Amplitude consistency between co-located H1-H2 detectors
  - » Cross correlation of data from pairs of detectors
  - » Check environmental and auxiliary channels for:
    - – Earthquakes, airplanes, trains, instrumental misbehaviour, ...
  - » Remove times of poor data quality
  - » Veto events associated to known noise sources
- Compare remaining events with background estimated by repeating analysis with large time shifts of detector data.

# Upper Limits

- No GW bursts detected through S4
  - set limit on rate vs signal strength.

$$R \propto \frac{1}{\epsilon(h_{\mathrm{rss}})\, T}$$



Lower rate limits from longer observation times

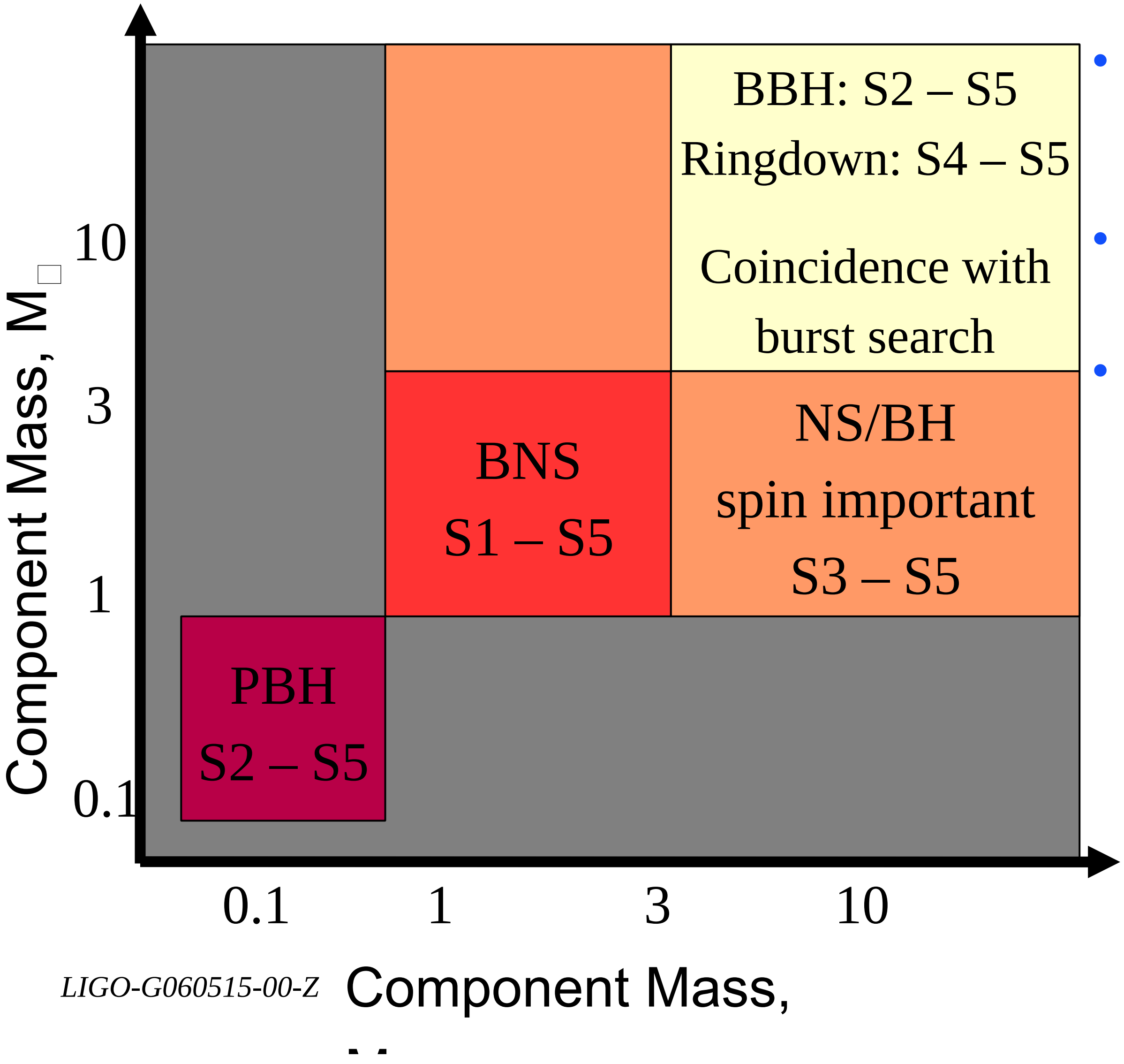
Lower amplitude limits from lower detector noise

# Inspiral and Merger of Compact Binaries

- Binary Neutron Star Rates
  - » Theoretical estimates give upper bound of 1/3yr for LIGO S5 (Kalogera et. al, Ap J Lett **601**, L179 (2004))
  - » n.b. Rates predicted for initial LIGO, based on identification of short GRBs as binary inspirals (astro-ph/0511254), higher than typical population synthesis modelling
- Binary Black Hole Rates
  - » Theoretical estimates give upper bound of 1/yr for LIGO S5

Best candidate for short GRBs: binary inspirals, NS-NS, BH-NS N. Gehrels et al., Nature **437**, 851 (2005), and R. Narayan et al., Ap. J. Lett. **395** L83 (1992)

# Target Sources

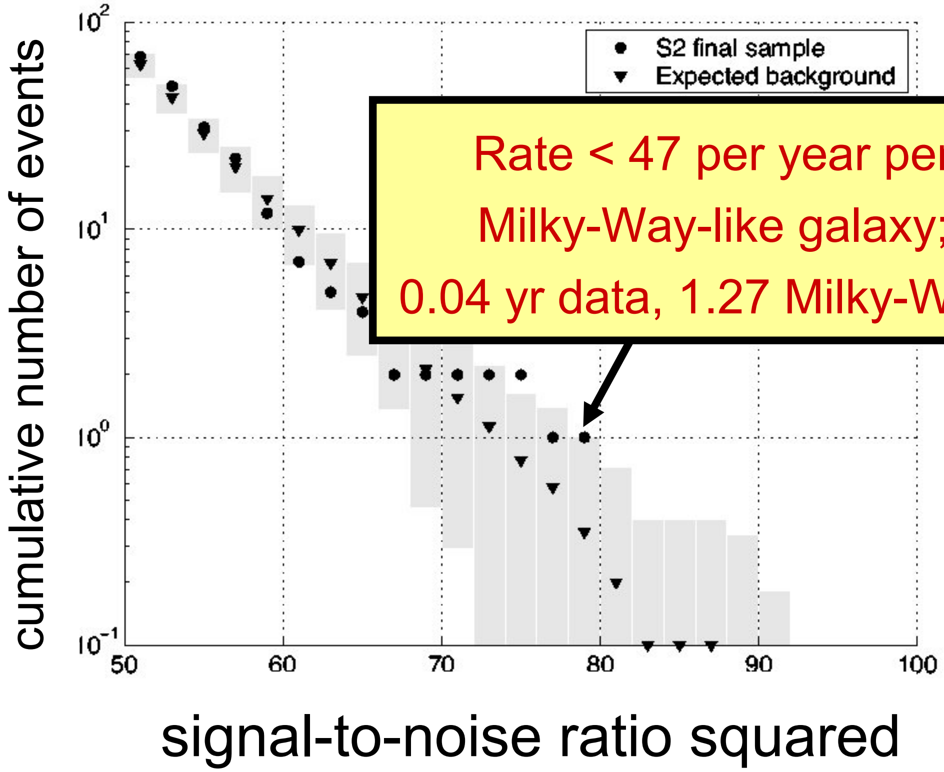


- Use templated search
    - Require waveform consistency
- Use detection templates for higher masses
- Require time and mass coincidence between 2 or more detectors

# Binary Neutron Stars

## S2 Observational Result

*Phys. Rev. D. 72, 082001 (2005)*



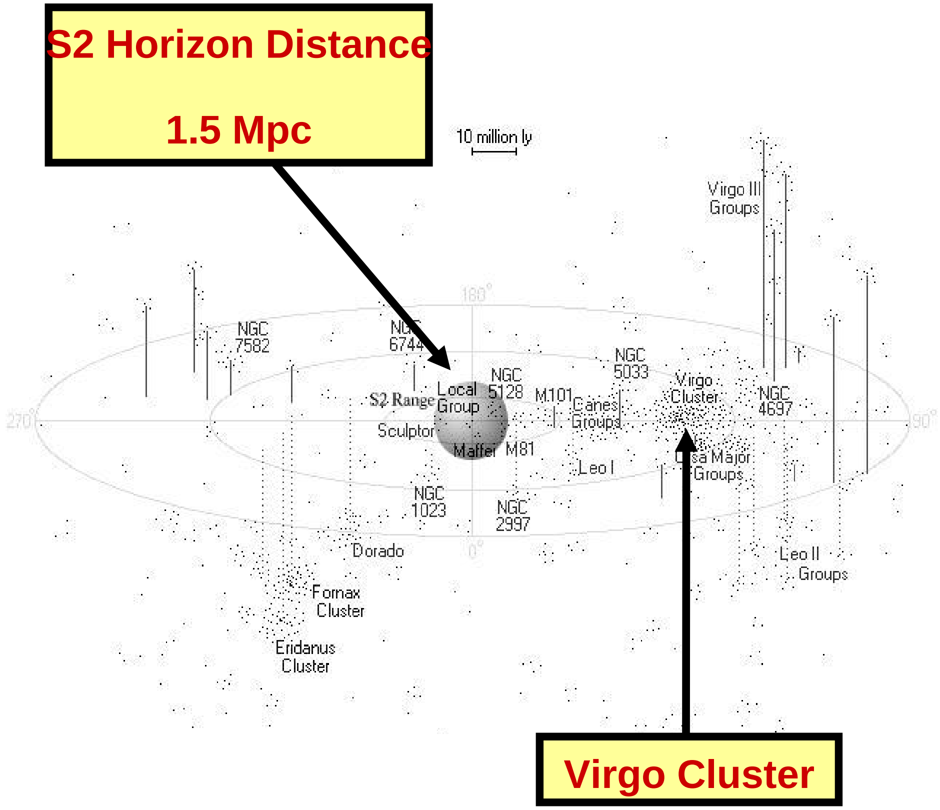
Rate < 47 per year per Milky-Way-like galaxy; 0.04 yr data, 1.27 Milky-Ways

- S3 search complete
  - » Under internal review
  - » 0.09 yr of data
  - » ~3 Milky-Way like galaxies for 1.4 – 1.4 M
- S4 search complete
  - » Under internal review
  - » 0.05 yr of data
  - » ~24 Milky-Way like galaxies for 1.4 – 1.4 M

# S5 Binary Neutron Stars

- First three months of S5 data have been analyzed

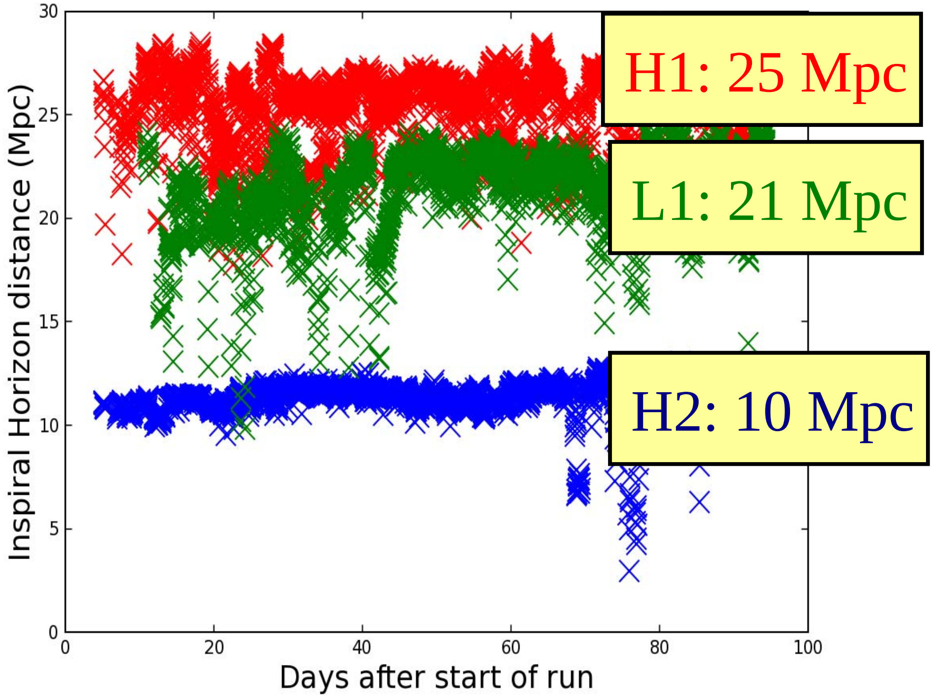
- Horizon distance
  - Distance to 1.4-1.4 $M_\odot$ optimally oriented & located binary at SNR 8



**S2 Horizon Distance**

**1.5 Mpc**

**Virgo Cluster**

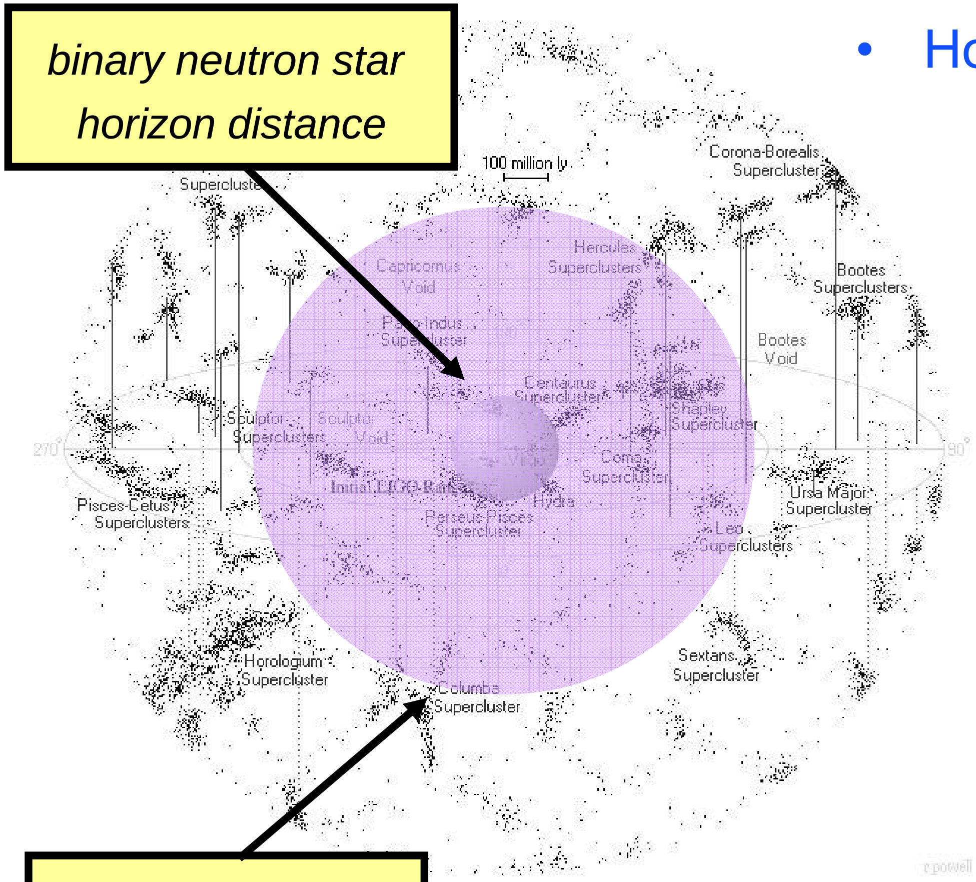


H1: 25 Mpc

L1: 21 Mpc

H2: 10 Mpc

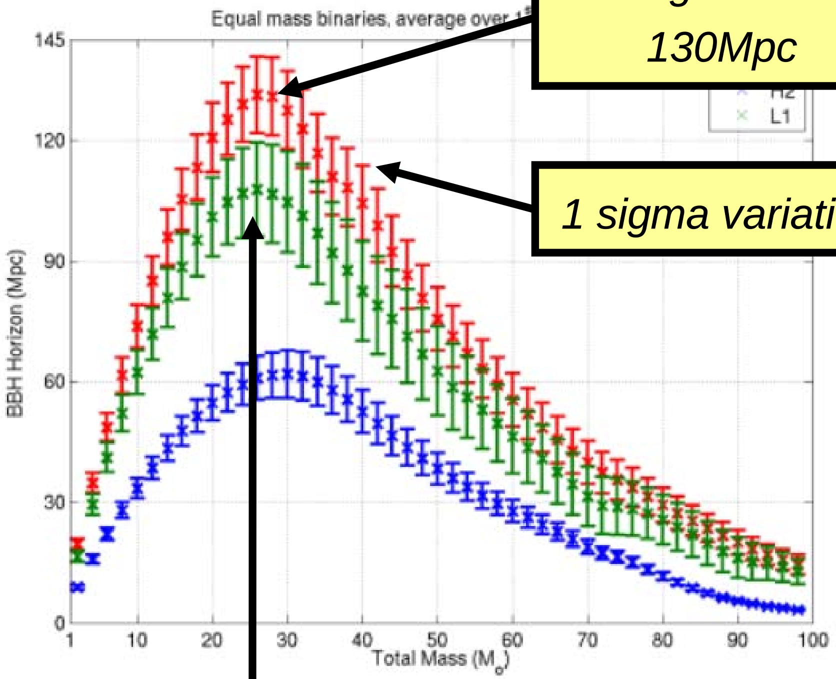
# S5 Binary Black Holes



*binary neutron star horizon distance*

*binary black hole horizon distance*

- Horizon distance vs mass for BBH



*Average over run 130Mpc*

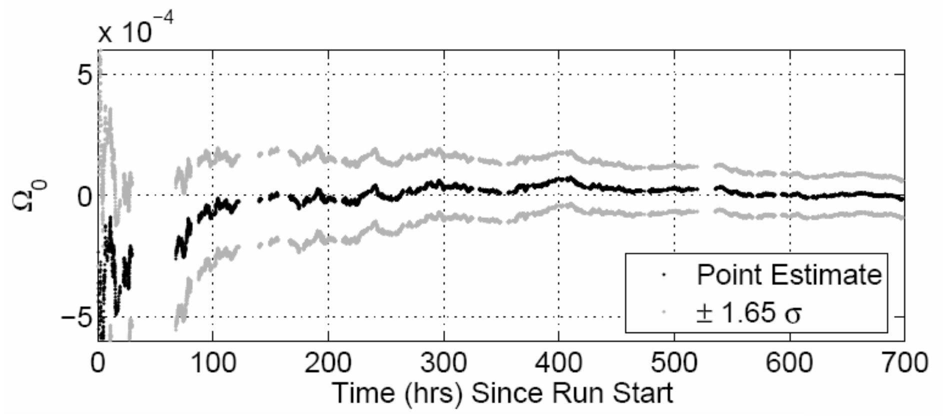
*1 sigma variation*

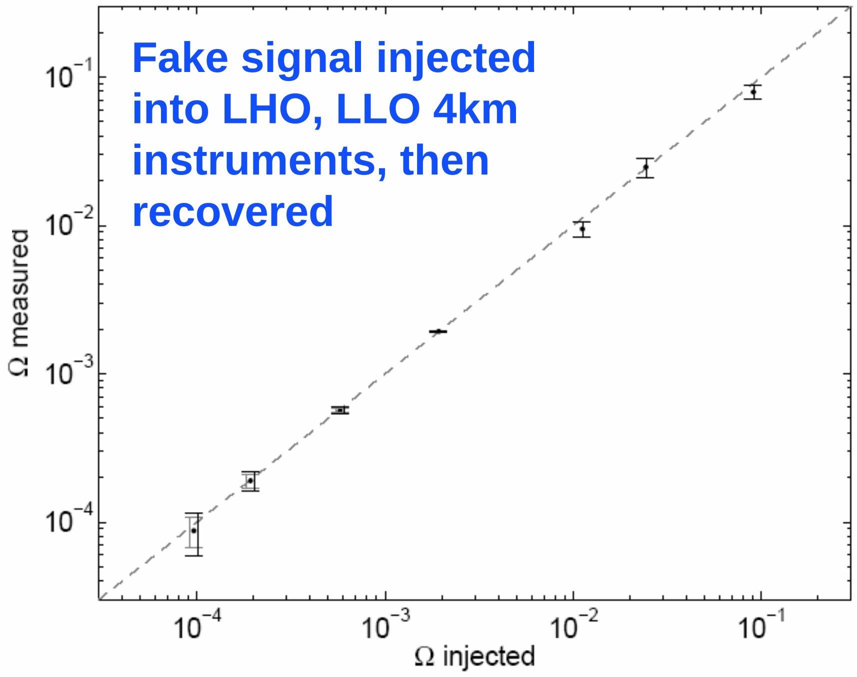
*Peak at total mass ~ 25M*

# Search for stochastic gravitational waves

- Cosmological relic, or, summation of noise sources from astrophysical epoch
- Cross correlate detectors: uncorrelated noise integrates away while the signal to noise integrates up as the square root of time
- Make use of optimal filter, which includes overlap reduction function
- Searches include
  - » LHO-LLO
  - » H1-H2
  - » LLO-Allegro
- $\Omega_{GW}$ is the gravitational wave energy density per logarithmic frequency interval, divided by $\rho_c$, the energy density required to close the universe

# S4 stochastic background results





**Fake signal injected into LHO, LLO 4km instruments, then recovered**

Fig. 13.— Injections using H1L1 data: 10 trials were performed for software injections with amplitudes $\Omega_0 = 1 \times 10^{-4}$, $2 \times 10^{-4}$, $6 \times 10^{-4}$, and $2 \times 10^{-3}$. The left(gray) error bars denote the theoretical errors, while the right(black) error bars denote the standard errors over the 10 trials. The remaining points correspond to the three hardware injections listed in Table 3; their error bars correspond to statistical and systematic errors added in quadrature, as shown in Table 3.

***New S4 result (astro-ph/0608606): Bayesian 90% U.L.***

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

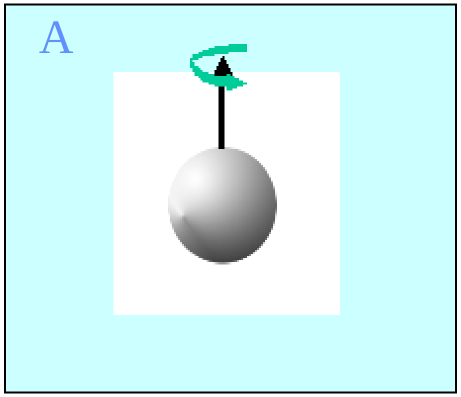
***submitted to Ap. J.***

# Search for continuous waves

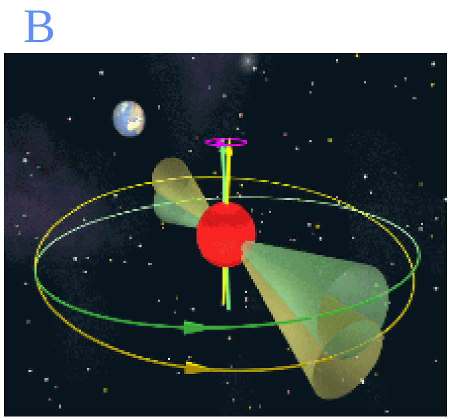
## Searches for g.w. :

- I. Known pulsars
- II. S4 all-sky (incoherent)
- III. S3 all-sky (coherent)

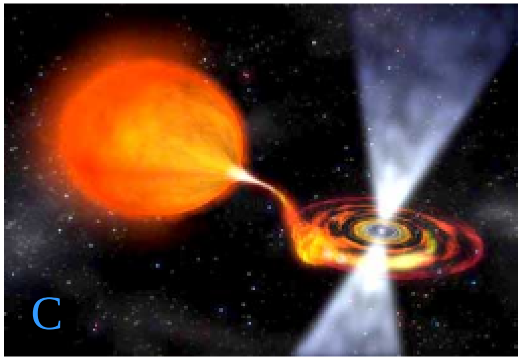
## Analysis goal for S5: hierarchical search



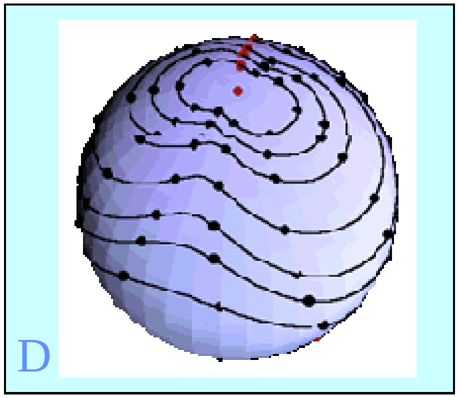
Mountain on neutron star



Precessing neutron star



Accreting neutron star



Oscillating neutron star

Credits:

A. image by Jolien Creighton; LIGO Lab Document G030163-03-Z.

B. image by M. Kramer; Press Release PR0003, University of Manchester - Jodrell Bank Observatory, 2 August 2000.

C. image by Dana Berry/NASA; NASA News Release posted July 2, 2003 on Spaceflight Now.

D. image from a simulation by Chad Hanna and Benjamin Owen; B. J. Owen's research page, Penn State University.

# Analyses for continuous gravitational waves I

- S5 Time domain analysis
  - Targeted search of known objects: 73 pulsars with rotational frequencies > 25 Hz at known locations with phase inferred from radio data (knowledge of some parameters simplifies analysis) from the Jodrell Bank Pulsar Group (JBPG) and/or ATNF catalogue
  - Limit this search to gravitational waves from a neutron star (with asymmetry about its rotational axis) emitted at twice its rotational frequency, $2*f_{rot}$
  - Signal would be frequency modulated by relative motion of detector and source, plus amplitude modulated by the motion of the antenna pattern of the detector
  - Analyzed from 4 Nov - 31 Dec 2005 using data from the three LIGO observatories Hanford 4k and 2k (H1, H2) and Livingston 4k (L1)
  - Upper limits defined in terms of Bayesian posterior probability distributions for the pulsar parameters
  - Validation by hardware injection of fake pulsars
  - Results

early S5 data

# CW source model

The expected signal has the form:

$$h(\mathrm{t}) = \mathrm{F}_{+}(\mathrm{t};\psi)\,\mathrm{h}_0\left(\frac{1+\cos^2\iota}{2}\right)\cos\Phi(t) - \mathrm{F}_{\times}(\mathrm{t};\psi)\,\mathrm{h}_0\cos\iota\sin\Phi(t)$$

- $F_+$ and $F_x$ : strain antenna patterns of the detector to plus and cross polarization, bounded between -1 and 1
- Here, signal parameters are:
  - » $h_0$ – amplitude of the gravitational wave signal
  - » $\psi$ – polarization angle of signal
  - » $\iota$ – inclination angle of source with respect to line of sight
  - » $\phi_0$ – initial phase of pulsar; $\Phi(t=0)$, and $\Phi(t) = \phi(t) + \phi_0$

Heterodyne, i.e. multiply by: $e^{-i\phi(t)}$

so that the expected demodulated signal is then:

$$\mathrm{y}(\mathrm{t}_\mathrm{k};\mathbf{a}) = \frac{1}{4}\mathrm{F}_{+}(\mathrm{t}_\mathrm{k};\psi)\mathrm{h}_0(1+\cos^2\iota)e^{i\phi_0} - \frac{i}{2}\mathrm{F}_{\times}(\mathrm{t}_\mathrm{k};\psi)\mathrm{h}_0(\cos\iota)e^{i\phi_0}$$

Here, **a** = **a**($h_0$, $\psi$, $\iota$, $\phi_0$), a vector of the signal parameters.

# Aside: Injection of fake pulsars during S2

*Two simulated pulsars, P1 and P2, were injected in the LIGO interferometers for a period of ~ 12 hours during S2*

## Parameters of P1:

**P1: Constant Intrinsic Frequency**

Sky position: **0.3766960246** latitude (radians)
**5.1471621319** longitude (radians)

Signal parameters are defined at SSB GPS time **733967667.026112310** which corresponds to a wavefront passing:

**LHO** at GPS time **733967713.000000000**

**LLO** at GPS time **733967713.007730720**

In the SSB the signal is defined by

**$f = 1279.123456789012$ Hz**

**fdot = 0**

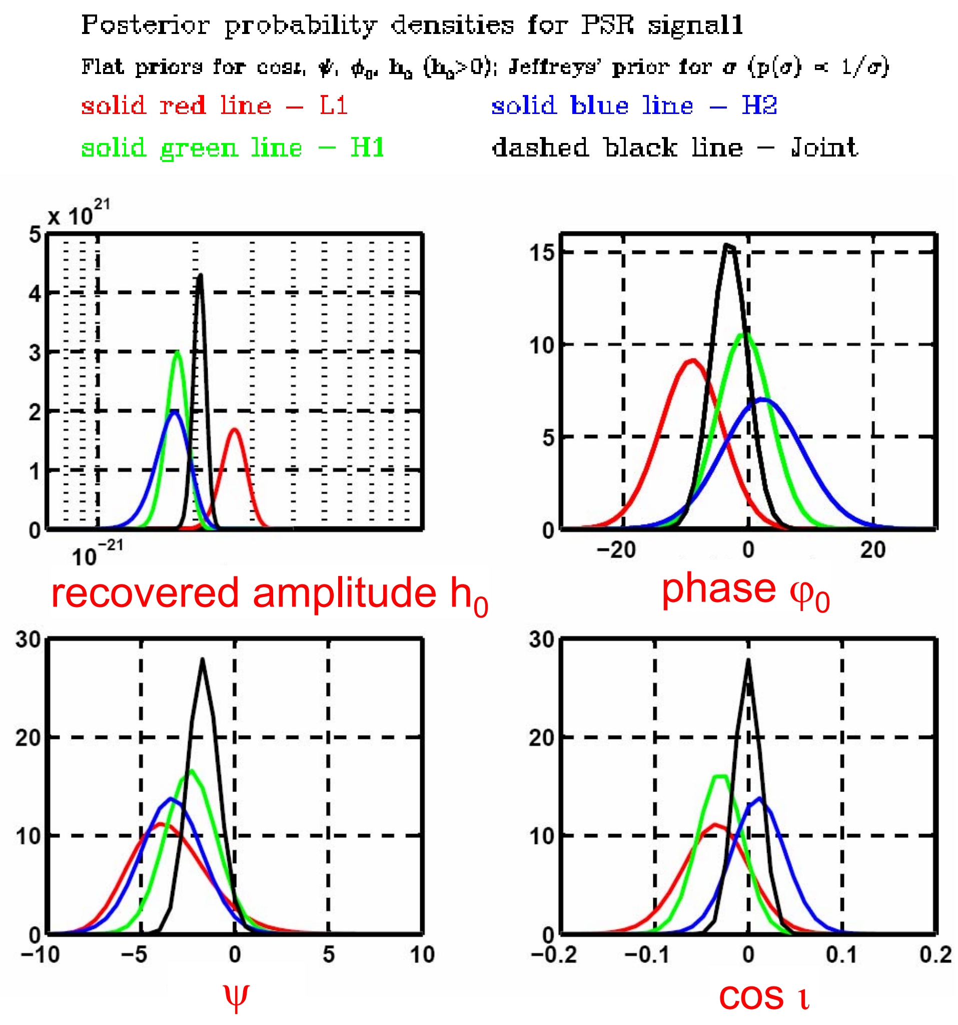
**phi = 0**

**psi = 0**

**iota = $\pi/2$**

**$h_0 = 2.0 \times 10^{-21}$**

injected amplitude $h_0$



recovered amplitude $h_0$

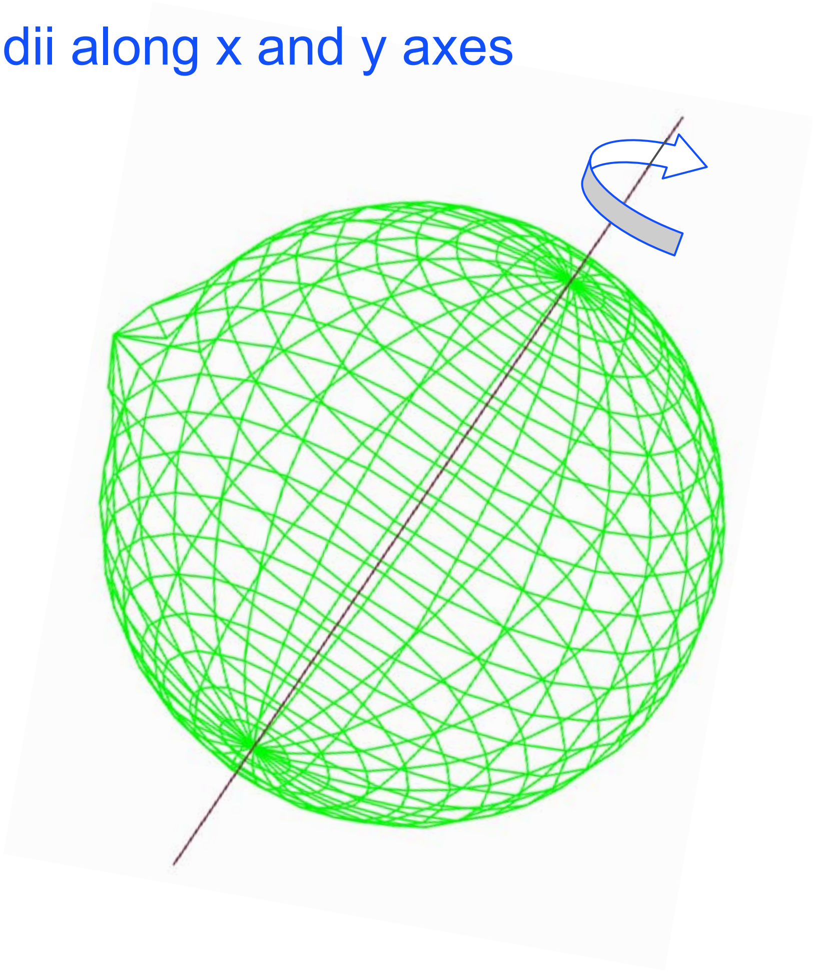
phase $\varphi_0$

$\psi$

cos $\iota$

# Equatorial ellipticity

- Results on $h_0$ can be interpreted as upper limit on equatorial ellipticity
- Ellipticity scales with the difference in radii along x and y axes



$$\varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}, \qquad \varepsilon = \frac{c^4}{4\pi^2 G} \cdot \frac{r}{f_{gw}^2} \cdot \frac{h_0}{I_{zz}}$$

- Distance r to pulsar is known, $I_{zz}$ is assumed to be typical, $10^{45}$ g cm$^2$

# S5 Results, 95% upper limits

| $h_0$ | Pulsars |
|---|---|
| $1\times10^{-25} < h_0 < 5\times10^{-25}$ | 44 |
| $5\times10^{-25} < h_0 < 1\times10^{-24}$ | 24 |
| $h_0 > 1\times10^{-24}$ | 5 |

Lowest $h_0$ upper limit:

PSR J1603-7202 ($f_{gw}$ = 134.8 Hz, r = 1.6kpc) $h_0 = 1.6\times10^{-25}$

Lowest ellipticity upper limit:

PSR J2124-3358 ($f_{gw}$ = 405.6Hz, r = 0.25kpc) $\varepsilon = 4.0\times10^{-7}$

| Ellipticity | Pulsars |
|---|---|
| $\varepsilon < 1\times10^{-6}$ | 6 |
| $1\times10^{-6} < \varepsilon < 5\times10^{-6}$ | 28 |
| $5\times10^{-6} < \varepsilon < 1\times10^{-5}$ | 13 |
| $\varepsilon > 1\times10^{-5}$ | 26 |

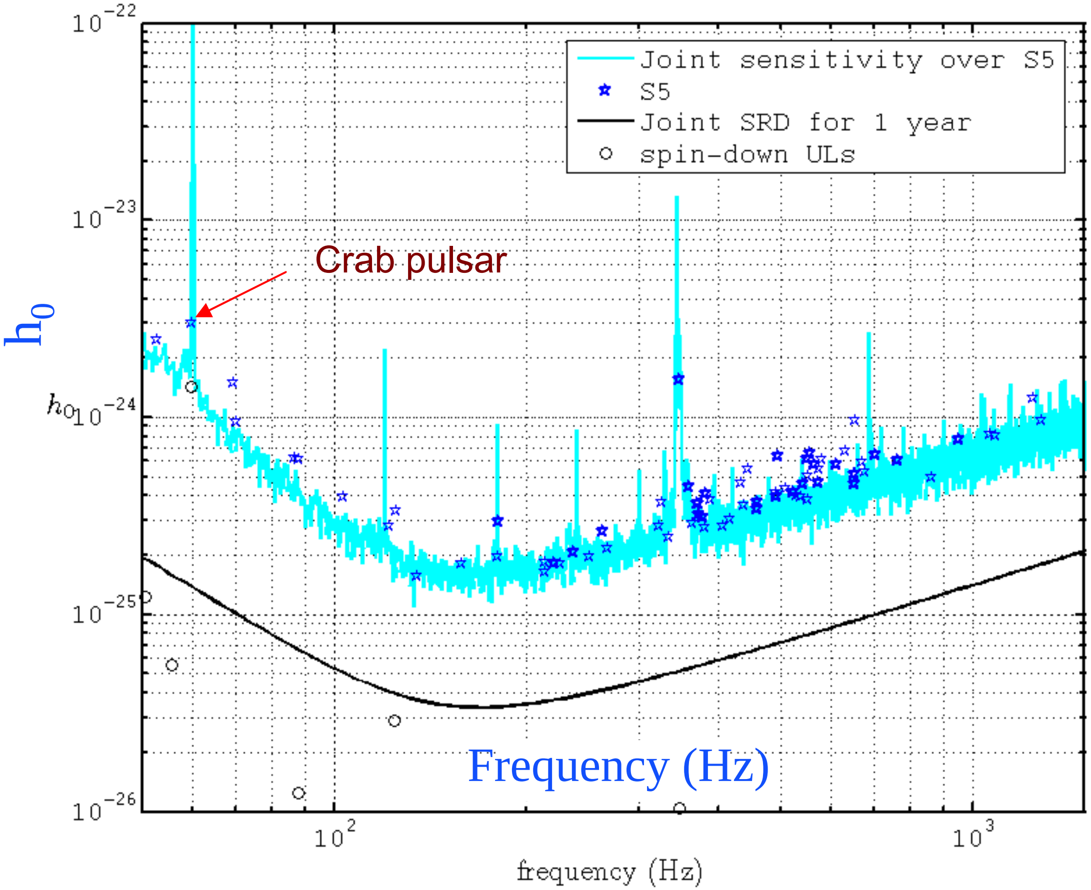
All values assume I = $10^{38}$ kgm$^2$ and no error on distance

$$\varepsilon = 0.237 \frac{h_0}{10^{-24}} \frac{r}{1\text{kpc}} \frac{1\text{Hz}^2}{\nu^2} \frac{10^{38}\,\text{kgm}^2}{I_{zz}}$$

PRELIMINARY

# $h_0$ Results

- Closest to spin-down upper limit
  - » Crab pulsar ~ **2.1** times greater than spin-down ($f_{gw}$ = 59.6 Hz, dist = 2.0 kpc)
  - » $h_0 = 3.0\text{x}10^{-24}$, $\varepsilon = 1.6\text{x}10^{-3}$
  - » Assumes $I = 10^{38}$ kgm$^2$
- Our upper limits are generally well above those permitted by spin-down constraints and neutron star equations-of-state
- Our most stringent ellipticities ($4.0\text{x}10^{-7}$) are starting to reach into the range of neutron star structures for some neutron-proton-electron models (B. Owen, **PRL**, 2005).

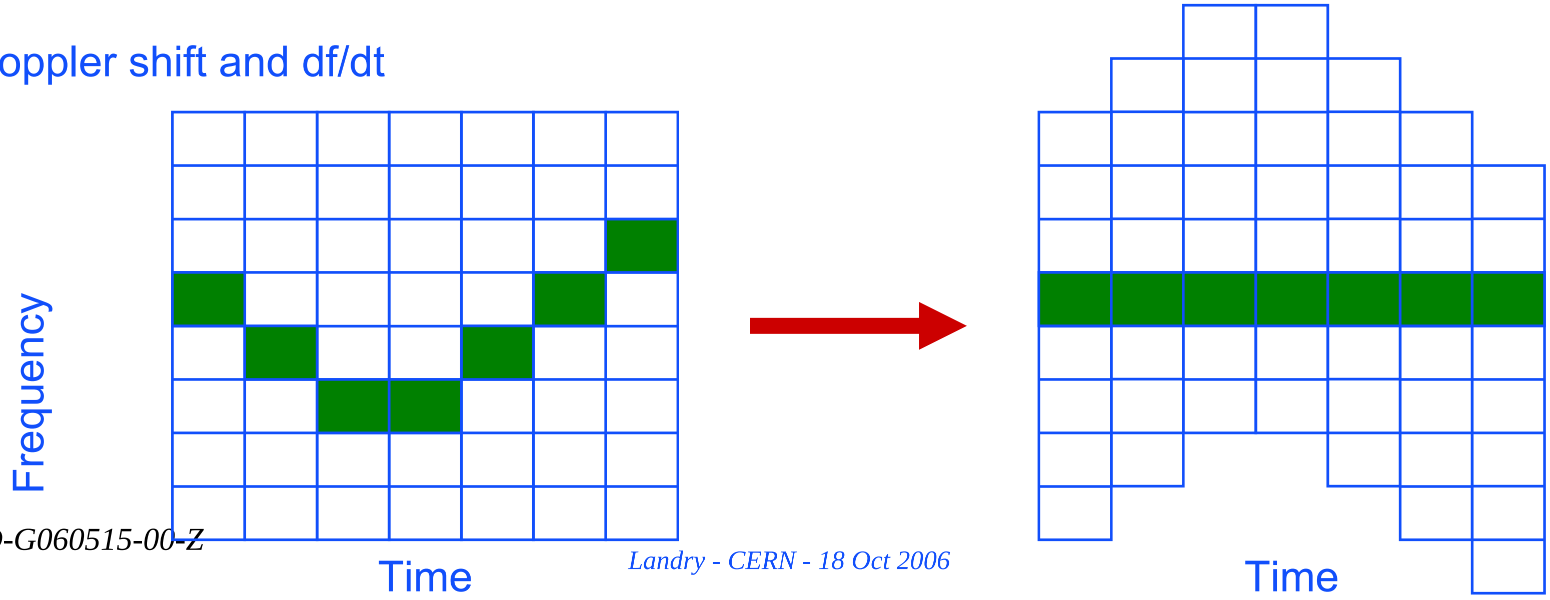


PRELIMINARY

# Analyses for continuous gravitational waves II

- “Stack Slide Method”: break up data into segments; FFT each, producing Short (30 min) Fourier Transforms (SFTs) = coherent step.
- StackSlide: stack SFTs, track frequency, slide to line up & add the power weighted by noise inverse = incoherent step.
- Other semi-coherent methods:
  - Hough Transform: Phys. Rev. D72 (2005) 102004; gr-qc/0508065.
  - PowerFlux
- Fully coherent methods:
  - Frequency domain match filtering/maximum likelihood estimation

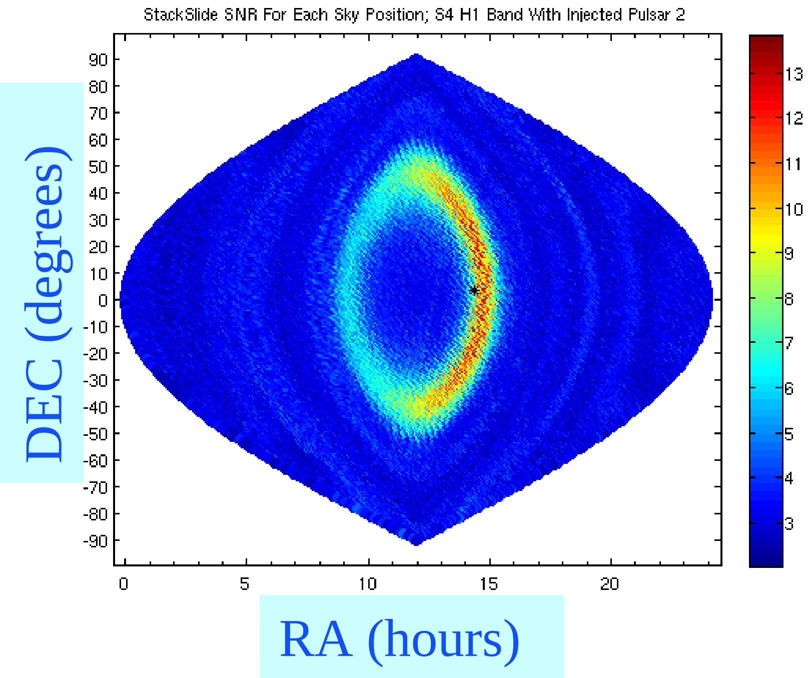
Track Doppler shift and df/dt

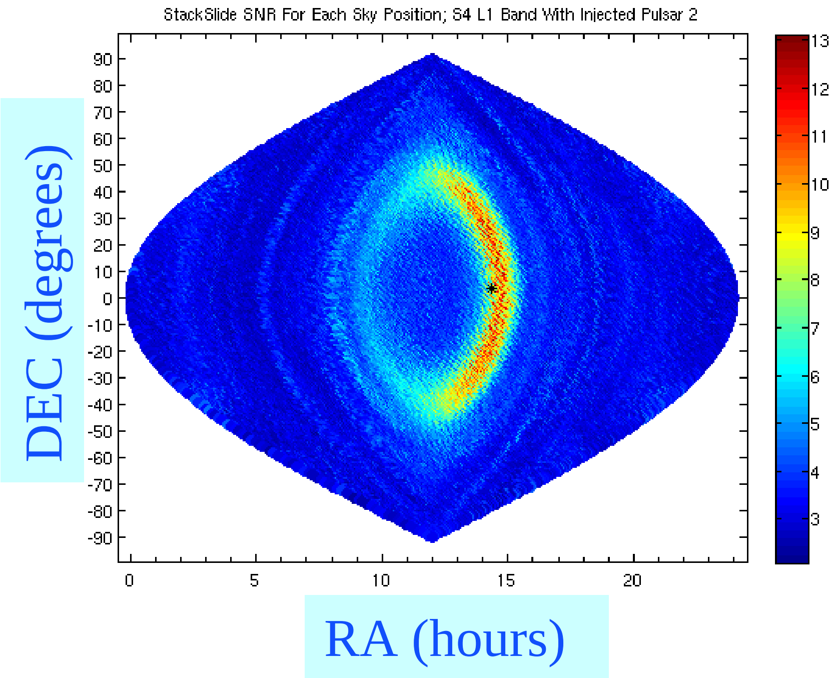


PRELIMINARY

# Analysis of Hardware Injections

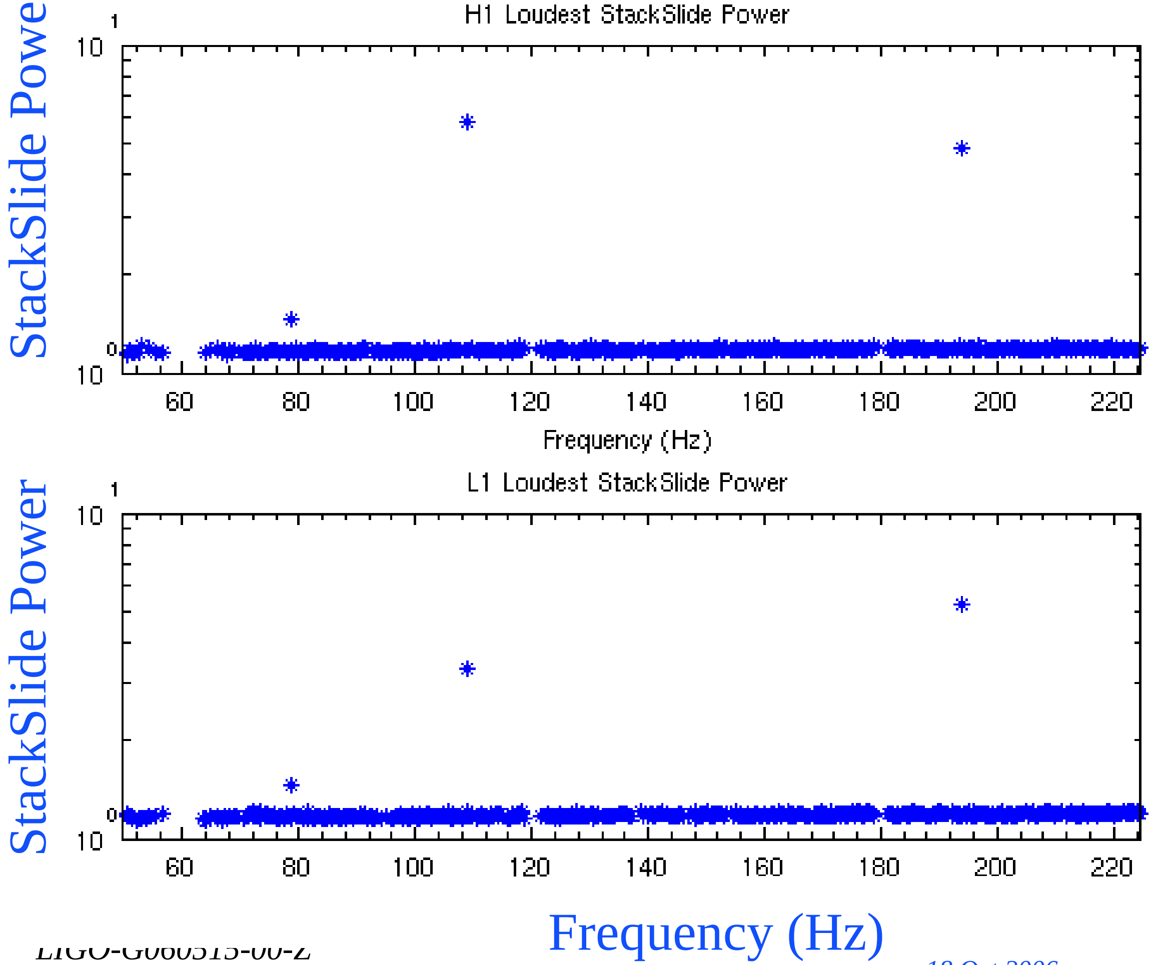
Fake gravitational-wave signals corresponding to rotating neutron stars with varying degrees of asymmetry were injected for parts of the S4 run by actuating on one end mirror. Sky maps for the search for an injected signal with $h_0$ ~ 7.5e-24 are below. Black stars show the fake signal’s sky position.





# S4 StackSlide “Loudest Events” 50-225 Hz

PRELIMINARY



- Searched 450 freq. per .25 Hz band, 51 values of df/dt, between 0 & -1e-8 Hz/s, up to 82,120 sky positions (up to 2e9 templates). The expected loudest StackSlide Power was ~ 1.22 (SNR ~ 7)
- Veto bands affected by harmonics of 60 Hz.
- Simple cut: if SNR > 7 in only one IFO veto; if in both IFOs, veto if abs($f_{H1}$-$f_{L1}$) > 1.1e-4*f0

# S4 StackSlide “Loudest Events” 50-225 Hz

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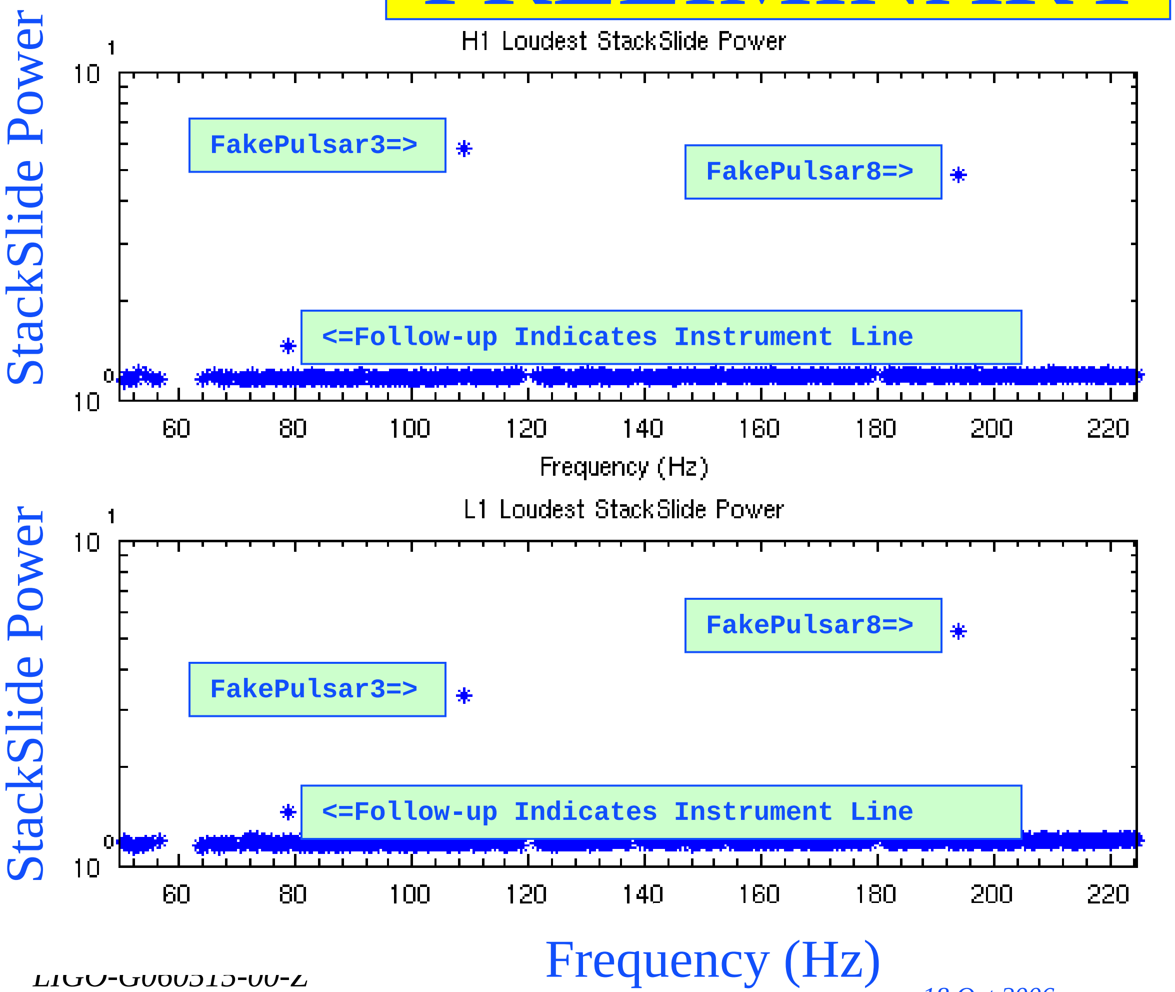

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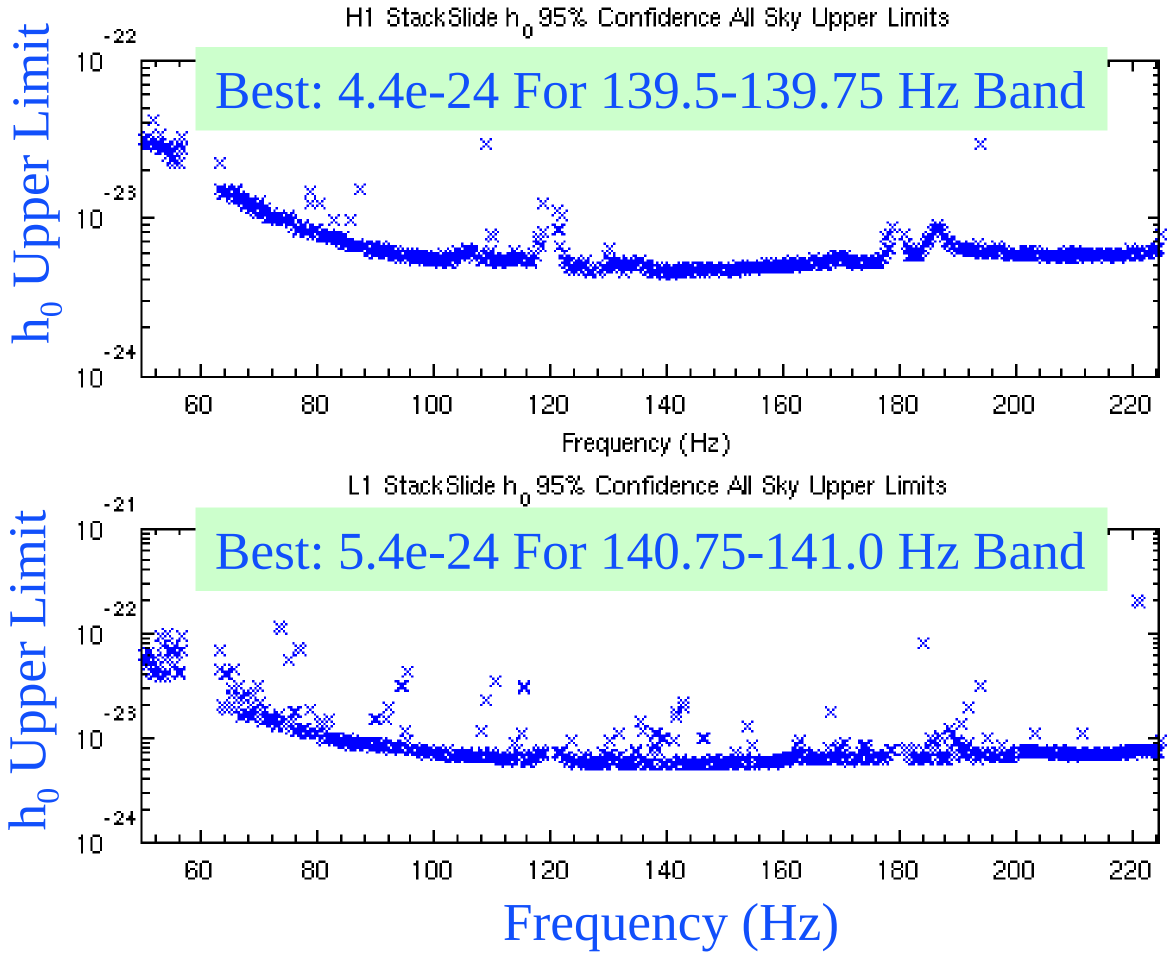
# S4 StackSlide $h_0$ 95% Confidence All Sky Upper Limits 50-225 Hz

PRELIMINARY



Best: 4.4e-24 For 139.5-139.75 Hz Band

Best: 5.4e-24 For 140.75-141.0 Hz Band

**S5: ~ 2x better sensitivity, 12x or more data**

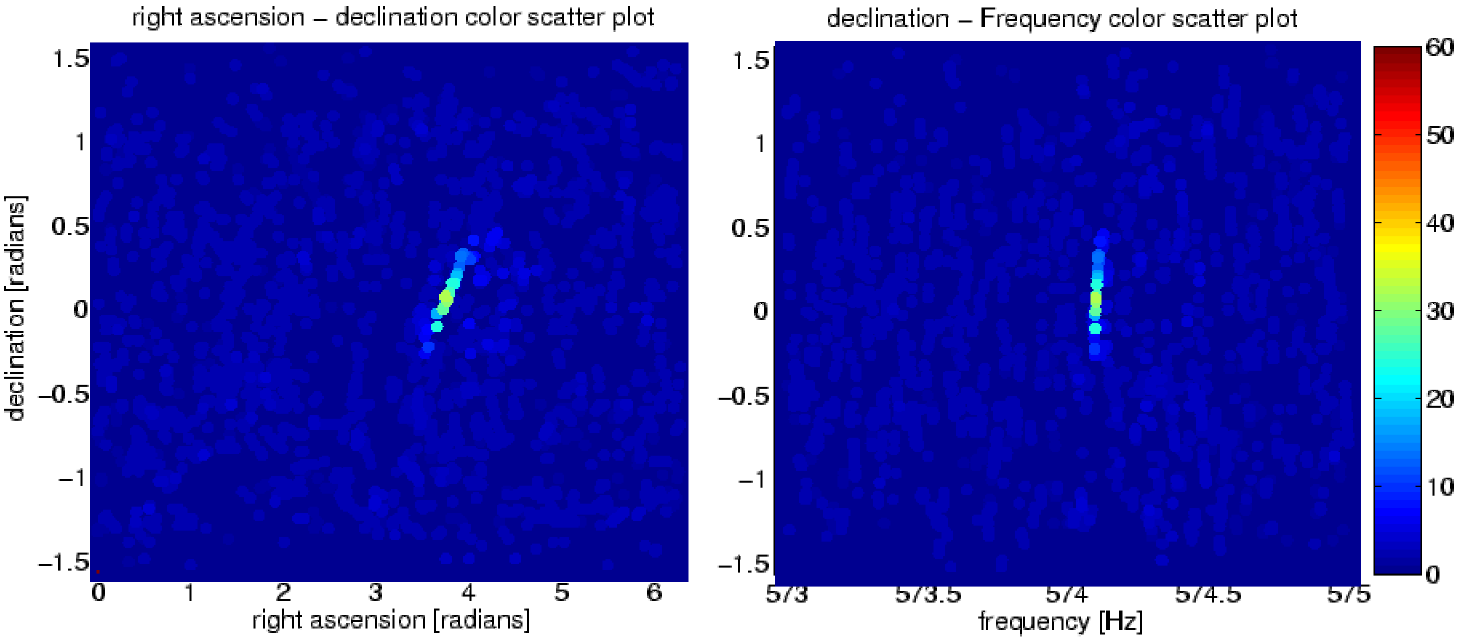
**This incoherent method (and other examples, Hough and Powerflux techniques) is one piece of hierarchical pipeline**

# Analyses for continuous gravitational waves III

- All-sky search is computationally intensive, e.g.
  - searching 1 year of data, you have 3 billion frequencies in a 1000Hz band
  - For each frequency we need to search 100 million million independent sky positions
  - pulsars spin down, so you have to consider approximately one billion times more templates
  - Number of templates for each frequency: ~$10^{23}$
- S3 Frequency-domain (“F-statistic”) all-sky search
  - The F-Statistic uses a matched filter technique, minimizing chisquare (maximizing likelihood) when comparing a template to the data
  - ~$10^{15}$ templates search over frequency (50Hz-1500Hz) and sky position
  - For S3 we are using the 600 most sensitive hours of data
  - We are combining the results of multiple stages of the search incoherently using a coincidence scheme

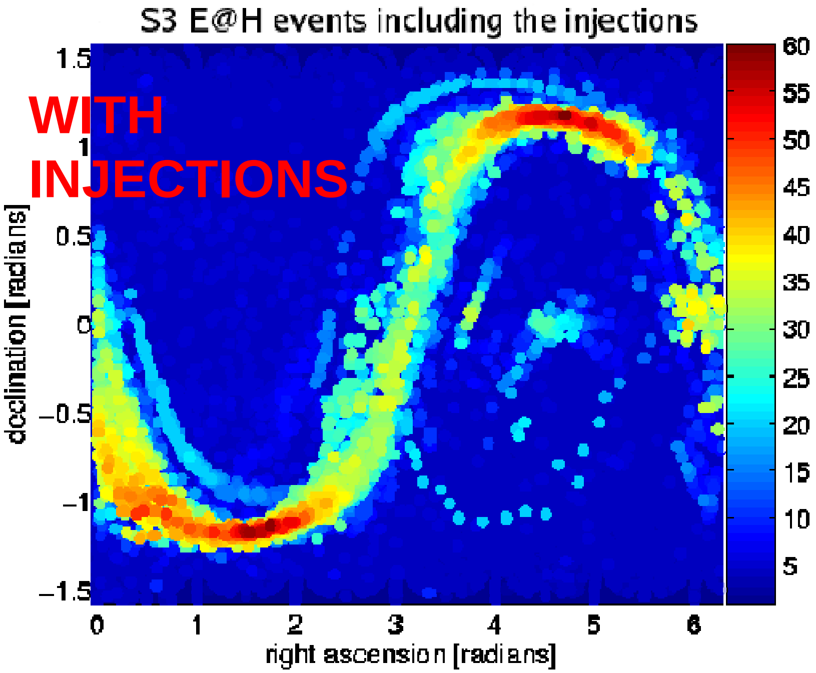
# What would a pulsar look like?

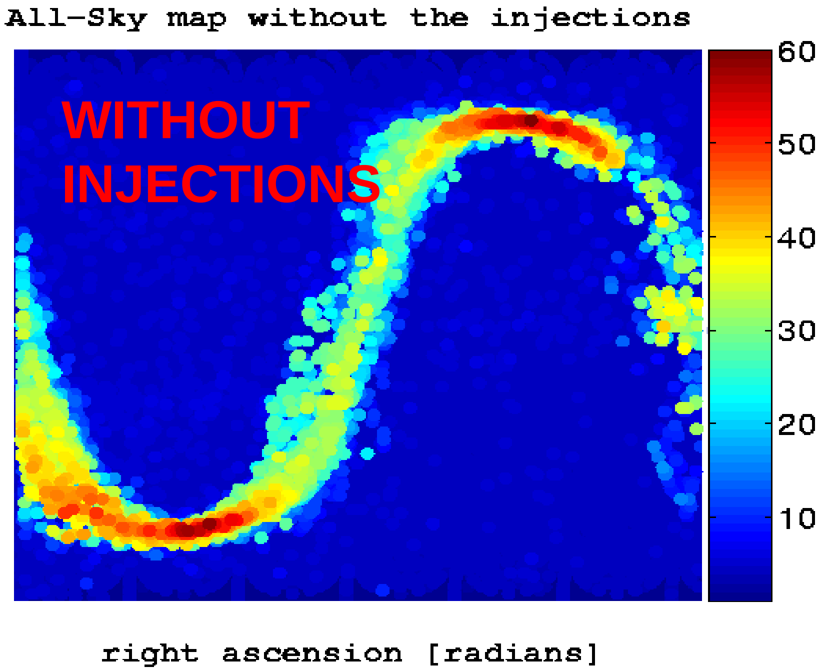
- Post-processing step: find points on the sky and in frequency that exceeded threshold in many of the sixty ten-hour segments
- Software-injected fake pulsar signal is recovered below



Simulated (software) pulsar signal in S3 data

# Final S3 analysis results



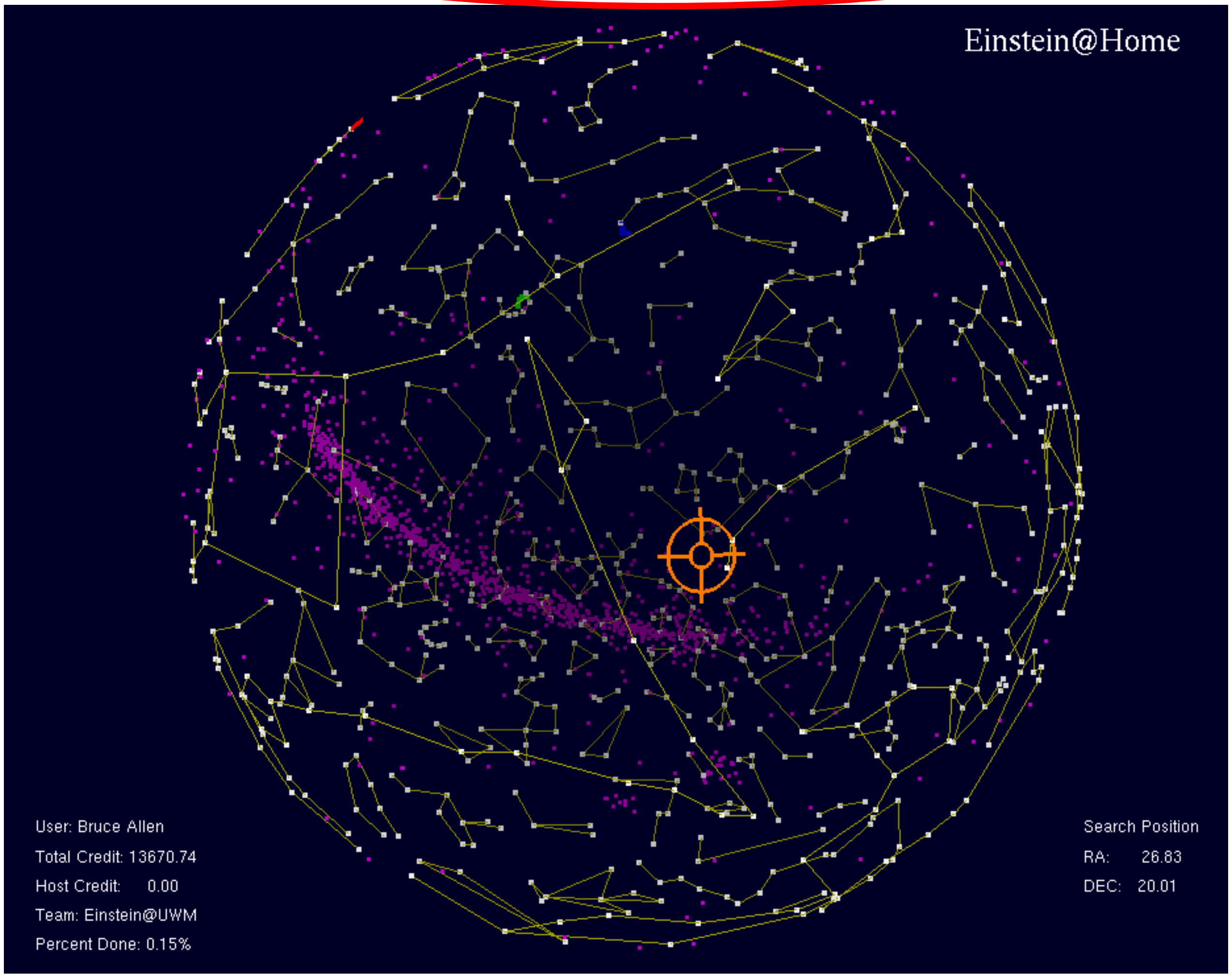


- Data: 60 10-hour stretches of the best H1 data
- Post-processing step on centralized server: find points in sky and frequency that exceed threshold in many of the sixty ten-hour segments analyzed
- 50-1500 Hz band shows no evidence of strong pulsar signals in sensitive part of the sky, apart from the hardware and software injections. There is nothing “in our backyard”.
- Outliers are consistent with instrumental lines. All significant artifacts away from r.n=0 are ruled out by follow-up studies.

# Einstein@home

- Like SETI@home, but for LIGO/GEO data
- American Physical Society (APS) publicized as part of World Year of Physics (WYP) 2005 activities
- Use infrastructure/help from SETI@home developers for the distributed computing parts (BOINC)
- Goal: pulsar searches using ~1 million clients. Support for Windows, Mac OSX, Linux clients
- From our own clusters we can get ~ thousands of CPUs. From Einstein@home hope to get order(s) of magnitude more at low cost
- Great outreach and science education tool
- Currently : ~110,000 active users corresponding to about 42Tflops, about 250 new users/day

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

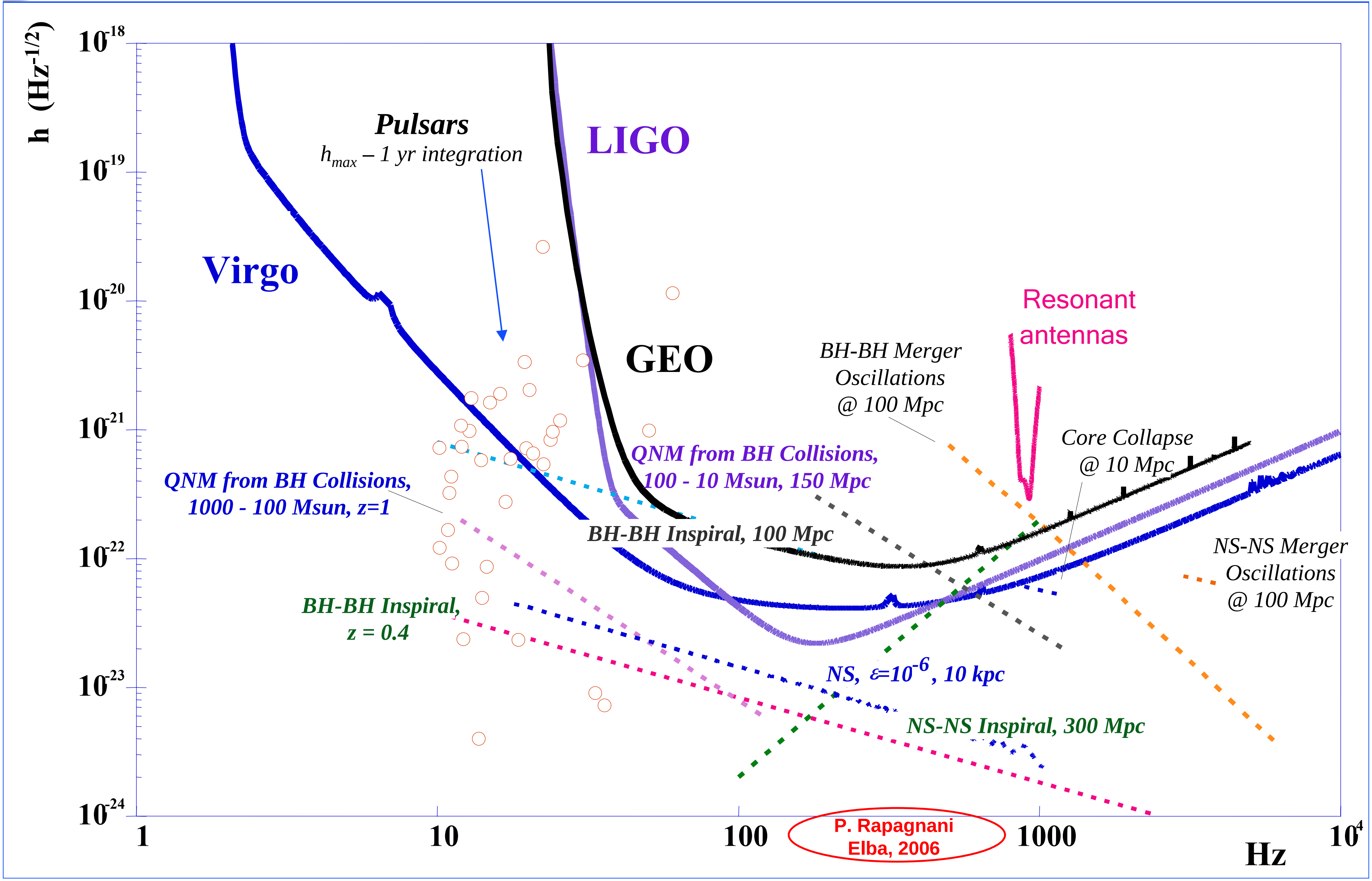


Einstein@Home

User: Bruce Allen
Total Credit: 13670.74
Host Credit: 0.00
Team: Einstein@UWM
Percent Done: 0.15%

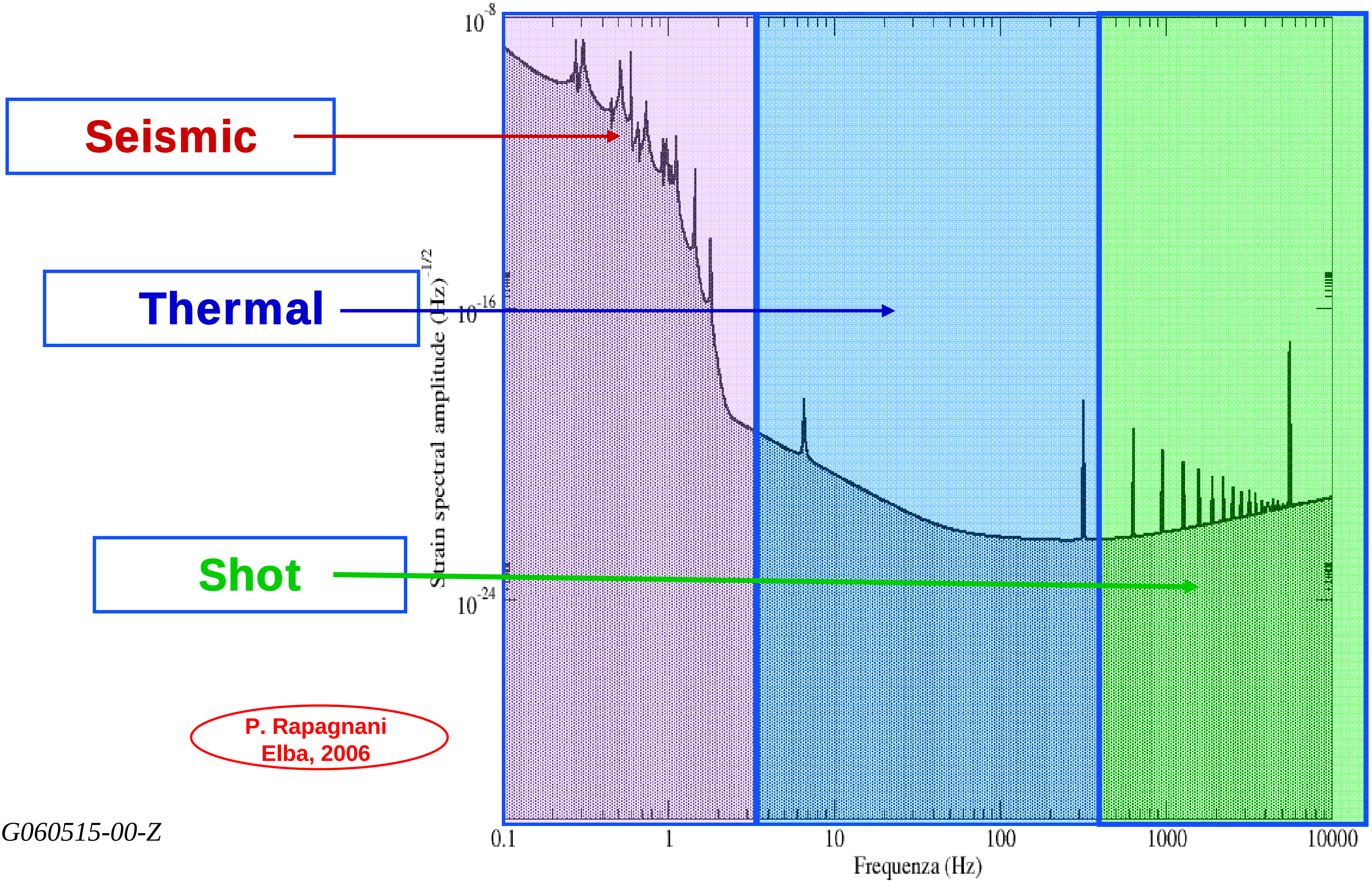
Search Position
RA: 26.83
DEC: 20.01

# First Generation Detectors



# After 2007: Expanding the Accessible Universe:

*Where and how can we reduce the detector noise?*



**Seismic**

**Thermal**

**Shot**

P. Rapagnani
Elba, 2006

# Advanced LIGO

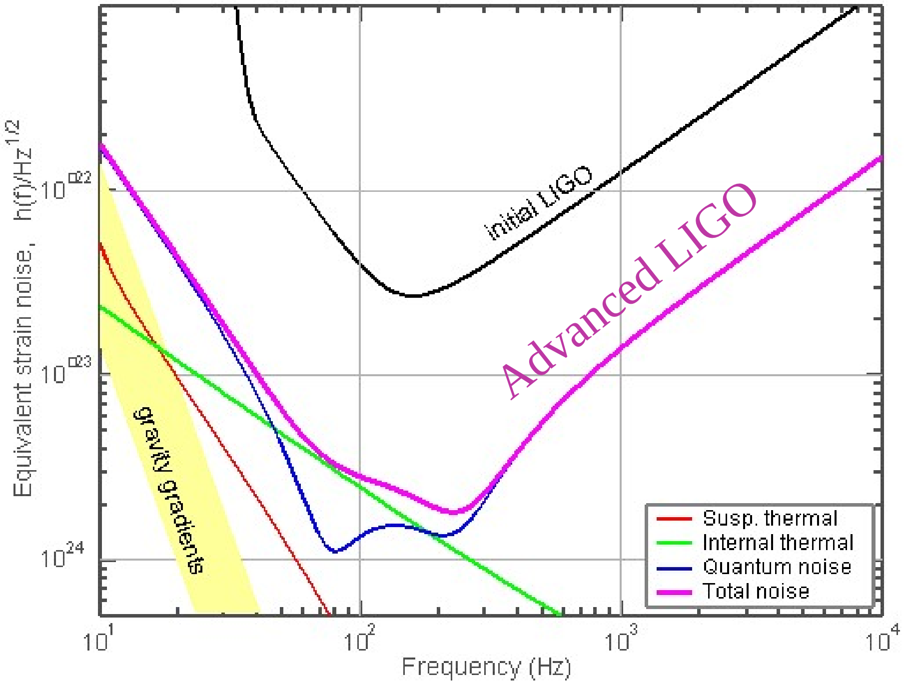
➔Advanced LIGO is the LIGO Lab proposal for the next generation instrument to be installed at the LIGO Observatory

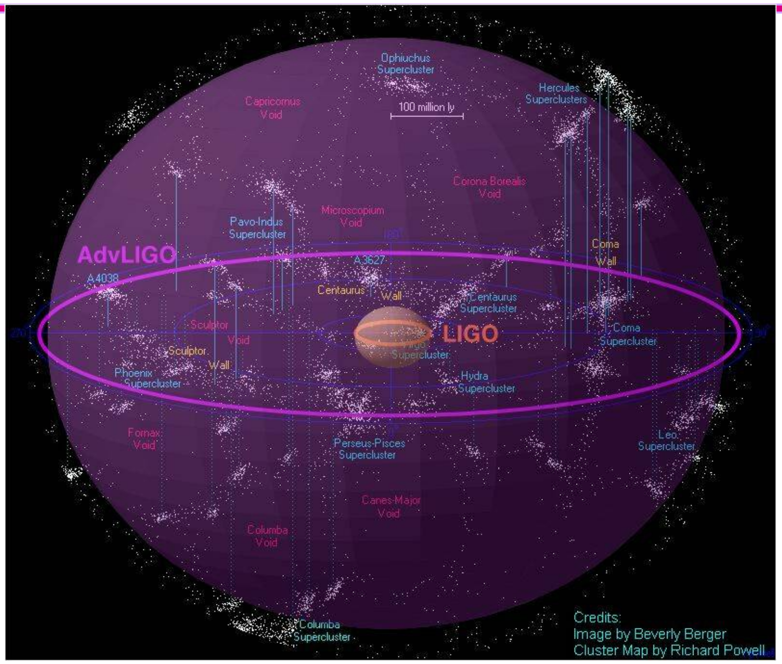
**Upgrade all 3 Interferometers and convert Hanford 2K to 4K Interferometer**

- **Factor of 10 better amplitude sensitivity**
- **Factor of 4 lower frequency bound**
- **Potential for tunable, narrow band searches**
  - **Change transmission of recycling mirrors by changing mirrors or using tunable transmission mirror**

# LIGO detectors: future

- □□**Neutron Star Binaries:**
  Initial LIGO: ~10-20 Mpc →
  Advanced LIGO: ~200-350 Mpc
  **Most likely rate: 1 every 2 days !**
- **Black hole Binaries:**
  Up to 10 $M_o$, at ~ 100 Mpc
  → up to 50 $M_o$, in most of the observable Universe!





Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

x10 better amplitude sensitivity

⇒ x1000 rate=(reach)³

⇒ 1 year of Initial LIGO
< 1 day of Advanced LIGO !

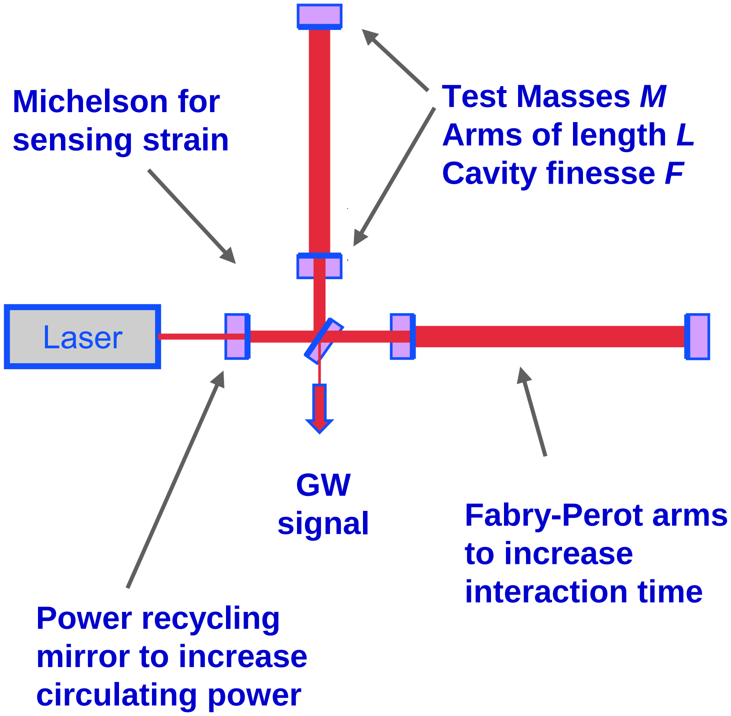
Planned NSF Funding
in FY’08 budget.

# Advanced LIGO Detector Improvements

**Retain infrastructure, vacuum chambers, and Initial LIGO layout of power recycled interferometer**

- Replace passive seismic isolation with multi-staged system with inertial sensing and feedback control
- Increase number of passive suspension isolation steps and use lower noise activation techniques
- Use lower mechanical-loss materials and construction in suspensions, optical substrates and coatings to reduce thermal noise
- Increase laser power ~20x and reduce optical losses to improve shot noise limits and signal strength
- Add GW signal recycling at output to increase sensitivity and allow narrow band frequency tuning.

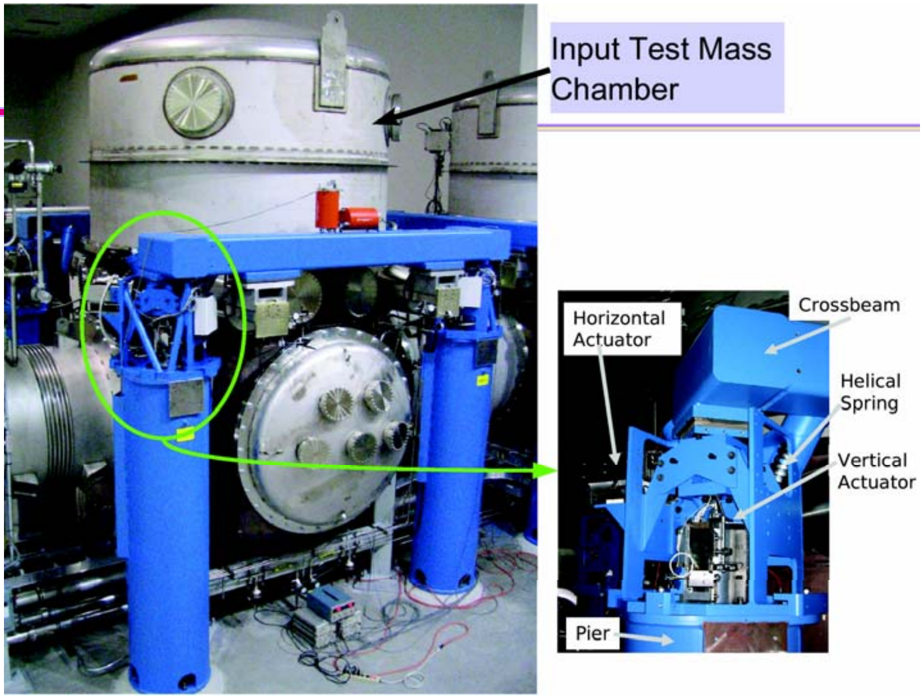
INITIAL LIGO LAYOUT

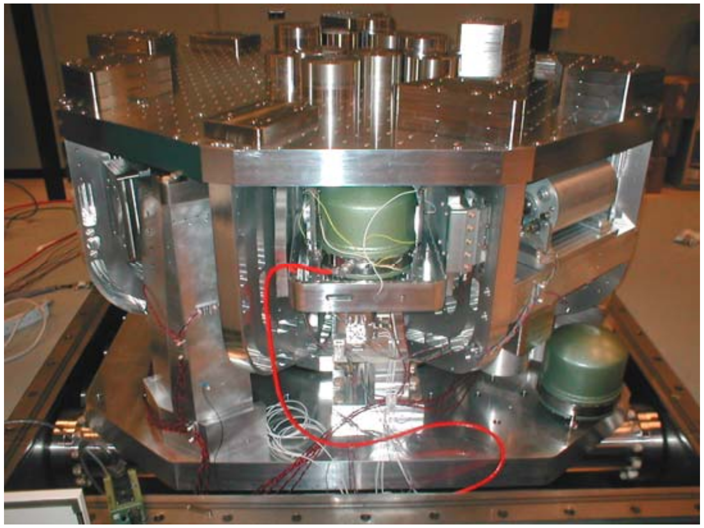


# Full-Scale Seismic Prototypes & Early Implementation

External pre-isolator installed and operating at Livingston

- Performance meets initial LIGO and exceeds Advanced LIGO requirements





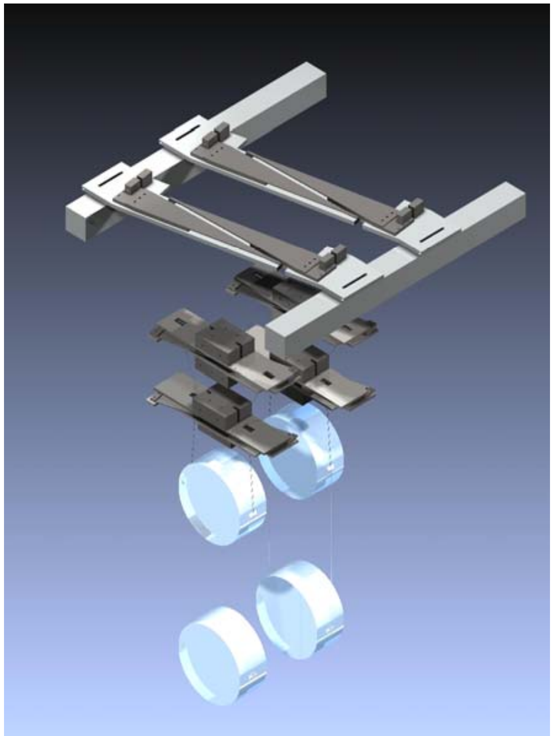
Technology Demonstrator at Stanford in characterization

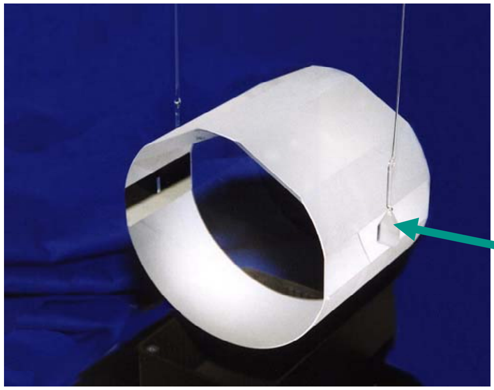
- 1000x Isolation at GW frequencies demonstrated
- 1-10 Hz performance testing in progress

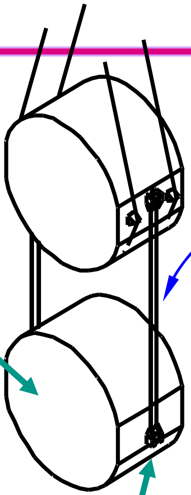
Planned future testing of full scale, integrated seismic isolation and suspensions at MIT's test facility.

# Thermal Noise Suppression

- Minimise thermal noise from pendulum modes and their electronic controls
  - » Thermally induced motion of the test masses sets the sensitivity limit in the range ~10 — 100 Hz
  - » Required noise level at each of the main optics is $10^{-19}$ m/√Hz at 10 Hz, falling off at higher frequencies







**Test mass with mirror coating**

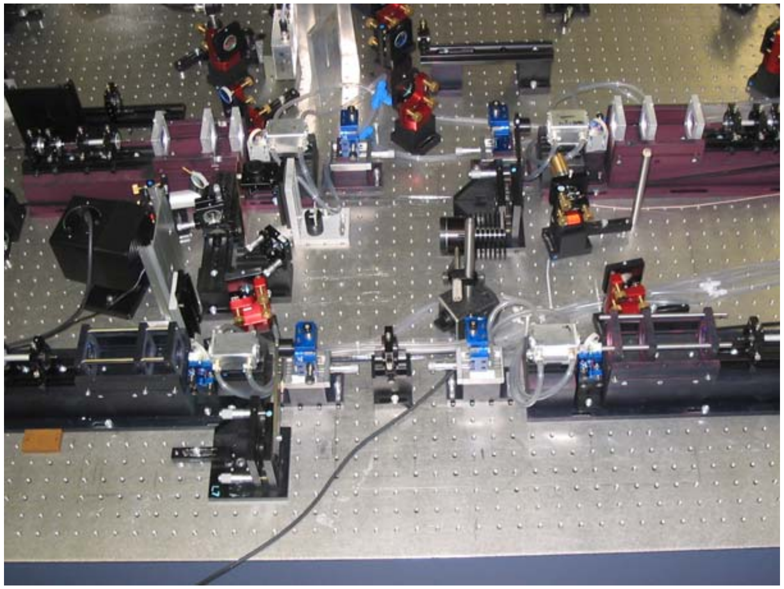
**Silica fibres**

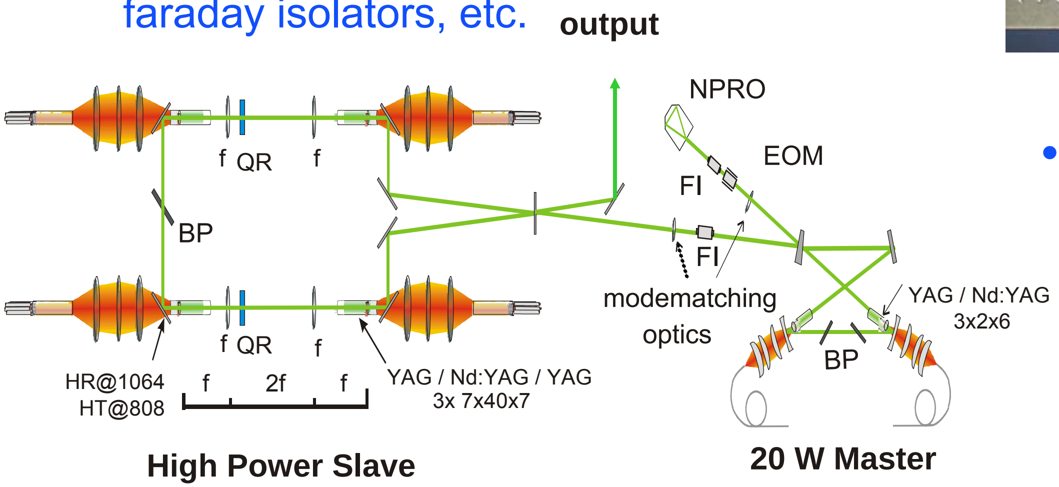
**Silicate bonds**

- Choose quadruple pendulum suspensions for the main optics and triple pendulum suspensions for less critical optics
- Create quasi-monolithic pendulums using fused silica ribbons to suspend 40 kg test mass

# Shot Noise Limits

- Increase laser power to lower shot noise
  - » Require TEM00, stability in frequency and intensity
  - » Significant motion due to photon pressure – quantum limited
  - » ~180 W input power is practical limit
- Increased laser power (~0.8MW in FP cavities) leads to increased requirements on many components
  - » Photo-diodes, optical absorption, thermal lensing compensation, modulators and faraday isolators, etc.

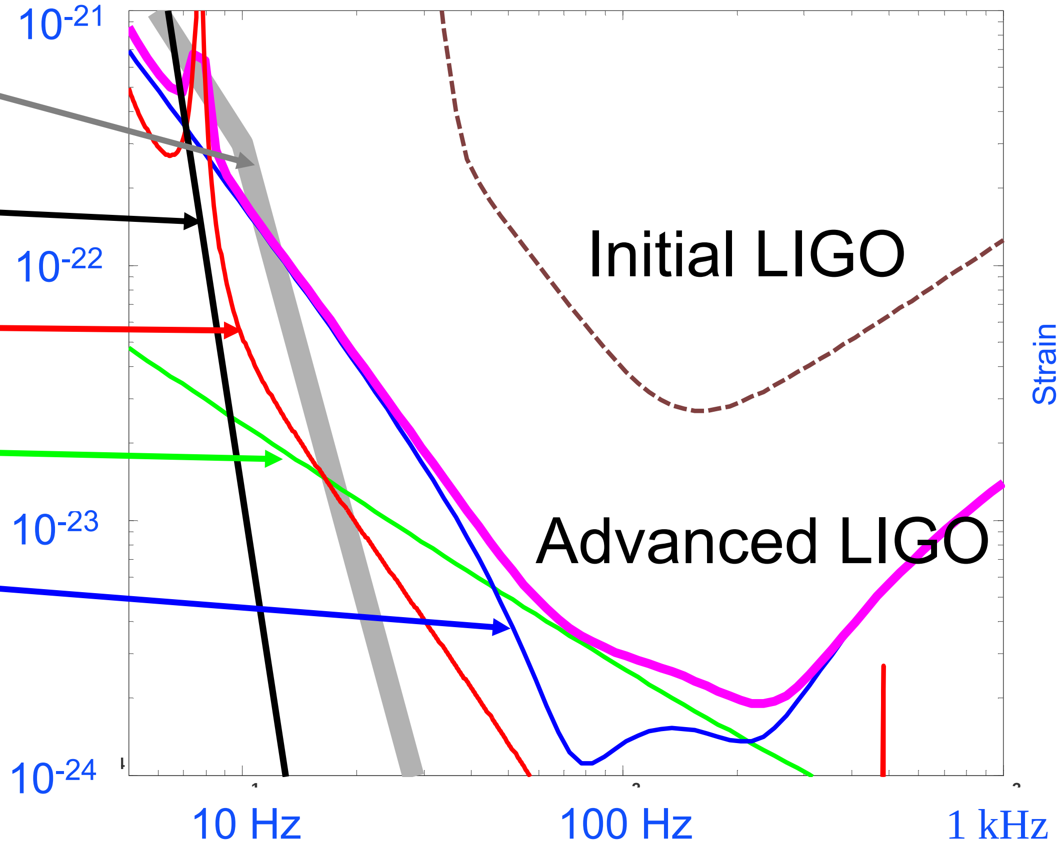




- Full injection locked master-slave system running, 200 W, linear polarization, single frequency, many hours of continuous operation

# Projected Adv LIGO Detector Performance

- Newtonian background, estimate for LIGO sites
- Seismic ‘cutoff’ at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning



Advanced LIGO's Fabry-Perot Michelson Interferometer is flexible – can tailor to what we learn before and after we bring it on line, to the limits of this topology and fundamental noise limits.

# Advanced VIRGO

**2006-2007**

- Working groups activity
  - » Signal Recycling
  - » High Power
  - » New optics and optical configuration
- Technical design

**2008-2009**

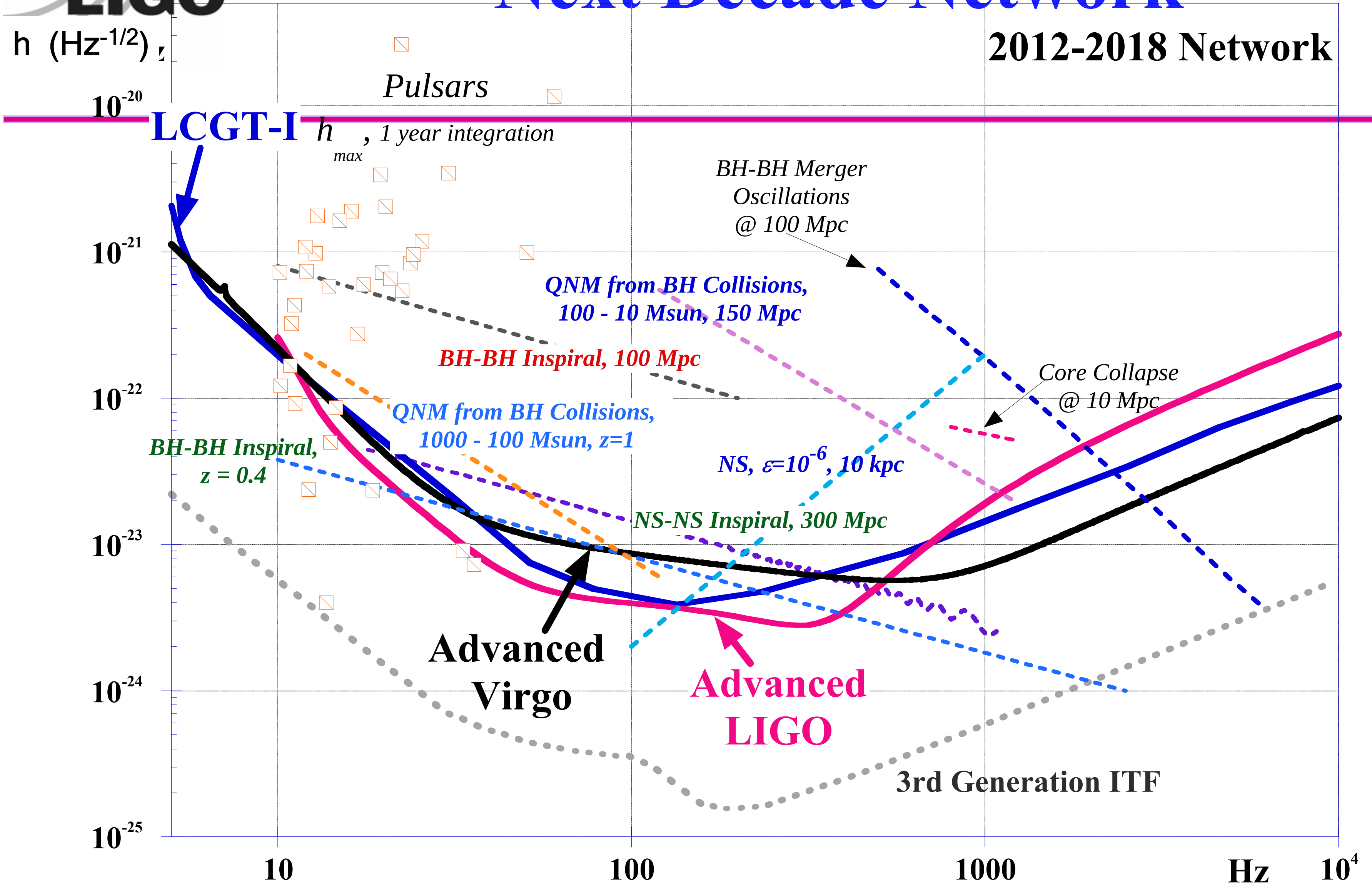
- Engineering activities for **Advanced Virgo**

**> 2010**

- **Advanced Virgo** upgrades

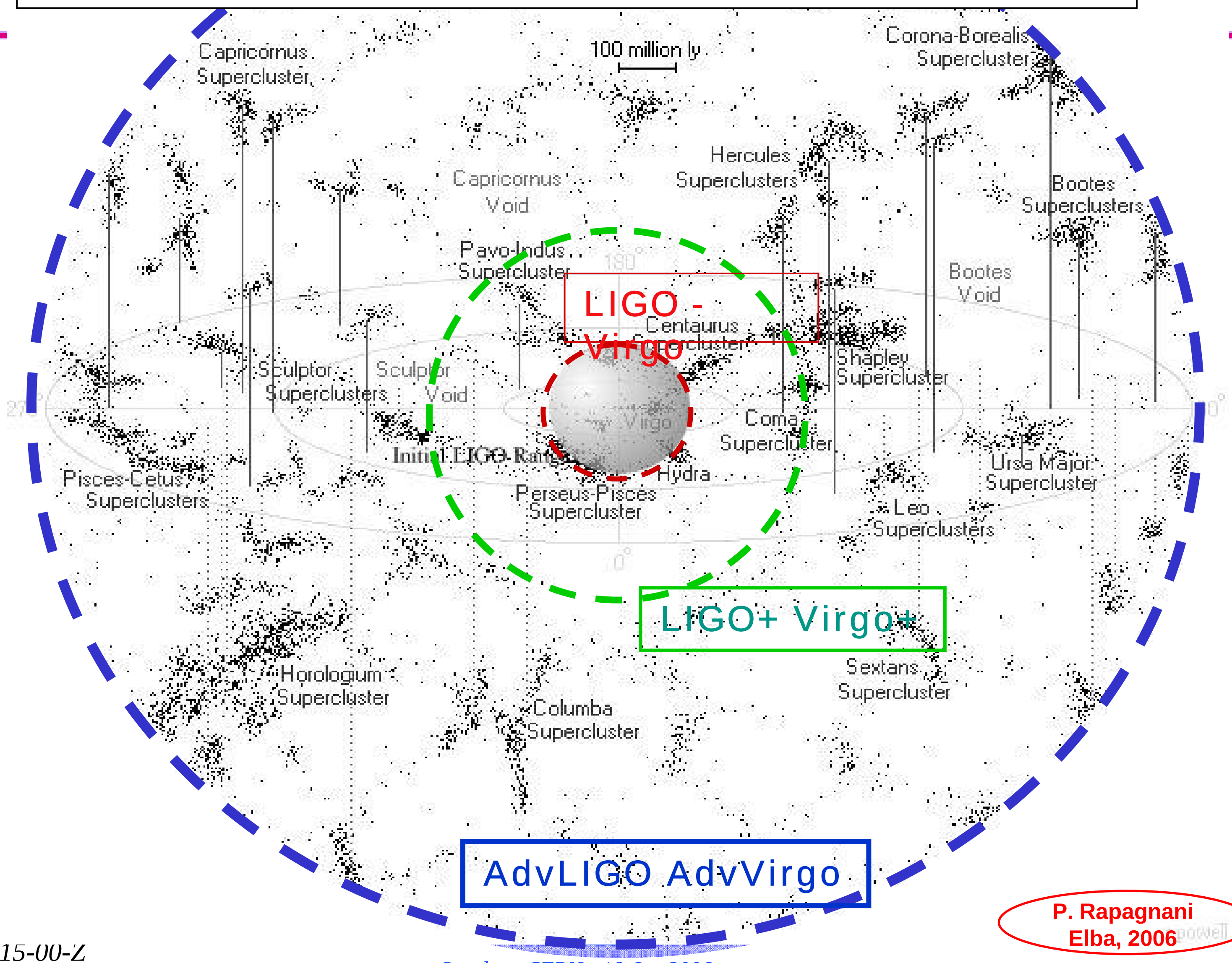
**P. Rapagnani**
**Elba, 2006**

# Next Decade Network



P. Rapagnani
Elba, 2006

# A hope for the near future:
# The Beginning of a New Astronomy...



LIGO - Virgo

LIGO+ Virgo+

AdvLIGO AdvVirgo

**P. Rapagnani**
**Elba, 2006**

# Comparing IGEC and LIGO

- S2 run

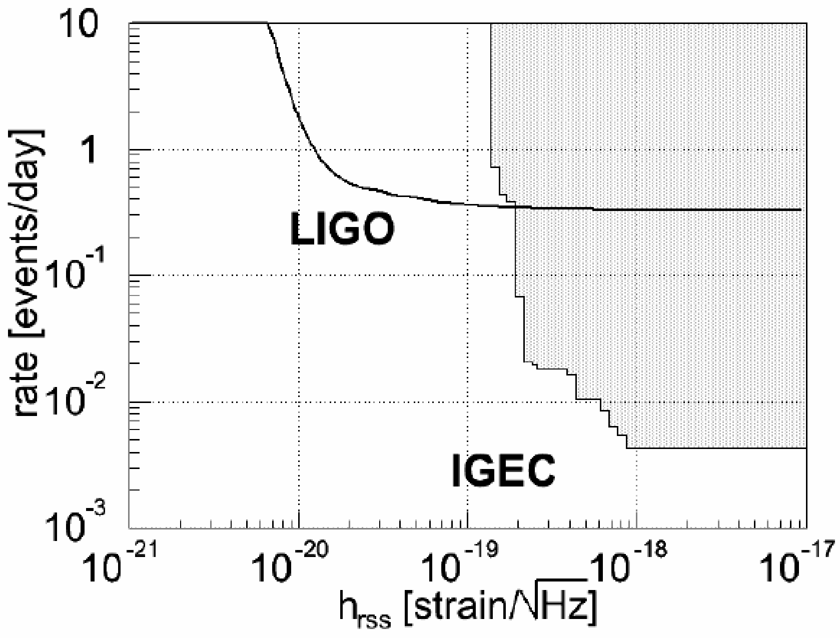


FIG. 14: Rate versus $h_{\rm rss}$ exclusion curves at the 95% confidence level for optimally oriented Gaussians of $\tau$=0.1 ms. The solid curve displays the 95% confidence level measurement obtained by LIGO with this search. The IGEC exclusion region is shown shaded and it is adapted from Fig. 13 of [46]. If the comparison were performed using Q=8.9, 849 Hz sine-Gaussians, the LIGO and IGEC curves would move to smaller amplitudes by factors of 1.1 and ~3, respectively.