GRAVITATIONAL WAVE ASTRONOMY

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1. GW: physics & astronomy
2. **Current- & next-gen detectors & searches**
3. Burst sources: CBC, SN → GR, cosmology
4. Periodic sources: NS → subatomic physics

LECTURE TWO

- LIGO: design and progress

- **Data analysis:** general principles
- Periodic signals: coherent, semi-coherent
- Some results of recent searches

- Importance of a **worldwide** detector network

PROJECTS

DETECTOR	BAND ("BUCKET")	PSD ($Hz^{-1/2}$)	SOURCES
Resonant sphere (Schenberg) or bar (Nautilus)	1 kHz	$3\ \ 10^{-22}$	PSR, SN
Advanced LIGO interferometer	0.3 kHz	$3\ \ 10^{-24}$	CBC (NS-NS, BH-BH), PSR, SN, stochastic
Einstein Telescope interferometer	0.2 kHz	$2\ \ 10^{-25}$	ditto
LISA interferometer – satellite	3 mHz	$1\ \ 10^{-20}$	WD-WD binary, EMRI, SMBH merger
Pulsar Timing Array	1 nHz	???	SMBH merger

LIGO: 1st DETECTION BY 2015

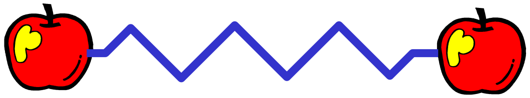
Relativity experiment → astronomical telescope

DETECTION PHYSICS

Size of detector $\ll \lambda$ (e.g. LIGO)

$$\ddot{\xi}_i = \tfrac{1}{2}\ddot{h}_{ij}^{TT}\xi^j + (\text{non GW})$$

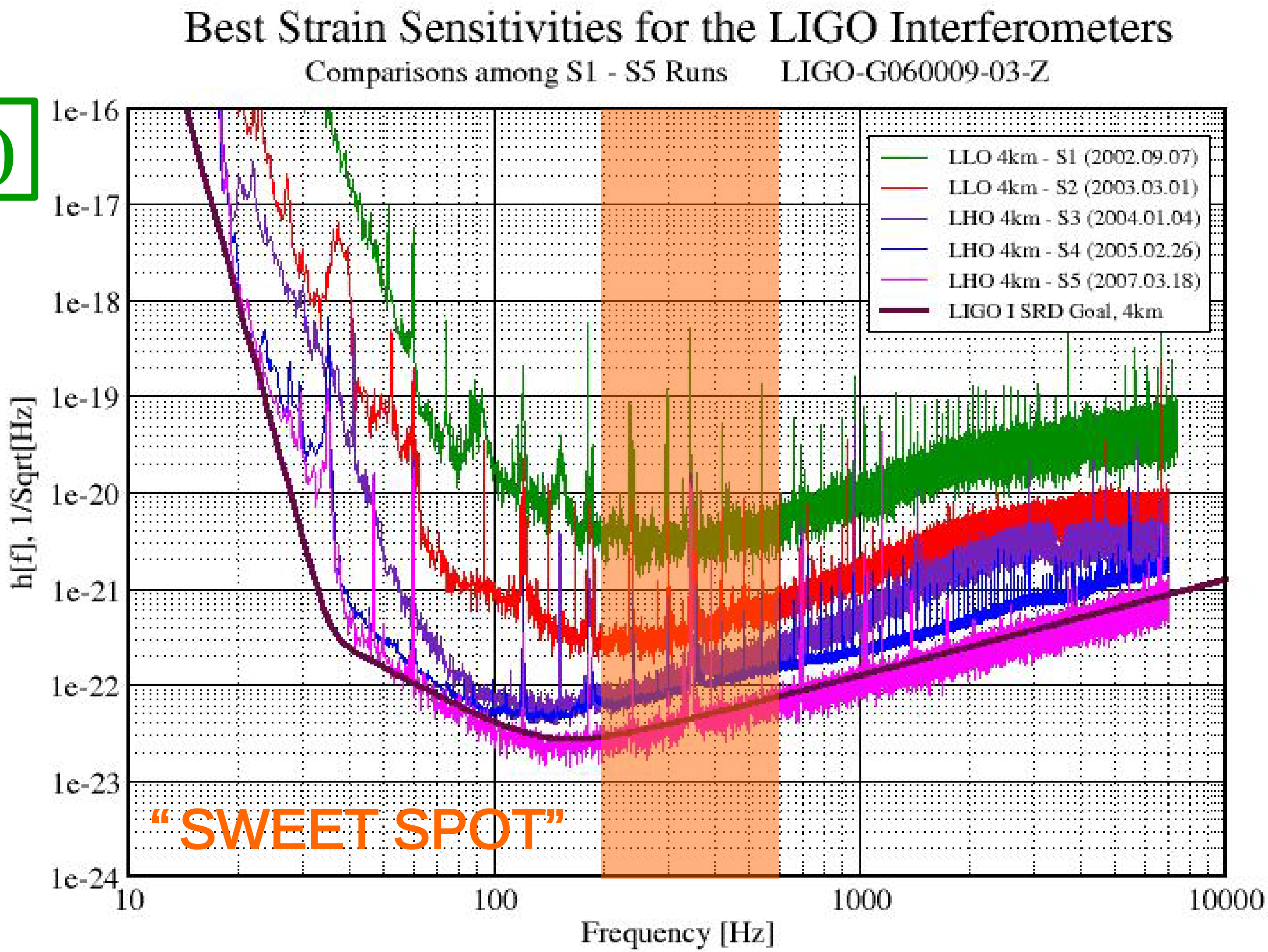
- Free masses: $\Delta\xi \sim h\xi$
- Masses joined by internal forces: $\Delta\xi \sim h(\omega\tau)^2\xi$



Size of detector $\gg \lambda$ (e.g. LISA, PSR timing array, Doppler tracking of spacecraft, microwave cavities)

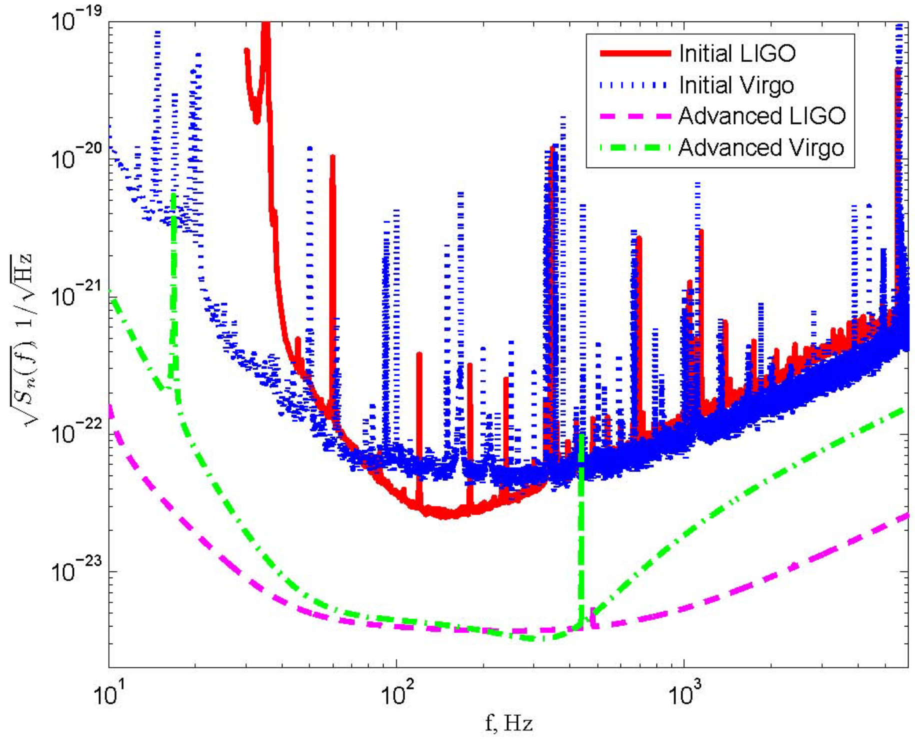
- Free masses: $\Delta\xi \sim h\lambda/2\pi \,\sin(2\pi\xi/\lambda)$

$S_h(f)$



- Signal : noise $= \int df \, |h(f)|^2 / S_h(f)$
- Strongest sources have $\Delta L = 10^{-4}$ **fm**

ADVANCED LIGO



arXiv:1003.2480

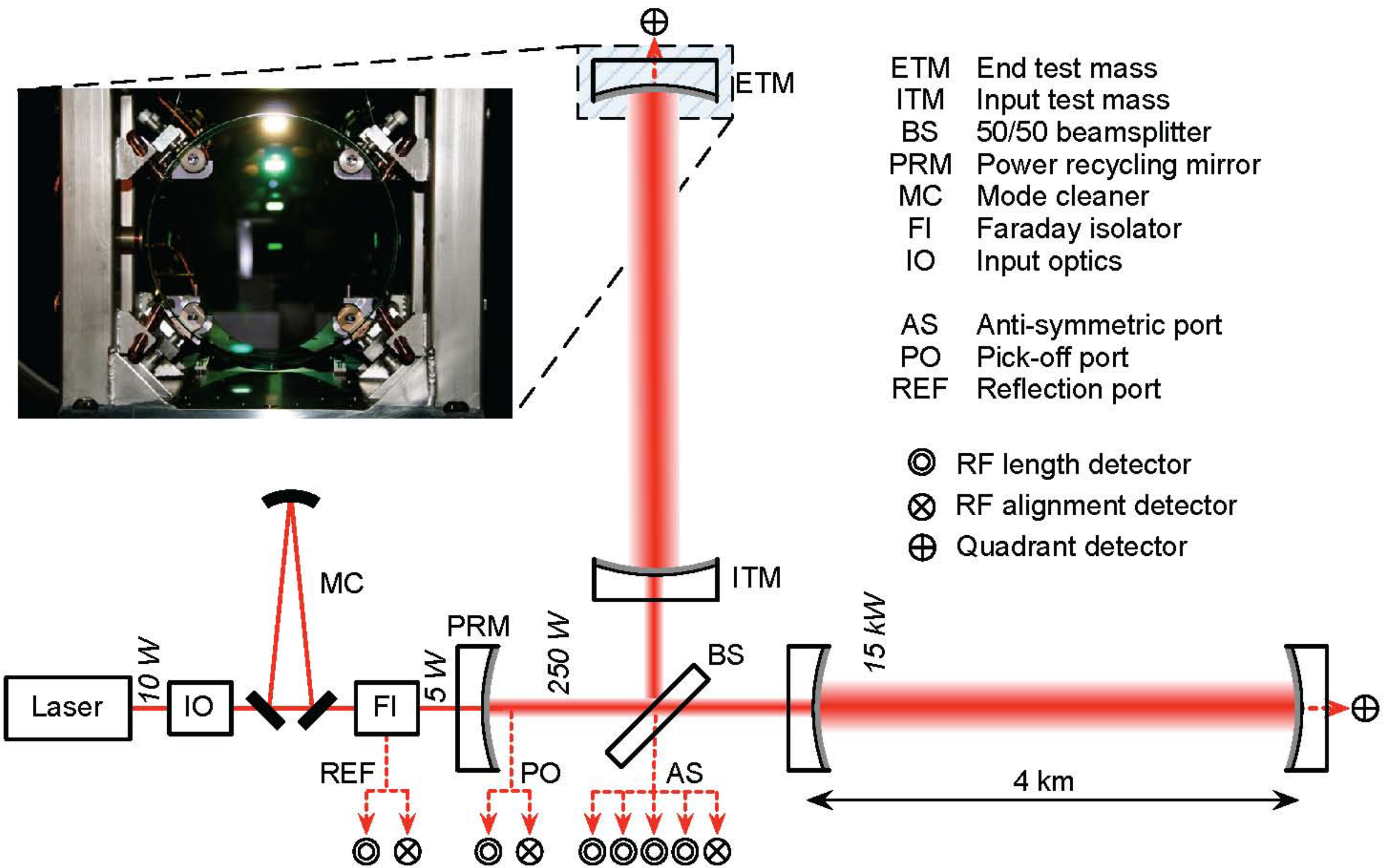
- Improved lasers, mirrors, suspensions, CPU
- Sensitivity × **10**, sources × **10³**, tunable

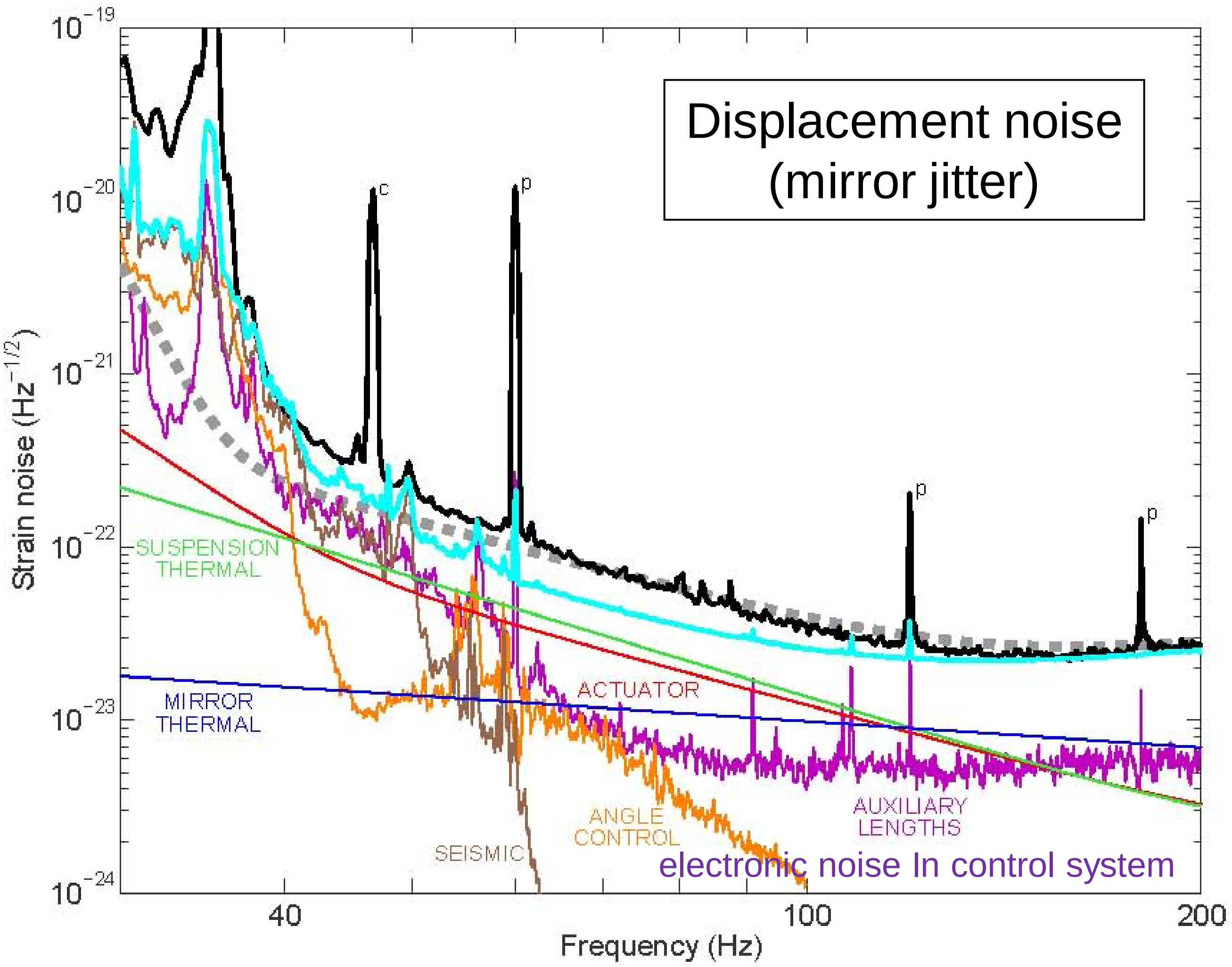
VITAL STATISTICS

- 4 km   4 km **Michelson interferometer**
- Laser 4.5W $\rightarrow$ 15 kW in **Fabry-Perot** cavity
- Active feedback to stay in lock
- Fused silica mirrors (11 kg), isolation stacks (four-stage, 80 dB @ 10^2 Hz)

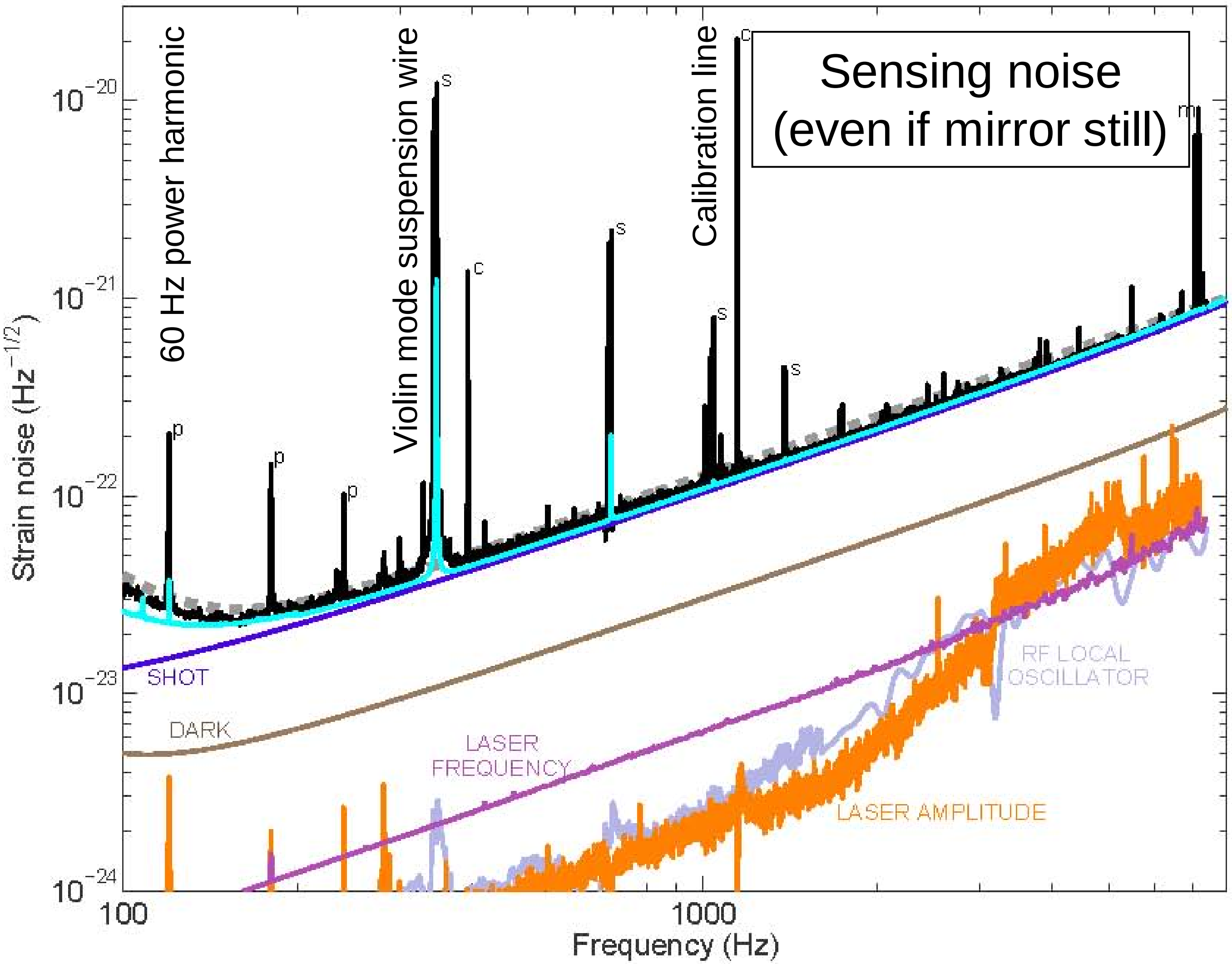
- Adv LIGO: **100 W** laser, **40 kg** mirrors

Petabytes! $h(t)$ @ 16 kHz plus 10^4 environmental

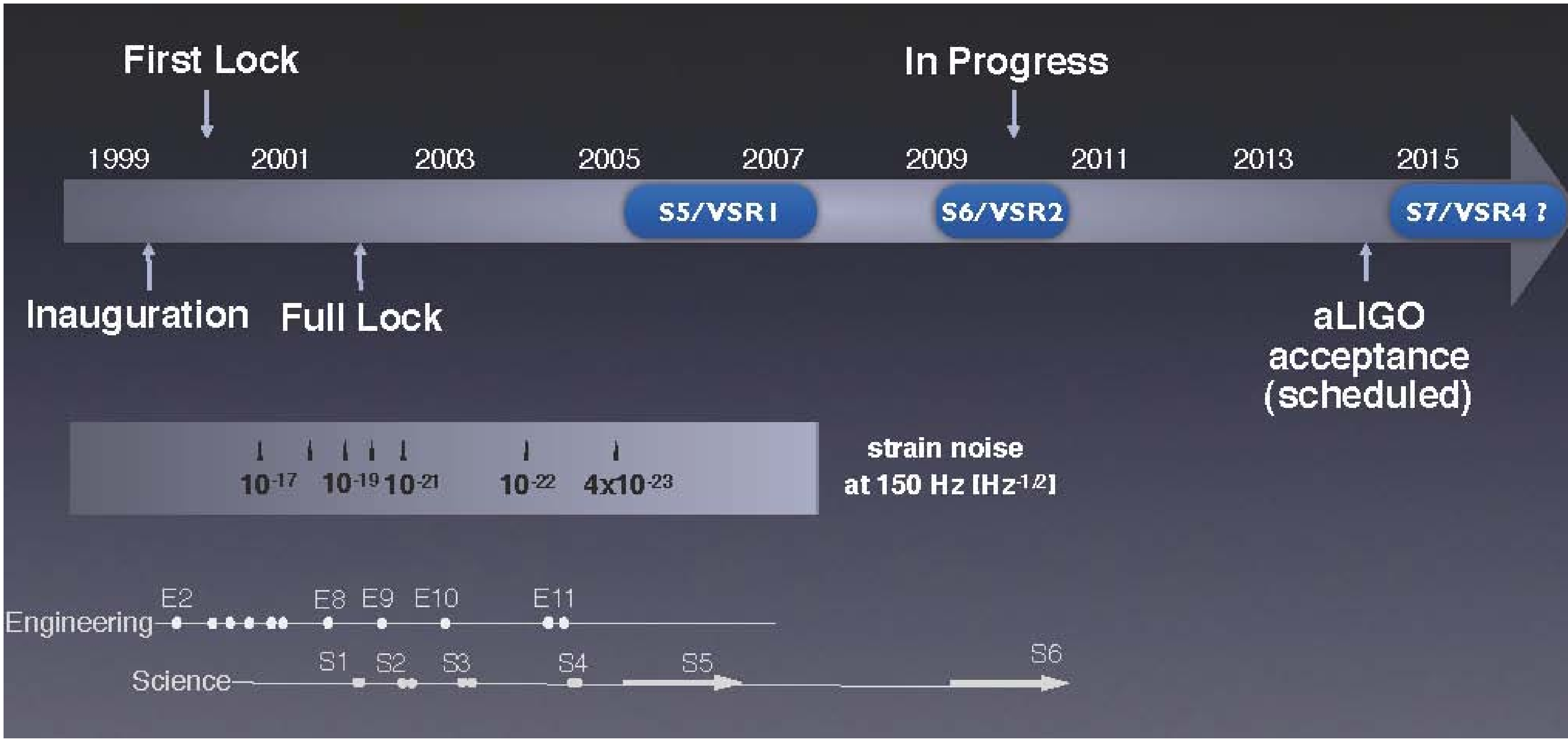

ETM
ETM End test mass
ITM Input test mass
BS 50/50 beamsplitter
PRM Power recycling mirror
MC Mode cleaner
FI Faraday isolator
IO Input optics
AS Anti-symmetric port
PO Pick-off port
REF Reflection port
RF length detector
RF alignment detector
Quadrant detector
MC
ITM
PRM
250 W
15 kW
BS
Laser
10 W
IO
FI
5 W
REF
PO
AS
4 km



- **Seismic wall** < 45 Hz excludes many PSRs ☹
- **Thermal noise** $\propto$ mechanical dissipation



- Shot noise $\propto f$ (squeezed states beat Heisenberg)
- Brighter laser → less shot noise → more thermal


First Lock
In Progress
1999
2001
2003
2005
2007
2009
2011
2013
2015
S5/VSR1
S6/VSR2
S7/VSR4 ?
Inauguration
Full Lock
aLIGO acceptance (scheduled)
10^{-17} 10^{-19} 10^{-21} 10^{-22} 4×10^{-23}
strain noise at 150 Hz $[Hz^{-1/2}]$
Engineering
E2
E8
E9
E10
E11
Science
S1
S2
S3
S4
S5
S6

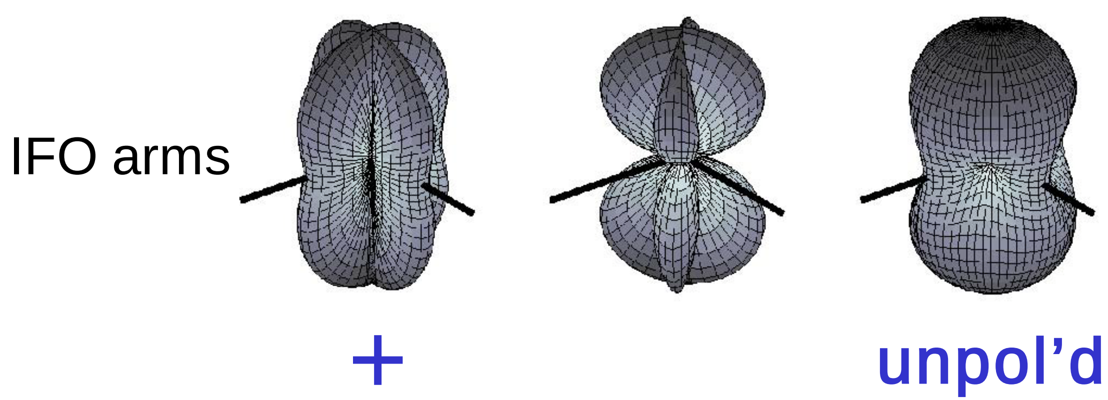
(from P. Brady)

SHORT PRIMER ON GW DATA ANALYSIS

… minus the challenging bits!

DATA

- Detector response $x(t) = \boldsymbol{h(t)} + \boldsymbol{n(t)}$
- Stationary, Gaussian noise $\boldsymbol{n(t)}$
- GW signal $\boldsymbol{h(t)} = \boldsymbol{F_+(t)}\, h_+(t) + \boldsymbol{F\ (t)}\, h\ (t)$
- Antenna $\boldsymbol{F_{+,}}$ are 24-hr periodic functions of sky position (α, δ) and polarization angle ψ



MATCHED FILTERING

- {source, antenna} = template $h(f)$
- Many pipelines, including low-latency

$$z(t) = 4\int_0^\infty df\, e^{2\pi i f t} h(f)^* x(f) / S_h(f)$$

$$\sigma^2 = 4\int_0^\infty df\, h(f)^* h(f) / S_h(f)$$

"PARSEVAL'S THEOREM"

- Trigger when **$SNR(t) = |z(t)| / \sigma > 5.5$**
- Data quality vetoes (five levels)

(Abadie et al. 11; arXiv:1102.3781)

PERIODIC: COHERENT

- **F statistic** (Jaranowski et al. 98) on 30-min SFTs
- **Maximum likelihood** over h_0, i, ψ, f_0 (if sky position known)

$$F = \ln\Lambda = (x\,|\,h) - \tfrac{1}{2}(h\,|\,h)$$

$$(x\,|\,y) = 4\,\mathrm{Re}\int_0^\infty df\,\frac{x(f)\,y(f)^*}{S_h(f)}$$

- Noise → $PDF(2F)$ = central χ^2 with 4 DOF
- Signal → χ^2 with non-centrality $(h|h)^{1/2}$
- Sensitivity: $$\langle h_0\rangle_{i,\psi,\alpha,\delta} \approx 11.4\left[S_h(f_0)/T_{obs}\right]^{1/2}$$

SQUARE ROOT

- Generic: beat down noise as **square root** of the number of *tracked* cycles

- Choose **template spacing** to lose $\leq$ ¼ cycle (say) over T_{obs}
- Clever tricks to match contours of the "error metric" $\boldsymbol{d(SNR)/d\theta_i d\theta_j}$ (Fisher matrix)

- NS mountain: $\mathbf{10^{10}}$ cycles per yr $\rightarrow$ $\boldsymbol{h_0 \sim 10^{-25}}$
- CBC: $\mathbf{10^{4}}$ cycles in min $\rightarrow$ $\boldsymbol{h_0 \sim 10^{-22}}$

PERIODIC: INCOHERENT

- Coherent is computationally expensive
- **Semi-coherent:** break into coherent **chunks**
  - $\longrightarrow$ **StackSlide** (Brady & Creighton 02)
  - $\longrightarrow$ **Hough** (Krishnan et al. 04)
  - $\longrightarrow$ **PowerFlux** (Dergachev 05)
- Lose sensitivity by (number of chunks)$^{1/4}$

$$\langle h_0 \rangle \approx 8 N_{chunk}^{-1/4} [S_h(f_0)/T_{chunk}]^{1/2} = 8 N_{chunk}^{1/4} [S_h(f_0)/T_{obs}]^{1/2}$$

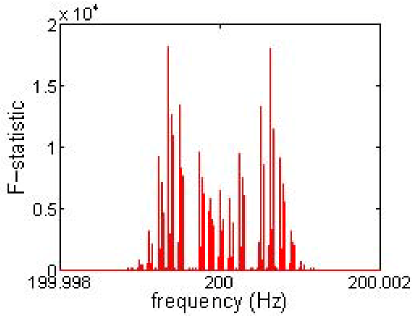
- Constant from **false alarm & dismissal** rate

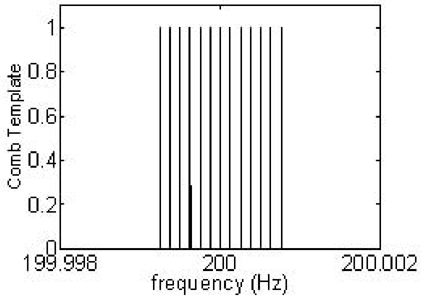
SCO X-1: COMB SEARCH

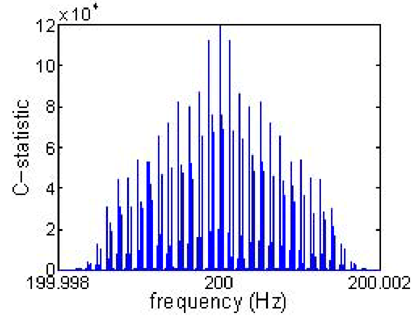
- Melbourne, AEI, Penn State

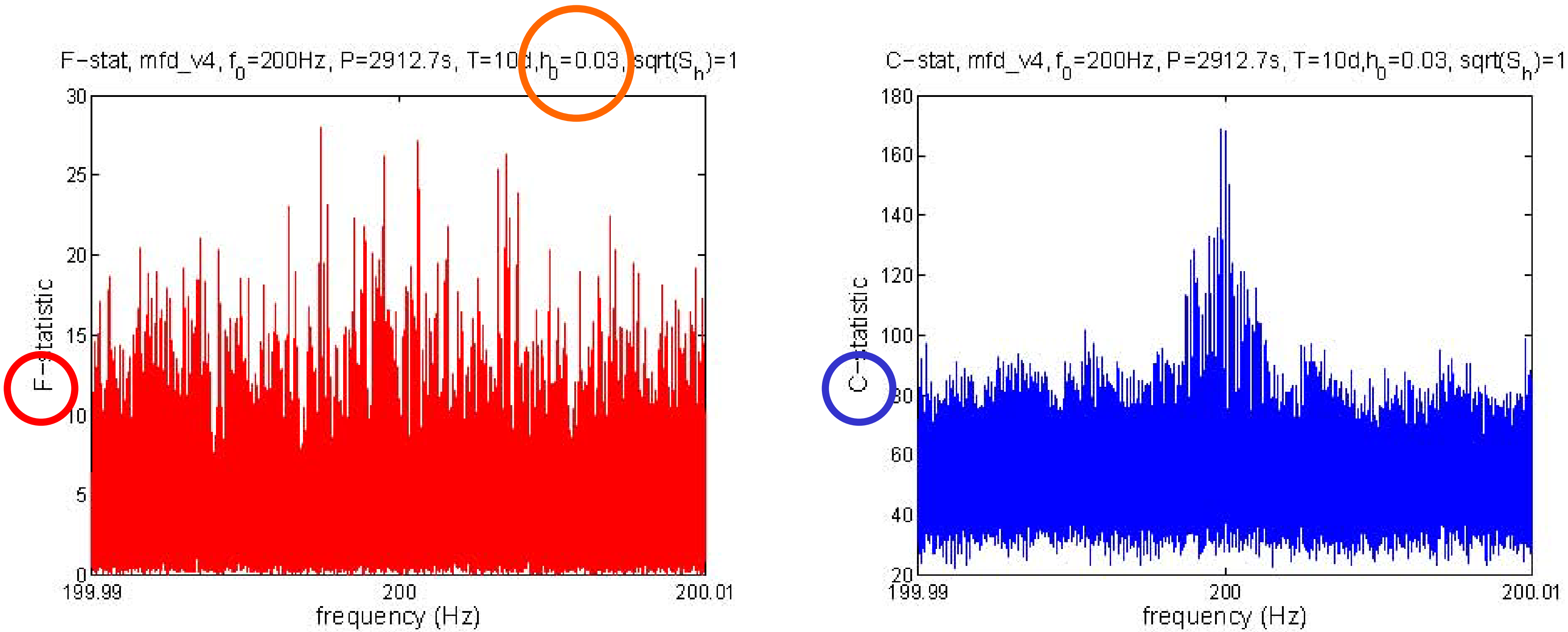
- Unknown spin period
- **Semi-coherently** add signal at teeth of Doppler comb

- AM sidebands = Earth spin
- FM sidebands = Sco X-1 orbit








F−stat, mfd_v4, f_0=200Hz, P=2912.7s, T=10d,h_0=0.03, sqrt(S_h)=1
F−statistic
30
25
20
15
10
5
0
199.99
200
200.01
frequency (Hz)
C−stat, mfd_v4, f_0=200Hz, P=2912.7s, T=10d,h_0=0.03, sqrt(S_h)=1
C−statistic
180
160
140
120
100
80
60
40
20
199.99
200
200.01
frequency (Hz)

LIGO S5 RESULTS

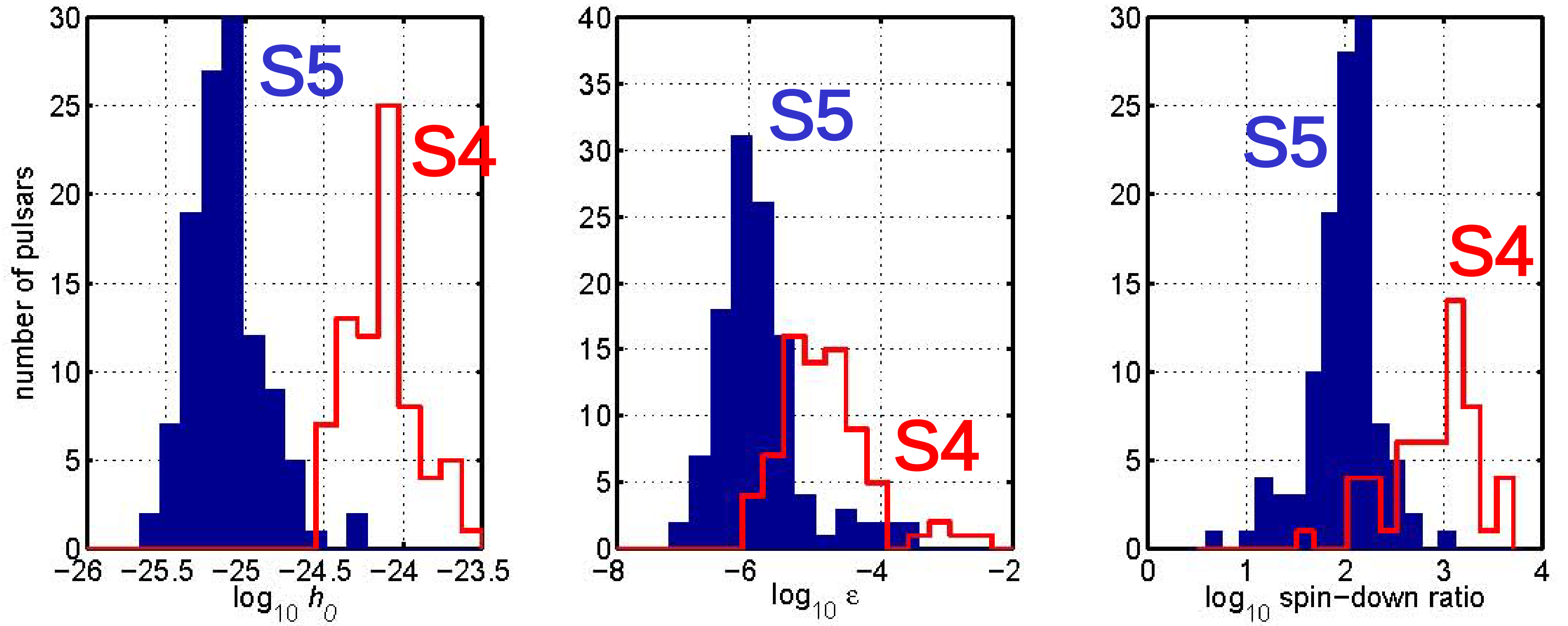
Some fruits of data analysis so far

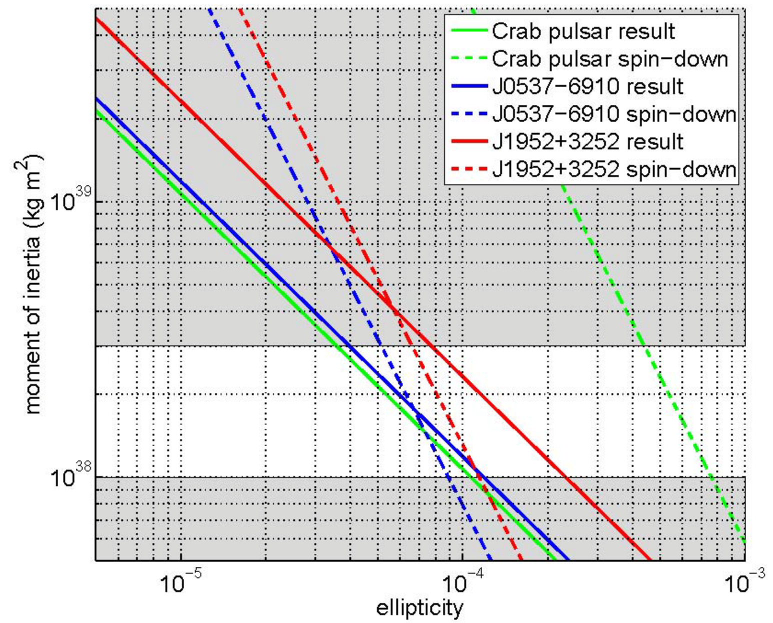
CRAB QUADRUPOLE

- Indirect **spin-down** limit on **ellipticity** $\varepsilon(B_{int})$
- **LIGO S5** beats spin down limit (Abbott et al. 08)
- Coherent F-statistic search (max. likelihood, sinusoidal matched filter) "at" radio ephemeris

$\mathbf{L_{GW}<0.02L_{SD}}$ AND $\boldsymbol{\varepsilon<1\times10^{-4}}$ AND $\mathbf{B_{int}<10^{16}\ G}$

- **Recycled pulsars** spin down slowly
- Best ellipticity bound is $\boldsymbol{\varepsilon<7\times10^{-8}}$ in J2124!





$$h \propto I\varepsilon\Omega^2$$

$$d\Omega/dt \propto I\varepsilon^2\Omega^5$$

(Abbott et al. 2010)

BLIND S5 PSR SEARCHES

All-sky PowerFlux (Abbott et al. 09)

- Eight months, $0.5 < f < 1.1$ kHz, $df/dt > -5 \ 10^{-9}$
- $h_0 < 10^{-24}$ @ 150 Hz, $\varepsilon < 10^{-6}$, births < 0.03 yr^{-1}

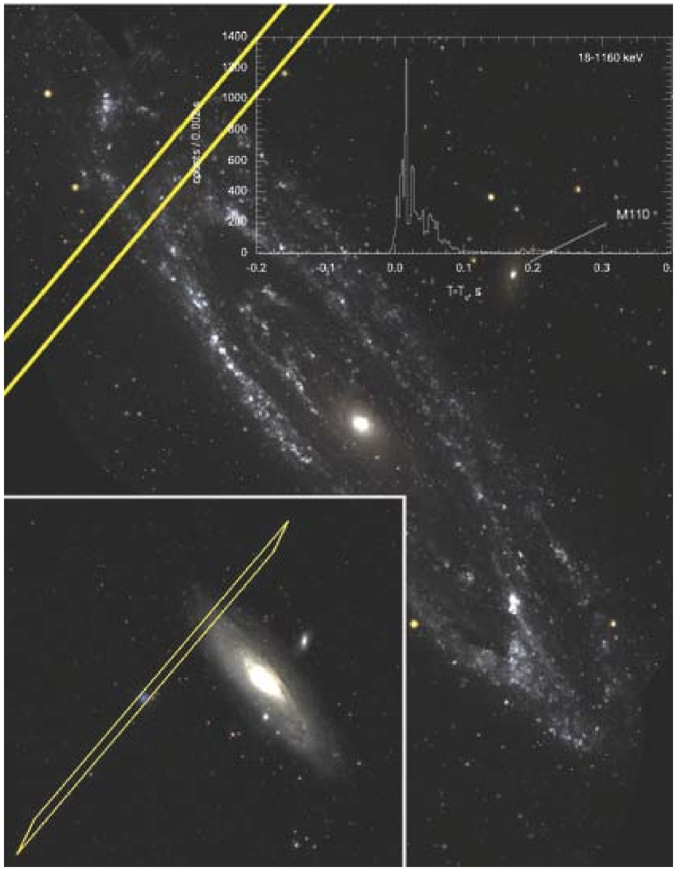
Einstein@Home (Abbott et al. 09)

- Similar ranges, $h_0 < 3 \ 10^{-24}$ @ 125-225 Hz

Cassiopeia A (Wette et al. 08)

- Spin unknown: 0.1-0.3 kHz, df/dt, d^2f/dt^2
- Beat spin down limit, $h_0 < 8 \ 10^{-25}$ @ 150 Hz

GRB 070201



- Interplanetary Network error box covered M31

- BUT LIGO would see CBC at 0.7 Mpc!
- Cannot rule out SGR

(Abbott et al. 08, arXiv:0711.1163)

BLIND INJECTION CHALLENGE

- Inserted **secretly** into LIGO data in hardware
- Poisson process $\sim 1\ \mathrm{yr}^{-1}$, **two** in S5

  → burst at $58\ \mathrm{Hz}$, $12\ \mathrm{ms}$ duration

  → CBC with $(1.1M_{\mathrm{Sun}}, 5.1M_{\mathrm{Sun}})$ and low spins
- One burst found, false alarm probability 10%
- Zero CBC found after all vetoes imposed
- **"Envelope opened"**
- With high-noise veto off, one CBC emerged
- False alarm rate $< 0.07\ \mathrm{yr}^{-1}$ … borderline

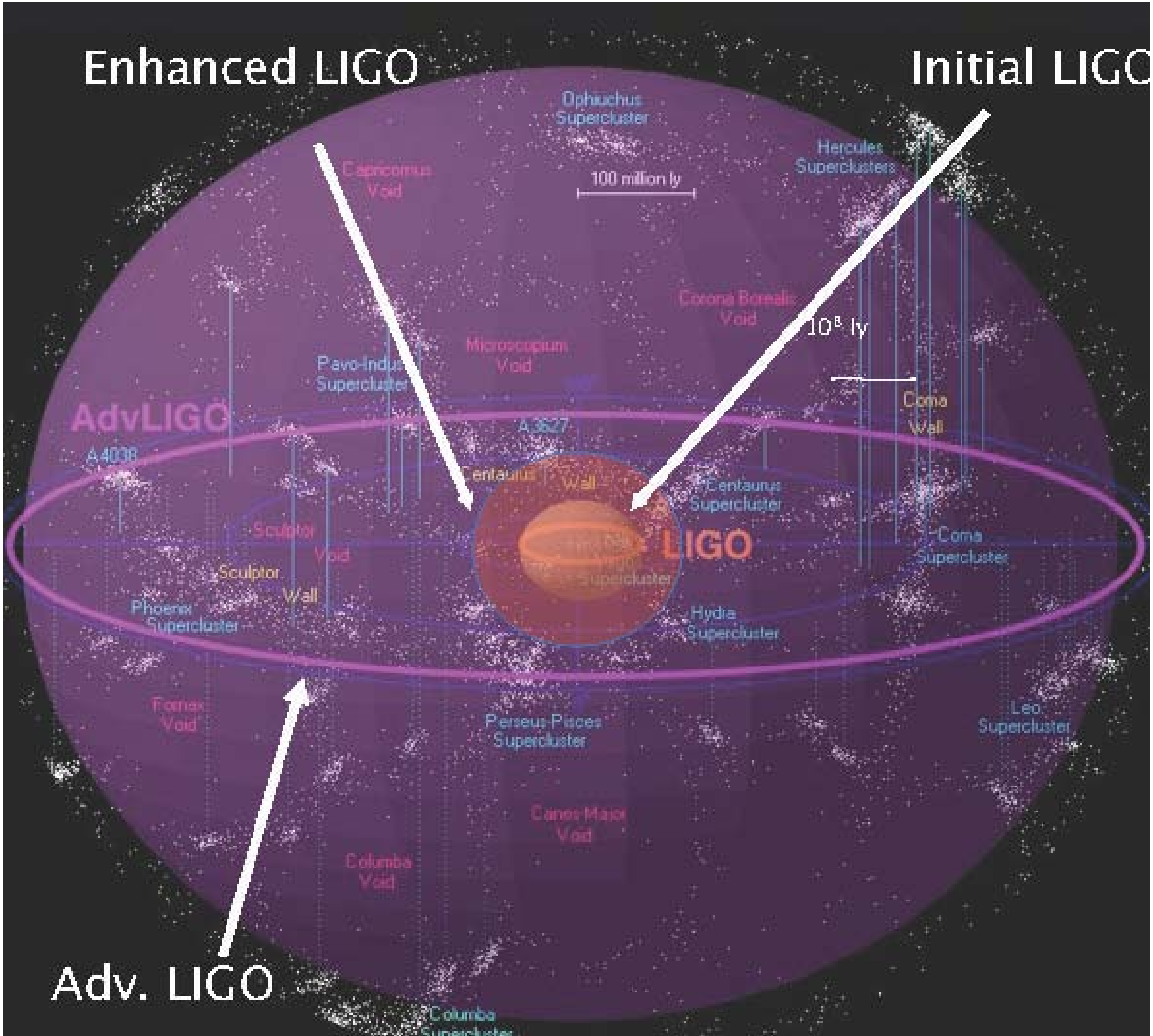
MULTI-MESSENGER – SOON

- Build **low-latency CBC** and **burst** pipelines (analysis 2 min, human vetting 30 min)
- Calibrate and aggregate $h(t)$ on-line
- Identify significant **three-site events**
- Evaluate **background**, apply **vetoes**
- Reconstruct **sky position**
- Submit event to candidate database
- Alert humans, evaluate, **request EM TOO**

MULTI-MESSENGER – NOW

- Swift target-of-opportunity (TOO)
- High-energy neutrino-triggered searches
- Wide-field optical follow-up
- Joint radio observations
- 2009-10: cooperation TAROT, QUEST, Swift

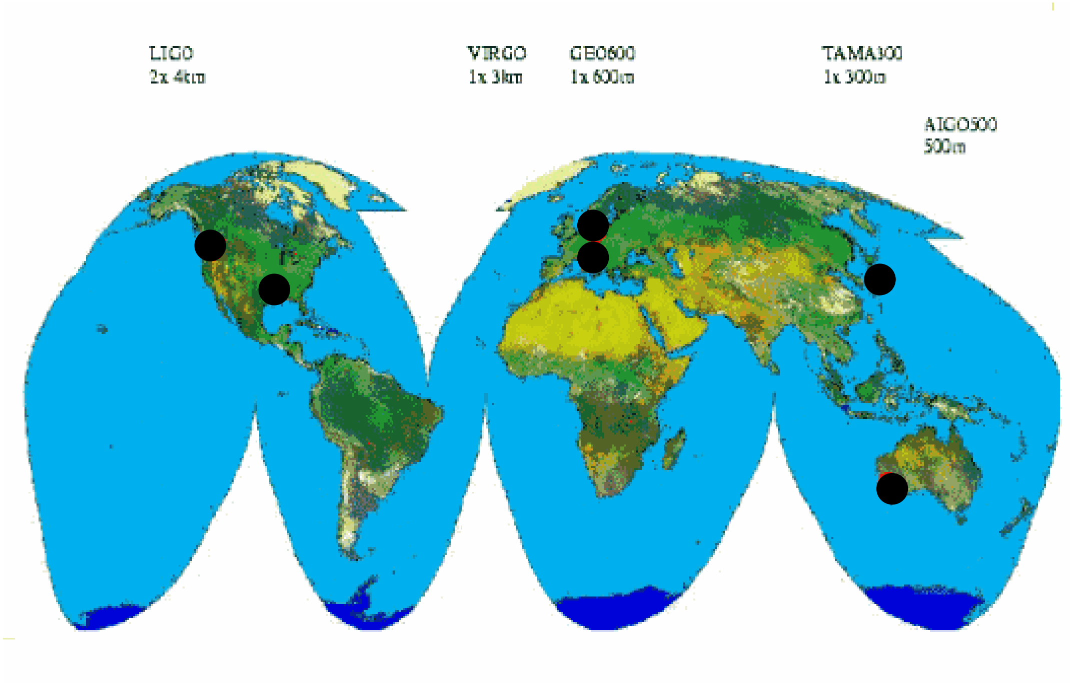
Transient factories: Palomar, Skymapper, ASKAP



Enhanced LIGO
Initial LIGO
Adv. LIGO
AdvLIGO
LIGO
Ophiuchus Supercluster
100 million ly
Hercules Superclusters
Capricornus Void
Corona Borealis Void
10^8 ly
Microscopium Void
Pavo-Indus Supercluster
Coma Wall
A3627
A4038
Centaurus Wall
Centaurus Supercluster
Sculptor Void
Sculptor Wall
Coma Supercluster
Phoenix Supercluster
Hydra Supercluster
Fornax Void
Perseus-Pisces Supercluster
Leo Supercluster
Canes Major Void
Columba Void
Columba Supercluster

IMPORTANCE OF A WORLDWIDE NETWORK

Example: LIGO Australia


LIGO
2x 4km
VIRGO
1x 3km
GEO600
1x 600m
TAMA300
1x 300m
AIGO500
500m


LIGO Hanford
GE600
LIGO Livingston
Virgo

Report of NSF Review

- “No brainer”
- Angular resolution improves 5- to 10-fold

  → triangulation and EM follow up (vital for astronomy)
- Parameter estimation

  → resolves distance versus inclination degeneracy
- Polarization information if orient arms optimally
- Reduce false alarm rate and non-Gaussian tails

  → new, coherent search algorithms solve simultaneously for signal in each detector and sky position (not simple coincidence)
- Minimize environmental correlations
- Issues: timing, logistics, personnel, funding

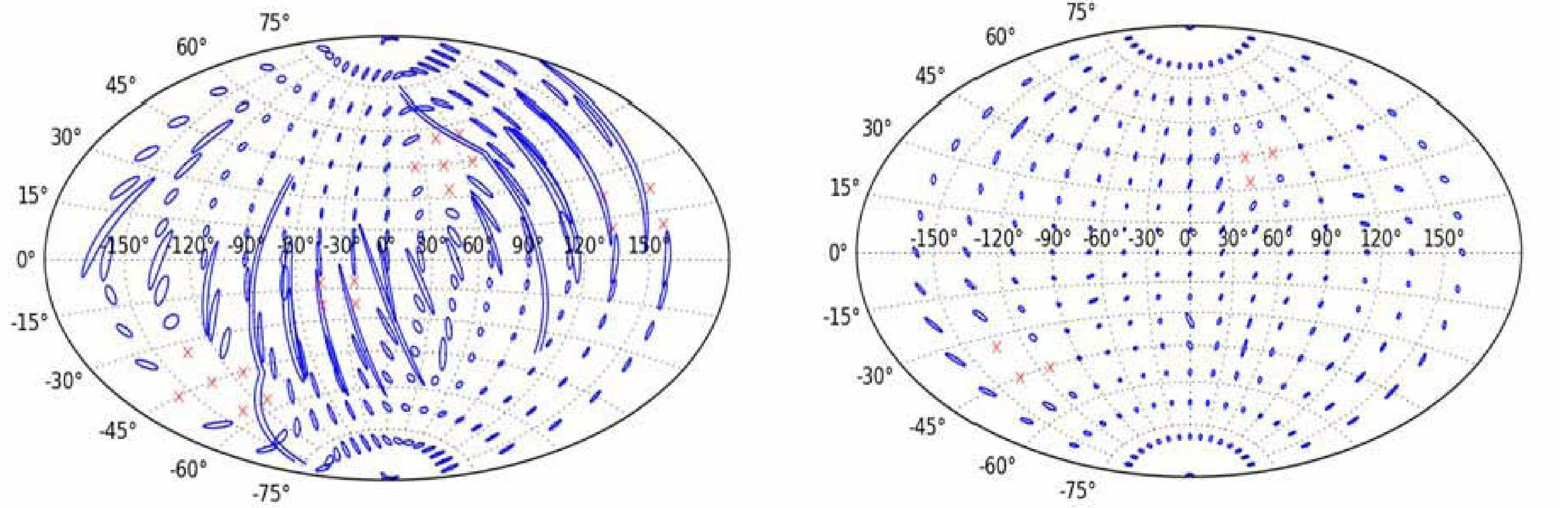


Figure 5 Left: Sky localization with the HHLV network. Right: Sky localization with the AHLV network. The plots show the 90% confidence contours for binary NS sources face on and at a horizon distance of 200Mpc. The plot assumes that the advanced detectors would achieve a SNR =8 for these sources at a horizon distance of 180Mpc. The red X's are points in the sky where the signal would be poorly detected with a network combined SNR < 12 .

Sky localization

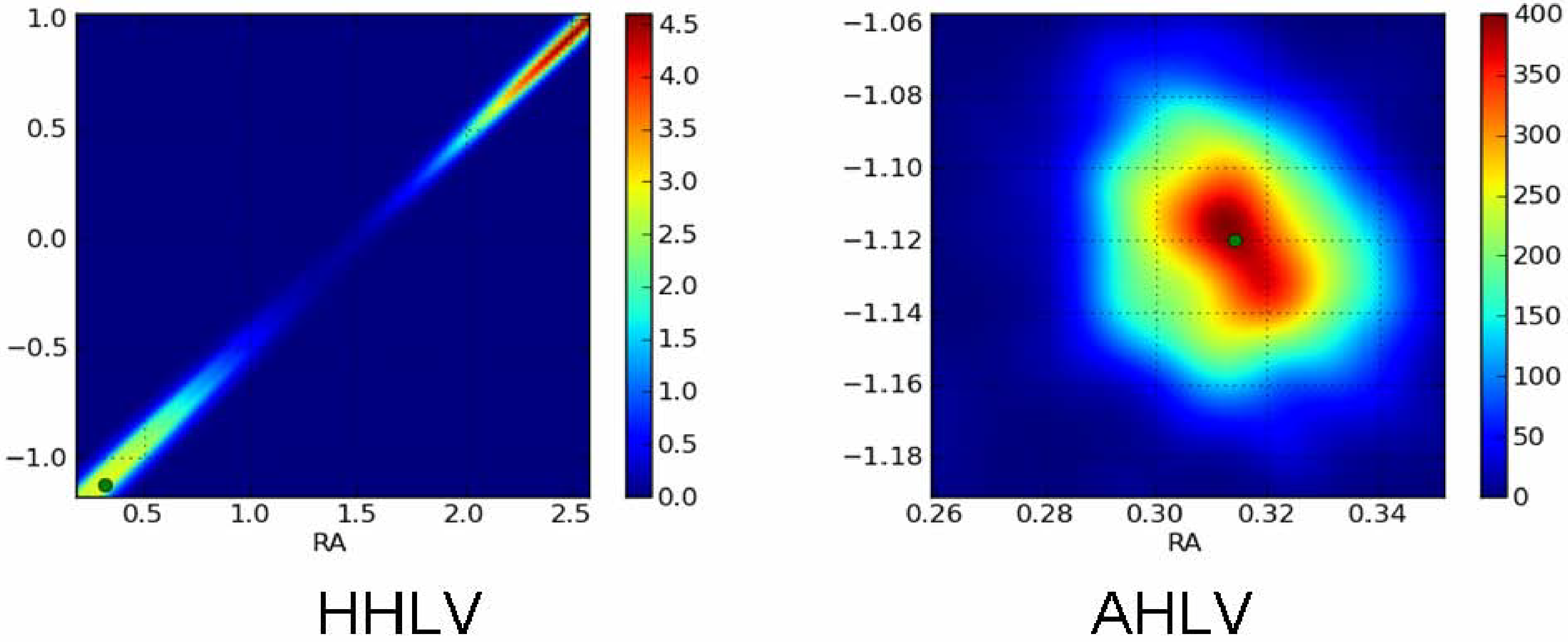


Figure 6 Examples of the sky localization contours in the two networks. The green dot shows the true position of the source in the modeling. The color coding indicates the probability density in units of 1/steradian

Localization contour shape

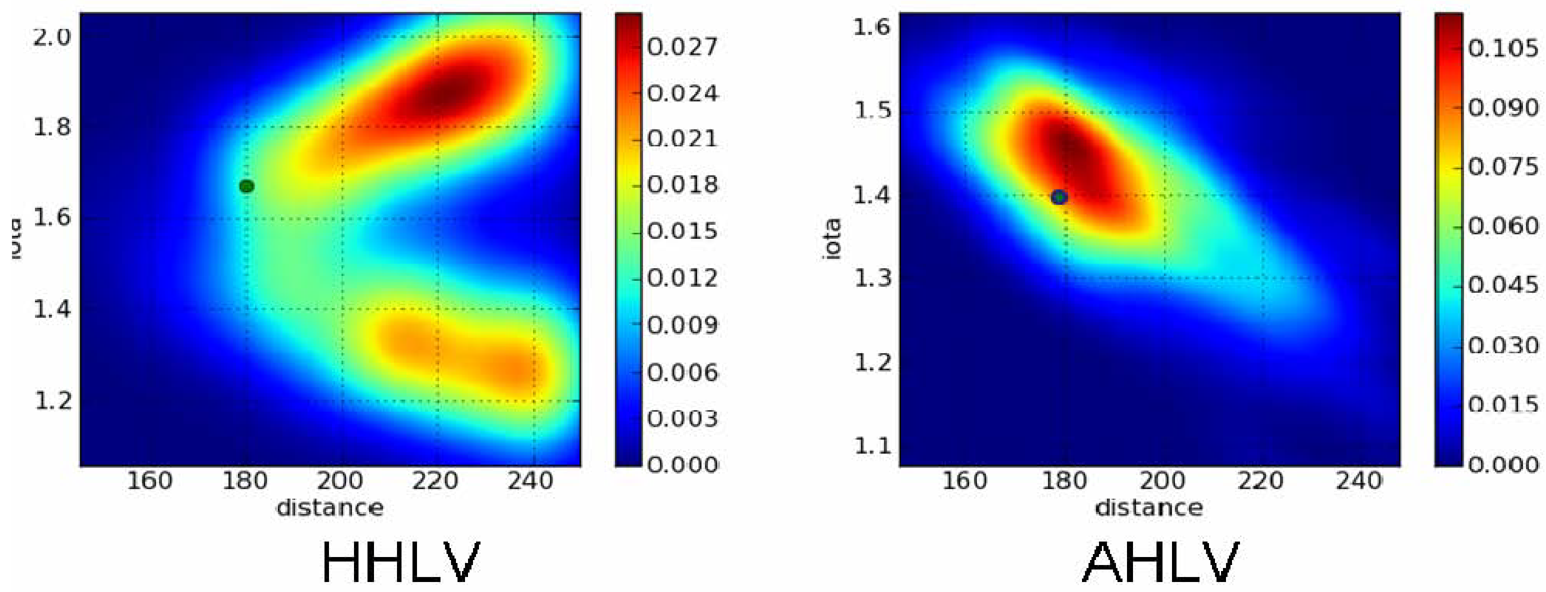


Figure 9 Two dimensional probability density contours for the model parameters of a binary neutron star system's luminosity distance and orbital inclination angle relative to the line of site in the two networks. The green dot shows the input value of the model parameter (iota is symmetric about π). The solution using the HHLV network is bimodal. The degeneracy is broken in the AHLV network. The color coding indicates the amplitude of the probability density in units of 1/(Mpc*radian).

Parameter estimation

Remove with coherent algorithm

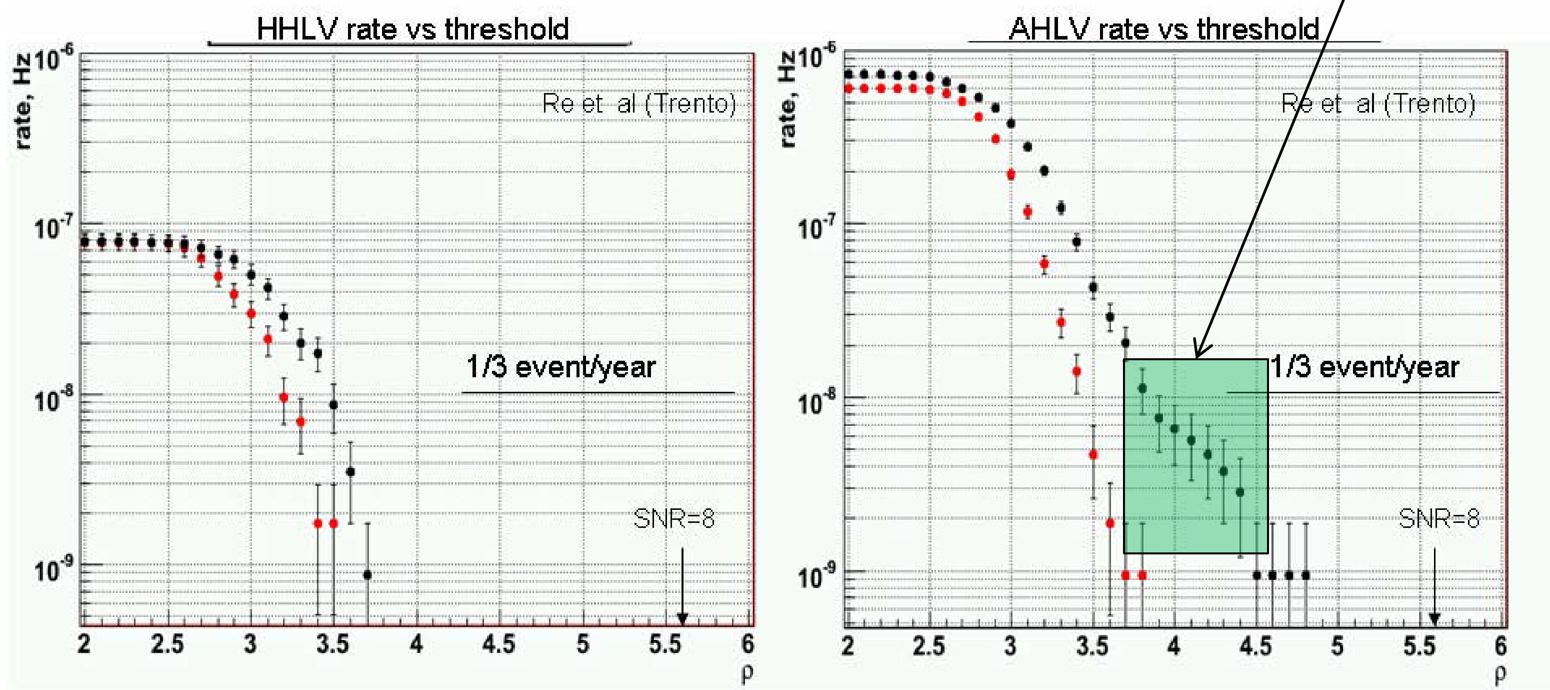


Figure 12 Background rate vs detection threshold for the two networks in a search for unmodeled burst sources. Black dots represent the low frequency band (64 -200Hz) and red dots the high frequency (200 – 2048 Hz) band. The significant change in the non-Gaussian tails relative to **Figure 11** is due to having four rather than three detectors in the network.

False alarm rate

LIGO-Virgo Collaboration

LIGO

VIRGO

University of Maryland

Michigan

University of Strathclyde

清華大学

Tsinghua University

University of Cambridge

ACIGA

Montana State University

PAH

University of Washington

Loyola University New Orleans

Syracuse University

Trinity University

San José State University

UWMilwaukee

University of Wisconsin

ANU

The Australian National University

University of Glasgow

Università degli Studi del Sannio

UTB TSC

The University of Western Australia

NASA

Goddard Space Flight Center

LSU

California Institute of Technology

Northwestern University

Andrews University

Massachusetts Institute of Technology

Southeastern

Moscow State University

R·I·T

The University of Adelaide Australia

PAN

GEO 600

Embry-Riddle Aeronautical University

University of Massachusetts Amherst

University of Southampton

The University of New Hampshire

PennState

Carleton

Cardiff University

Universitat de les Illes Balears

Washington State University

UF University of Florida

The University of Mississippi

Charles Sturt University

NAOJ

University of Rochester

Southern University

University of Minnesota

Hobart College

William Smith College

Science & Technology Facilities Council

Rutherford Appleton Laboratory

Universität Hannover

SUMMARY

- LIGO: design and progress

- **Data analysis:** general principles
- Periodic signals: coherent, semi-coherent
- Some results of recent searches

- Importance of a **worldwide** detector network