Detection and reconstruction of gravitational waves with networks of detectors

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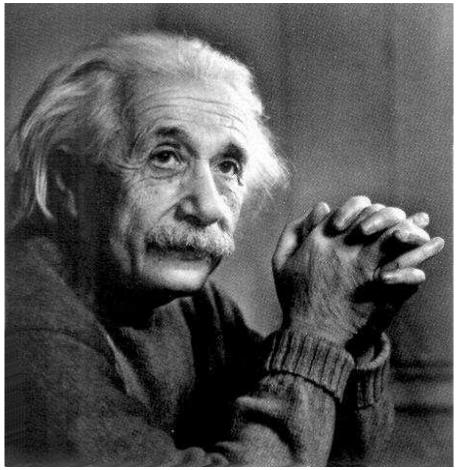
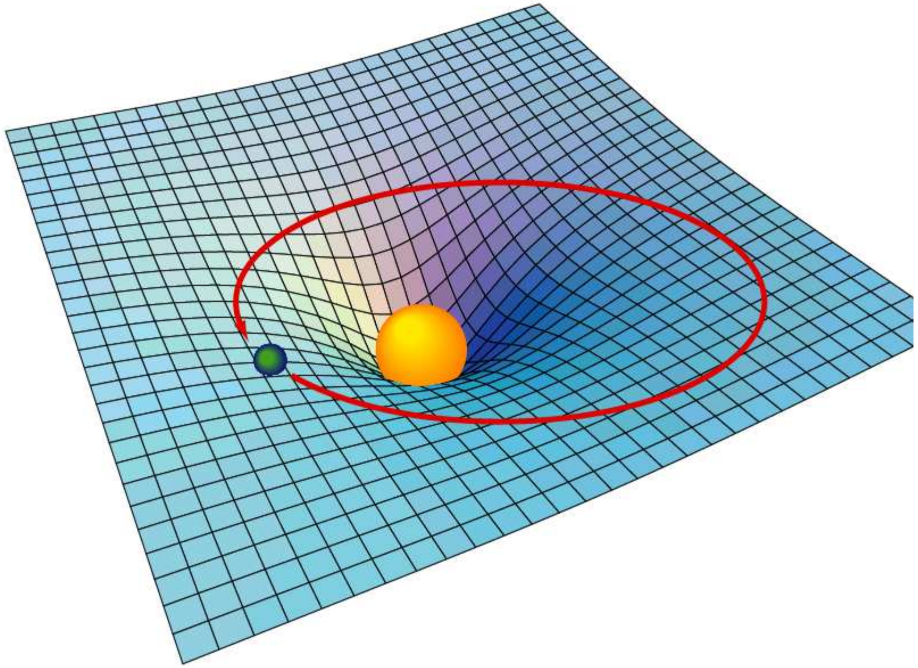
for LSC and Virgo Collaboration

“Colliding Black Holes”, Werner Benger, AEI, CCT, LSU

General Relativity

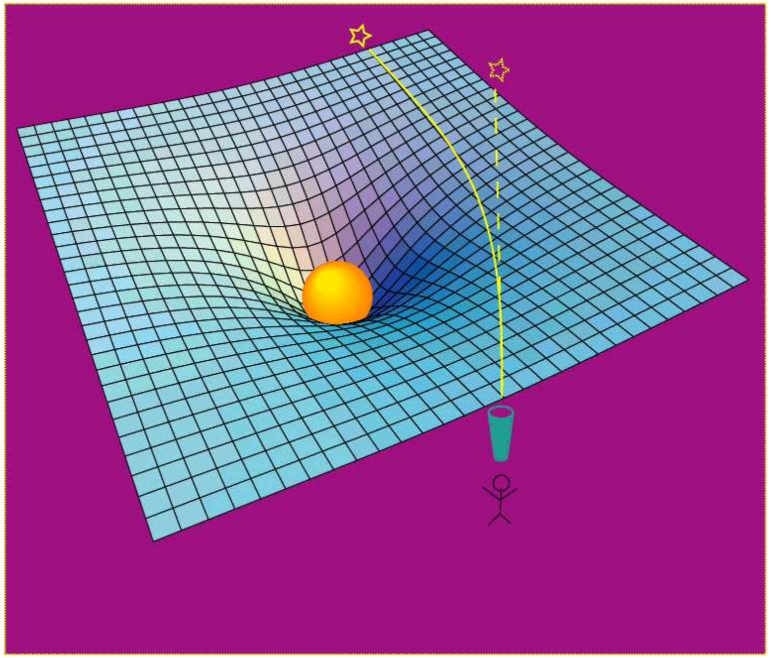


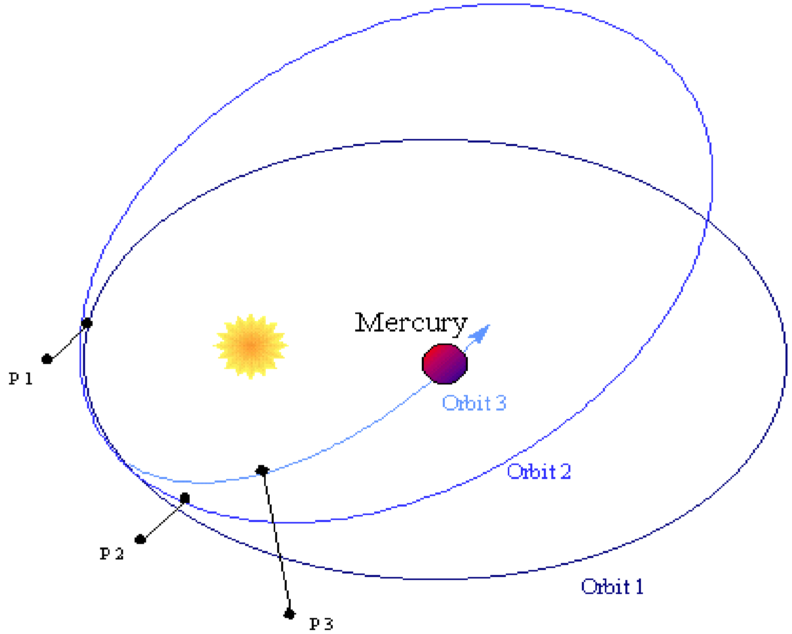
Einstein theorized that smaller masses travel toward larger masses because the smaller objects travel through space that is warped by the larger object



- **Imagine space as a stretched rubber surface.**
- **A mass on the surface will cause a deformation.**
- **Another mass dropped onto the surface will roll toward that mass.**

GR experimental tests





Bending of light
First observed during the solar eclipse of 1919 by Sir Arthur Eddington, when the Sun was silhouetted against the Hyades star cluster

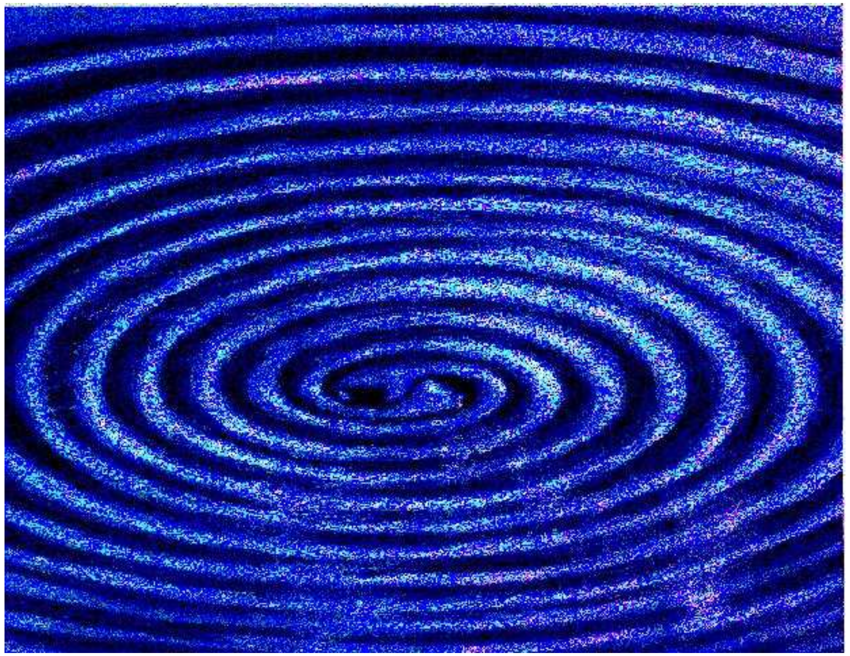
Mercury's orbit
perihelion shifts forward an extra 43"/century compared to Newton's theory

gravitational waves

- **time dependent gravitational fields come from the acceleration of masses and propagate away from their sources as a space-time warpage at the speed of light**

- **In the weak-field limit, linear equation in "transverse-traceless gauge"**

$$\nabla^2 h - \frac{\partial^2 h}{c^2 \partial t^2} = 16\pi \frac{G_N}{c^4} T$$



gravitational radiation
binary inspiral of compact objects

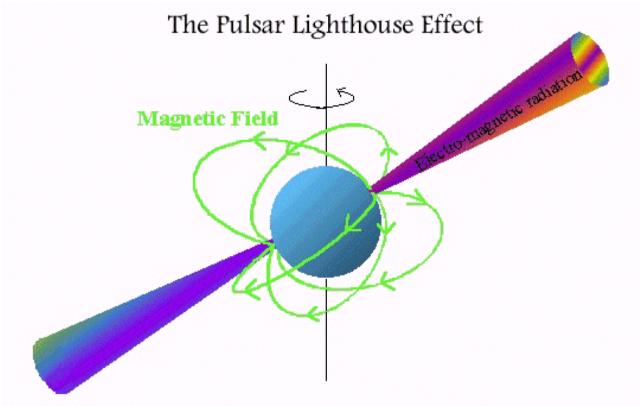
where $h_{\mu\nu}$ is a small perturbation of the space-time metric

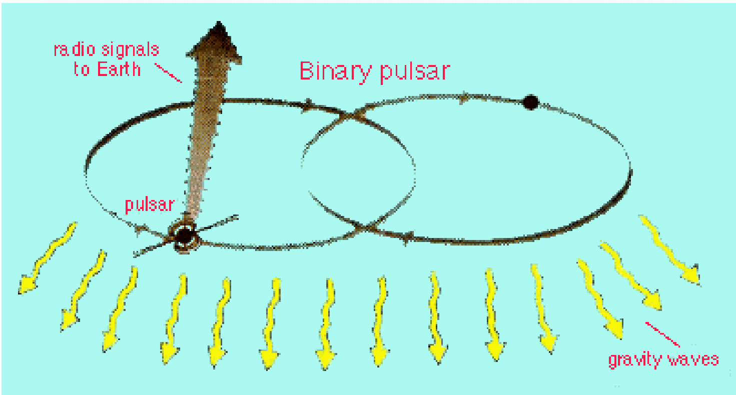
$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

Gravitational Waves: *the evidence*

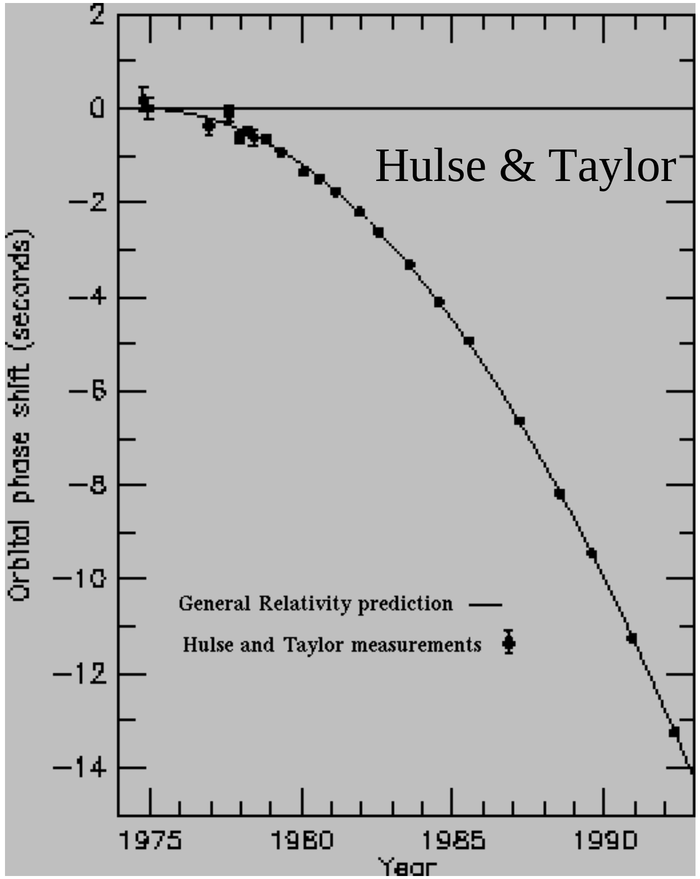
PSR 1913 + 16 Neutron Binary System

Separated by 10^6miles,
$m_1 = 1.4m_{\odot}$; $m_2 = 1.36m_{\odot}$;





Emission of gravitational waves



<u>Prediction from general relativity</u>

- **spiral in by 3 mm/orbit**
- **merge in 300 million years**

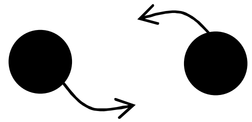
time of periastron relative to that expected if the orbital separation remained constant.

GW strength

- **Quadrupole radiation**
  - **monopole forbidden by conservation of E**
  - **dipole forbidden by mom. conservation**

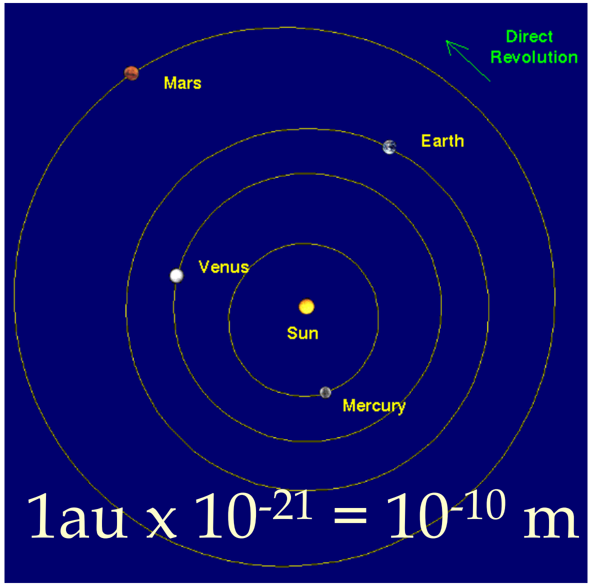
$$h \approx \frac{G_N}{c^4}\frac{\ddot{Q}}{r}$$

- **For highly non-spherical source, like binary system with mass M and separation L solar mass neutron stars at L=20km located at**
  - **Solar system (1au)** $h \sim 10^{-9}$
  - **Milky Way (10kpc)** $h \sim 10^{-18}$
  - **Virgo cluster (15Mpc)** $h \sim 10^{-21}$
  - **“Deep space” (200Mpc)** $h \sim 10^{-22}$
  - **Hubble distance (3000Mpc)** $h \sim 10^{-23}$

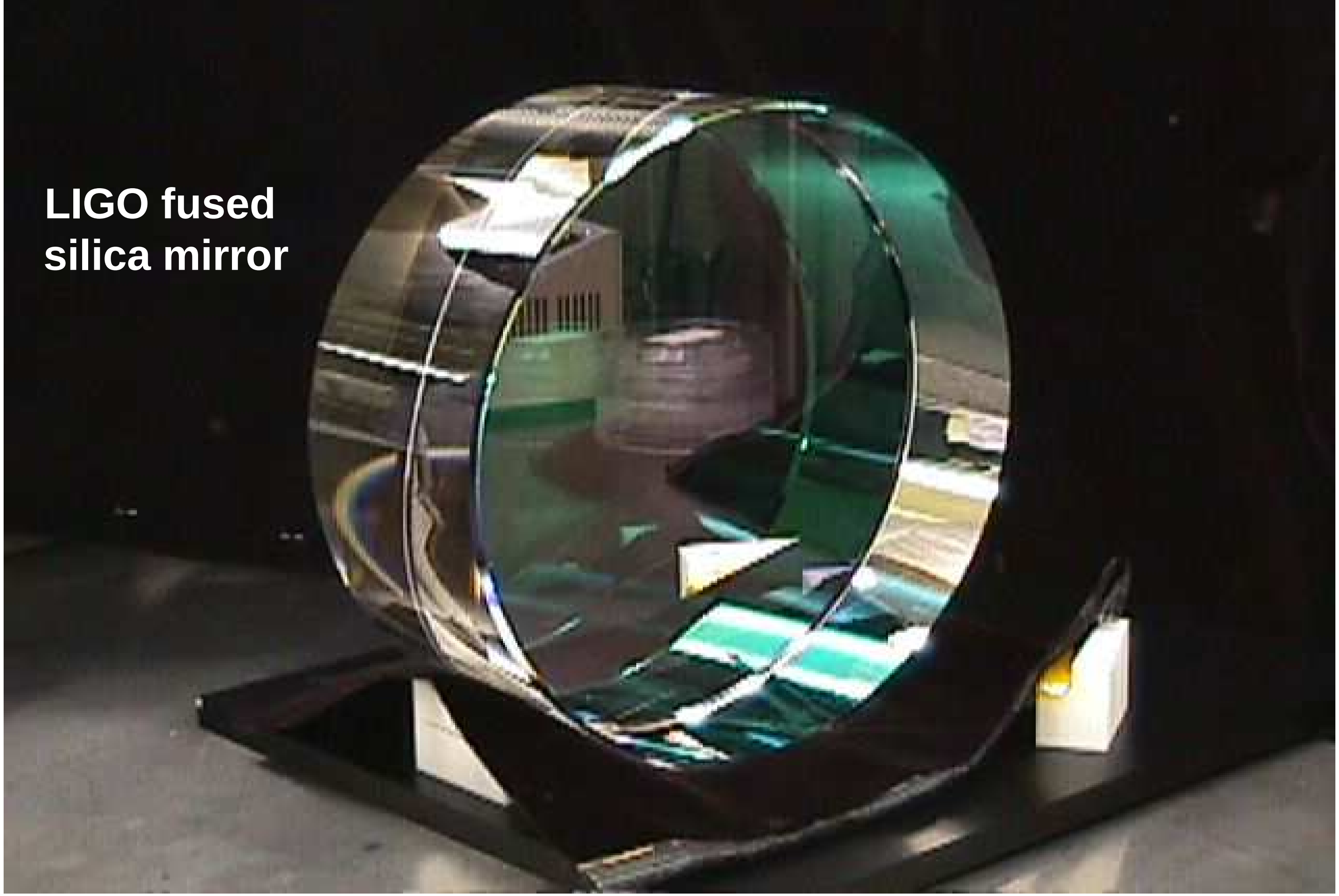


$$Q \approx ML^2$$

1 pc = 3 x 10^{16} m



Detectors



Detectors

Bars

narrowband (~1Hz)

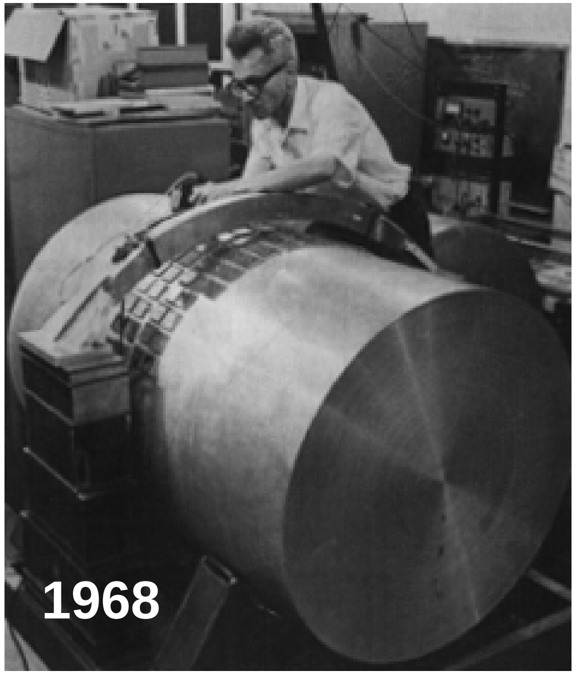
recent improvements (~10Hz)

ALLEGRO, AURIGA, EXPLORER, NAUTILUS, NIOBE, …

Interferometers

wideband (~10000 Hz)

LIGO, VIRGO, GEO, TAMA, AIGO, …

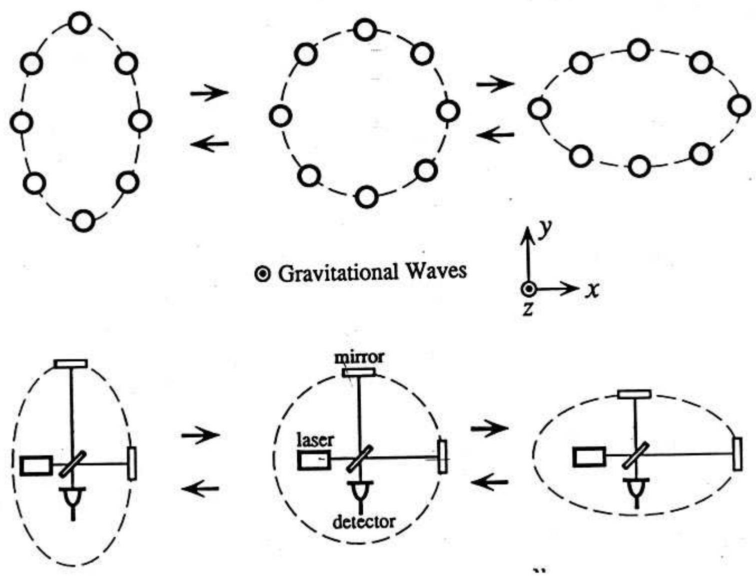


J.Weber working on the bar

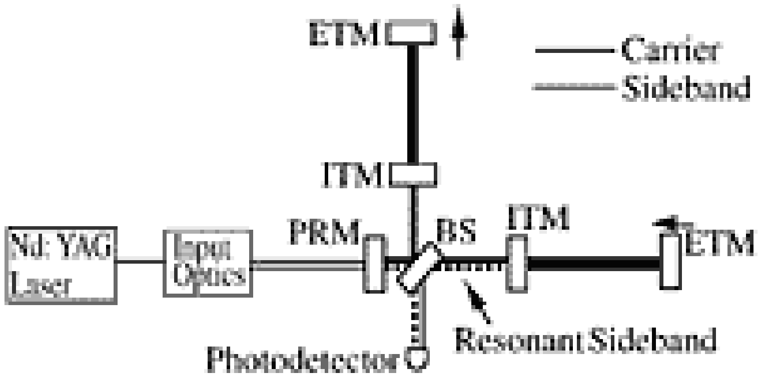
UF graduate student Kate Dooley inspecting a LIGO optic.

How LIGO works

free masses



suspended test masses

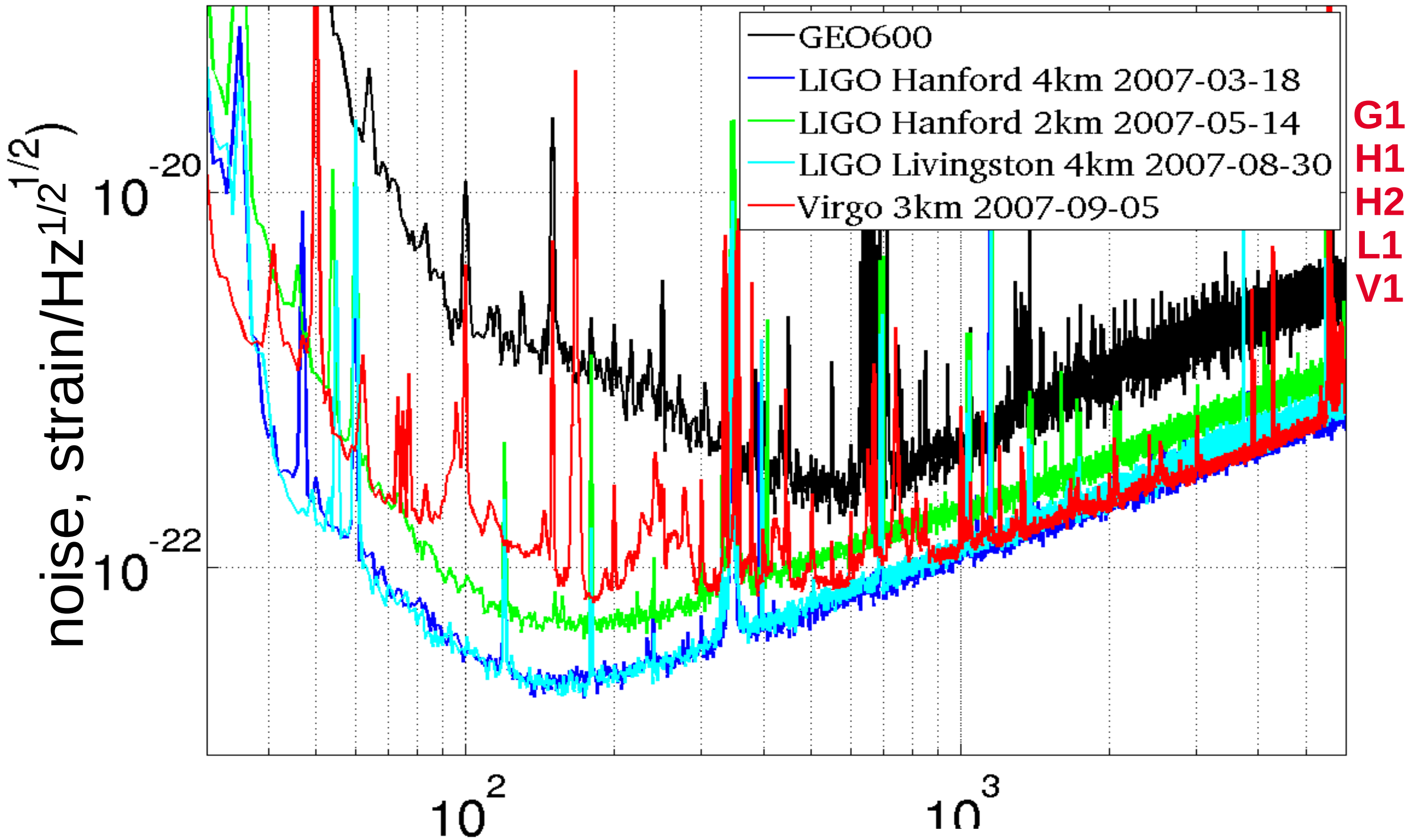


for L=4000m
and h~10^{-21}
$\Delta L \sim 10^{-17}$ m

measure differential arm length
$\Delta L = \Delta Lx - \Delta Ly$
$h \sim \Delta L/L$

Detectors

- This is the first untriggered all-sky search with LIGO and Virgo detectors



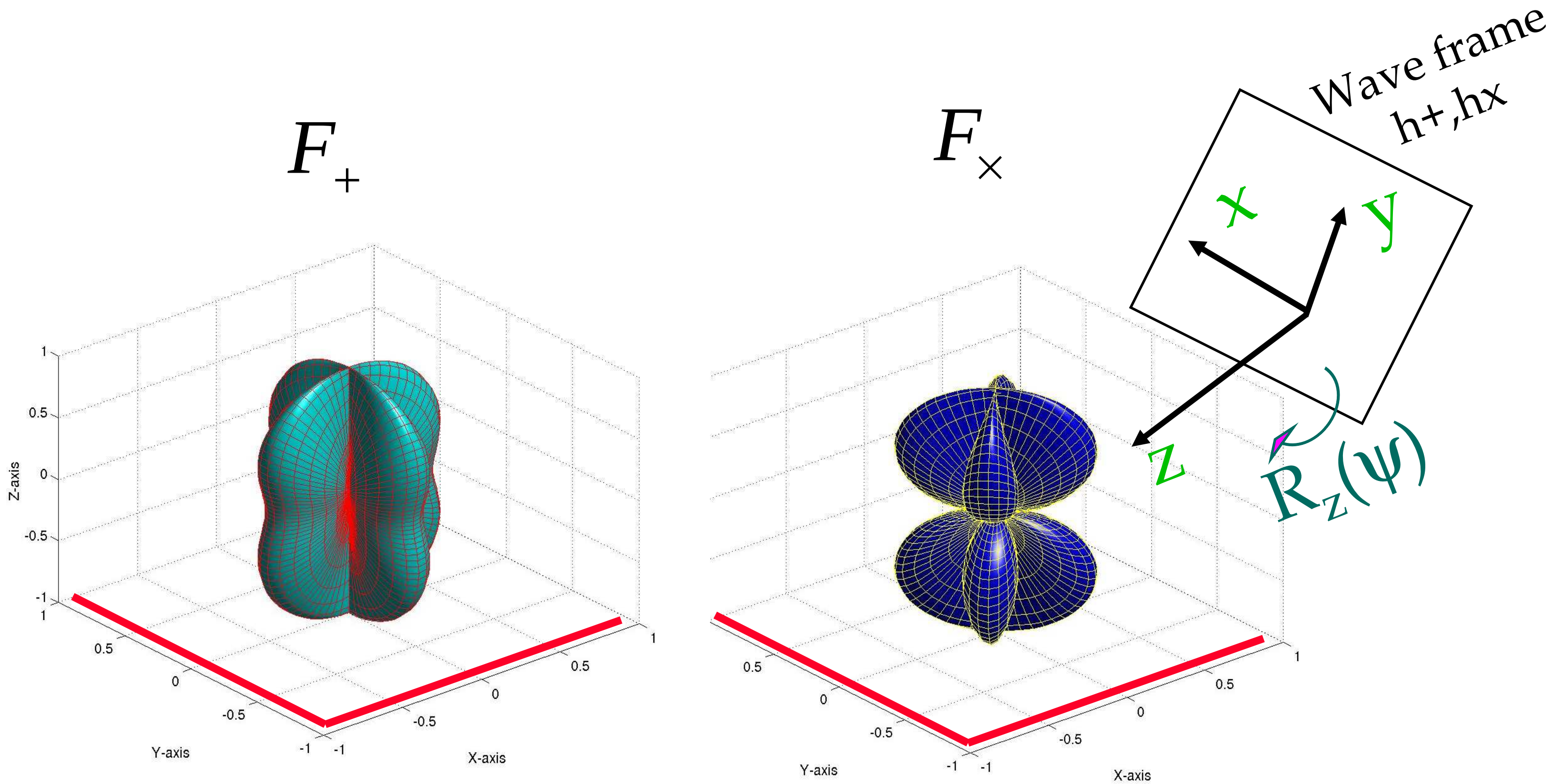
strain noise: $\sqrt{S(f)} = \dfrac{x(f)}{4000m} \approx 2.5\times10^{-23}\,\dfrac{1}{\sqrt{\mathrm{Hz}}}$

Angular sensitivity

Detector response to two GW polarizations

$$\xi = F_+(\theta,\phi,\psi)h_+ + F_\times(\theta,\phi,\psi)h_\times$$

θ,φ – source coordinates in the detector frame, ψ – polarization angle

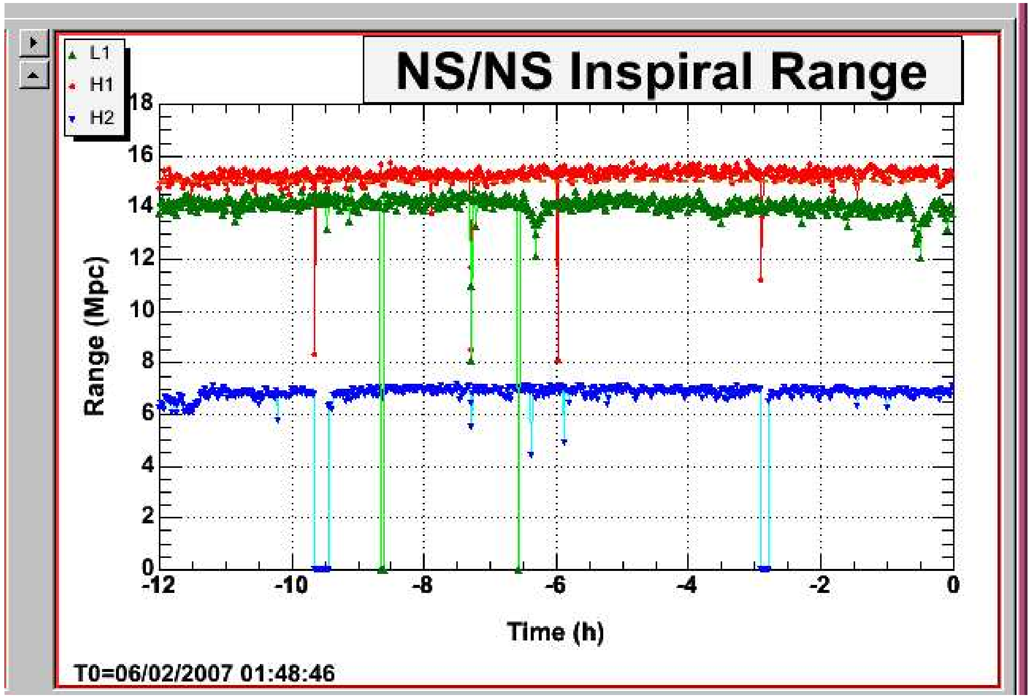


Binary Neutron Stars (BNS) range

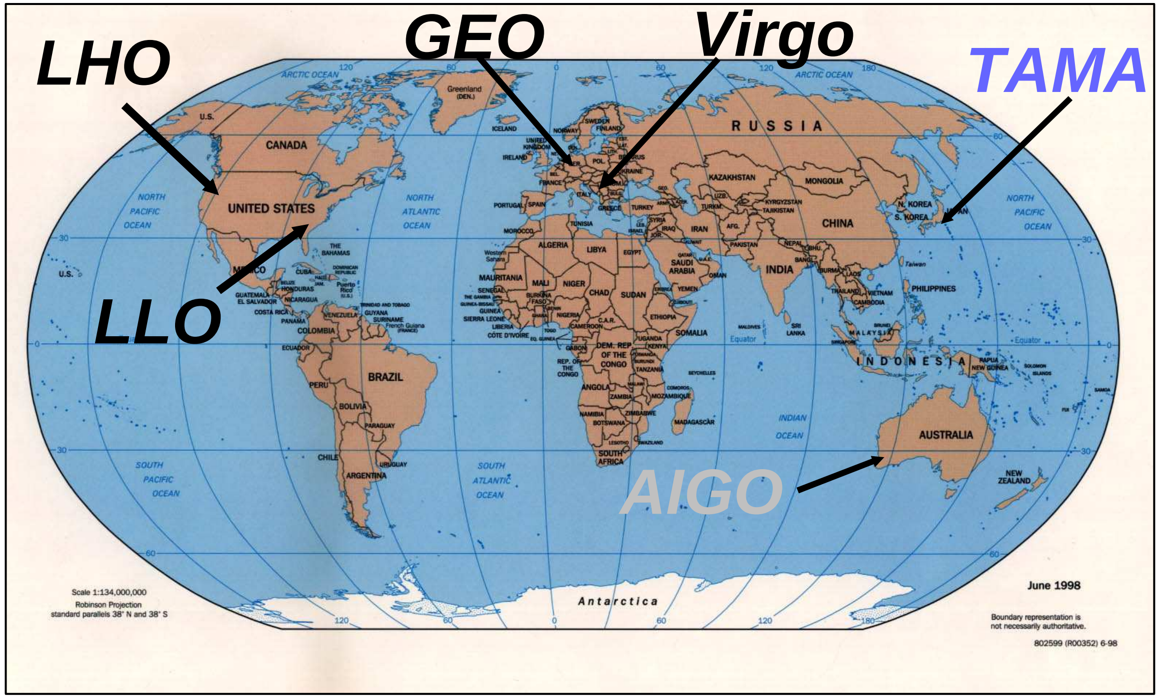
1 pc = 30.8x10^{12} km = 3.26 light years

BNS range: distance to a 1.4-1.4 M binary detected at Signal-to-Noise Ratio (SNR) of 8 averaged over sky and polarization angle

$$SNR = 2\sqrt{\int_0^\infty \frac{|\xi(f)|^2}{S(f)} df}$$

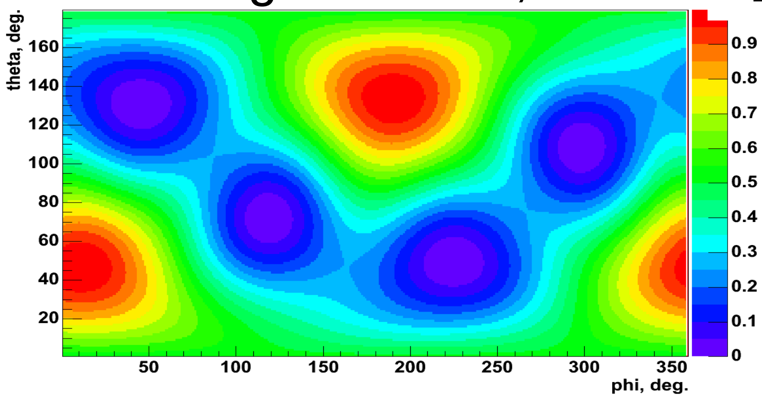


Network of GW interferometers



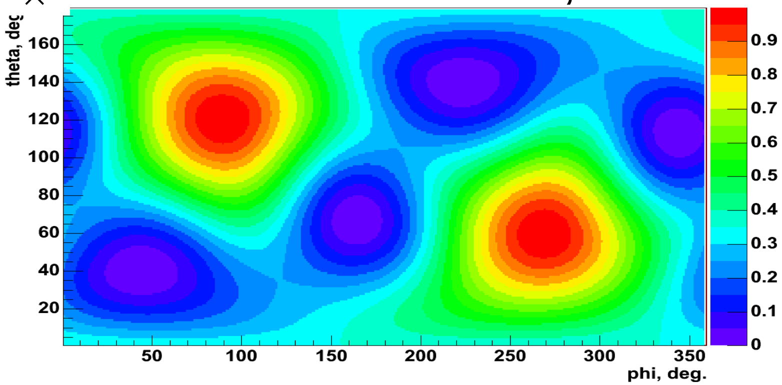
- increase sky coverage
- increase detection confidence
- reconstruction of GW sources, including waveforms and sky coordinates → GW astronomy

Virgo detector, V1



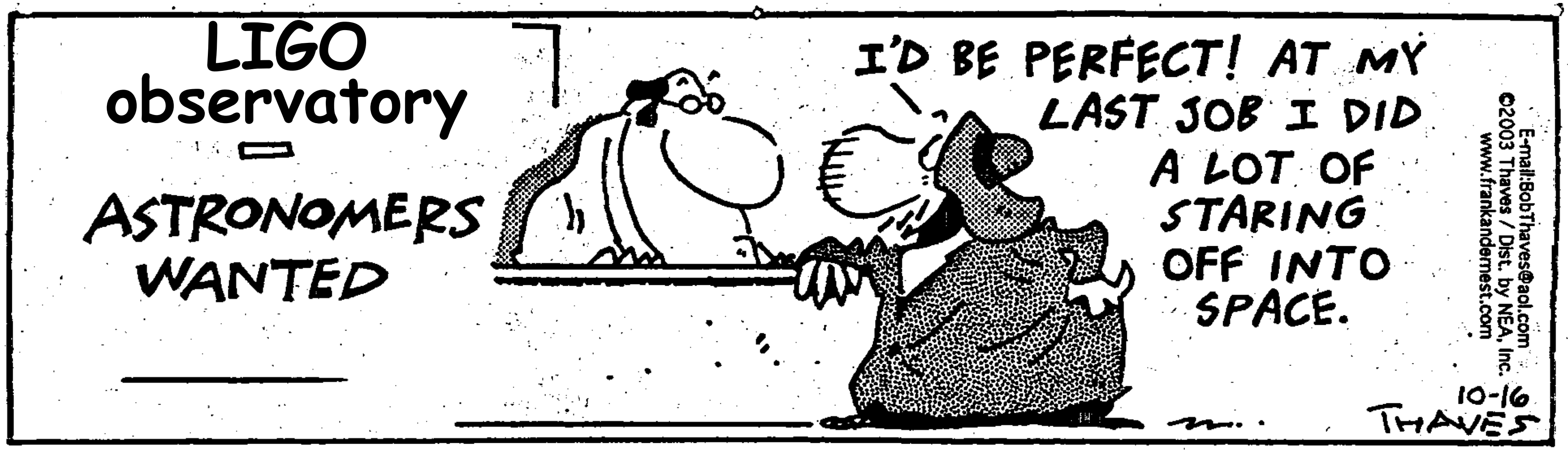
$$F_+^2 + F_\times^2$$

LLO detector, L1



LSC and Virgo

- more than 670 scientists with wide diversity of backgrounds



- during the S5 the Virgo detector joined the run and the LIGO-Virgo collaboration was formed

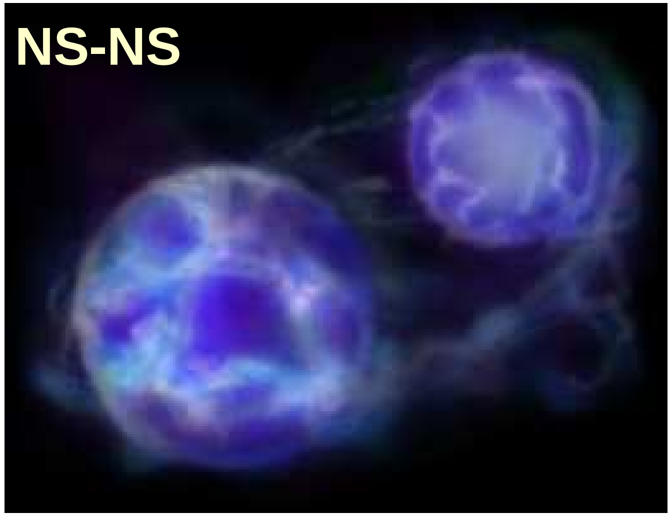
Gravitational Wave Sources

- “un-modeled bursts”
  - Supernovae, GRBs, mergers, SGR, ….
- “inspiral” - Compact Binary Coalescence
  - particular class of modeled bursts
- “periodic” - pulsars
- “stochastic” - unresolved signals, GWs from Big Bang

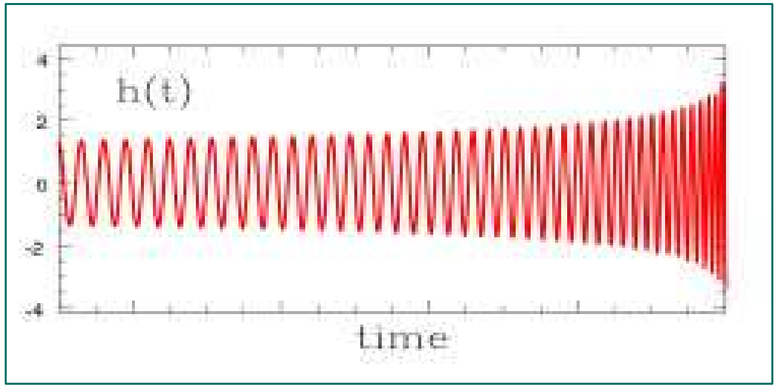
focus of this talk

Compact Binary Coalescence

NS-NS, NS-BH, BH-BH binary systems

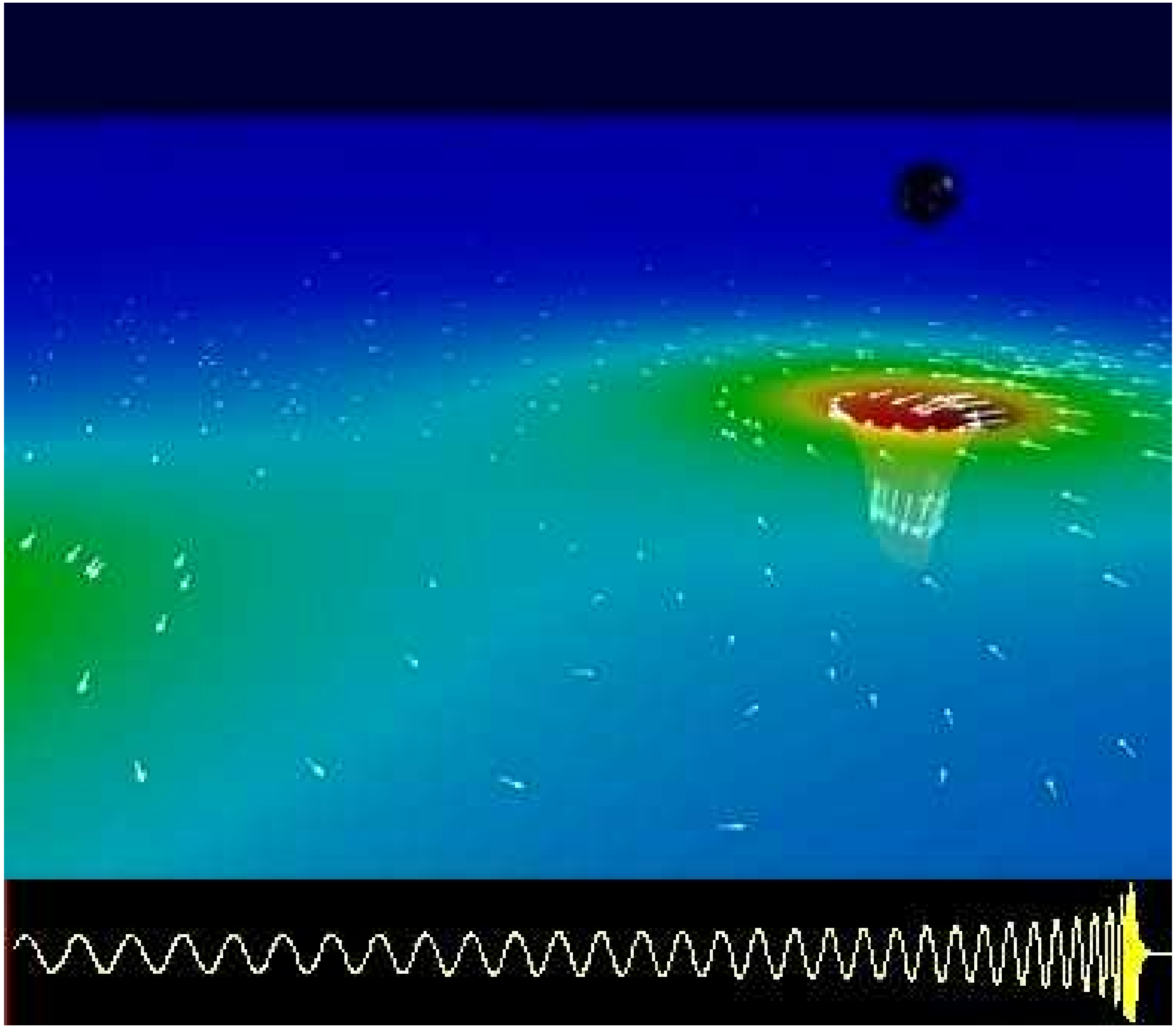


Chirp waveform



- Standard candle for LIGO
  - large expected signal
  - rich physics at high field regime
  - well understood theoretically
- Template searches
  - correlate pre-calculated signal templates with data → need exact source model

Binary Black Holes (BH-BH)



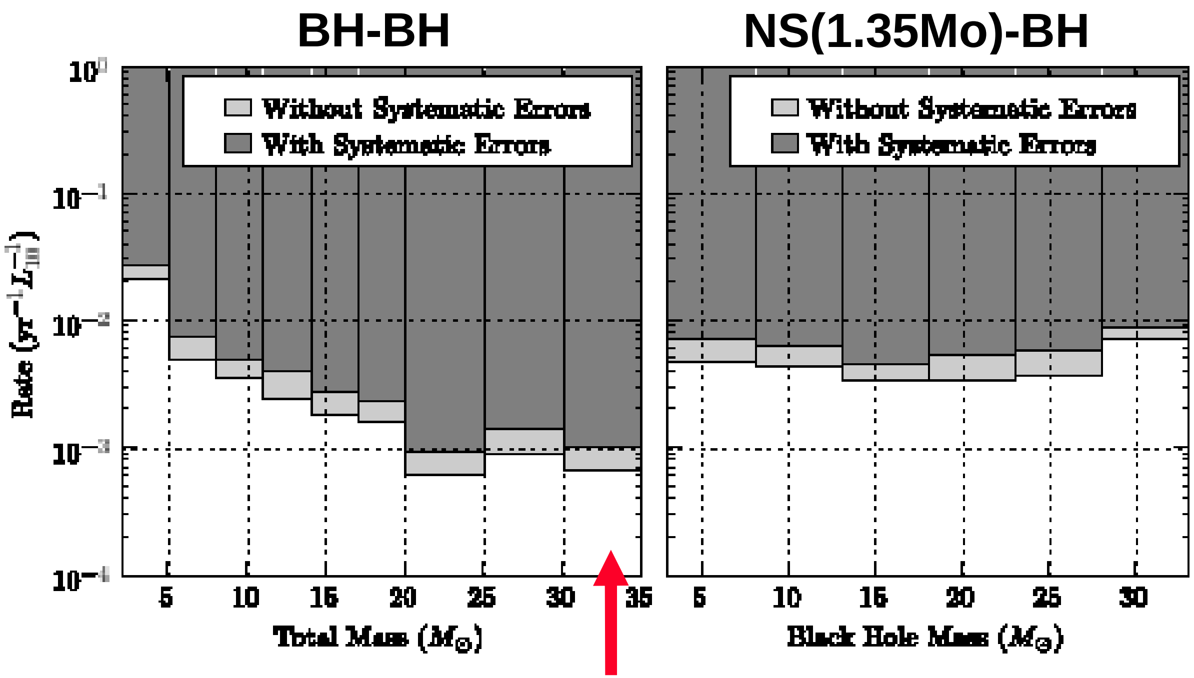
Caltech-Cornell http://www.black-holes.org/

Low Mass CBC sources

- **First year of S5 run: [Preprint arXiv:0901.0302v3]**
- **Measured rate limits:** $\mathrm{NS(1.35Mo)-NS(1.35Mo)}: 3.8\cdot 10^{-2}\ \mathrm{y^{-1}L_{10}^{-1}}$

$$\mathrm{rate} \propto \frac{1}{TC_L}$$

T- observation time



- **Cumulative luminosity C_L ~ 10000 L_{10}**

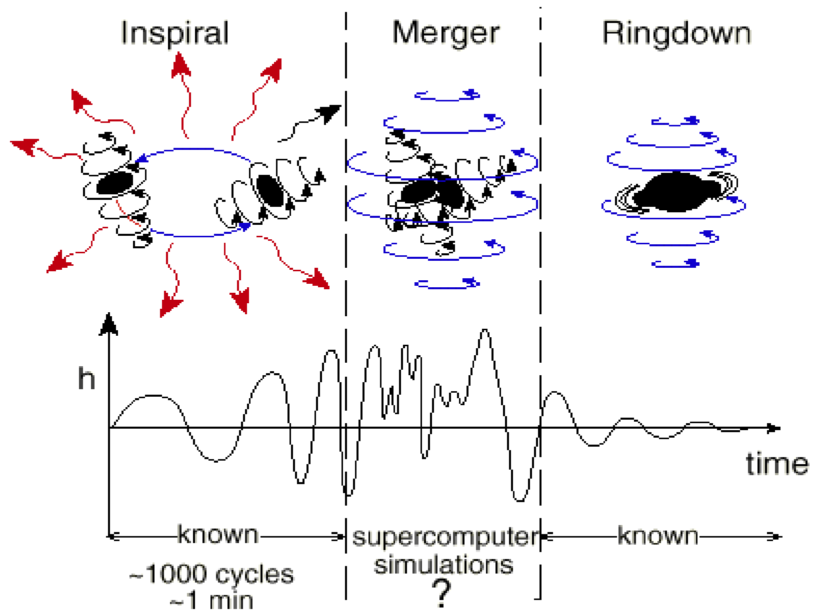
$L_{10} = 10^{10}\ L_{\odot,B}$
(1 Milky Way = 1.7 L_{10})

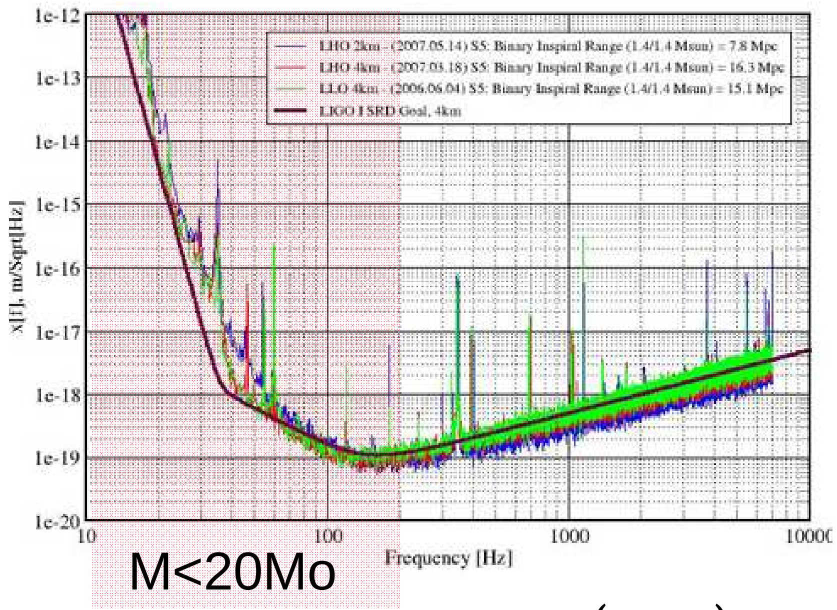
- **Expected rates**

$\mathrm{NS-NS}: (5\cdot 10^{-5} - 5\cdot 10^{-4})\ \mathrm{y^{-1}L_{10}^{-1}}$
$\mathrm{BH-NS}: (2\cdot 10^{-6} - 6\cdot 10^{-5})\ \mathrm{y^{-1}L_{10}^{-1}}$
$\mathrm{BH-BH}: (4\cdot 10^{-7} - 6\cdot 10^{-5})\ \mathrm{y^{-1}L_{10}^{-1}}$

Inspiral Mergers

Compact binary mergers



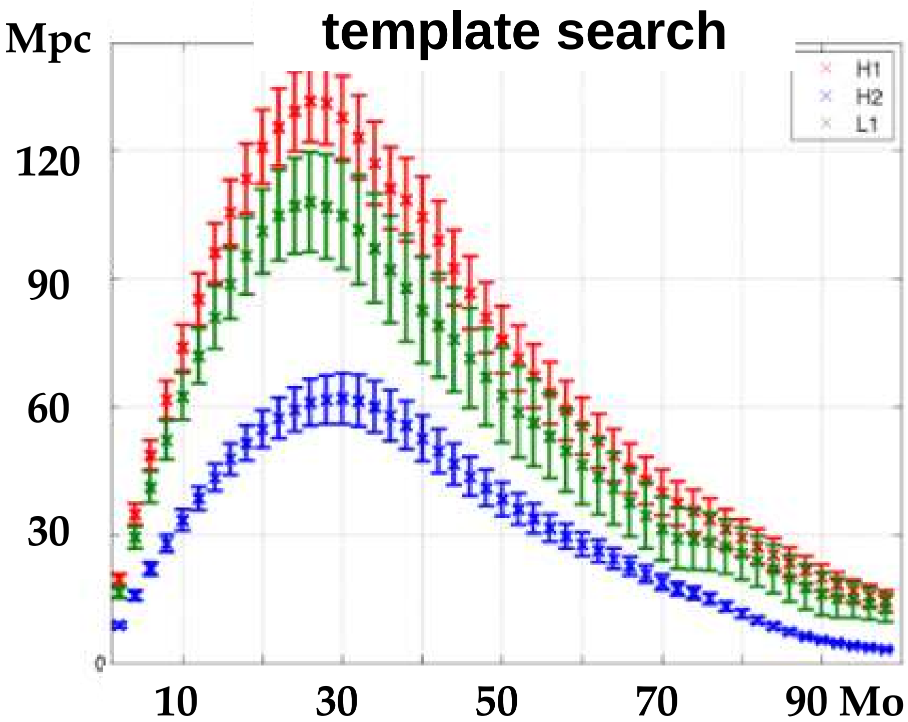


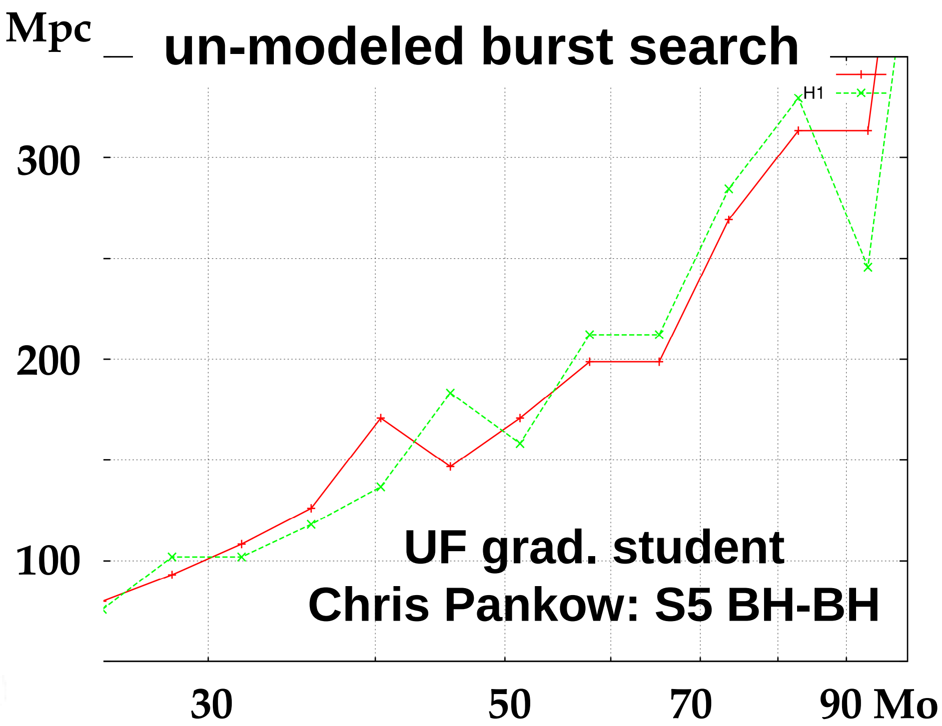
$$f_{merger} \approx 205Hz \cdot \left(\frac{20M_o}{M}\right)$$

- high mass CBC (>25Mo) are better detected via their merger and ring-down waves
- merger waveforms can be calculated numerically, but
  - computationally expensive
  - no numerical waveforms for NS-NS and NS-BH

Covering CBC parameter space

- Detection of CBC sources in a wide range of source parameters requires construction of large template banks





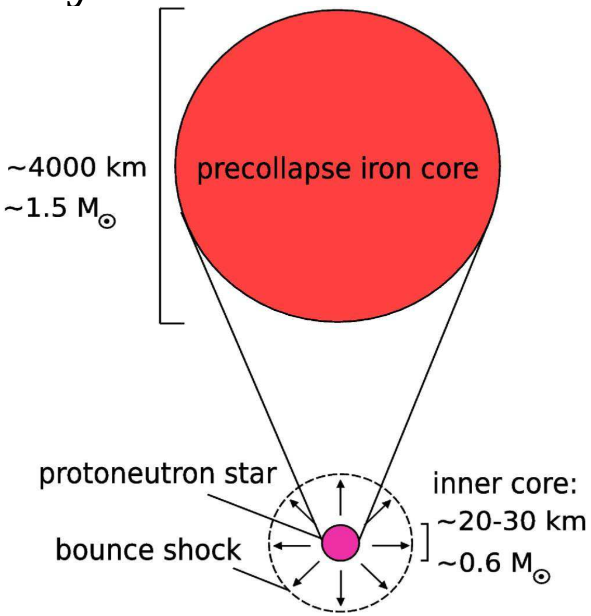
BH-BH horizon distance as a function of total mass for optimally oriented sources detected at SNR of 8

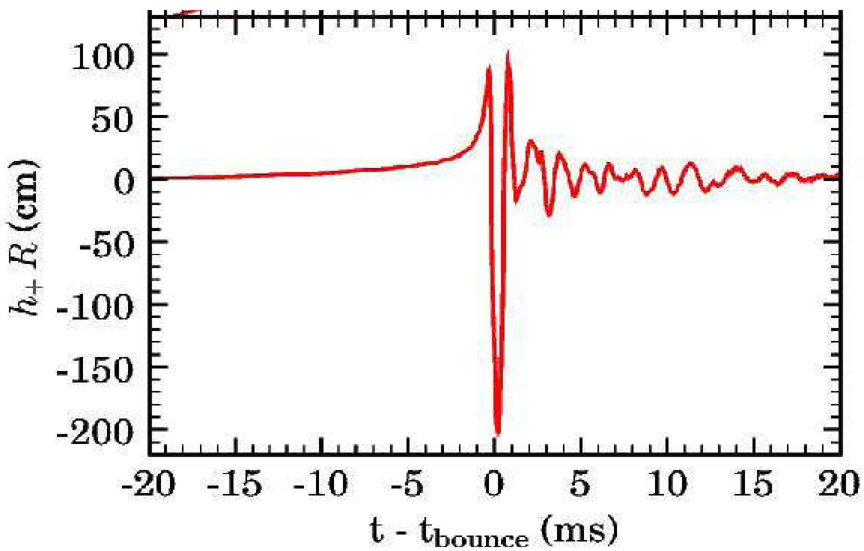
- Develop complementary burst search for more robust detection of CBC sources that may be missed by template searches due to incomplete template banks: particularly massive BH-BH, BH-NS

Supernova

- GW from supernova
  - Several Core-Collapse SN Mechanisms
  - Direct "live" information from the supernova engine.
  - Directly linked to the ubiquitous multi-D dynamics in the post-shock region

Axisymmetric core collapse

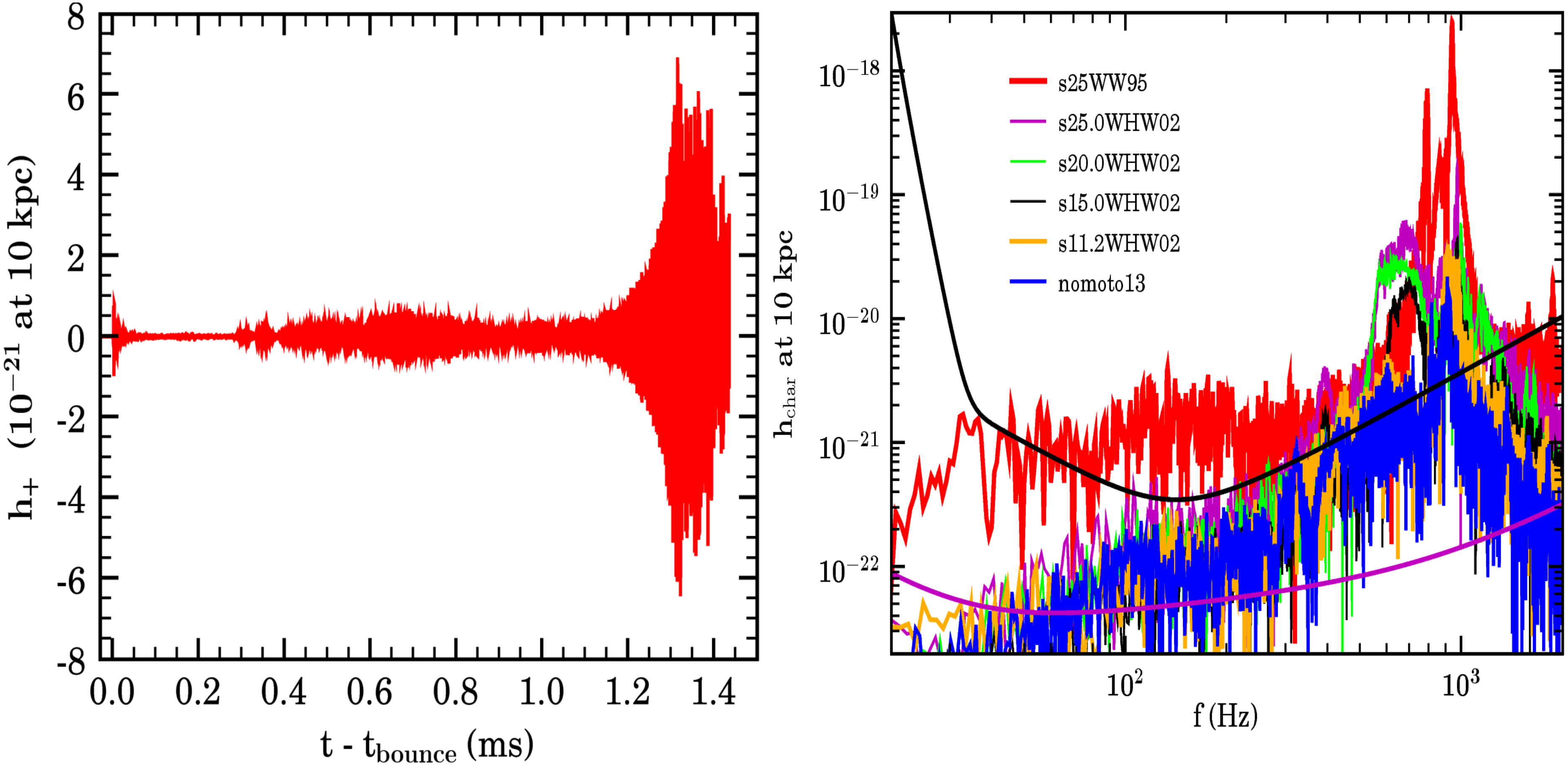




$$E_{GW} \approx 10^{-8} - 10^{-5} M_{\oplus} c^2$$

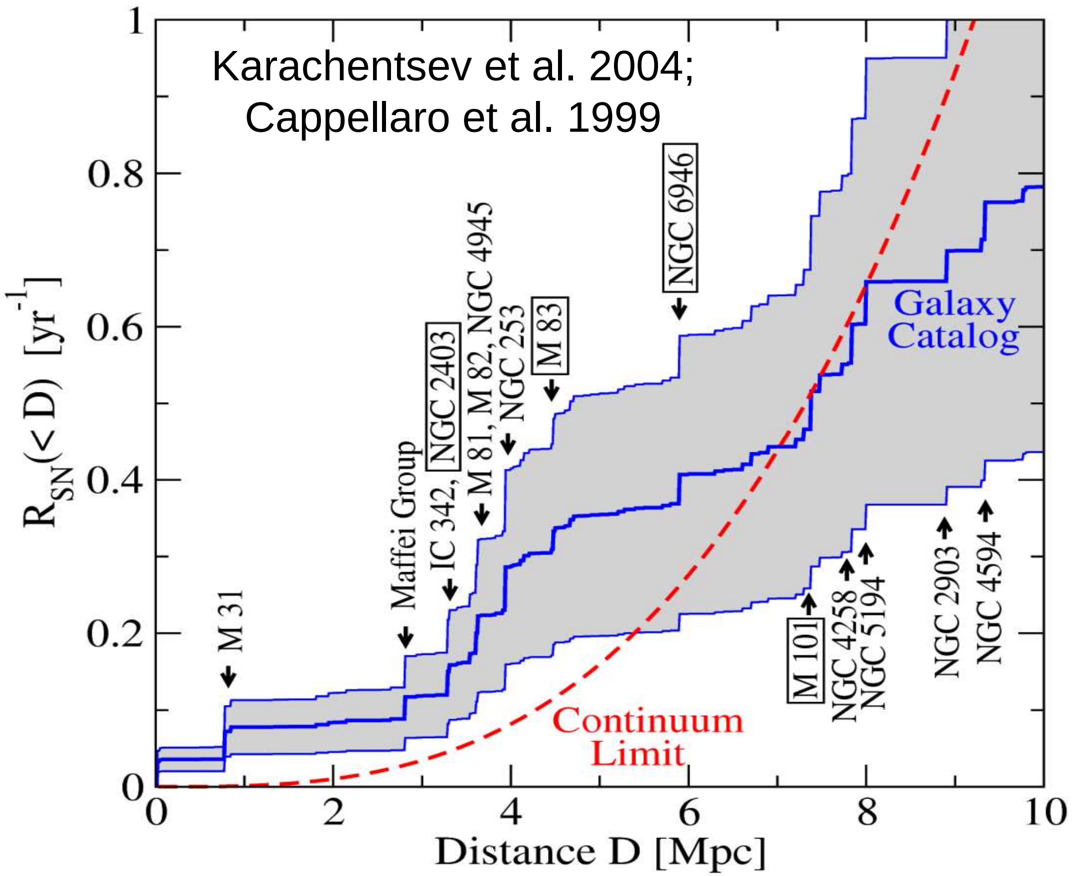
G-modes

Burrows et al. 2006, 2007, Ott et al. 2006



$$E_{GW} \approx 10^{-8} - 10^{-5} M_{\oplus} c^2$$

Supernova rate



SN Rate

1/50 yr - Milky Way (~10kpc)

3/yr - out to Virgo cluster (16Mpc)

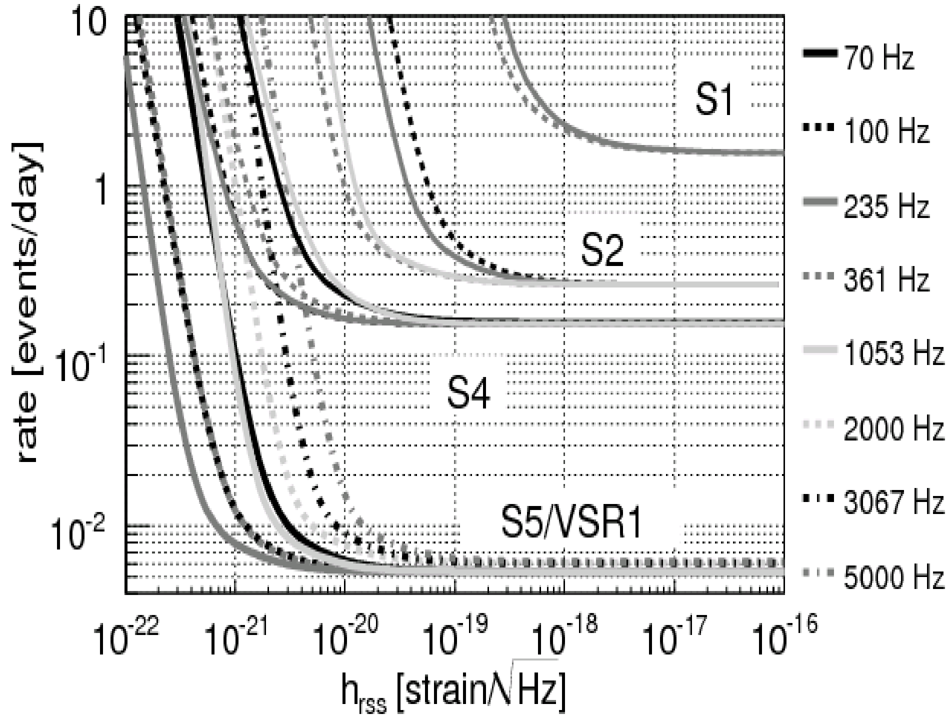
SN	Host Galaxy	Date	Type	Distance
2008bk	NGC 7793	20080325 [132]	II-P	~ 3.9 [133]
2005af	NGC 4945	20050208 [134]	II-P	~ 3.6 [133]
2004dj	NGC 2403	20040731 [135]	II-P	~ 3.3 [133]
2004am	M 82	20040305 [136]	II-P	~ 3.5 [137]
2002kg	NGC 2403	20021026 [138]	IIn	~ 3.3 [133]

S5/VSR1 All-Sky Burst Search

- model independent, however sensitive to a wide class of sources: binary mergers, SN, SGR,..
- frequency band 64–2000 Hz (64-6000 Hz for S5); no GW bursts signals seen in S1/S2/S3/S4
- use ad-hoc waveforms (Sine-Gaussian, Gaussian, etc.) to determine detection sensitivity
- Several algorithms, including cWB used for previous S2,S3,S4 searches

arXiv:1002.1036

Combined upper limits for the entire S5/VSR1



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

Local experts: G.Vedovato, M.Drago, G.Prodi,V.Re, F.Salemi (now AEI)

Comparison with previous measurements

- LIGO 2009: first year of S5 run (64-6000 Hz) PRD **80** 102001 (2009) PRD **80** 102002 (2009)

  3.6 events/year below 2kHz and 5.4 events/year above 2kHz at 90% and best sensitivity of 6×10^{-22} $Hz^{-1/2}$

- IGEC 2007: (~50 Hz around 900 Hz) PRD 76, 102001 (2007)

  8.4 events/year at 95% CL and sensitivity of $\sim 10^{-20}$ $Hz^{-1/2}$

- LIGO 2007: S4 run (64-1600Hz) CQG **24** (2007)

  55 events/year at 90% and best sensitivity of 1.5×10^{-21} $Hz^{-1/2}$

- IGEC 2003: (few Hz around 900 Hz) PRD 68, 022001 (2003)

  1.5 events/year at 95% CL, and sensitivity of $\sim 10^{-19}$ $Hz^{-1/2}$

- LIGO-Virgo 2010: (50-6000kHz) entire S5/VSR1 run

  2 events/year below 2kHz and 2.2 events/year above 2kHz at 90% and best sensitivity of 5.6×10^{-22} $Hz^{-1/2}$

  the most sensitive un-triggered burst search performed so far

Astrophysical sensitivity

- To estimate the astrophysical sensitivity we calculate the amount of mass (M_{GW}), converted into isotropic GW burst energy at a given distance r, that would be sufficient to be detected by the search with 50% efficiency.

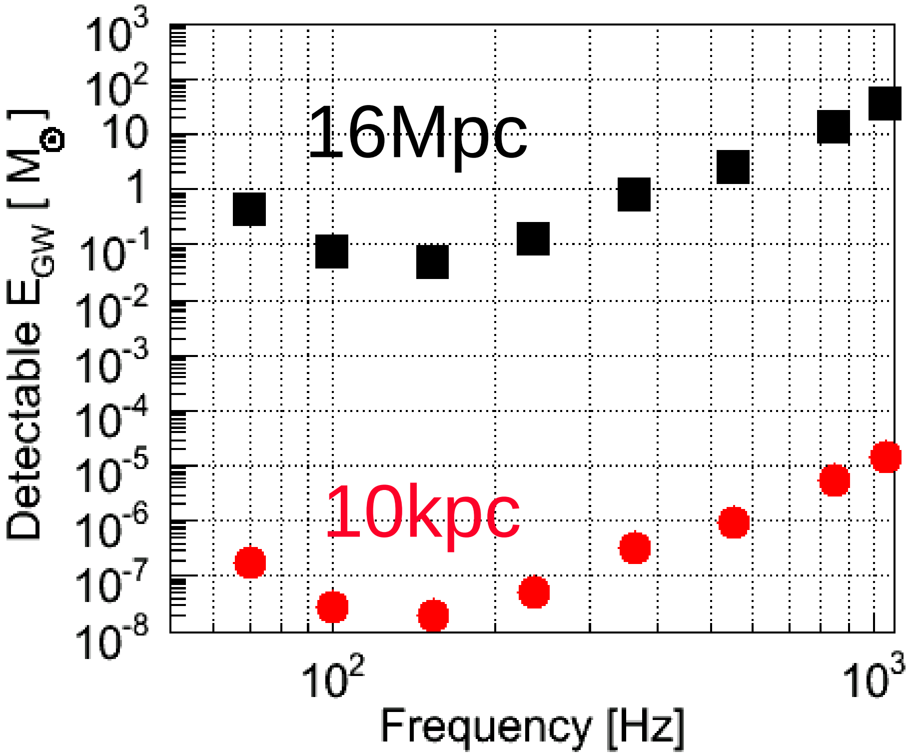
$$M_{GW} = \frac{\pi^2 c}{G} r^2 f^2 h_{rss}^2$$

- For 153 Hz, Q = 9 sine-Gaussians, $h_{rss} = 6\times10^{-22}\ \mathrm{Hz}^{-1/2}$.
- Assuming isotropic emission at a distance of 10 kpc, this corresponds to $M_{GW} = 1.8 \times10^{-8}$ M (10^{-7} M for S4) where M is the solar mass.
- For a source in the Virgo galaxy cluster, approximately 16Mpc away, the same hrss50% would be produced by a mass conversion of roughly 0.046M (0.25 in S4).

Mass equivalent sensitivity

- strain sensitivity can be converted to energy sensitivity assuming isotropic GW emission

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



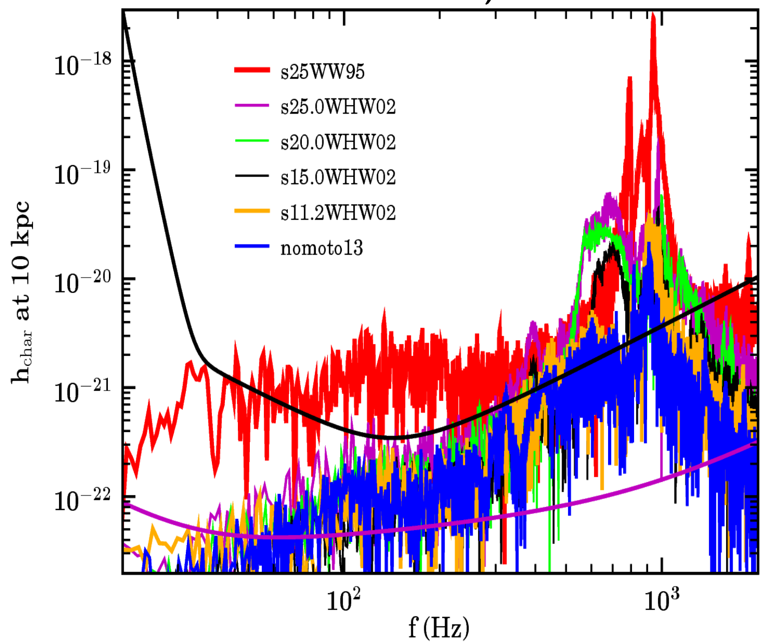
supernova:
expected yield
10^{-9} – 10^{-5}Mo
Ott, et al.

need advanced detectors to see beyond our Galaxy

Supernova

- GW signals from a core collapse supernova are expected to be produced at a much higher frequency (up to a few kHz) and also with a relatively small GW energy output (10^{-9}–10^{-5} Mc^2).
- The axi-symmetric core collapse signals D1 and D4 have most of the signal energy in the 2−6 kHz frequency band and $M_{GW} < 10^{-8}$ M - consistent with the estimated detection range
- For the acoustic supernova model s25WW as much as 8×10^{-5} M may be converted to gravitational waves with frequency around 940 Hz → detection range 35 kpc.

Ott et al, 2006



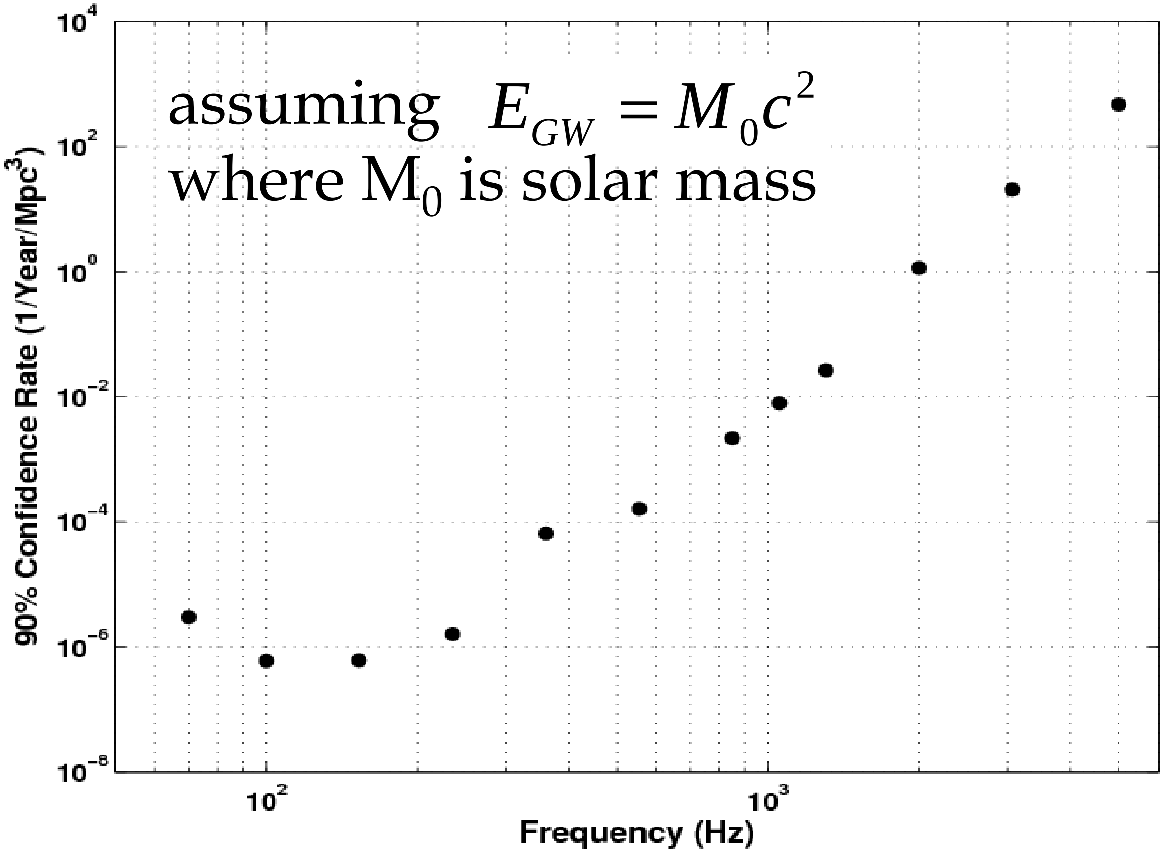
- **Given an isotropic distribution of sources with amplitude ho at a distance ro the rate density limit is**

$$R_{90} = \frac{2.3}{4\pi T(h_o r_o)^3 \int_0^\infty \varepsilon(h) h^{-4} dh}$$

- **The result can be interpreted as a rate density limit for a source with isotropic GW emission of** $E_{GW} = M_0 c^2$

$$h_0 r_0 = (\pi \cdot f)^{-1} \sqrt{\frac{GM_0}{c}}$$

results: rate density ULs

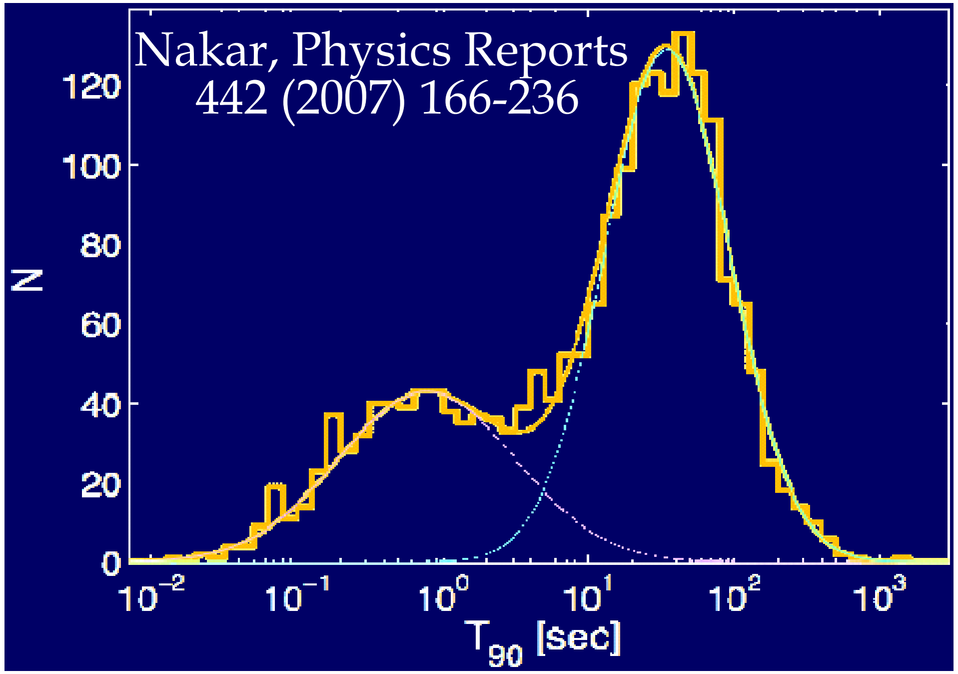


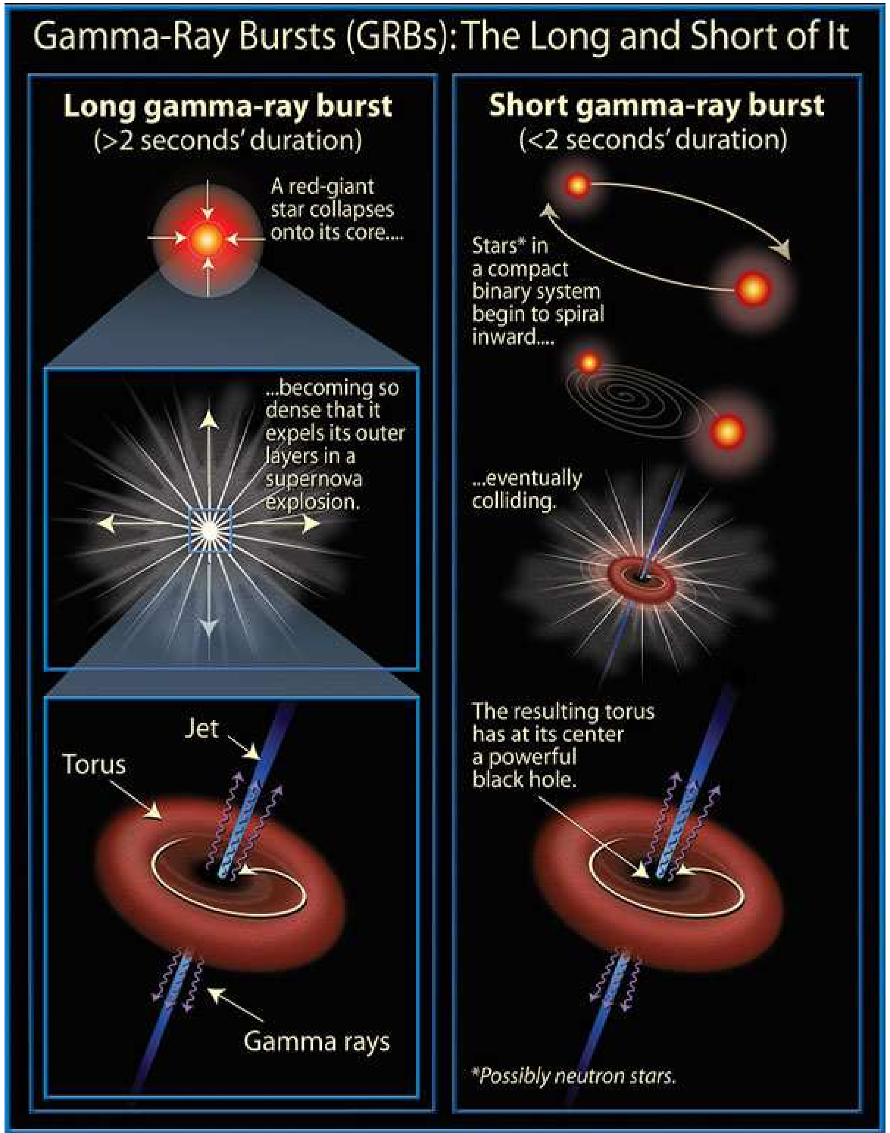
- **Rate density limit is rescaled as** $R_{90}(f,M) = R_{90}(f,M_0)\left(\frac{M_0}{M}\right)^{3/2}$

For a source emitting $E_{GW} = 0.01 M_0 c^2$ **at 150 Hz**

$$R_{90} = 6 \cdot 10^{-4}\,\mathrm{yr}^{-1}\mathrm{Mpc}^{-3}$$

Gamma-ray bursts

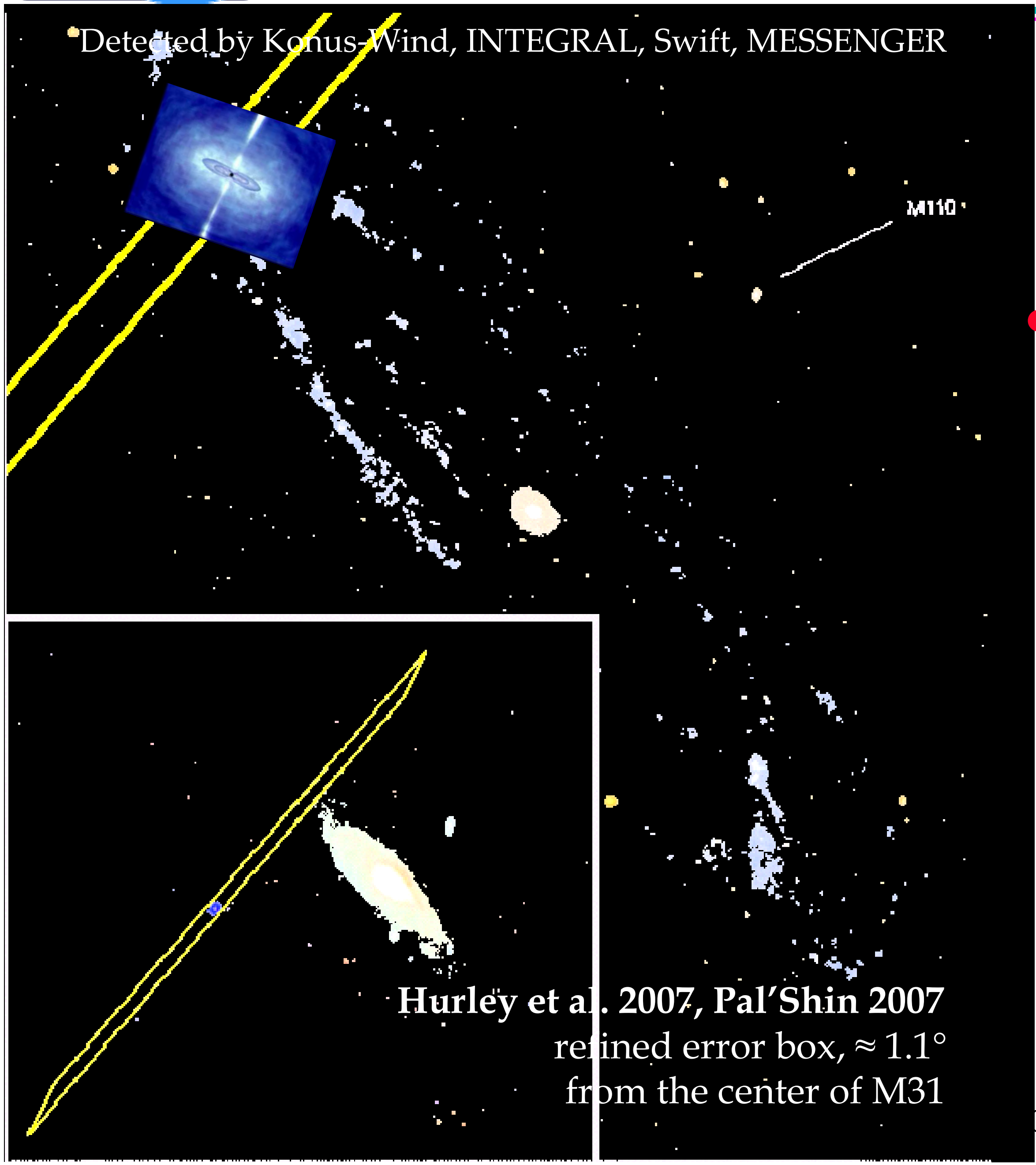




Based on Eric Chassande-Mottin's ILLIAS slide.

- **long and short GRBs**
  - **Collaps of massive stars**
  - **NS/NS or NS/BH mergers**
  - **Soft Gamma Repeaters (Chapman et al., 2008)**

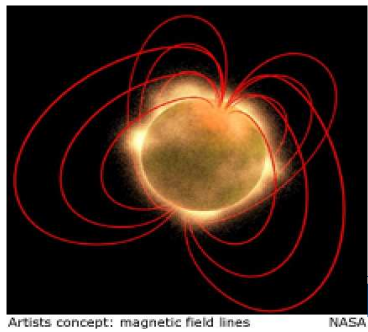
GRB 070201 – short (<1sec)



R.A. = 11.089 deg,
Dec = 42.308 deg

$$D_{M31} \approx 770 \text{ kpc}$$

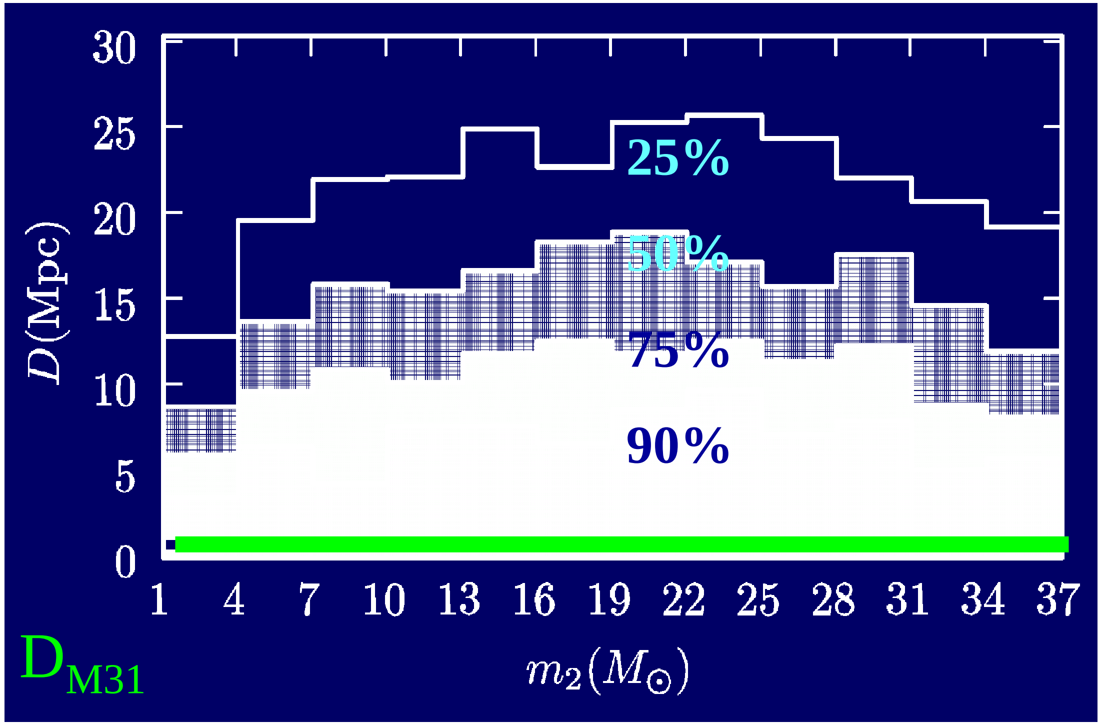
- **Possible progenitors for short GRBs:**
  - **NS/NS or NS/BH mergers -** emit strong gravitational waves
  - **Soft Gamma Repeater (SGR) - ma**y emit GW but weaker



GRB070201 triggered search

No gravitational waves detected

- Inspiral search:
  - excludes binary progenitor at >99% confidence level
  - Exclusion of merger at larger distances: see plot



- Burst search:
  - Cannot exclude a Soft Gamma Repeater (SGR) at M31 distance
  - Upper limit: E_{GW}<8x10^{50} ergs (<4x10^{-4} $M_o c^2$)

There were 137 GRBs (35 with redshifts) during the S5/VSR1 run with data from two or more LIGO+Virgo detectors

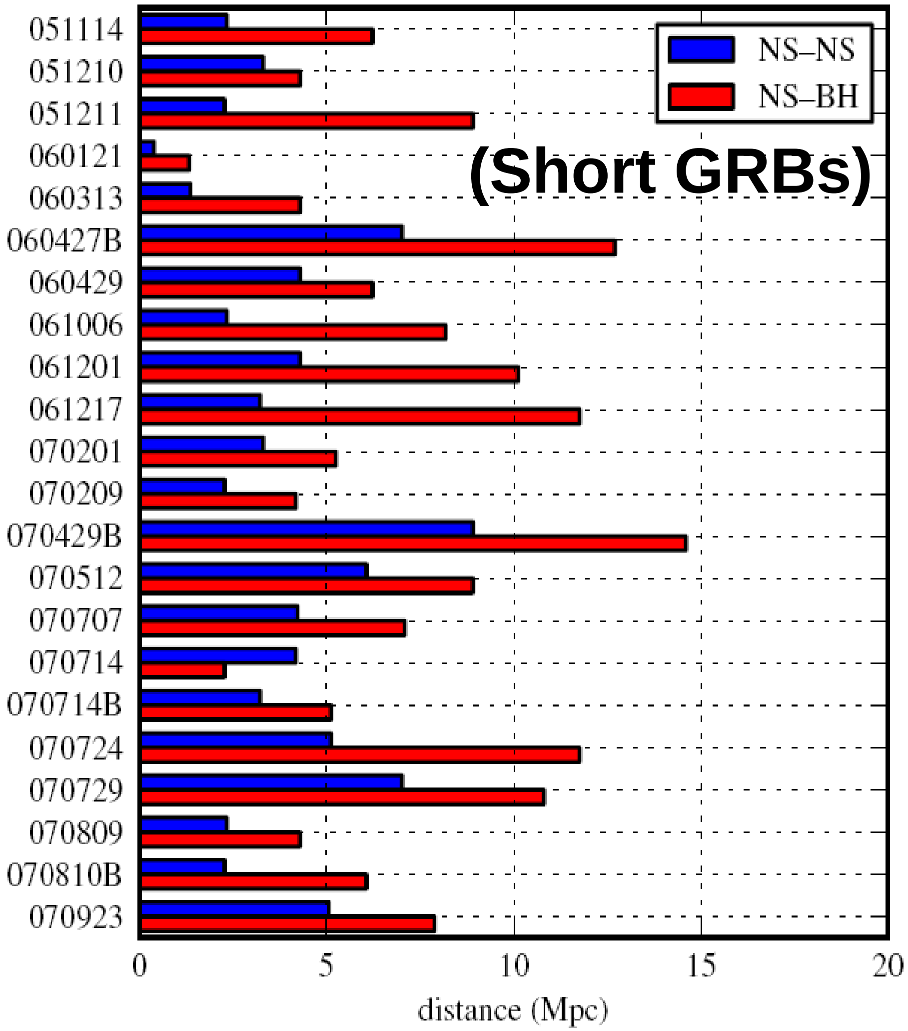
- Inspiral search
  - Sub-sample of 22 short GRBs
  - [–5,+1] second time window around time of GRB
  - Matched filtering followed by coincidence test based on time and mass parameters
  - "Loudest event" analysis
- Burst search
  - All 137 GRBs
  - [–120,+60] second time window around time of GRB
  - Coherent multi-detector burst search with 2, 3, or 4 detectors
  - "Loudest event" analysis

➔ No significant signal found for any individual GRB, and no statistical excess for any subset

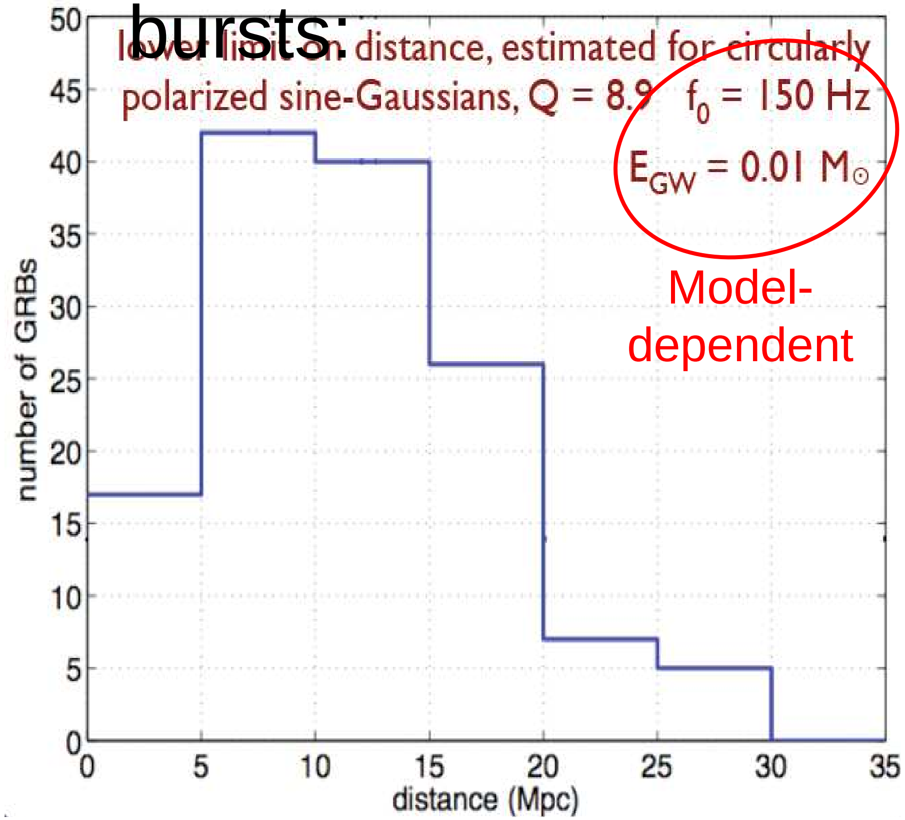
Preprint: arXiv:0908.3824

(For details, see: B13.04 – González, "Searches for coalescence of binary systems in LIGO and Virgo data" and K13.03 – Cadonati, "Probing the Association of GW and Gamma-Ray Bursts with LIGO and Virgo")

Lower Limits on Distance to Each S5/VSR1 GRB



- For hypothetical GW bursts:



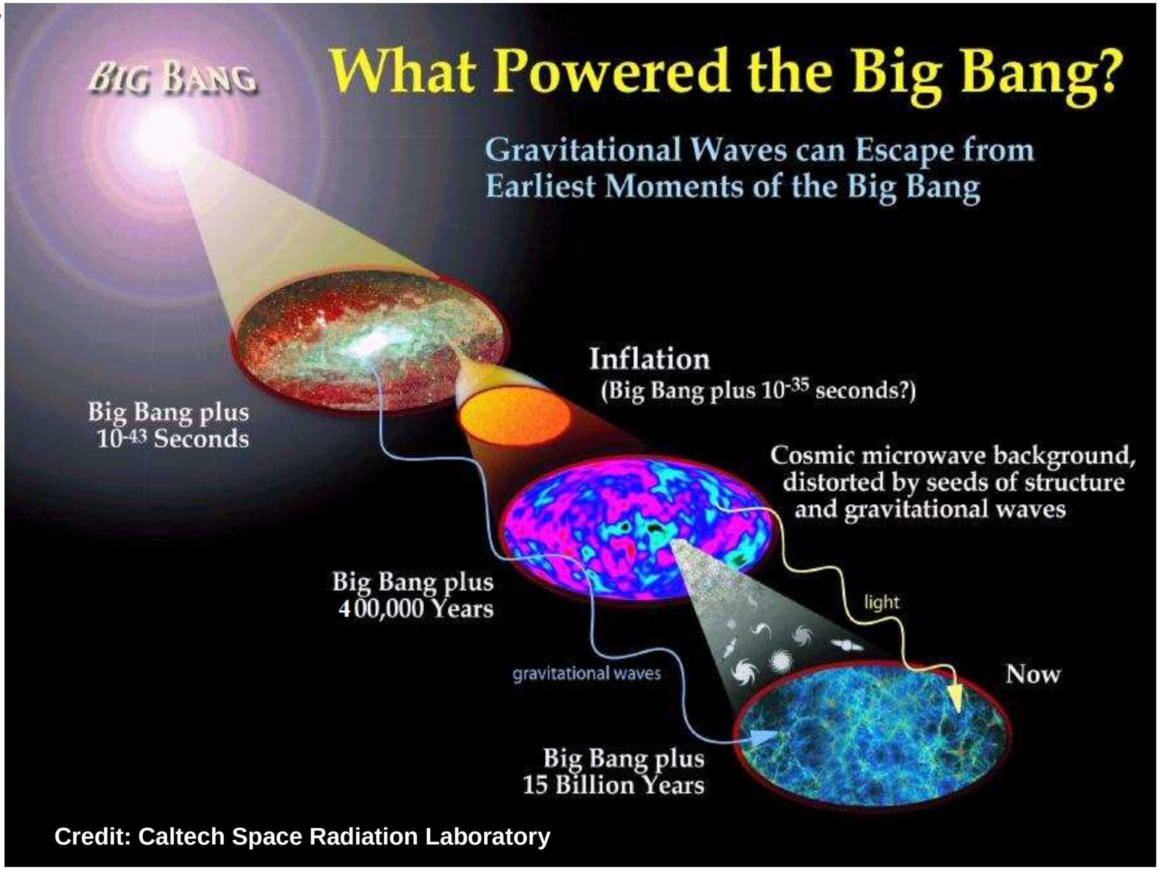
➔ We didn't get lucky with a close-enough event

The stochastic GW background

- An isotropic Stochastic GW background could come from:
  - Primordial universe (inflation)
  - Incoherent sum of point emitters isotropically distributed over the sky
- of

$$\Omega_{GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{GW}(f)}{d\ln f},$$

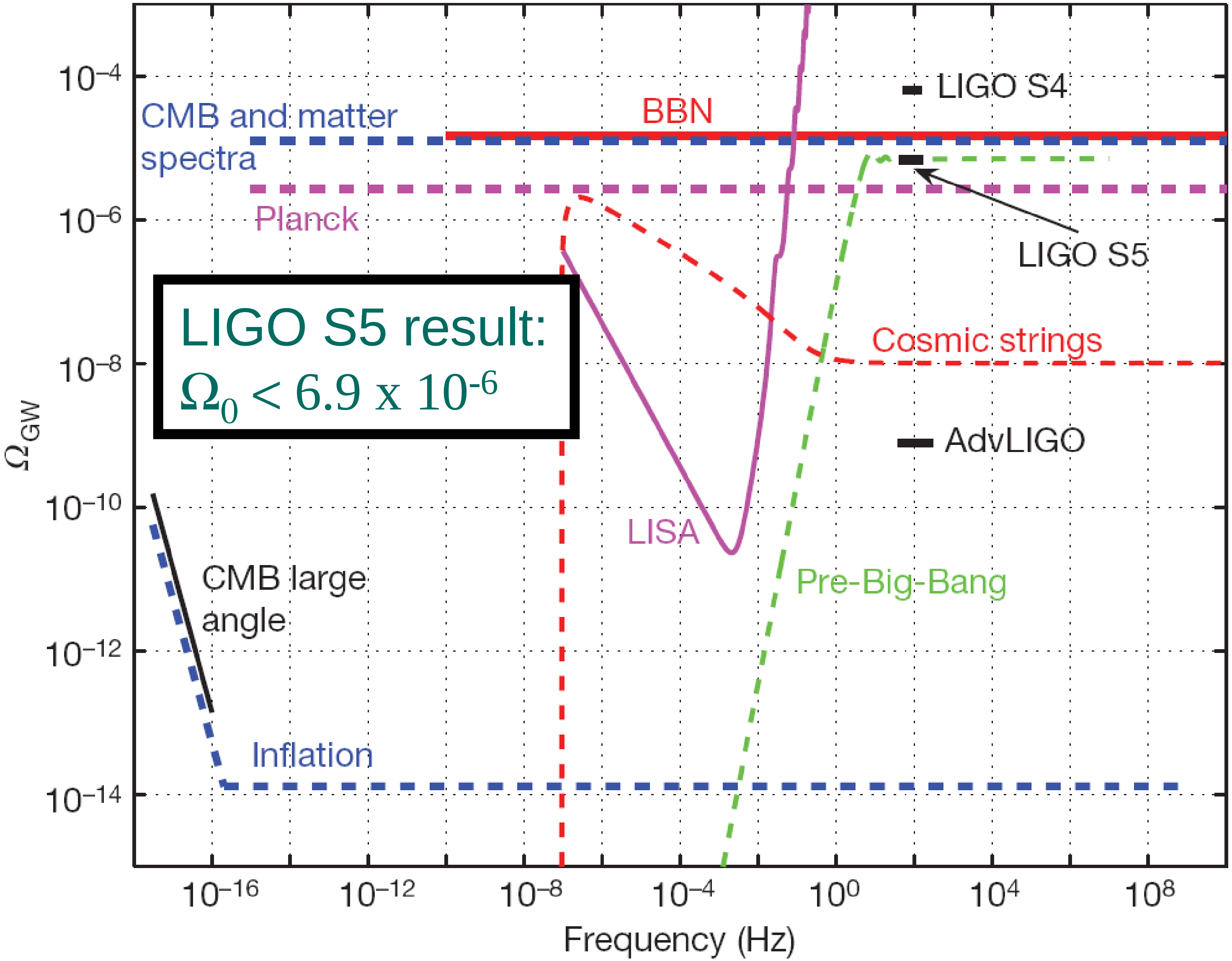
$$\int \Omega_{GW}(f)\, d(\ln f) = \frac{\rho_{GW}}{\rho_c} \equiv \Omega_0$$



$\Omega_{0,\ BBN} < 1.1 \times 10^{-5}$

- Big Bang Nucleosynthesis limit:

Abbott, et al. "*An upper limit on the stochastic gravitational-wave background of cosmological origin*", Nature., V460: 990 (2009).



LIGO S5 result:

$\Omega_0 < 6.9 \times 10^{-6}$

UNIVERSITY of FLORIDA

Advanced Algorithms

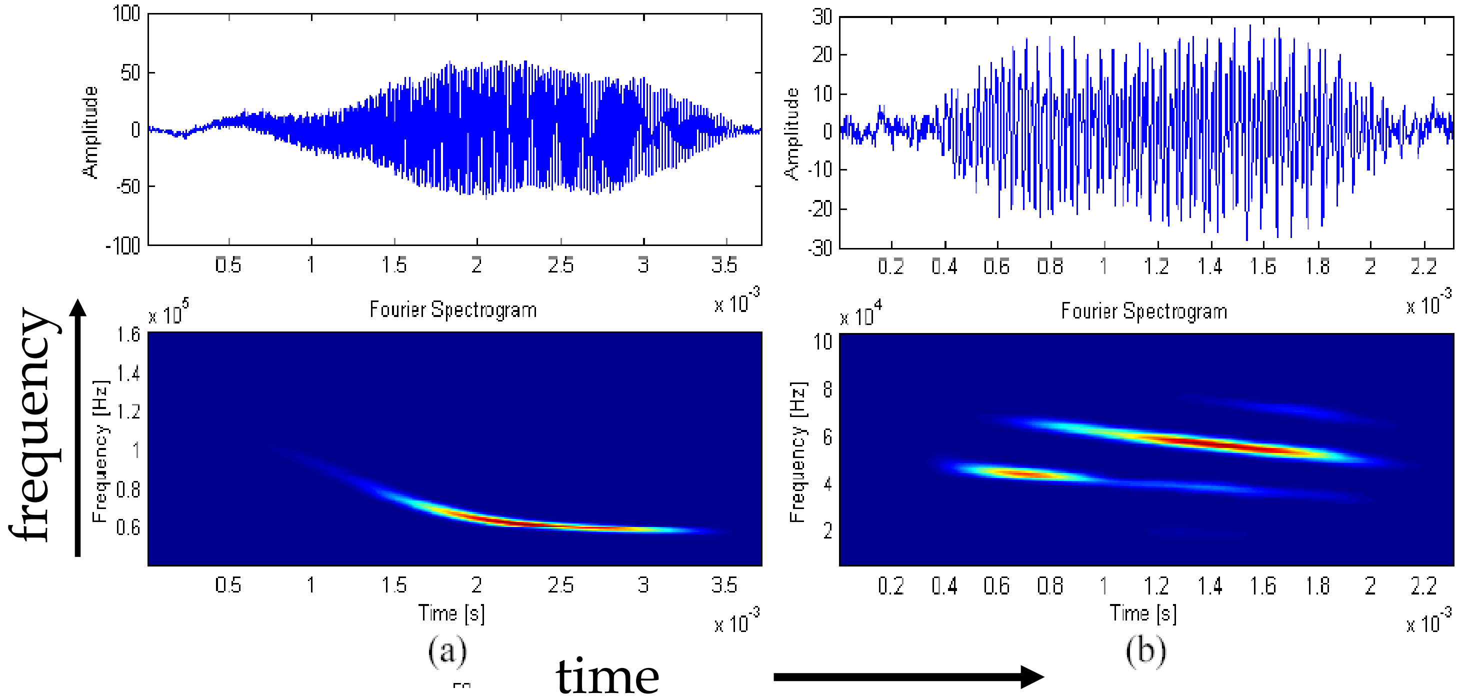
- time-frequency analysis
- coherent network analysis

L1H1V1 x-sensitivity

time-frequency analysis

Ecological calls of

the Miniopterus australis | **the Macroderma gigas**



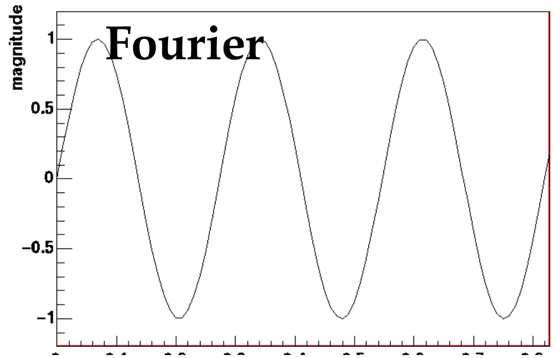
- **Identify GW "ecological calls" as a patterns on the TF plane**
- **Characterize by strength, duration, frequency band,...**
- **Particularly useful if signal is buried in the broad-band noise**

Wavelet transformations

- basis *{Ψ(t)}* :
  - bank of template waveforms
  - Ψ_0 -mother wavelet

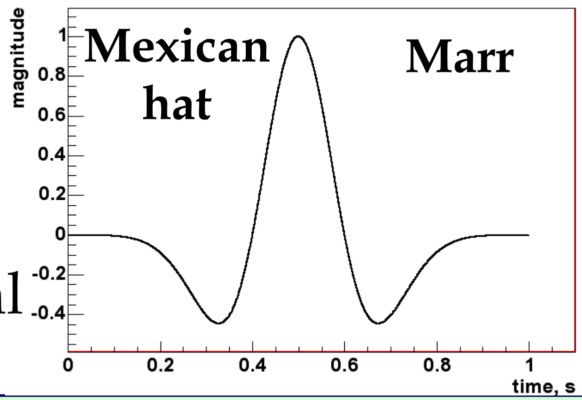
$$\Psi_{jk} = 2^{j/2}\Psi_0\left(2^j t - k\right)$$

not local



local
orthogonal
not smooth

local,
smooth,
not
orthogonal



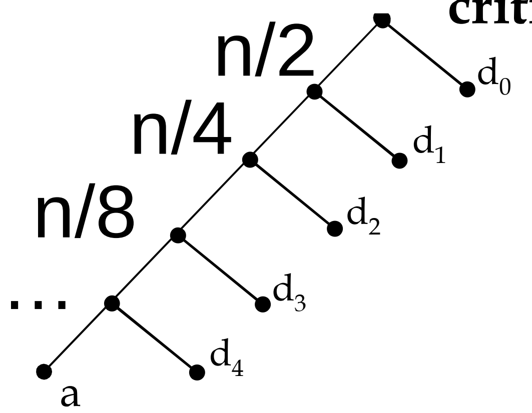
local
orthogonal
smooth

wavelet - natural basis for bursts, low spectral leakage
used to produce TF data with good localization of transients

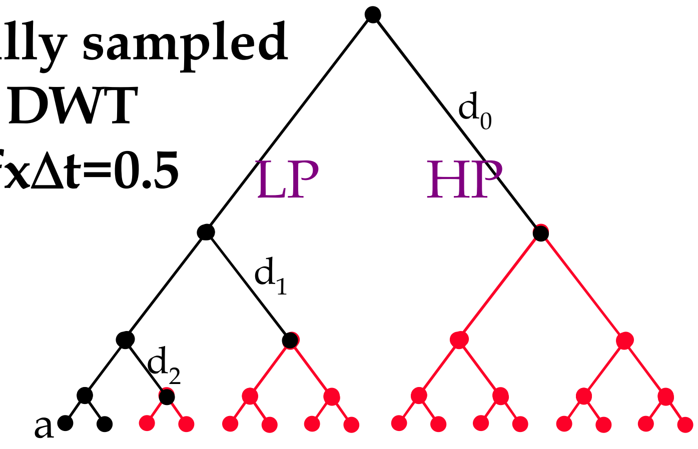
Wavelet scalograms

decomposition of discrete time series x[t] with sampling rate R and n samples in basis $\{\Psi_i(t)\}$

critically sampled DWT
$\Delta f \times \Delta t = 0.5$

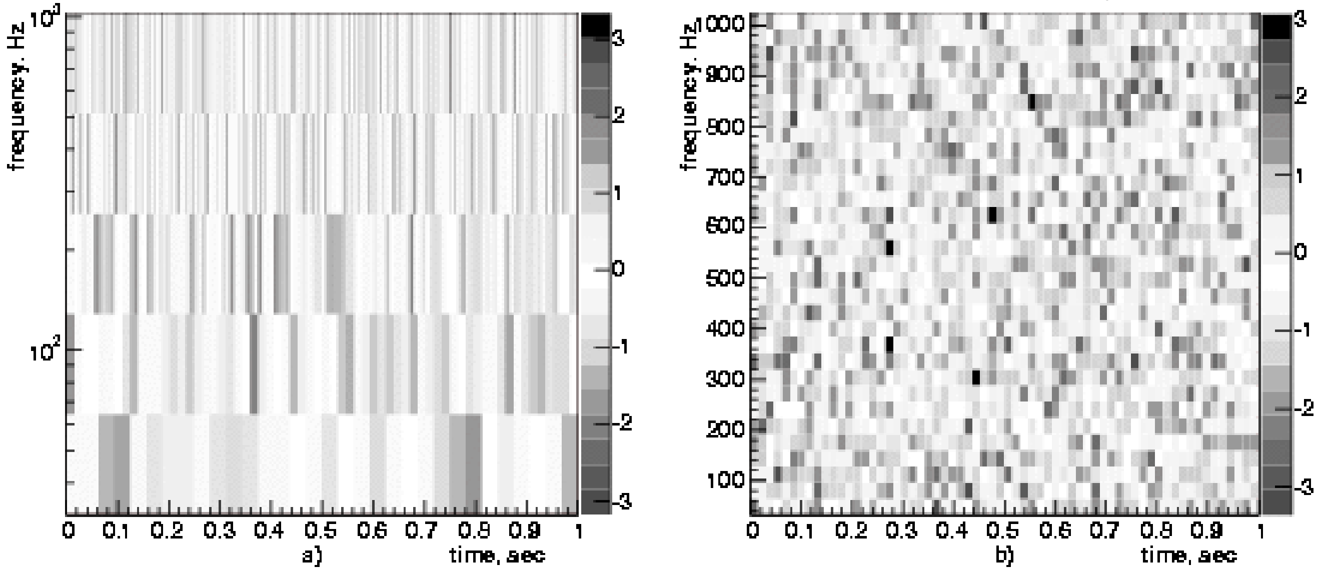


a. wavelet dyadic tree



b. wavelet binary tree

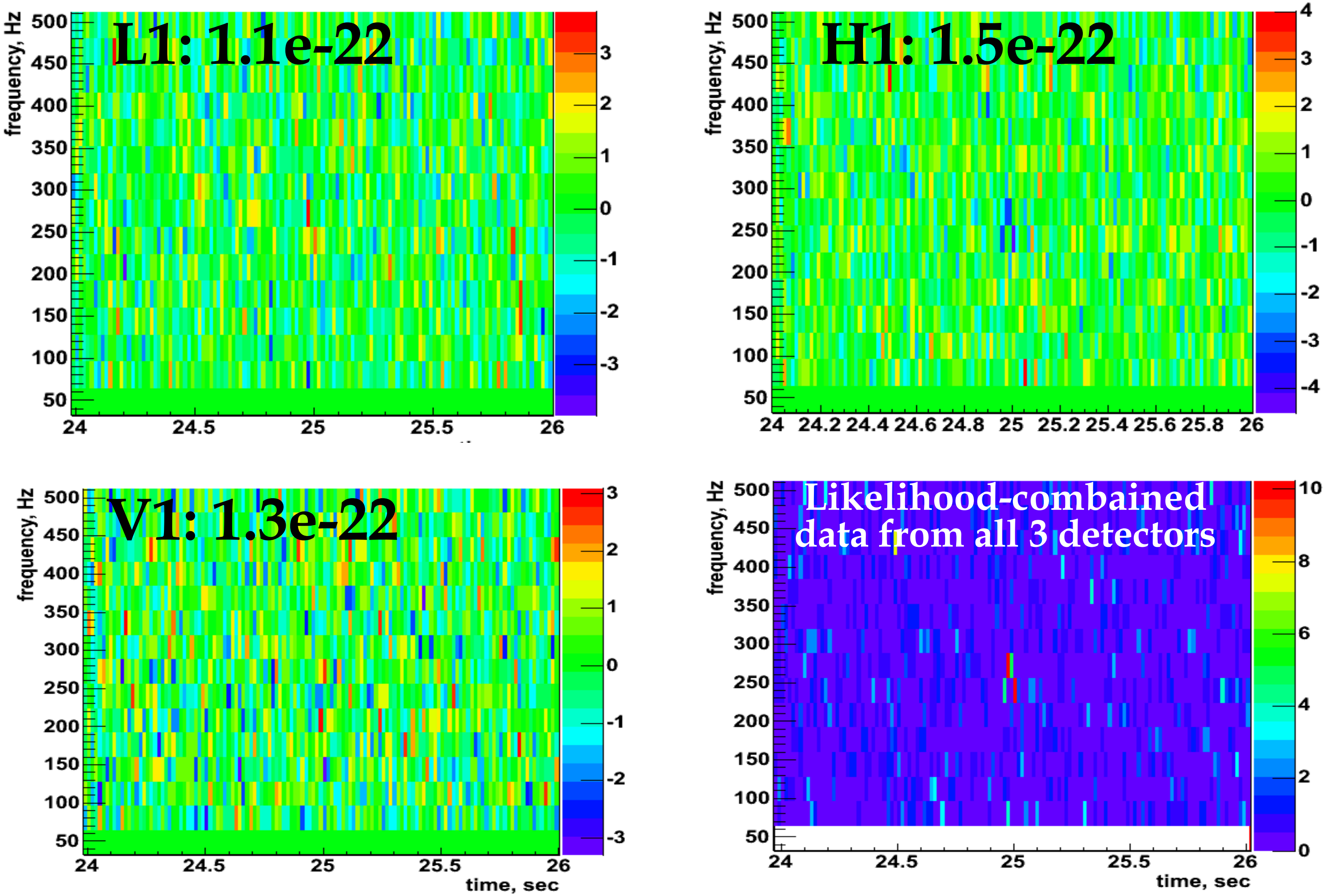
$f_N = R/2$



$T = n/R$

Observations with multiple detectors

noise+sg250Hz (τ=0.02sec, θ=20, ϕ=150)



Likelihood Analysis

- **Likelihood ratio** $\Lambda = \dfrac{p(X \mid h)}{p(X \mid 0)}$ (global fit to the data)

Flanagan, Hughes, PRD 57 4577 (1998)
Klimenko et al, PRD 72, 122002 (2005)
Klimenko et al, CQG 25, 114029, (2008)

- **Matched filter for bursts**
  - **Noise model:** usually multivariate Gaussian noise

    $$p(X \mid 0) \propto \exp[-X\Sigma^{-1}X^T]$$ Σ-noise covariance matrix

  - **signal model (detector response)**

    $$\vec{\xi}[i] = h_+[i]\vec{F}_+ + h_\times[i]\vec{F}_\times, \quad h_+, h_\times - \text{free parameters}$$

    $$p(X \mid h) \propto \exp[-(X-\xi)\Sigma^{-1}(X-\xi)^T]$$

  - **find best solution for h_+,h_x at maximum of Λ**
    - **variation of Λ over h_+,h_x – large number of free parameters**

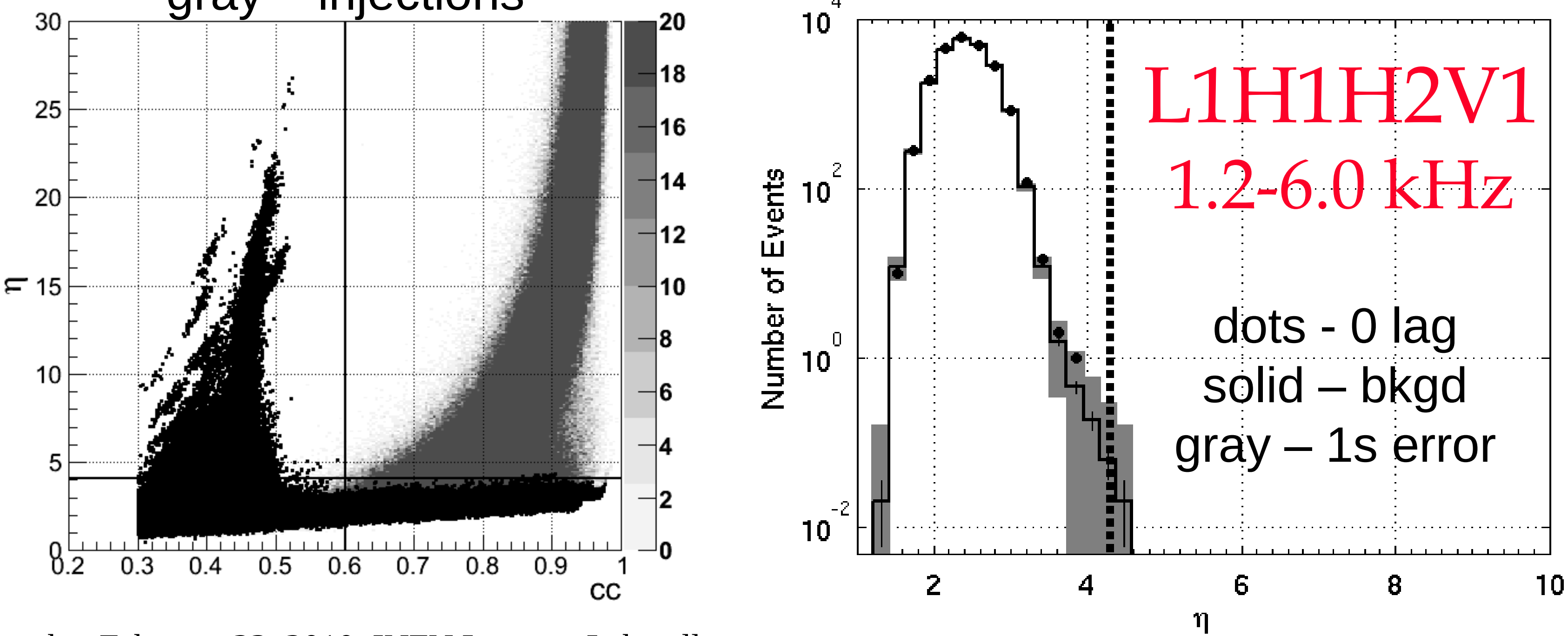
- **Need at least 2 detectors, but preferably 3 or more**

Search Algorithms: cWB

- **Coherent WaveBurst: coherent network algorithm based on constrained likelihood analysis. (64-6000Hz)**
- **Detection statistics**
  - **Network correlation coefficient cc - rejection of glitches**
  - **network correlated amplitude η – event ranking statistic**

black - background
gray – injections

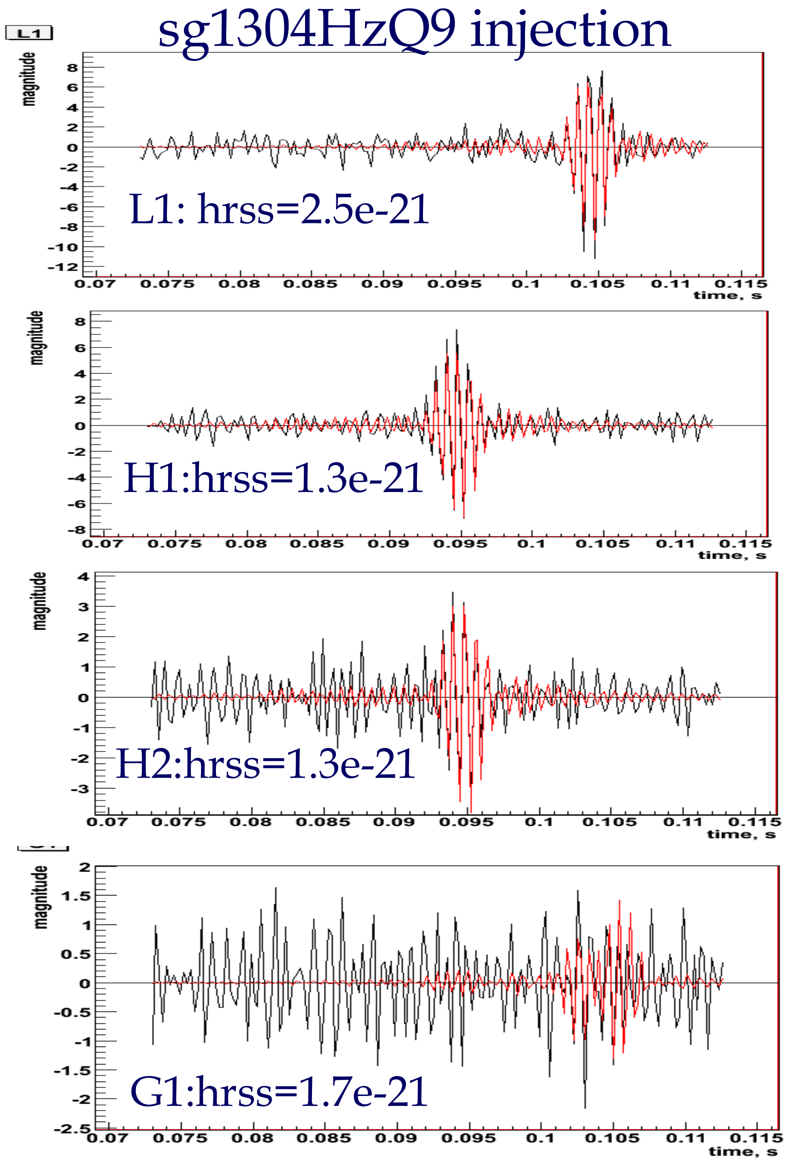
CQG 25, 114029 (2008)



Reconstruction of signal waveforms

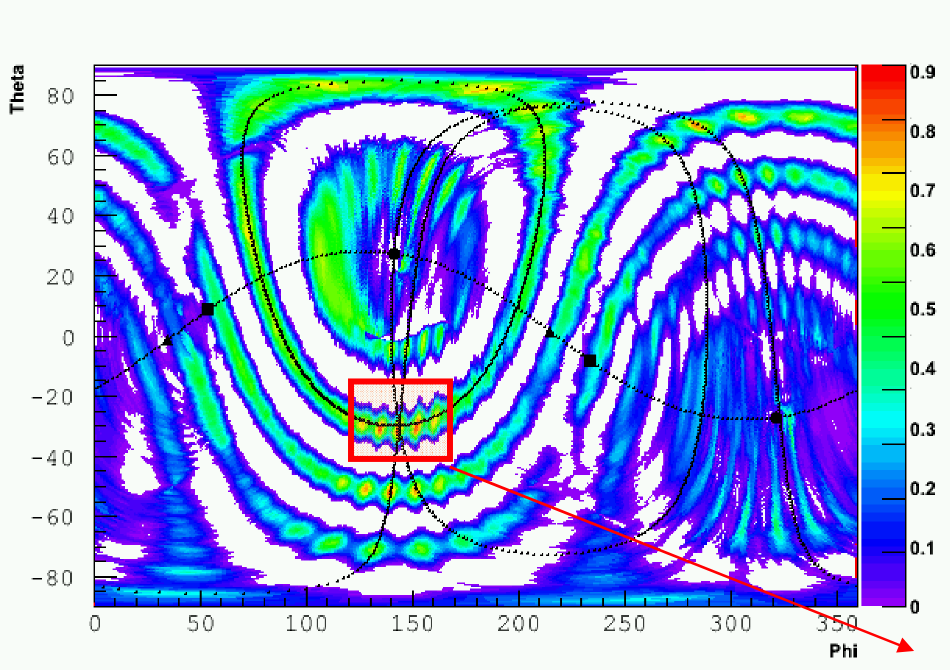
black
band-limited
time series

red
reconstructed
response



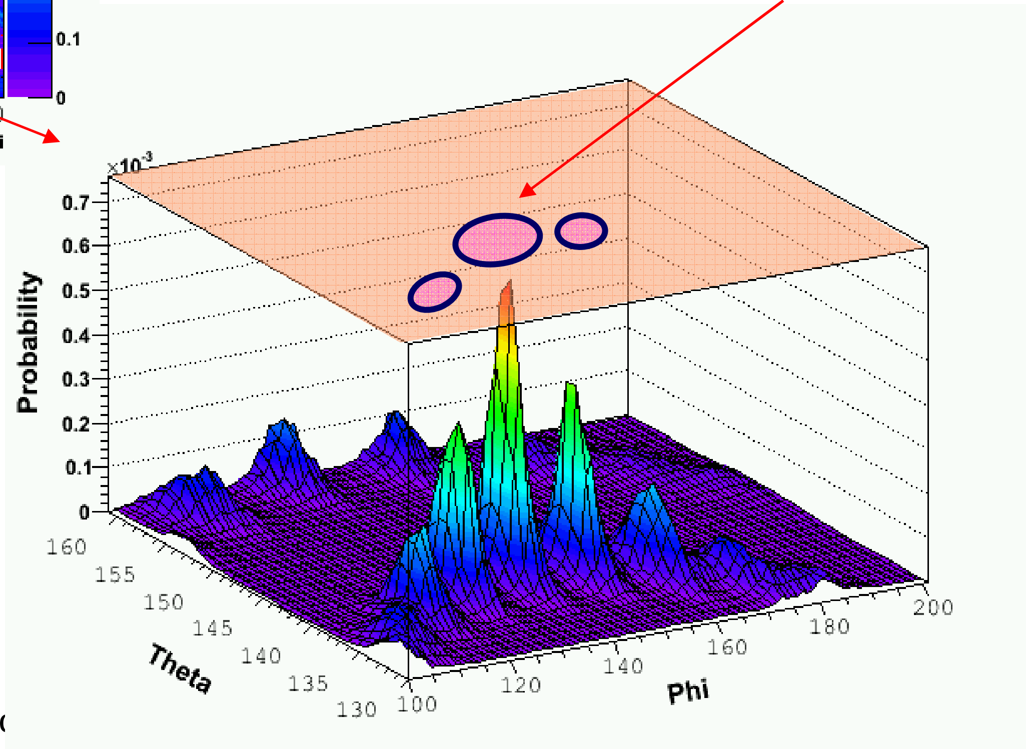
- **If GW signal is detected, two polarizations and detector responses can be reconstructed and confronted with source models for extraction of the source parameters**

- **network analysis experts: G.Vedovato & M.Drago**



Likelihood Sky Map shows how consistent are reconstructed waveforms and time delays as function of θ,ϕ. Max likelihood point to source location.

Error Region

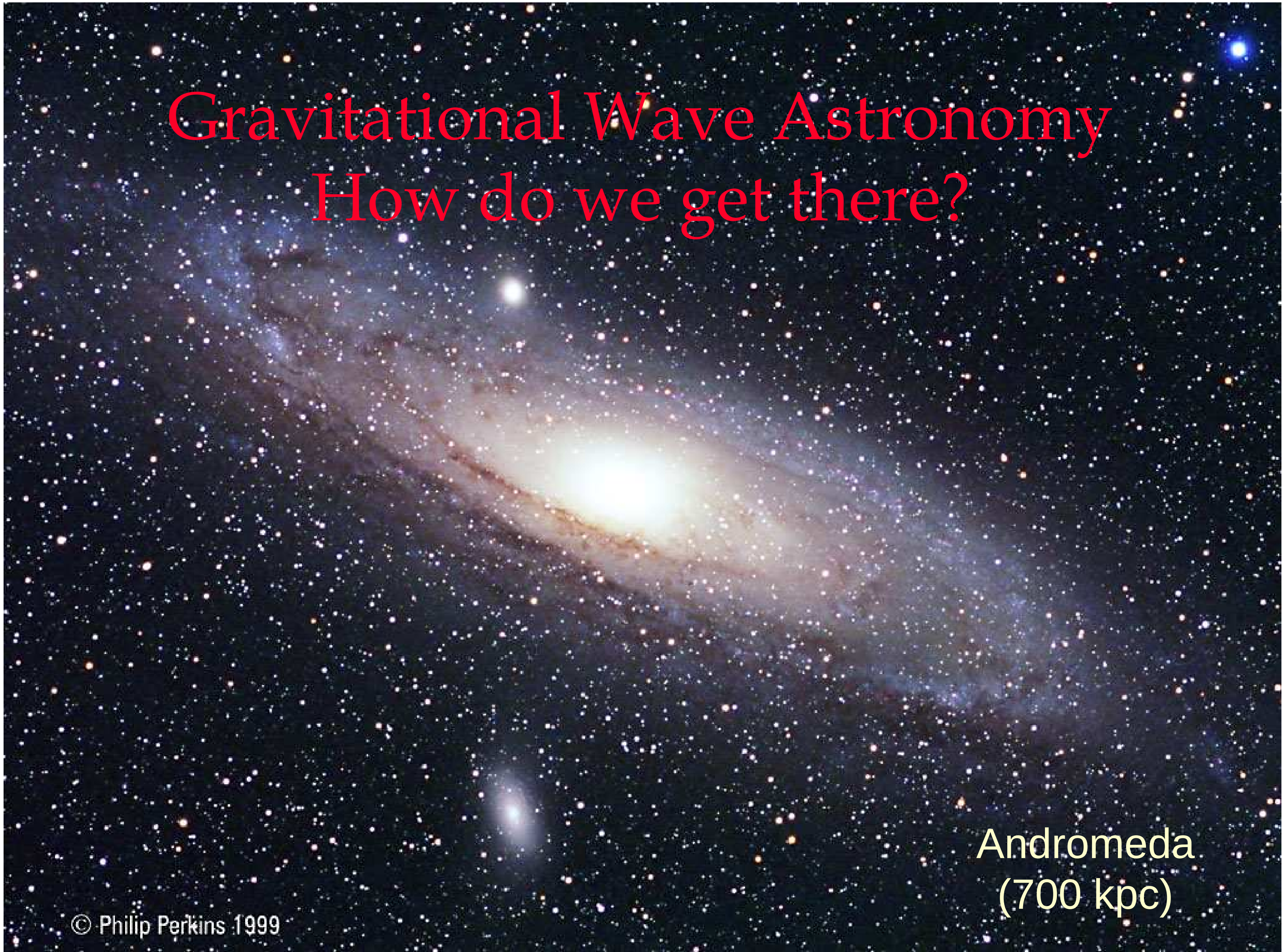


- **Source location is characterized by a spot in the sky (Error Region) rather than by a (θ,ϕ) direction**
  - x% error region - a sky area which covers with x% probability)
- **Error Regions should be reported for optical/radio followup**
  - may consist of disjoint sky areas

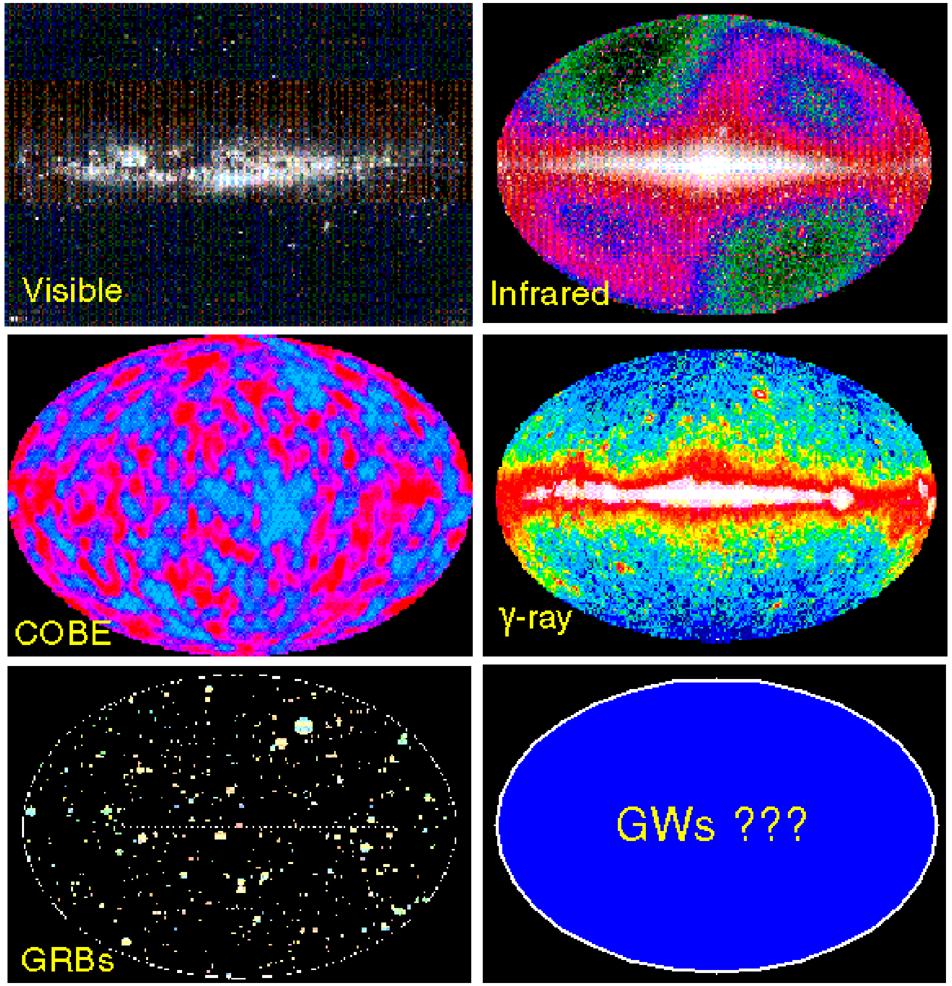
Coherent WaveBurst

- baseline algorithm used by LIGO for S2, S3, S4 and S5 all-sky burst searches
  - uses wavelets
  - constructs coherent statistics for confident detection
  - rejects instrumental and environmental artifacts
  - reconstructs of waveforms and source coordinates
  - performs search over ~165000 sky locations
  - performs analysis for ~1000 time shifts for background estimation
- application of constraints allows test of source models and extraction of source parameters.
- Developed at UF, upgraded and improved by UF, Padova, Trento & AEI

Gravitational Wave Astronomy
How do we get there?



New Window on Universe



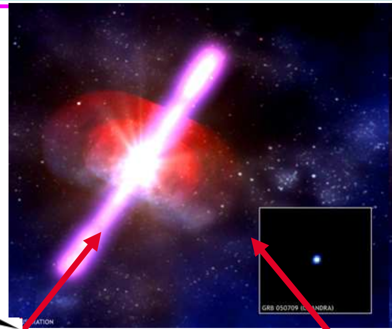
GRAVITATIONAL WAVES PROVIDE A NEW AND UNIQUE VIEW OF THE DYNAMICS OF THE UNIVERSE.

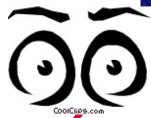
coincident observations

- **externally triggered**
  - **gamma ray bursts**
  - **neutrinos**
- **GW triggered**
  - **EM transients**
  - **reconstruction of source coordinates**

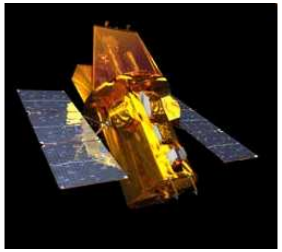
Multimessenger Astronomy

- observation and measurement of the same astrophysical event
  - better confidence of GW event
  - extract physics of source engine





- Externally triggered strategy
  - fold in measured time of arrival and source location into GW searches



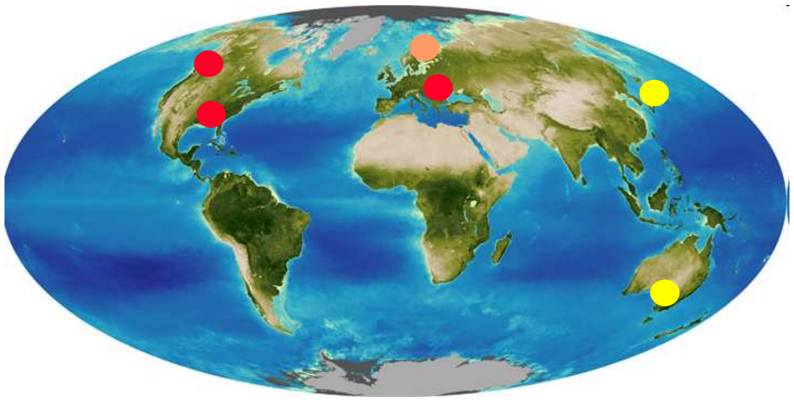
- Look-Up strategy
  - search for EM counterpart with optical and radio telescopes
  - need development of prompt pointing capabilities for GW detectors

GW triggered searches

- **Need accurate coordinate reconstruction**
  - **dependence on antenna patterns & detector noise**
  - **dependence on GW waveforms and polarization state**
  - **reconstruction bias due to algorithmic assumptions**
  - **effect of calibration errors**
  - **high computational cost**

- **….there are many ways to get it wrong**
  - **need “smart” algorithms**
  - **eventually need more detectors**

- LIGO, VIRGO (operational)
- GEO600 (limited sensitivity, HF?)
- LCGT, AIGO (future detectors)



The Future: Enhanced and Advanced LIGO

S5 Run | S6 | S7?

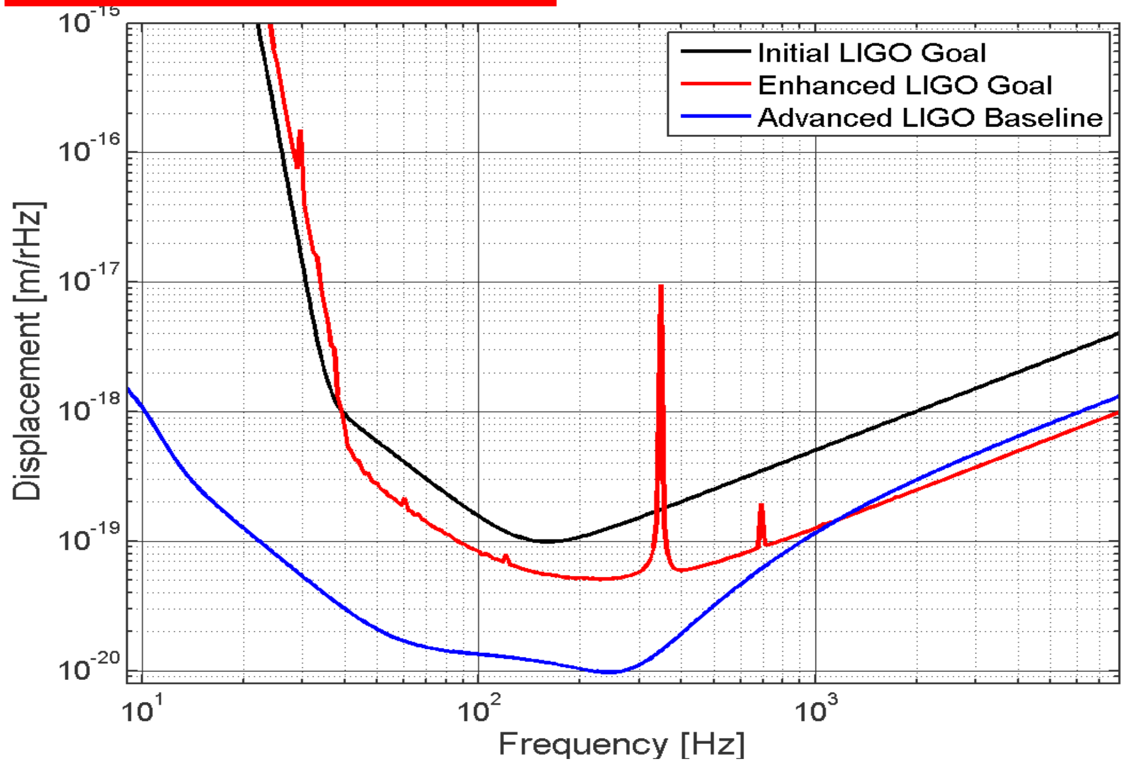
2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014

LIGO | ***enhanced* LIGO**

Advanced LIGO

build hardware | installation | science

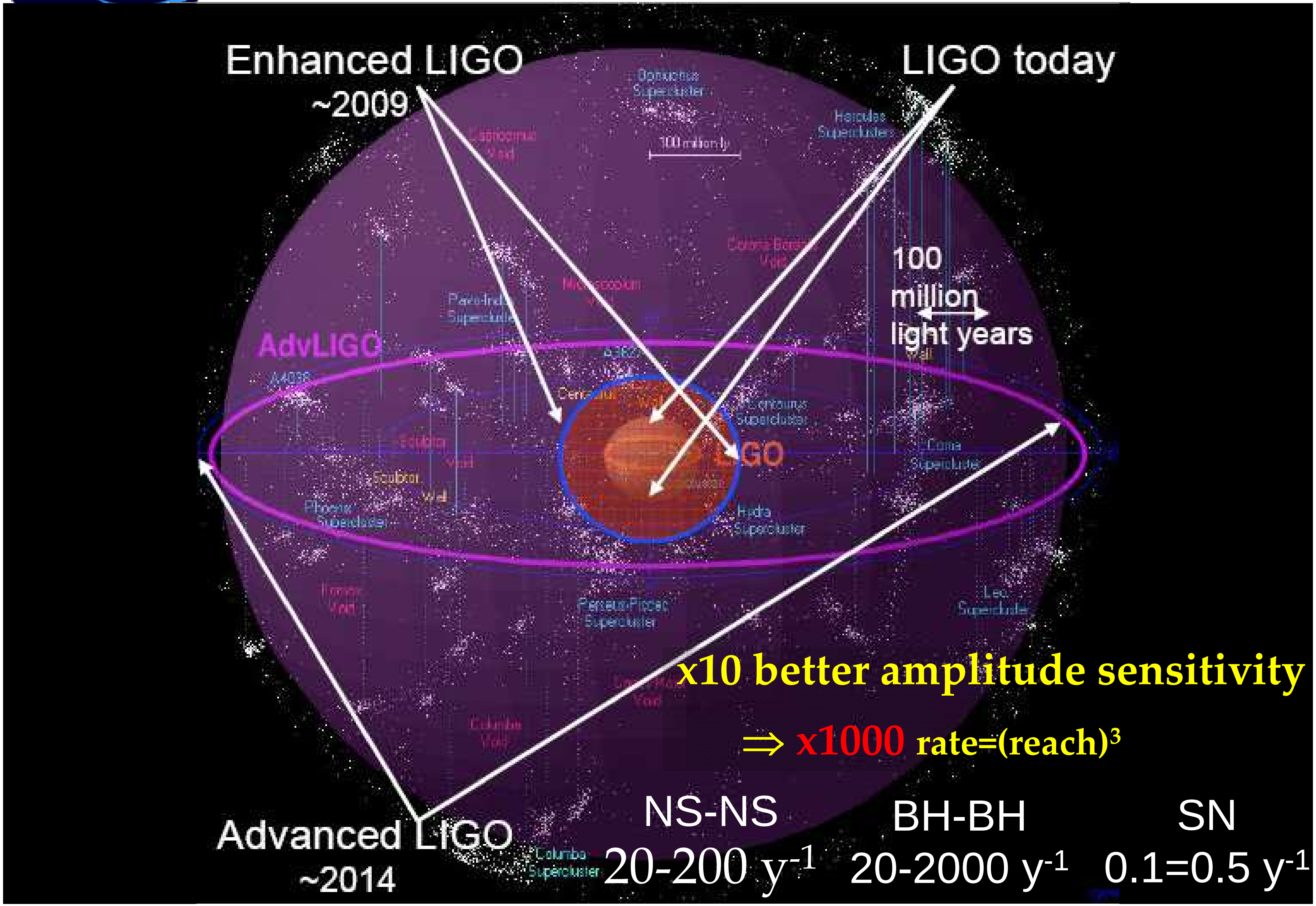
Advanced LIGO funded as of 2008



Enhanced LIGO (S6)

- readout noise; laser power
- $\times$2 better sensitivity
- commission AdLIGO DC readout with real IFOs
- reduce AdLIGO startup time

Astronomical Reach



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