Astrophysical Sources, Analysis Methods and Current Results in LIGO's Quest for Gravitational Waves

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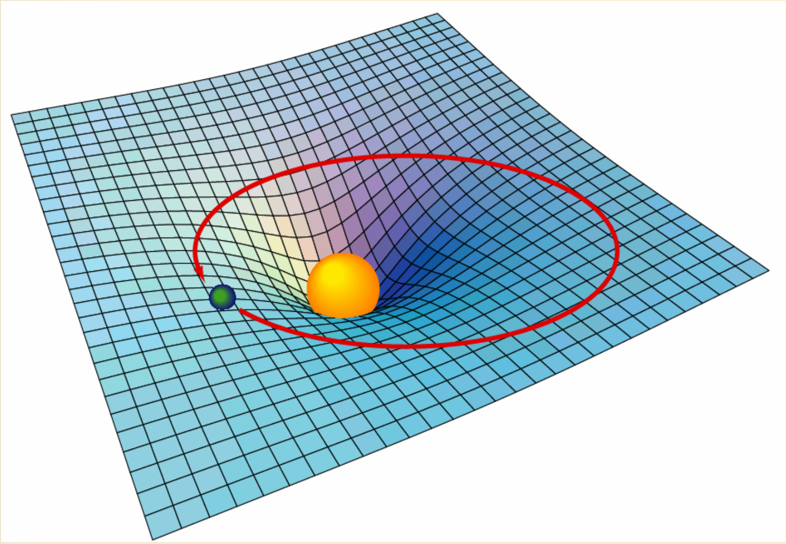
For the LIGO Scientific Collaboration
SESAPS 2006
Williamsburg VA, November 9 2006

LIGO-G060582-00-Z

Einstein's Vision



General Relativity:
gravity is not a force,
but a property of space-time

Smaller masses travel toward larger masses, not because they are "attracted" by a mysterious force, but because the smaller objects travel through space that is warped by the larger object.

"Mass tells space-time how to curve,
and space-time tells mass how to move."
J. A. Wheeler

Einstein's Equations:

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

LIGO Science Goals

Test of General Relativity

Are gravitational waves quadrupole radiation?

Do they travel at the speed of light?

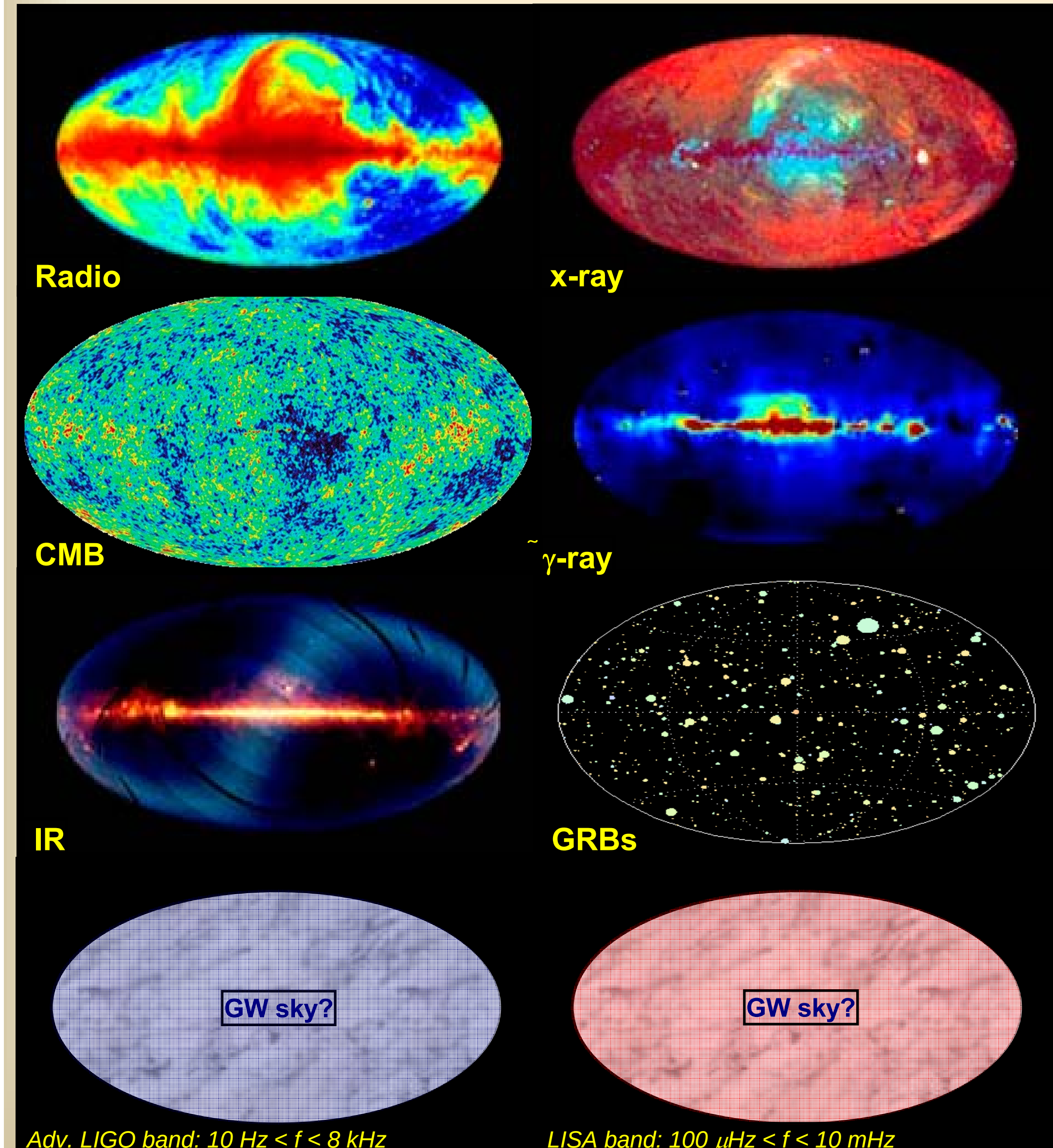
Direct observation of black-hole and their physics

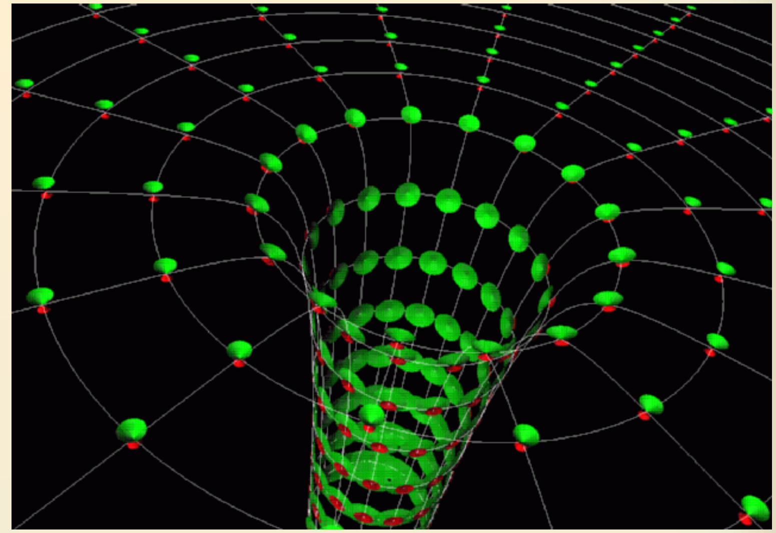
Gravitational-Wave Astronomy

Gravitational waves will give us insight in some of the most interesting and least understood topics:

Black hole formation, Supernovae, Gamma Ray Bursts, the abundance of compact binary systems, low-mass X-ray binaries, stochastic background and Big-Bang, properties of neutron stars, pulsars…

A New Probe into the Universe





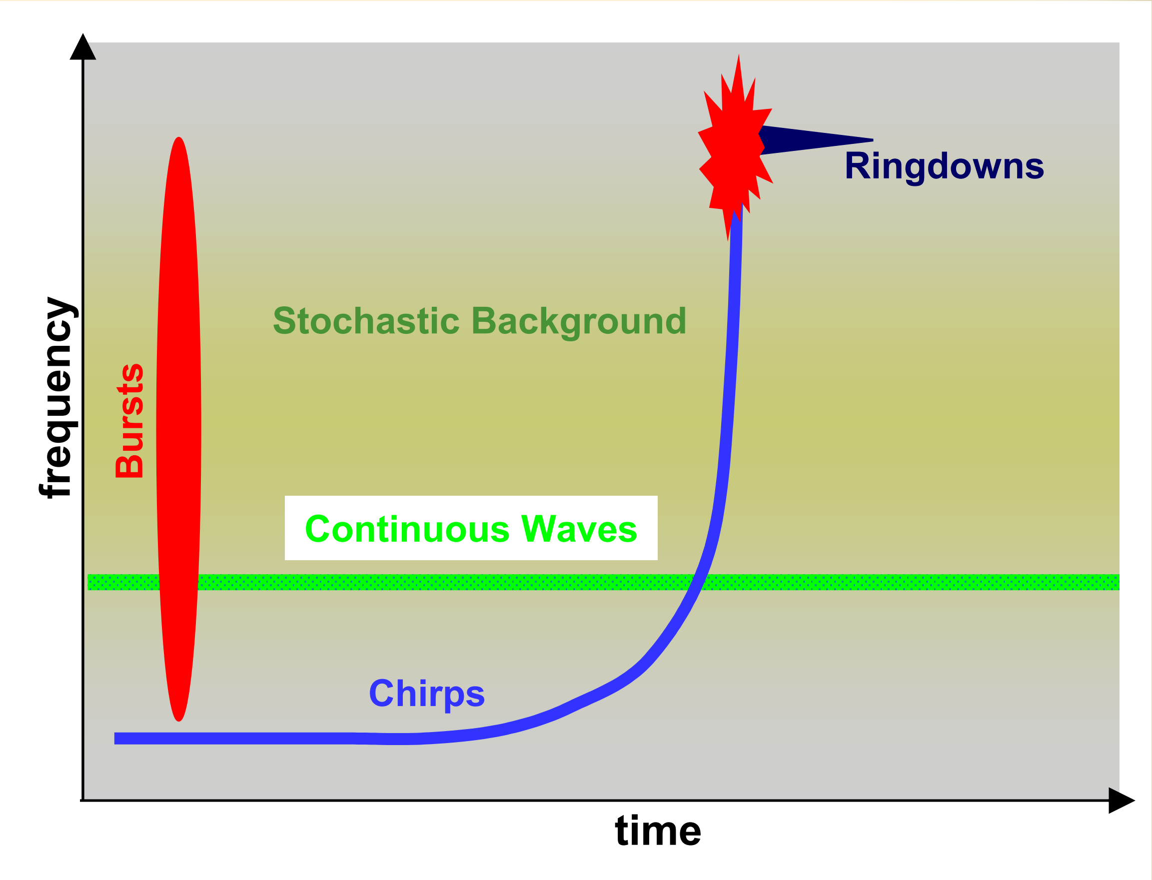
Gravitational Waves will give us a different, non electromagnetic view of the universe, and open a new spectrum for observation.

This will be complementary information, as different from what we know as hearing is from seeing.

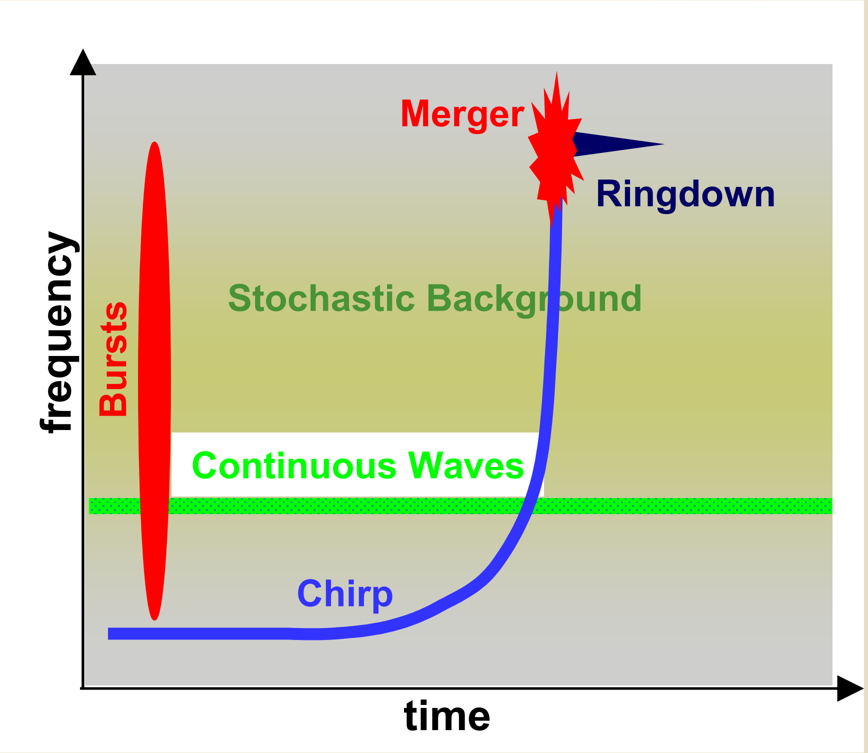
POSSIBILITY FOR THE UNEXPECTED IS VERY REAL!

Astrophysical Searches with LIGO Data

- Coalescing compact binary systems:
  "Inspirals"
- Supernovae / Gamma Ray Bursts:
  "Bursts"
- Pulsars in our galaxy:
  "Continuous Waves"
- Cosmological Signals:
  "Stochastic Background"

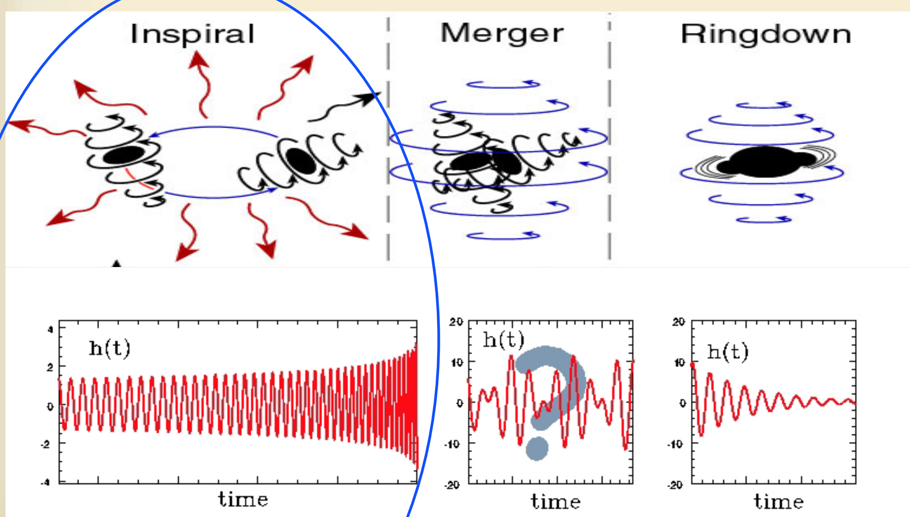


Inspirals: The Wedding Song of Coalescing Binaries



Inspirals: The Wedding Song of Coalescing Binaries

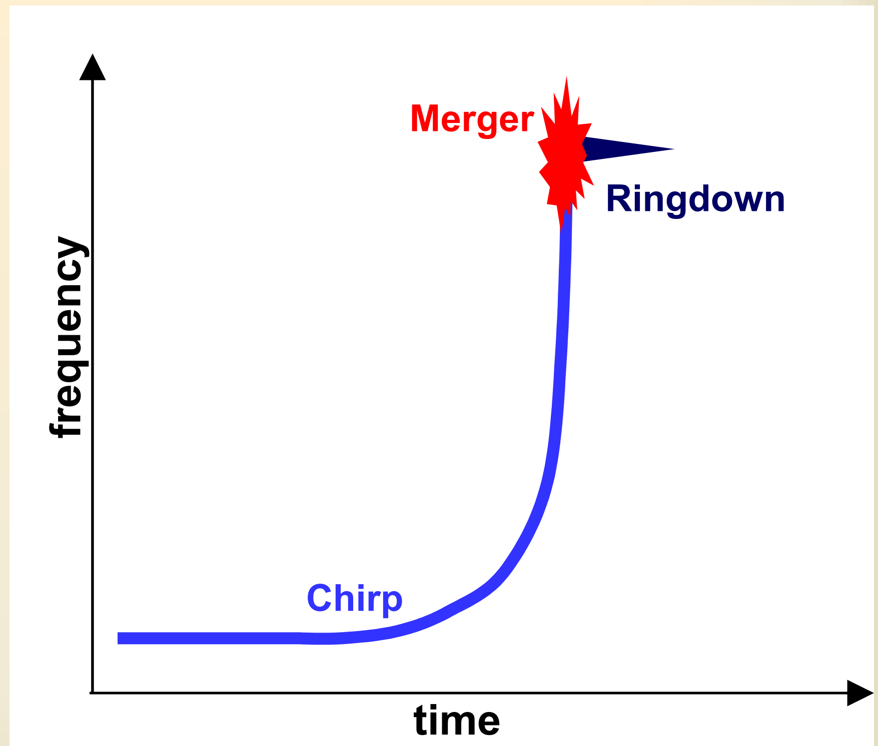
LIGO is sensitive to gravitational waves from neutron star (BNS) and black hole (BBH) binaries.
Waveforms depend on masses and spins.
Detection would probe internal structure and populations

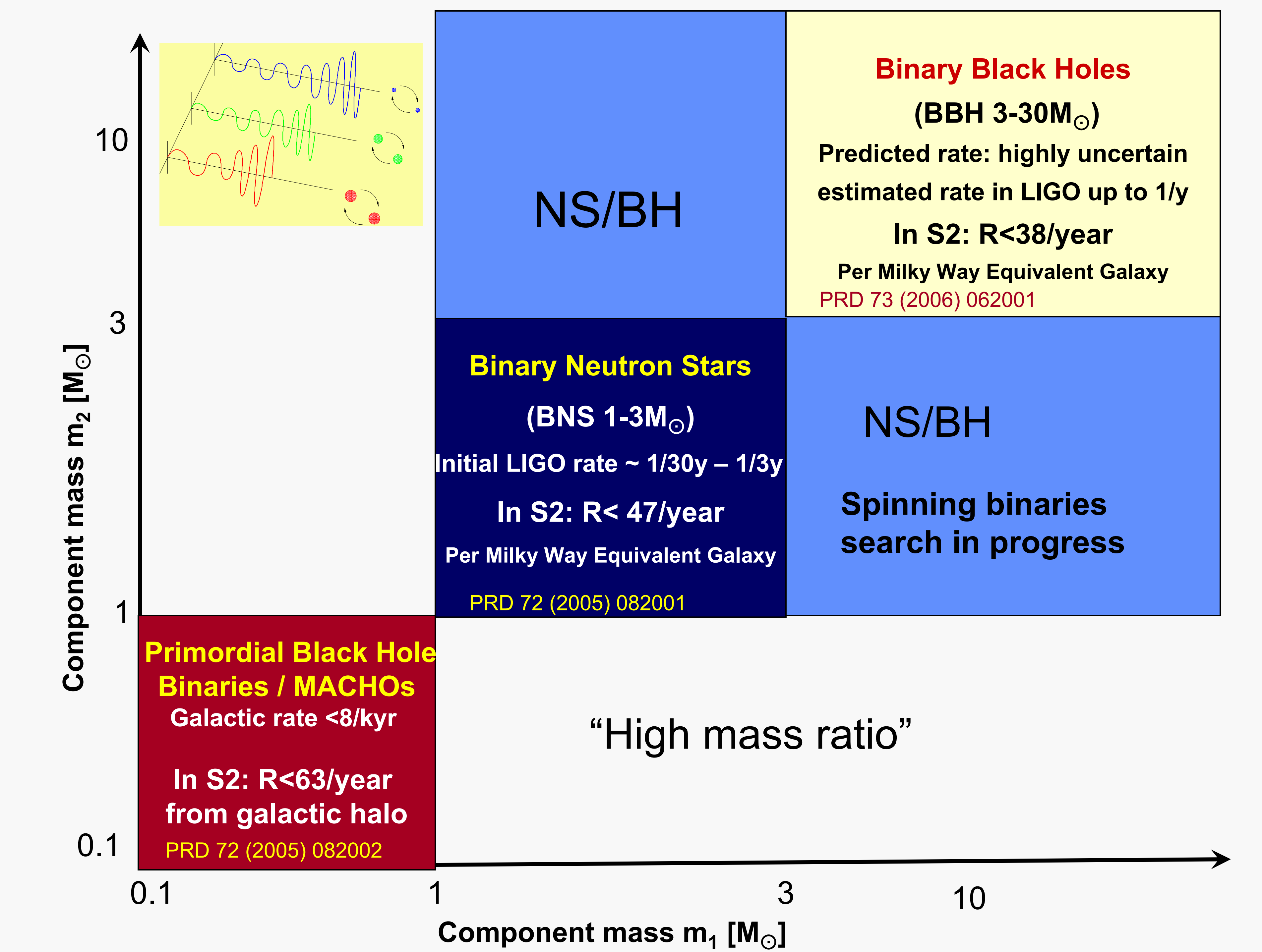


Matched filter

Template-less

Matched filter



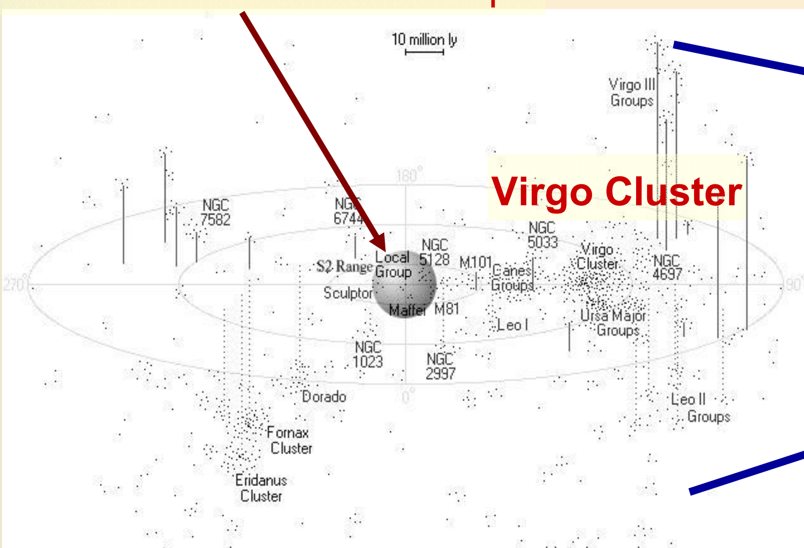


Binary Black Holes
(BBH 3-30M⊙)
Predicted rate: highly uncertain
estimated rate in LIGO up to 1/y
In S2: R<38/year
Per Milky Way Equivalent Galaxy
PRD 73 (2006) 062001
NS/BH
Binary Neutron Stars
(BNS 1-3M⊙)
Initial LIGO rate ~ 1/30y – 1/3y
In S2: R< 47/year
Per Milky Way Equivalent Galaxy
PRD 72 (2005) 082001
NS/BH
Spinning binaries
search in progress
Primordial Black Hole
Binaries / MACHOs
Galactic rate <8/kyr
In S2: R<63/year
from galactic halo
PRD 72 (2005) 082002
"High mass ratio"
Component mass m2 [M⊙]
10
3
1
0.1
0.1
1
3
10
Component mass m1 [M⊙]

Horizon distance in S5

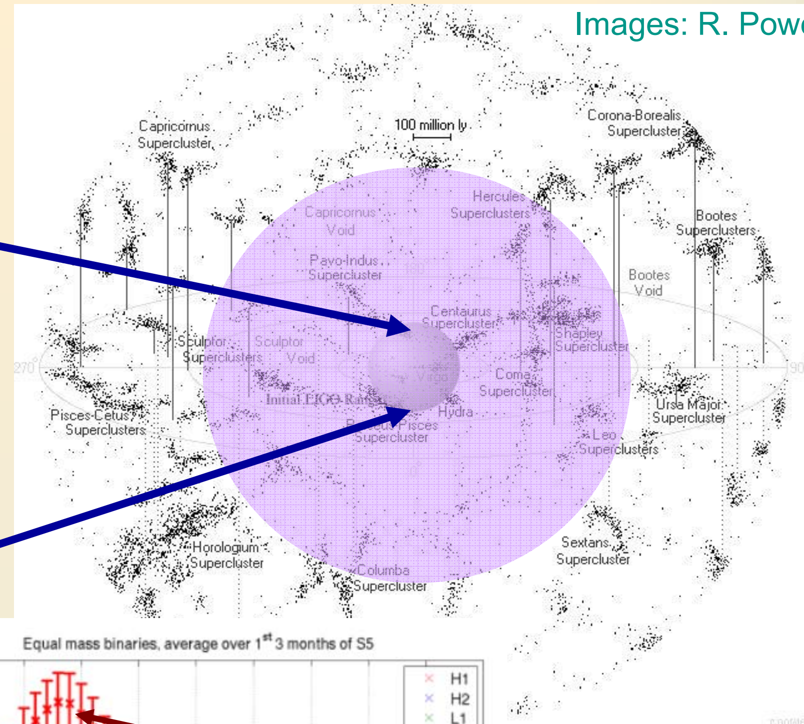
neutron star binaries

S2 Horizon Distance=1.5 Mpc



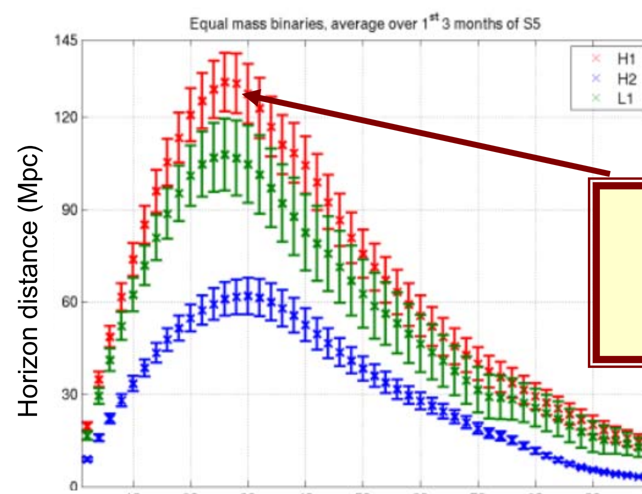
Virgo Cluster

black hole binaries



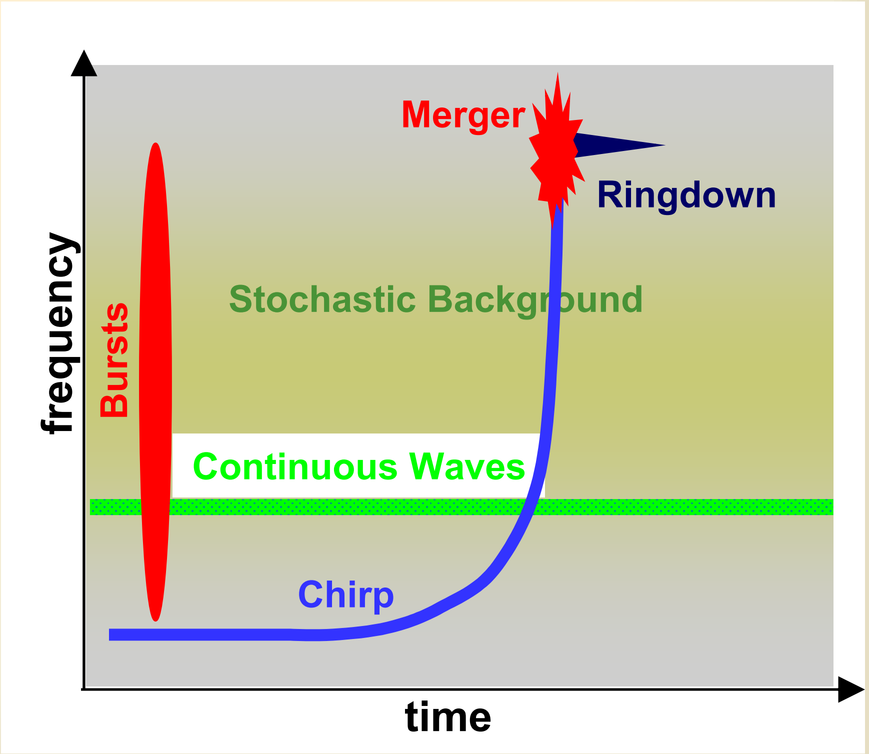
distance of optimally oriented and located 1.4-1.4 $M_\odot$ binary at SNR=8

Hanford-4km (H1): 25 Mpc
Livingston-4km (L1): 21 Mpc
Hanford-2km (H2): 10Mpc



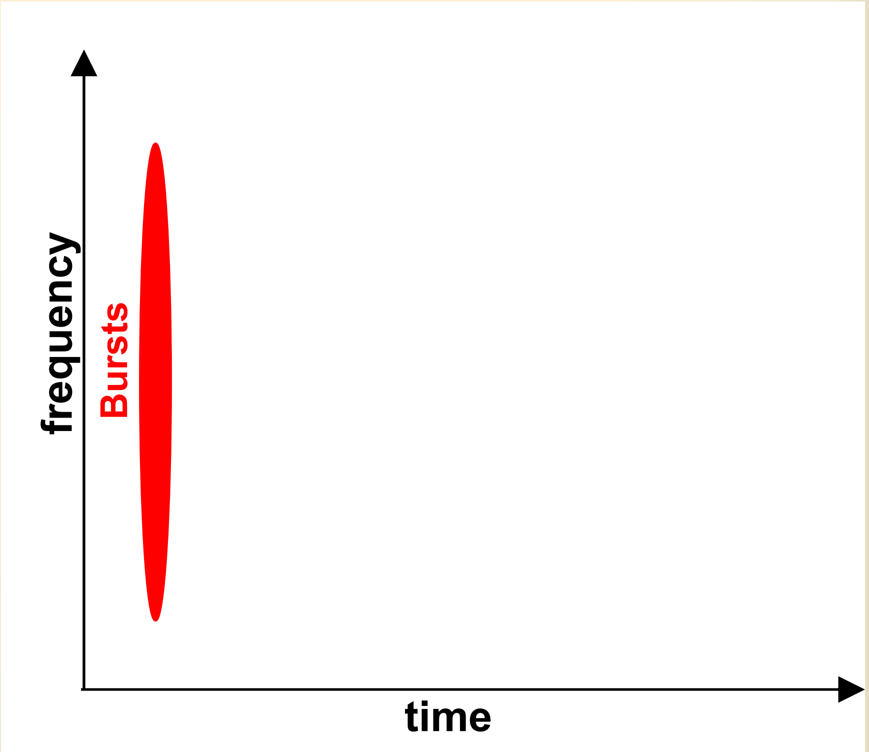
Peak for H1:
130Mpc ~ 25$M_\odot$

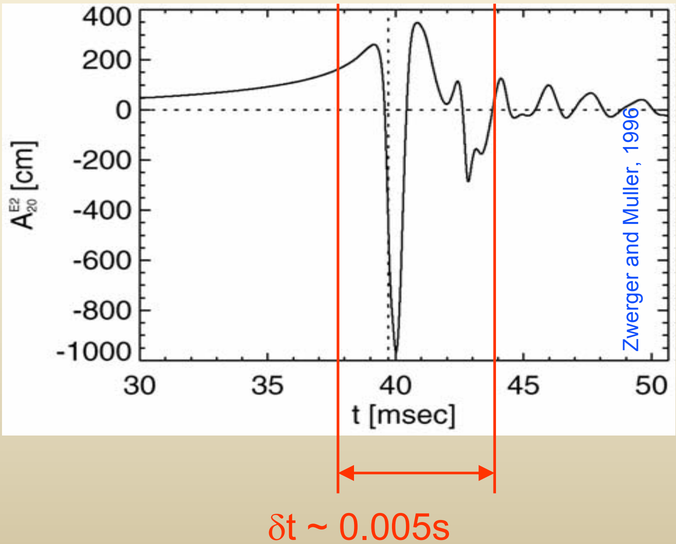
Bursts:
short duration (<1s) GW transients



Bursts:
short duration (<1s) GW transients

Plausible sources:
core-collapse supernovae
Accreting / merging black holes
gamma-ray burst engines
Instabilities in nascent neutron stars
Kinks and cusps in cosmic strings
SURPRISES!

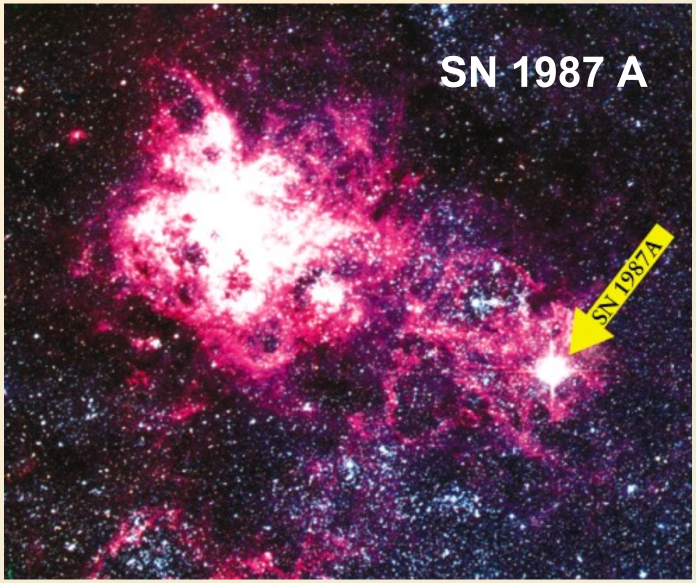




Simulated gravitational wave from core collapse

Bursts:
short duration (<1s) GW transients

Probe interesting new physics
Dynamical gravitational fields, black hole horizons, behavior of matter at supra-nuclear densities



Uncertainty of waveforms complicates the detection ⇒ minimal assumptions, open to the unexpected

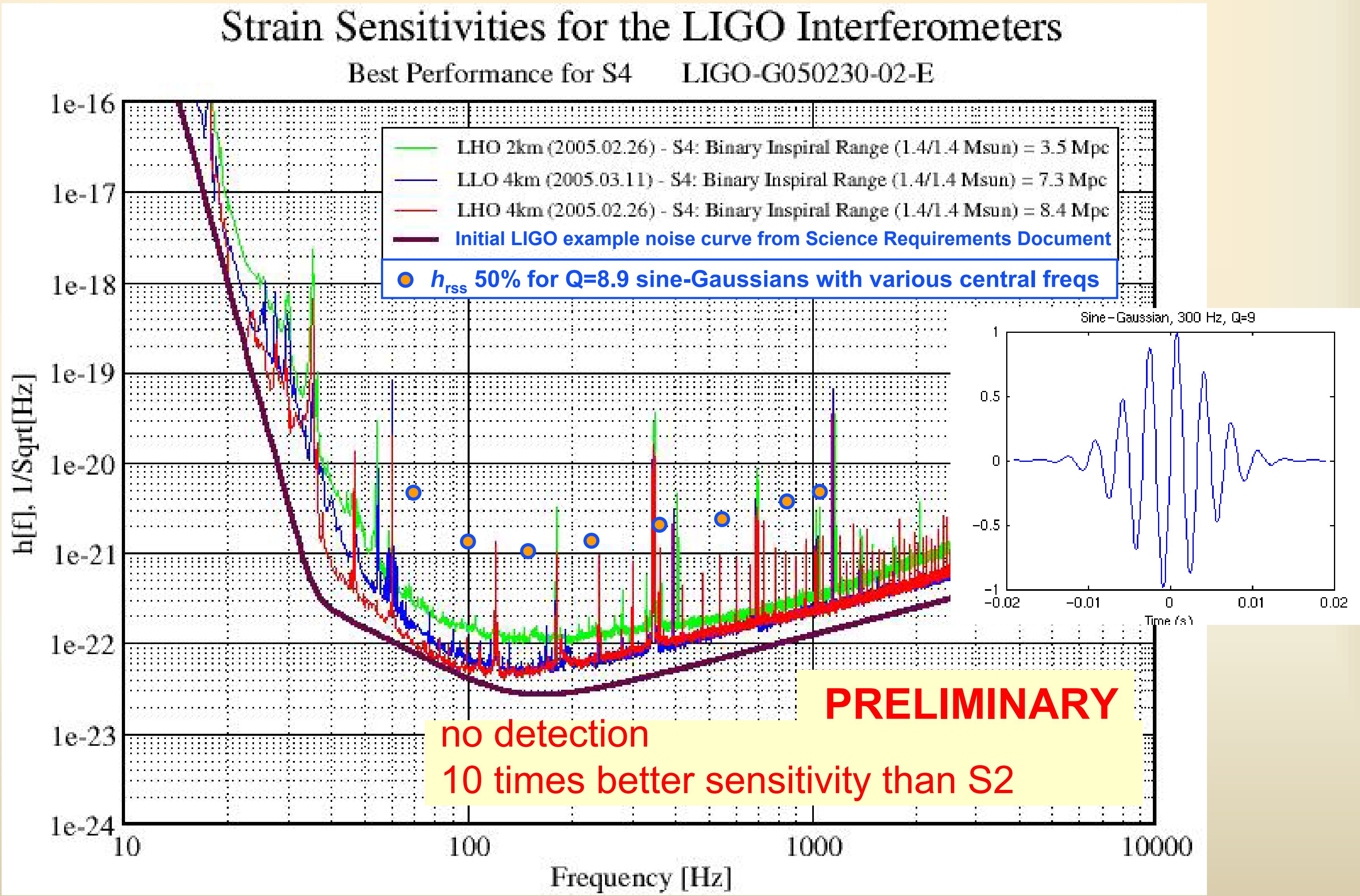
"Eyes-wide-open", all-sky, all times search
excess power indicative of a transient signal; coincidence among detectors.

Targeted matched filtering searches
e.g. to cosmic string cusps or black hole ringdowns

Triggered search
Exploit known direction and time of astronomical events (e.g., GRB), cross correlate pairs of detectors.

GRB030329: PRD 72, 042002, 2005

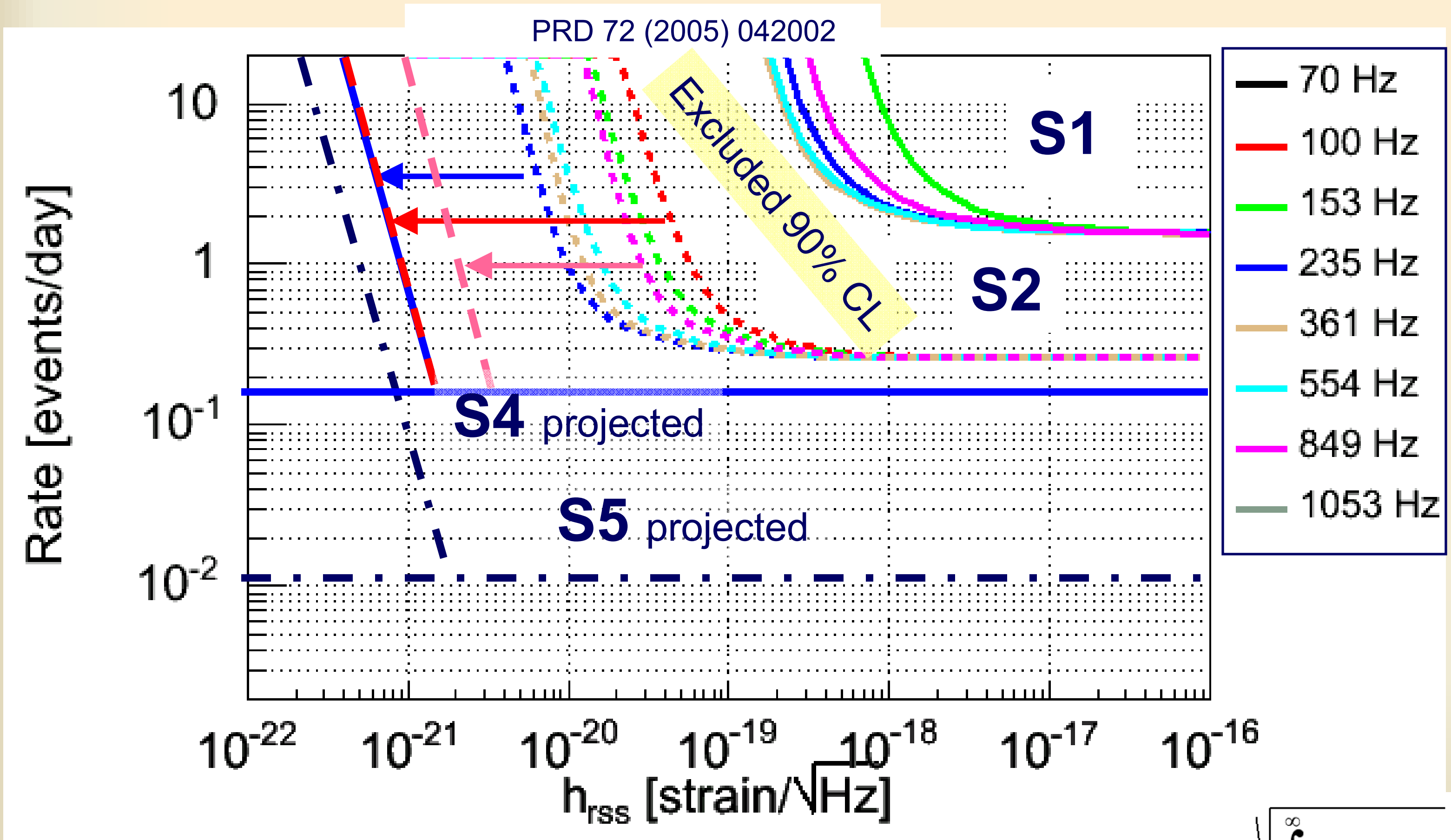
Sensitivity in Science Run 4 (S4)



All-Sky Burst Search

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

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



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

S5 sensitivity: minimum detectable in-band GW energy

$E_{GW} > 1\ M_\odot$ @ 75Mpc

$E_{GW} > 0.05\ M_\odot$ @ 15Mpc (Virgo cluster)

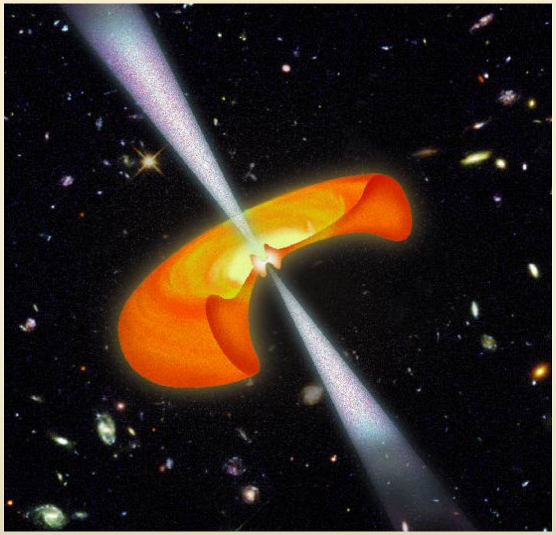
Triggered Searches

Follow-up on interesting astronomical events.

- Know time of event
  - » Can concentrate efforts to probe sensitively small amount of data around the event time.
- Often know sky position
  - » Can account for time delay, antenna response of instrument in consistency tests
- Sensitivity improvement:
  - » Often a factor of ~2 in amplitude.

GRB: bright bursts of gamma rays

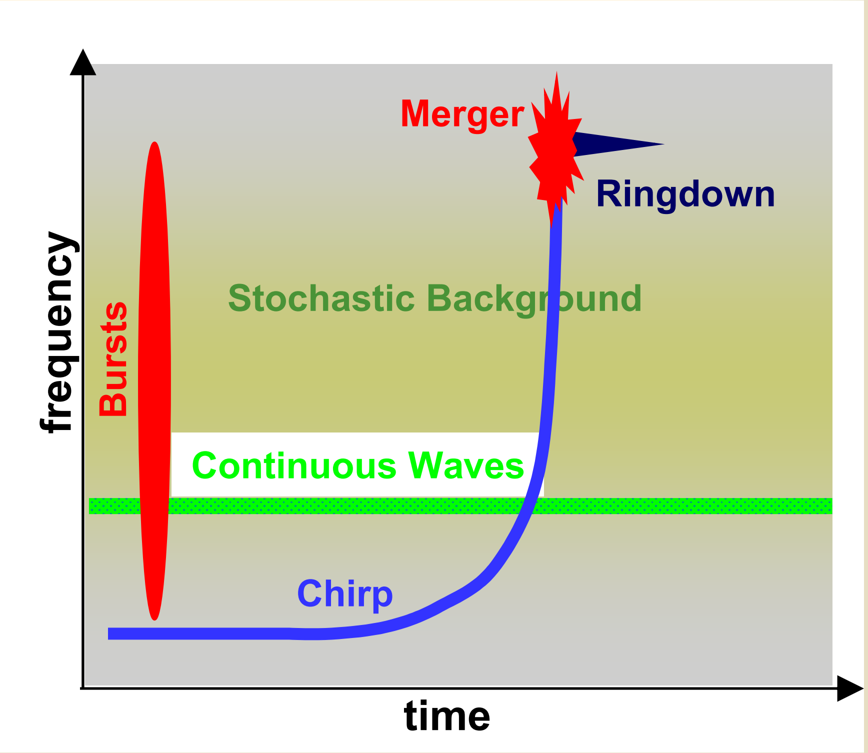
- » occur at cosmological distances
- » seen at rate ~1/day.



- Long duration > 2s
  - » associated with “hypernovae” (core collapse to black hole)
  - » Hjorth et al, Nature **423** 847 (2003).
- Short duration < 2 s
  - » Binary NS-NS or NS-BH coalescence?
  - » Gehrels et al., Nature **437**, 851–854 (2005).

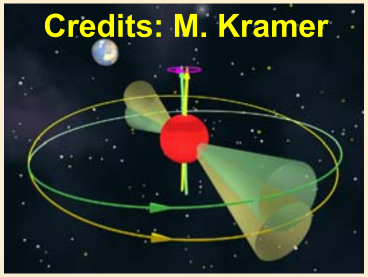
Cross correlate data between pairs of detectors around time of triggers from satellites

Continuous Waves: Spinning Neutron Stars

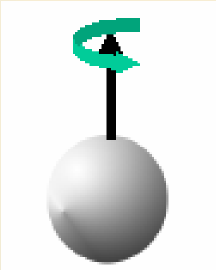


Continuous Waves: Spinning Neutron Stars

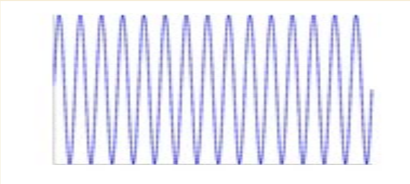
Accreting NS

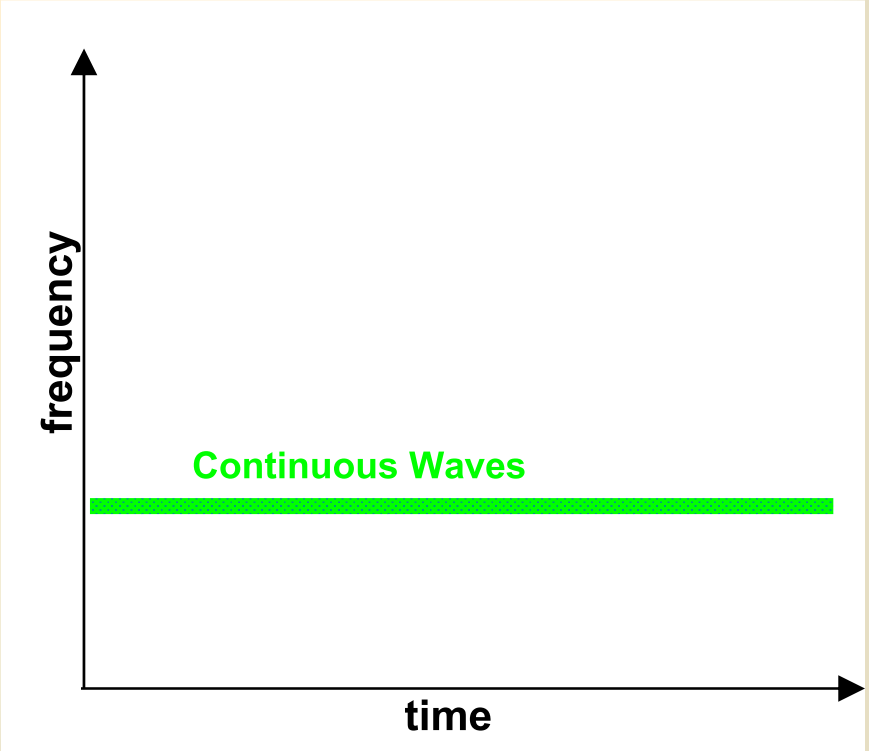


Wobbling NS



"bumpy" NS





» Pulsars are known to exist. They emit GW if they have asymmetries
» Isolated neutron stars with mountains (mm high!) or wobbles in the spin
» Low-mass x-ray binaries
» Probe internal structure and populations

Spin-down limits for known pulsars are set assuming ALL angular momentum is radiated as GW

Continuous Waves Searches

Search for a sine wave, with amplitude and frequency modulated by Earth's motion, and possibly spinning down: easy, but computationally expensive

Parameters: position (may be known), inclination angle, polarization, amplitude, frequency (may be known), frequency derivatives (may be known), initial phase.

- Known pulsars
  - Coherent, time-domain
  - fine-tuned over a narrow parameter space
  - Use catalog of known pulsars and ephemeris
- All-sky incoherent
  - Fast, robust wide parameter search
  - Piece together *incoherently* result from shorter segments
- Wide-area
  - coherent matched filtering in frequency domain
  - All-sky, wide frequency range: computationally expensive
  - Hierarchical search under development

Results from S2:

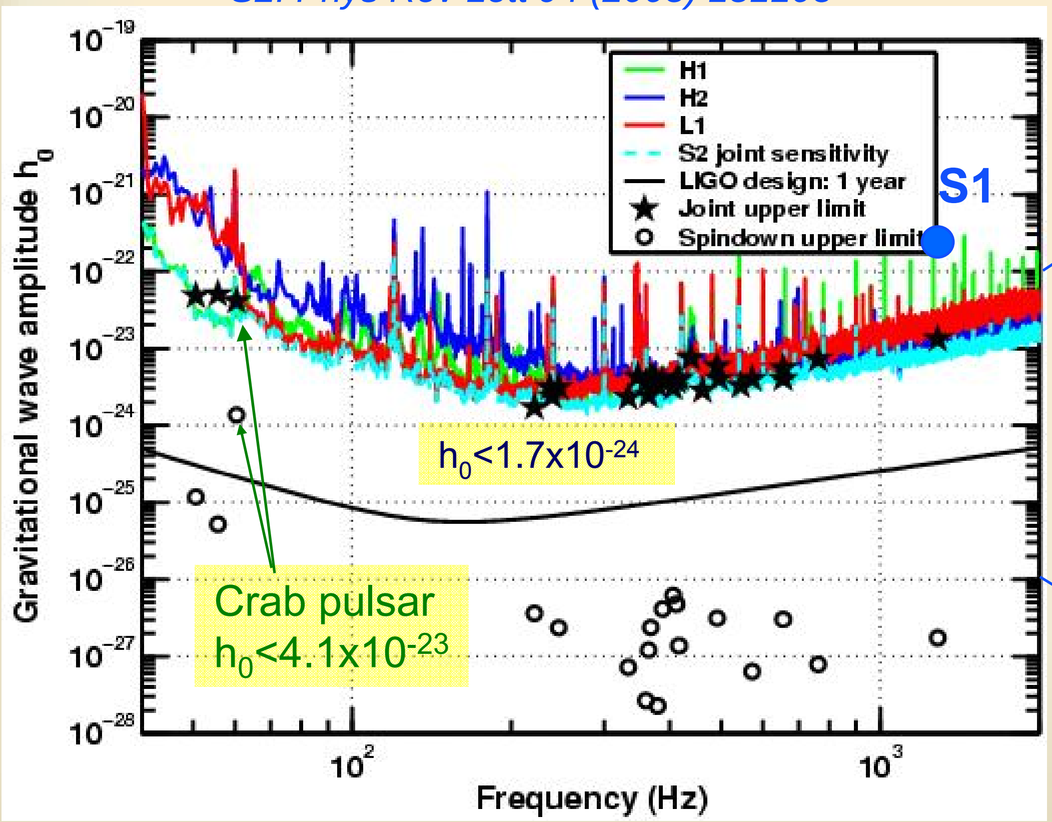
- No GW signal.
- First direct upper limit for 26 of 28 sources studied (95%CL)
- Equatorial ellipticity constraints as low as: $\varepsilon < 10^{-5}$

$$\epsilon = (I_{xx} - I_{yy})/I_{zz}$$

Known pulsars

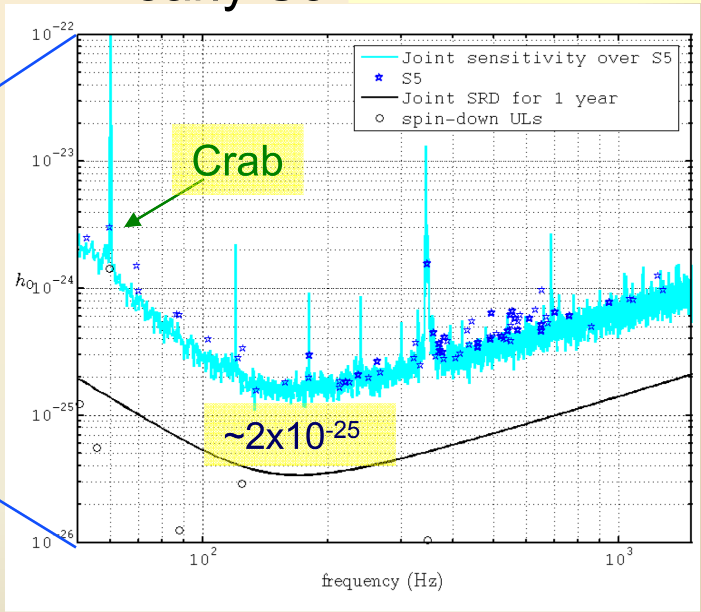
ephemeris is known from EM observations

S2: Phys Rev Lett 94 (2005) 181103



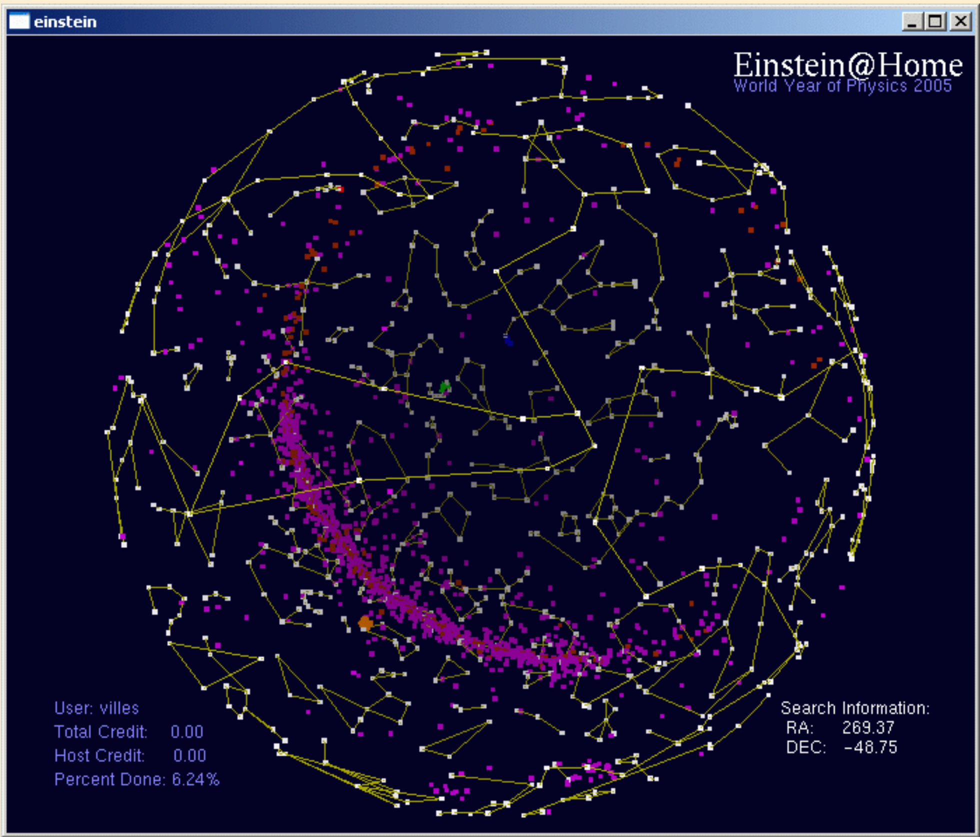
early S5

PRELIMINARY



Lowest ellipticity upper limit:
PSR J2124-3358
(f_{gw} = 405.6Hz, d = 0.25kpc)
ellipticity = $4.0x10^{-7}$

The Einstein@home Project



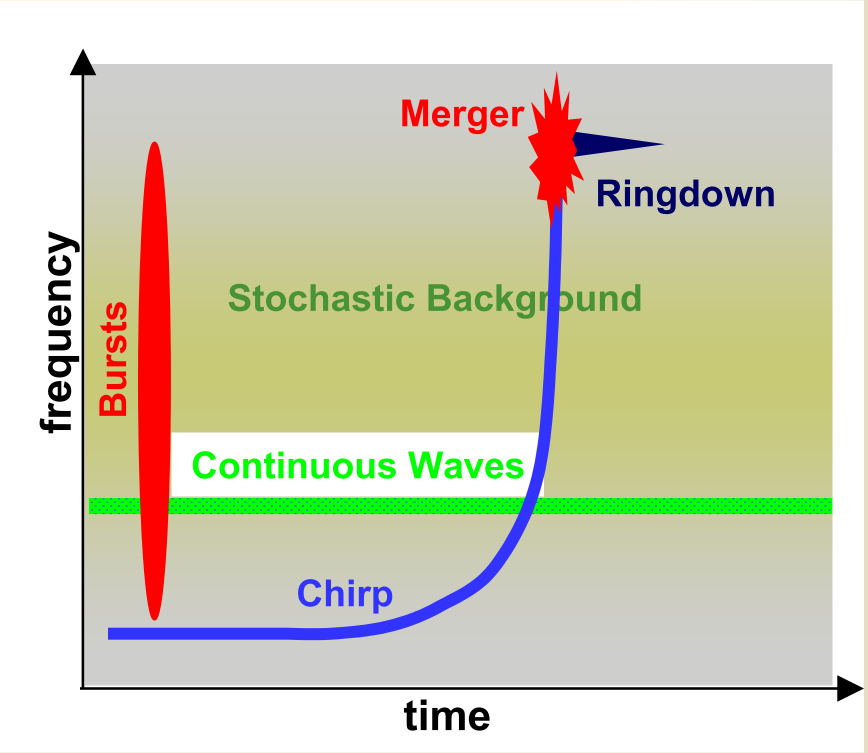
To sign up:
http://www.physics2005.org

Users and Computers

As of Thur Nov 9 15:14 UTC

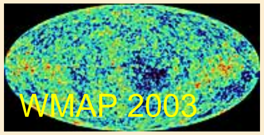
USERS	Approximate #
in database	229,674
with credit	145,882
registered in past 24 hours	197
HOST COMPUTERS	**Approximate #**
in database	552,155
registered in past 24 hours	939
with credit	300,421
active in past 7 days	76,857
floating point speed[1)]	81.6 TFLOPS

Stochastic Background: Murmurs from the Big Bang



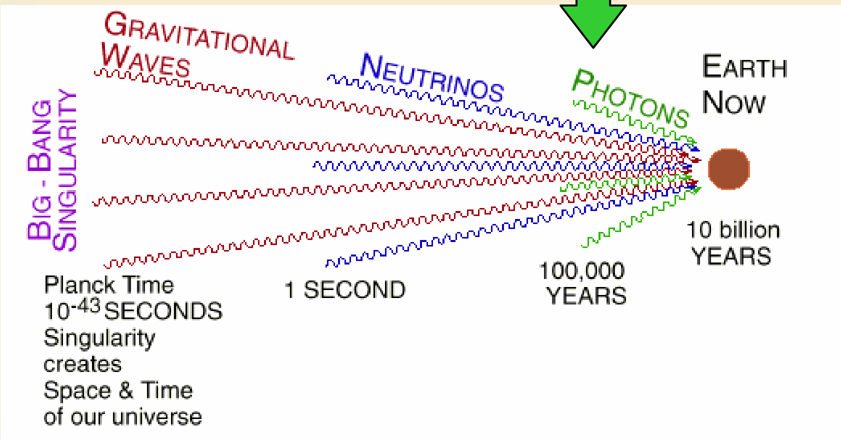
Stochastic Background: Murmurs from the Big Bang

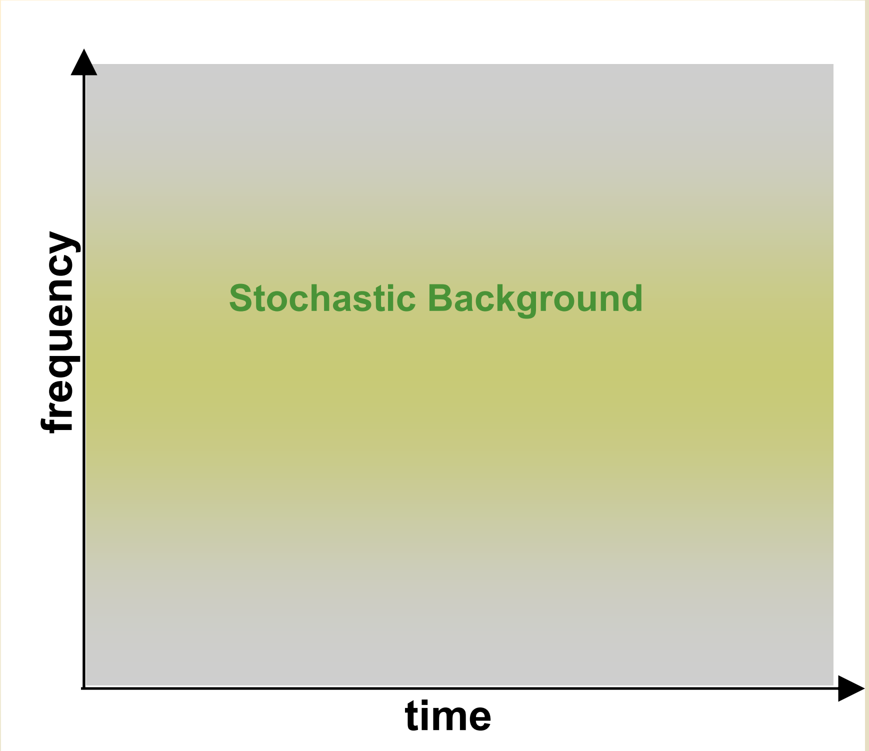
Cosmological background:
Big Bang



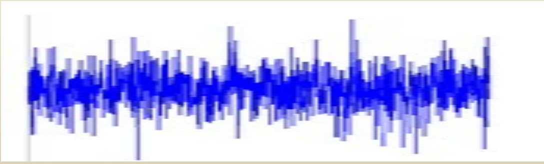
cosmic GW background (10^{-22}s)

CMB (10^{+12}s)





Astrophysical background:
Unresolved individual sources



e.g.: black hole mergers, binary neutron star inspirals, supernovae

Stochastic Background

Random radiation described by its spectrum (assumed isotropic, unpolarized and stationary)

Its strength is expressed as the fractional contribution to critical energy density of the Universe

$$\int_0^\infty (1/f)\,\Omega_{GW}(f)\,df = \frac{\rho_{GW}}{\rho_{critical}}$$

Assume: $\Omega_{GW}(f) =$ constant Ω_0

Also test $\Omega_{GW}(f) = \Omega_\alpha (f/100\text{Hz})^\alpha$

Energy density

$$\rho_{GW} = \frac{c^2}{32\pi G} < \dot{h}_{ab}\,\dot{h}^{ab} >$$

Log-frequency spectrum

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

Strain power spectrum associated to Ω_{gw}

$$S(f) = \frac{3H_0^2}{10\pi^2}\,\frac{\Omega_{GW}(f)}{f^3}$$

Search Strategy

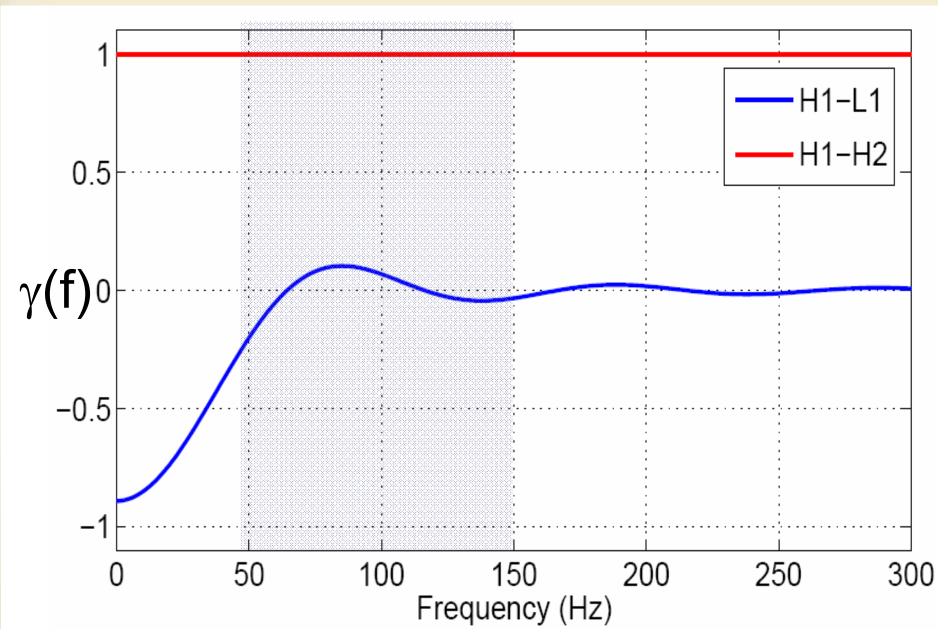
cross-correlate output of two GW detectors x_1 and x_2

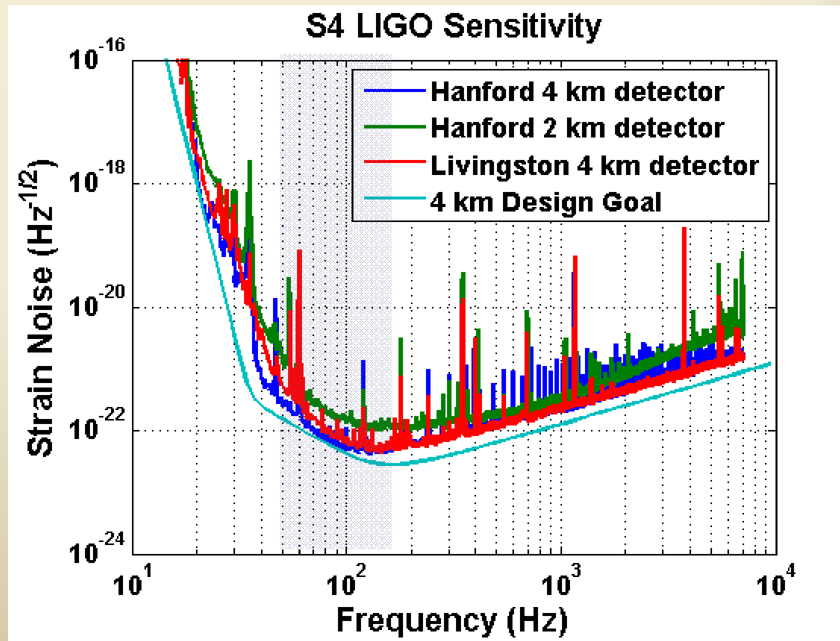
Optimal statistics
For all-sky search :

$$Y = \int_{-\infty}^{\infty} df\, \tilde{x}_1^*(f) \frac{\gamma(f)\,\Omega_{GW}(f)}{N f^3\, P_1(f)\, P_2(f)} \tilde{x}_2(f)$$

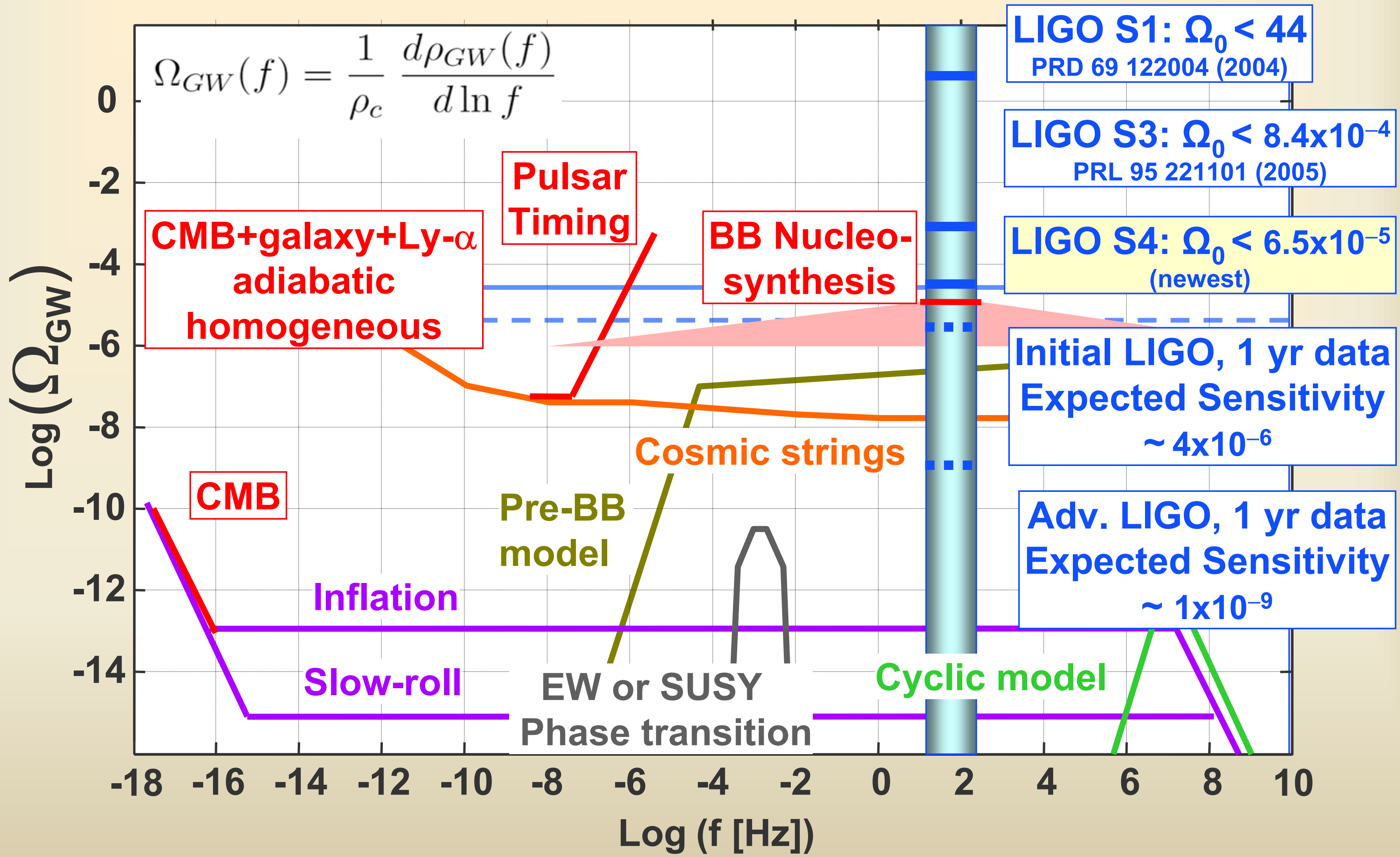
"Overlap Reduction Function"
(determined by network geometry)

Detector noise spectra



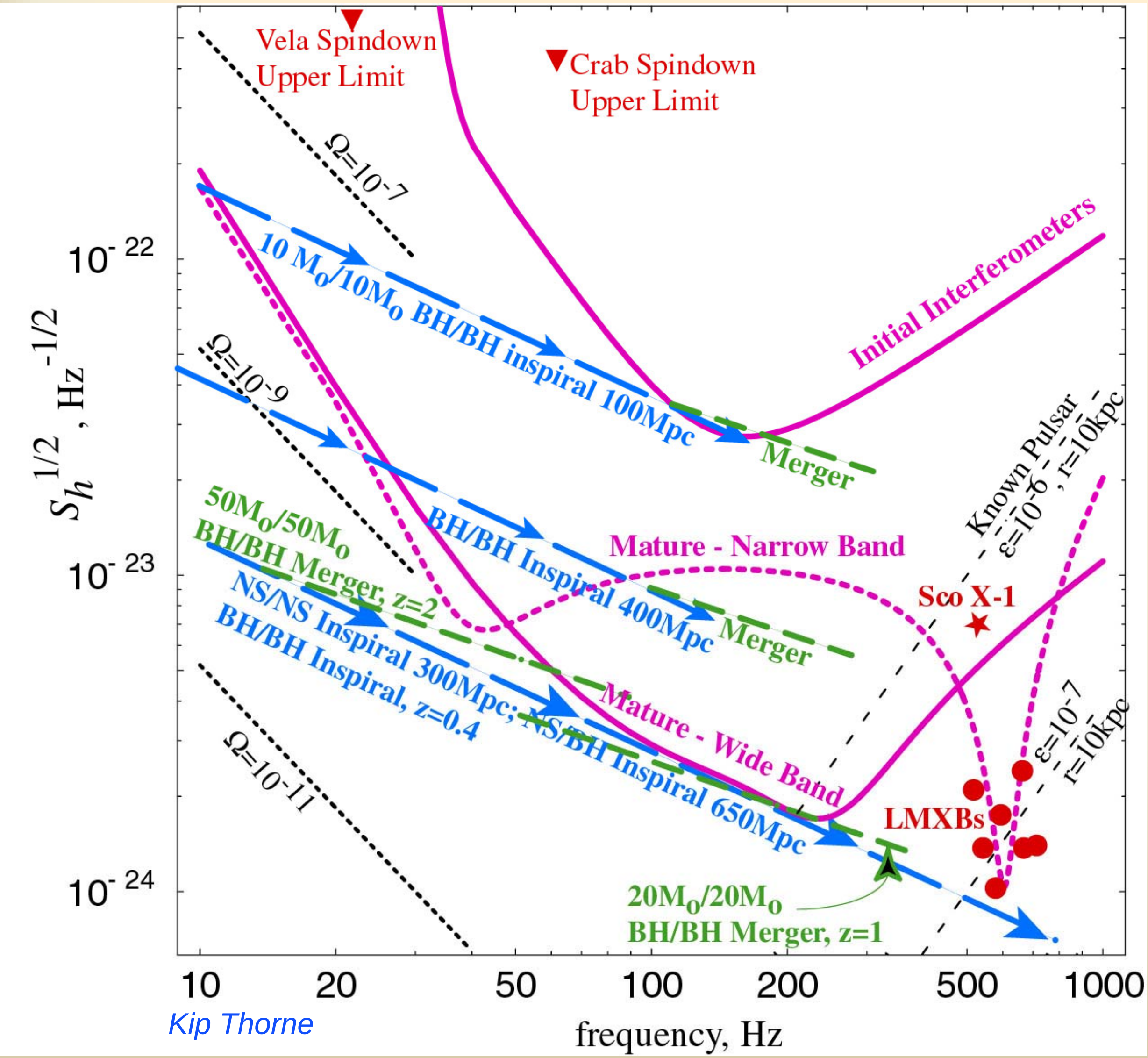


Landscape



$\Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d\ln f}$
LIGO S1: $\Omega_0 < 44$
PRD 69 122004 (2004)
LIGO S3: $\Omega_0 < 8.4\text{x}10^{-4}$
PRL 95 221101 (2005)
LIGO S4: $\Omega_0 < 6.5\text{x}10^{-5}$
(newest)
Initial LIGO, 1 yr data
Expected Sensitivity
~ $4\text{x}10^{-6}$
Adv. LIGO, 1 yr data
Expected Sensitivity
~ $1\text{x}10^{-9}$
Pulsar Timing
CMB+galaxy+Ly-α adiabatic homogeneous
BB Nucleo-synthesis
Cosmic strings
CMB
Pre-BB model
Inflation
Slow-roll
EW or SUSY Phase transition
Cyclic model
$\text{Log}(\Omega_{GW})$
Log (f [Hz])
0
-2
-4
-6
-8
-10
-12
-14
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10

From Initial to Advanced LIGO



Binary neutron stars:

From ~20 Mpc to ~350 Mpc

From 1/30y(<1/3y) to 1/2d(<5/d)

Binary black holes:

From $10M_\odot$ to $50M_\odot$

From ~100Mpc to z=2

Known pulsars:

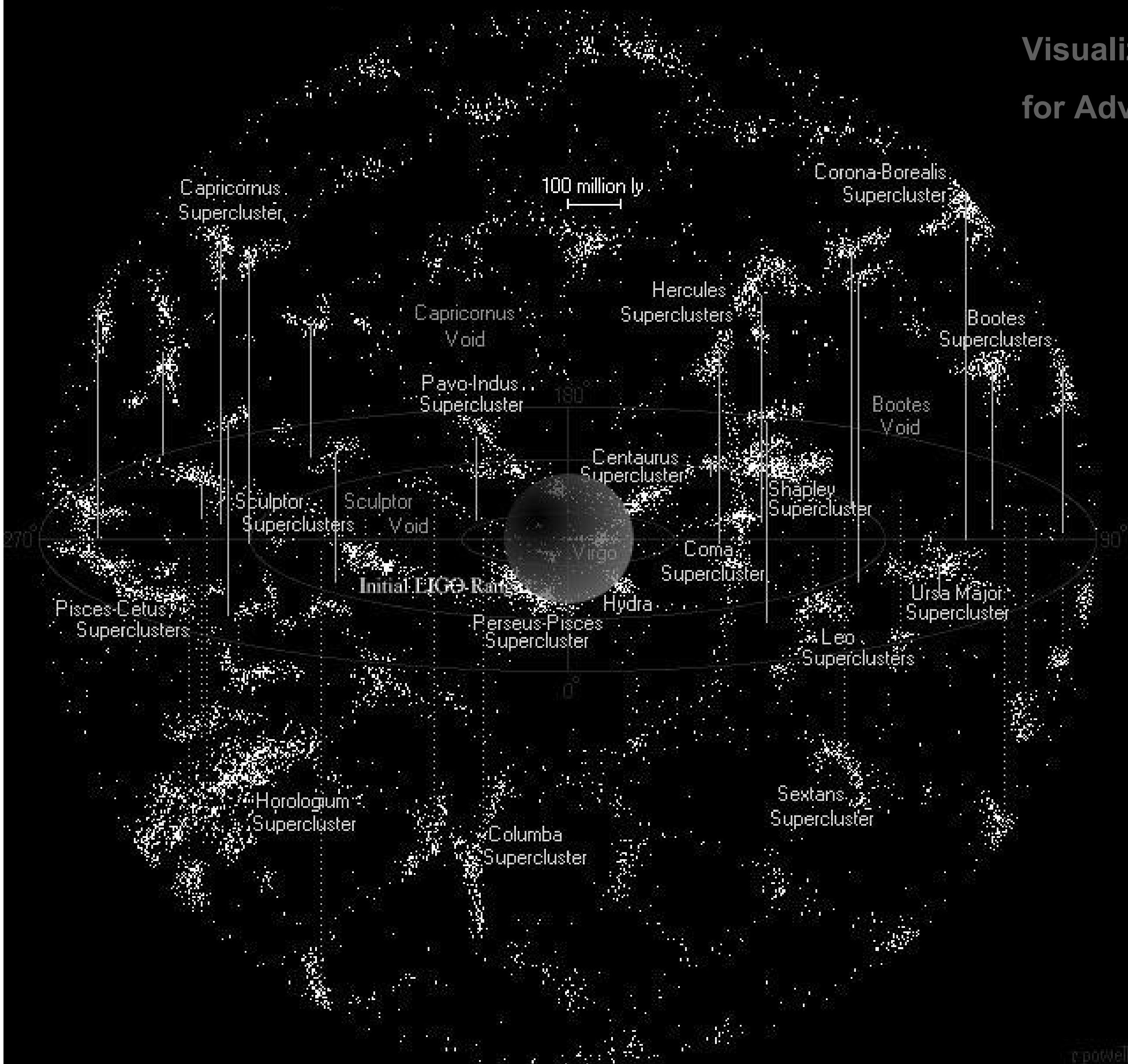
From $\varepsilon = 3x10^{-6}$ to $2x10^{-8}$

Stochastic background:

From Ω_{GW} ~$3x10^{-6}$ to ~$3x10^{-9}$

See Brian Lantz's talk
In this session

Range Estimates for Binary Coalescence Sources



Visualized reach estimate

for Advanced LIGO target sensitivity

Images: R. Powell, The Atlas of The Universe, http://www.anzwers.org/free/universe/index.html