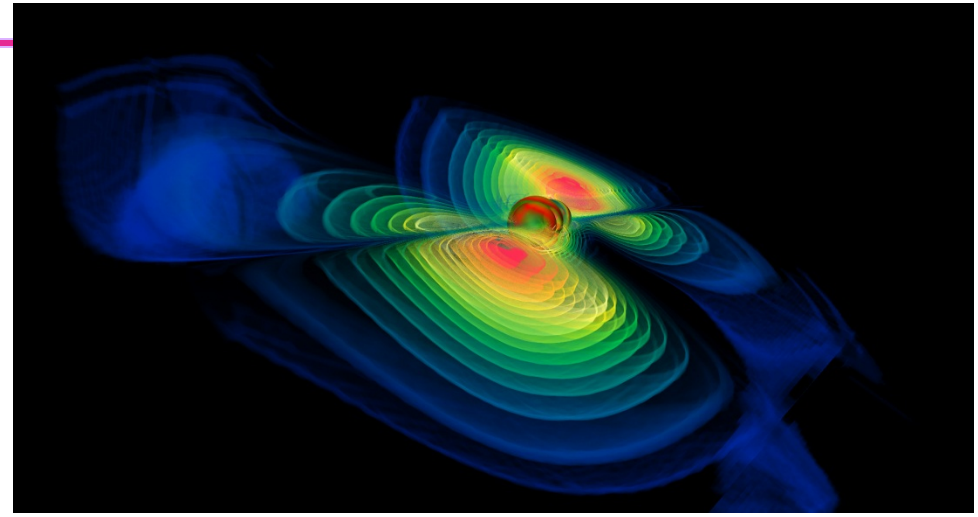
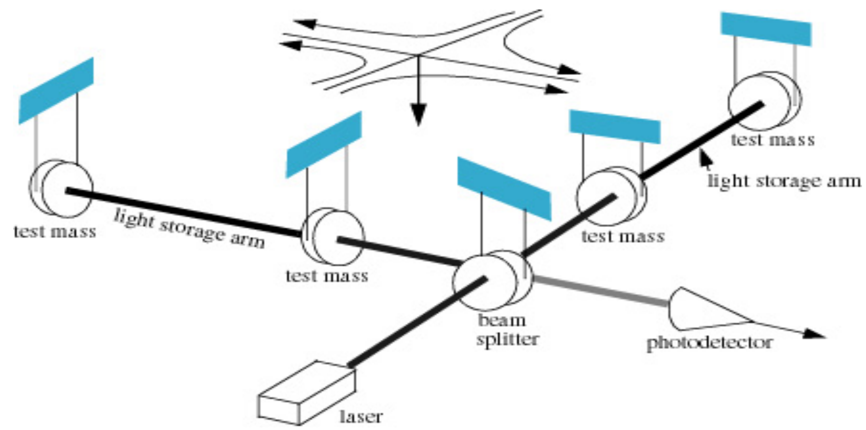
Computational challenges in gravitational-wave data analysis

- Lightning introduction to gravitational waves, the detectors, and the astrophysical sources.
- Techniques for detection and study of Compact Binary Coalescence (CBC)
- Template banks
- Waveforms
- Challenges ahead.



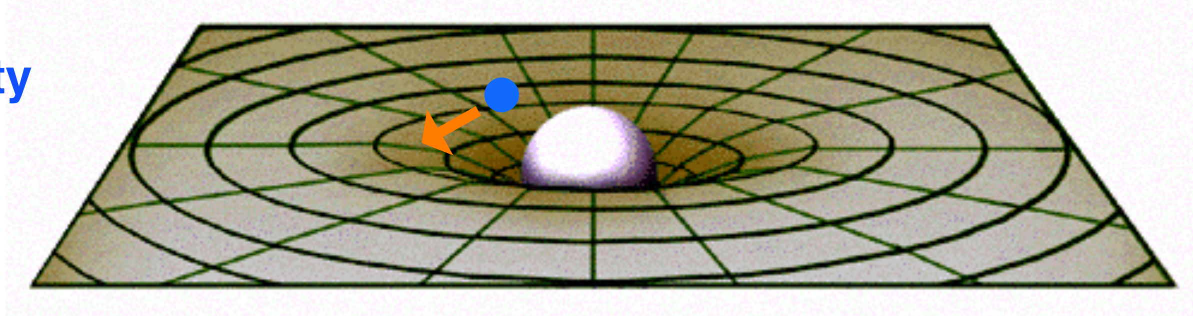
"Colliding Black Holes"
National Center for Supercomputing Applications (NCSA)



Alan Weinstein, Caltech
LIGO-G1300617
ROM in GR Workshop, Caltech, 6-7 June 2013

Gravitational Waves

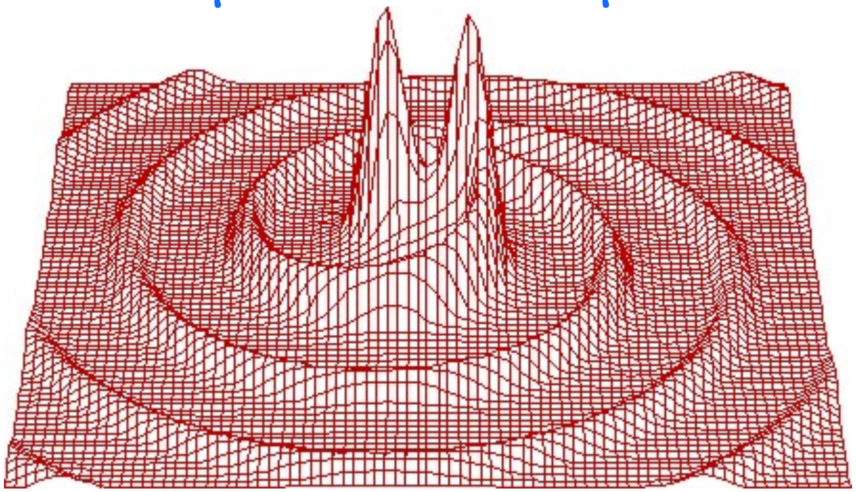
Static gravitational fields are described in General Relativity as a curvature or warpage of space-time, changing the distance between space-time events.



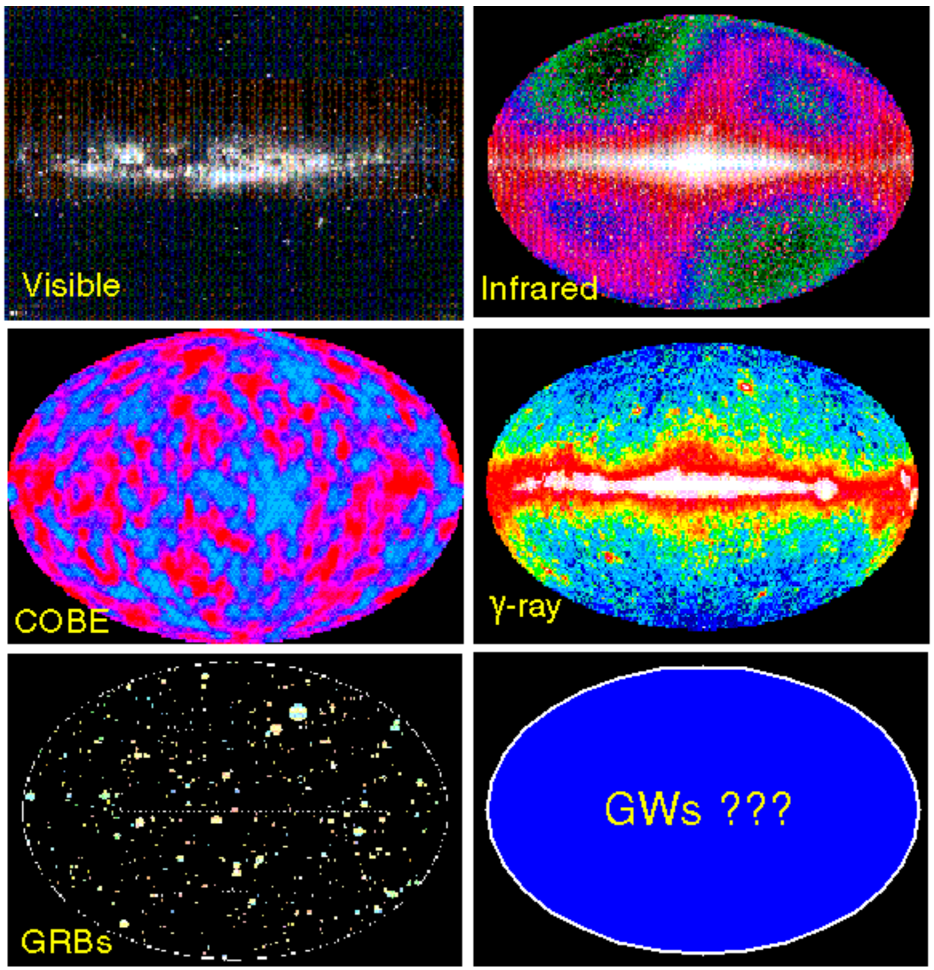
Shortest straight-line path of a nearby test-mass is a ~Keplerian orbit.

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

If the source is moving (at speeds close to c), *eg,* because it's orbiting a companion, the "news" of the changing gravitational field propagates outward as gravitational radiation – a wave of spacetime curvature



A NEW WINDOW ON THE UNIVERSE



The history of Astronomy:
new bands of the EM spectrum opened → major discoveries!

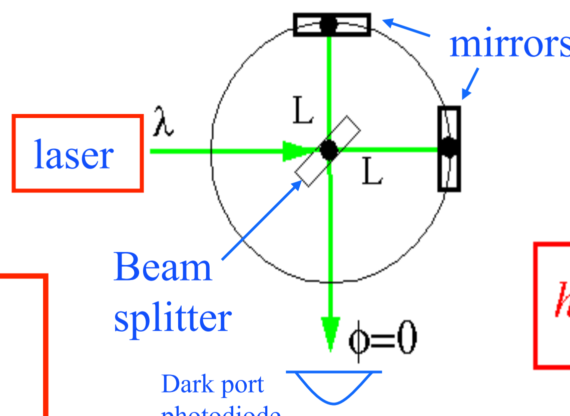
GWs aren't just a new band, they're a new spectrum, with very different and complementary properties to EM waves.

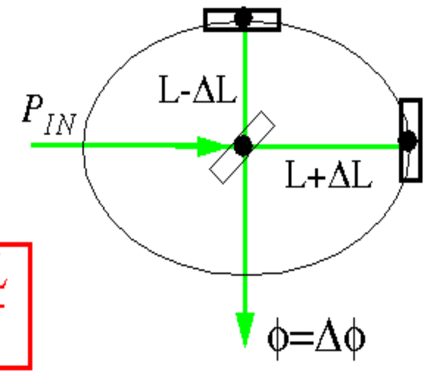
- Vibrations *of* space-time, not *in* space-time
- Emitted by coherent motion of huge masses moving at near light-speed; not vibrations of electrons in atoms
- Can't be absorbed, scattered, or shielded.

GW astronomy is a totally new, unique window on the universe

Interferometric detection of GWs

GW acts on freely falling masses:



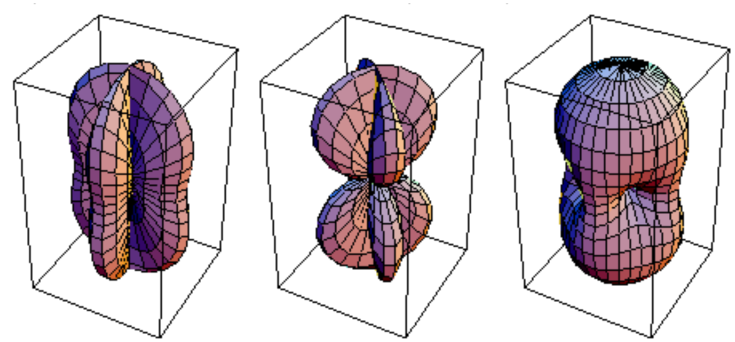


$$h = \frac{\Delta L}{L}$$

$$P_{out} = P_{in} \sin^2(2k\Delta L)$$

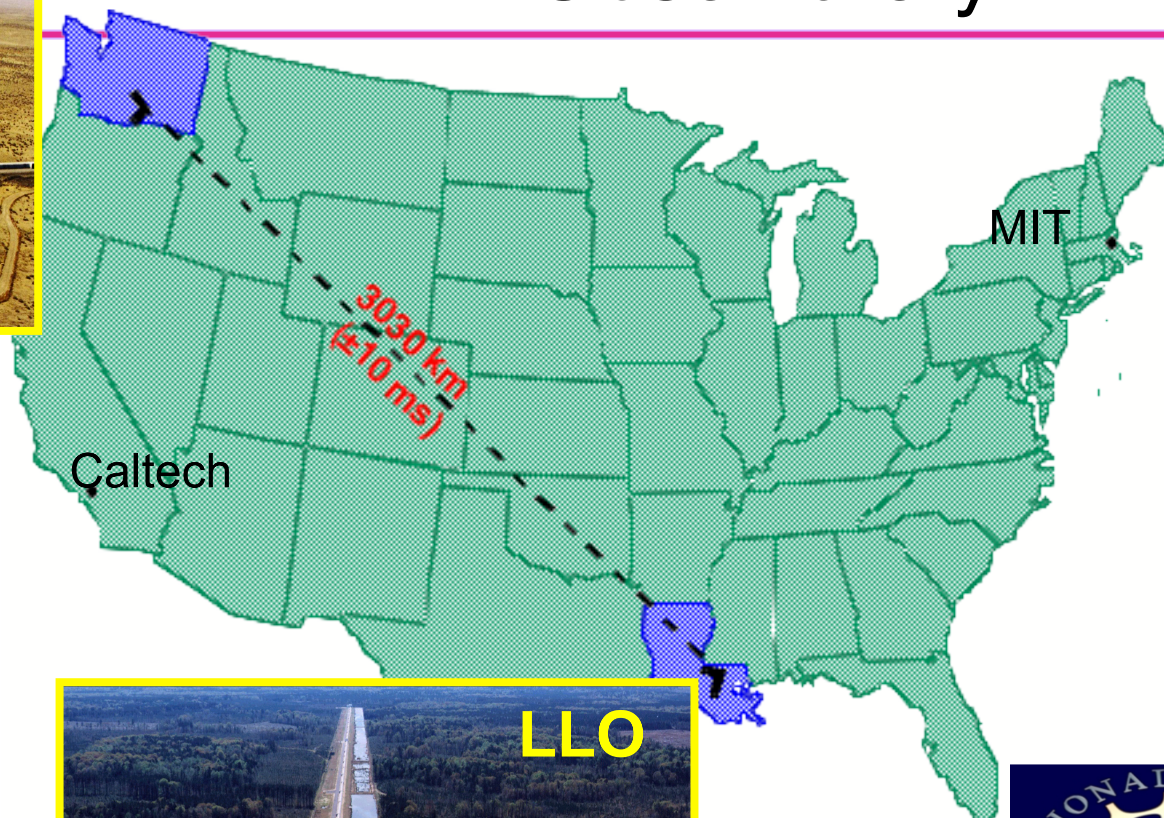
For fixed ability to measure ΔL, make L as big as possible!

Antenna pattern:
(not very directional!)

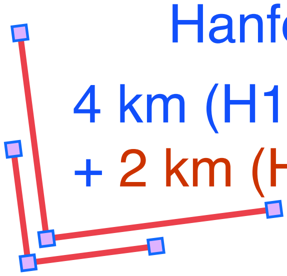


+ polarization × polarization unpolarized

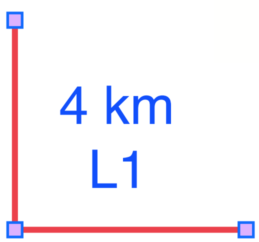
LIGO: Laser Interferometer Gravitational-wave Observatory



Hanford, WA

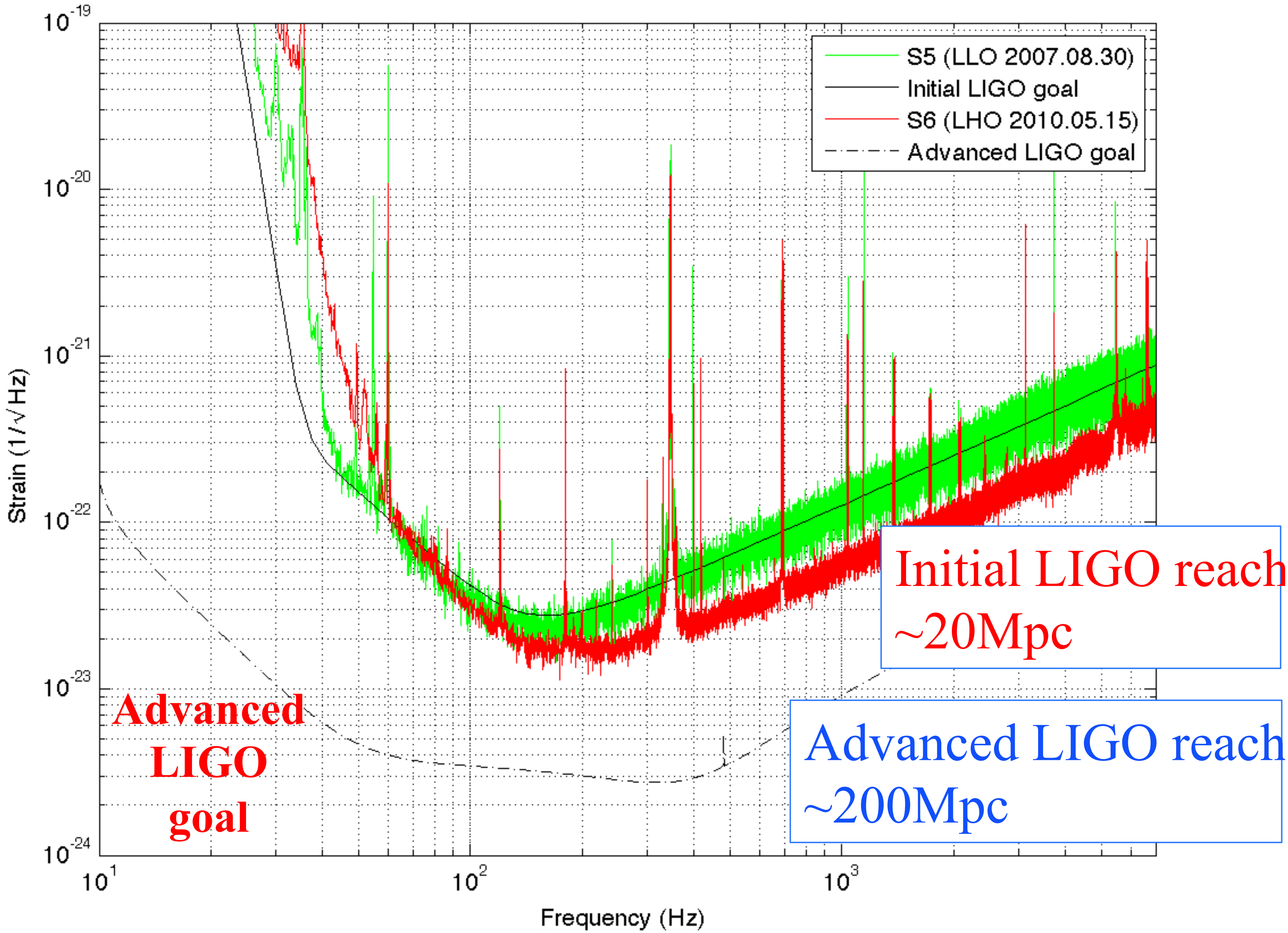


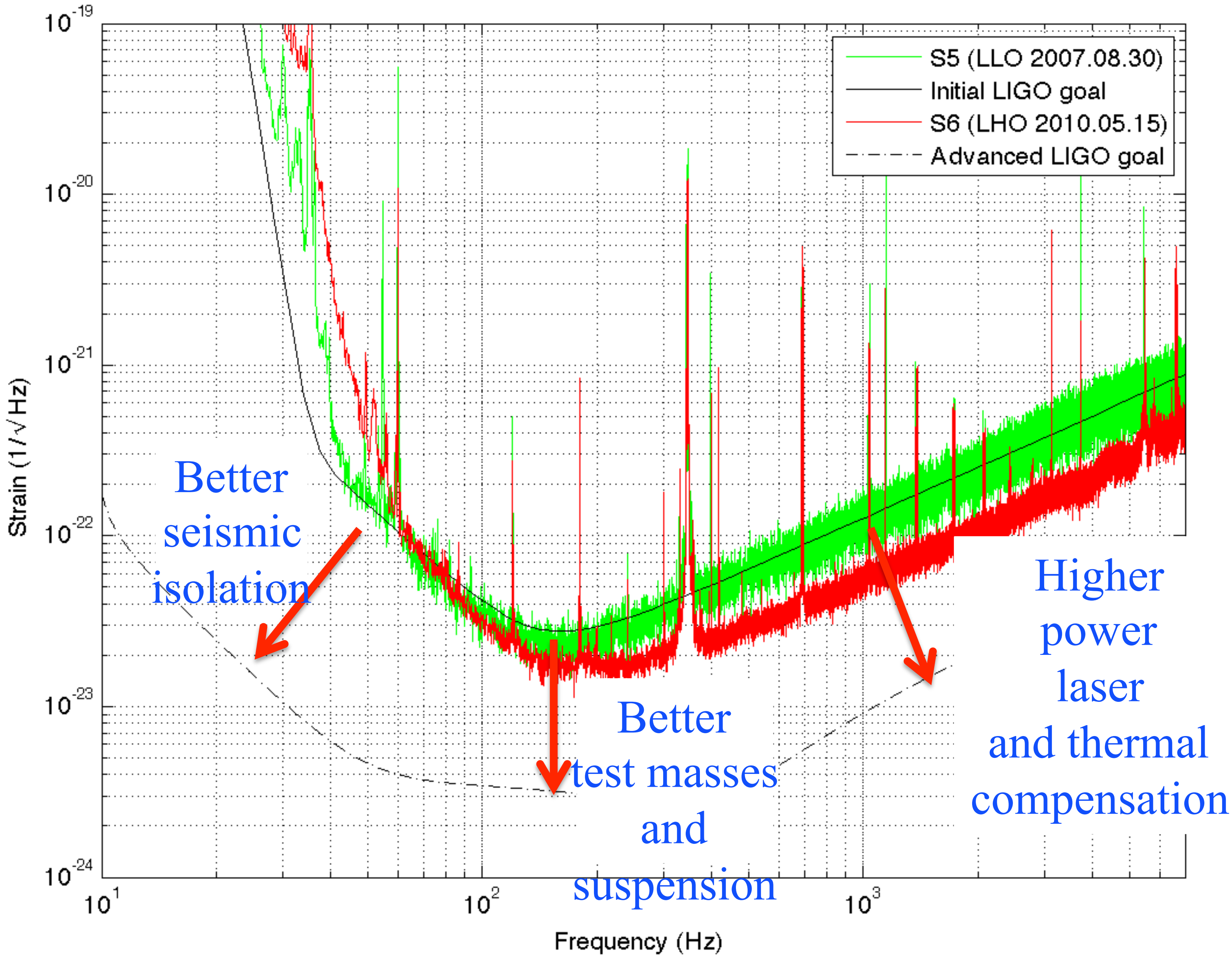
4 km (H1)
+ 2 km (H2), c.2010



4 km
L1

Livingston, LA


S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
Frequency (Hz)
Initial LIGO reach ~20Mpc
Advanced LIGO reach ~200Mpc
Advanced LIGO goal



S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Strain (1/√Hz)
Frequency (Hz)
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
Better seismic isolation
Better test masses and suspension
Higher power laser and thermal compensation

Advanced LIGO schedule

now

2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015

S5 data run

e-LIGO installation and commissioning

S6 data run

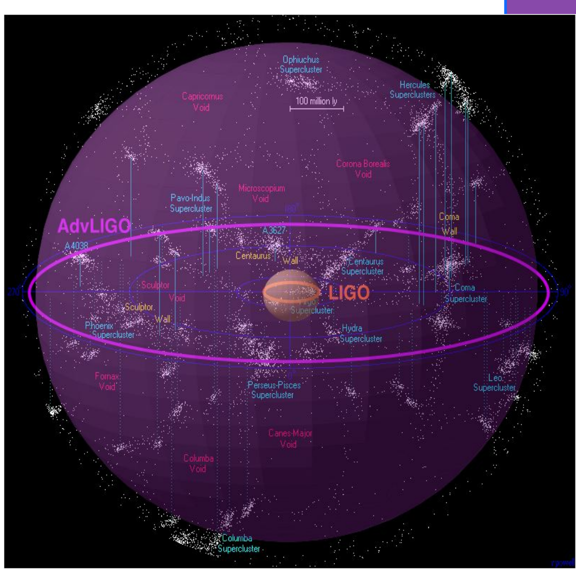
Dark period

S6 data analysis & preparations for Advanced LIGO commissioning and open data

Advanced LIGO Project

Adv LIGO Installation begins

Commissioning & initial data With Advanced LIGO

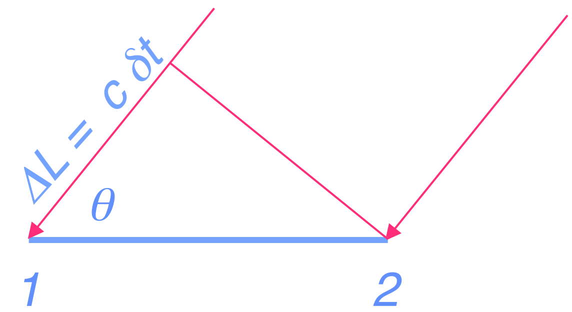


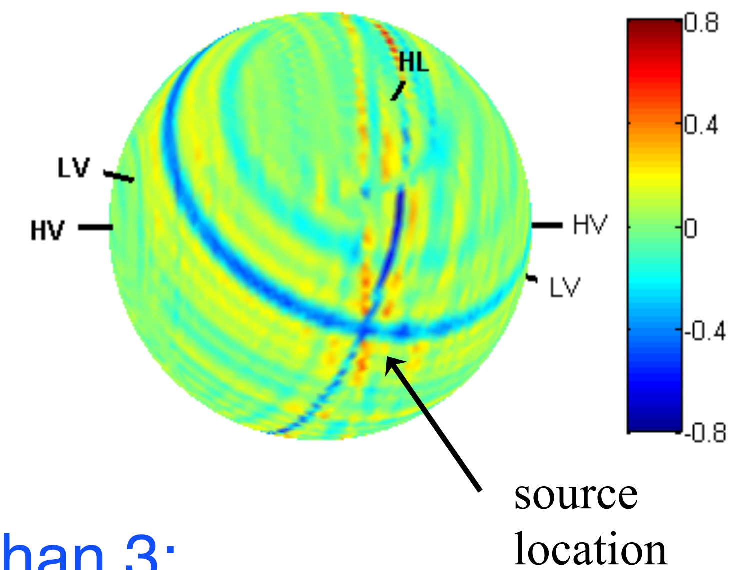
Improve amplitude sensitivity by a factor of 10x, and…

⇒ Number of sources goes up 1000x!

Advanced GW Networks

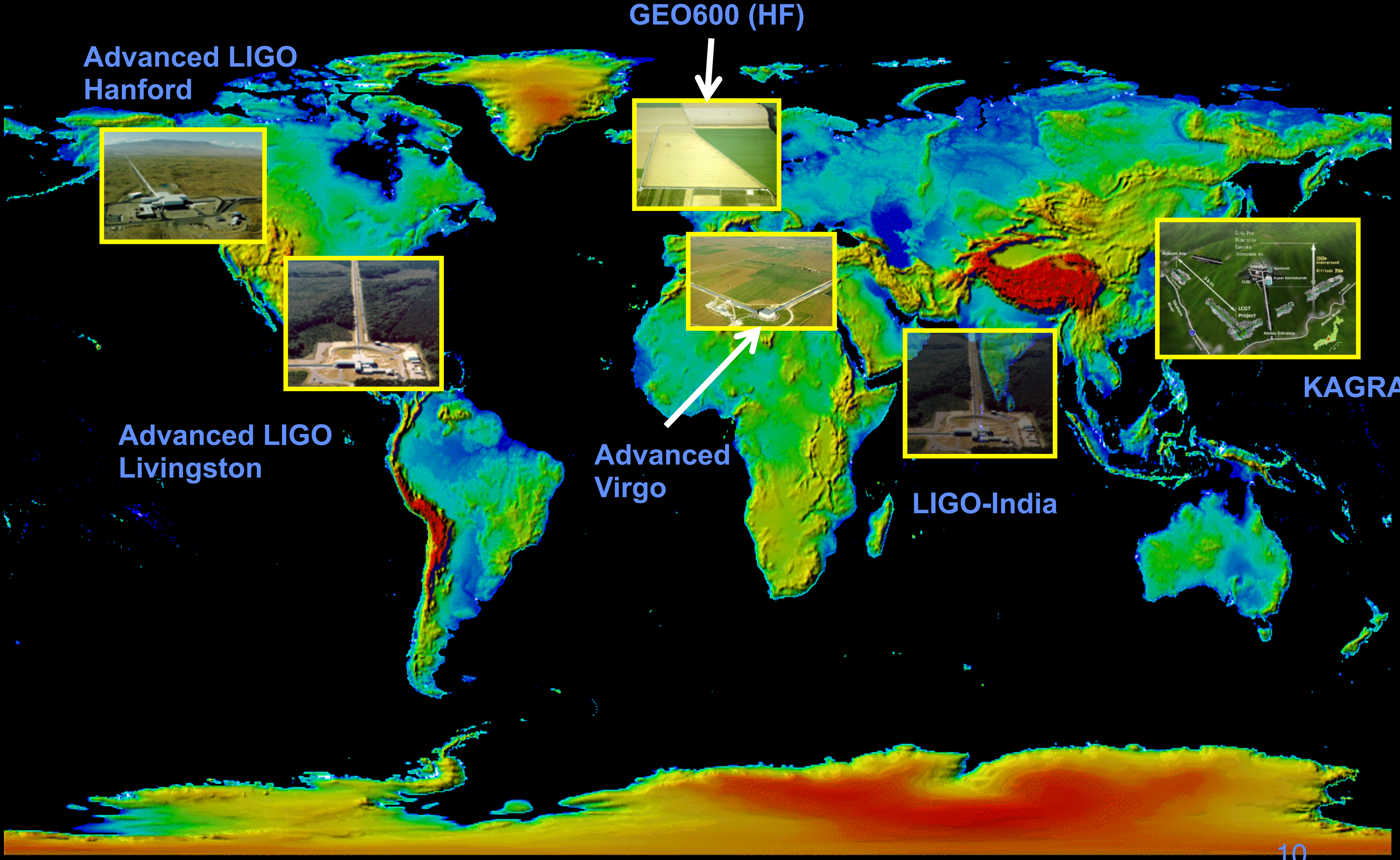
- Gravitational-wave astronomy is *greatly* enhanced by having a multiplicity of interferometers distributed over the globe.
  - GW interferometry, ‘Aperture synthesis’
- Advantages include:
  - Source localization *in near real time*
  - Enhanced network sky coverage
  - Maximum time coverage – a fraction of the detectors are‘always listening’
  - Detection confidence - coincidence
  - Source parameter estimation
  - Polarization resolution





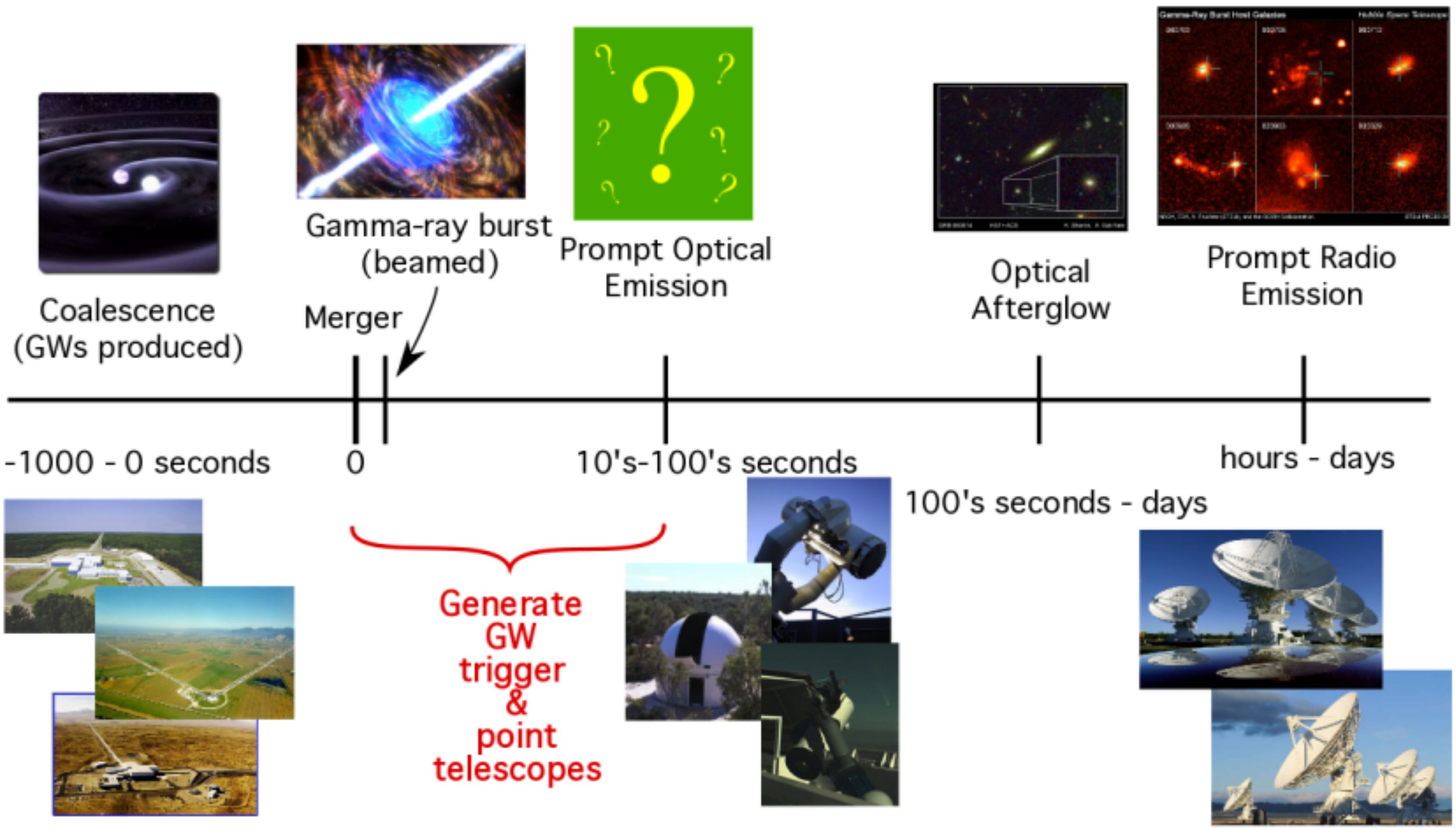
4 properly located detectors is better than 3;
5 is even better than 4

The Advanced GW Detector Network

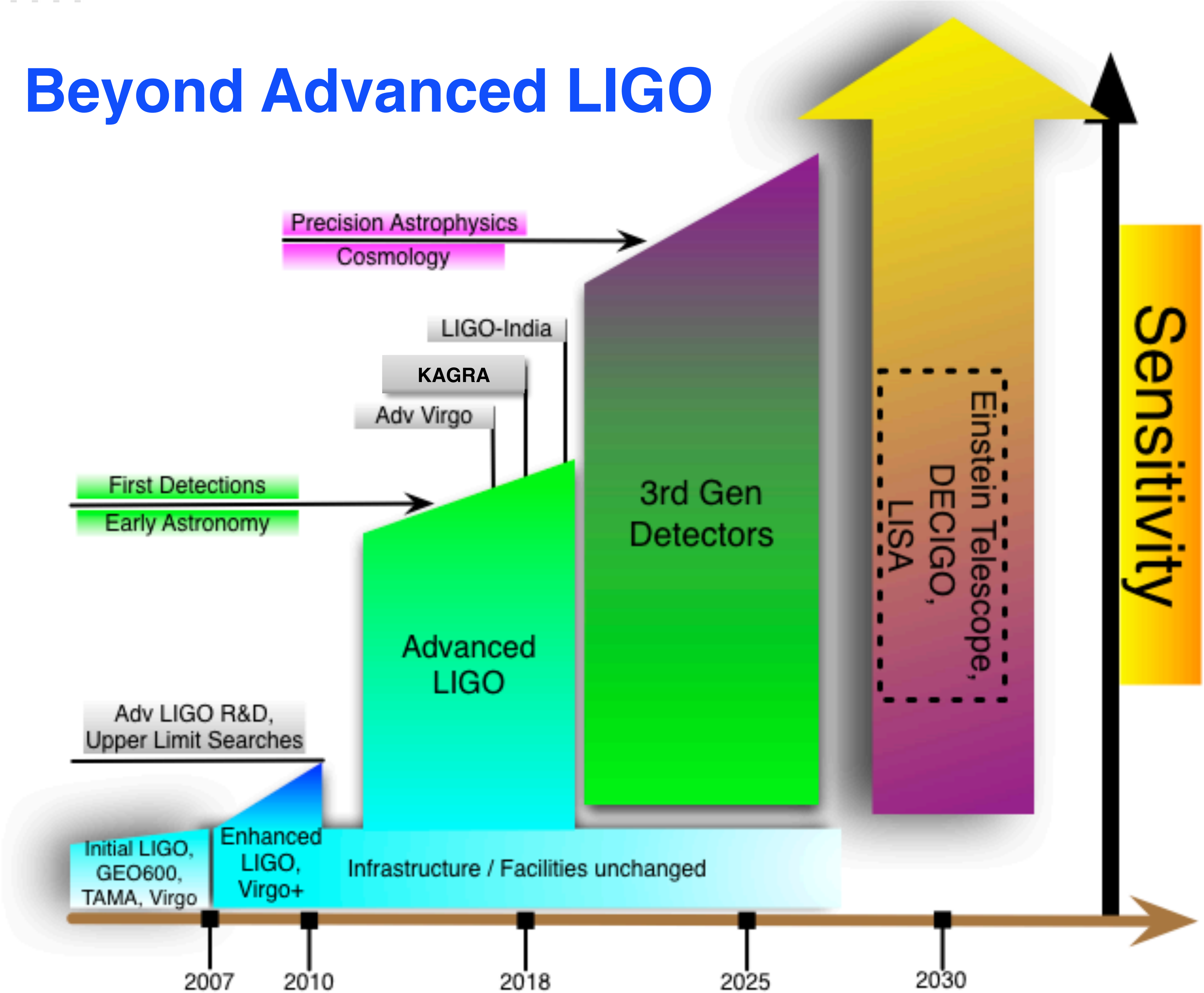


Low-latency identification of transients for rapid (< ~100s) followup

EM counterparts to GW sources (if any) are short-lived and faint

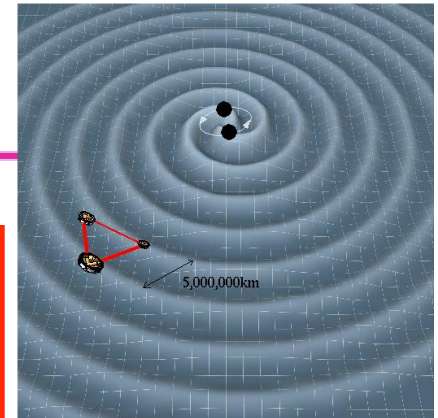


Beyond Advanced LIGO



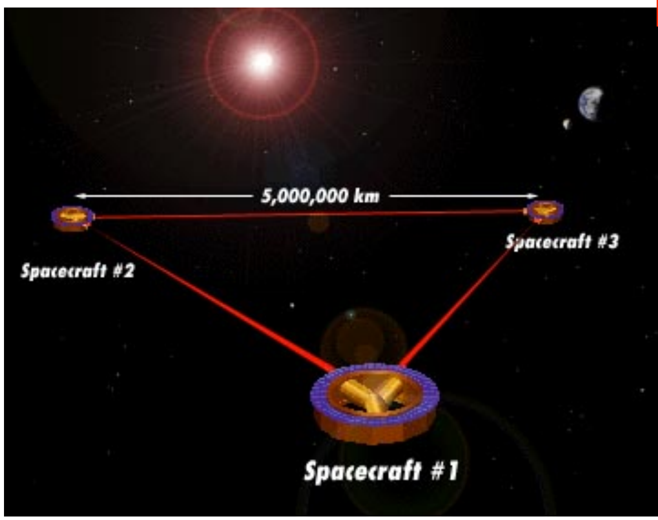
The Laser Interferometer Space Antenna

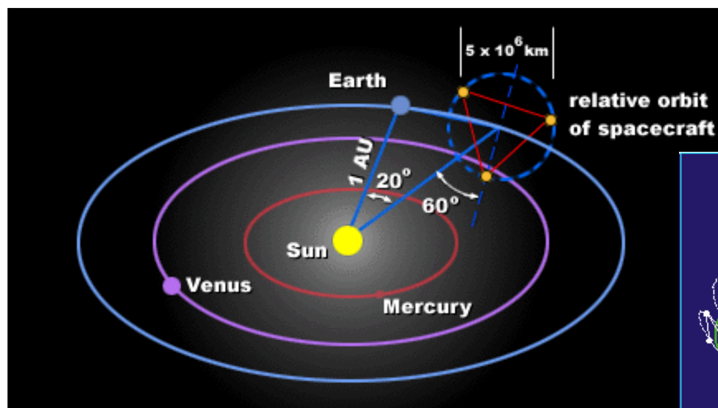
LISA

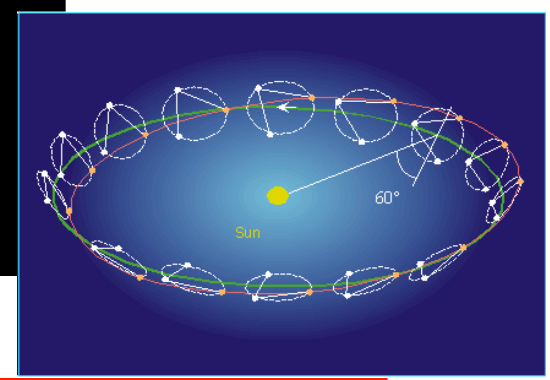


Three spacecraft in orbit about the sun,
with 5 million km baseline

The center of the triangle formation will be in the ecliptic plane
1 AU from the Sun and 20 degrees behind the Earth.

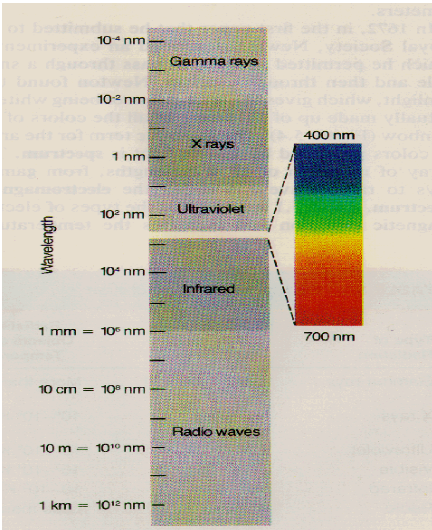






LISA (NASA/JPL, ESA) may fly in the next 10 years!

Frequency range of GW Astronomy

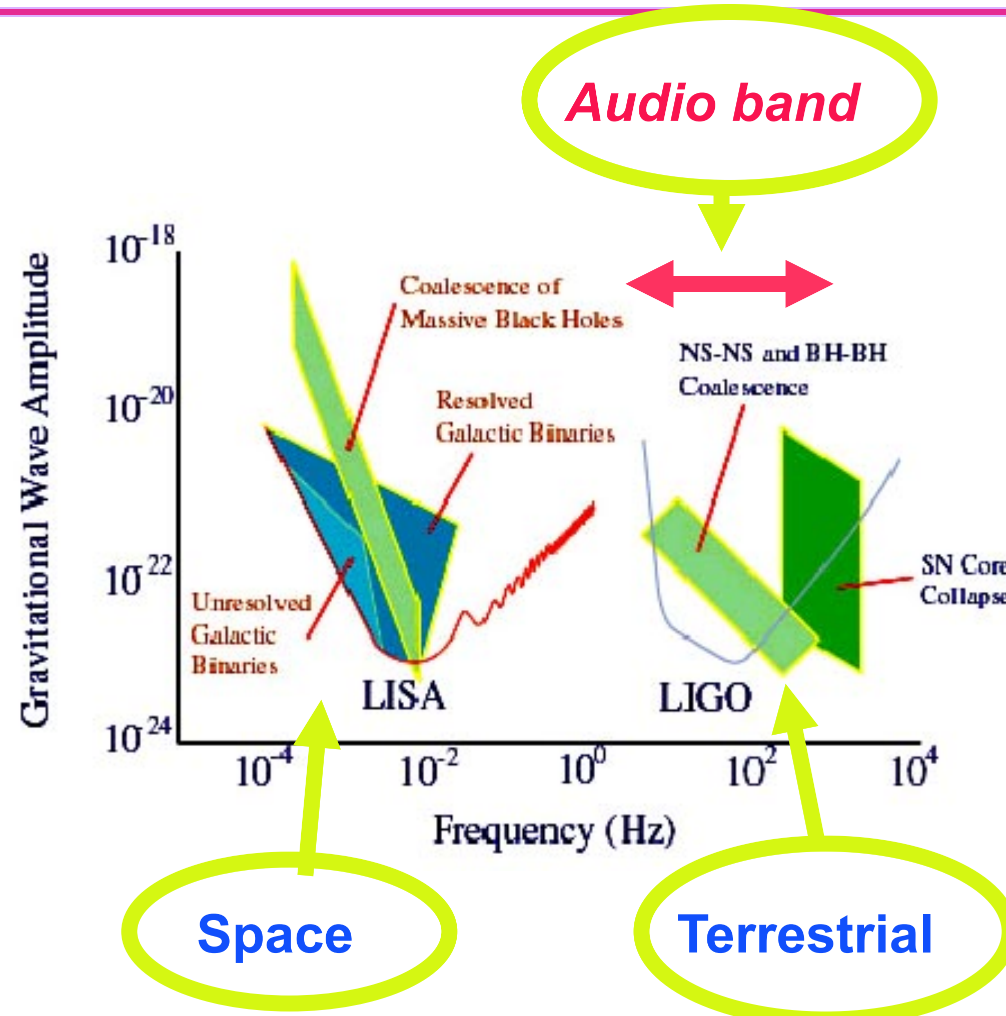


Electromagnetic waves

- over ~16 orders of magnitude
- Ultra Low Frequency radio waves to high energy gamma rays

Gravitational waves

- over ~8 orders of magnitude
- Terrestrial + space detectors

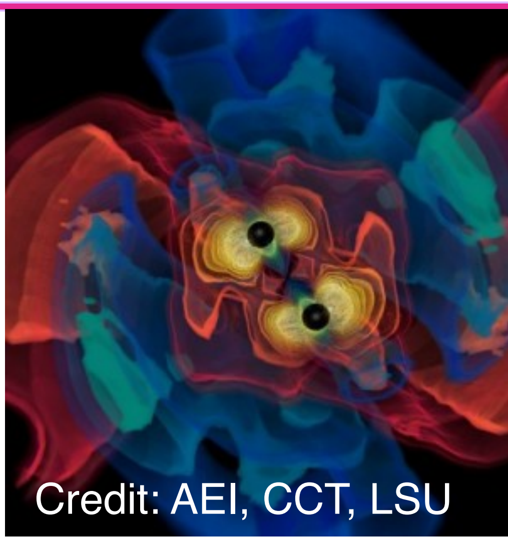


Data analysis algorithms must be optimal!

- These detectors are "precision measurement science" writ large!
- They are marvels of engineering, and arguably the most precise measuring devices ever built - and at great expense (several $100M for the network).
- But it is needed, because our signals are so weak (and so far, not yet detected!).
- There is no excuse for losing even a small amount of SNR due to imperfect data analysis; it is *imperative* to use techniques that are *as close to optimal* as possible, given finite / practical computing resources.

LIGO Scientific Collaboration

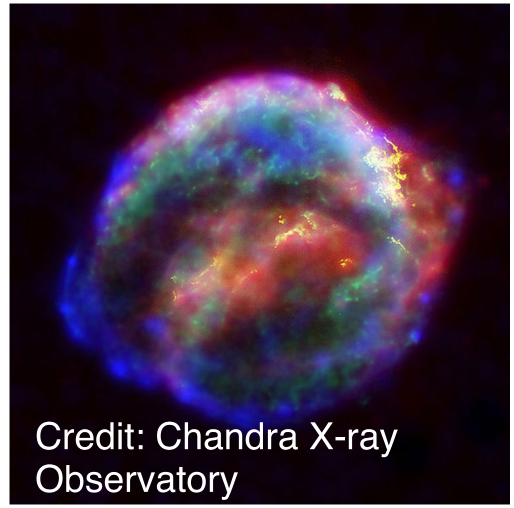
LIGO GW sources for ground-based detectors: The most energetic processes in the universe



<u>Coalescing Compact Binary Systems</u>: Neutron Star-NS, Black Hole-NS, BH-BH

- Strong emitters, well-modeled,

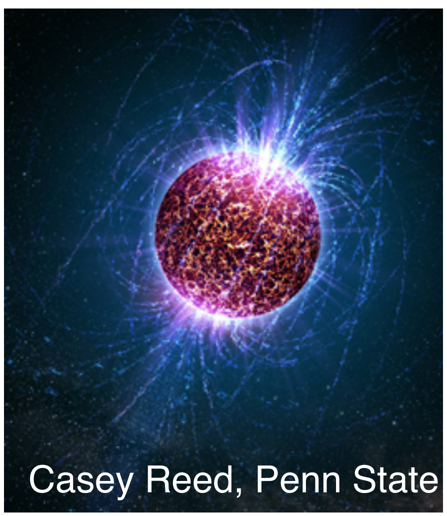
- (effectively) transient



<u>Asymmetric Core Collapse Supernovae</u>

- Weak emitters, not well-modeled ('bursts'), transient

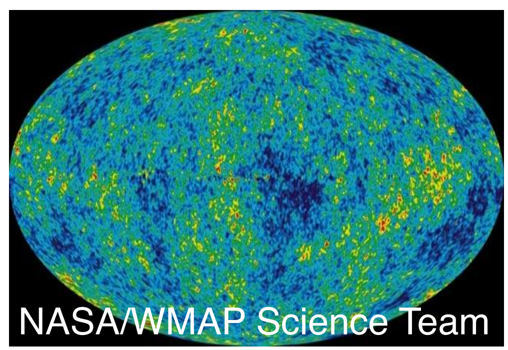
- Cosmic strings, soft gamma repeaters, pulsar glitches also in 'burst' class



<u>Spinning neutron stars</u>

- (effectively) monotonic waveform

- Long duration

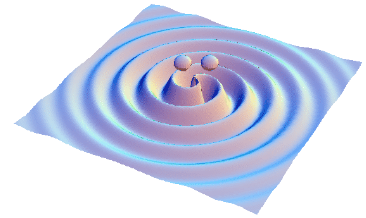


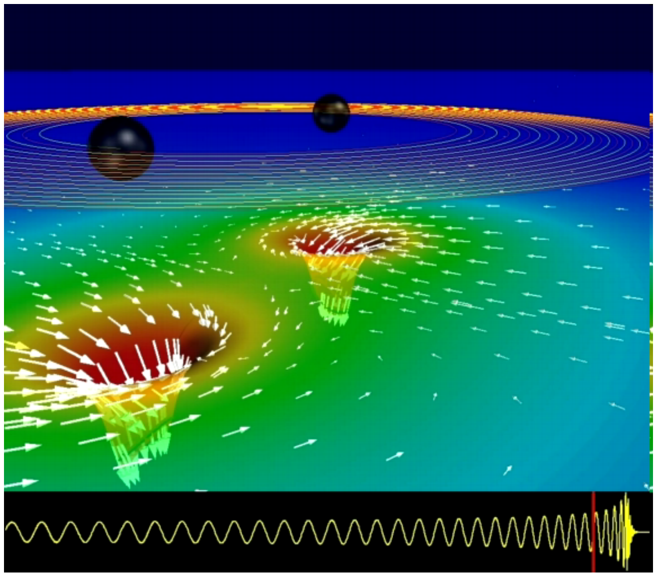
<u>Cosmic Gravitational-wave Background</u>

- Residue of the Big Bang, long duration

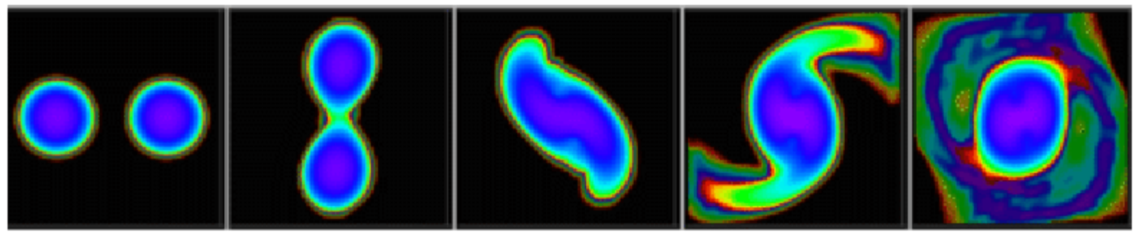
- Long duration, stochastic background

GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)





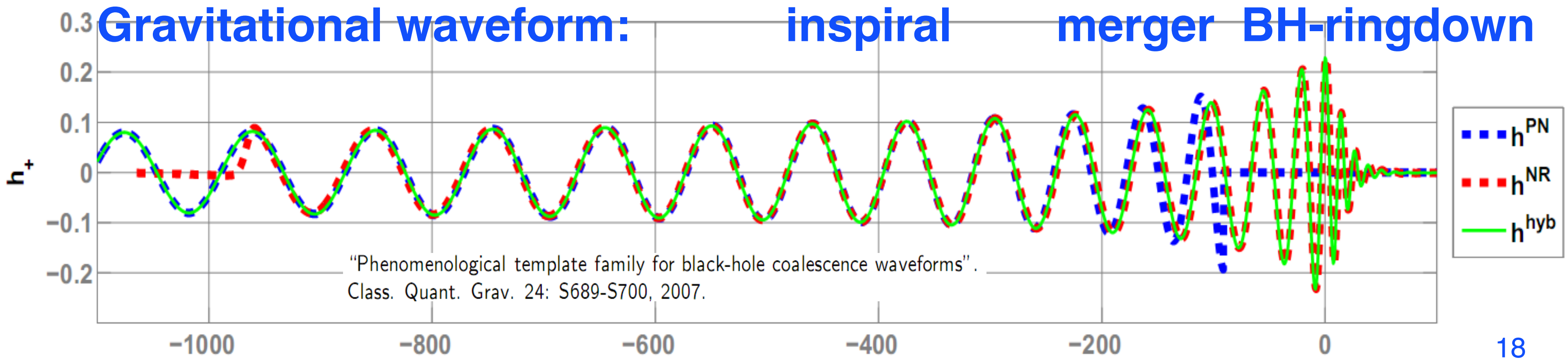
- Neutron star – neutron star (Centrella et al.)



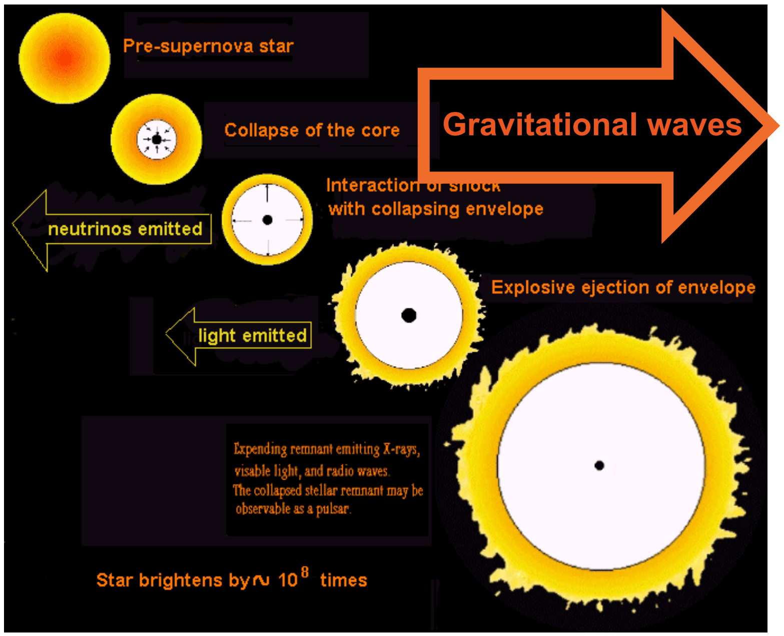
Tidal disruption of neutron star

A unique and powerful laboratory to study strong-field, highly dynamical gravity and the structure of nuclear matter in the most extreme conditions

Gravitational waveform: inspiral merger BH-ringdown

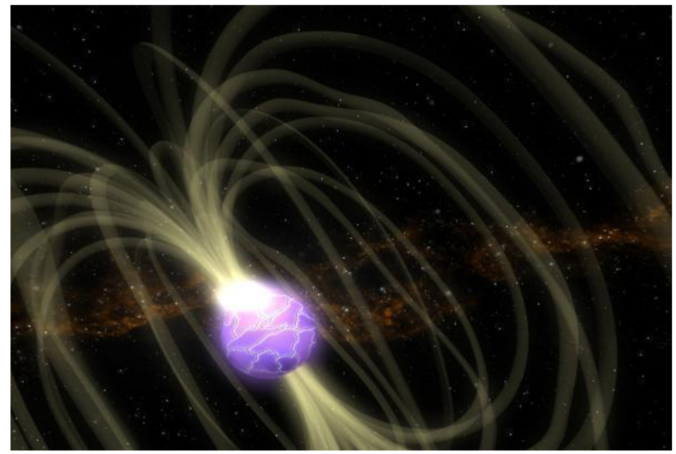


Unmodeled, short-duration (<~ 1 s) GW Bursts



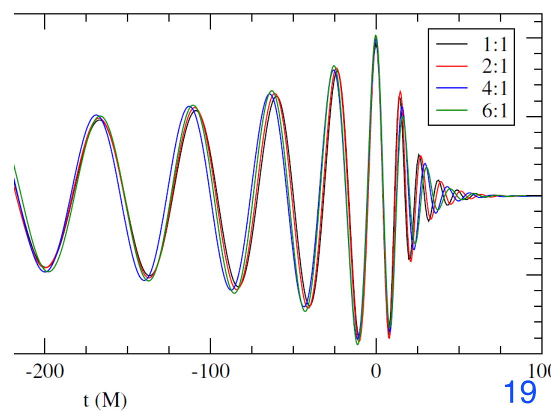
Supernova collapse

Credit: Chandra X-ray



Magnetar flares / storms

High-mass binary merger and ringdown



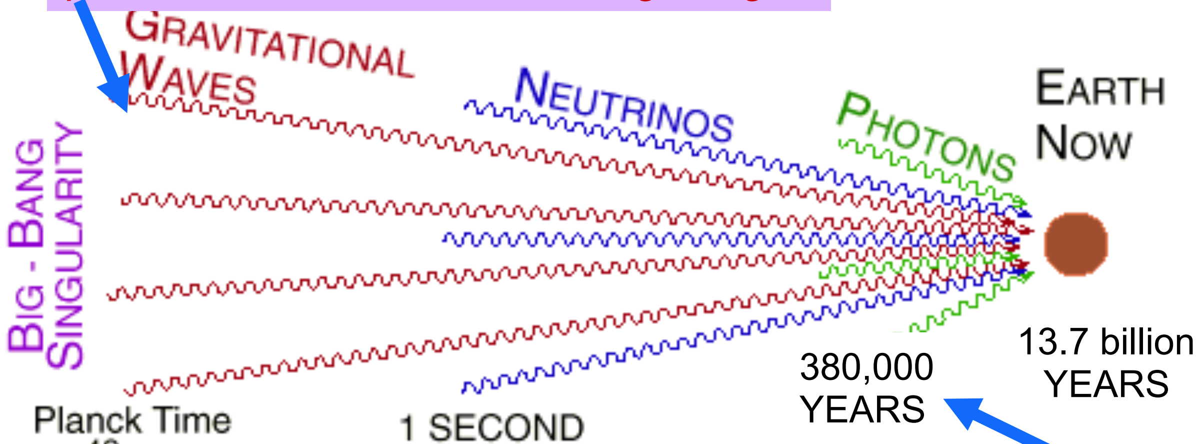
Gravitational waves from Big Bang

Waves now in the LIGO band were produced 10^{-22} sec after the big bang

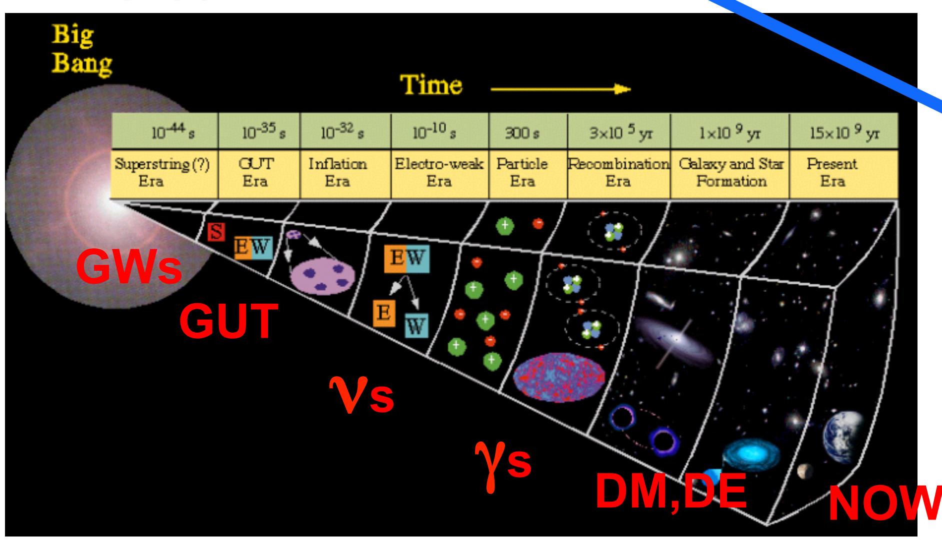
$$\Omega_{GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{GW}(f)}{d\ln f}$$

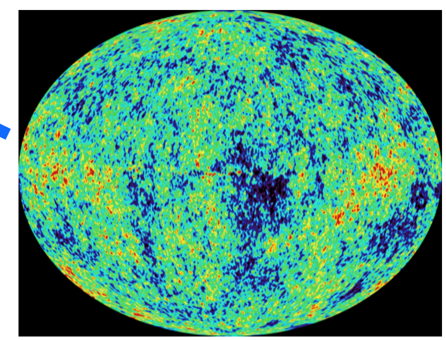
$$\rho_{GW} = \frac{c^2}{32\pi G} < \dot{h}_{ab}\,\dot{h}^{ab} >$$

$$h(f) = 6.3 \times 10^{-22}\sqrt{\Omega_{GW}(f)}\left(\frac{100\text{ Hz}}{f}\right)^{3/2}\text{Hz}^{-1/2}$$



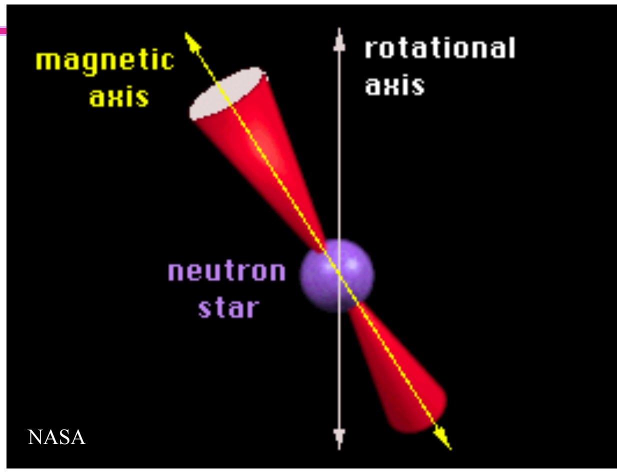
Planck Time
10^{-43} SECONDS
Singularity creates Space & Time of our universe





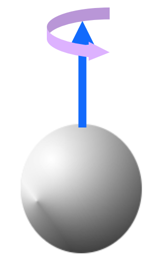
cosmic microwave background -- WMAP 2003

Pulsars and continuous wave sources

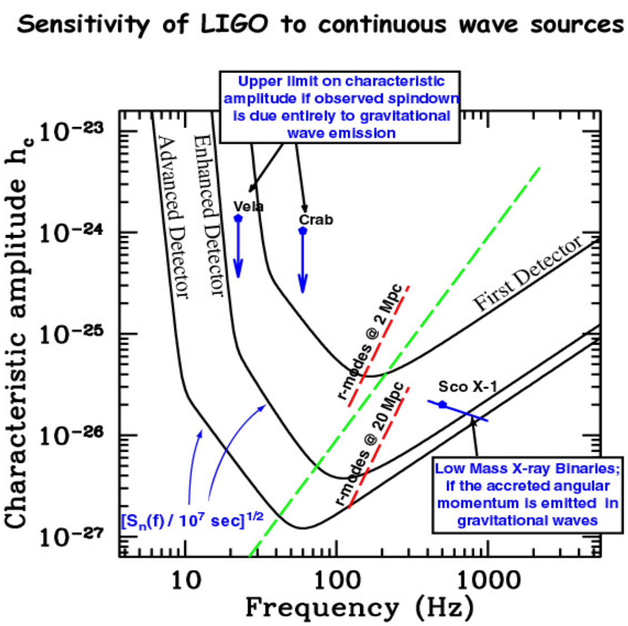


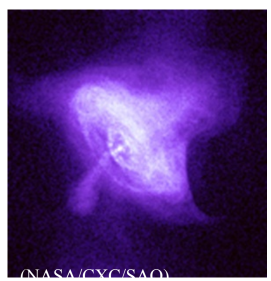
- **Pulsars in our galaxy**
  - »non axisymmetric: 10-4 < ε < 10-6
  - »science: EOS; precession; interiors
  - »"R-mode" instabilities
  - »narrow band searches best

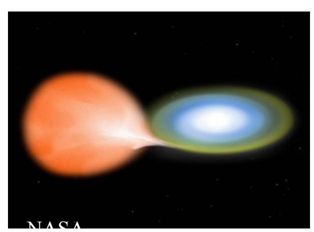
$$h = \frac{4\pi^2 G}{c^4} \frac{I f_{GW}^2}{d} \varepsilon$$

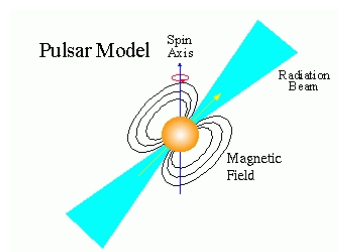


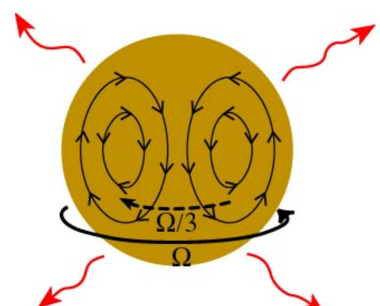
$$f_{GW} = 2 f_{ROT}$$





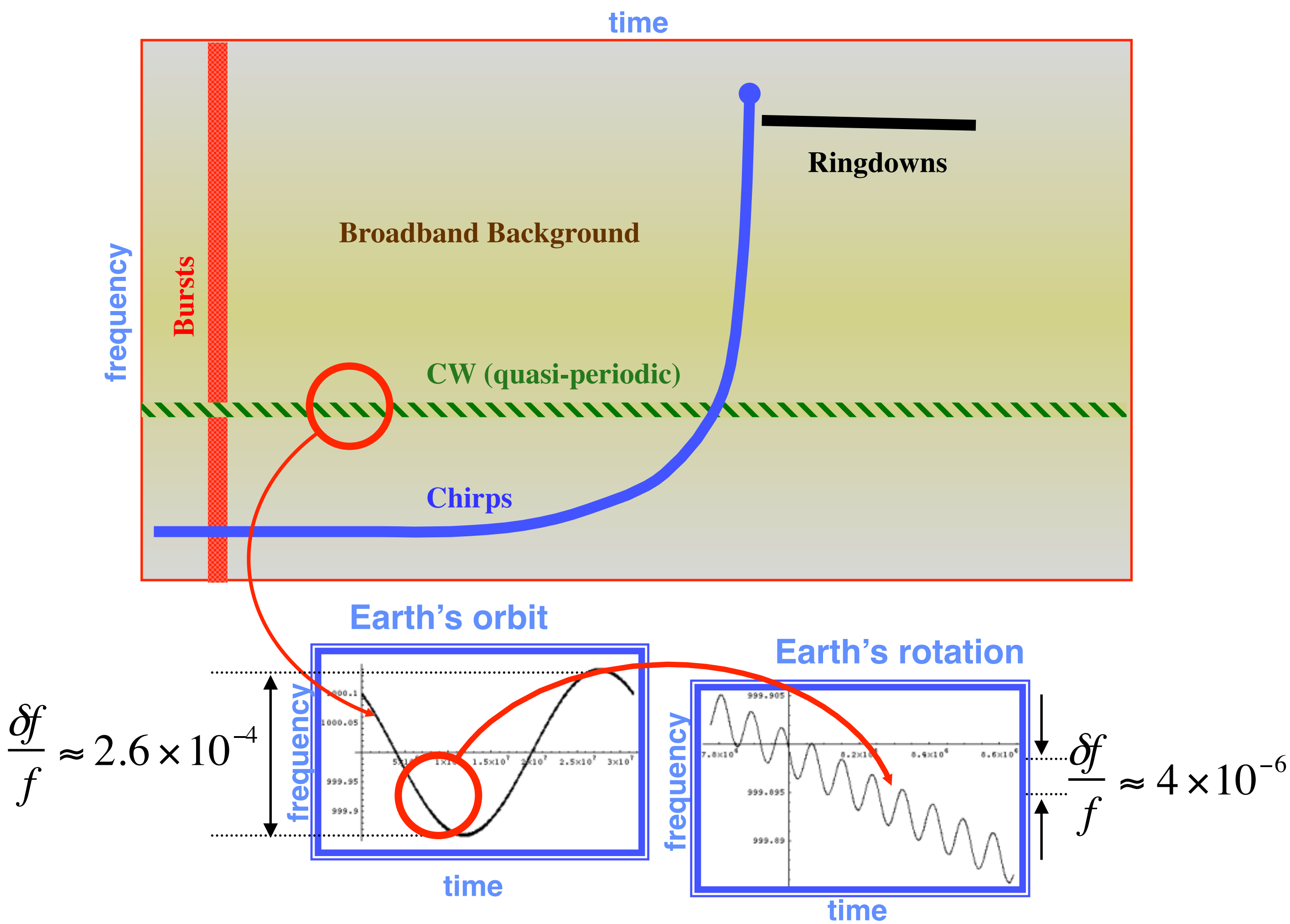






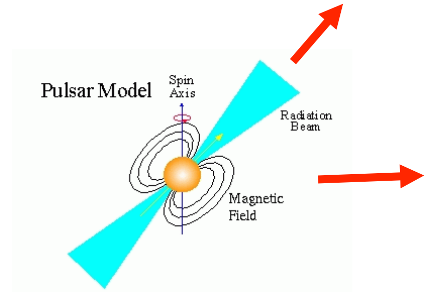
R-modes

Frequency-Time Characteristics of GW Sources



The CW challenge: All sky and frequency searches for GWs from spinning neutron stars

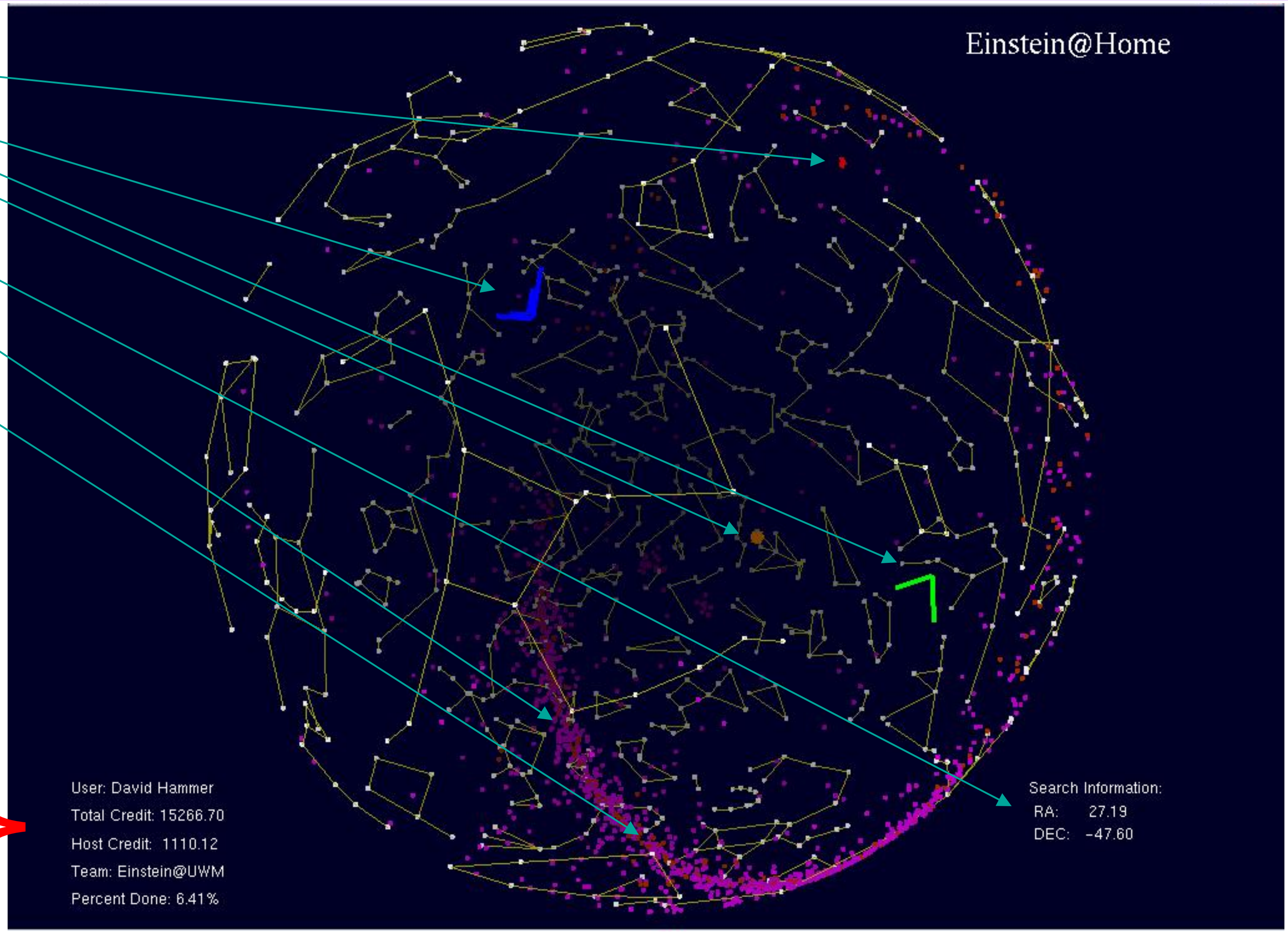
- Most spinning neutron stars are not observed pulsars; EM dim and hard to find.
- But they all emit GWs in all directions
- Some might be very close and GW-loud!
- Must search over huge parameter space:
  - sky position: 150,000 points @ 300 Hz, more at higher frequency or longer integration times
  - frequency bins: $1/T_{obs}$ over hundreds of Hertz sensitive detection band
  - df/dt: tens(s) of bins
  - Spin axis inclination and azimuthal angle
  - Binary orbit parameters (if in a binary system)



- This can add up to ~ 10^{15} templates or more…
- Computationally limited! Full coherent approach on only a fraction of observing time requires ~100,000 computers (Einstein@Home)

Einstein@Home: the Screensaver

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



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

Einstein@Home is one of the largest distributed computing projects in the world!

Project stats info

Project name	Users	last day	Hosts	last day	Teams	last day	Countries	last day	Total credit	last day
BOINC combined	2,591,677	706	9,146,874	-4,895	98,433	12	273	0	1,525,795,095,184	1,469,151,807
Einstein@Home	342,993	57	4,283,556	4,727	10,698	-1	222	0	80,458,550,275	86,908,255
SETI@Home	1,397,169	482	3,417,140	1,696	61,527	3	233	0	189,671,473,004	64,583,578
World Community Grid	406,774	48	1,739,067	477	22,039	5	224	0	103,086,777,592	71,248,098
Rosetta@Home	360,274	44	1,121,279	139	10,170	0	225	0	23,058,096,753	11,874,586
Climate Prediction	270,011	14	555,789	56	7,690	0	221	0	20,361,132,625	7,346,165
MilkyWay@home	161,532	99	328,502	186	3,584	0	210	0	170,118,702,983	73,157,891
LHC@Home Classic	112,930	49	294,149	54	4,652	3	195	0	1,603,698,281	6,032,892
PrimeGrid	54,547	8	191,648	47	2,609	0	187	0	234,029,966,084	172,811,383
Malaria Control	68,419	10	164,157	47	2,211	0	208	0	3,249,170,284	2,316,289
Spinhenge@home	58,706	0	152,959	0	2,139	0	183	0	2,415,881,597	0
SIMAP	42,933	6	147,503	49	2,314	0	182	0	3,638,340,201	3,590,609
ABC@home	75,111	8	140,449	27	1,832	0	196	0	4,376,657,649	494,415
QMC@Home	49,838	0	130,406	0	2,188	0	177	0	5,159,038,236	0
POEM@HOME	40,585	14	109,330	45	1,467	0	170	0	48,724,355,440	128,086,877
Cosmology@Home	54,686	13	103,964	37	1,802	0	190	0	3,967,898,340	2,891,700
SZTAKI Desktop Grid	36,662	6	99,354	16	1,555	0	177	0	641,690,393	415,325
Docking@Home	32,683	11	86,647	16	1,105	1	142	0	4,261,126,321	3,616,316

Snapshot circa May 2013

The Gravitational Wave Signal Tableau

Short duration — Long duration

Waveform known — Waveform unknown

Cosmic string cusp / kink

NS / BH ringdown

Low-mass inspiral

Asymmetric spinning NS

LISA binary

High-mass inspiral

Newborn NS Rotation-driven instability

Binary merger

Cosmological stochastic background

Stellar core collapse

Astrophysical stochastic background

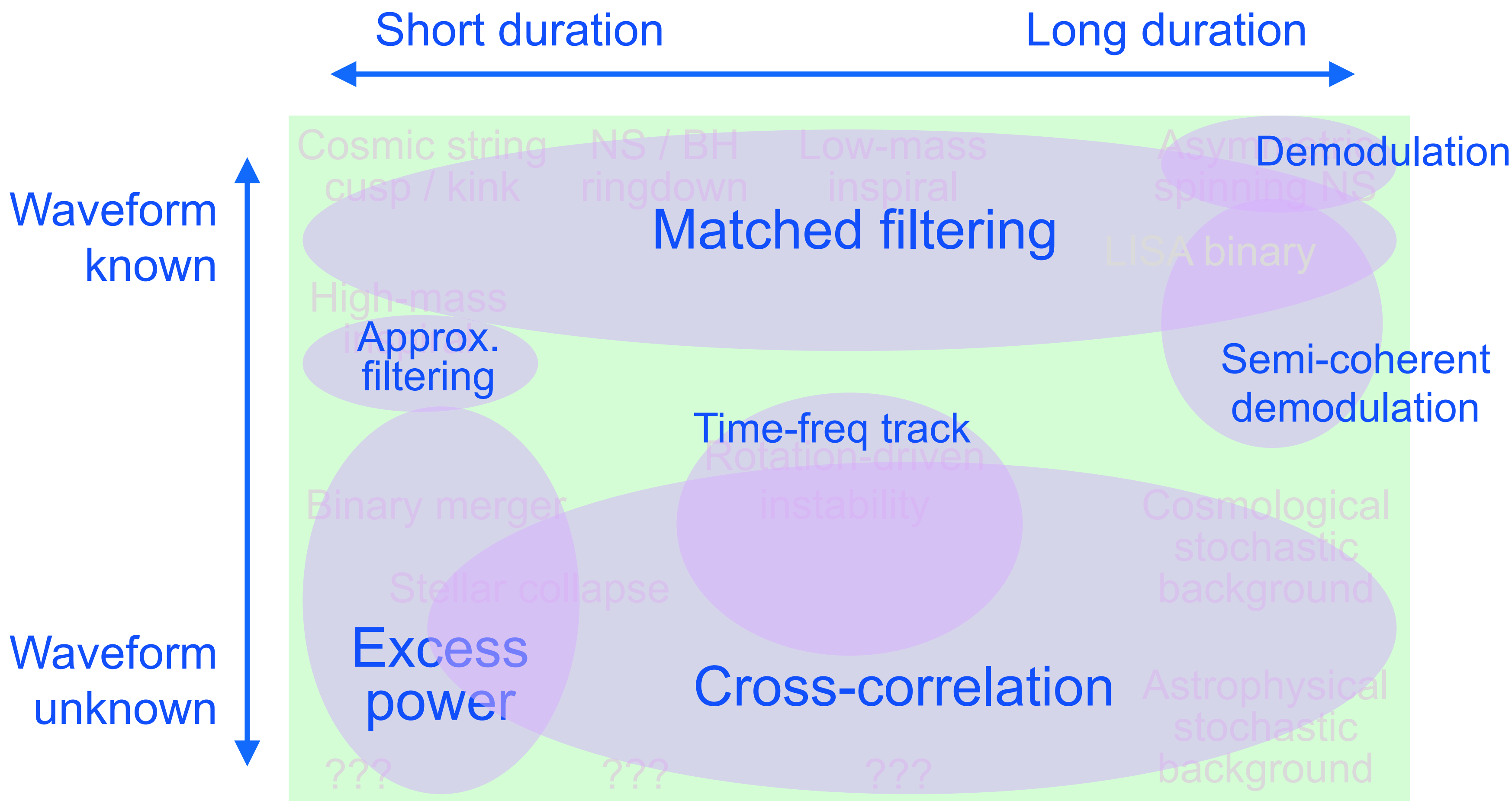
???

???

???

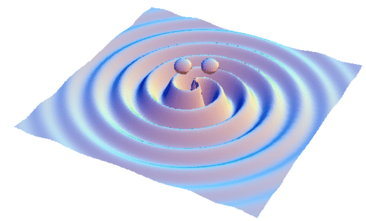
courtesy of Peter Shawhan

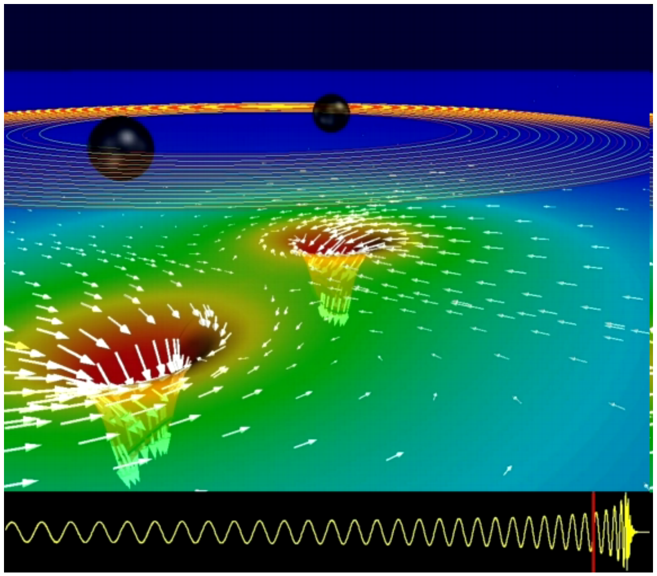
Summary of Data Analysis Methods



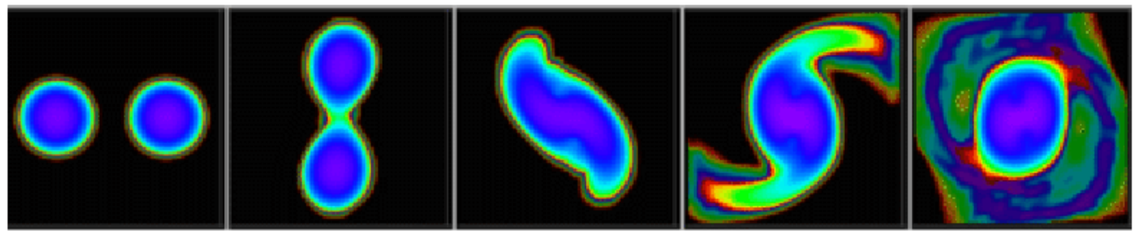
courtesy of Peter Shawhan

GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)





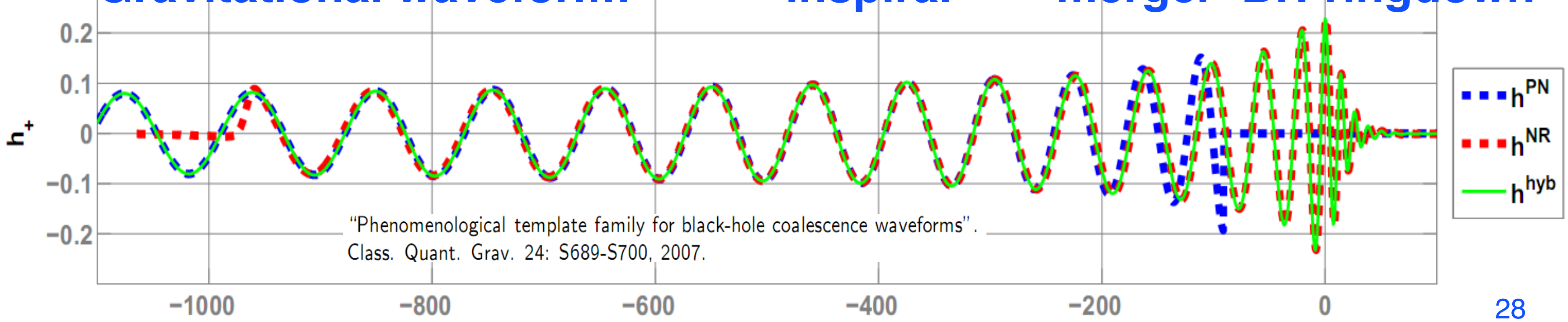
- Neutron star – neutron star (Centrella et al.)



Tidal disruption of neutron star

A unique and powerful laboratory to study strong-field, highly dynamical gravity and the structure of nuclear matter in the most extreme conditions

Gravitational waveform: inspiral merger BH-ringdown

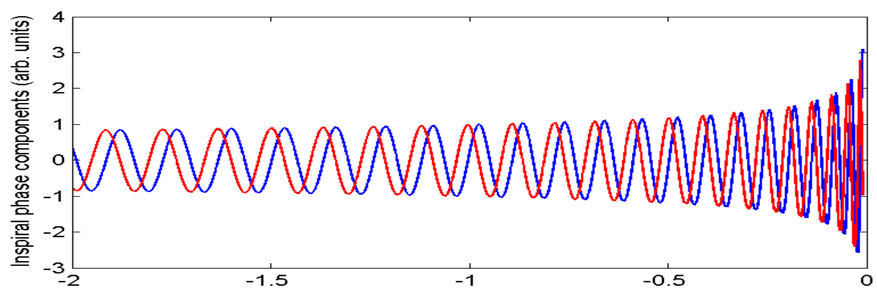


Source Parameters vs. Signal Parameters

- Inspiral source parameters (**19!**)
  - » Masses (m_1, m_2) → masses and spins are "intrinsic" parameters
  - » Spins $\mathbf{S}_1$, $\mathbf{S}_2$ → Negligible for neutron stars, at least
  - » Orbital phase at coalescence, φ → Maximize analytically when filtering
  - » Inclination of orbital plane, ι
  - » Sky location (α, δ)

  → Simply multiplicative for a given detector (long-wavelength limit)
  - » Distance *d* → Simply multiplicative
  - » Coalescence time t_c

Filter with orthogonal templates, take quadrature sum



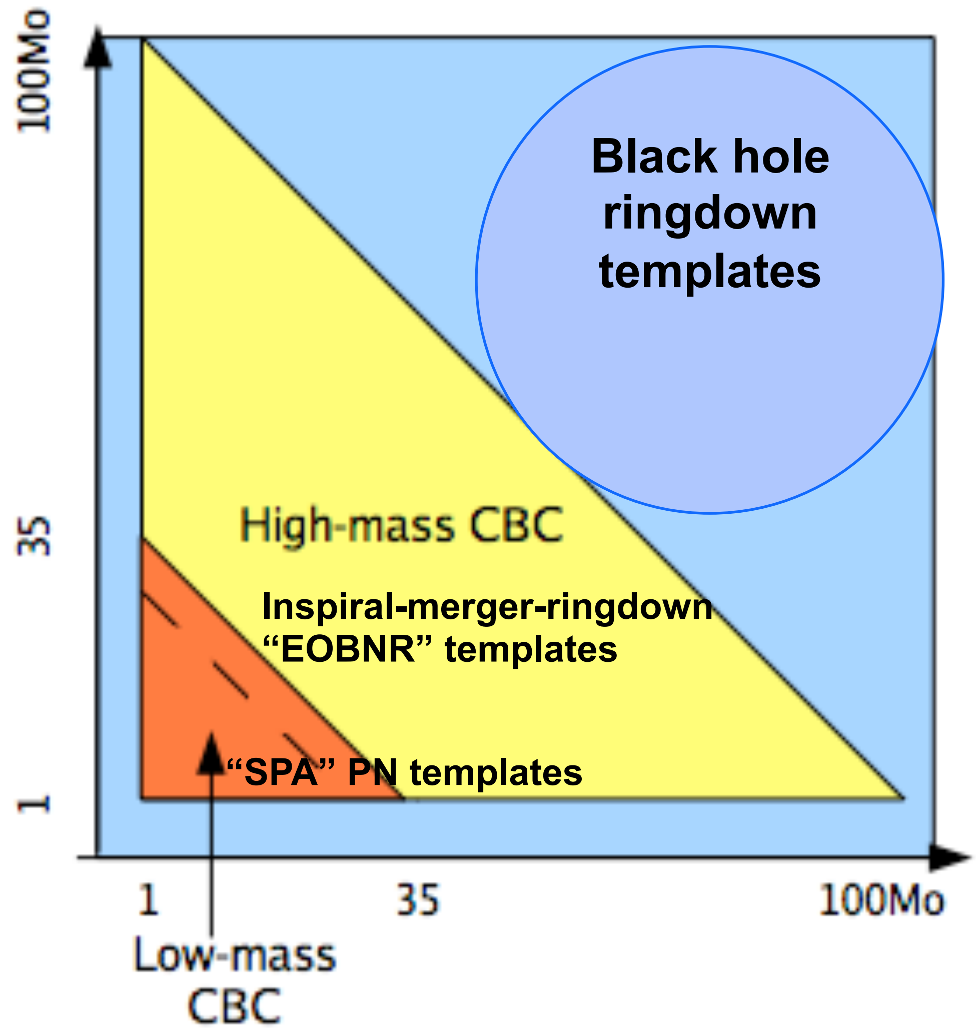
➔ Only have to explicitly search over masses and coalescence time ("intrinsic parameters")

What are waveform templates used for in GW data analysis?

- Detection, via matched (Weiner) filtering through template banks (*optimal* technique in Gaussian noise)
- Detection pipeline validation / testing by injections into real, noisy (non-Gaussian, non-stationary) detector data.
- Evaluating detection pipeline sensitivity in real data using injections, evaluating sensitive volume (in Mpc^3) as a function of parameter space.
- Parameter estimation: extracting source parameters (all ~15 of them), including 15-dim posterior PDFs.
- In most of these applications, need waveforms for arbitrary values of parameters in target space.

Mass space for template-based search

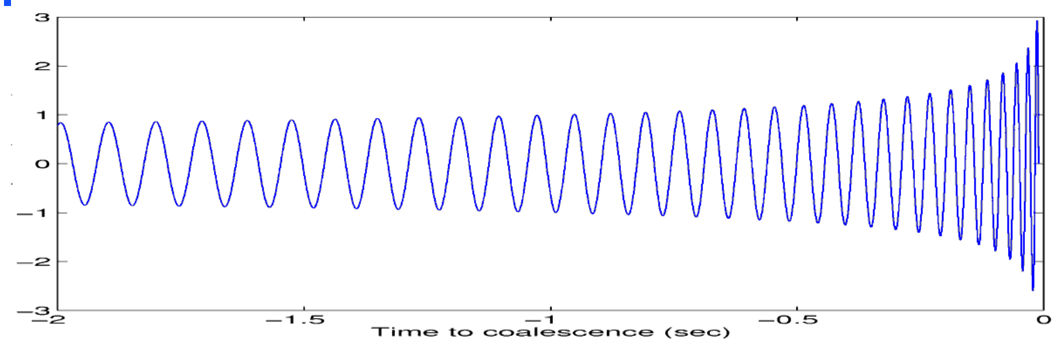
- The more massive the system, the lower the GW frequency at merger.
- Binary neutron star (BNS) waveforms are in LIGO band during inspiral; merger & ringdown are out-of-band.
- Higher-mass Binary black hole (BBH) waveforms merge in-band
- Above ~few 100 M_{sun}, all LIGO can see is the merger and ringdown



Searching for Known Waveforms

Example: low-mass inspiral

h(t)



- $h(t) = A(t)\cos(\,\Psi(t)\,)$
- Waveform known well, or fairly well, in some parameterized space
  - » e.g. inspiral with 1.4+1.4 $M_\odot$
  - » or with 10+1.4 $M_\odot$

This and the next dozen slides are lifted from the excellent lectures at the CGWA Summer School in May 2012 by Peter Shawhan, U Maryland

Phase Evolution of an Inspiral

- Accurate knowledge of the phase is crucial for matched filtering
- Orbital phase vs. time → orbital phase vs. frequency during chirp
- "Post-Newtonian expansion" if spins are negligible:

$$\Psi(f) = 2\pi f t_c + \frac{3}{128\eta}(\pi m f)^{-5/3}$$ Newtonian

$$+ \frac{5}{96\eta}\left(\frac{743}{336} + \frac{11}{4}\eta\right)(\pi m f)^{-1}$$ 1PN

$$- \frac{3\pi}{8\eta}(\pi m f)^{-2/3}$$ 1.5PN

$$+ \frac{15}{64\eta}\left(\frac{3058673}{1016064} + \frac{5429}{1008}\eta + \frac{617}{144}\eta^2\right)(\pi m f)^{-1/3}$$ 2PN

$$+ \cdots$$

Relativistic effects

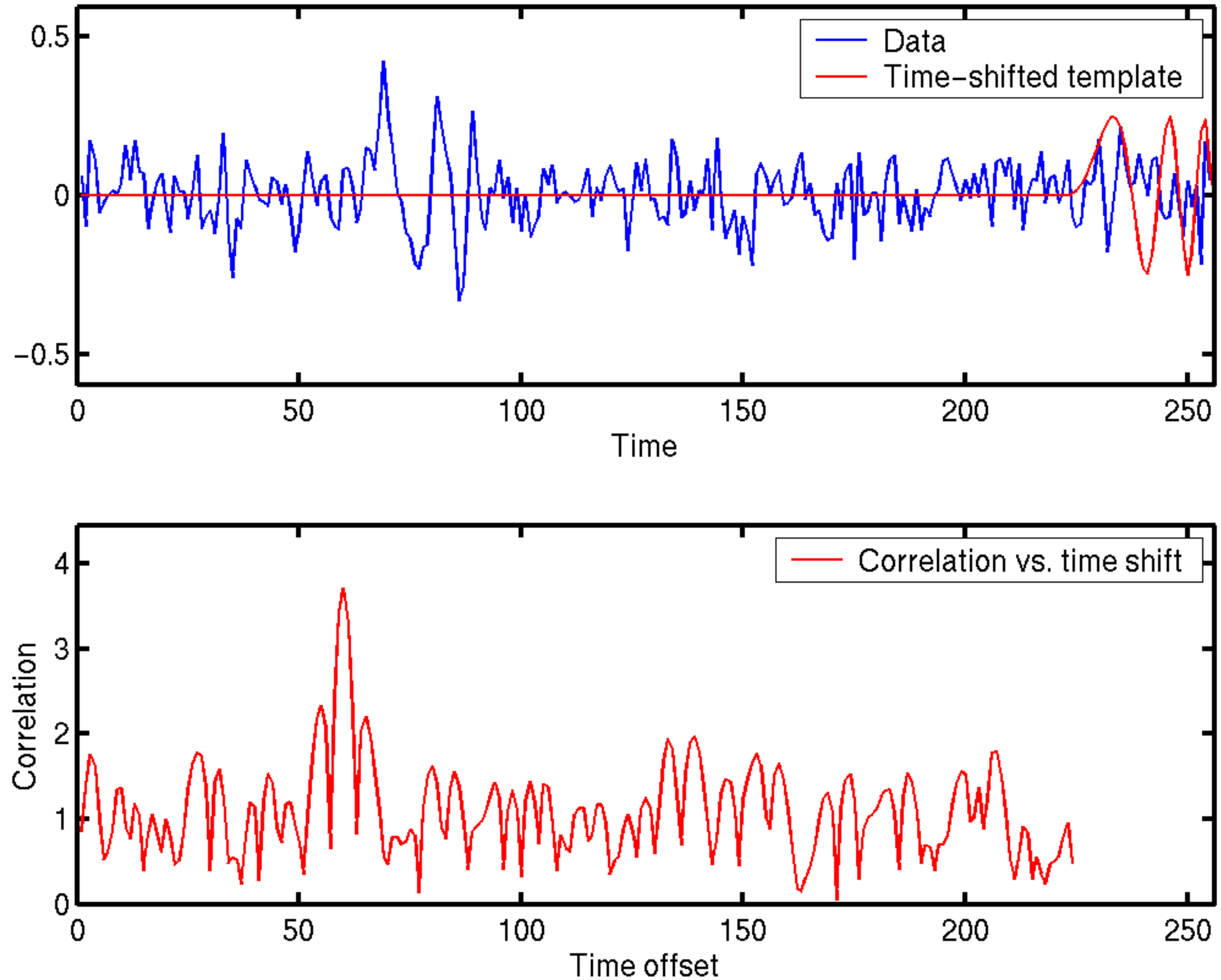
- where $m = (m_1 + m_2)\,, \quad \eta = \frac{m_1\, m_2}{m^2}$ **and "chirp mass" is** $m\eta^{3/5}$

Inspiral Phase to 3.5PN

$$
\begin{aligned}
\Psi(f;M,\eta) &= 2\pi f t_C - 2\phi_C - \pi/4 \\
&+ \frac{3}{128\eta\,v^5}\left\{1 + \left(\frac{3715}{756} + \frac{55}{9}\eta\right)v^2 - 16\pi v^3 + \left(\frac{15\,293\,365}{508\,032} + \frac{27\,145}{504}\eta + \frac{3085}{72}\eta^2\right)v^4\right. \\
&+ \pi\left[\frac{38\,645}{756} - \frac{65}{9}\eta\right]\left[1 + 3\ln\left(\frac{v}{v_0}\right)\right] + \left\{\frac{11\,583\,231\,236\,531}{4\,694\,215\,680} - \frac{640}{3}\pi^2 - \frac{6\,848}{21}(\gamma + \ln(4\,v))\right. \\
&+ \left.\left(-\frac{15\,335\,597\,827}{3\,048\,192} + \frac{2\,255}{12}\pi^2\right)\eta + \frac{76\,055}{1\,728}\eta^2 - \frac{127\,825}{1\,296}\eta^3\right\}v^6 \\
&+ \left.\pi\left[\frac{77\,096\,675}{254\,016} + \frac{378\,515}{1\,512}\eta - \frac{74\,045}{756}\eta^2\right]v^7\right\},
\end{aligned}
$$

- … where $\upsilon = (\pi M f)^{1/3}$

Basic Illustration of Matched Filtering



Filtering compresses signal into (approximately) a δ-function

Matched Filtering in Frequency Domain

$$C(t) = \int_{-\infty}^{\infty} dt'\, s(t')\, h(t'-t)$$

Time offset

Data

Template with time offset

- Rewrite correlation integral using Fourier transforms…

$$\Rightarrow \quad C(t) = 4 \int_{0}^{\infty} \tilde{s}(f)\, \tilde{h}^{*}(f)\, e^{2\pi i f t}\, df$$

This is simply the inverse FFT of $\tilde{s}(f)\, \tilde{h}^{*}(f)$

Computationally efficient way to calculate filter output for a range of times!
Can compute $h(f)$ in advance, and $s(f)$ once for many filters.

Optimal Matched Filtering with Frequency Weighting

FFT of data

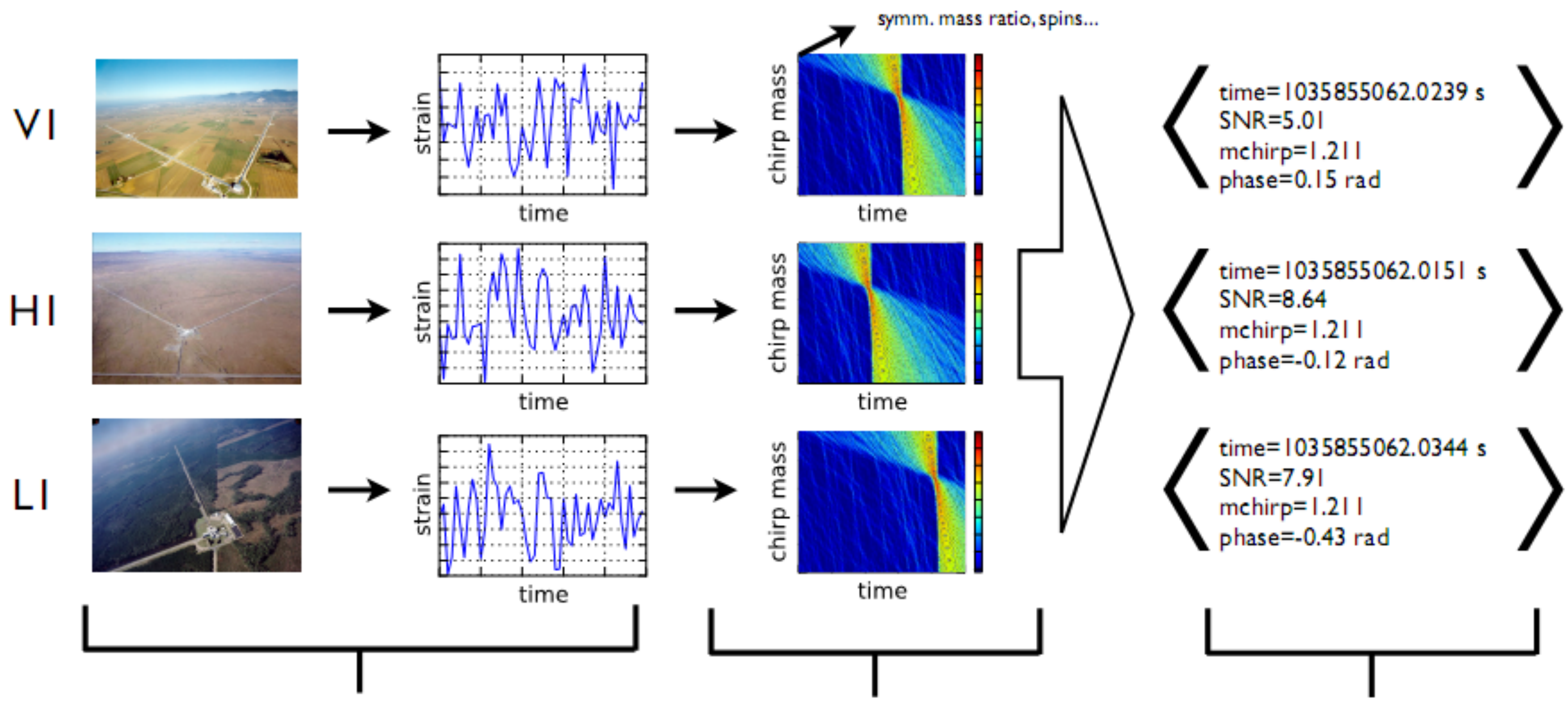
Template; can be generated in frequency domain using stationary phase approximation

$$C(t) = 4 \int_0^{\infty} \frac{\tilde{s}(f)\ \tilde{h}^*(f)}{S_n(f)}\ e^{2\pi i f t}\ df$$

Noise power spectral density

- Equivalently, "whiten" *h(f)* and *s(f)* by dividing by sqrt of noise power spectral density (noise amplitude SD, "ASD")
- $|C(t)|$ automatically maximizes over coalescence phase φ
- Look for maximum of $|C(t)|$ above some threshold ➔ trigger

Coincidence (in time, intrinsic parameters) between detectors



Strain transduced by detectors

also: data quality, vetoes, aggregate data to analysis clusters

Matched filter

sliding dot product of strain data w/ sampling of all possible inspiral signals

Triggering, coincidence

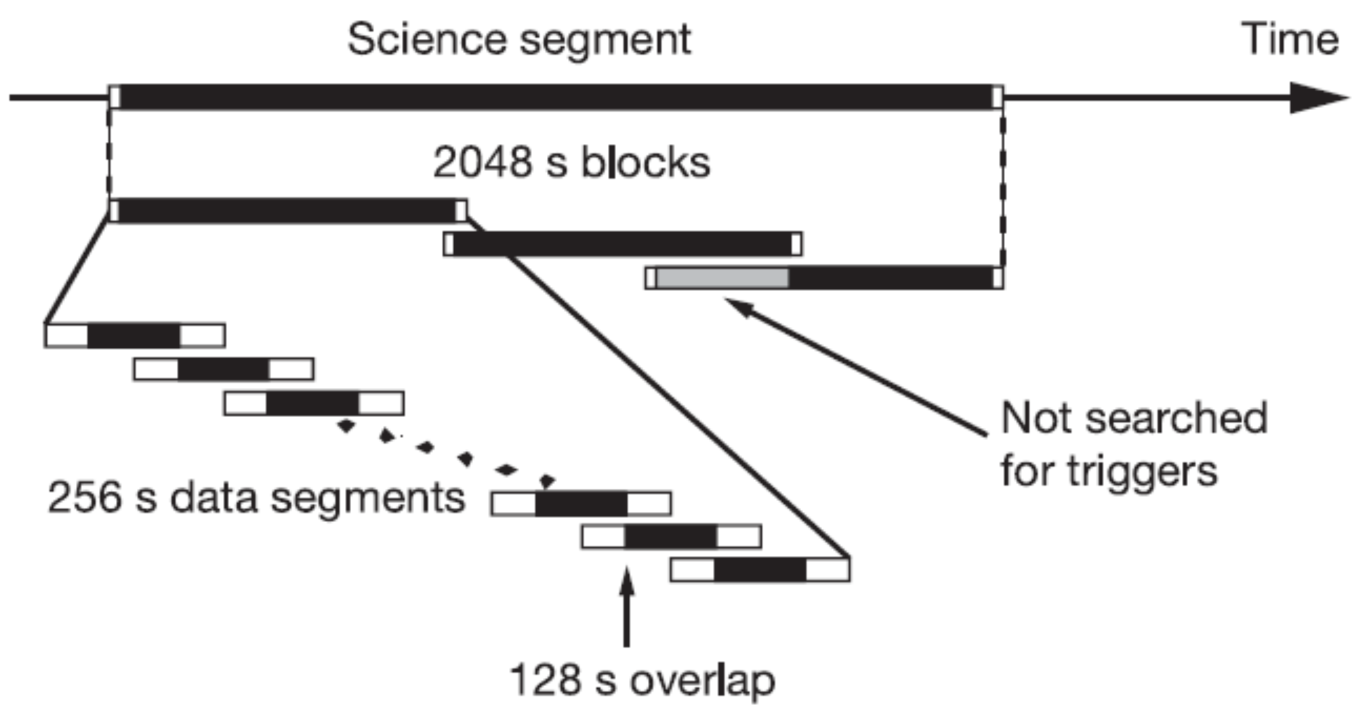
excursion in matched filter *signal-to-noise ratio (SNR)* at similar times in all detectors

Searching a Full Data Set

Search overlapping intervals to cover science segment, avoid wrap-around effects

Do inverse FFTs on, say, 256 s of data at a time

Estimate power spectrum from bin-by-bin median of fifteen 256-sec segments



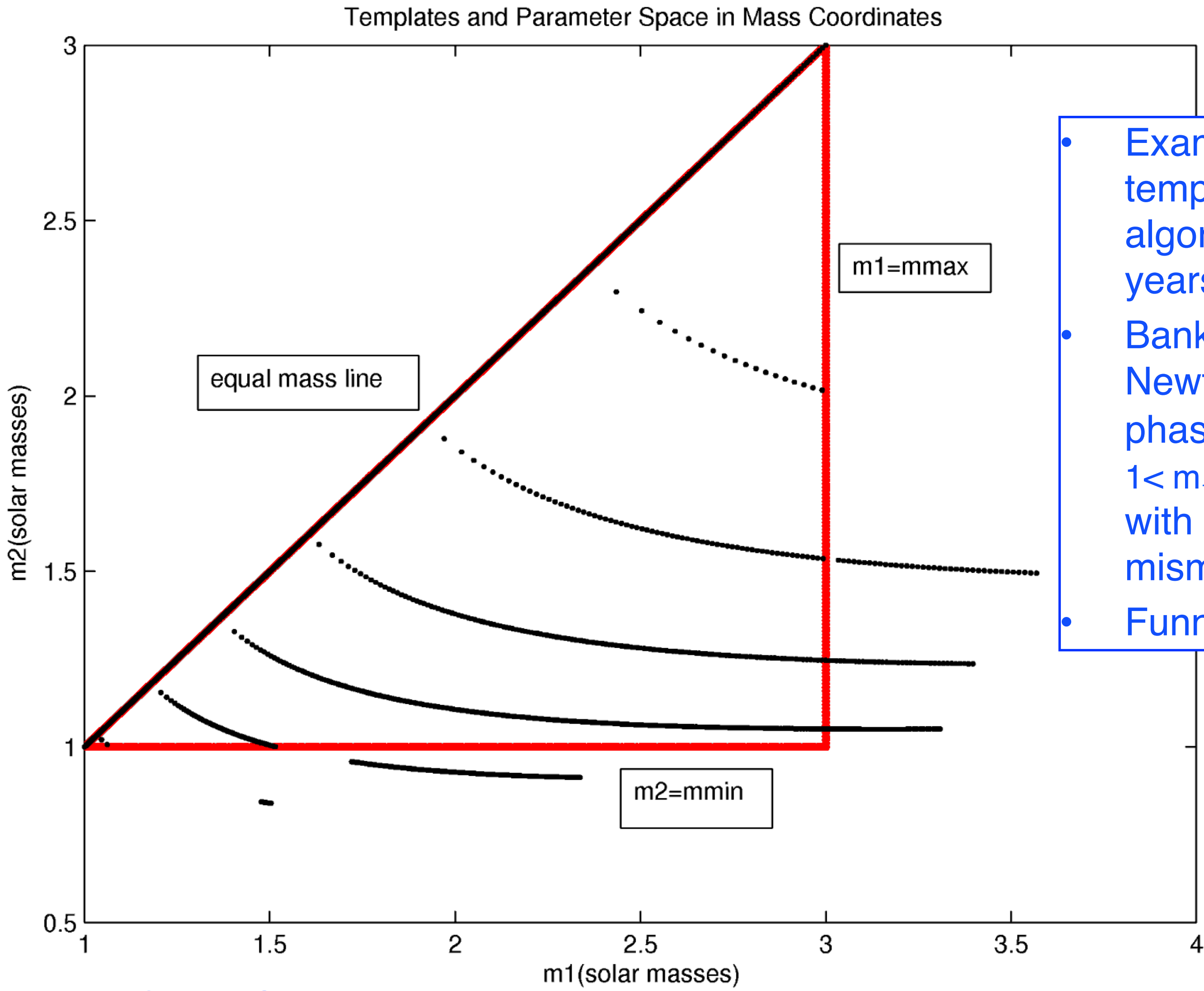
Template Banks

- Want to be able to detect any signal in a *large parameter space* of possible signals
  - » All with different phase evolution
  - » Current astrophysical knowledge gives few clues for masses, spins
- … but do it with a finite set of templates!
- So build a bank of templates
  - » Make sure there is a “close enough” template for every part of the signal space
  - » Require a minimum overlap between signal and template, e.g. 0.97
- Often can calculate a “metric” which parameterizes the mismatch for small mismatches

Filtering through a bank of templates

- $h(t) \rightarrow z_i(t)$, i = 1…N(templates)
- This isn't data reduction, this is data explosion!
- In the end, we find peaks in $|z_i(t)|$ (triggers) and threshold on trigger SNR, greatly reducing the data (especially if it is Gaussian!)
- A low-mass search might have N ~ 10,000 templates, but the templates overlap greatly; only ~10% or fewer "independent" templates.
- One second of data (16,384 samples) lives in a 16384-dim space, mostly noise; the signal space spanned by independent physical templates is only ~1000-dim subspace. Filtering throws away the non-signal-like noise living in the rest of the full space.

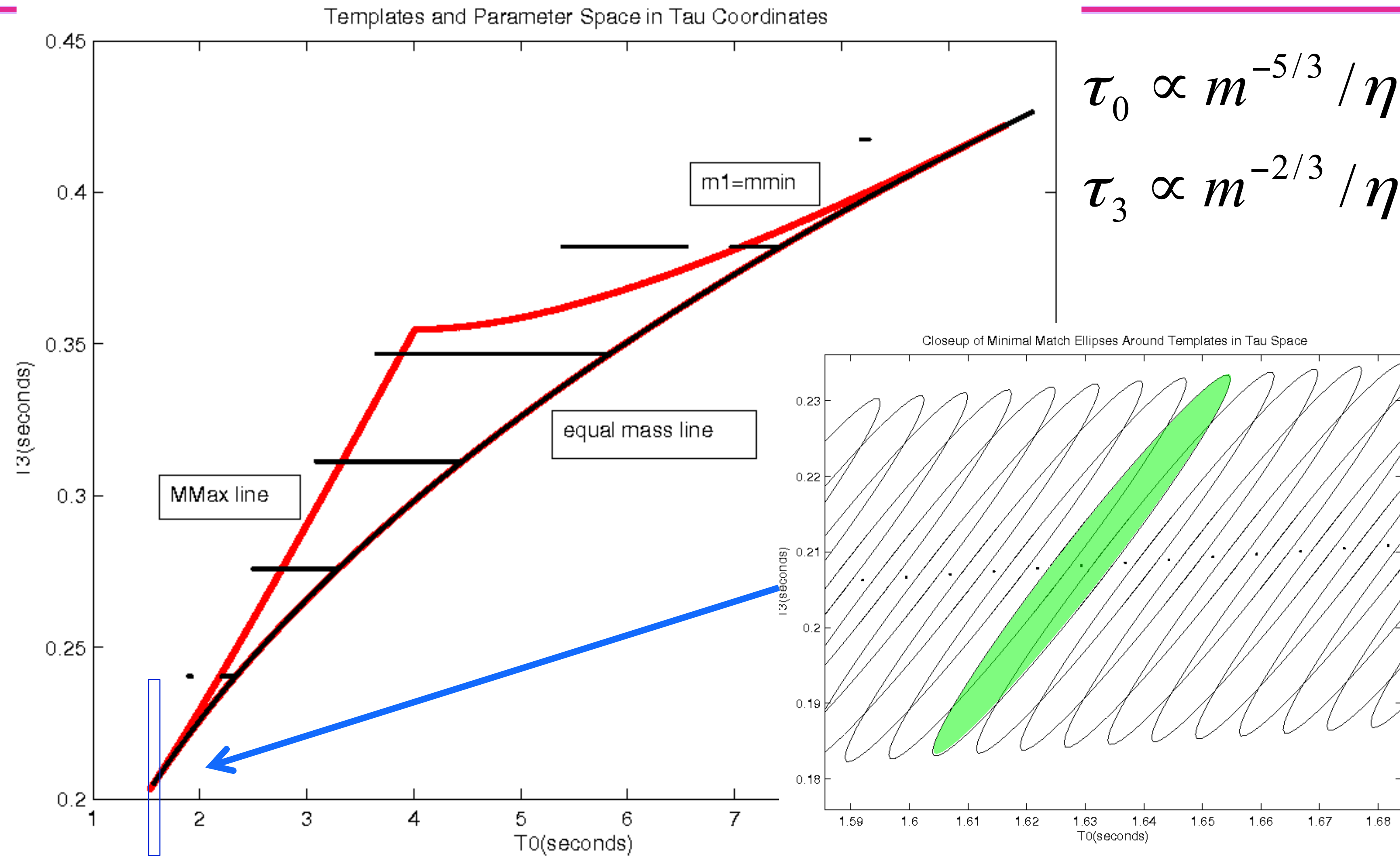
Template Bank Construction



- Example from LAL template bank placement algorithm as of some years ago
- Bank of 2110 post^2 – Newtonian stationary-phase templates for $1 < m_1 \leq m_2 < 3\ M_\odot$ with 3% maximum mismatch.
- Funny shape, huh?

Figures by Sarah Caudill

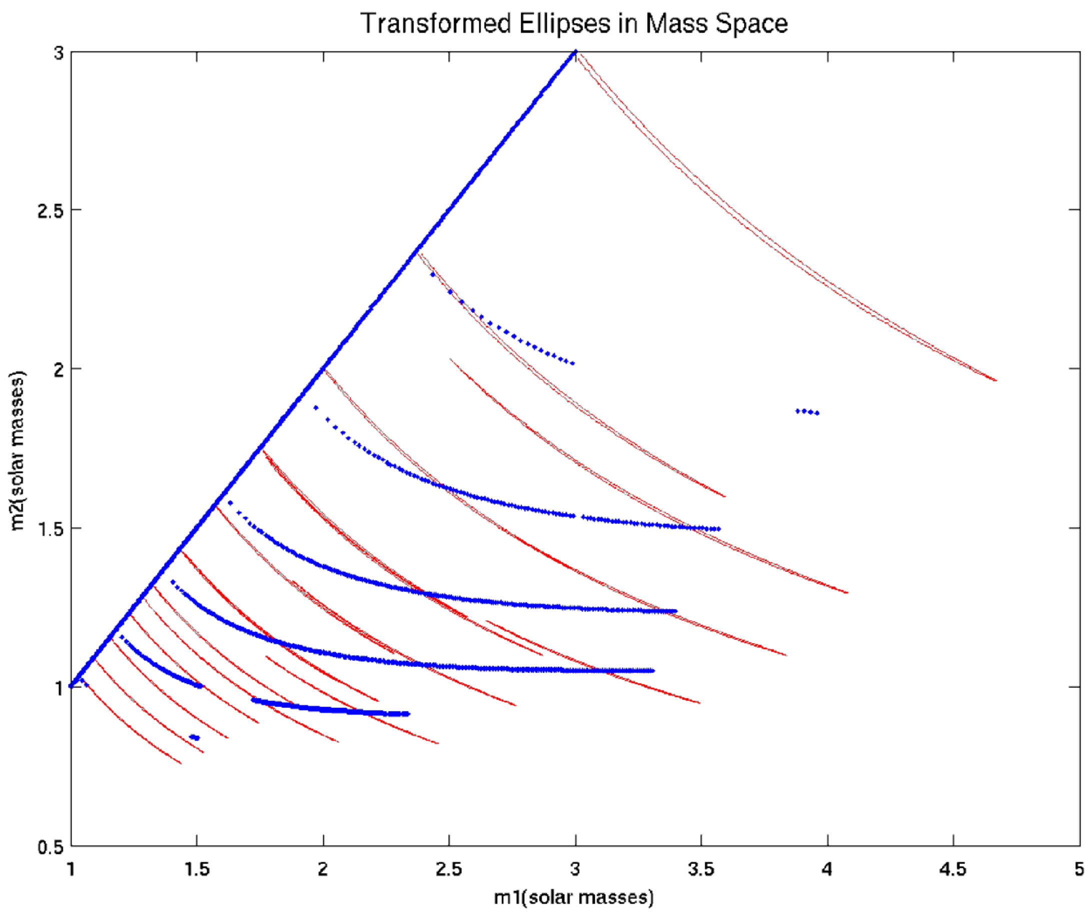
Template Bank Construction in (τ_0,τ_3) space (flat metric)



$$\tau_0 \propto m^{-5/3} / \eta$$

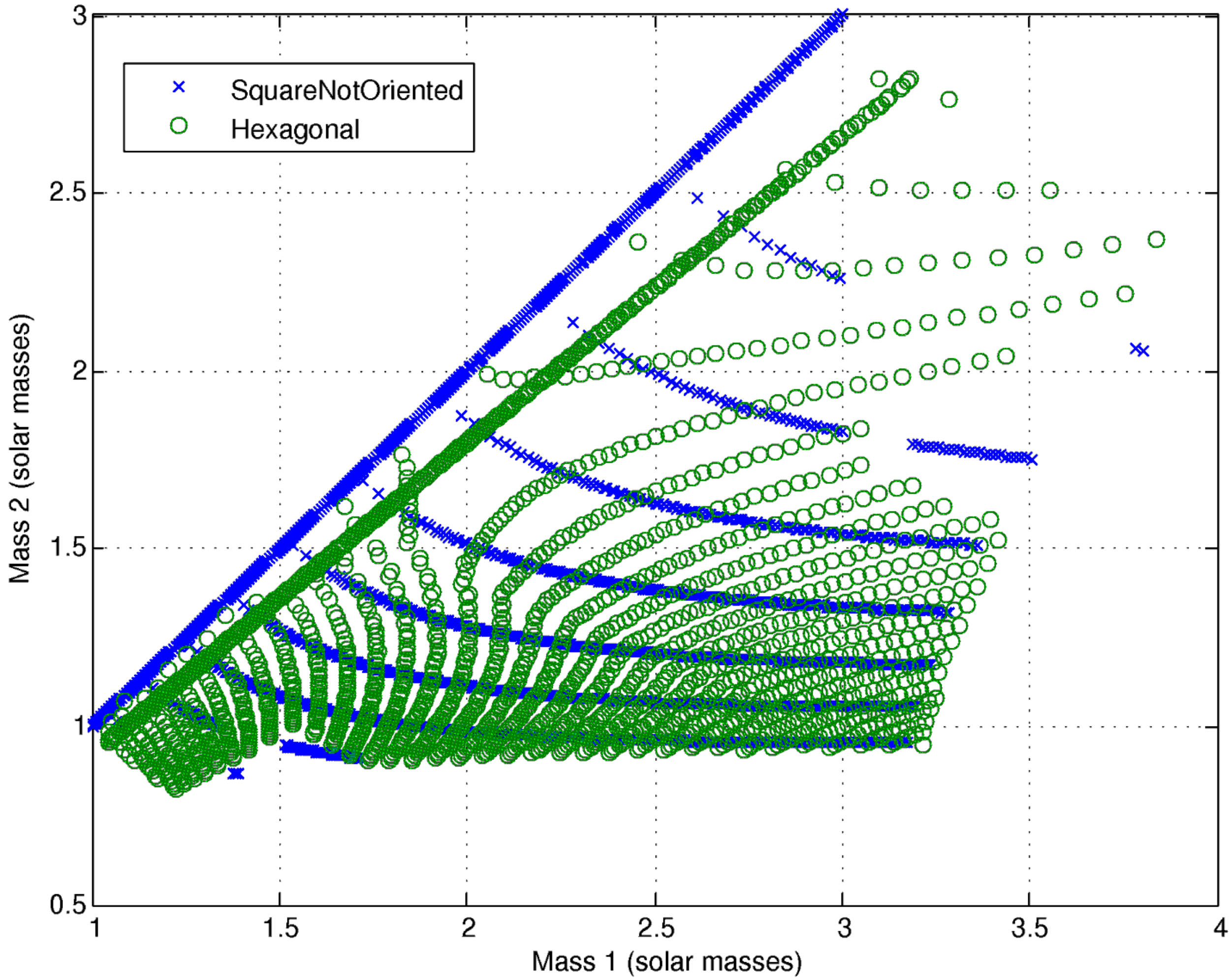
$$\tau_3 \propto m^{-2/3} / \eta$$

Ellipses in Mass Space
determine spacing for minimal match



Only a few (red) error ellipses shown, to motivate the template placement.

Different Bank Layout Methods



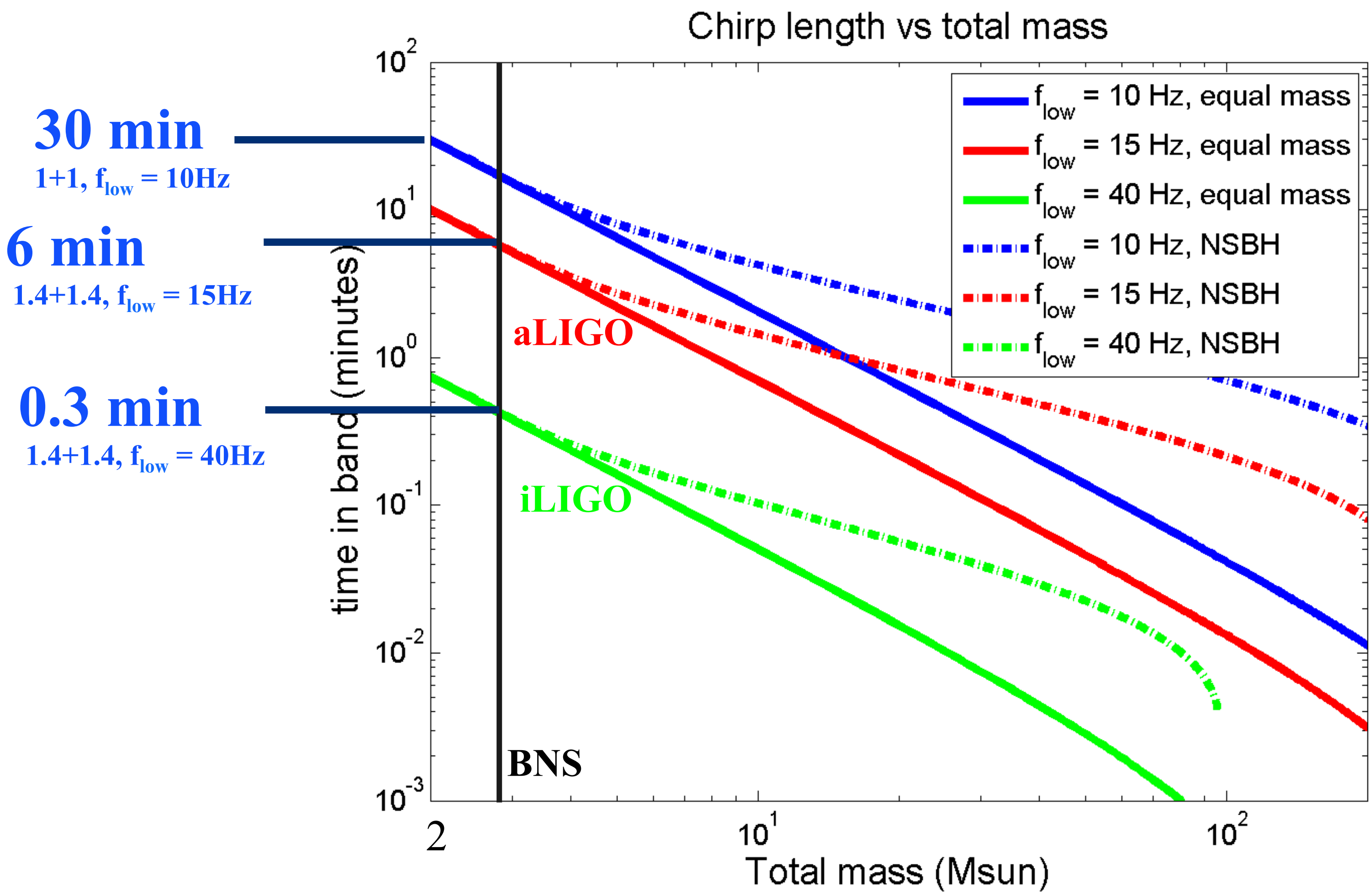
Hexagonal placement is easily automatable, and generalizable to N dimensions.

However, in higher dim, and/or if the metric is unknown or complicated, stochastic methods can be used to place templates at a specified min match.

Reducing the order of the problem

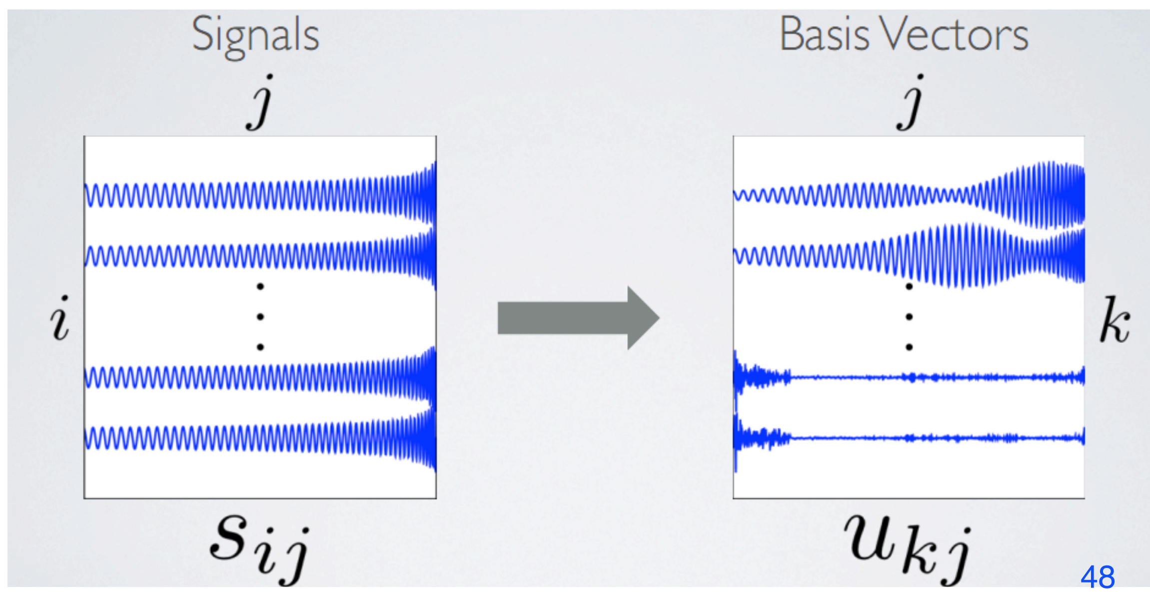
- Why filter through ~10,000 overlapping templates, when only a fraction of them are "independent"?
- Use ROM methods to decompose the template bank, find the "independent" templates, filter the data only through them, and reconstruct the response to the original templates in the bank afterwards.
- Will this save CPU time (at the expense of extra effort)?
- We think it *will* be necessary, specially as we move to:
  - » (much) longer waveforms (up to 30 min)
  - » (much) larger template banks covering larger parameter spaces (total mass, mass ratio, spins, …)
- Example: GstLAL: multi-banding, SVD, …

In-band chirp length

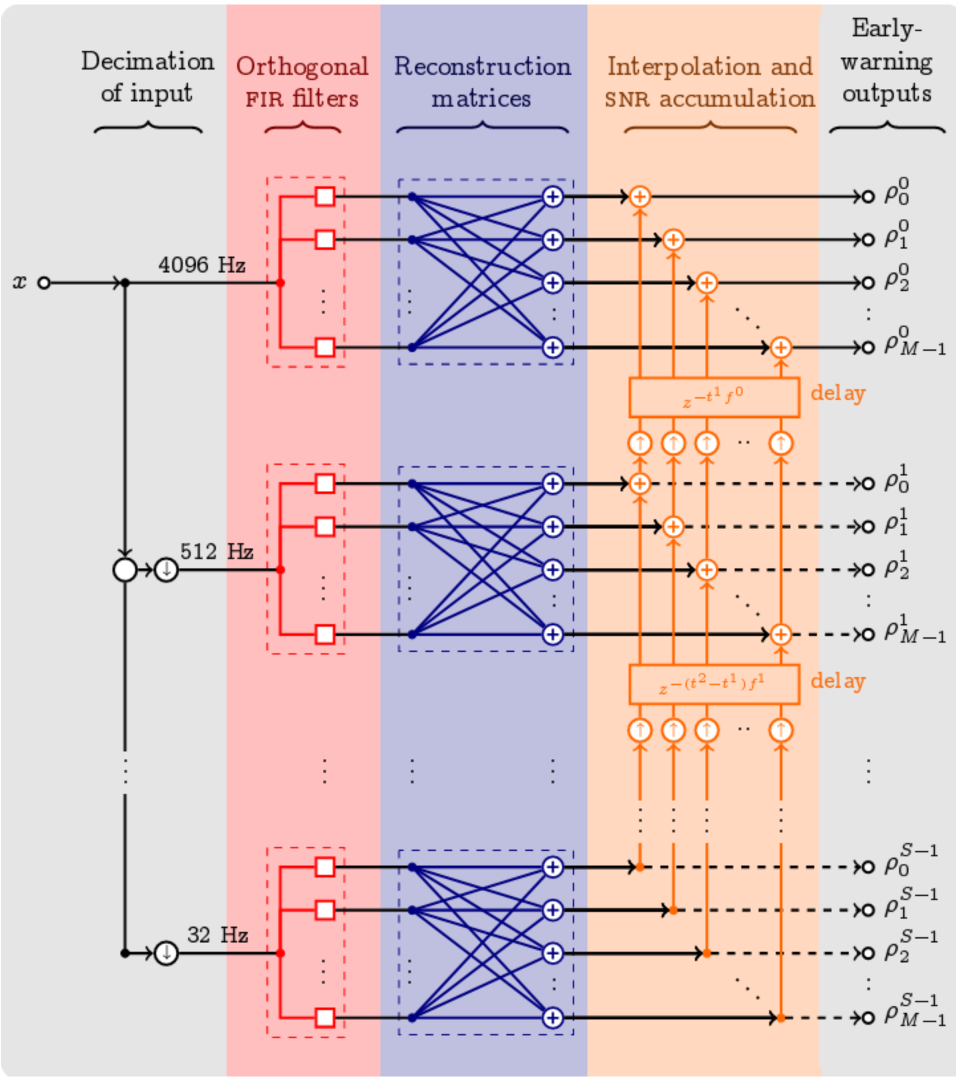


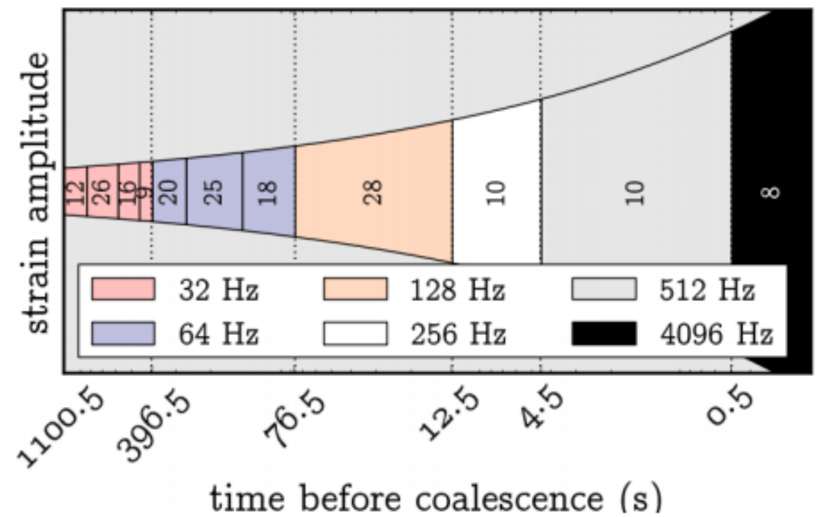
GstLAL_inspiral

- Built from “off the shelf” open-source signal processing tools (Gstreamer).
- Time-domain signal processing to handle long aLIGO waveforms.
- Multi-band / multi-rate filtering.
- Adaptive whitening.
- SVD to reduce the number of filters.
- Real-time trigger generation and adaptive event significance (FAR).
- Capable of very low (~s) latency.



GstLAL_inspiral multi-banding





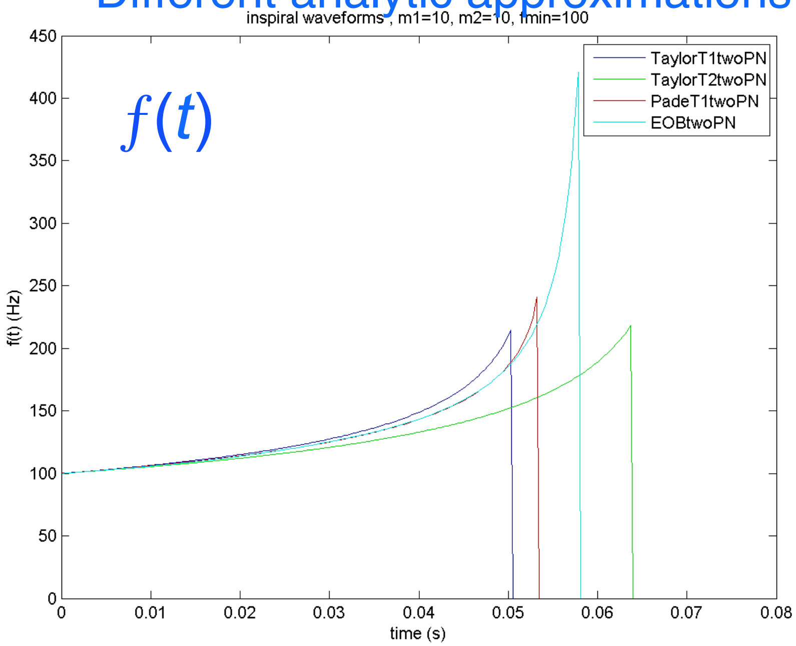
Cannon et al. (2012, ApJ 748:136)
http://dx.doi.org/10.1088/0004-637X/748/2/136

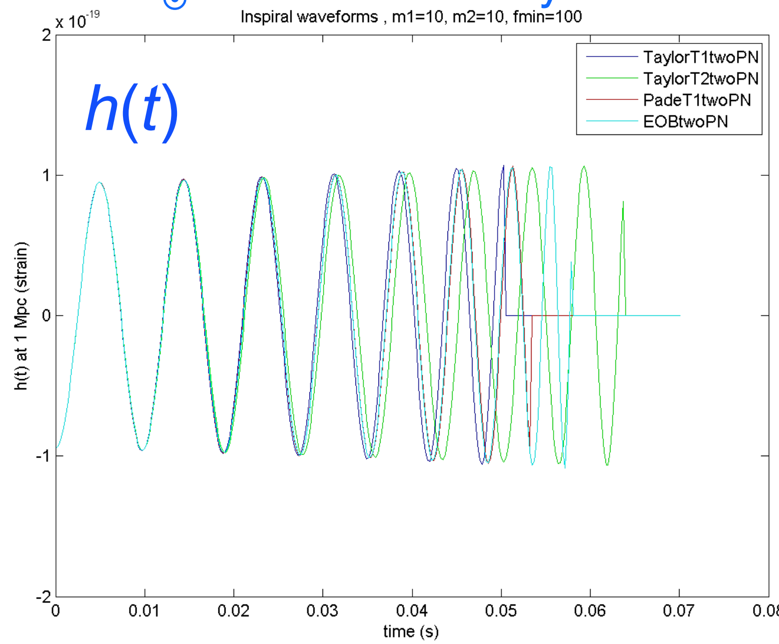
More & better waveforms needed!

- Optimal filtering requires accurate waveforms across the full detection band, phase coherent up to ~25,000 cycles!
- Phase evolution depends on spin as well as masses.
- Spins non-aligned with orbital L will cause precession of the orbital plane, AM at the detectors.
- Binaries with total mass above ~15 $M_{\odot}$ will merge in-band.
- We do not yet have fully parameterized waveforms covering precessing spin and merger & ringdown!
- Waveforms from binary neutron stars will be tidally distorted above 500 Hz, disrupted above 1000 Hz.
- What if GR fails in these extremely strong-field, highly dynamical regimes?

Analytic Waveforms are increasingly less accurate for high-mass binaries

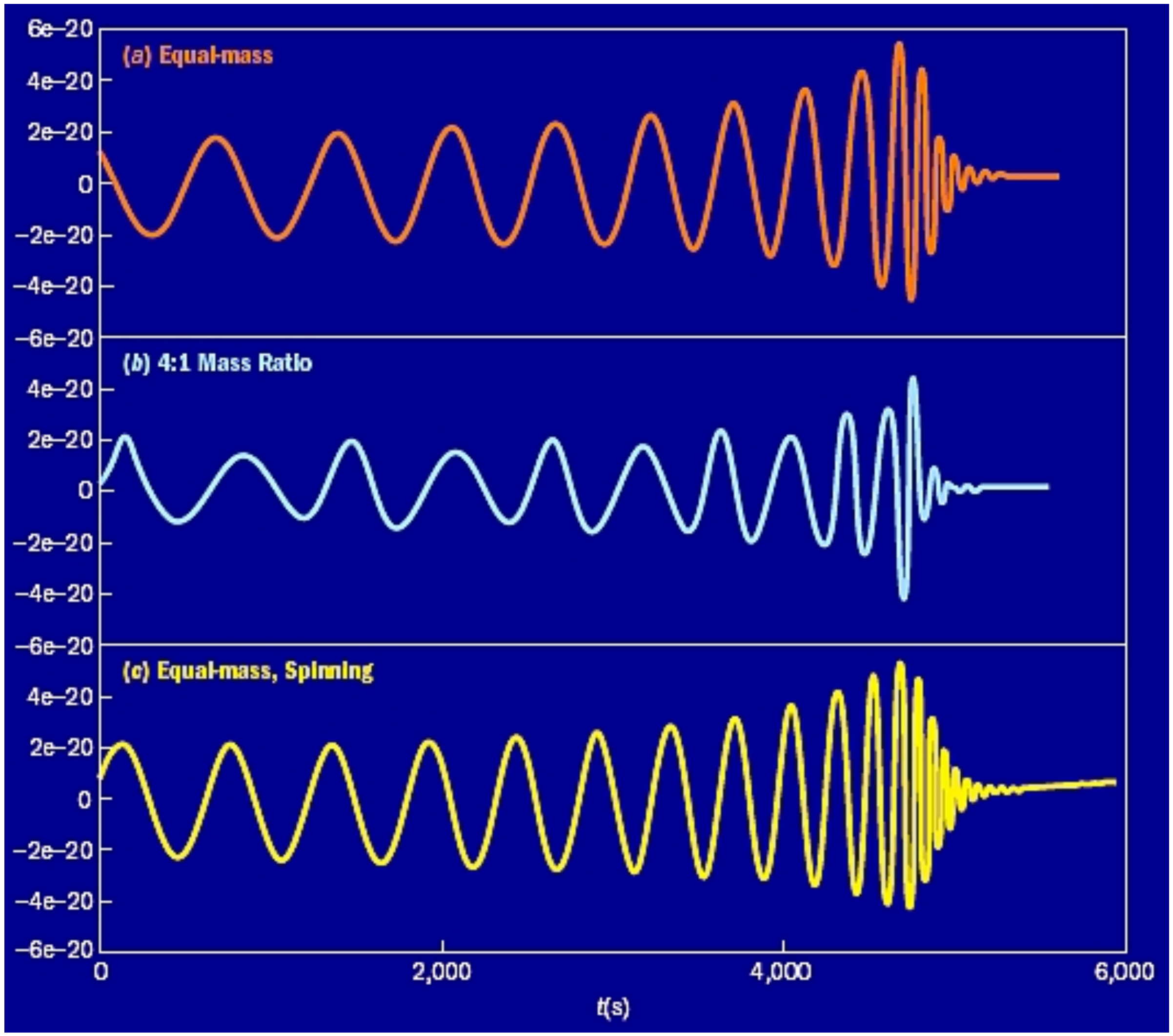
- Different analytic approximations for 10+10 $M_\odot$ black hole binary



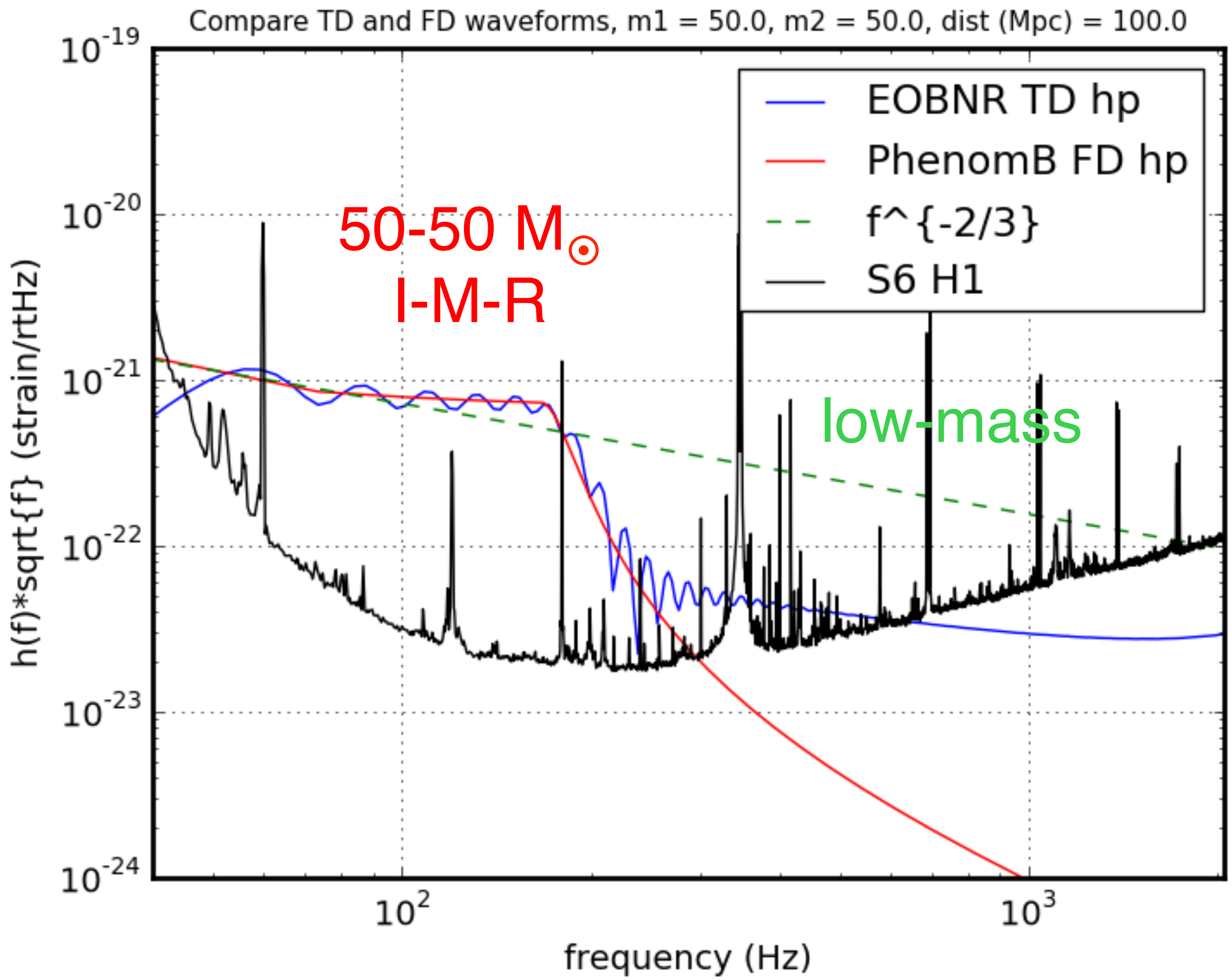


- PPN expansion for inspiral phase (in powers of v/c) breaks down as $v/c \rightarrow 1$, and increasingly depends on how the expansion is done.
- Also, black hole spin can have a large effect on the waveform, both in phase evolution and amplitude
- Higher mass systems transition from inspiral to merger and ring-down, in the detection band!

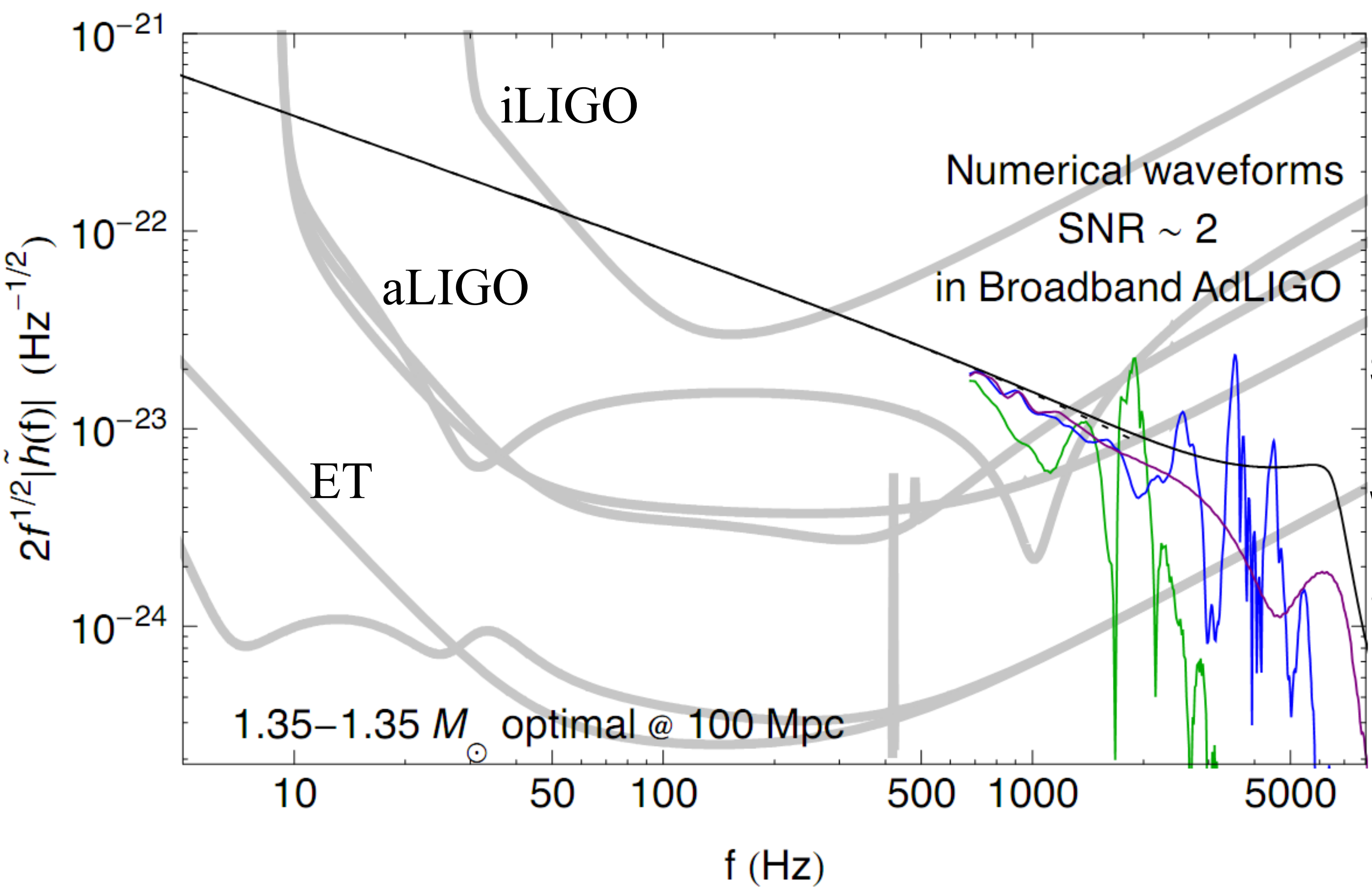
Phase evolution depends on mass ratio and spins

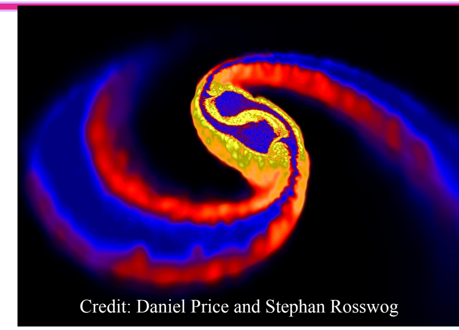


Higher mass systems merge in detection band



Effects of tidal disruption of neutron stars near merger



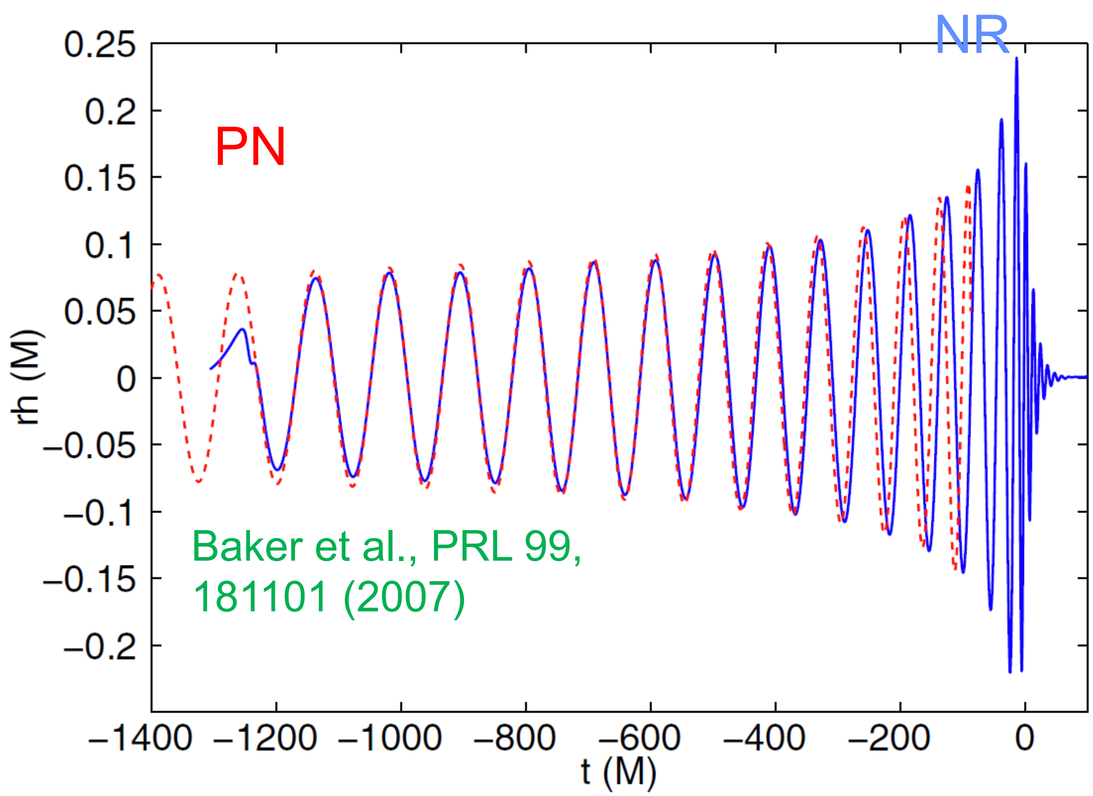


binary neutron stars

Waveforms from Shibata et al

Numerical Relativity to the Rescue !

- It's now possible to accurately calculate final stages of inspiral, merger, and subsequent ringdown
- Can construct "hybrid" waveforms, "stitching" PPN early inspiral to late-inspiral NR, to extend to detection band f_{min}:

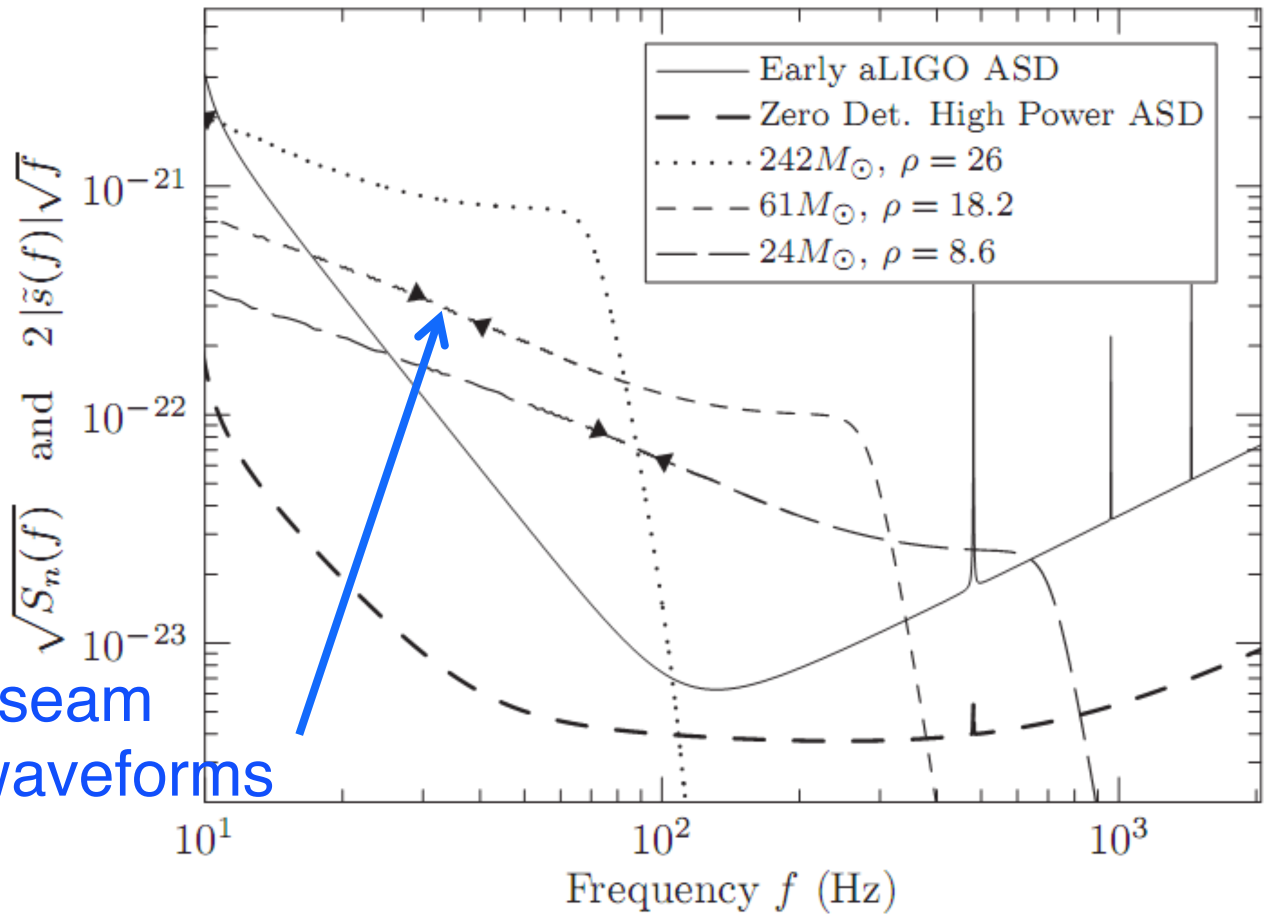


Can’t we just use NR waveforms?

- They currently only span the last few (tens) of cycles to merger.
  - Extend backward (to detection band f_{min}) by stitching to PPN analytical waveforms.
- They are very expensive to compute, especially for high mass ratios, high spin.
- We need to cover a large parameter space, 8-dim (masses and spins). This is a large space to sample finely!
- AND we need to have smooth, continuous coverage of that parameter space, especially for parameter estimation.
  - Use analytical or phenomenological waveform models “tuned” to NR.
- Can we make use of a small number of hybridized NR waveforms that sample the parameter space, and “interpolate” between them using ROM methods?

Higher-mass BBH systems merge and ring down in the detection band

Class. Quantum Grav. **29** (2012) 124001 P Ajith *et al*

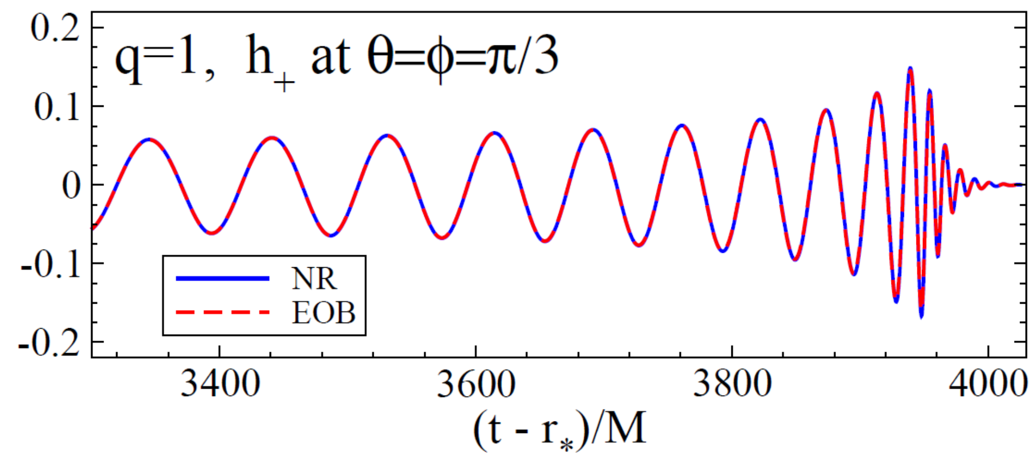


stitching seam
to PPN waveforms

Analytic Model Tuned Using NR

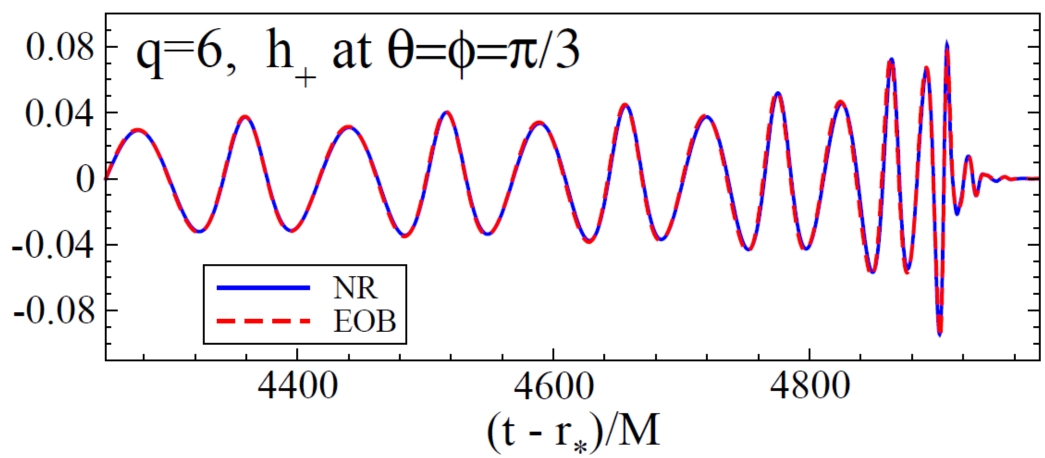
- "EOBNR" : Effective One-Body model, with some parameters adjusted to match NR waveforms

Equal mass
(non-spinning)



Pan et al., PRD 84, 124052 (2011)

Mass ratio 6:1



Coarse sampling of 3-dim parameter space (NINJA2)

Class. Quantum Grav. **29** (2012) 124001 P Ajith *et al*

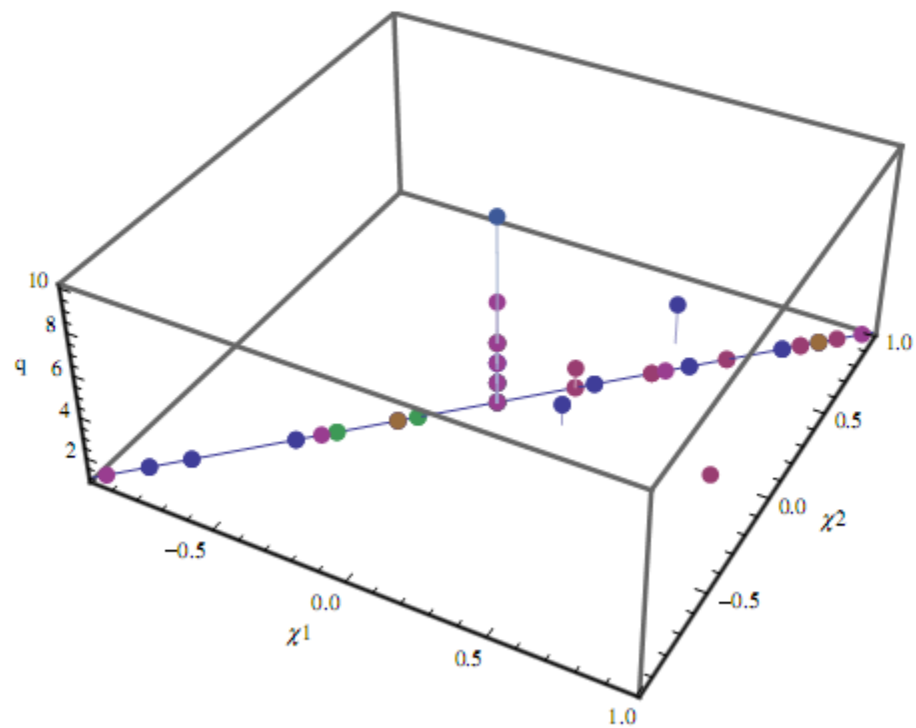
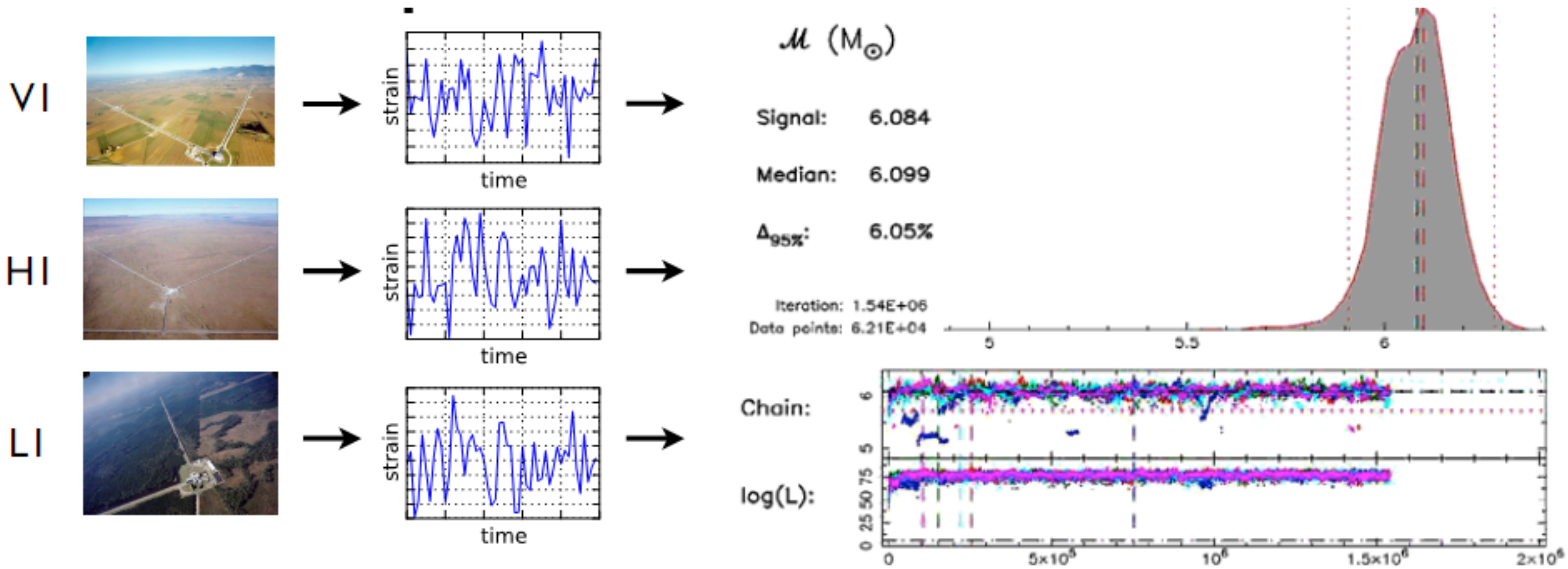


Figure 2. The mass ratio q and dimensionless spins χ_i of the NINJA-2 hybrid waveform submissions.

LIGO Parameter estimation using Markov Chain Monte Carlo (MCMC) sampling



Vivien Raymond, <http://www.ligo.caltech.edu/~vraymond/>

- Input: strain time series from all detectors
- Stochastically sample from parameter space, compute overlap of signal with data in each detector
- Sample distribution converges to posterior
- Can be computationally expensive
- Takes hours to days, currently

Some conclusions

- GW signals from astrophysical sources come in a huge variety of morphologies, durations, bands, and level of understanding / model-ability.
- They share one common property: by the time they reach us, they are *weak*.
- Pulling these signals out of noisy data, and extracting their astrophysical parameters, is a huge challenge, computationally and intellectually.
- We need all the clever and powerful techniques we can bring to bear on the problem… like ROM.