Gravitational Wave Searches in the Advanced Detector era

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for the LIGO Scientific Collaboration

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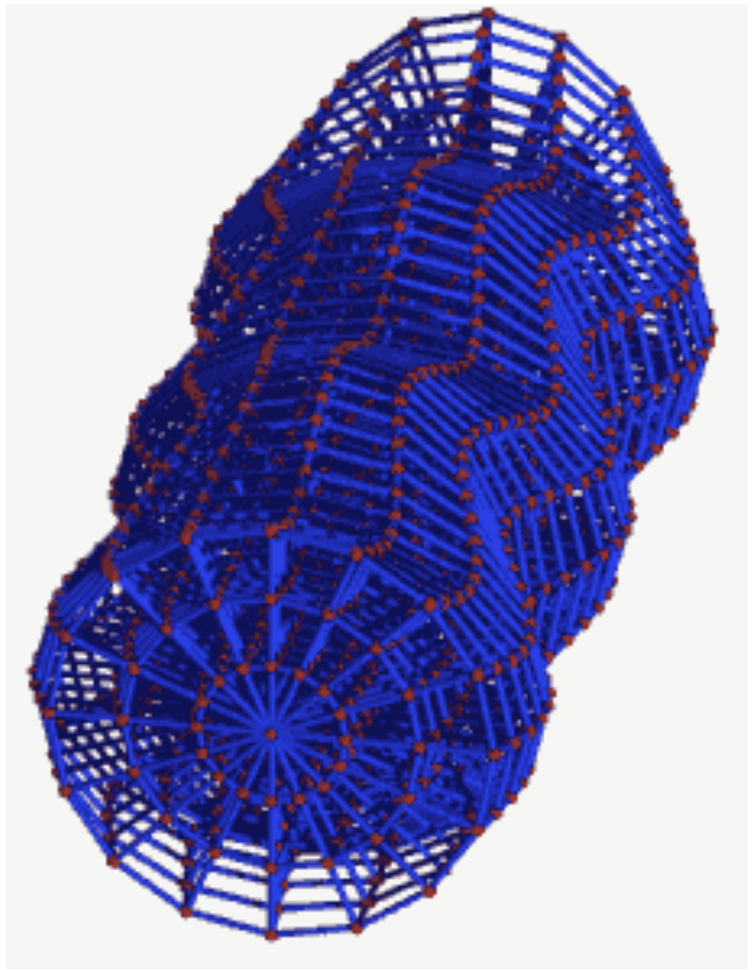
Gravitational waves

- Changing curvature of space around moving objects
- Information about change propagates outward at speed of light
- Linearized GR → wave equation
- GW stretch and squeeze the distance between freely-falling objects
- Measure strain: h ~ ΔL/L (amplitude, not energy)
- Two polarizations: + and x

Face-on particle responses

Propagation



Example source

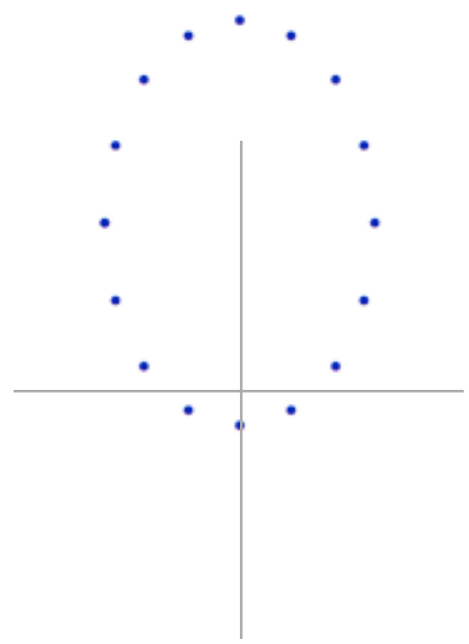
Massive objects orbit

$$L_{\mathrm{GW}} \sim \left(\frac{c^5}{G}\right)\left(\frac{v}{c}\right)^6\left(\frac{R_{\mathrm{S}}}{r}\right)^2$$

$$\sim 10^{59}\ \mathrm{erg/s}$$

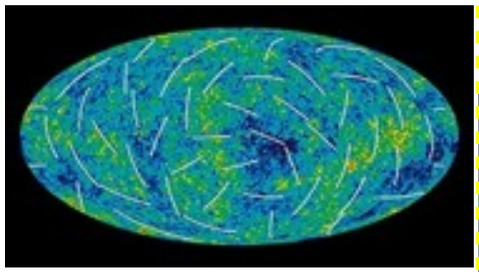
$$L_{\mathrm{GRB}} \sim 10^{49\text{-}52}\ \mathrm{erg/s}$$

Waves seen from above orbital plane



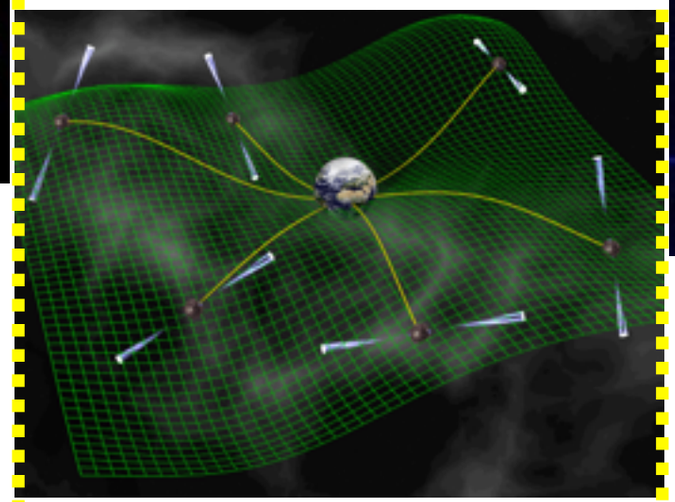
$$h \sim \frac{G}{c^4}\frac{E_{\mathrm{NS}}}{r} \sim 10^{-21}$$

The gravitational wave spectrum: potential measurements



Cosmic Microwave Background

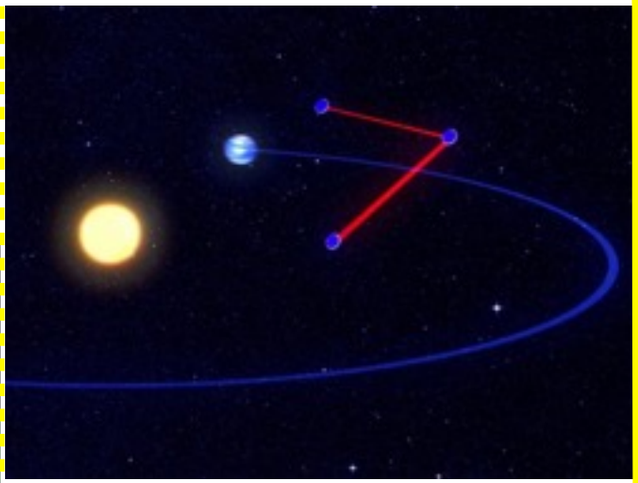
10^{-16} (today)



IPTA

Pulsar timing

10^{-8} (~cycle/year)



eLISA

Space-based interferometer

10^{-4}

LIGO

KAGRA

LIGO

Virgo

Ground-based interferometers

10^{2} (audio)

GW frequency (Hz)

Sources of gravitational waves: mass in motion

Early Universe:

Inflation, Phase Transitions

Supermassive binary black hole mergers

Compact objects captured by supermassive black holes

Compact object binaries

10^{-16} (today)

10^{-8} (~cycle/year)

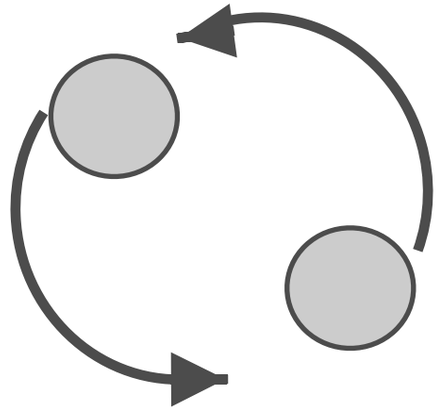
10^{-4}

10^{2} (audio)

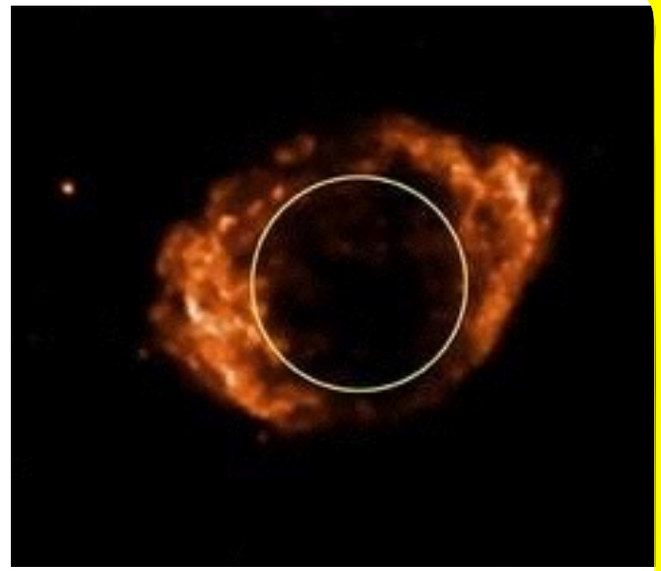
GW frequency (Hz)

Sources of gravitational waves in LIGO band

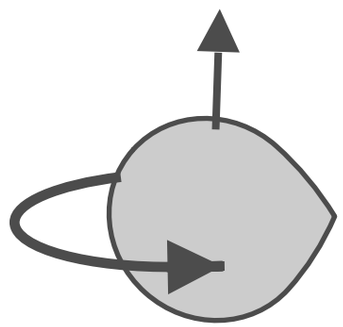
Merging neutron stars & black holes



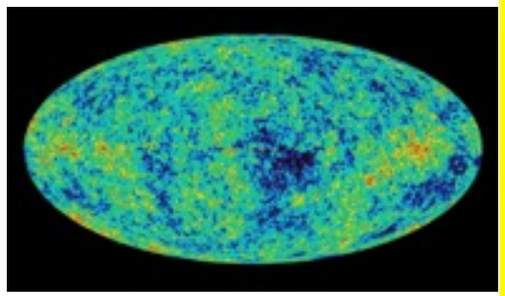
Non-spherical explosions (supernova)



Spinning neutron star with asymmetry, long-lived oscillations



Stochastic signals: inflation, phase transitions



Surprises

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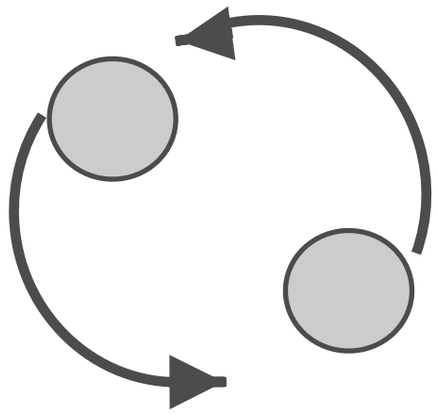
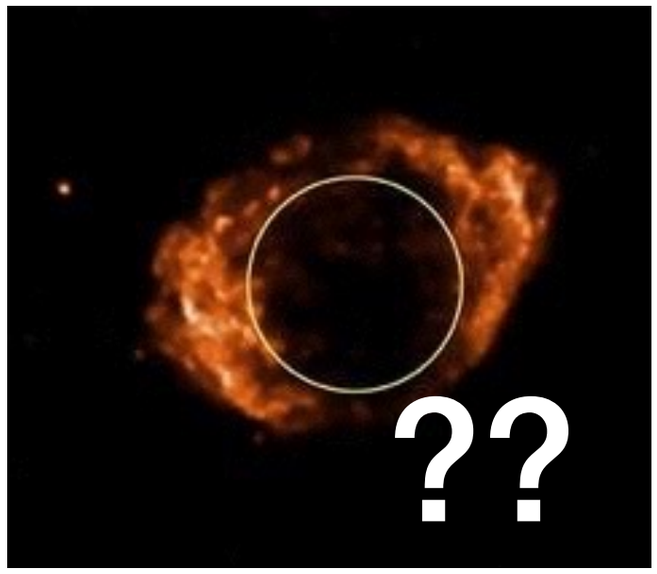
Major Searches for GW in LIGO band

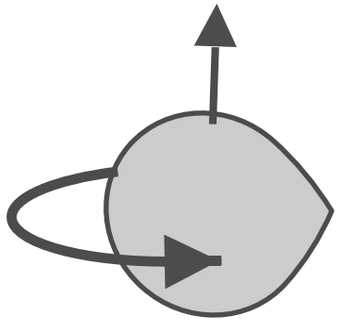
Template-based matched filters



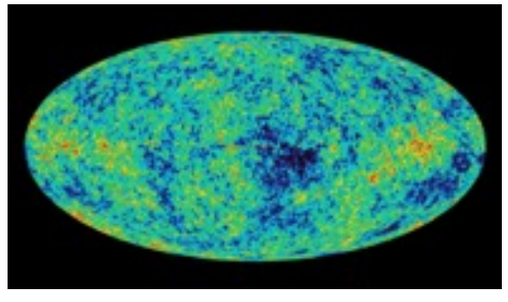
Unmodeled burst



Continuous wave

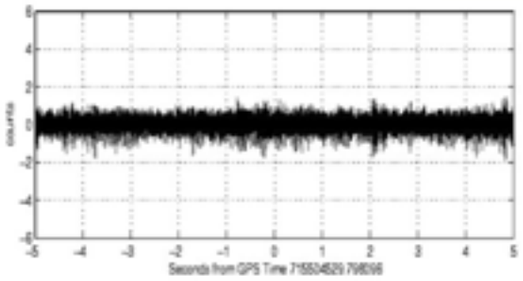


Stochastic



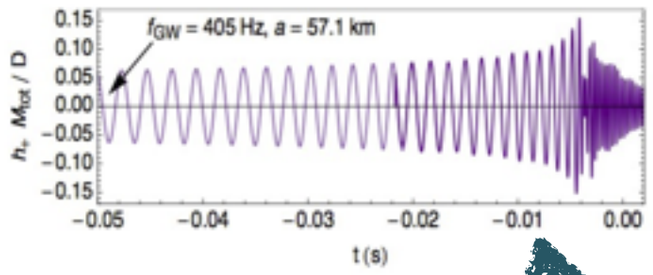
Matched Filtering for compact binary coalescence

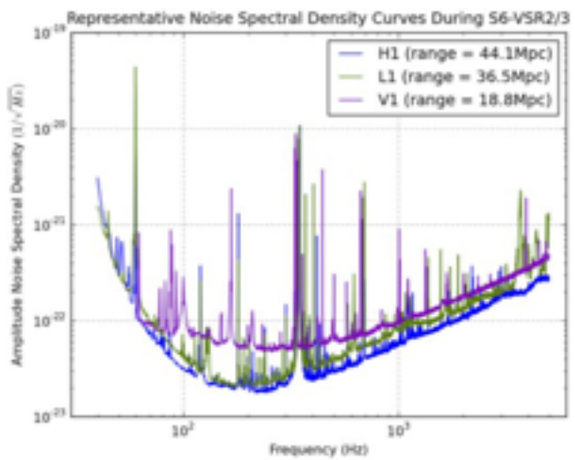
Data



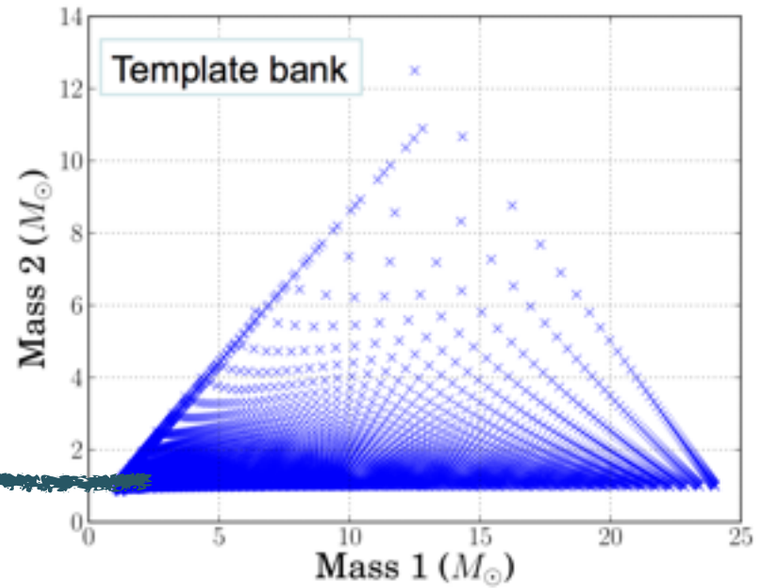
X

Template





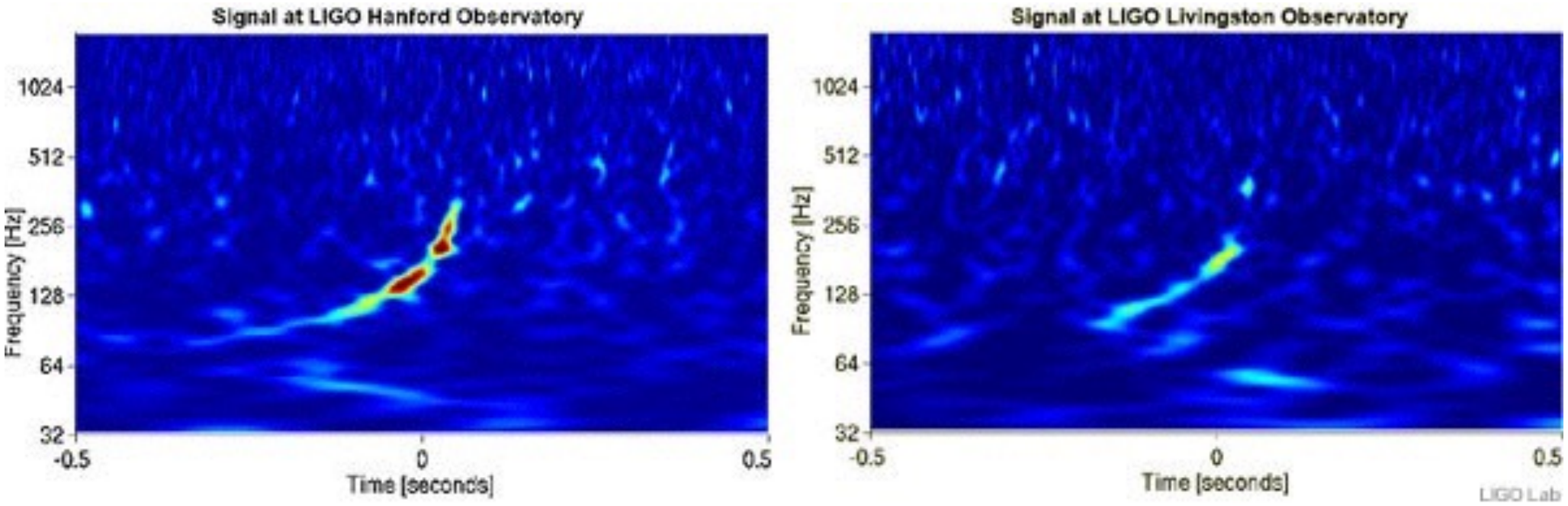
Noise



- Integrate known signal prediction against data over many cycles
- Coincident time and template in all detectors
- Distribution of SNR consistent with signal (χ^2 test)
- Previous results: http://arxiv.org/abs/1111.7314, http://arxiv.org/abs/1209.6533

Bursts

- transient signals with no assumed model waveform
- coherent signal in multiple detectors
- “excess power”: decompose in time-frequency space (fourier, wavelet…), identify and cluster loud pixels
- Previous results: http://arxiv.org/abs/1202.2788

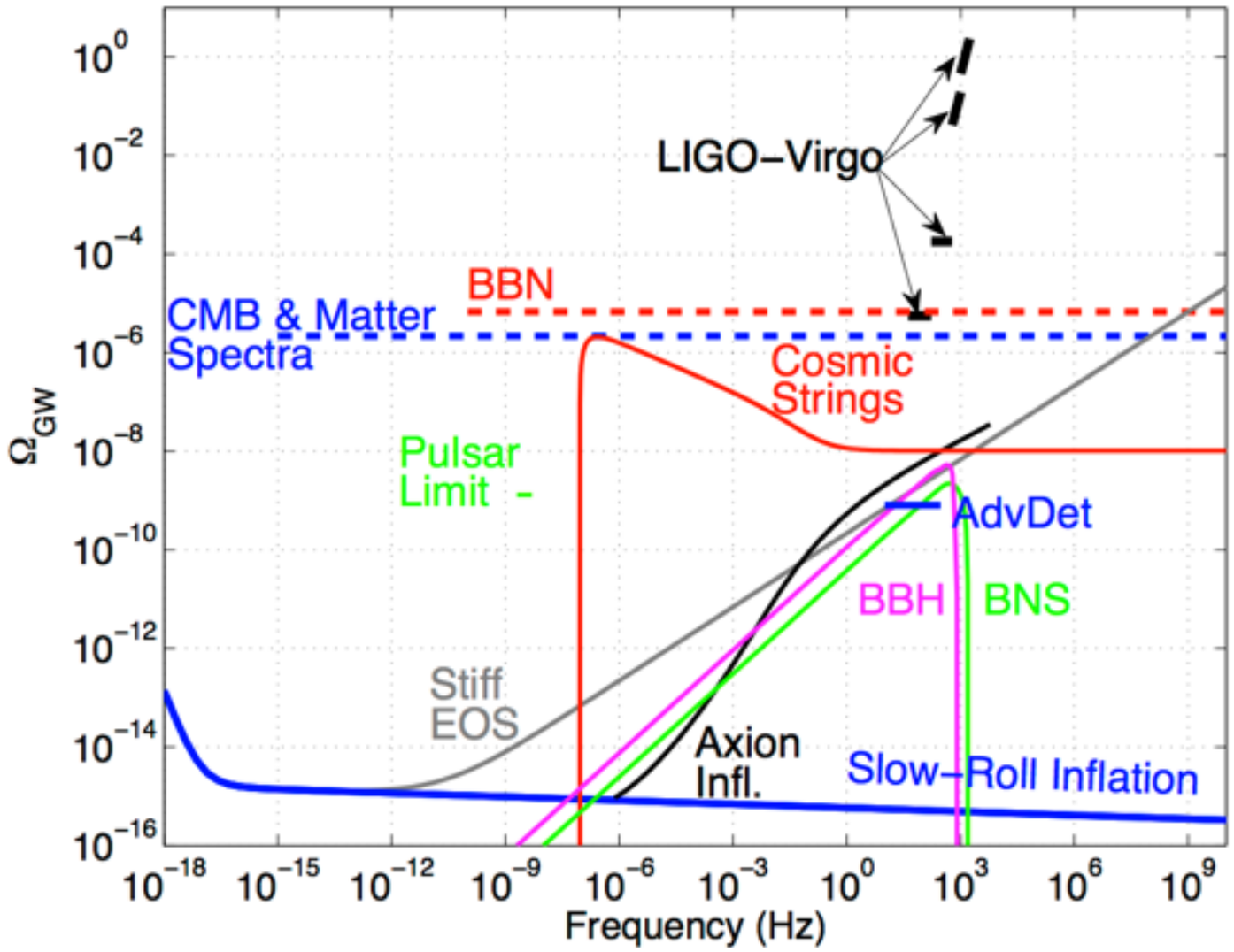


blind injection spectrograms (http://www.ligo.org/news/blind-injection.php)

Stochastic

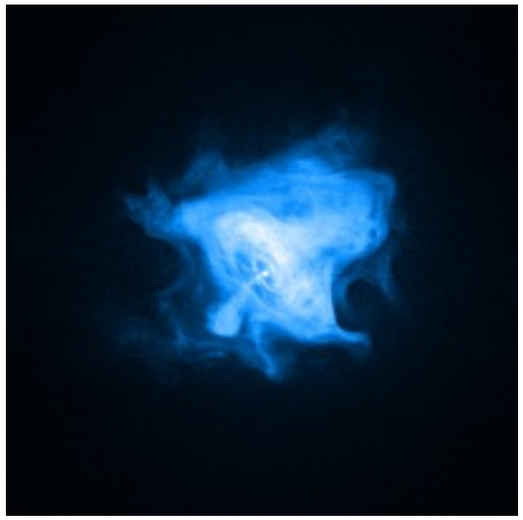
- Cross-correlating between multiple detectors to check for steady background “hum” of gravitational waves
- Background may come from superposition of weaker astrophysical sources or from early universe dynamics
- Previous result: http://arxiv.org/abs/1406.4556

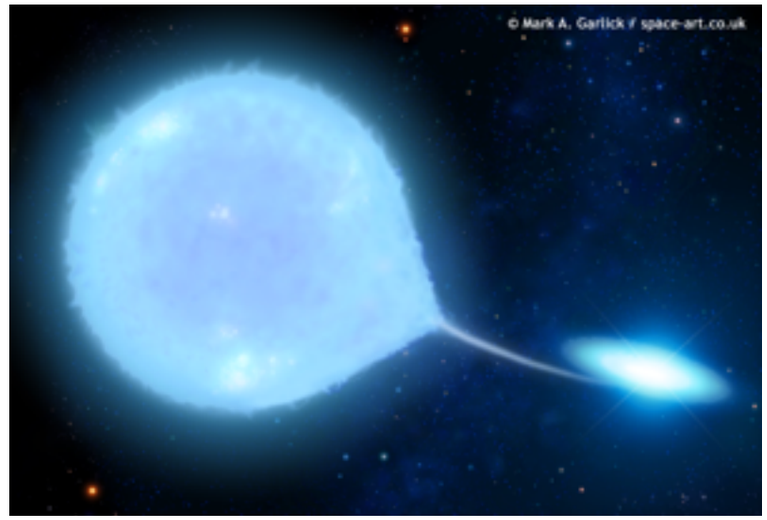
$$\hat{Y} = \int_{-\infty}^{\infty} df \int_{-\infty}^{\infty} df' \delta_T(f - f') \tilde{s}_1^*(f) \tilde{s}_2(f') \tilde{Q}(f')$$

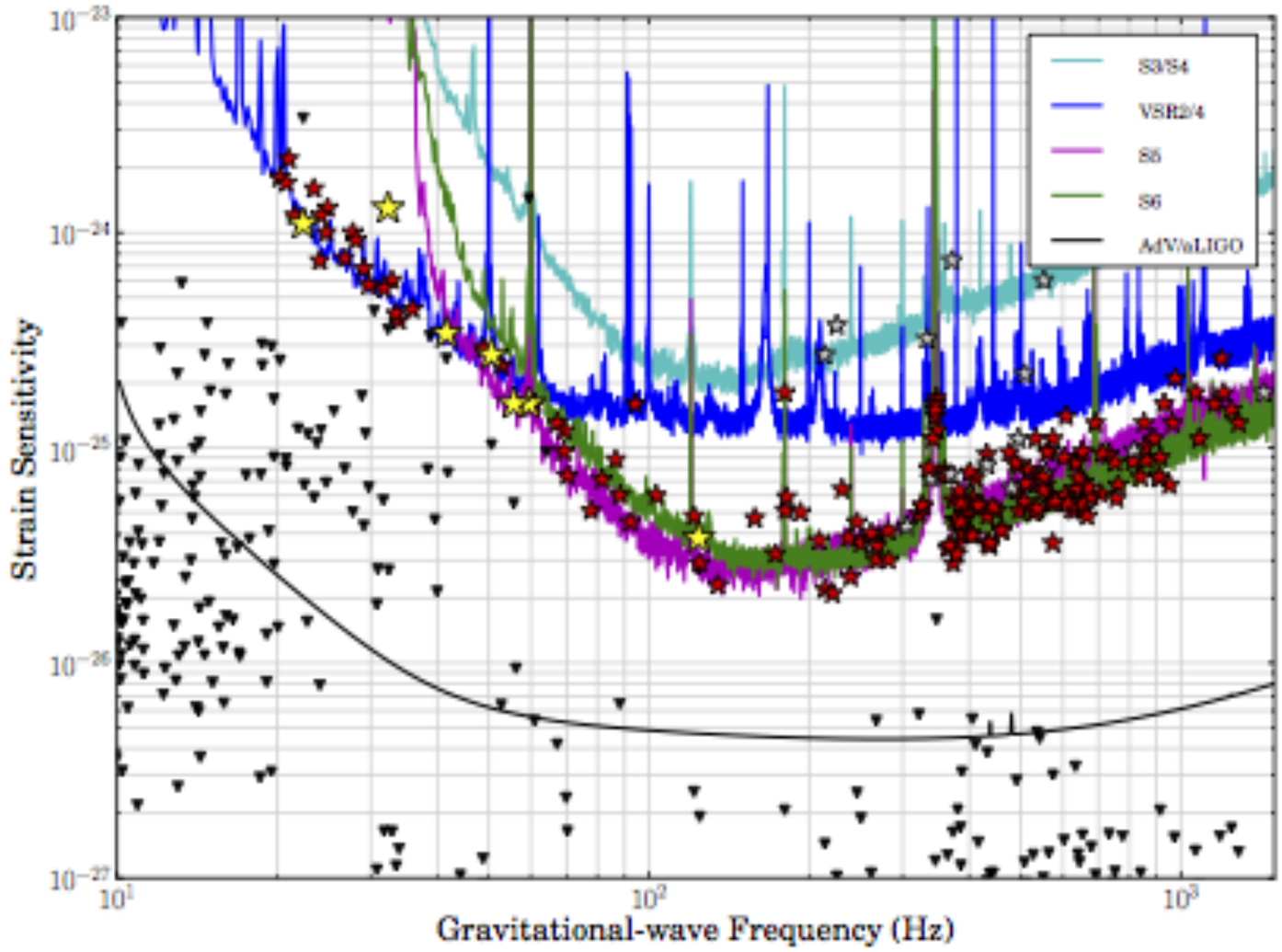


Continuous

- Assumed sources: asymmetric rotating neutron stars
- Computationally challenging complications: Doppler modulation, spin-down
- “Directed”: Sky position known but not frequency (e.g. Cas A supernova remnant)
- “Targeted”: Sky position and frequency known
- Advanced LIGO expects to beat spin-down limits for ~dozen pulsars (2014 White Paper)







Previous result: http://arxiv.org/abs/1309.4027

Many other searches and constraints (no GW candidates) from Initial LIGO and Virgo data (taken 2002-2010).

See:
https://www.lsc-group.phys.uwm.edu/ppcomm/Papers.html

General-audience summaries:
http://www.ligo.org/science/outreach.php

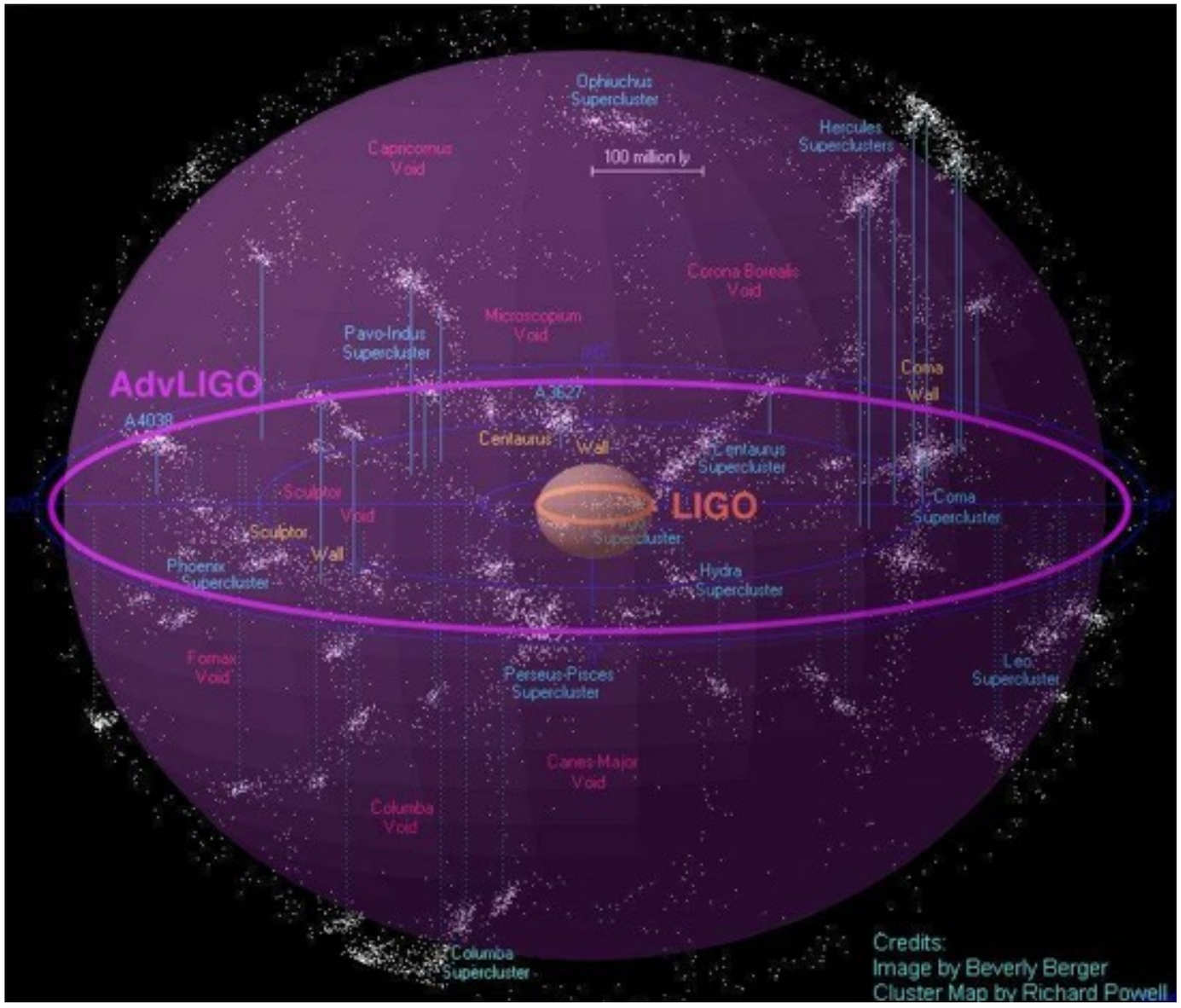
Advanced LIGO (2015+)

August 2013 installation of quadruple suspension in Hanford, Washington

Detection prospects of Advanced LIGO design

- binary neutron star mergers to ~200 Mpc
- binary black hole mergers to ~1 Gpc
- neutron star–black hole mergers to ~0.5 Gpc
- unmodeled transients with energy of some galactic supernovae predictions
- (LIGO White Paper: https://dcc.ligo.org/LIGO-T1400054/public, rates above sky-averaged)

initial LIGO range: up to 20 Mpc



BNS rate of 0.4 - 400 yr^{-1}

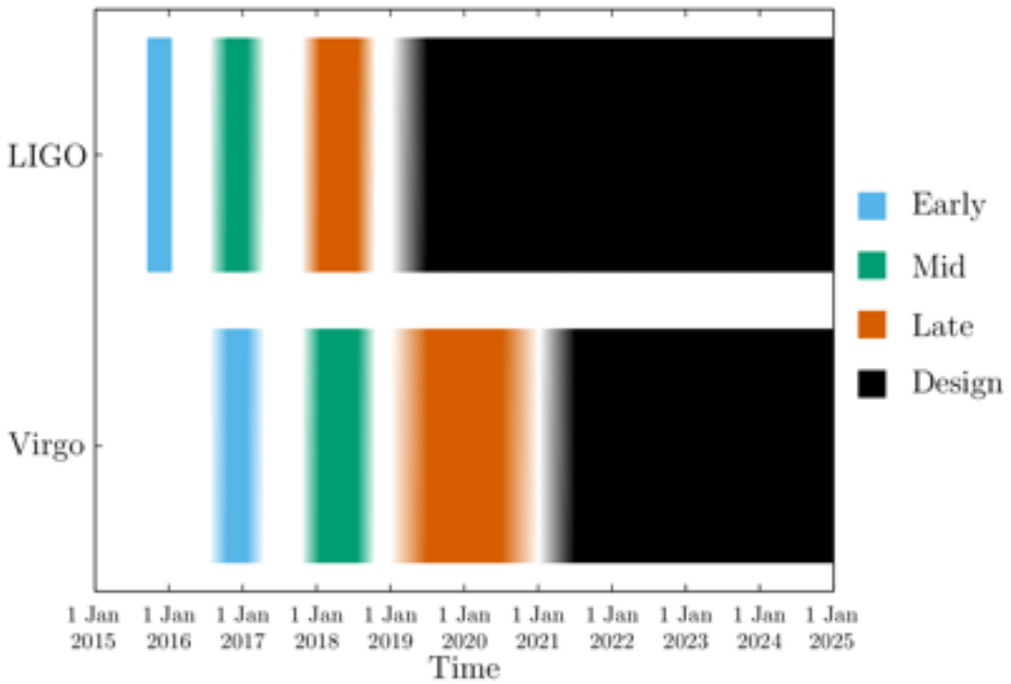
BBH rate of 0.4 - 1000 yr^{-1}

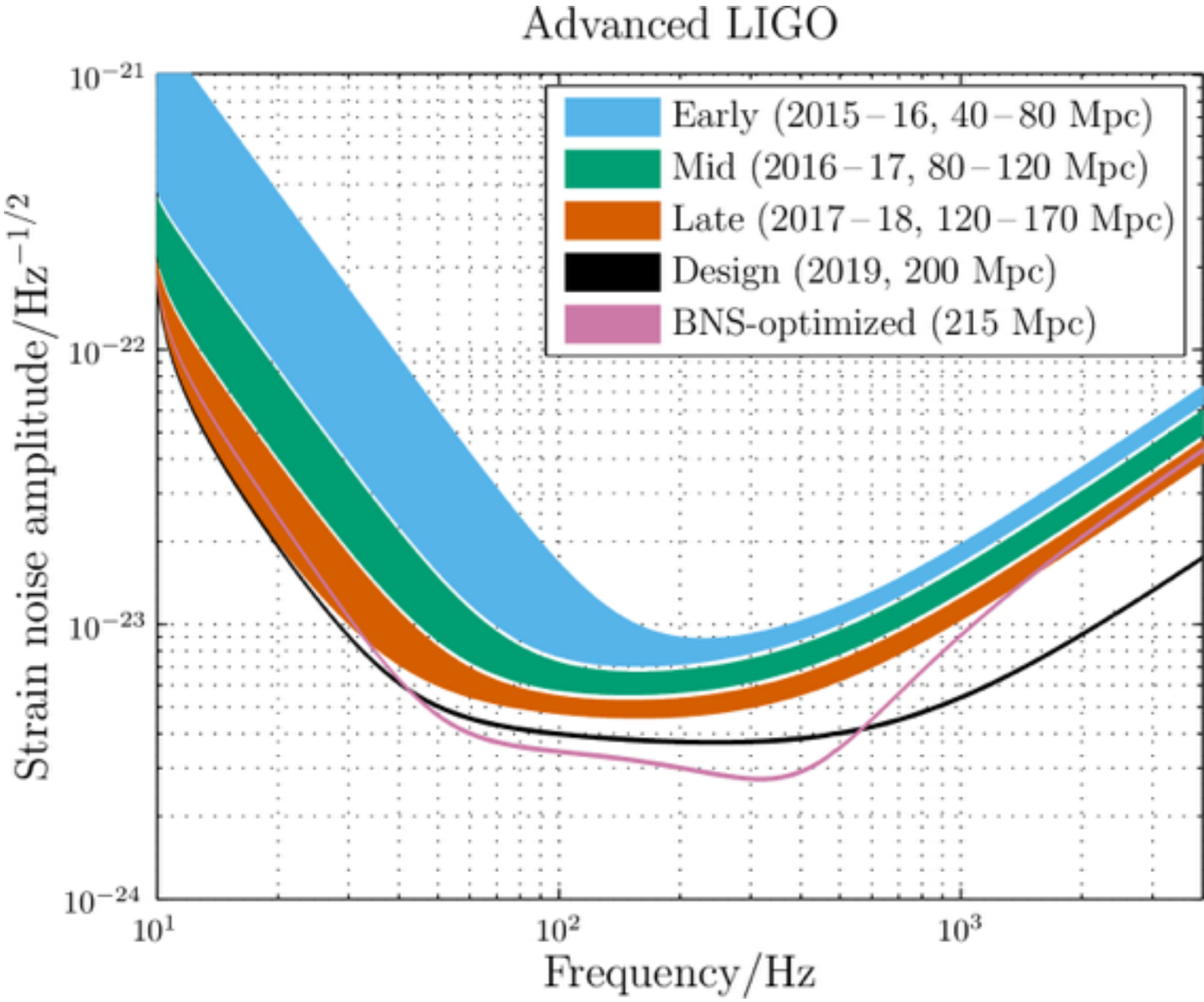
NSBH rate of 0.2 - 300 yr^{-1}

LSC/VSC arxiv:1003.2480v2

Commissioning and observing roadmap

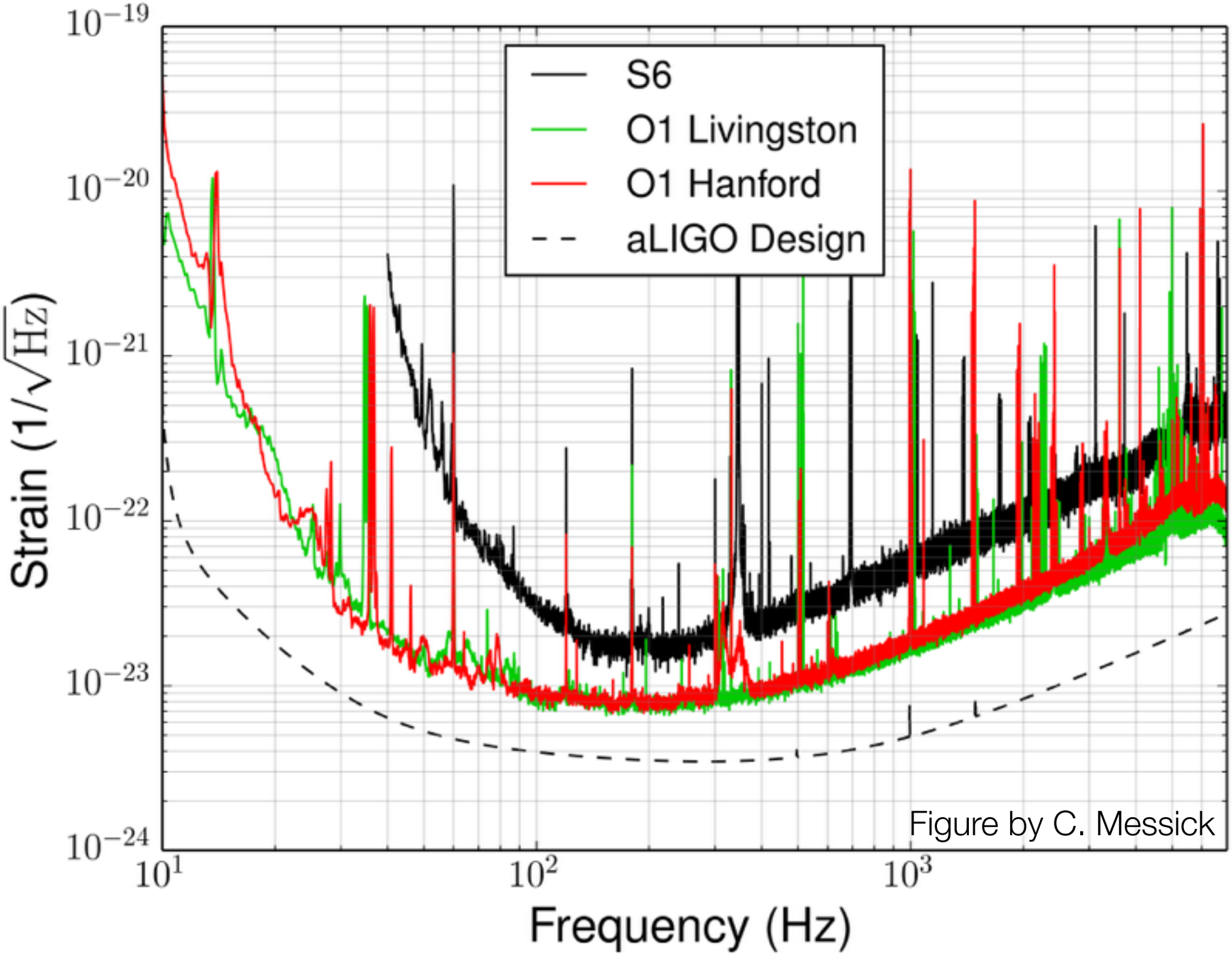
- LSC/VSC Living document at: http://arxiv.org/abs/1304.0670





Epoch		2015 – 2016	2016 – 2017	2017 – 2018	2019+
Estimated run duration		4 months	6 months	9 months	(per year)
Burst range/Mpc	LIGO	40 – 60	60 – 75	75 – 90	105
	Virgo	—	20 – 40	40 – 50	40 – 80
BNS range/Mpc	LIGO	40 – 80	80 – 120	120 – 170	200
	Virgo	—	20 – 60	60 – 85	65 – 115
Estimated BNS detections		0.0005 – 4	0.006 – 20	0.04 – 100	0.2 – 200

First observing run (O1) from Sept 18 2015 to Jan 12 2016



https://dcc.ligo.org/LIGO-G1500623/public , https://dcc.ligo.org/LIGO-T1100338/public,

Merging binaries: most expected GW detections

- How many mergers are there? (Population constraints)
- What are black hole and neutron star masses and spins?
- Do binary coalescences produce short gamma ray bursts? (Other EM?)
- What is inside a neutron star? (Equation of State)
- Test General Relativity in dynamic strong-field regime: merger dynamics, black hole hair

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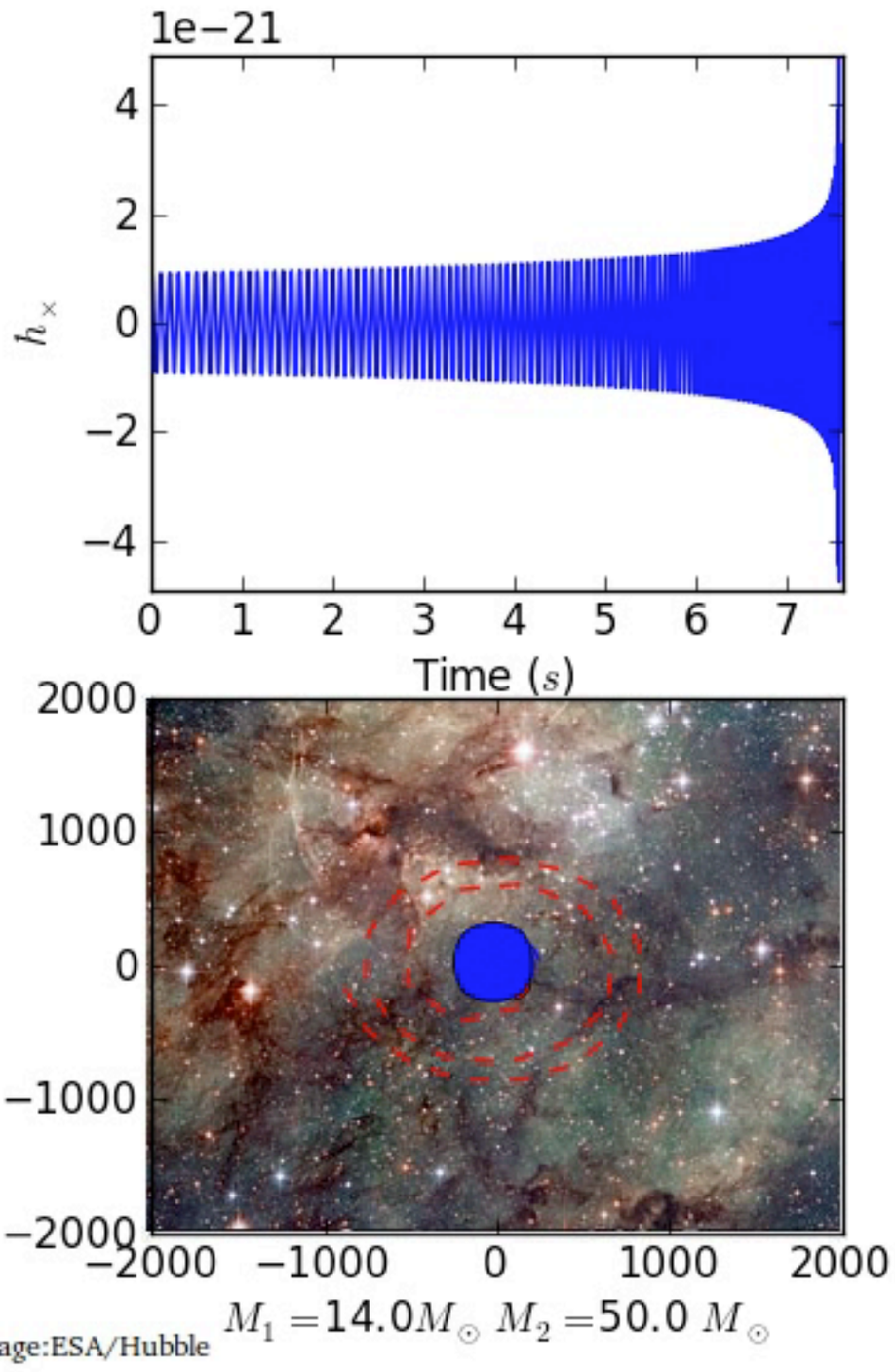
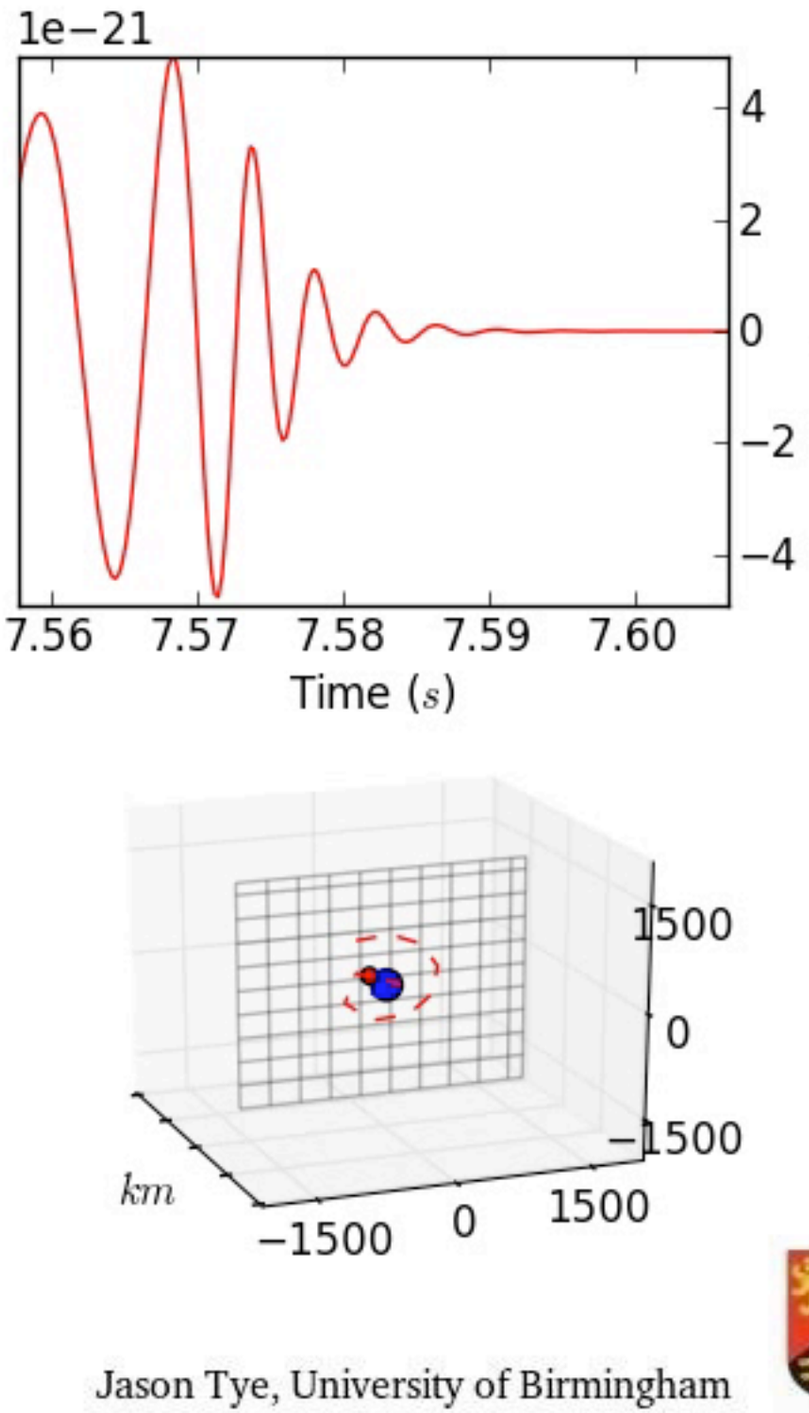
Frequency of a GW traces the frequency of orbits



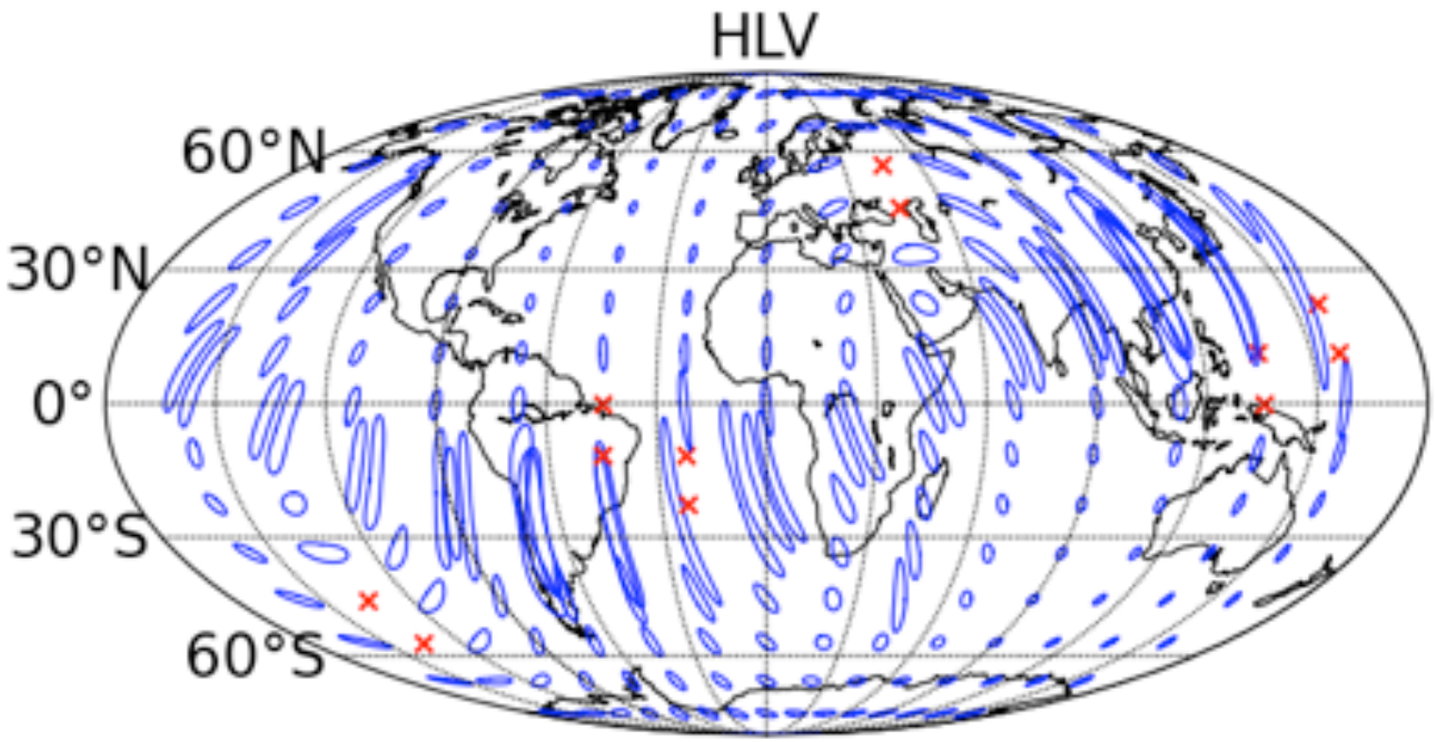


- Movie:
- 14 $M_\odot$ and 50 $M_\odot$ black holes
- slowed down by a factor of 4 to see/hear detail

Parameters that affect the signal (may be measurable)

- Masses
- Sky position
- Luminosity distance and orientation
- Spins
- Neutron-star tides/ disruptions
- Eccentricity

Sky localization for source at 160 MPc with 3 detectors ~2019 (http://arxiv.org/abs/1304.0670)

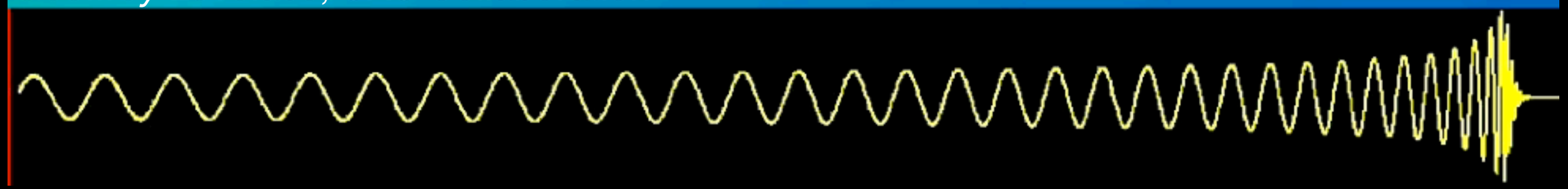


Phase evolution of wave

$$\Psi(f) = 2\pi i f(1+z)t_c + \phi_c + \frac{3}{128}\frac{1}{\eta\,(M\pi f(1+z))^{5/3}} \times \left(1 + \mathrm{PN} - 625\frac{\lambda}{M^5}(\pi M(1+z)f)^{10/3}\right)$$

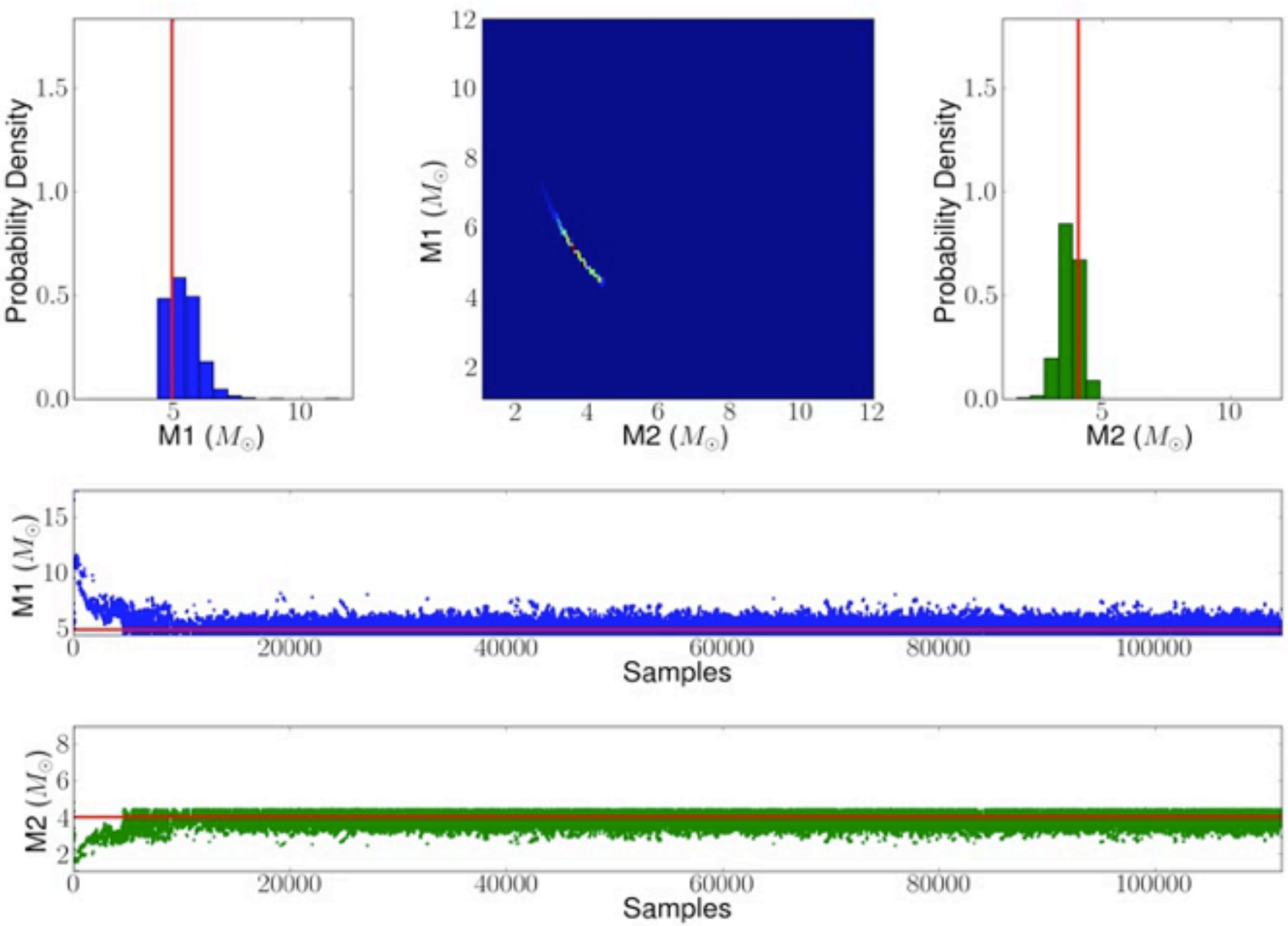
Binary Black Holes: numerical simulation

Movie courtesy Harald Pfeiffer,
Geoffrey Lovelace, SXS Collaboration



depth: spacetime curvature colors: flow of time arrows: flow of space

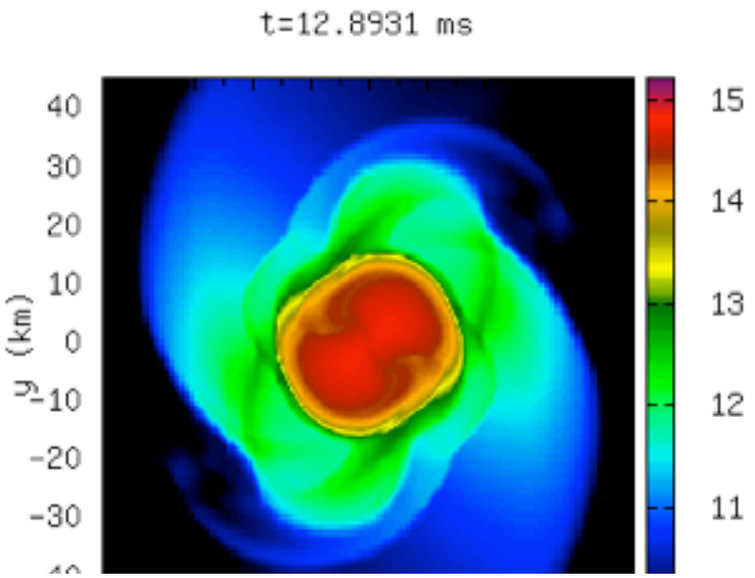
Parameter estimation: masses

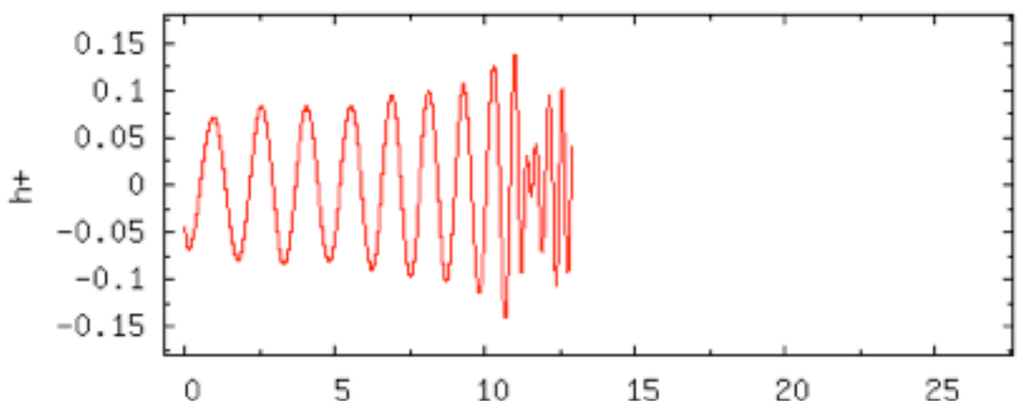


- LSC/VSC http://arxiv.org/abs/1304.1775
- Status of parameter estimation pipelines
- LEFT: example estimate of masses in BBH

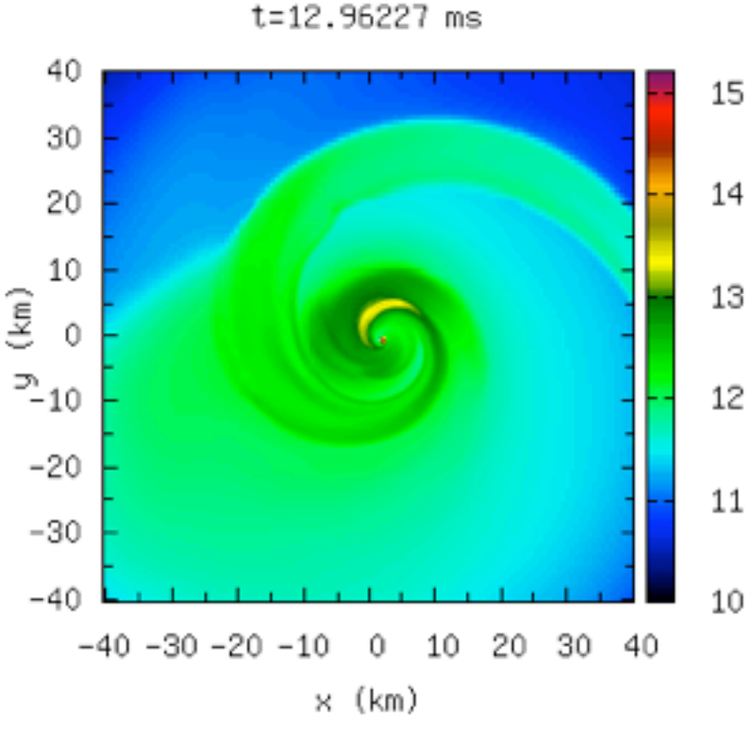
Effects of dense matter on neutron-star mergers

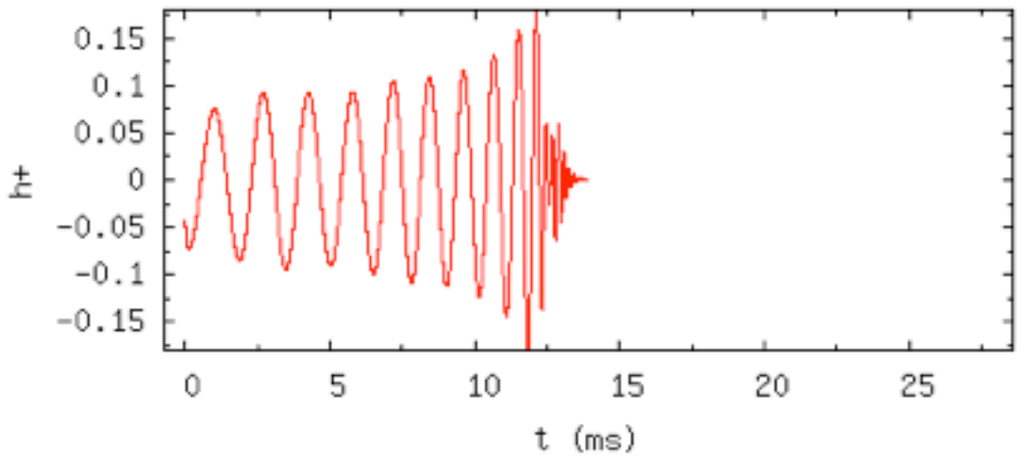
Large neutron stars





Compact neutron stars





Simulations/ animations by K Hotokezaka,
impact for Advanced LIGO http://arxiv.org/abs/1306.4065

LIGO as an astrophysical-scale collider

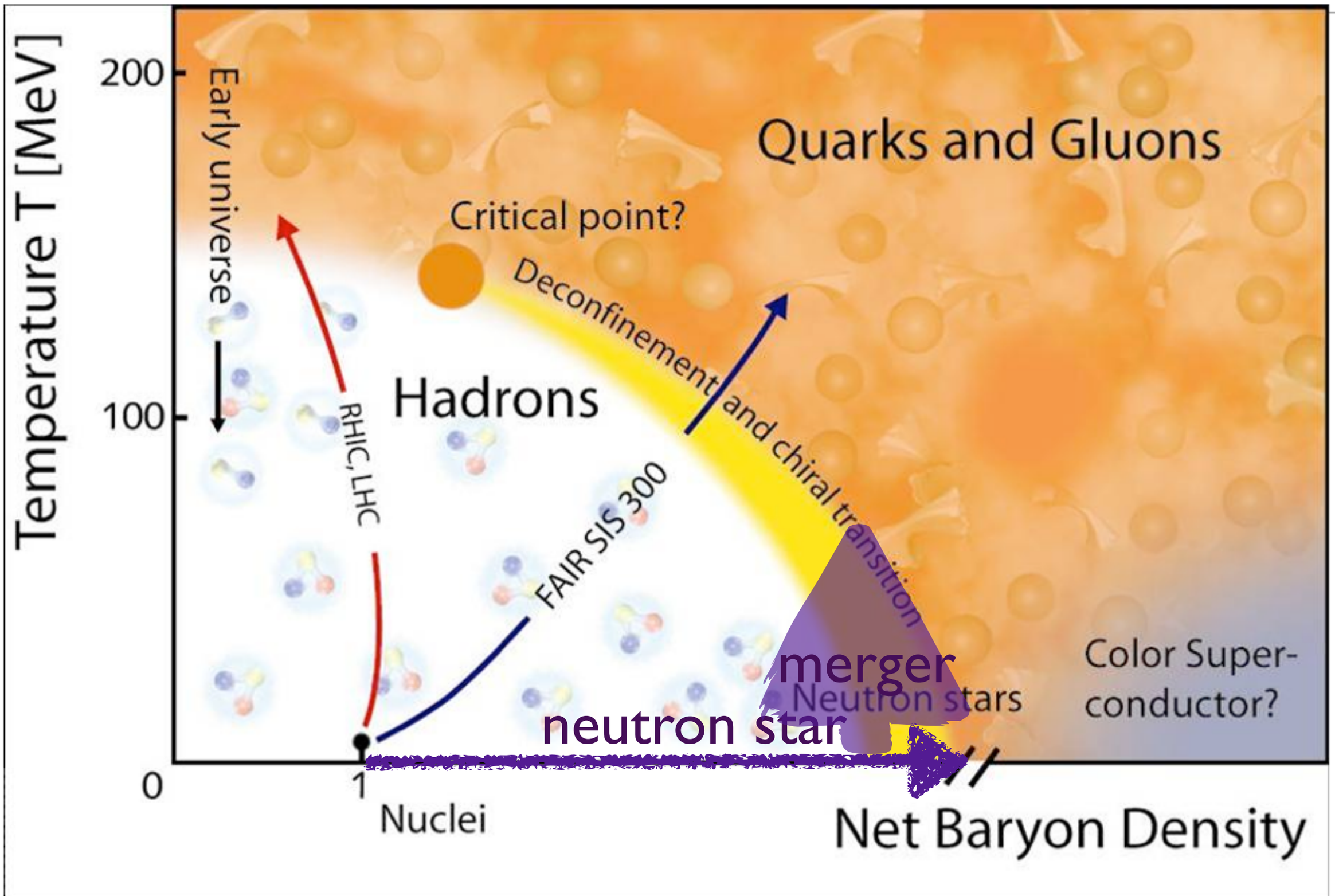


figure from FAIR CBM experiment

Current status summary

- First Advanced LIGO observing run concluded this week; on track with schedule and sensitivity in line with planned observation scenarios (http://arxiv.org/abs/1304.0670)
- Analyzing, interpreting and reviewing results takes several months - stay tuned!