MAX PLANCK INSTITUTE
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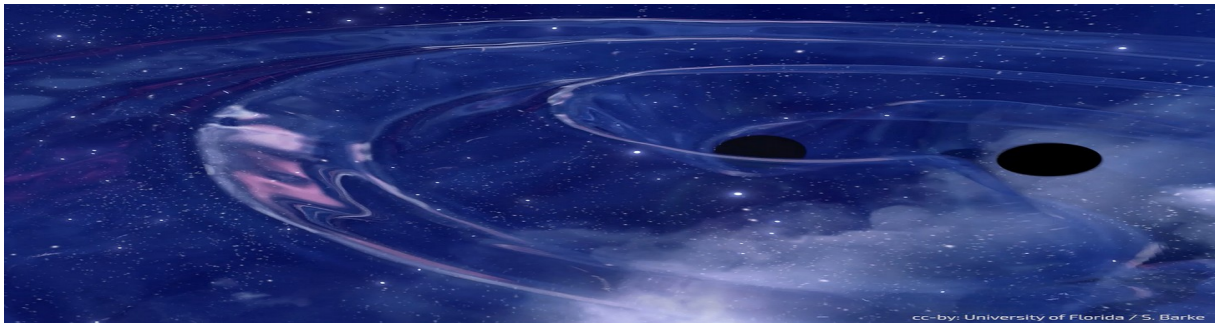
(ALBERT EINSTEIN INSTITUTE)



Gravitational Wave Observations: LIGO Introduction for students & researchers

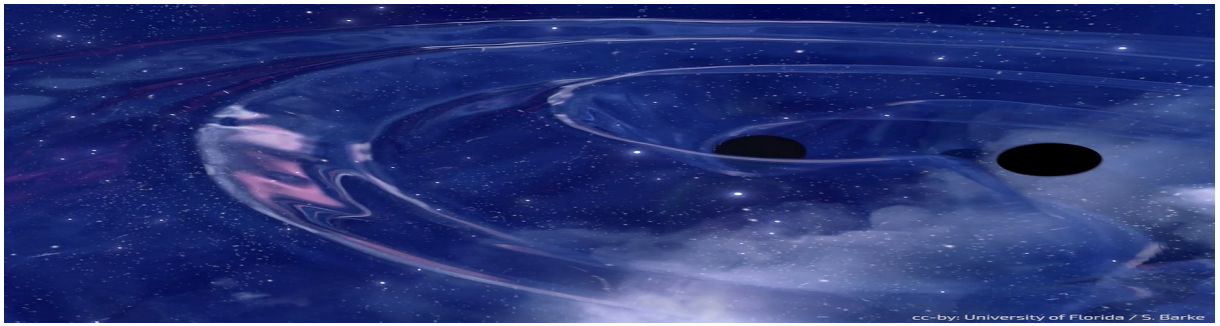
Ofek Birnholtz

on behalf of LIGO & VIRGO Collaborations

LIGO Scientific Collaboration

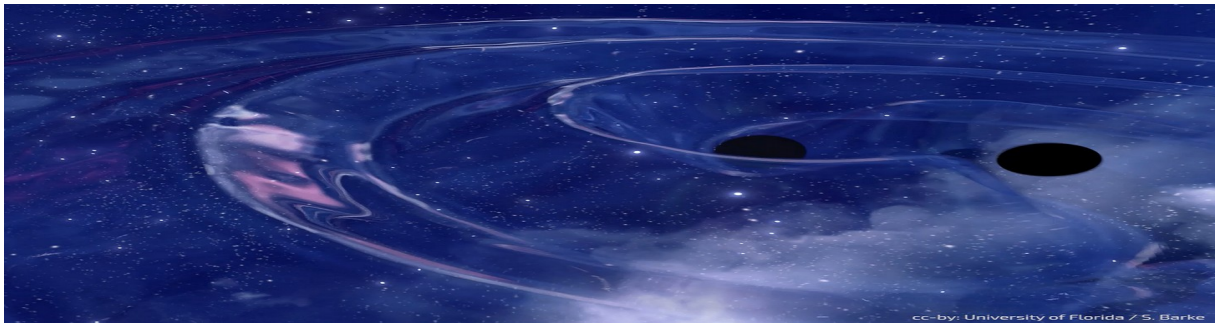
Ben-Gurion University, Be'er-Sheva, Israel
19 April 2017

LVC References



[1] GW150914 Detection, arXiv:1602.03837
[2] CBC Searches, arXiv:1602.03839
[3] Parameter Estimation (PE), arXiv:1602.03840, arXiv:1606.01210
[4] Testing GR, arXiv:1602.03841
[5] Detector Characterization (DetChar), arXiv:1602.03844
[6] Basic Physics, arXiv:1608.01940
[7] GW151226, arXiv:1606.04855
[8] O1 BBH, arXiv:1606.04856
[9] Numerical Rel., arxiv:1606.01262

What are Gravitational Waves?



$$GM = \omega^2 r^3$$

$$F = -\frac{Gm_1m_2}{r^2}$$

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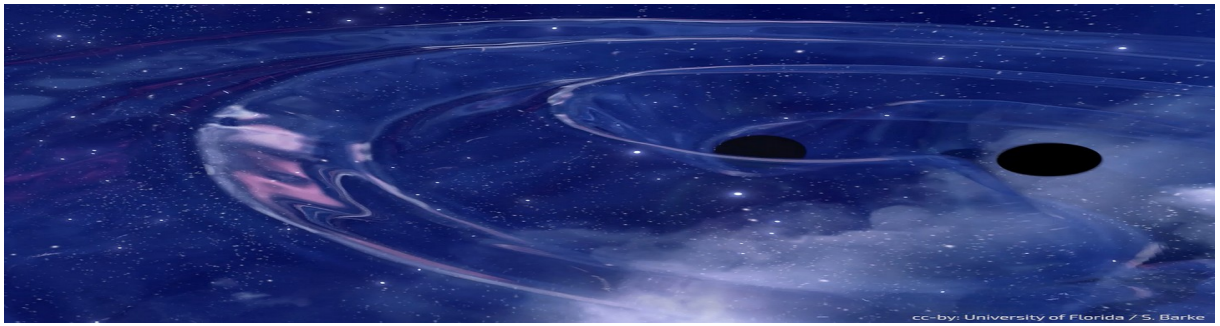

$$F = -\frac{Gm_1m_2}{r^2} \quad \longrightarrow \quad F = \frac{kq_1q_2}{r^2}$$

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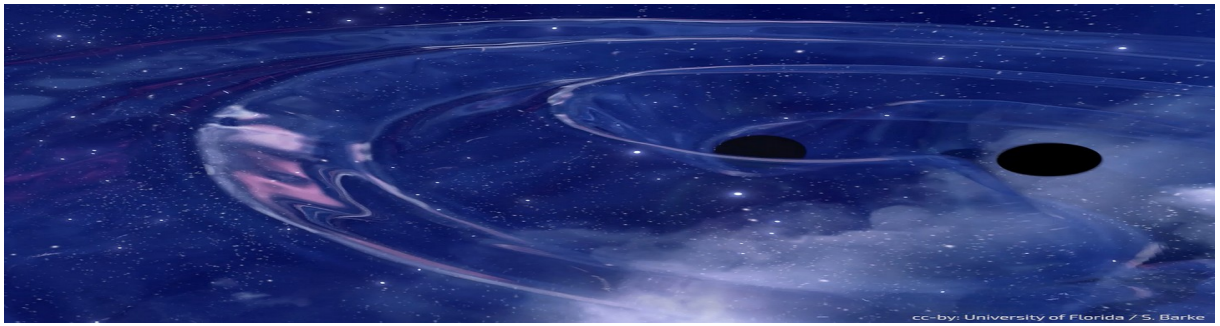
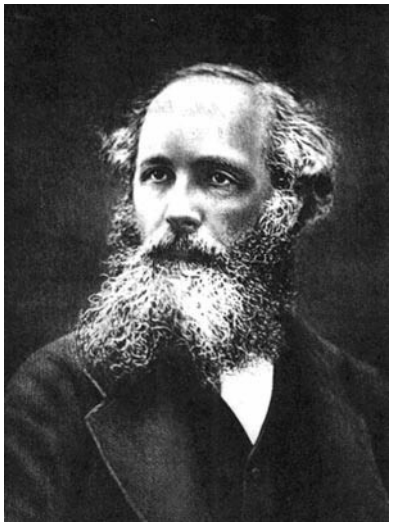


$$F = -\frac{Gm_1m_2}{r^2} \quad \longrightarrow \quad F = \frac{kq_1q_2}{r^2}$$

$$\nabla \cdot \vec{B} = 0$$
$$\nabla \cdot \vec{E} = 4\pi\rho$$
$$\nabla \times \vec{E} + \frac{1}{c}\frac{\delta \vec{B}}{\delta t} = 0$$
$$\nabla \times \vec{B} - \frac{1}{c}\frac{\delta \vec{E}}{\delta t} = \frac{4\pi}{c}\vec{J}$$



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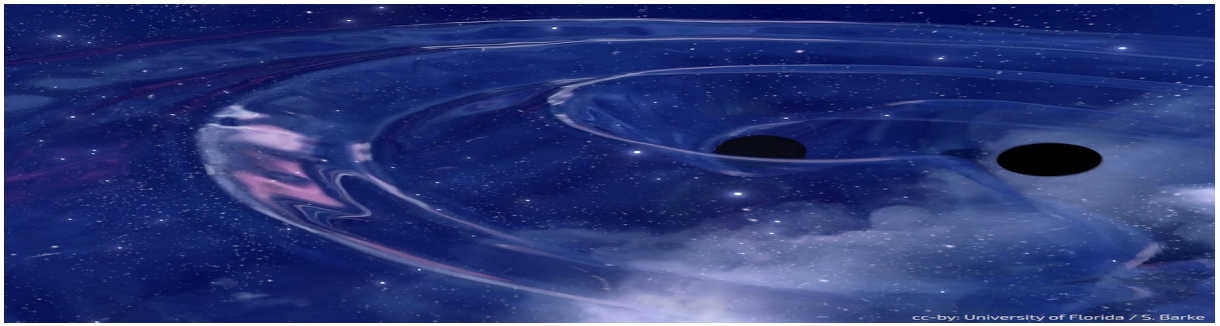

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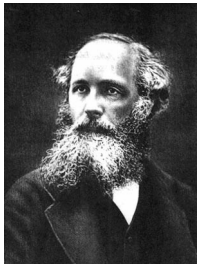

$$\Box A^\mu = j^\mu$$

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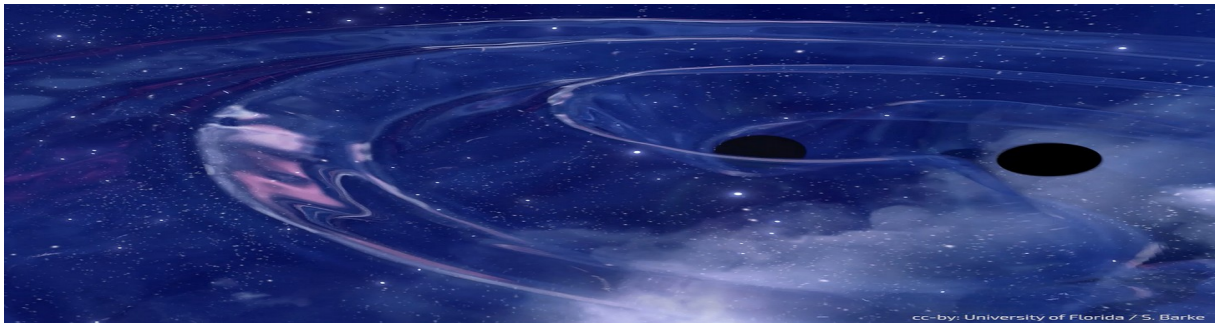

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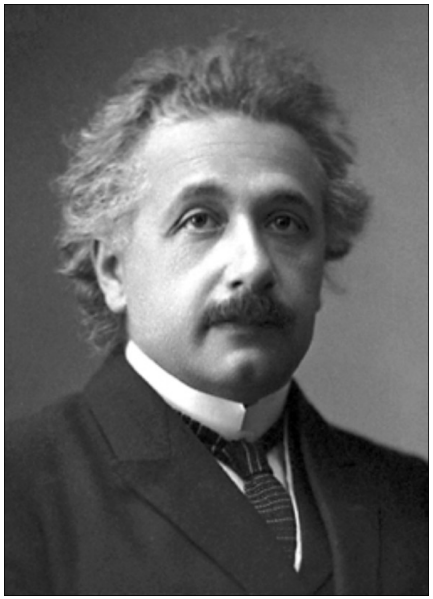

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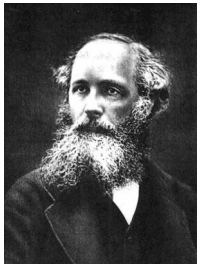

$$\downarrow$$

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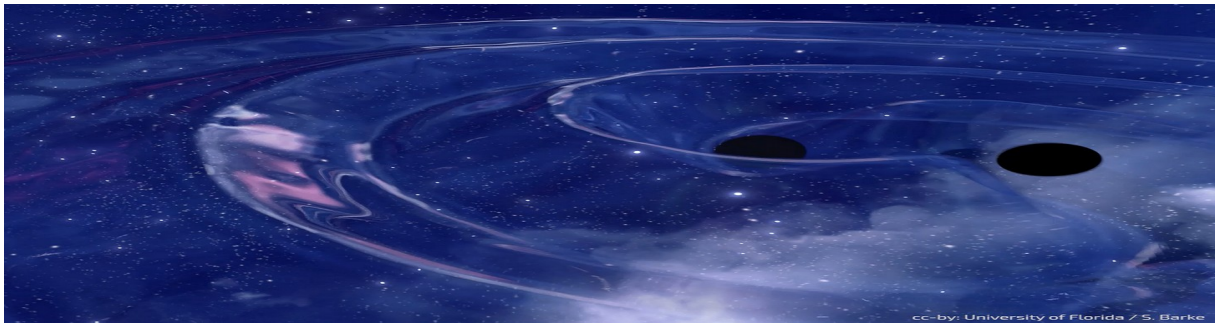

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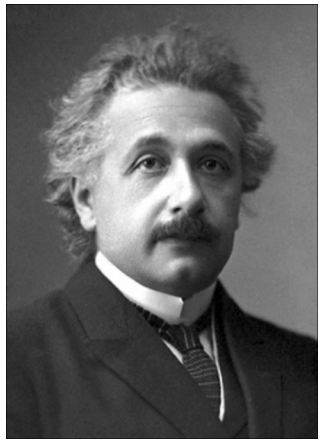

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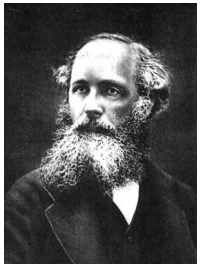

$$R_{\mu\nu} - \frac{1}{2}R\,g_{\mu\nu} = T_{\mu\nu} \longleftarrow \Box A^{\mu} = j^{\mu}$$

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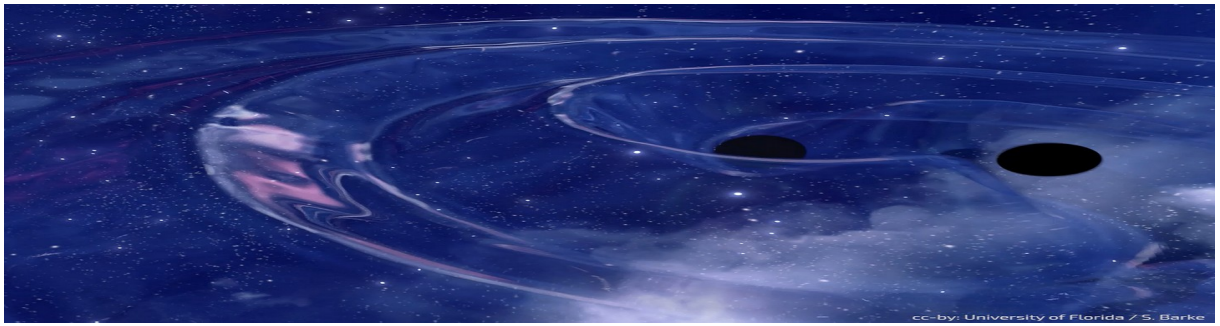

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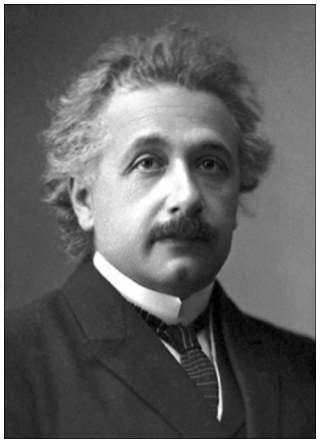

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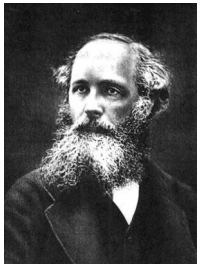
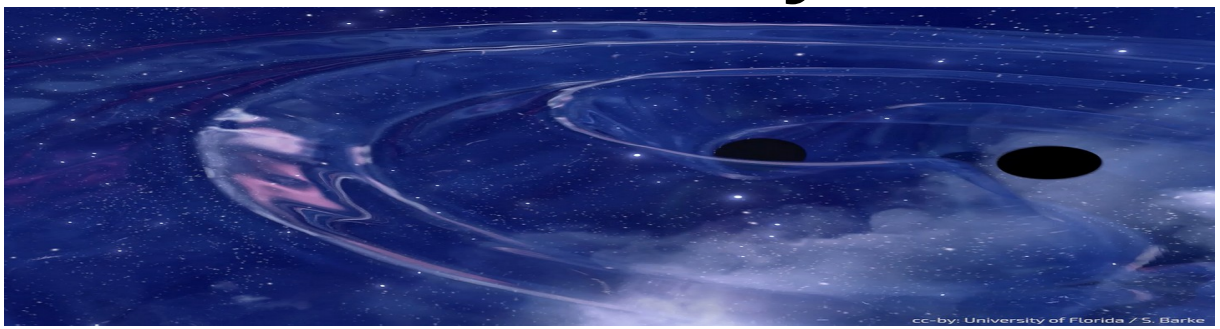
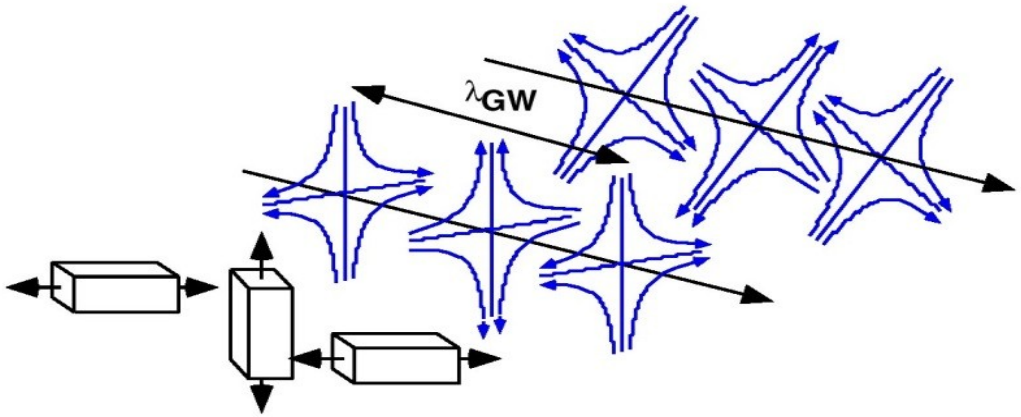


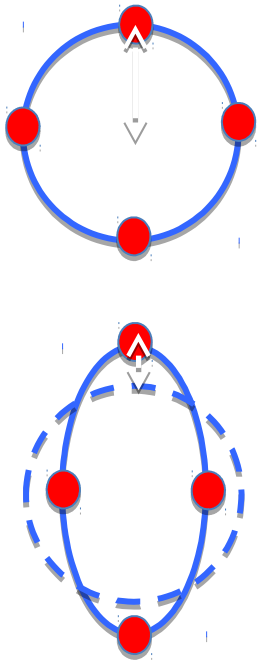
$$R_{\mu\nu} - \frac{1}{2}R\,g_{\mu\nu} = T_{\mu\nu} \longleftarrow \Box A^{\mu} = j^{\mu}$$

$$\boxed{\Box \bar{h}^{\alpha\beta} = -16\pi T^{\alpha\beta}}$$

What do they do?







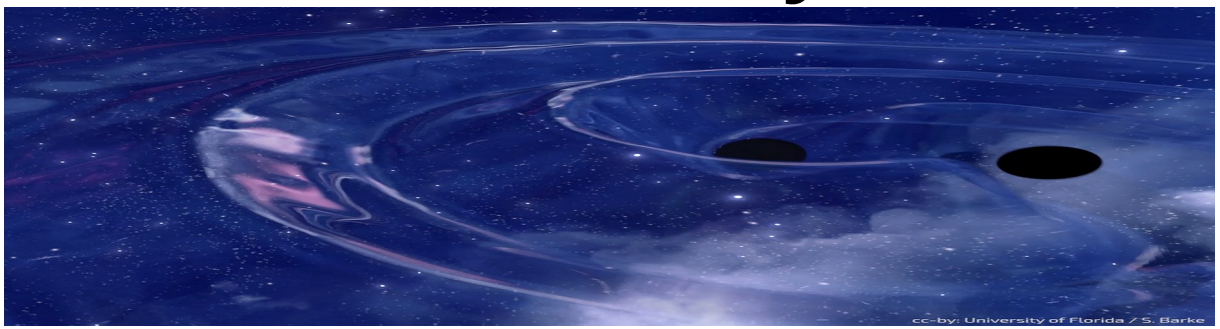
$$h \sim \delta L / L$$

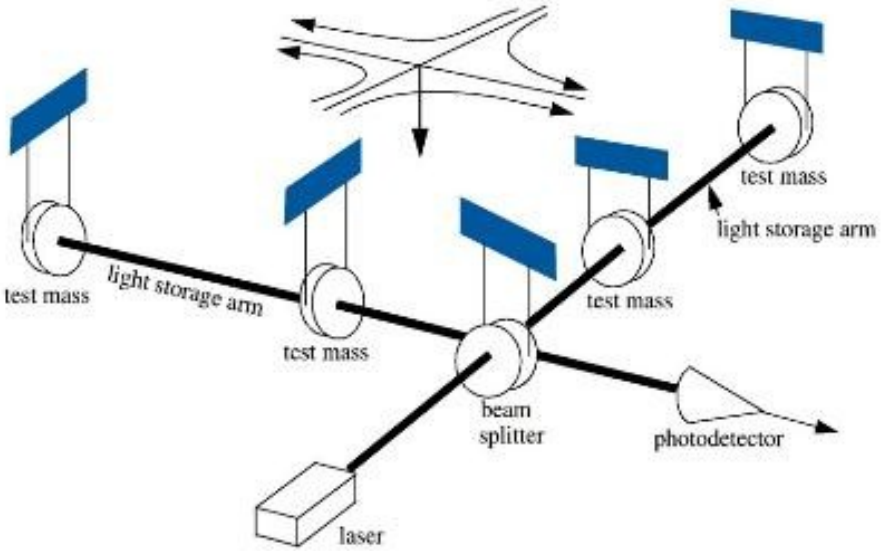
Two Polarizations: + , x

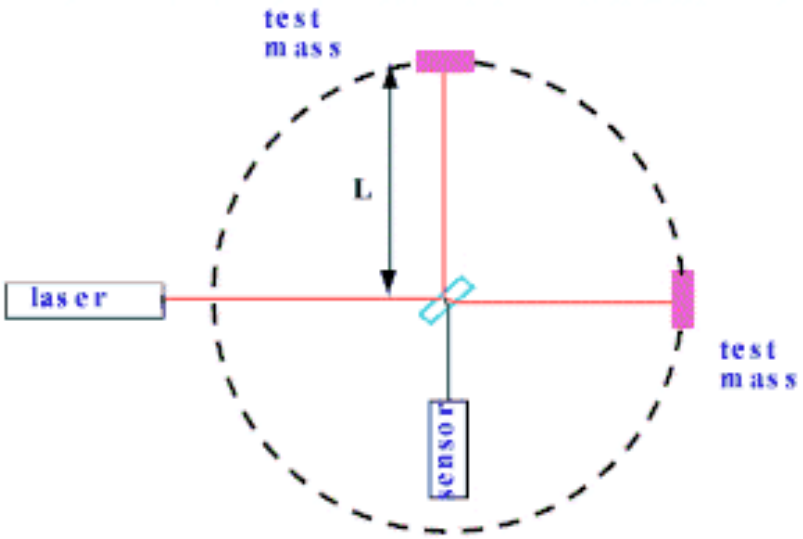
(transverse-traceless gauge)

Images: Barry Barish

What do they do?

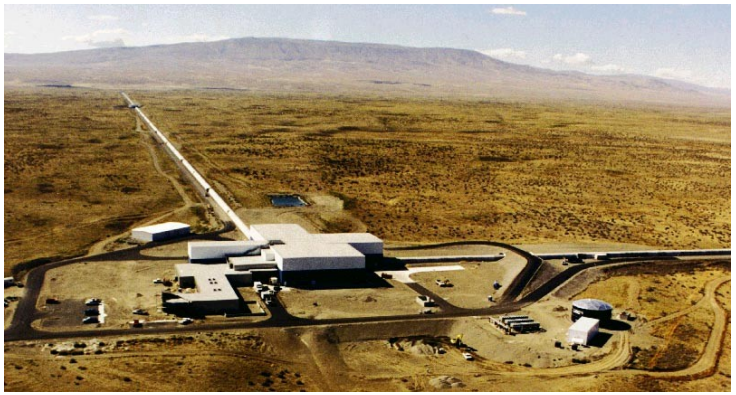






Images: Barry Barish

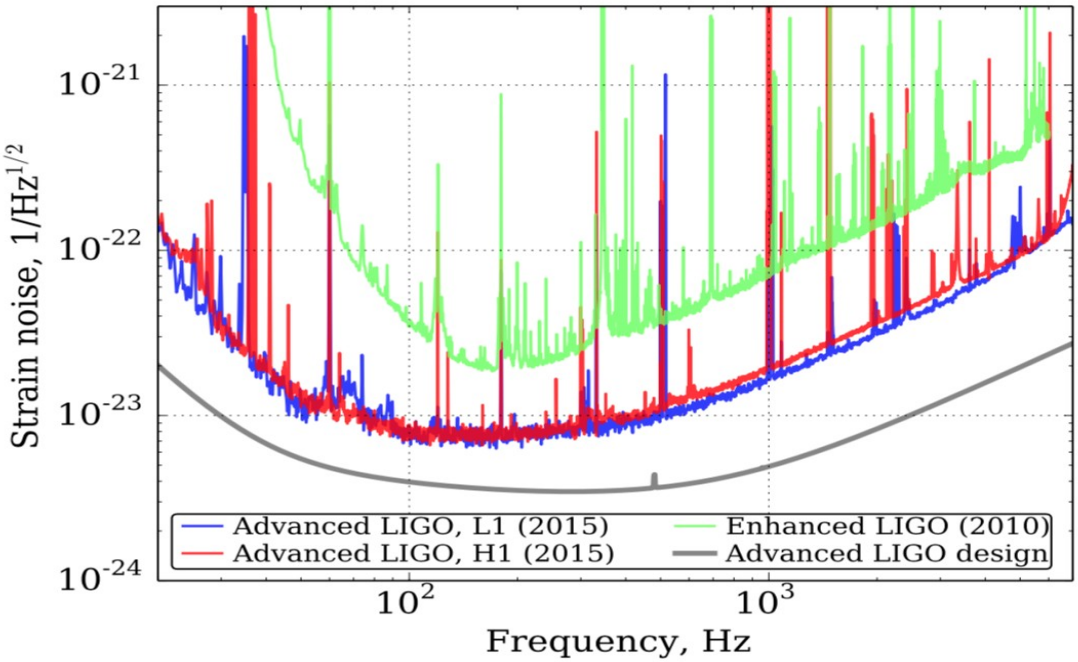
What is LIGO?



- 2 active Advanced detectors:
  - H1 at Hanford, WA, USA
  - L1 at Livingstone, LA, USA
- 2 more detectors:
  - VIRGO at Cascina, Italy
    - under commissioning
  - GEO600 at Hanover, Niedersachsen, Germany
    - active at lower sensitivity, equipment R&D
- **LIGO Scientific & VIRGO Collaborations**:
  - > 1000 scientists, > 130 institutions, 18 countries
  - Always open for more!

Status

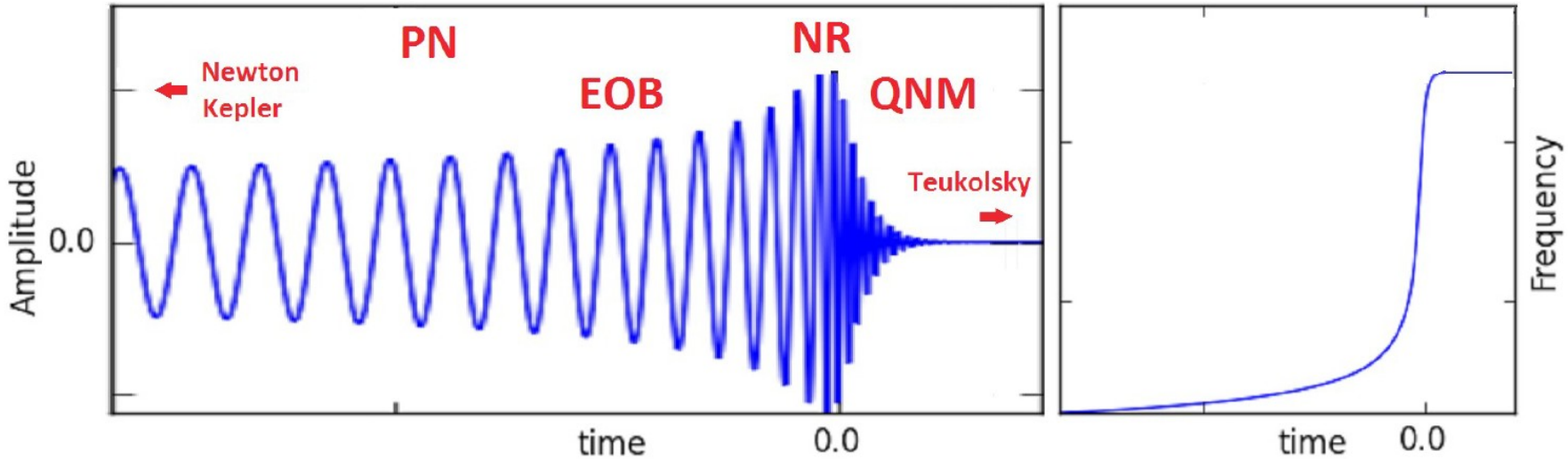
- O1 Sep 2015 – Feb 2016
  - ~3 Binary Black Hole (BBH) Detections
  - Burst connections examined
  - Longer signals still analyzed
- O2 from Nov 2016
  - Alerts issued to Astro partners
  - **Currently running!**
  - Waiting for VIRGO to join
- O3 planned 2017-2018



Modelled CBC Searches

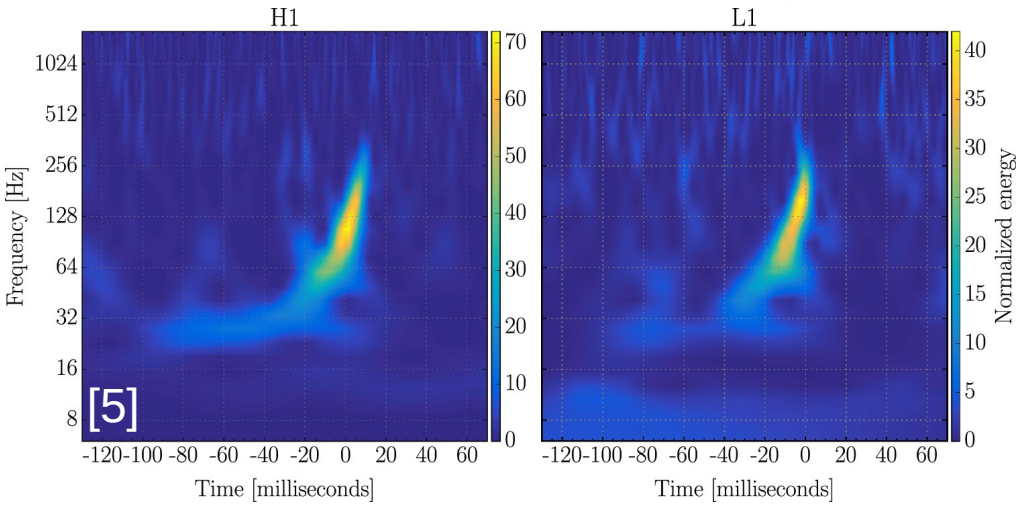
- What we search for
- How we do it
- What we do when we find it

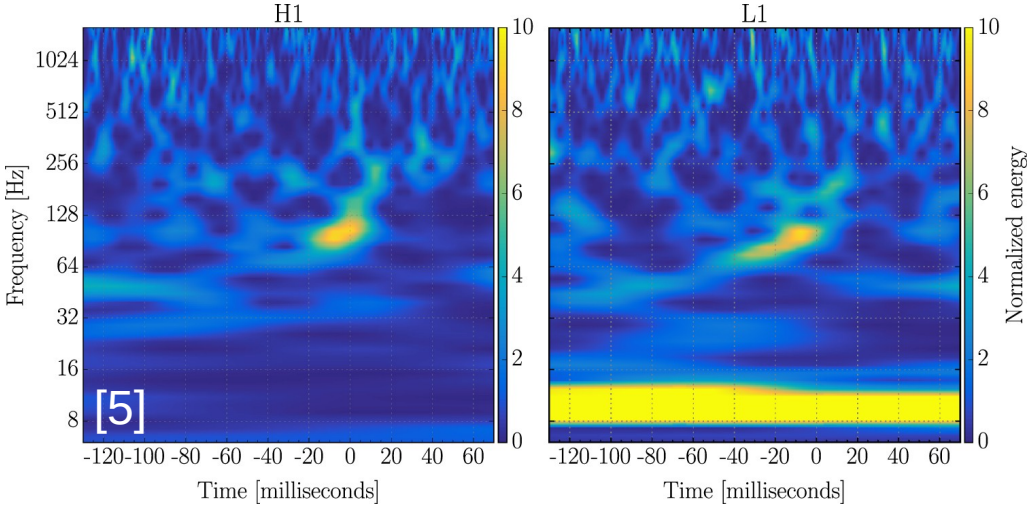
What a signal looks like

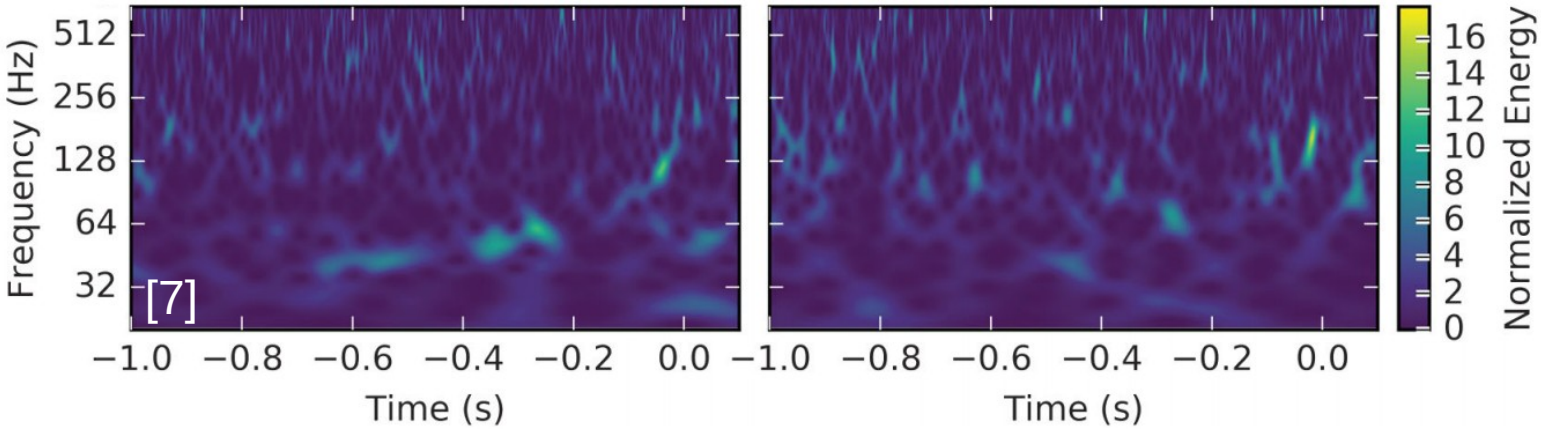


- The post-Newtonian parameter x : $\sqrt{x} = v/c = \omega r/c = \sqrt[3]{\pi G M f_{GW}}/c$
- For $x \sim 0.1$: $\frac{M}{20\,\mathrm{M}_\odot} \sim \frac{100\,\mathrm{Hz}}{f_{GW}}$
- $M = m_1 + m_2$ $\left(\frac{G\,\mathrm{M}_\odot}{c^3} \sim 5\mu s\right)$

What a signal ***really*** looks like







The window

- The Quadrupole Formula: $h_{ij} = \frac{2\,G}{c^4\,d_L}\frac{\mathrm{d}^2 Q_{ij}}{\mathrm{d}t^2}$

$$\frac{\mathrm{d}E_{\mathrm{GW}}}{\mathrm{d}t} = \frac{c^3}{16\pi\,G}\iint |\dot{h}|^2 \mathrm{d}S = \frac{1}{5}\frac{G}{c^5}\sum_{i,j=1}^{3}\frac{\mathrm{d}^3 Q_{ij}}{\mathrm{d}t^3}\frac{\mathrm{d}^3 Q_{ij}}{\mathrm{d}t^3}$$

- Defining the chirp mass:

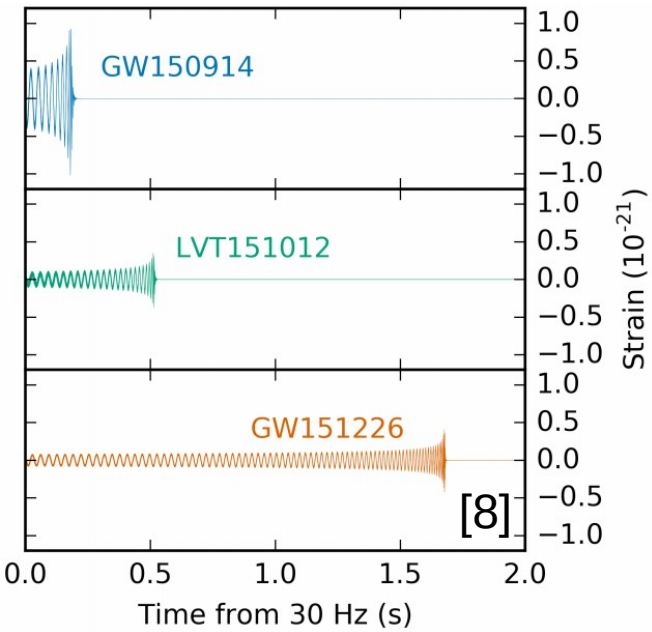
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$

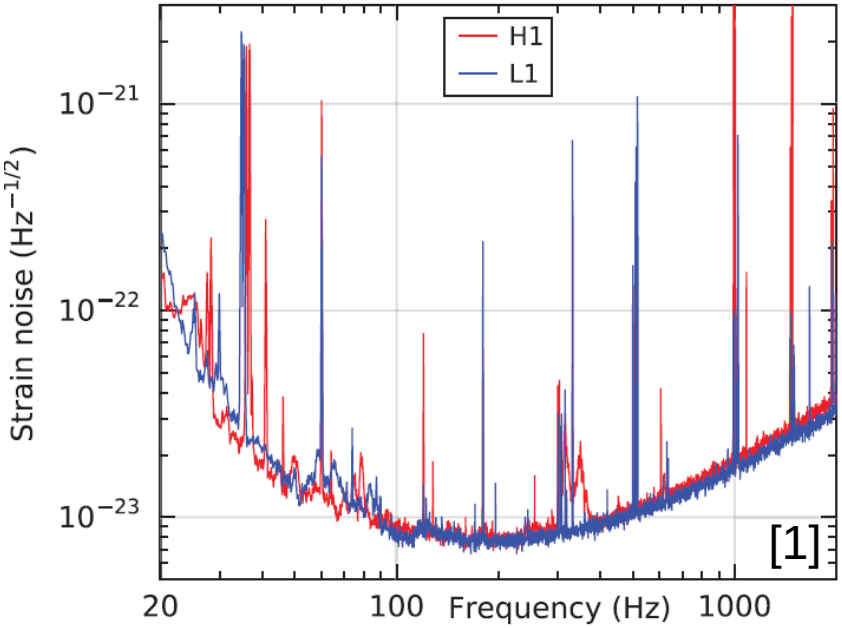
- Frequency evolution:

$$\dot{f} = \frac{96}{5}\pi^{8/3}\left(\frac{G\,\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}$$

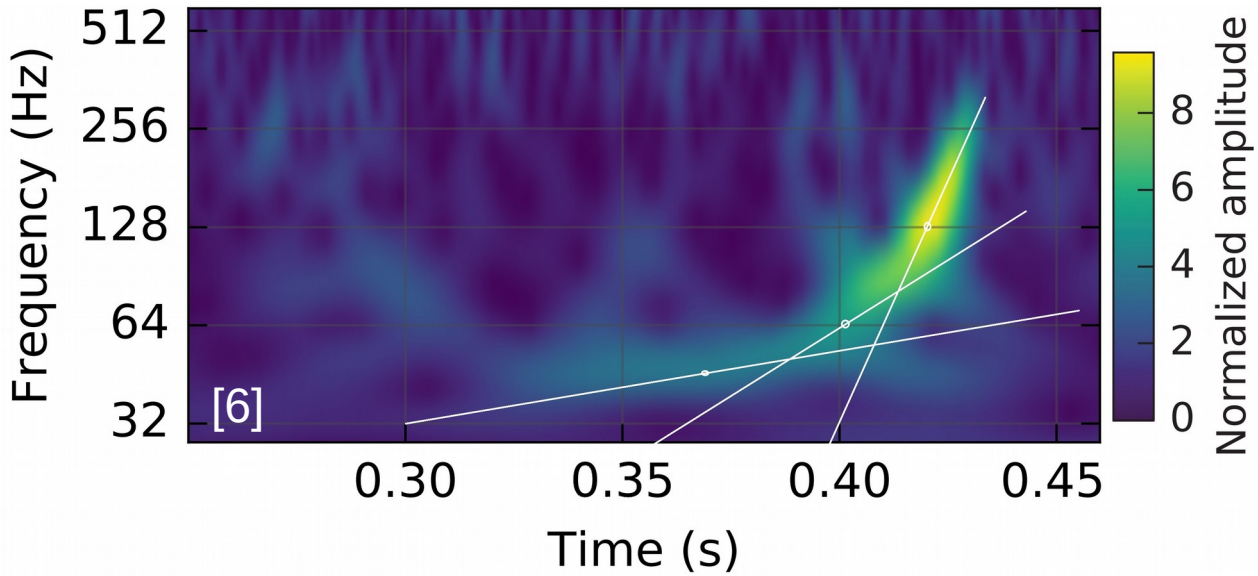
- Time in the band:

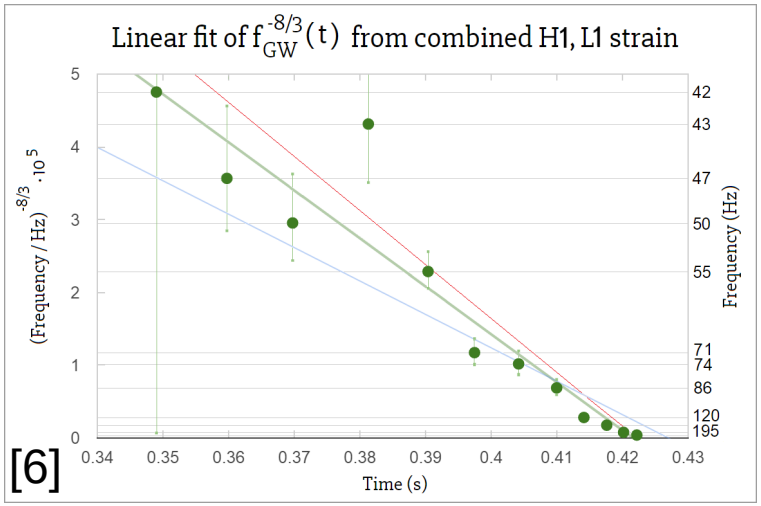
$$\tau_0 = \frac{5}{256}\left(\pi f_{ref}\right)^{-8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{-5/3}$$





GW150914: BBH Merger





$$\dot{f} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}$$

$$f^{-8/3}(t) = -\frac{(8\pi)^{8/3}}{5}\left(\frac{G\,M_c}{c^3}\right)^{5/3}(t - t_0)$$

$$\Rightarrow \quad \mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \cong 30\,\mathrm{M}_\odot$$

GW150914: BBH Merger

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \quad \cong 30\,\mathrm{M}_\odot$$

- The Simplest case:
  - Equal masses $m_1 = m_2 = 35\,\mathrm{M}_\odot$, $M = m_1 + m_2 = 70\,\mathrm{M}_\odot$
  - Circular orbit $\omega_{\mathrm{Kepler-max}} = 2\pi f_{\mathrm{GW-max}}/2 = 2\pi \times 75\ \mathrm{Hz}$

    From Kepler's Law: effective separation $R = \left[\frac{GM}{\omega^2_{\mathrm{Kepler-max}}}\right]^{1/3} = 350\ \mathrm{km}$
  - No Spin: $r_{\mathrm{Schwarz}}(M) = \frac{2GM}{c^2} = 200\mathrm{km}$

$$\text{compactness ratio } \mathcal{R} = 350\mathrm{km}/200\mathrm{km} \sim 1.75$$

Compact + Heavy => Black Holes

Matched Filtering

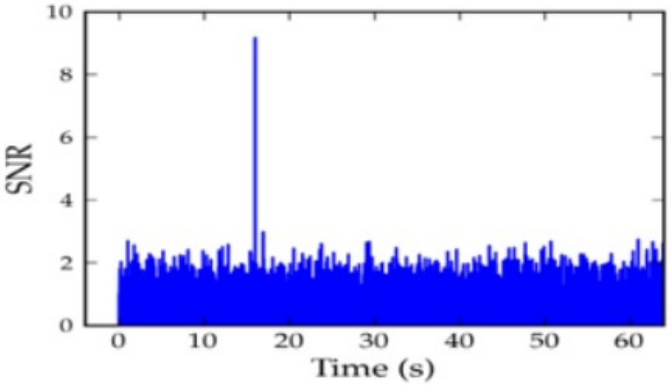
- Measure the Noise Power Spectrum Density (PSD) $S_n(f)$
- Define Scalar product

$$<a|b> = 4\int_0^\infty \frac{\tilde{a}^*(f)\,\tilde{b}(f)}{S_n(f)}df$$

- Signal-to-(Gaussian)Noise Ratio (SNR) of template h in measured strain s

$$\rho = \frac{|<h|s>|}{\sqrt{<h|h>}}$$

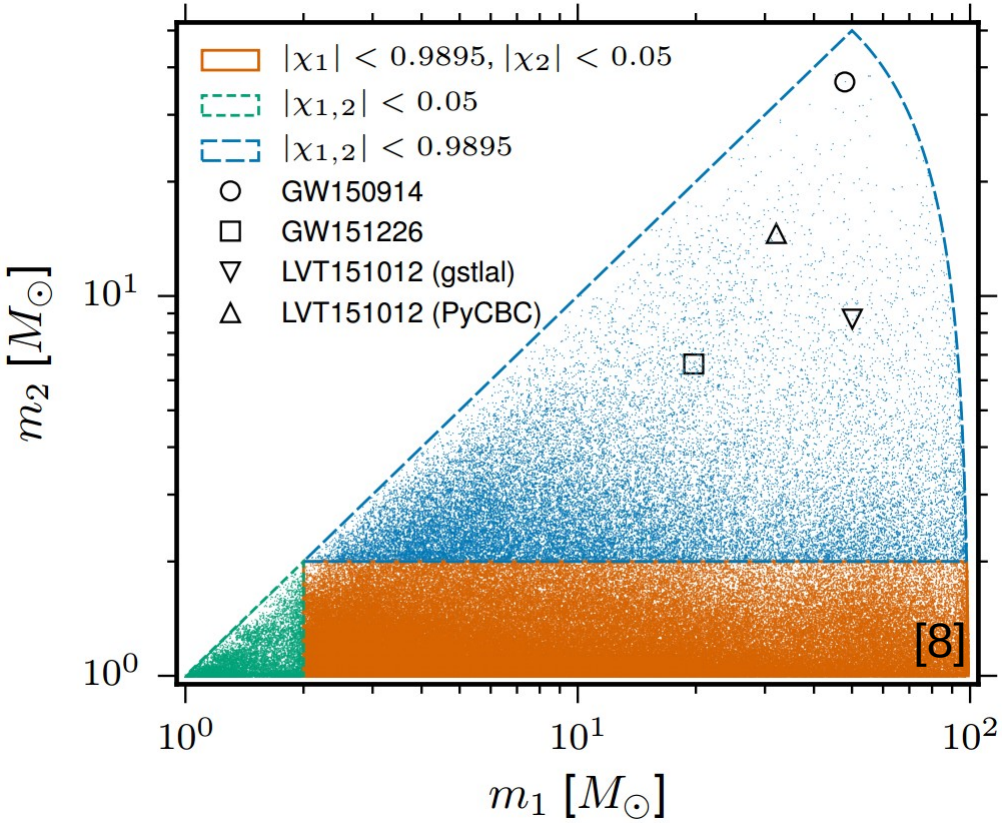
- Find ***Triggers***, which maximize $\rho(t)$



Courtesy of A. H. Nitz

The Template “Über”-bank

- 4 free parameters:
  - $m_{1,2}$ masses
  - $\chi_{1,2} = \frac{c\,\mathbf{S}_{1,2}\cdot\hat{\mathbf{L}}}{G\,m_{1,2}^2}$ aligned spins
- 2 waveform models:
  - TaylorF2 $M < 4\mathrm{M}_\odot$
  - SEOBNRv2 $M > 4\mathrm{M}_\odot$
- 2 population methods:
  - Geometric $\mathcal{M} < 1.5\mathrm{M}_\odot$
  - Stochastic $\mathcal{M} > 1.5\mathrm{M}_\odot$



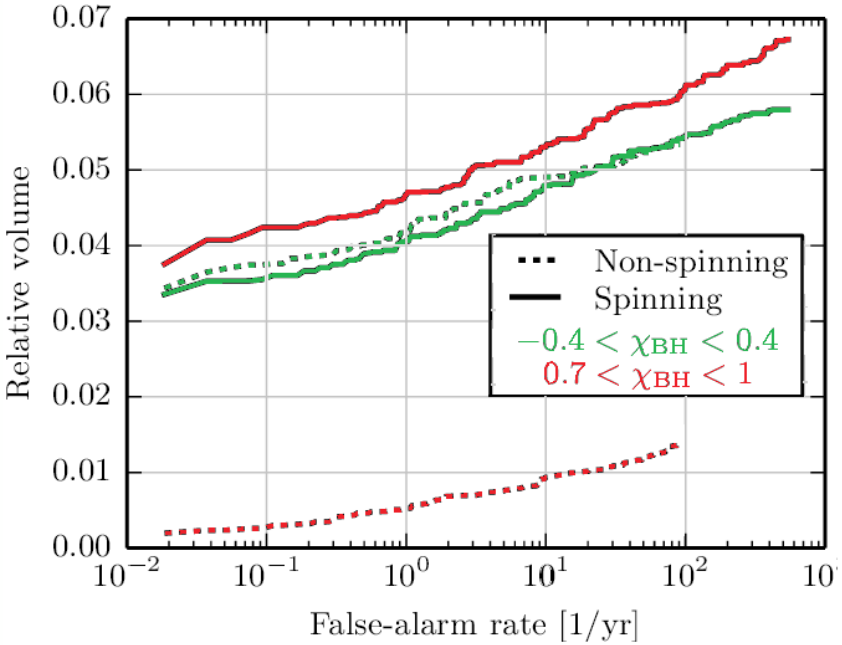
- Mismatch >3% for <1% of signals (ER8 PSD)
- ~250,000 templates

Precession

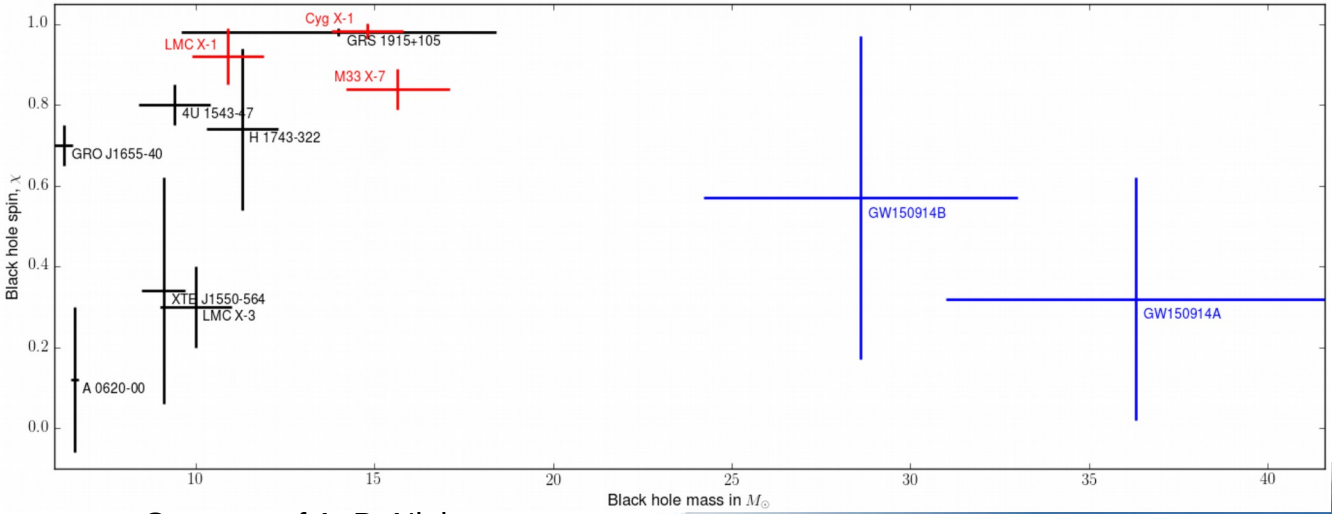
- Überbank effectual if only little precession
- Generally, precession adds ~10 spin+sky free parameters

↓ ↓

Aligned search
+
precession in post-analysis



T. Dal Canton et. al, PRD 90, 082004, 2014

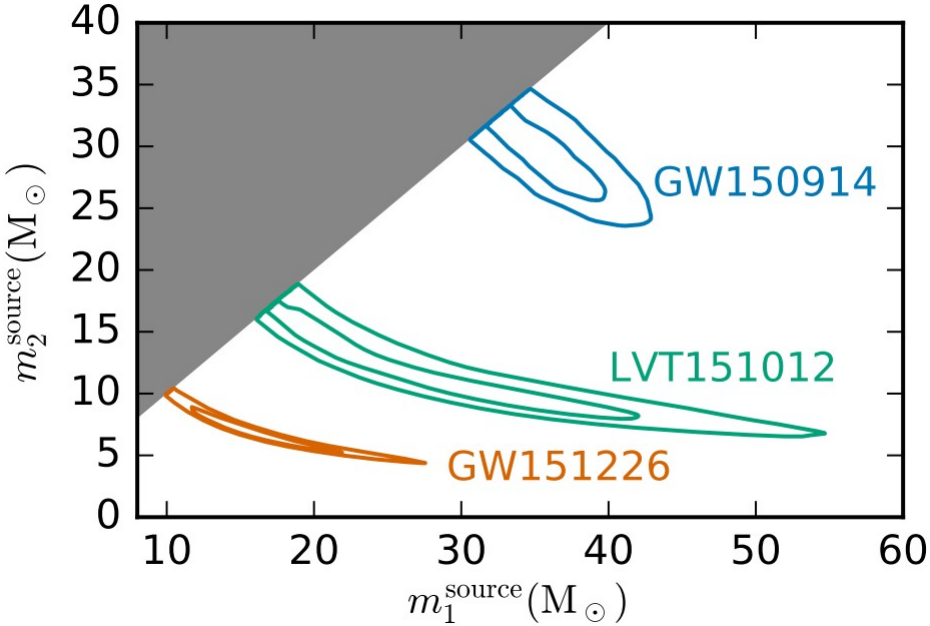


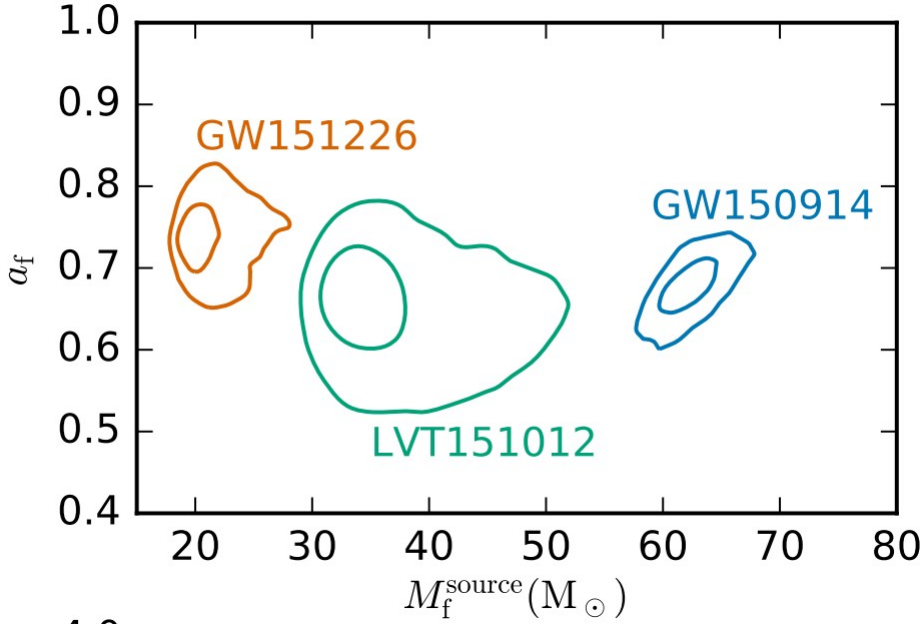
Courtesy of A. B. Nielsen

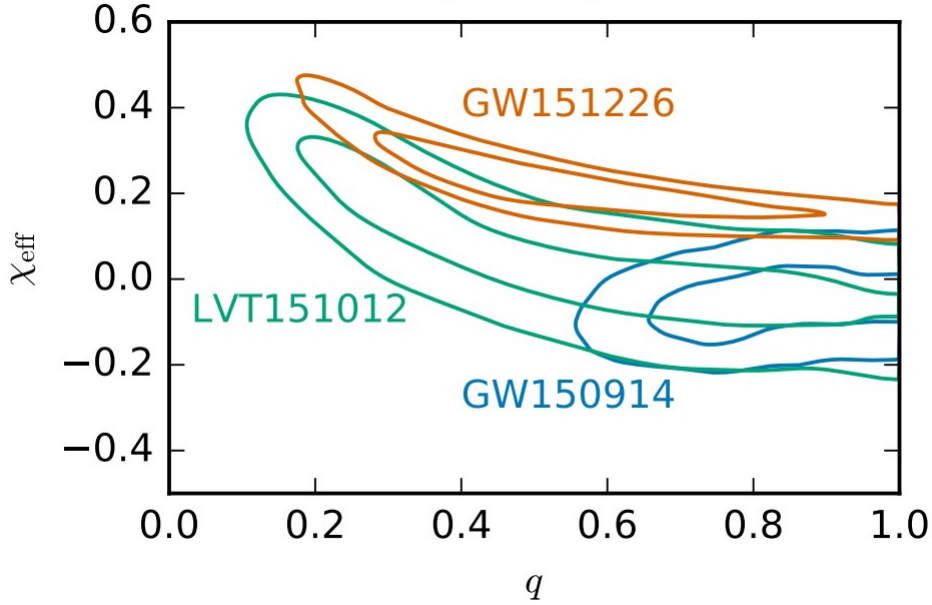
Parameter Estimation (PE)

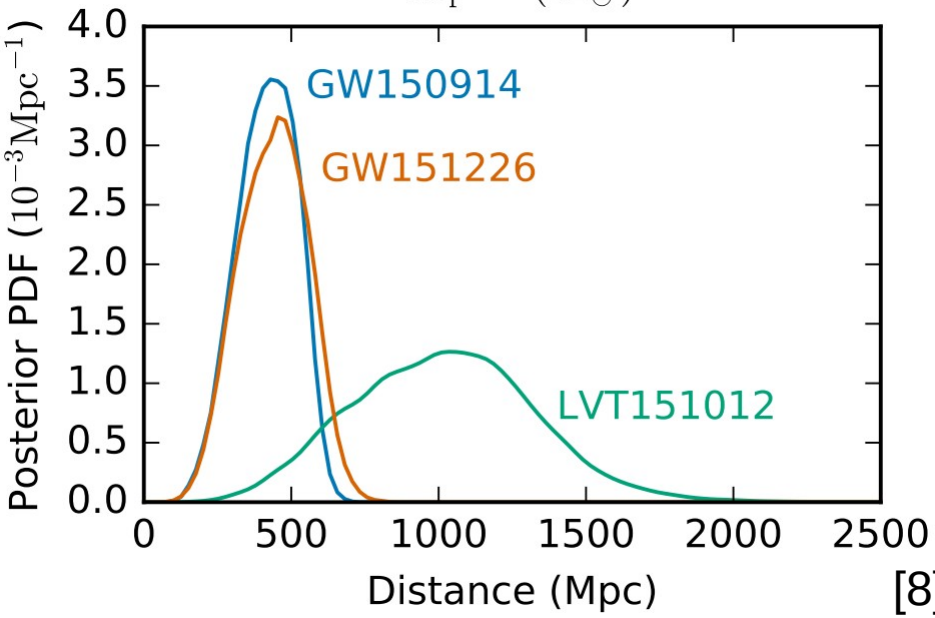
- Follow-up on Events
- “Opposite” problem to Searches:
  - maximum resolution, few triggers
- Stochastic Sampling Engines:
  - Markov Chain Monte-Carlo
  - Nested Sampling
- Priors from identified trigger (time)

PE – sample results





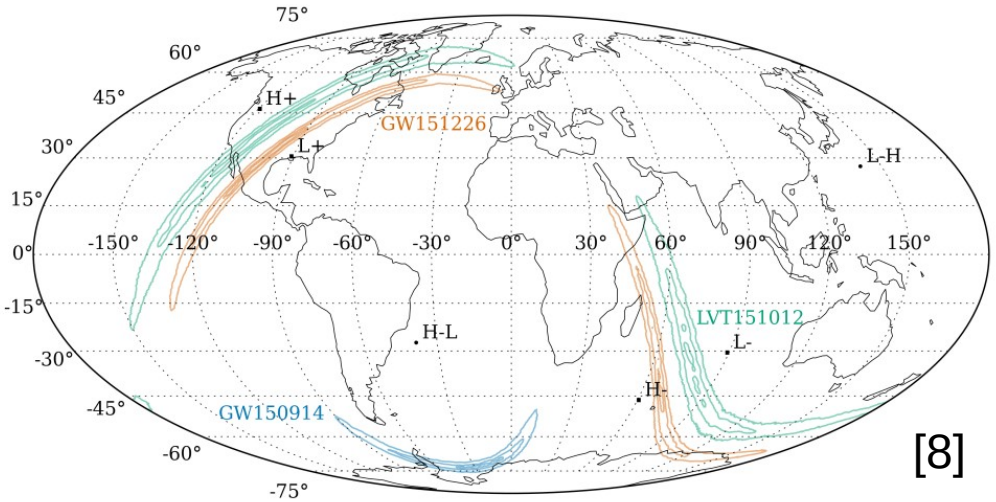




[8]

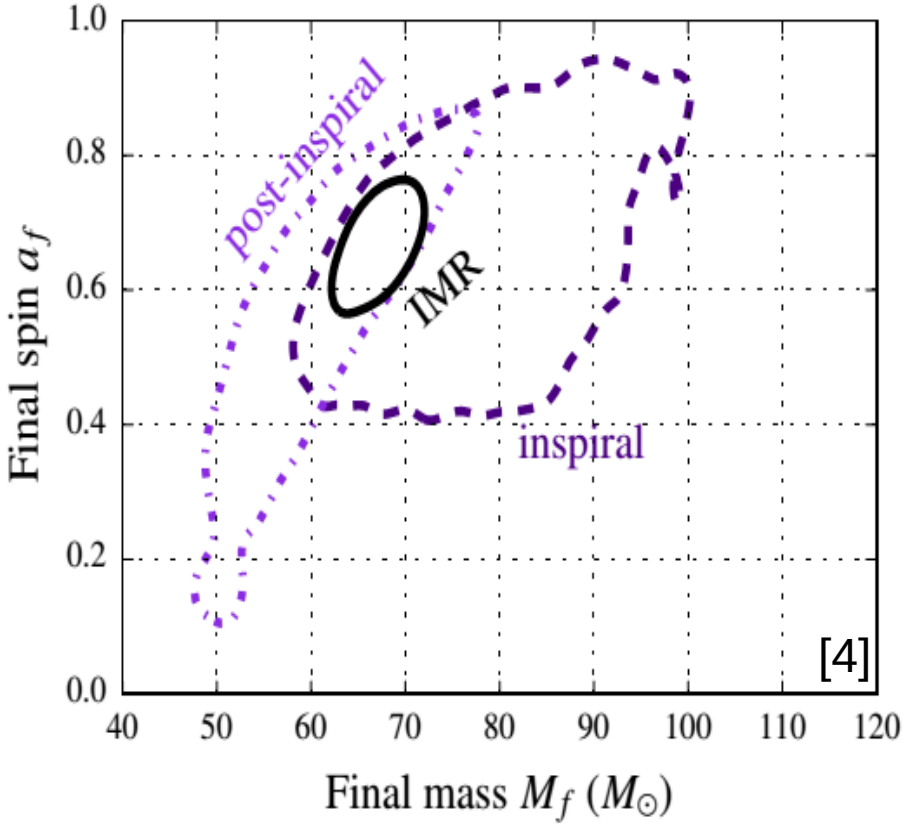
PE – richer physics

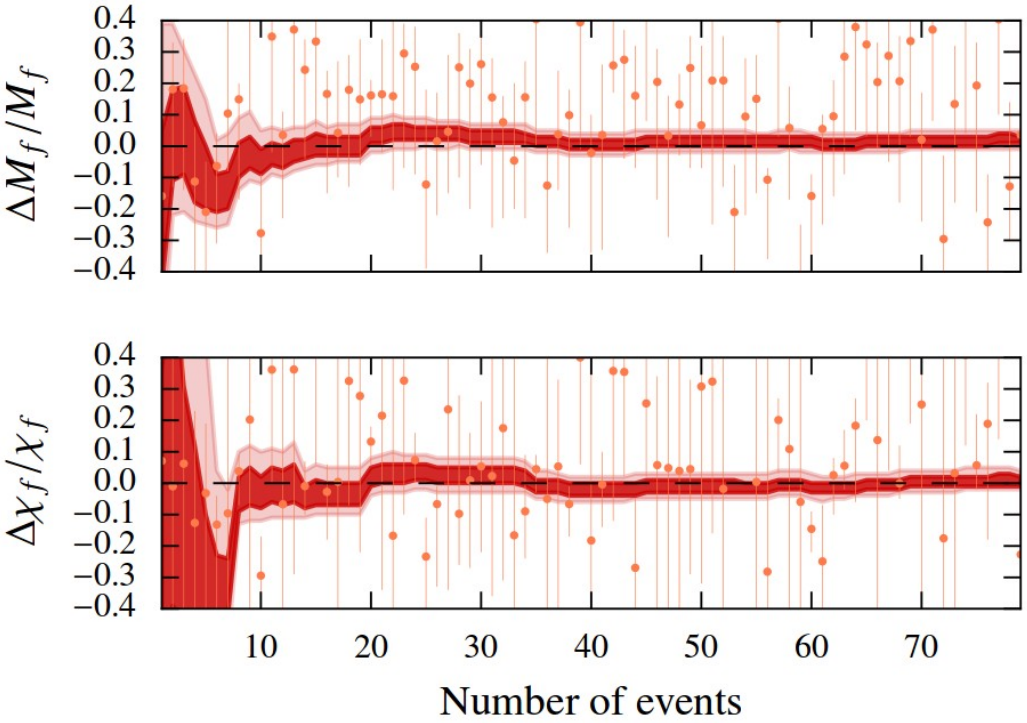
- Sky Location
- More waveform approximants:
  - IMRPhenomD
  - Precession: IMRPhenomP, SEOBNRv3
    - Little precession / small mass ratio
    - Effective spin
- Modified waveforms:
  - Eccentricity
  - Matter effects, NS E.O.S
  - Modifications to GR
- Focus on particular parts (inspiral, ringdown...)



[8]

Testing GR Consistency





Ghosh et al 1602.02453, PRD94 021101

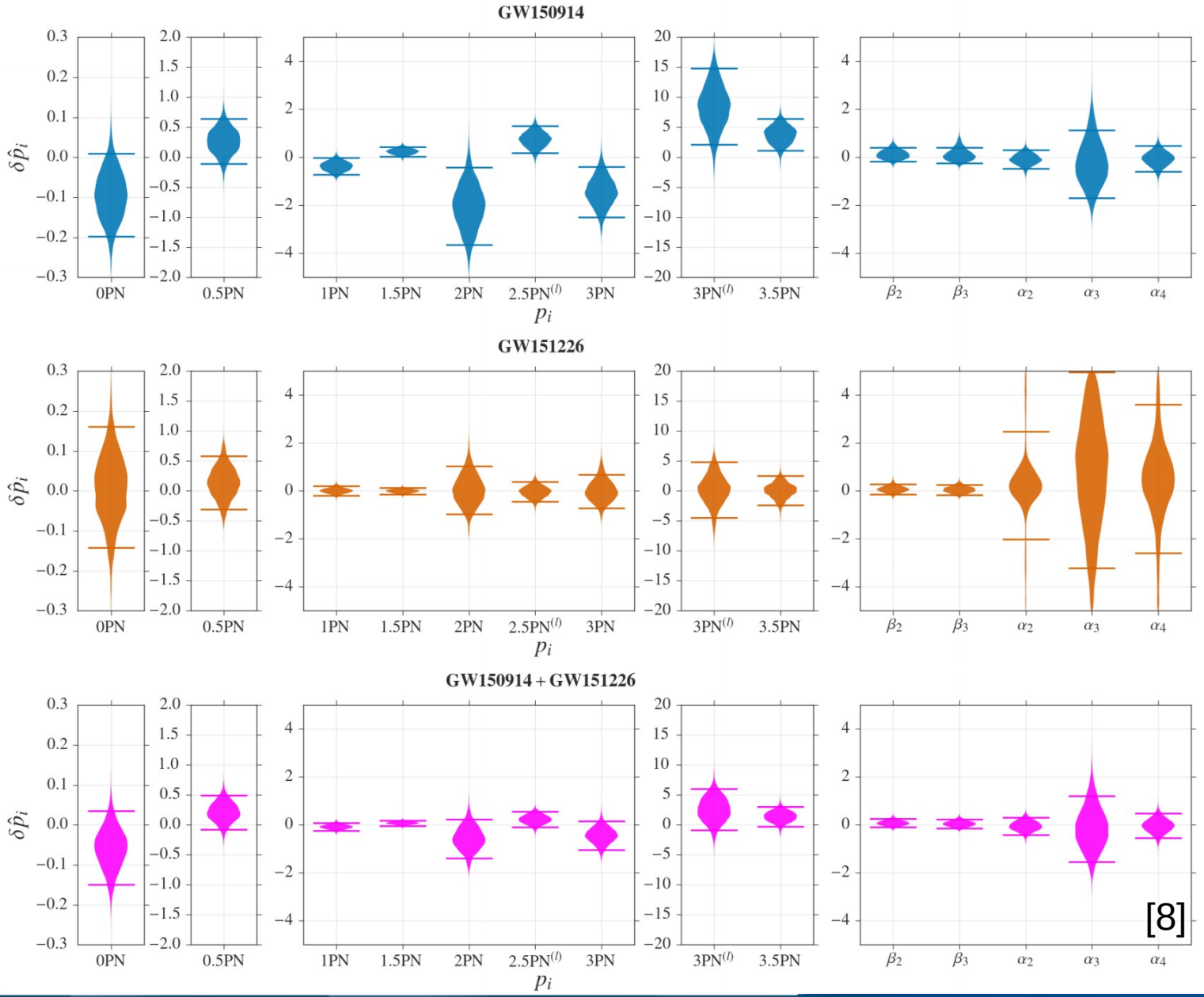
Testing GR: post-Newtonian

- "Early" part
- J0737-3039:
  $M \sim M_{sun}$
  $v \sim 10^{-3}c$
  $dP/dt \sim 10^{-12}$
- GW150914:
  $M \sim 60\ M_{sun}$
  $v \sim 0.5c$
  $dP/dt \sim 1$

PN order	Includes (amongst other things)
0PN	Kepler Newtonian Gravity
0.5PN	Zero in GR
1PN	Pericenter advance (cf zero) PPN parameters γ, β, ξ
1.5PN	Spin-orbit couplings Gravitational tails (backscatter)
2PN	Spin-spin couplings (Newtonian) quadrupole-monopole (GR BH) (Newtonian) magnetic dipole-dipole (cf zero)
3PN	Tails of tails
5PN	(Newtonian) Adiabatic tidal deformations

Courtesy of A. B. Nielsen

Testing GR - PN Modifications

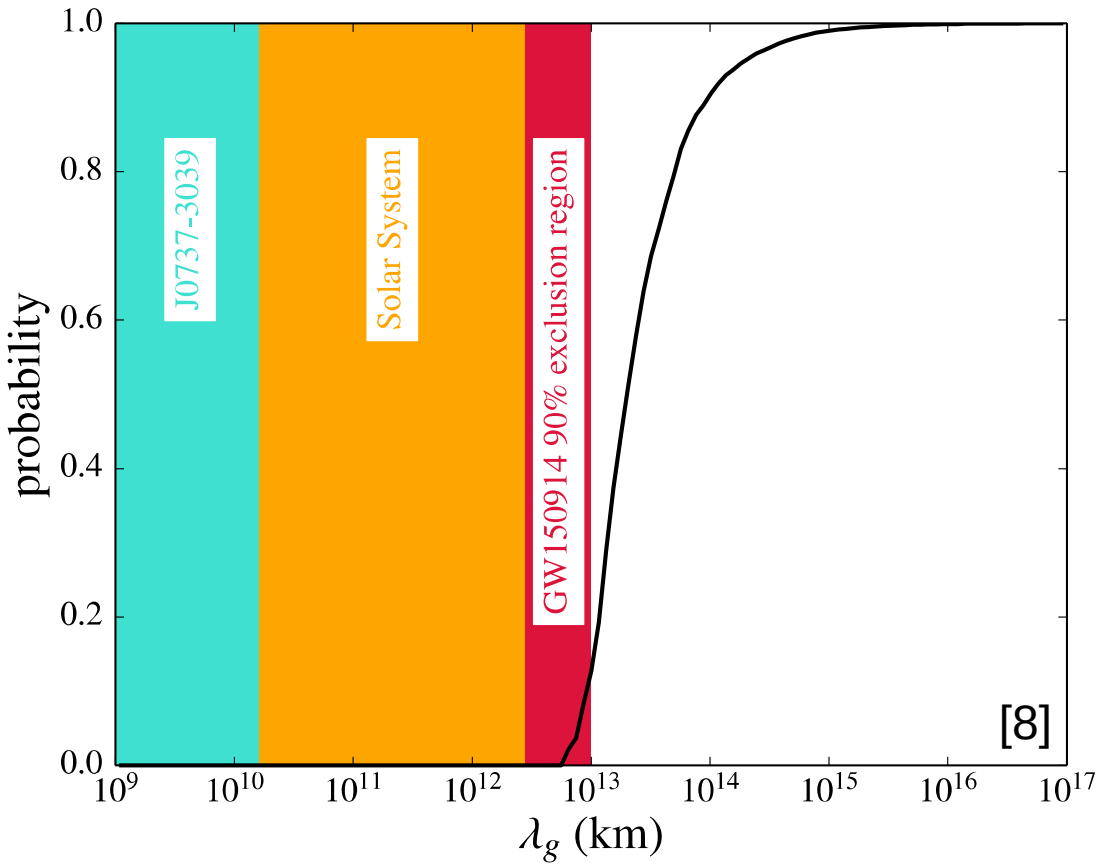


[8]

Testing GR - graviton mass?

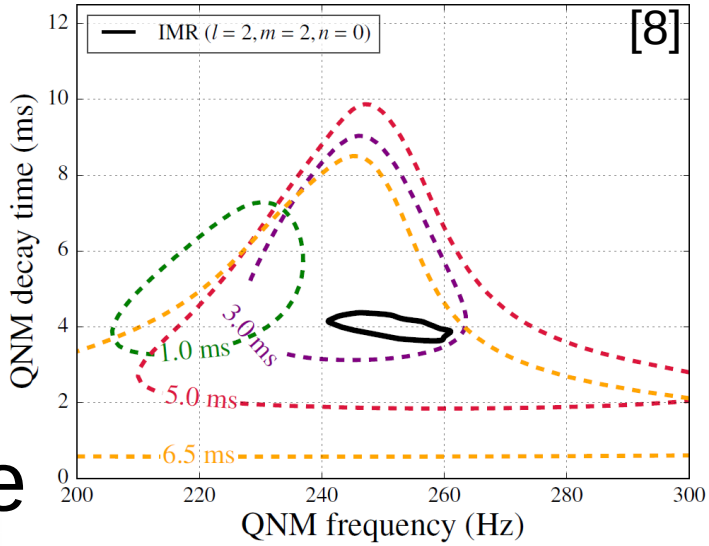
$$\lambda_g > 10^{13}\mathrm{km}$$

$$m_g < 1.2 \cdot 10^{-22}\mathrm{eV}/c^2$$

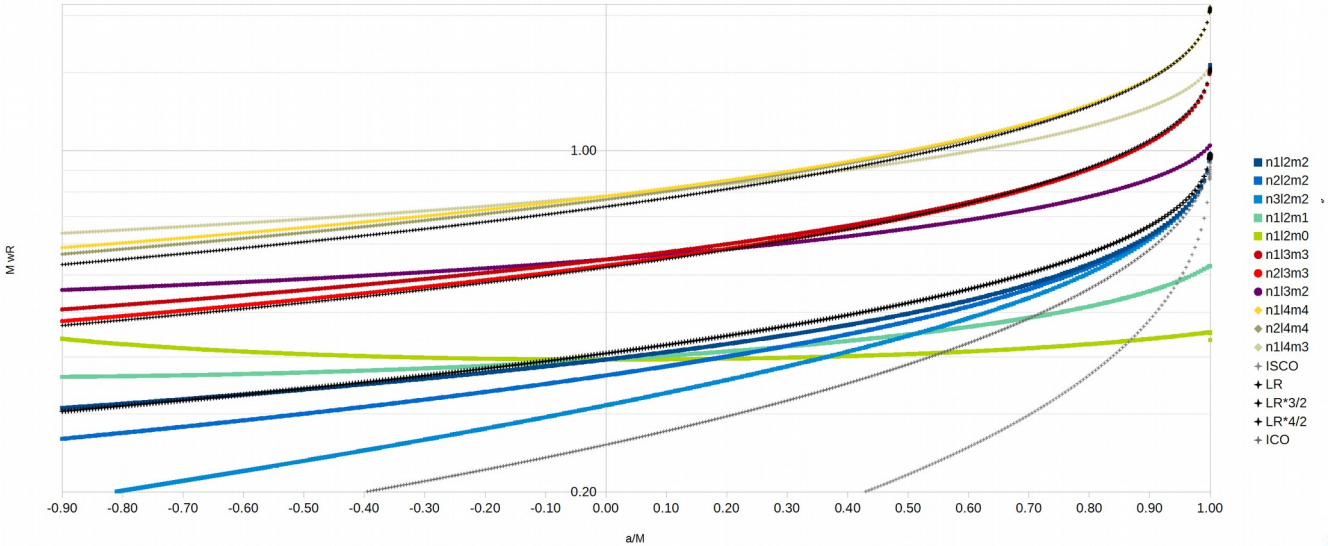


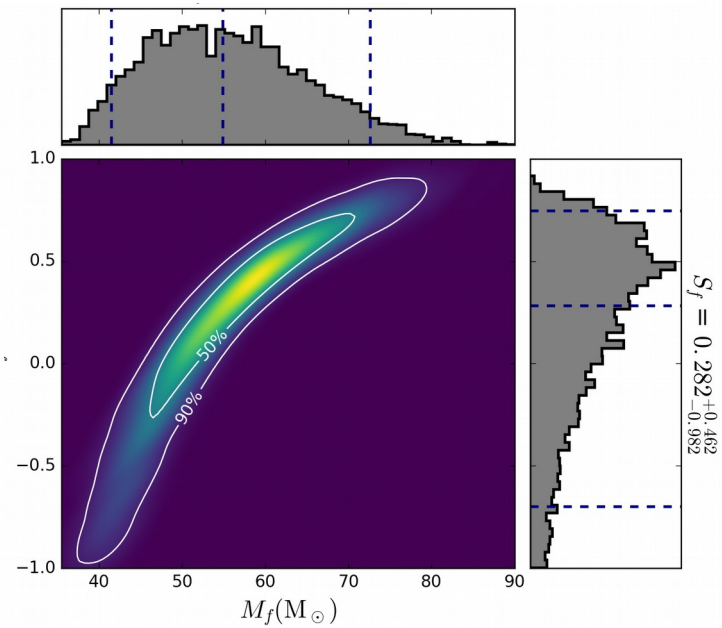
Testing GR: Ringdown

- “Late” part
- “No Hair Theorem”:
  - Determined by by mass & spin
  - Perturbations “ringdown” at $f_{lmn}(M,a)$
- Proxy: Light Ring / Photon-Sphere



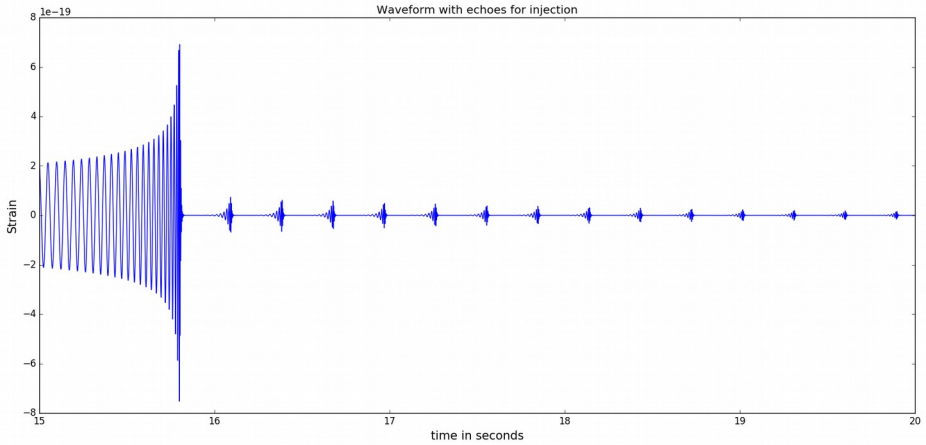
$$\omega_{orb} = \frac{\sqrt{GM}}{r^{3/2} + \chi \left(\sqrt{GM}/c\right)^3}$$





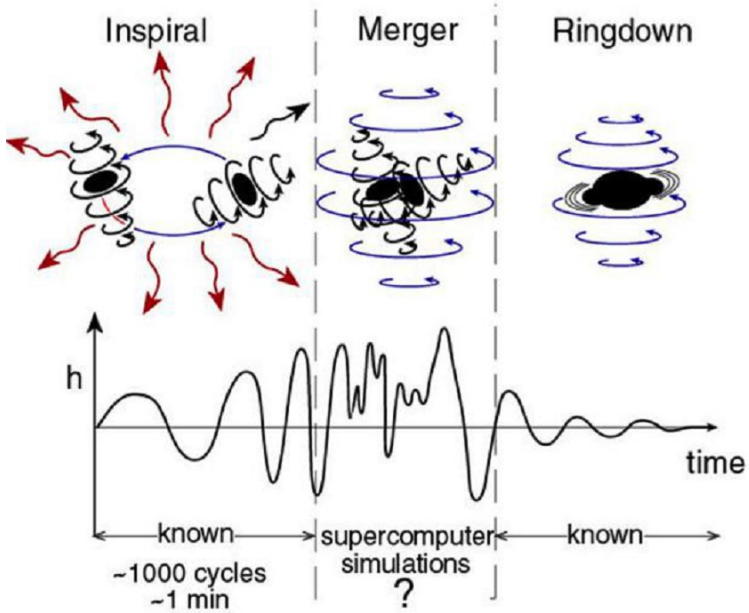
Testing GR: Ringdown

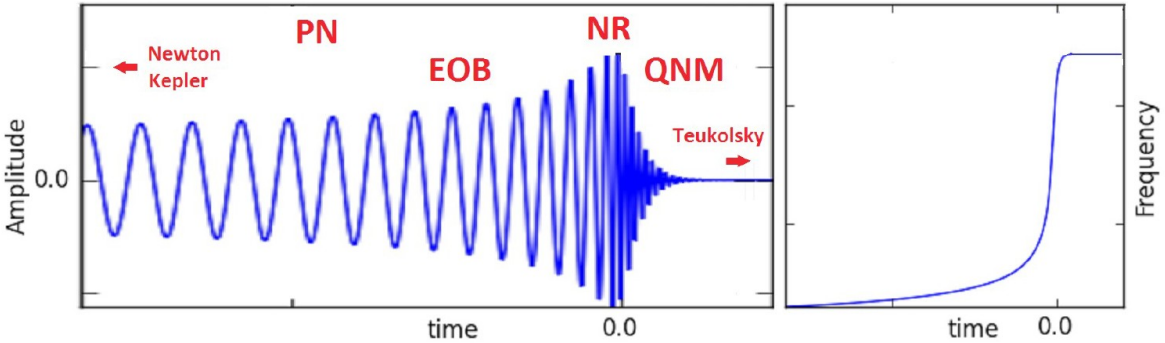
- Compare higher modes for “No Hair Theorem”
- Test Area Theorem
  - Allow for templates of alternative theories
- Test features beyond the Light Ring:
  - “Black Hole Mimickers”:
    - gravastars, boson stars, hydro models, strings
  - Test “Echoes”

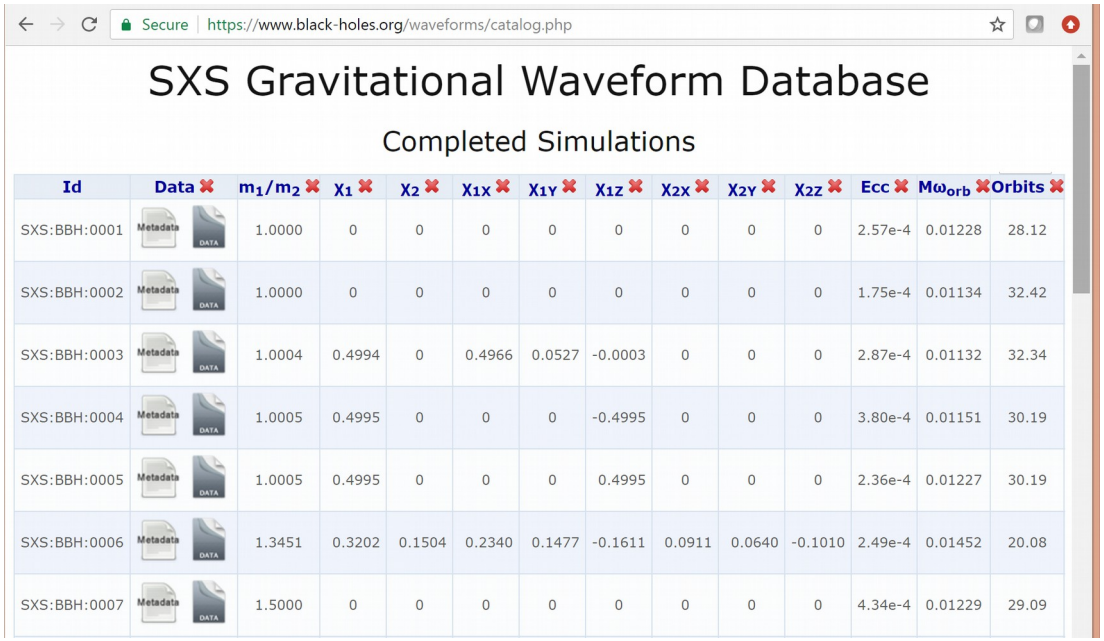


Numerical Relativity

Before 2005: Kip Thorne's sketch







SXS Gravitational Waveform Database

Completed Simulations

Id	Data	m_1/m_2	χ_1	χ_2	χ_{1x}	χ_{1y}	χ_{1z}	χ_{2x}	χ_{2y}	χ_{2z}	Ecc	$M\omega_{orb}$	Orbits
SXS:BBH:0001	Metadata DATA	1.0000	0	0	0	0	0	0	0	0	2.57e-4	0.01228	28.12
SXS:BBH:0002	Metadata DATA	1.0000	0	0	0	0	0	0	0	0	1.75e-4	0.01134	32.42
SXS:BBH:0003	Metadata DATA	1.0004	0.4994	0	0.4966	0.0527	-0.0003	0	0	0	2.87e-4	0.01132	32.34
SXS:BBH:0004	Metadata DATA	1.0005	0.4995	0	0	0	-0.4995	0	0	0	3.80e-4	0.01151	30.19
SXS:BBH:0005	Metadata DATA	1.0005	0.4995	0	0	0	0.4995	0	0	0	2.36e-4	0.01227	30.19
SXS:BBH:0006	Metadata DATA	1.3451	0.3202	0.1504	0.2340	0.1477	-0.1611	0.0911	0.0640	-0.1010	2.49e-4	0.01452	20.08
SXS:BBH:0007	Metadata DATA	1.5000	0	0	0	0	0	0	0	0	4.34e-4	0.01229	29.09

- Mass ratio $q = m_1/m_2 \lesssim 10$
- Spins: $\chi_{1,2} = S_{1,2}/m_{1,2}^2 \lesssim 0.6$
- Number of orbits $N \lesssim 15$

What next?

- New Compact Binary Coalescence sources:
  - Neutron Stars
  - BH-NS
- Matter effects:
  - Tides, Disruptions
  - E/M Fields
- New waveforms:
  - Precession (especially transitional precession)
  - GR modifications
  - Different remnants

2nd Observation Run (O2): Now running!

What next?

- 3rd detector – VIRGO => source localization
  => multi-messenger hunt
  => signal coherence

Wider detector network:

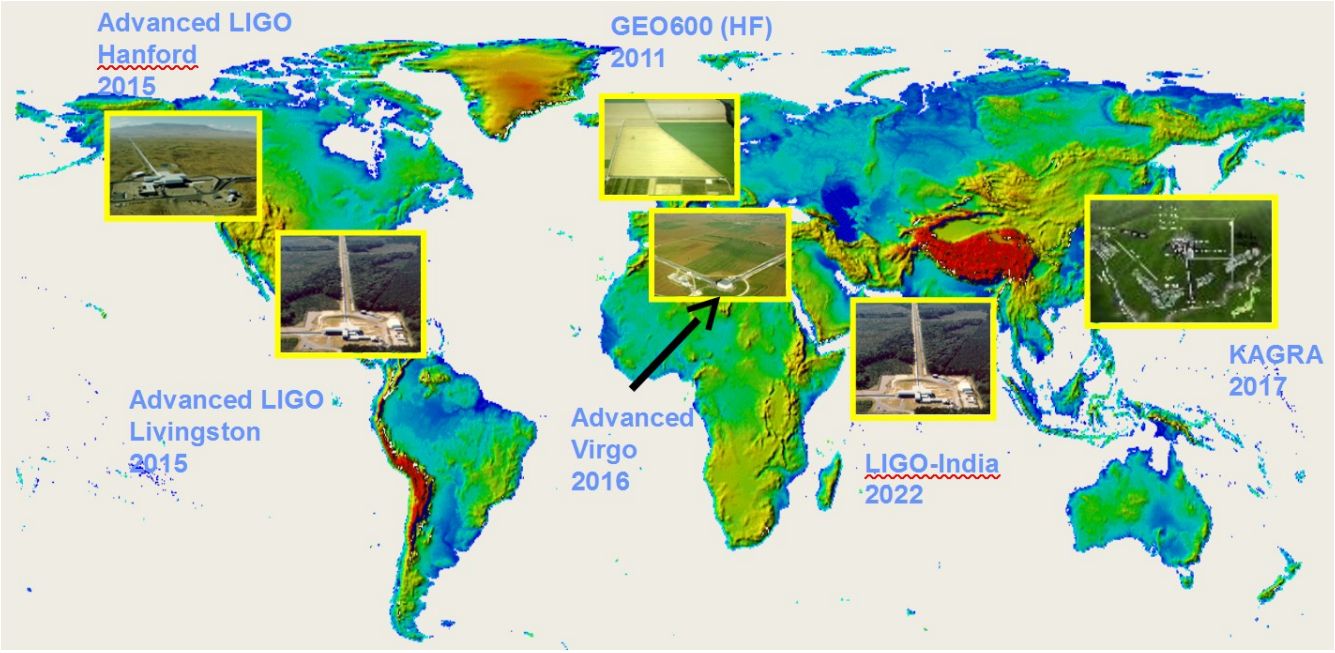
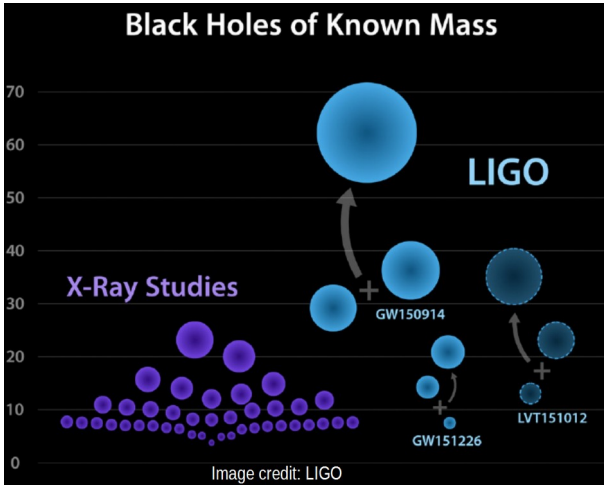


Image: Barry Barish

What next?

- Louder SNR => Higher modes
- Populations & Statistics => evolution models
- Other Sources:
  - Stochastic Background
  - Bursts:
    - Pulsar Glitches
    - Supernovae
  - Continuous Waves: Deformed Neutron Stars



- With new data come new surprises:
  - New noise analyses, new reduction techniques
  - New tests constrain theory => new theories…

Opportunities

- LIGO Open Science Center (LOSC)
  - Data Release with every detection publication
  - Codes & tutorials online
  - Full data release at ~2yr latency
- LIGO Algorithm Library code (LAL): open-source
- Einstein@home - crowd-sourced search
- Internships at LIGO sites and at AEI
- 73rd Scottish Universities Summer School
  http://www.supa.ac.uk/research/sussp73.php
- Online course (Sonoma State):
  Testing General Relativity with LIGO
  http://www.ssuexed.com/course.php?id=2839&sem=2&year=2017