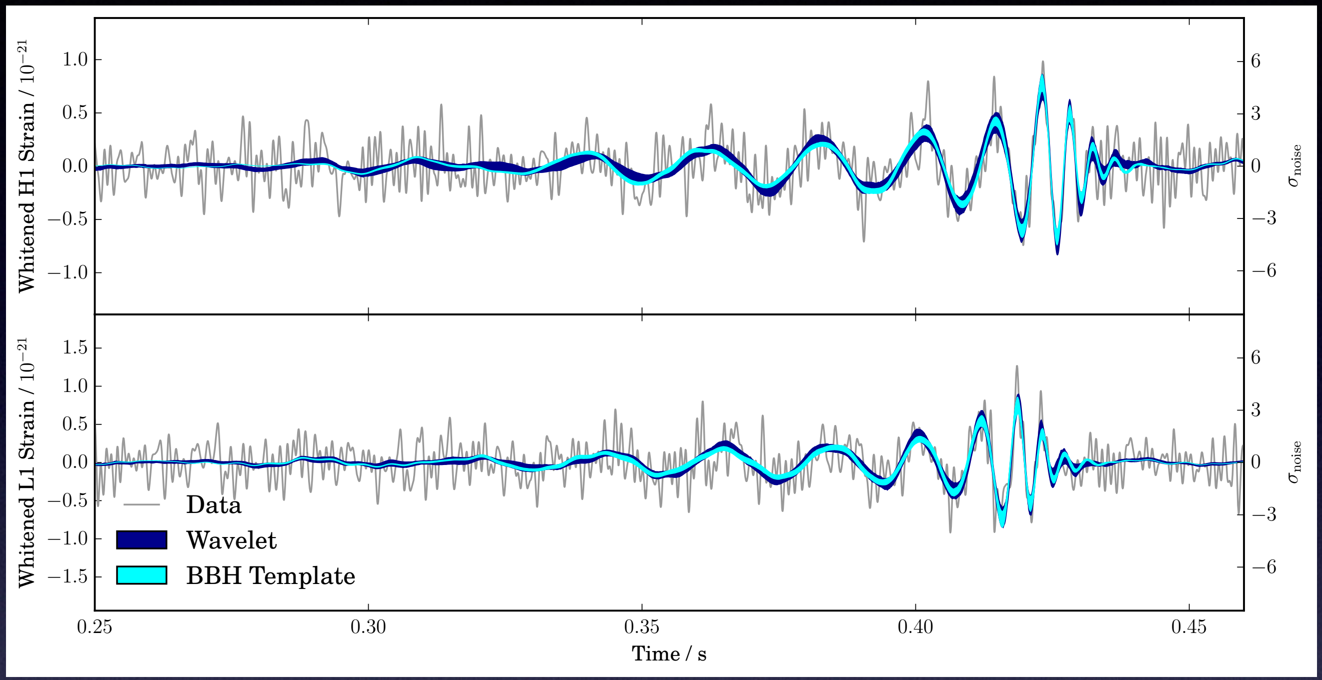
LIGO Discovery of a Binary Black-Hole Merger



Vicky Kalogera

Dept of Physics & Astronomy
Center for Interdisciplinary Exploration and Research in Astrophysics (CIERA)

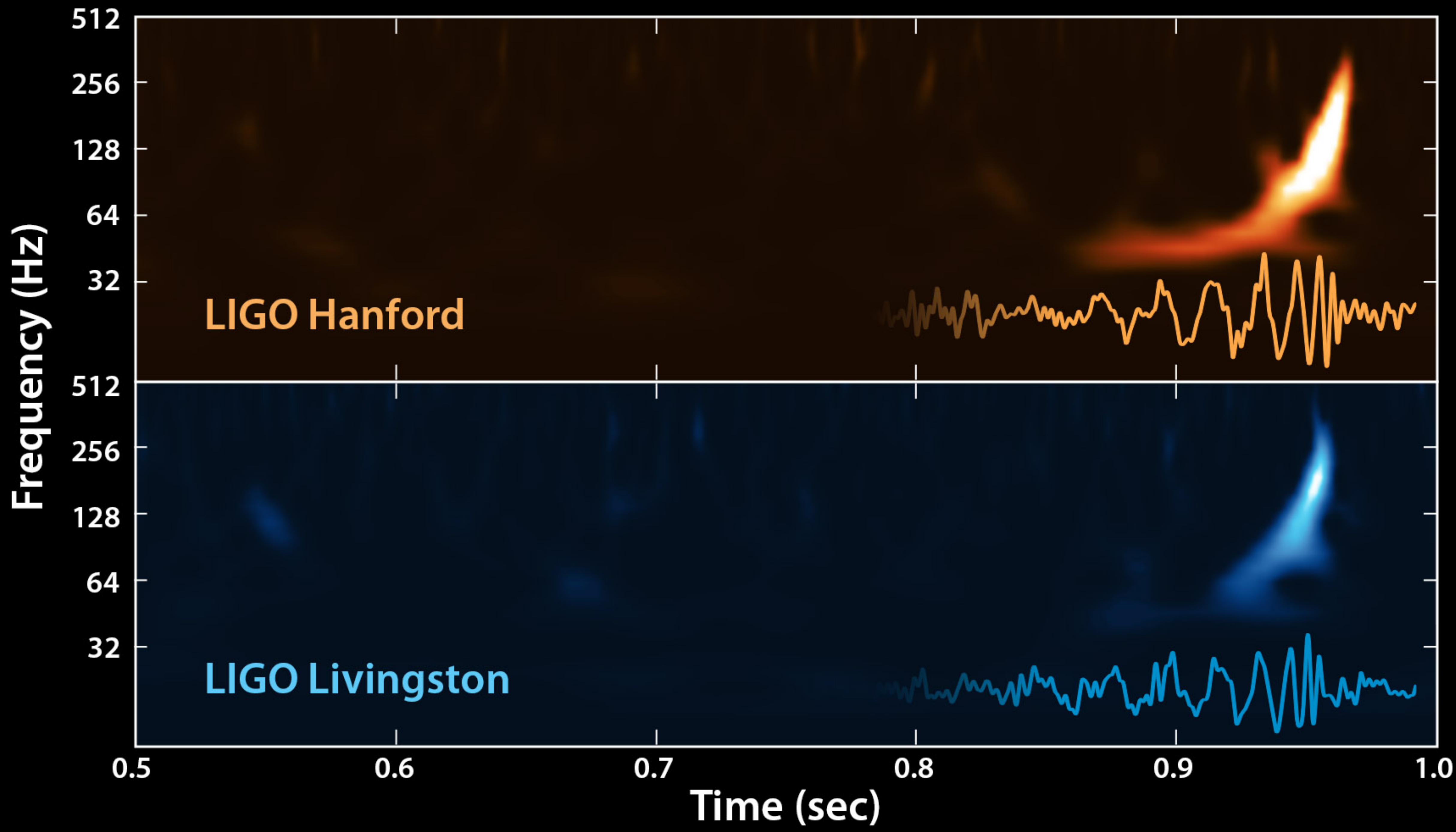
for the LIGO-Virgo Collaborations

NORTHWESTERN UNIVERSITY

LSC VIRGO

CIERA

GW150914



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LIGO Timeline

1970s
Early work on gravitational-wave detection by laser interferometers, including a 1972 MIT study describing a kilometer-scale interferometer and estimates of its noise sources.

1979
The National Science Foundation (NSF) funds a new group at Caltech for laser interferometer research and a prototype interferometer. It funds MIT to complete its prototype and design and lead industry study of technology, costs and sites for a kilometer-scale interferometer.

1983
MIT and Caltech jointly present results of the kilometer-scale interferometer study to NSF. Receive NSF committee endorsement on new large programs in physics.

1984
LIGO founded as a Caltech/MIT project. National Science Board approves LIGO development plan.

1986
Physics Decadal Survey and special NSF Panel on Gravitational Wave Interferometers endorse LIGO.

1990
The National Science Board (NSB) approves LIGO construction proposal, which envisions initial interferometers followed by advanced interferometers.

1992
NSF selects LIGO sites in Hanford, Washington, and Livingston, Louisiana. NSF and Caltech sign LIGO Cooperative Agreement.

1994-95
Site construction begins at Hanford and Livingston locations.

1997
The LIGO Scientific Collaboration (LSC) is established and expands LIGO beyond Caltech and MIT, including the British/German GEO collaboration, which operates the GEO600 interferometer in Hannover, Germany.

2002
First coincident operation of initial LIGO interferometers with GEO600 interferometer.

2004
NSB approves Advanced LIGO.

2006
Initial LIGO design sensitivity achieved. First gravitational wave search at design sensitivity.

2007
Joint data analysis agreement ratified between LIGO and the Virgo Collaboration, which operates the Virgo interferometer in Cascina, Italy. Joint observations with enhanced initial LIGO interferometer and Virgo.

2008
Start of Advanced LIGO construction.

2010
Initial LIGO operations conclude; Advanced LIGO installation begins.

2011-14
Advanced LIGO installation and testing.

2014
Advanced LIGO installation complete.

2014-15
Advanced LIGO sensitivity surpasses initial LIGO.

9/2015
During an engineering test a few days before the first official search begins, Advanced LIGO detects strong gravitational waves from collision of two black holes.

Image credit: Werner Benger/ Max Planck Institute for Gravitational Physics

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LIGO Team

- **Astrophysics of LIGO sources**
  - computational modeling of compact object binaries
  - predictions for LIGO observations
  - interpretation of observed systems

- **LIGO data analysis**
  - advanced method development
  - data characterization
  - source parameter estimation

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LIGO Team

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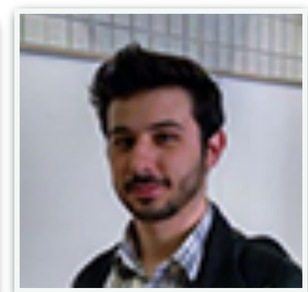

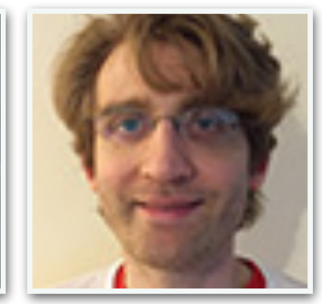

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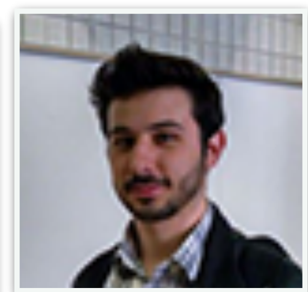

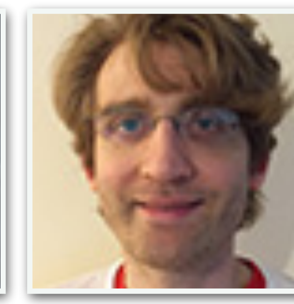



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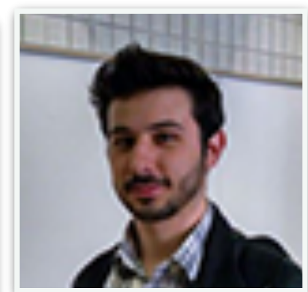
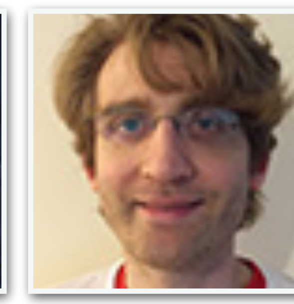
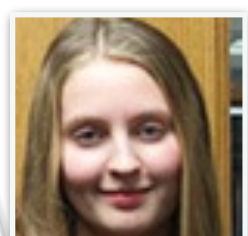
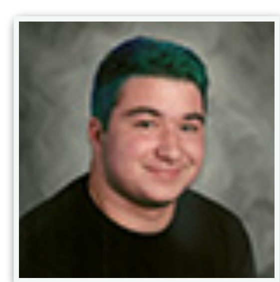
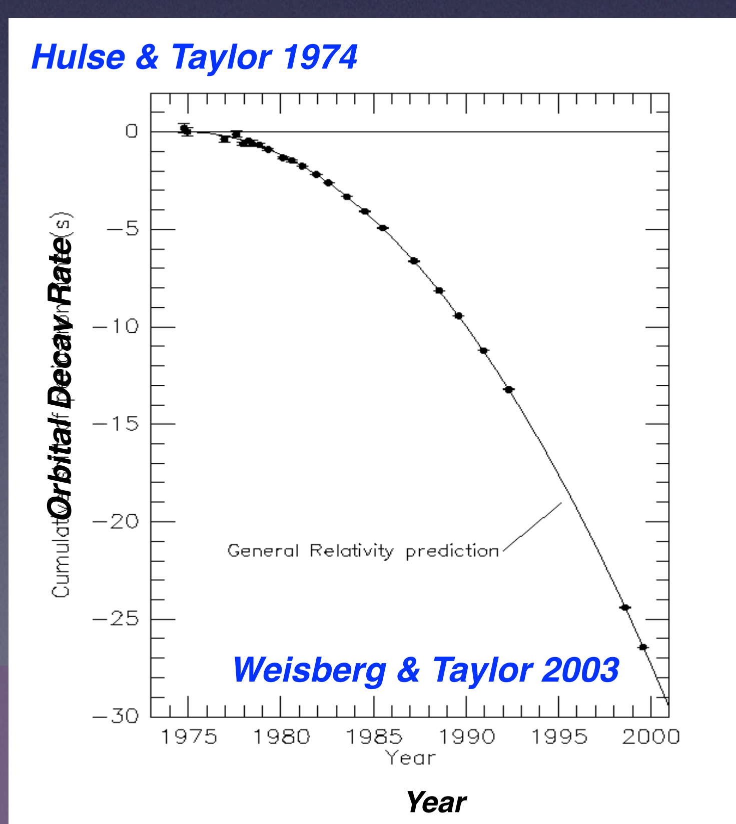


LIGO Detectors

Binary Inspiral
Source of Gravitational Waves



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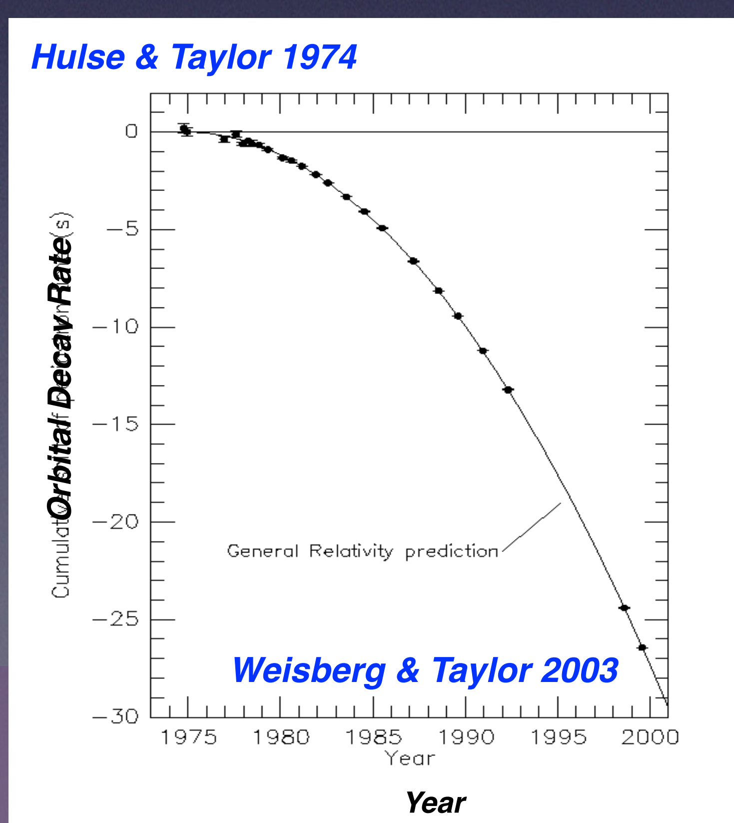

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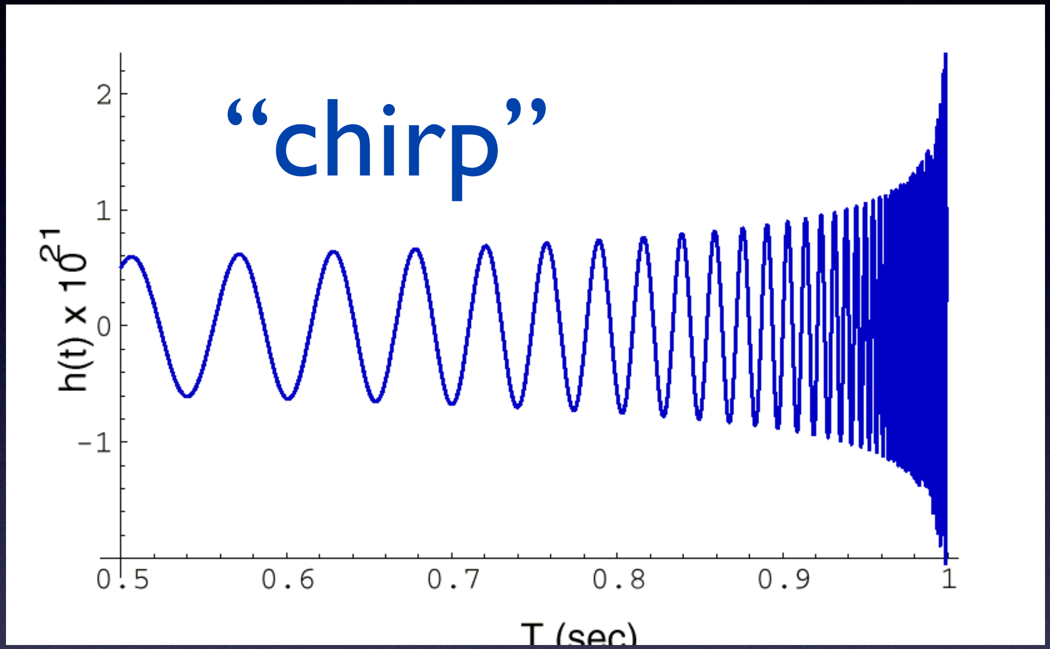

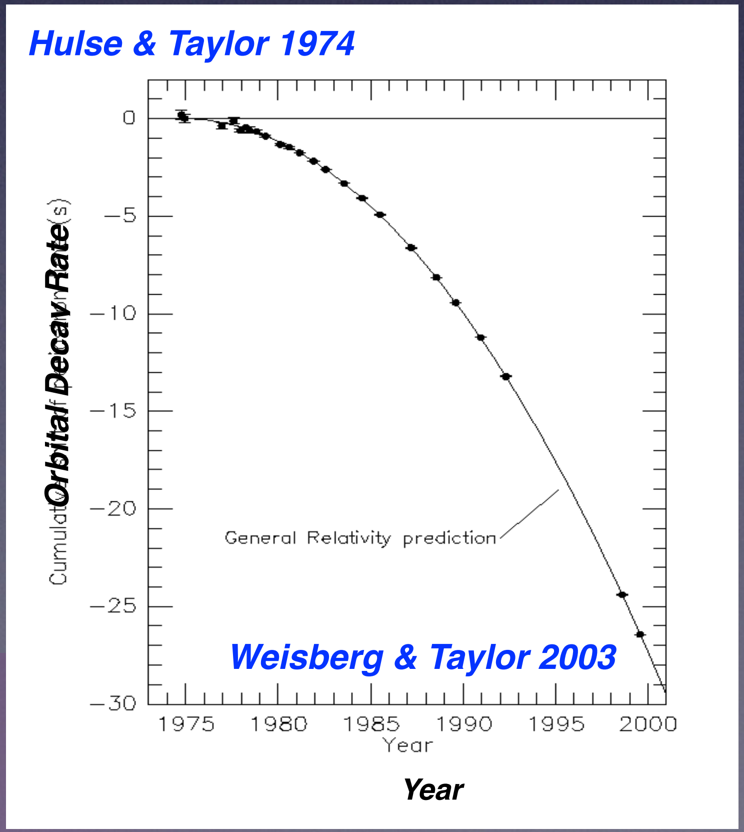

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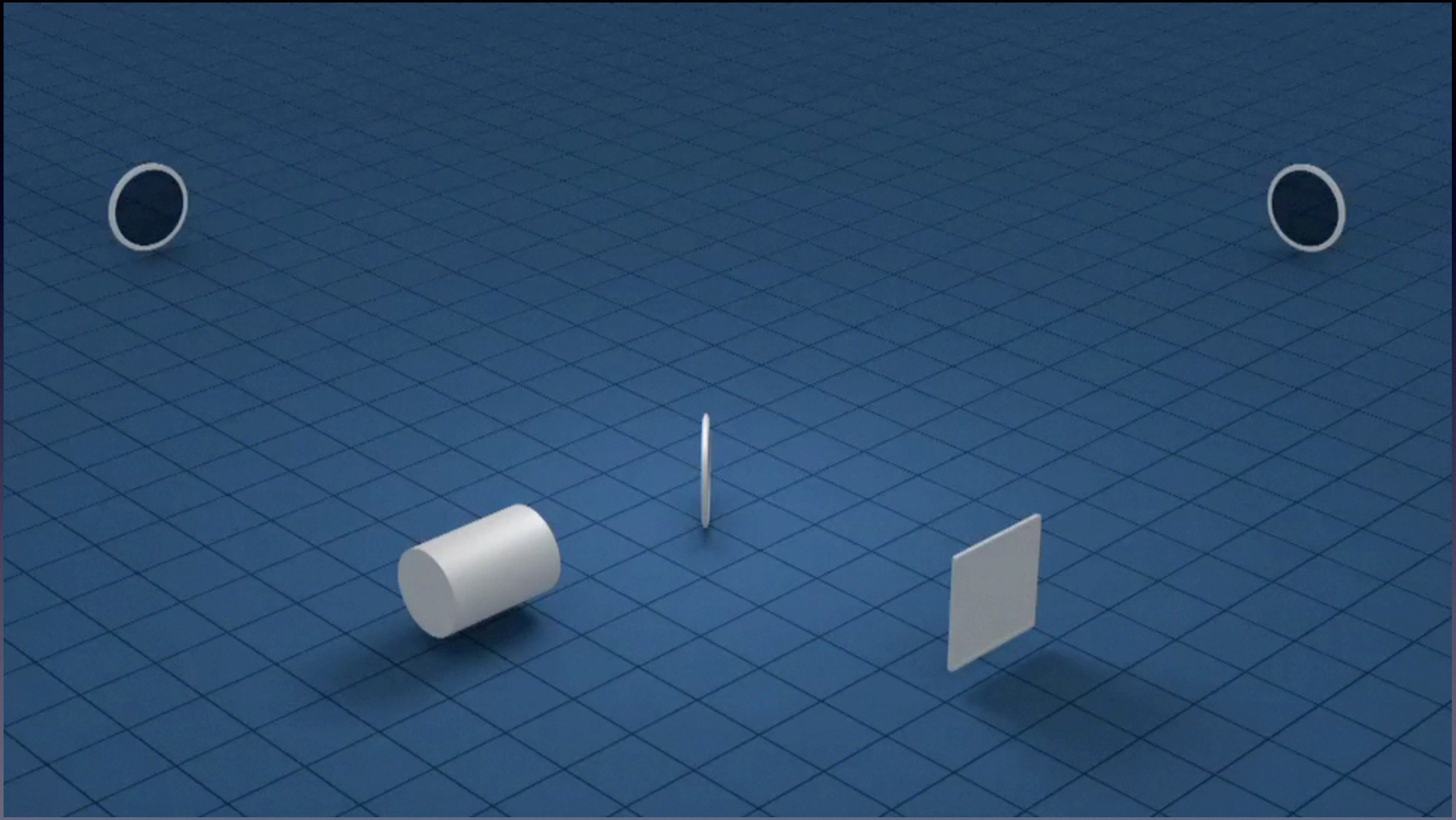
Two LIGO detectors

Initial LIGO

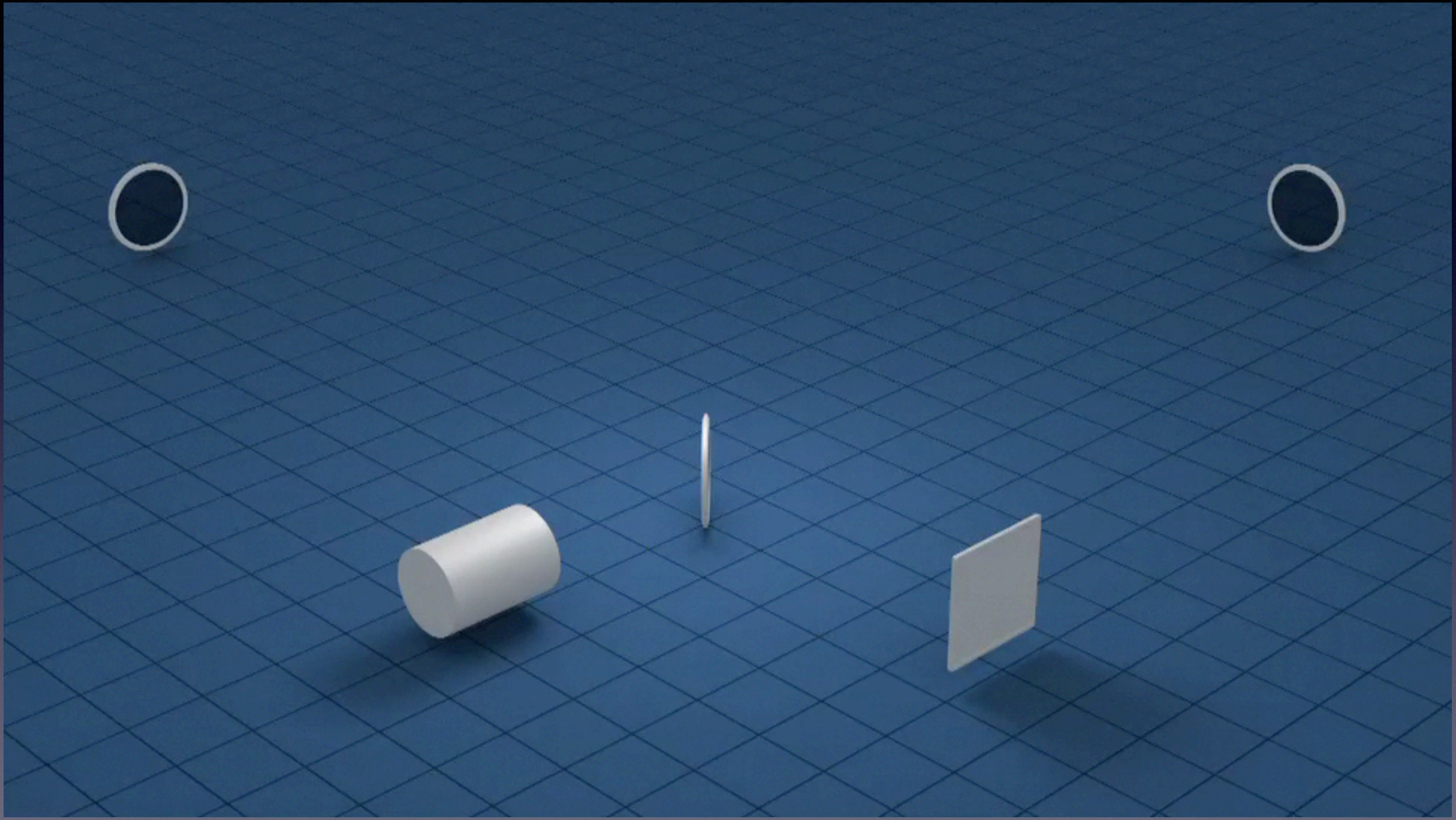
2001 - 2006

2006 - 2010

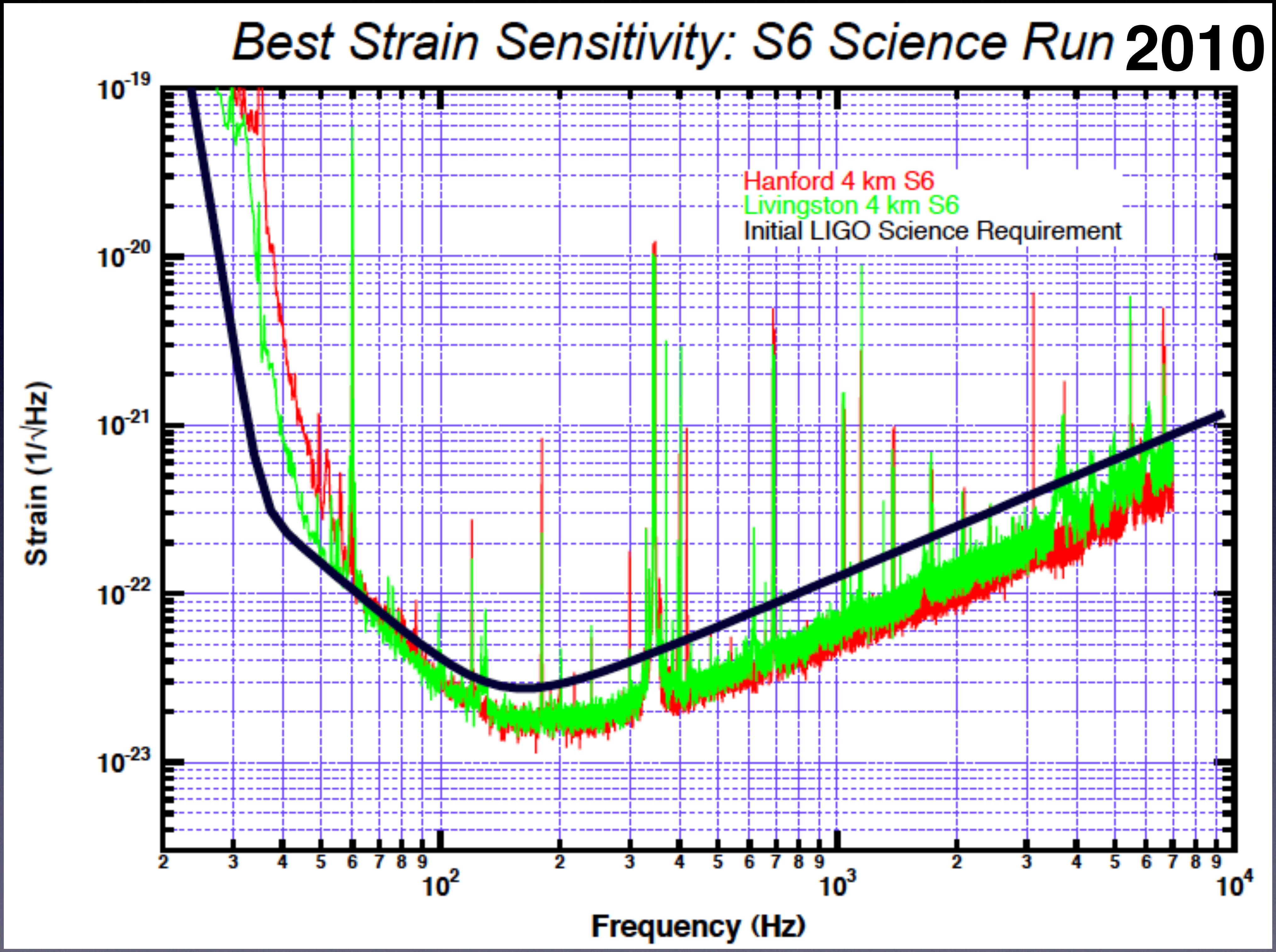
Laser Interferometer



Laser Interferometer



Initial LIGO



Advanced LIGO: Plan for Observing Runs

You are here

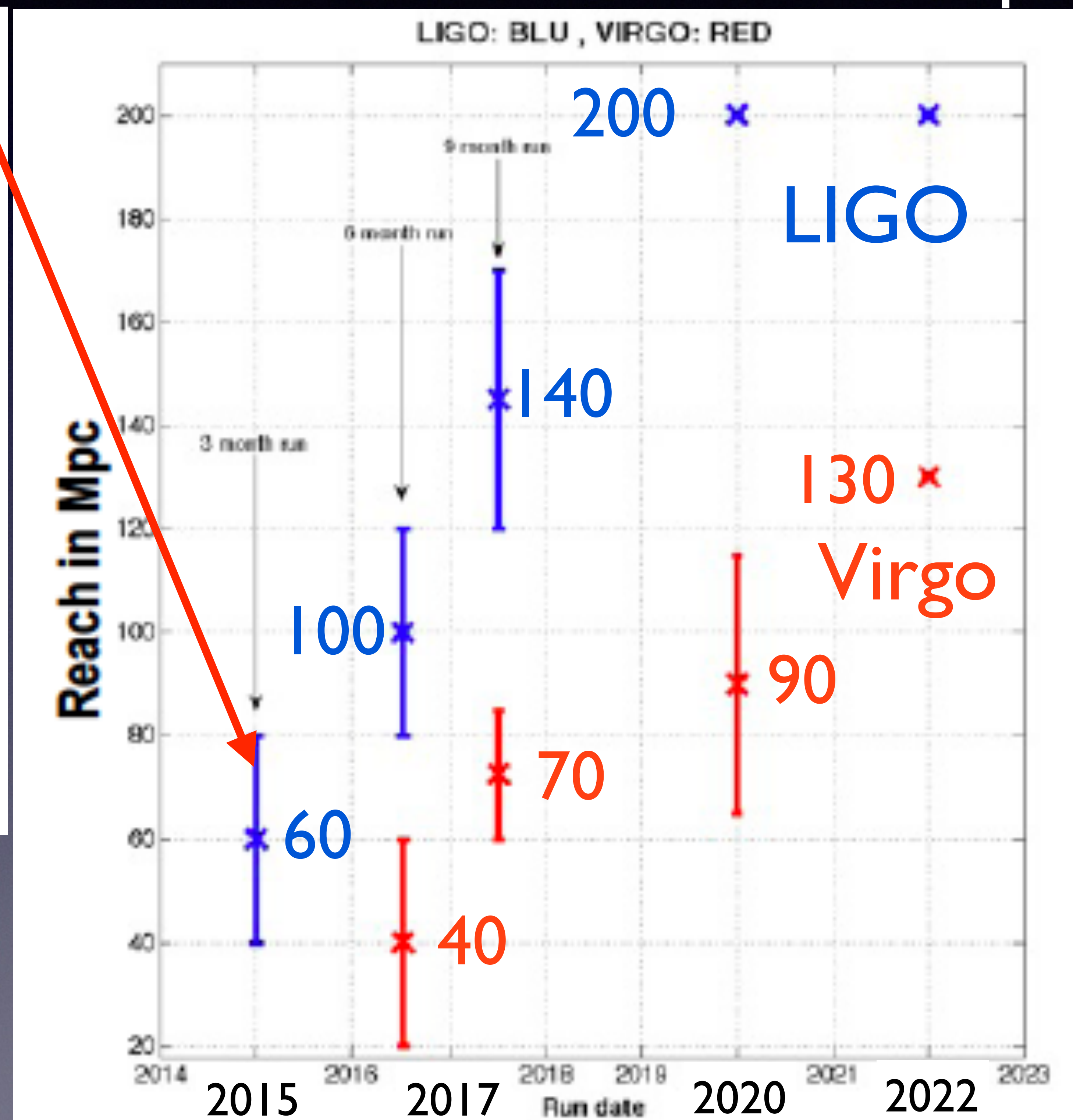
Second generation interferometers to begin science operations:

- Advanced LIGO (2 interferometers) – 2015
- Advanced Virgo (1 interferometer) – 2016

Approximate run schedule:

- **Advanced LIGO:**
  ~ 3 month run in 2015,
  ~ 6 month run in 2016-17
  ~ 9 month run in 2017-18
- **Advanced Virgo:**
  ~ 6 month run in 2016-17
  ~ 9 month run in 2017-18
- *Modification of run schedules is likely as we learn more about the instruments*

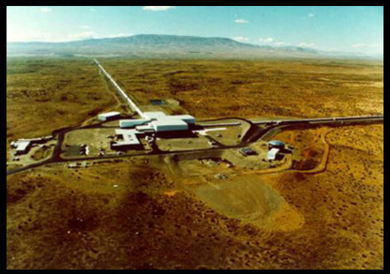
NS-NS Reach in Mpc

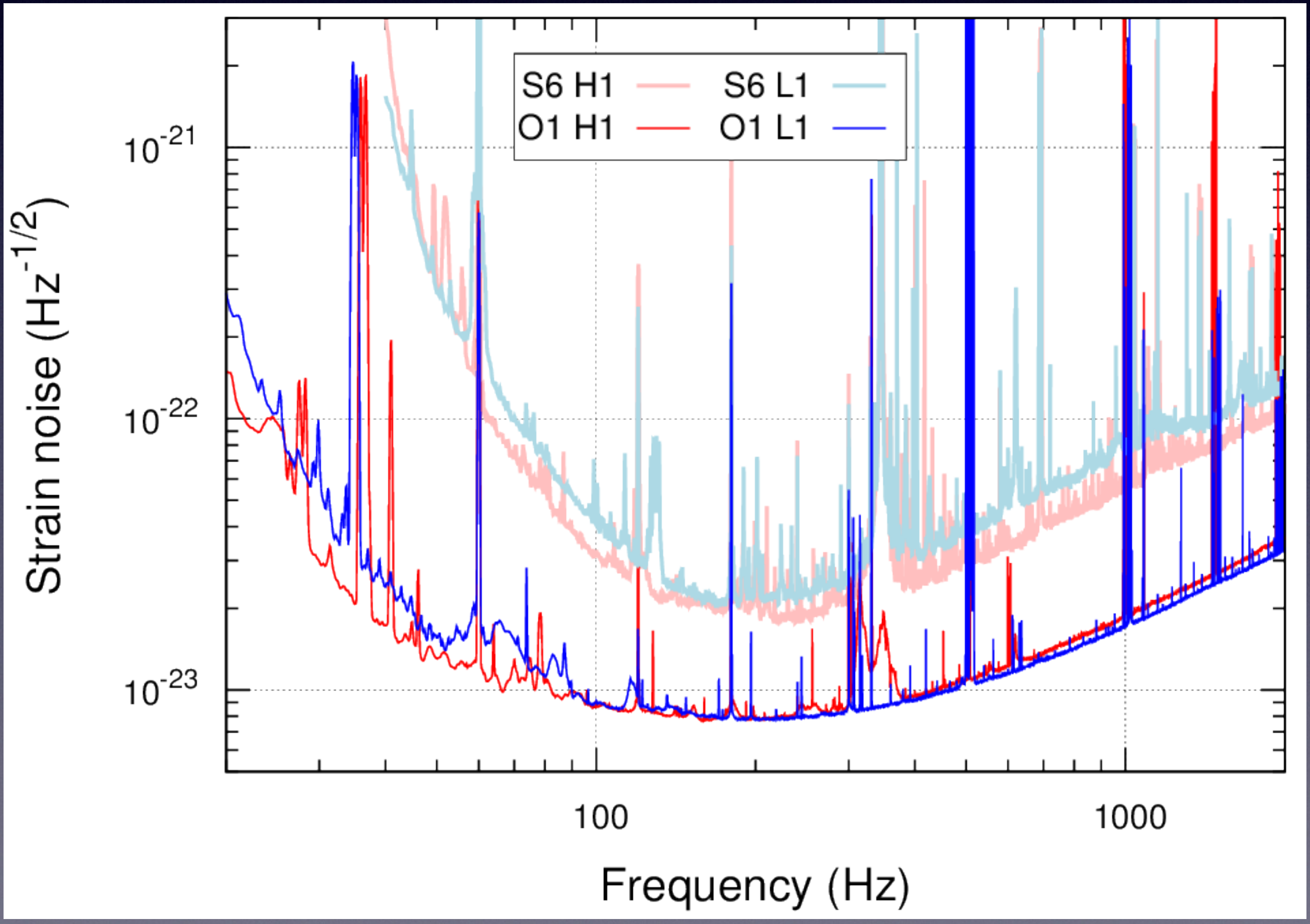


Advanced LIGO

Key Detector Upgrades

- Increased Laser Power
- Bigger Mirror Masses
- Better Mirror Coatings
- Improved Seismic Isolation

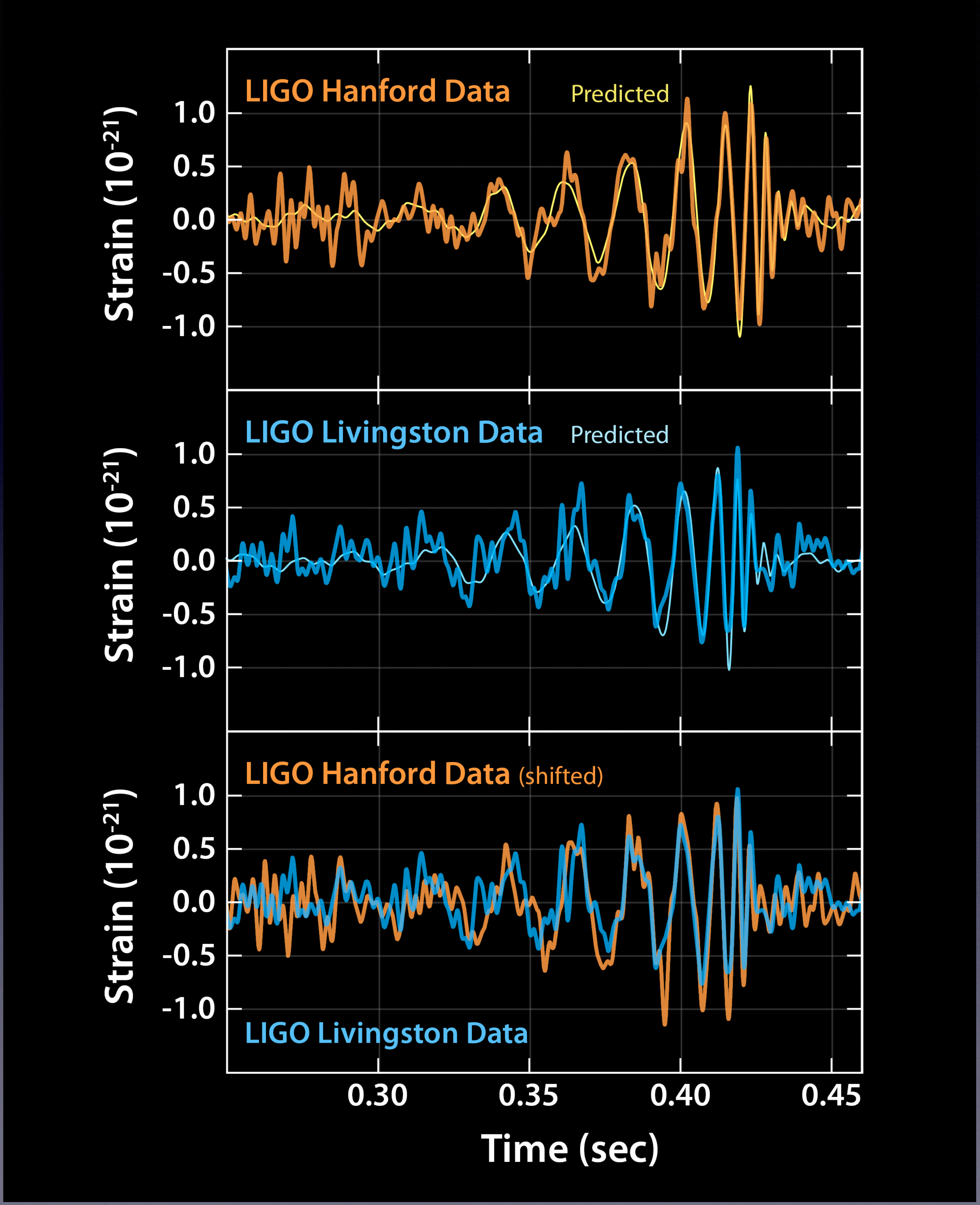




GW150914

S/N ~ 20

peak strain:
1e-21



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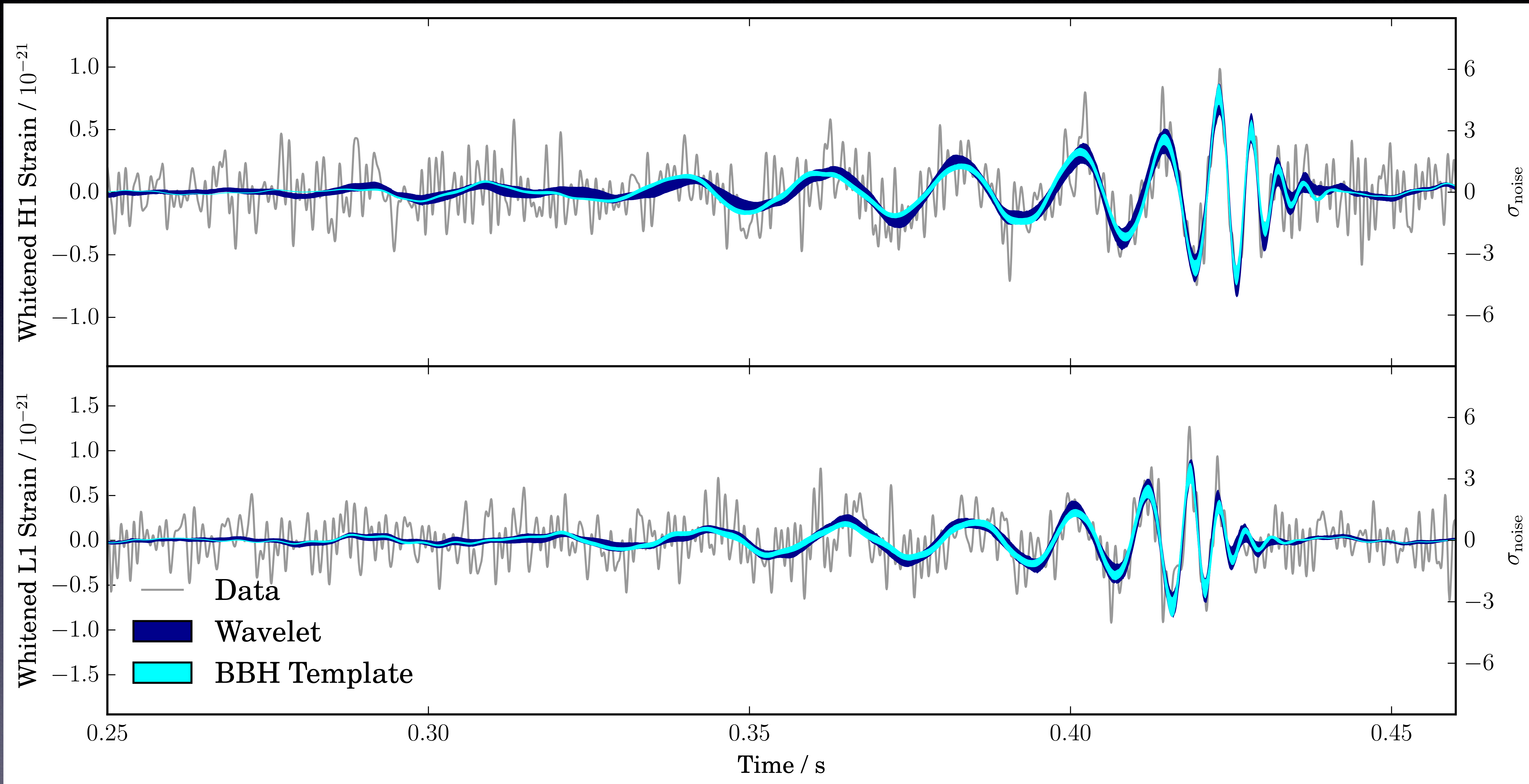

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GW150914

signal and source

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3}f^{-11/3}\dot{f}\right]^{3/5}$$

chirp mass

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	less than 1 in 5 million
false alarm rate	1 in 200,000 yr
Source Masses	M⊙
total mass	65
chirpmass	28
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	62
mass ratio	0.6 to 1
primary BH spin	< 0.7
secondary BH spin	< 0.9
remnant BH spin	0.7
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameters with a range (e.g. distance) are 90% credible bounds; fractional error on parameters without a range is less than 10%. **Acronyms**: L1=LIGO

GW150914

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signal and source

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3} \dot{f}\right]^{3/5}$$

chirp mass

observed by	LIGO L1, H1
source type	black hole (BH) binary
date	14 Sept 2015
time	09:50:45 UTC
likely distance	0.75 to 1.9 Gly 230 to 570 Mpc
redshift	0.054 to 0.136
signal-to-noise ratio	24
false alarm prob.	less than 1 in 5 million
false alarm rate	1 in 200,000 yr
Source Masses	M⊙
total mass	65
chirpmass	28
primary BH	32 to 41
secondary BH	25 to 33
remnant BH	62
mass ratio	0.6 to 1
primary BH spin	< 0.7
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remnant BH spin	0.7
signal arrival time delay	arrived in L1 7 ms before H1
likely sky position	Southern Hemisphere
likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^5 km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

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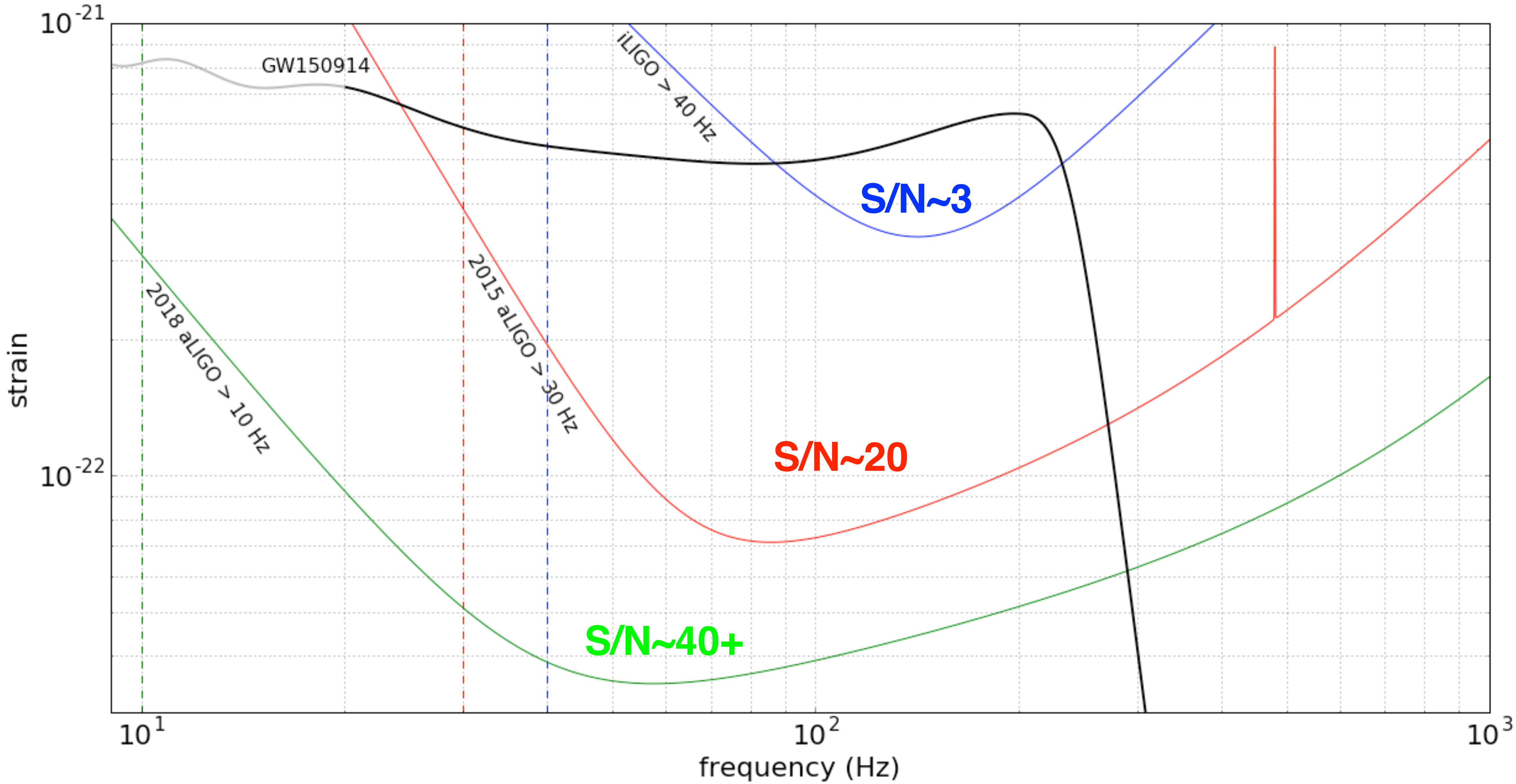
GW150914

credit: C. Pankow



GW150914 Papers

Discovery paper

"Observation of Gravitational Waves from a Binary Black Hole Merger"
Published in PRL 116, 061102 (2016)

Companion papers:

"Astrophysical Implications of the Binary Black-Hole Merger GW150914”
Published in ApJL 818, L22 (2016)

"Observing gravitational-wave transient GW150914 with minimal assumptions”

"GW150914: First results from the search for binary black hole coalescence with Advanced LIGO”

"Properties of the binary black hole merger GW150914”

"The Rate of Binary Black Hole Mergers Inferred from Advanced LIGO Observations Surrounding GW150914"

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GW150914 Papers

Companion papers:

"Tests of general relativity with GW150914”

"GW150914: Implications for the stochastic gravitational-wave background from binary black holes"

"Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914"

"Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914"

"High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with IceCube and ANTARES"

"GW150914: The Advanced LIGO Detectors in the Era of First Discoveries"

"Localization and broadband follow-up of the gravitational-wave transient GW150914"

LSC VIRGO

Data release at **LIGO Open Science Center** (LOSC)

GW150914 Analyses Results

LIGO Searches

39 days of LIGO observations: Sep 12 - Oct 20
16 days of coincident time

Data searched with 5 independent pipelines:

- 3 burst pipelines
- 2 binary-coalescence pipelines

all give consistent results!!!

- Key analysis method: “time slides”

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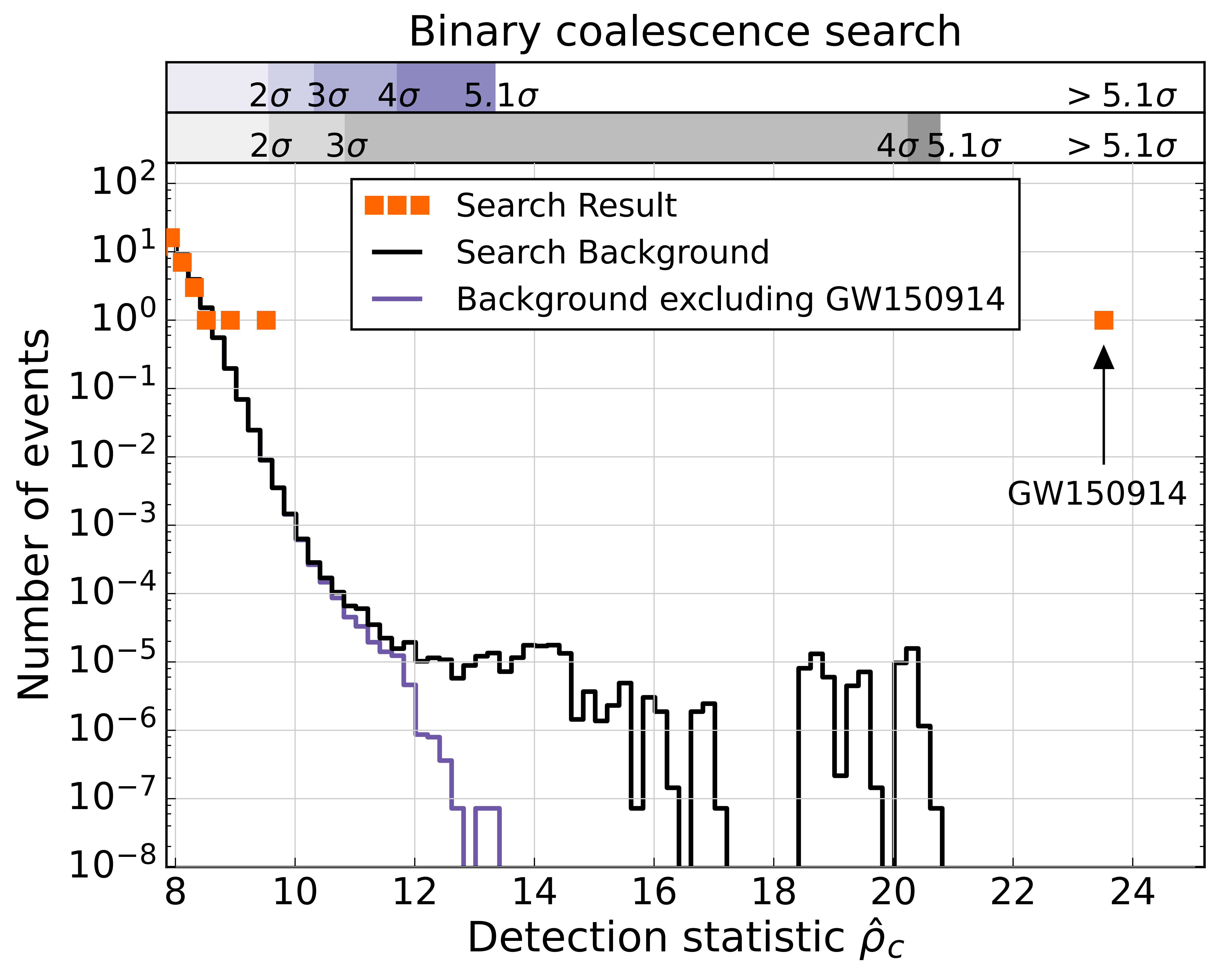
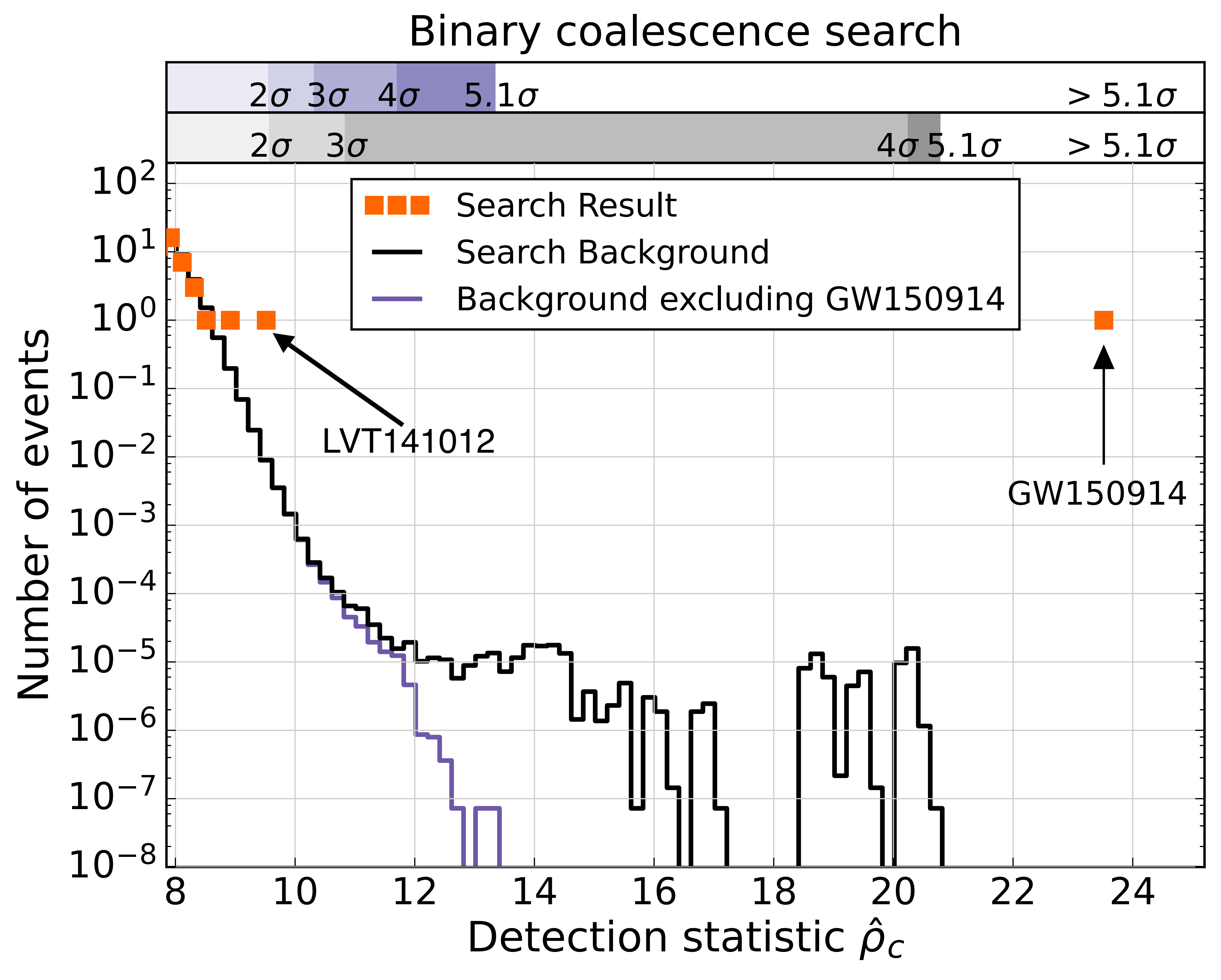
LIGO Search for Compact Binary Coalescence



The LVC, PRL, published, arxiv/1602.03837

LIGO Search for Compact Binary Coalescence



The LVC, PRL, published, arxiv/1602.03837

GW150914

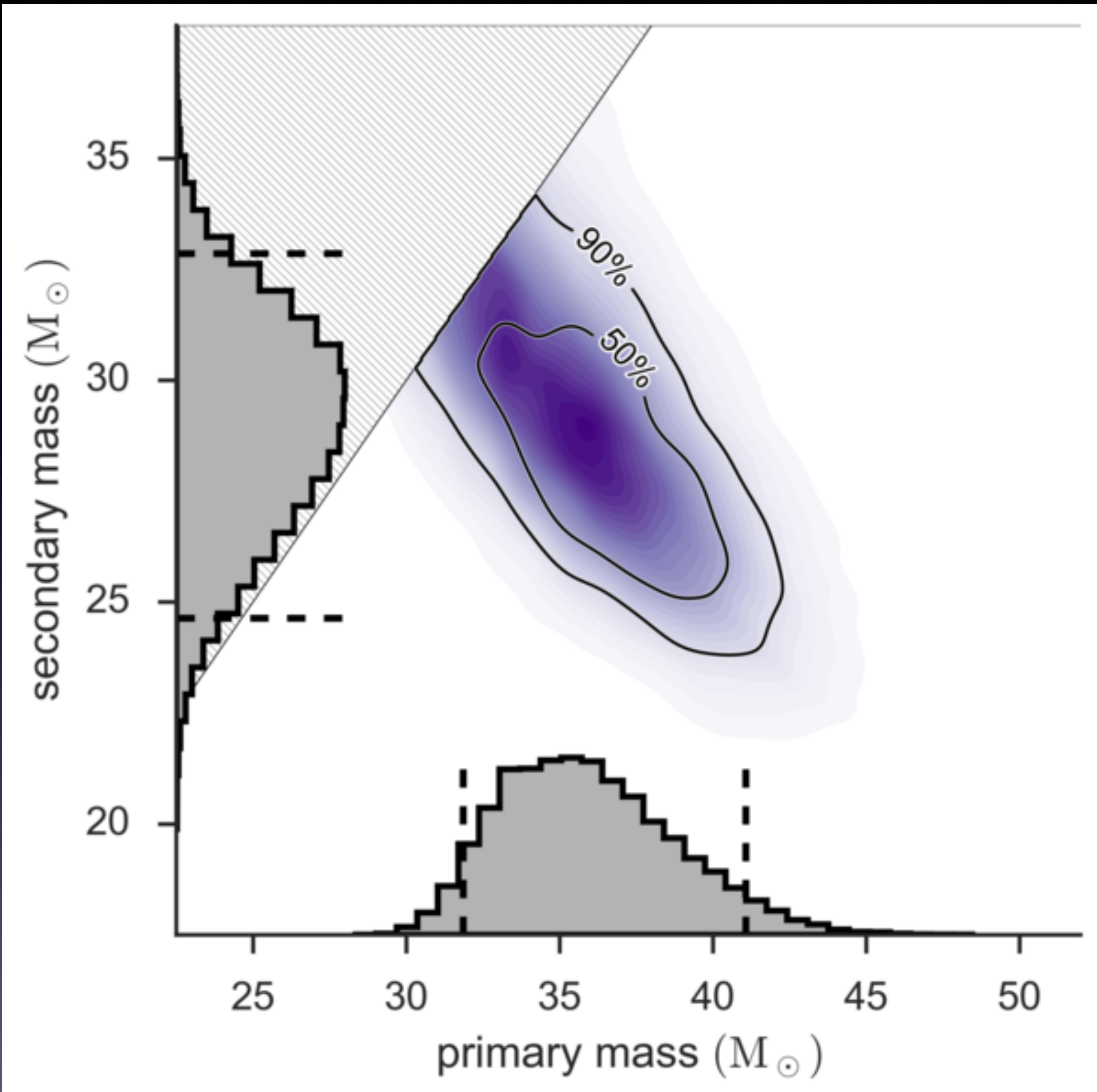
Physical Parameter Estimation

Bayesian stochastic sampling of 12D parameter space:

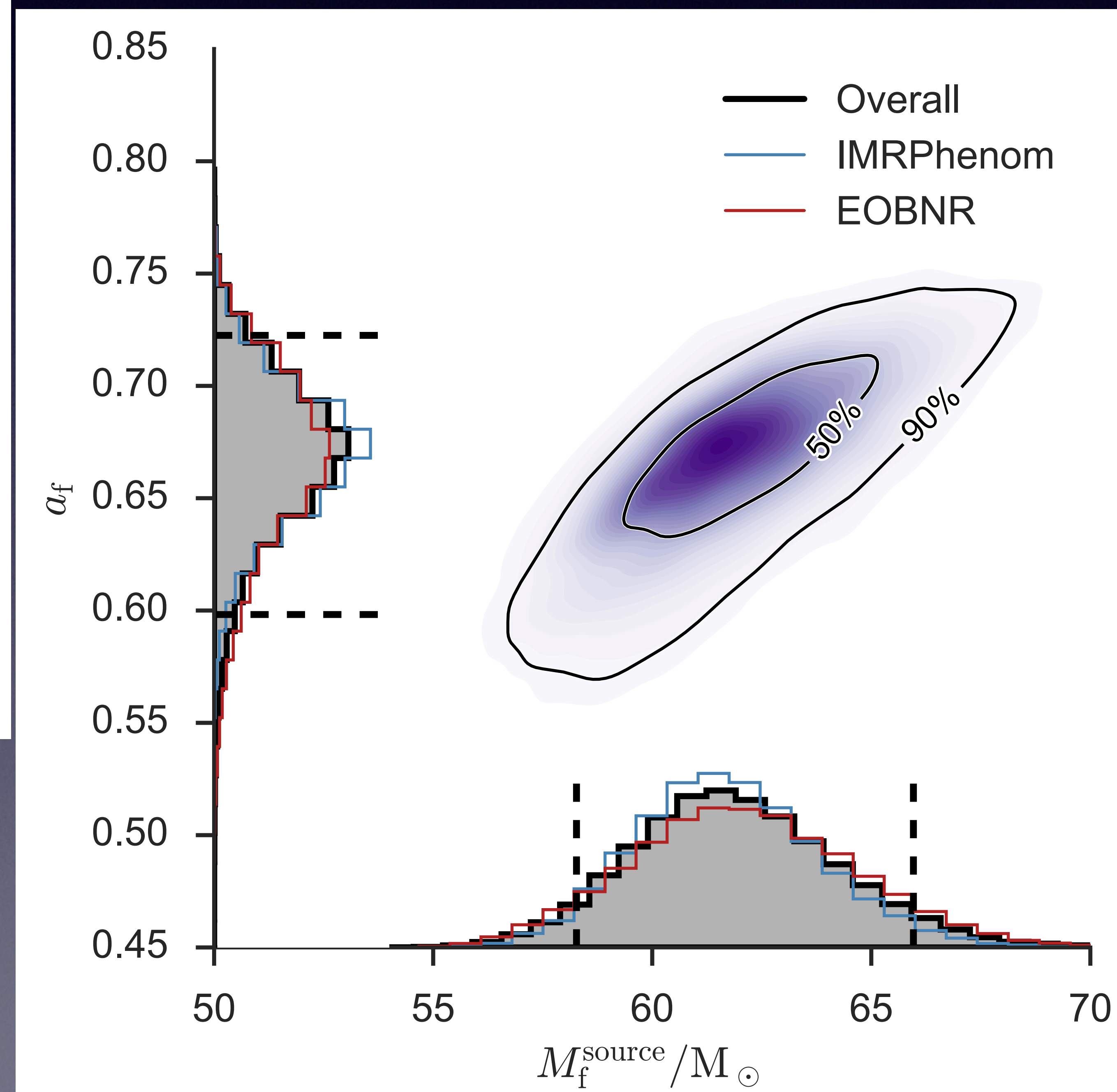
- 2 different samplers
- 2 different binary-coalescence waveforms
- 1 generic "waveform"

all give consistent results!!!

GW150914: Masses



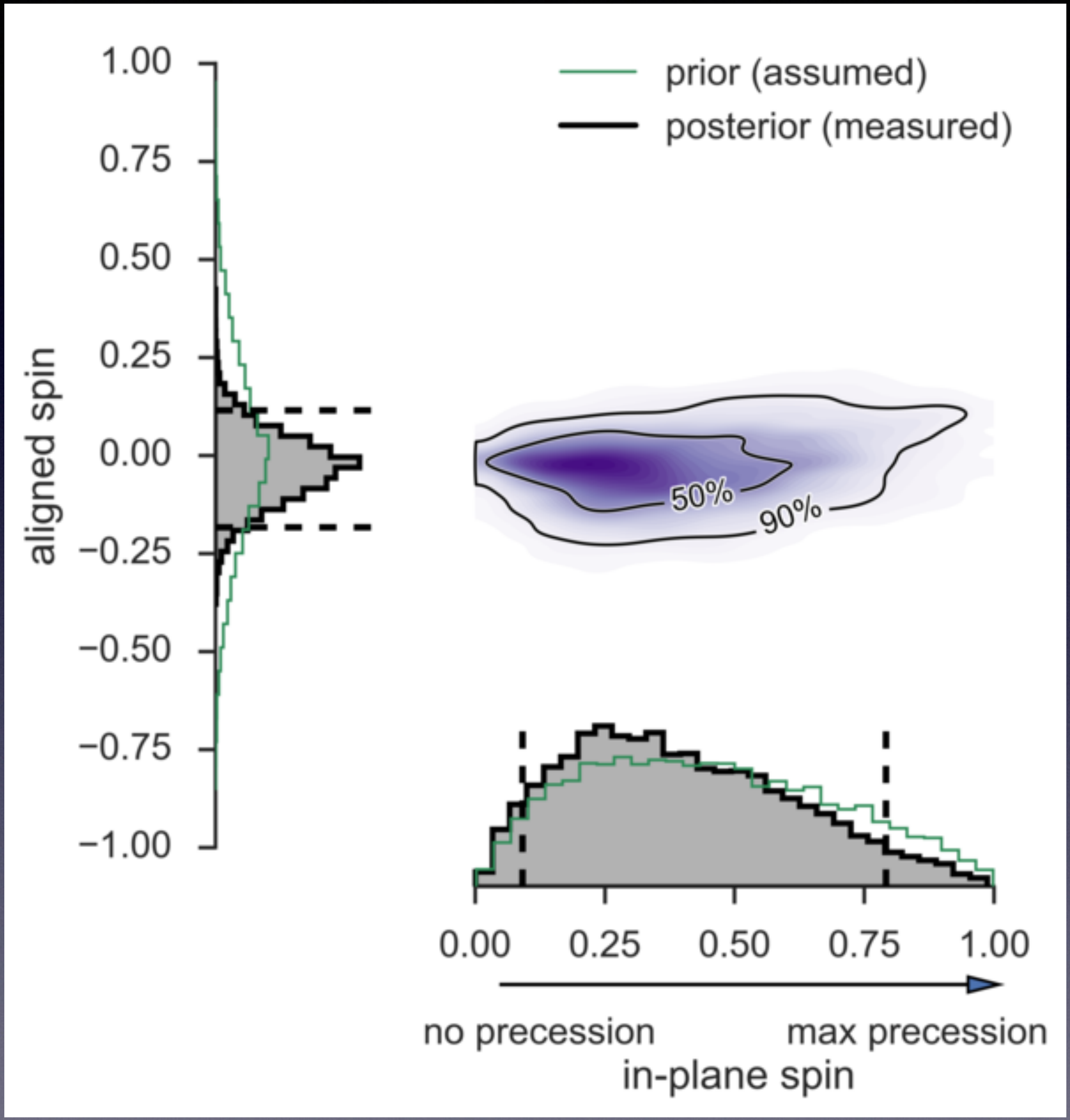
final mass and spin
(from NR fits)



individual masses

The LVC, PRL, arxiv/1602.03840

GW150914: Spins

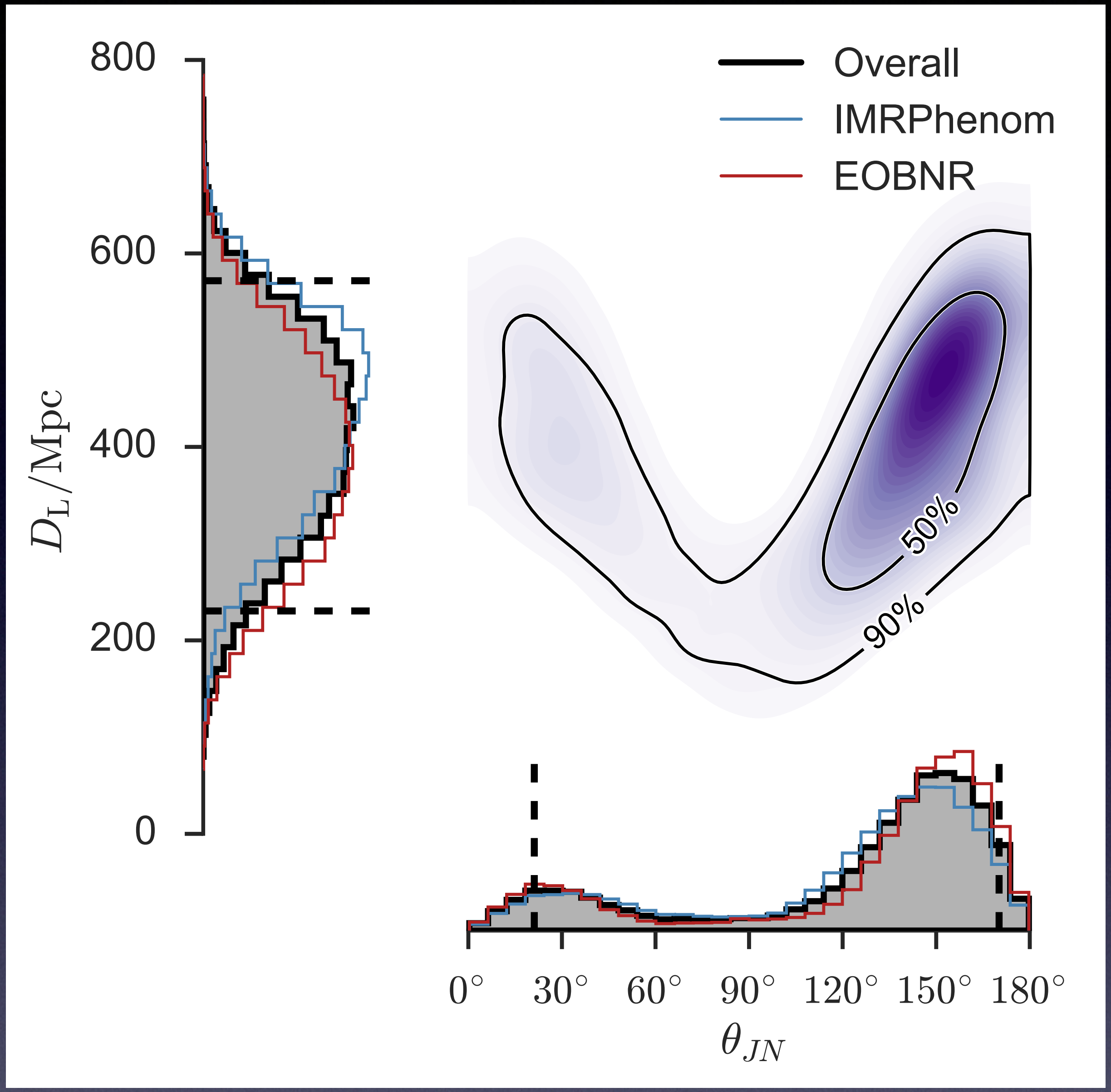


spins aligned with orb. ang.mom. are constrained to be small

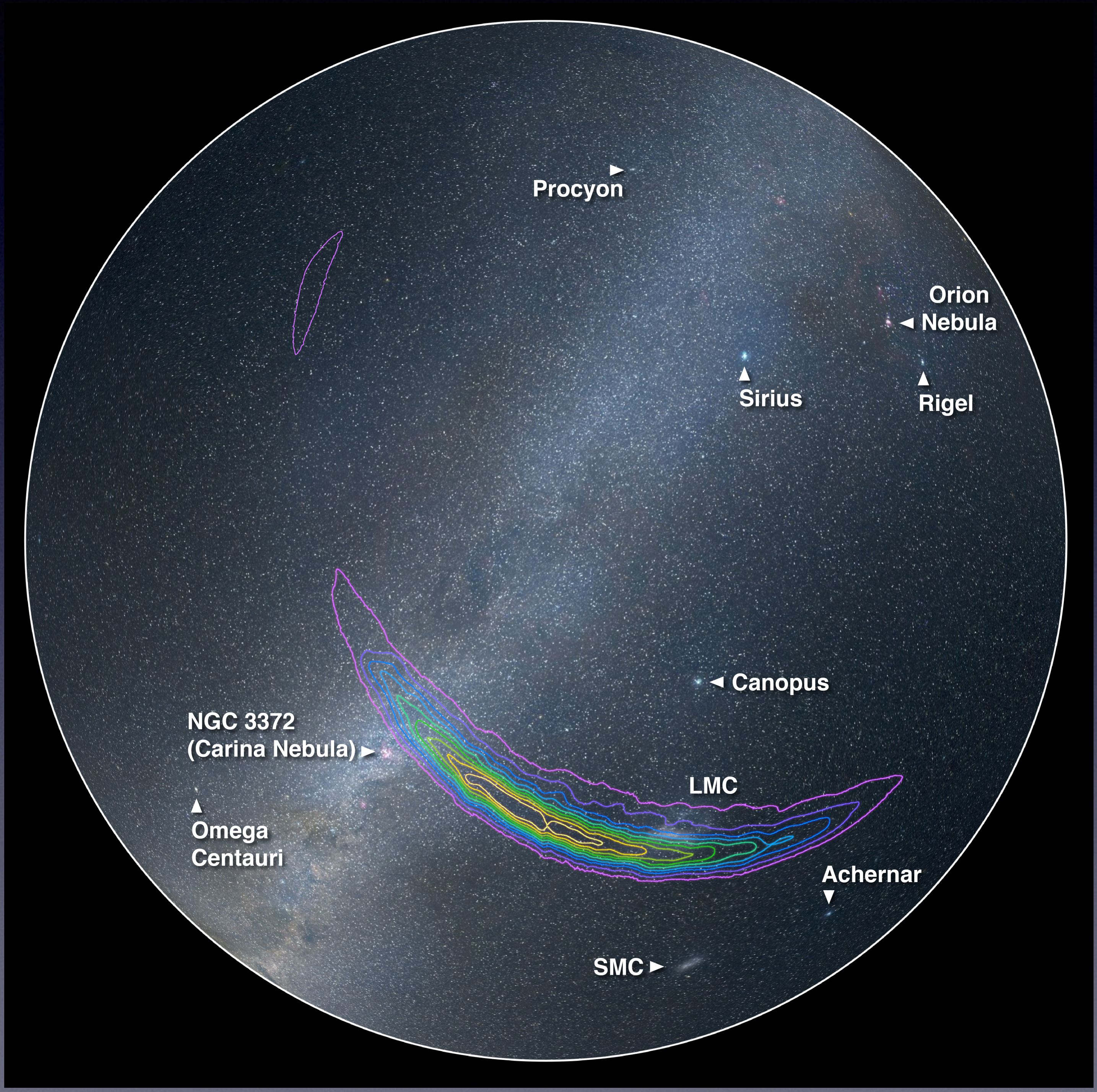
in-plane spins are unconstrained

The LVC, PRL, arxiv/1602.03840

GW150914: distance - inclination



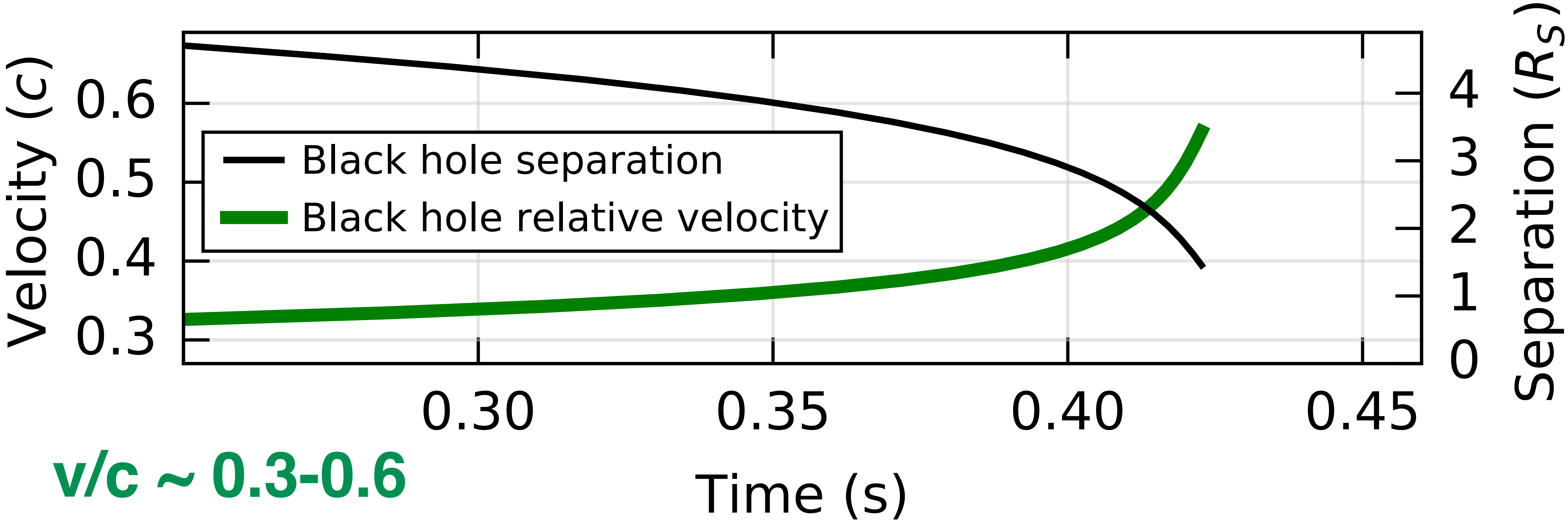
~600 square degrees



The LVC, PRL, arxiv/1602.03840

GW150914: sky map

GW150914: first-ever strong-field GR tests

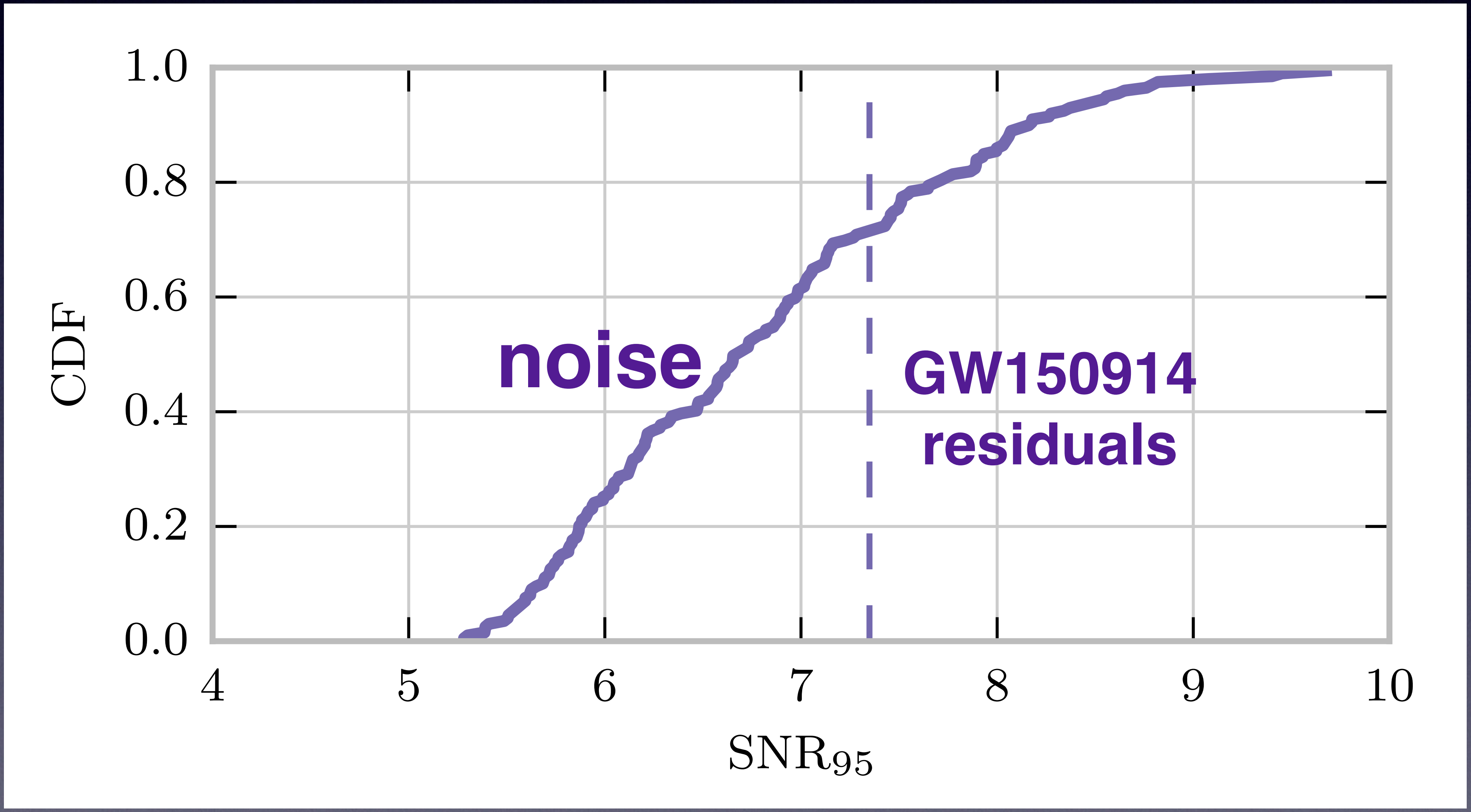


v/c ~ 0.3-0.6

The LVC, PRL, published, arxiv/1602.03837

GW150914: strong-field GR tests

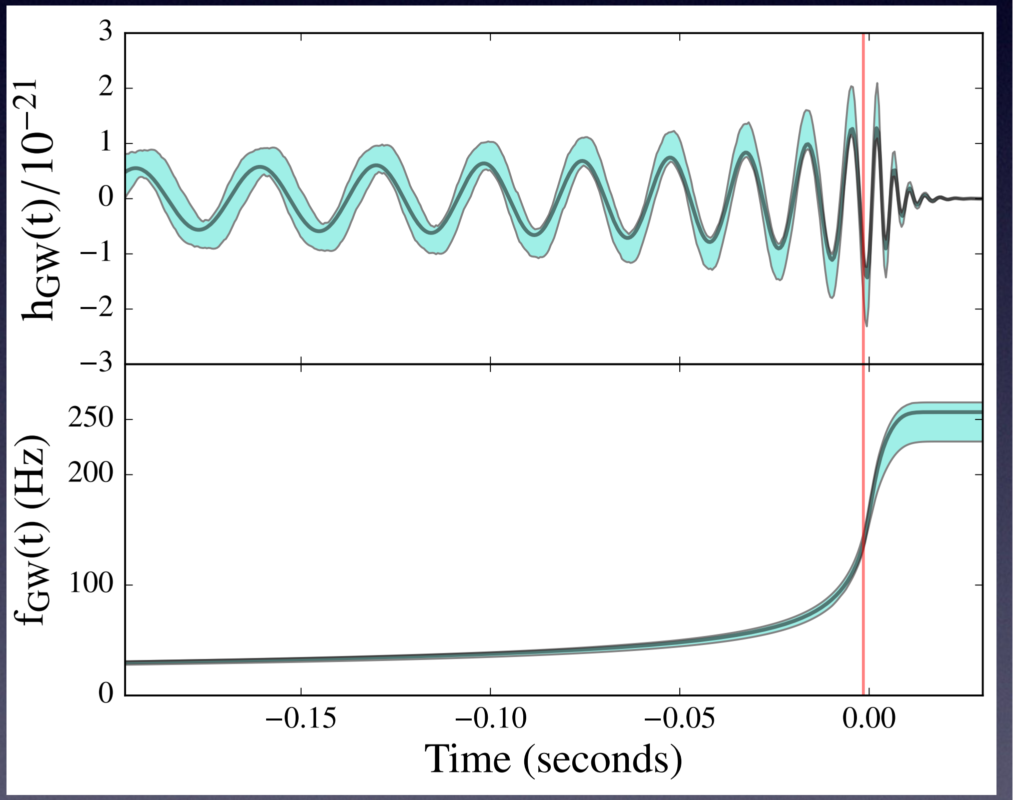
after NR waveform is removed, residuals are consistent with noise

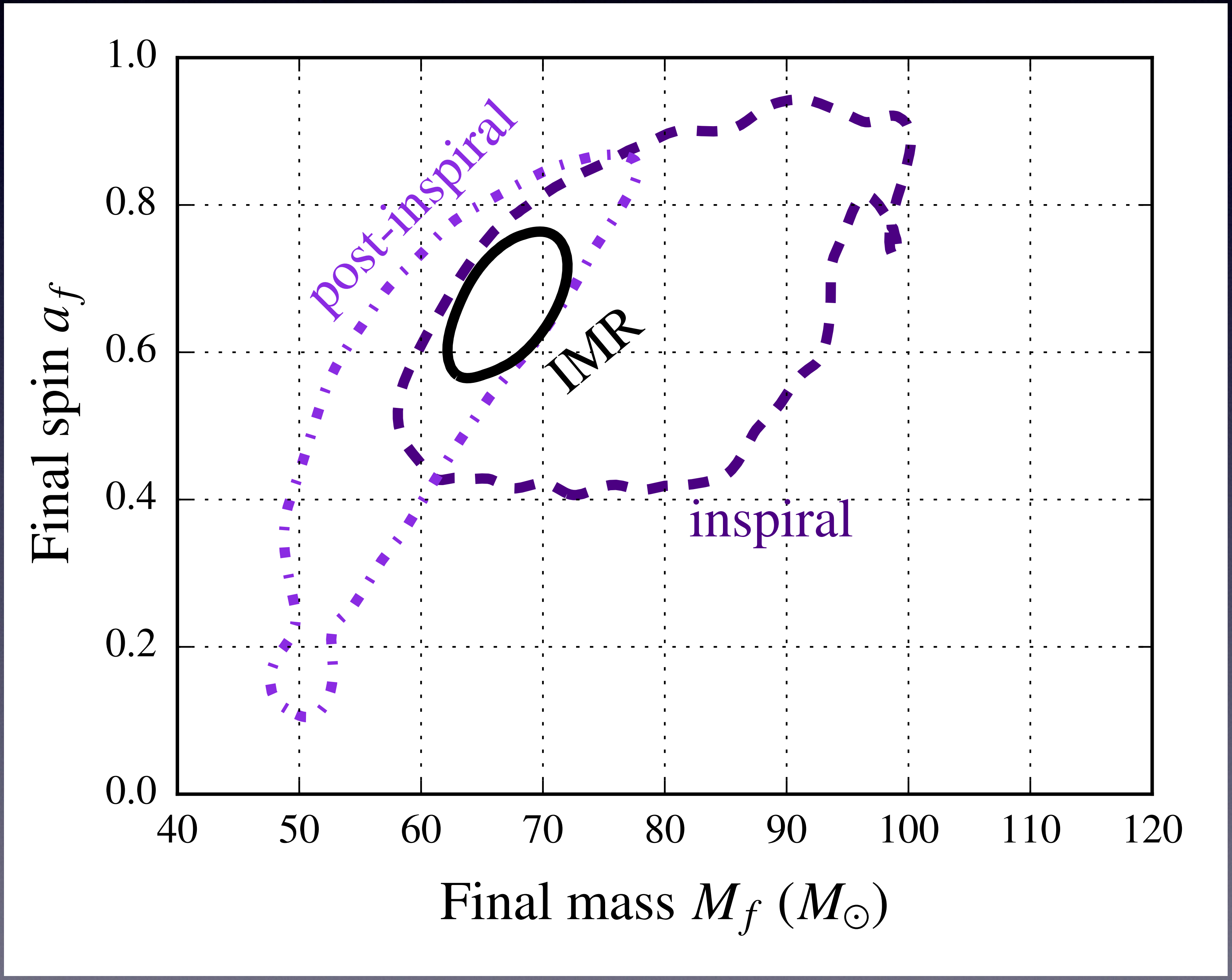


LSC VIRGO The LVC, PRL, submitted, dcc.ligo.org/P1500213/public/main

GW150914: strong-field GR tests

final-BH properties consistent with and without including strong-field GR models

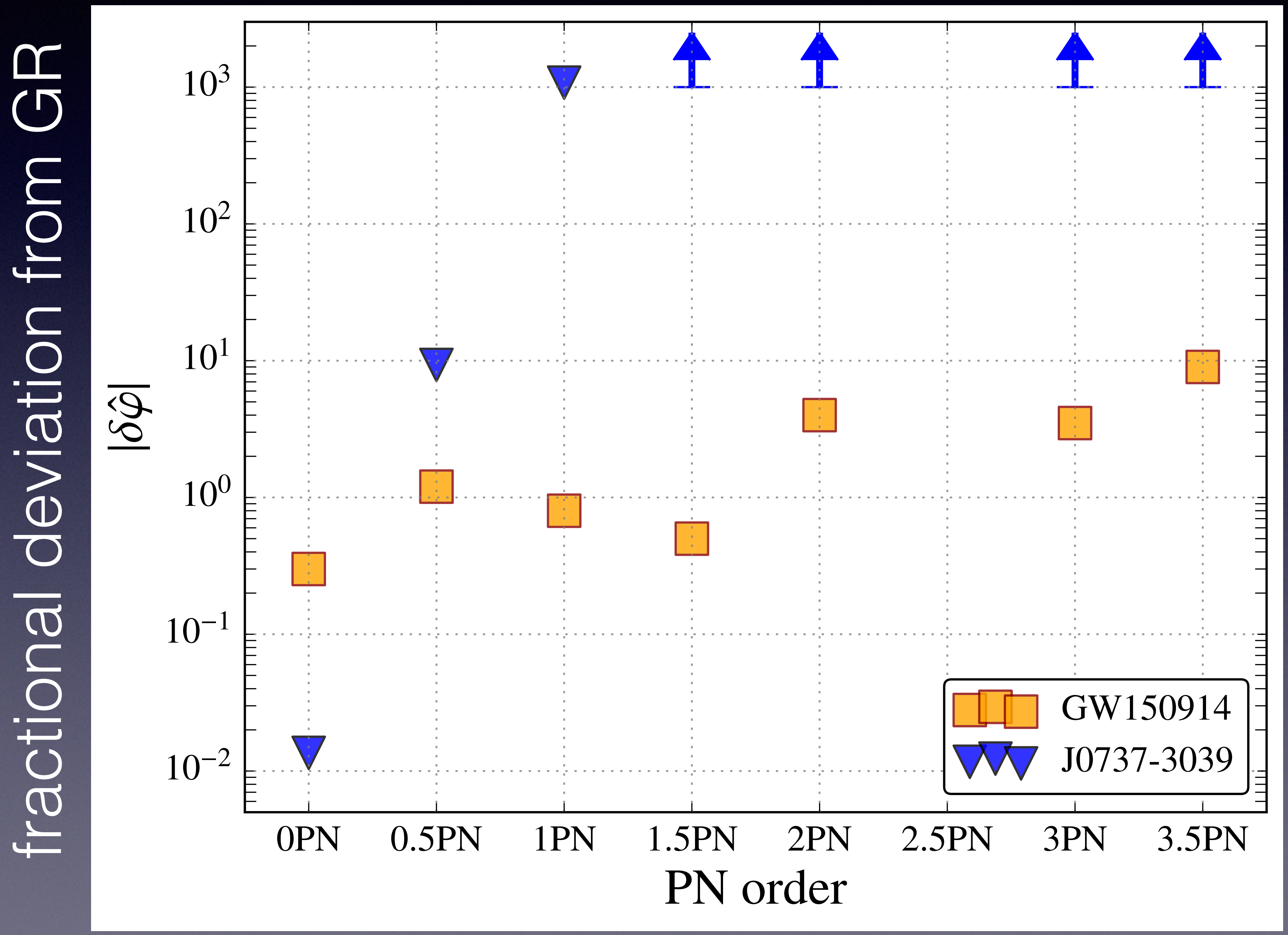




LSC VIRGO The LVC, PRL, submitted, dcc.ligo.org/P1500213/public/main

GW150914: strong-field GR tests

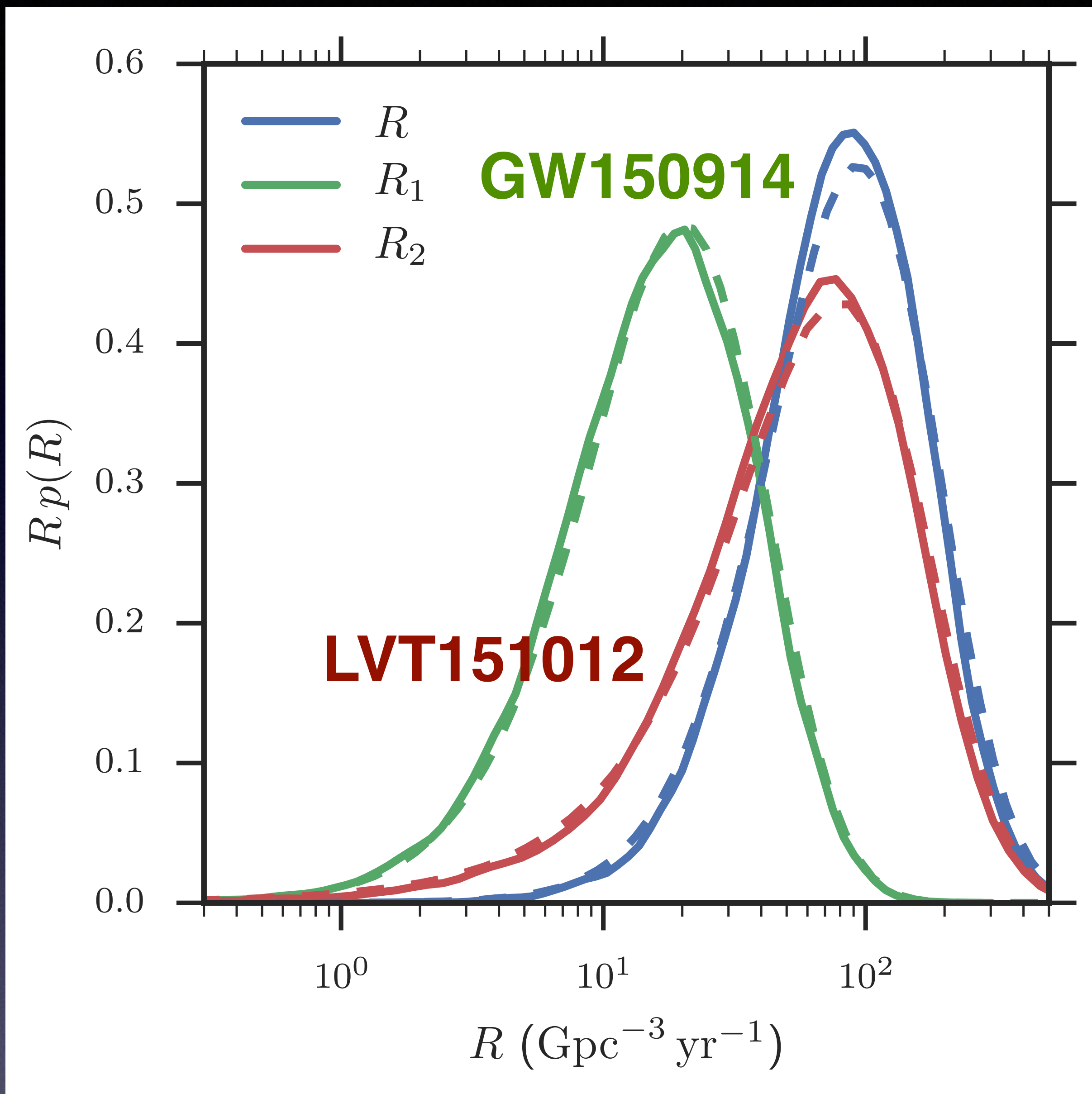
First ever high PN-order limits on deviations from GR

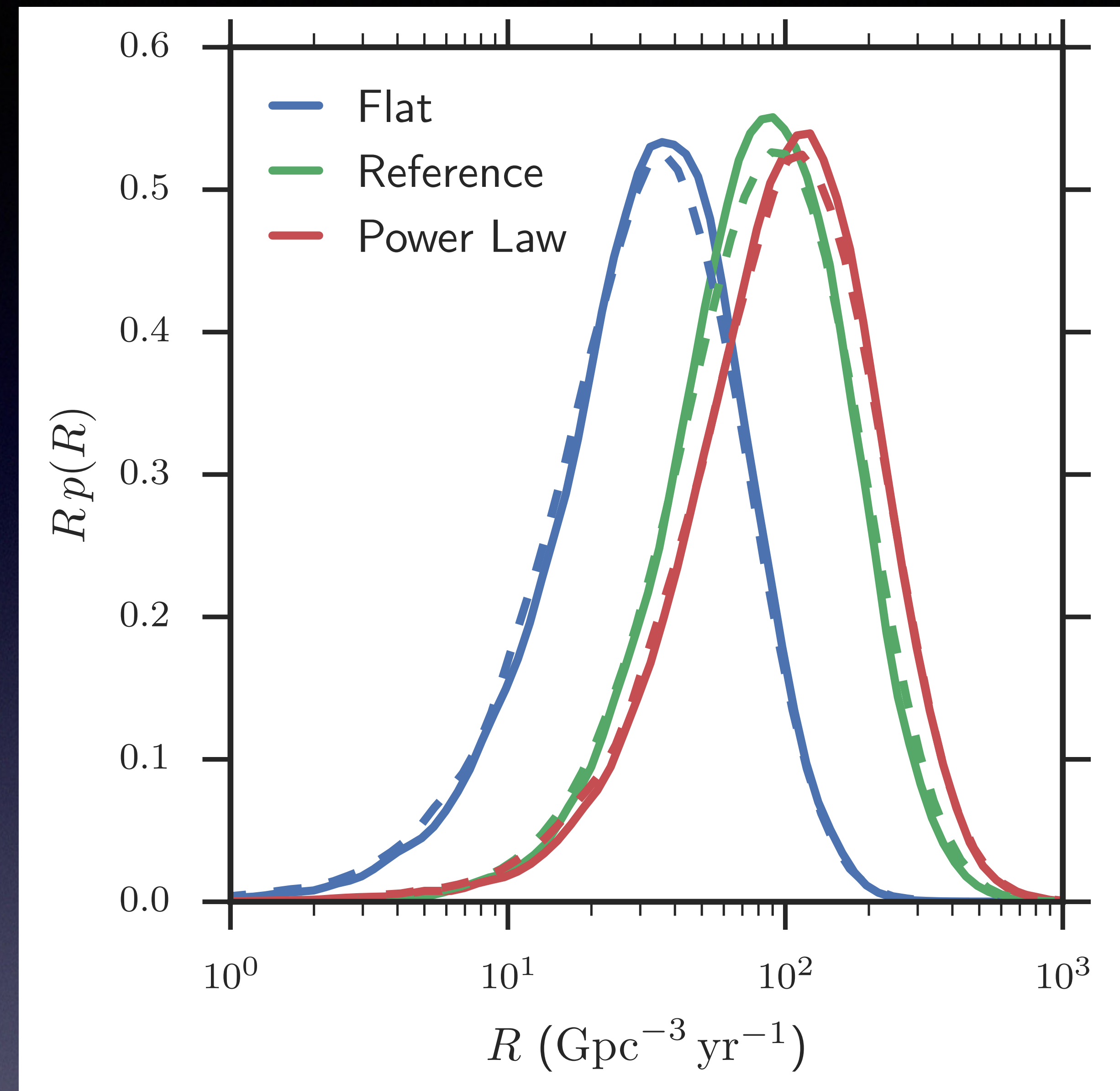


1PN ~ $(v/c)^2$

The LVC, PRL, submitted, dcc.ligo.org/P1500213/public/main

GW150914: Binary BH merger rate





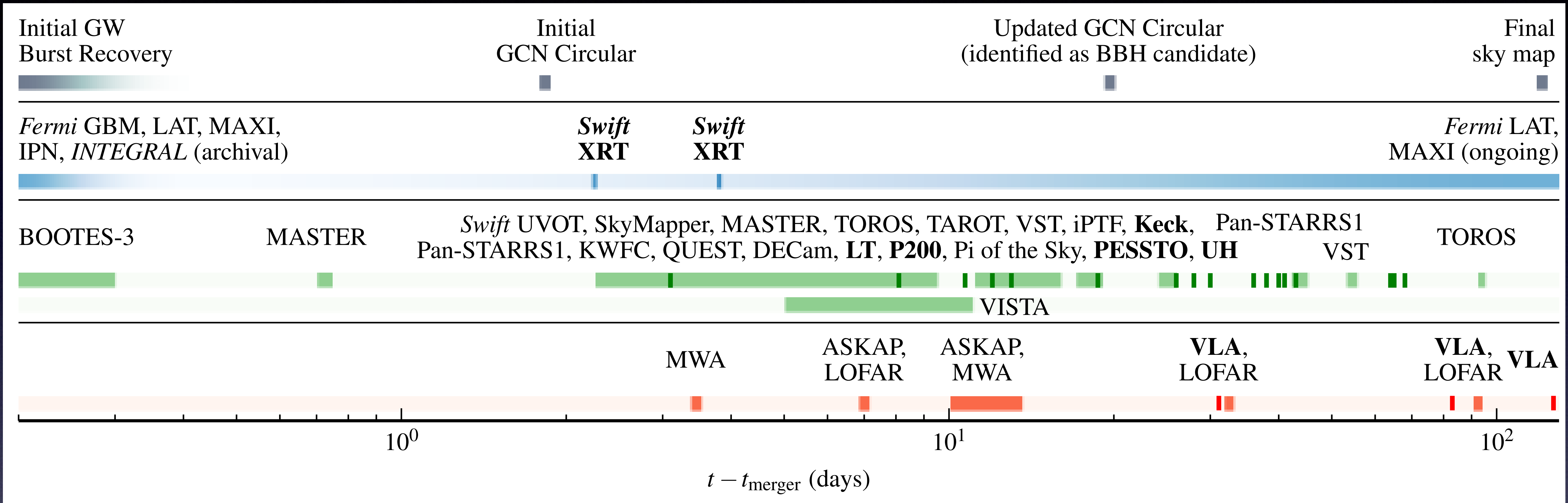
current estimate: 2 - 400 per Gpc^3 per yr

model predictions: 0 - 1,000 per Gpc^3 per yr

rates below ~1 per Gpc^3 per yr are excluded

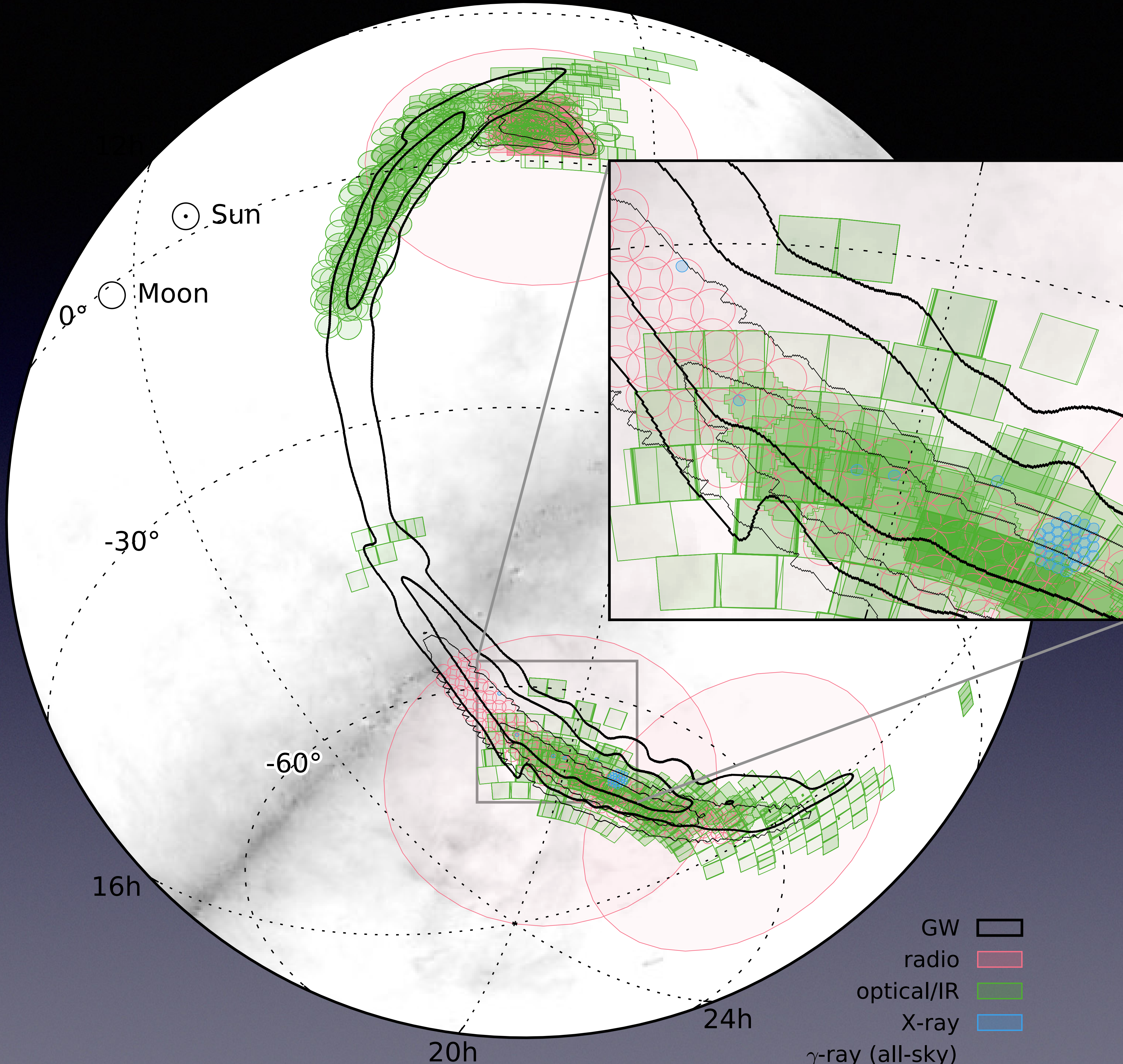
The LVC, ApJL, arxiv/1602.03842

GW150914 EM Follow-up



All upper limits except potential Fermi GBM counterpart?

The LVC, EM Collabs, ApJL, arxiv/1602.08492



The LVC, EM Collabs, ApJL, arxiv/1602.08492

GW150914 Astrophysics

GW150914: Binary BH Astrophysics

- **First Binary BH system**
- **Heaviest stellar-mass Black Holes (>~ 25 Msun)**

Belczynski et al. 2010

Spera et al. 2015

The LVC, ApJL, published, arxiv/1602.03846

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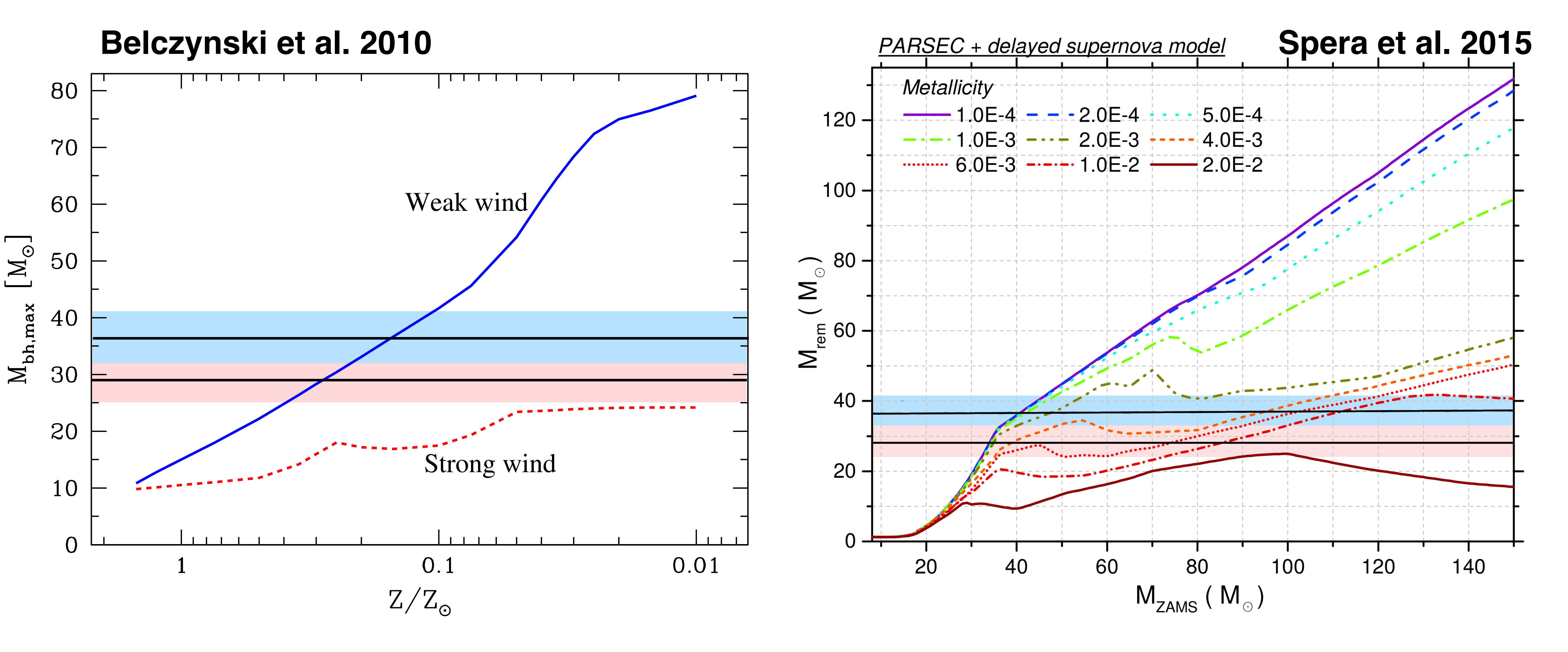


Z < 1/2 solar

The LVC, ApJL, published, arxiv/1602.03846

GW150914: Binary BH Astrophysics

BBH Formation

Isolated Binaries

low - Z to PopIII

rapid rotation

Dense Clusters

globular clusters

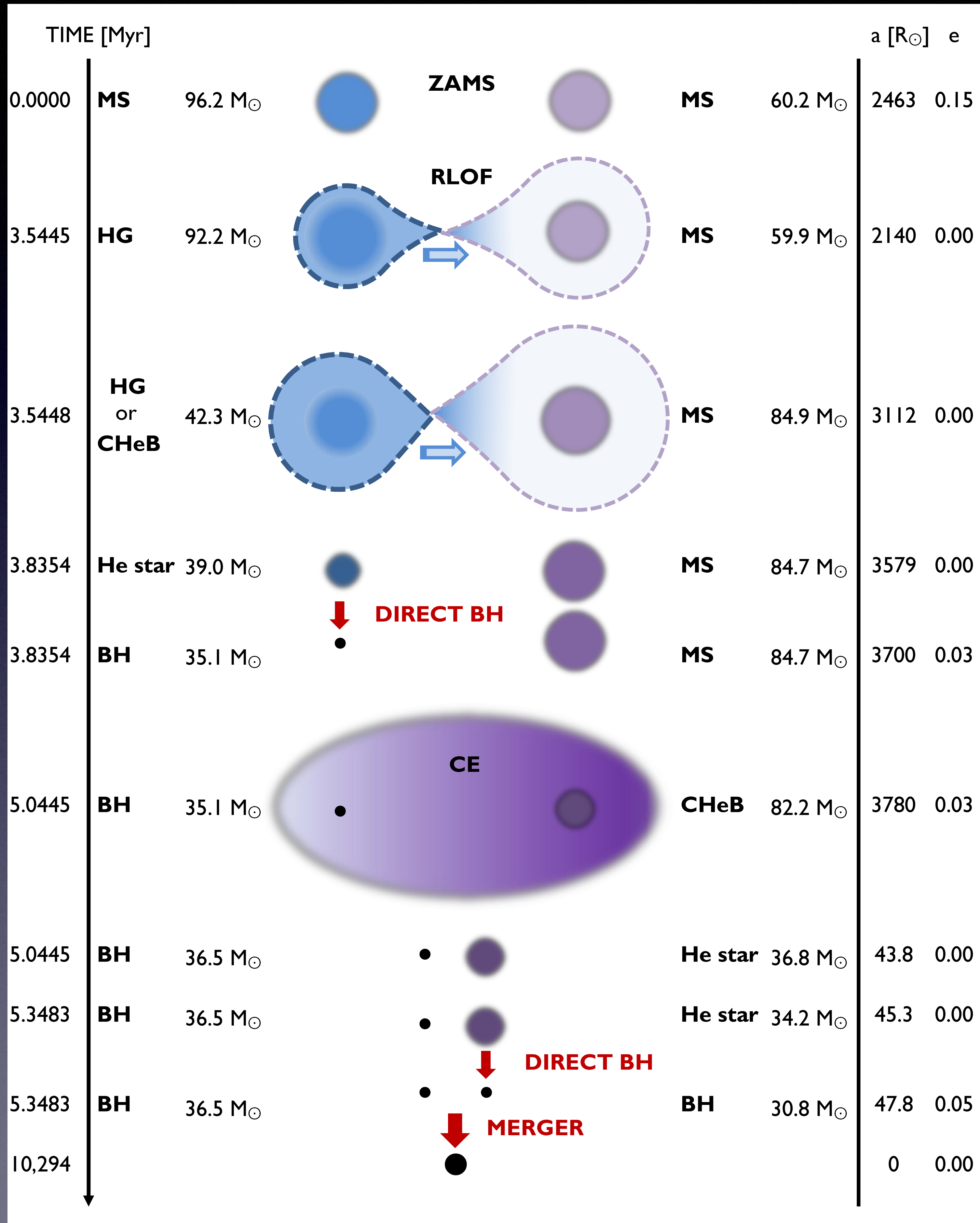
young clusters

galactic centers

The LVC, ApJL, published, arxiv/1602.03846

BBH Formation from Isolated Binaries

BH masses
&
BBH rates:
consistent



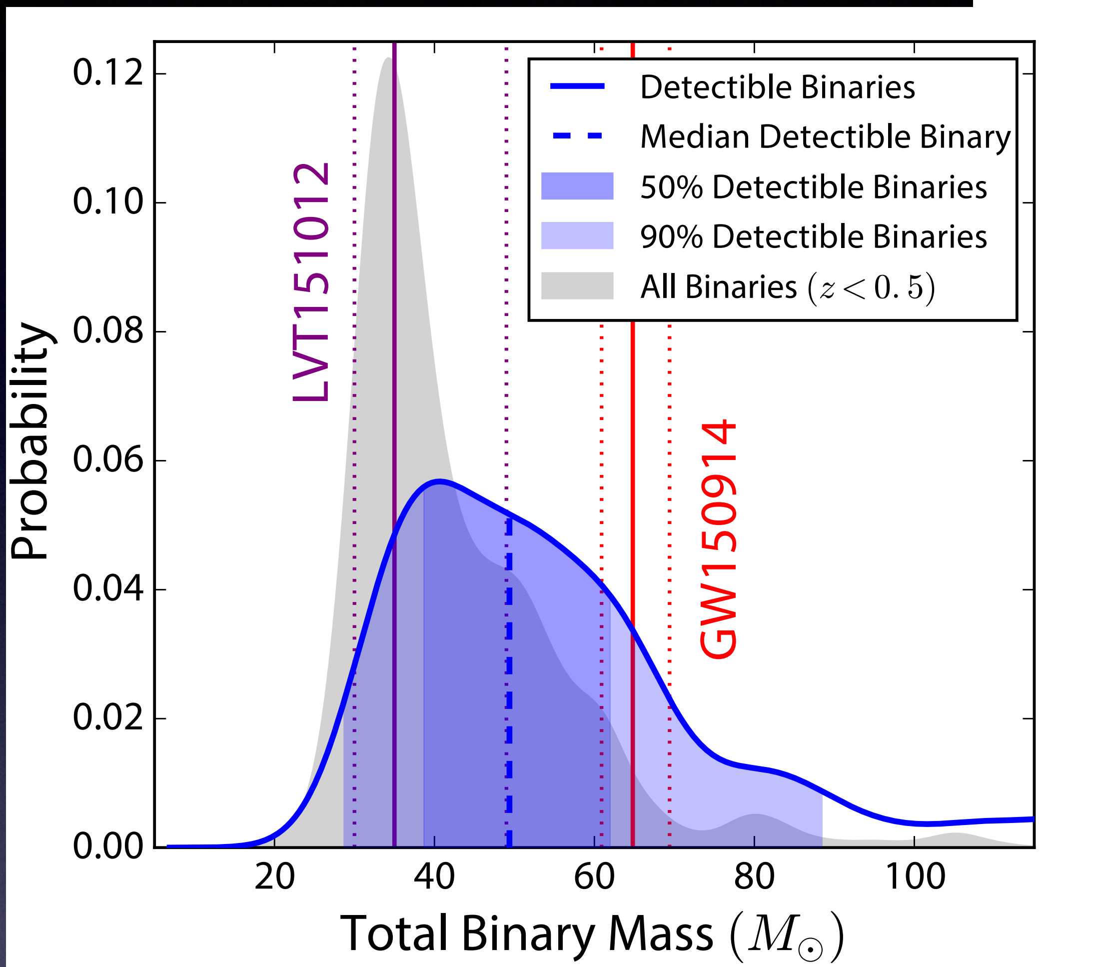
stable
mass transfer

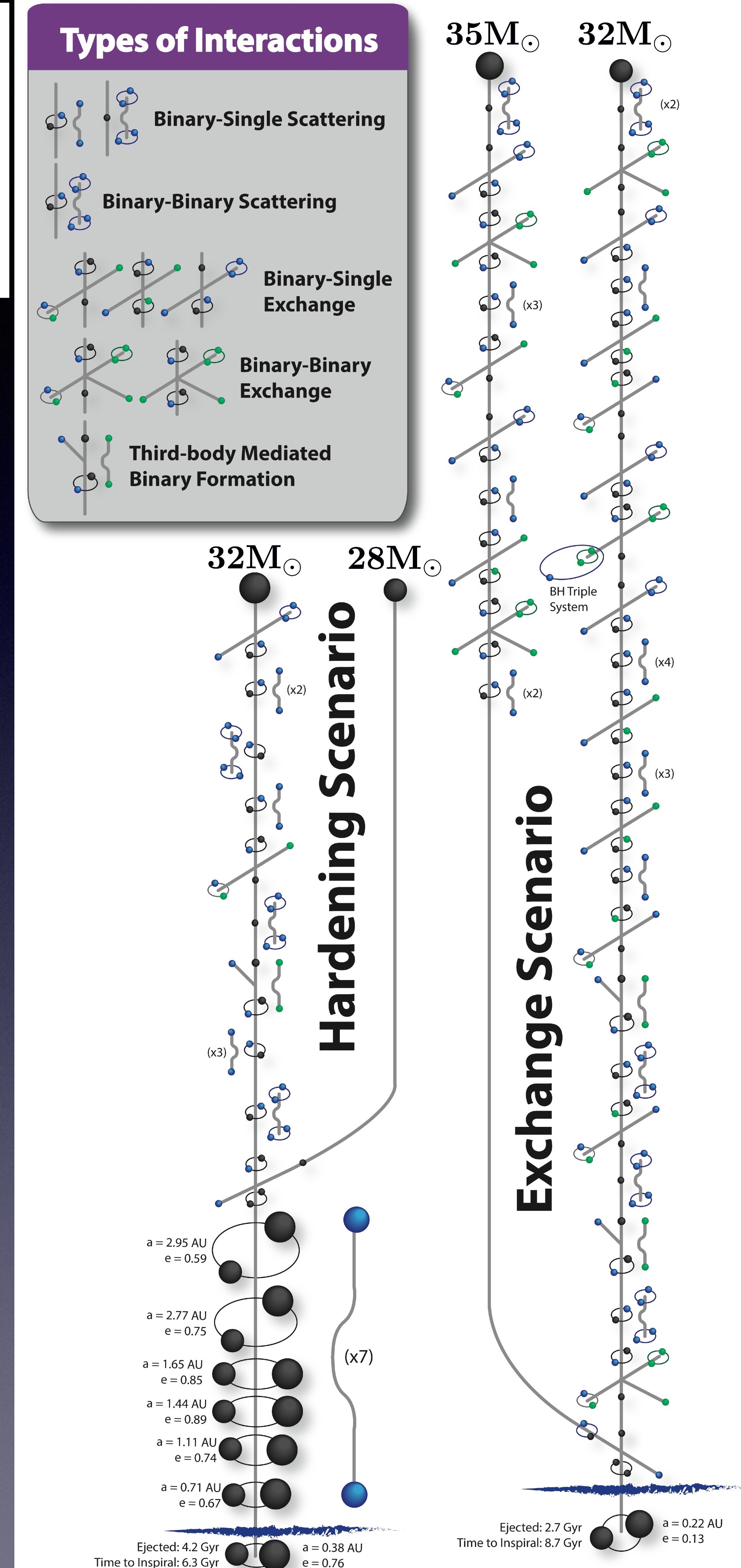
common
envelope

low
BH kicks

Belczynski et al. 2016

BBH Formation in Dense Clusters





Optimal host globular cluster:

typical mass: ~5e5 solar masses

larg-ish virial radius: 2pc

Predicted rates:

2 - 20 per Gpc^3 per yr

Rodriguez et al. 2016

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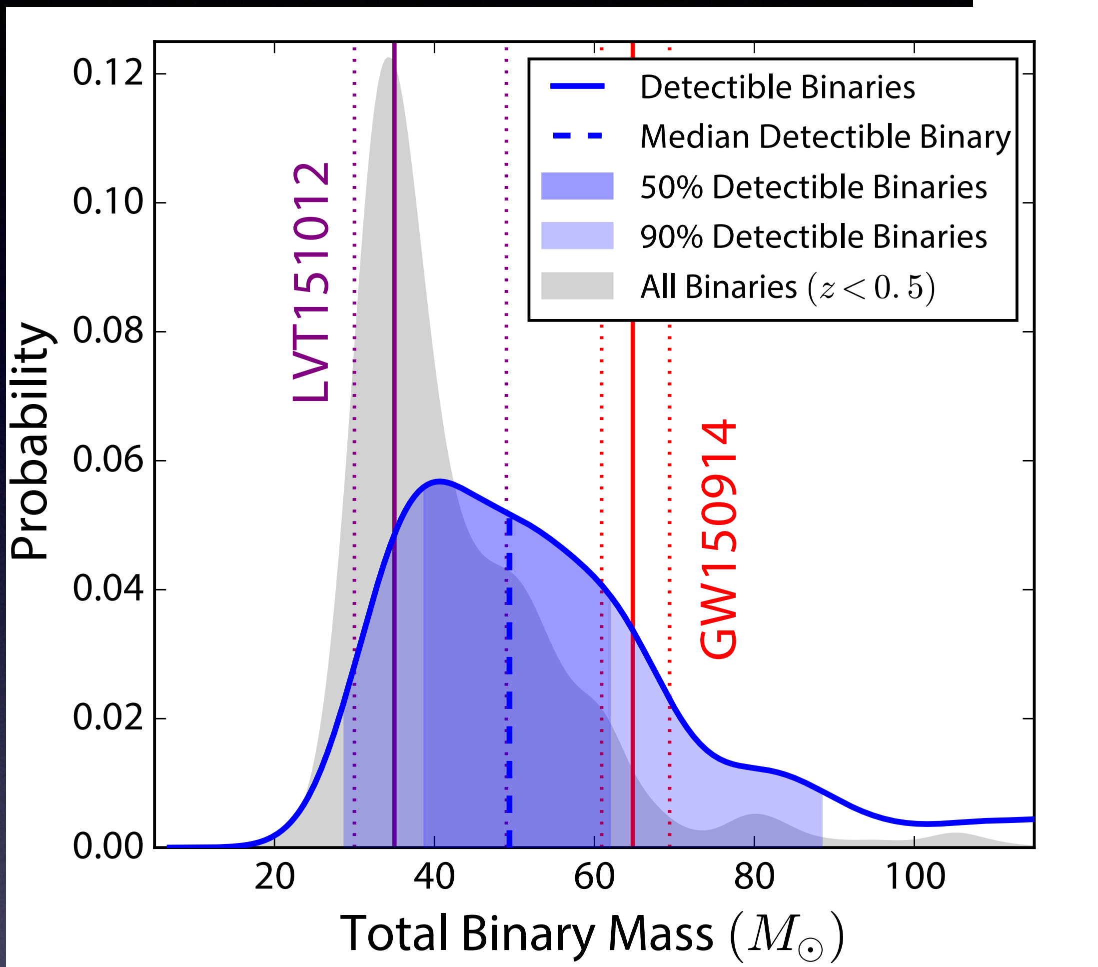

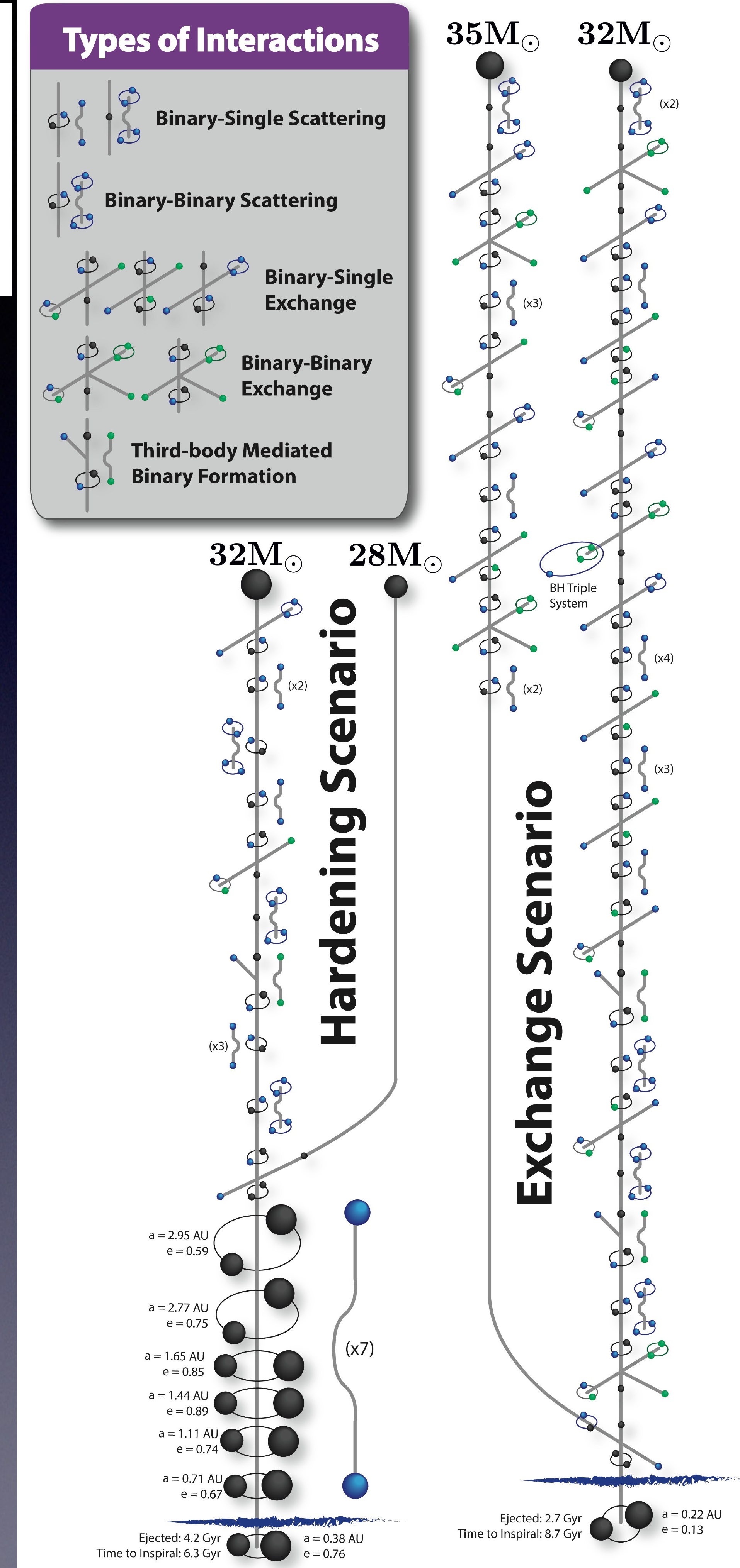

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GW150914 and BBH Formation

- heavy black holes exist in merging binaries
- their formation requires an origin from low-metallicity environments (1/2 solar or less)
- such BBH can form both isolated binaries and dynamical processes
- both formation channels produce merger rates compatible with the event
- the low end of rate predictions (<1 per Gpc^3 per yr) is excluded

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Ready for the Era of Gravitational-Wave Astrophysics?

The LVC, ApJL, published, arxiv/1602.03846

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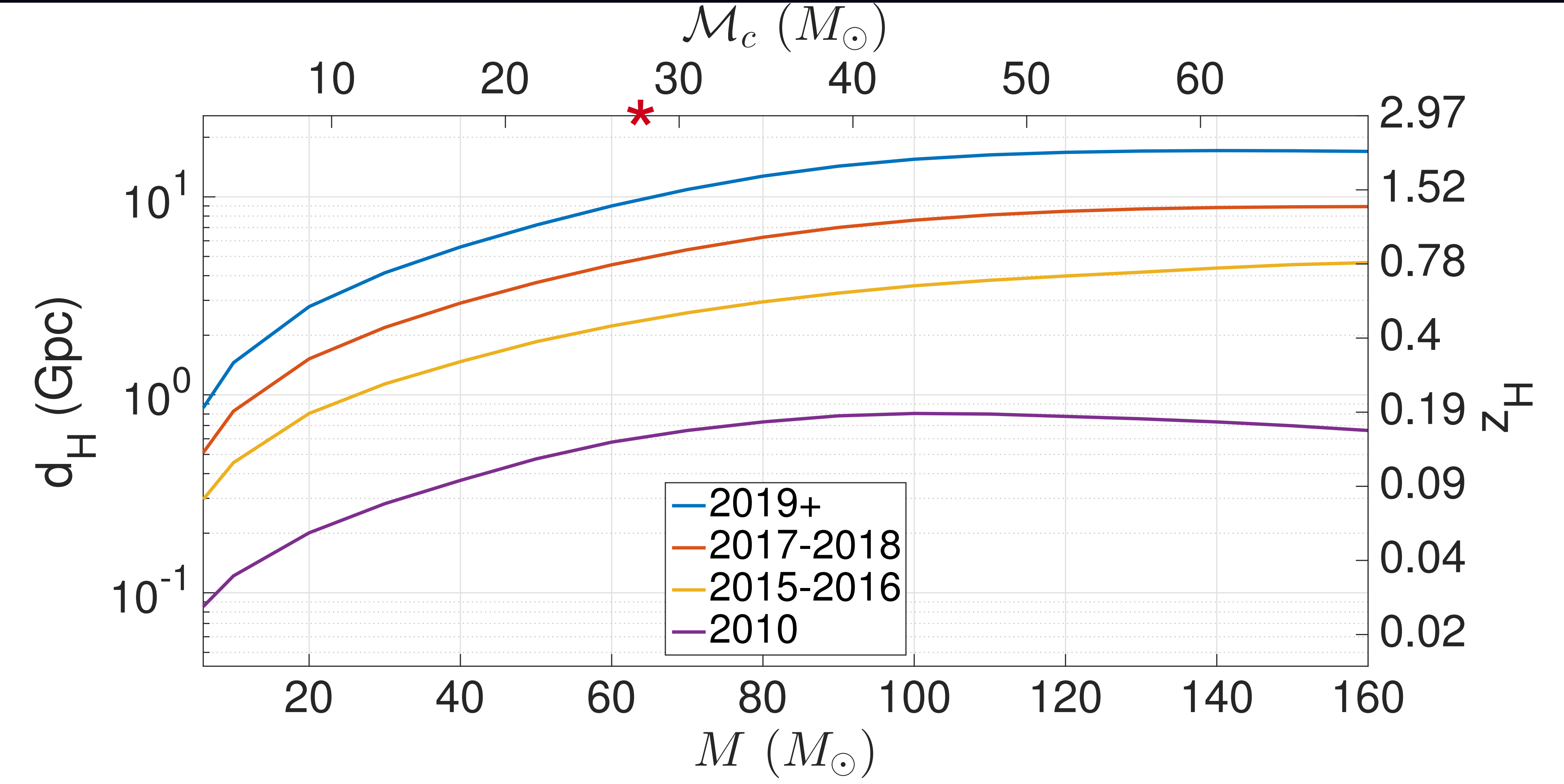


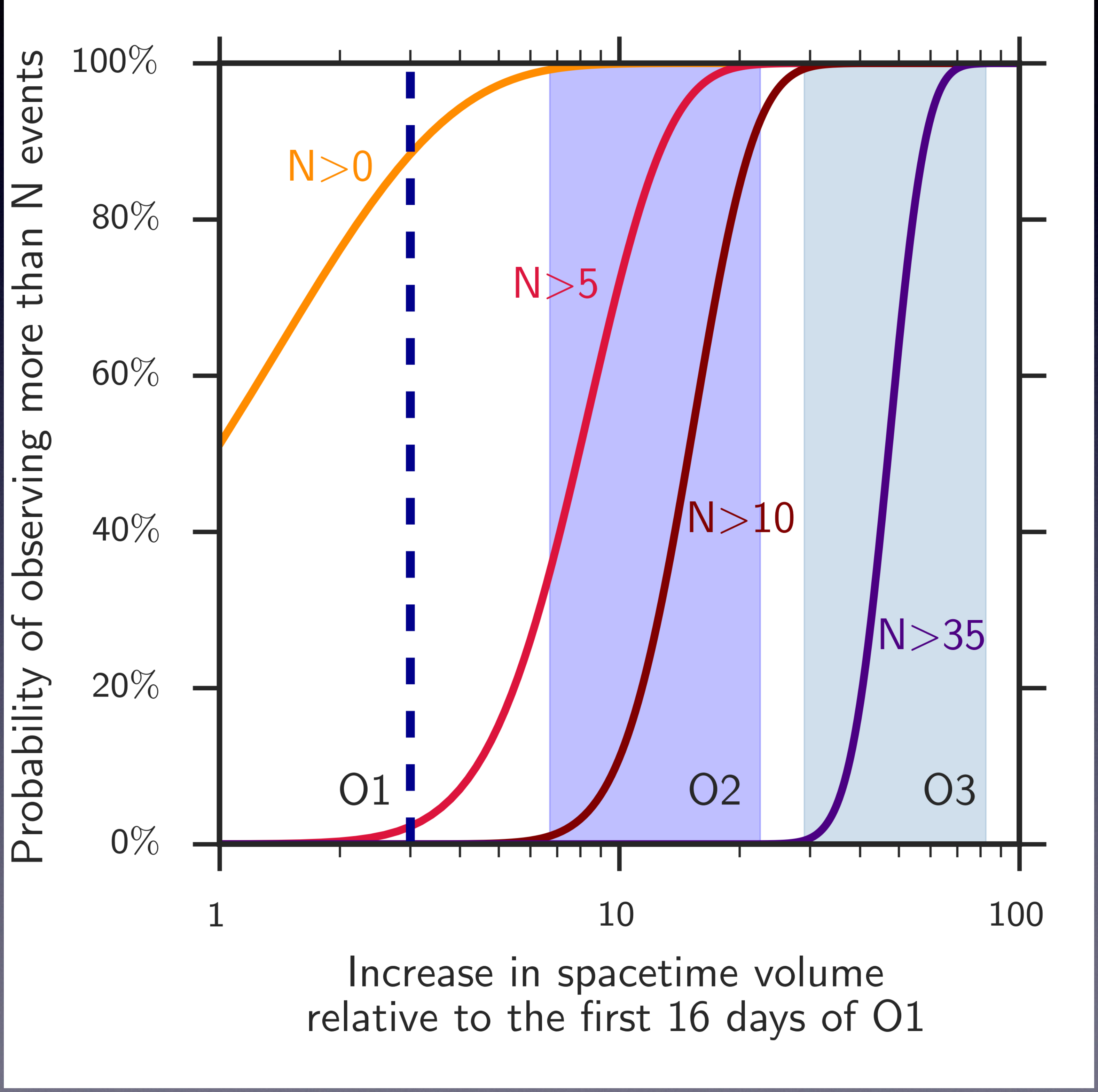
LSC VIRGO The LVC, ApJL, published, arxiv/1602.03846

Ready for the Era of Gravitational-Wave Astrophysics?

More BBH detections to come …

Reveal underlying BBH mass distribution

Quantitative model constraints



The LVC, ApJL, arxiv/1602.03842

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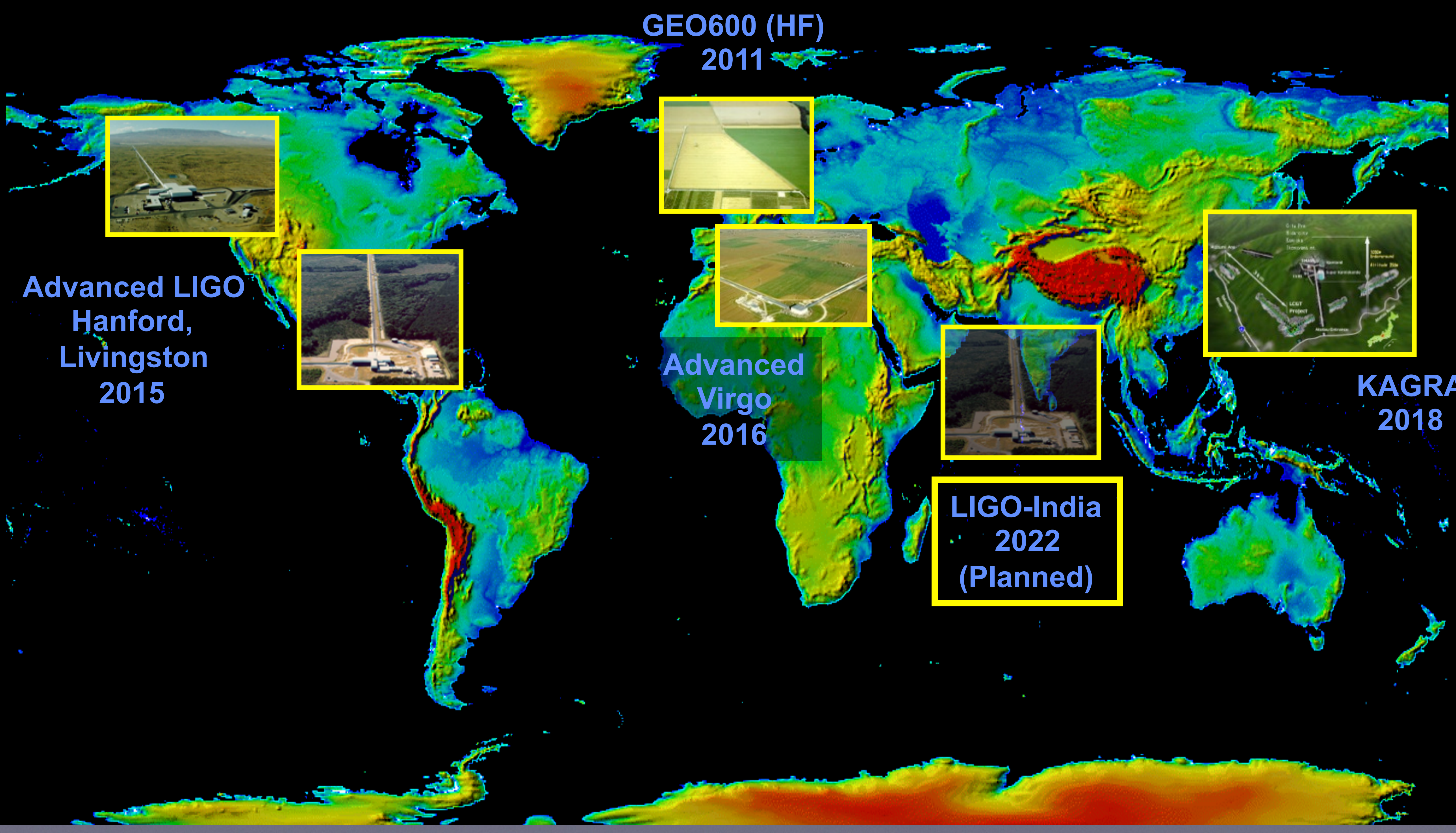
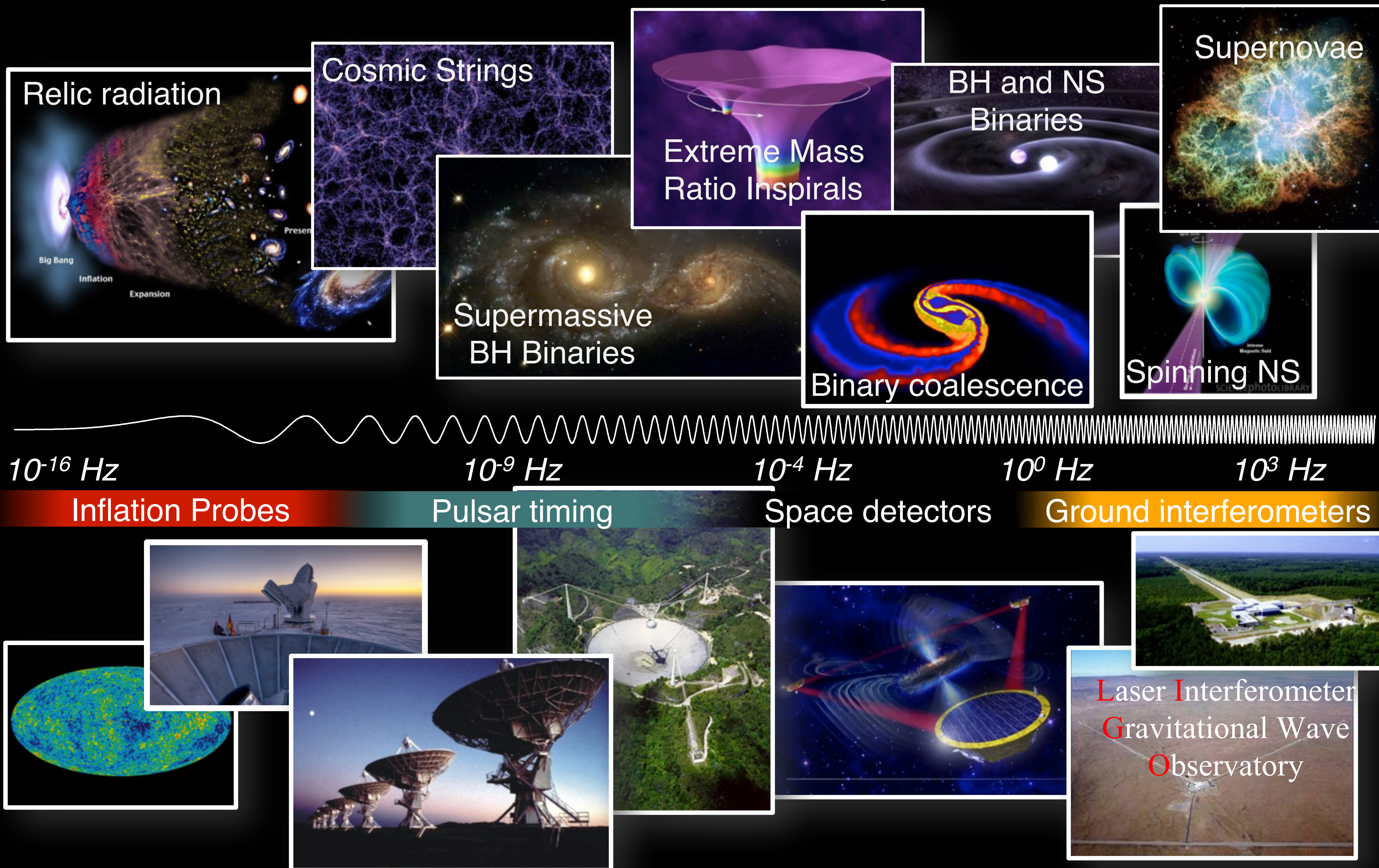
The advanced GW detector network

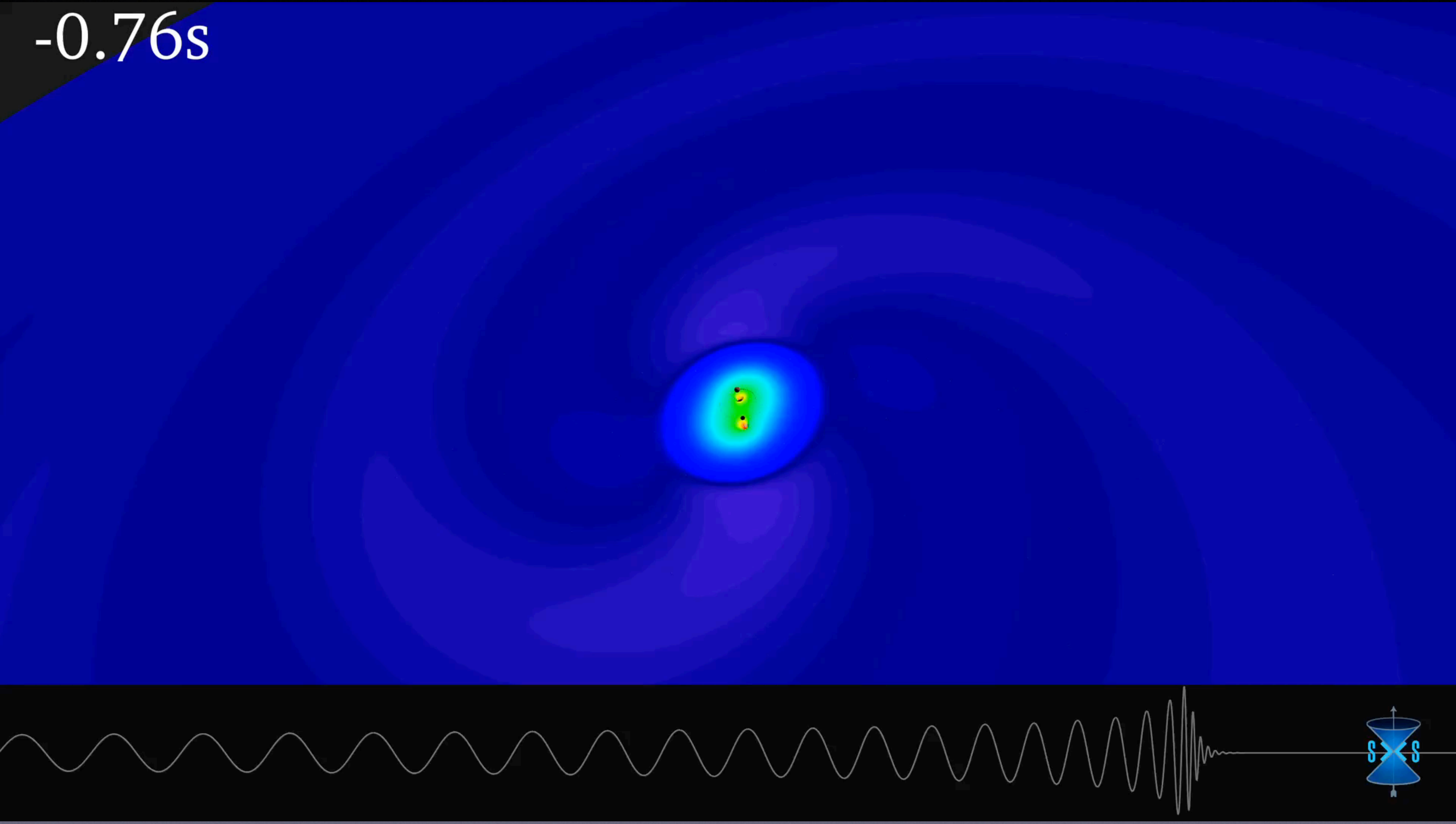


The Gravitational Wave Spectrum



Slide: Matt Evans (MIT)

GW150914: our first Binary BH merger



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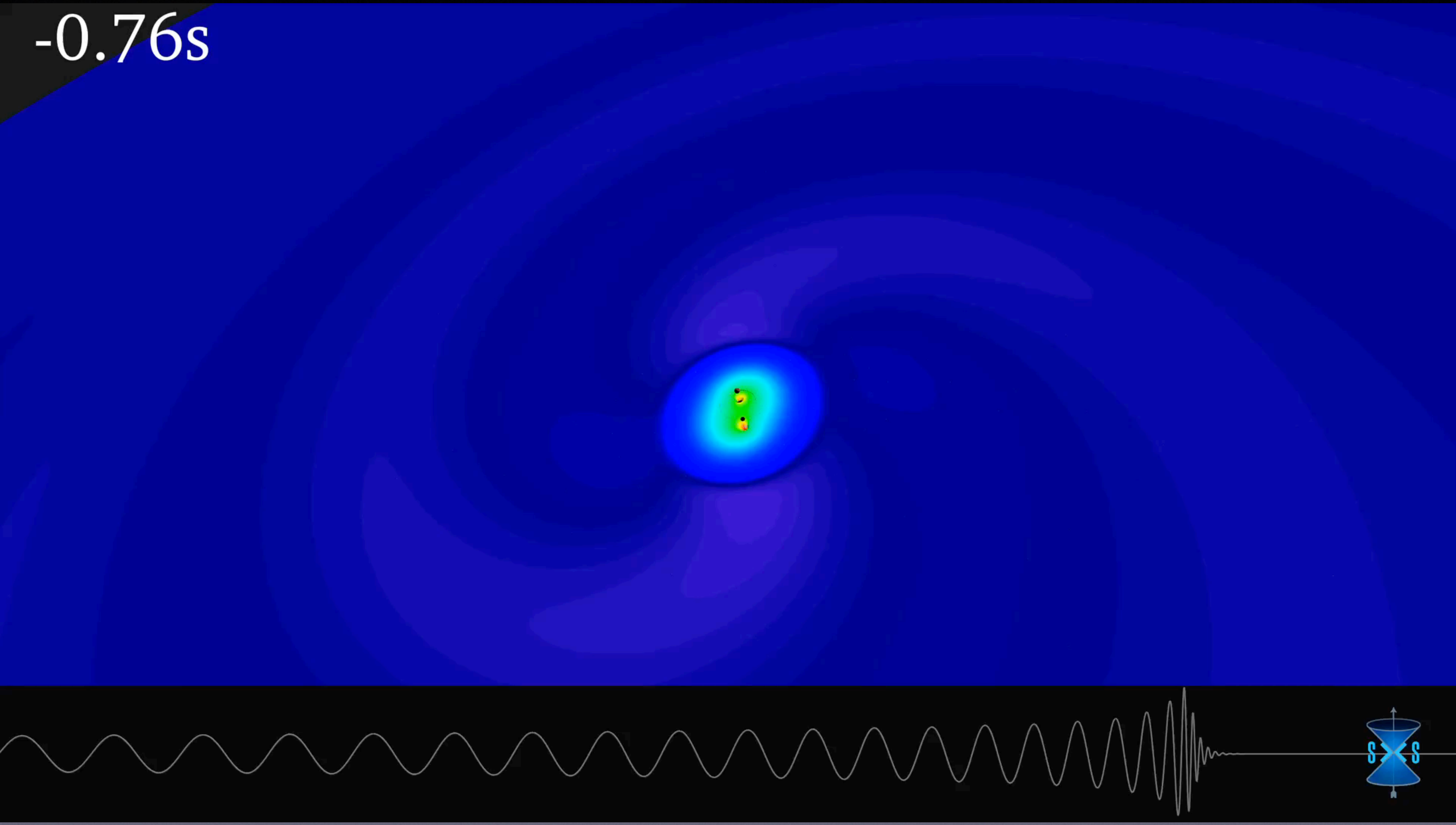
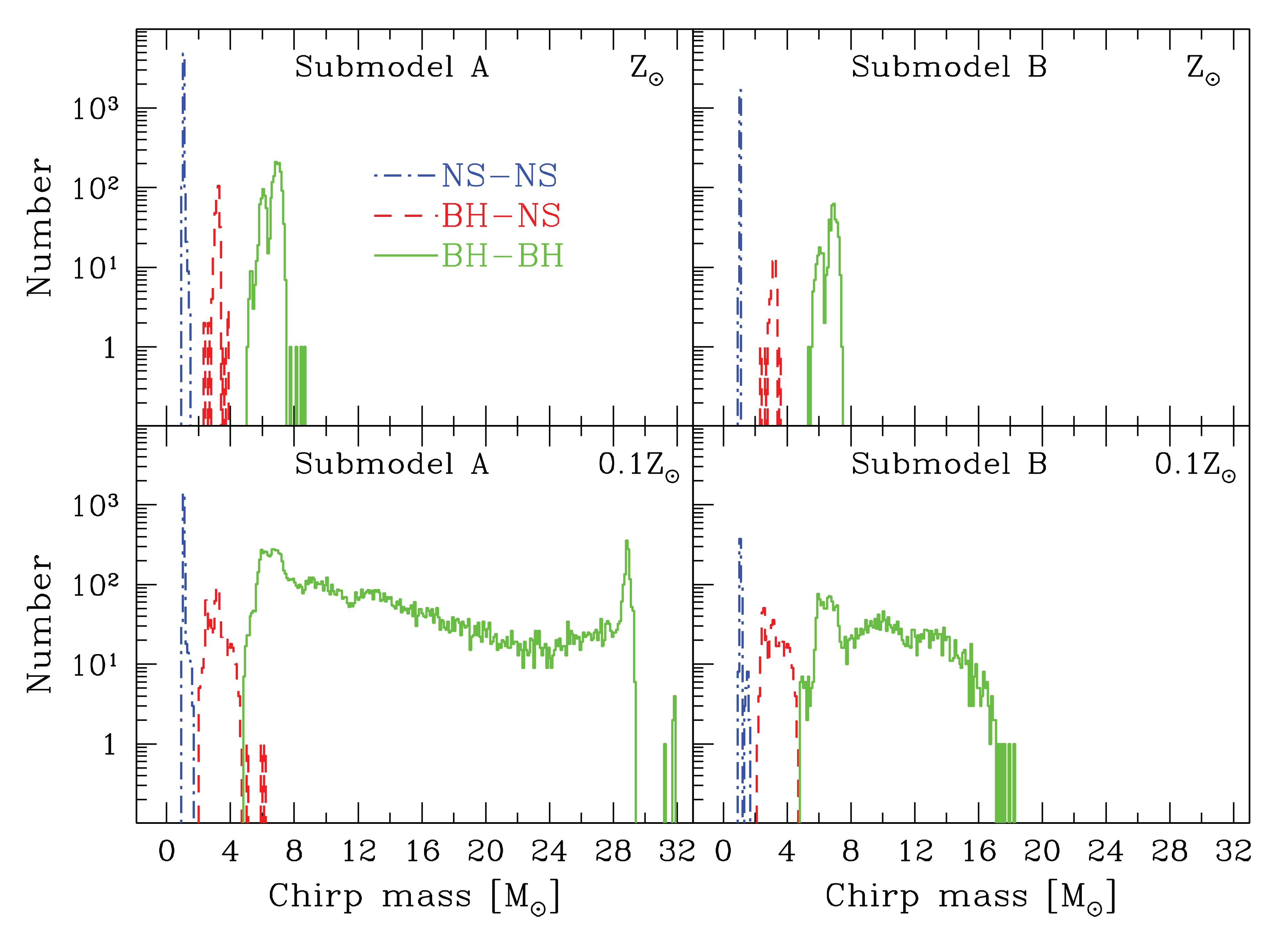


BBH Formation from Isolated Binaries

Common-Envelope & Metallicity Influence

Dominik, Belczynski, …, Holz, …, Bulik, Mandel, O’Shaughnessy 2012

CE before & on Giant Branch **CE only Giant Branch**



solar metallicity

0.1xsolar metallicity

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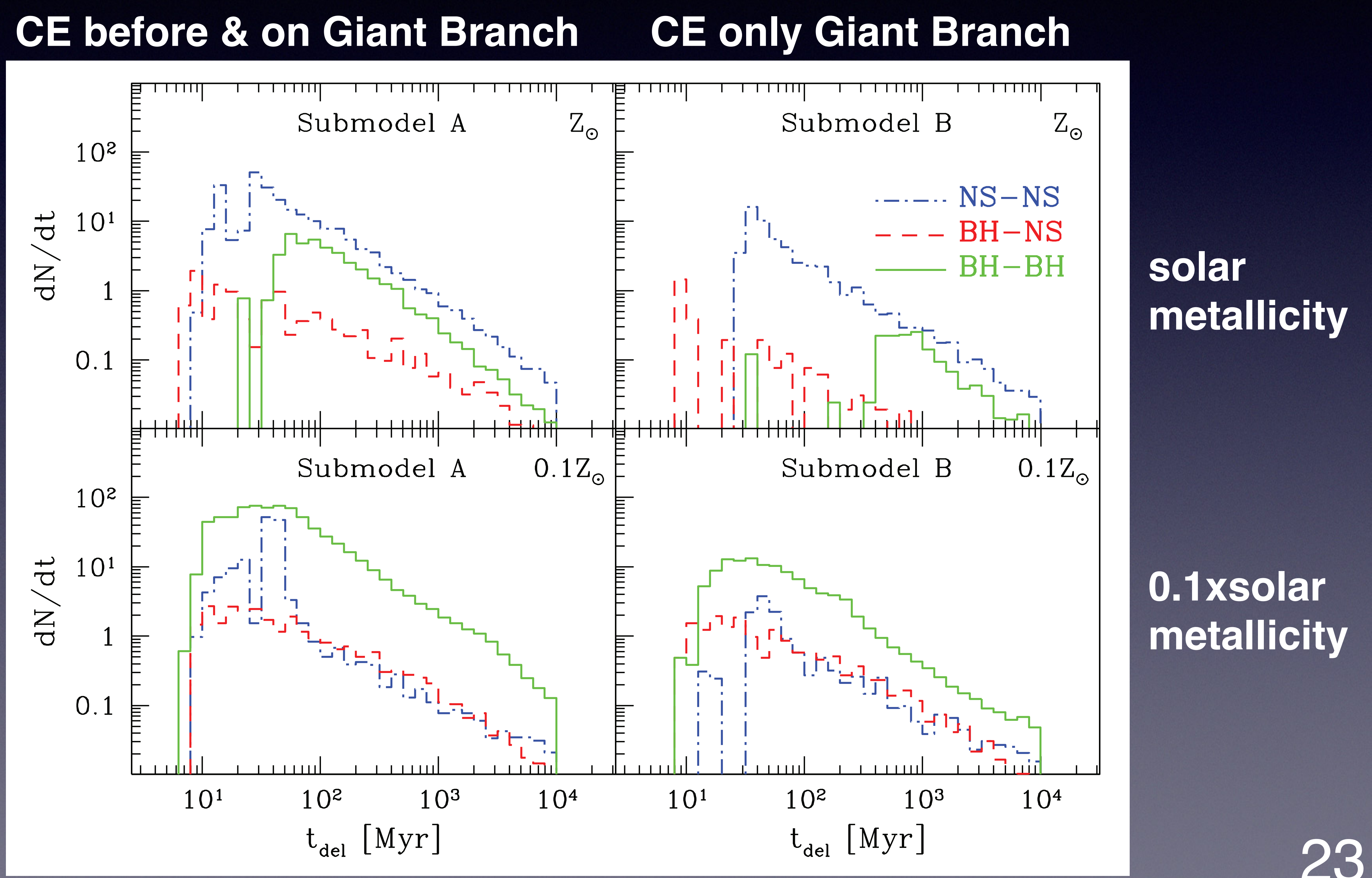
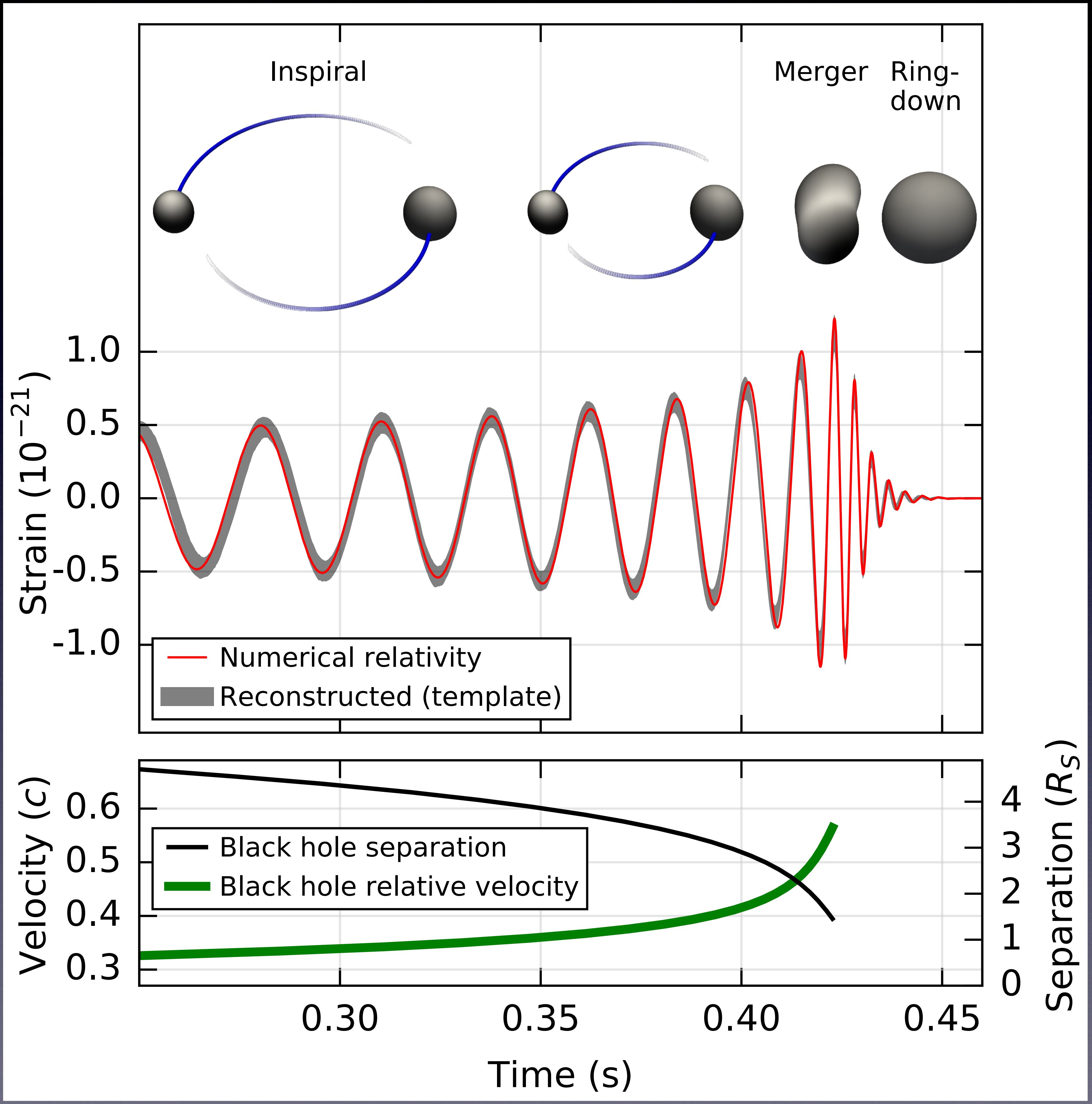


GW150914



LSC VIRGO

GW150914

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likely orientation	face-on/off
resolved to	~600 sq. deg.

duration from 30 Hz	~ 200 ms
# cycles from 30 Hz	~10
peak GW strain	1×10^{-21}
peak displacement of interferometers arms	±0.002 fm
frequency/wavelength at peak GW strain	150 Hz, 2000 km
peak speed of BHs	~ 0.6 c
peak GW luminosity	3.6×10^{56} erg s^{-1}
radiated GW energy	2.5-3.5 M⊙
remnant ringdown freq.	~ 250 Hz
remnant damping time	~ 4 ms
remnant size, area	180 km, 3.5×10^{5} km^2
consistent with general relativity?	passes all tests performed
graviton mass bound	$< 1.2 \times 10^{-22}$ eV
coalescence rate	2 to 400 Gpc^{-3} yr^{-1}
online trigger latency	~ 3 min
# offline analysis pipelines	5
CPU hours consumed	~ 50 million (=20,000 PCs run for 100 days)
papers on Feb 11, 2016	13
# researchers	~1000, 80 institutions in 15 countries

Detector noise introduces errors in measurement. Parameters with a range (e.g. distance) are 90% credible bounds; fractional error on parameters without a range is less than 10%. **Acronyms**: L1=LIGO

GW150914: parametr estimation

	EOBNR	IMRPhenom	Overall
Detector-frame total mass $M/\mathrm{M}_\odot$	$70.3^{+5.3}_{-4.8}$	$70.7^{+3.8}_{-4.0}$	$70.5^{+4.6\pm0.9}_{-4.5\pm1.0}$
Detector-frame chirp mass $\mathcal{M}/\mathrm{M}_\odot$	$30.2^{+2.5}_{-1.9}$	$30.5^{+1.7}_{-1.8}$	$30.3^{+2.1\pm0.4}_{-1.9\pm0.4}$
Detector-frame primary mass $m_1/\mathrm{M}_\odot$	$39.4^{+5.5}_{-4.9}$	$38.3^{+5.5}_{-3.5}$	$38.8^{+5.6\pm0.9}_{-4.1\pm0.3}$
Detector-frame secondary mass $m_2/\mathrm{M}_\odot$	$30.9^{+4.8}_{-4.4}$	$32.2^{+3.6}_{-5.0}$	$31.6^{+4.2\pm0.1}_{-4.9\pm0.6}$
Detector-frame final mass $M_\mathrm{f}/\mathrm{M}_\odot$	$67.1^{+4.6}_{-4.4}$	$67.4^{+3.4}_{-3.6}$	$67.3^{+4.1\pm0.8}_{-4.0\pm0.9}$
Source-frame total mass $M^\mathrm{source}/\mathrm{M}_\odot$	$65.0^{+5.0}_{-4.4}$	$64.6^{+4.1}_{-3.5}$	$64.8^{+4.6\pm1.0}_{-3.9\pm0.5}$
Source-frame chirp mass $\mathcal{M}^\mathrm{source}/\mathrm{M}_\odot$	$27.9^{+2.3}_{-1.8}$	$27.9^{+1.8}_{-1.6}$	$27.9^{+2.1\pm0.4}_{-1.7\pm0.2}$
Source-frame primary mass $m_1^\mathrm{source}/\mathrm{M}_\odot$	$36.3^{+5.3}_{-4.5}$	$35.1^{+5.2}_{-3.3}$	$35.7^{+5.4\pm1.1}_{-3.8\pm0.0}$
Source-frame secondary mass $m_2^\mathrm{source}/\mathrm{M}_\odot$	$28.6^{+4.4}_{-4.2}$	$29.5^{+3.3}_{-4.5}$	$29.1^{+3.8\pm0.2}_{-4.4\pm0.5}$
Source-fame final mass $M_\mathrm{f}^\mathrm{source}/\mathrm{M}_\odot$	$62.0^{+4.4}_{-4.0}$	$61.6^{+3.7}_{-3.1}$	$61.8^{+4.2\pm0.9}_{-3.5\pm0.4}$
Mass ratio q	$0.79^{+0.18}_{-0.19}$	$0.84^{+0.14}_{-0.21}$	$0.82^{+0.16\pm0.01}_{-0.21\pm0.03}$
Effective inspiral spin parameter χ_eff	$-0.09^{+0.19}_{-0.17}$	$-0.03^{+0.14}_{-0.15}$	$-0.06^{+0.17\pm0.01}_{-0.18\pm0.07}$
Dimensionless primary spin magnitude a_1	$0.32^{+0.45}_{-0.28}$	$0.31^{+0.51}_{-0.27}$	$0.31^{+0.48\pm0.04}_{-0.28\pm0.01}$
Dimensionless secondary spin magnitude a_2	$0.57^{+0.40}_{-0.51}$	$0.39^{+0.50}_{-0.34}$	$0.46^{+0.48\pm0.07}_{-0.42\pm0.01}$
Final spin a_f	$0.67^{+0.06}_{-0.08}$	$0.67^{+0.05}_{-0.05}$	$0.67^{+0.05\pm0.00}_{-0.07\pm0.03}$
Luminosity distance $D_\mathrm{L}/\mathrm{Mpc}$	390^{+170}_{-180}	440^{+140}_{-180}	$410^{+160\pm20}_{-180\pm40}$
Source redshift z	$0.083^{+0.033}_{-0.036}$	$0.093^{+0.028}_{-0.036}$	$0.088^{+0.031\pm0.004}_{-0.038\pm0.009}$
Upper bound on primary spin magnitude a_1	0.65	0.71	0.69 ± 0.05
Upper bound on secondary spin magnitude a_2	0.93	0.81	0.88 ± 0.10
Lower bound on mass ratio q	0.64	0.67	0.65 ± 0.03
Log Bayes factor $\ln \mathcal{B}_\mathrm{s/n}$	288.7 ± 0.2	290.1 ± 0.2	—

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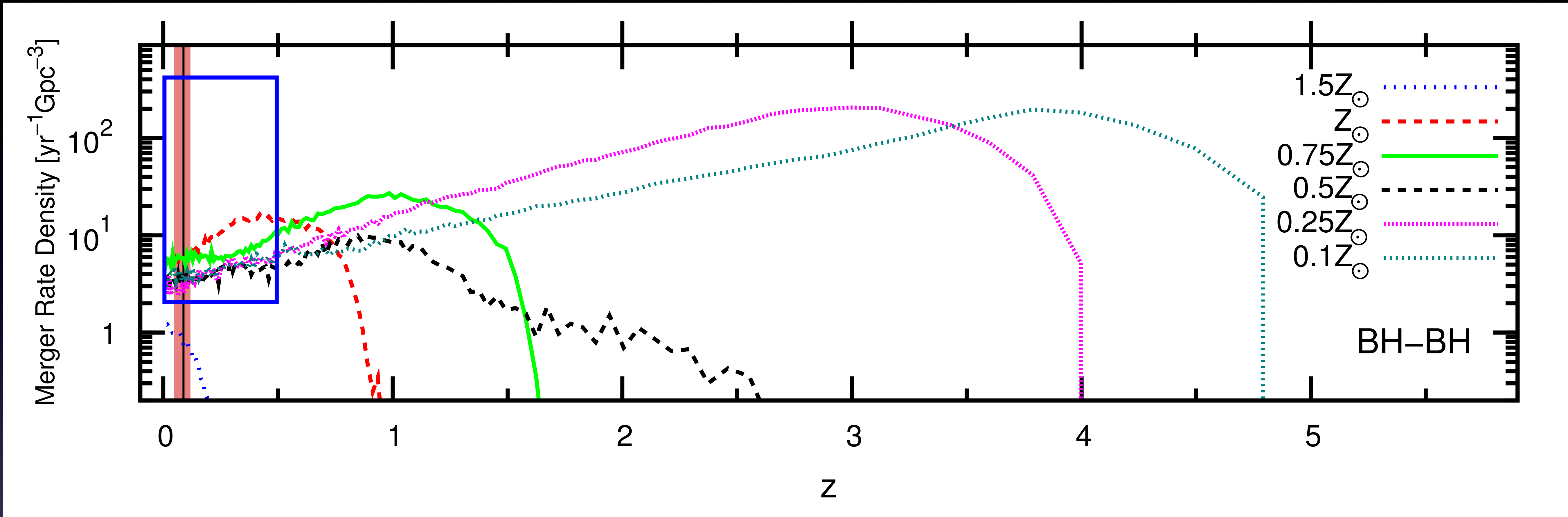
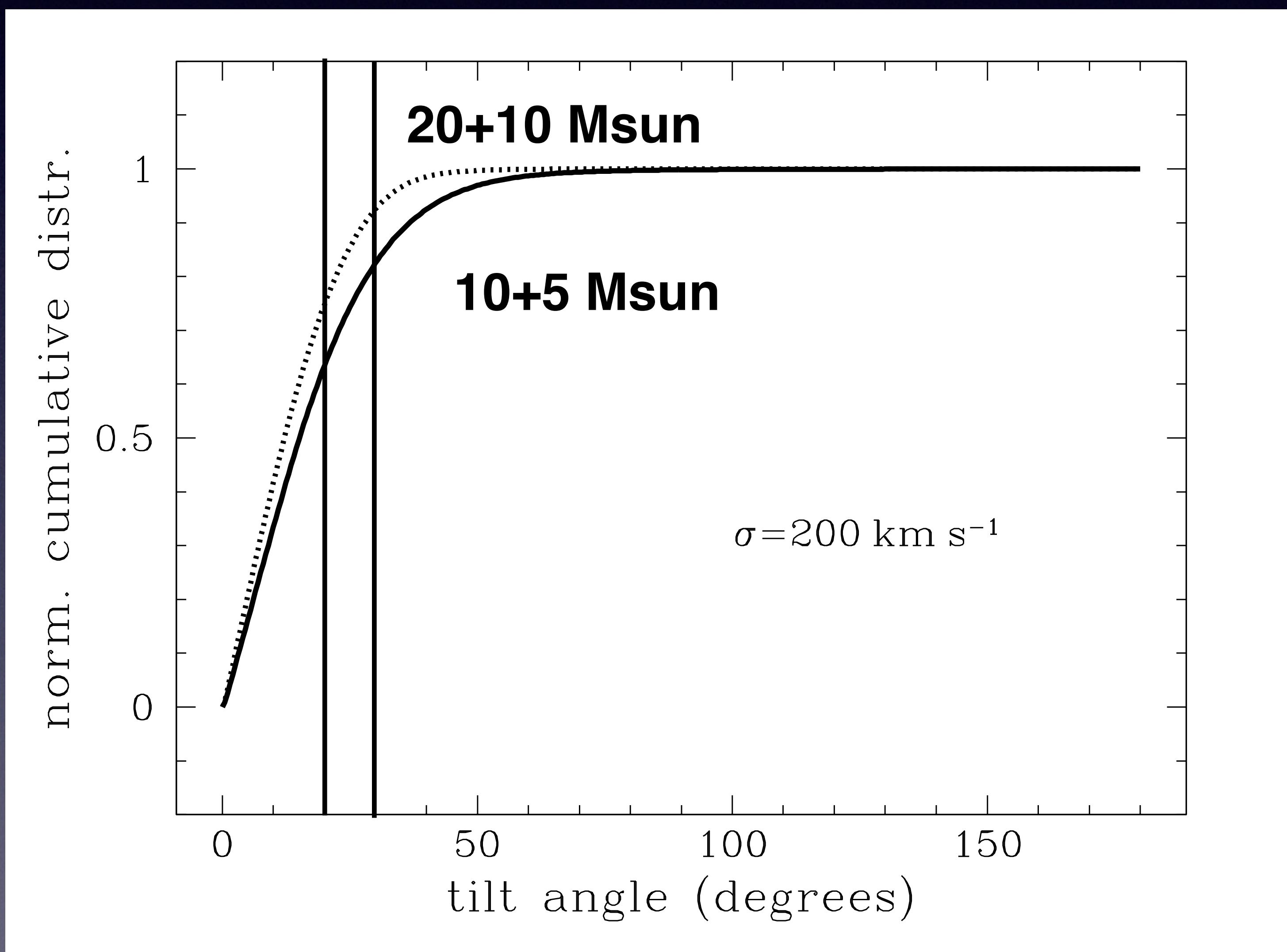
GW150914: Binary BH Astrophysics



BBH Formation from Isolated Binaries
Spin Tilts

VK 2000



even smaller tilts for more massive BBH and smaller BH kicks

anti-alignment highly unlikely

see also:
Gerosa, …, O'Shaughnessy, Sperhake 2013

On that ordinary Monday …

On September 14th …

a message from the online GW-burst pipeline

GraceDB Processor

To: klimenko@phys.ufl.edu , reed.essick@ligo.org , Marco Drago

action required for GraceDB event : G184098 (burst_cwb_allsky)

~ 6am ET September 14, 2015 5:54 AM

Details

Inbox - UF exchange

```
action required for GraceDB event : https://gracedb.ligo.org//events/view/G184098
(burst_cwb_allsky)
cwb_eventcreation
```

LSC VIRGO

On September 14th …

~7am: “a very interesting event in the last hour”

LSC VIRGO

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+20min: "no scheduled hardware injection"

LSC VIRGO

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+15min: "This is clean and very significant inspiral with Mchirp = 27 +- 2 Mo… FAR << 1.e-10 Hz.
If this is not injection,
I guess, we need to do the detection checklist…"

On September 14th …

~7am: “a very interesting event in the last hour”

+20min: “no scheduled hardware injection”

+10min: “very interesting indeed! looks like a high-mass inspiral?”

+25min: “The Omega scans have finished and I do not see any DQ issues at the time of the trigger. The data looks quite clean at both detectors”

and off we went on an unexpected ride

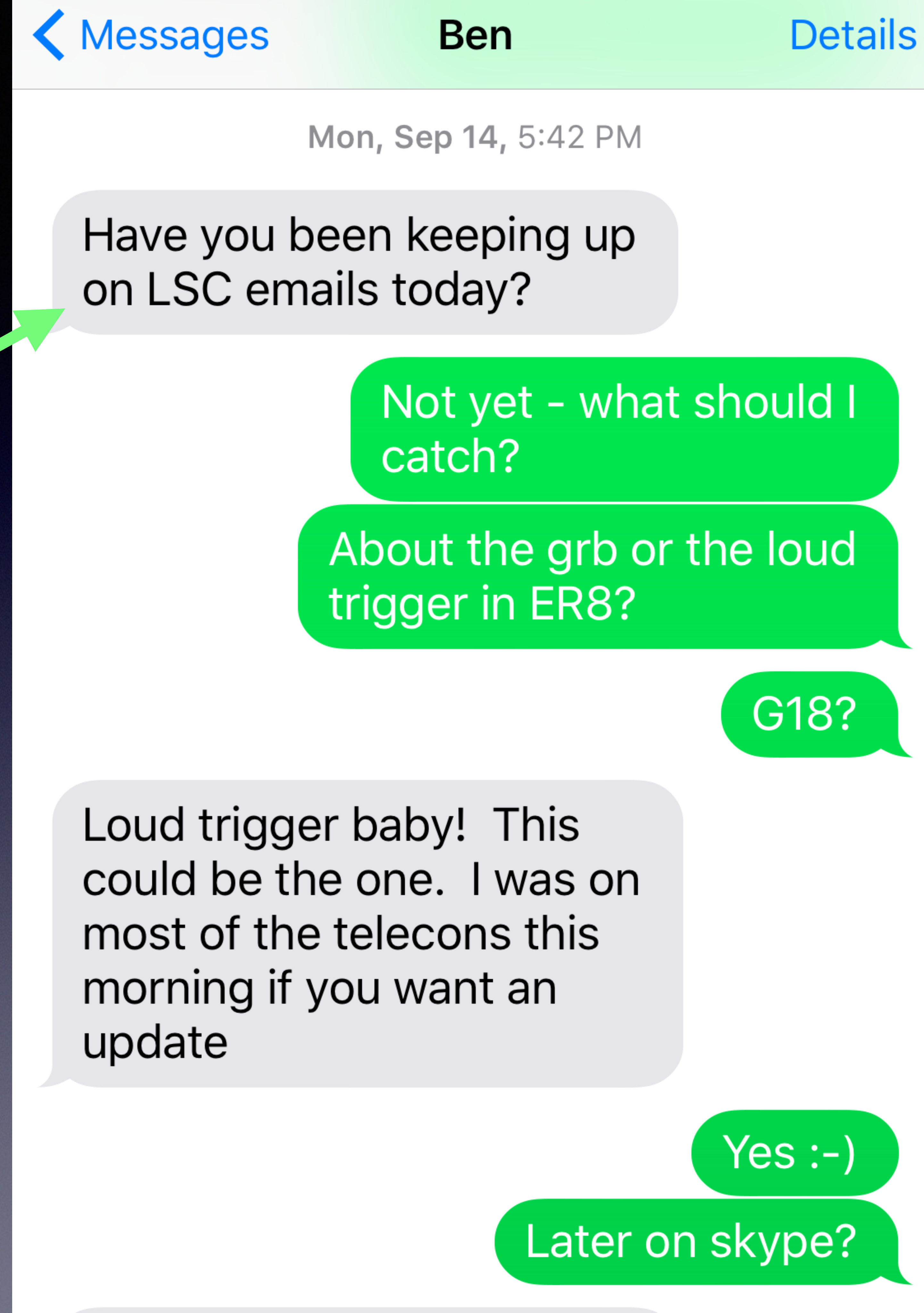
+15min: “This is clean and very significant inspiral with Mchirp = 27 +- 2 Mo… FAR << 1.e-10 Hz.
If this is not injection,
I guess, we need to do the detection checklist…”

LSC VIRGO

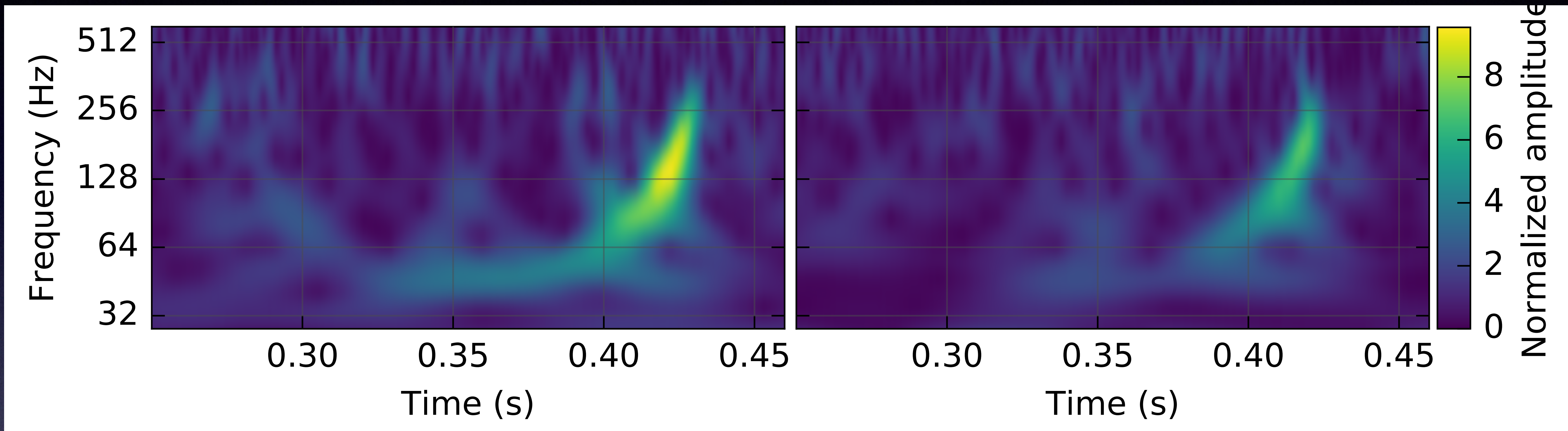
On September 14th …

On September 14th …
~12 hours later …

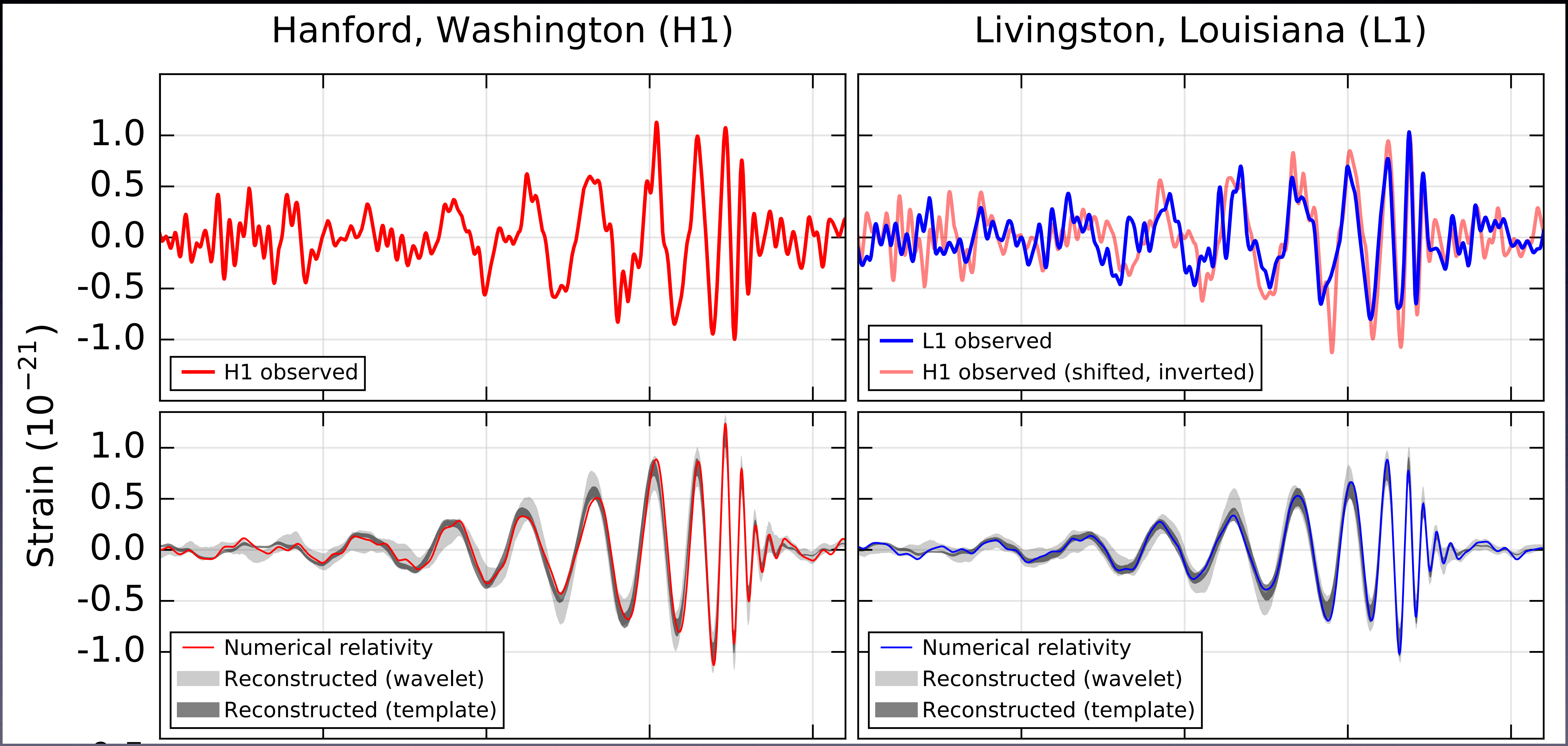
Text message
from my
past grad student
Ben Farr



GW150914

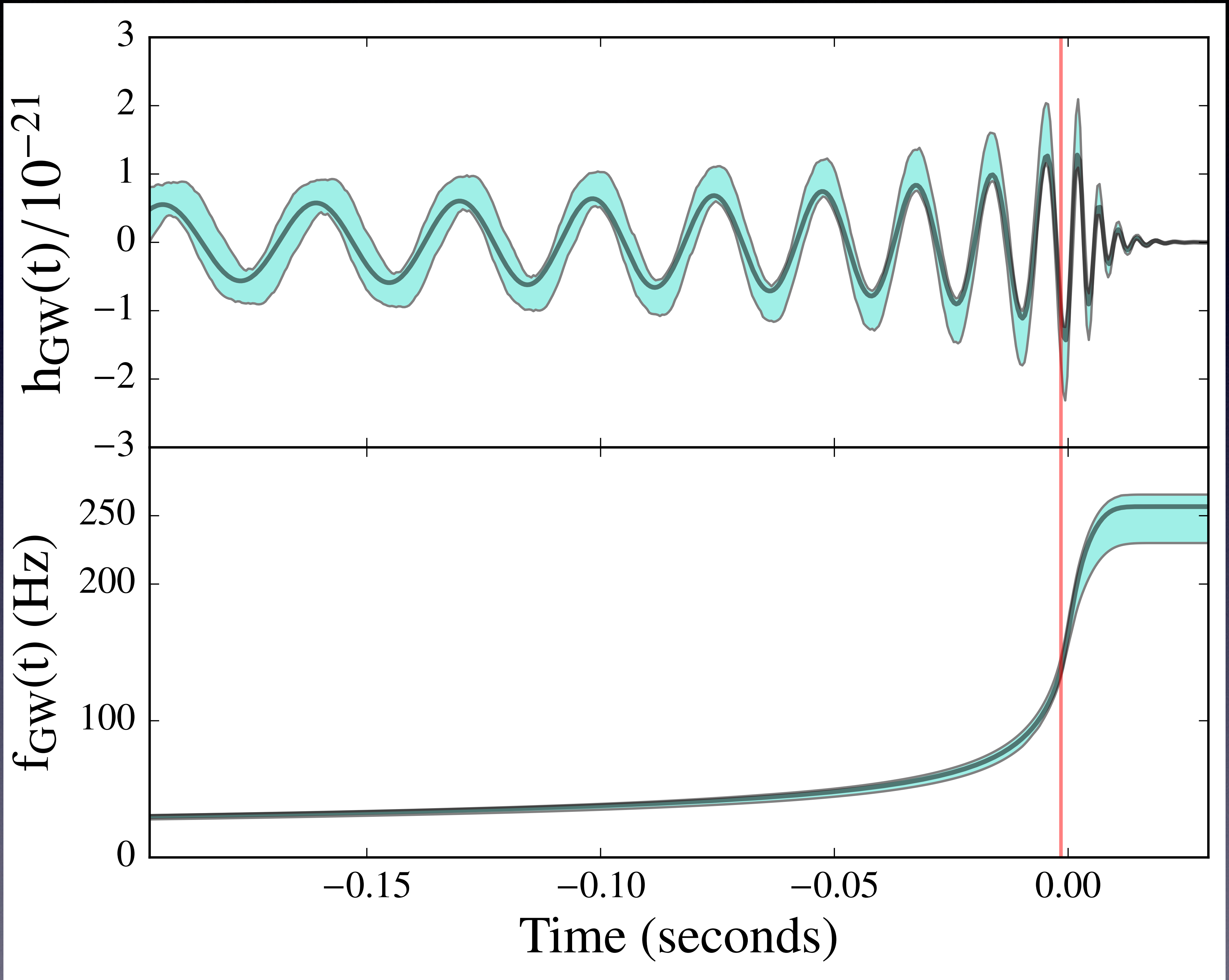

Frequency (Hz)
512
256
128
64
32
0.30
0.35
0.40
0.45
Time (s)
0.30
0.35
0.40
0.45
Time (s)
8
6
4
2
0
Normalized amplitude

GW150914



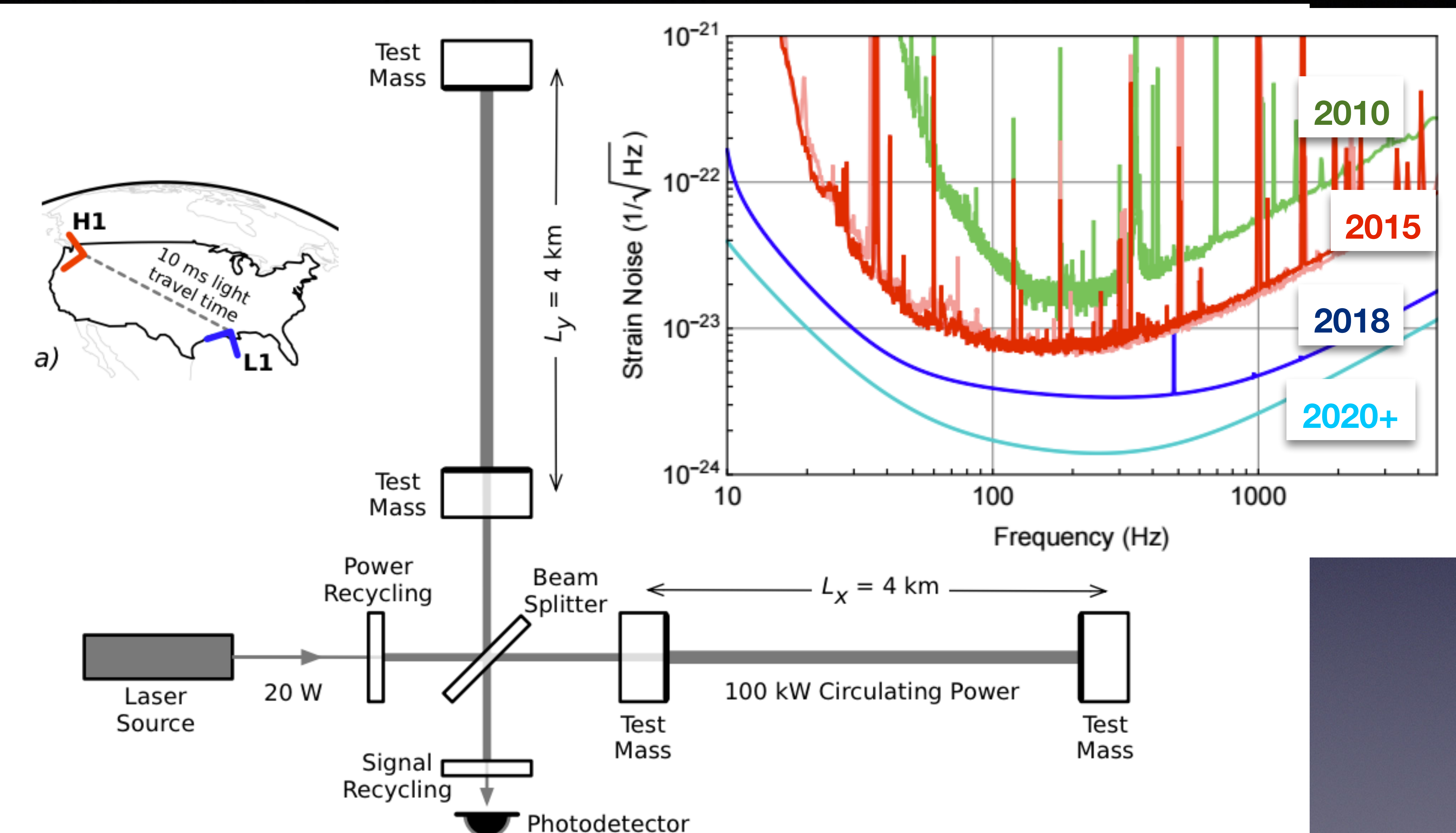
Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)

GW150914



$h_{GW}(t)/10^{-21}$
3
2
1
0
−1
−2
−3
$f_{GW}(t)$ (Hz)
250
200
100
0
−0.15
−0.10
−0.05
0.00
Time (seconds)

Advanced LIGO



GW150914: Binary BH merger rate

assumed to be constant
within current sensitive volume
out to z~0.5

for GW150914-like BBH mergers:
2 - 53 per Gpc^3 per yr

BUT … search reveals many more triggers (<2 sigma)

what if we assume they are all from the same population accounting for their probability of being astrophysical?

6-400 Gyr^3 per yr

Binary Population Synthesis: some bibliography

Kornilov & Lipunov 1984
Dewey & Cordes 1987

including BBH:

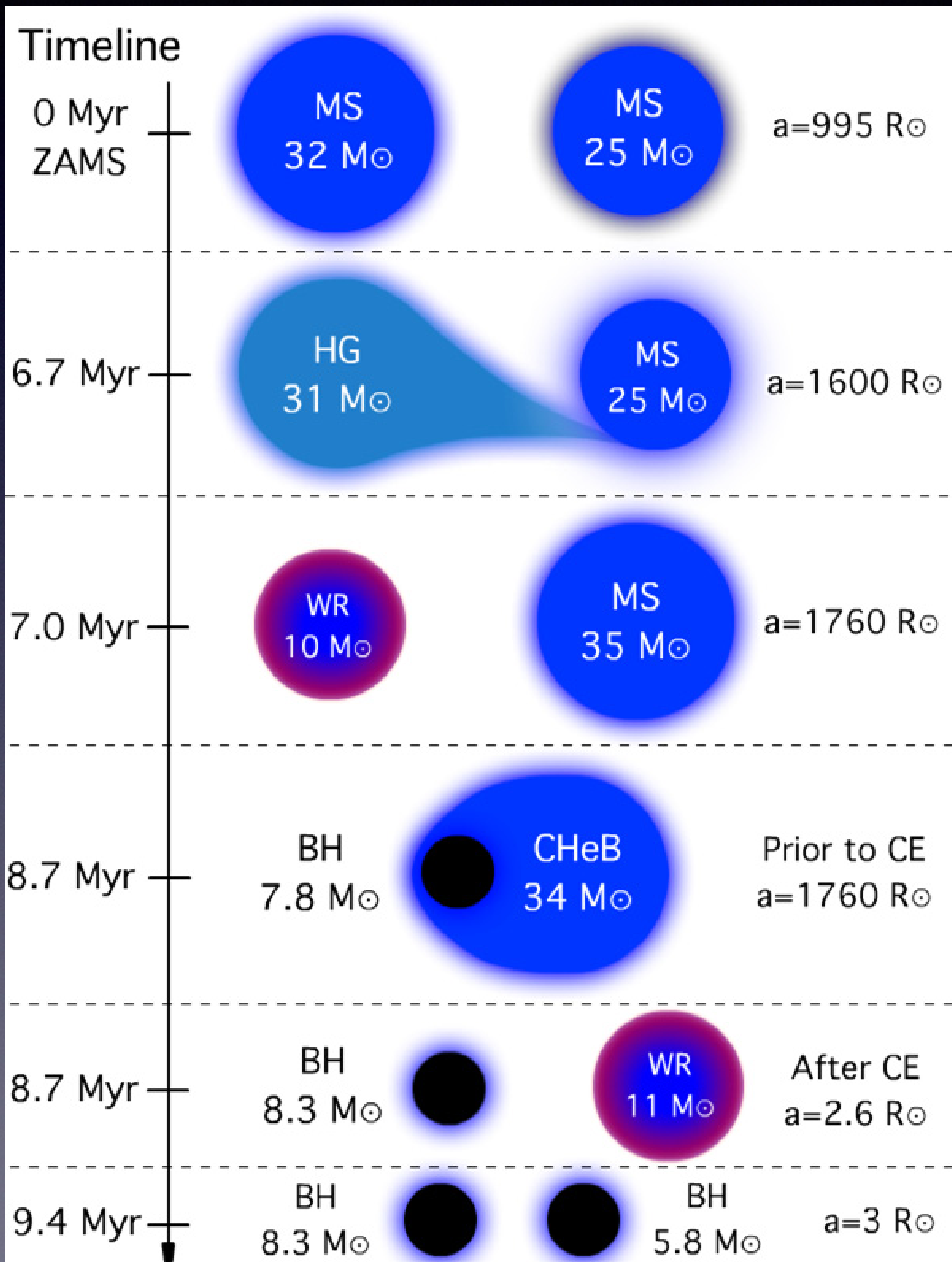
Lipunov et al. 1997
Bethe & Brown 1998
DeDonder & Vanbeveren 1998, 2004
Portegies Zwart & Yungelson 1998
Belczynski & Bulik 1999
Bloom et al. 1999
Fryer et al. 1999
Grishchuk et al. 2001
Nelemans et al. 2001
Belczynski, VK, & Bulik 2002
Voss & Tauris 2003
O'Shaughnessy, Kim, …, VK, Belczynski 2005
Belczynski et al. 2008
O'Shaughnessy, VK, Belczynski 2010

including massive BBH:

Belczynski et al. 2010
Fryer et al. 2012
Dominik et al. 2012, 2013, 2015
Belczynski et al. 2015
Spera et al. 2015

BBH Formation from Isolated Binaries

Belczynski, …, Bulik, O’Shaughnessy, …, Holz 2010
Dominik, Belczynski, …, Holz, …, Bulik, Mandel, O’Shaughnessy 2012
Dominik, Belczynski, …, Holz, Bulik, Mandel, O’Shaughnessy 2013



BBH Formation from Isolated Binaries

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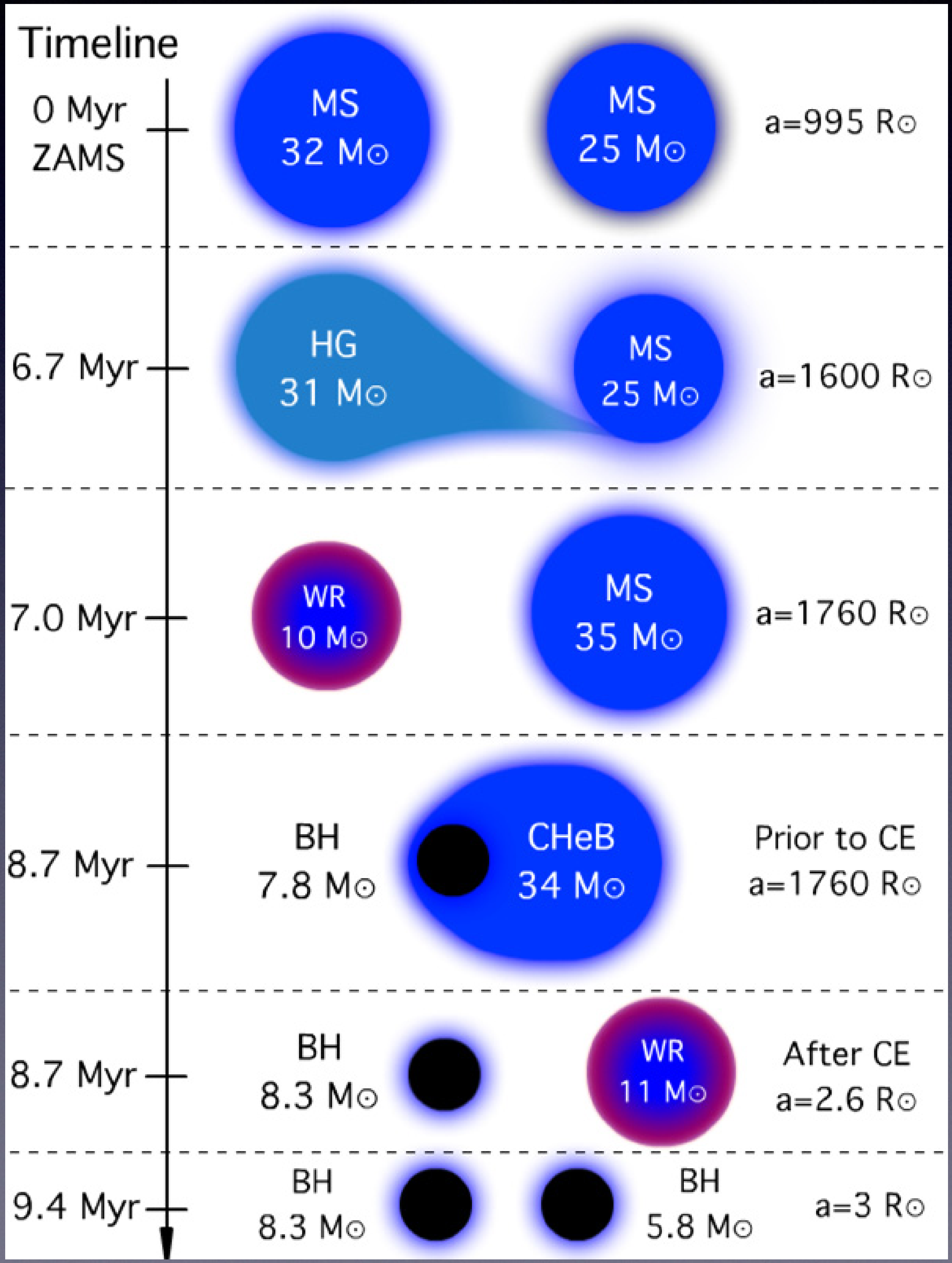
Dominik, Belczynski, …, Holz, …, Bulik, Mandel, O'Shaughnessy 2012
Dominik, Belczynski, …, Holz, Bulik, Mandel, O'Shaughnessy 2013



Branching Ratios for this Evolutionary Channel:

99% of BBH at solar metallicity
90% of BBH at 0.1xsolar metallicity

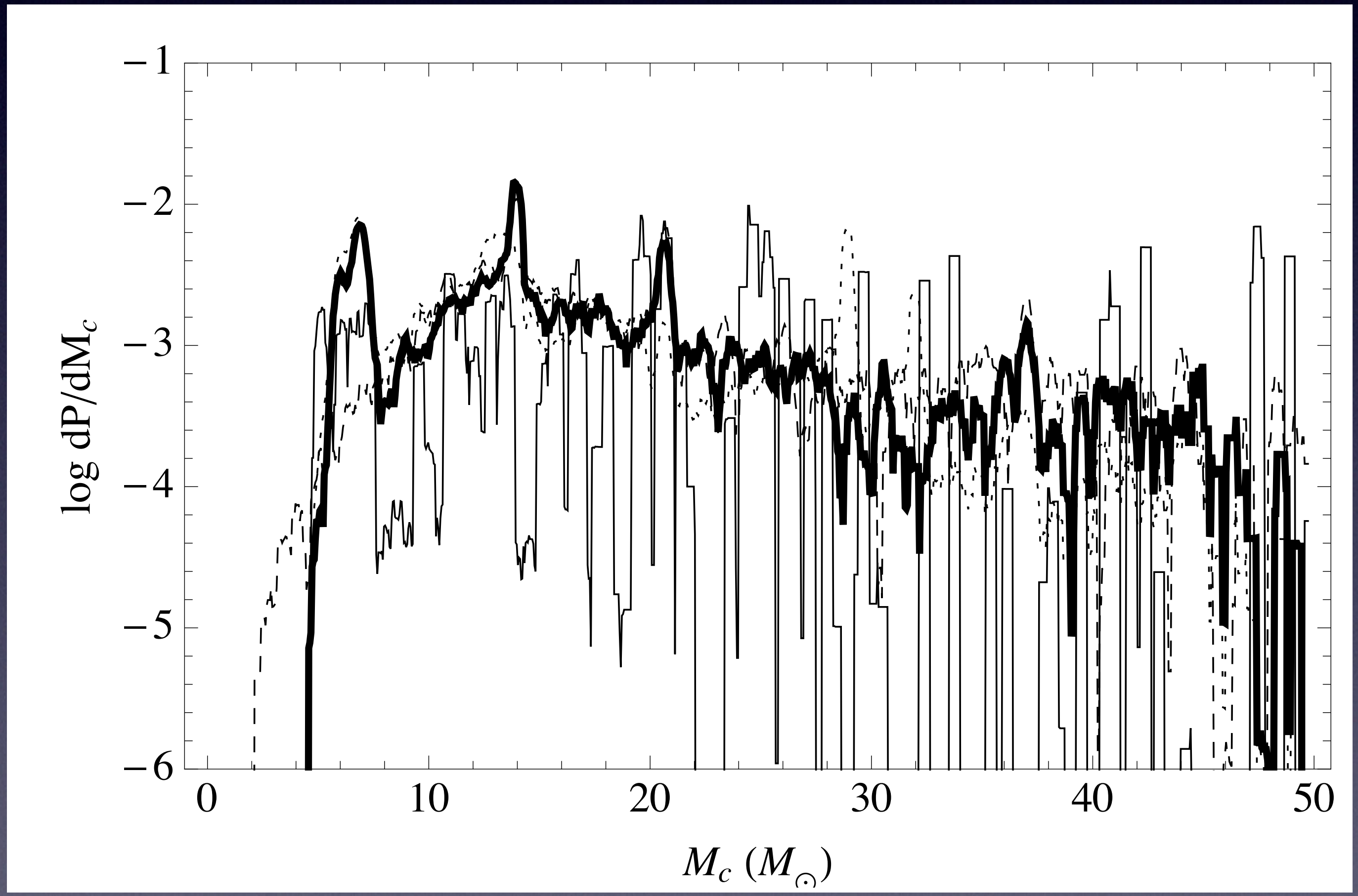
Most important factors:
- Stellar Winds & Metallicity
- Common-Envelope Treatment
- BH Natal Kicks

Other model factors:
- Initial binary properties
- Stellar models & properties
- Mass Transfer
- Tides in binaries
- …

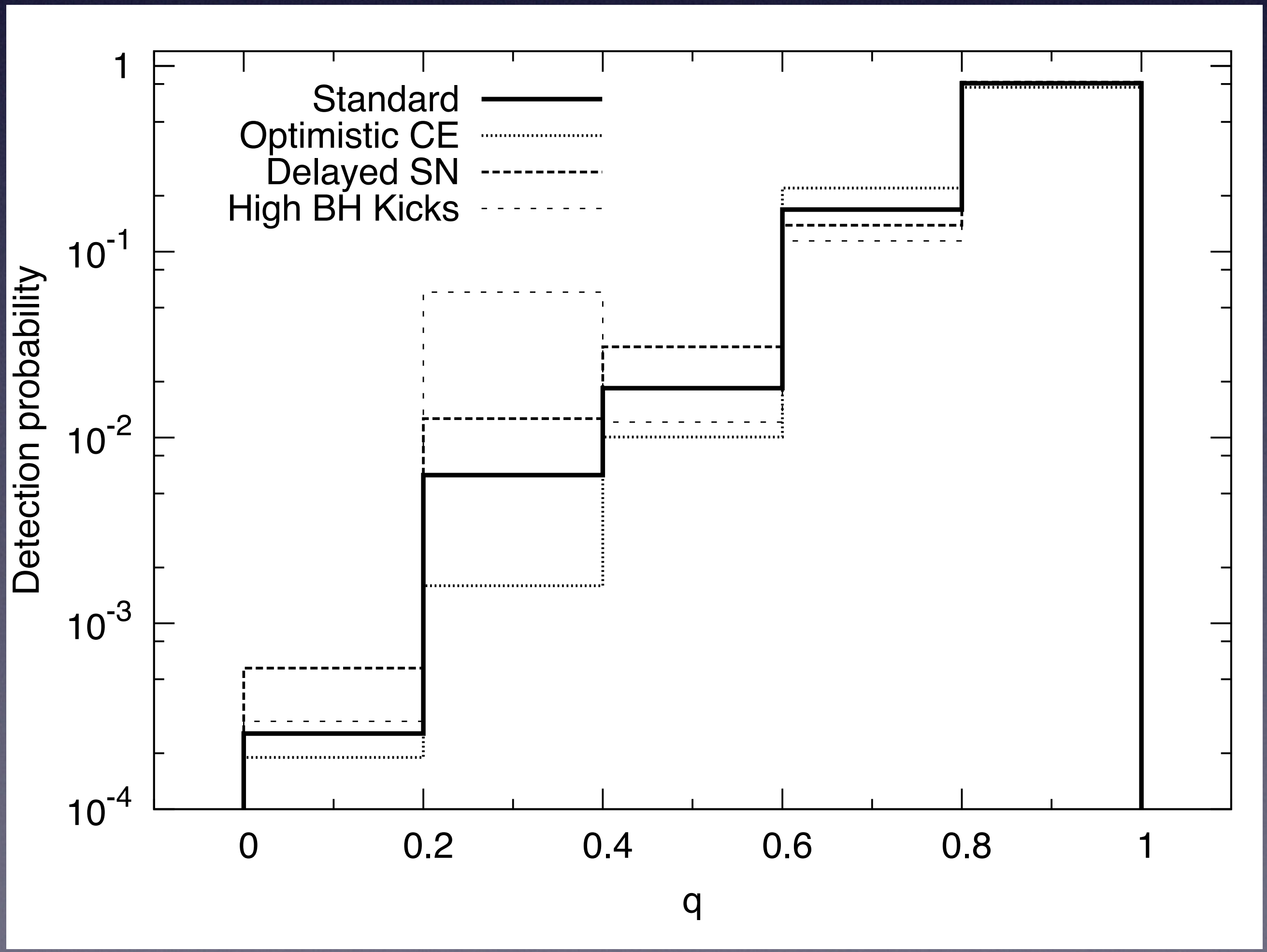
BBH Formation from Isolated Binaries with SFH & IMR waveforms

Dominik, …, O'Shaughnessy, Mandel, Belczynski, …, Holz, Bulik, Pannarale 2015

detectable BBH



chirp mass



mass ratio

BBH from Dense Stellar Environments

some bibliography ...

Globular Clusters

> Just BH dynamics

Sigurdsson & Hernquist 1993
Portegies Zwart & McMillan 2000
Gultekin et al. 2004, 2006
Kocsis, Gaspar, & Marka 2006
Banerjee et al. 2010
Bae, Kim, & Lee 2014

> Binary Evolution & Semi-Dynamics

O'Leary, …, O'Shaughnessy 2006
O'Leary, O'Shaughnessy, & Rasio 2007
Sadowski et al. 2008

> Dynamics & Binary Evolution

Downing et al. 2010
Downing et al. 2011

Pattabiraman, …, VK, Rasio 2013
Morscher et al. 2013
Morscher et al. 2015
Antonini, …, VK, Rasio 2015

Galactic Centers

> Just BH dynamics

Miller & Lauburg 2009
O'Leary et al. 2009
cf. Tsang 2013
Kocsis & Levin 2012

Young Star Clusters

Goswami, Kiel, & Rasio 2014
Ziosi, …, Branchesi, & Tormen 2014

BBH from clusters key model elements

All from binary evolution

Most important factors:
- Stellar Winds & Metallicity
- Common-Envelope Treatment
- BH Natal Kicks

Other model factors:
- Initial binary properties
- Stellar models & properties
- Mass Transfer
- Tides in binaries
- …

+

Cluster Models

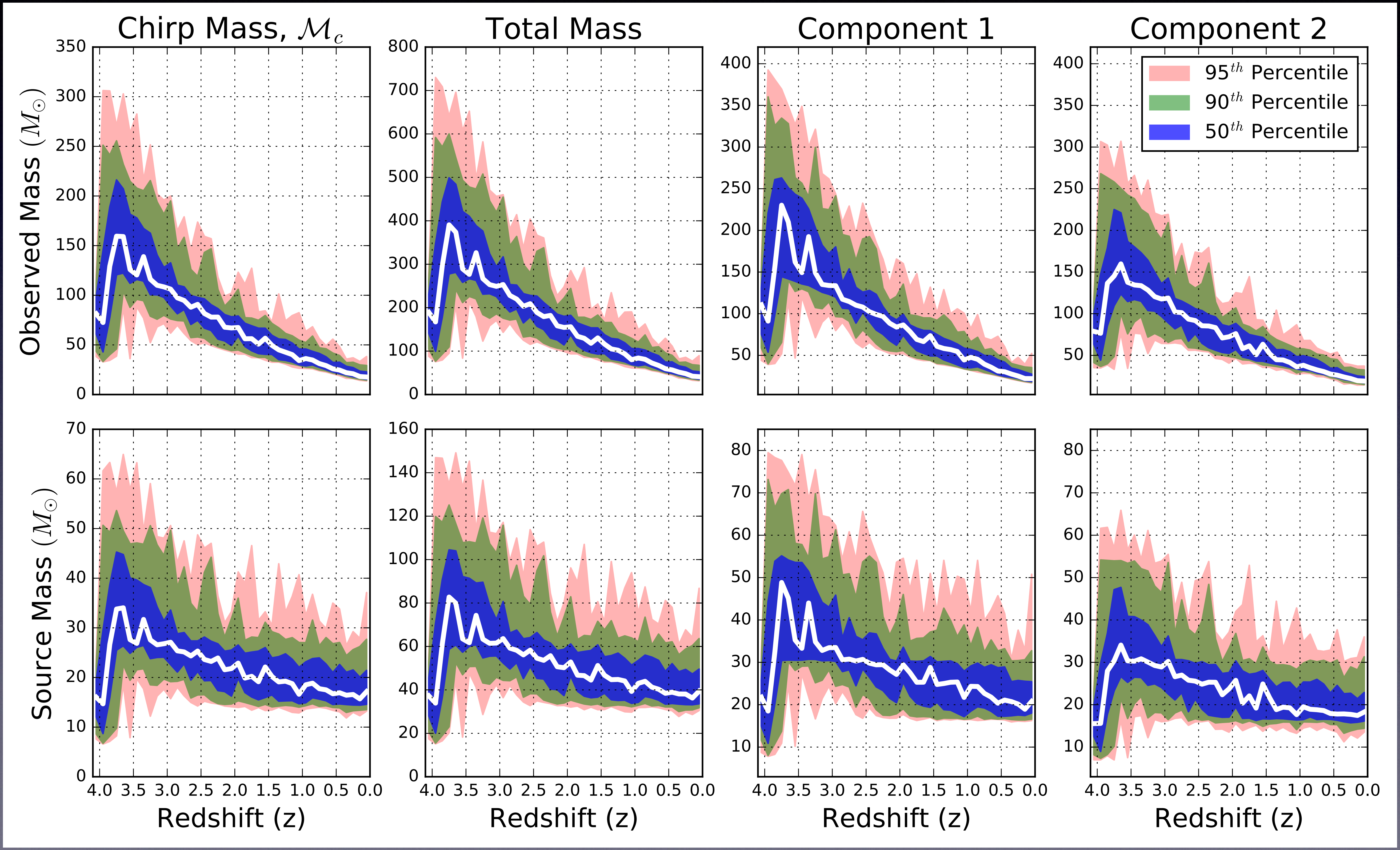
Realistic N particles
Few-body dynamics/interactions

Cluster:
Total Mass
Size
Central Density
Metallicity
Age

Mass Function
Volume Density of Clusters

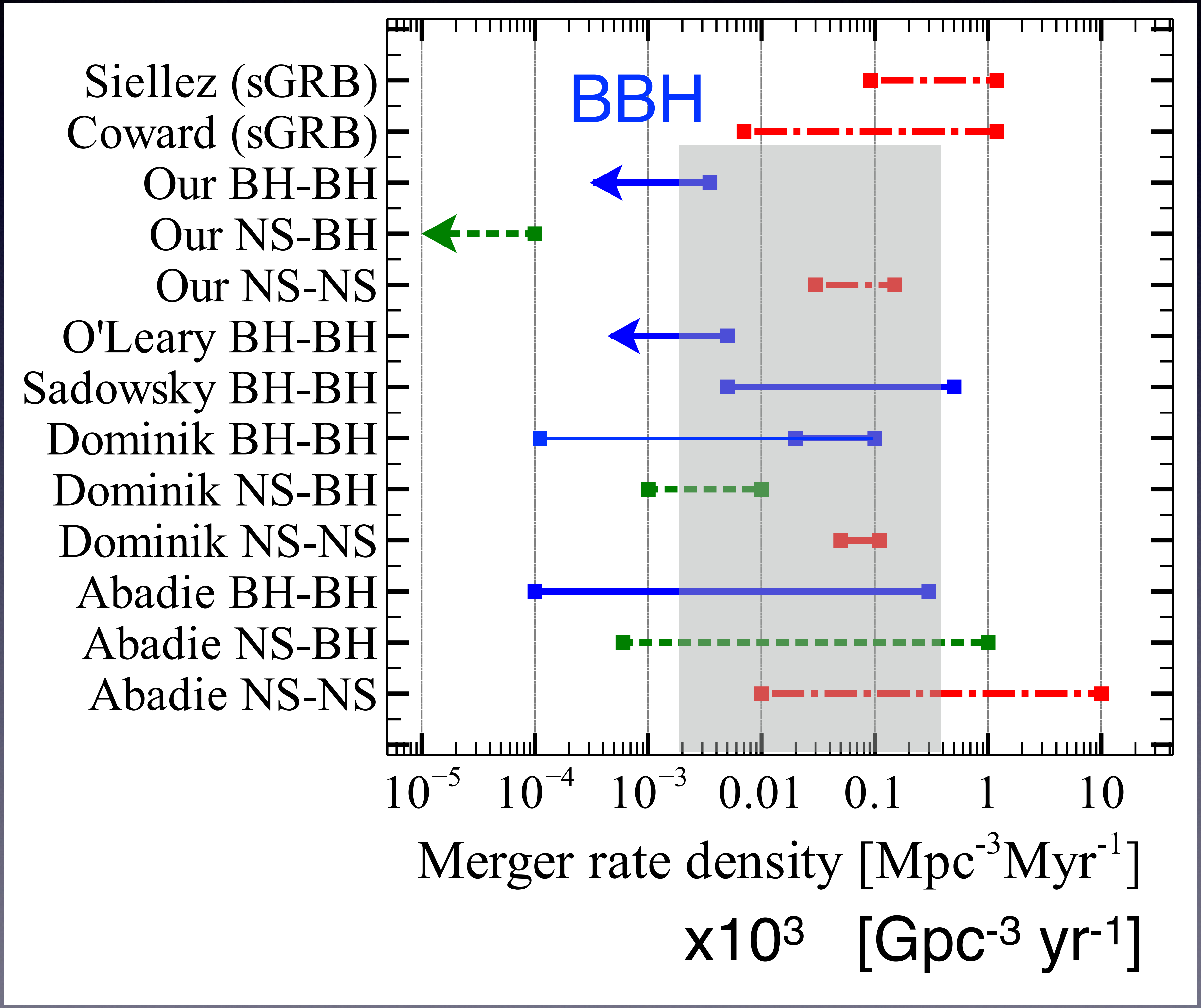
BBH from globular clusters

Rodriguez, Chatterjee, Rasio 2016



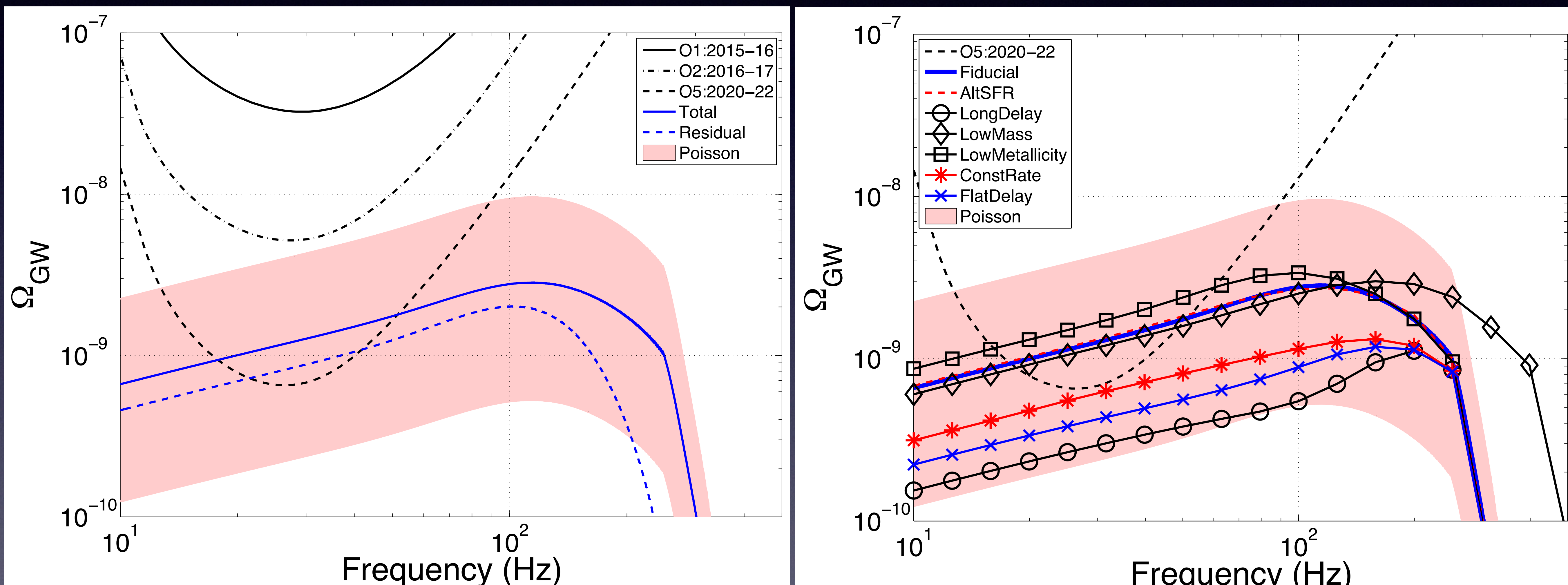
BBH Rates: Field & Clusters

Ziosi, …, Branchesi, & Tormen 2014



Ready for the Era of Gravitational-Wave Astrophysics?

Stochastic Background from BBH mergers …



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Ready for the Era of Gravitational-Wave Astrophysics?

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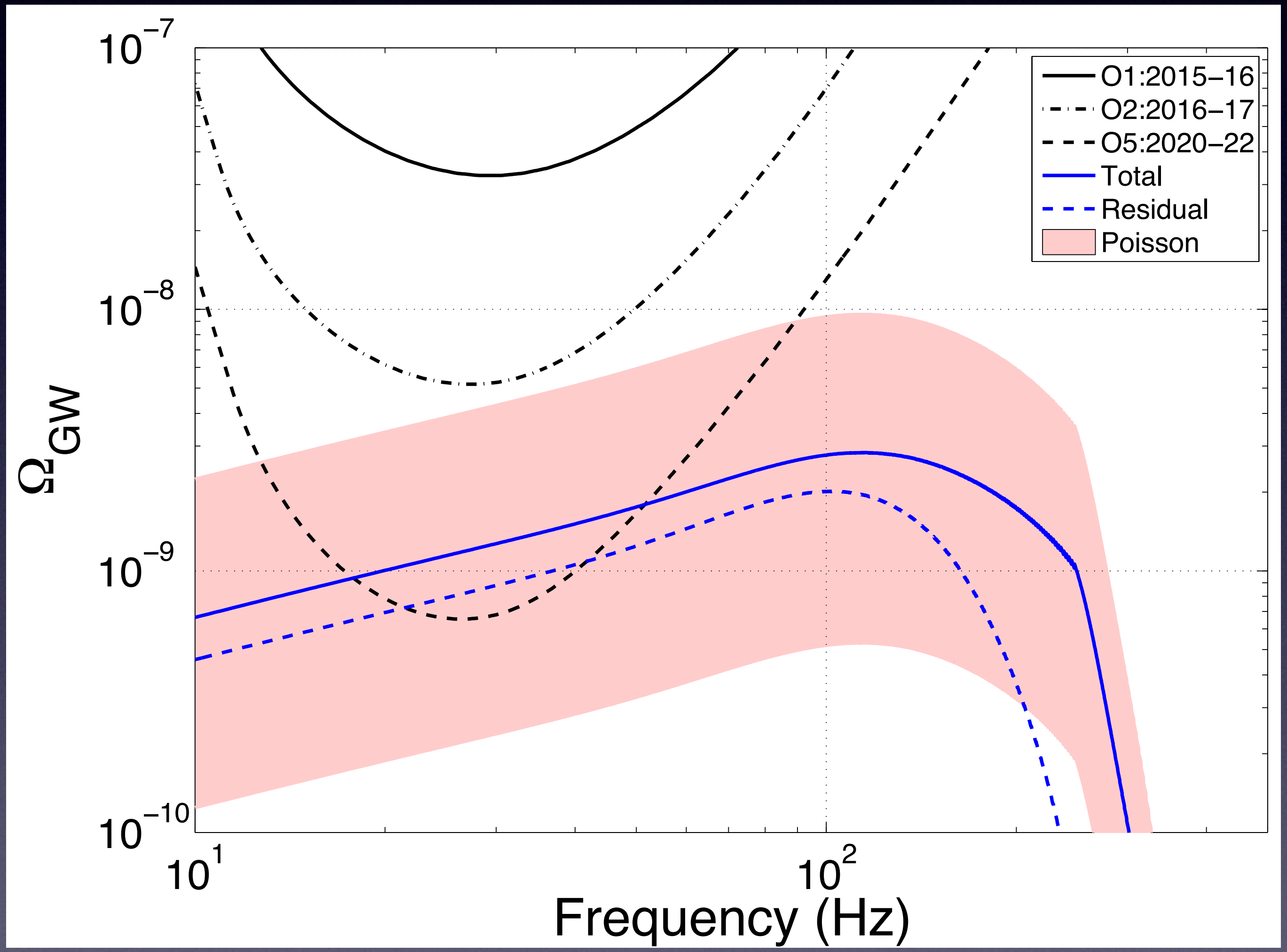

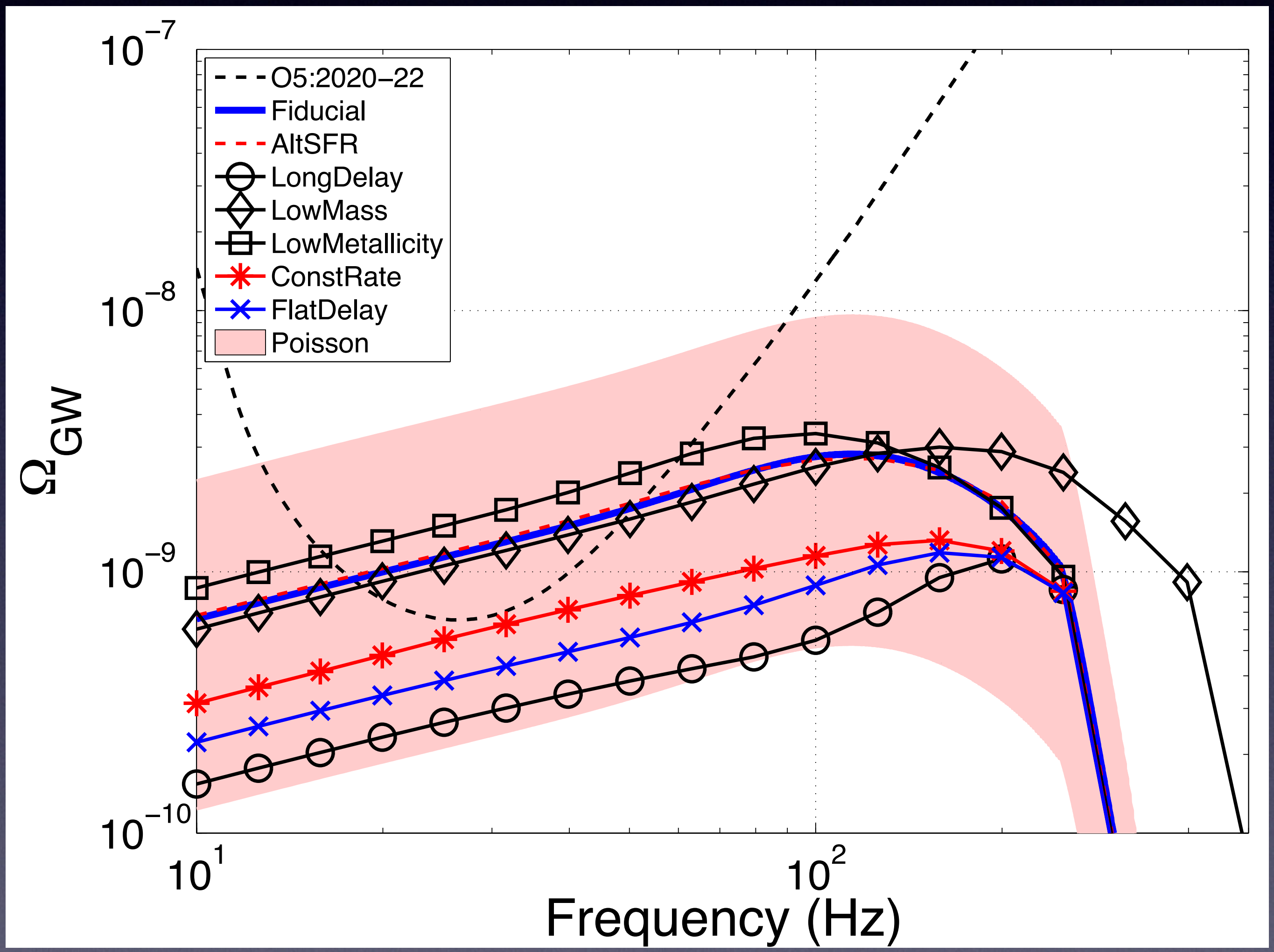

within reach at design sensitivity

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Binaries with Two Compact Objects

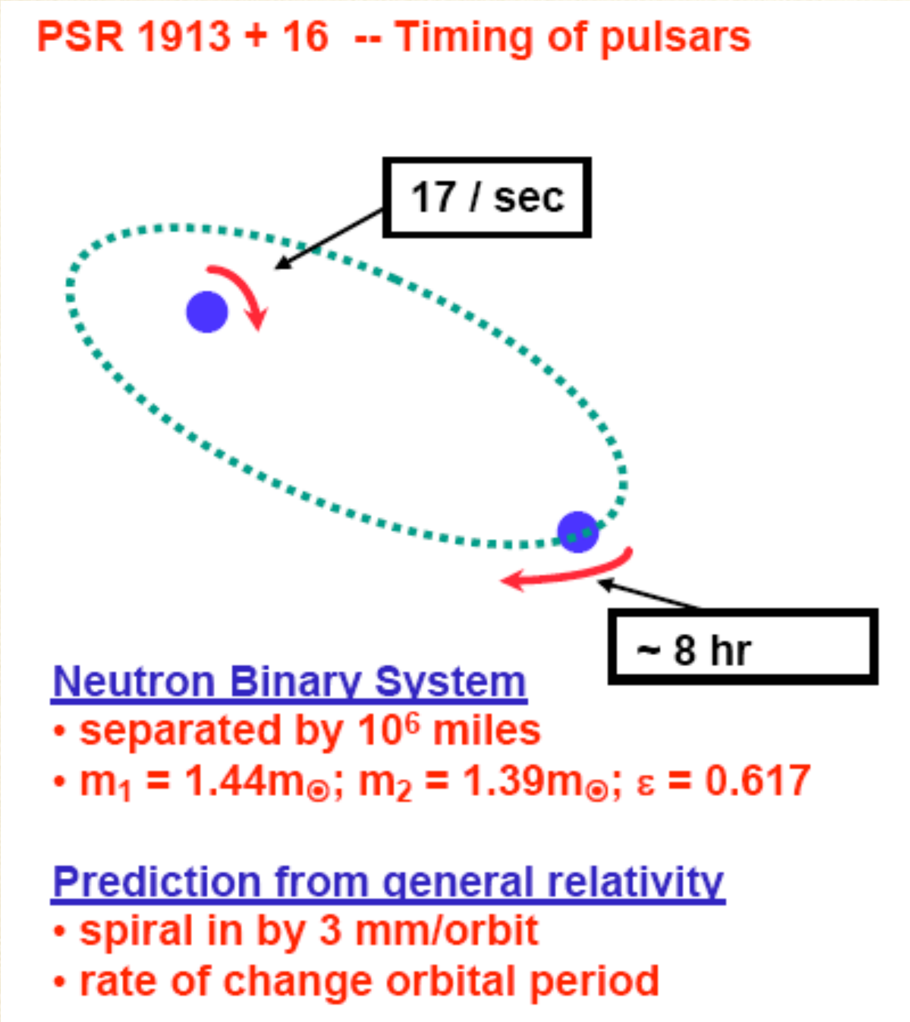
Binaries with Two Compact Objects

Hulse-Taylor Binary Pulsar: The first relativistic binary pulsar

Binaries with Two Compact Objects

Hulse-Taylor Binary Pulsar: The first relativistic binary pulsar

A radio pulsar with a NS
as its binary companion

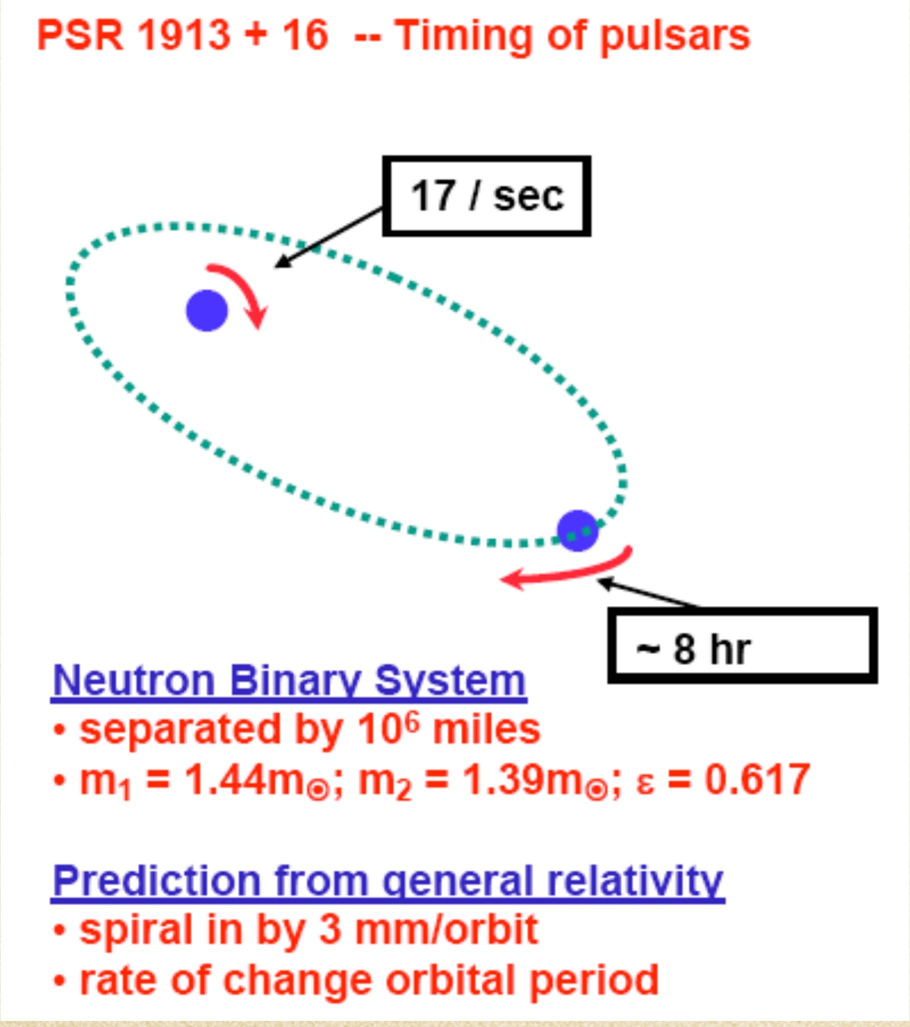


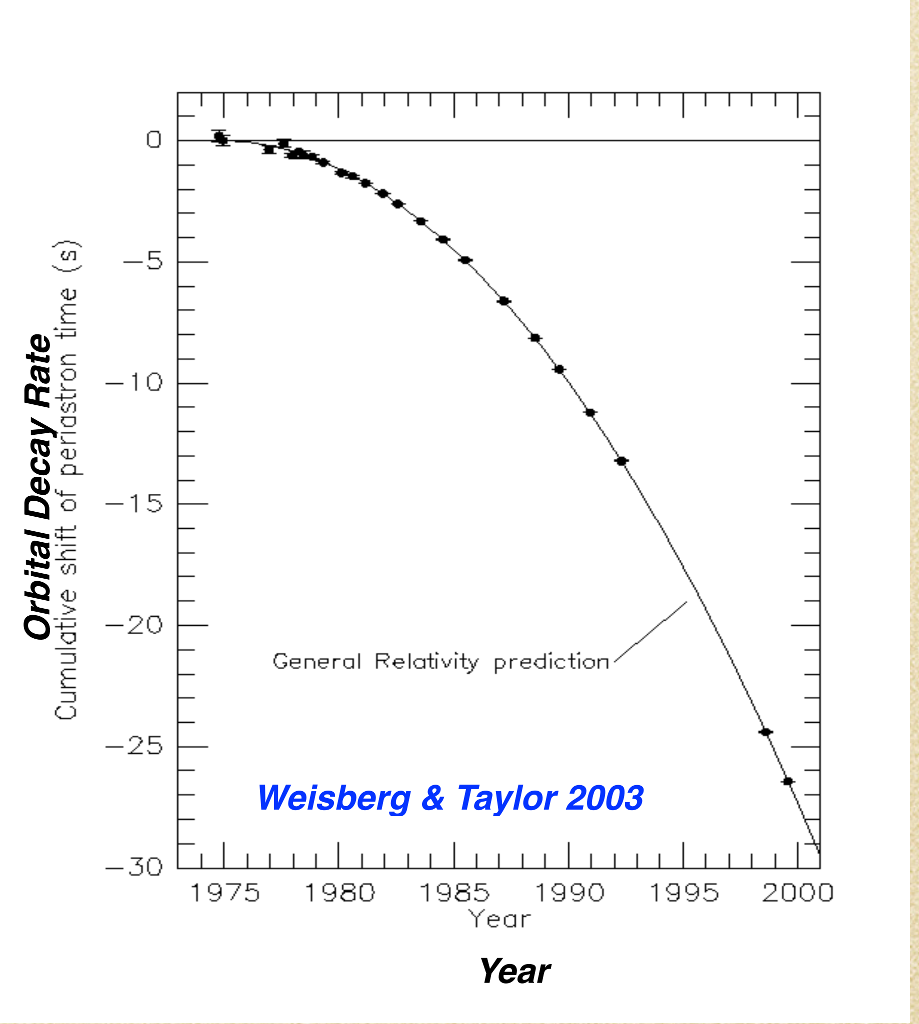
Binaries with Two Compact Objects

Hulse-Taylor Binary Pulsar: The first relativistic binary pulsar

A radio pulsar with a NS as its binary companion

Rate of orbital decay consistent with gravitational wave losses within 0.3%





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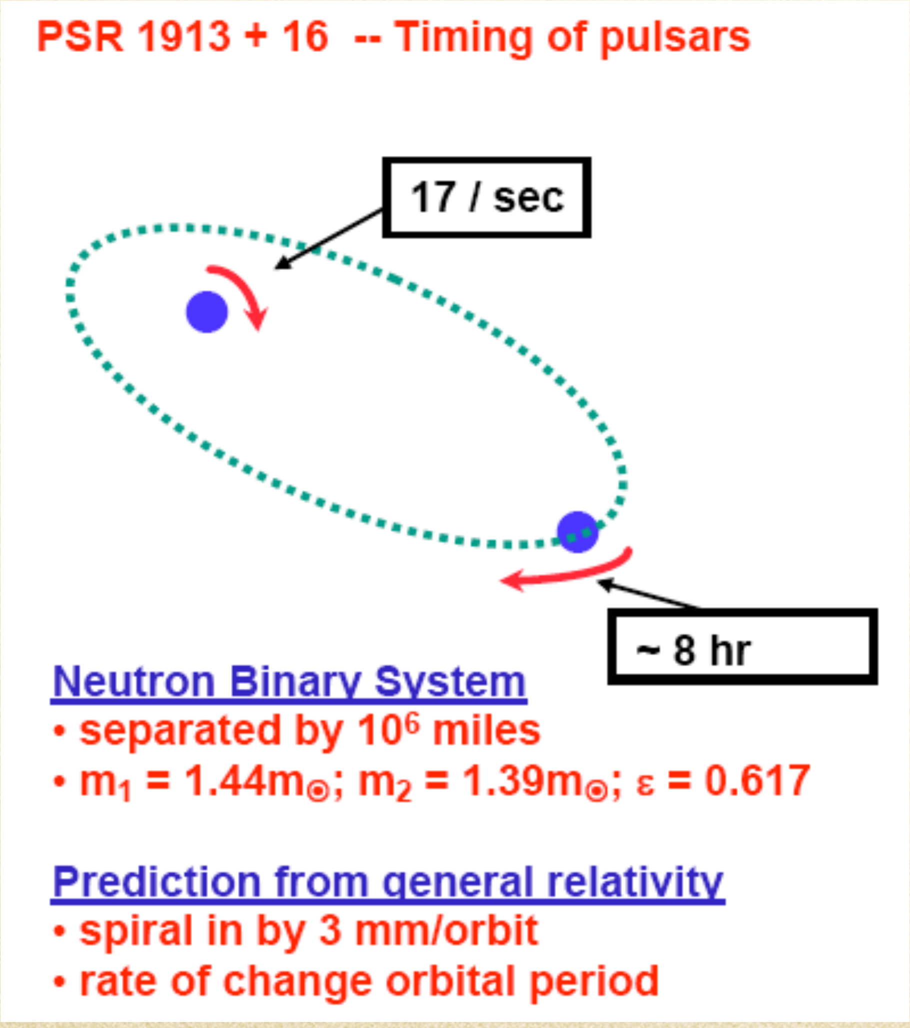
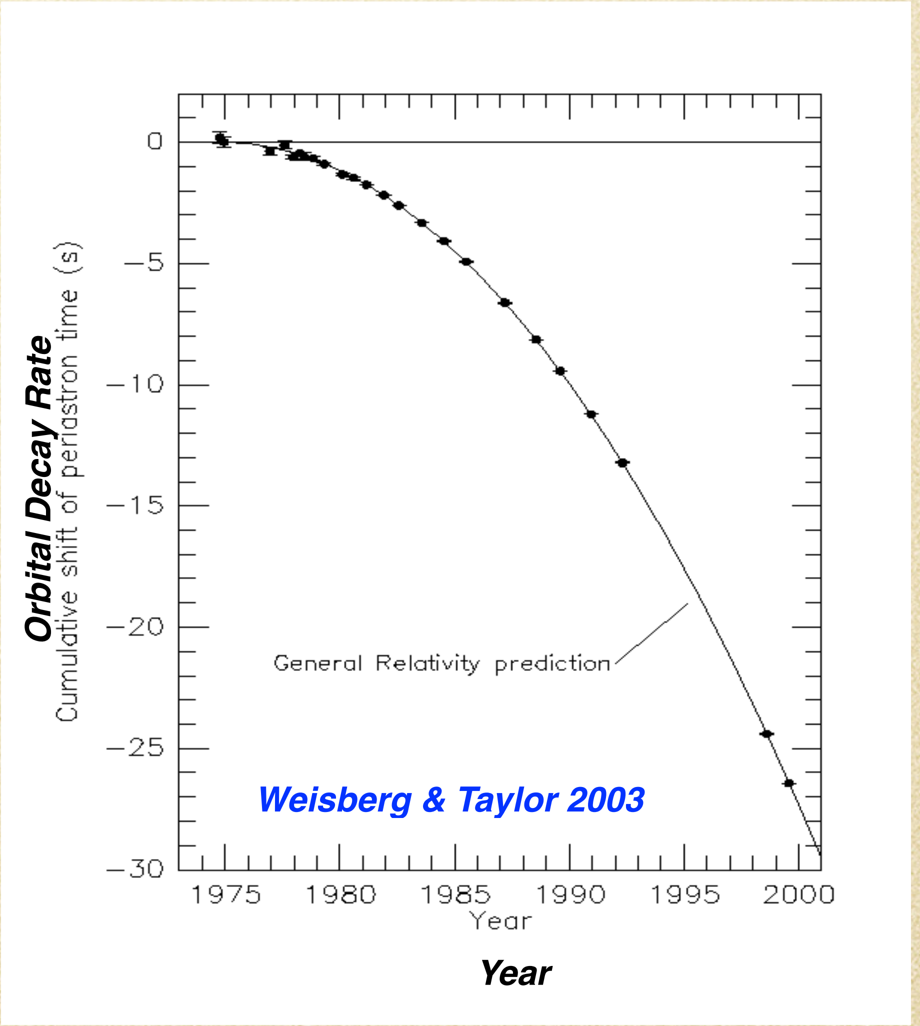
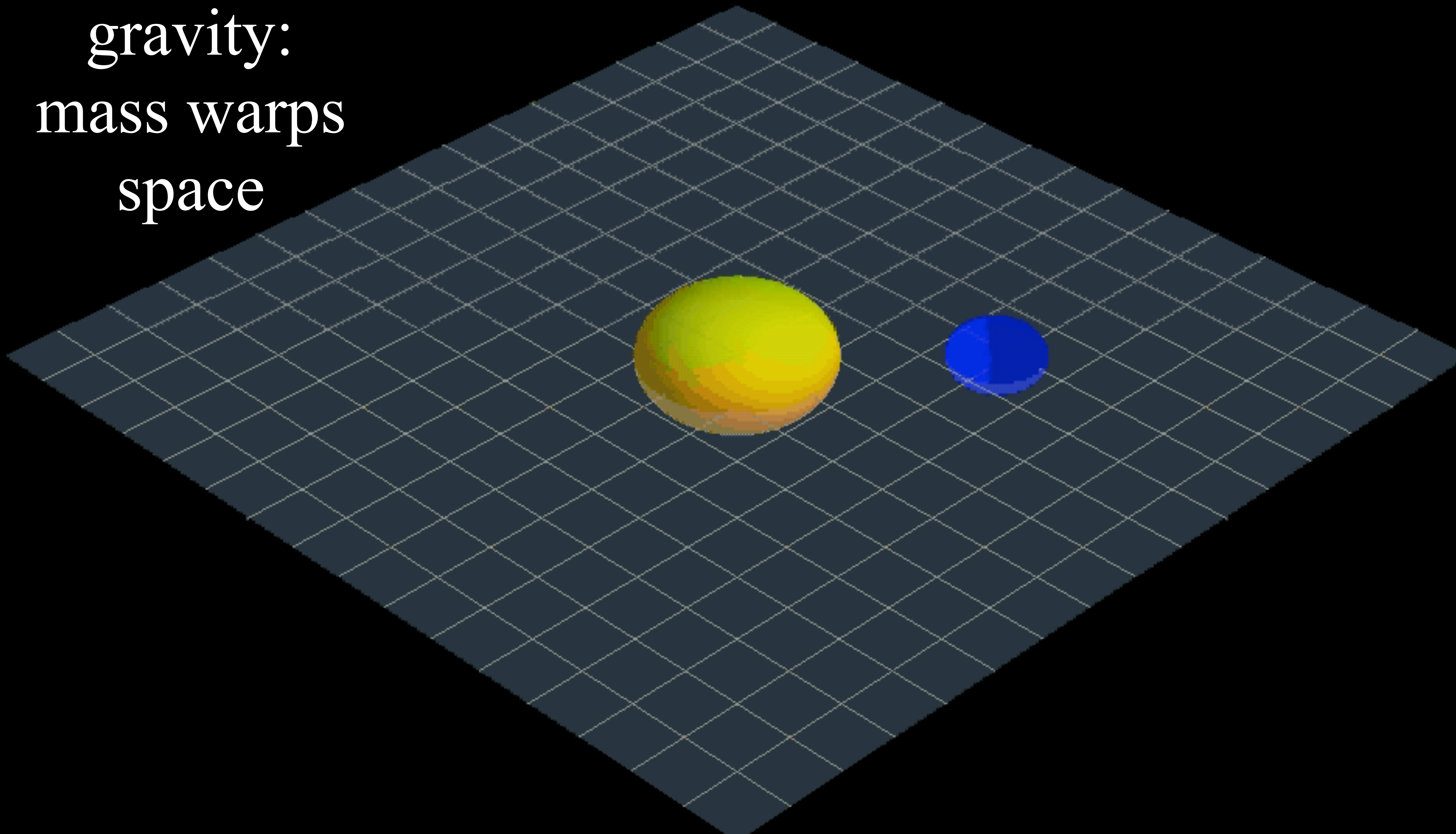




5 more relativistic NS-NS have been discovered

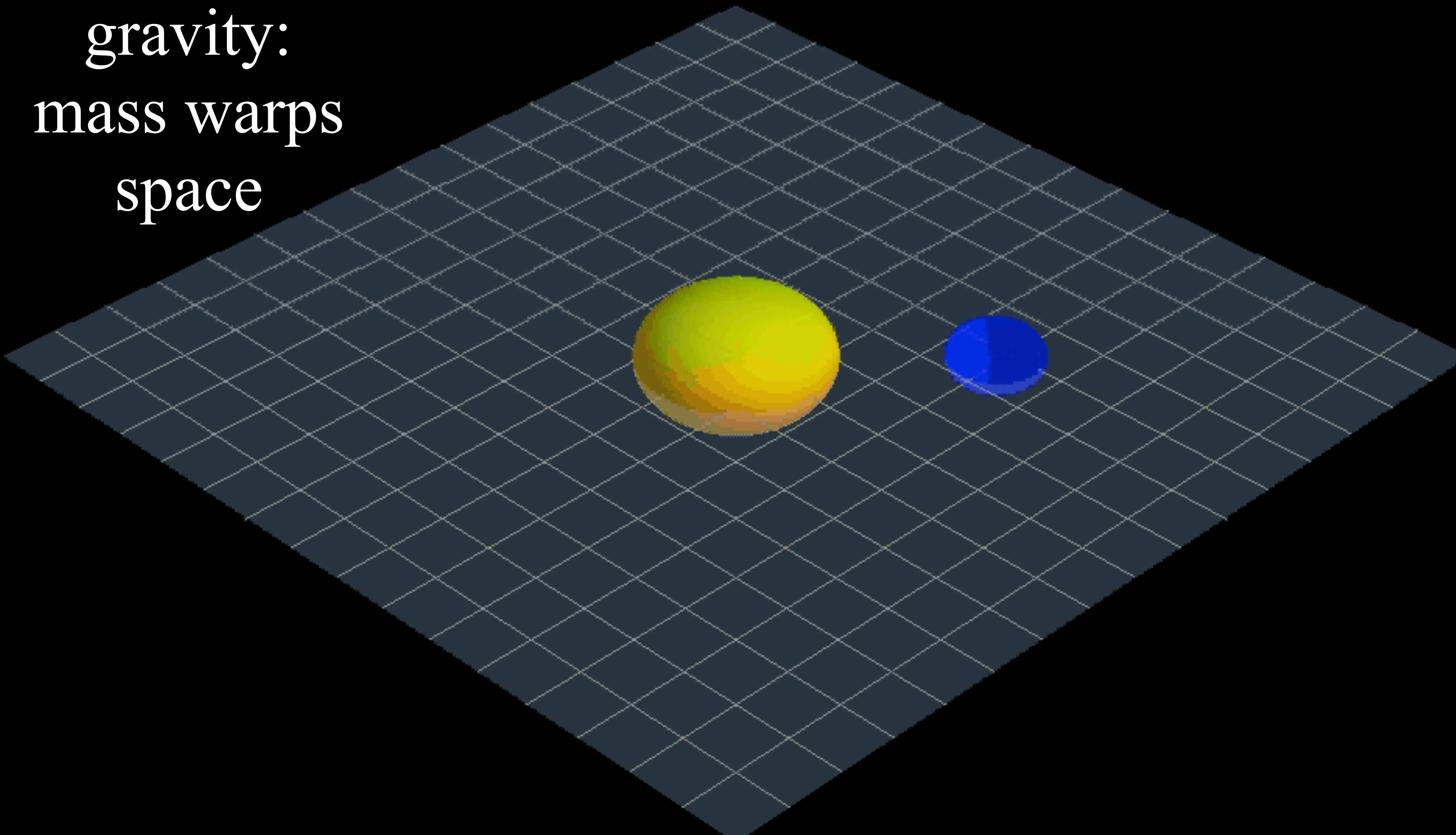
credit: C. Rodriguez

Einstein's gravity: mass warps space



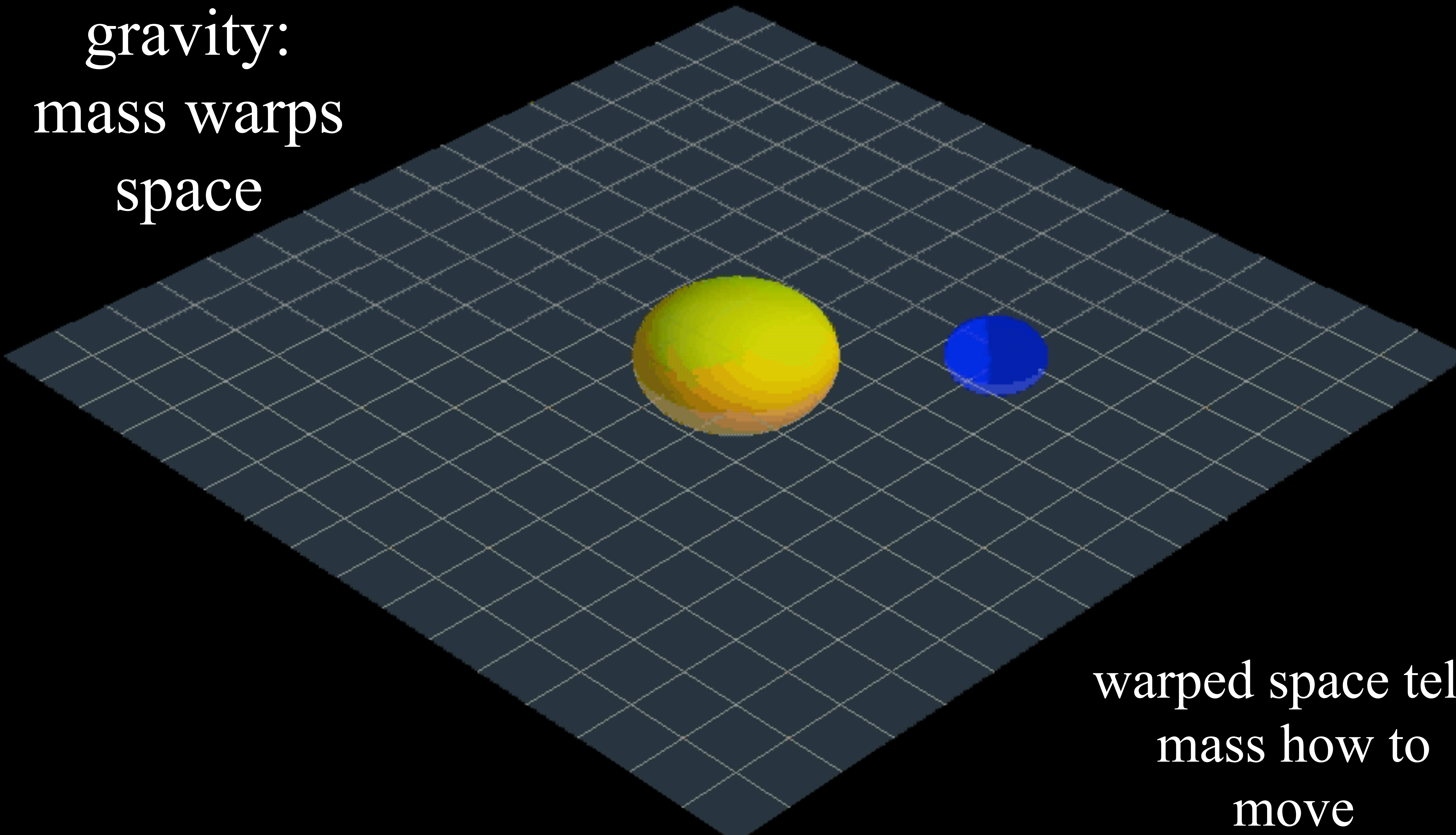
credit: C. Rodriguez

Einstein's gravity: mass warps space



credit: C. Rodriguez

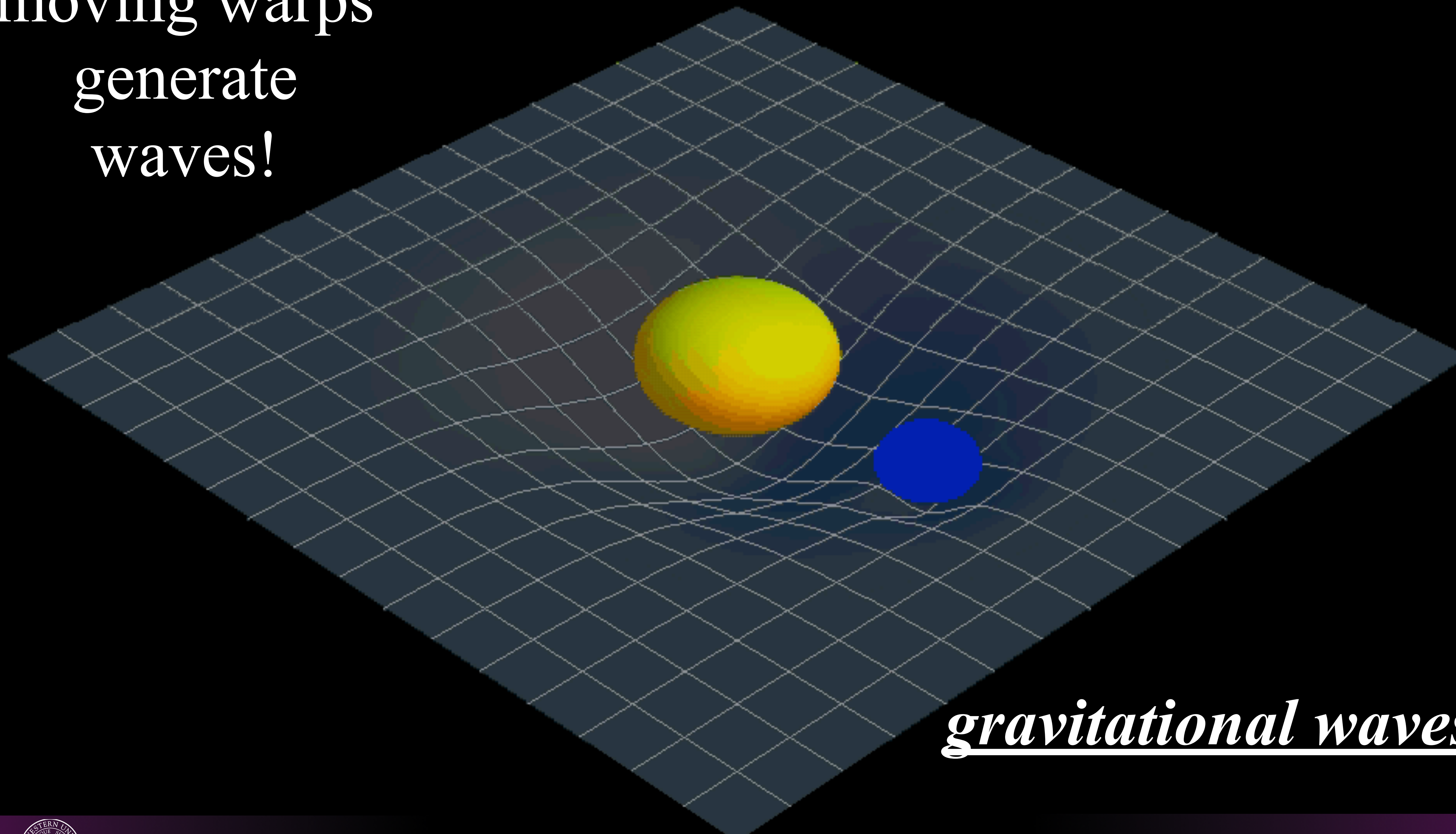
Einstein's gravity: mass warps space



warped space tells mass how to move

credit: C. Rodriguez

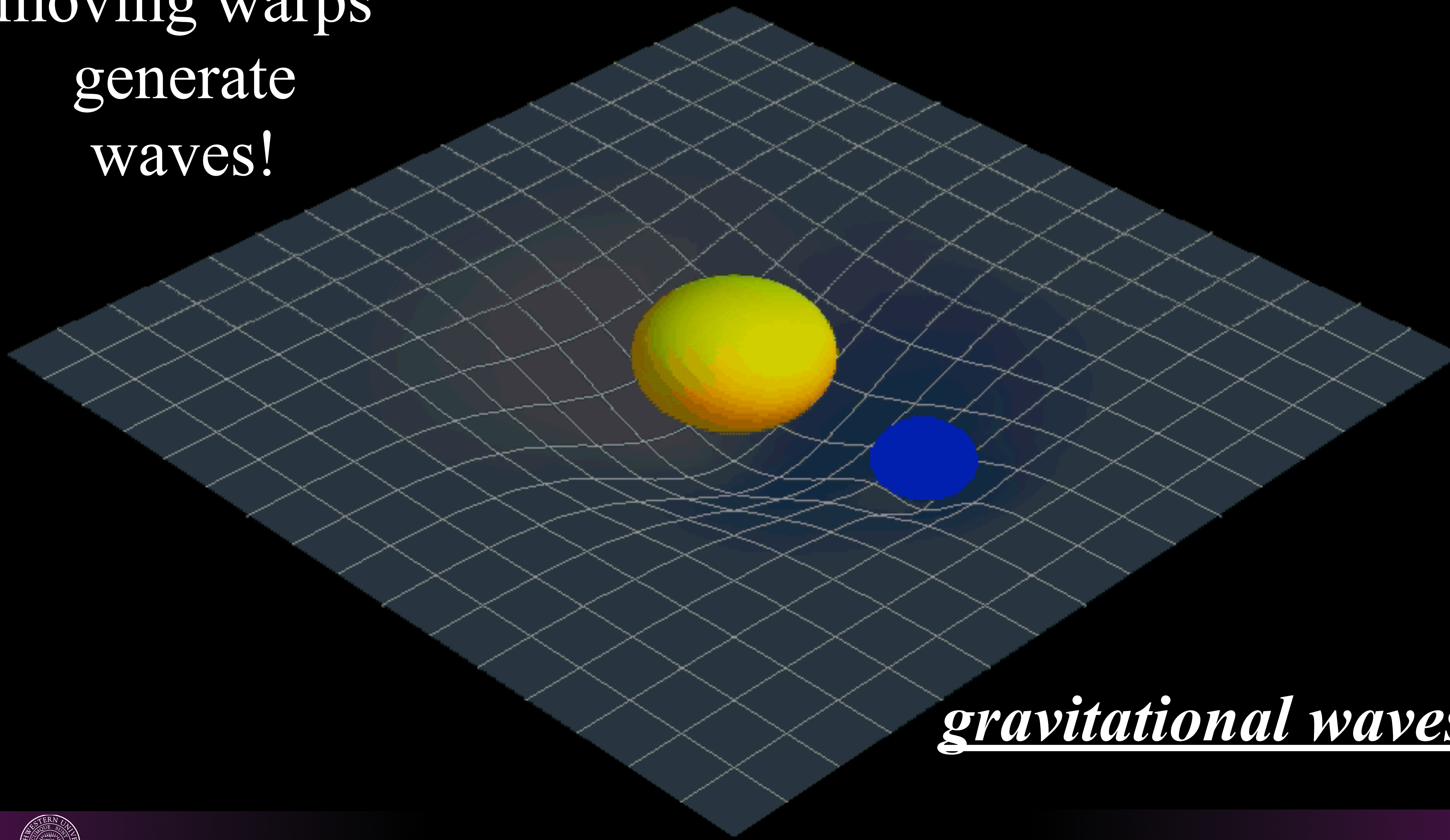
Einstein's gravity: moving warps generate waves!



gravitational waves

credit: C. Rodriguez

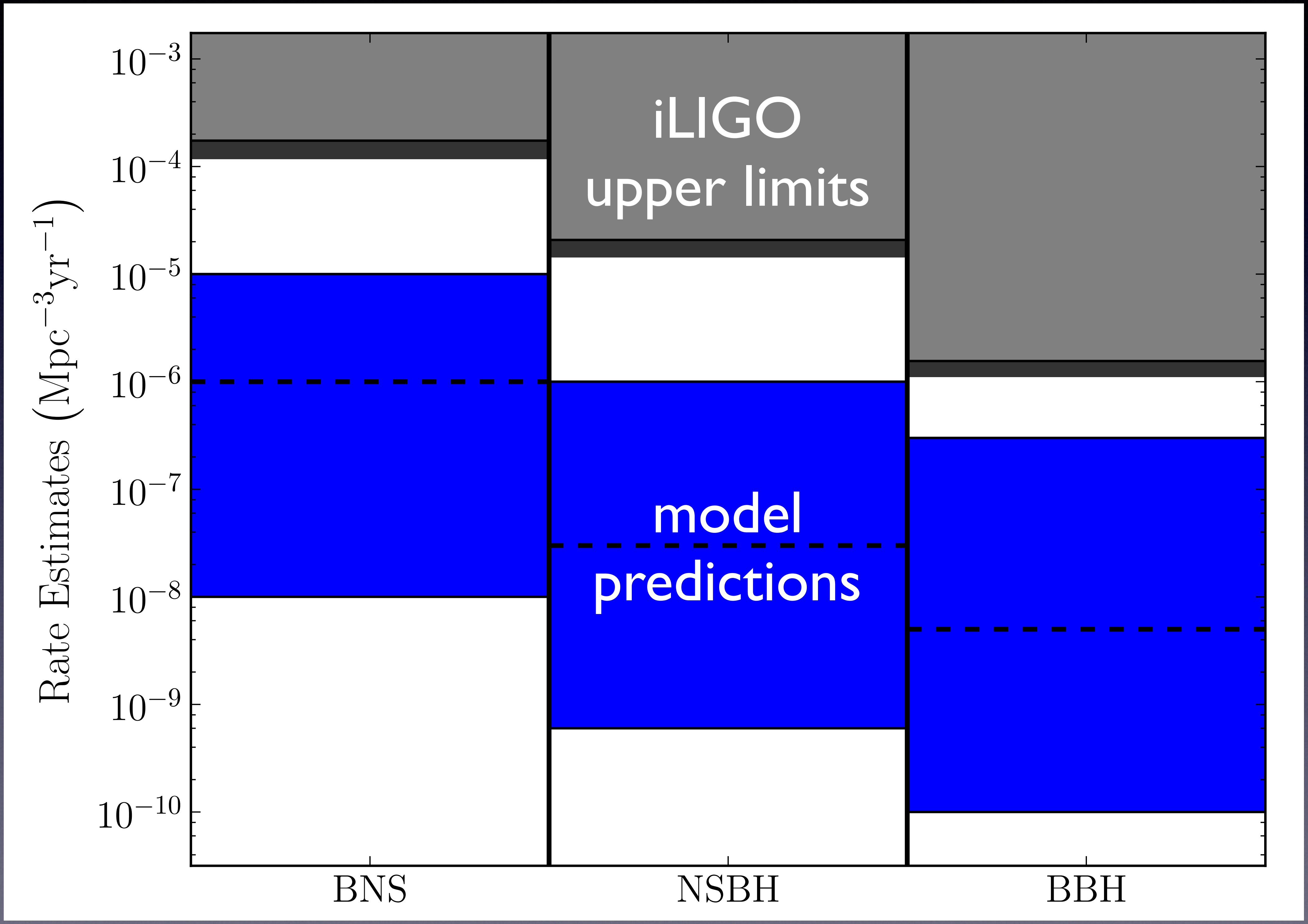
Einstein's gravity: moving warps generate waves!



gravitational waves

Initial LIGO: Binary Coalescence Upper Limits

Abadie et al 2012

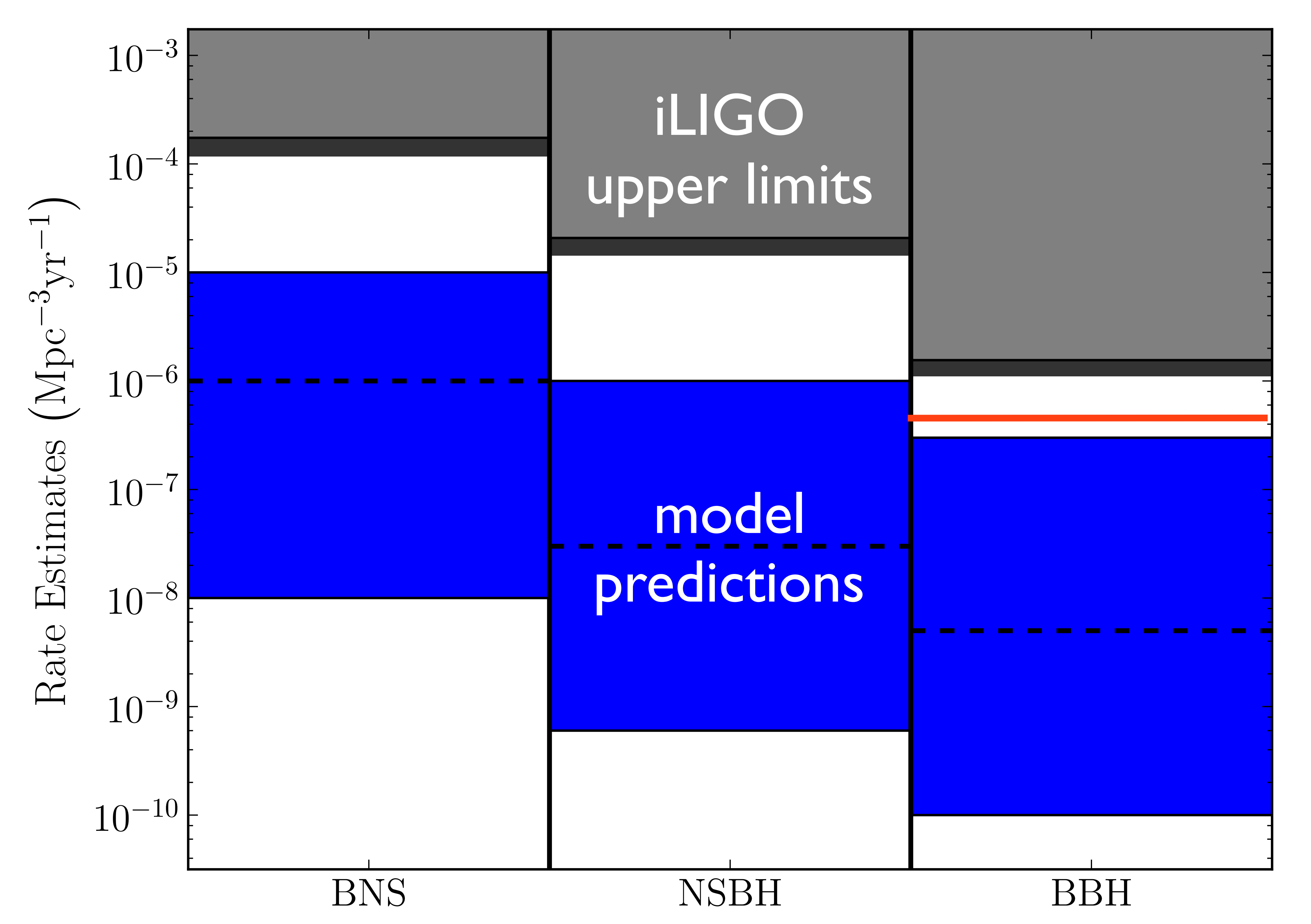


BH mass: 5 Msun

90% Upper Limits

Initial LIGO: Binary Coalescence Upper Limits

Abadie et al 2012



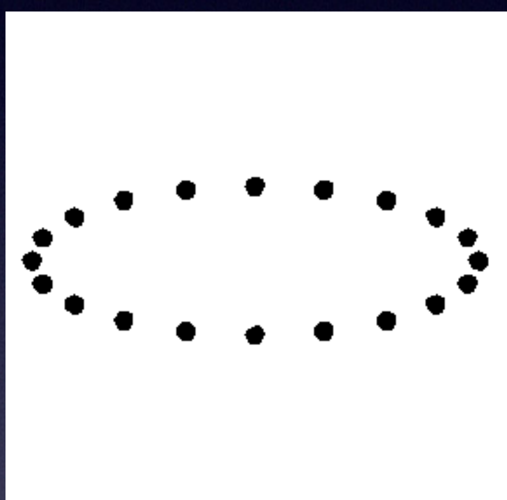
BH mass: 5 Msun

90% Upper Limits

BH mass: 20 Msun

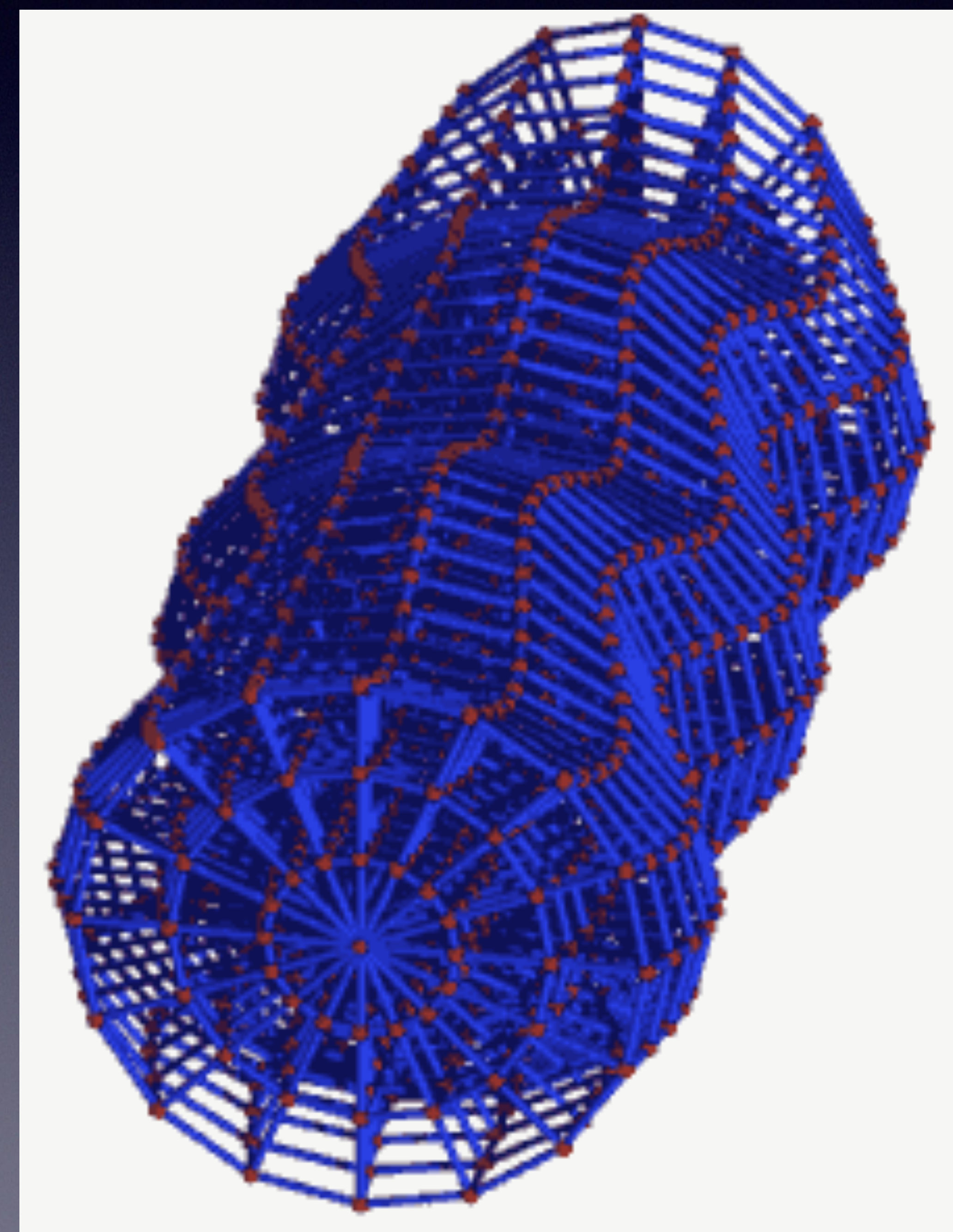
The Effect of Gravitational Waves

oscillatory disturbances of spacetime
quadrupole nature: 2 polarizations at 45 degree angle



$$h_{xx} = -h_{yy}$$

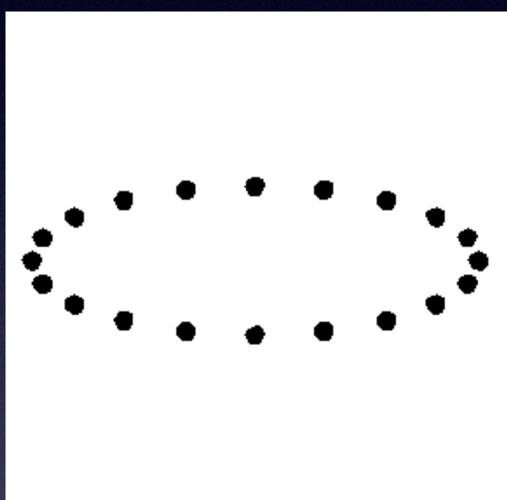
$$\frac{\Delta x}{x} = \frac{1}{2} h_{xx}$$



The Effect of Gravitational Waves

oscillatory disturbances of spacetime

quadrupole nature: 2 polarizations at 45 degree angle



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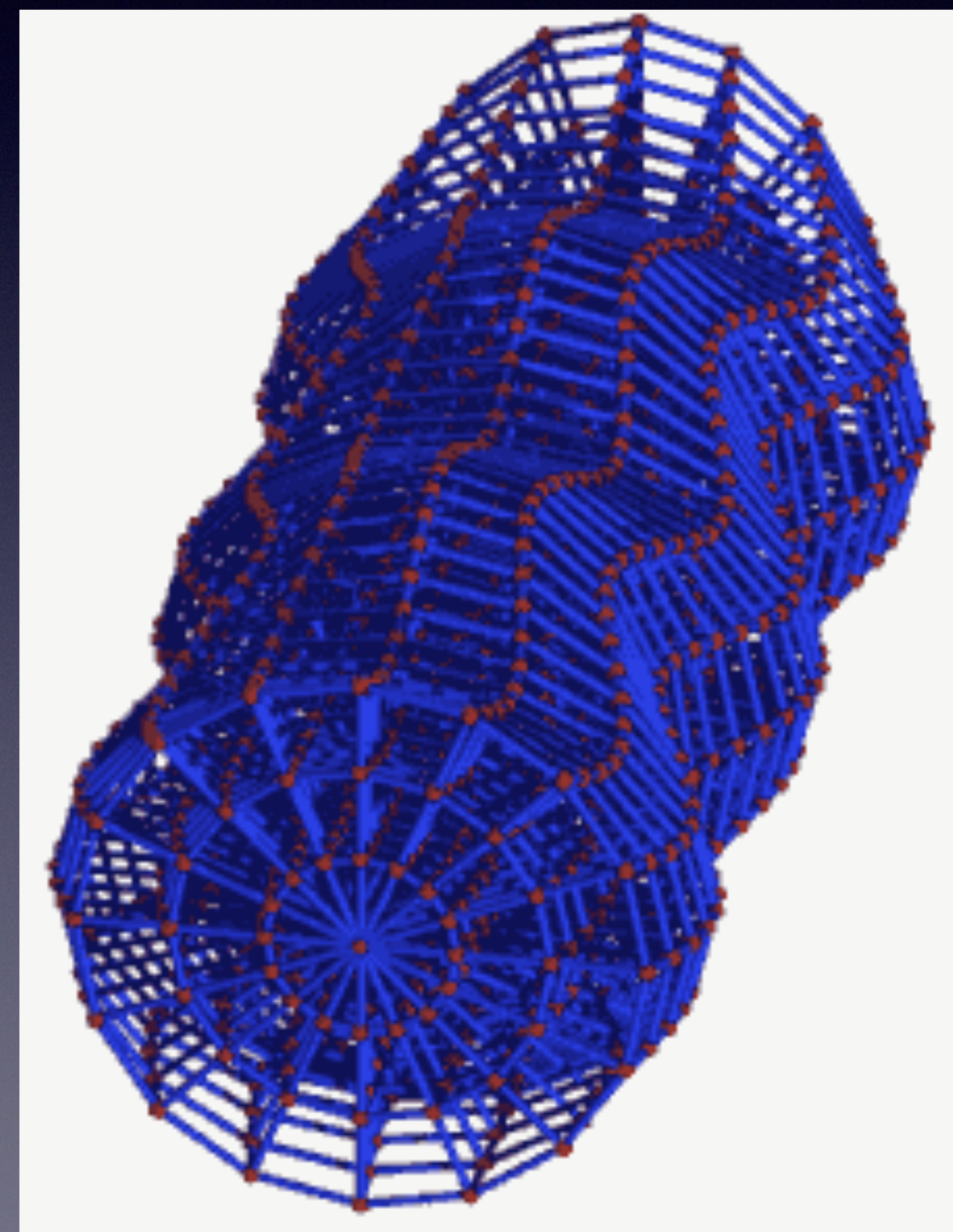
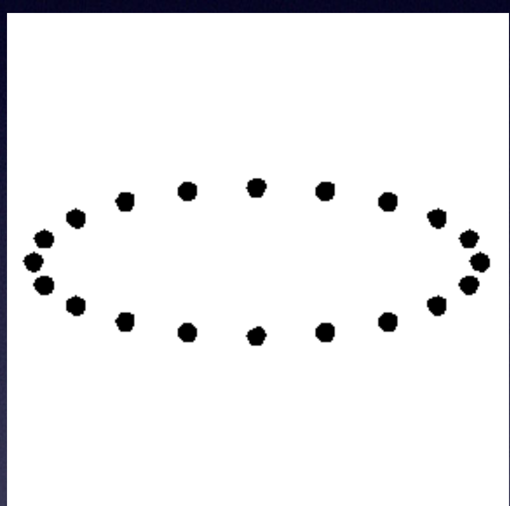
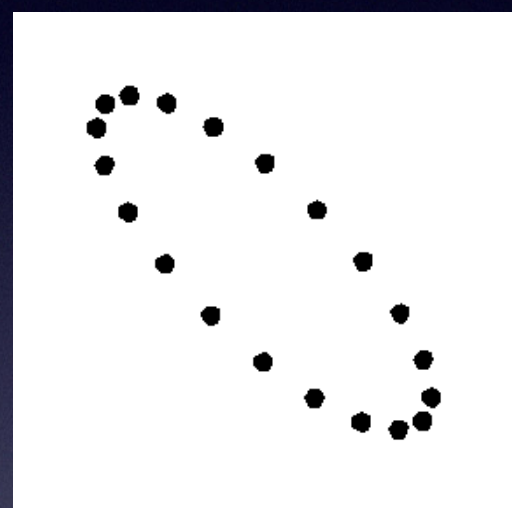


The Effect of Gravitational Waves

oscillatory disturbances of spacetime
quadrupole nature: 2 polarizations at 45 degree angle

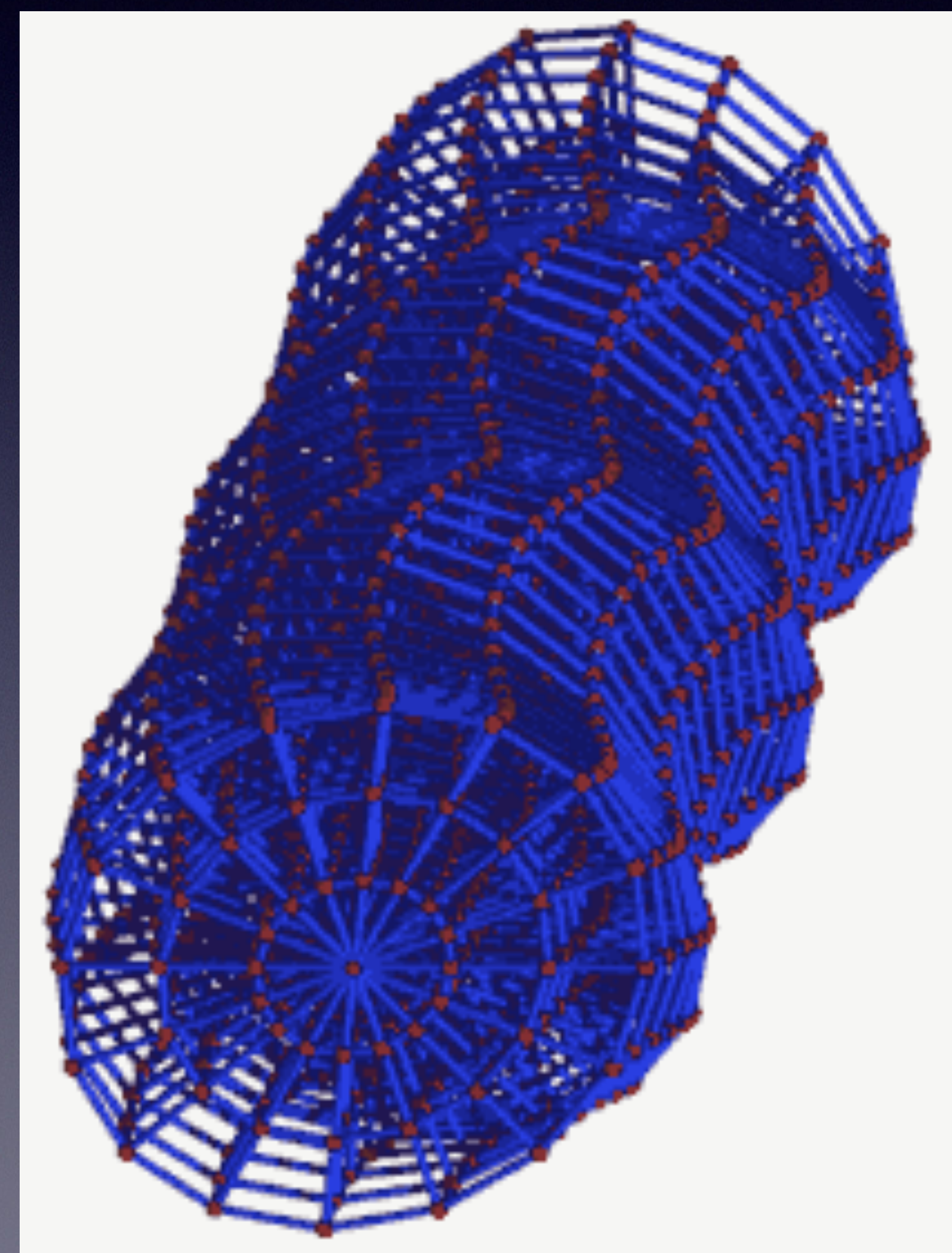


$$h_{xx} = -h_{yy}$$



$$h_{xy} = -h_{yx}$$

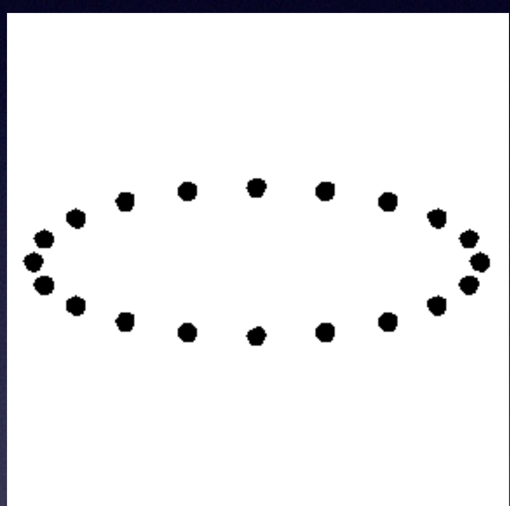
$$\frac{\Delta x}{x} = \frac{1}{2} h_{xx}$$



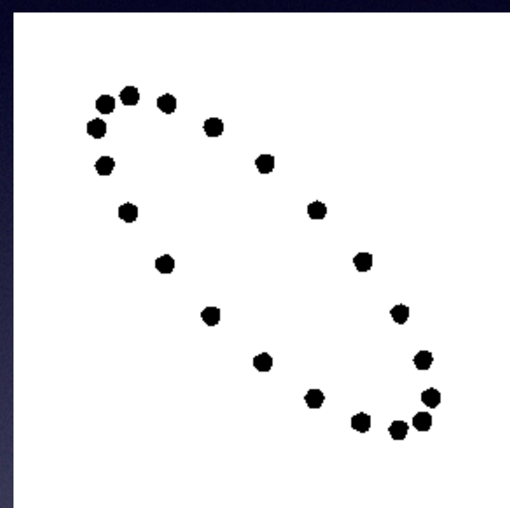
The Effect of Gravitational Waves

oscillatory disturbances of spacetime

quadrupole nature: 2 polarizations at 45 degree angle



$$h_{xx} = -h_{yy}$$



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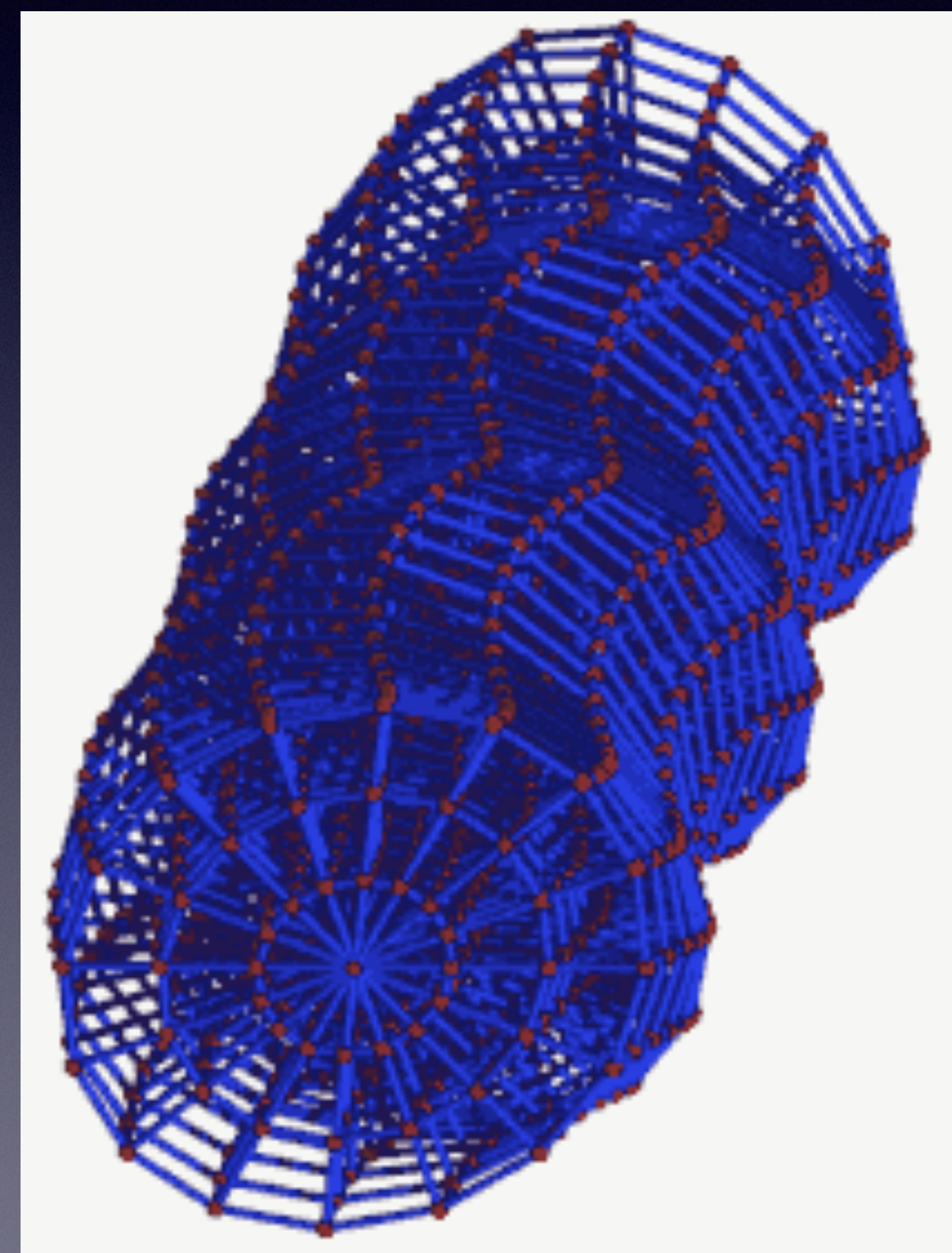

The Effect of Gravitational Waves

very weak:

$$h \sim \frac{1}{r}\frac{G}{c^4}\frac{MR^2}{T^2} \sim \frac{GM/c^2}{r}\frac{u^2}{c^2} \sim \frac{R_{sch}}{r}\left(\frac{u}{c}\right)^2$$

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Black Hole of 10 solar masses at the speed of light located
at the Galactic center: ***$h \sim 10^{-17}$***
at the Virgo cluster: ***$h \sim 10^{-20}$***