How DiRAC helps us measure black holes

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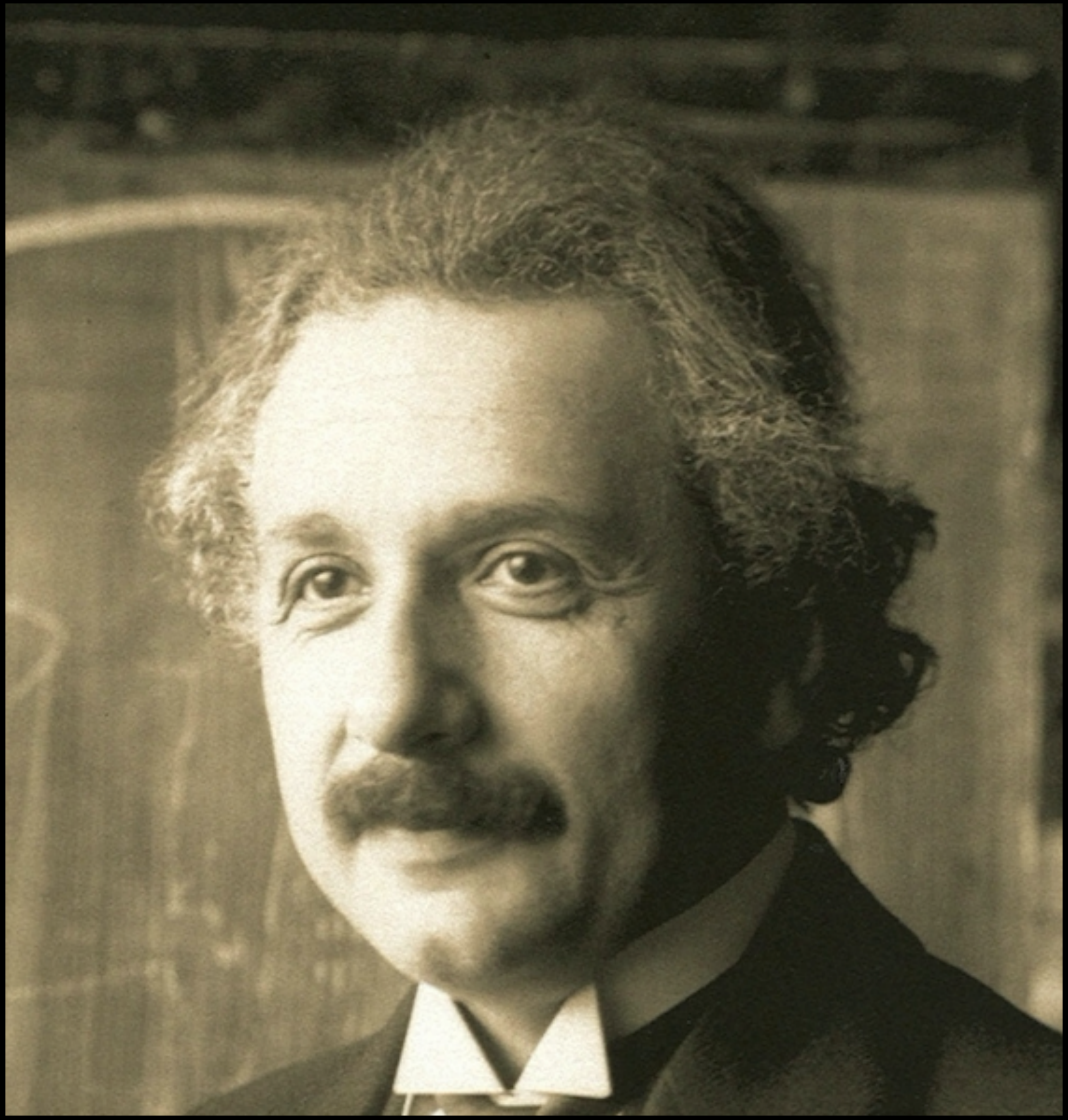
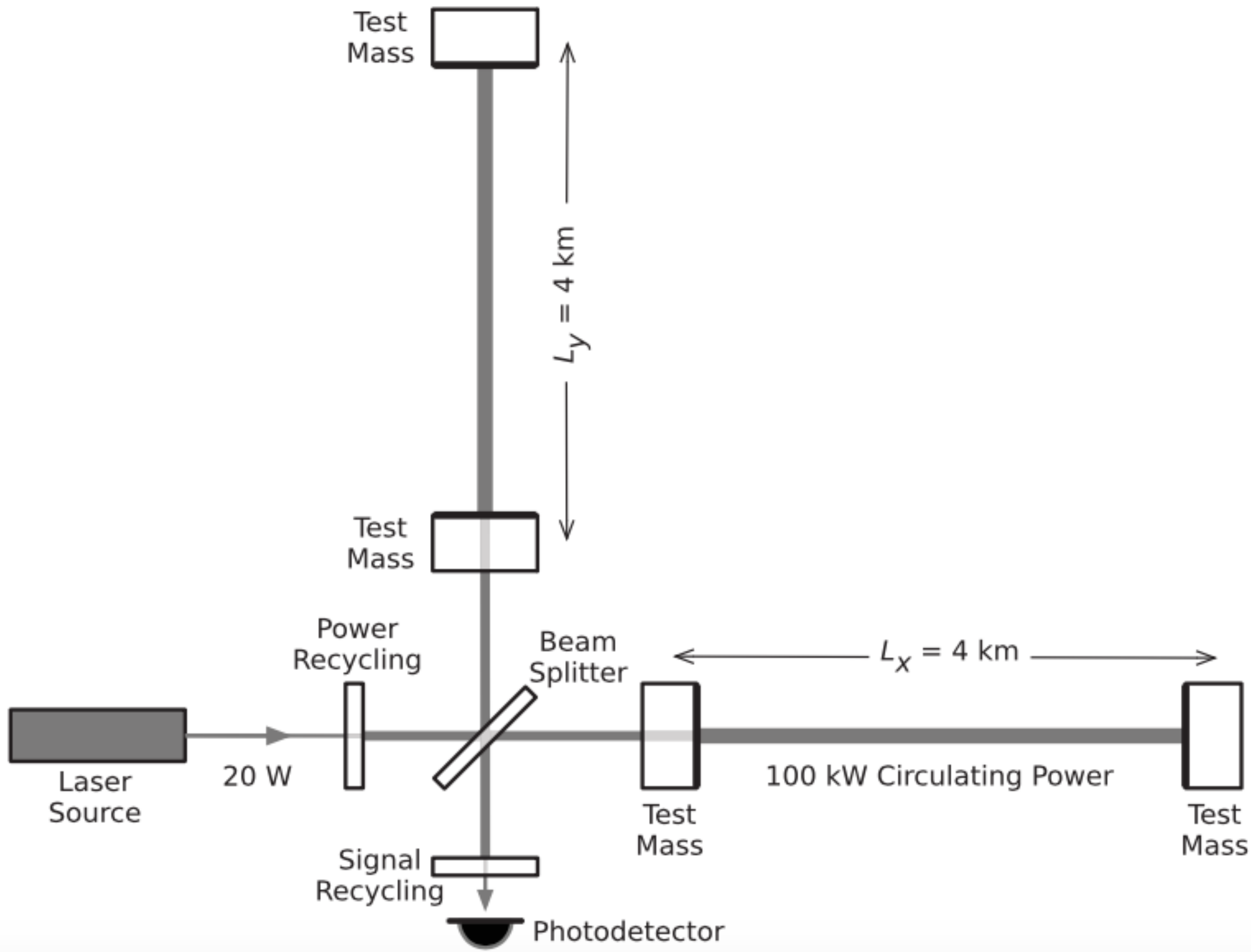
Cardiff University

DiRAC Day, Swansea
September 12 2018

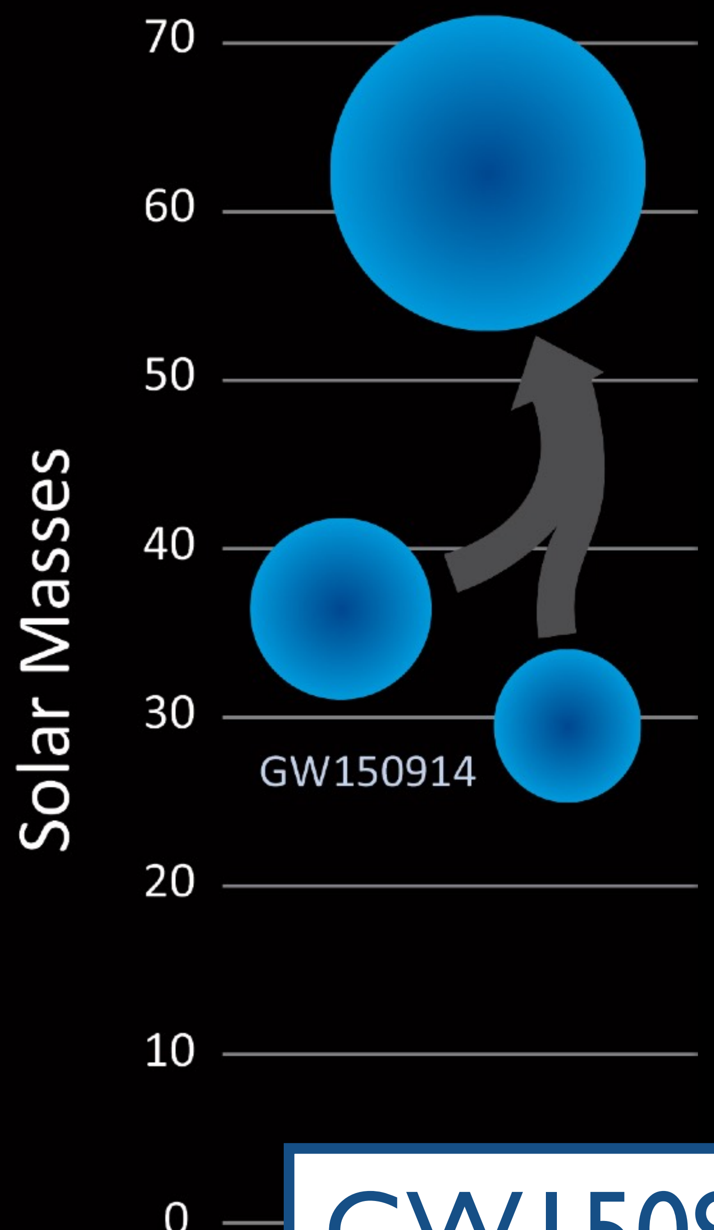



Test Mass
L_y = 4 km
Test Mass
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
Test Mass
100 kW Circulating Power
Test Mass
Signal Recycling
Photodetector

First observing run (O1) (September 2015—January 2016)

LIGO/VIRGO

First observing run (O1)
(September 2015—January 2016)



GW150914
"The Event"

First GW Detection!

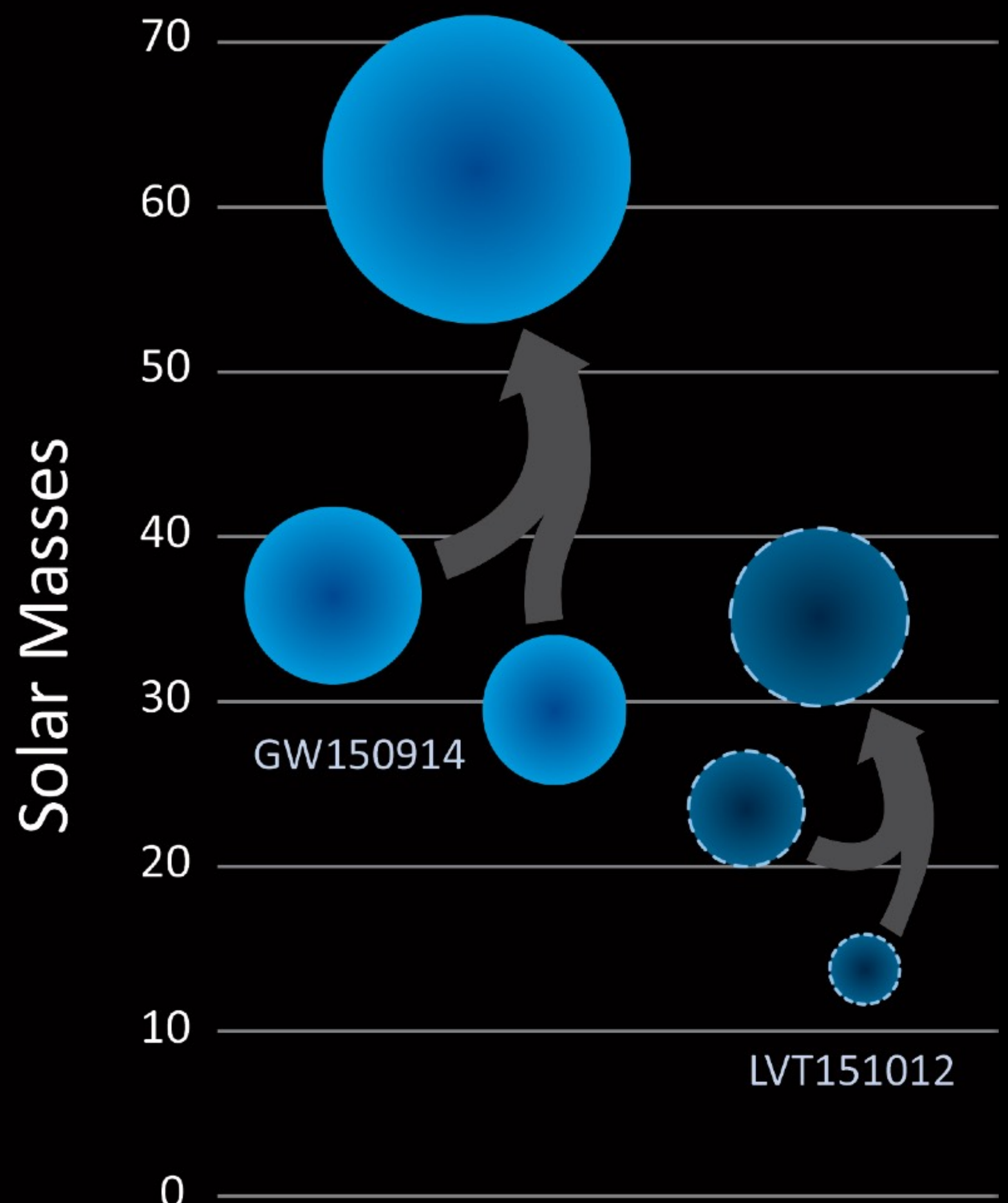
First binary-black-hole!

Both black holes 10s of solar masses!

First direct observation of a BH?

LIGO/VIRGO

First observing run (O1) (September 2015—January 2016)

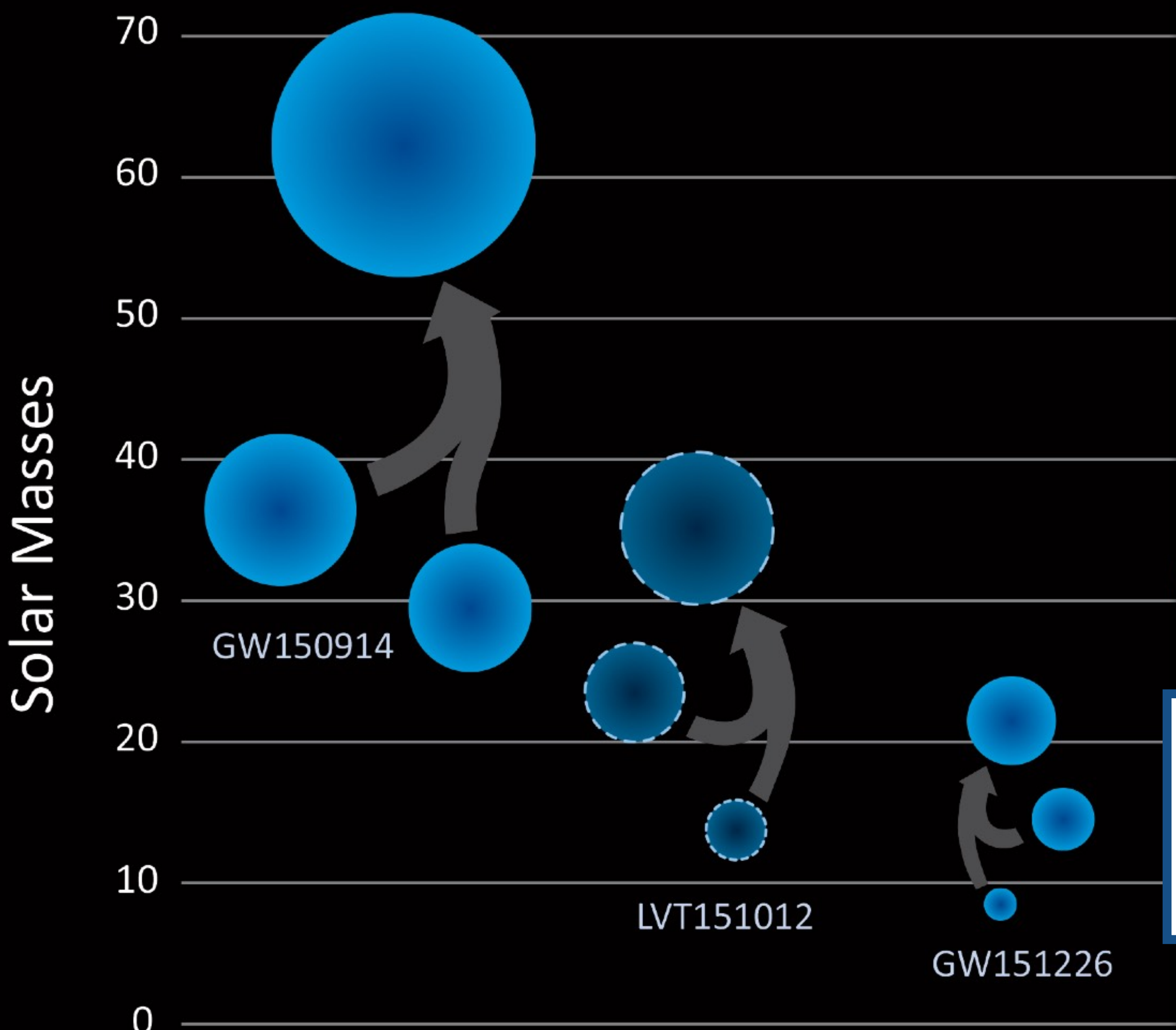


The fish we threw back.

LVT = “LIGO-Virgo Transient”

LIGO/VIRGO

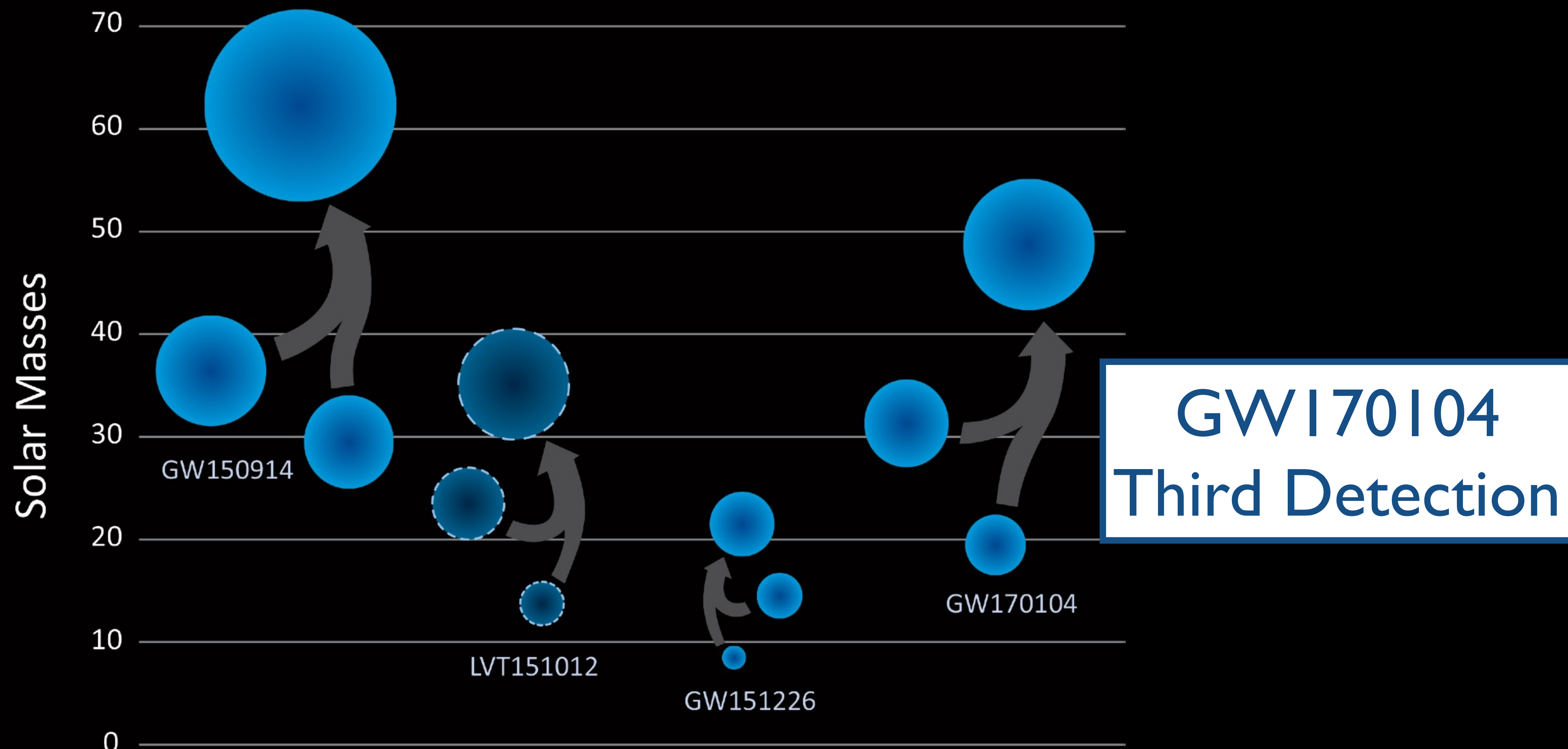
First observing run (O1) (September 2015—January 2016)



GW151226
"Boxing Day"

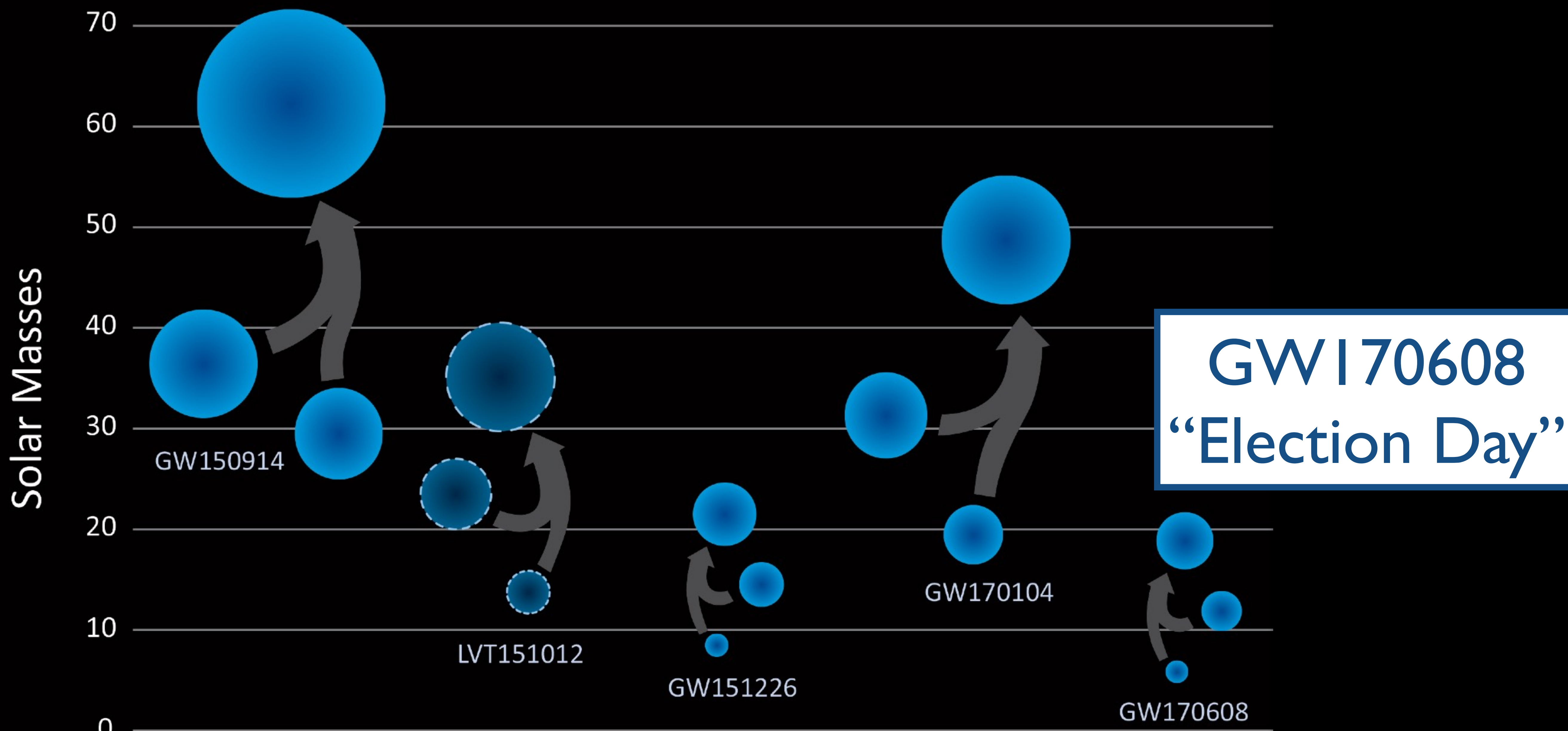
LIGO/VIRGO

Second observing run (O2)
(December 2016—August 2017)



LIGO/VIRGO

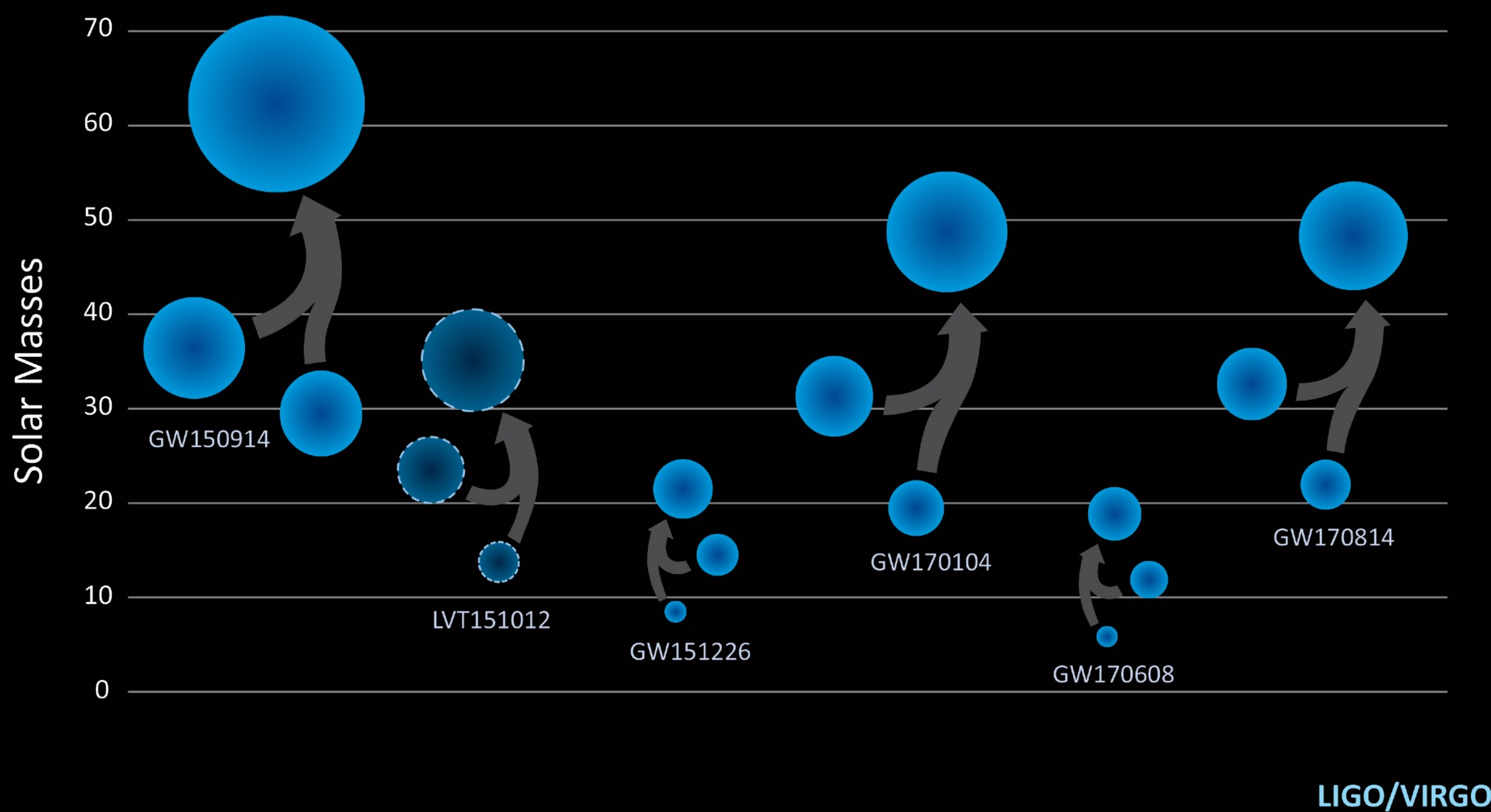
Second observing run (O2)
(December 2016—August 2017)



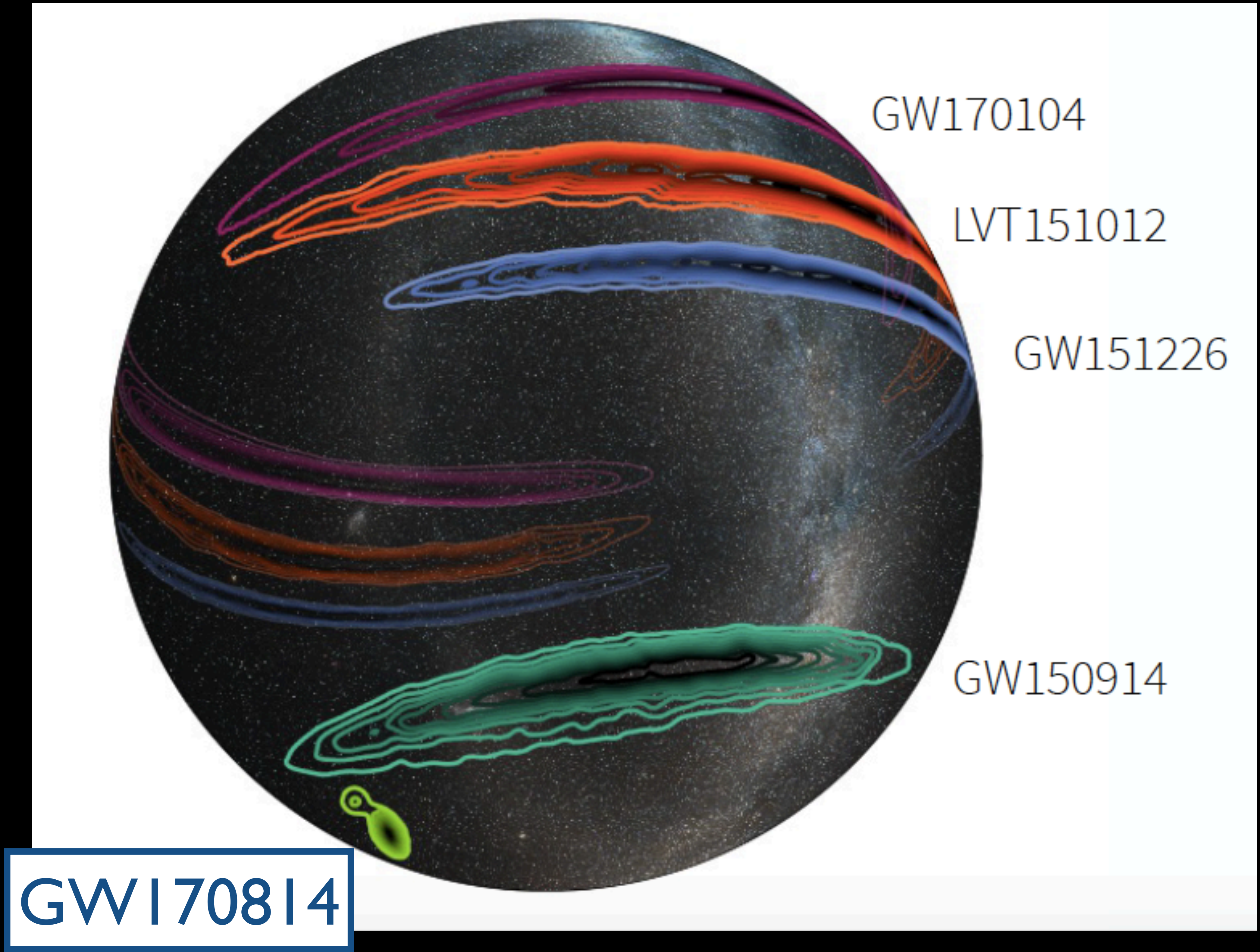
LIGO/VIRGO

Enter Virgo!

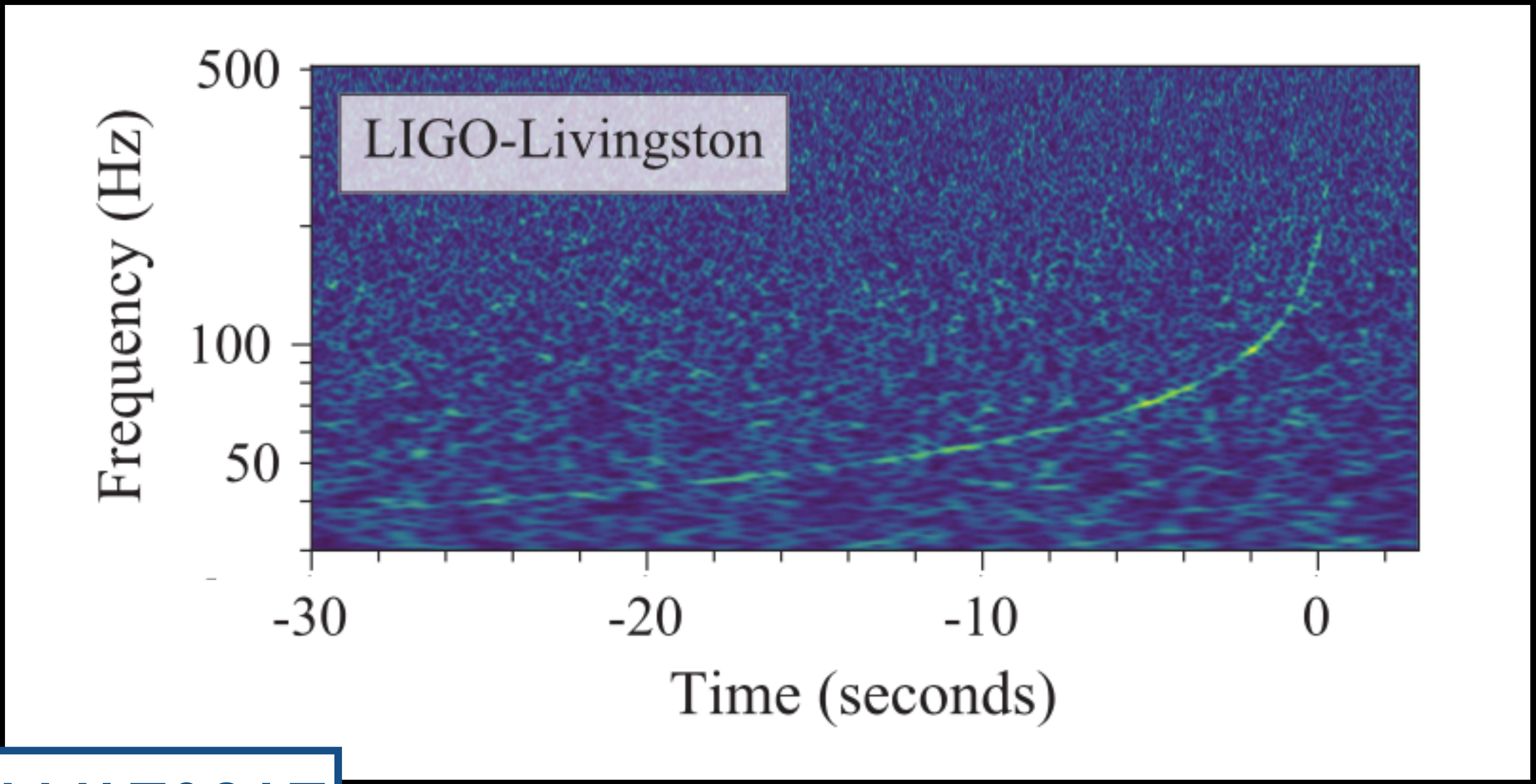
Second observing run (O2) (December 2016—August 2017)



Enter Virgo!



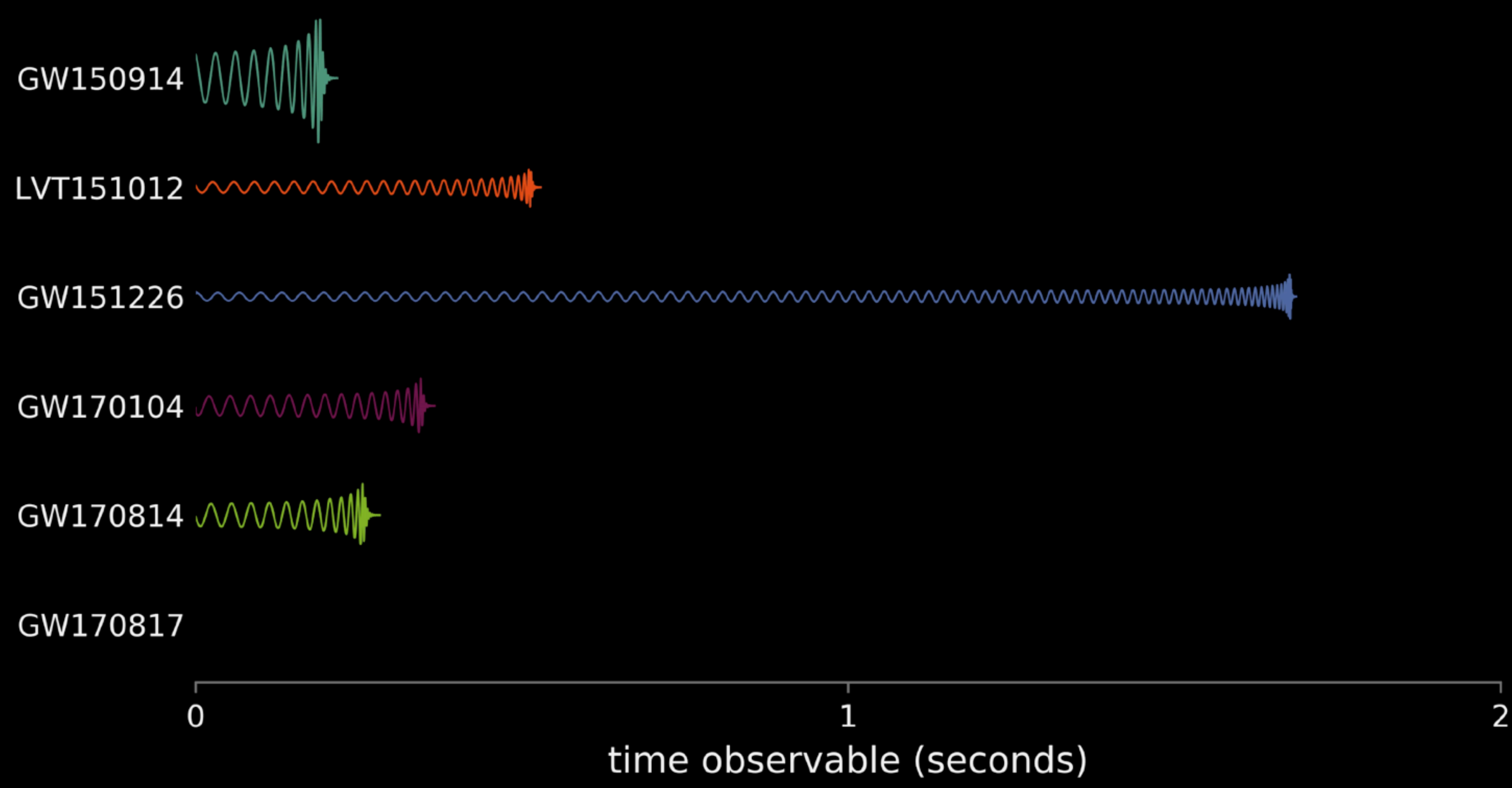
Binary neutron stars!



GW170817

A rare event

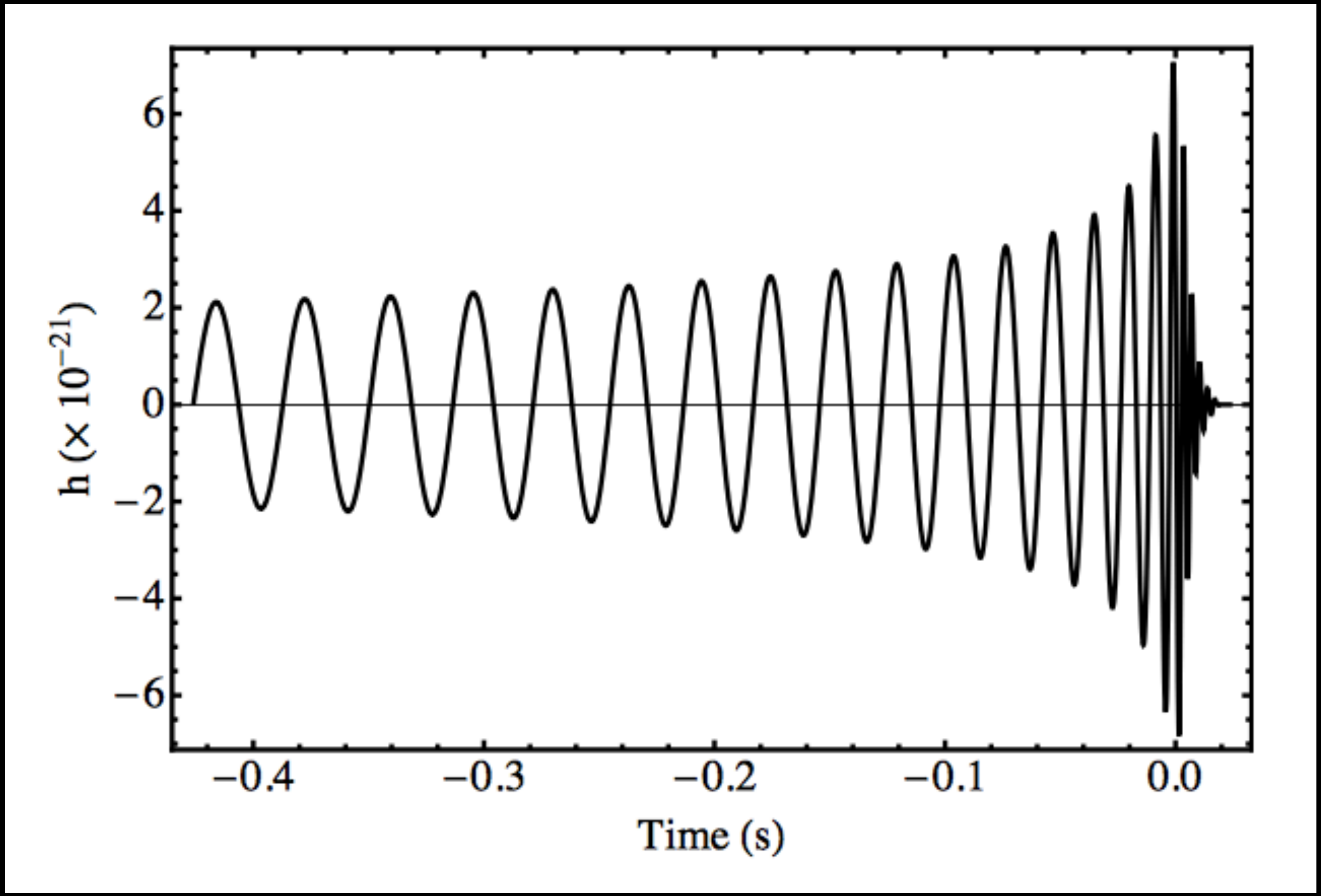
- 10x closer than GW150914; loudest yet (SNR ~32)
- BNS identified as source of short GRBs
- Constraints on NS tidal deformability (i.e, EOS, radius, etc)
- Independent measurement of Hubble constant



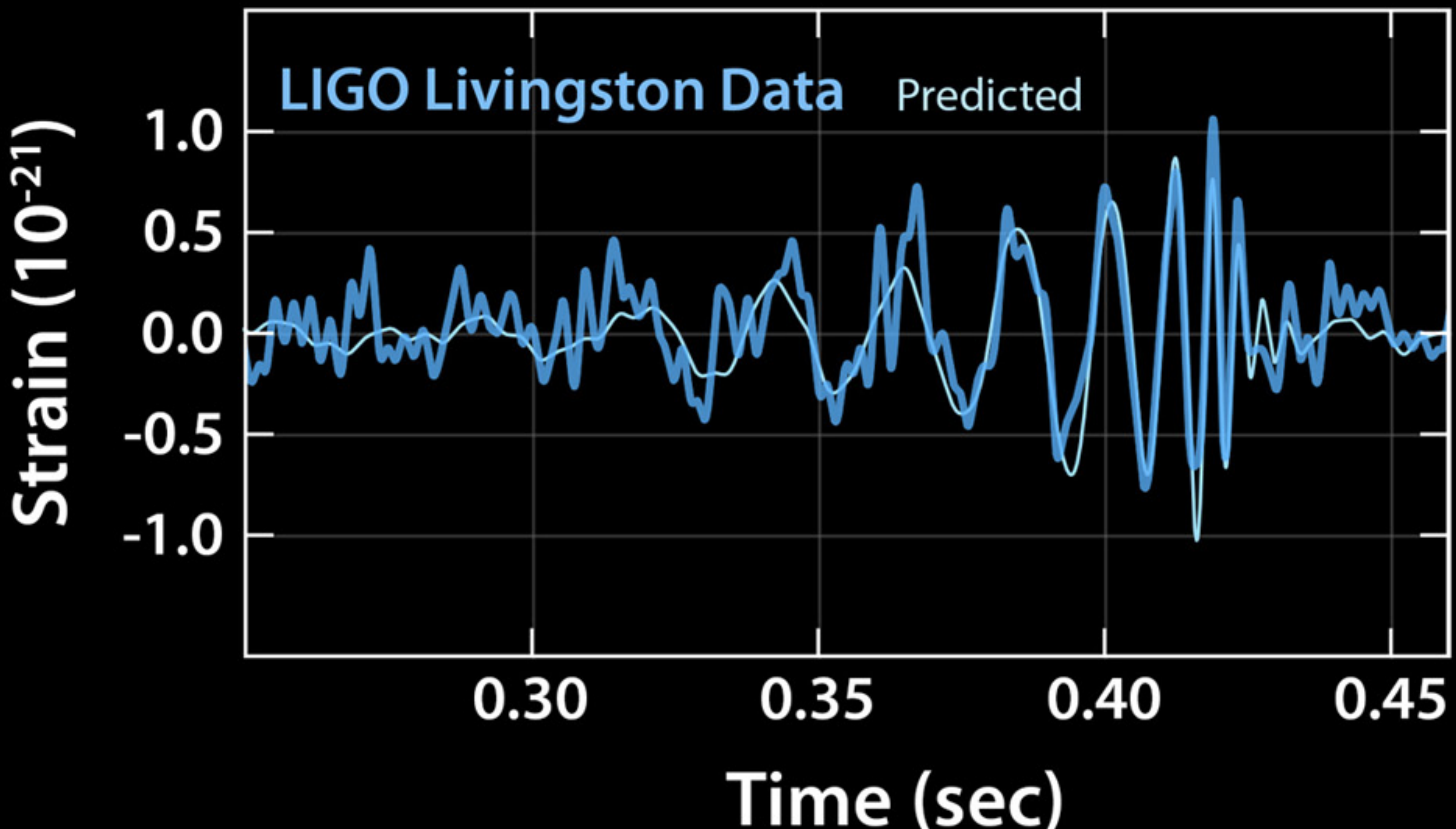
How to do GW astronomy

- Build a network of sensitive detectors
- Comb the data for signals until you find one
  (e.g., convolve with a template bank of theoretical BBH signals)
- Carefully compare with theoretical predictions, to measure signal parameters.
  (e.g., Bayesian MCMC codes identify range of BBH masses, spins, etc., that best match data)

- Need accurate, complete theoretical signals!



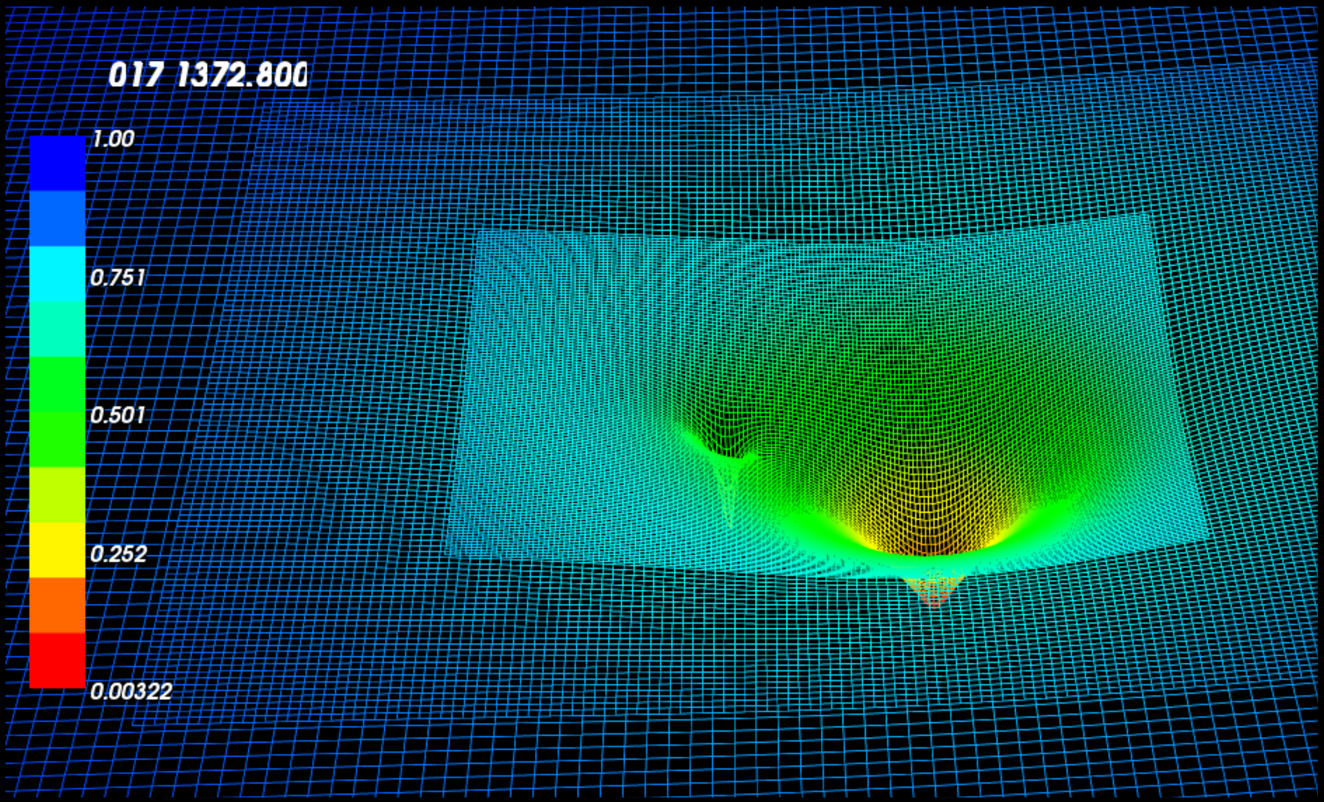
(equal-mass, nonspinning, $50M_\odot$, face-on, 100Mpc)

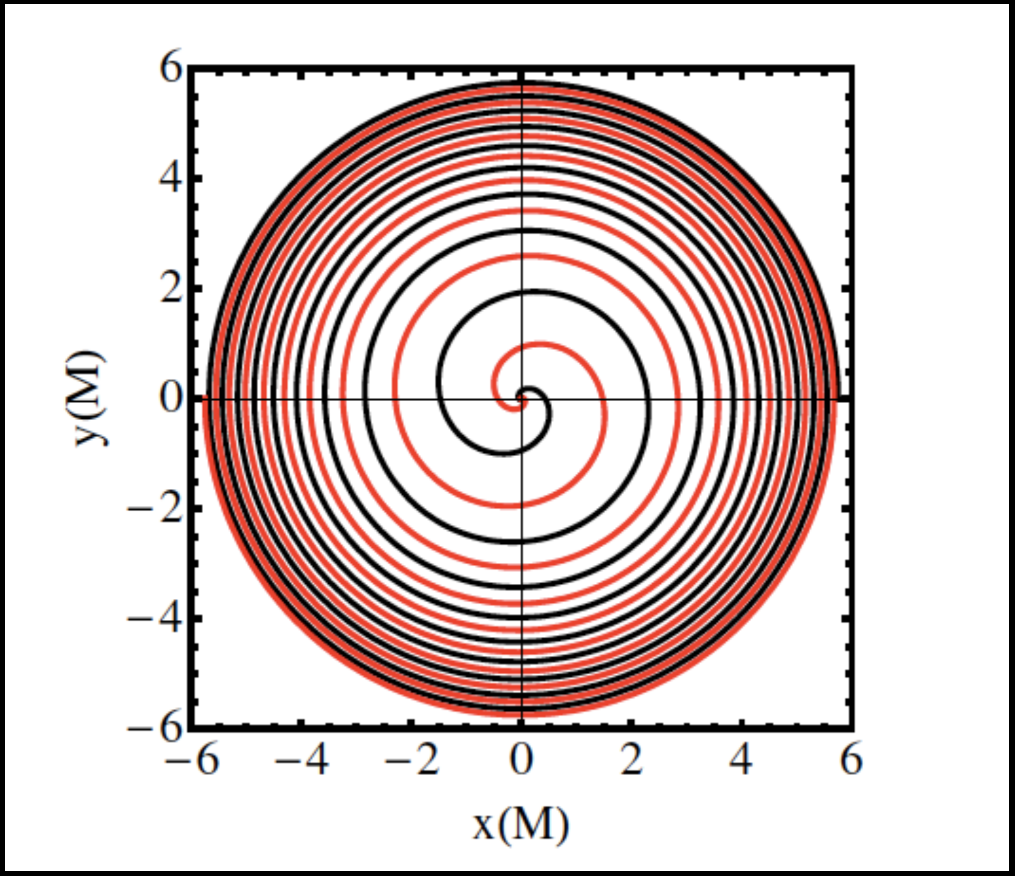

LIGO Livingston Data
Predicted
1.0
0.5
0.0
-0.5
-1.0
Strain (10^-21)
0.30
0.35
0.40
0.45
Time (sec)

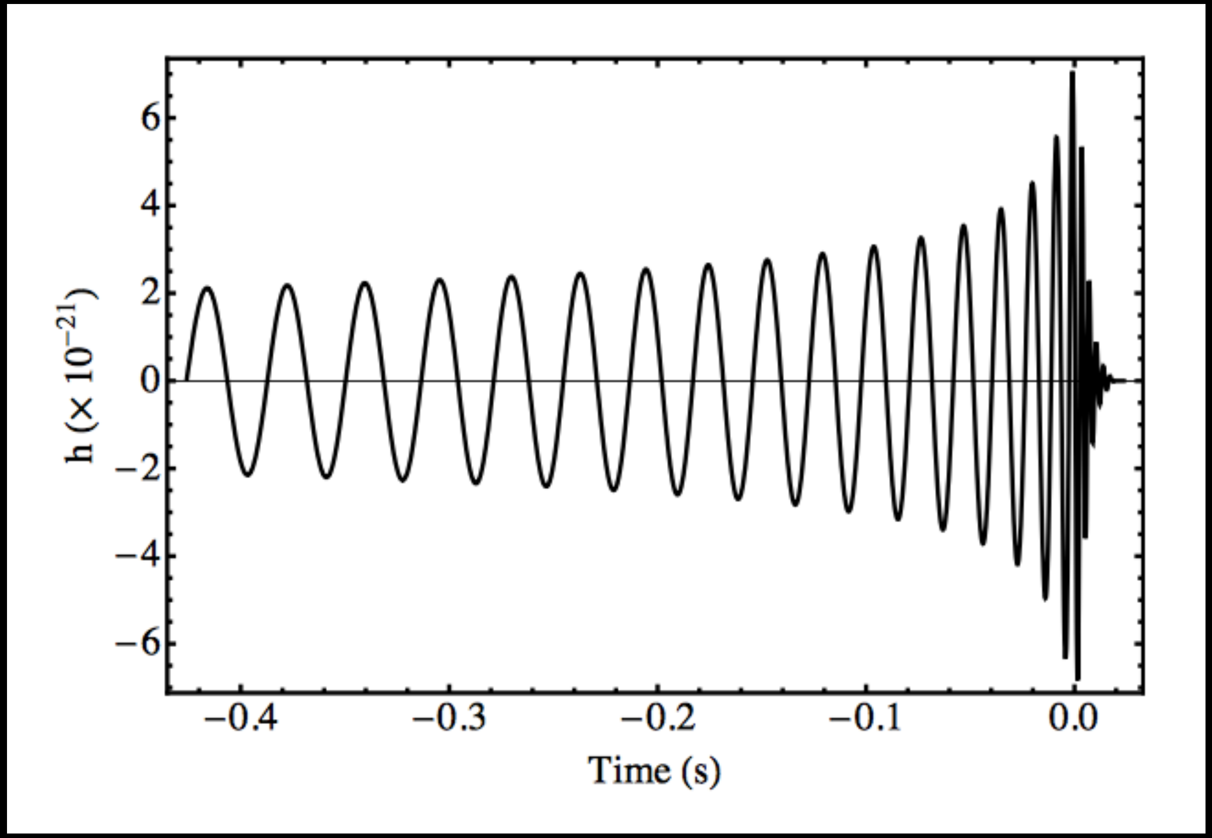
Numerical relativity

numerically solve
full Einstein equations
on 3D (mesh-refined) grids

Requires weeks to months
on 100s of cores.







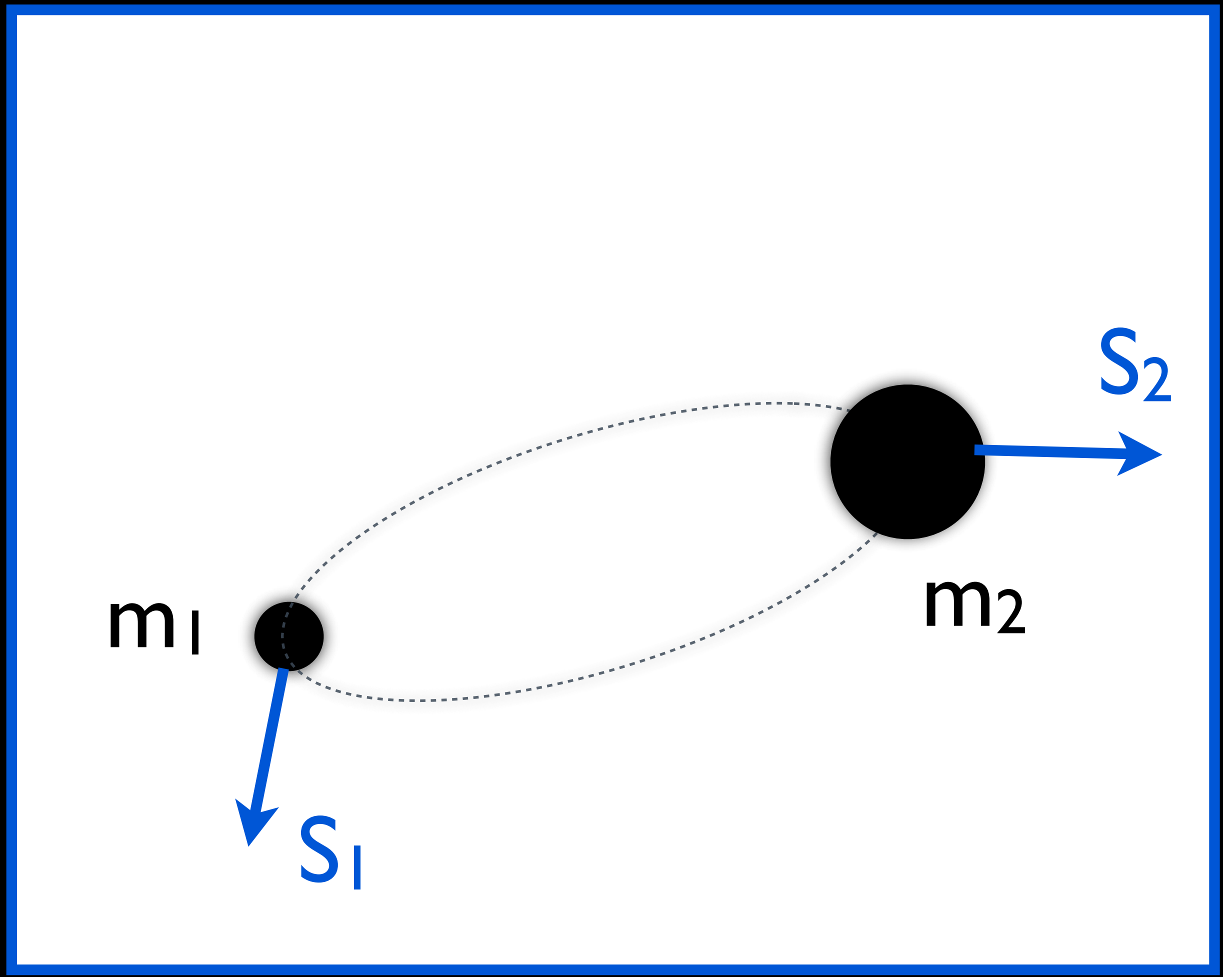
Masses: m_1, m_2

Spins: $\mathbf{S}_1, \mathbf{S}_2$

(8 parameters)

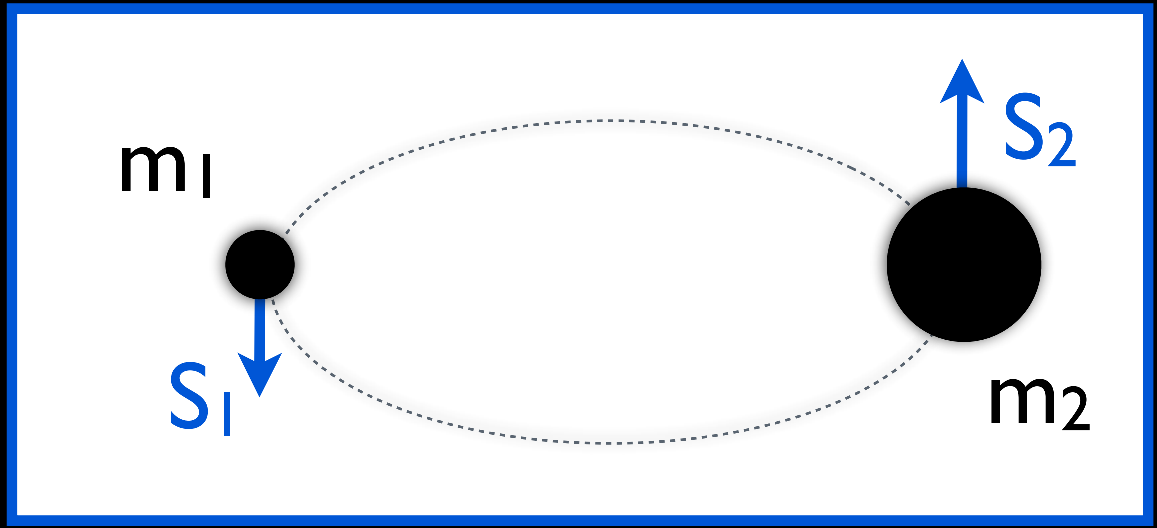
useful combinations:

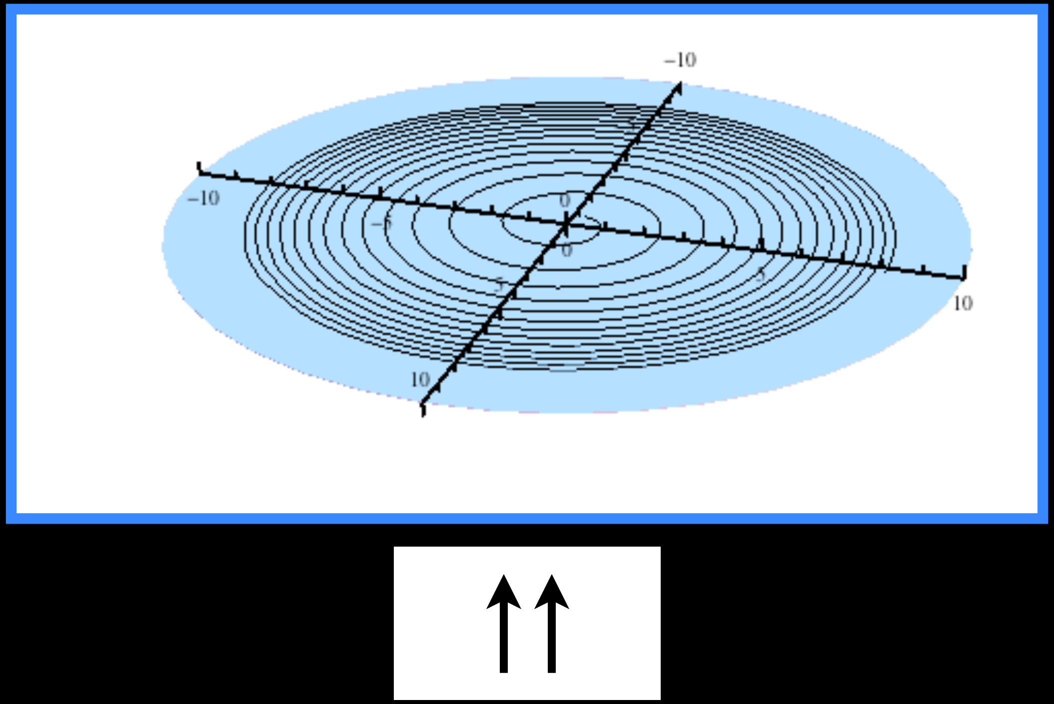
$$M = m_1 + m_2$$
$$q = m_2 / m_1$$
$$\eta = m_1 m_2 / M^2$$
$$\chi = S/m^2$$

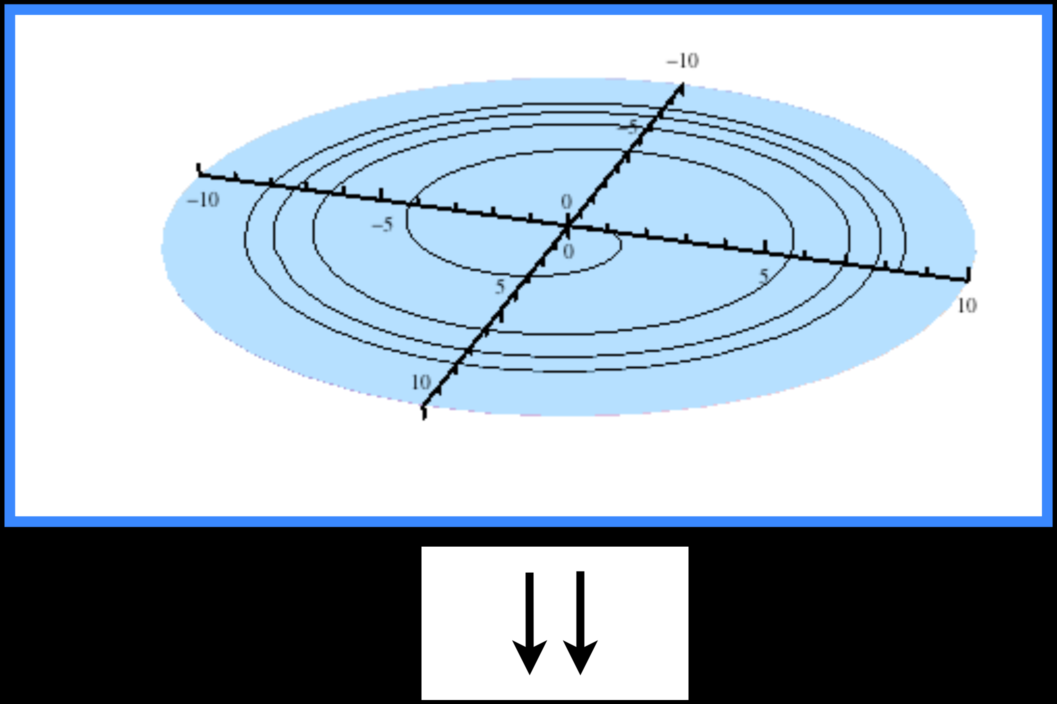


Plus: distance, sky location, orientation, polarisation

Aligned spins

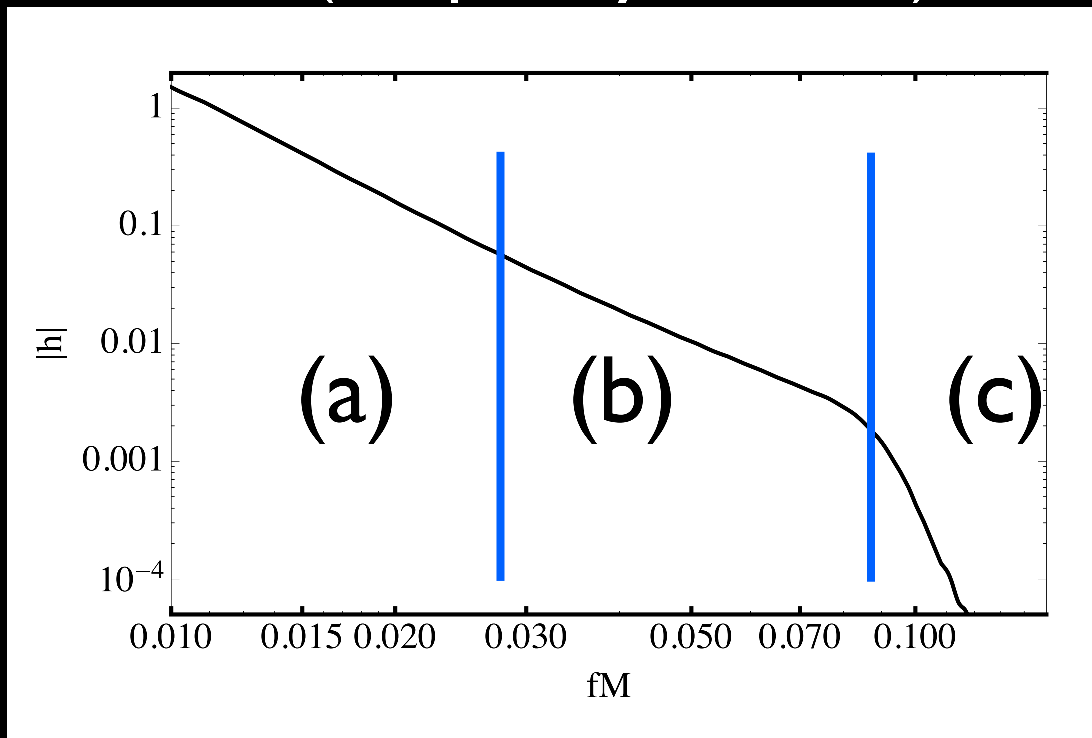






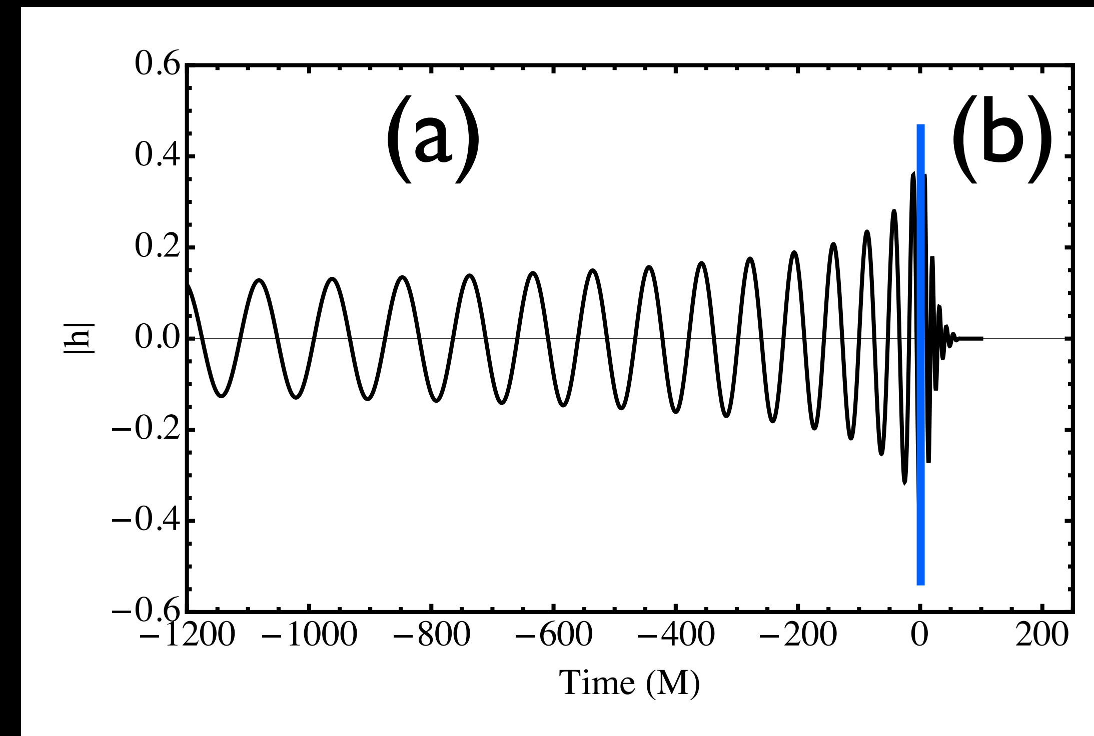
(Dominant spin effect is a weighted sum of the spins)

IMRPhenom
(frequency domain)

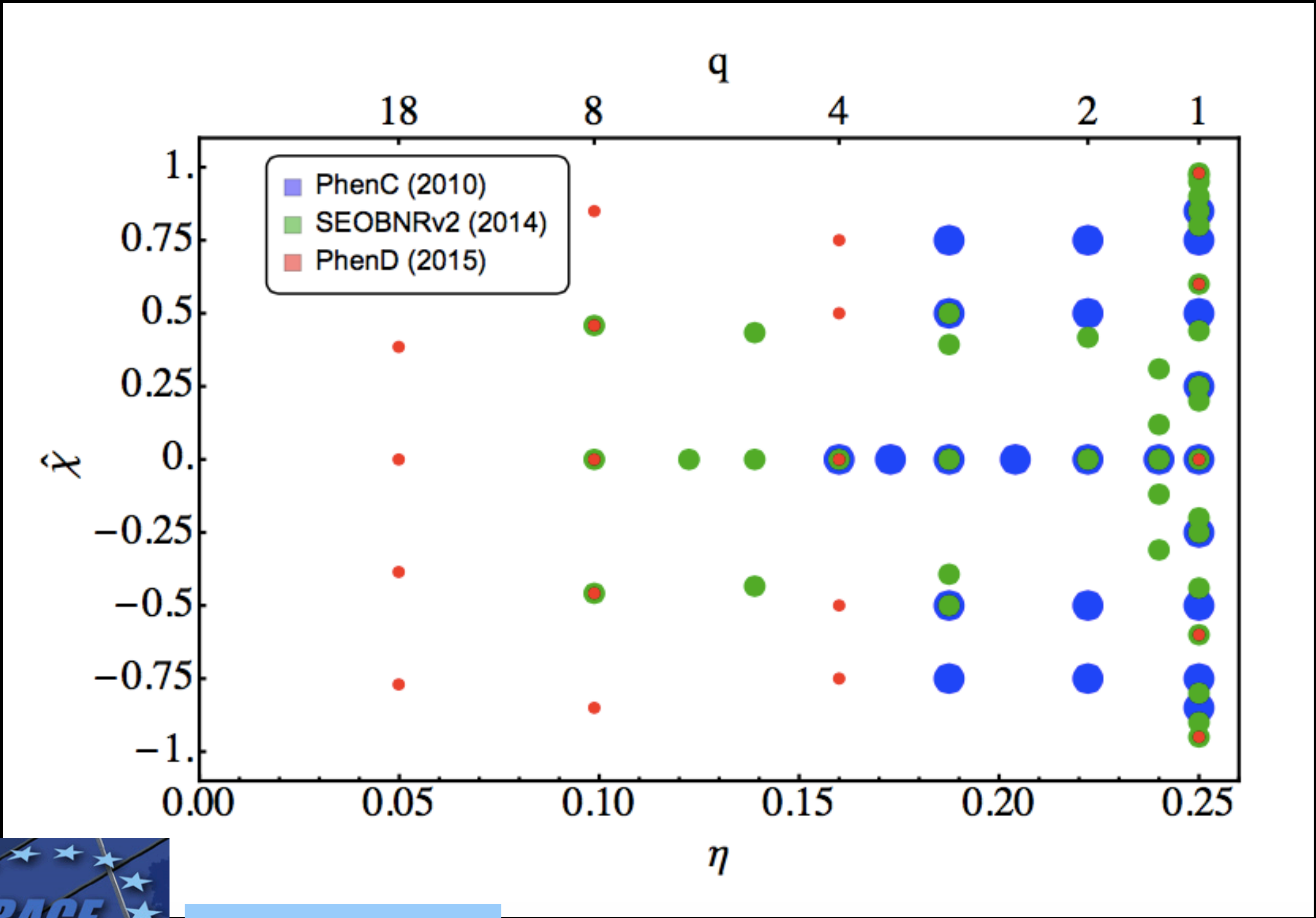


- (a) PN-based ansatz
- (b) phenomenological fit (based on NR behaviour)
- (c) FFT of ringdown waveform (Lorentzian)
- Analytic: fast

EOBNR
(time domain)

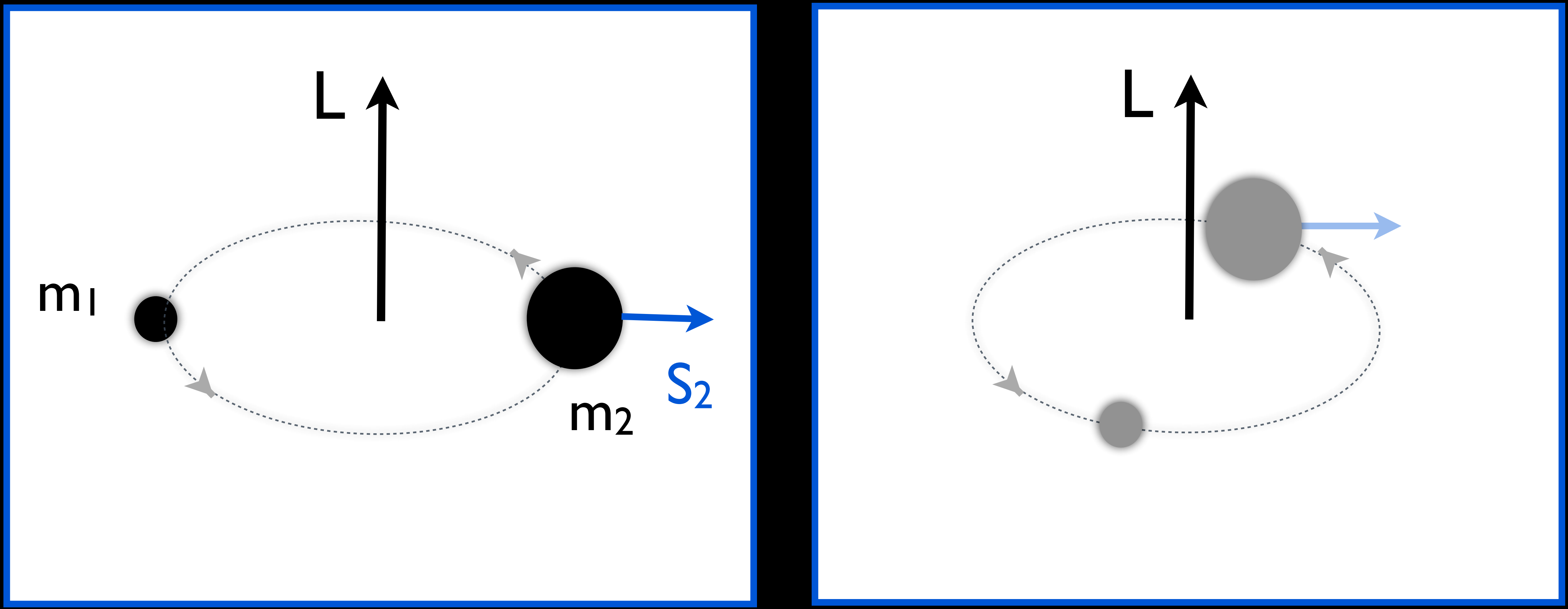


- (a) EOB + terms tuned to NR waveforms
- (b) Smooth transition to ringdown
- Includes both spins
- Numerically solve ODEs: slow
- Speed-up: Reduced-order models



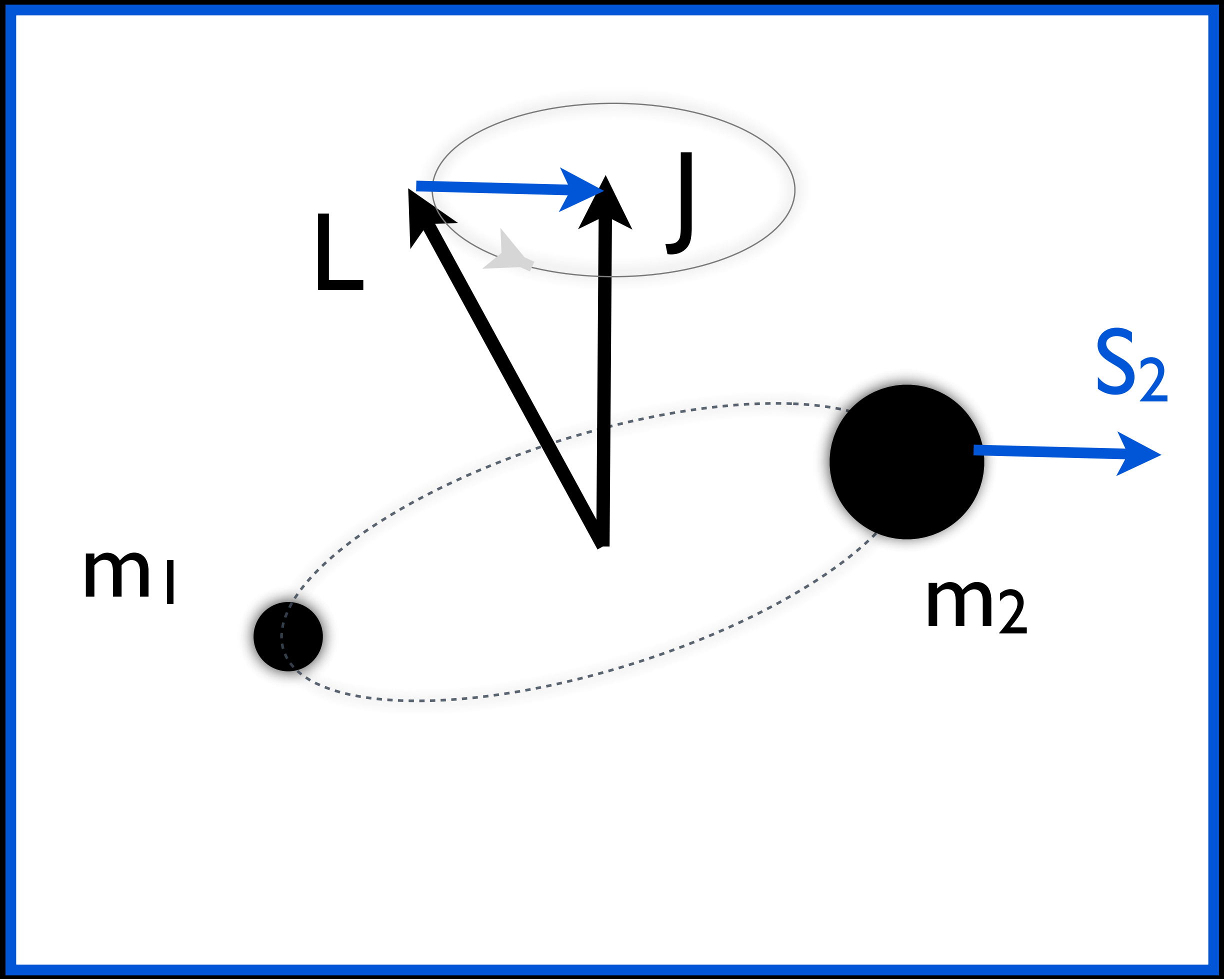
[Khan, *et. al* (2016)]

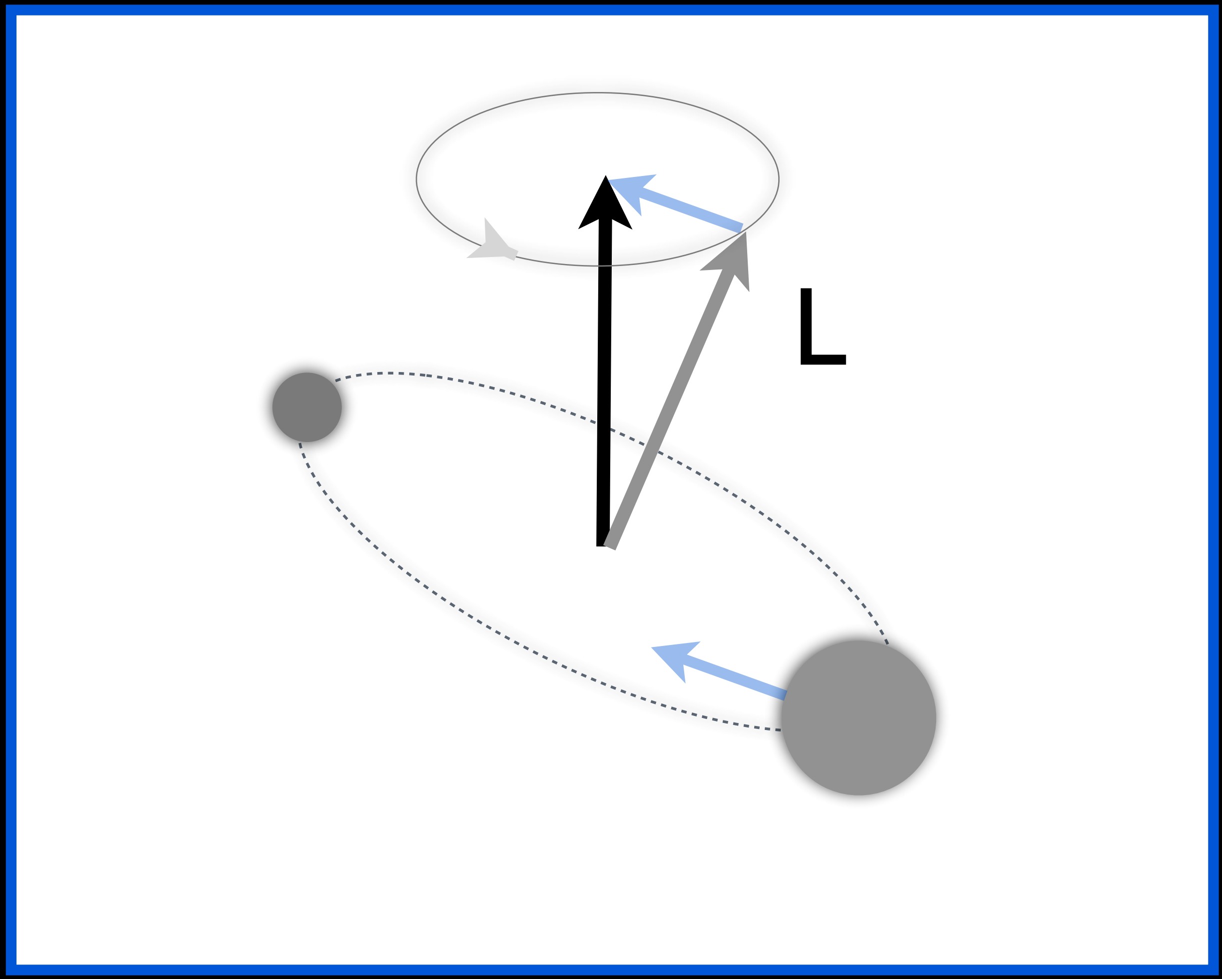
Orbital precession



Newtonian gravity:
L, S_1, S_2 remain fixed

Orbital precession





General relativity

(L, S_1, S_2) precess around J

Orientation dependence

q=3, $|\mathbf{S}_2|$ = 0.75 (in plane)

Observer aligned with $\boldsymbol{J}$

Orientation dependence

q=3, $|\mathbf{S}_2|$ = 0.75 (in plane)

Observer aligned with ***J***

Observer inclined $\pi/6$ to ***J***

Observer inclined $\pi/3$ to ***J***

Observer inclined $\pi/2$ to ***J***

Precession models

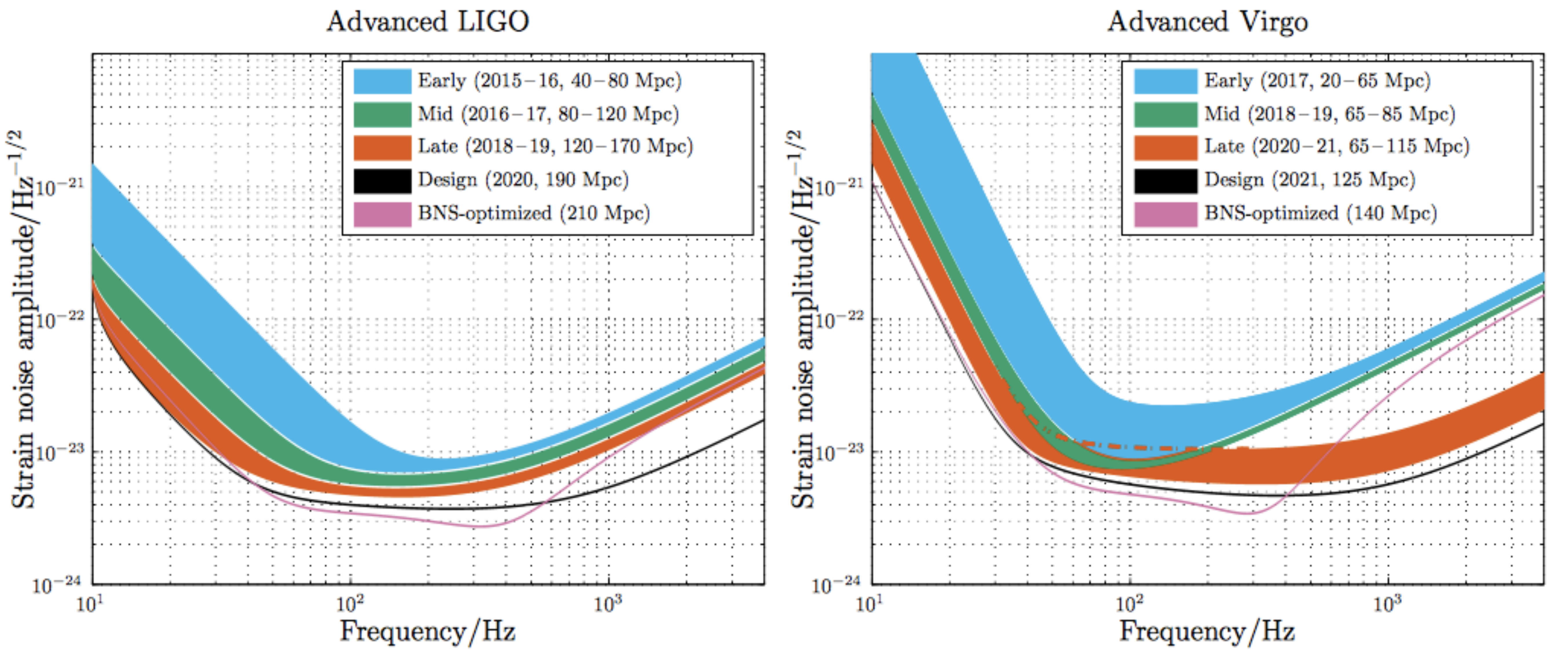
- Main idea: "twist" non-precessing models
- "IMRPhenomP" [Hannam, et al. (2014)]
  (Analytic frequency-domain — fast)
  - Use PN approximation of precession
  - Use degeneracies (two spin parameters)

!!! No tuning to precessing NR simulations !!!

Standard generic model
used for all LVC observations

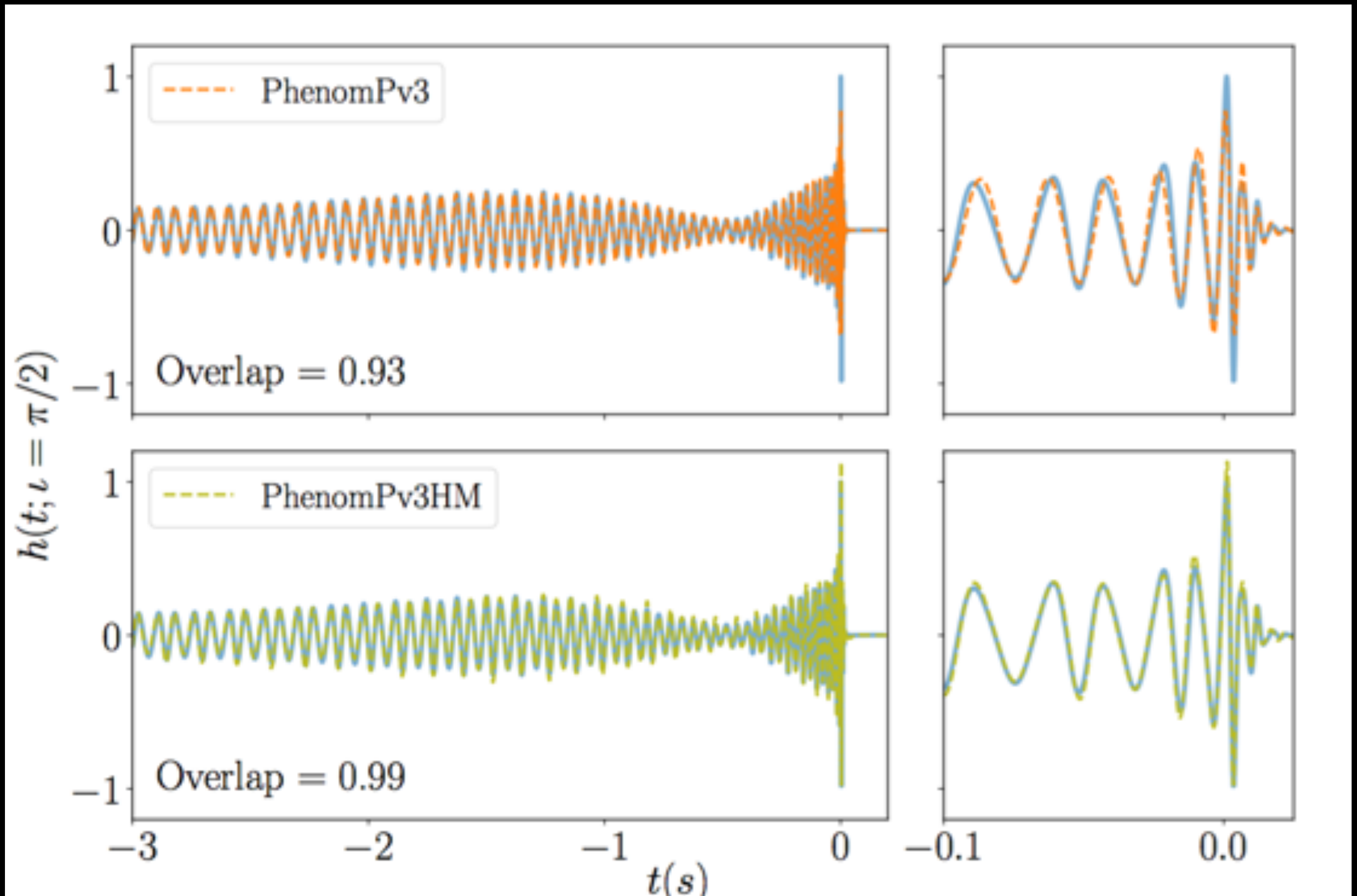
Observing Run 3: 2019

- One signal per month… or week!
- Much stronger signals are likely!

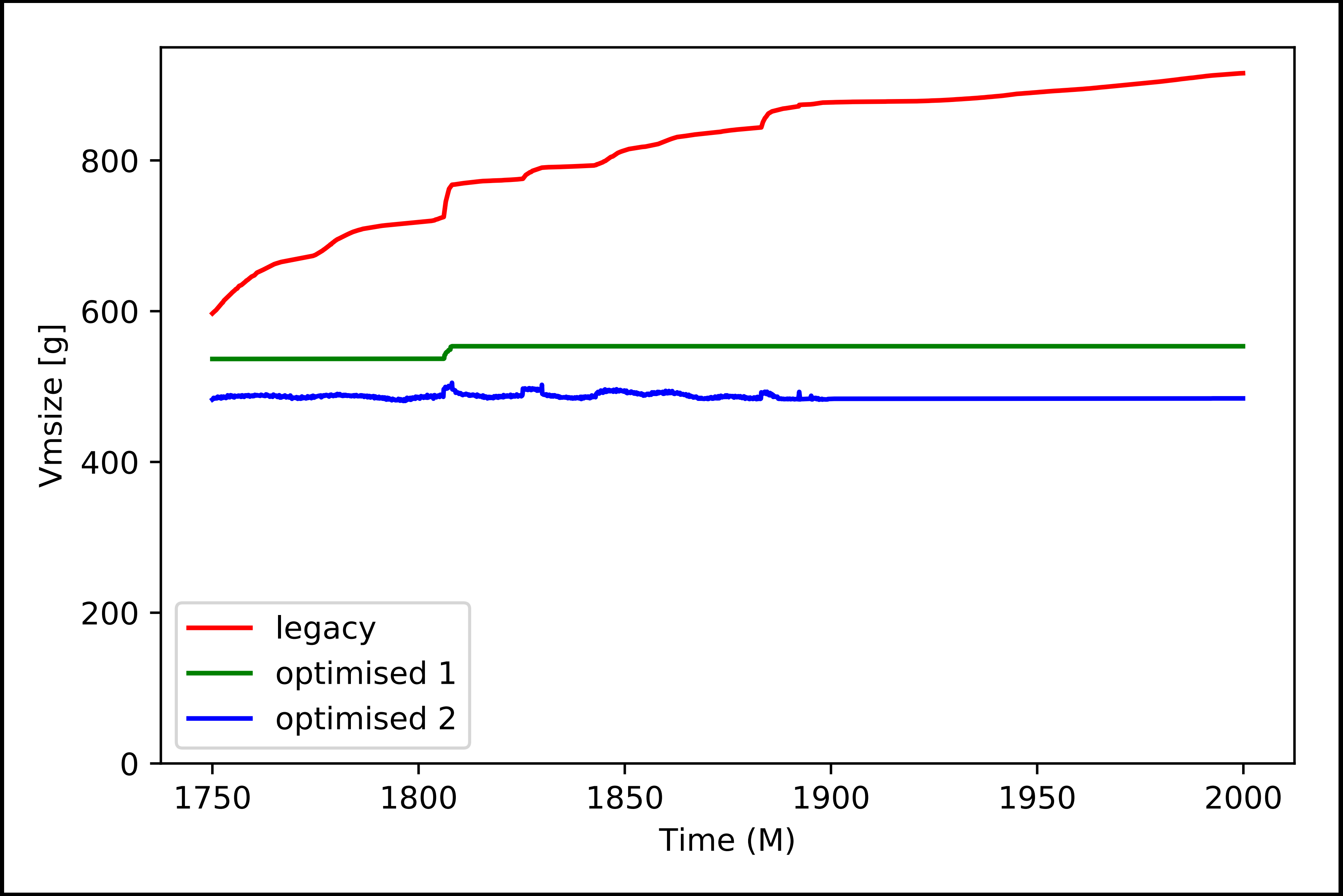


Model improvements

- Include tidal effects (for BNS)
- Approximate higher modes (PhenomHM)
- Improved two-spin inspiral precession
- Combine: higher-mode precessing model

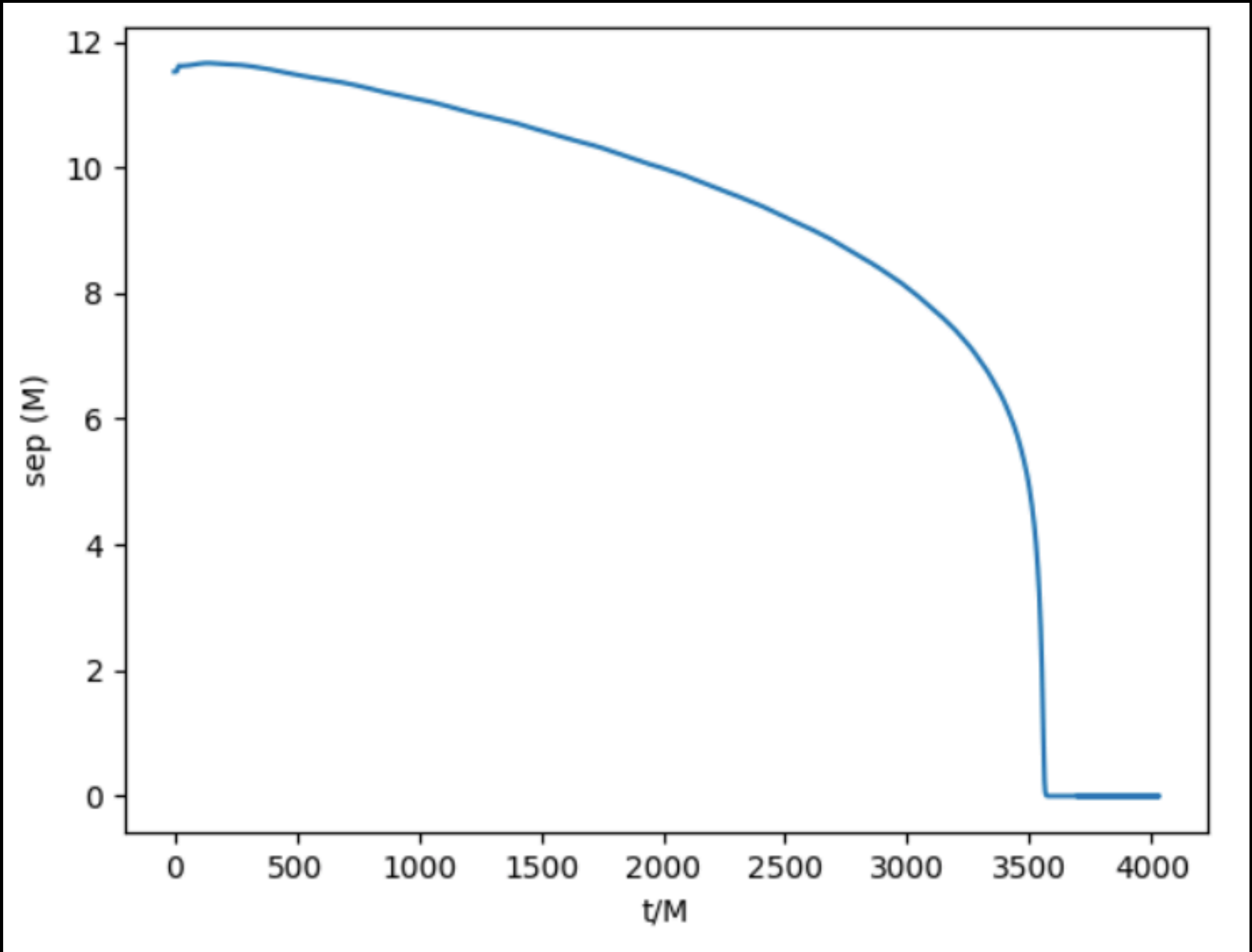


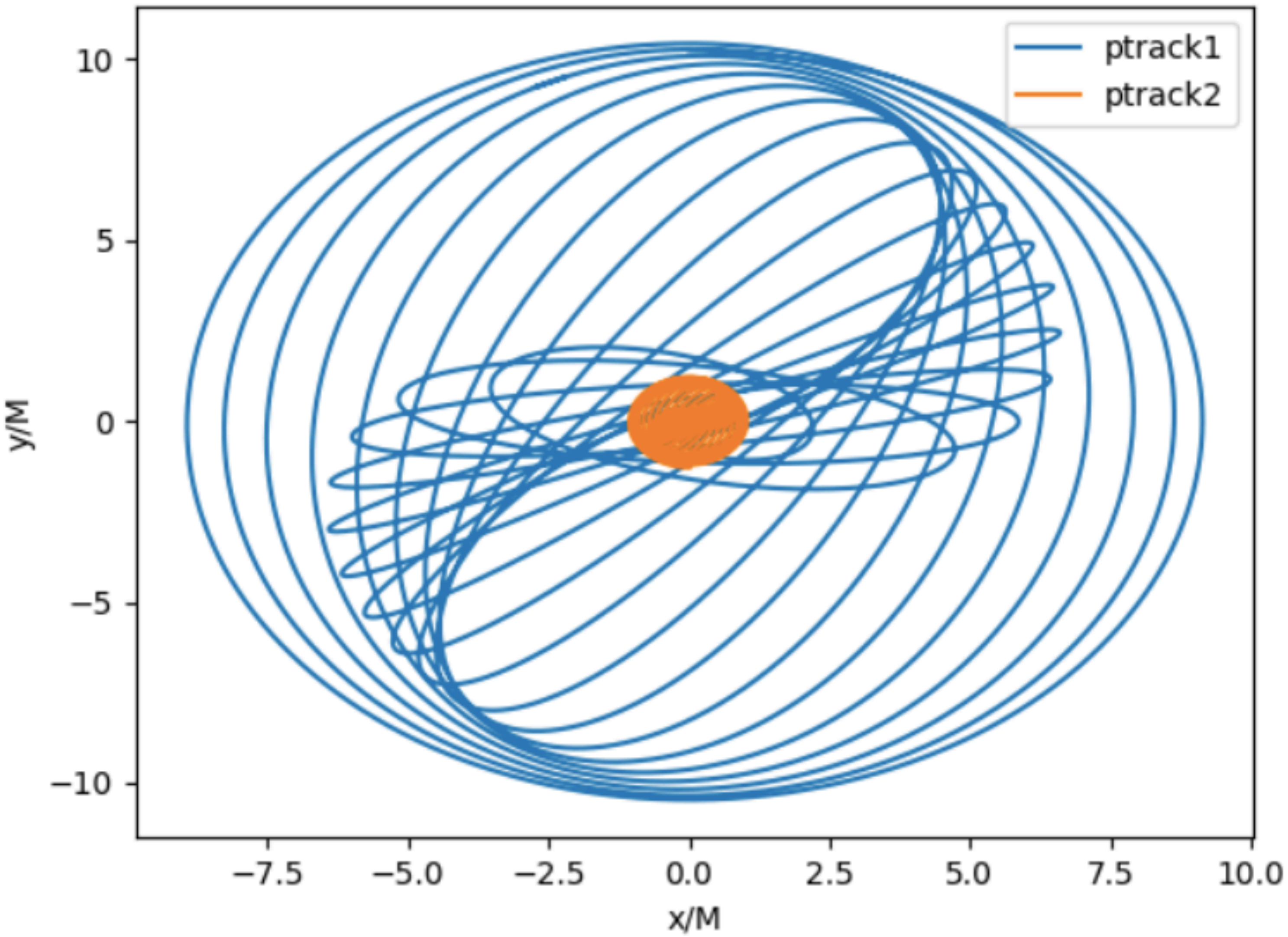
Code improvements

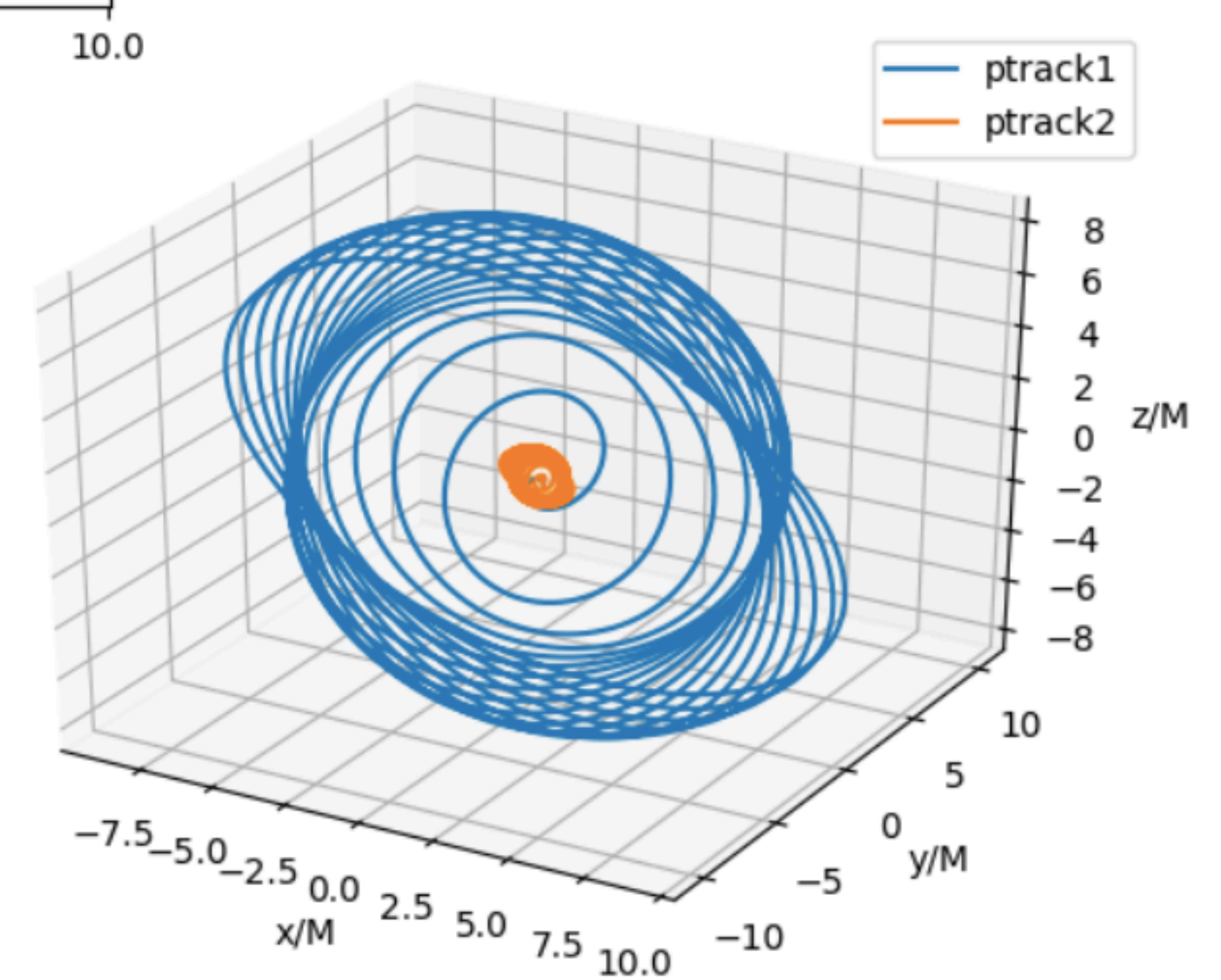


NR-tuned precession: Precessing simulations

- Mass ratios 1, 2, 4, 8
- Spin magnitudes 0.4 & 0.8.
- Spin angles: 30, 60, 90, 120, 150 degrees.
- 40 configurations in total.


12
10
8
6
4
2
0
sep (M)
0
500
1000
1500
2000
2500
3000
3500
4000
t/M


ptrack1
ptrack2
y/M
x/M
10
5
0
−5
−10
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0


ptrack1
ptrack2
z/M
8
6
4
2
0
−2
−4
−6
−8
y/M
10
5
0
−5
−10
x/M
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5
10.0

Conclusions

- Over the next decade, we will observe 10s-100s of BHs
- Expect to observe ~10s of BNS systems
- Current signal models **not** tuned to precessing NR
- Ongoing DiRAC simulation campaign will fix that!
- Longer-term: two-spin effects, recoils, greater precision