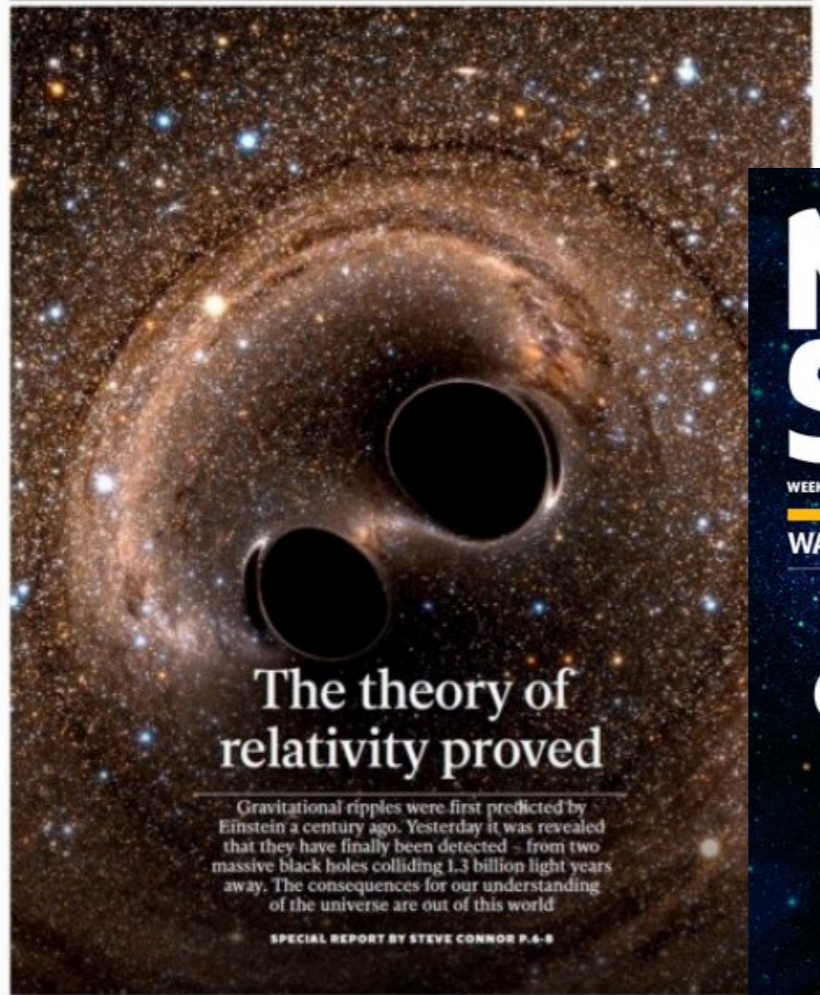


# Gravitational Waves, Numerical Relativity, and measuring Black Holes

Mark Hannam  
Cardiff University

DiRAC Day  
Edinburgh, September 8, 2016





# The theory of relativity proved

Gravitational ripples were first predicted by Einstein a century ago. Yesterday it was revealed that they have finally been detected - from two massive black holes colliding 1.3 billion light years away. The consequences for our understanding of the universe are out of this world

SPECIAL REPORT BY STEVE CONNOR P.4-8

# New Scientist

WEEKLY February 20 - 26, 2016

WARM, WARMER, REALLY WARM! Can we find our way to the 1.5°C climate target?

MISINFORMATION AGE  
Nobody is safe from the internet mindwarp

LOOSE CORALS  
How to seduce them to spawn in captivity

FOREVER PREMATURE  
The lasting legacy of being born too soon

SPECIAL REPORT

# GRAVITATIONAL WAVES

What they will reveal about reality

Neutron stars Black holes Big bang Dark energy Theory of everything



Science and technology news  
www.newscientist.com  
US jobs in science

HOW CONSCIOUS ARE YOU? The number that defines self-awareness

February 2016  
e Baftas  
Who should win film awards?  
United spree  
Old Trafford club targets world's best players  
Free tomorrow  
32-page booklet  
The Big Brain Workout

# The Daily Telegraph

## EU deal could split Tories

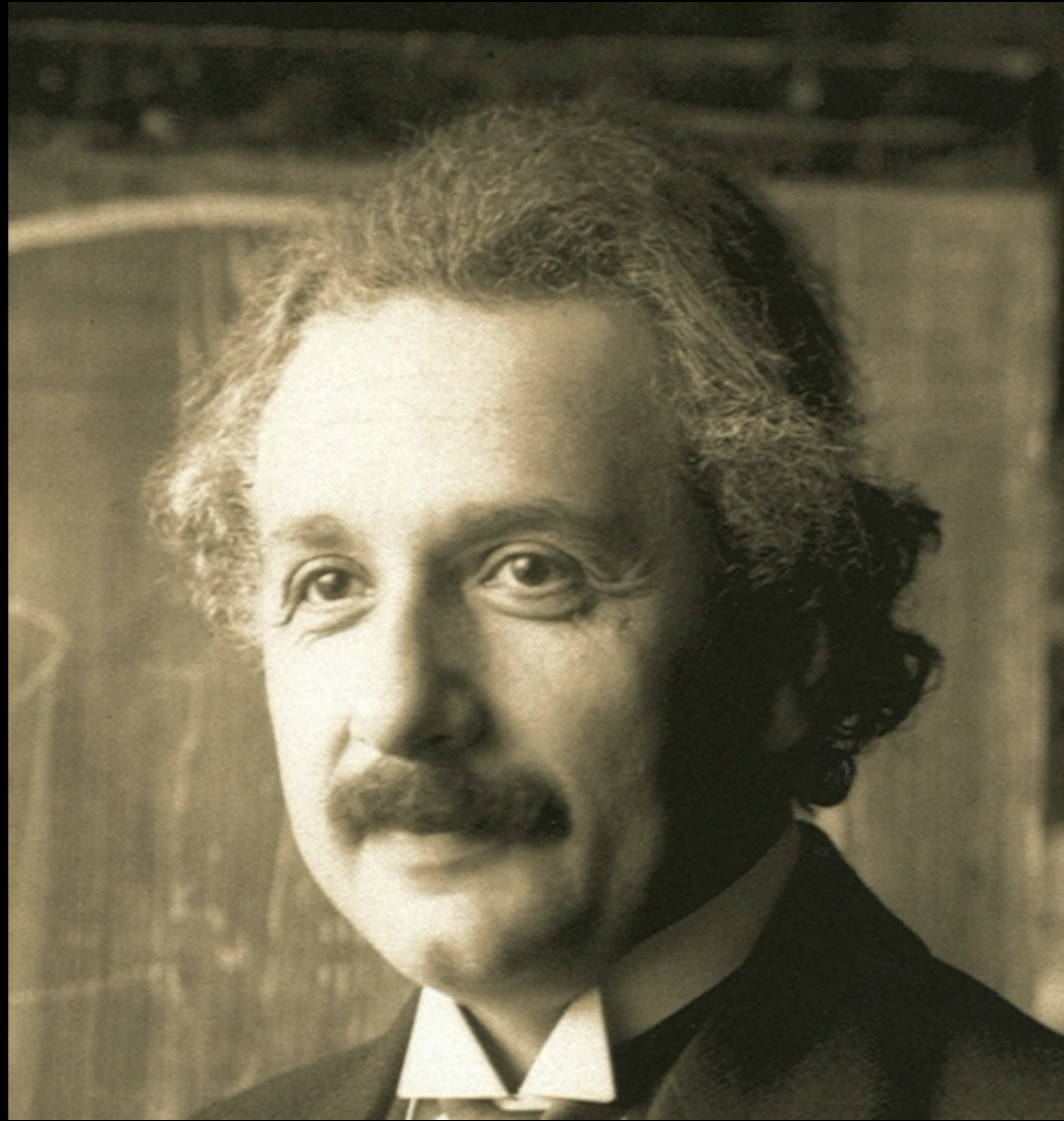
EU deal could split Tories  
The deal you wanted in Europe was made but not the accompanying...  
EU deal you wanted in Europe was made but not the accompanying...  
EU deal you wanted in Europe was made but not the accompanying...

## Man behind discovery of the century misses party

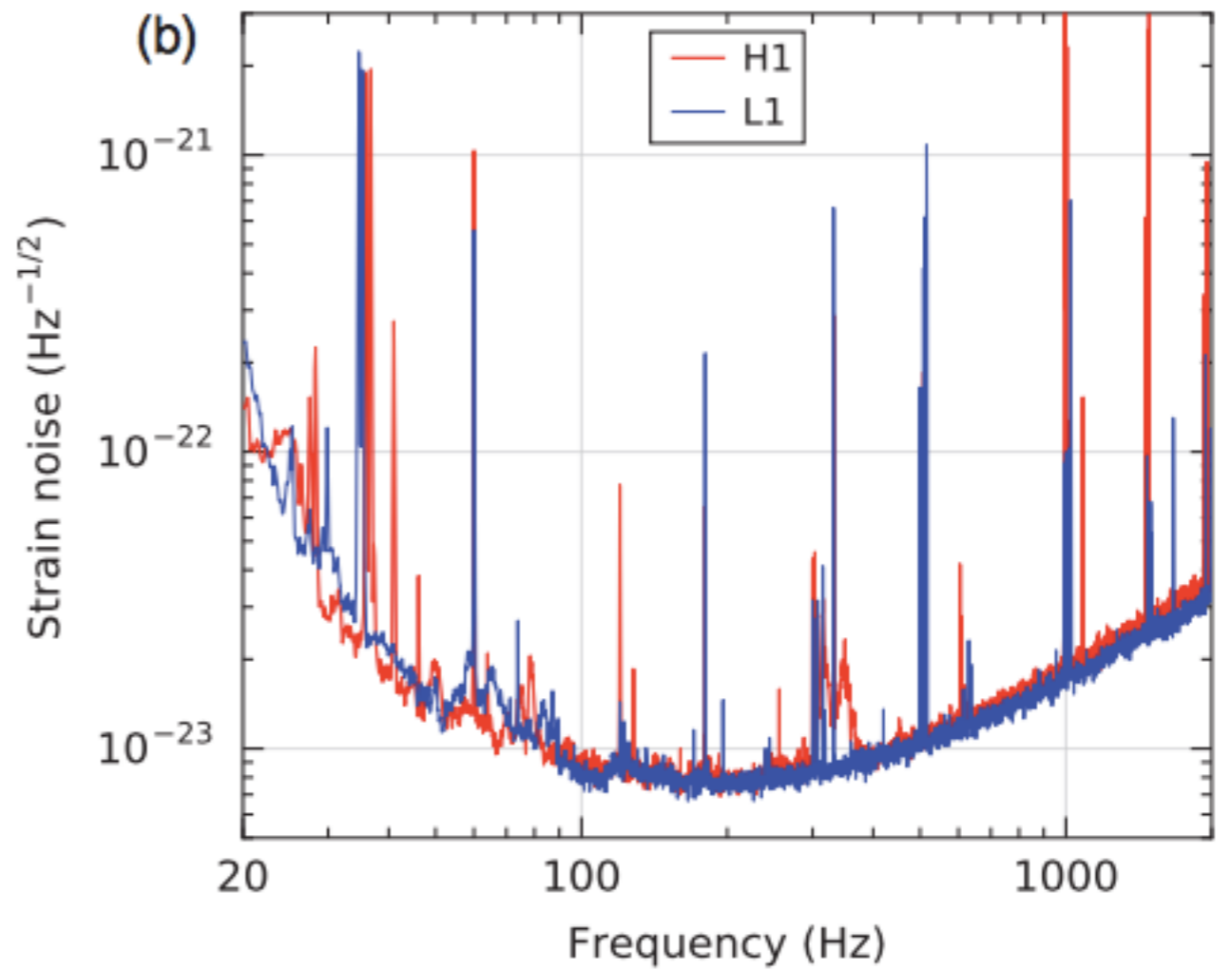
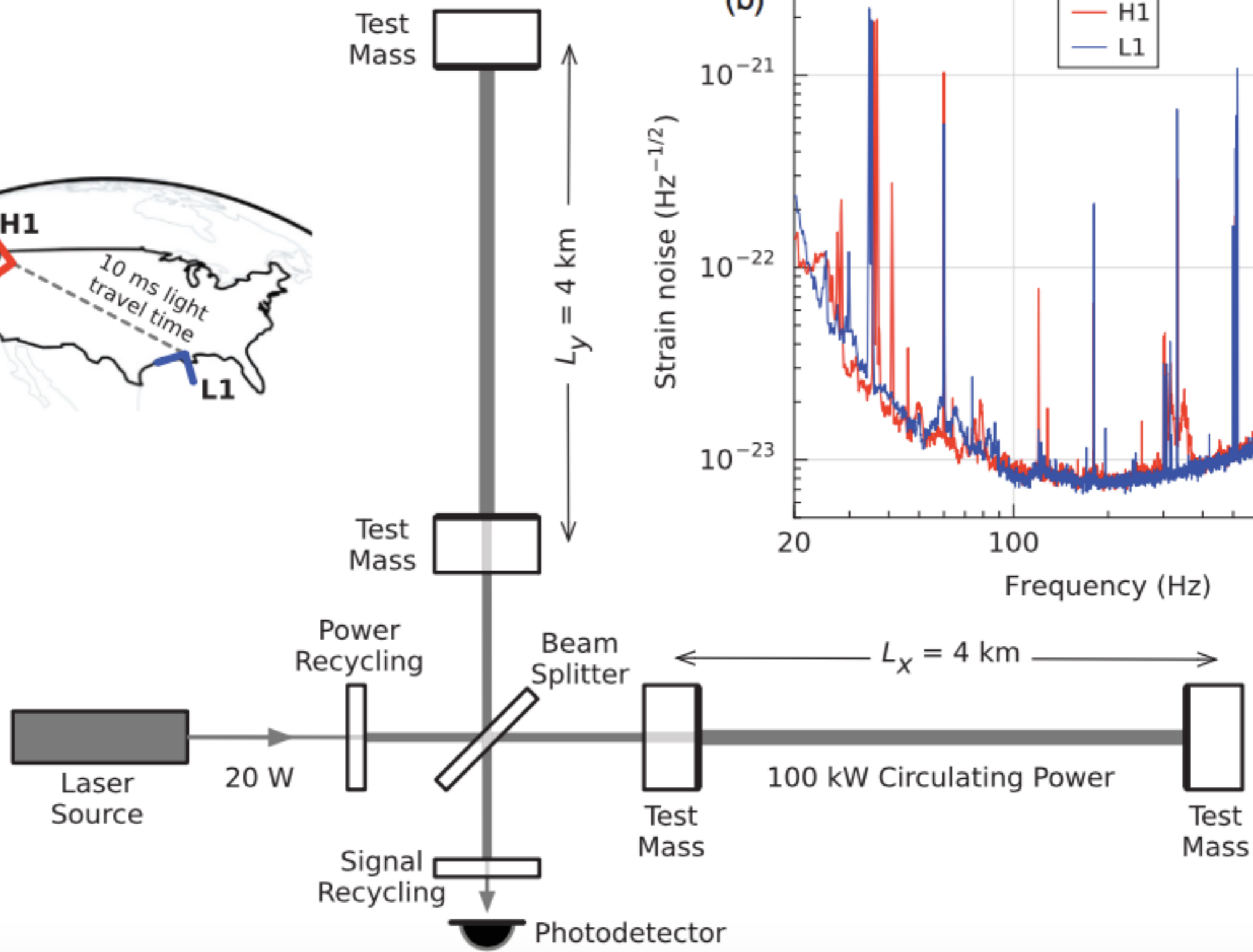
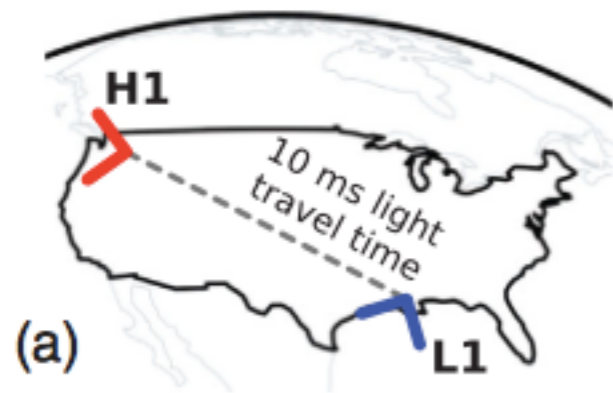
Man behind discovery of the century misses party  
A BRITISH scientist who was granted the right to dress as Einstein...  
A BRITISH scientist who was granted the right to dress as Einstein...  
A BRITISH scientist who was granted the right to dress as Einstein...

Rush for gold as panic grows  
Firms 'shamed' over pay gap  
TV listings  
Weather  
Financial Review

OUR GIFT TO YOU  
this Valentine's Day  
Sandals  
SAVE AN EXTRA 10% - ONLY 100000







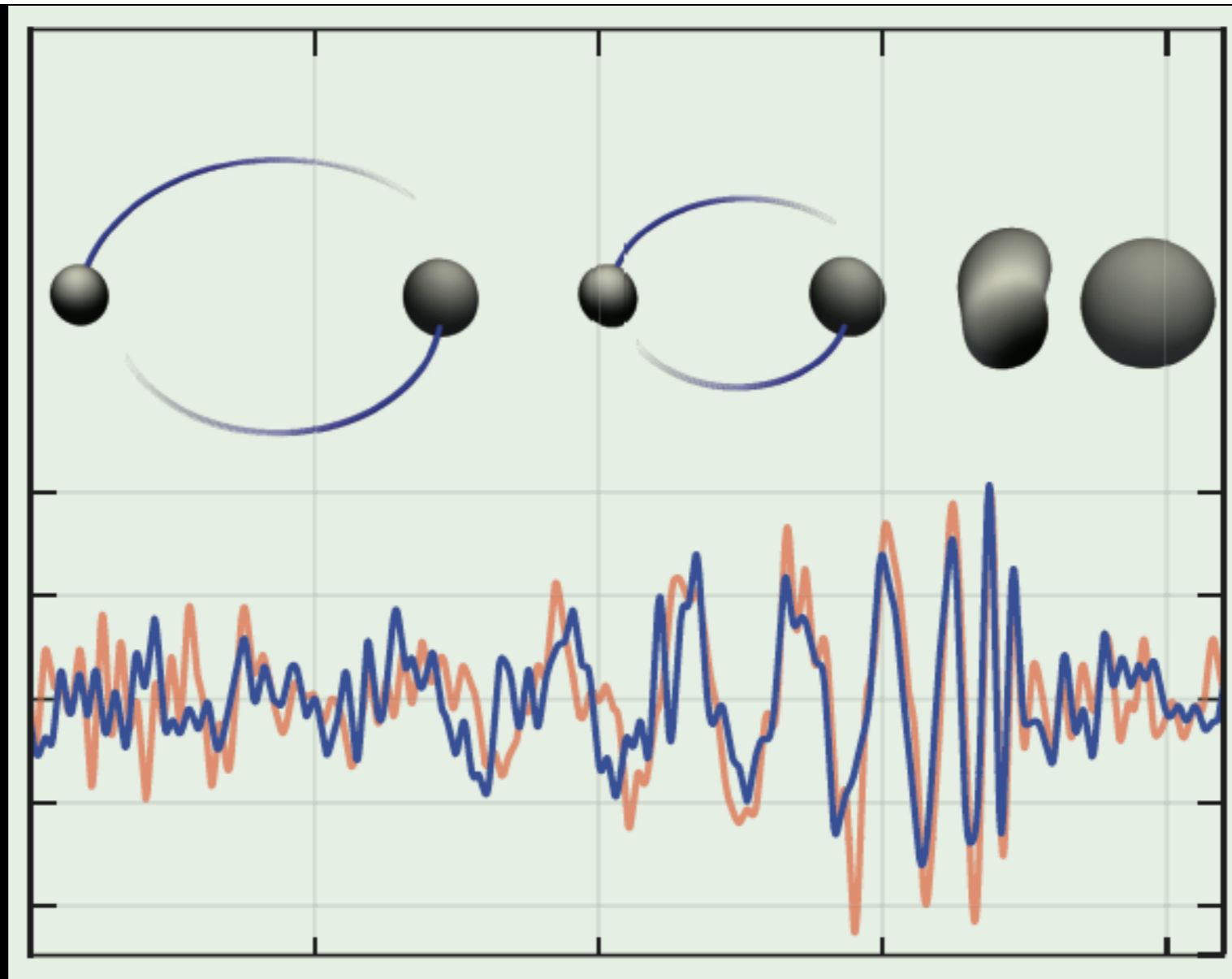


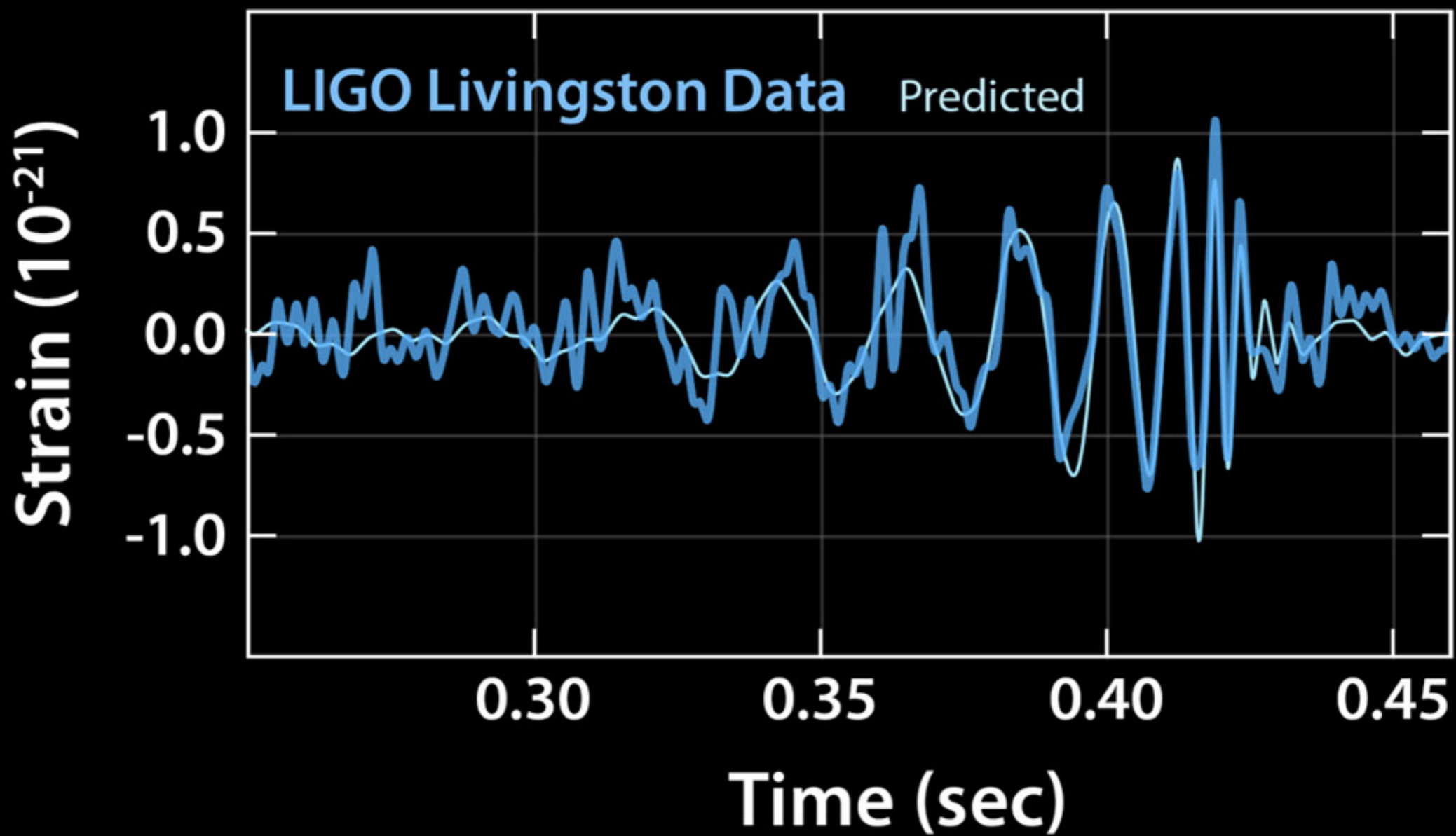
# Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*\*

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

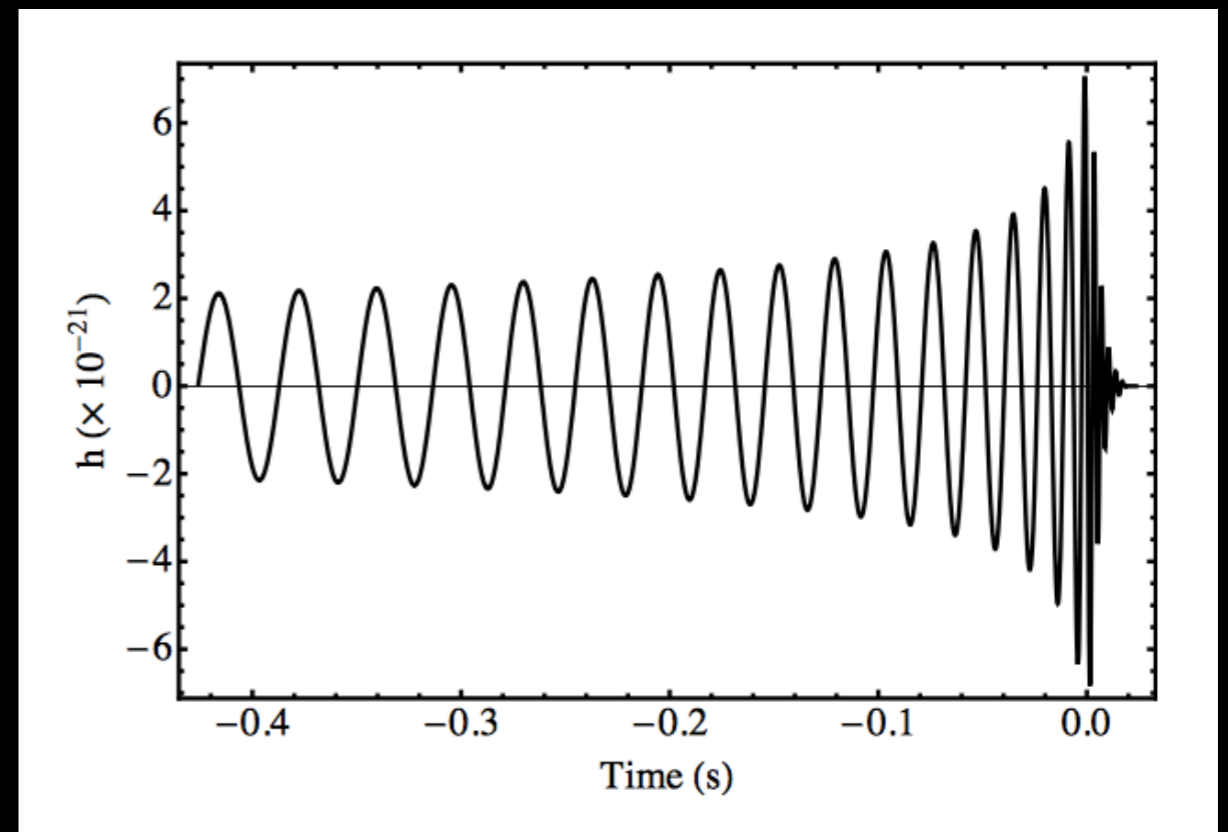
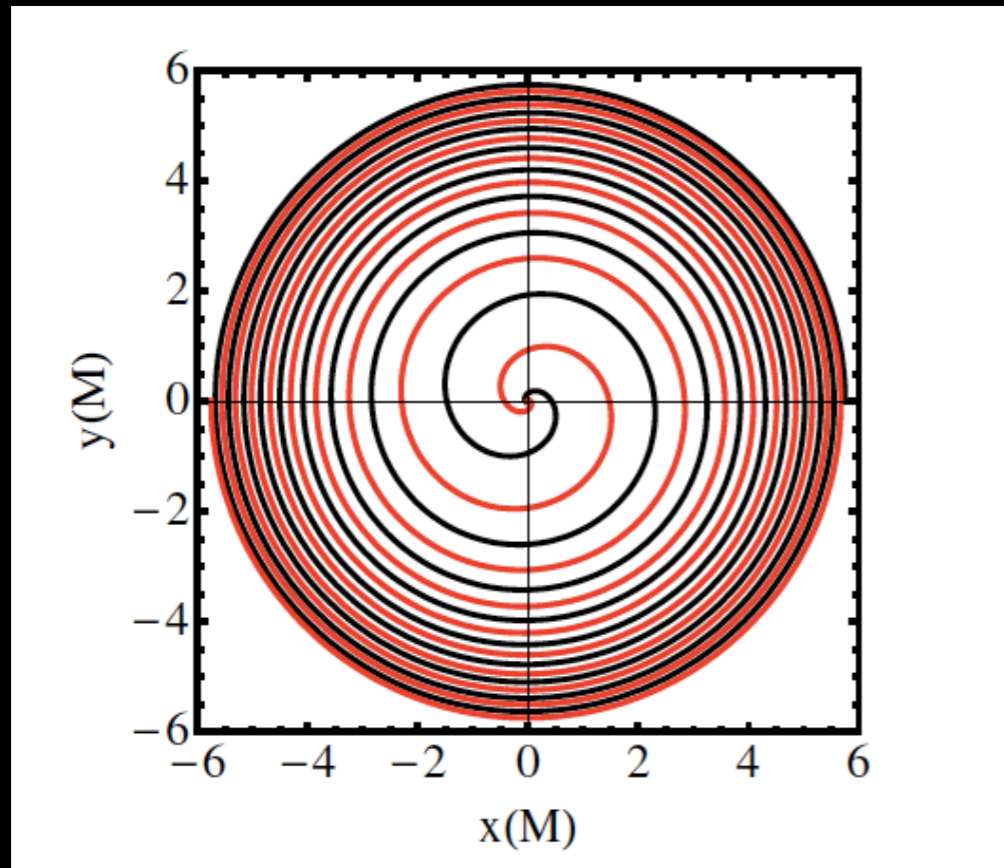
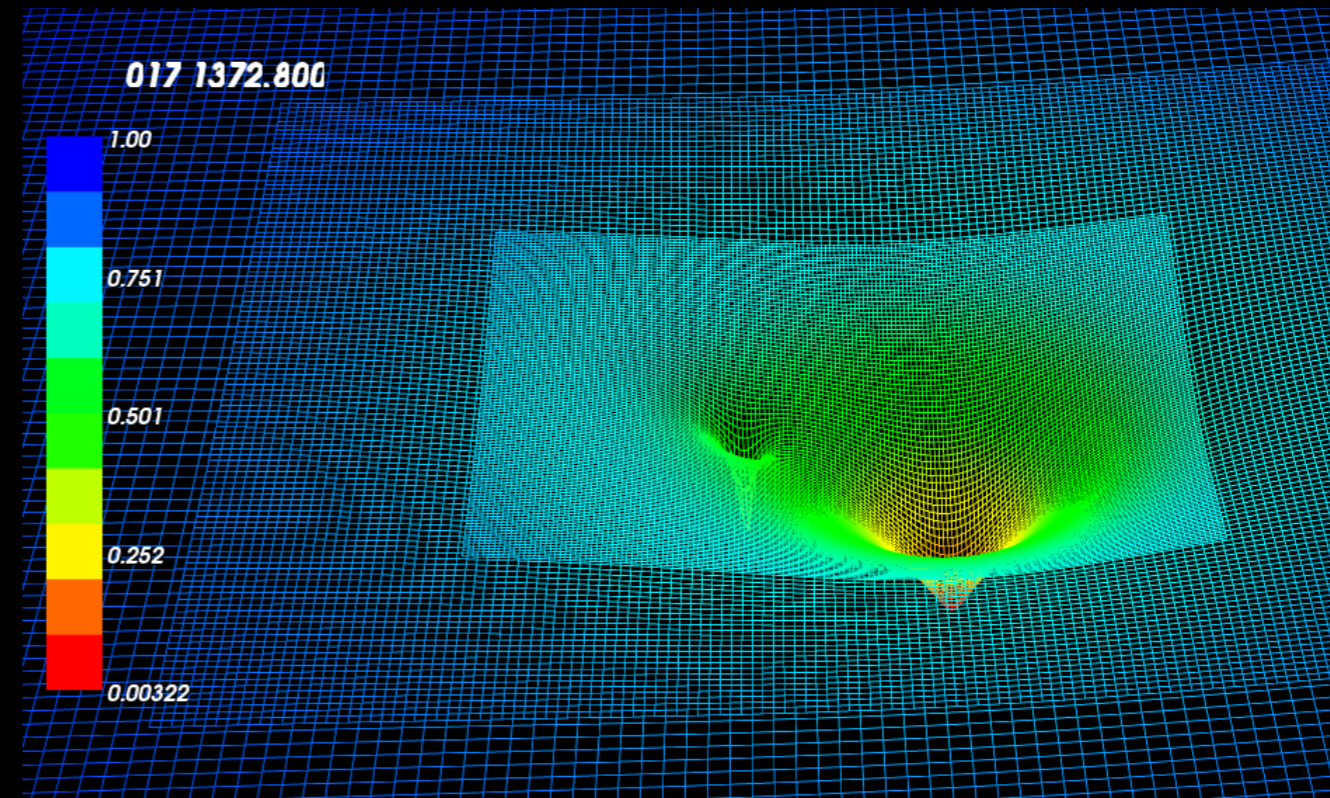




# Numerical relativity

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)

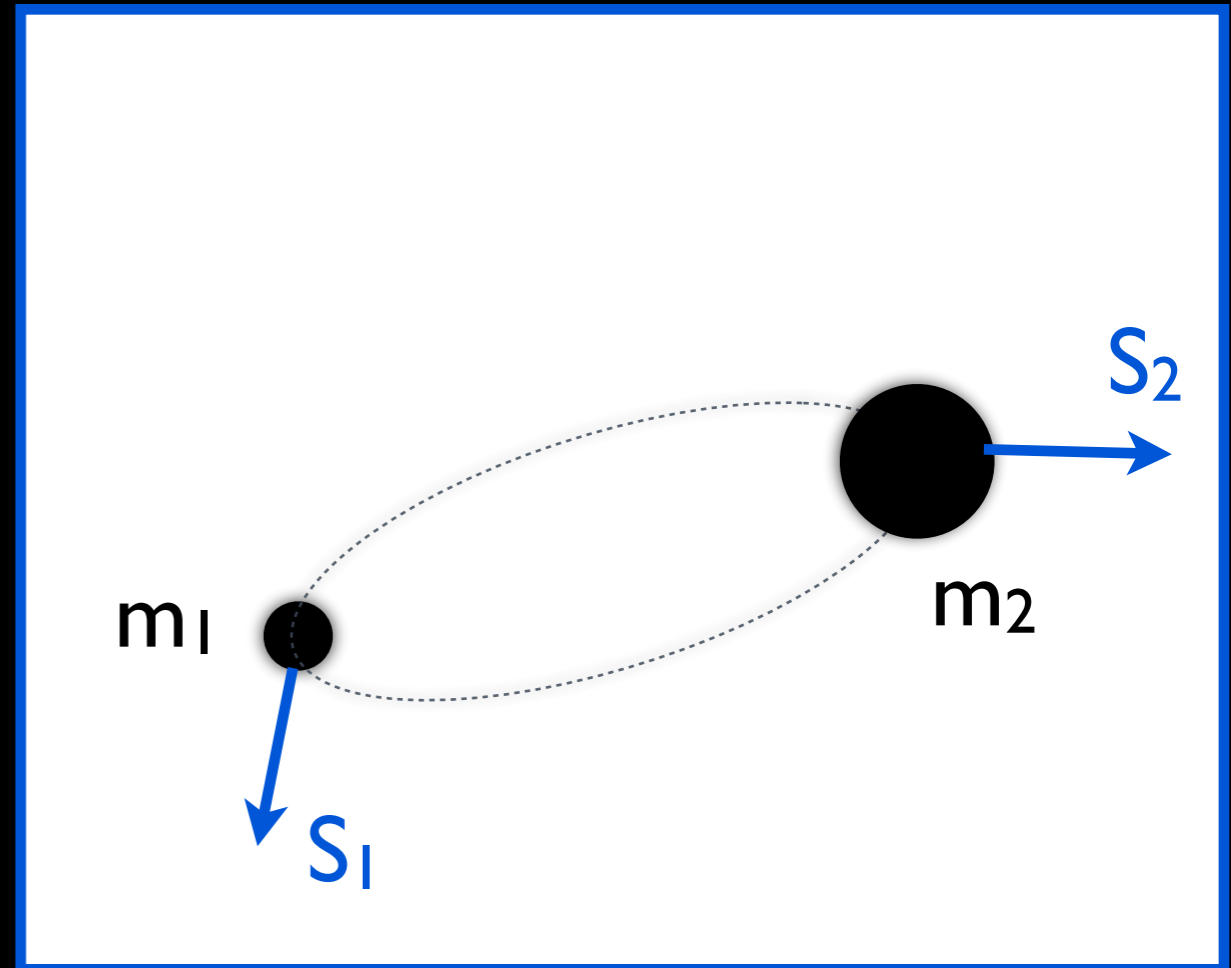
useful combinations:

$$M = m_1 + m_2$$

$$q = m_2 / m_1$$

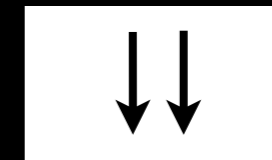
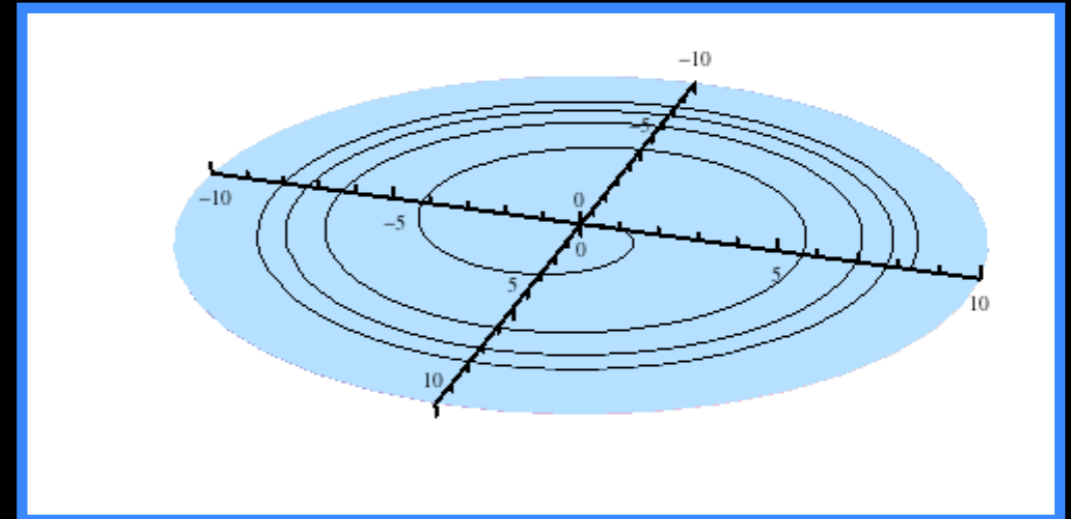
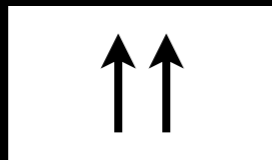
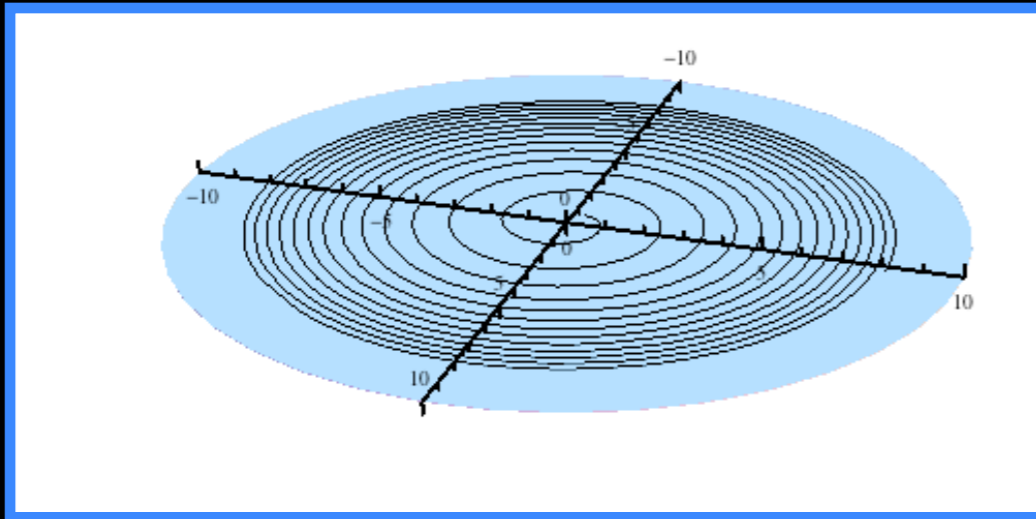
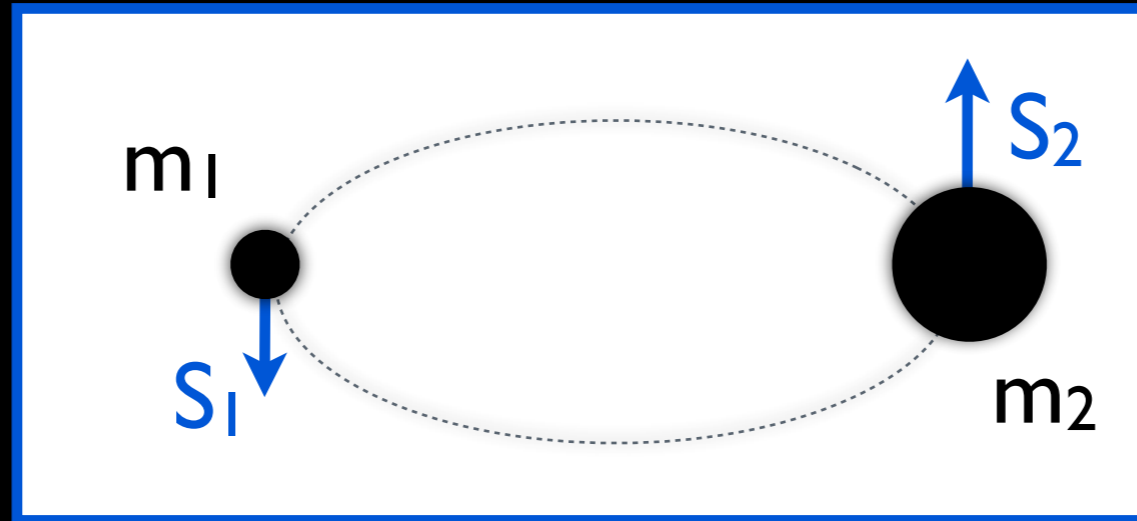
$$\eta = m_1 m_2 / M^2$$

$$\chi = S/m^2$$



**Plus:** distance, sky location,  
orientation, polarisation

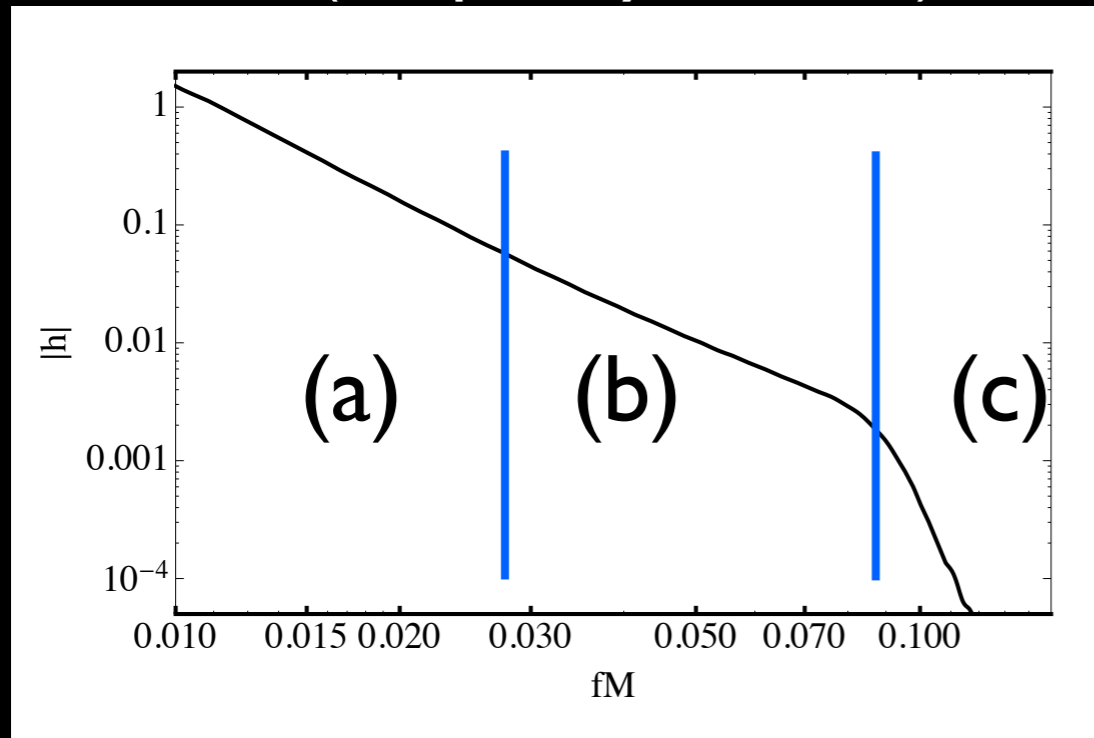
# Aligned spins



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

# IMRPhenom

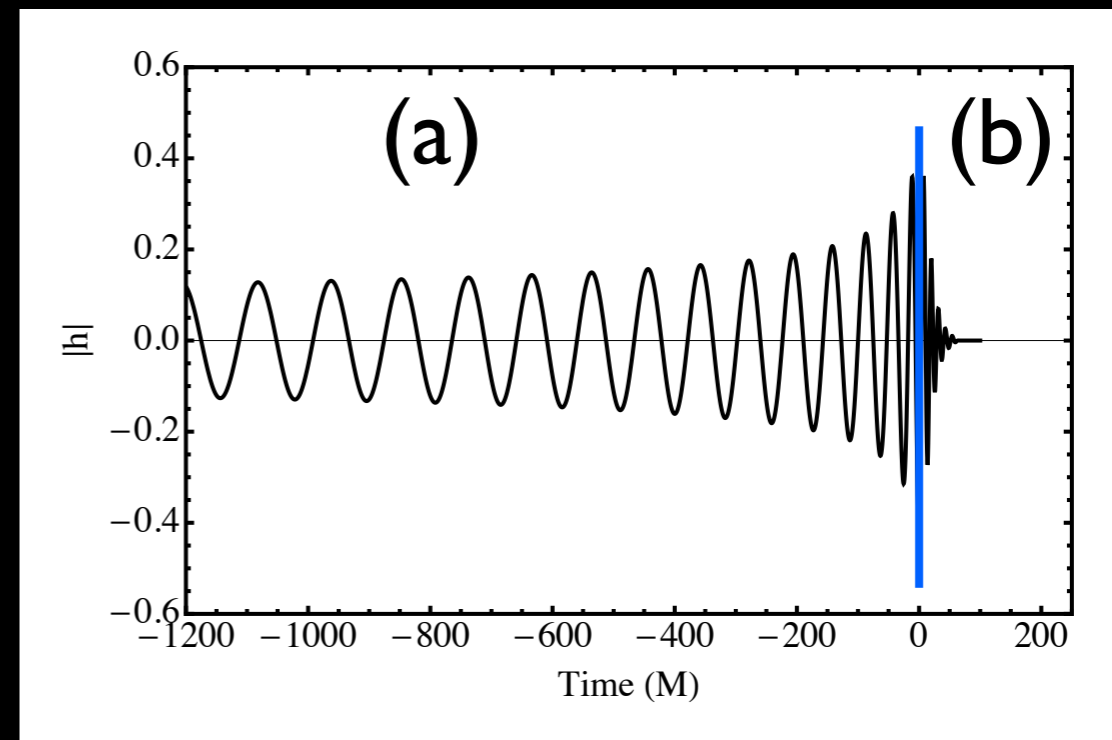
(frequency domain)



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

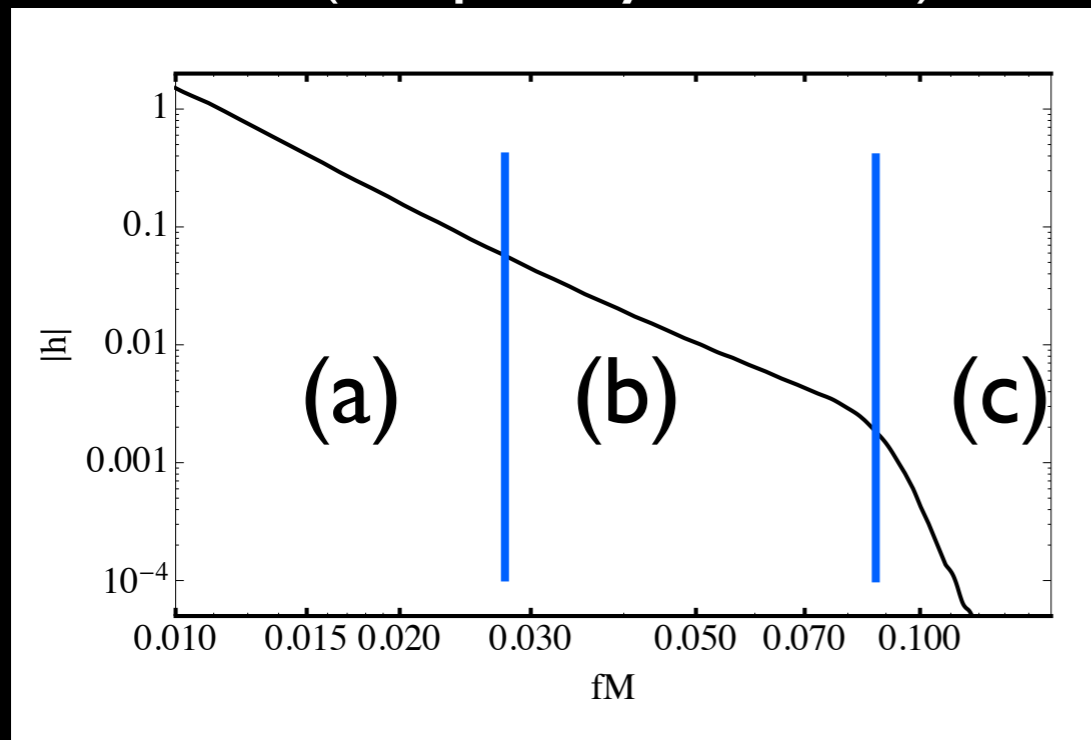
# EOBNR

(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

# Phenom (frequency domain)

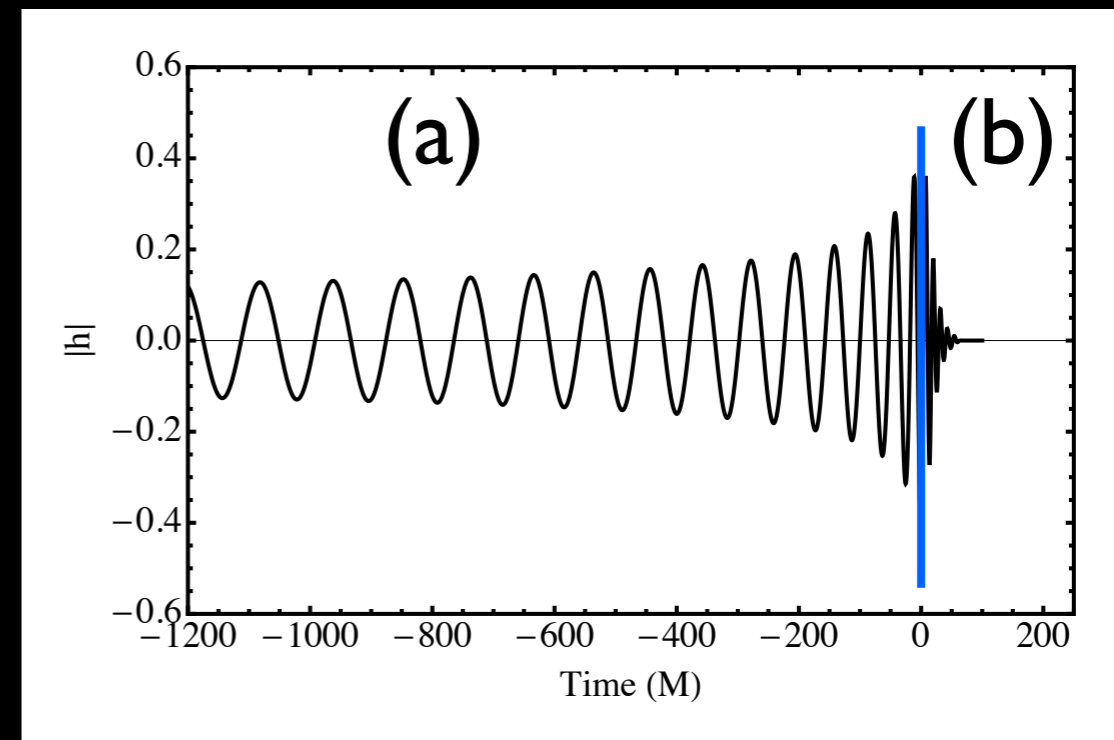


- (a) PN-based ansatz
- (b) phenomenological fit (based on NR behaviour)
- (c) FFT of ringdown waveform (Lorentzian)
- Analytic: fast

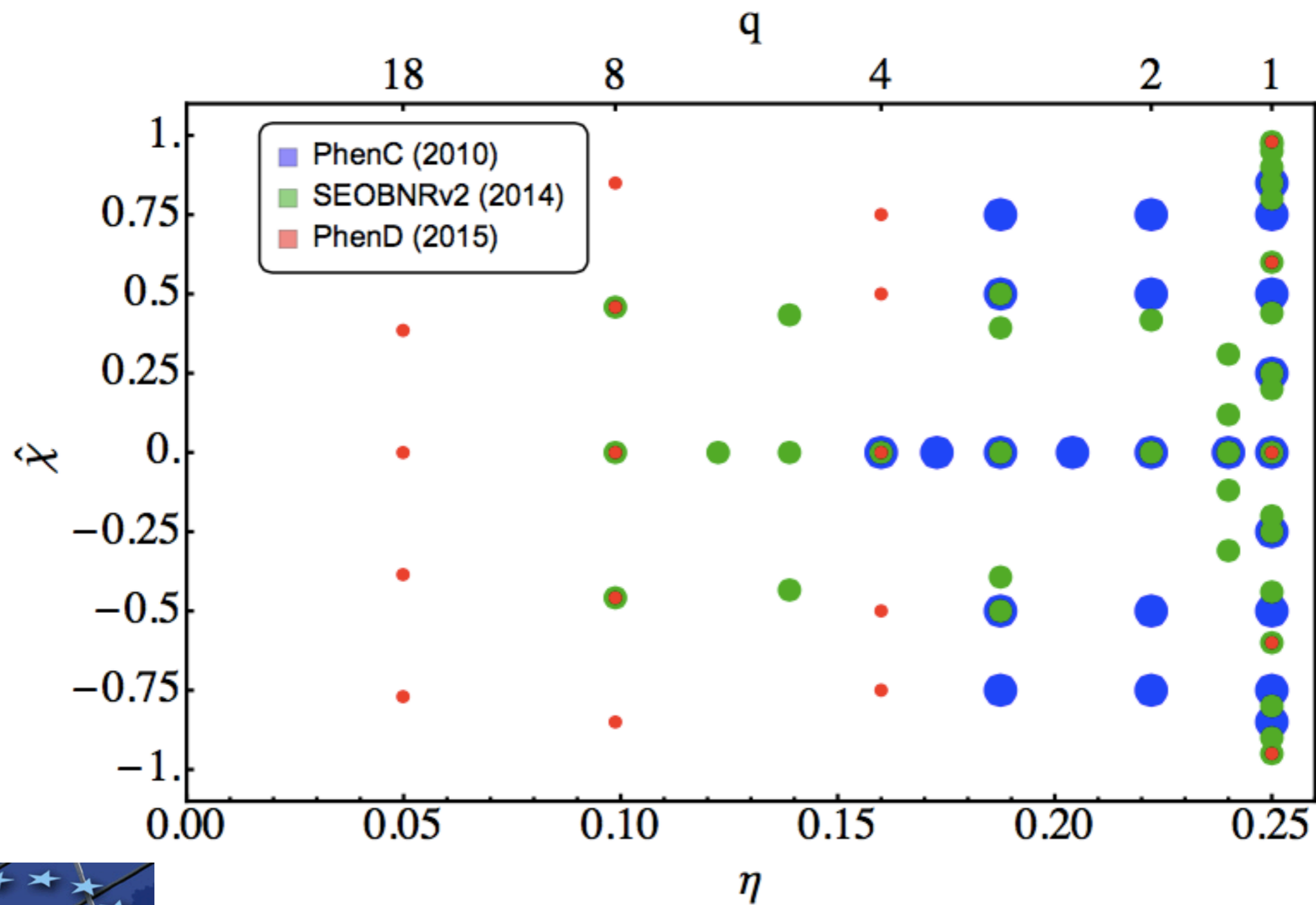
**DiRAC**



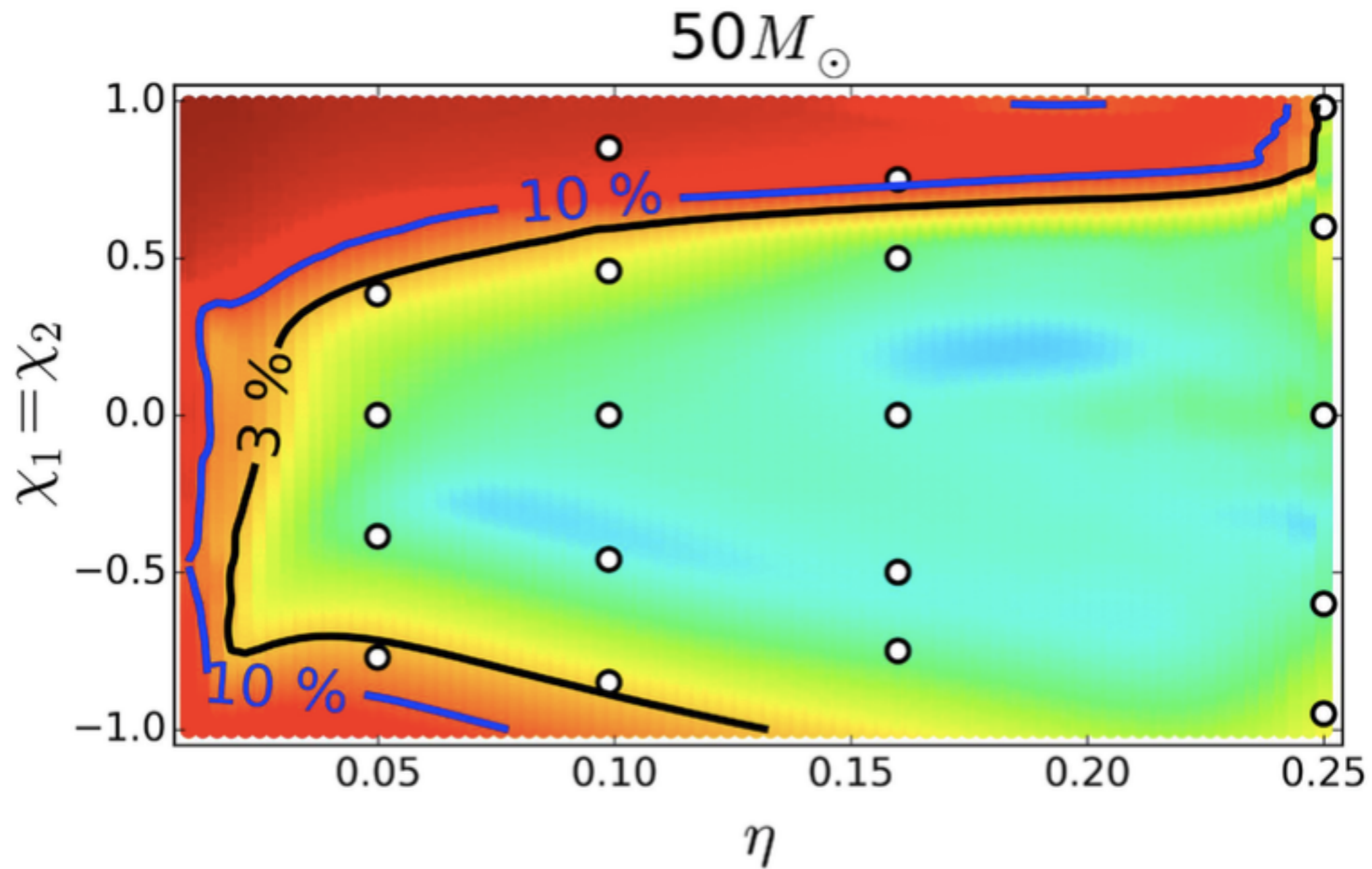
# EOB-NR (time domain)



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

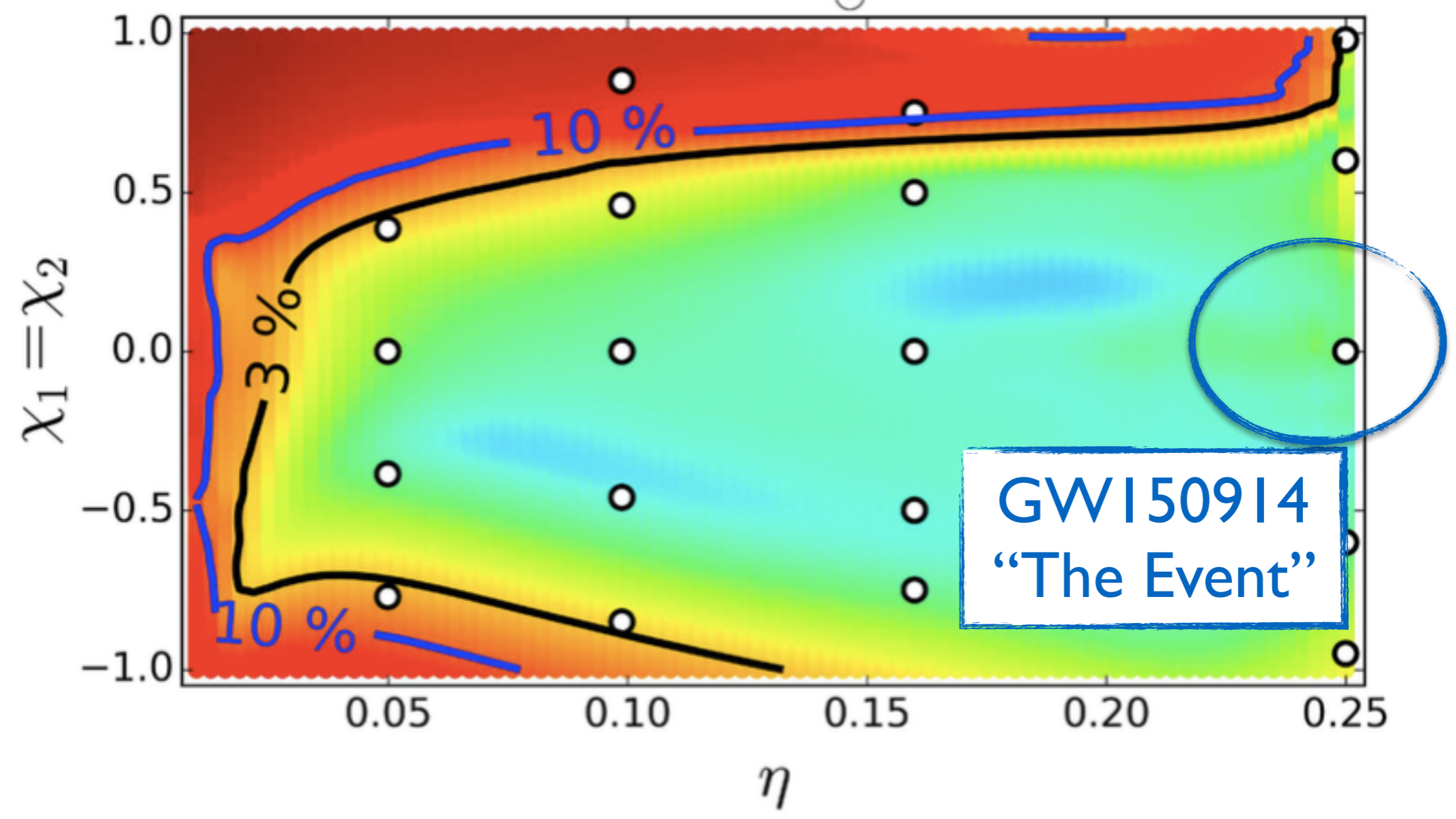


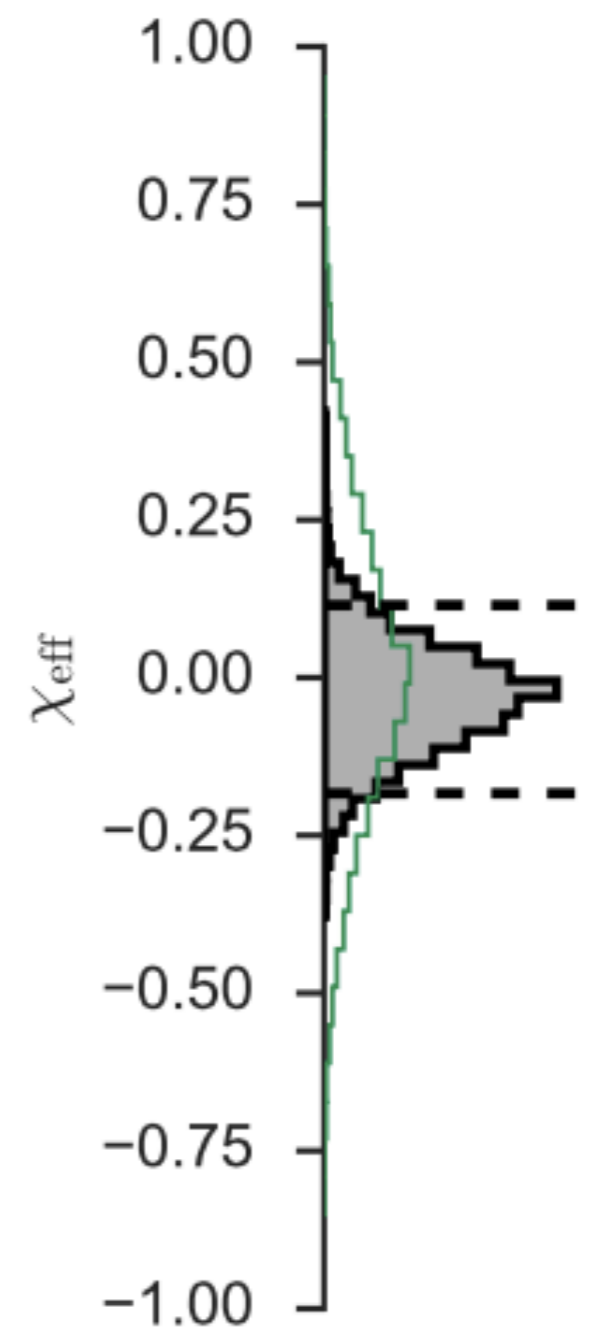
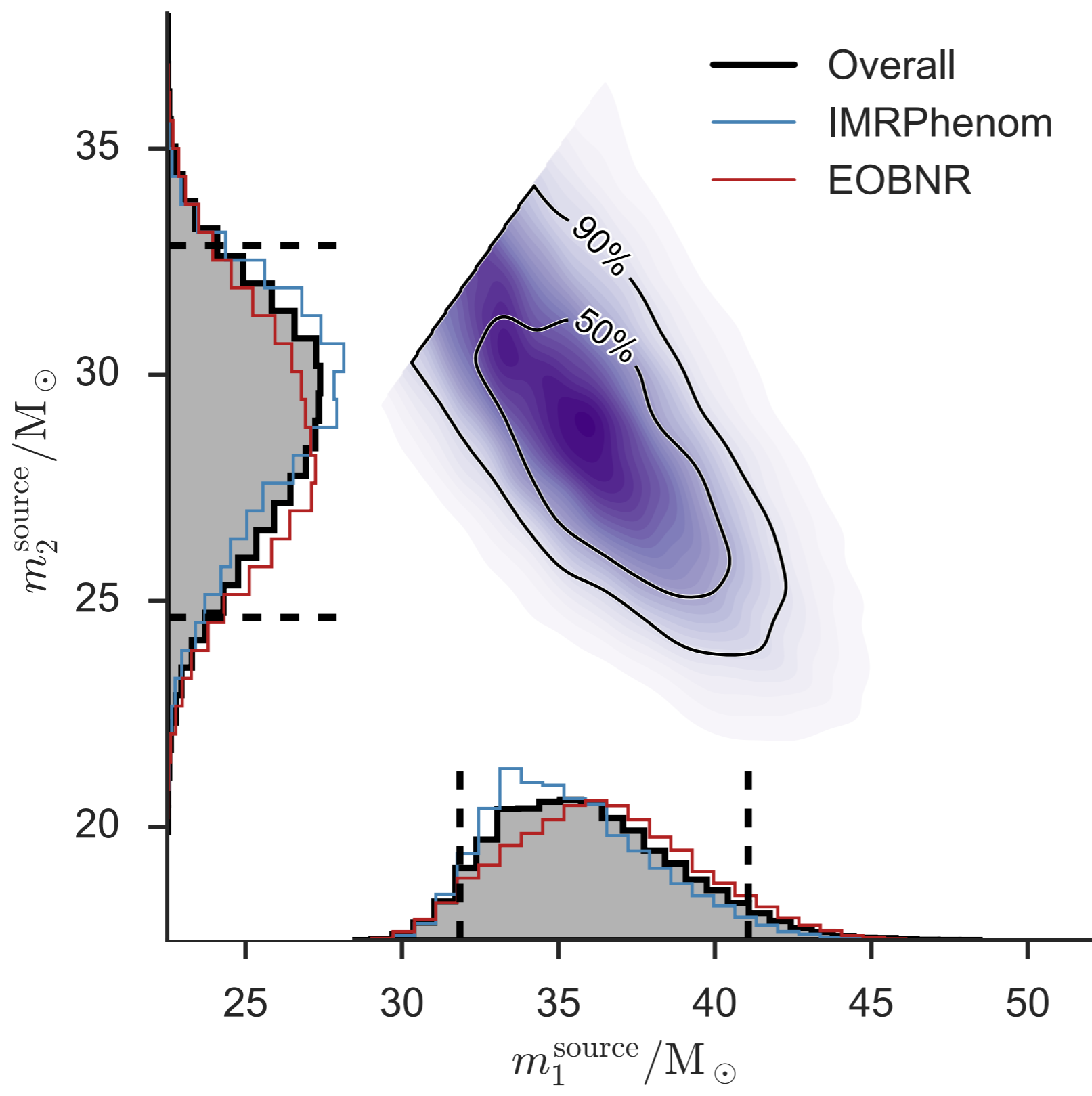
[Khan, et. al (2016)]



[Khan, et. al (2016)]

$50M_{\odot}$



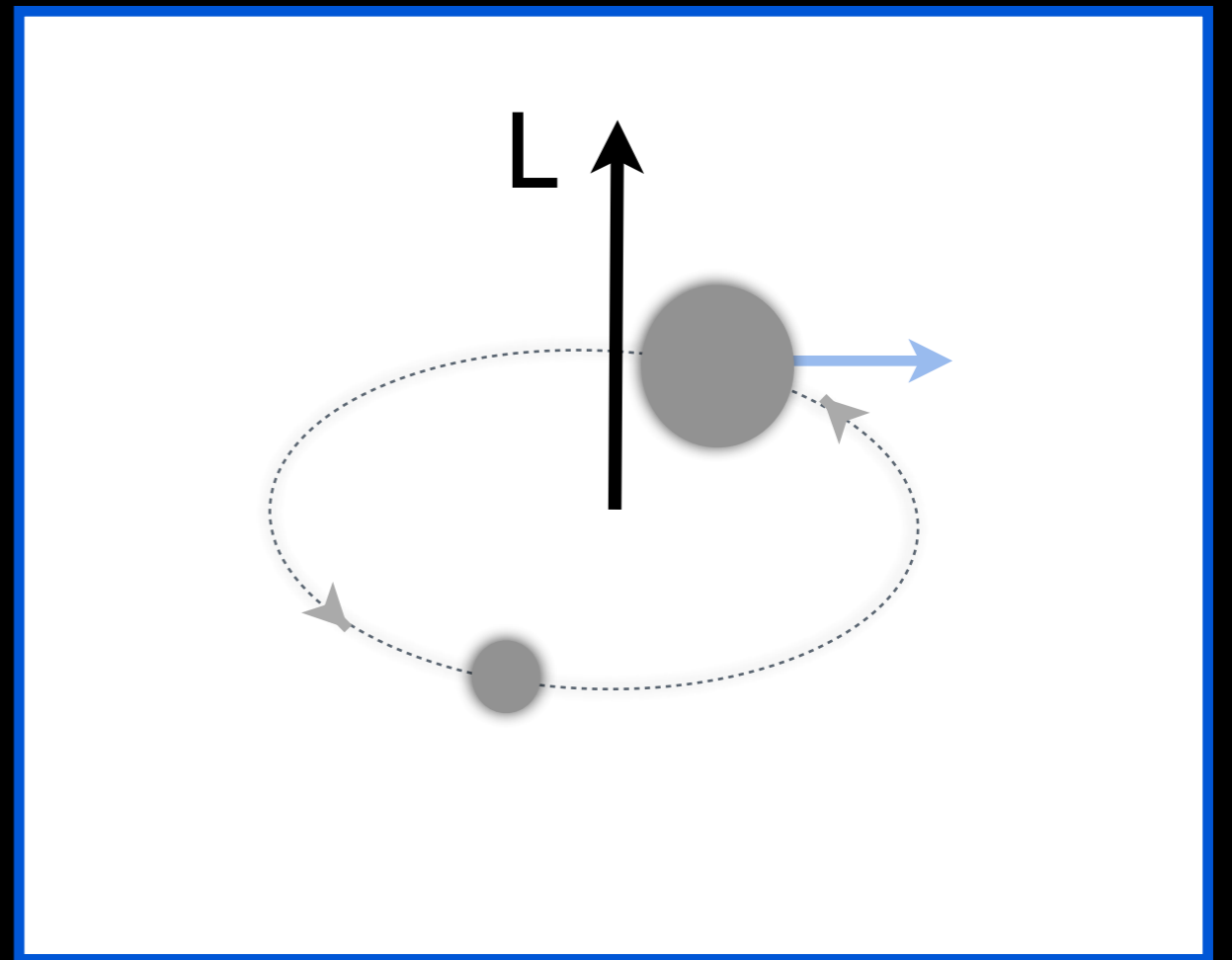
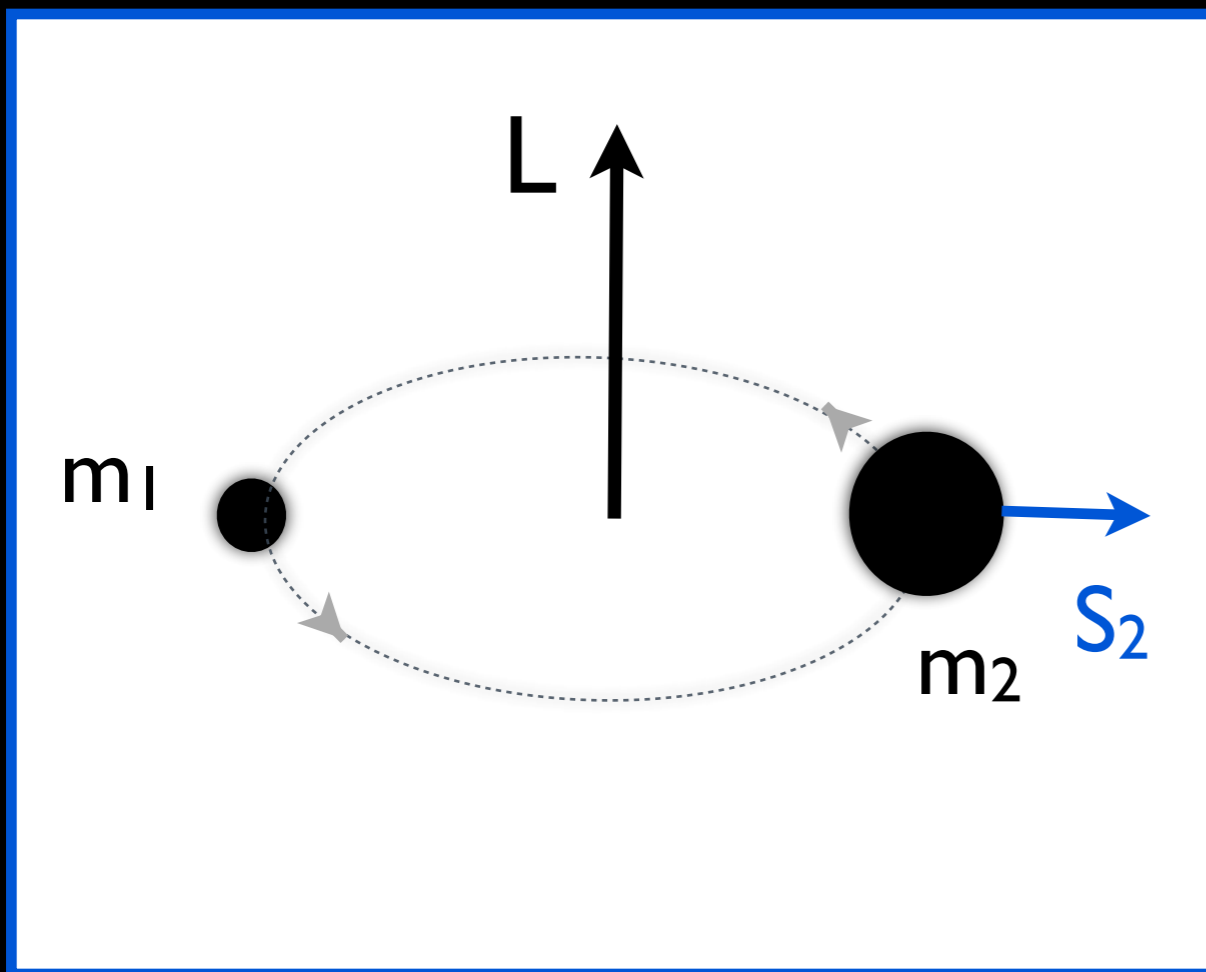


**GW150914**  
**“The Event”**

**[LVC (2016)]**

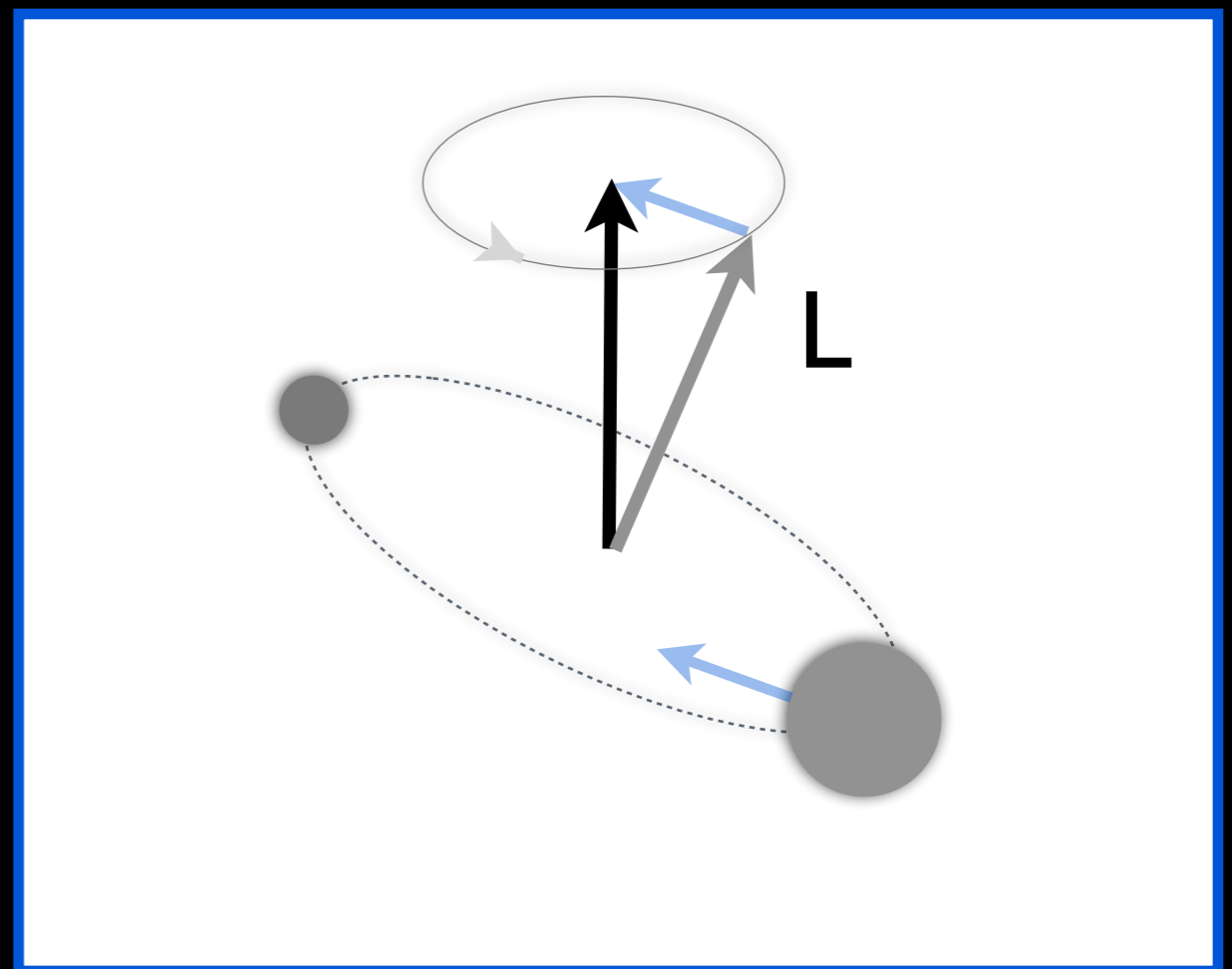
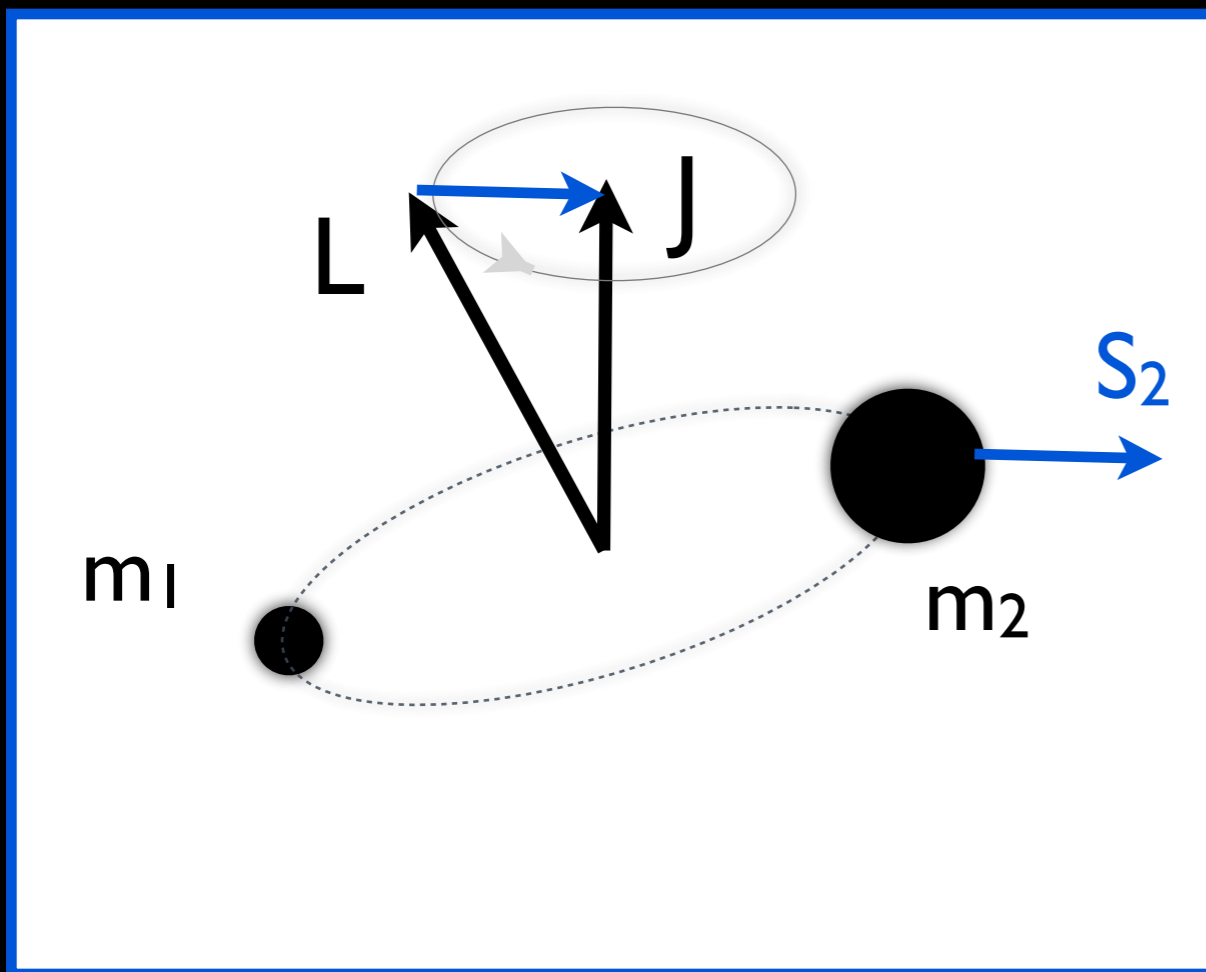


# Orbital precession



Newtonian gravity:  
 $L, S_1, S_2$  remain fixed

# Orbital precession



General relativity  
( $L, S_1, S_2$ ) precess around  $J$

# Orientation dependence

$q=3$ ,  $|S_2| = 0.75$  (in plane)



Observer aligned  
with  $J$

# Orientation dependence

$q=3, |S_2| = 0.75$  (in plane)



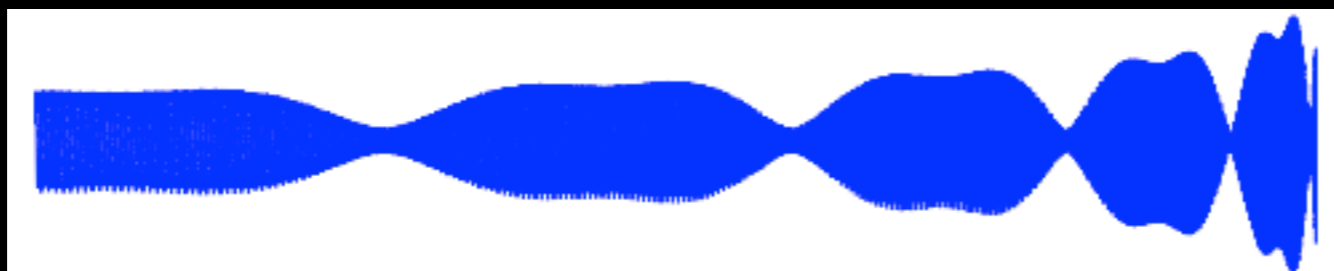
Observer aligned  
with  $J$



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

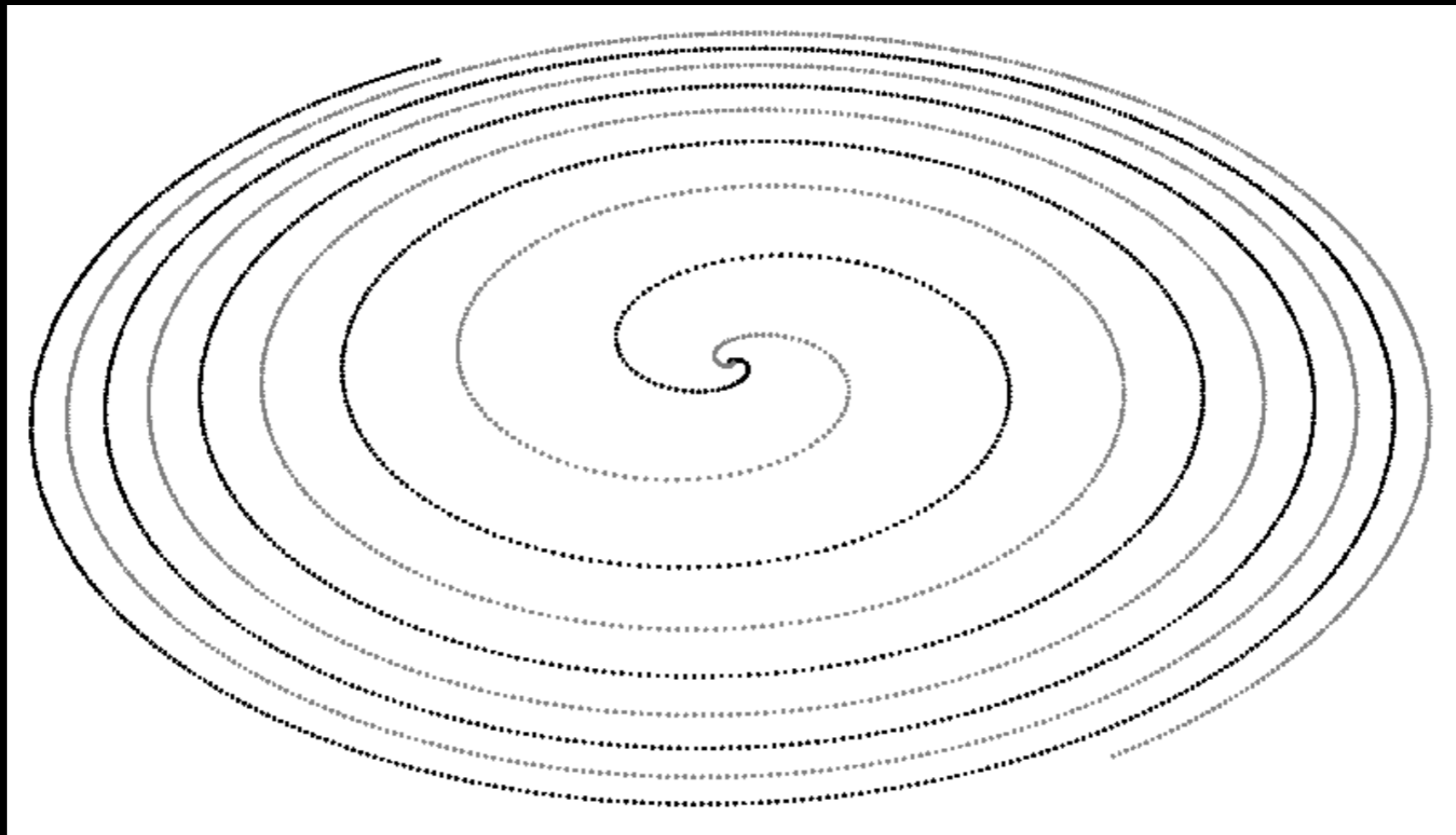


Observer inclined  
 $\pi/3$  to  $J$

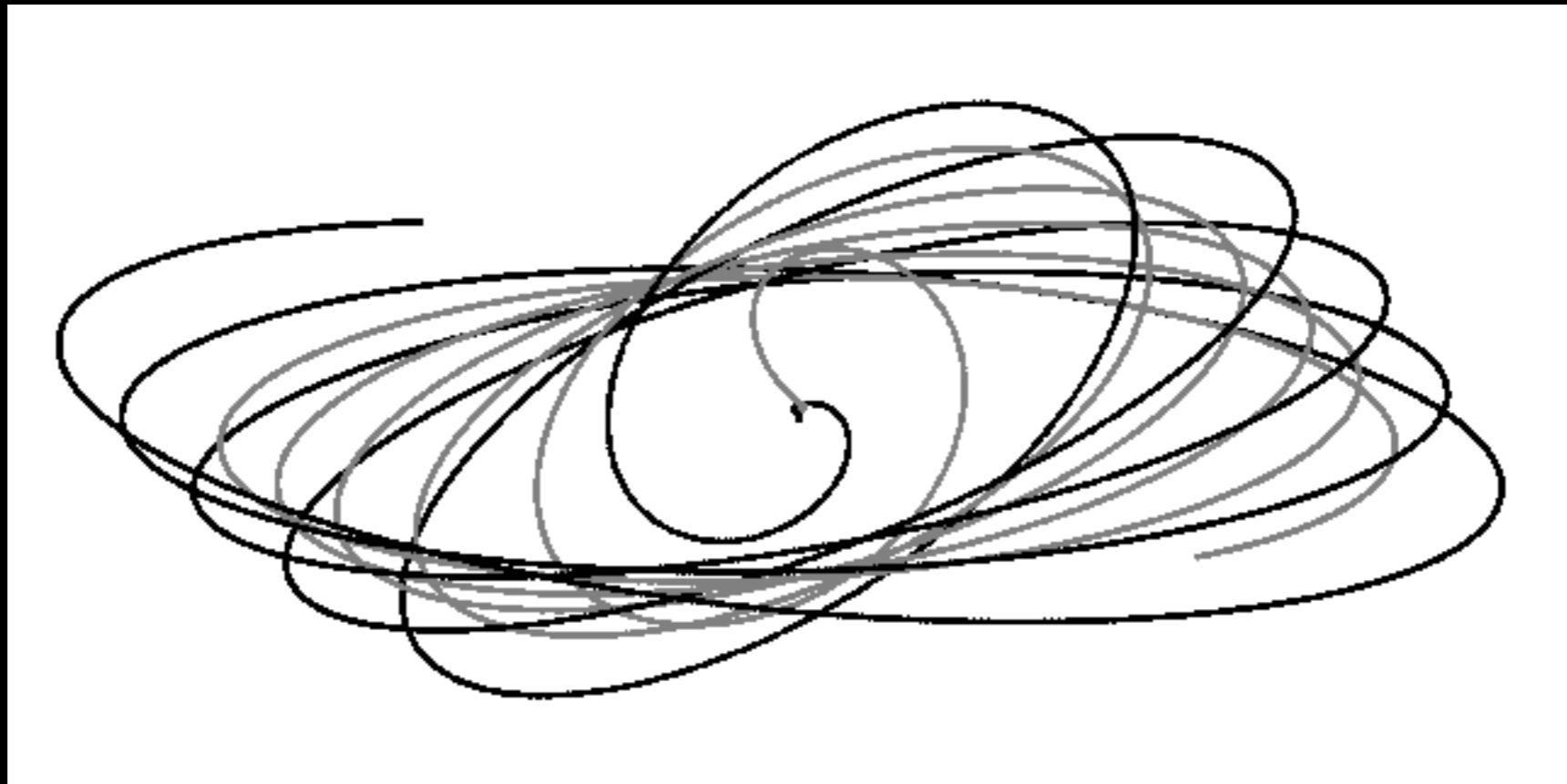


Observer inclined  
 $\pi/2$  to  $J$

# Equal-mass nonspinning BBH consistent with GW150914

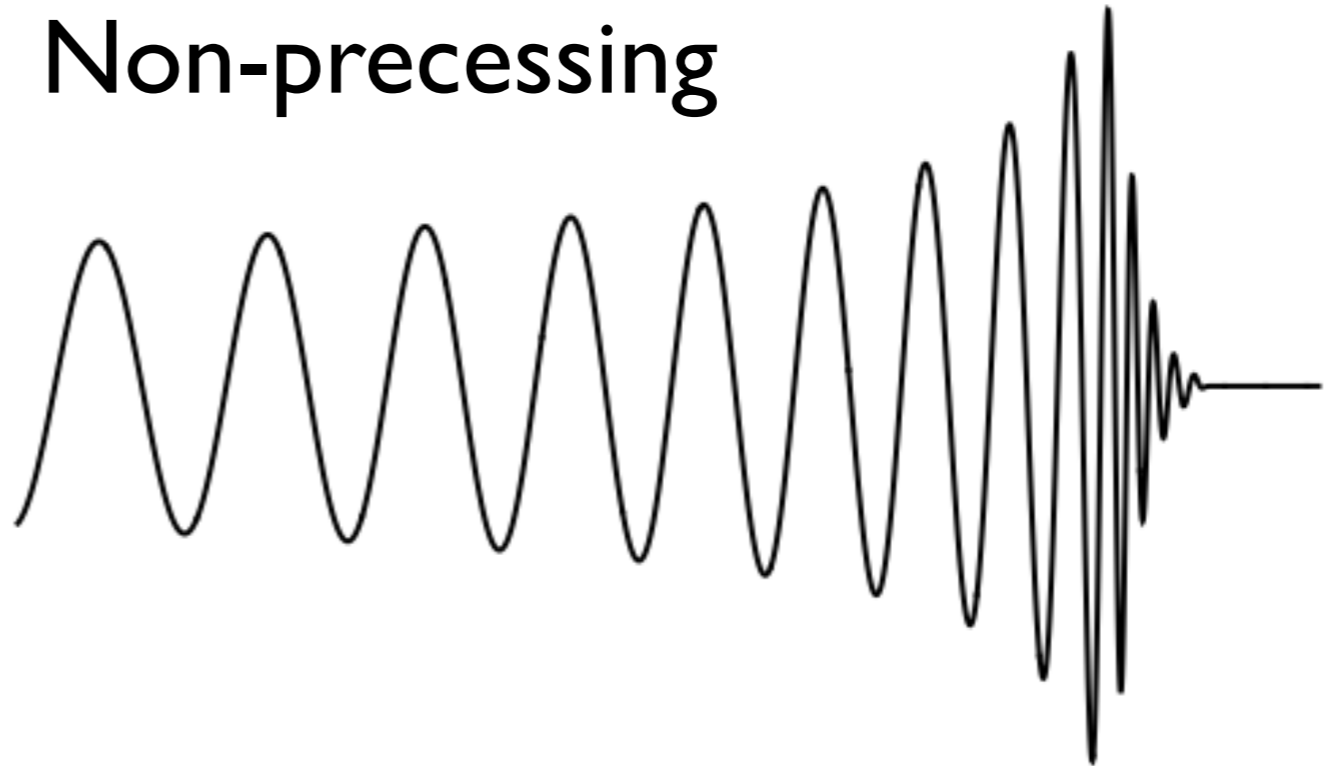


# Unequal-mass precessing BBH consistent with GW150914

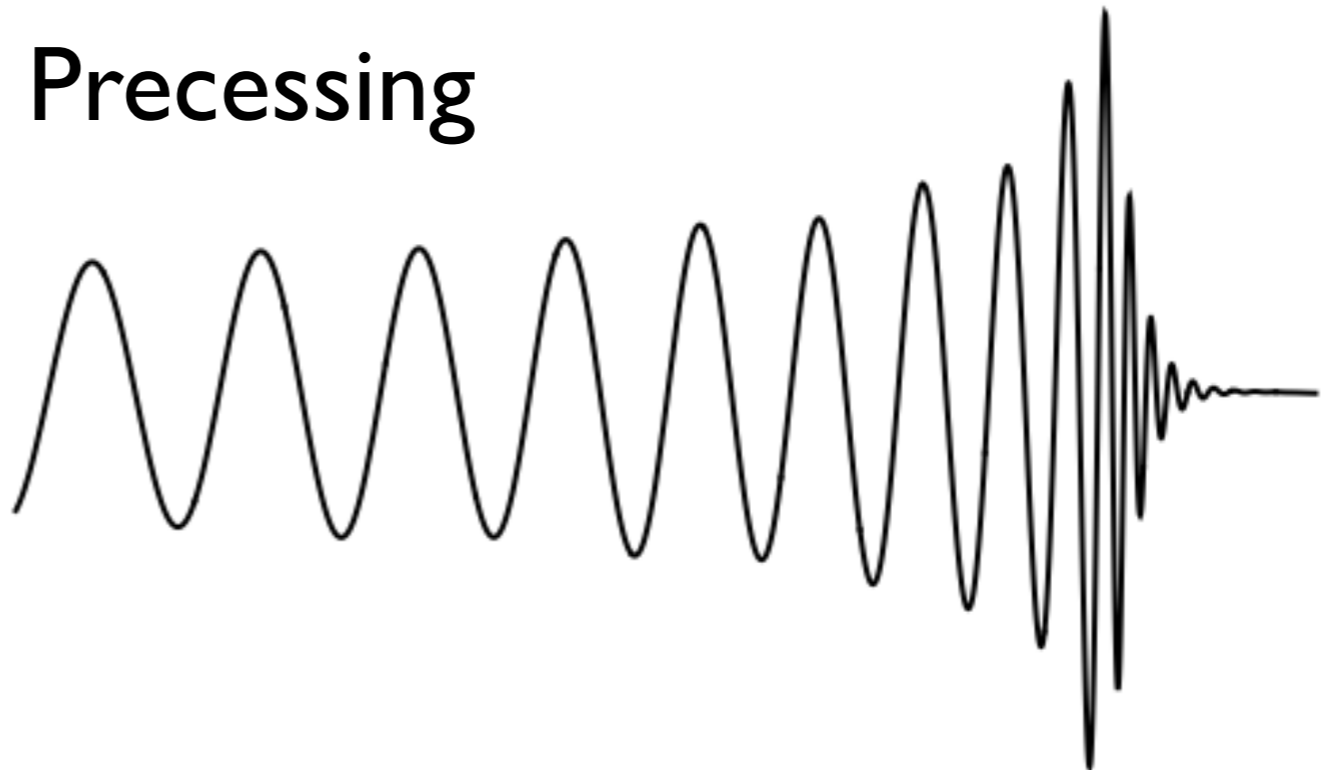


“Face-on”  
to the  
source

Non-preprocessing

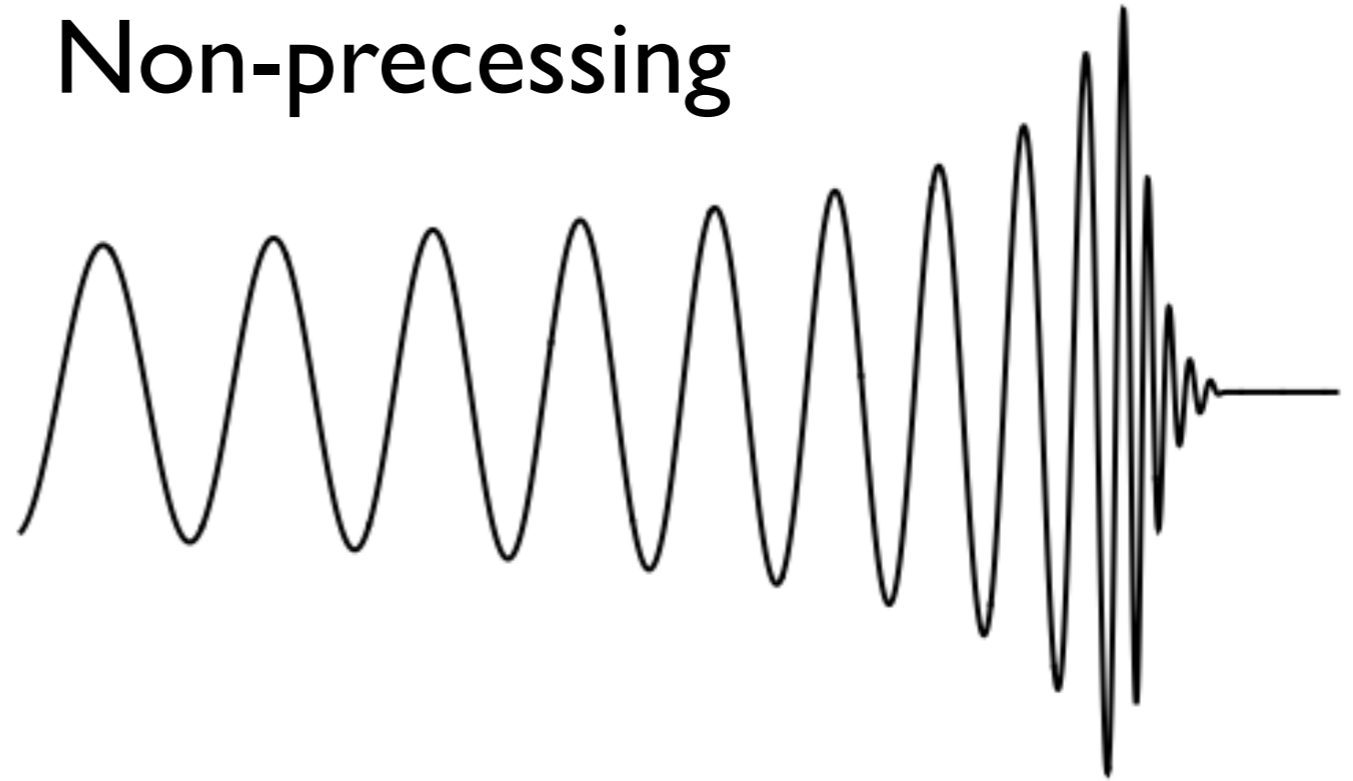


Preprocessing

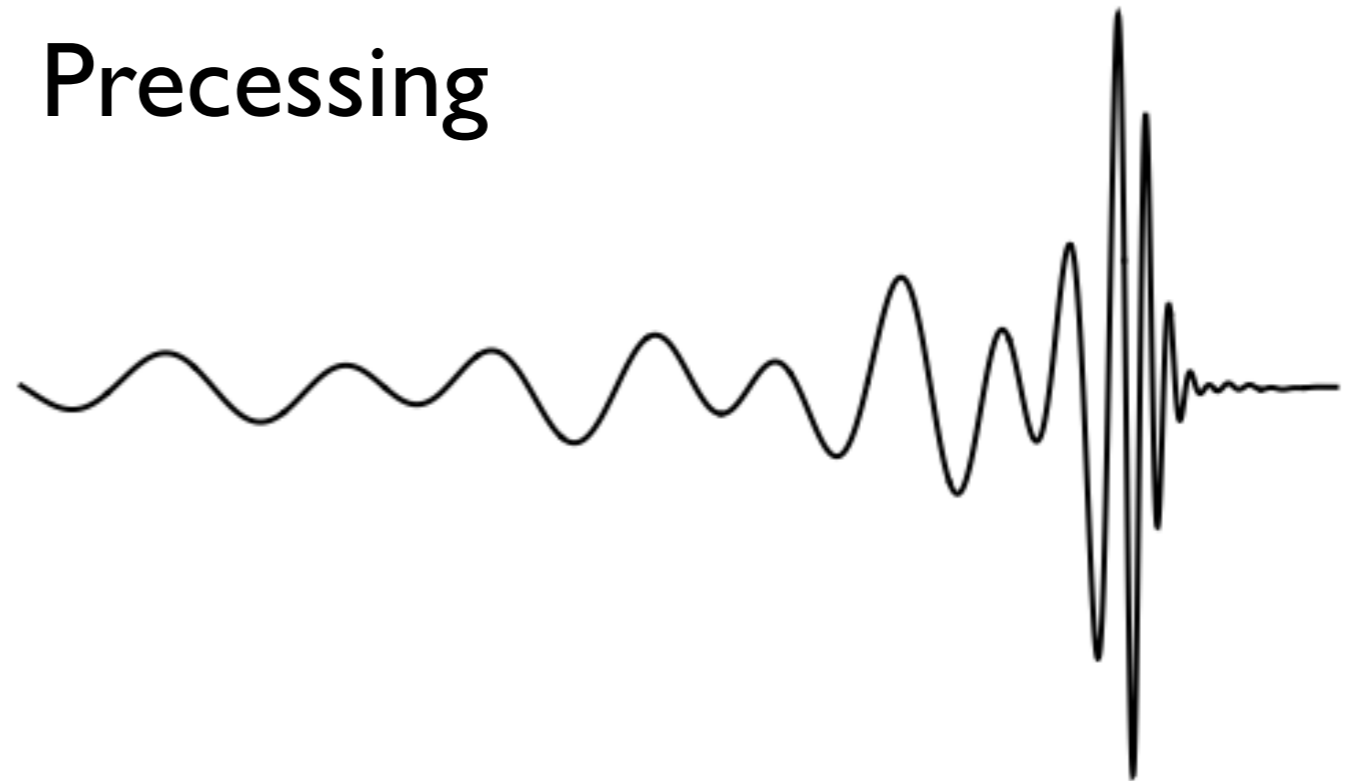


“Edge-on”  
to the  
source

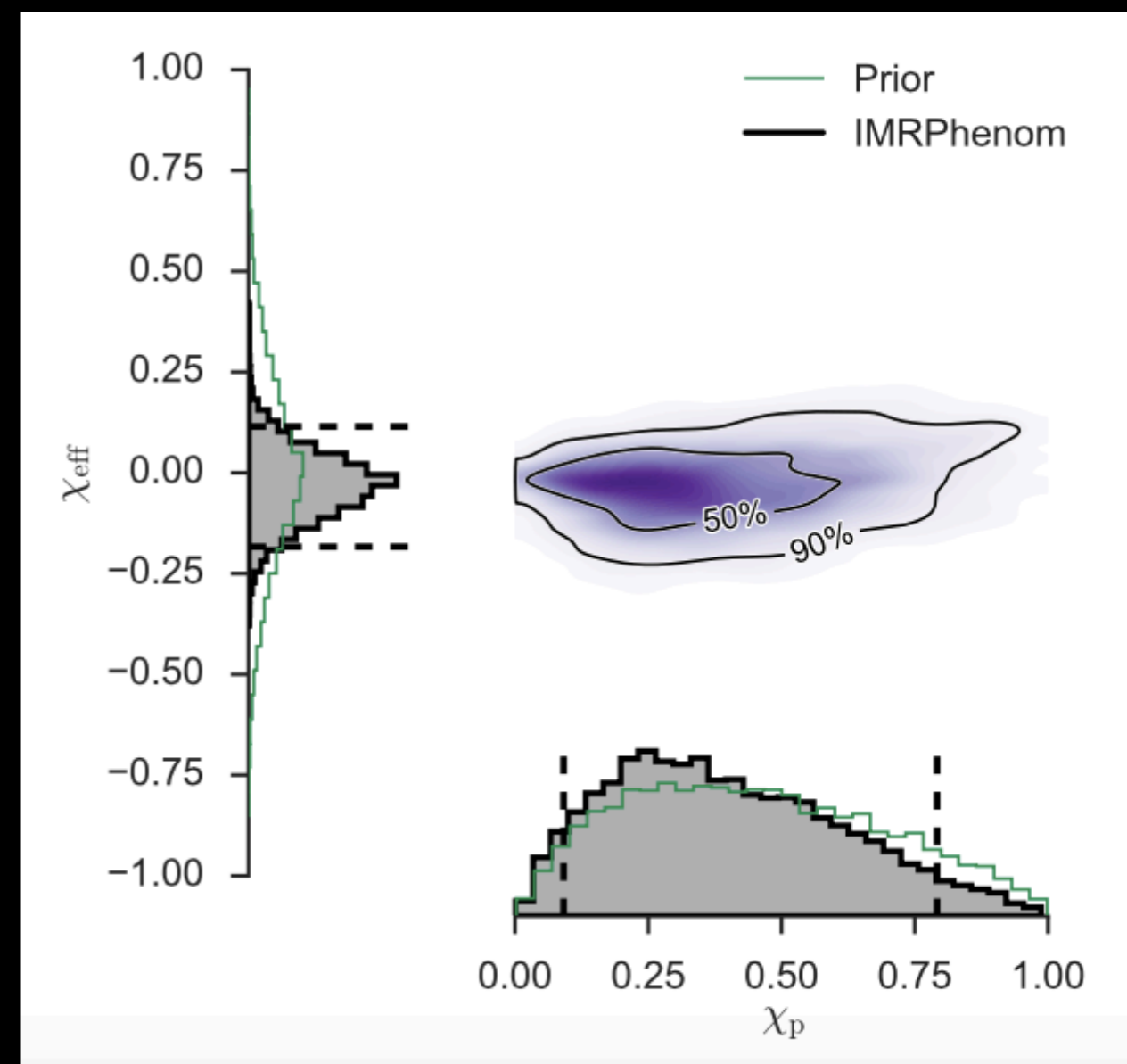
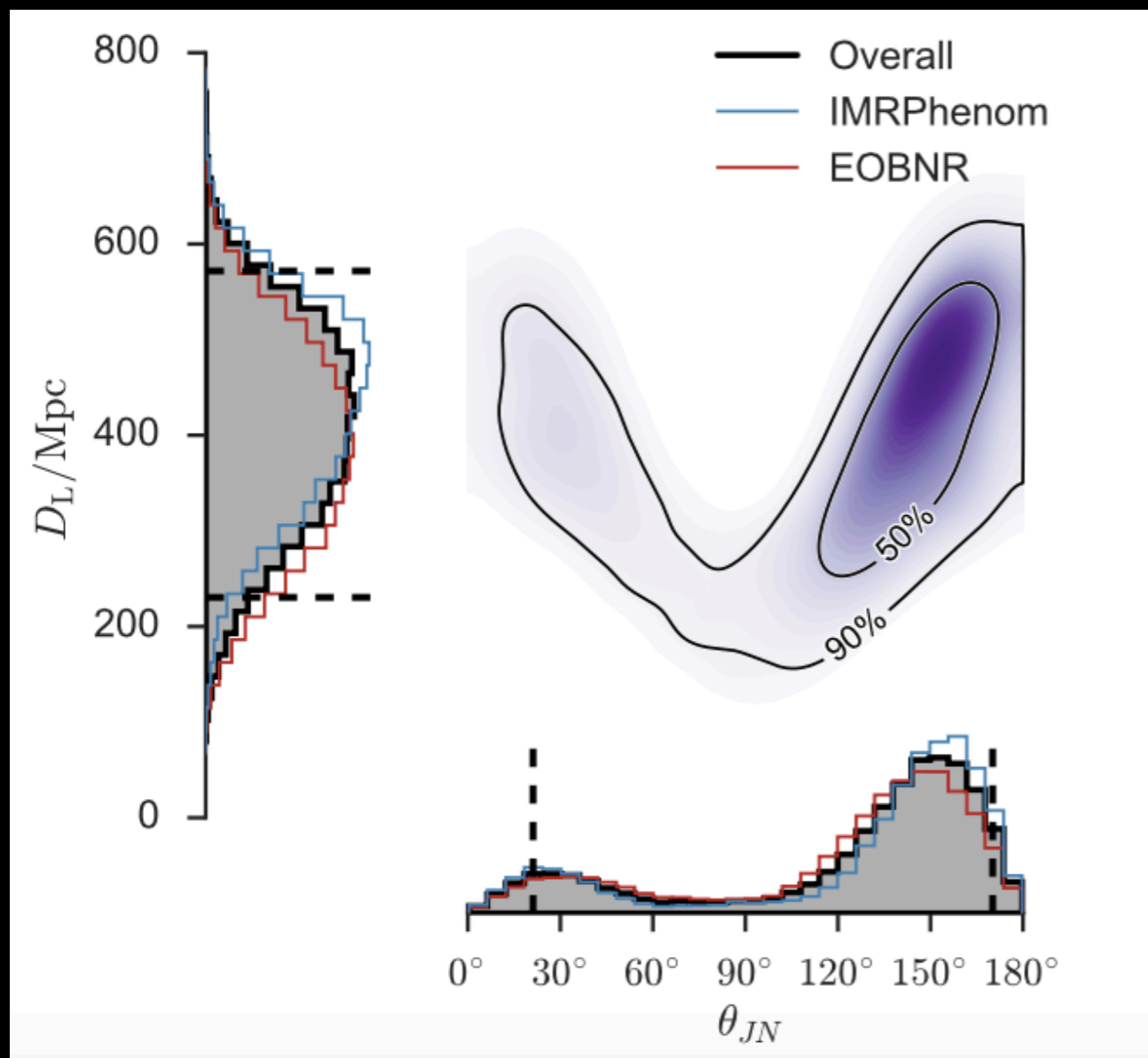
Non-precessing



Precessing





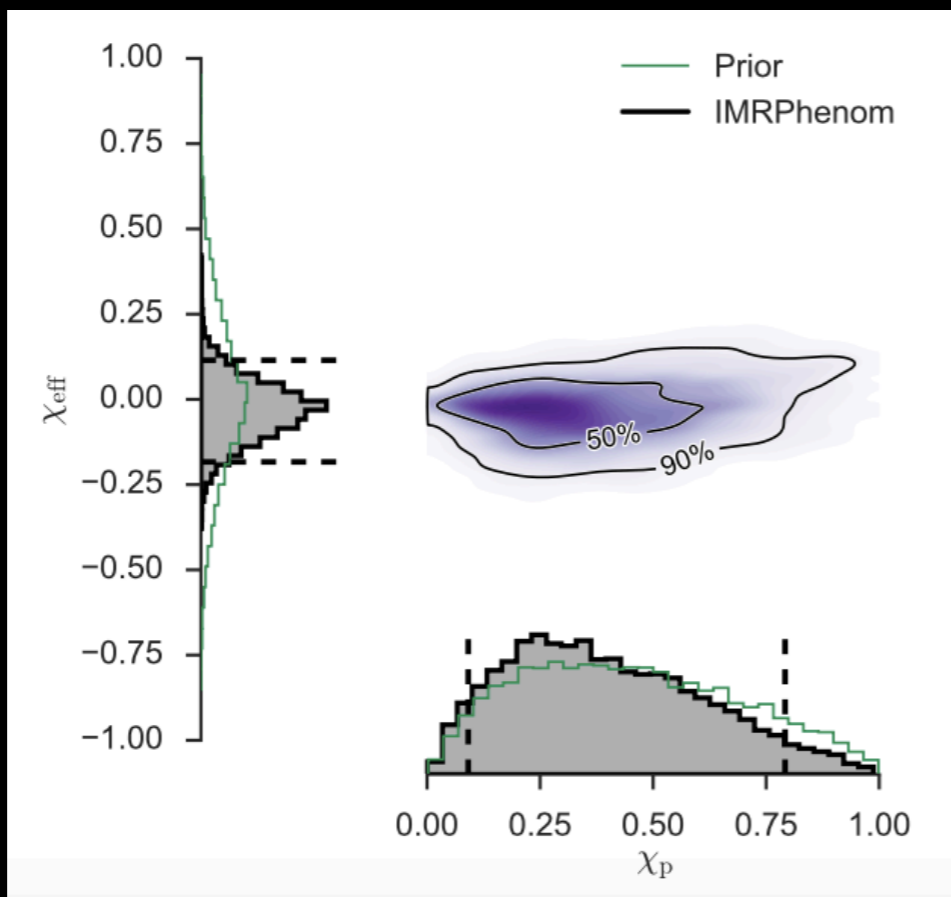
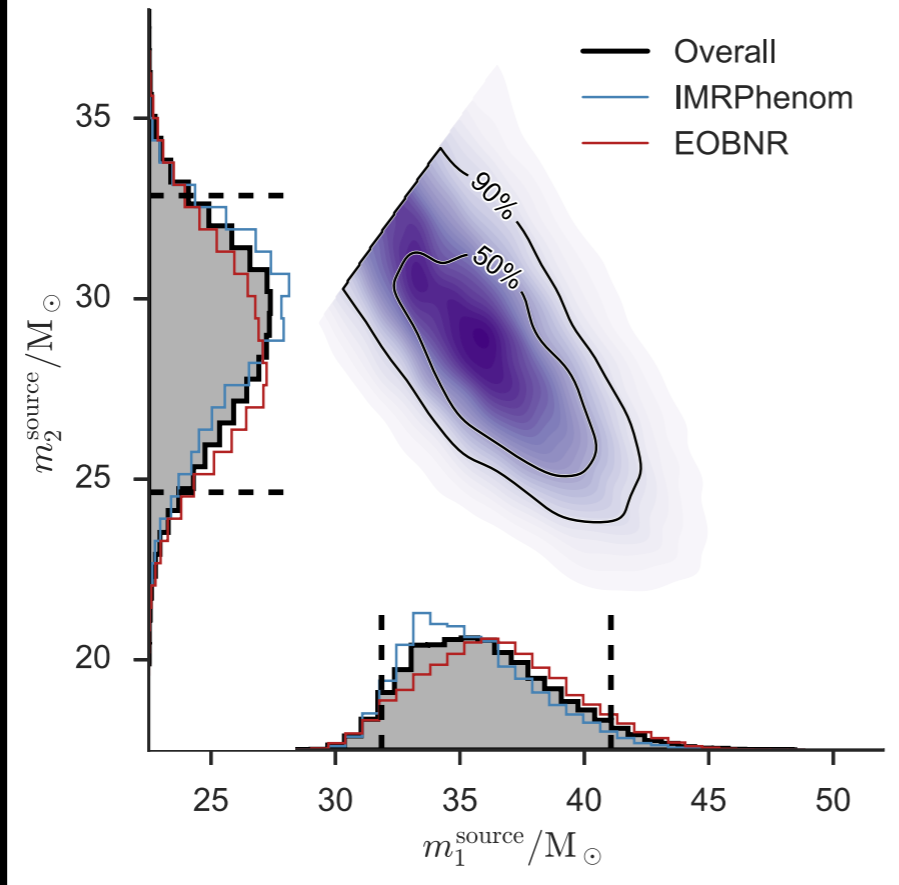


[LVC (2016)]

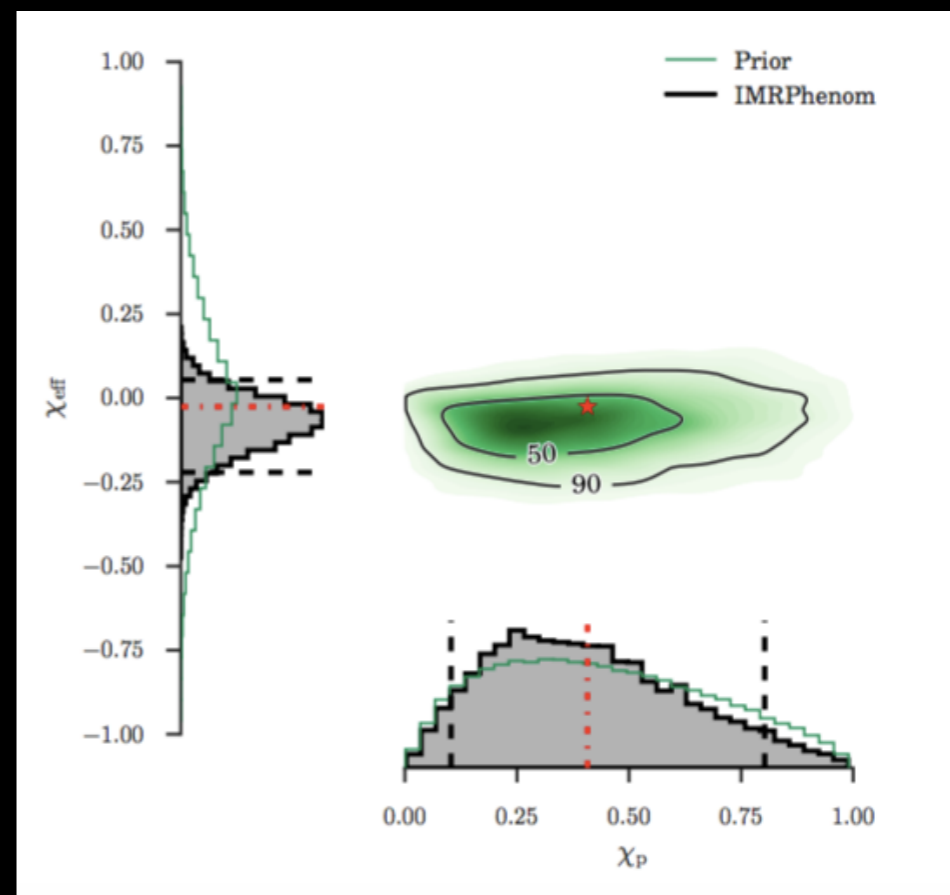
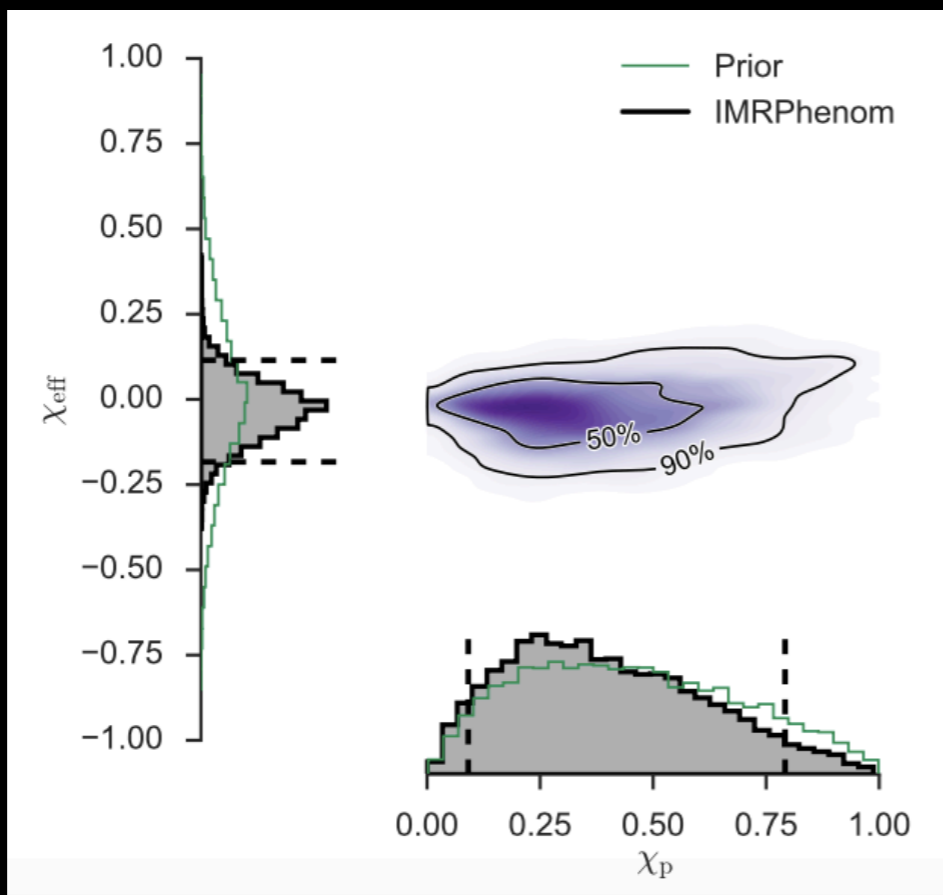
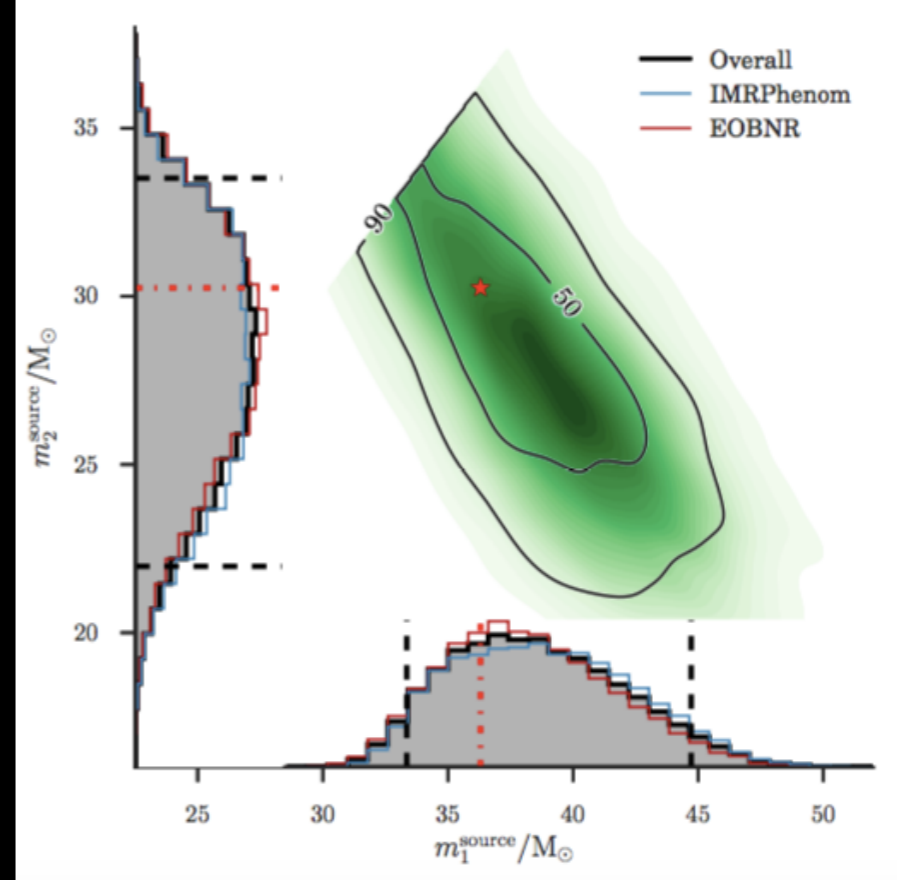
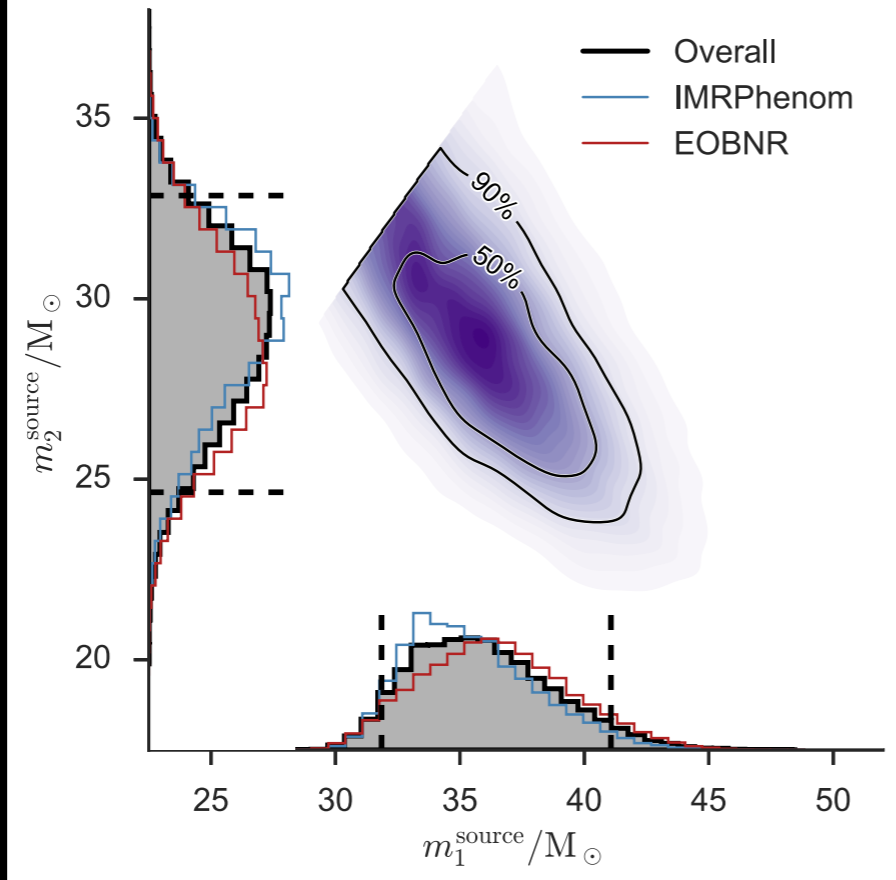
# Follow-up simulations

- Perform simulations near “best-guess” parameters
- Study systematic errors in the waveform models
- “Local” models could improve measurements
- 100s of simulations (SXS, Cardiff-UIB, GATech, RIT)
- DiRAC: 29 simulations on Cosma.
  - Required ~1 million CPU hours

# GW150914



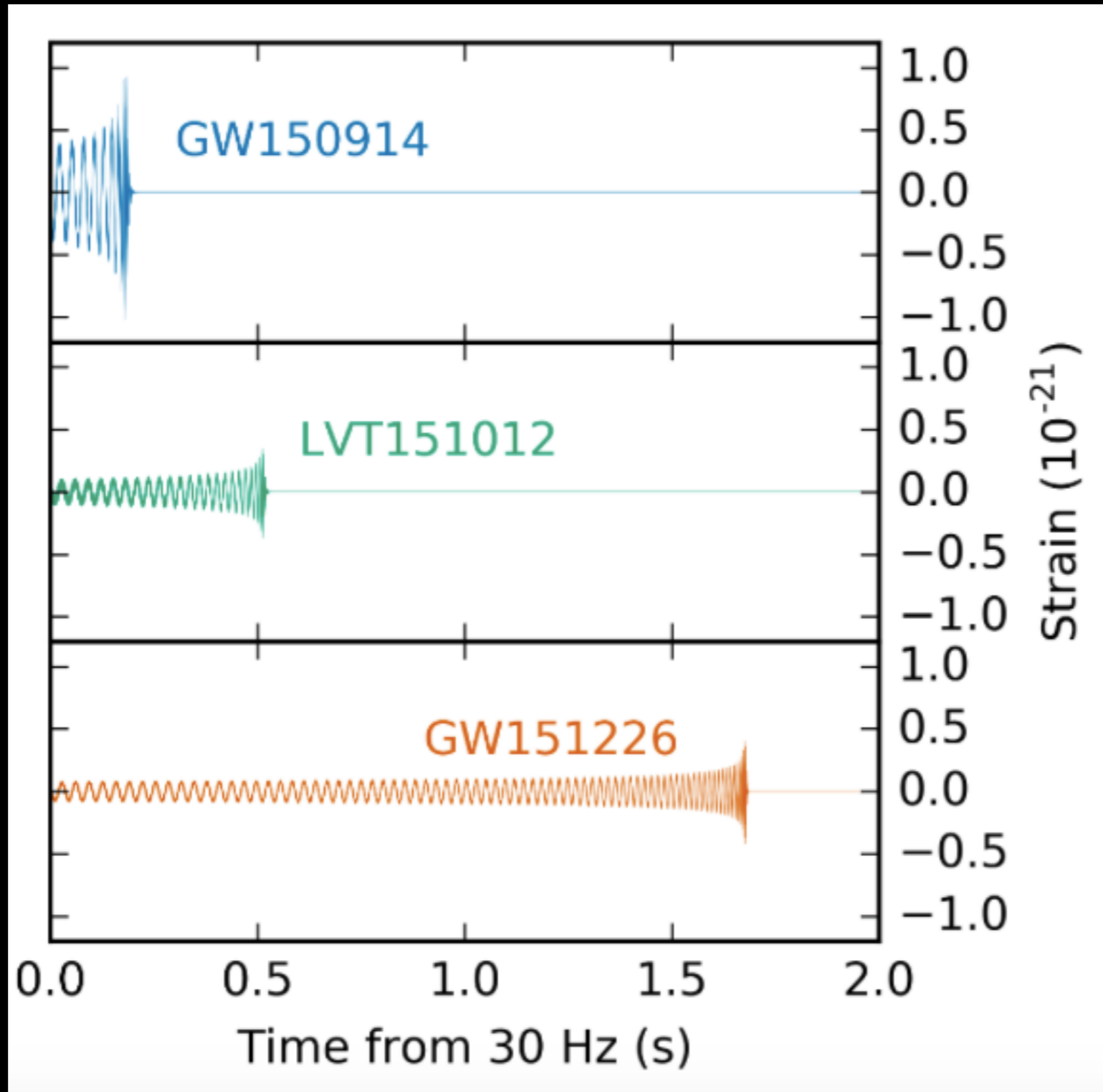
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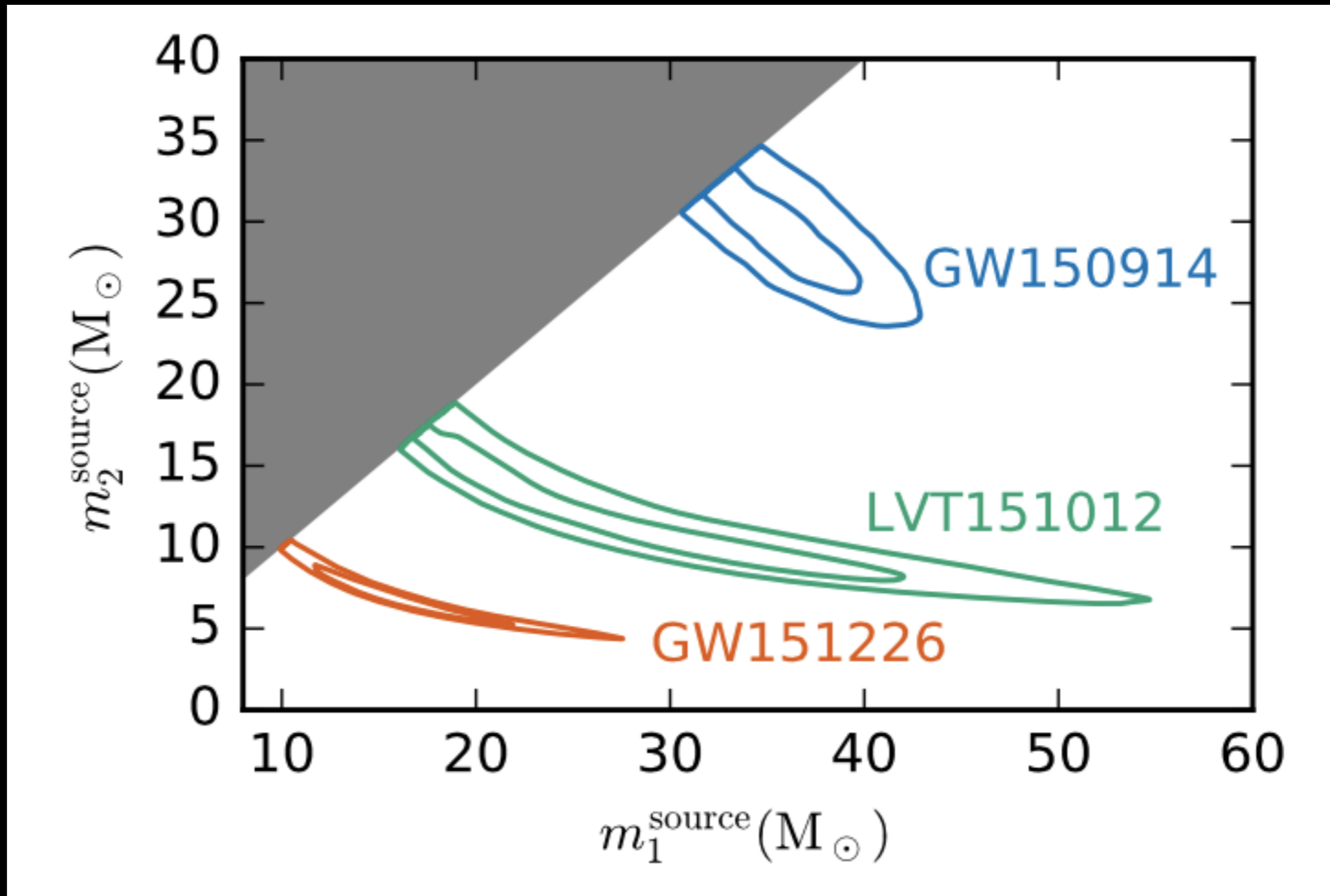
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[LVC, in preparation (2016)]

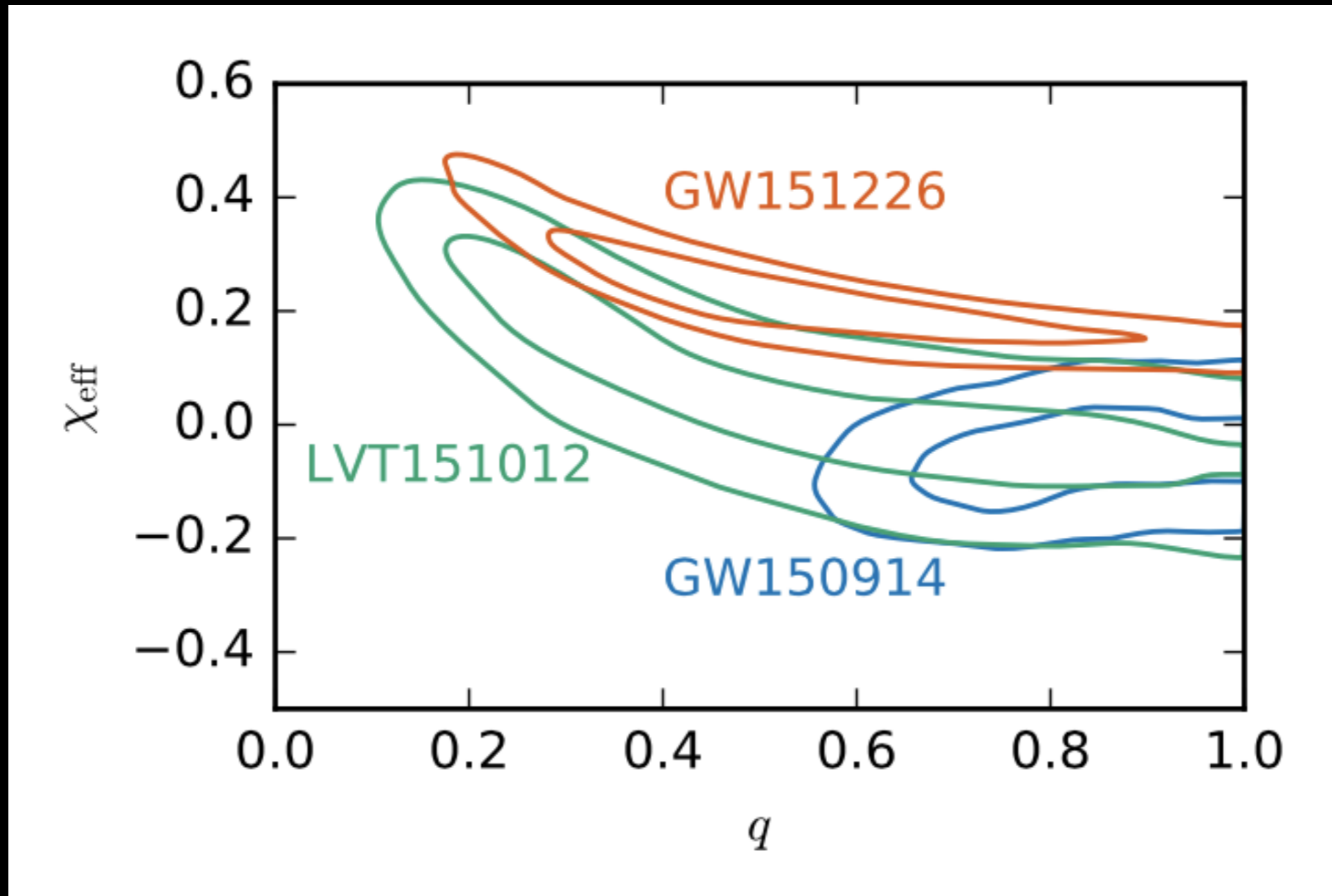
# All observations



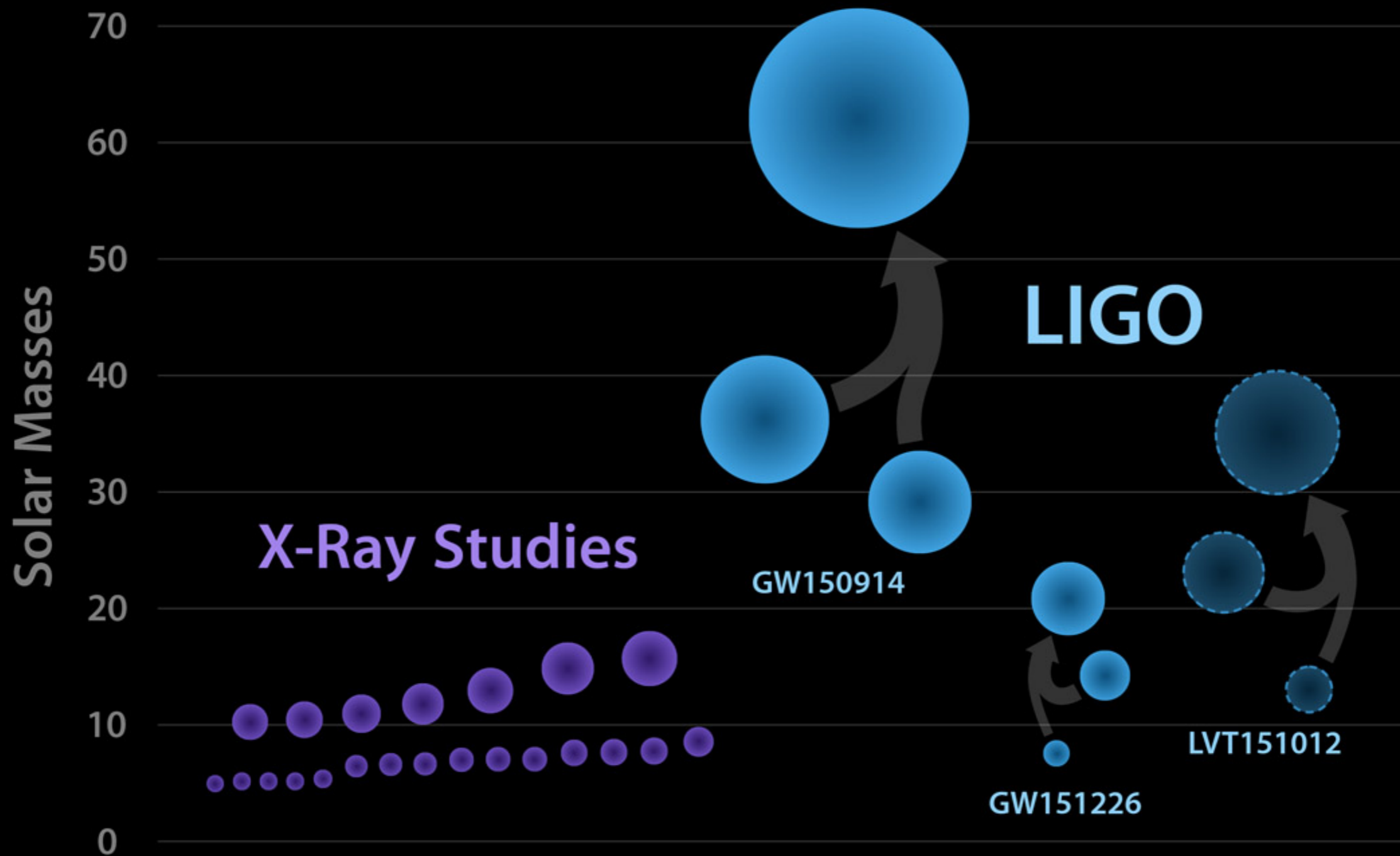
# All observations



# All observations

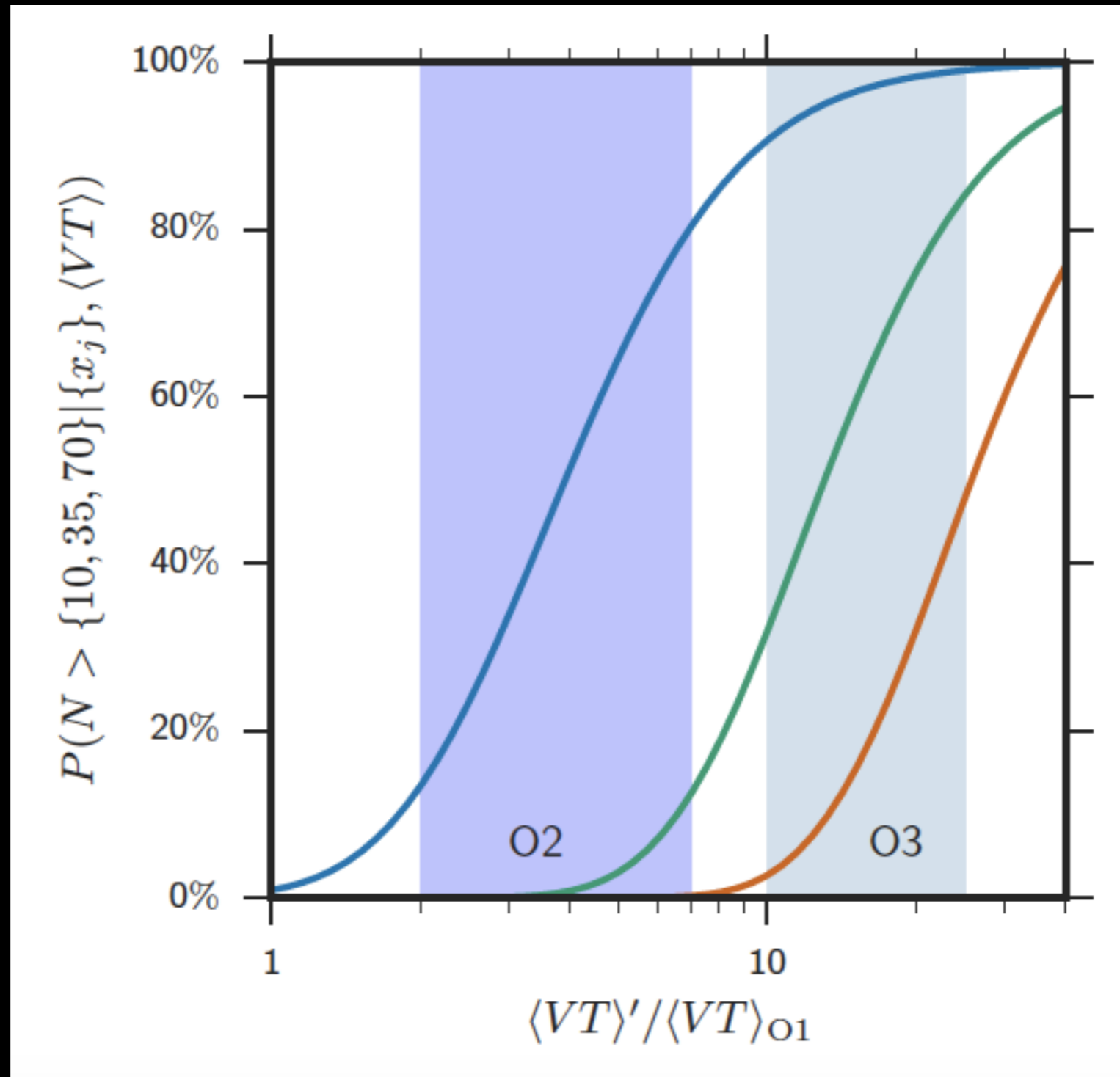


# Black Holes of Known Mass

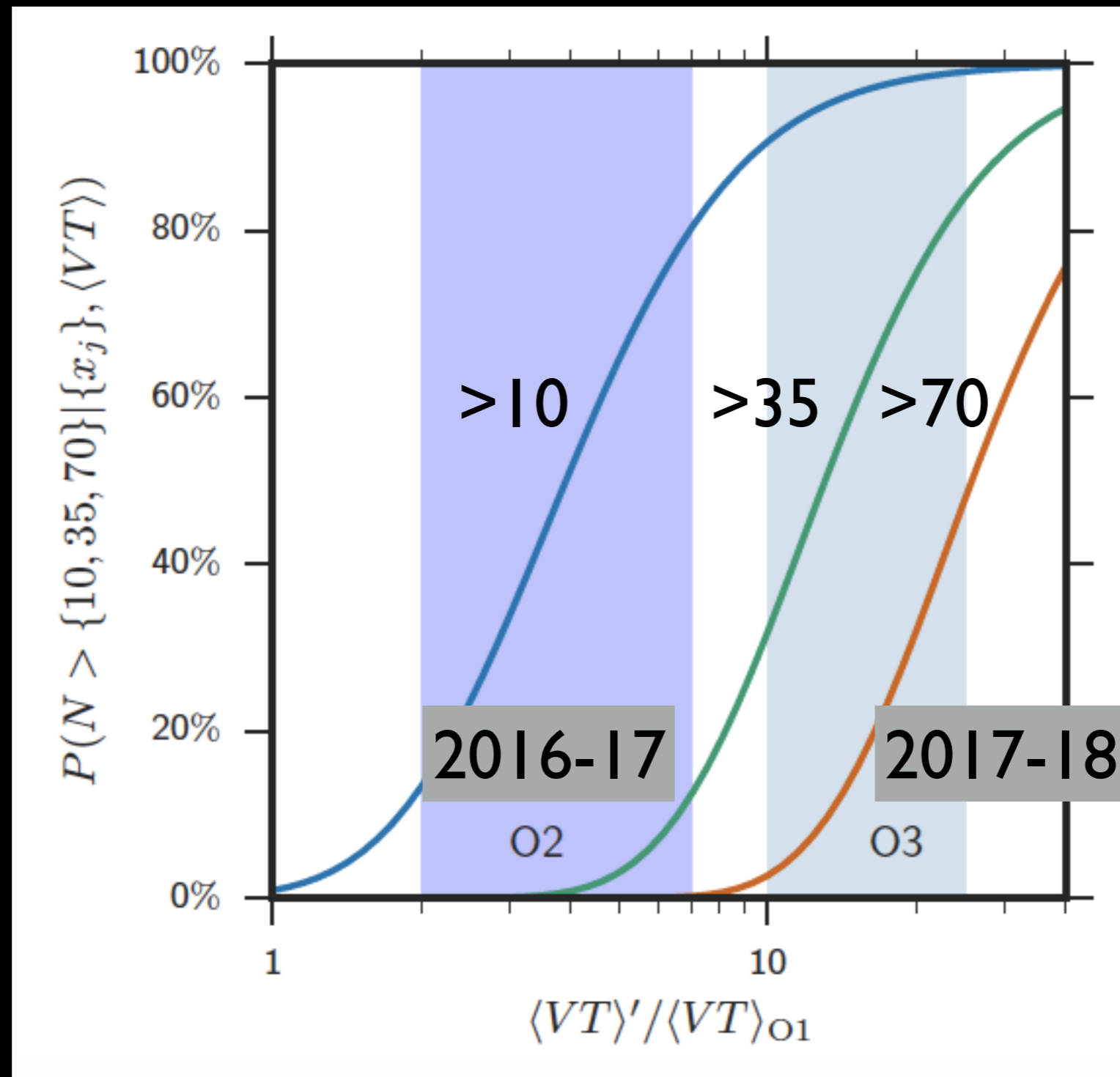




# Future observations



# Future observations



# The future

- The field of gravitational-wave astronomy has begun!
- 100s of black hole observations expected in next 5 years
- We need to be ready to extract the maximum science!
  
- For future signals, we will need better models:
  - higher harmonics
  - more precession physics
- A large NR simulation campaign is underway...