Detection and characterization of eccentric compact binary coalescence at the interface of analytical and numerical relativity and machine learning

Huerta et al, *Phys. Rev.* D 97, 024031 (2018)

Eliu Huerta
Gravity Group
gravity.ncsa.illinois.edu
National Center for Supercomputing Applications
Computer Science and Engineering
Department of Astronomy
University of Illinois at Urbana-Champaign

NCSA: Daniel George, Roland Haas, Daniel Johnson, Derek Glennon, Adam Rebei, Miguel Holgado
Chris Moore (IST-CENTRA), Prayush Kumar (Cornell), Alvin Chua (JPL),
Erik Wessel (University of Arizona), Jon Gair (Edinburgh), and Harald Pfeiffer (AEI/CITA)

2018 APS April Meeting, April 16, Columbus Ohio

Outline

Motivation

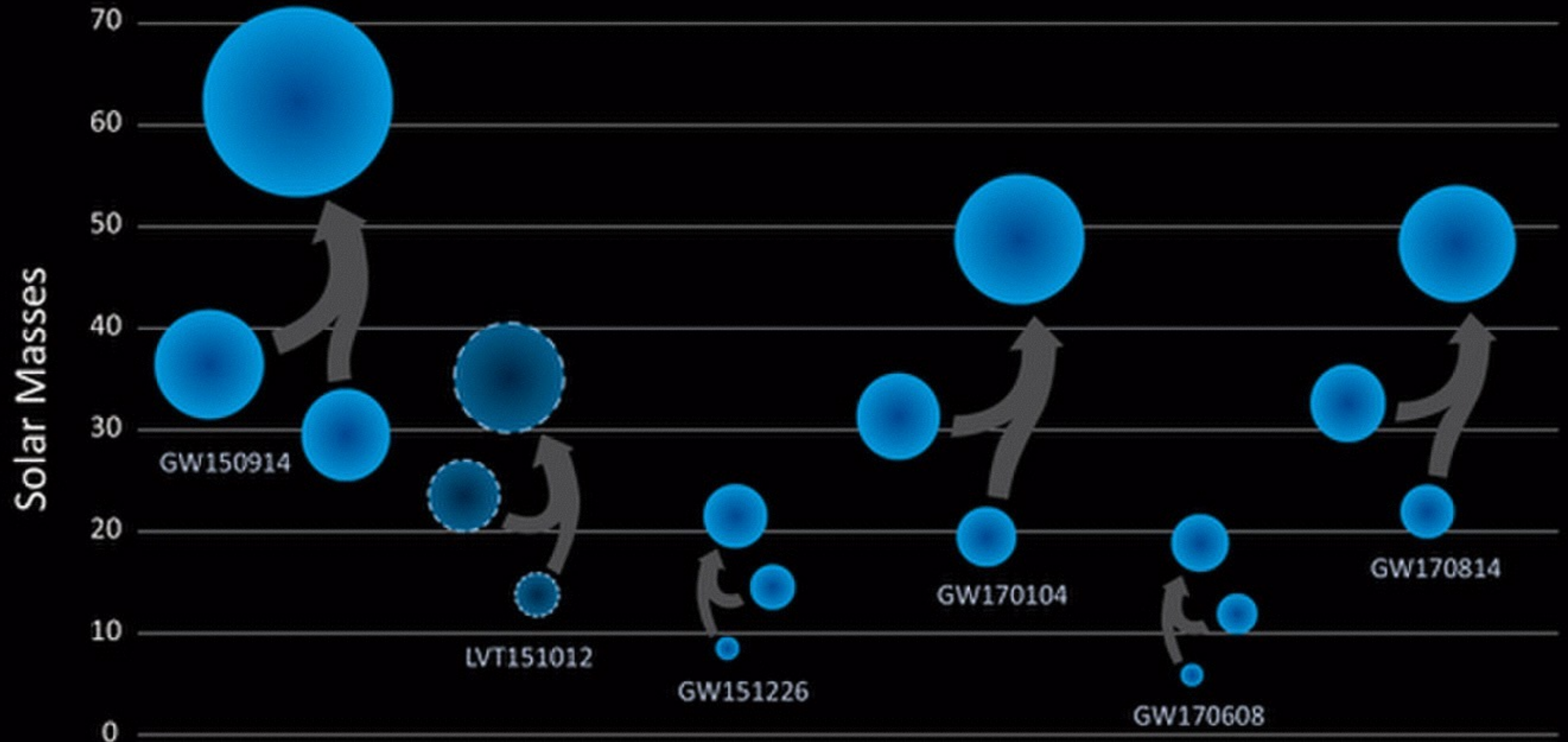
Recent results in the literature

State-of-the-art

Future work

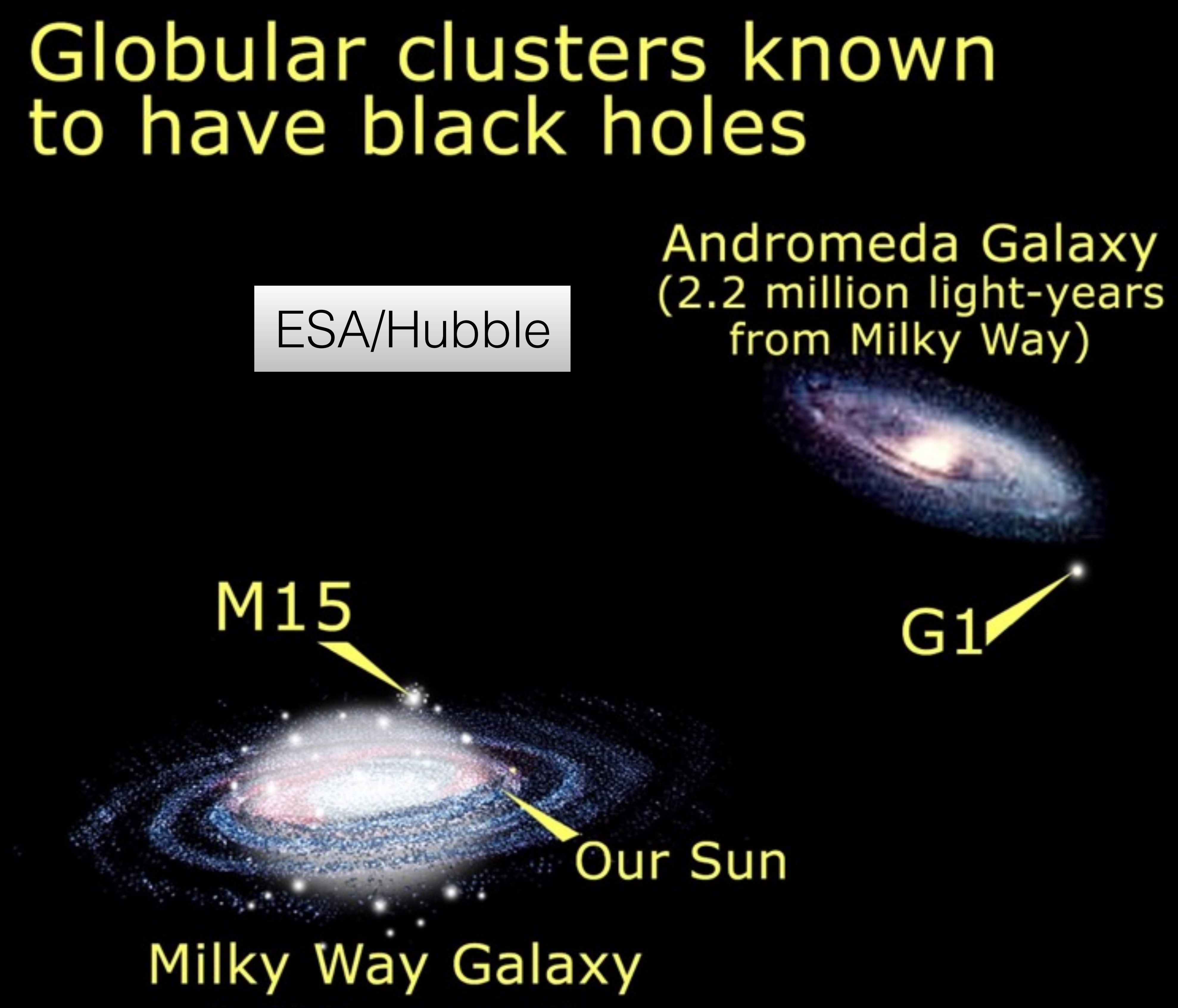
Black Holes of Known Mass

Are we close to routine detection?

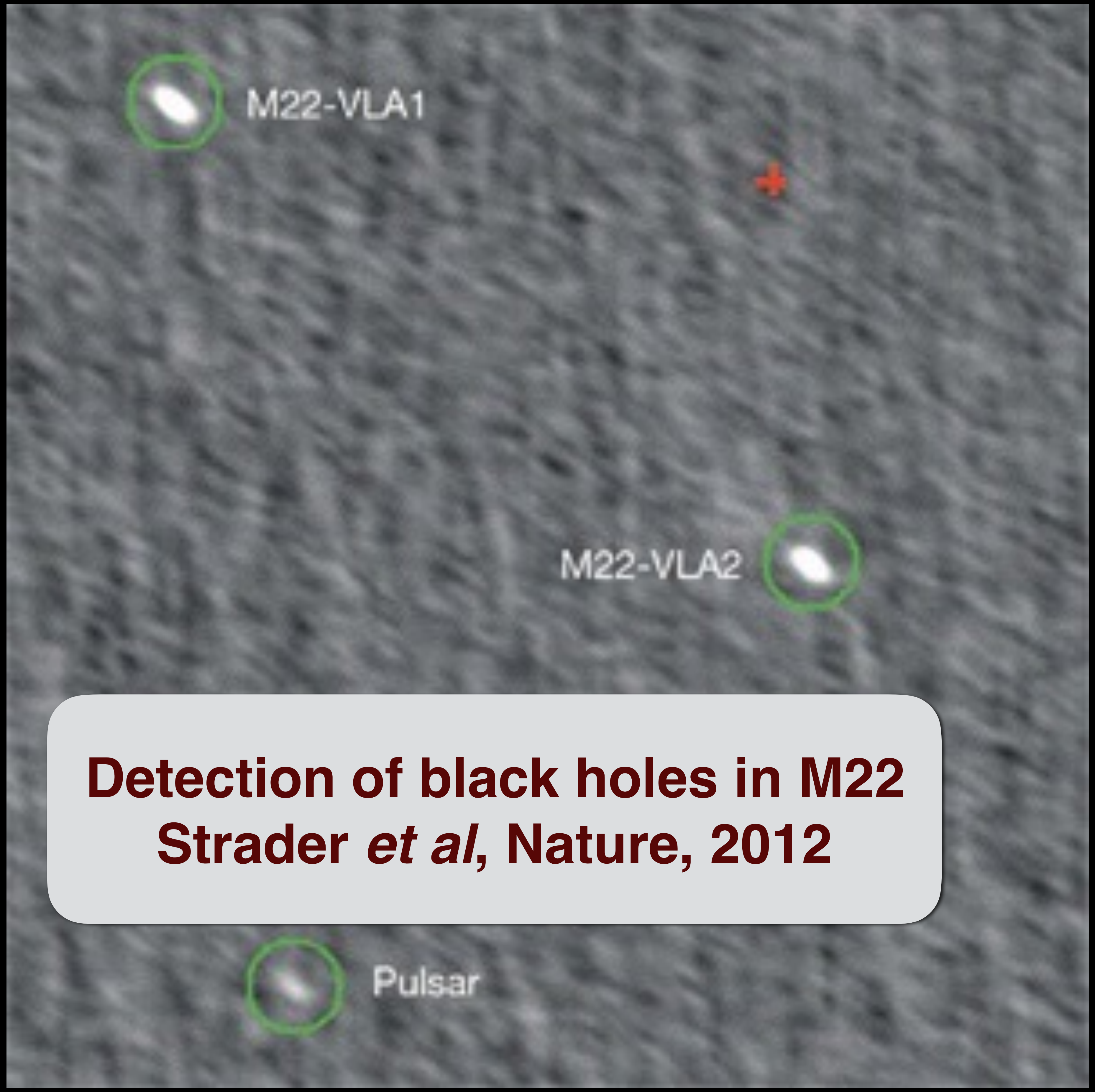


LIGO/VIRGO

Compact binary populations in dense stellar environments

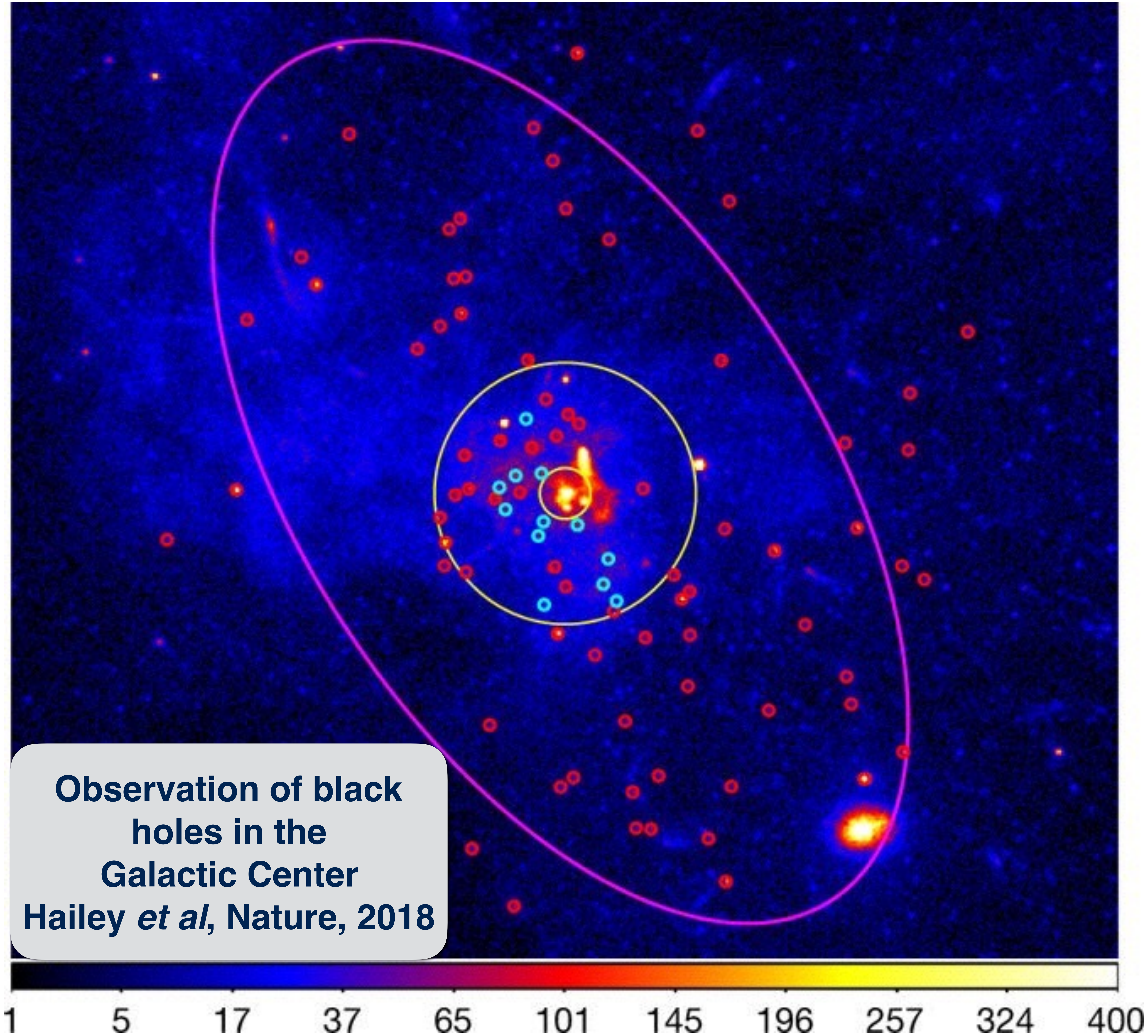


N-body algorithms predict existence of
compact binary populations in clusters
Antonini, ApJ, 2013



Eccentricity "cleanest signature"
of black hole mergers in clusters
Samsing, ApJ, 2014

Compact binary populations in dense stellar environments



Evidence of compact source populations both in Galactic Clusters and the Galactic Center

Search for compact binary populations in these environments is warranted!

Compact binary populations in dense stellar environments

Disclaimer: not a comprehensive list!

First detection of gravitational waves
LVC, PRL, 2016

No available tools to constrain eccentricity of first LVC detection
C Miller, GRG 2016

Unlikely to detect eccentric binary black hole mergers with LIGO
C Rodriguez, PRD 2016

First complete waveform model used to constrain eccentricity of first two black hole mergers
Huerta *et al*, PRD, 2017

Timeline to detection

Merger rate of eccentric black hole mergers under predicted by a factor of 100
Samsing, ApJ, 2017

Updated rate estimates for LIGO's eccentric mergers
Rodriguez *et al*, 2017

Boom of waveform modeling
Cao *et al*, PRD 96, 044028
Hinderer *et al*, PRD 96, 104048
Hinder *et al*, 1709.02007
Huerta *et al*, PRD 97, 024031

We got good ears, what else is needed?

Consider the source

Astrophysically motivated

Field Binaries
e=0

Abundant source modeling tools

Community efforts to streamline analyses

Search algorithms started development decades ago

Dense Stellar Environments
Non-negligible eccentricity

Dearth of source modeling tools

Difficult to search for and characterize

Signals may go unnoticed with existing detection algorithms

Push the frontiers of source modeling

Huerta *et al*, Phys. Rev. D 97, 024031 (2018)

Goal: measure deviations from quasi-circular motion

Assumption: eccentric systems circularize prior to merger

Solution I: analytical framework that describes both quasi-circular and eccentric systems

Solution II: Gaussian Process Emulator waveform trained with numerical relativity waveforms

Combine I and II to create ENIGMA:
Eccentric **N**onspinning **I**nspiral **G**aussian-process **M**erger **A**pproximant

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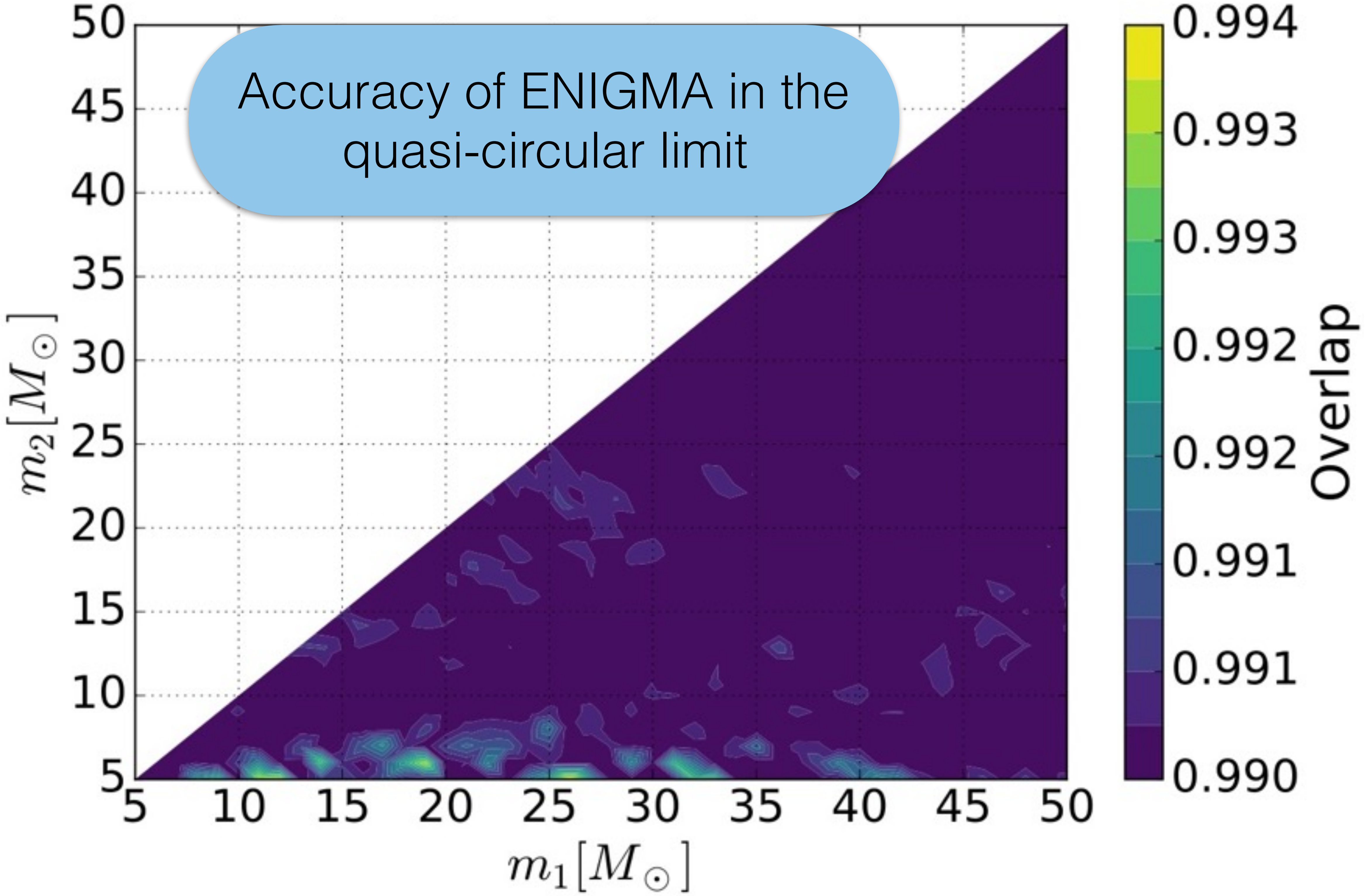
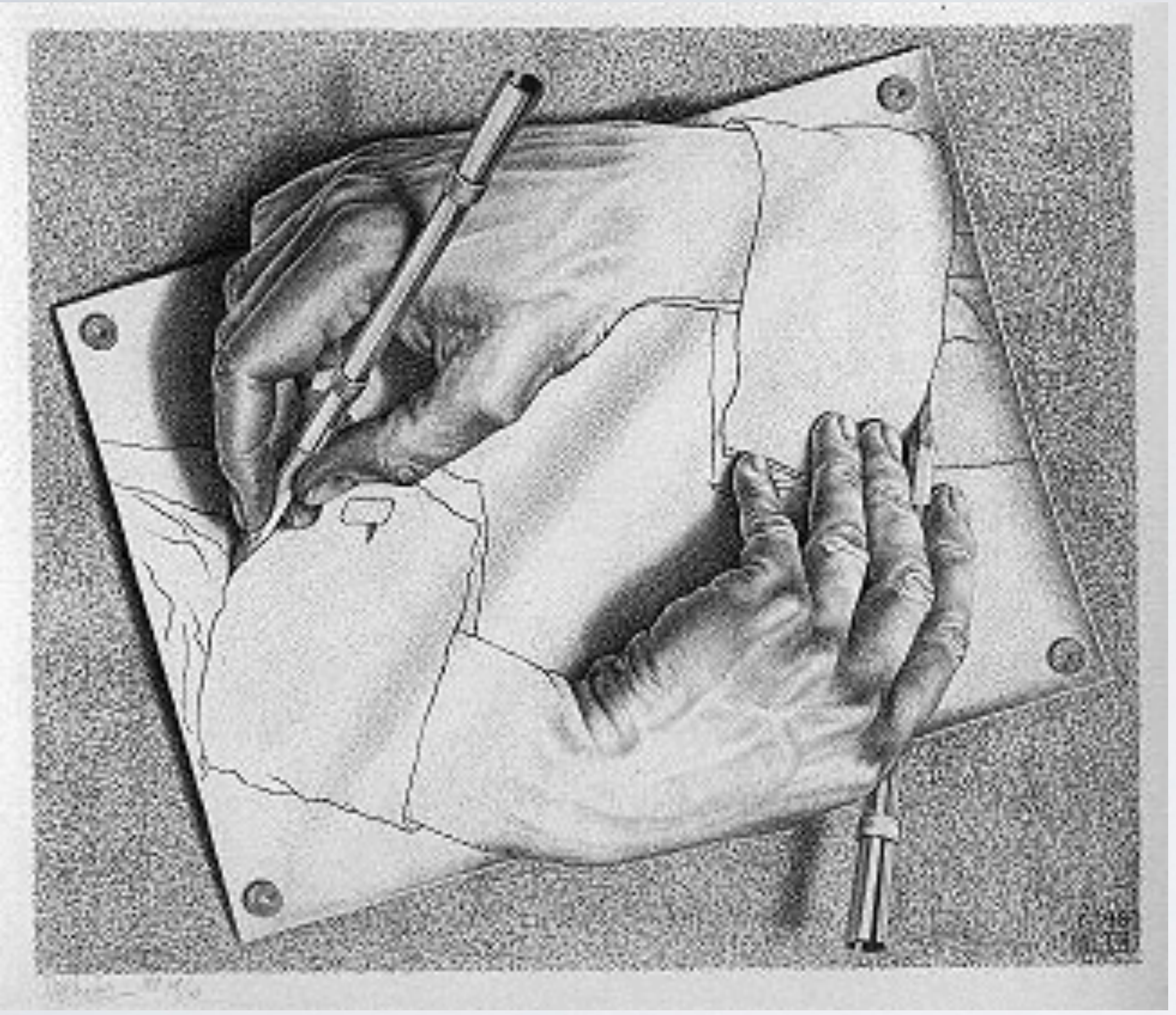
Accuracy of ENIGMA in the quasi-circular limit



Analytical Relativity



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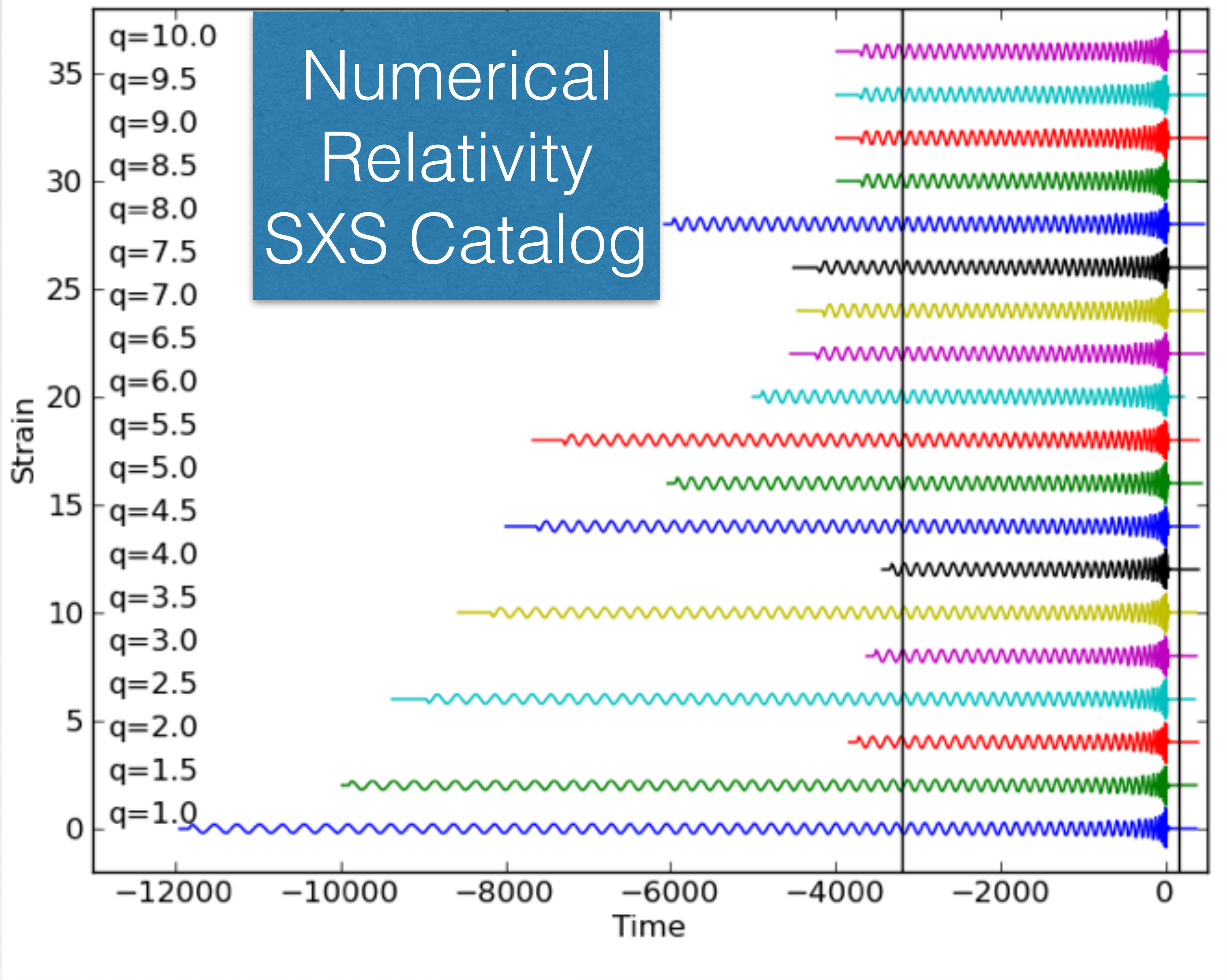
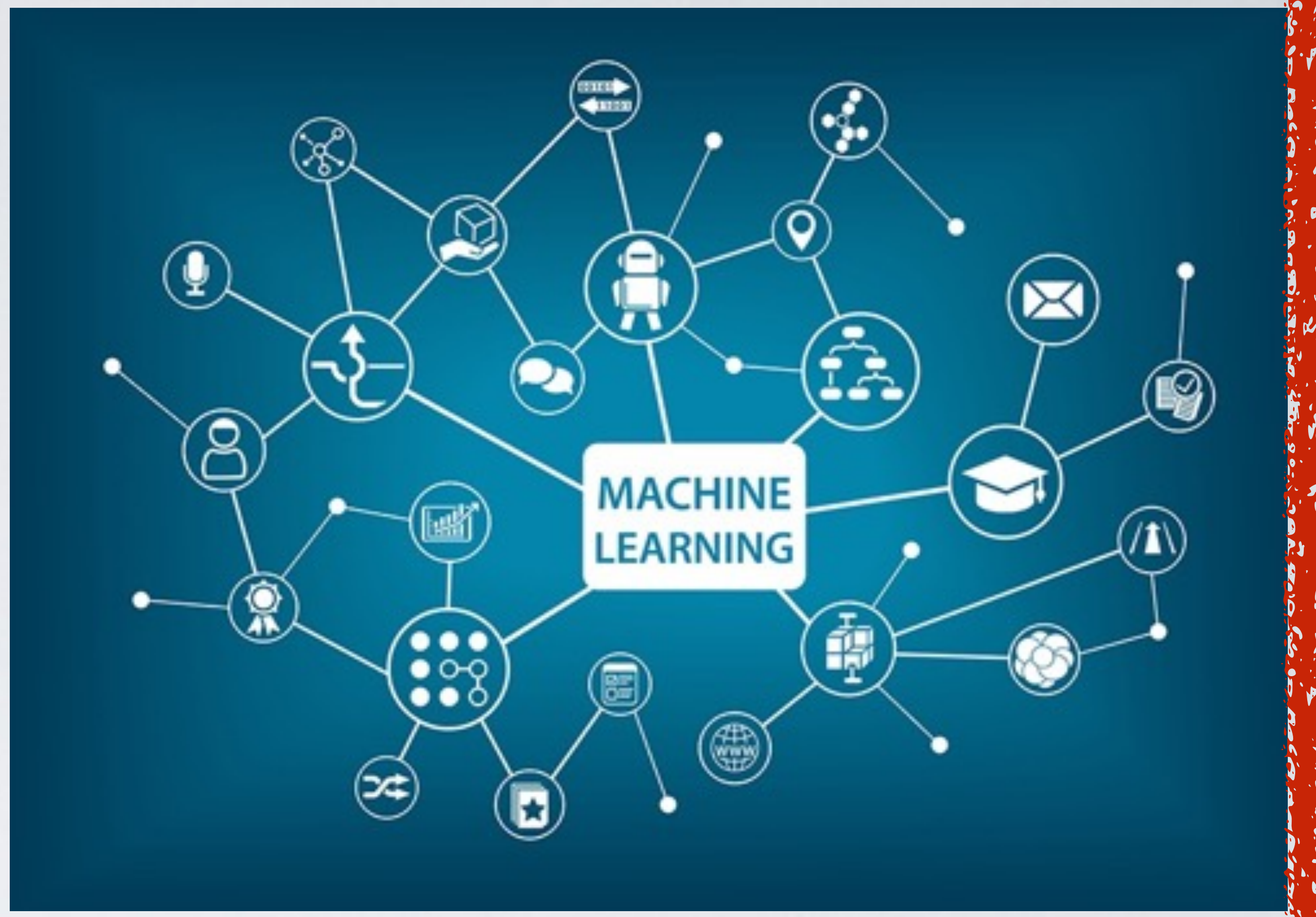
Numerical Relativity SXS Catalog





No resummations

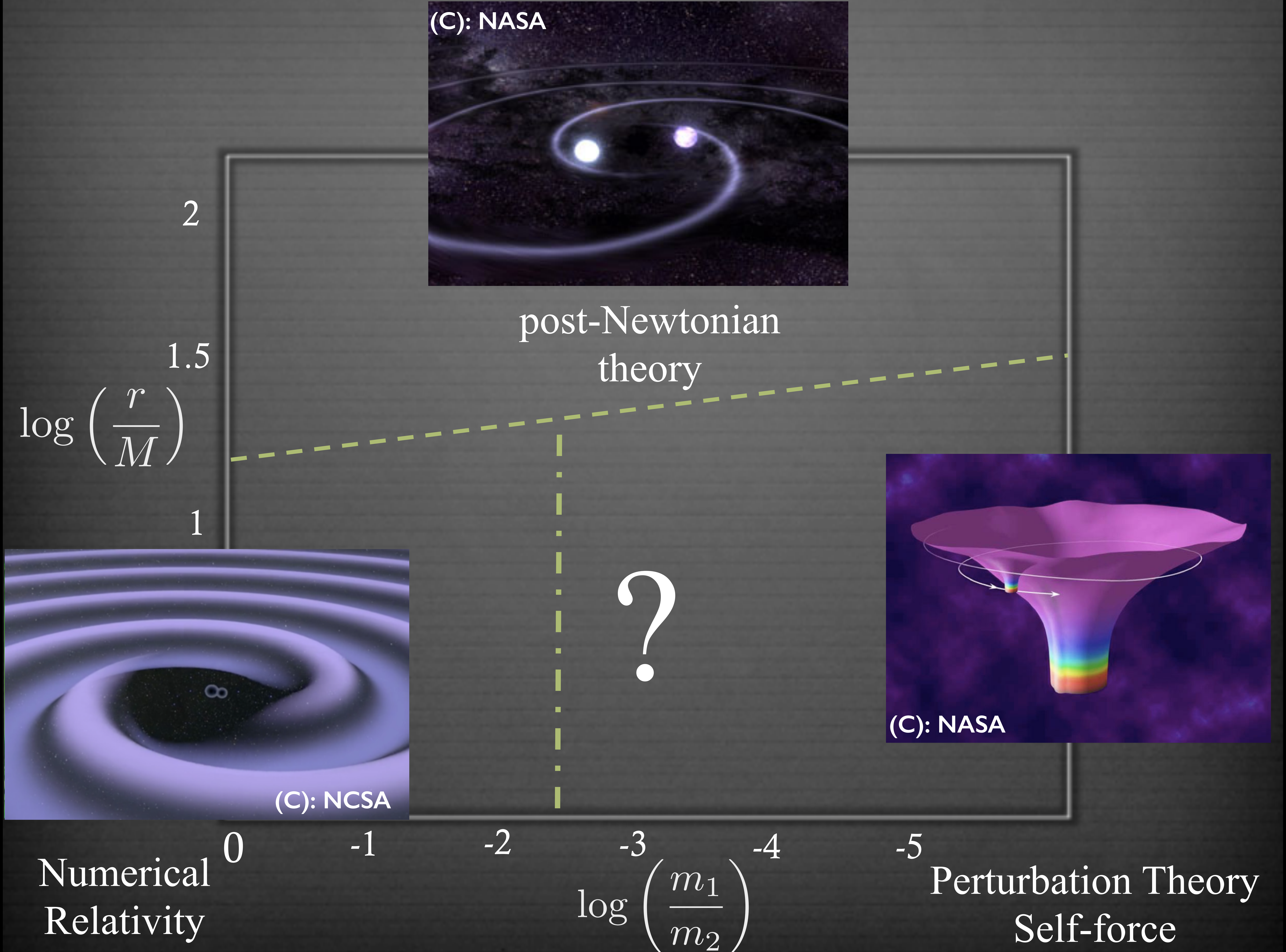
No free parameters

Blend in analytical and numerical relativity

ENIGMA

Stand alone merger waveform with NR quality

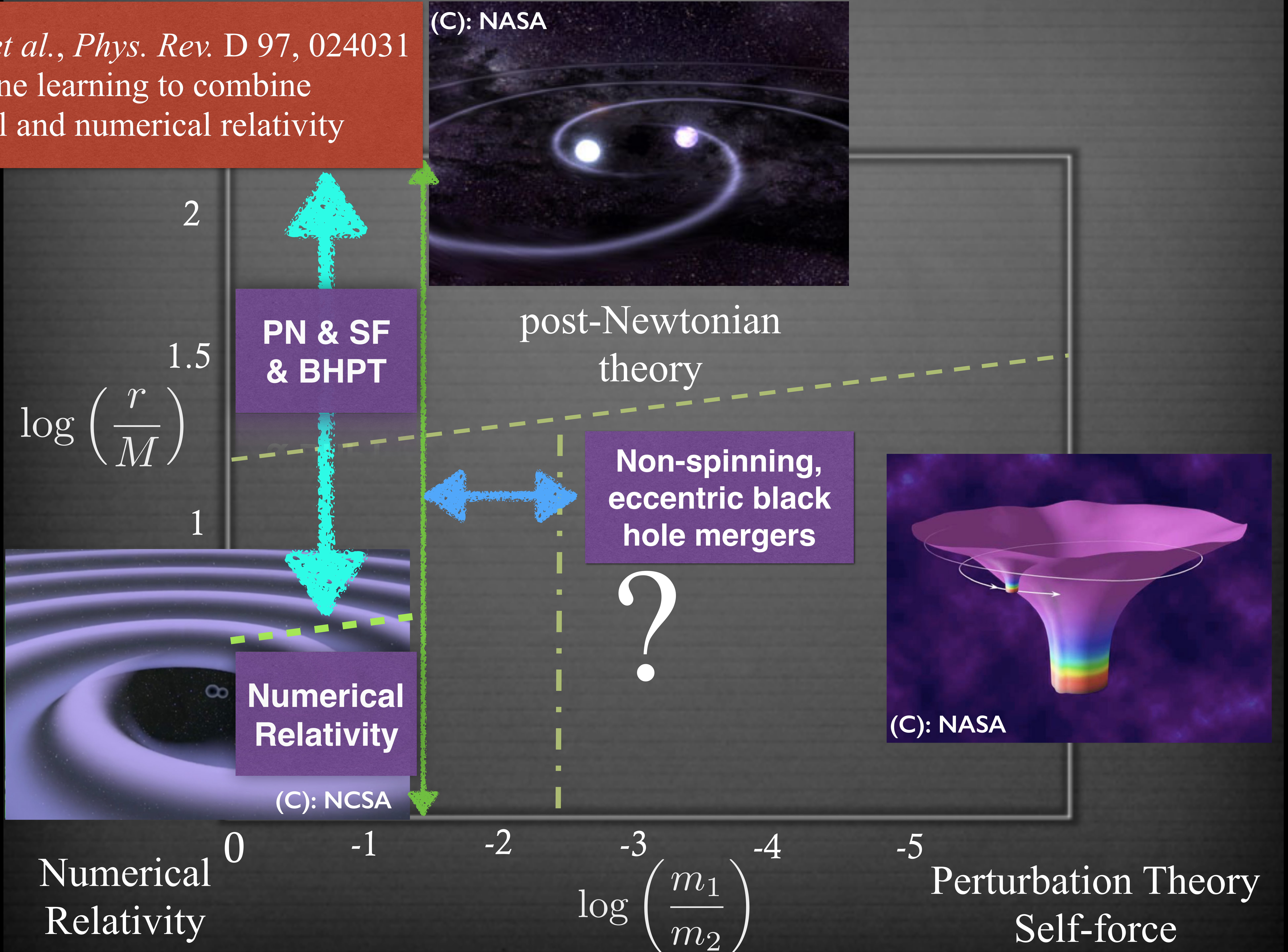
No phenomenology needed to model merger evolution



(C): NASA
post-Newtonian theory
2
1.5
$\log\left(\frac{r}{M}\right)$
1
?
(C): NASA
(C): NCSA
0
-1
-2
-3
-4
-5
Numerical Relativity
$\log\left(\frac{m_1}{m_2}\right)$
Perturbation Theory Self-force

E. A. Huerta *et al.*, *Phys. Rev.* D 97, 024031

Machine learning to combine analytical and numerical relativity



ENIGMA

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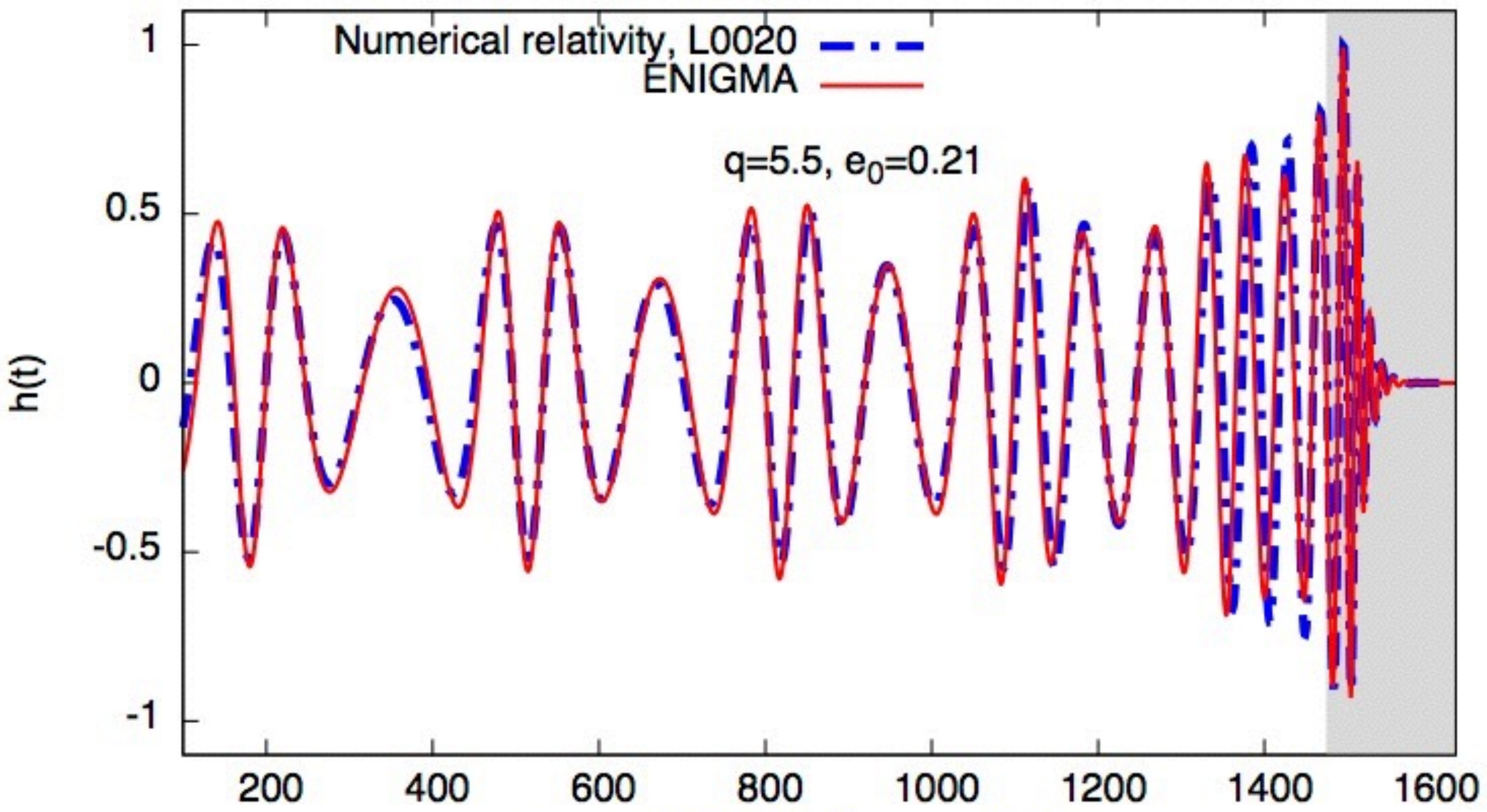
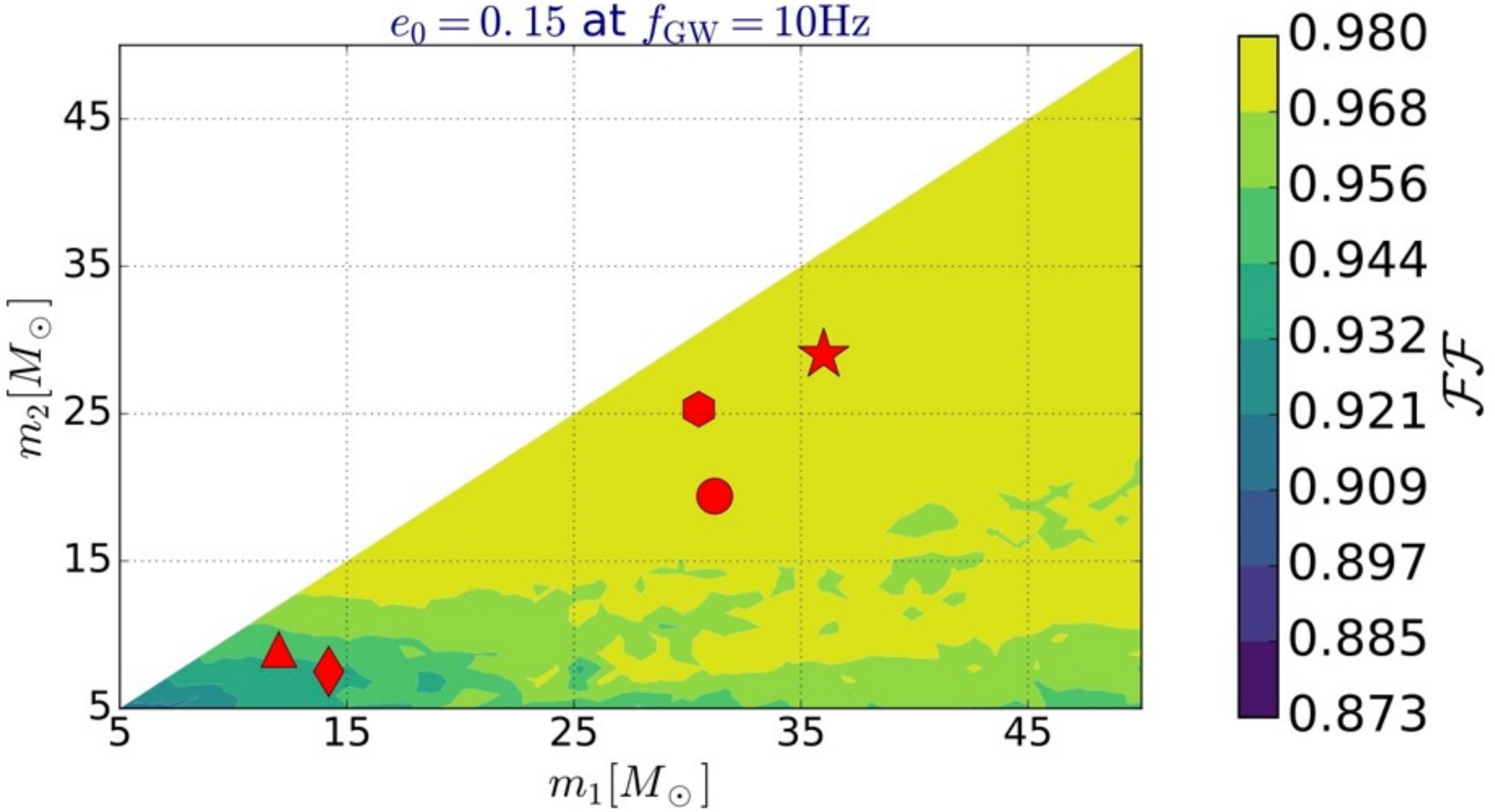


Encapsulates the dynamics of quasi-circular and eccentric black hole mergers

Validated with numerical relativity simulations

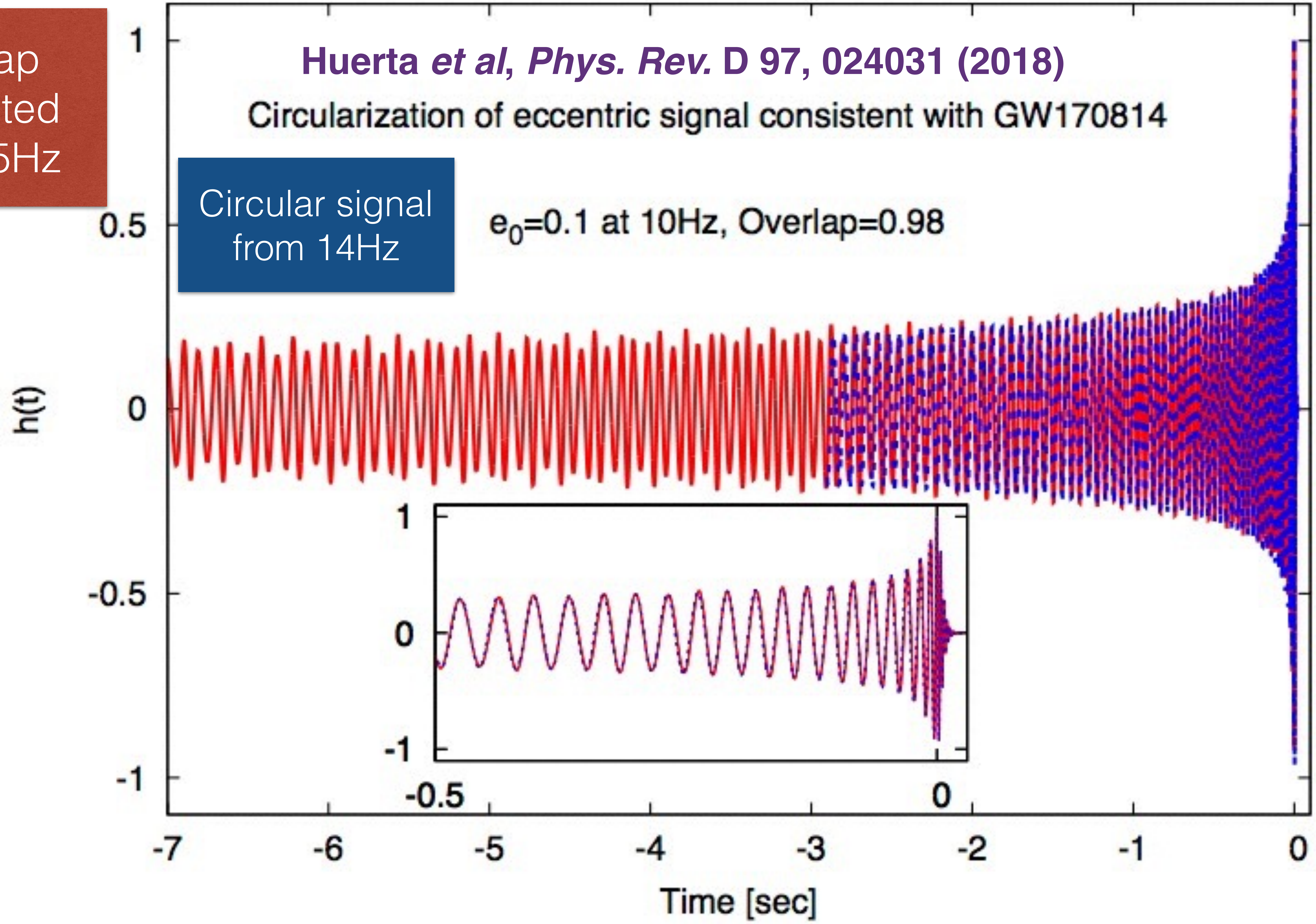


Spin and eccentricity lead to parameter degeneracies

Moderately eccentric signals at lower frequencies may be undistinguishable from circular ones

ENIGMA

Overlap computed from 15Hz

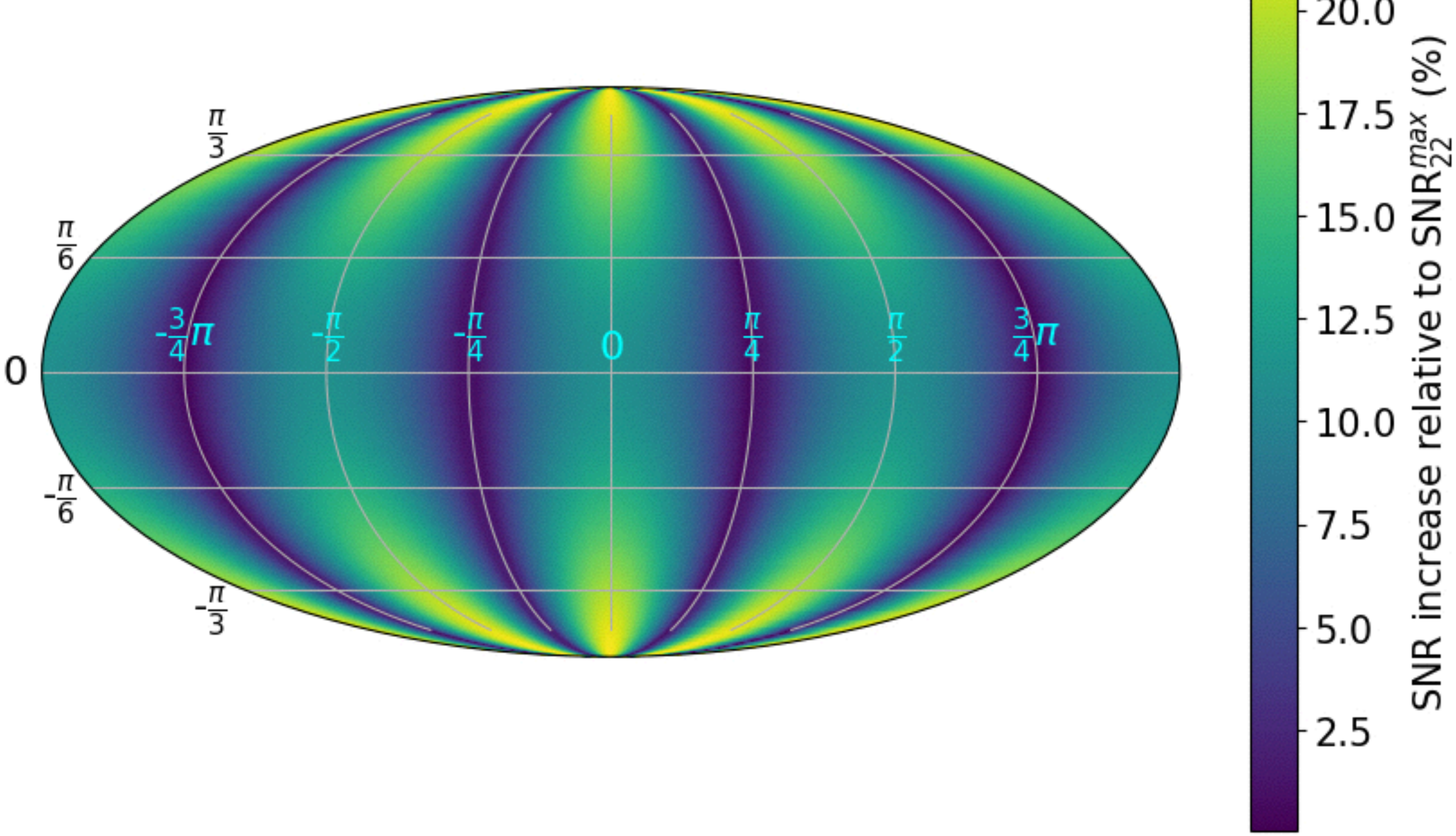


Improved sensitivity will help identify eccentricity content at lower frequencies

What about higher order modes?

Adam Rebei

Rebei et al, in preparation



Essential to search for asymmetric mass-ratio binary black hole mergers

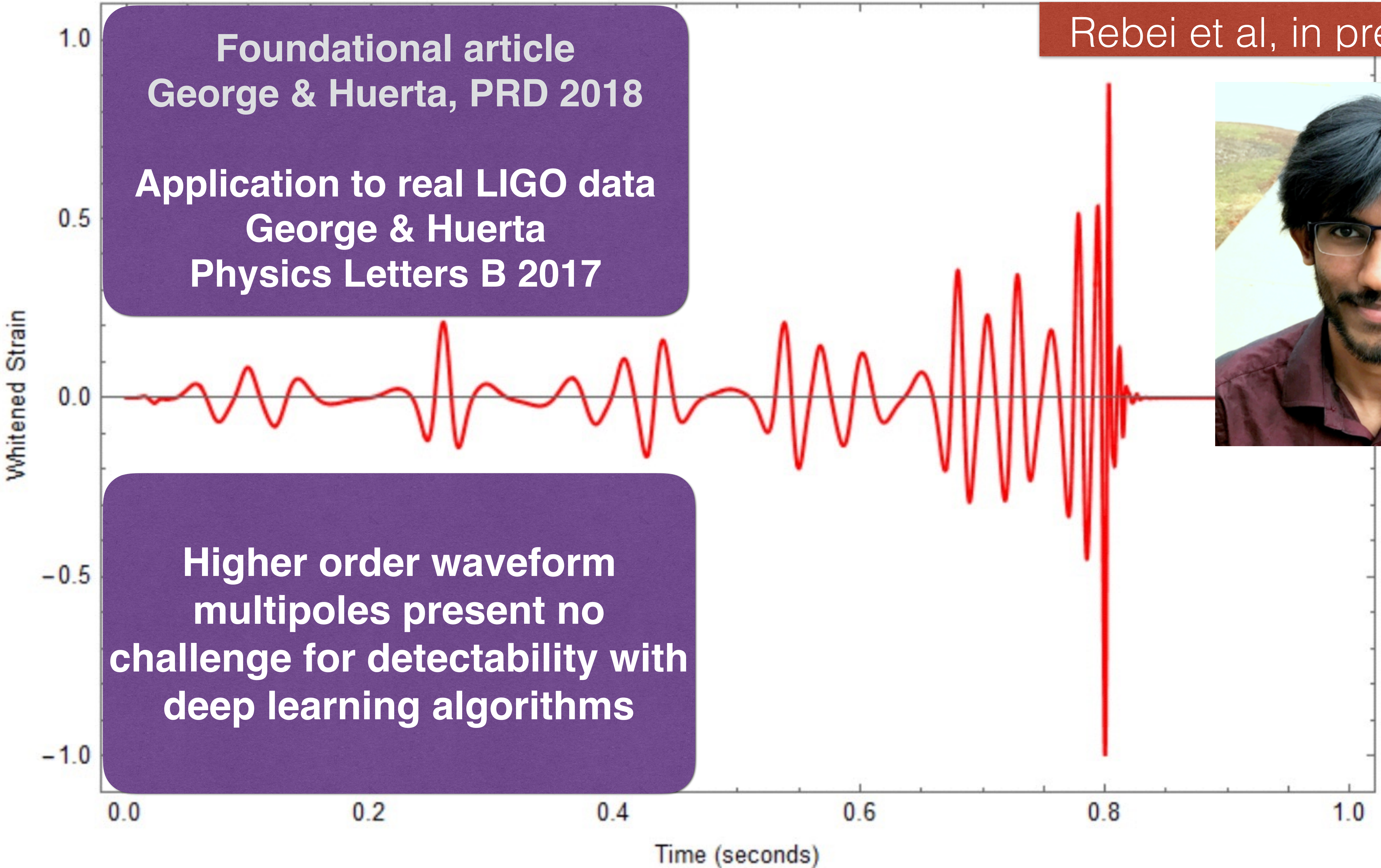
Increase up to 20% in signal-to-noise ratio for mass-ratio 8 black hole mergers

Transforming how we do science with Deep learning

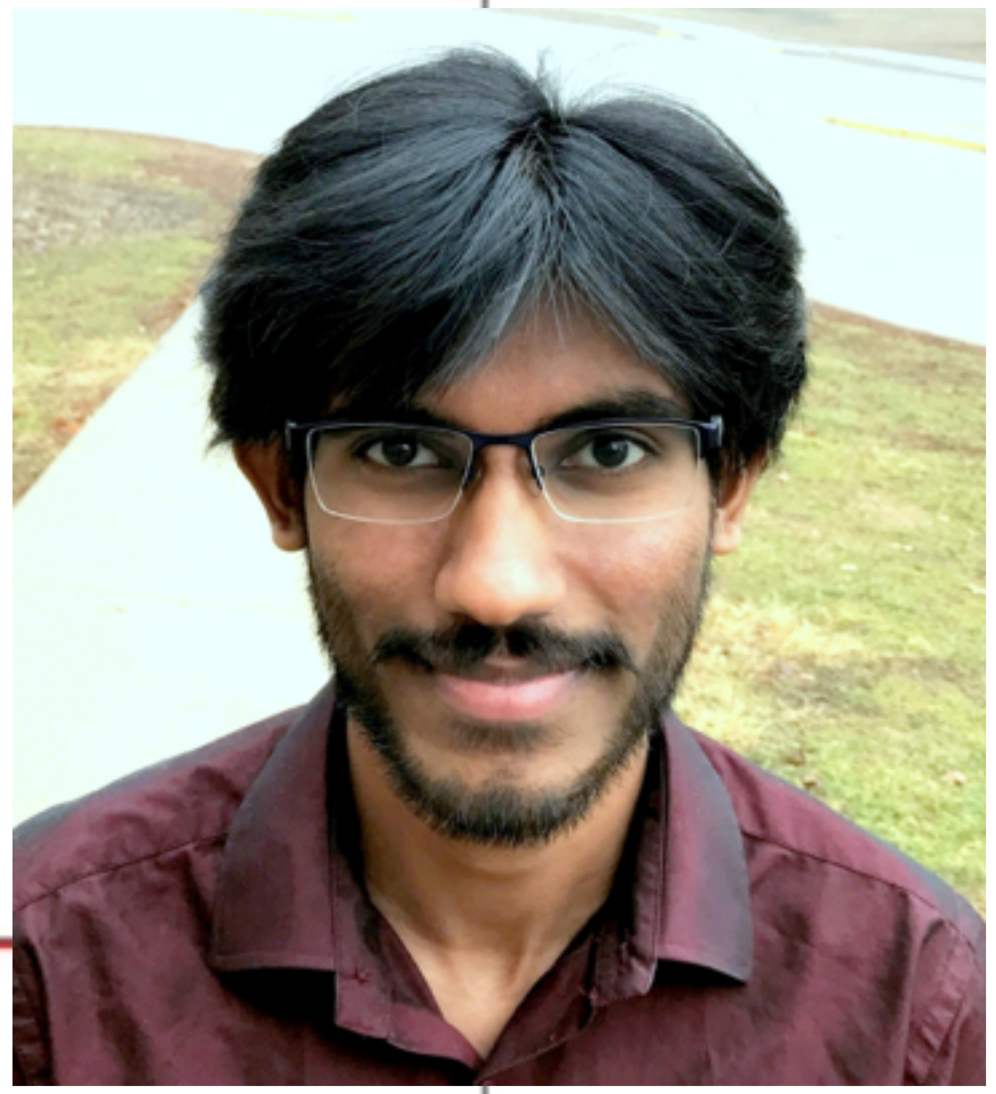
Foundational article
George & Huerta, PRD 2018

Application to real LIGO data
George & Huerta
Physics Letters B 2017

Higher order waveform multipoles present no challenge for detectability with deep learning algorithms



Rebei et al, in preparation



Conclusions

ENIGMA: state-of-the-art model to search for and detect eccentric binary black hole mergers

ENIGMA reproduces established quasi-circular waveform models and eccentric numerical relativity simulations

Extension to describe spinning black holes on eccentric orbits is well underway

NCSA Gravity Group at 2018 APS April Meeting

1. Ed Seidel. Numerical Relativity 1980-2000s: The era of sharpening our tools and exploring Einstein's physics
2. Daniel George: Deep Learning for Real-time Gravitational Wave Detection and Parameter Estimation: Results with Advanced LIGO Data
3. Adam Rebei: Influence of higher-order waveform multipoles for the detection of eccentric binary black hole mergers
4. Roland Haas: Assessing confidence in numerical relativity waveforms of binary neutron star mergers
5. Hongyu Shen: Glitch Classification and Clustering for LIGO with Deep Transfer Learning (poster)
6. Eliu Huerta: Detection and characterization of eccentric compact binary coalescence at the interface of numerical relativity, analytical relativity and machine learning
7. Hongyu Shen: Denoising Gravitational Waves using Deep Learning with Recurrent Denoising Autoencoders
8. Roland Haas: BOSS-LDG using Blue Waters for LIGO data analysis (poster)
9. Vedant Puri: Scheduled Relaxation Jacobi Method for Initial Data Problems
10. Shawn Rosofsky: Study of f-mode Oscillations in Numerical Relativity Simulations of Perturbed Neutron Stars and Highly Eccentric Binary Neutron Star Mergers
11. Pablo Brubeck: On the Schur complement of the nearest Kronecker product preconditioner for elliptic boundary value problems
12. Haris Markakis: Helmholtz's third theorem in numerical general relativity
13. Miguel Holgado: Pulsar Timing Constraints on the Fermi Massive Black-Hole Binary Blazar Population