Black holes, alone and in binaries

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Canadian Institute for Theoretical Astrophysics

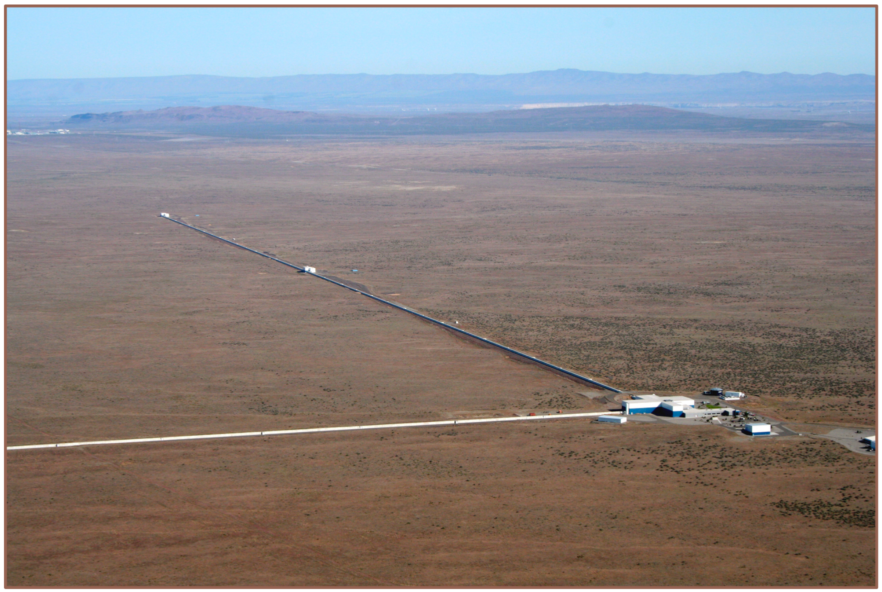
SMU Physics Colloquium
January 22, 2018

Outline

- Motivation
- Black holes in binaries - two-body problem
- Black holes alone- BH ringdown
- Gravitational wave astronomy: LIGO's second observational run

Advanced LIGO and Virgo

Cascina, Italy

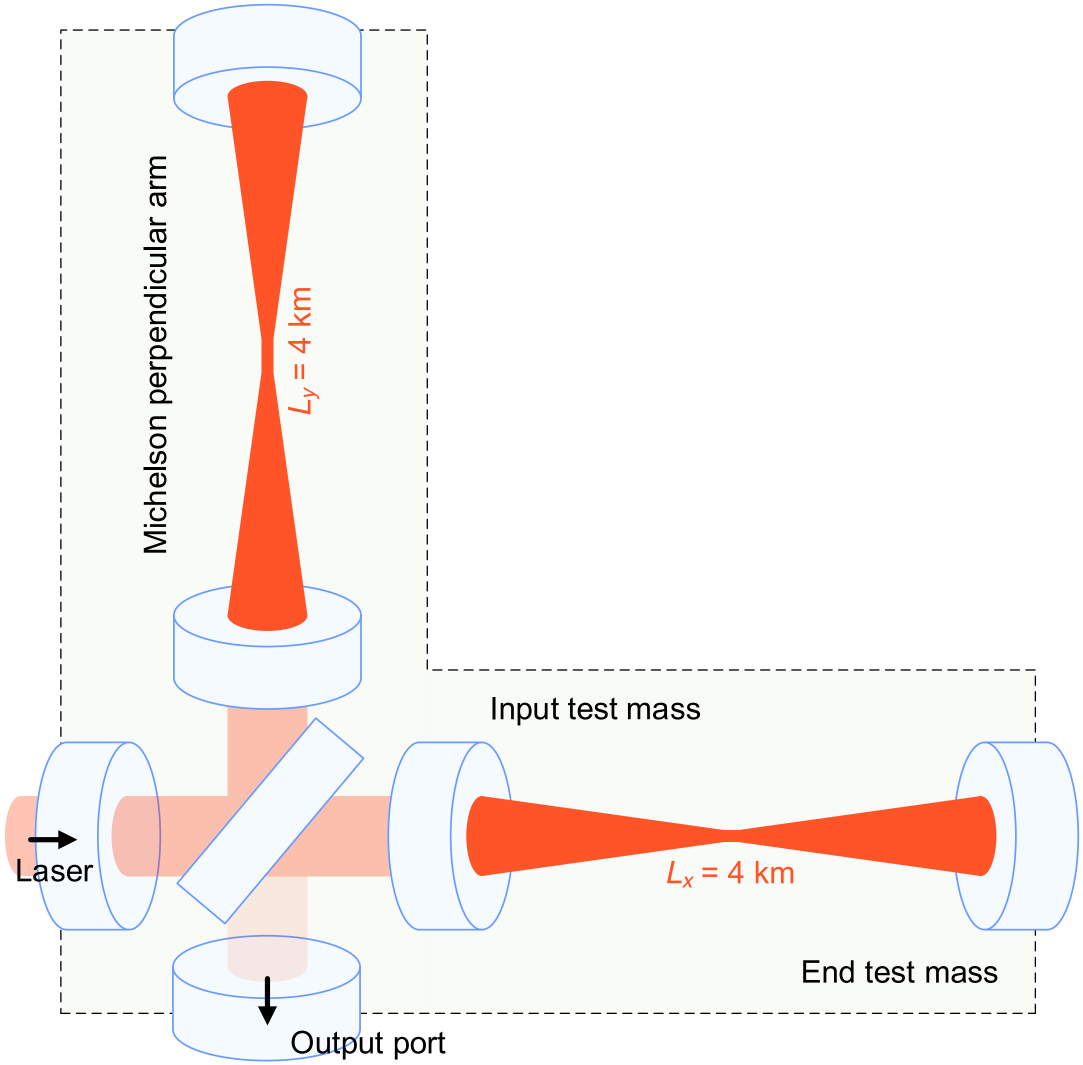


Hanford, WA

Livingston, LA

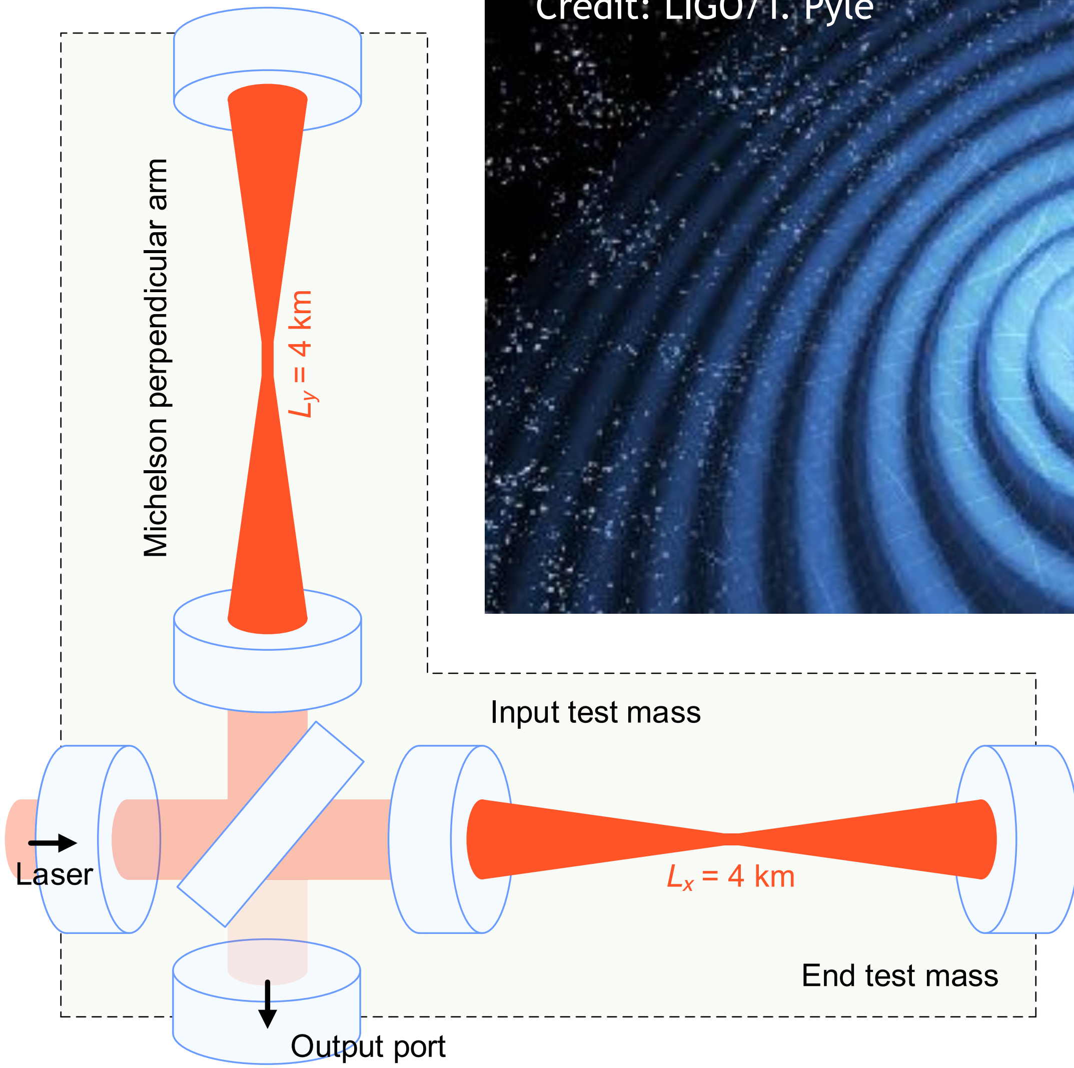
Photos courtesy LVC

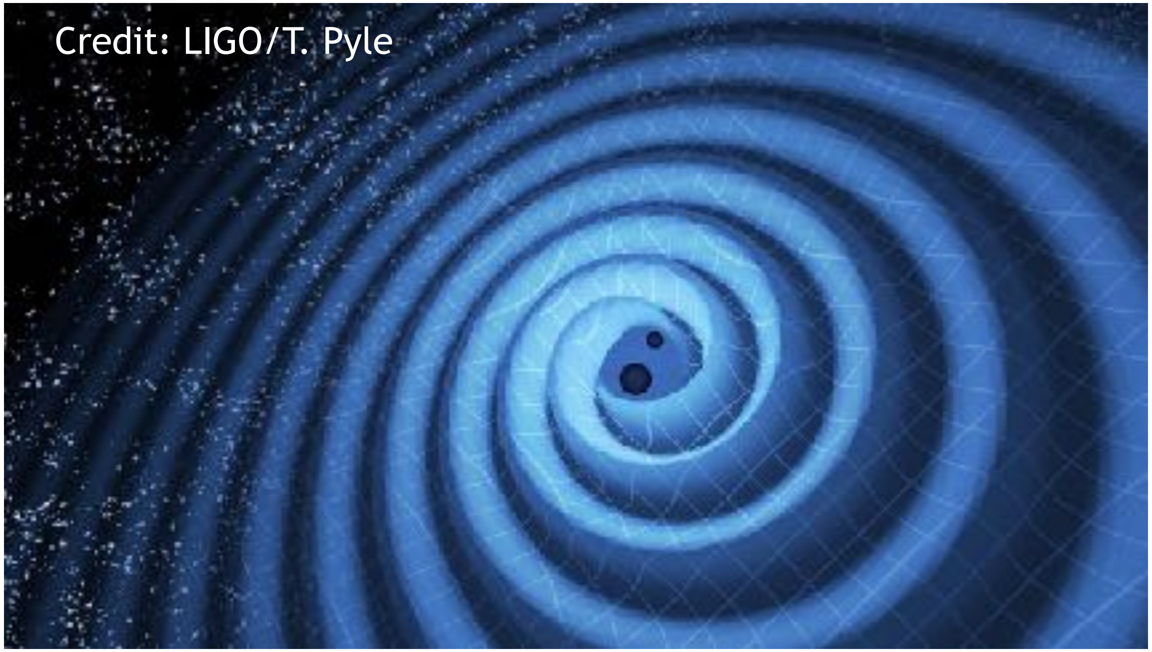
A new window



LVC PRL 116, 131103 (2016)

A new window





LVC PRL 116, 131103 (2016)

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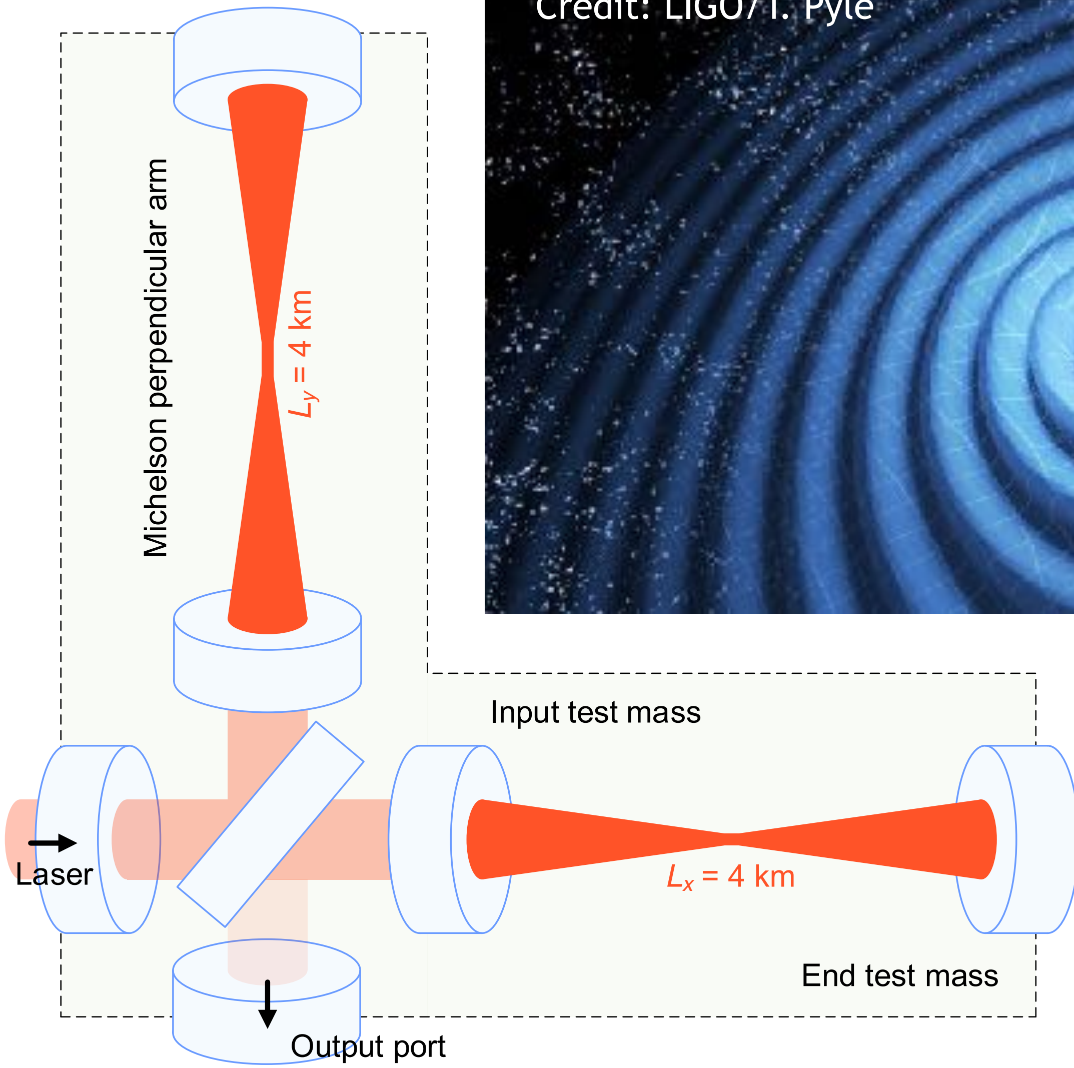
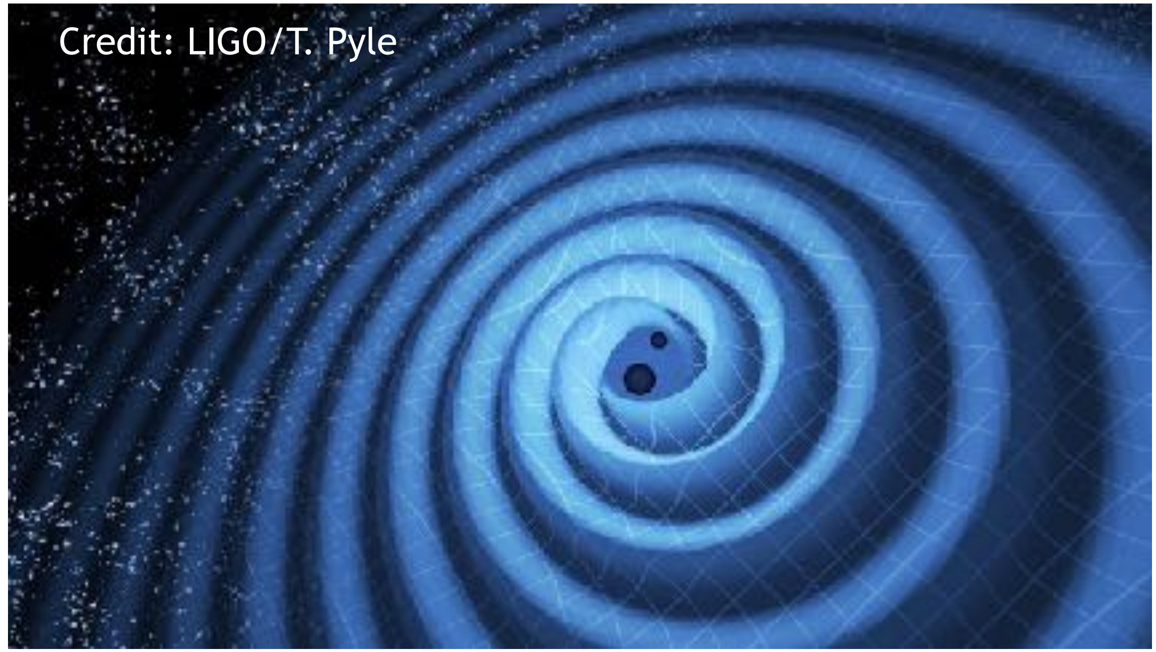
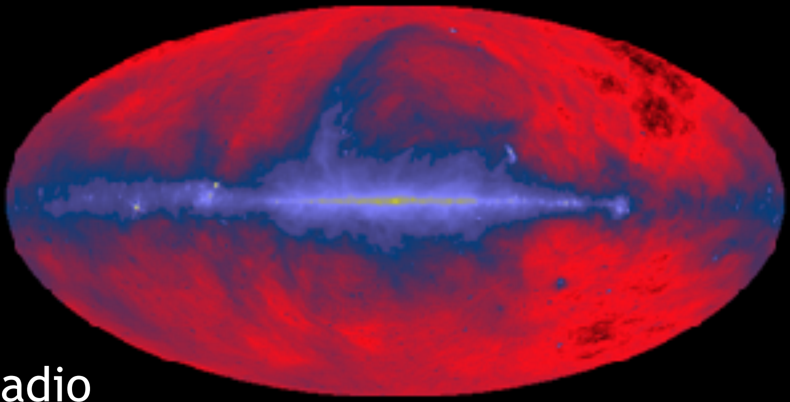


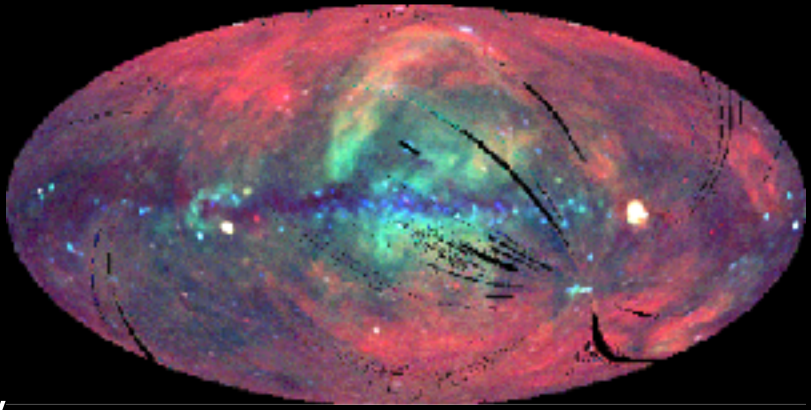


$$\frac{\Delta L}{L} \sim 10^{-23}$$

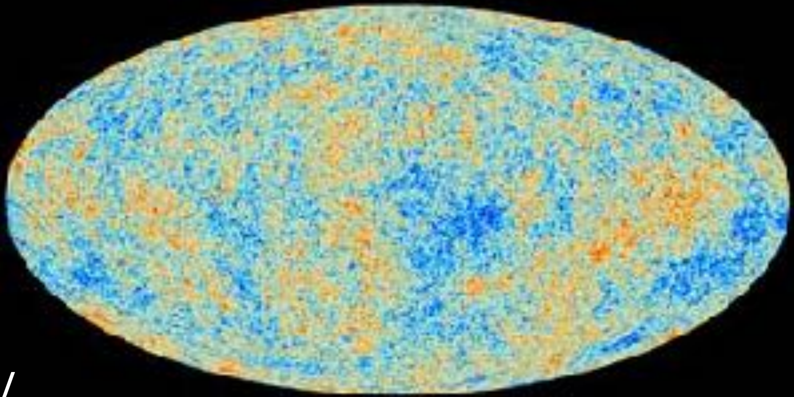
LVC PRL 116, 131103 (2016)



Radio
Composite

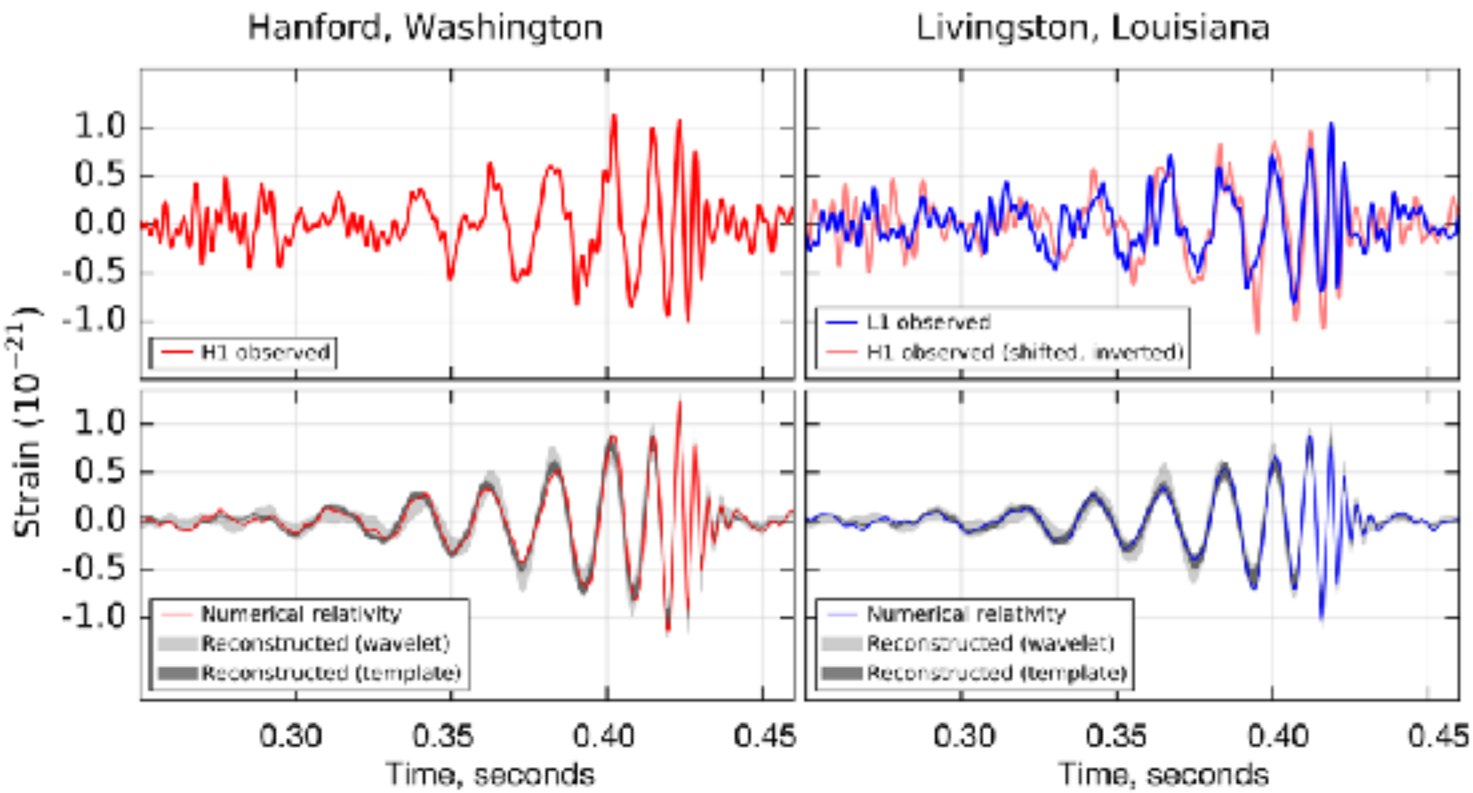


X-ray
ROSAT



Microwave/
Planck

First detection: GW150914

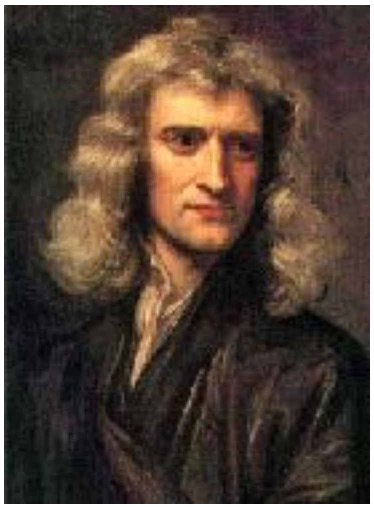


- Masses $m_1 = 36^{+5}_{-4} M_\odot$ $m_2 = 29^{+4}_{-4} M_\odot$
- Final black hole $M_f = 62^{+4}_{-4} M_\odot$ $\chi_f = 0.67^{+0.05}_{-0.07}$
- Luminosity $L \sim 10^{23} L_\odot \sim 10^{13} L_{\mathrm{MWG}}$

LVC PRL 116, 061102 (2016)

THE TWO-BODY PROBLEM

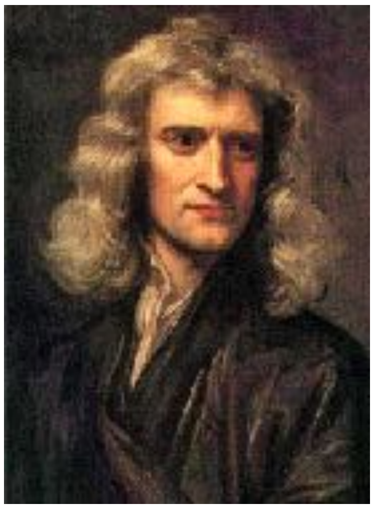
Newtonian two-body problem

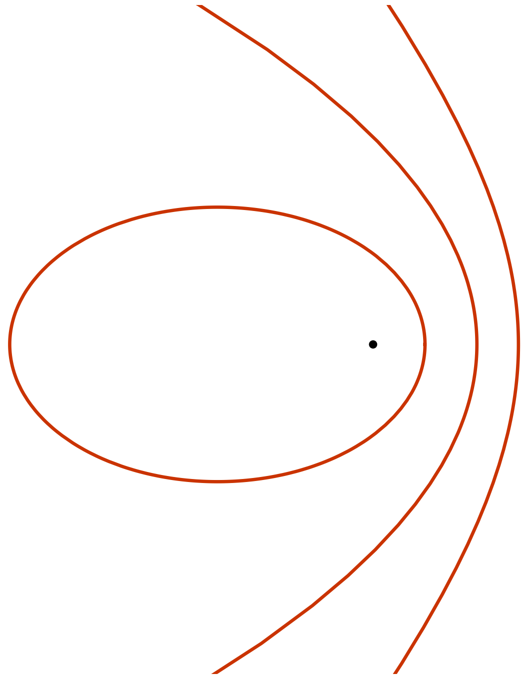


$$\vec{F} = m\vec{a}$$

$$\vec{F}_g = -G\frac{m_1 m_2}{r^2}\hat{r}$$

Newtonian two-body problem





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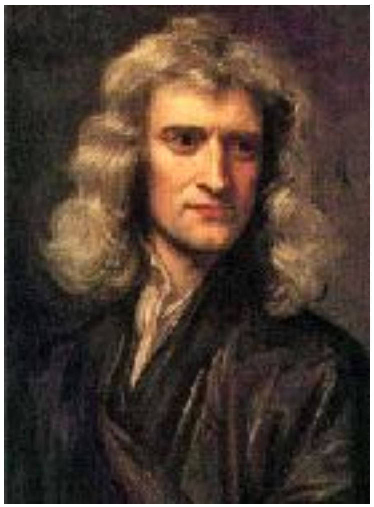
$$r = \frac{a(1-e^2)}{1+e\cos\psi}$$

Newtonian two-body problem



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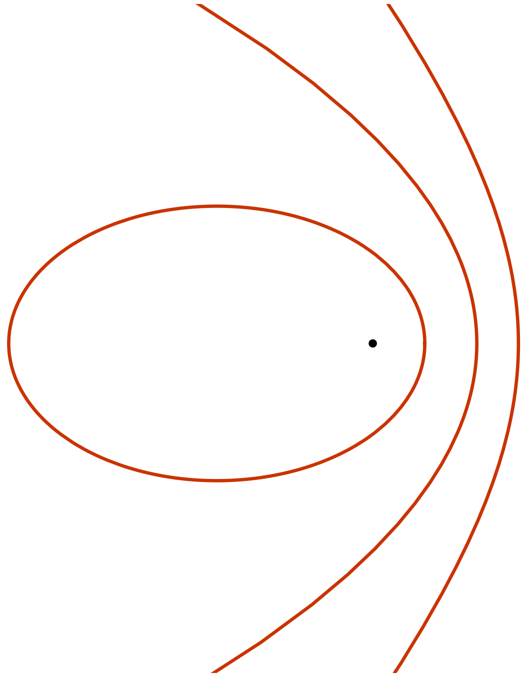

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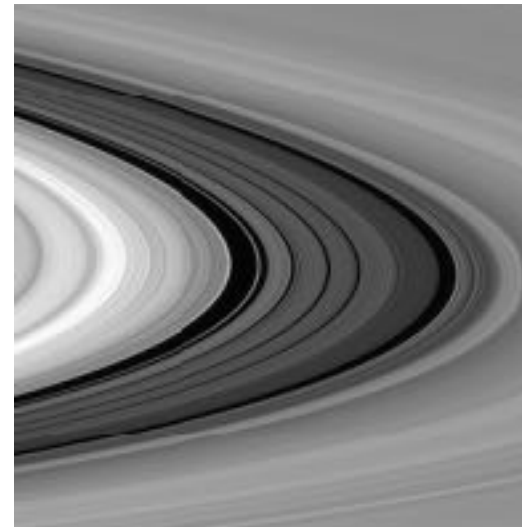
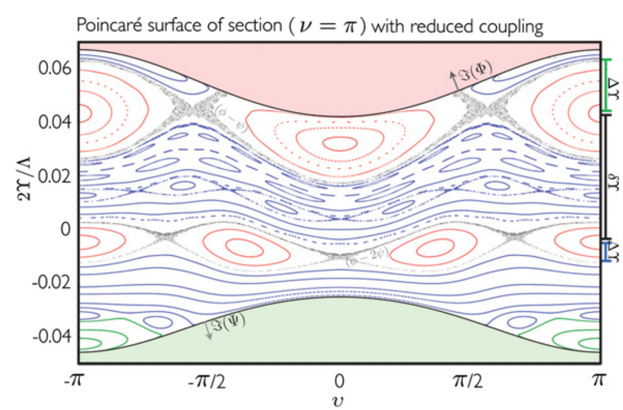
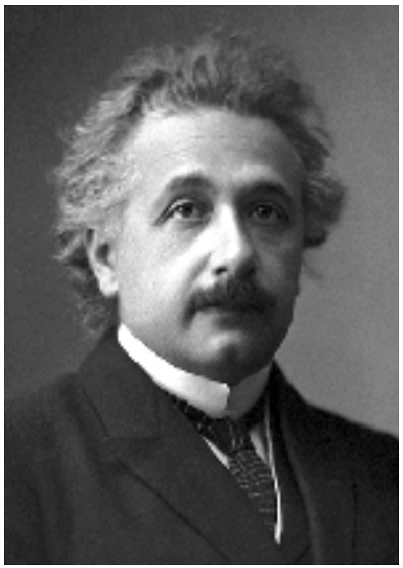


Credit: NASA/Cassini



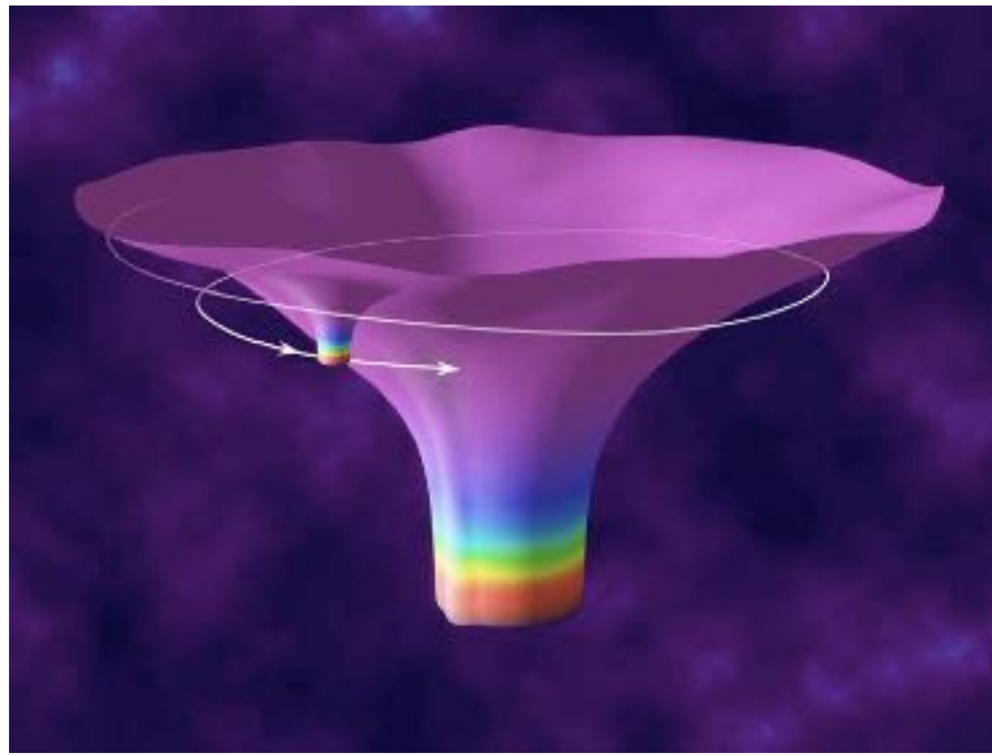
Batygin, Morbidelli, Holman (2015)

Enter general relativity



$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$\nabla^{\mu} T_{\mu\nu} = 0$$

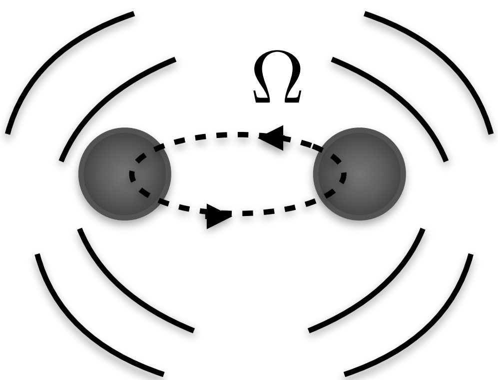


Credit: NASA

Emission of gravitational waves

$$P \sim \frac{G}{c^5}(\dddot{Q}_{ij})^2$$

$$E = -\frac{Gm_1 m_2}{2r}$$



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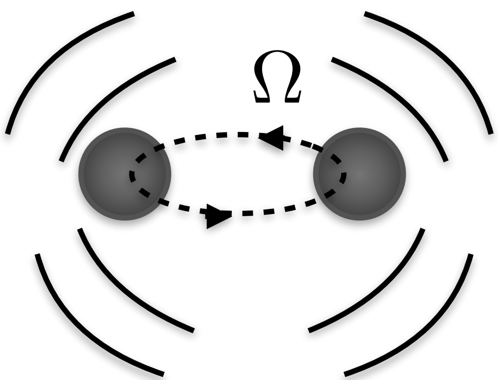
$$\xrightarrow[\dot{E} = -P]{GM = \Omega^2 r^3}$$



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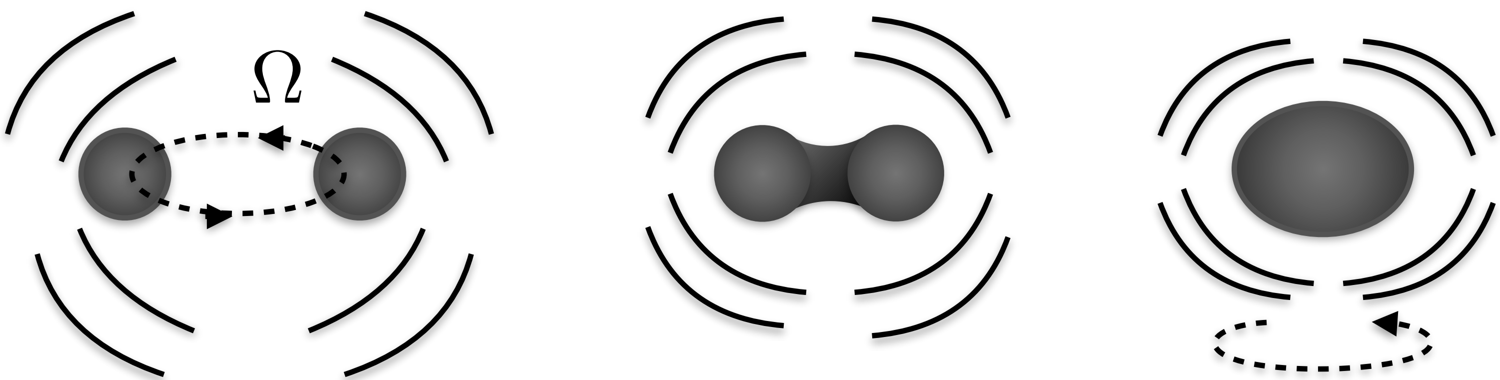
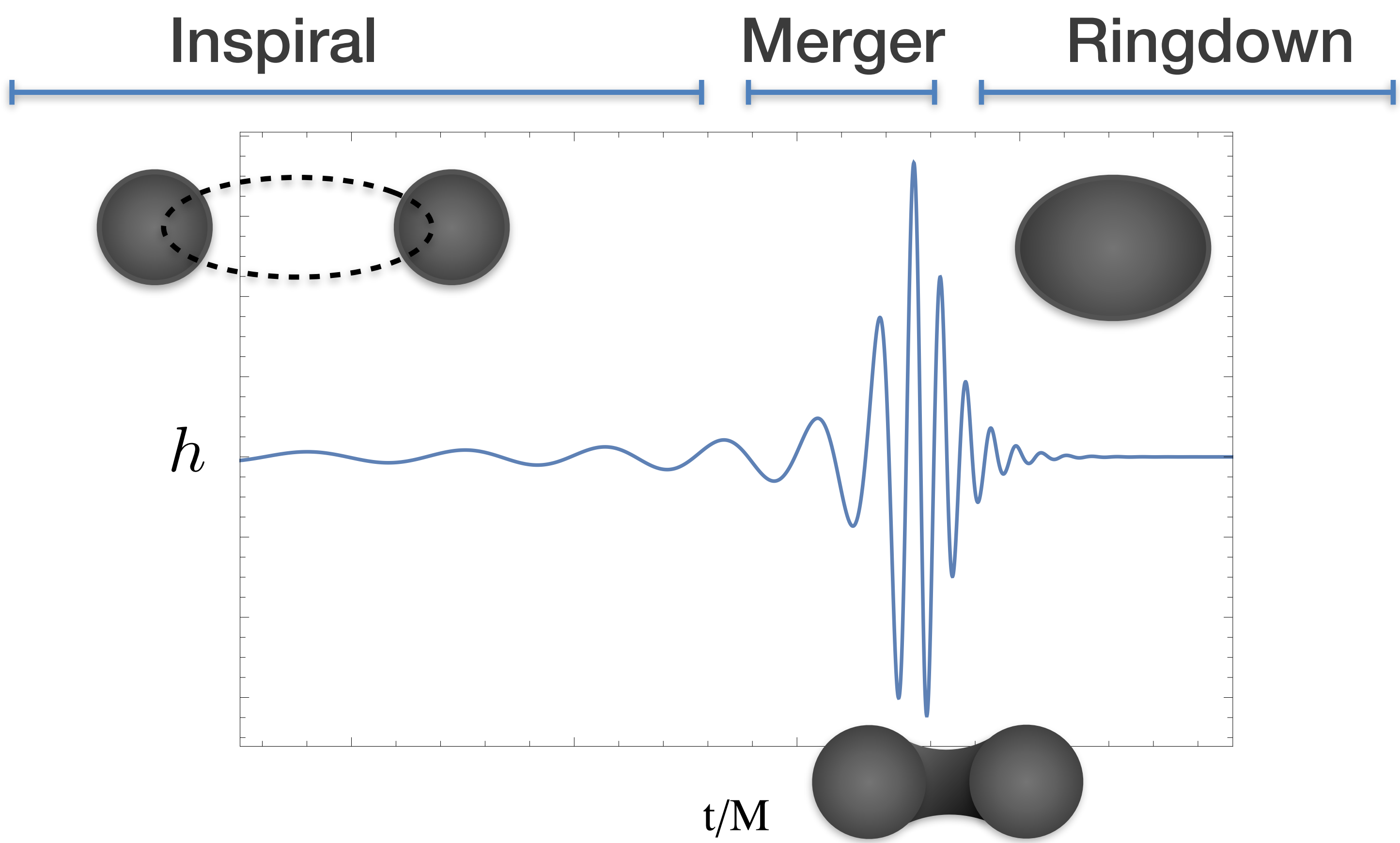
$$\Omega \propto (t - t_c)^{-3/8}$$

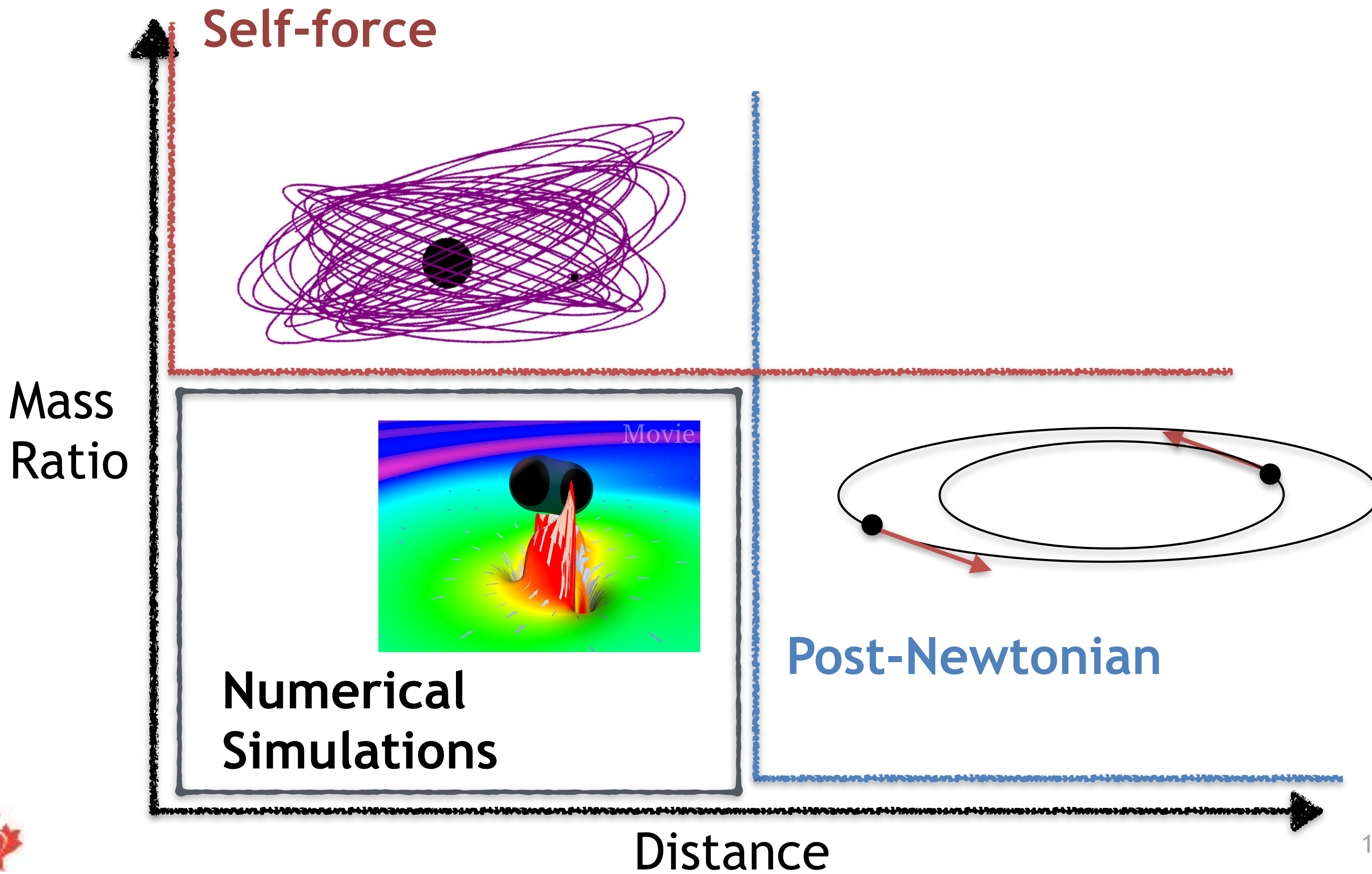


GWs from black hole binaries

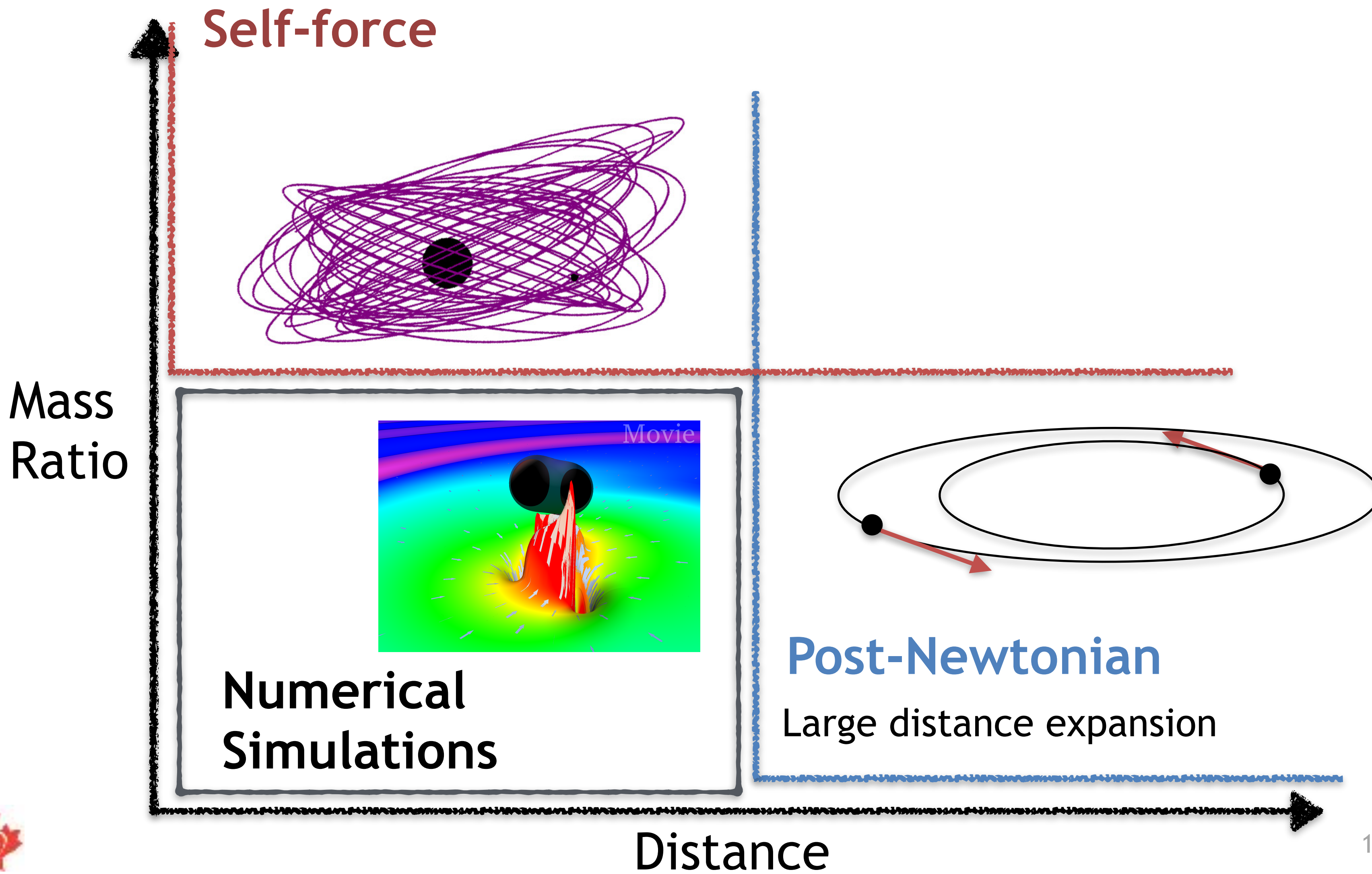


BLACK HOLES IN BINARIES

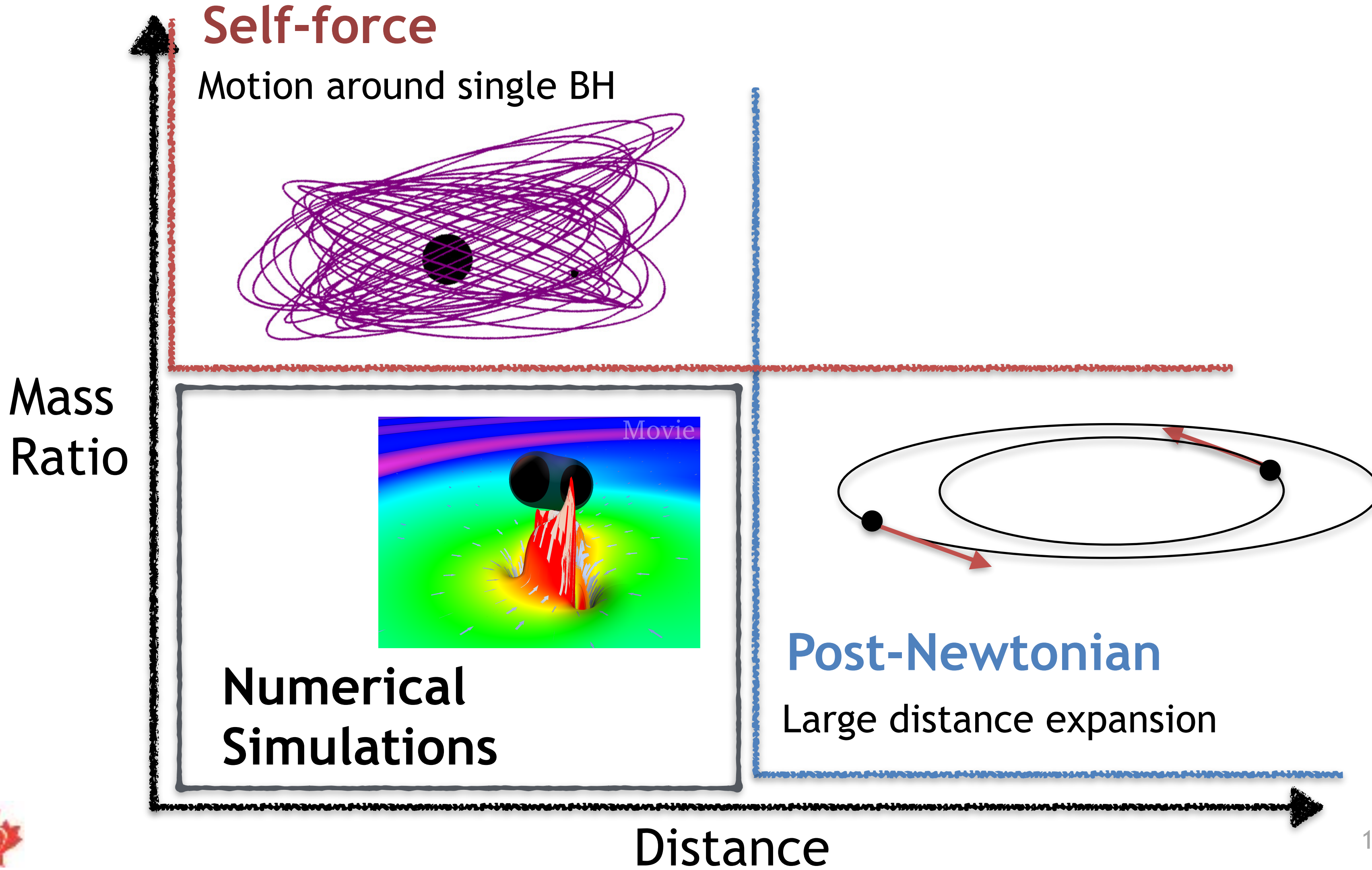
Modeling the two-body problem



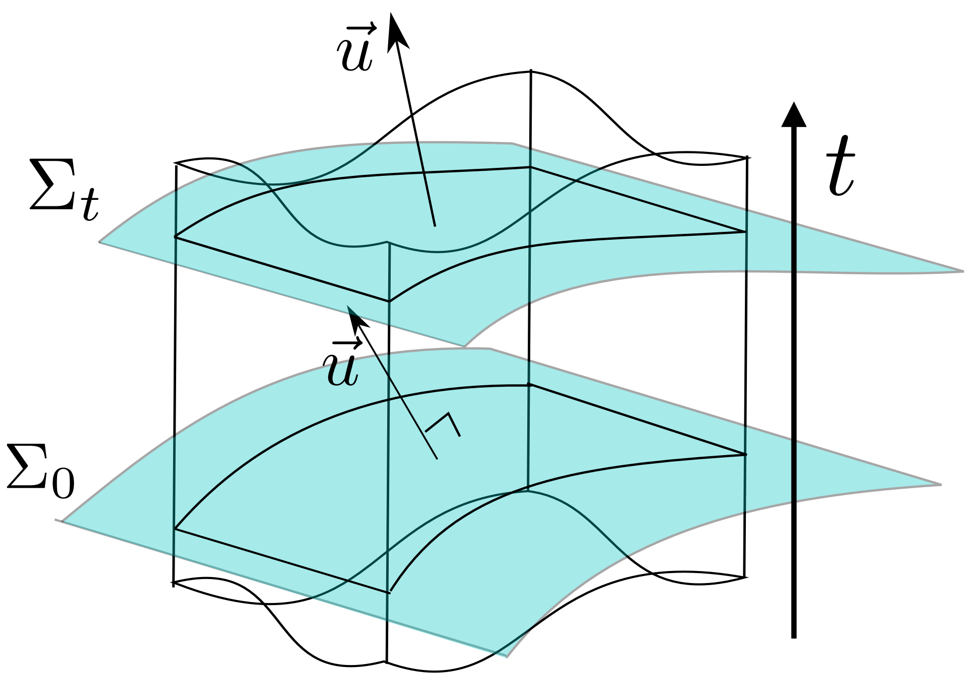
Modeling the two-body problem



Modeling the two-body problem



Numerical relativity



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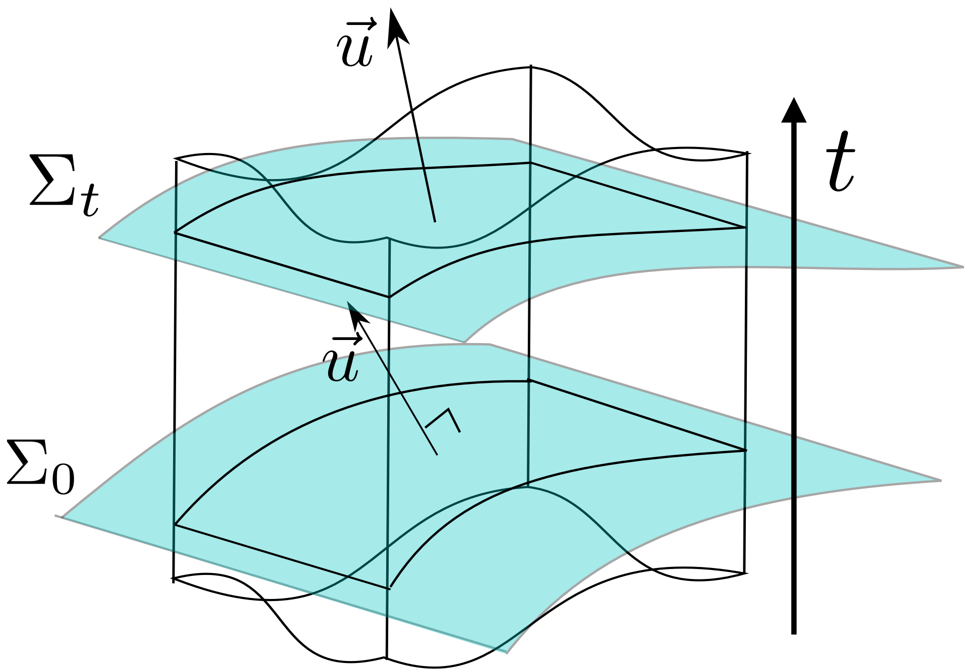
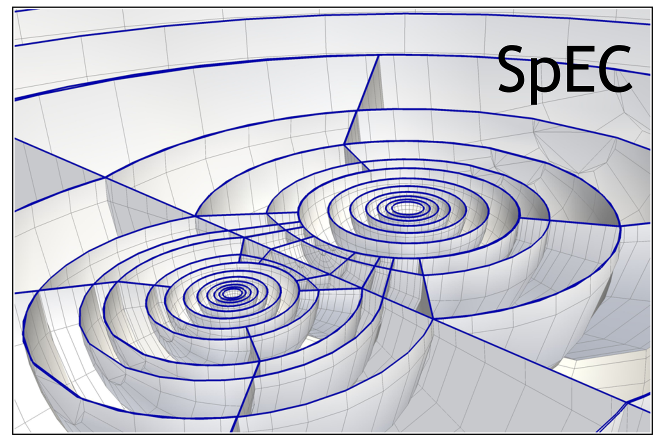
3+1 split →

4 constraints
12 evolution eqns

Numerical relativity





Buchman et al. (2012)

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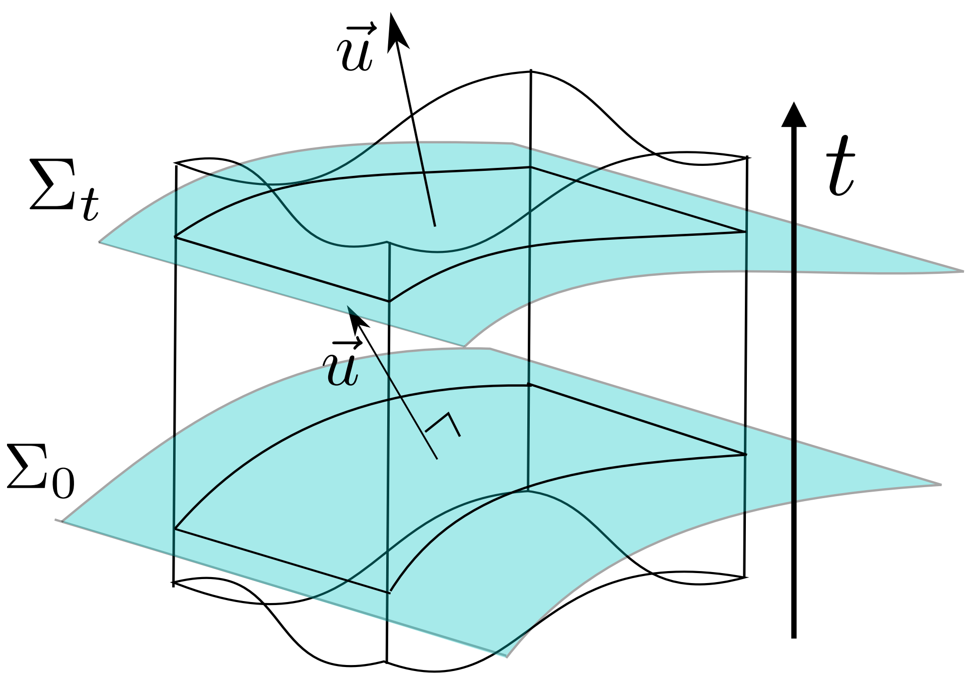

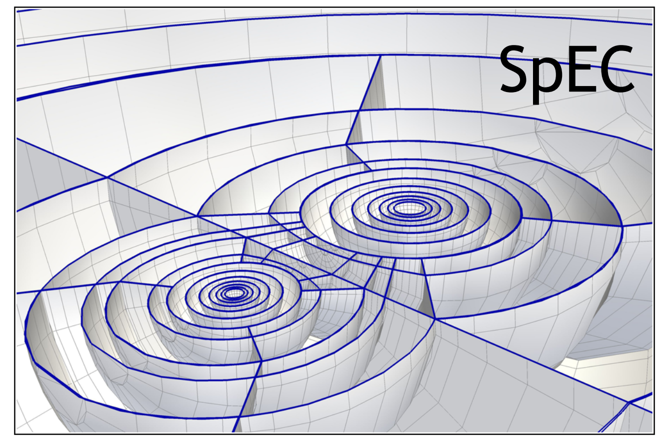

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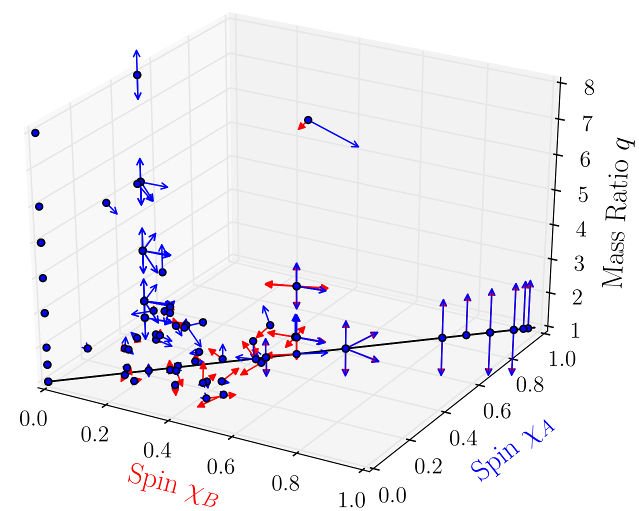
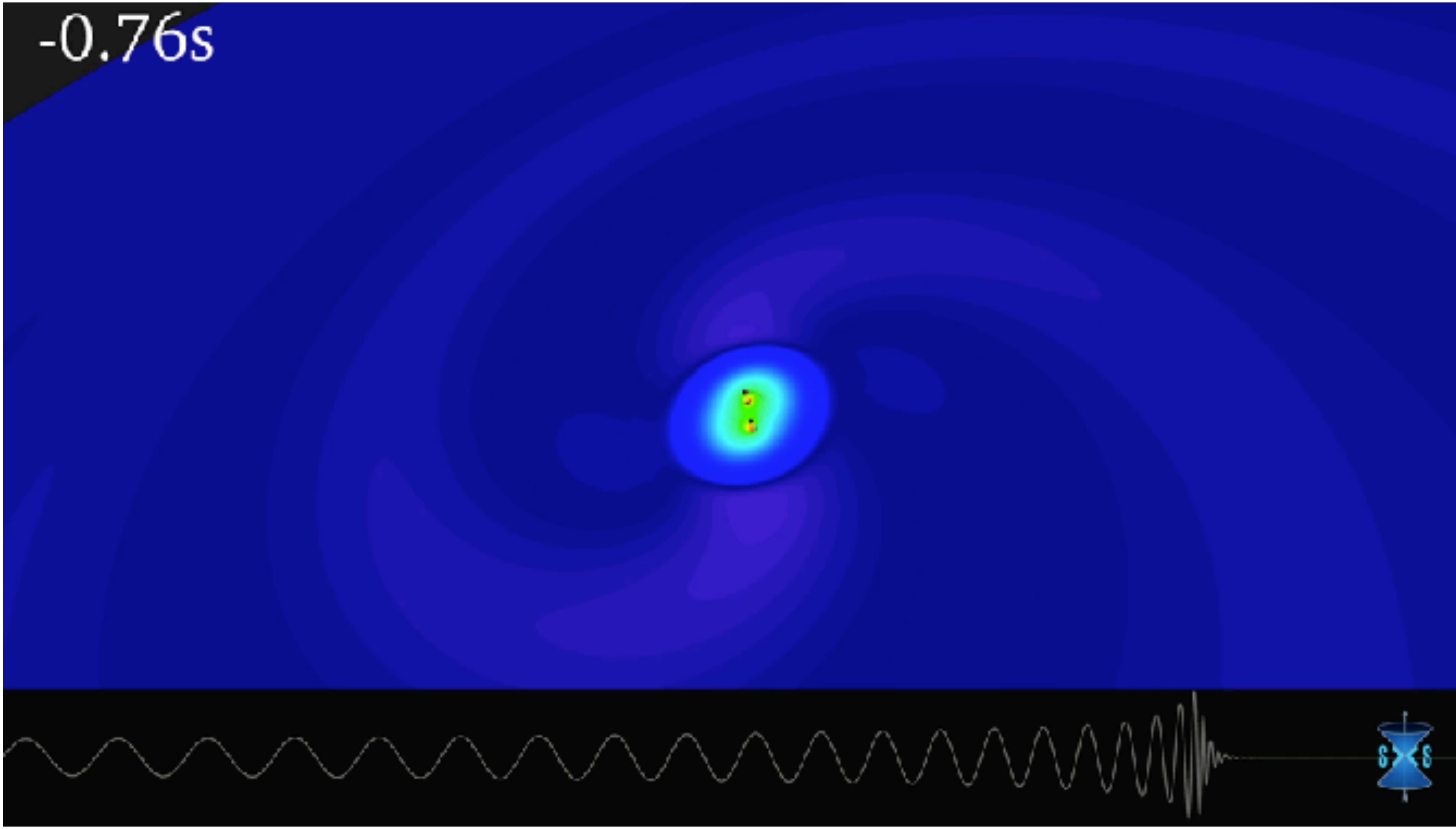


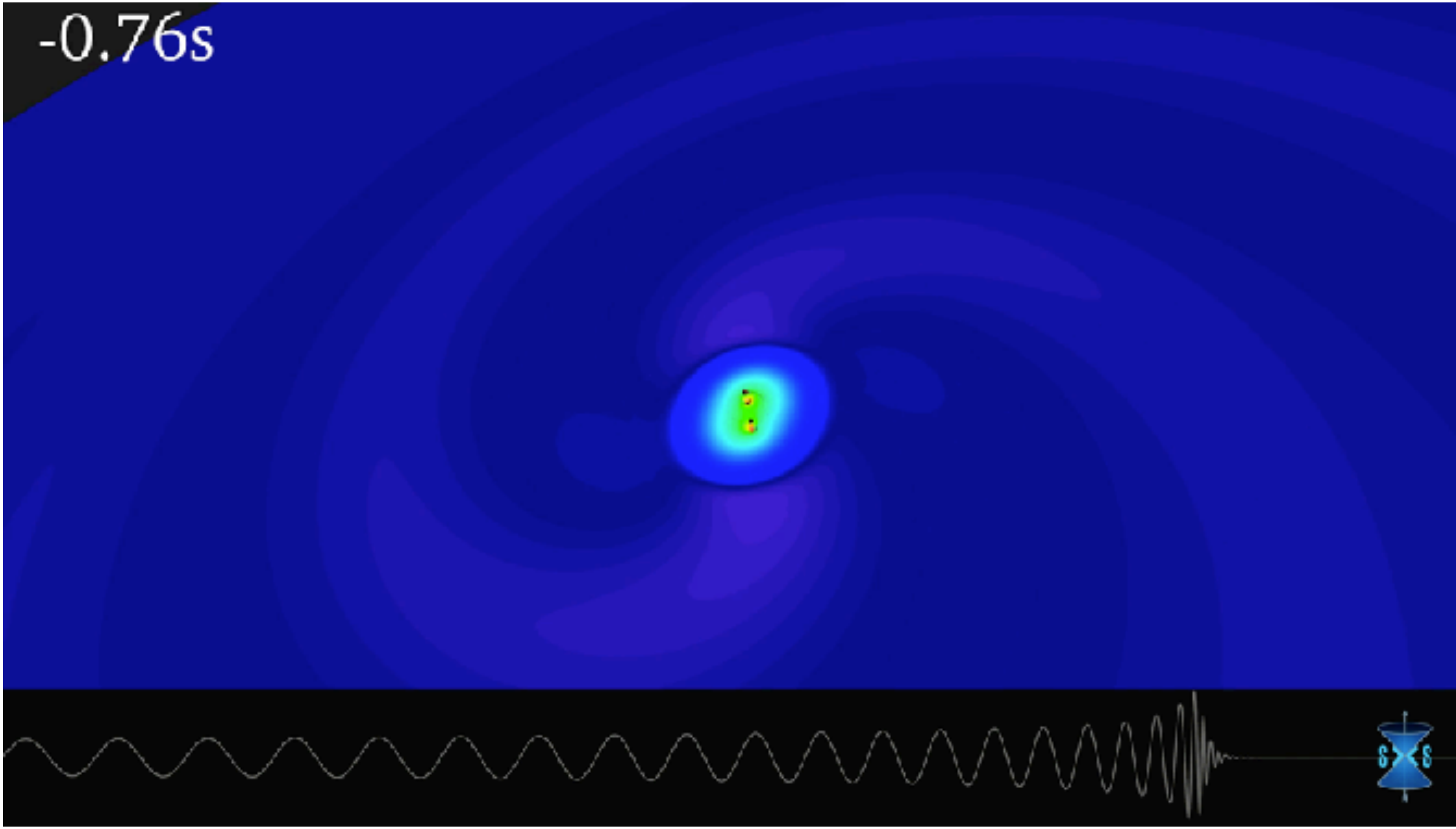
Mroue et al. PRL (2013)

Black hole mergers



Credit: H. Pfeiffer/SXS Collaboration

Black hole mergers



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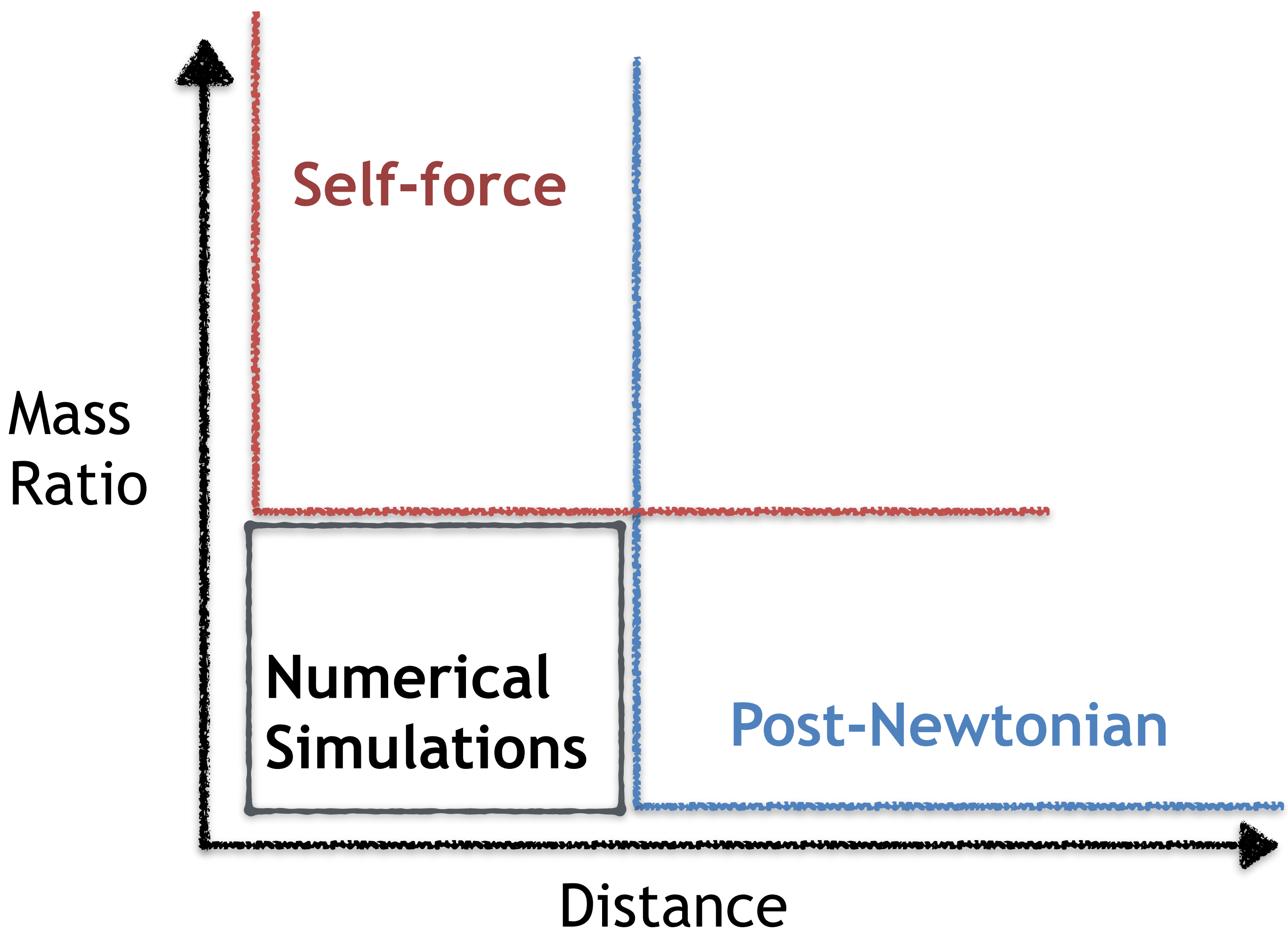
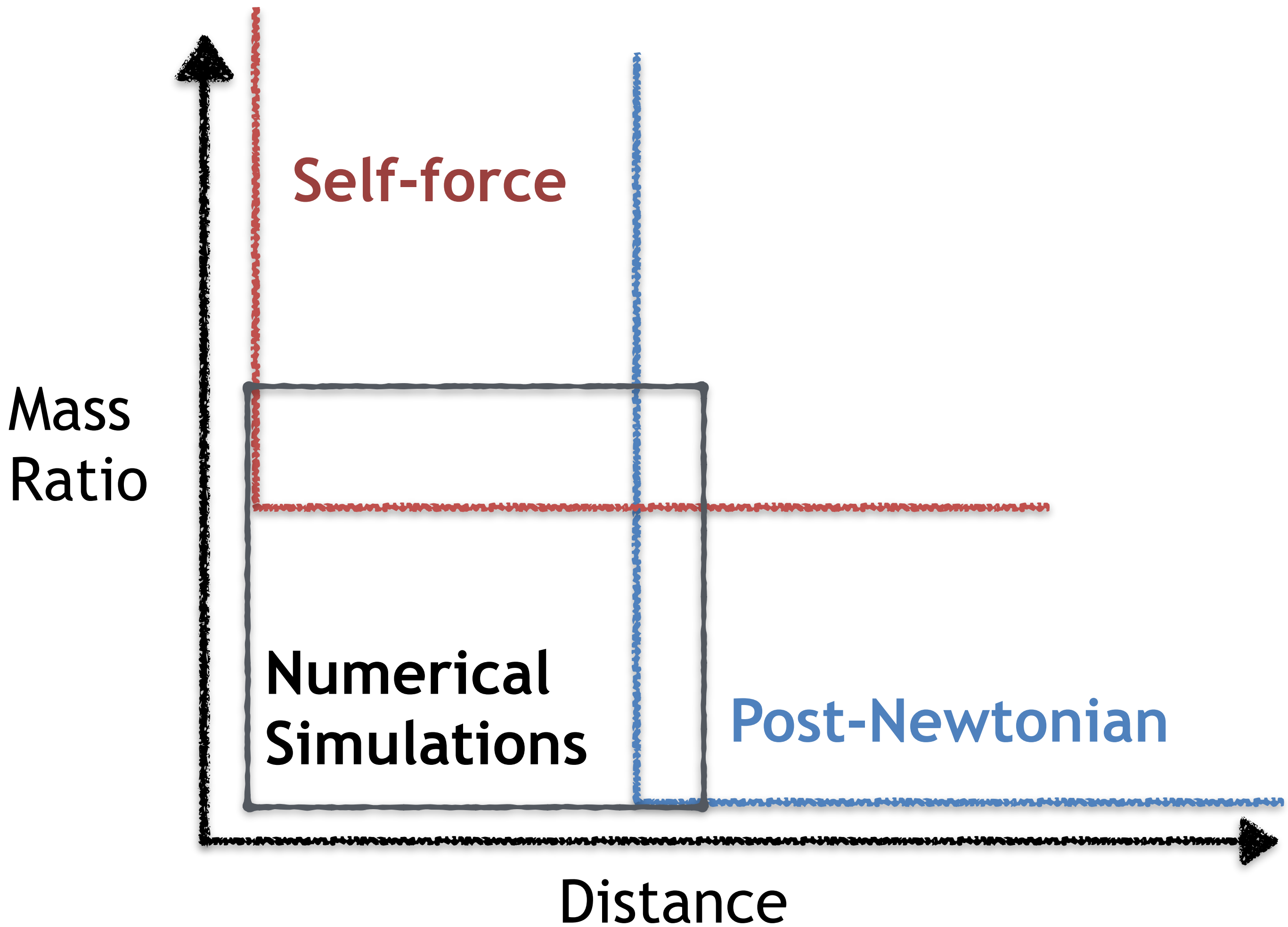
At the intersection



At the intersection



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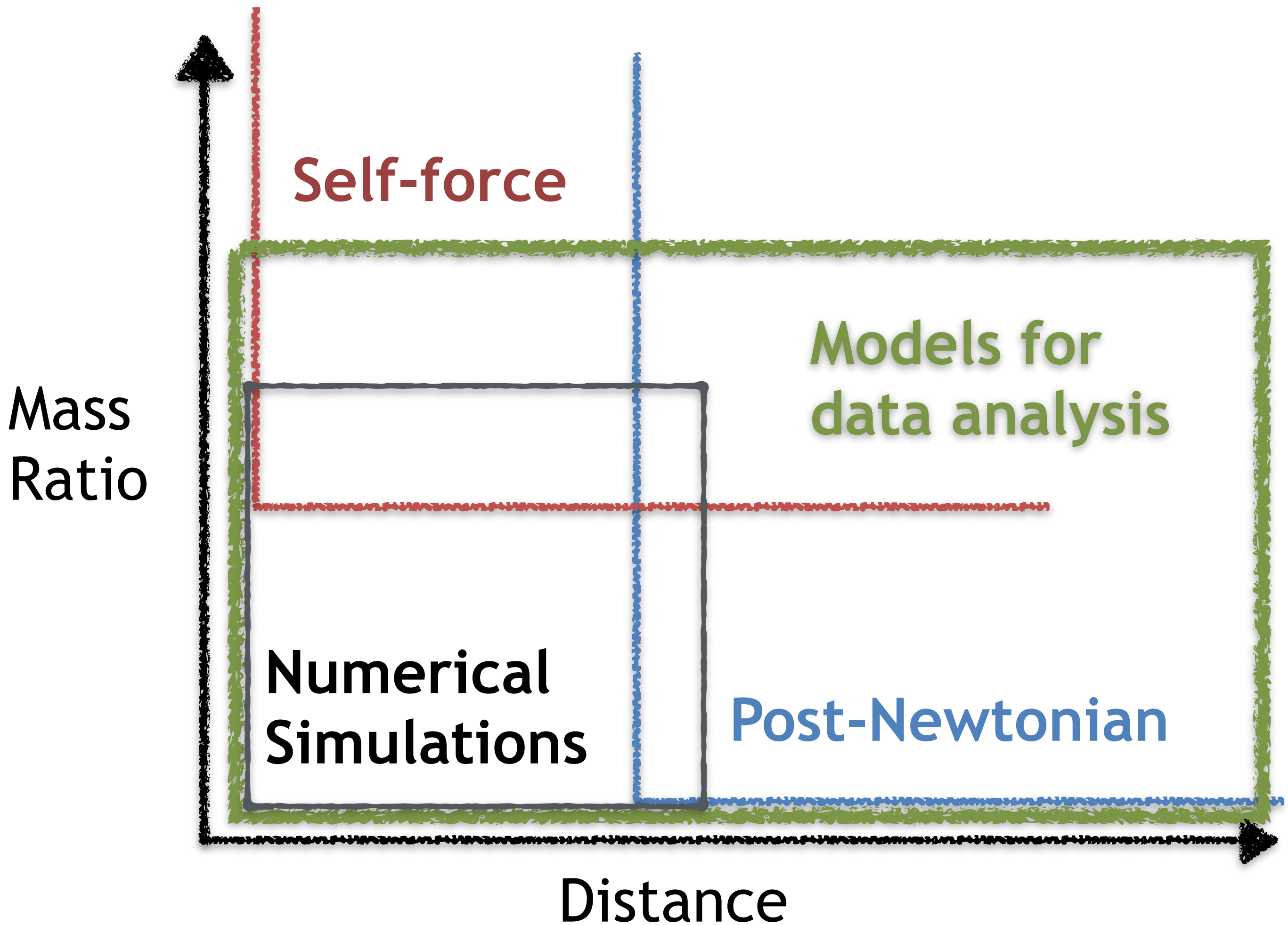

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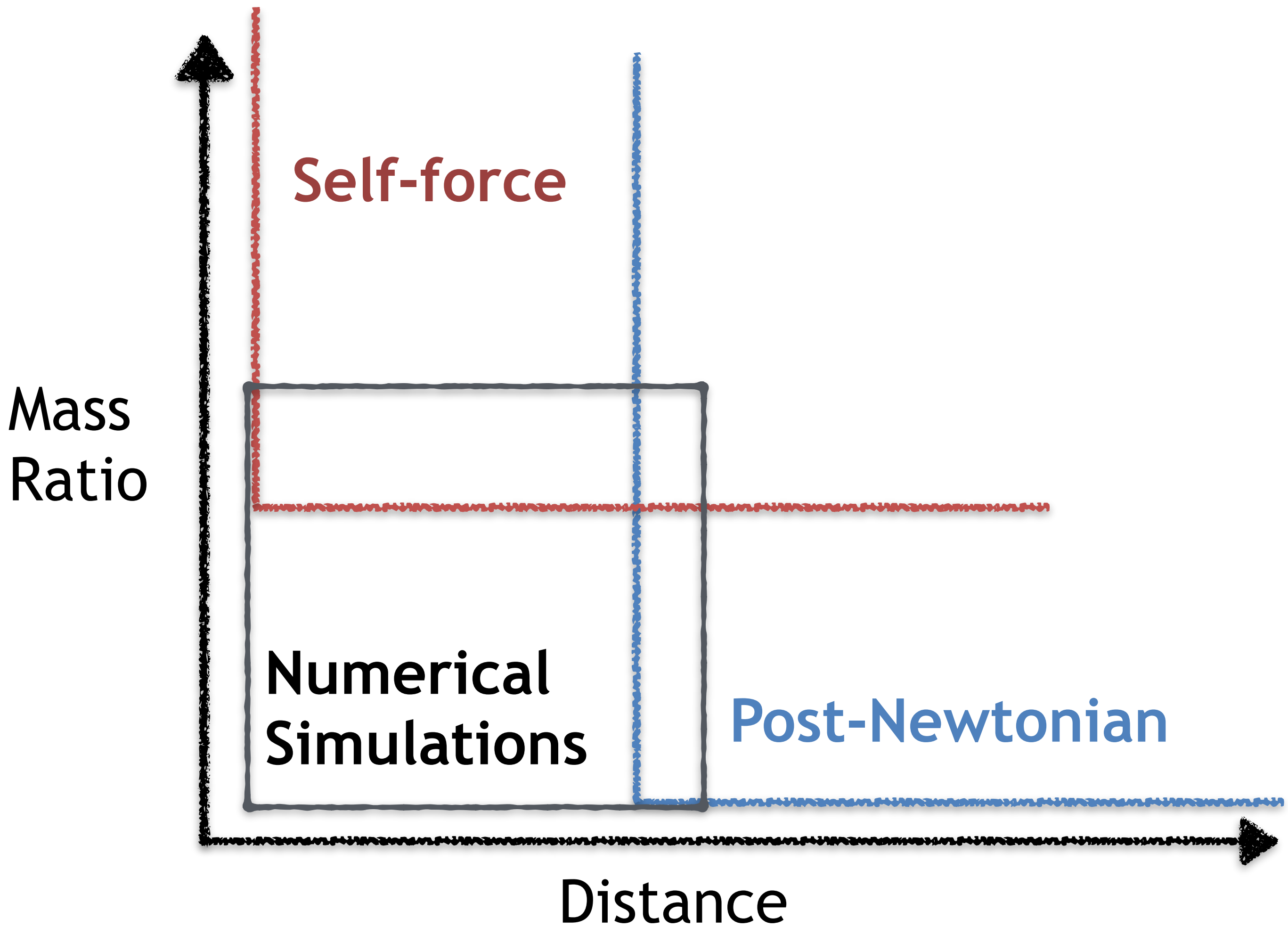

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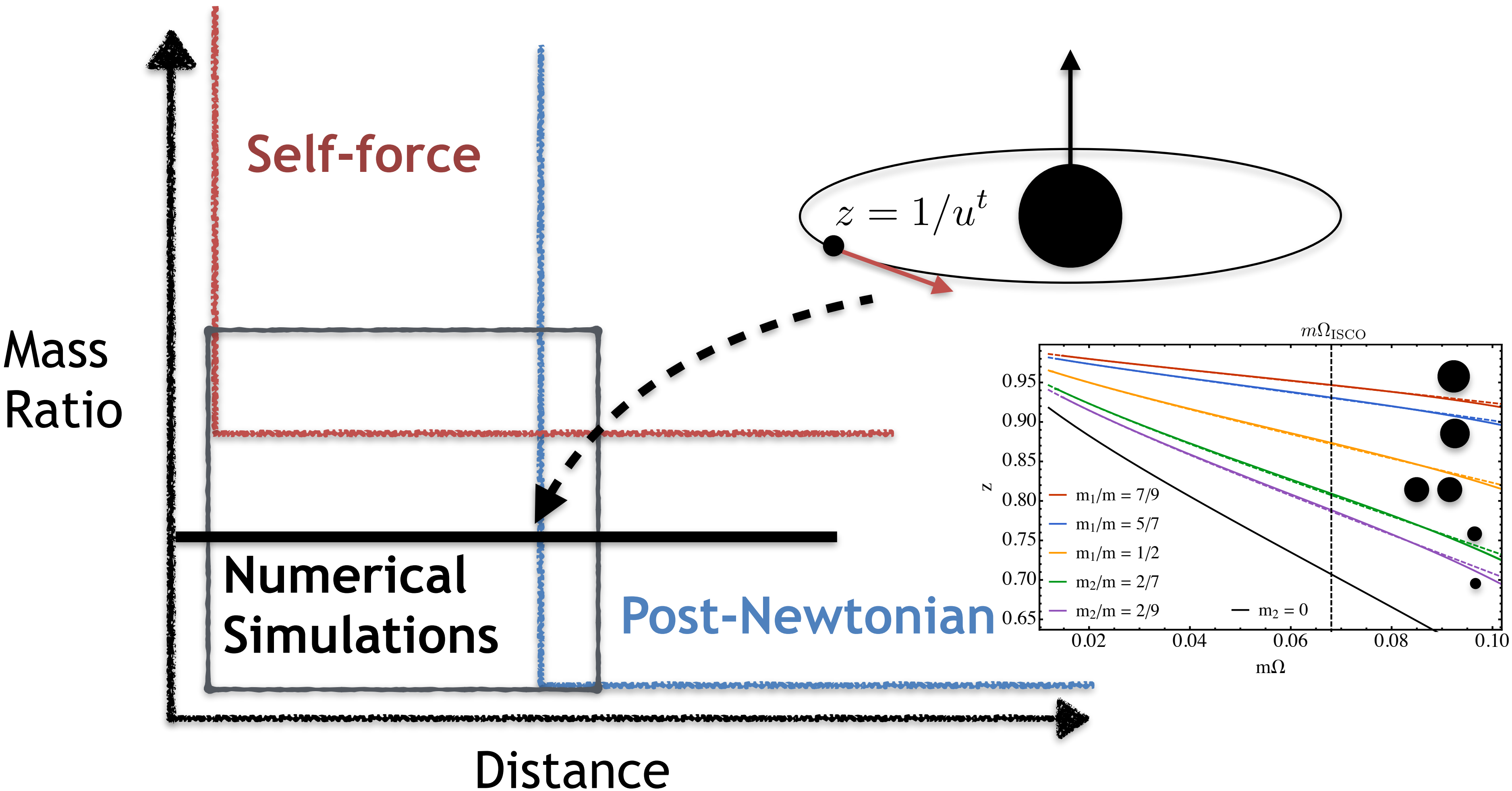
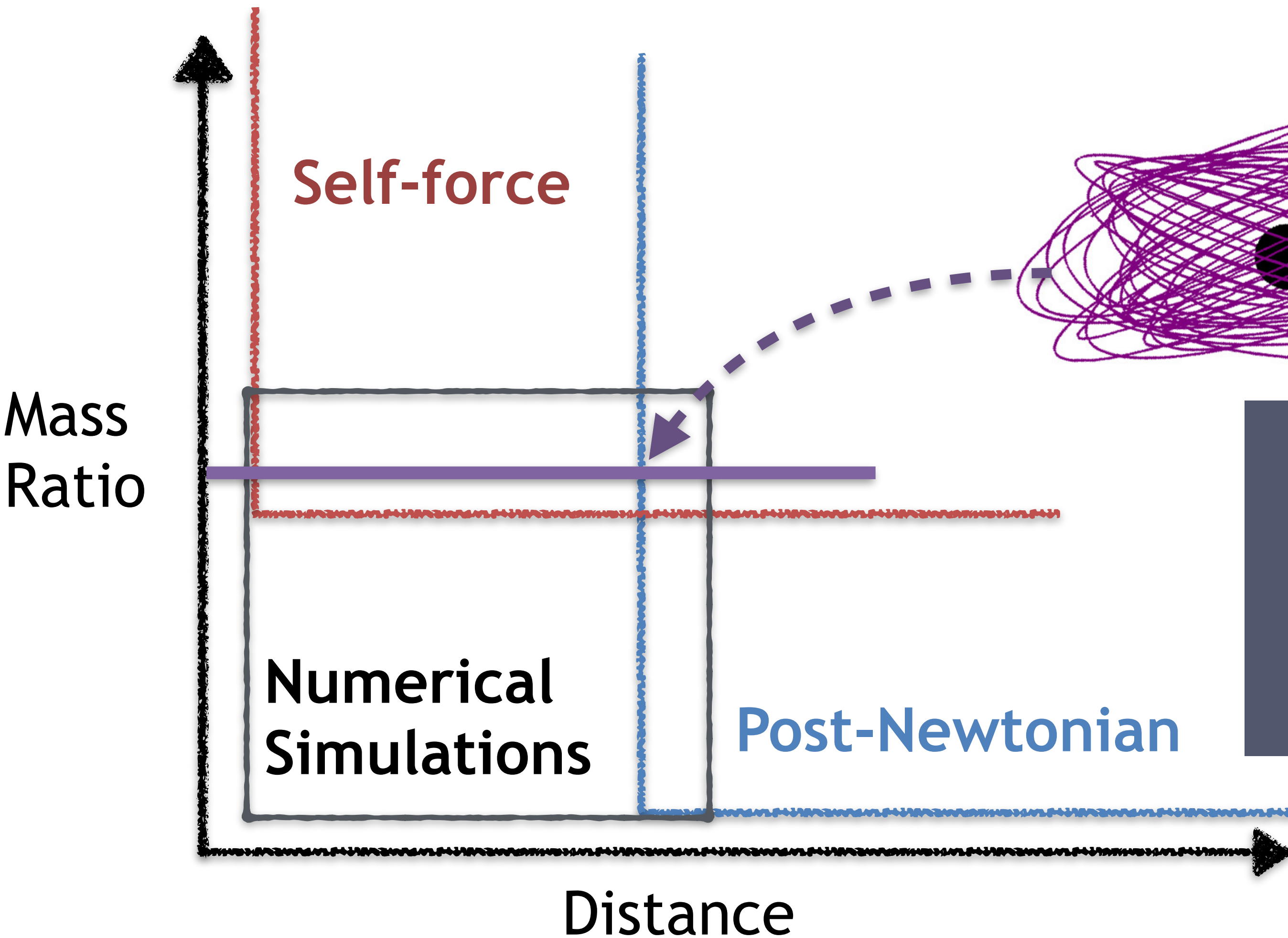
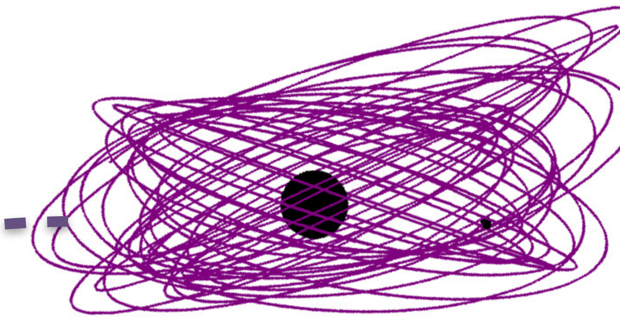
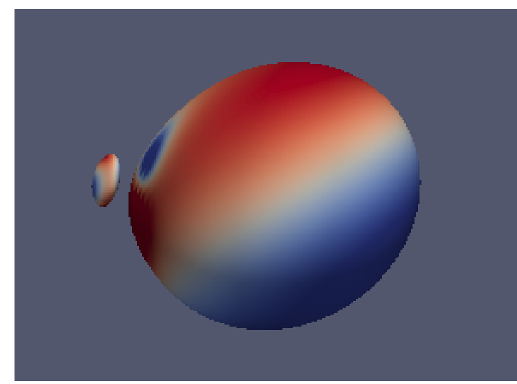


AZ, Lewis, Pfeiffer, PRL (2016)

At the intersection

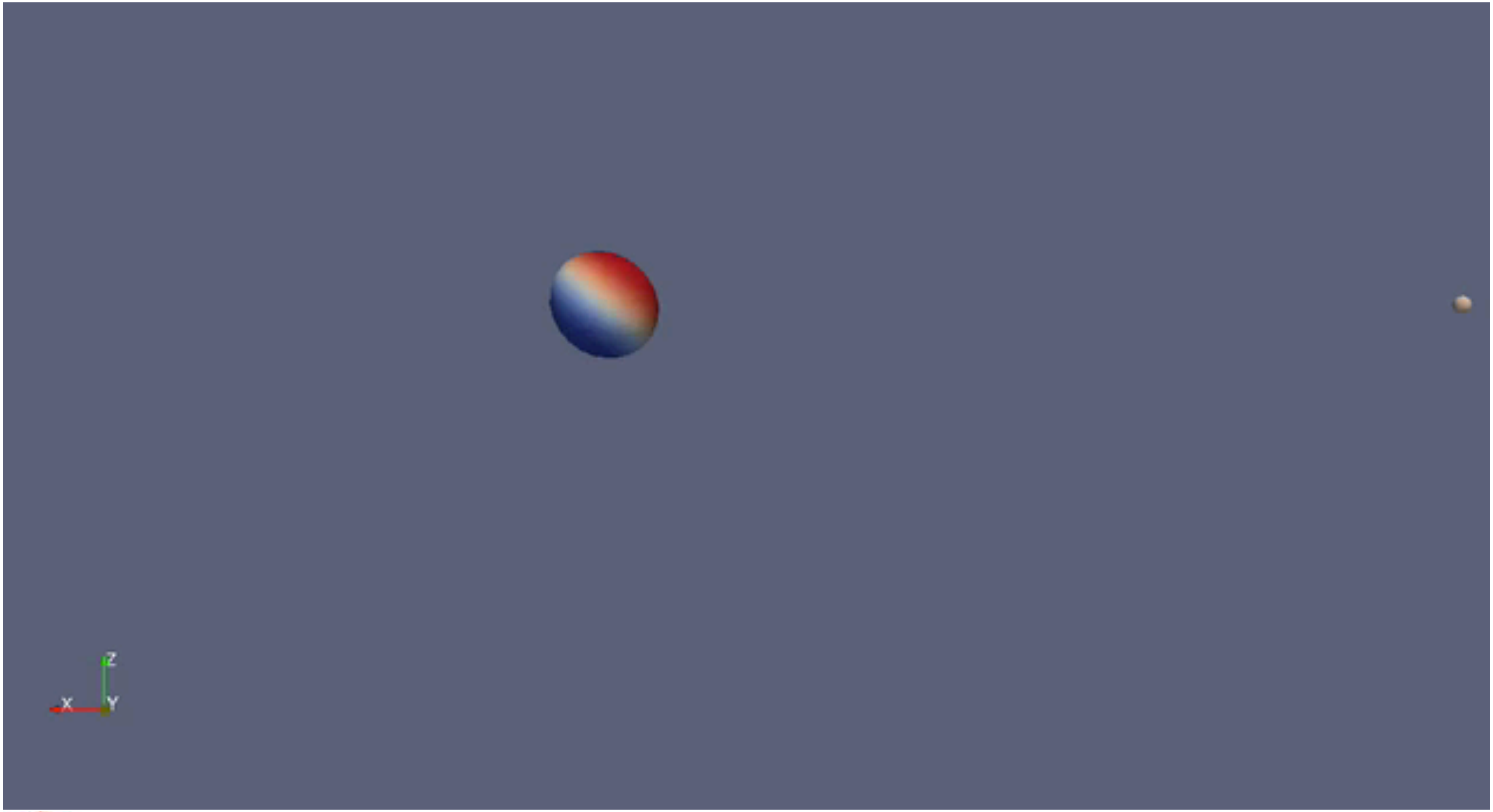






Lewis, AZ, Pfieffer, CQG (2017)

Eccentric, precessing motion



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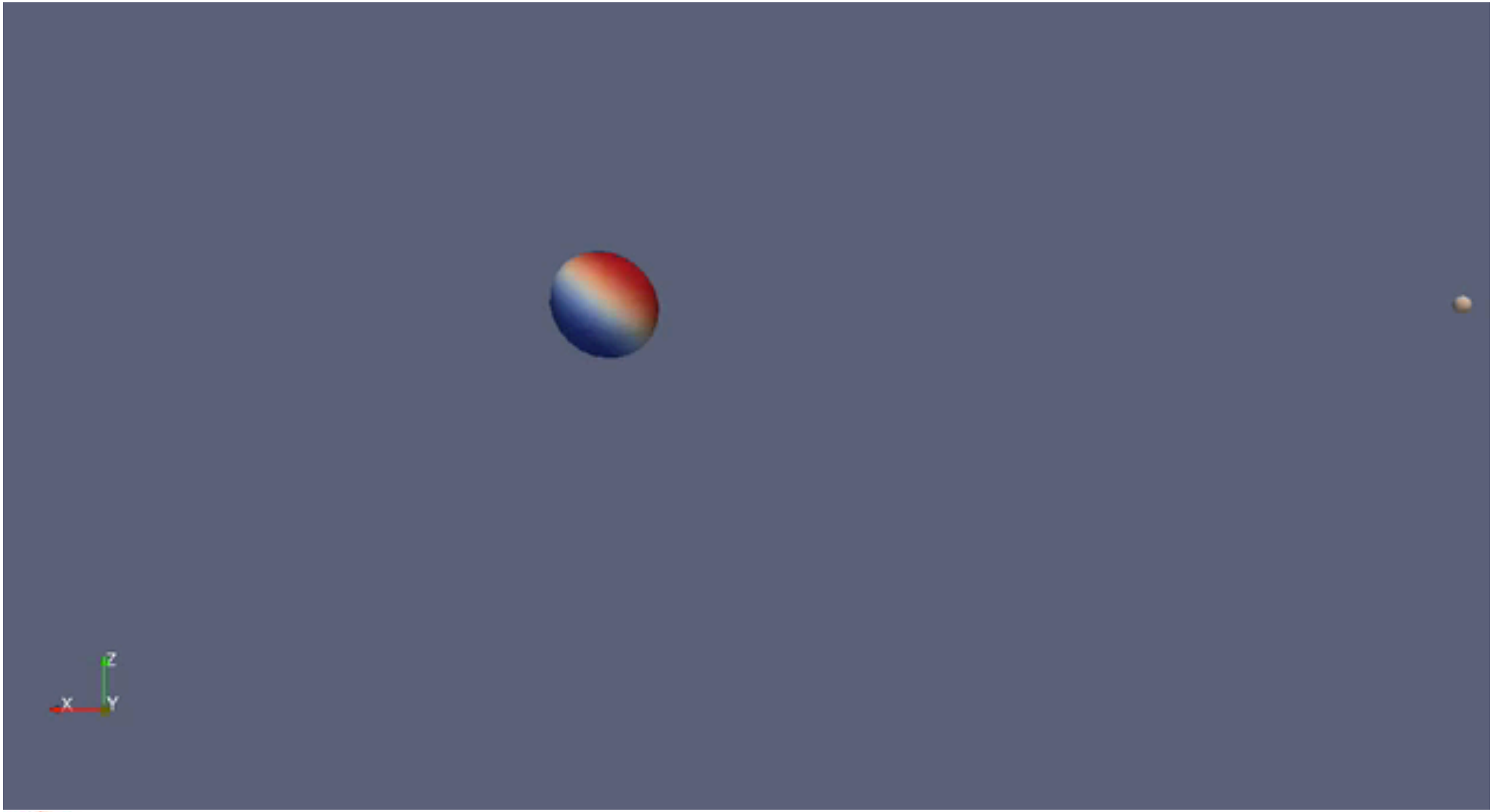
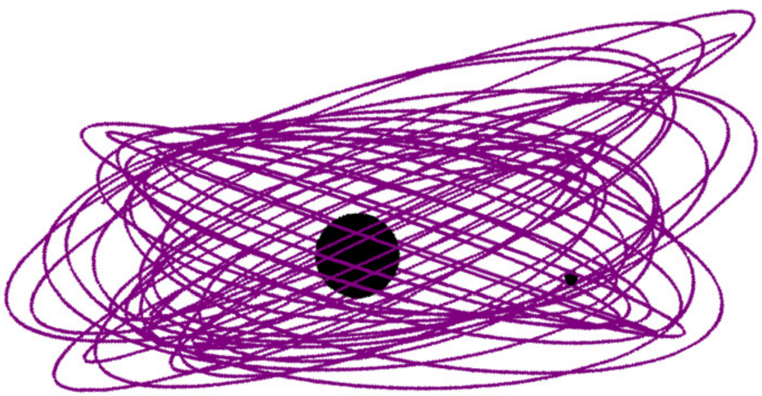
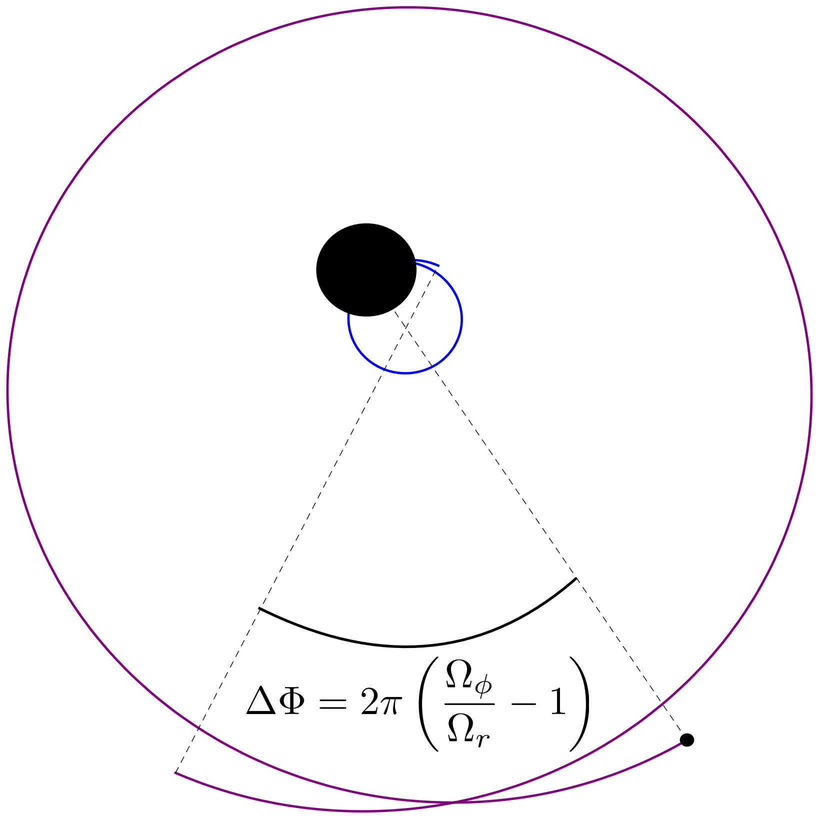


Precession





Lewis, AZ, Pfieffer, CQG (2017)

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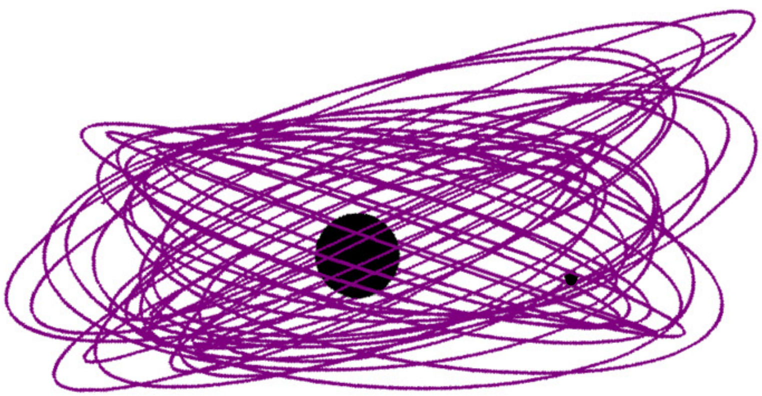
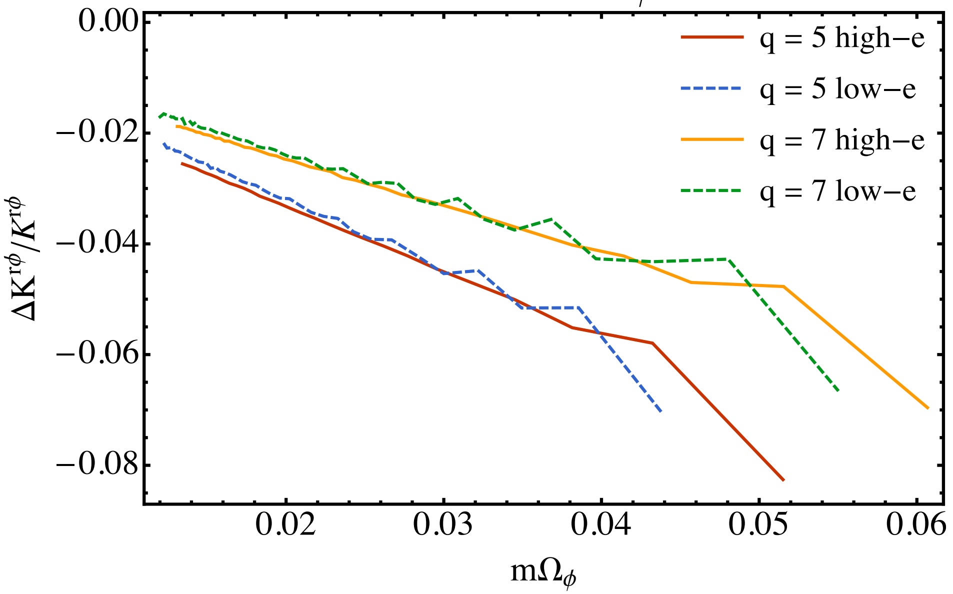


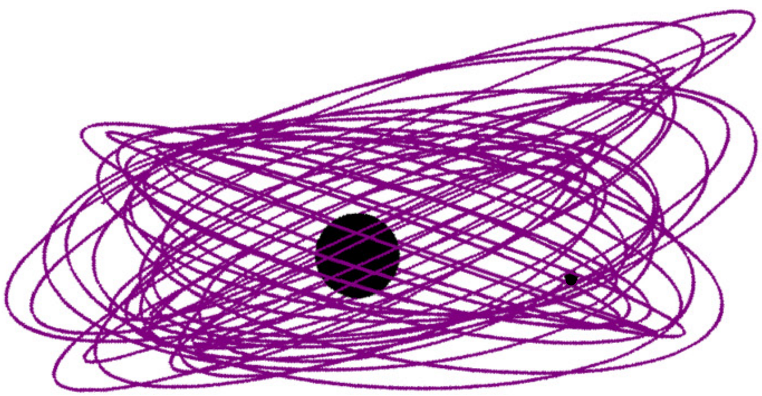
$$K^{r\phi} = \frac{\Omega_r}{\Omega_\phi}$$



Self-force correction to periastron advance

Lewis, AZ, Pfieffer, CQG (2017)

Resonant orbits



Lewis, AZ, Pfieffer, CQG (2017)

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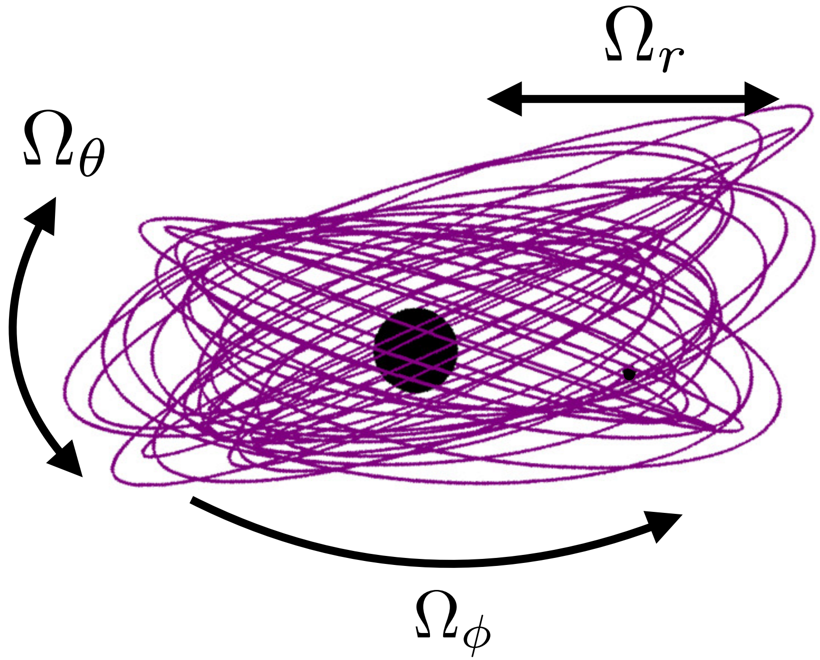
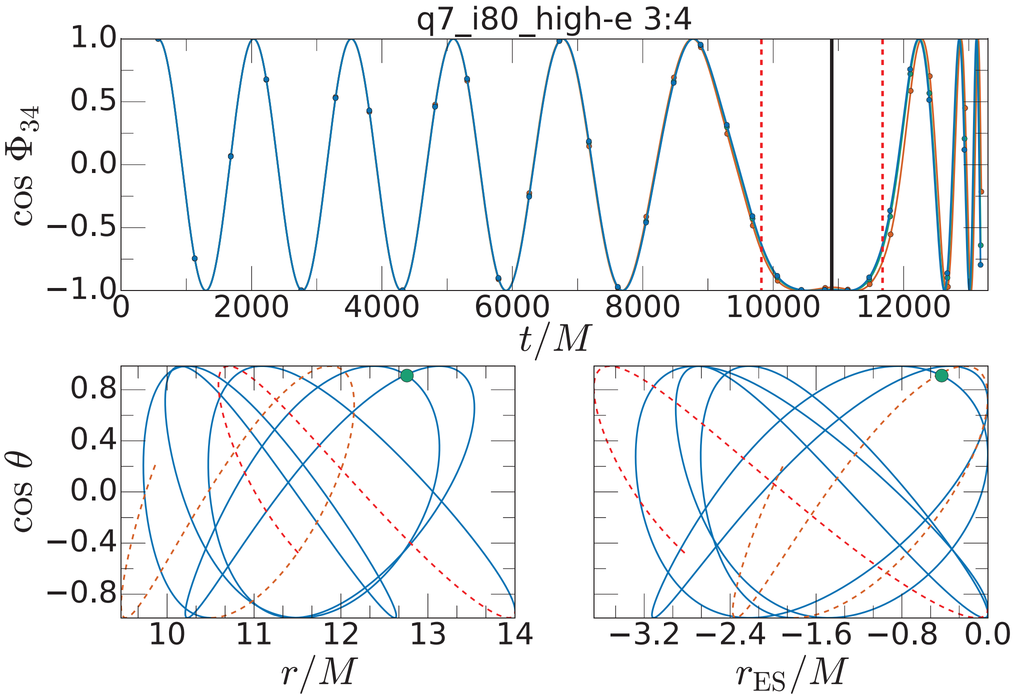
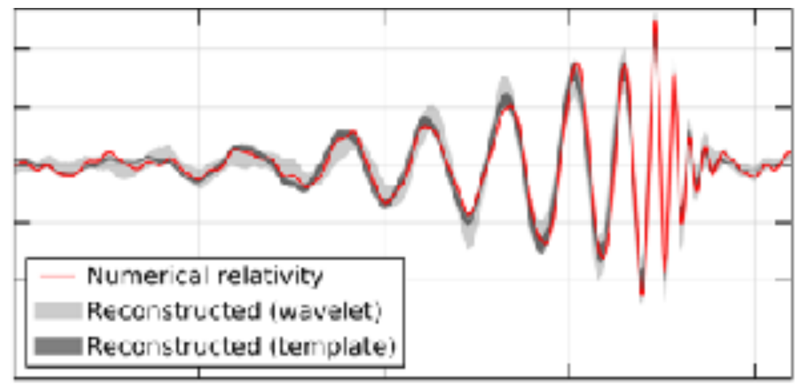


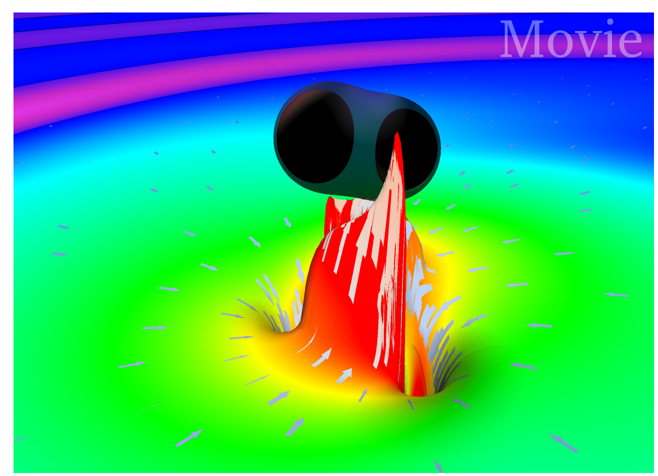


Lewis, AZ, Pfieffer, CQG (2017)

Black holes in binaries

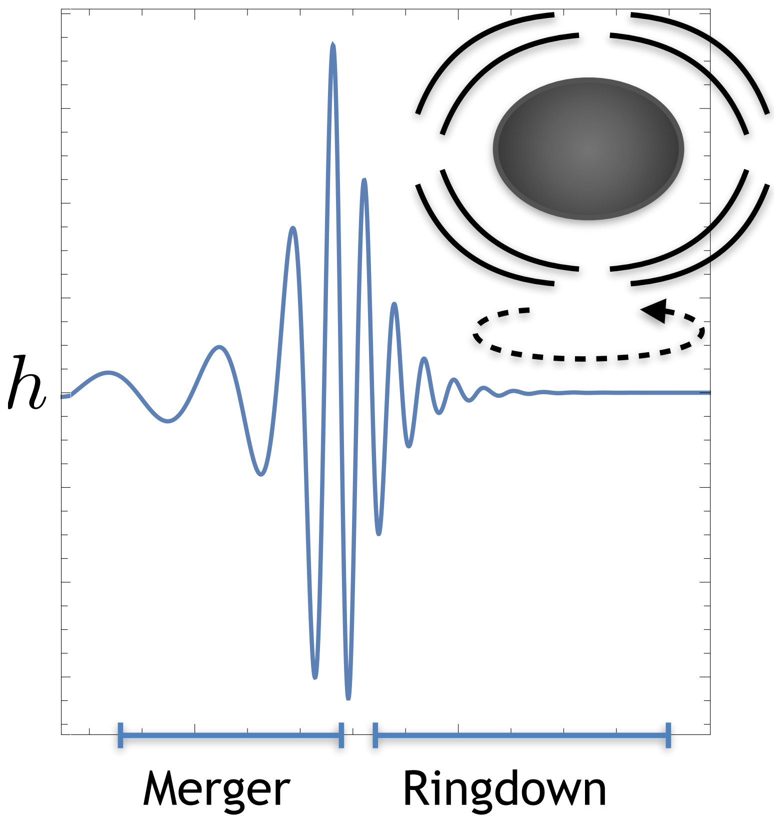
- Relativistic two body problem
- Analytic appx and numerical sims needed
- Discoveries at the intersection
- Models for GW astronomy
- Future: higher mass ratios, drive theory
- Advances required: next gen code SpECTRE

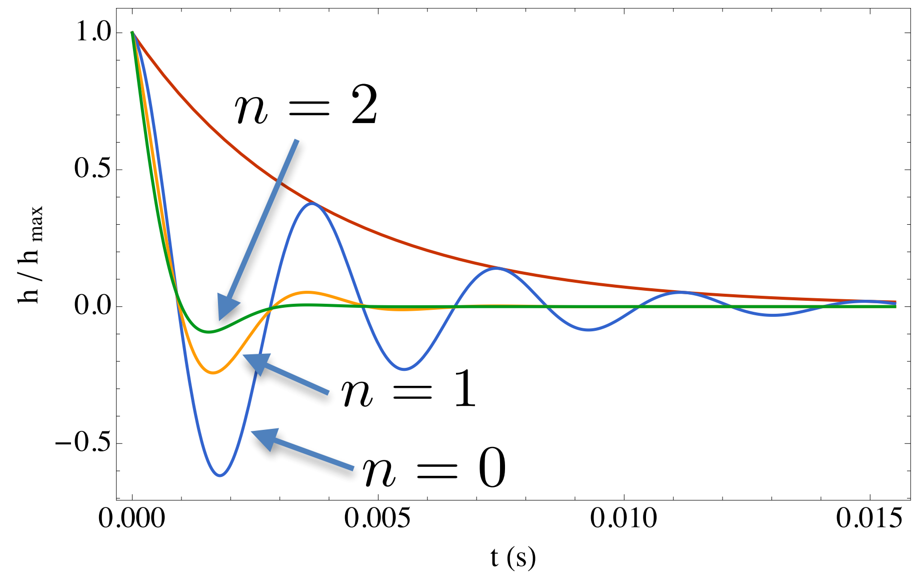




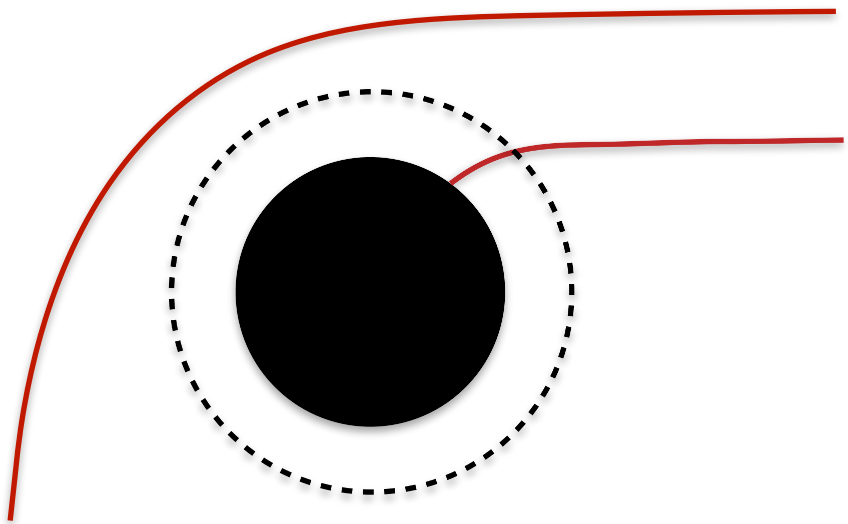
BLACK HOLE RINGDOWN

Black hole ringdown



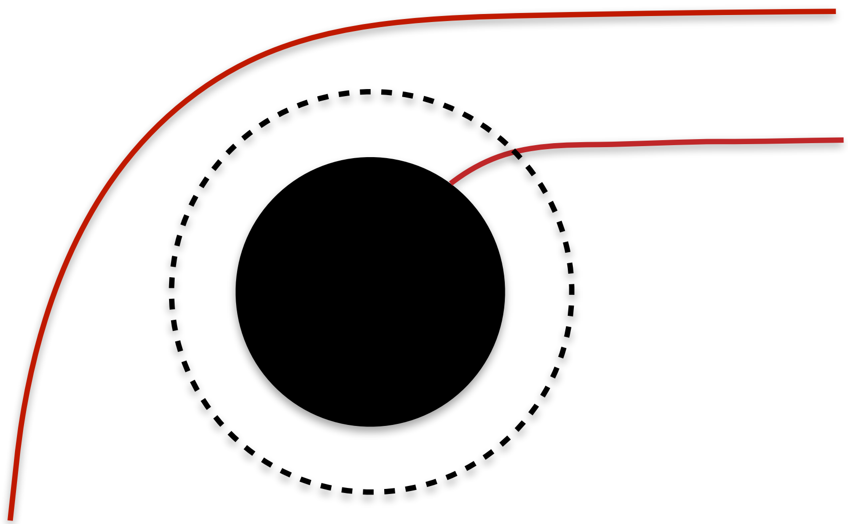


Waves around black holes



Yang et al. w/AZ (2012)

Waves around black holes

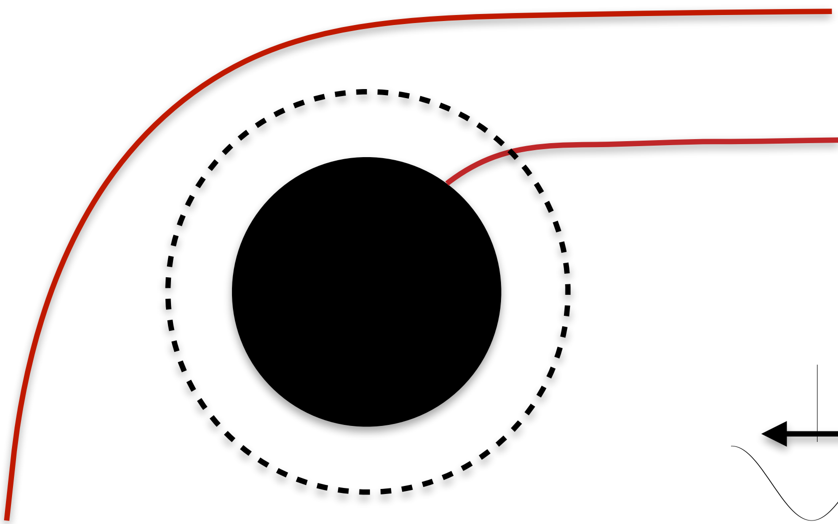


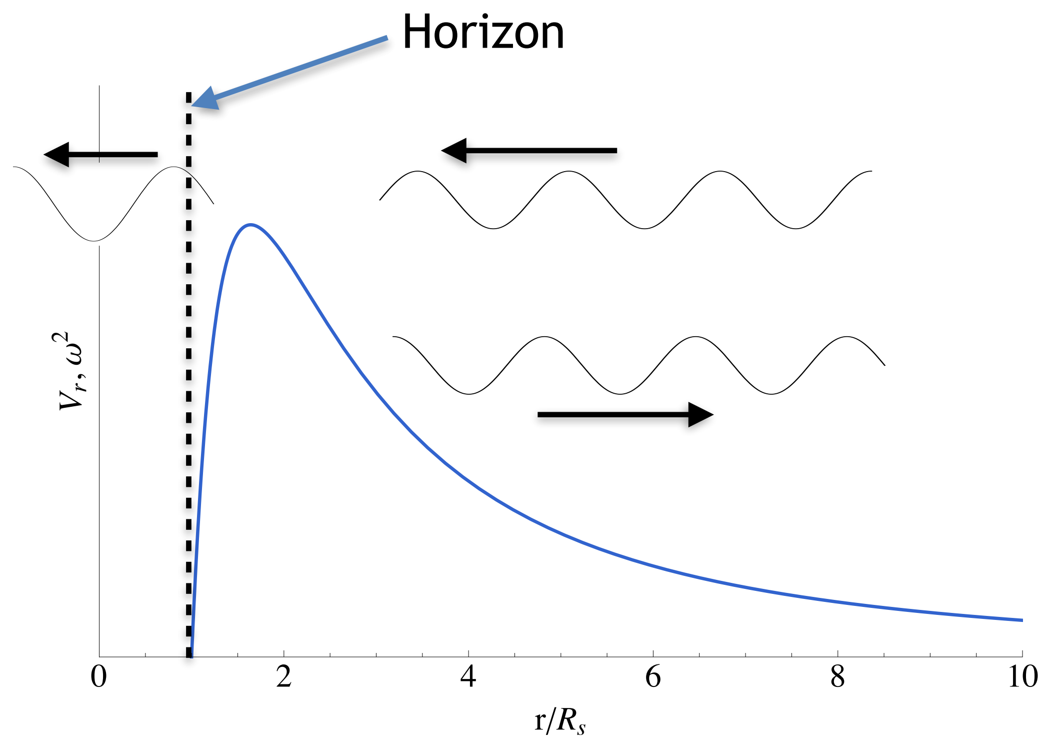
$$\psi_{\omega lm} \sim \frac{1}{r} e^{-i\omega t} u_{\omega lm}(r) Y_{lm}(\theta, \phi)$$

$$\frac{d^2 u_{\omega lm}}{dr_*^2} + \left(\omega^2 - V\right) u_{\omega lm} = 0$$

Yang et al. w/AZ (2012)

Waves around black holes





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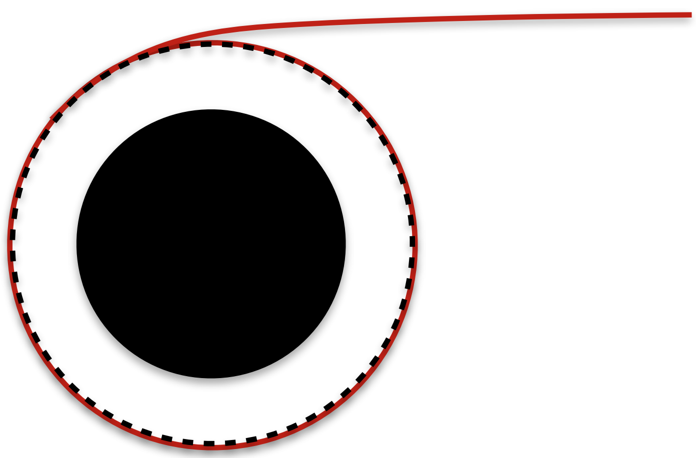
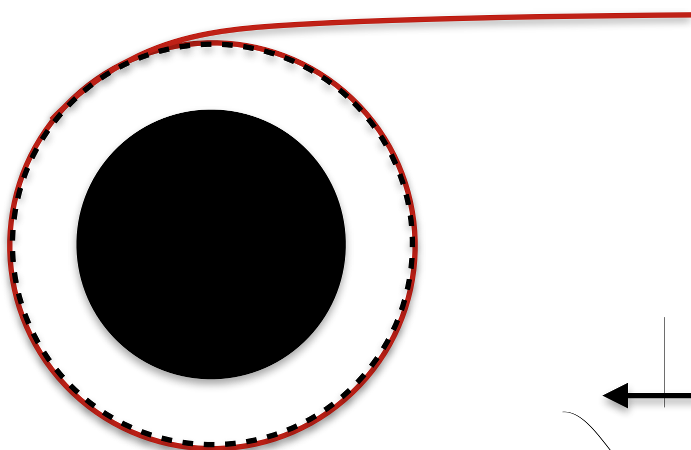
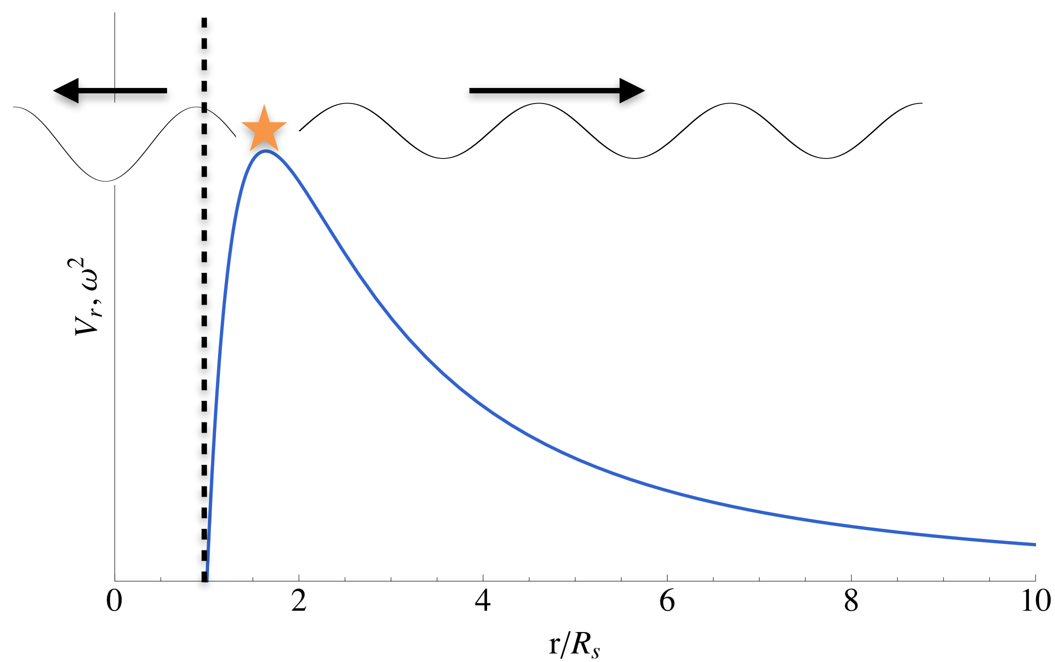
Quasinormal modes



Yang et al. w/AZ (2012)

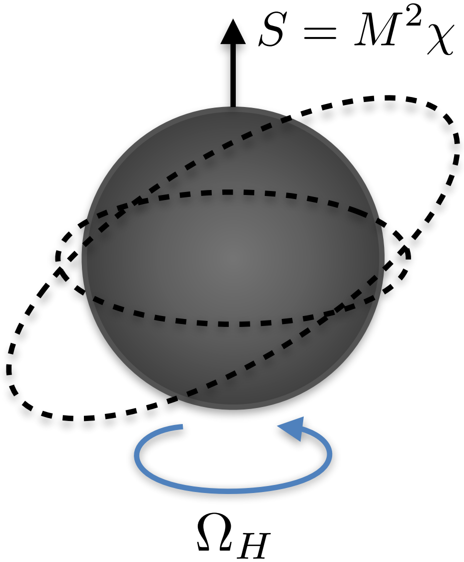
Quasinormal modes





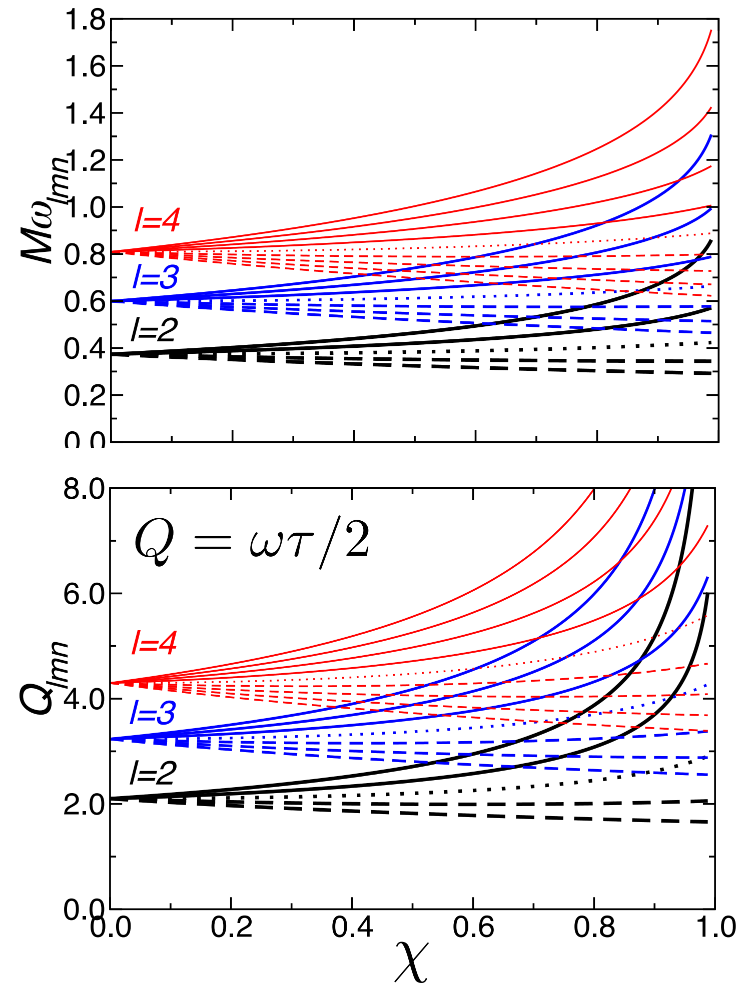
Yang et al. w/AZ (2012)

Modes of rotating black holes



- Orbits split with inclination
- Modes split
- Slower decay with higher spin

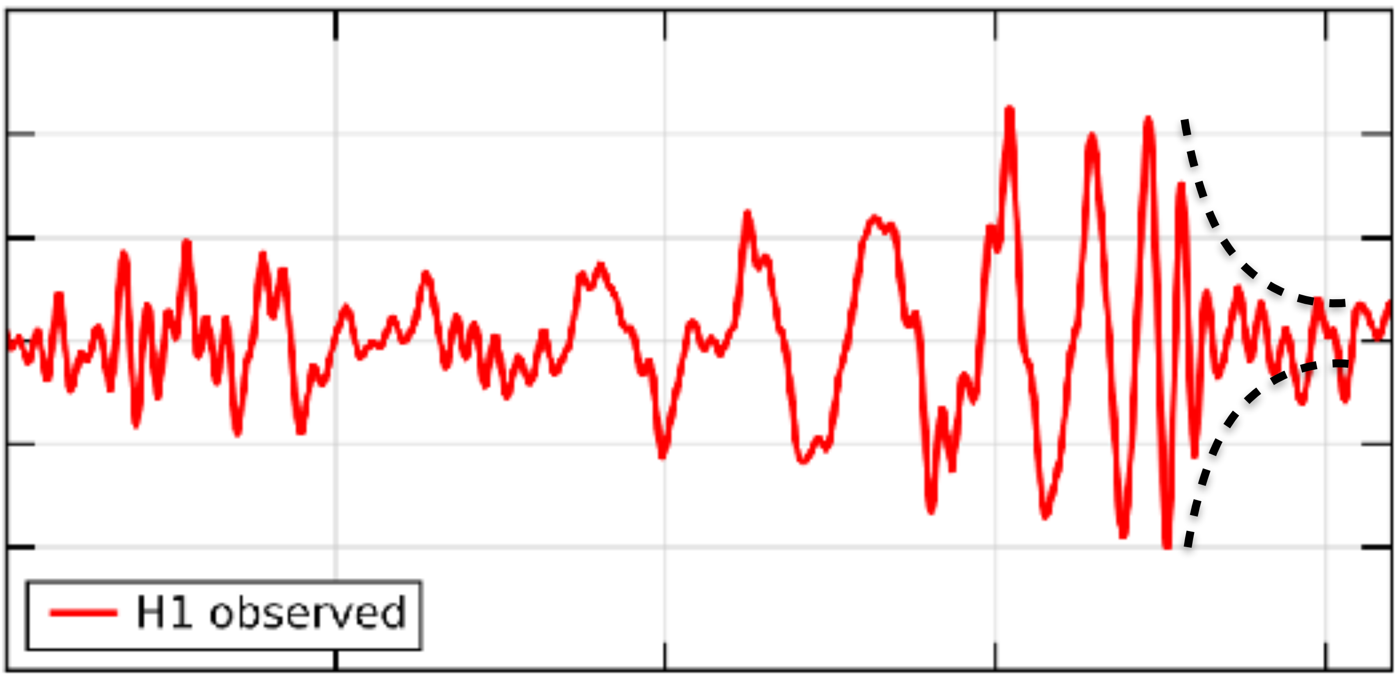
$$(\omega, \tau) \rightarrow (M, \chi)$$



Yang et al. w/AZ (2012)

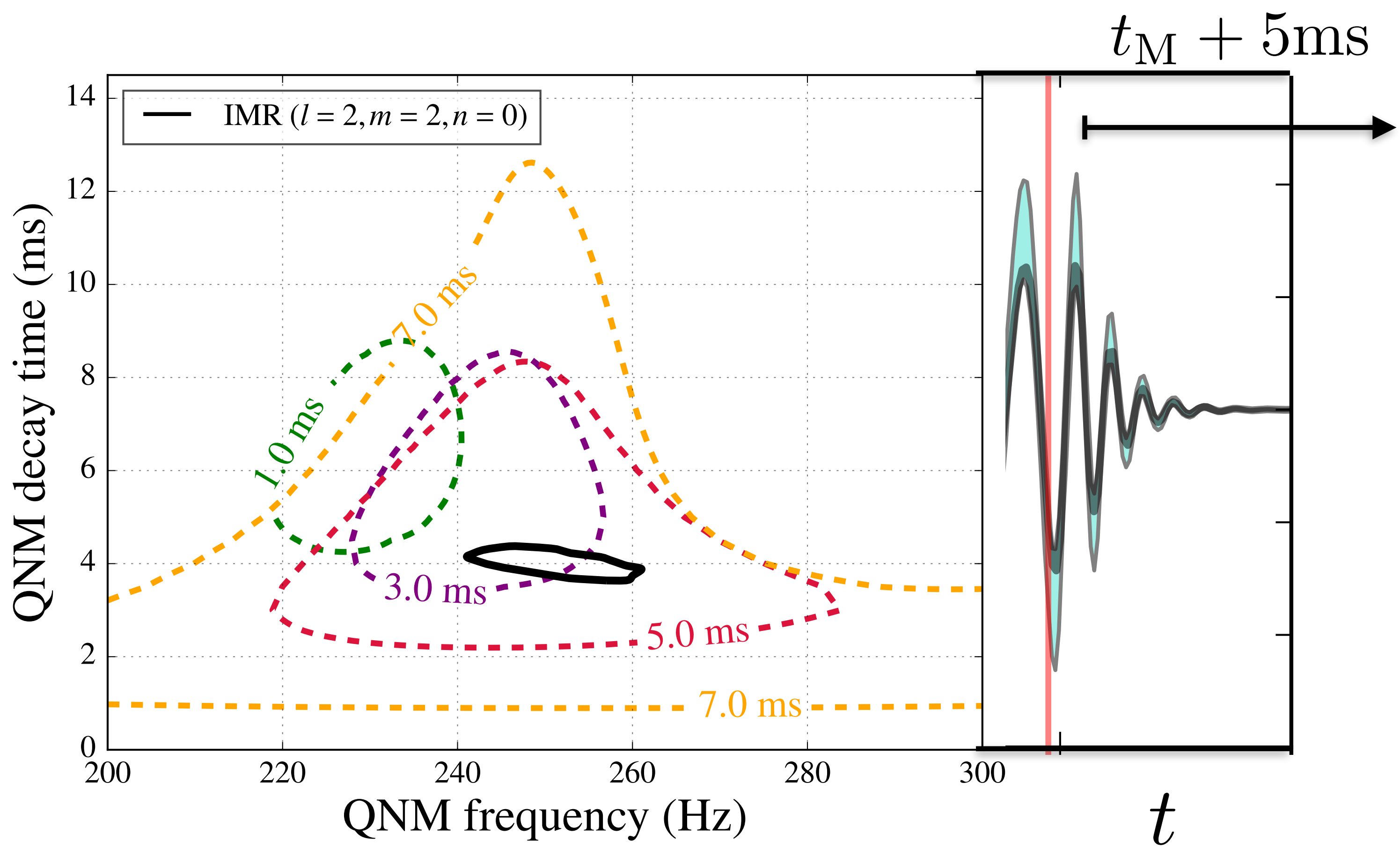
Berti, Cardoso, Starinets (2009)

The ringdown of GW150914



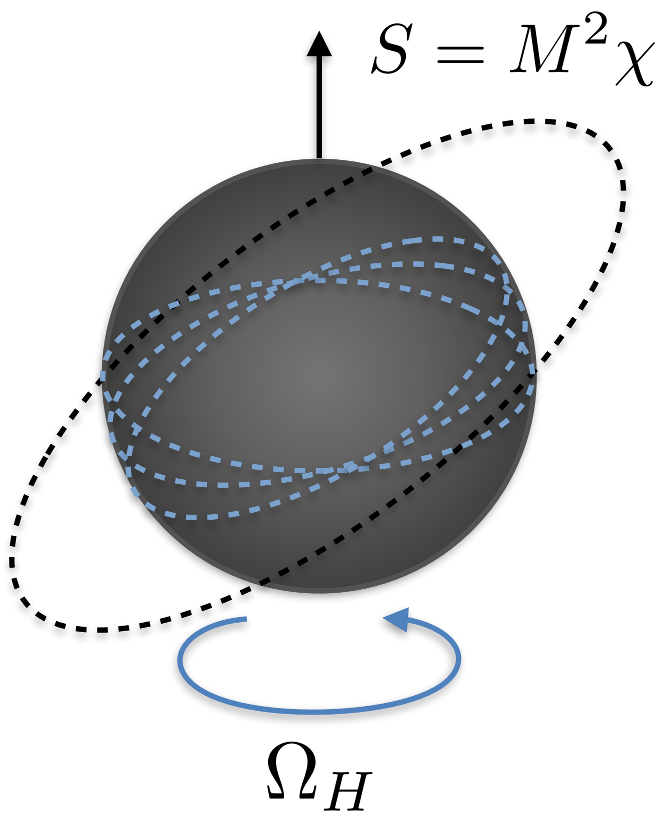
LVC PRL 116, 061102 (2016)

The ringdown of GW150914



LVC PRL 116, 221101 (2016)

Modes of rapidly rotating BHs



- Black holes spins have a theoretical max
- Near maximum spin, new approx

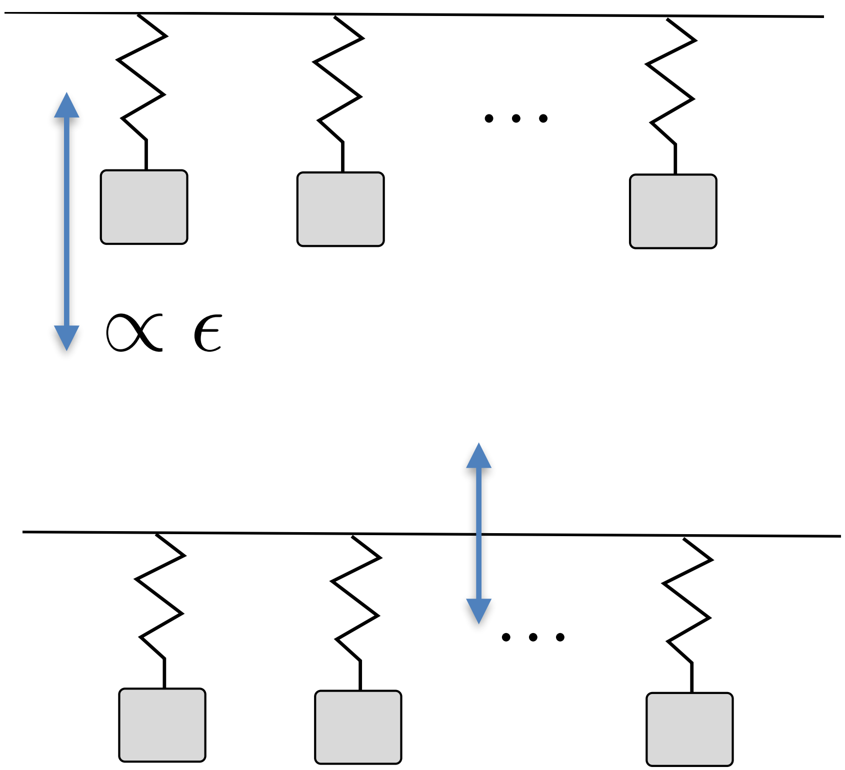
$$\epsilon^2 = 1 - \chi^2$$

$$\omega \approx m\Omega_H \qquad \tau \approx \frac{1}{\epsilon(n+1/2)}$$

Slow decay!

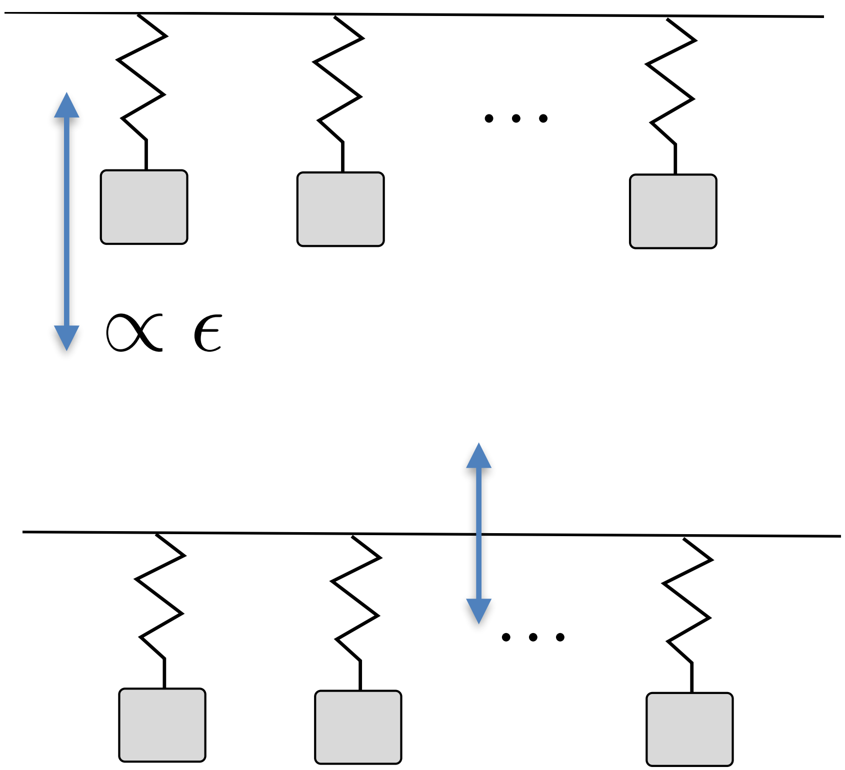
Teukolsky and Press (1974), Detweiler (1980), Hod (2008), Yang et al w/ AZ (2012), Yang, AZ et al. (2013a, 2013b)

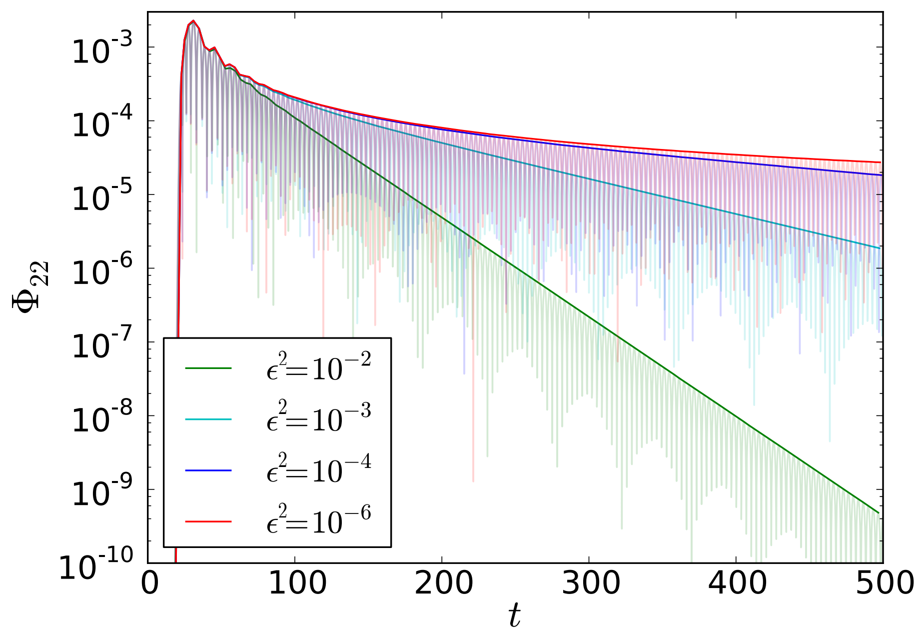
Collective oscillation of modes



Yang, AZ et al. (2013b)

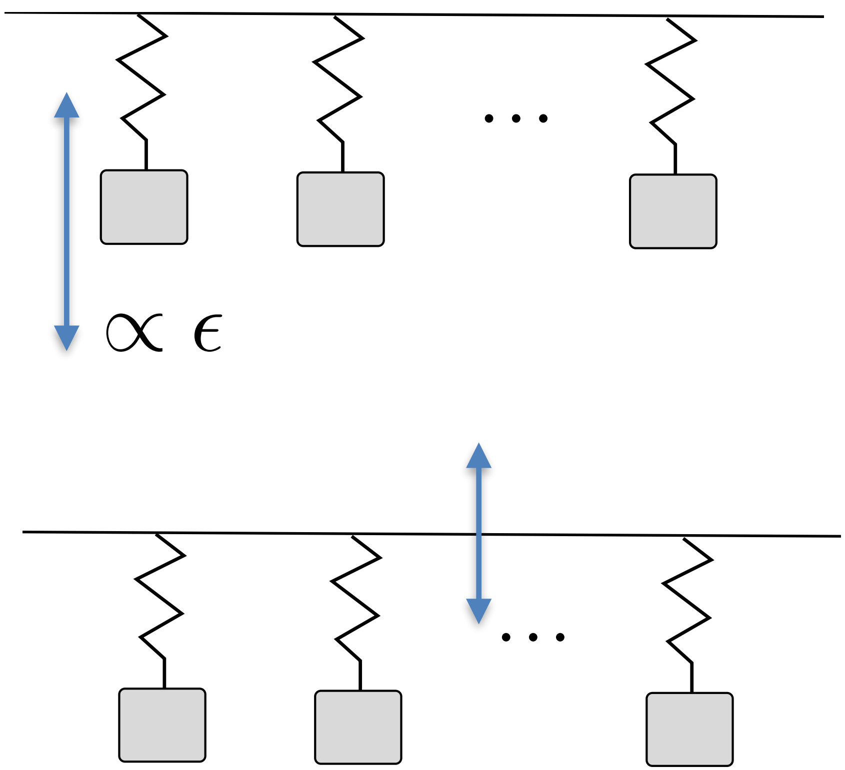
Collective oscillation of modes

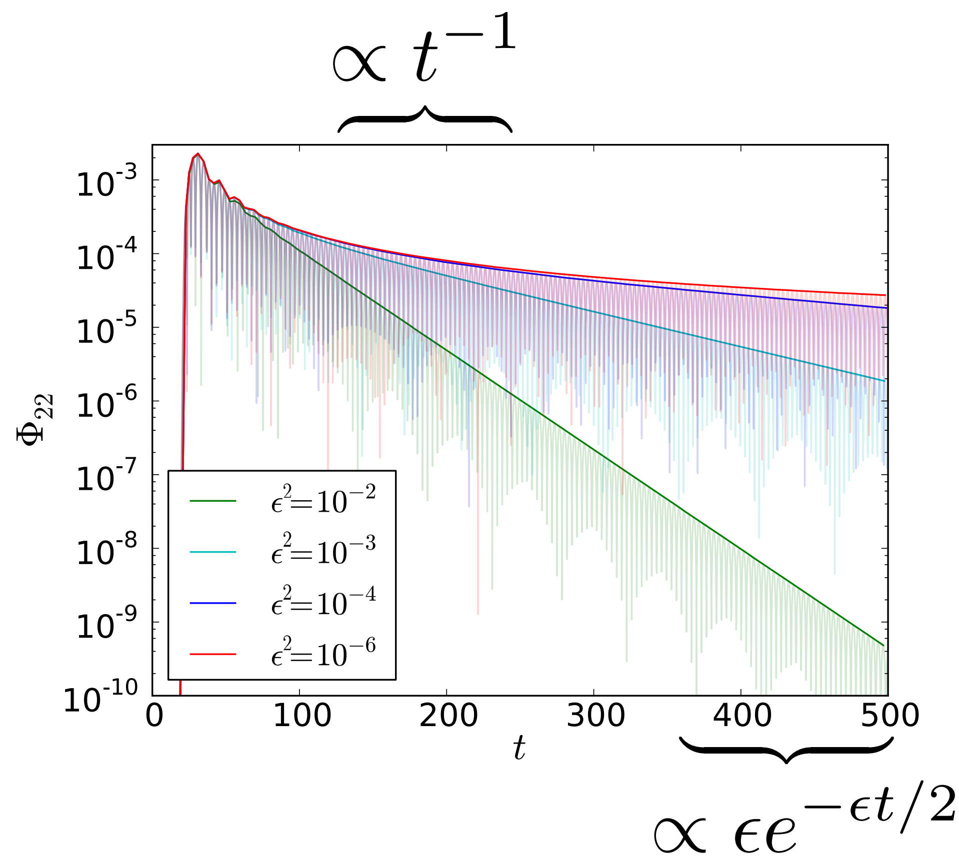




Yang, AZ et al. (2013b)

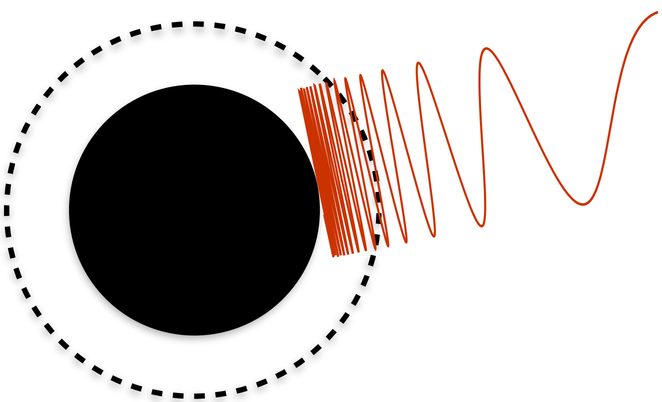
Collective oscillation of modes

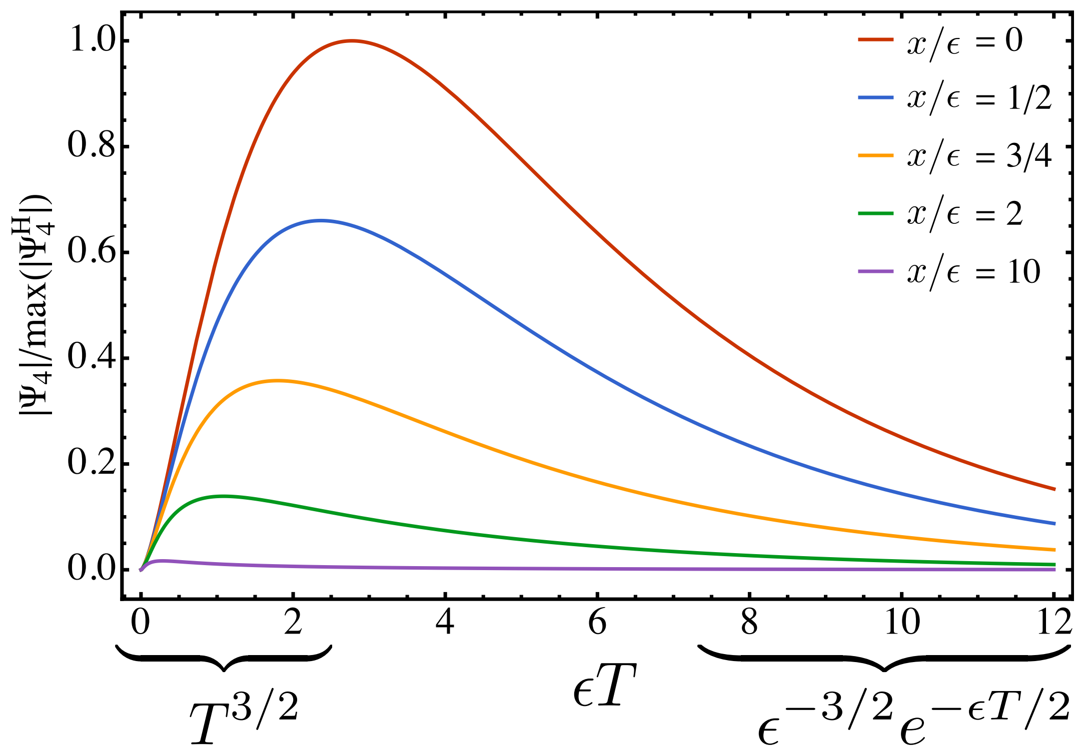




Yang, AZ et al. (2013b)

Near-horizon response

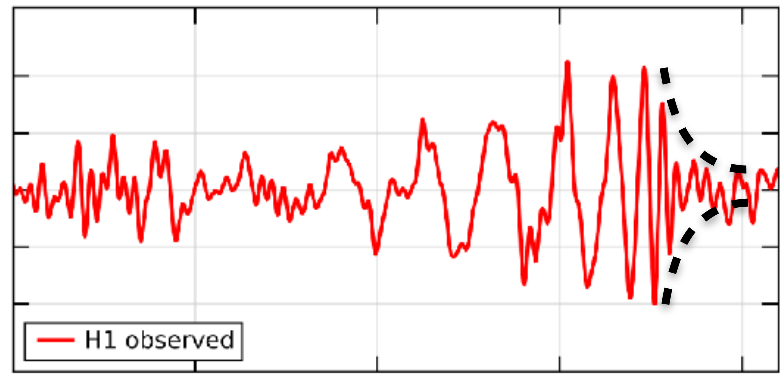


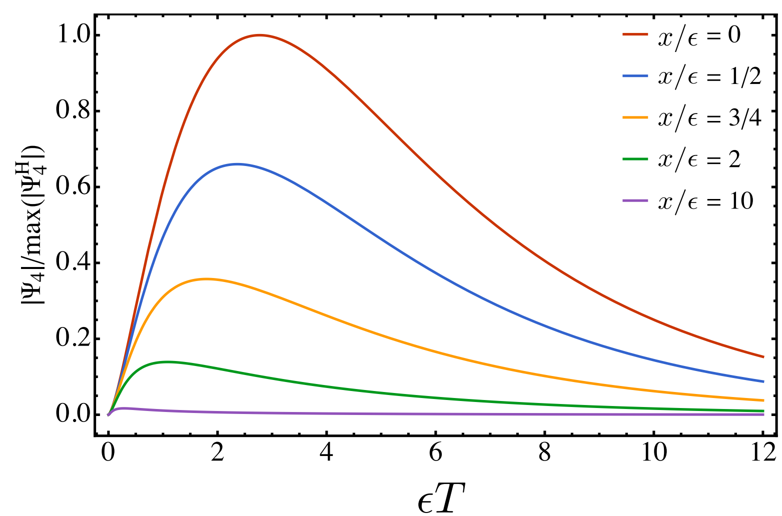


Gralla, AZ, P Zimmerman (2016)

Ringdown of black holes

- Unique probe of BHs, tests of GR
- Weak signals, combine many observations
- Rapidly rotating BHs: collective oscillations
- Transient instabilities
- Nonlinear ringdown: resonances, turbulence





GW ASTRONOMY: THE SECOND OBSERVING RUN

LIGO

LSC

LIGO Scientific Collaboration

Trinity University

University of Maryland

Andrews University

Washington State University

California State University Fullerton

The University of Alabama in Huntsville

Sonoma State University

indigo

Montclair State University

University of Glasgow

Australian National University

Whitman College

American University, Washington, DC

University of the West of Scotland (UWS)

Texas Tech University

清華大學 Tsinghua University

R·I·T

Max Planck Institute for Gravitational Physics, Albert Einstein Institute

University of Strathclyde

Michigan

РАН

Università degli Studi del Sannio

CITA | ICAT, Canadian Institute for Theoretical Astrophysics, L'institut Canadien d'astrophysique theorique

NASA Goddard Space Flight Center

ICTP SAIFR

The University of Western Australia

ACU

Monash University

University of Cambridge

The University of Chicago

Montana State University

Southern University and Agricultural & Mechanical College

Columbia University in the City of New York

The University of Mississippi

The University of Adelaide, Australia

University of Birmingham

Caltech

University of Minnesota

The University of Melbourne

UIB Universitat de les Illes Balears

University of Washington

GEO 600

UTRGV

University of Wisconsin Milwaukee

Northwestern

Universität Hamburg

Syracuse University

Cardiff University, Prifysgol Caerdydd

Monash University

INPE

UF University of Florida

Georgia Institute of Technology

Korean Gravitational-Wave Group

LSU Louisiana State University

ACIGA

University of Southampton

Charles Sturt University

Embry-Riddle Aeronautical University

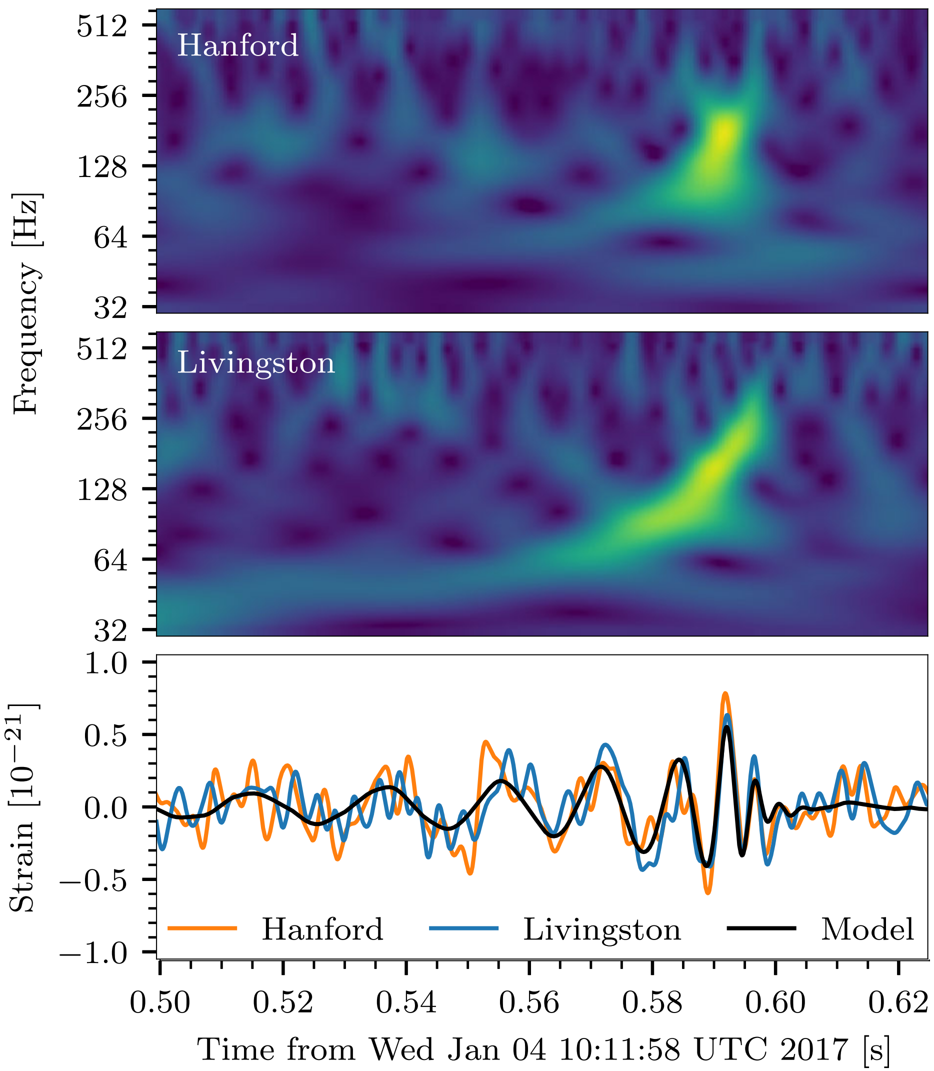
Leibniz Universität Hannover

PennState

Hobart and William Smith Colleges

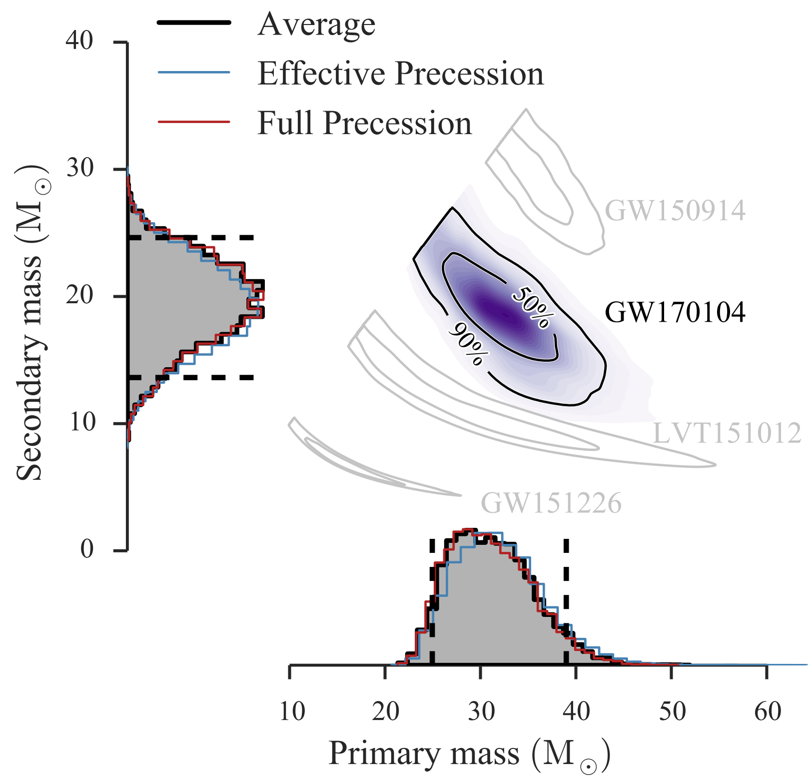
Science & Technology Facilities Council, Rutherford Appleton Laboratory

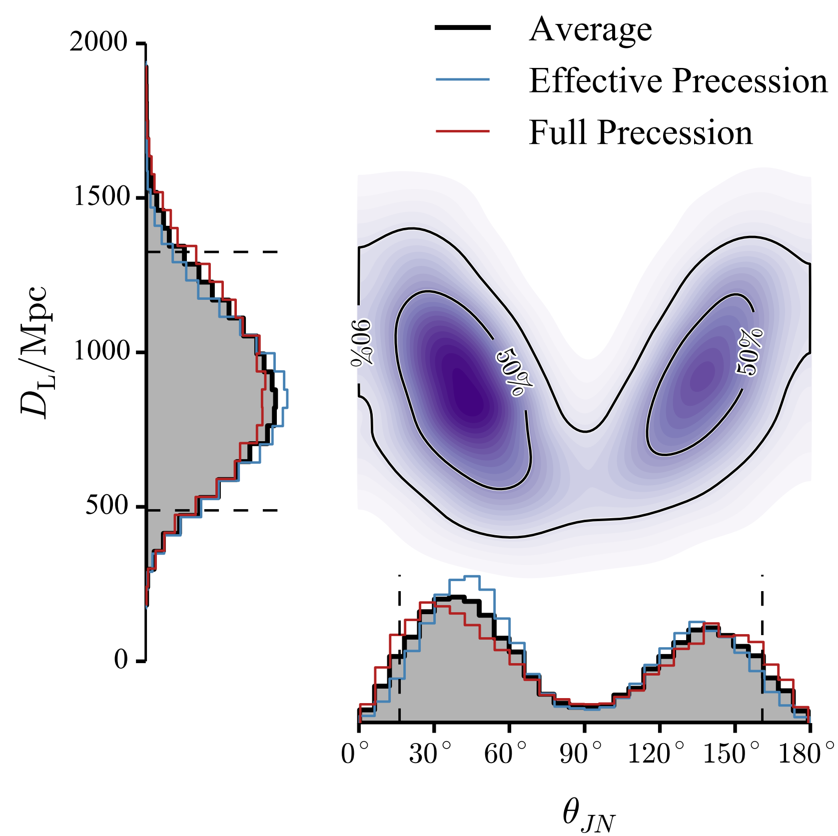
GW170104: A distant BH binary



LVC w/ AZ PRL 118, 221101 (2017)

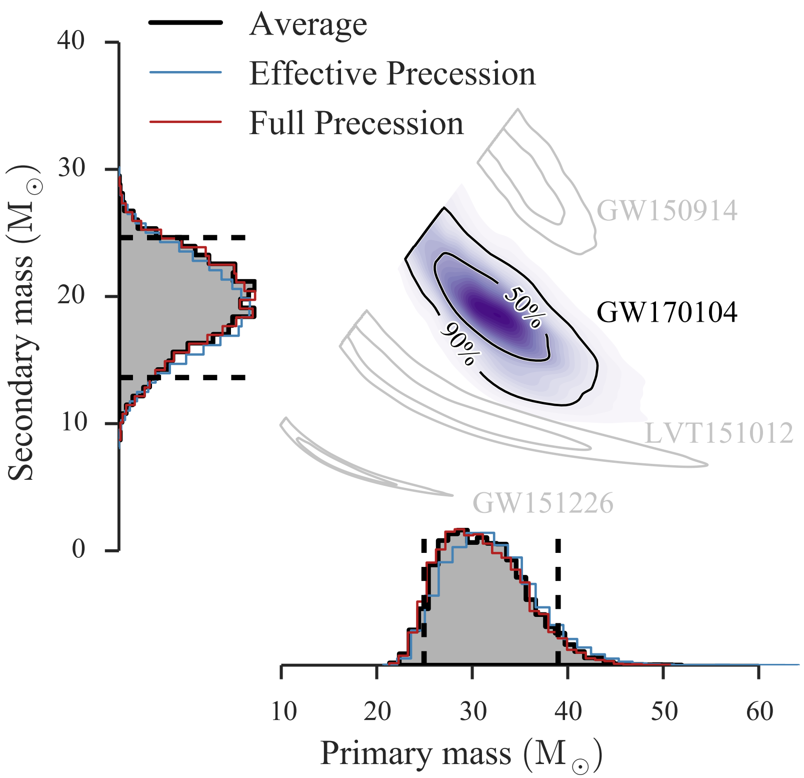
GW170104: A distant BH binary

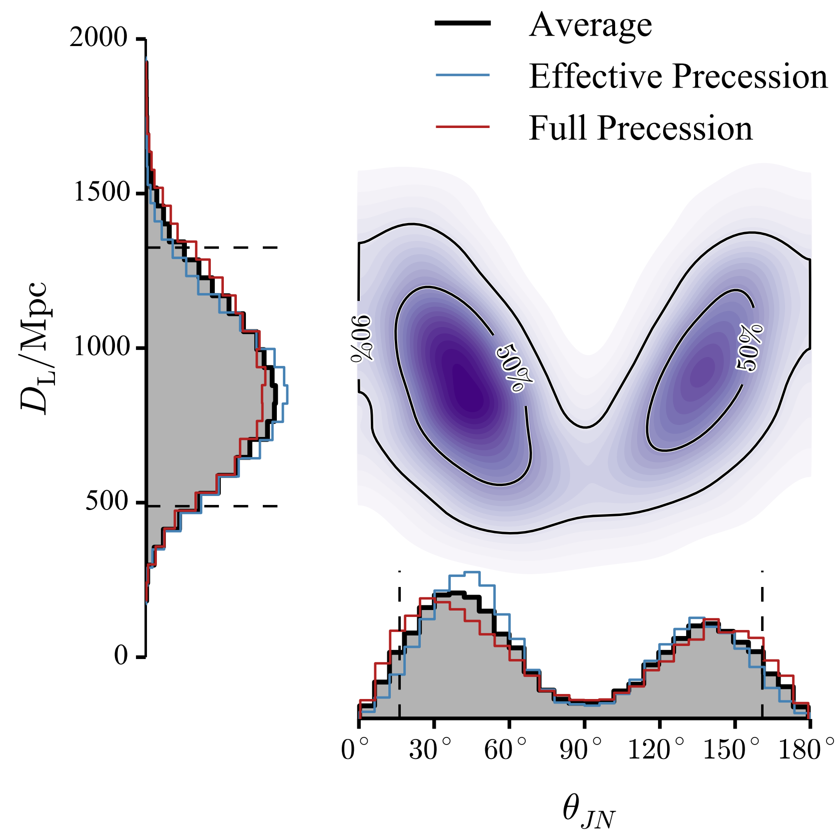




LVC w/ AZ PRL 118, 221101 (2017)

GW170104: A distant BH binary



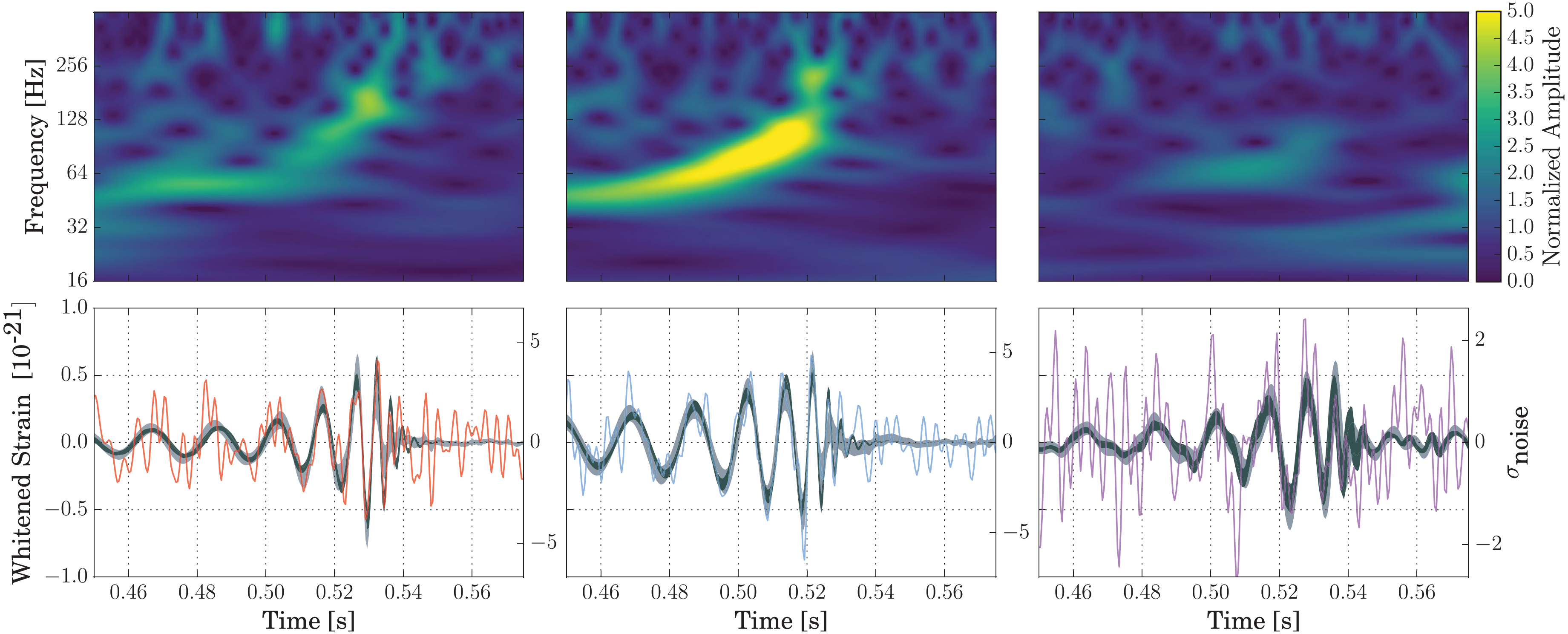


$$E^2 = p^2c^2 + m_g^2c^4$$

$$m_g \leq 7.7 \times 10^{-23} \mathrm{eV} c^{-2}$$

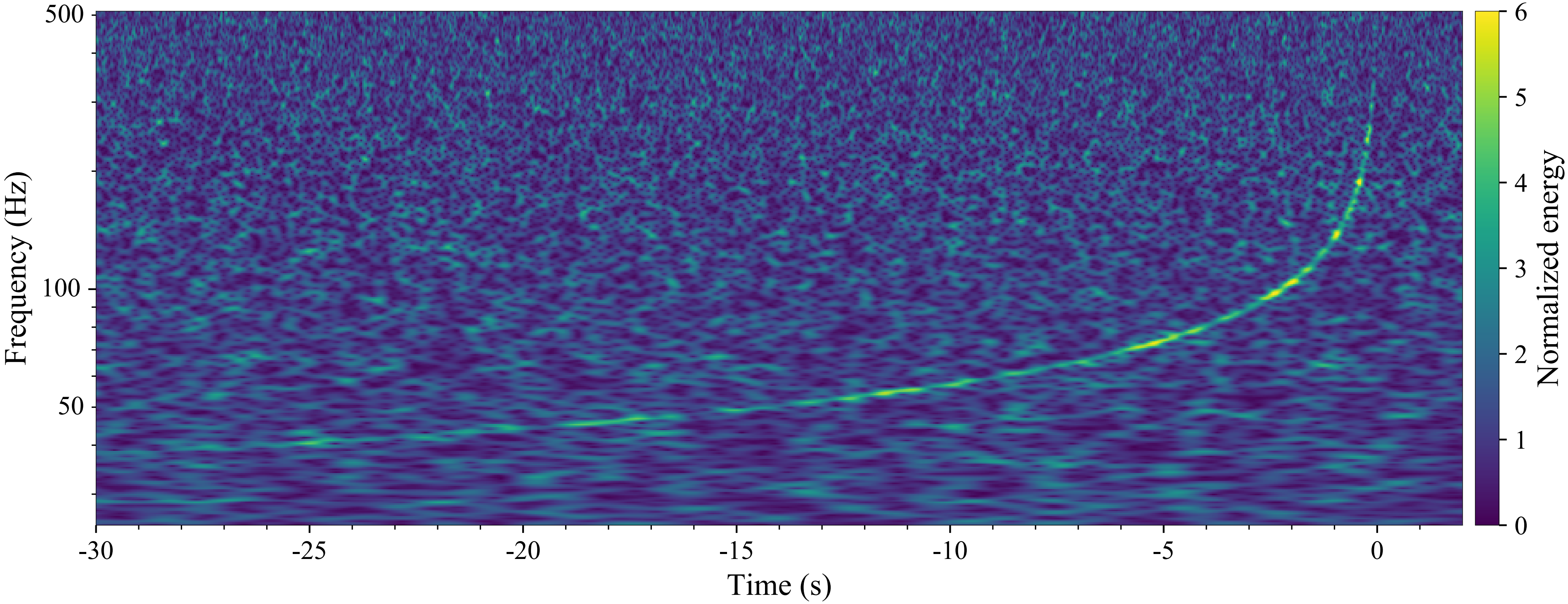
LVC w/ AZ PRL 118, 221101 (2017)

GW170814: First three-detector observation



LVC w/ AZ PRL 119, 141101 (2017)

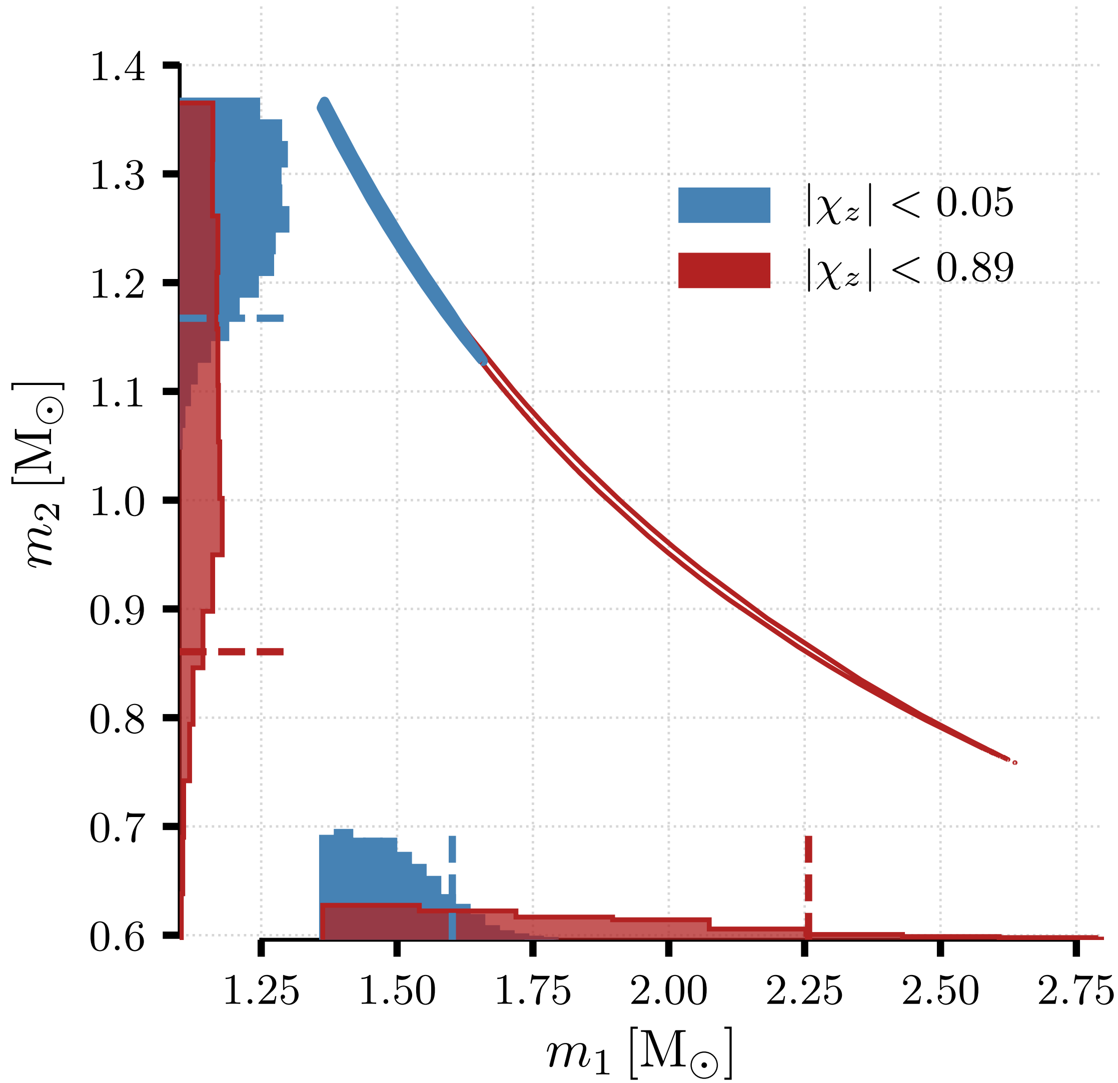
GW170817: Something new



Credit: Alex Nitz/Max Planck Institute for Gravitational Physics/LIGO

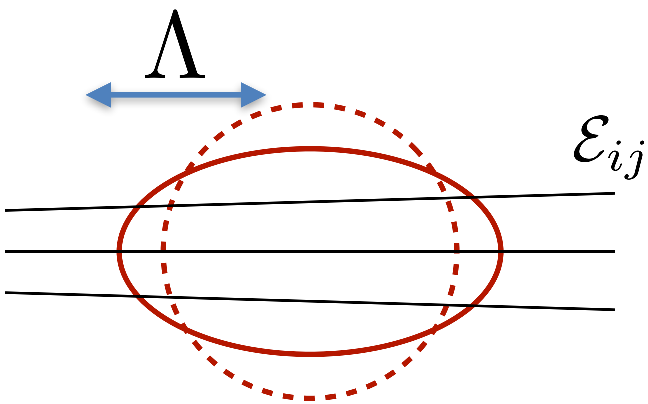
LVC w/ AZ PRL 119, 161101 (2017)

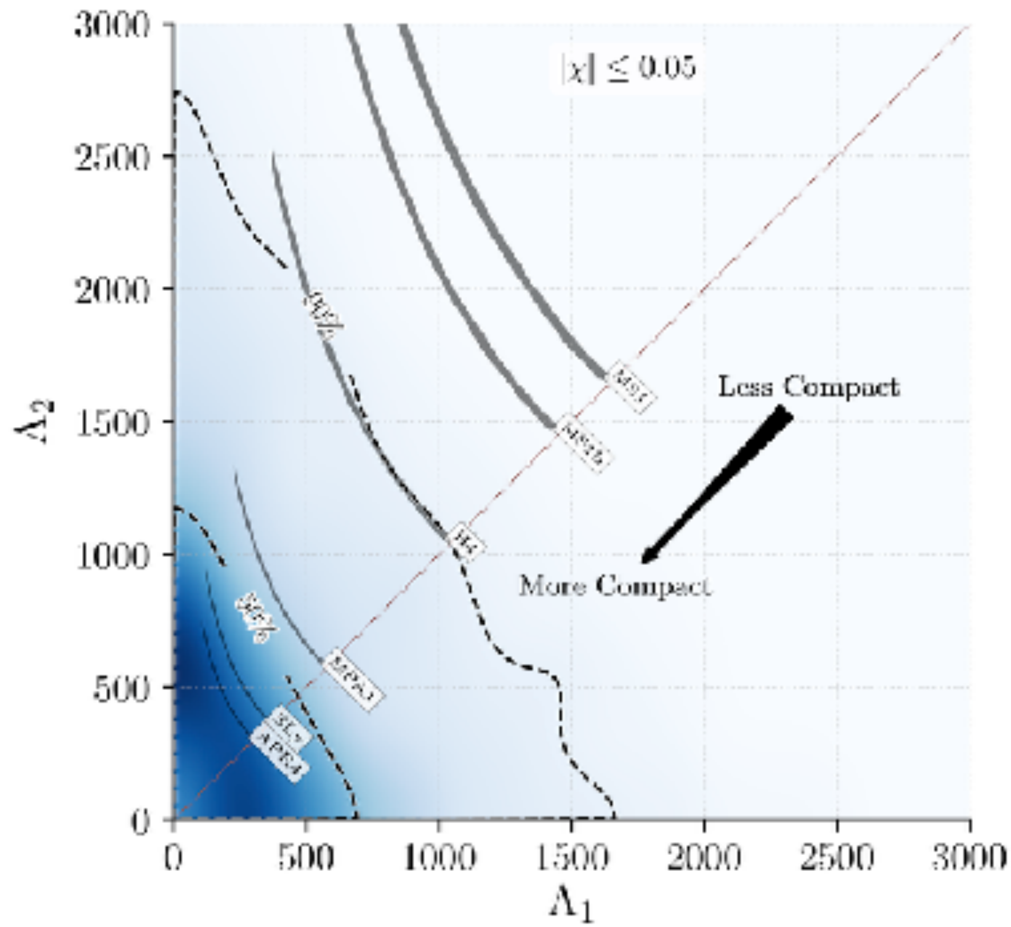
Component masses



LVC w/ AZ PRL 119, 161101 (2017)

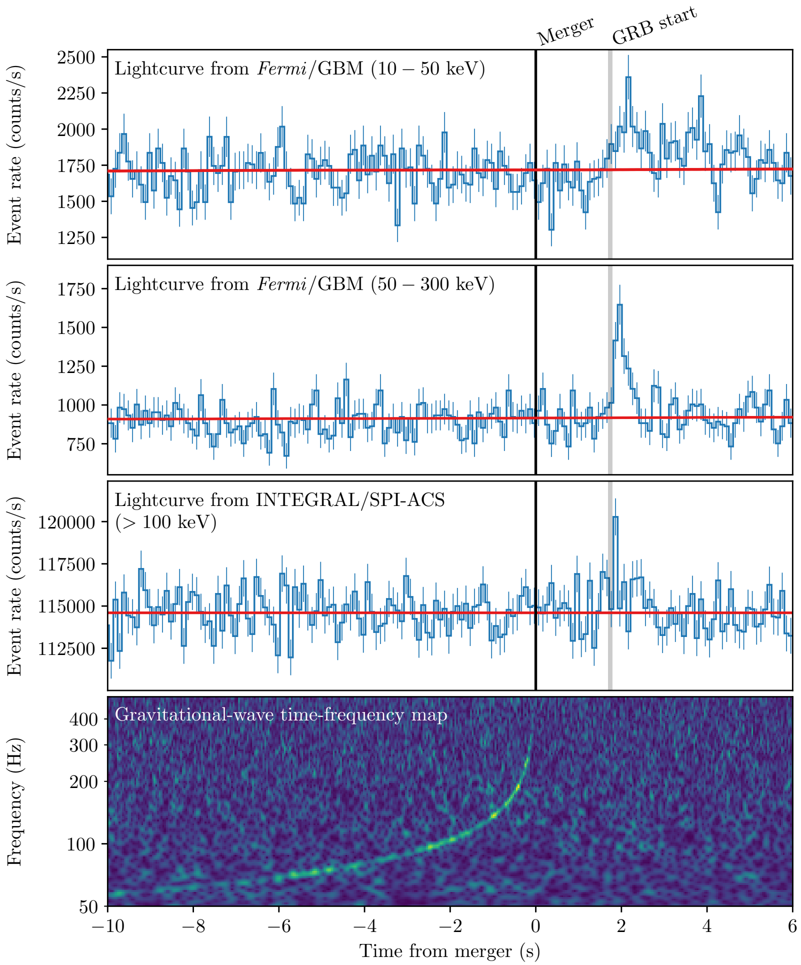
Nuclear physics with GW170817

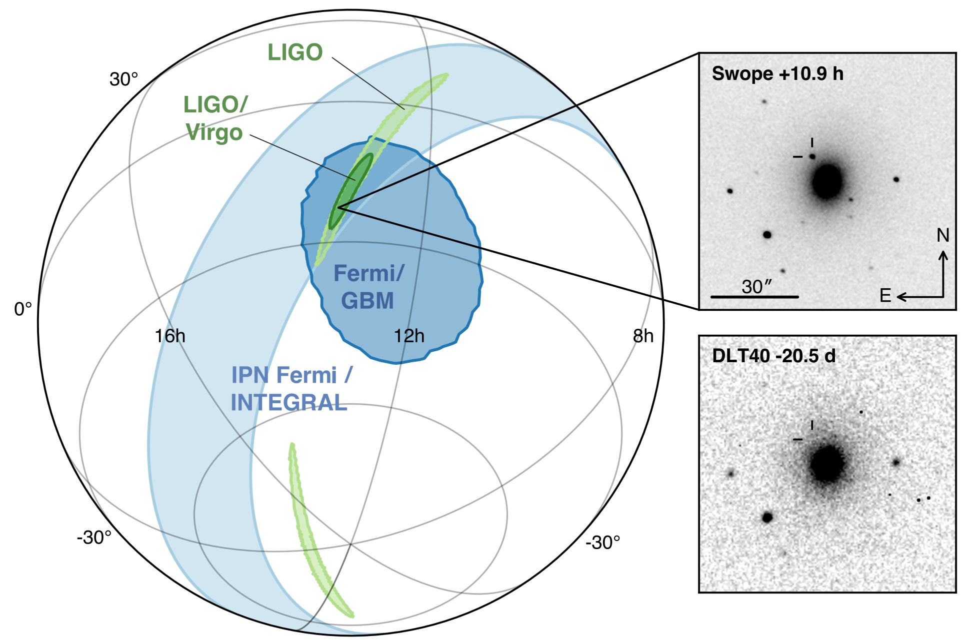




LVC w/ AZ PRL 119, 161101 (2017)

Electromagnetic counterpart

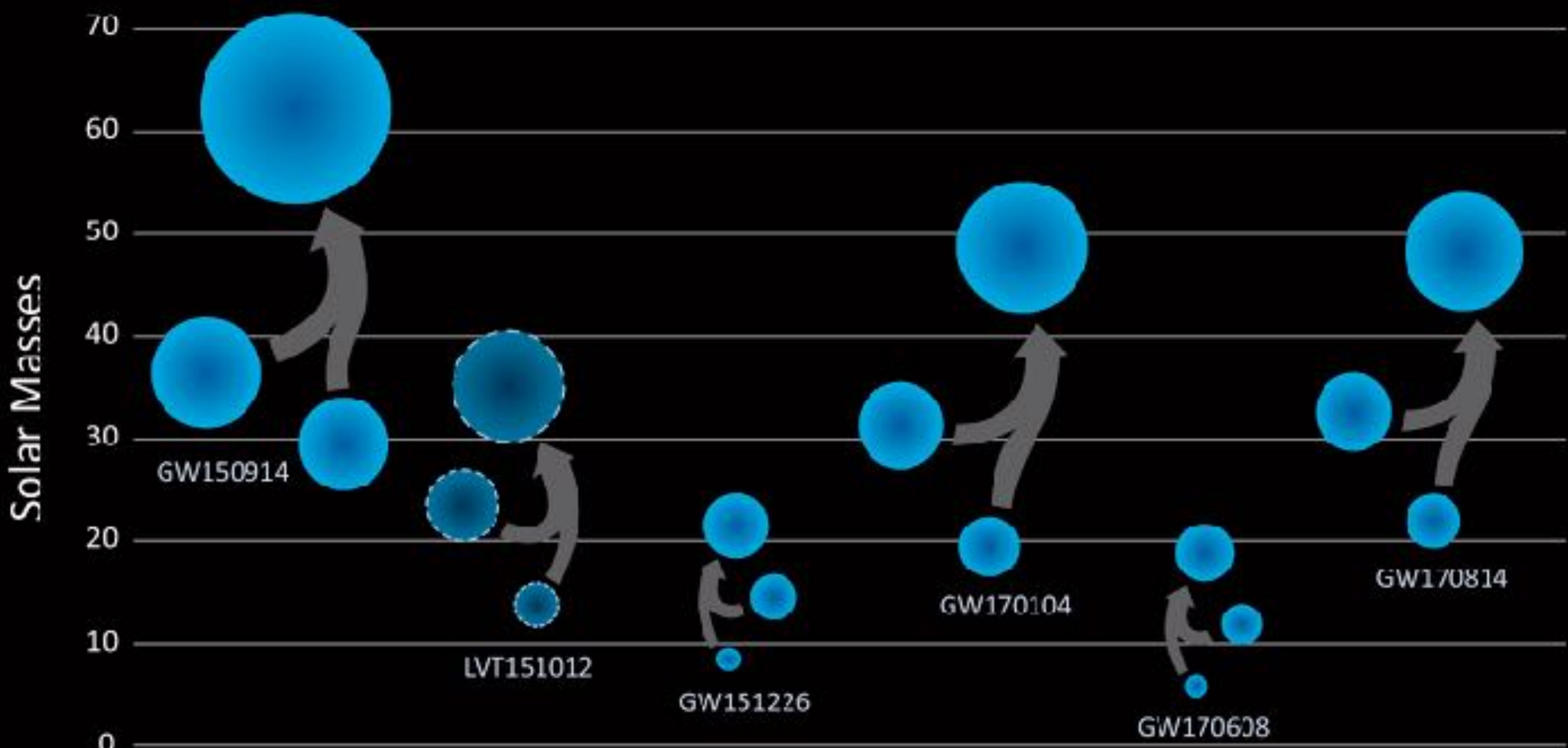




LVC and Fermi/INTEGRAL w/ AZ
ApJ Lett 848, L13 (2017)

LVC and EM partners w/ AZ
ApJ Lett 848, L12 (2017)

Black Holes of Known Mass



LIGO/VIRGO

Summary

- Sources for GW astronomy: a new window on the universe
- Two-body problem
  - Intersection of analytic theory and sims
- Black hole ringdown
  - Probes nature of BHs, tests of GR
- GW astronomy: second observational run
  - Tests of GR, nuclear physics, cosmology
  - Binary parameters reveal lives and deaths of stars