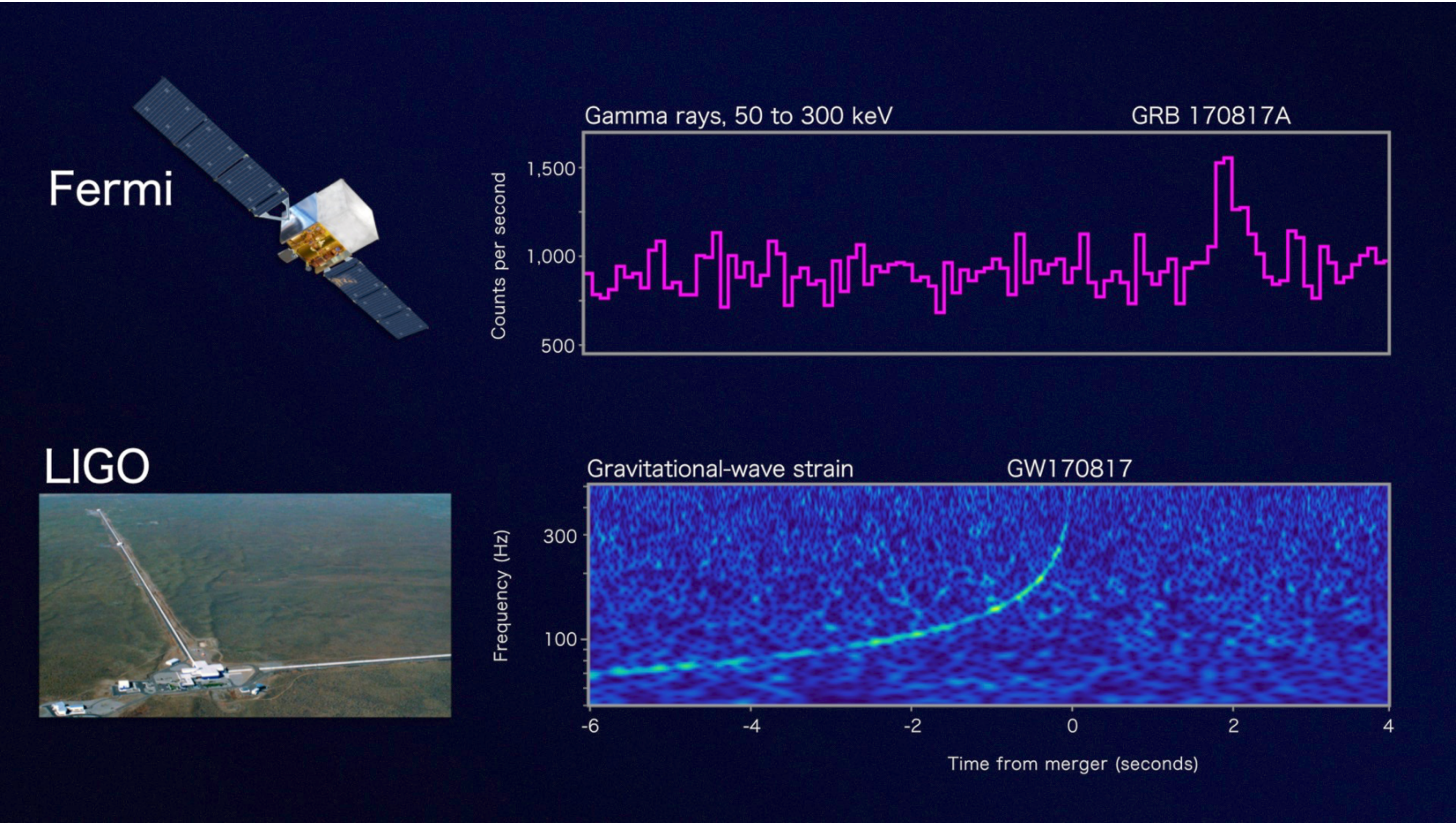
# Applications on ARIS HPC Infrastructure: Neutron Stars and Gravitational Waves


NIKOLAOS STERGIOULAS

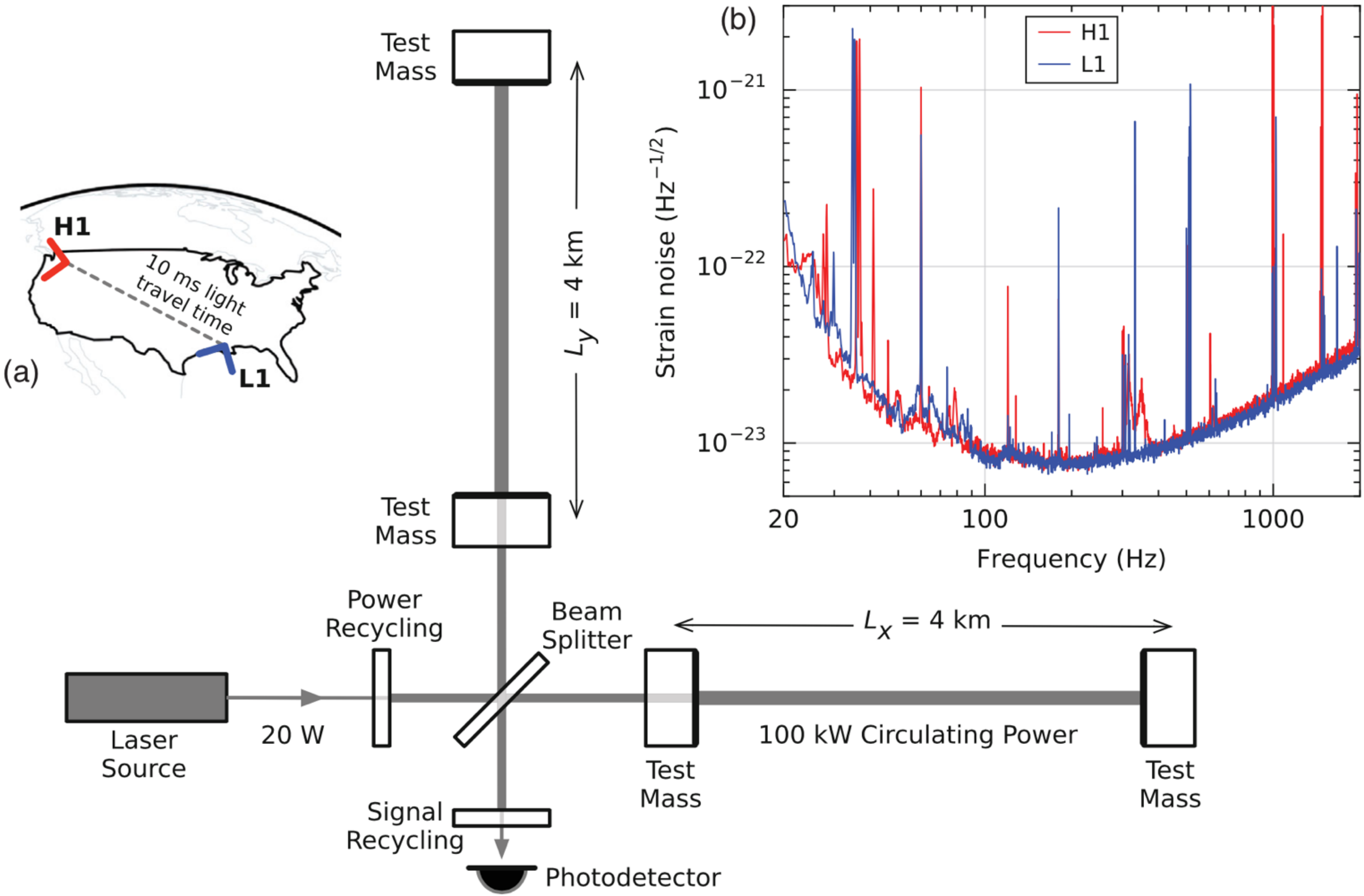
DEPARTMENT OF PHYSICS
ARISTOTLE UNIVERSITY OF THESSALONIKI


Thessaloniki, December 11, 2017

# The First Binary Neutron Star Merger



# LIGO Gravitational Wave Detector



# VIRGO Detector (Pisa)

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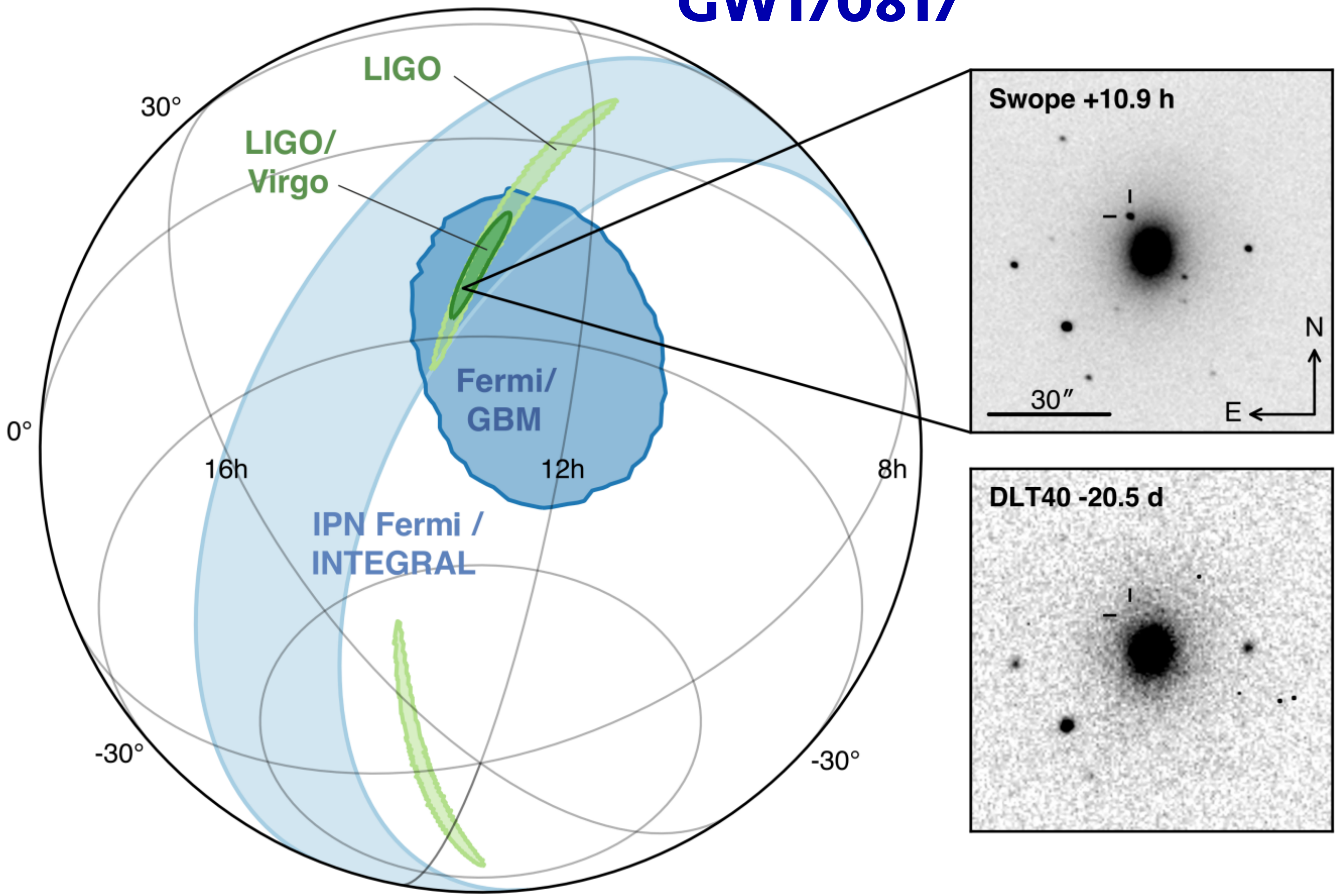
Member of the Executive Council of the
Virgo-Ego Scientific Forum (VESF)

# The First Binary Neutron Star Merger

## GW170817



# Spacetime Evolution

**90´s** Nakamura, Oohara, Kojima / Shibata, Nakamura / Baumgarte, Shapiro

## Definitions

$$\tilde{\gamma}_{ij} = e^{-4\phi}\gamma_{ij}$$

$$e^{4\phi} = \gamma^{1/3} \equiv \det(\gamma_{ij})^{1/3}.$$

$$\tilde{A}_{ij} = e^{-4\phi}A_{ij} \quad A_{ij} = K_{ij} - \frac{1}{3}\gamma_{ij}K,$$

$$\tilde{\Gamma}^i := \tilde{\gamma}^{jk}\tilde{\Gamma}^i_{jk} = -\tilde{\gamma}^{ij}{}_{,j}$$

## "1+log" lapse function

$$\partial_t \alpha = -2\alpha A$$

$$\partial_t A = \partial_t K$$

## "Gamma-driver" shift condition

$$\partial_t \beta^i = B^i$$

$$\partial_t B^i = \frac{3}{4}\alpha \partial_t \tilde{\Gamma}^i - e^{-4\phi}\beta^i$$

## Time evolution

$$\frac{d}{dt}\tilde{\gamma}_{ij} = -2\alpha\tilde{A}_{ij}, \qquad \frac{d}{dt} = \partial_t - \mathcal{L}_\beta$$

$$\frac{d}{dt}\phi = -\frac{1}{6}\alpha K.$$

$$\frac{d}{dt}K = -\gamma^{ij}D_iD_j\alpha + \alpha\left[\tilde{A}_{ij}\tilde{A}^{ij} + \frac{1}{3}K^2 + \frac{1}{2}(\rho + S)\right],$$

$$\frac{d}{dt}\tilde{A}_{ij} = e^{-4\phi}[-D_iD_j\alpha + \alpha(R_{ij} - S_{ij})]^{TF}$$

$$+ \alpha(K\tilde{A}_{ij} - 2\tilde{A}_{il}\tilde{A}^l_j),$$

$$\frac{\partial}{\partial t}\tilde{\Gamma}^i = -2\tilde{A}^{ij}\alpha_{,j} + 2\alpha\left(\tilde{\Gamma}^i_{jk}\tilde{A}^{kj} - \frac{2}{3}\tilde{\gamma}^{ij}K_{,j} - \tilde{\gamma}^{ij}S_j + 6\tilde{A}^{ij}\phi_{,j}\right)$$

$$-\frac{\partial}{\partial x^j}\left(\beta^l\tilde{\gamma}^{ij}{}_{,l} - 2\tilde{\gamma}^{m(j}\beta^{i)}{}_{,m} + \frac{2}{3}\tilde{\gamma}^{ij}\beta^l{}_{,l}\right).$$

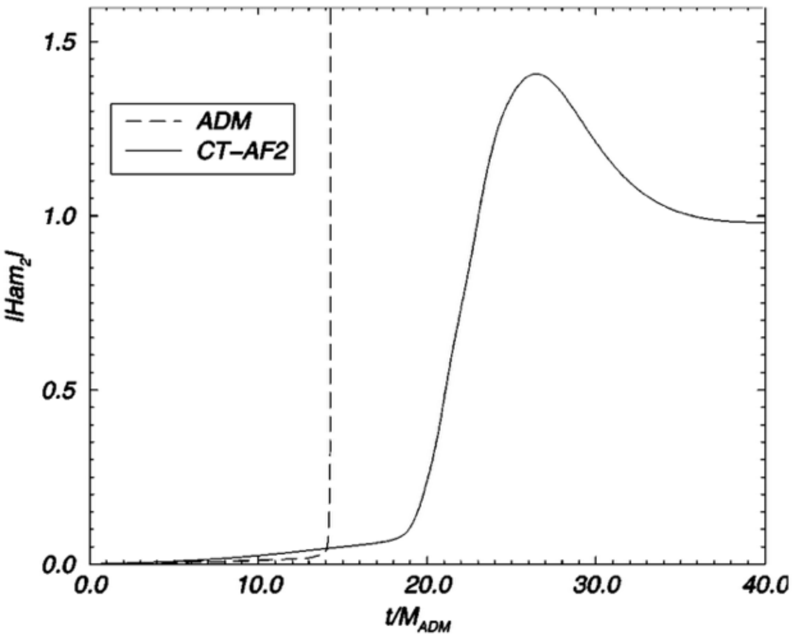
# First Stable Simulation in 3D

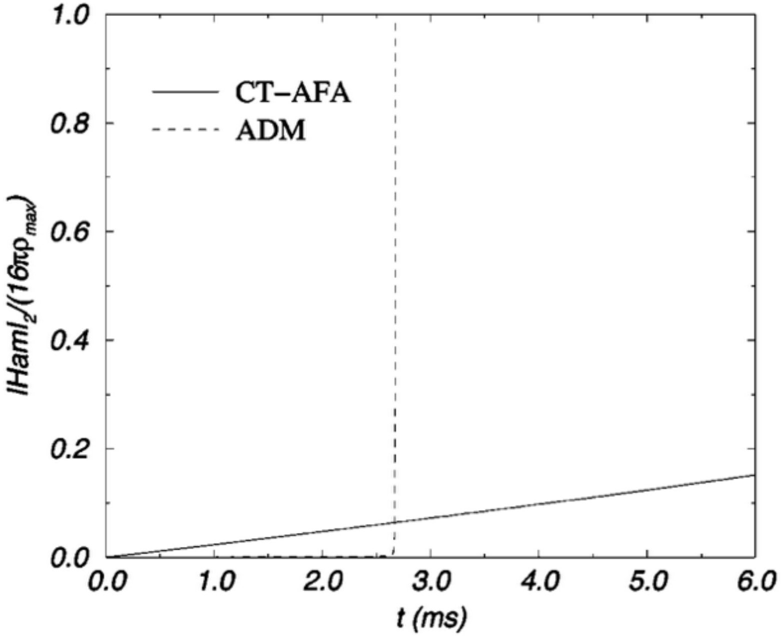
***2000:***

PHYSICAL REVIEW D, VOLUME 62, 044034

**Towards a stable numerical evolution of strongly gravitating systems in general relativity: The conformal treatments**

Miguel Alcubierre,[1] Bernd Brügmann,[1] Thomas Dramlitsch,[1] José A. Font,[2] Philippos Papadopoulos,[3] Edward Seidel,[1,4] Nikolaos Stergioulas,[1,5] and Ryoji Takahashi[1]
[1]*Max-Planck-Institut für Gravitationsphysik, Am Mühlenberg 1, D-14476 Golm, Germany*
[2]*Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85740 Garching, Germany*
[3]*School of Computer Science and Maths, University of Portsmouth, Portsmouth PO1 2EG, United Kingdom*
[4]*National Center for Supercomputing Applications, Beckman Institute, 405 N. Mathews Ave., Urbana, Illinois 61801*
[5]*Department of Physics, Aristotle University of Thessaloniki, Thessaloniki 54006, Greece*
(Received 20 March 2000; published 24 July 2000)



# einsteintoolkit.org

Open Source code for 3D simulations in General Relativity
C/C++/Fortran90 with MPI+OpenMP

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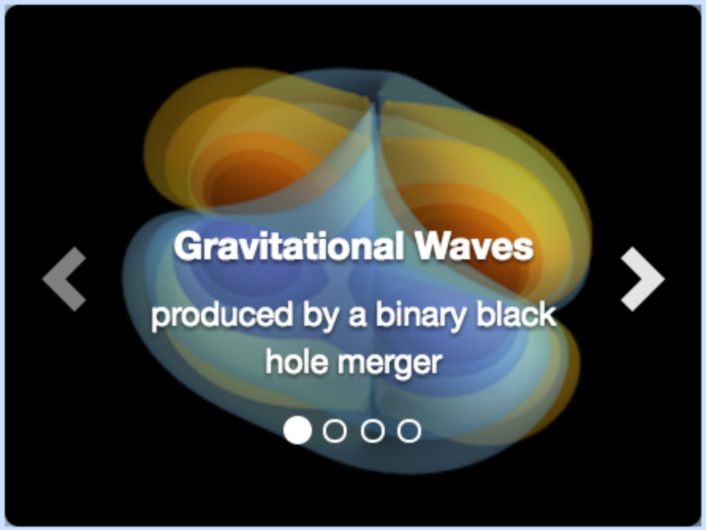
## The Einstein Toolkit




Gallery

### About

The Einstein Toolkit is a community-driven software platform of core computational tools to advance and support research in relativistic astrophysics and gravitational physics.

About

### Documentation

A lot of the documentation within the Einstein Toolkit is generated from comments in the source code, and more can be found on the Einstein Toolkit Wiki or other documents. We provide links to guides, tutorials and references.

Documentation

### Download

We provide a convenient method to get all of the Einstein Toolkit with just a few commands, and explain the whole process.

Download  Try it now!

### Contribute

The Einstein Toolkit would not exist without numerious contributions from its community. It is easy to learn how you can contribute as well.

Contribute

20+ years of development
(started as private version)

# Gallery of Examples

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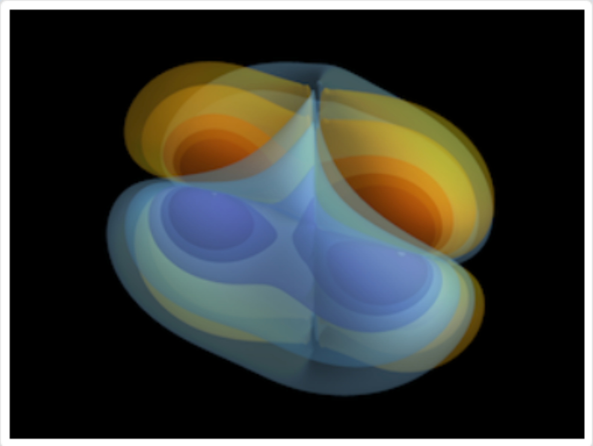
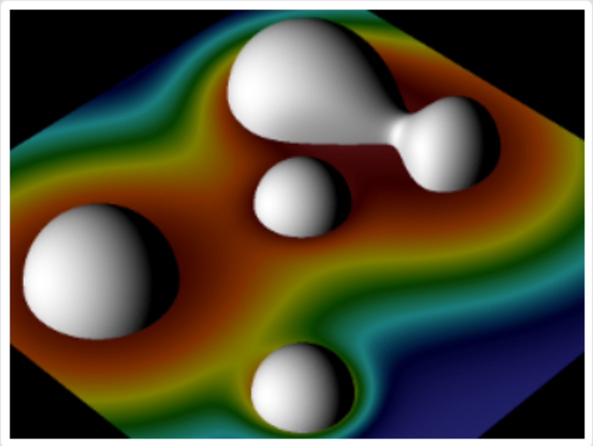
## Einstein Toolkit Gallery

This page contains example simulations that can be run using the Einstein Toolkit, either exclusively or in combination with external codes. The parameter files and thornlists required to reproduce the simulations are provided. Some examples also include images and movies, analysis and visualisation scripts, example simulation data, and tutorials.

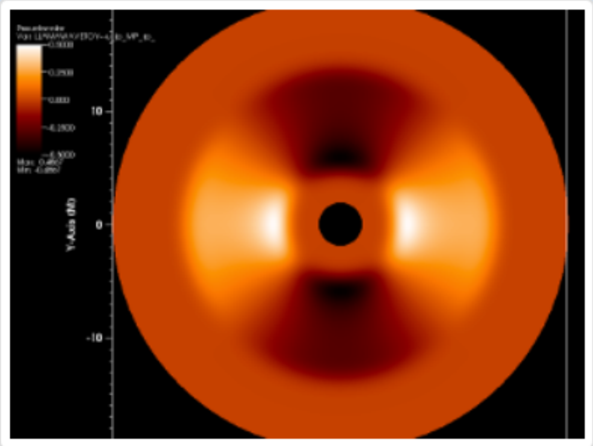
**Binary black hole GW150914**



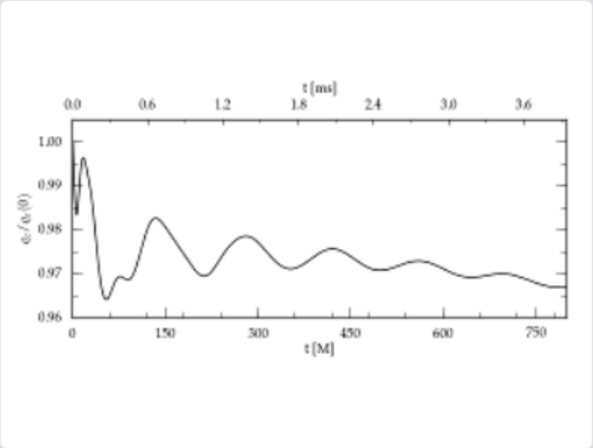
**Poisson equation**



**Multi Patch Energy Equation**




**Single, stable neutron star**




**Binary neutron star**

# Gallery of Examples

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## Einstein Toolkit Gallery

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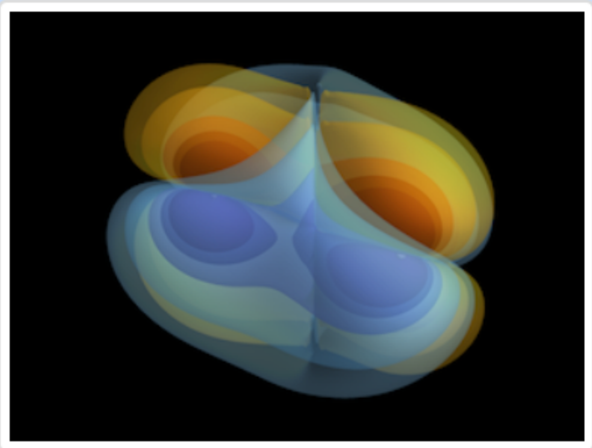
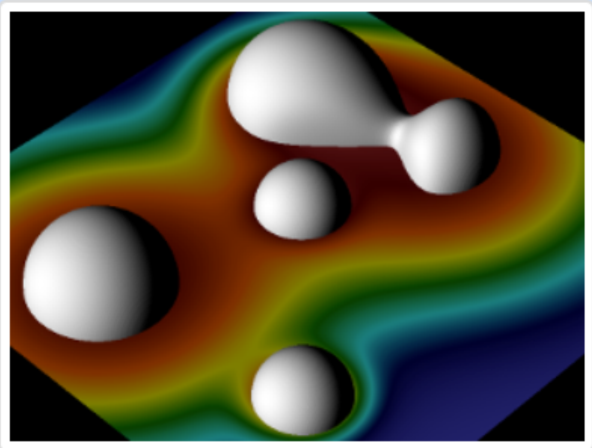


**Poisson equation**



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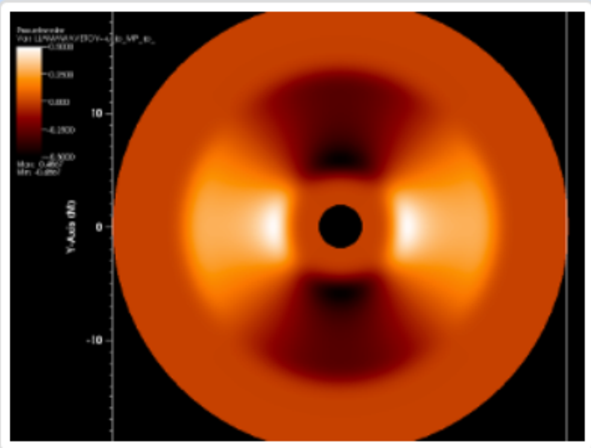

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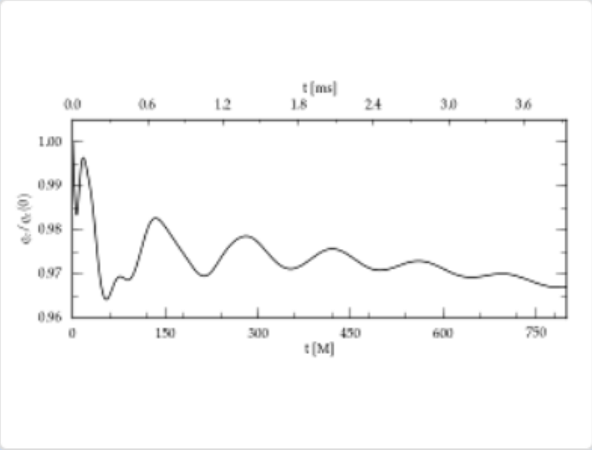
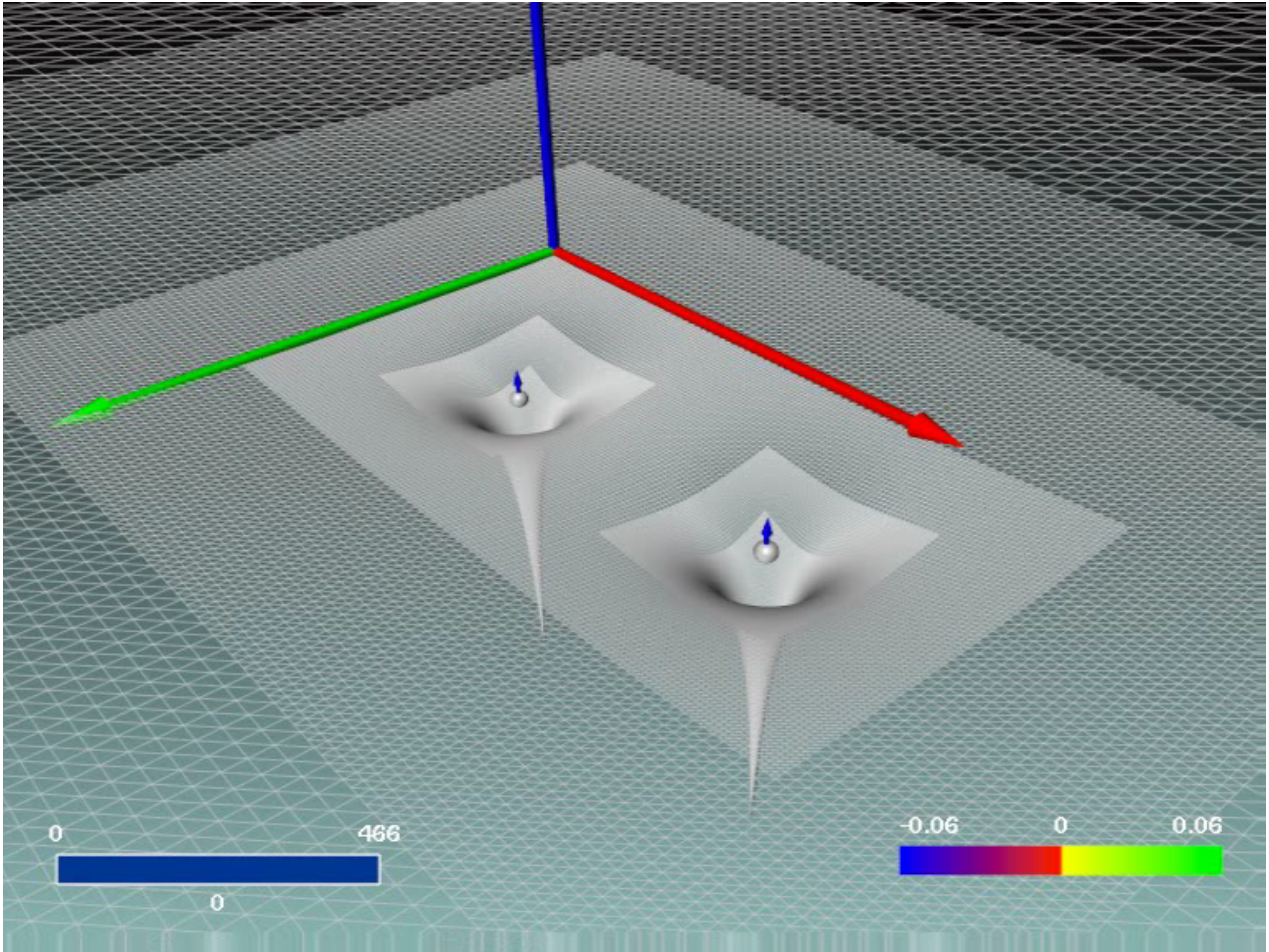



**Binary neutron star**

**RNSID**: Initial Data for Rotating Neutron Stars

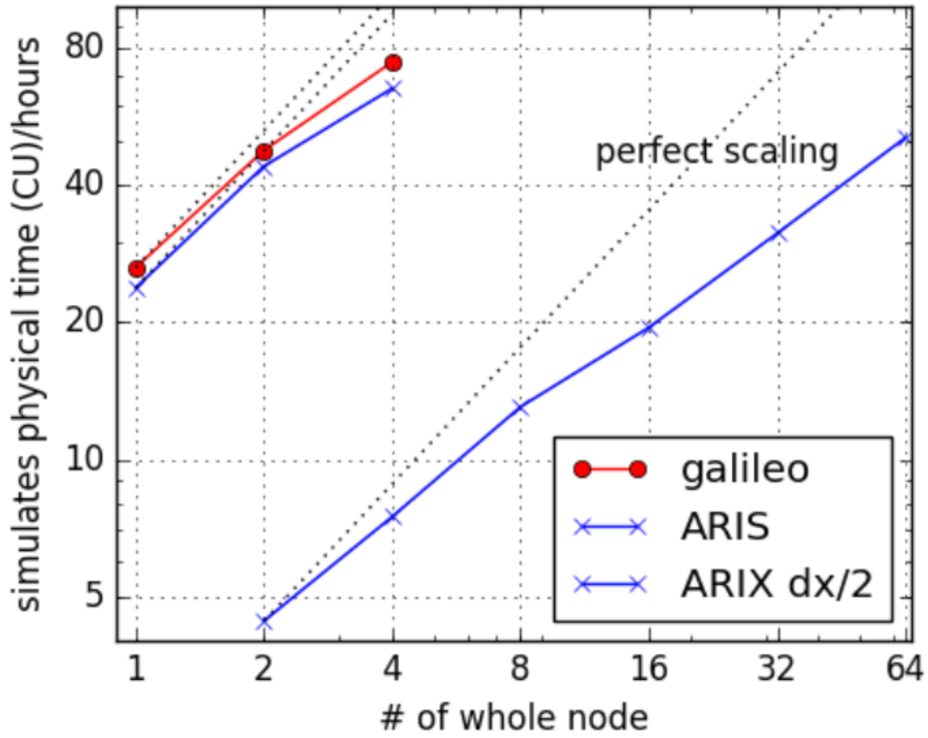
(developed at AUTH)

# Adaptive Mesh Refinement



# Running on ARIS

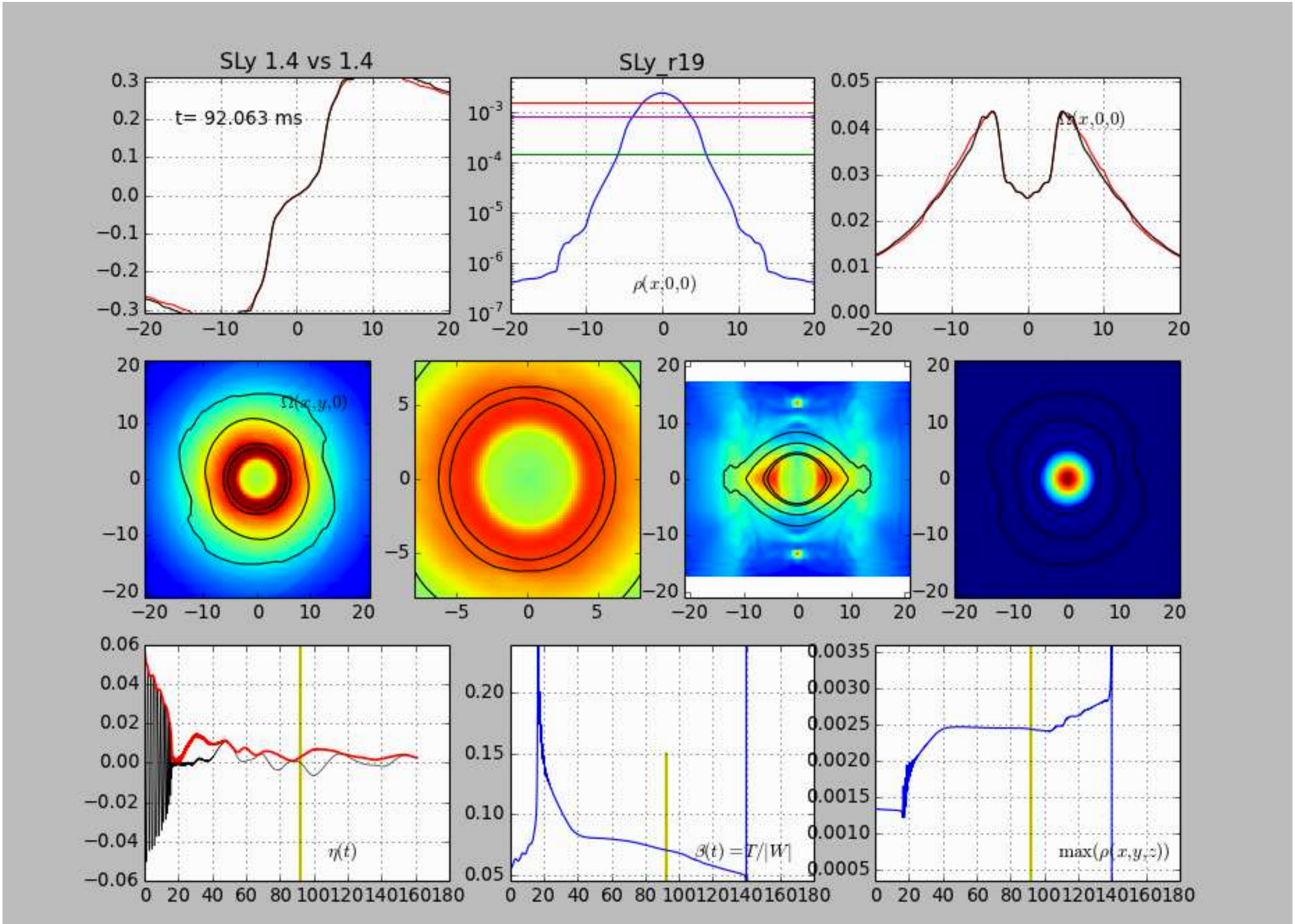
**2016** (pr002022) 900.000 CPU hours




**2017** (pr004019) 900.000 CPU hours

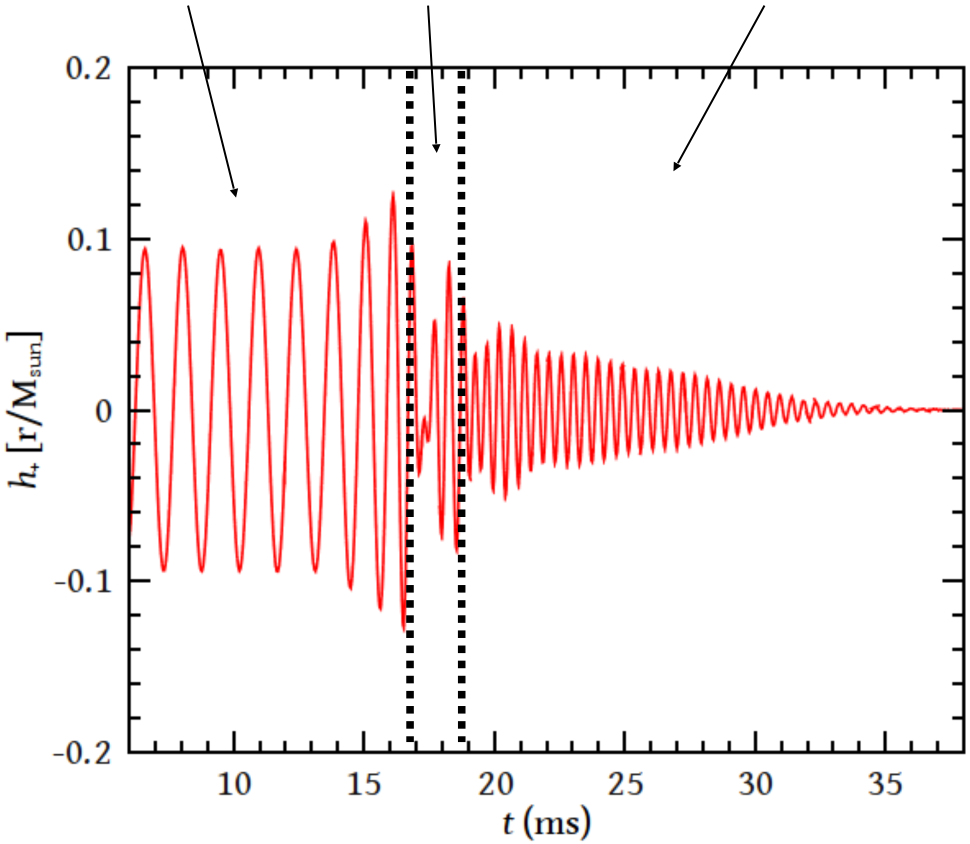
| Run type | # Runs | # Steps/Run | Walltime (seconds)/Step | # CPU cores | Total core hours/Type Run |
|---|---|---|---|---|---|
| Merger<br>$\Delta x = 0.185$<br>(360,360,100)<br>6 levels | 12 | 90000 | 4.6 | 320 | 73000 |

# Visualization of HDF5 Output with VisIt

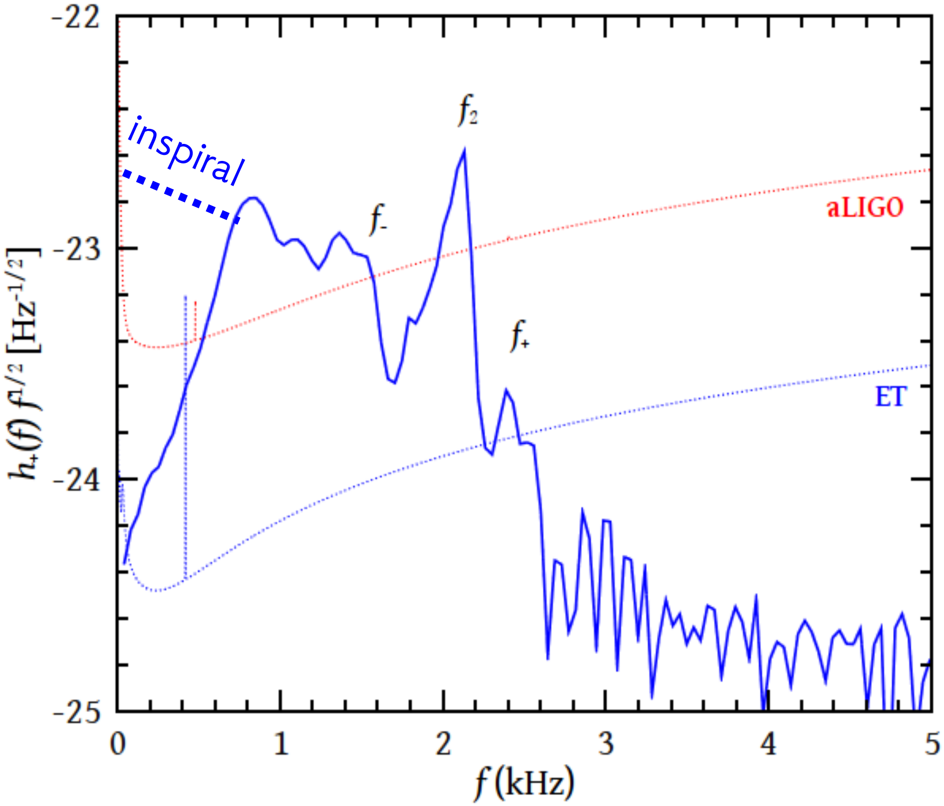


# Post-Merger Gravitational Waves

The GW signal can be divided into three distinct phases: *inspiral*, *merger* and *post-merger ringdown*.




@40Mpc



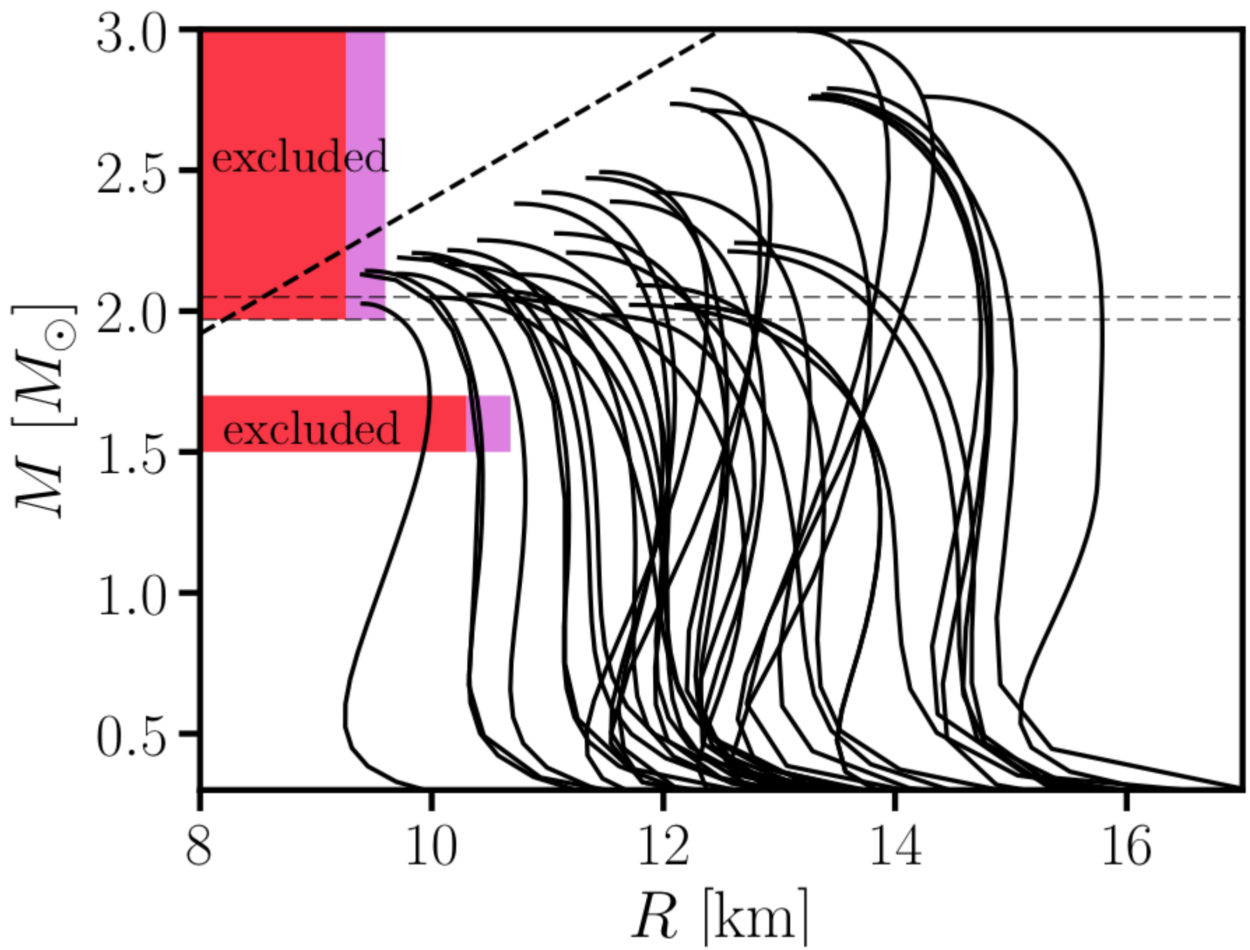

*Several peaks* stand above the aLIGO/VIRGO or ET sensitivity curves and are potentially detectable. Are these *oscillations* of the merger remnant?

# First Radius Constraints From GW's

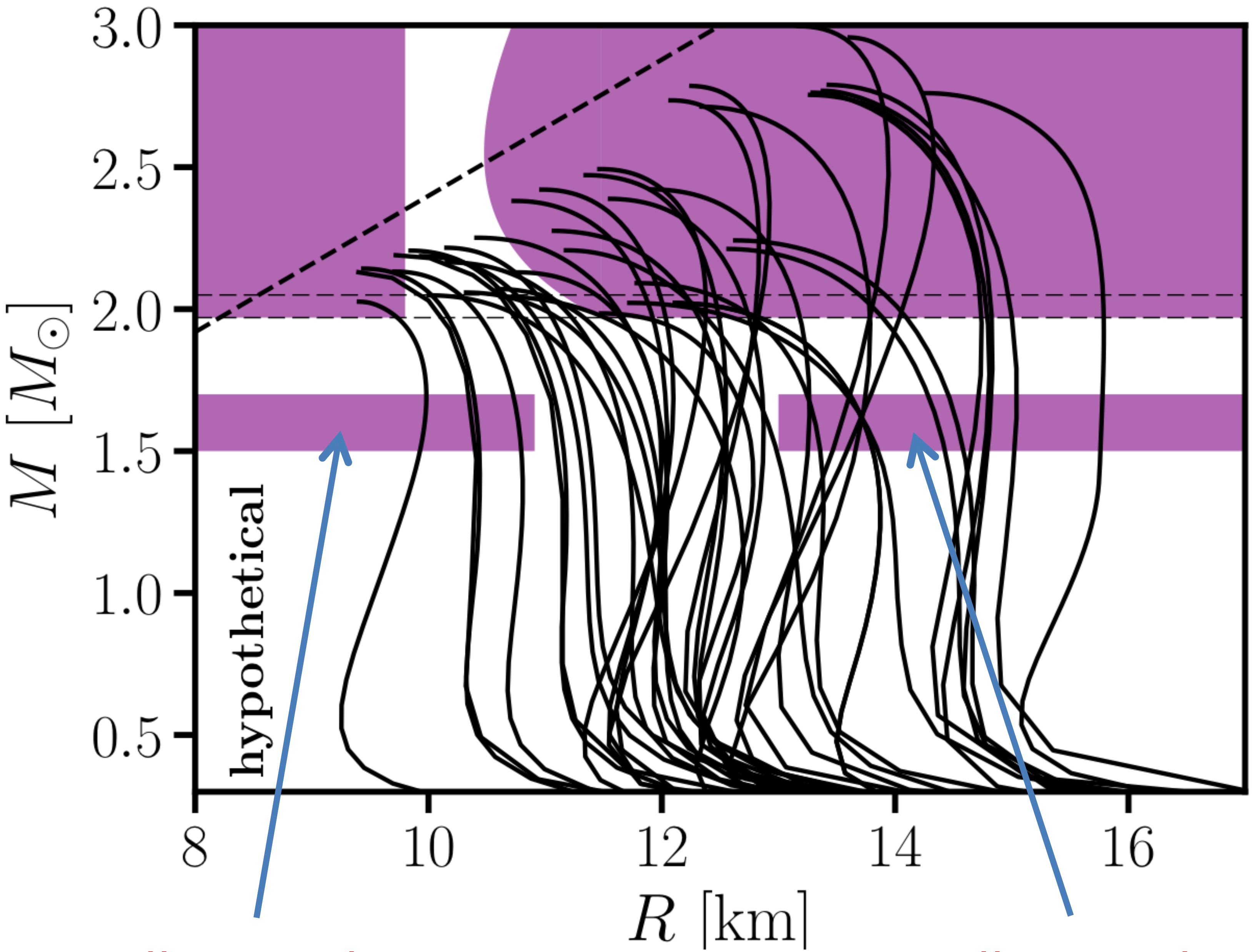
The Astrophysical Journal Letters, 850:L34 (5pp), 2017 December 1

**Neutron-star Radius Constraints from GW170817 and Future Detections**

Andreas Bauswein[1], Oliver Just[2], Hans-Thomas Janka[3], and Nikolaos Stergioulas[4]
[1] Heidelberger Institut für Theoretische Studien, Schloss-Wolfsbrunnenweg 35, D-69118 Heidelberg, Germany; andreas.bauswein@h-its.org
[2] Astrophysical Big Bang Laboratory, RIKEN, Saitama 351-0198, Japan
[3] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85748 Garching, Germany
[4] Department of Physics, Aristotle University of Thessaloniki, GR-54124 Thessaloniki, Greece
*Received 2017 October 18; revised 2017 November 8; accepted 2017 November 8; published 2017 November 29*



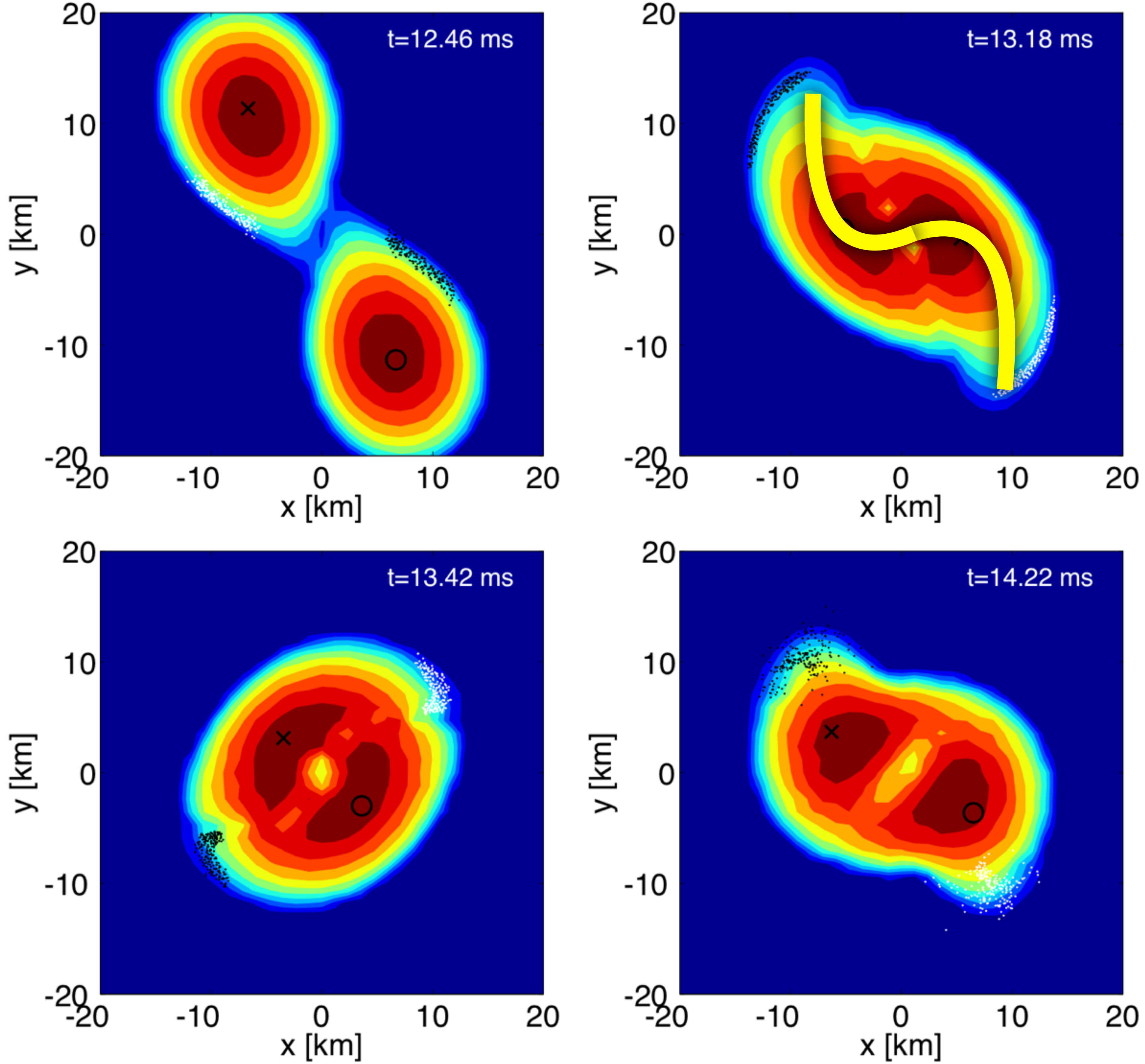
# Constraints From Future Detections




No collapse with M=2.9Msun

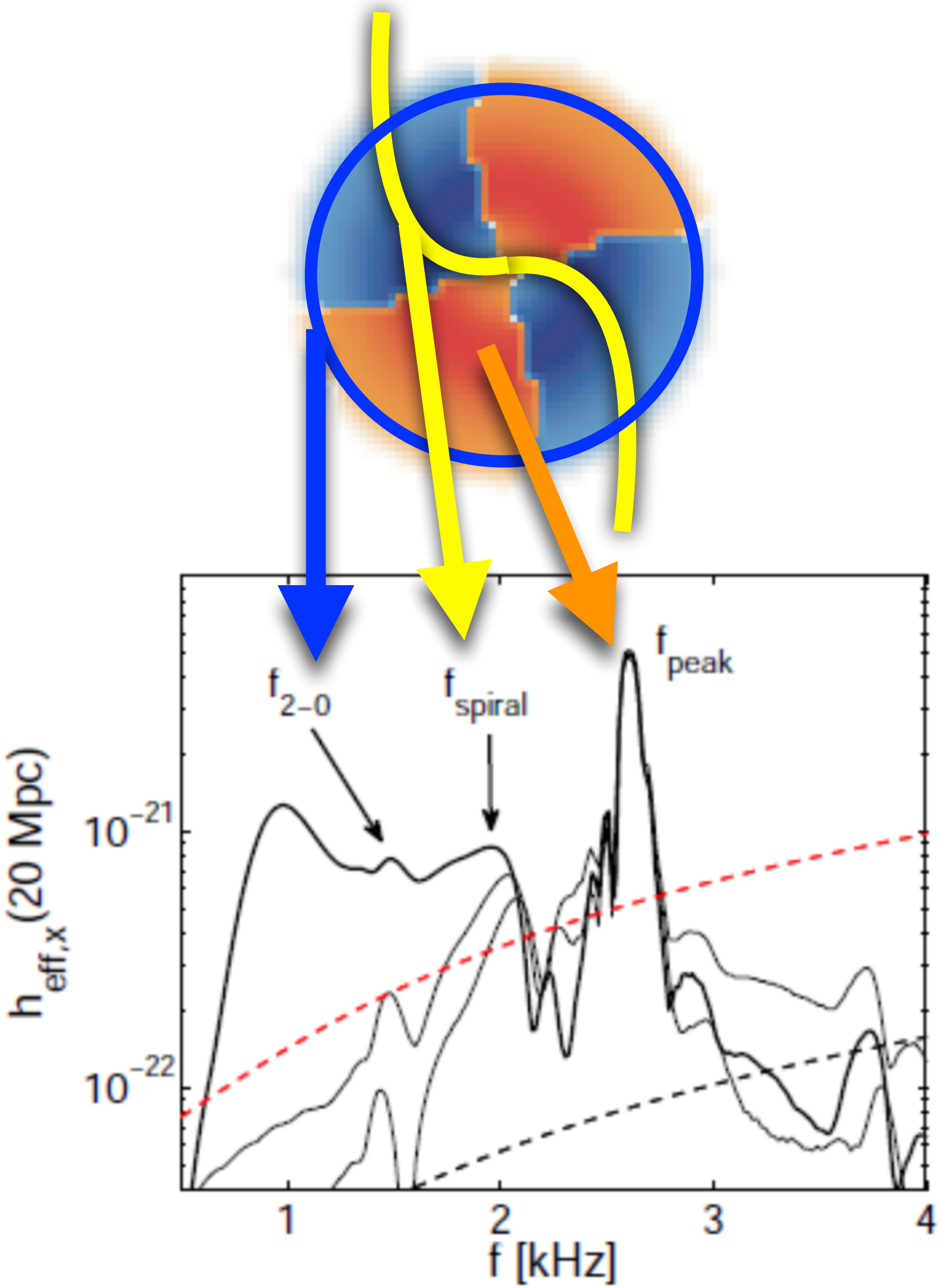
Collapse with M=3.1Msun

# Spiral Deformation

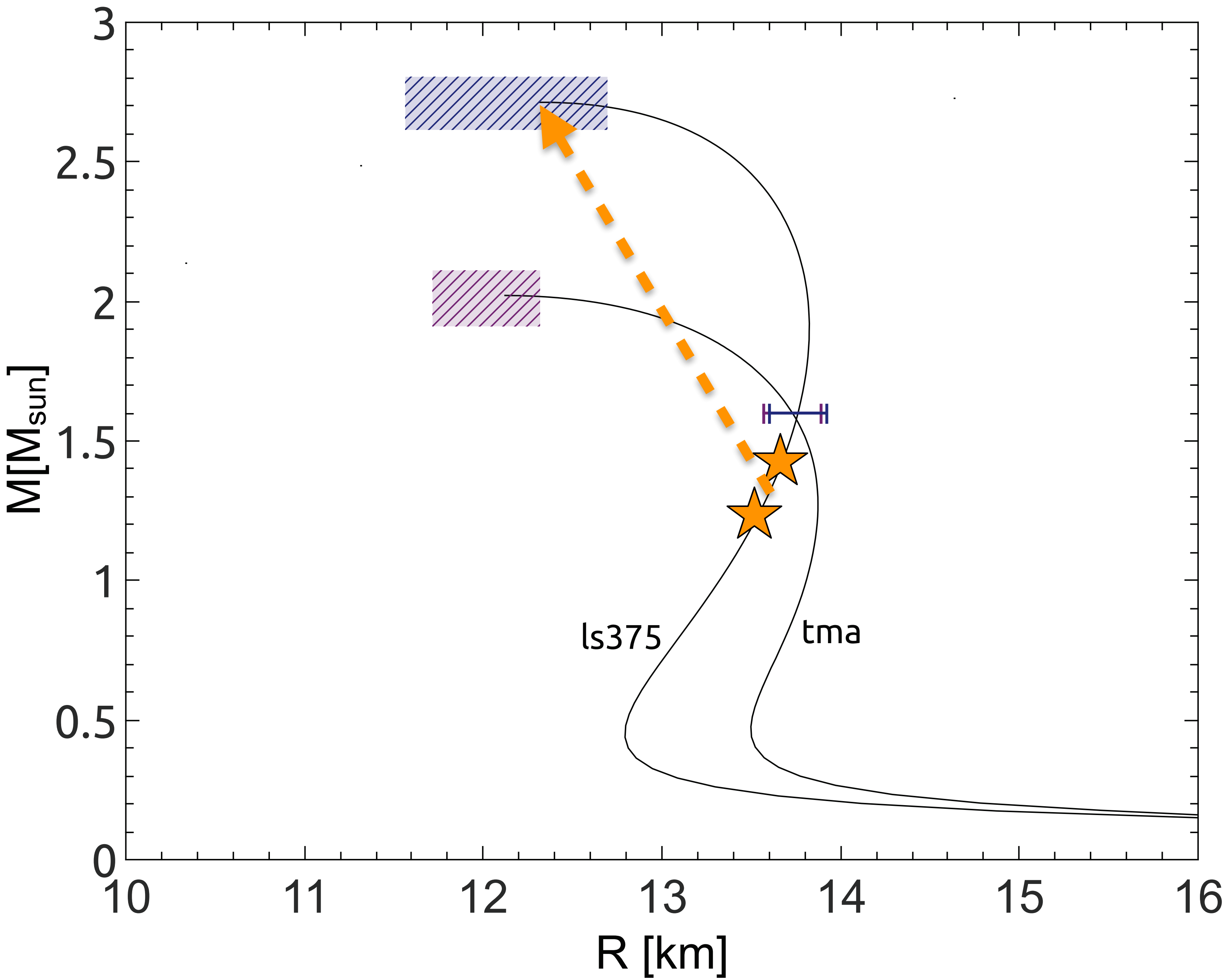



Bauswein & NS (2015)

# linear + quasi-linear + nonlinear



# Breaking the EOS Degeneracy



# Summary

- Gravitational-wave asteroseismology is a viable method for constraining the equation of state of neutron stars
- Accurate 3D simulations of the expected waveforms require at least hundreds of CPU cores and hundreds of GB of memory
- The Einstein Toolkit is a highly scalable, MPI/OpenMP hybrid parallel, open source code (with AUTH participation in the development)
- The two ARIS allocations of 1.8m CPU hours have enabled us to set a strong constraint on the minimum size of neutron stars, based on the first gravitational-wave observation of a binary neutron star merger.