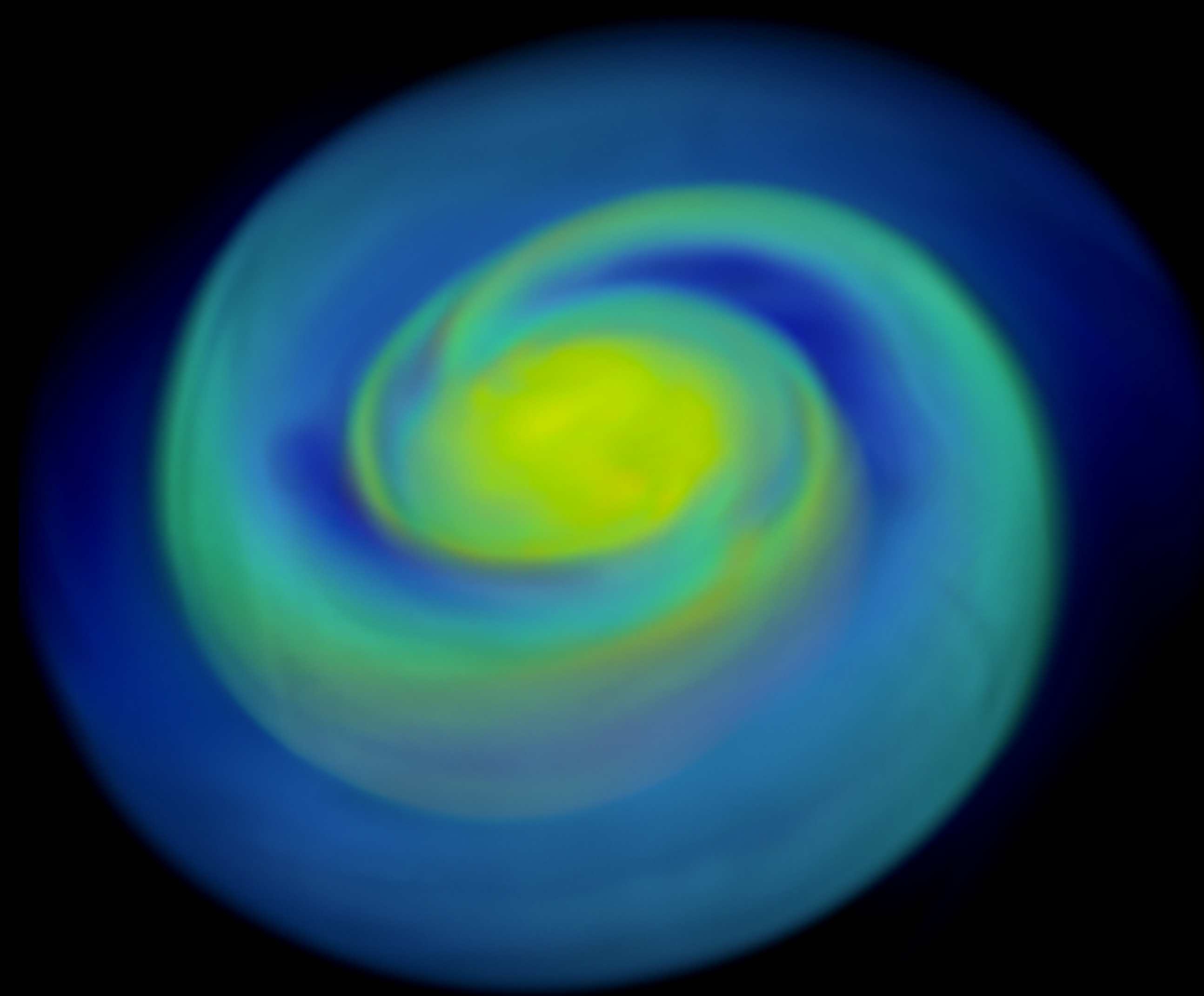
From Chirps to Jets:
The extreme world of Black Holes and Neutron Stars



Francois Foucart
LBNL, Einstein Fellow

University of Virginia
March 1st 2017

Black Holes and Neutron Stars

Neutron Stars: (1-2?) M_{sun} within R~(10-15) km

Black Holes: M=1 M_{sun} => horizon at (1.5-3)km

Black Holes and Neutron Stars

BH & NS test extreme environments

Very compact -> Strong gravity: **Test General Relativity**

Unknown nuclear interactions in NS: **Test nuclear physics**

Black hole-Neutron star merger

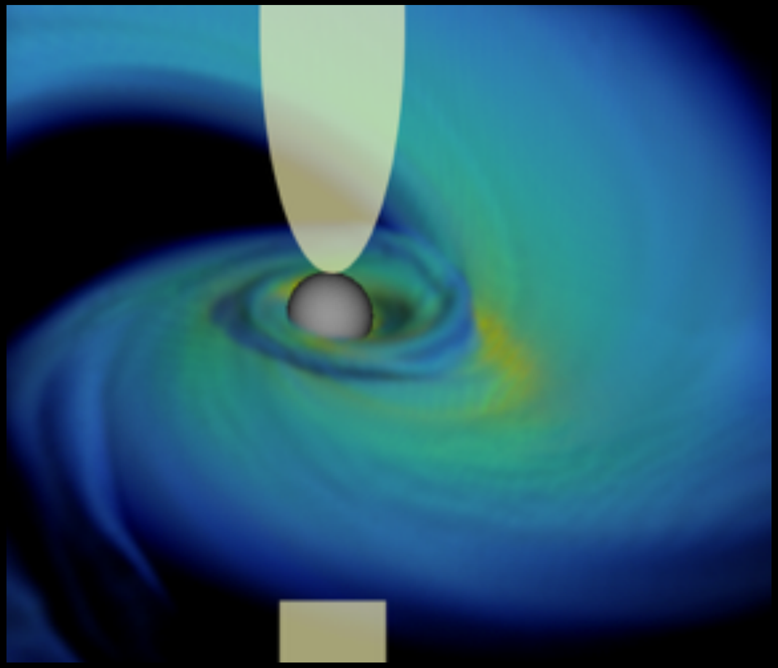


Image: Foucart et al 2017

SgrA* (center of the Milky Way)

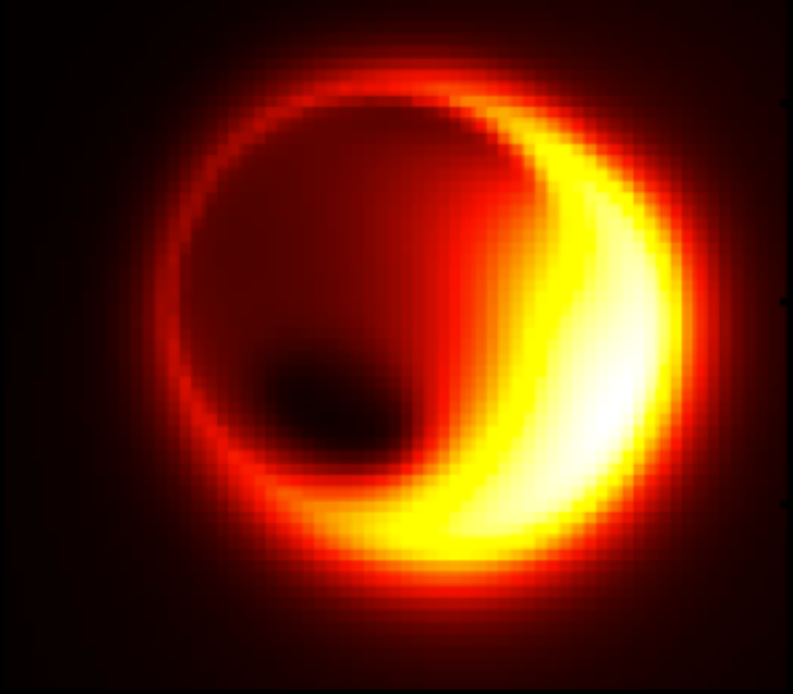
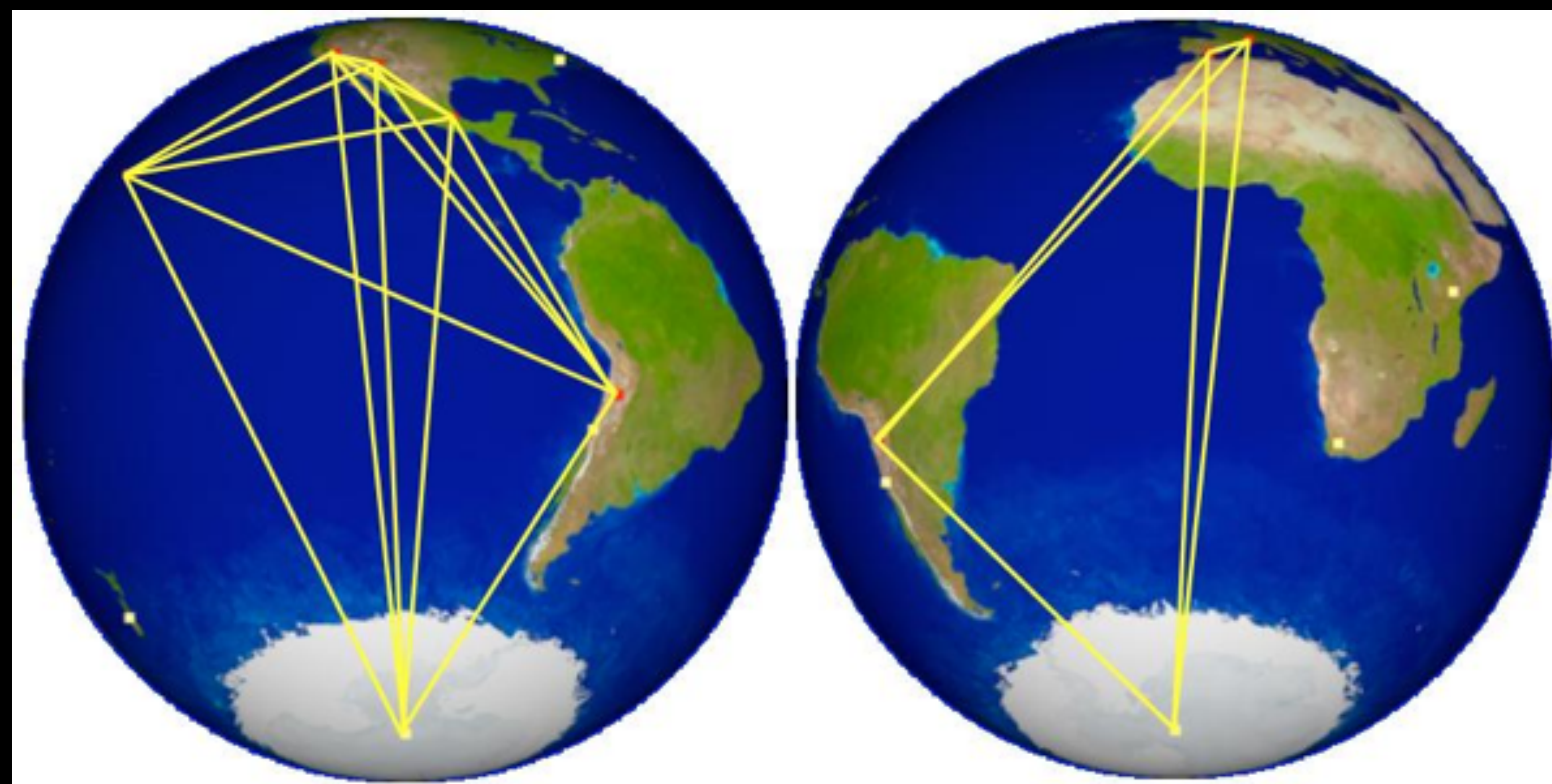


Image: Broderick et al 2016

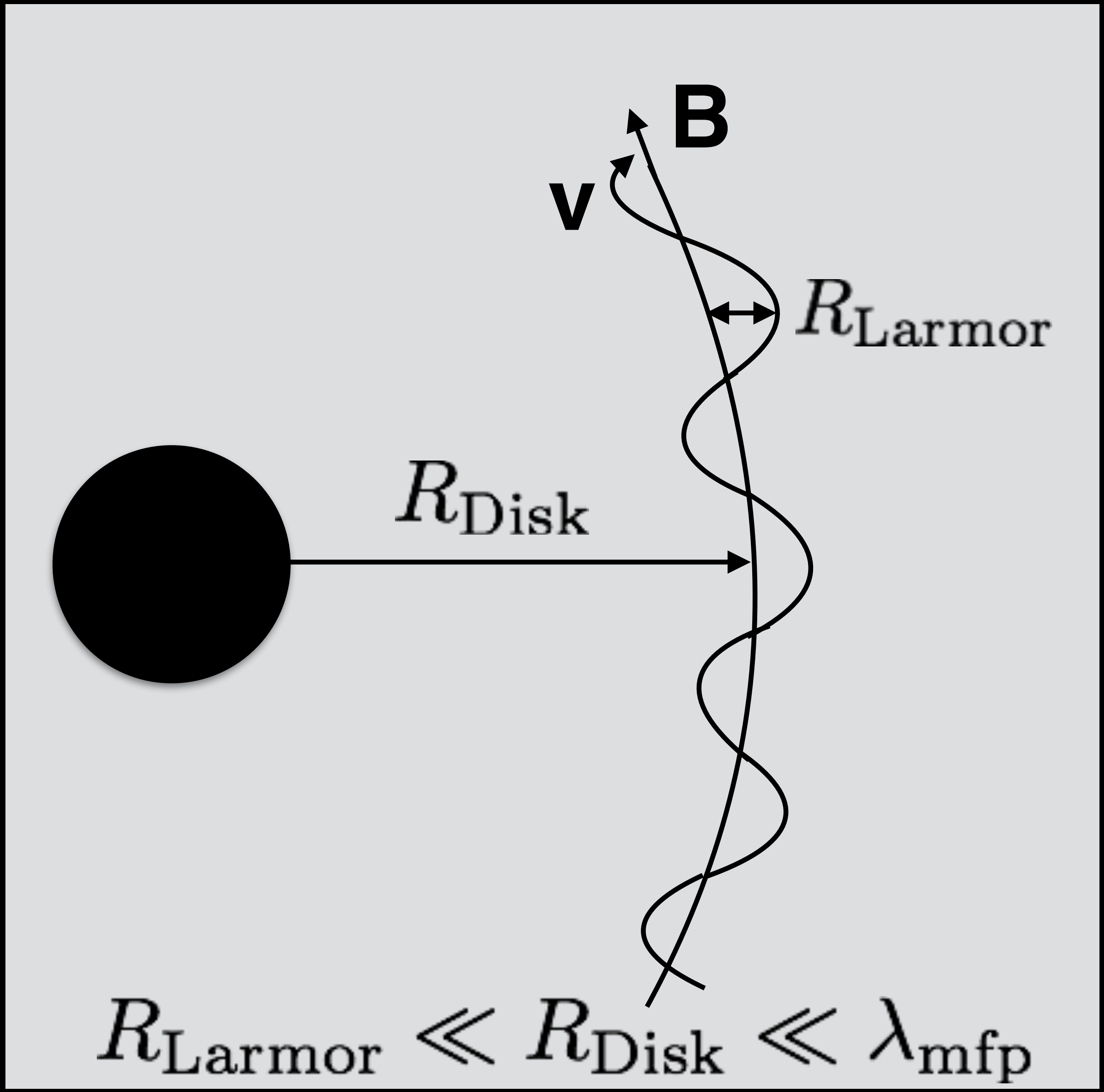
Part I
Slowly Accreting Supermassive Black Holes

Event Horizon Telescope



- Very long baseline interferometry:
  - 1.3 mm wavelength, baseline the size of the earth, aim for 12 participating telescopes (incl. soon ALMA)
- Objective: resolve accretion flows to sub-Horizon resolution!

Plasma physics in disks



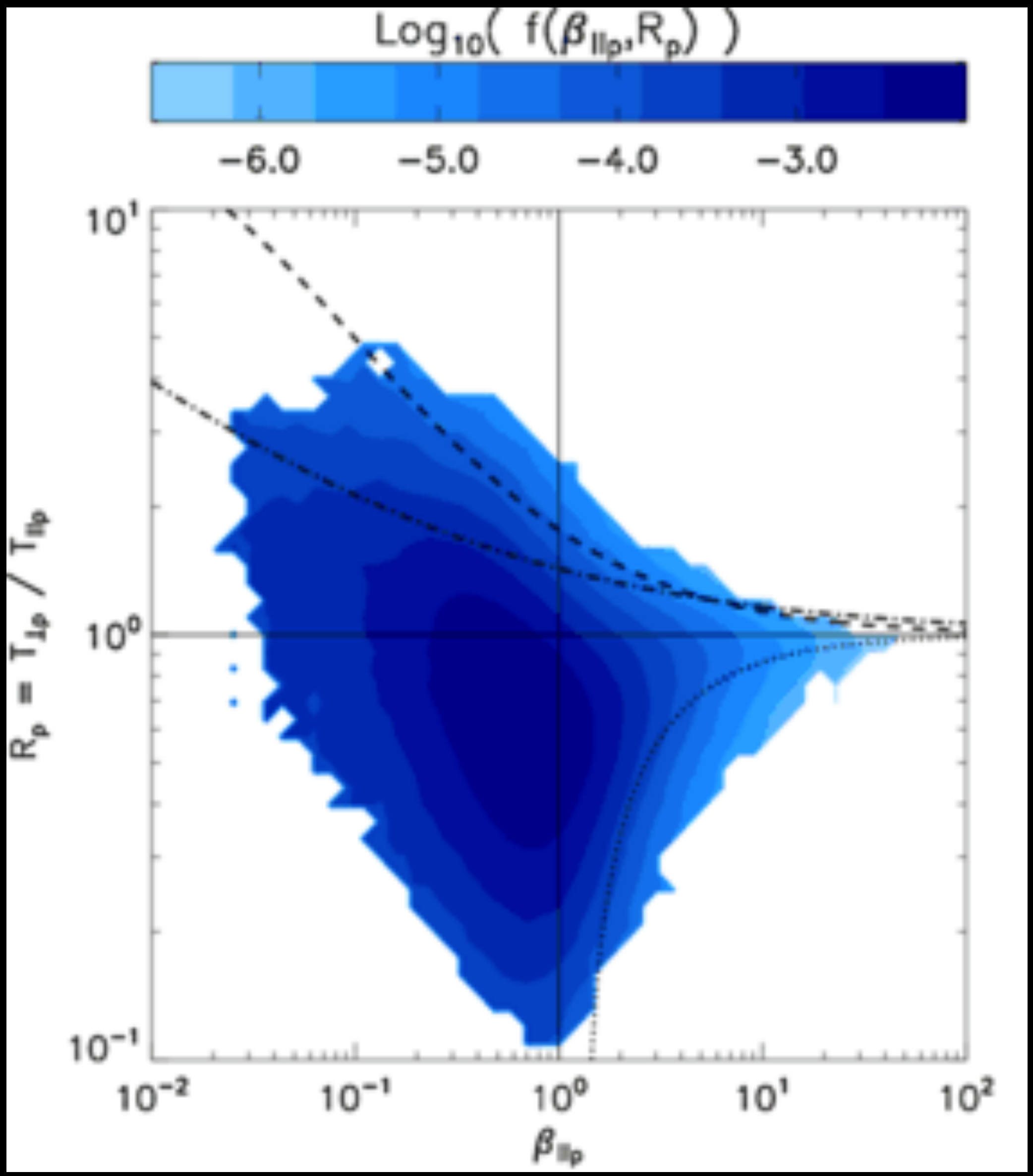
Low density +
High Temperature
=>
Very large mean free path
Not an ideal fluid!

Model the disk as a *weakly collisional* plasma.
Includes: **heat conduction**, **anisotropic pressure**

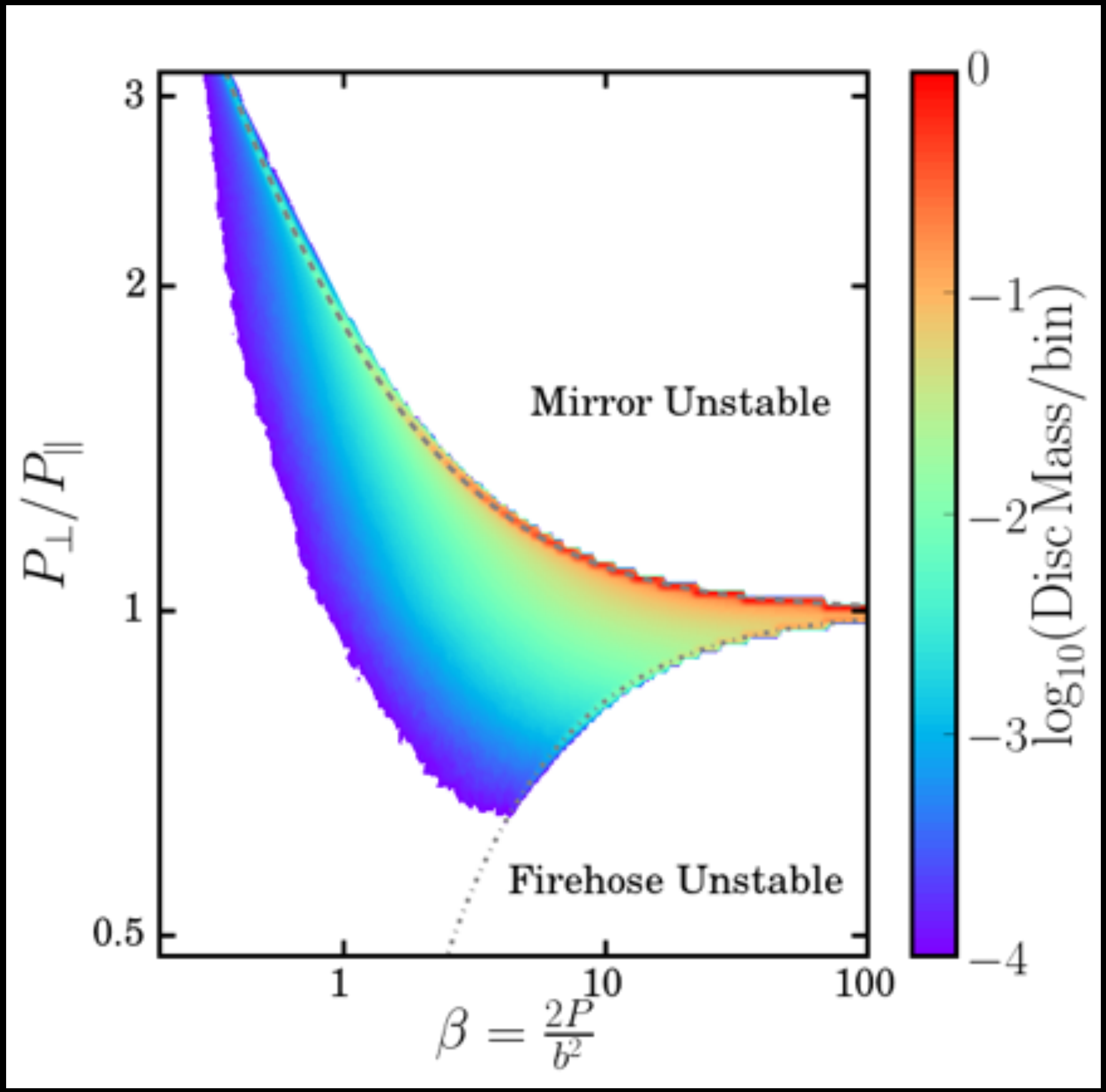
(see Chandra, Foucart et al 2015)

Pressure anisotropy

Solar Wind (1AU) Kasper et al. 2016



Accretion disk Foucart et al., in prep

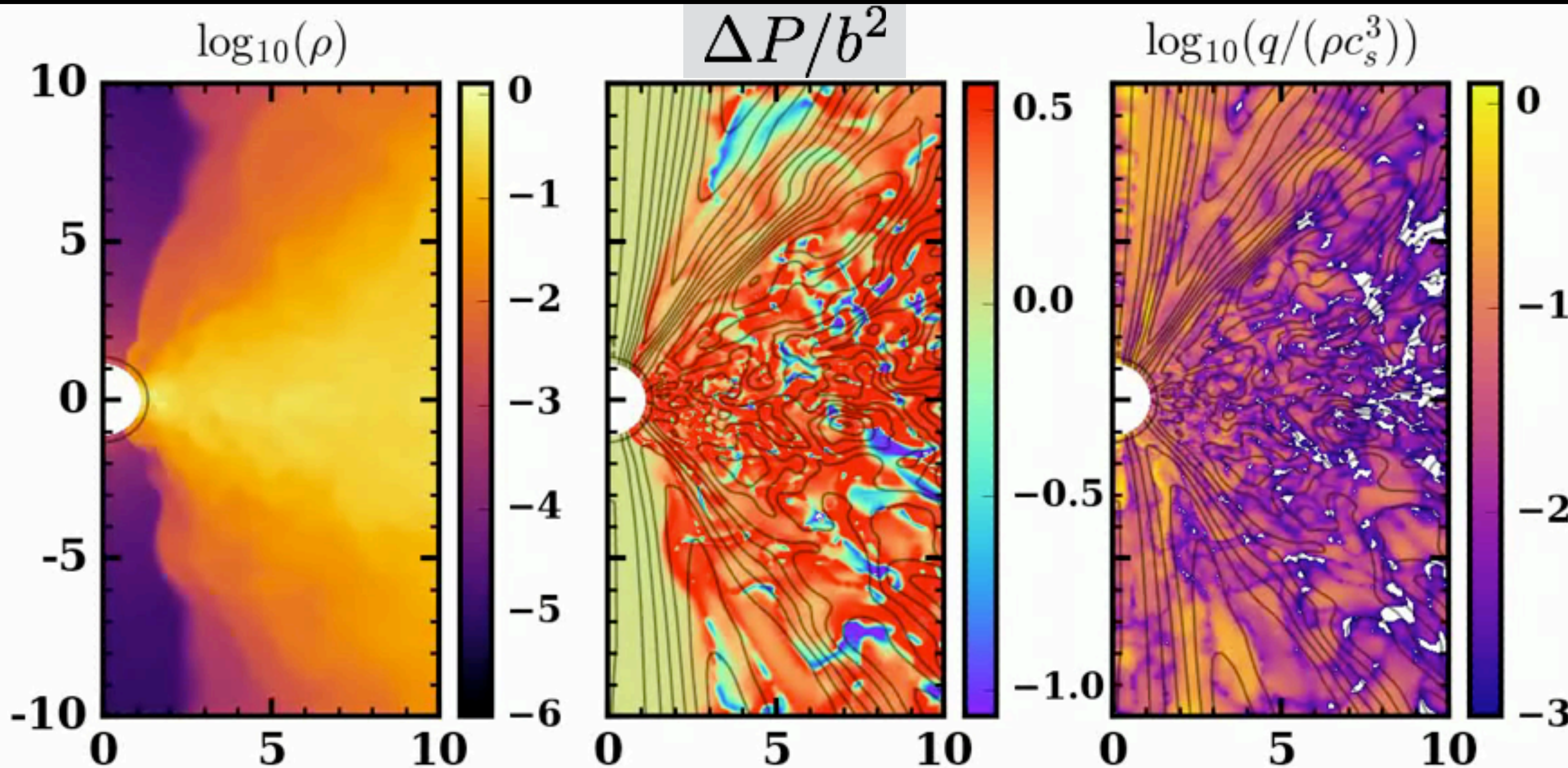


Plasma remains at mirror instability threshold

Pressure anisotropy ~ Magnetic pressure

First global 3D simulations of a disk with ΔP, q

Foucart et al., in prep



For a compact torus with small magnetic field:

Many similarities with ideal MHD disks

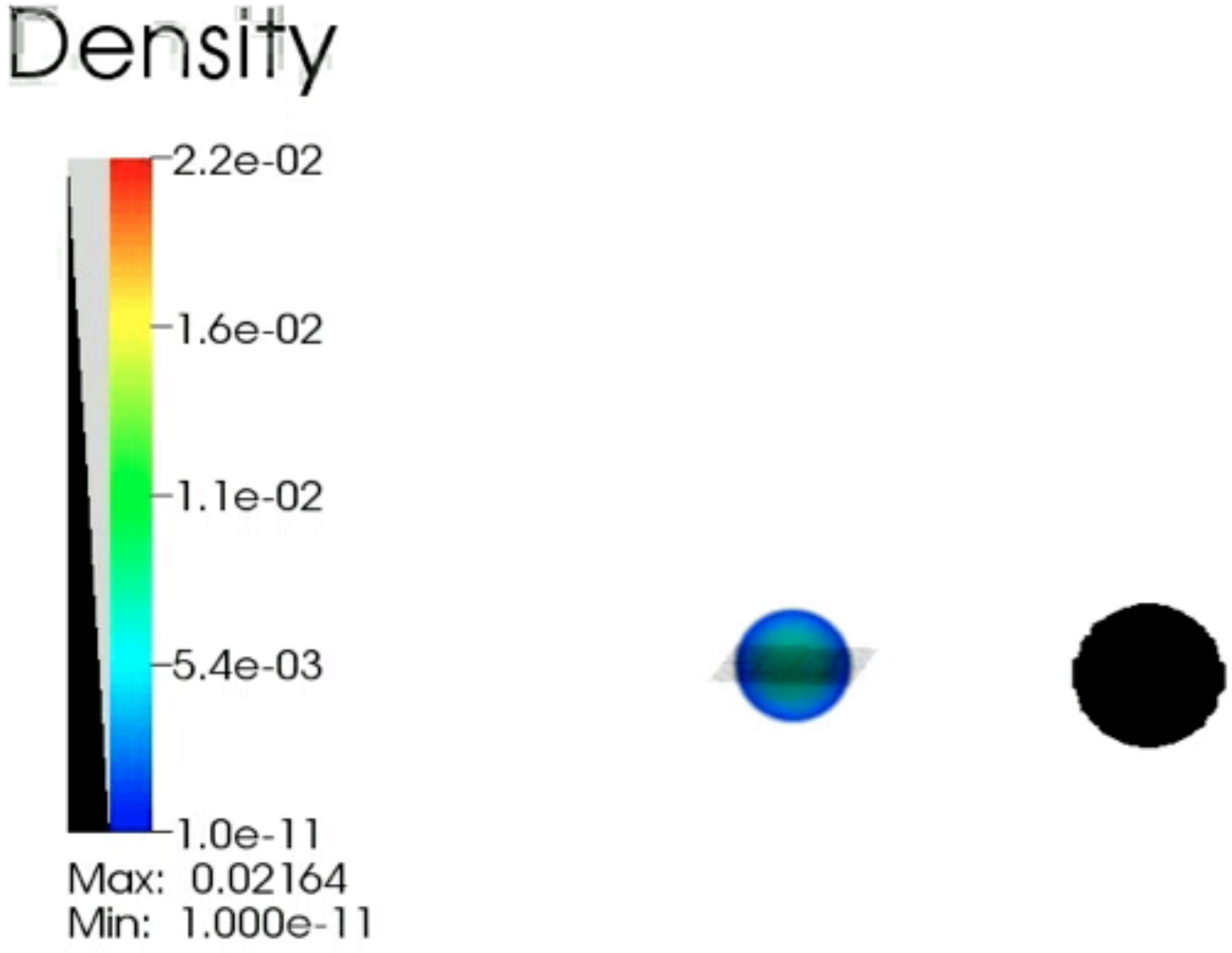
(With some magnetic shear replaced by viscous shear)

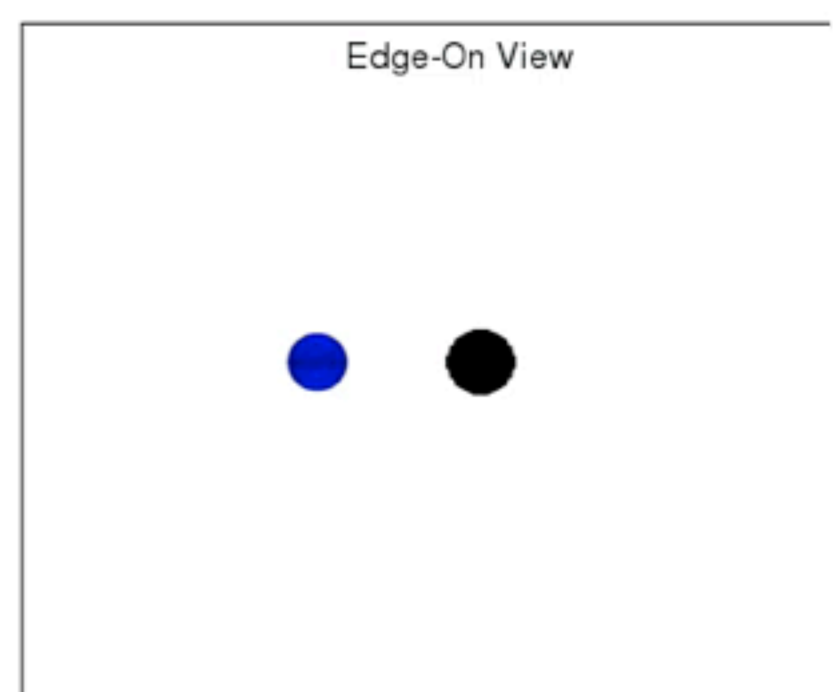
Current status

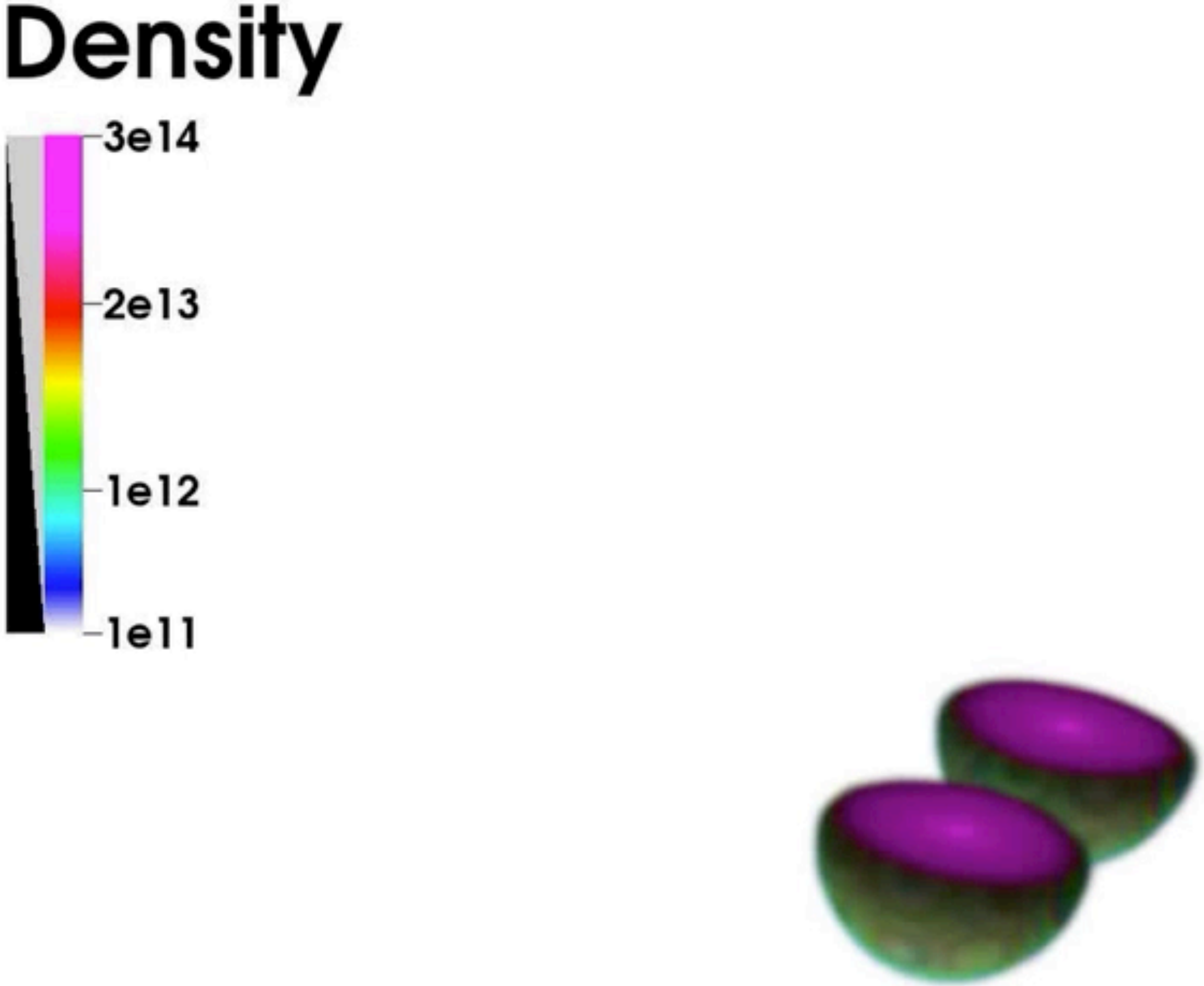
- First global simulations of disks capturing non-ideal effects in plasma (Foucart et al. 2016, Foucart et al. in prep)
- Saturation of pressure anisotropy at mirror instability threshold (dP~magnetic pressure)
- Practical effect on dynamics of compact, low magnetization disk is small.
- More significant effects likely for
  - Larger B-fields
  - Wider disks with resolved outflows

Part II
Merging Black Holes and Neutron Stars Simulations in General Relativity

Movie: B. Garcia
Simulation: F. Foucart et al. 2011







Movie: D. Faiez
Simulation: F. Foucart et al. 2016

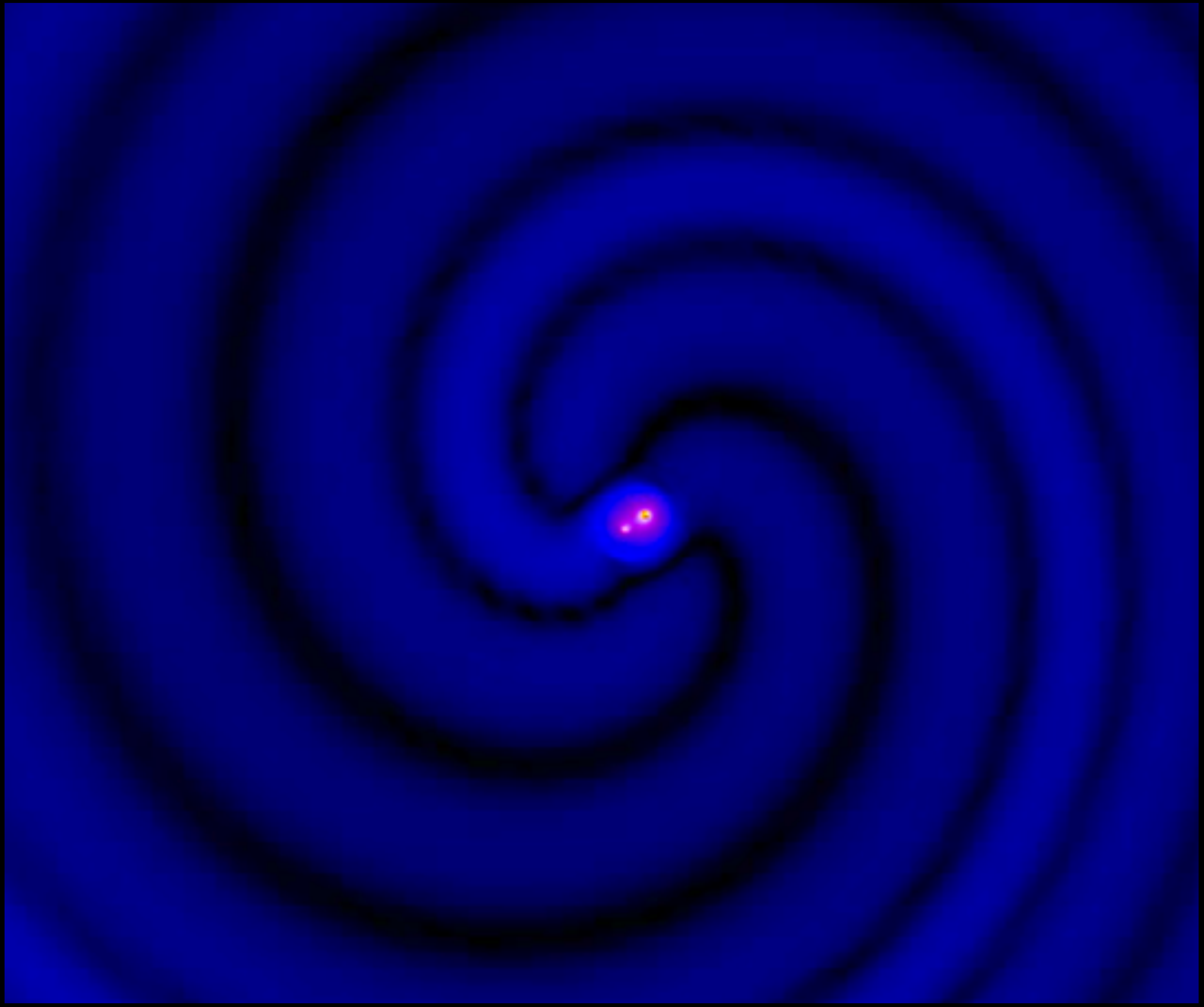
Gravitational waves and the Neutron Star equation of state

Gravitational Waves

General relativity:

Mass/Energy creates Spacetime curvature

Masses moving in curved space generate gravitational waves



To first order:

Quadrupole formula

$$L_{\rm GW} \propto \sum_{i,j} (\partial_t^3 Q_{ij})^2$$

For binaries:

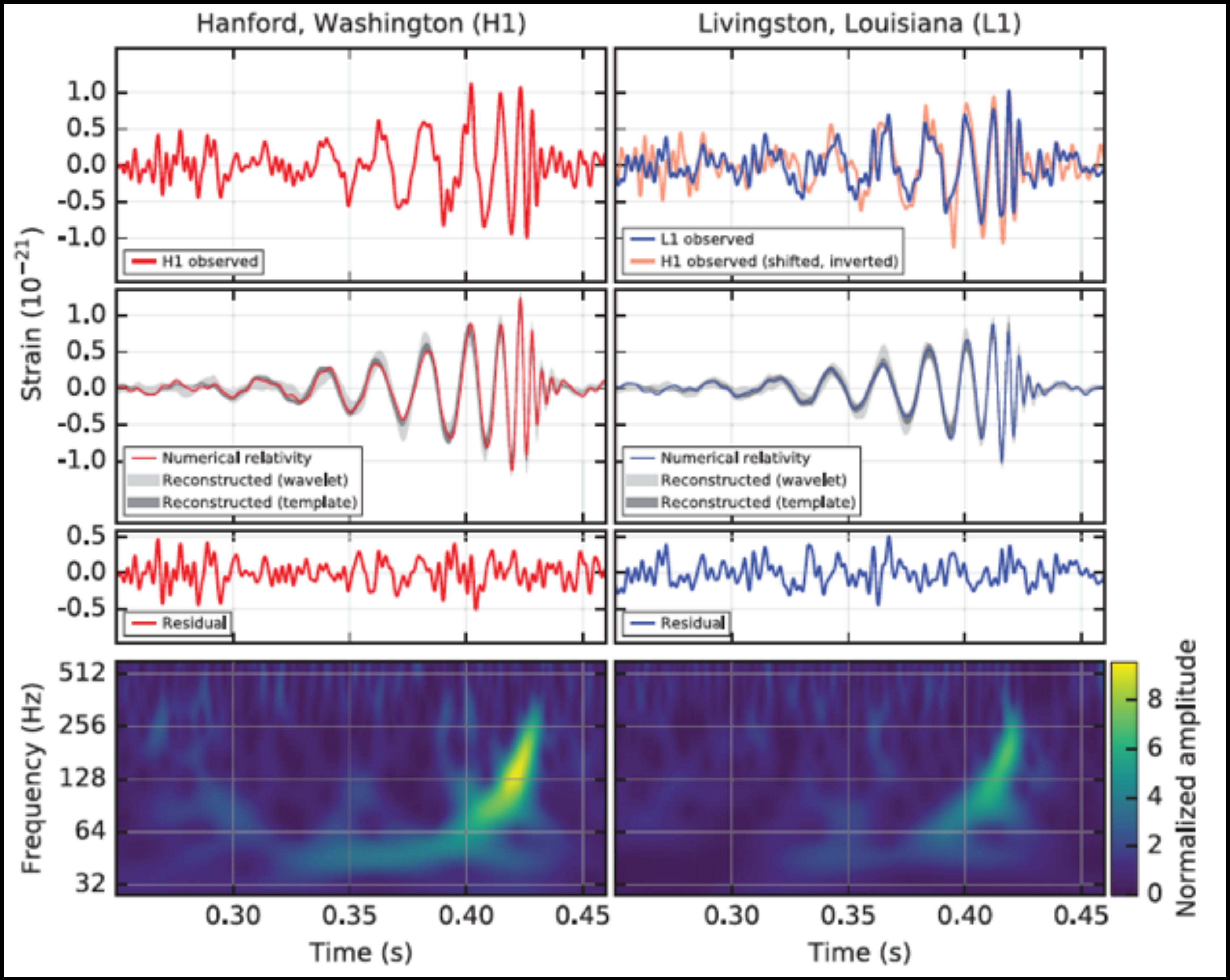
$$L_{\rm GW} \propto M^2 \Omega^6 d^4$$

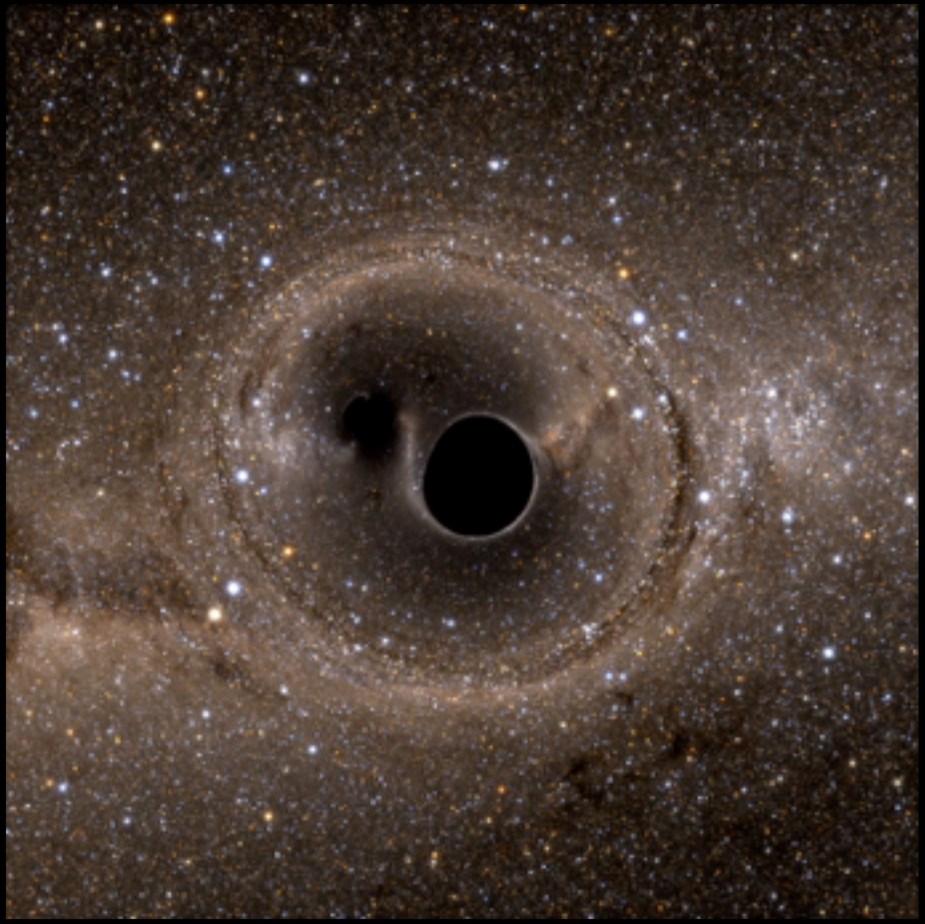
$$\propto (M/d)^5$$

=> strong emission for very compact systems (e.g. BH, NS)

Gravitational Waves

First Detection: GW150914





Movie : SxS Collaboration

Image: LIGO Collaboration, PRL

Nuclear physics and the neutron star equation of state

Measurements of neutron star radii
=
Constraints on nuclear physics!!

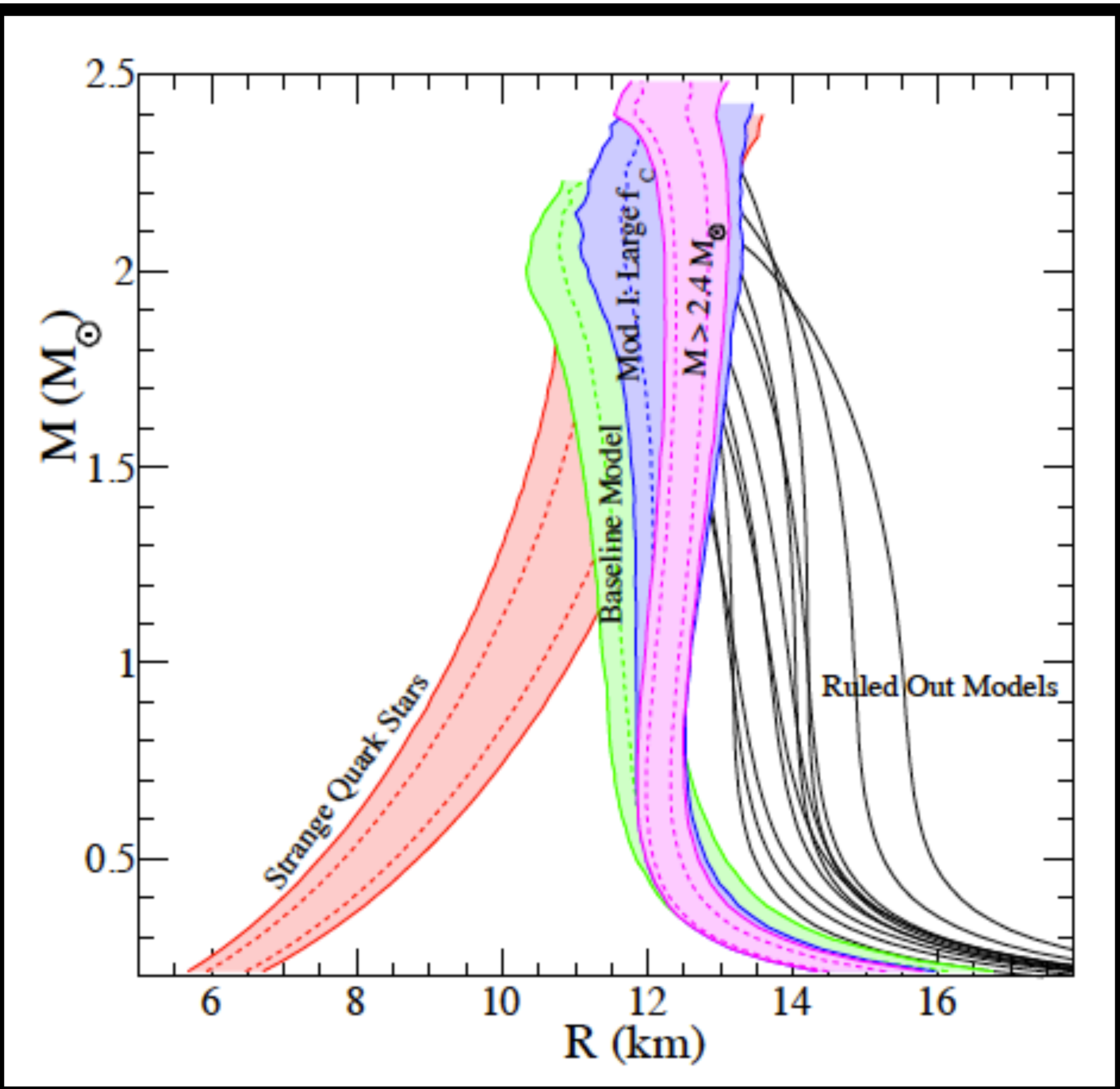
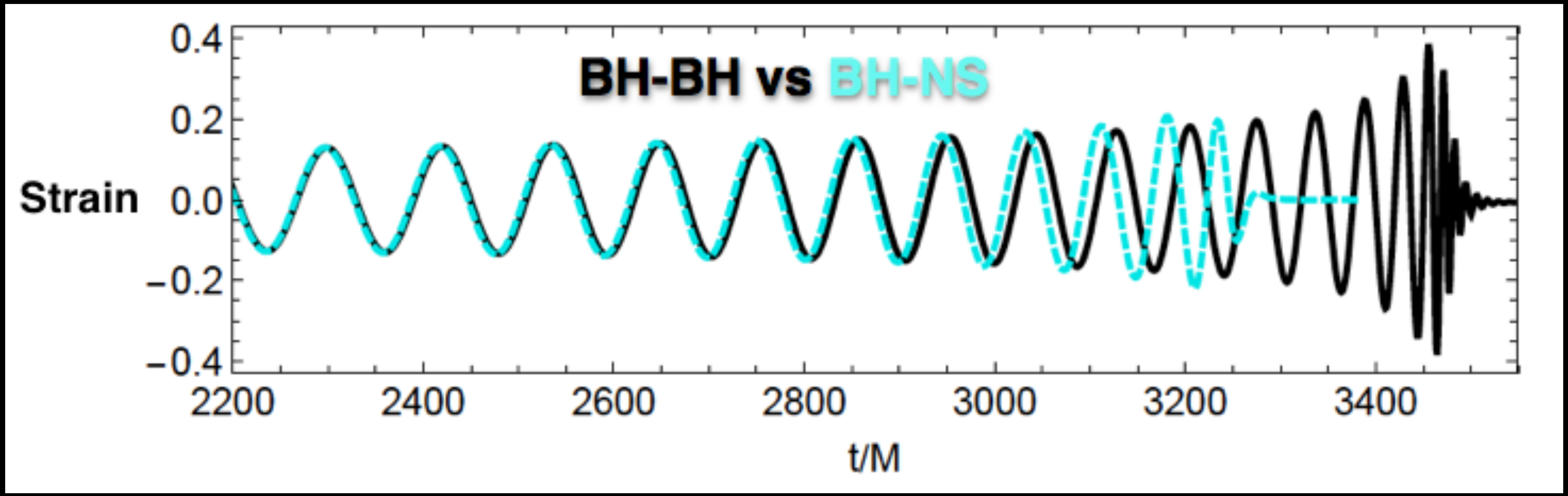


Image: Steiner, Lattimer & Brown 2012

Equation of state effects during inspiral



Quadrupole formula: $L_{\rm GW} \propto \sum_{i,j} (\partial_t^3 Q_{ij})^2$

Tides in neutron stars cause large stars to merge faster!

Tidal dephasing (leading order in Ω): **$\delta\Phi \sim R^5\, \Omega^{5/3}$**

~**40 NS-NS mergers** [NOT BH-NS]

➡

Radii measured to ~10%

(see Del'Pozzo et al. 2013 , Lackey & Wade 2015)

Important caveat:

Assumes perfect waveform model (Lackey & Wade 2015)

Modeling BHNS/NSNS inspirals

New simulations with high-order methods:

- **Rules out simplest static tides models**
- Allowed derivation of new model including dynamical tides (Hinderer,.., FF et al., 2016)
- Still *~25% numerical error* in tidal dephasing!

Numerical simulation vs Theoretical model

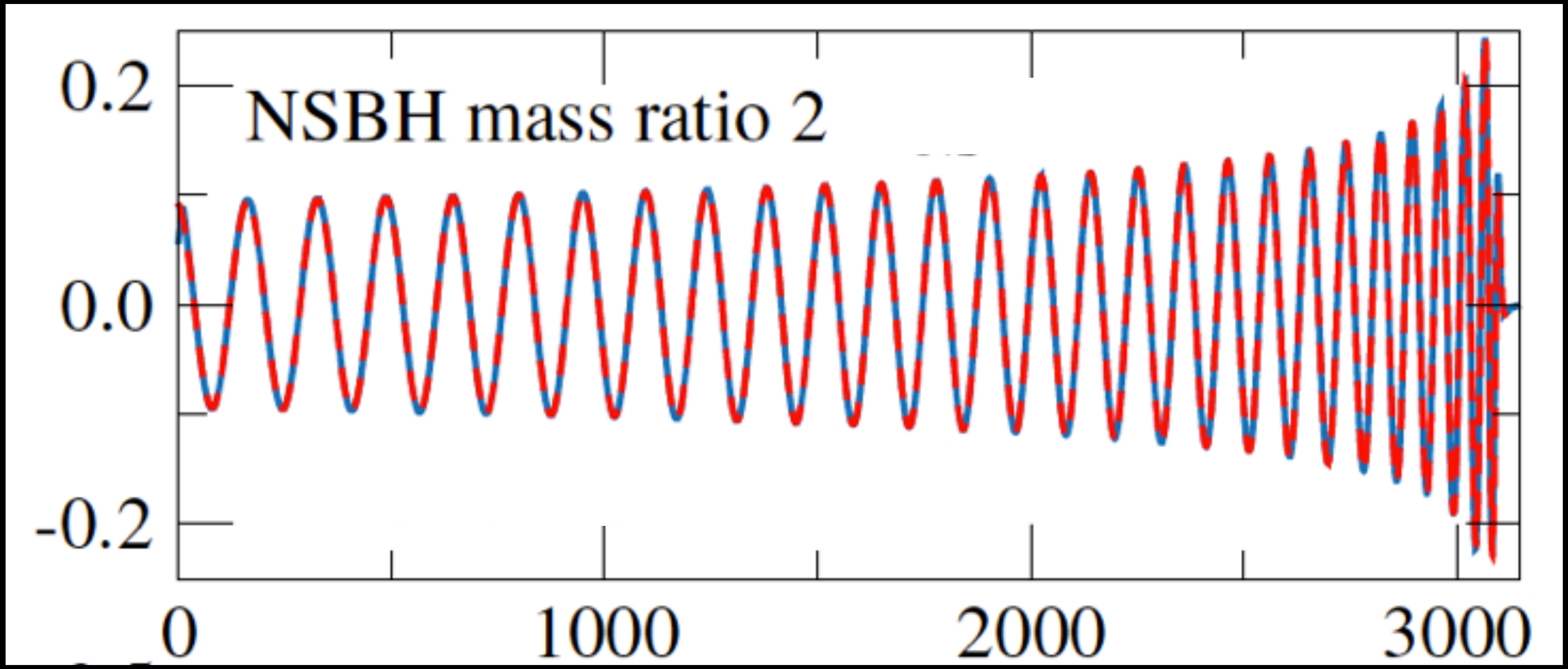


Image Hinderer, ..FF et al. 2016

Post-merger emission (NS-NS mergers)

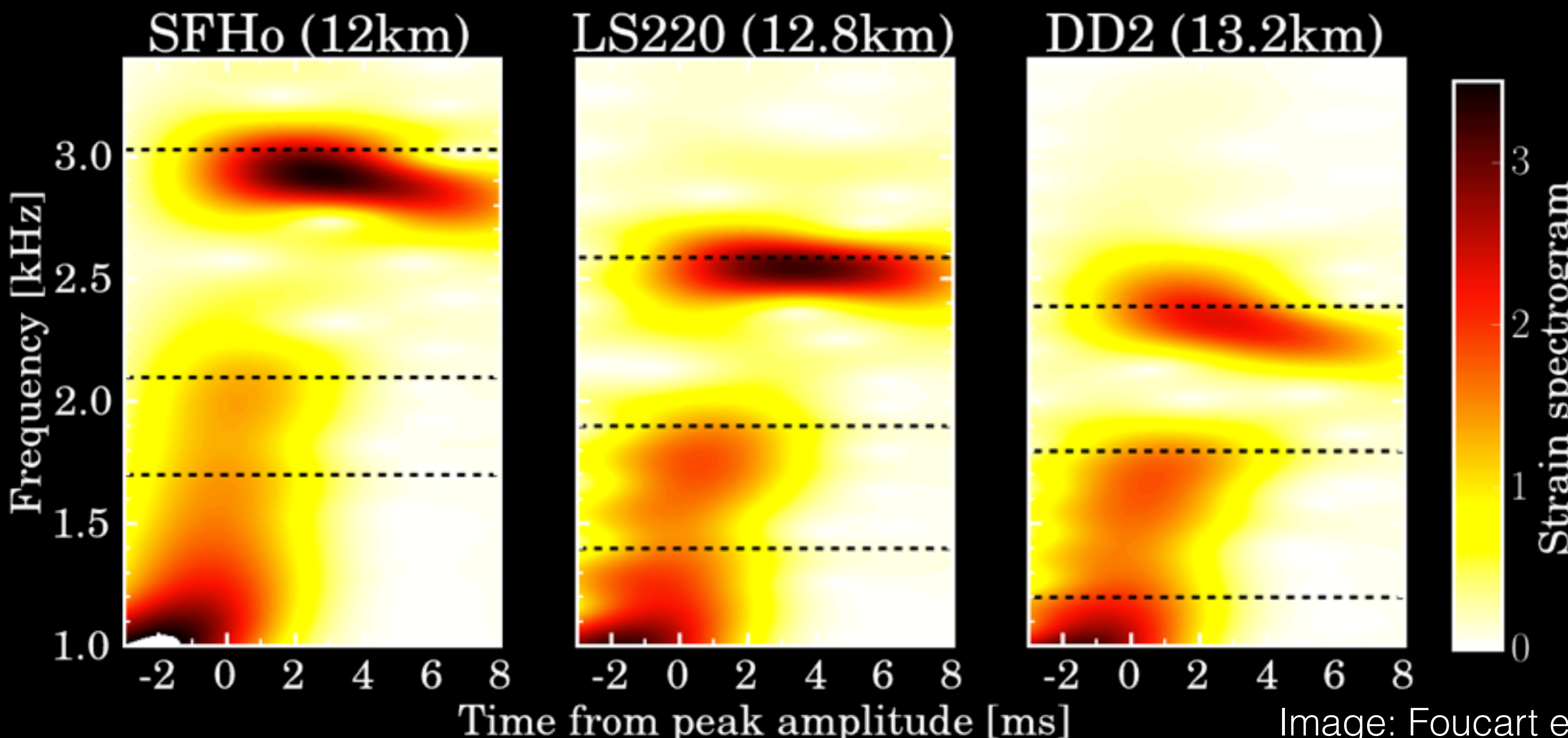


Image: Foucart et al. 2016

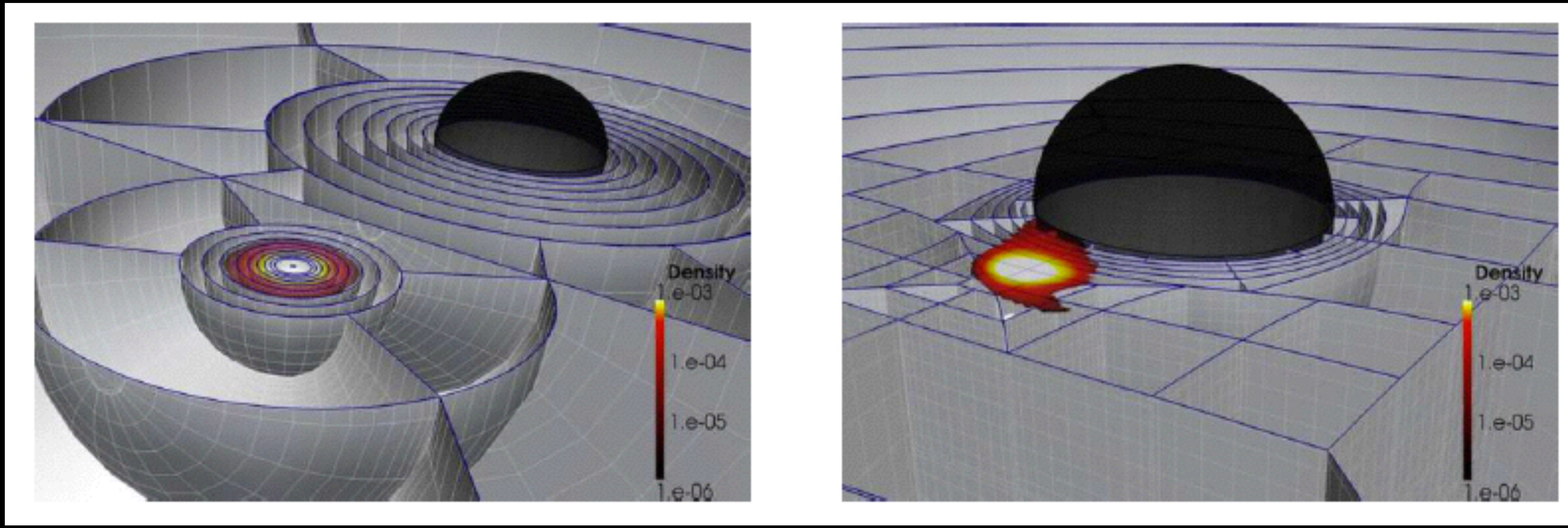
- Clear dominant frequency in post-merger signal
- Probe fundamental l=2, m=2 excitation mode of remnant
- **Reliable models** (Bauswein et al. 2012, Takami et al. 2015, Lehner et al. 2016), but **hard to detect**

Merger simulations with SpEC

http://www.black-holes.org/SpEC.html

Numerical Simulations with SpEC

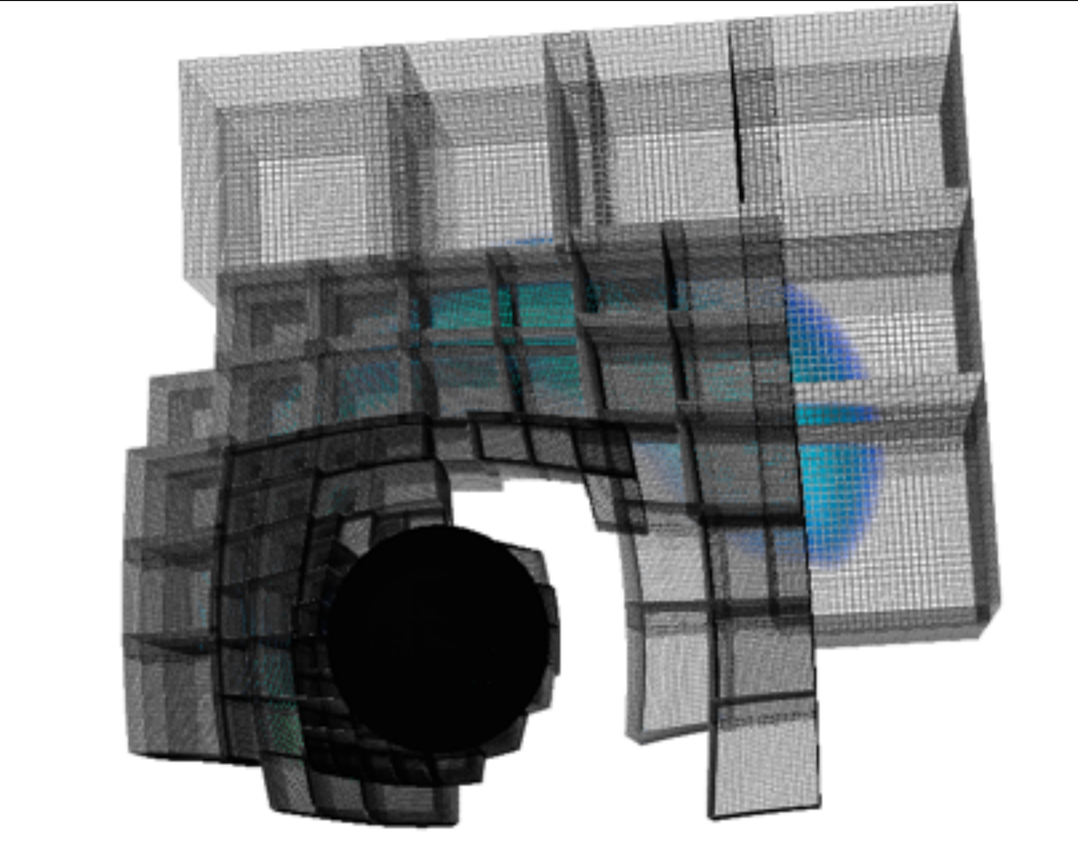
Image: Foucart et al. 2013



Evolve Einstein's equations with sources:

Pseudospectral methods, comoving grid, ~100 coupled diff. eq.

Image: Foucart et al. 2017



General relativistic hydrodynamics:

High-order shock capturing methods

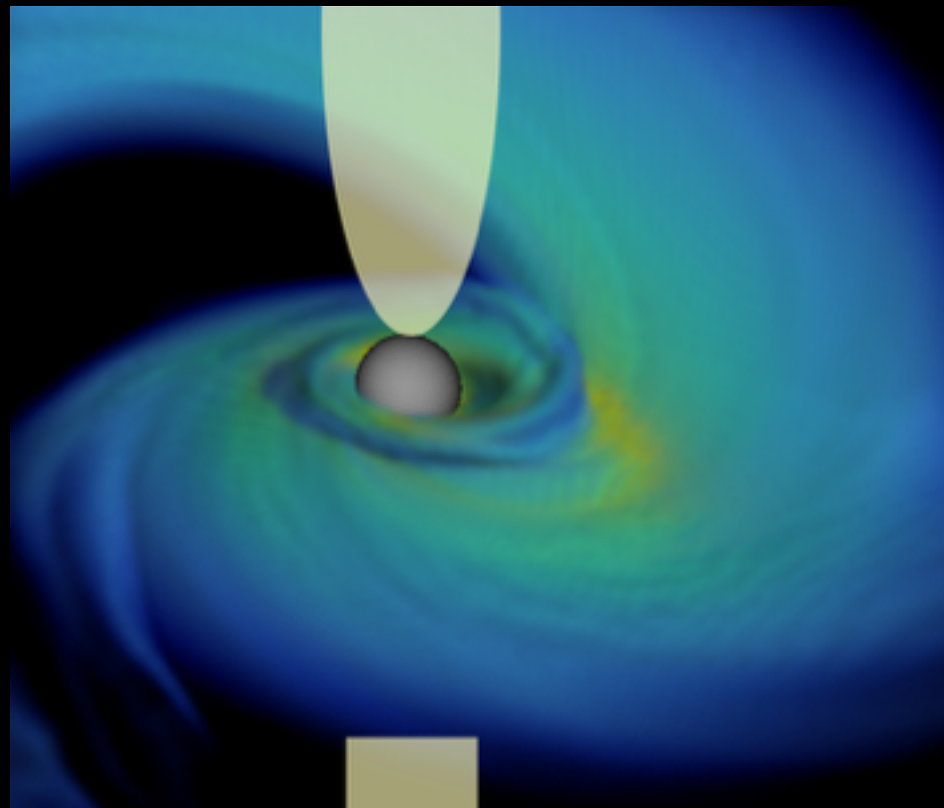
Mesh refinement

Excised black hole interior

Modules for MHD/Neutrinos (Two-moment formalism)/Composition

Electromagnetic Transients and r-process nucleosynthesis

Short Gamma-Ray Bursts



Kilonovae + r-process!

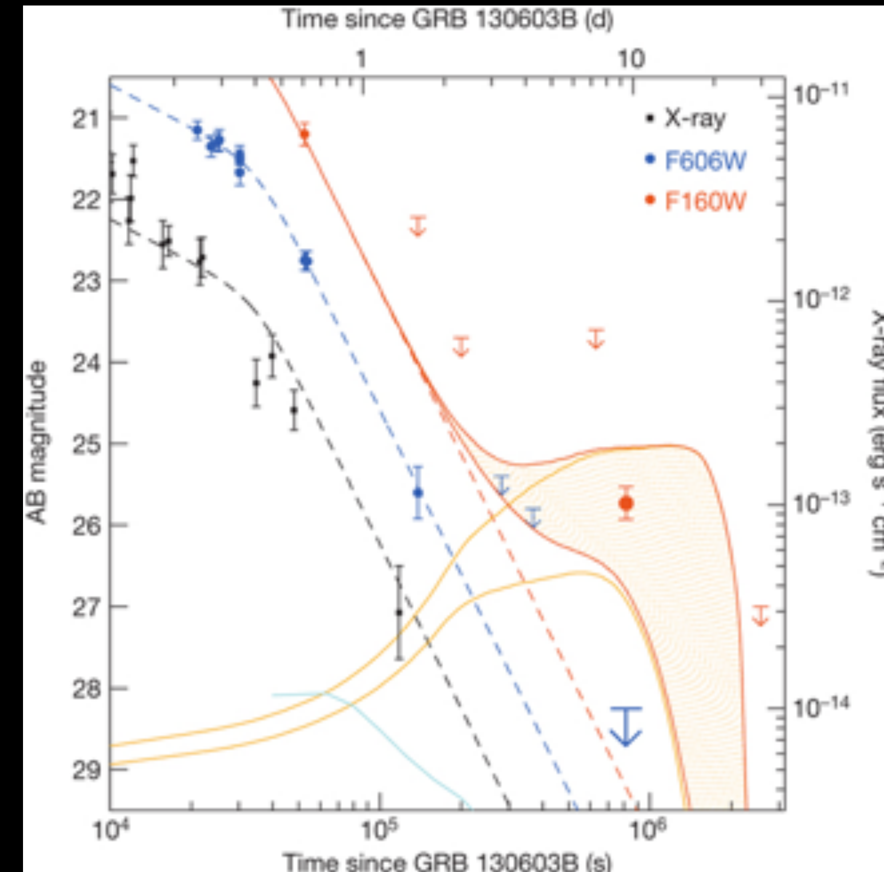


Image: Tanvir et al. 2013

Pre-merger Signals

Image: Tsang et al. 2012

Long-duration radio emission

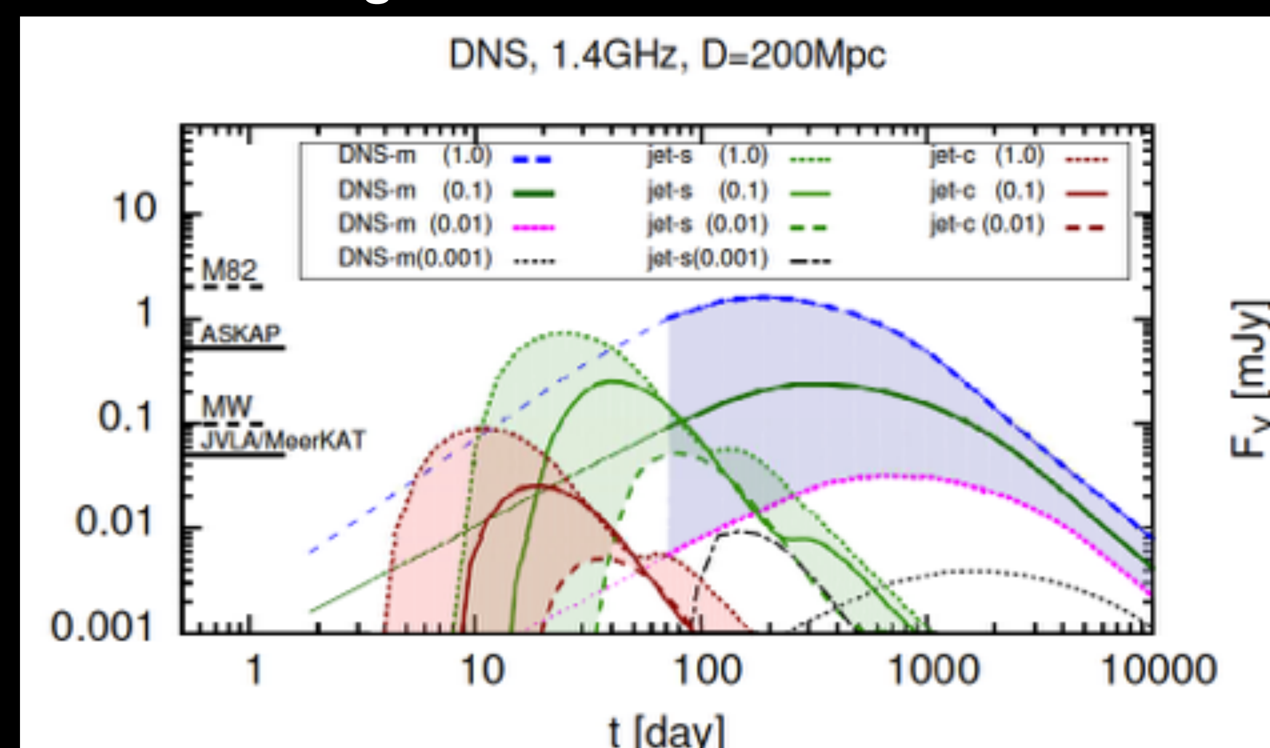


Image: Hotokezaka et al. 2016

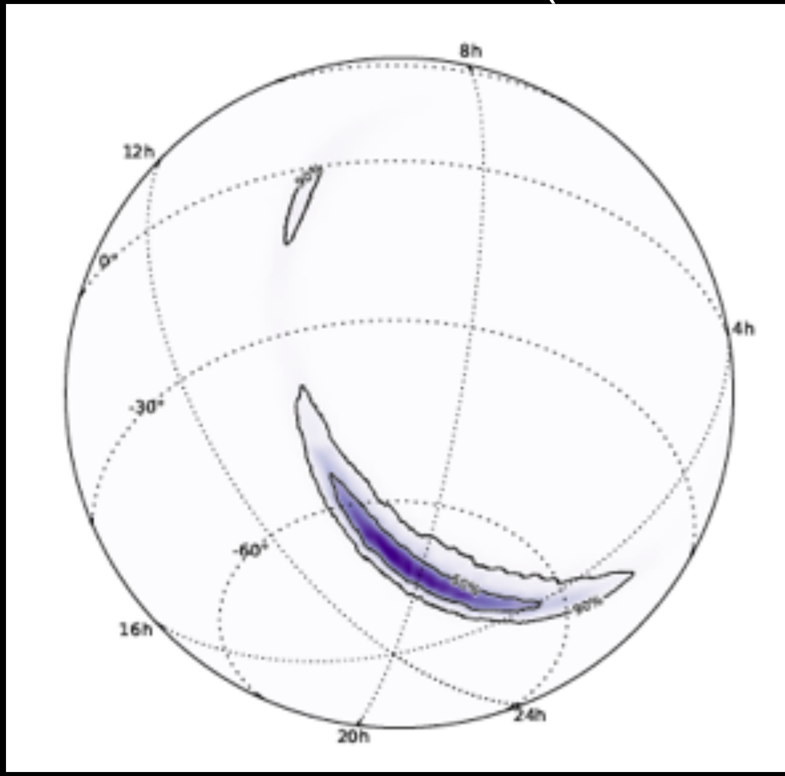
Francois Foucart

UVa

What can we learn from EM transients?

Demonstrate origin of SGRBs
Estimate contributions to r-process elements production
Merger environment: host galaxy, ISM density

Sky localization of GW150914 (LIGO Collaboration)

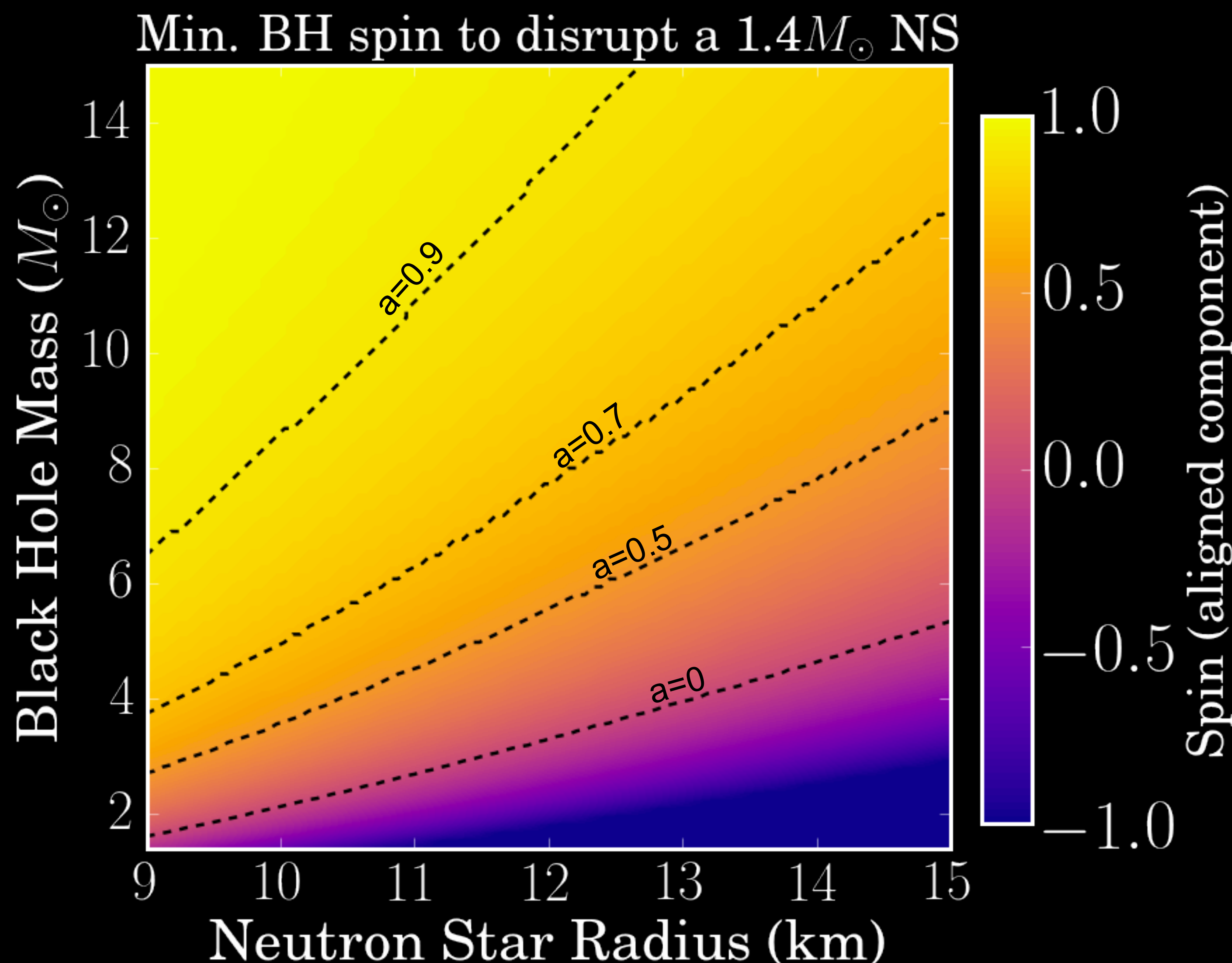


Independent constraints on NS/BH properties

1) From existence of EM counterpart in BHNS mergers
2) From IR/Optical lightcurves

Merger outcome : BH-NS binaries

Simulations from Foucart et al. 2013; Hinderer, ..FF et al. 2016



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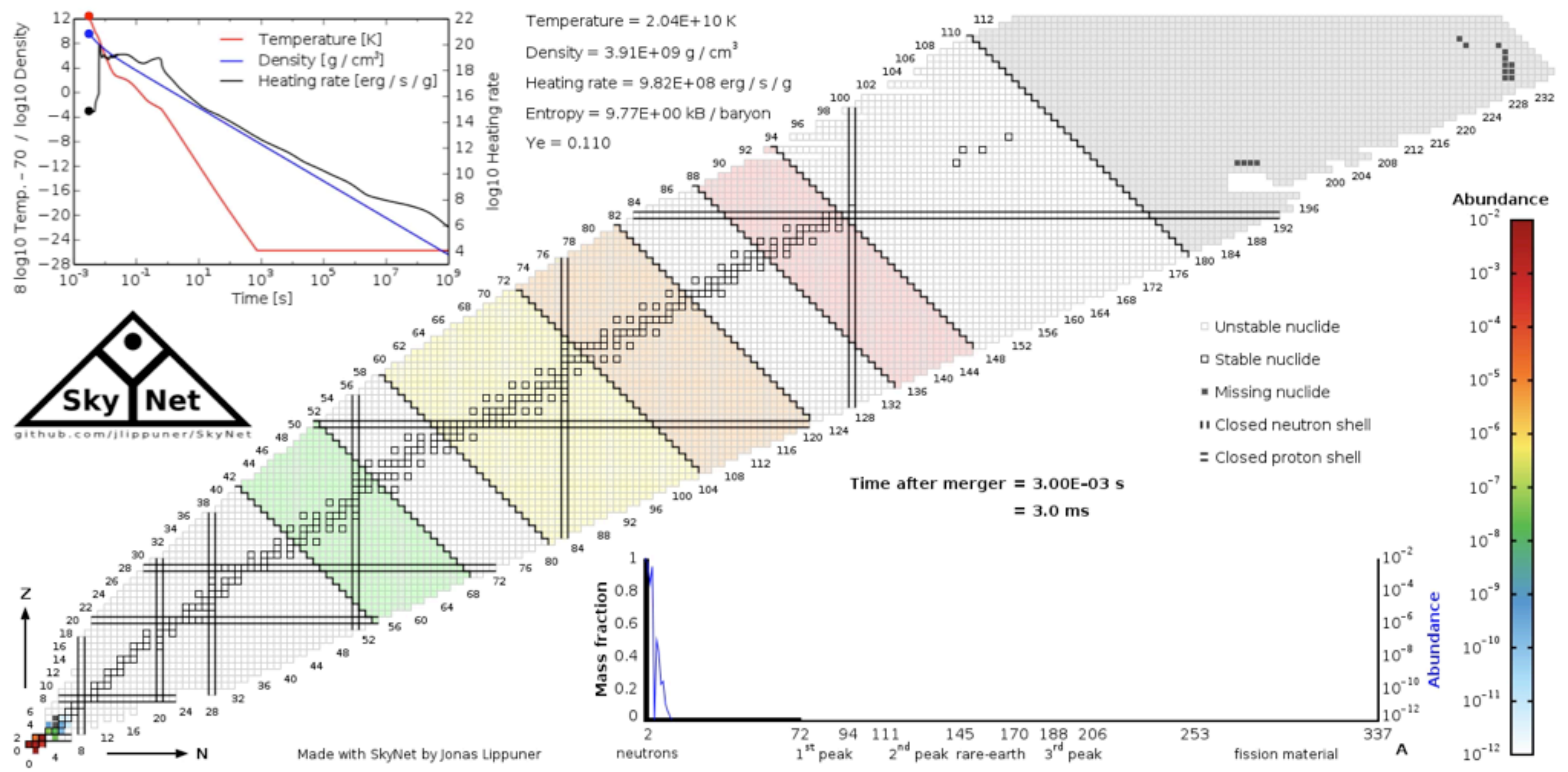
(see Foucart 2012)

UVa

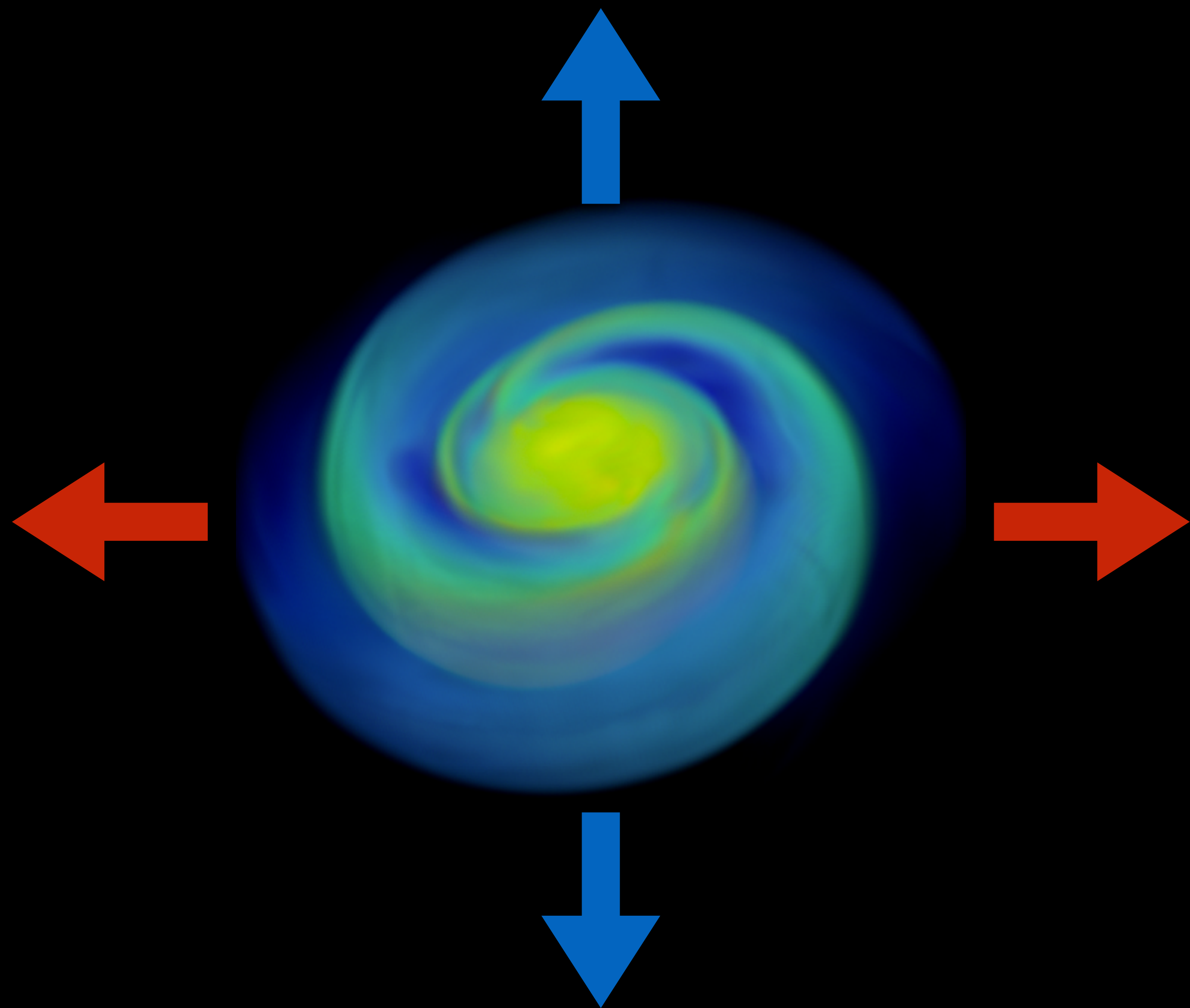
r-process nucleosynthesis and kilonovae

Nucleosynthesis in **neutron rich material** (e.g. tidal ejecta from BH-NS binary)



Visualization: Jonas Lippuner (Caltech), SkyNet code

Kilonovae and r-process



Tidal Ejecta
Cold, mostly neutrons
Favored by:
Large stars
Asymmetric mergers
IR transient

Shocked Ejecta
Hot, less neutrons
Only for NS-NS
Favors small radii
Optical transient (?)

Post-Merger Disks:
Winds (B-fields, ν)
Strong ν effects
Uncertain EM counterpart

Nucleosynthesis in kilonovae

Dynamical ejecta produces heavy elements
Disk outflows produce lighter elements
Solar system abundances if the two components have similar masses

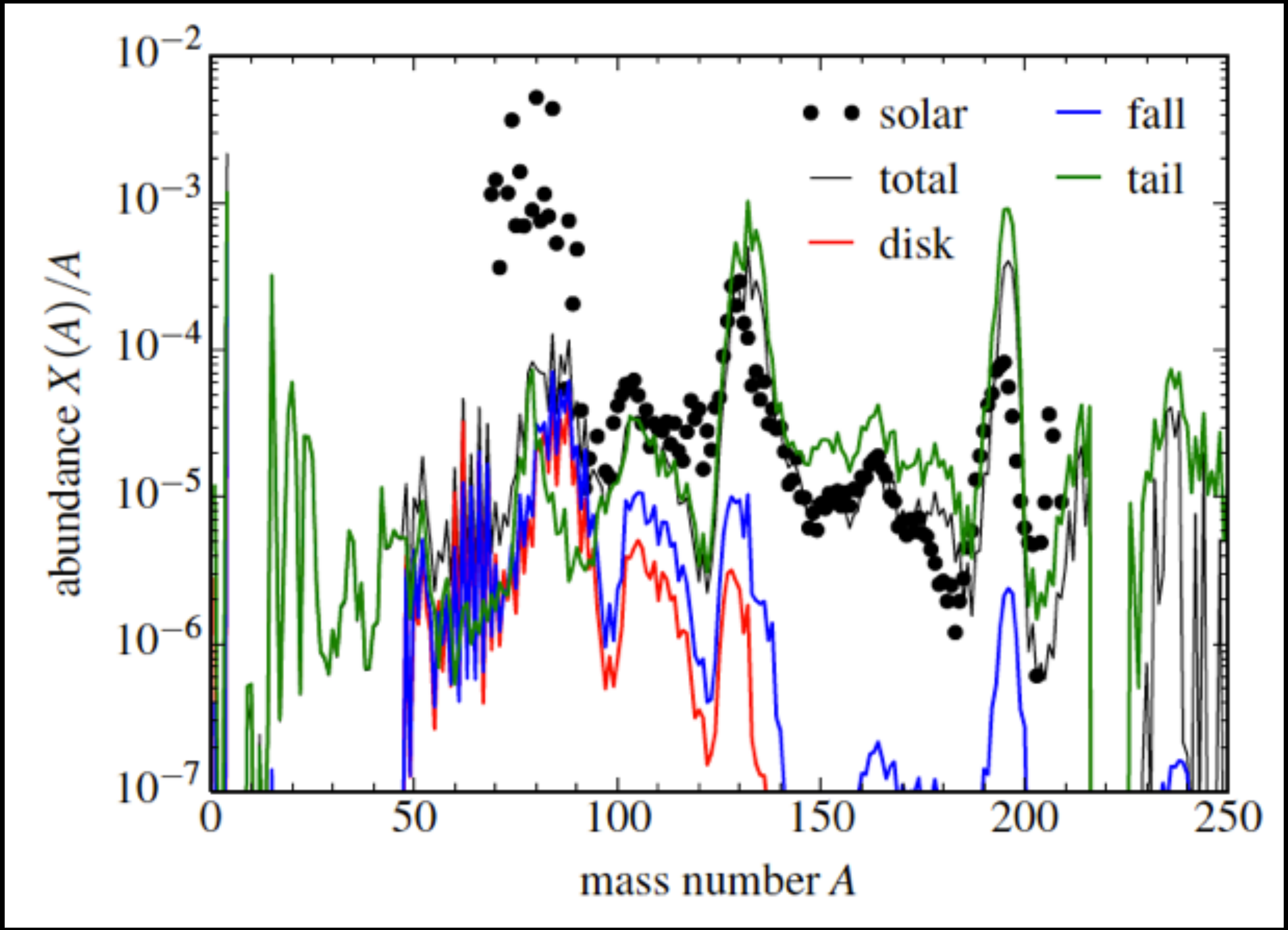


Image: R. Fernandez, FF, et al., subm.
Abundances from SkyNet (J. Lippuner, L. Roberts)

Neutron star mergers:
Current status and Future work

- Wide range of physical effects can be studied through BH-NS / NS-NS mergers
- Merger dynamics and outcome can only be studied with general relativistic simulations
- Good qualitative understanding of merger dynamics
- Improving waveform models for NS, more work needed to prepare for LIGO observations
- More detailed microphysics in mergers is beginning to make EM / nucleosynthesis predictions possible