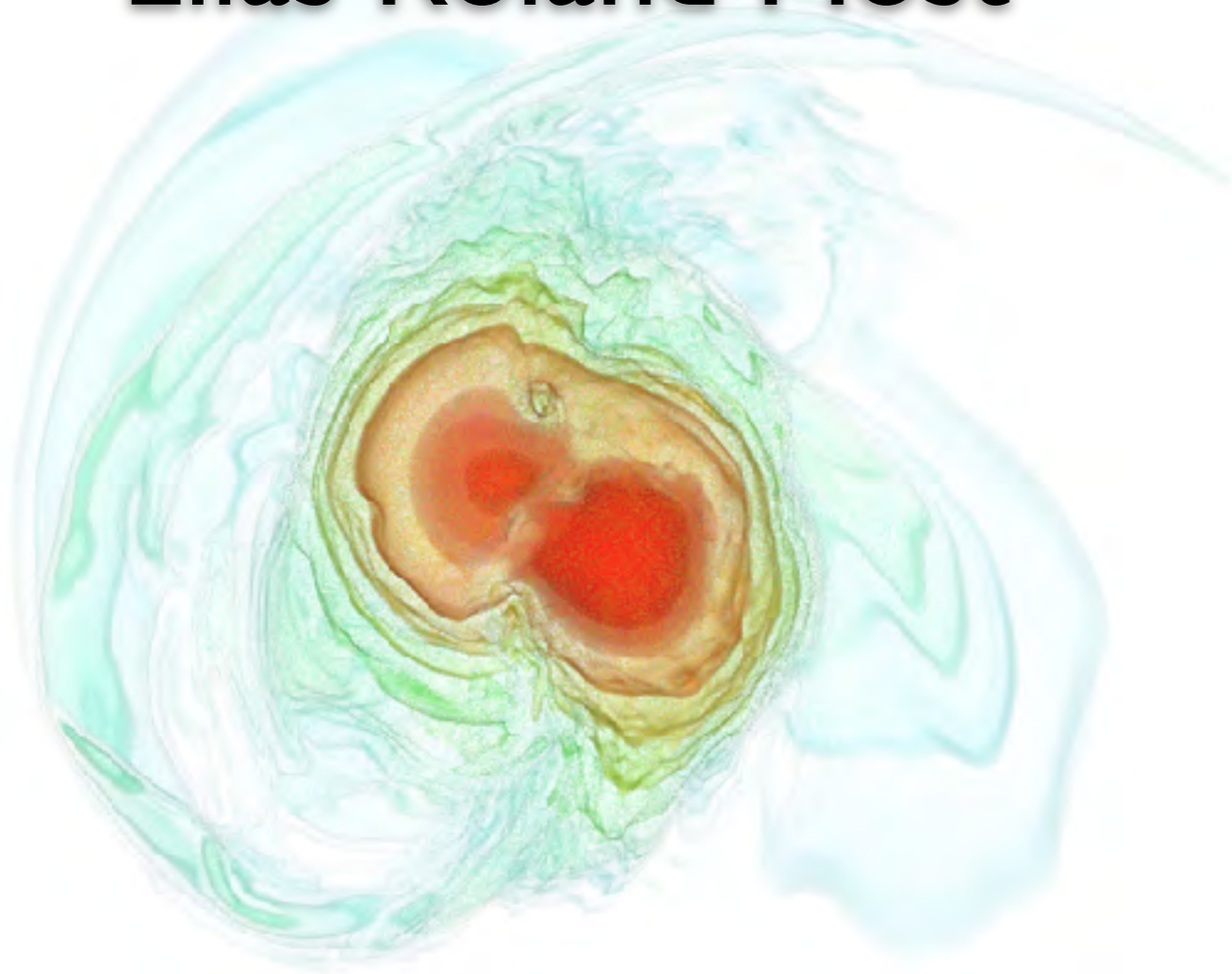
Computational Relativistic Astrophysics

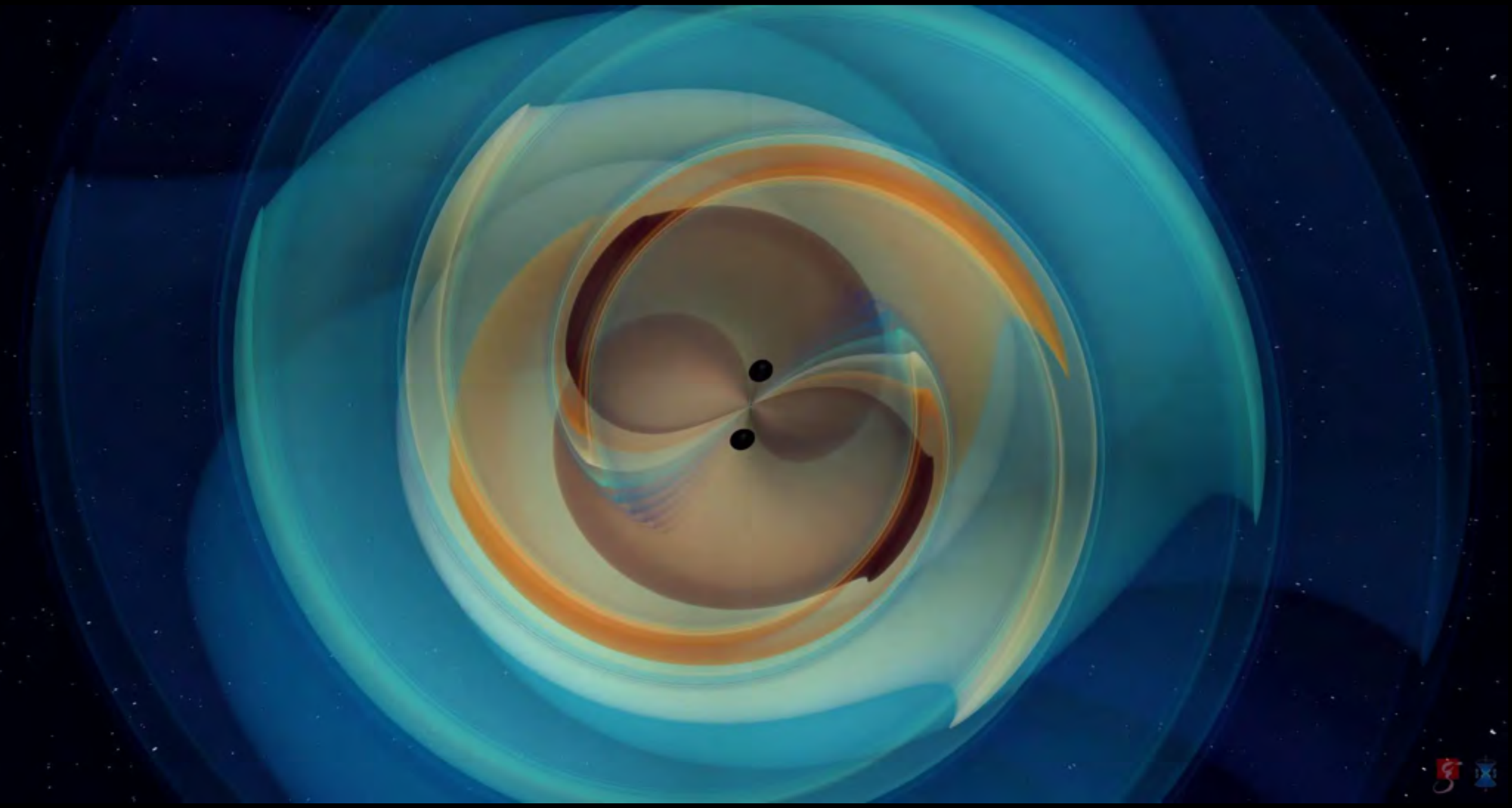
Elias Roland Most



Caltech | Computational Relativistic Astrophysics
comp-relastro.caltech.edu

TAPIR

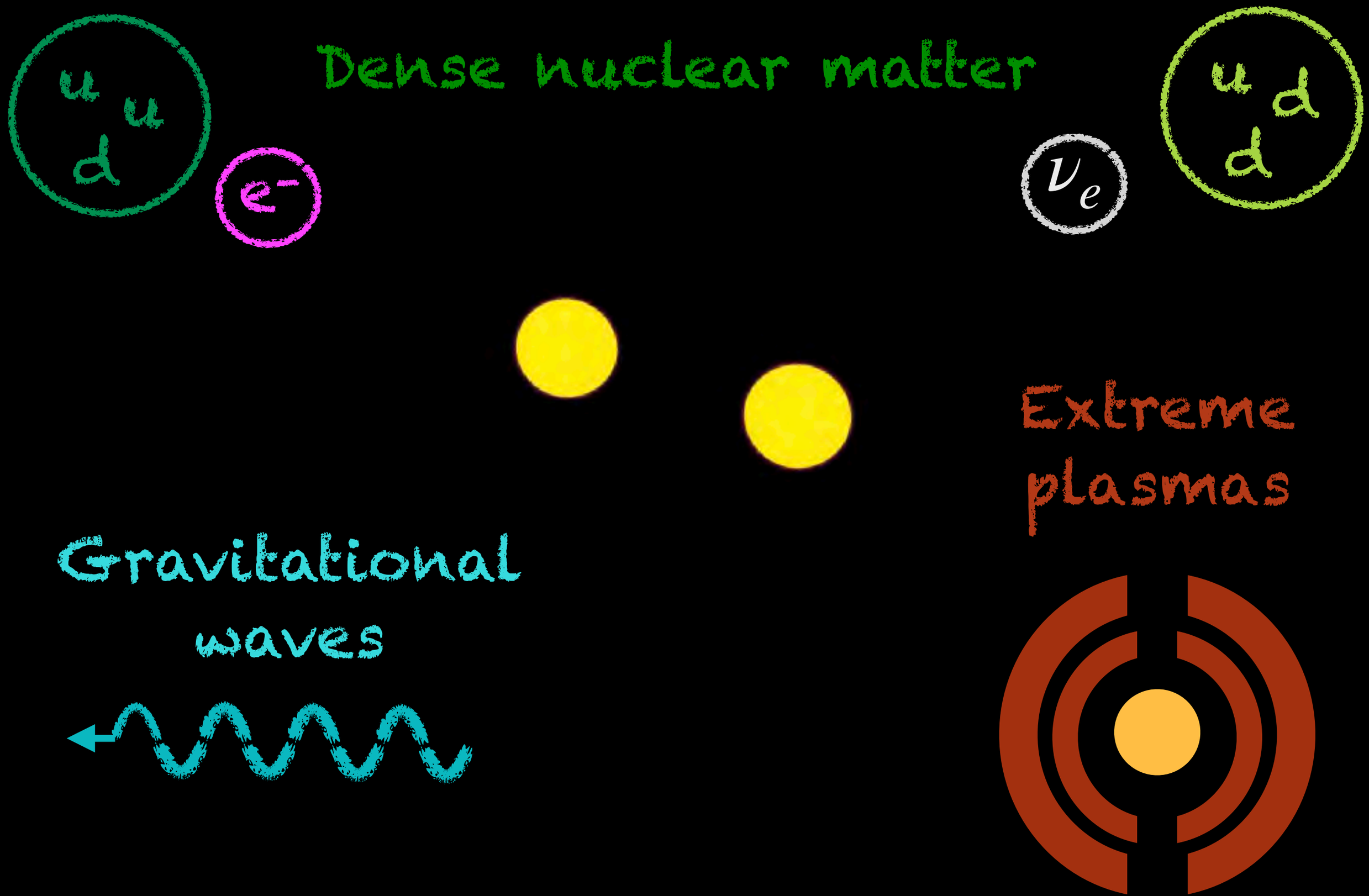
Numerical Relativity



SIMULATING eXTREME SPACETIMES

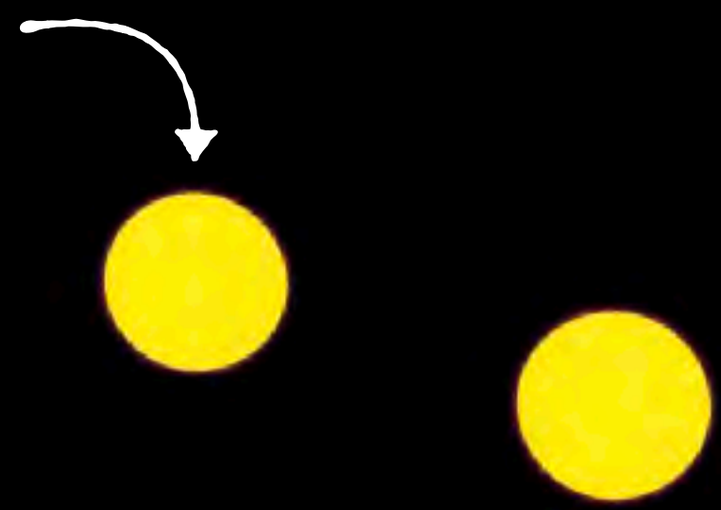
Black holes, neutron stars, and beyond...

The physics of extreme cosmic collisions



Today's protagonist:

Neutron star



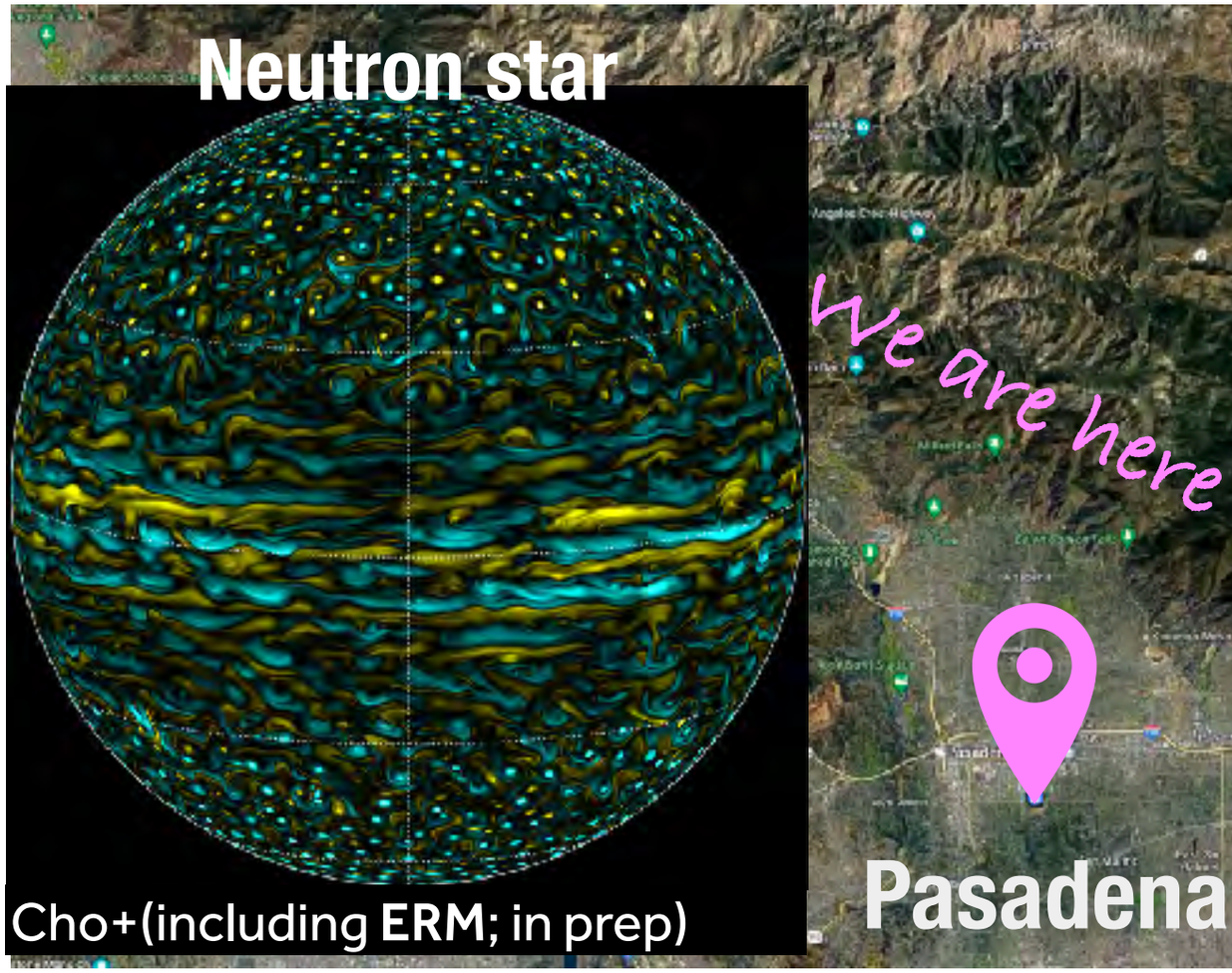
What does a neutron star look like?

How big is a neutron star?

About 20-30 km in diameter

How massive is a neutron star?

Around 1-2 solar masses

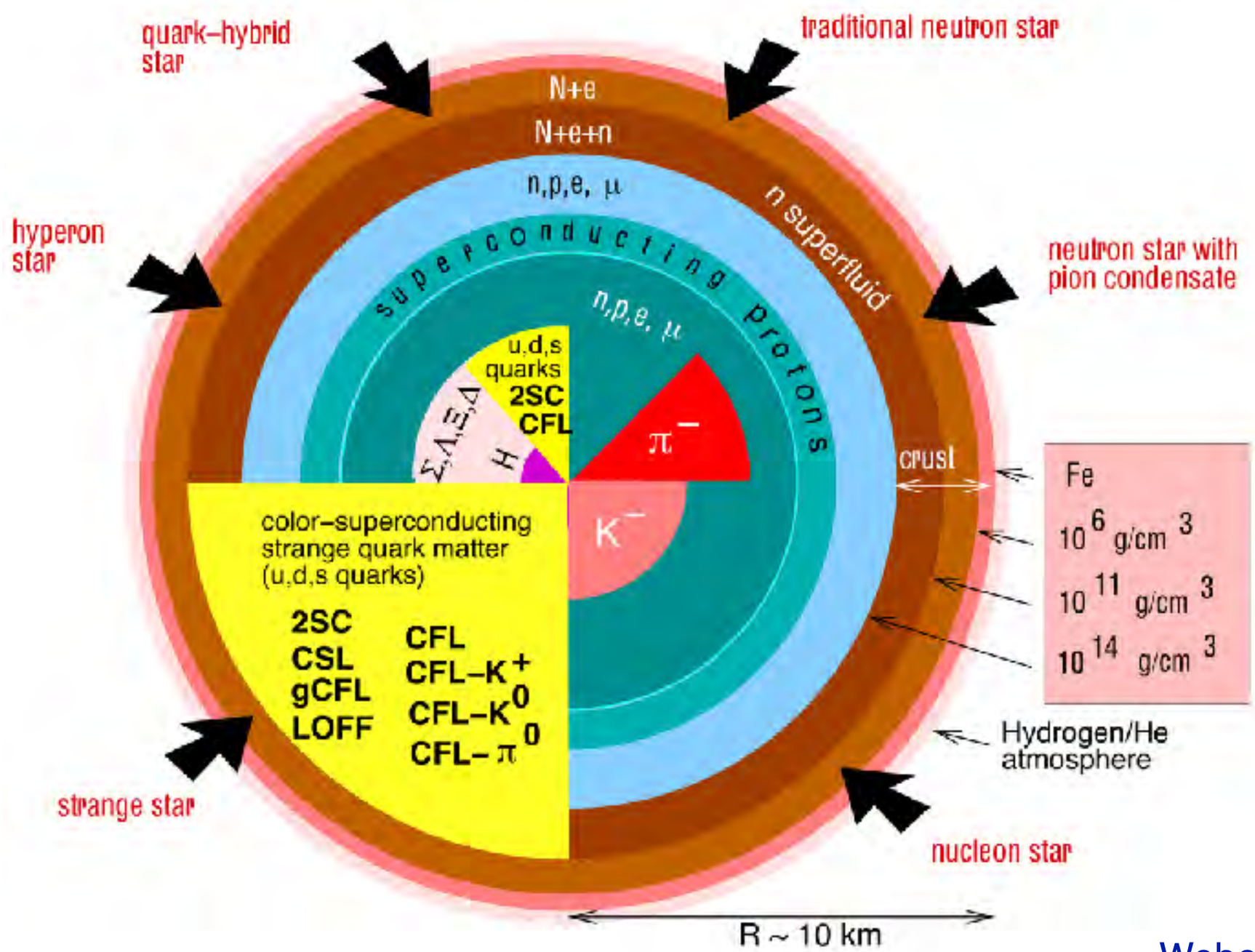


What is a neutron star made of?

Nuclear densities

$$\bar{\rho} \simeq \frac{\text{mass}}{\text{volume}} \simeq \frac{M}{\frac{4}{3}\pi R^3} \simeq \frac{2\times 10^{33}\,\text{g}}{4\times\left(10^5\,\text{cm}\right)^3} \approx 5\times 10^{14}\frac{\text{g}}{\text{cm}^3} \simeq 2\times\rho_{\text{nuclear}}$$

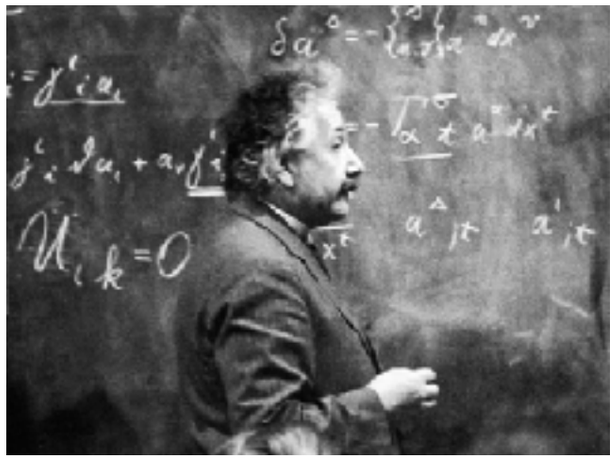
Neutron stars as probes of fundamental physics!



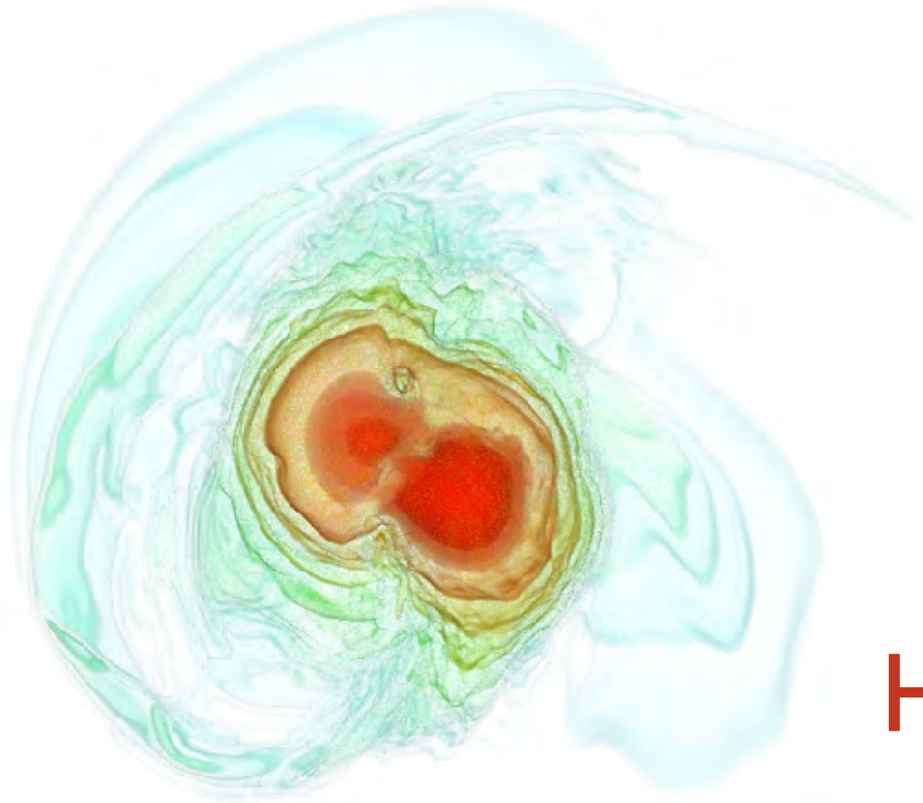
Weber+(2007)

The physics of compact binary mergers

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



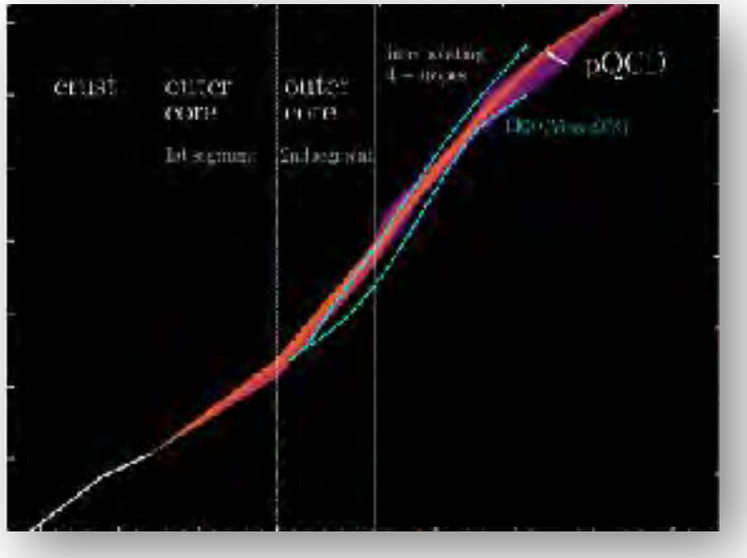
General relativity



$$\nabla_\mu T^{\mu\nu} = 0$$

Hydrodynamics

$$p = p\left(\rho, T, Y_e\right)$$

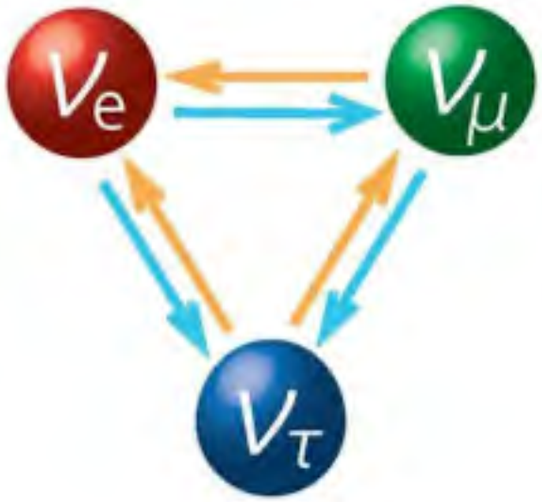


Nuclear physics

$$\nabla_\mu F^{\nu\mu} = 4\pi \mathcal{J}^\nu$$

Electrodynamics

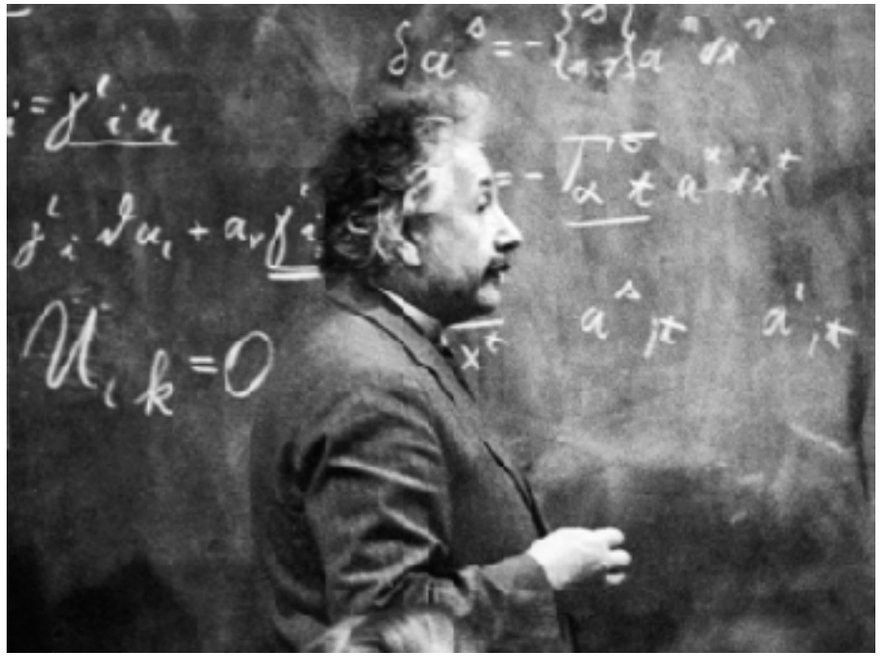
$$n \rightarrow p + e^- + \bar{\nu}_e$$



Weak interactions

Modeling compact binary mergers

General relativity is very hard to solve using analytical tools, especially when matter is dynamically important.



High-performance computing

General relativity is very hard to solve using analytical tools, especially when matter is dynamically important.

Numerical relativity solves Einstein field equations & magnetohydrodynamics on supercomputers.

High-performance computing

General relativity is very hard to solve using analytical tools, especially when matter is dynamically important.

Image credit: Gigabyte

New era of computing: GPUs

Current applications show speed-up of $> 10\times$

High-performance computing

General relativity is very hard to solve using analytical tools, especially when matter is dynamically important.

Image credit: Gigabyte

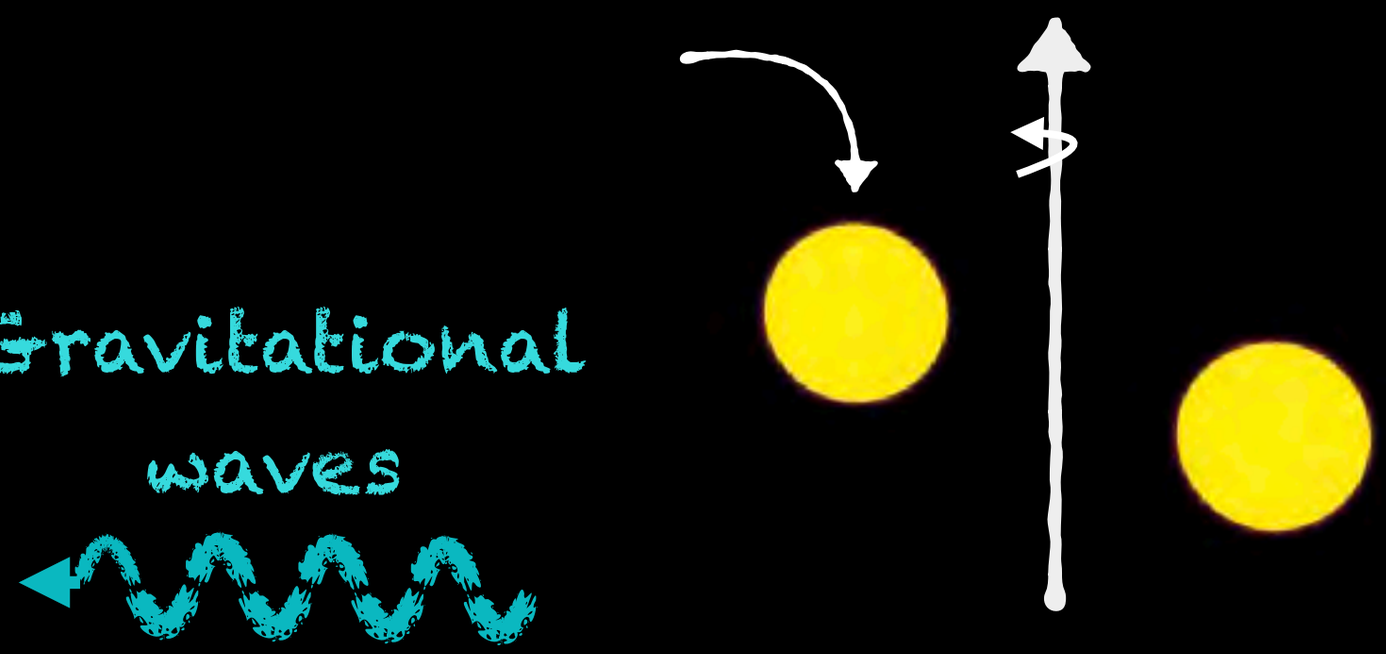
New era of computing: GPUs

Current applications show speed-up of $> 10\times$

Today's protagonist:

Time to impact
-15ms

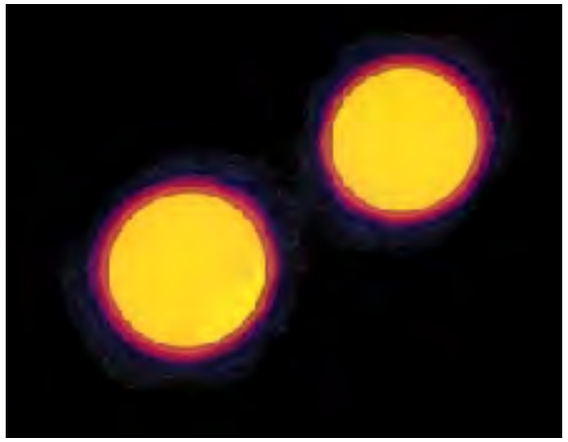
Neutron star



Late stage gravitational wave emission
leads to inspiral and merger!

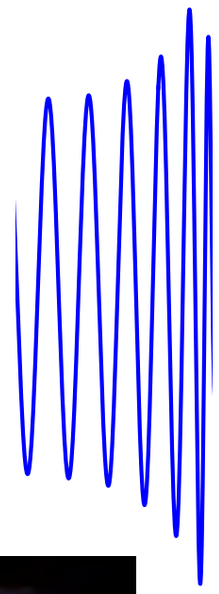
Animations: Breu et al.

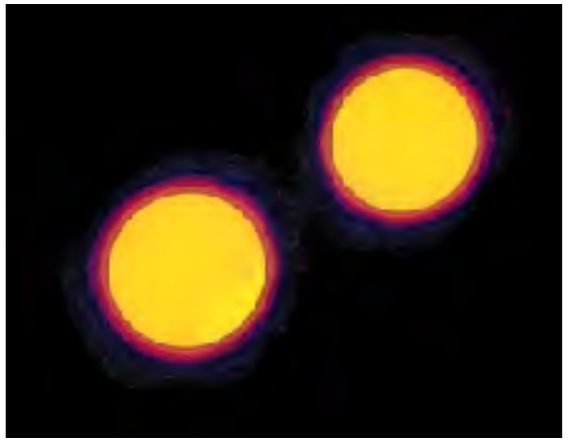
The final fate of a neutron star binary



The final fate of a neutron star binary

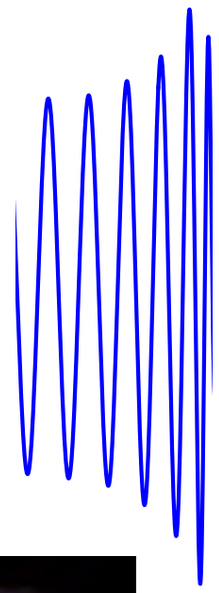
Gravitational waves

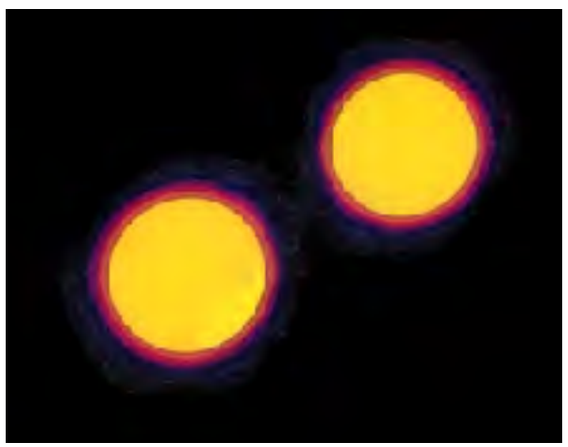


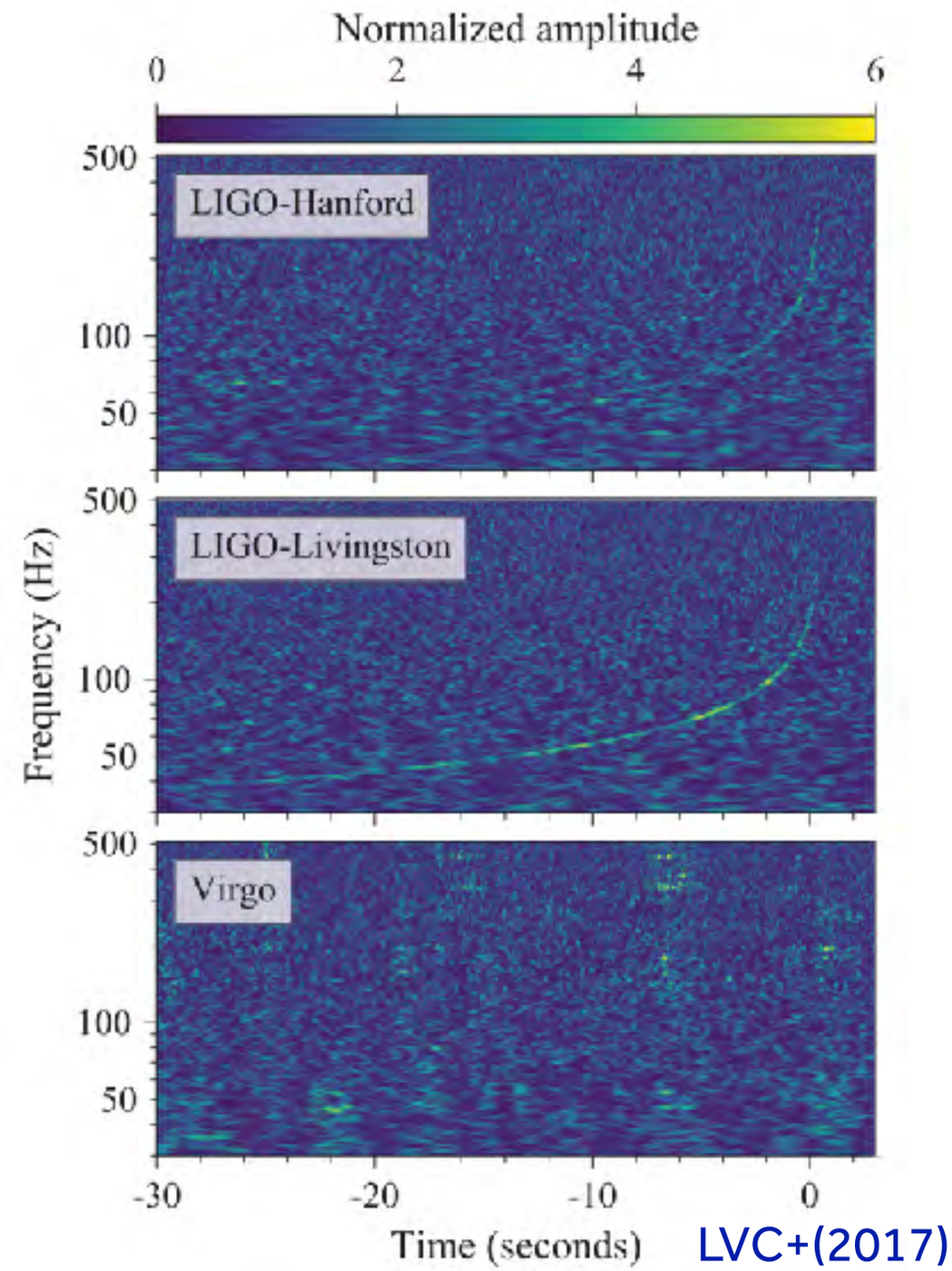


The final fate of a neutron star binary

Gravitational waves

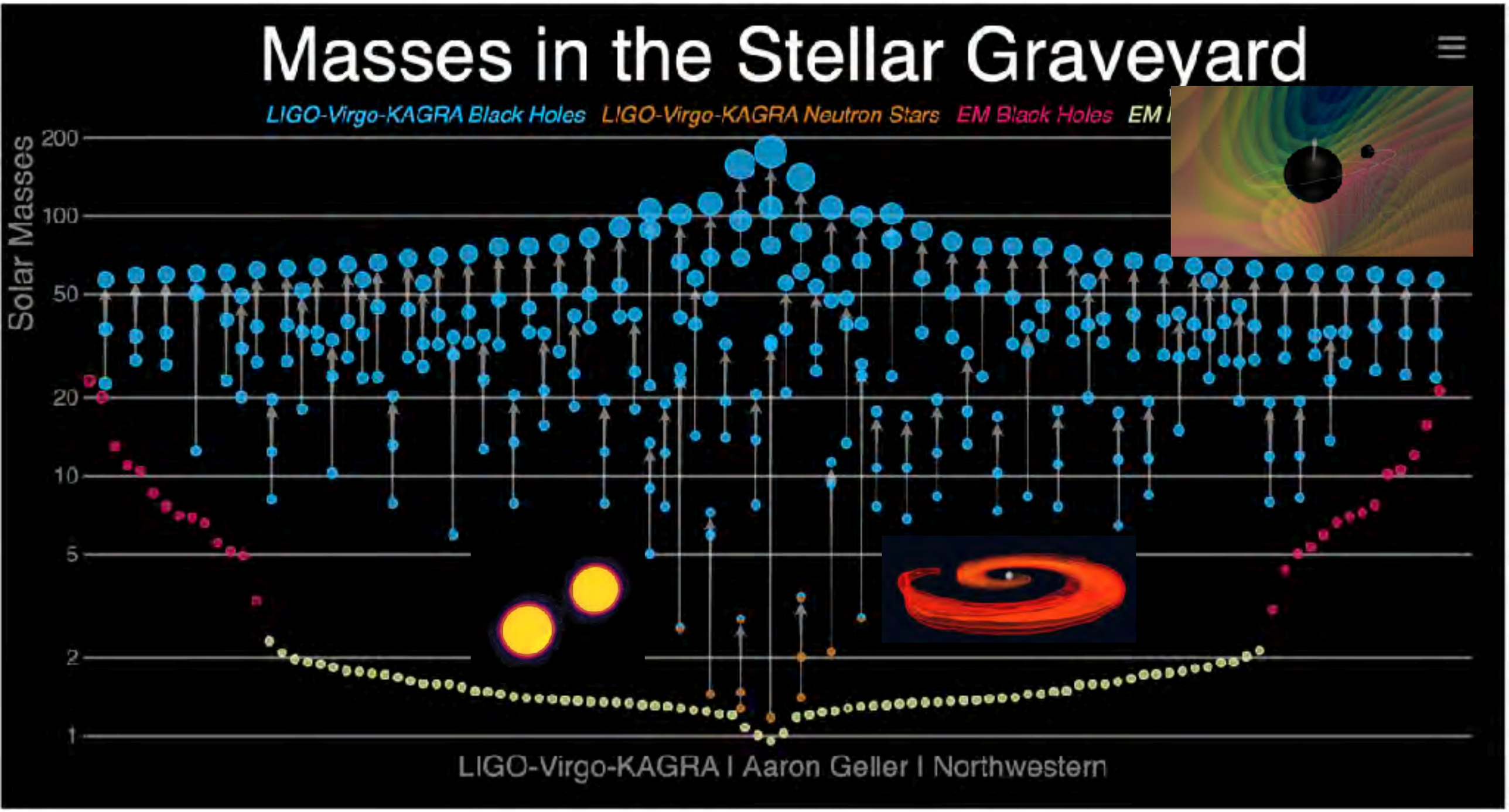


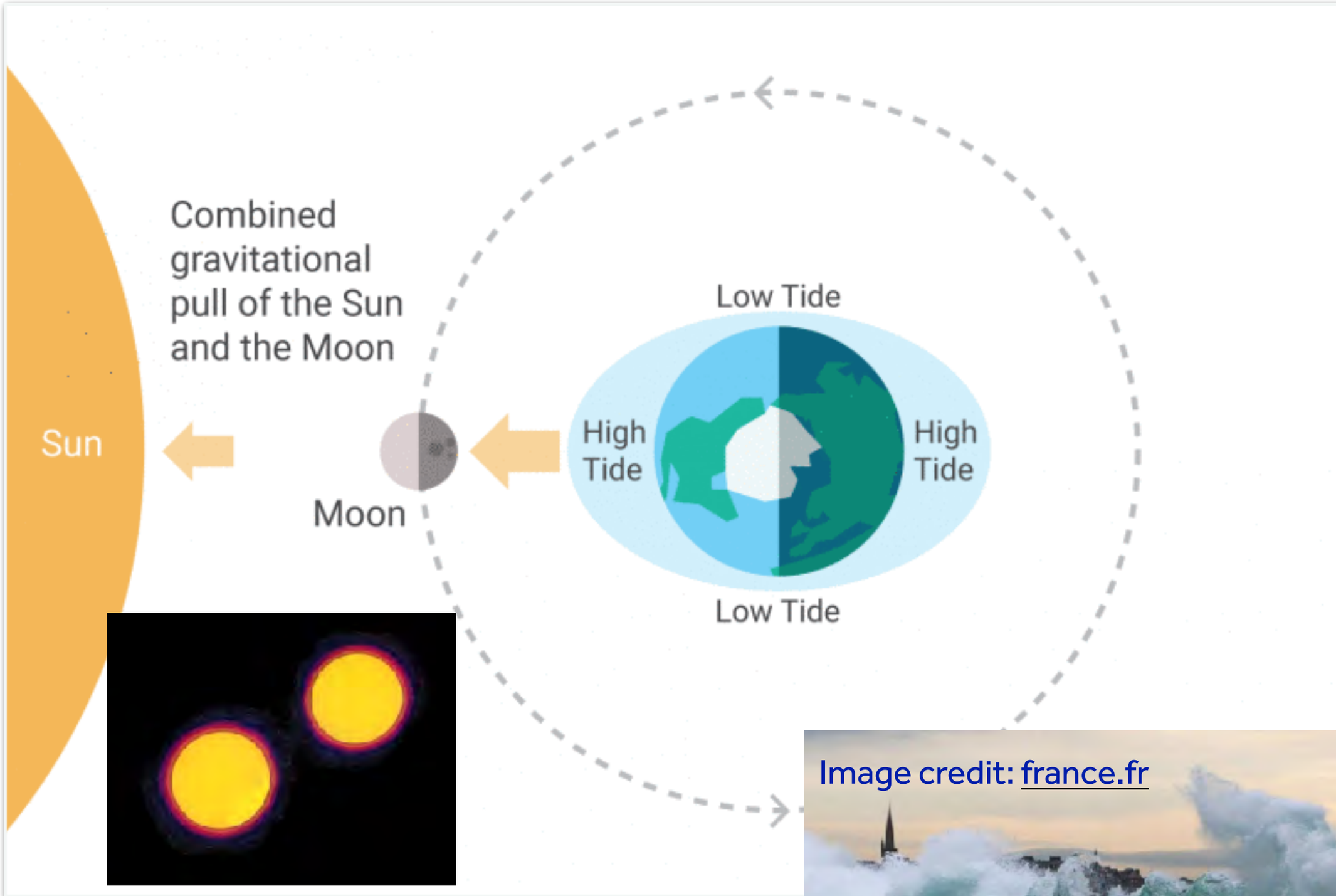




LVC+(2017)

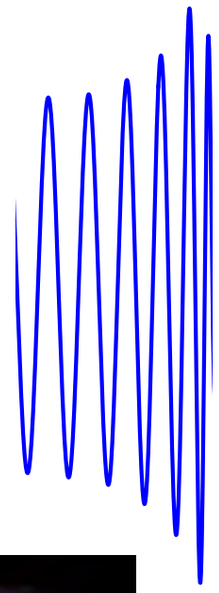
First direct detection of a gravitational wave signal from neutron star coalescence happened only in 2017.


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

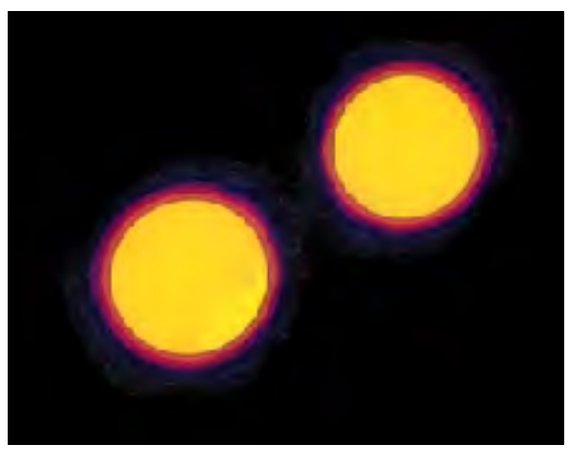


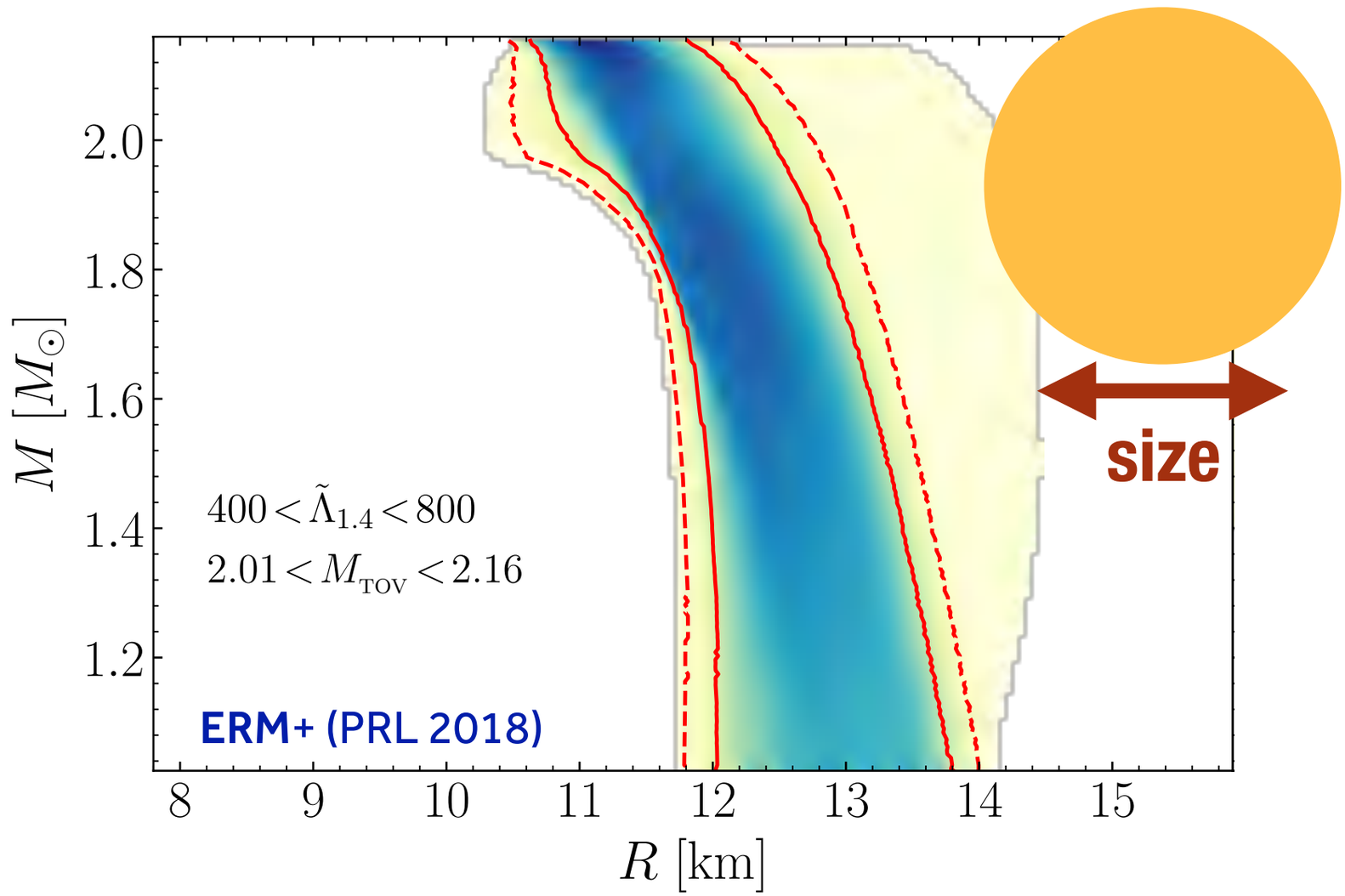
Tidal deformation correlates with the size of neutron stars.

The final fate of a neutron star binary



Gravitational waves





How large can neutron stars be?

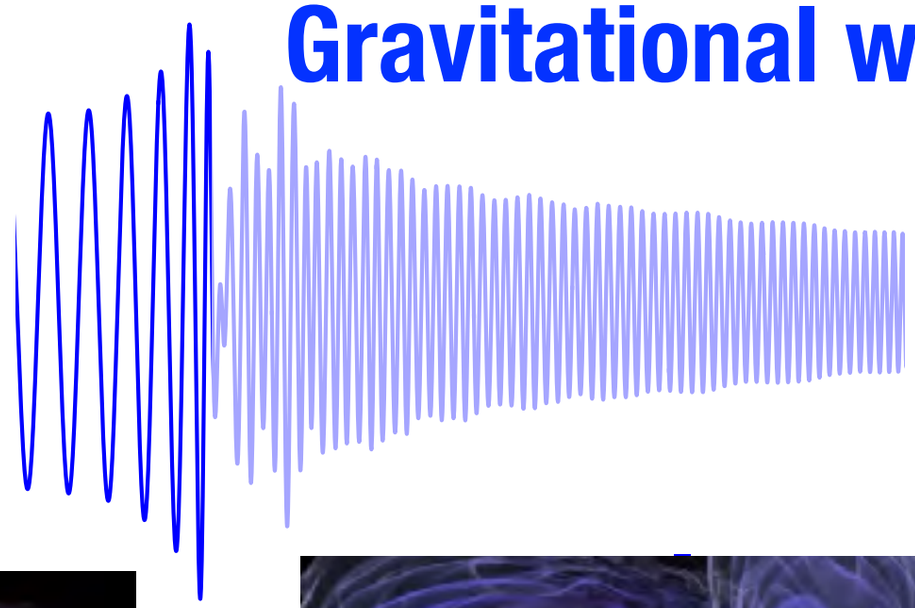
e.g. Annala+, De+, **ERM+ (PRL 2018)**, Chatziioannou+, Raithel+ and many others

+ X-ray constraints: Riley+, Miller+, Raaijmakers+, Dietrich+ and others!

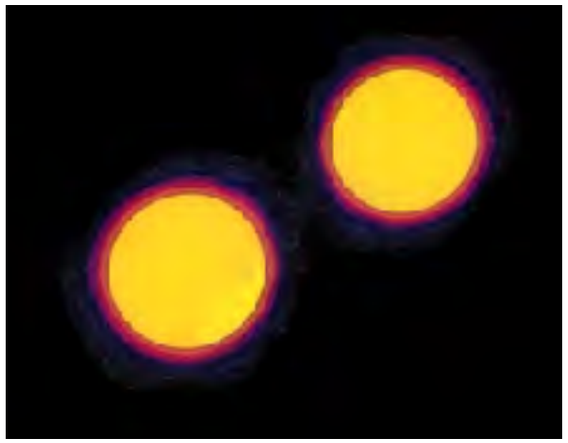
Constraining neutron star radii with gravitational waves from the inspiral.

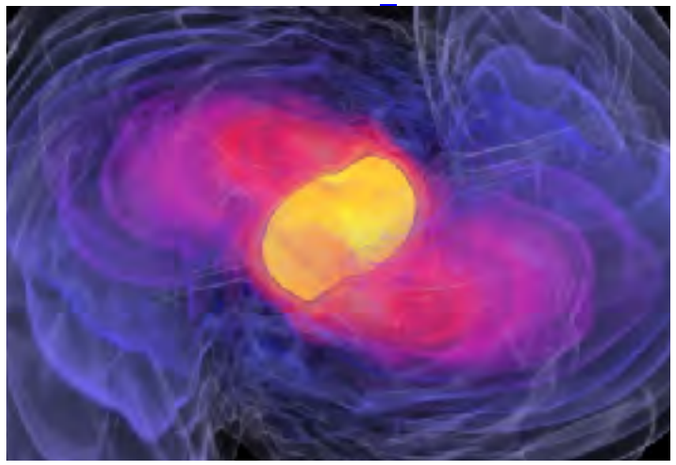
The final fate of a neutron star binary

Gravitational waves

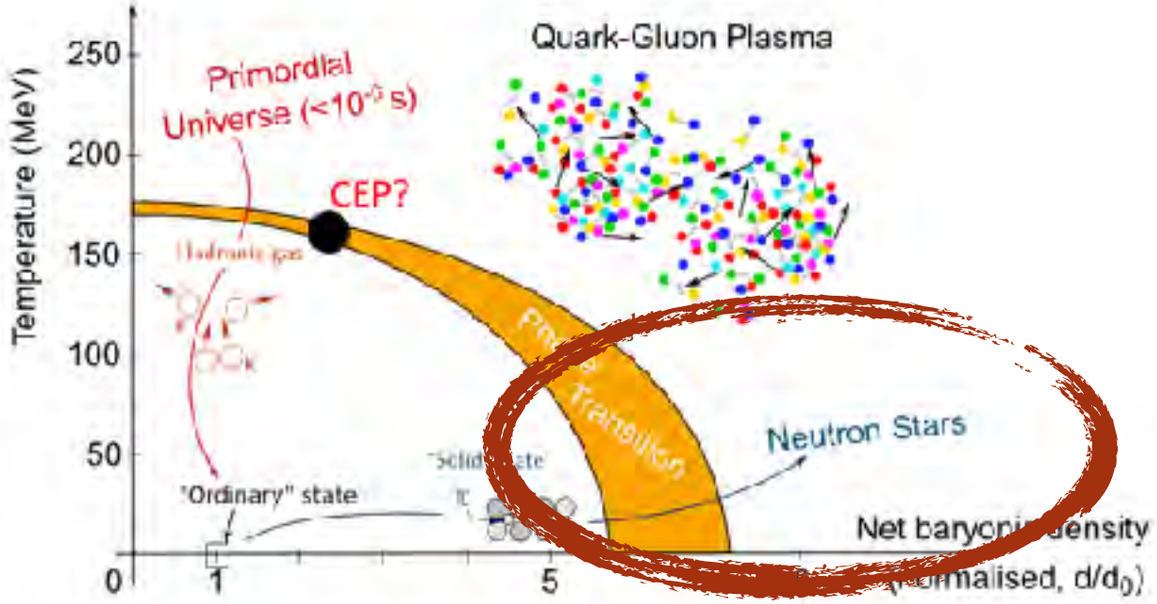


Neutron star mergers as cosmic colliders?





Can these events reveal extreme states of matter?



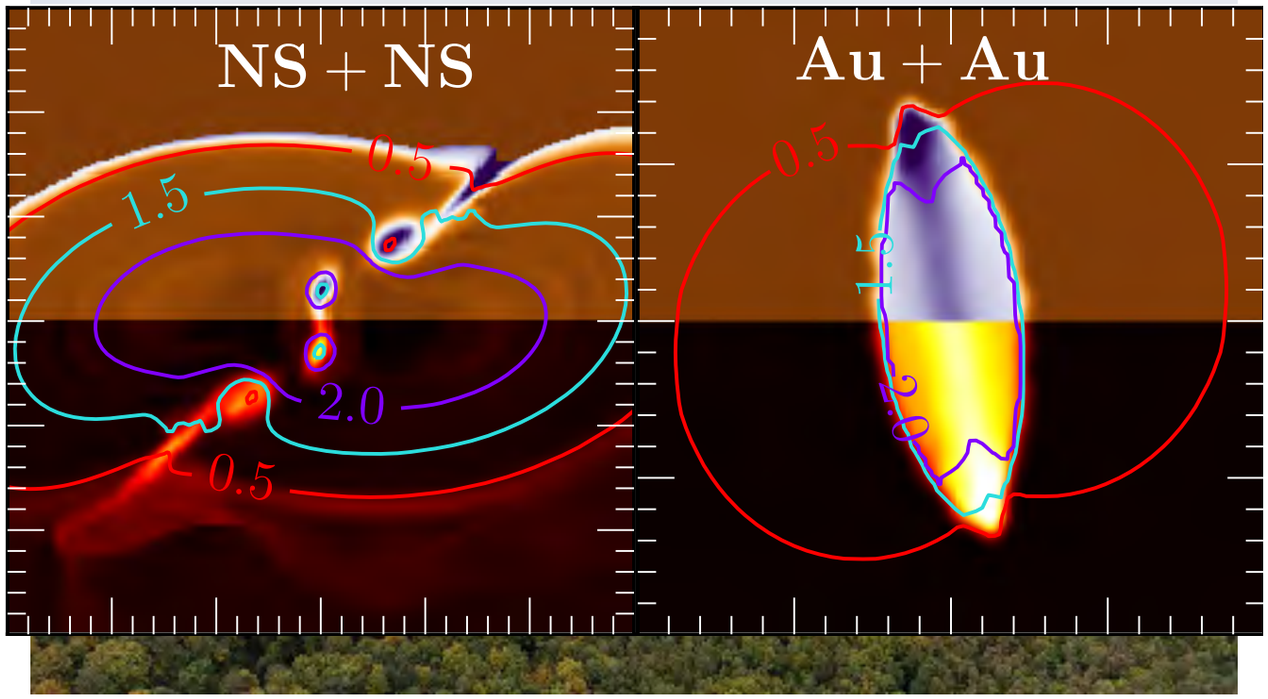
Probing dense baryon-rich matter with virtual photons

Nature Physics **15**, 1040–1045 (2019)

The HADES Collaboration*

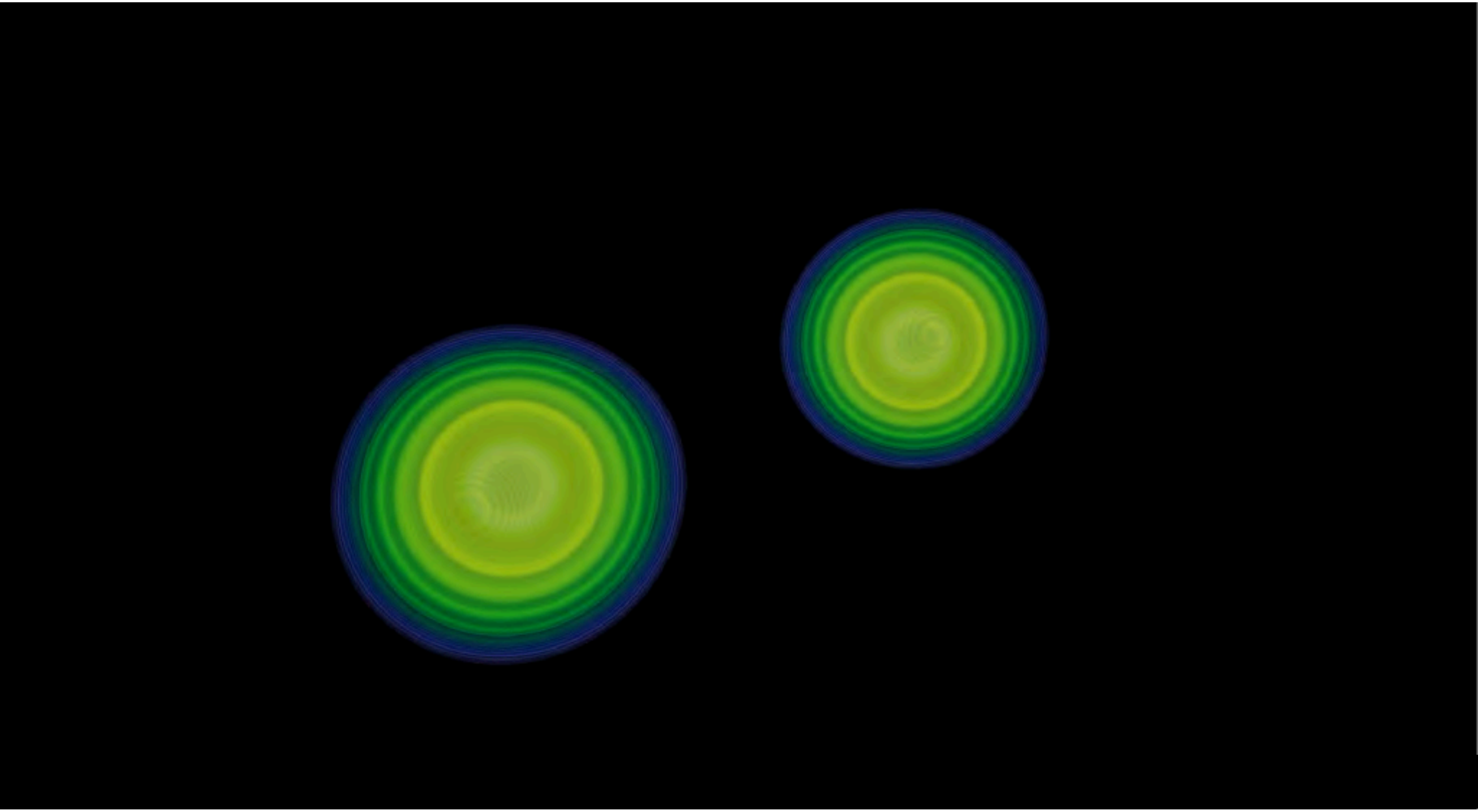
Image credit: GSI

ERM+(PRD 2023)



Comparison with Au+Au collision!

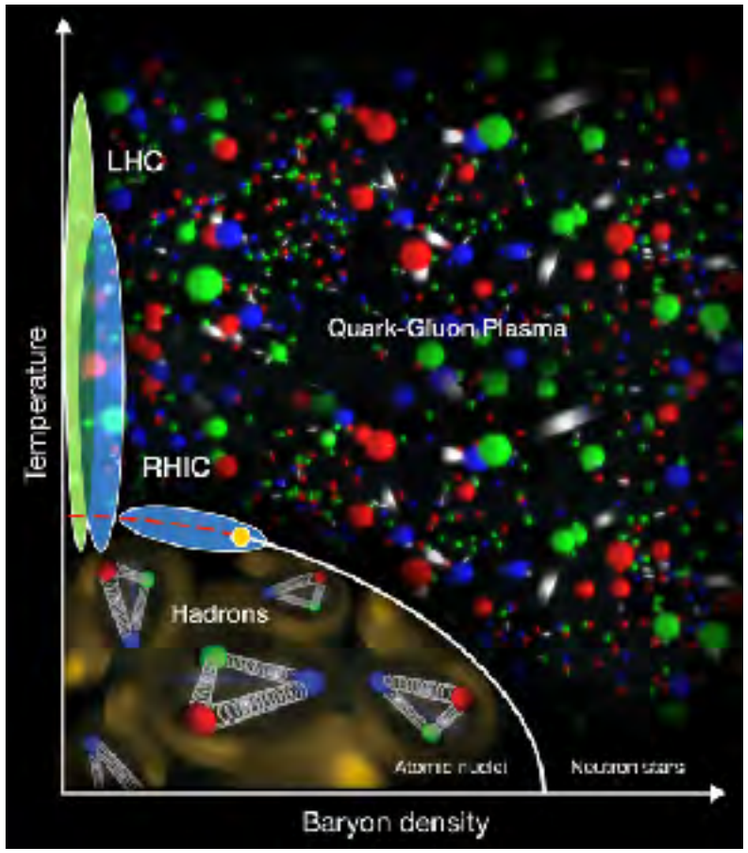
Probing exotic states of matter



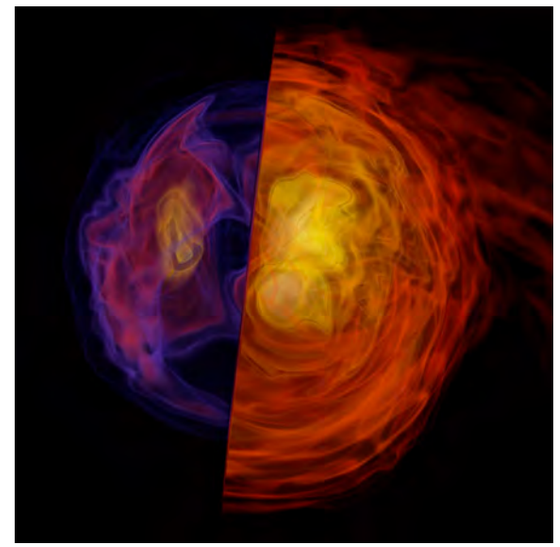
Elias R. Most

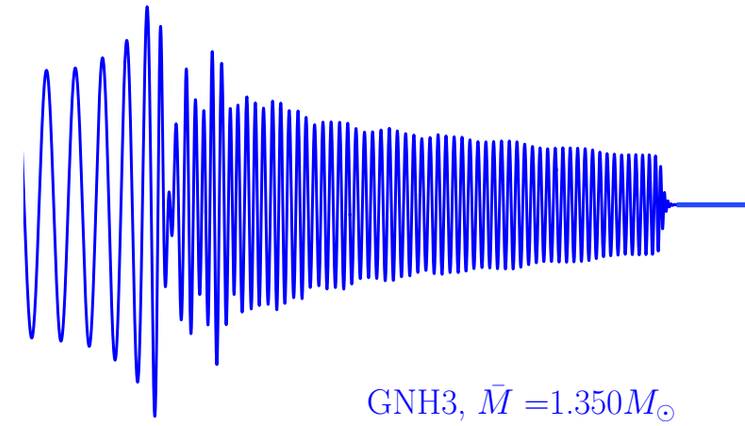
Systematically probing dense matter

Nuclear theory

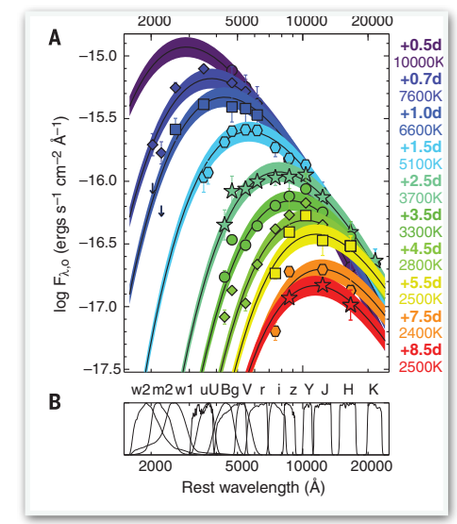


Numerical relativity simulations





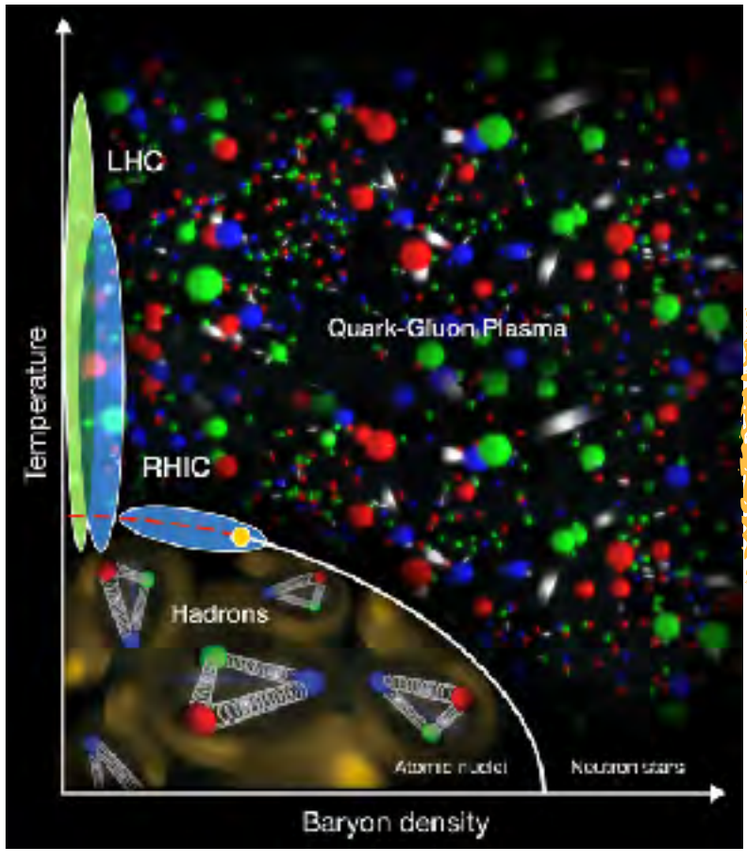
Observables



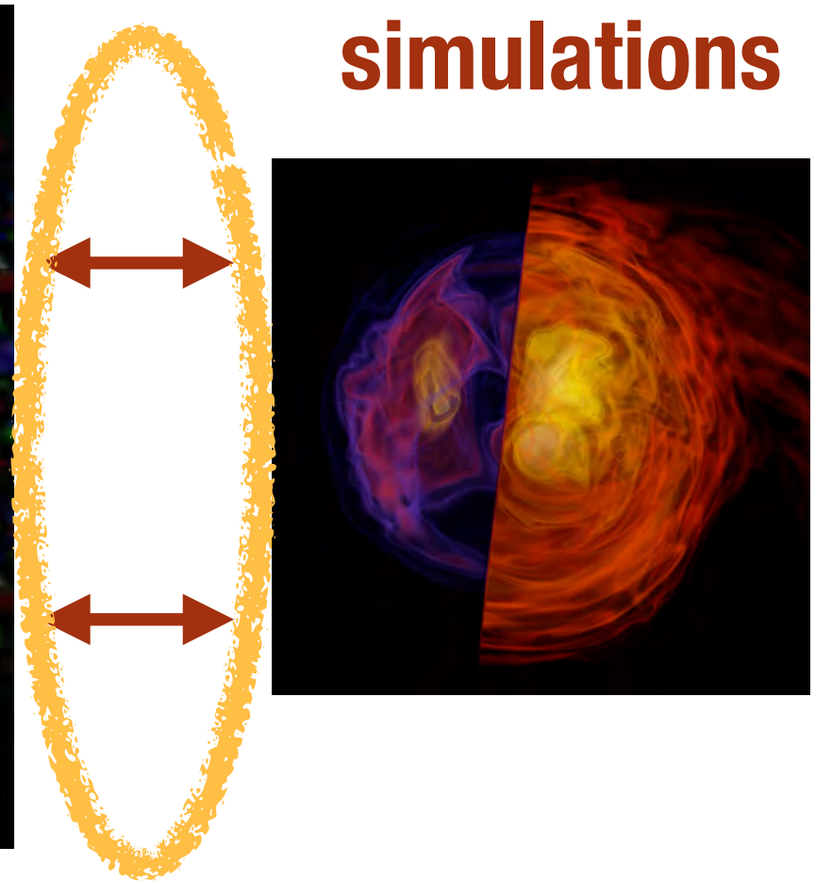
Can we systematically survey dense matter imprints?

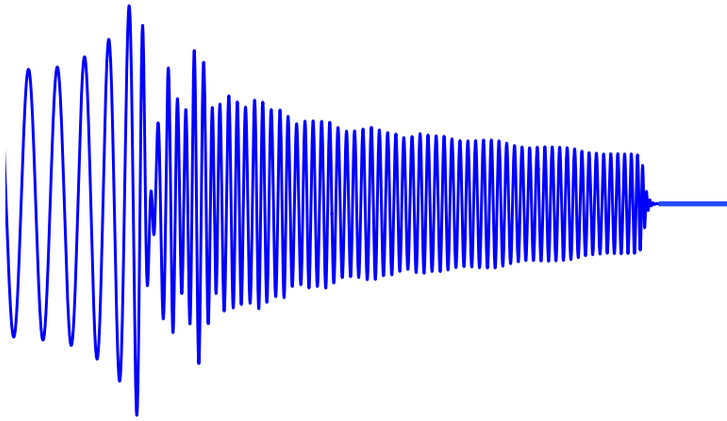
Systematically probing dense matter

Nuclear theory

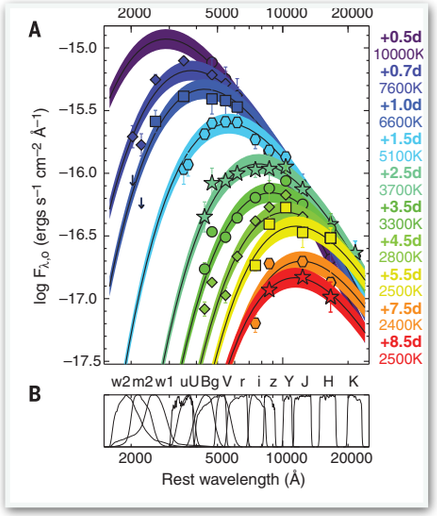


Numerical relativity simulations





Observables



Breakthrough computing:

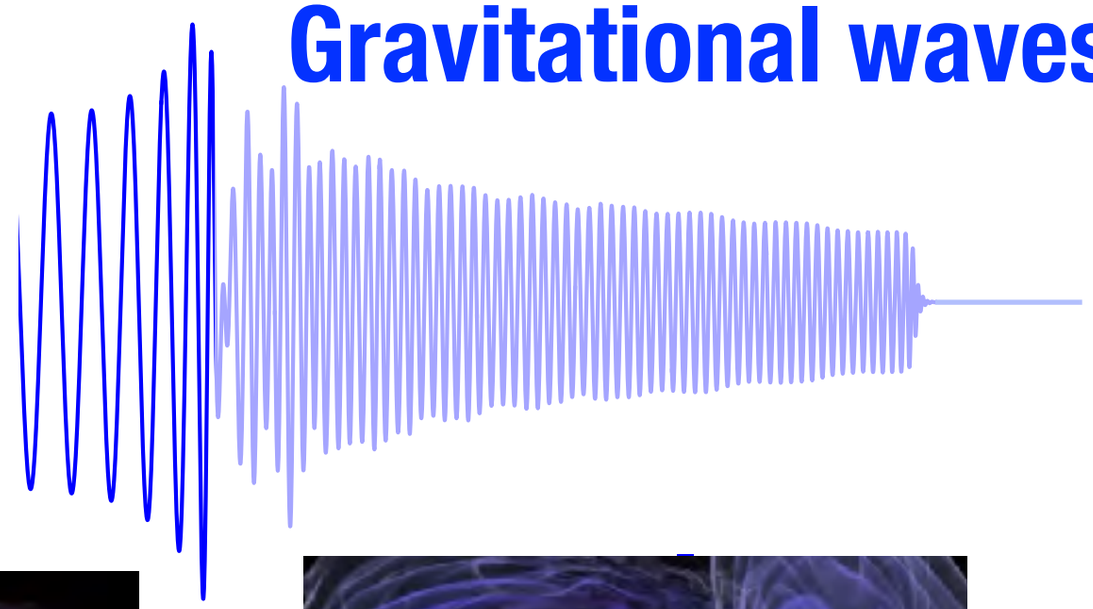
Modular **U**nified **S**olver of the **E**quation of **S**tate

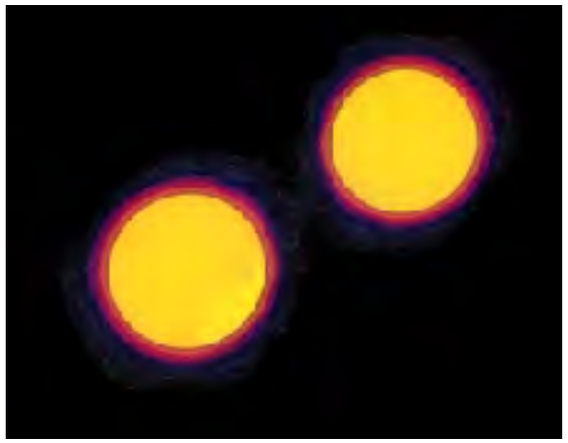
https://musesframework.io

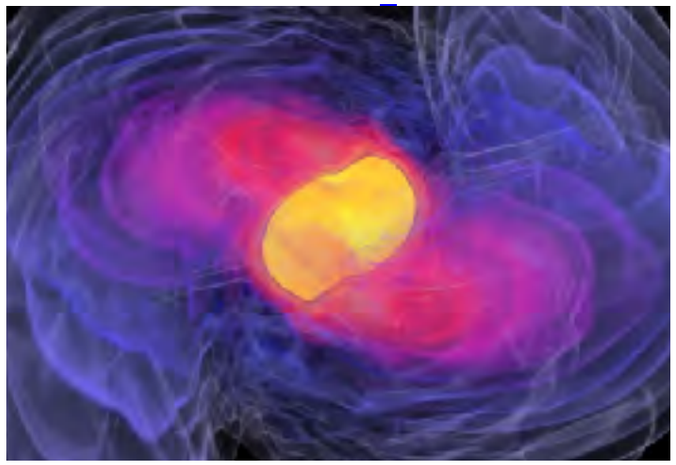
Elias R. Most

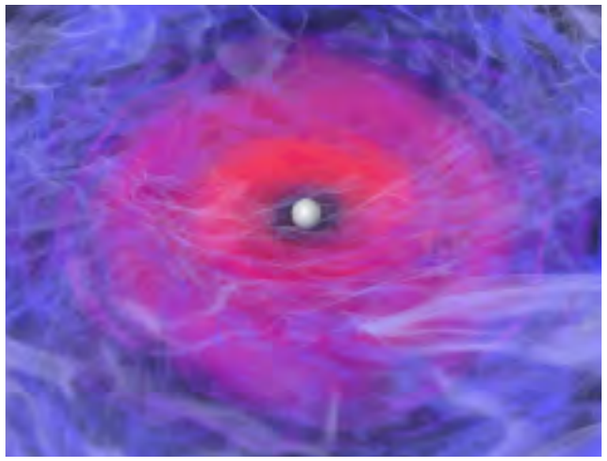
The final fate of a neutron star binary

Gravitational waves









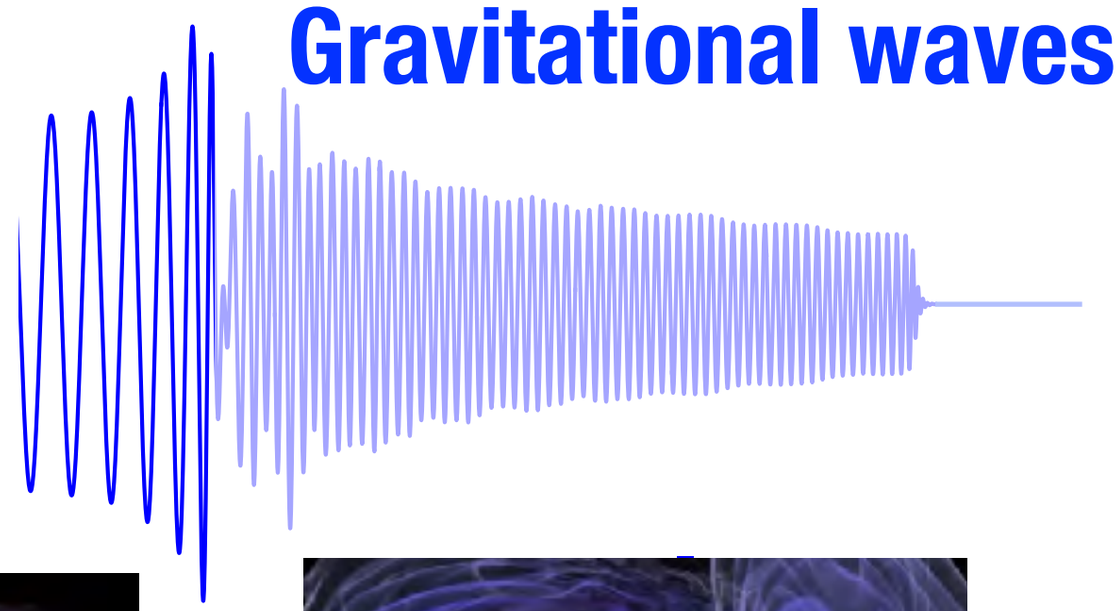
Tuojin Yin
(CalBridge/WAVE Fellow 2023)

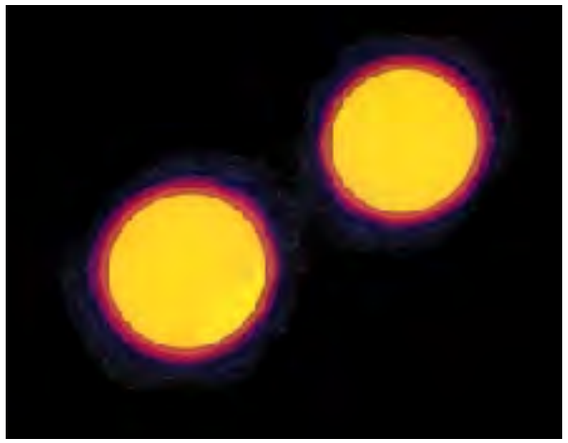
The lifetime of the system depends on different physics (magnetic fields, neutrinos, nuclear physics…)

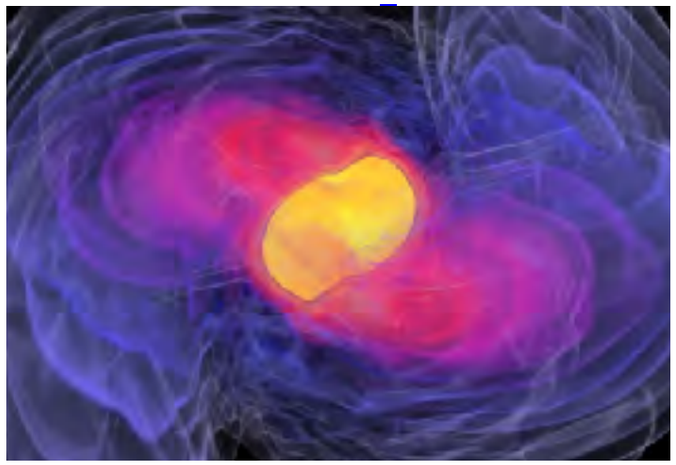
Yin & Most (In prep)

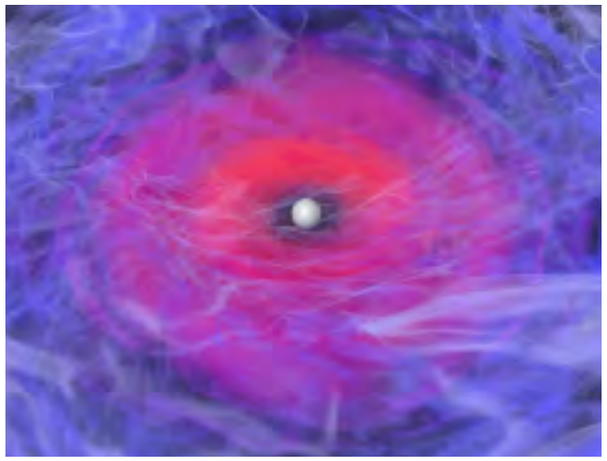
New insights needed!

The final fate of a neutron star binary







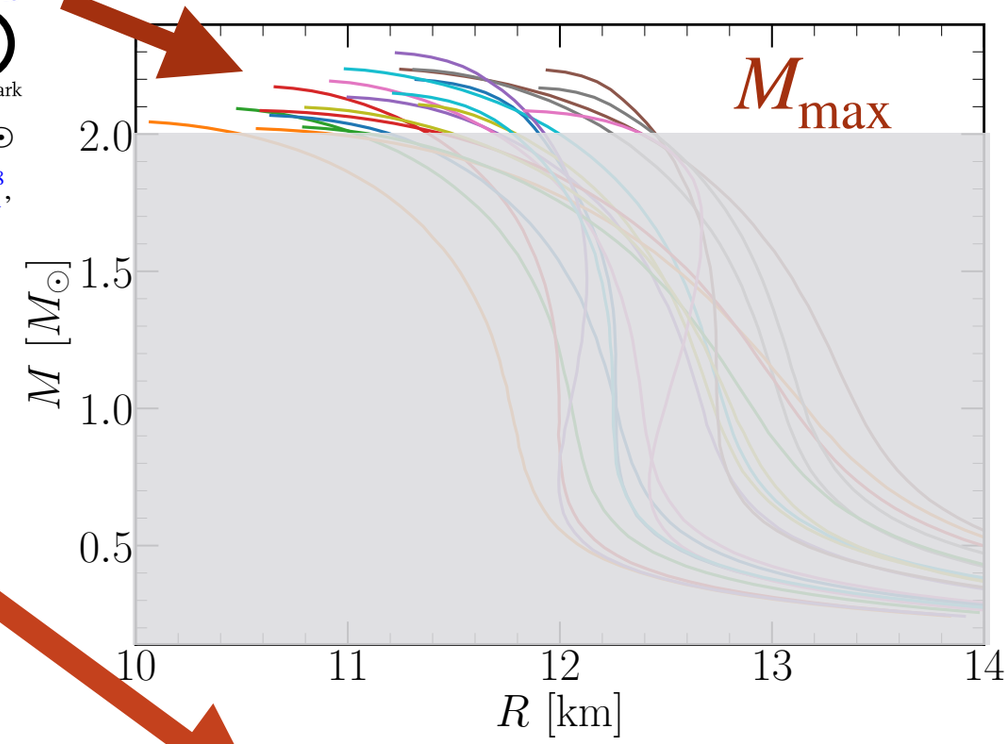


Collapse or no collapse?

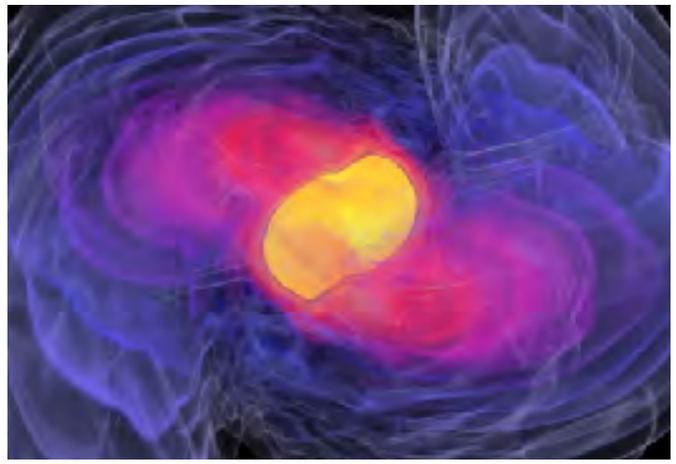
The Astrophysical Journal Letters, 892:L3 (24pp), 2020 March 20 https://doi.org/10.3847/2041-8213/ab75f5
© 2020. The Author(s). Published by the American Astronomical Society.
OPEN ACCESS

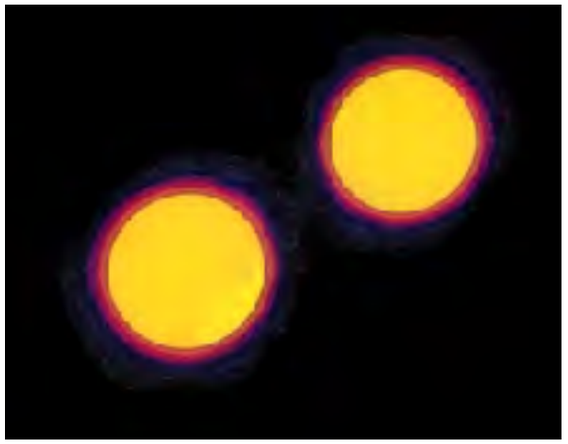
GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4 M_\odot$

B. P. Abbott[1], R. Abbott[1], T. D. Abbott[2], S. Abraham[3], F. Acernese[4,5], K. Ackley[6], C. Adams[7], R. X. Adhikari[1], V. B. Adya[8],



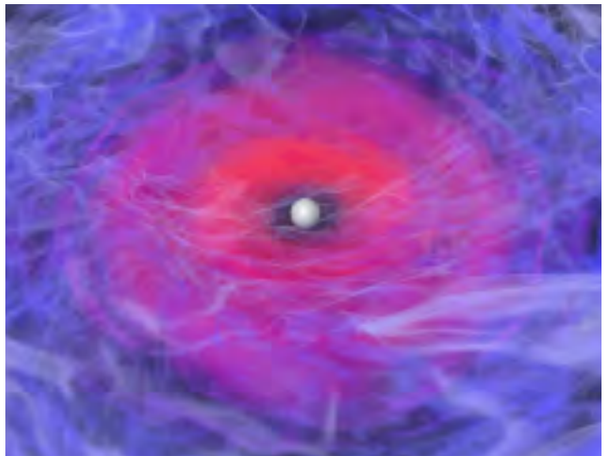
?





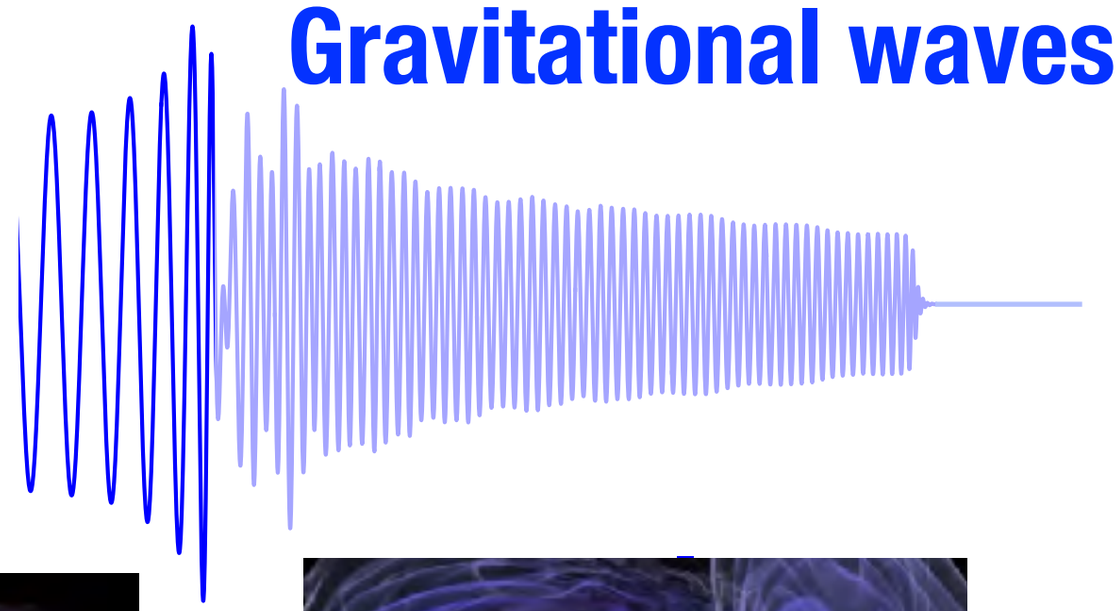
?

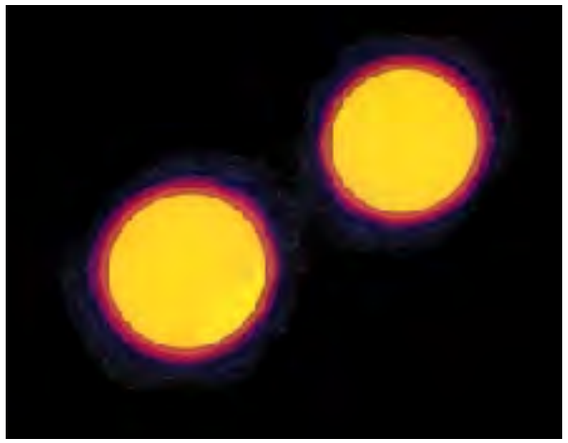
Tootle+(including **ERM**; ApJL 2021)
see also: Bauswein+, Köppel+, Kölsch+, Perego+ and others

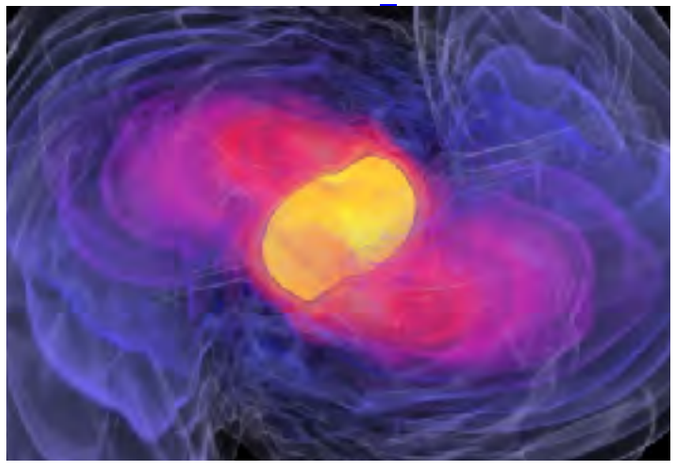


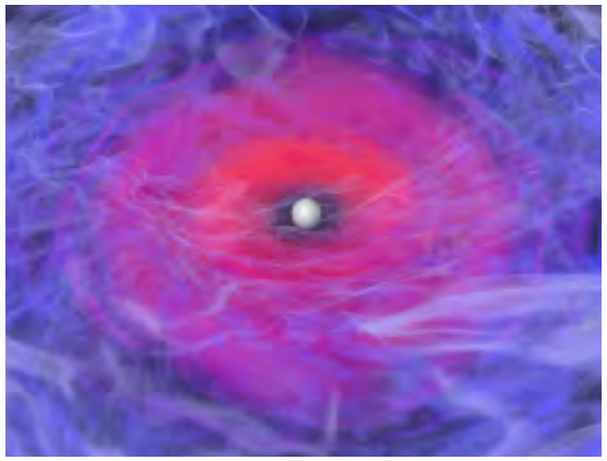
Answering this question can give crucial insights into neutron star properties.

The final fate of a neutron star binary









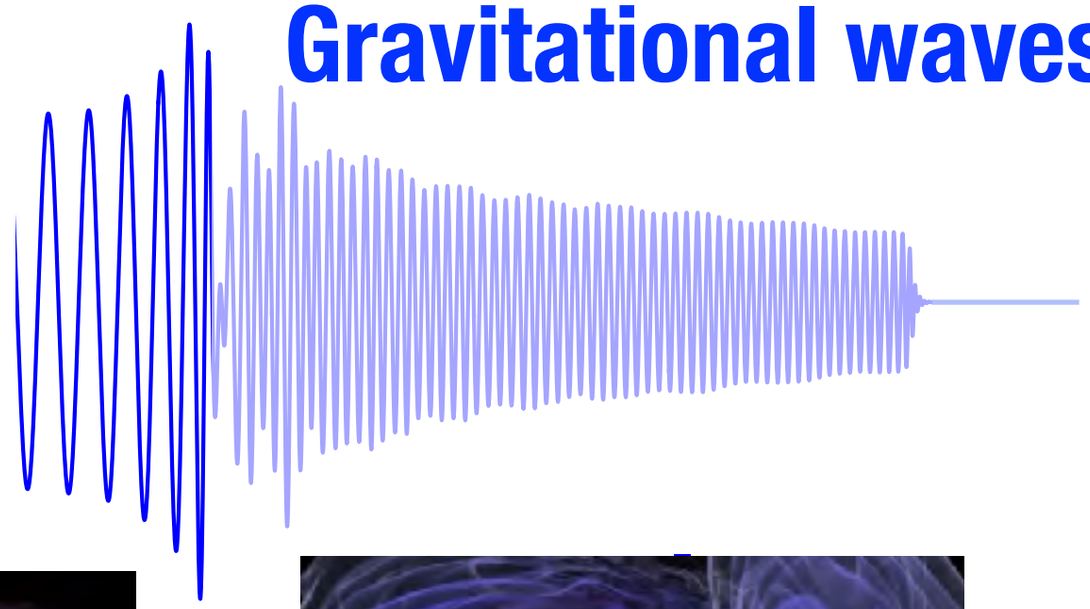
The multi-messenger picture

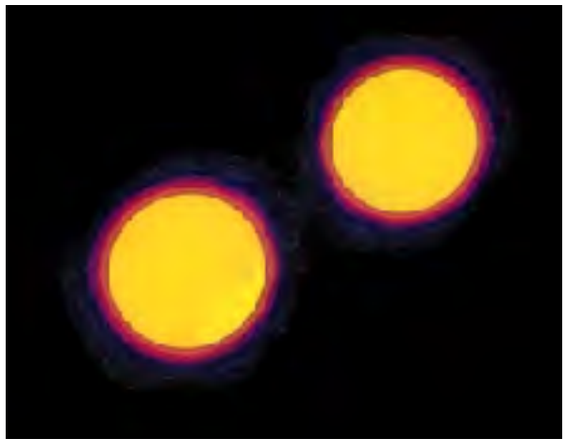
Electromagnetic counterparts as new windows into the physics of the merger!

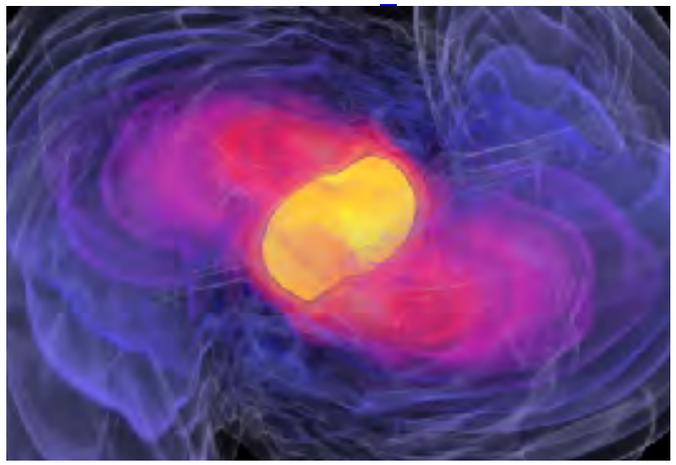

Image credit: iStock.com

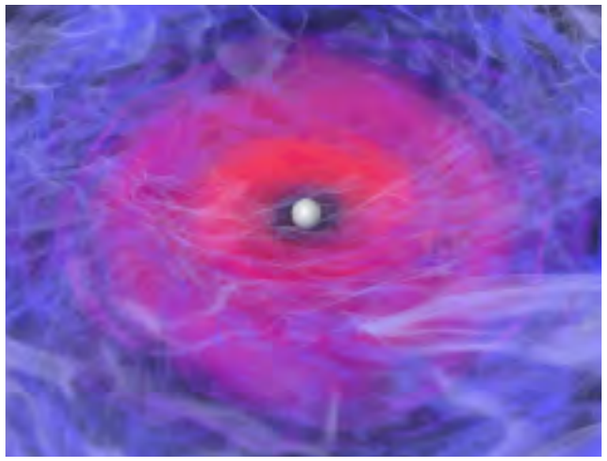
The final fate of a neutron star binary

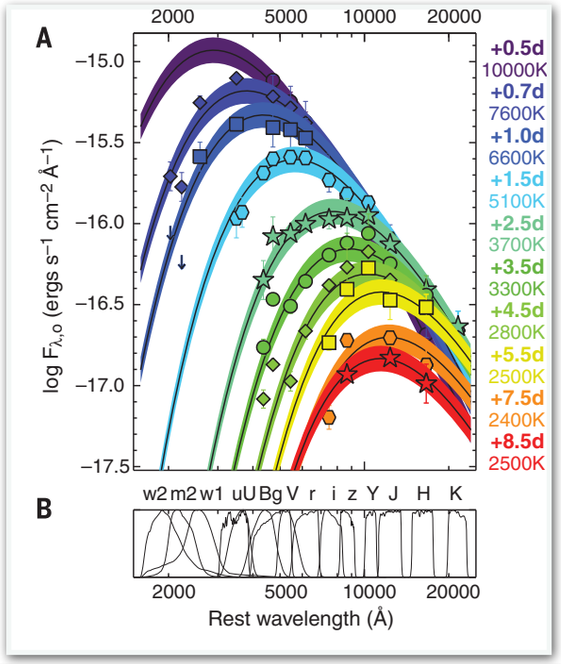
Gravitational waves



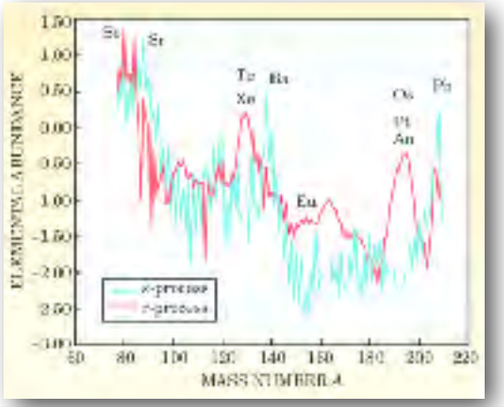






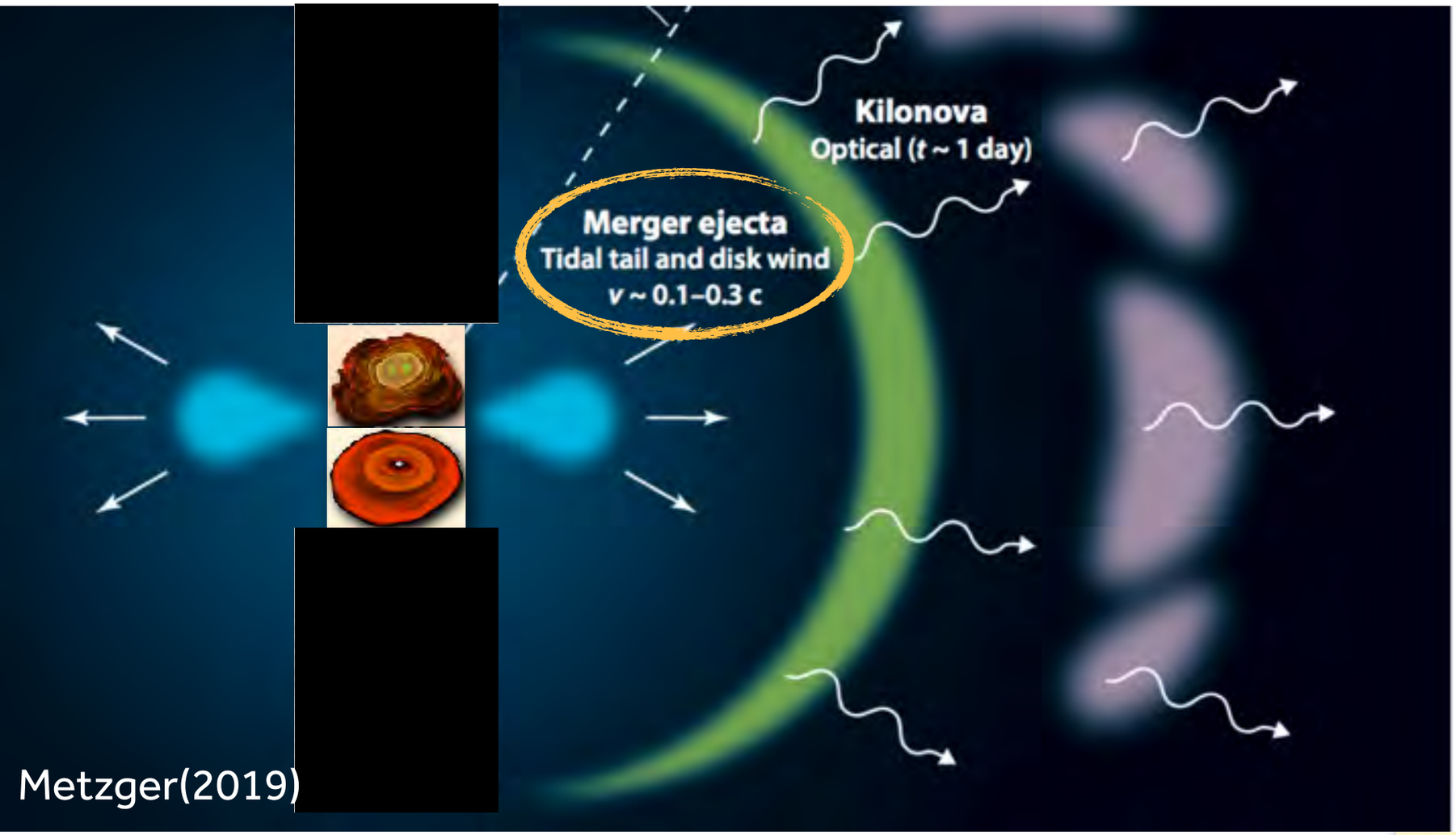


Kilonova Afterglow

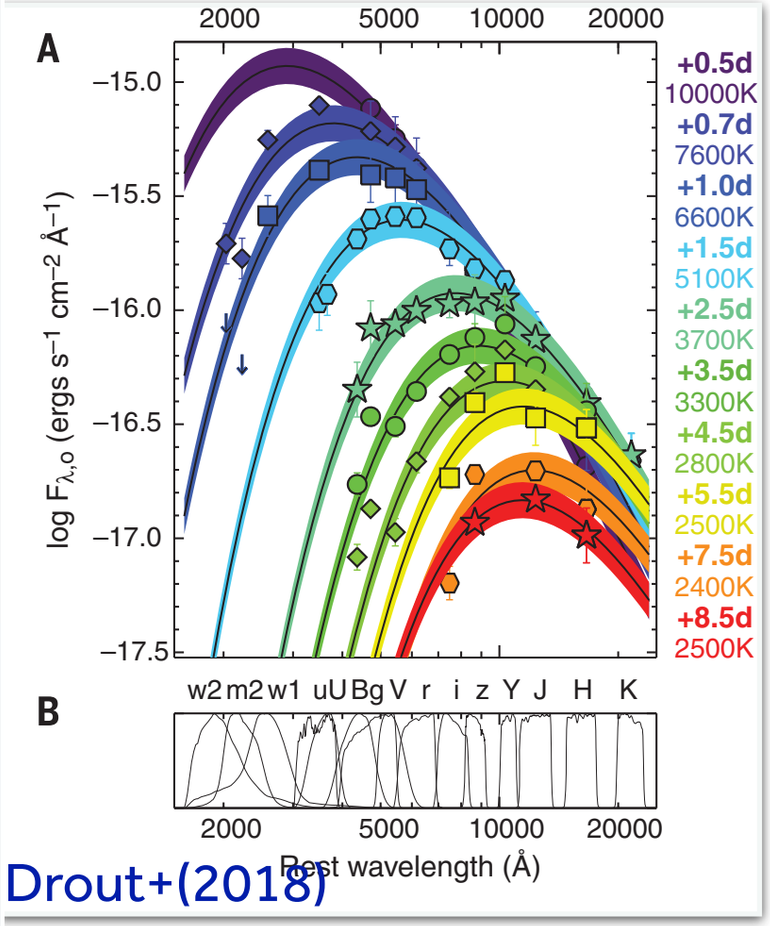


- Mass ejecta are a site for **heavy element production.** (r-process nucleosynthesis)

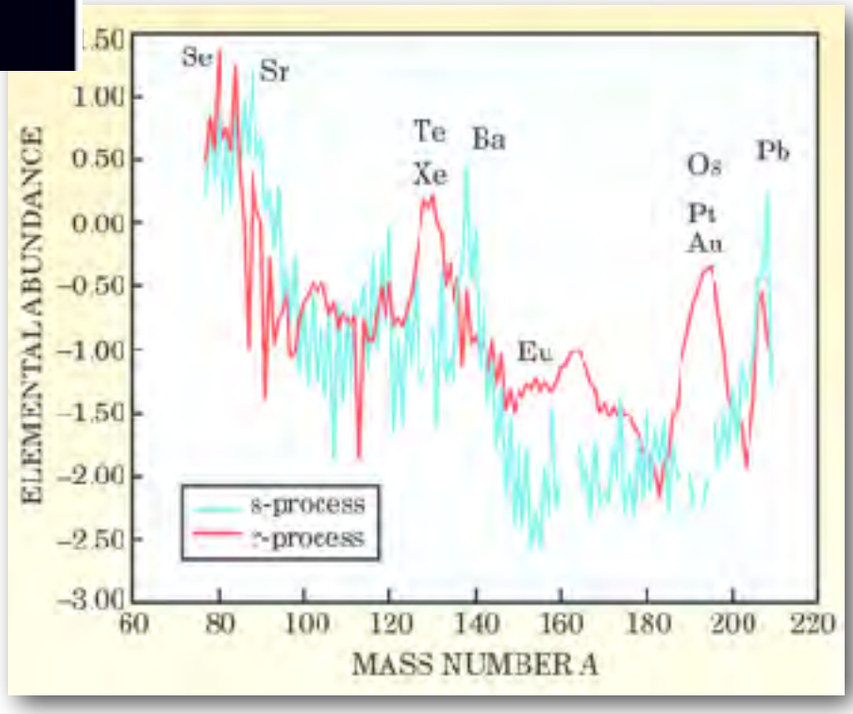
The multi-messenger picture



Metzger(2019)



Drout+(2018)

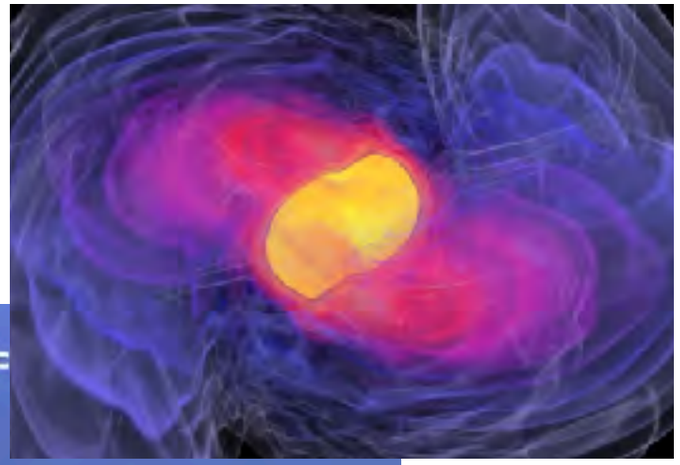


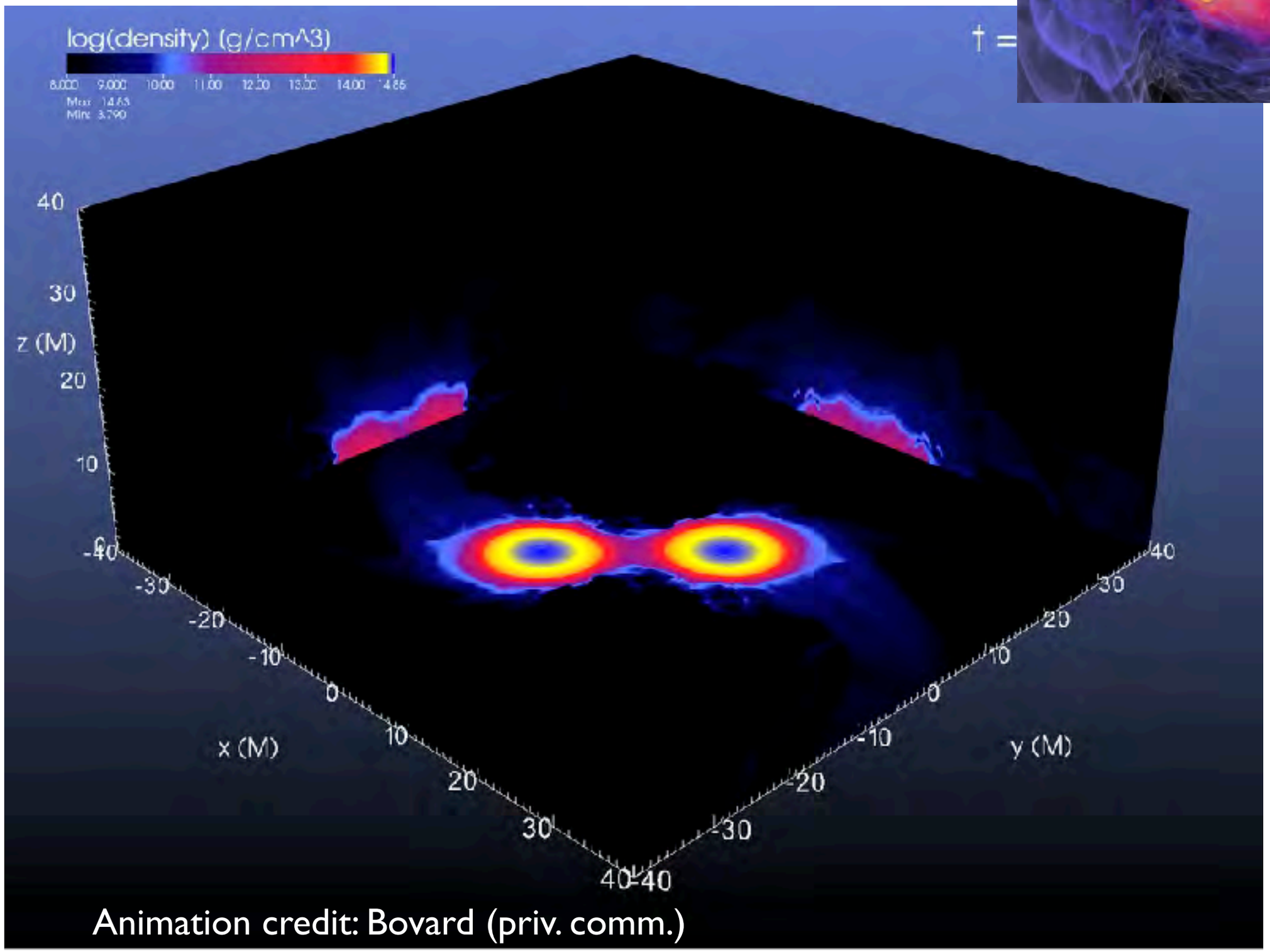
Kilonova afterglow

- Mass ejecta are a site for **heavy element production.**
  (r-process nucleosynthesis)

Mass ejection

Dynamical mass ejection

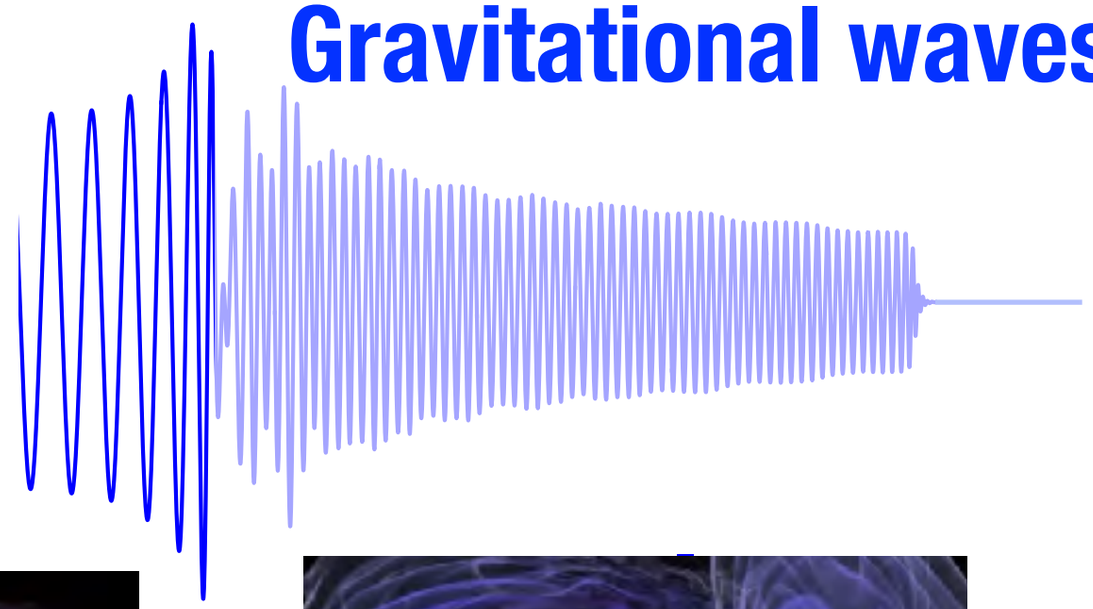




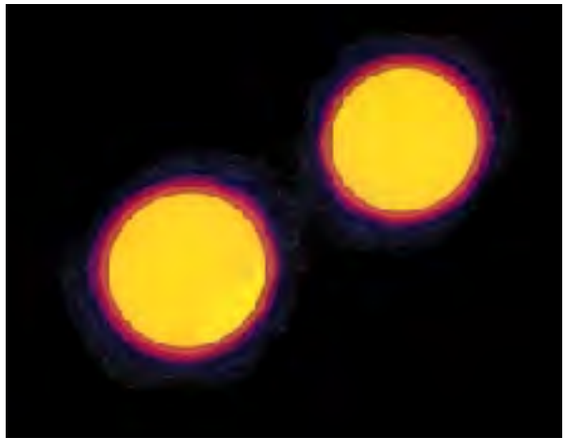
Animation credit: Bovard (priv. comm.)

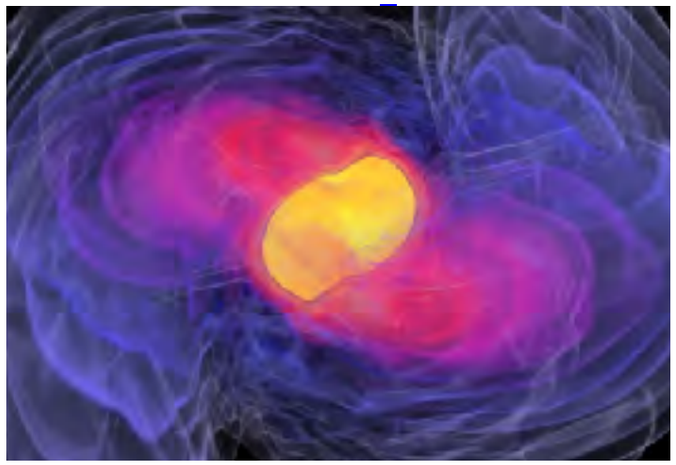
The final fate of a neutron star binary

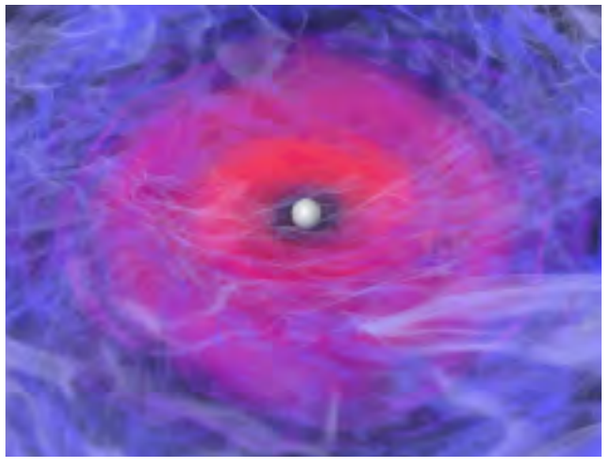
Gravitational waves

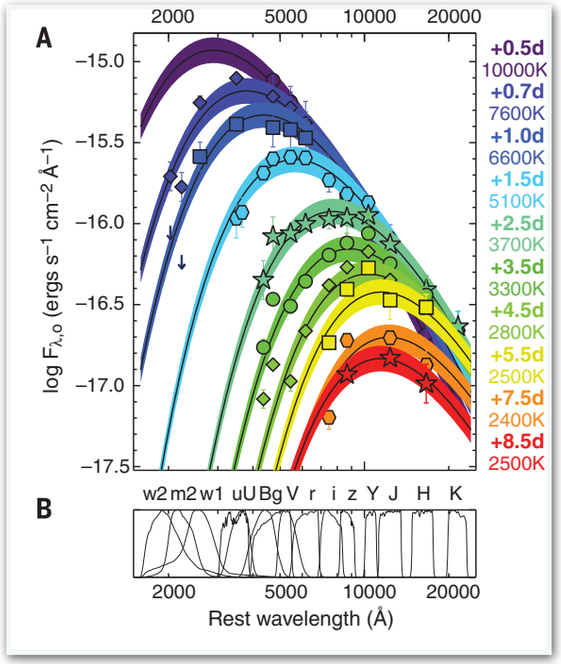


sGRB

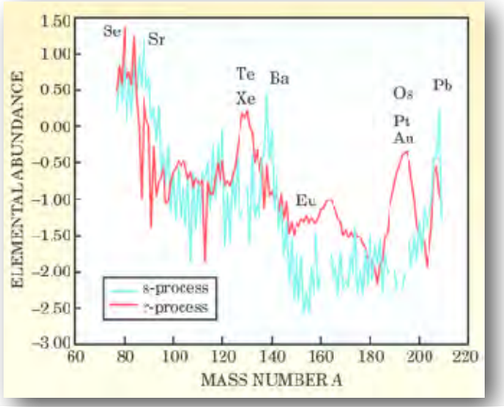






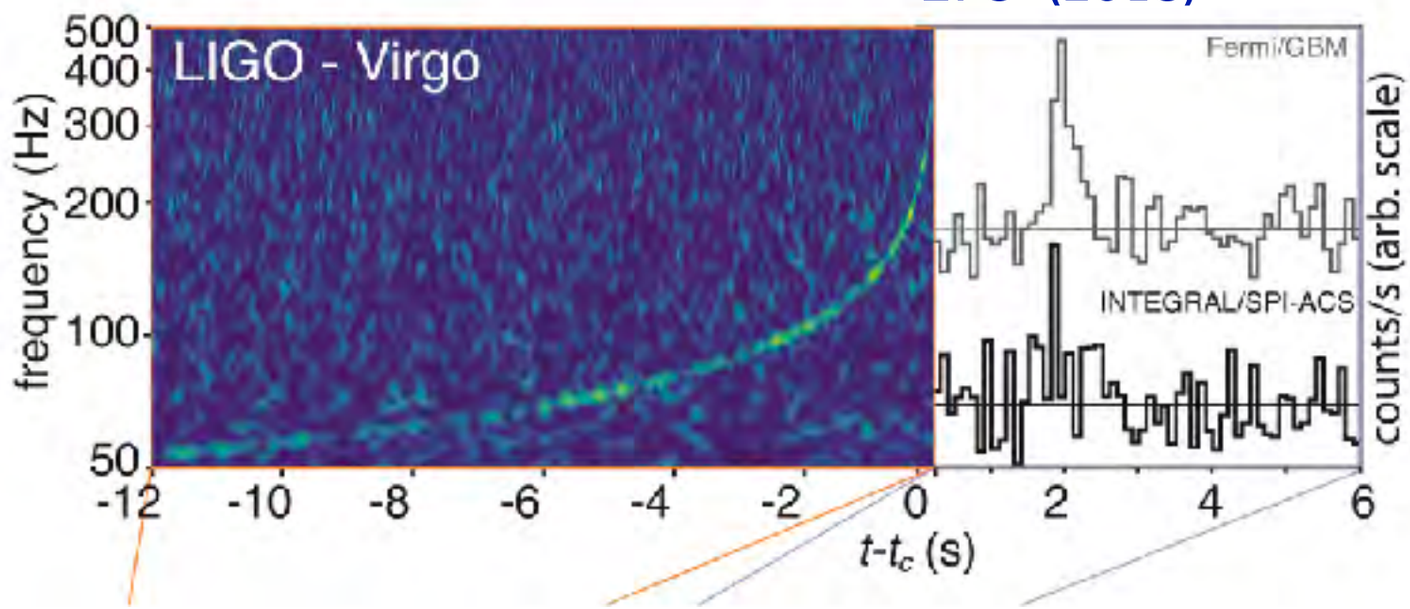


Kilonova Afterglow

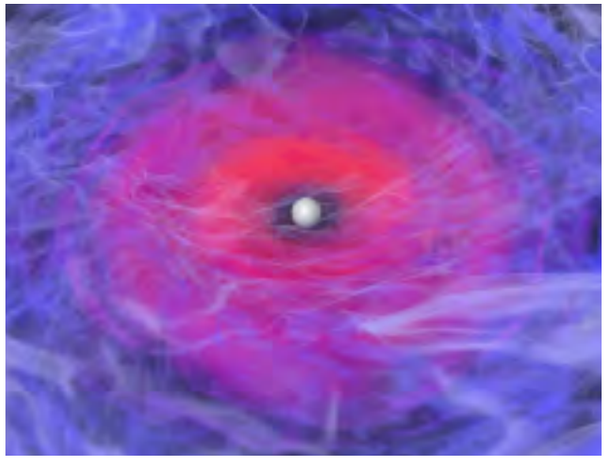


The multi-messenger picture

LVC+(2018)



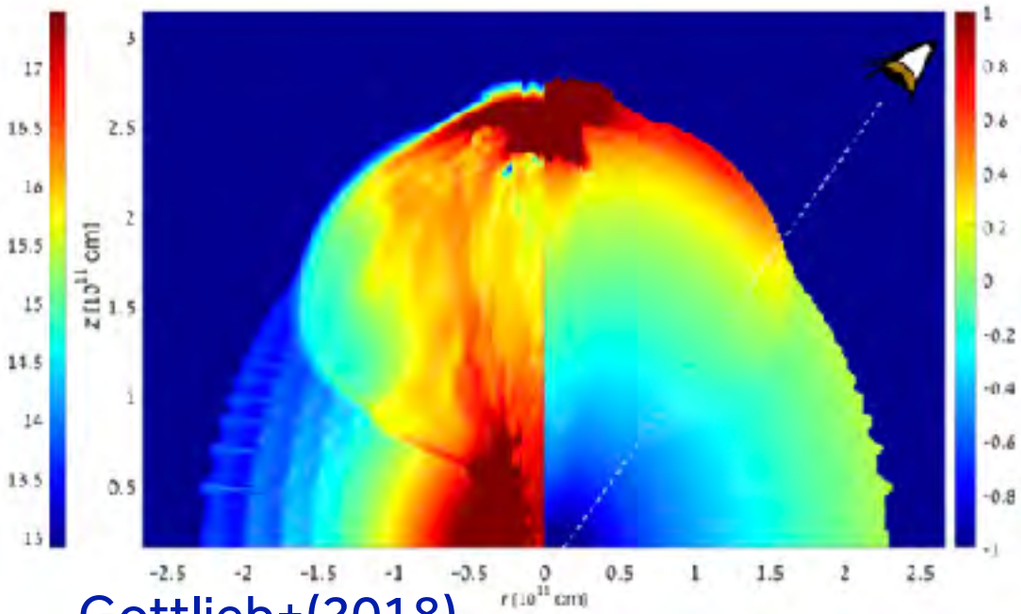
sGRB



- Coincident short gamma-ray burst (sGRB) detection ~2s after merger!

LVC+(2018)

- Consistent with off-axis viewed structured jet emission Alexander+(2018)

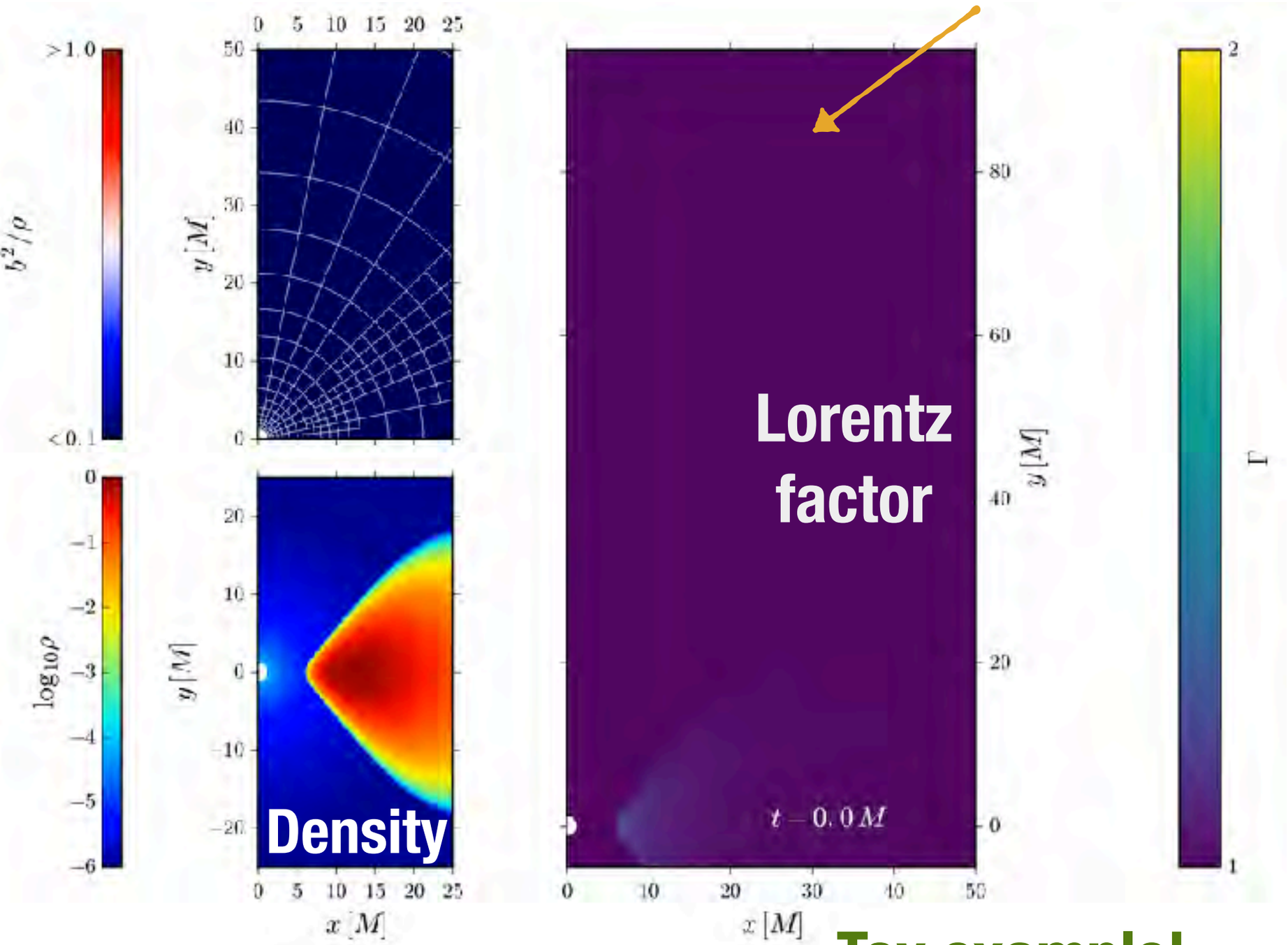


Gottlieb+(2018)

Do all mergers feature jet launching?

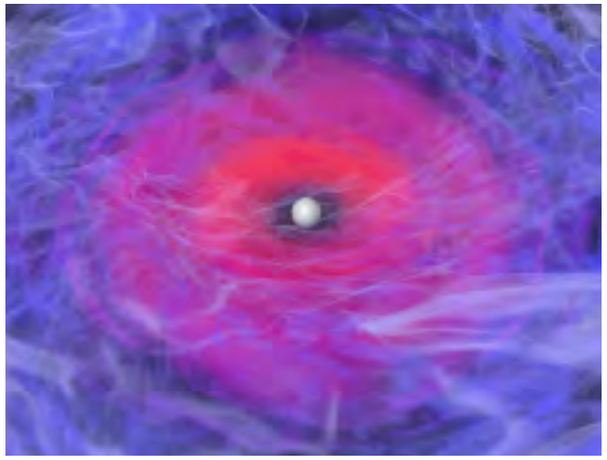
sGRB

Magnetization **Relativistic outflow**



Toy example!

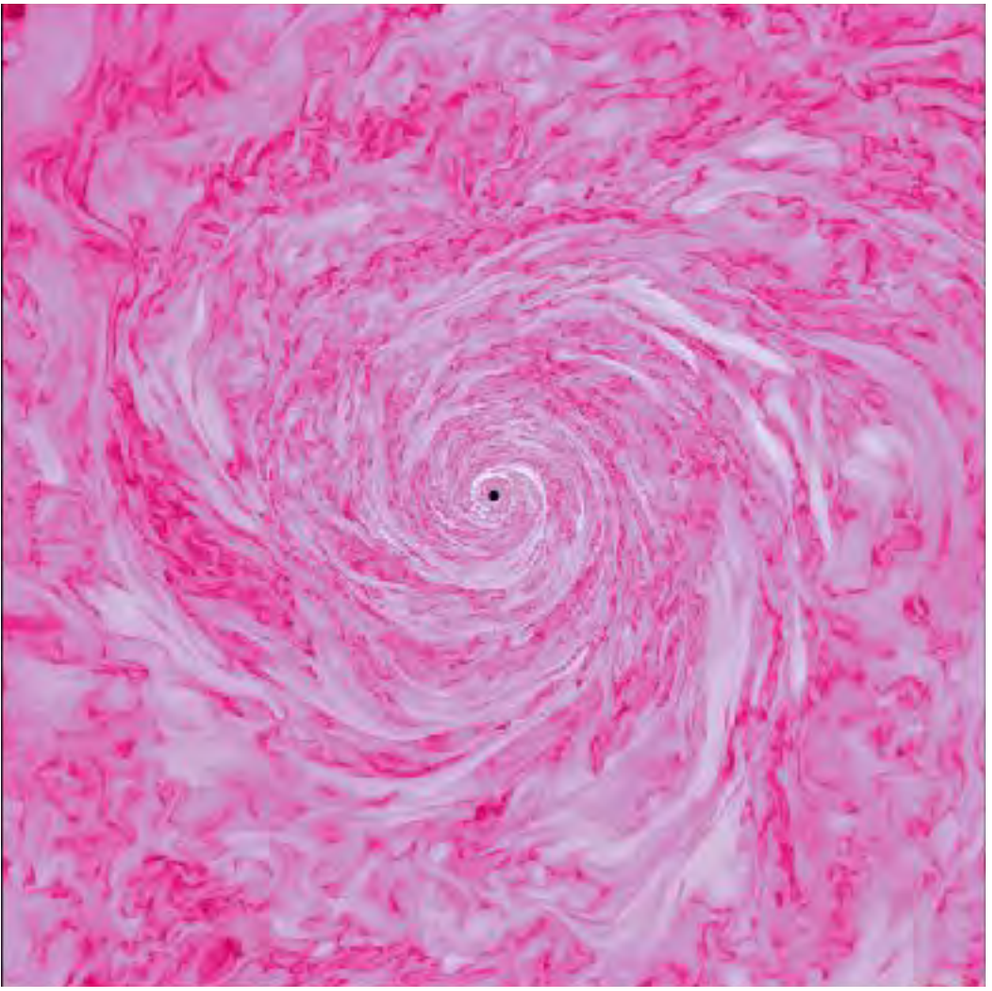
Animation credit: O. Porth
based on Olivares, Porth+ (incl. **ERM**, A&A 2019)



Big picture question:

How does a jet launch in the merger?

Do all mergers feature jet launching?

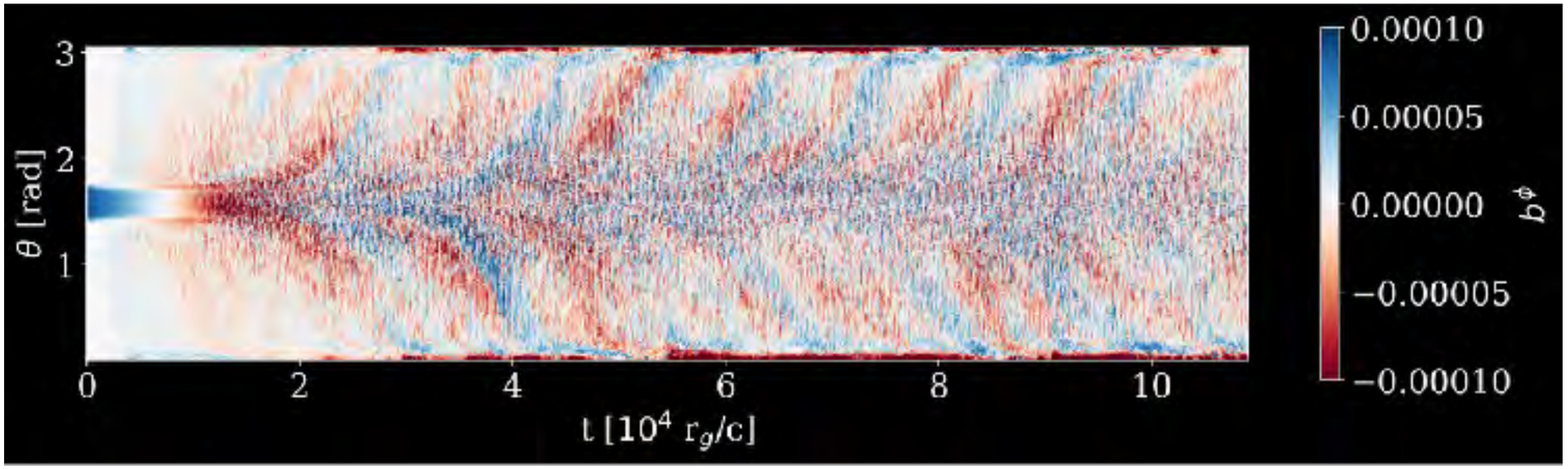


- Leverage availability of large-scale GPU resources for ultra-high resolution simulations!

Image Credit: NERSC

Northwestern Postdoc

Halevi, **ERM**, Stone (in prep) see also Christie+, Liska+, Gottlieb+, Jacquemin-Ide+



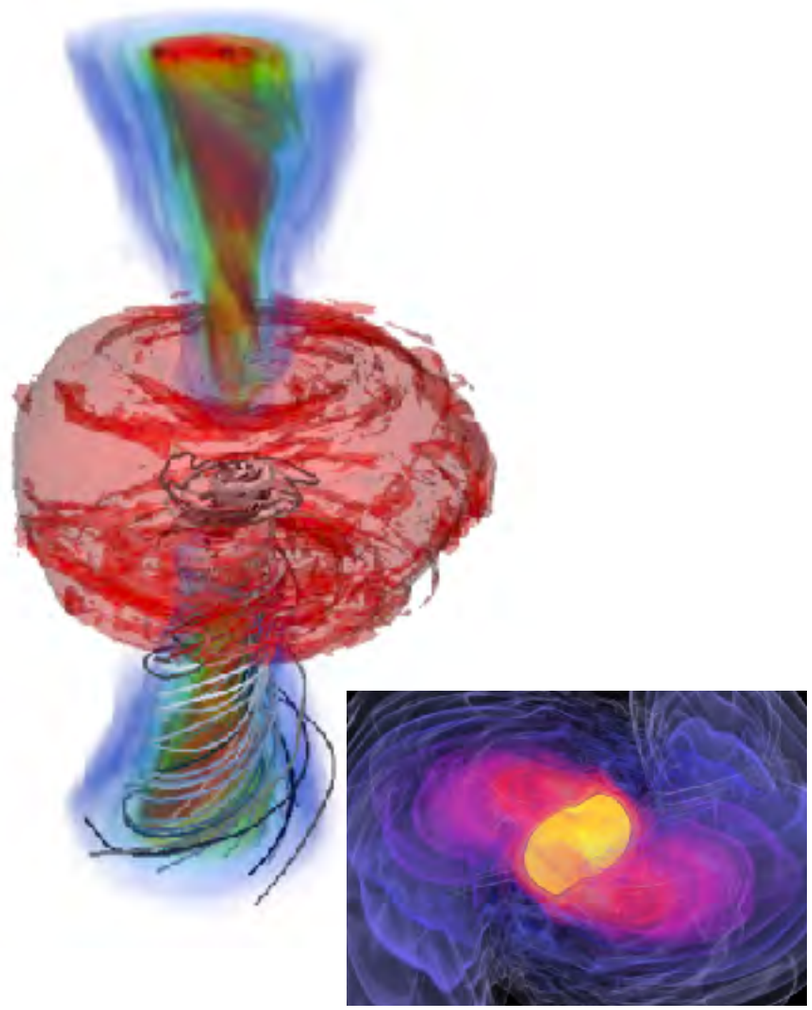
Goni Halevi

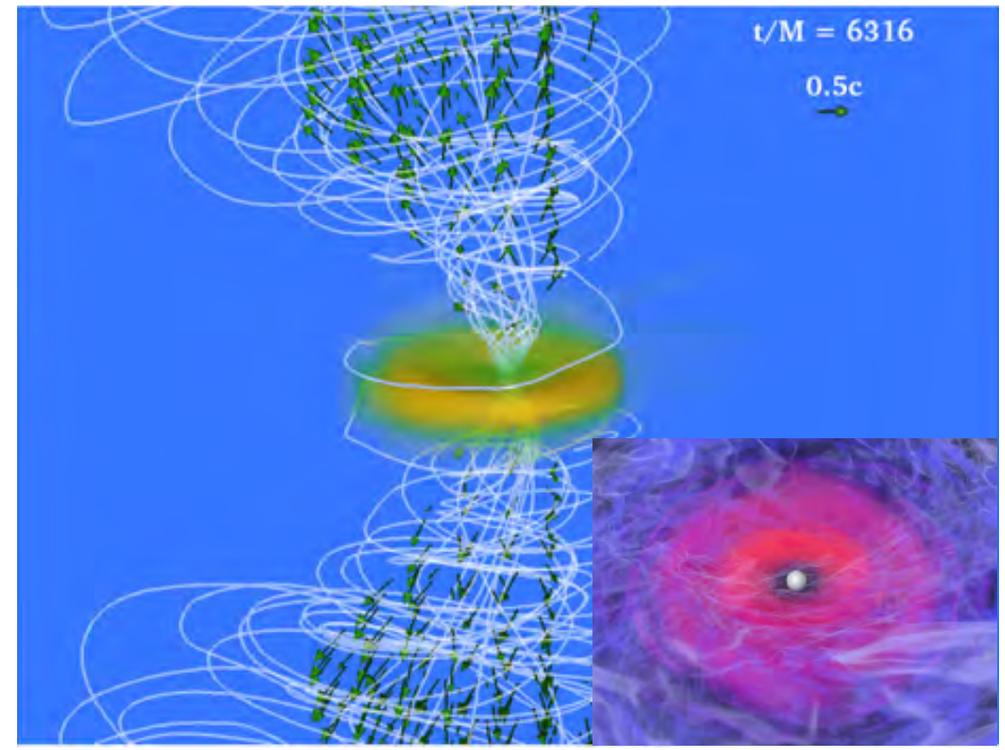
News from the frontier: An unlikely engine!

What's the engine behind gamma-ray bursts in mergers?

Black hole!

Mösta et al 2020





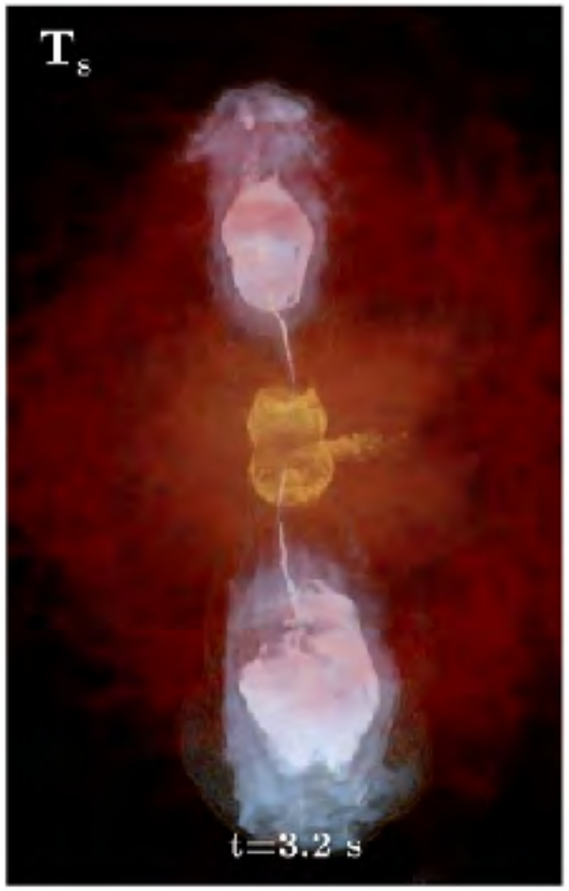
Paschalidis et al 2015; **Ruiz** et al.

Hypermassive neutron star?

Can we also get sGRBs from neutron stars? What's the expected fraction?

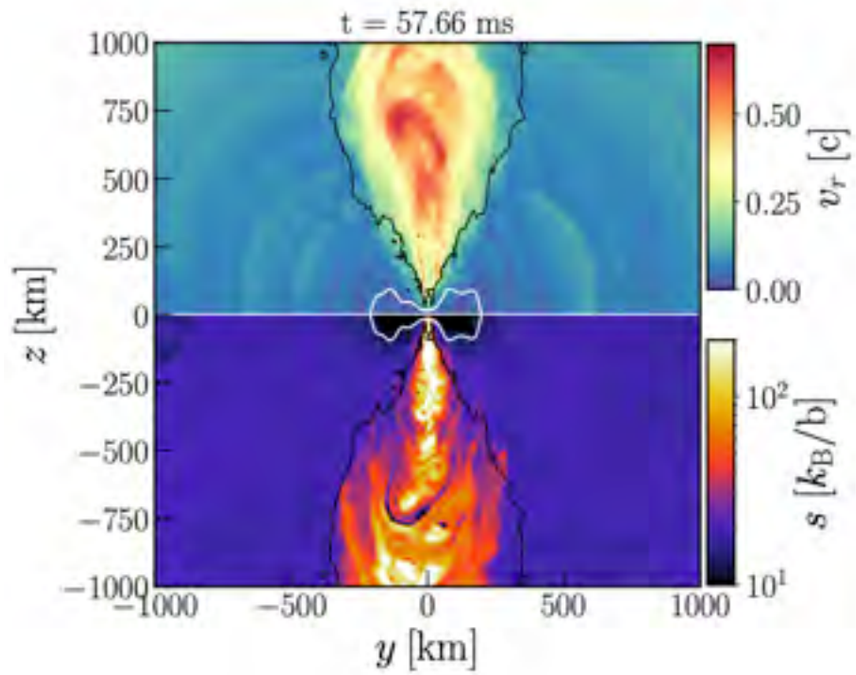
Gamma-ray bursts from stellar remnants?

Not a magnetar, but strong constraints on BH-disk engine

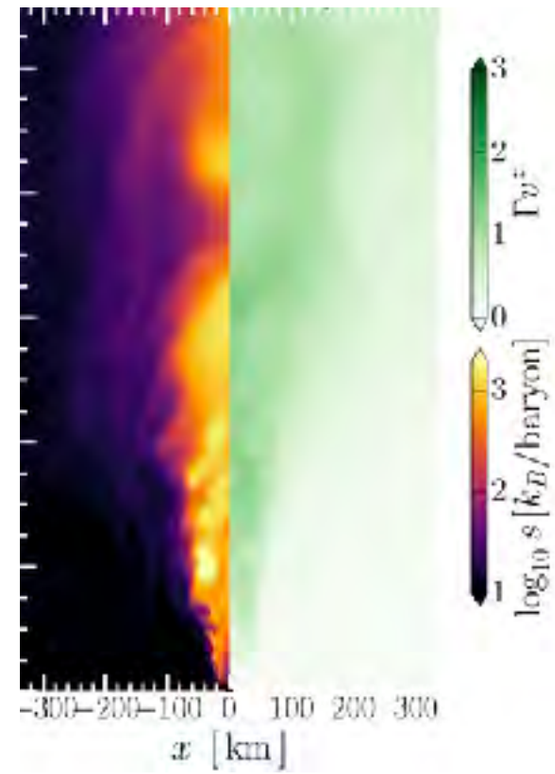


Gottlieb+2023

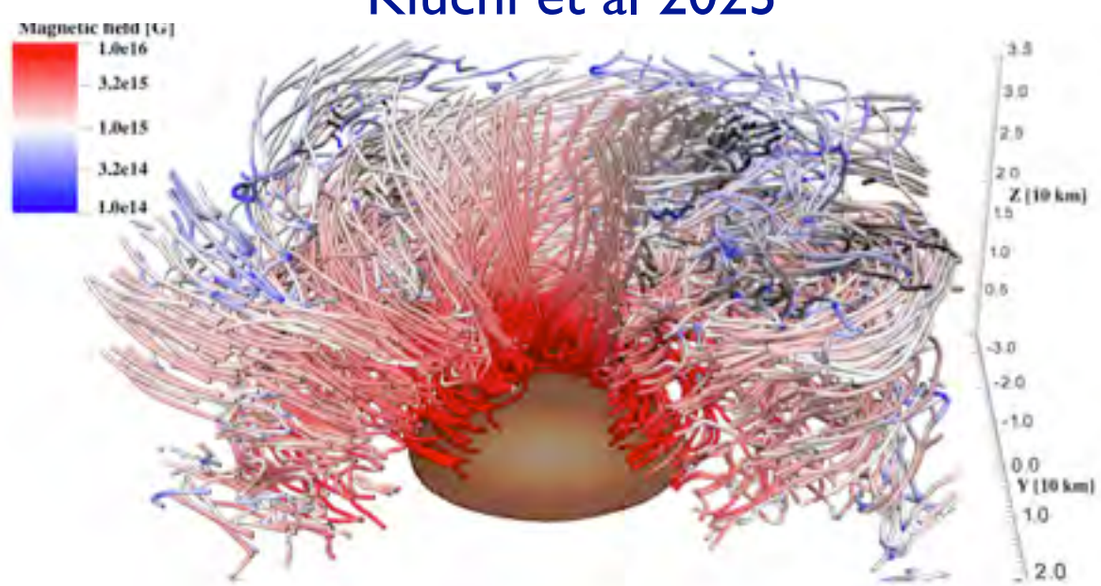
Combi & Siegel 2023

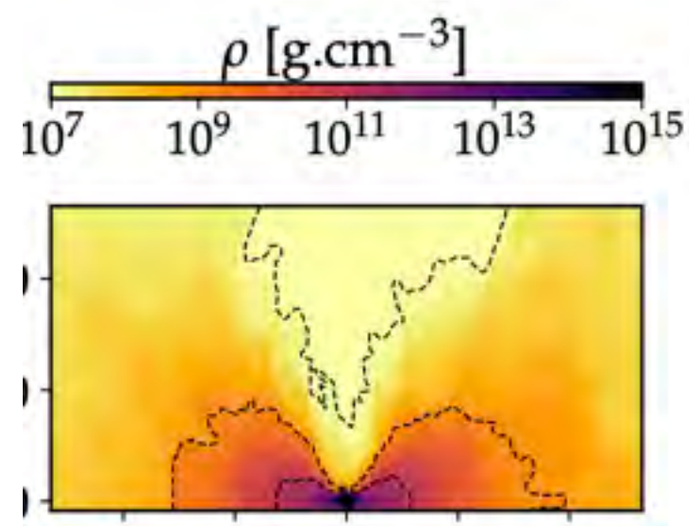


ERM & Quataert 2023
ERM 2023



Kiuchi et al 2023



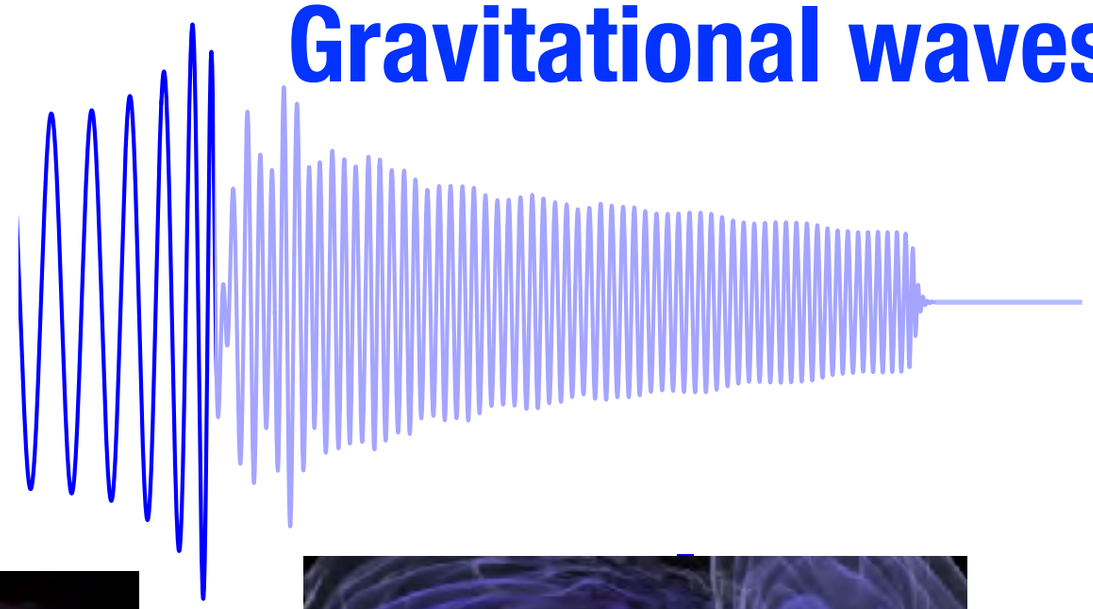


Curtis+ 2023; de Haas+2023

Major breakthroughs in numerical relativity <u>this</u> year!

The final fate of a neutron star binary

Gravitational waves



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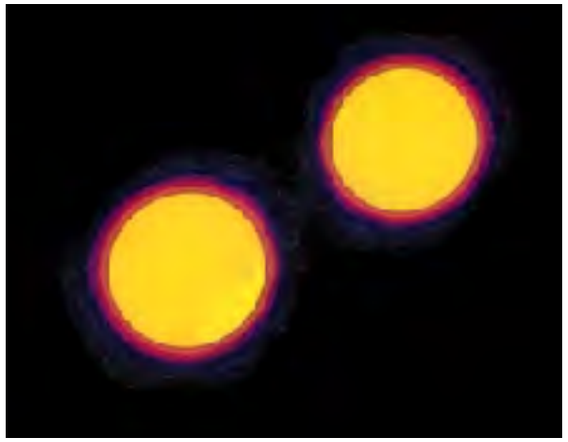
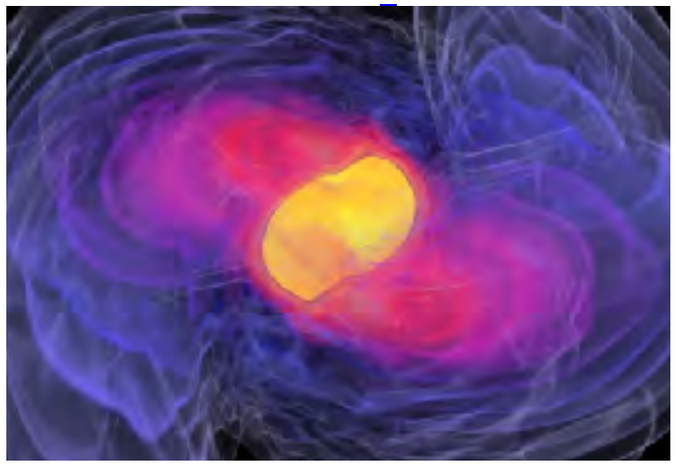
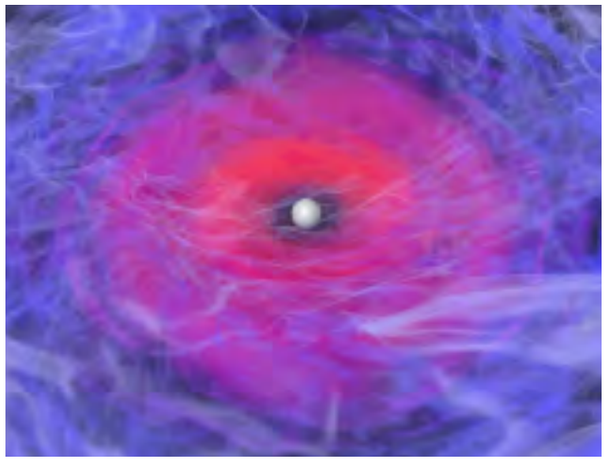
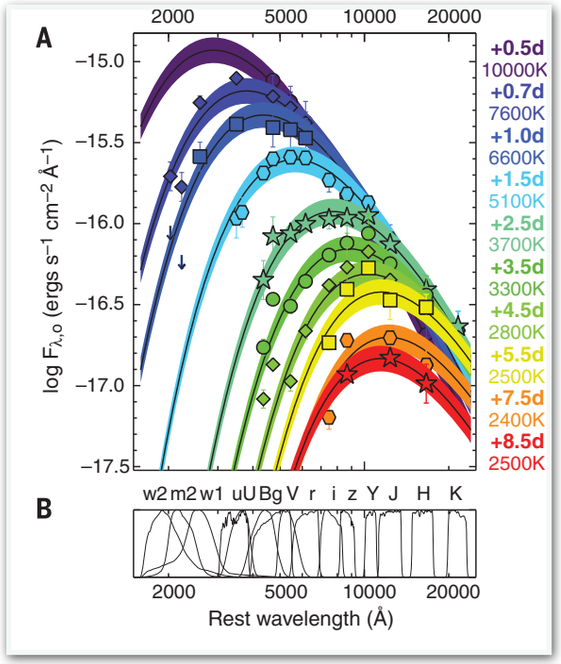


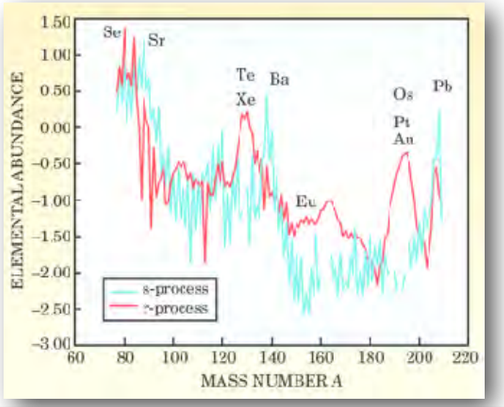




?

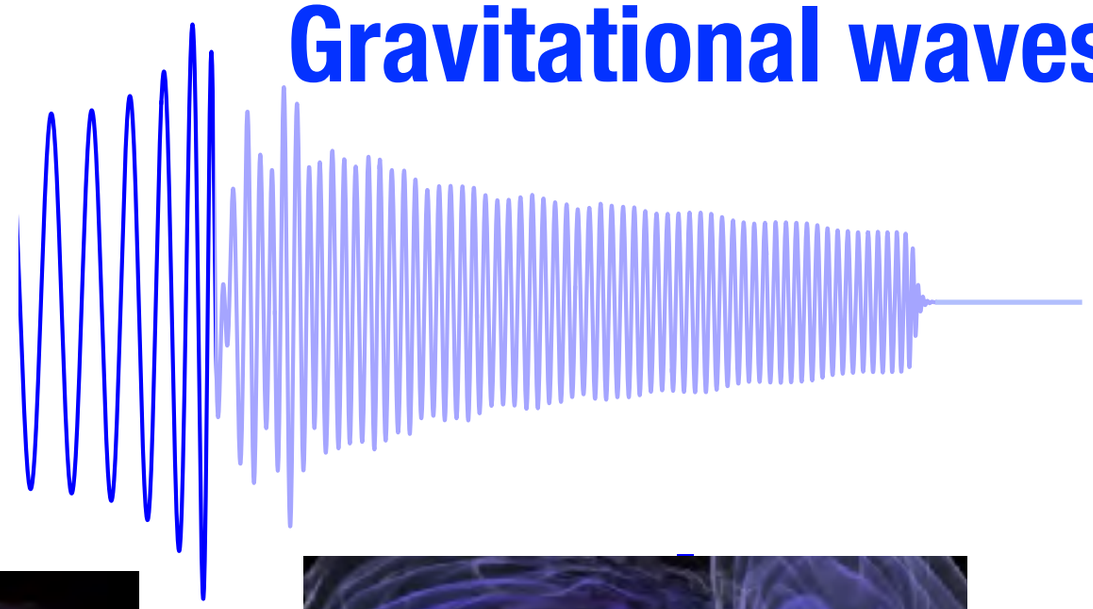


Kilonova Afterglow



The final fate of a neutron star binary

Gravitational waves



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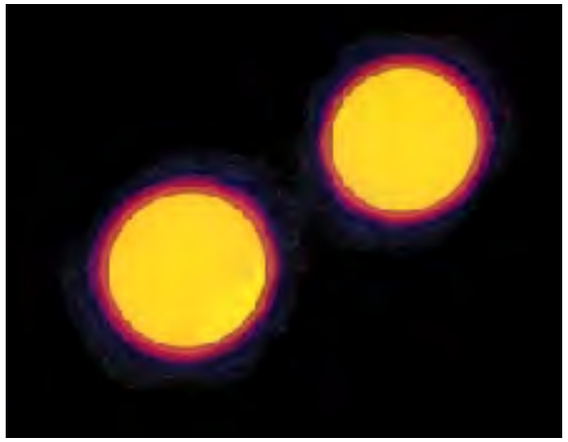
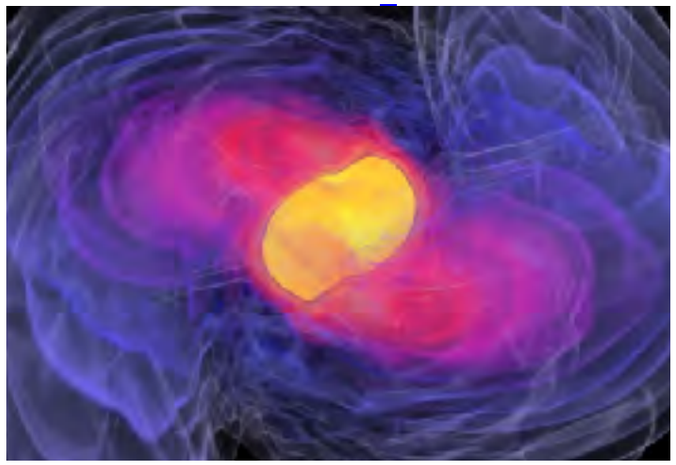
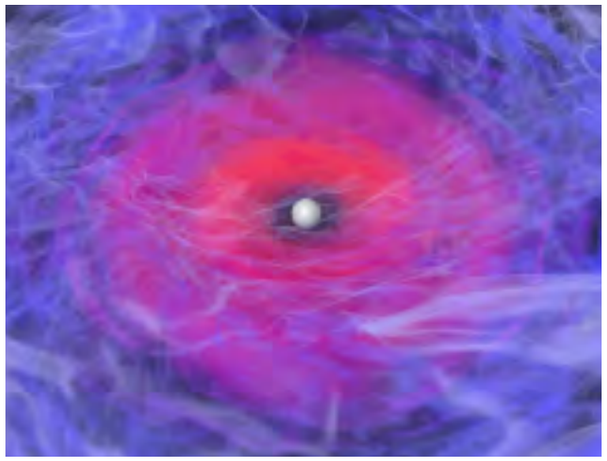
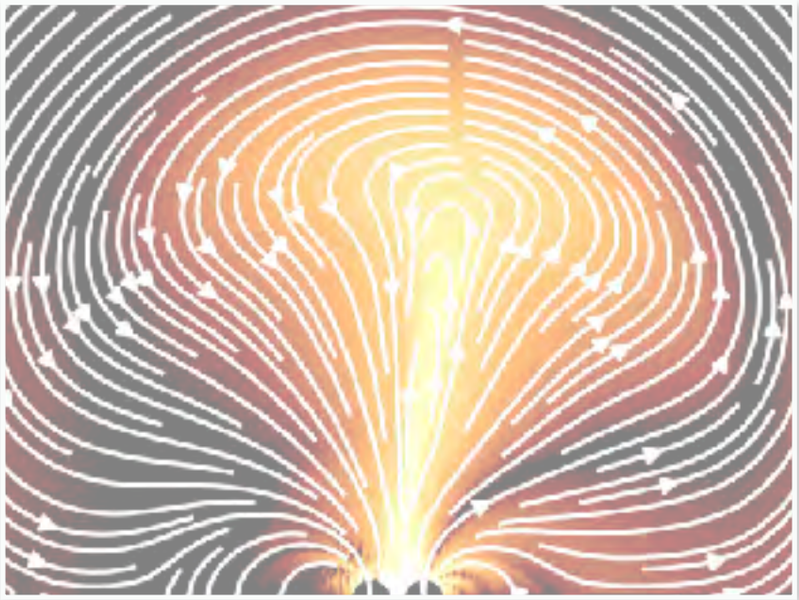
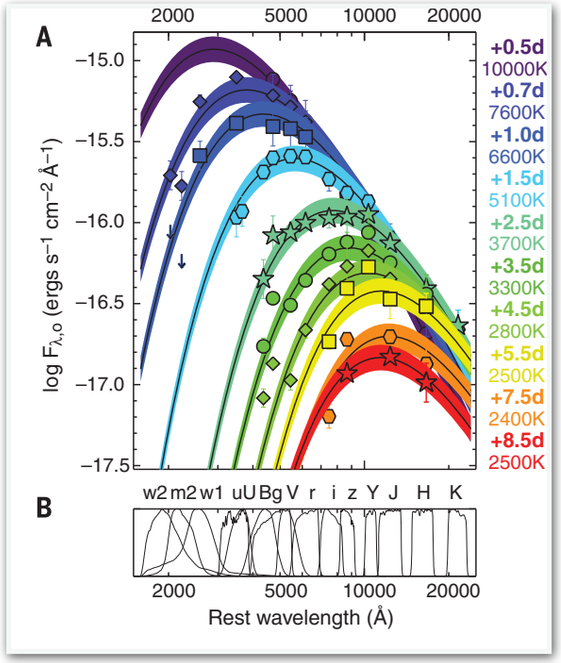




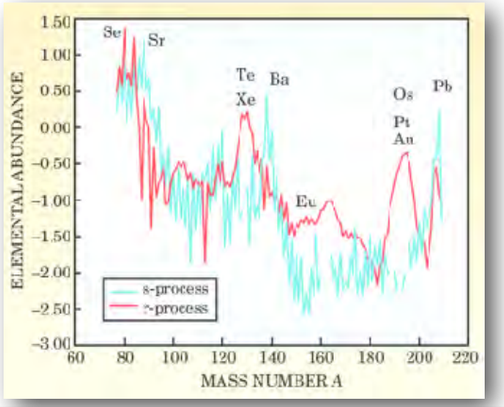




Precursor Emission??

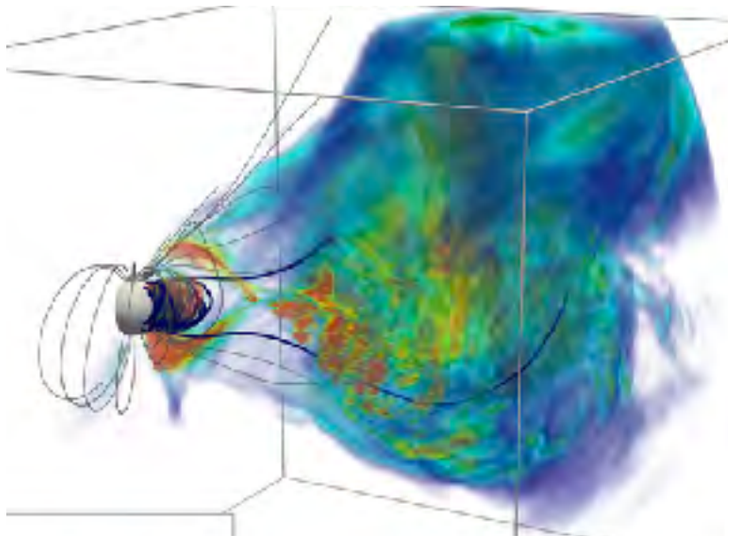


Kilonova Afterglow



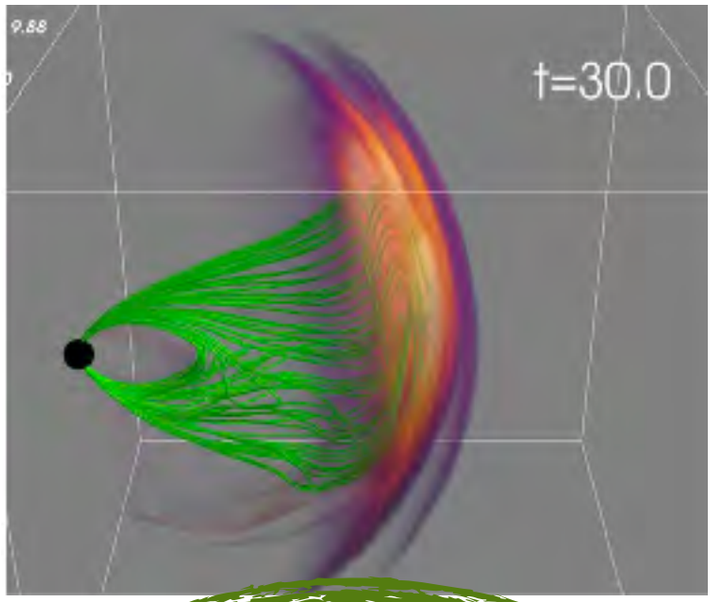
Magnetospheric transients

Flares



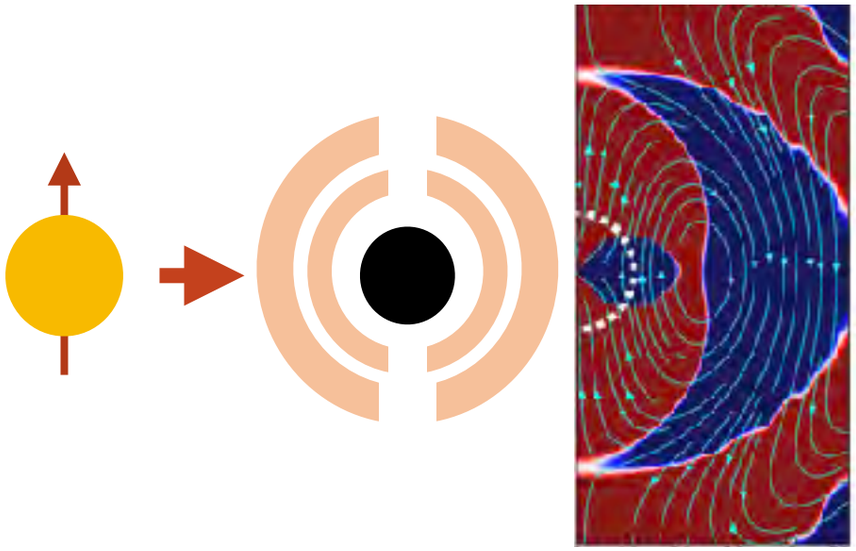
Mahlmann+(incl. ERM, 2023)
see also Parfrey+, Carrasco+, Sharma+

(Non-linear) Alfven waves



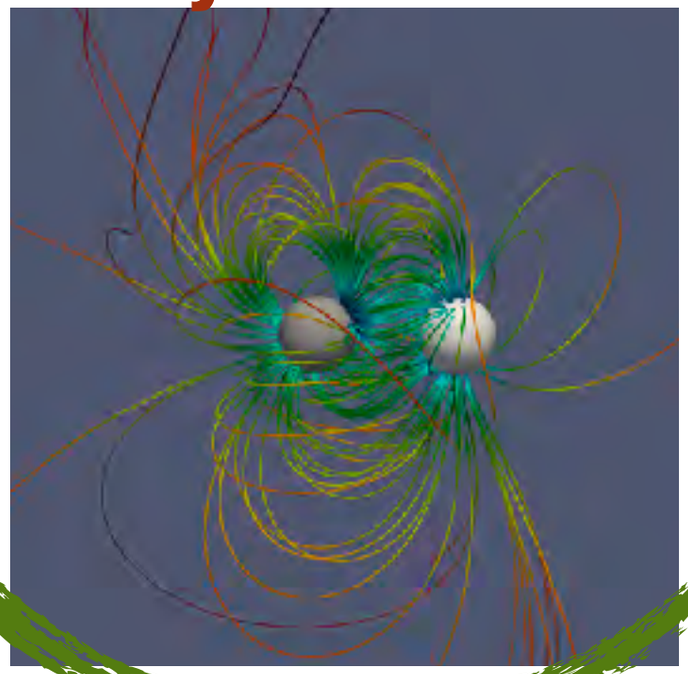
Yuan (2020), (incl. ERM, 2022)

Balding transients



ERM+(2018),Nathanail,ERM+(2017)
see also Lehner+, Palenzuela,Dionysopoulou+

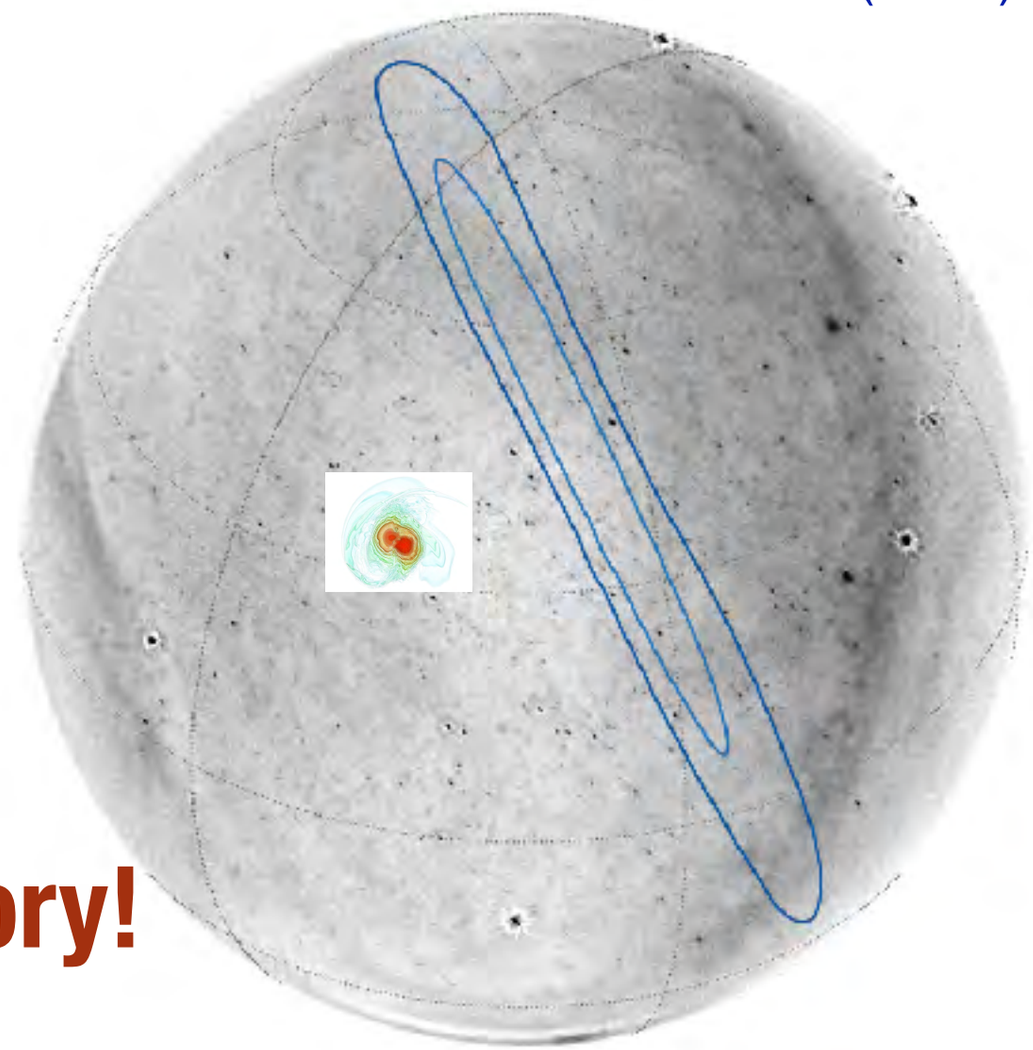
Binary interactions



ERM, Philippov (2020, 2022a,b; in prep.)
see also Palenzuela+, Paschalidis+,Ponce+, East+, Carrasco+

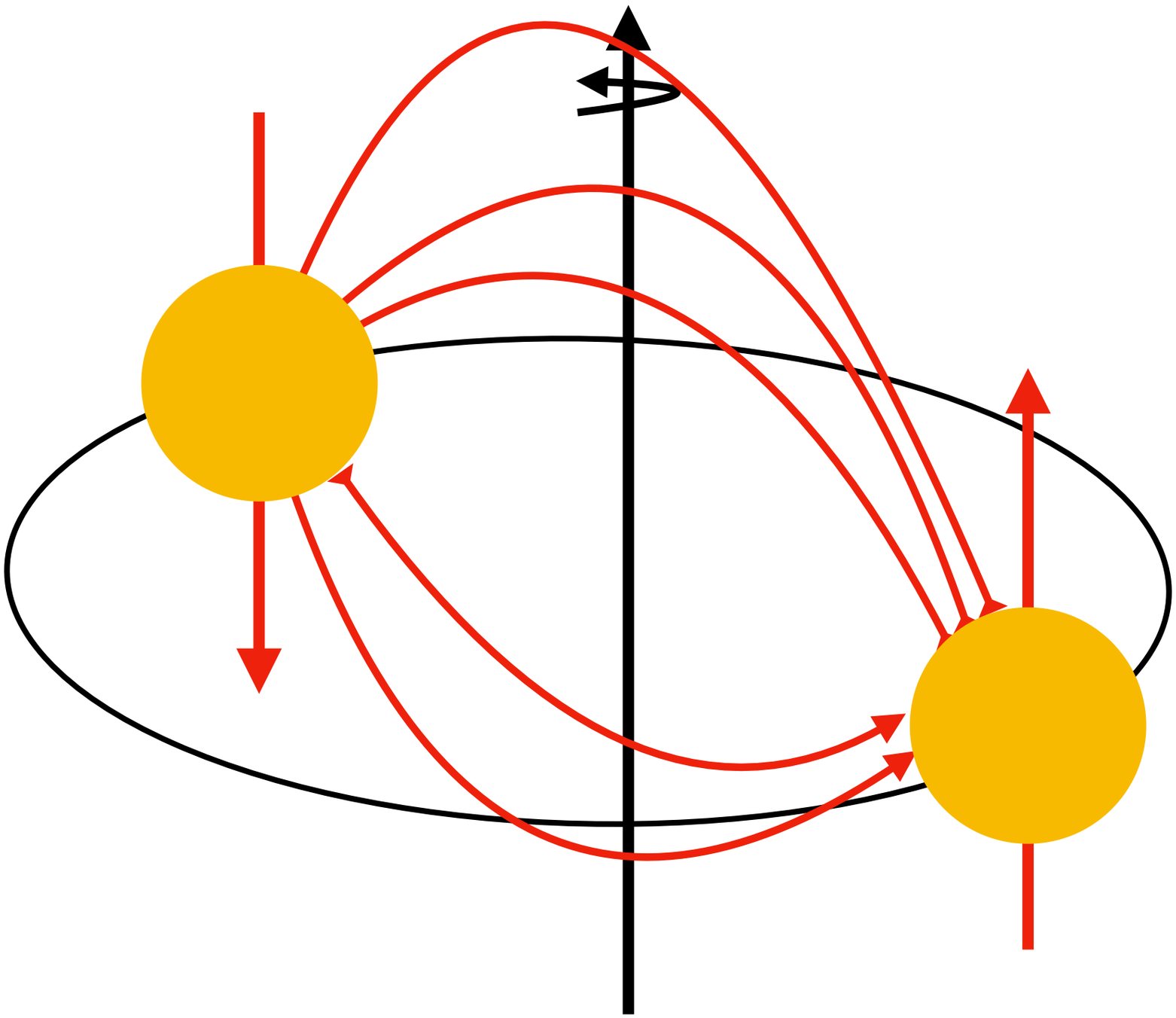
Observational prospects

Callister+ (2019)

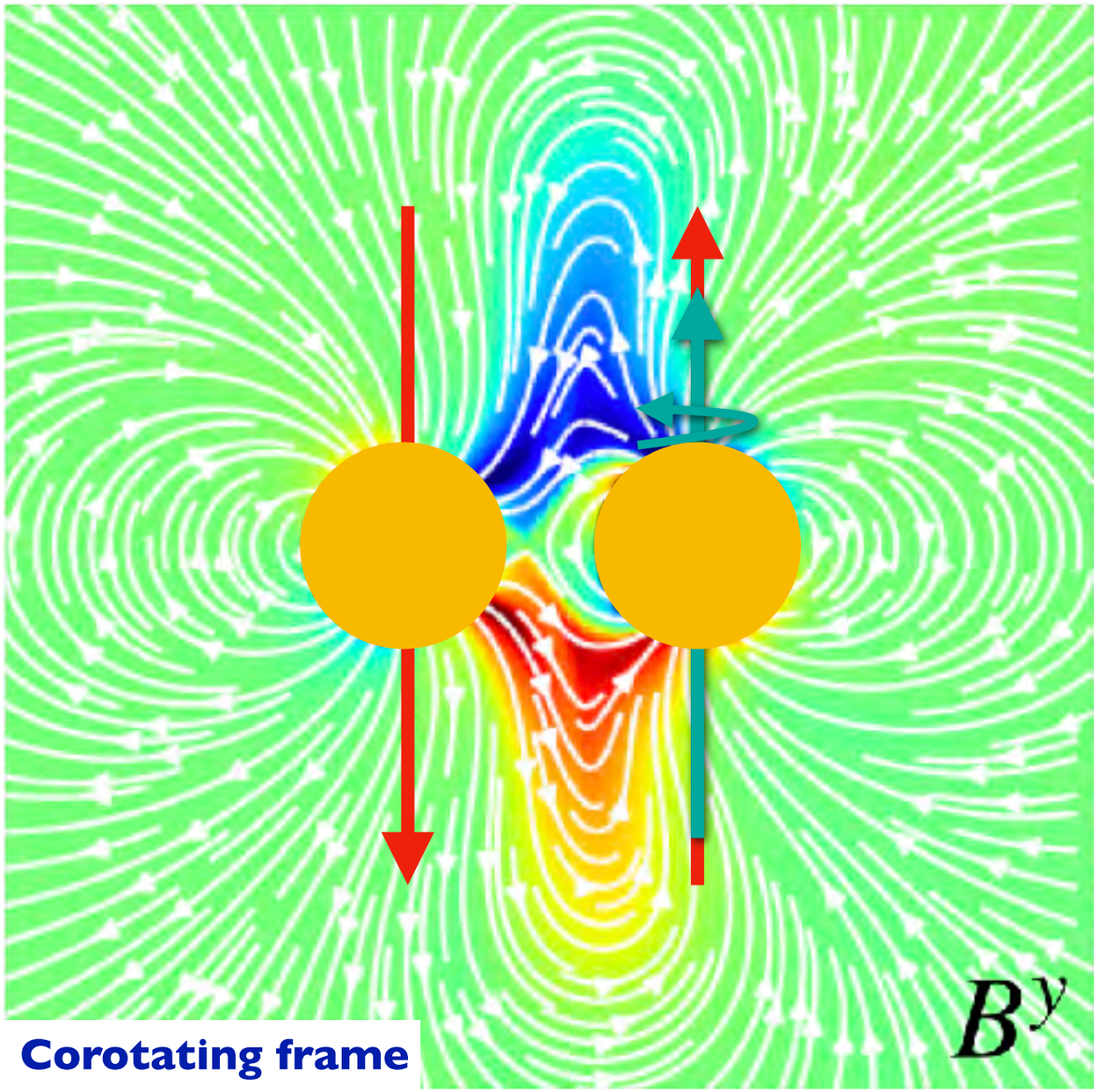


Need better predictions and theory!

Magnetospheric dynamics prior to merger

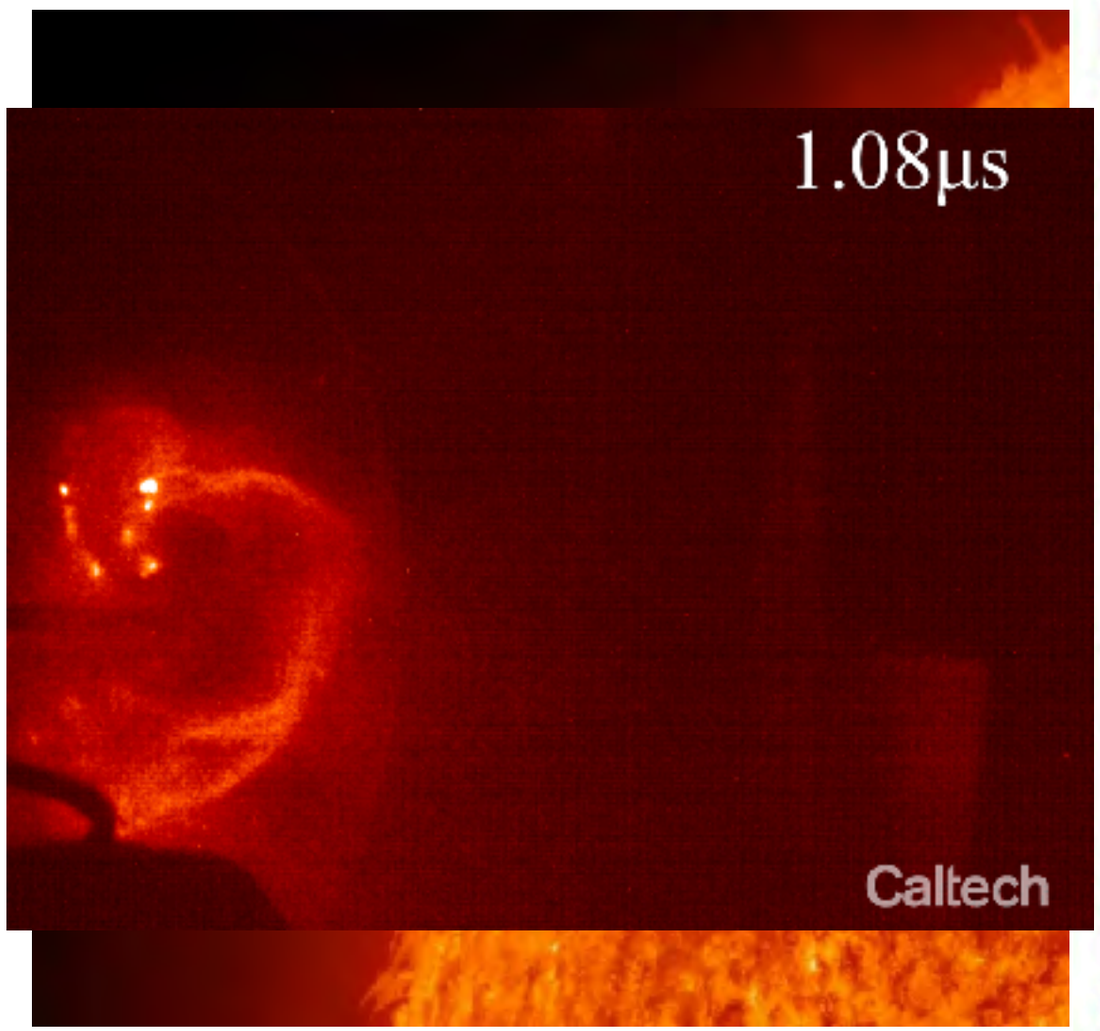


Magnetospheric dynamics prior to merger

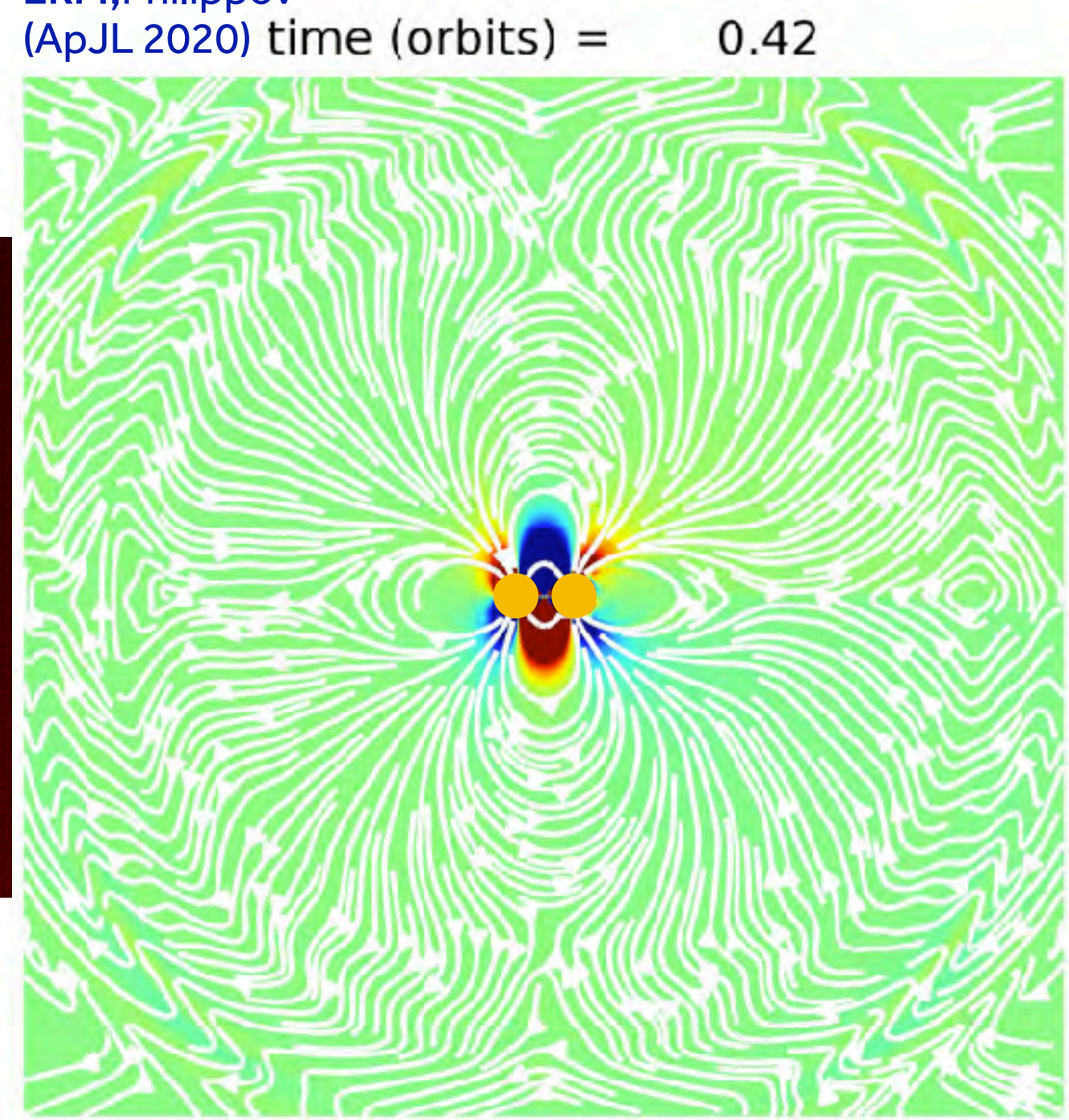


ERM & Philippov
(ApJL 2020)

Radio transients from flares?



ERM,Philippov
(ApJL 2020)



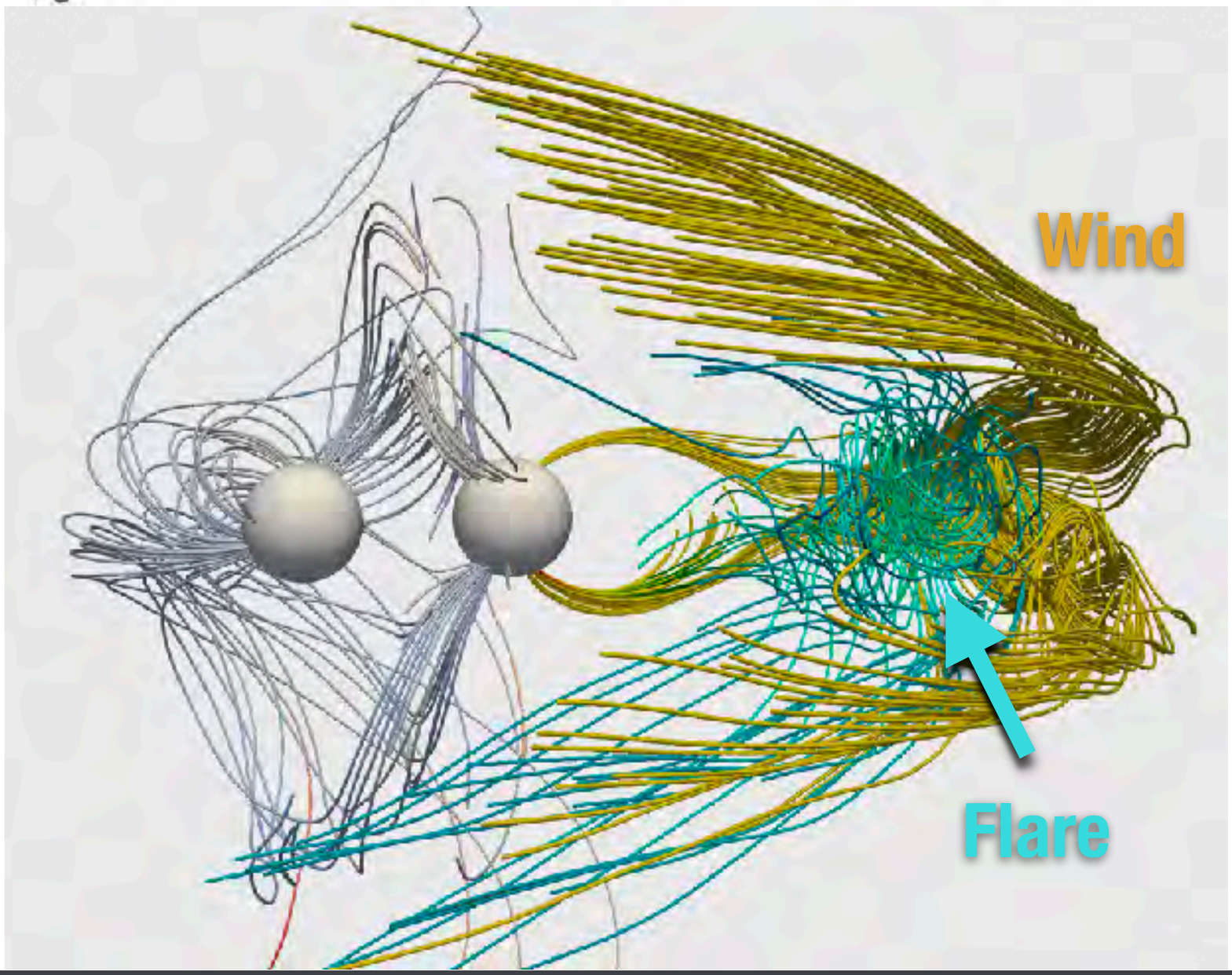
SYNOPSIS

Physics

Radio Bursts Precede Coalescence of Neutron Stars

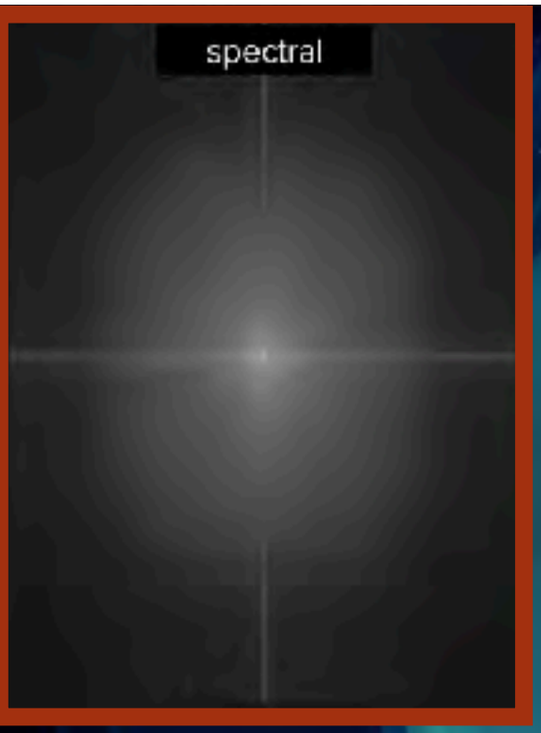
June 16, 2023 • *Physics* 16, s88

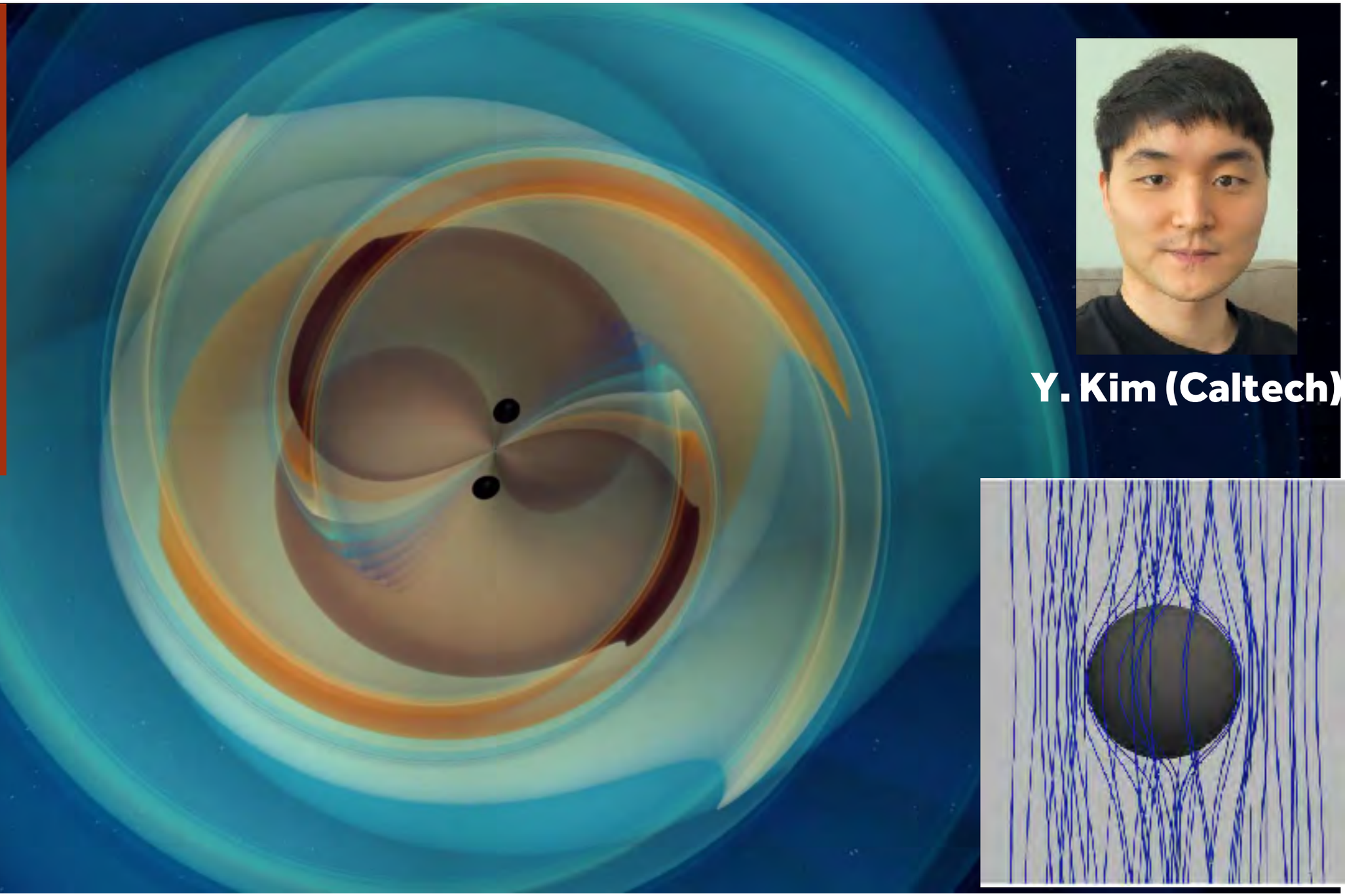
Warning of the catastrophic collapse of a neutron star could come in the form of potentially detectable radio bursts in the 10–20 gigahertz range.



ERM & Philippov
(Physical Review Letters 2023)

Leveraging numerical advances

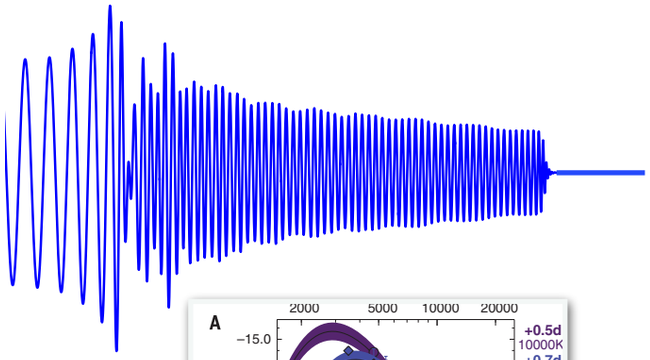


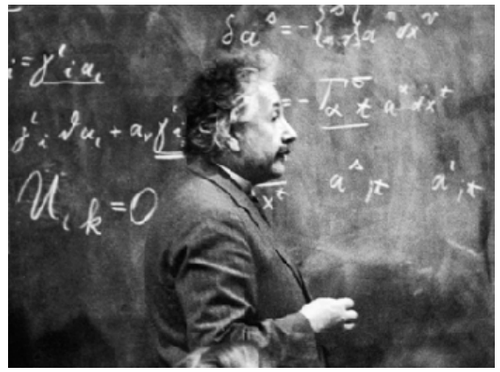


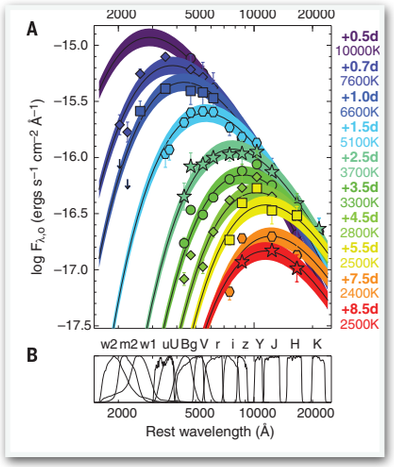
Spectral methods:

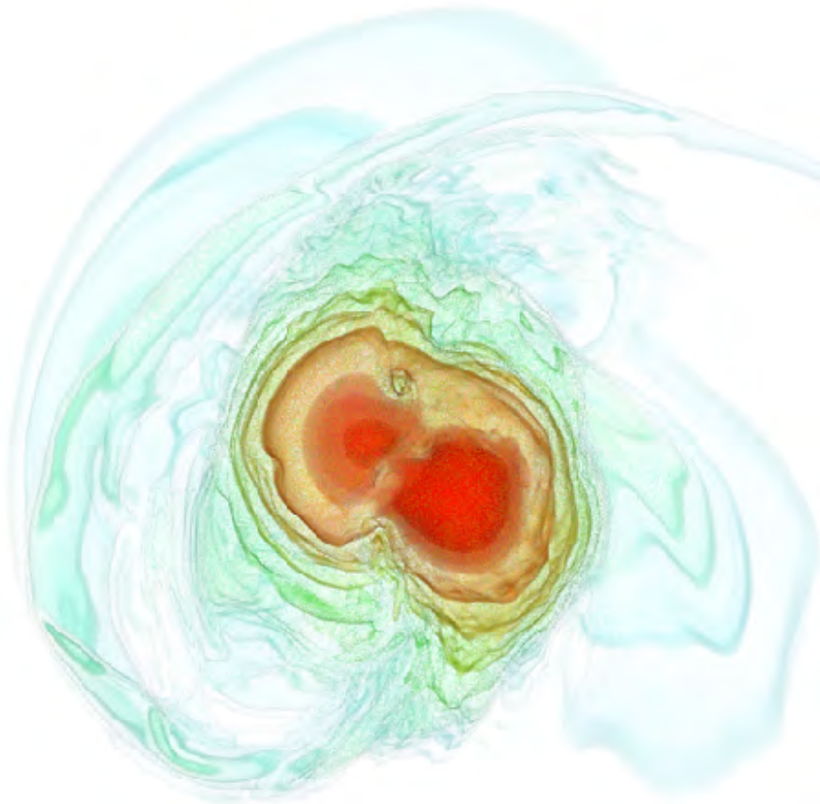
Apply leading tools from binary black hole coalescence to magnetospheric problem!

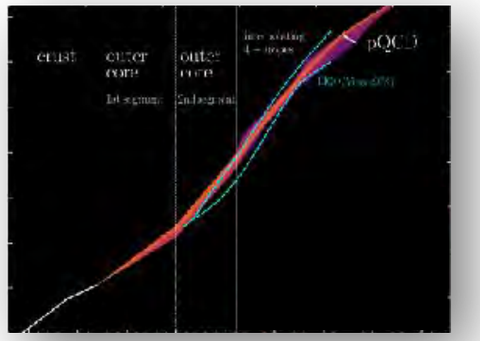
Computational relativistic astrophysics

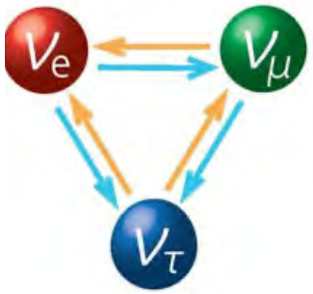


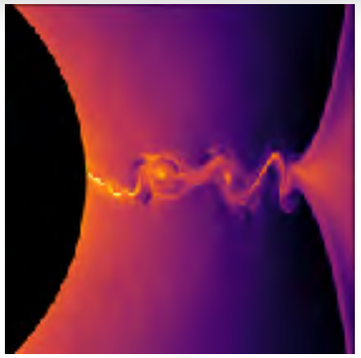






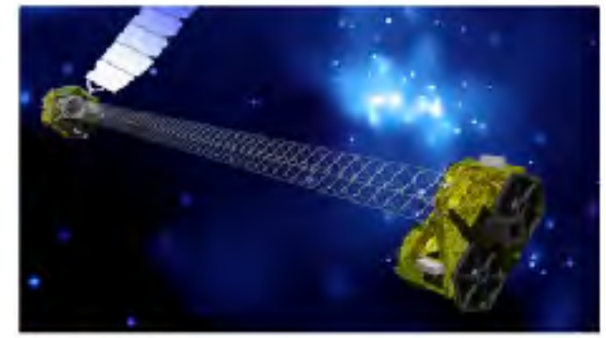






Need a multi-scale, multi-physics approach to interpret multi-messenger events!

Palomar Observatory

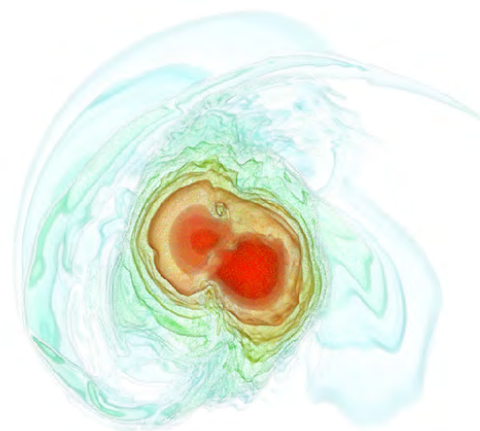


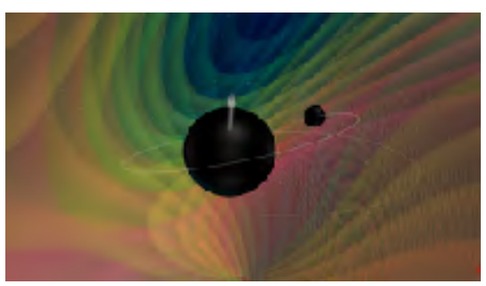
NuSTAR

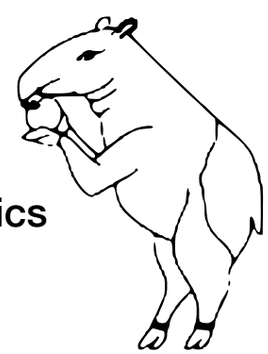
LIGO

Caltech

Owens Valley Radio Observatory



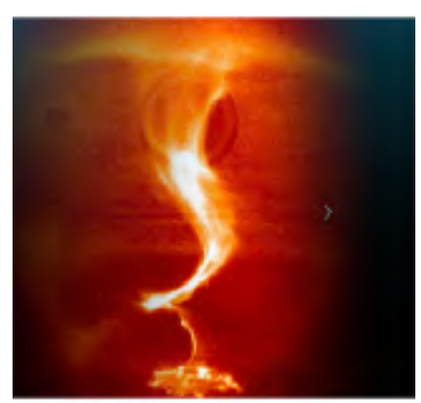




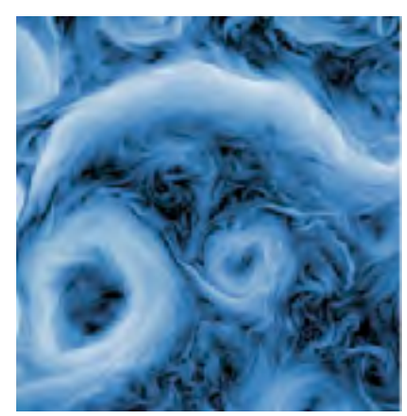
Theoretical Astrophysics Including Relativity (TAPIR)

SIMULATING EXTREME SPACETIMES

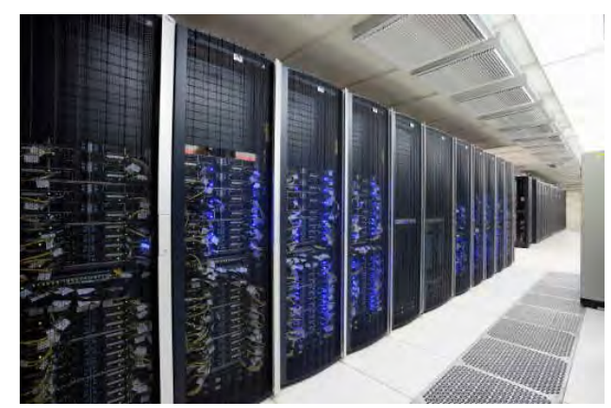
Black holes, neutron stars, and beyond...



Applied Physics and Materials Science

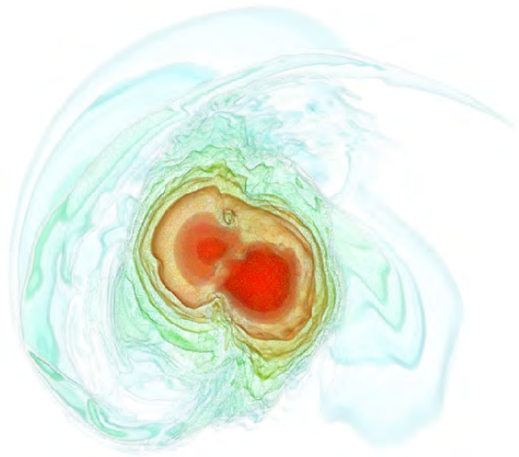


Geological and Planetary Sciences

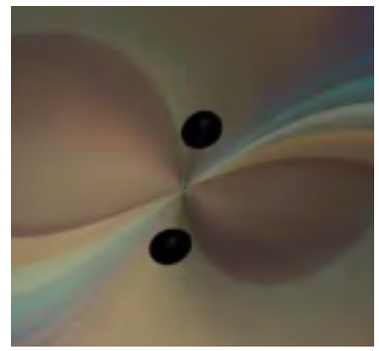


Resnick High-Performance Computing Center

Computational relativistic astrophysics

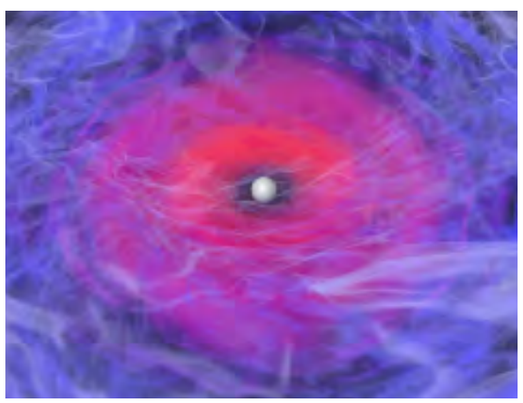


Multi-messenger

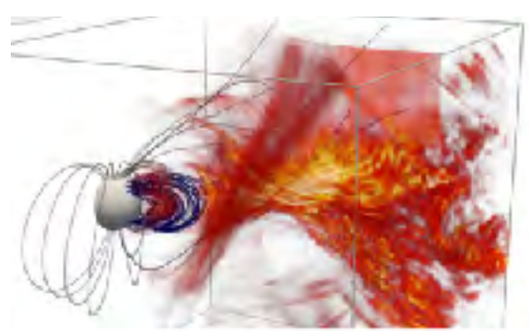


Spacetime dynamics

Explosive transients



Black hole accretion

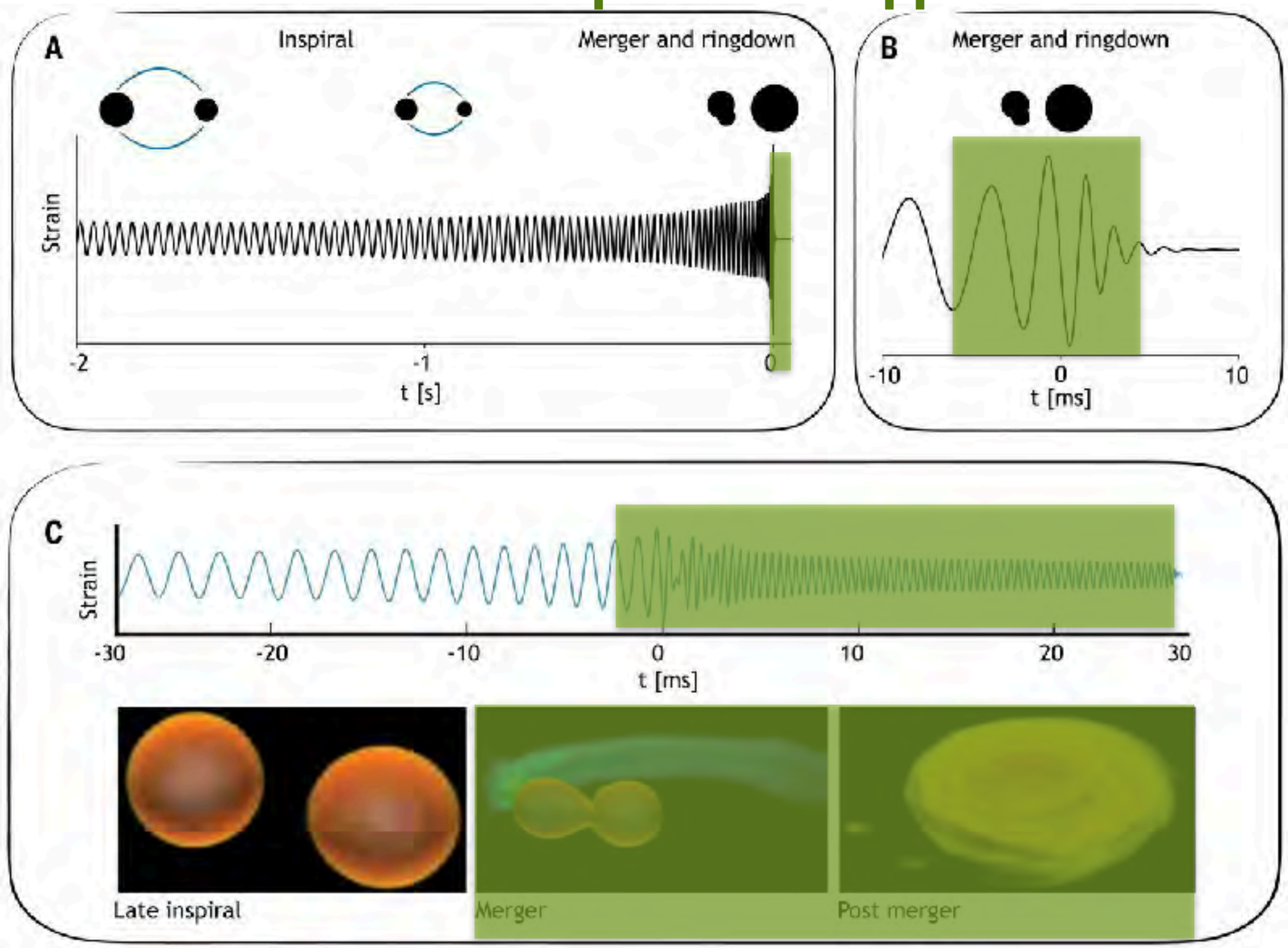


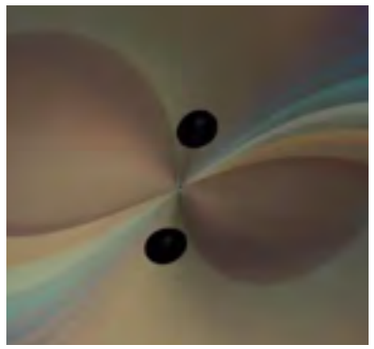
Relativistic Magnetospheres

Relativistic outflows

Why a computational approach?

Computational approach needed





Spacetime dynamics

Data-driven need for accuracy!

Image credit: Vitale+2021

Computational challenges

Non-linear interplay of physics at different scales!

Non-linear dynamics

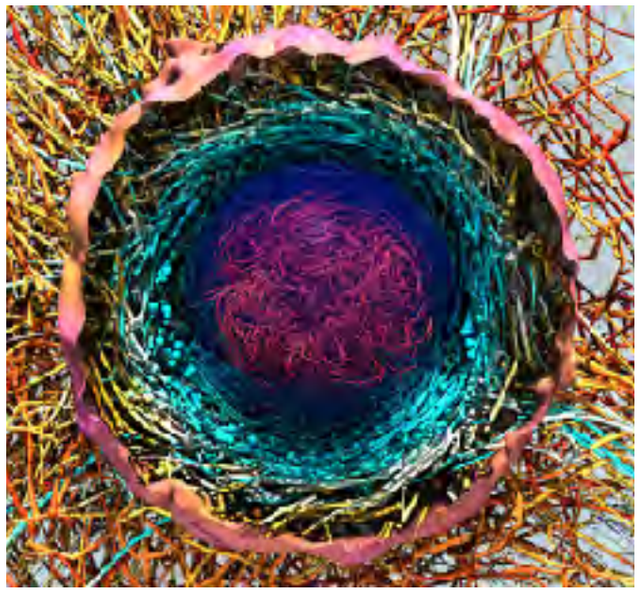


Image credit: Burrows

Complex equations

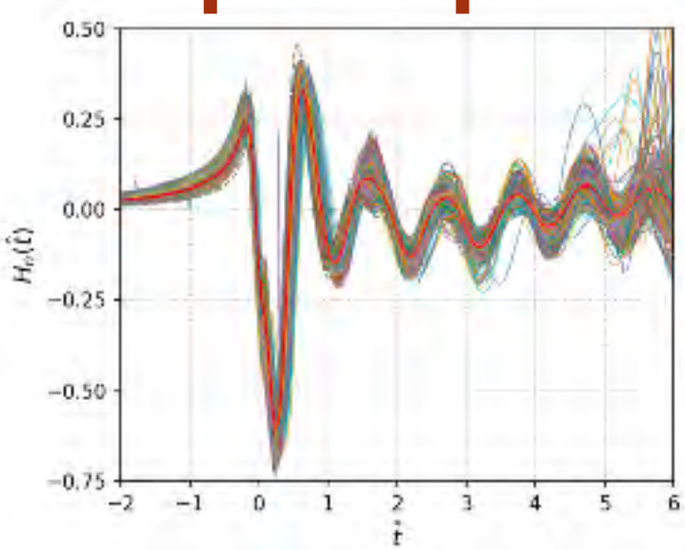


Image credit: Pastor-Marcos+23

No symmetries

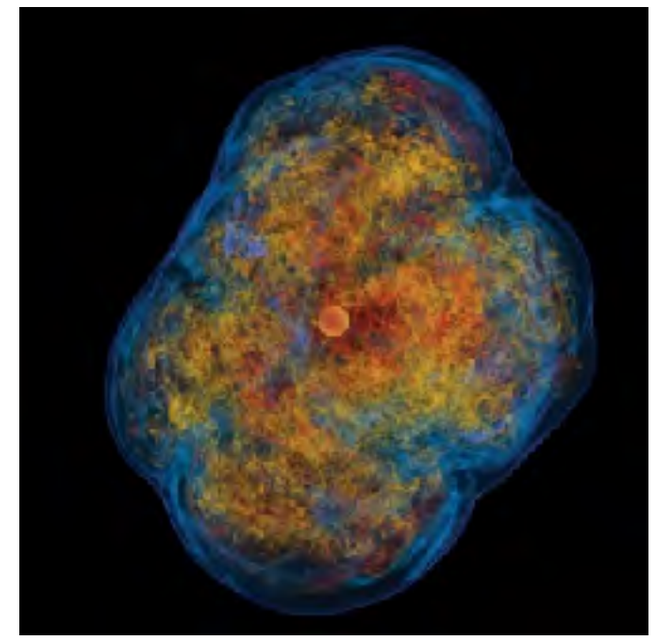


Image credit: Nordhaus

Multi physics

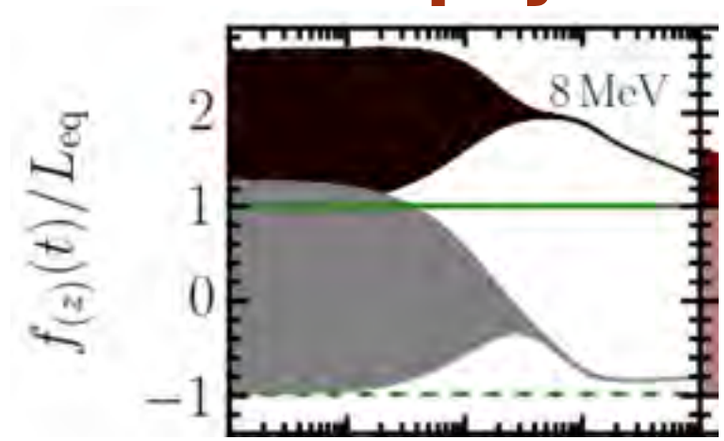


Image credit: Richers

Choosing the right approach

Black hole accretion for collisionless plasma

$$p^\mu \partial_\mu f + \left(\mathfrak{q} F^\alpha_\mu + \Gamma^\alpha_{\mu\nu} p^\nu \right) p^\mu \partial_{p^\alpha} f = \mathscr{C}\left[f\right]$$

Six dimensional phase space!
Can't possibly solve this directly?

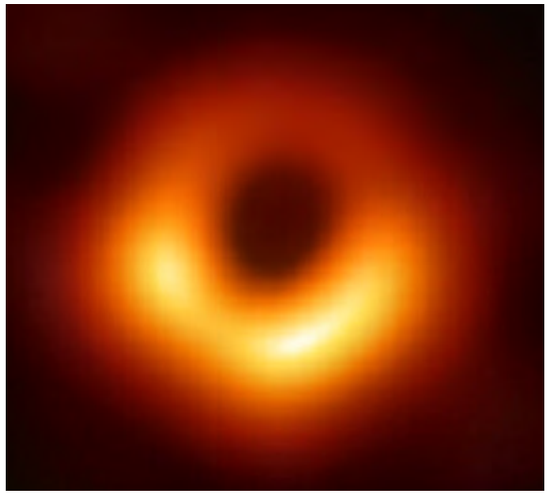


Image credit: EHT

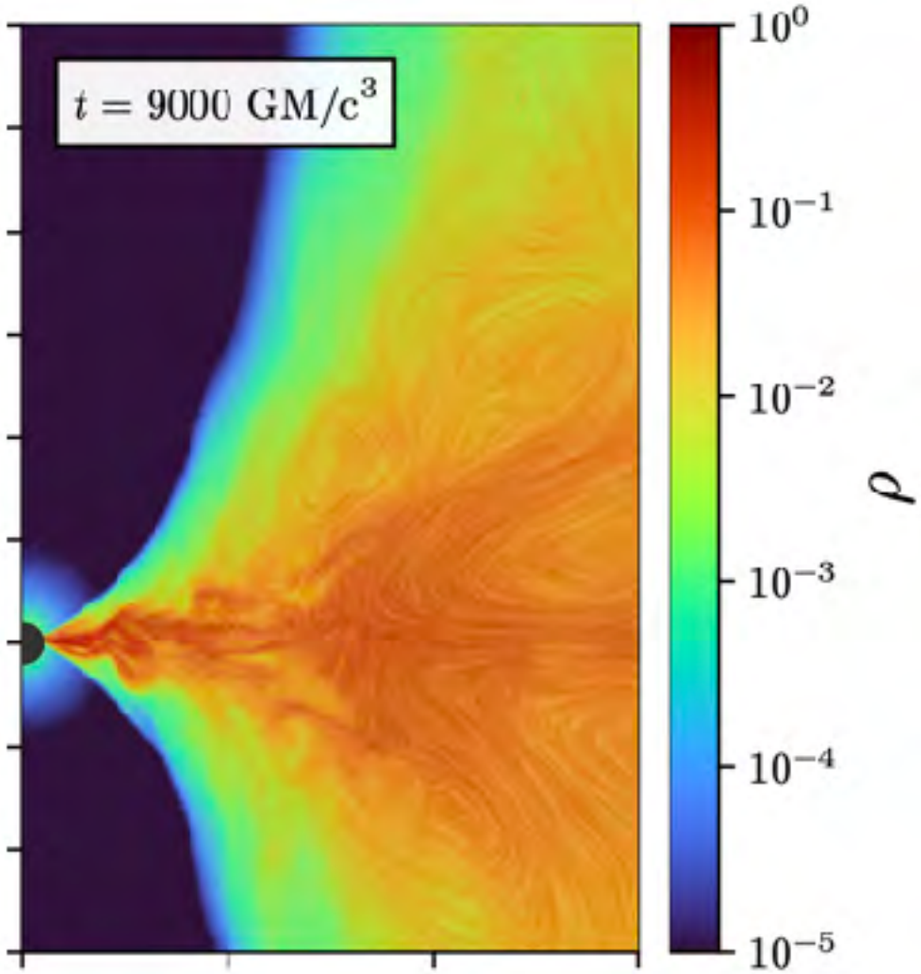


Image credit: Wong

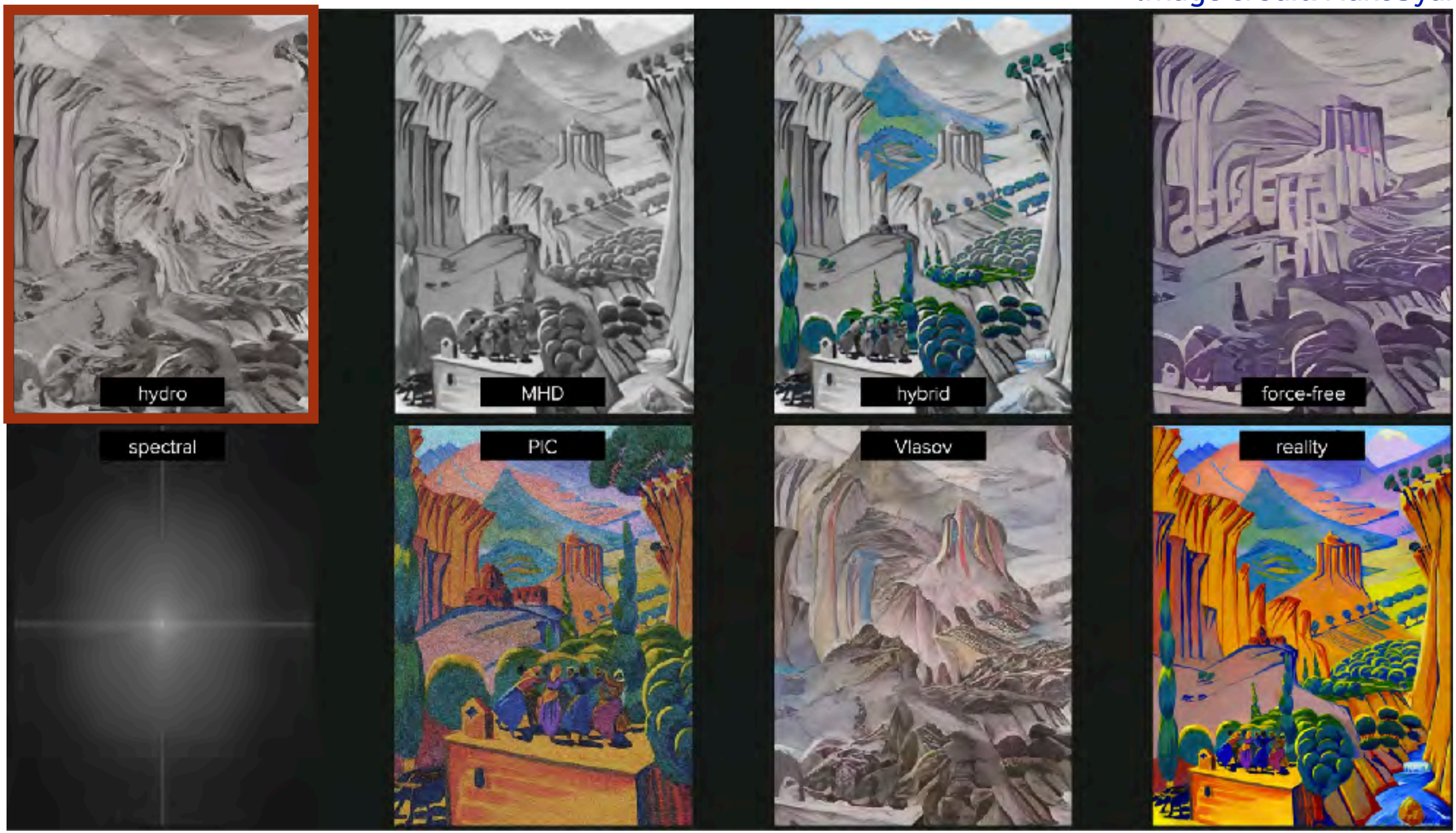
Event Horizon Telescope image sourced by gas dynamics

- Different accretion regimes?
- Precise history of gas???
- Plasma scales???
- Imprints of space time can be highly degenerate!

A simulation based viewpoint!

Choosing the right approximation

Image credit: Hakobyan

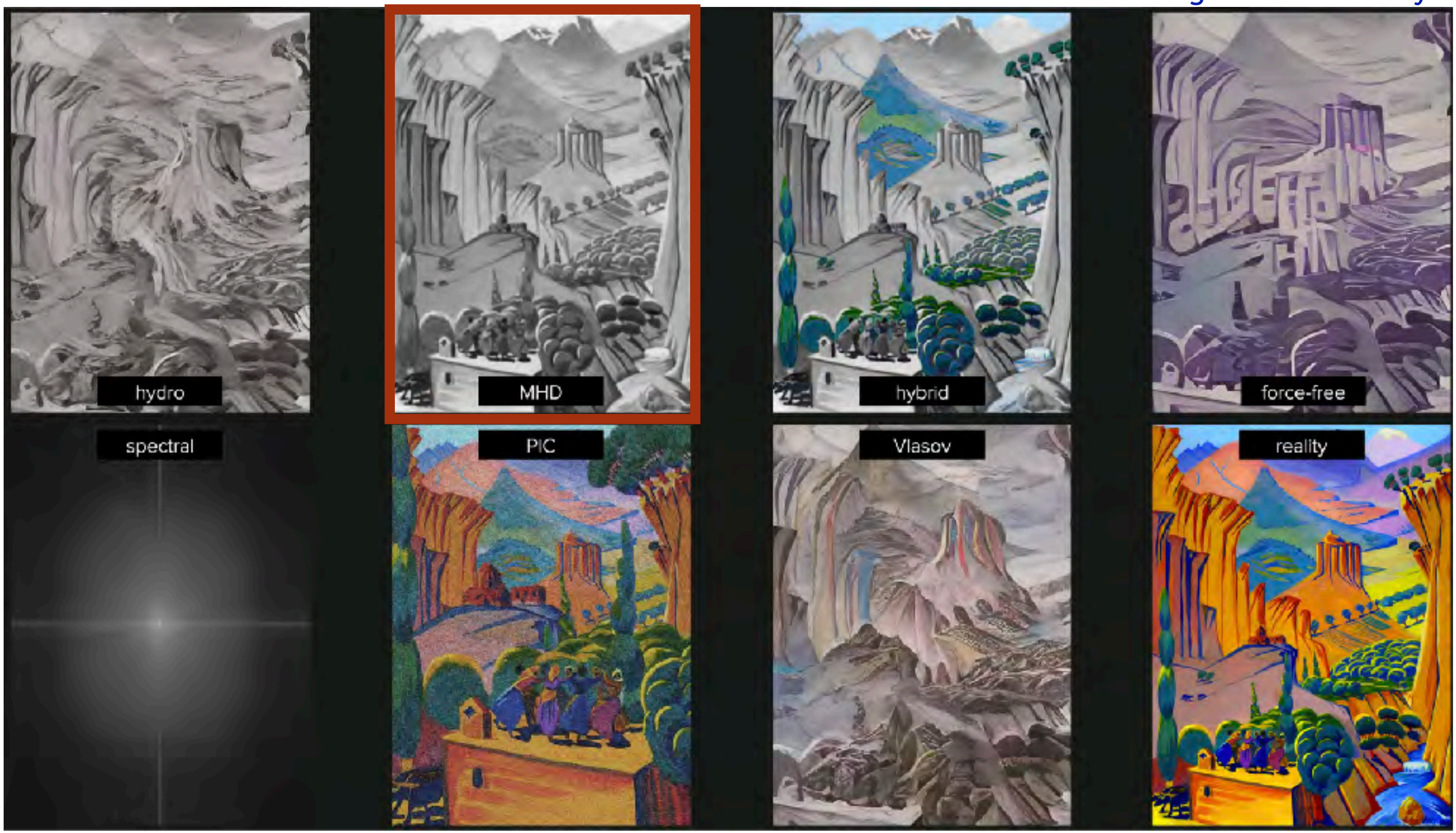


Hydrodynamics:

Inexpensive, no magnetic fields, global features wrong

Choosing the right approximation

Image credit: Hakobyan

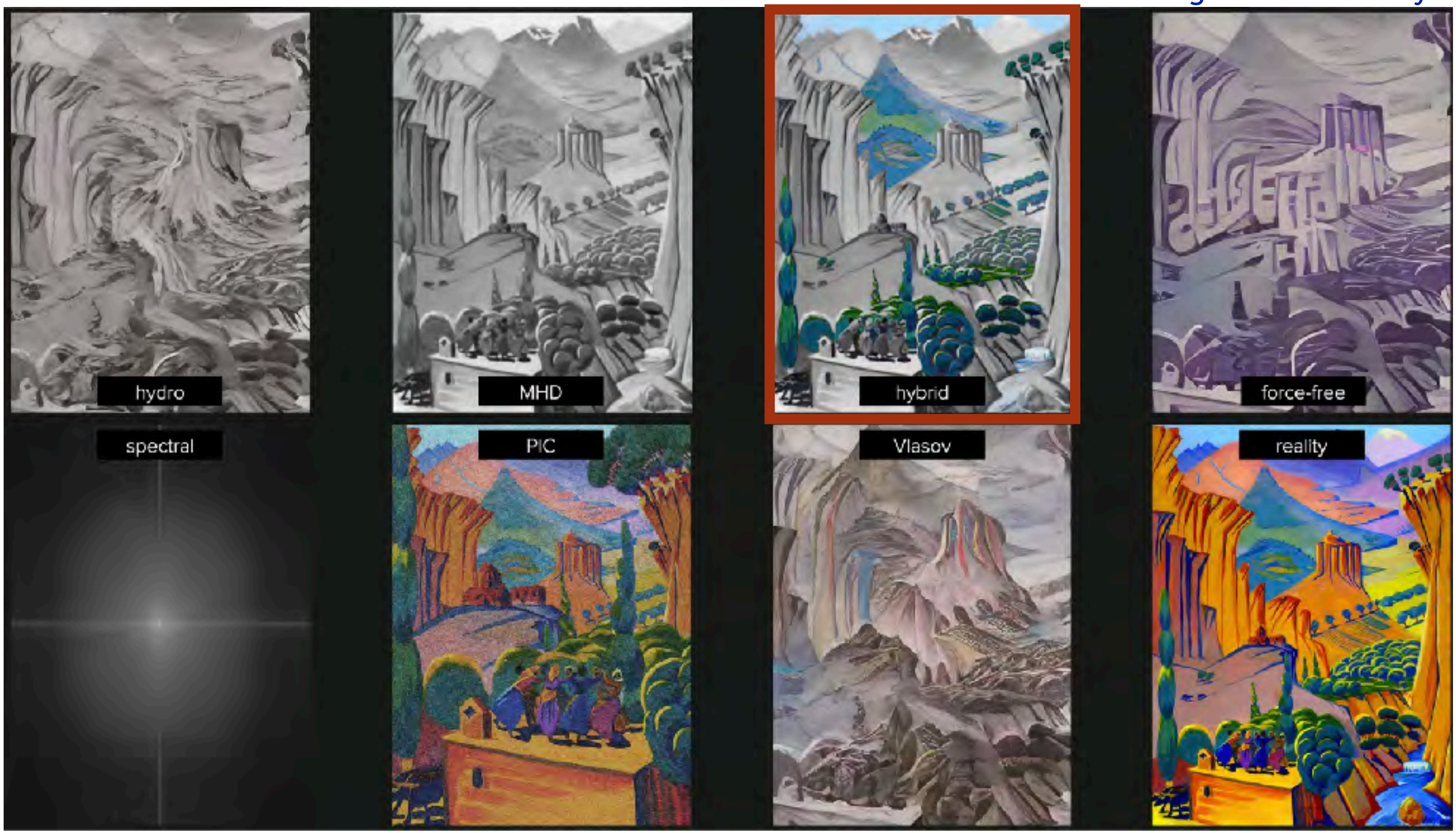


Magnetohydrodynamics:

Inexpensive, global features about right. Emission features?

Choosing the right approximation

Image credit: Hakobyan

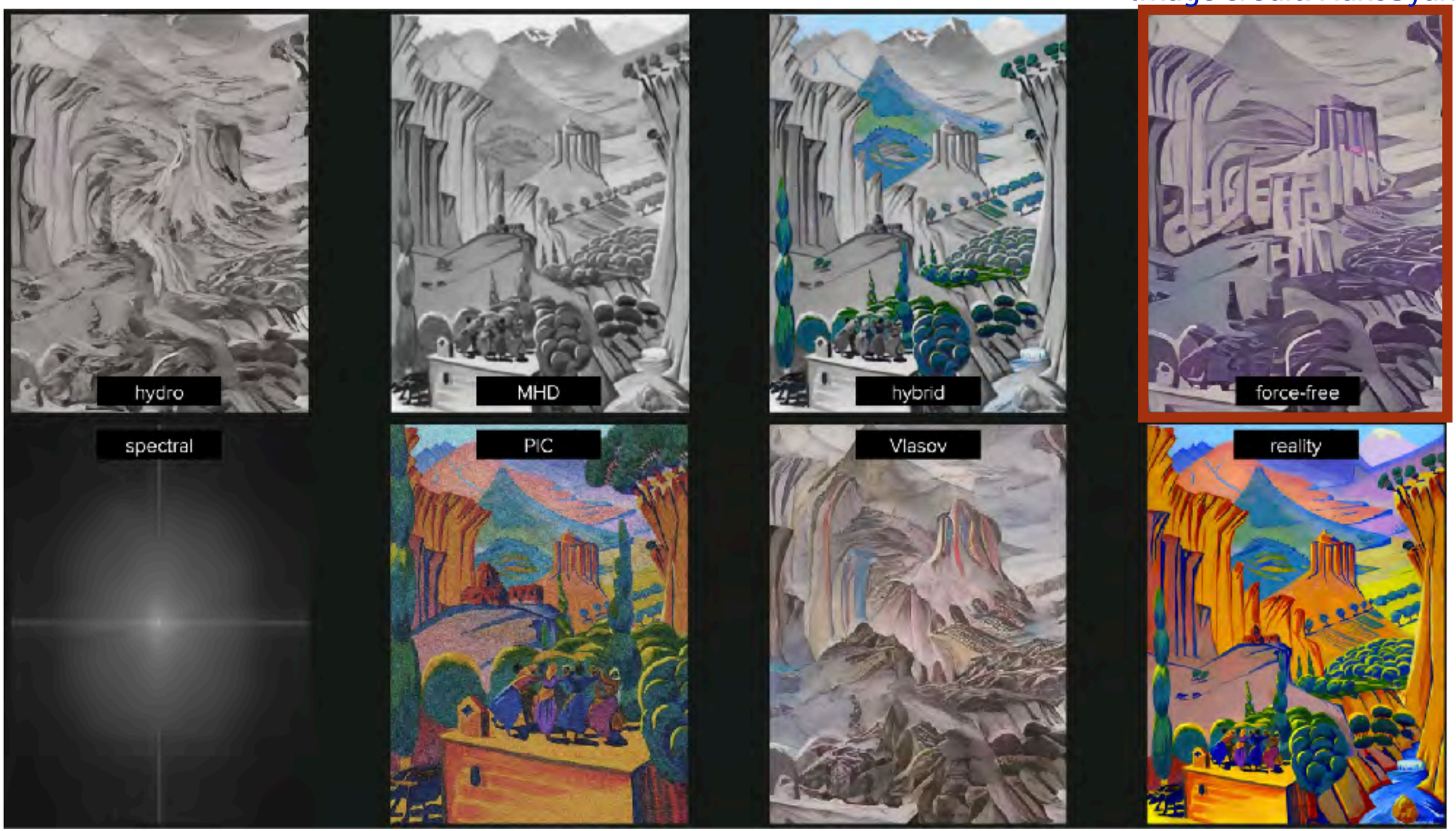


Hybrid particle-in-cell:

Expensive, global features about right, electron fluid; relativity?!

Choosing the right approximation

Image credit: Hakobyan

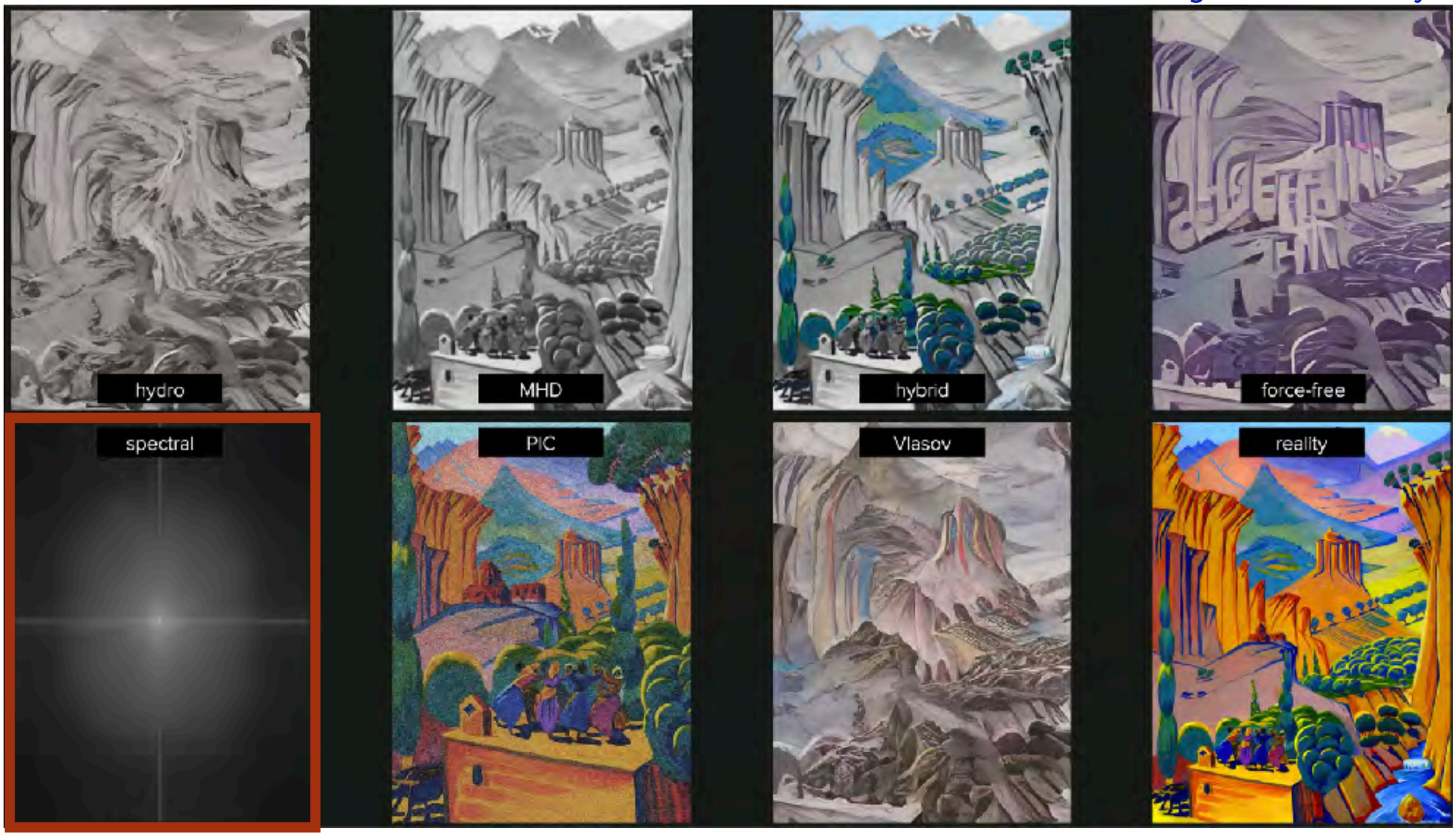


Force-free electrodynamics:

Cheap, gets global dynamics of the jet ok, no disk accretion

Choosing the right approximation

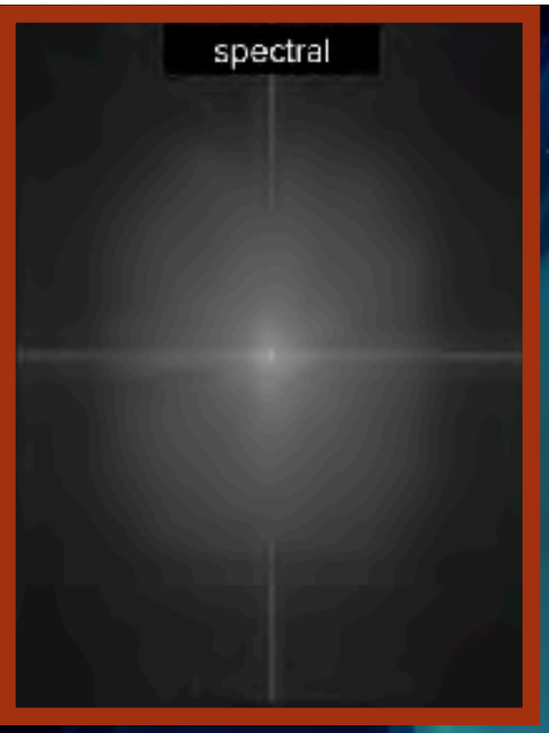
Image credit: Hakobyan

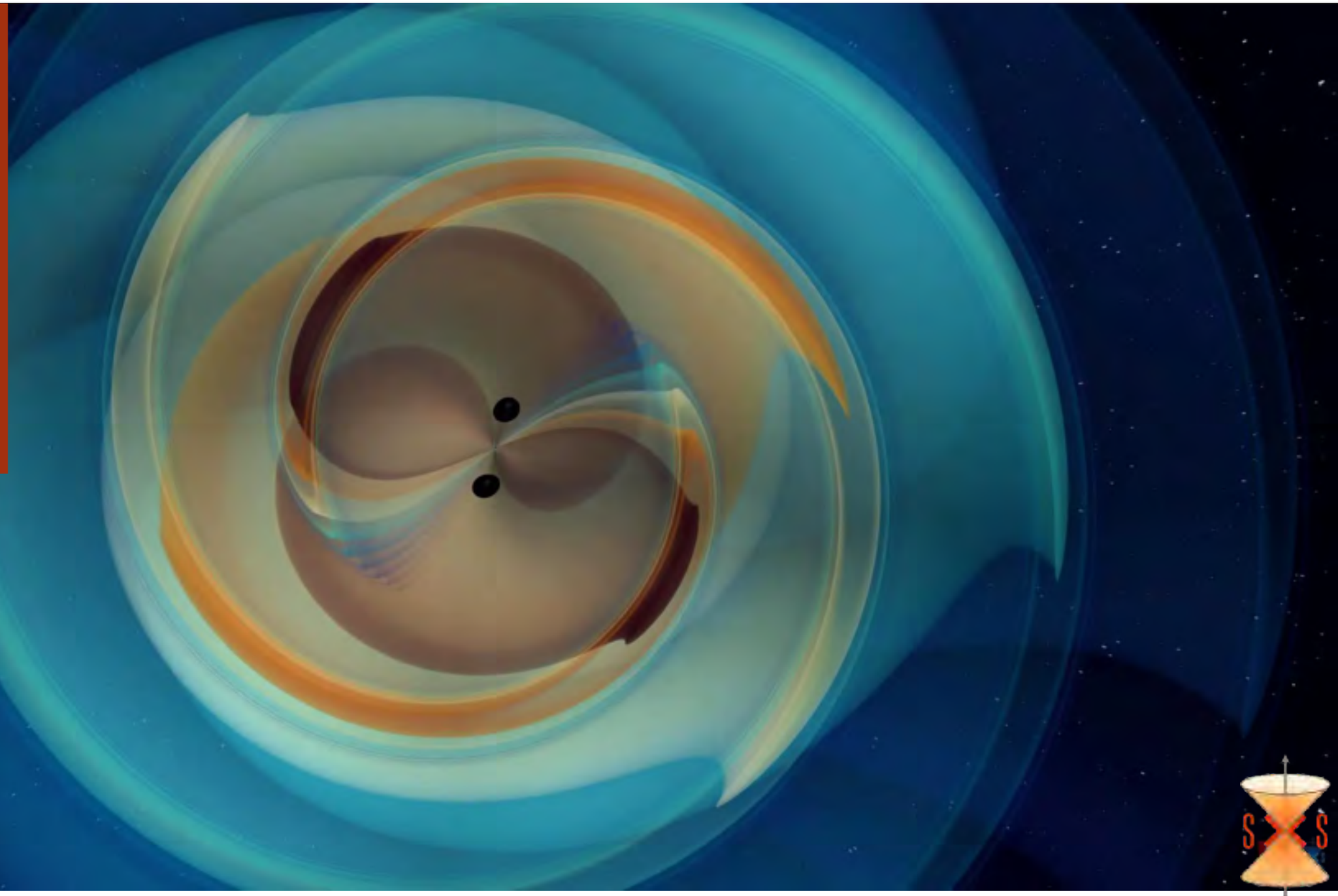


Spectral methods:

Complicated! Very hard to do for fluid problems/shocks. BUT…

Choosing the right approximation



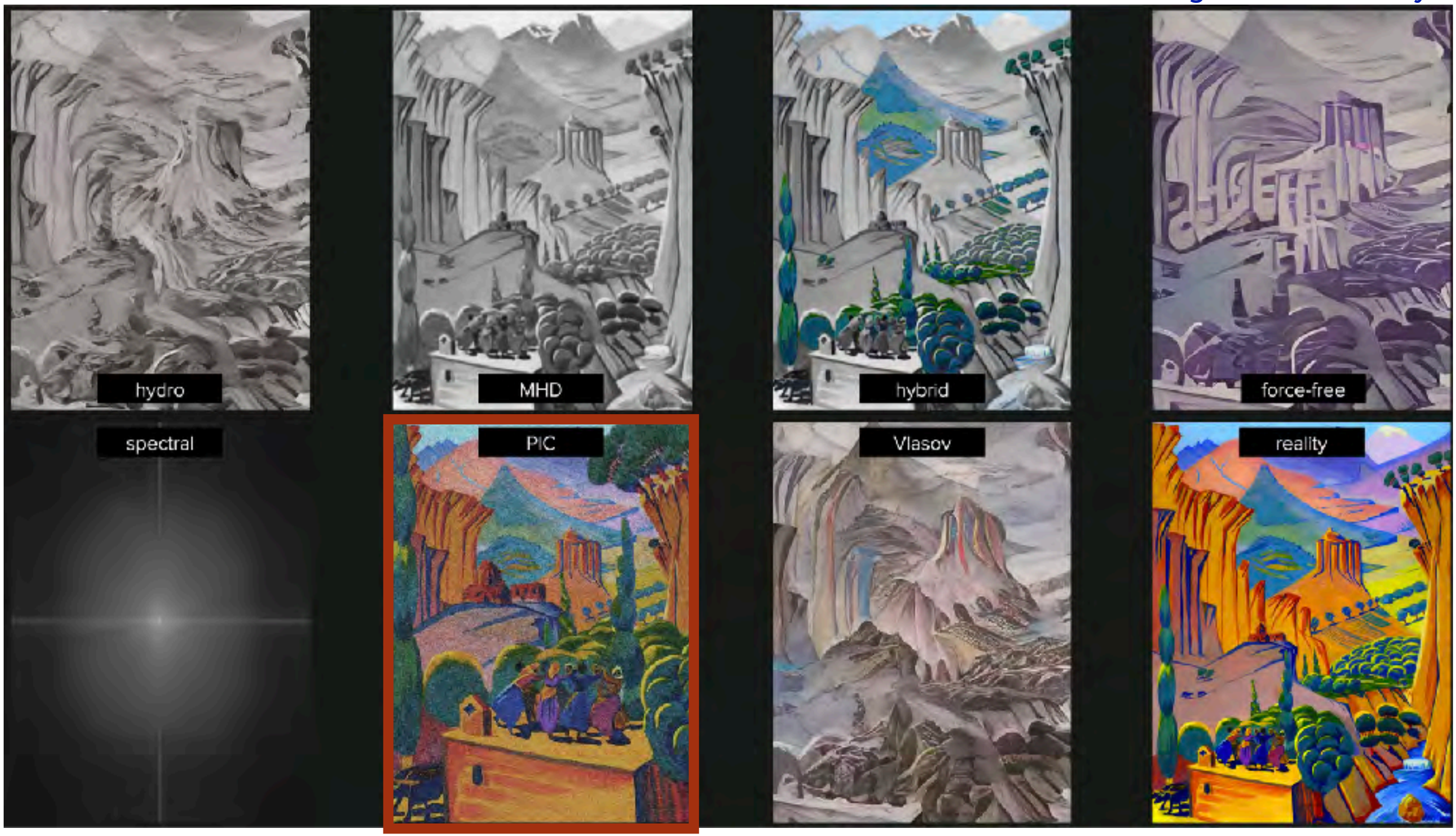


Spectral methods:

Work extremely well for black holes and gravitational waves!

Choosing the right approximation

Image credit: Hakobyan

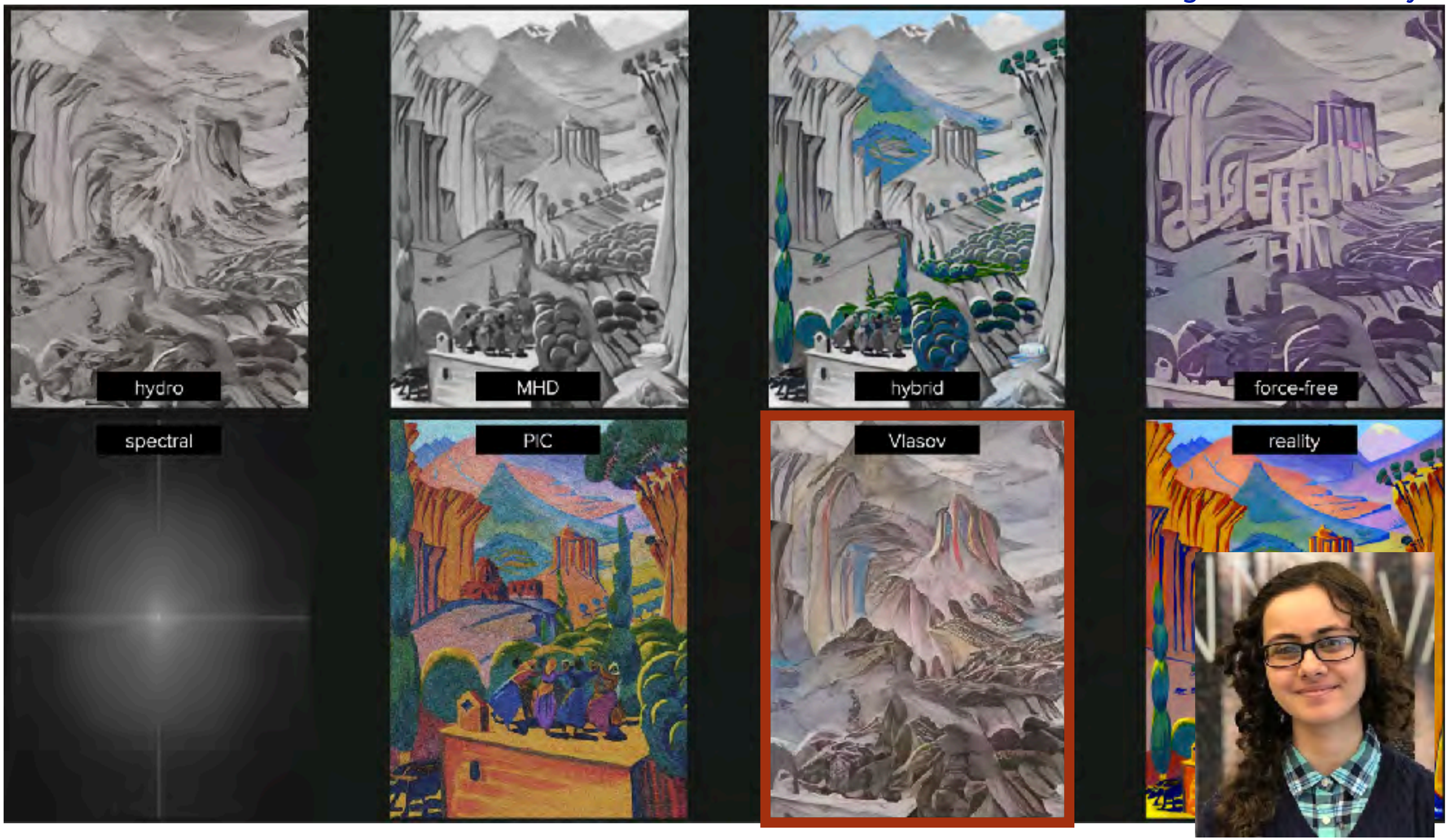


Particle-in-cell (Monte-Carlo-type sampling approach):

Extremely expensive! Includes all the physics. Scale separation...?

Choosing the right approximation

Image credit: Hakobyan



Sarah Habib

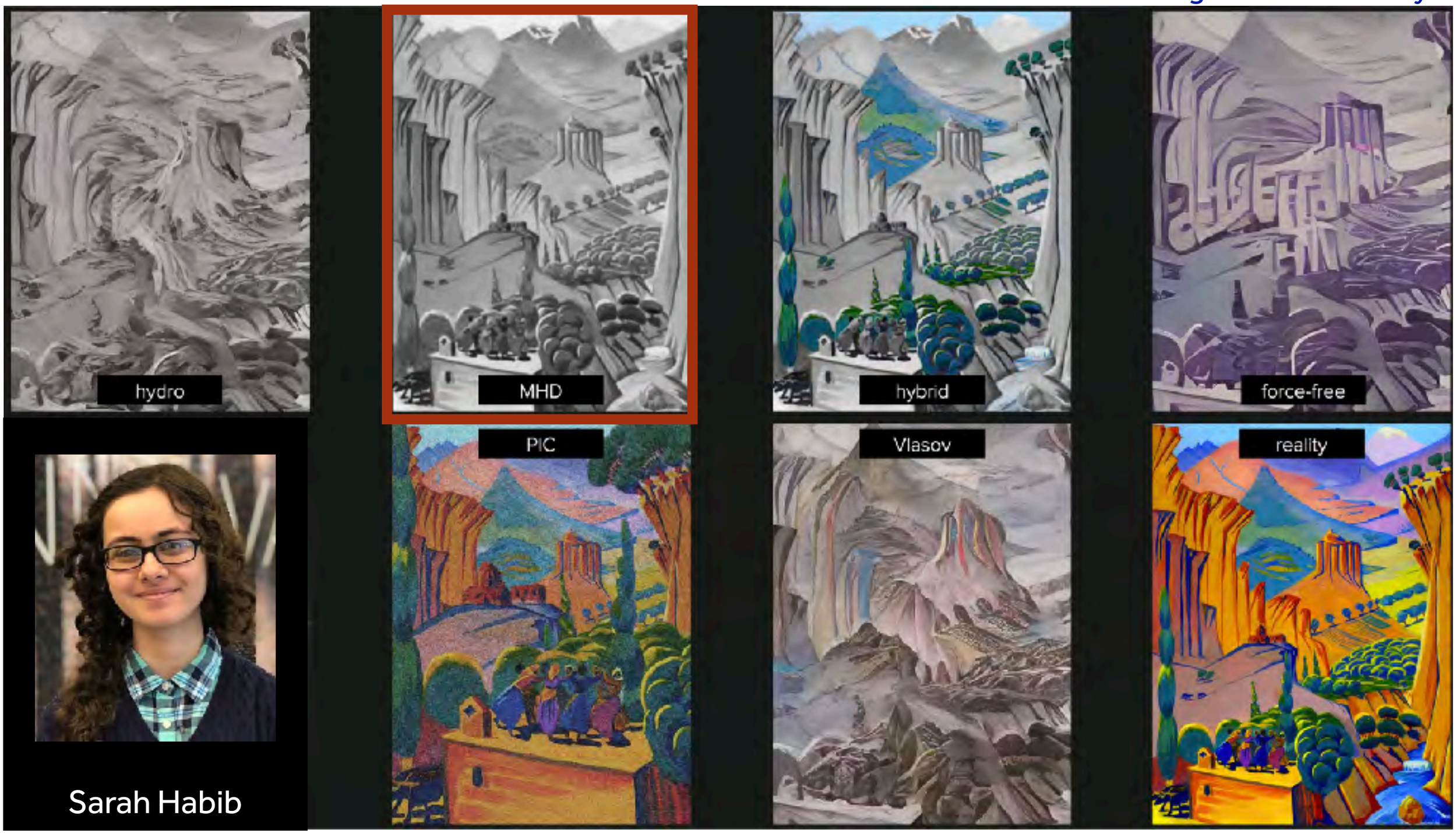
Vlasov Solver (Brute force 6D phase space):

How accurate can a computer draw?

Extremely expensive! Does it really work for global problems?

Choosing the right approximation

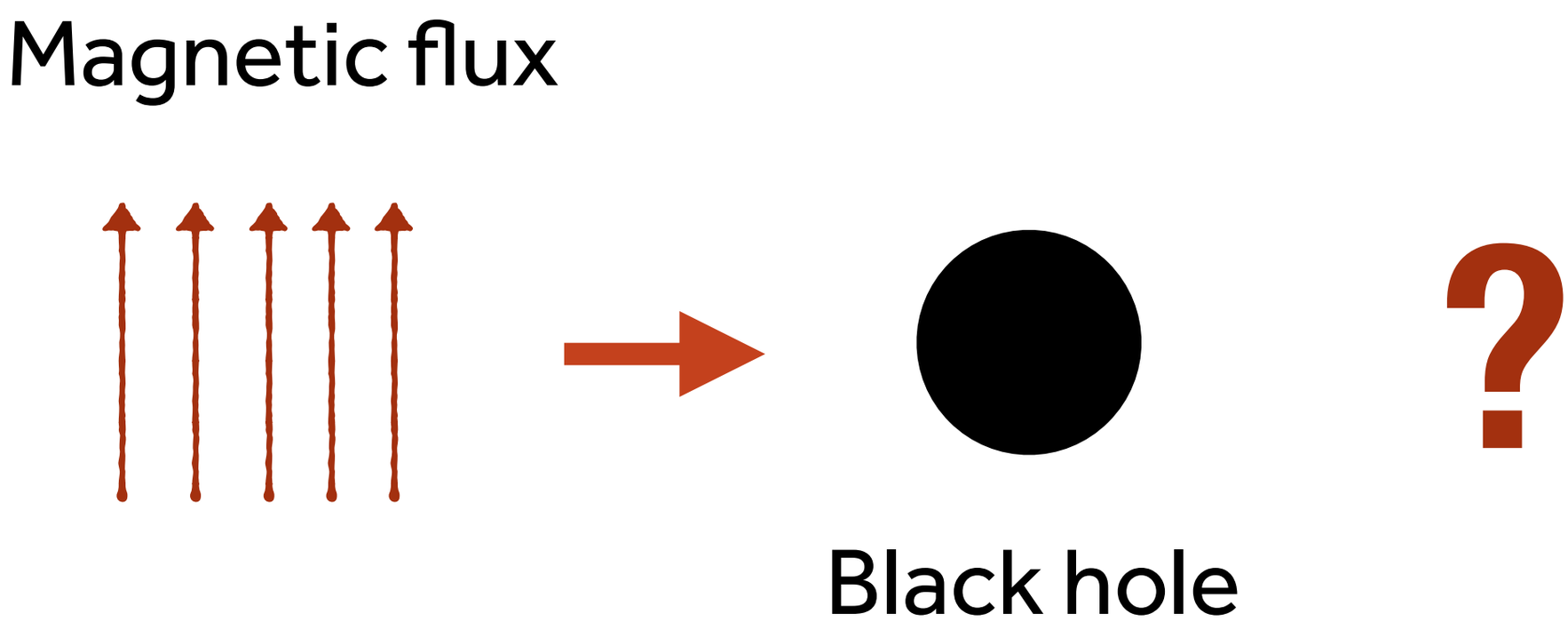
Image credit: Hakobyan



Sarah Habib

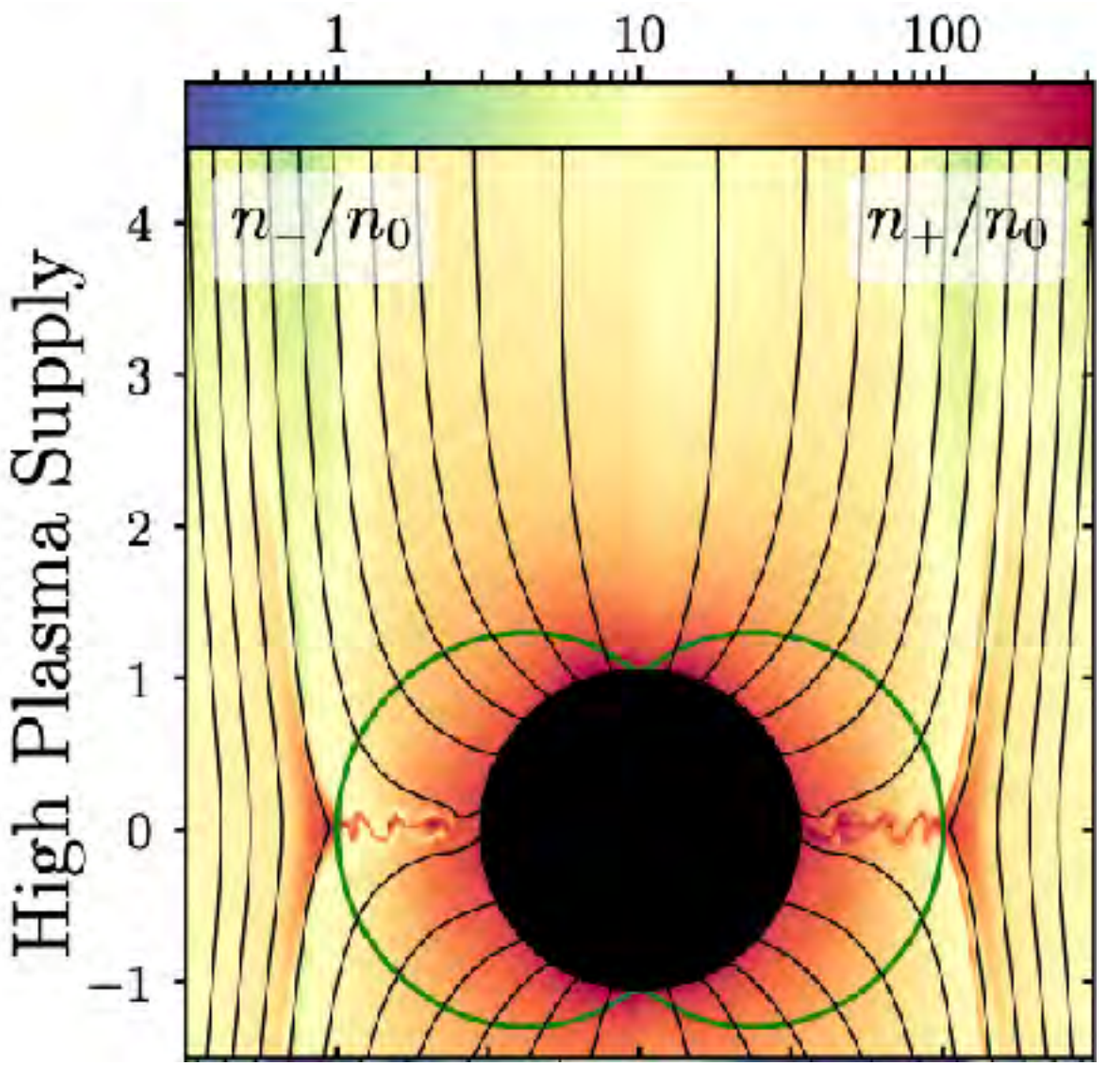
How accurate can a computer draw?

Choosing what is feasible!

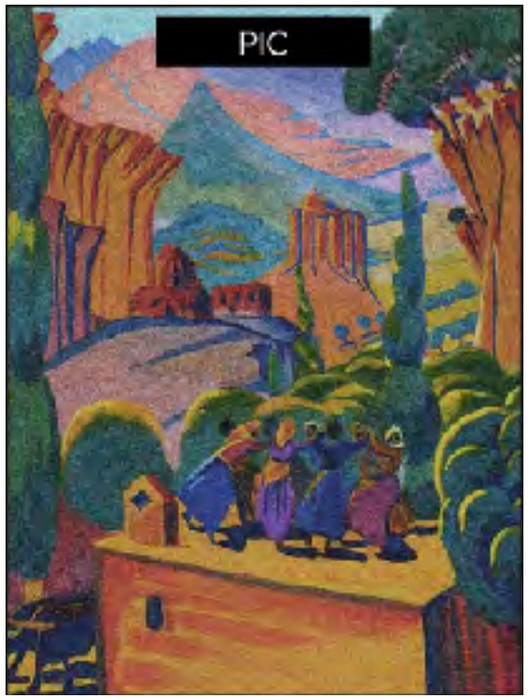


For conducting background

Black hole accretion

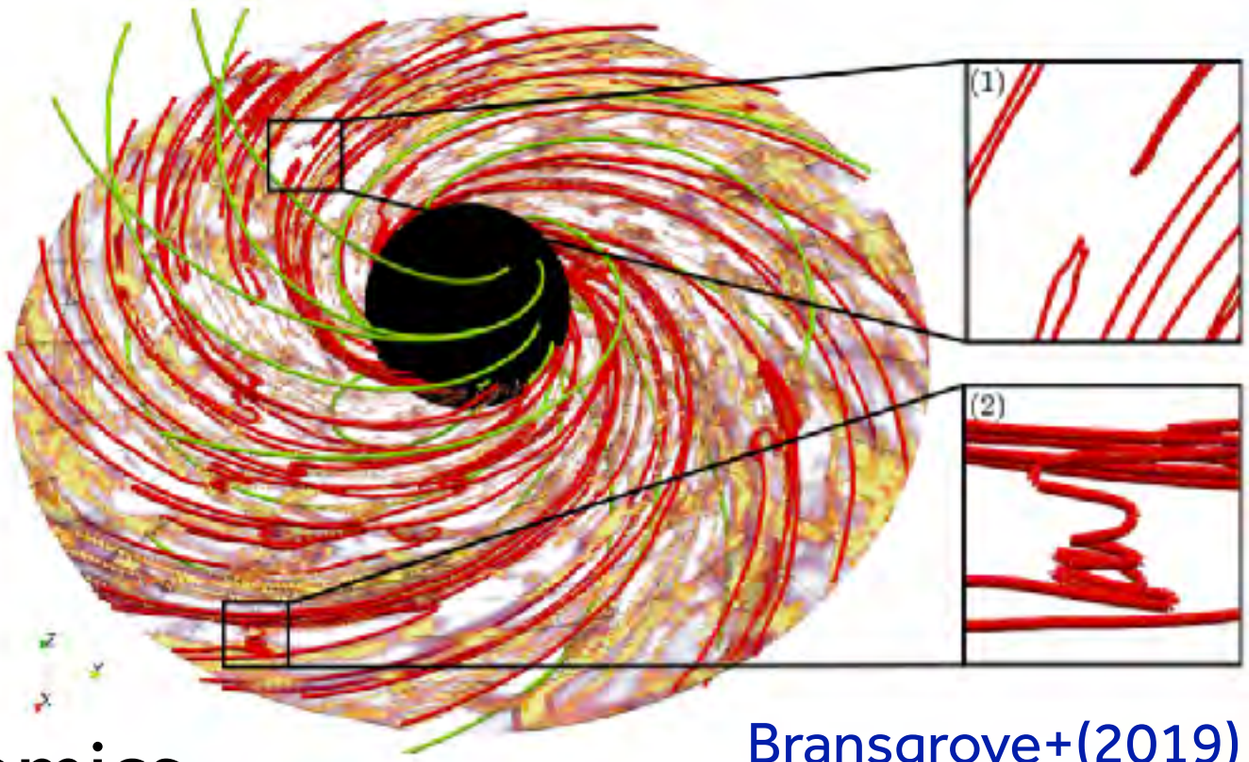


Parfrey+(2019)



Develop current sheet within ergosphere.

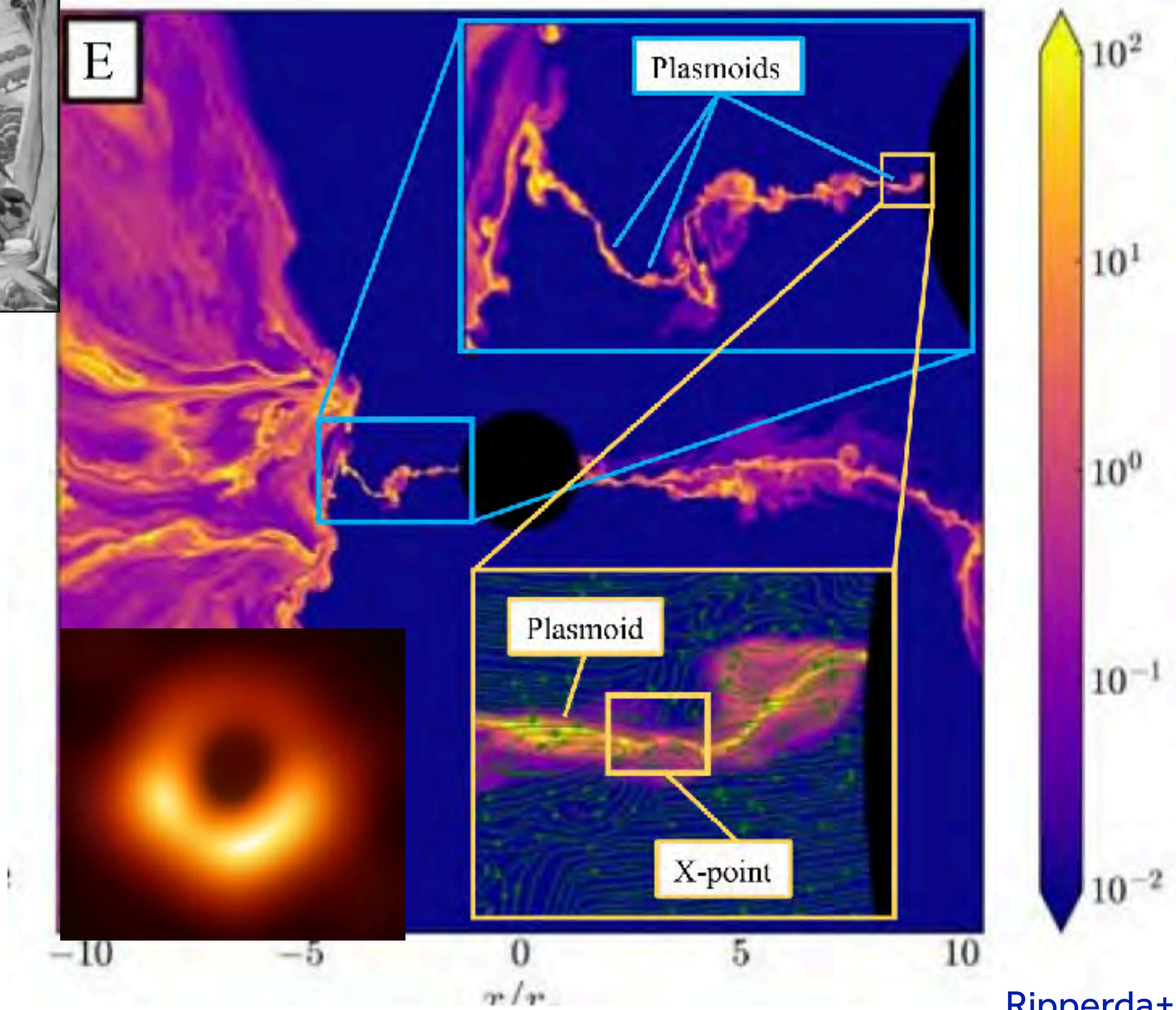
Dynamics governed by magnetic reconnection!



Bransgrove+(2019)

Observational signatures and time scales can be influenced by reconnection dynamics

Black hole accretion



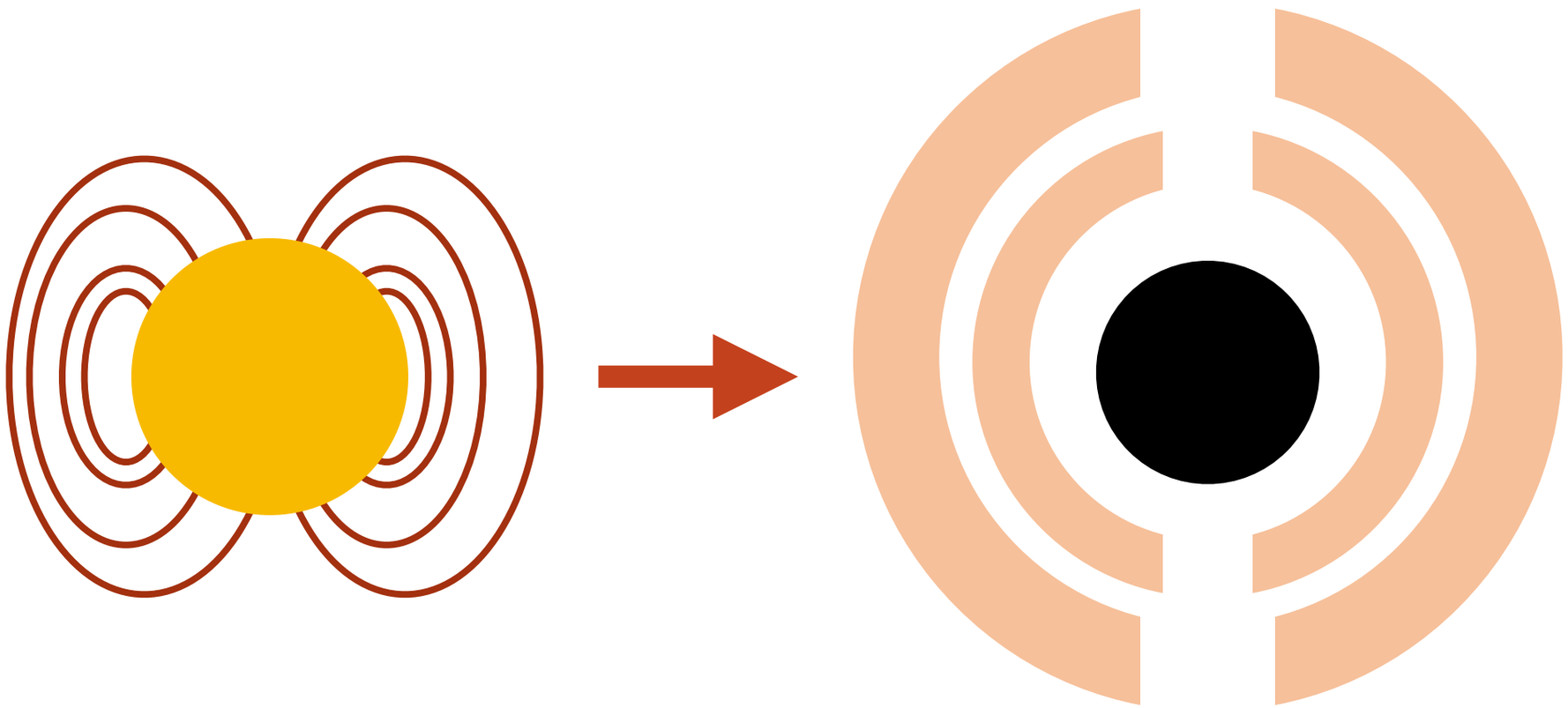
Ripperda+(2021)

A new take on collapsing neutron stars

Hypermassive neutron stars formed in mergers eventually collapse to black holes

Lifetime can be up to ~ 1 day

Ravi & Lasky 2014



Essentially Oppenheimer-Snyder with magnetic fields!

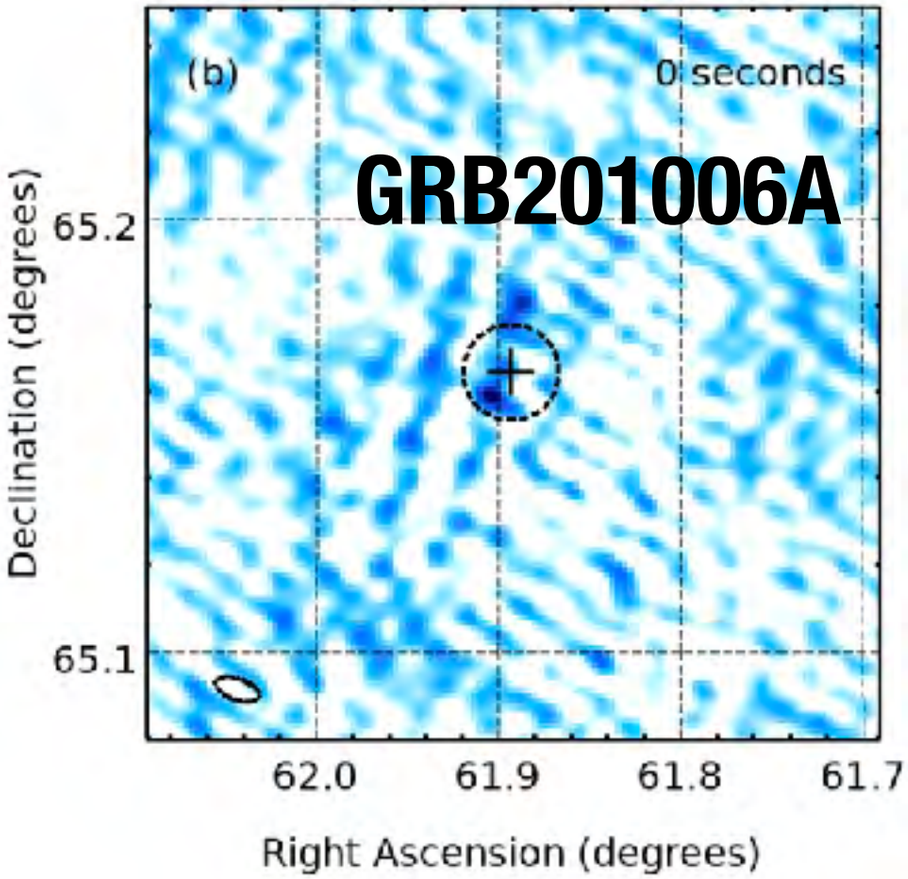
Thorne (1971), Price (1972), Baumgarte & Shapiro (2003)

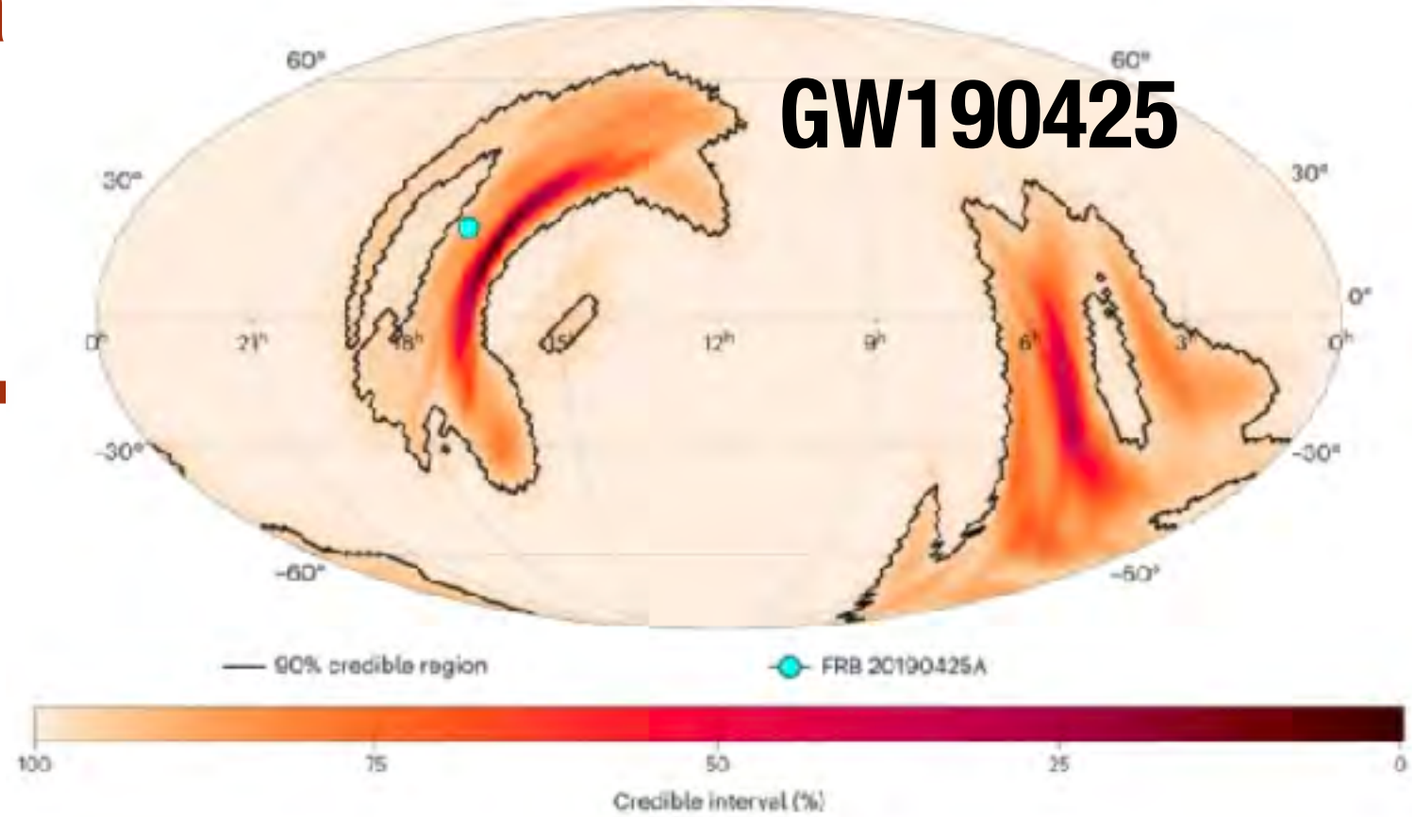
Radio bursts after merger?

Recent interest due to claimed association of radio bursts with neutron star mergers Moroianu+(2023); Rowlinson+(2023)

Caveat: *Dense ejecta environment…* Bhardwadj+(2023), Radice+(2023)

Radio? Rowlinson+ (2023) Moroianu+(2023)

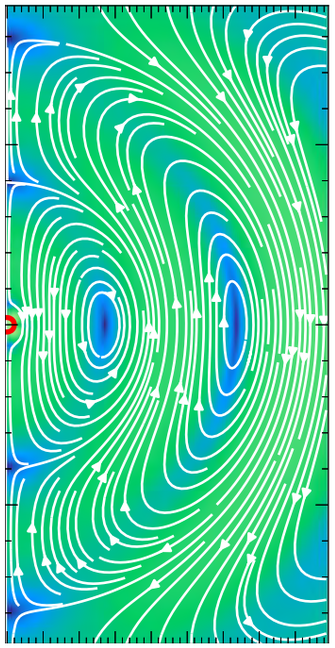




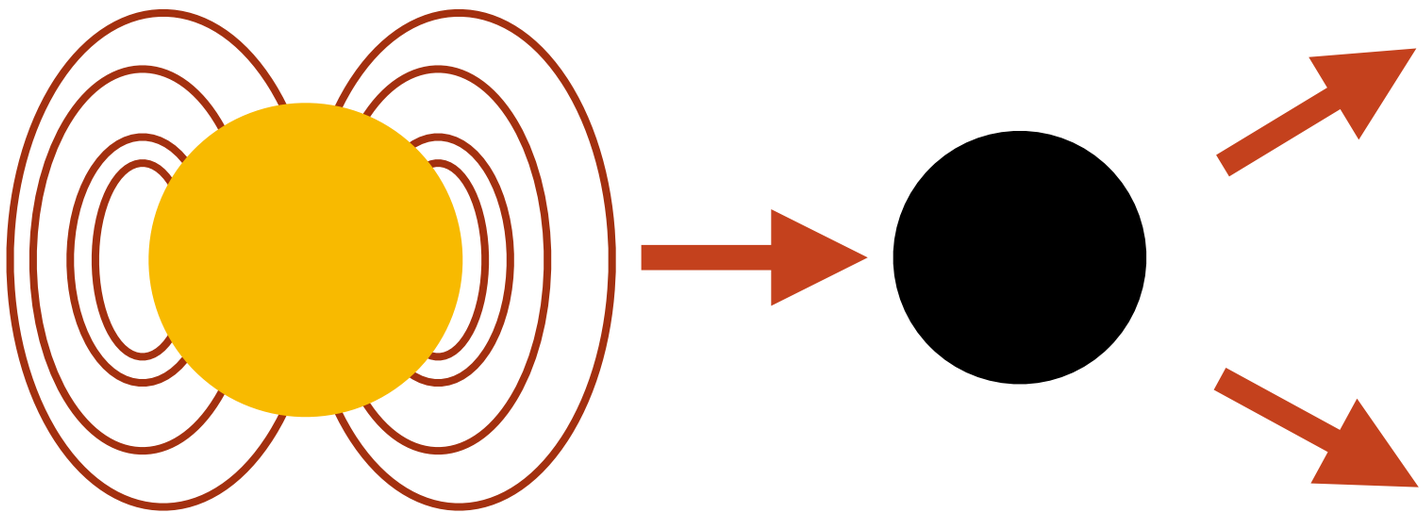
ERM+ (ApJ 2018), see also Baumgarte

EM burst from collapsing neutron stars

Numerical relativity +

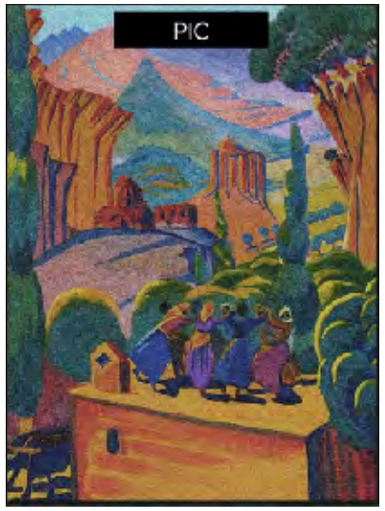


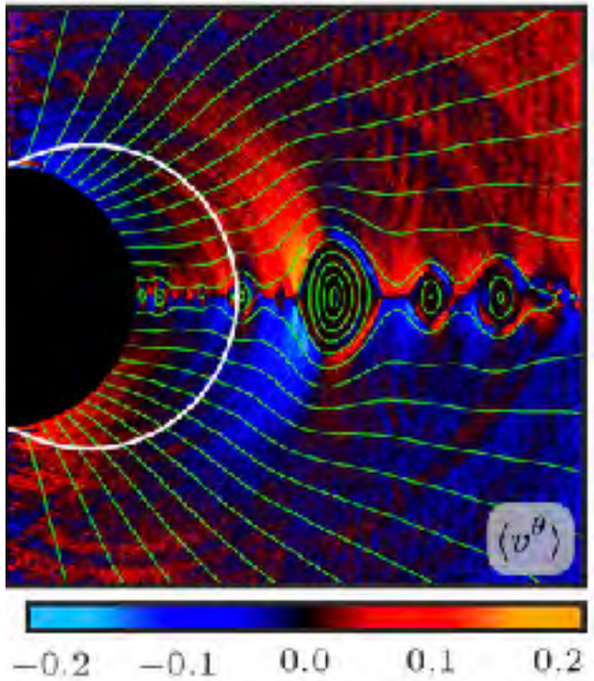
Radio?



Neutron star

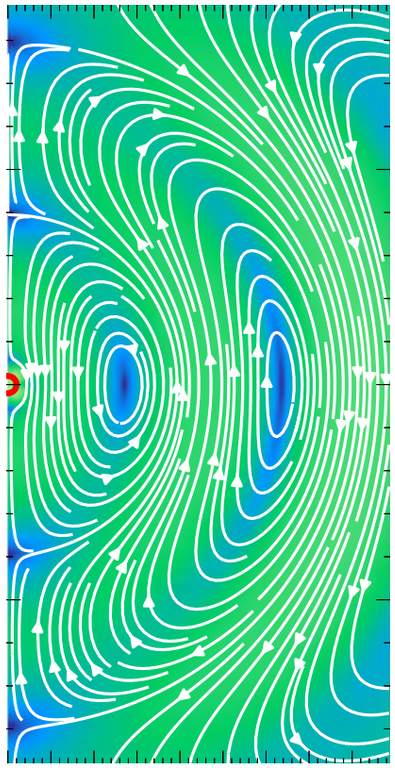
Toy model +





X-Ray?

EM burst from collapsing neutron stars

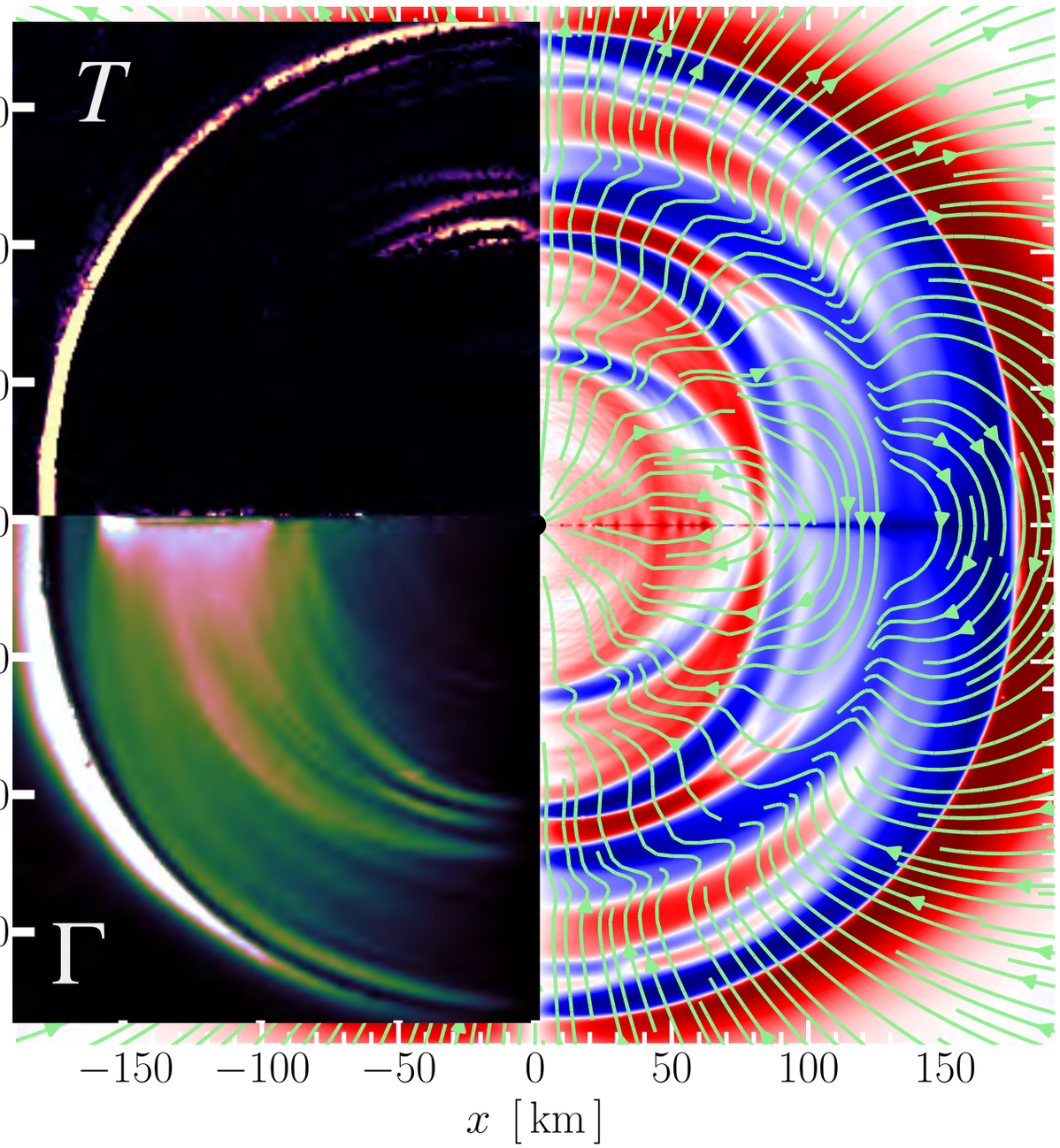


Plasma has large but finite conductivity.

Wave stumbles, forms monster radiative shock!

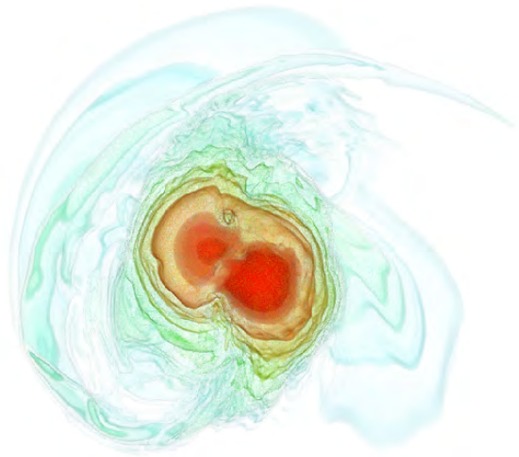
Beloborodov (2023)

Gamma ray bursts delayed by a day?!

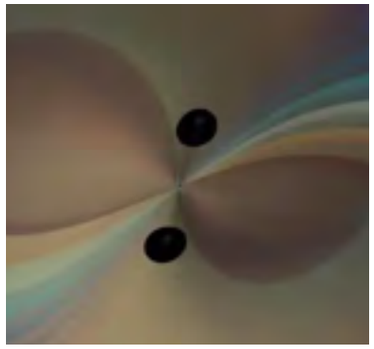


ERM, Beloborodov, Ripperda (in prep)

Computational relativistic astrophysics

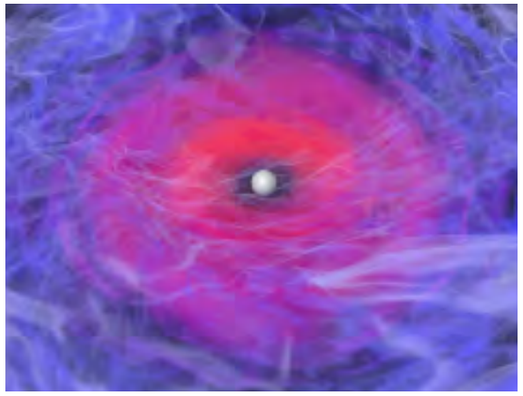


Multi-messenger

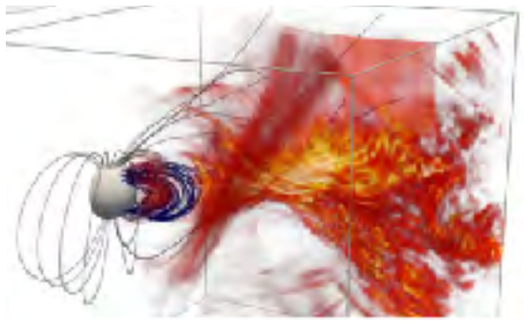


Spacetime dynamics

Explosive transients



Black hole accretion



Relativistic Magnetospheres

Relativistic outflows

Computational Relativistic Astrophysics

Questions?
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