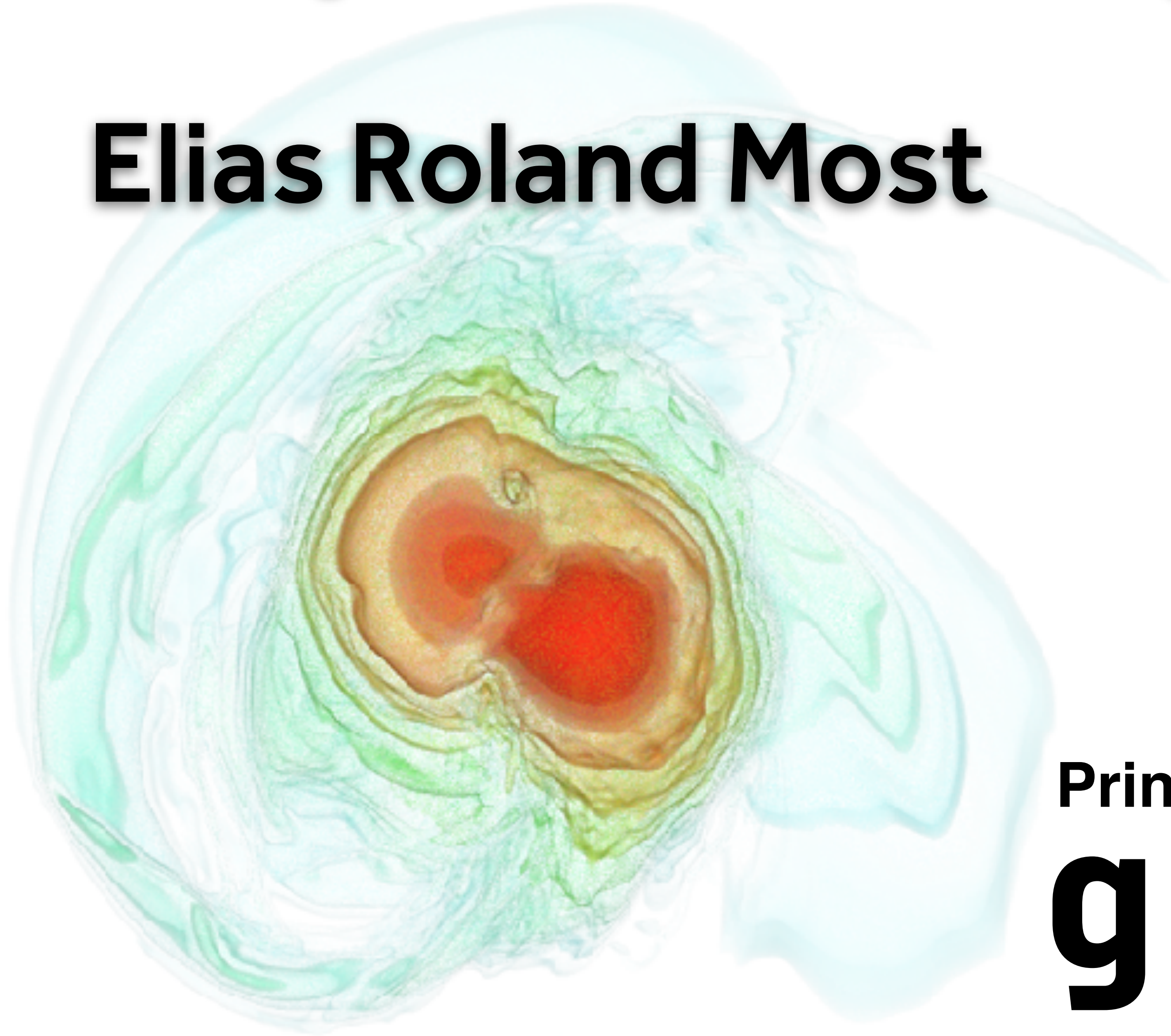
Simulations of Compact Binary Mergers: From Gravity to Nuclear Physics

Part I

Elias Roland Most



PRINCETON CENTER FOR THEORETICAL SCIENCE

Princeton gravity Initiative

IAS INSTITUTE FOR ADVANCED STUDY

PRINCETON UNIVERSITY

Today's talk

Dense nuclear matter

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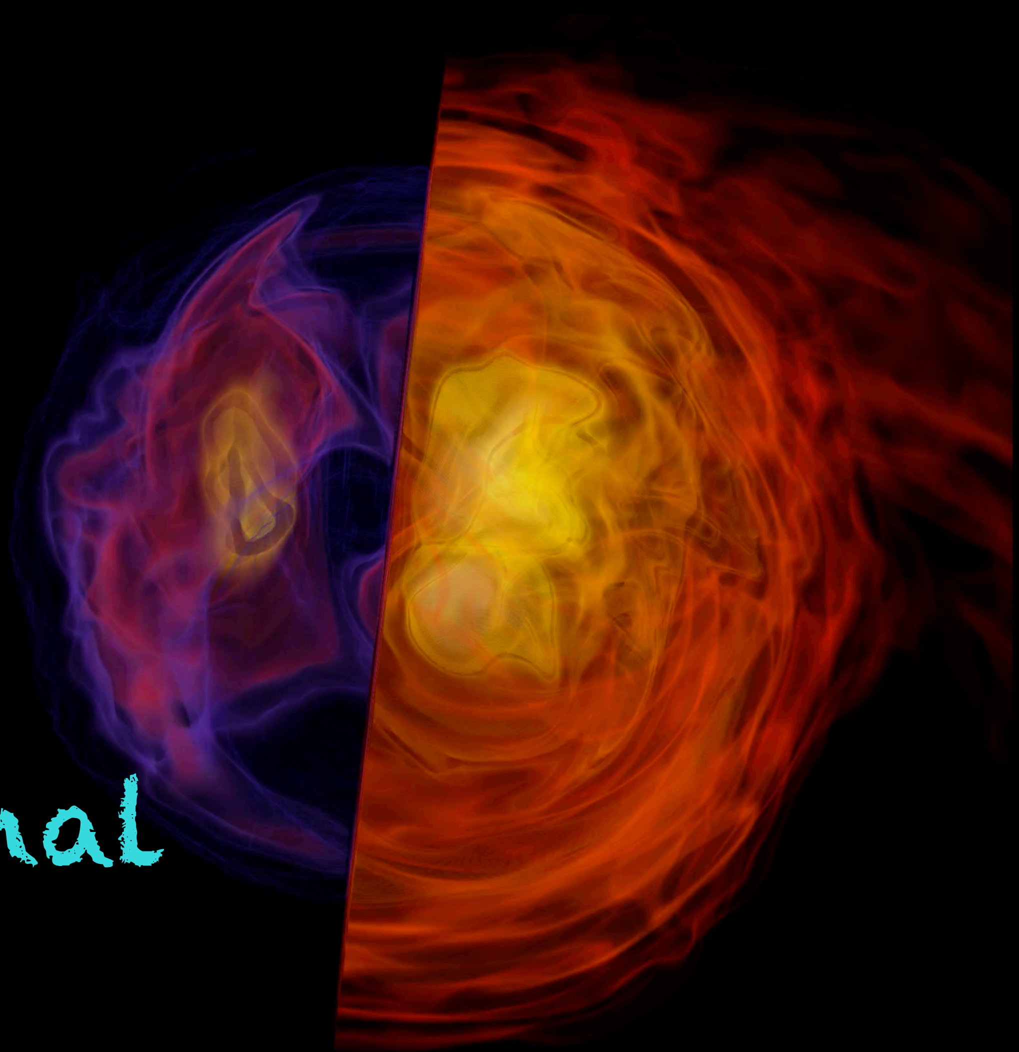
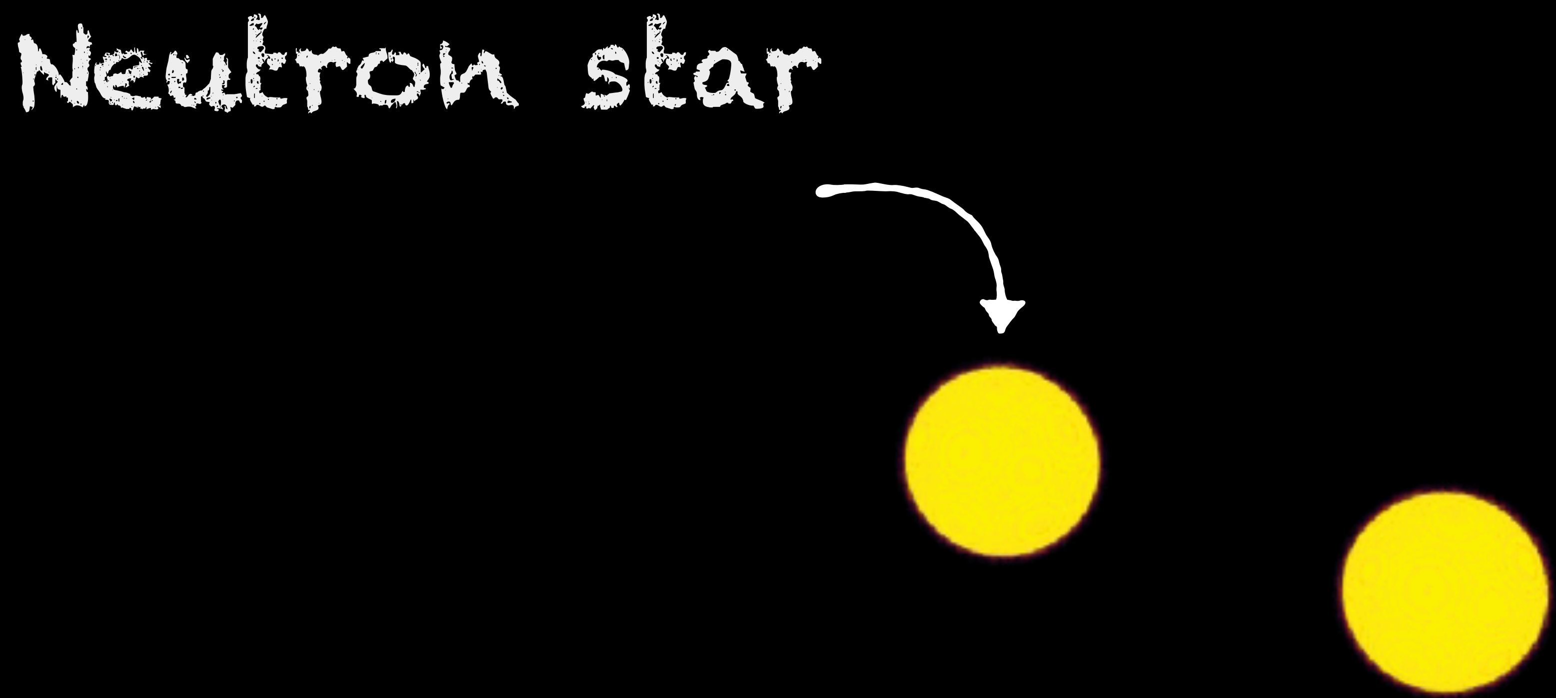


Extreme plasmas

Gravitational waves

Today's protagonist:



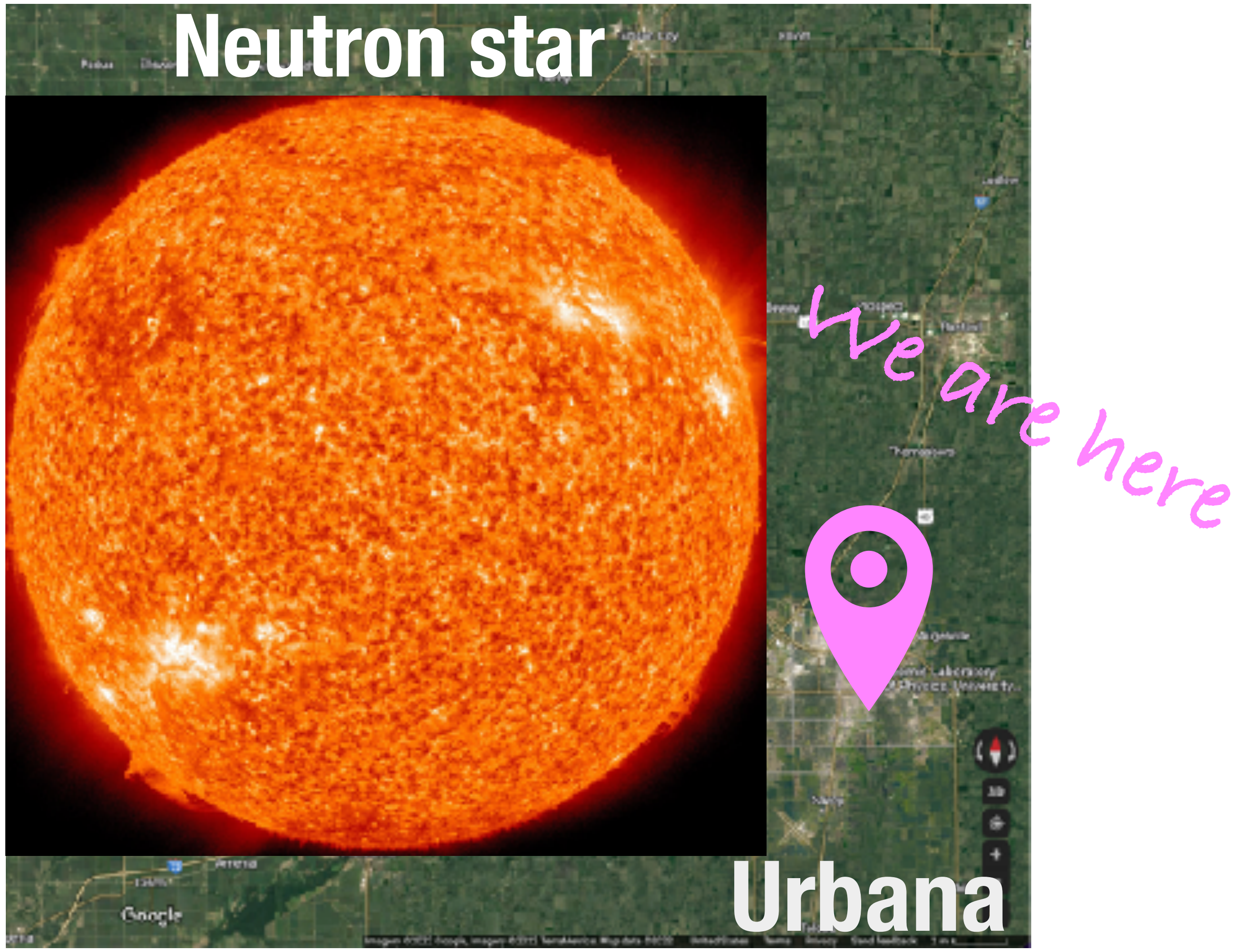
What does a neutron star look like?

How big is a neutron star?

About 20-30 km in diameter

How massive is a neutron star?

Around 1-2 solar masses



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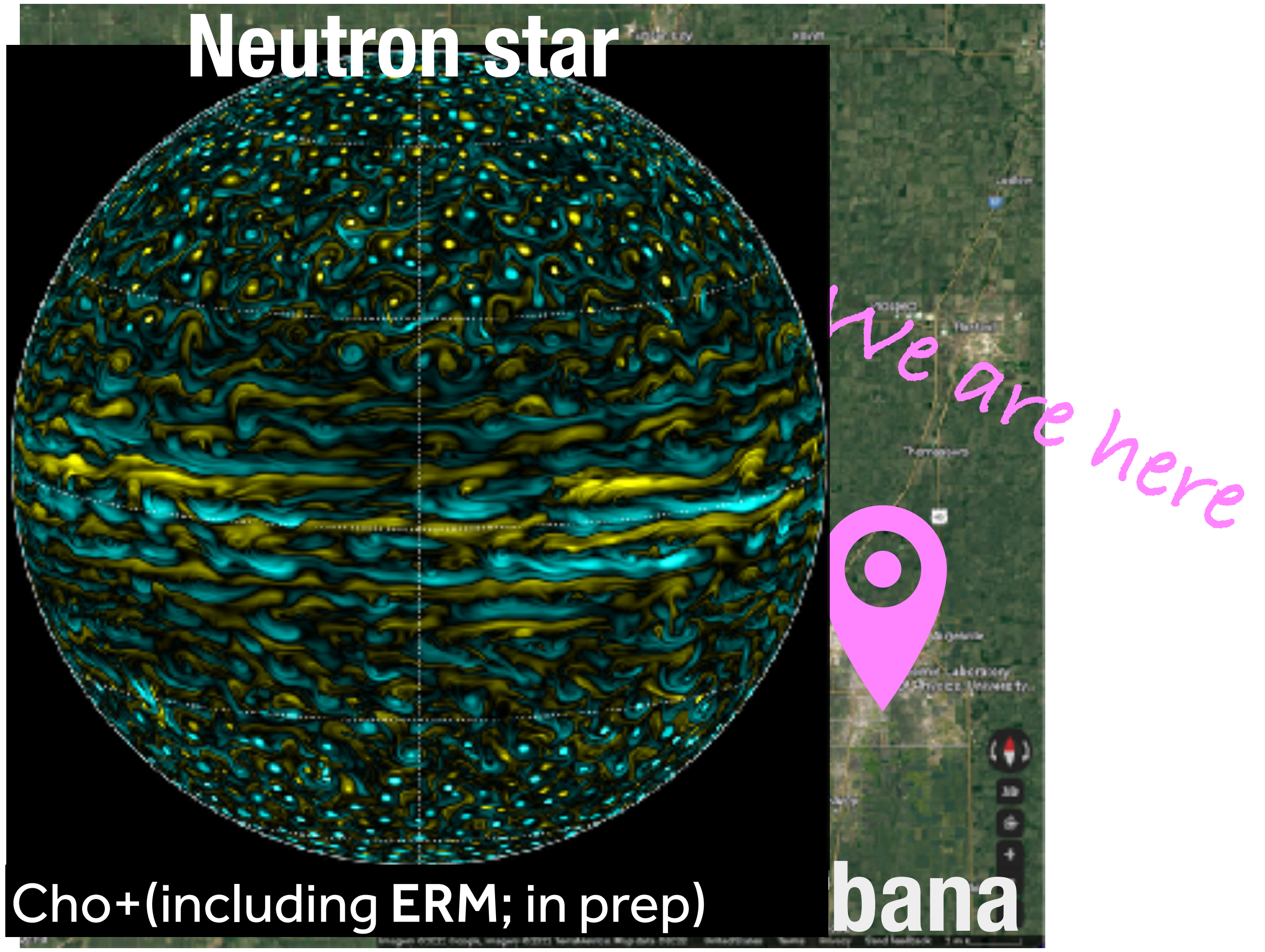
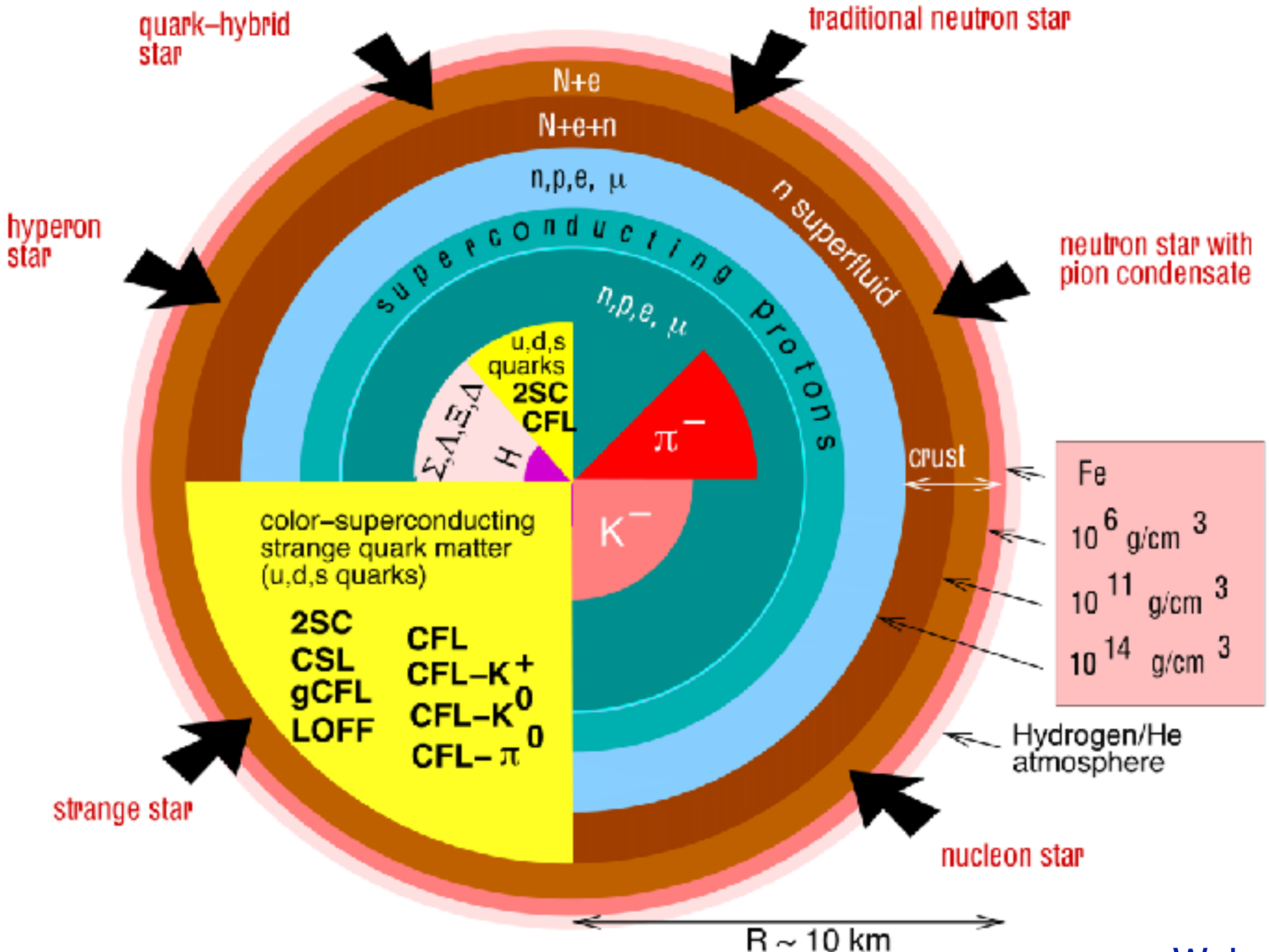


What is a neutron star made of?

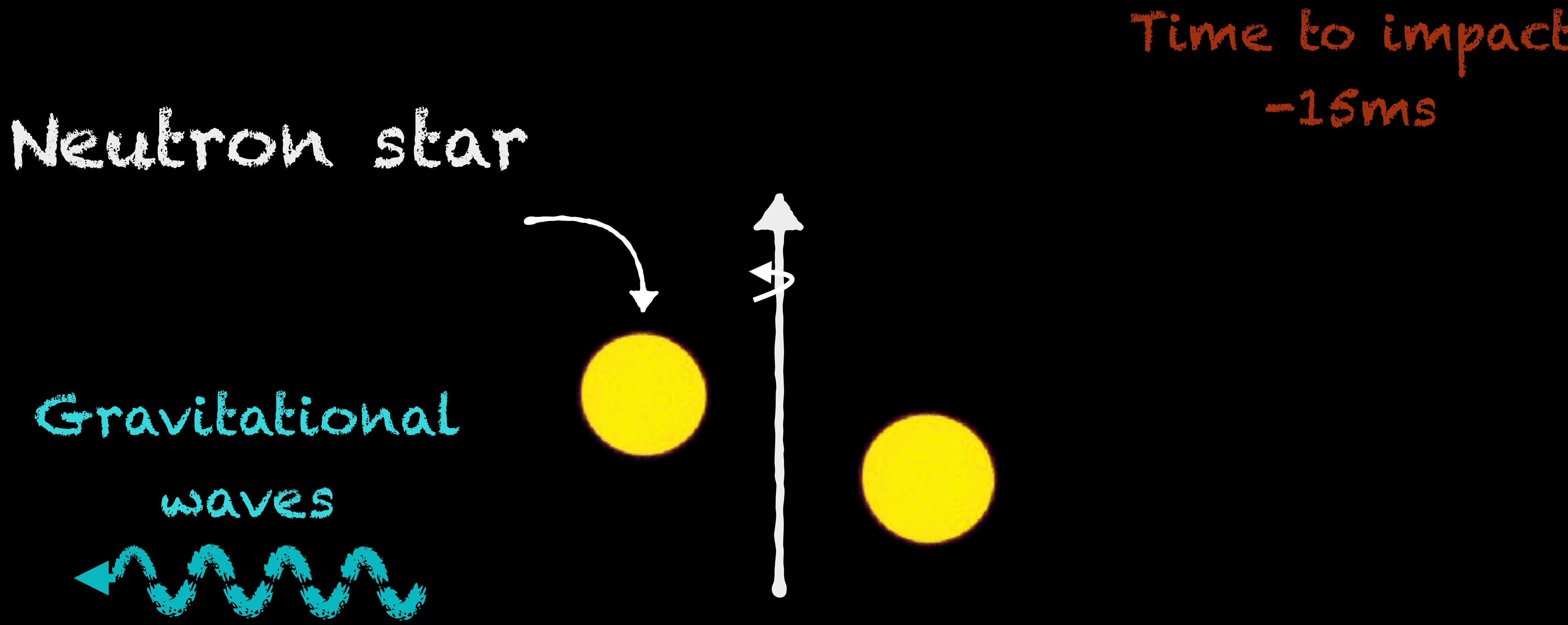
$$\bar{\rho} \simeq \frac{\text{mass}}{\text{volume}} \simeq \frac{M}{\frac{4}{3}\pi R^3} \simeq \frac{2\times 10^{33}\,\text{g}}{4\times\left(10^5\,\text{cm}\right)^3} \approx 5\times 10^{14}\frac{\text{g}}{\text{cm}^3}$$

Neutron stars as probes of fundamental physics!



Weber+(2007)

Today's protagonist:

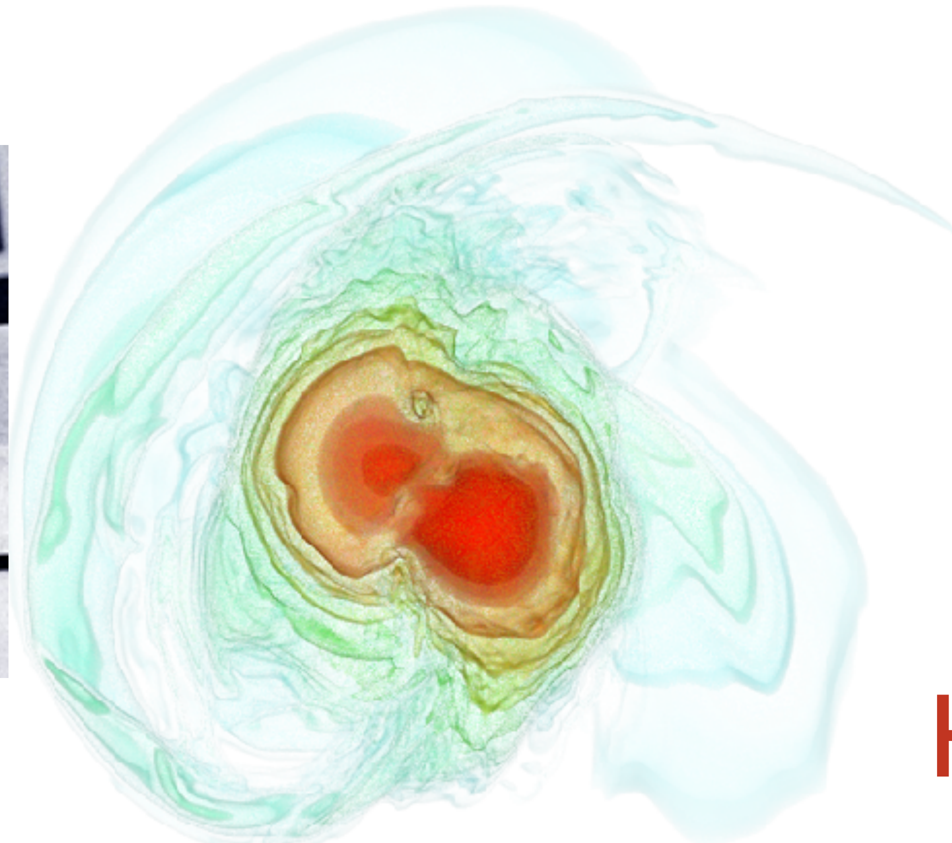


Late stage gravitational wave emission leads to inspiral and merger!

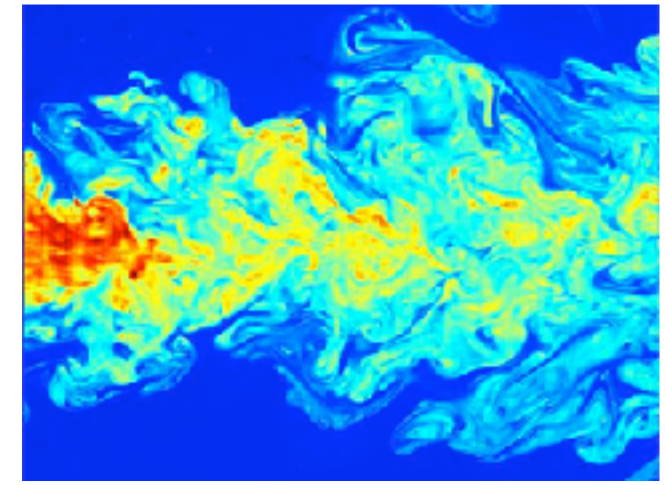
The physics of compact binary mergers

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

General relativity

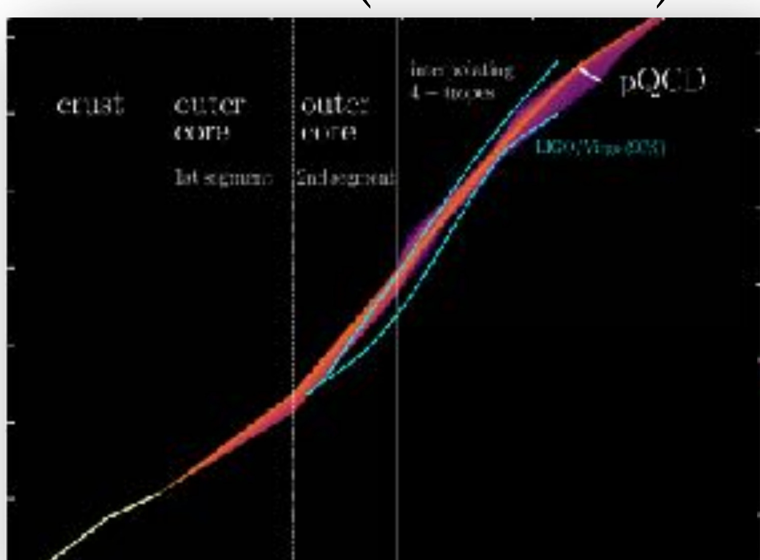


$$\nabla_\mu T^{\mu\nu} = 0$$



Hydrodynamics

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

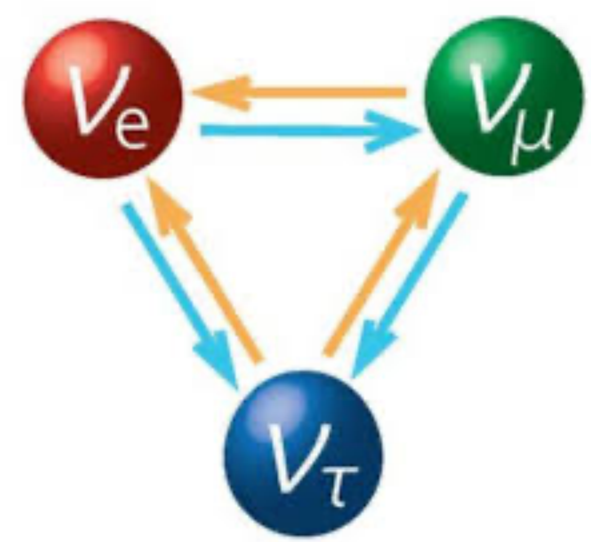


Nuclear physics

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

Electrodynamics

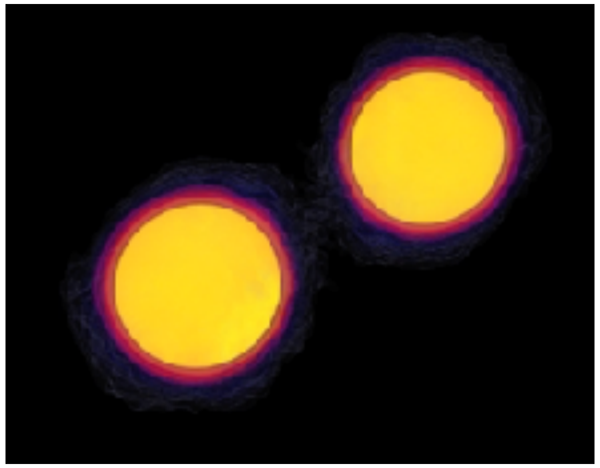
$$n \to p + e^- + \bar{\nu}_e$$



Weak interactions

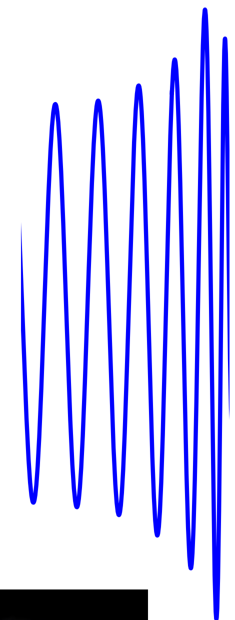
Animations: Breu et al.

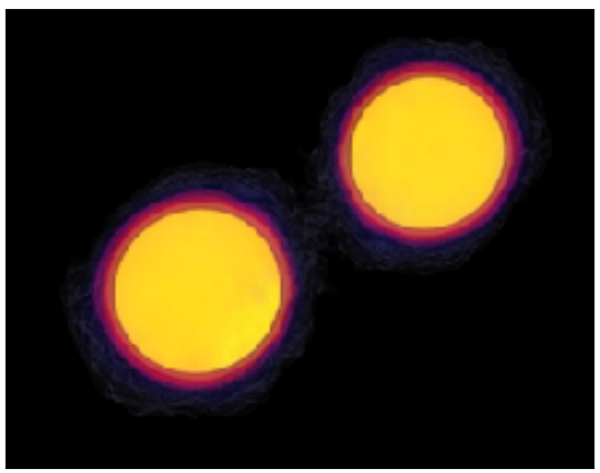
The final fate of a neutron star binary



The final fate of a neutron star binary

Gravitational waves





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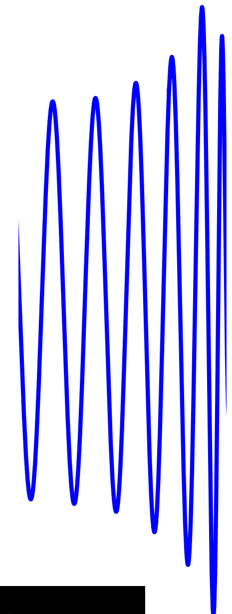
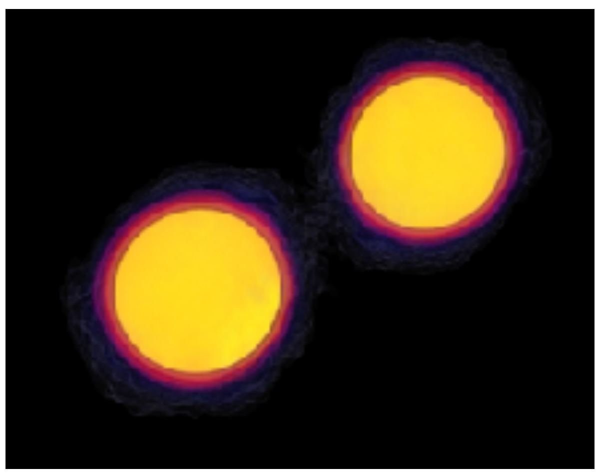
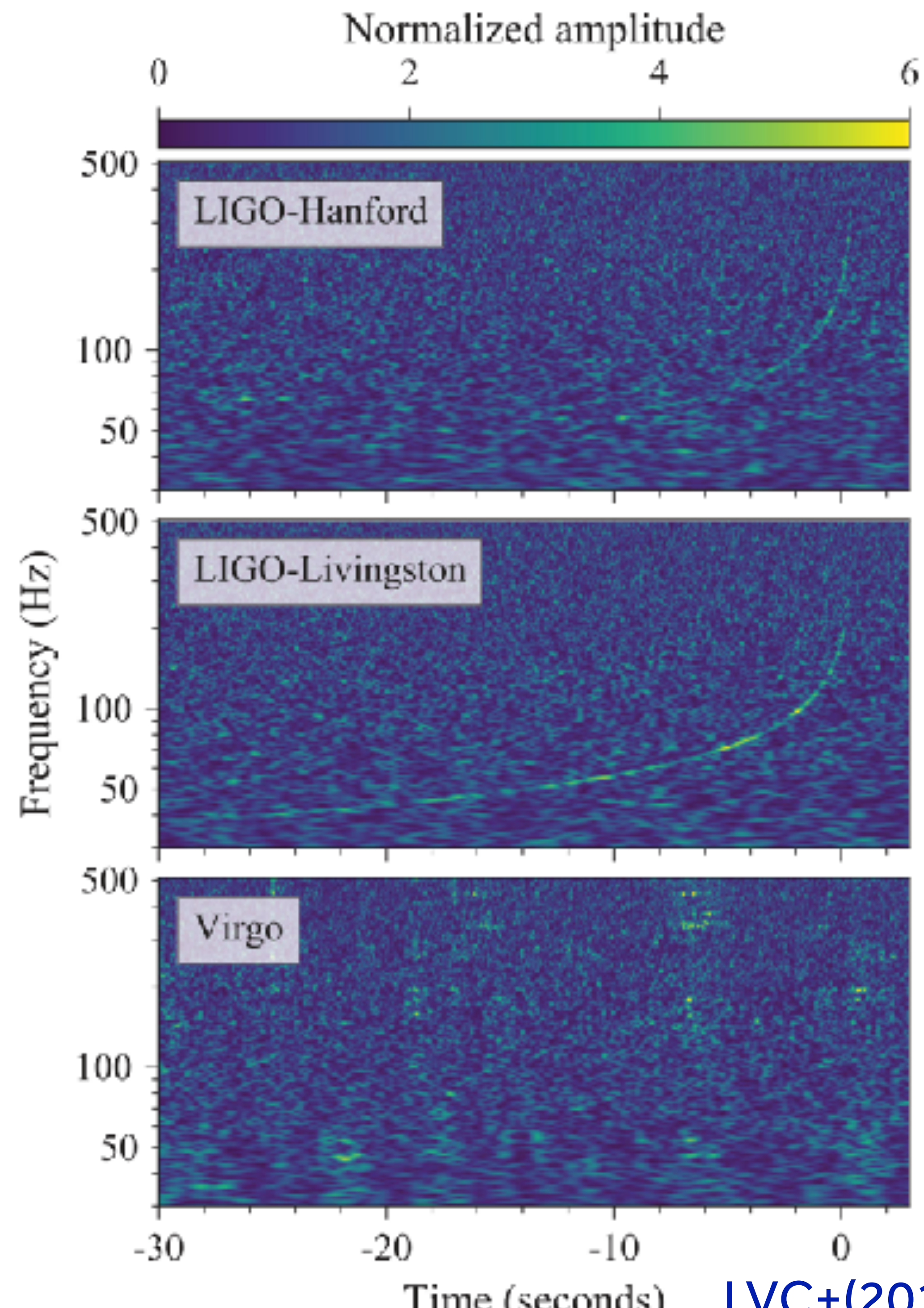


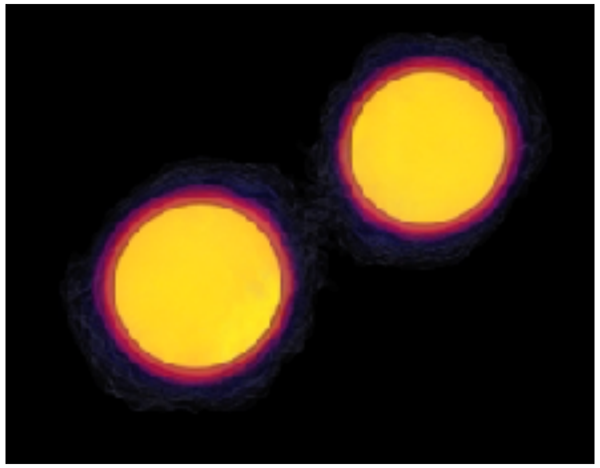




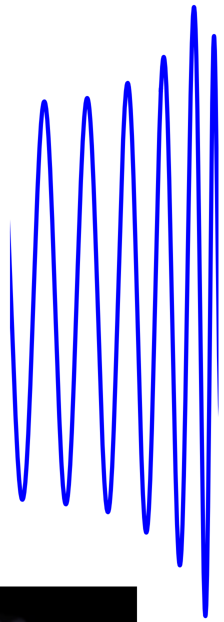
LVC+(2017)

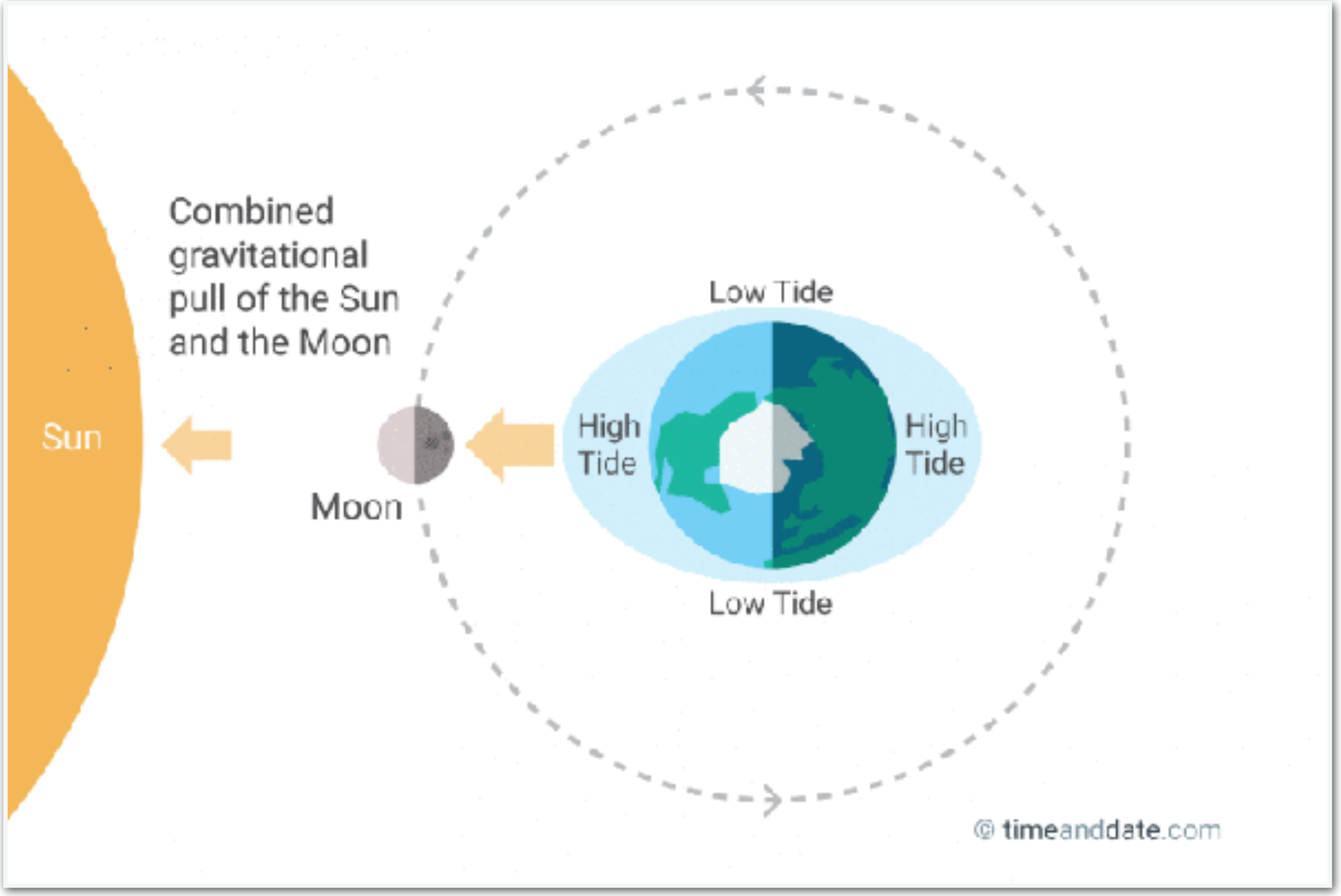
First direct detection of a gravitational wave signal from neutron star coalescence happened only in 2017.

The final fate of a neutron star binary



Gravitational waves



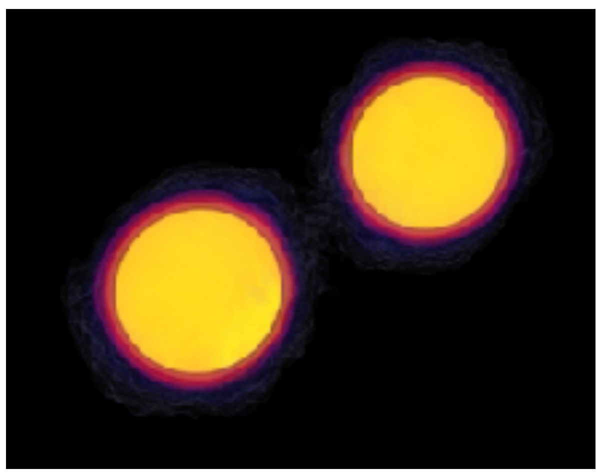


Neutron stars in binary are tidally deformed by companion

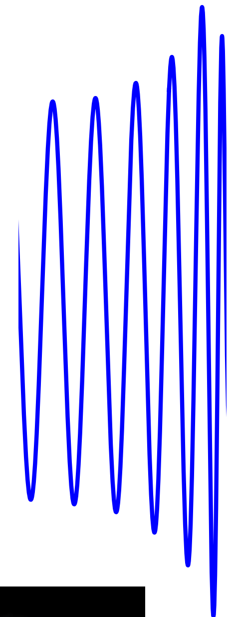
Tidal deformation correlates with the size of neutron stars.

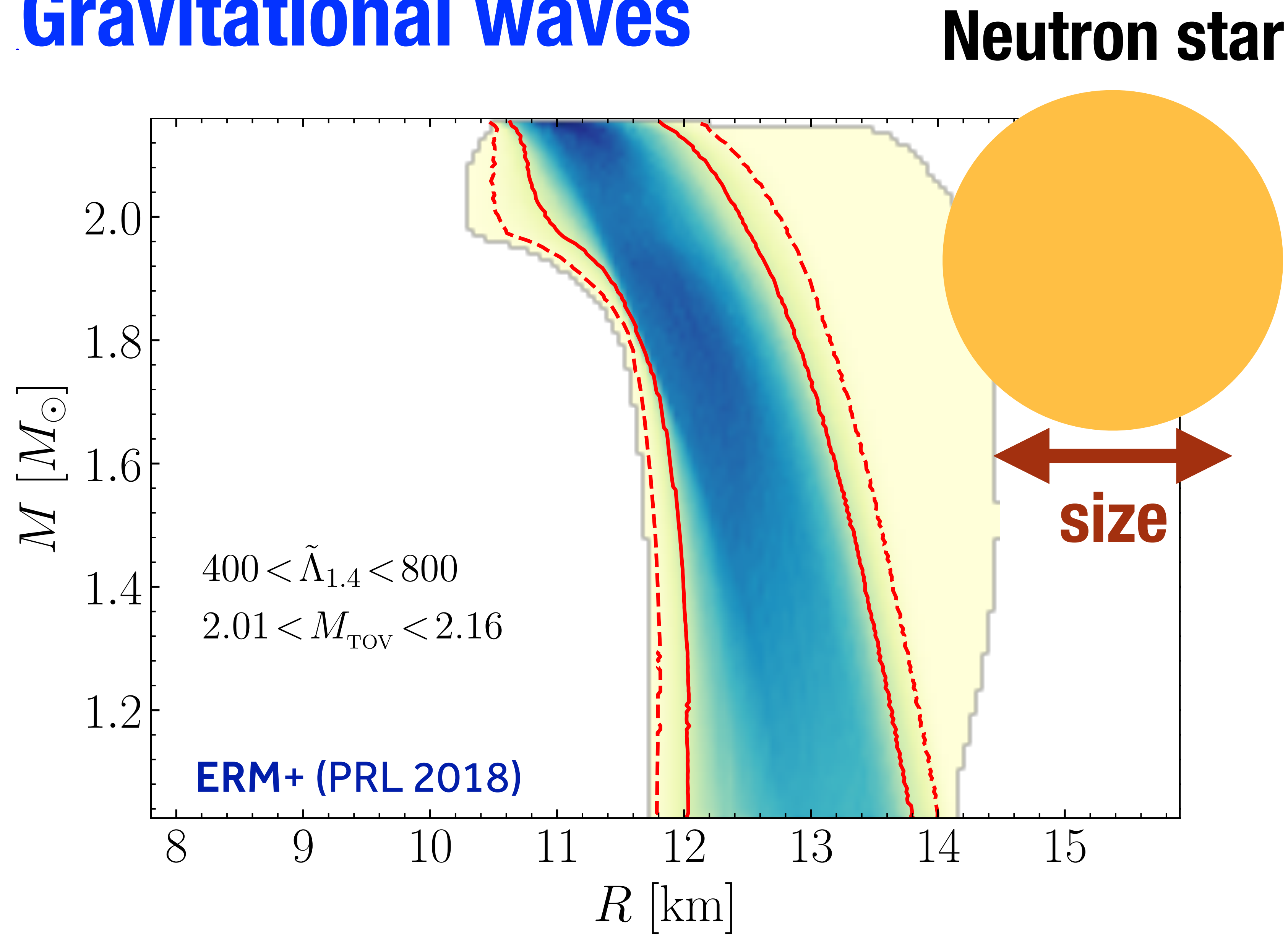
e.g. Flanagan & Hinderer (2008)

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

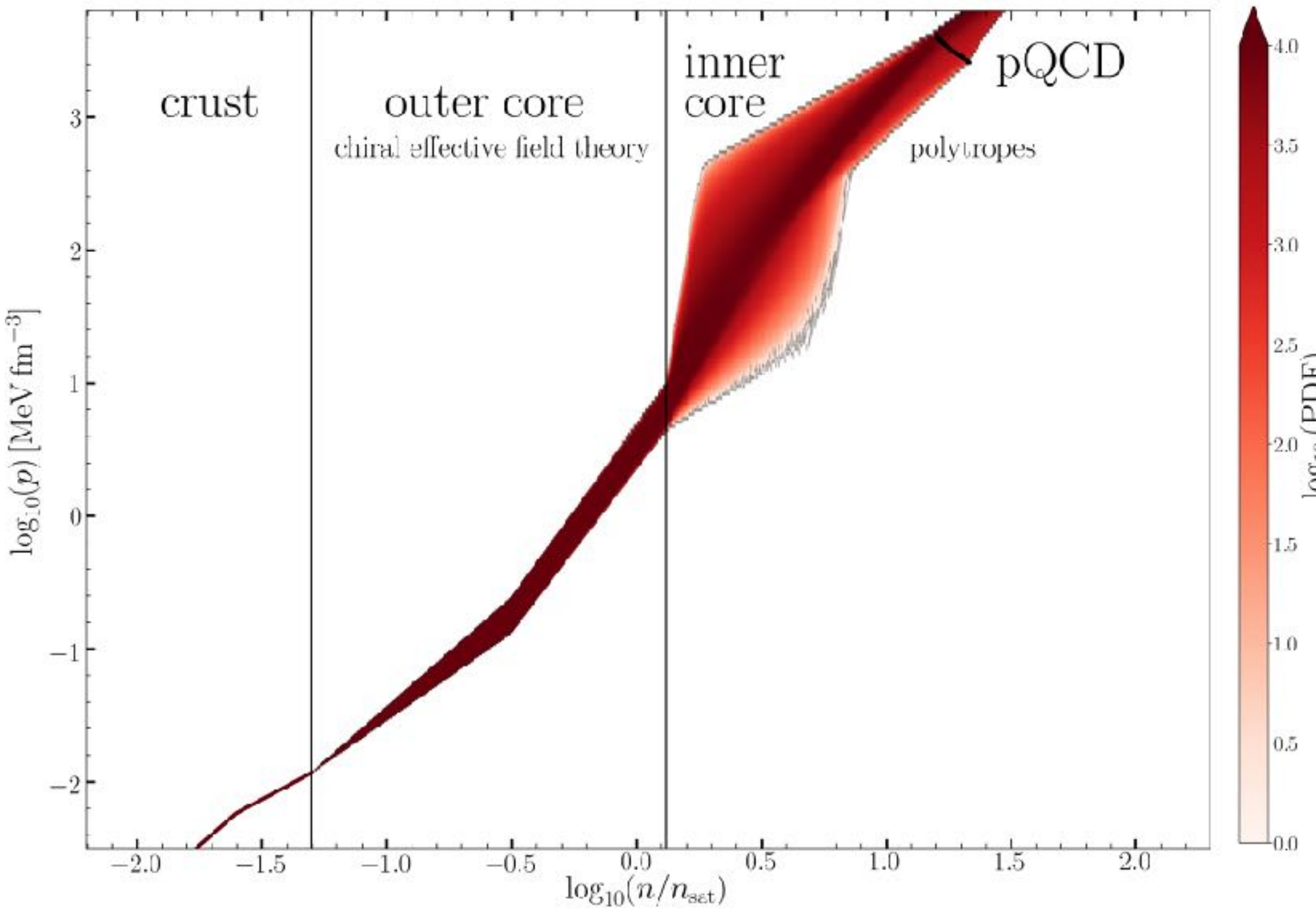
+ X-ray constraints: Riley+, Miller+, Raaijmakers+, Dietrich+ and others!

Constraining neutron star radii with gravitational waves from the inspiral.

The equation of state after GW170817

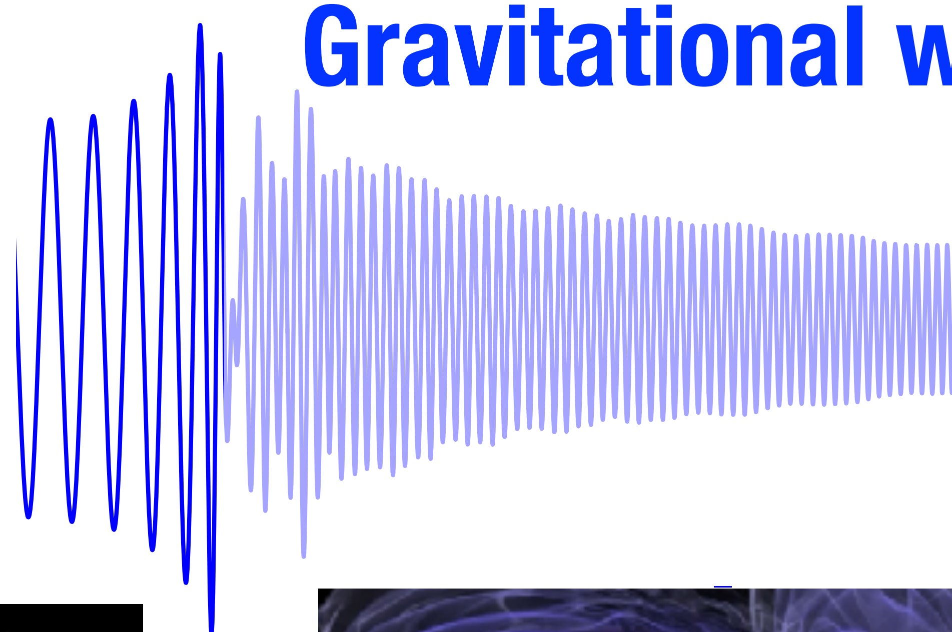
see works by Annala+, Chatziioannou+, Essick+, Dai+, Landry+, LVC+, De+, Margalit+, Ruiz+, Shibata+, Radice+, Raithel+, *and many more!*

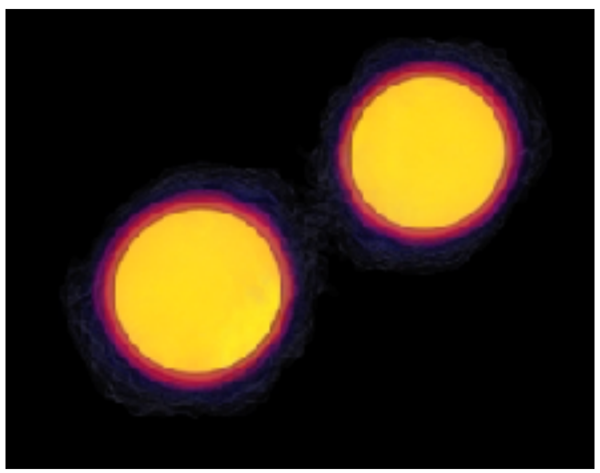
also joint constraints with NICER: Riley+, Miller+, Raaijmakers+, Dietrich+ and others*!*

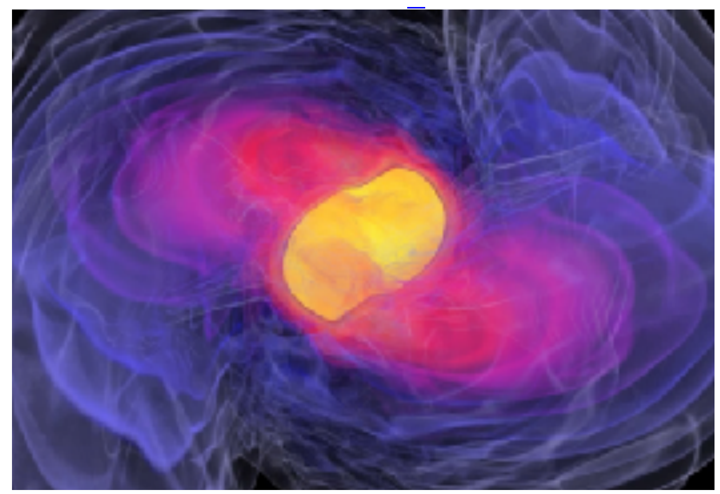


The final fate of a neutron star binary

Gravitational waves







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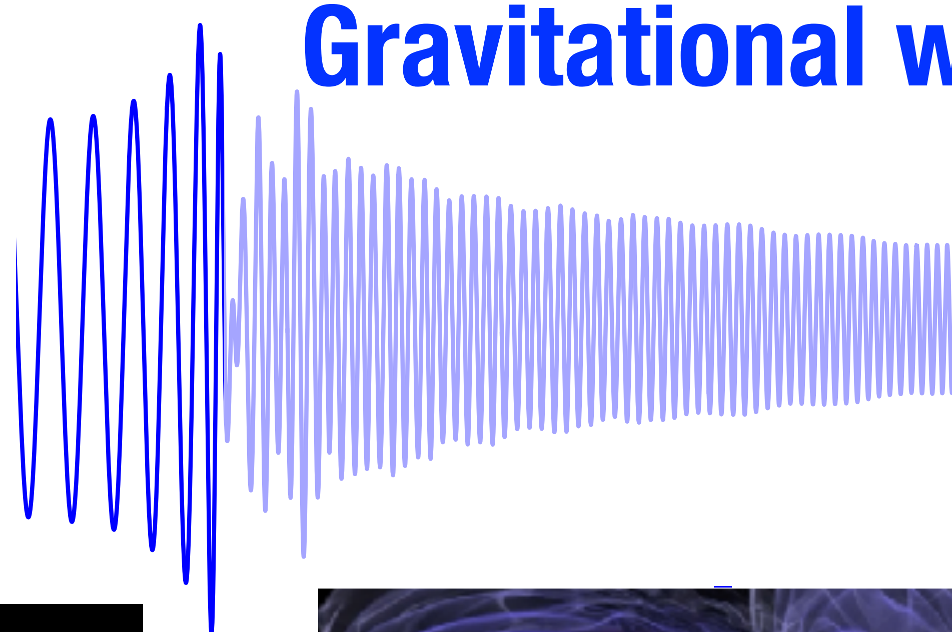
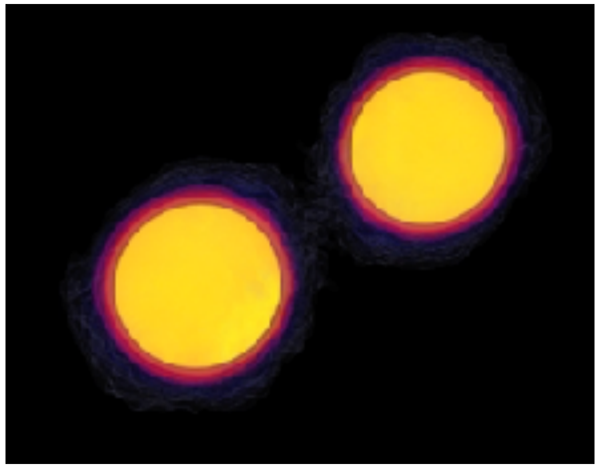
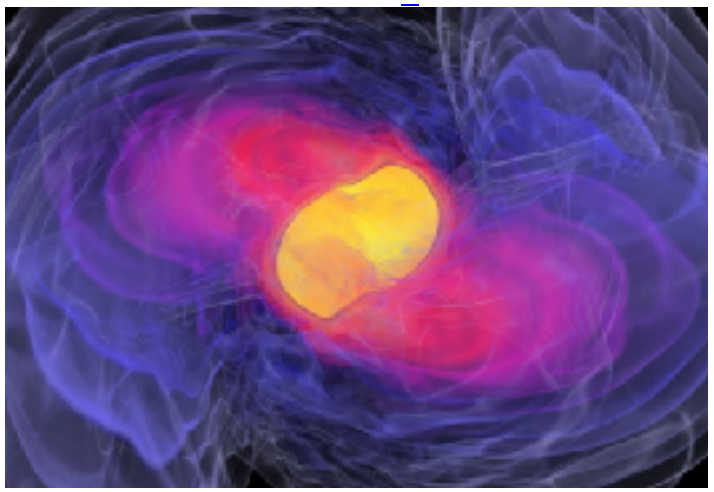
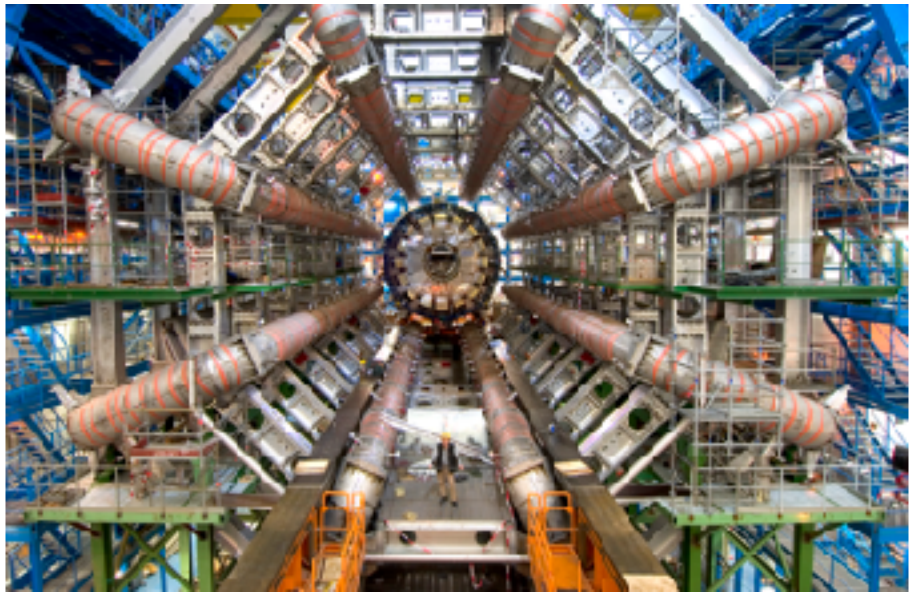


Gravitational waves

Neutron star mergers as cosmic colliders?

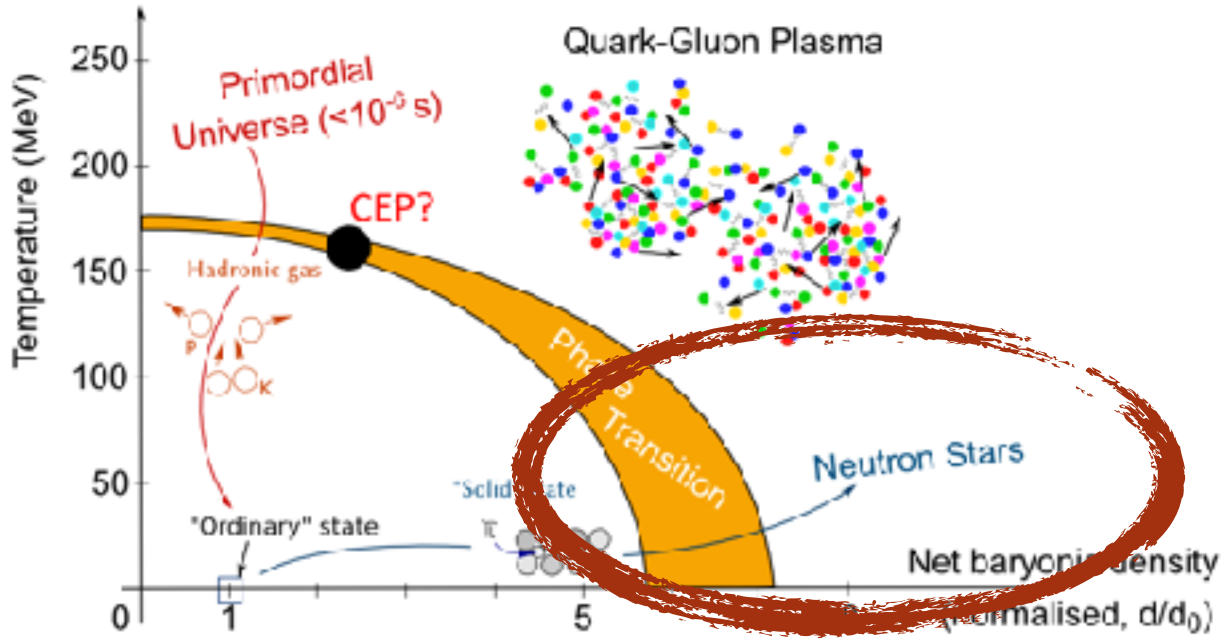






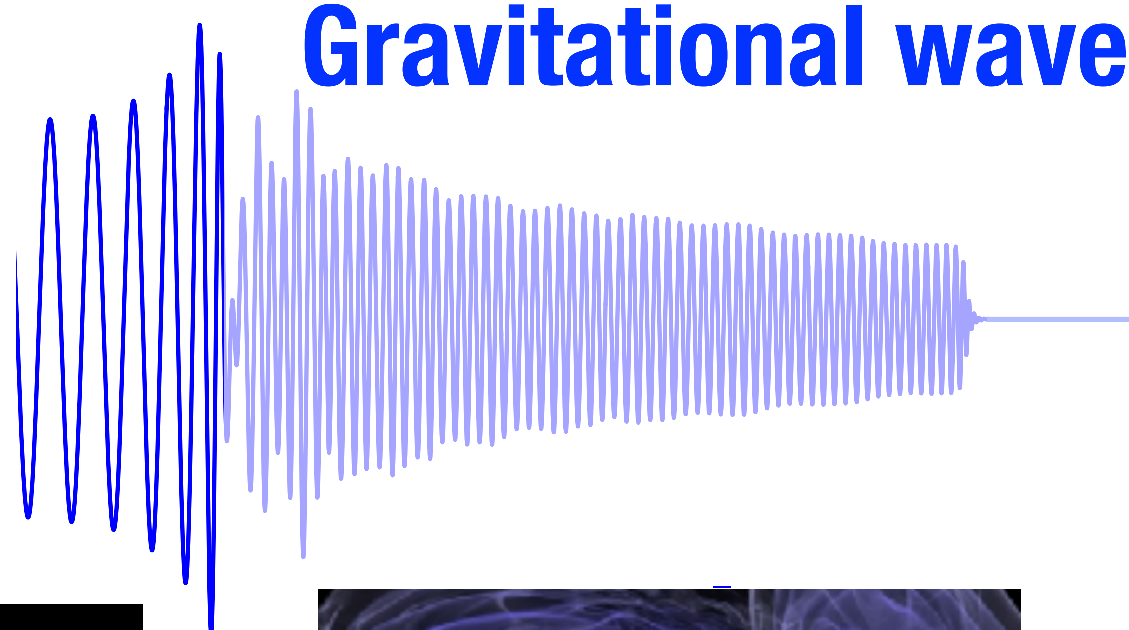
Can these events reveal extreme states of matter?

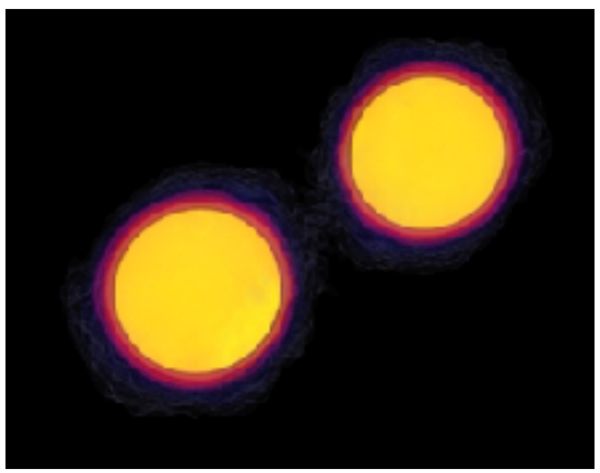
e.g. **ERM**+ (PRL 2019);
ERM+ (EPJA 2020);
ERM & Raithel (2021)

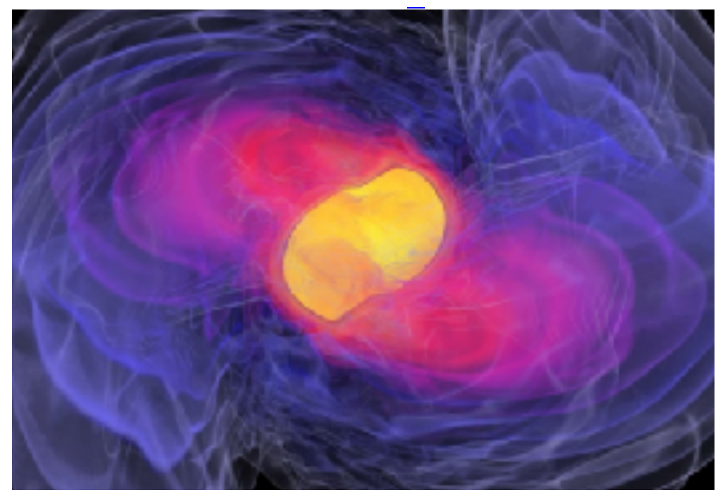


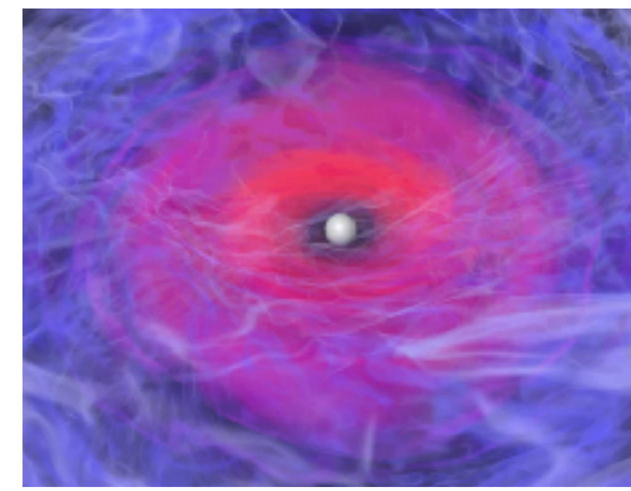
The final fate of a neutron star binary

Gravitational waves







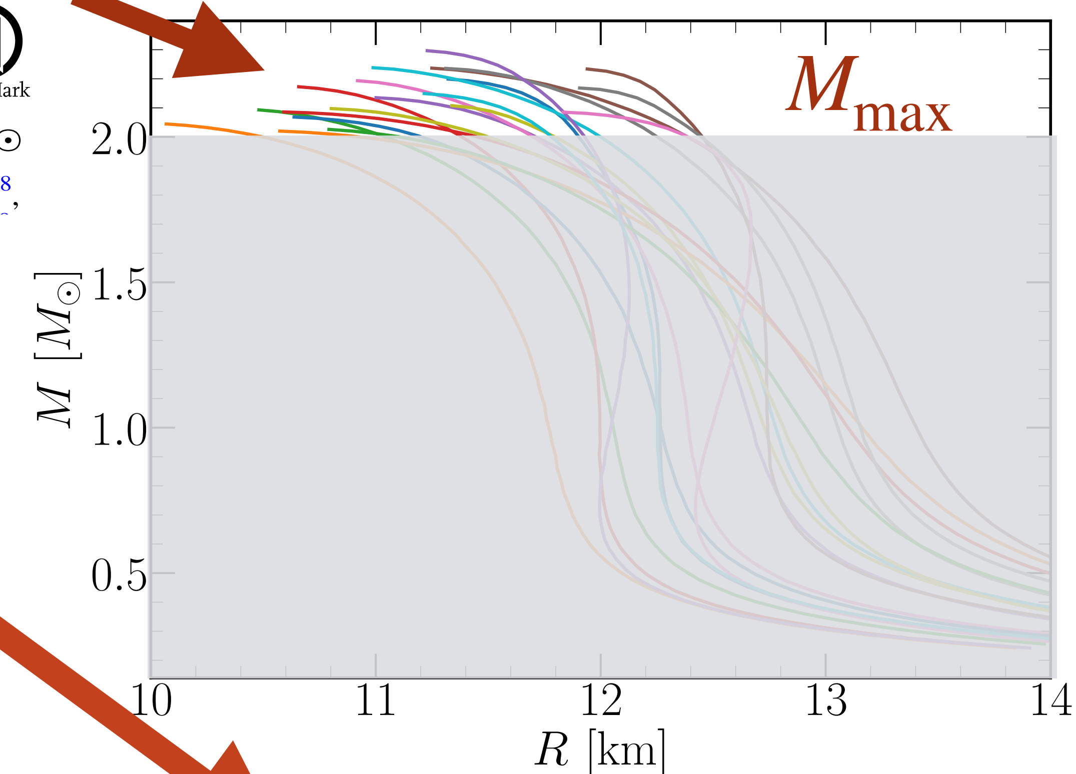


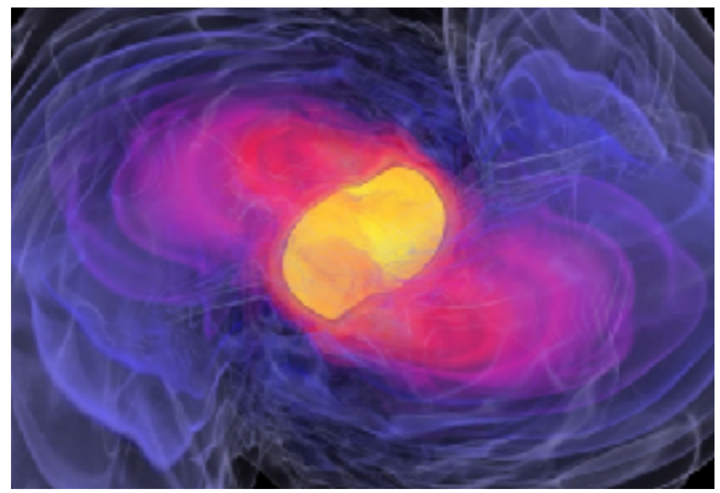
Collapse or no collapse?

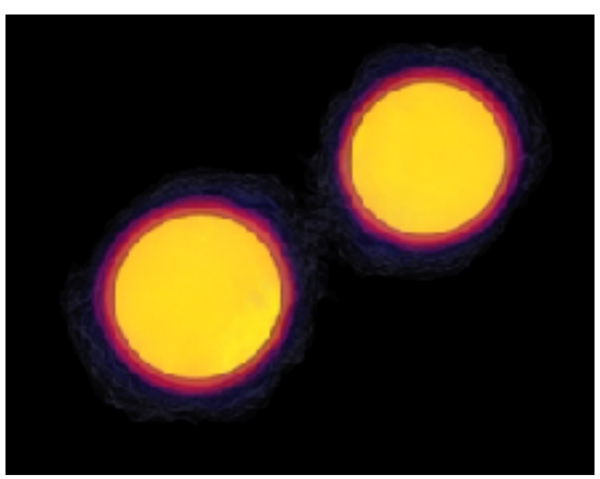
The Astrophysical Journal Letters, 892:L3 (24pp), 2020 March 20 https://doi.org/10.3847/2041-8213/ab75f5

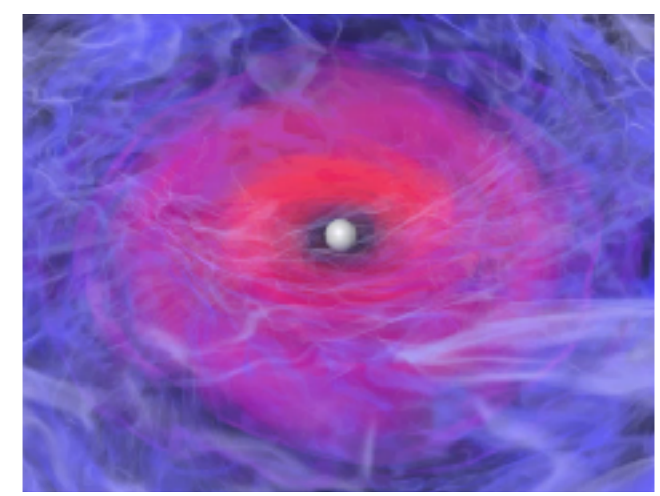
GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4 M_\odot$

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],







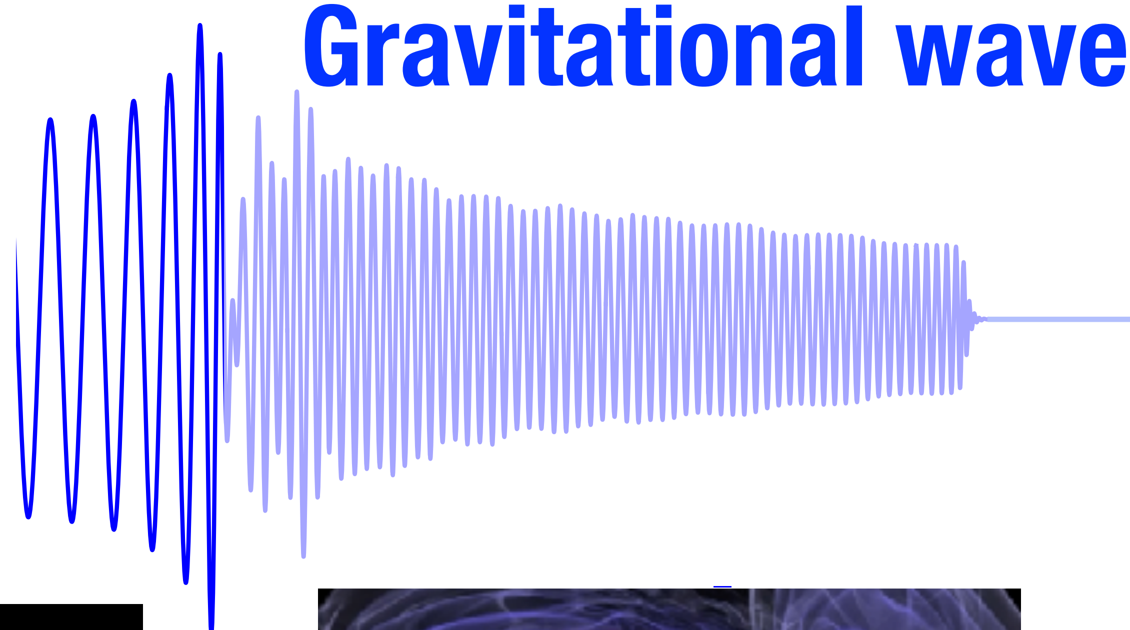


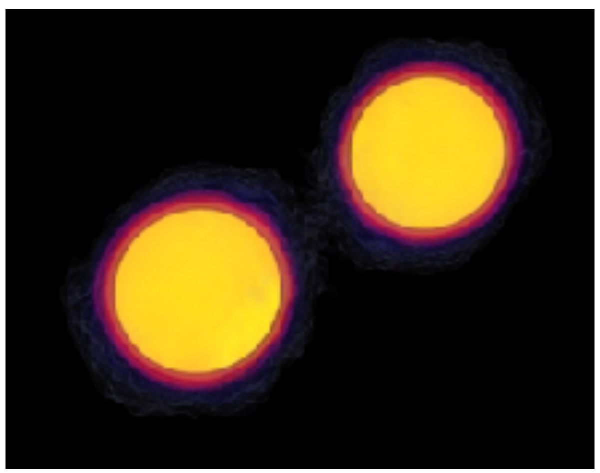
Tootle+(including **ERM**; ApJL 2021)
see also: Bauswein+, Köppel+, Kölsch+, Perego+ and others

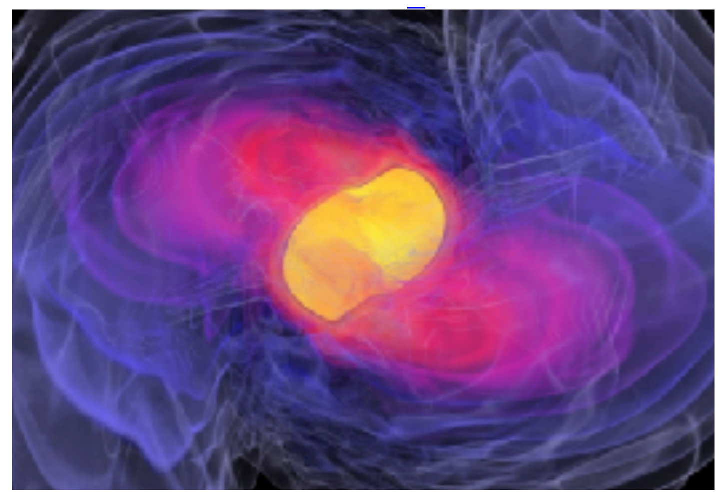
Answering this question can give crucial insights into neutron star properties.

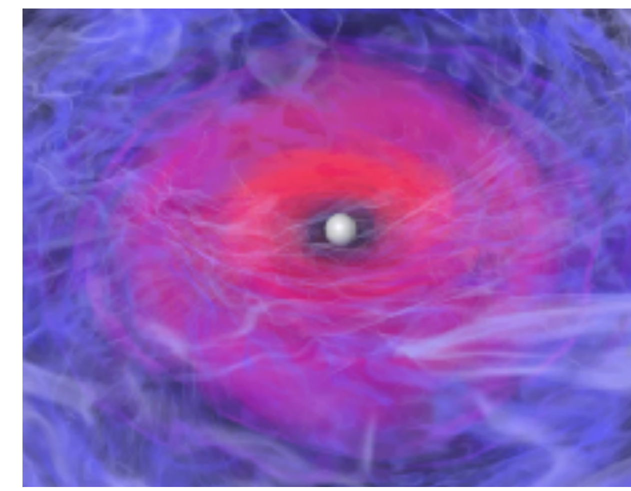
The final fate of a neutron star binary

Gravitational waves









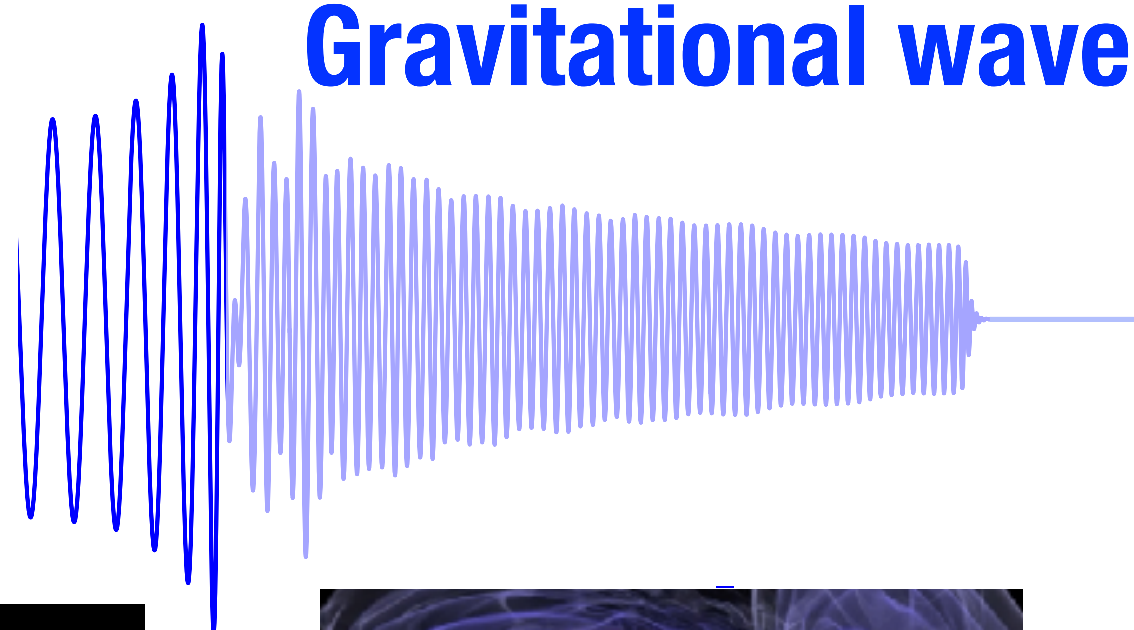
The multi-messenger picture

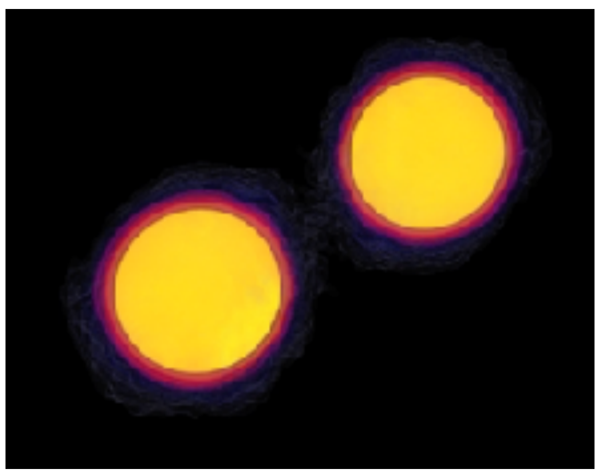
Electromagnetic counterparts as new windows into the physics of the merger!

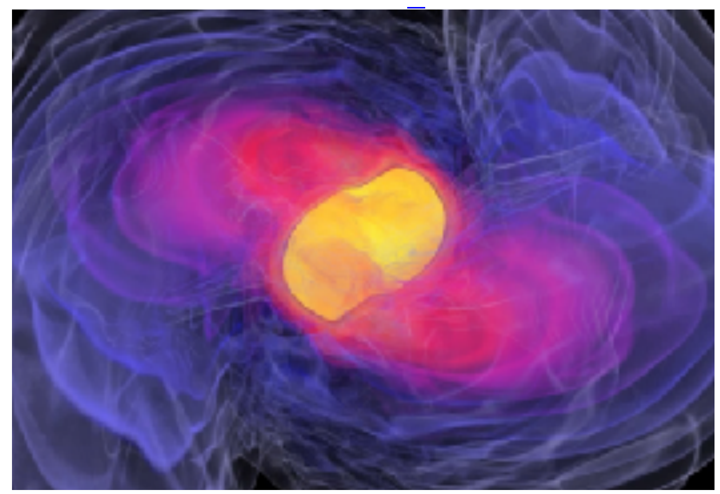

Image credit: iStock.com

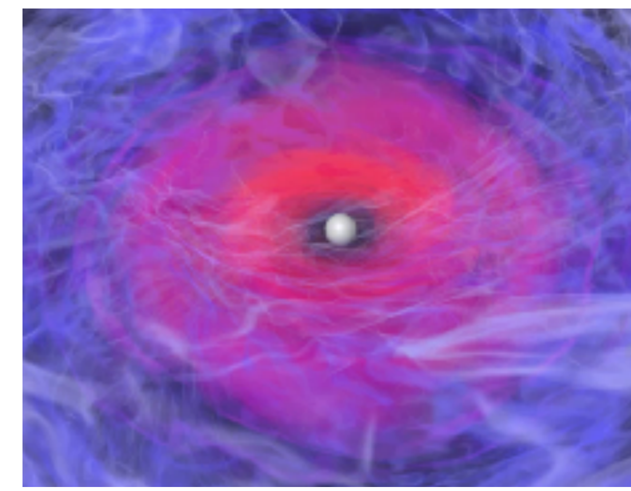
The final fate of a neutron star binary

Gravitational waves

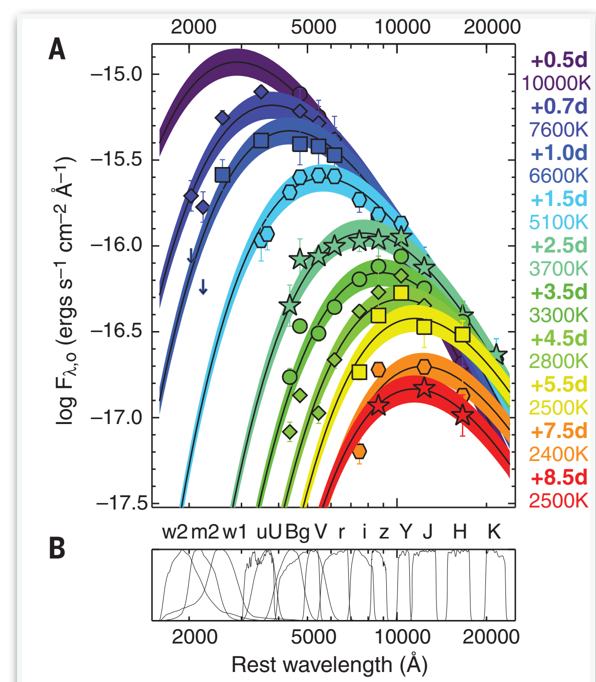




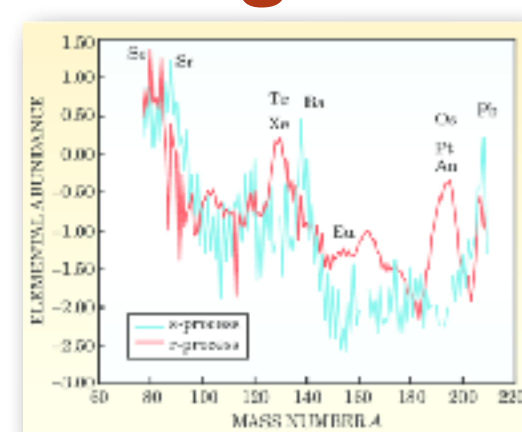




- <u>Mass ejecta</u> are a site for **heavy element production.** (r-process nucleosynthesis)

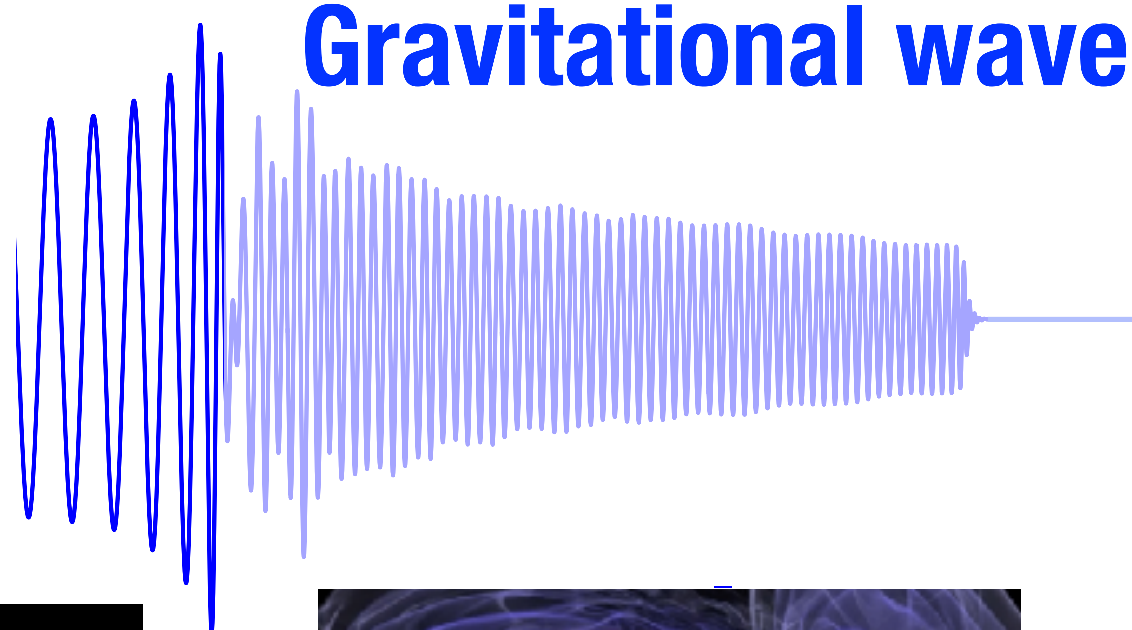


Kilonova Afterglow

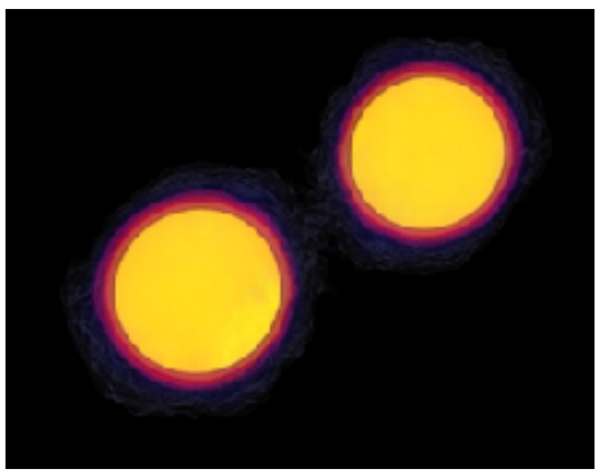


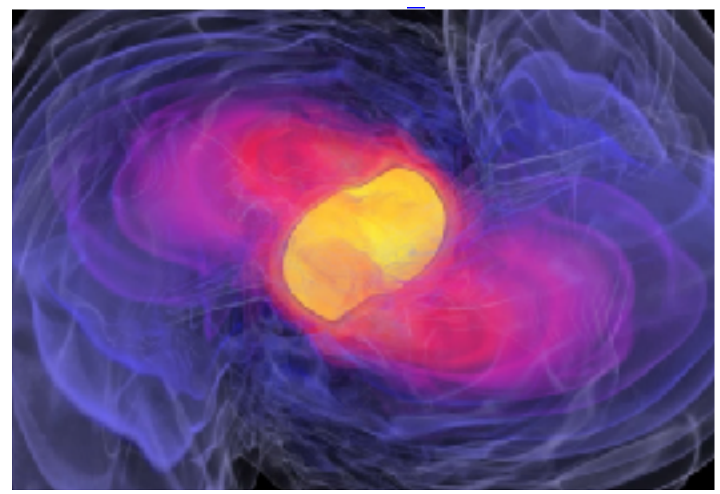
The final fate of a neutron star binary

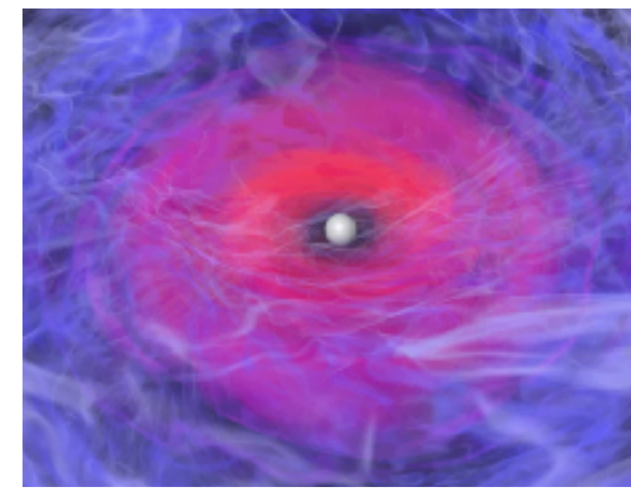
Gravitational waves

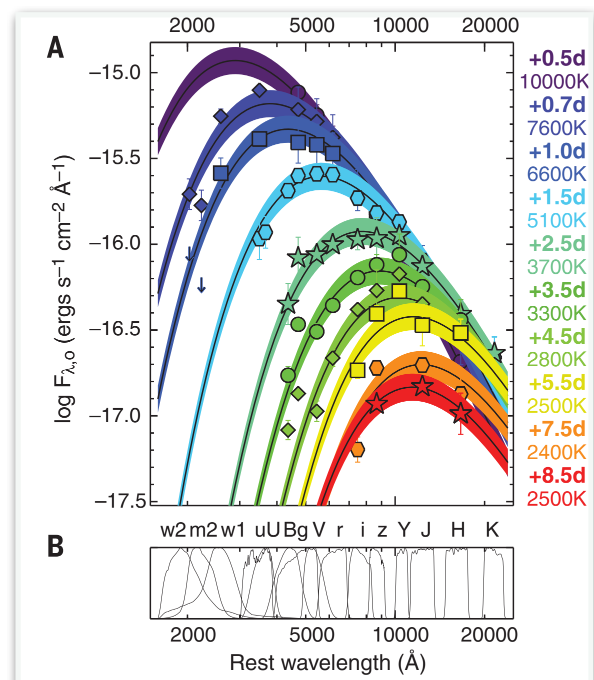


sGRB



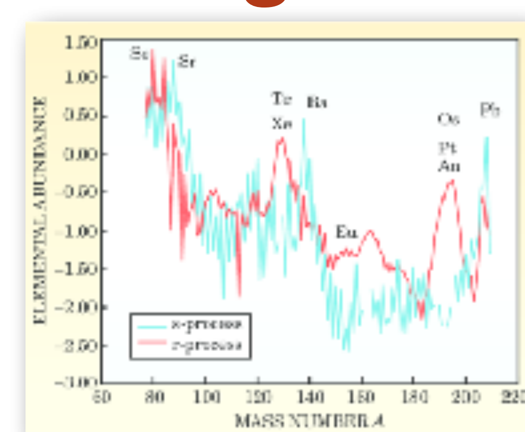






Kilonova

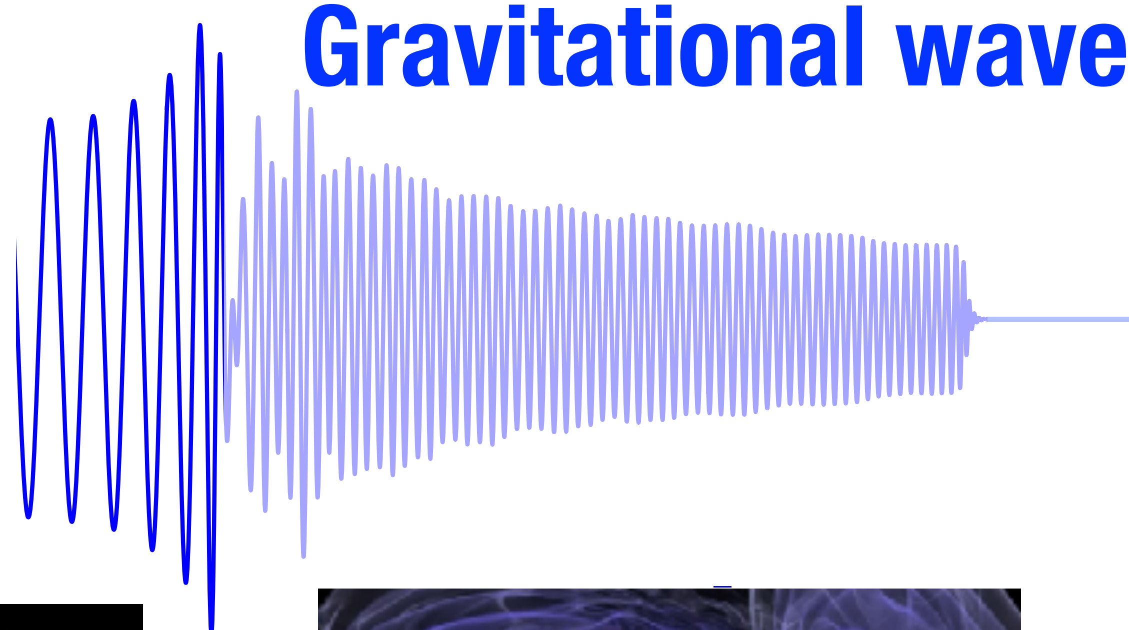
Afterglow

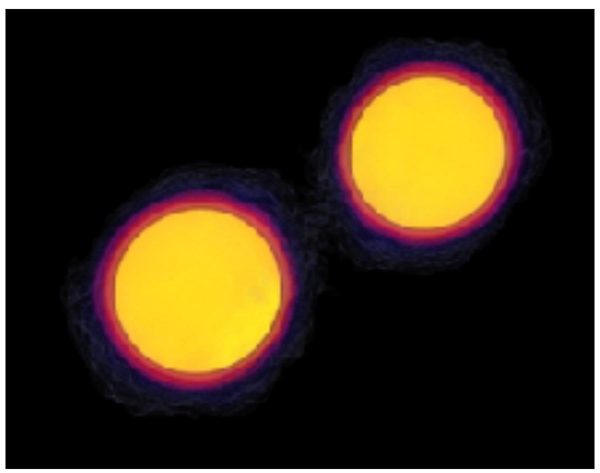


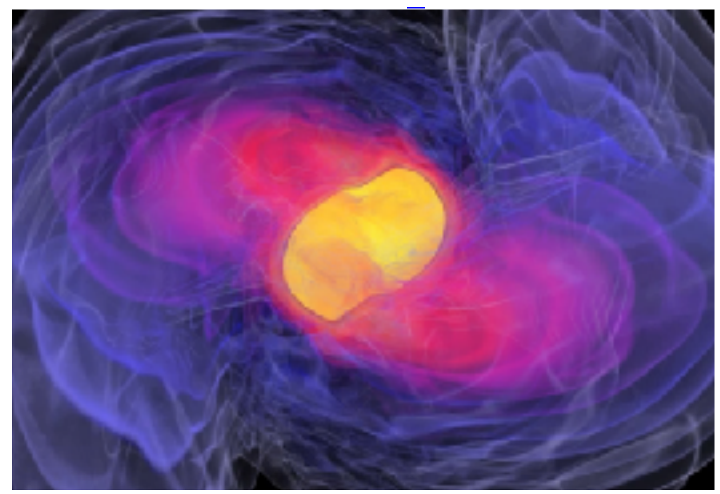
The final fate of a neutron star binary

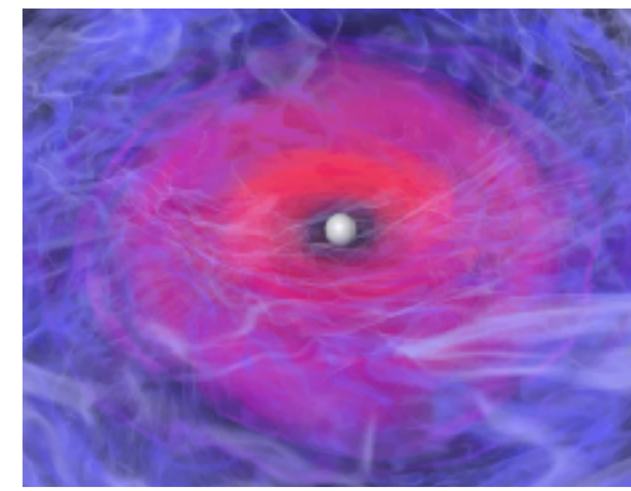
Gravitational waves

sGRB









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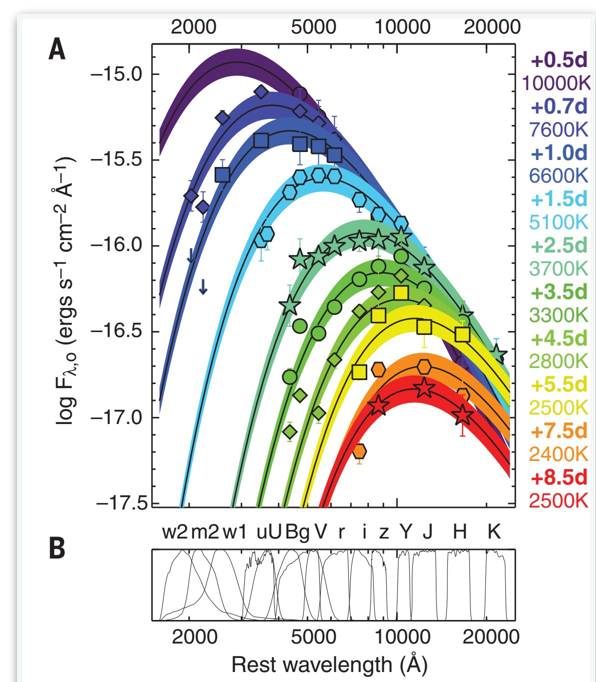
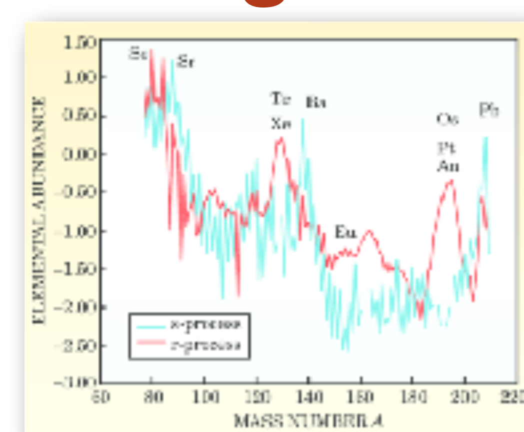


Kilonova

Afterglow



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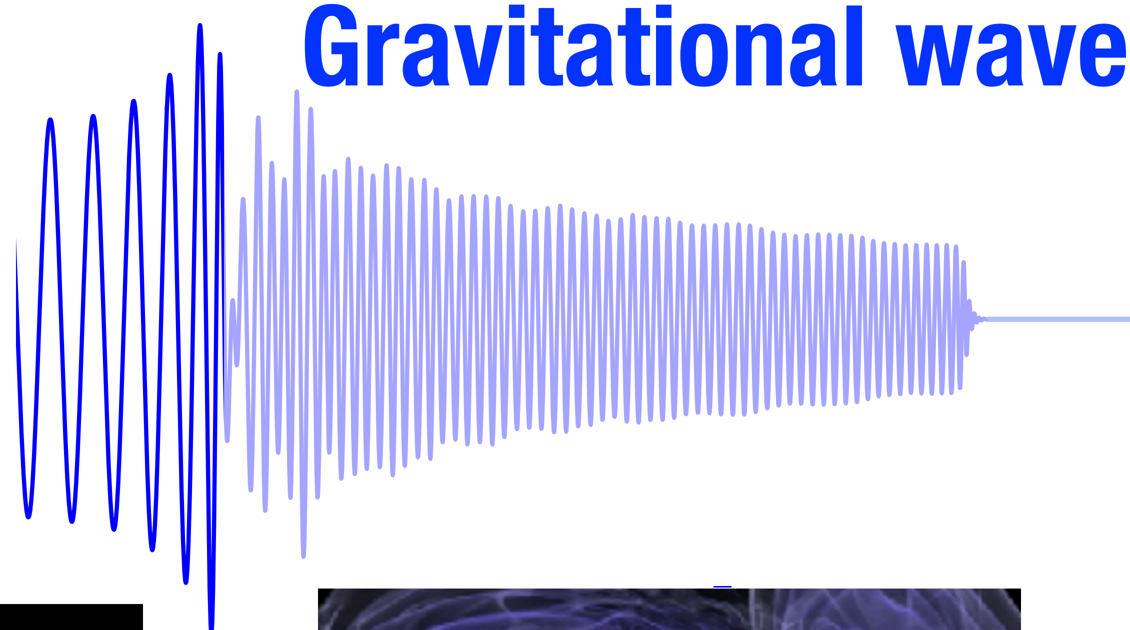

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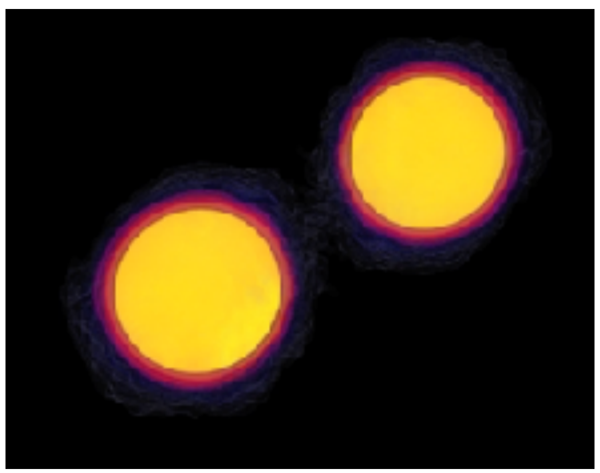
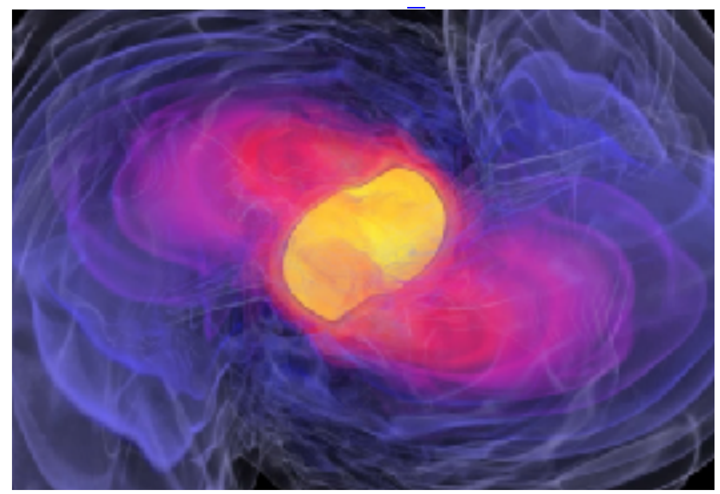
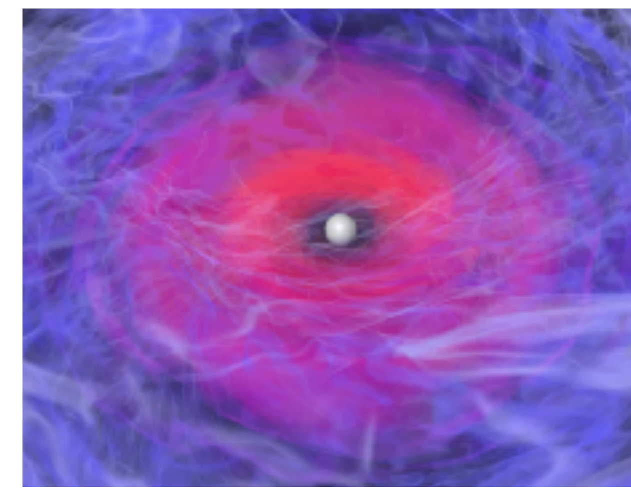
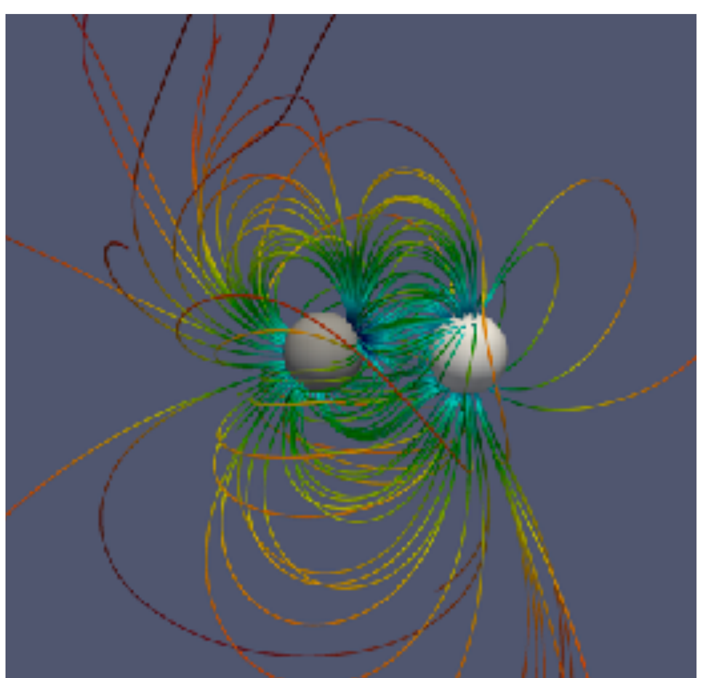
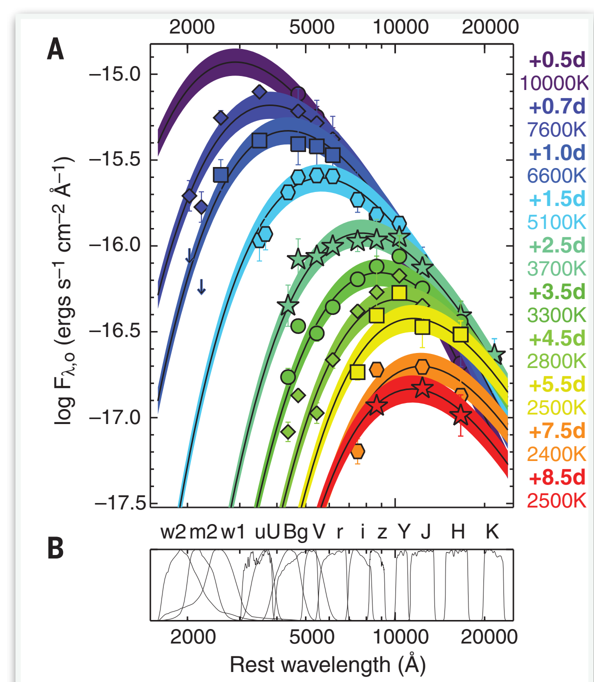






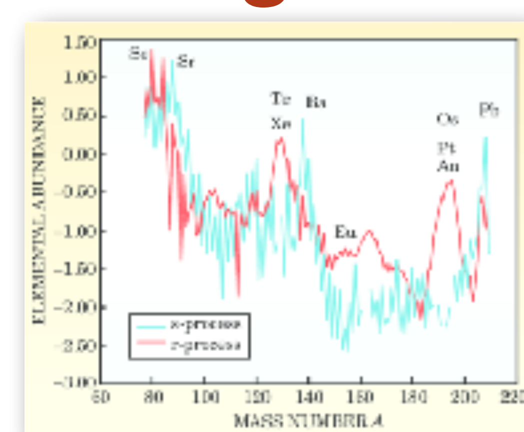


ERM & Philippov (ApJL 2020)



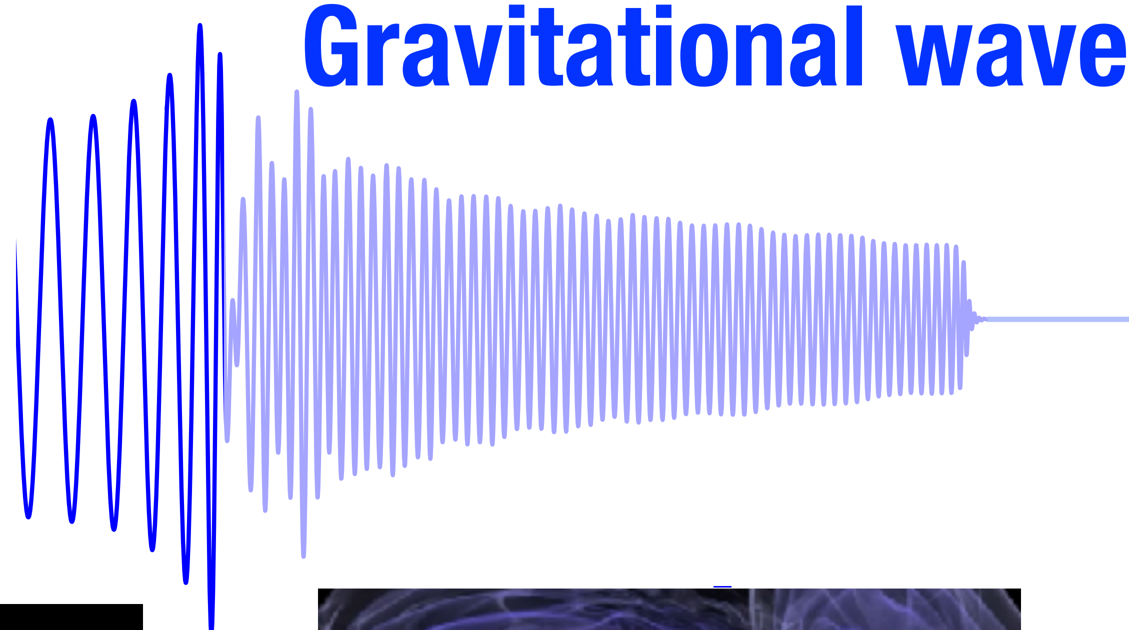
Kilonova

Afterglow

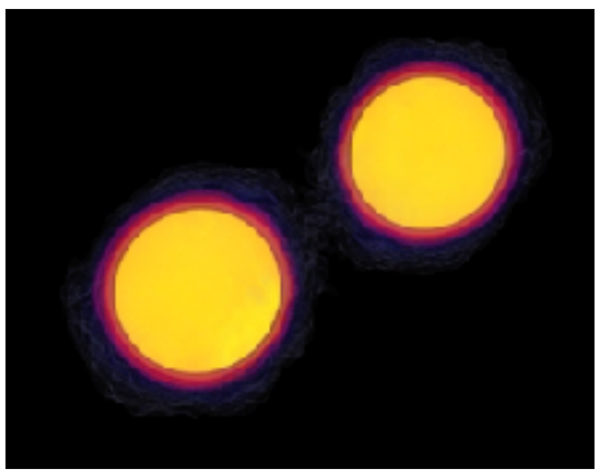


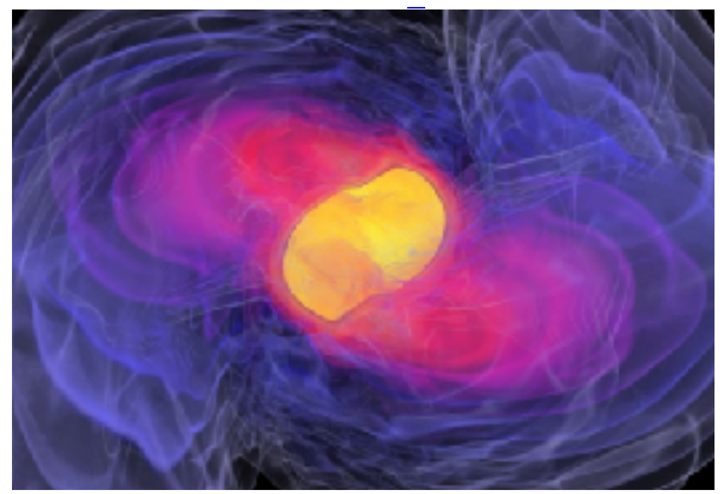
The final fate of a neutron star binary

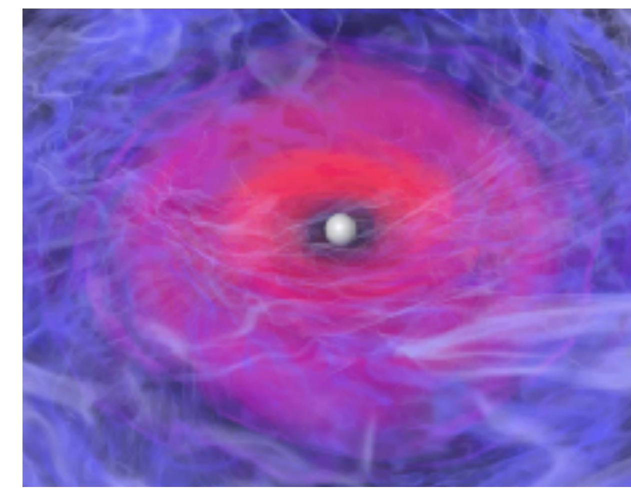
Gravitational waves

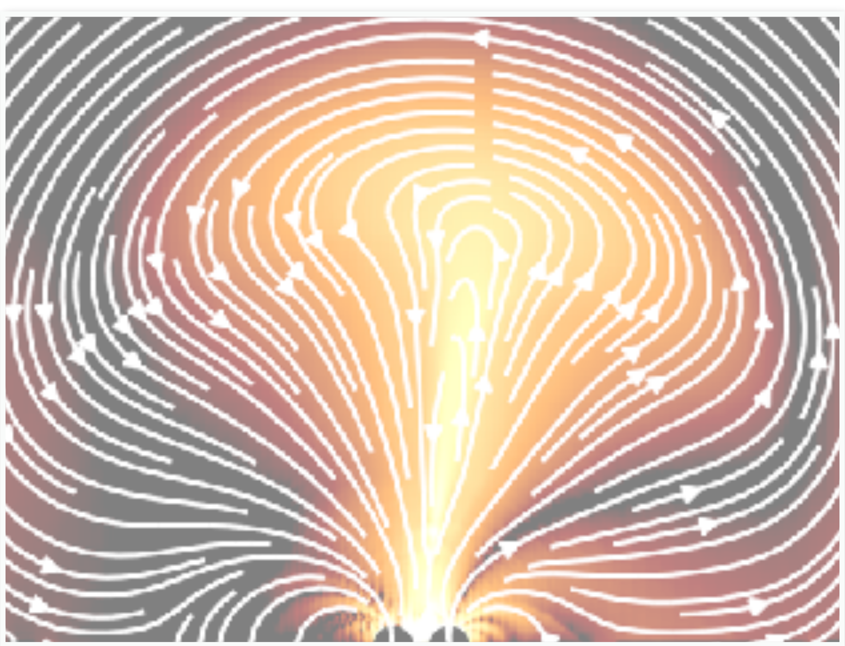


sGRB









Precursor Emission??

ERM & Philippov
(ApJL 2020; arXiv:2022)
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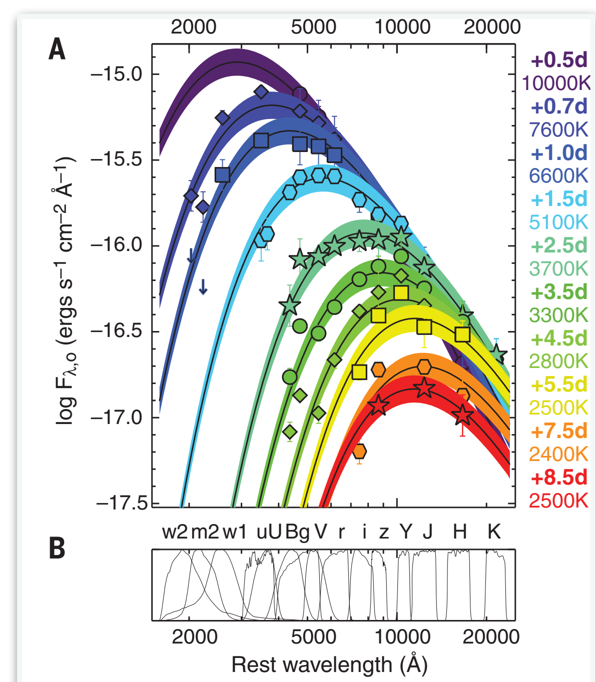
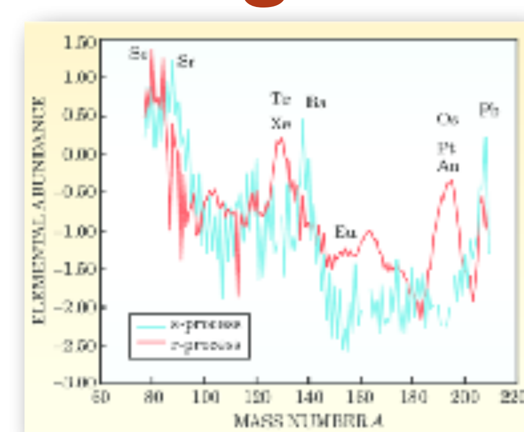
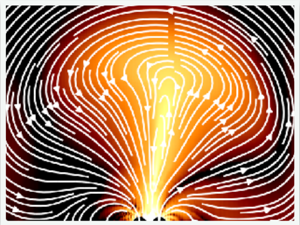
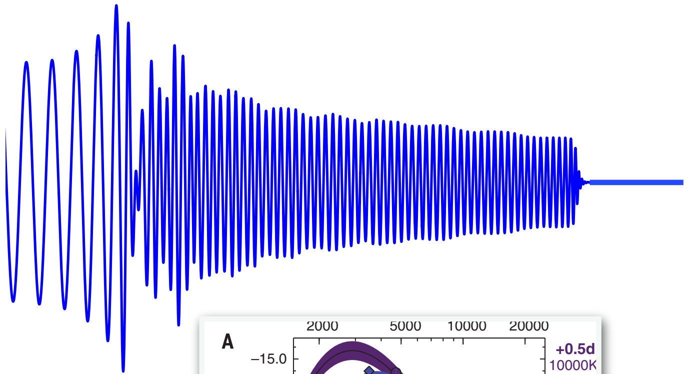


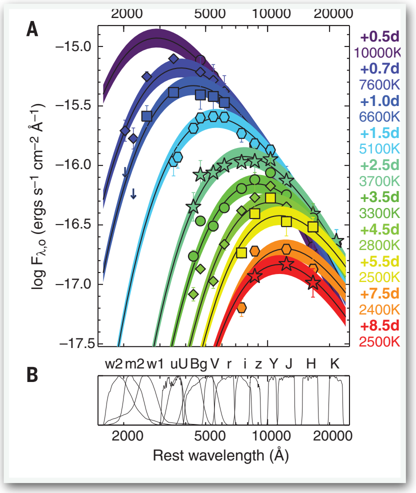
Kilonova Afterglow

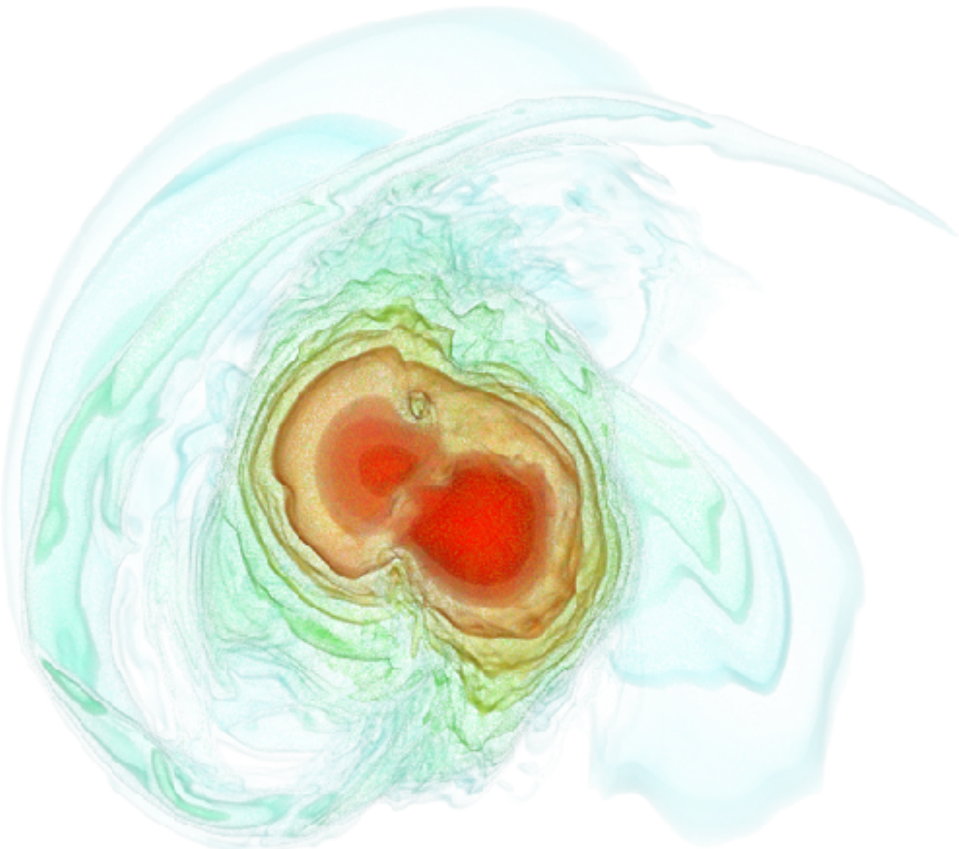


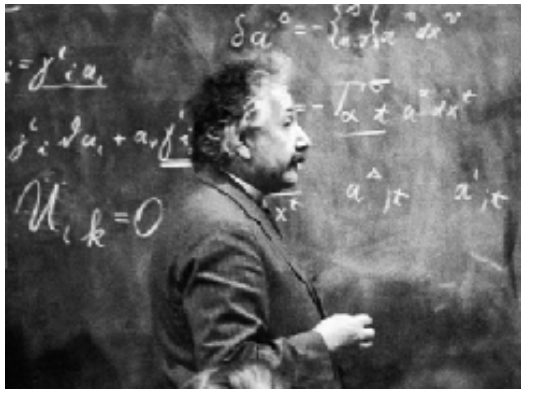
A challenge for computational relativistic astrophysics

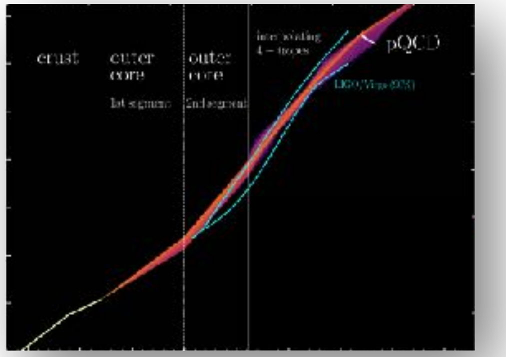


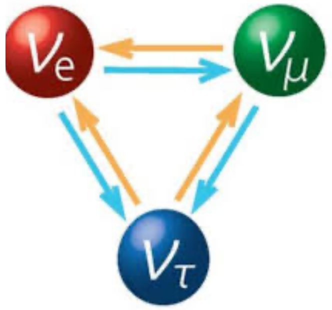


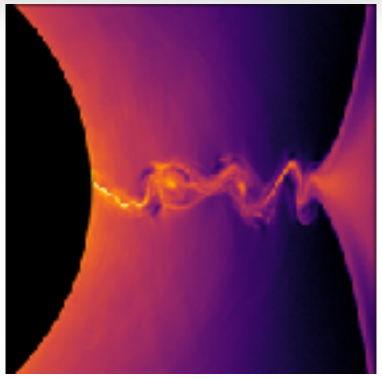






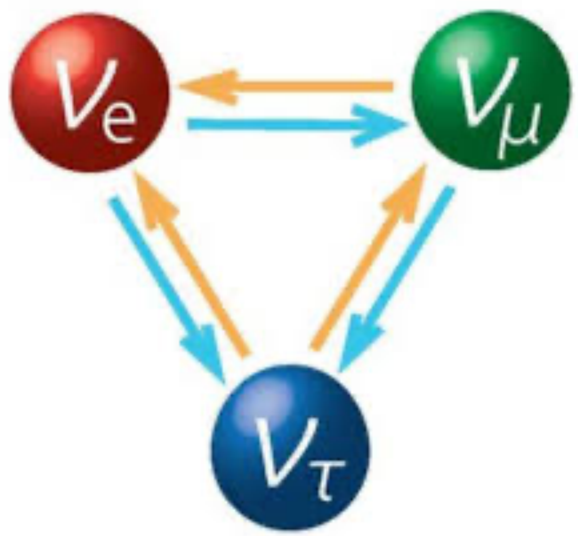




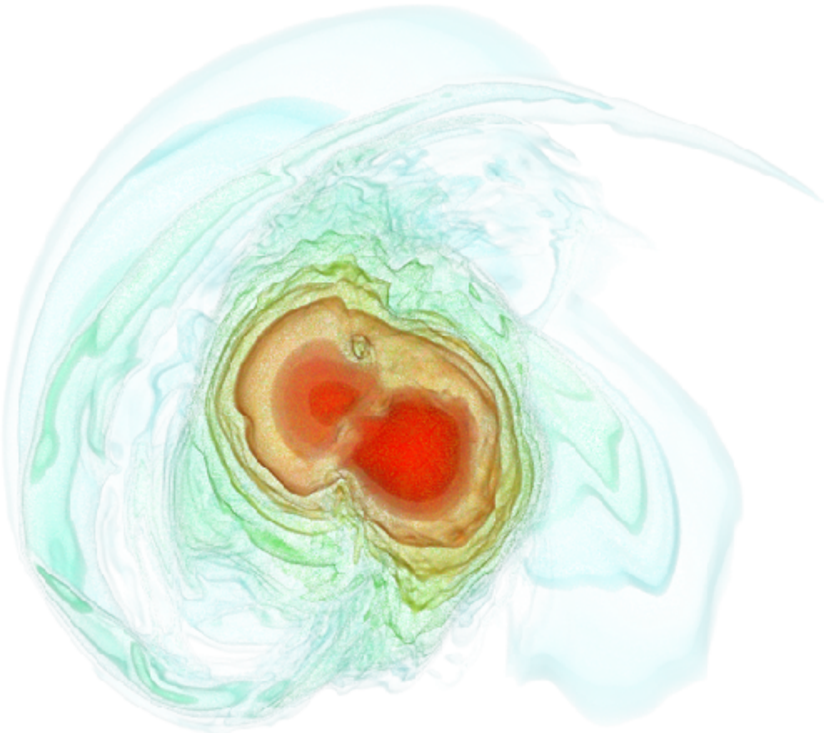


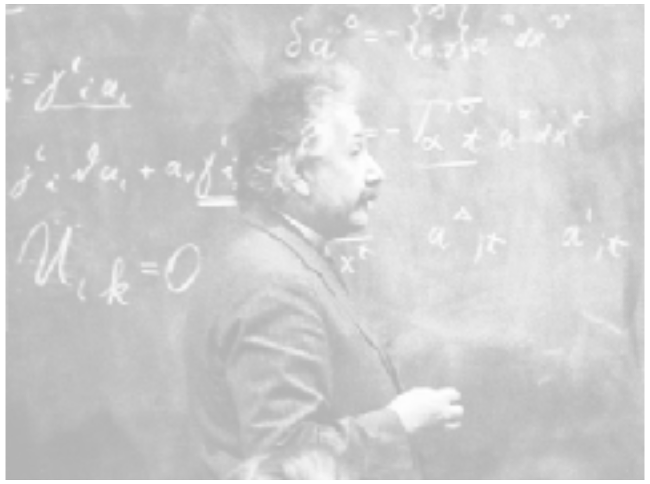
Need a multi-scale, multi-physics approach to interpret multi-messenger events!

The many faces of neutron star mergers

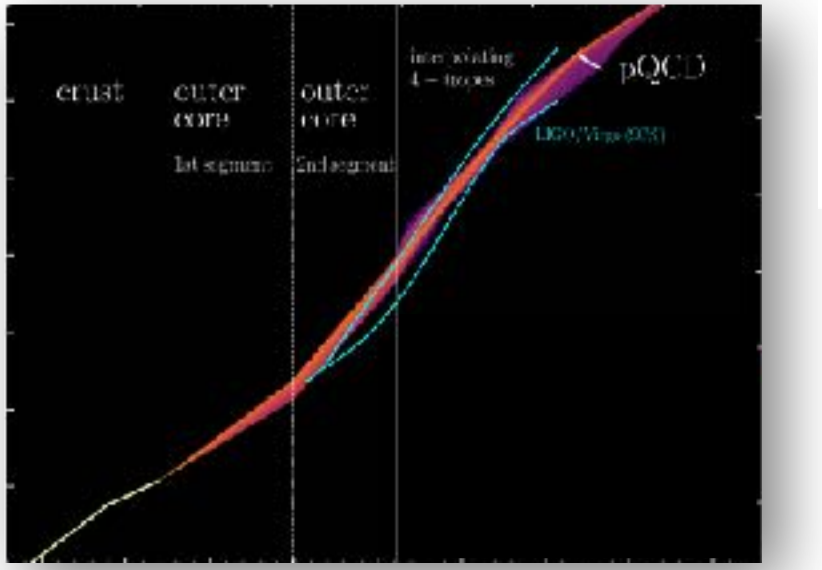


Neutrino physics

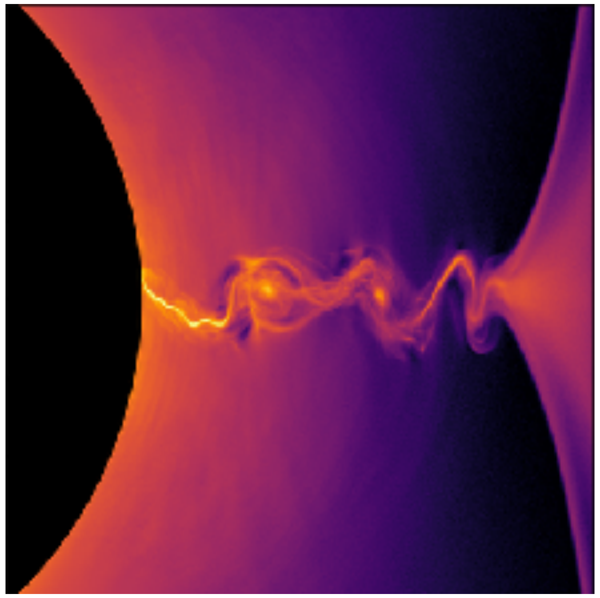




Gravitational physics

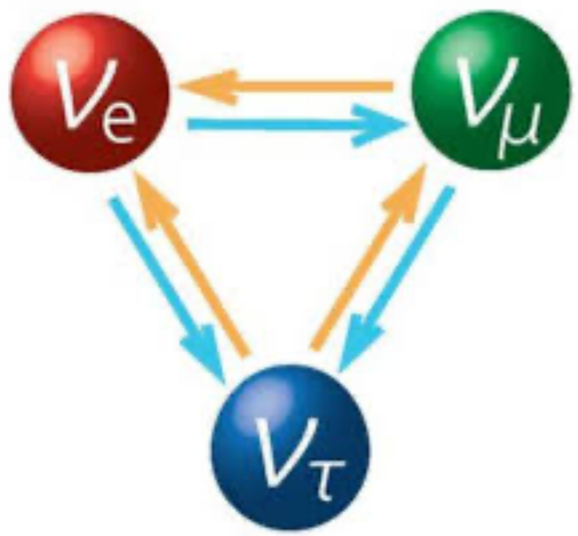


Nuclear physics

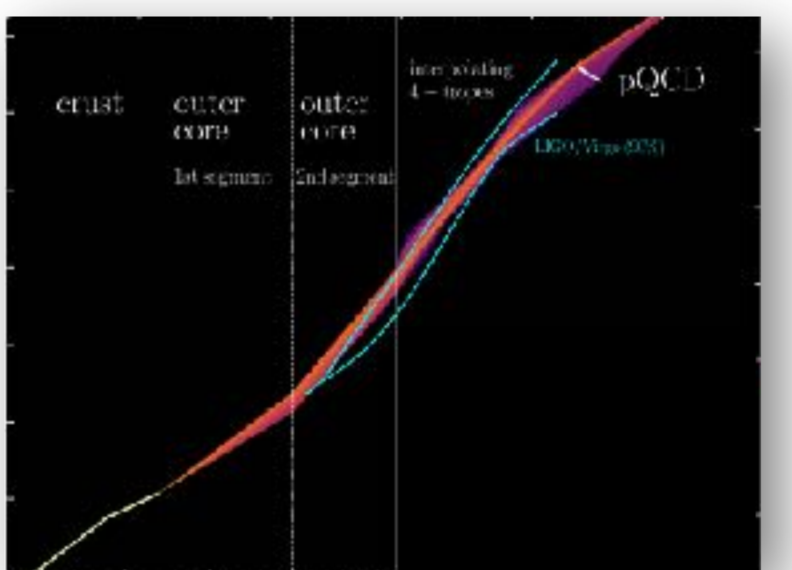


Plasma physics

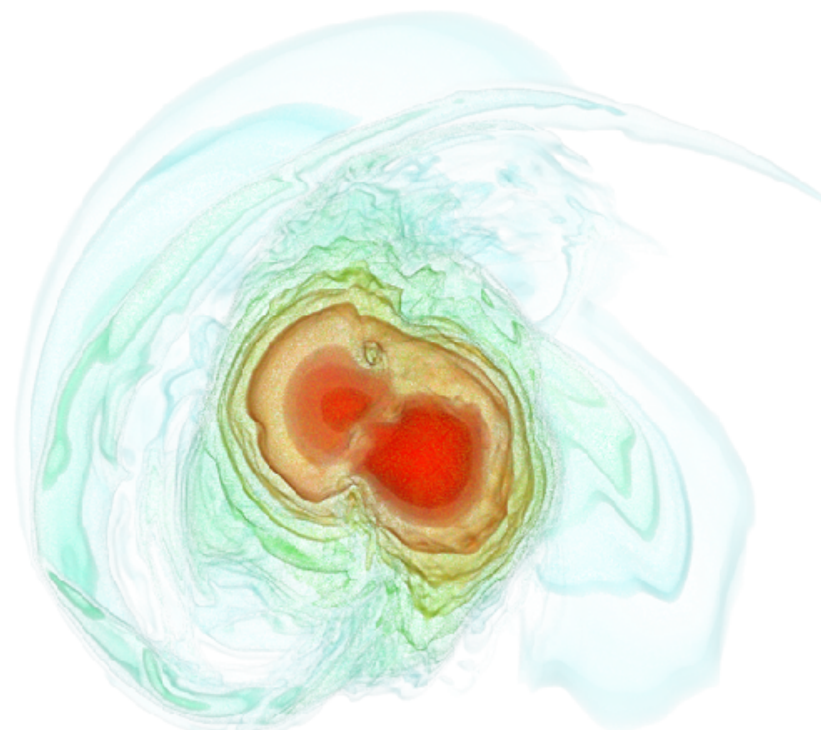
The many faces of neutron star mergers

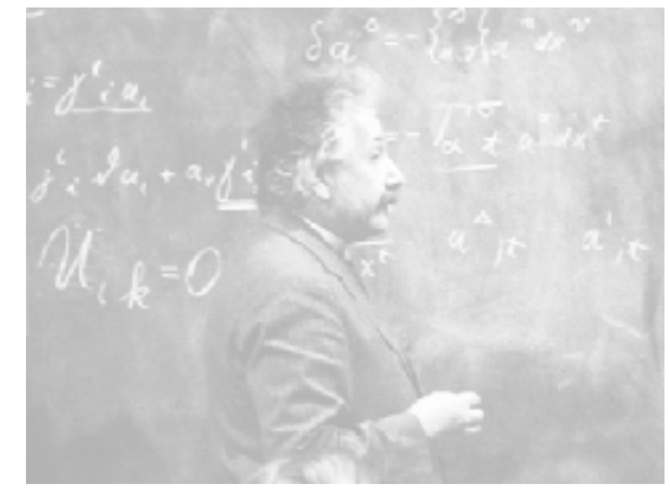


Neutrino physics

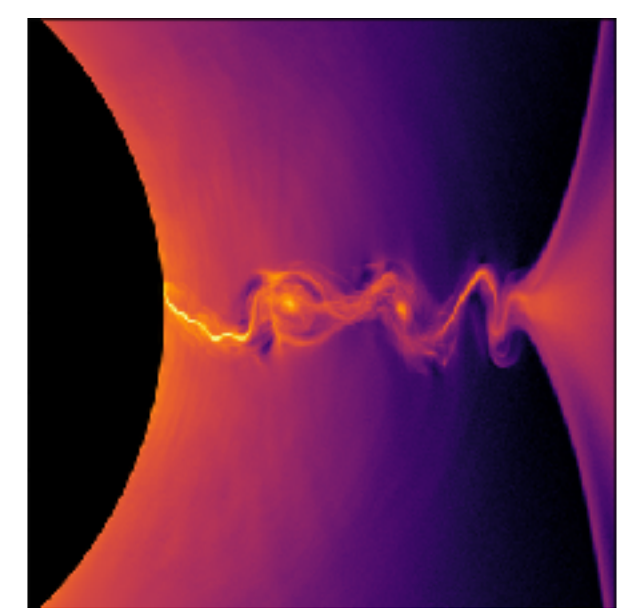


Nuclear physics





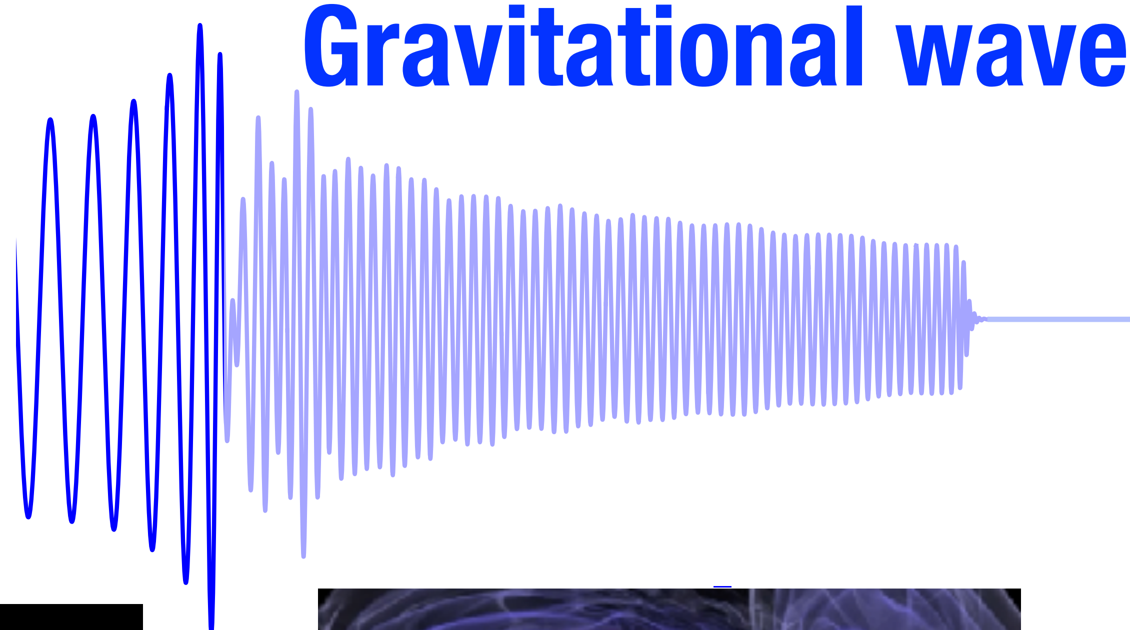
Gravitational physics



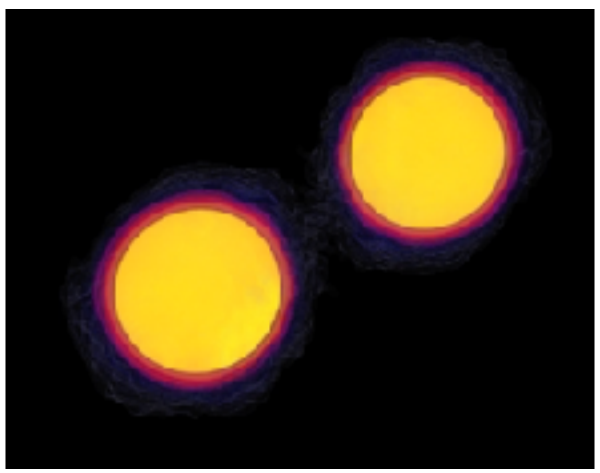
Plasma physics

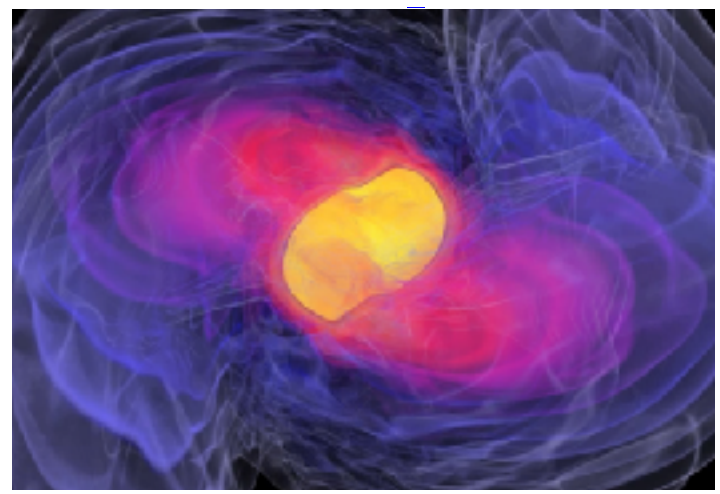
The final fate of a neutron star binary

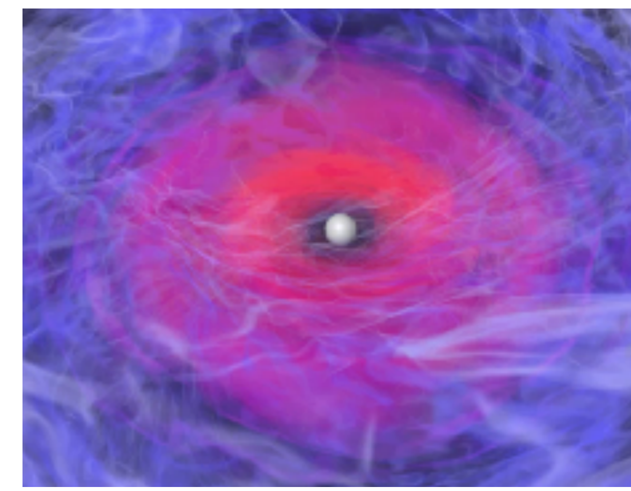
Gravitational waves

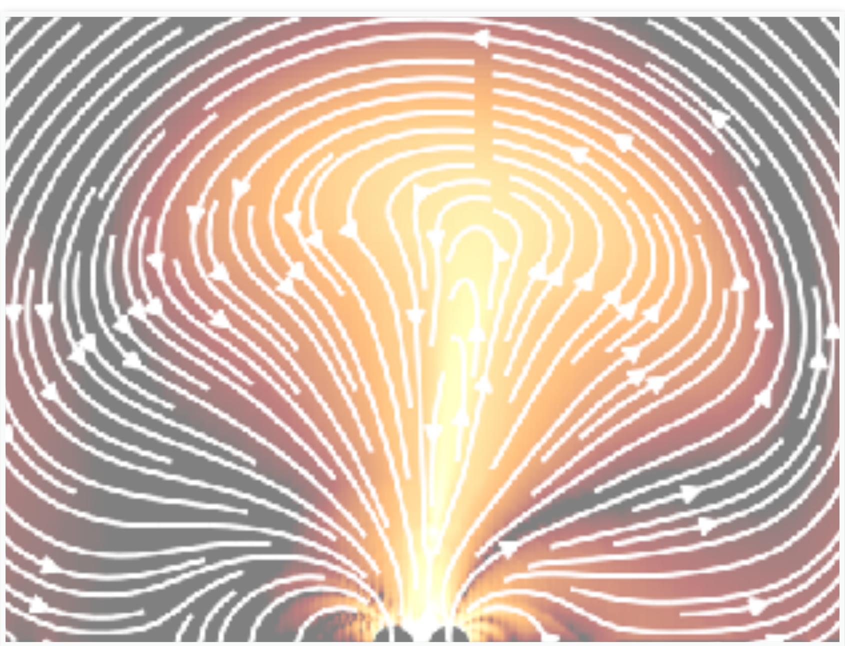


sGRB









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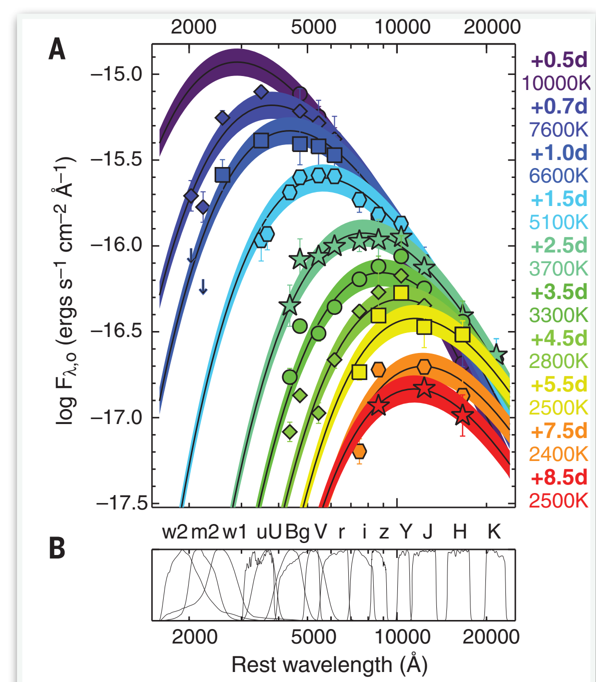
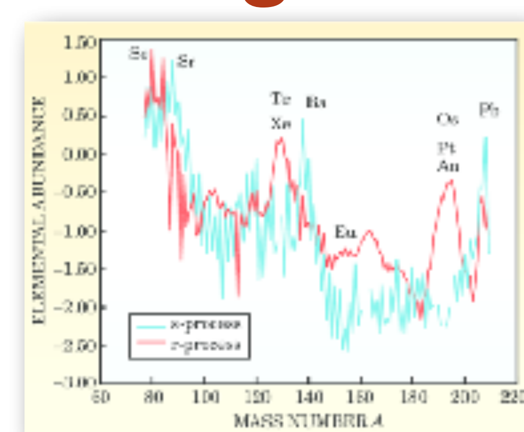
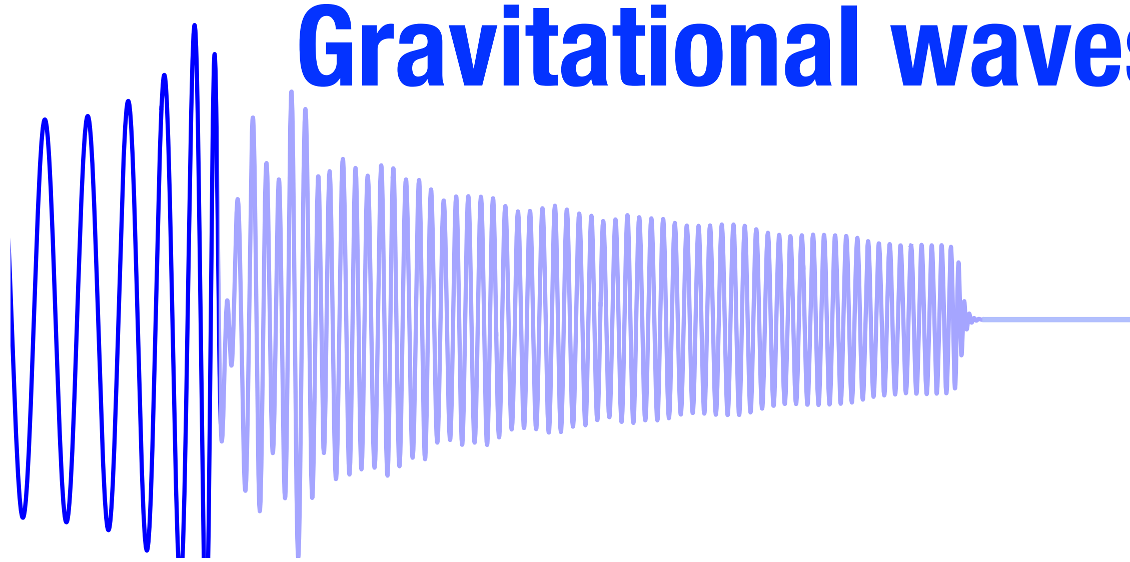


Kilonova Afterglow



From gravity to nuclear physics

Gravitational waves



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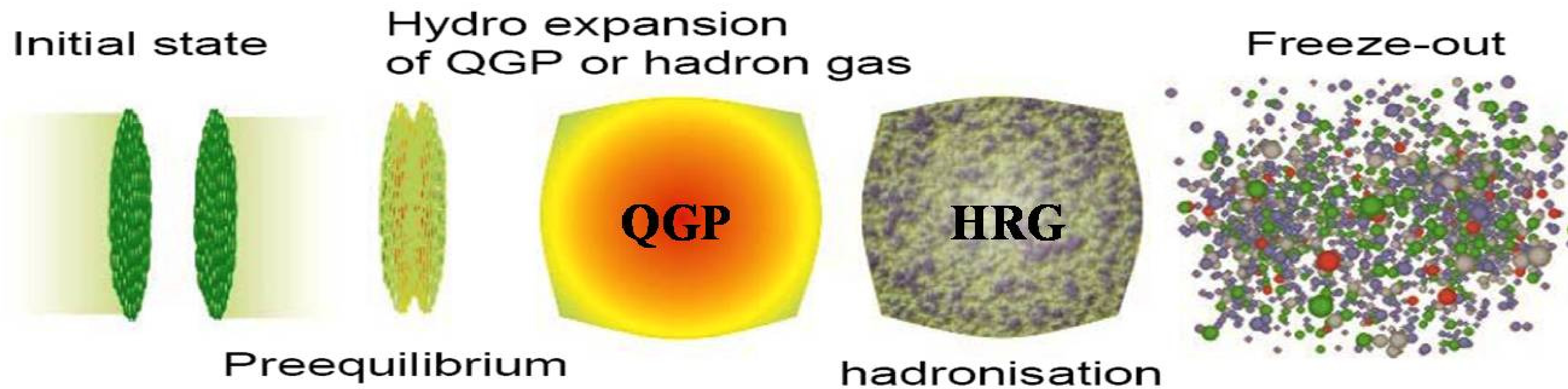
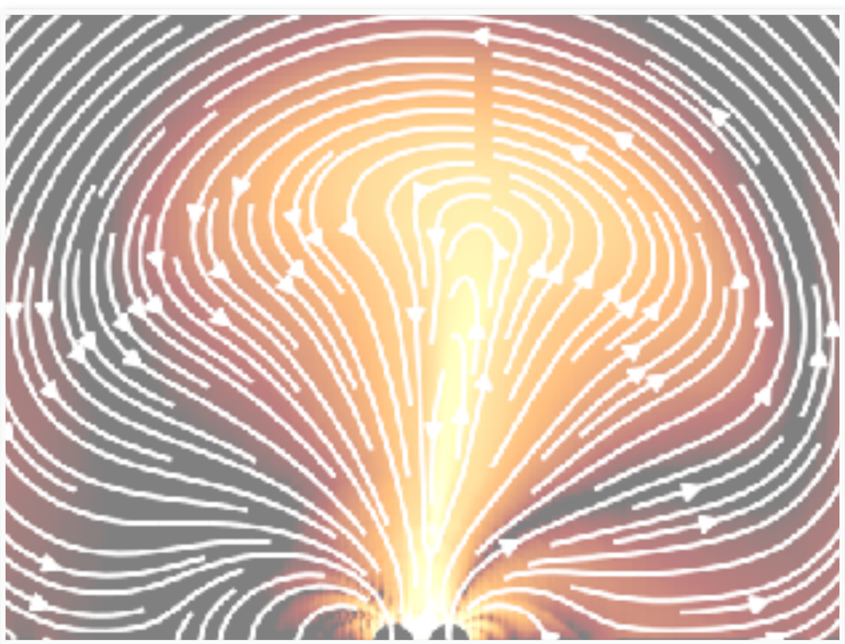
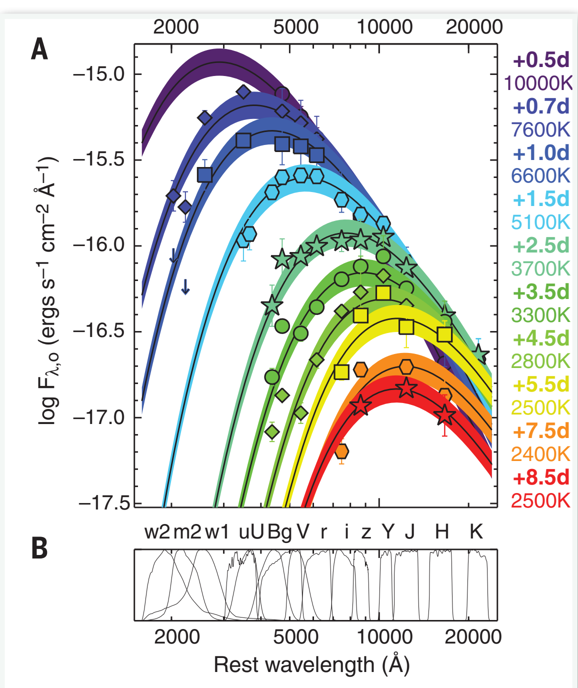


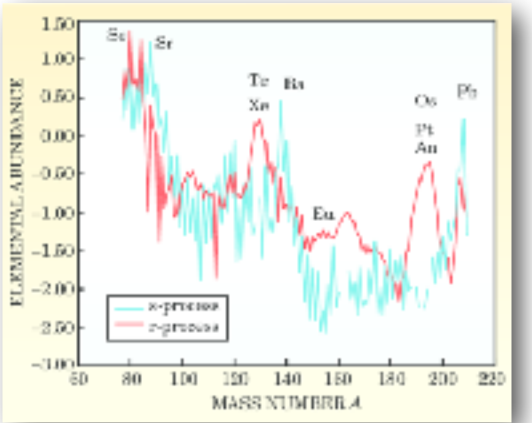
S.Bass



Precursor Emission ??



Kilonova Afterglow



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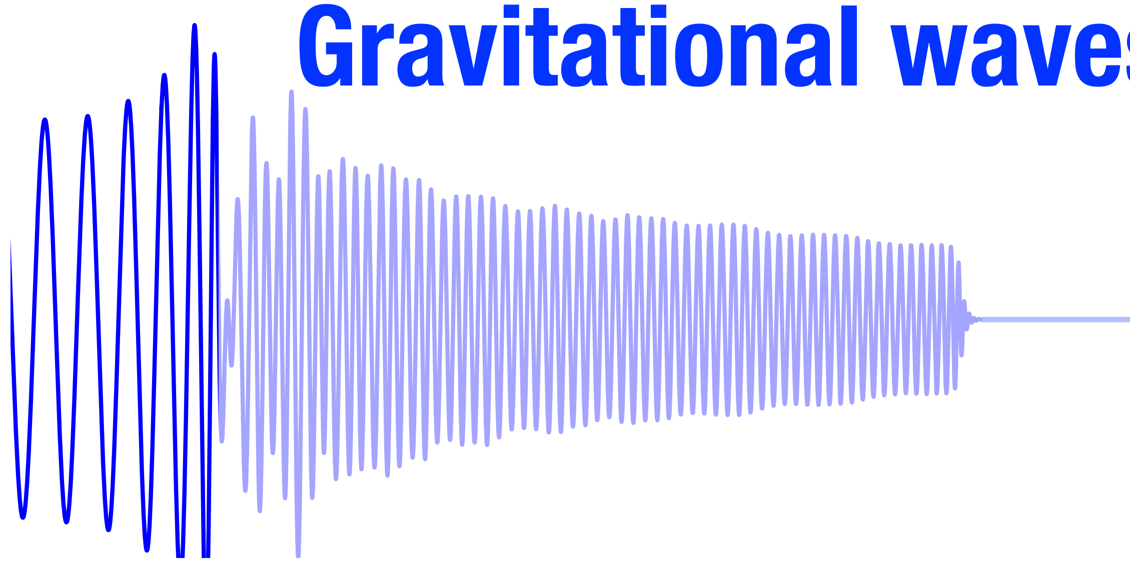

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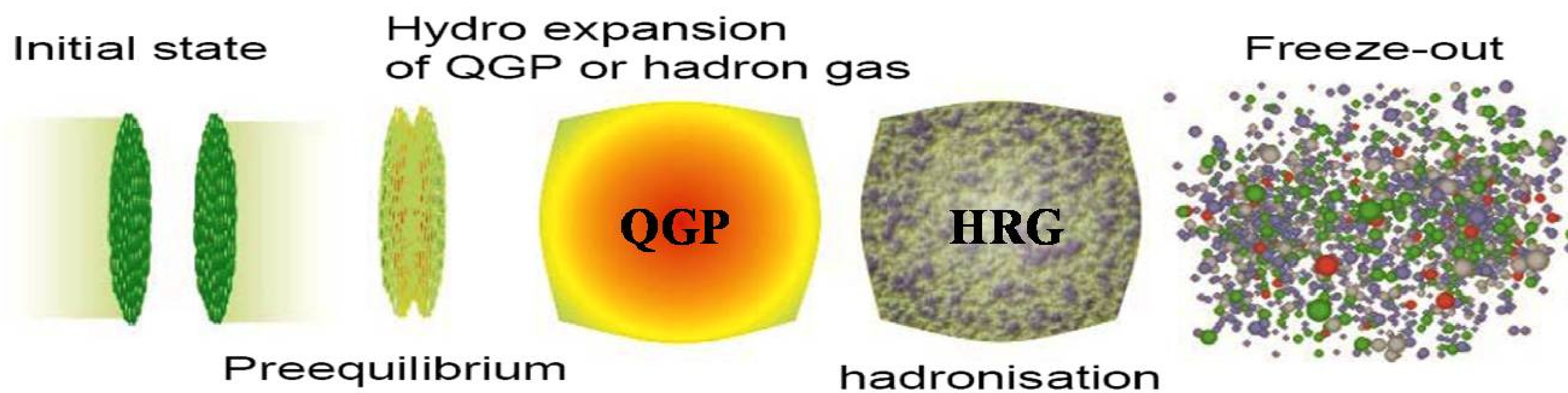

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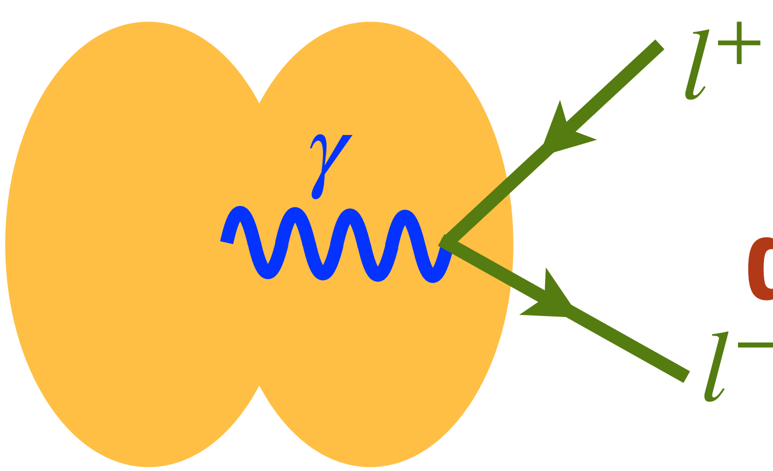
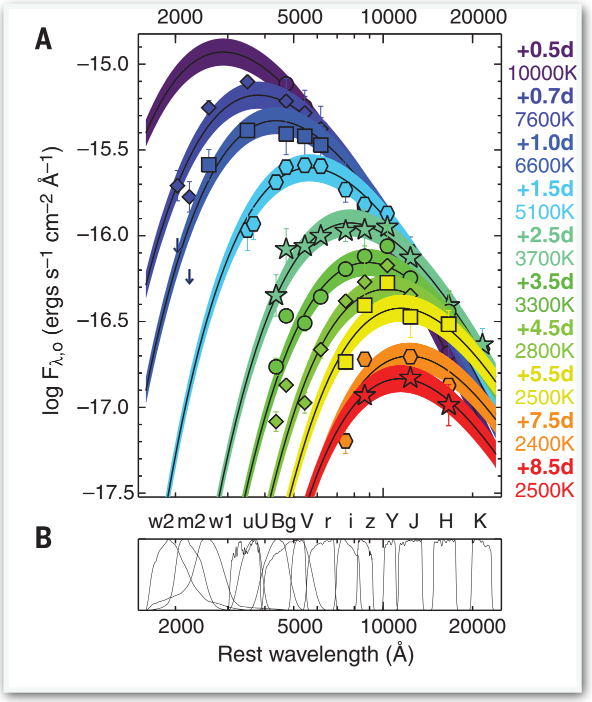


Early di-leptons?



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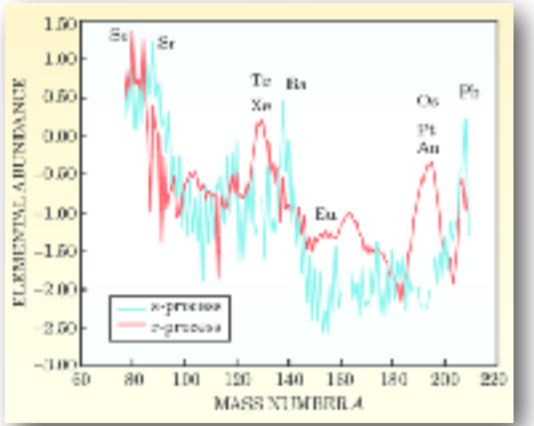

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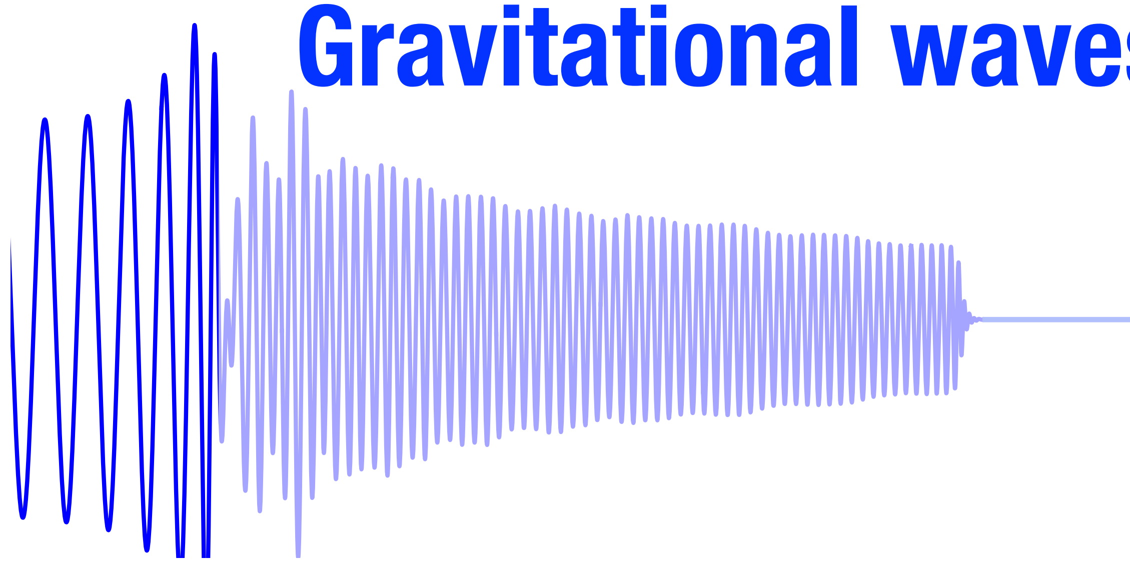

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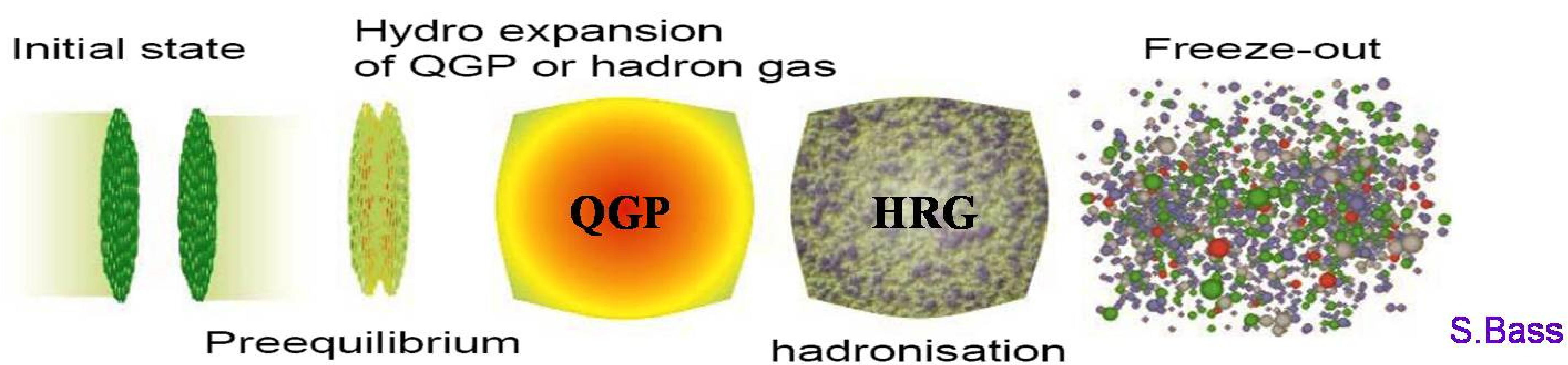
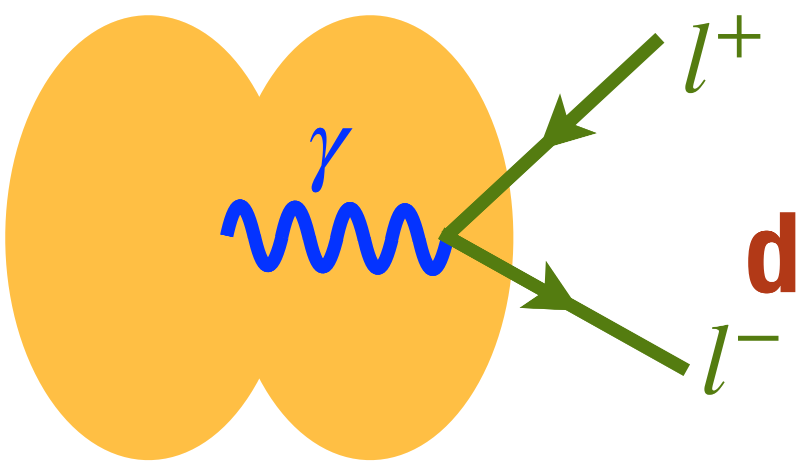
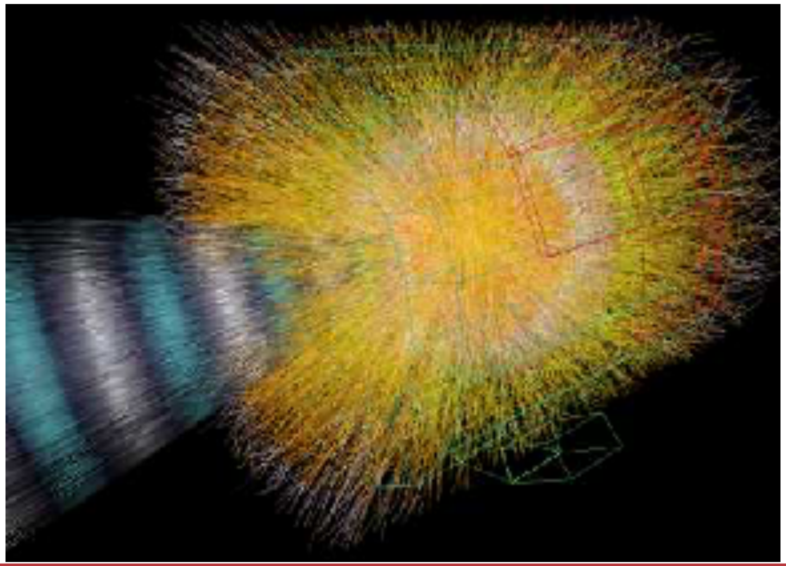


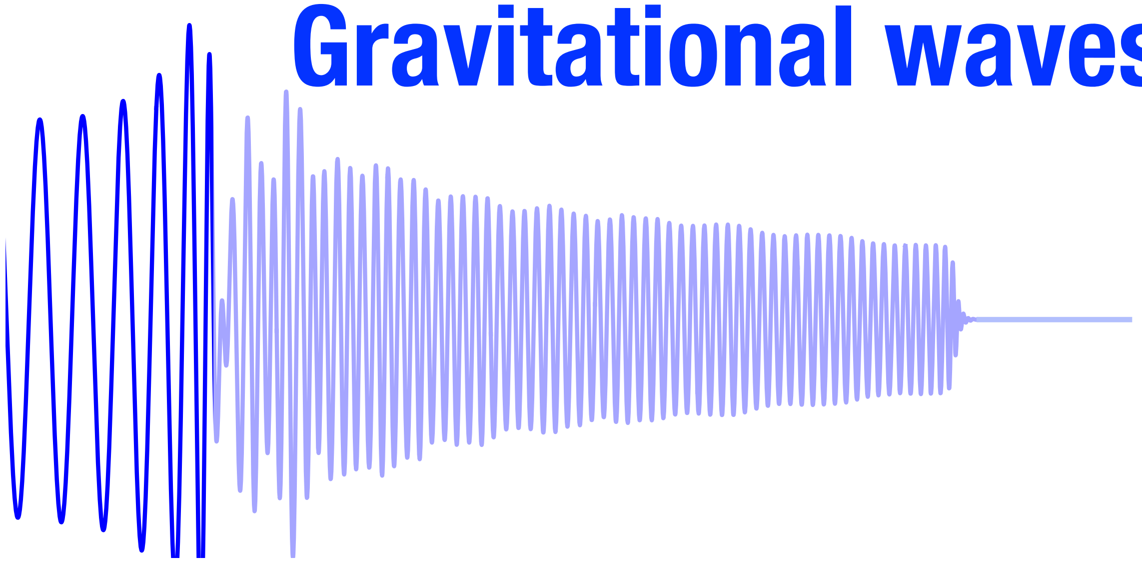


Early di-leptons?

Decay channels

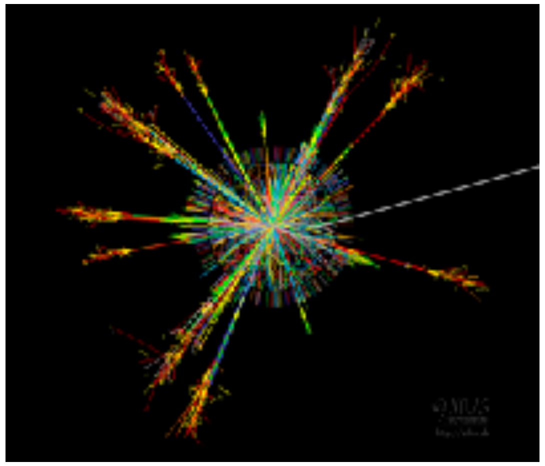


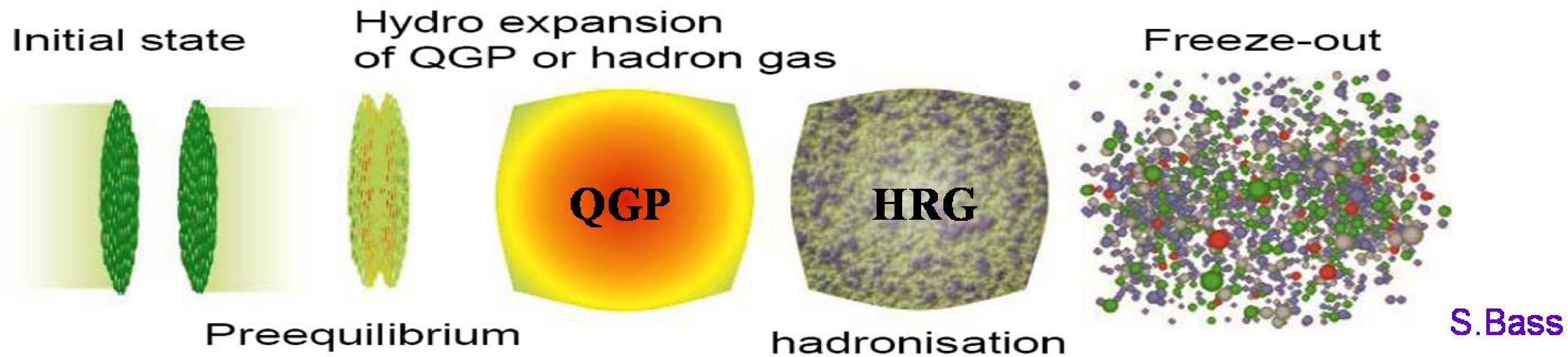
From gravity to nuclear physics



Gravitational waves

Jets





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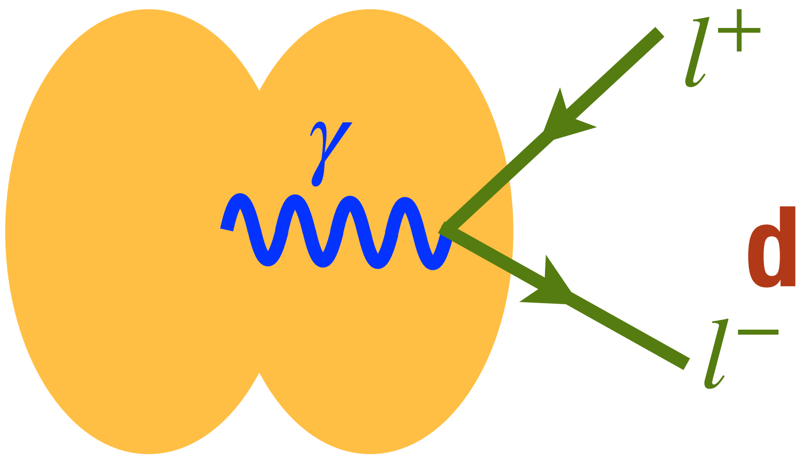

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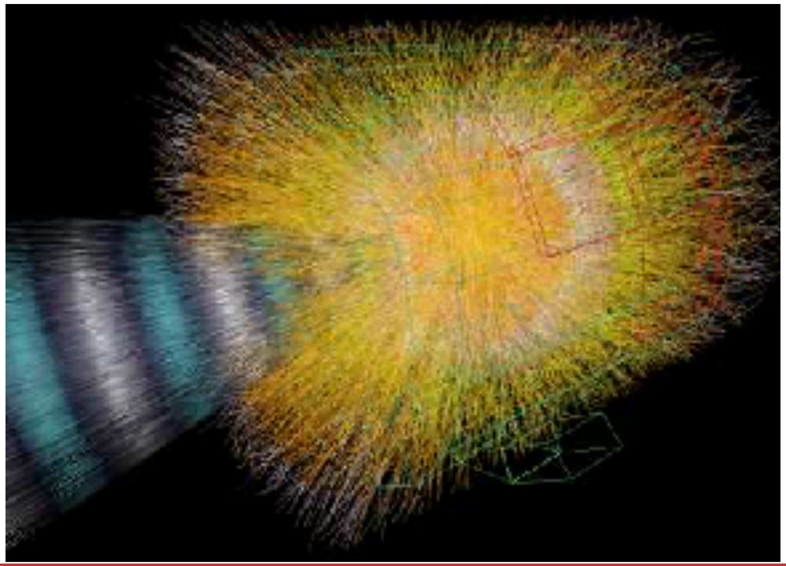
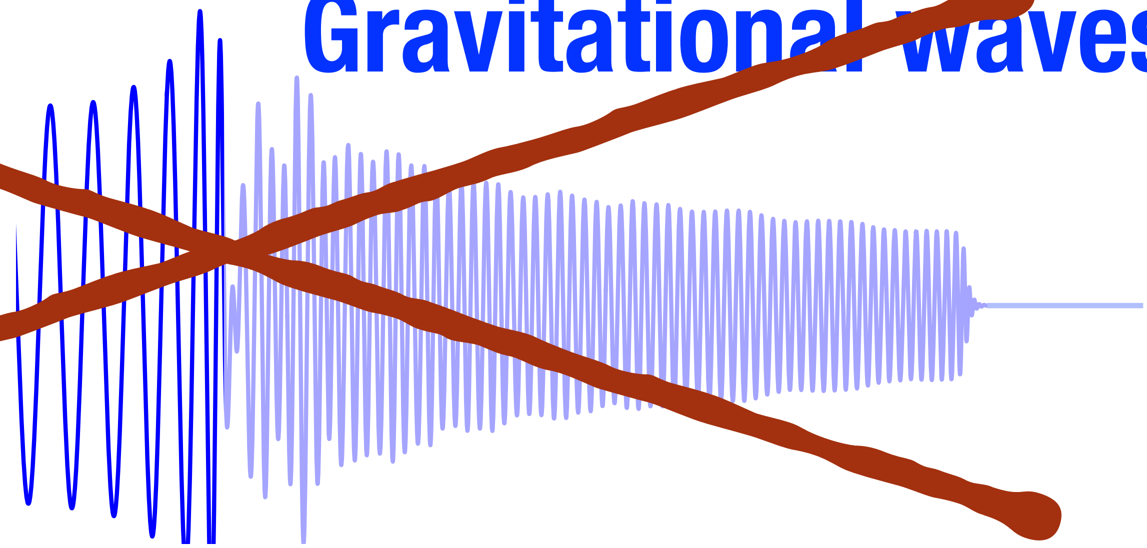
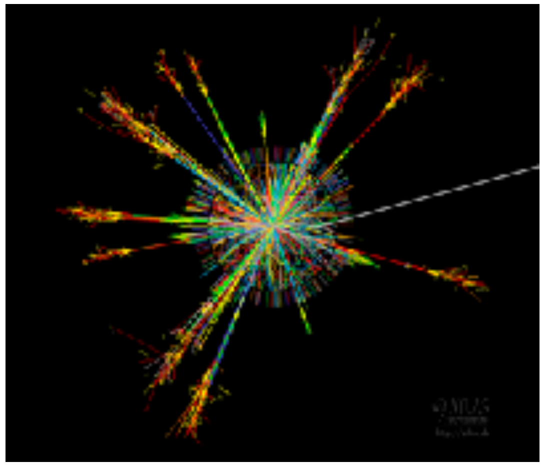


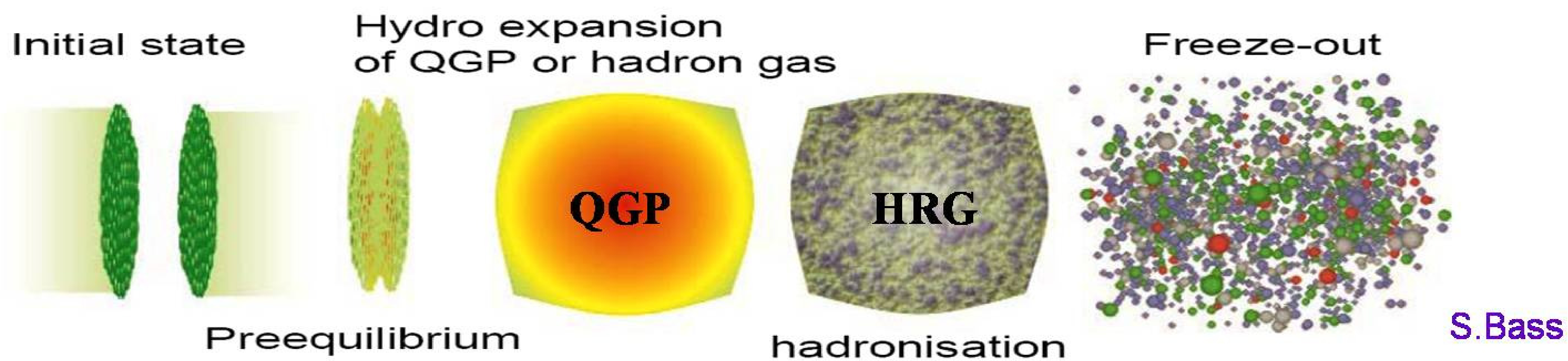
From gravity to nuclear physics

~~Gravitational waves~~



Jets





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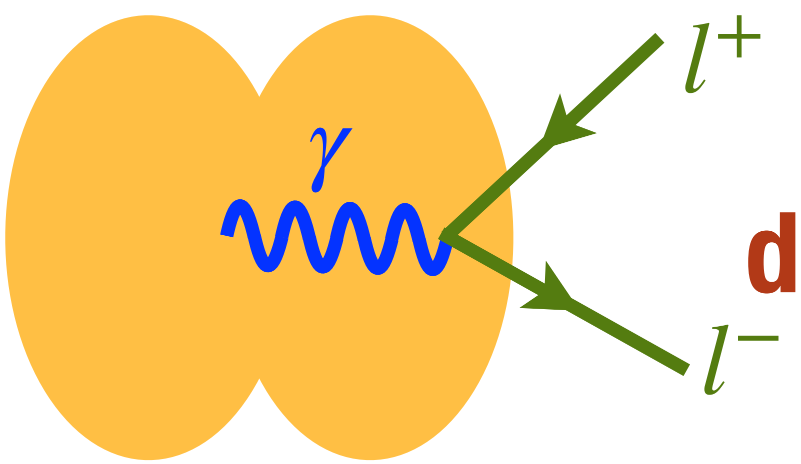

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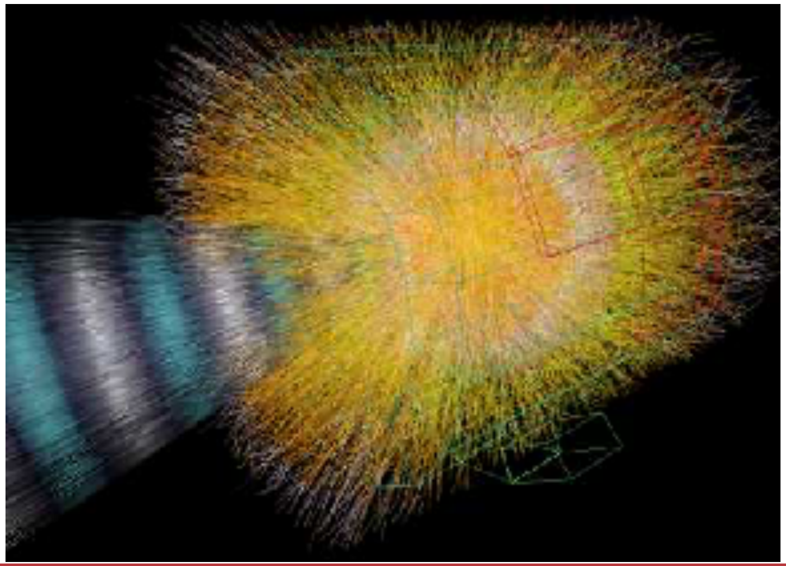

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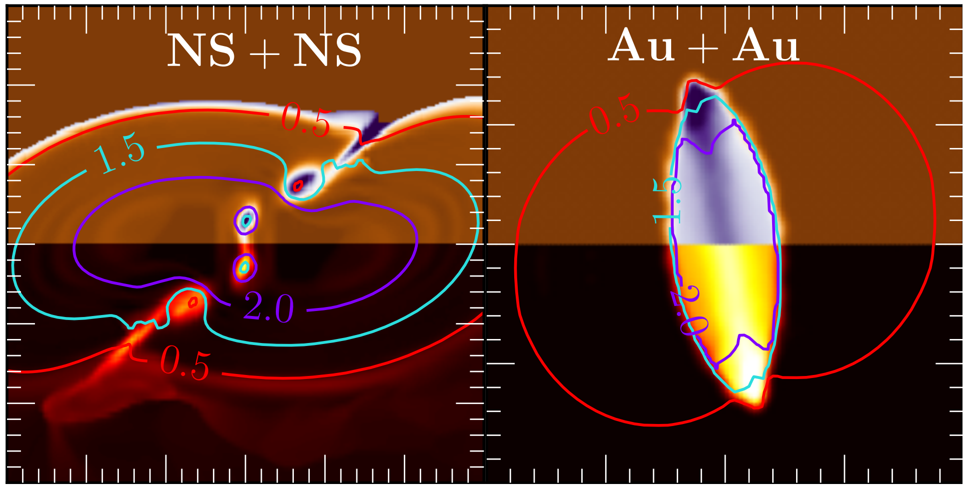
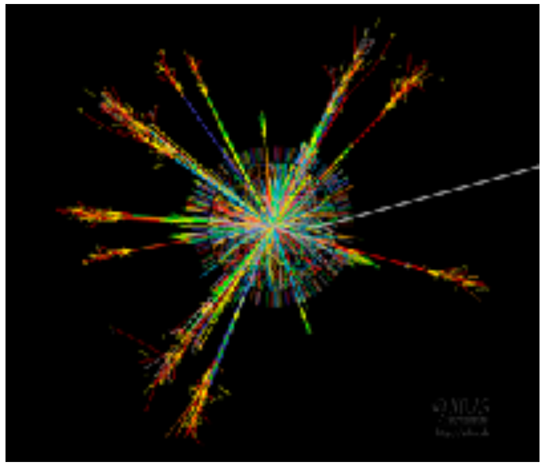


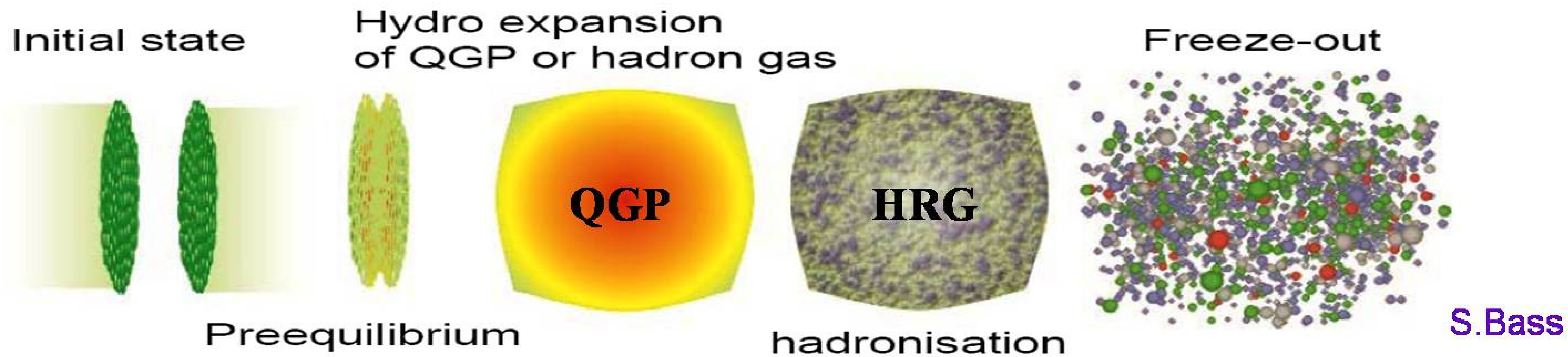
Comparison with Au+Au!

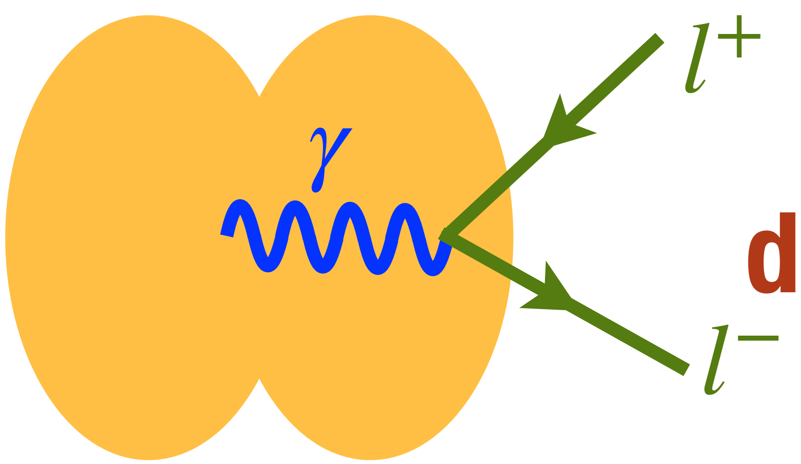
Neutron star mergers as cosmic colliders!

ERM+(arXiv:2022)

Jets







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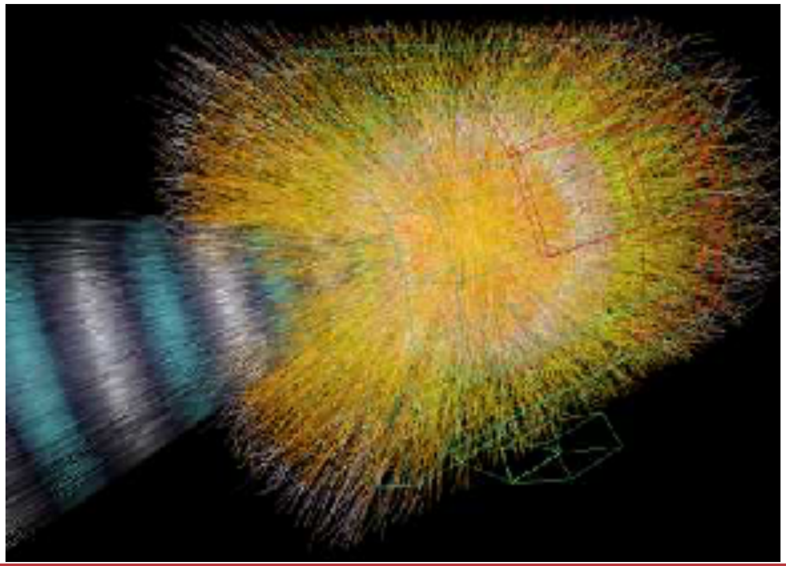
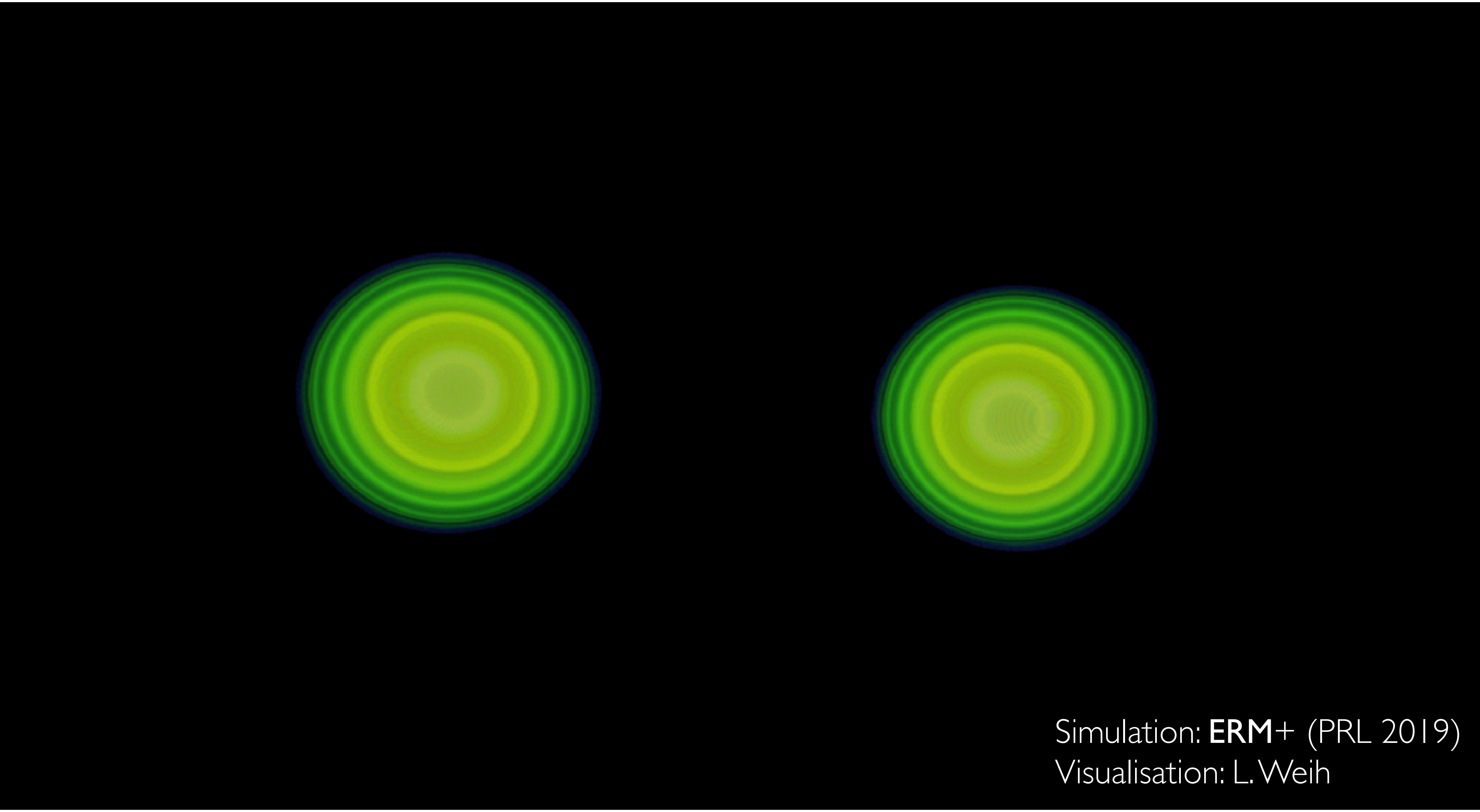
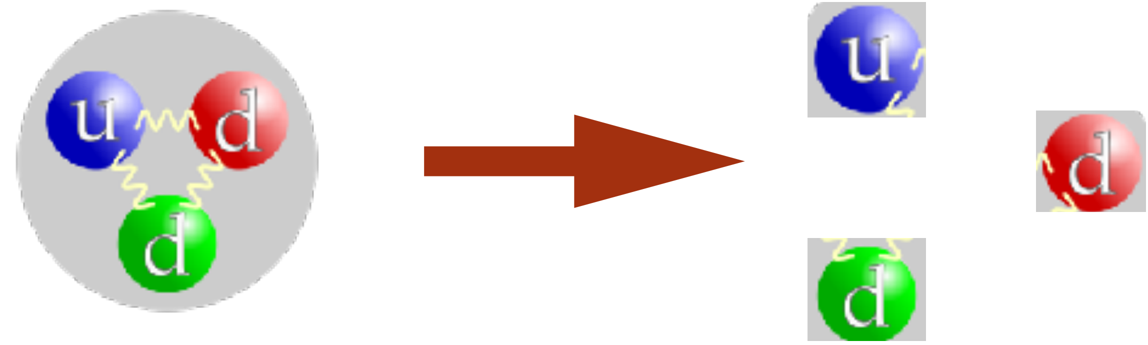
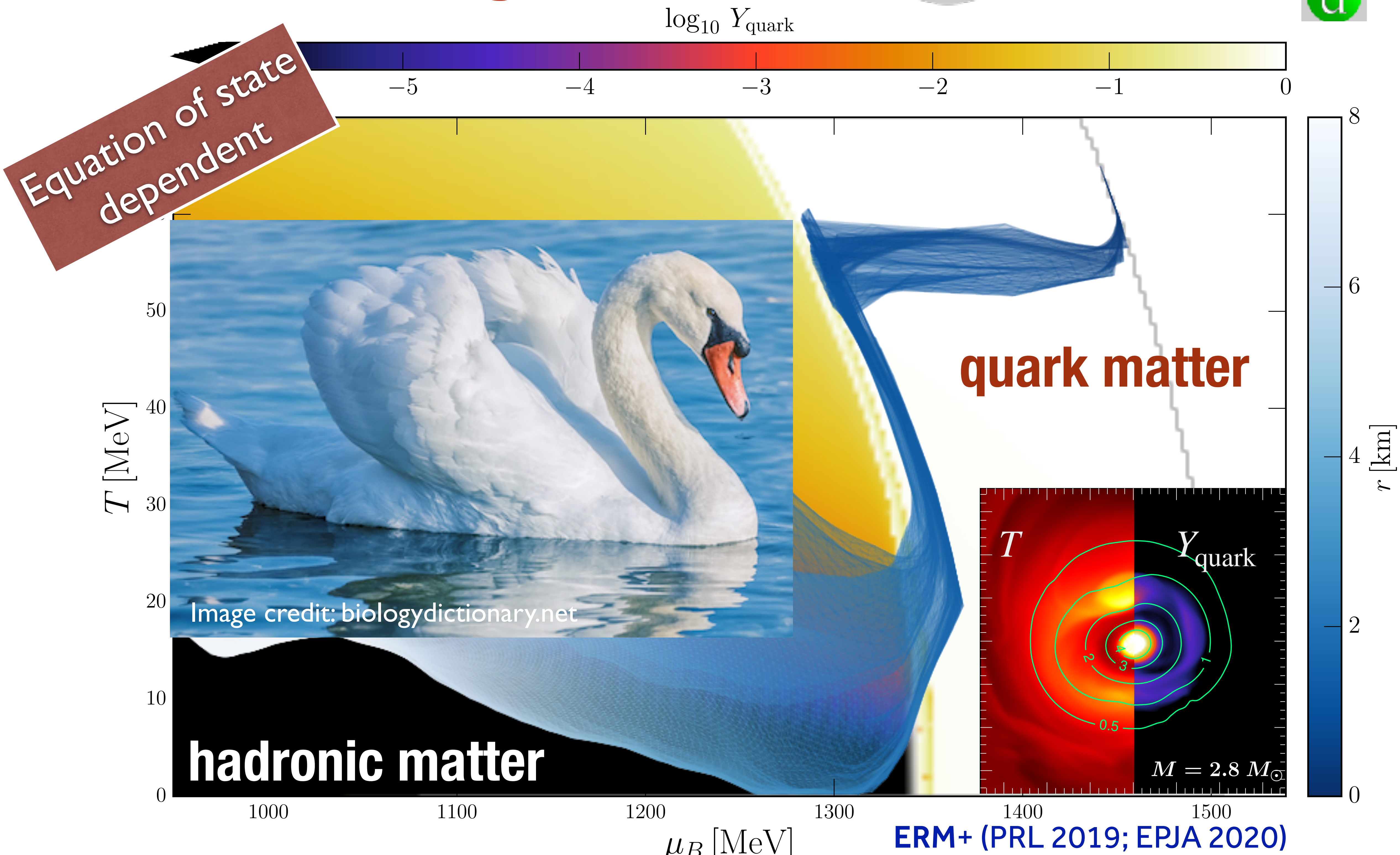


Probing exotic states of matter



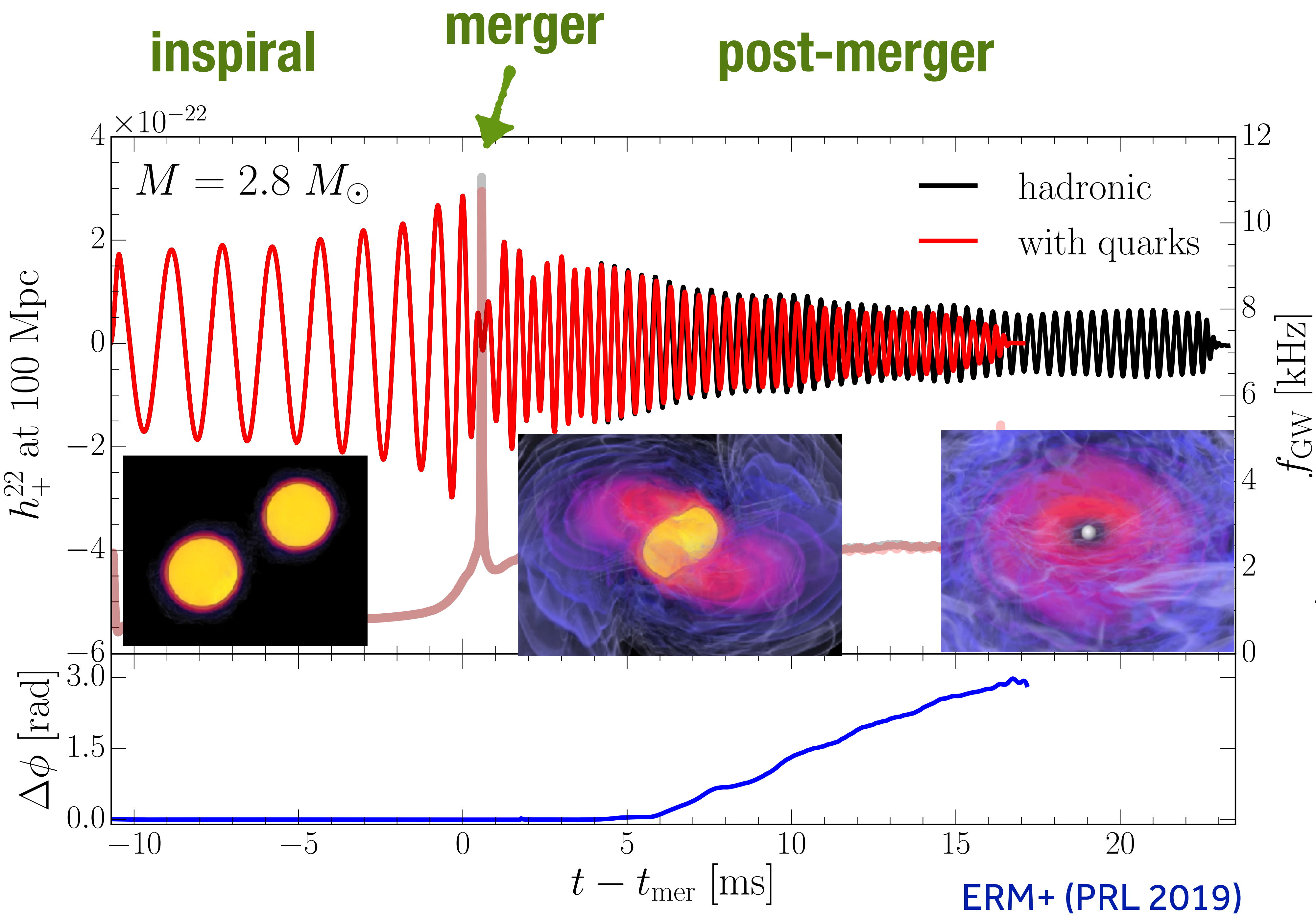
Mergers in the phase diagram





ERM+ (PRL 2019; EPJA 2020)
See also Bauswein+, Prakash+

Can quarks be seen in gravitational waves?



Wave strain

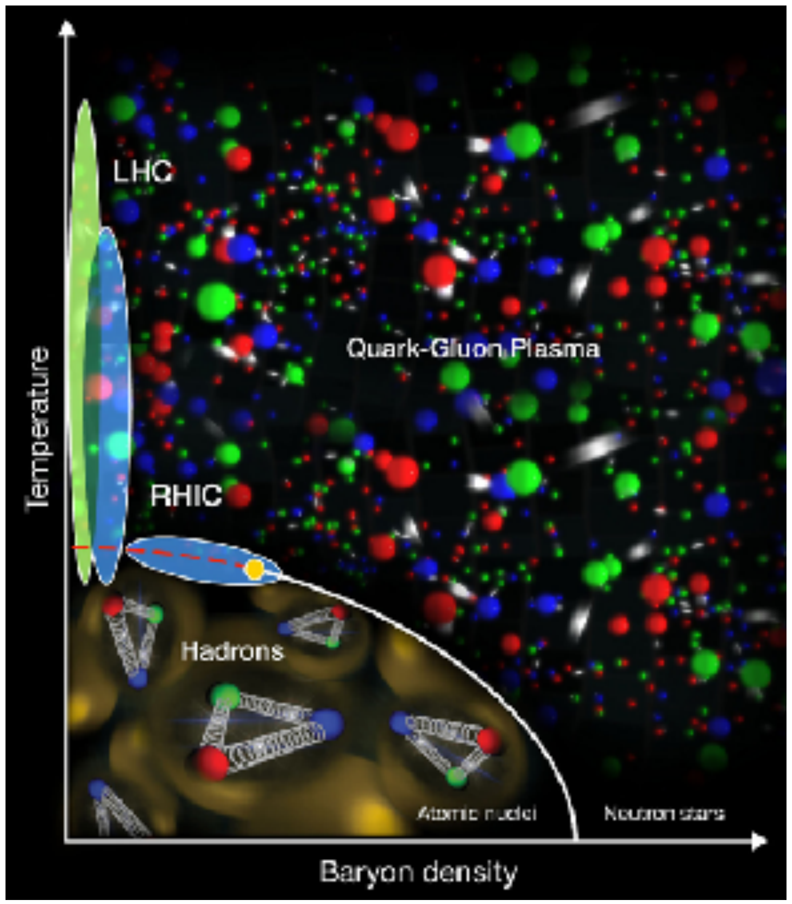
Instantaneous frequency

Phase difference

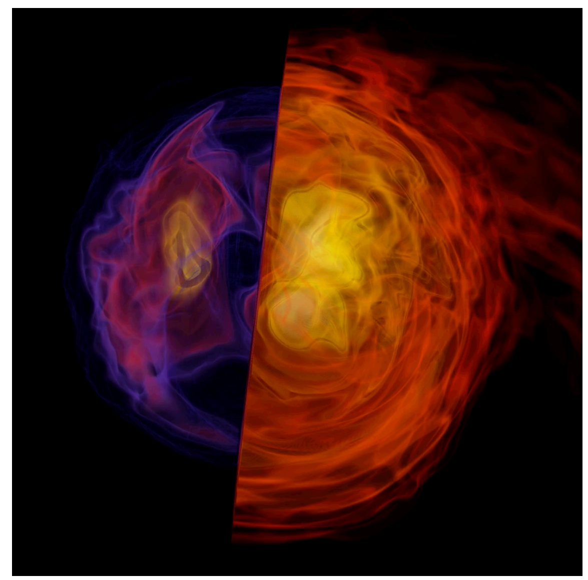
Continued presence of small quark fraction leads to a de-phasing of the waveform in the post merger

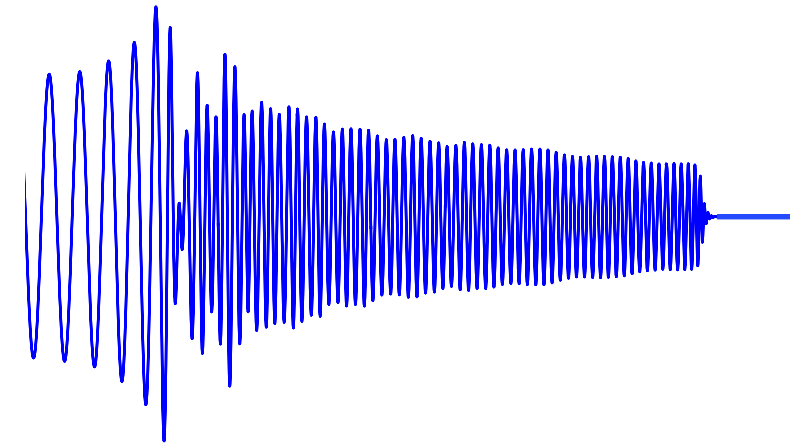
Systematically probing dense matter

Nuclear theory

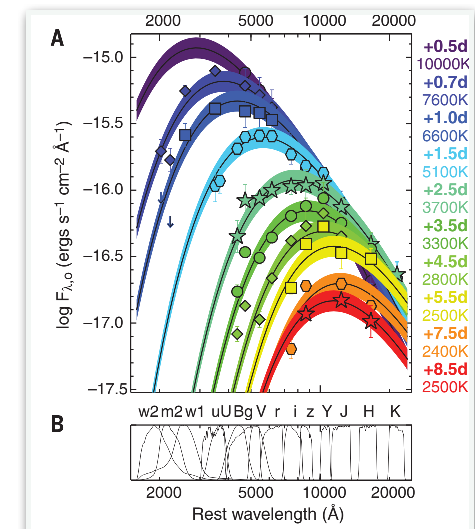


Numerical relativity simulations





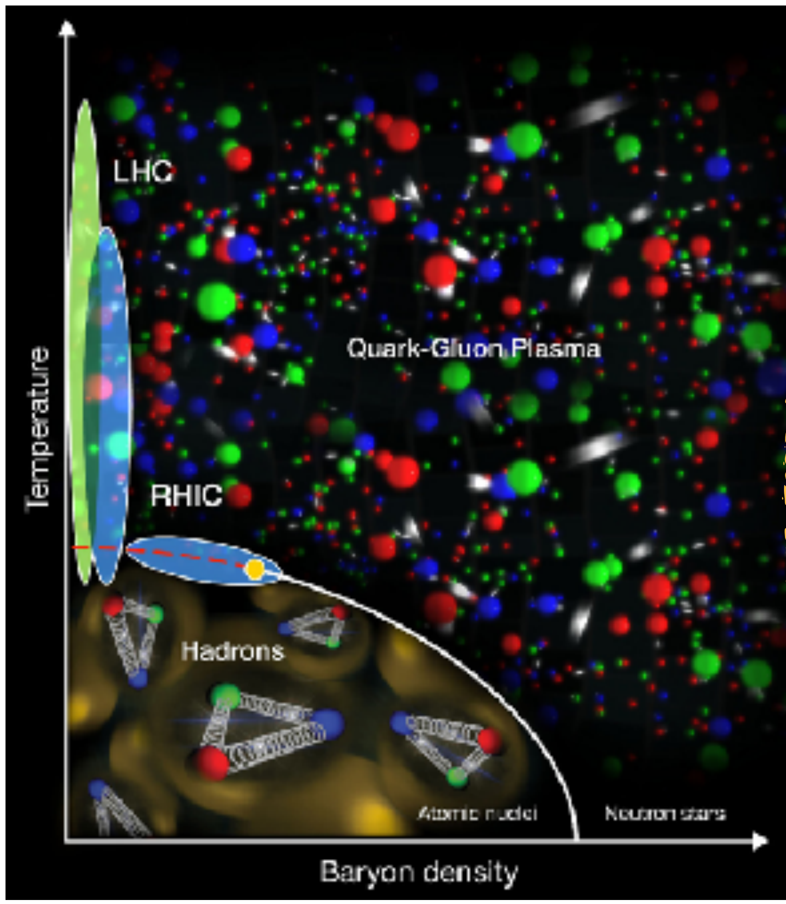
Observables



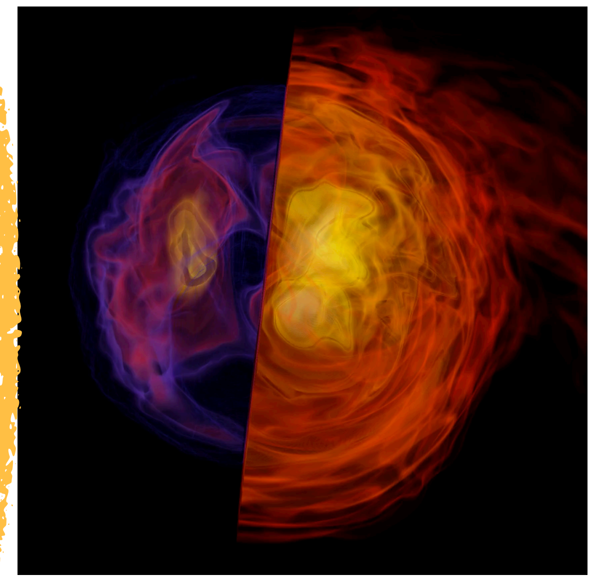
Can we systematically survey dense matter imprints?

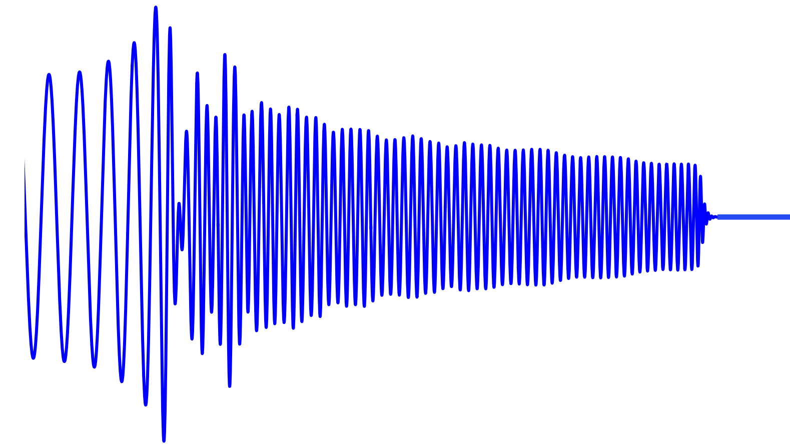
Systematically probing dense matter

Nuclear theory

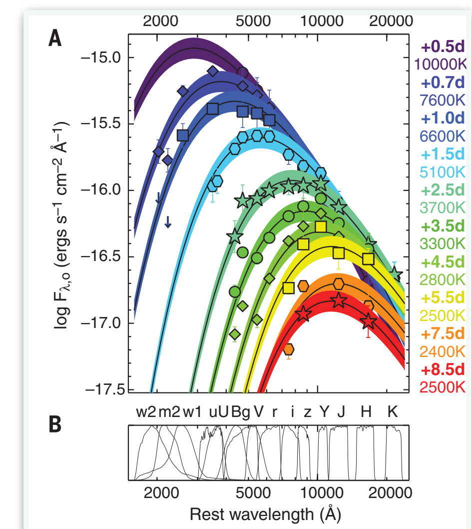


Numerical relativity simulations





Observables



First proof-of-principle!

ERM & Raithel (2021)

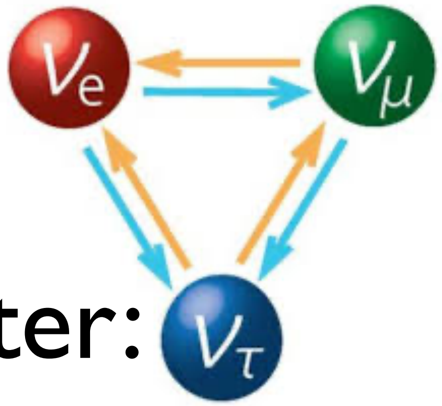
Breakthrough computing:

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

muses

https://musesframework.io

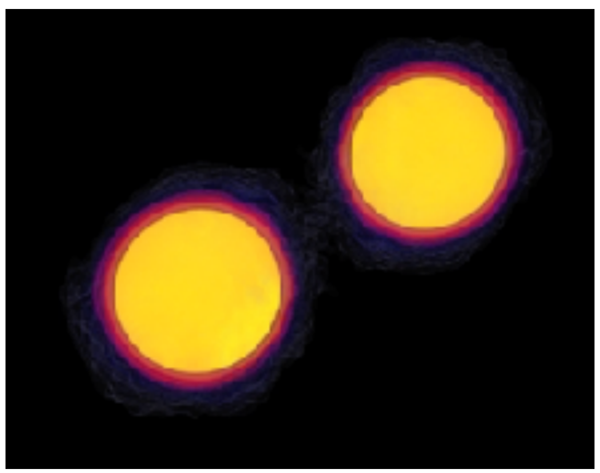
Beyond the equation of state!



Weak interactions are crucial for neutron star matter:

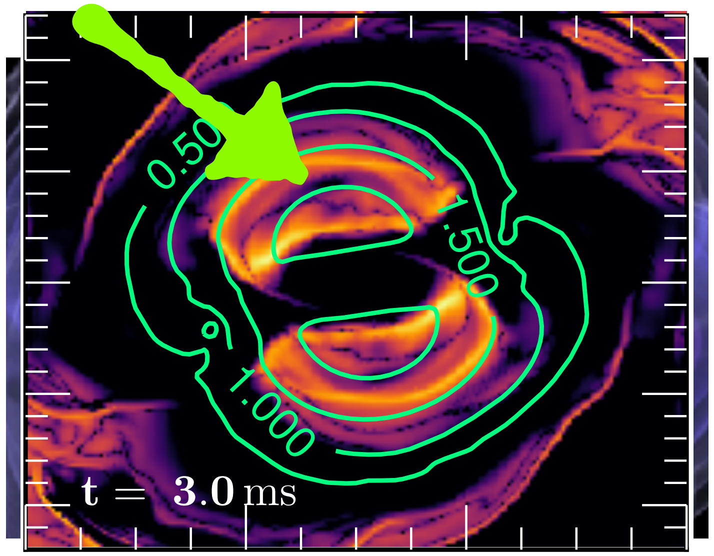
$$n \rightarrow p + e^- + \bar{\nu}_e$$
$$p + e^- \rightarrow n + \nu_e$$

Equilibrium
(reactions balance)



merger

Out-of-equilibrium
(reactions do NOT balance)



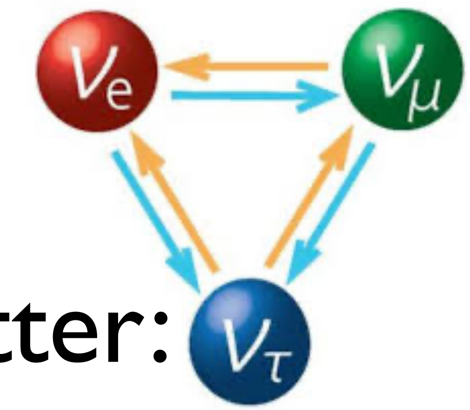
ERM+ (MNRAS 2022)

Feedback on the matter during merger can act as an effective bulk viscosity.

Alford+ (2017,2021), **ERM**+ (MNRAS 2022), Hammond+(2021)

Feedback on matter can (drastically) alter post-merger dynamics!

Beyond the equation of state!

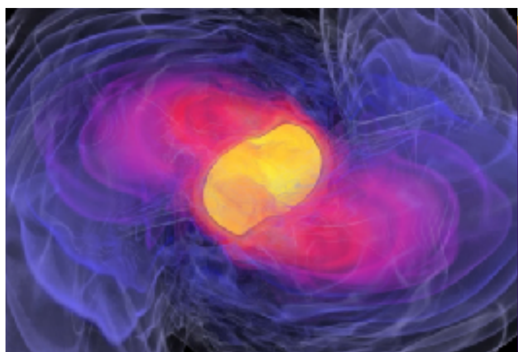


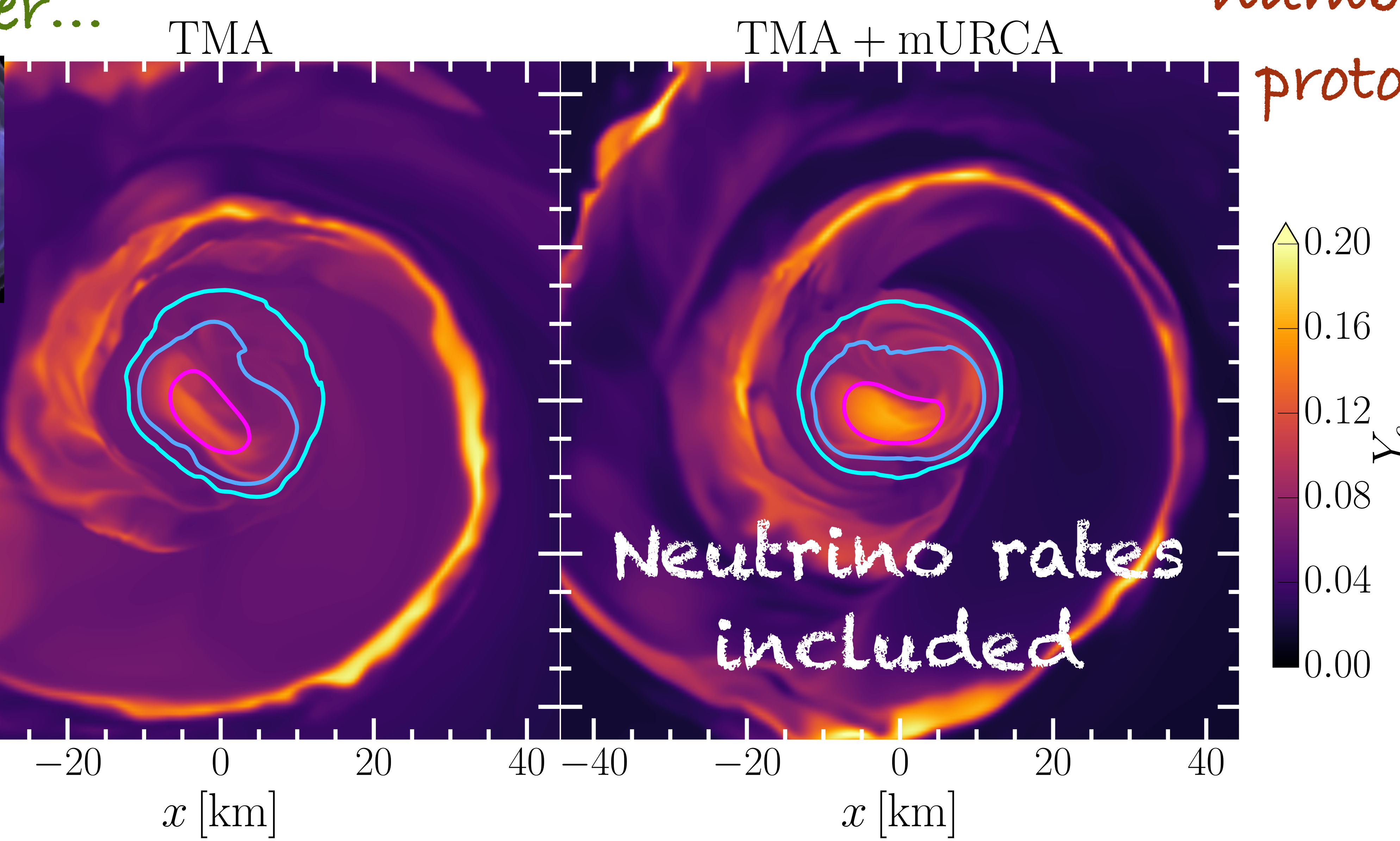
Weak interactions are crucial for neutron star matter:

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

$$N + p + e^- \to n + \nu_e + N$$

After merger...





Relative number of protons

ERM+ (in prep)

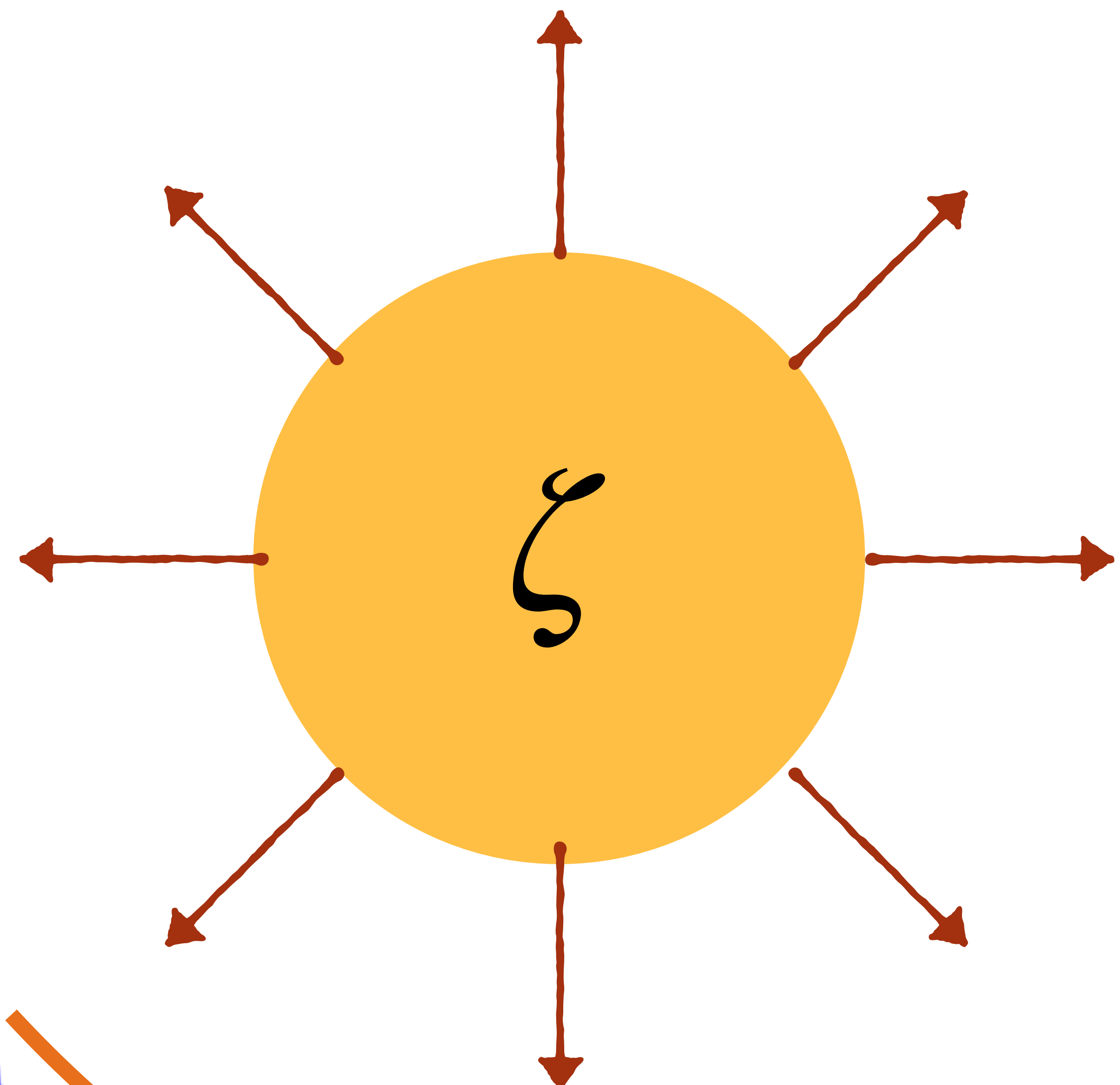
What does bulk viscosity do?

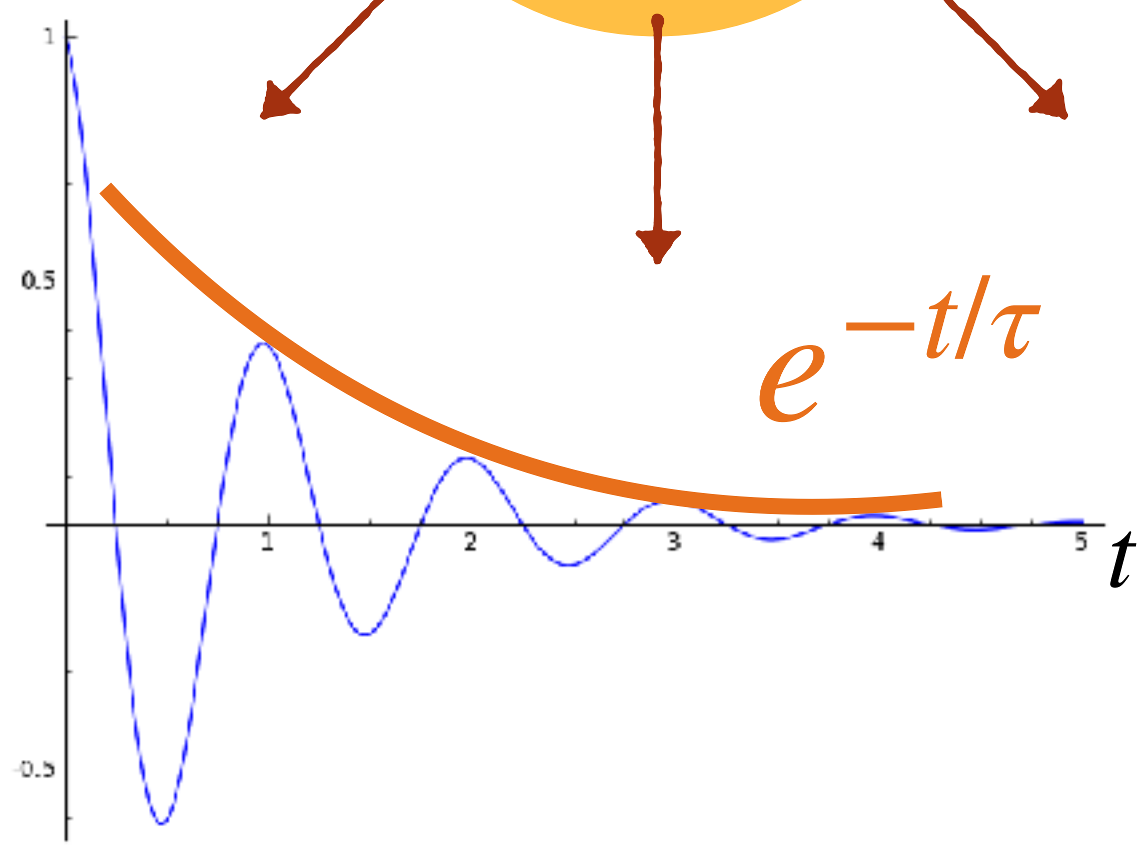
An oscillating neutron star (periodic compression and expansion) then would damp on a characteristic time scale

$$\tau = \frac{2\rho c_s^2}{\zeta \omega^2}$$

Cerda-Duran (2010)

where ω is the oscillation frequency.





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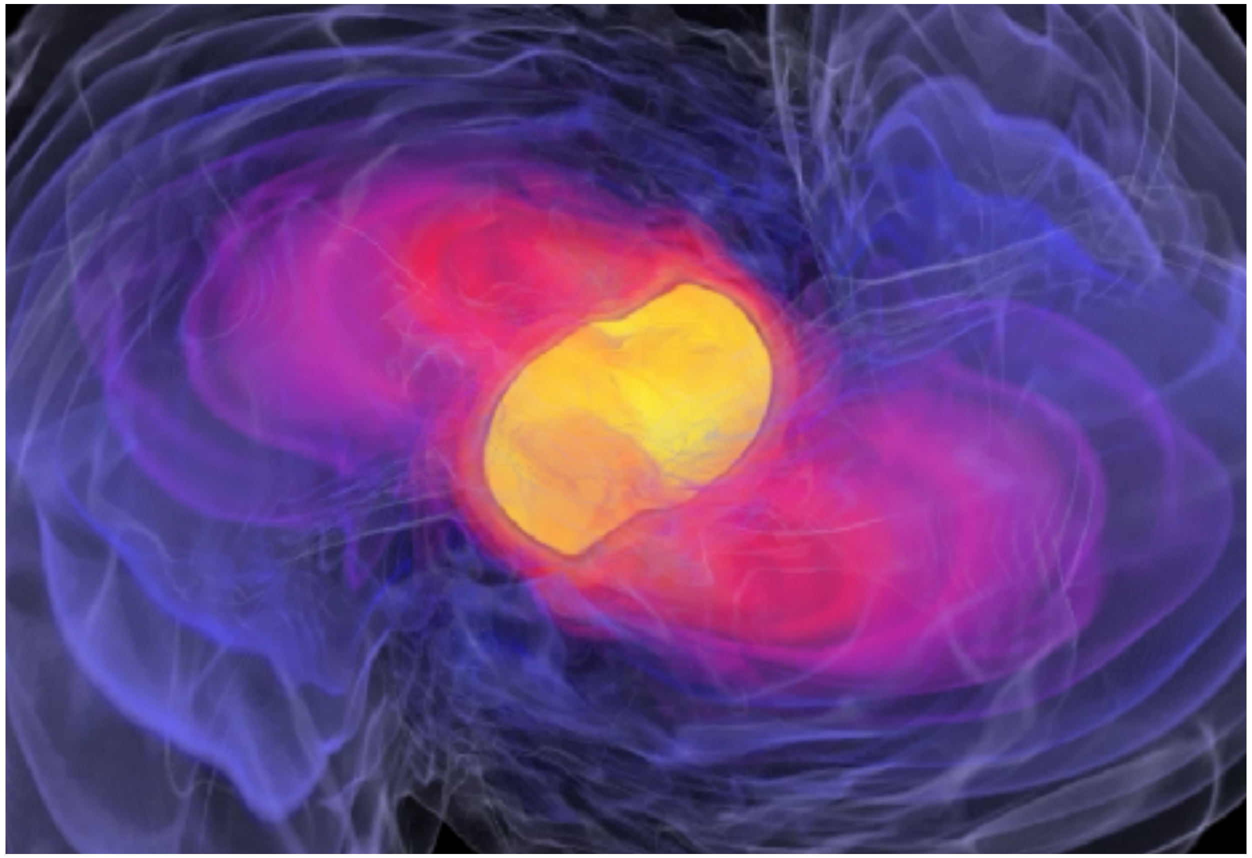
Cerda-Duran (2010)



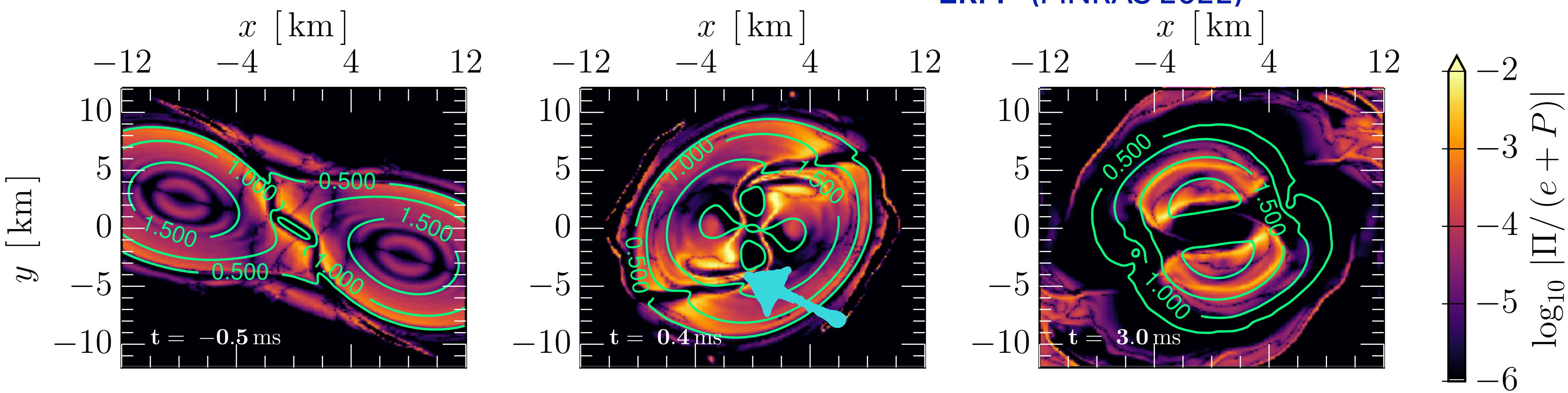
where ω is the oscillation frequency

Can bulk viscosity damp post-merger oscillations?

Alford+ (PRL 2017)

Projected impact of bulk viscosity

ERM+ (MNRAS 2022)

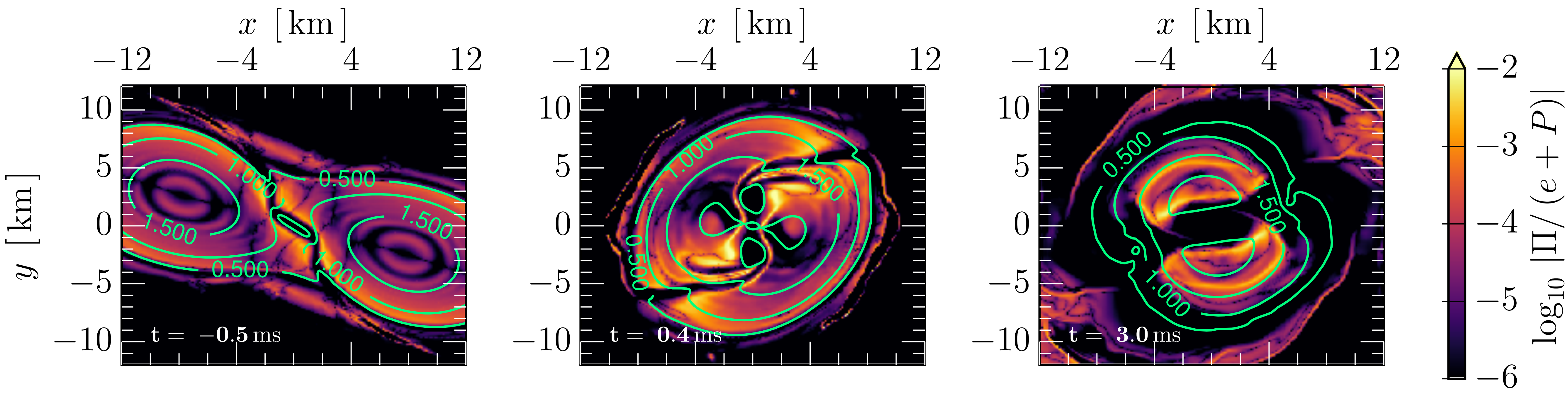


Quantify potential impact using bulk pressure scalar Π.

Locally, up to 4% difference in pressure due to neutrino bulk viscosity!

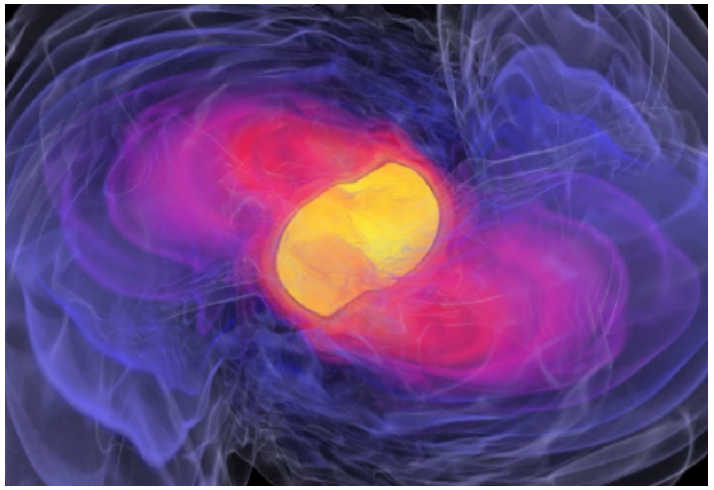
Projected impact of bulk viscosity

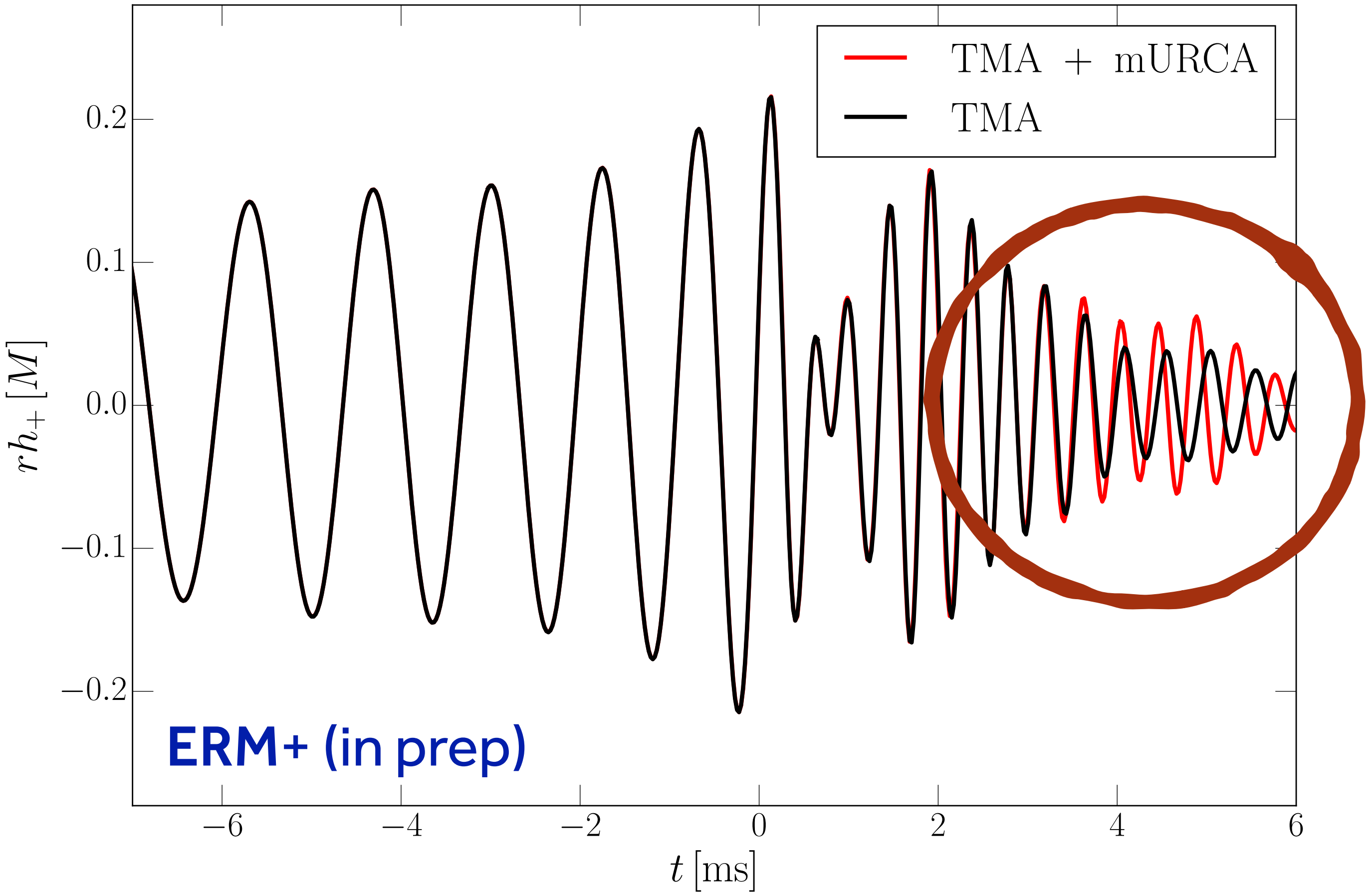
ERM+ (MNRAS 2022)



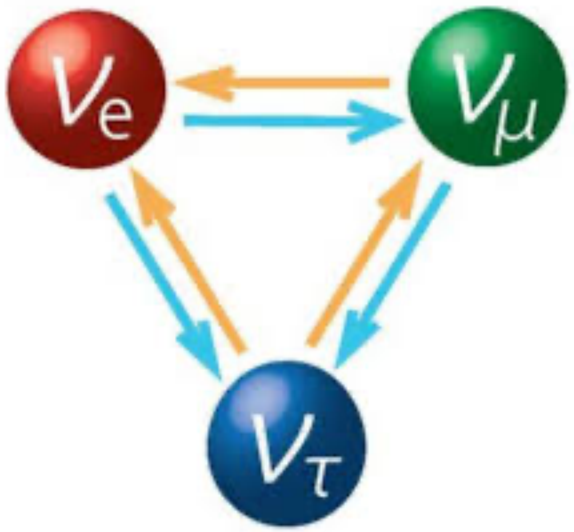
Quantify potential impact using bulk pressure scalar Π.

Difference in post-merger GW emission!

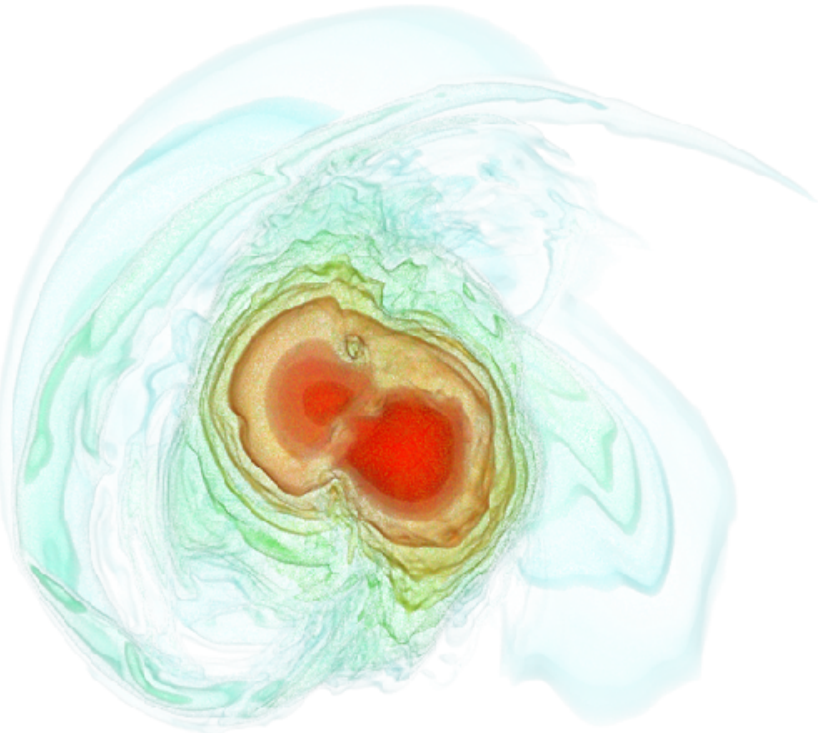


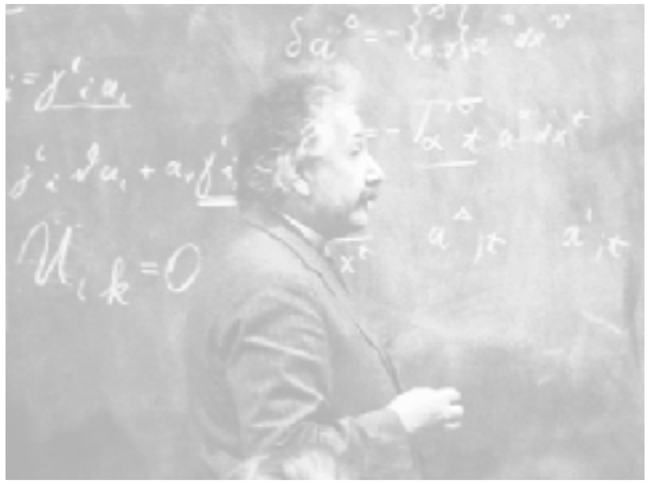


The many faces of neutron star mergers

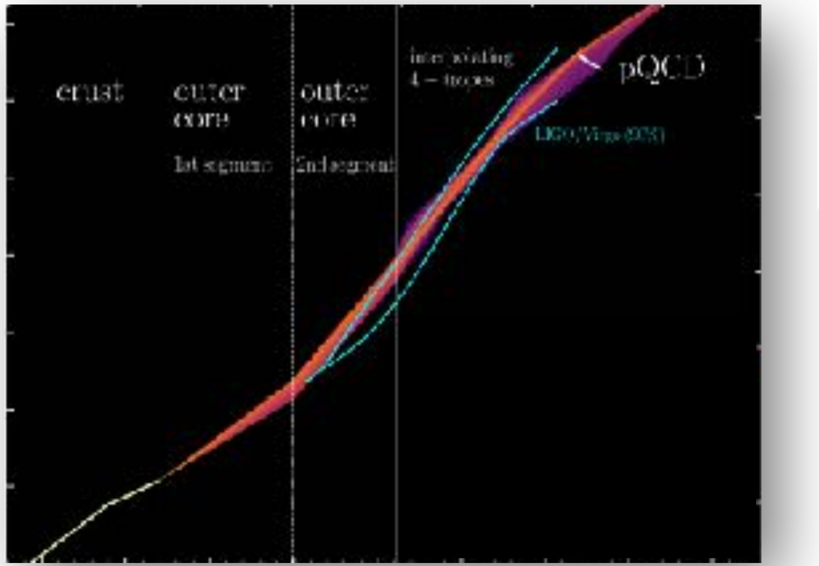


Neutrino physics

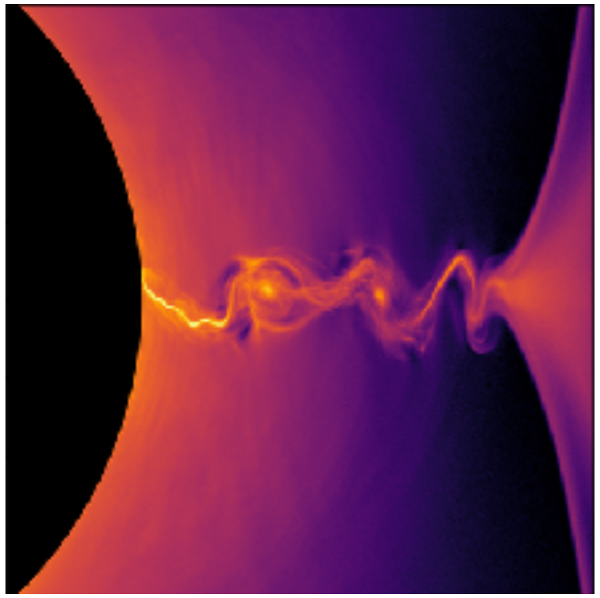




Gravitational physics



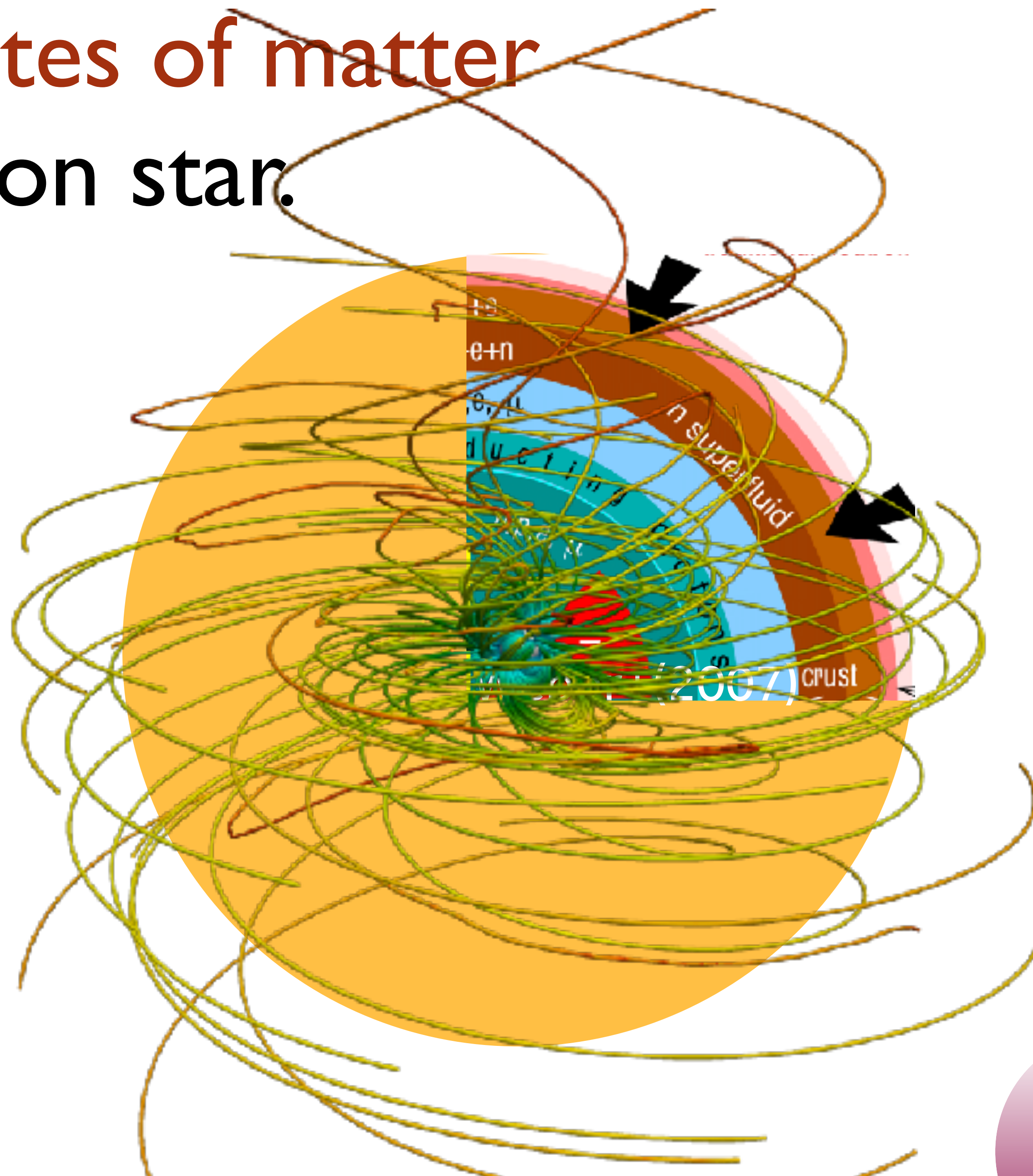
Nuclear physics

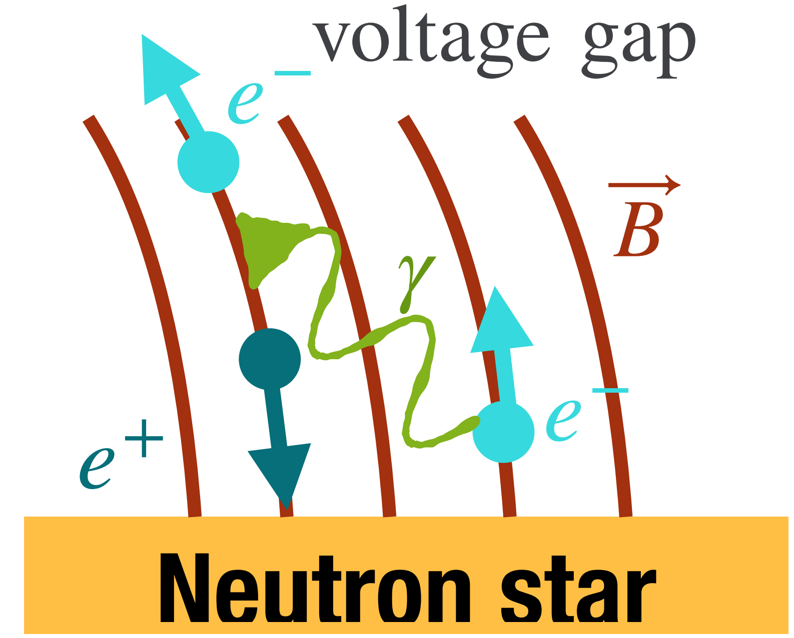


Plasma physics

Extreme plasmas on the outside!

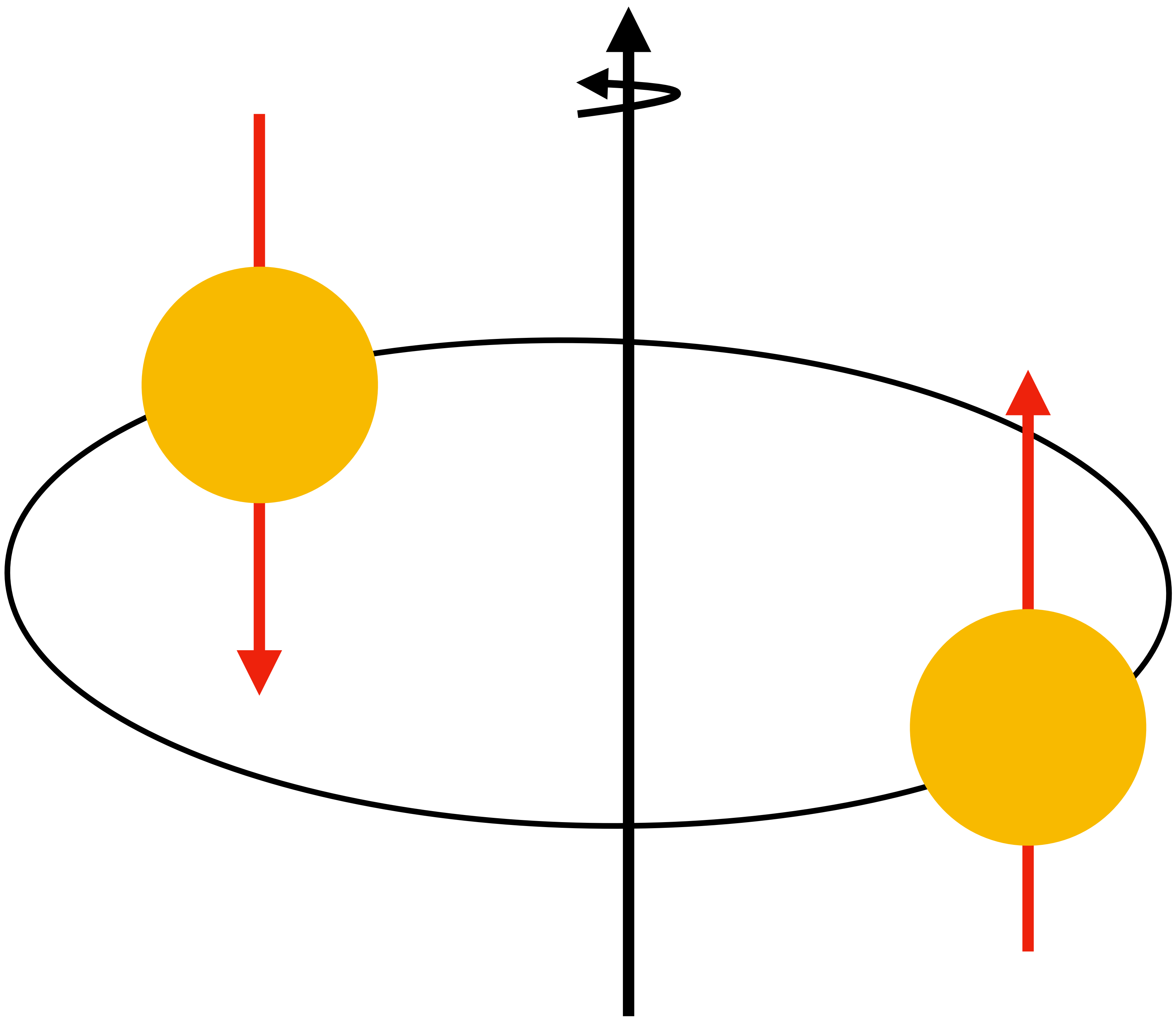
So far we have focused on the extreme states of matter inside the neutron star.



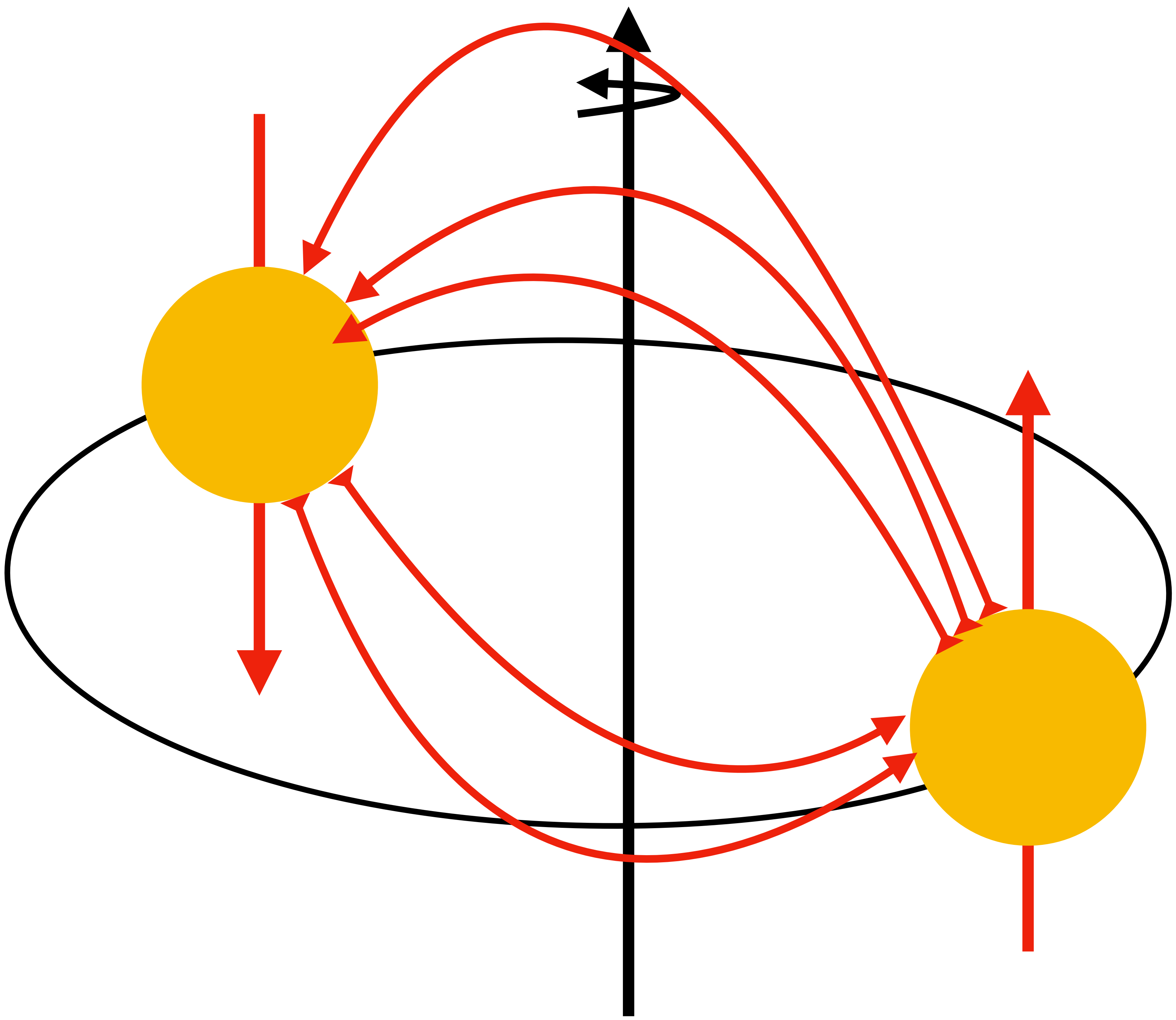


What about the extreme plasma surrounding it?

Electromagnetic precursors

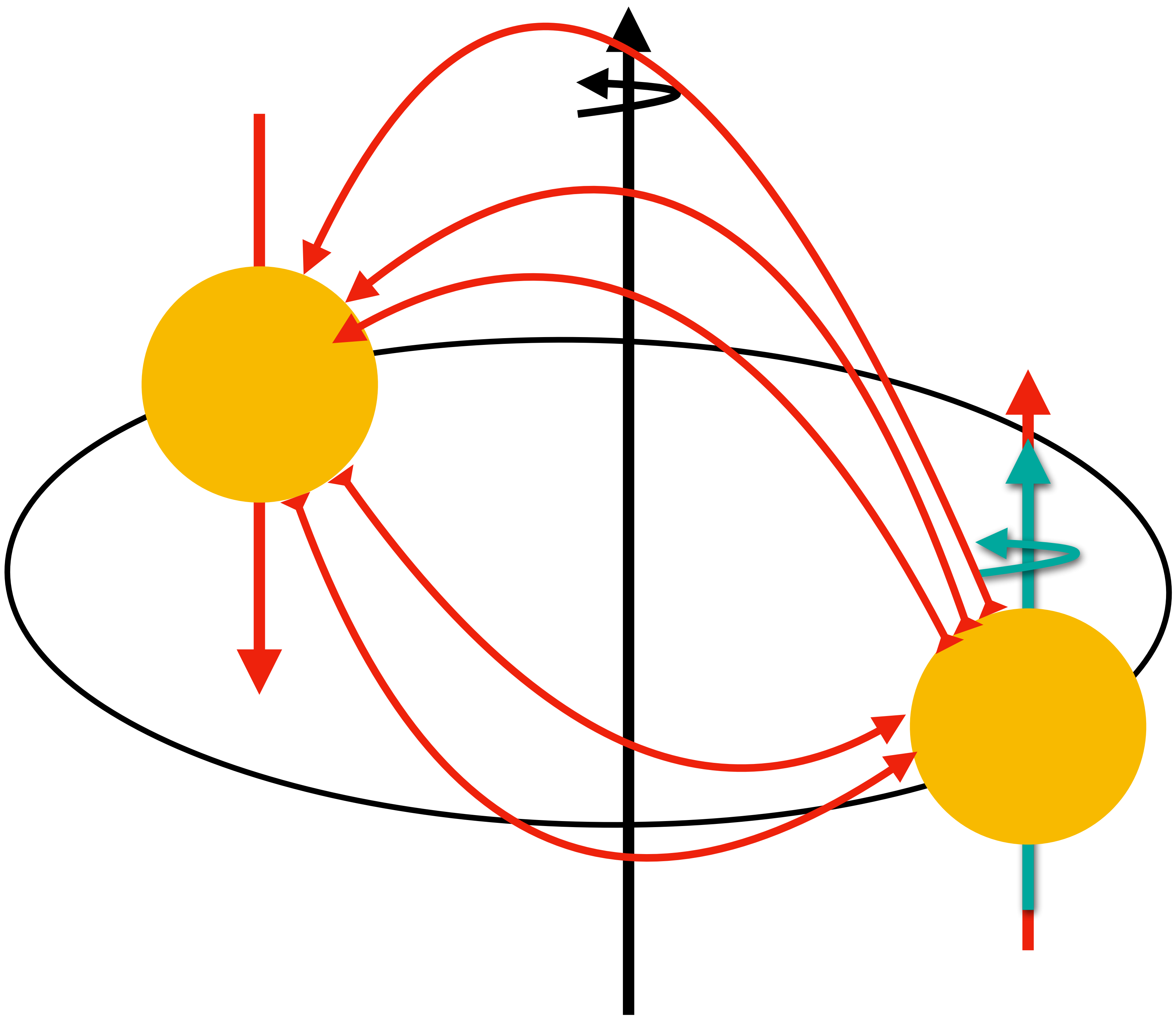


Electromagnetic precursors



Electromagnetic precursors

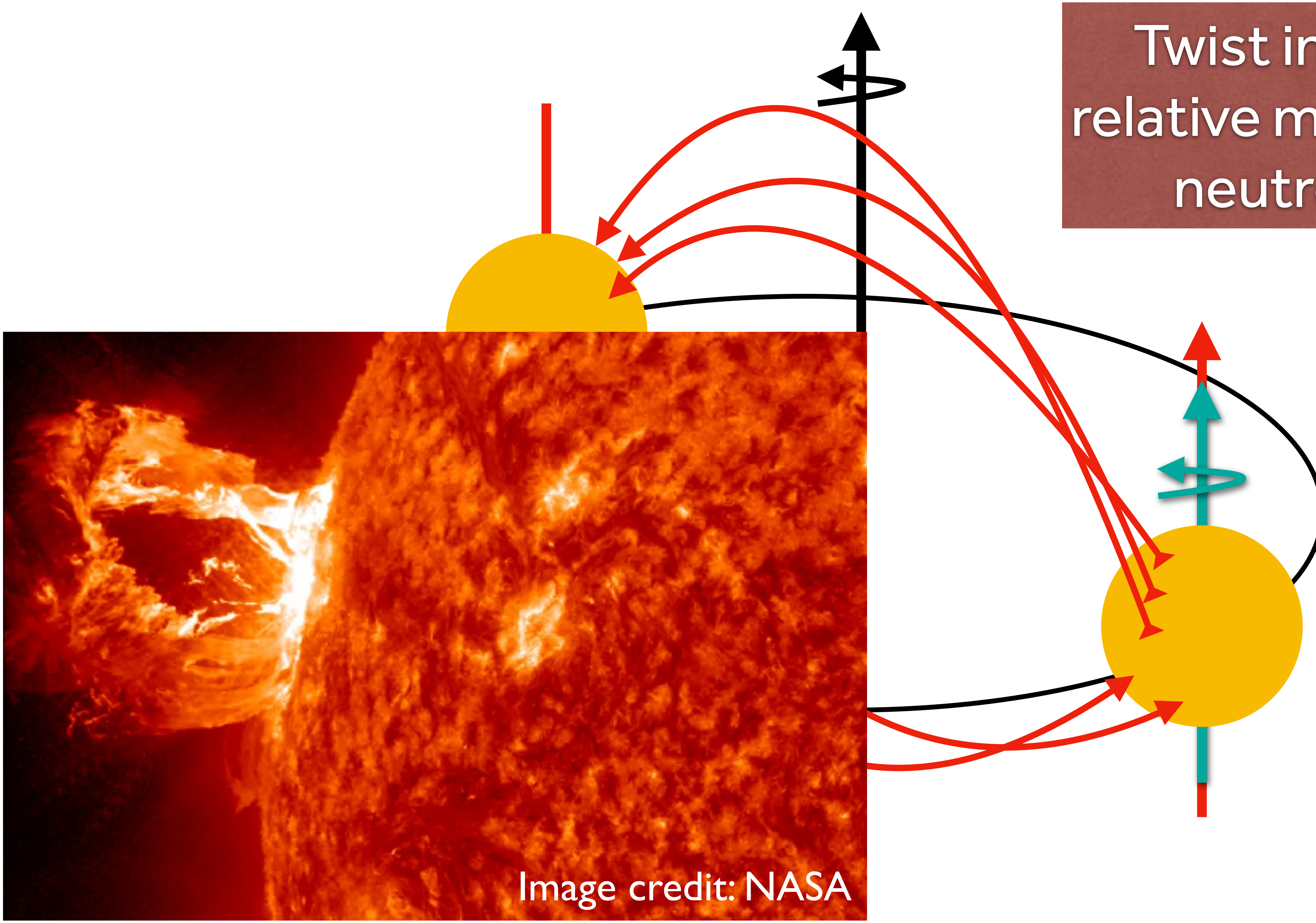
Adding the right twist



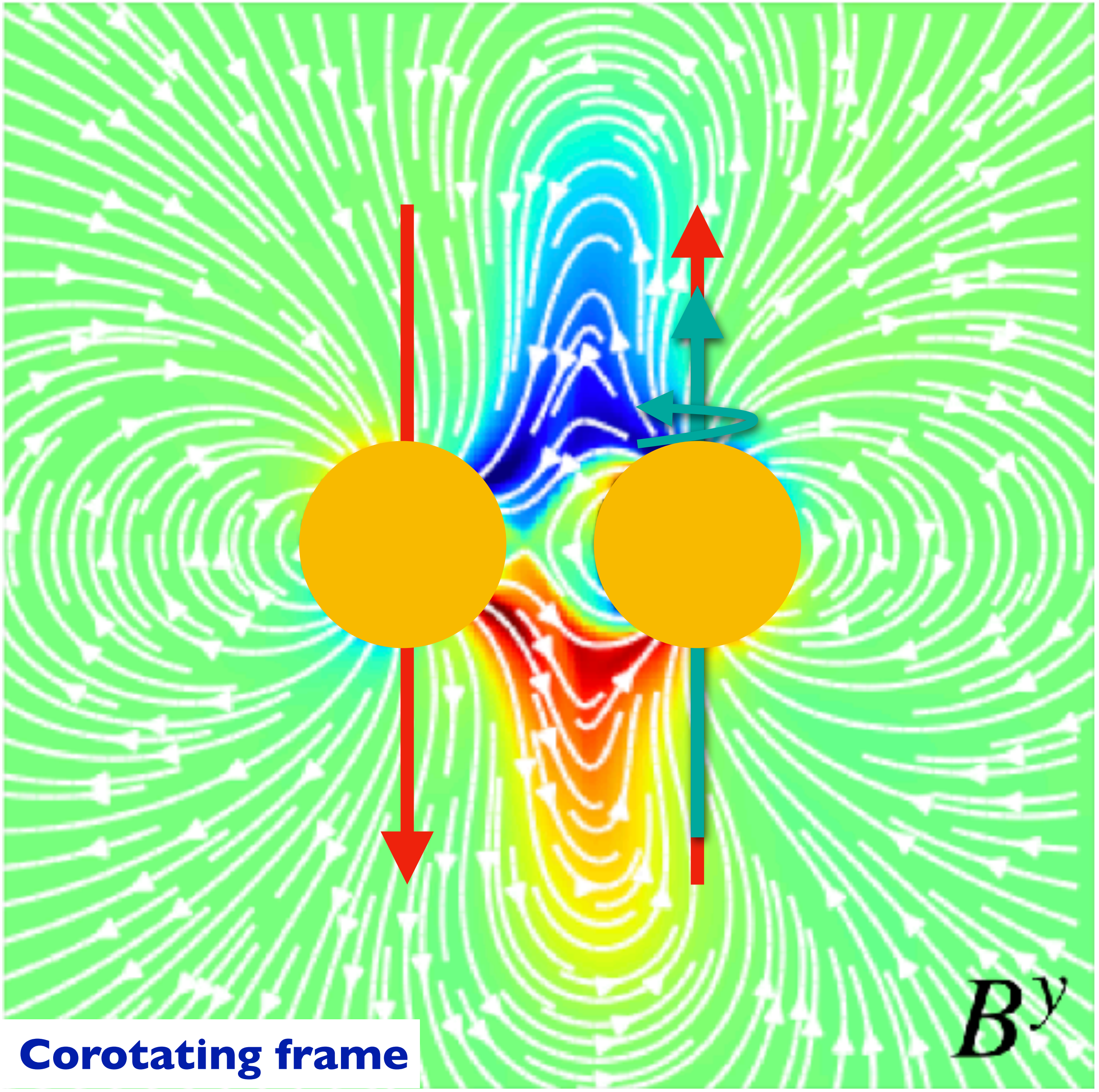
Electromagnetic precursors

Adding the right twist

Twist induced by relative motion of the neutron stars



Electromagnetic precursors
Adding the right twist



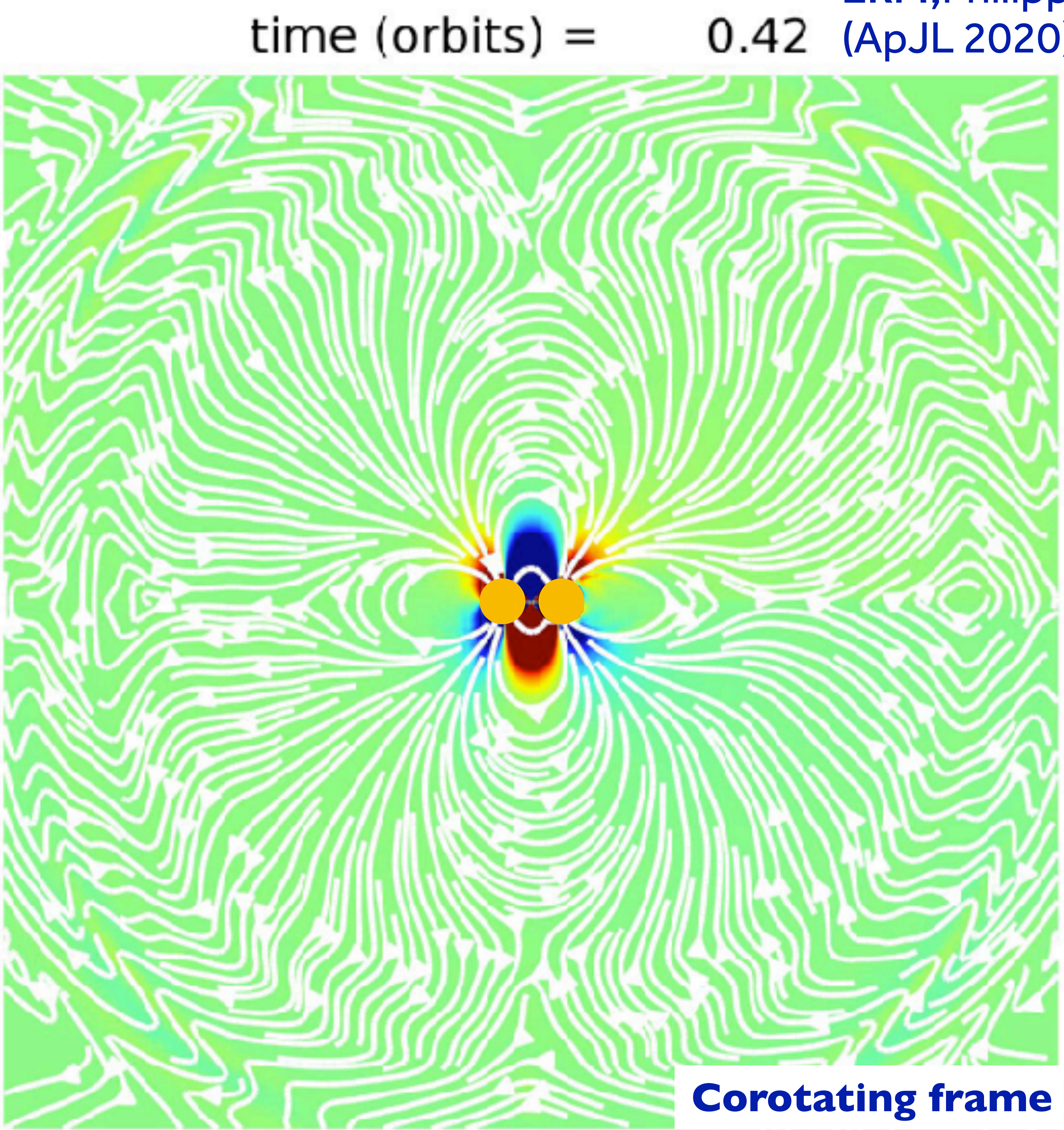
ERM & Philippov
(ApJL 2020)

A new radio transient?

Differential motion leads to the emission of strong electromagnetic flares.

Relativistic force-free electrodynamics simulations in corotating frame

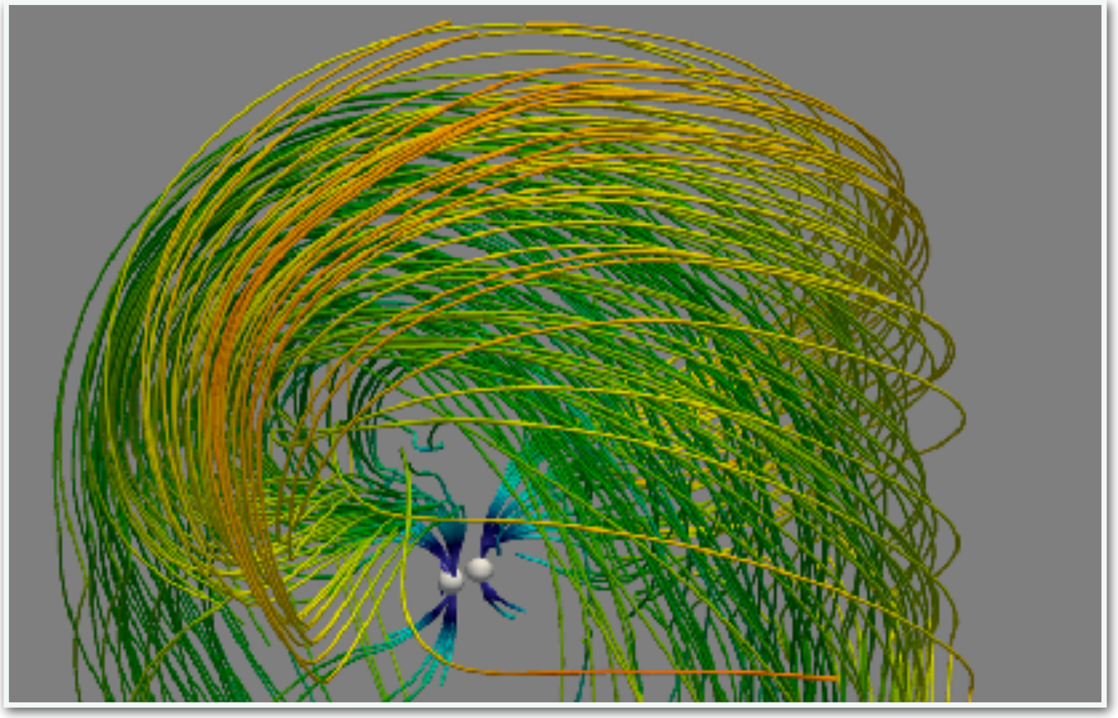
ERM,Philippov (ApJL 2020)

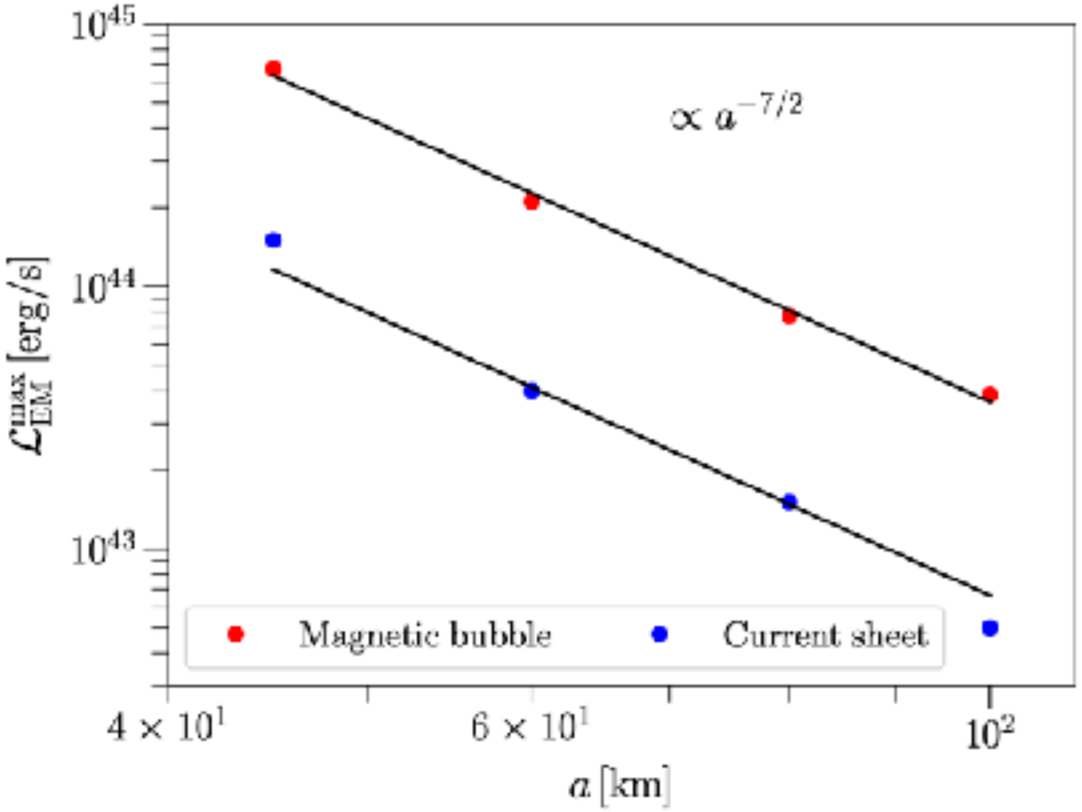


A new radio transient?

Prior to merger, potentially up to 20* sufficiently strong flares could be emitted

(*: for $B \simeq 10^{11}$ G). ERM,Philippov (arXiv:2022)

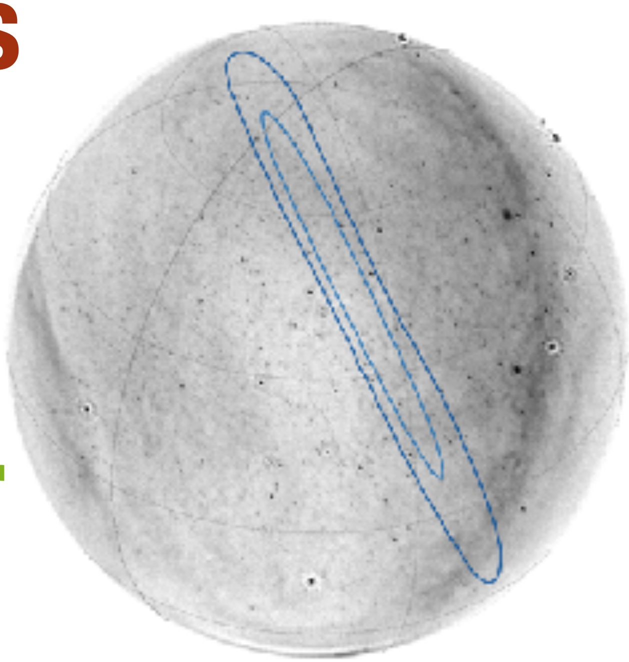




ERM,Philippov (ApJL2020)

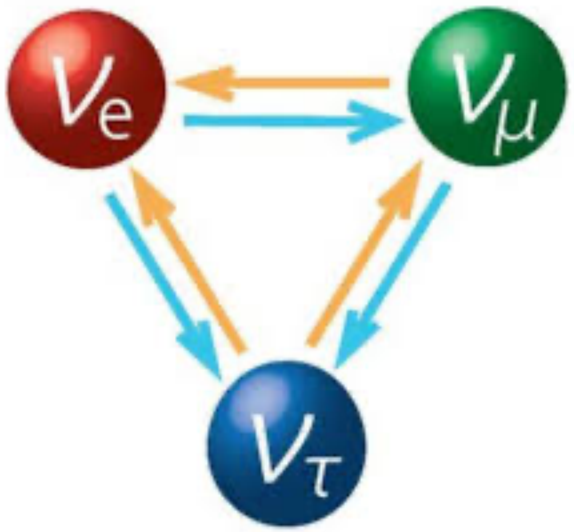
Are these flares observable?

Radio search for GW170817

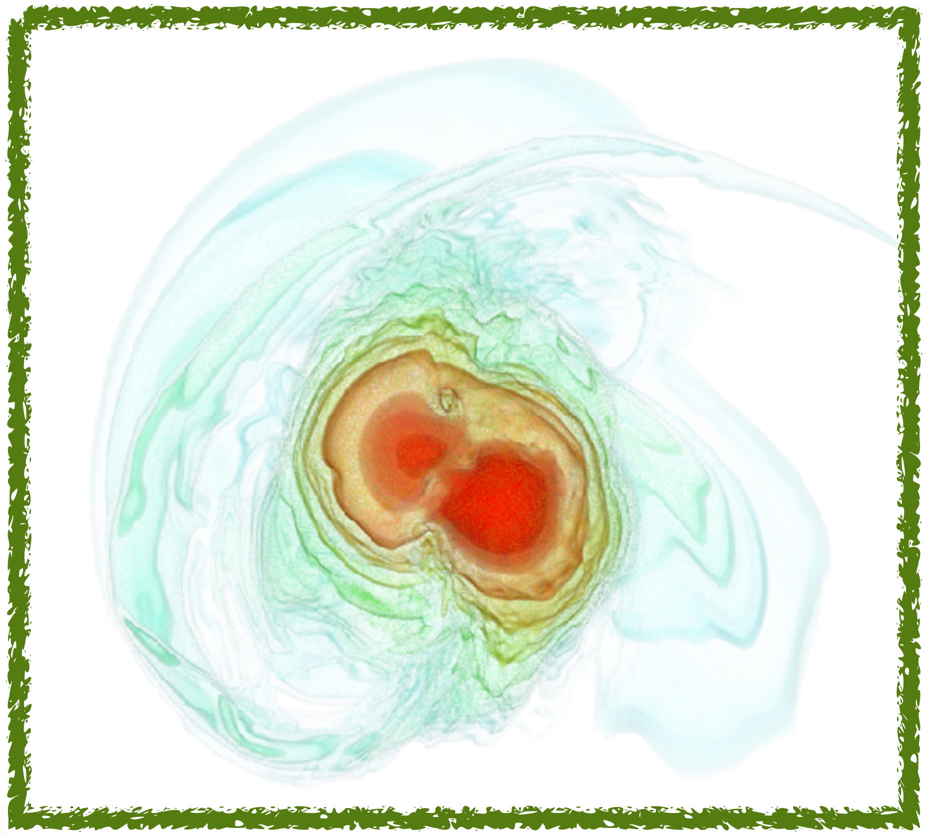


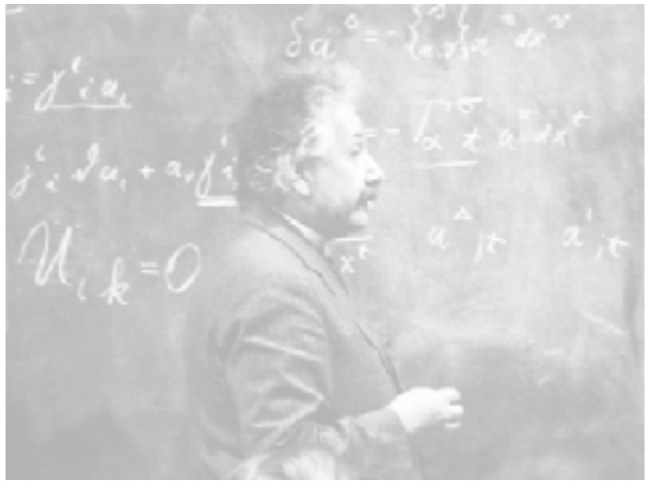
Callister+ (2019)

The many faces of neutron star mergers

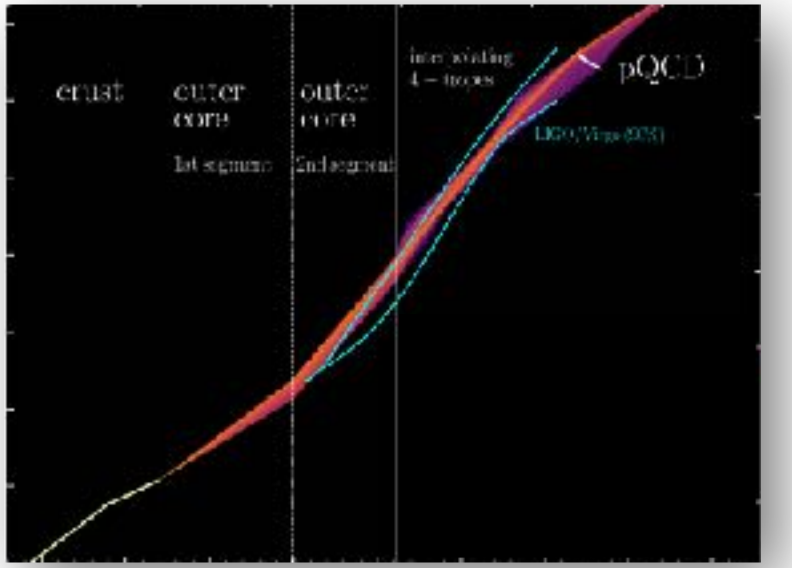


Neutrino physics

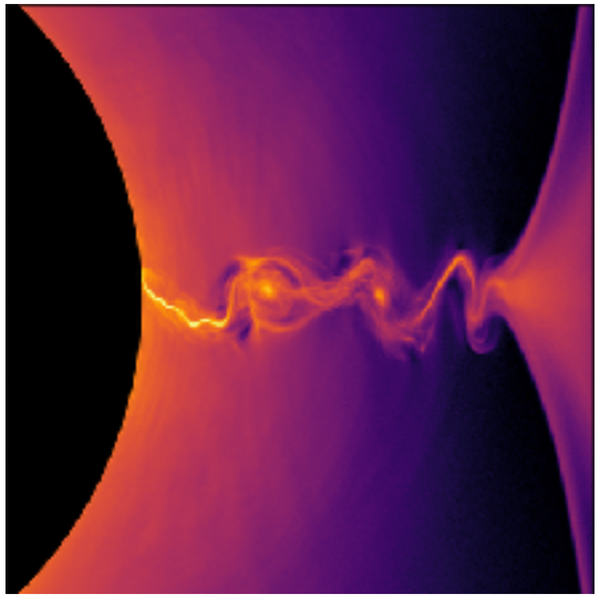




Gravitational physics



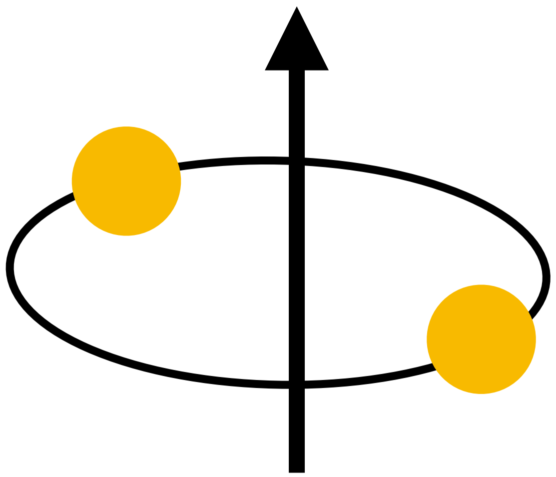
Nuclear physics



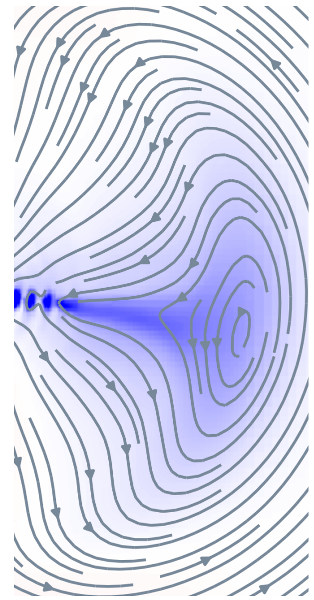
Plasma physics

Vastly different scales

$\sim 50\,\text{km}$

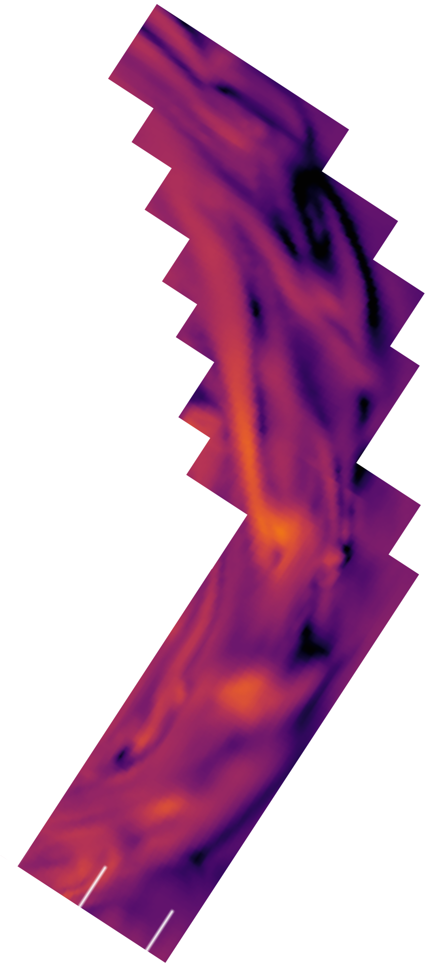


$\sim 200\,\text{km}$



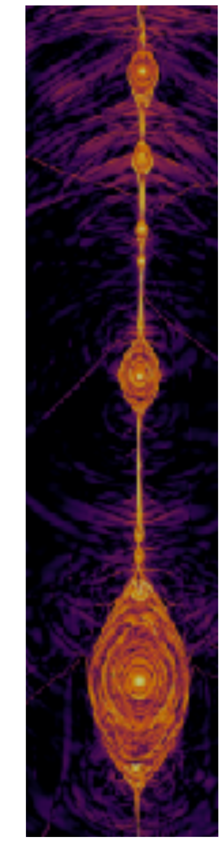
flare

$\sim 1000\,\text{km}$



current sheet

$\sim 10^{-5}\,\text{km}$



reconnection

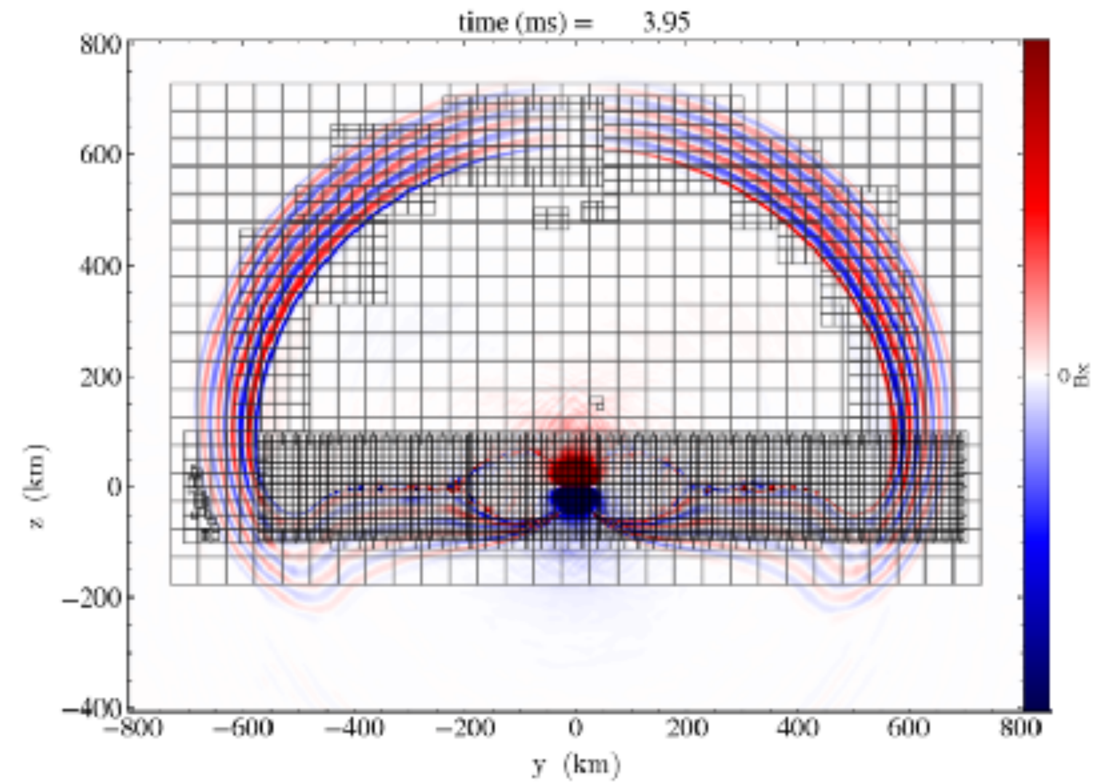
Need a multi-scale approach to capture (effects of) all scales!

✗ **Ab-initio modeling**
(e.g.,particle-in-cell) **?**

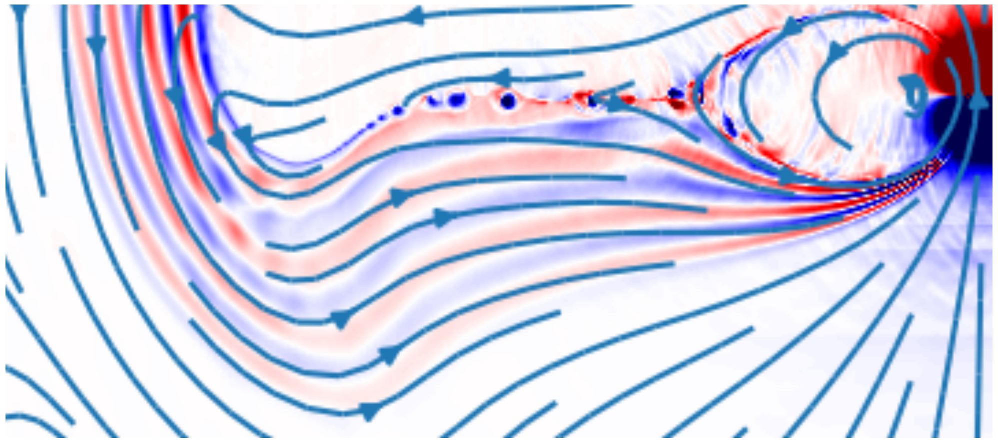
✓ **Effective models**
(e.g.,moment methods) **?**

Model local AND global scales

While accounting for microphysics on small scales, we want to capture global dynamics within the same simulation.



Adopting a fluid-like* description, allows to implicitly overstep scales, and to use mesh-refinement techniques.

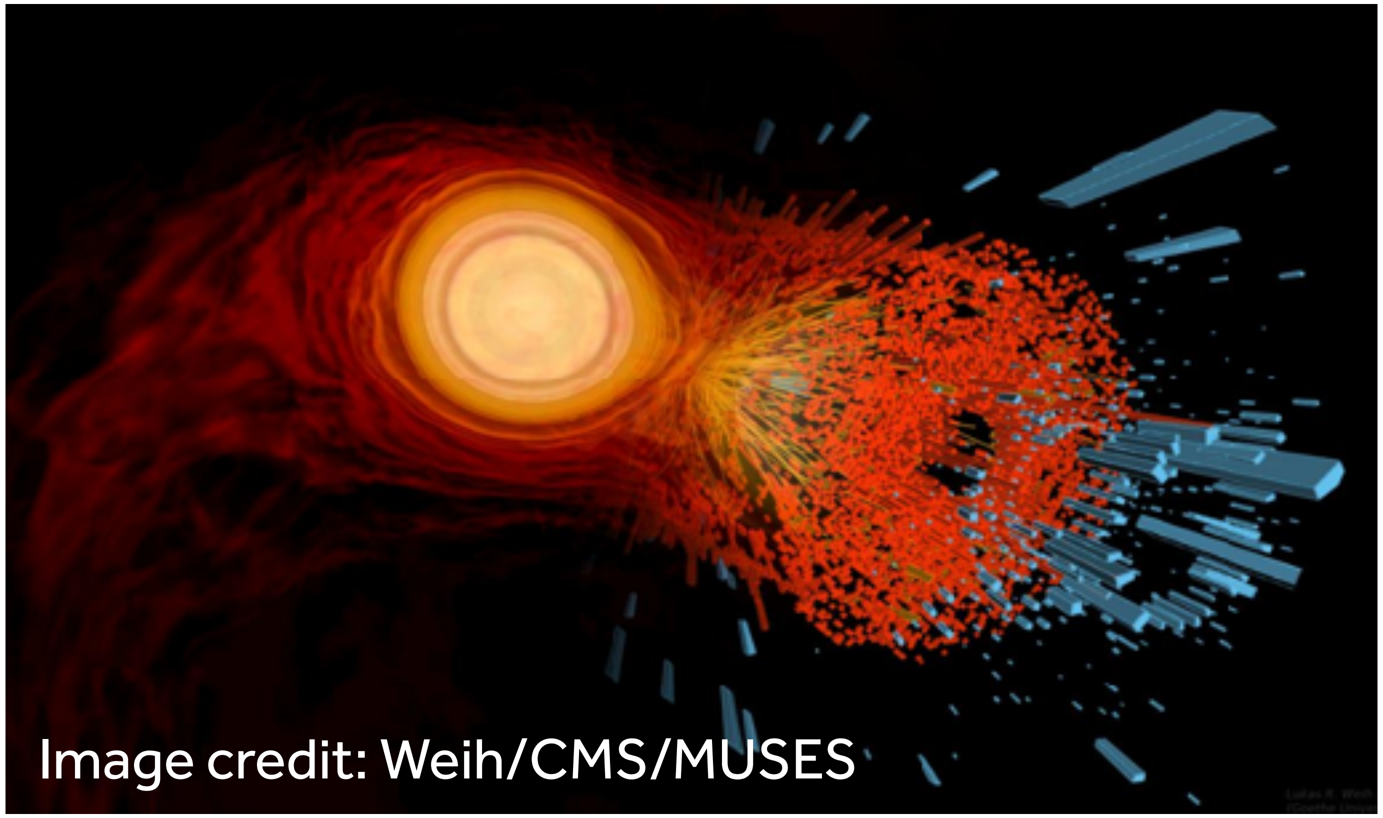


ERM+ (in prep)

* Caveat:
Single-velocity description

Inspiration from nuclear physics

Non-equilibrium transport is critical to understand momentum anisotropies in heavy-ion collisions.



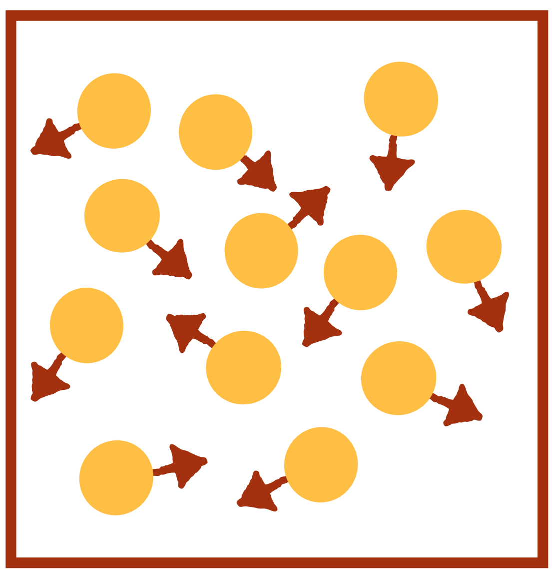
e.g., Romatschke+(2008), Denicol+(2012,2018,2019), Kovtun+(2017), Bemfica+(2017,2022), and many others

Leverage advances made by the nuclear physics community to study astrophysical systems!

Hydrodynamics as an effective theory

Hydrodynamics

$$\nabla_\mu T^{\mu\nu}_{\text{hydro}} = 0$$



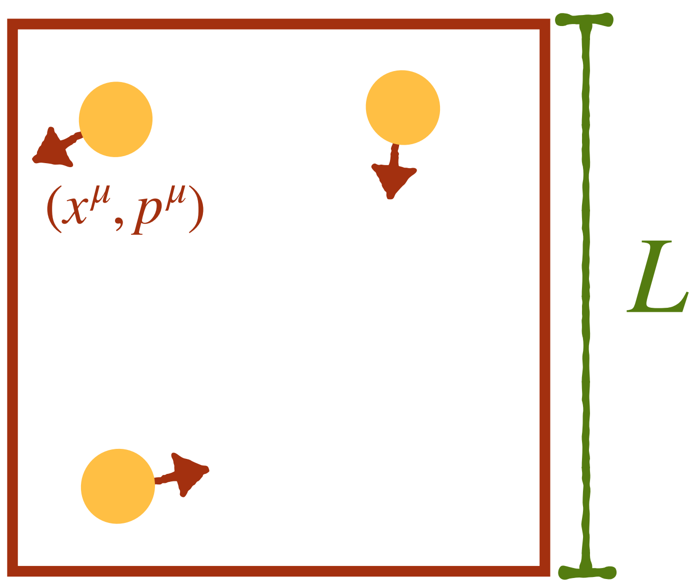
Collisional $(\lambda \simeq 0)$

mean free path λ →

…

Kinetic theory

$$p^\mu \partial_\mu f = \mathscr{C}\left[f\right]$$



Collisionless $(\lambda \simeq L)$

Hydrodynamics as an effective theory

Perturbatively include corrections to hydrodynamics

$$T^{\mu\nu} = \boxed{T^{\mu\nu}_{\rm hydro}} + \boxed{\epsilon T^{\mu\nu}_{(1)} + \epsilon^2 T^{\mu\nu}_{(2)}} + \dots \qquad \epsilon \sim \frac{\lambda}{L} \ll 1$$

Hydrodynamics

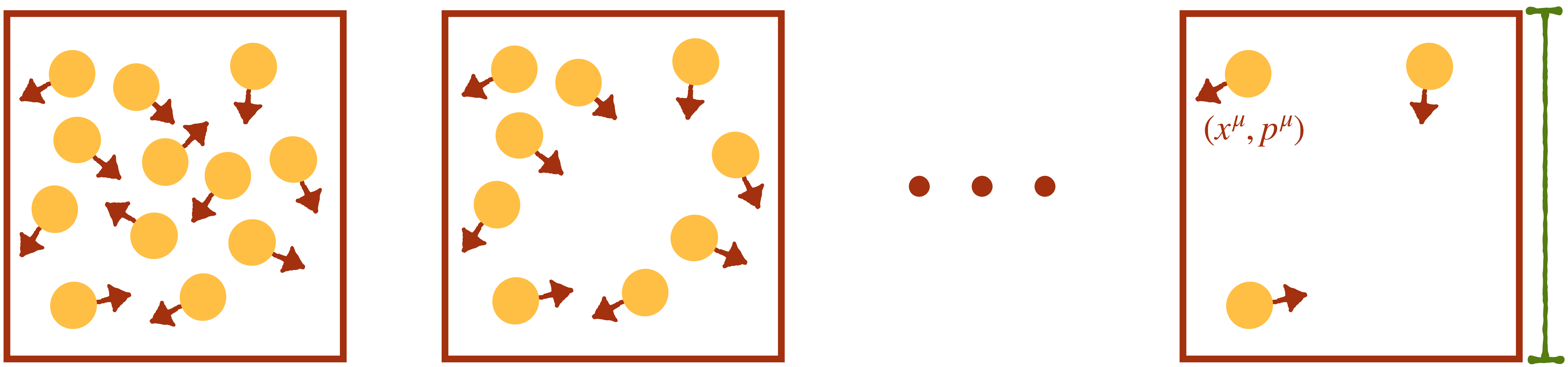
$$\nabla_\mu T^{\mu\nu}_{\rm hydro} = 0$$

Dissipative Hydrodynamics

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

Kinetic theory

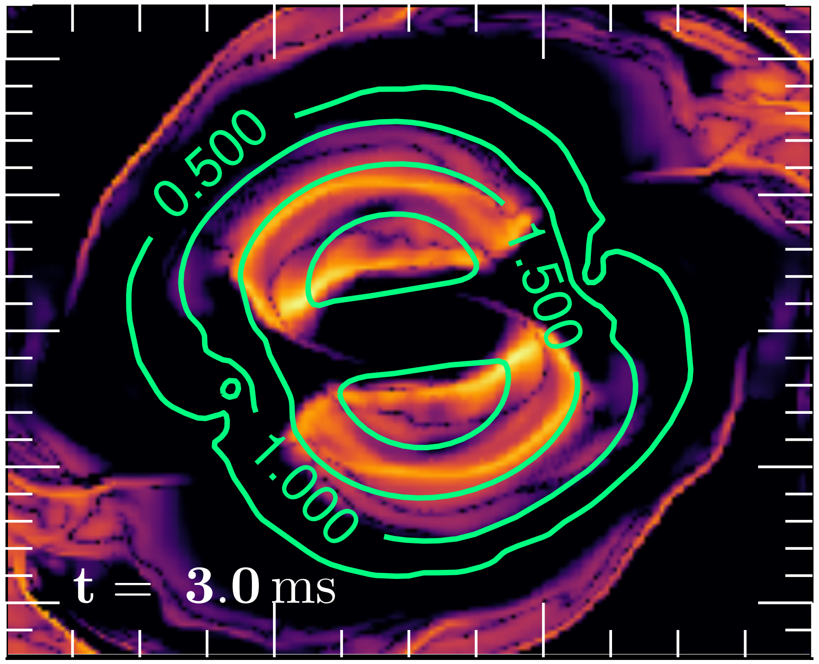
$$p^\mu \partial_\mu f = \mathscr{C}\left[f\right]$$



Collisional $(\lambda \simeq 0)$ — **mean free path** λ → **Collisionless** $(\lambda \simeq L)$

New Physics at every order!

$$T^{\mu\nu} = T^{\mu\nu}_{\rm hydro} + \boxed{\epsilon T^{\mu\nu}_{(1)}}$$



ERM+ (MNRAS 2022)

Bulk viscosity in neutron star mergers

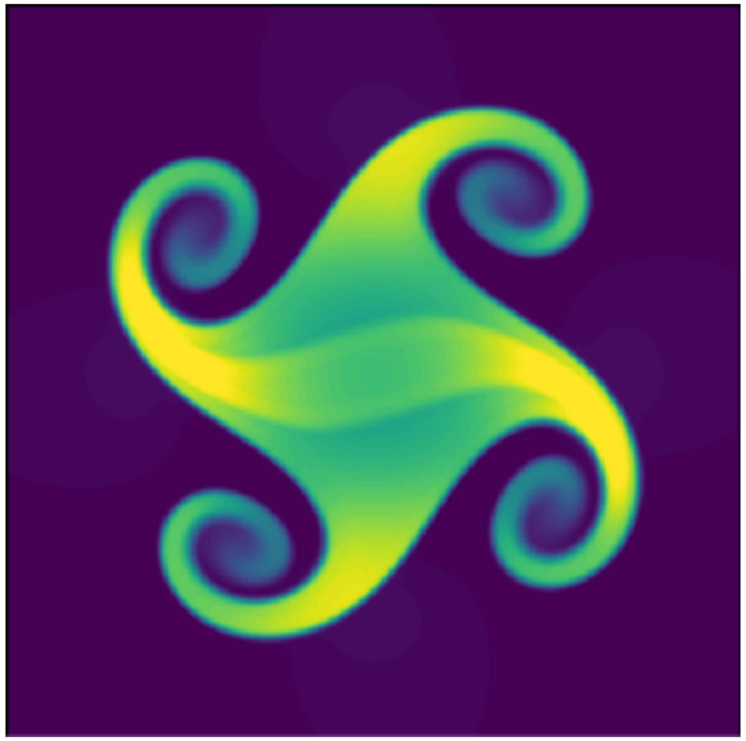
See also Alford+, Celora+, Hammond+

PU Grad. Student

Alex Pandya

Novel approaches to simulations of first-order relativistic hydrodynamics

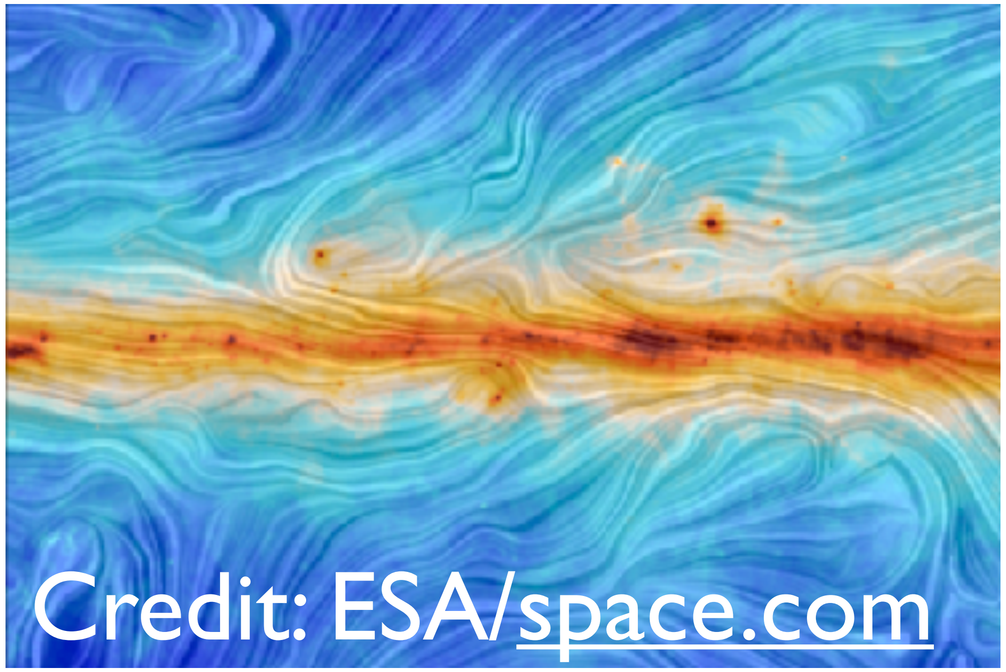
Mathematical formulation based on:
Bemfica+(2017,2022), Kovtun+(2017)



Pandya, **ERM**, Pretorius (PRD, in press)

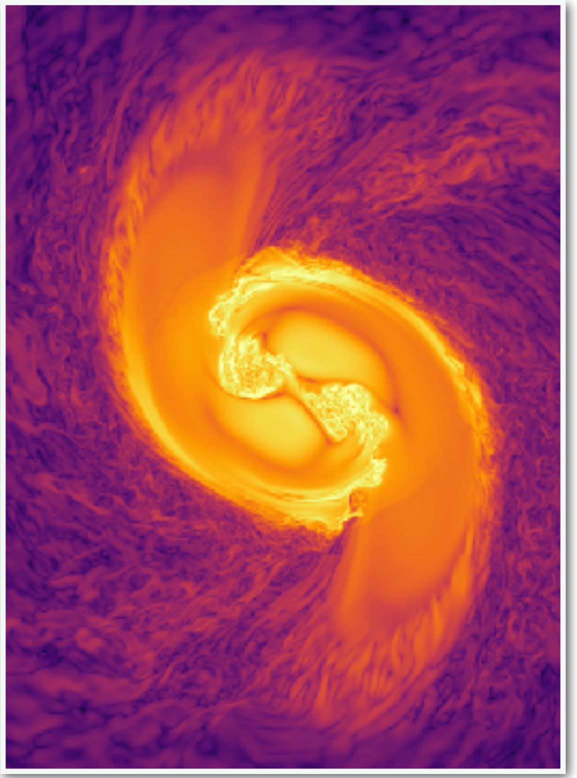
New Physics at every order!

$$T^{\mu\nu} = T^{\mu\nu}_{\text{hydro}} + \boxed{\epsilon T^{\mu\nu}_{(1)}}$$



"Magnetic fields are the Unsung Workhorses of Astrophysics" P.Sutter (space.com)

Dynamos and resistive effects in neutron star mergers



ERM+ (in prep)

➡Dissipative Magnetohydrodynamics

ERM & Noronha (PRD 2021); **ERM**, Noronha & Philippov (arXiv, 2021)

Novel numerical scheme to simulate this!

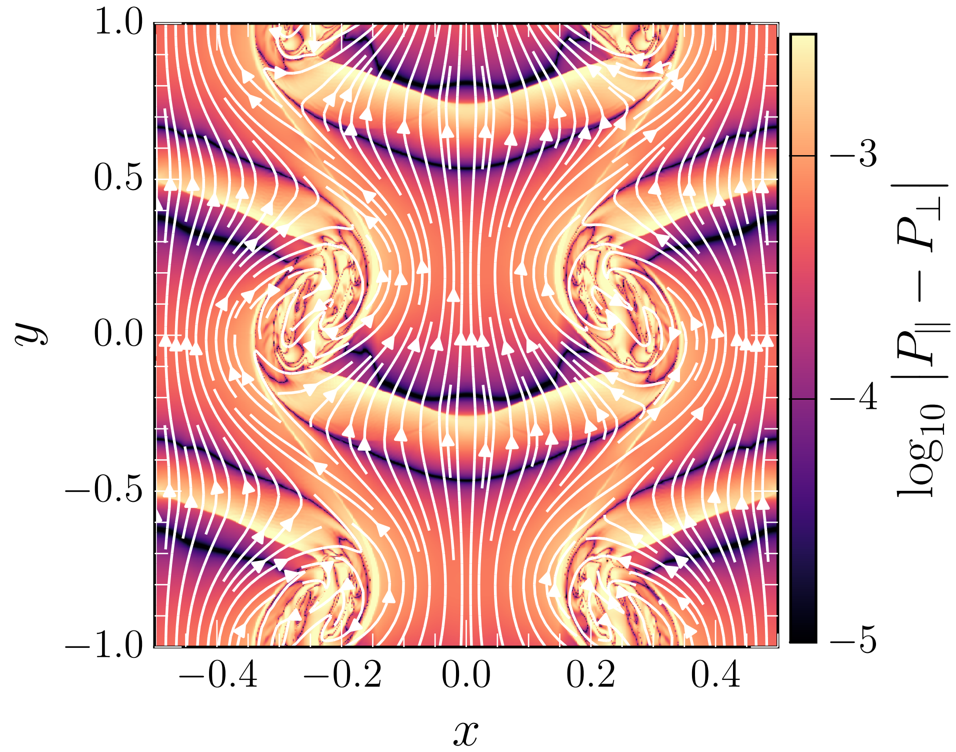
Alternative formulations:
Andersson+,Chandra+, Dommes+,Gusakov+, Rau & Wasserman,...

Dissipative Magnetohydrodynamics

First numerical scheme to handle general viscosities in the presence of magnetic fields for relativistic fluids.

ERM & Noronha (PRD 2021)

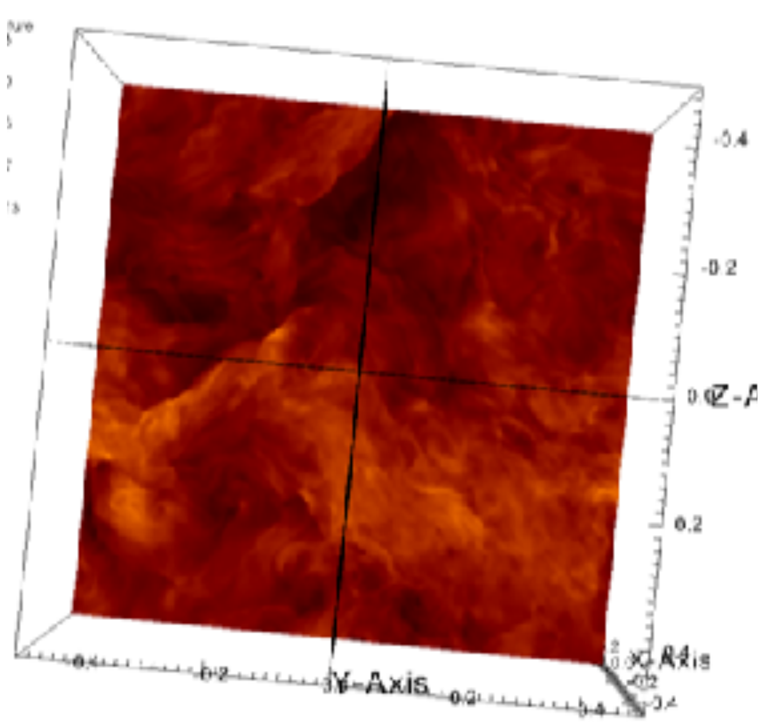
Pressure anisotropy



ERM & Noronha (PRD 2021)

Leverages a 14-moment closure derived from kinetic theory by the nuclear physics community.

Denicol+(2018,2019)



ERM+ (in prep)

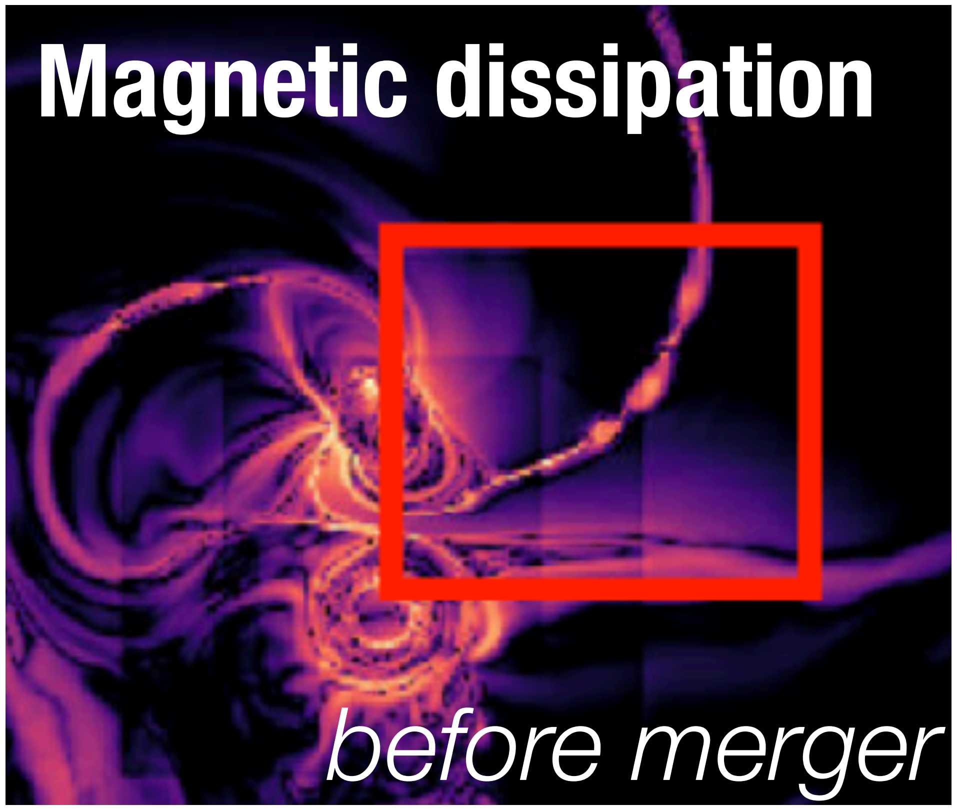
Novel <u>fully flux conservative approach</u> with stiff relaxation.

Well suited to handle highly turbulent astrophysical flows!

New Physics at every order!

$$T^{\mu\nu} = T^{\mu\nu}_{\rm hydro} + \epsilon T^{\mu\nu}_{(1)} + \boxed{\epsilon^2 T^{\mu\nu}_{(2)}}$$

ERM & Philippov (in prep)

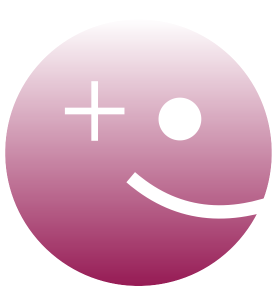


Reconnection powered transients

Current force-free electrodynamics simulation cannot capture reconnection physics correctly.

(timescale, dissipation rate, ...)

Need to model $e^+ e^-$ dynamics in global simulations.



Positrons

➡Dissipative Two-Fluid MHD

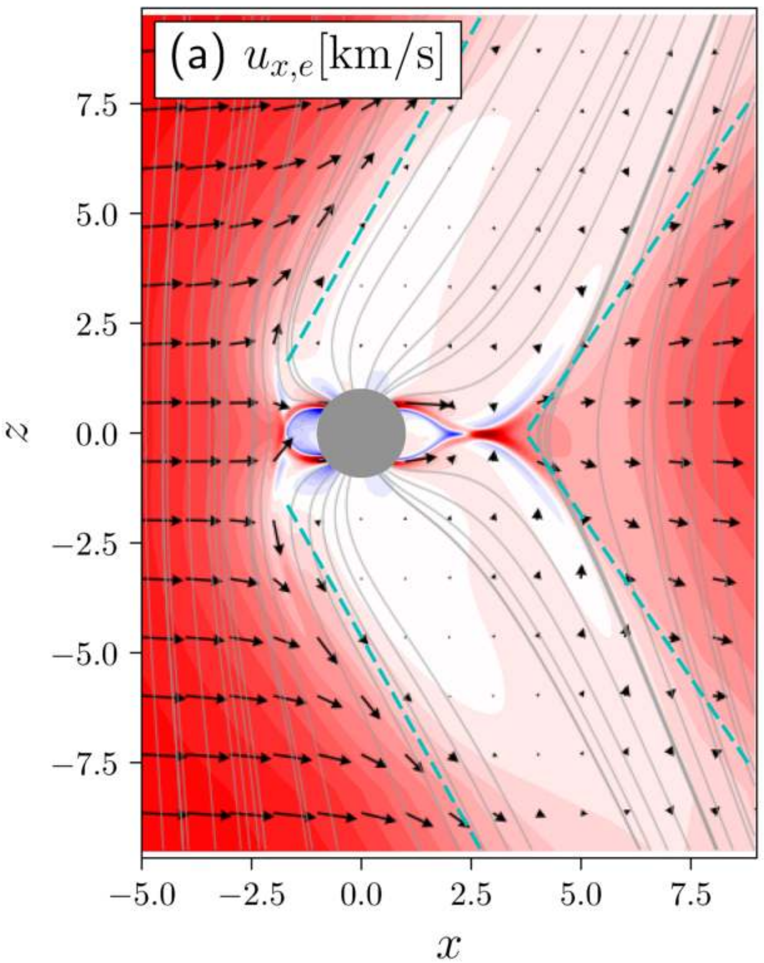
ERM, Noronha & Philippov (arXiv:2021)

Electrons

New Physics at every order!

$$T^{\mu\nu} = T^{\mu\nu}_{\text{hydro}} + \epsilon T^{\mu\nu}_{(1)} + \boxed{\epsilon^2 T^{\mu\nu}_{(2)}}$$

Ganymede

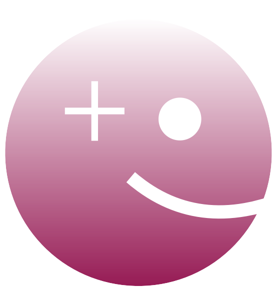


Wang+(2018)

A (not so) surprising source of inspiration

Generalize 10-moment two-fluid approach from space physics to relativistic setting!

Need to model $e^+ e^-$ dynamics in global simulations.



Positrons

➡Dissipative Two-Fluid MHD

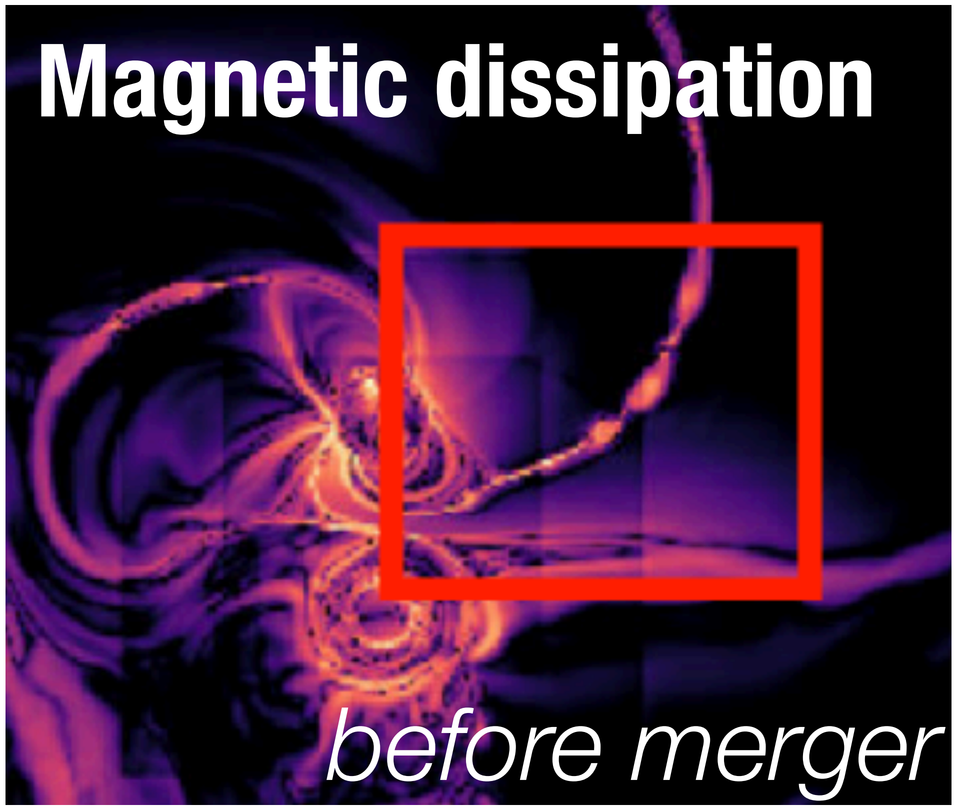
ERM, Noronha & Philippov (arXiv:2021)

Electrons

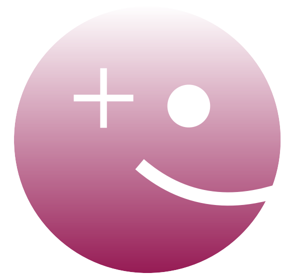
New Physics at every order!

$$T^{\mu\nu} = T^{\mu\nu}_{\rm hydro} + \epsilon T^{\mu\nu}_{(1)} + \boxed{\epsilon^2 T^{\mu\nu}_{(2)}}$$

ERM & Philippov (in prep)



Reconnection powered transients



Positrons

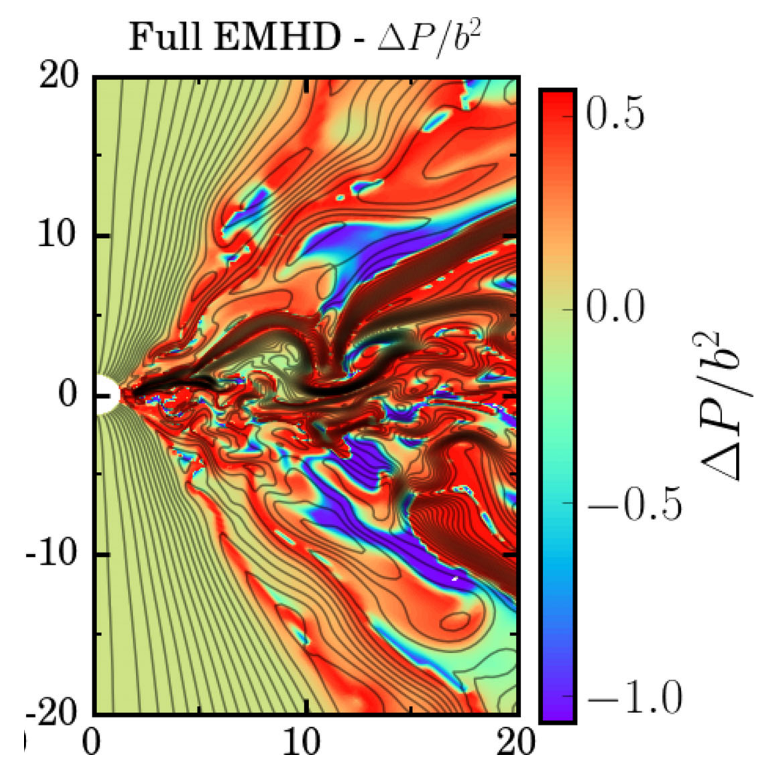
Pair plasmas

Electrons

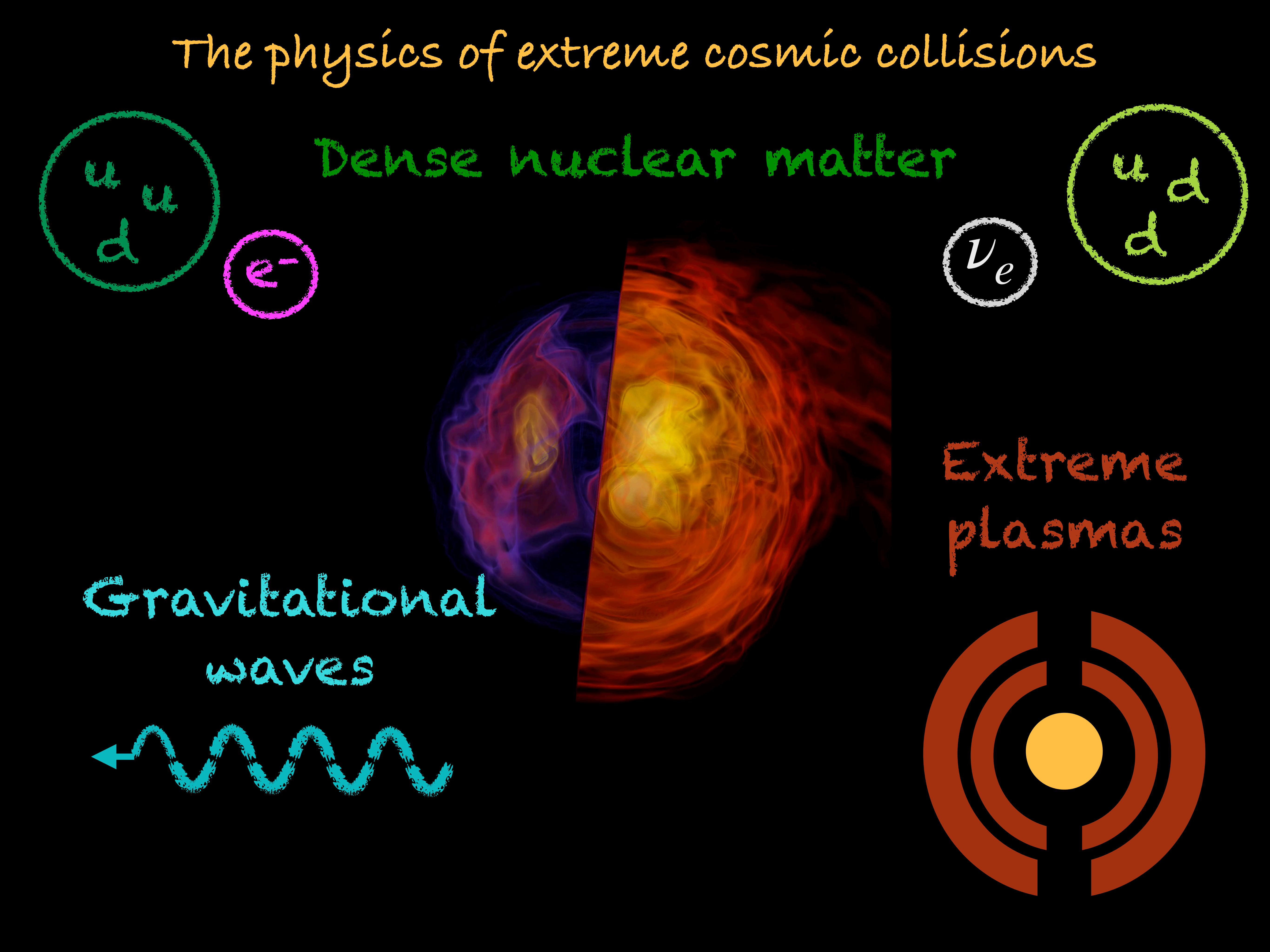
ERM, Noronha & Philippov (arXiv:2021)

Black-hole accretion

Chandra+(2015),
Foucart+(2016,2017)



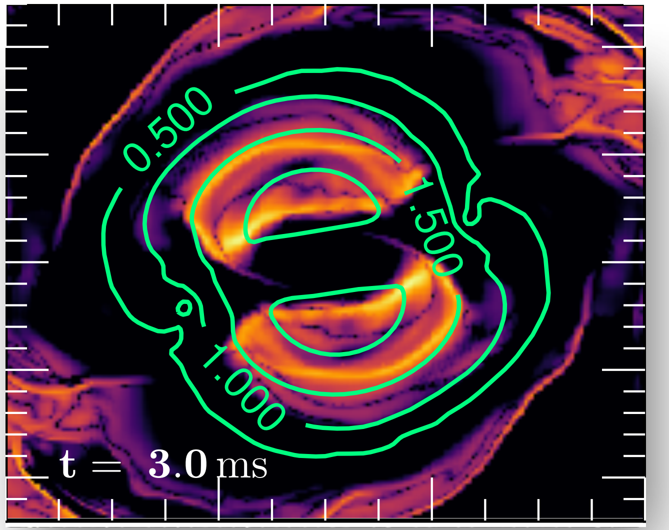
Electron-Ion


The physics of extreme cosmic collisions
Dense nuclear matter
u u d
e⁻
ν_e
u d d
Extreme plasmas
Gravitational waves

Outlook

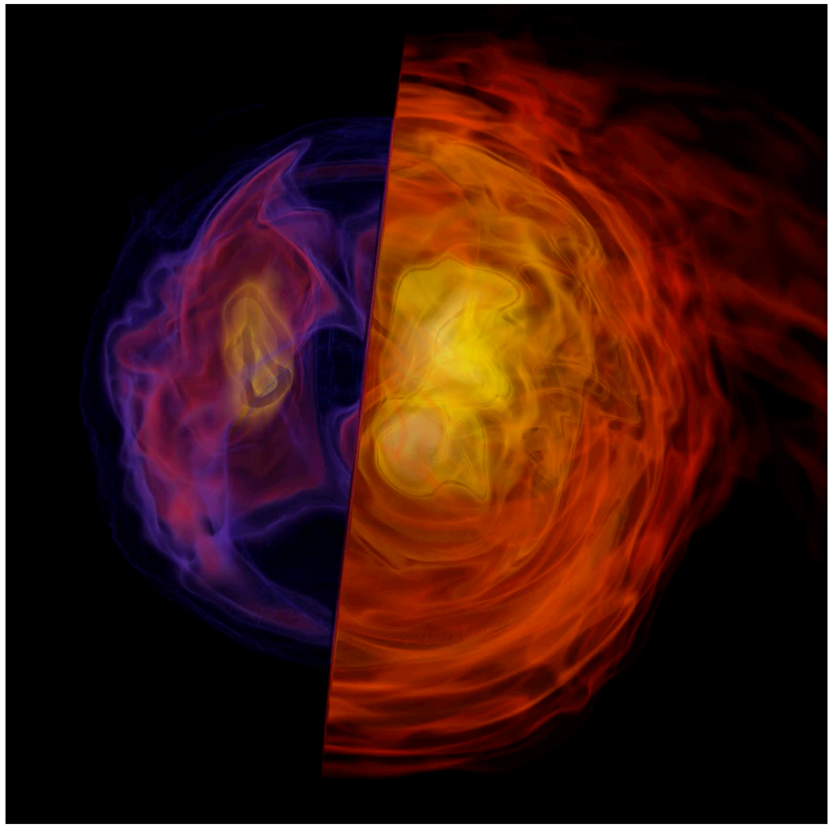
Neutron star mergers combine different physics on many scales!

ERM & Noronha (2021)
ERM+ (MNRAS 2022)

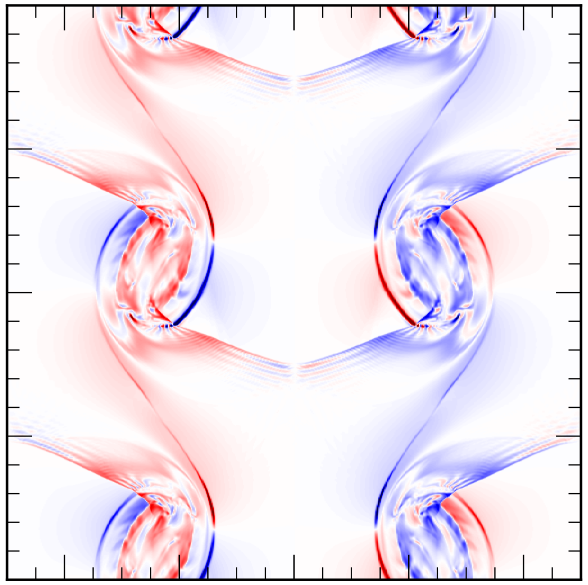


Nuclear physics

Neutron star mergers



ERM & Philippov (2020,in prep)
ERM, Noronha, Philippov (arXiv:2022)



Plasma physics

These can be captured with novel out-of-equilibrium transport models adapted to highly turbulent astrophysical flows!