Title: How neutron star mergers can be used to study hadron-quark phase transitions

Speakers: Elias Most

Series: Strong Gravity

Date: November 28, 2019 - 1:00 PM

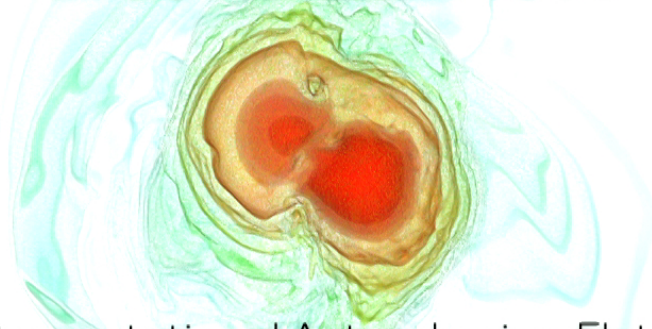
URL: http://pirsa.org/19110147

Abstract: With the detection of GW170817 we have observed the first multi messenger signal from two merging neutron stars. This signal carried a multitude of information about the underlying equation of state (EOS) of nuclear matter, which so far is not known for densities above nuclear saturation. In particular it is not known if exotic states or even a phase transition to quark matter can occur at densities so extreme that they can't be probed by any current experiment.

I will show how the information carried in the gravitational wave signal of GW170817 can be used to constrain the EOS at densities above saturation and what we can learn about the possible existence of phase transitions. I will
also comment on how we can improve on those limits with upcoming observations of the NICER mission.In the second part of the talk I will focus on what we can learn about exotic states of matter from neutron star mergers.I will comment briefly on the impact of high spins in mergers and the importance of accurate numerical modelling in the context of these studies.Finally I will show how neutron star mergers can be used to study quark phase transitions and the phase diagram of QCD.

How neutron star mergers can be used to study hadron-quark phase transitions

Elias Roland Most



Center for Computational Astrophysics, Flatiron Institute
Institute for Theoretical Physics, Goethe University Frankfurt

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HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

FLATIRON INSTITUTE
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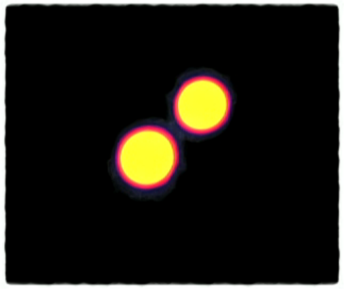
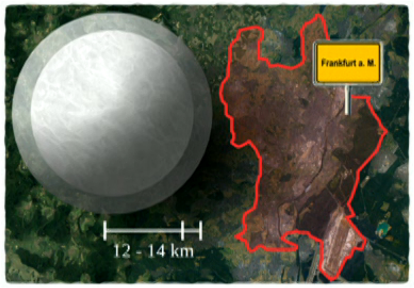
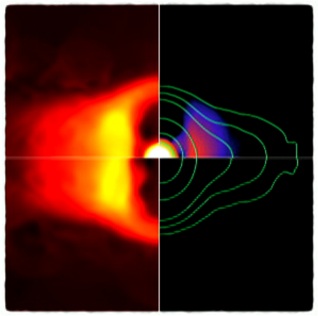
Overview



✶Brief overview of neutron star mergers

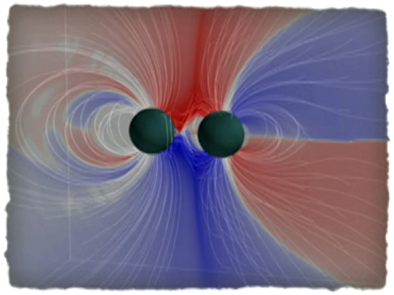
✶GW170817: implications on matter under extreme conditions





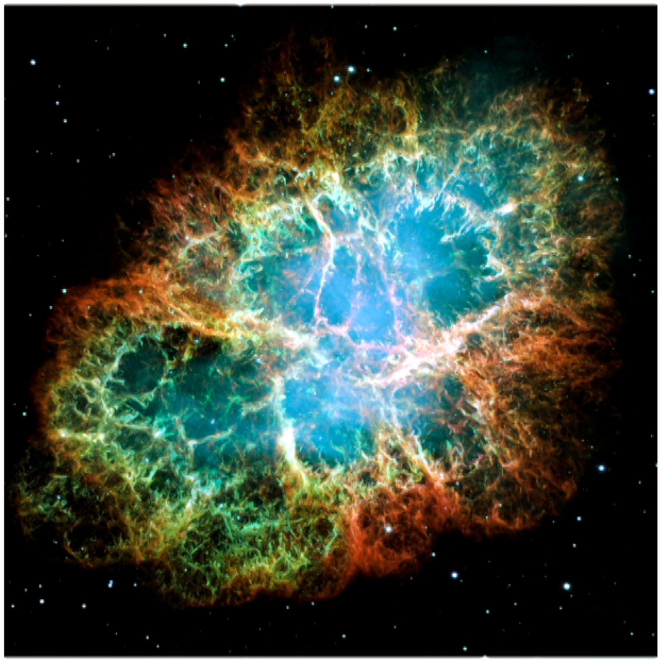
✶Unveiling first-order phase transitions with gravitational waves

✶Electromagnetic precursors from neutron star mergers



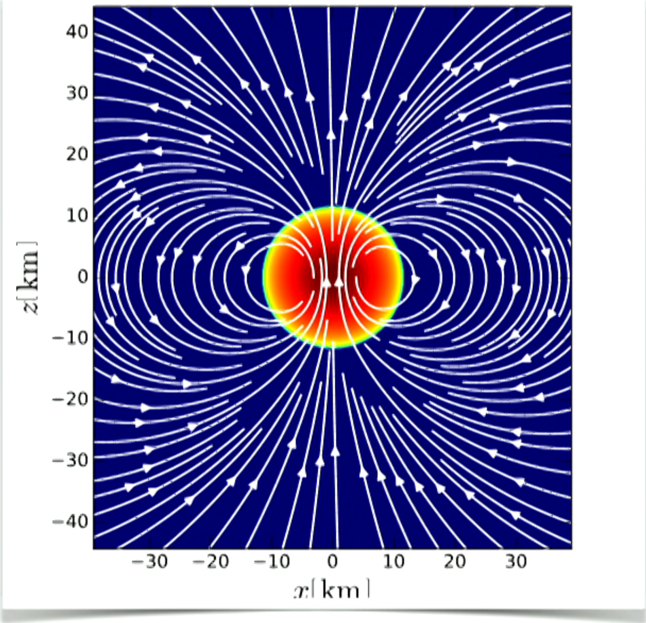
Neutron stars in a nutshell

- Neutron stars are formed in supernova explosions



Neutron stars in a nutshell

- Neutron stars are formed in supernova explosions
- Feature some of the strongest magnetic fields in the universe $|\mathbf{B}| \simeq 10^{11} - 10^{15}$ G



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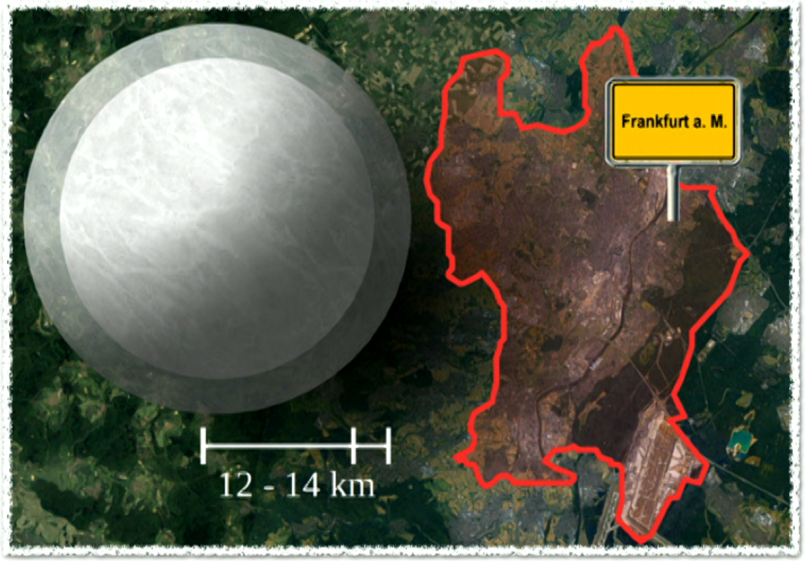

Neutron stars in a nutshell

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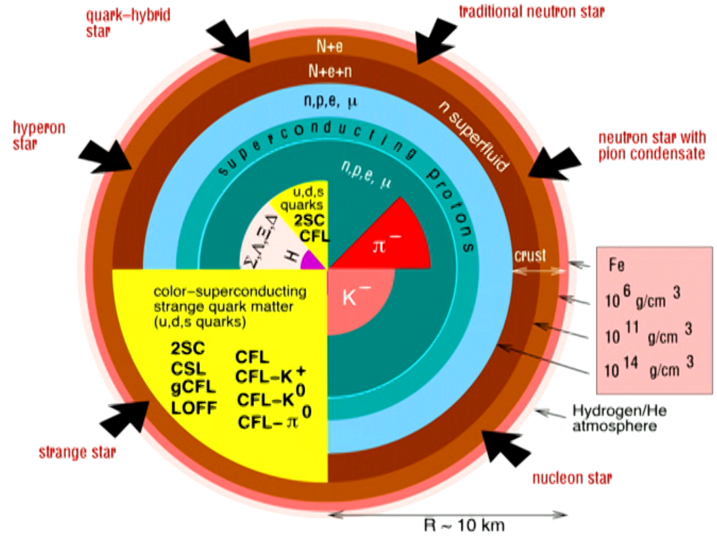
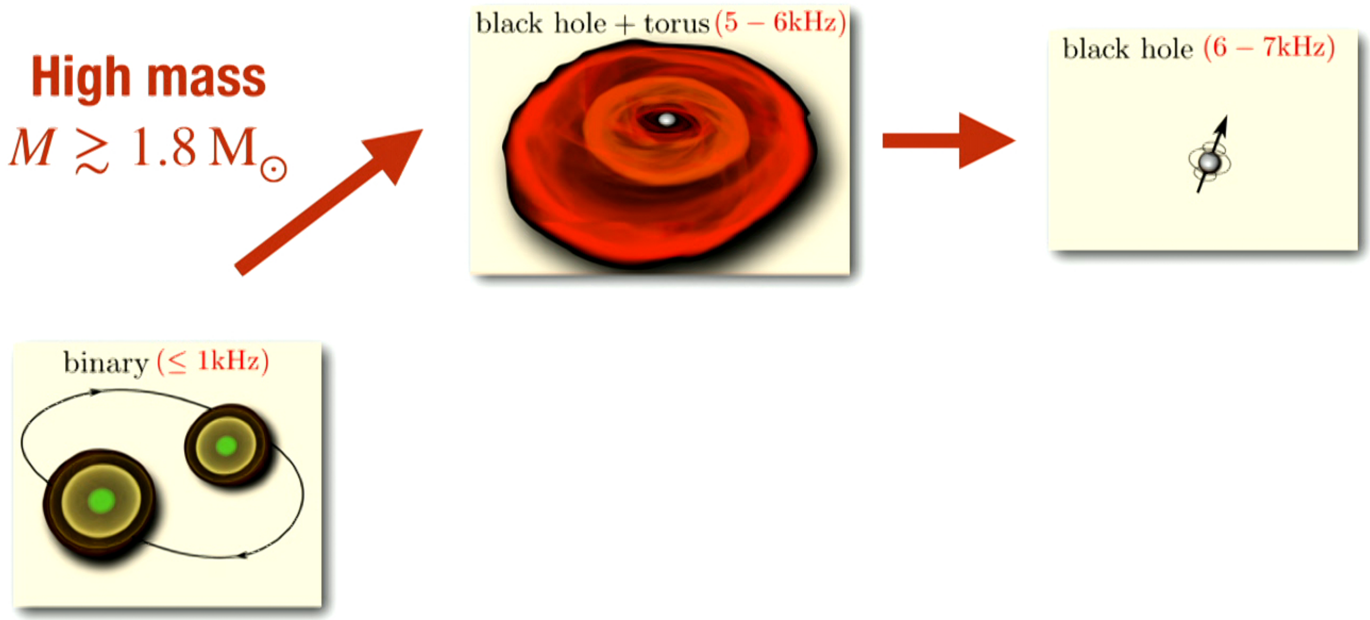


- Neutron stars are as heavy as the sun but only have the size of a larger city!

- Neutron stars have extreme densities and potentially exotic states in their cores

The fate of a neutron star binary

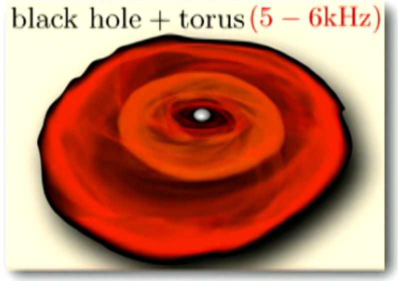


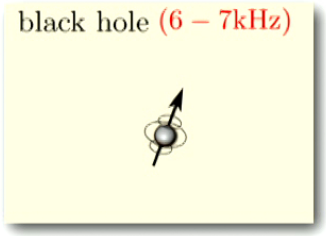
Adapted from Baiotti+ (2018)

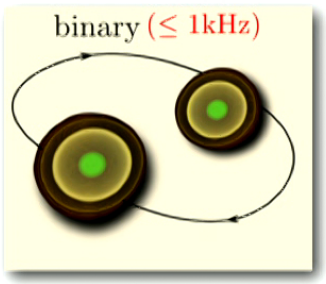
The fate of a neutron star binary

High mass

$M \gtrsim 1.8\,\mathrm{M}_\odot$







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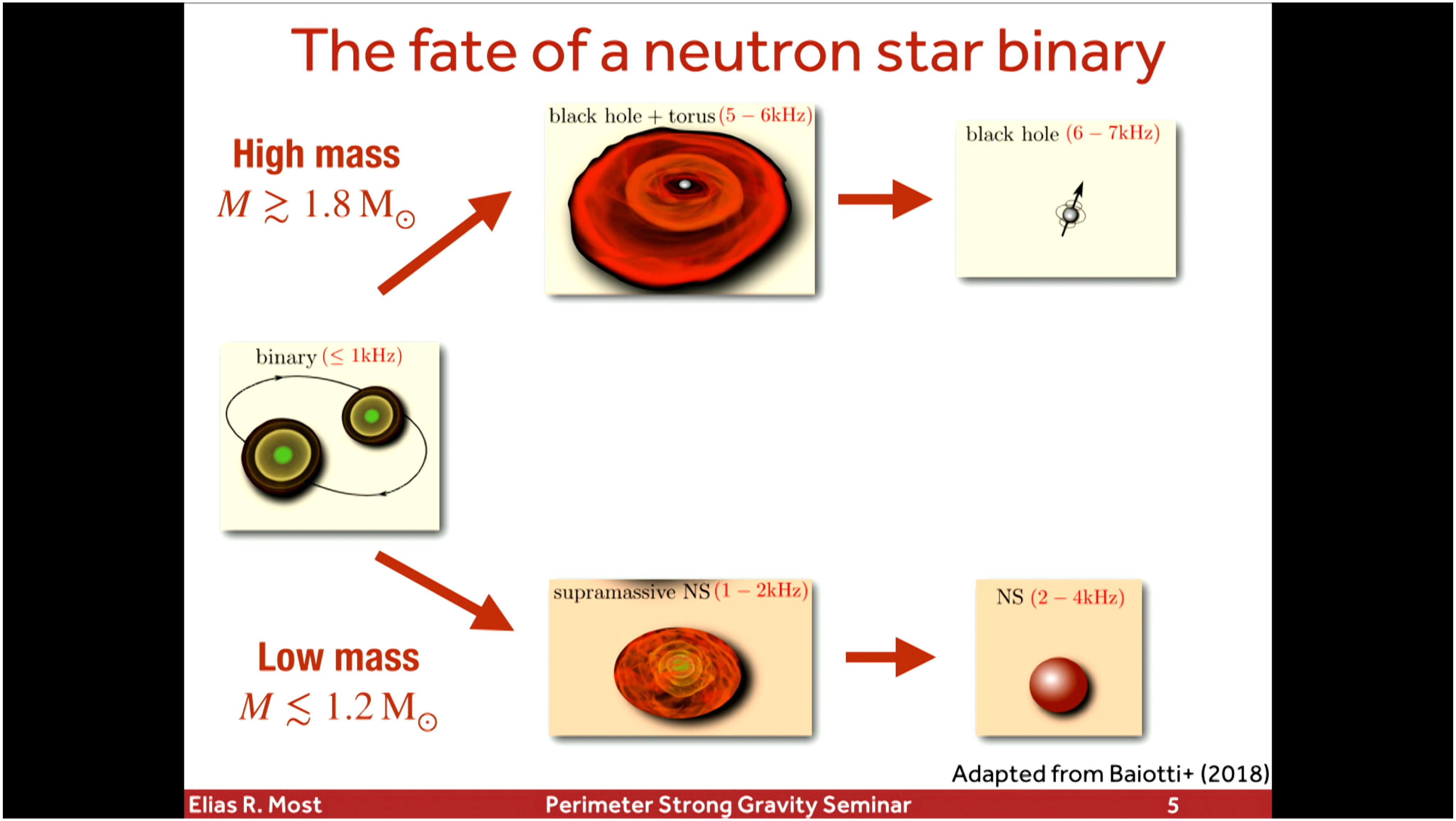
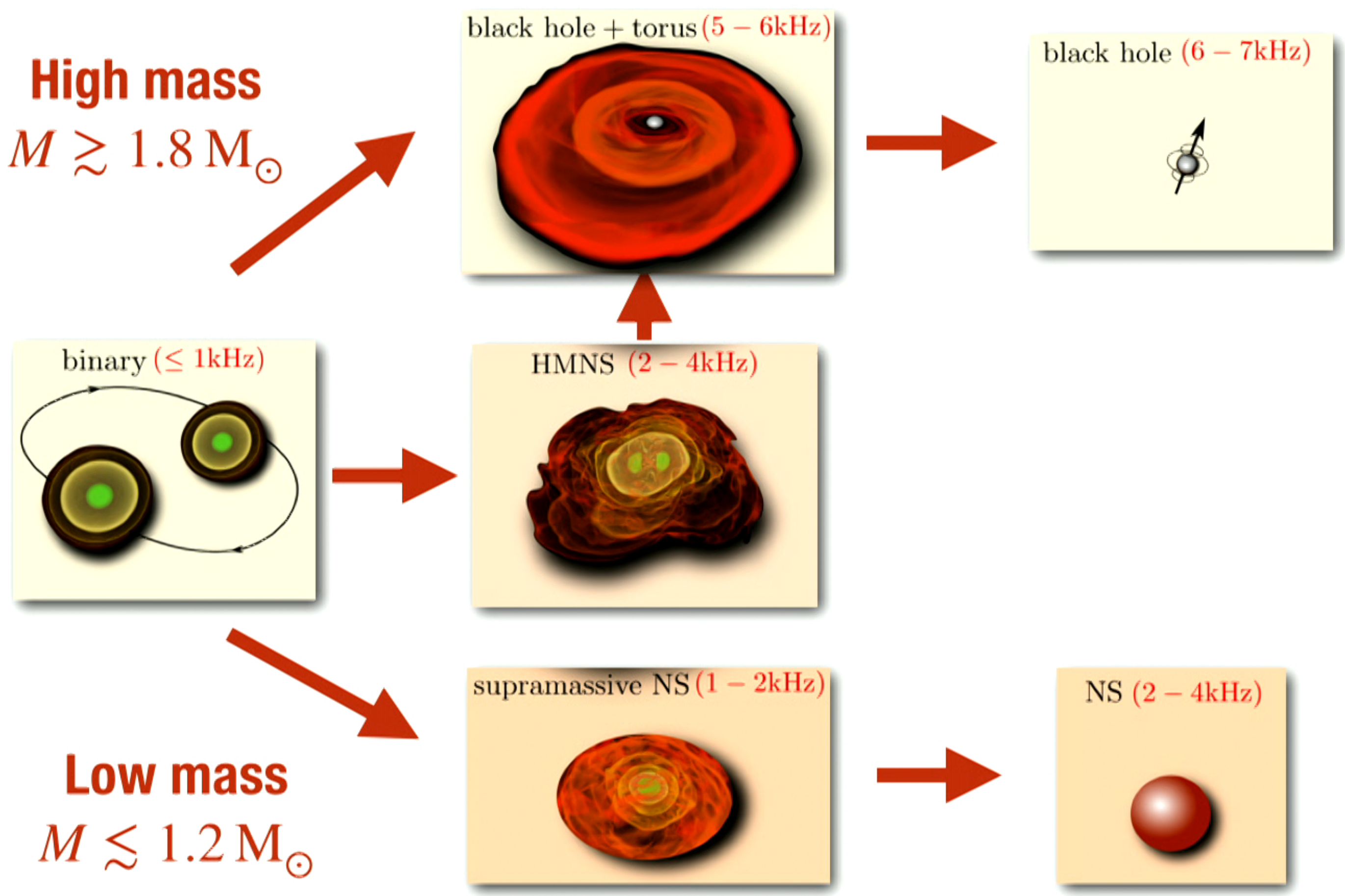

The fate of a neutron star binary
High mass
$M \gtrsim 1.8\,M_\odot$
black hole + torus (5 – 6kHz)
black hole (6 – 7kHz)
binary (≤ 1kHz)
Low mass
$M \lesssim 1.2\,M_\odot$
supramassive NS (1 – 2kHz)
NS (2 – 4kHz)
Adapted from Baiotti+ (2018)
Elias R. Most
Perimeter Strong Gravity Seminar
5

The fate of a neutron star binary



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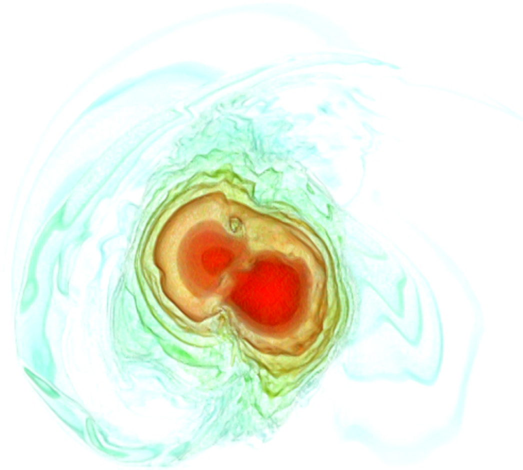
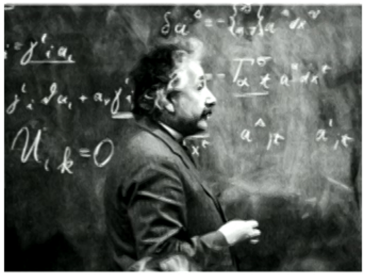
Modelling compact binary mergers

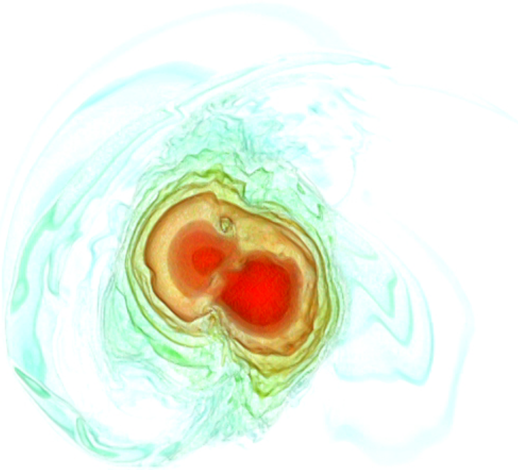


Modelling compact binary mergers

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



Numerical relativity



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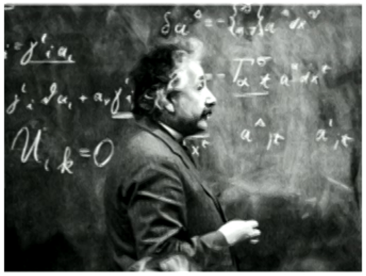

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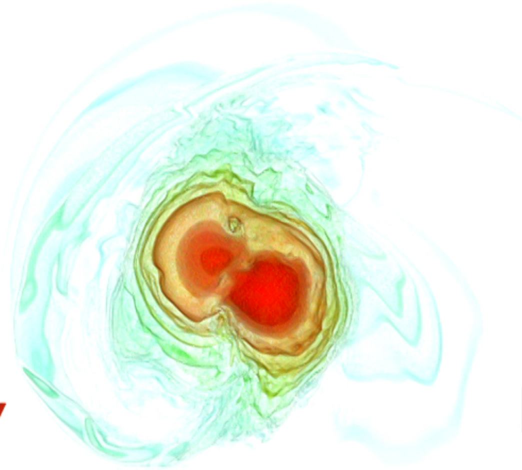
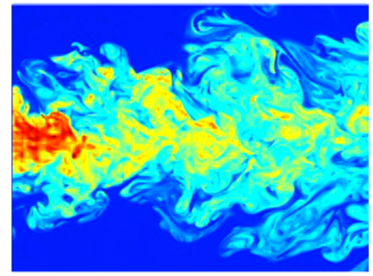
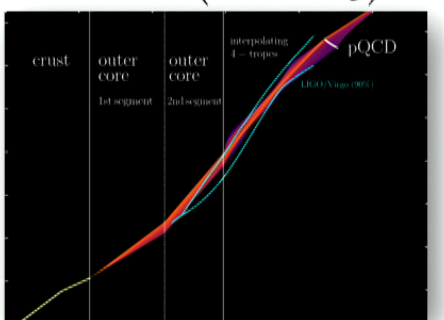


$$\nabla_\mu T^{\mu\nu} = 0$$



Hydrodynamics

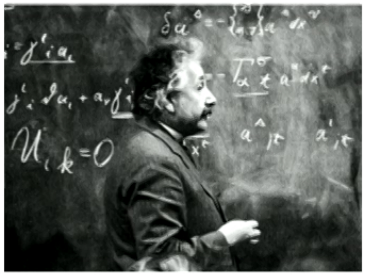
$$p = p\left(\rho, T, Y_e\right)$$



Nuclear physics

Modelling compact binary mergers

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



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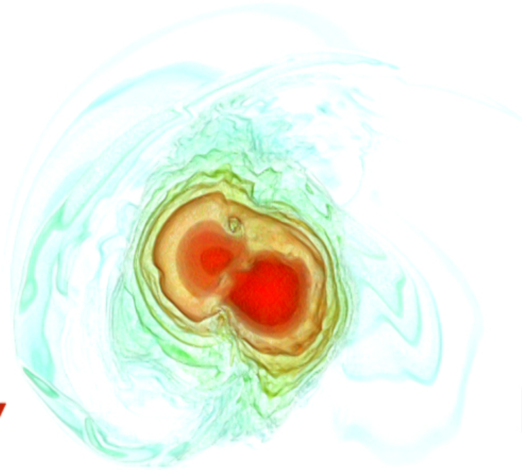

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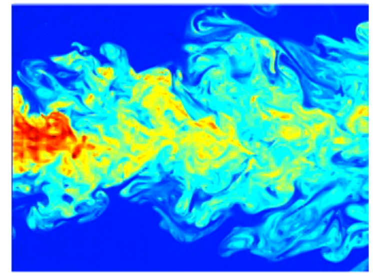

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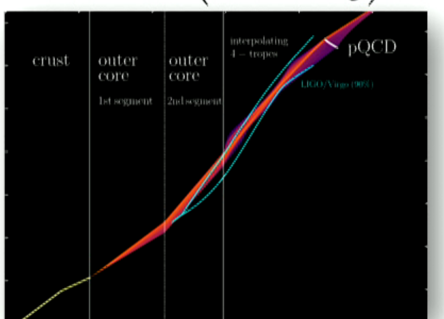


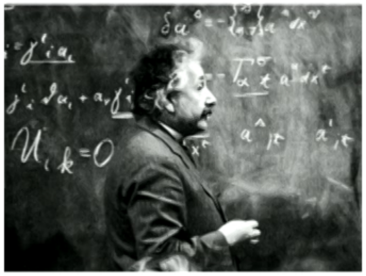
Nuclear physics

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

Electrodynamics

Modelling compact binary mergers

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



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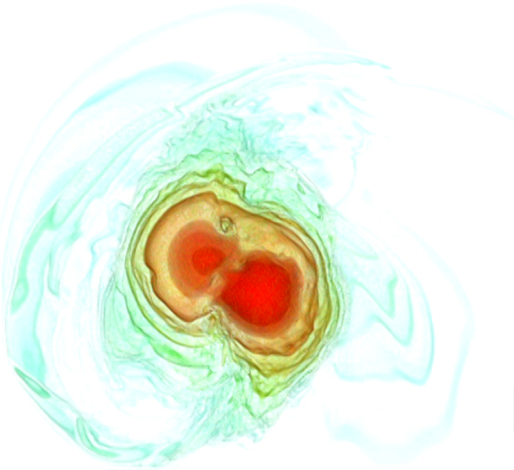

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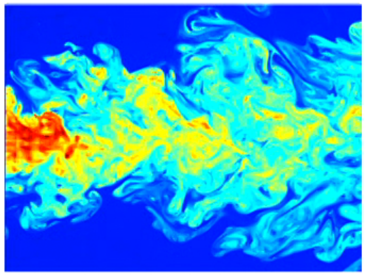

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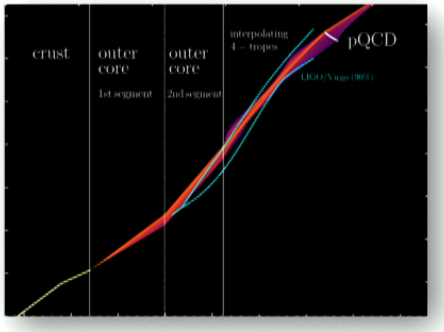

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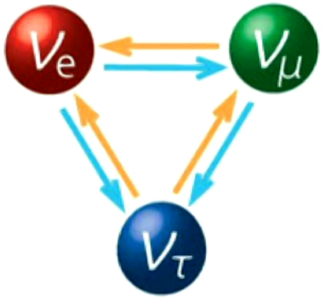
$$\nabla_\mu F^{\nu\mu} = 4\pi \mathcal{J}^\nu$$

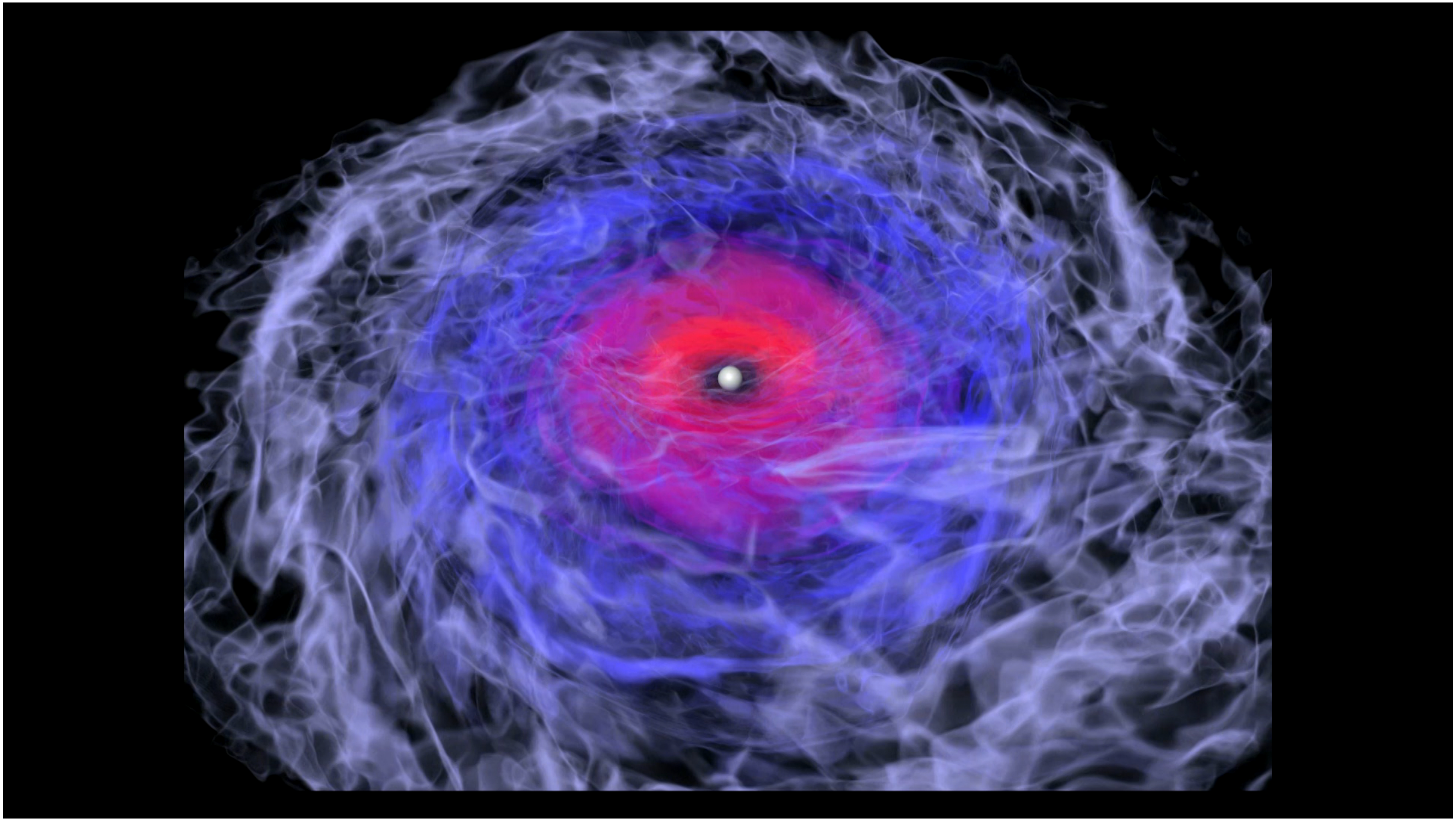
Electrodynamics

$$p^{\hat{\mu}} \frac{\partial f}{\partial x^{\hat{\mu}}} - \Gamma^{\hat{\imath}}{}_{\hat{\nu}\hat{\mu}} p^{\hat{\nu}} p^{\hat{\mu}} \frac{\partial f}{\partial p^{\hat{\imath}}} = C[f]$$



Radiation transport

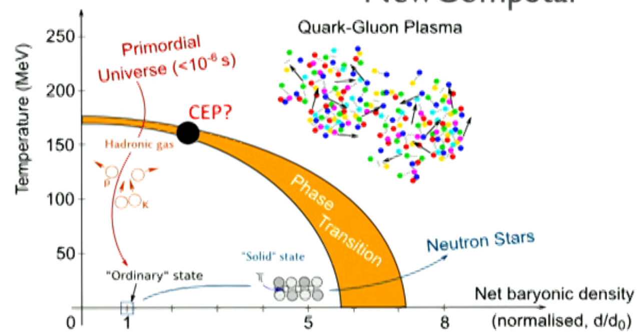

Animations: Breu, Radice, Rezzolla
$M = 2 \times 1.35\,M_\odot$
LS220 EOS

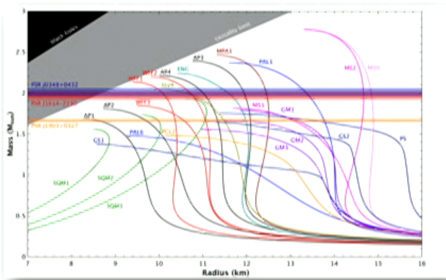


Fundamental physics with neutron stars

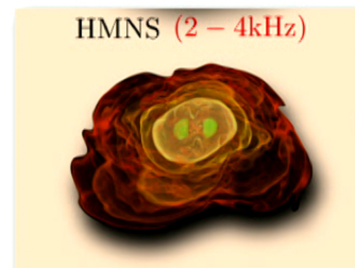
- Late inspiral and post-merger **gravitational waves** can reveal densest states of matter.

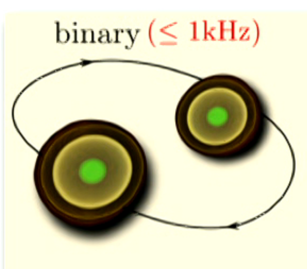
NewCompStar

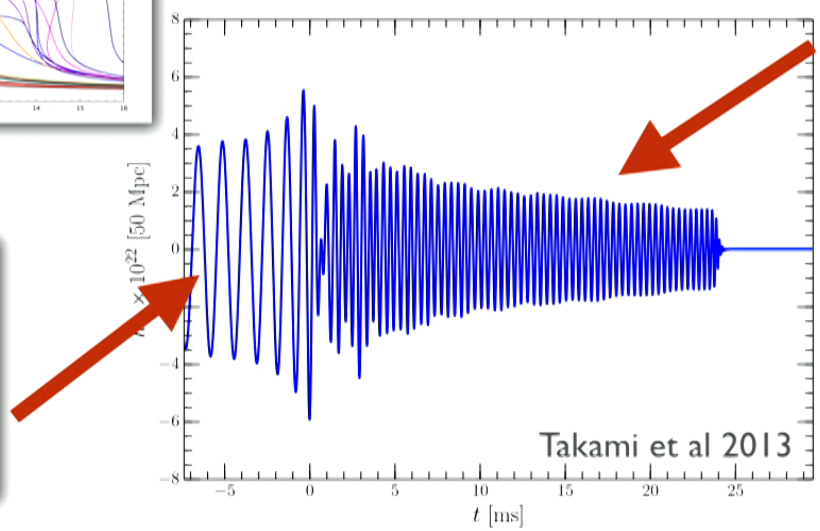




Wex 2016







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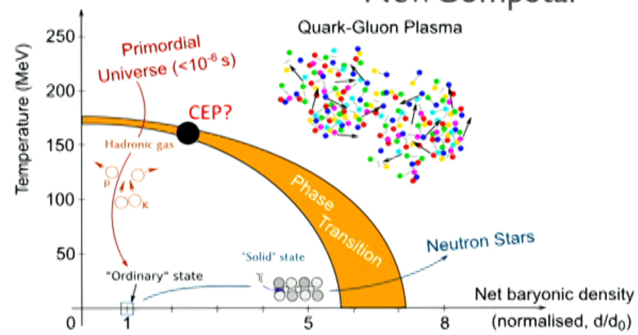
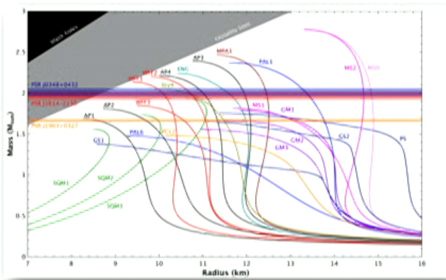
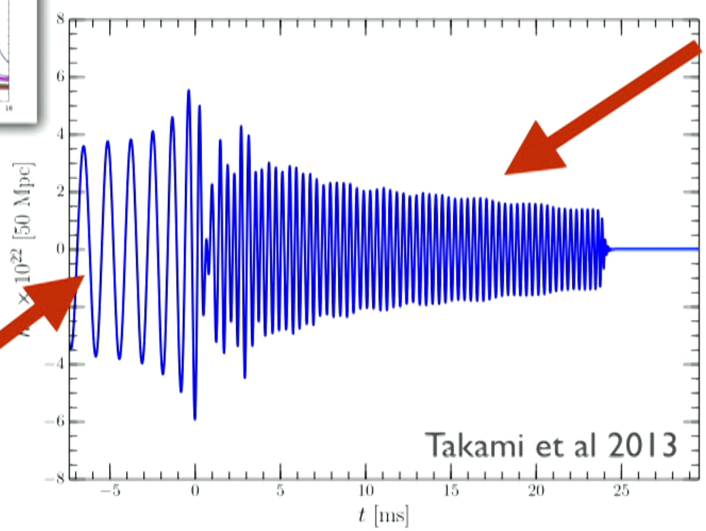
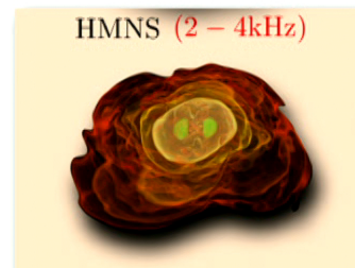


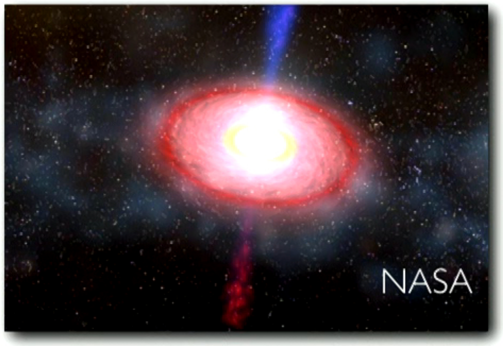


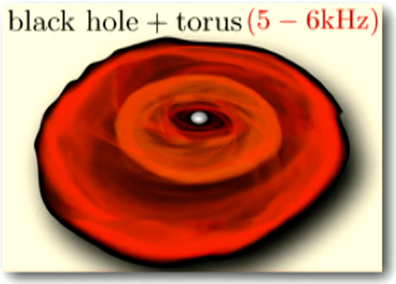
Wex 2016



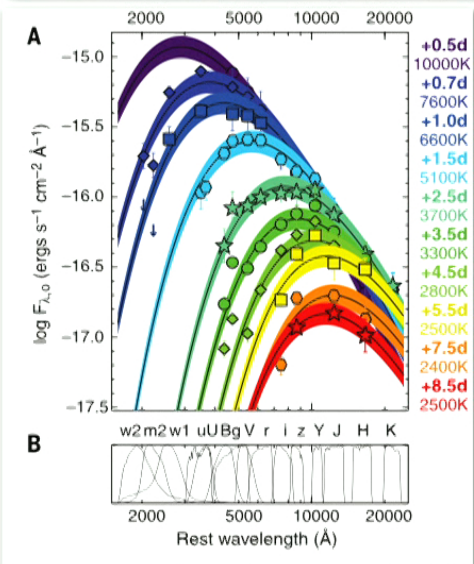


Fundamental physics with neutron stars

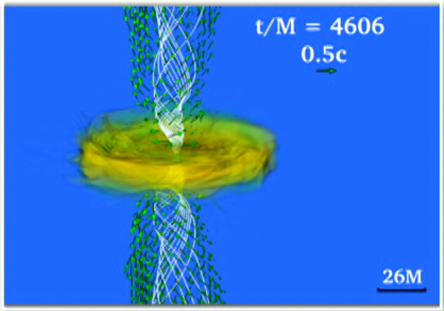




- **Electromagnetic counterparts** (kilonova, sGRBs) open additional window into properties of the system.

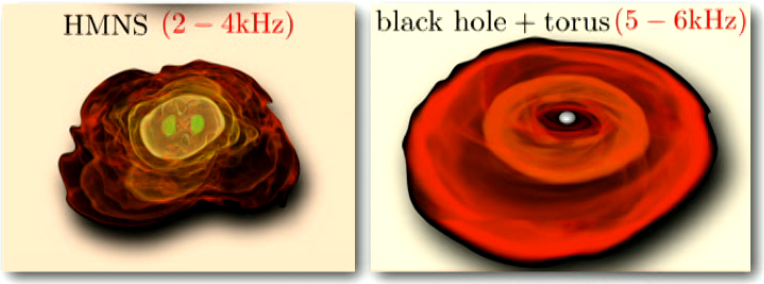


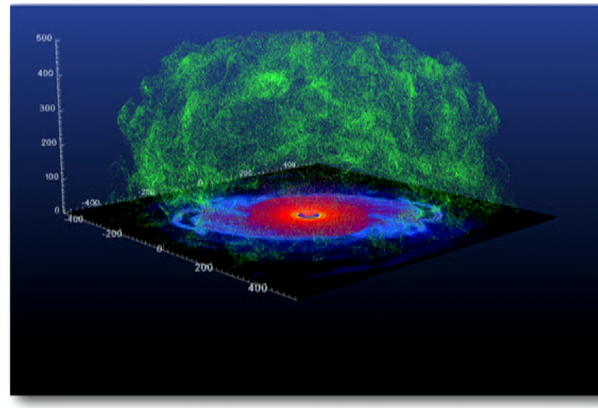
Drout et al 2017



Ruiz et al 2016

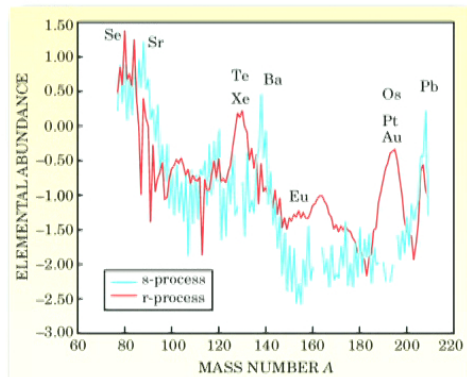
Fundamental physics with neutron stars





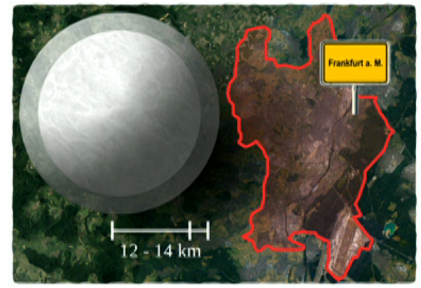
Bovard (priv. comm.)

- Matter ejected on short (~1 ms) and long (~500ms) timescales can produce the **heaviest elements in the universe** (r-process nucleosynthesis)

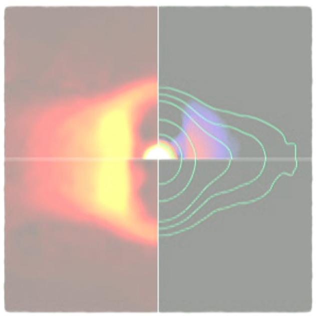


Overview

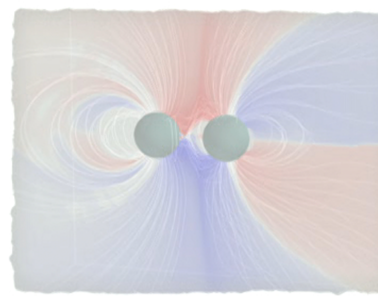
* Brief overview of neutron star mergers



* GW170817: implications on matter under extreme conditions



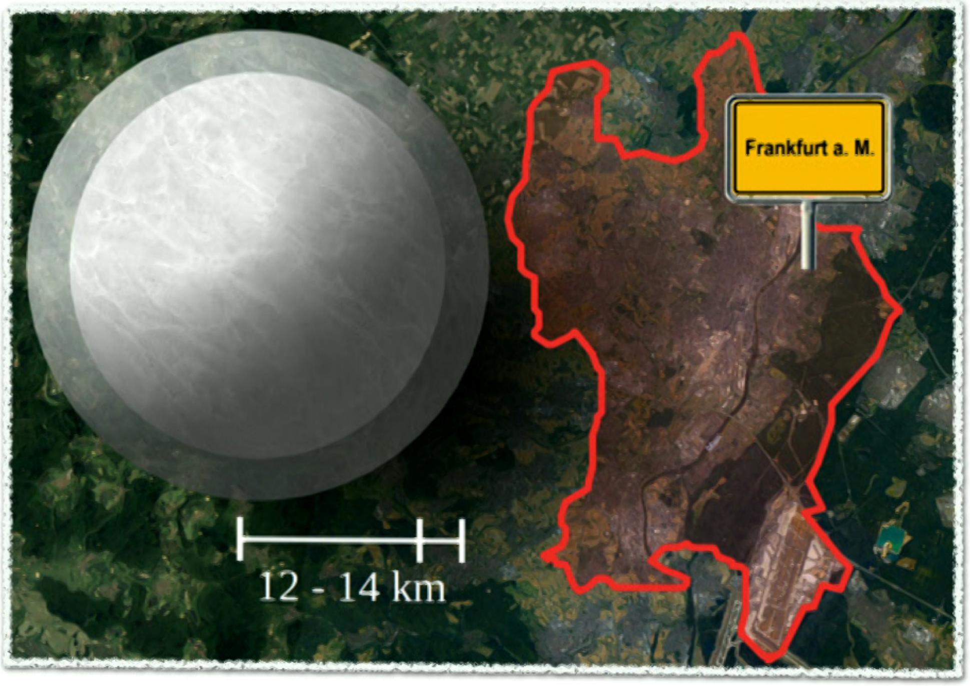
* Unveiling first-order phase transitions with gravitational waves



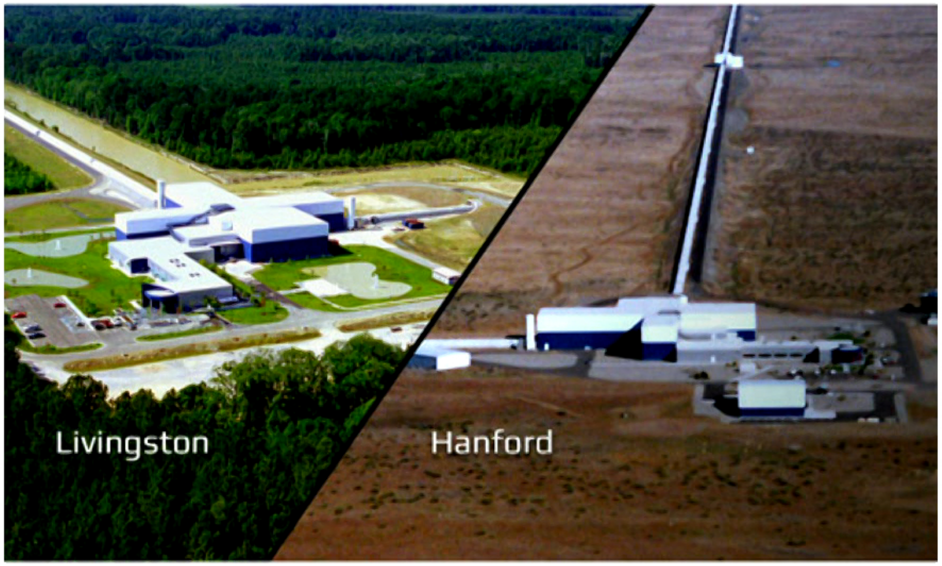
* Electromagnetic precursors from neutron star mergers

Equation of state constraints from GW170817:

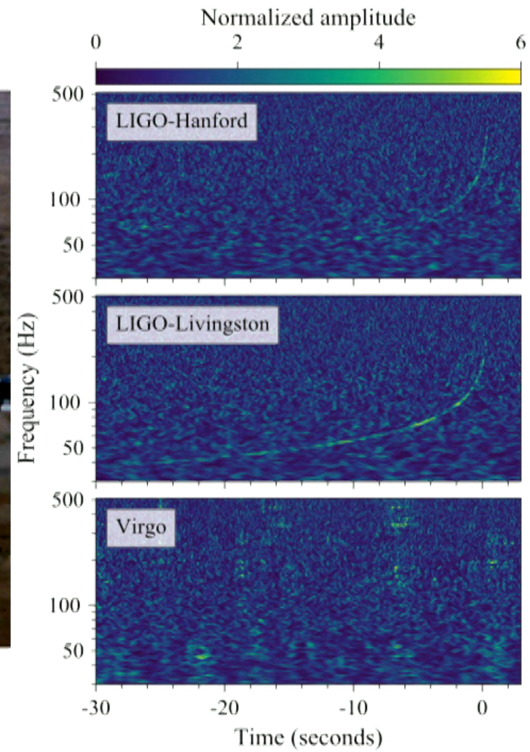
A Frankfurt perspective



GW170817

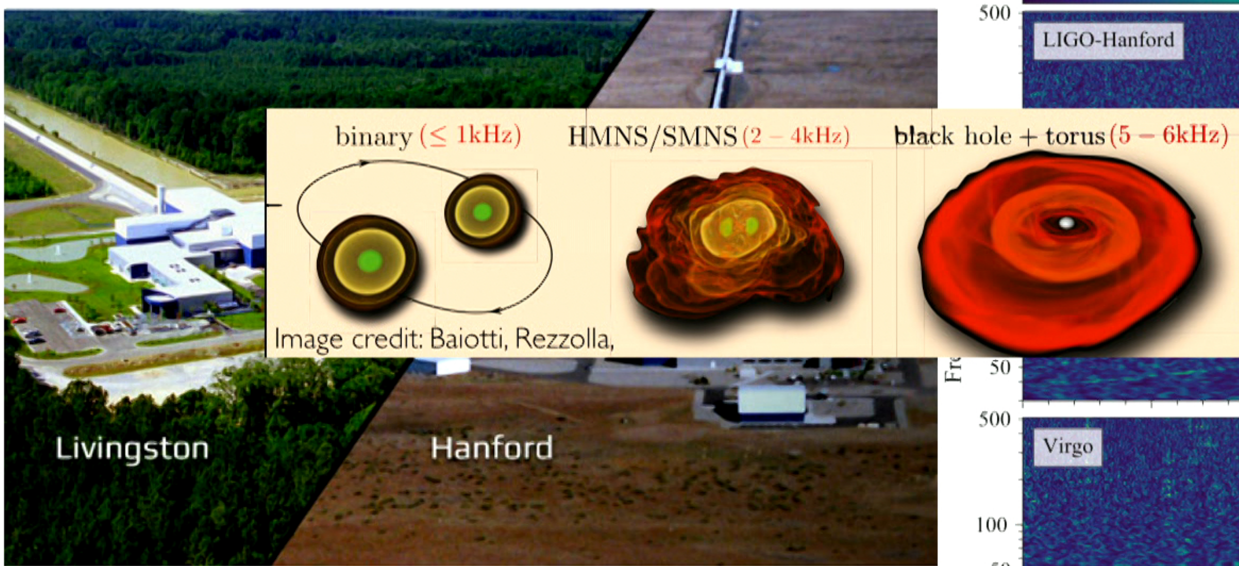


LIGO Lab MIT/Caltech



Abbott et al 2017

GW170817



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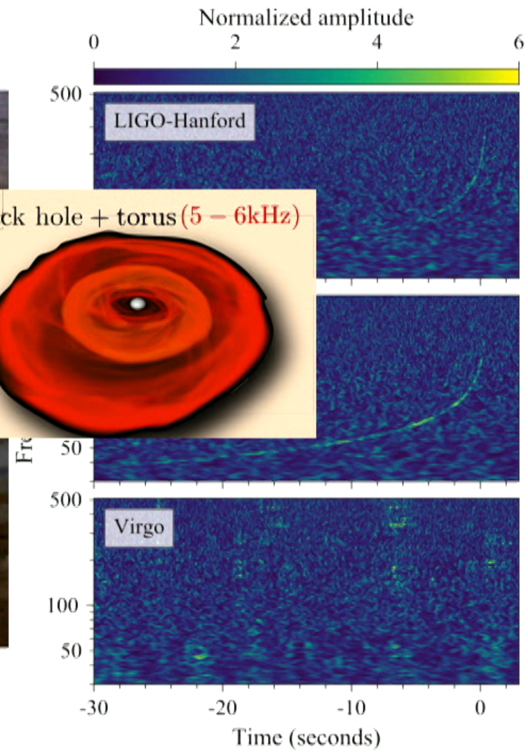

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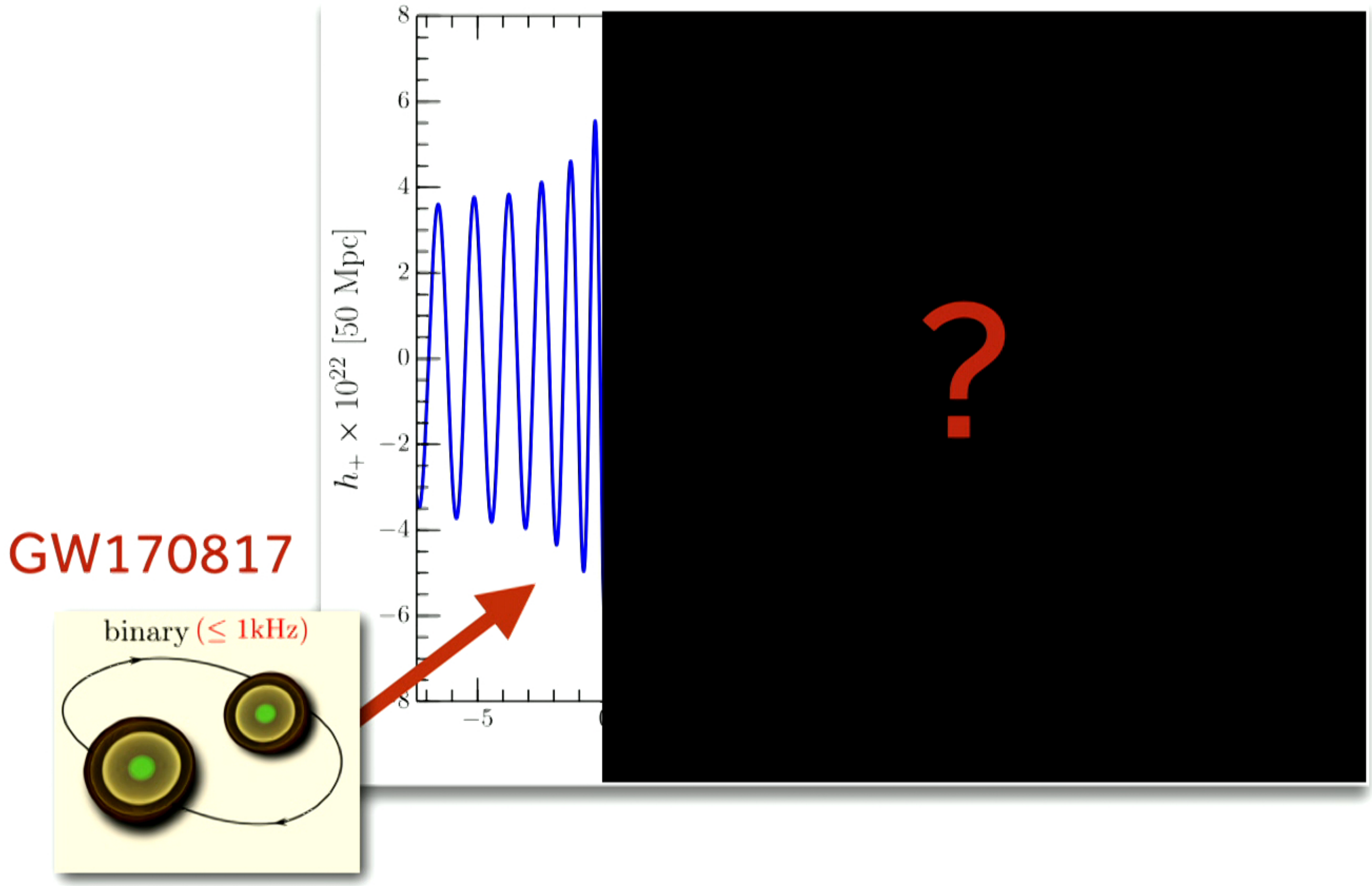
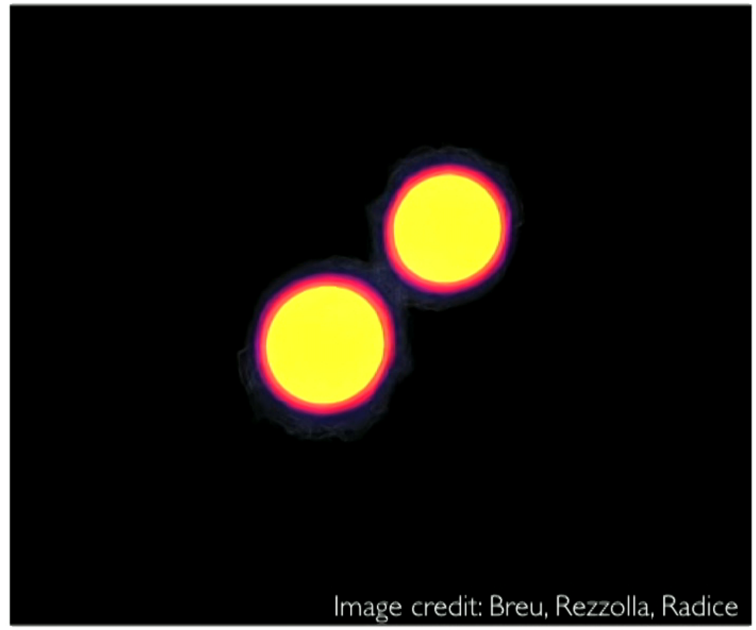
GW170817

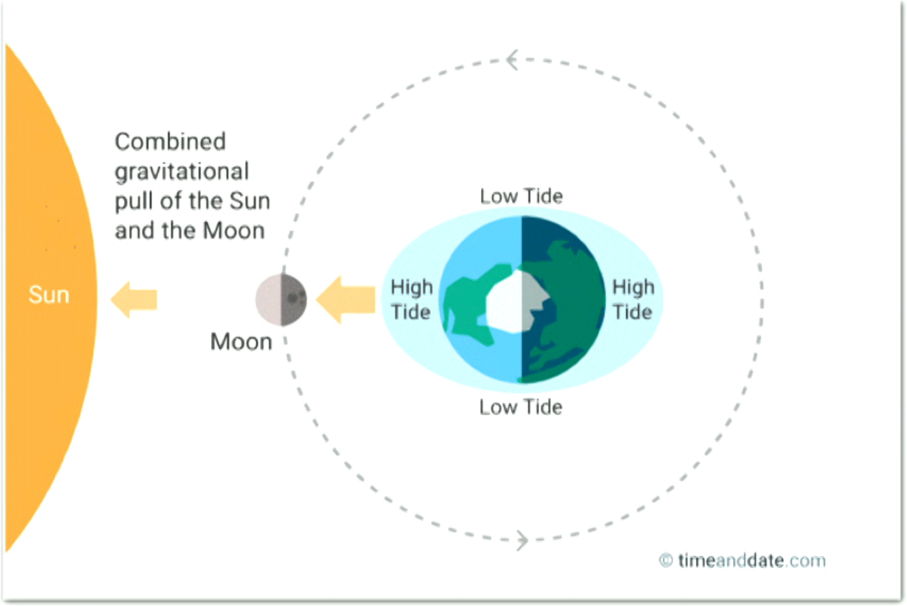


How is BH-BH different from NS-NS?



How is BH-BH different from NS-NS?

Neutron stars in binary are tidally deformed by companion



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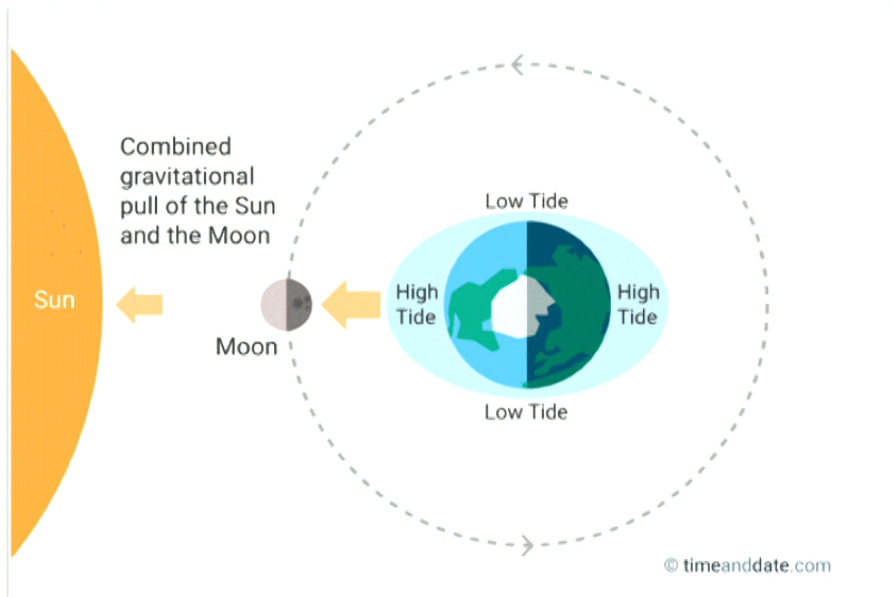
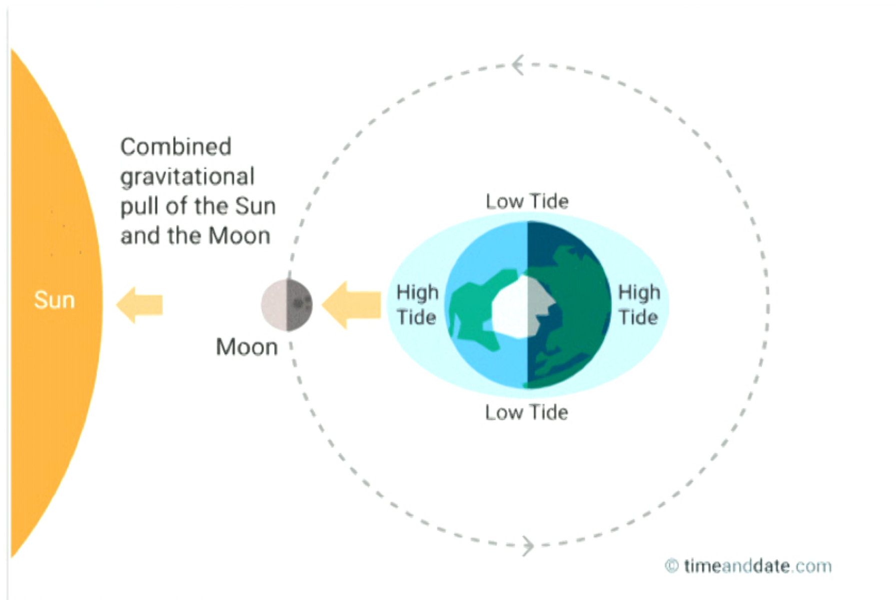


$$\Lambda = \frac{2}{3}\kappa_2 \left(\frac{Rc^2}{MG} \right)^5$$

Tidal deformability of an isolated neutron star

How is BH-BH different from NS-NS?

Neutron stars in binary are tidally deformed by companion

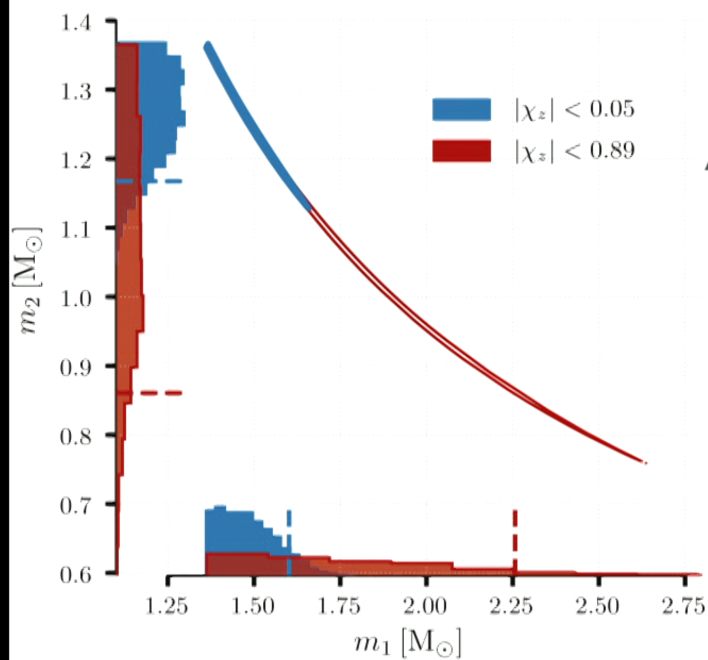


EOS

$$\Lambda = \frac{2}{3} \kappa_2 \left(\frac{R c^2}{M G} \right)^5$$

Tidal deformability of an isolated neutron star

GW170817: What do we know?



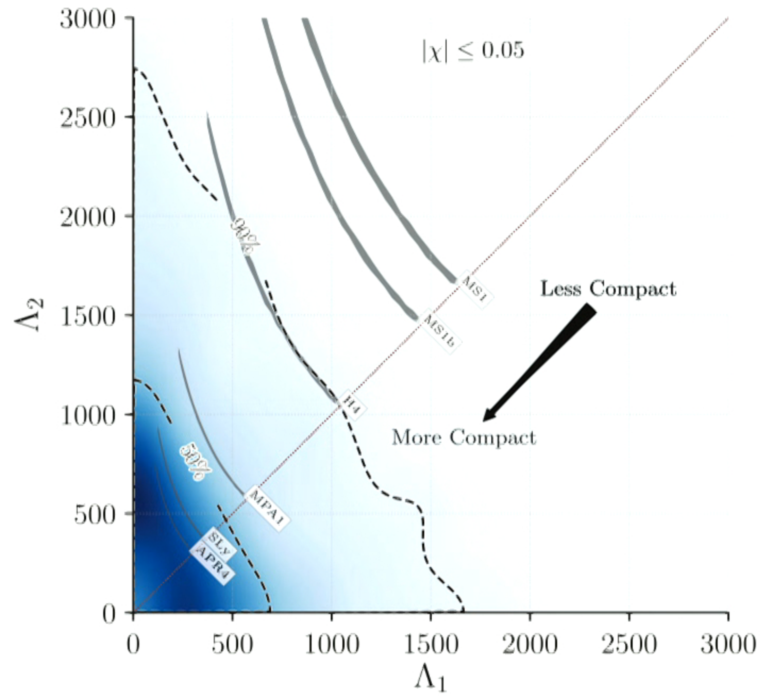
$$M_1 + M_2 = 2.74^{+0.04}_{-0.01} M_\odot$$

$$M_1 = 1.36 - 1.60 M_\odot$$

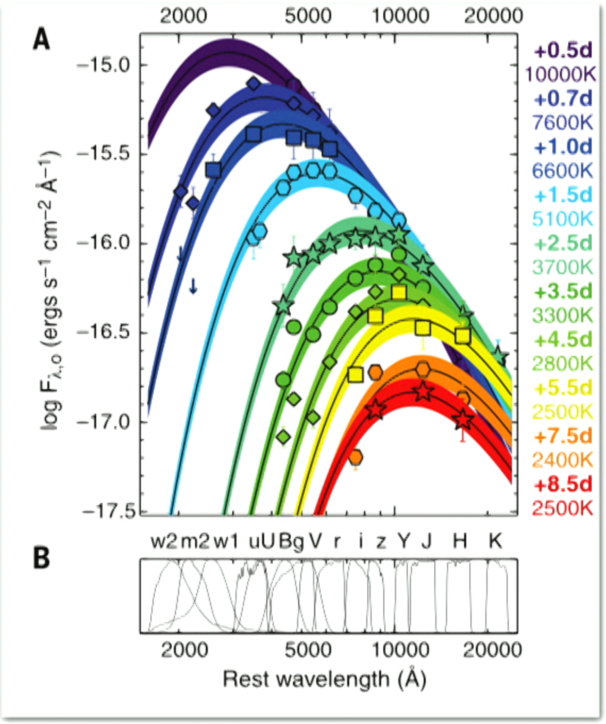
$$M_2 = 1.17 - 1.36 M_\odot$$

$$\tilde{\Lambda}_{1.4} < 800$$

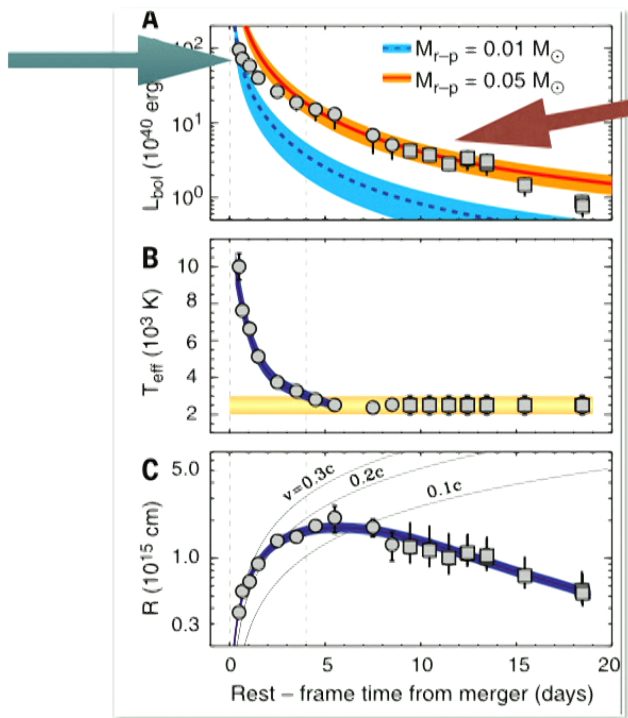
Abbott et al 2017



Light curves



Observations consistent with two component model



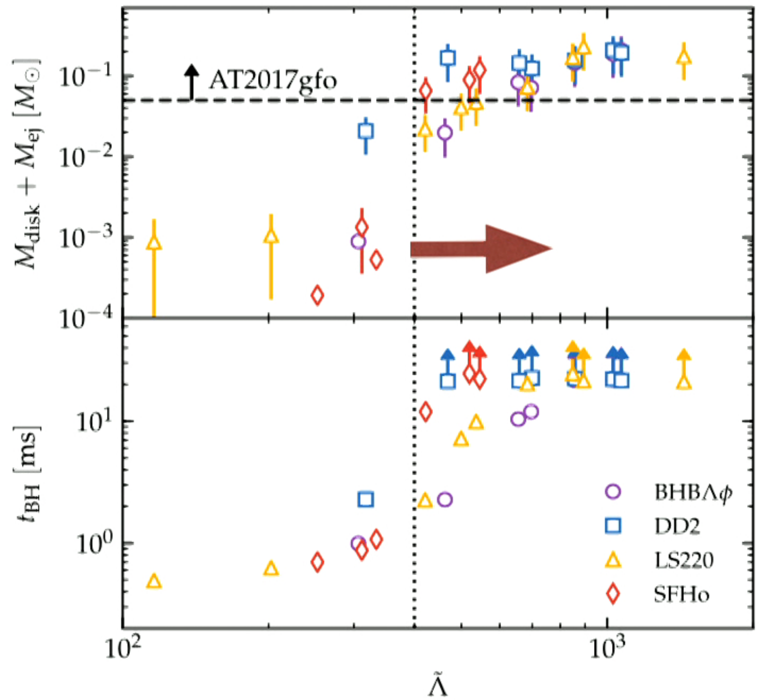
Drout et al 2017

Kilonova constraints on the tidal deformability

- Consistency with kilonova modelling (mass ejection) requires lower limit on tidal deformability

$$\tilde{\Lambda} = \frac{16}{13}\left[\frac{(M_A + 12M_B)M_A^4\Lambda_2^{(A)}}{(M_A+M_B)^5} + (A \leftrightarrow B)\right],$$

Errors unclear
Might be as low as ~200
(Coughlin+ 2018, Kiuchi+ 2019)



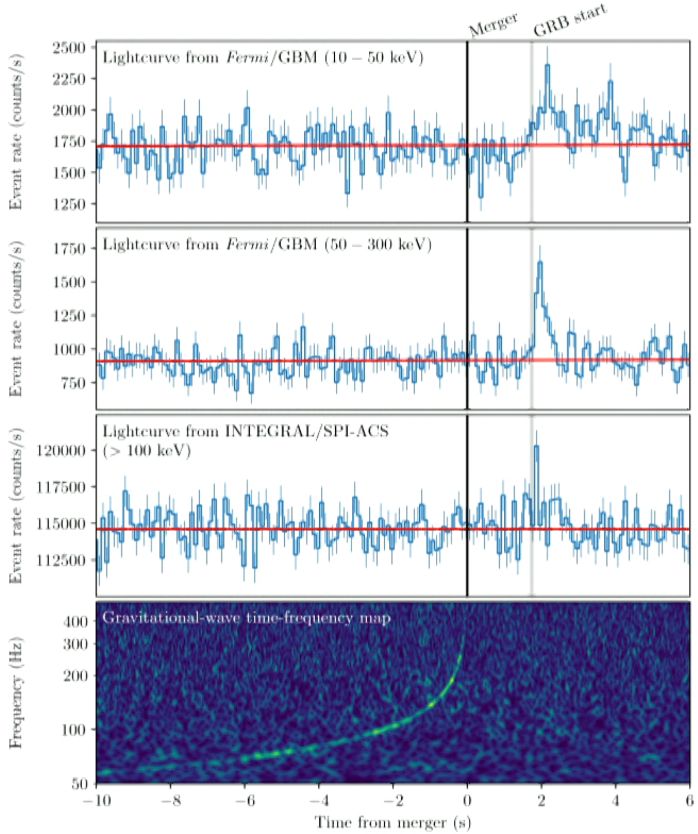
Radice et al 2018

GRB170817A

Coincident detection of sGRB

Multimessenger astronomy for neutron stars now possible

Most models of sGRBs assume the formation of a black hole!

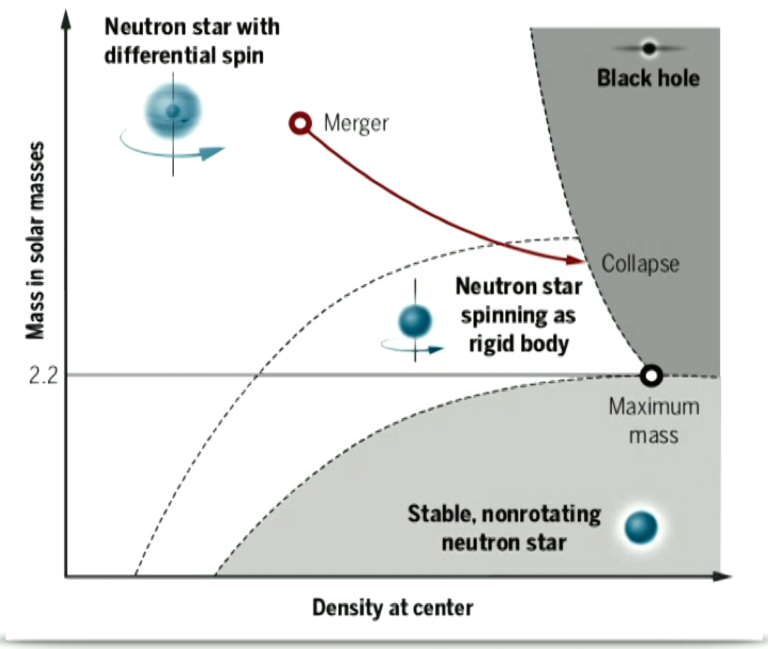


Abbott et al 2017

Limits on the maximum mass of neutron stars

Assuming that GW170817 has collapsed to a black hole several groups have proposed an upper limit for the mass of isolated neutron stars

(Margalit+2017; Shibata+2017; Rezzolla, **ERM**+2018; Ruiz+2018)



Cho, Bicknell, Science 2018

pulsar timing $2.01^{+0.04}_{-0.04} \leq M_{\rm TOV}/M_\odot \lesssim 2.16^{+0.17}_{-0.15}$ Rezzolla, **ERM**, Weih 2018

Limits on radii and deformabilities

- Constraining NS radii of neutron stars is an effort with thousands of papers published over the last 40 years.
- Question is deeply related with EOS of nuclear matter.
- Can new constraints be set by GW170817?

Limits on radii and deformabilities

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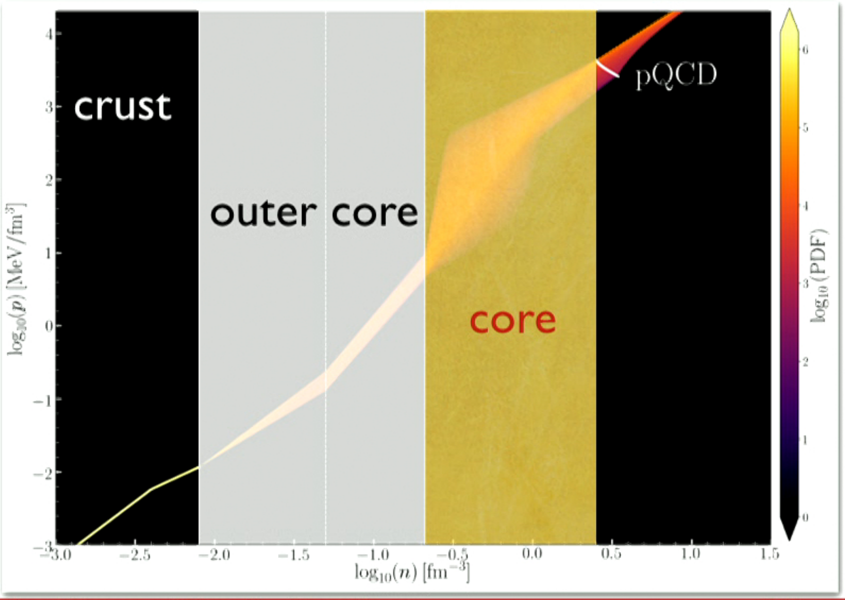
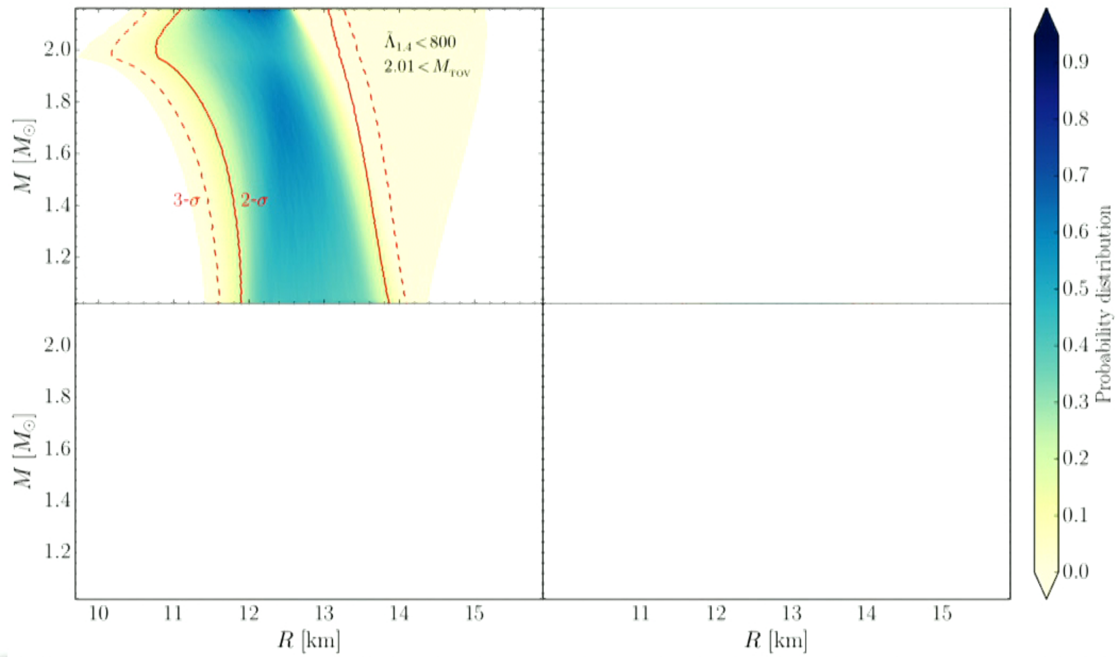
- Question is deeply related with EOS of nuclear matter.
- Can new constraints be set by GW170817?
- Ignorance can be parameterised and EOSs can be built arbitrarily as long as they satisfy specific **constraints** on **low** and **high** densities.



Mass-radius relations

We have produced **10^6 EOSs** with about **10^9 stellar models.**

Can impose differential constraints from the **maximum mass** and from the **tidal deformability** from **GW170817**



ERM+ (PRL 2018)

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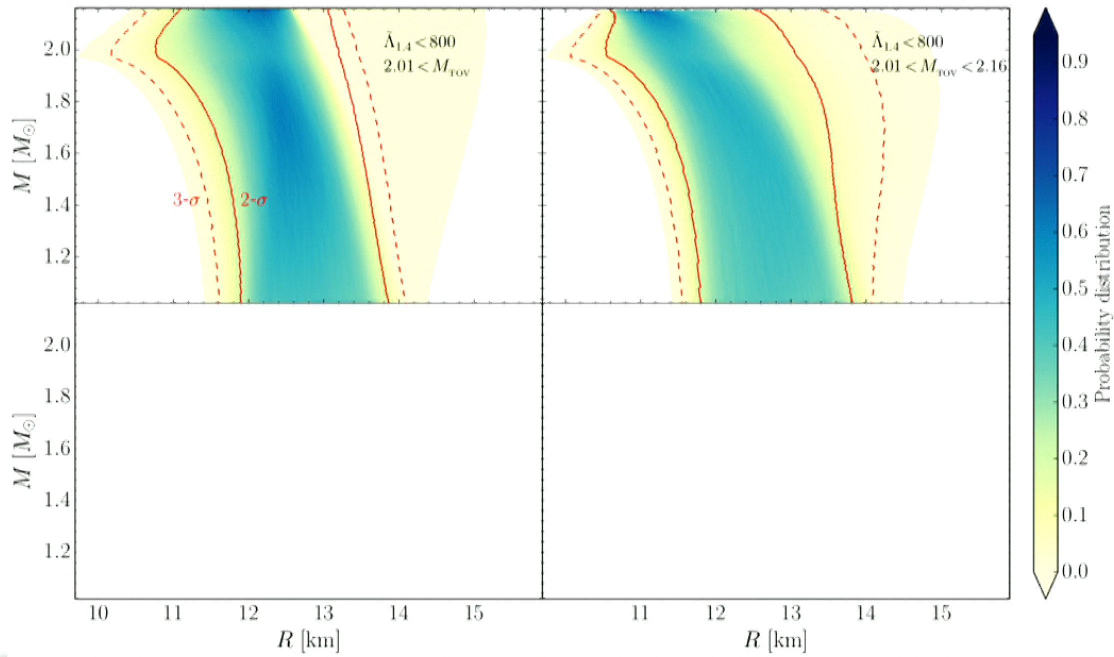

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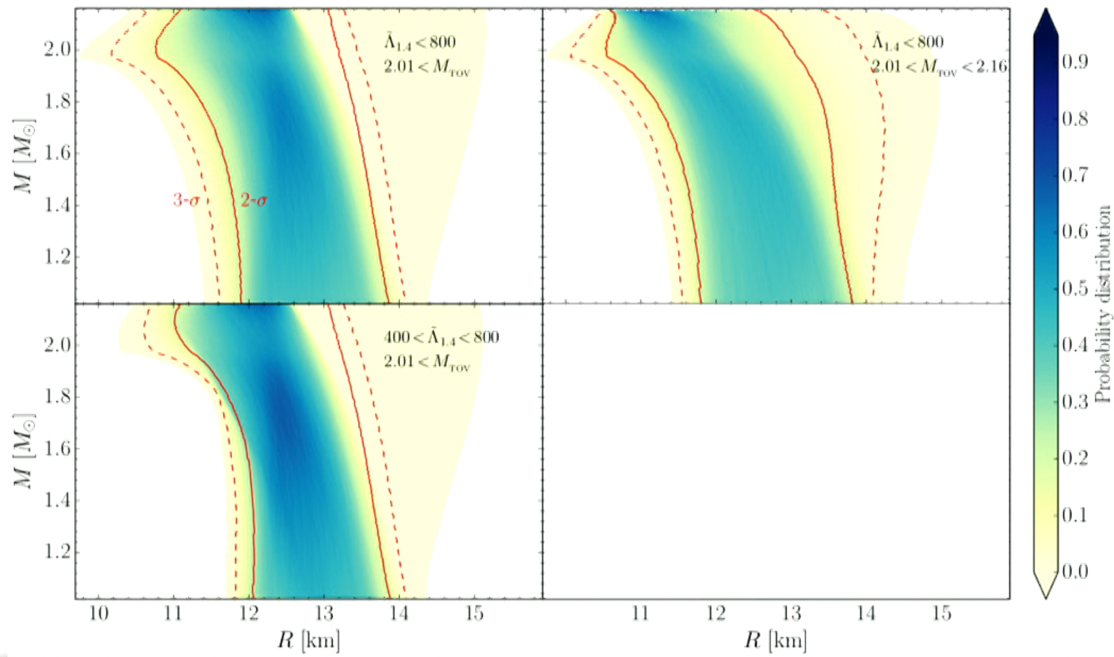

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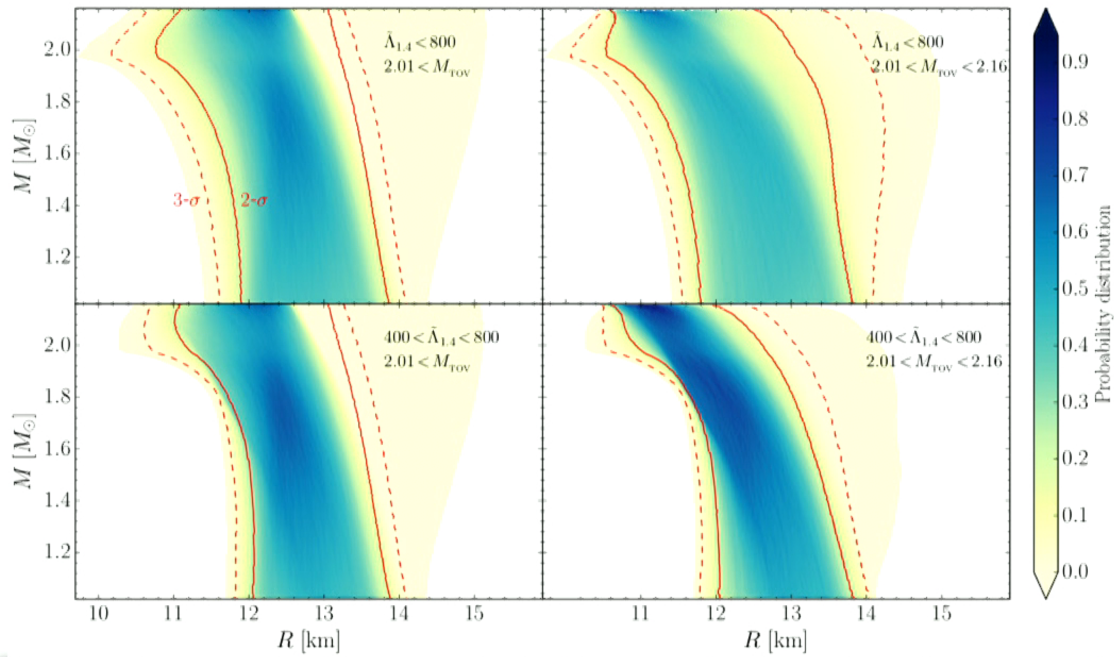
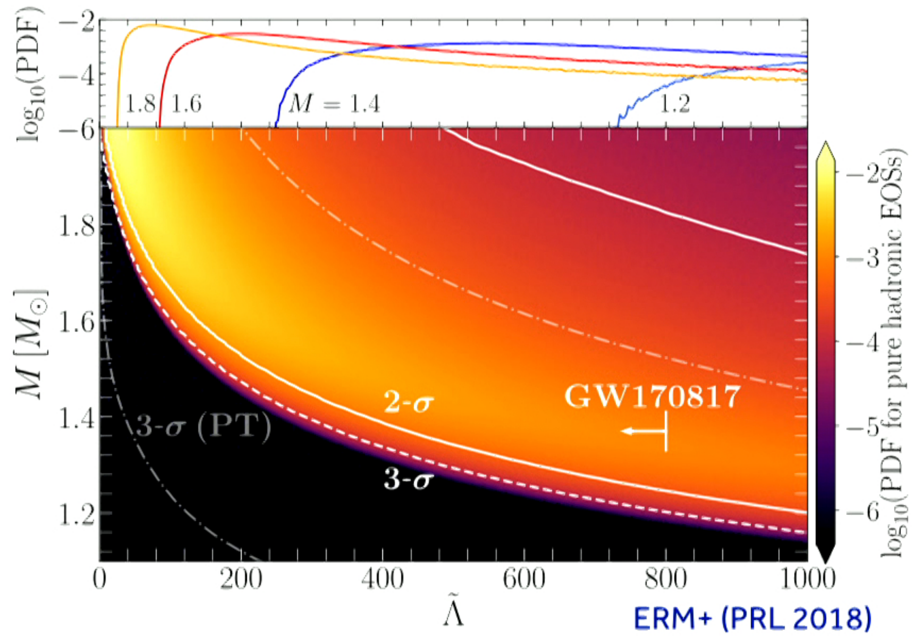


ERM+ (PRL 2018)

Constraining tidal deformability

- Can explore statistics of all properties of our 10^9 models.
- In particular can study PDF of tidal deformability: $\tilde{\Lambda}$



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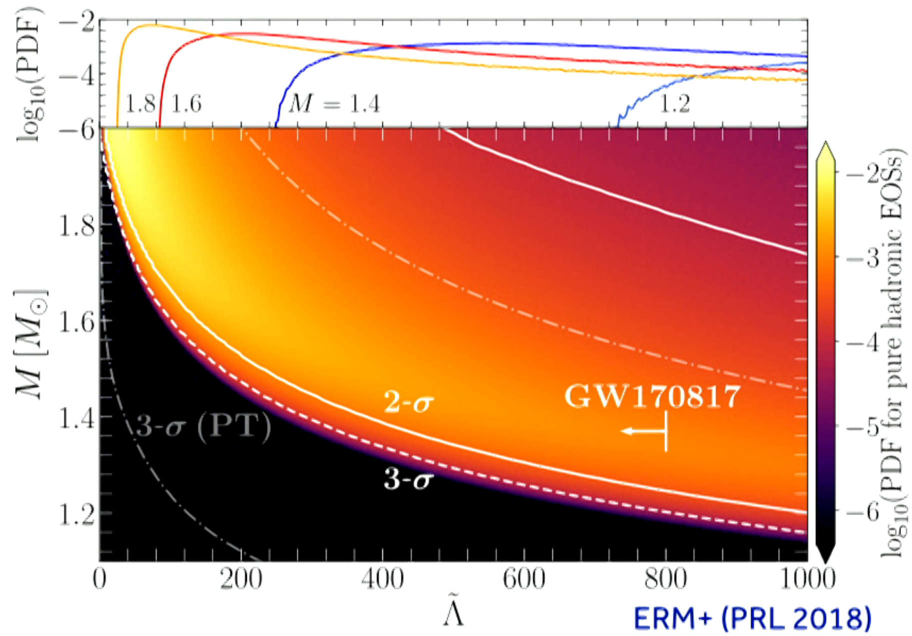


ERM+ (PRL 2018)

Constraining tidal deformability

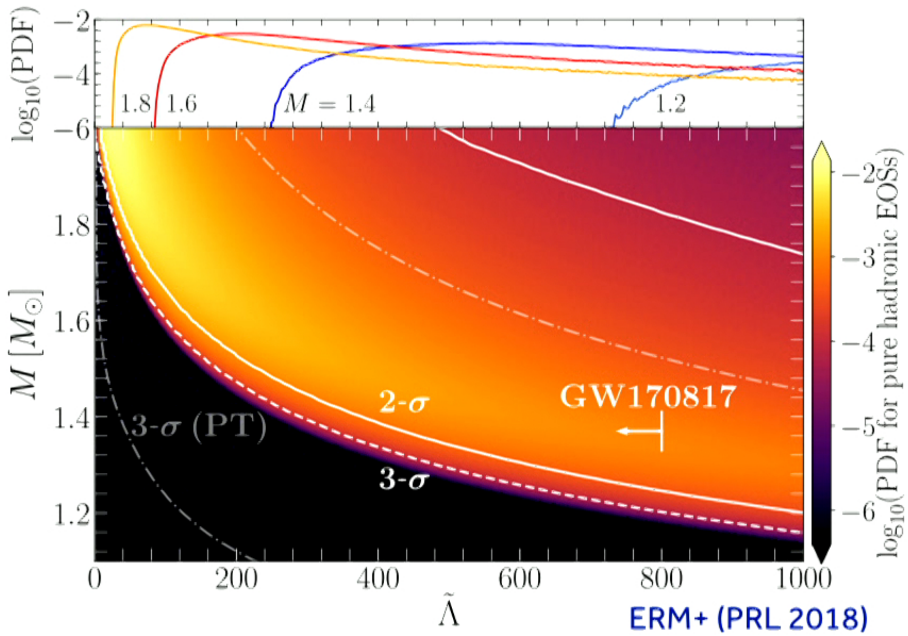
- Can explore statistics of all properties of our 10^9 models.
- In particular can study PDF of tidal deformability: $\tilde{\Lambda}$

- LIGO has already set upper limit:

$$\tilde{\Lambda}_{1.4} \lesssim 800$$

- Our sample naturally sets a lower limit:

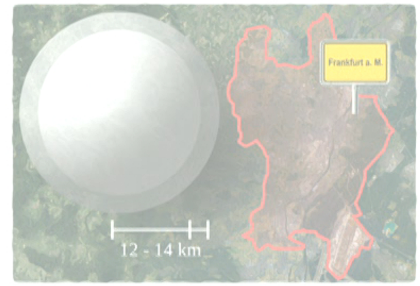
$$\tilde{\Lambda}_{1.4} > 375$$



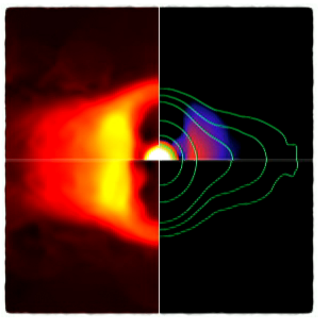
ERM+ (PRL 2018)

Overview

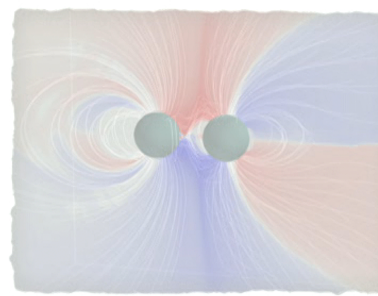
- Brief overview of neutron star mergers



- GW170817: implications on matter under extreme conditions



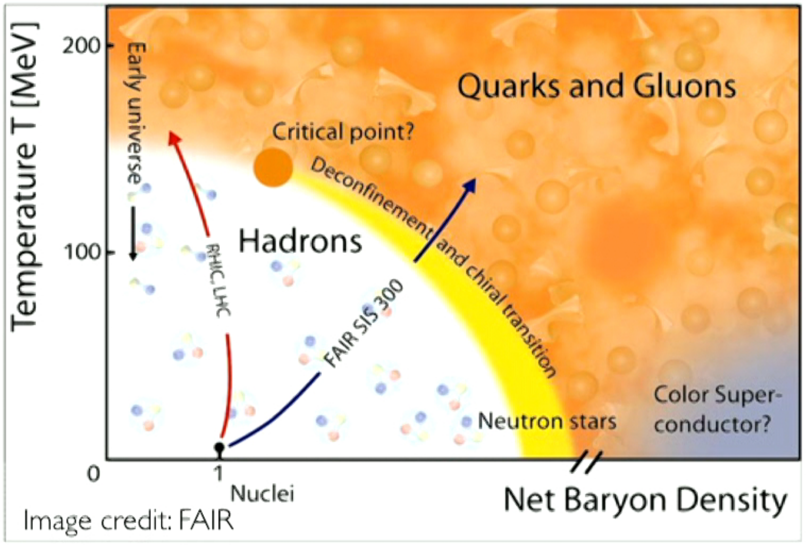
- Unveiling first-order phase transitions with gravitational waves



- Electromagnetic precursors from neutron star mergers

Different states of QCD matter

- QCD matter comes in different states
- Different physical systems probe different parts
- Neutron stars are at high densities (chemical potentials)

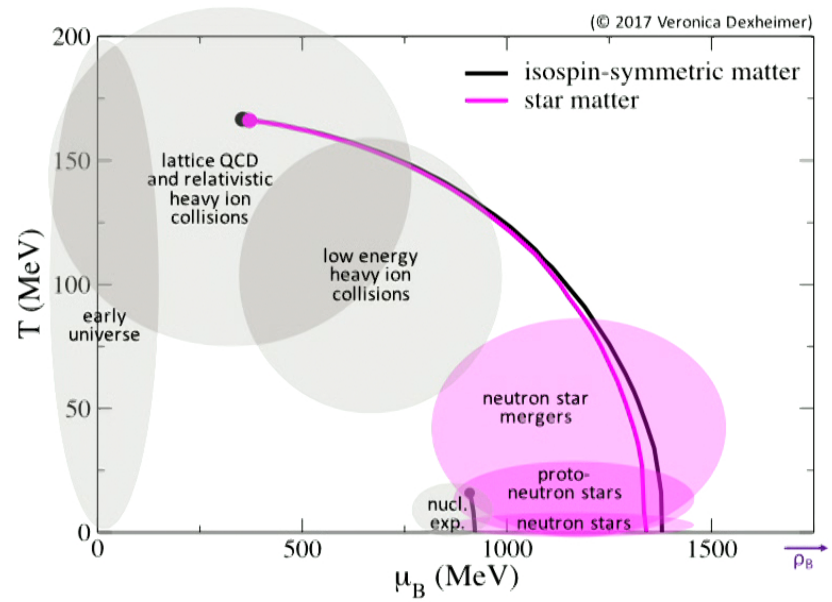


- Quark gluon plasma formed at high temperature /high density

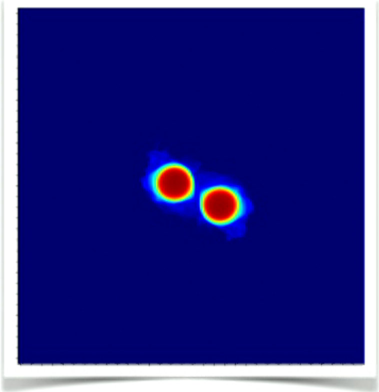
What mergers can tell us

- Cold neutron stars can only probe a tiny fraction of the phase diagram

- Neutron star mergers reach temperatures up to 80 MeV and probe regions not reached by any experiment!



Revealing phase transitions from gravitational wave signals

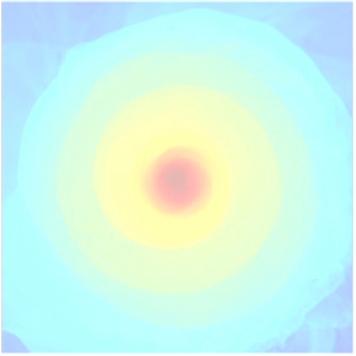


Signals from the inspiral

ERM+ PRL **120**, 261103 (2018)

Signals from the post-merger

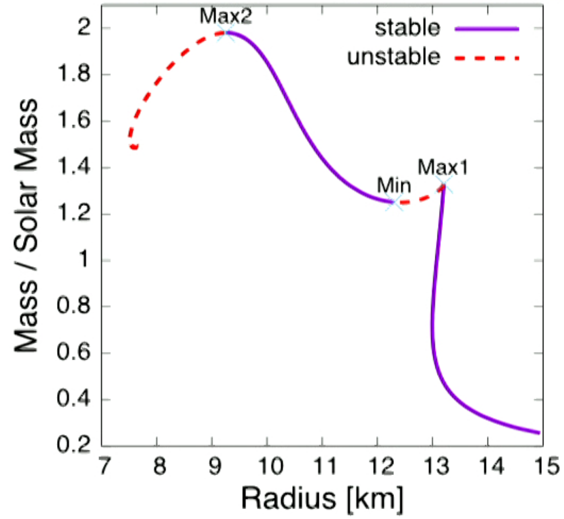
ERM+ PRL **122**, 061101 (2019)



Mass-radius relations

Christian+ (2018)

- Presence of a phase transition leads to second stable branch and "twin-star" models.



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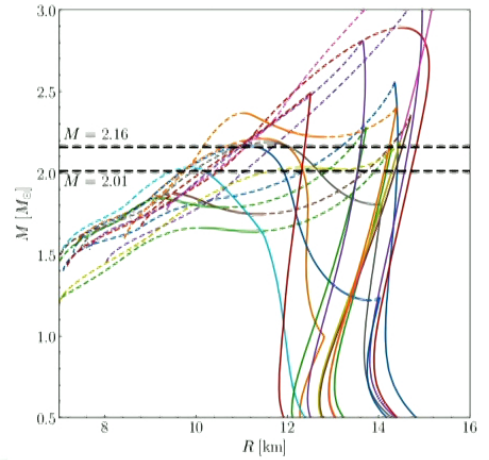
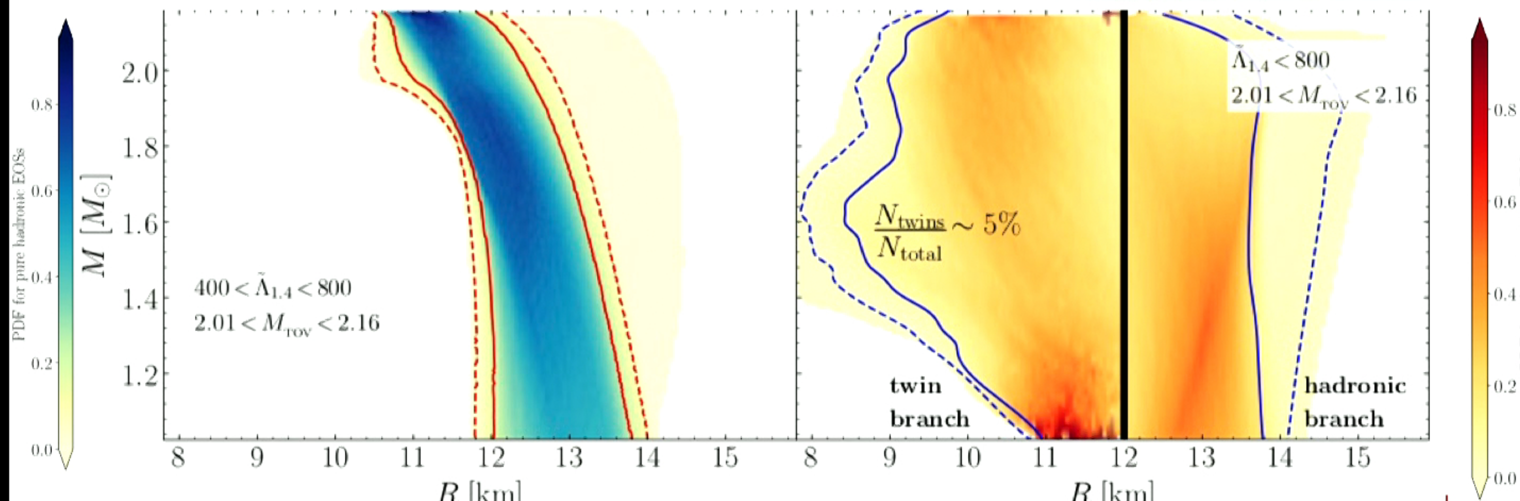
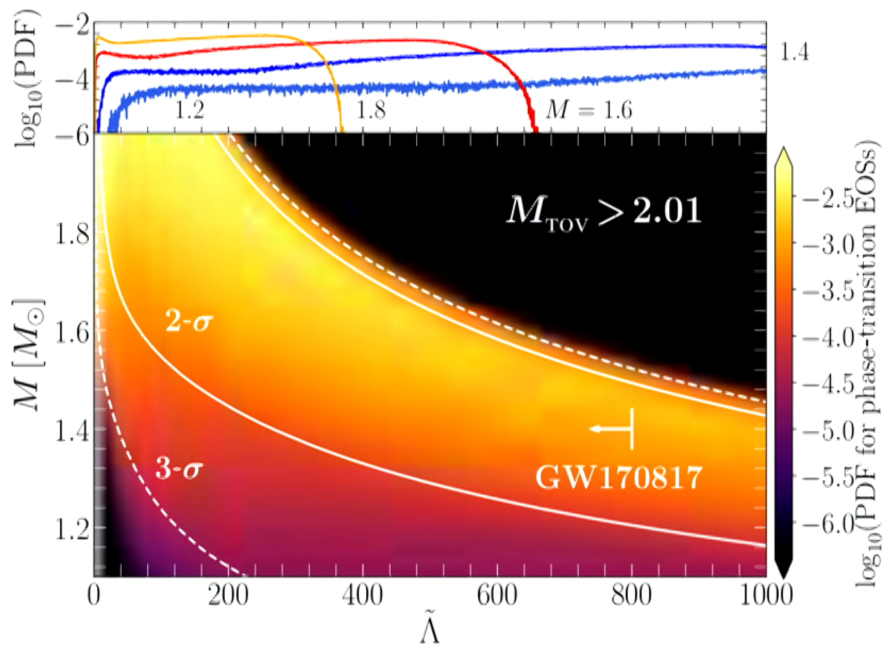


ERM+ (PRL 2018)



Constraining tidal deformability: PTs

- Can repeat considerations with EOSs having PTs

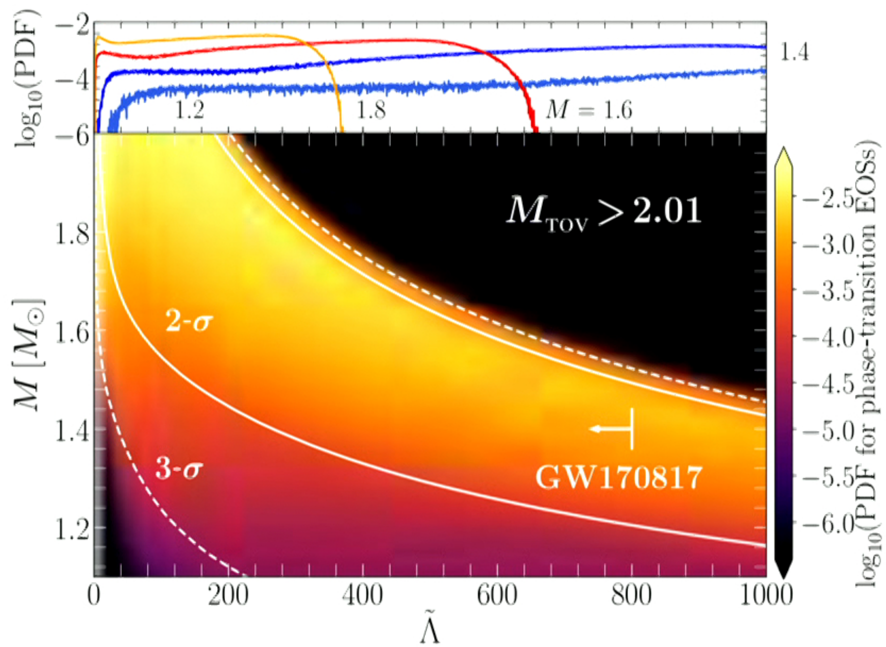


Constraining tidal deformability: PTs

- Can repeat considerations with EOSs having PTs
- Lower limit much weaker: $\tilde{\Lambda}_{1.4} \gtrsim 35$
- Large masses have sharp cut-off on upper limit:

$$\tilde{\Lambda}_{1.7} \lesssim 460$$

GW detection with $\tilde{\Lambda}_{1.7} \sim 700$ would rule out twin stars!



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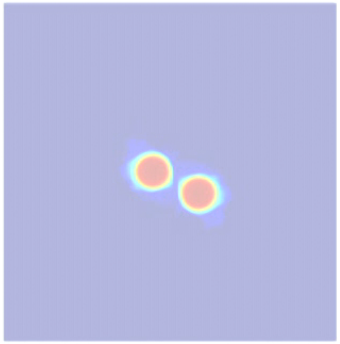

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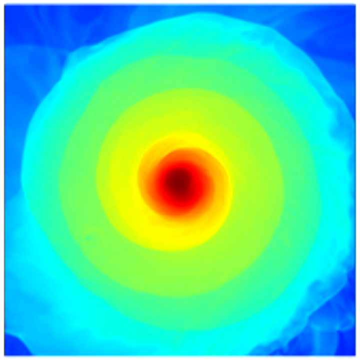

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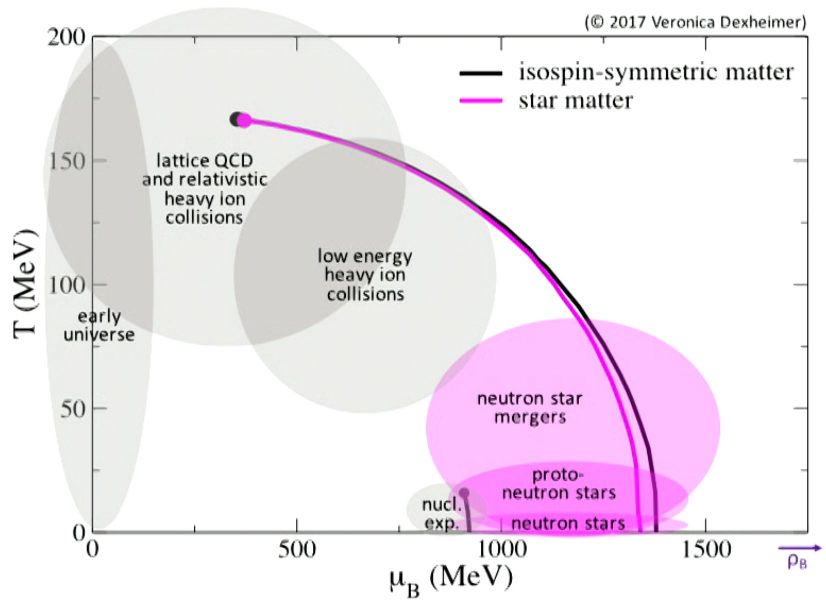
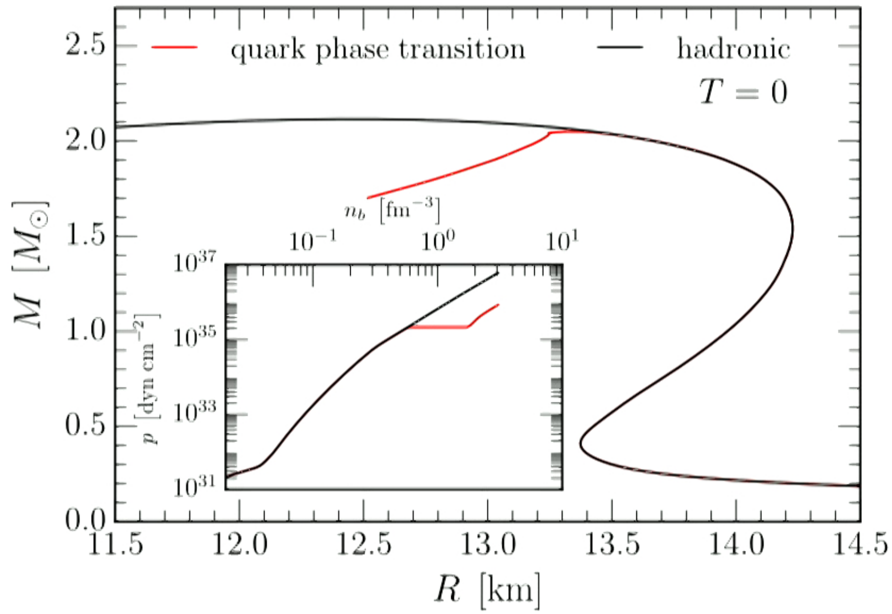


Chiral Mean Field Model

Dexheimer & Schramm

- Includes hyperons and quarks (can be turned off)
- Uses Polyakov loop to implement a strong first order phase transition
- Includes a cross-over transition at high temperatures

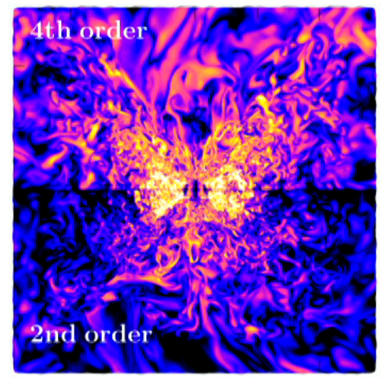


Frankfurt/IllinoisGRMHD code

ERM+ (MNRAS 2019)

- GRMHD: Solve GRMHD equations using fully fourth order flux update in space and time
  High order methods such as WENO-Z & MP5 available
  compatible with staggered constraint transport (ECHO scheme Del Zanna+ 2007)

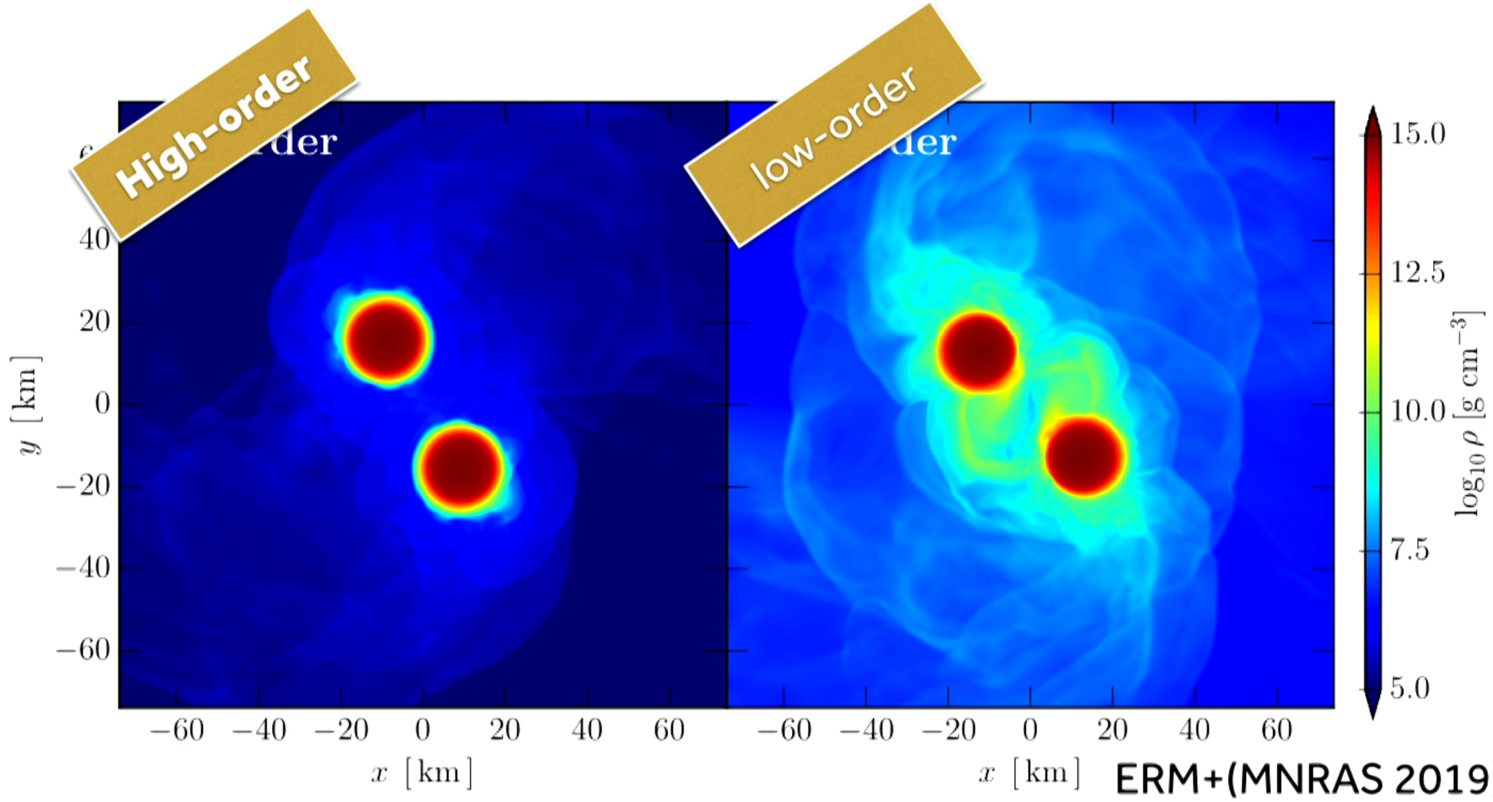
$$\hat{f}^i = f^i - \frac{1}{24}\Delta^2 f^i$$



- Microphysics : Support for finite temperature EOS with approximate neutrino treatment in terms of cooling (Leakage). Different primitive inversions.

- Dynamical space-time: Implements Z4c/BSSN equations

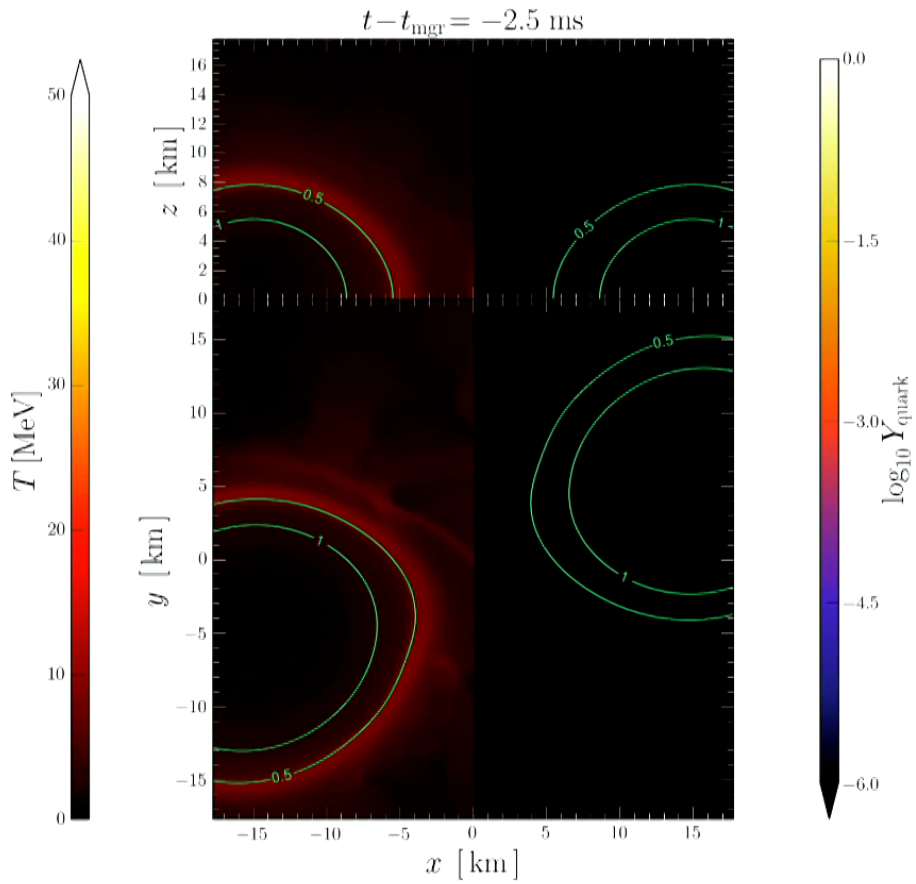
Importance of high order methods



ERM+(MNRAS 2019)

Insprial with finite temperature EOS and magnetic fields

Quark phase transition in mergers



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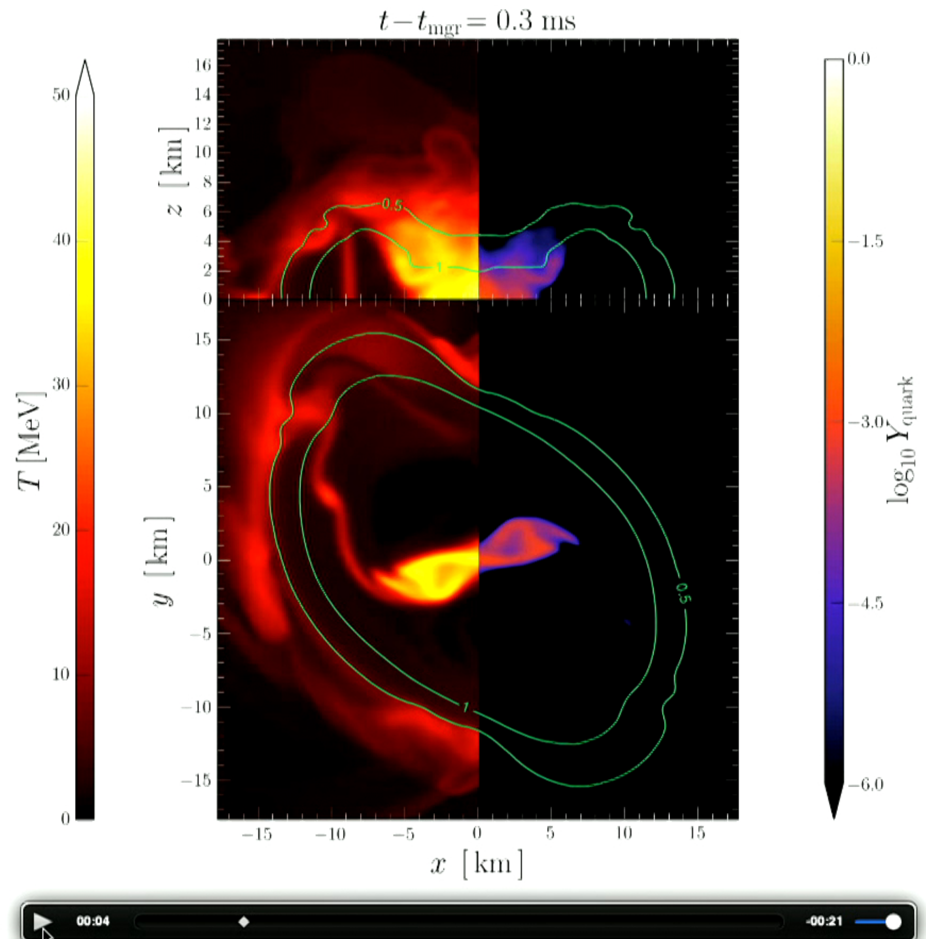

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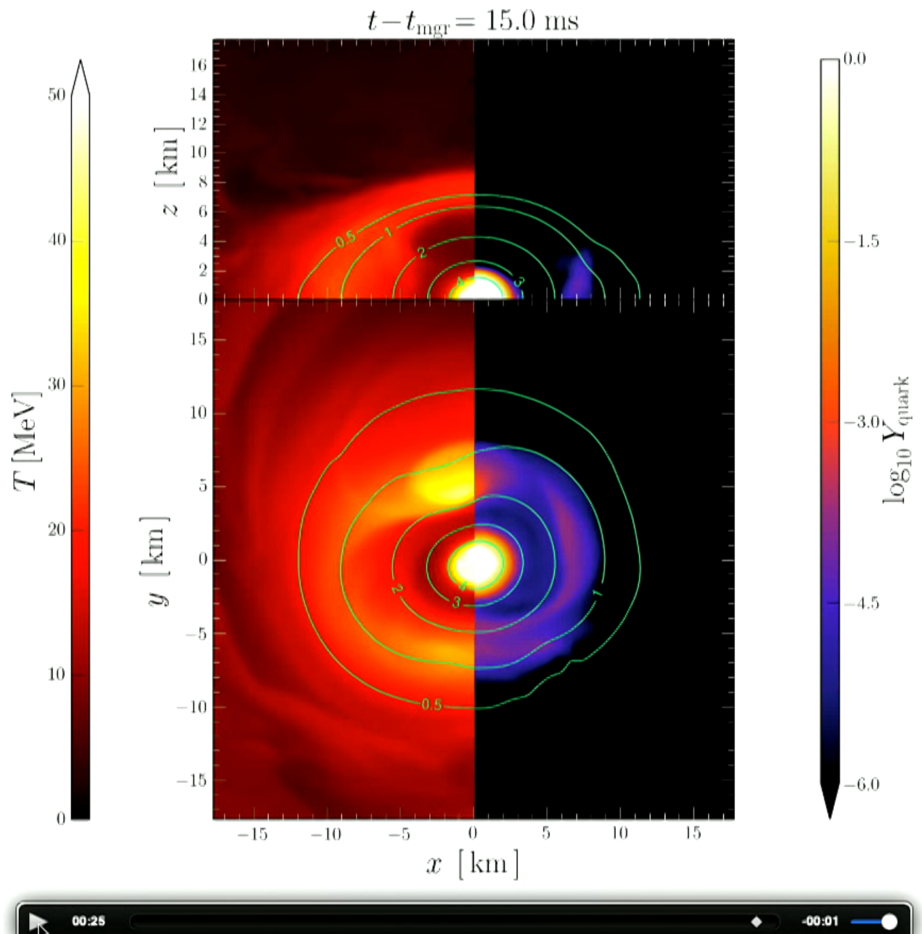

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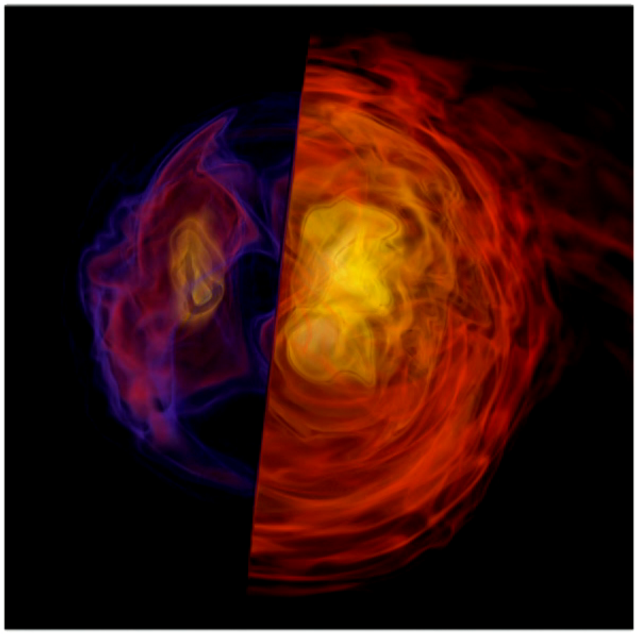
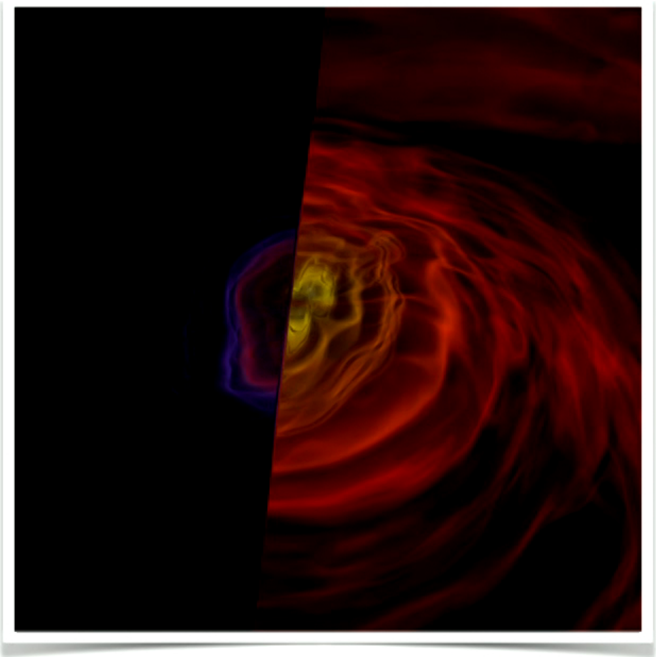


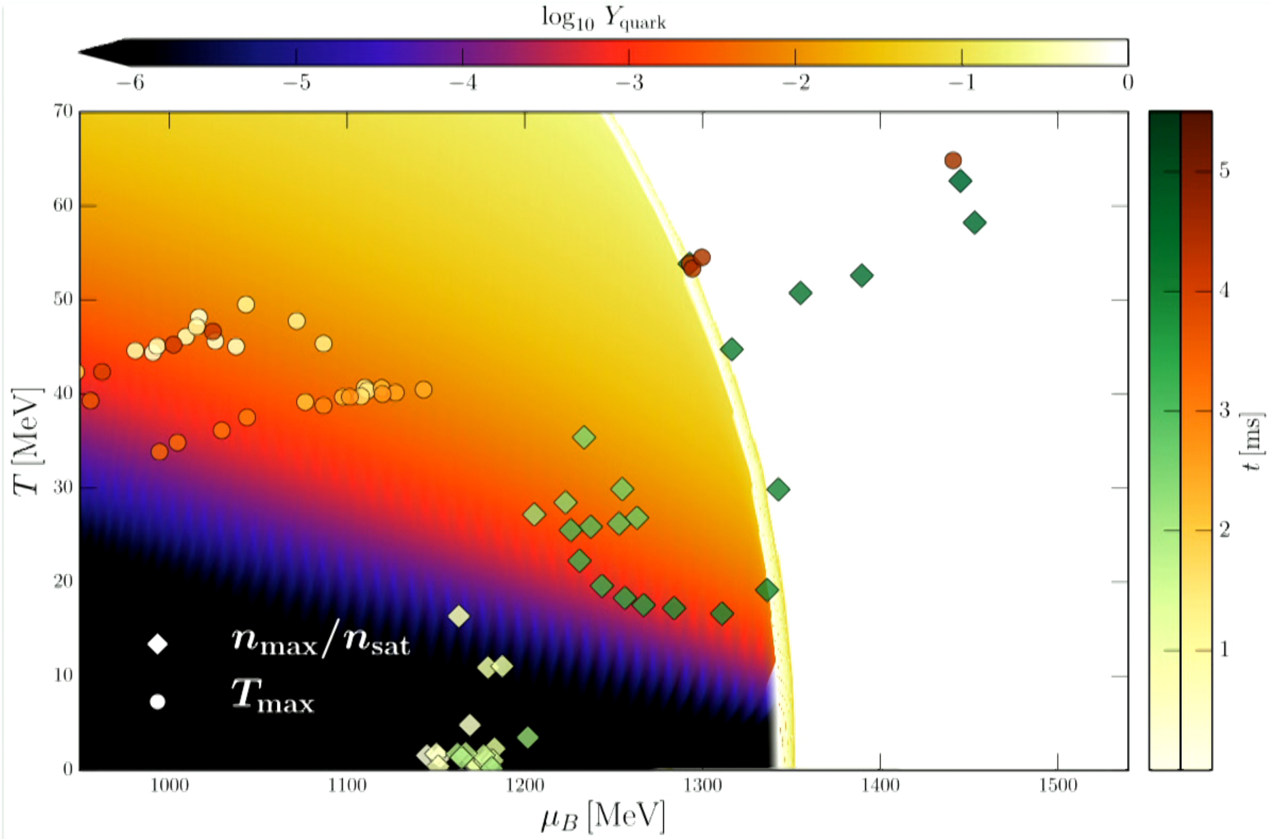
- Small fraction of quarks is present in hot regions at all times (cross-over transition)

Quark phase transition in mergers

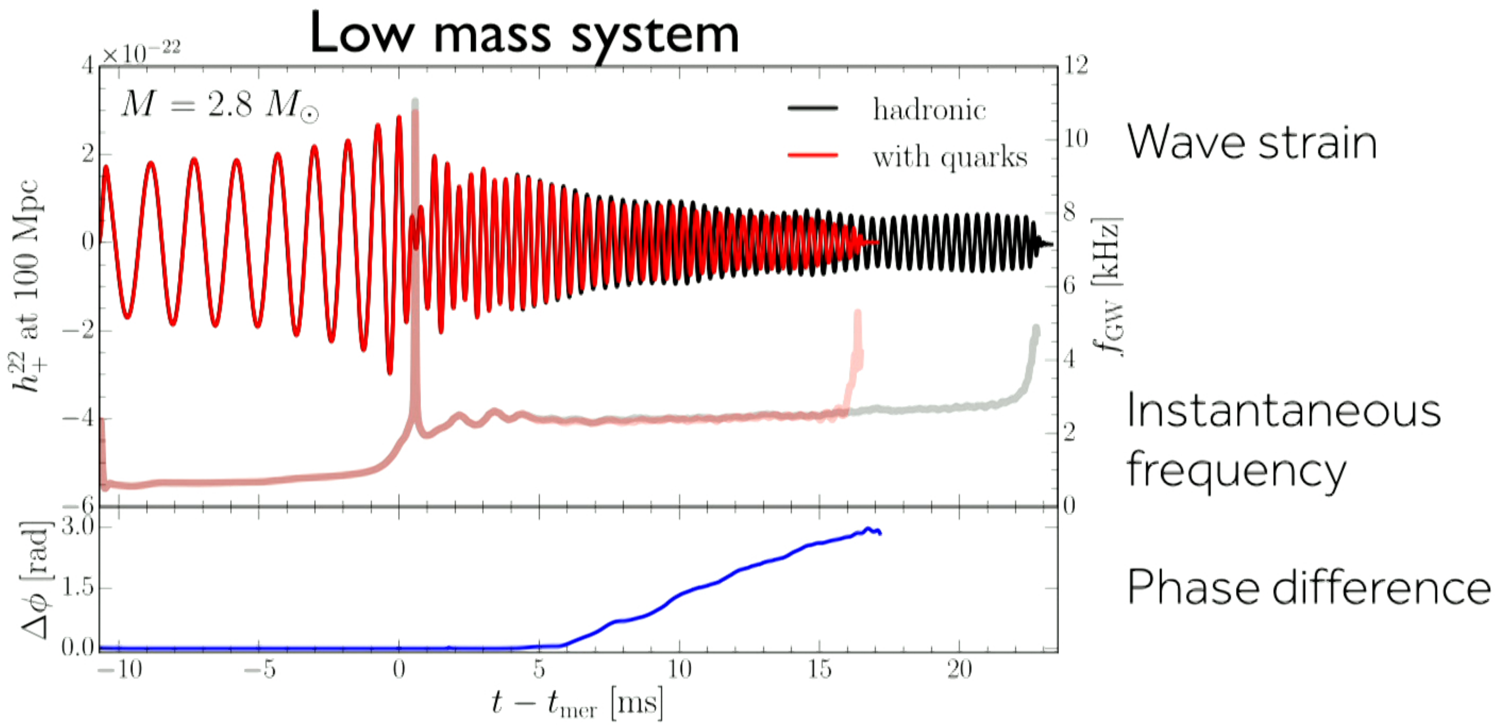


- Small fraction of quarks is present in hot regions at all times (cross-over transition)
- Hot quark core is formed as soon as the phase transition sets in
- Quark phase is unstable and triggers early collapse

Mergers in the phase diagram

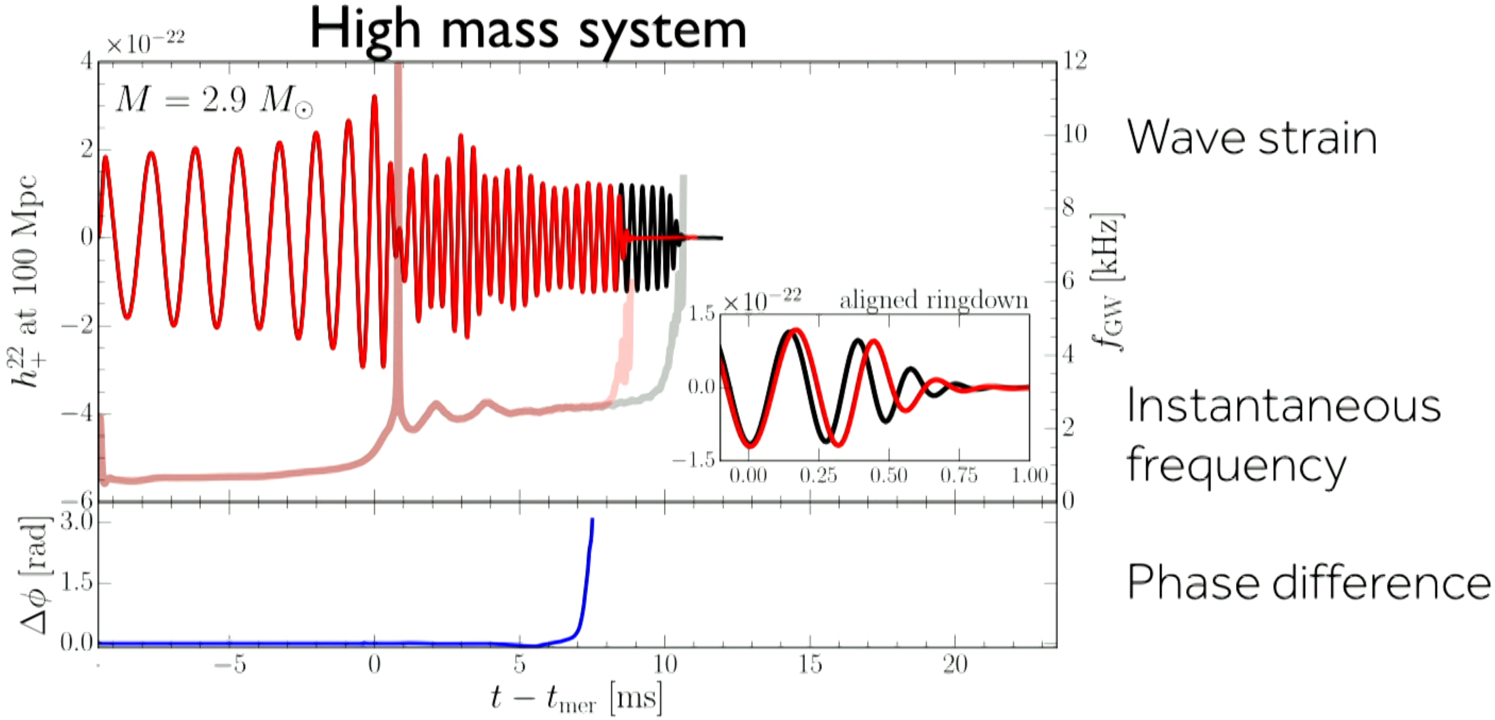


Can quarks be seen in gravitational waves?



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

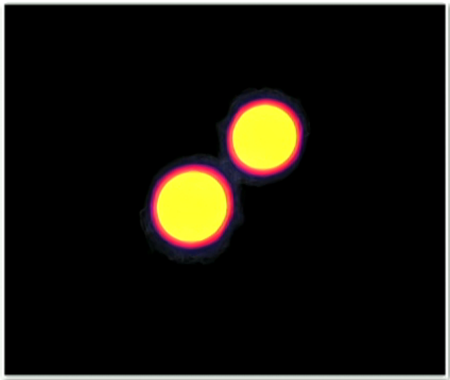
Can quarks be seen in gravitational waves?

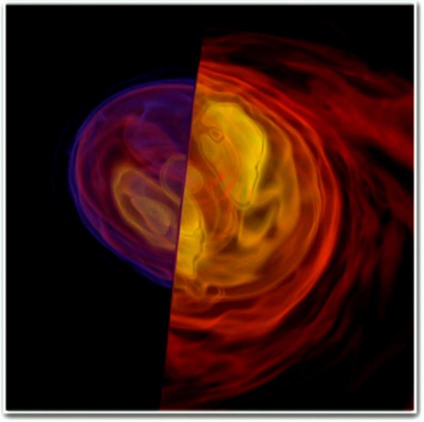


When the hot quark core collapses to a black hole the ringdown of the black hole is modified.

Can quarks be seen in gravitational waves?

- A quark phase transition in the inspiral is hard to spot. If quarks are already present in the stars, they will most likely have small Λ
- Large neutron stars at high masses can rule out such hybrid solutions!



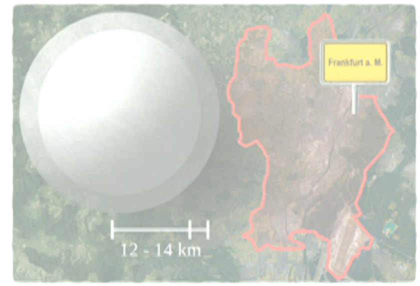


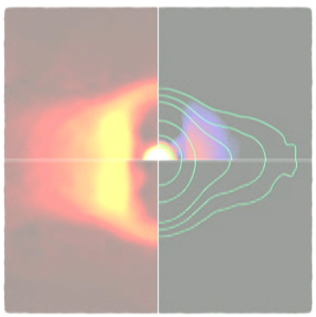
- Small amounts of quarks in the merger already cause a de-phasing of the waveform
- If the quark phase collapses to a black hole the ringdown is modified

Overview

✶ Brief overview of neutron star mergers

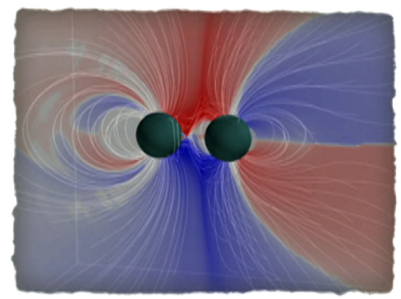
✶ GW170817: implications on matter under extreme conditions



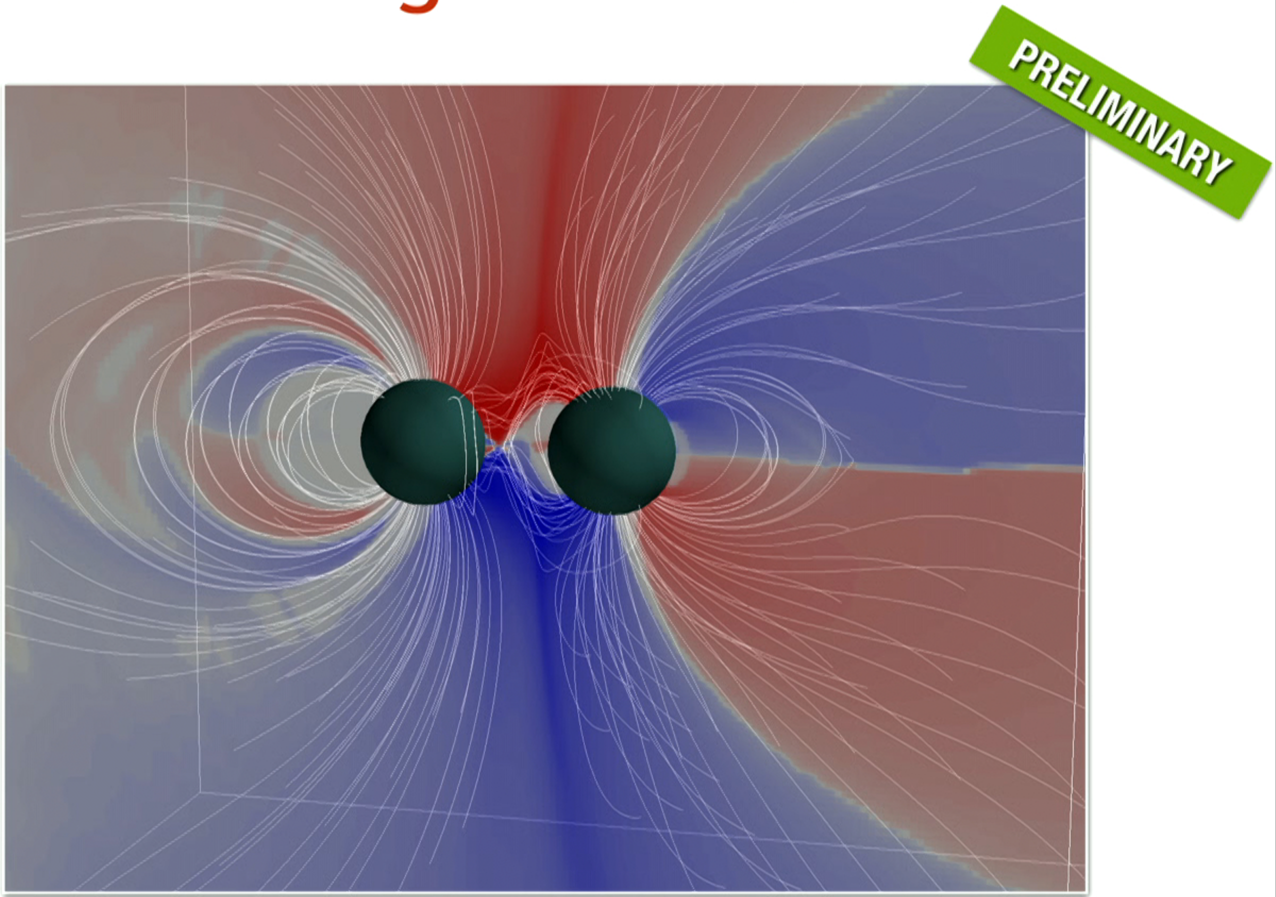


✶ Unveiling first-order phase transitions with gravitational waves

✶ Electromagnetic precursors from neutron star mergers

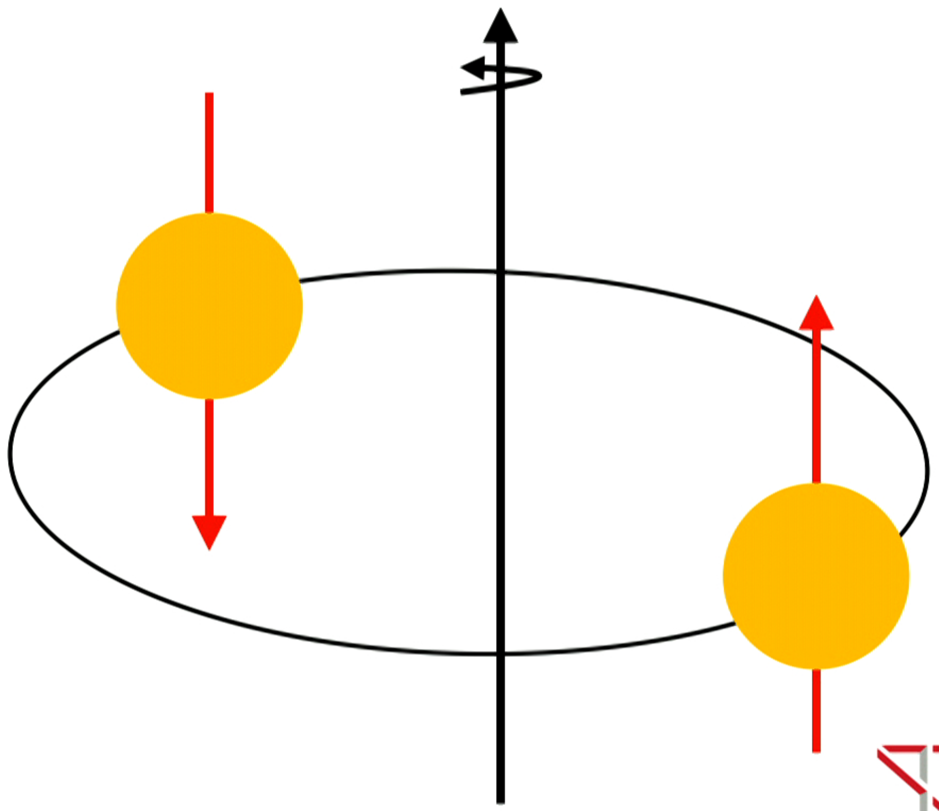


Electromagnetic Precursors



ERM+ (in prep)

Electromagnetic precursors



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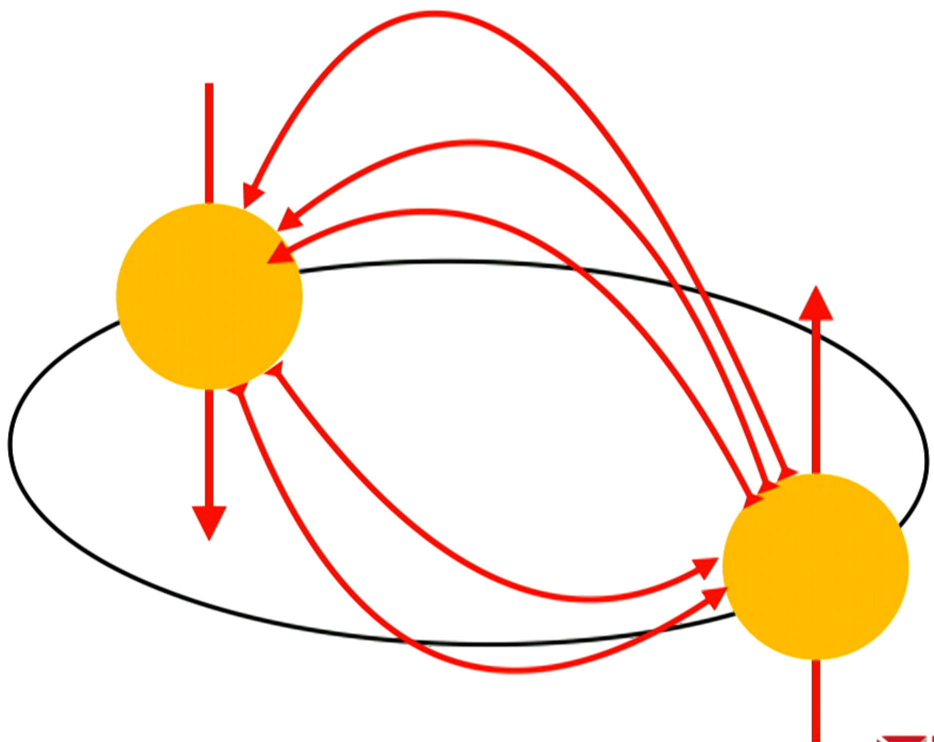
Elias R. Most | Perimeter Strong Gravity Seminar | 45

Electromagnetic precursors



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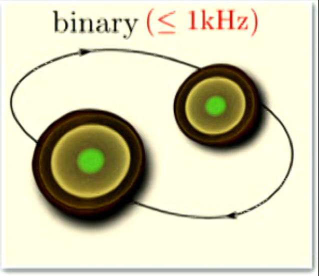
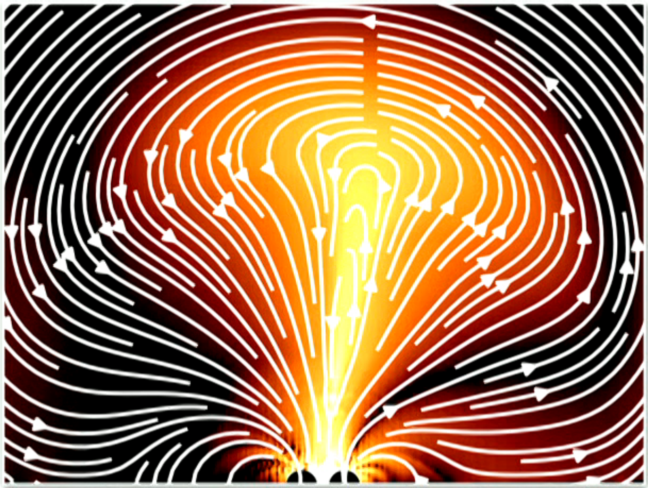
Electromagnetic precursors



- Magnetospheric interaction can release of significant amounts of EM energy
- EM precursors can aid sky localisation or constrain binary parameters (e.g. spin)



ERM+ (in prep)

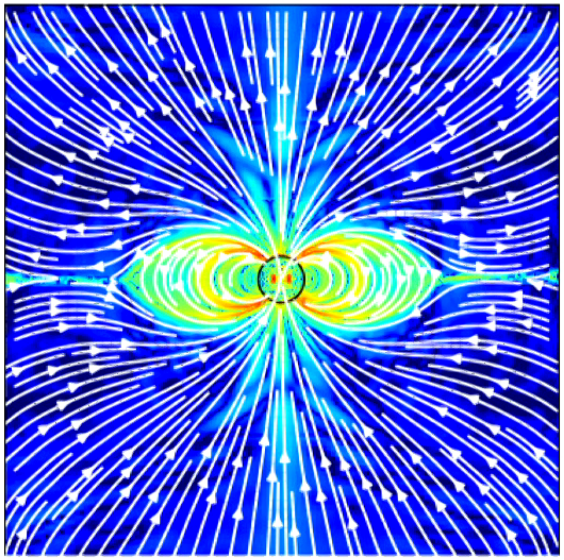
$$\mathscr{L}_{\rm diss} = 7.4 \times 10^{42}\, \zeta_\phi \left(\frac{B_*}{10^{12}\,\mathrm{G}}\right)^2 \left(\frac{a}{30\,\mathrm{km}}\right)^{-13/2} \mathrm{erg\,s^{-1}}$$

Lai (2012)

Twisting of field lines can enhance emission ($\zeta_\phi \gg 1$)

Pulsar magnetospheres

- Pulsars are equipped force-free magnetospheres consisting of a highly conducting $e^- - e^+$ pair plasma Goldreich&Julian (1969)
- Field lines beyond the light cylinder open up



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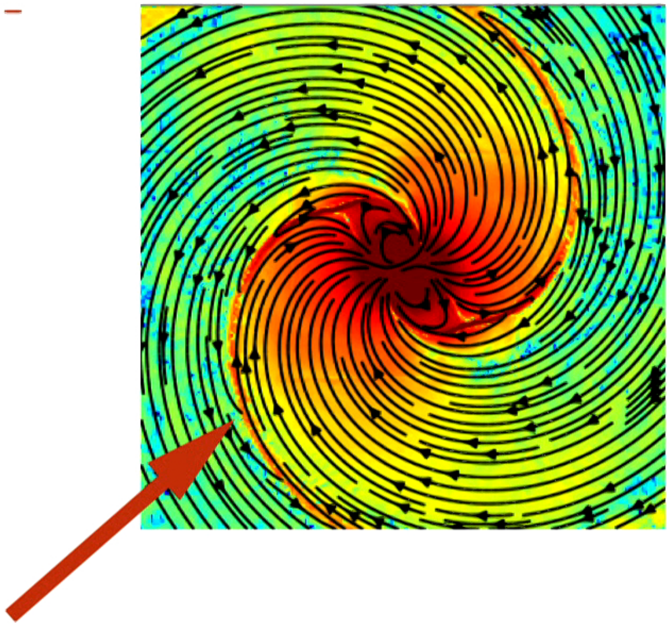
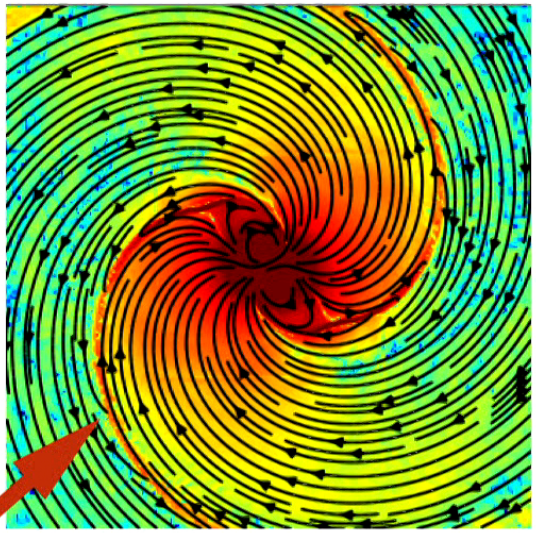
- Pulsars are equipped force-free magnetospheres consisting of a highly conducting $e^- - e^+$ pair plasma Goldreich&Julian (1969)
- Field lines beyond the light cylinder open up
- Strong current sheets are present that might be responsible for coherent radio emission Philippov+(2019)

ERM+ (in prep)

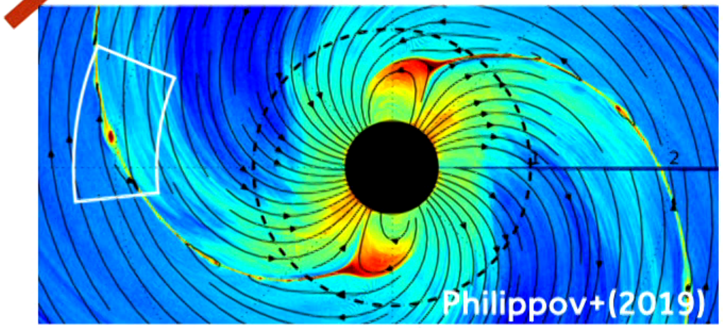


Pulsar magnetospheres

ERM+ (in prep)



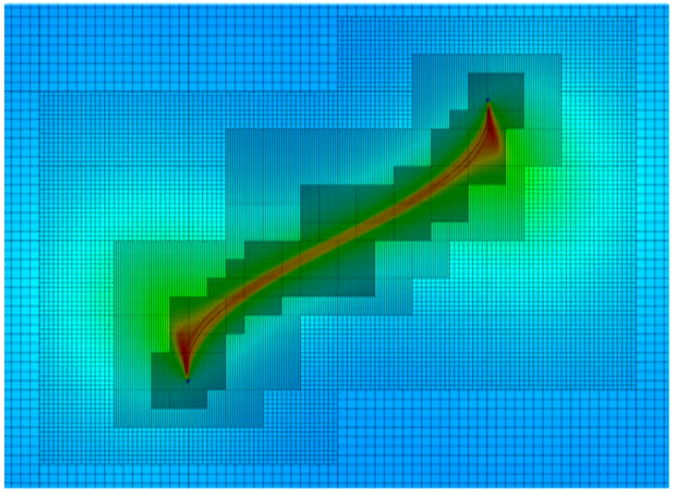
- Pulsars are equipped force-free magnetospheres consisting of a highly conducting $e^- - e^+$ pair plasma Goldreich&Julian (1969)
- Field lines beyond the light cylinder open up
- Strong current sheets are present that might be responsible for coherent radio emission Philippov+(2019)



GReX code [Most et al. (in prep)]

$$\nabla_\mu \left(T^{\mu\nu}_{\rm hydro} + T^{\mu\nu}_{\rm EM} \right) = 0 \qquad G_{\mu\nu} = \frac{8\pi G}{c^4} \left(T^{\mu\nu}_{\rm hydro} + T^{\mu\nu}_{\rm EM} \right)$$

- GRMHD with dynamical spacetime, both fourth order accurate $\hat{f}^i = f^i - \frac{1}{24}\Delta^2 f^i$
- Solves GRMHD in local frame with optional HLLD Riemann solver
- Dynamical space-time evolution using Z4c
- Full dynamical AMR capability through AMReX framework
- Recently extended to fully resistive GRMHD with force-free coupling

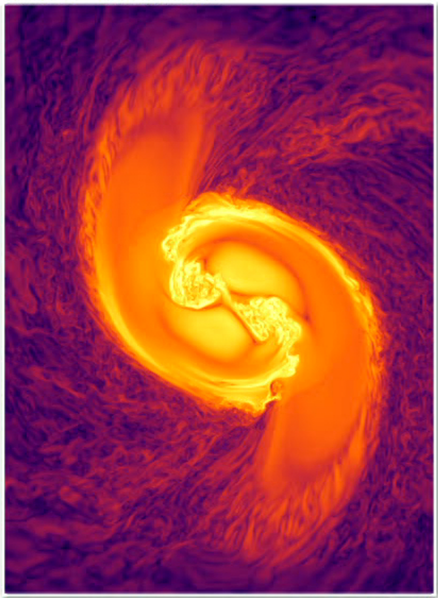


Binary black holes in ambient gas

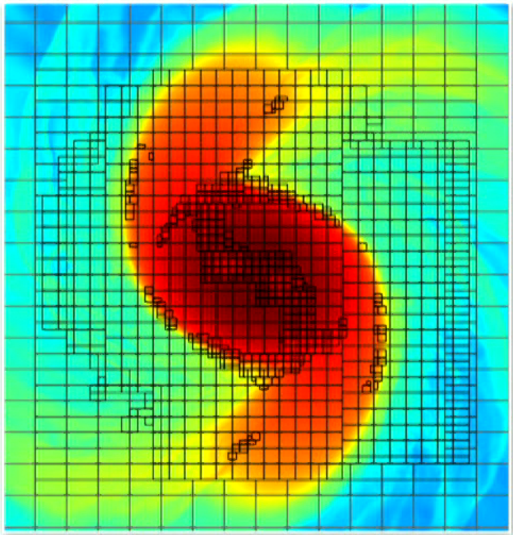
Kelvin-Helmholtz instability in neutron star mergers

- At the time of merger a shear layer forms at the contact interface of the two stars
- Additional perpendicular compression due to gravity between the two stars

Most+ (in prep)



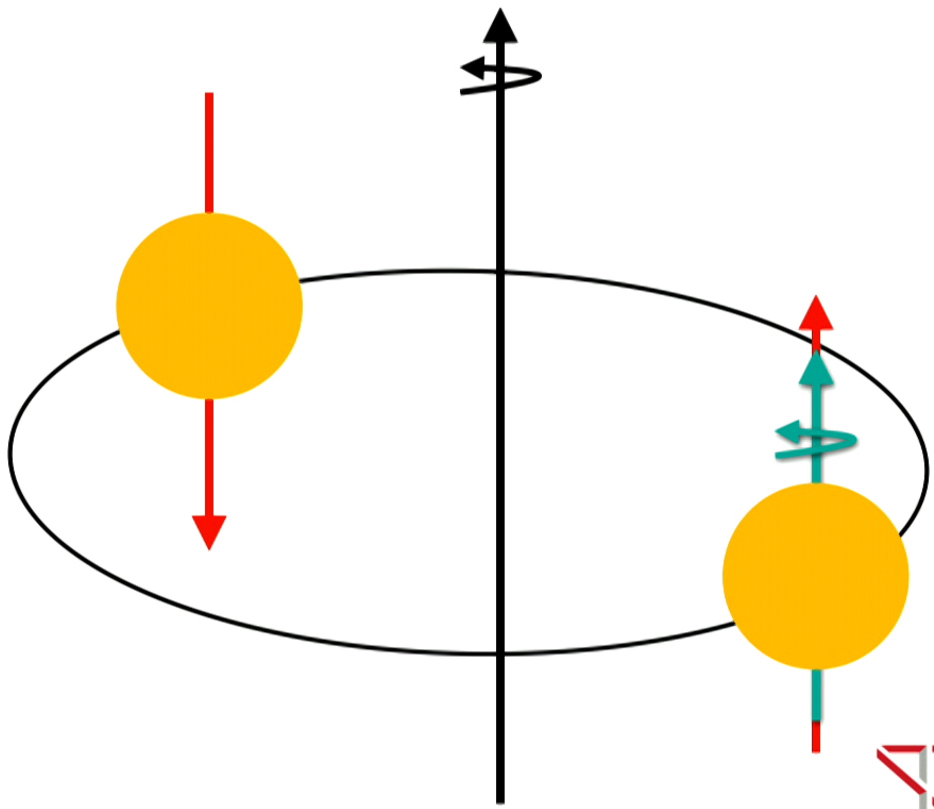
35m resolution
on 12,000 cores
computed with GReX



Most+ (in prep)

- Kelvin-Helmholtz instability can amplify the magnetic field strength by several orders of magnitude
- No convergence observed in numerical simulations. Need resolutions < 1m.

Electromagnetic precursors
Adding the right twist



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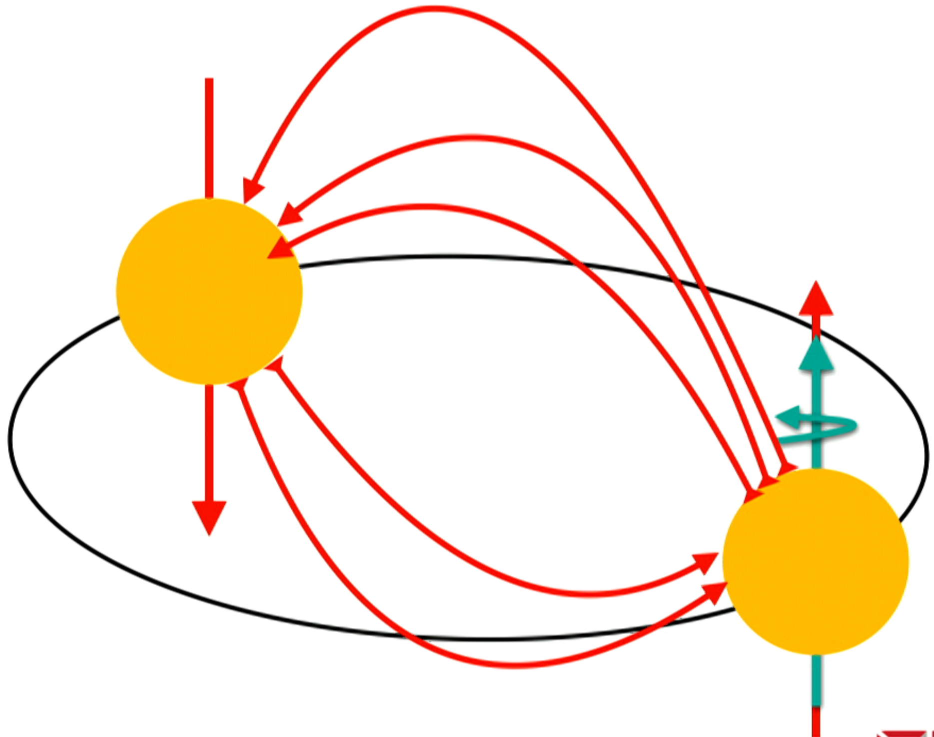
Electromagnetic precursors

Adding the right twist



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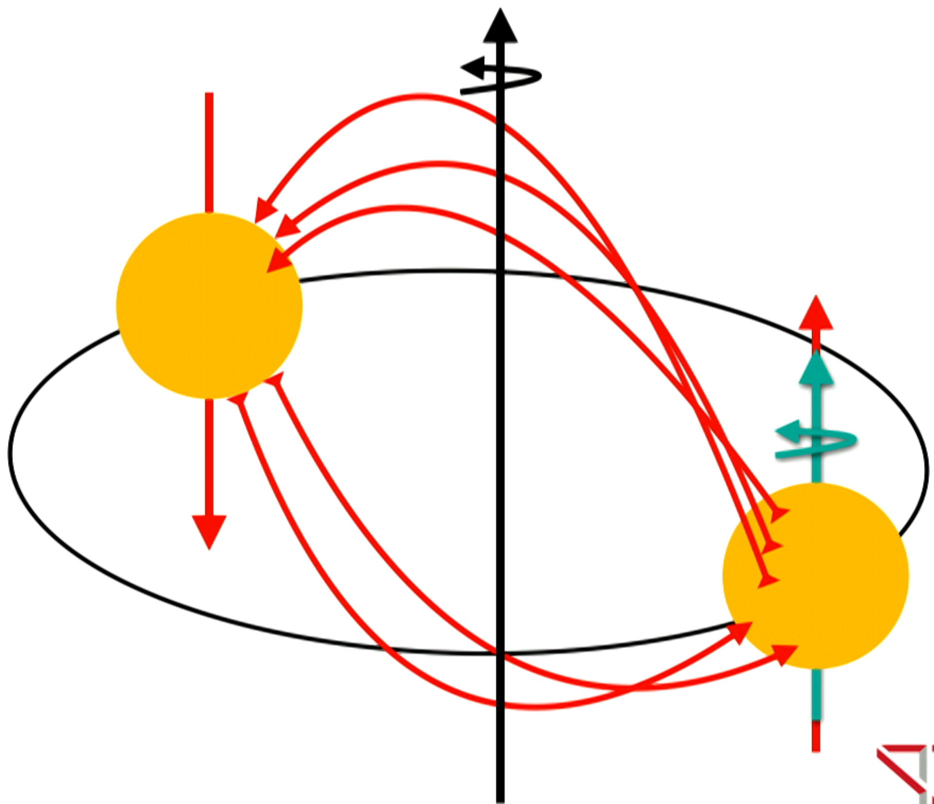

Electromagnetic precursors

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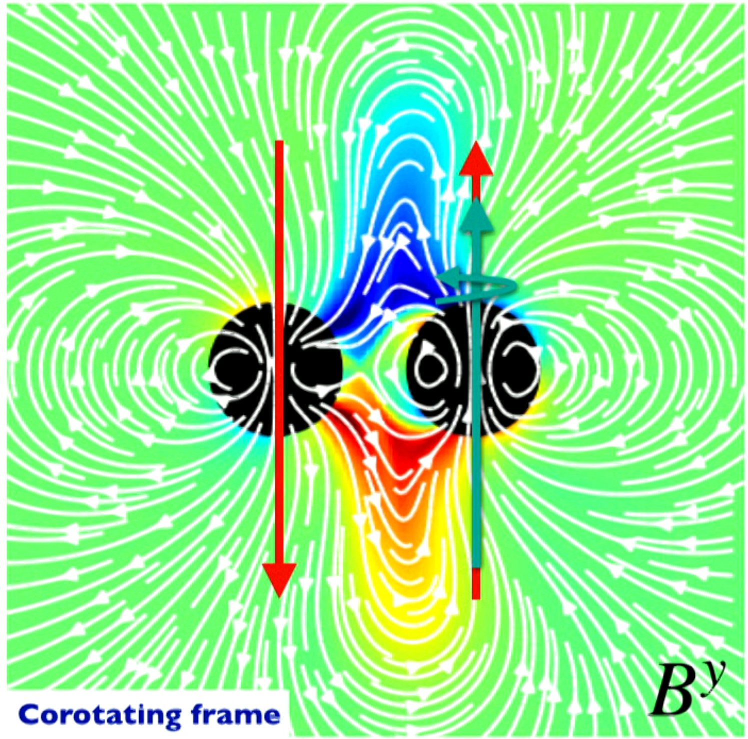

ERM+ (in prep)

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Electromagnetic precursors

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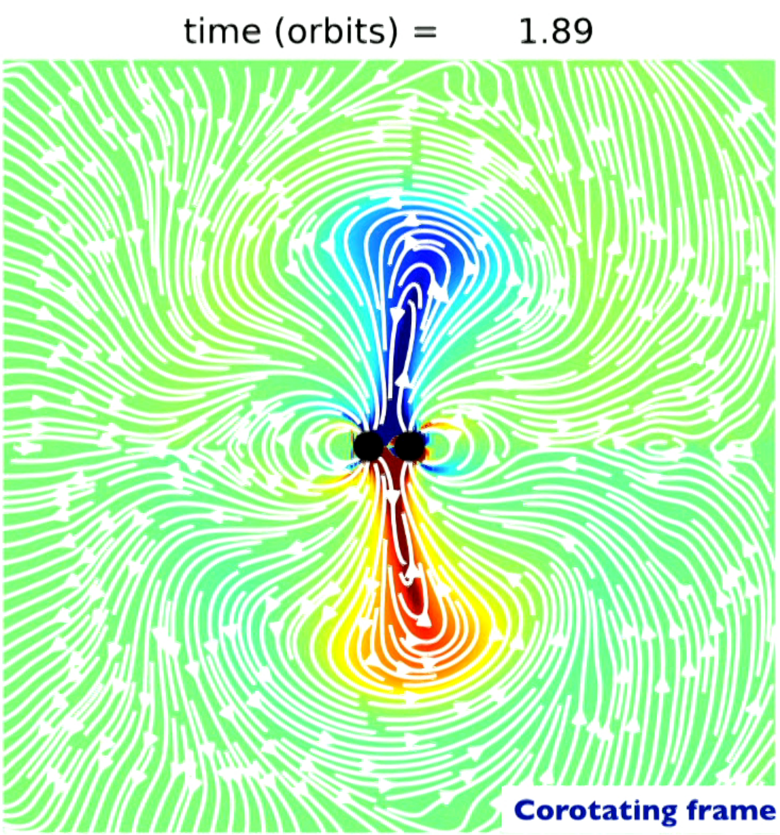

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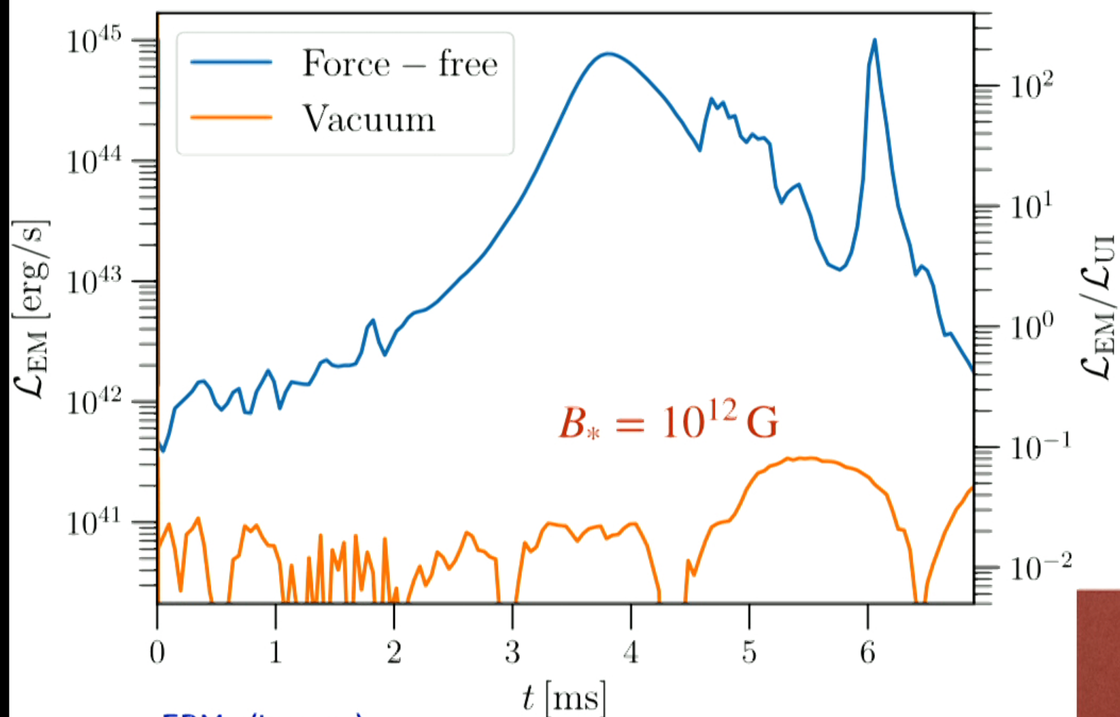
Properties of the fireball

PRELIMINARY



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Enhance luminosity by $\zeta_\phi \simeq 100$

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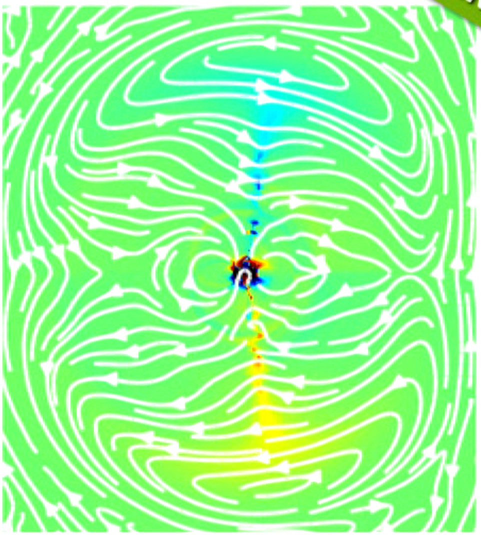

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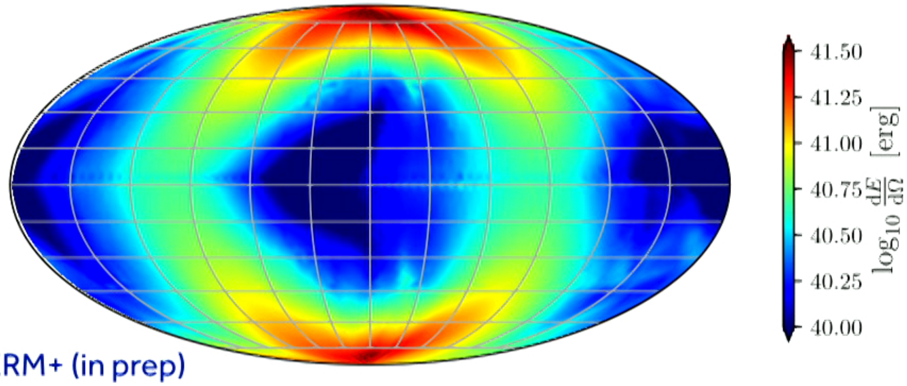

ERM+ (in prep)

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How much energy can we dissipate?

PRELIMINARY

- Estimate upper limit of the available energy by computing dissipation in the current sheet

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\left(\mathbf{E}^2+\mathbf{B}^2\right)\right)+\nabla\cdot(\mathbf{E}\times\mathbf{B})=\mathscr{L}_{\rm diss}$$

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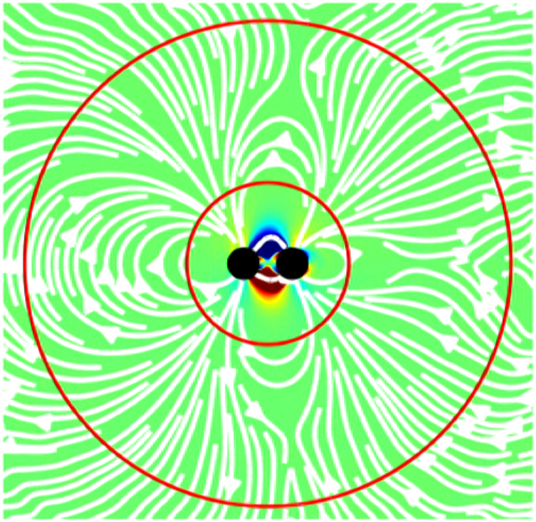

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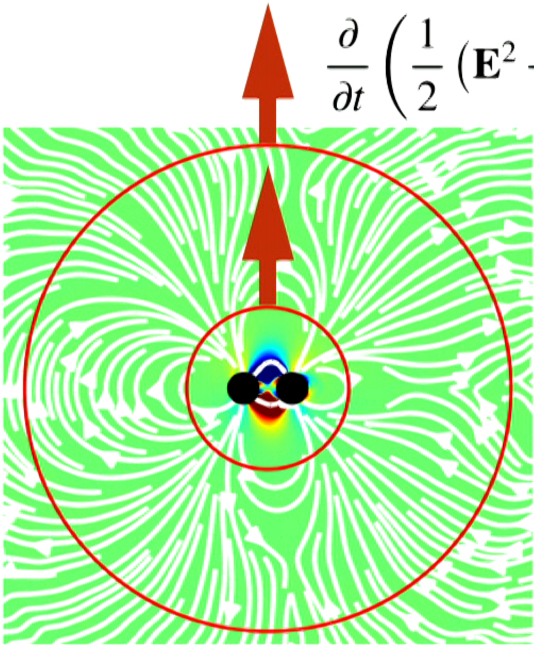

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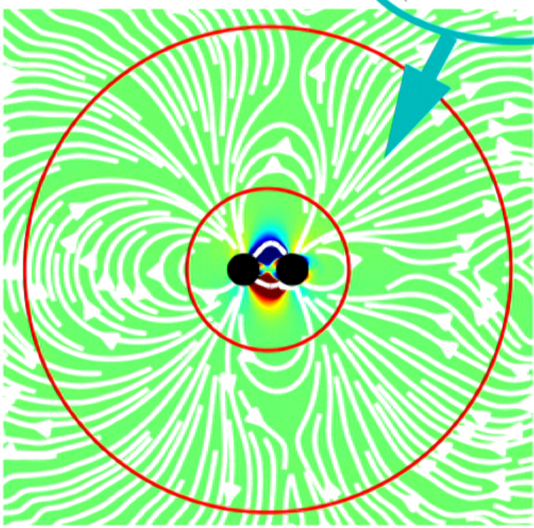

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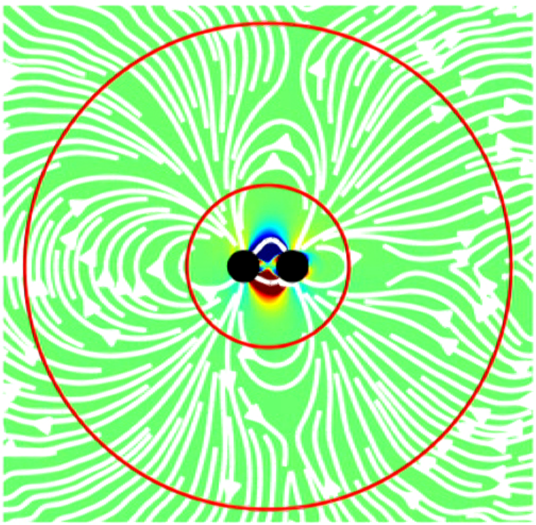

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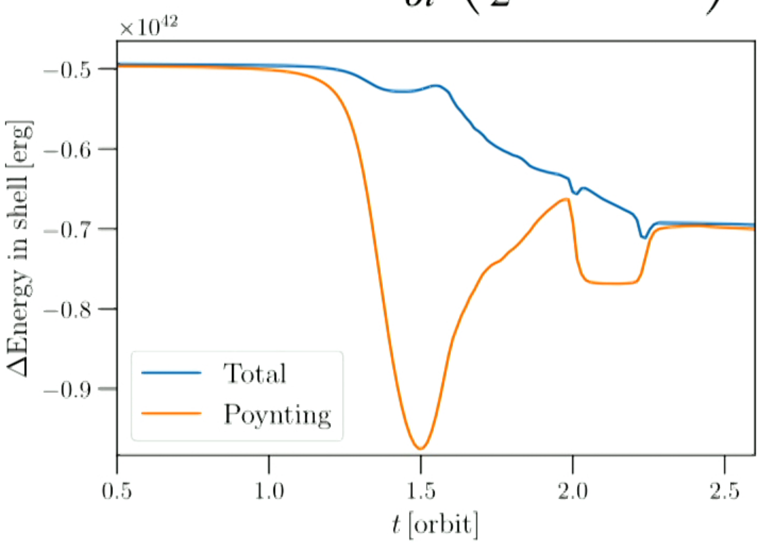

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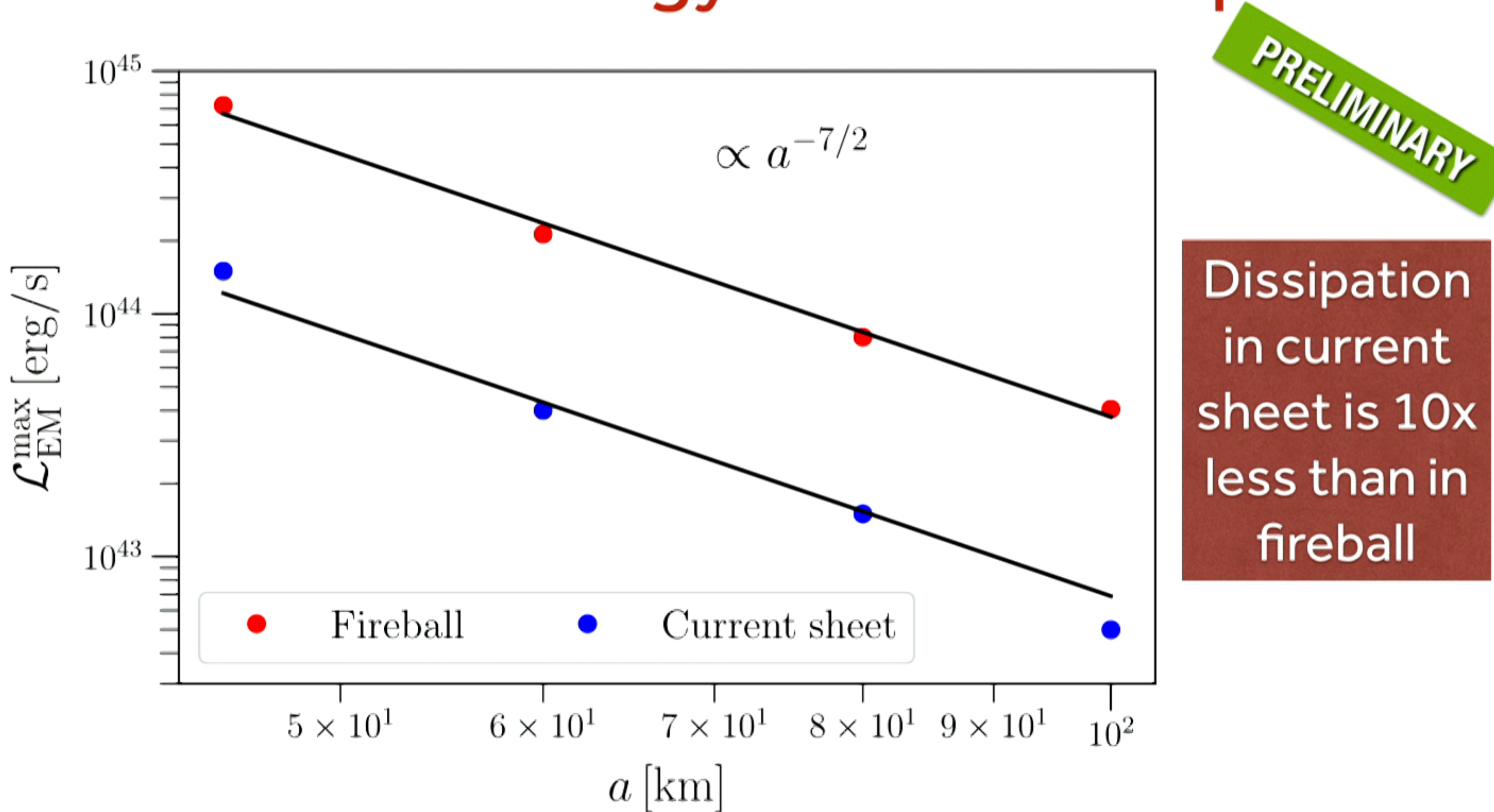

Dissipation in current sheet is 10x less than in fireball

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- Caveat: Scaling at small separation will be modified by inspiral

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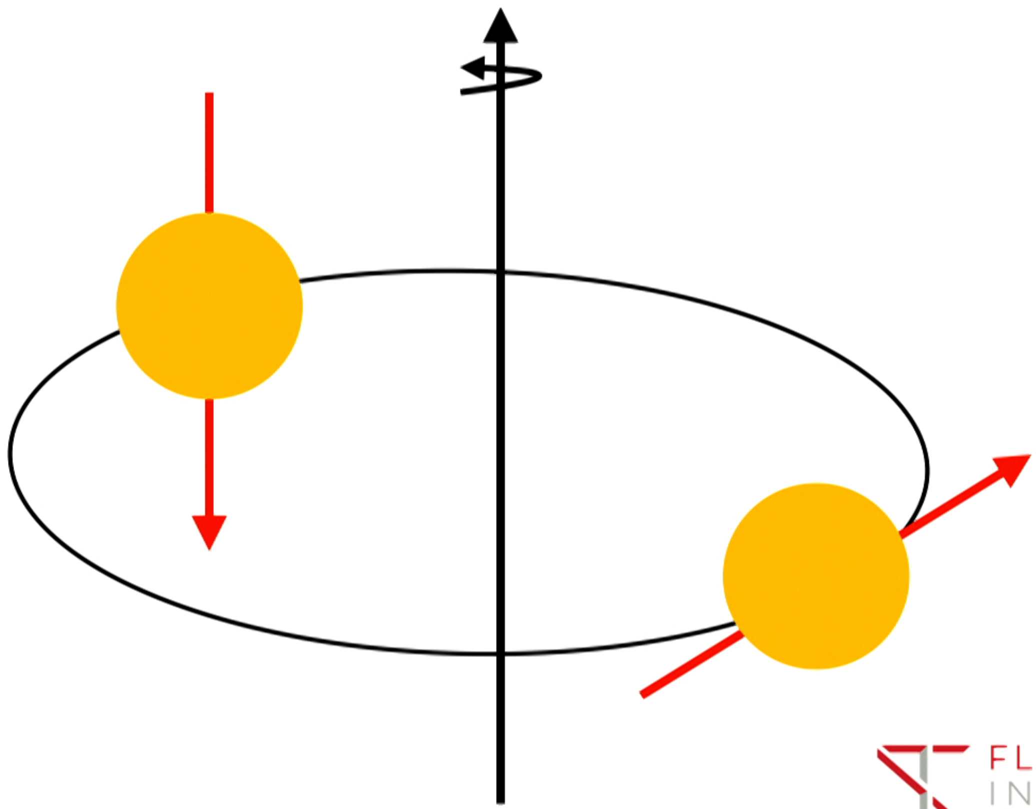
Electromagnetic precursors
Towards the generic case



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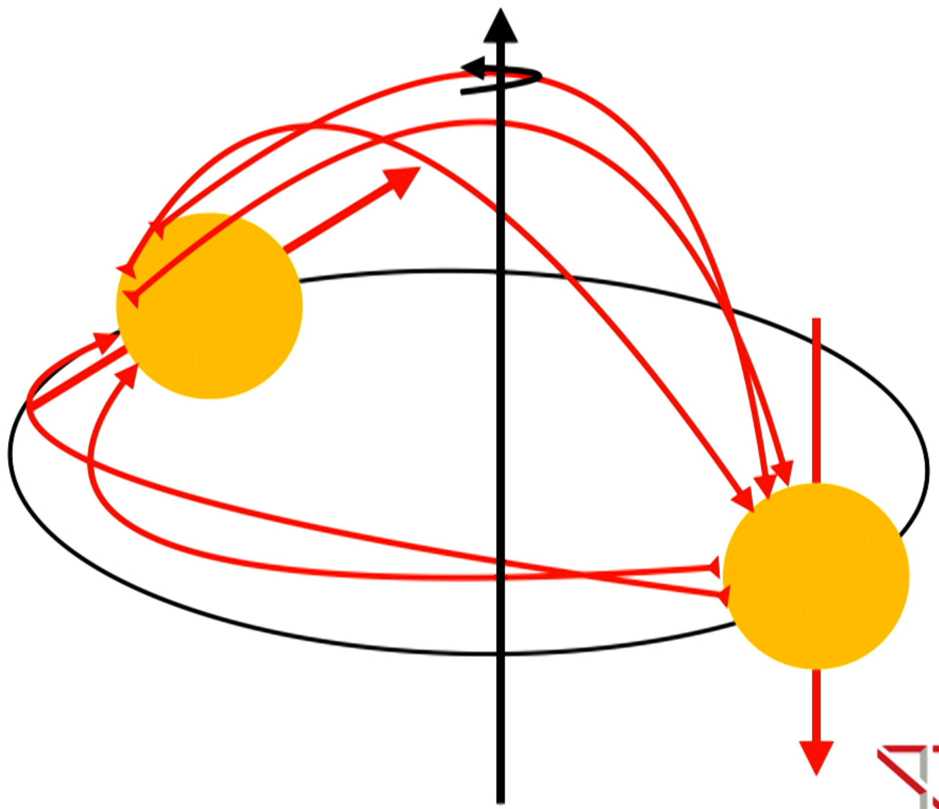

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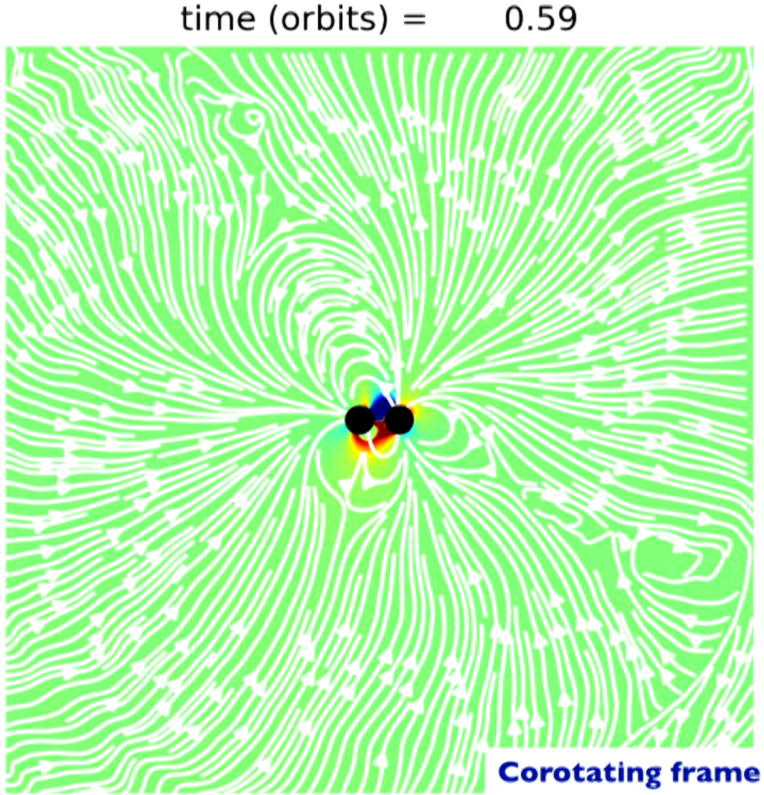

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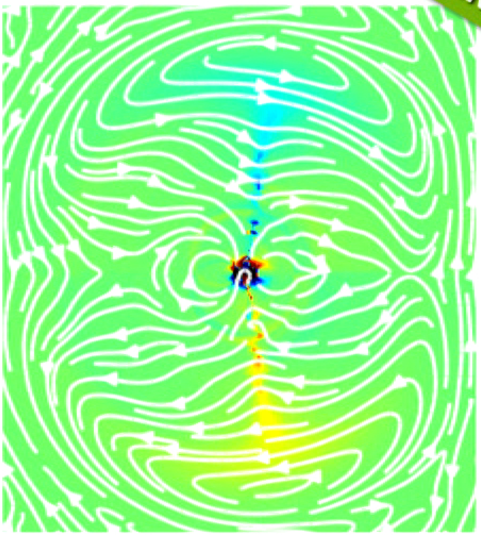

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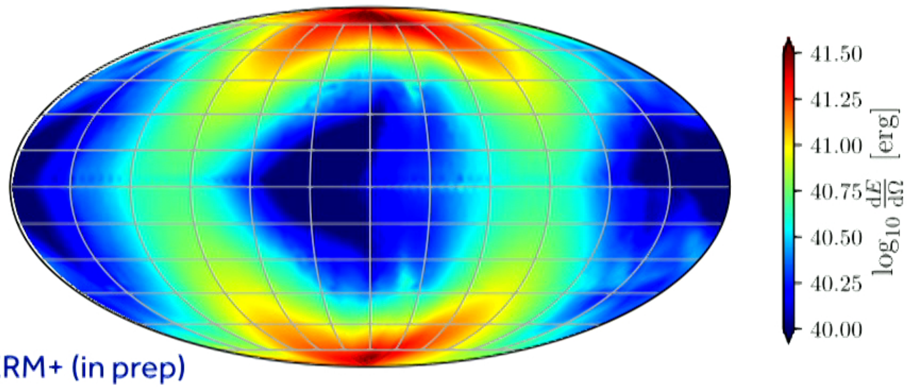

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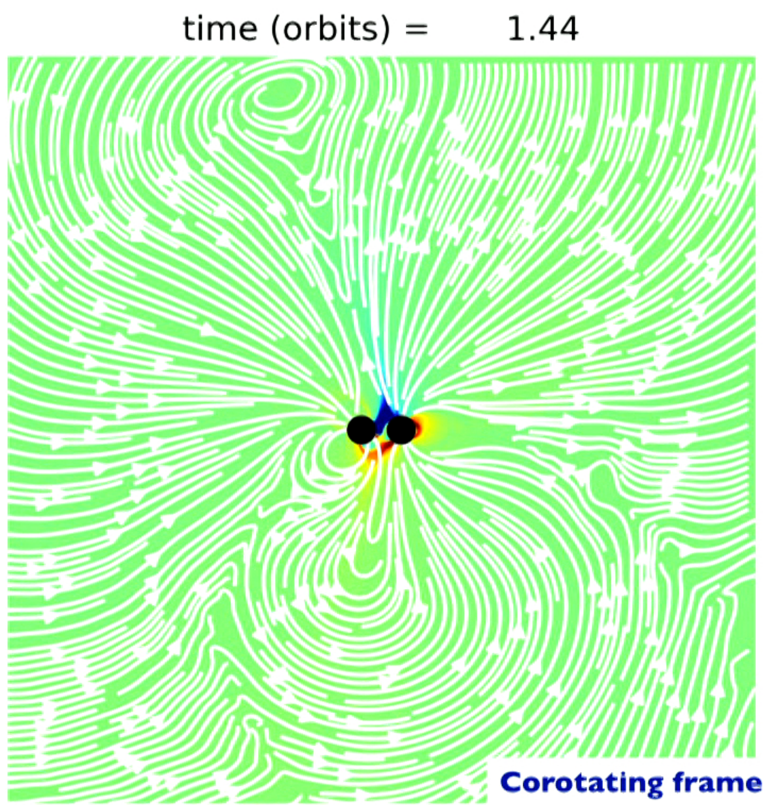
PRELIMINARY



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