Double-Neutron-Star Origins:
The Interplay of Strong Gravity, Nuclear Microphysics, and Macroscopic Astrophysics

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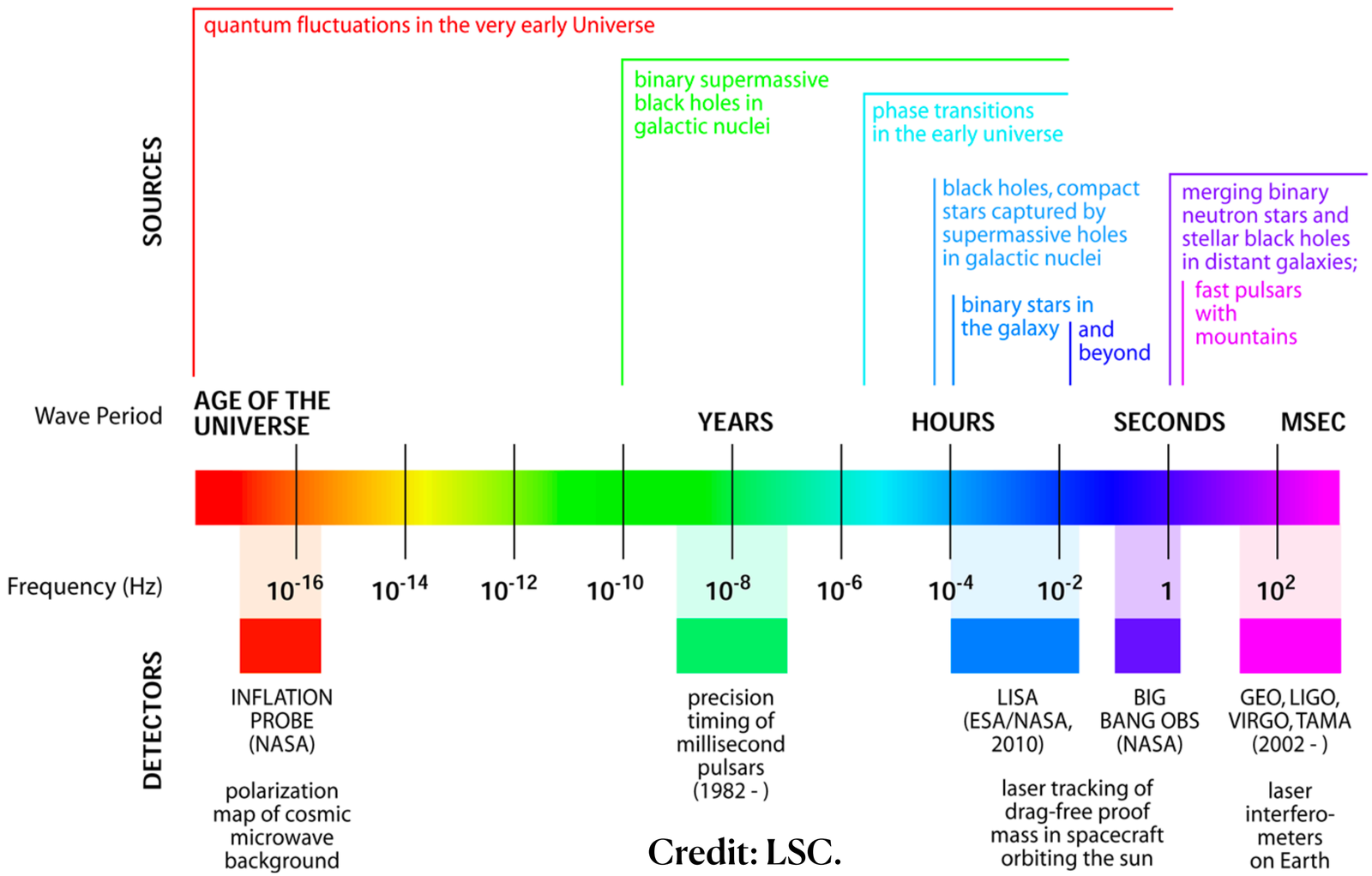
Gravitational waves: spacetime ripples that allow us to probe the Universe in an entirely new way.

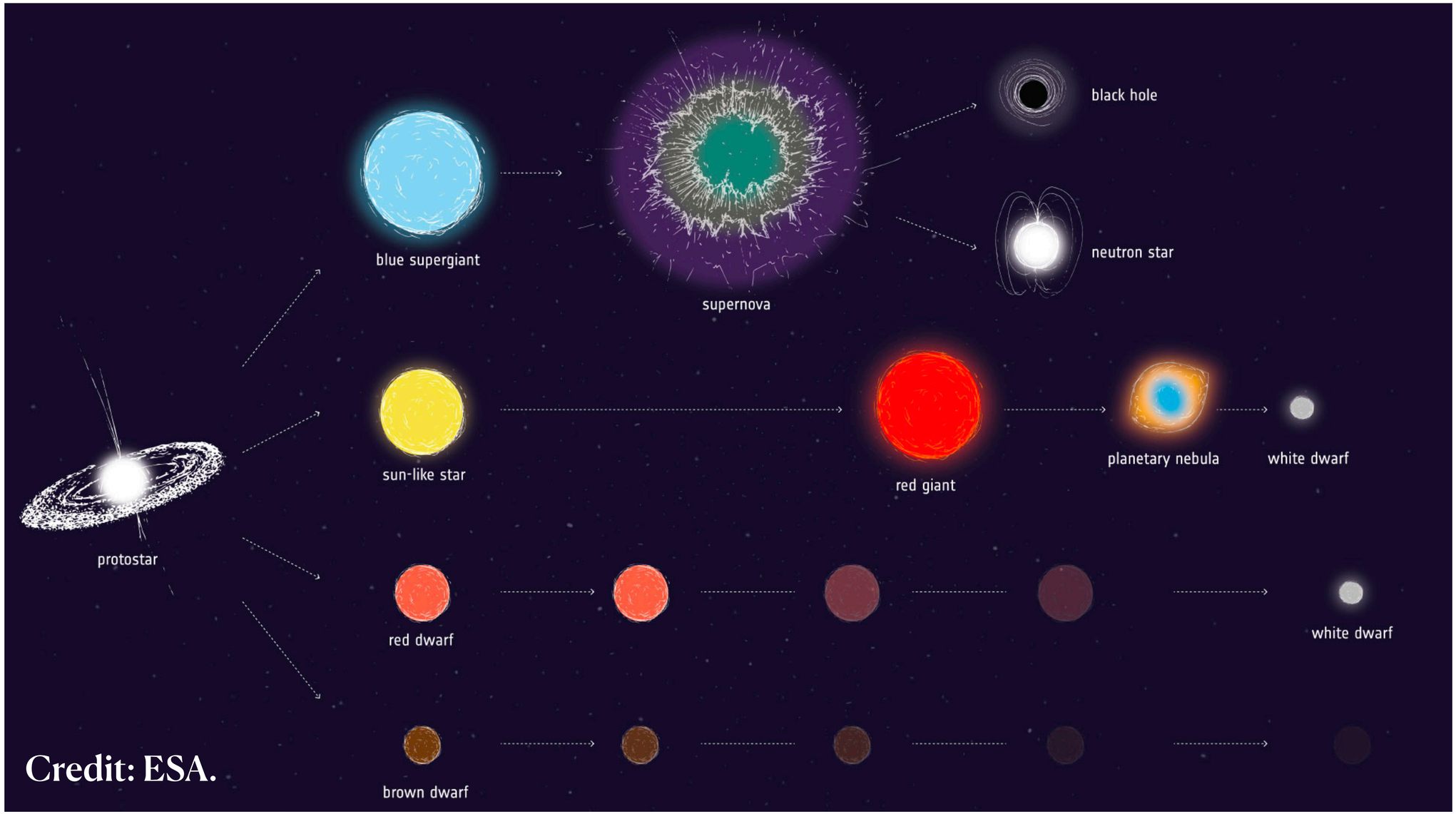
- Stellar astrophysics
- Gravitational physics
- Nuclear physics
- Particle physics
- Cosmology
- Galaxy evolution

The Gravitational-Wave Spectrum:



Credit: LSC.

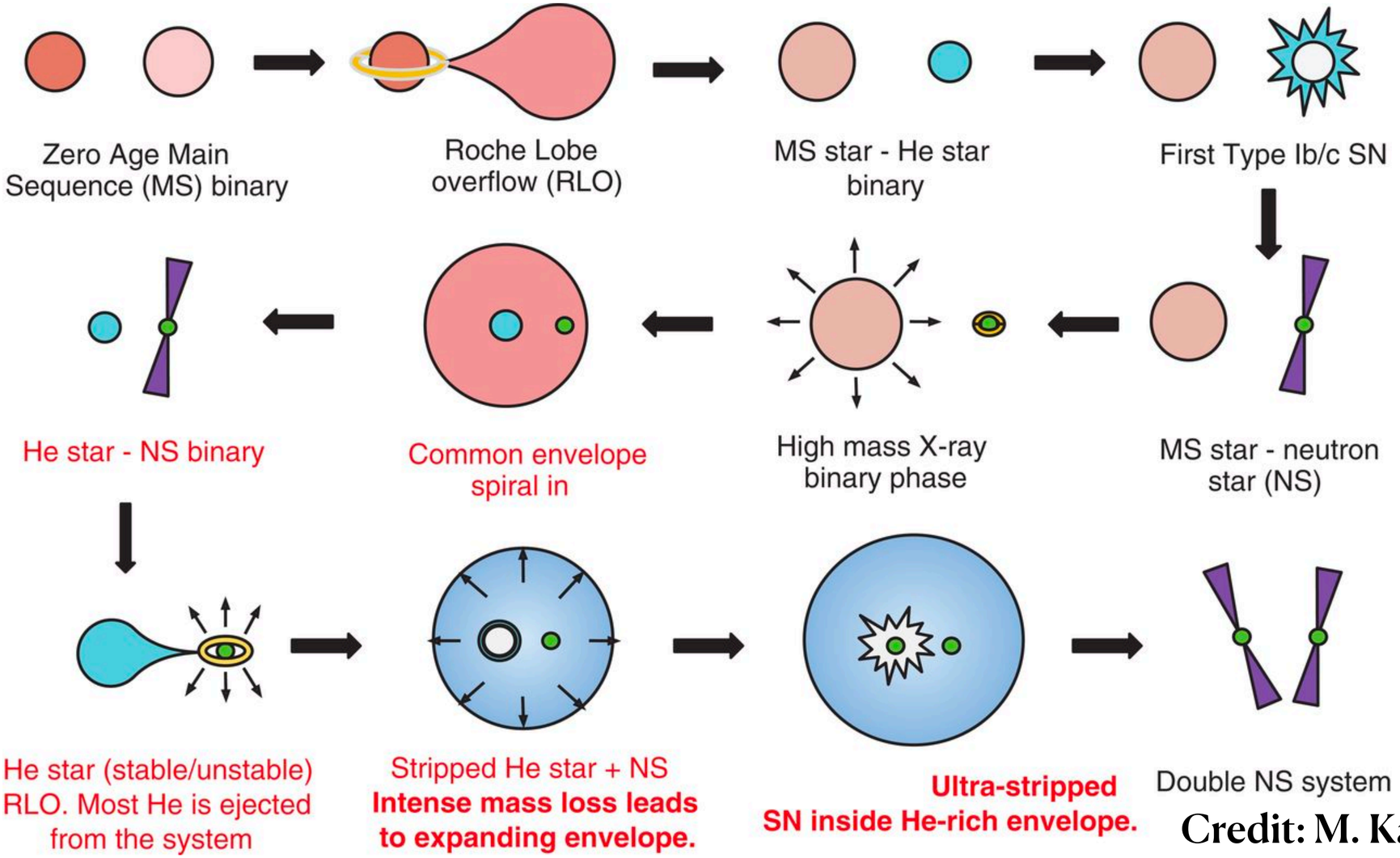
How do such gravitational-wave sources form? Stellar-mass black holes and neutron stars arise from the deaths of massive stars.



Credit: ESA.

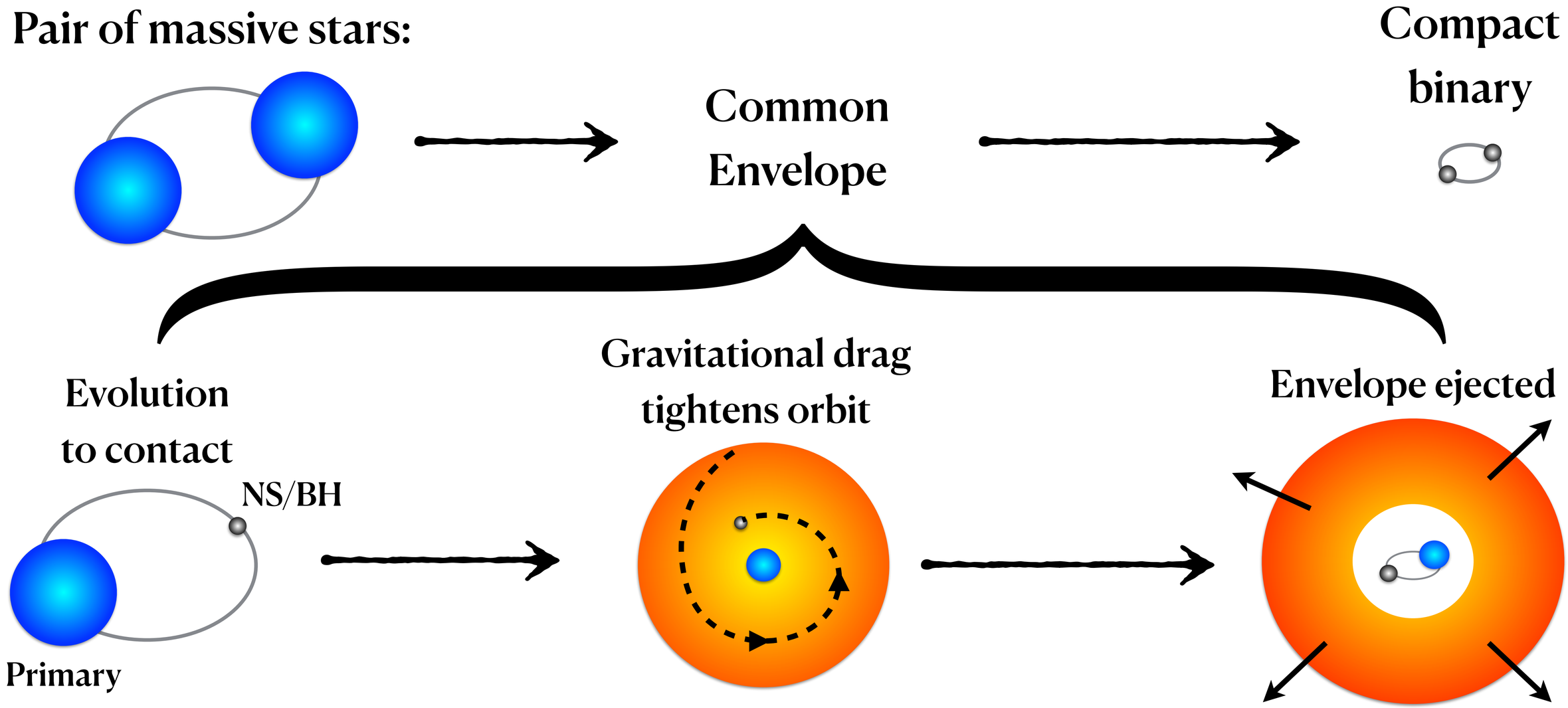
Gravity is weak at large separations. Binary interactions are essential for forming double NSs that merge within the age of the Universe.

Isolated binary formation channel for double NSs:



Credit: M. Kasliwal.

Common-envelope evolution: orbital decay driven by gravitational drag. If the envelope is successfully ejected, a compact binary eventually forms.



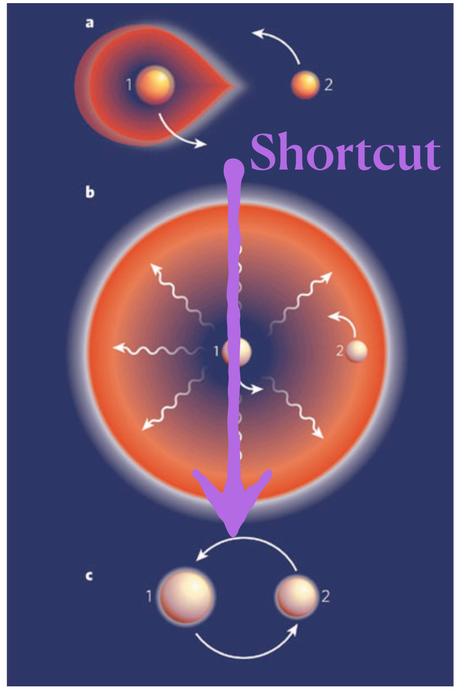
Various approaches have been used to model common-envelope evolution. Population studies often use the analytic model.

Model complexity →

Analytic model:

$\alpha \Delta E_{orb}$ goes into envelope ejection

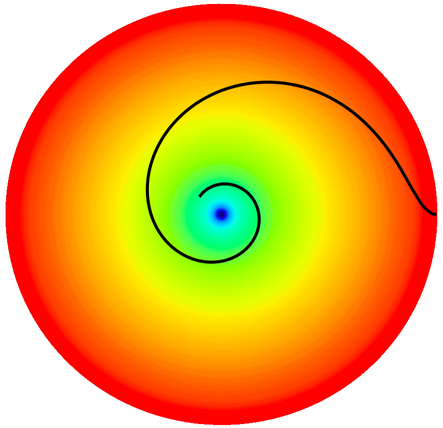
(e.g., Webbink 1984).



Semi-analytic model:

Inspiral driven by local drag forces.

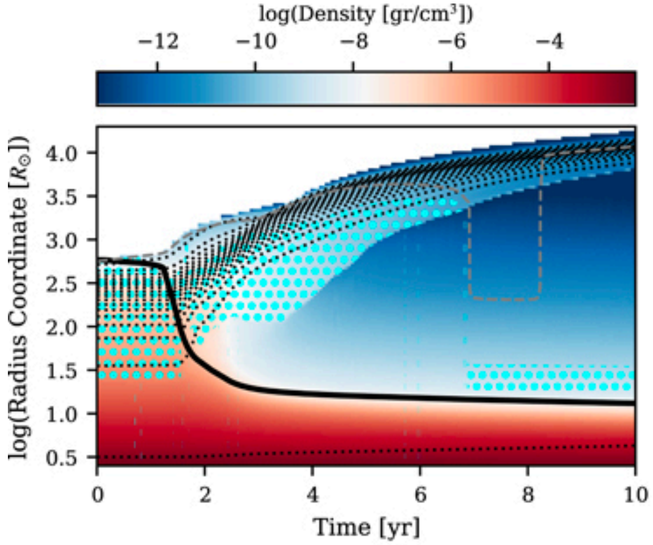
Static envelope assumed:



e.g., MacLeod & Ramirez-Ruiz 2015, AMH+ 2018, 2021.

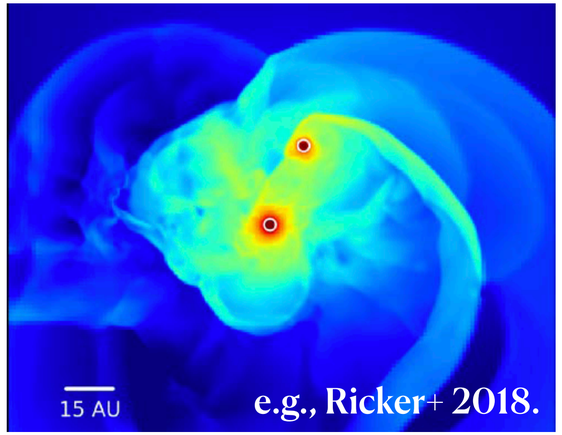
Radiation hydro in 1D:

Envelope back-reaction from NS inspiral:



Fragos+ 2019.

Radiation hydro in 3D:



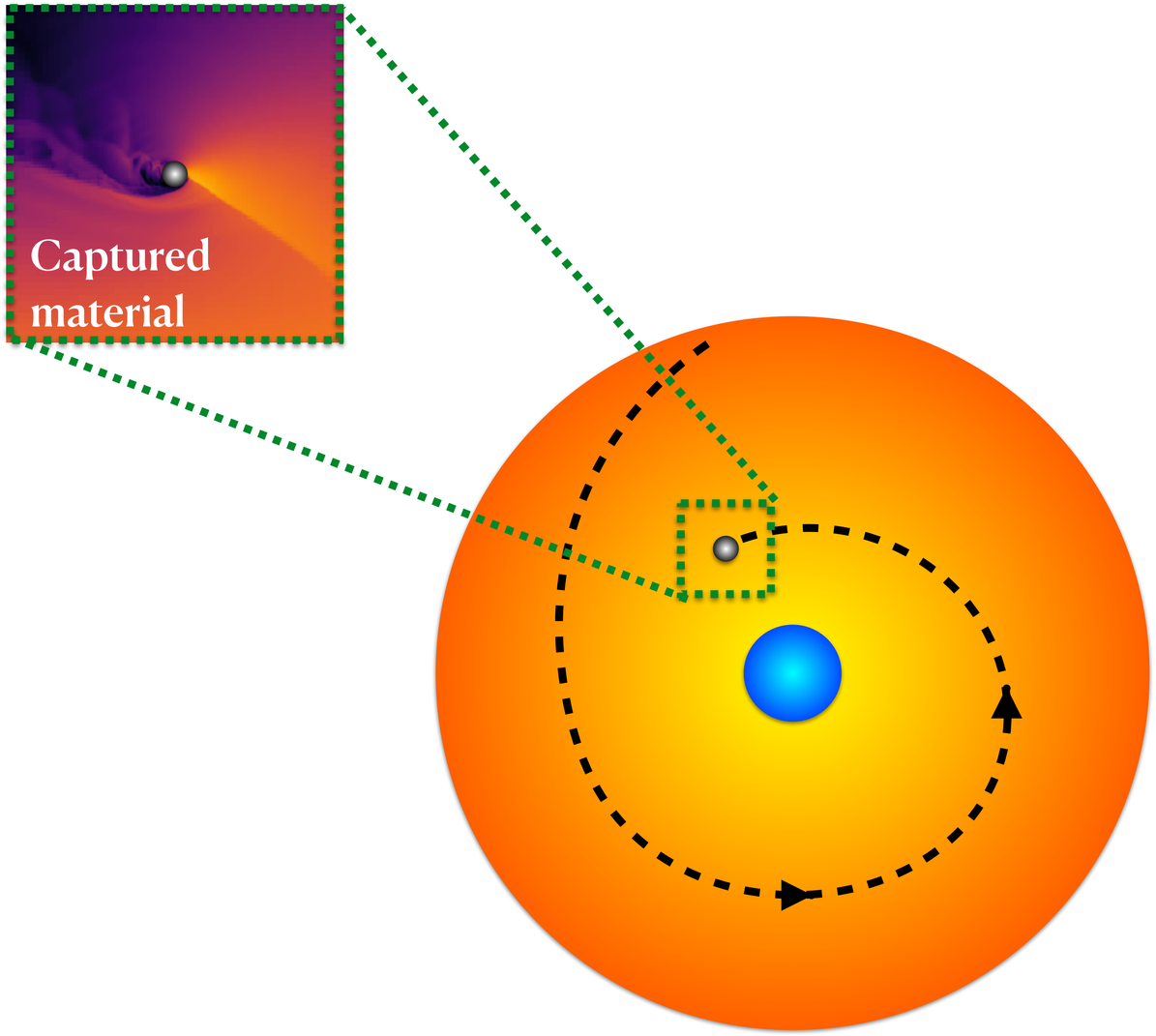
See also Law-Smith+ 2021.

Towards multiscale multiphysics:

- Recombination energy
- Radiation transport
- Sub-grid feedback

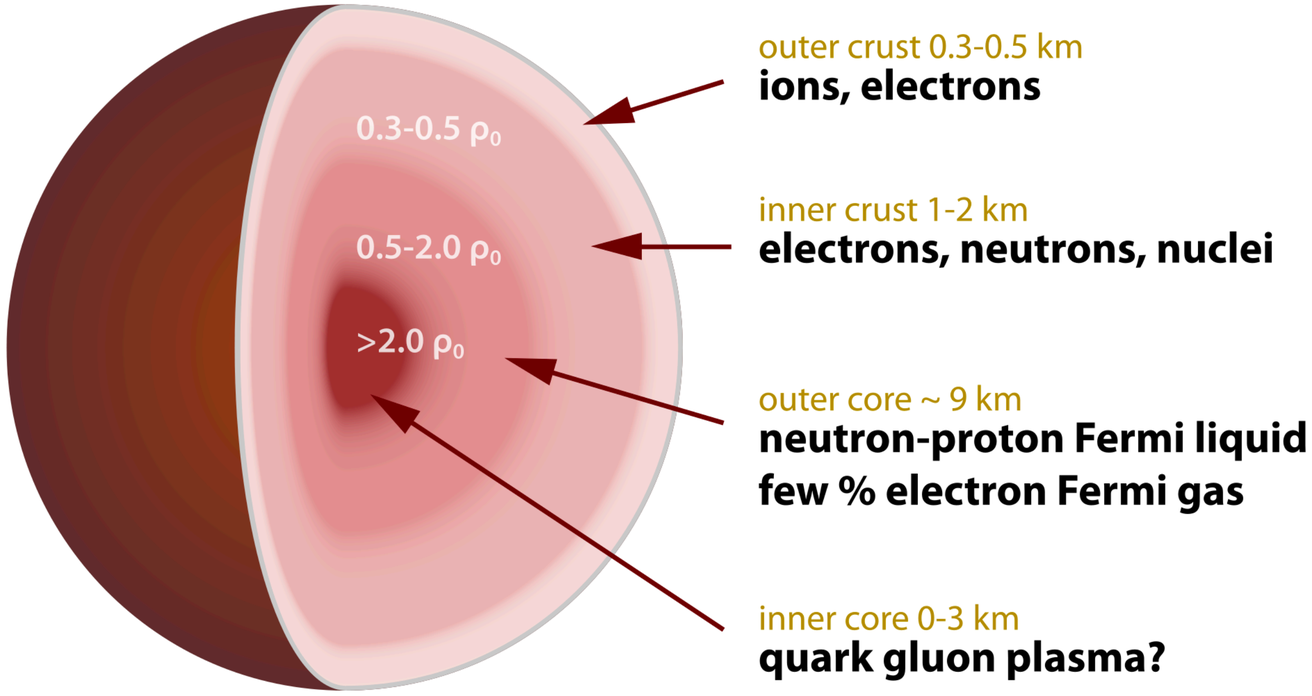
What happens to neutron stars that undergo common-envelope evolution?

- Neutron stars don't accrete enough material to exceed their maximum mass (MacLeod & Ramirez-Ruiz 2015).
- How do neutron-star properties and thus its equation of state (EoS) affect how it accretes?
- Since neutron stars are compact, they have substantial binding energy.



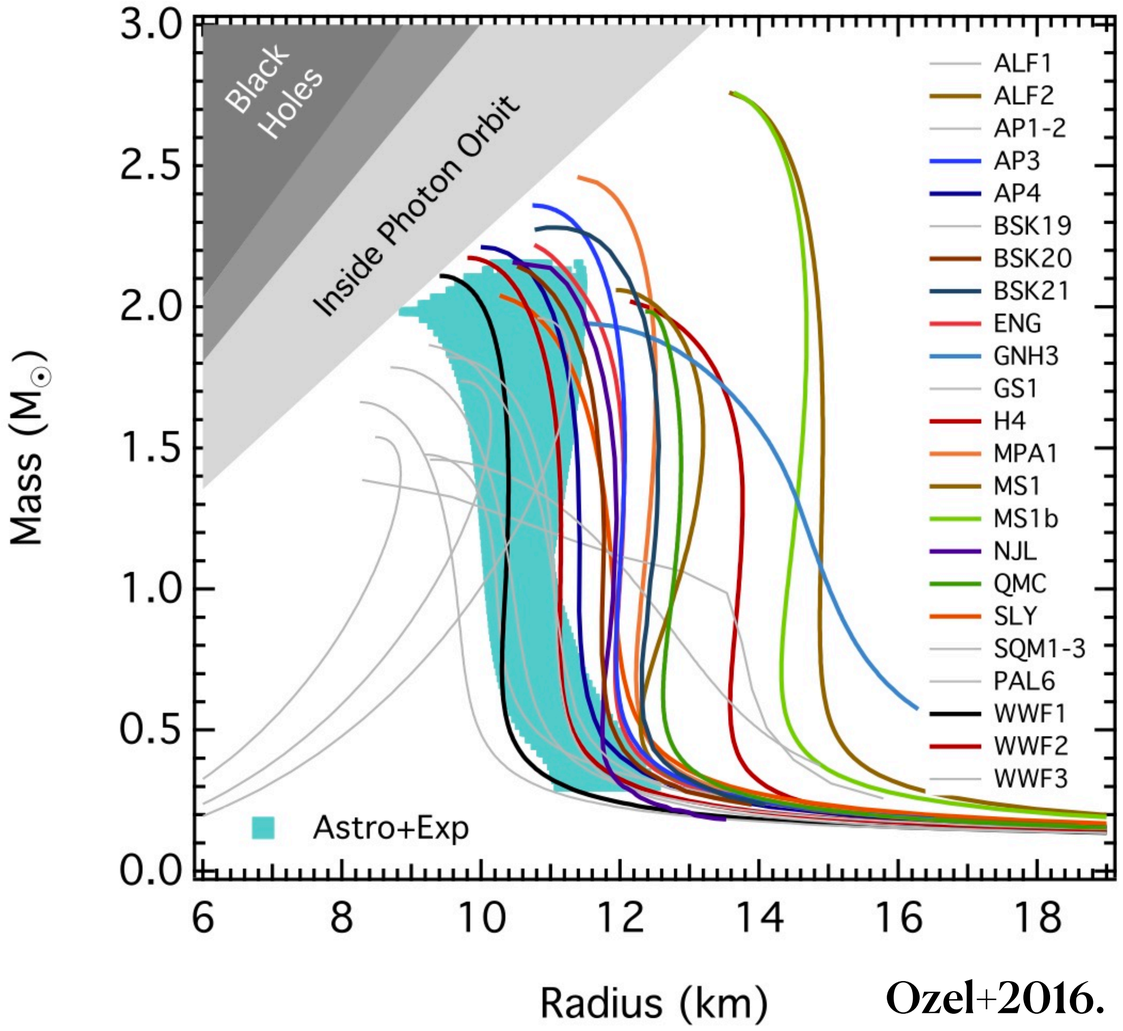
The NS interior can achieve supra-nuclear densities. The dense-matter equation of state determines NS macroscopic properties.

NS interior:



Credit: R. Schulze.

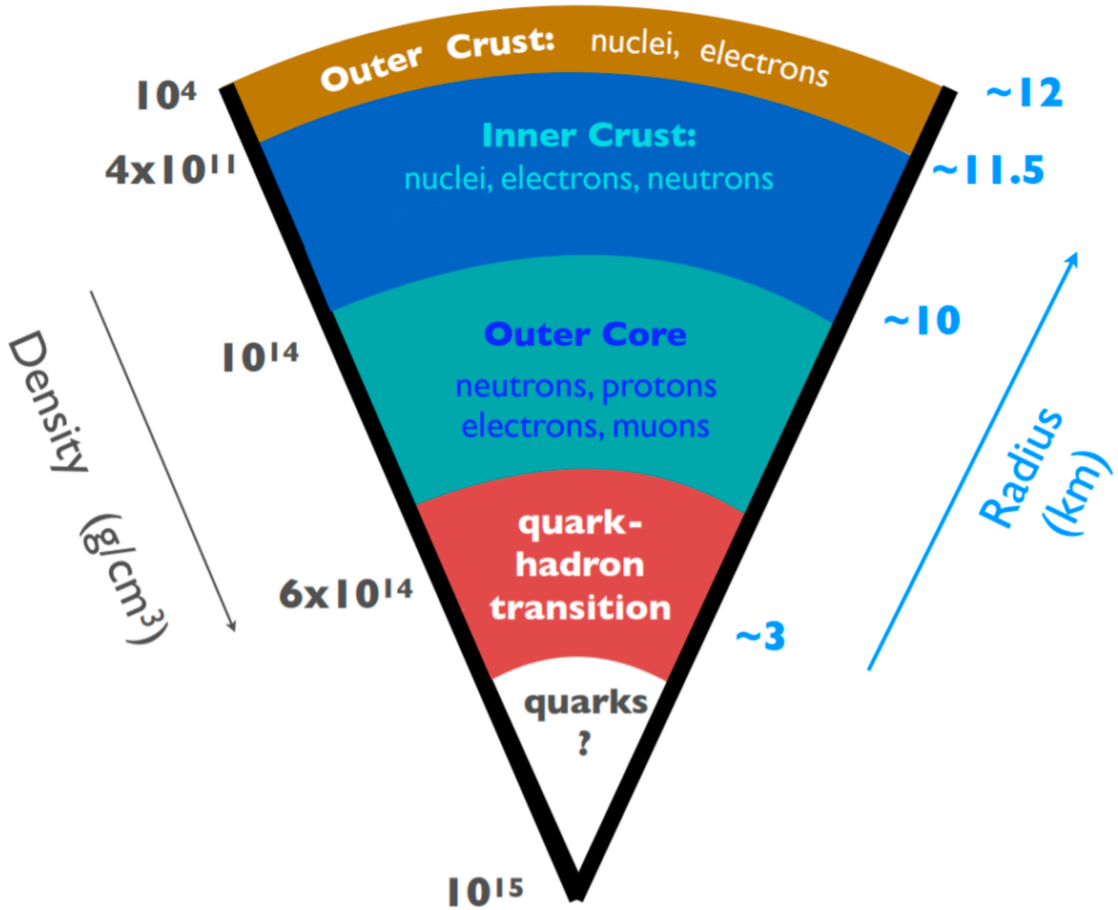
Mass-radius curves with different EoSs.



Ozel+2016.

NSs have substantial binding energy, i.e., ~10% of the total mass-energy budget.

NS interior structure:



e.g., Maggiore+ 2020.

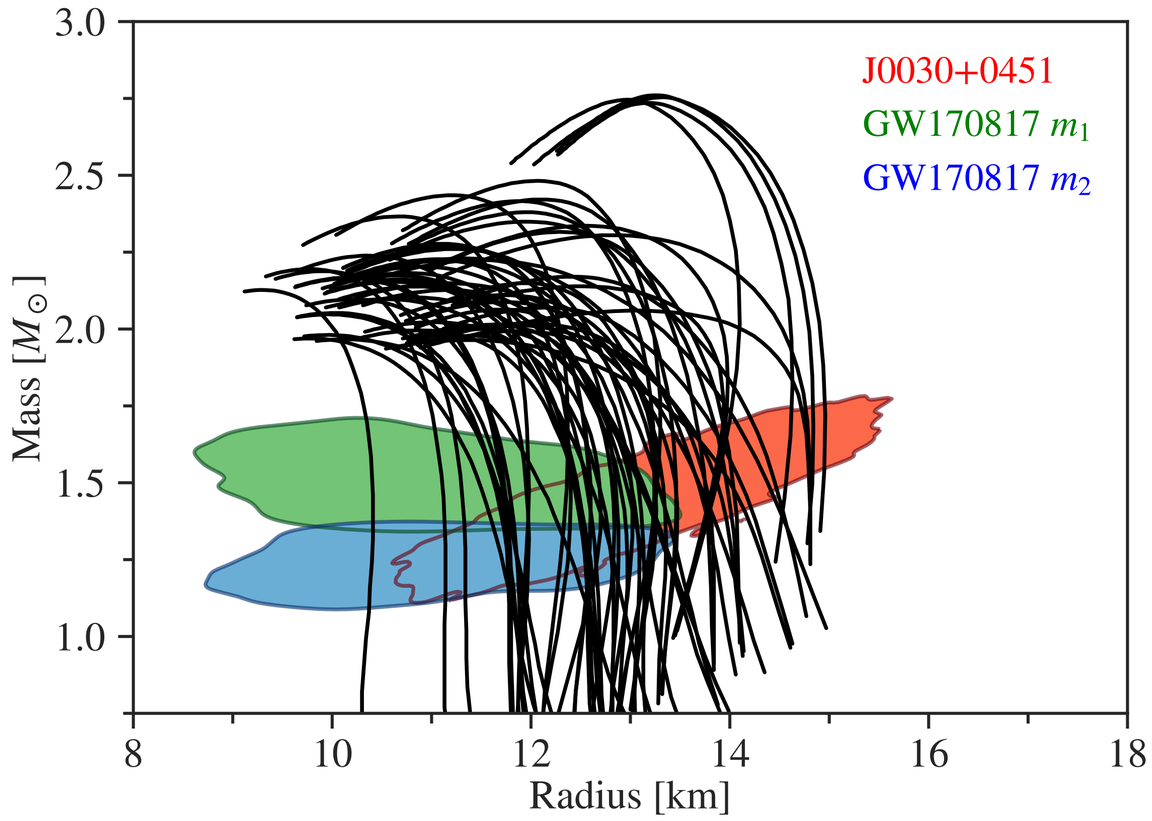
Analogy: atomic nucleus

Neutron star:

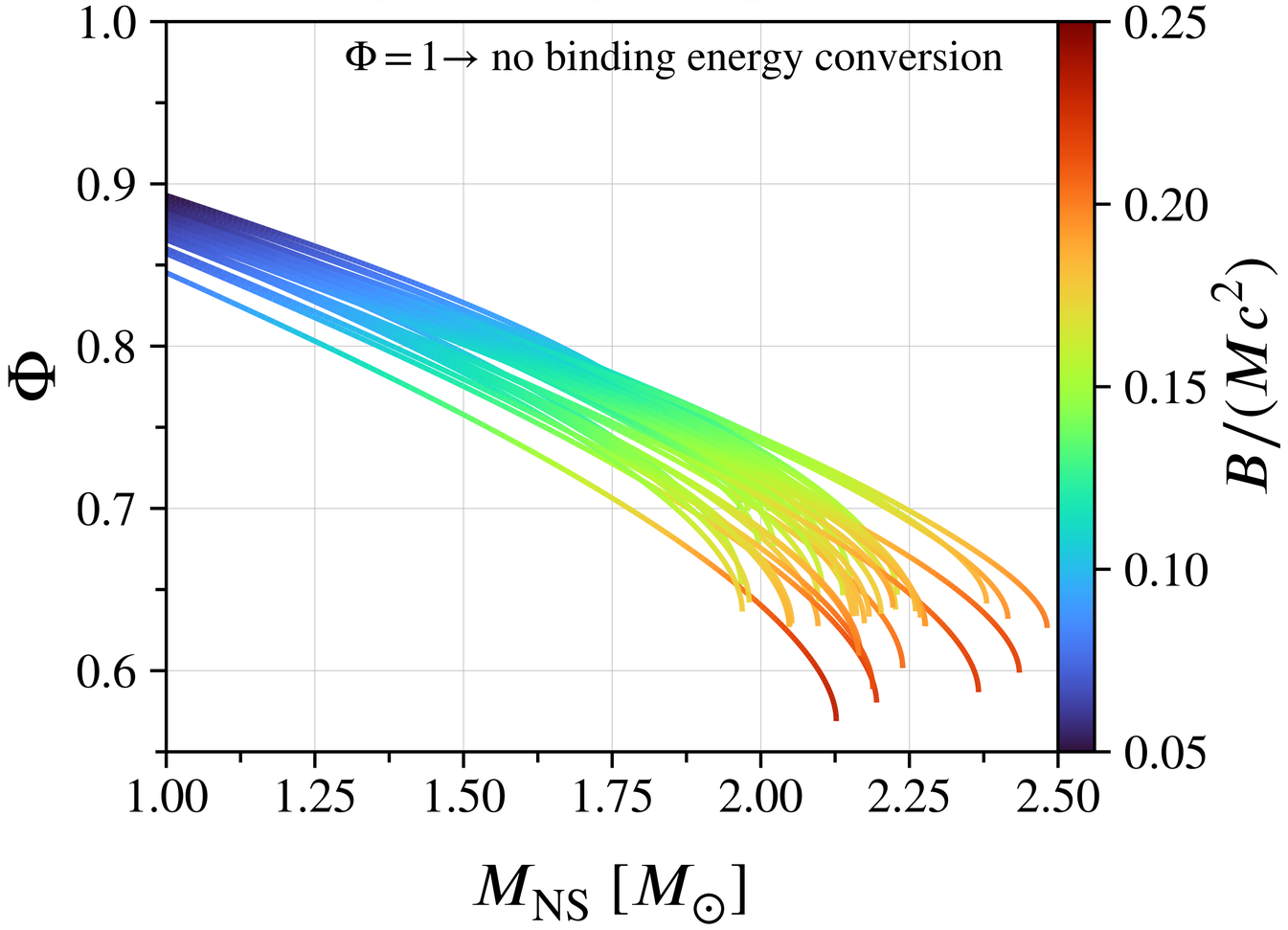
Gravitational mass + | Binding energy | = Total baryonic mass

Some fraction of what a NS accretes gets converted into binding energy instead of gravitational mass.

Mass-radius curves with different EoSs.

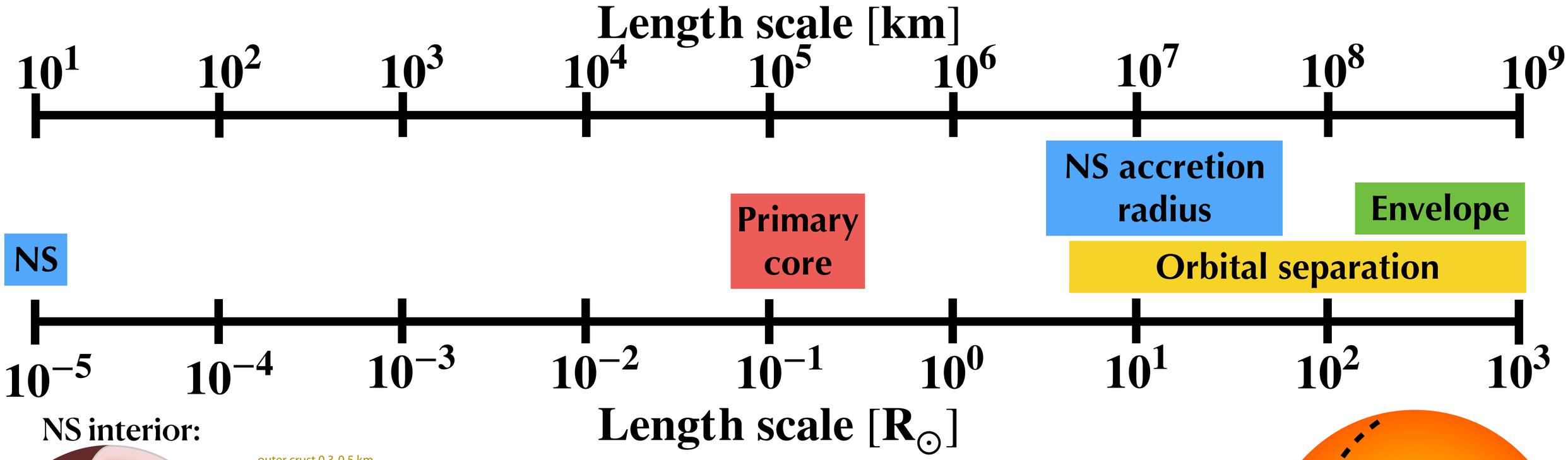


Gravitochemical potential vs. gravitational mass for different EoSs.

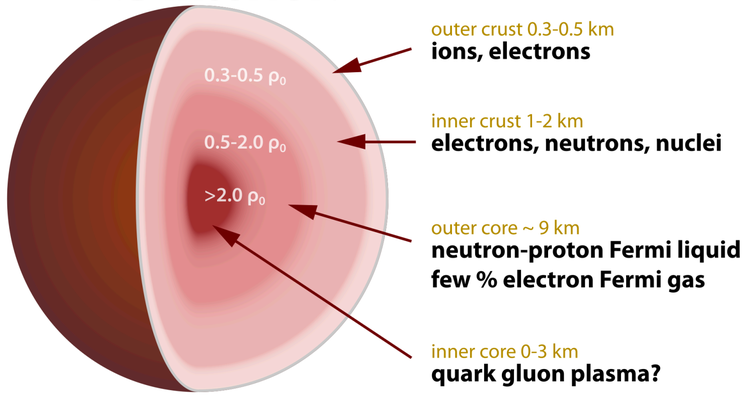


AMH, Silva, Ricker, & Yunes+ 2021.

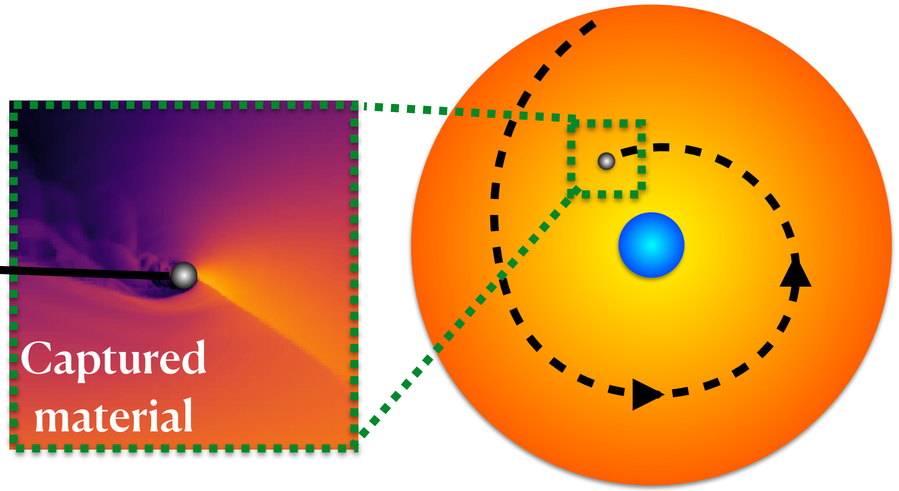
Common-envelope inspiral is a multiscale multiphysics problem. We evolve a NS using semi-analytic models at different length scales.



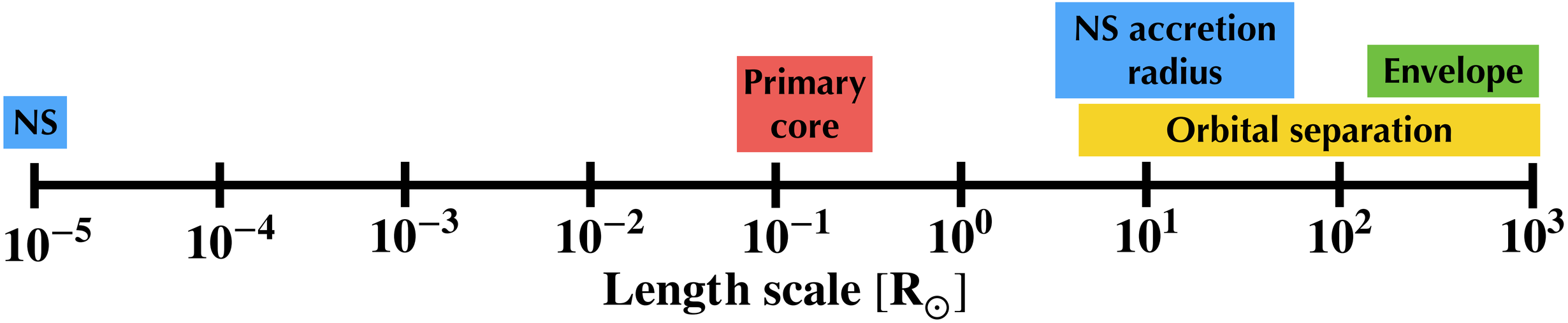
NS interior:



Credit: R. Schulze.



Models for the primary massive star, NS inspiral, baryonic-mass accretion, gravitational-mass gain, and spin-up:



Stellar properties: Generate primary massive-star models with MESA + Generate tables of NS properties for each EoS

Orbit integration and NS evolution:

Common-envelope NS inspiral via local drag forces + Compute baryonic mass accretion + Compute NS gravitational mass gain and spin-up

$$\dot{E}_{\rm orb} = -F_{\rm drag} v_{\rm orb}$$

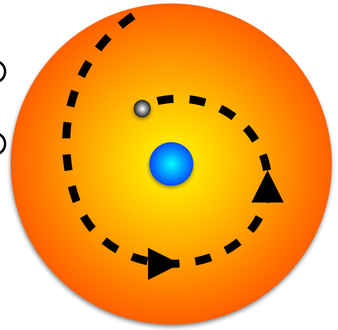
$$\dot{M}_{\rm b} = \dot{M}_{\rm b}(\mathcal{M}, q, R_{\rm sink})$$

$$\dot{M}_{\rm NS} = \Phi \dot{M}_{\rm b} + \frac{\Omega}{c^2}\dot{J}$$

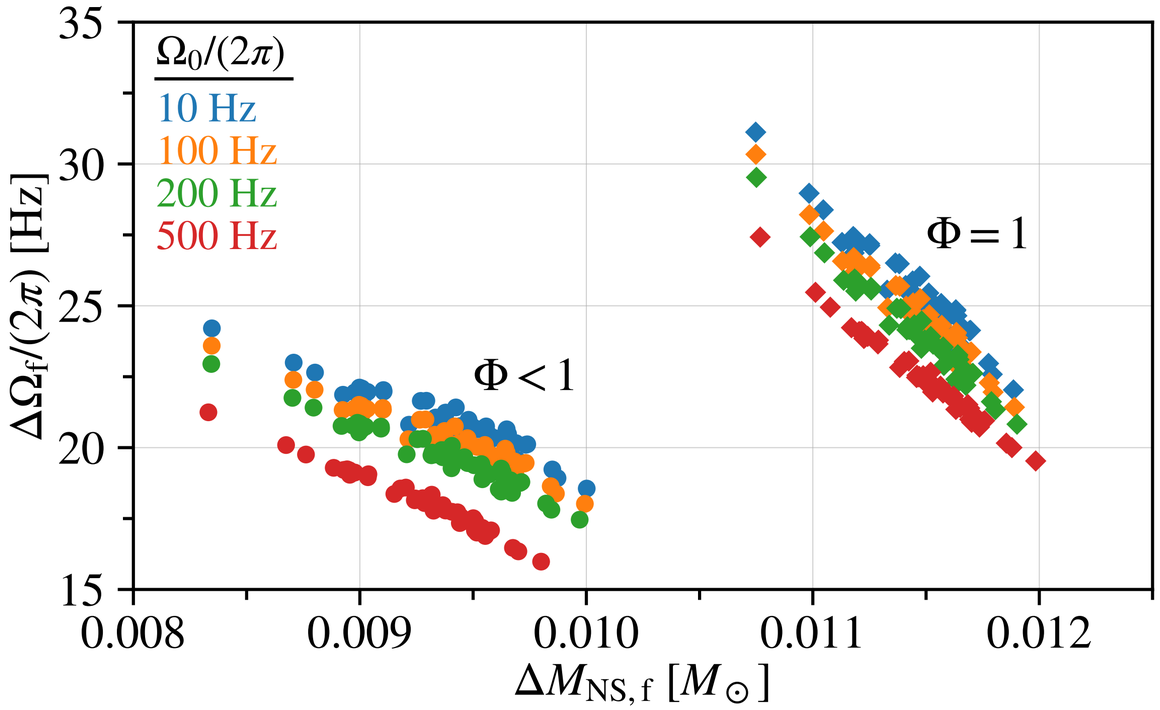
NSs with smaller radii spin-up faster and gain less gravitational mass. More massive NSs gain less gravitational mass.

$M_\star = 12 M_\odot$

$M_{\rm NS,0} = 1.4 M_\odot$

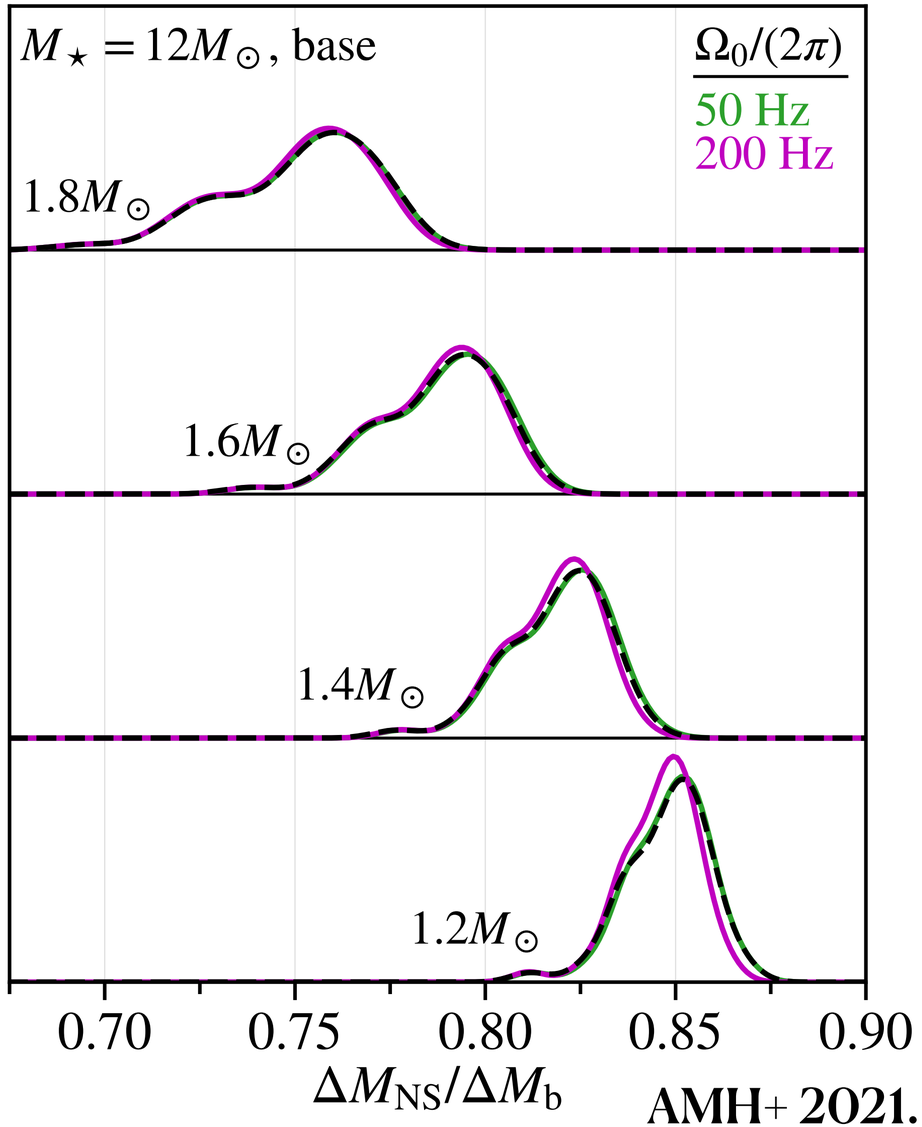


Final spin-up



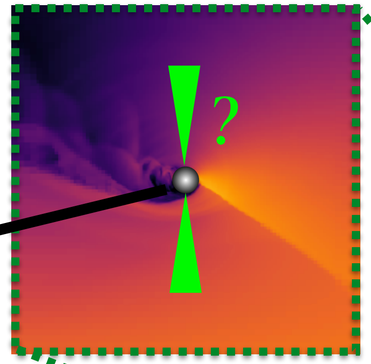
Final mass gain

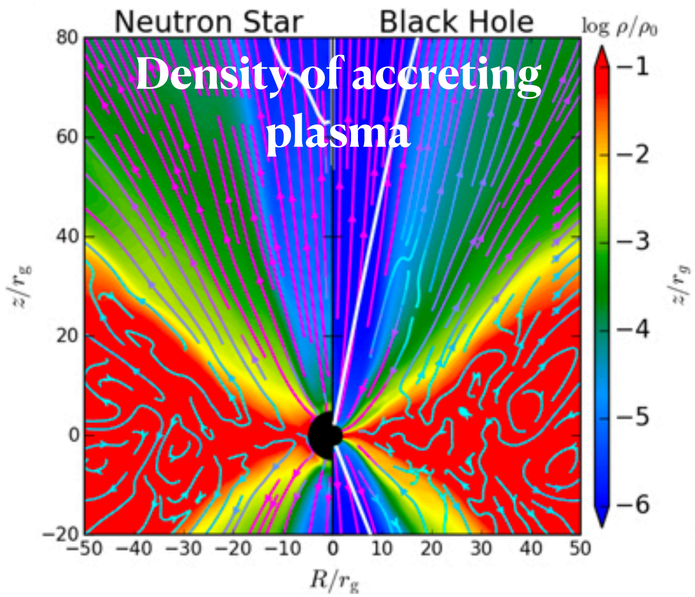
Ratio distributions of gravitational mass gain to accreted baryonic mass:

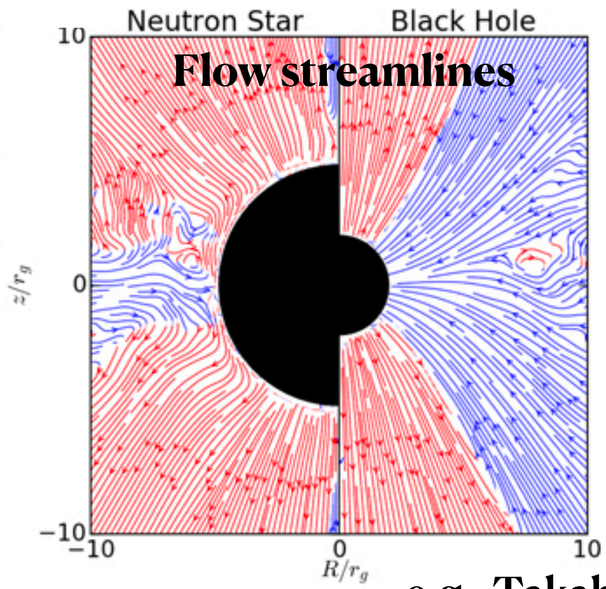


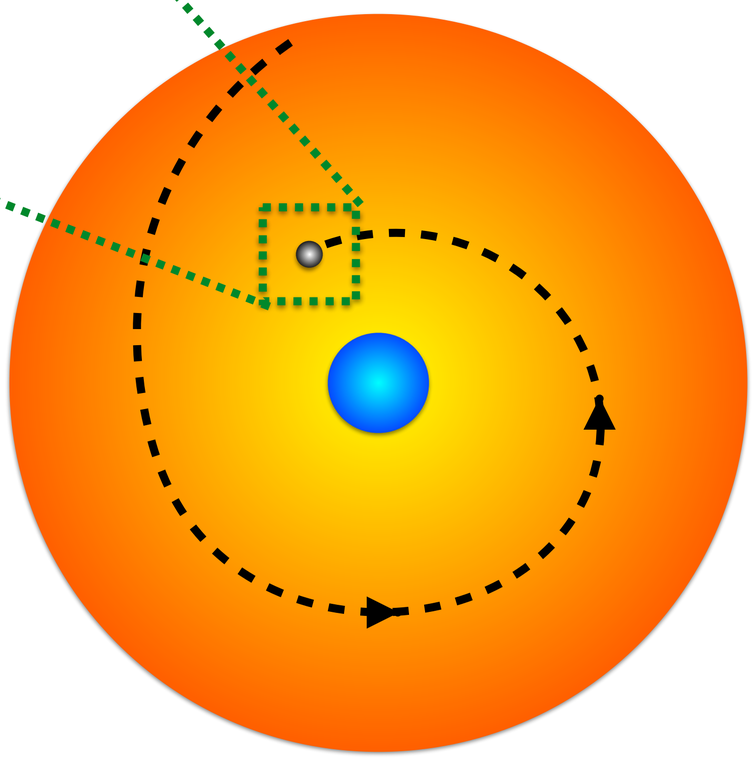
AMH+ 2021.

Is there feedback? Accretion onto a compact object may result in outflows. Would such outflows aid in envelope ejection?









e.g., Takahasi+ 2018.

Double Neutron Star Origins: The Interplay of Strong Gravity, Nuclear Microphysics, and Macroscopic Astrophysics.

- Gravitational waves from merging compact binaries can provide new insights on astrophysics, gravitational physics, nuclear physics, particle physics, etc.
- Because gravity is weak at large separations, macroscopic astrophysical interactions are necessary to form compact binaries.
- Neutron stars have substantial binding energy and thus gain less gravitational mass than what they accrete.
- Strong gravity and nuclear microphysics may affect the population properties of double neutron stars and the rate at which they merge across the Universe.

Acknowledgments:

- DOE NNSA and Krell Institute
- Collaborators:

  P. Anninos, A. Cárdenas-Avendaño, Y. Chen, D. Cruz, J. Goldstein, H. Guo, K. Herrera, E. Huerta, W. Liao, X. Liu, P. Ricker, A. Sesana, H. Silva, N. Yunes, and many others.

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