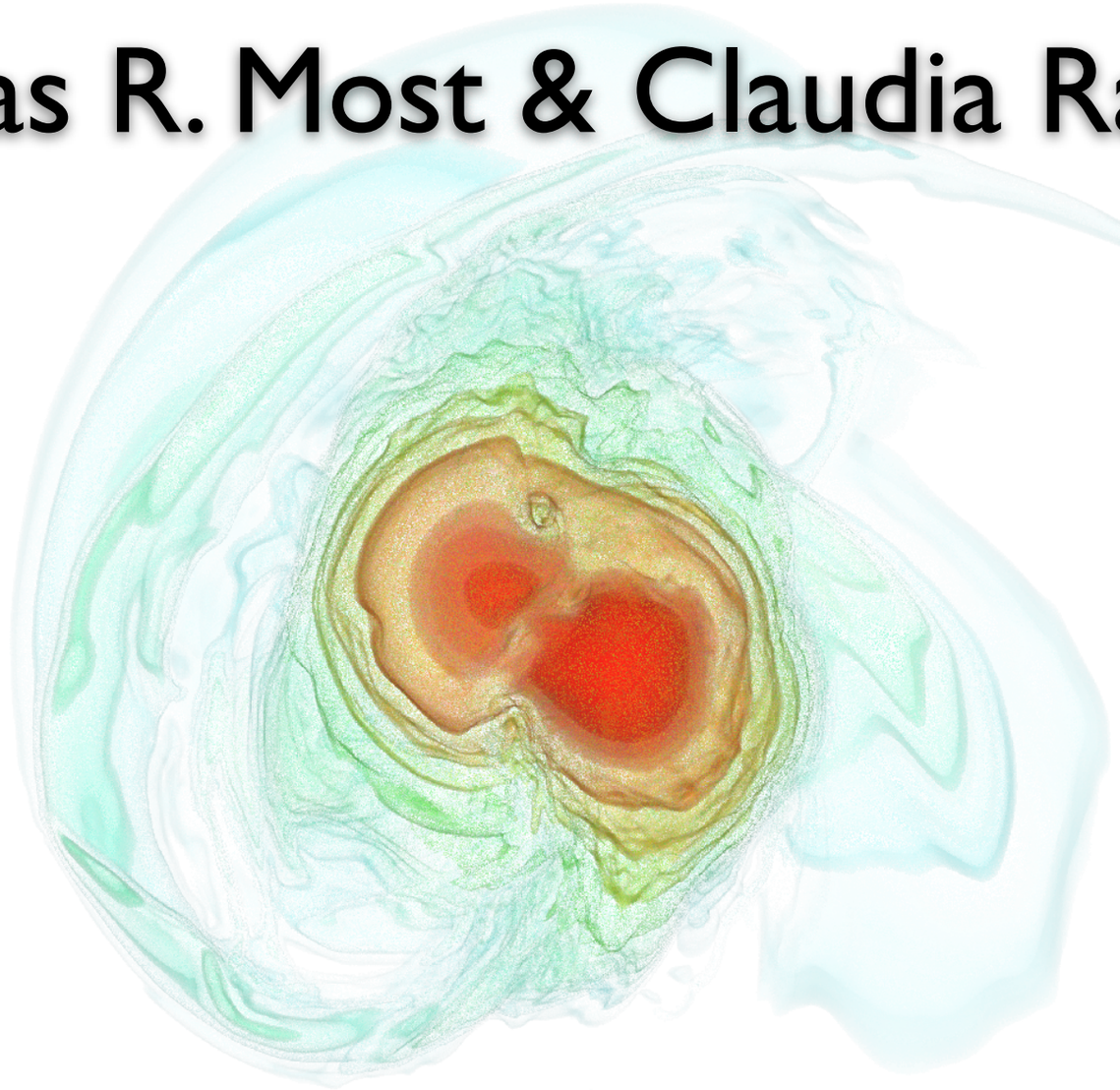
Nuclear physics with gravitational waves
Opportunities in the CE era

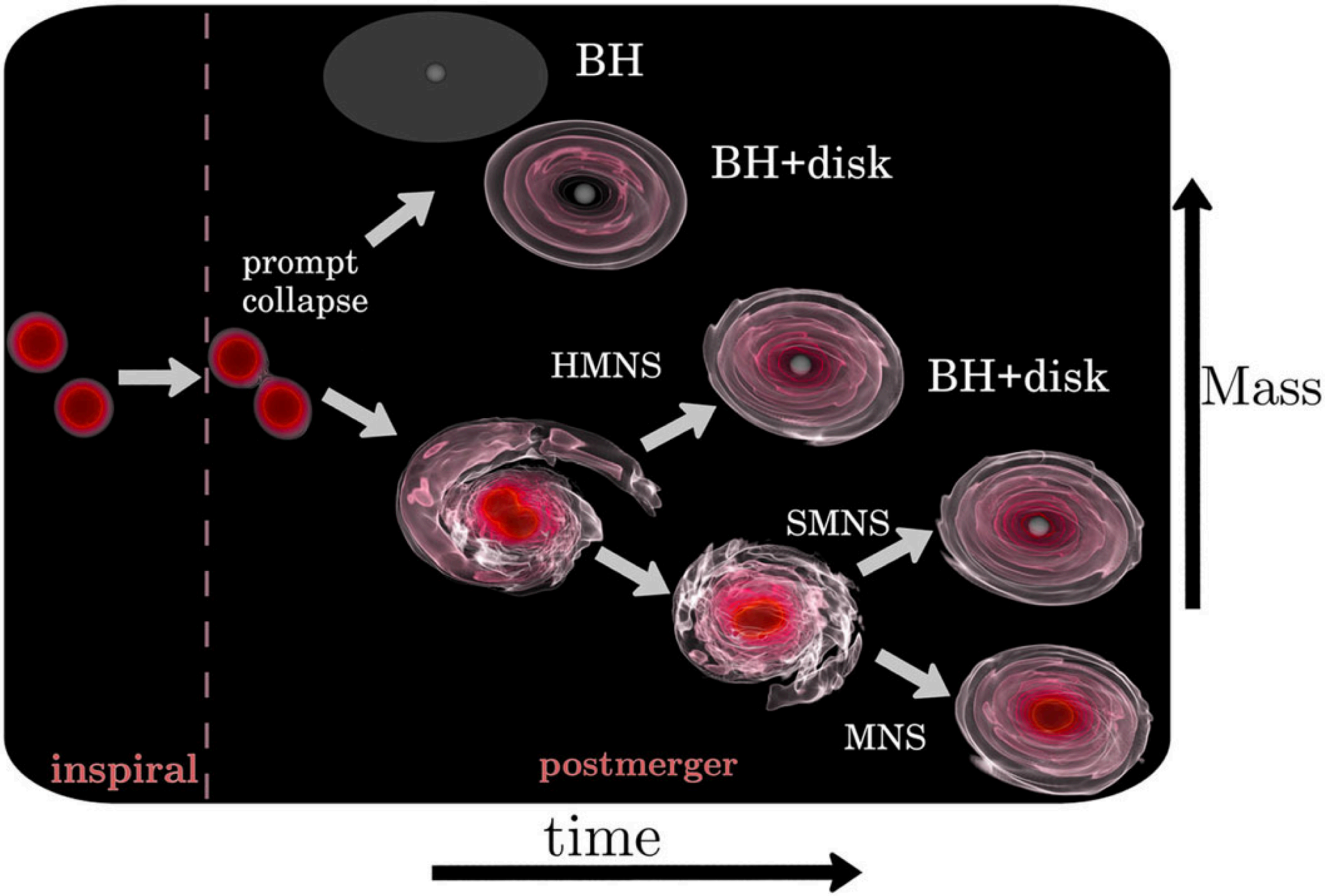
Elias R. Most & Claudia Ratti



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

Anatomy of a neutron star merger

Dietrich, Hinderer, Samajdar (2020)



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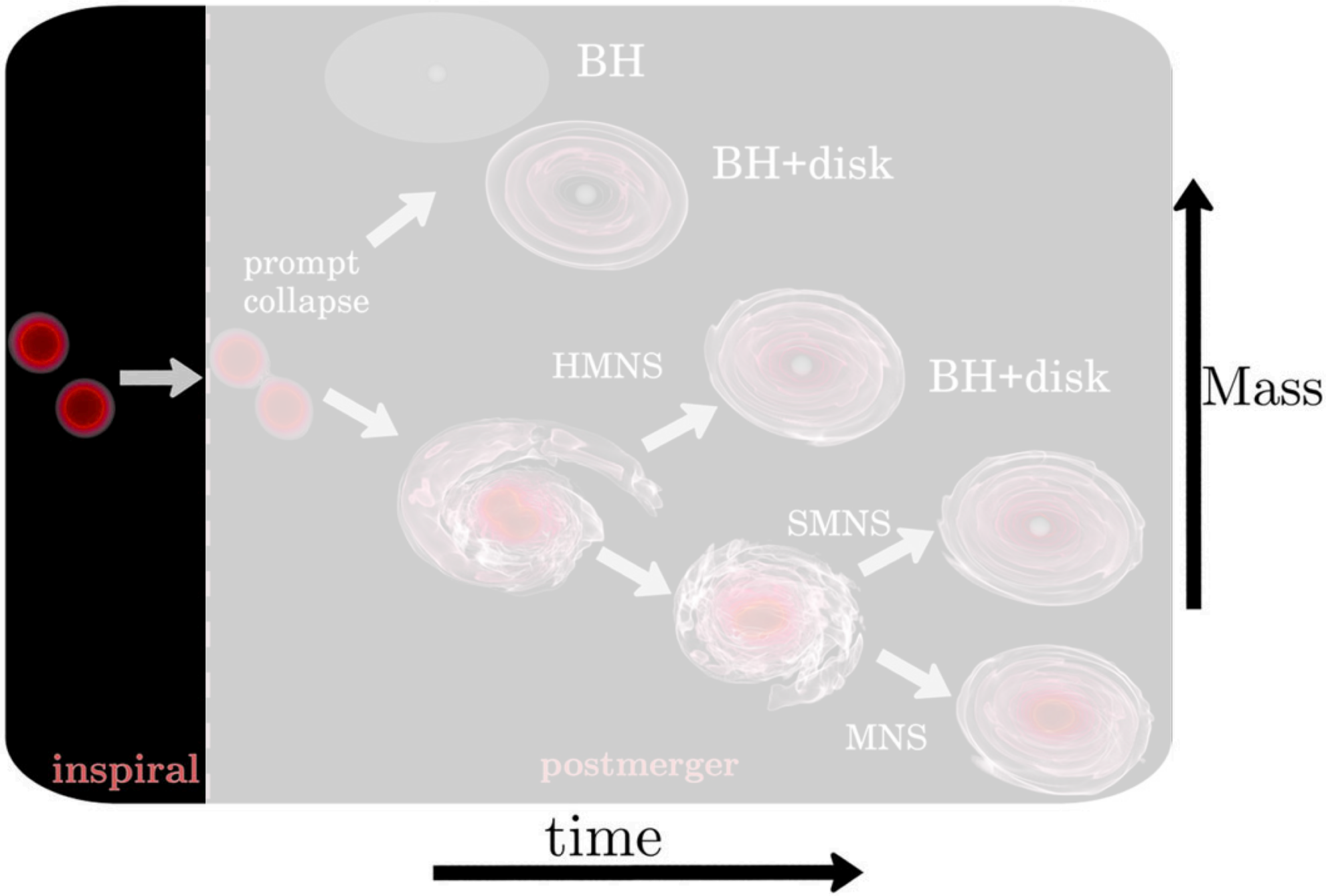
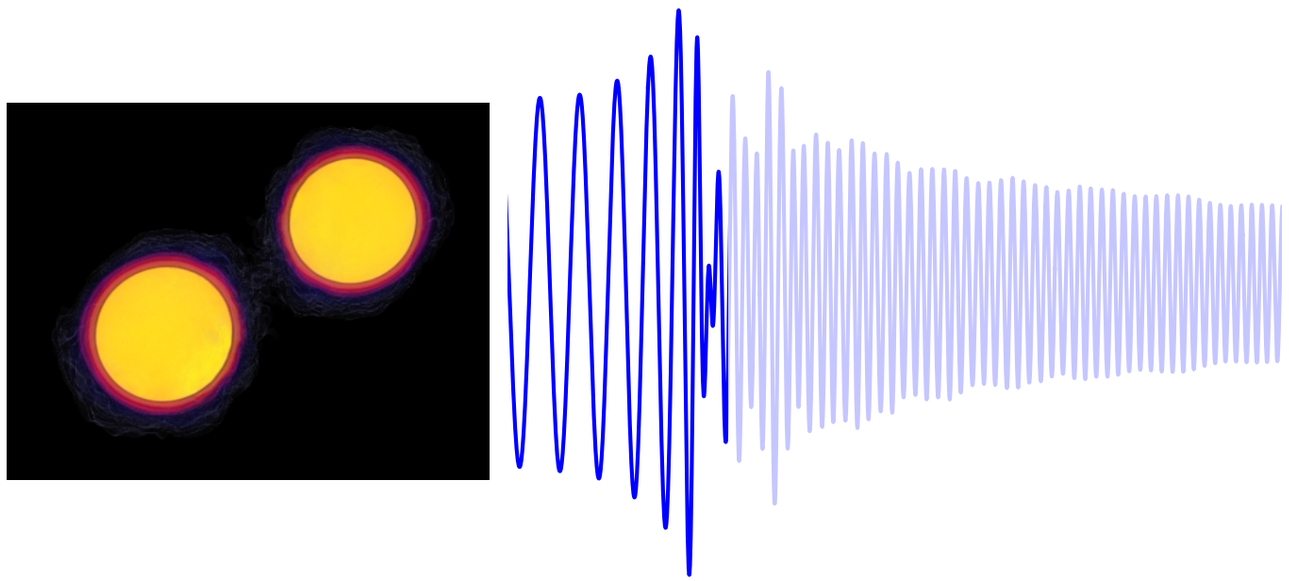
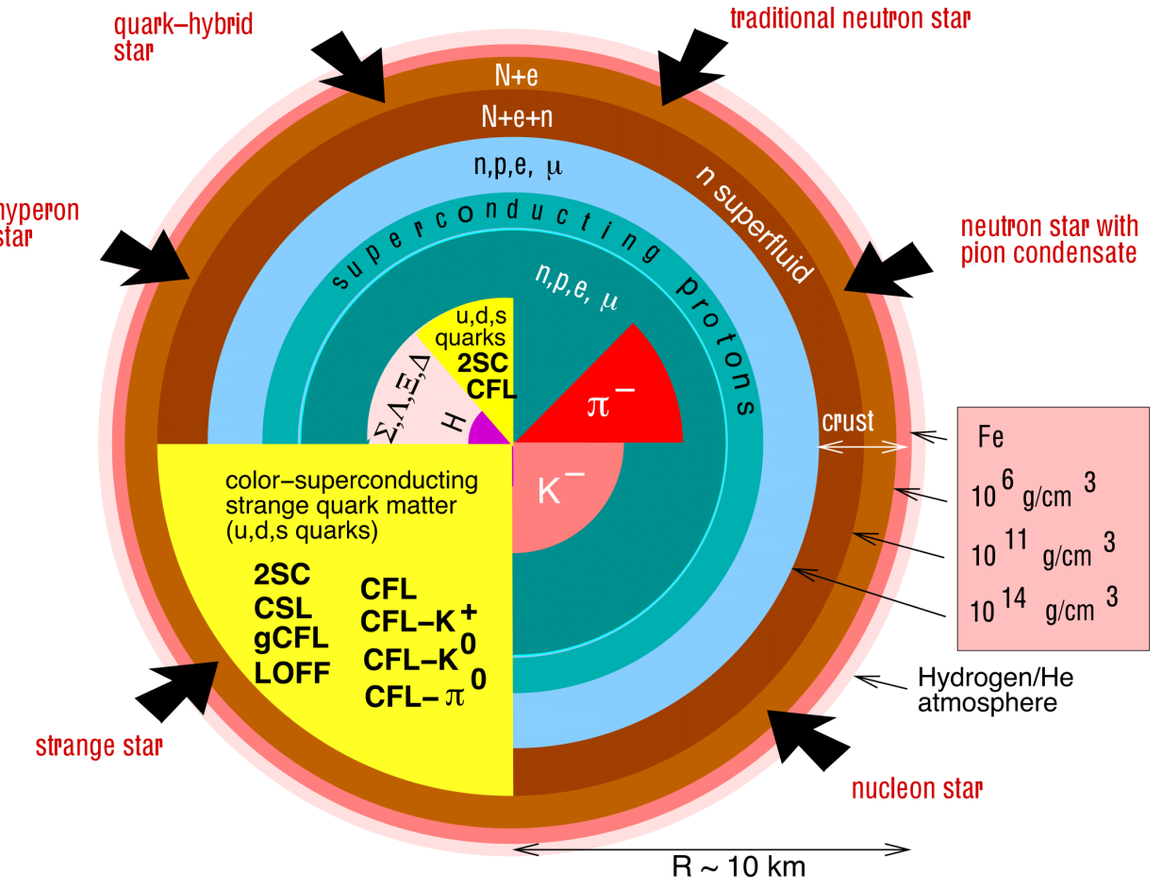


Equation of state from inspiral

Weber+(2007)



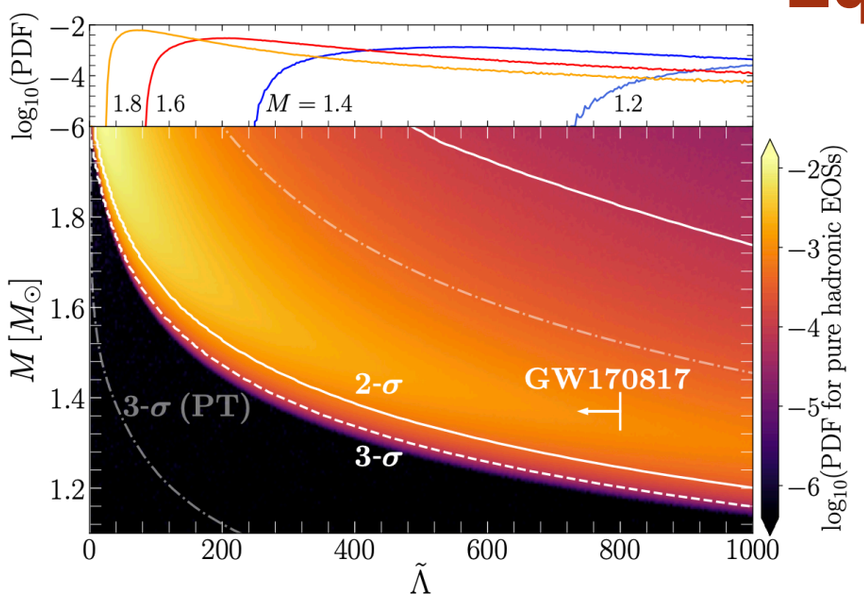


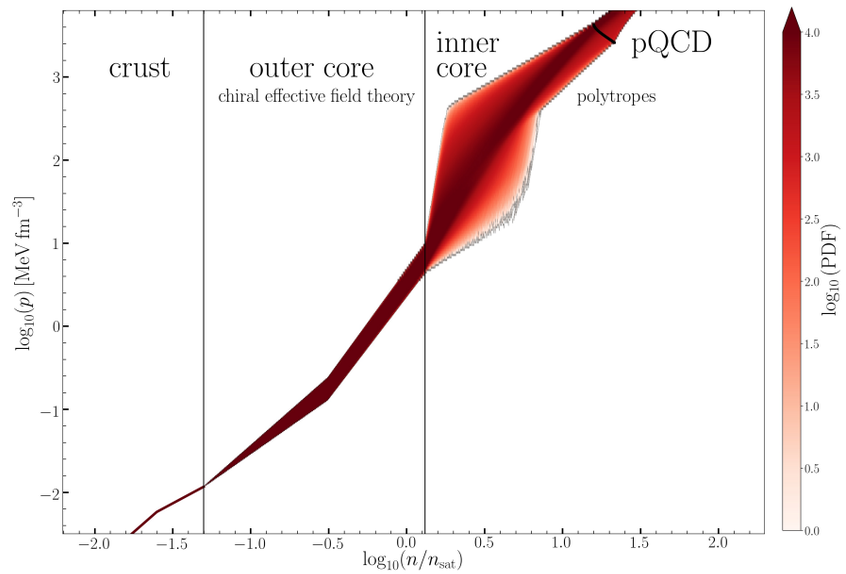
Tidal deformability

$\tilde{\Lambda}$

Equation of state

Claudia's talk!





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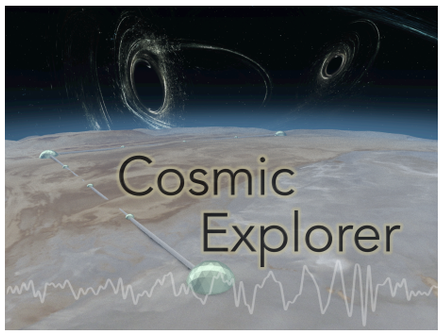
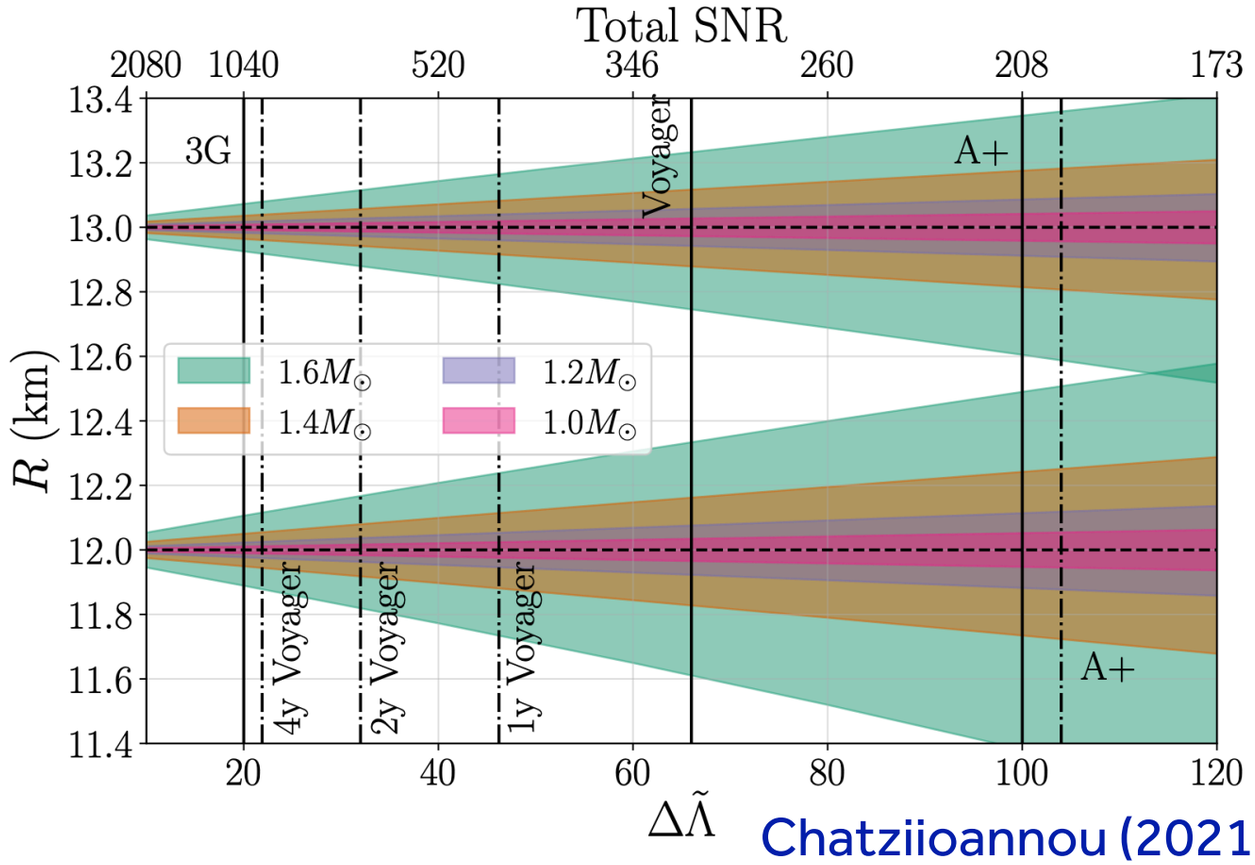


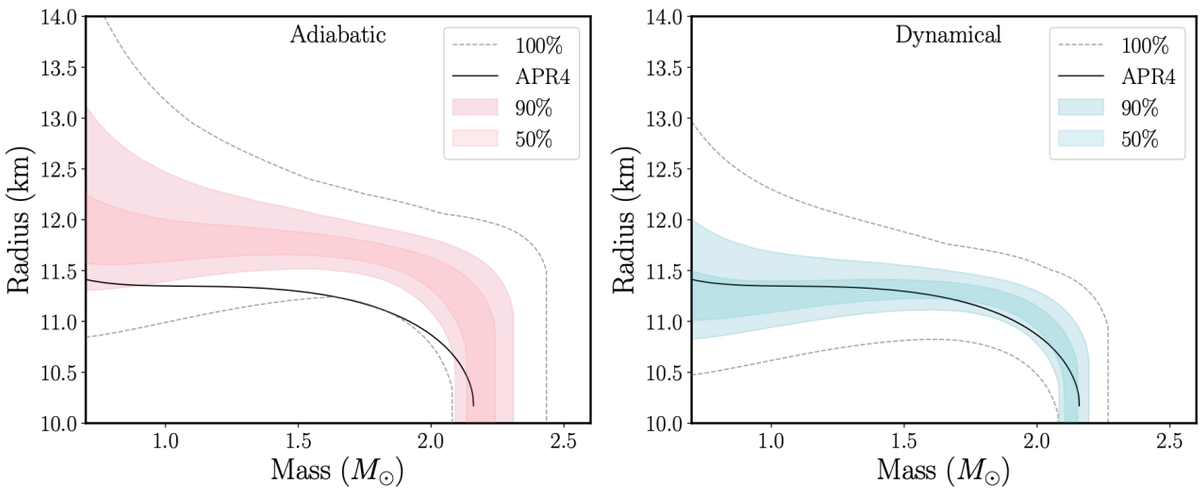
Evans+ arXiv:2109.09882

CE-era: $\mathcal{O}\left(10^5\right)$ inspirals per year, $\mathcal{O}(100)$ with SNR 100



Chatziioannou (2021)

Large number of high SNR events promises tight constraints on EoS



Pratten, Schmidt, Williams (2022)

Waveform systematics (e.g., dynamical tides)

Hinderer+, Steinhoff+,Pratten+, Gamba+

Uncertainties in recovery of $\tilde{\Lambda}$

Gamba+,Read+,Yagi+,Raithel+,Chen+,...

Nuclear physics from the inspiral

Highly accurate inspirals could constrain nuclear matter parameters

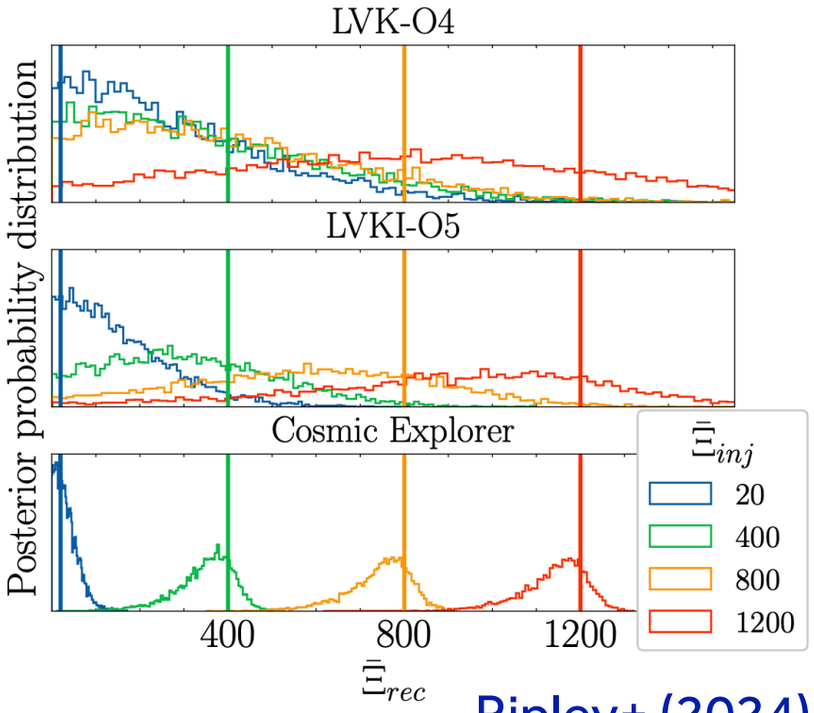
Phase transitions at $\mu_B > 900\,\mathrm{MeV}$

Chatziioannou+, Han+, De+, Tews+, Essick+, Mroczek+, Tan+, Drischler+, Pang+, Annala+,Gorda+,...

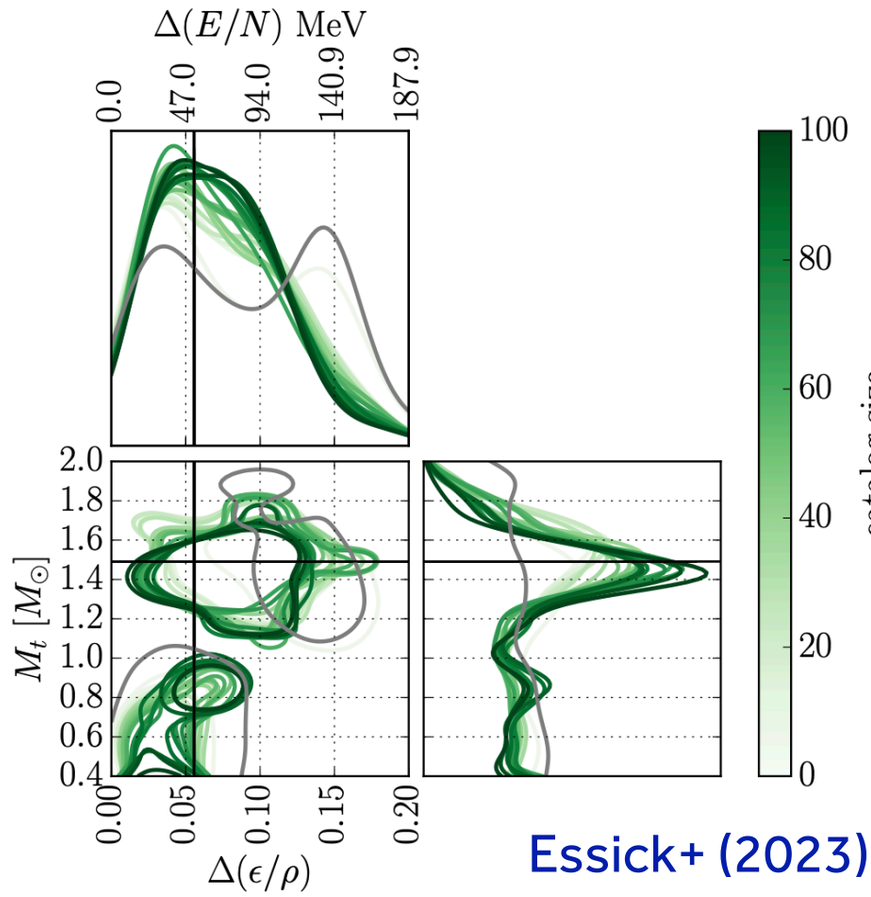
best for strong first-order transitions

Nuclear symmetry energy

Essick+, Li+,Holt+,...



Ripley+ (2024)



Essick+ (2023)

Can also use data to try an look for dynamical EoS corrections

Chemical equilibration Yang+,Arras+,Weinberg+,Most+,..

General viscosities Cutler+, Ripley+,...

Phase conversion dissipation Han+,...

Anatomy of a neutron star merger

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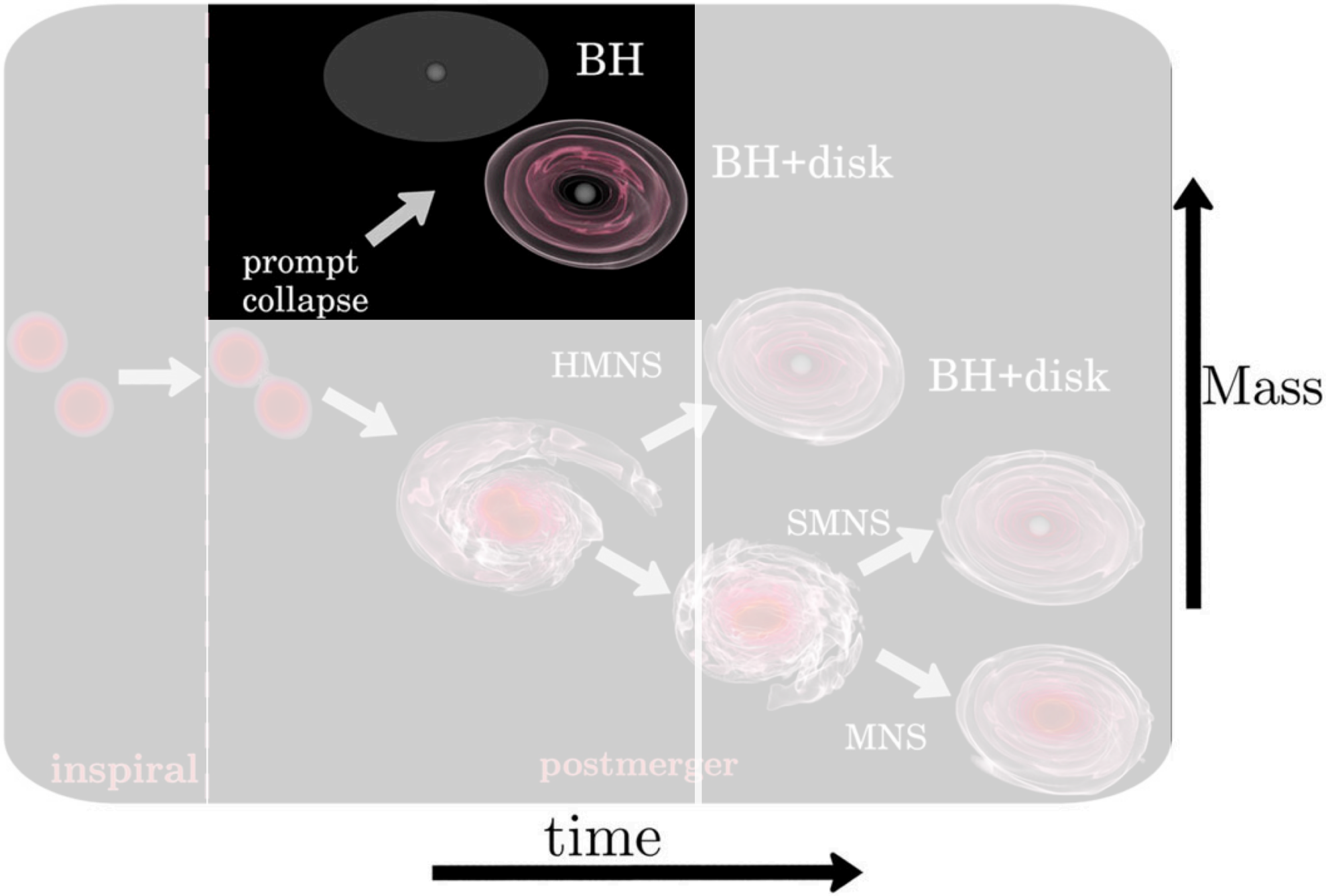


Prompt-collapse and the maximum mass

See also Ye+, Fishbach+,Tan+,Landry+, Most+, Dexheimer+, Fattoyev+, Zevin+

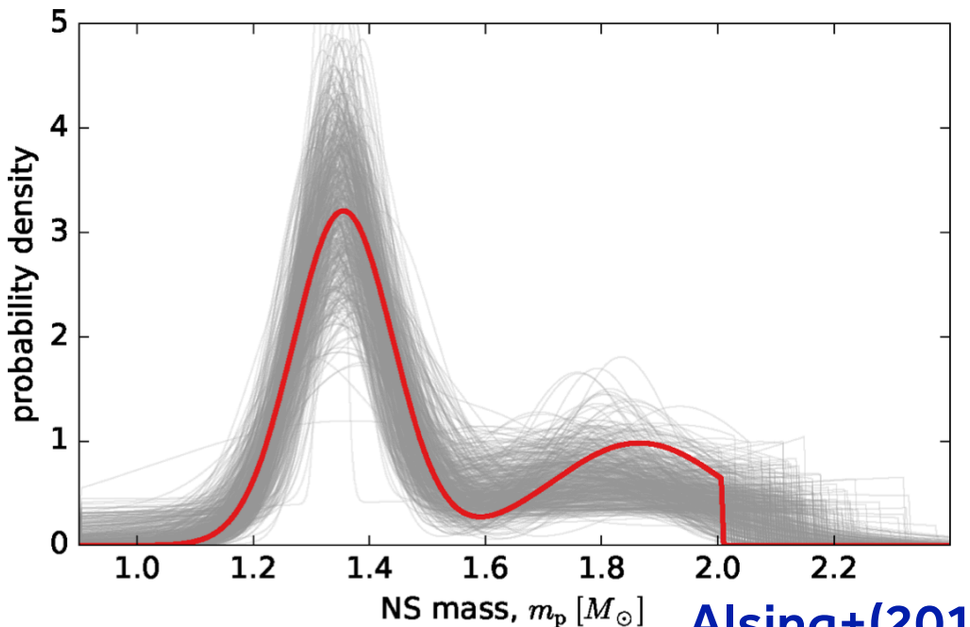
Highest densities probed in maximum mass neutron stars

Can directly probe QCD and sound speed

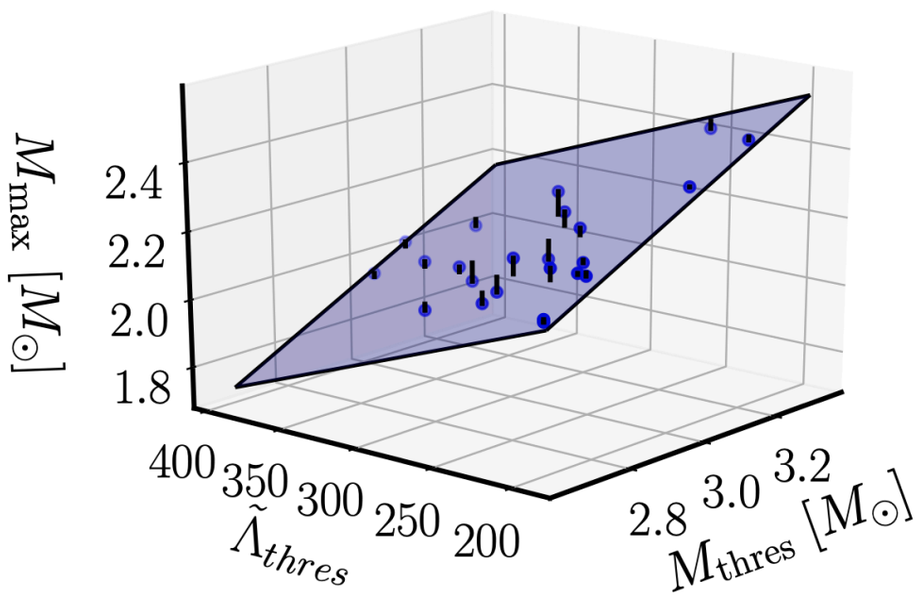
Drischler+, Ecker+, Gorda+,Tews+...

Mergers may not probe higher densities

Ujevic+



Alsing+(2018)



Bauswein+(2020)

Numerical relativity simulations (in various approximations) have shown strong correlations between prompt black hole formation and maximum mass

$$M_{\rm max}(M_{\rm thres}, \tilde{\Lambda}_{\rm thres}) = aM_{\rm thres} + b\tilde{\Lambda}_{\rm thres} + c,$$

Bauswein+,Köppel+,Tootle+,Kölsch+,Kashyap+

Threshold mass may reveal compressibility

Perego+

Anatomy of a neutron star merger

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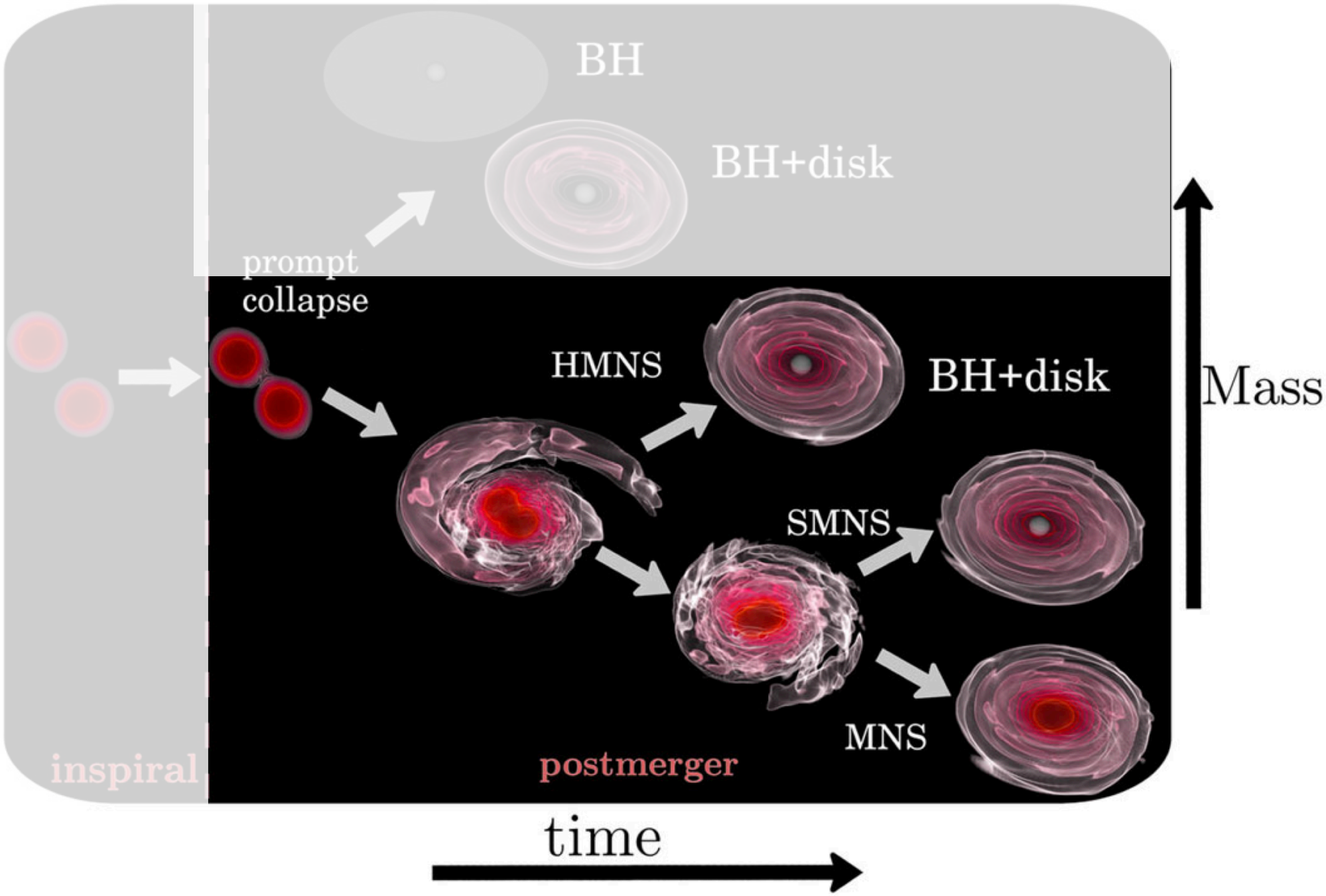
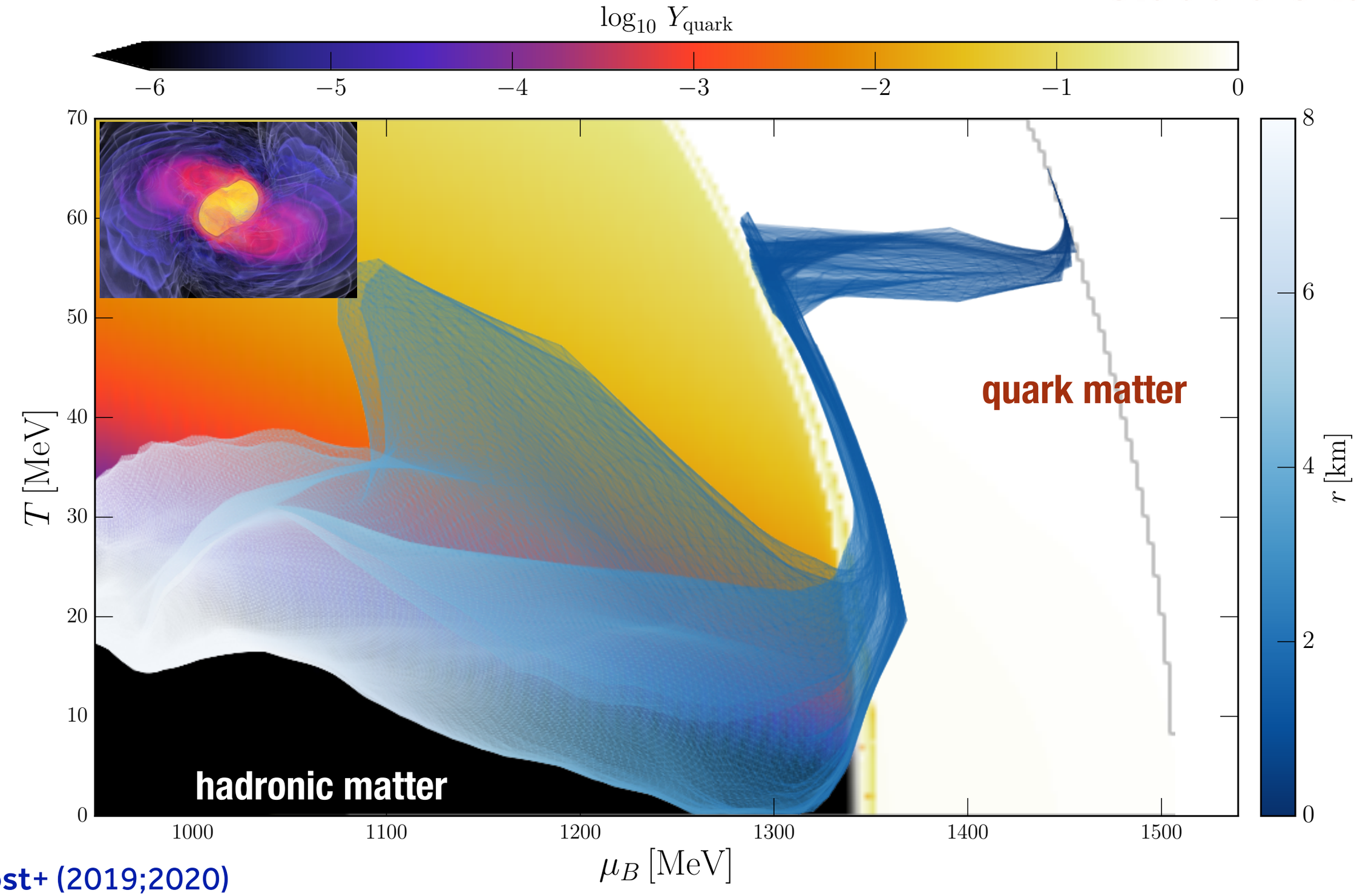


Cosmic Colliders: Hot and dense matter!

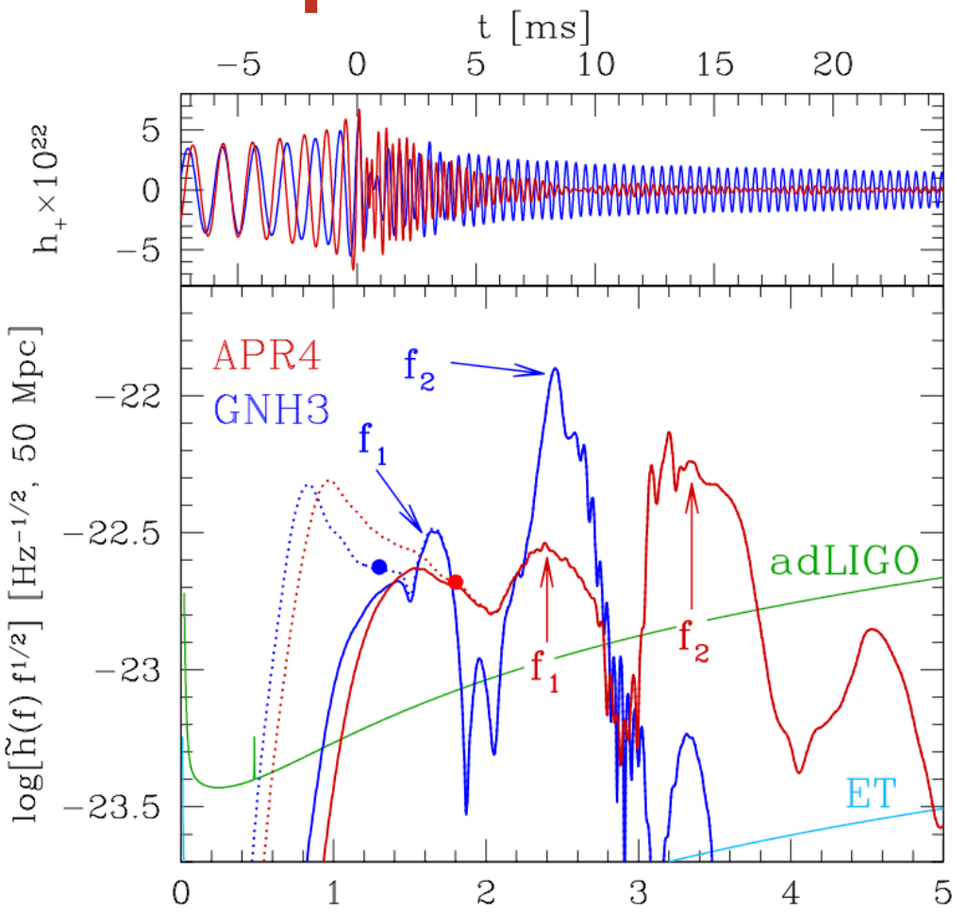
Bauswein+,Öchslin+,Most+, Raithel+, Figura+, Kastaun+,Prakash+, Blacker+,Liebling+, Huang+, Perego+,Hammond+,Radice+...

Claudia's talk!

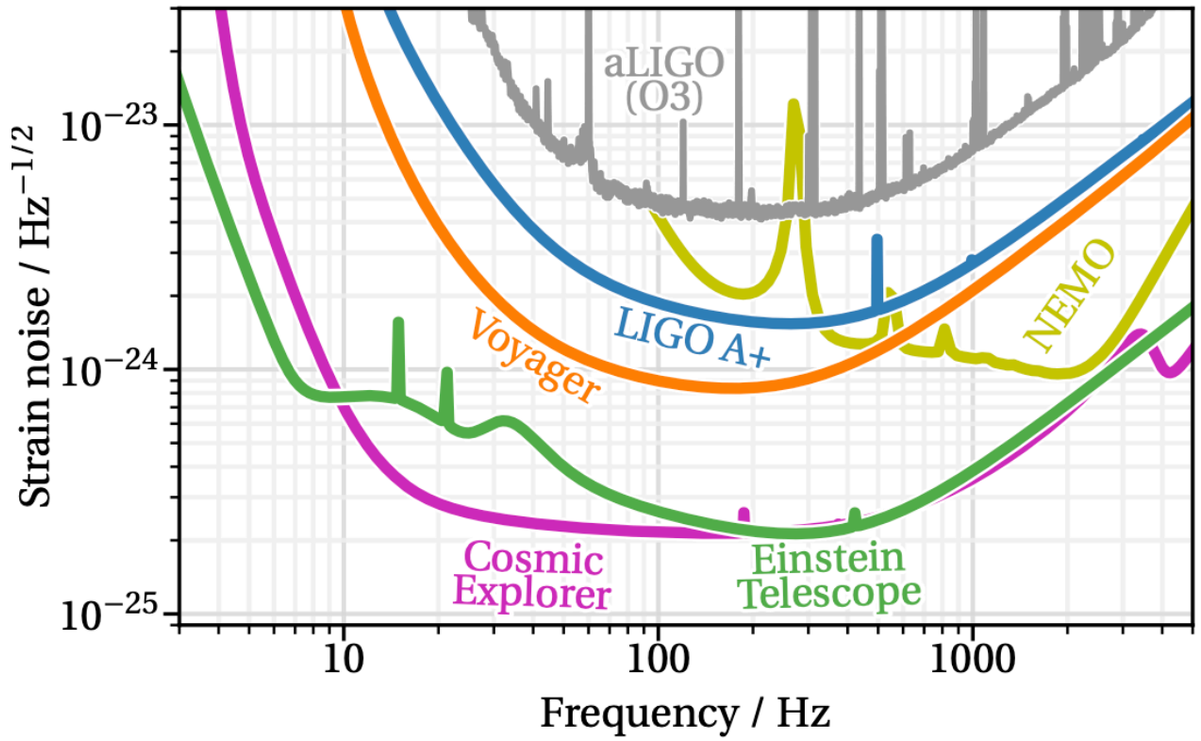


Most+ (2019;2020)

Equation of state from post-merger



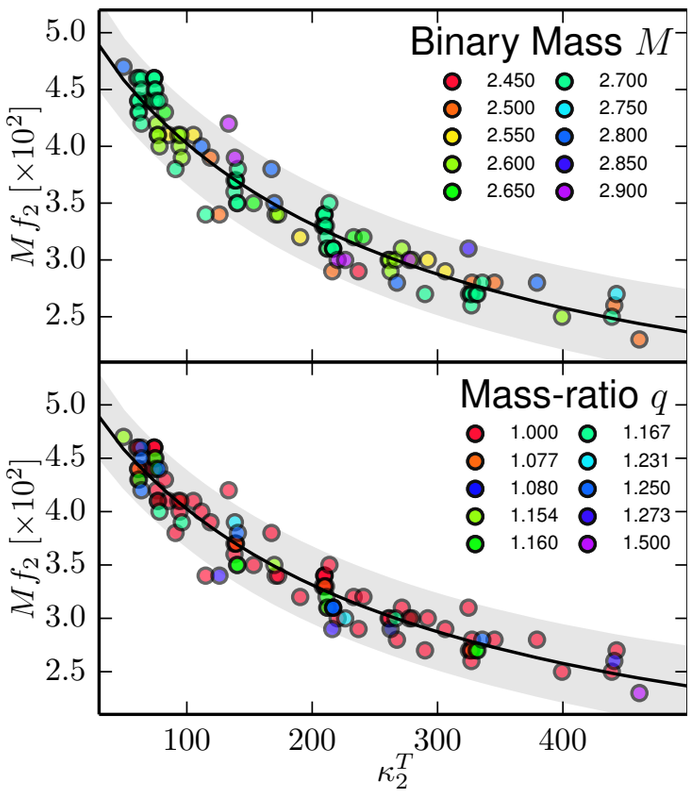
Takami+ (2014, 2015)



Post-merger frequency spectrum is quasi-universal!

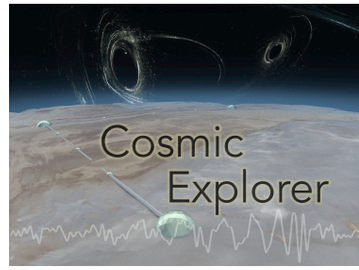
Can correlate $f_2/f_{\rm peak}$ with EoS!

Shibata, Bauswein+, Stergioulas+, Hotokezaka+, Takami+, Bernuzzi +,Rezzolla+, Raithel+, Vretinaris+,...

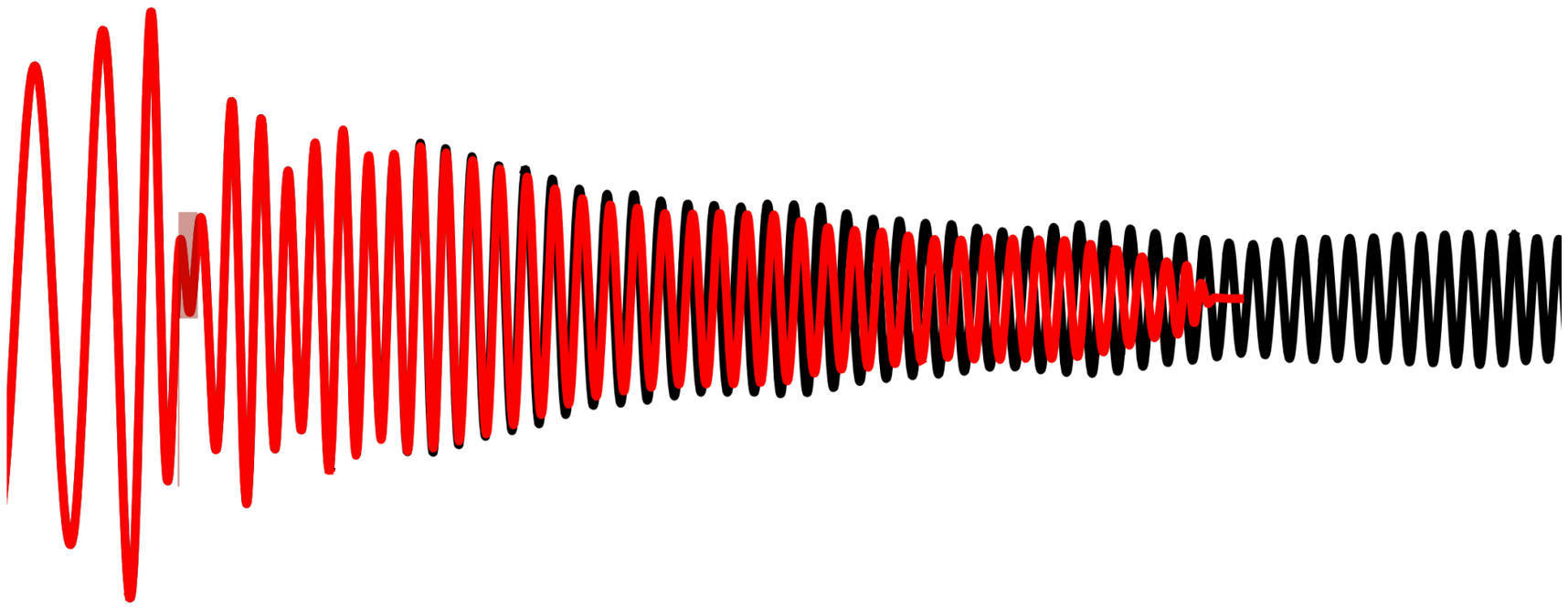


Bernuzzi+ (2015), see also Bauswein+(2014)

A true multi-physics problem



Post-merger gravitational wave emission probes new regimes of physics!



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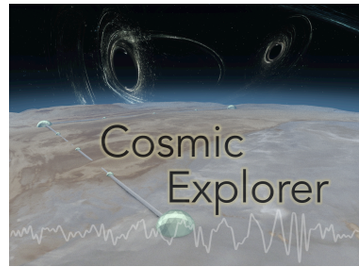

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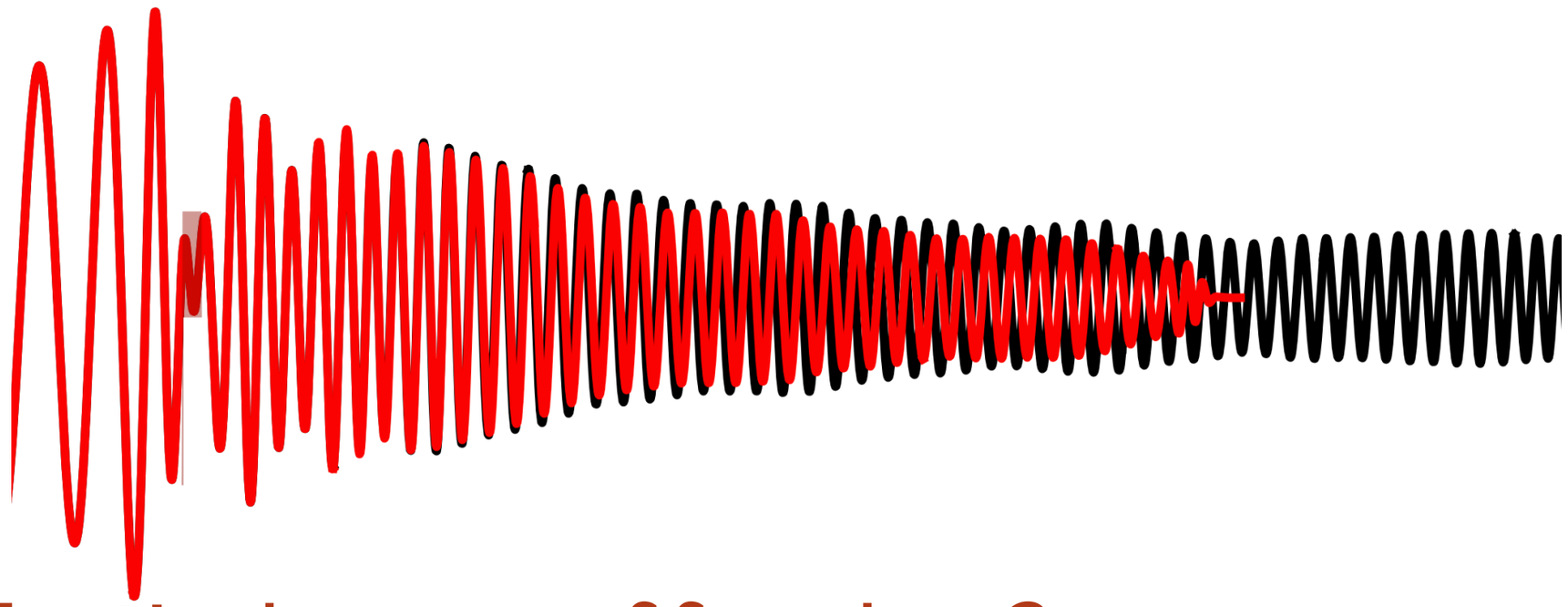
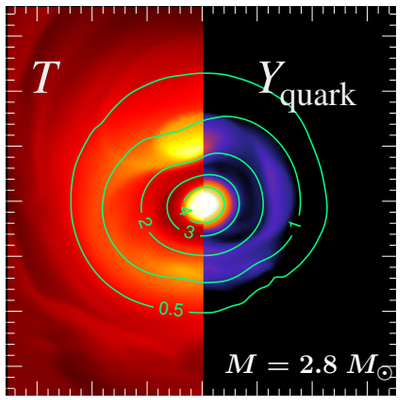


Exotic degrees of freedom?

Bauswein+, Huang+, Most+,Prakash+,
Radice+,Sekiguchi+,Weih+... (+ many more for EoS uncertainty!)



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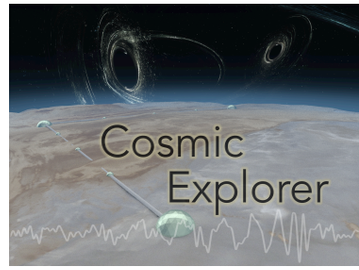

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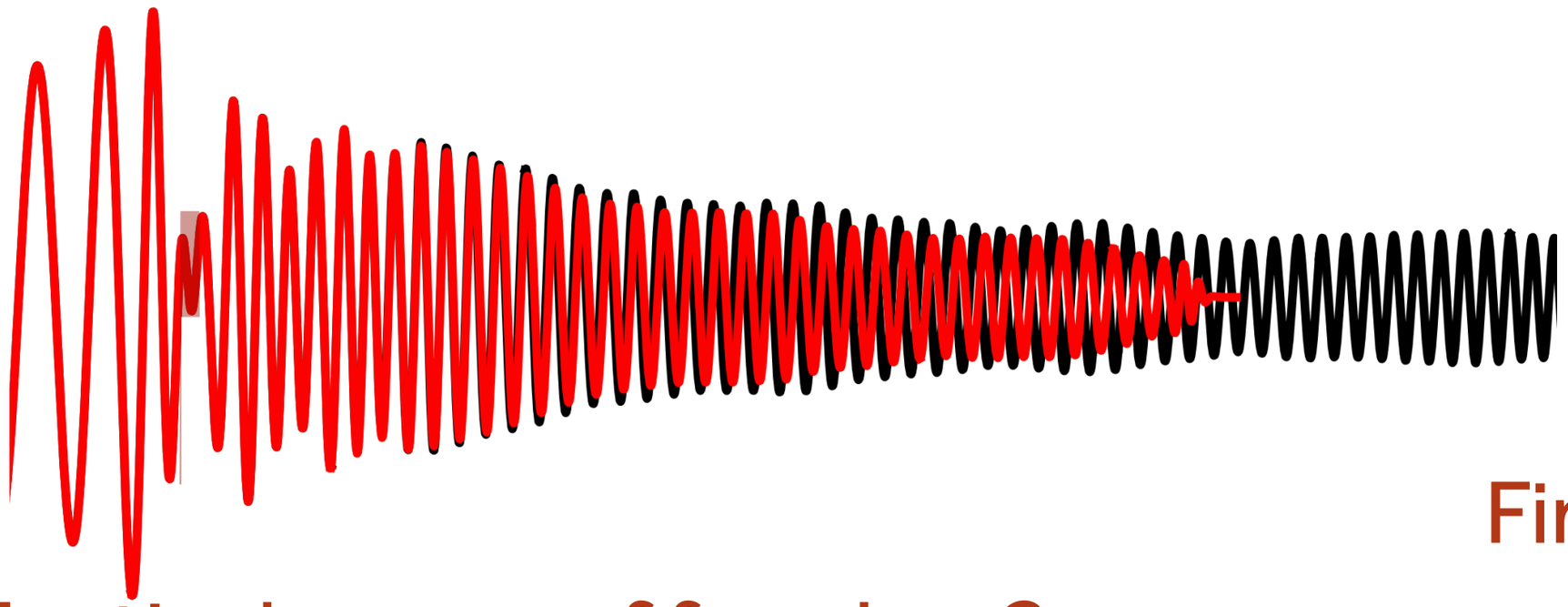

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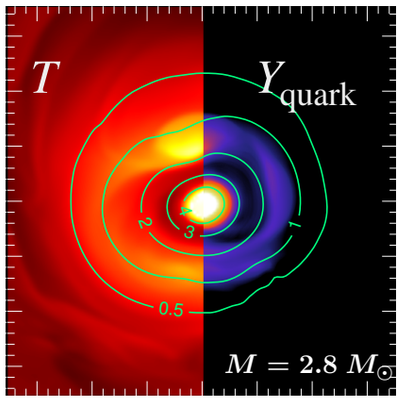
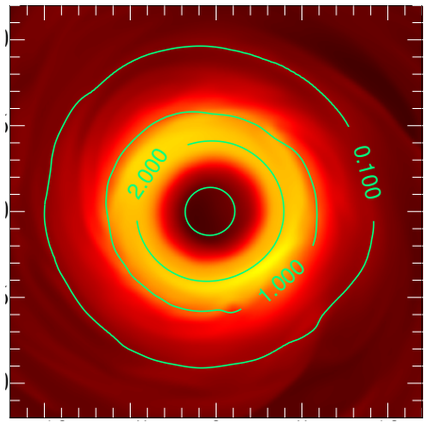


Finite-temperature and composition?

Bauswein+,Figura+, Hammond+,
Hanauske+,Perego+,Raithel+...



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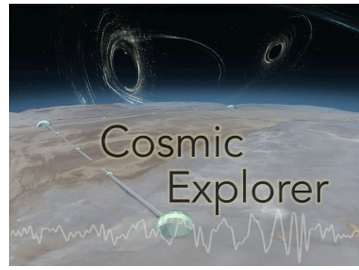

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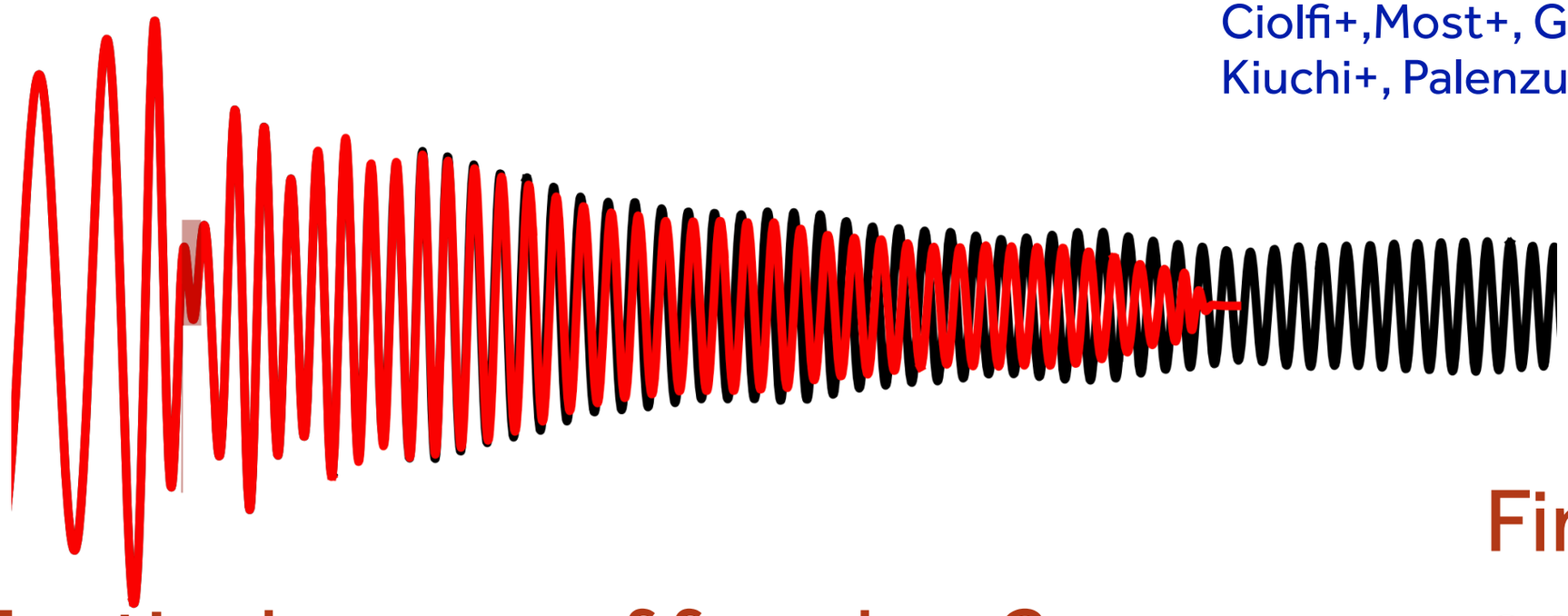
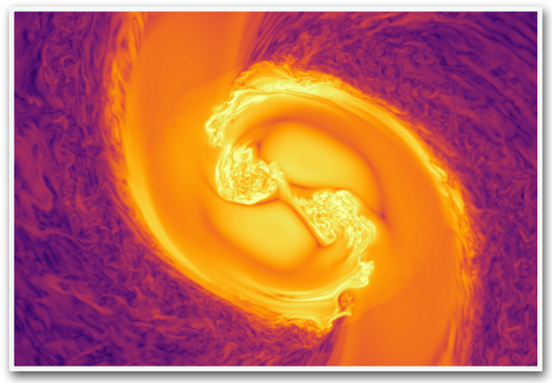


Magnetic fields?

Ciolfi+,Most+, Giacomazzo+,
Kiuchi+, Palenzuela+,...



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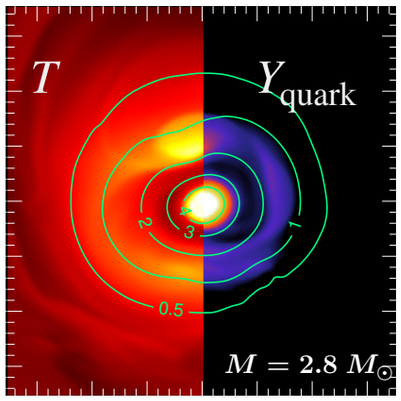

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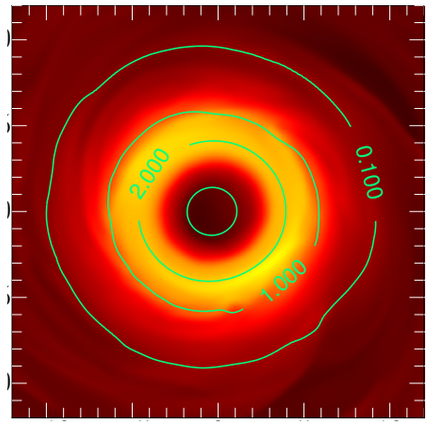

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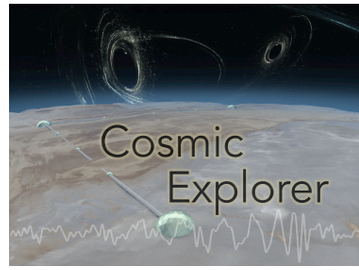

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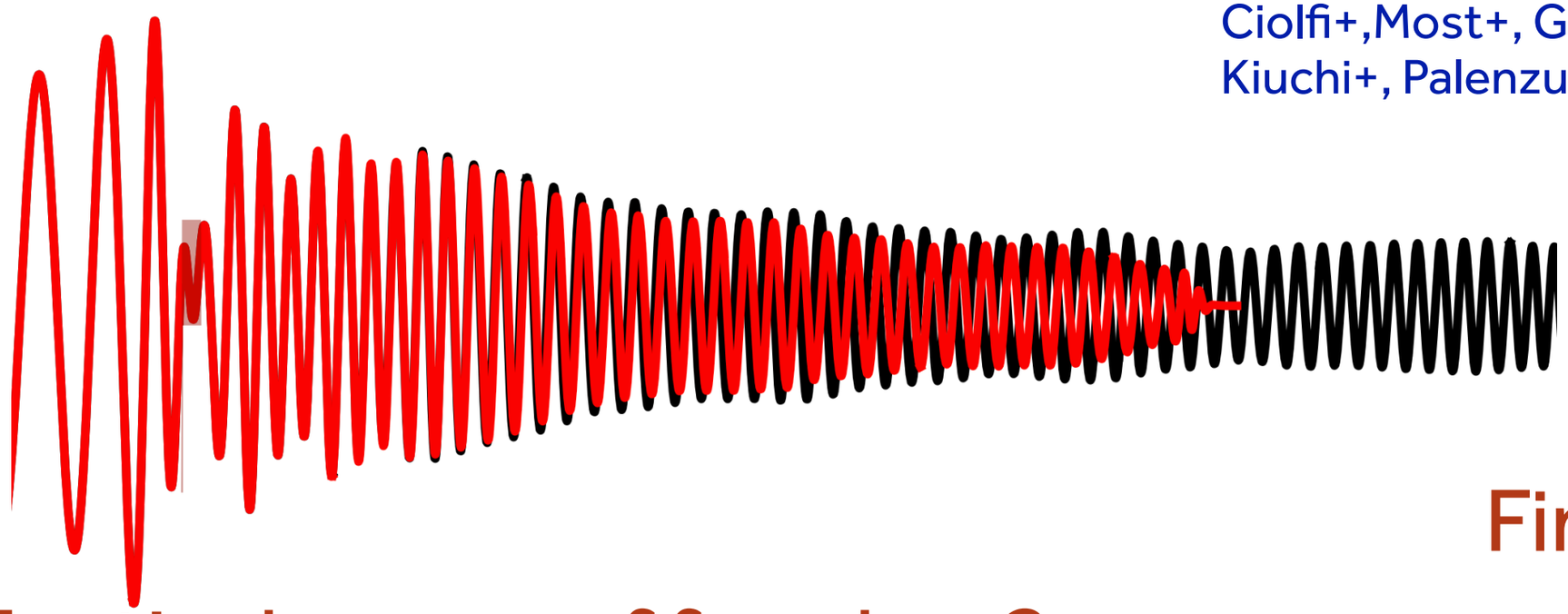

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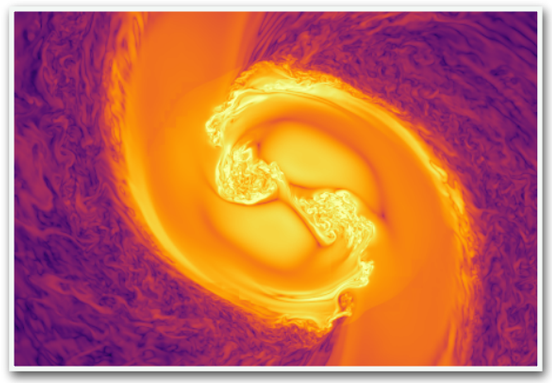

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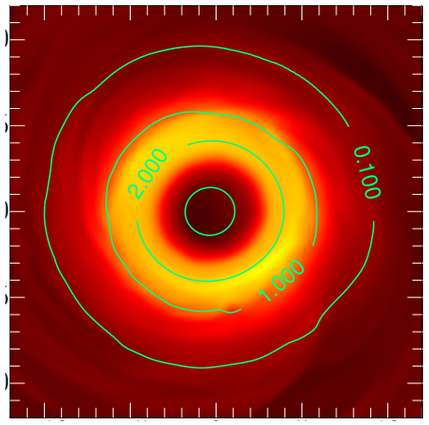

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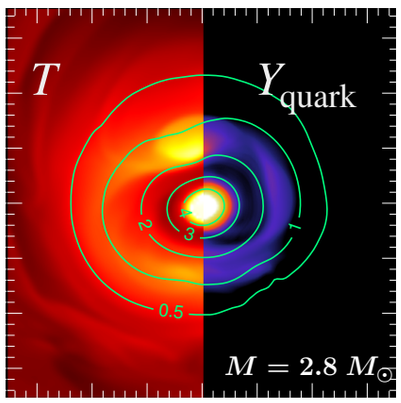
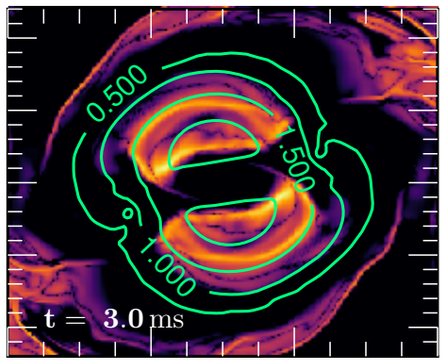


Neutrino effects?

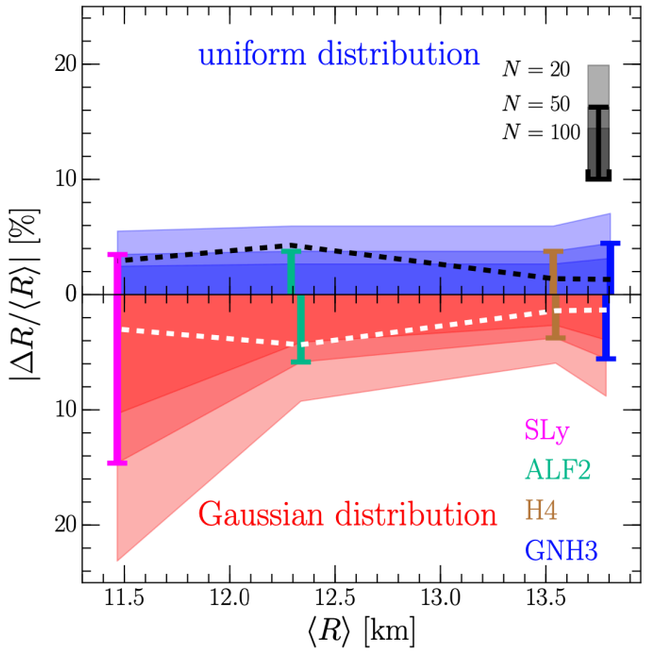
(in dense matter)

Alford+, Camelio+, Foucart+, Hammond+, Most+, Radice+, Shibata+,...



Nuclear physics from the post-merger

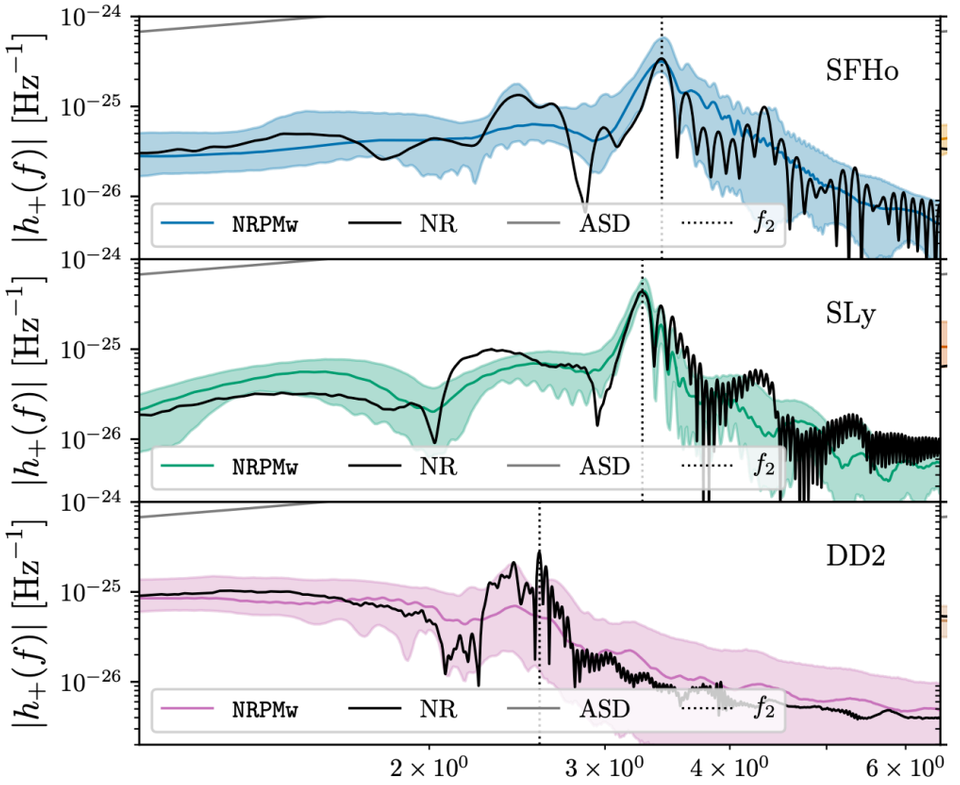
Inferences of the post-merger signal can be correlated with expectation from inspiral



Bose+(2019)

Improved radius constraints!

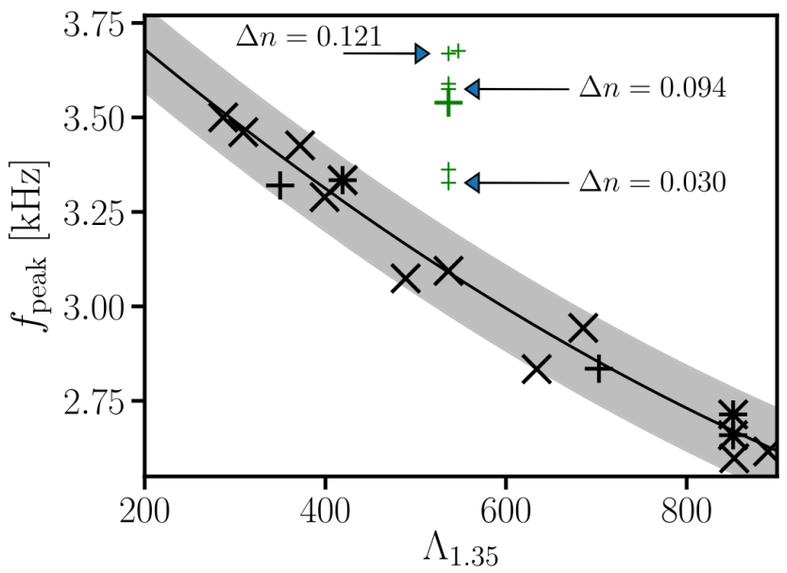
Bose+, Breschi+, Criswell+, Wijngaarden+, Chatziioannou+,...



Breschi+(2022)

Deviations from inspiral could reveal new phases of matter (first-order PT)

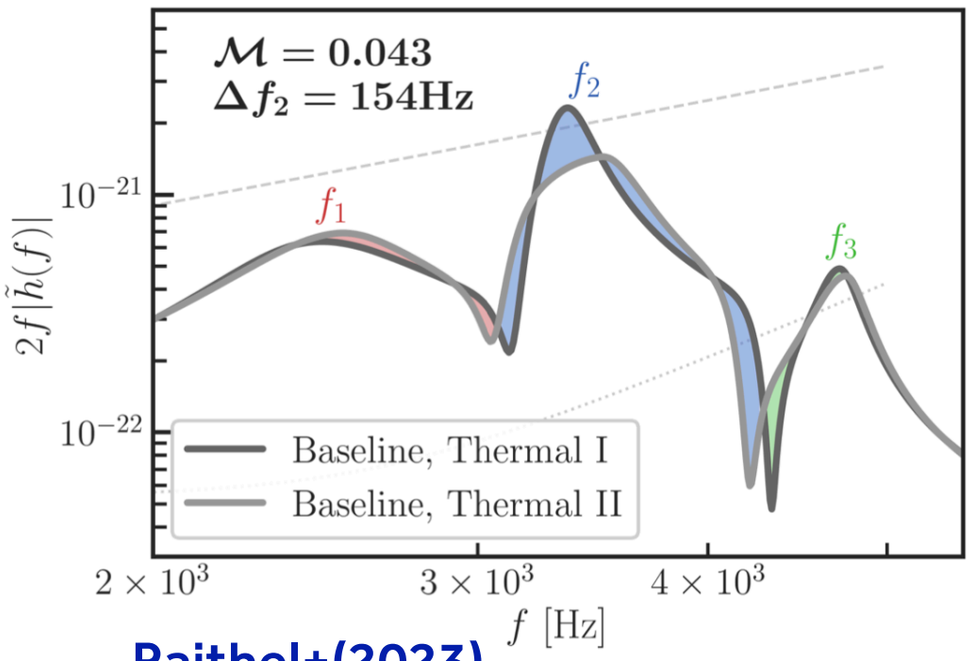
Bauswein+, Most+, Huang+, Prakash+, Raithel+,...



Bauswein+(2019)

Nuclear physics from the post-merger

Beyond the equation of state



Raithel+(2023)

The merger probes hot matter.

Finite temperature correction

Bauswein+, Figura+, Raithel+, Hammond+, Fields+,...

May depend on phases of matter (e.g., hyperons, muons, etc.)

Blacker+, Mroczek+,...

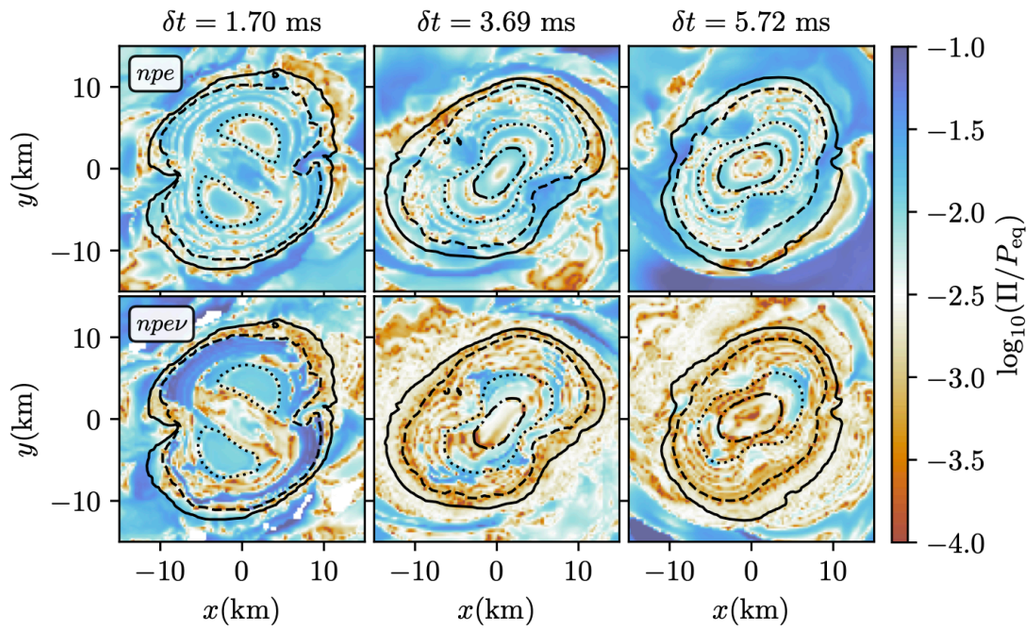
Nuclear composition can potentially leave direct imprints

Bulk viscosity/chemical equilibration?

Alford+,Hammond+,Most+,Espino+,Zappa+,Chabanov+

Phase conversion dissipation??

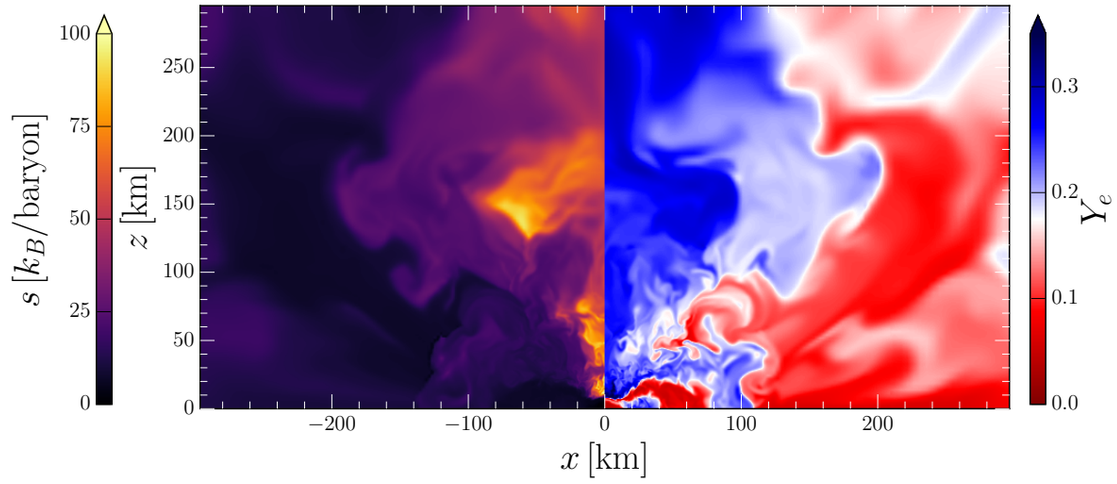
Han+



Espino+ (2023)

Nuclear physics from multi-messenger

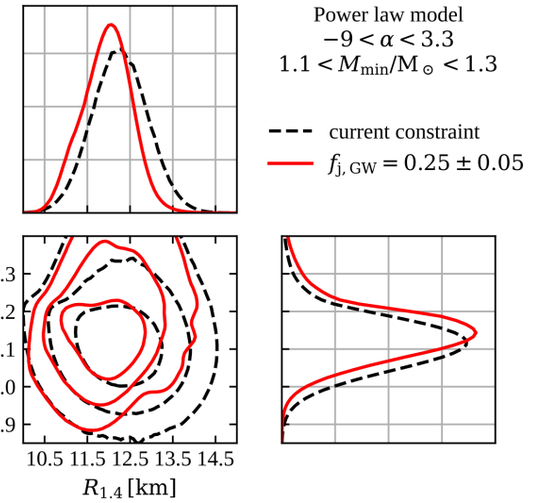
Mass ejecta and relativistic outflows can power afterglows and gamma-ray bursts!



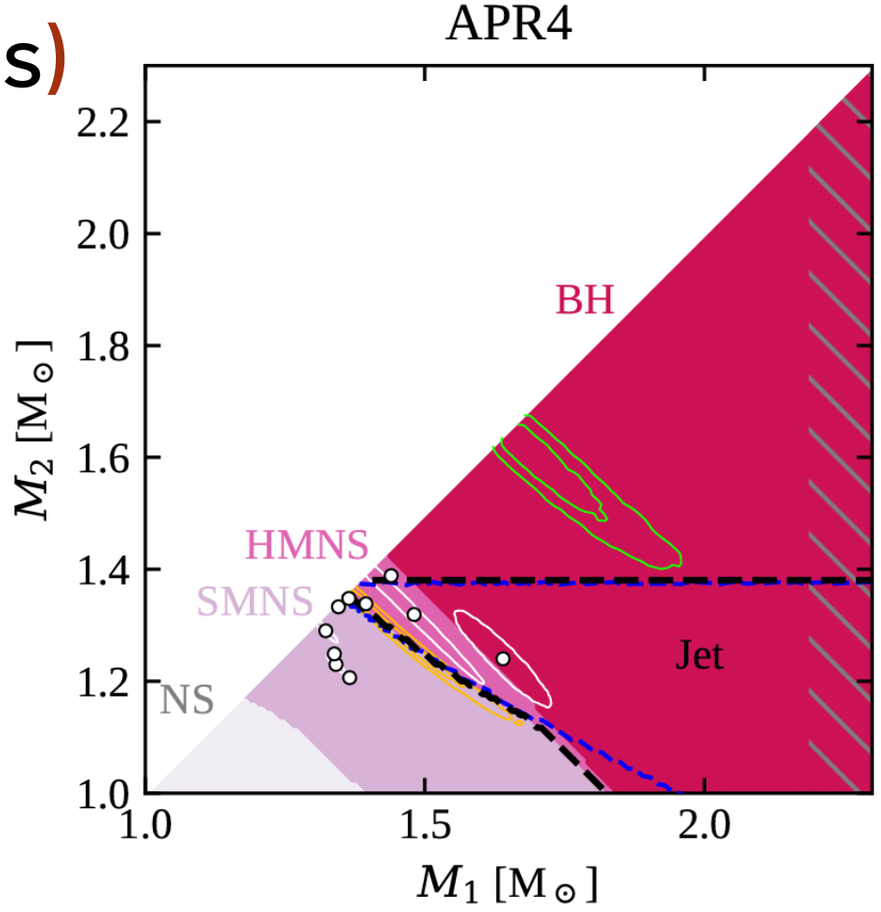
Multi-messenger constraints

on $M_{\mathrm{TOV/max}}$ and $\tilde{\Lambda}$? Margalit+, Rezzolla+,Shibata+,Ruiz+, Perego+ Nathanail+,Radice+,Coughlin+,Kiuchi+...

(remnant life time & mass)



Salafia+(2022), also Sarin+



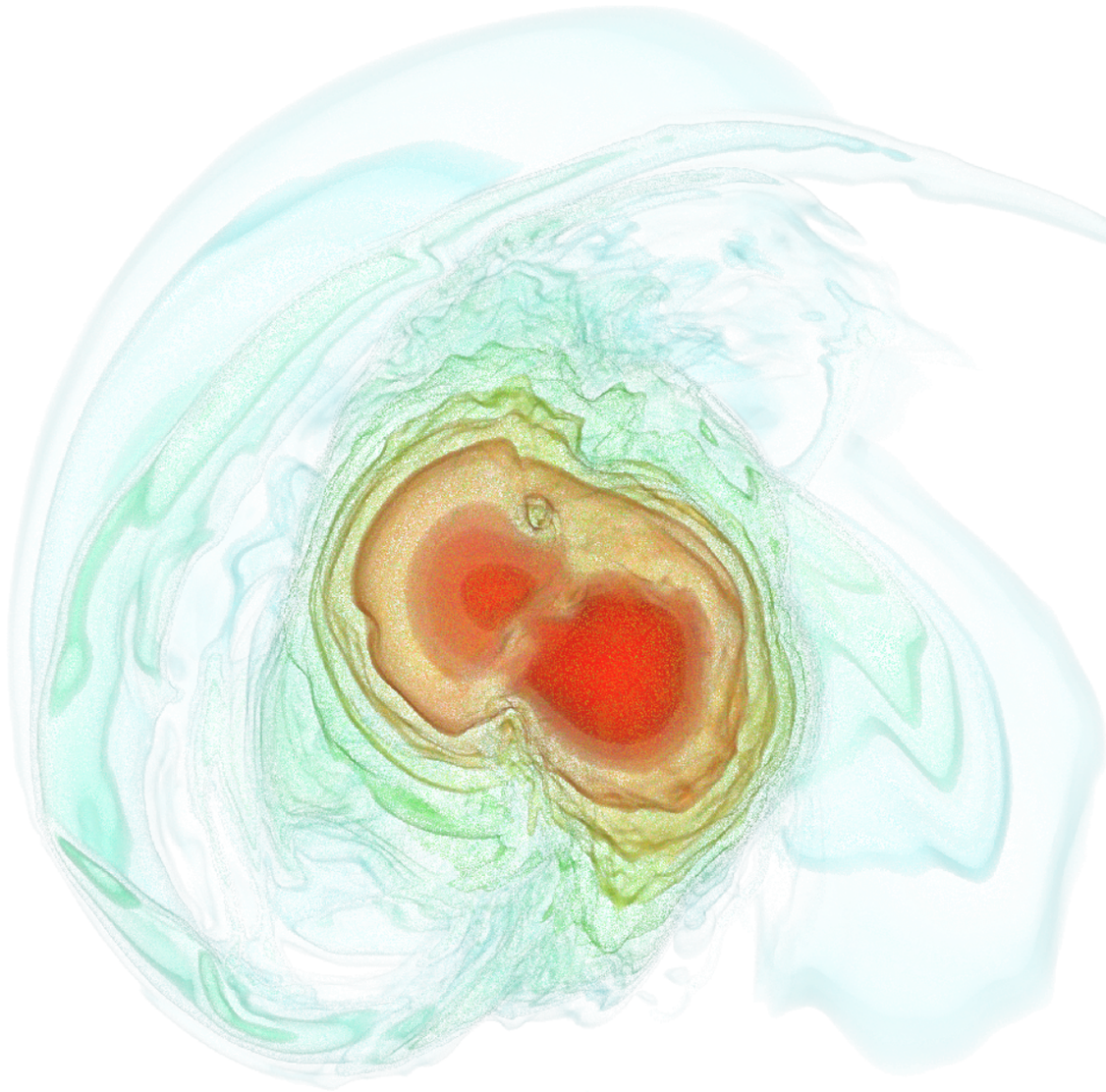
Other scenarios:

Resonant shattering flares?? Tsang+, Neill+

GRB QPOs?? Chirenti+

Connections with GRB population!

Thank you!



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