GRAVITATIONAL WAVE IMPRINT OF NON-CONVEX DYNAMICS IN BINARY NEUTRON STAR MERGER

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G. Rivieccio et al. (2024) Phys. Rev. D **109**, 064032

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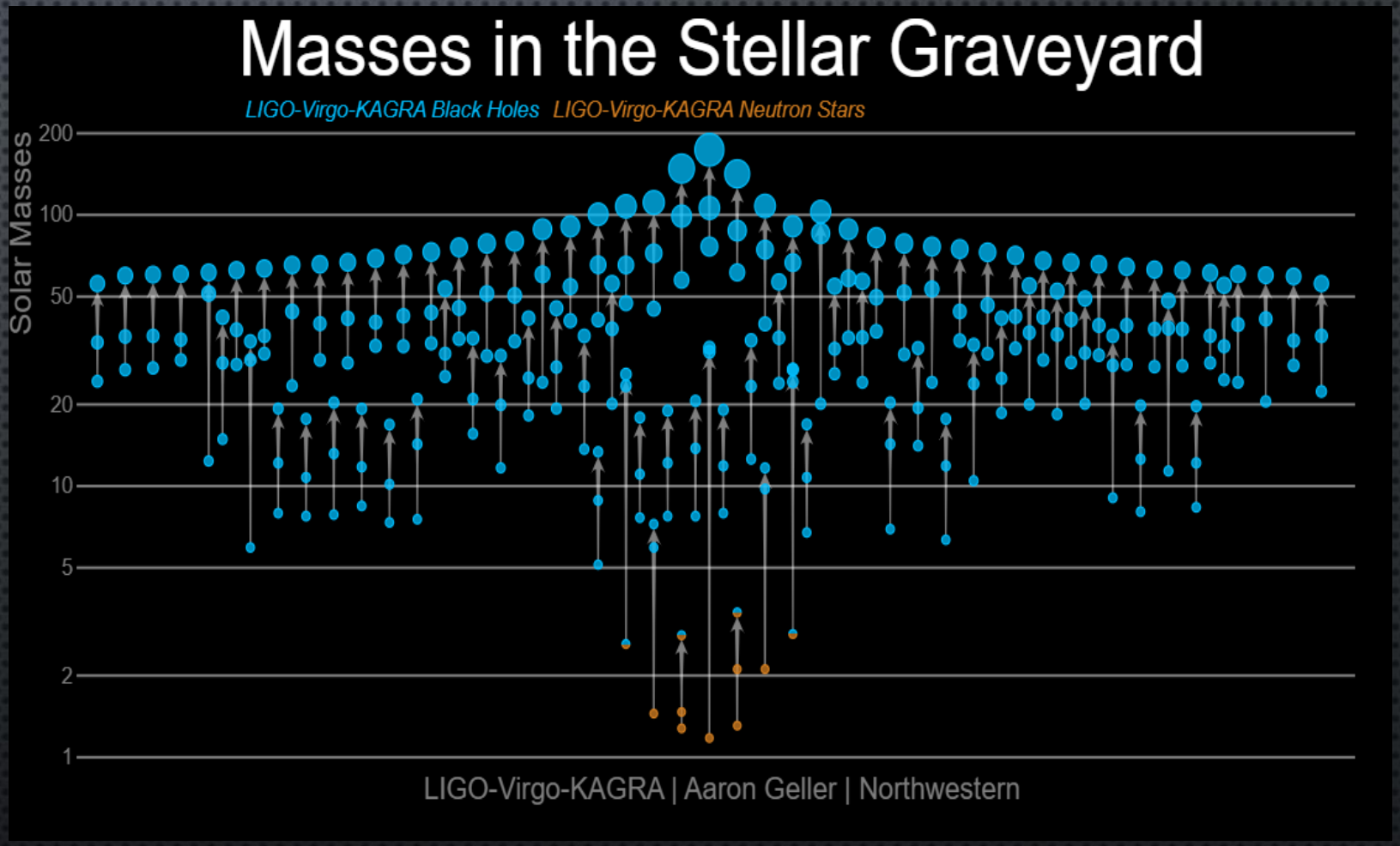
QUARK AND NUCLEAR PHYSICS CONFERENCE

BARCELONA 2024

GRAVITATIONAL WAVES

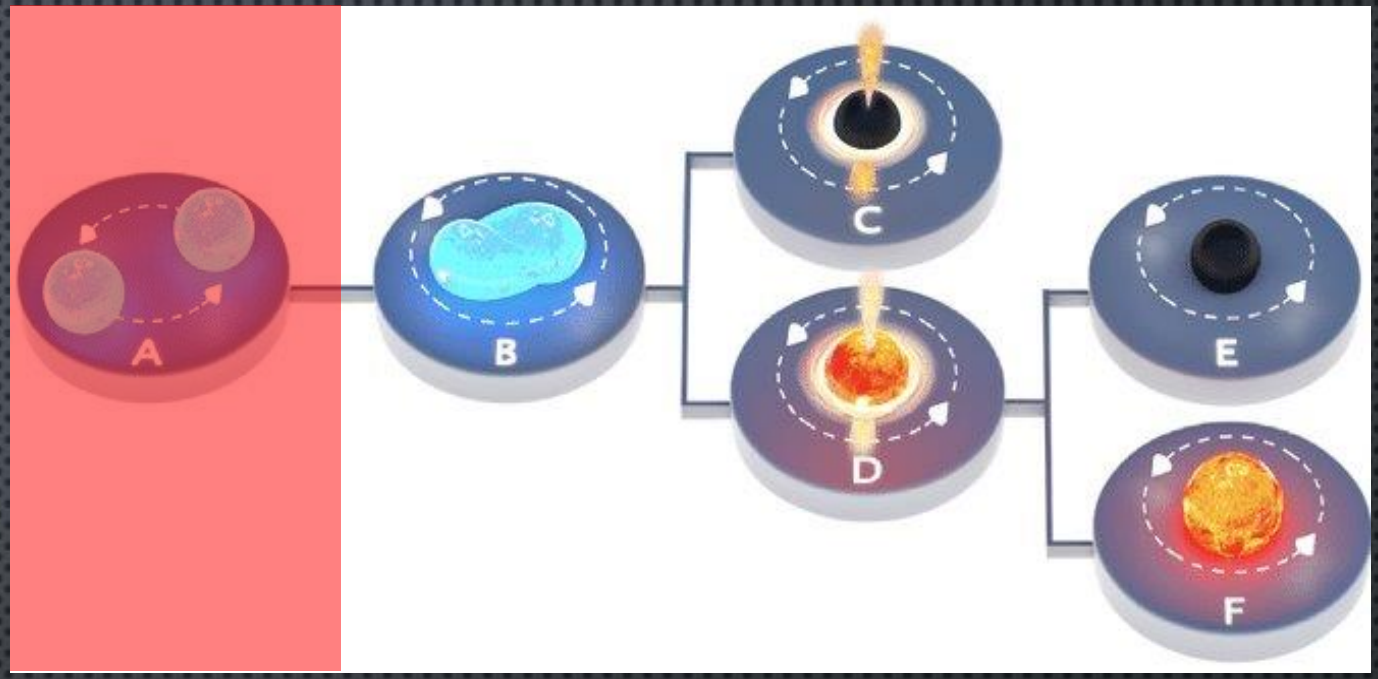
- BINARY BLACK HOLE (BBH)
- BINARY NEUTRON STAR (BNS)
  - KILONOVAE E.G. AT2017GFO
  - SHORT GAMMA RAY BURST (SGRB) 170817A
- SUPERNOVAE, PRIMORDIAL BH, …

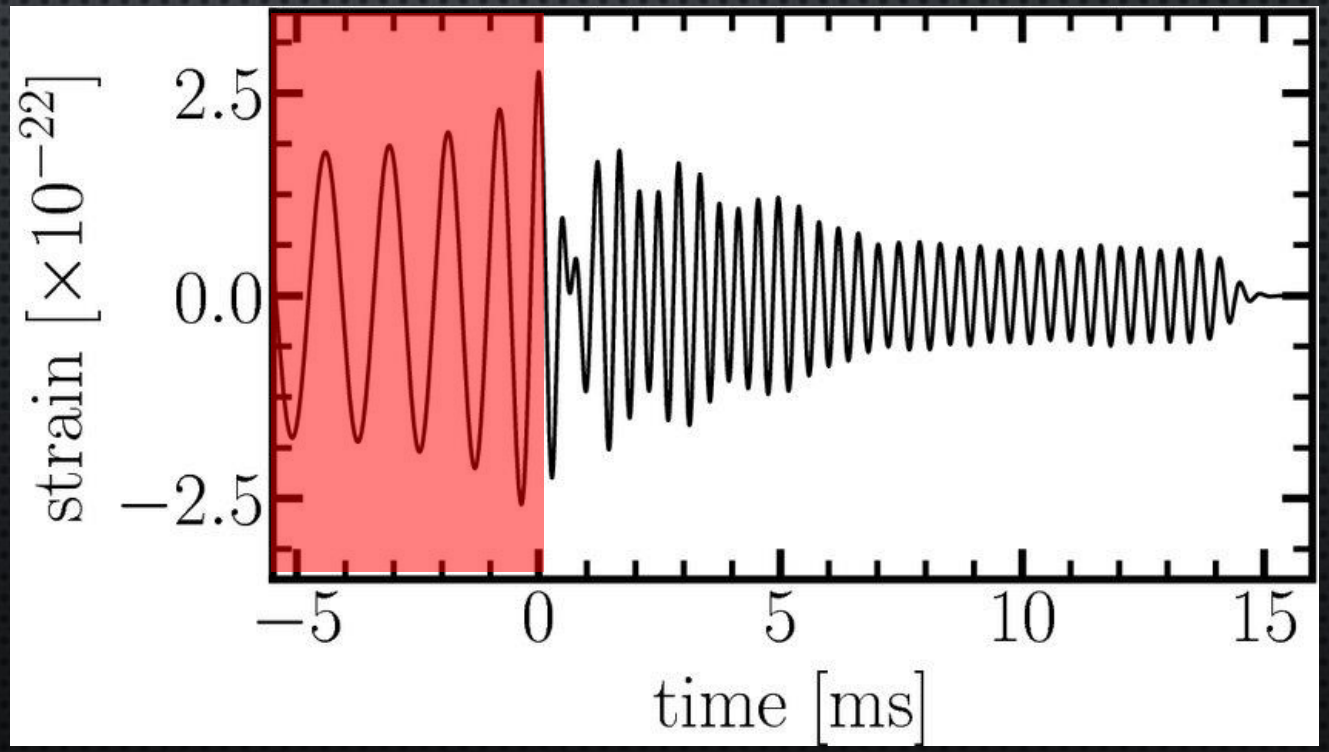


https://media.ligo.northwestern.edu/gallery/mass-plot

GRAVITATIONAL WAVES

- **INSPIRAL**
- POST MERGER
- HYPERMASSIVE NS
- BLACK HOLE / SUPRAMASSIVE NS





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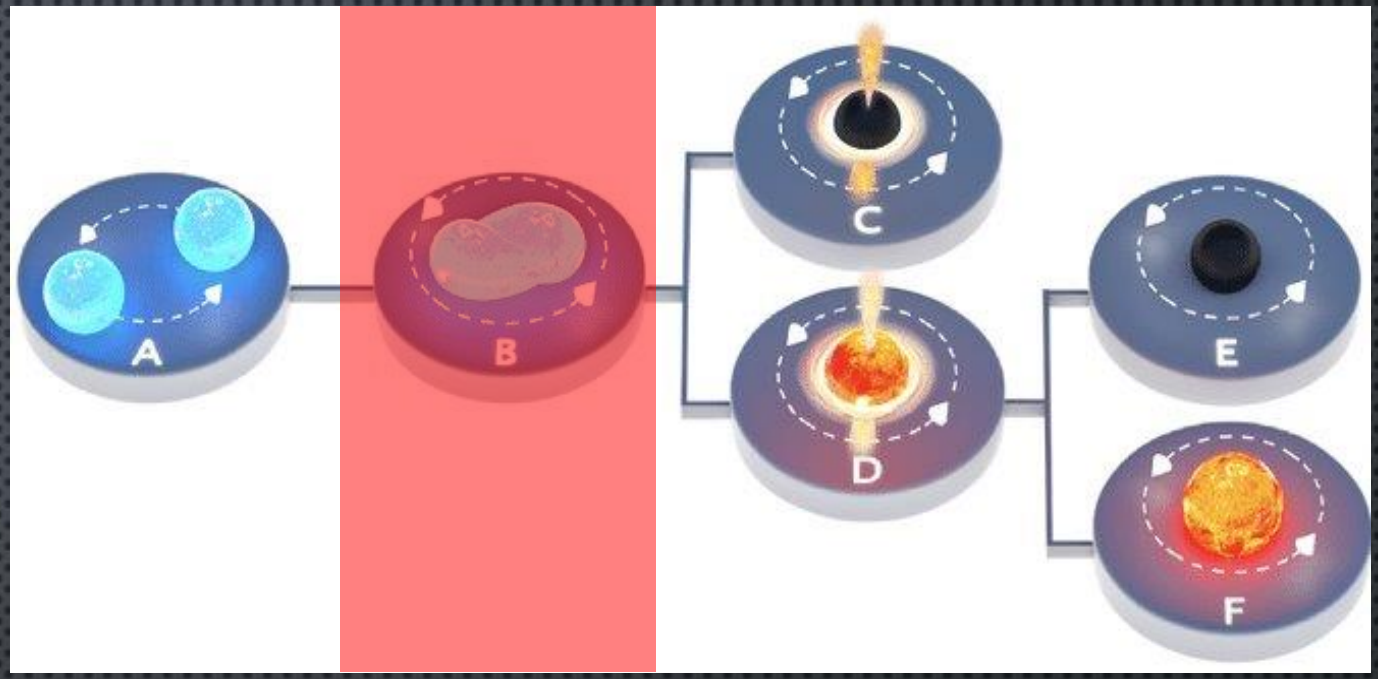

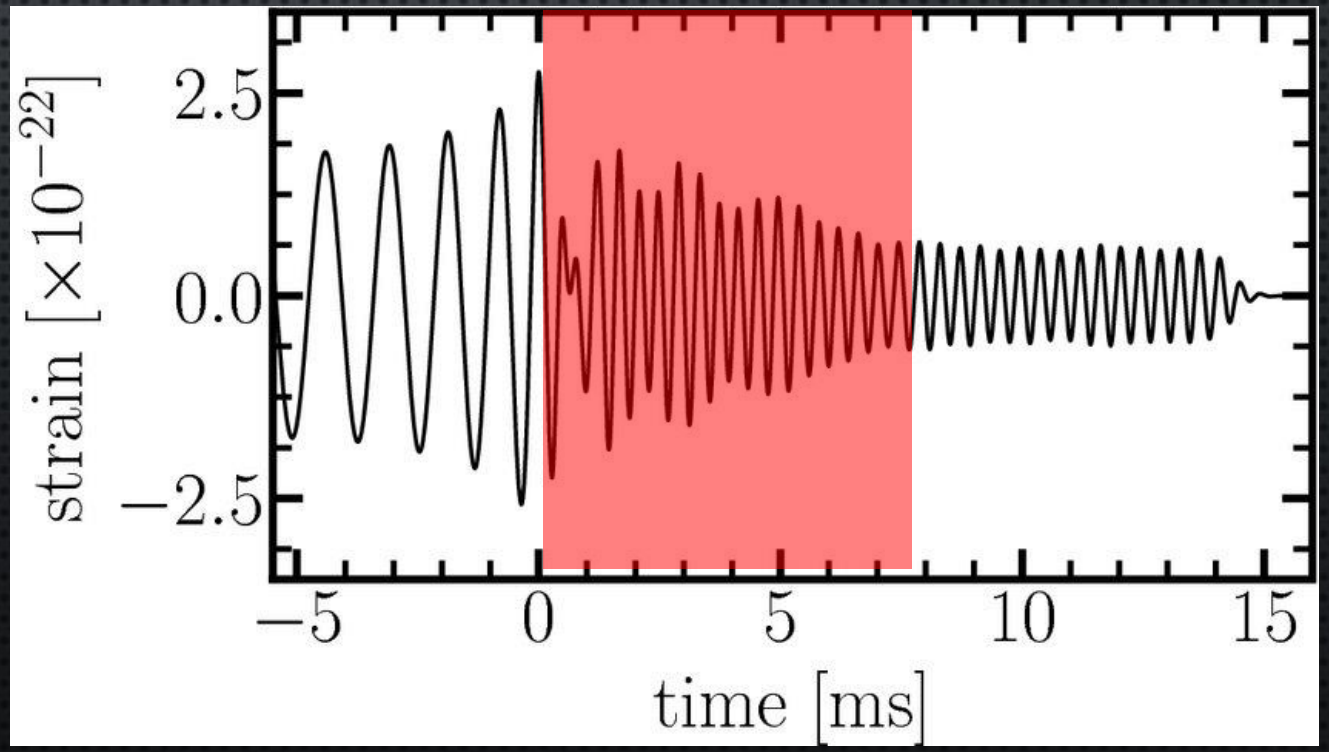

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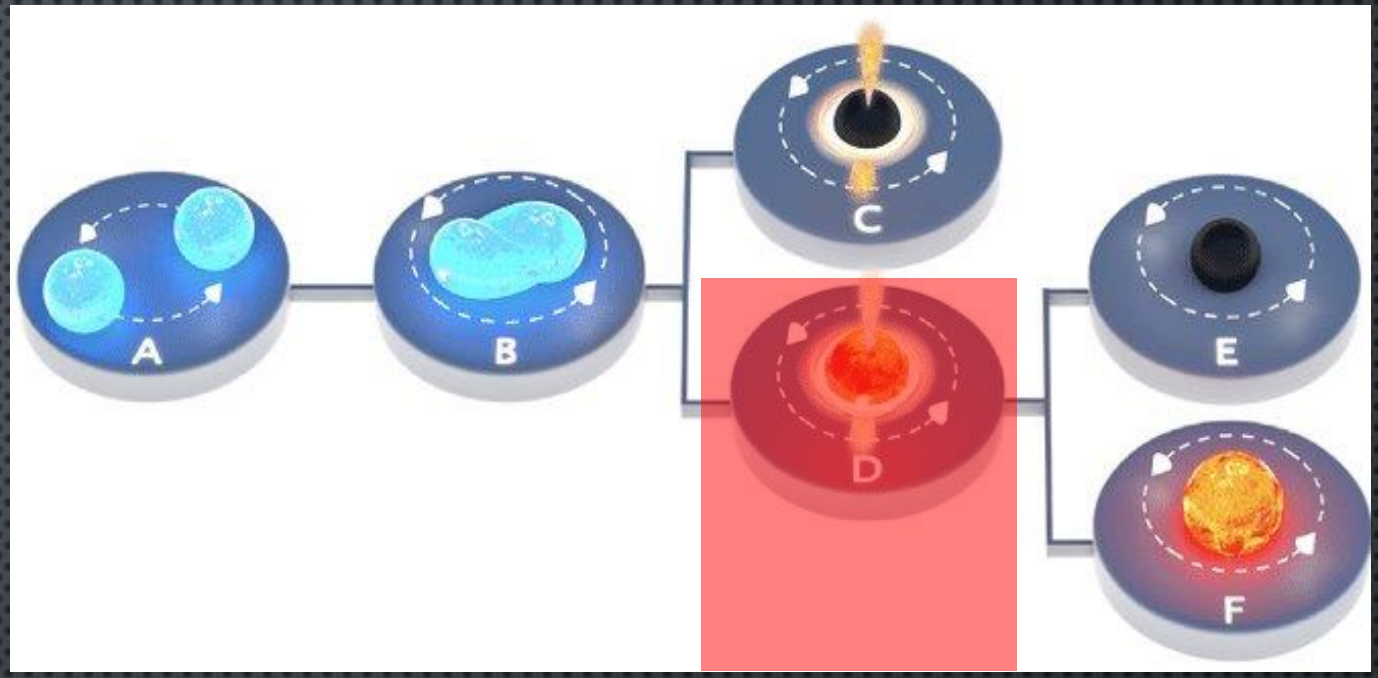

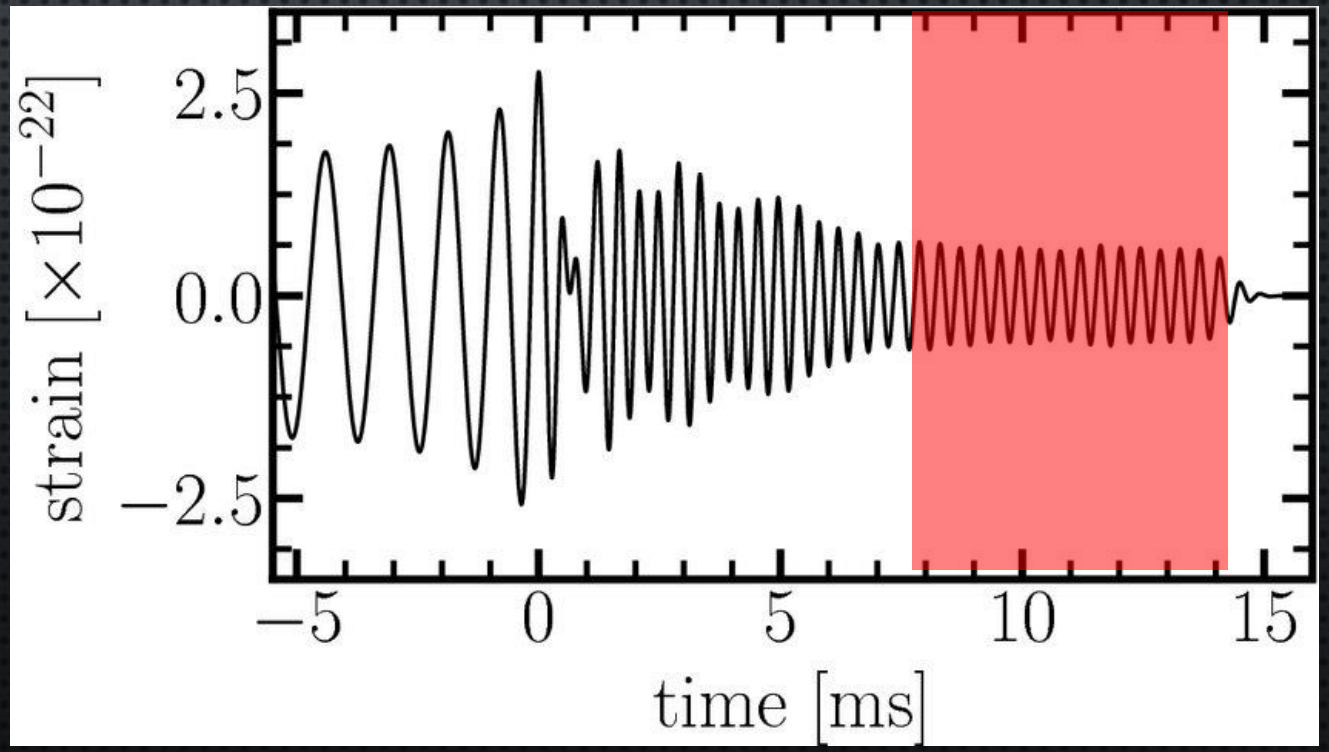

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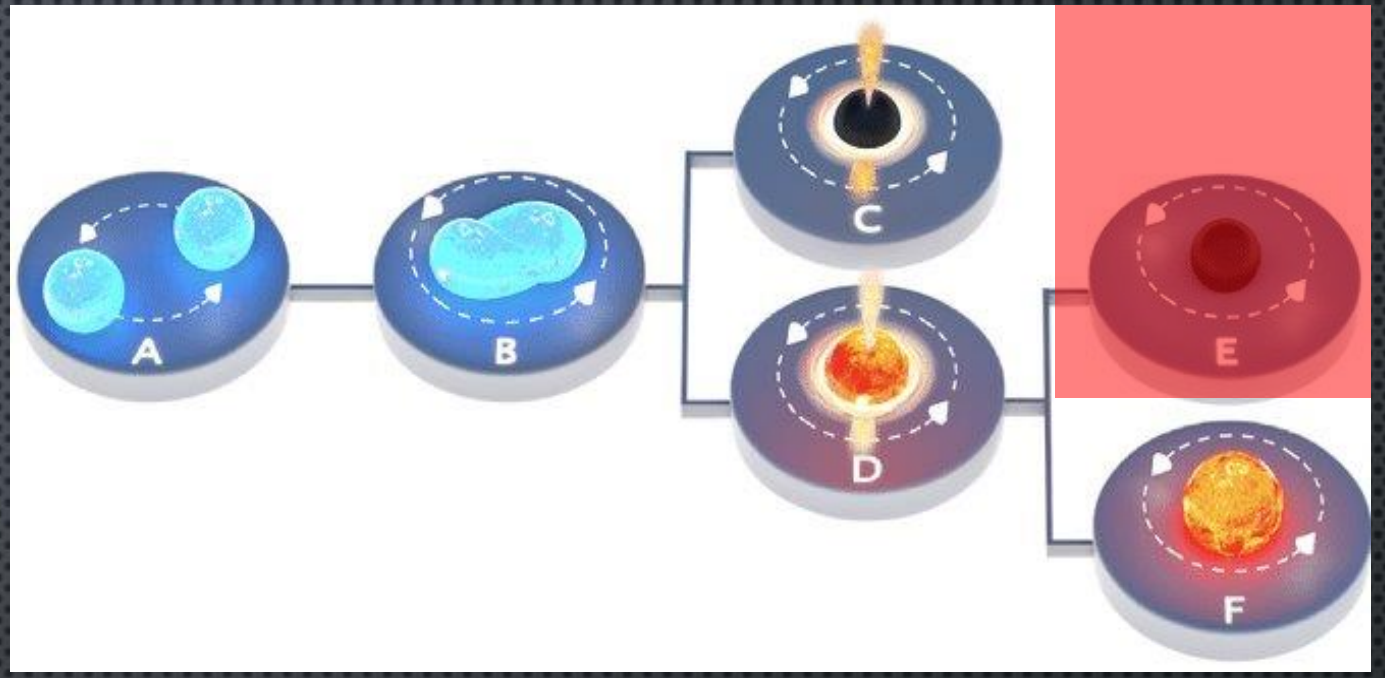
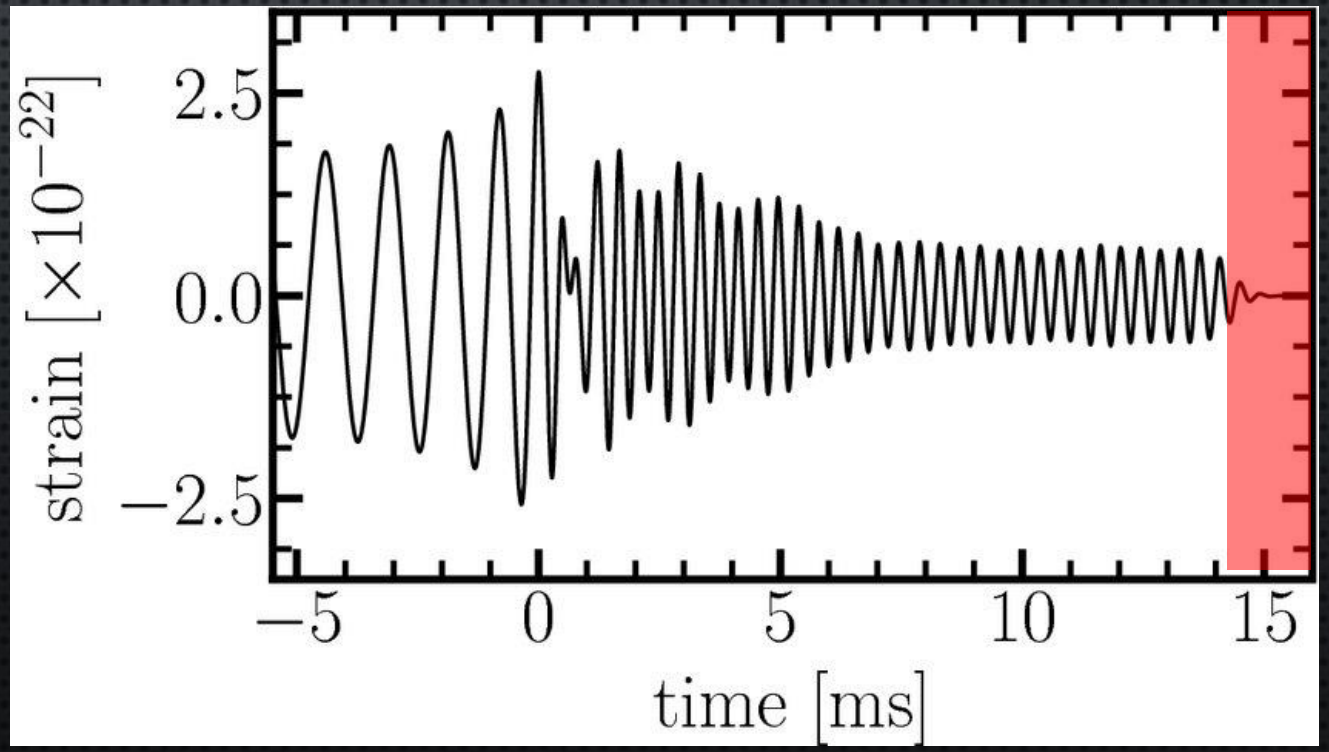




NUMERICAL SIMULATION OF BNS MERGER

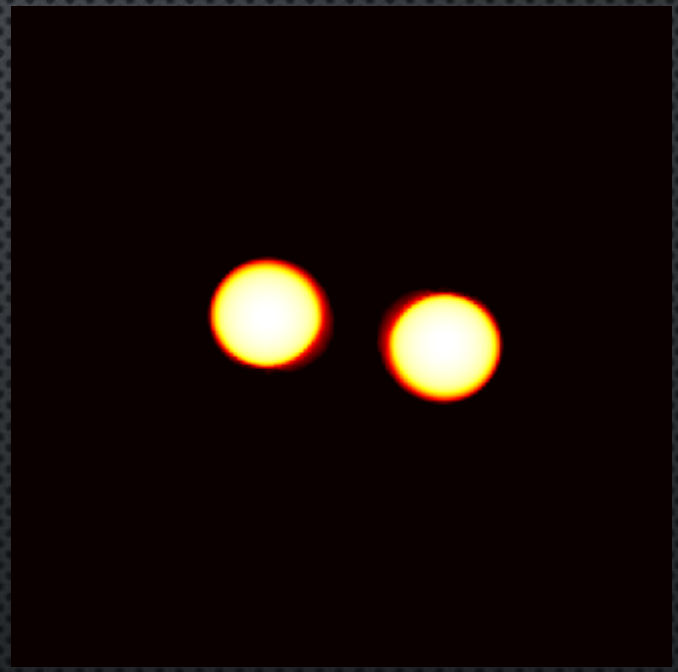
CODE FOR GENERAL RELATIVISTIC HYDRODYNAMIC SIMULATION:

EINSTEIN TOOLKIT

WWW.EINSTEINTOOLKIT.ORG

Equation of State (EoS):

- Tabulated
- Piecewise Polytrope (Approximation)



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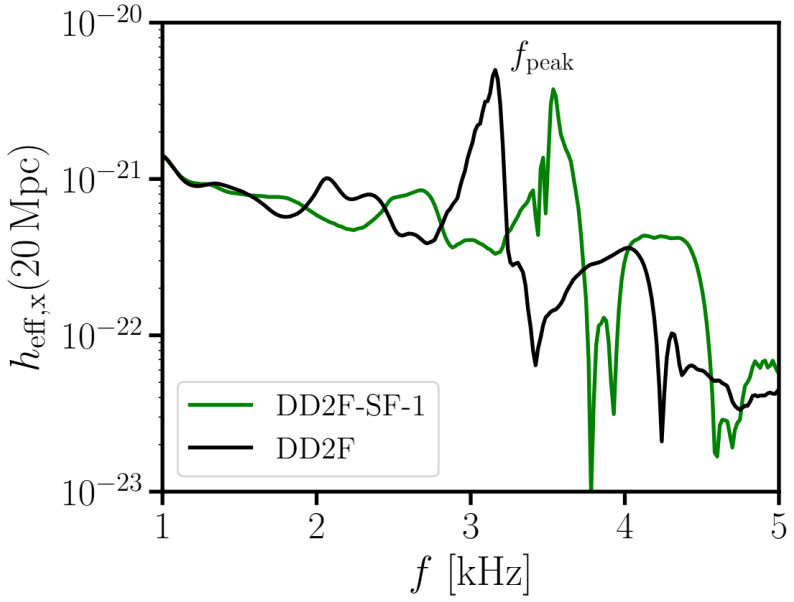
Equation of State (?)

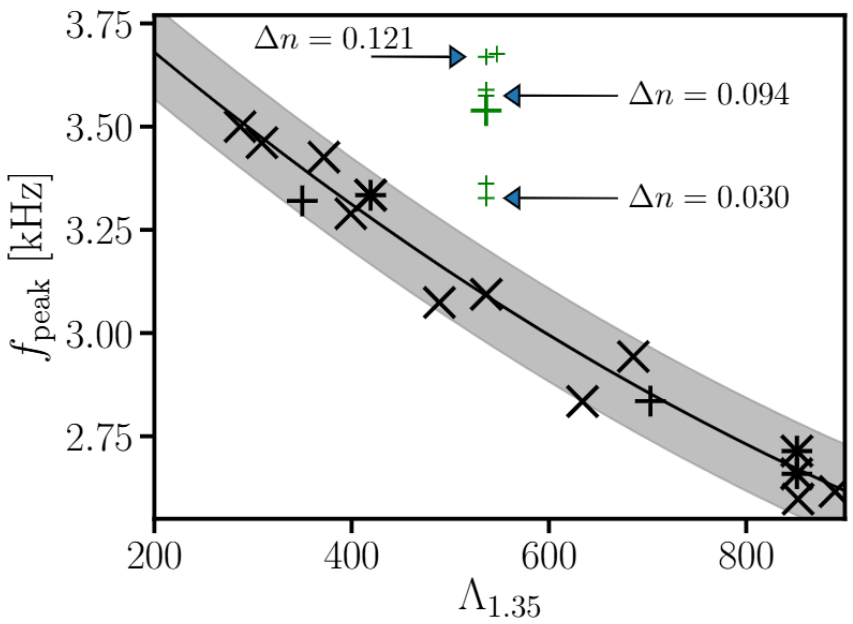
EOS: PHASE TRANSITIONS (PT)

- First order PT or Cross-over
- Hyperons or Deconfined Quark Matter (DQM)

Fourier Transformation of Gravitational Wave



Universal Relation: Tidal deformability vs Freq. peak



First order PT to DQM

Nucleonic EoS

Bauswein et al. 2019 Phys. Rev. Lett. **122**, 061102

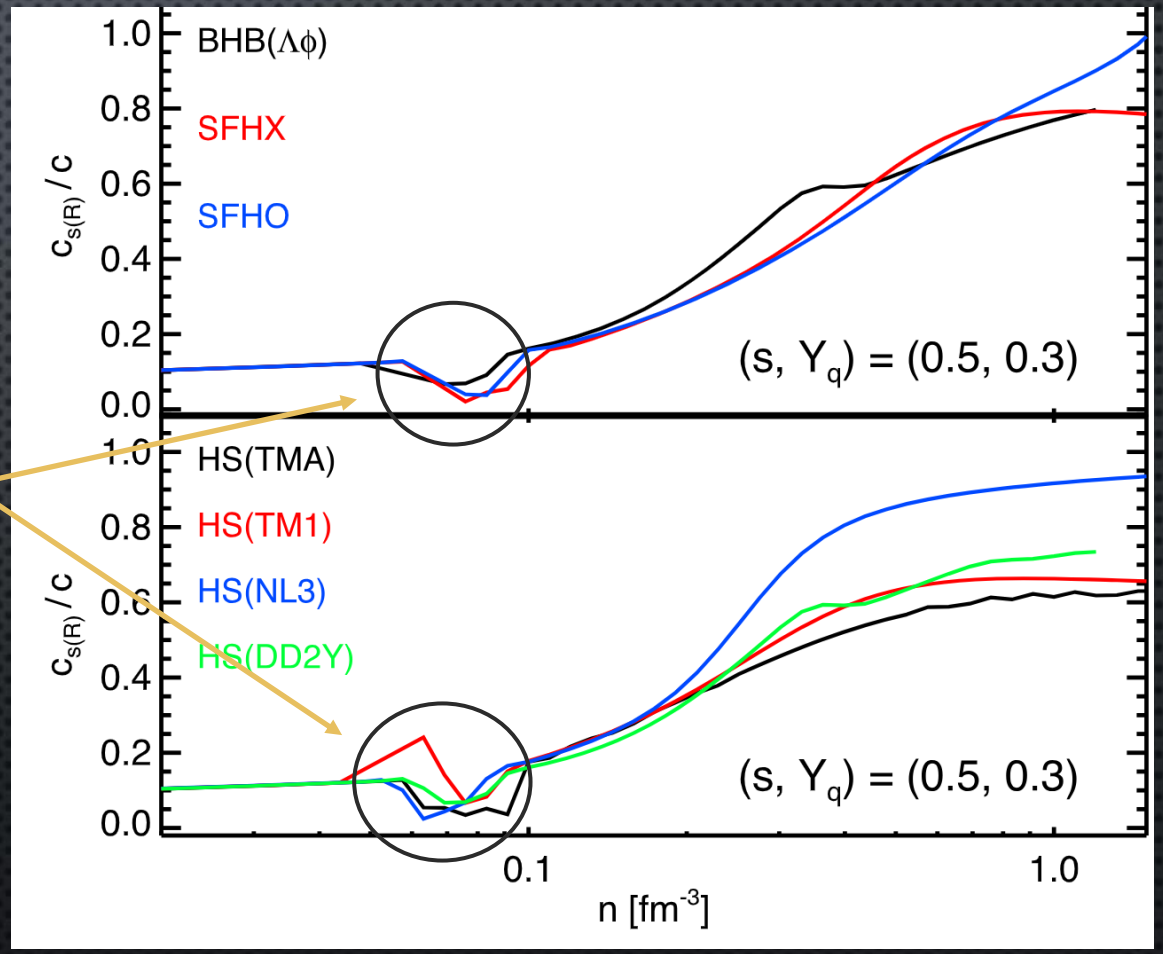
EOS: ANOMALOUS DYNAMICS IN PHASE TRANSITION

- SOUND SPEED $c_s^2 = \left.\frac{\partial P}{\partial \rho}\right|_S$

Non-Monotonic

- Phase Transition are in general **Non-Convex**

R Menikoff and B. Plohr Rev. Mod. Phys. 61, 75



M. A. Aloy et al. MNRAS 484, 4980 (2019)

EOS: CONVEXITY

FUNDAMENTAL DERIVATIVE $\mathrm{G} = 1 + \left.\frac{\partial \, ln \, c_s^2}{\partial \, ln \, \rho}\right|_S$

- MATERIAL IN EQUILIBRIUM ⇒ METASTABLE STATE
- SHOCKS ⇒ LOSS OF CONVEXITY ⇒ PHASE TRANSITION

$\mathrm{G} < 0 \Rightarrow$ Non-convex

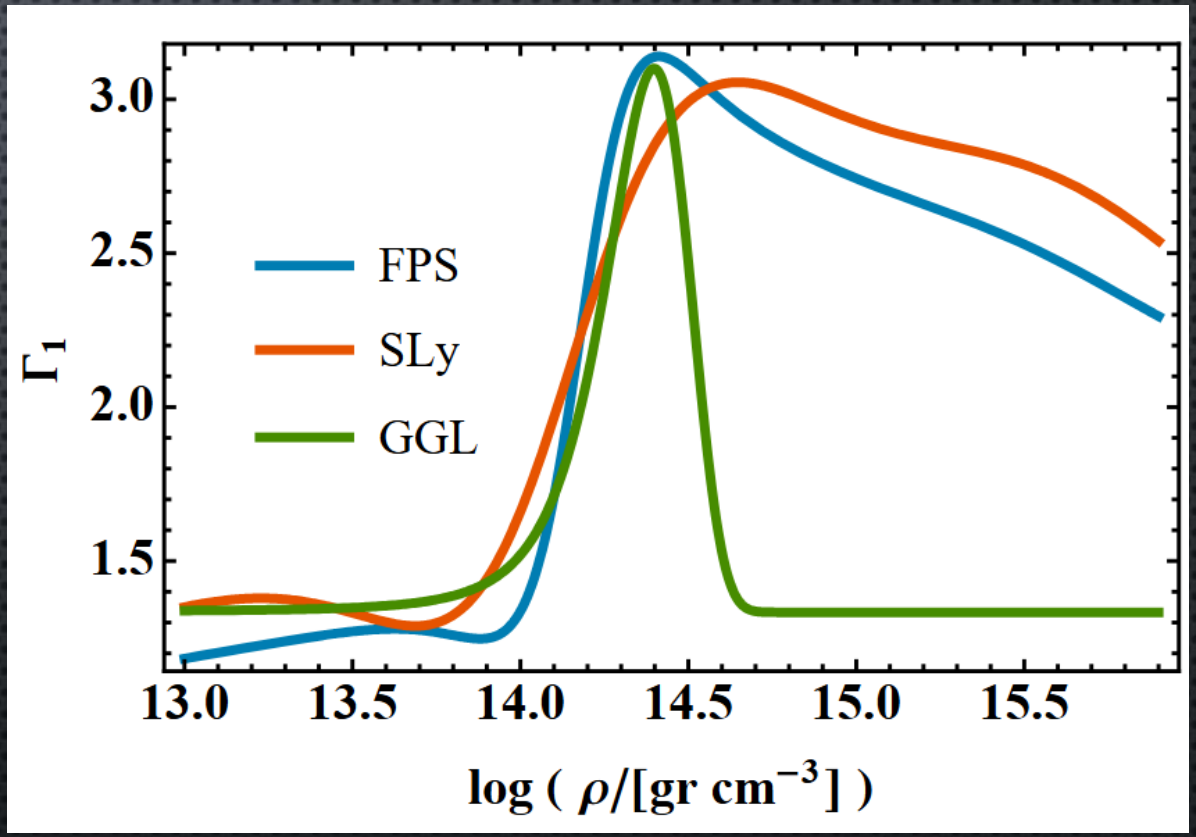
What is the contribution of Non-Convexity?

EOS: GGL MODEL

- Piecewise Polytrope:

$$P_{th} = (\Gamma - 1)\epsilon_{th} n$$

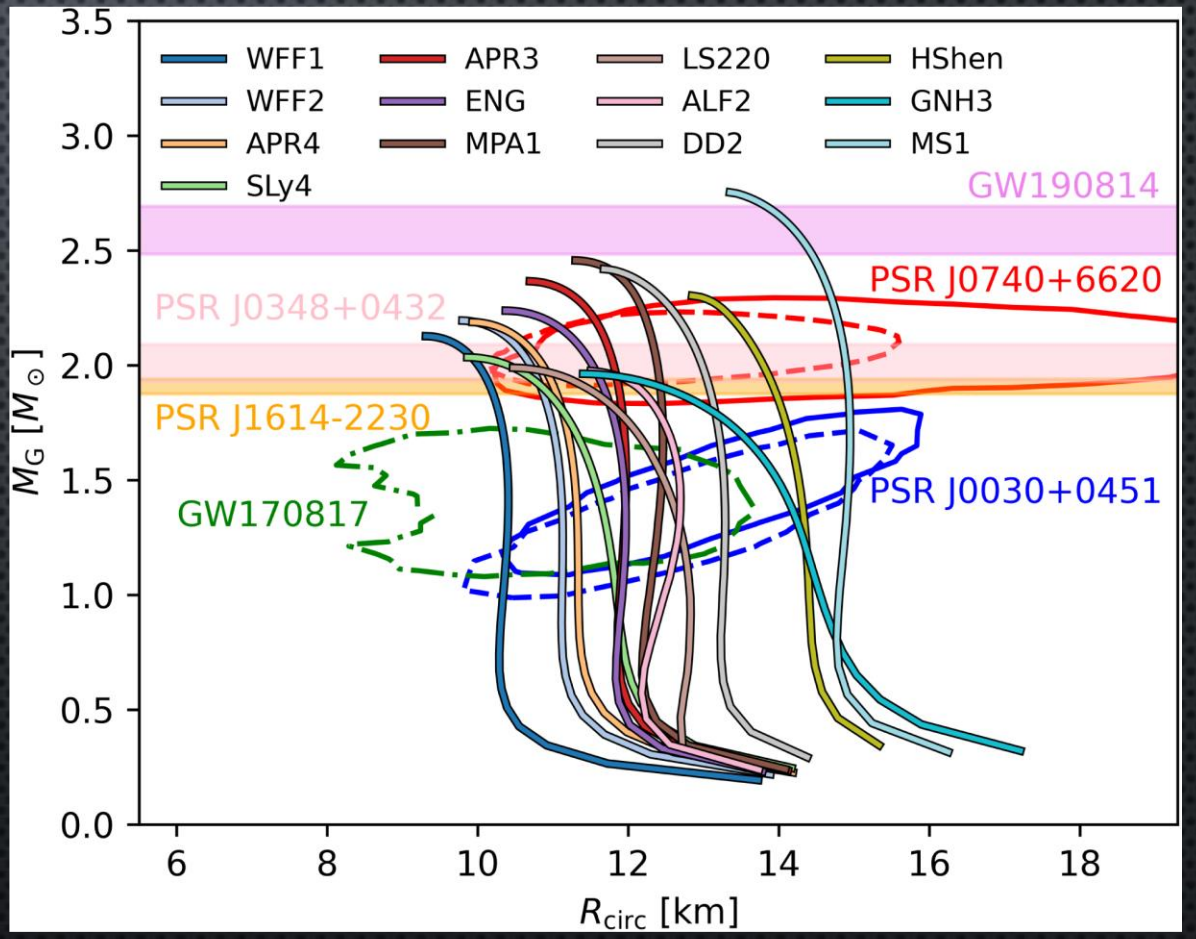
  - Typically $\Gamma = 1.8$ **constant!**
- Gaussian Gamma Law EoS:
  - $\Gamma(\rho) = \Gamma_0 + (\Gamma_1 - \Gamma_0) e^{-\frac{(\rho-\rho_1)^2}{\Sigma^2}}$
  - $\Gamma_0 = 1.8$



M. A. Aloy et al. (2018)

EOS: INITIAL DATA

EOS	M	$\mathcal{C}$	Λ	$M_{\rm ADM}$	$J_{\rm ADM}$	Ω	$\rho_{0,\rm max}$
WFF1	1.26	0.18	406.07	2.50	6.45	1.76	$10^{15.01}$
WFF2	1.27	0.17	1115.06	2.52	6.54	1.76	$10^{14.90}$
APR4	1.28	0.17	440.75	2.52	6.56	1.77	$10^{14.93}$
SLy4	1.28	0.16	511.70	2.54	6.62	1.77	$10^{14.93}$
APR3	1.28	0.16	620.00	2.53	6.61	1.77	$10^{14.86}$
ENG	1.28	0.16	636.35	2.53	6.60	1.77	$10^{14.87}$
MPA1	1.28	0.15	784.52	2.54	6.64	1.77	$10^{14.81}$
LS220	1.29	0.15	899.05	2.55	6.69	1.77	$10^{14.84}$
ALF2	1.29	0.15	941.42	2.54	6.66	1.77	$10^{14.79}$
DD2	1.29	0.13	1113.92	2.56	6.73	1.78	$10^{14.76}$
HShen	1.30	0.14	1633.24	2.58	6.82	1.78	$10^{14.69}$
GNH3	1.30	0.13	1371.15	2.58	6.81	1.78	$10^{14.77}$
MS1	1.30	0.13	2020.75	2.58	6.83	1.79	$10^{14.63}$



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EVOLUTION

Code for General Relativistic Hydrodynamic Simulation:

Einstein Toolkit

www.einsteintoolkit.org

→

Cold Piecewise Politrope

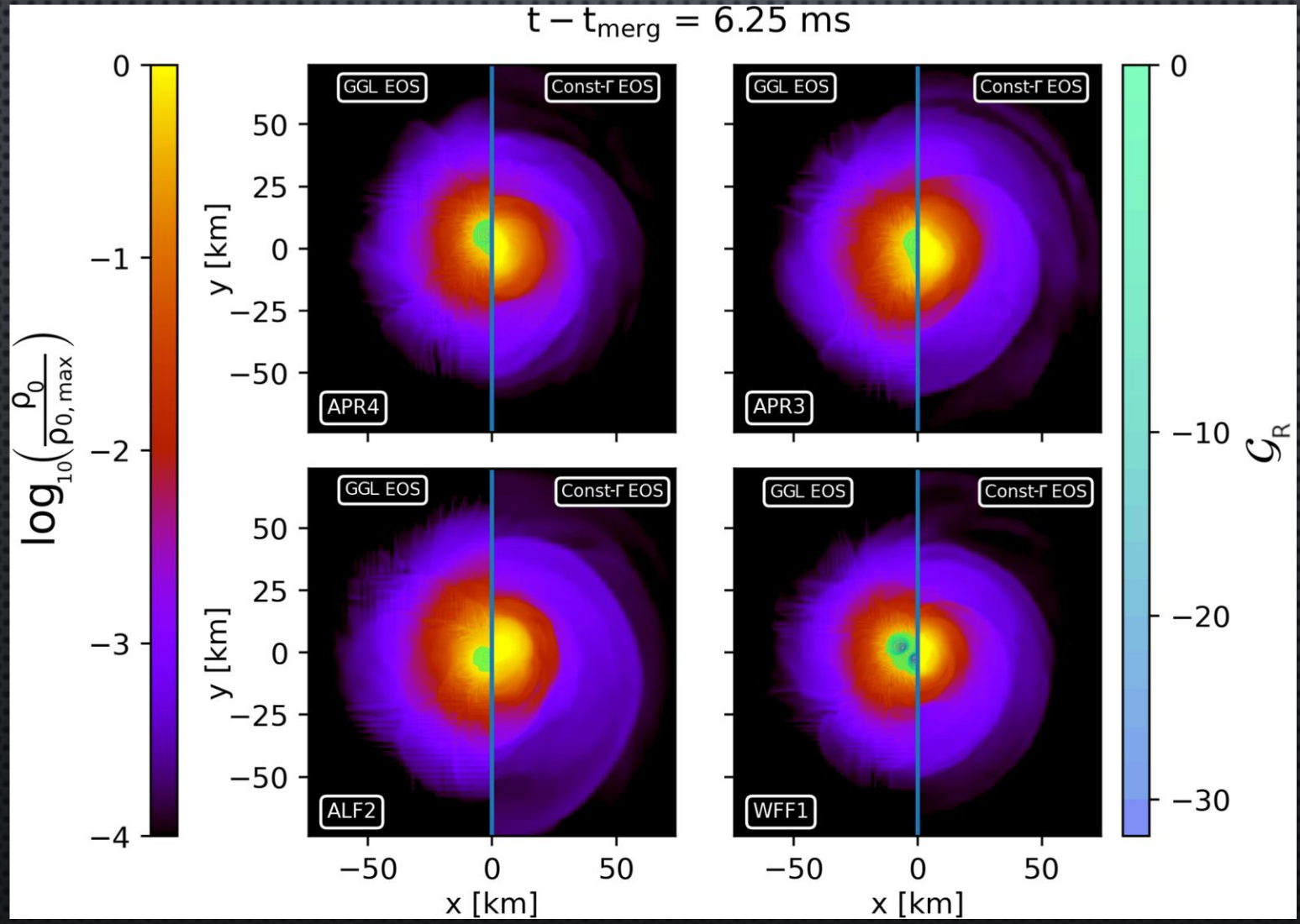
+

$$P_{th} = (\Gamma - 1)\epsilon_{th} n$$

→ $\Gamma = \text{const}$

→ GGL EOS

RESULTS: NON-CONVEX CORE AND NO SPIRAL ARM



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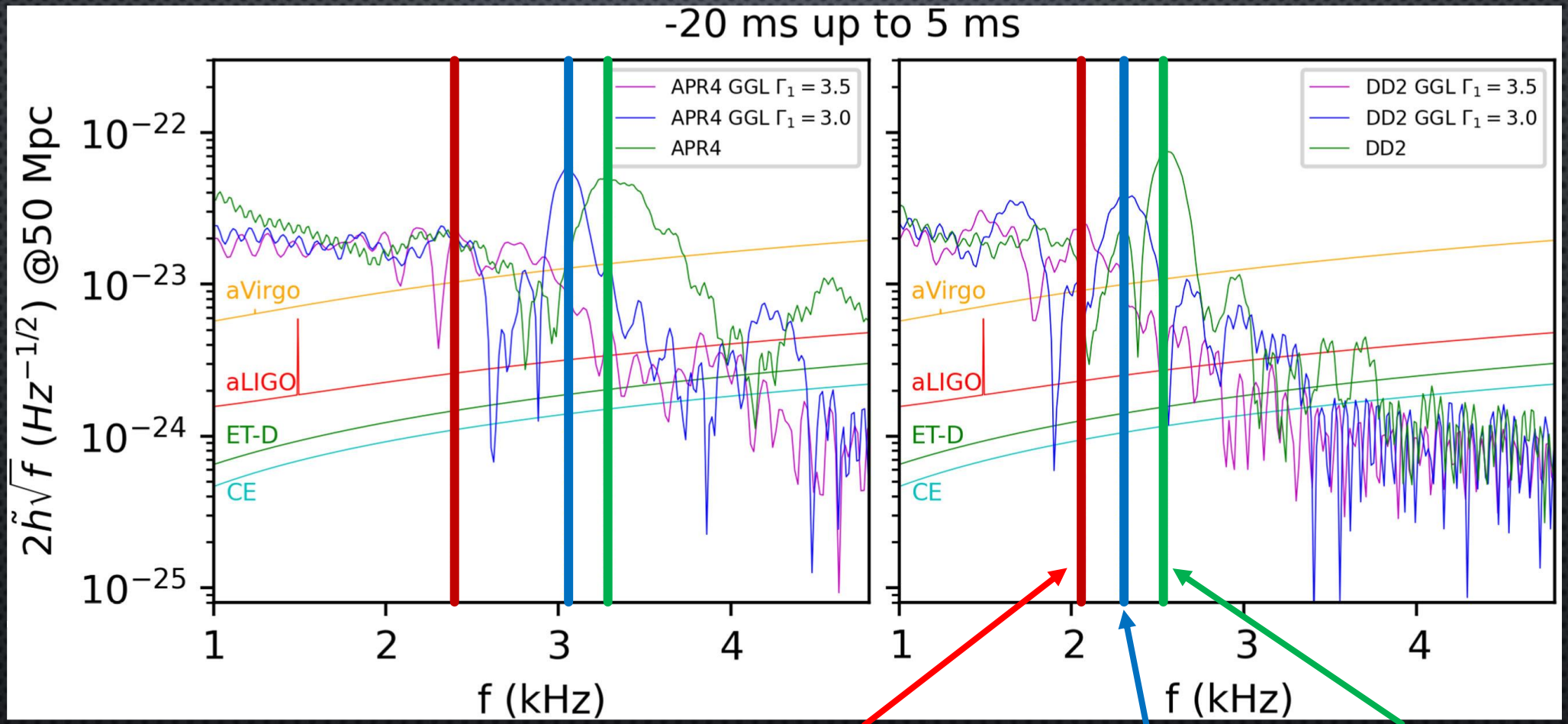
RESULTS: GENERAL SHIFT ON THE LEFT OF THE MAIN POST-MERGER PEAK IN FREQUENCY



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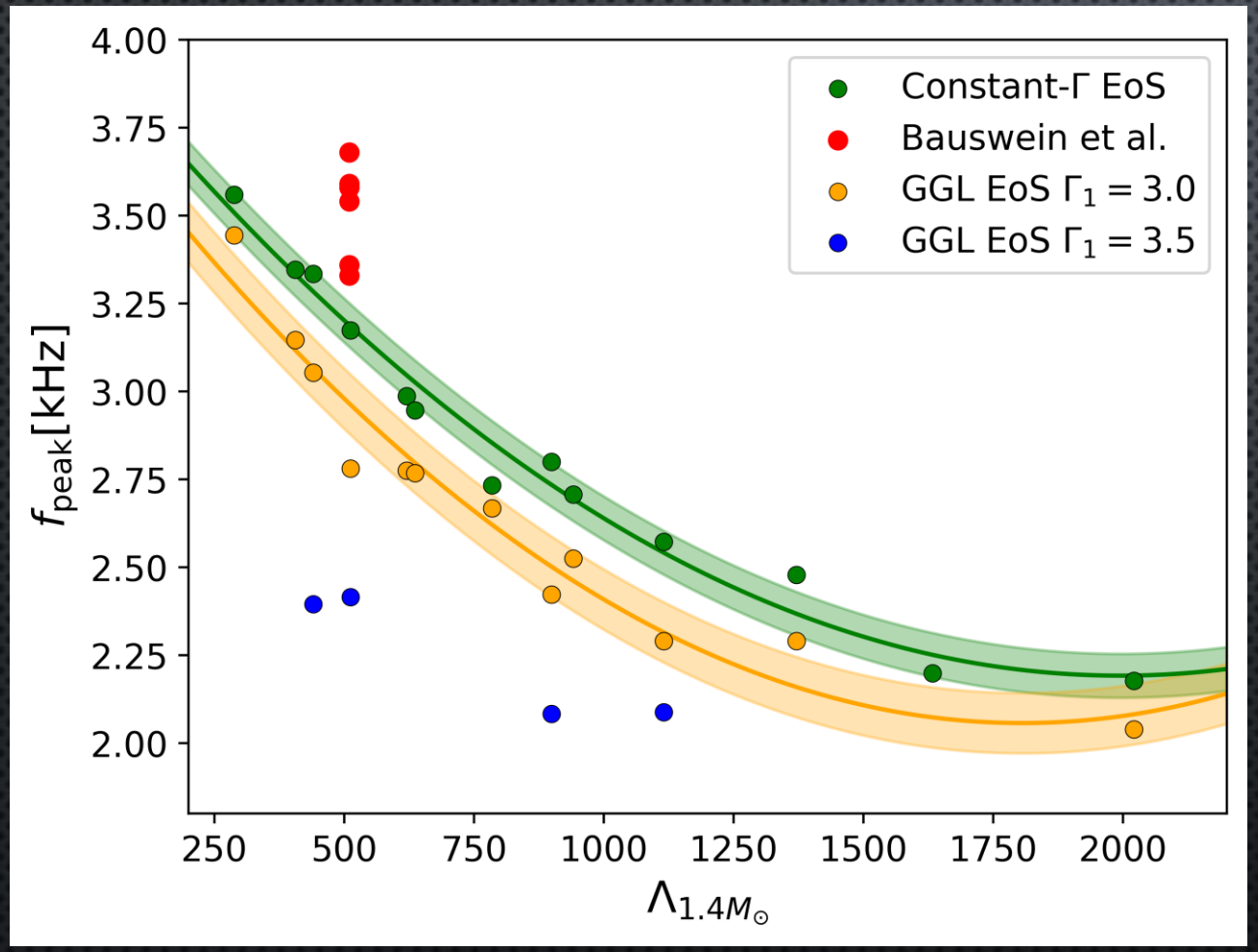
GGL $\Gamma_1 = 3.5$

GGL $\Gamma_1 = 3.0$

STANDARD $\Gamma = 1.8$

QUASI-UNIVERSAL RELATION



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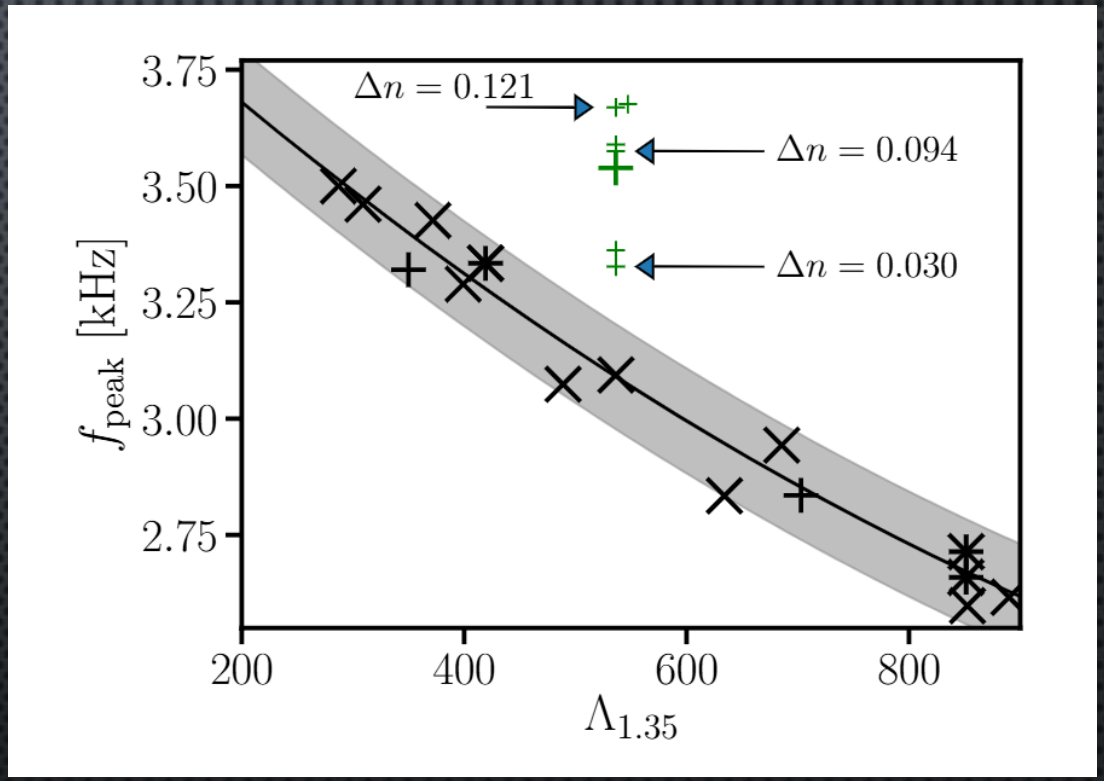

Bauswein et al. 2019 Phys. Rev. Lett. **122**, 061102

Take-home messages

- Numerical Simulation to constrain EoS
- Non-Convexity Enhances the effect of transition
- **Evaluate the Fundamental Derivative to better understand the EoS properties and observables**

THANKS!

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