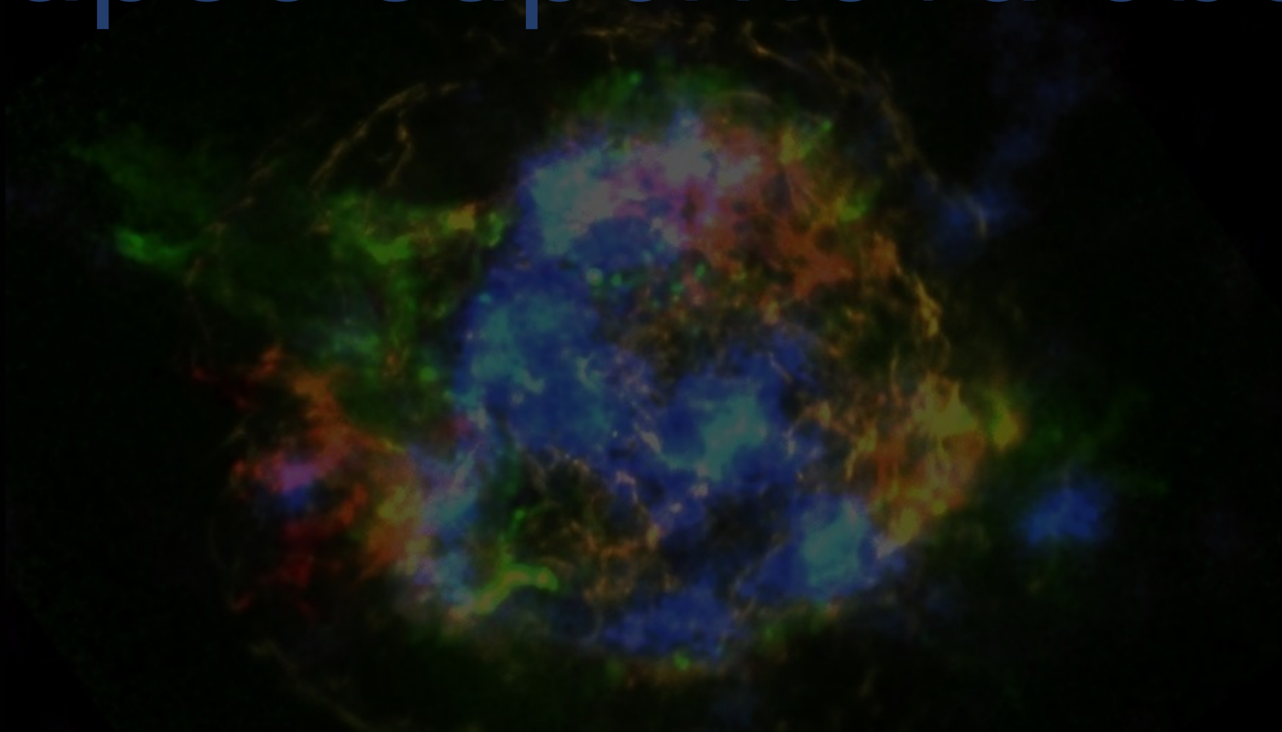
The nuclear equation of state and core-collapse supernova observables



Carla Fröhlich

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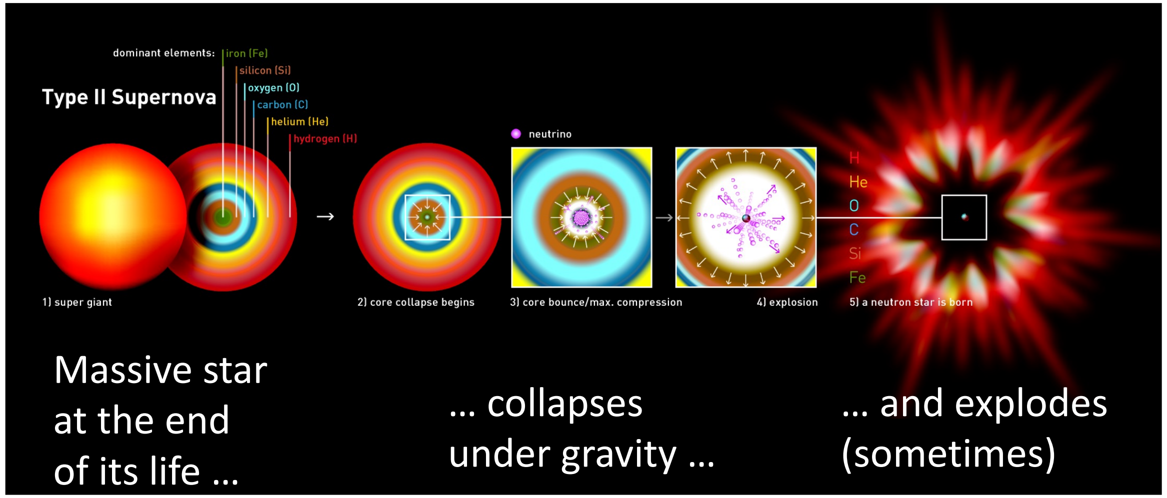
23 Jan 2024

Core-collapse supernova simulations

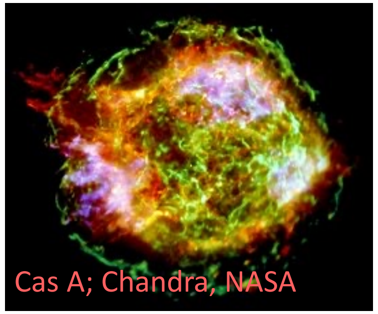


Massive star at the end of its life …

… collapses under gravity …

… and explodes (sometimes)

- Multi-dimensional problem
- Multi-physics problem:
  - General relativity
  - Nuclear physics of dense matter
  - Neutrino transport (trapped, diffusive, free-streaming regimes)
- Multi-scale problem:
  - shock formation at ~200 km vs entire star 10^8 km
  - collapse and shock formation ~1 s vs shock breakout ~1 day



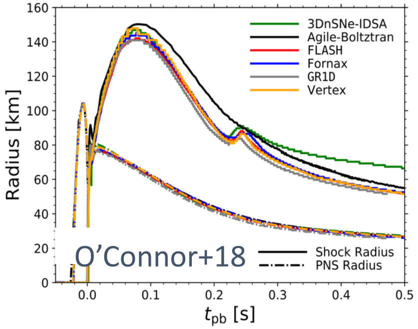
Cas A; Chandra, NASA

Simulation Status:

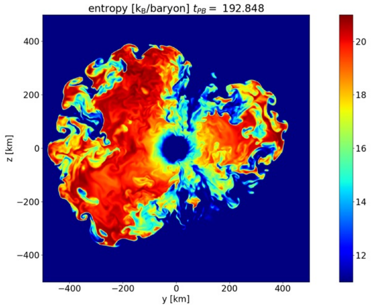
1D: in general no self-consistent explosions
~10 CPUh/model

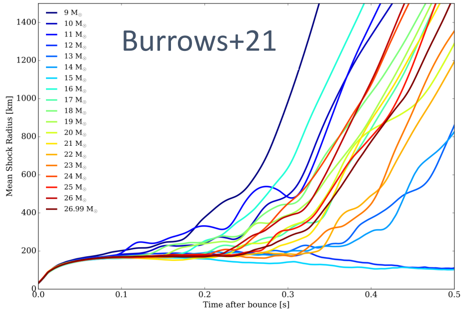
2D: models have converged

3D: mixed results
~ Mio CPUh/model



O'Connor+18





Burrows+21

Paths forward?

- Self-consistent 3D simulations (only a few)
- Effective models (many, O(1000))

Effective Supernova Models

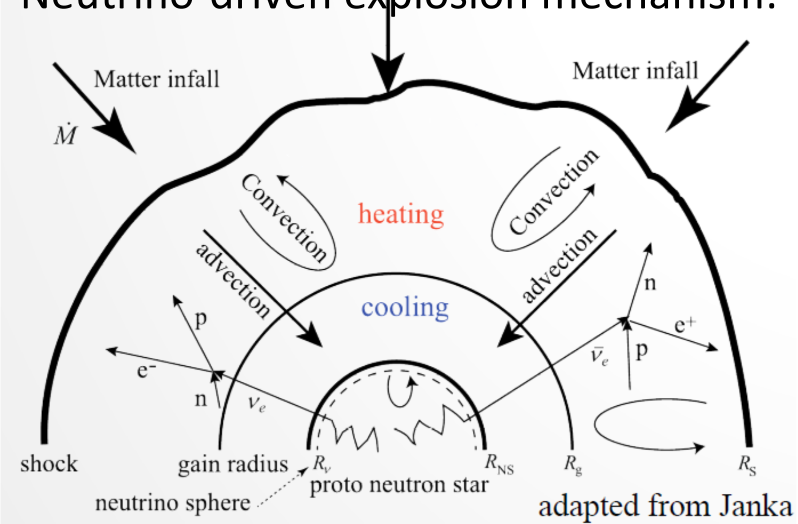
- Parametrize an aspect of multidimensional simulations in spherical symmetry
  - Pro: Computationally efficient → many simulations are possible
  - Con: Have parameters that require tuning

- Examples of effective models and semi-analytic models
  - PUSH Perego+15, Ebinger+19
  - PHOT-B Ertl+16, Ugliano+12
  - STIR Couch+20

  Semi-analytic models:
  - Pejcha+15
  - Muller+16

- Self-consistent within the model framework → make predictions

Neutrino-driven explosion mechanism:



adapted from Janka

From explosions to observables

progenitor

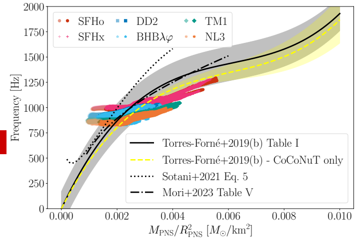
EOS

PUSH

Hydrodynamics simulation With Neutrino transport

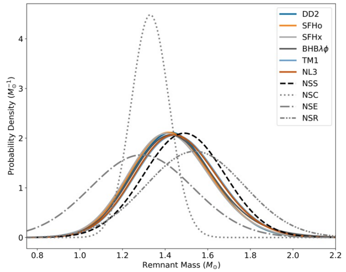
GW Frequencies

Wolfe+23



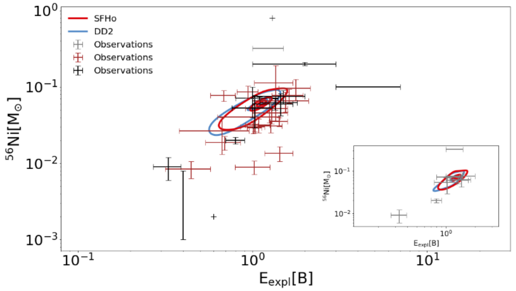
Remnant properties

Meskhi+22



Explosion properties

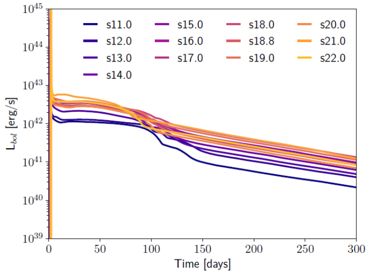
Ebinger+19; Ebinger+20; Ghosh+22



SNEC Radiation-hydro

Bolometric lightcurves

Curtis+21



SuperNu MC photon transport

Broadband LCs Spectra

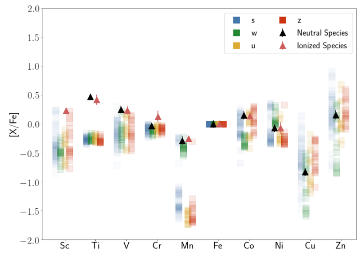
Curtis+21

Mass tracers

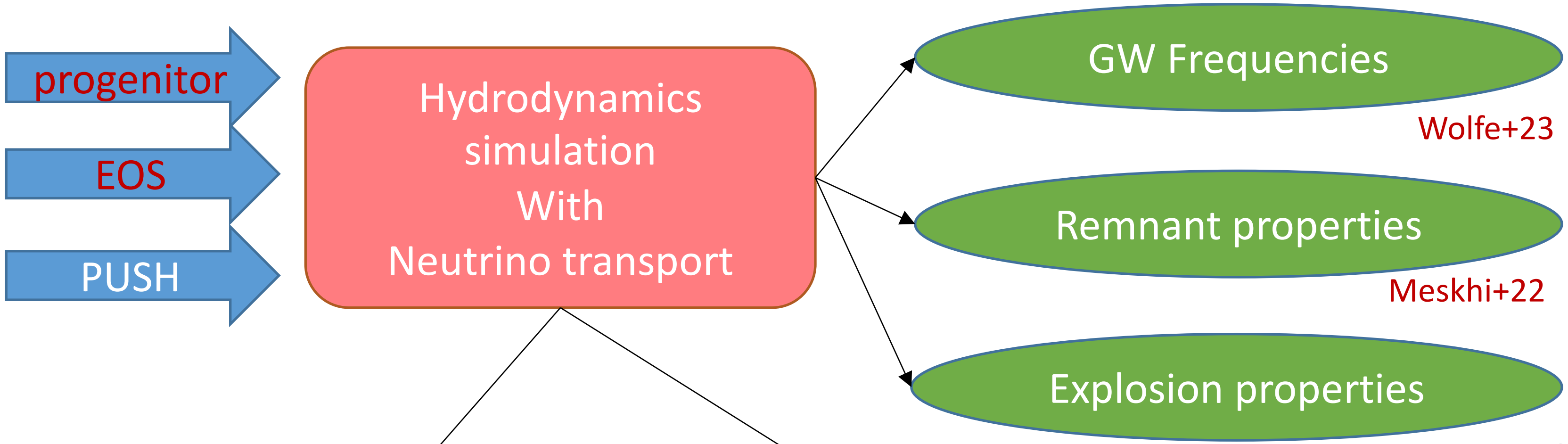
Nuclear Reaction Network

Nucleosynthesis Yields

Curtis+19



From explosions to observables



progenitor

EOS

PUSH

Hydrodynamics simulation With Neutrino transport

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Wolfe+23

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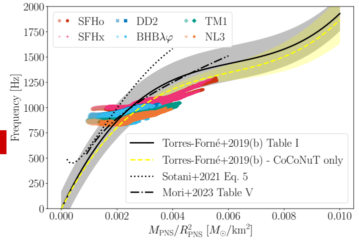

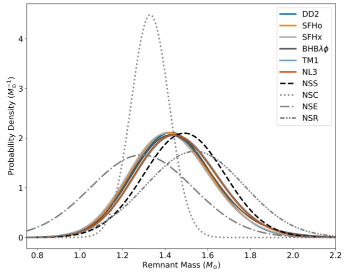

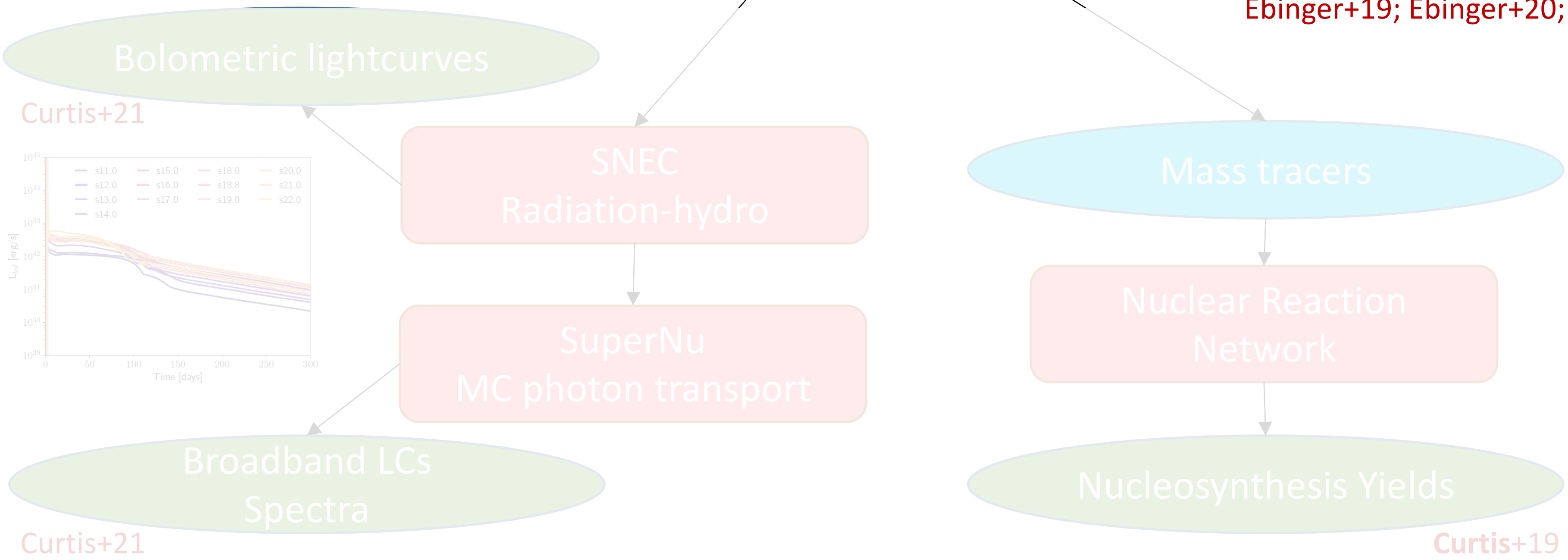

Bolometric lightcurves

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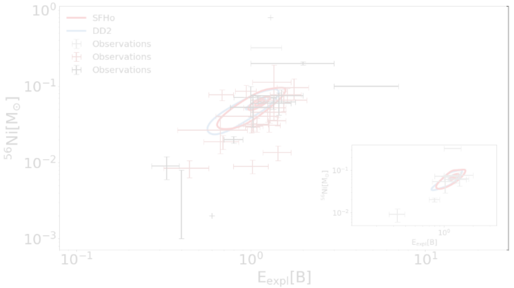
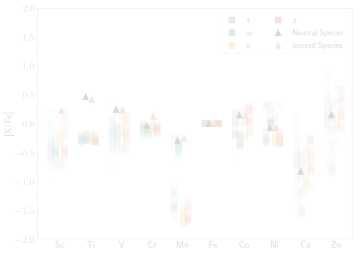
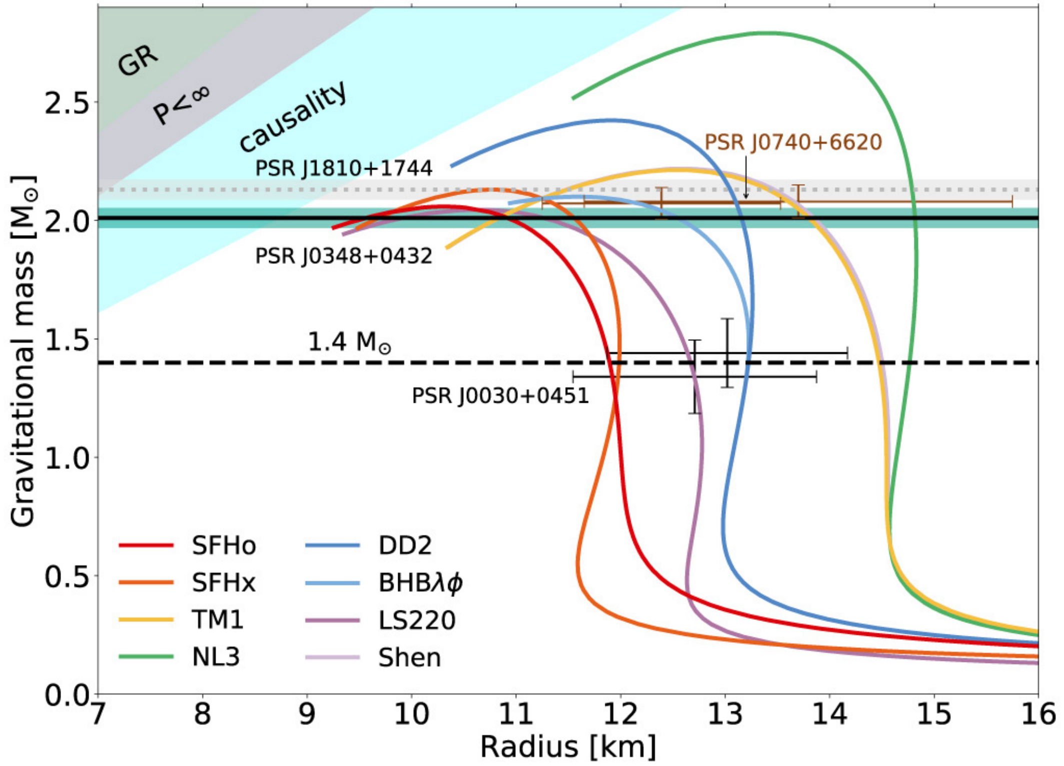




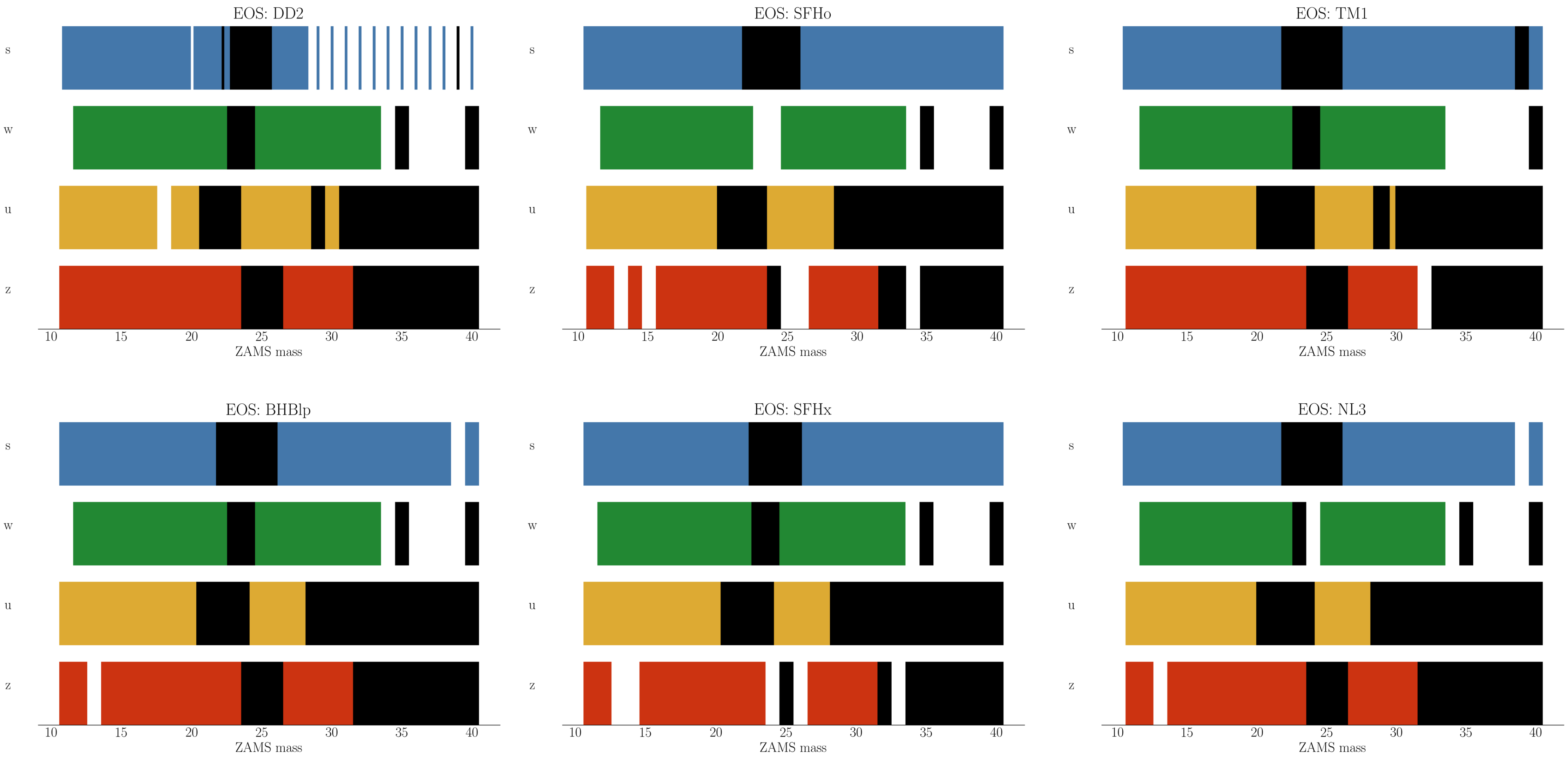
Inputs: progenitors and nuclear EOSs



Progenitors:

- 11-40 Msun (mostly 1Msun increments)
- Three metallicities: solar, low, zero

1500 Supernova Simulations: What can we learn about the EOS?



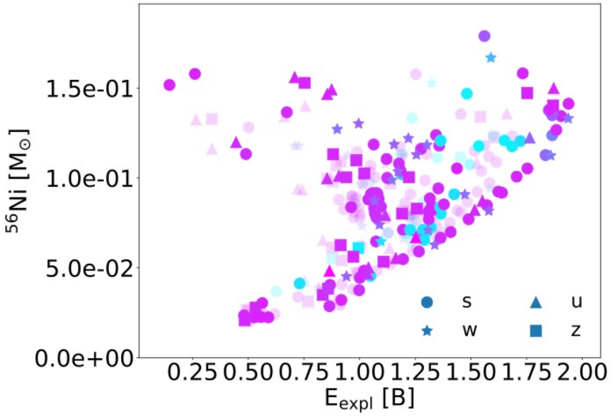
1500 Supernova Simulations: What can we learn about the EOS?

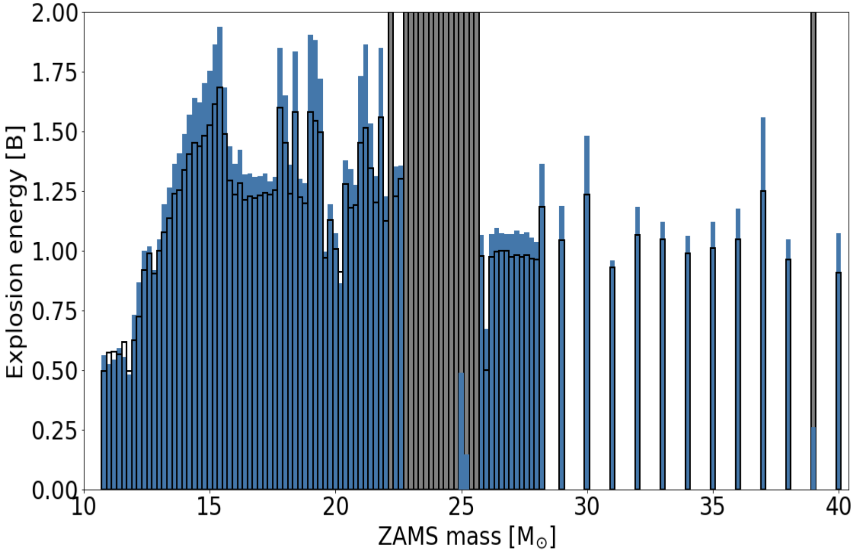
- "Obvious" supernova observables: 56Ni and explosion energy
- Statistical analysis of remnant mass distributions
- GW eigenfrequency analysis for neutron stars

Explosion energy and ^{56}Ni yields

Ghosh+22

→ In PUSH: Explosion energy and 56Ni mass emerge self-consistently with each other





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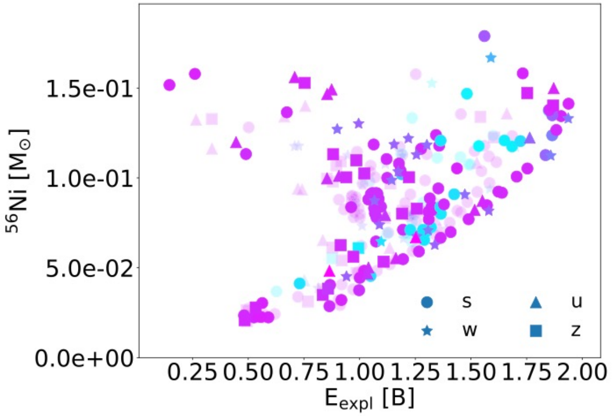
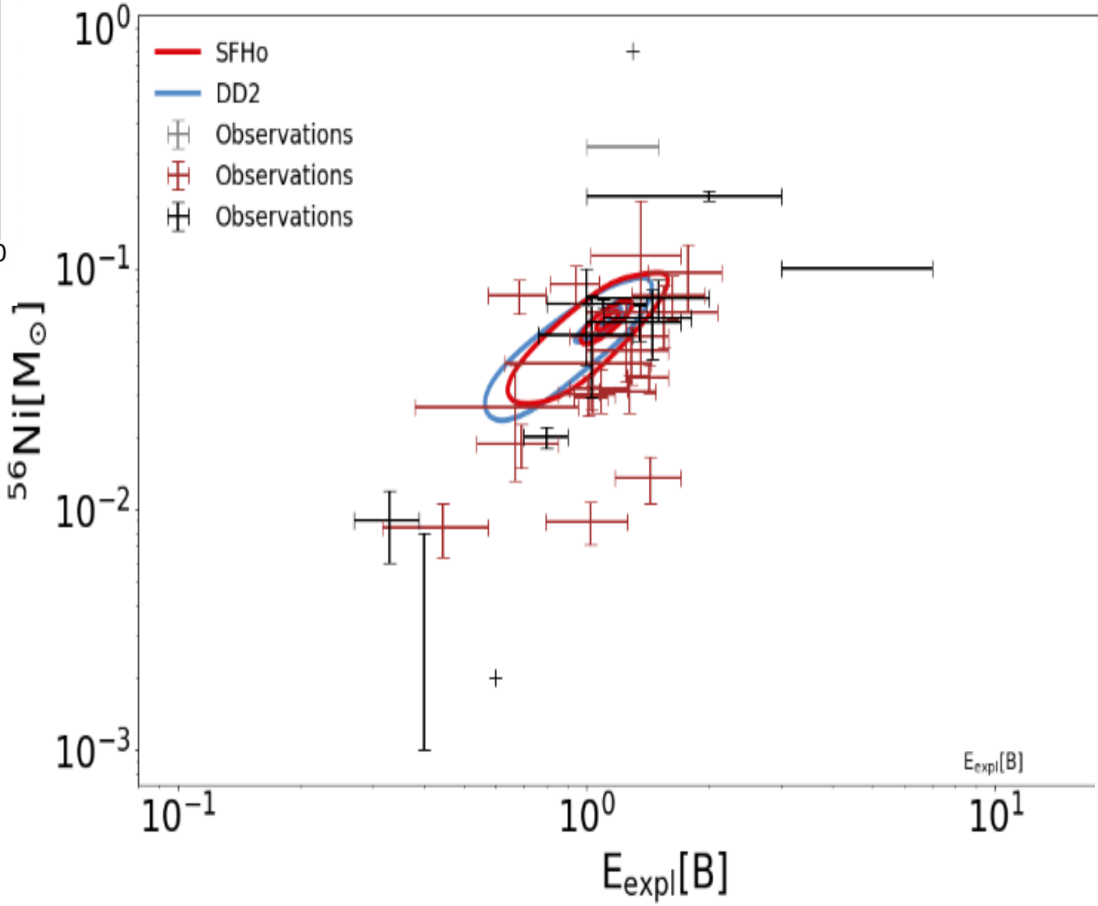
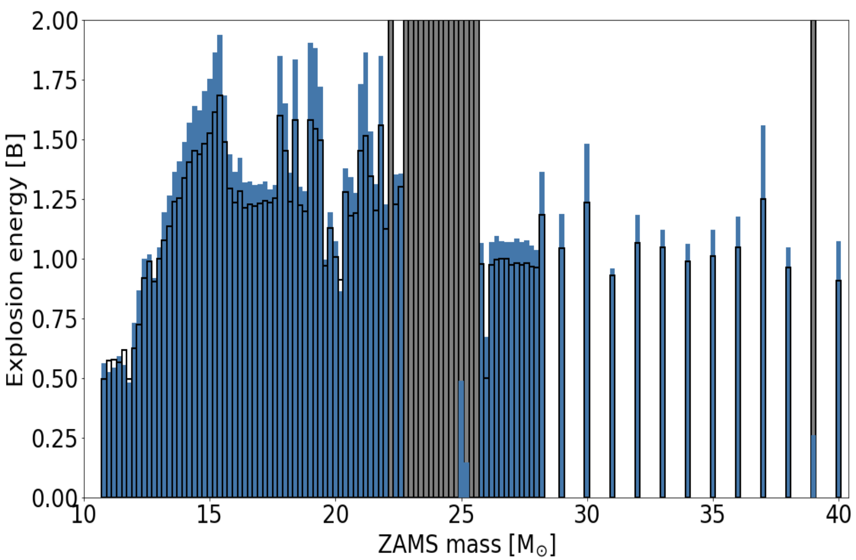
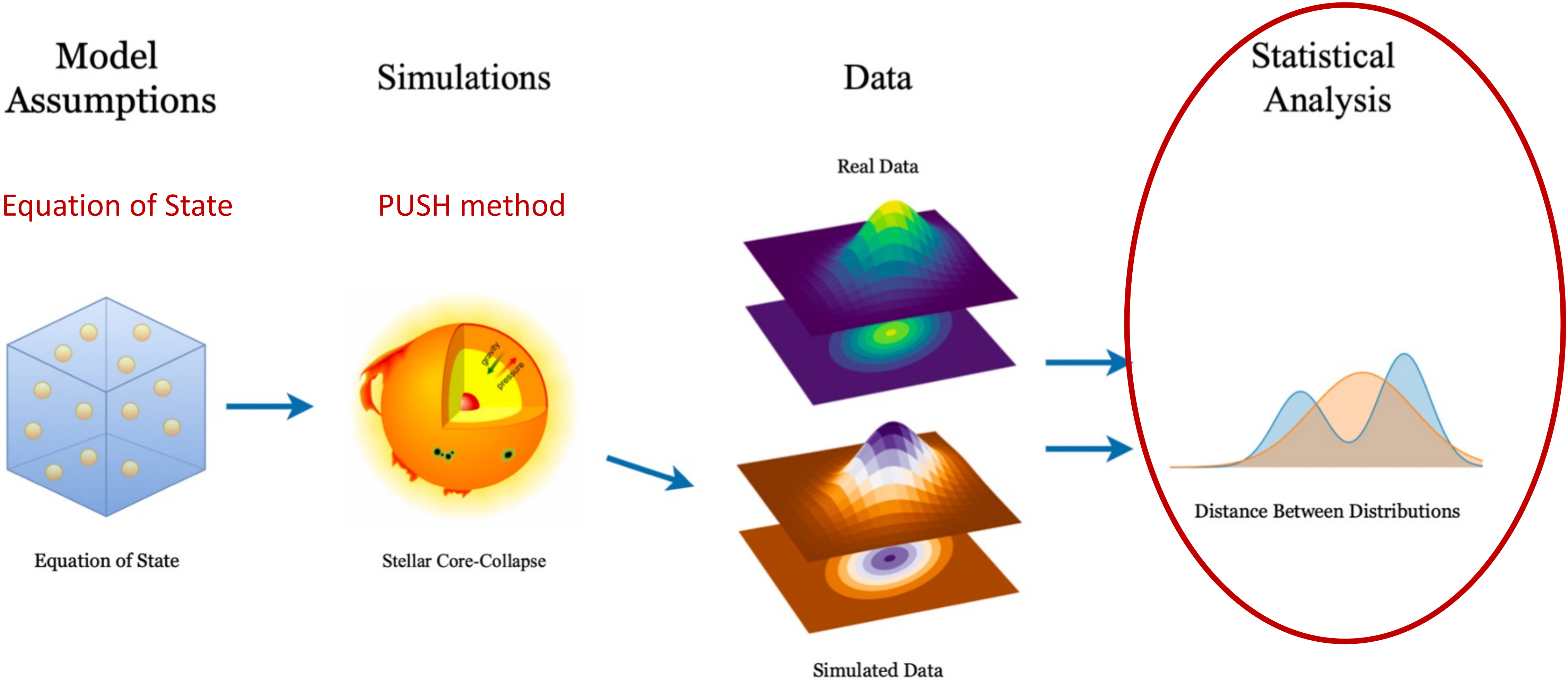




Cannot distringuish between DD2 and SFHo EOS



Comparing (marginal) distributions

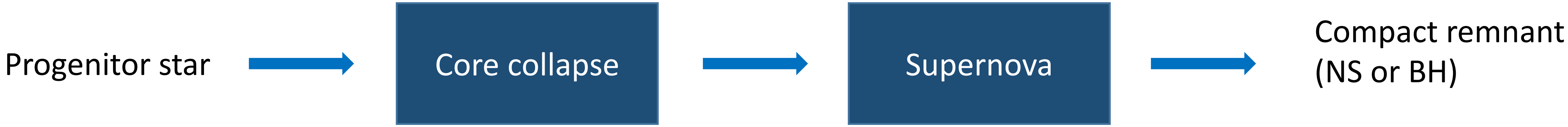


Equation of State

PUSH method

Nature vs simulations

Simulation:

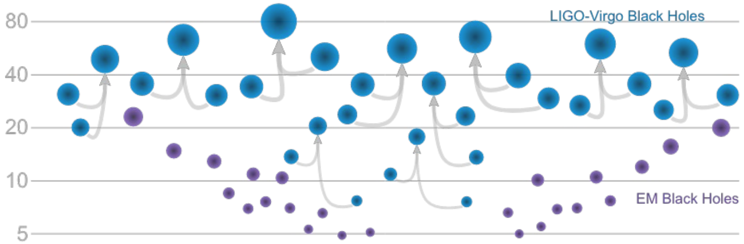


Progenitor star → Core collapse → Supernova → Compact remnant (NS or BH)

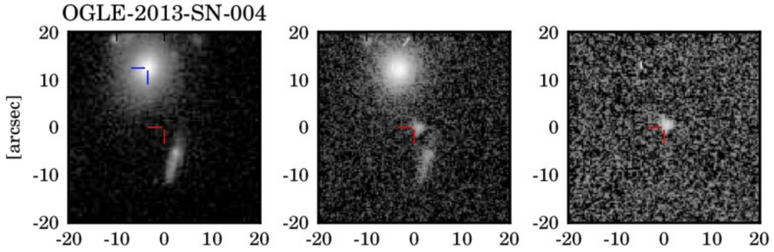
→ compare marginal distributions since we do not have (input,output) pairs from nature

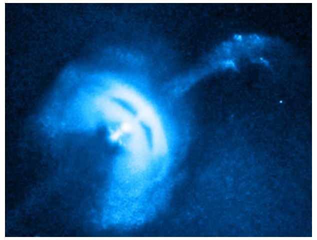
Nature:

Black holes



Supernovae



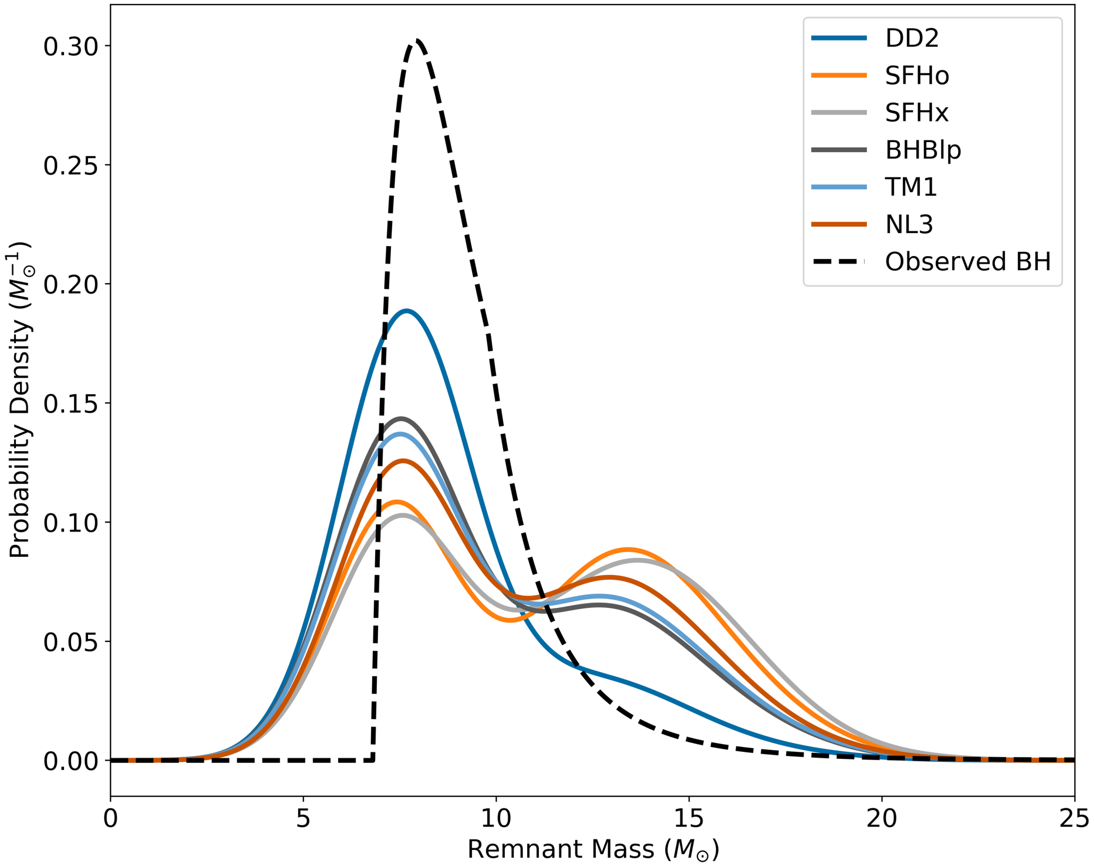


Neutron stars

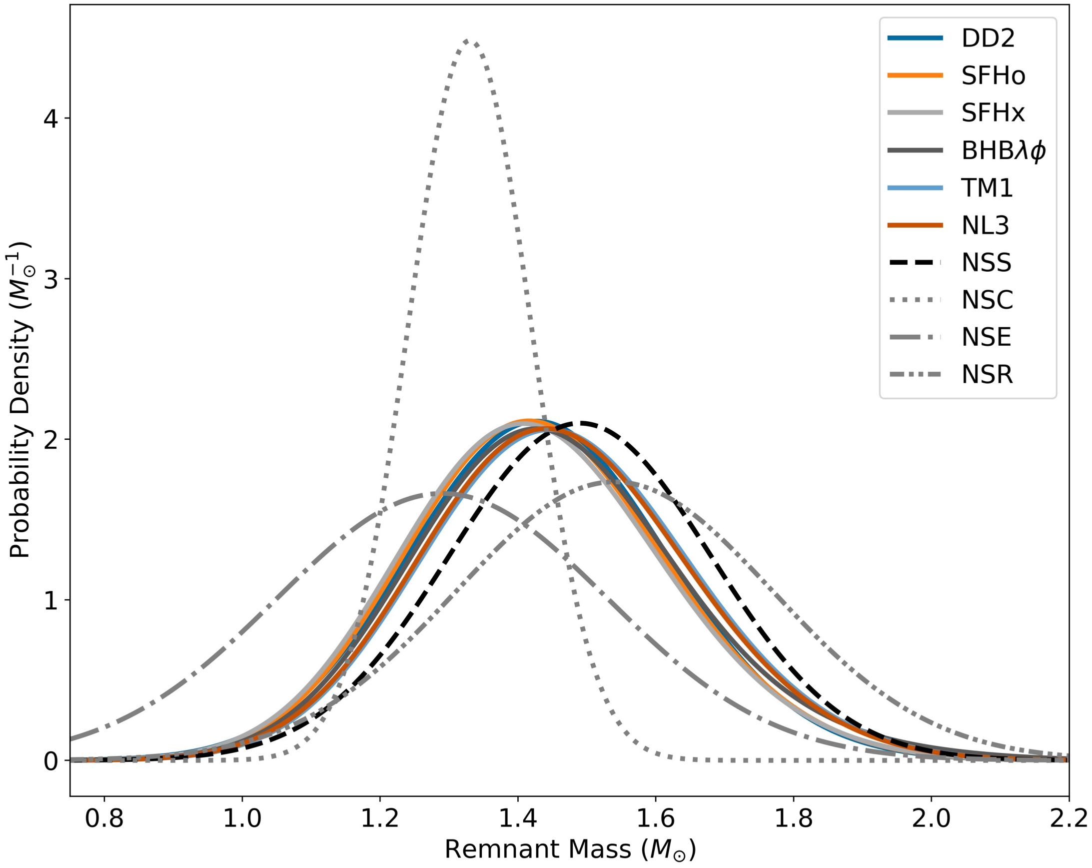
Stars

Probability Density Functions

Black holes



Neutron stars



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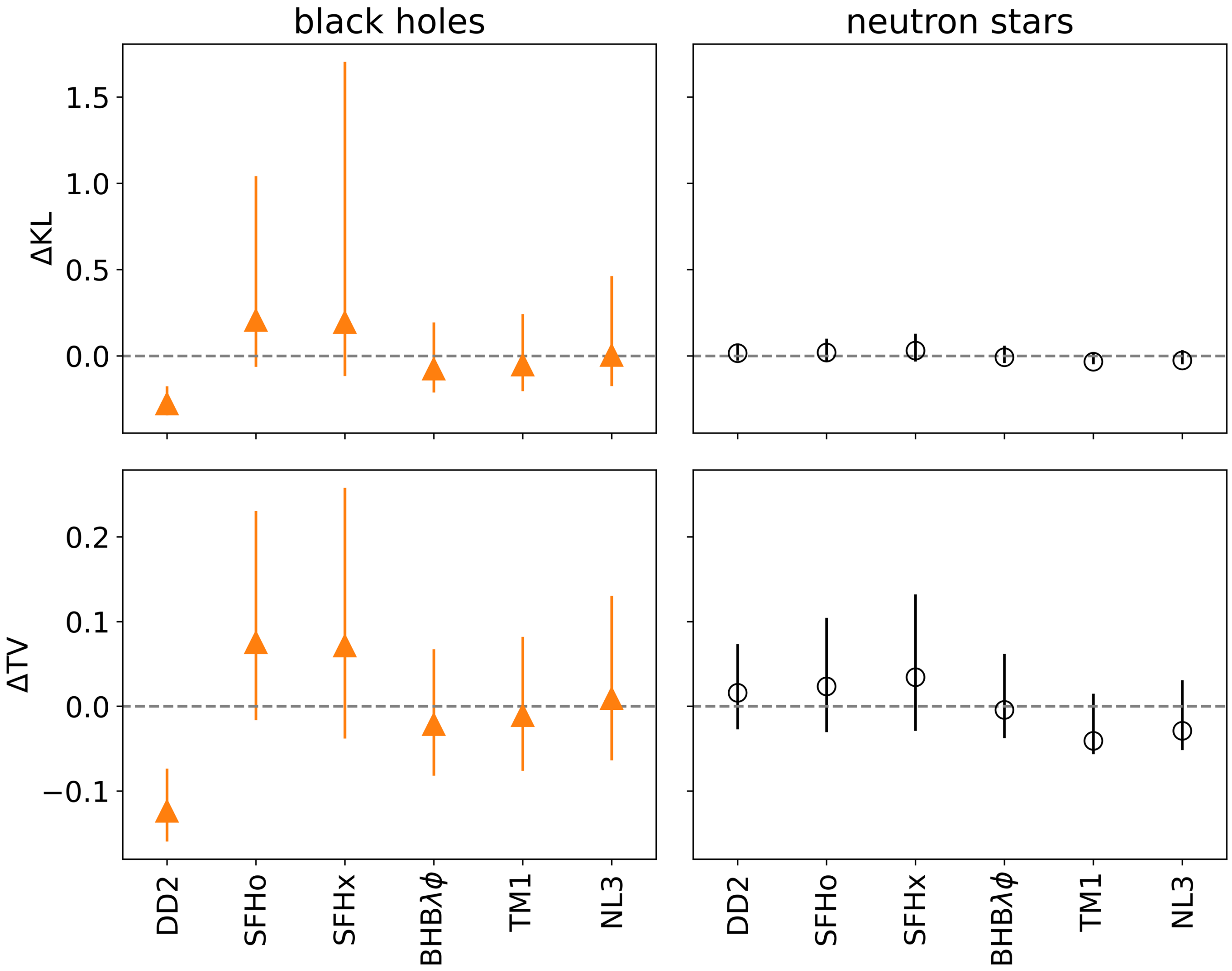
Results: nuclear EOS

$$\Delta = D_{EOS} - \overline{D}$$

$\Delta < 0$ → more favored

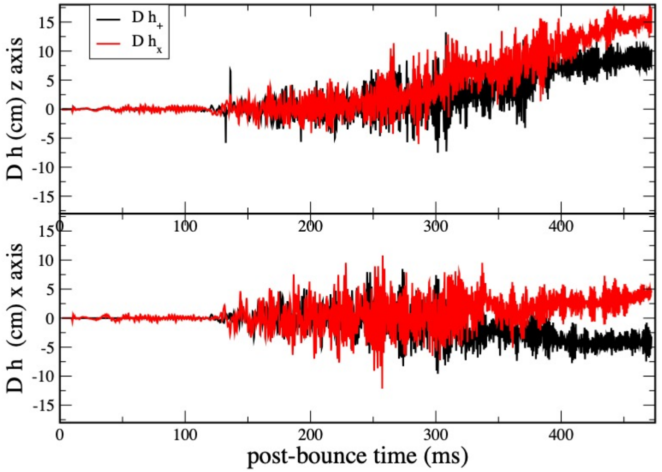
$\Delta > 0$ → less favored

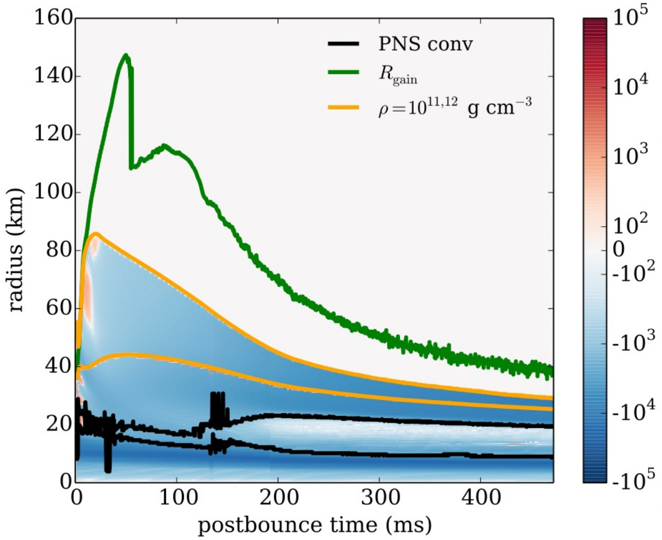


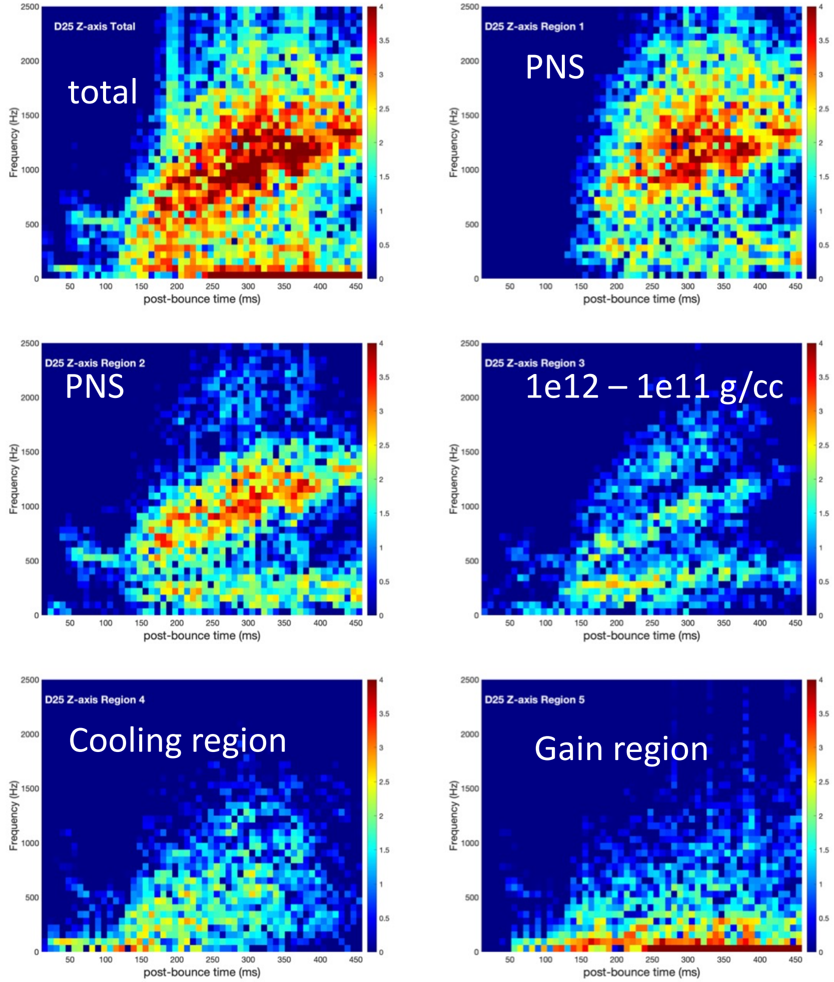
- Caveats:
  - No progenitors of 8-11Msun → lowest-mass NSs are missing
  - Based on single stars → binarity not considered
- Next steps:
  - Include other observables

Gravitational Waves from CCSNe

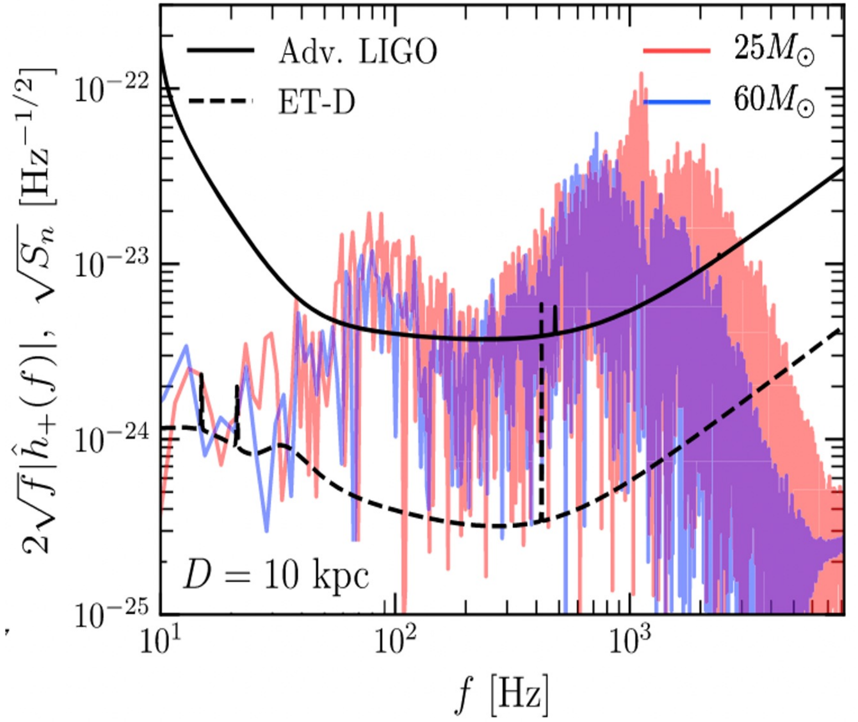
Mezzacappa+23







Radice+19



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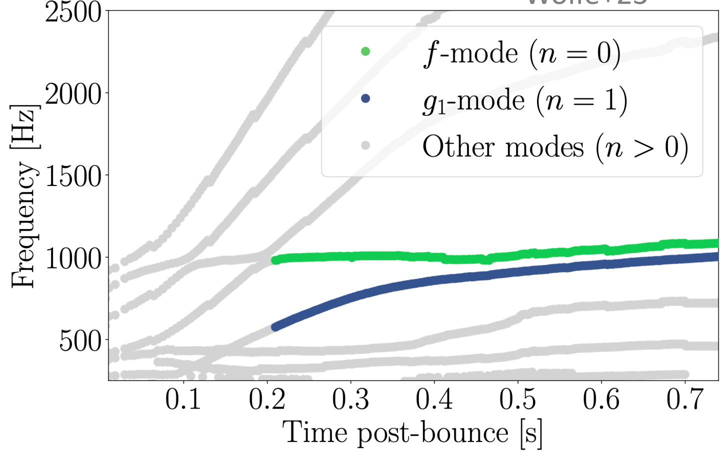
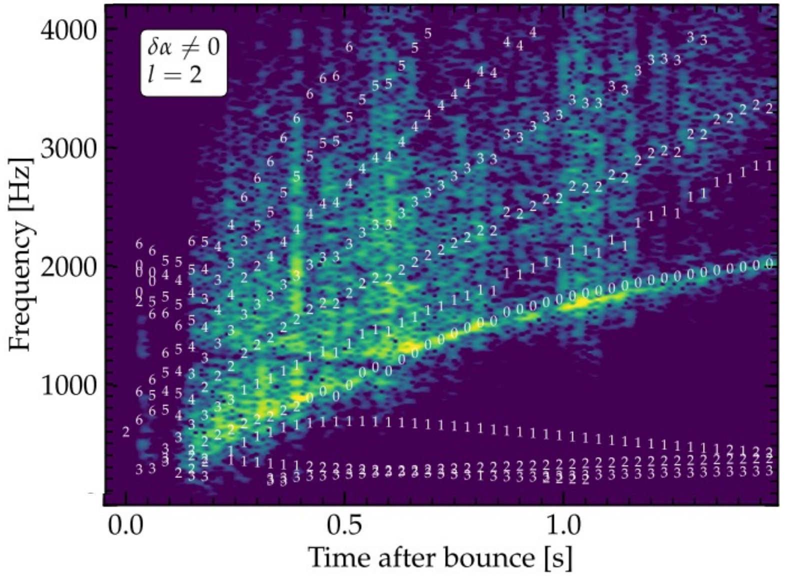
Eigenfrequencies from perturbation analysis

Wolfe+2023

Wolfe+23



Morozova+18



Identification of:

- f-mode
- g-mode

(Cowling scheme)

Comparison betw eigenfrequency analysis and full simulation

- Linear perturbation analysis of general-relativistic hydrodynamics background

  Torres-Forné+18, Morozova+18, Torres-Forné+19, Sotani+20

- Calculate time-frequency evolution (without amplitudes) from spherically-symmetric proto-neutron star background

- Identify frequencies that characterize astrophysical properties of proto-neutron star
  - Universal relations for PNS surface gravity

    Torres-Forne+19

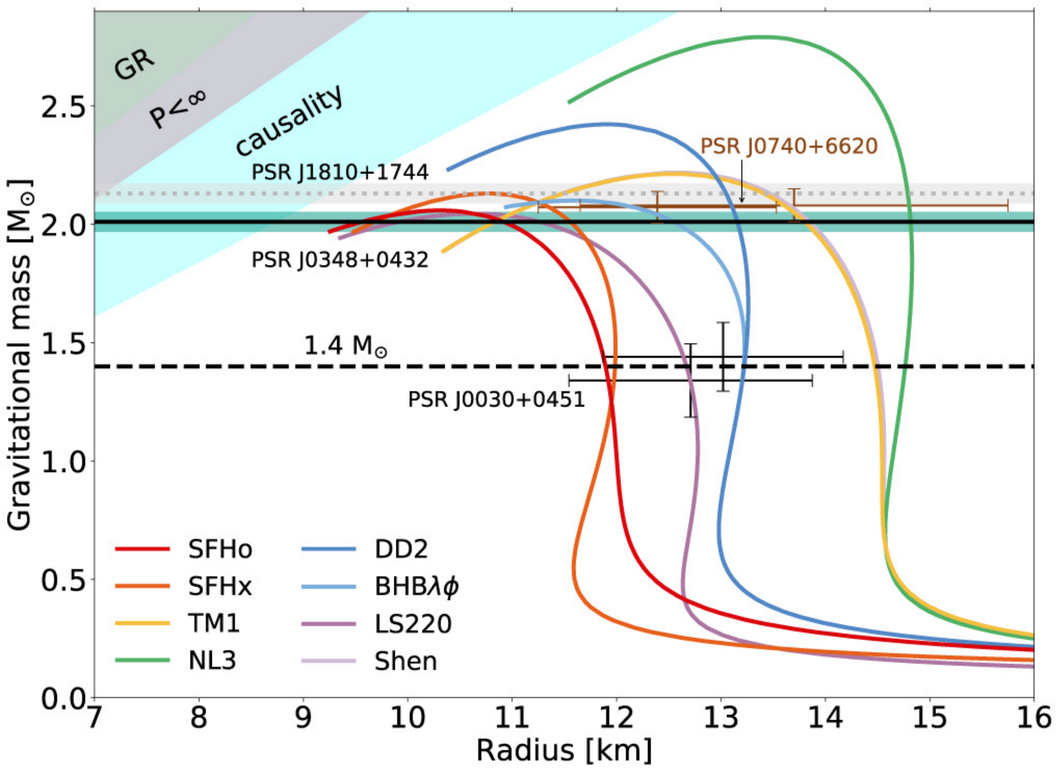
  - Multi-messenger observations of core-collapse

    Warren+20, Nakamura+22

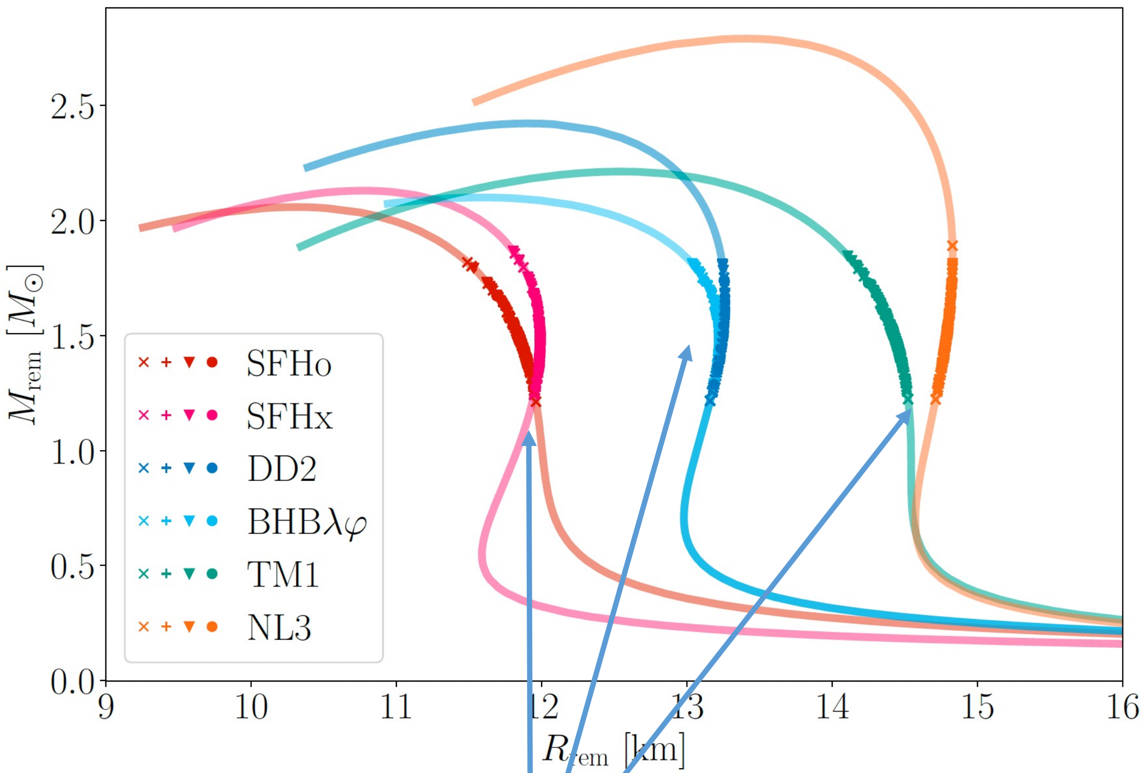
  - Parameter estimation

    Bizouzard+21, Powell+22

Neutron star masses from our simulations



Ghosh+22

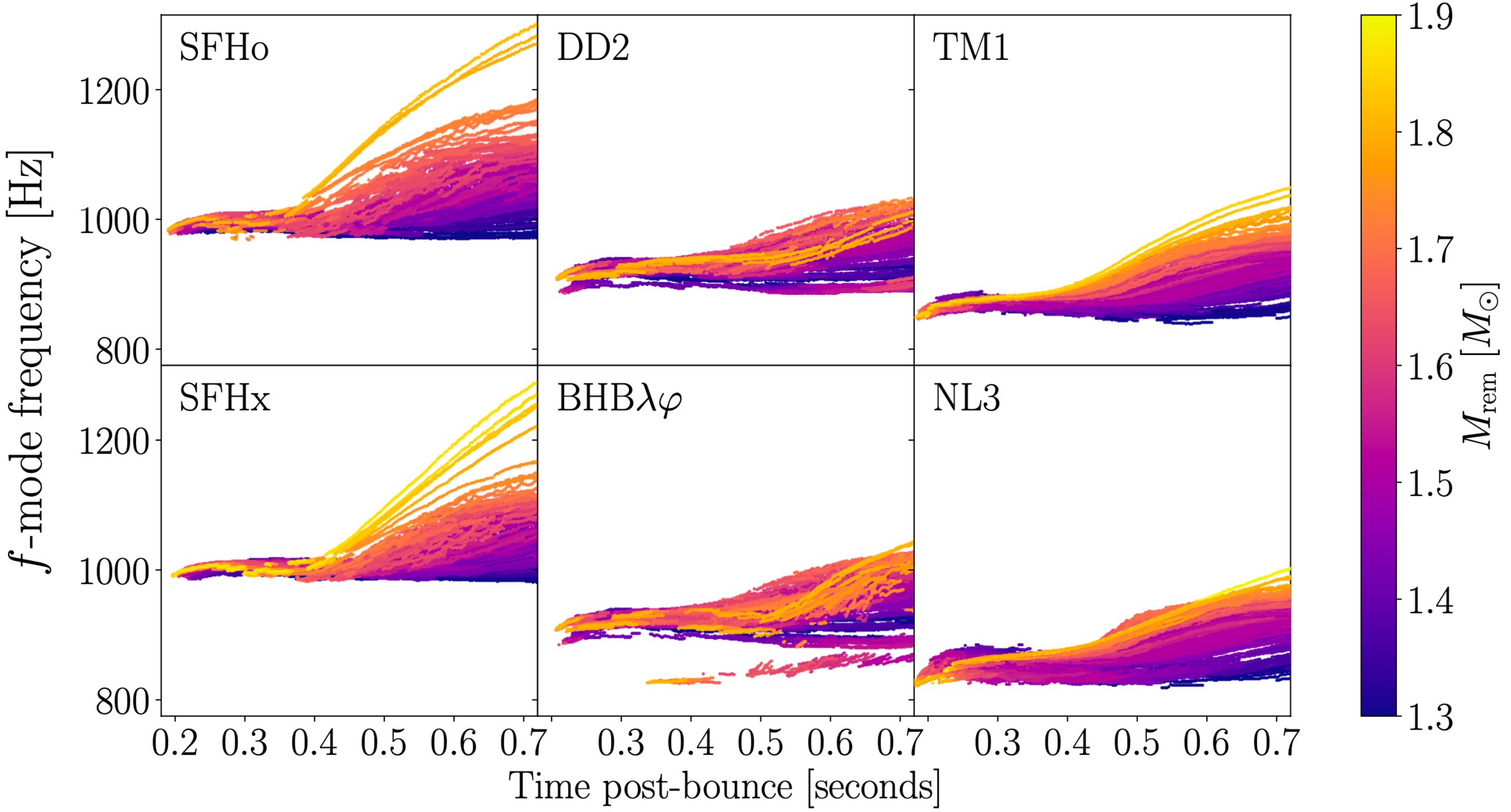


Wolfe+23

>1000 simulations

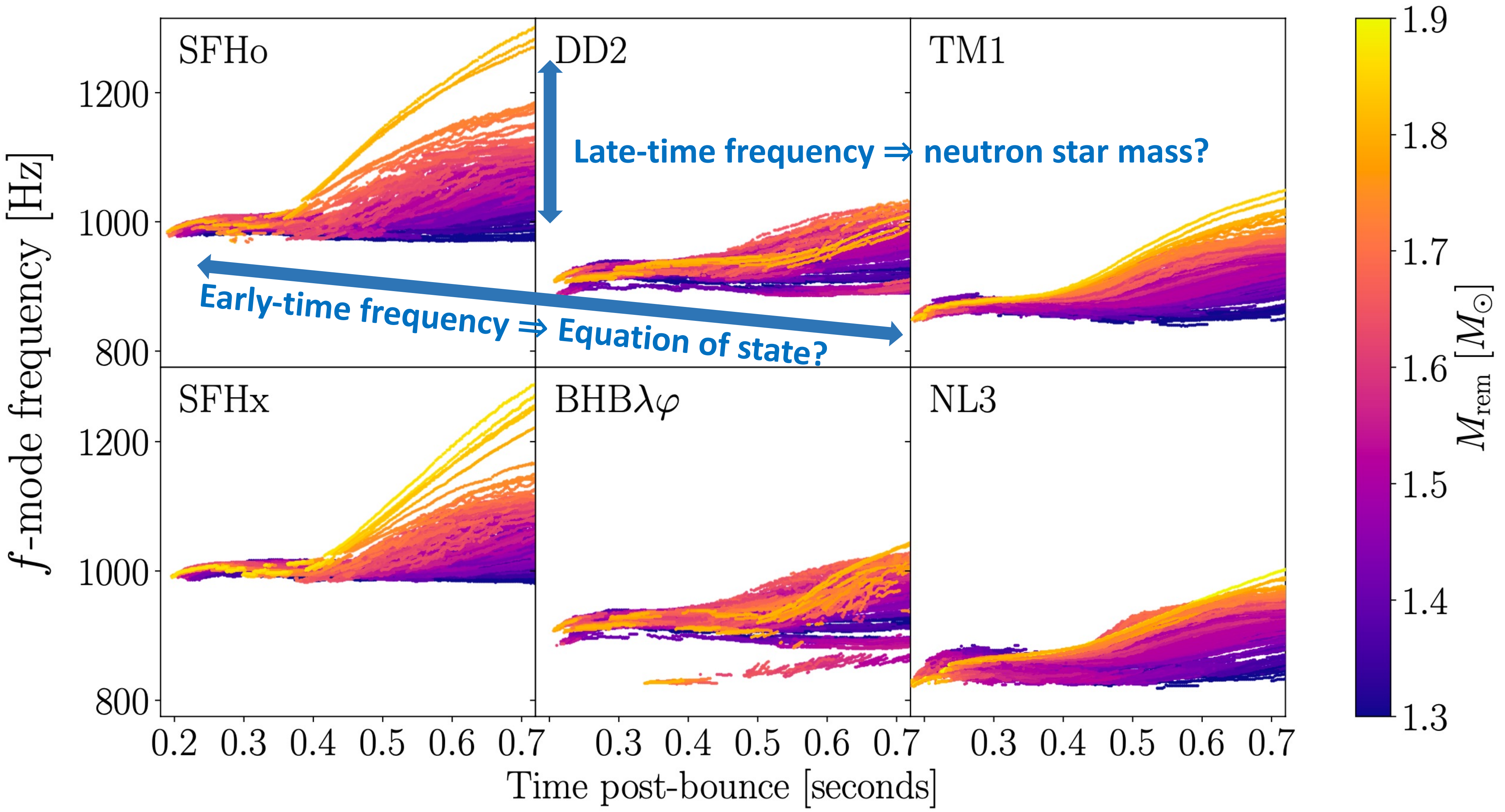
Frequencies depend on nuclear EOS

Wolfe+2023



Frequencies depend on nuclear EOS

Wolfe+2023

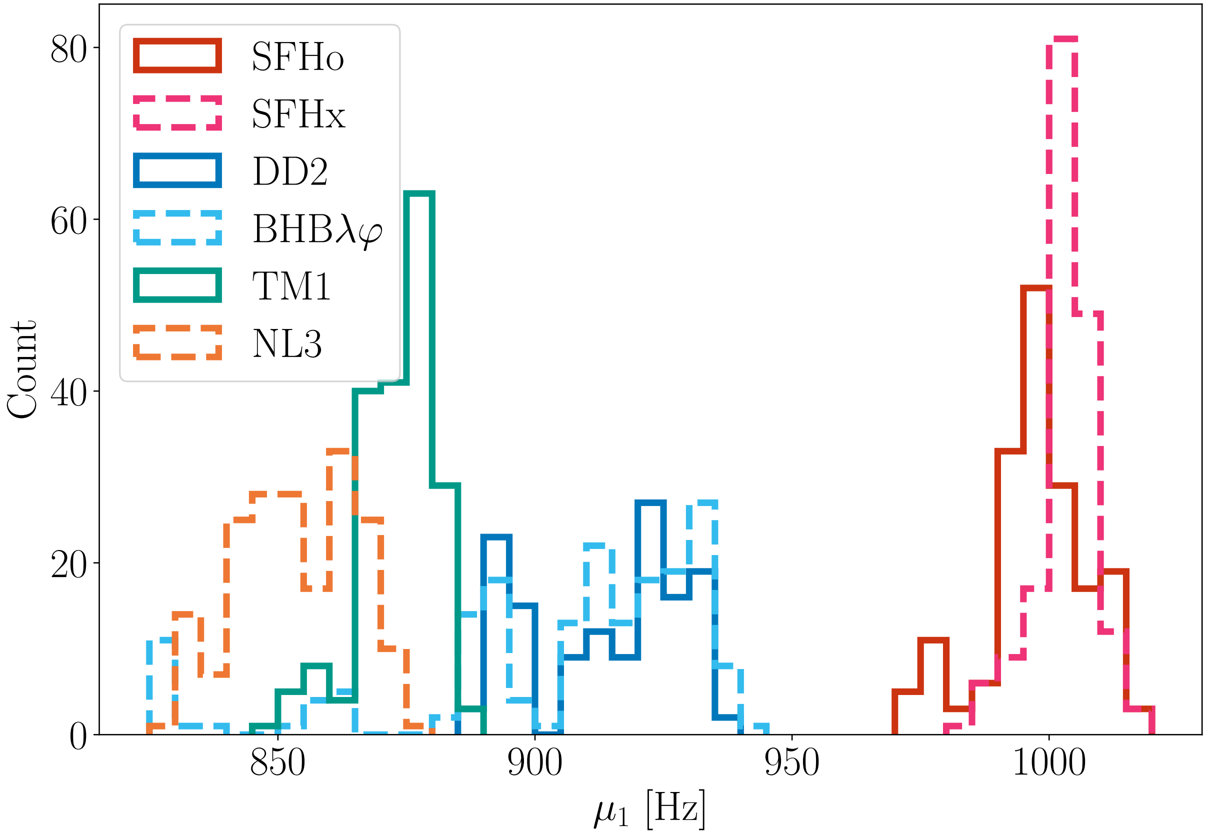


Late-time frequency ⇒ neutron star mass?

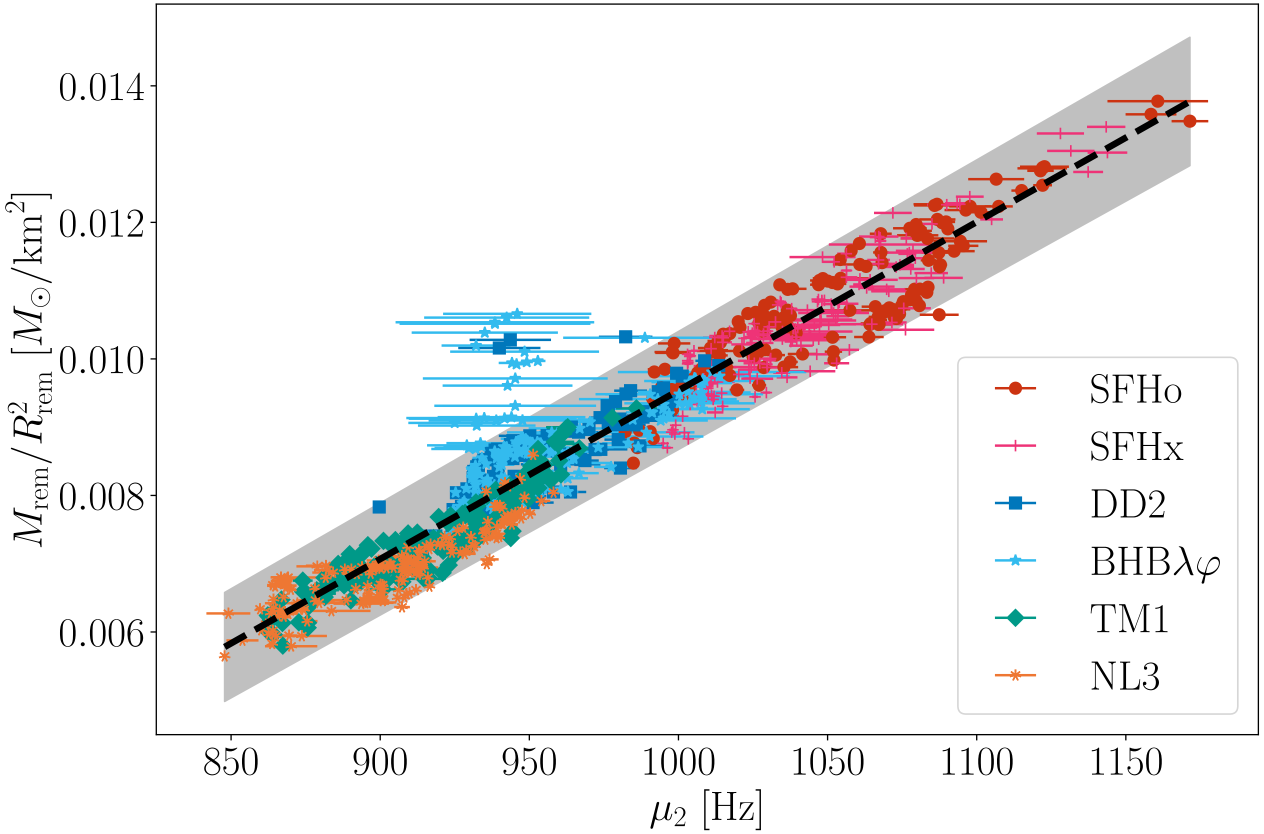
Early-time frequency ⇒ Equation of state?

Characteristic frequencies

Wolfe+2023



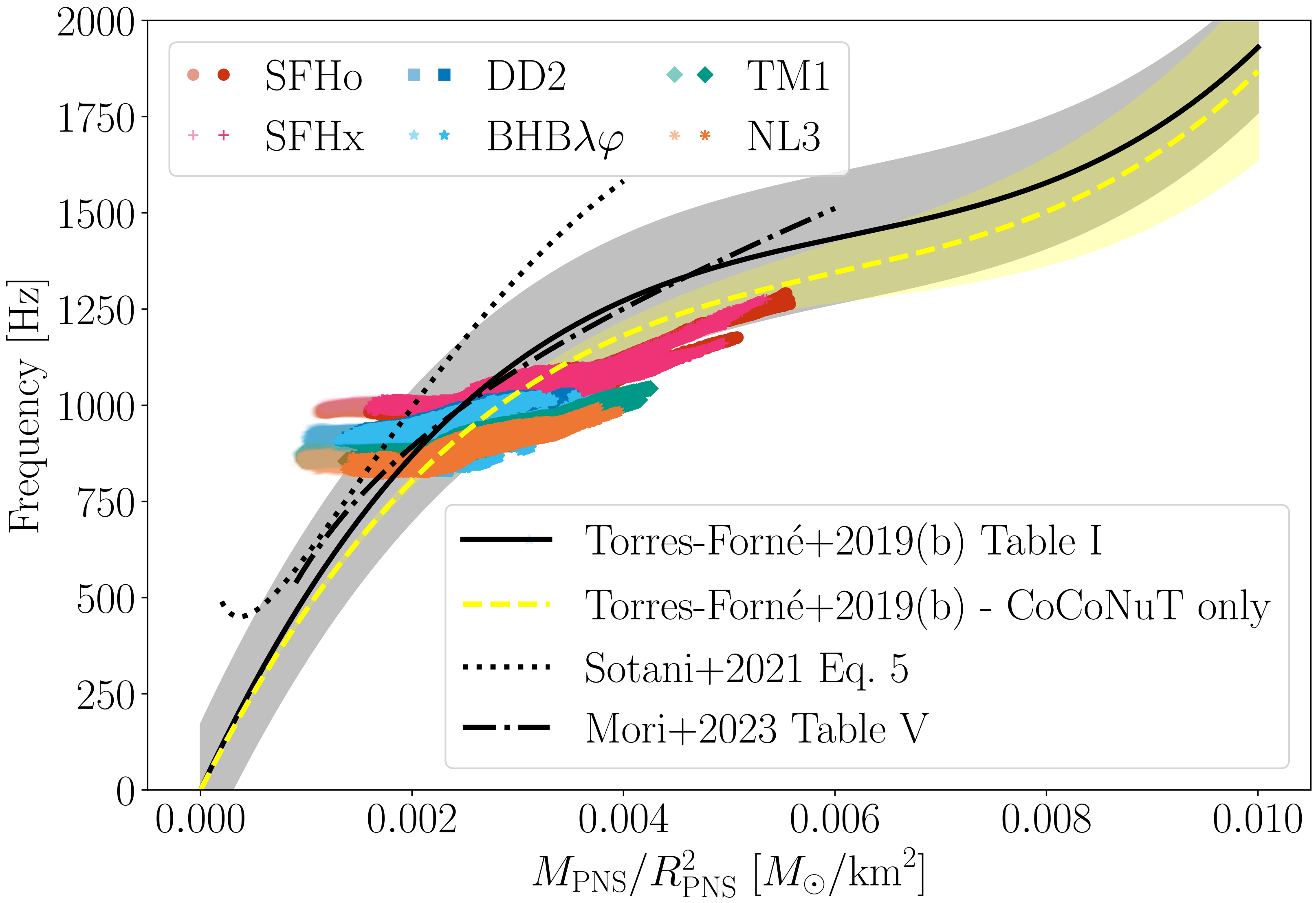
Characteristic early-time frequency



Characteristic late-time frequency

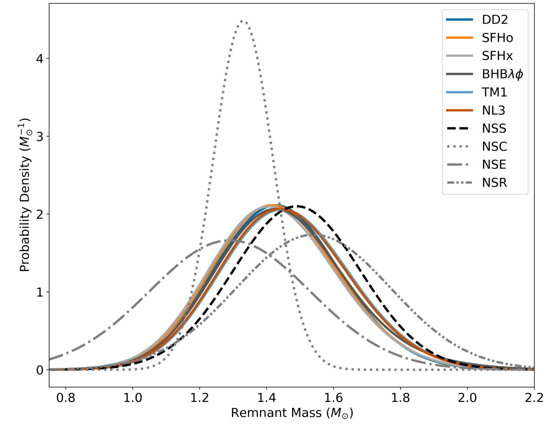
Universal Relationships

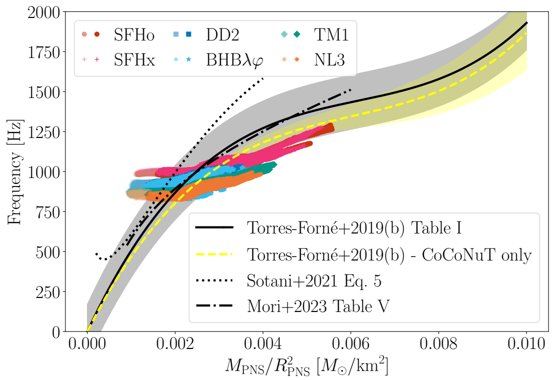
Wolfe+2023



Summary

- How to harness supernova simulations to learn about the nuclear EOS
  - Perform many (~1000) simulations without prescribing the outcome → NS and BH masses
  - Statistical analysis: Distance between distributions
  - GW eigenfrequency analysis: time-evolution of f-mode





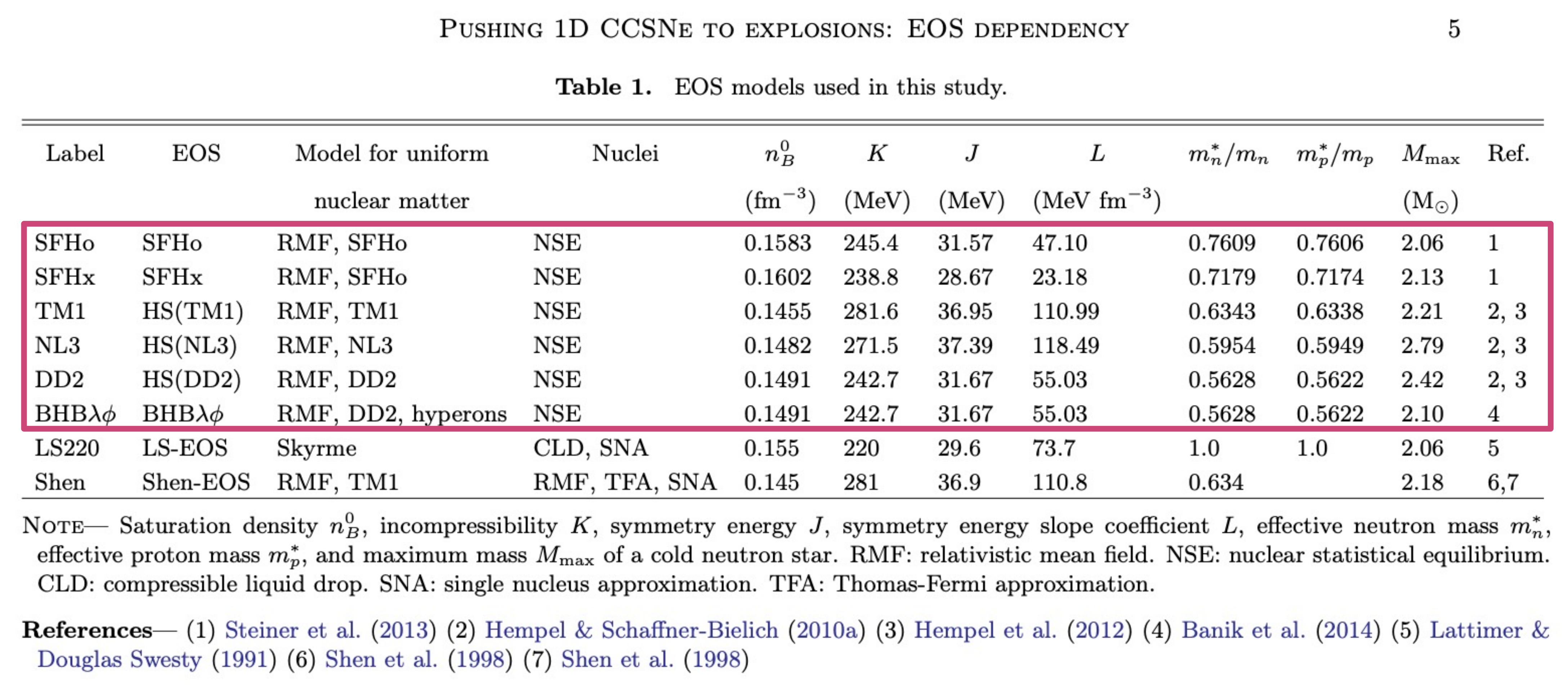


Table 1. EOS models used in this study.

Label	EOS	Model for uniform nuclear matter	Nuclei	n_B^0 (fm^{-3})	K (MeV)	J (MeV)	L (MeV fm^{-3})	m_n^*/m_n	m_p^*/m_p	$M_{\max}$ ($M_\odot$)	Ref.
SFHo	SFHo	RMF, SFHo	NSE	0.1583	245.4	31.57	47.10	0.7609	0.7606	2.06	1
SFHx	SFHx	RMF, SFHo	NSE	0.1602	238.8	28.67	23.18	0.7179	0.7174	2.13	1
TM1	HS(TM1)	RMF, TM1	NSE	0.1455	281.6	36.95	110.99	0.6343	0.6338	2.21	2, 3
NL3	HS(NL3)	RMF, NL3	NSE	0.1482	271.5	37.39	118.49	0.5954	0.5949	2.79	2, 3
DD2	HS(DD2)	RMF, DD2	NSE	0.1491	242.7	31.67	55.03	0.5628	0.5622	2.42	2, 3
BHB$\lambda\phi$	BHB$\lambda\phi$	RMF, DD2, hyperons	NSE	0.1491	242.7	31.67	55.03	0.5628	0.5622	2.10	4
LS220	LS-EOS	Skyrme	CLD, SNA	0.155	220	29.6	73.7	1.0	1.0	2.06	5
Shen	Shen-EOS	RMF, TM1	RMF, TFA, SNA	0.145	281	36.9	110.8	0.634		2.18	6,7

NOTE— Saturation density n_B^0, incompressibility K, symmetry energy J, symmetry energy slope coefficient L, effective neutron mass m_n^*, effective proton mass m_p^*, and maximum mass $M_{\max}$ of a cold neutron star. RMF: relativistic mean field. NSE: nuclear statistical equilibrium. CLD: compressible liquid drop. SNA: single nucleus approximation. TFA: Thomas-Fermi approximation.

References— (1) Steiner et al. (2013) (2) Hempel & Schaffner-Bielich (2010a) (3) Hempel et al. (2012) (4) Banik et al. (2014) (5) Lattimer & Douglas Swesty (1991) (6) Shen et al. (1998) (7) Shen et al. (1998)

Table 1 from Ghosh, Wolfe, Fröhlich (2022)