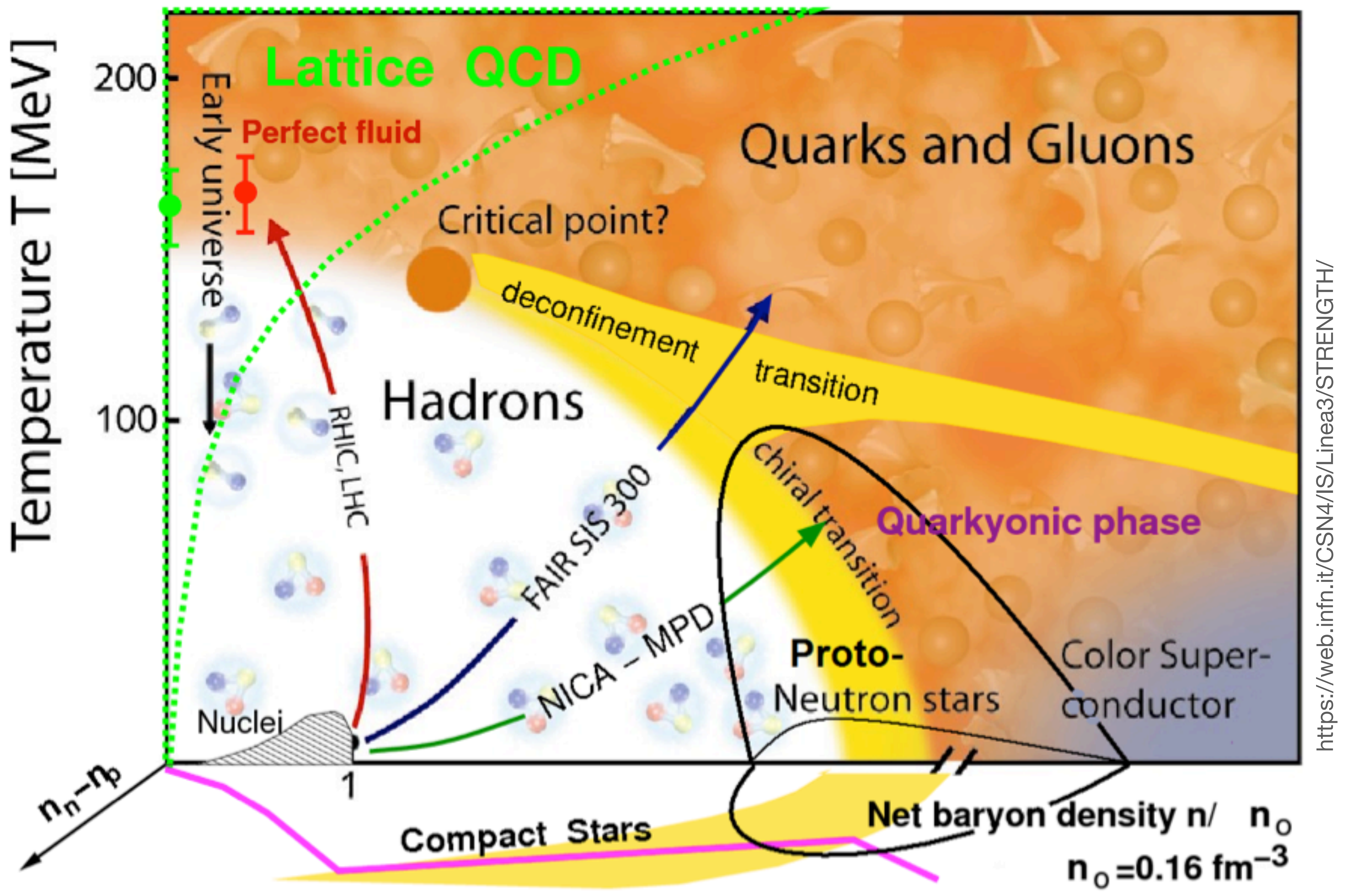
Constraining the EOS and Symmetry Energy with Neutron Star Mergers

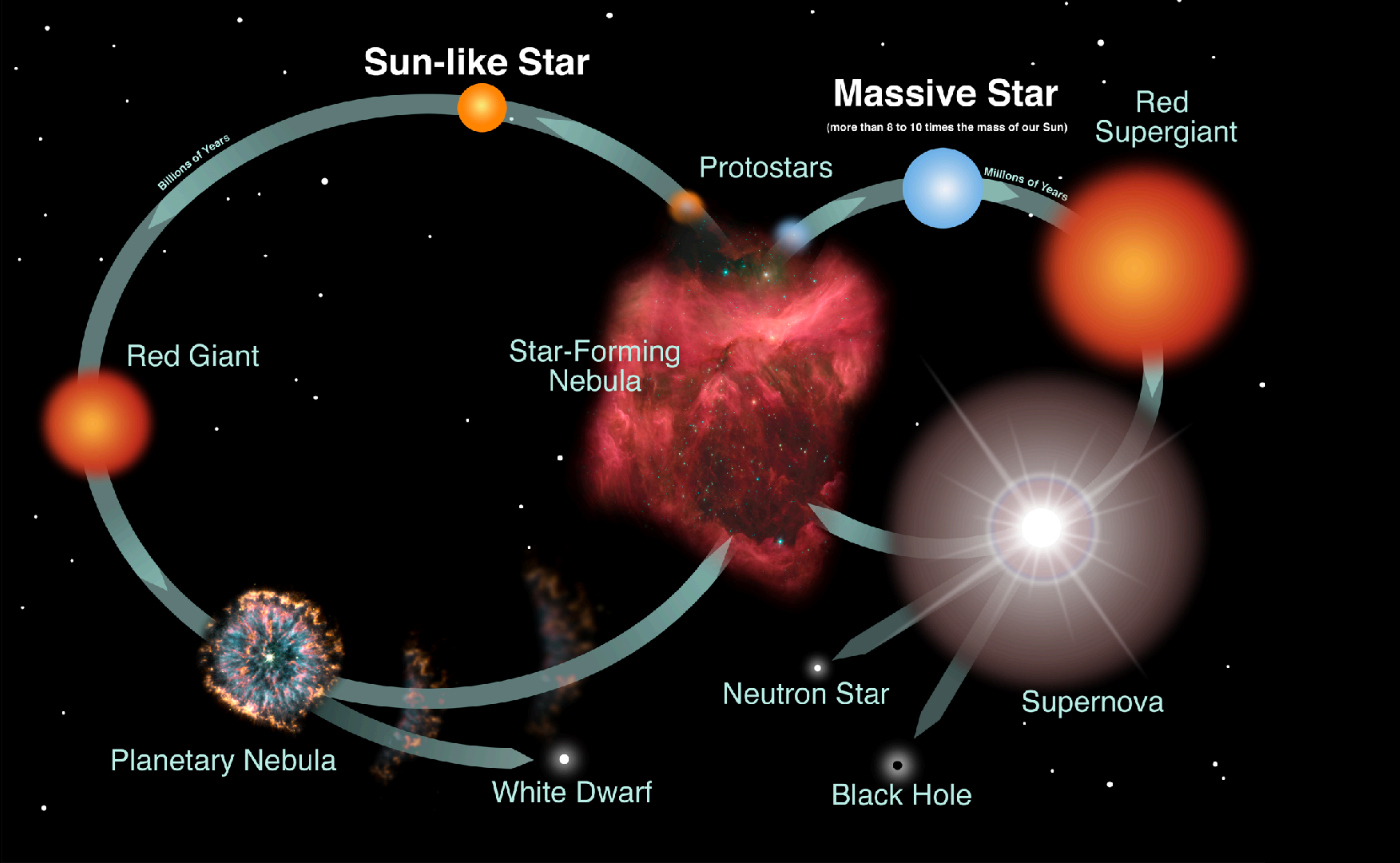
NuSym2024, Caen France
Sept 10, 2024

David Tsang, University of Bath

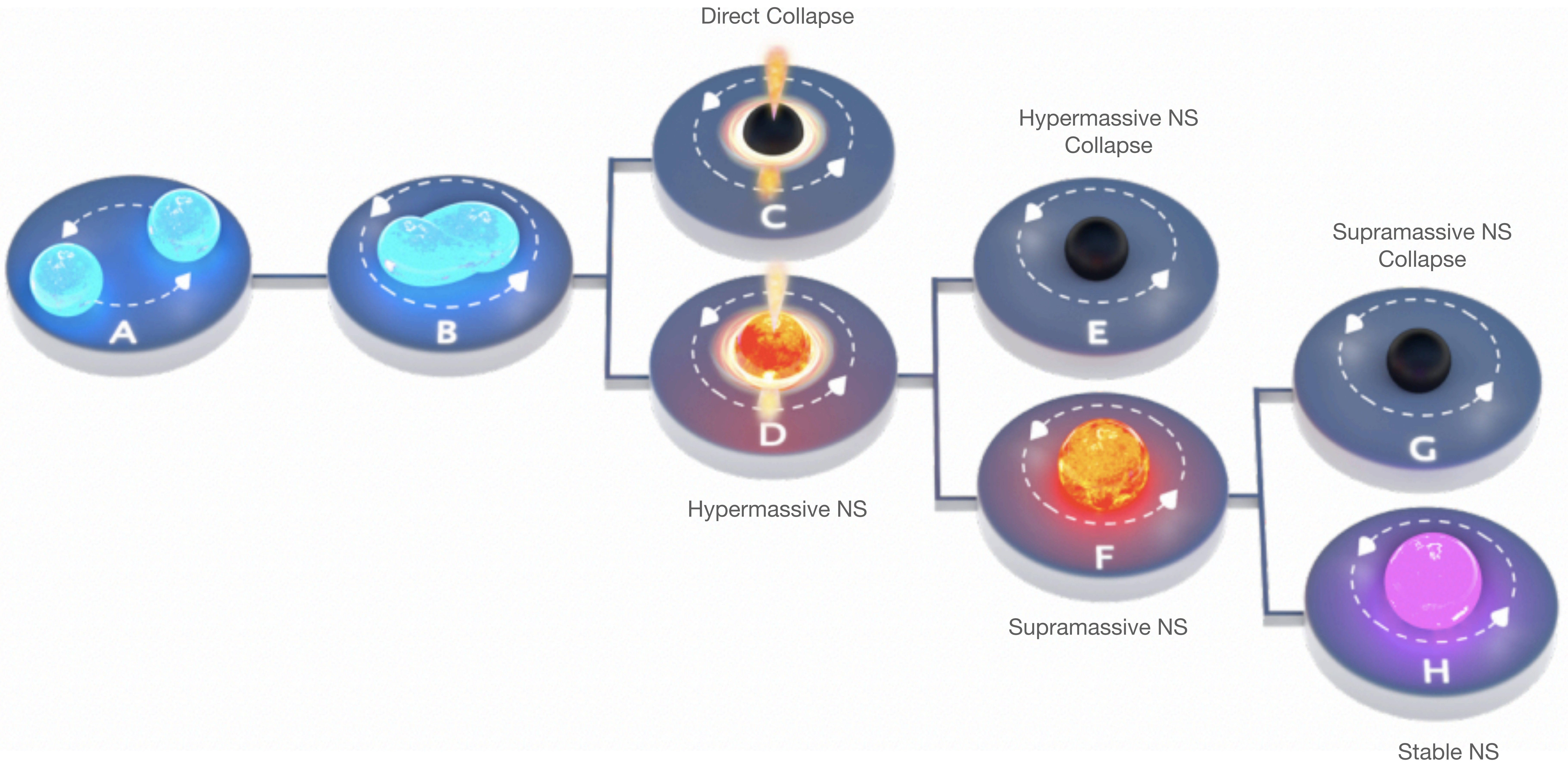
Illustration: NASA CXC/M.Weiss



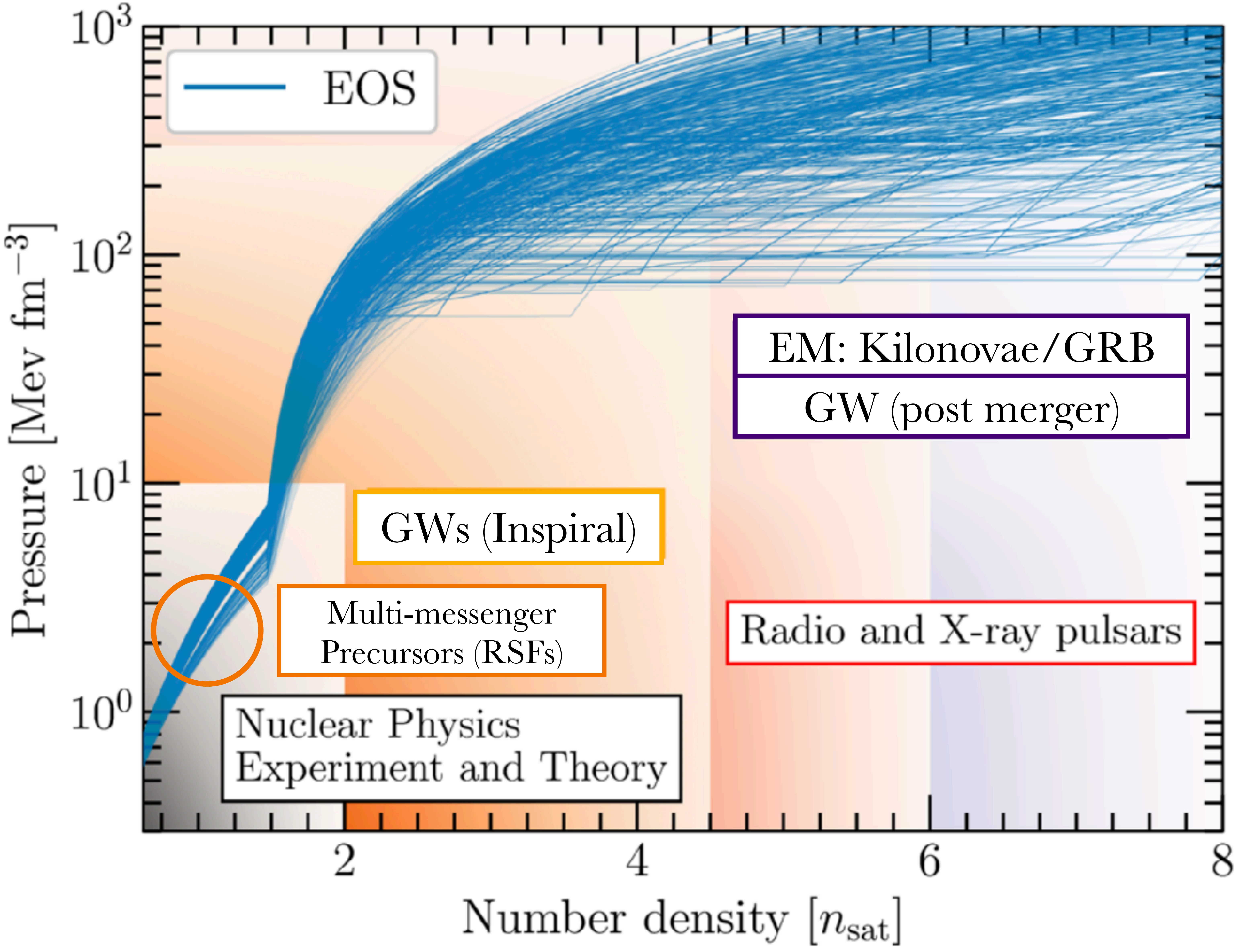
Lattice QCD
Temperature T [MeV]
200
100
Early universe
Perfect fluid
Quarks and Gluons
Critical point?
deconfinement
transition
Hadrons
RHIC, LHC
FAIR SIS 300
NICA – MPD
chiral transition
Quarkyonic phase
Proto-
Neutron stars
Color Super-
conductor
Nuclei
1
n_n-n_p
Compact Stars
Net baryon density n/ n_o
n_o=0.16 fm^{-3}
https://web.infn.it/CSN4/IS/Linea3/STRENGTH/


Sun-like Star
Billions of Years
Massive Star
(more than 8 to 10 times the mass of our Sun)
Red Supergiant
Protostars
Millions of Years
Red Giant
Star-Forming Nebula
Neutron Star
Supernova
Planetary Nebula
White Dwarf
Black Hole

Watts et al. (2016) Rev. Mod. Phys., 88, 021001

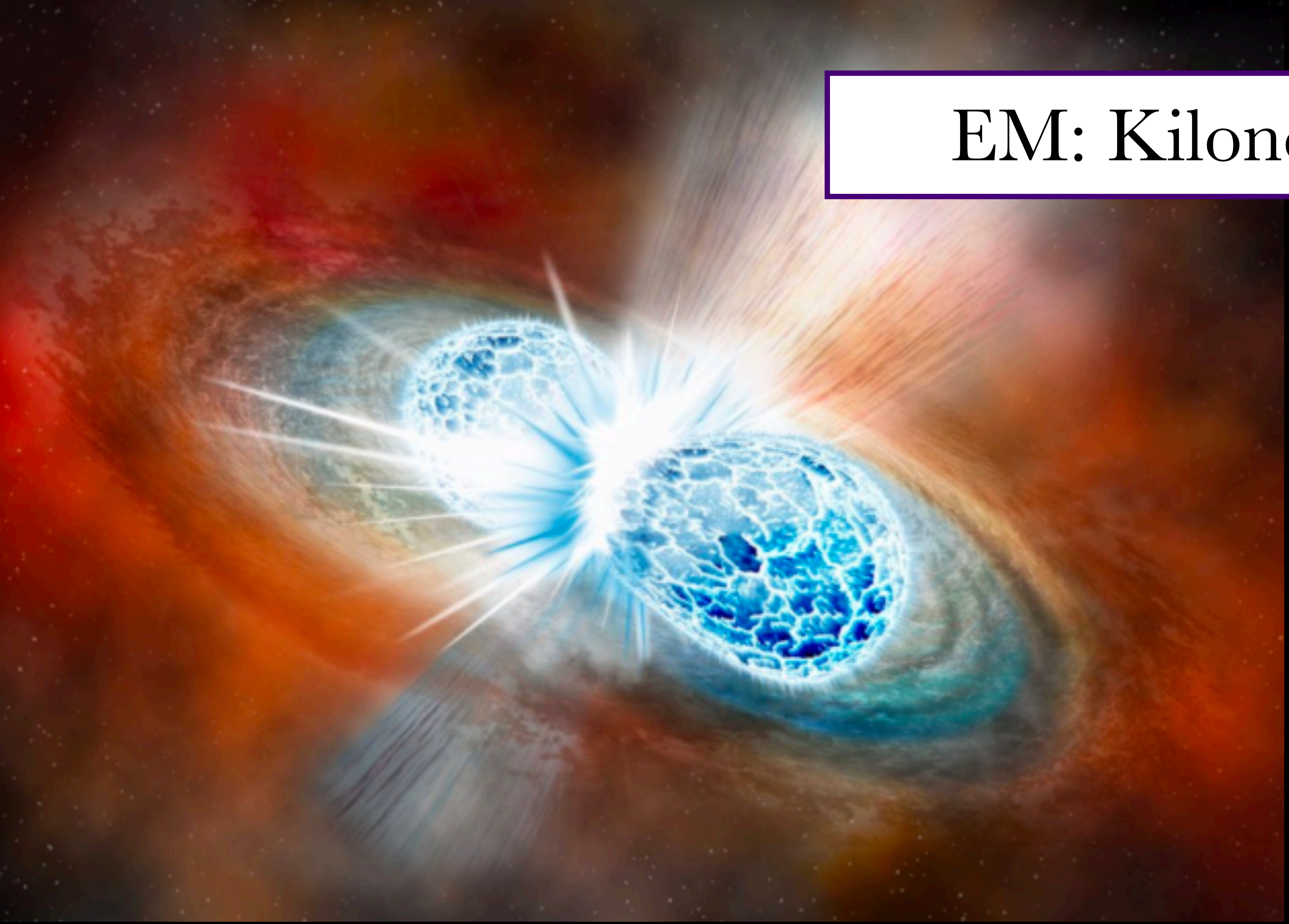


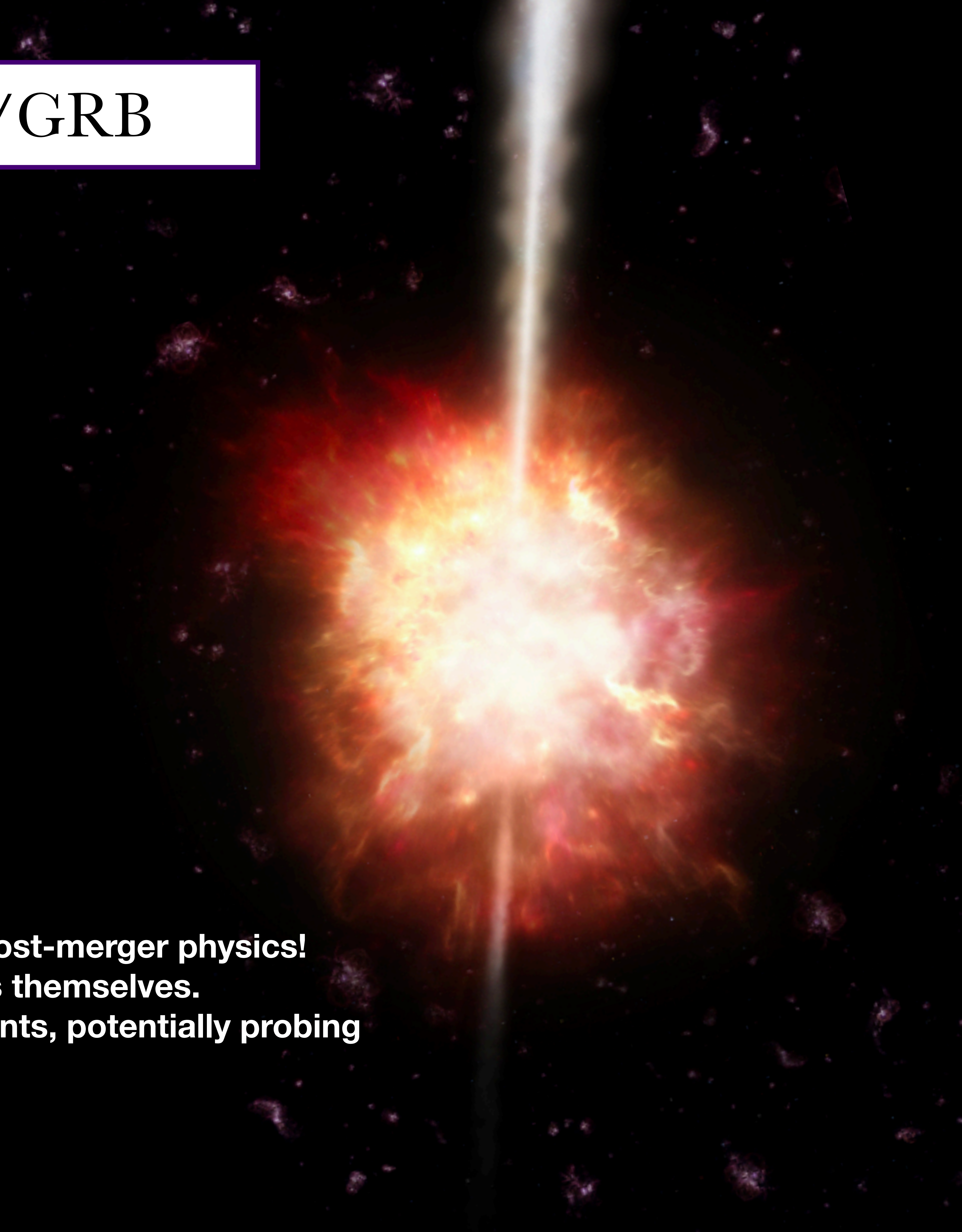
Adapted from Sarin & Lasky (2021) GR&G, 53, 6, 59



Adapted from Pang et al., (2023) Nature Comm, 14:8352

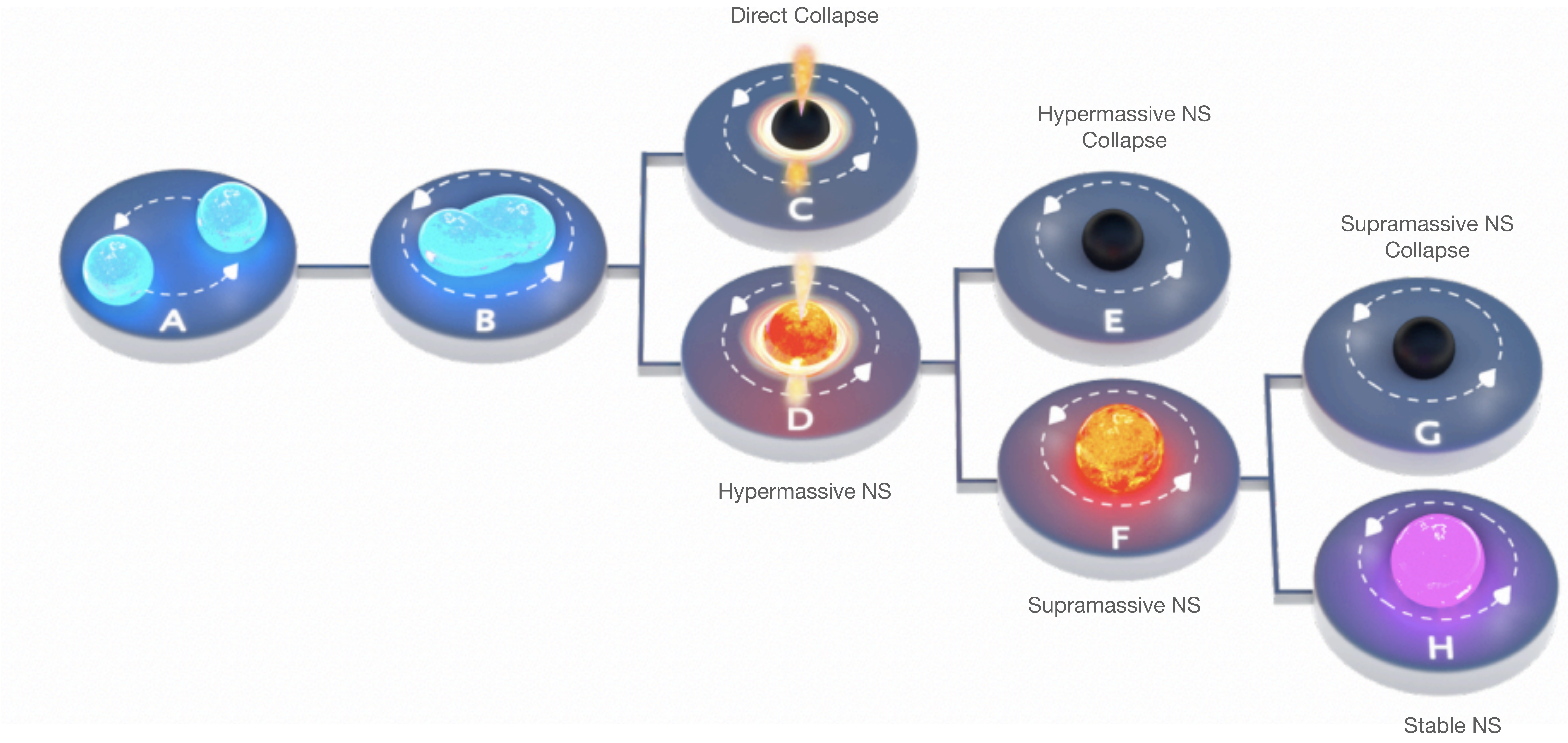
EM: Kilonovae/GRB





Kilonovae and Short Gamma Ray Bursts tell us a lot about the messy post-merger physics!
But it's difficult to extract info about the neutron star progenitors themselves.
However, they can provide some (qualitative) information on merger remnants, potentially probing the even higher density cores of HMNSs/SMNSs.

EM: Kilonovae/GRB



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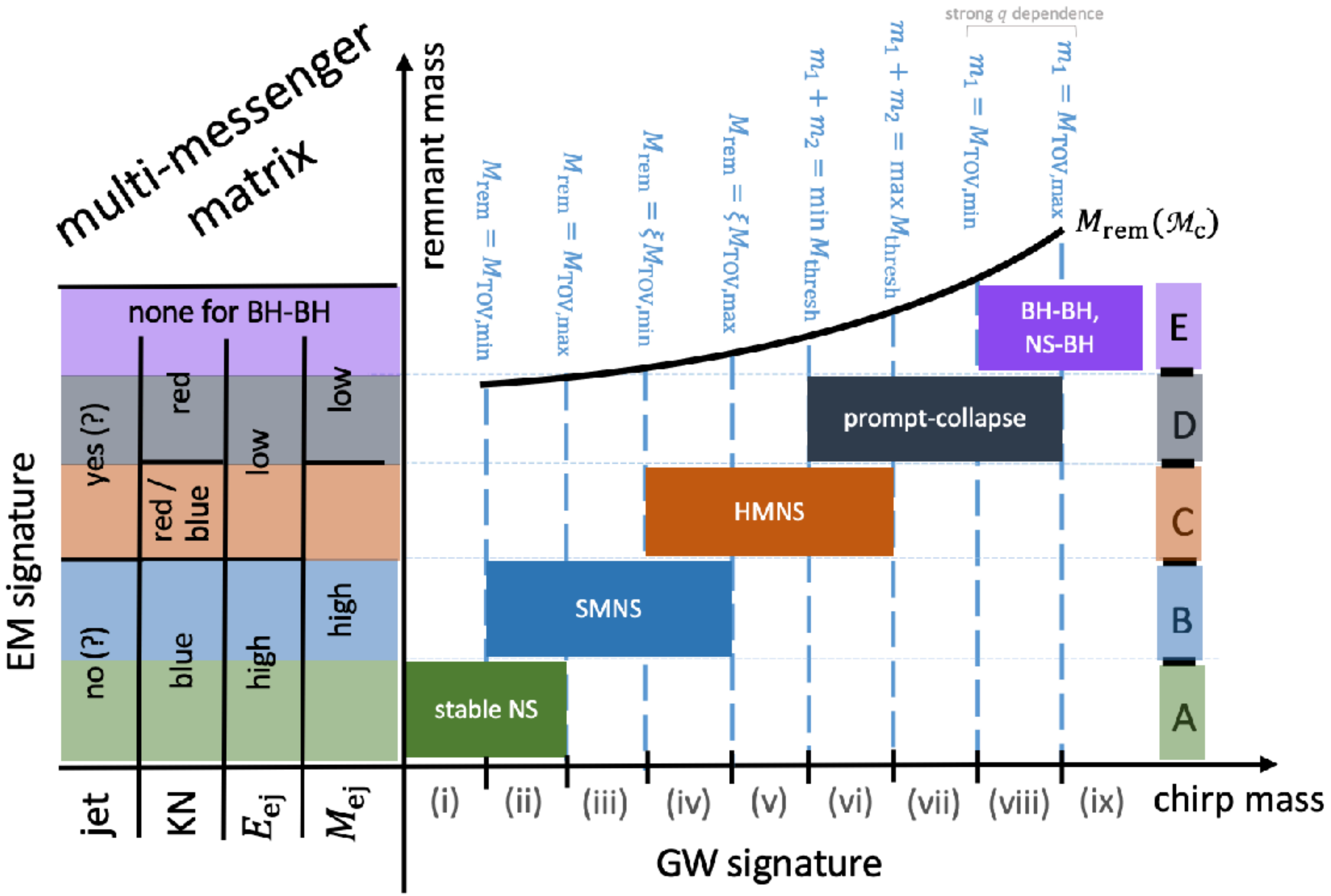
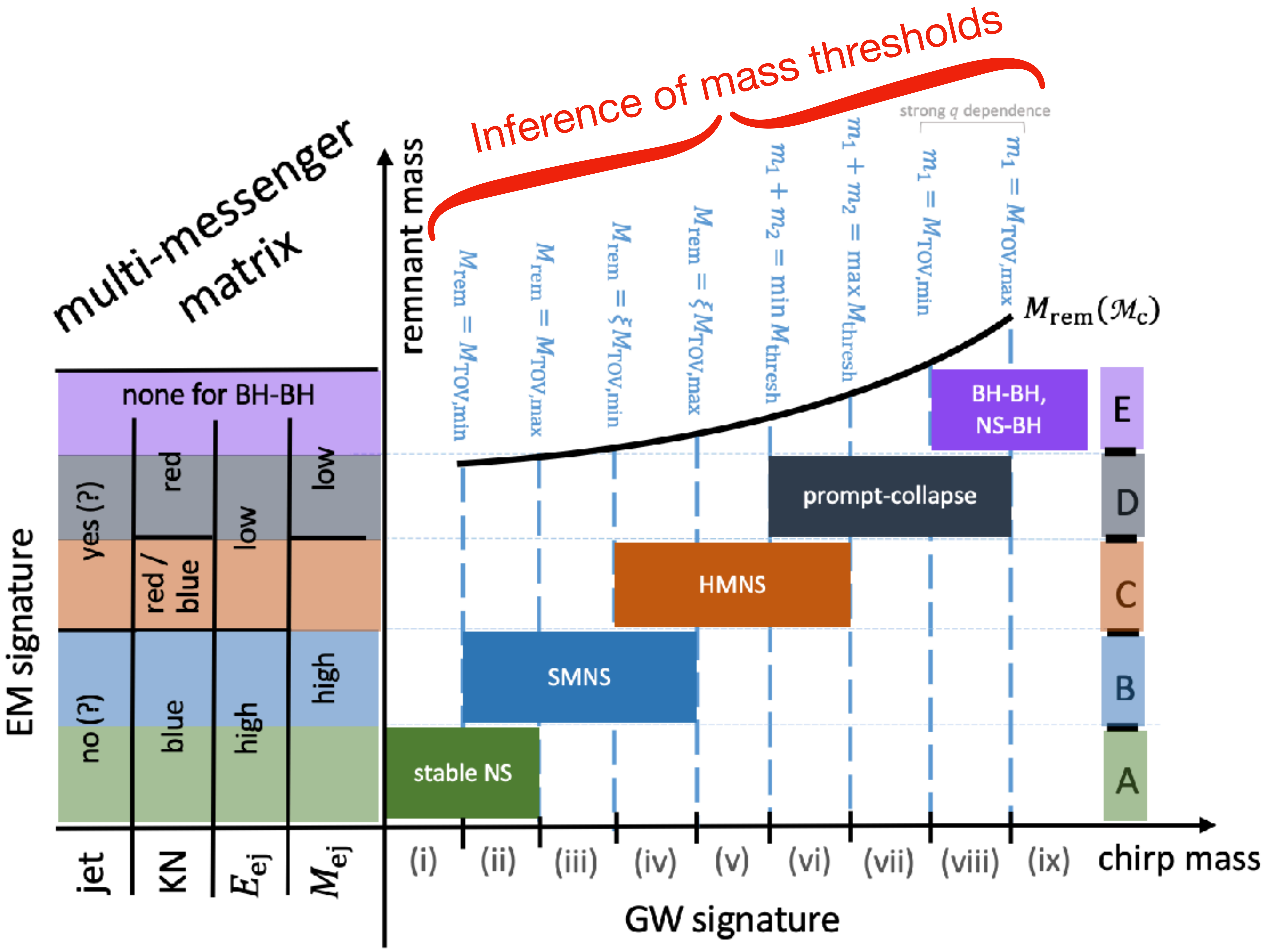


Margalit & Metzger (2019) ApJL, 880, L15

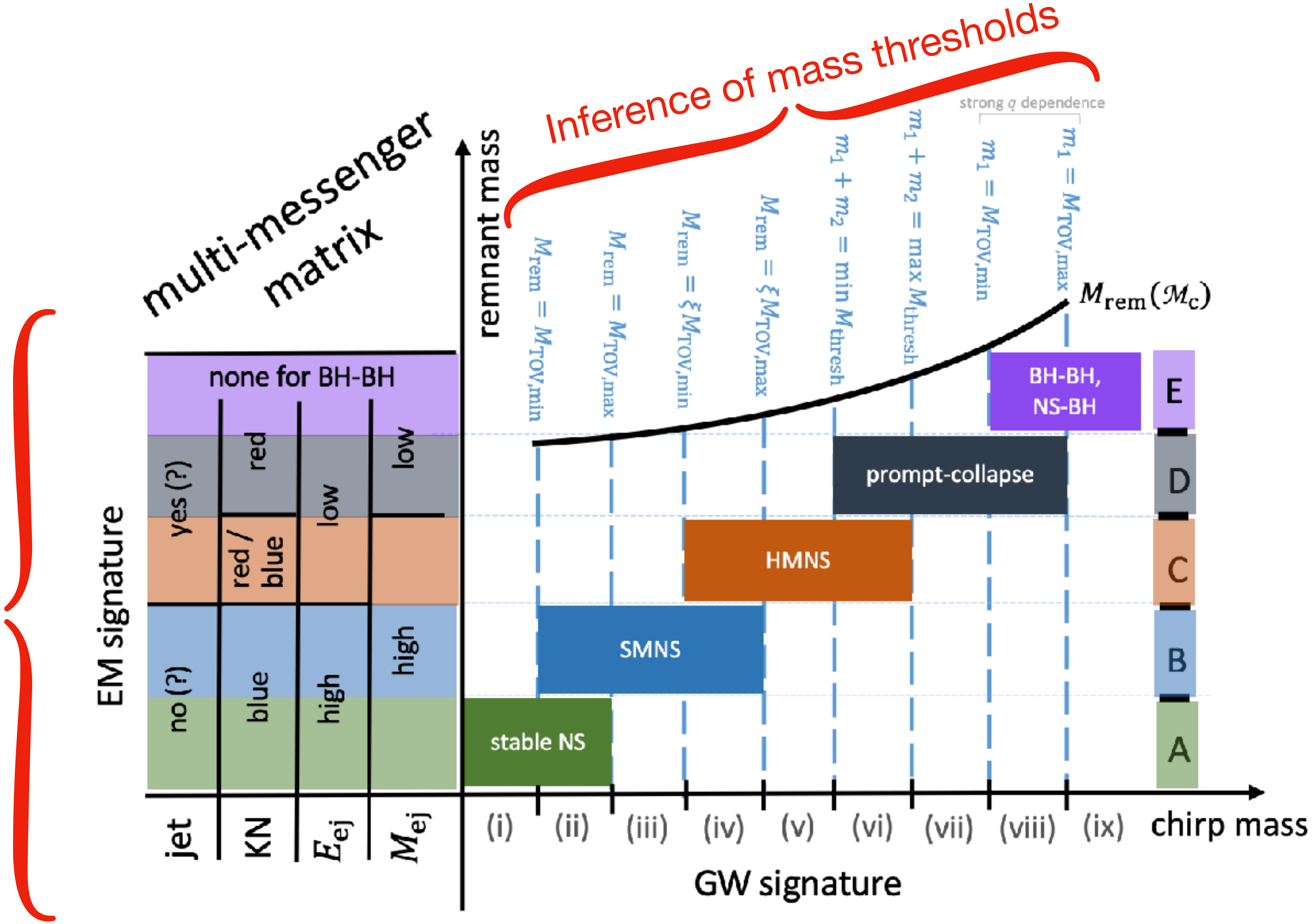
EM: Kilonovae/GRB



Margalit & Metzger (2019) ApJL, 880, L15

EM: Kilonovae/GRB

Qualitative Interpretation To Determine Type



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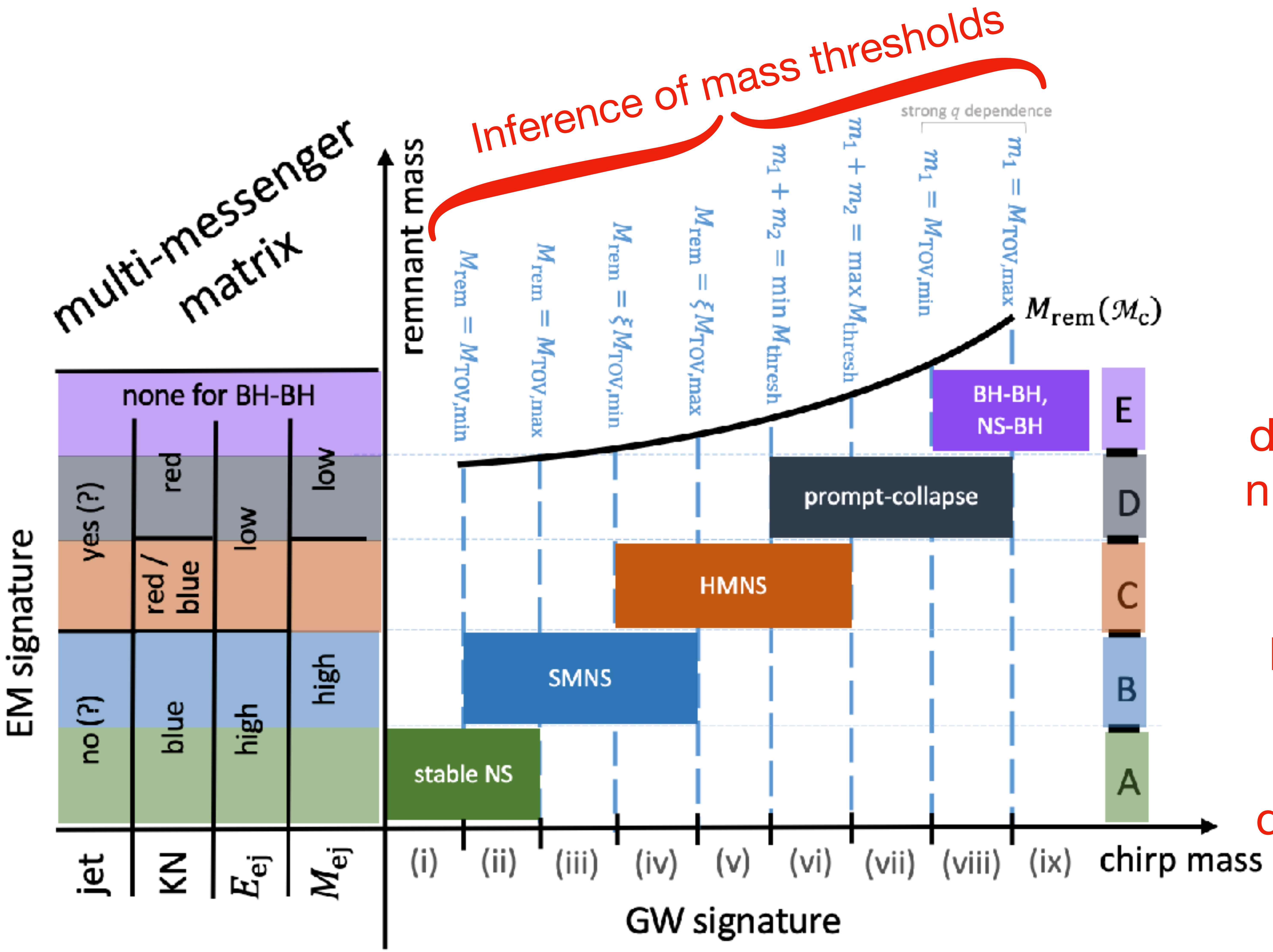
Qualitative Interpretation To Determine Type

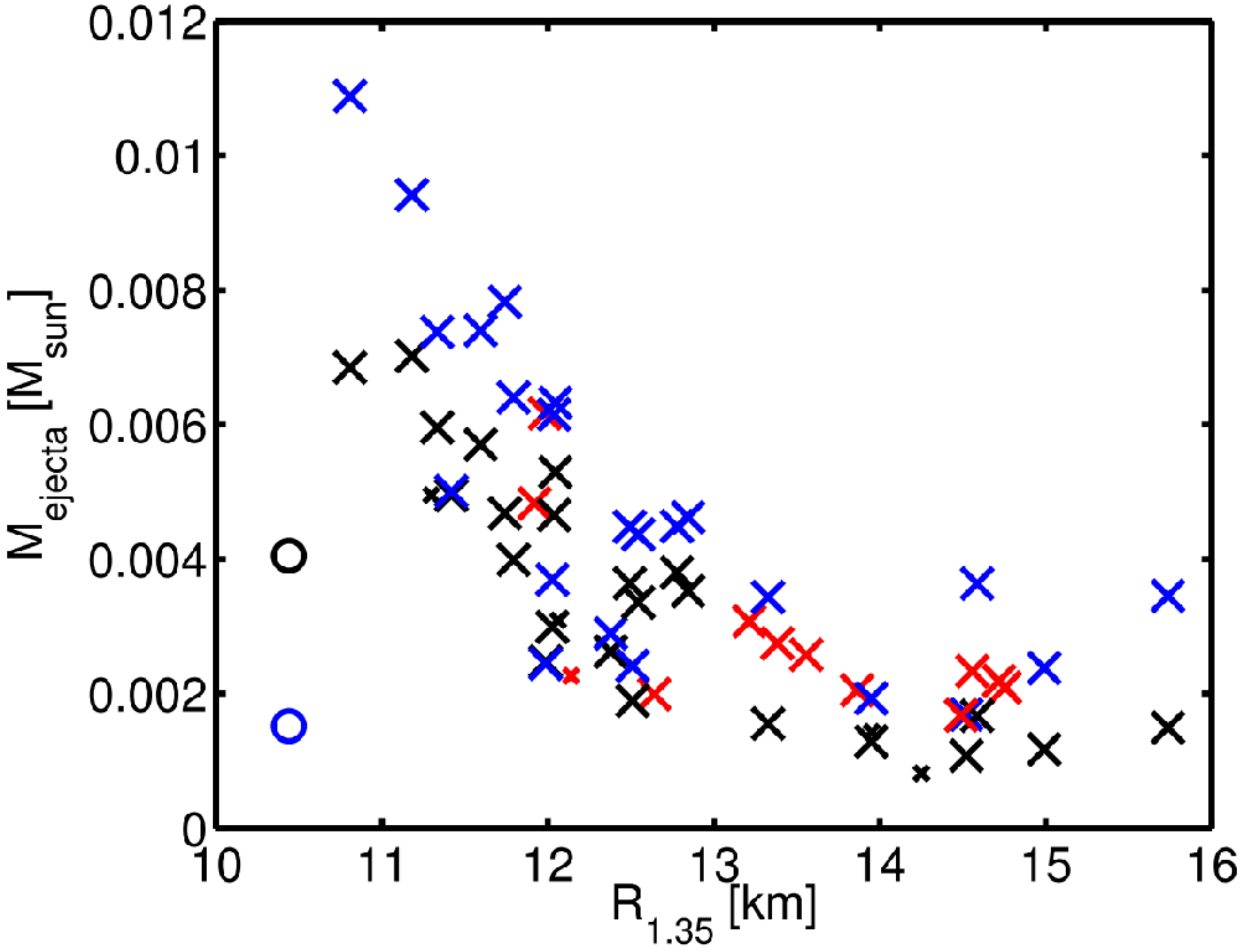


Huge uncertainties due to systematics in numerical simulations and choice of EOS

Perhaps more solid once you have many events of qualitatively different types

Margalit & Metzger (2019) ApJL, 880, L15

EM: Kilonovae/GRB

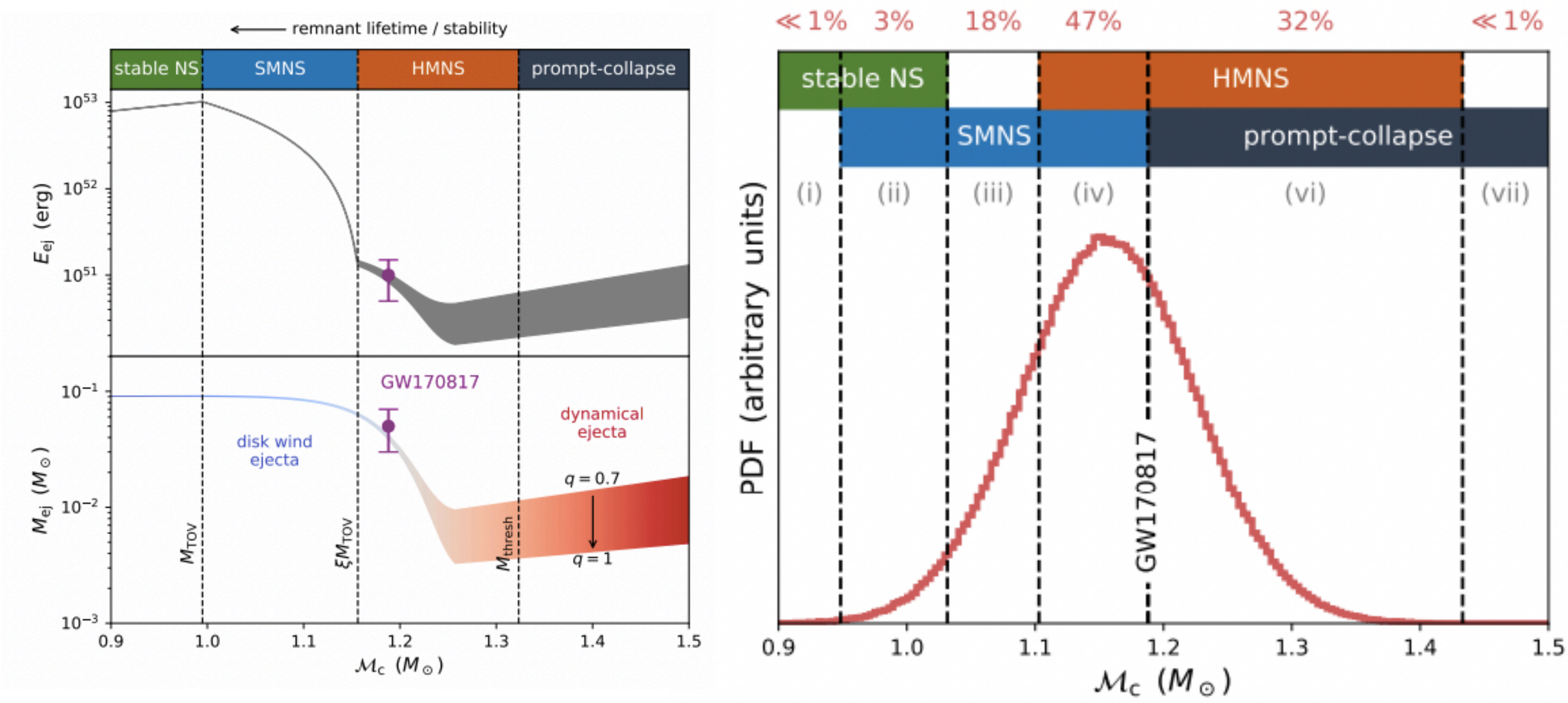


Bauswein (2019) Ann. of Phys., 411, 167958

20-50% mass error
100% vej error
(Due to thermalisation or nuclear model)

Brethauer, Kasen, Margutti, & Chernock, arXiv:2408.02731

EM: Kilonovae/GRB



Margalit & Metzger (2019) ApJL, 880, L15

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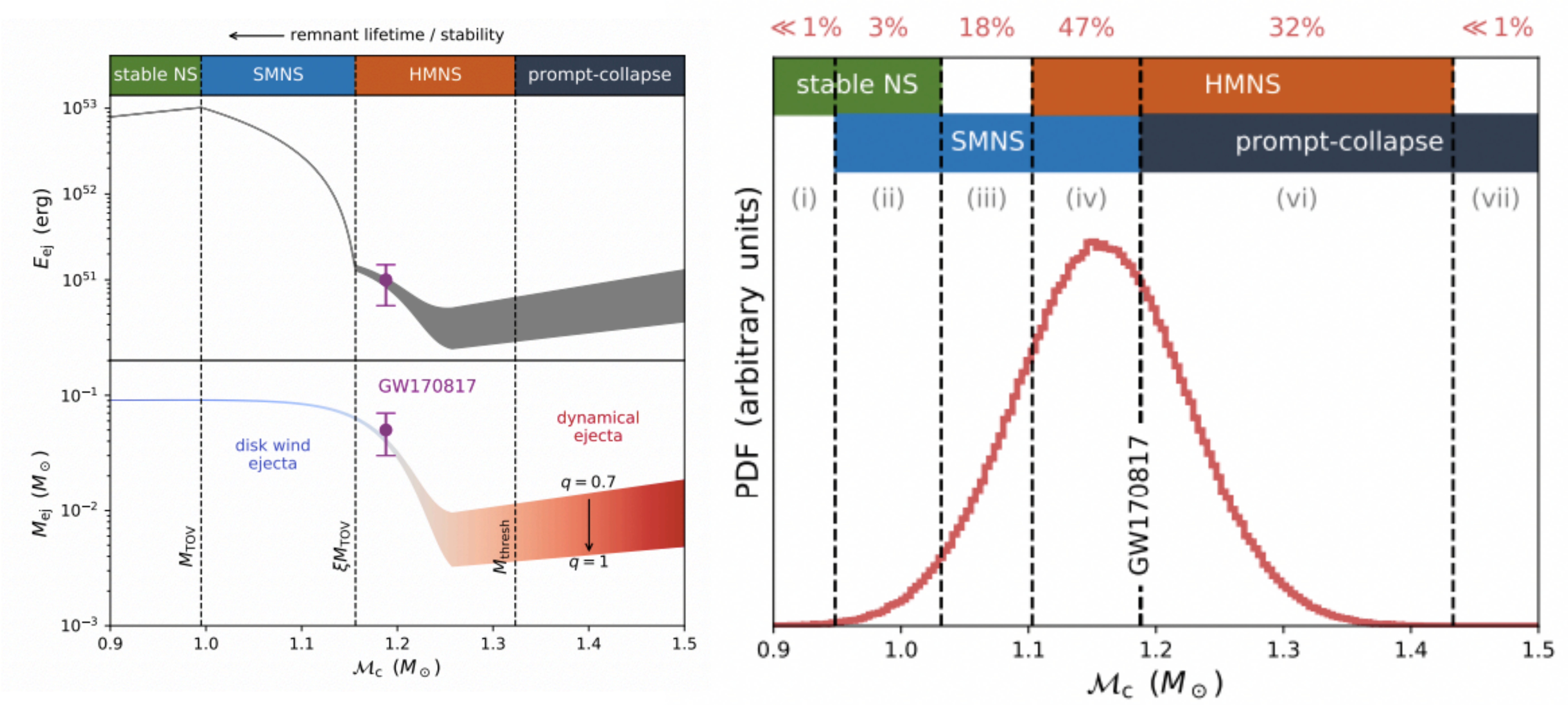
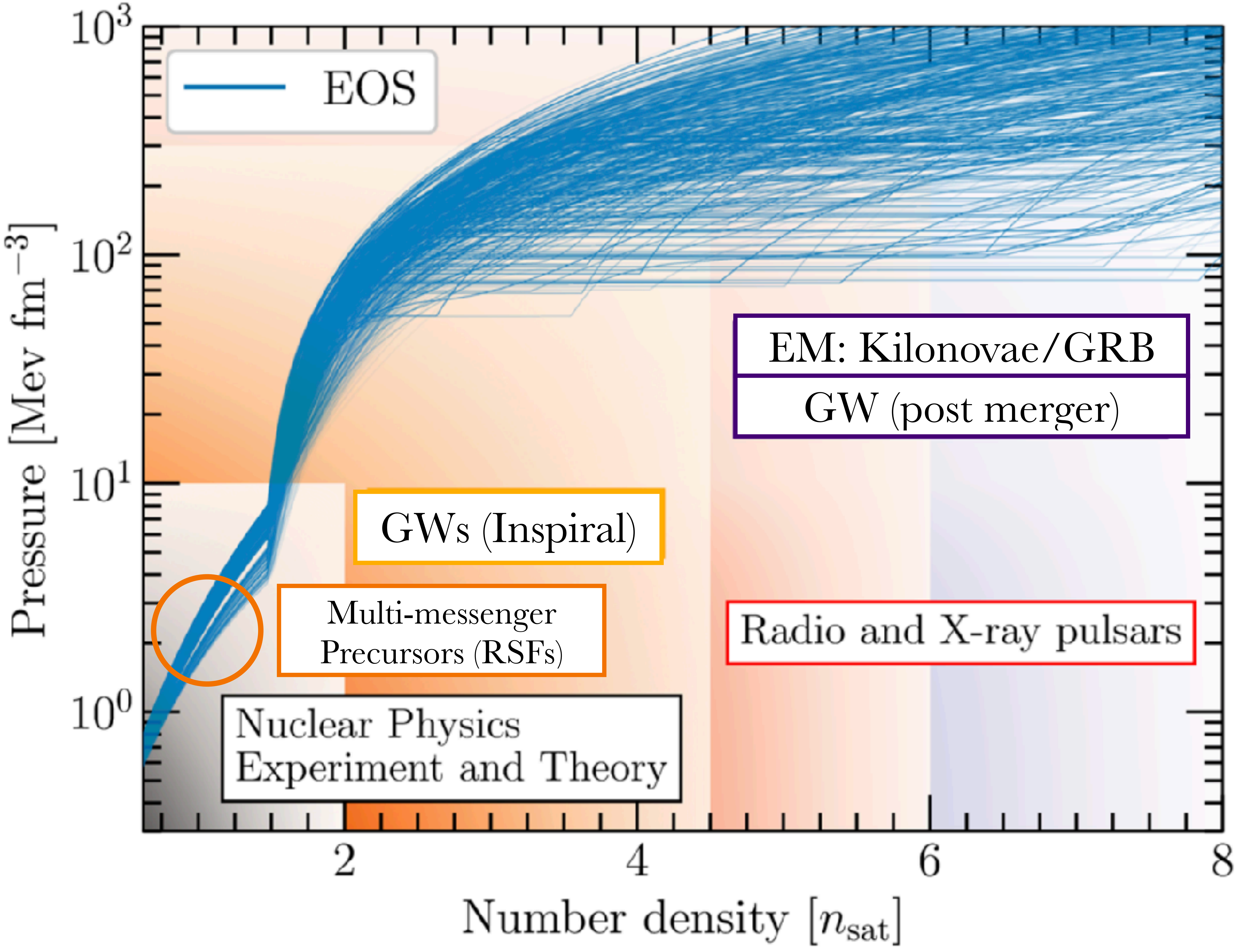


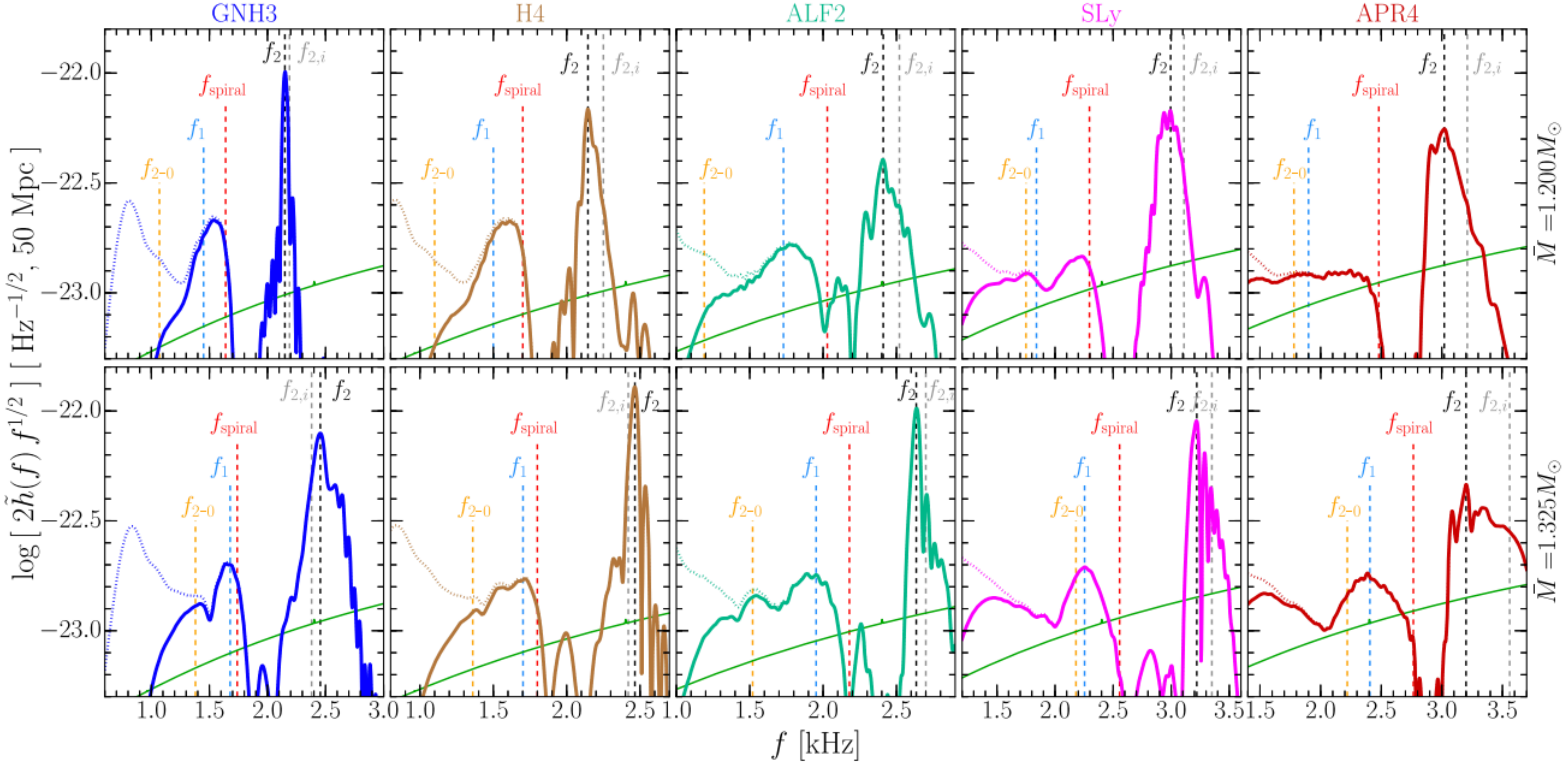
Huge systematics for individual events/interpretations!

Margalit & Metzger (2019) ApJL, 880, L15



Adapted from Pang et al., (2023) Nature Comm, 14:8352

GW (post merger)



Rezzolla & Takami (2016, PRD, 93, 124051

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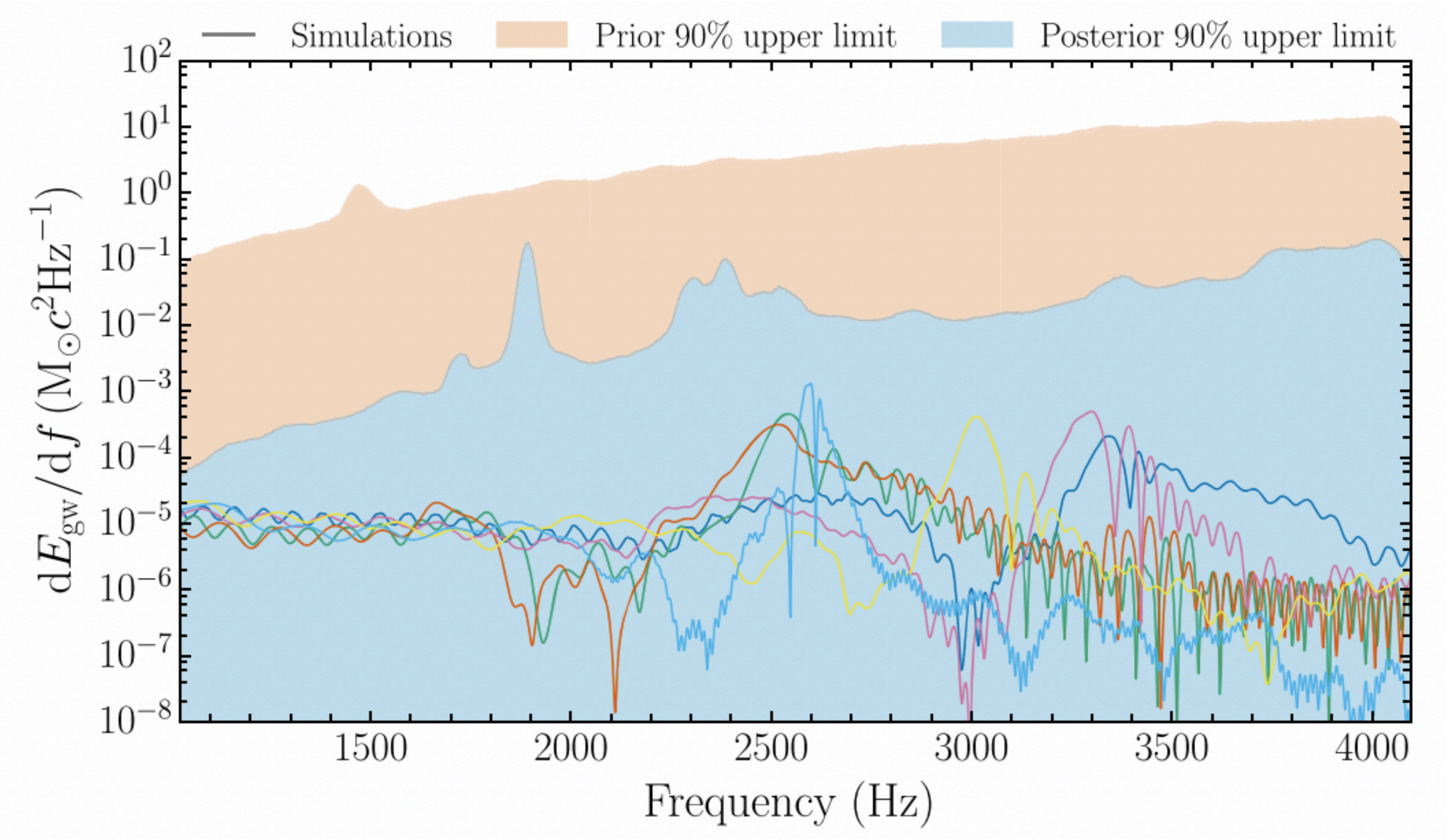
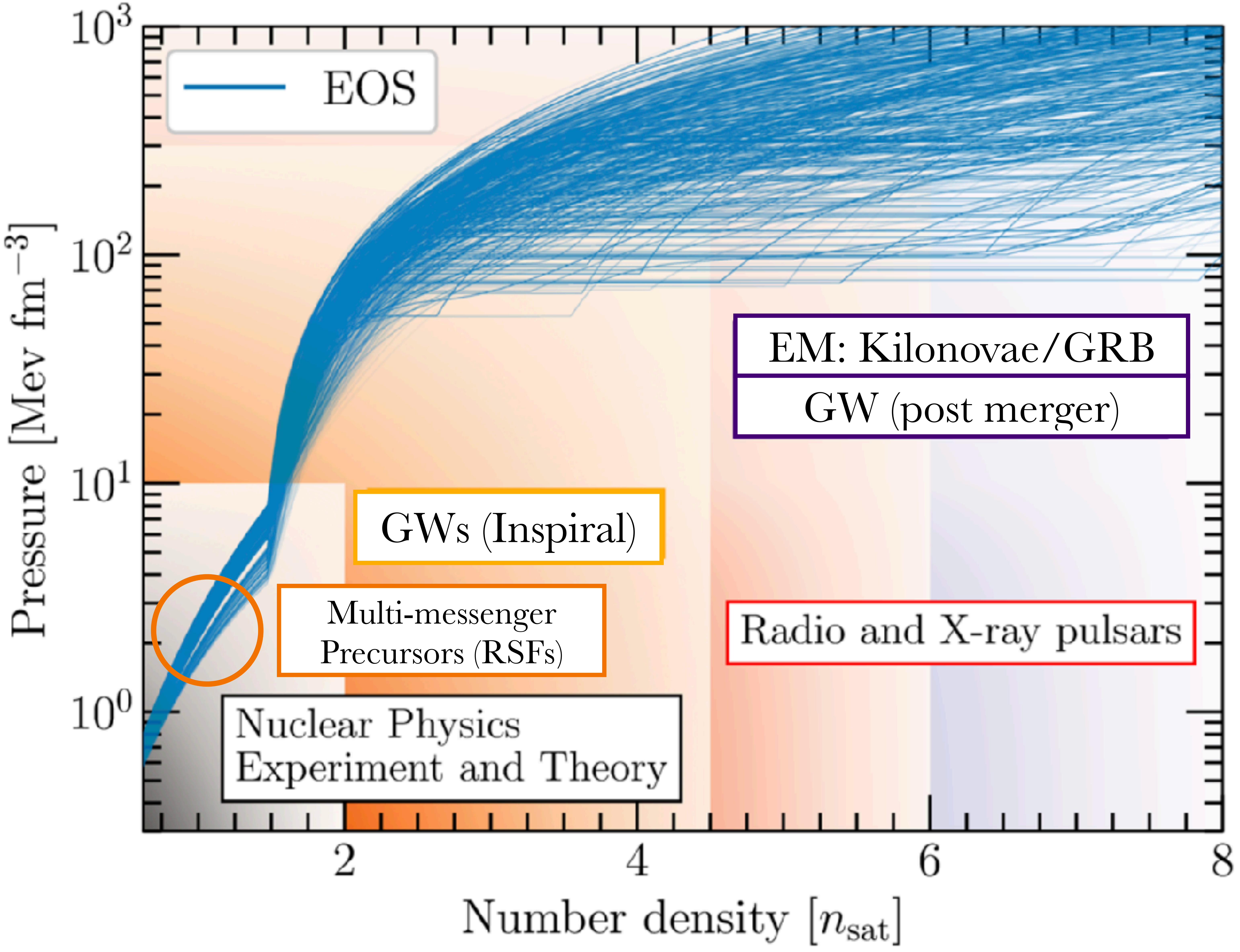


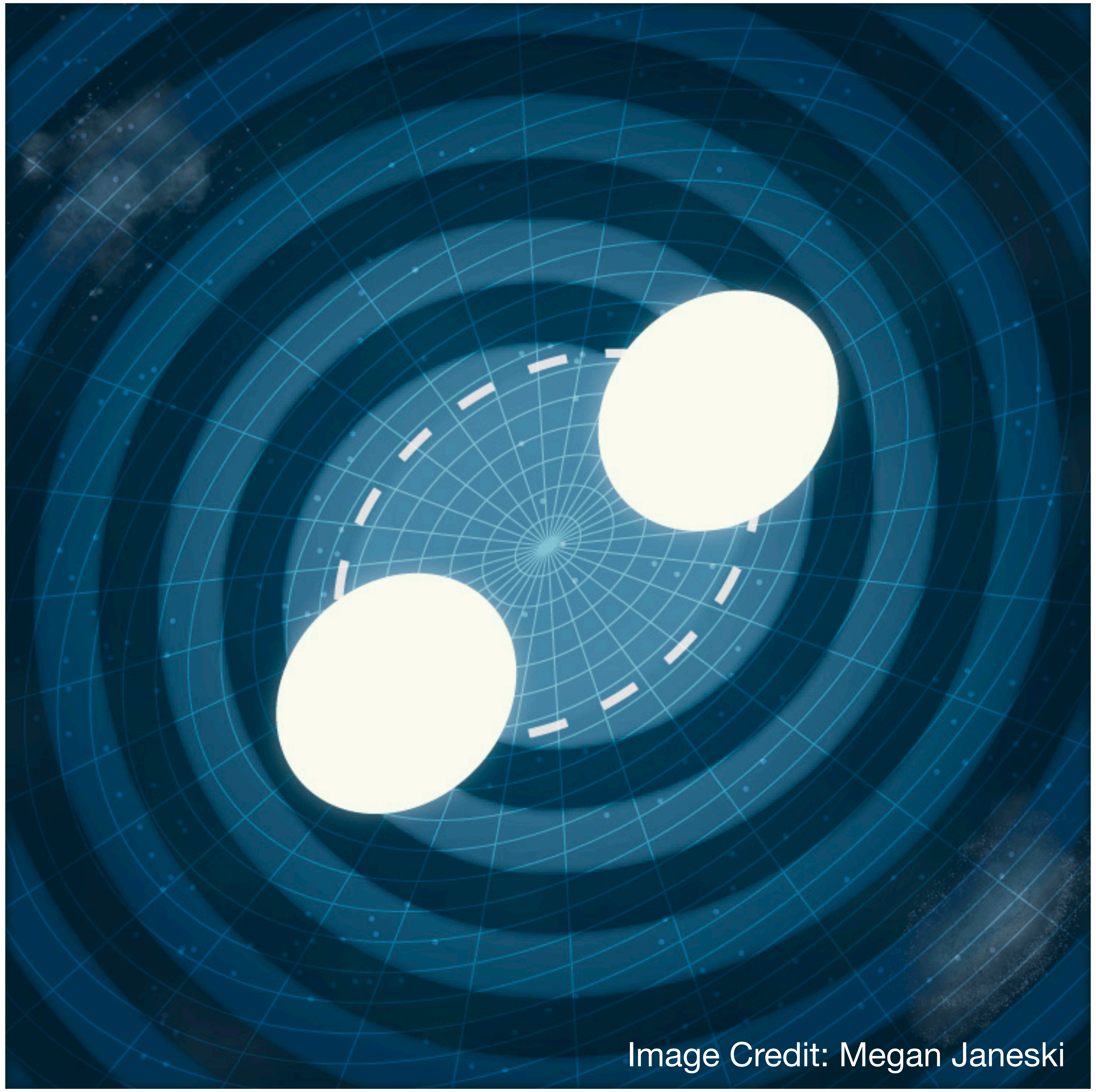
Post Merger Ringing of SMNS/HMNS. Not detectable with this generation - but likely with 3G

LVC (2019) PRX, 9, 011001



Adapted from Pang et al., (2023) Nature Comm, 14:8352

GWs (Inspiral)

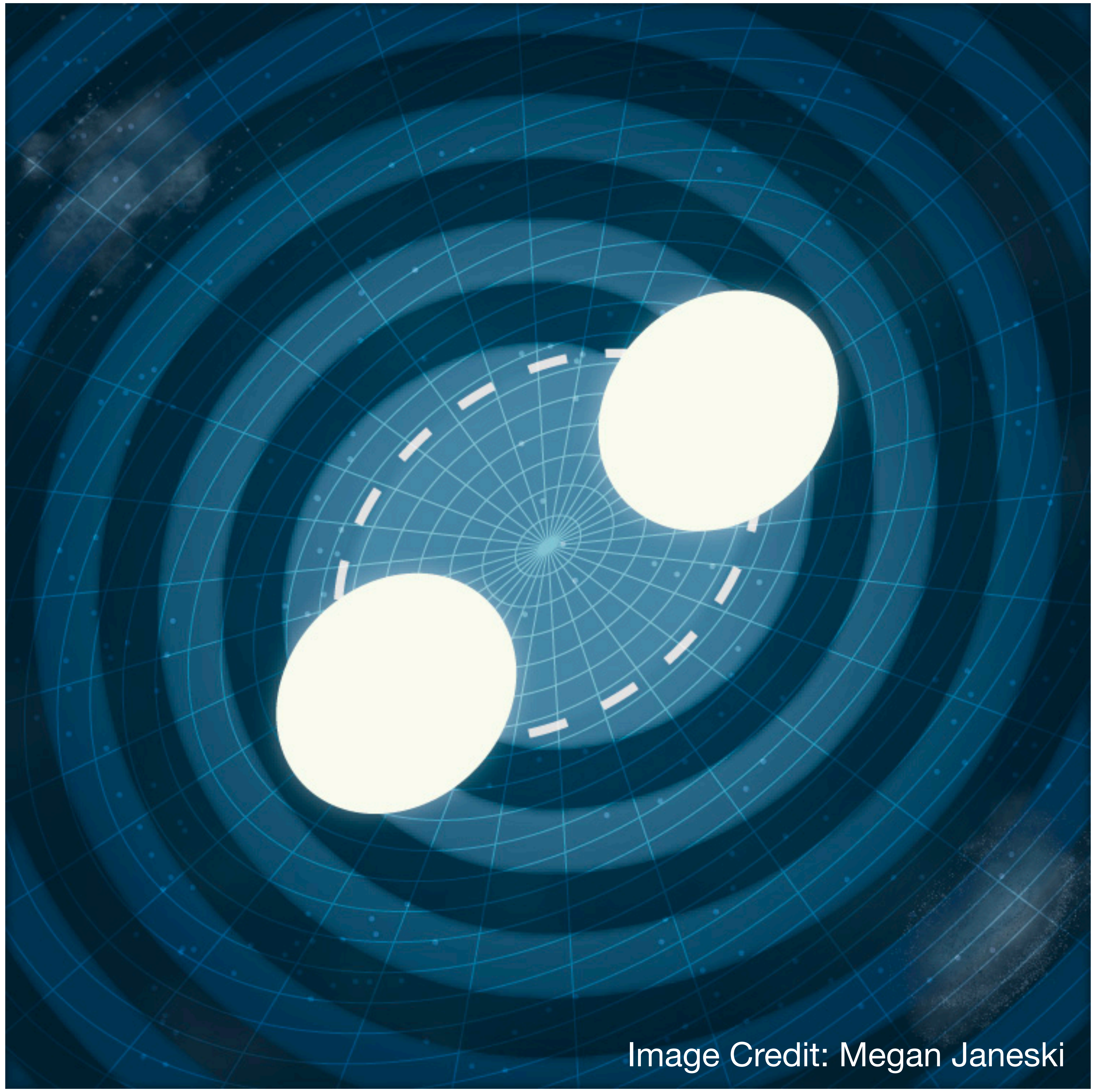


$$Q_{ij} = -\Lambda \frac{\partial \Phi_{\text{ext}}}{\partial x^i \partial x^j}$$

GWs (Inspiral)

The lowest order at which the EOS contributes to the the GW waveform is through the “tidal deformability” Λ

(Quadrupolar polarizability?)



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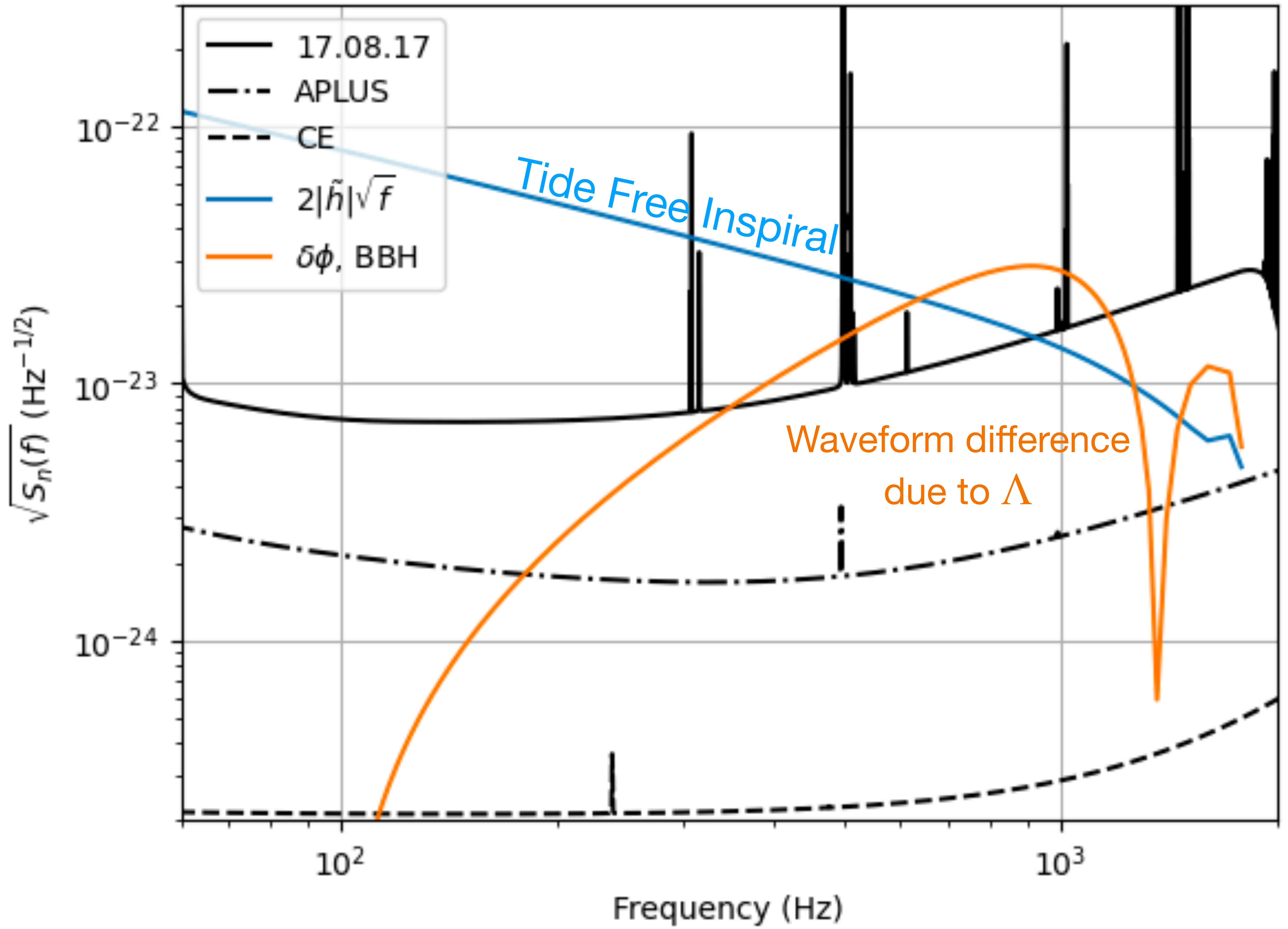
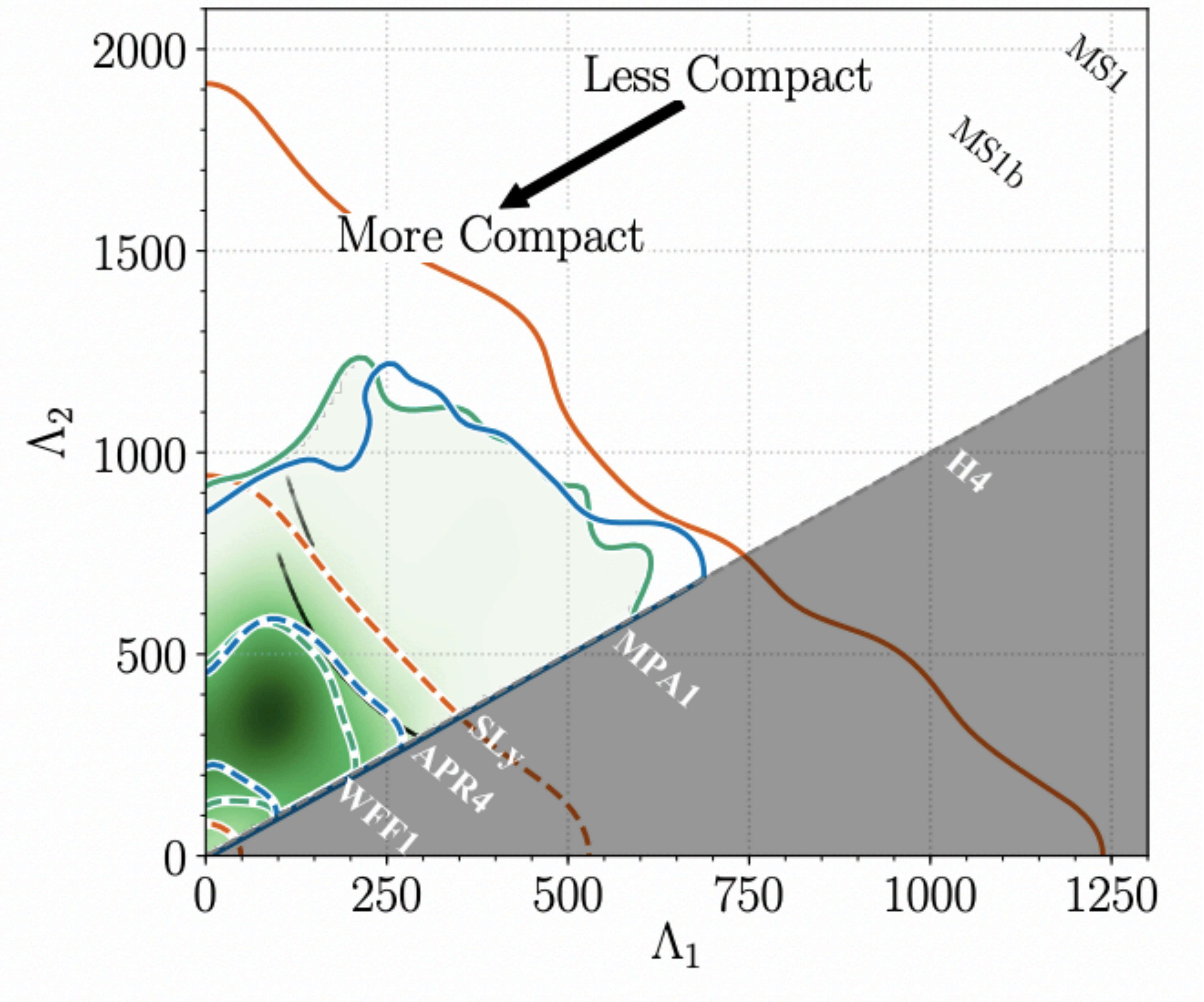


Courtesy of J. Read, adapted from Read (2023) CQG, 40 135002

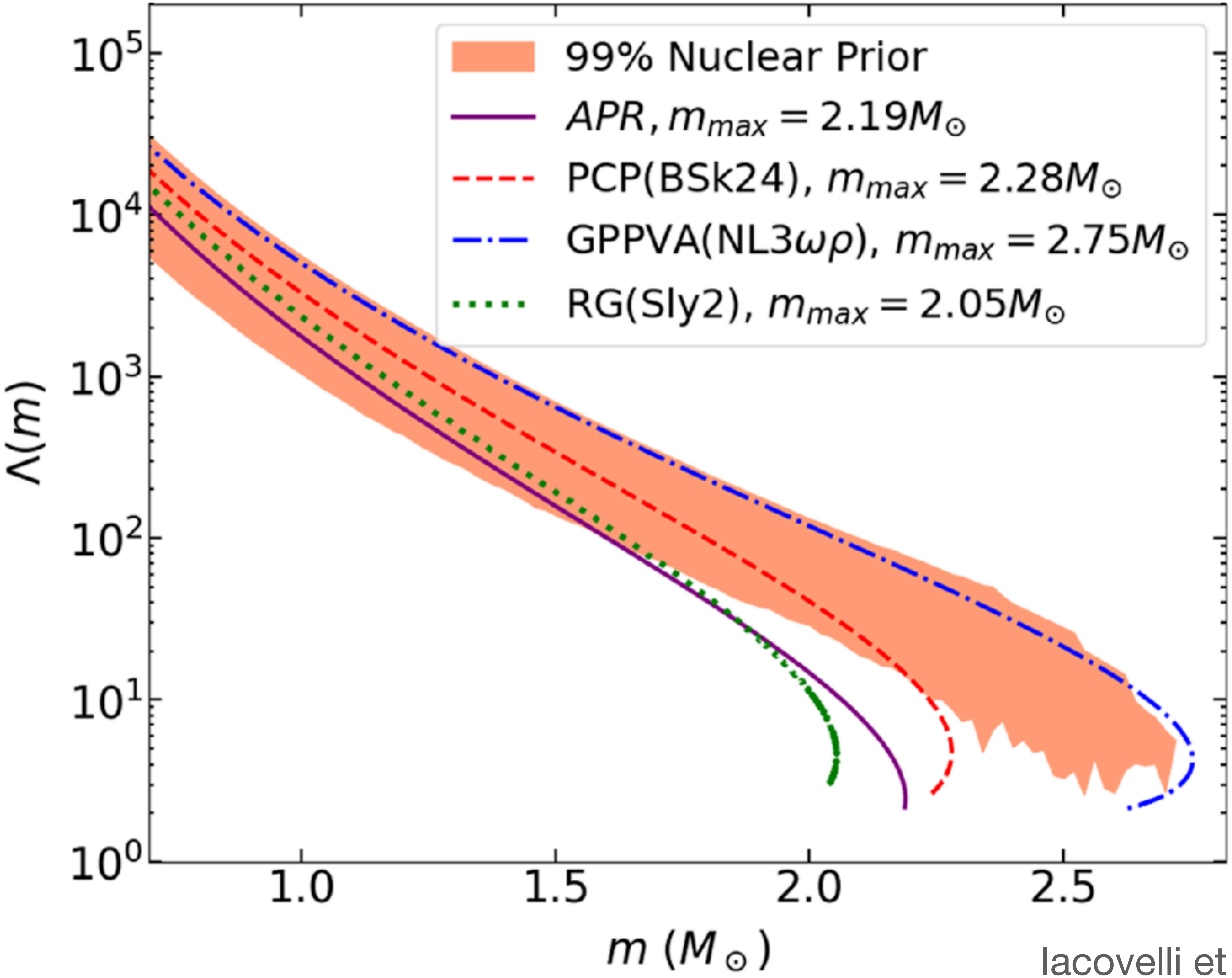
GWs (Inspiral)



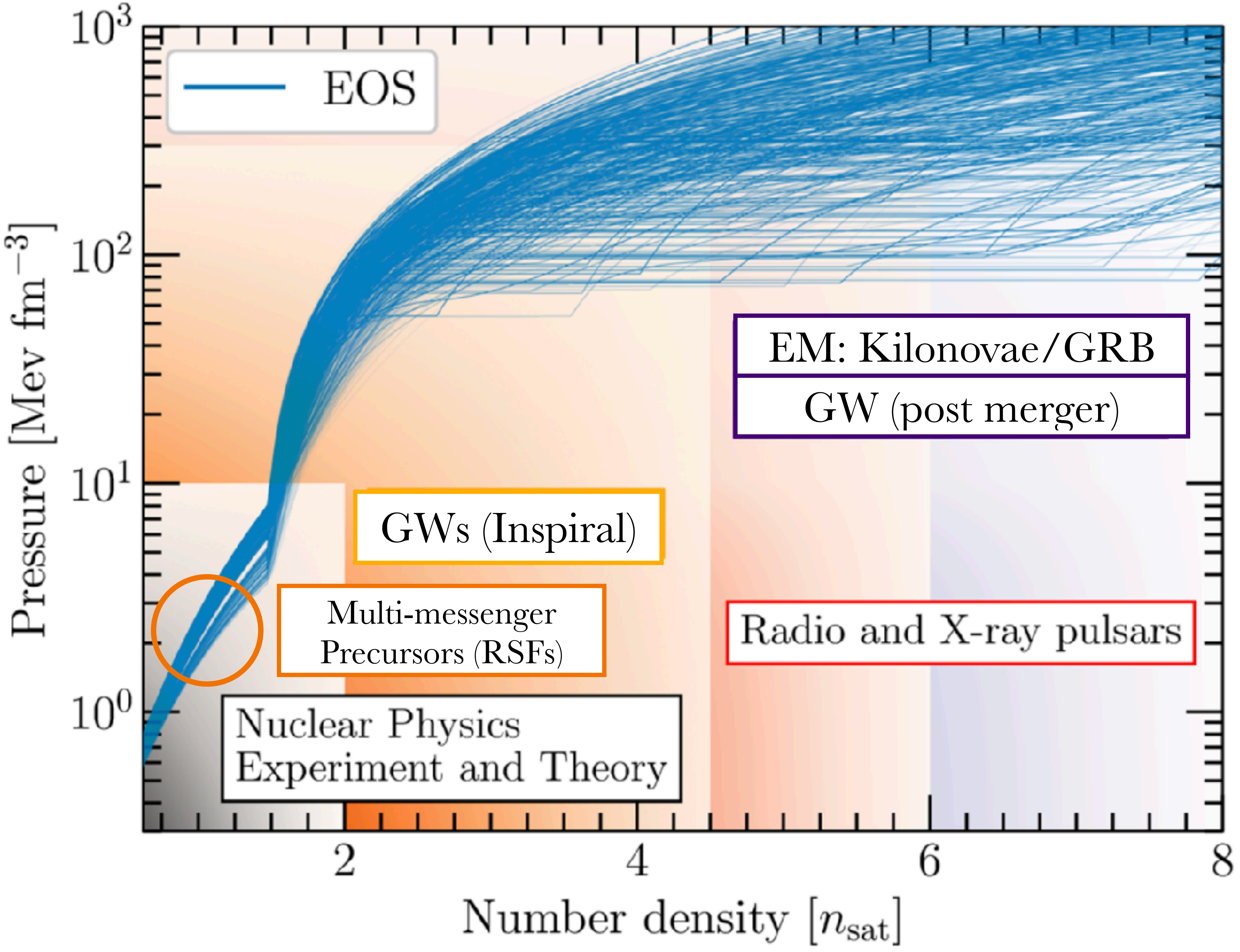
GW170817

LVC (2018), PRL, 121, 161101

GWs (Inspiral)



Iacovelli et al. (2023) PRD, 108, 122006



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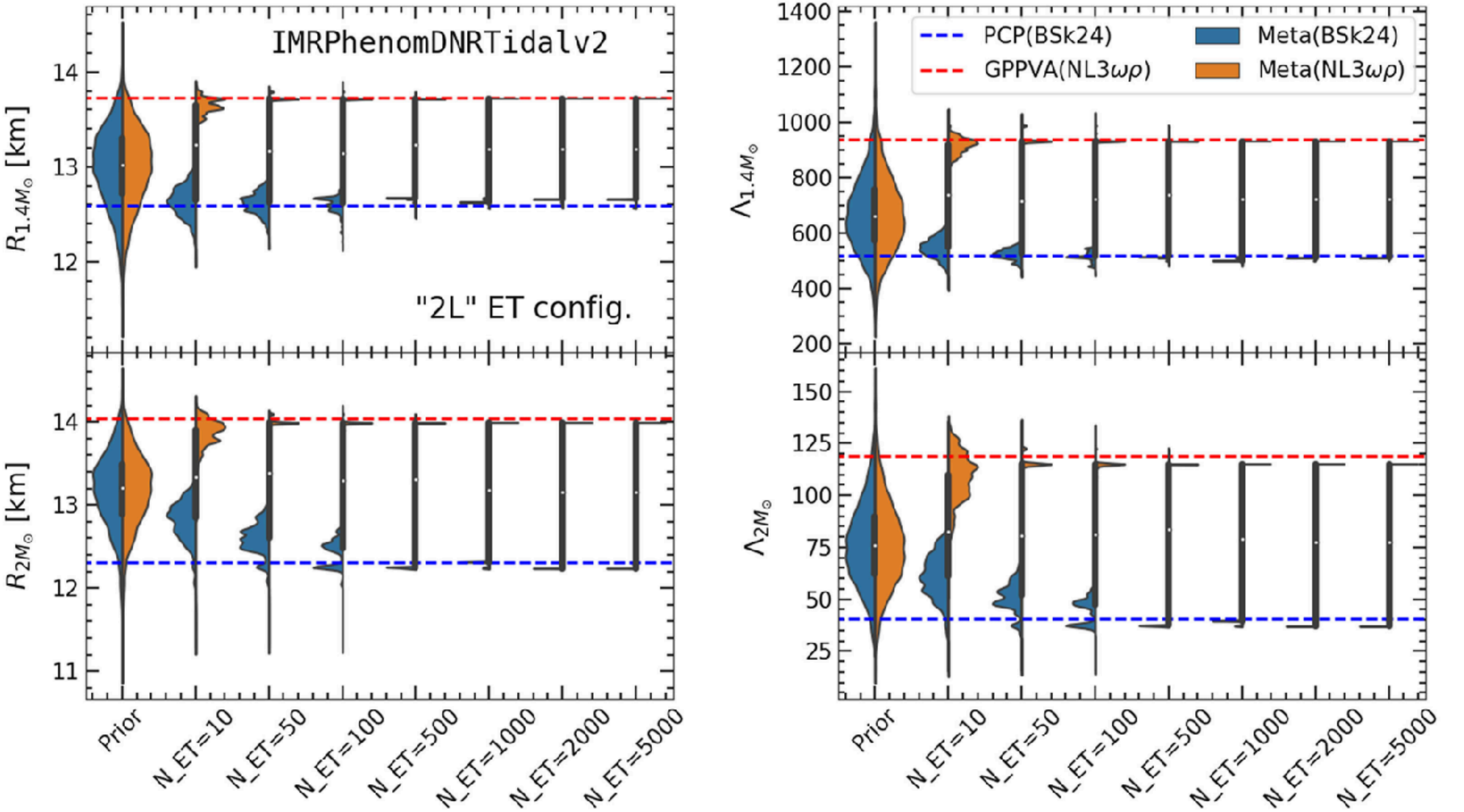
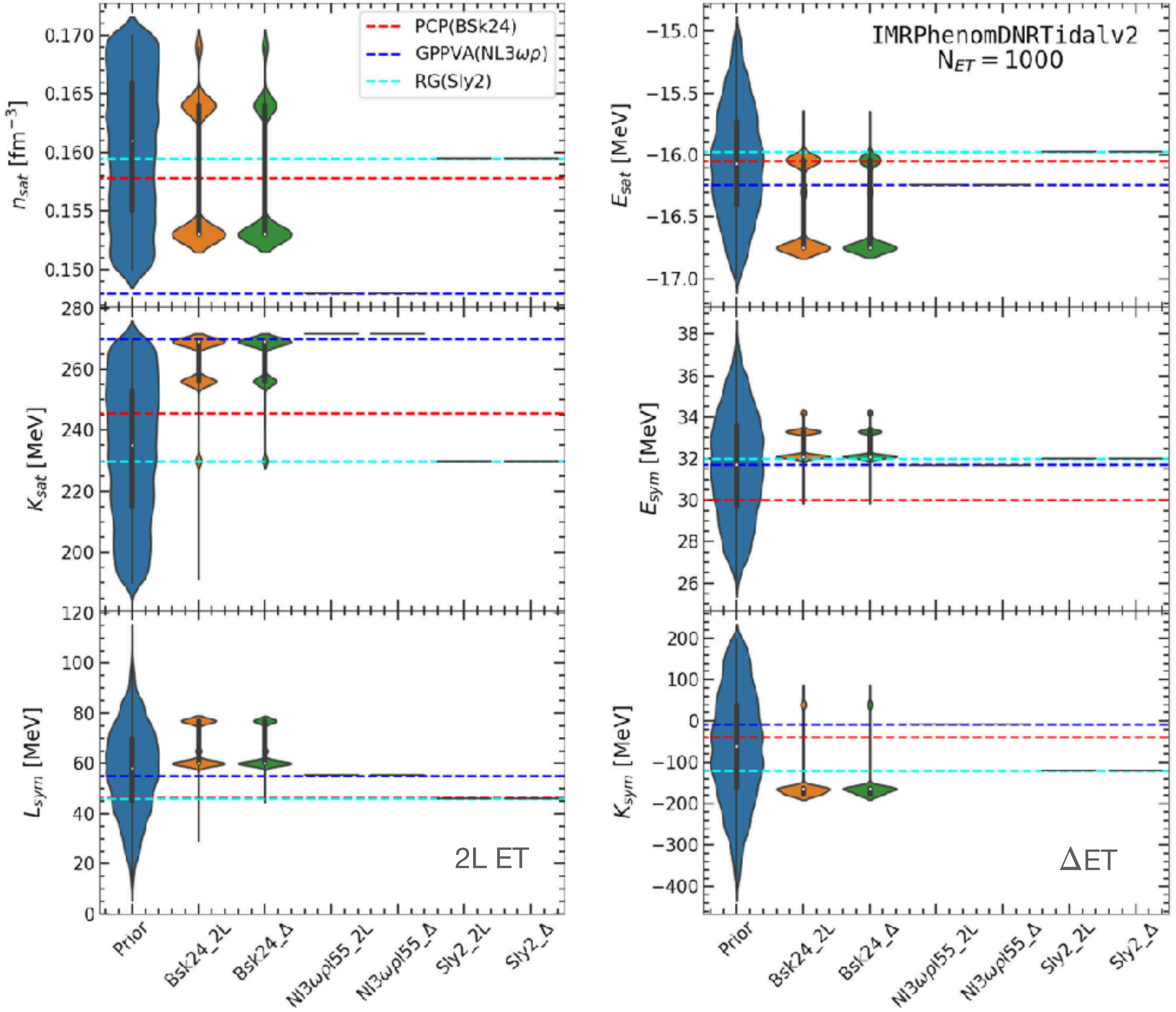


Iacovelli et al. (2023) PRD, 108, 122006

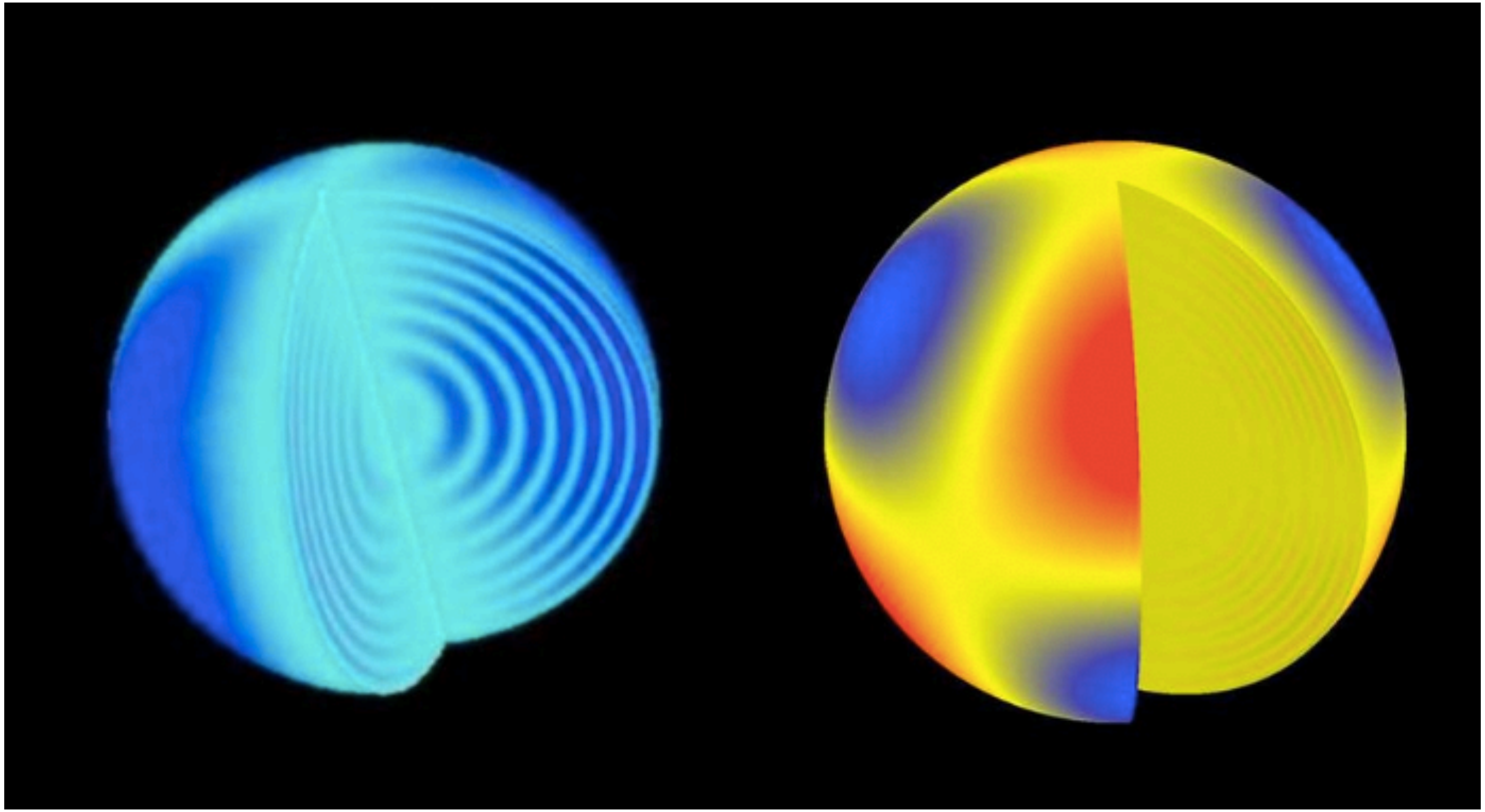
GWs (Inspiral)

Assuming the star is nucleonic constraints can be placed on the isovector/isoscalar parameters



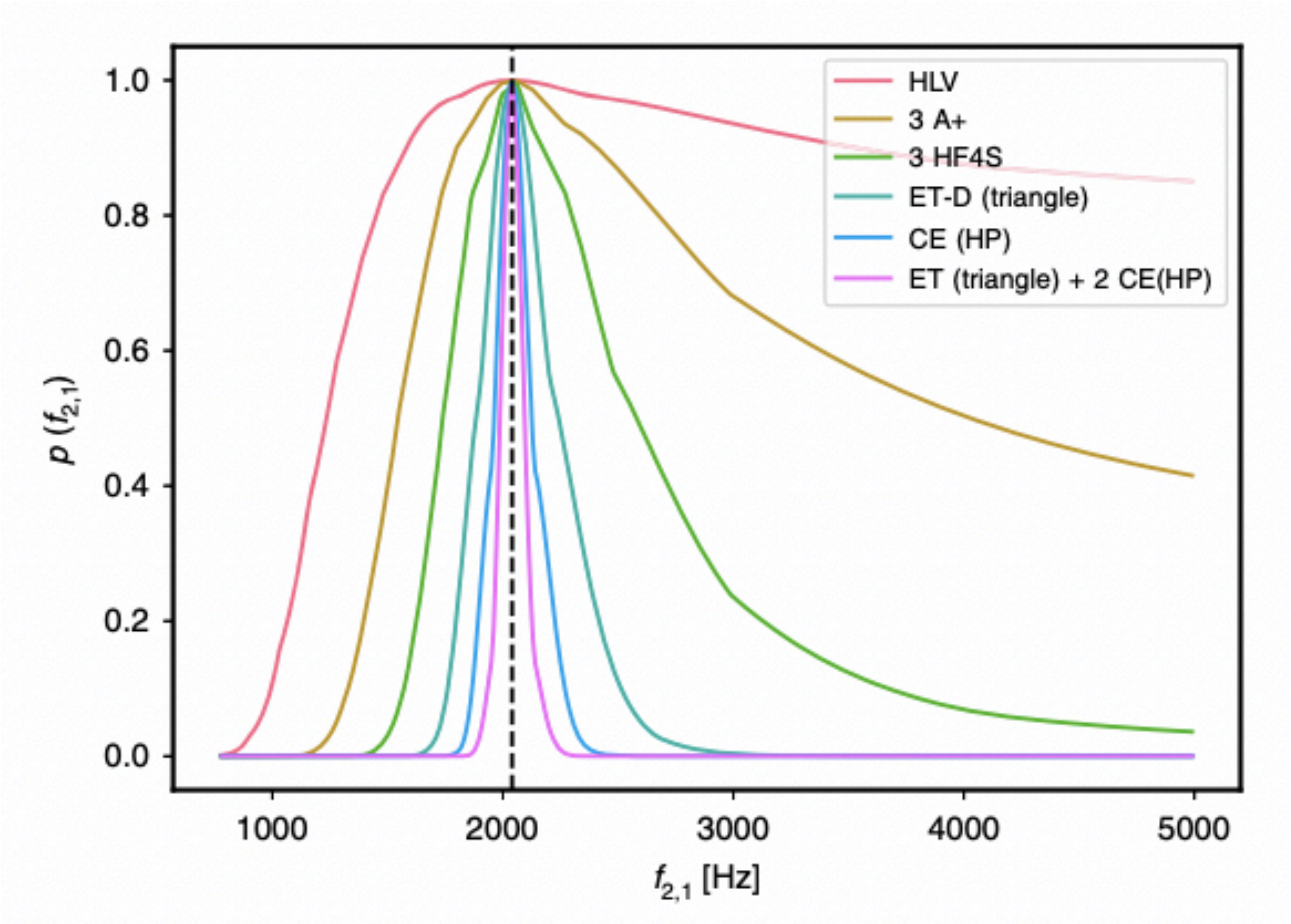
Iacovelli et al. (2023) PRD, 108, 122006

GWs (Inspiral) Asteroseismology!



Modes probe the structure where their eigenfunctions are concentrated

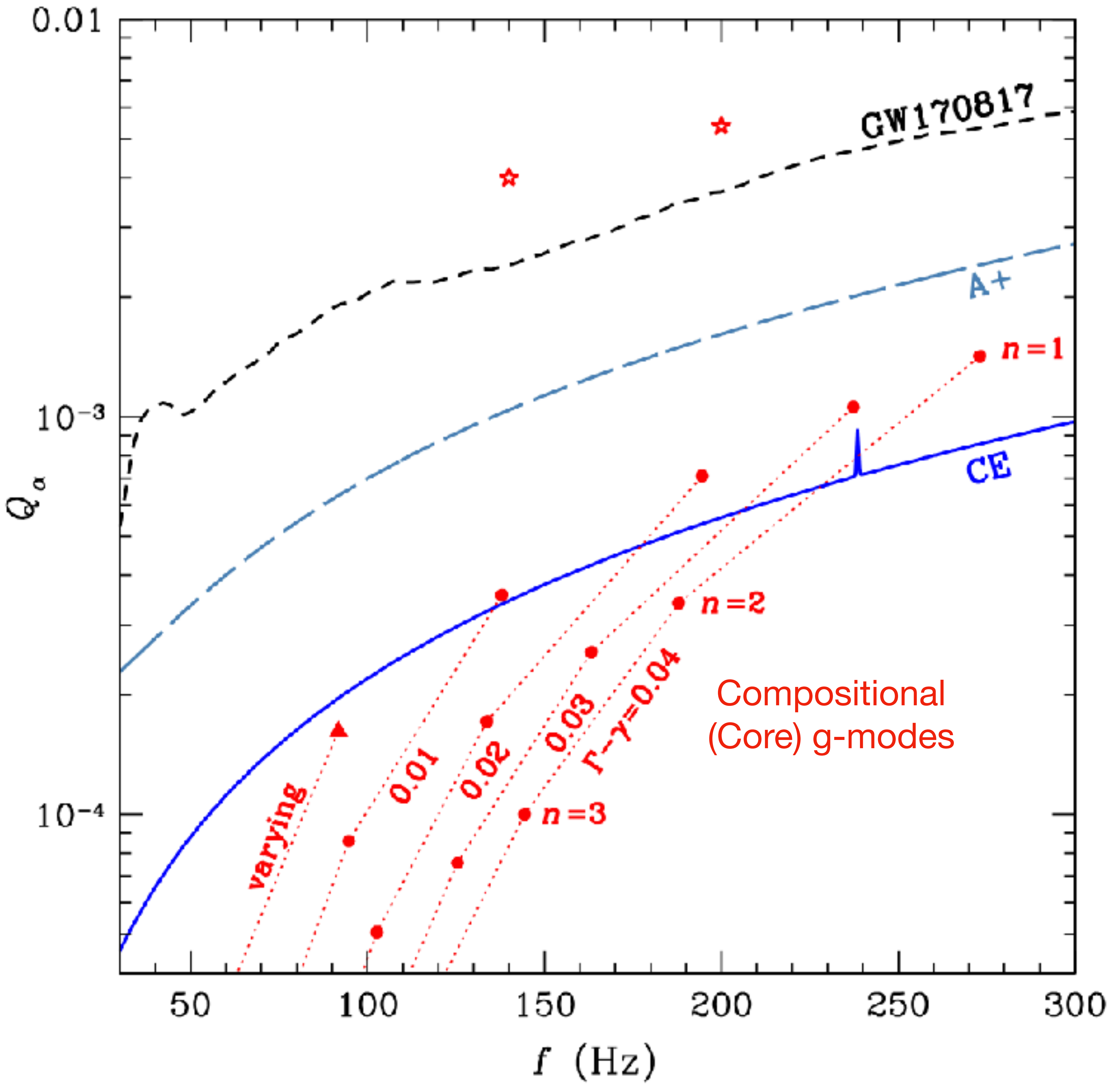
GWs (Inspiral) Asteroseismology!



Fundamental modes (same EOS info as Λ)
(non-resonant during inspiral)

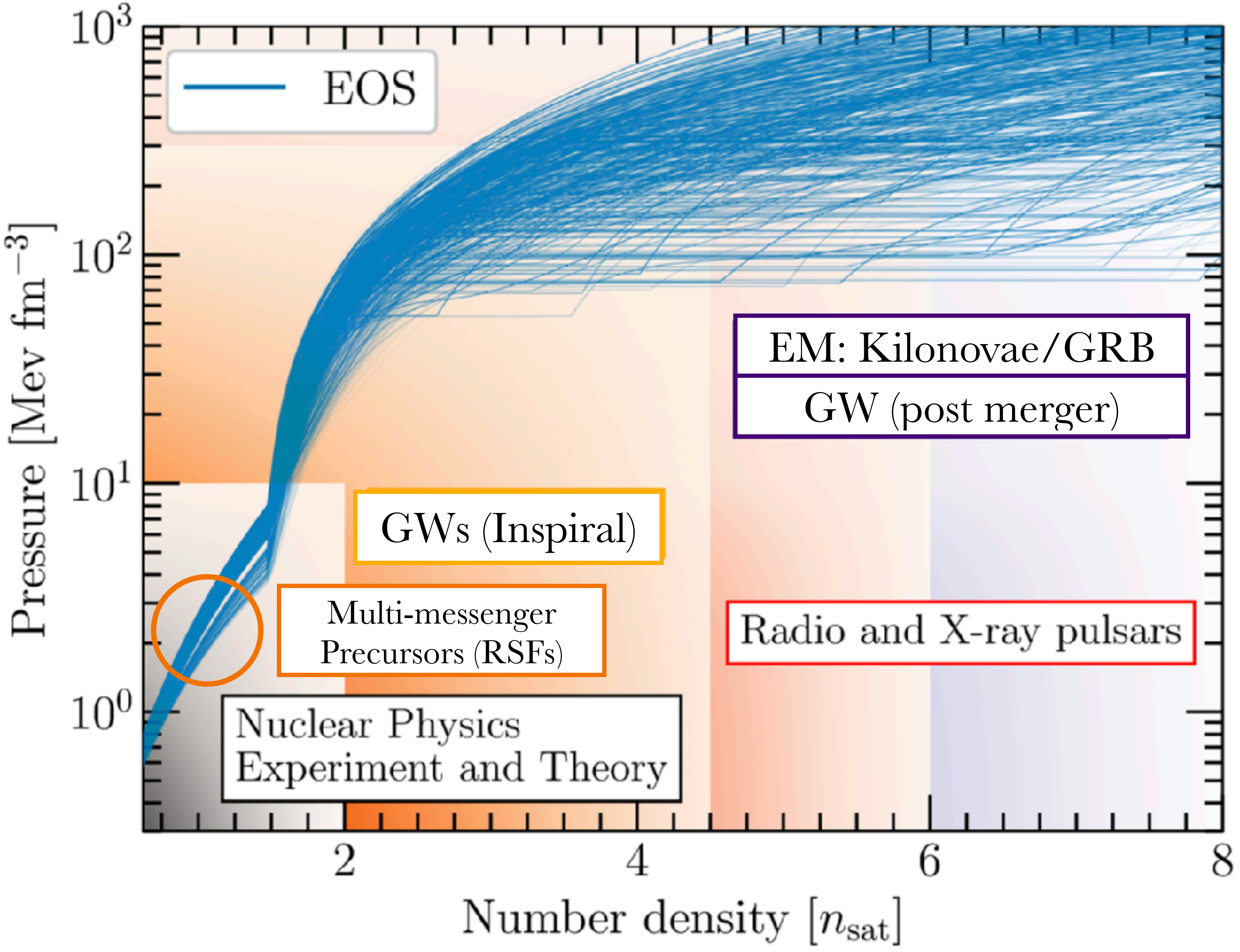
Giant Quadrupole Resonance?

Pratten, Schmidt, & Hinderer (2020) Nature Comm., 11, 2553



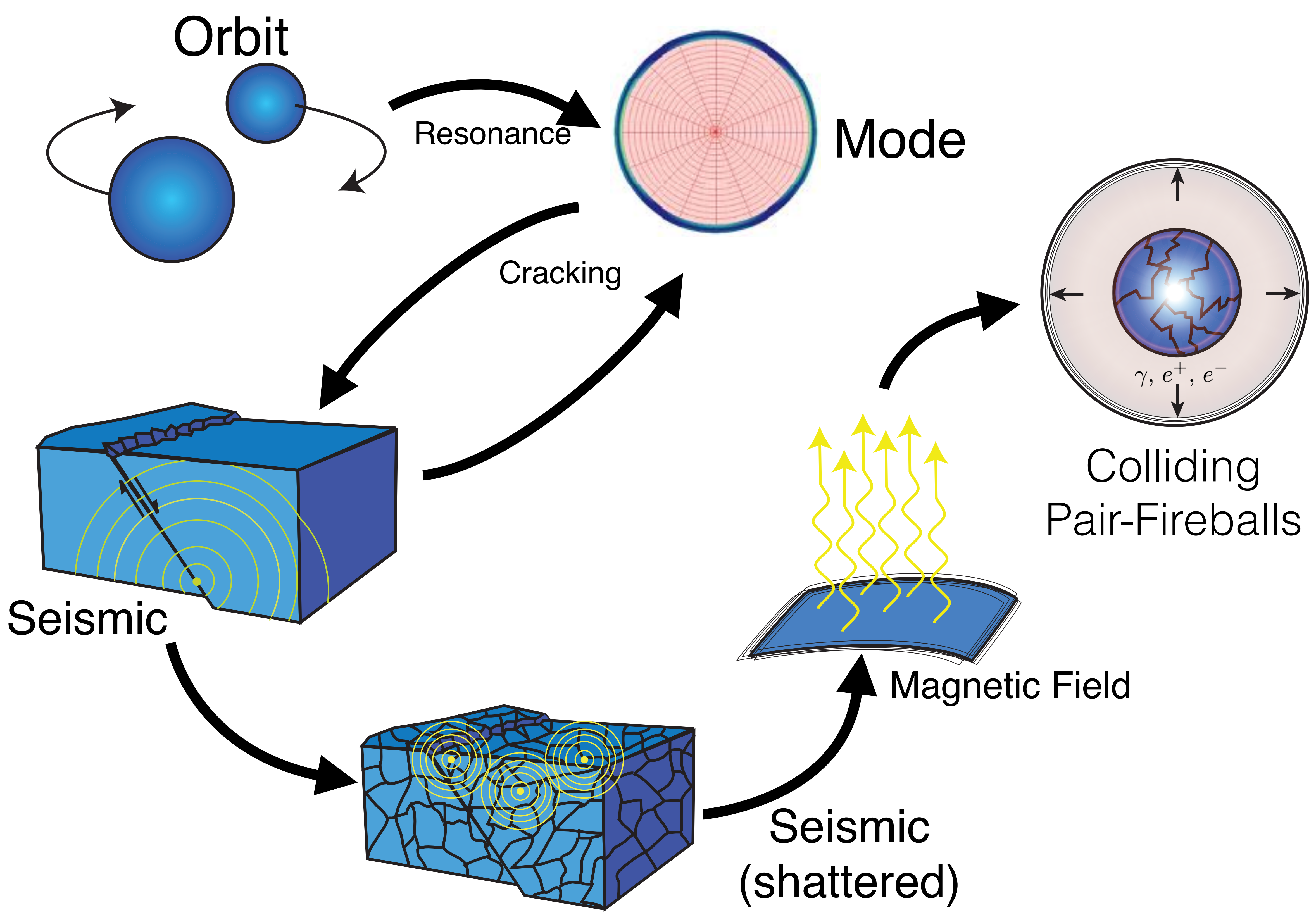
Other asteroseismic modes
(resonant during inspiral)

Ho & Andersson (2023), PRD 108, 043003

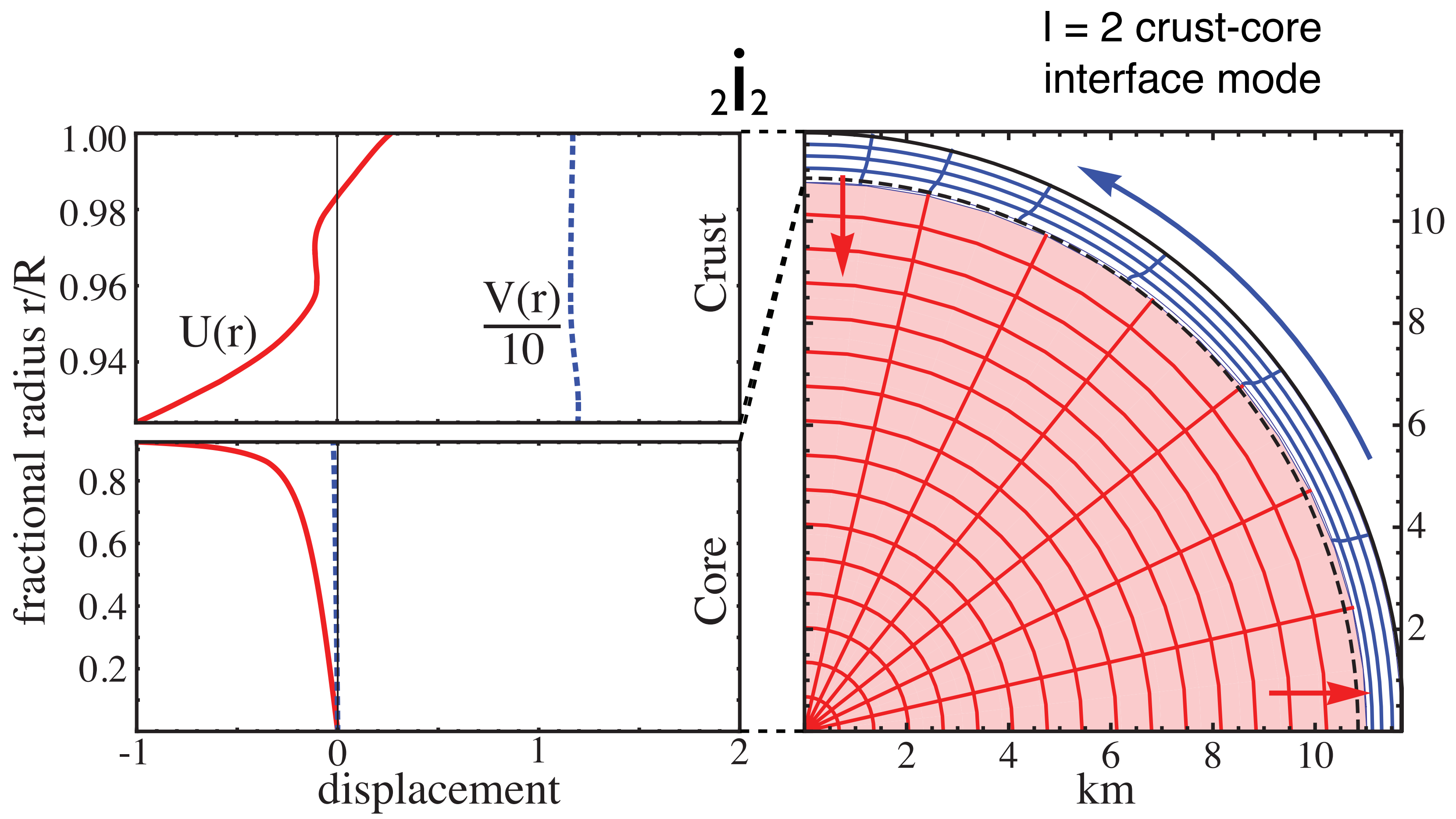


Adapted from Pang et al., (2023) Nature Comm, 14:8352

Multi-messenger Precursors (RSFs)

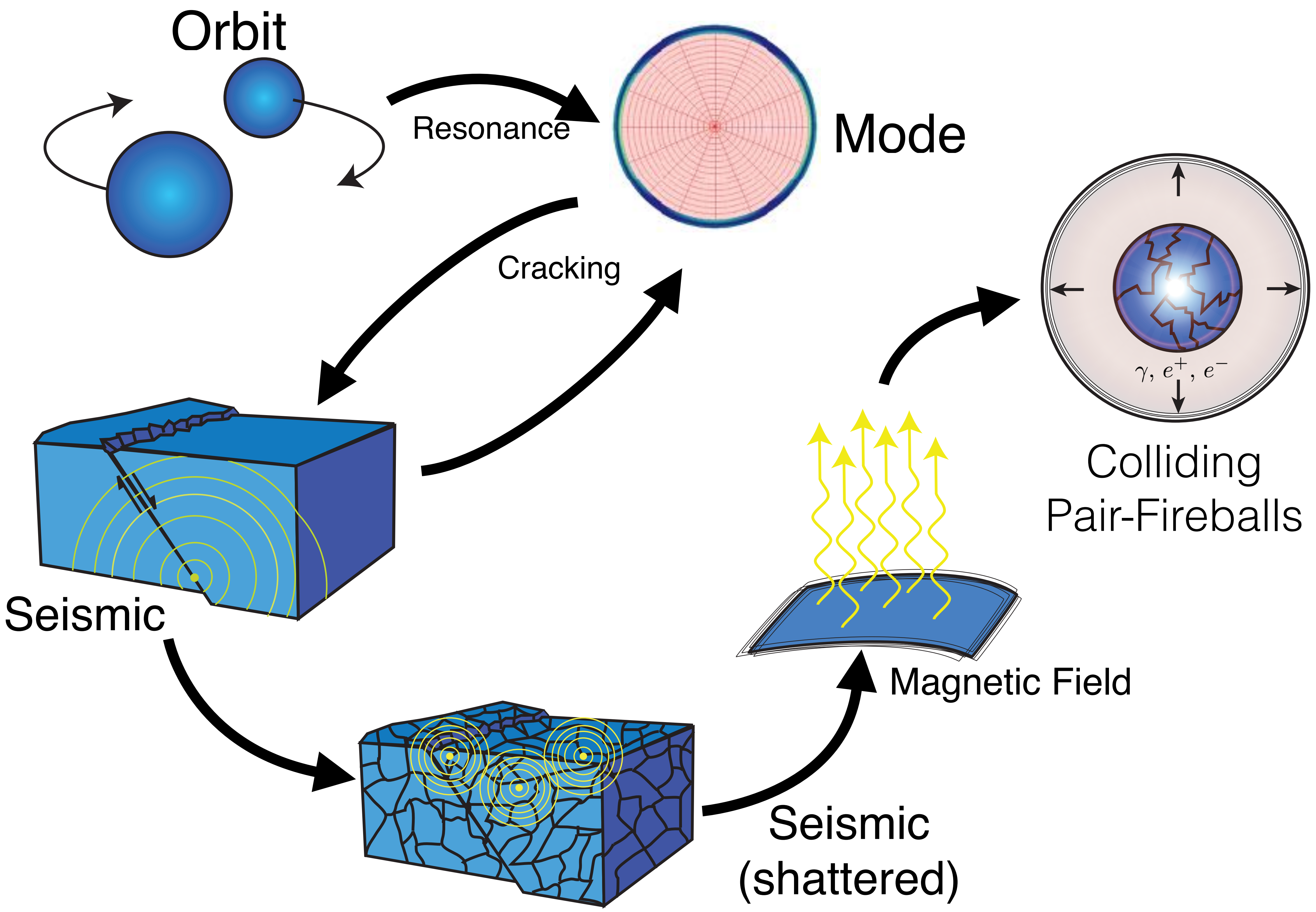


Pygmy Quadrupole Resonance?



DT, et al. (2012) PRL 108, 011102
DT (2013) ApJ 777, 103
Neill, DT, Van Eerten, Ryan, & Newton (2022) MNRAS, 514, 4

Multi-messenger Precursors (RSFs)



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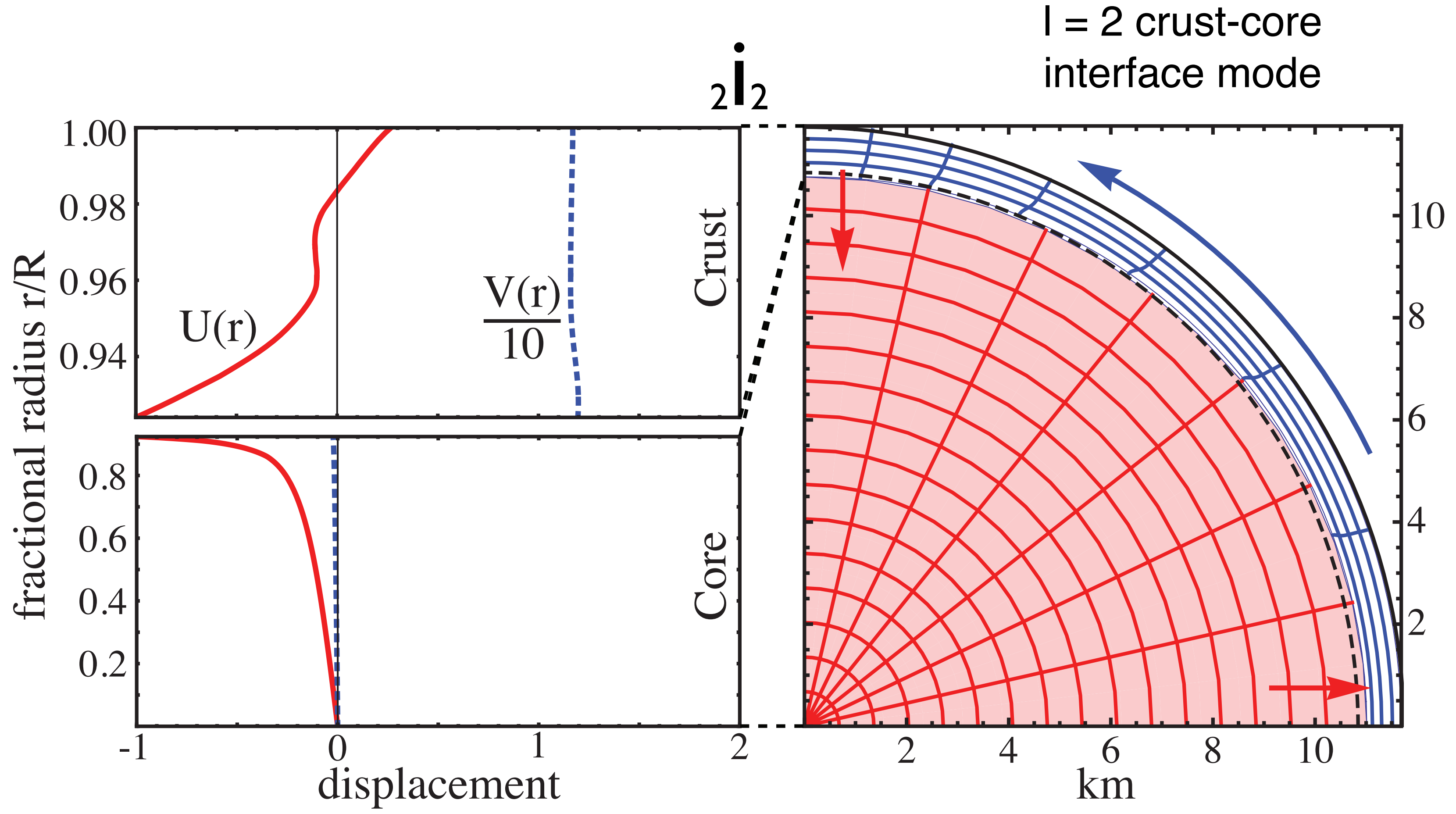

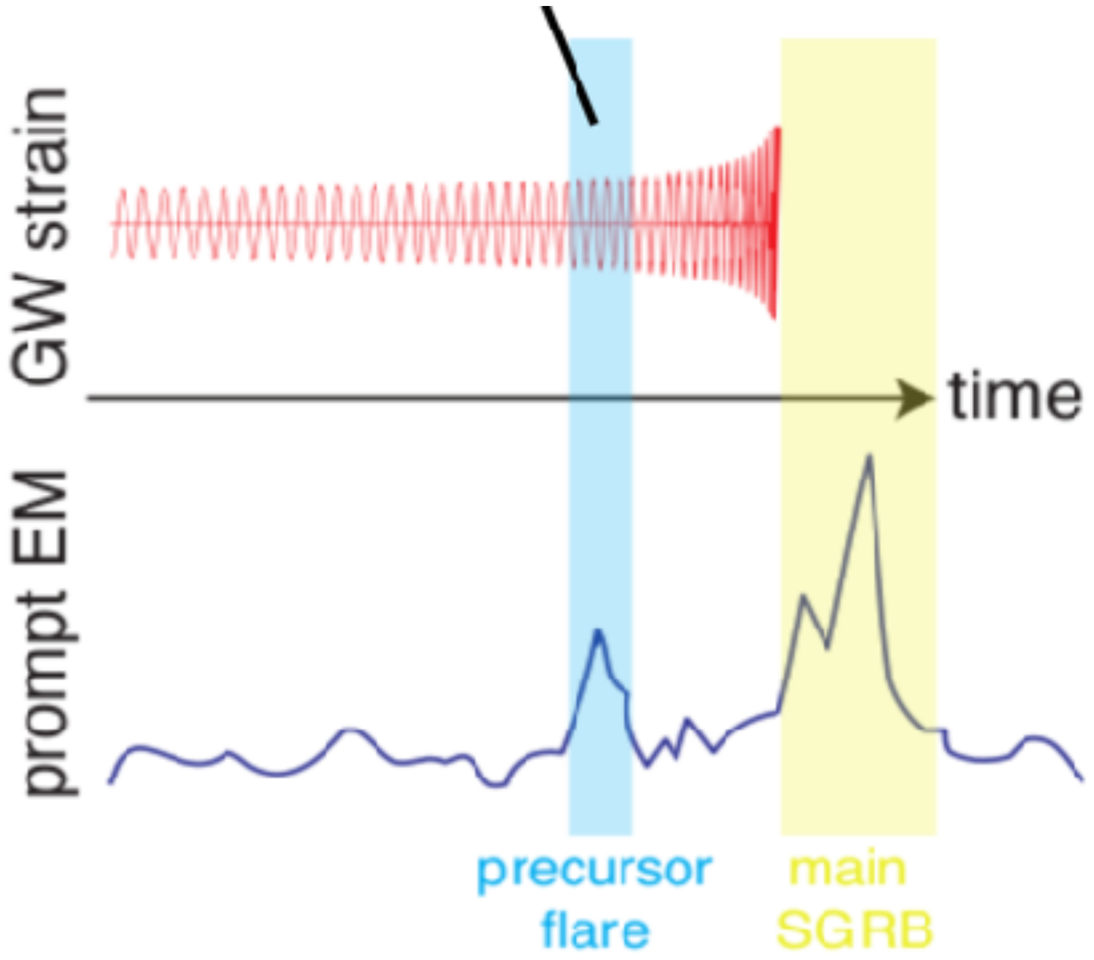

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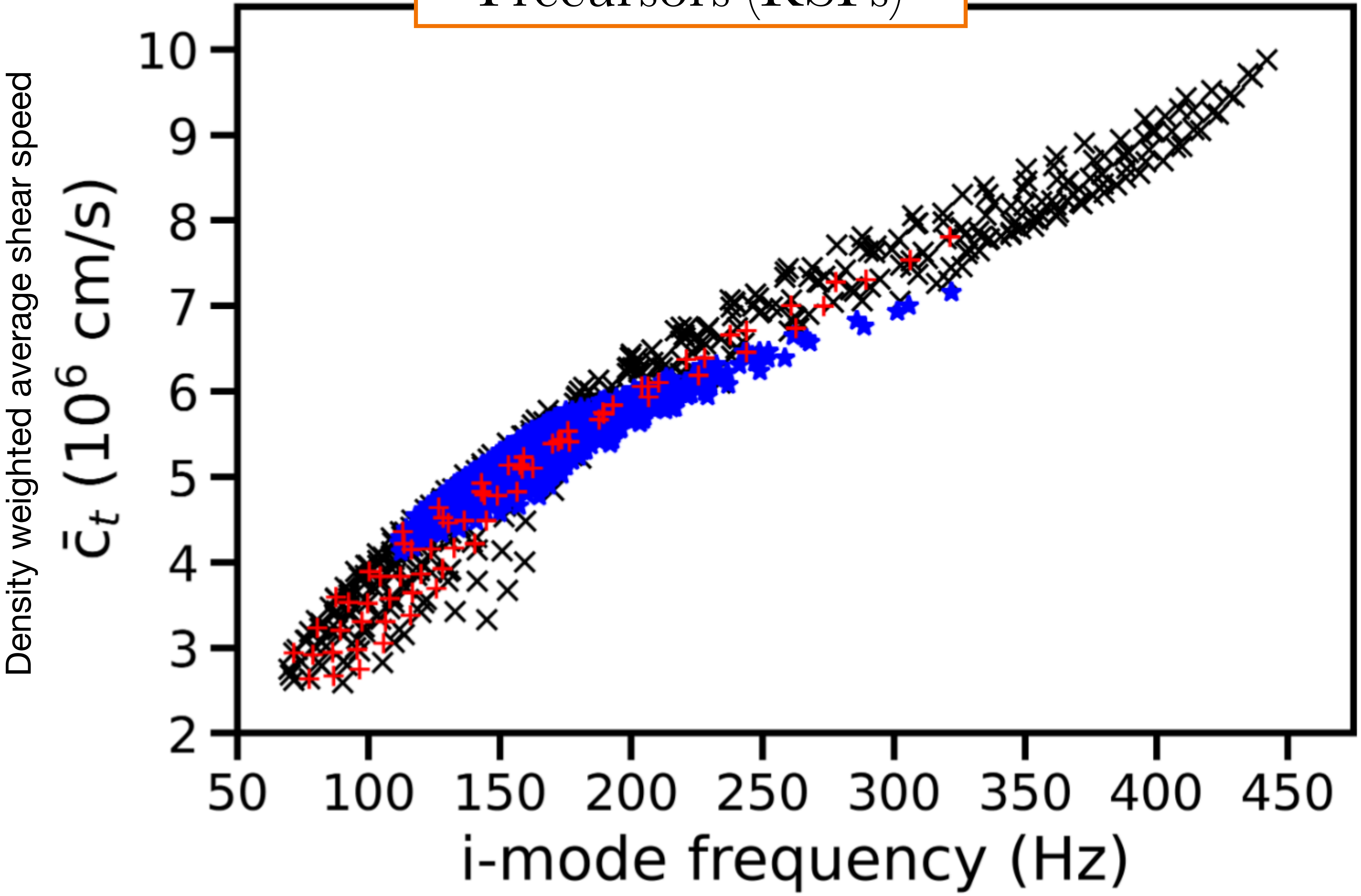

Neill, Newton, & DT (2021), MNRAS 504, 1, 1129

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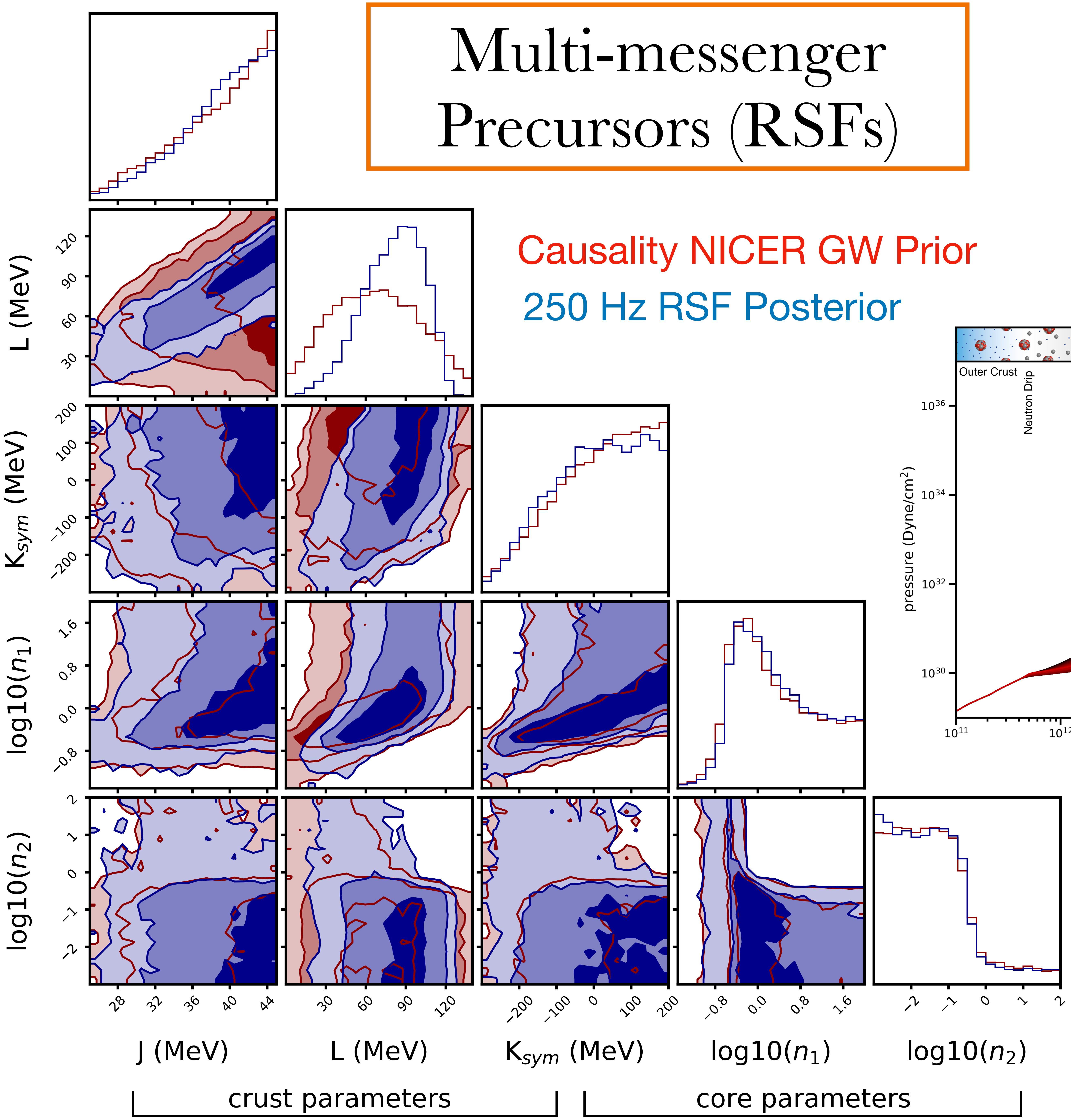
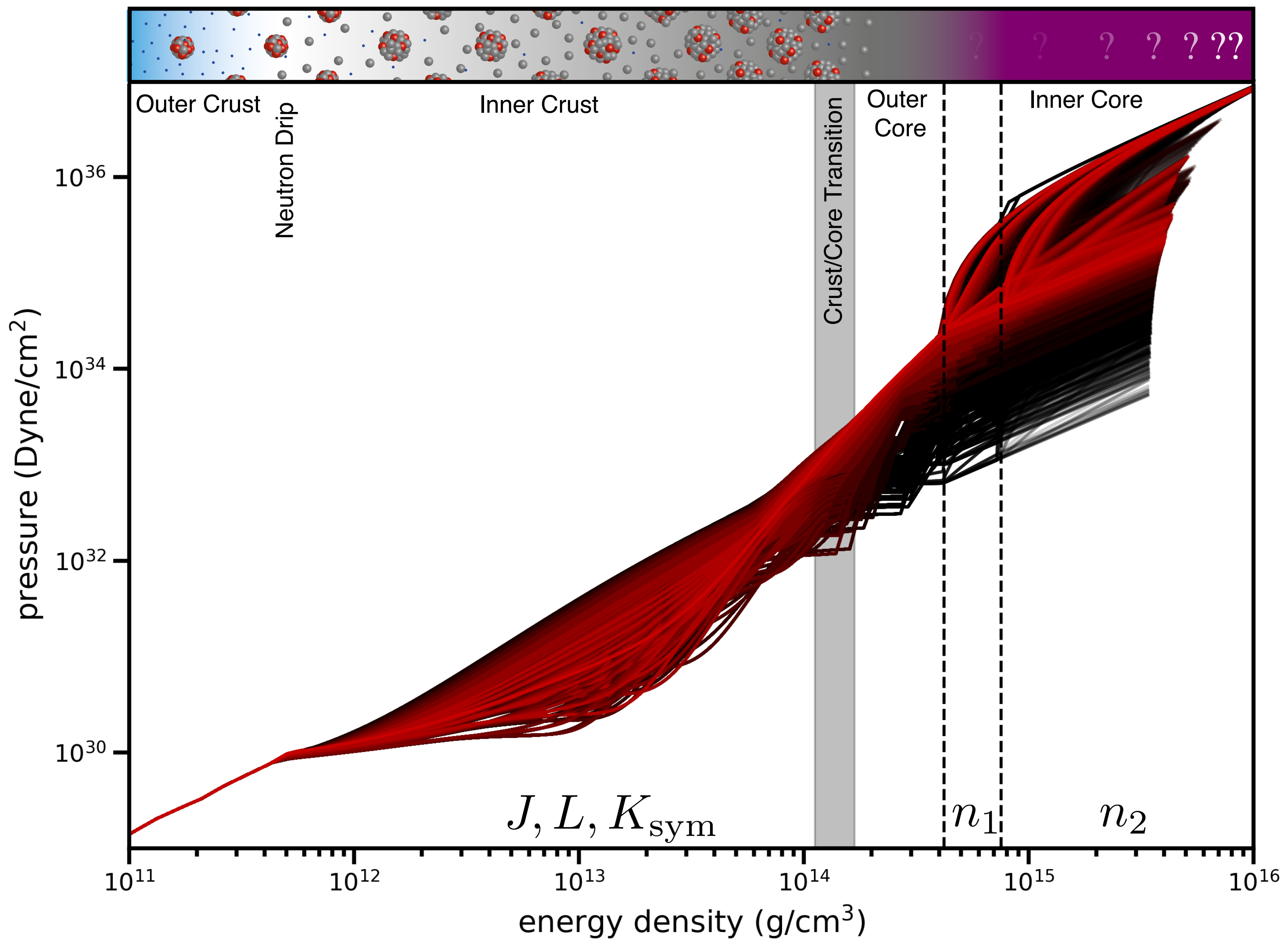
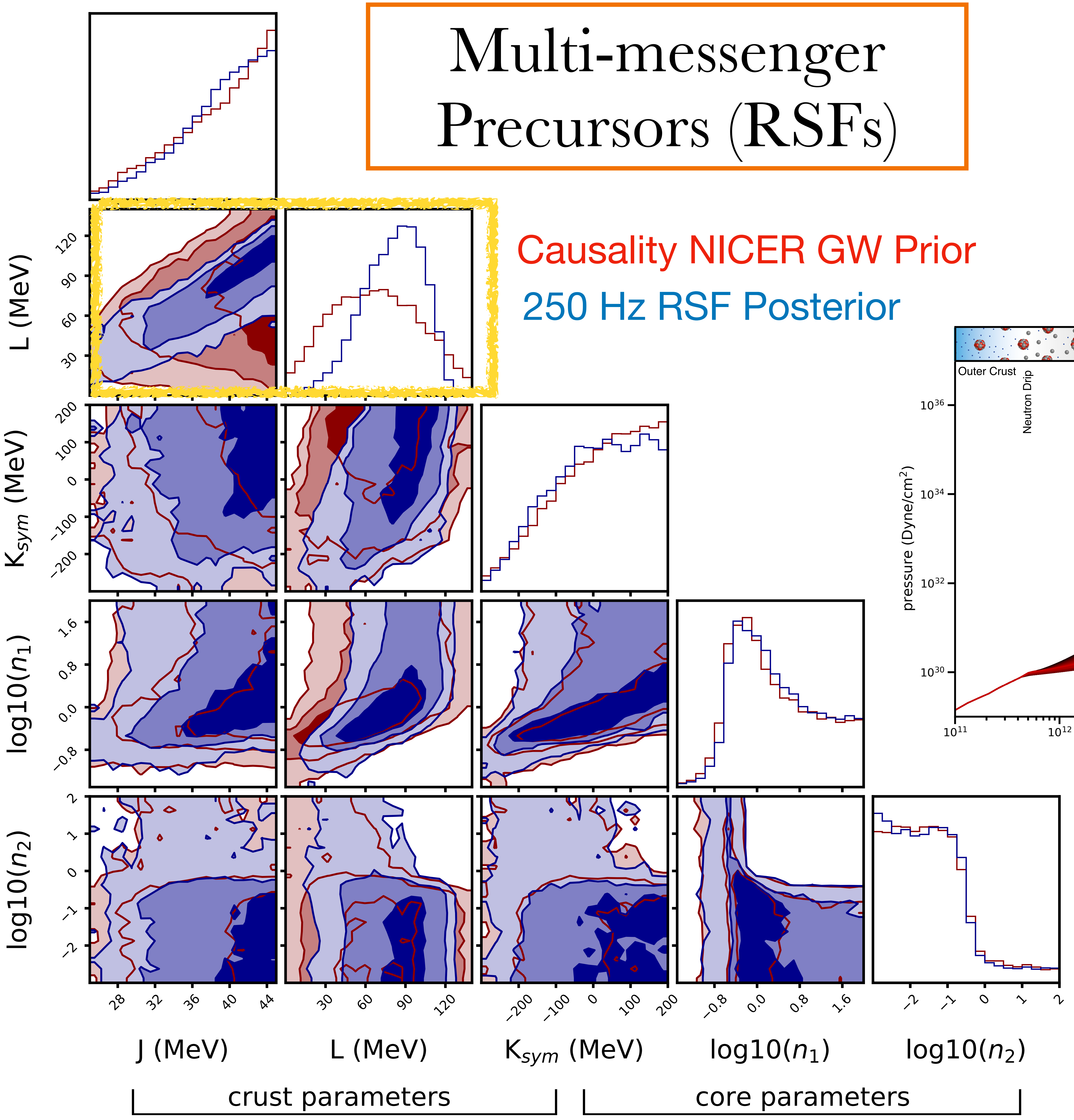
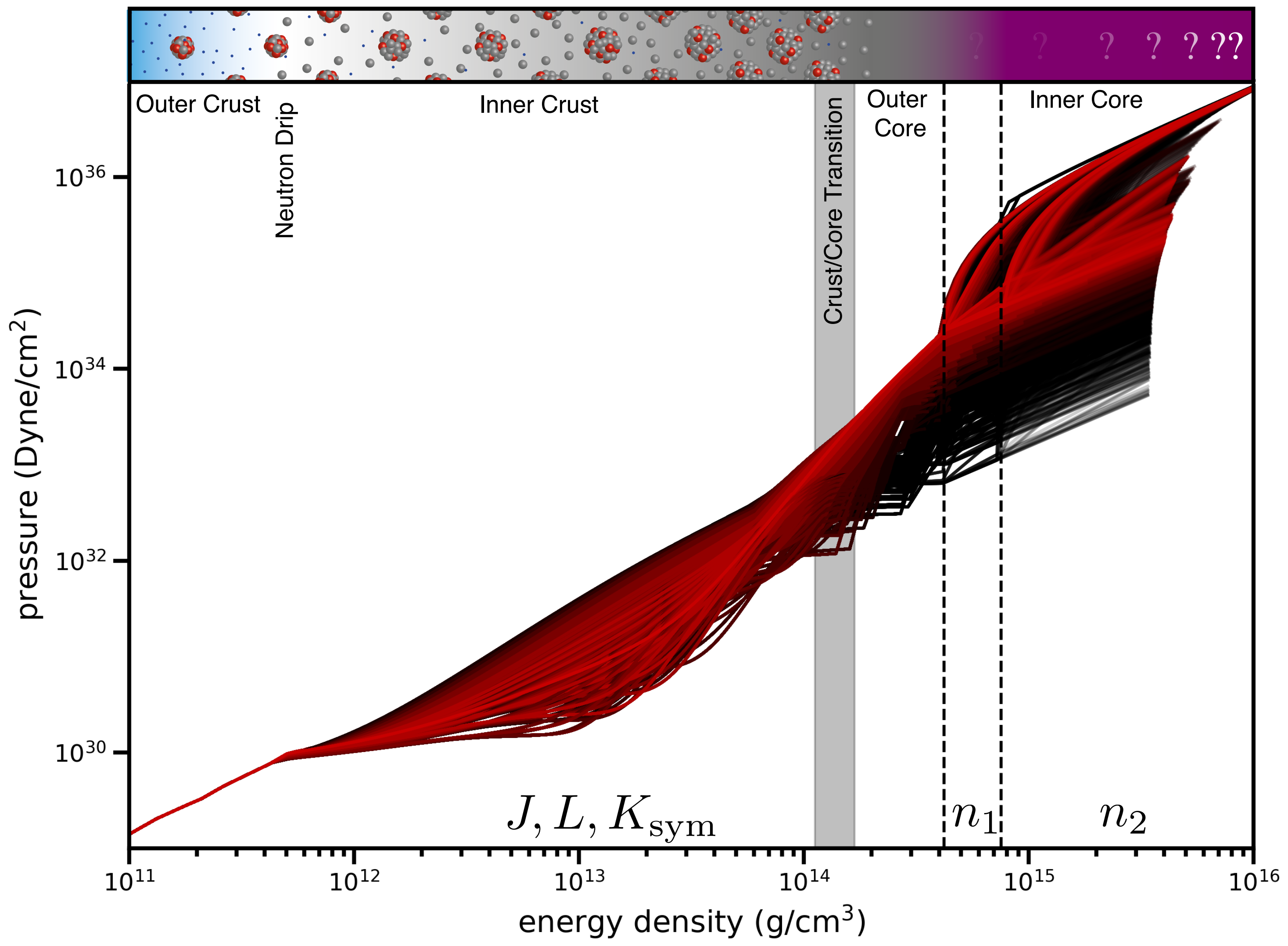




Neill, Preston, Newton & DT (2023), PRL, 130, 112701

Multi-messenger Precursors (RSFs)





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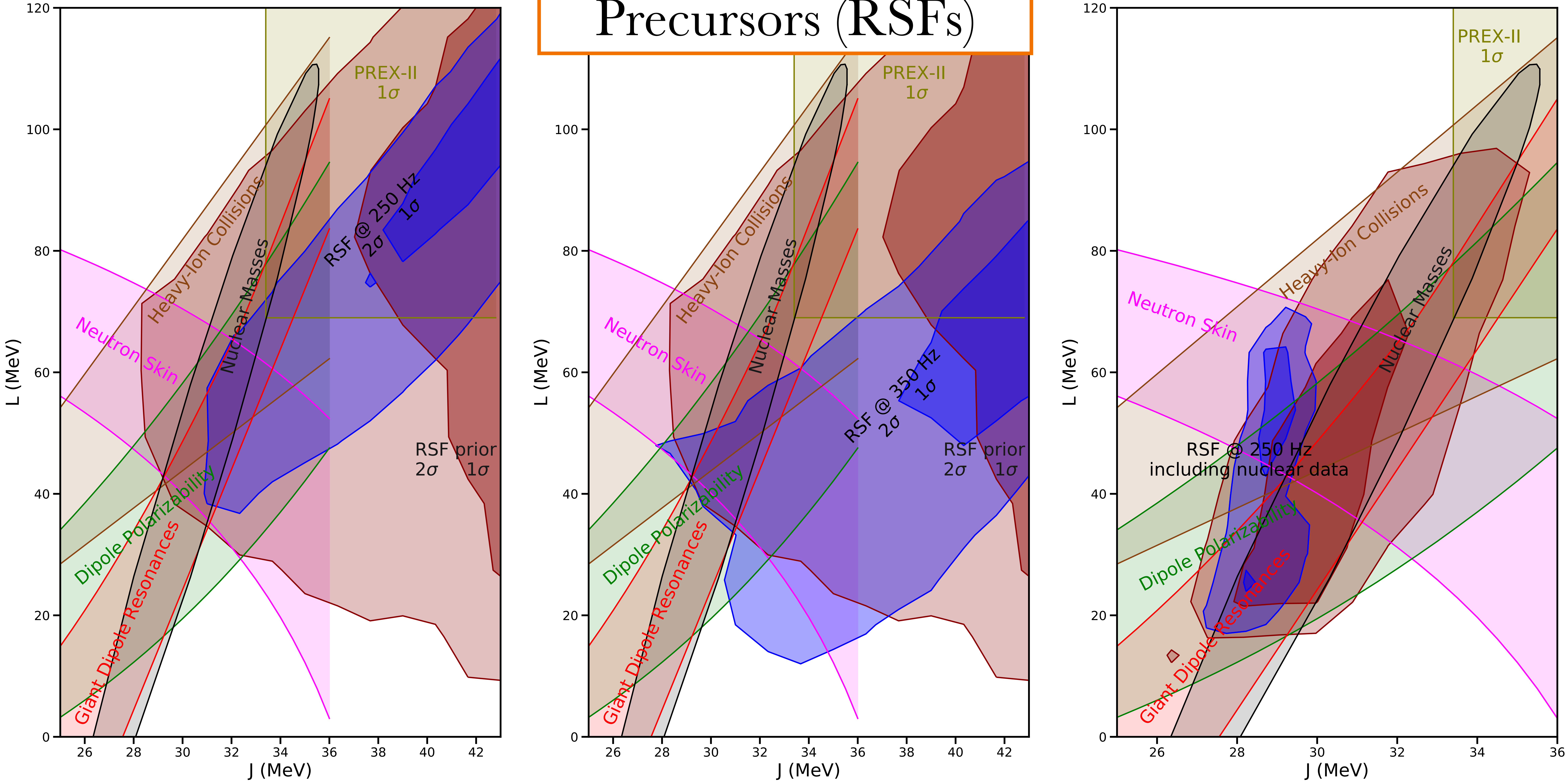

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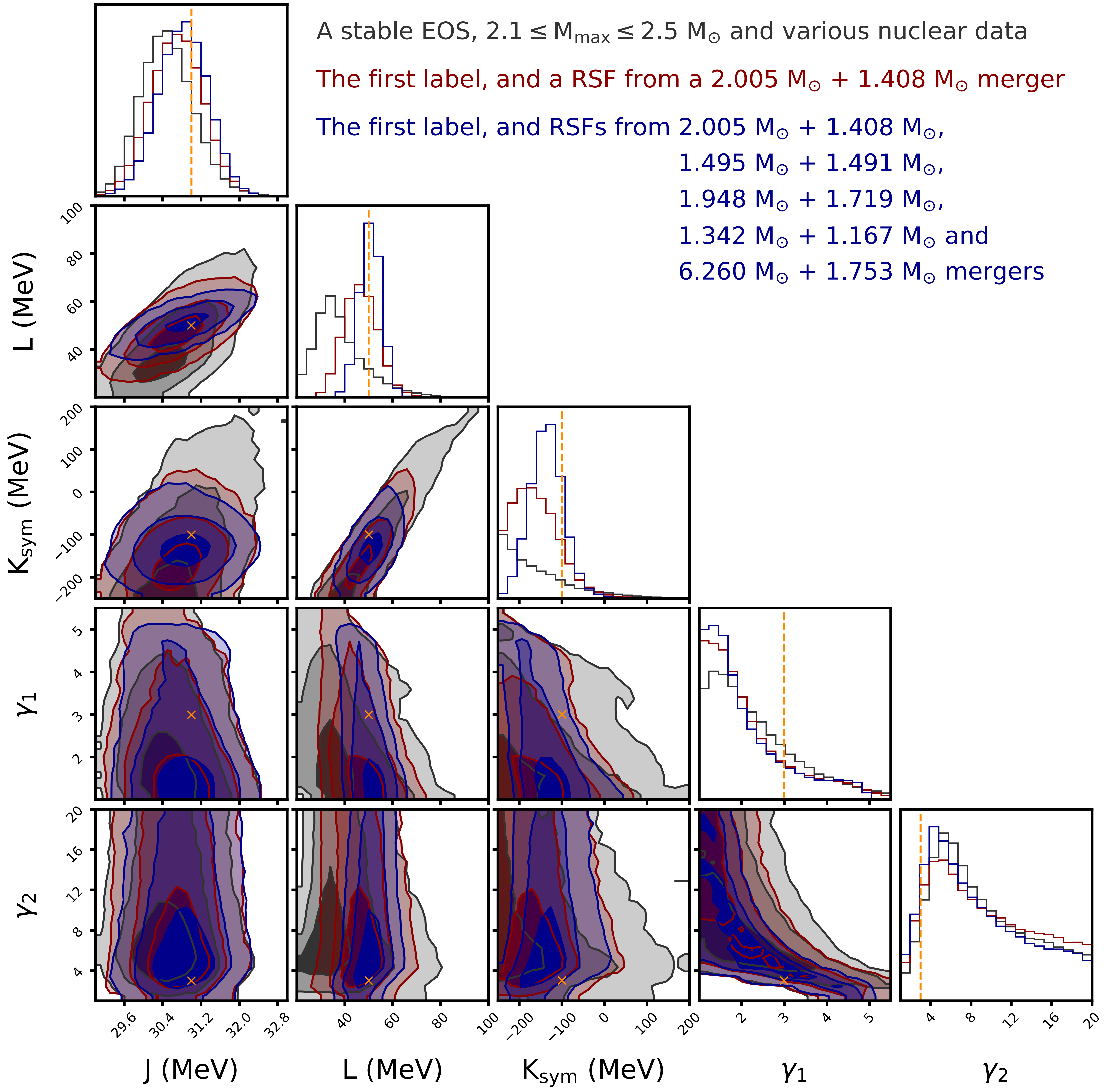
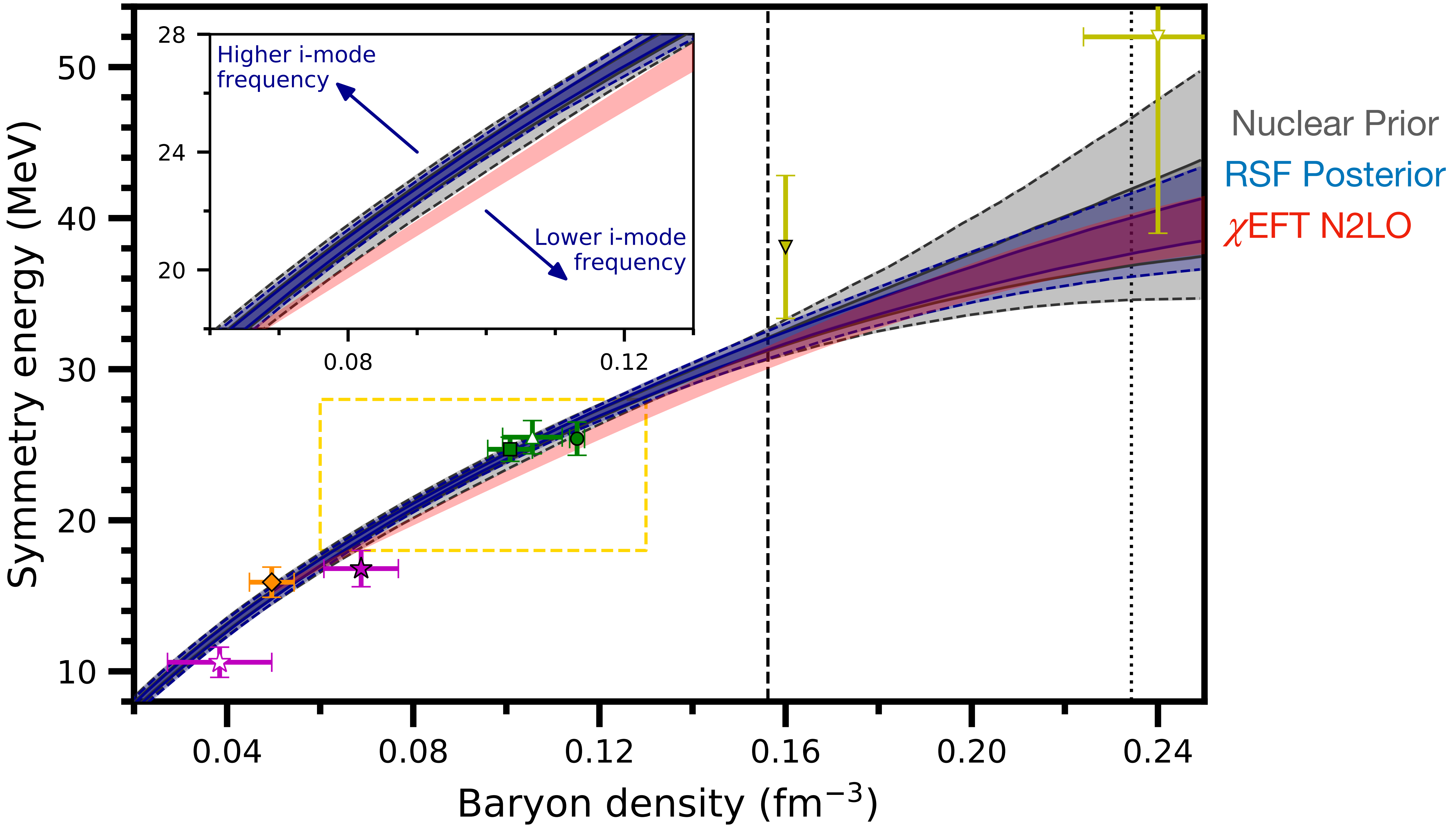


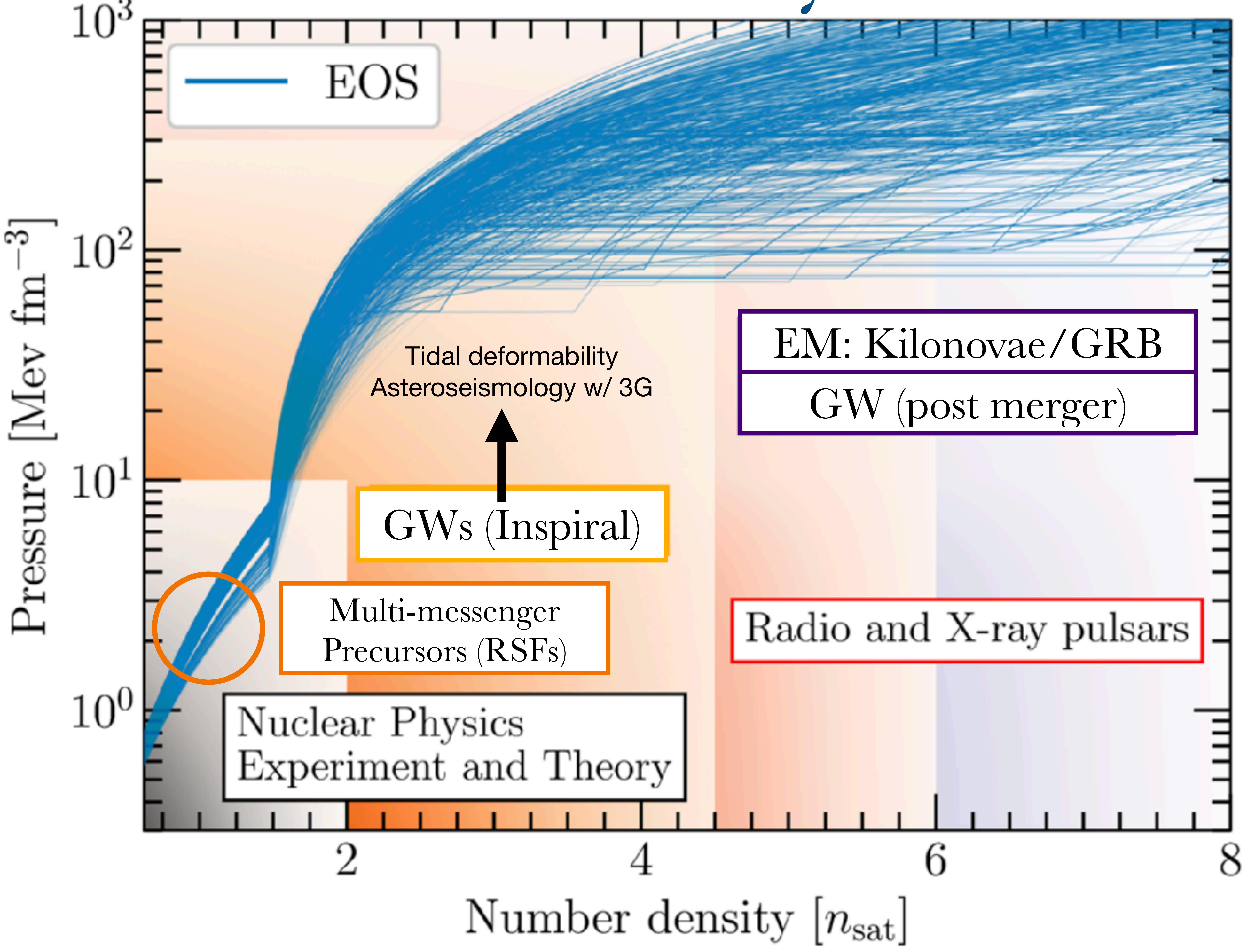
Neill, DT & Newton (2024)



See talk by Duncan Neill on Thursday

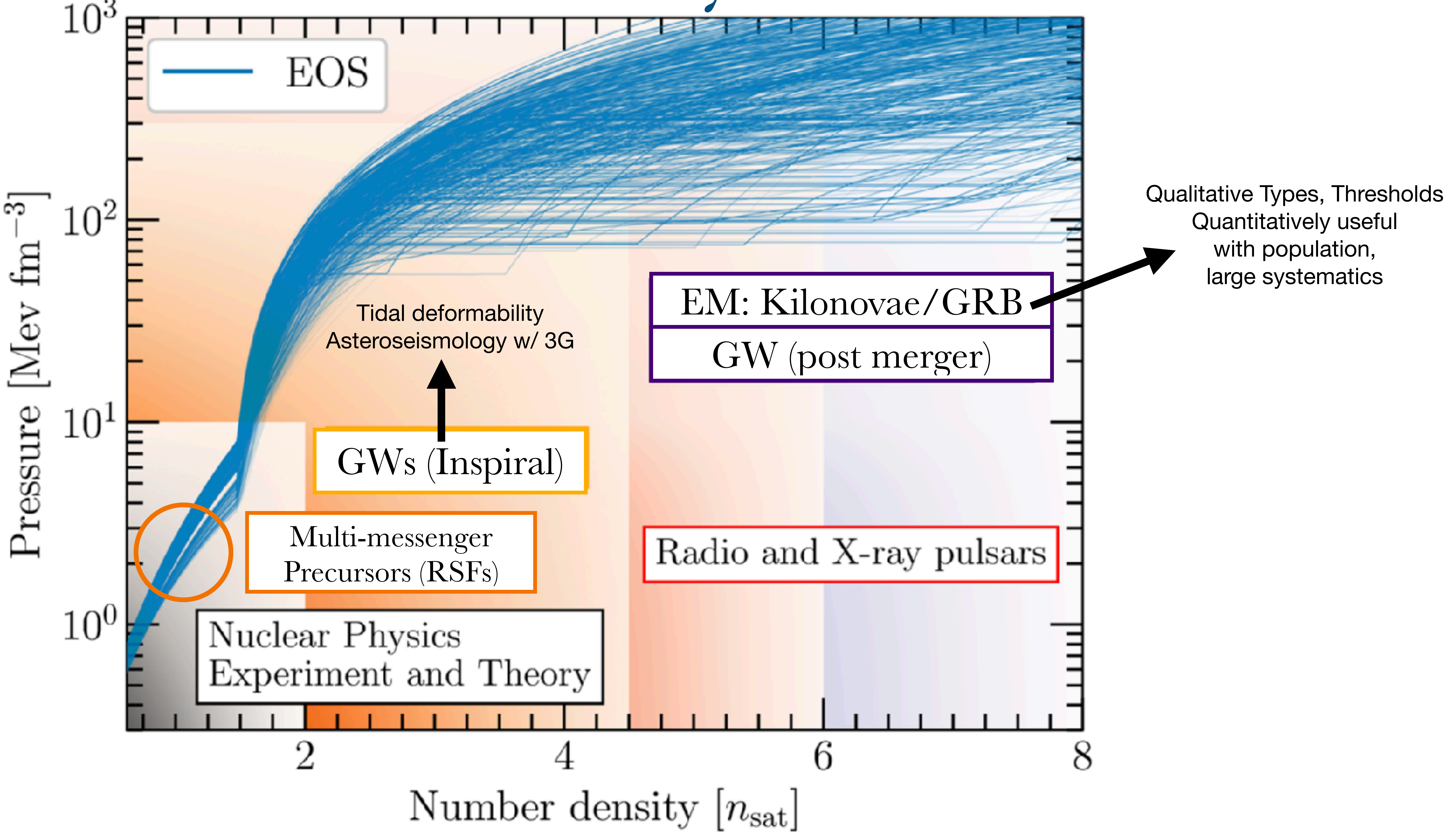
Neill, Drischler, Holt, Newton & DT (2024) in prep

Summary



EOS
Pressure [Mev fm^{-3}]
10^3
10^2
10^1
10^0
Tidal deformability
Asteroseismology w/ 3G
EM: Kilonovae/GRB
GW (post merger)
GWs (Inspiral)
Multi-messenger
Precursors (RSFs)
Radio and X-ray pulsars
Nuclear Physics
Experiment and Theory
2
4
6
8
Number density [n_{sat}]

Summary



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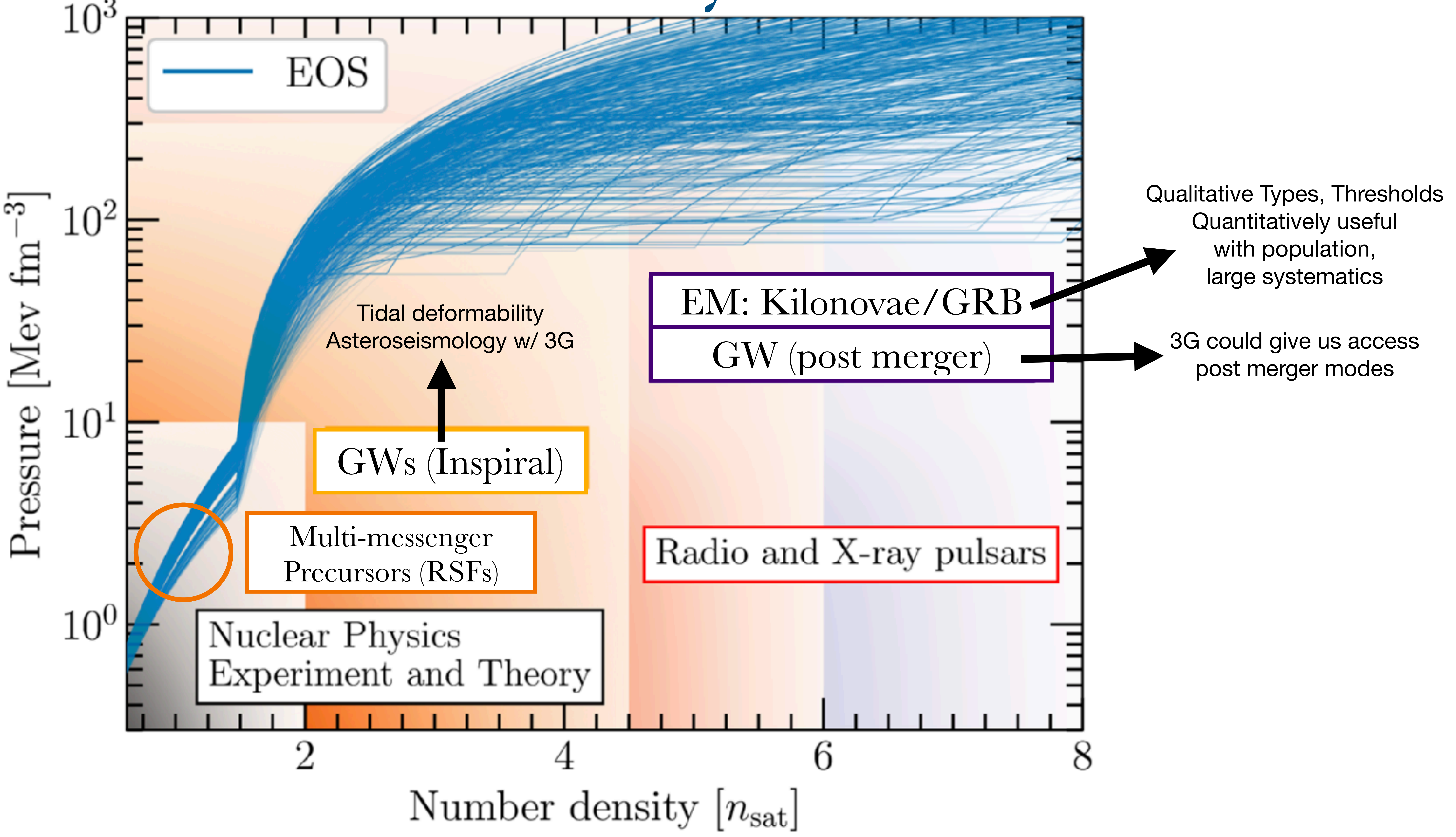
Qualitative Types, Thresholds
Quantitatively useful
with population,
large systematics

Summary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Qualitative Types, Thresholds
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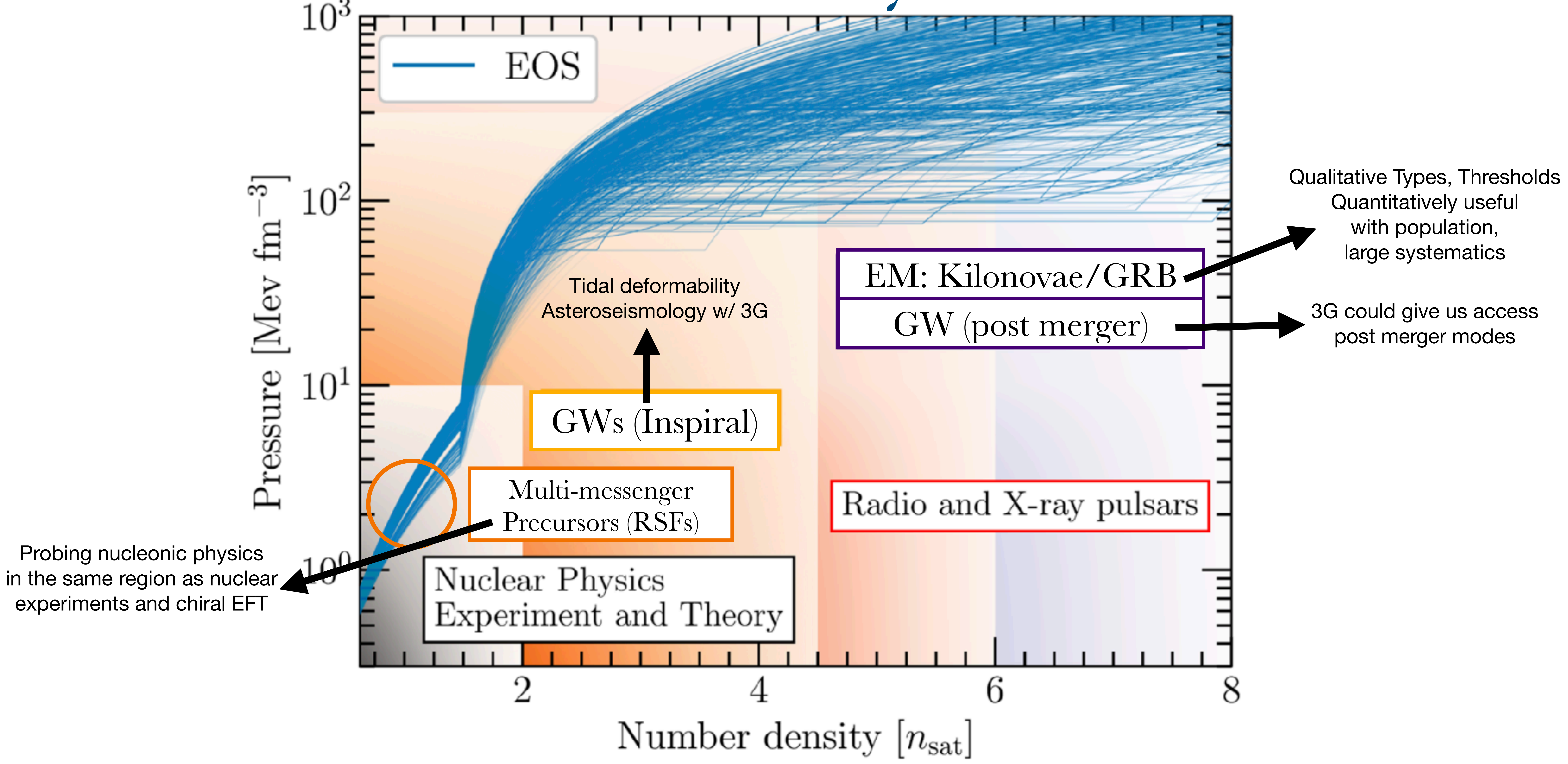
3G could give us access
post merger modes

Summary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Probing nucleonic physics
in the same region as nuclear
experiments and chiral EFT

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