Dense-Matter Nuclear Physics and Astrophysics in the Multimessenger Era

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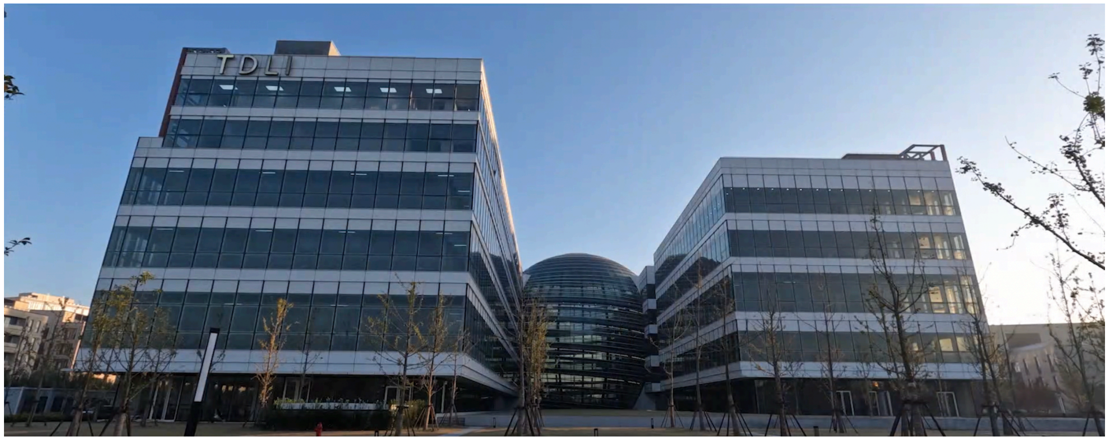
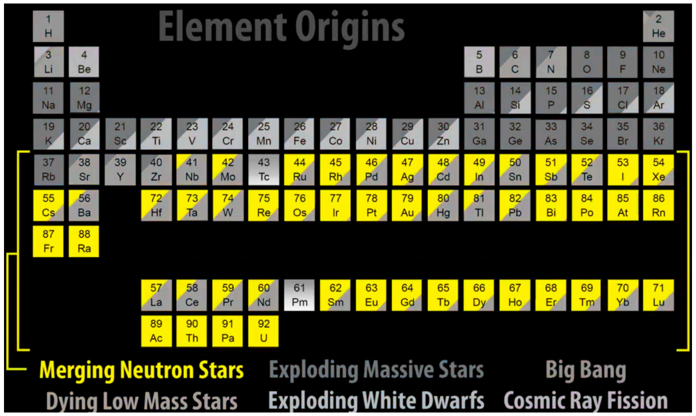


C3NT Inaugural Symposium

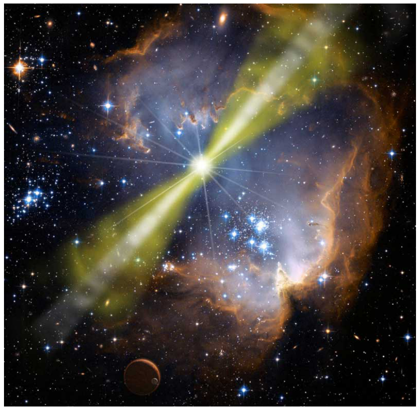
May 17-18th, 2025 @CCNU

How does matter behave under cosmic extreme conditions?

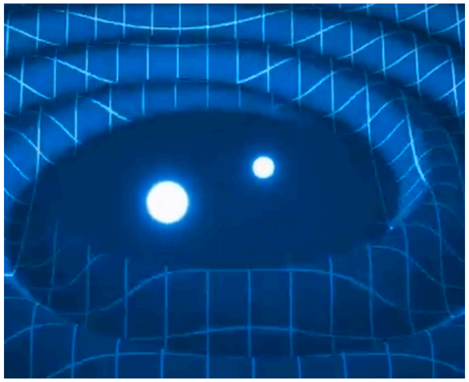
- heavy element production



- short gamma-ray bursts

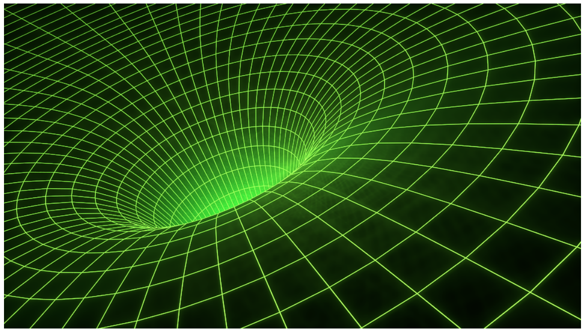


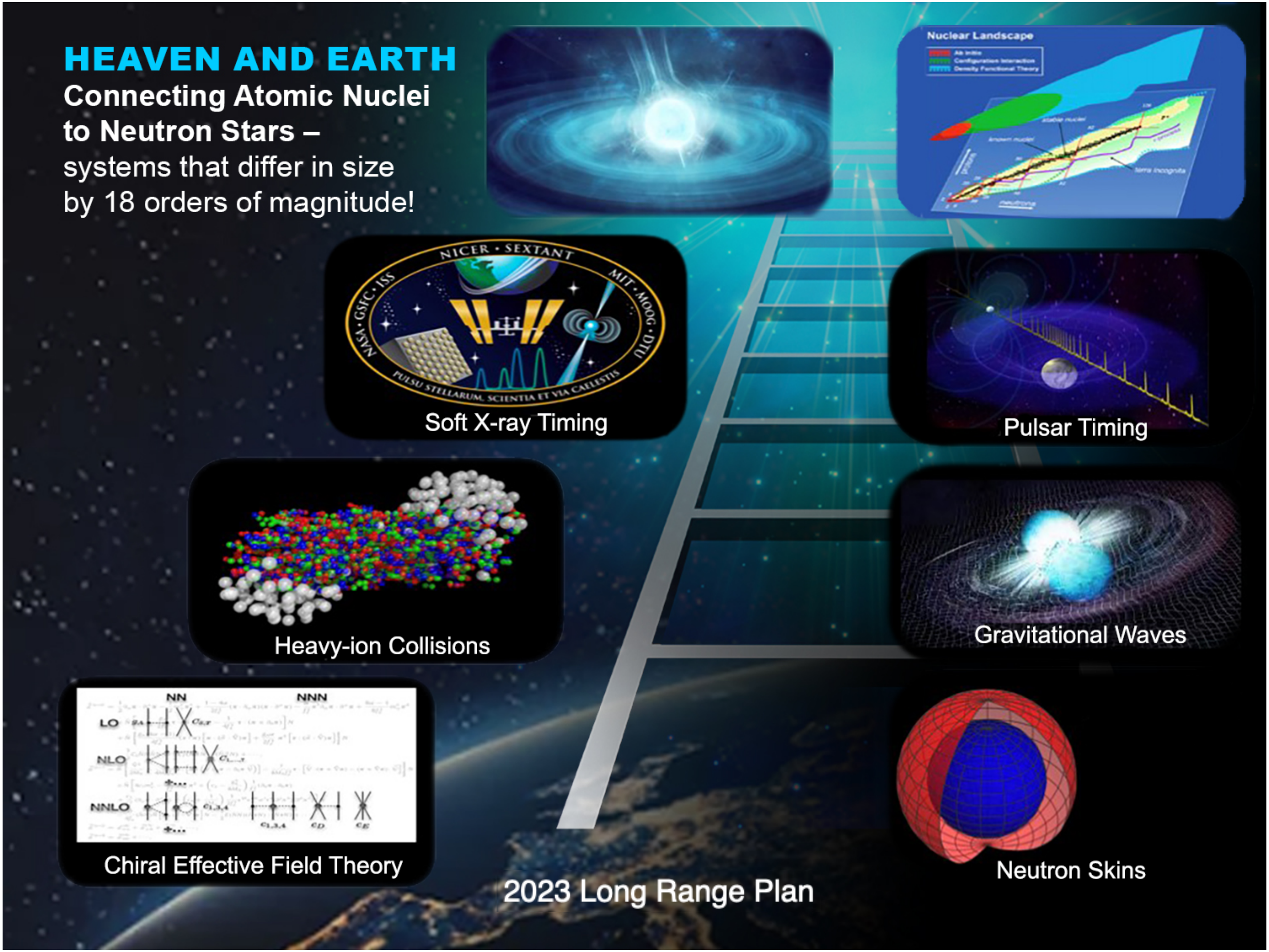
- binary mergers



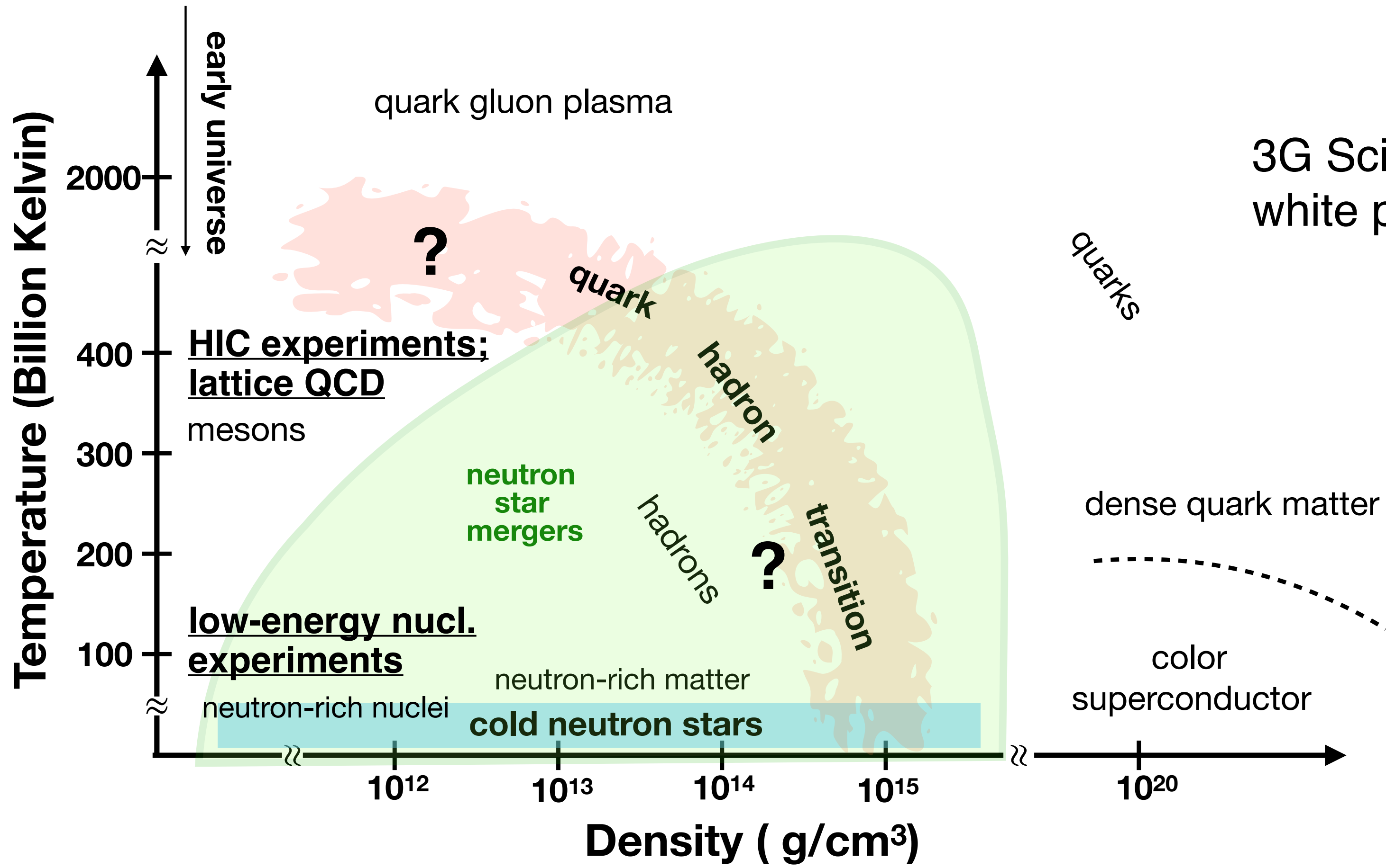
- core-collapse supernovae

- tests of strong-field GR




HEAVEN AND EARTH
Connecting Atomic Nuclei to Neutron Stars –
systems that differ in size by 18 orders of magnitude!
Nuclear Landscape
NICER · SEXTANT
Soft X-ray Timing
Pulsar Timing
Heavy-ion Collisions
Gravitational Waves
NN
NNN
LO
NLO
NNLO
Chiral Effective Field Theory
Neutron Skins
2023 Long Range Plan

Laboratory for theoretical physics



- no terrestrial experiments can probe such high densities
- reliable first-principle calculations break down at the strongly-interacting regime

- can’t calculate properties of cold dense matter; must **observe**!

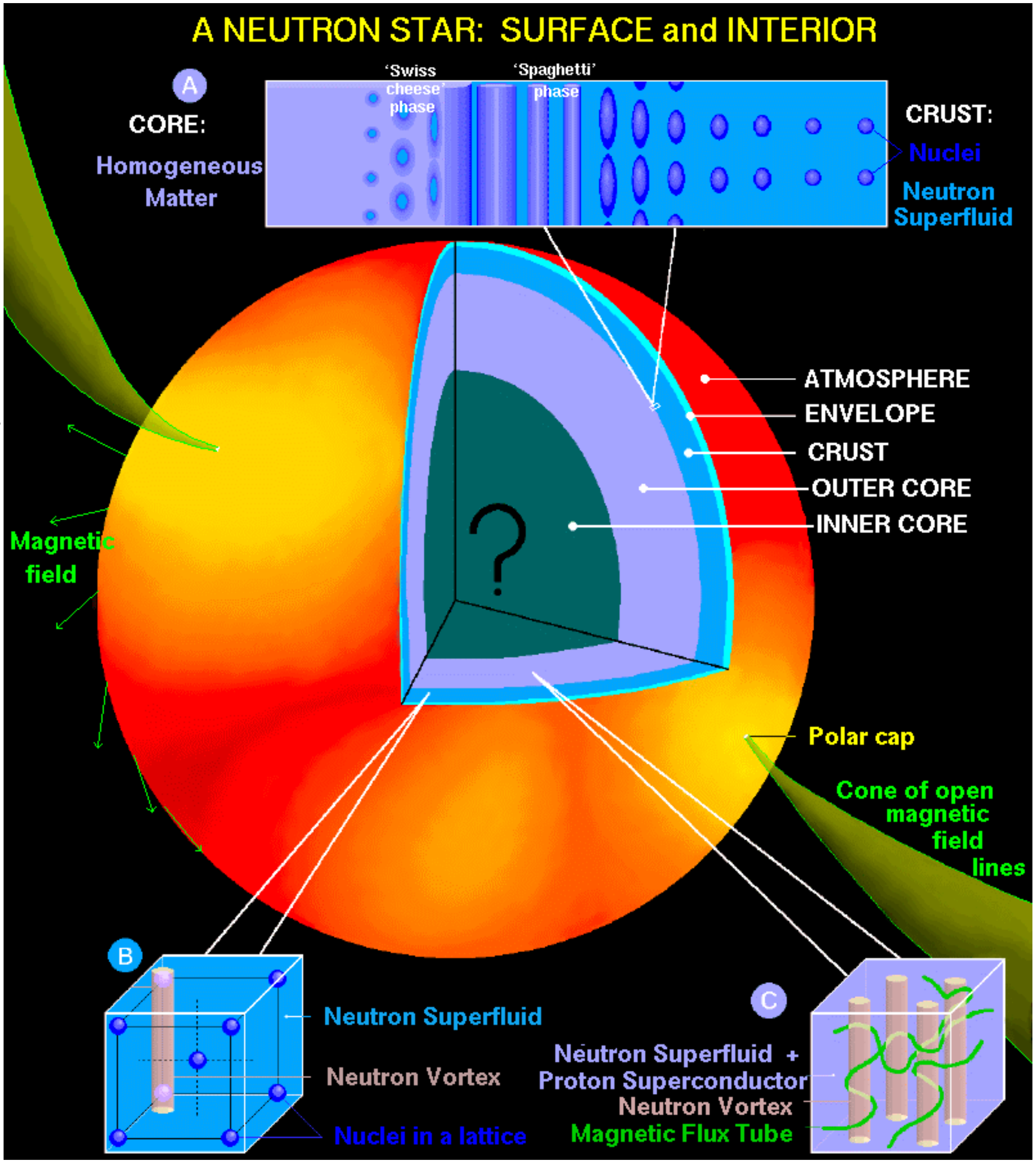
credit: Dany Page

Dense matter in NSs

- stable nuclei
- neutron-rich nuclei
- neutron-rich nuclei with quasi-free neutrons

. . . .

- homogeneous nucleonic matter
- exotica



Fundamental questions

- what are the most relevant lower-energy degrees of freedom?
- how does deconfinement evolve as T->0 on the QCD phase diagram?

Limiting ground state EoS: mass-radius obs.

pulsar timing (radio) can accurately measure masses

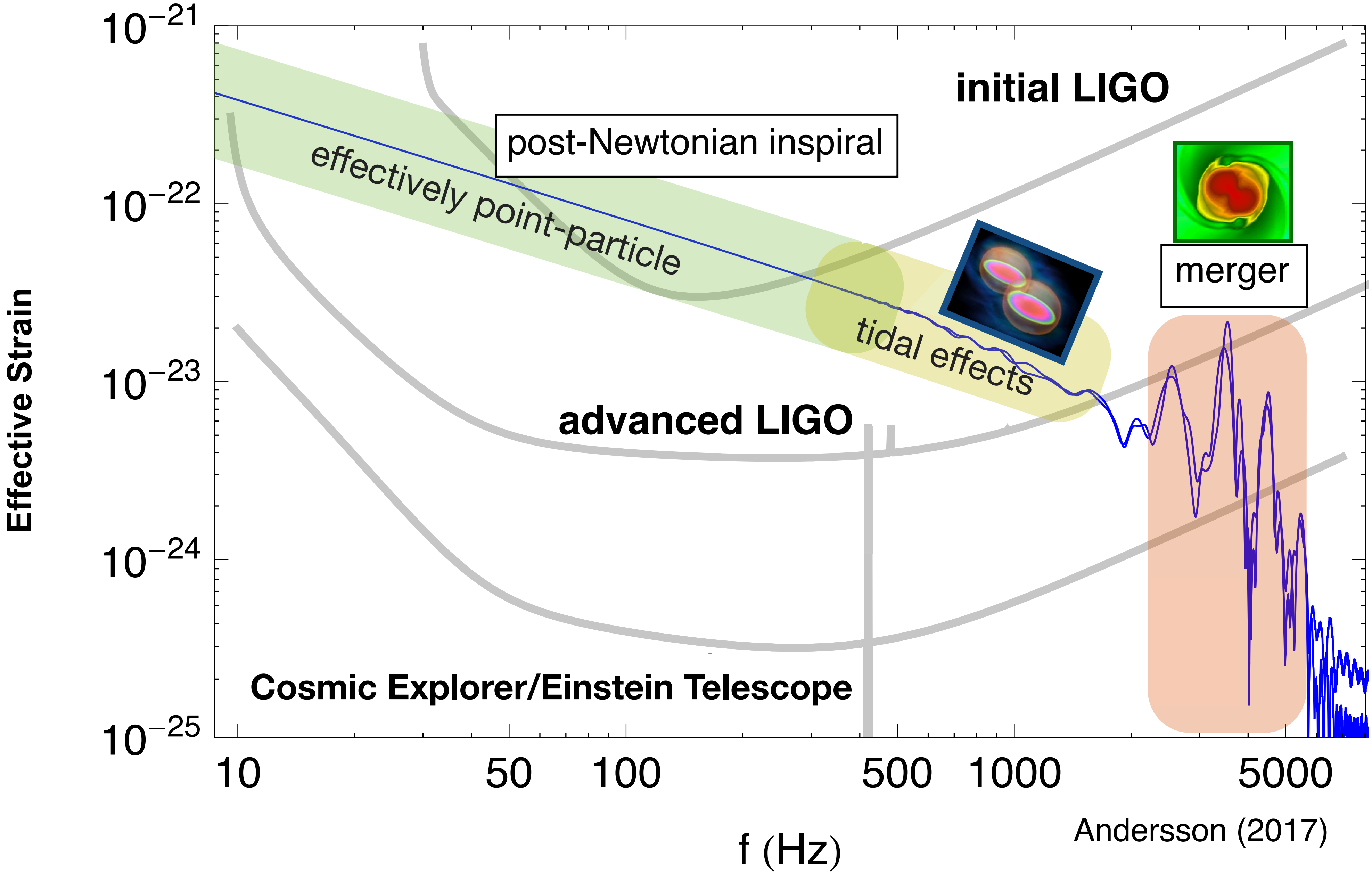
- most are between $1.2M_\odot$ and $1.5M_\odot$; lowest well-measured mass is $1.174 \pm 0.004M_\odot$, highest are $2.08 \pm 0.07M_\odot$ and $2.01 \pm 0.04M_\odot$
- higher masses are found for some sources (notably black widow pulsars) but these estimates have large uncertainties

x-ray observations yield radii, but uncertain to a few km:

- quiescent binary sources in globular clusters
- thermonuclear explosions leading to photospheric radius expansion bursters on accreting neutron stars in binaries
- pulse **profile modeling of hot spots** on rapidly rotating neutron stars, e.g., *Neutron Star Interior Composition ExploreR (NICER)* mission

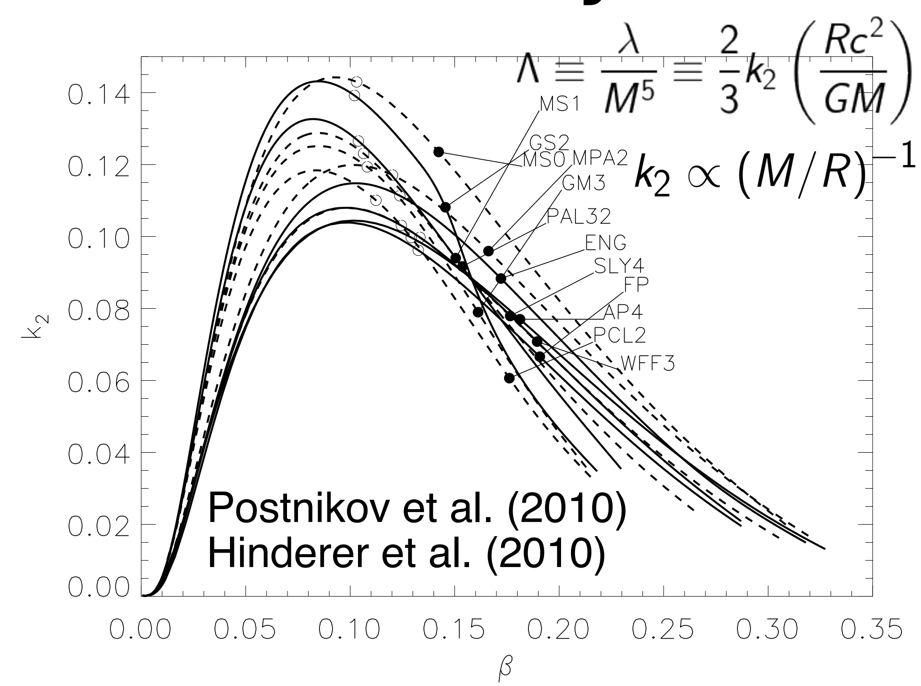
gravitational waves from merging binary neutron stars (BNSs) measure masses and tidal deformabilities

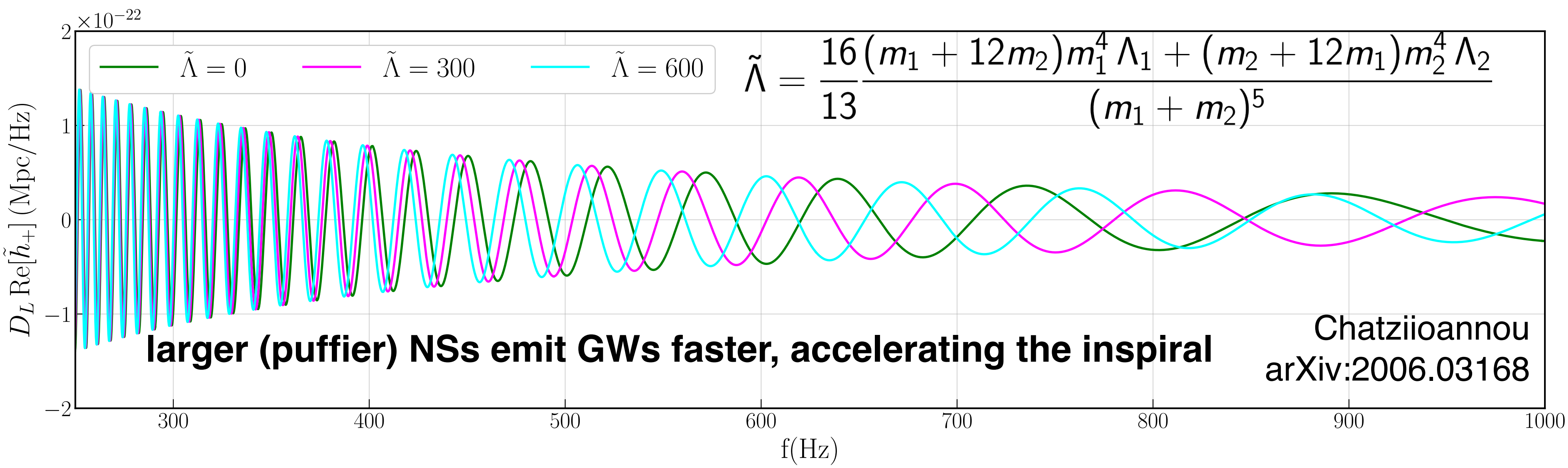
GW probes of NS radii/deformability



GW probes of NS radii/deformability

- tidal deformability depends on the **EoS** and the **compactness** M/R
- matter effects [NSs] leave imprints in the waveform - distinguish from point-particles [BHs]
- much cleaner systematics

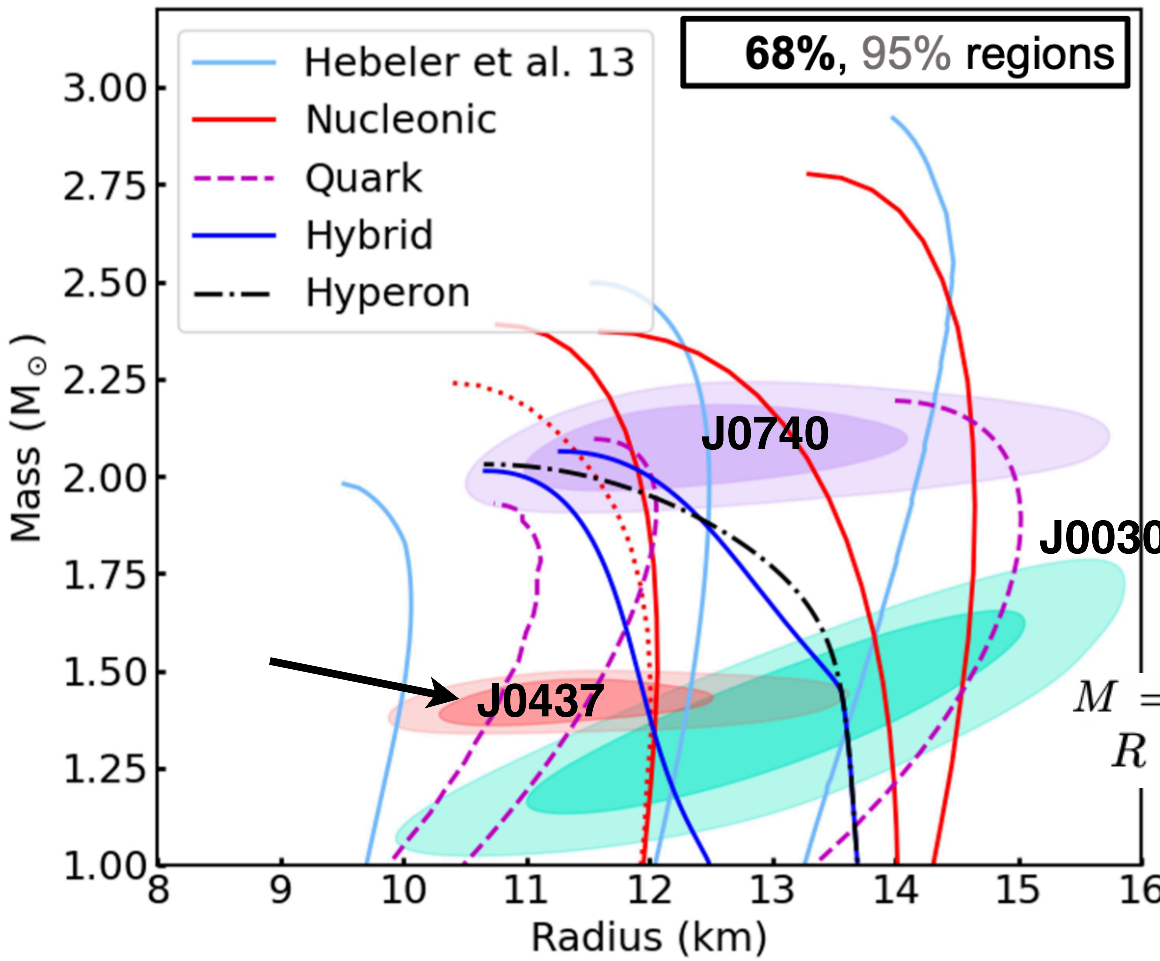




A NICER VIEW OF PSR J0437−4715 (new!)

arXiv:2407.06789
arXiv:2407.06790

nearest and brightest millisecond pulsar



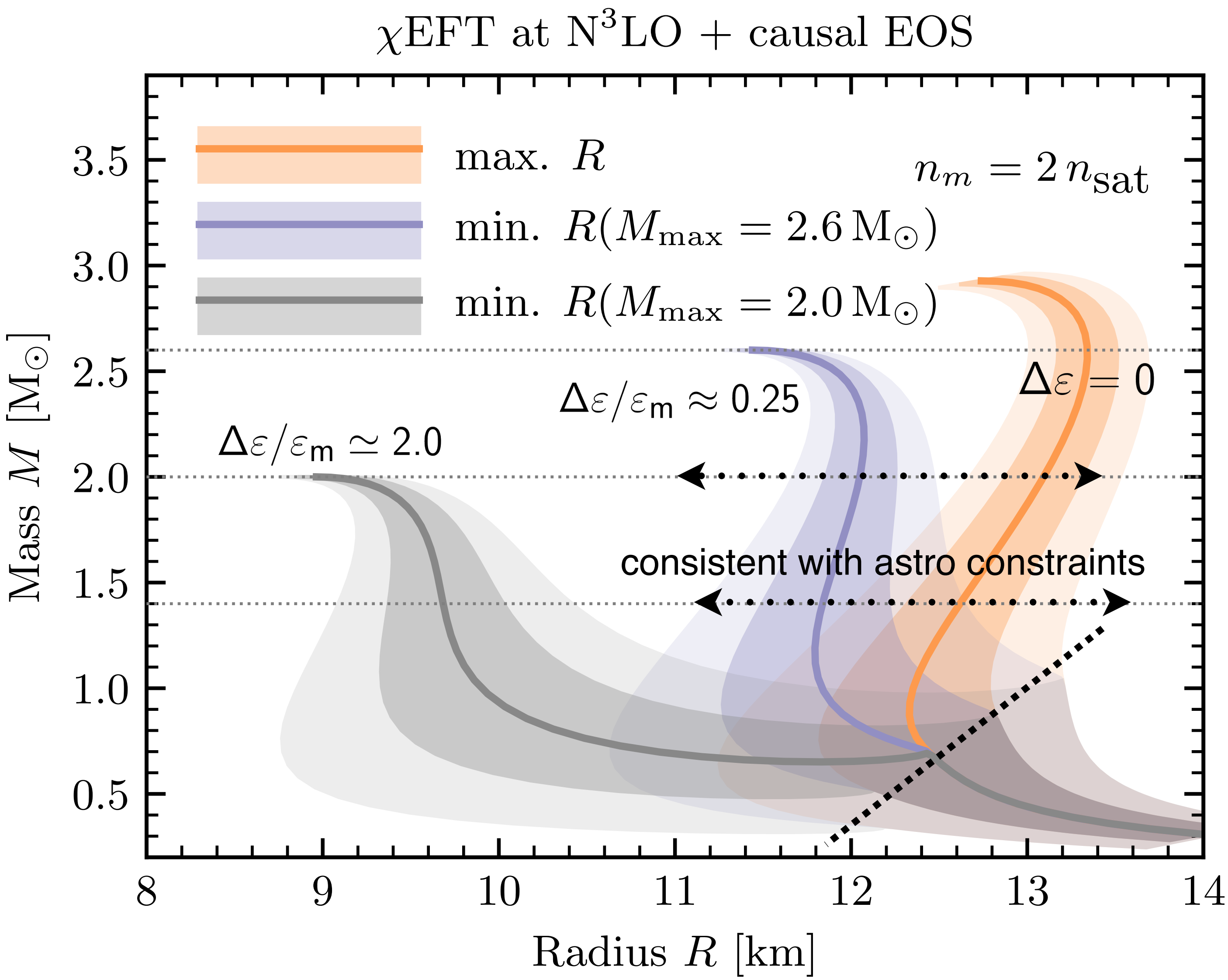
$$M = 1.418 \pm 0.037 \ \mathrm{M}_\odot$$
$$R = 11.36^{+0.95}_{-0.63} \ \mathrm{km}$$

mass, distance, inclination all well known from pulsar timing

Courtesy: Anna Watts

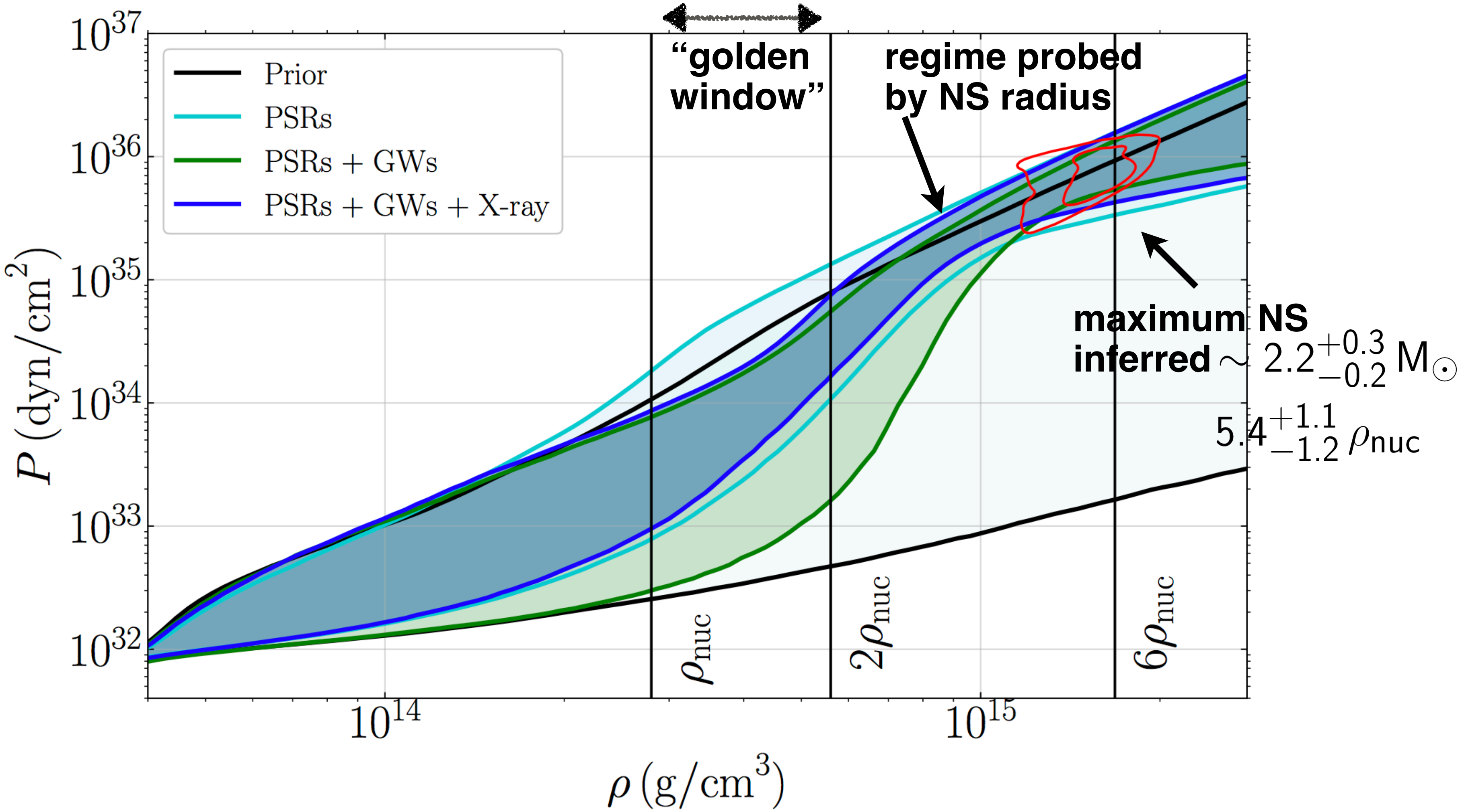
Bounds from nucl-th + causality

Drischler, **SH**, Lattimer, Prakash, Reddy and Zhao, **arXiv:2009.06441**



- pressure at low densities **[outer core]** controls typical NS radii: stiff or soft?
- reliably **quantified** uncertainties from chiEFT for beta-equilibrated NSM
- absolute **causal** limits imposed at high densities
- confronted with data**: interplay** between M_max and NS radii

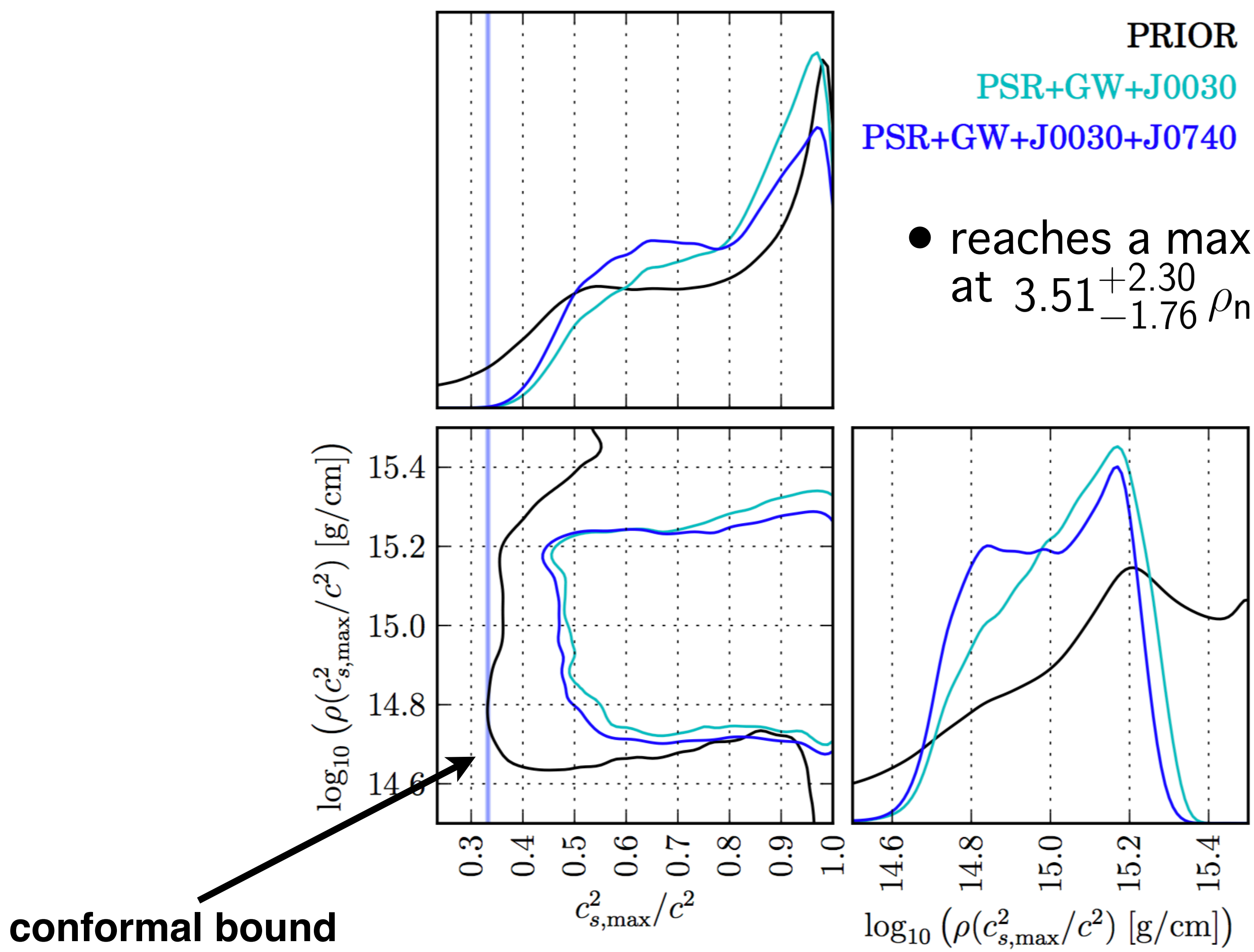
Pressure vs. density - current status



- towards a converging picture of the EoS at intermediate densities
- GW170817+190425, NICER J0030 & J0740, and massive pulsars

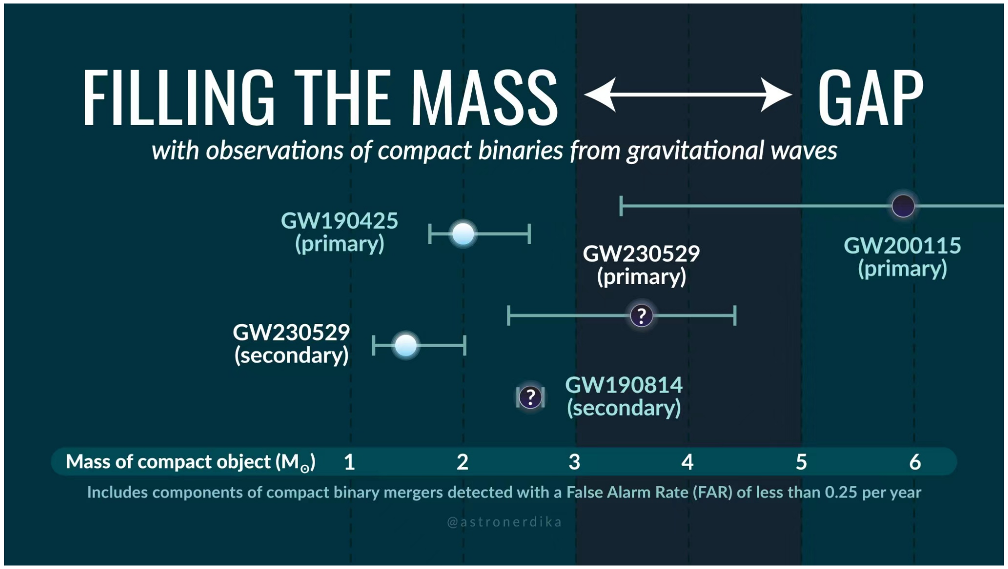
Speed of sound constraints

Legred et al. (including **SH**), **arXiv:2106.05313**

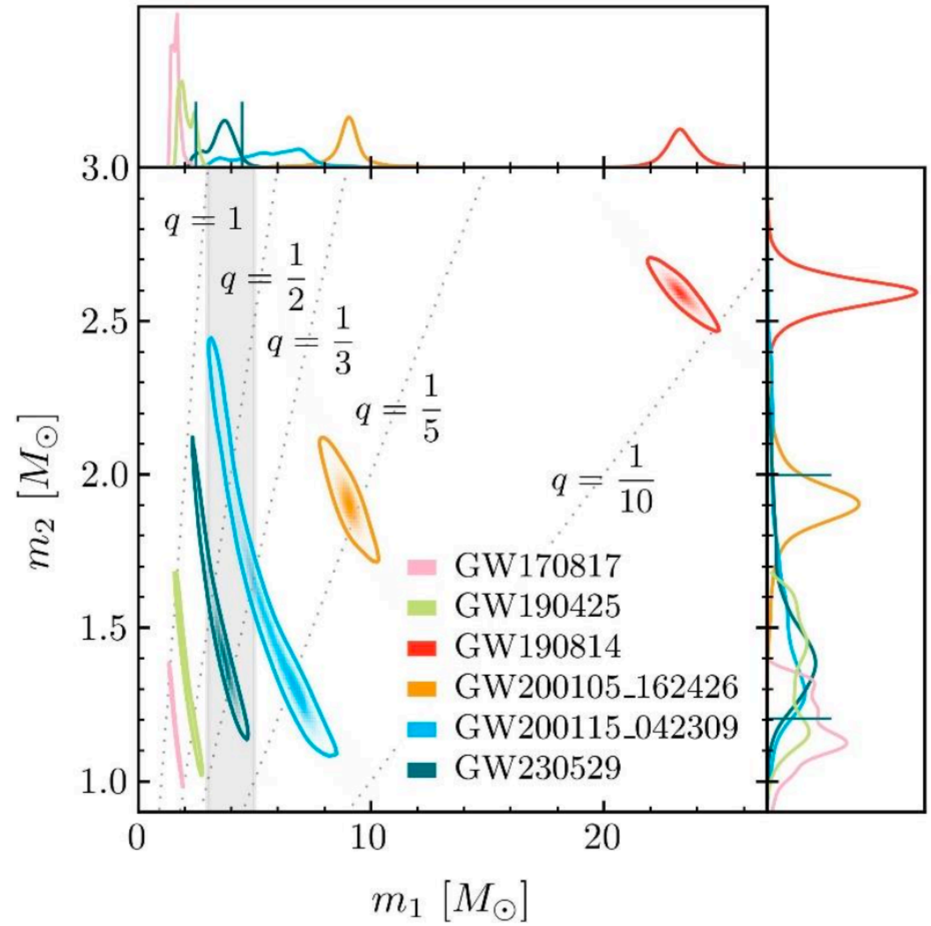


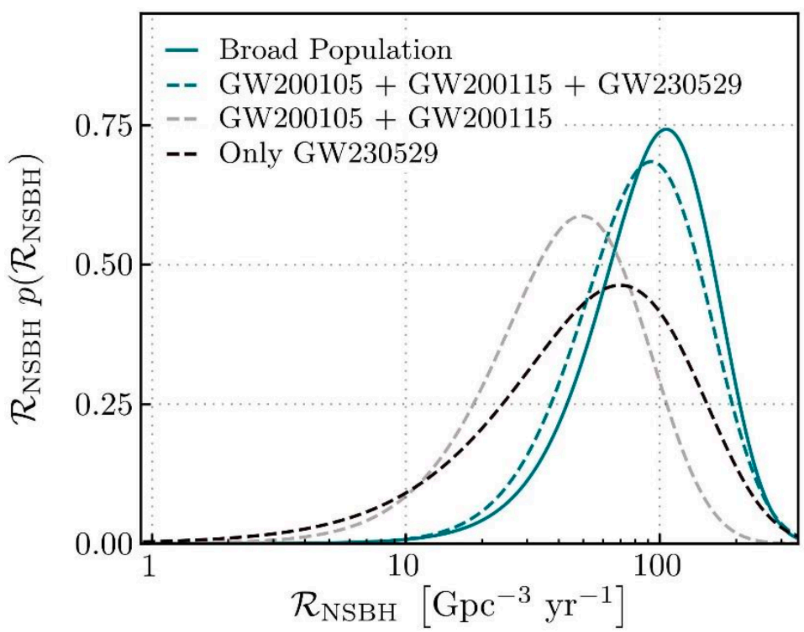
- reaches a maximum of $0.79^{+0.21}_{-0.26}$ at $3.51^{+2.30}_{-1.76}\,\rho_{\rm nuc}$

GW230529 (new!)



LVK collaboration
arXiv:2404.04248





- ~1.4 (NS) + ~3.6 (BH) solar masses
- most <u>**symmetric**</u> NSBH event so far

NSBH mergers

LVK collaboration
arXiv:2106.15163

THE ASTROPHYSICAL JOURNAL LETTERS, 915:L5 (24pp), 2021 July 1 https://doi.org/10.3847/2041-8213/ac082e
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Observation of Gravitational Waves from Two Neutron Star–Black Hole Coalescences

Table 2
Source Properties of GW200105 and GW200115

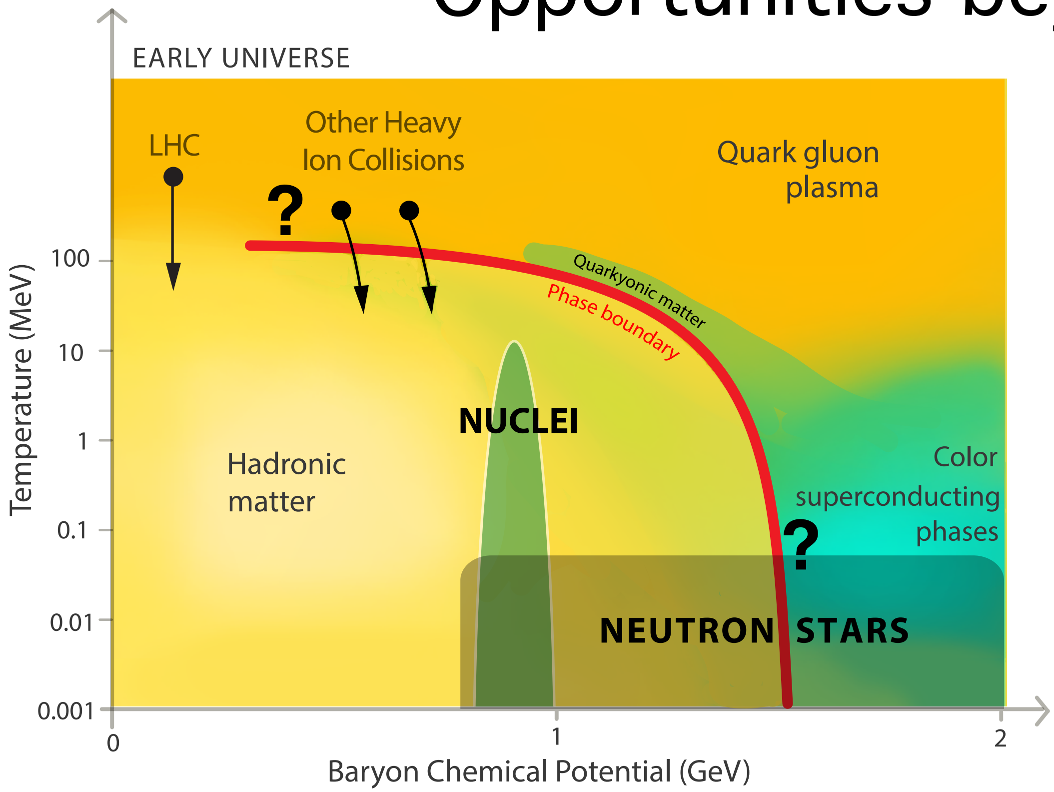
	GW200105		GW200115	
	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)	Low Spin ($\chi_2 < 0.05$)	High Spin ($\chi_2 < 0.99$)
Primary mass $m_1/M_\odot$	$8.9^{+1.1}_{-1.3}$	$8.9^{+1.2}_{-1.5}$	$5.9^{+1.4}_{-2.1}$	$5.7^{+1.8}_{-2.1}$
Secondary mass $m_2/M_\odot$	$1.9^{+0.2}_{-0.2}$	$1.9^{+0.3}_{-0.2}$	$1.4^{+0.6}_{-0.2}$	$1.5^{+0.7}_{-0.3}$
Mass ratio q	$0.21^{+0.06}_{-0.04}$	$0.22^{+0.08}_{-0.04}$	$0.24^{+0.31}_{-0.08}$	$0.26^{+0.35}_{-0.10}$
Total mass $M/M_\odot$	$10.8^{+0.9}_{-1.0}$	$10.9^{+1.1}_{-1.2}$	$7.3^{+1.2}_{-1.5}$	$7.1^{+1.5}_{-1.4}$
Chirp mass $\mathcal{M}/M_\odot$	$3.41^{+0.08}_{-0.07}$	$3.41^{+0.08}_{-0.07}$	$2.42^{+0.05}_{-0.07}$	$2.42^{+0.05}_{-0.07}$
Detector-frame chirp mass $(1+z)\mathcal{M}/M_\odot$	$3.619^{+0.006}_{-0.006}$	$3.619^{+0.007}_{-0.008}$	$2.580^{+0.006}_{-0.007}$	$2.579^{+0.007}_{-0.007}$
Primary spin magnitude χ_1	$0.09^{+0.18}_{-0.08}$	$0.08^{+0.22}_{-0.08}$	$0.31^{+0.52}_{-0.29}$	$0.33^{+0.48}_{-0.29}$
Effective inspiral spin parameter $\chi_{\rm eff}$	$-0.01^{+0.08}_{-0.12}$	$-0.01^{+0.11}_{-0.15}$	$-0.14^{+0.17}_{-0.34}$	$-0.19^{+0.23}_{-0.35}$
Effective precession spin parameter χ_p	$0.07^{+0.15}_{-0.06}$	$0.09^{+0.14}_{-0.07}$	$0.19^{+0.28}_{-0.17}$	$0.21^{+0.30}_{-0.17}$
Luminosity distance D_L/Mpc	280^{+110}_{-110}	280^{+110}_{-110}	310^{+150}_{-110}	300^{+150}_{-100}
Source redshift z	$0.06^{+0.02}_{-0.02}$	$0.06^{+0.02}_{-0.02}$	$0.07^{+0.03}_{-0.02}$	$0.07^{+0.03}_{-0.02}$

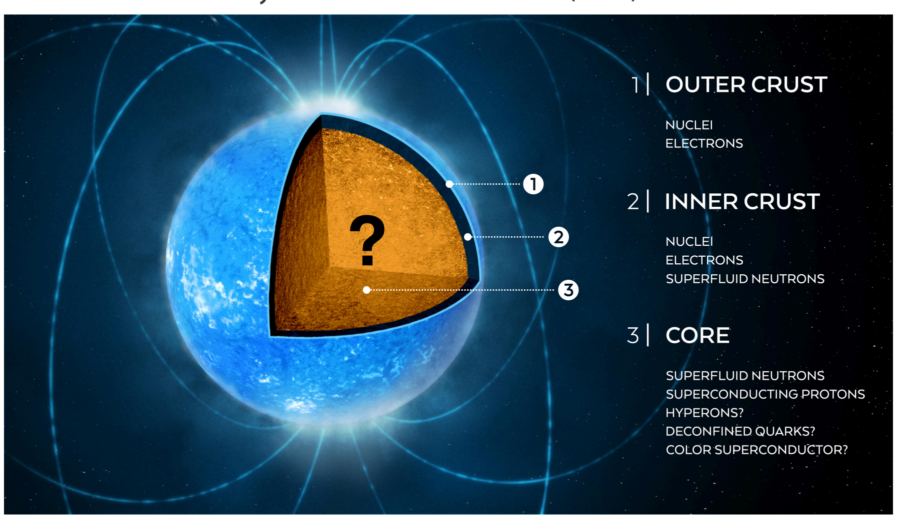
- GW200105: ~1.9 + ~9 solar masses
- GW200115: ~1.5 + ~6 solar masses

no information on matter effects
no significant EM detections

see events of GWTC-3: arXiv:2111.03606

Opportunities beyond the EoS





- thermal evolution - neutrino emissivity, stellar superfluids **[nuclear theory, transport prop.]**
- merger dynamics with astro/GW signals - out-of-equilibrium (visc.) physics; composition details **[simulations, nucleosynthesis]**
- next Galactic supernova? **[neutrino physics]**
- spin-down, glitches, asteroseismology, **[hydrodynamics, GR, nucl-th]**
- ...and more - add your own!

Rev. Mod. Phys. 88, 021001 (2016)

Long-term thermal evolution

Core: neutrino losses; isothermal

Crust & envelope: dominates early evolution of young NSs <~100 yrs

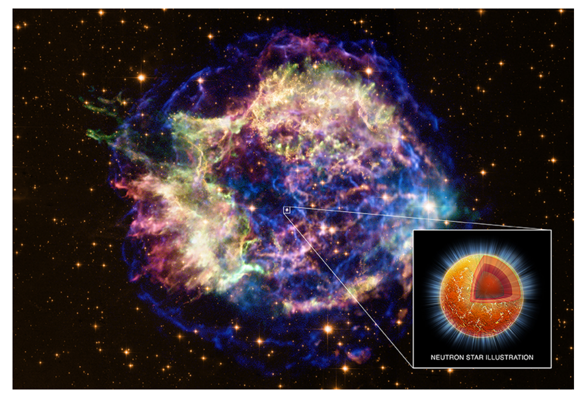
- heat flow (inwards & outwards): conduction

$$\frac{dT(r)}{dr} = -\frac{1}{K}\frac{L_\gamma(r)}{4\pi r^2}$$

- heavy vs. light elements
- crust thickness

$$\tau_{\rm th} \sim \frac{C_v l^2}{K}$$

©NASA



Surface: photon emission; observable

Neutrino reactions

$$\frac{dE_{th}}{dt} = C_v\frac{dT}{dt} = -L_\nu - L_\gamma$$

- **enhanced** (core dUrca)
- slow: mUrca, brems.
- medium: pair-breaking-formation

$\left.\begin{array}{l}\text{slow}\\ \text{medium}\end{array}\right\}$ **standard**

e.g. cooling accreting NSs

transiently accreting NSs in LMXBs (with low magnetic fields)

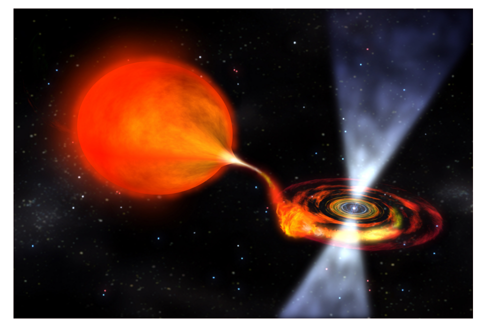
Surface, ocean & envelope

- thermonuclear bursts; shallow heating (?)

Deep-crustal heating   Brown et al. (1998); Haensel & Zdunik (1990, 2003)

- electron capture; pycnonuclear; neutron emission, transfer & absorption
- time-averaged accretion rate

$$L_{\rm dh} = Q \times \frac{\dot{M}}{m_{\rm N}} \approx 6.03 \times 10^{33} \left(\frac{\dot{M}}{10^{-10}\,{\rm M}_\odot\,{\rm yr}^{-1}} \right) \frac{Q}{\rm MeV}\, erg\; s^{-1}$$



- accreted crust replaces original (catalyzed) crust

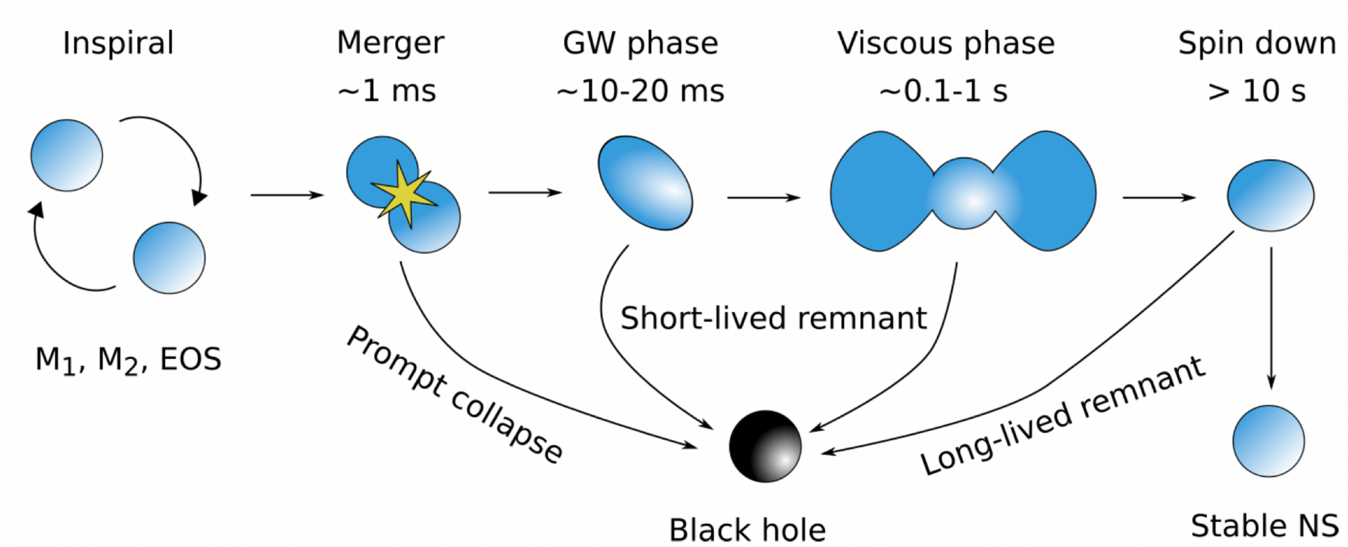
Quiescent NSs: thermal equilibrium

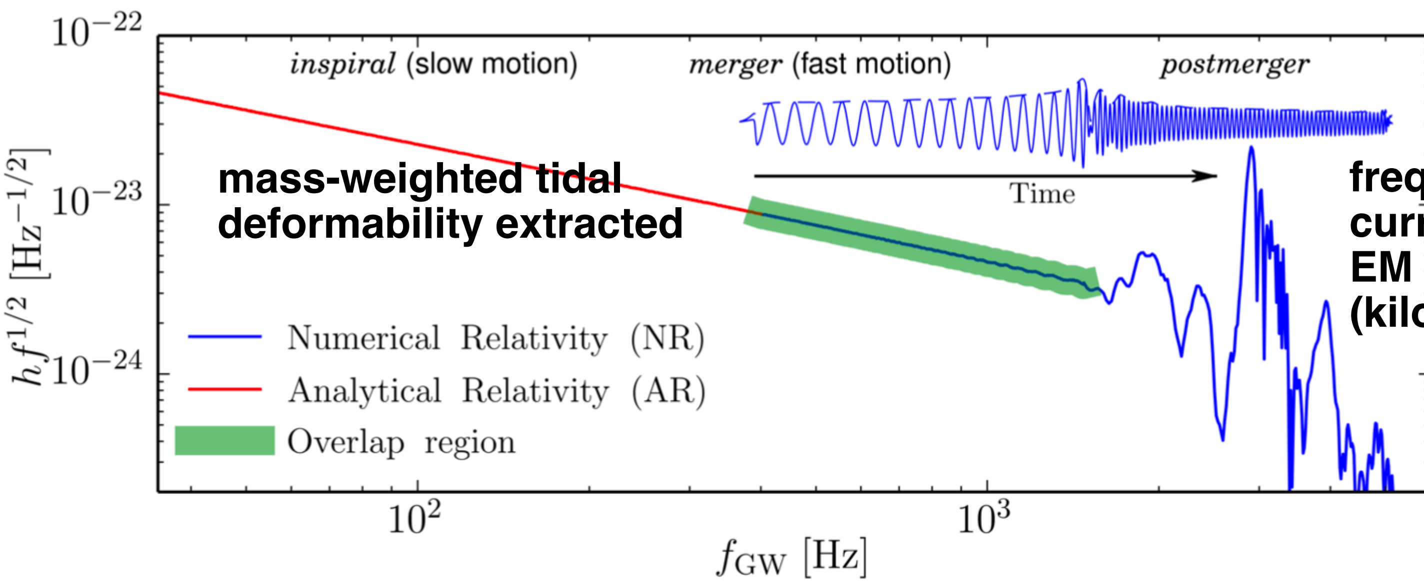
observables

- quasi-stationary state $L_{\rm dh}^\infty(\dot{M}) = L_\gamma^\infty(T_s) + L_\nu^\infty(T_i),\; T_s = T_s(T_i)$

BNS merger dynamics

Radice et al. (2020)

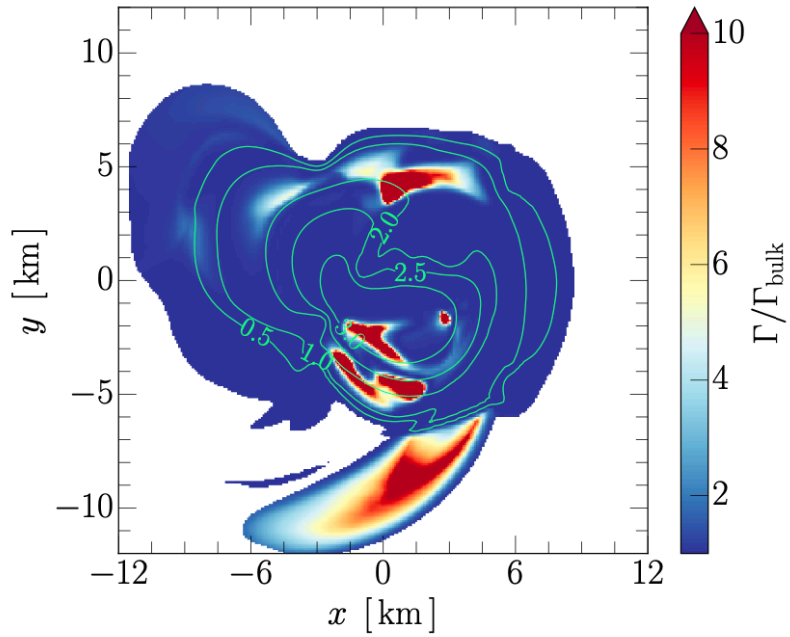


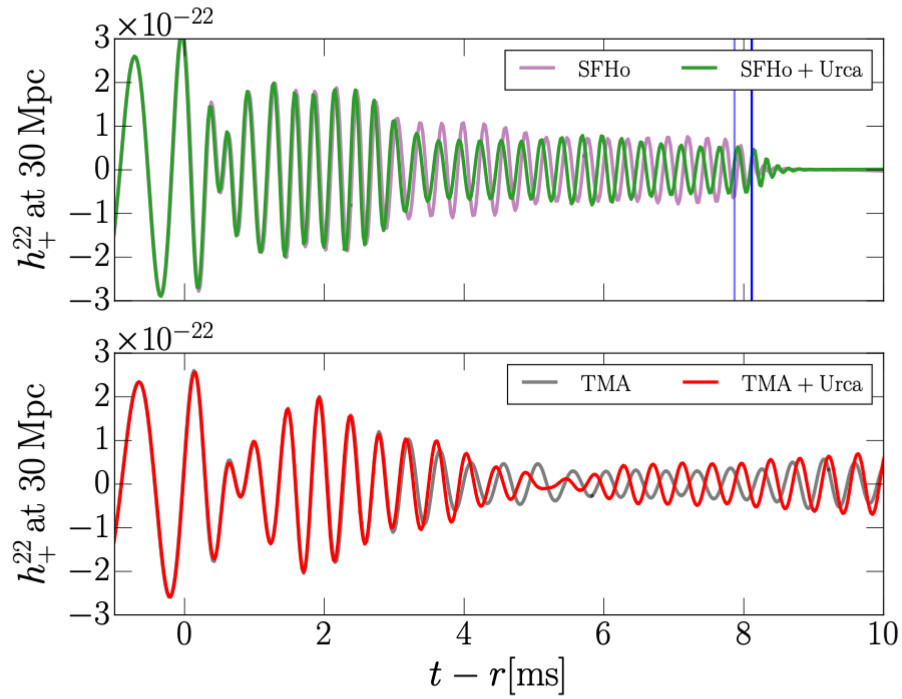


mass-weighted tidal deformability extracted

freq. too high wrt current sensitivity; EM counterparts (kilonovae) seen

Bulk viscous phase in merger



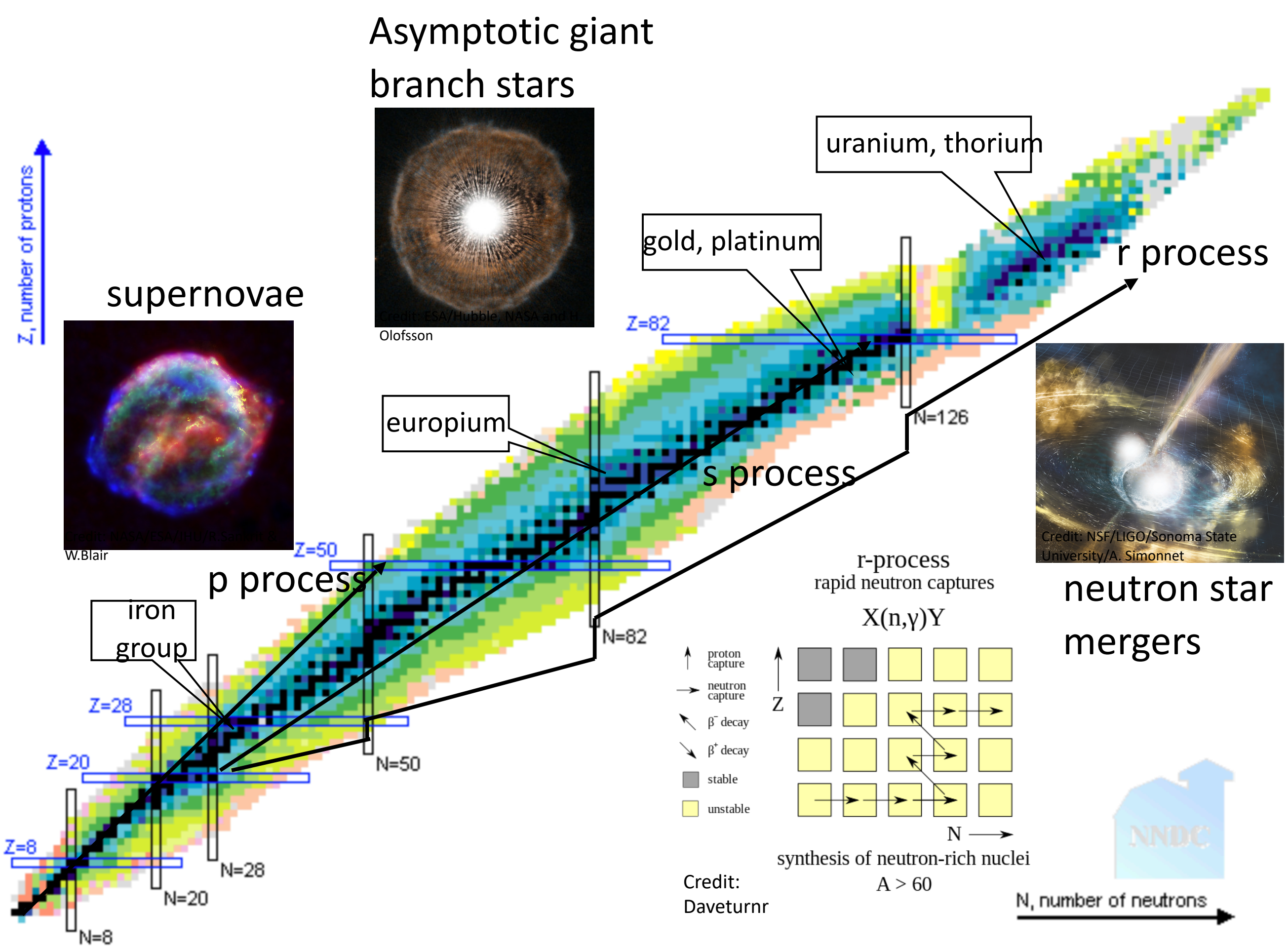


Most et al. ApJL 967, L14 (2024)

- remnant evolution: impact of weak-interaction driven out-of-equilibrium dynamics; phase shift of the gravitational-wave spectrum
- dissipation via **nucleonic** Urca processes on a millisecond timescale
- different channels of chemical equilibration for **hyperons, quarks etc.** -> bulk viscosities with different dependencies on temperature and density

Courtesy: Xilu Wang

Nucleosynthesis - origin of heavy elements



Heavy elements (heavier than iron):
the nucleosynthesis was a mystery for decades

Main processes:
Proton-rich process (p process)- ~0.1%-1% ;
neutron capture process:
s process (slow neutron capture) ~50%, up to ^{210}Bi;
r process (rapid neutron capture) ~50%

Heavy element nucleosynthesis---multi-messenger astronomy

NS physics and MMA - a glimpse

Supernovae and BNS mergers

- explosive environment: high entropy, short expansion, neutron-rich matter
- high-performance computing (HPC)
- observatories for GW & electromagnetic counterparts

Theory & simulation

- neutrino scattering & absorption in a dense medium: dynamical response
- sensitivity to finite-temperature EoSs: electron fraction Ye; heat transport (diffusion, convection) by neutrinos
- neutrino oscillation: luminosity in different flavors
- nucleosynthesis: predict amount & composition of ejecta
- hydrodynamics, numerical relativity, magnetic field..

NS physics and MMA - a glimpse

GW detection in mergers

- pre-merger (inspiral): dense matter EoS and tidal effects are important; mass, radius and tidal deformability affect GW spectra -> distinguish EoSs!
- merger: complicated evolution of temperature and density; viscosity & oscillation modes; ejecta, r-process nucleosynthesis and jets..
- post-merger: remnant GW signals (NS or BH? evolution of rotation?); attendant gamma-ray, x-ray, optical and infrared signals: multi-messenger tools

Future

- more data from merger events will enable systematic analysis: prospects for future detections to discern possible phase transition at supra nuclear densities
- continuous GW sources, e.g. mountains on a NS or CFS-unstable modes

Stellar vibrations - asteroseismology

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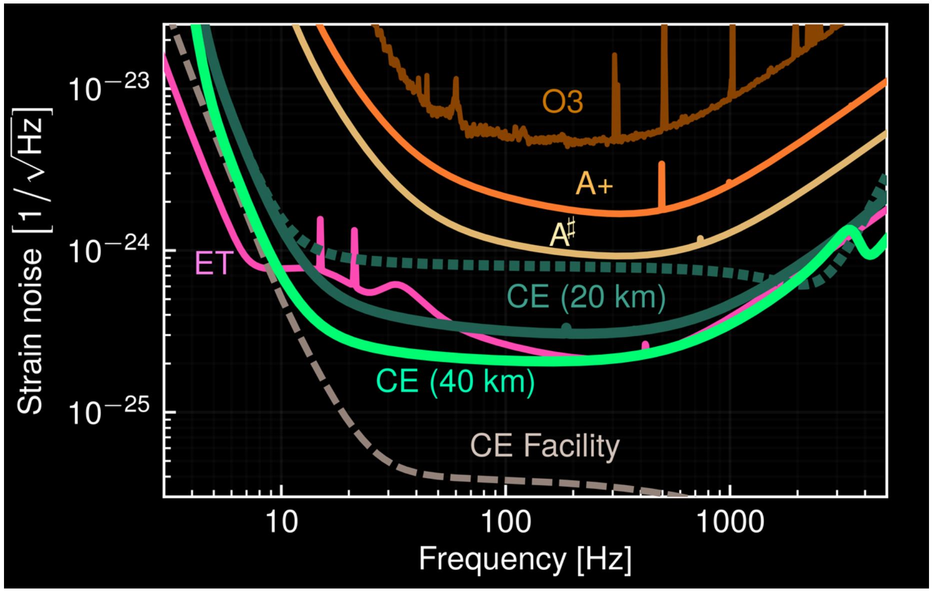
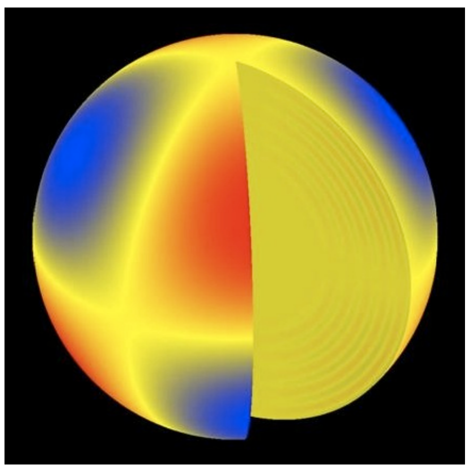


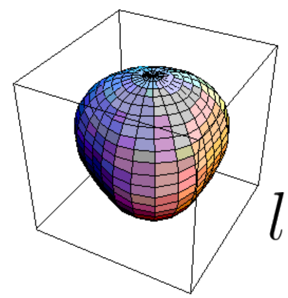
stable oscillation modes ("ringing") -

- ***f*-mode (fundamental mode)** scales with average density
- *p*-mode (pressure mode) probes the sound speed
- ***g*-mode (gravity mode)** sensitive to **composition**/thermal gradients
- w-mode, s-mode, i-mode/r-mode..

©NASA/Kepler

promising sources for XG detectors



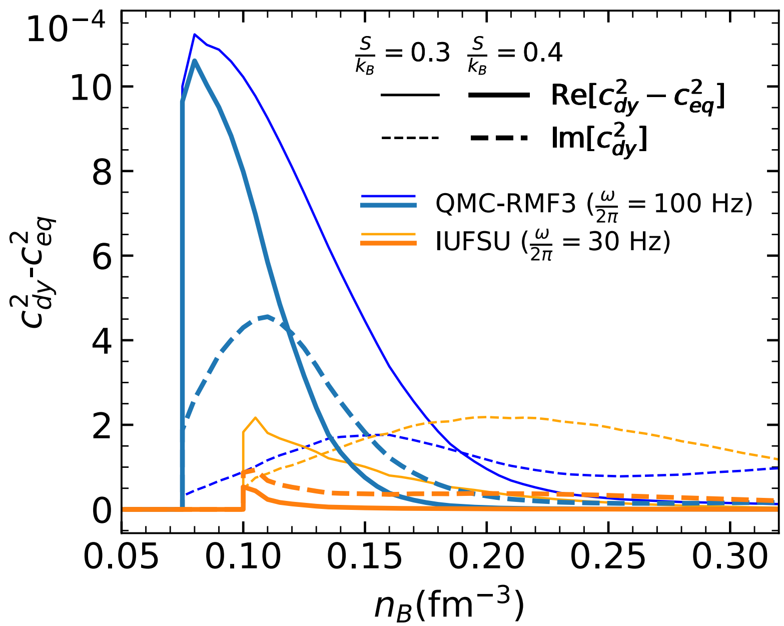


$l = 3,\ m = 3$

small amplitude oscillations ->
weak, continuous emission of GWs

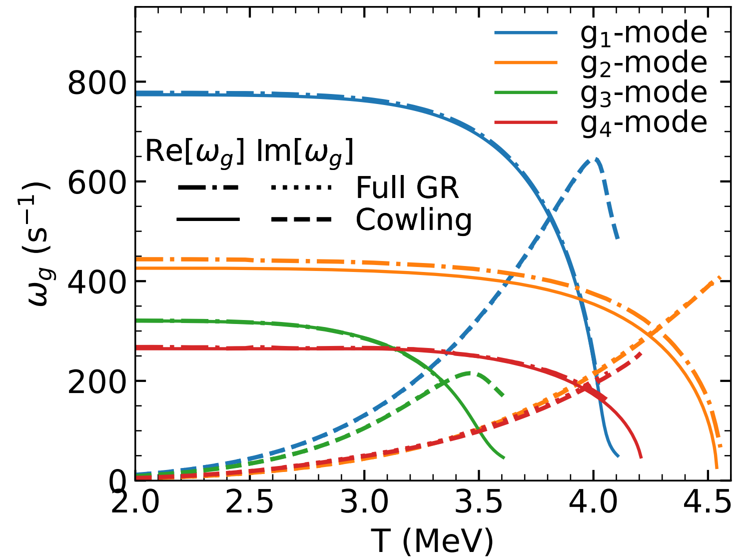
g-mode with bulk viscous phase

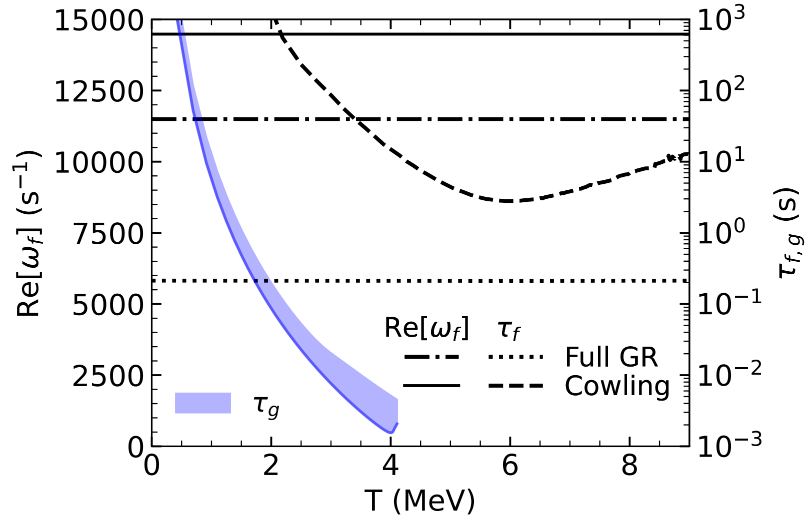
- complex, frequency-dependent generalization of the adiabatic sound speed - “dynamical” sound speed



- bulk viscous damping increases significantly with temperature

- **dissipative effects** can completely suppress composition g-modes

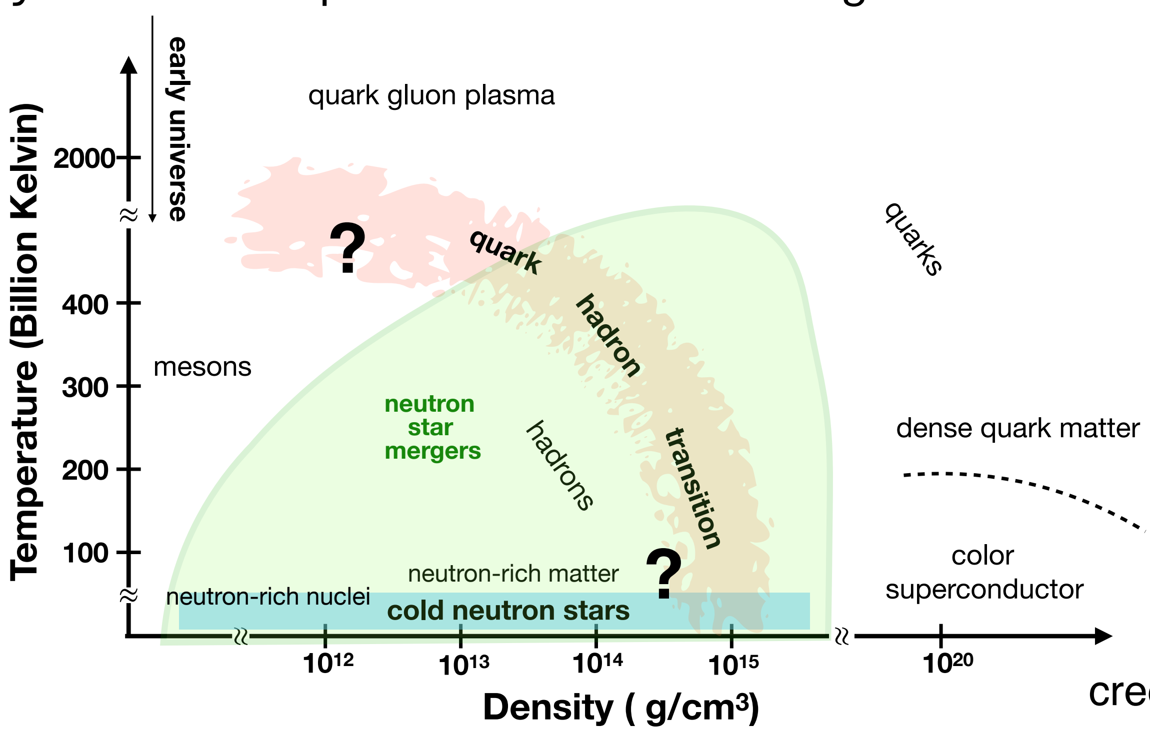




Zhao et al. (including **SH**), arXiv:2504.12230

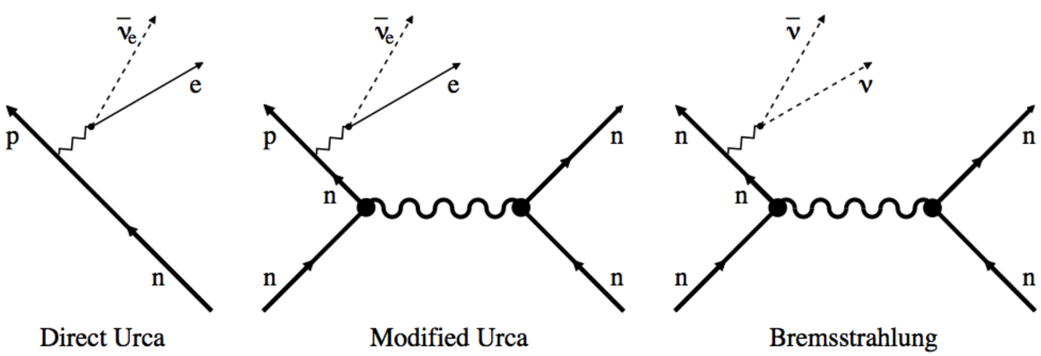
Recap: Dense matter science with NSs

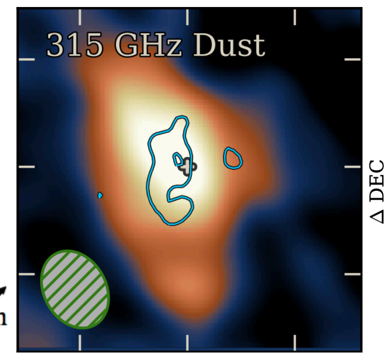
- Can we relate multi-messenger observations of NSs to terrestrial experiments and ultimately understand the connections to QCD?
- MMA window on matter at densities and isospins not otherwise reachable
- some guidance on transport properties from experimental measurements
- range of validity for microscopic theories and modeling of dense matter

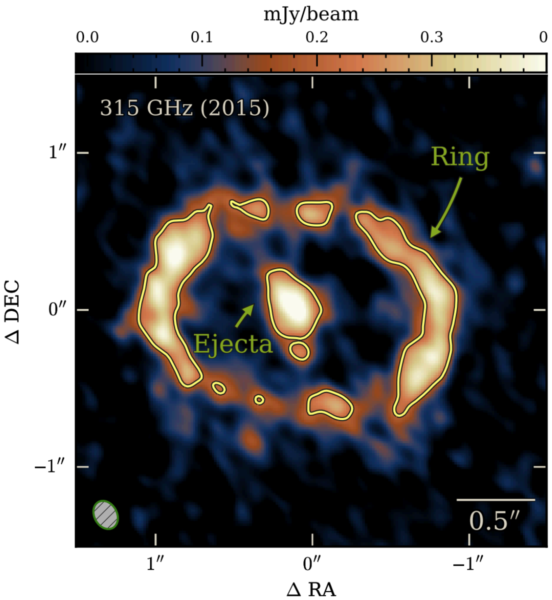


credit: Sanjay Reddy

Key Questions of Interest II

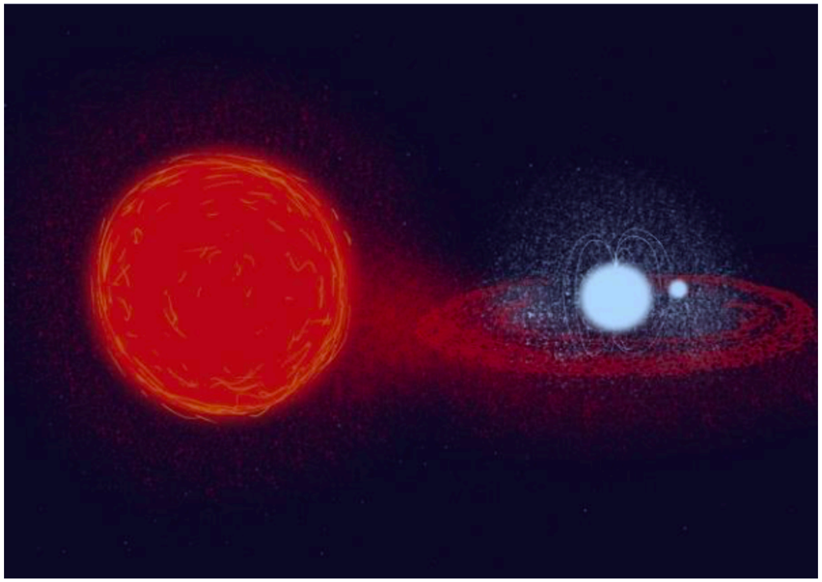






- NS cooling studies provide unique information on its composition
- unknown origin of enhanced nu-emission observed in transiently accreting NSs
- direct Urca processes with exotic particles or prevalent superfluid component?
- brand new opportunity - upcoming data from the youngest NS1987A!

Key Questions of Interest III

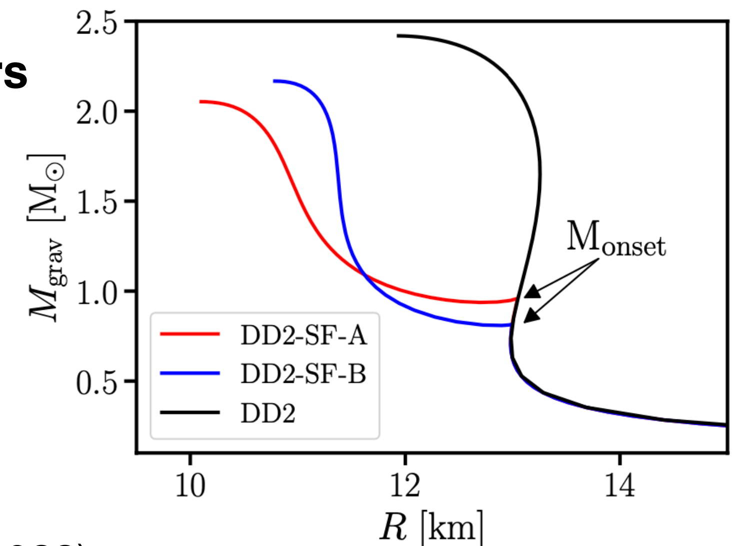


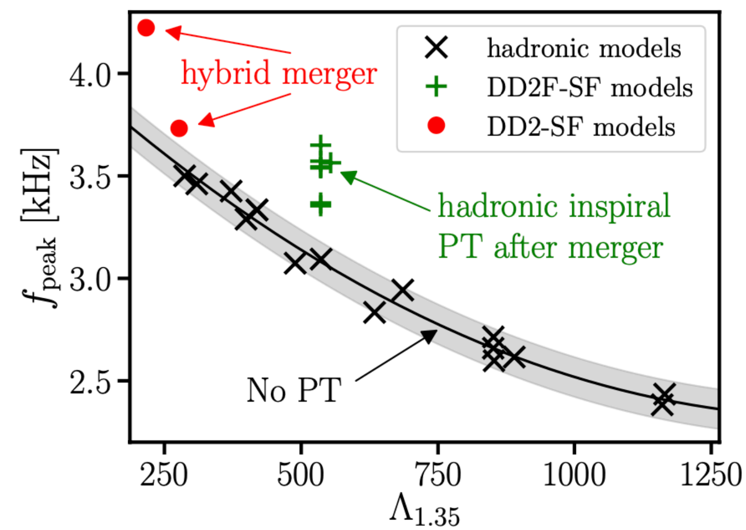
- Future prospects of detecting continuous GWs
- the most promising source? implications for dense matter properties
- “mountains” on NSs - crust ellipticity; excited fluid modes of oscillation - core viscosity
- Post-merger dynamics, next Galactic supernova - test numerical simulations
- the universality of phase transition-like signatures? what about smooth crossovers?

e.g. softening effects on post-merger GWs

third-family stars

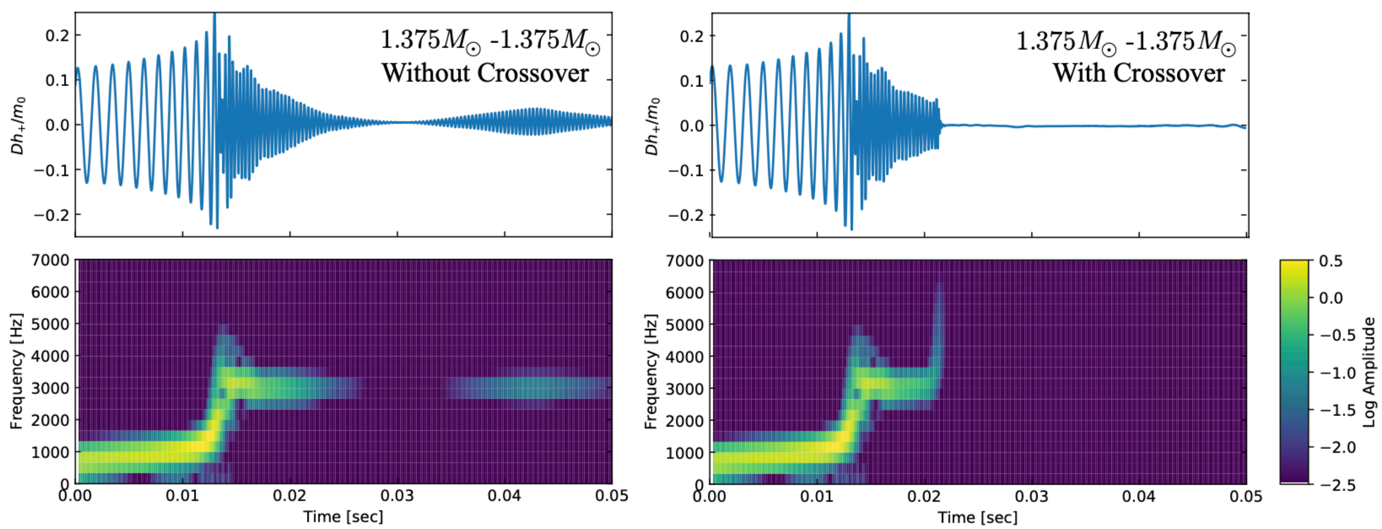
- ***stiff*** EoS at low density -DD2
- strong **1st-OPT** to ***stiff*** quark matter **before merger**





Bauswein & Blacker (2020)

Fujimoto et al. (2022)

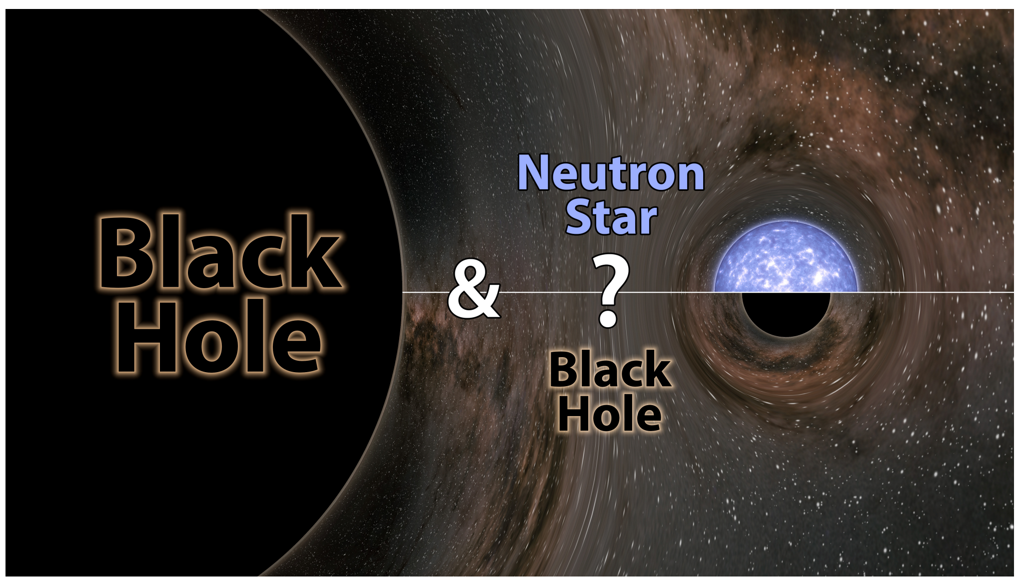


- ***soft*** EoS at low density ~N3LO chiEFT
- rapid ***stiffening*** within the crossover regime

crossover into *soft* quark matter after merger

Key Questions of Interest IV

- What are the maximum and minimum masses of neutron stars?
- implications for the EoS, the fate of CCSNe and post-merger remnant evolution
- BH minimum mass (is there a mass gap?); the total number of stellar-mass BHs
- puzzles about stellar evolution, the progenitor mass, and formation mechanism
- do DM particles interact with NSs and manifest themselves somehow?



THANK YOU!

Q & A