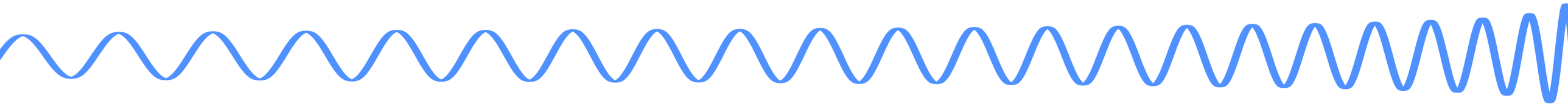

Probing subatomic physics with gravitational waves from neutron star binary inspirals

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Utrecht University

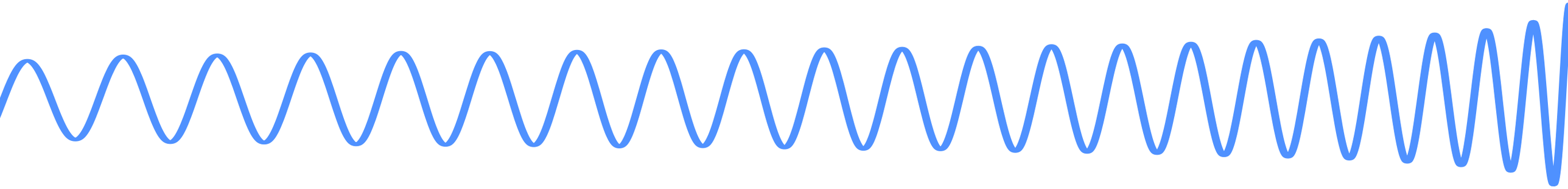
Talk at Meeting of the National Research Group on Gravitational Waves

March 30, 2021

Overview

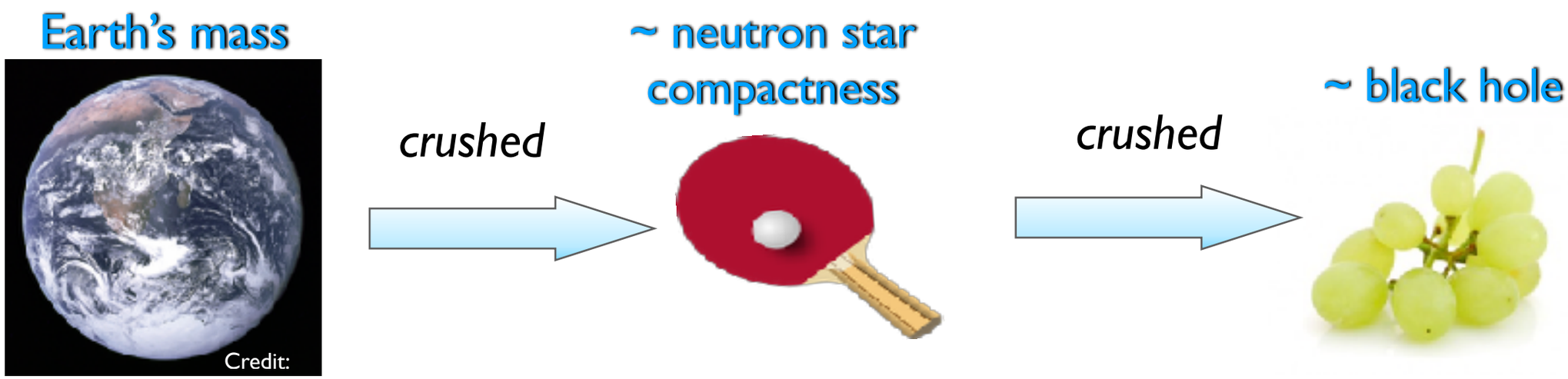
- Gravitational waves (GWs) now available for probing fundamental physics in unexplored regimes

- Interpretation of GW signals from binaries relies on theoretical models
- Required: detailed understanding of GW signatures of matter
  - Focus in this talk on the inspiral: clean, cumulative, currently accessible regime
- What have we learned so far?
- Outlook to future prospects



Neutron stars (NSs)

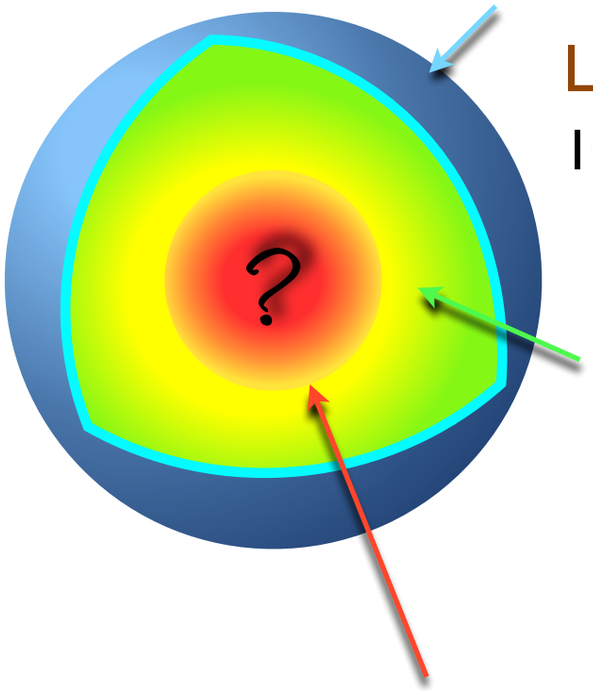
- Gravity compresses matter to up to several times nuclear density



- Thousands observed to date, some masses > 2 Msun
- Quantum pressure (neutron degeneracy) can only support up to ~ 0.7 Msun
- Unique window onto strongly-interacting subatomic matter

Conjectured NS structure

[density of iron ~ 10 g/cm^3]



crust ~ *km*

Lattice of neutron rich nuclei ~ 10^6 g/cm^3 inverse β-decay

10^{10} times stronger than steel

free neutrons ~ 10^{11} g/cm^3 neutron drip

outer core

uniform liquid (neutron superfluid, superconducting protons, electrons, muons)

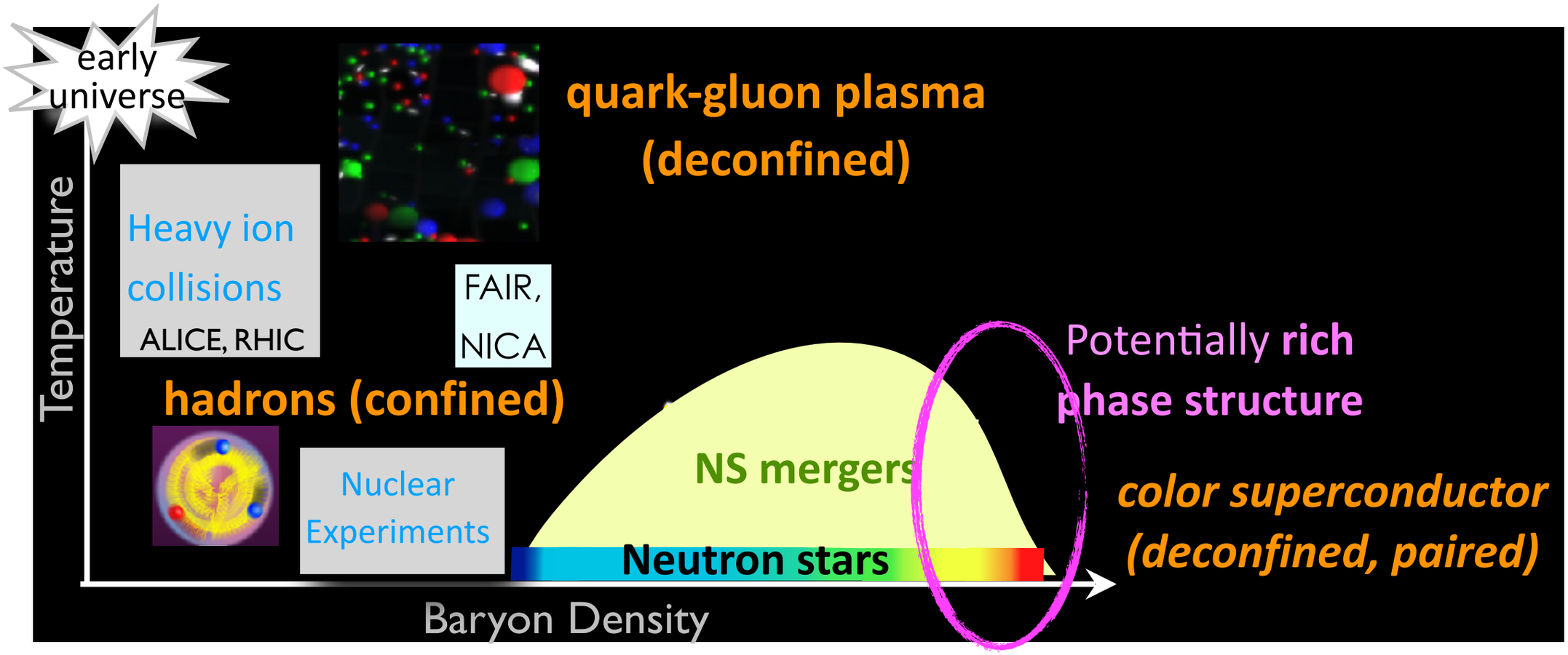
deep core ~ few x 10^{14} g/cm^3

$\gtrsim$2x nuclear density, nucleons overlap -

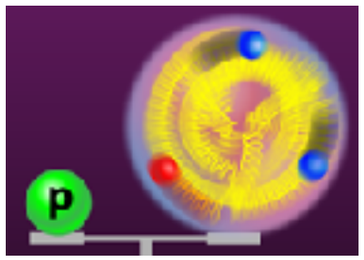
new degrees of freedom relevant

condensates? deconfined quarks?

Neutron stars as QCD labs



- Characterize phases of QCD, probe deconfinement
- Deeper understanding of strong interactions, their unusual properties, e.g.
  - asymptotic freedom (weaker force at shorter distances)
  - Vacuum (condensate) has important effects, e.g. mass

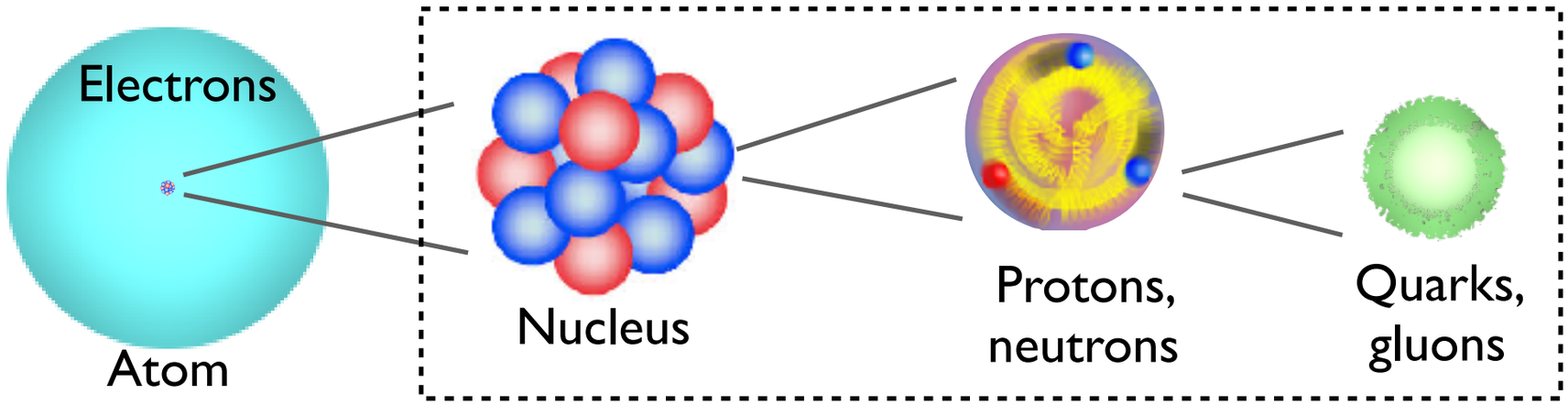


proton mass: ~ 938 MeV

only ~ 1% due to Higgs

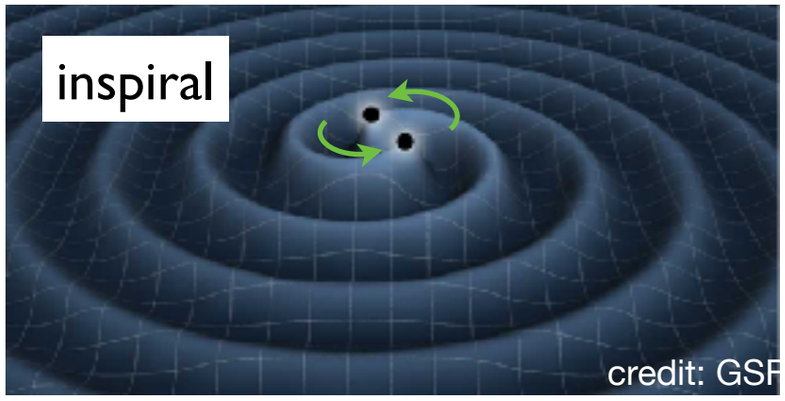
NSs as labs for emergent structural complexity

Building blocks of matter



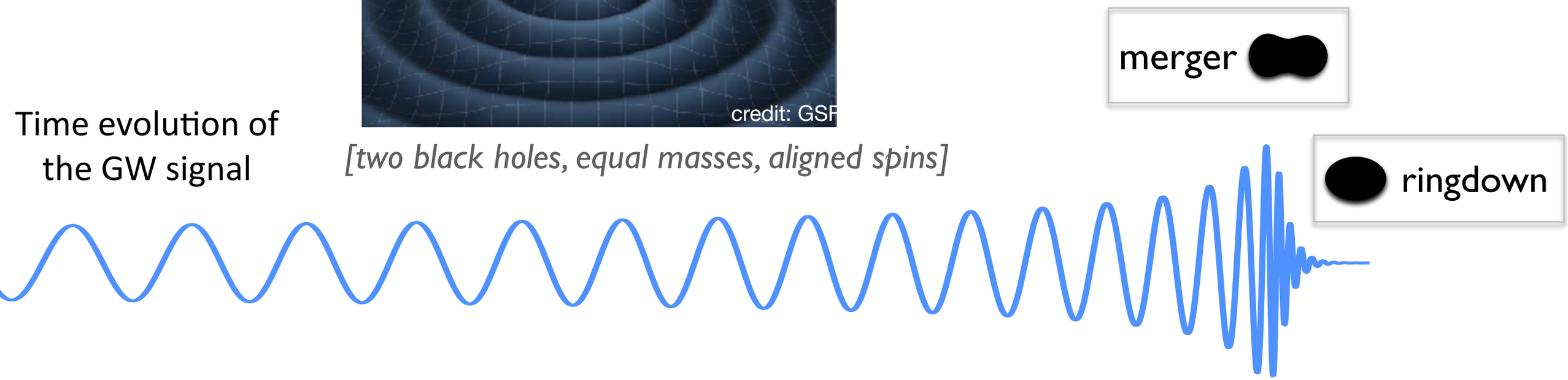
- Collective phenomena, multi-body interactions
- Effects of the excess of neutrons over protons (isospin asymmetry)?
- How do nucleons and their quarks and gluons assemble and interact to create the structure of matter?

Gravitational waves (GWs) from binary systems

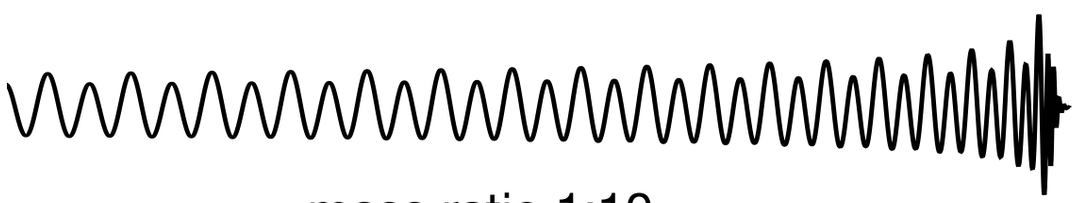


[two black holes, equal masses, aligned spins]

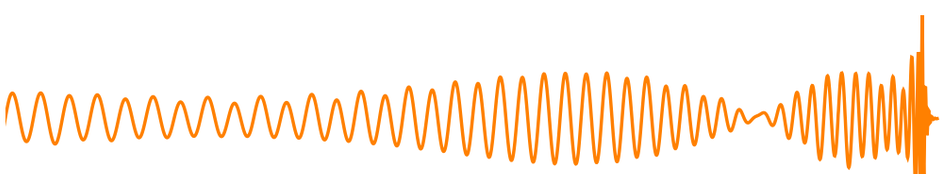
Time evolution of the GW signal



- Details of the waveform encode fundamental source properties



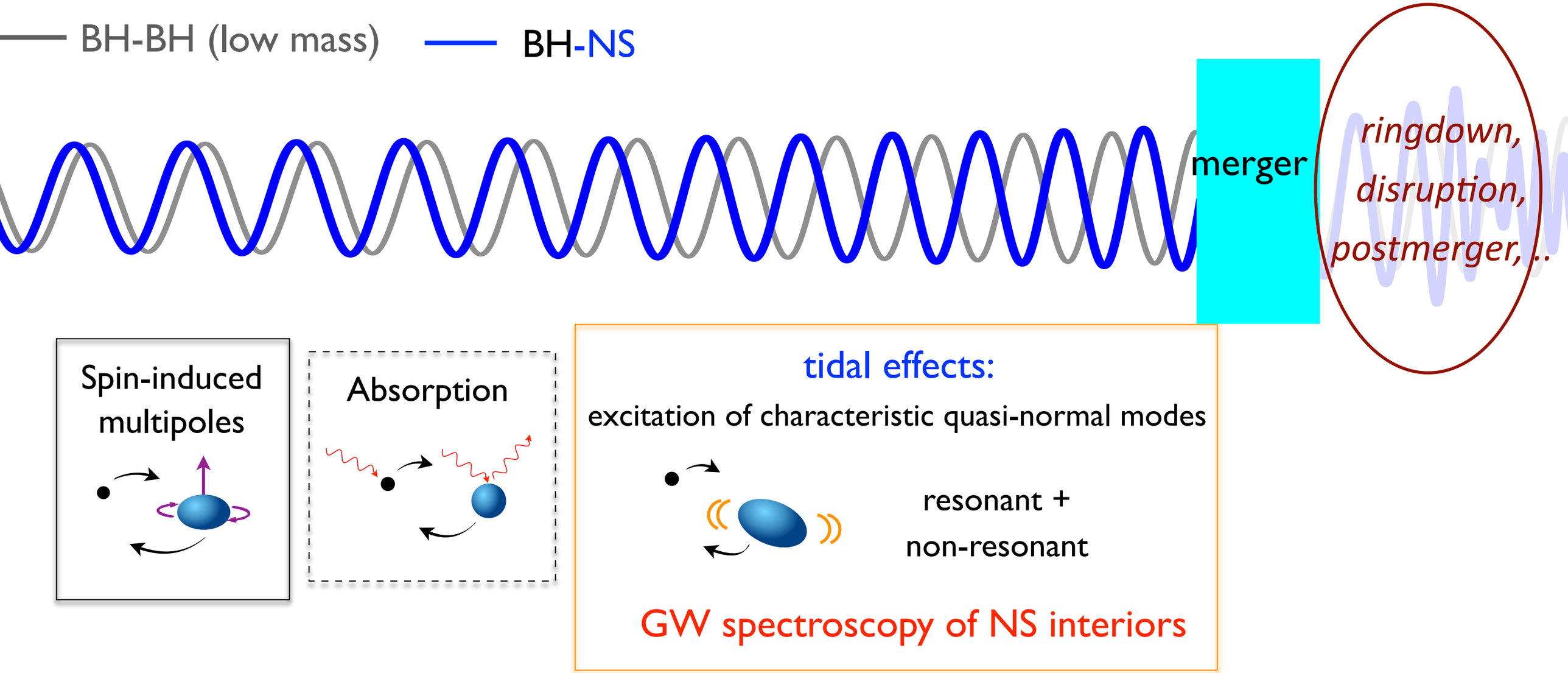
mass ratio 1:10



misaligned spins

- Measurements: data cross-correlated with theoretical waveform models

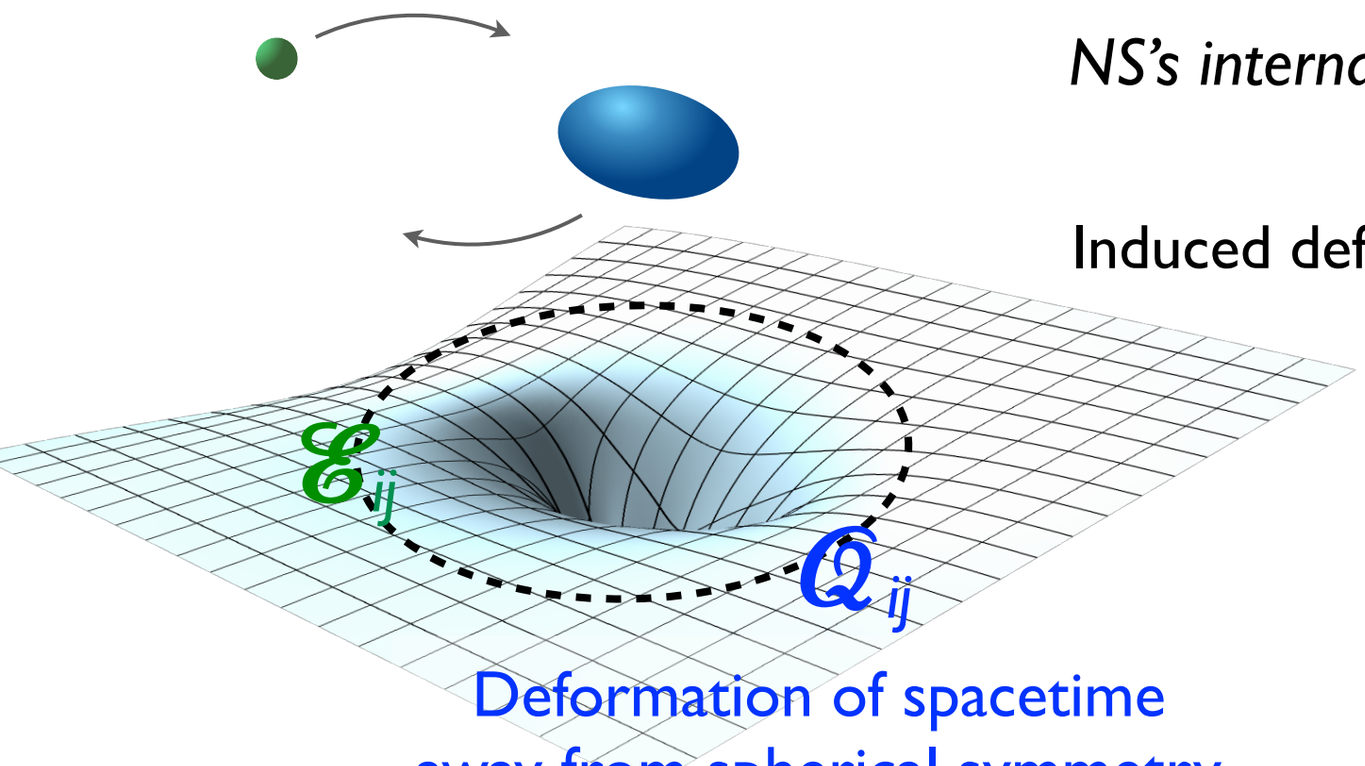
GW signatures of matter



Generic phenomena (any objects that are not classical GR black holes in 4d), associated characteristic parameters encode object's internal structure

Example of a characteristic matter parameter

- In a binary: tidal field $\mathcal{E}$ due to curvature from companion



Deformation of spacetime
away from spherical symmetry

When variations in tidal field are much faster than NS's internal timescales (adiabatic limit):

Induced deformation: $Q_{ij} = -\lambda \mathcal{E}_{ij}$

tidal deformability parameter

=0 for a BH

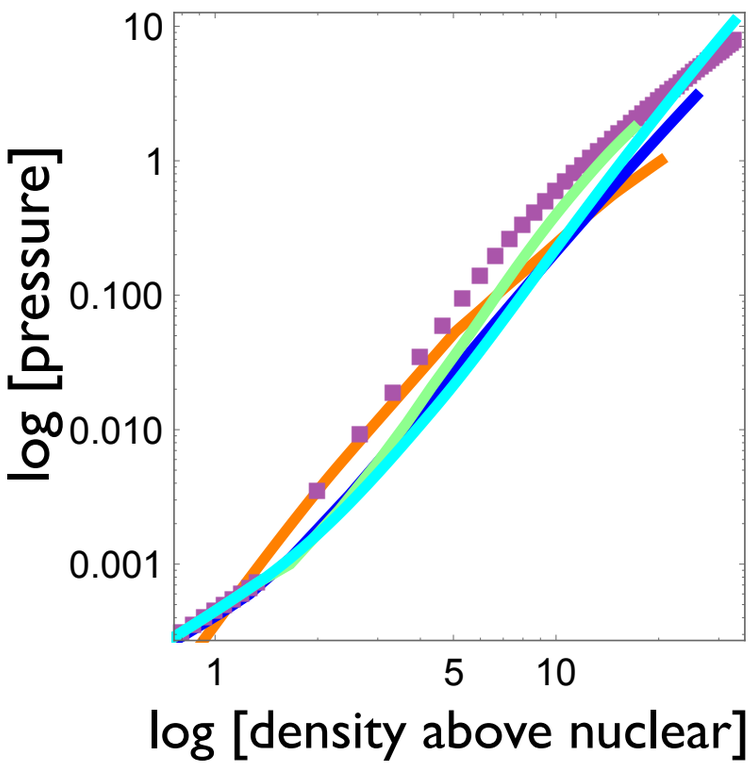
[Kol,Smolkin '11,Chia '20, Casals, LeTiec '20,...]

computed from Einstein's equations for linearized perturbations to equilibrium

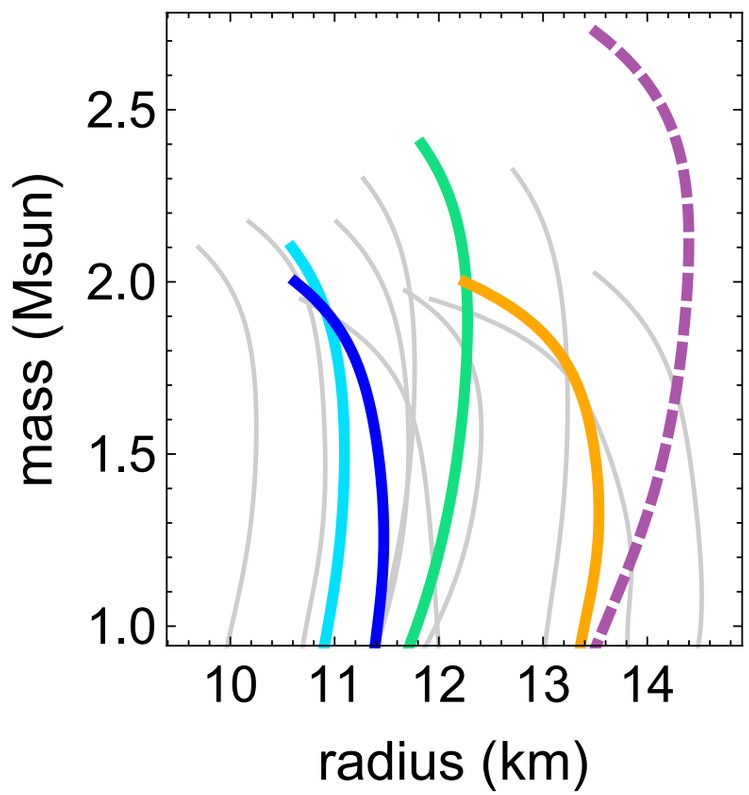
[TH 2008]

Properties of NS matter reflected in global observables

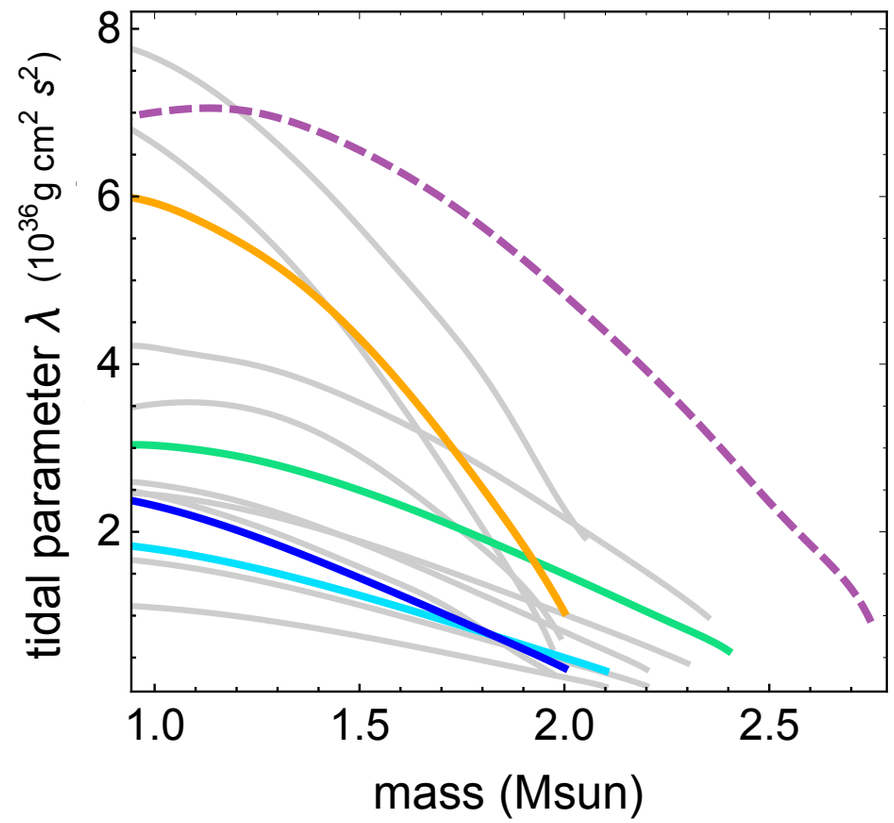
NS matter models
(equations of state)

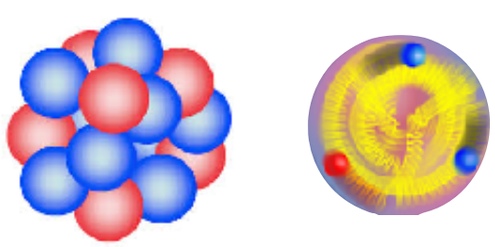


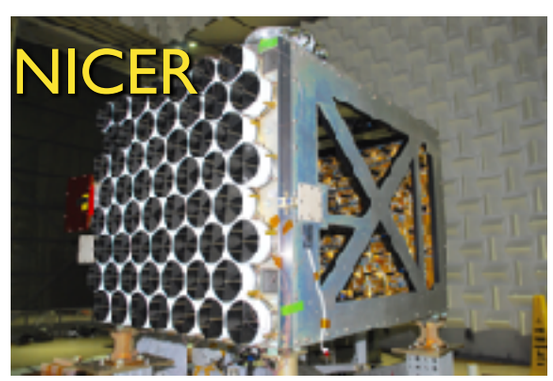
Mass vs. radius



tidal deformability λ vs. mass



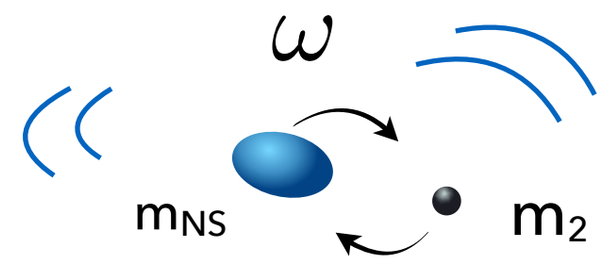




Influence on GWs

- Energy goes into deforming the NS

$$E \sim E_{\rm orbit} + \frac{1}{4} \mathcal{Q}\, \mathcal{E}$$



$M = m_{NS} + m_2$

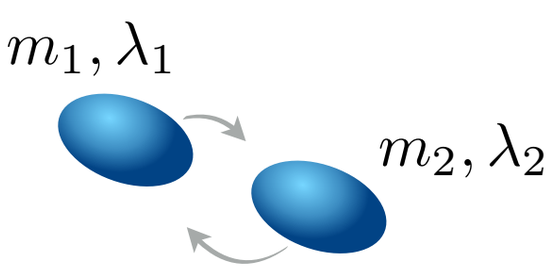
- moving multipoles contribute to gravitational radiation

$$\dot{E}_{\rm GW} \sim \left[\frac{d^3}{dt^3} \left(Q_{\rm orbit} + \mathcal{Q} \right) \right]^2$$

- approx. GW phase: $\frac{d\phi_{\rm GW}}{dt} = 2\omega$ $\qquad \frac{d\omega}{dt} = \frac{\dot{E}_{\rm GW}}{dE/d\omega}$

$$\Delta\phi_{\rm GW}^{\rm tidal} \sim \lambda \frac{(M\omega)^{10/3}}{M^5}$$

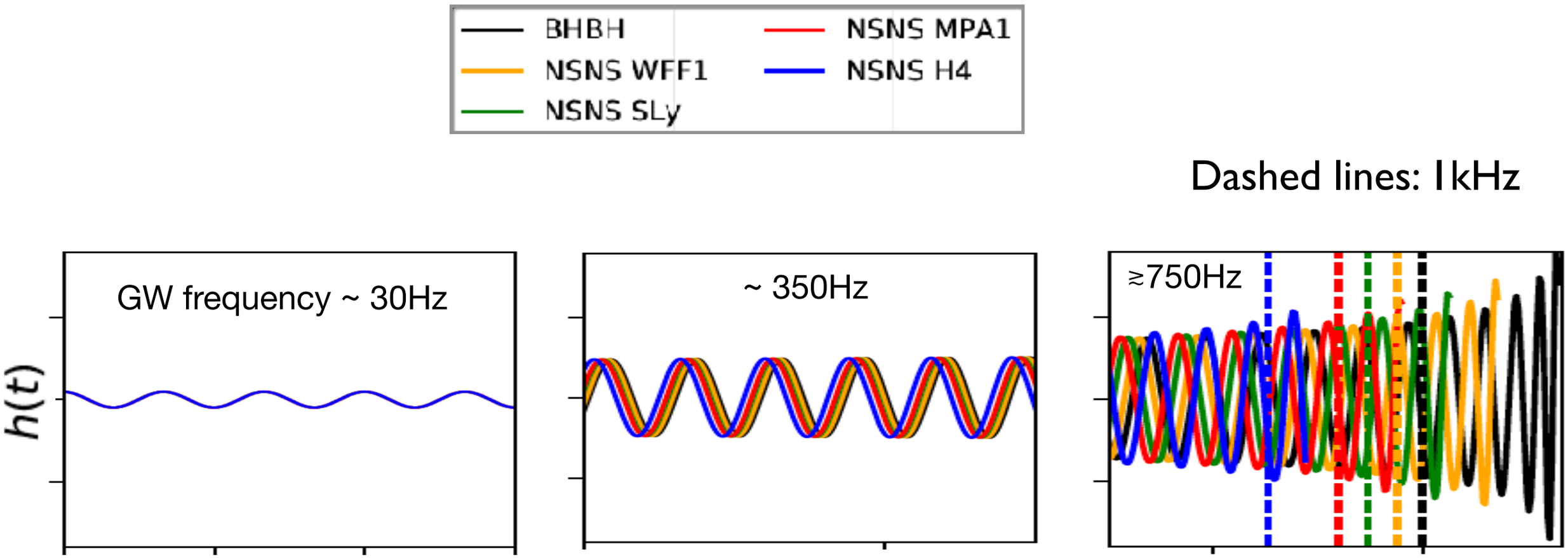
- for two NSs: most sensitive to:



$$\tilde{\Lambda} = \frac{13}{16\, M^5} \left[\left(1 + 12 \frac{m_2}{m_1} \right) \lambda_1 + \left(1 + 12 \frac{m_1}{m_2} \right) \lambda_2 \right]$$

[Flanagan,TH 2008, Vines, Flanagan, TH 2011, Damour, Nagar, Villain 2012, Henry, Faye, Blanchet 2020]

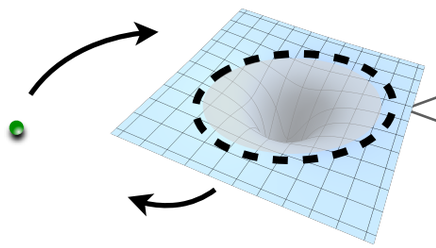
Example: nonspinning inspirals starting from 30 Hz



[from Guerra, TH 2019]

More general tidal coupling of NS matter to dynamics for slowly rotating NSs

spacetime near the NS viewed on the orbital scale:



worldline + multipoles

$$m, S^i, \underbrace{Q^{ij}, Q^{ij}_{\mathcal{B}}}_{}, \ldots$$

tidally induced mass & current multipoles (* matter contributions to them)

Effective action describing the binary dynamics:

redshift

magnetic piece of curvature, no Newtonian analog

$$S \approx S_{pp} + \int d\tau \left[-\frac{z}{2} Q_{ij} \mathcal{E}_{ij} - \frac{z}{2} \dot{Q}^{\mathcal{B}}_{ij} \mathcal{B}_{ij} + L^{\text{Coriolis}} + L^{\text{FD}} + L^{\text{osc}} + \ldots \right]$$

point-particle part

multipoles interact with companion's spacetime curvature

Effects of NS's spin on its tidal response

frame-dragging: Q's angular momentum interacts with orbital angular mom. & companion's spin

[Steinhoff, TH +2016, 2020, 2021]

More general tidal coupling of NS matter to dynamics for slowly rotating NSs

Multipoles (due to quasi-normal modes) behave as harmonic oscillators, e.g. one mode each:

$$L^{\rm osc} \approx \frac{z}{4\lambda z^2 \omega_f^2}\frac{dQ_{ij}}{d\tau}\frac{dQ_{ij}}{d\tau} - \frac{z}{4\lambda}Q_{ij}Q_{ij} + \ldots$$

dominated by fundamental (*f*-)modes

$$+\frac{3z}{32(\sigma_{\rm stat}-\sigma_{\rm irrot})}\frac{d\dot{Q}^{\mathcal{B}}_{ij}}{d\tau}\frac{d\dot{Q}^{\mathcal{B}}_{ij}}{d\tau} + \frac{2z\sigma_{\rm stat}}{3}\mathcal{B}_{ij}\mathcal{B}_{ij} + \ldots$$

subdominant, but mode frequencies $\propto$ NS's spin

two different magnetic tidal deformabilities [Landry, Poisson, Pani+, Damour, Nagar, ...]

$$S \approx S_{pp} + \int d\tau \left[-\frac{z}{2}Q_{ij}\mathcal{E}_{ij} - \frac{z}{2}\dot{Q}^{\mathcal{B}}_{ij}\mathcal{B}_{ij} + L^{\rm Coriolis} + L^{\rm FD} + L^{\rm osc} + \ldots\right]$$

point-particle part

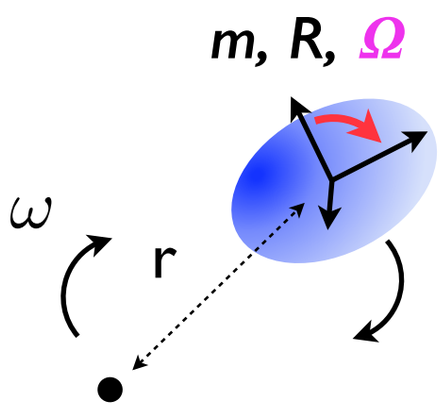
multipoles interact with companion's spacetime curvature

Effects of NS's spin on its tidal response

frame-dragging: *Q*'s angular momentum interacts with orbital angular mom. & companion's spin

[Steinhoff, TH +2016, 2020, 2021]

Impact of finite *f*-mode frequency during inspiral

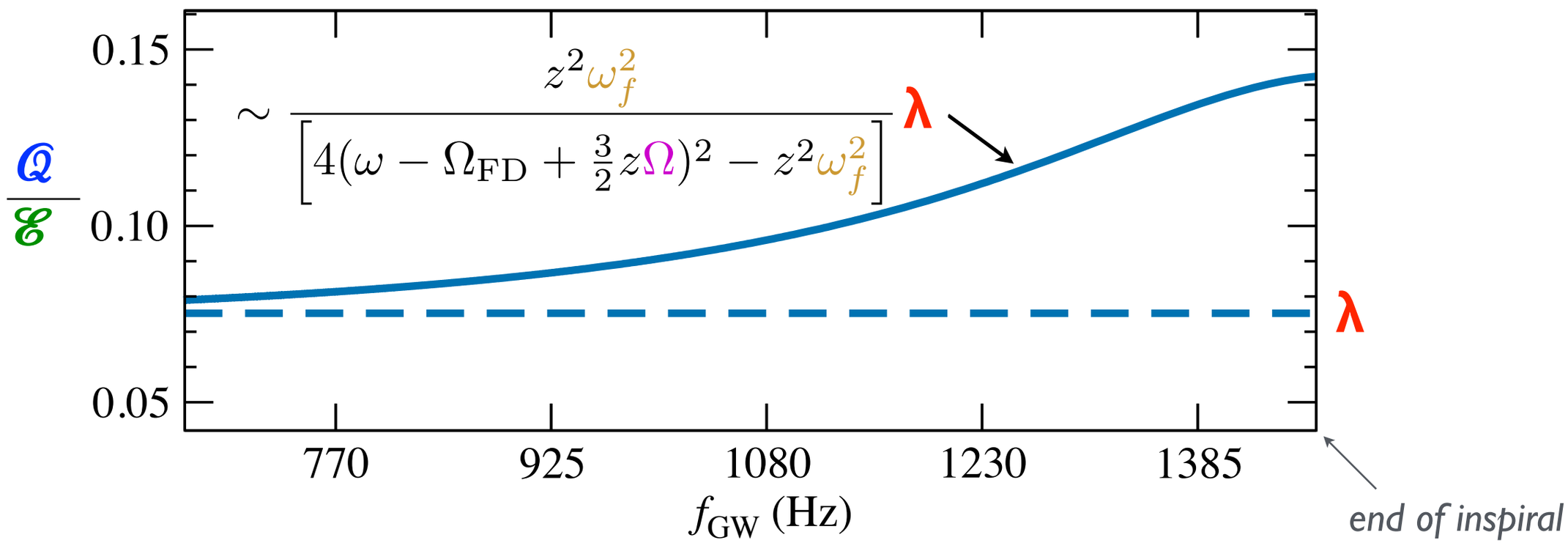


Scalings:

- ***f***-mode frequency: $\omega_f \sim \sqrt{m/R^3}$ (internal structure - dependent)
- **tidal forcing** frequency: $\sim 2\omega \sim 2\sqrt{M/r^3}$

Enhanced tidal effects even if the resonance is not fully excited

Example tidal response during a quasi-circular inspiral



f-modes effects included in the effective one body model SEOBNRv4T

[TH + 2016, Steinhoff, TH,+ 2017, Steinhoff, TH + 2021]

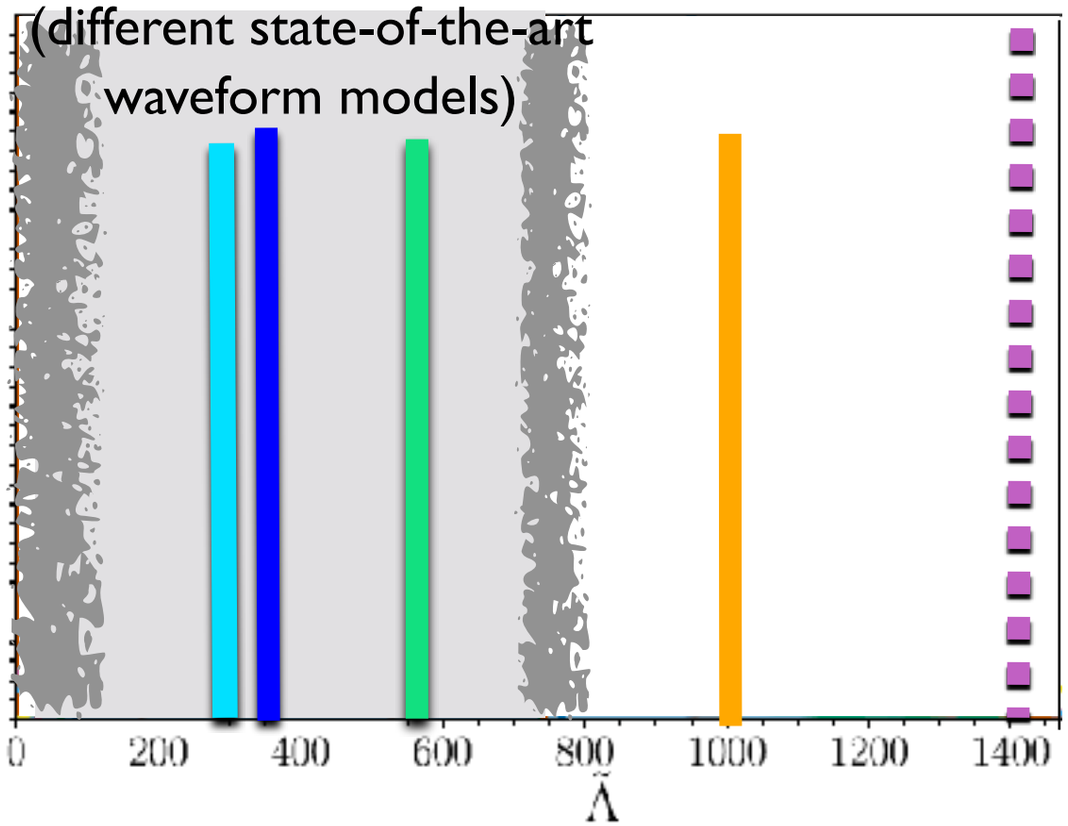
Results from NS binary GW events (low spin priors)

GW170817

LVC GWTC-1

90% credible interval

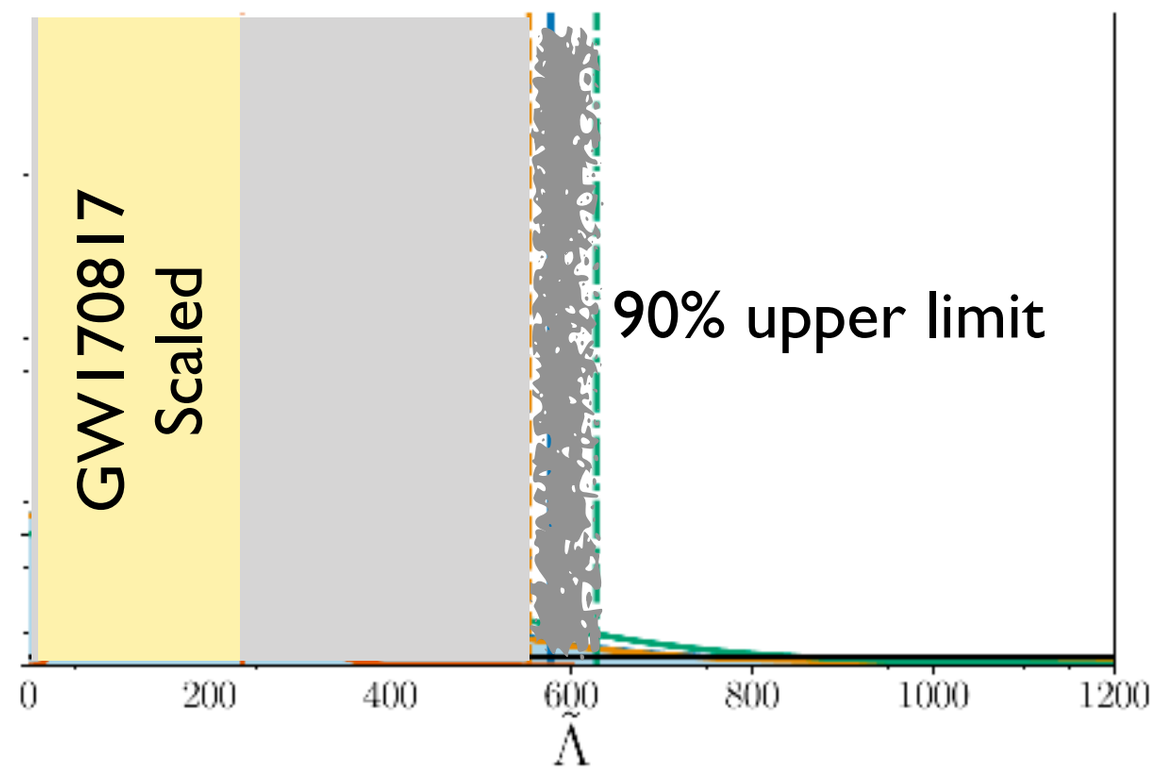
(different state-of-the-art waveform models)



Total mass ~ 2.8 Msun

GW190425 (?)

LVC ApJ Lett. 892 L3 (2020)

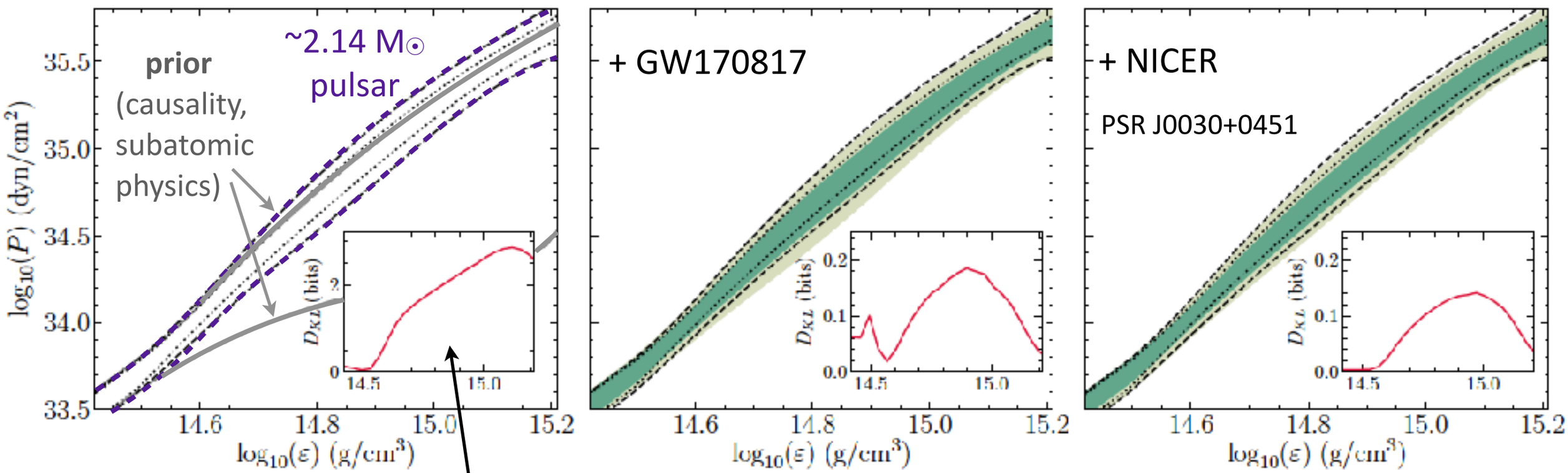


Total mass ~ 3.4 Msun

$$\tilde{\Lambda} = \frac{13}{16\,M^5}\left[\left(1+12\frac{m_2}{m_1}\right)\lambda_1 + \left(1+12\frac{m_1}{m_2}\right)\lambda_2\right]$$

Joint EoS constraints: 2.14 M⊙ pulsar, GWs, NICER

+ subatomic physics inputs:
- *Low density:* Fermi liquid theory, chiral effective theory
- *High density:* speed of sound conformal limit $c_s^2 \rightarrow 1/3^-$



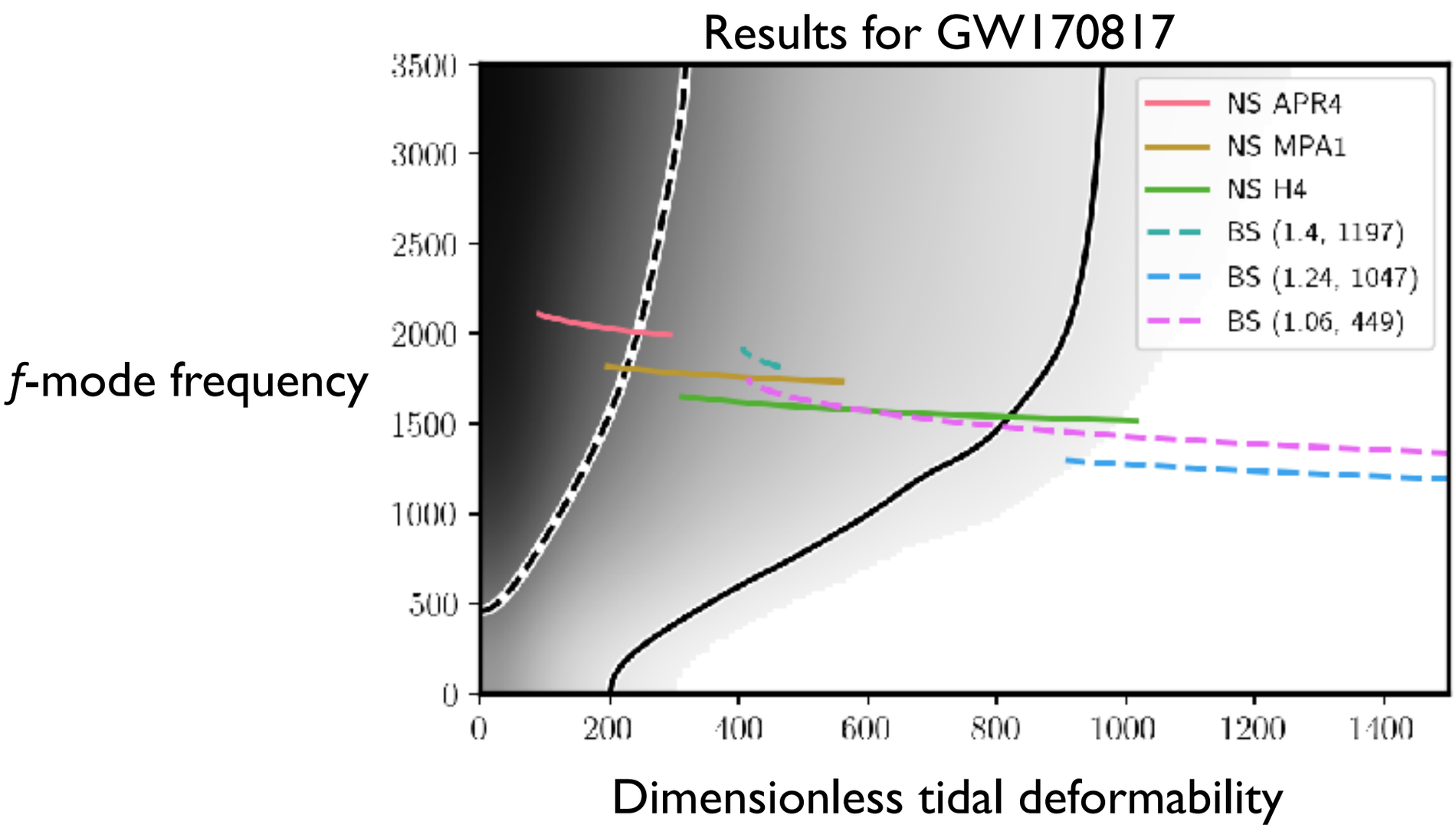
Measure of information gain vs. density

~ 1.4 M⊙ NSs - extremely high densities not probed

Raaijmakers, Greif, Riley, TH, Hebeler, Schwenk, Watts, Nissanke, Guillot, Lattimer, Ludlam ApJ.Lett. 893 (2020)

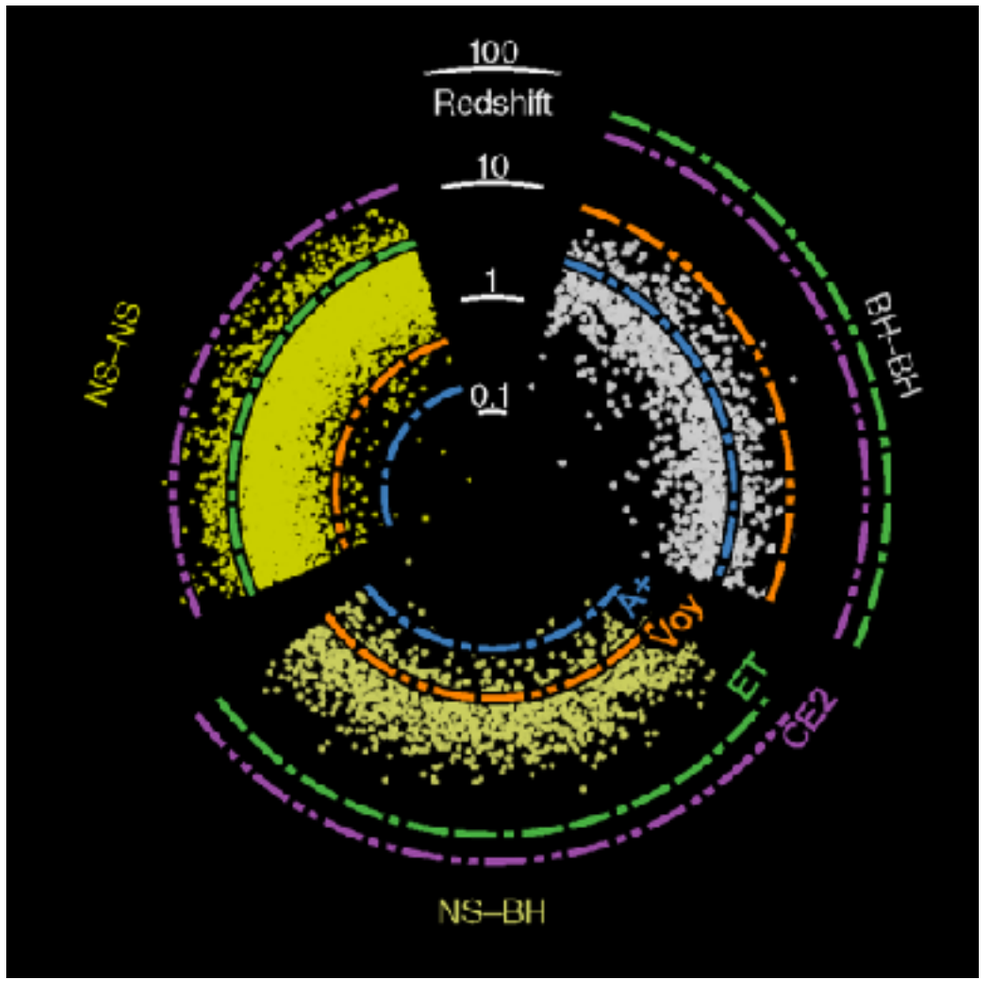
GW constraints on *f*-mode frequency

- Measuring both λ and ω_f (@ quadrupole & octupole for each NS - 8 matter parameters total)
- using an approximate efficient frequency-domain model [Schmidt, TH 2019]



Pratten, Schmidt, TH 2020

Planned detector developments



Next observing run O4 to start ~ mid-2022

(Near/reaching design sensitivity)

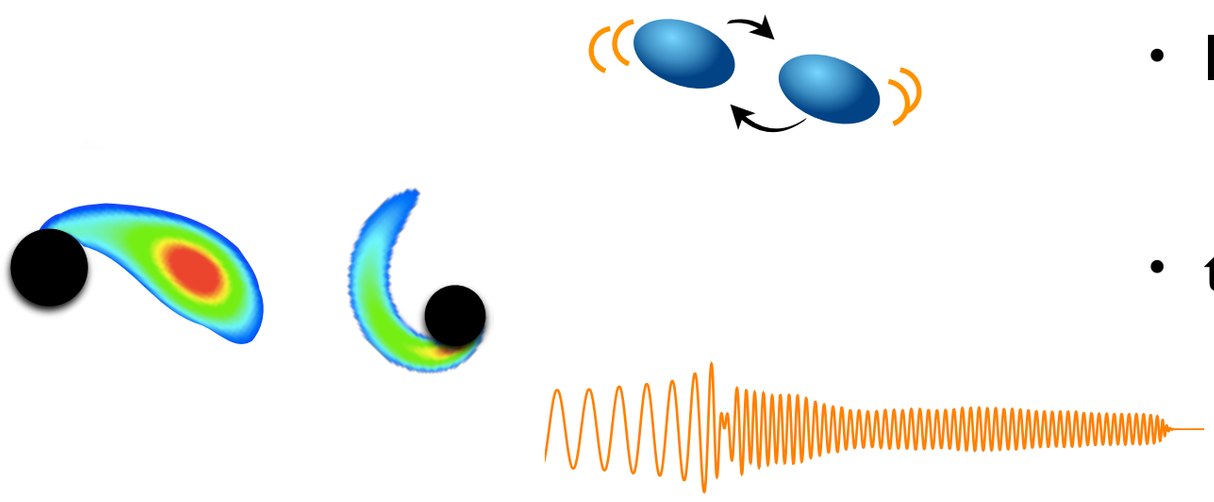
Further upgrades in mid-2020s

2030s (?): 3G detectors *(Einstein Telescope, Cosmic Explorers)*:

10x better sensitivity, wider bandwidth

More accurate measurements of nearby sources,

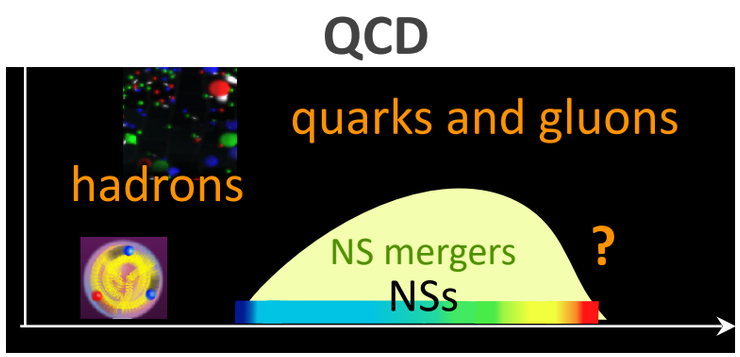
greater number & diversity of events

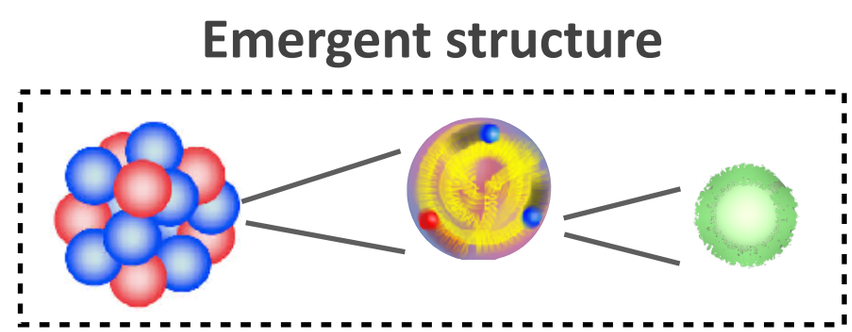


- map out tidal deformability vs mass
- look for subdominant effects
  - GW spectroscopy of NSs during inspiral
- tidal disruption/merger/postmerger

Conclusions

Neutron stars are unique testbeds for important questions in subatomic physics





- Progress and prospects for exploring them with GWs
- Significant further effort on accurate theoretical modeling required
- Important interdisciplinary connections, e.g. with
    - astronomy (NICER, radio, EM counterparts …)
    - experiments (neutron rich nuclei, heavy ion collisions, …)
    - theoretical advances (nuclear, QCD, …)