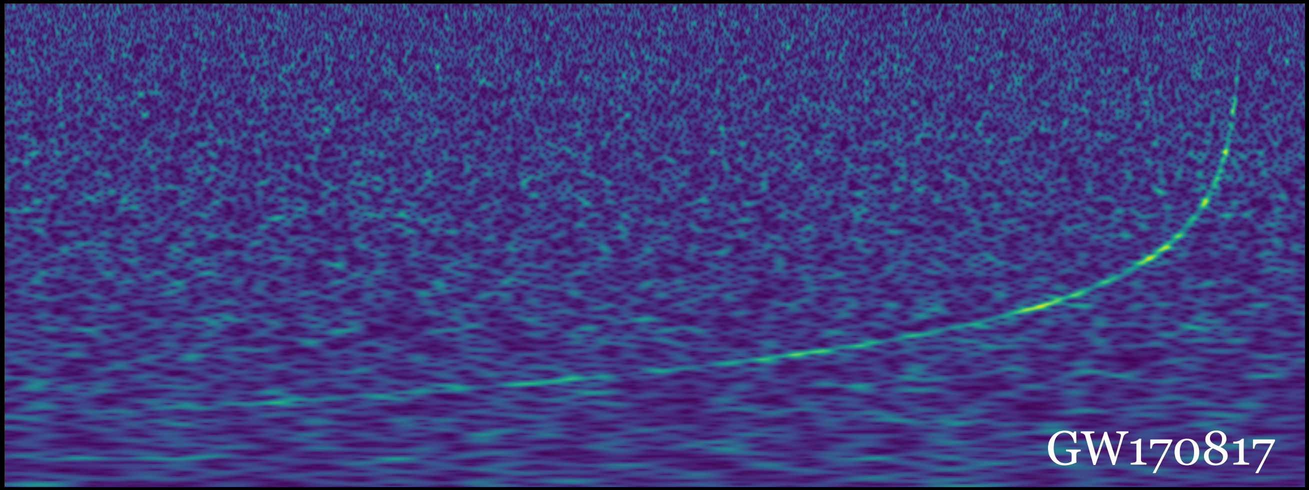
Neutron stars

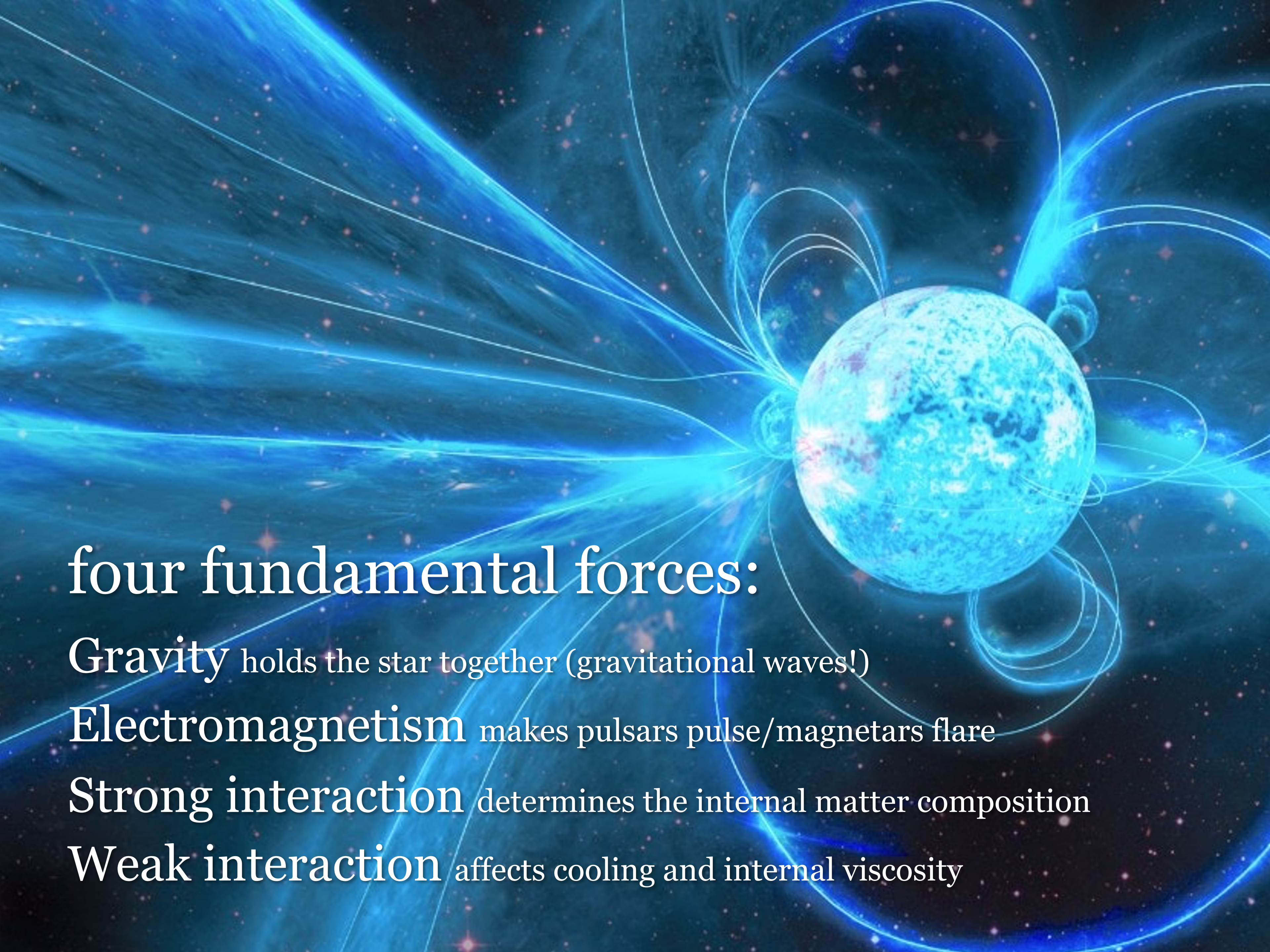
exploring the extremes of matter



Nils Andersson

STAG RESEARCH CENTRE

University of Southampton



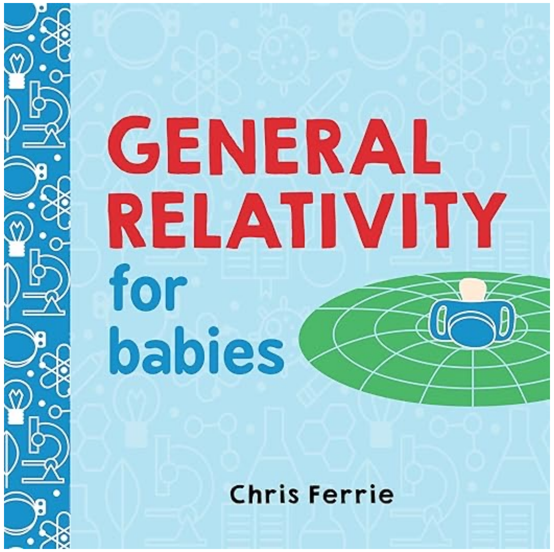
four fundamental forces:

Gravity holds the star together (gravitational waves!)

Electromagnetism makes pulsars pulse/magnetars flare

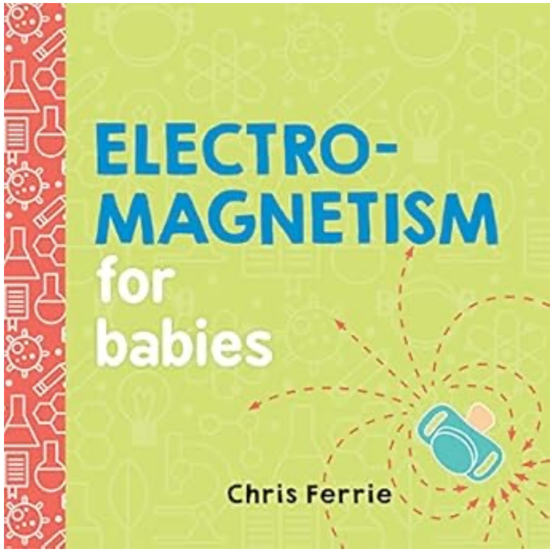
Strong interaction determines the internal matter composition

Weak interaction affects cooling and internal viscosity



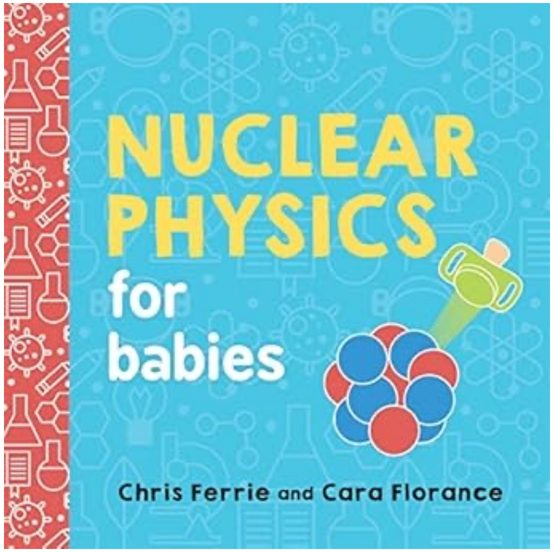
GENERAL RELATIVITY
for
babies

Chris Ferrie



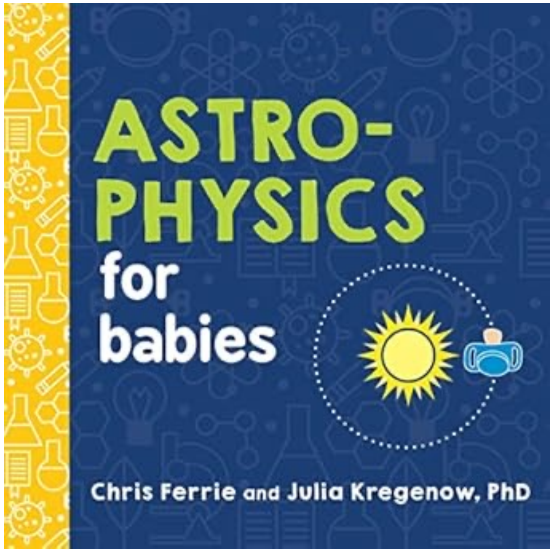
ELECTRO-
MAGNETISM
for
babies

Chris Ferrie



NUCLEAR
PHYSICS
for
babies

Chris Ferrie and Cara Florance



ASTRO-
PHYSICS
for
babies

Chris Ferrie and Julia Kregenow, PhD

seven states of matter?

Solid The outer kilometer of the star freezes to form an elastic crust.

Liquid The star's core remains fluid & accreted matter forms an ocean.

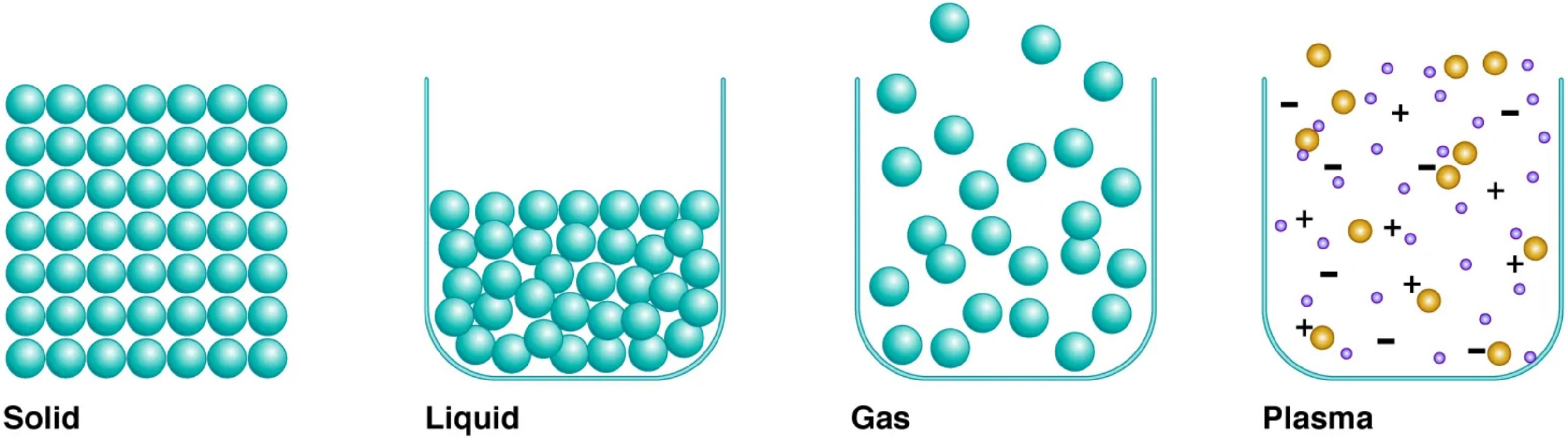
Gas There is a dilute atmosphere.

Plasma The star's exterior is dominated by an electron-positron plasma.

Quark-gluon plasma Neutrons and protons disintegrate.

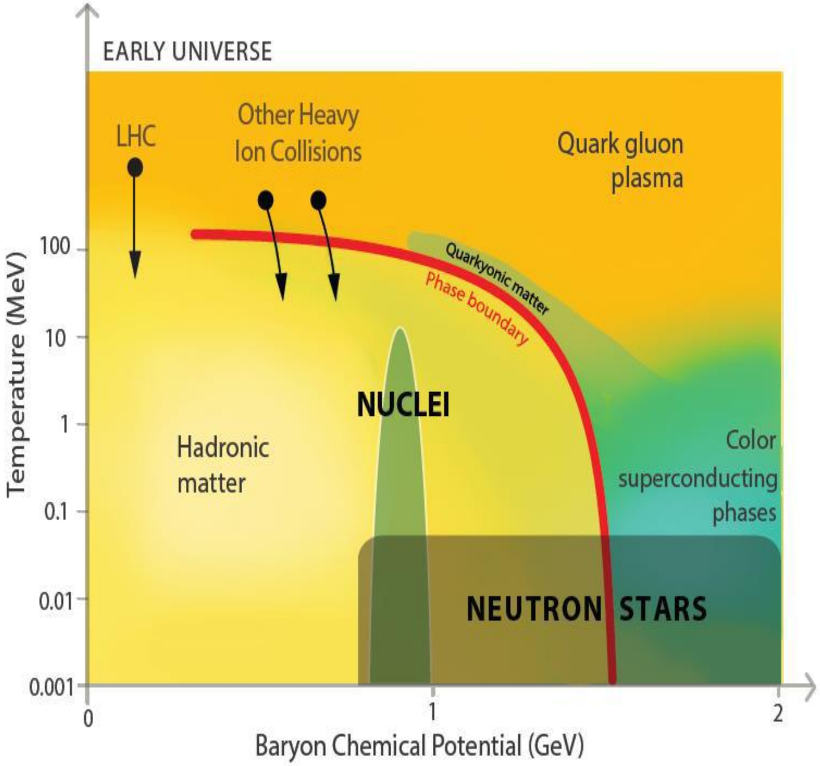
Superfluid The star's core is cold enough for neutrons to be superfluid.

Superconductor At high densities, protons form a superconductor.



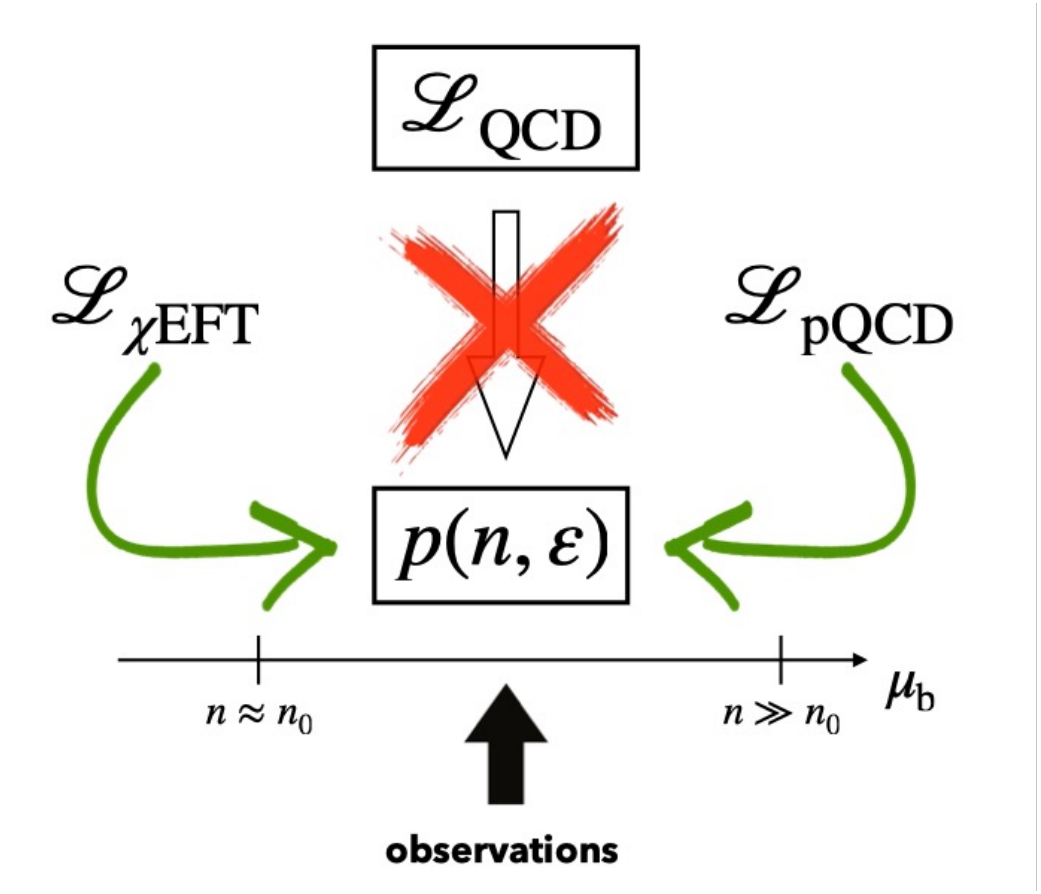
equation of state

The macroscopic diagnostic of microscopic many-body interactions is a pressure-density-temperature relation for matter in chemical and thermodynamical equilibrium – colloquially: **the equation of state.**



First principles calculations for many-body QCD systems are “problematic” at high densities (sign problem).

Have to (at some level) resort to “phenomenology” – parameterise the ignorance!

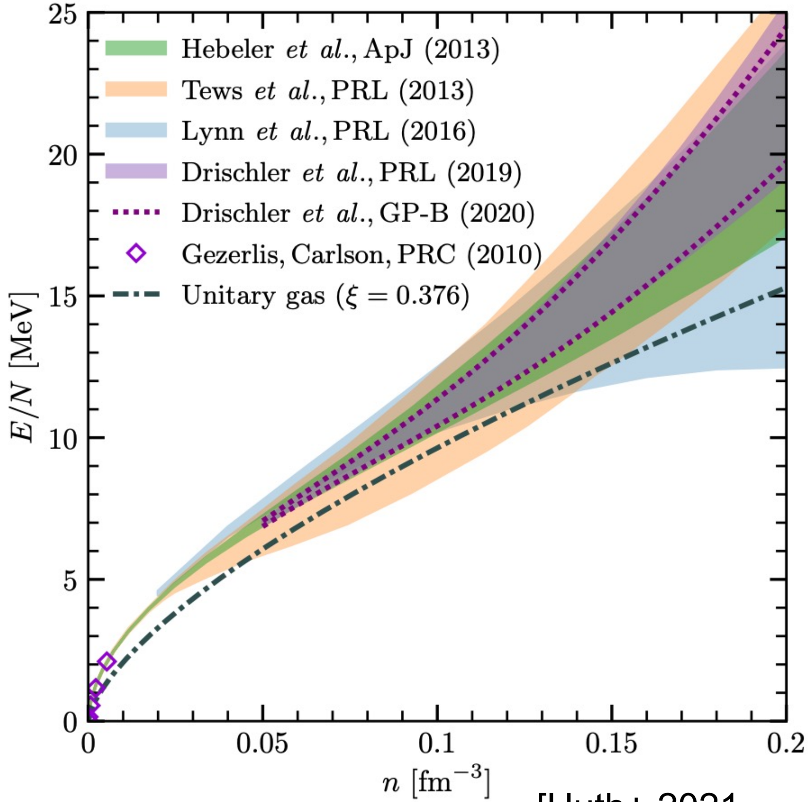


Need experiments and observations to test theory and drive progress!

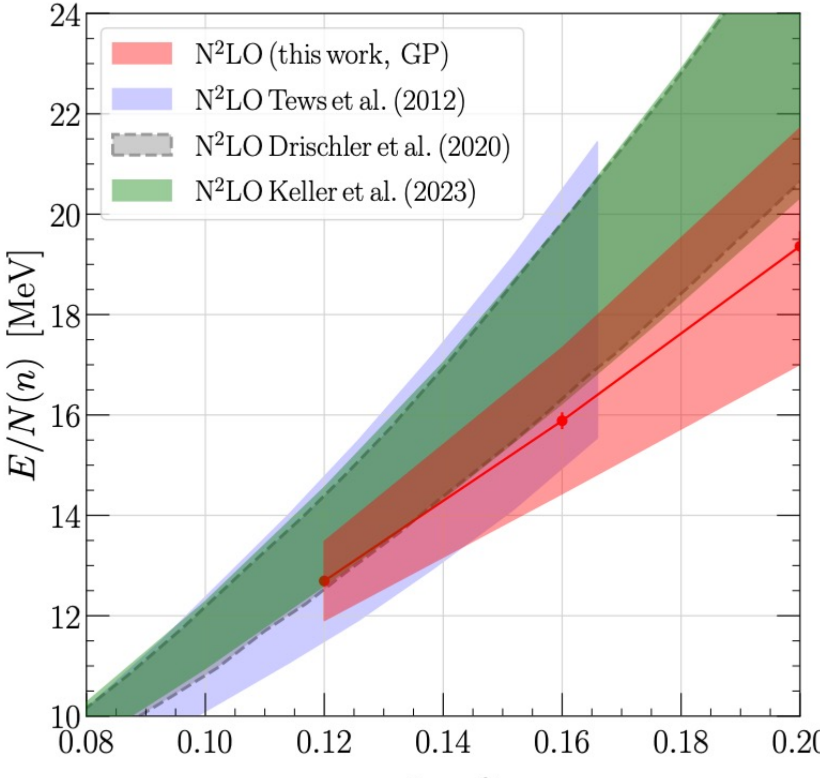
chiral EFT

Progress in **chiral effective field theory** provides important low-density constraint.

Key feature is that the calculations come with “error bars”.

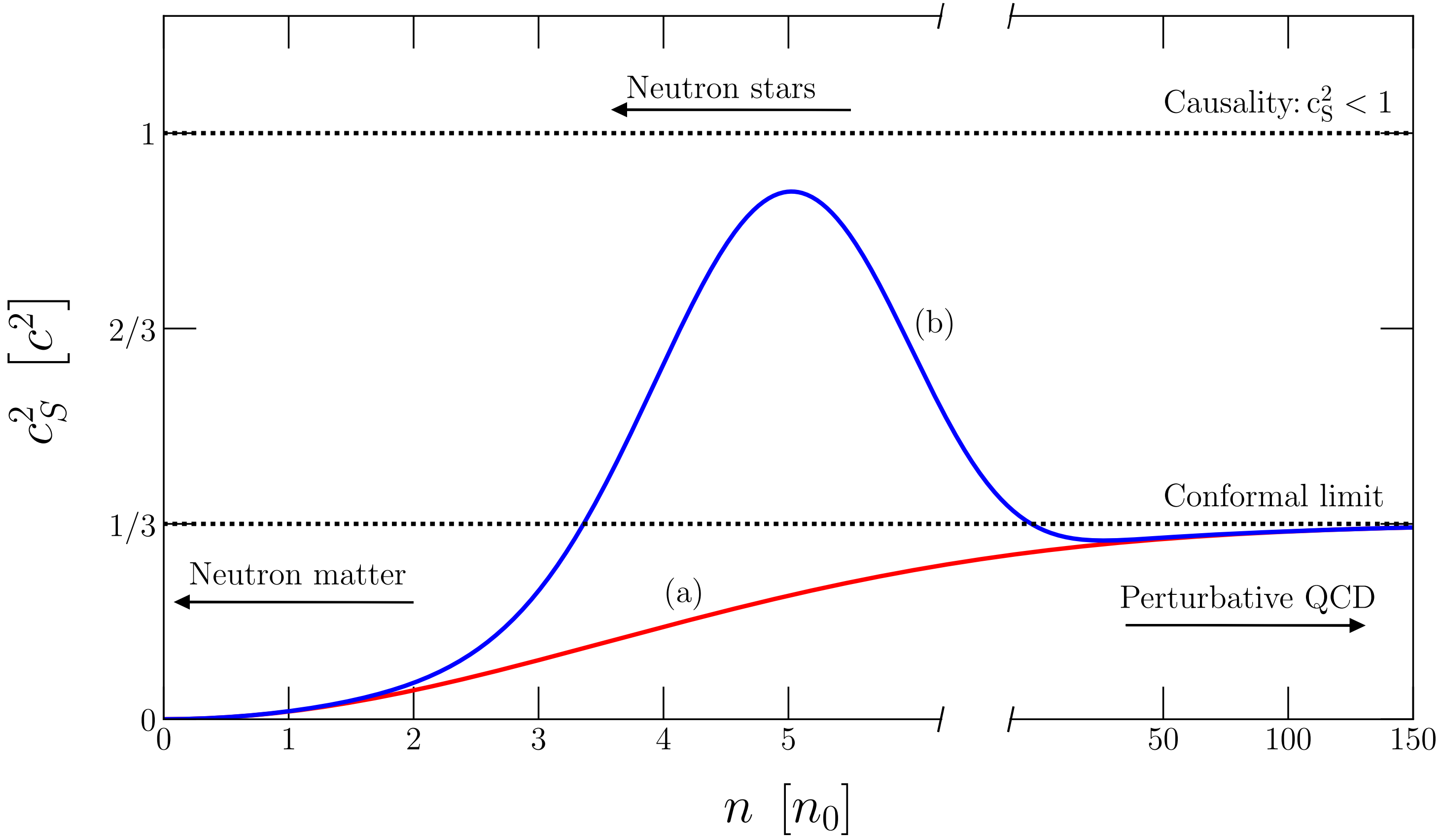


[Huth+ 2021]

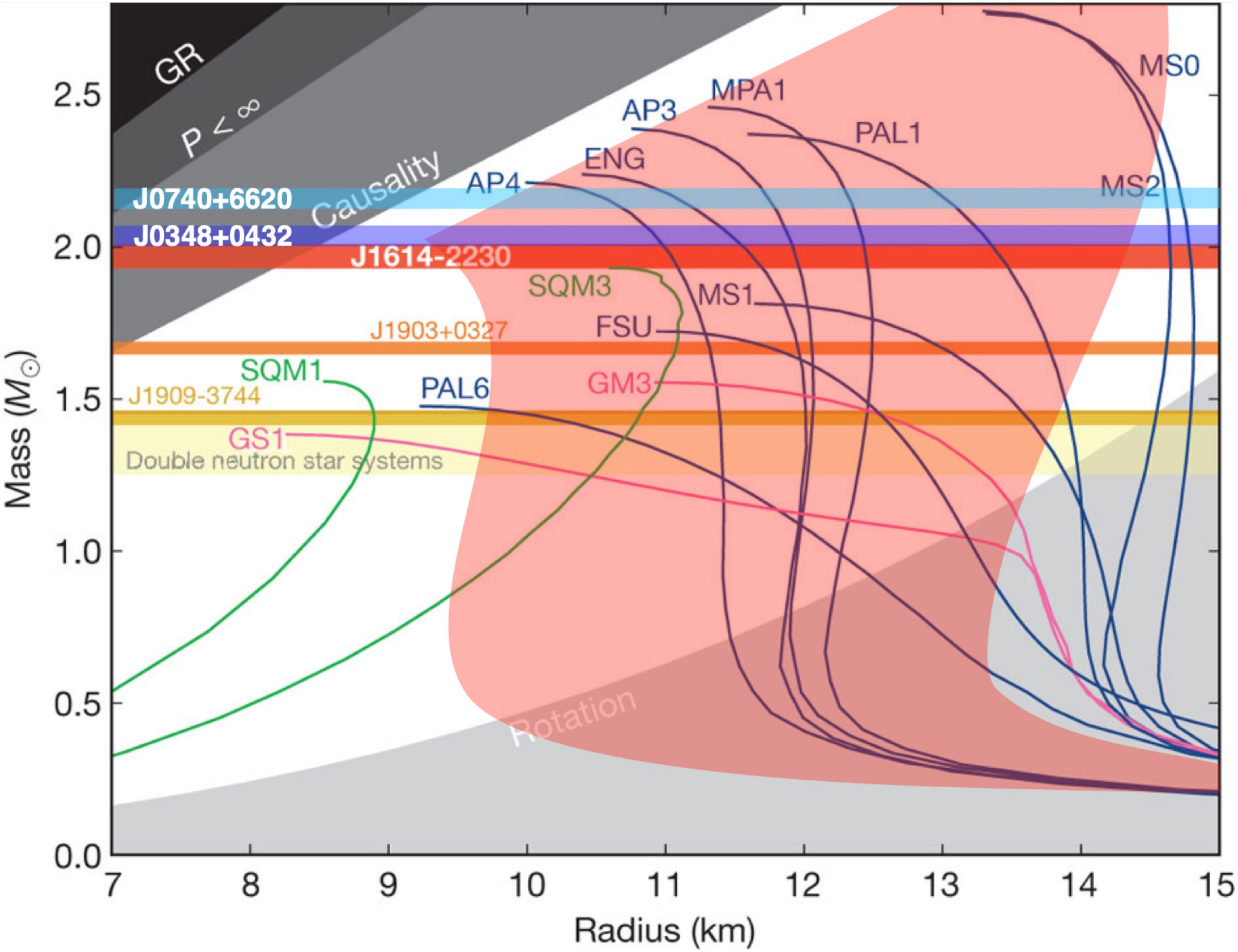


[Tews+ 2024]

Choice of “parameterisations” at high densities, e.g. speed of sound, polytropes…

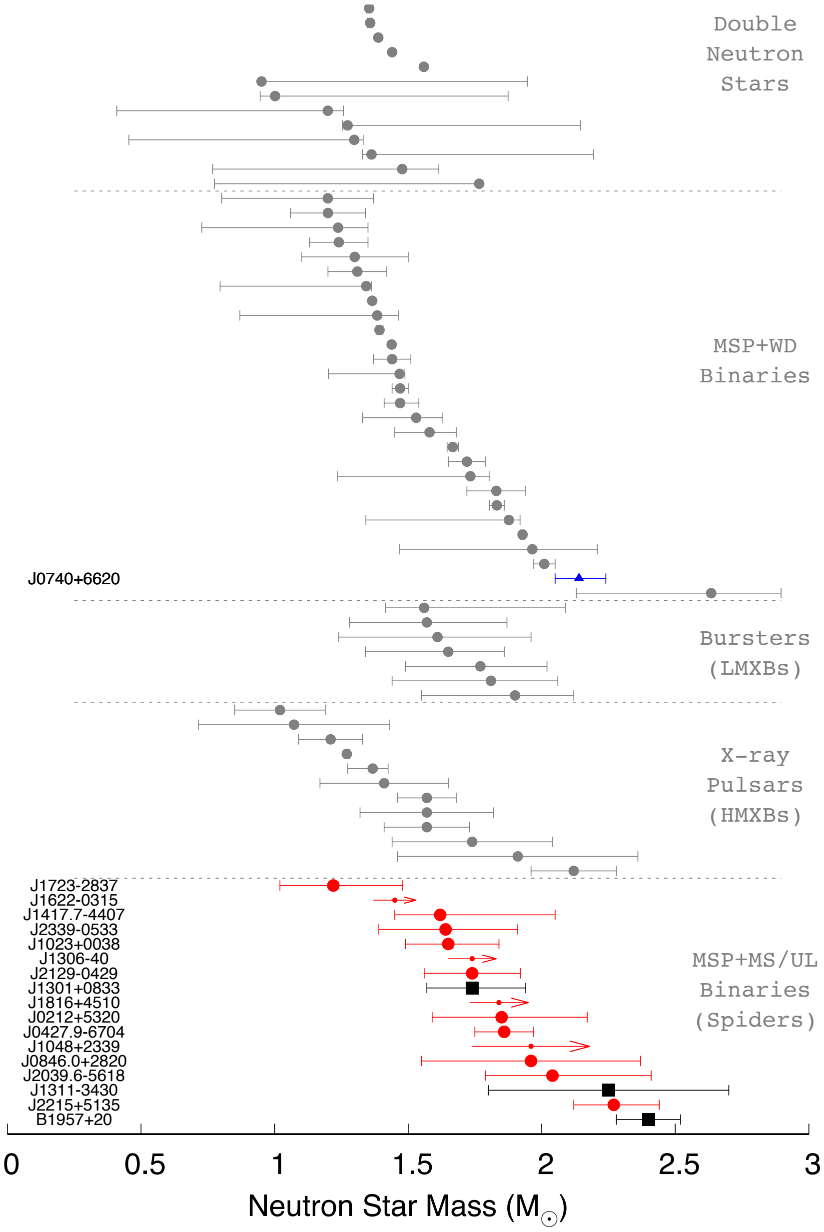


Different models predict distinct **mass-radius relations**.



[adapted from Antoniadis et al]

mass



[borrowed from Linares]

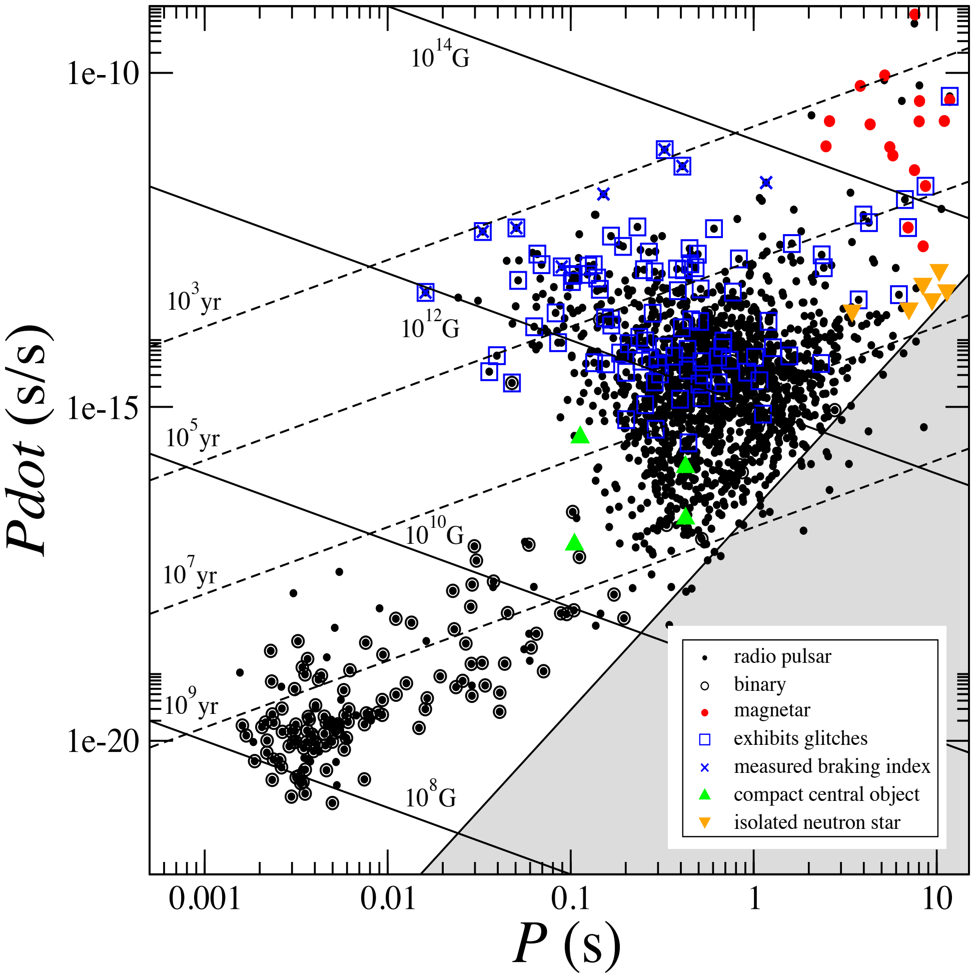
Masses deduced from binary dynamics tend to lie in a relatively narrow range, about 1.1-1.6$M_\odot$. Do not constrain nuclear physics (much).

Example: PSR J0348-0432 with a WD companion and a mass just over 2$M_\odot$.

Observation of ”Spiders” suggest even more massive NS?

Tricky systematics...

spin



The most precisely determined parameters are the spin and the spin-down rate.

Different classes of neutron stars populate different parts of the P-P-dot diagram.

Infer the star's magnetic field (or the star's "age")

$$B^2 \sim P\dot{P}$$

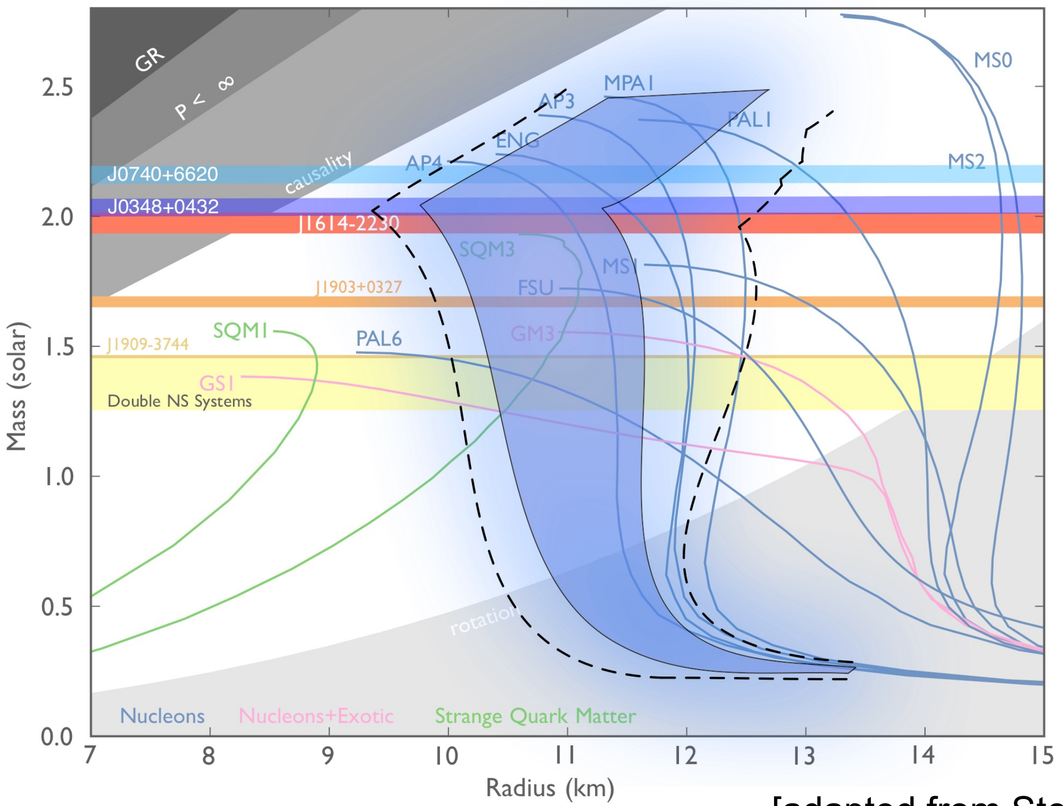
Sanity check provided by the "braking index". However, braking indices are not exactly 3, so we are missing something.

Why do we not see neutron stars spinning close to the break-up limit?

radius

The radius is “difficult” to infer from radio data (moment of inertia?), but progress has been made using observed x-ray observations.

Construct “empirical” equation of state (from Bayesian analysis) based on a combination of systems exhibiting type-I x-ray bursts with photospheric radius expansion and transient low-mass x-ray binaries.



[adapted from Steiner]

Constrains the radius of a canonical neutron star to (conservatively) the range 10-14 km.

The data is beginning to impact on the nuclear physics...

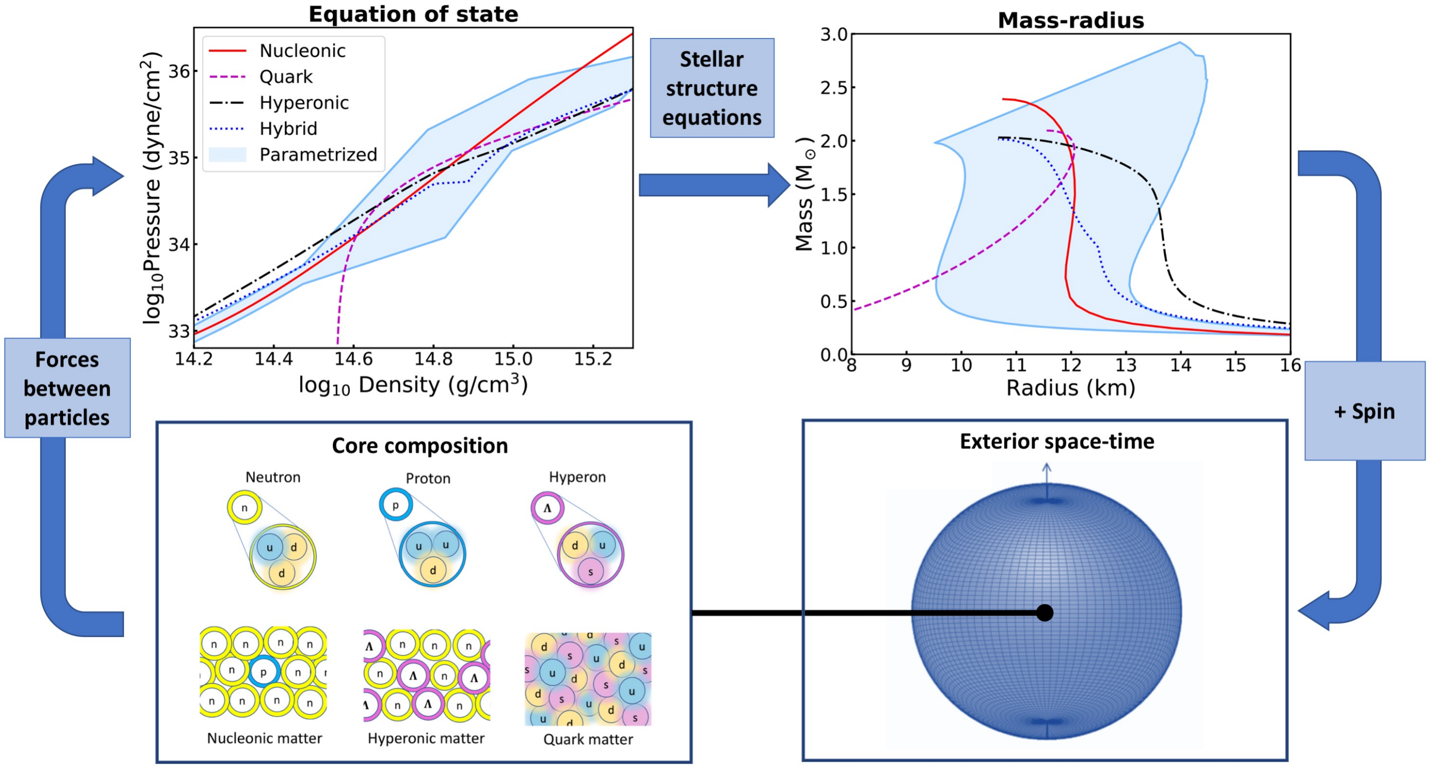
... but, again, the systematics are tricky.

NICER

NICER has been taking data since June 2017.

Aim to measure accurate pulse profiles associated with non-uniform thermal surface emission of rotation-powered pulsars.

Comparison to theory models yields the stellar compactness, and – assuming the mass is known – the star's radius.



Equation of state

Stellar structure equations

Mass-radius

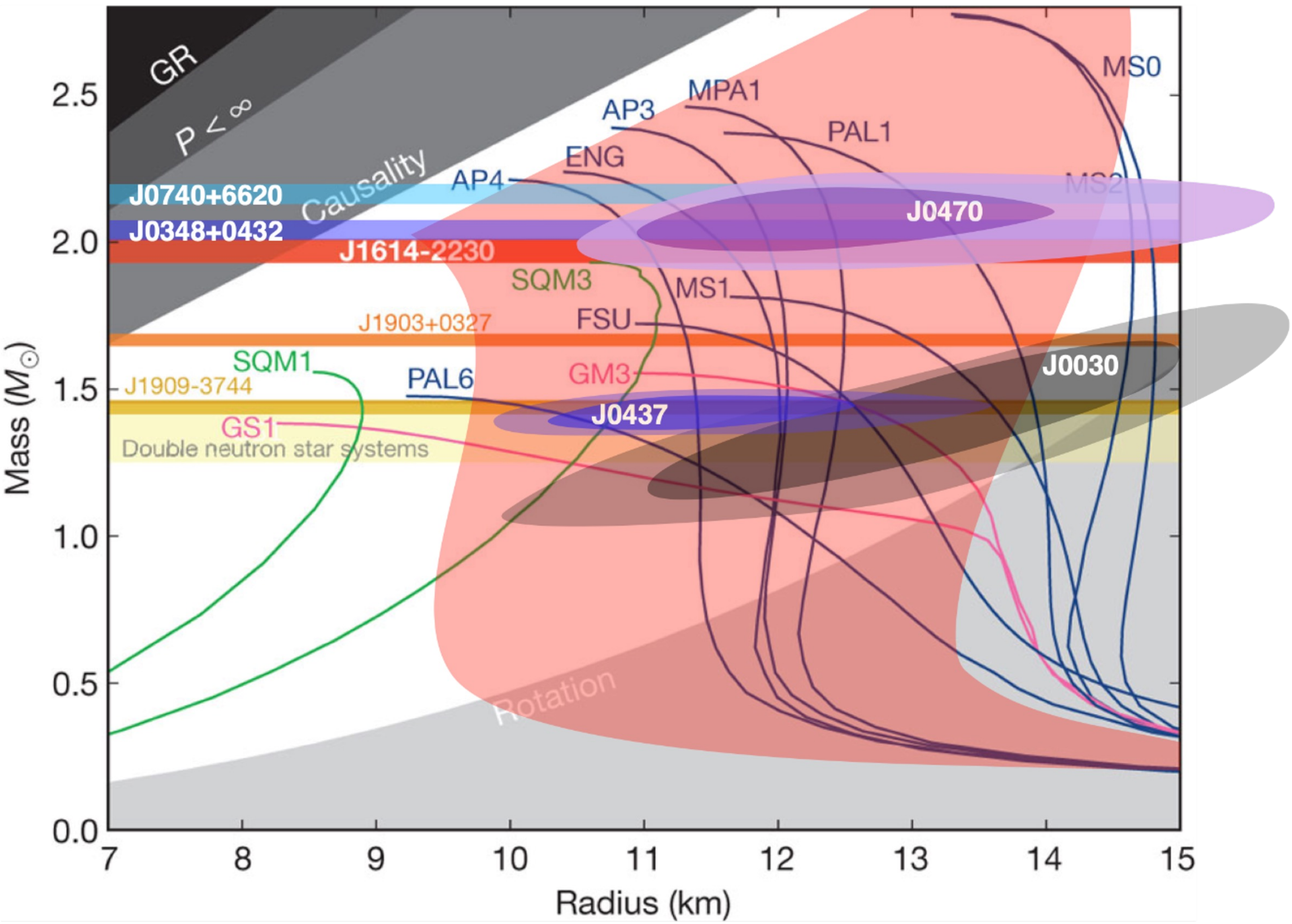
+ Spin

Forces between particles

Core composition

Exterior space-time

[borrowed from Anna Watts]

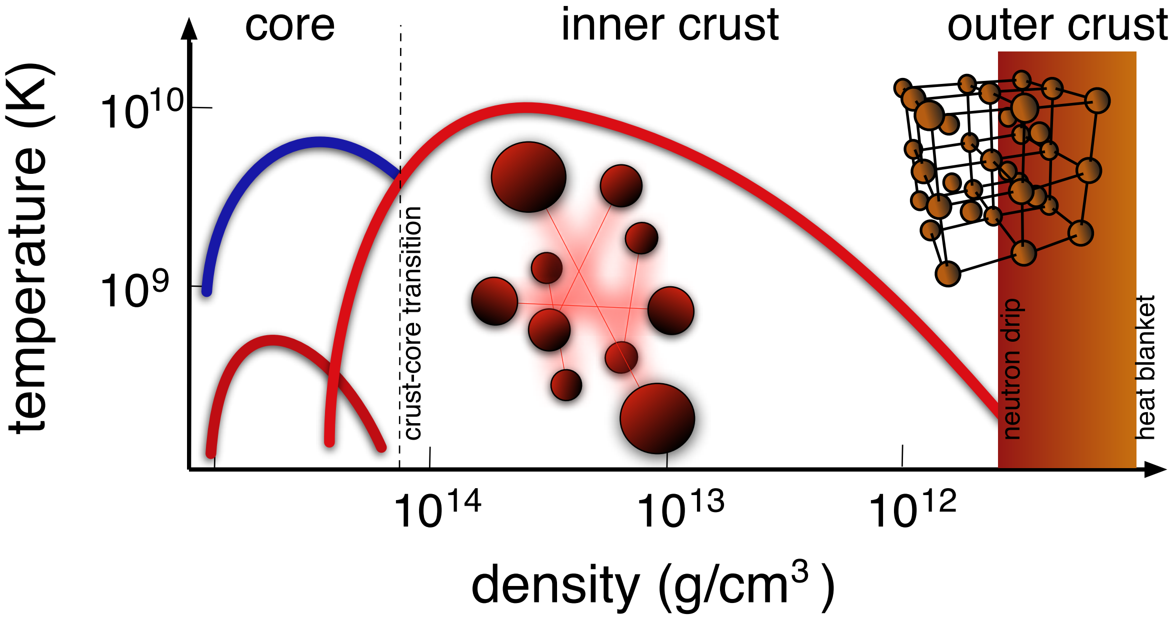


[adapted from Watts]

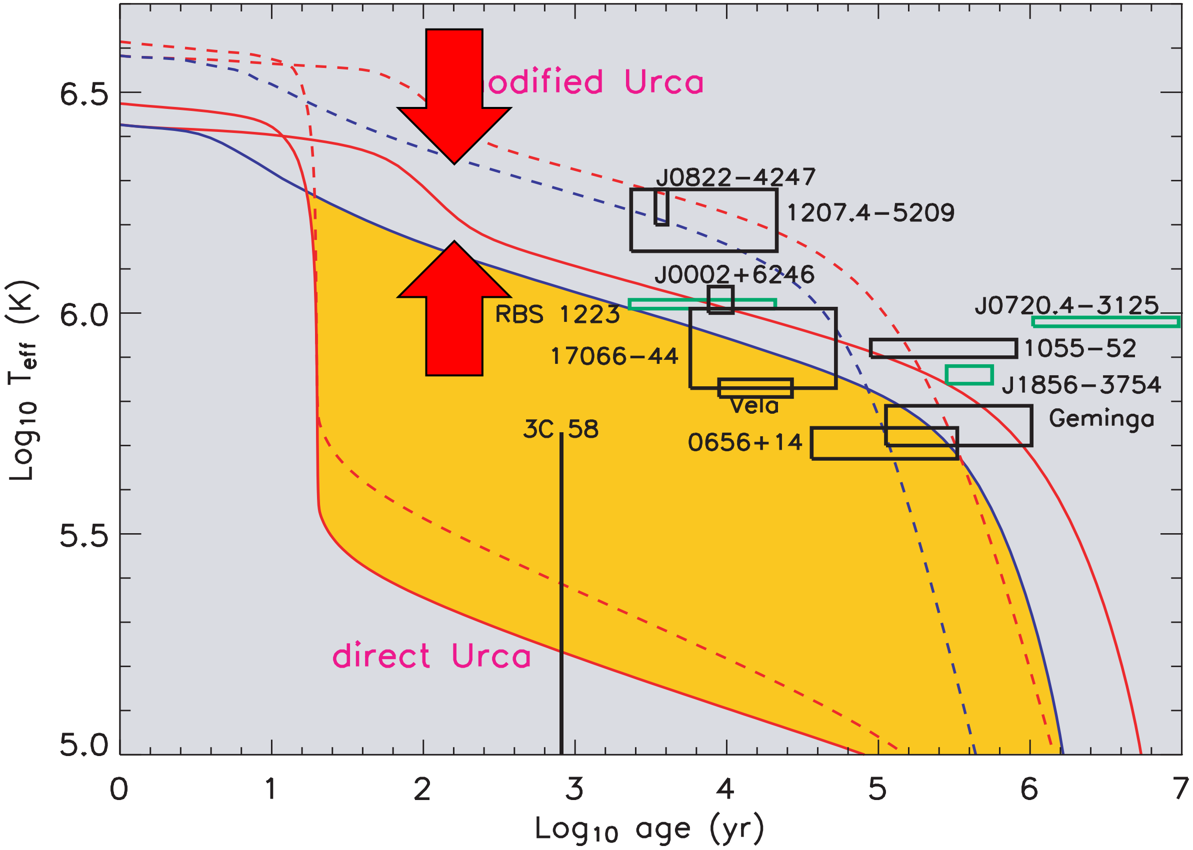
temperature

A neutron star cools rapidly (due to Urca reactions) after birth.

Mature systems are “cold” (10^8K<< T_{Fermi}=10^{12}K) so they **should be** either solid or superfluid.

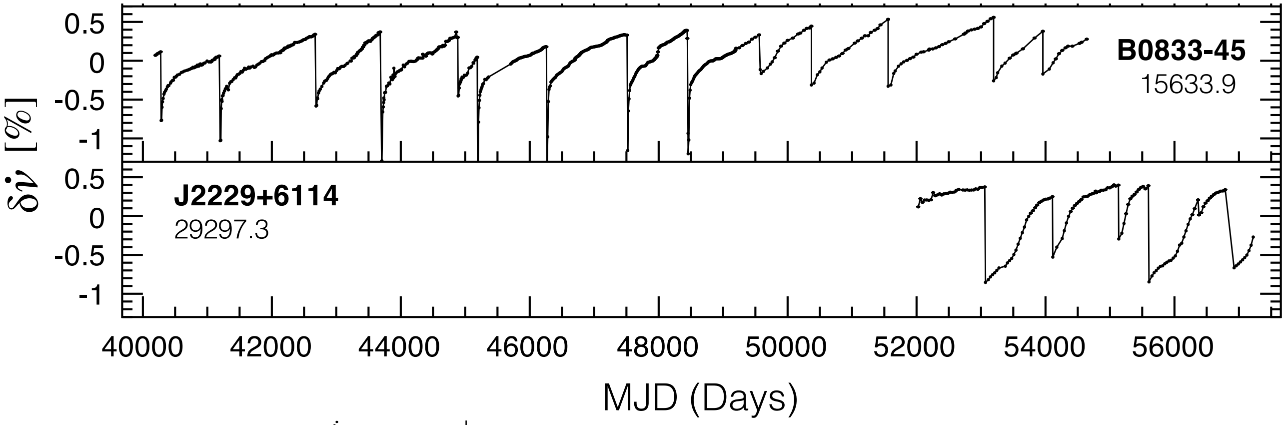


Neutron star superfluidity anticipated since late 1950’s; nuclear physics calculations indicate “BCS-like” pairing gaps for neutrons and protons.



Observational evidence for superfluidity from;

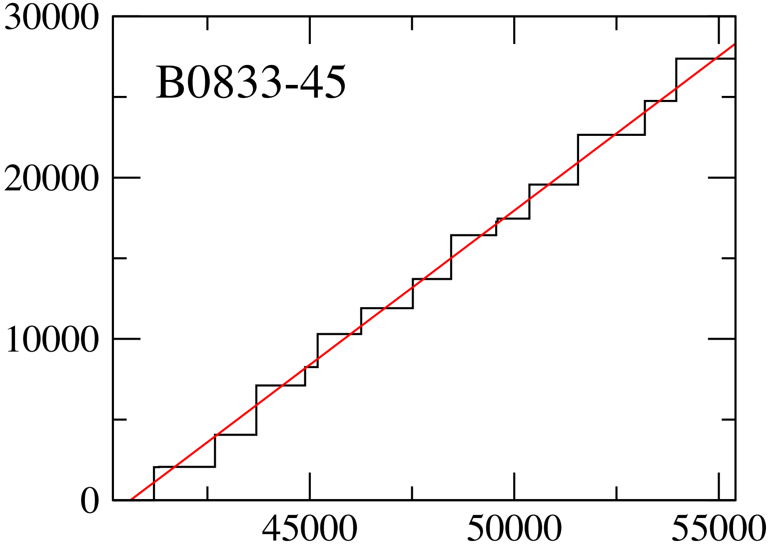
- cooling (the “curious case” of the Cas A remnant)
- thermal “recovery” in accreting transients
- pulsar timing variability (glitches, explained at “cartoon” level)



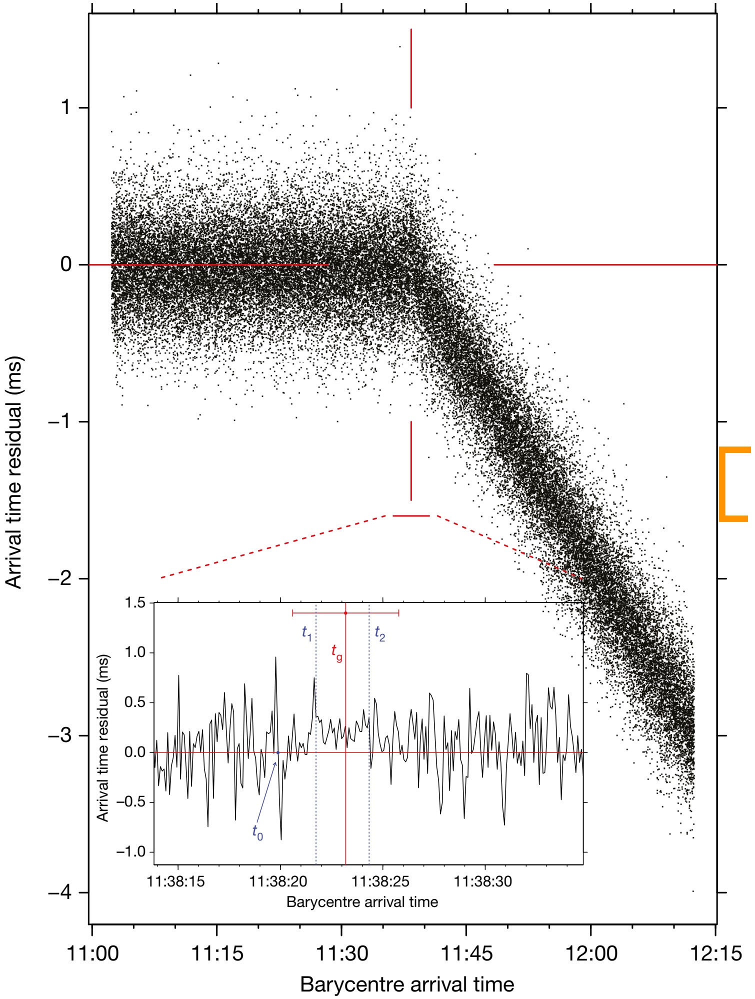
For regular glitchers one can estimate the superfluid inertia.

Need to involve up to 2% of the total moment of inertia.

The crust superfluid model accords with observations as long as we do not worry about the **entrainment**.



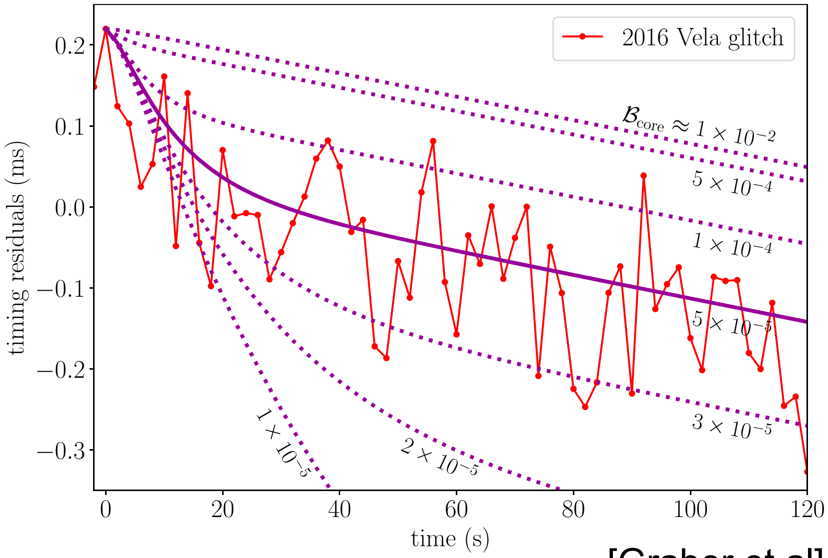
Vortex mutual friction is key to modelling glitch dynamics as it dictates the timescales involved.



[Palfreyman et al]

Example: The “resolved” Vela glitch from 2016.

The fast glitch rise (< 40s) and subsequent relaxation, provide an opportunity to contrast different models for the mutual friction.



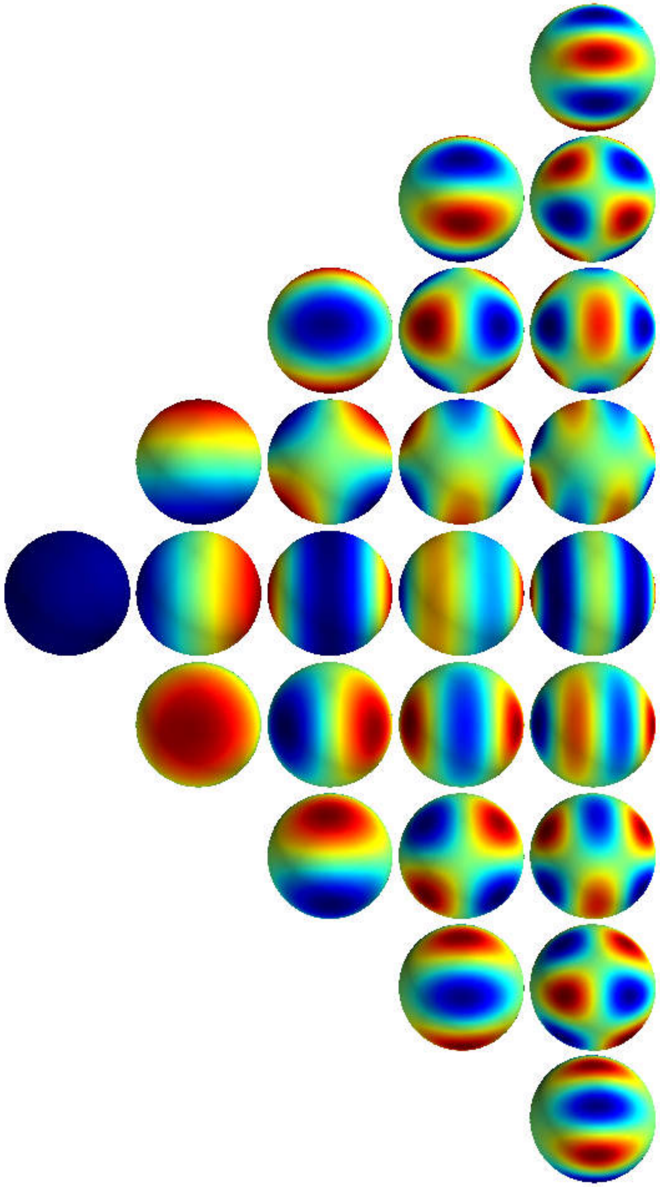
[Graber et al]

seismology

A neutron star has a rich spectrum of oscillation modes.

Different classes of waves depend (sometimes quite sensitively) on distinct pieces of physics, making "**asteroseismology**" a promising strategy for probing the composition and state of matter in the star's core.

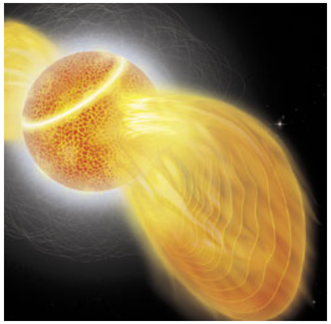
In order to lead to observable effects, the modes must be excited to large amplitude: **transients/instabilities/tides…**



From the GW perspective we need global modes which involve significant density variations.

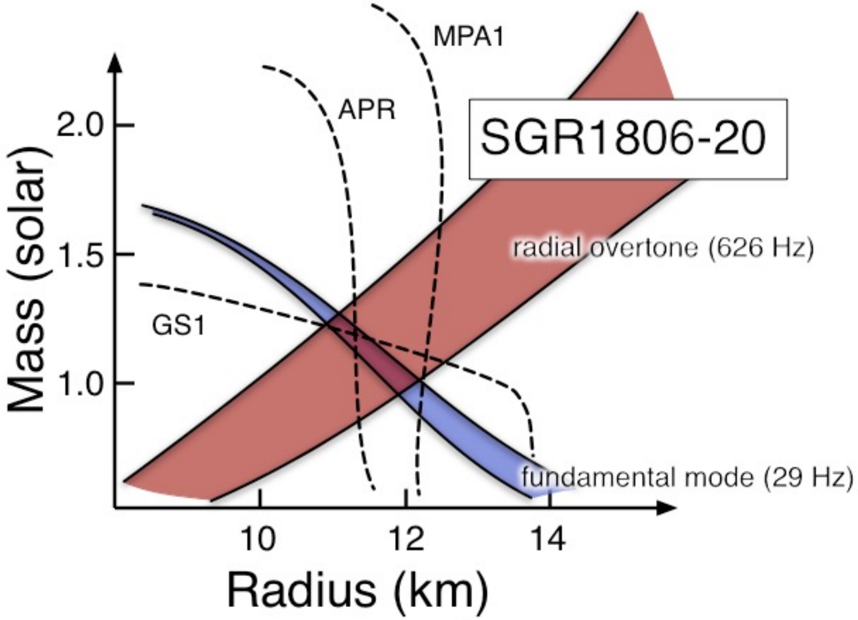
- **f-mode**: Fundamental oscillation of the star; scales with the average density, $\omega_n/(2\pi) \sim \sqrt{\frac{GM}{R^3}} \sim 1 - 2\mathrm{kHz}$
- **p-modes**: Restored by the pressure of the fluid (speed of sound); higher frequencies
- **g-modes**: Restored by buoyancy associated with temperature/composition gradients (frozen composition); lower frequencies, $\omega_n/(2\pi) \sim 100\mathrm{Hz}$.
- **inertial modes** (including the **r-mode**): Restored by rotation; may be driven unstable by GW emission; $\omega_n \sim \Omega$.
- **i-modes**: Associated with (for example) the core-crust interface; may induce crust fractures during binary inspiral and trigger short gamma-ray bursts; $\omega_n/(2\pi) \sim 100\mathrm{Hz}$.

magnetar flares



Observed quasi-periodic oscillations in x-ray tail from magnetar giant flares provide a proof of principle.

If the oscillations are associated with the neutron star crust then the observed spectrum constrains the equation of state.



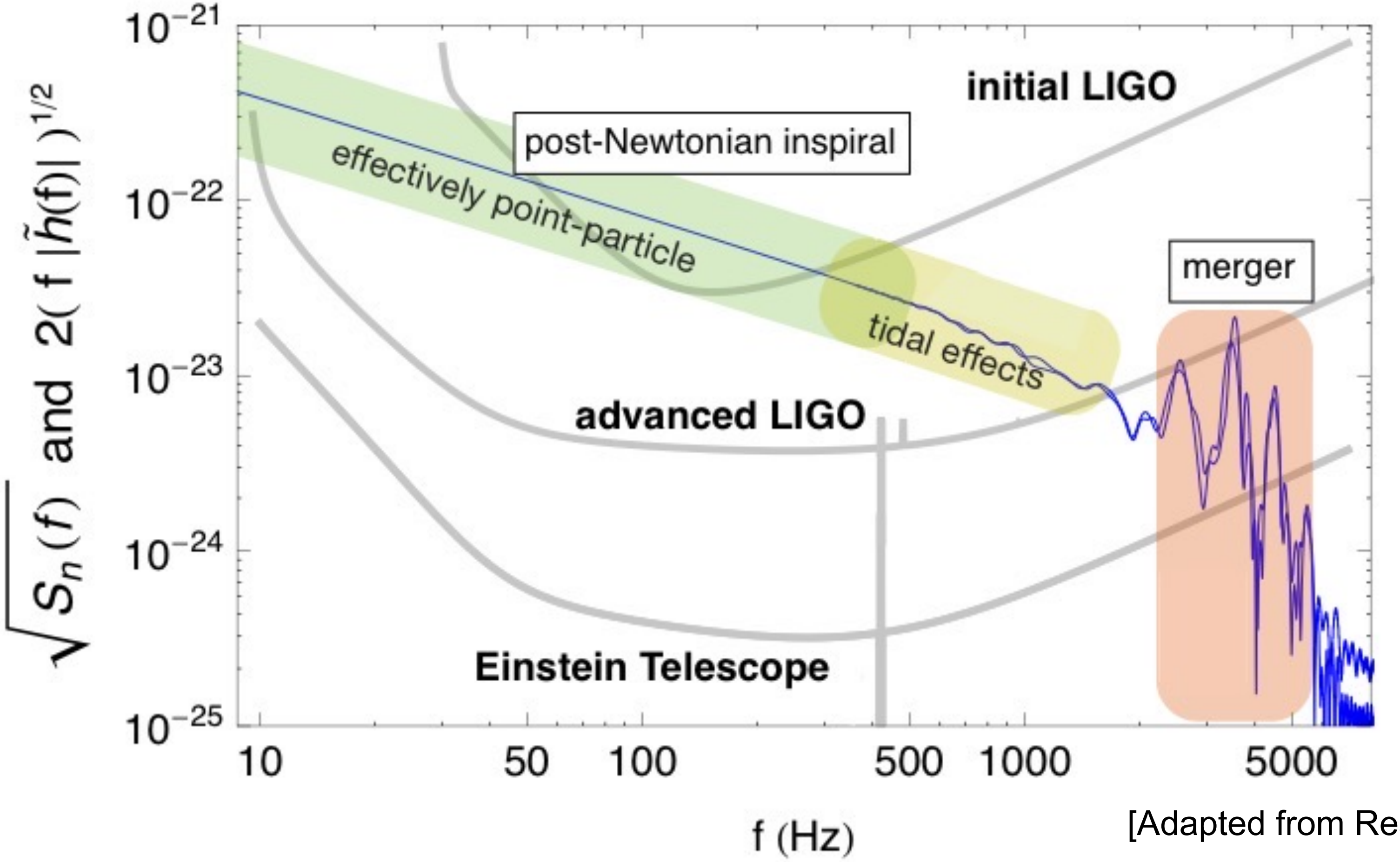
However…

- magnetic field couples the crust to the core (=tricky…)
- the presence of a superfluid component affects the oscillations:

$$\omega^2 \to \tilde{\omega}^2 \approx \frac{x_c}{\chi}\omega^2$$

where χ encodes the **effective mass** of the free neutrons.

binary inspiral

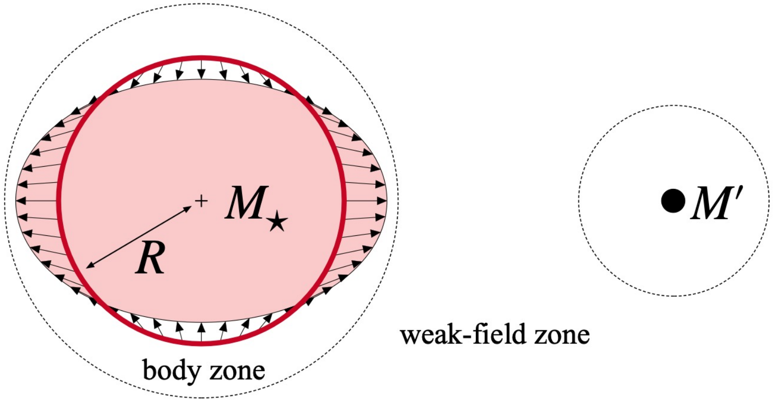


[Adapted from Read]

Gravitational-wave astronomy provides new opportunities.

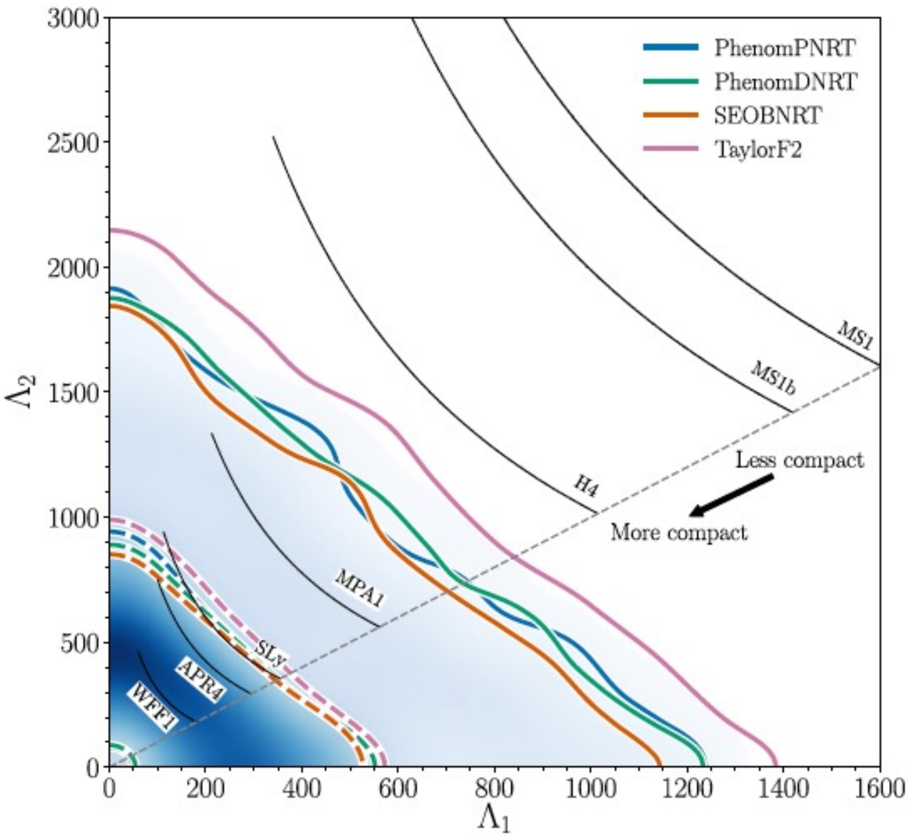
Finite size effects (=tides) become important during the late stages of binary inspiral.

GW signal from binary neutron stars differs from that of black holes due to **tidal deformability**.



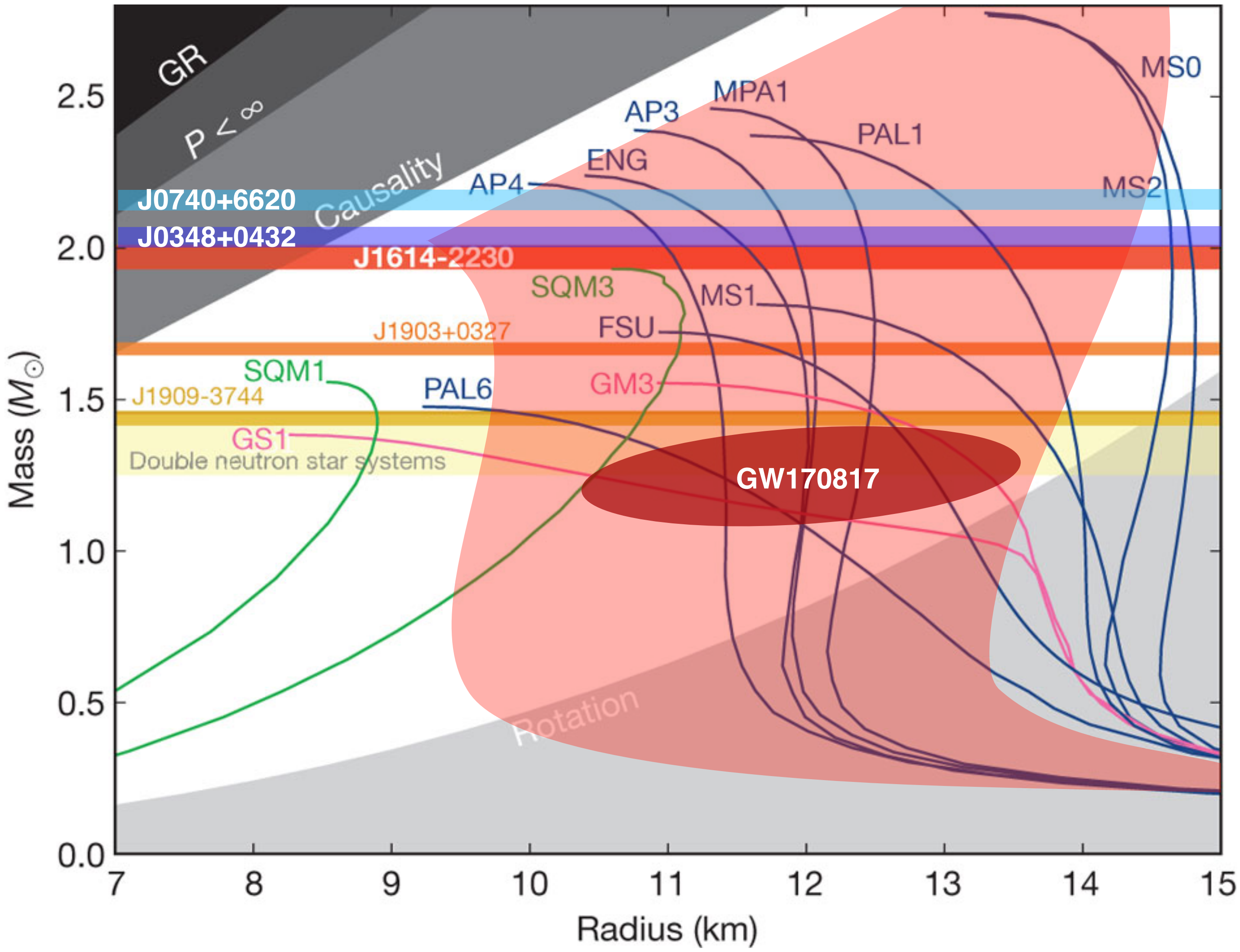
Static tide "enters at 5PN order" through the induced quadrupole moment. Characterised by the **Love numbers**

$$\Lambda_A = \frac{2}{3} k_{2A} \left(\frac{c^2 R_A}{G M_A} \right)^5$$

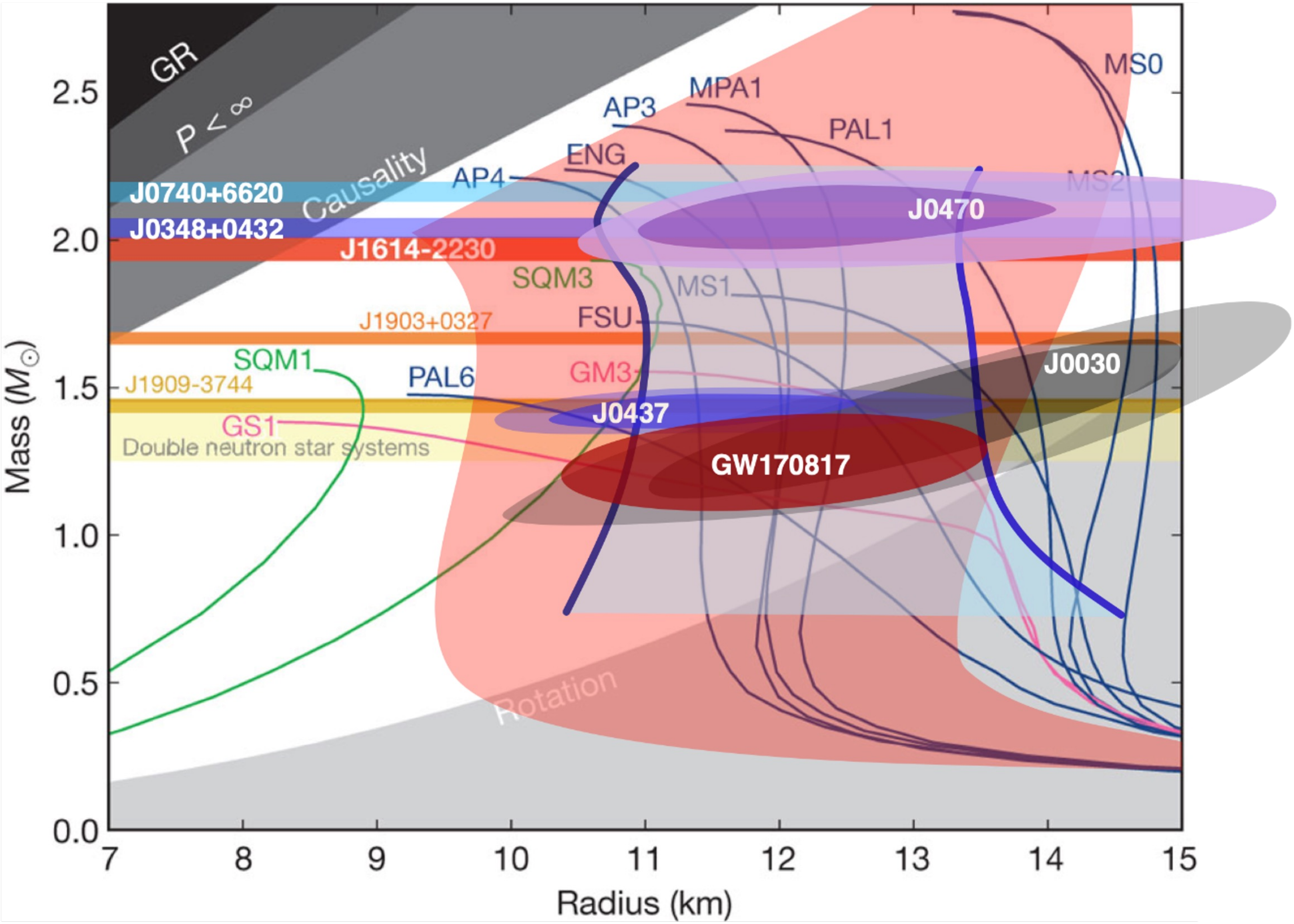


[Abbott+

Small effect: Difficult to alter GW phasing (e.g. 10^{46} erg at 100 Hz leads to shift of 10^{-3} radians).

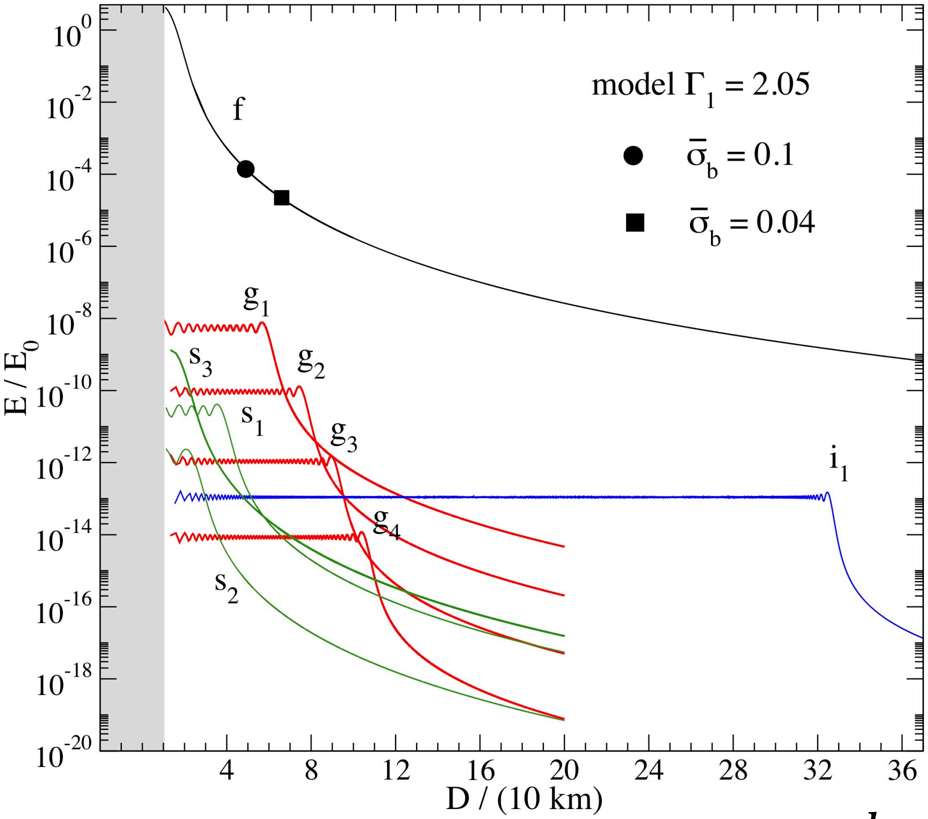


[adapted from LVK]



[adapted from Landry+]

Dynamical tide is represented by resonances with individual oscillation modes.



[Passamonti+]

Again, need “global modes" which involve significant density variations.

Fundamental f-mode induces significant enhancement of tide near merger.

Newtonian overlap integral

$$I_\alpha \equiv \int_0^R \delta\rho_\alpha(r) r^{l+2} dr$$

leads to an "effective" Love number:

$$k_{lm} = \frac{2\pi G}{(2l+1)R^{2l+1}} \sum_{\alpha'} \frac{I_\alpha^2}{\mathcal{A}_\alpha^2[\omega_\alpha^2 - (m\Omega)^2]}$$

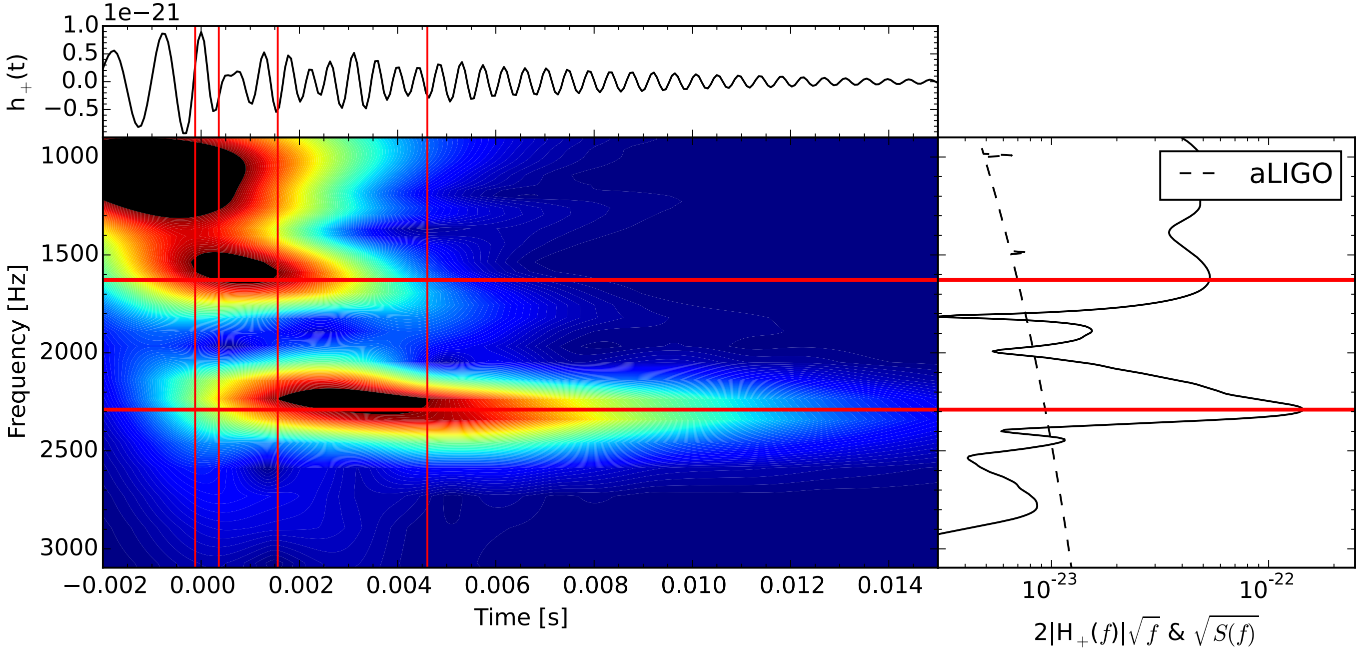
Individual low-frequency resonances encode composition etc.

binary mergers

Post-merger dynamics expected to be within reach of next-generation detectors (Cosmic Explorer+Einstein Telescope).

Requires **nonlinear simulations** with a reliable physics implementation.

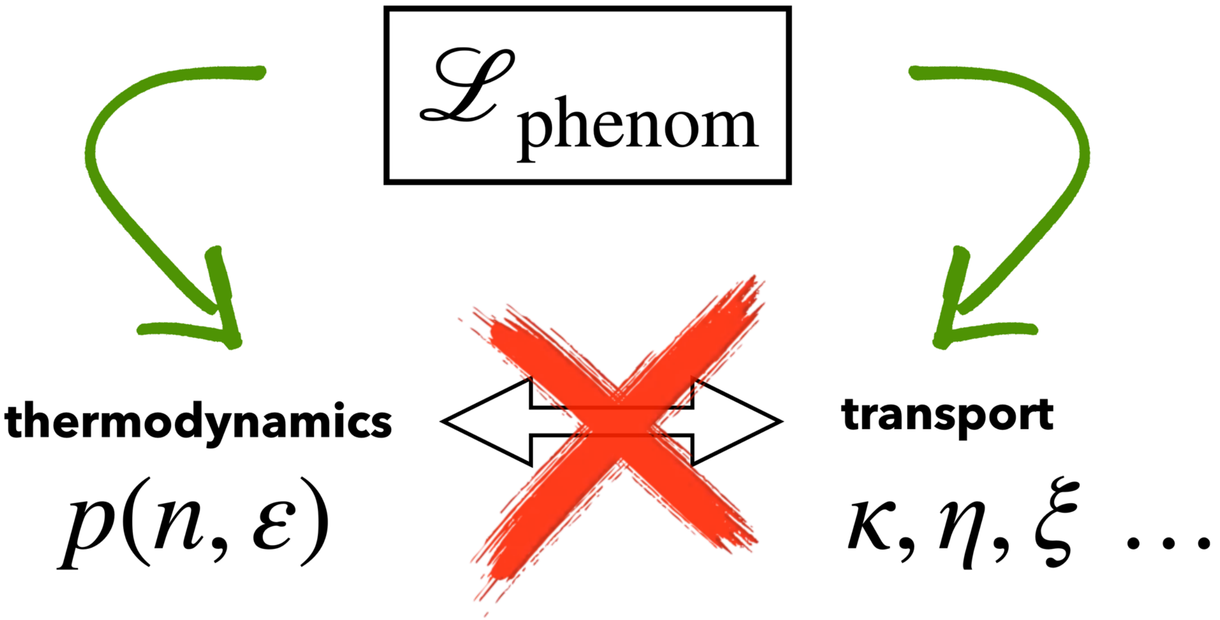
Main observable likely to be peak oscillation frequency of hot remnant.



[Clark et al]

“beyond the EoS”

Merger physics involve non-equilibrium aspects, e.g. transport coefficients associated with reaction rates (bulk viscosity) etc.



$\mathscr{L}_{\text{phenom}}$

thermodynamics

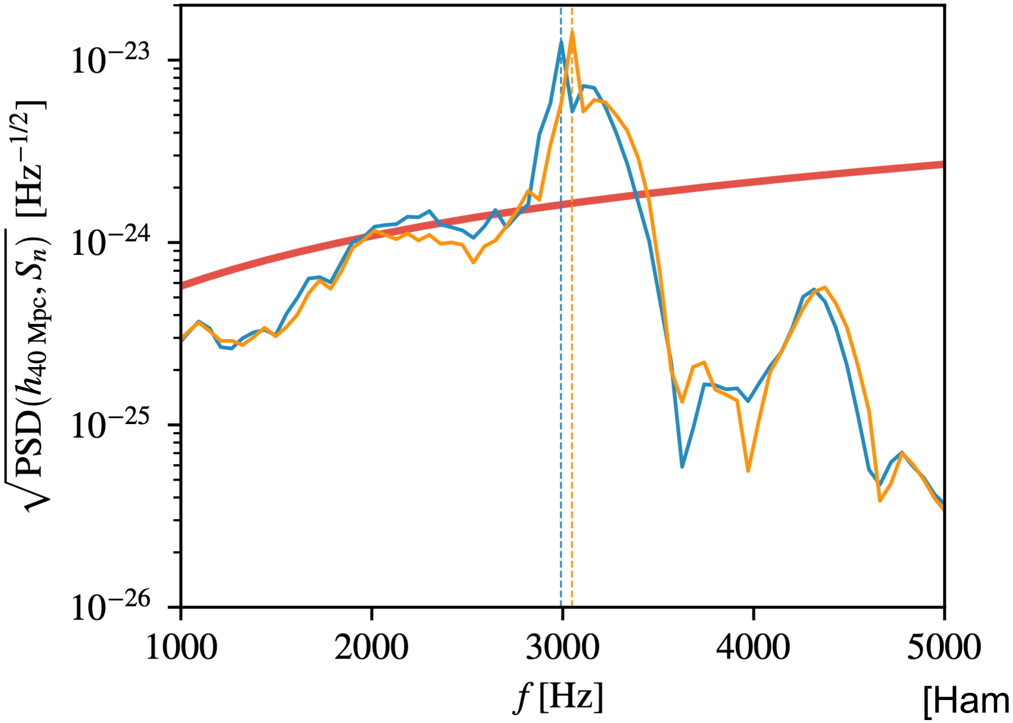
$p(n, \varepsilon)$

transport

$\kappa, \eta, \xi \ \ldots$

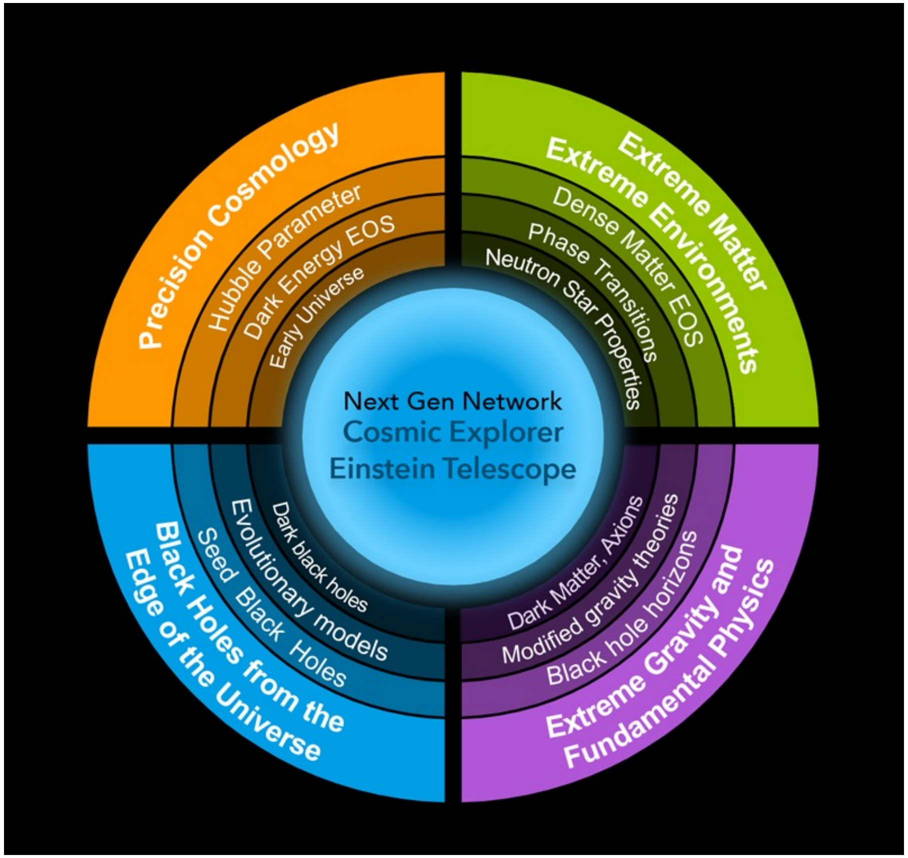
Starting from a 3-parameter model $p = p(n, \varepsilon, Y_\mathrm{e} = n_\mathrm{e}/n_\mathrm{b})$ and stepping up the complexity, we may

- assume that reactions are fast enough that matter remains in equilibrium, or
- slow enough that the composition is frozen, and/or
- add whatever other physics we may be interested in (neutrinos, MHD, ...)



[Hammond+

next-gen GW



Looking ahead to Cosmic Explorer and the Einstein Telescope, observations may be **limited by theory/simulations**.

Will bring added obstacles/opportunities:

- What if gravity is not GR?
- Additional fields/dark matter?

Is there a ”smoking gun” signature of extra physics or are we just dealing with “nuisance parameters”?