Constraining the Dense Matter Equation of State with Neutron Star Mergers

Carolyn Raithel
Institute for Advanced Study
Princeton Center for Theoretical Science
Princeton Gravity Initiative

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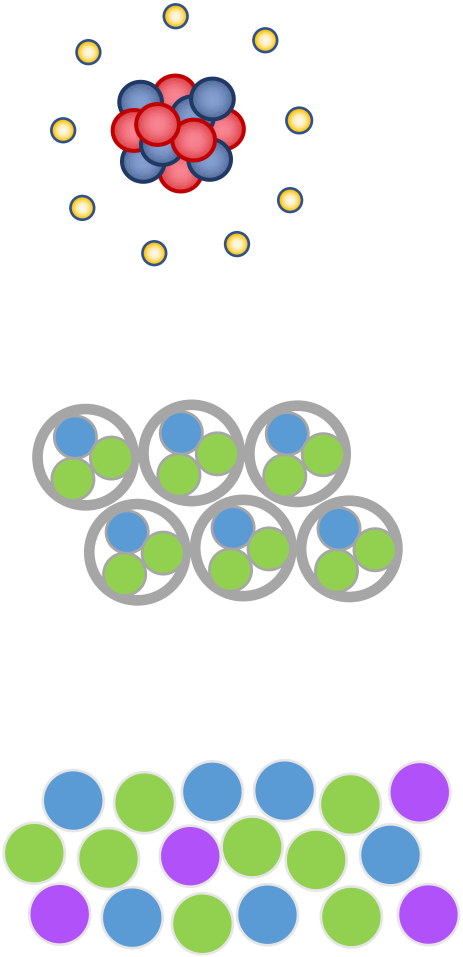
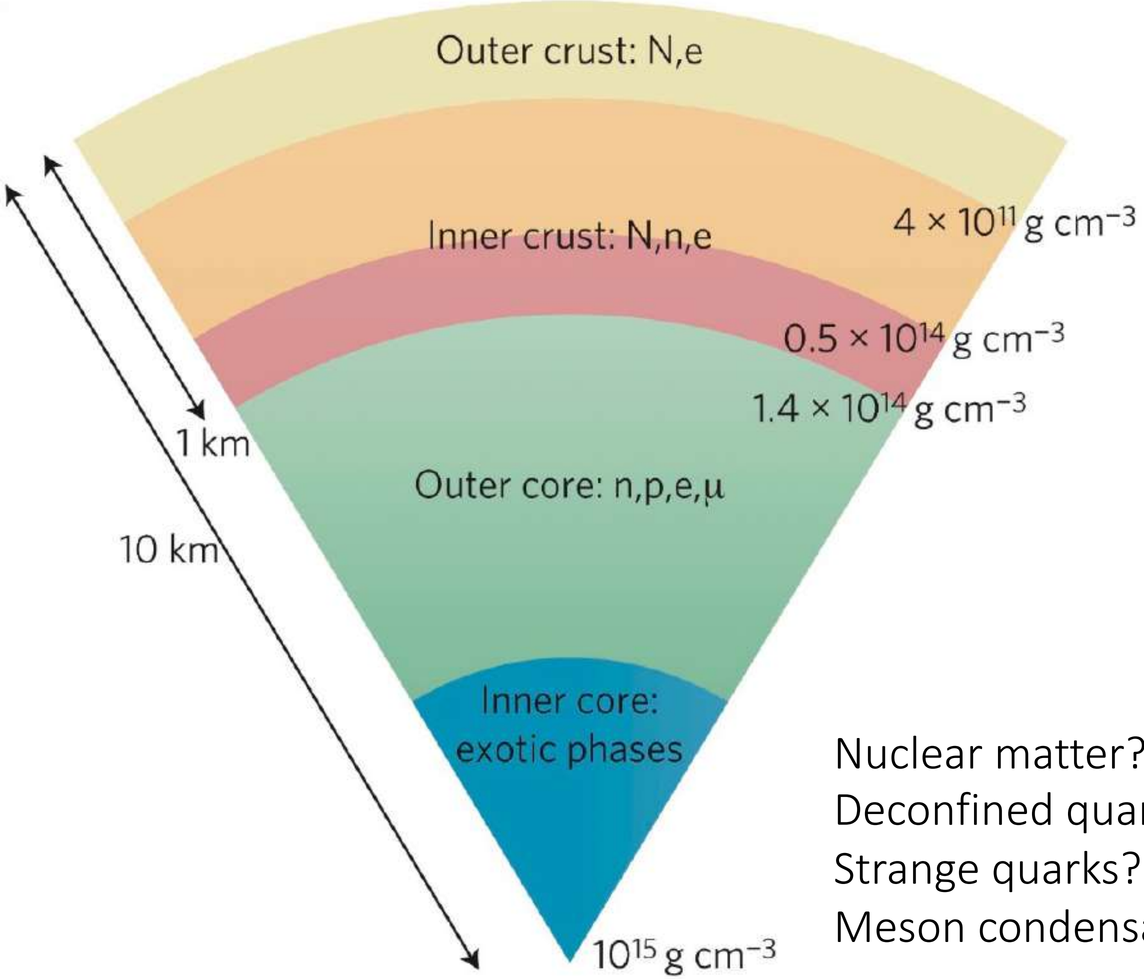
The neutron star interior

low density



high density

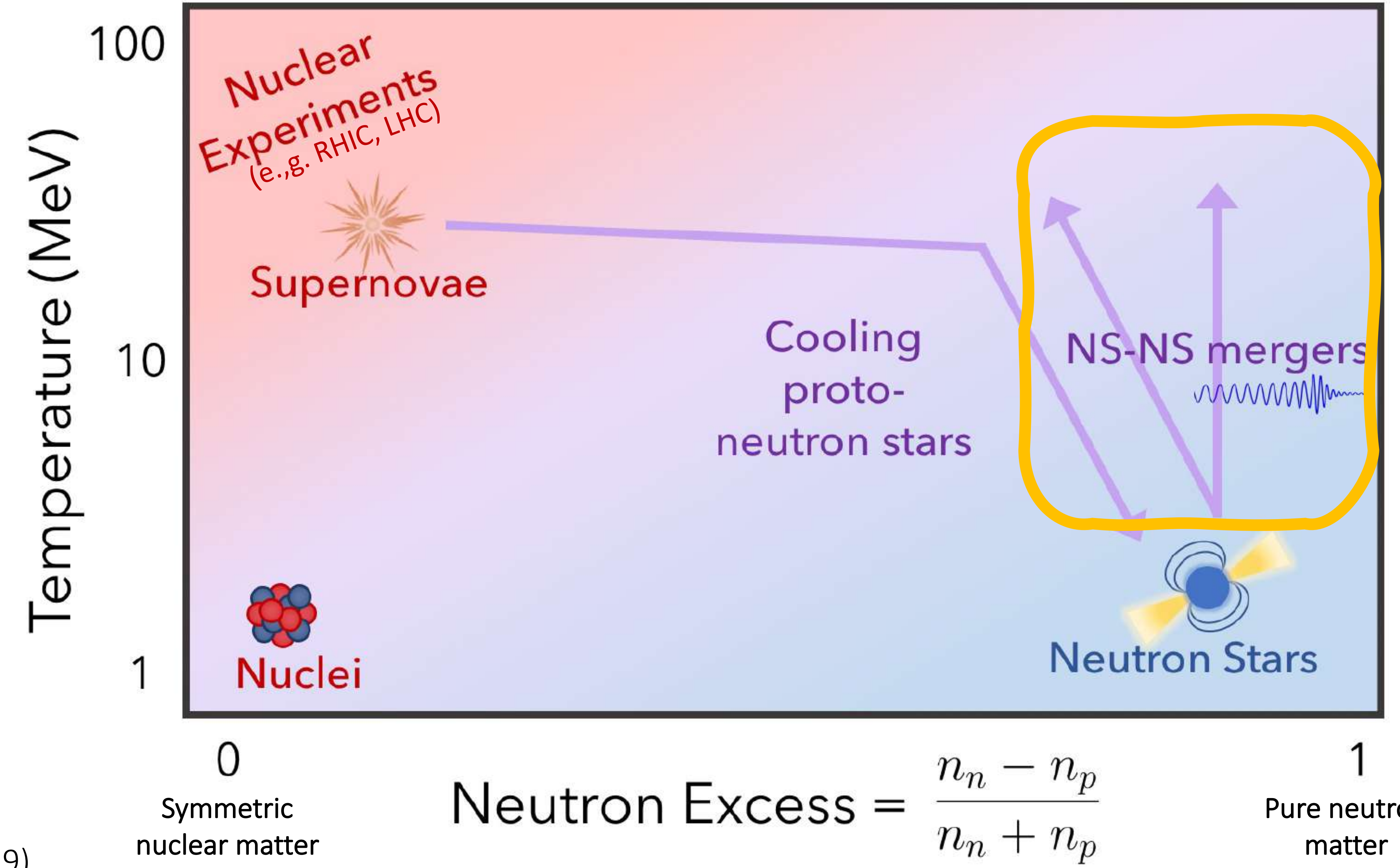
M = 1-2 $M_{\odot}$, R ~ 10 km



Nuclear matter?
Deconfined quark matter?
Strange quarks?
Meson condensates?

Newton (Nature Physics, 2013)

Experimental probes of dense matter



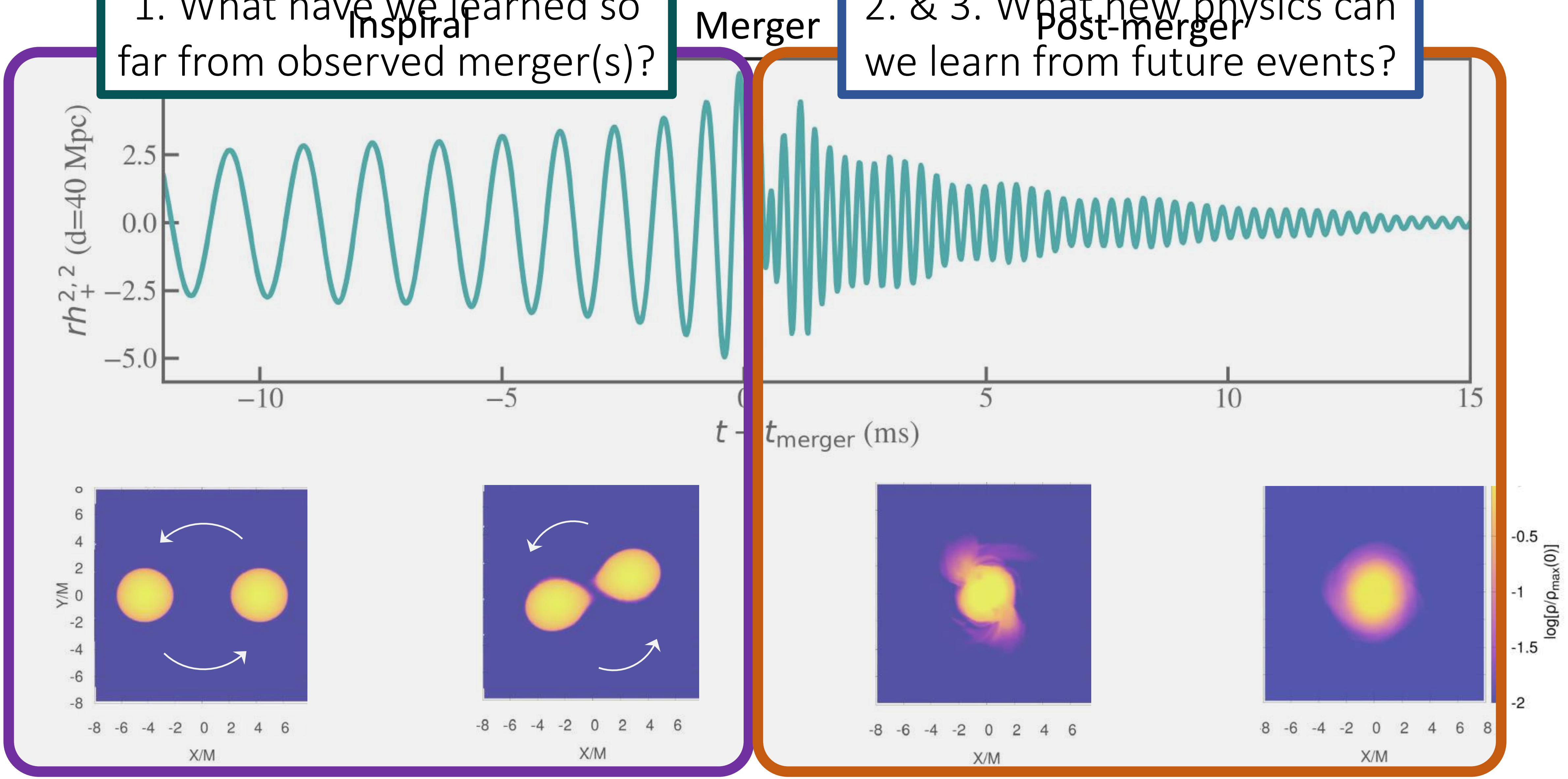
$$\text{Neutron Excess} = \frac{n_n - n_p}{n_n + n_p}$$

Raithel, Özel, & Psaltis (2019)

Anatomy of a neutron star merger

1. What have we learned so far from observed merger(s)?

2. & 3. What new physics can we learn from future events?



Neutron star mergers detected to date

PRL **119,** 161101 (2017) Selected for a Viewpoint in *Physics* PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

The first (and still most informative!) binary NS merger

THE ASTROPHYSICAL JOURNAL LETTERS, 892:L3 (24pp), 2020 March 20 https://doi.org/10.3847/2041-8213/ab75f5

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GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4 M_{\odot}$

Binary NS merger, but weak constraints on tidal deformability

THE ASTROPHYSICAL JOURNAL LETTERS, 896:L44 (20pp), 2020 June 20 https://doi.org/10.3847/2041-8213/ab960f

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GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object

Low-mass object possibly a NS (highly debated!)
No constraints on tidal deformability

THE ASTROPHYSICAL JOURNAL LETTERS, 915:L5 (24pp), 2021 July 1 https://doi.org/10.3847/2041-8213/ac082e

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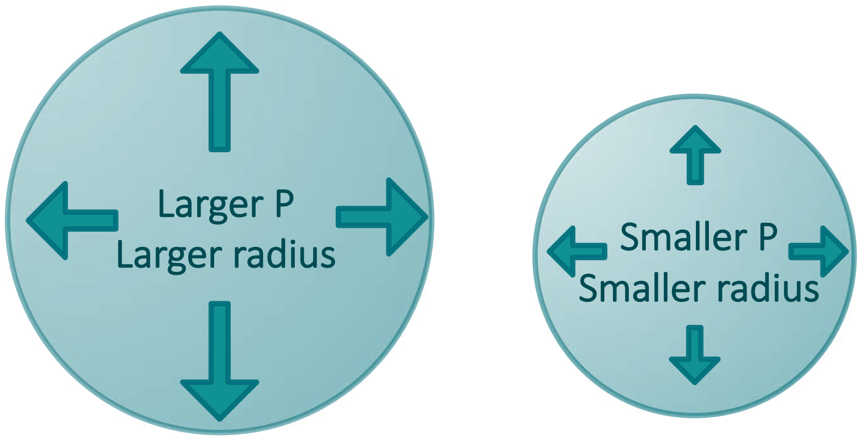
Observation of Gravitational Waves from Two Neutron Star–Black Hole Coalescences

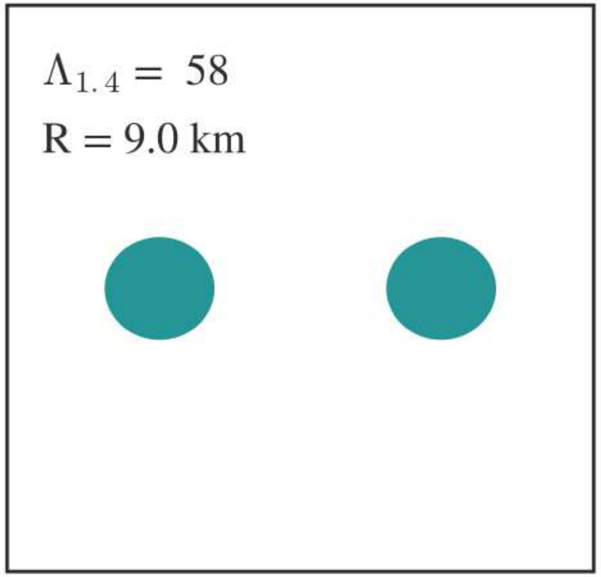
New! First confirmed NS-BH mergers!

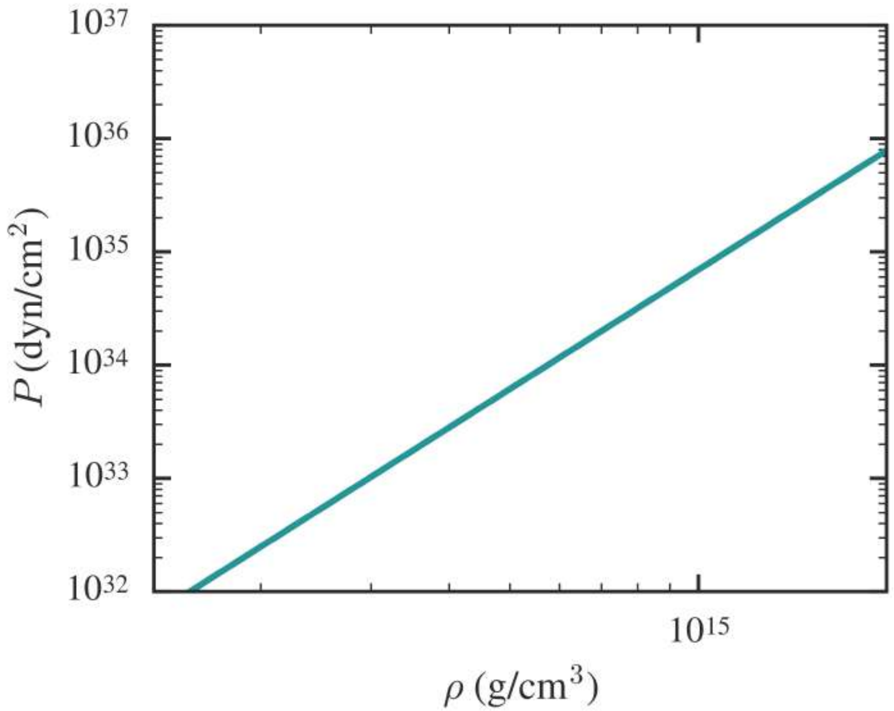
Neutron star tidal deformability

Quadrupolar response to the tidal potential of a binary companion

$$\Lambda = -\frac{Q_{ij}}{M^5 \varepsilon_{ij}}$$

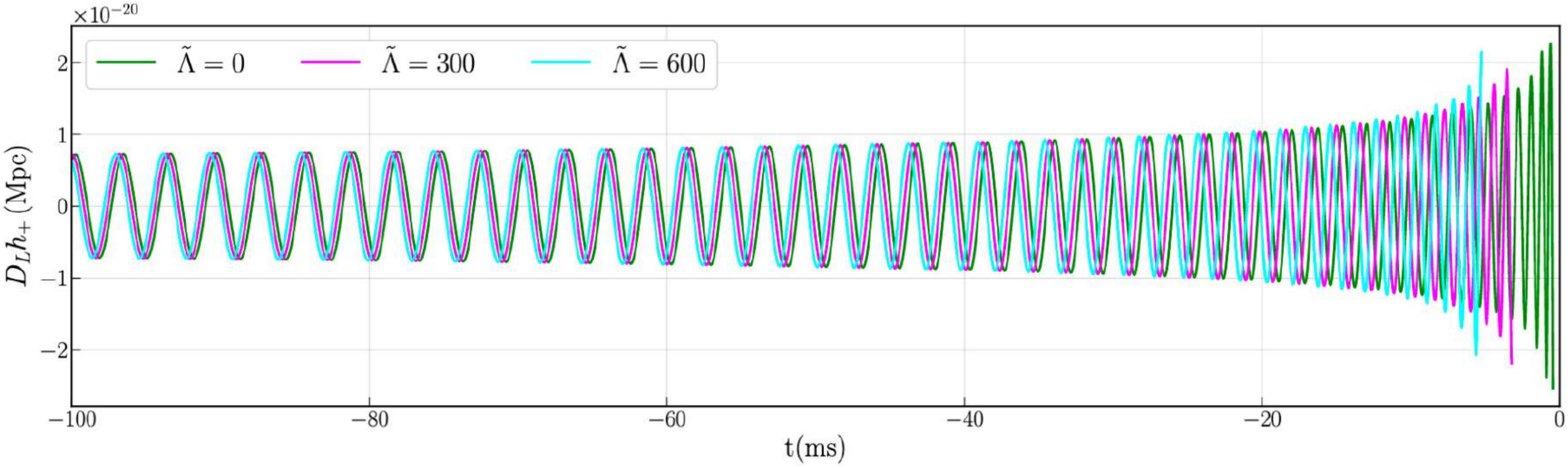






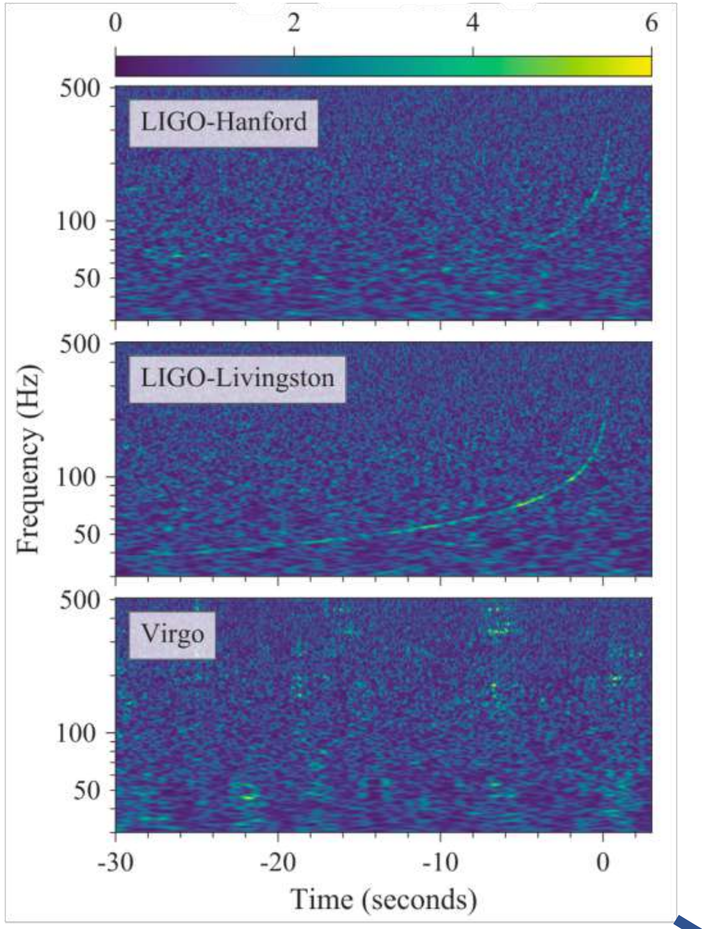
Measuring the tidal deformability

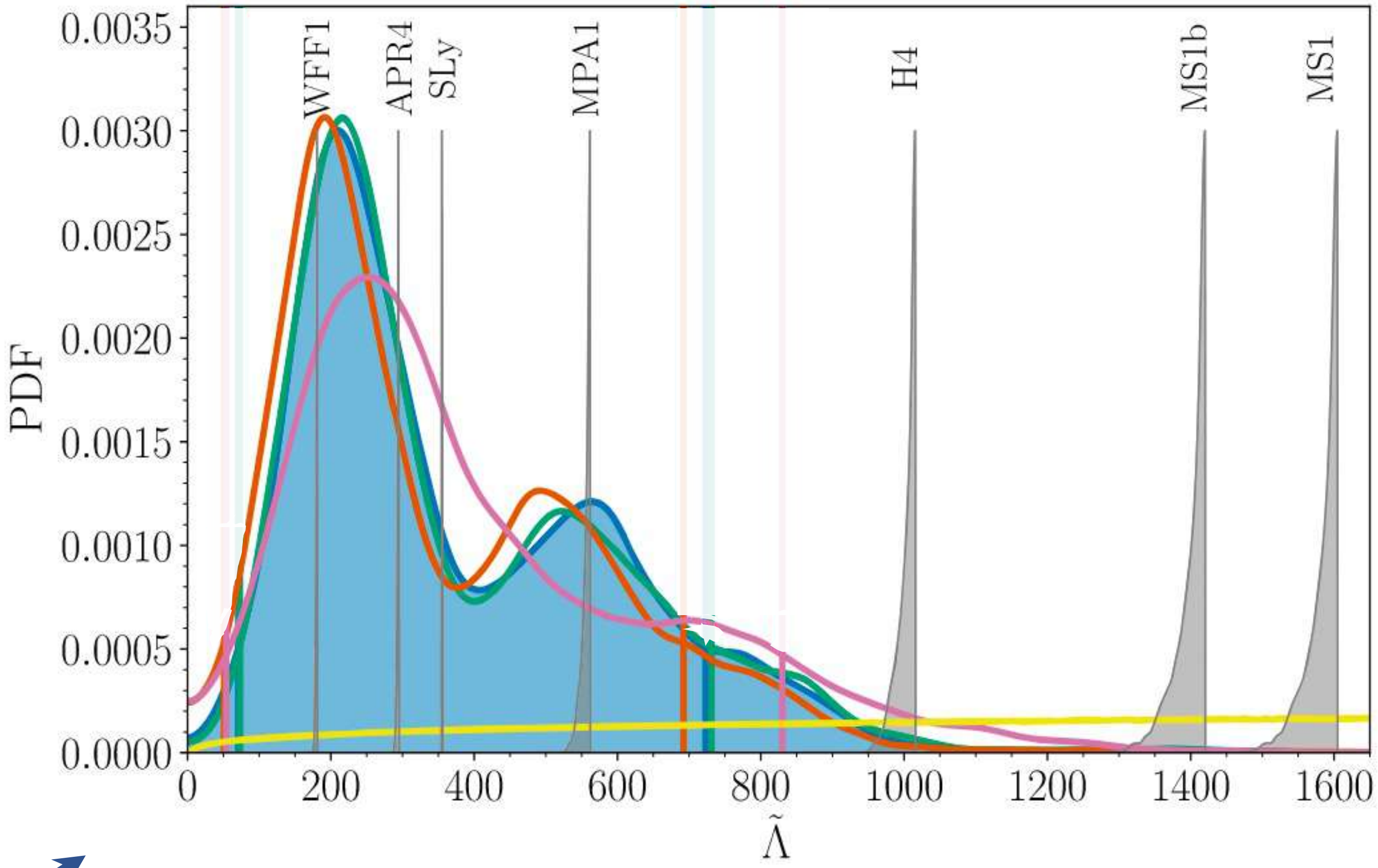
Tidal deformability acts to accelerate the inspiral



Chatziioannou (2020)

Tidal deformability from GW170817



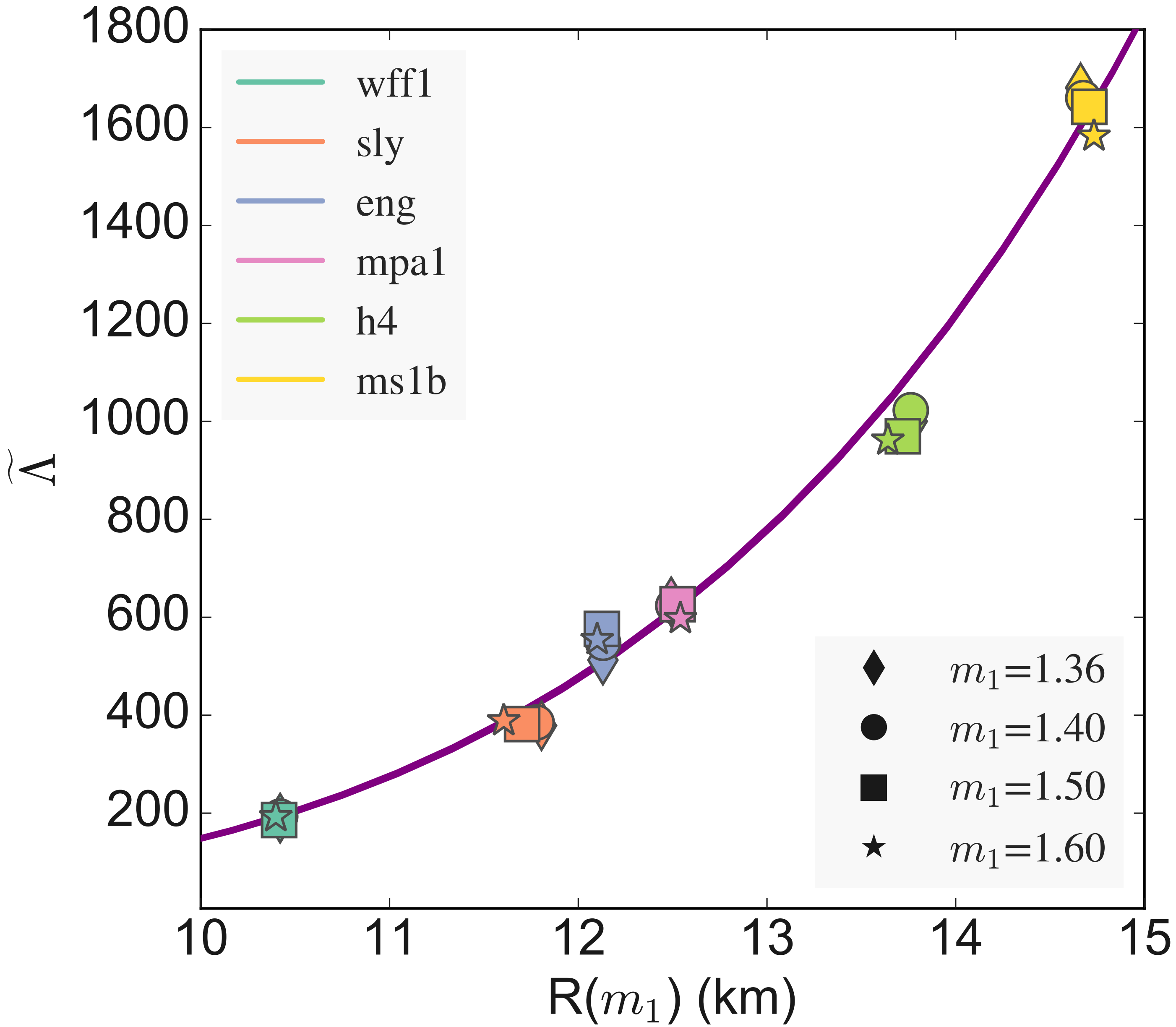


From analysis of binary waveform, can extract *effective* (or *binary*) tidal deformability:

$$\widetilde{\Lambda} = \frac{16}{13}\frac{(m_1 + 12m_2)m_1^4\,\Lambda_1 + (m_2 + 12m_1)m_2^4\,\Lambda_2}{(m_1+m_2)^5}$$

LVC (2017, 2019)

New one-to-one mapping between $\tilde{\Lambda}$ and the NS radius



Analytic derivation using a series expansion for quasi-Newtonian, n=1 polytrope:

$$\tilde{\Lambda} = \tilde{\Lambda}_0 \left[1 + \alpha \left(\frac{1-q}{1-0.7} \right)^2 + \ldots \right]$$

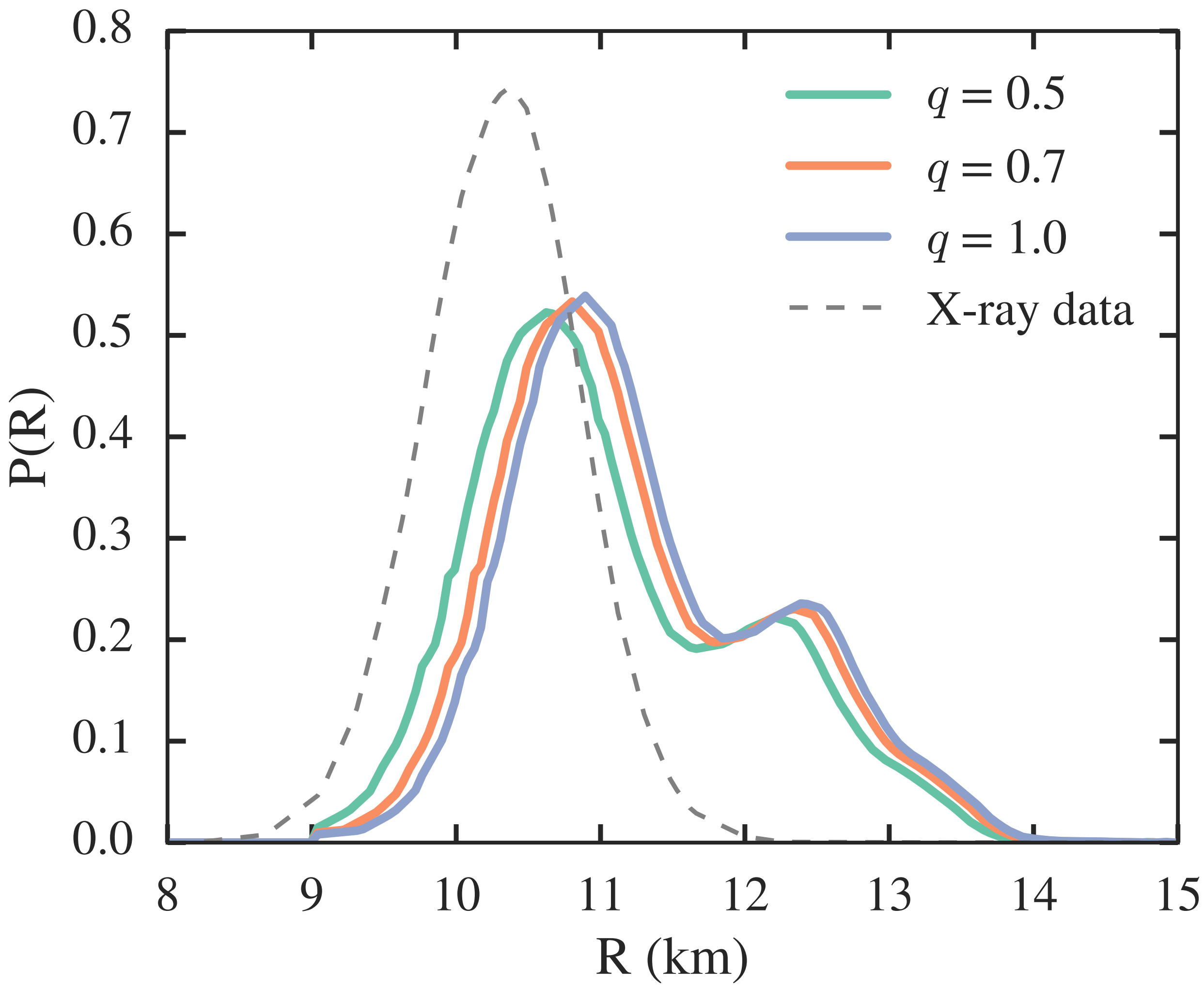
Depends on $\mathcal{M}_c$ and R

$\lesssim 0.04$

Very weak dependence on individual component masses!

Raithel, Özel, and Psaltis (2018), Raithel (2019)

Neutron star radii from GW and X-ray measurements



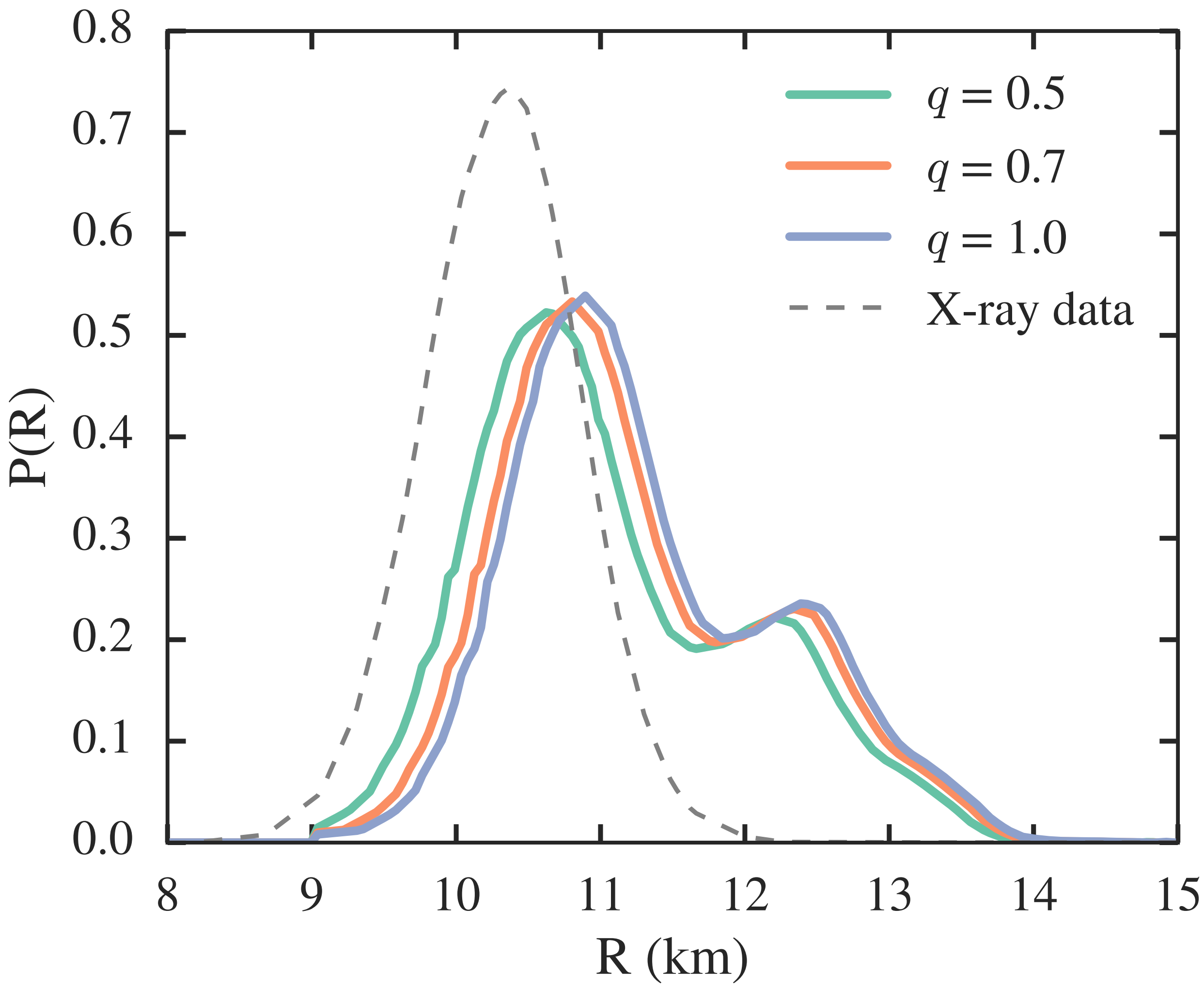
Raithel (2019); Raithel, Özel, and Psaltis (2021).
X-ray data from LMXB analysis of Özel+ 2016.

$$P(R) = P(\tilde{\Lambda}) \left| \frac{\partial \tilde{\Lambda}}{\partial R} \right|$$

$R_{GW170817}$ = 10.2 – 11.7 km
(68% HPD interval)

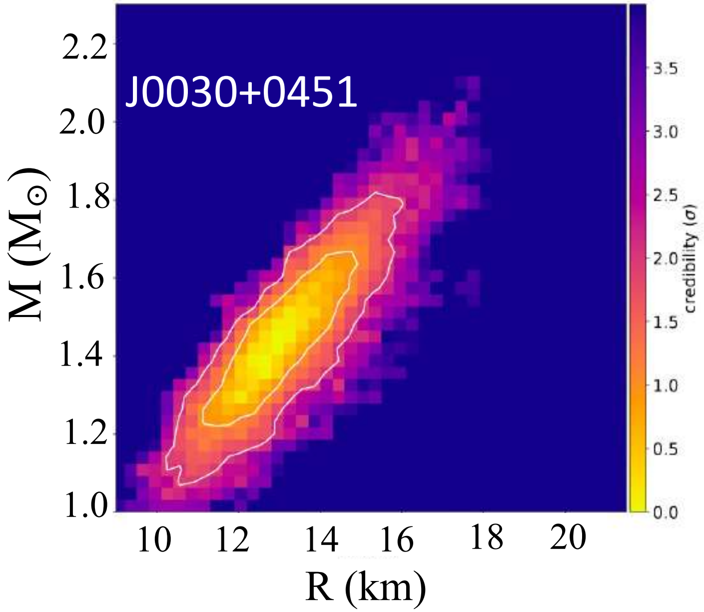
- See also De et al. (2018) and Zhao & Lattimer (2018) for similar $\tilde{\Lambda}(R)$ relationship, with different set of assumptions.
- And see Annala+ (2018), Abbott+ (2018), Most+ (2018), Tews+ (2018), Lim and Holt (2018), … for many more estimates of *R* from GW170817

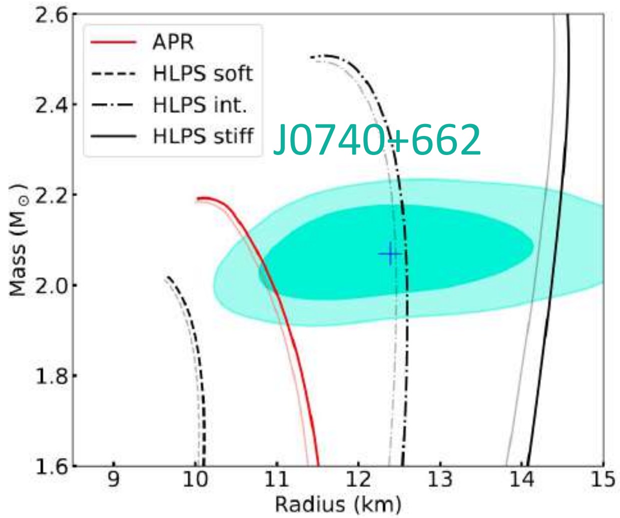
Neutron star radii from GW and X-ray measurements



Raithel (2019); Raithel, Özel, and Psaltis (2021).
X-ray data from LMXB analysis of Özel+ 2016.

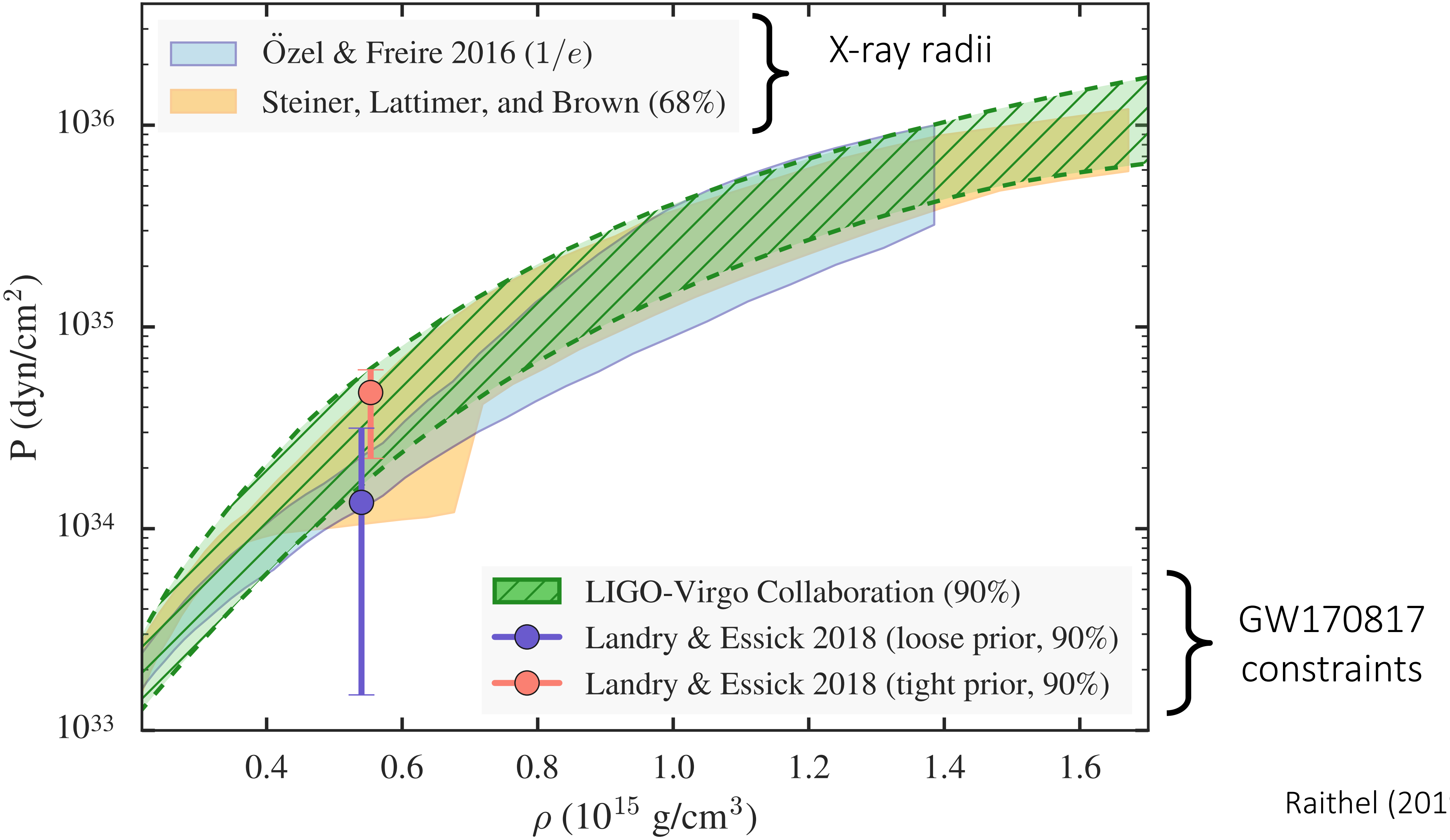
New data also coming from NICER





Miller et al. 2019,2021; Riley et al. 2019,2021

Summary of EOS constraints



Raithel (2019)

1. What have we learned so far from observed merger(s)?

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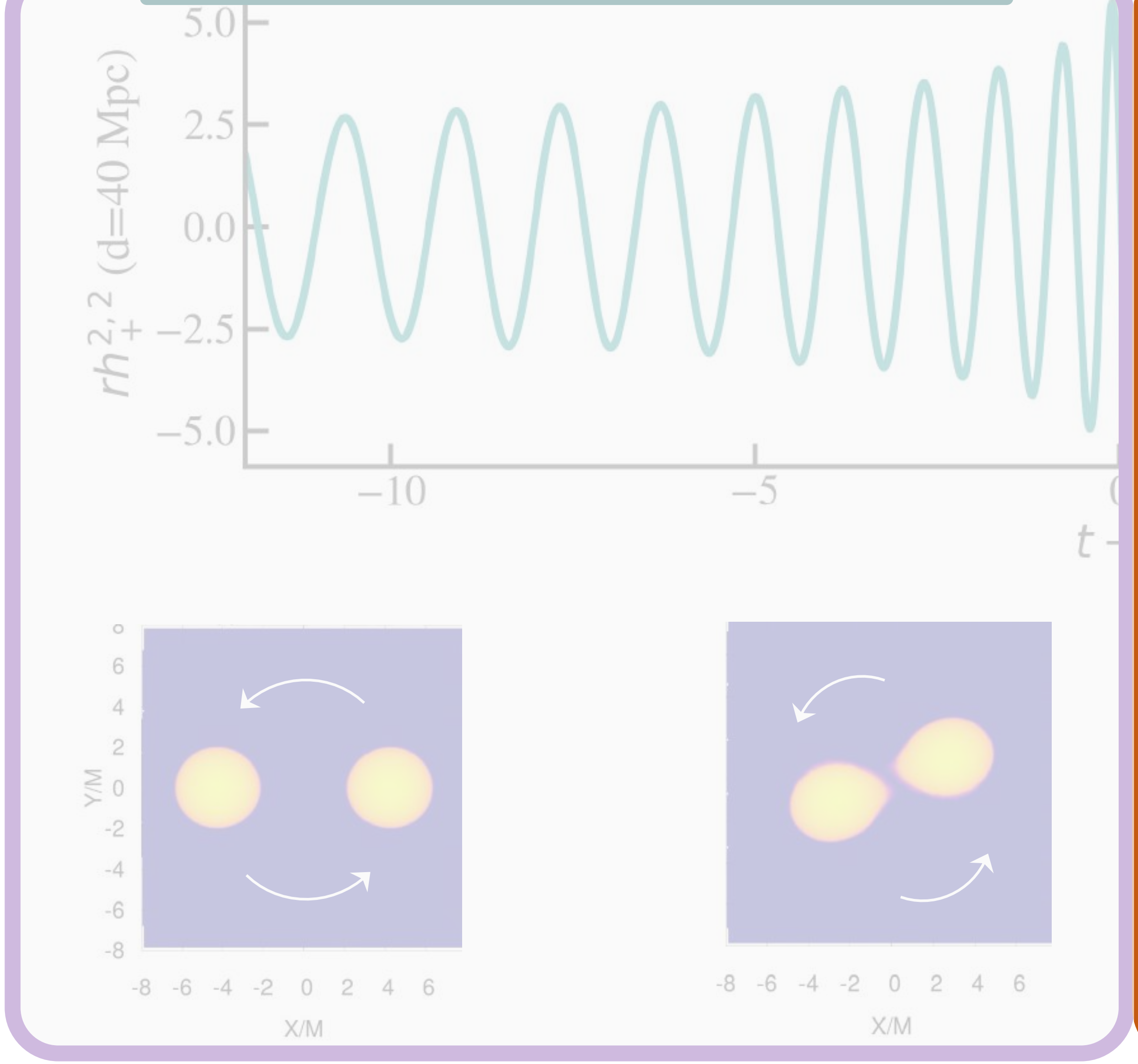
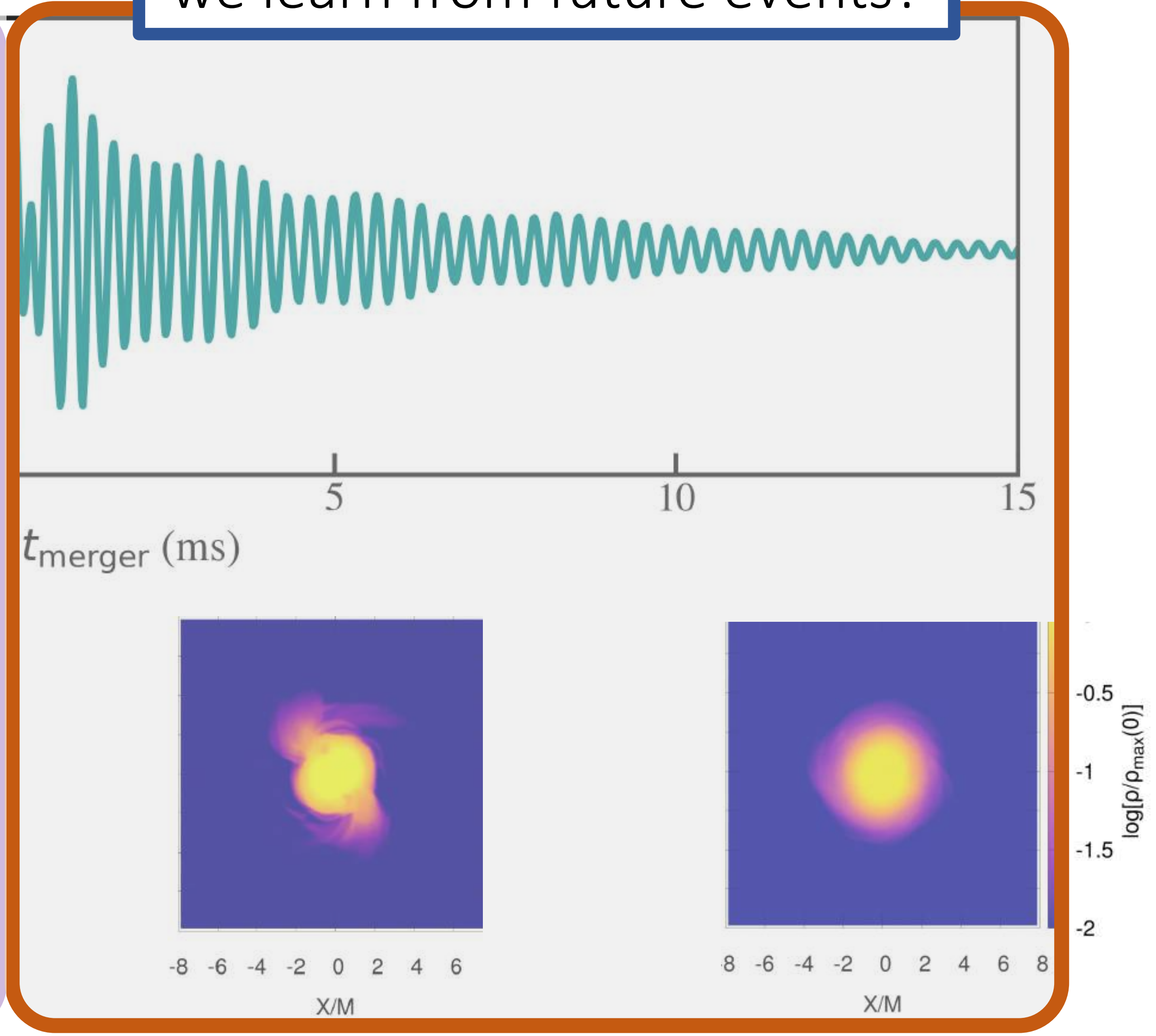
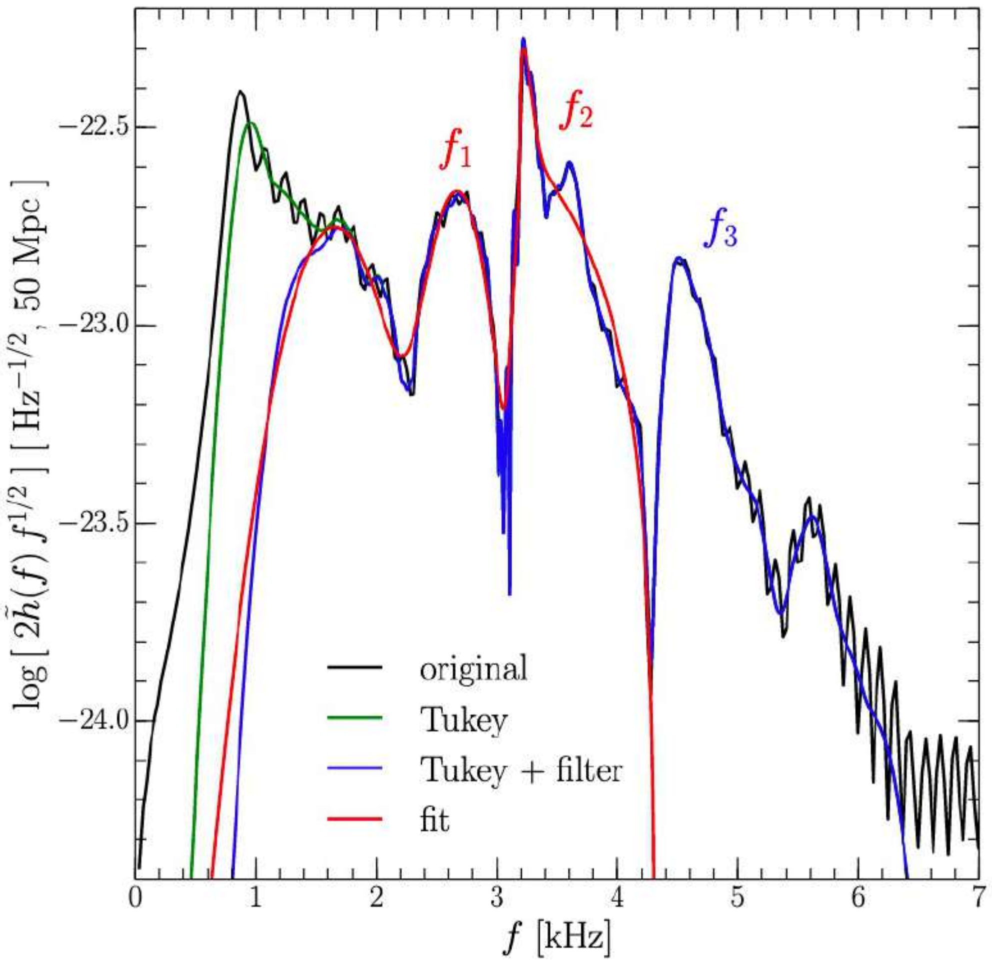




Asteroseismology with the post-merger GW power spectrum

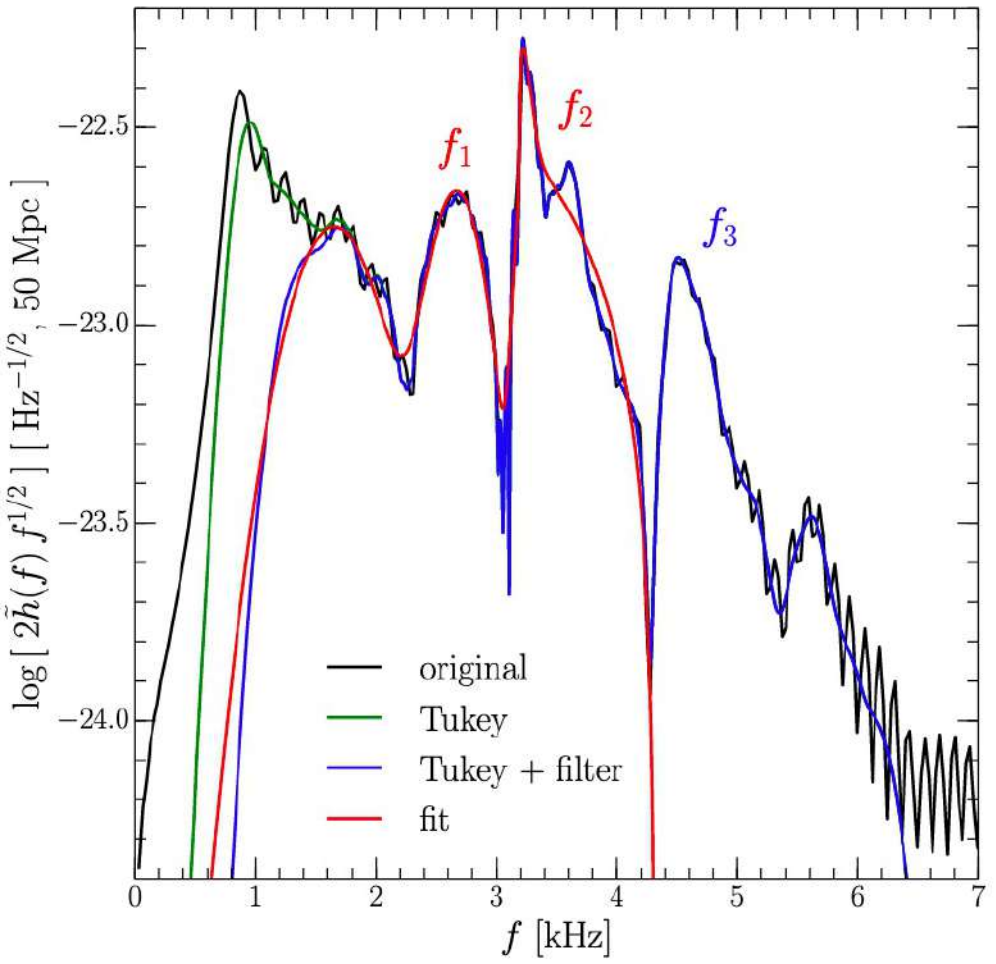


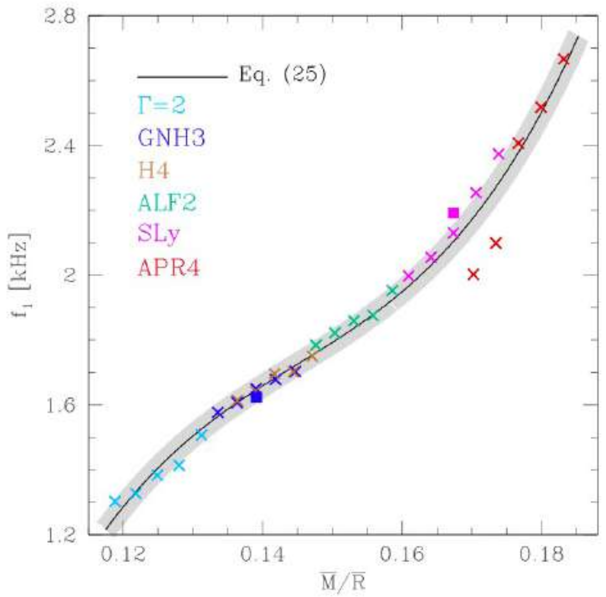
Spectral peaks are caused by oscillations of the post-merger remnant

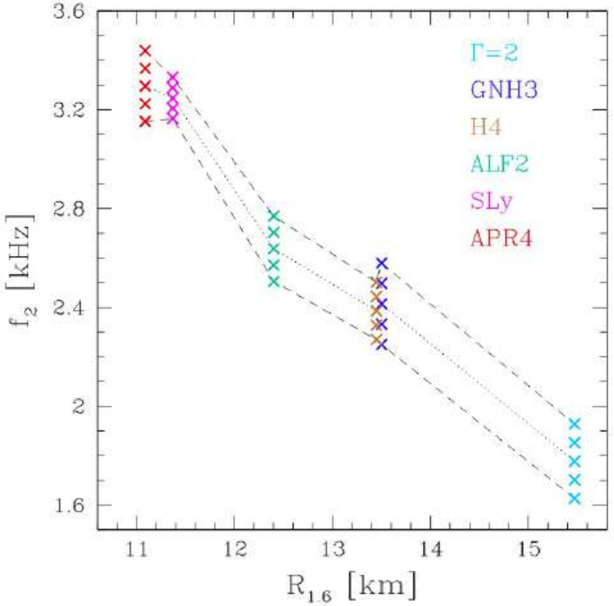
These oscillations depend on the structure of the remnant (and hence the EOS!)

Takami, Rezzolla, and Baiotti (2016)
(See also, e.g.,: Bauswein and Janka 2012, Bauswein and Stergiouslas 2015.)

Asteroseismology with the post-merger GW power spectrum







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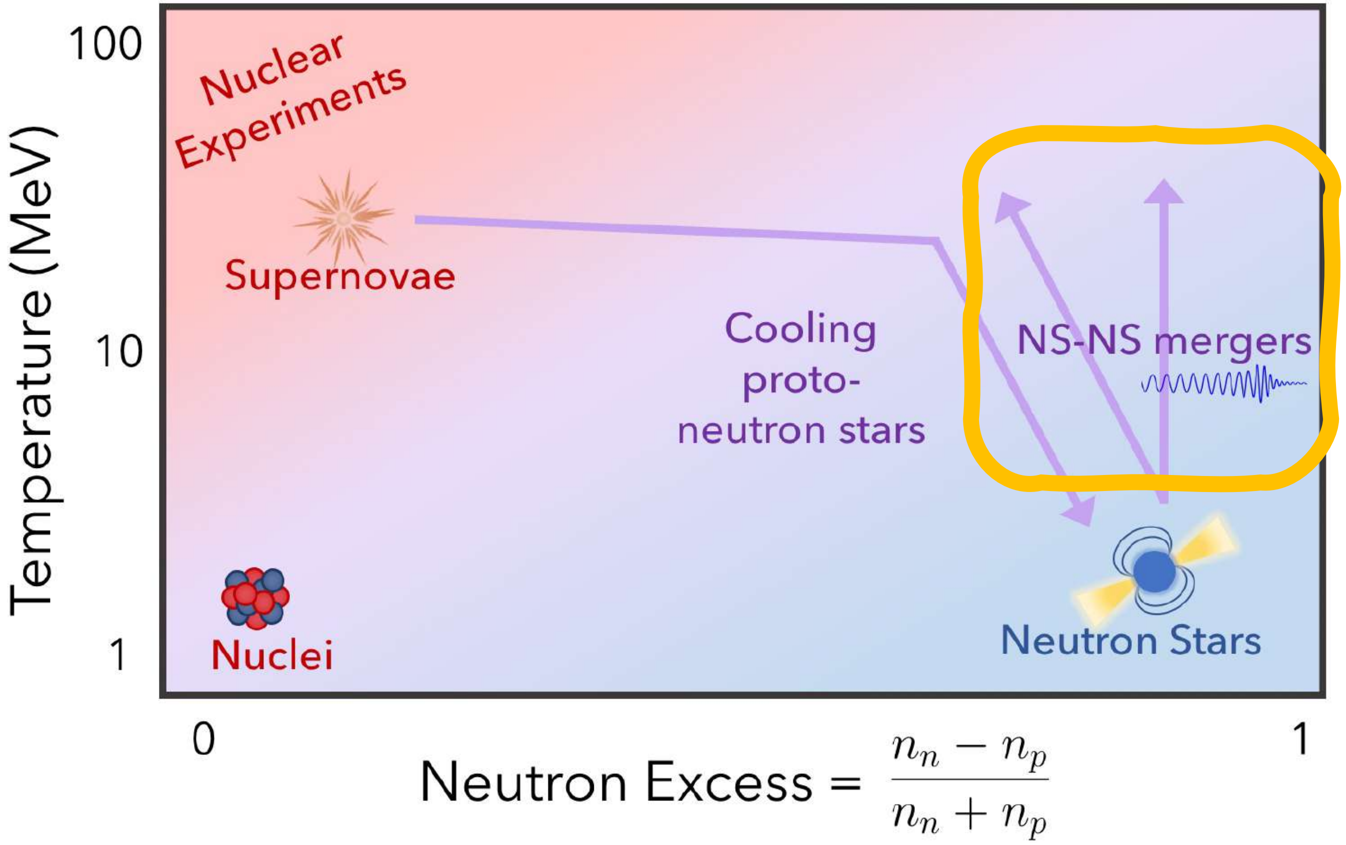


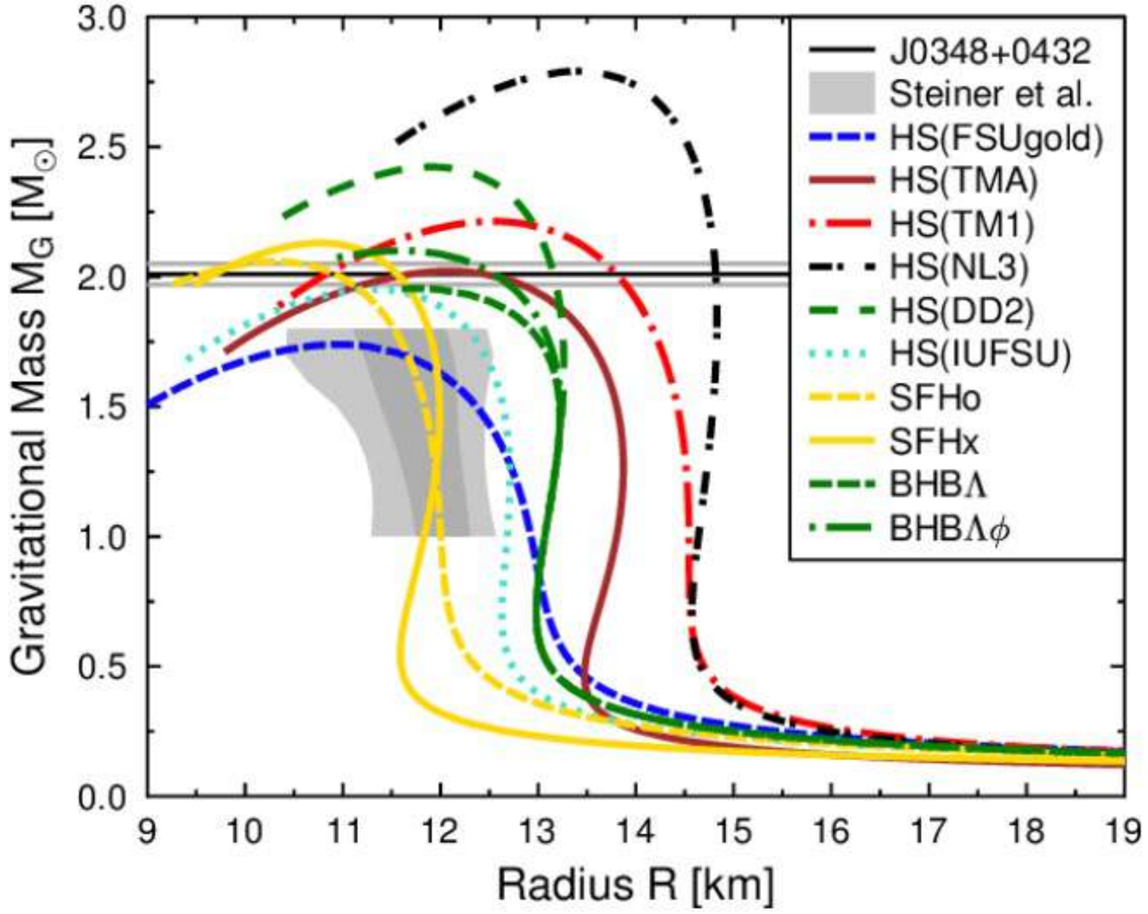
Part 2: Finite-temperature effects

To what extent does the post-merger phase depend on the cold EOS, and to what extent on finite-temperature effects?

Modeling the finite-temperature EOS

Option 1: Realistic EOS tables, with 3D table of $P(n, T, Y_p)$

Mass-radius curves for the cold (T=0) slice of commonly-used EOS tables



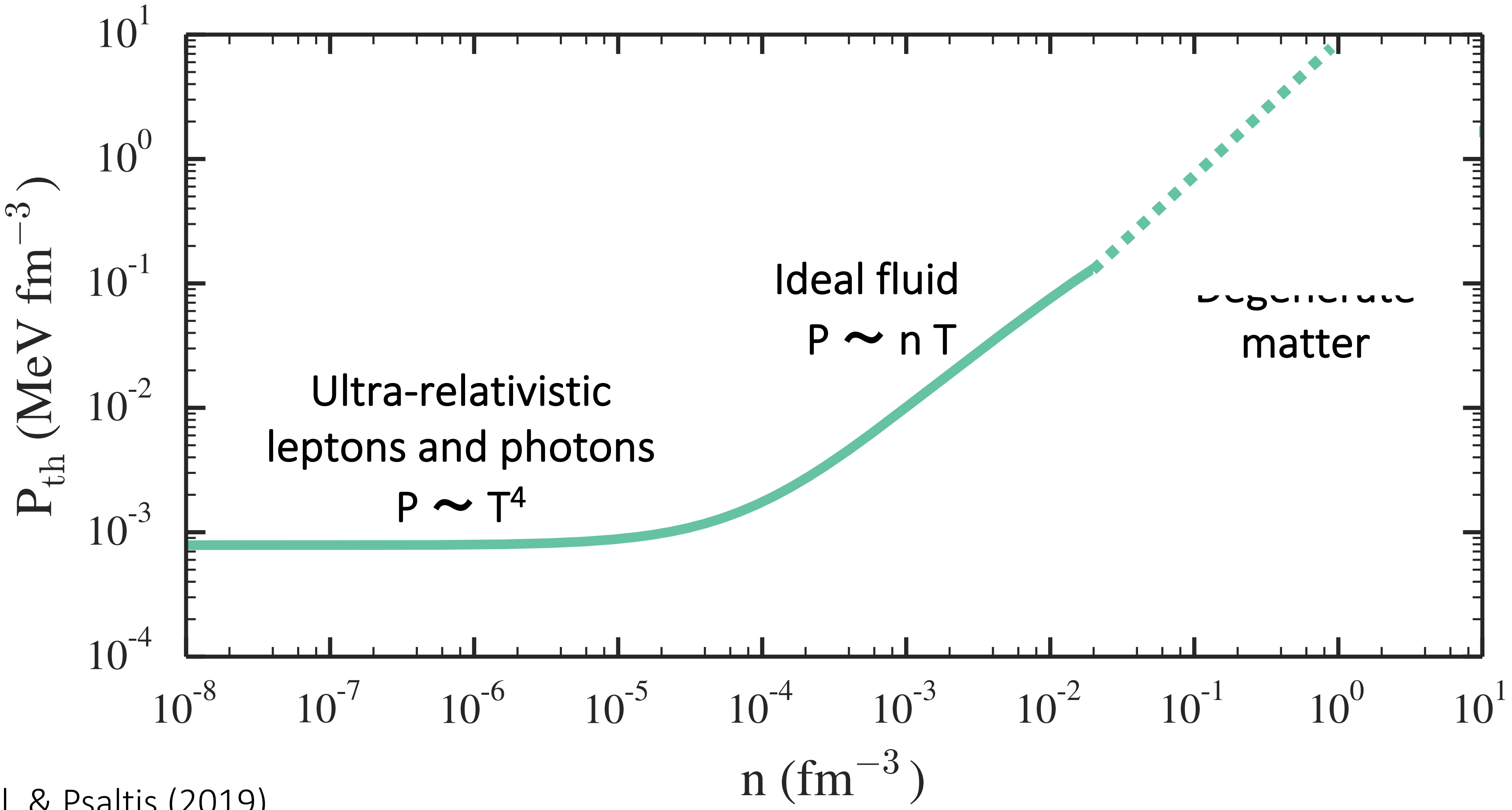
Downsides:

- Sparse sampling of parameter space
- Computationally expensive
- No clean way to separate thermal and cold physics

Image credit:
website of Matthias Hempel

Modeling the finite-temperature EOS

Option 2: analytic decomposition, assuming $P_{\mathrm{total}} = P_{\mathrm{cold}} + P_{\mathrm{th}}$



NL3
T = 10 MeV
$Y_p = 0.10$

Raithel, Özel, & Psaltis (2019)

New framework for calculating the EOS at arbitrary temperatures and proton fractions

Goals of the model:

- Maintain flexibility and computational efficiency of hybrid approach
- Improve thermal treatment
- Allow for proton fraction to vary

$$E(n, Y_p, T) = E_{\text{cold}}(n, Y_{p\beta}) + E_{\text{sym}}(n)\left[(1-2Y_p)^2 - (1-2Y_{p\beta})^2\right] + E_{\text{th}}(n, T)$$

Cold EOS in β-equilibrium

Symmetry energy-dependent penalty

Thermal energy

~~+ cross term ...~~

Degenerate thermal pressure from Fermi Liquid Theory

$$E_{\rm th}(n,T) = a(n,M^*)T^2$$

$$P_{\rm th}(n,T) = \frac{a(n,M^*)}{3}\left[1+\frac{M^{*2}}{m^{*2}}\left(1-3\frac{\partial \ln M^*}{\partial \ln n}\right)\right] nT^2$$

$$a(n,M^*) \equiv \frac{\pi^2}{2}\frac{\sqrt{M^*(n)^2+(3\pi^2 n)^{2/3}(\hbar c)^2}}{(3\pi^2 n)^{2/3}(\hbar c)^2}$$

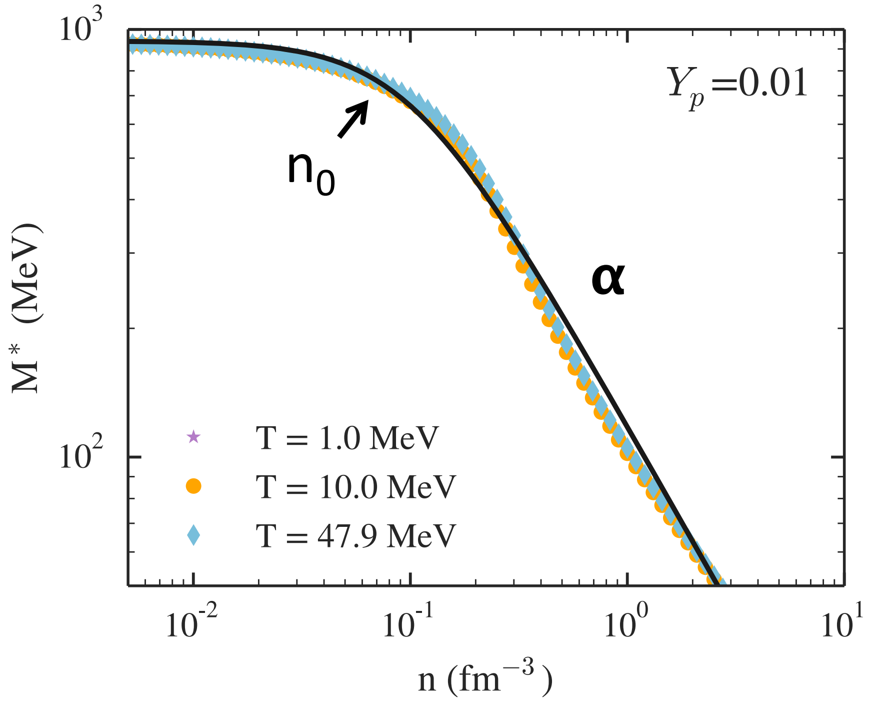
$$P_{th,\ deg} = f\,(n,\ T,\ M^*)$$

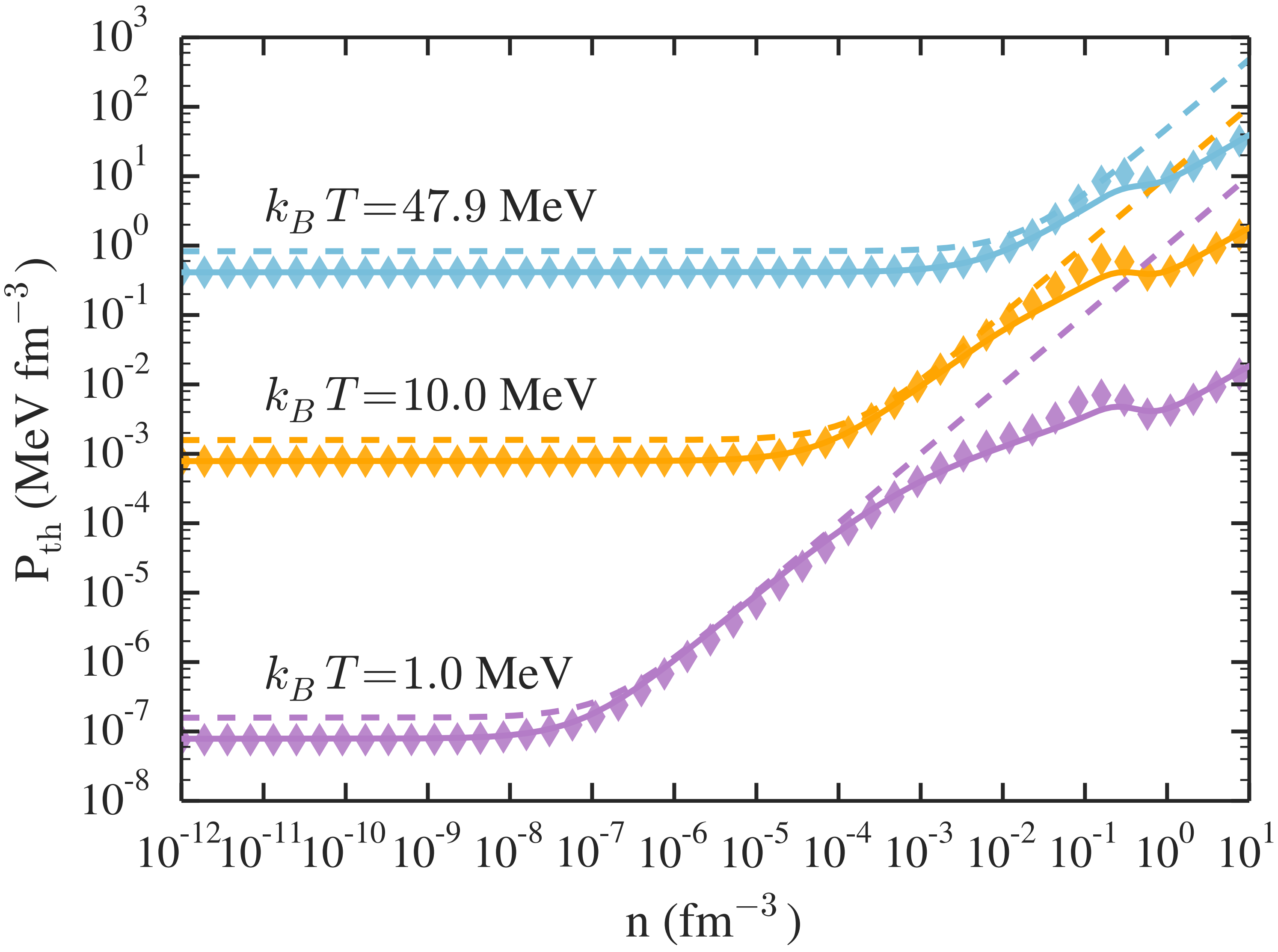
$$E_{th,\ deg} = g\,(n,\ T,\ M^*)$$

(For a derivation at next-to-leading order: Constantinou et al. 2015)

M*-approximation of the degenerate thermal pressure

$$M^*(n) = \left[(mc^2)^{-2} + \left(\frac{mc^2 n^{-\alpha}}{n_0^{-\alpha}}\right)^{-2}\right]^{-1/2}$$

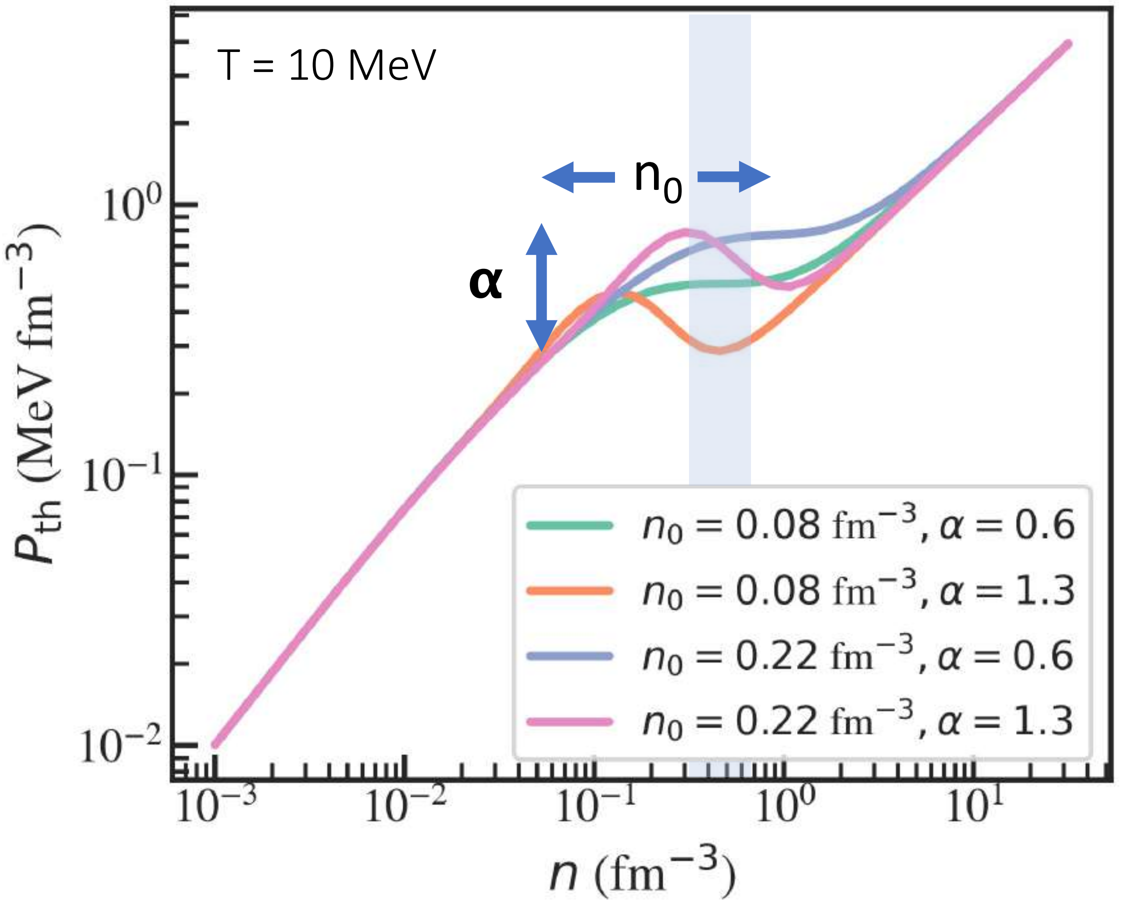




Raithel, Özel, & Psaltis (2019)

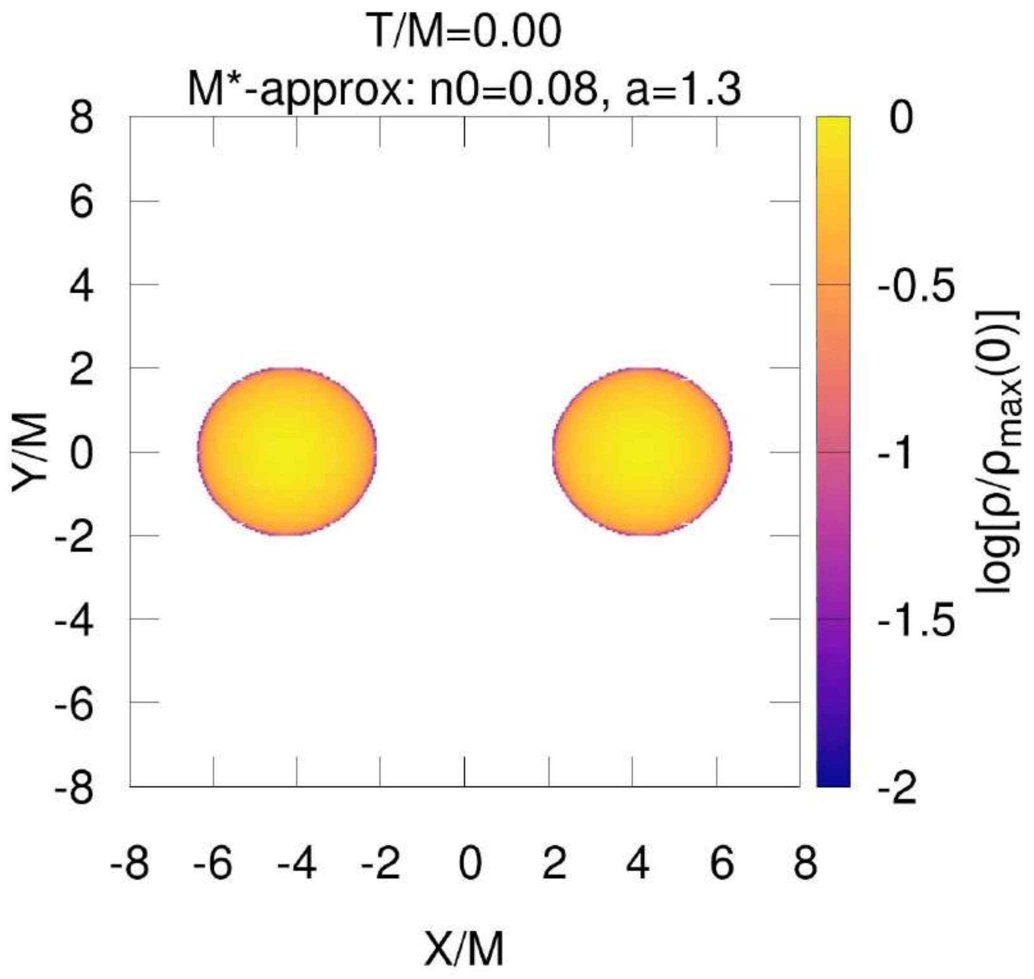
Exploring the parameters of the M*-framework with NS-NS merger simulations

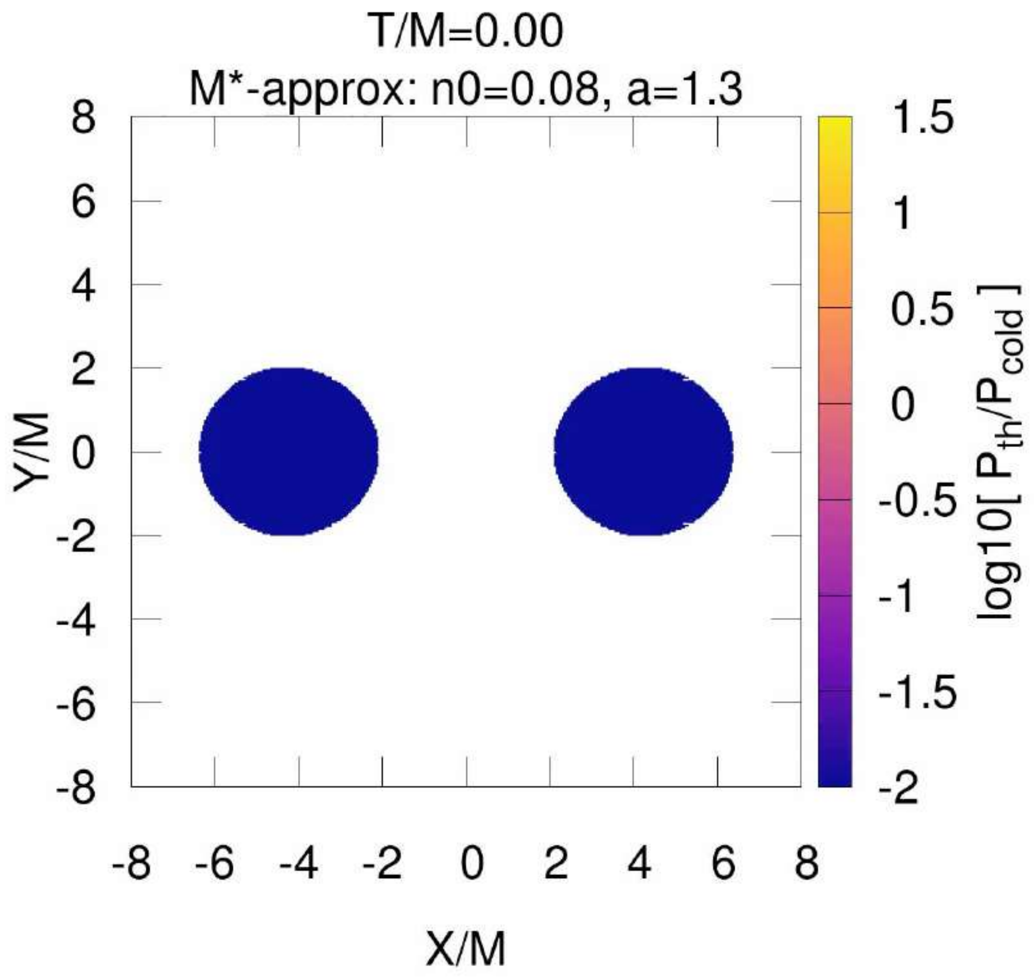
- **1.4 M⊙ + 1.4 M⊙** neutron star merger simulations
- Cold EOS: ENG ($R_{1.4}$ = 12 km, 2.24 M_{max})
- 4 simulations each with a different set of M*-parameters, to bracket range of uncertainty
- Simulations evolved with Illinois dynamical spacetime + GRMHD code (see e.g., Duez+2005, Etienne+ 2015)



Raithel, Paschalidis, Özel (arXiv:2104.07226)

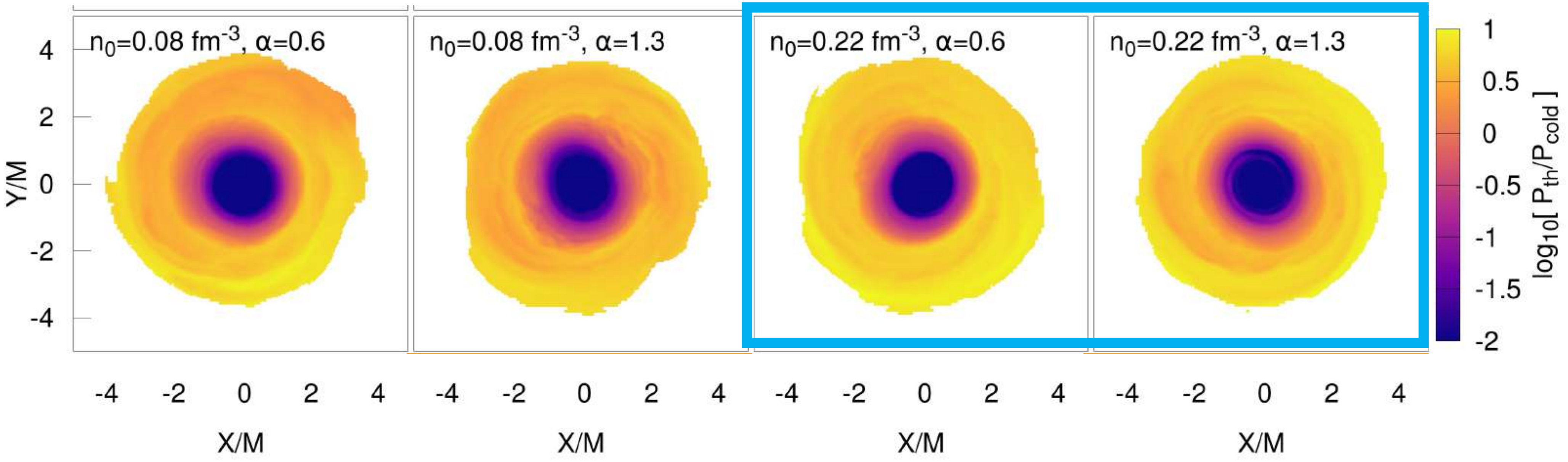
Simulation of 1.4 $M_\odot$ + 1.4 $M_\odot$ binary neutron star merger with M*-approximation





Raithel, Paschalidis, Özel (arXiv:2104.07226)

Thermal profiles with different M*-parameters

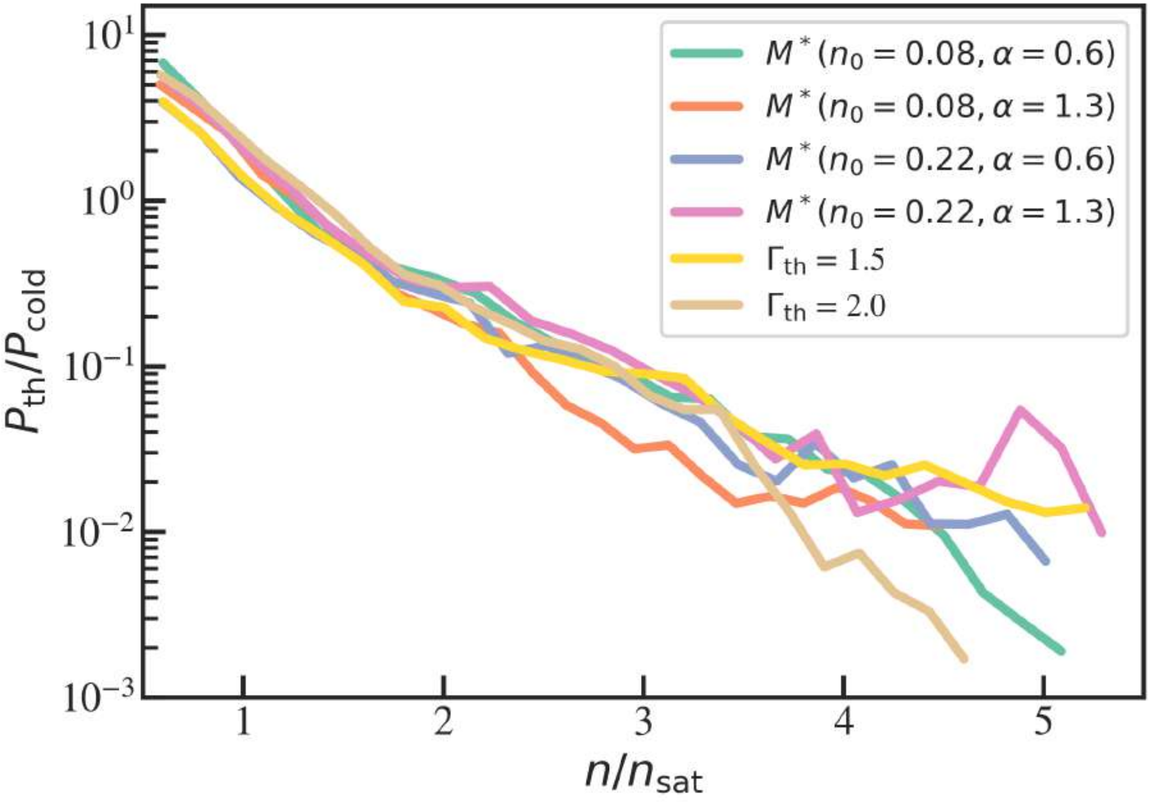


n_0 influences outer layers

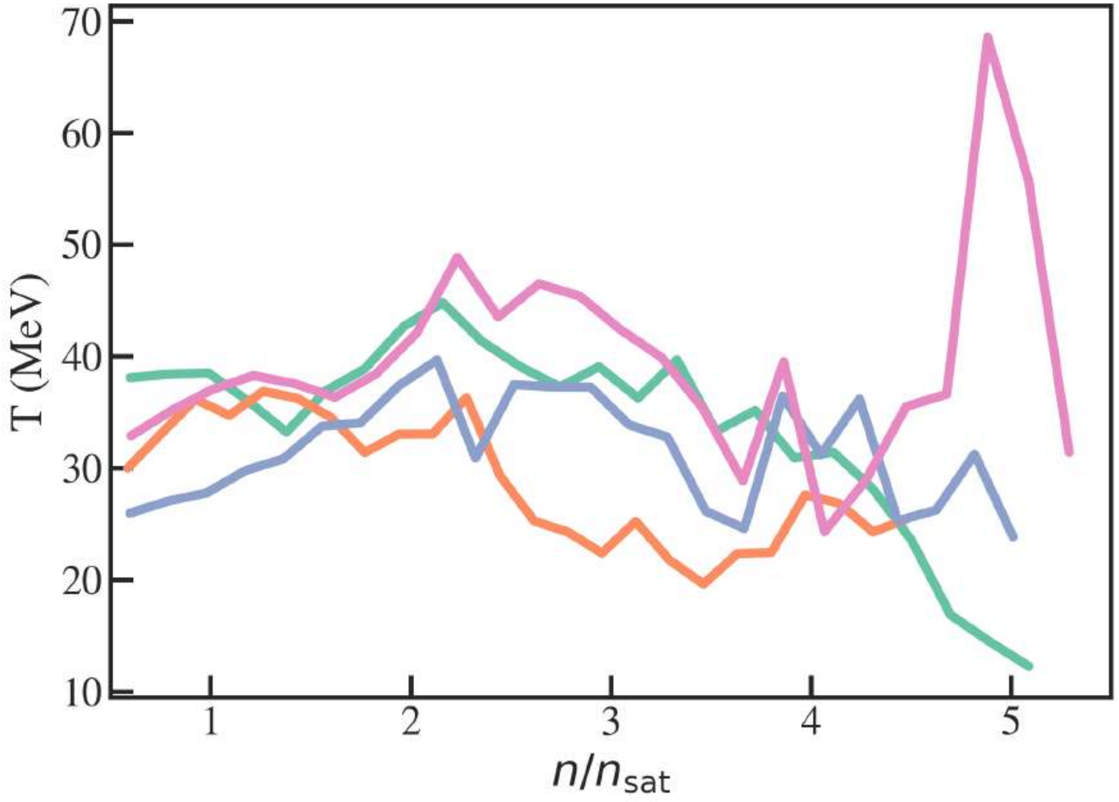
α influences inner core

Raithel, Paschalidis, Özel (arXiv:2104.07226)

Thermal profile shortly after merger

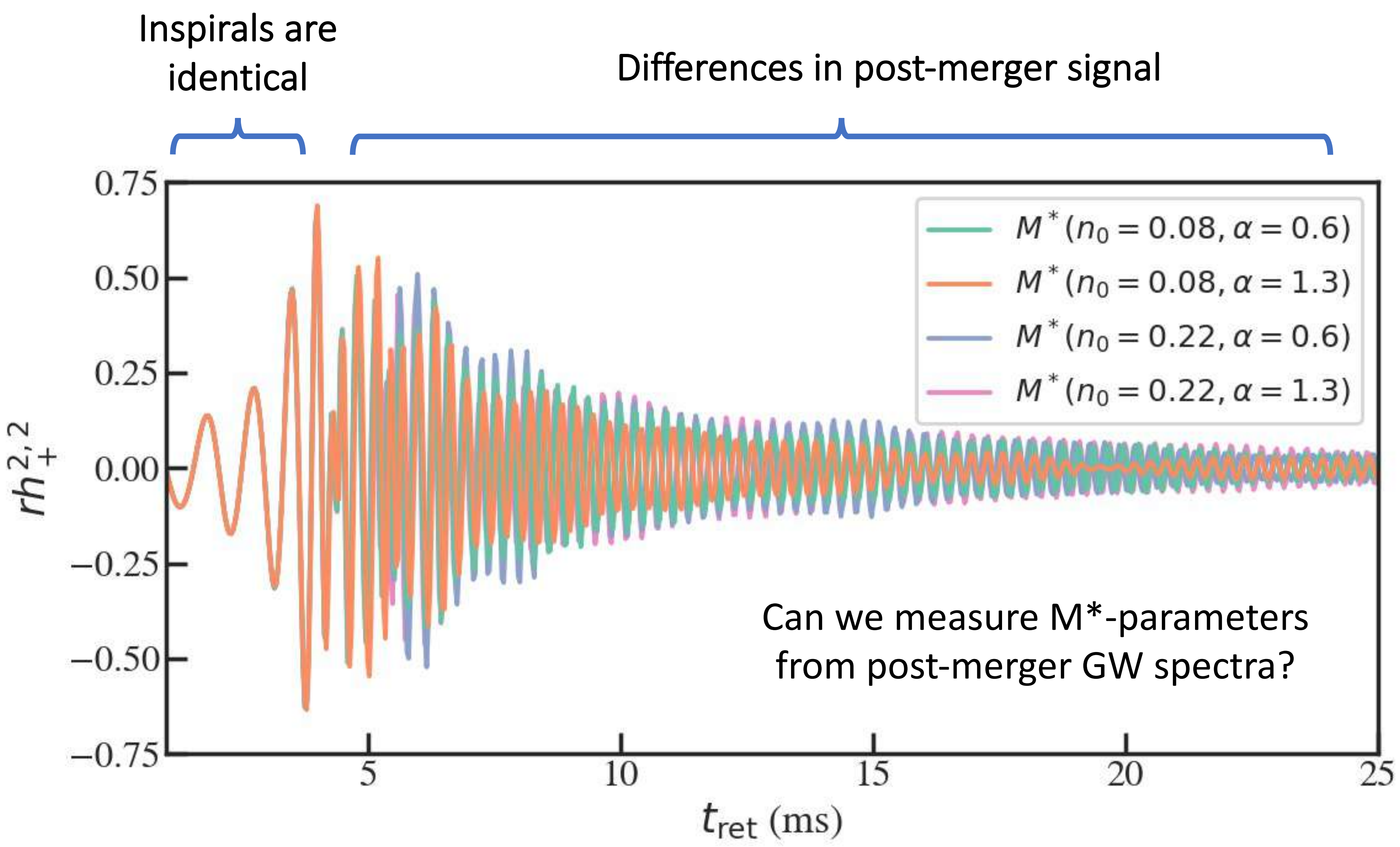


P_{th} influences oscillations of remnant, redistribution of matter



T affects neutrino emissivities, eventual cooling and neutrino irradiation of disk

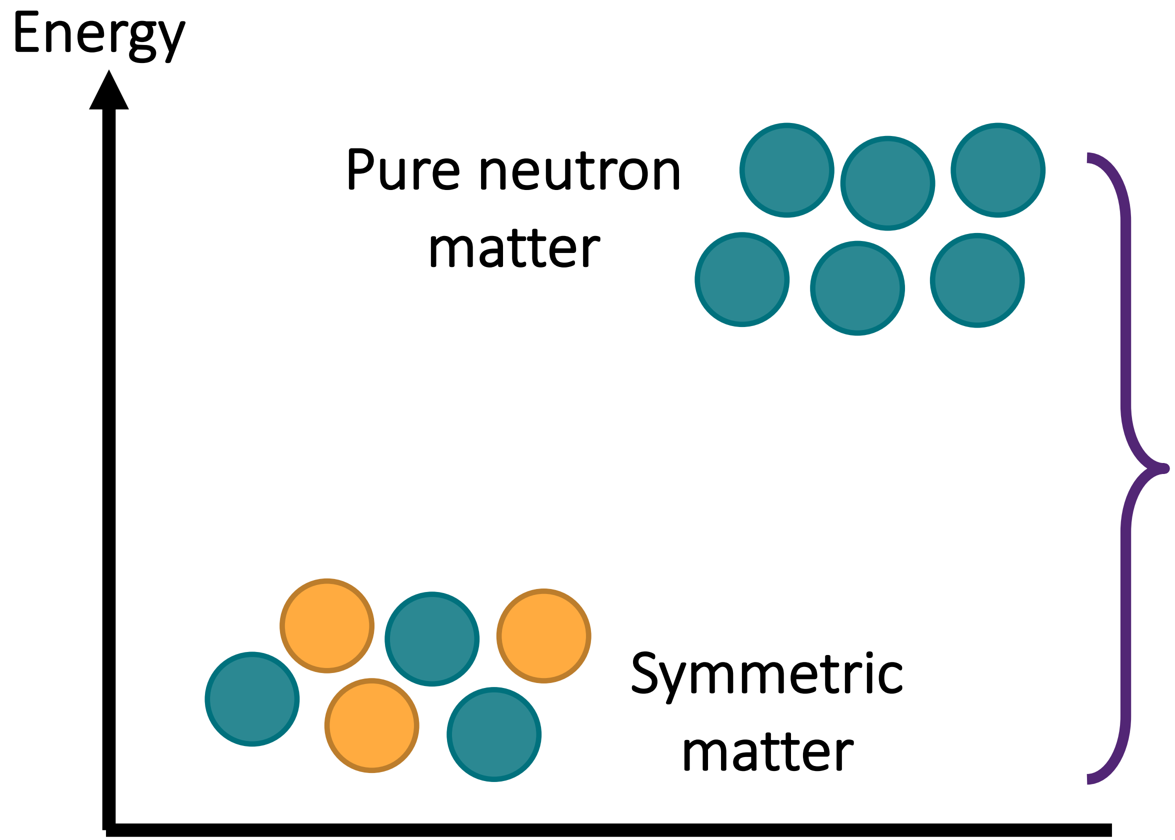
Raithel, Paschalidis, Özel (arXiv:2104.07226)



Raithel, Paschalidis, Özel (arXiv:2104.07226)

Part 3: Using the M^*-framework to study new parts of the *(cold)* EOS parameter space

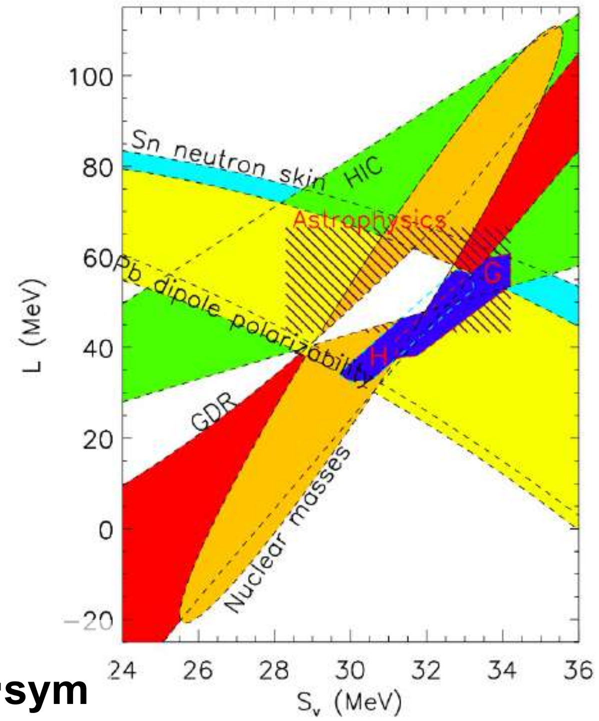
The nuclear symmetry energy



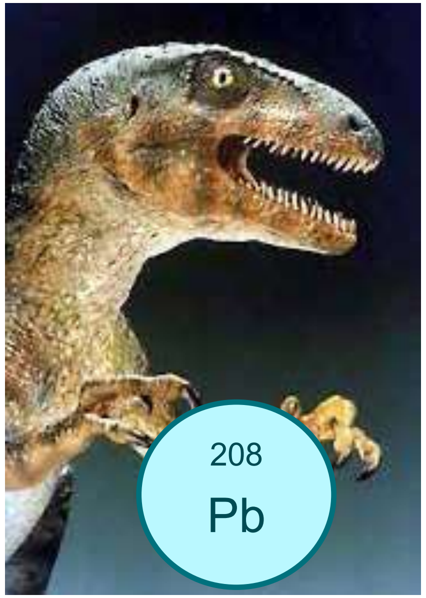
$\Delta E = E_{sym}$

$$E_{\rm sym}(n) = S_0 + \frac{L_0}{3}\left(\frac{n}{n_{\rm sat}} - 1\right) + \frac{K_{\rm sym}}{18}\left(\frac{n}{n_{\rm sat}} - 1\right)^2 + \quad \ldots$$

Lattimer & Lim 2013



Many experimental and theoretical constraints

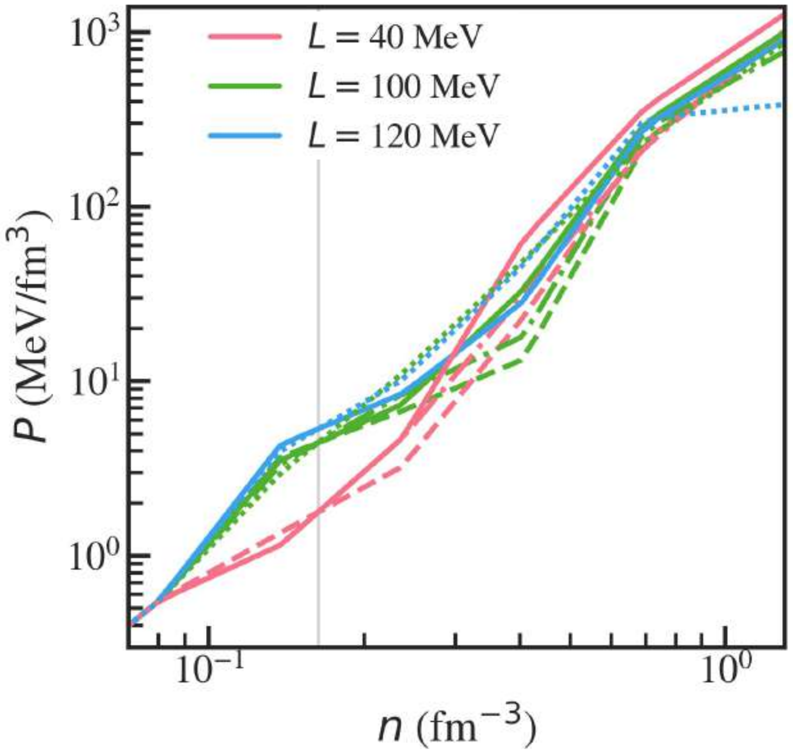


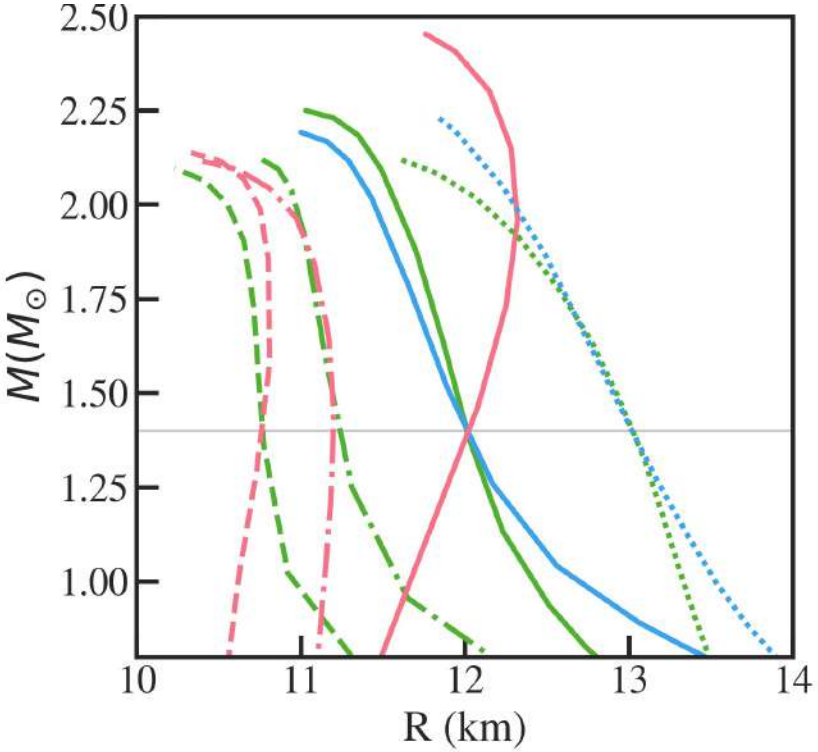
Recent exciting developments from PREX: the Lead (^{208}Pb) Radius Experiment

L = 106 ± 37 MeV

Adhikari et al. (2021), Reed et al. (2021)

Can we probe the **nuclear symmetry energy** with *post-merger* GWs?

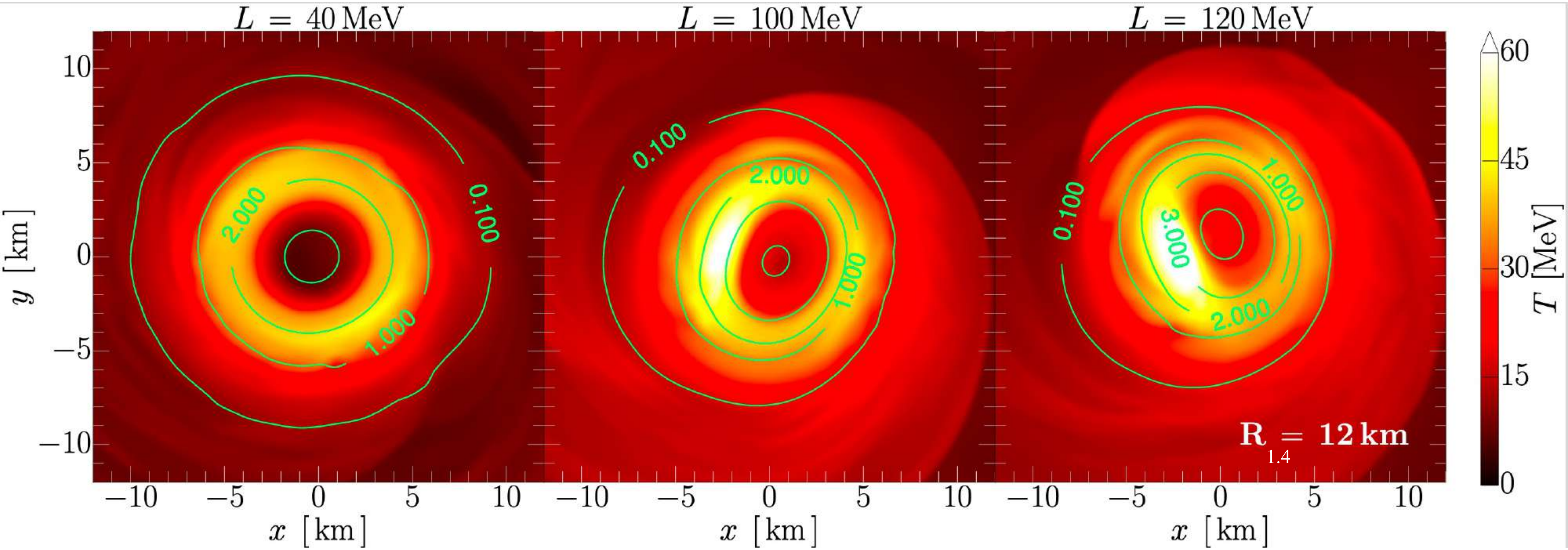




- New sample of EOSs constructed to systematically vary L, while keeping $R_{1.4}$ (or $\Lambda_{1.4}$) fixed
- Finite-temperature part of the EOS is *identical* in all cases (n_0=0.12 fm^{-3}, α=0.8)
- Simulated NS-NS mergers with GW170817-like parameters (q=0.85, M_{tot} =2.72 $M_\odot$)
- Simulations performed with IL-Frankfurt GRMHD + Carpet/Cactus spacetime

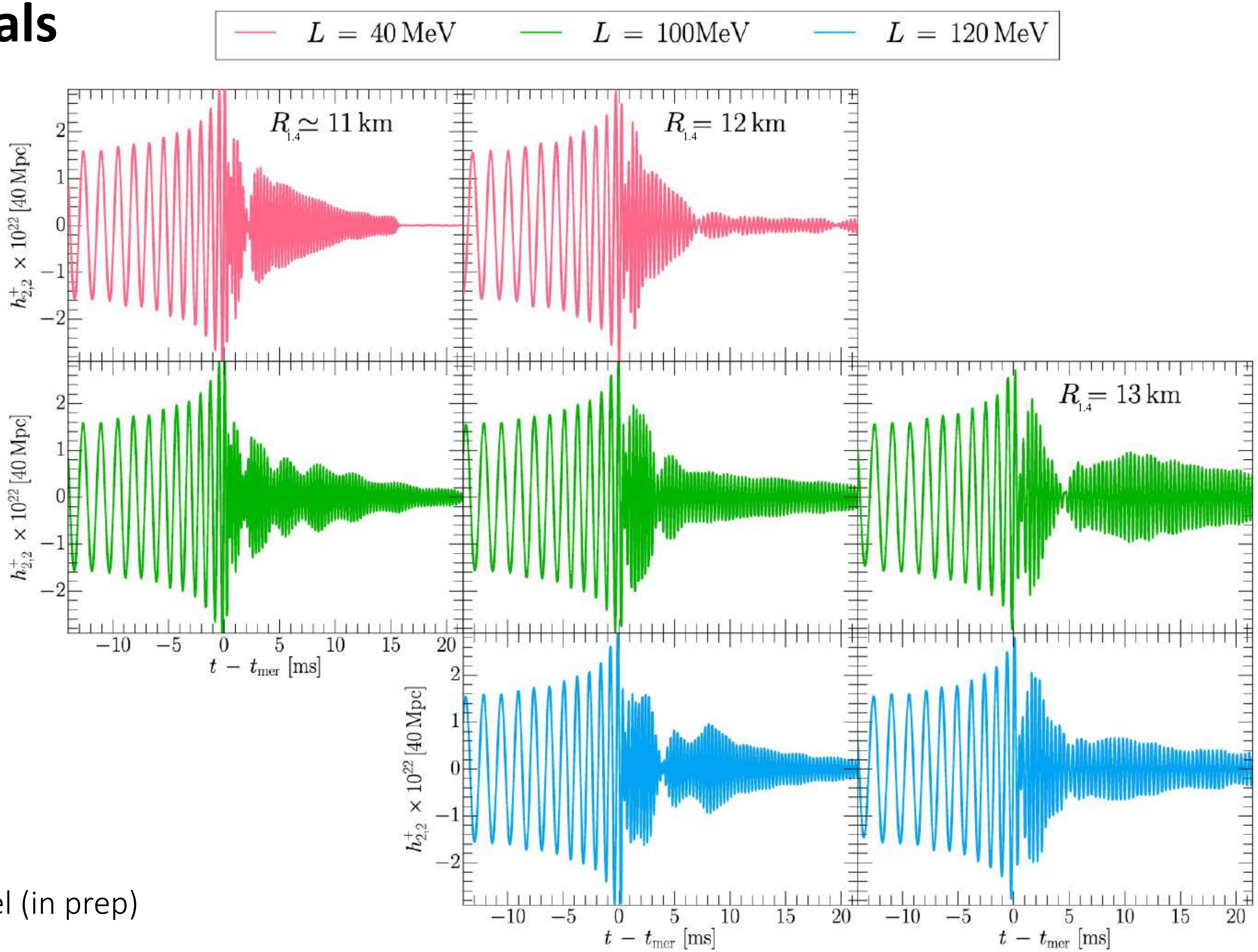
Most & Raithel (in prep)

Late-time temperature and density profiles of the post-merger remnant



Most & Raithel (in prep)

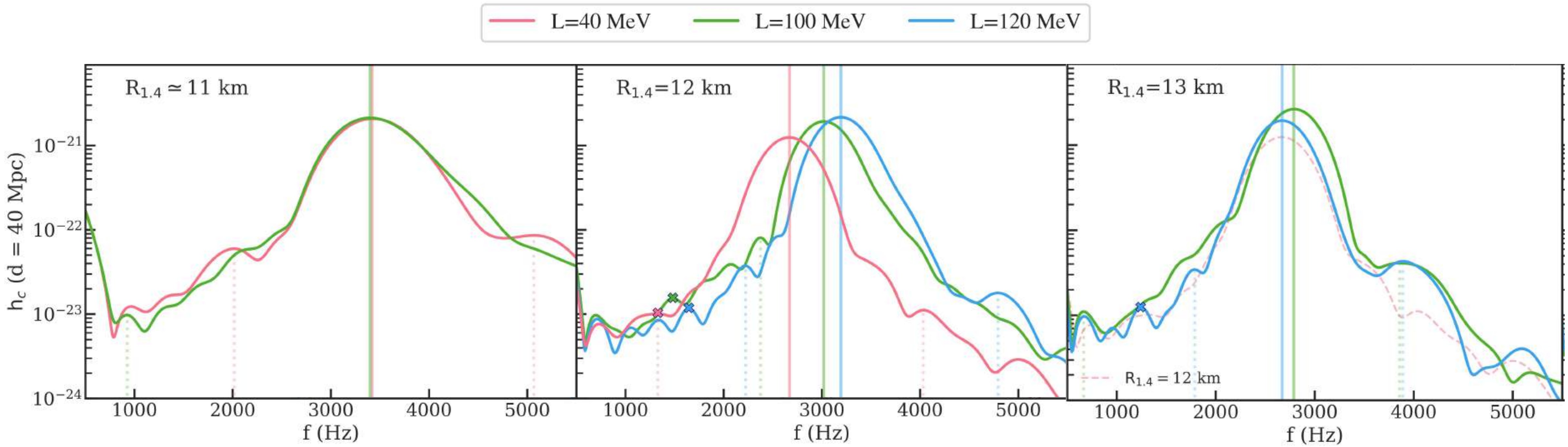
GW signals



Most & Raithel (in prep)

Post-merger GW power spectra

Most & Raithel (in prep)

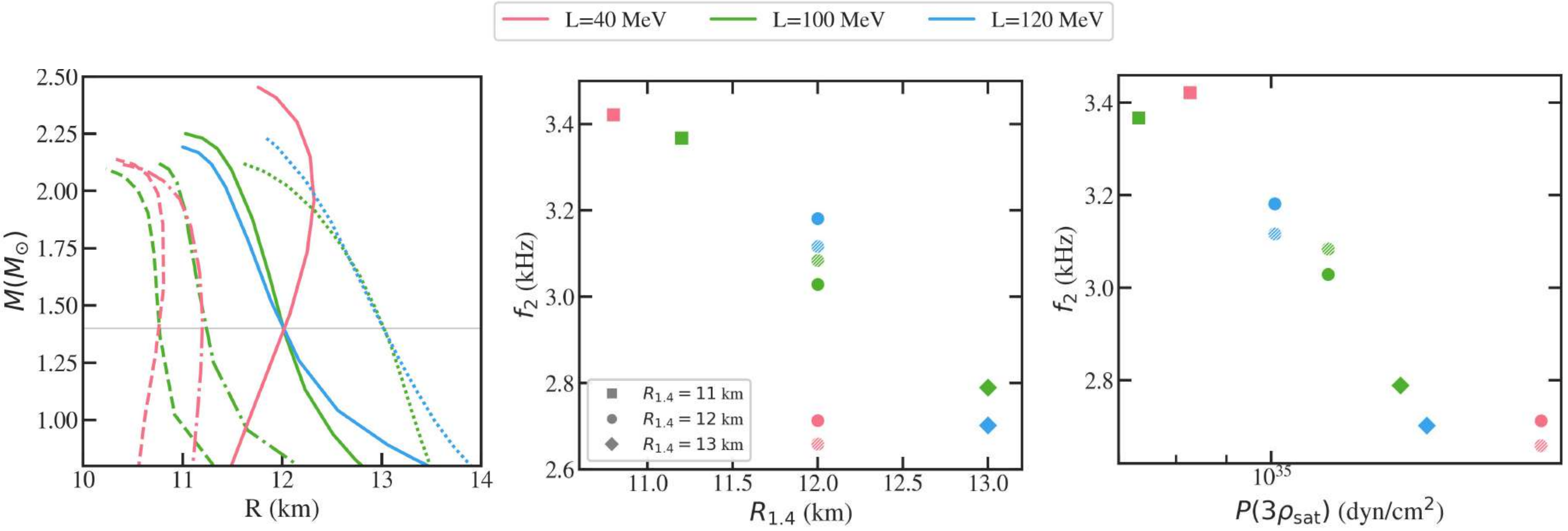


*R=11 km, L=40 MeV
binary collapses after 15 ms

No dependence on L for small stars, but significant trend (500 Hz shift!) for 12 km stars

Suggests that real dependence is on hidden parameter, which correlates with both L and $R_{1.4}$

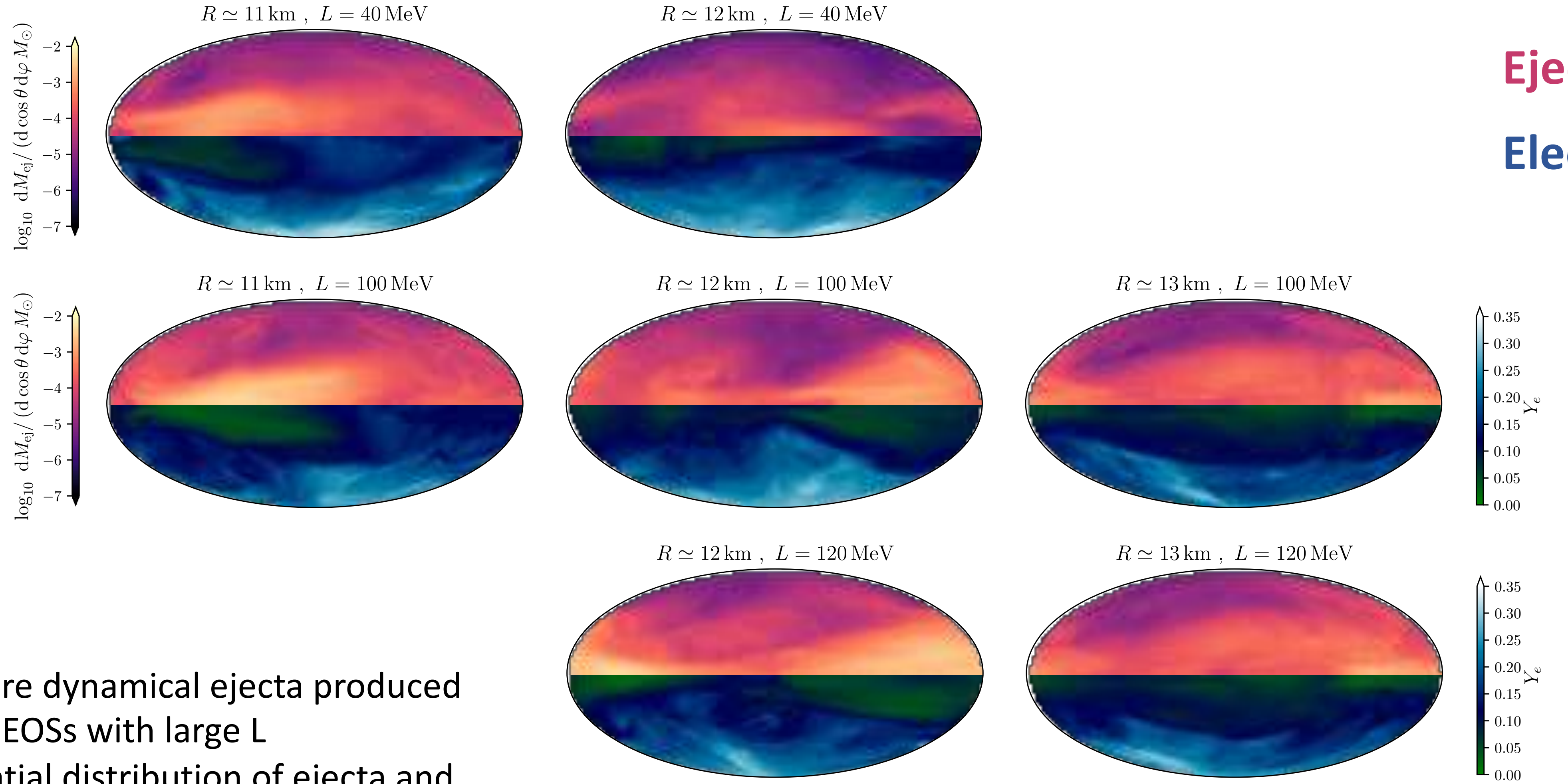
Dependence of post-merger GW spectrum on the *high-density* EOS



Most & Raithel (in prep)

(f_2 = location of main spectral peak)

Do ejecta properties depend on the slope of the symmetry energy?



Ejecta mass

Electron fraction

- More dynamical ejecta produced for EOSs with large L
- Spatial distribution of ejecta and composition both have weak dependence on L

Most & Raithel (in prep)

Summary & future directions

- Wealth of new information expected from post-merger GWs, but interpreting these signals requires detailed numerical simulations that use a *wide range* of EOSs with realistic microphysics
- M*-framework provides a robust treatment of thermal physics in merger simulations, and can added to *any* cold EOS (Raithel, Özel, Psaltis 2019)
    - M*-parameters can affect remnant structure and post-merger oscillations, providing possible new probe of finite-temperature part of EOS (Raithel, Paschalidis, Özel, 2021, arXiv:2104.07226)
- M*-framework can also be used to systematically explore differences in the cold part of the EOS – such as the nuclear symmetry energy – while keeping the thermal physics constant between models (Most & Raithel, in prep.)