

# Equation of state of high-density matter and QCD phase transitions

Snowmass CF-7 discussion, 3 Feb 2022, Jocelyn Read

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Sinha (kuver.sinha@ou.edu), Or Hen (hen@mit.edu)

# Schedule plans

- Team members have had significant schedule disruptions up to now; minimal opportunity for coordination
  - [Joint document](#) to established the outline
- Meeting planning next week to restart process and recruit additional contributions
- Please contact me [jread@fullerton.edu](mailto:jread@fullerton.edu) or Emmanuel Fonsesca [emmanuel.fonseca@mail.wvu.edu](mailto:emmanuel.fonseca@mail.wvu.edu) to get involved

# Letters of Interest

[Cold QCD Matter at High Densities](#)

[Discovering quark-matter cores in massive neutron stars](#)

[Illuminating the Dark Sector in Neutron Star Mergers](#)

[Probing Nuclear Astrophysics and Gravitation with Neutron Stars](#)

[Compact binaries as probes of dense matter and QCD phase transitions](#)

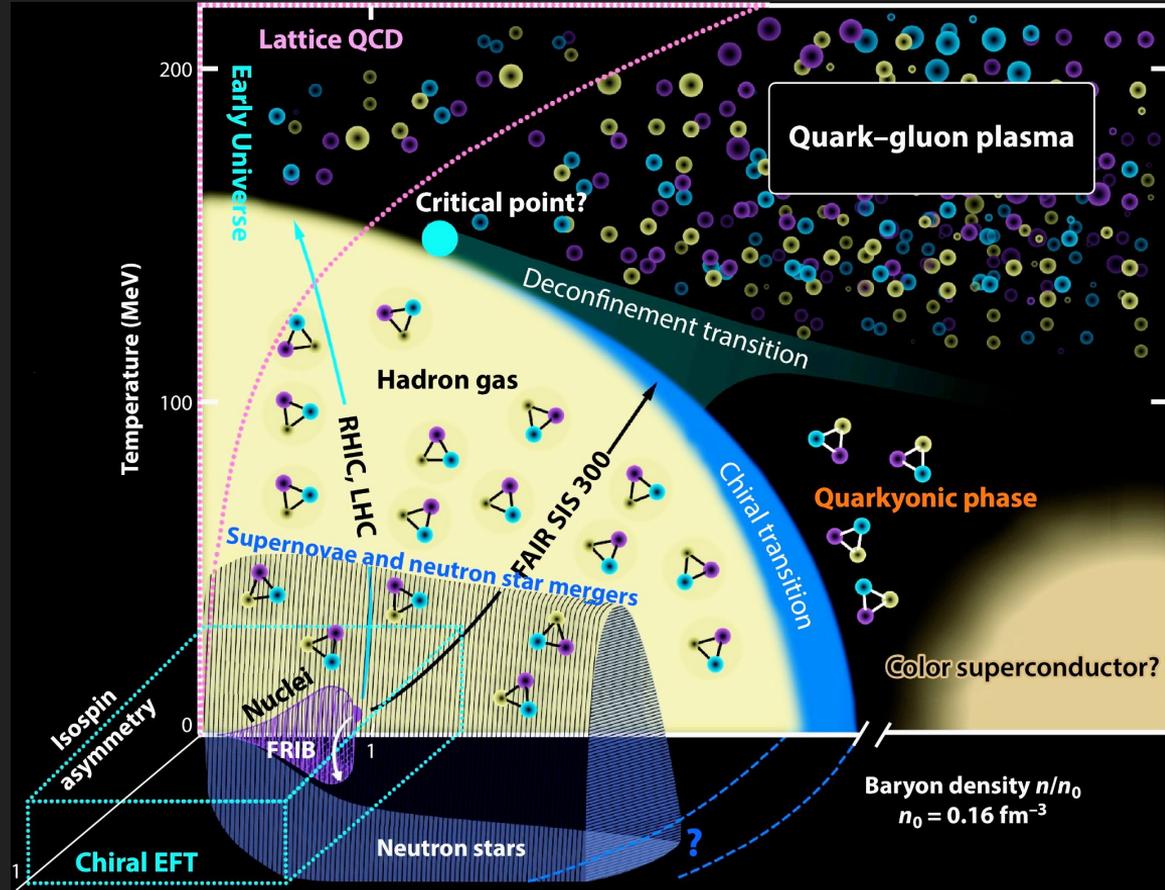
# Draft Outline

- Theoretical equation of state
  - developments: in ab-initio and EFT calculations of many-body hadronic systems, lattice Monte-Carlo simulations, perturbative QCD calculations
  - phase diagram: microscopic (i.e. quark-gluon) structure, nuclear and quark matter
  - model-independent descriptions
  - impact of dark-sector particles
- Connections with experiment
  - heavy ion collisions, neutron skin, proton-rich nuclei
  - nucleon-nucleon short-range correlations
- Neutron star observations
  - Connections between dense matter and NS properties (mass, radius, moment of inertia, cooling)
  - Radio observations of pulsars
  - X-ray spectroscopic observation
- Merger transient observations
  - Thermodynamic conditions of merger
  - GW observation
  - Kilonovae observations
  - GRB observations
- Future prospects and observing scenarios

# Theoretical EOS

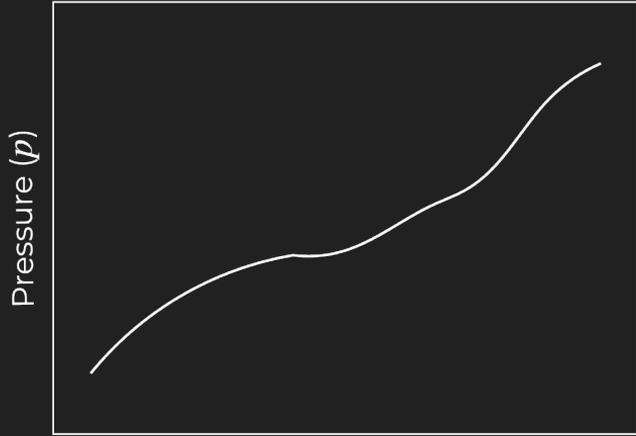
- Developments in ab-initio and EFT calculations, lattice Monte-Carlo simulations, perturbative QCD calculations
- Phase diagram: microscopic (i.e. quark-gluon) structure, nuclear and quark matter
- model-independent descriptions
- impact of dark-sector particles

## Connections to Experiment



# Cold Dense Matter and Neutron Stars

Equation of State

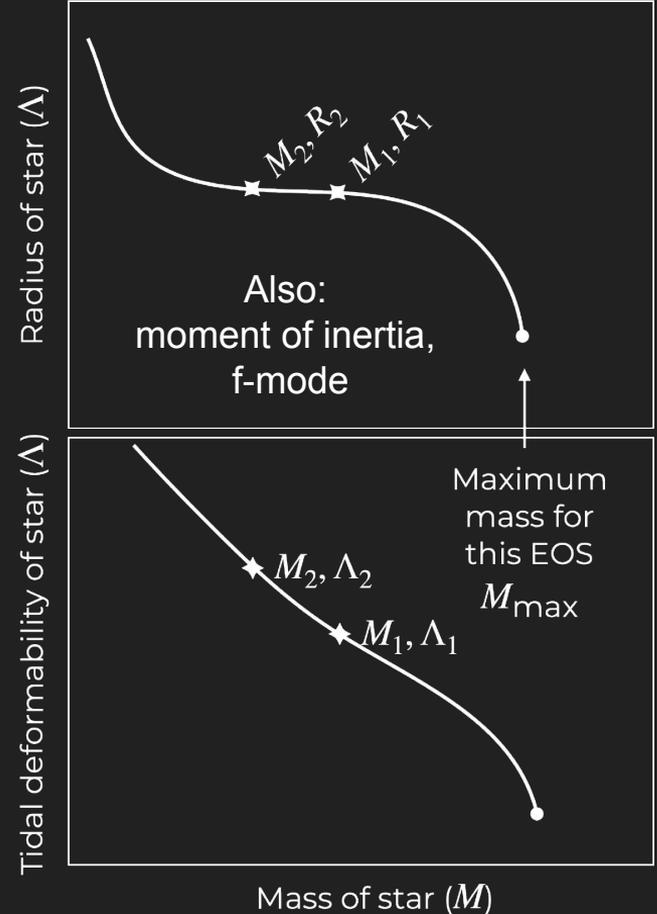


density ( $n, \rho$  or  $\epsilon$  depending)

1-1 mapping **unless**: dark sector contribution

Equilibria for  
range of central  
densities, giving  
range of  $M$

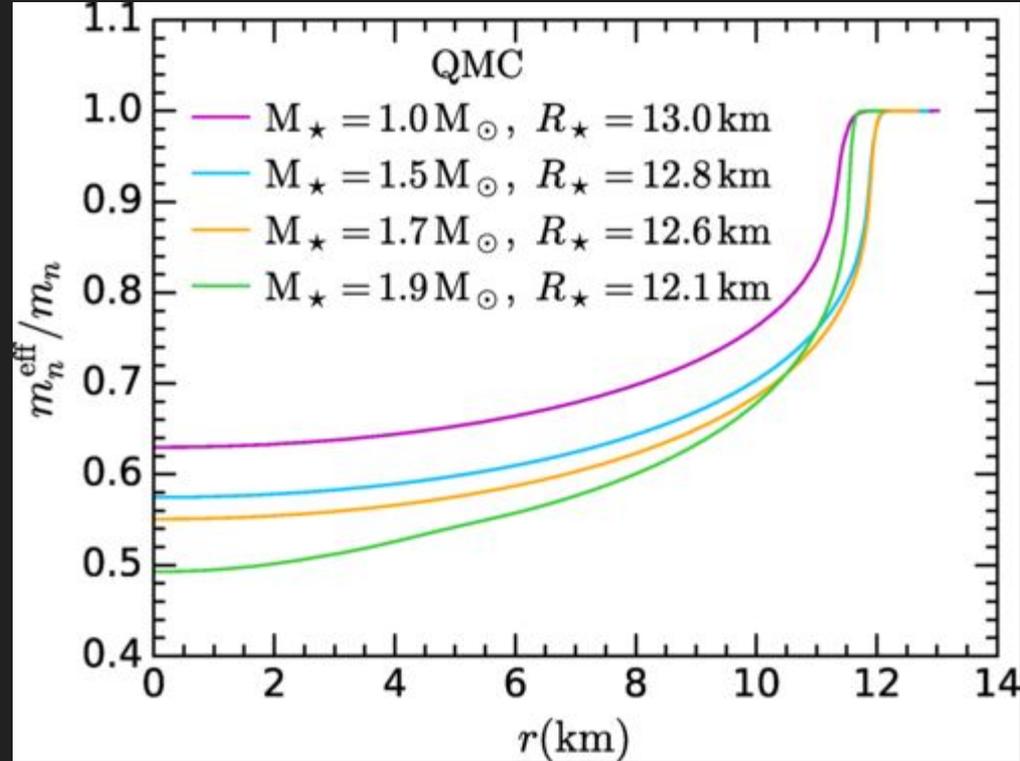
Stable stars for a given EOS



# Implications for dark matter

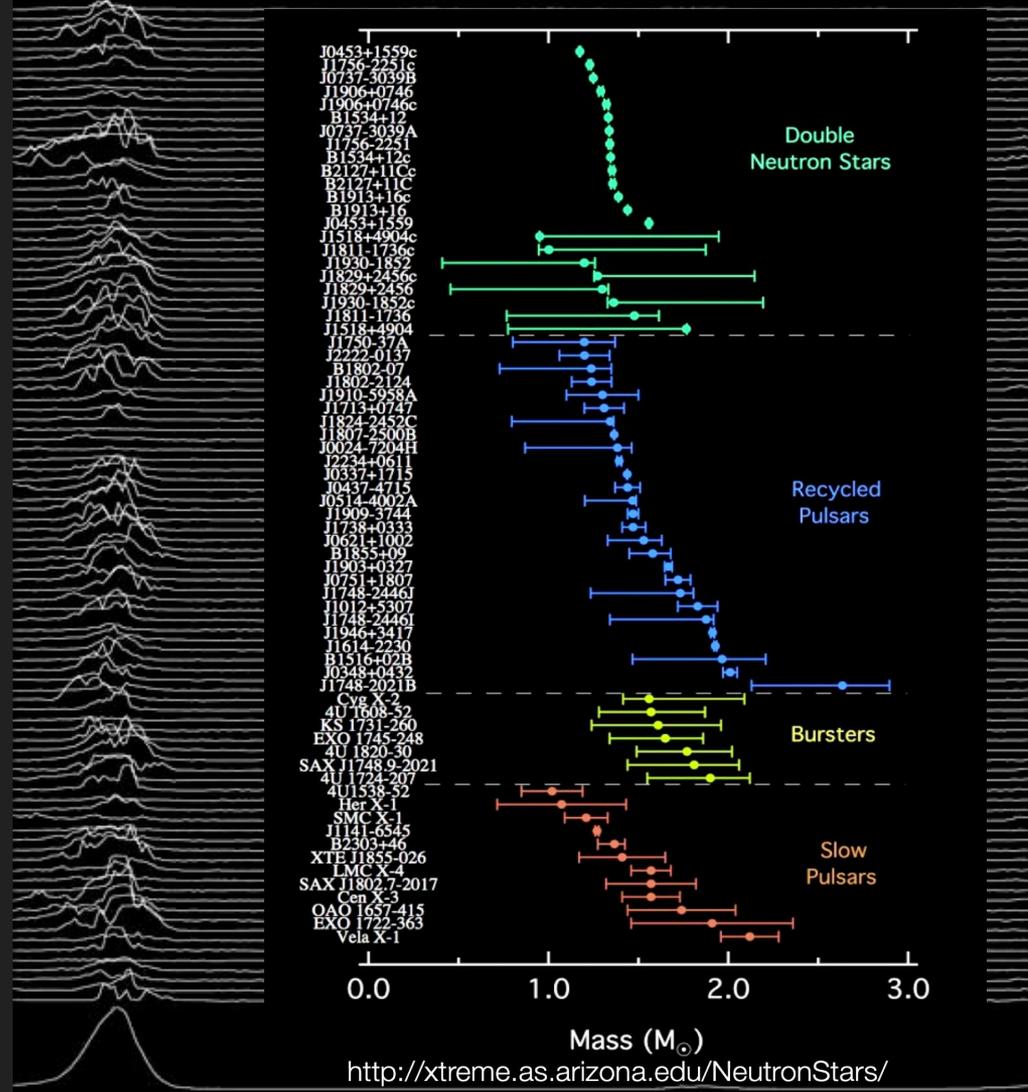
- NSs as cosmic probes of DM candidates (e.g., Kouvaris & Tinyakov, 2010, Phys. Rev. D, 82, 063531)
- Fermionic dark matter within NSs lead to observable variations in EOS structure (e.g., Panotopoulos & Lopes, Phys. Rev. D, 96 083004).
- Directly constrained by future observations

Bell et al  
Phys. Rev. Lett. 127, 111803



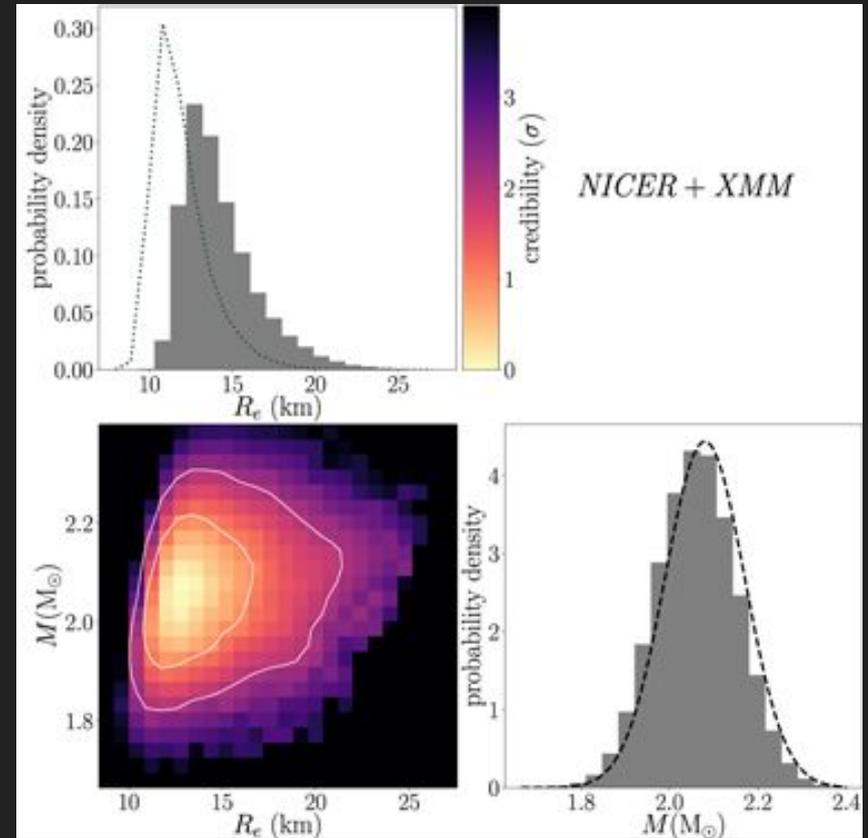
# Pulsar observations

- Radio pulsars timed with sub-microsecond precision
- Pulsar timing from binary systems reveals general-relativistic effects that depend on compactness and/or orientation of orbit, masses of components, etc. (see review by [Stairs, Living Reviews of Relativity](#), 6, 5).
- Measured properties include precise **neutron-star masses**



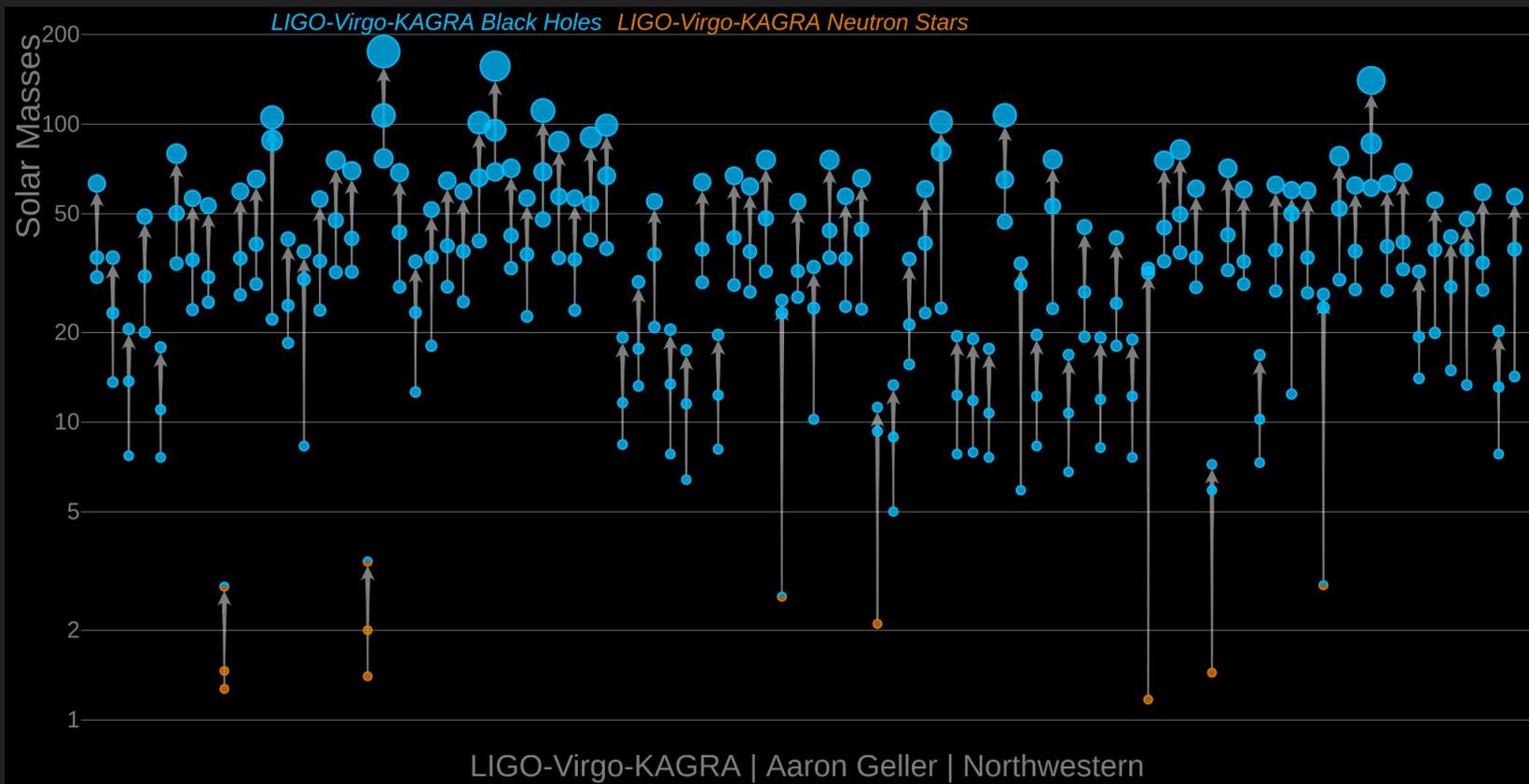
# X-ray observations

- X-ray thermal radiation from neutron stars is strongly affected by compactness and surface gravity.
- NICER, XMM-Newton
- [Focus on NICER Constraints on the Dense Matter Equation of State, Astrophysical Journal Letters](#)
  - PSR J0030+0451 in 2019
  - PSR J0740+6620 in 2021
- Also observed: X-ray burst transients and cooling



*M. C. Miller et al. (2021, ApJL, 918, L28)*

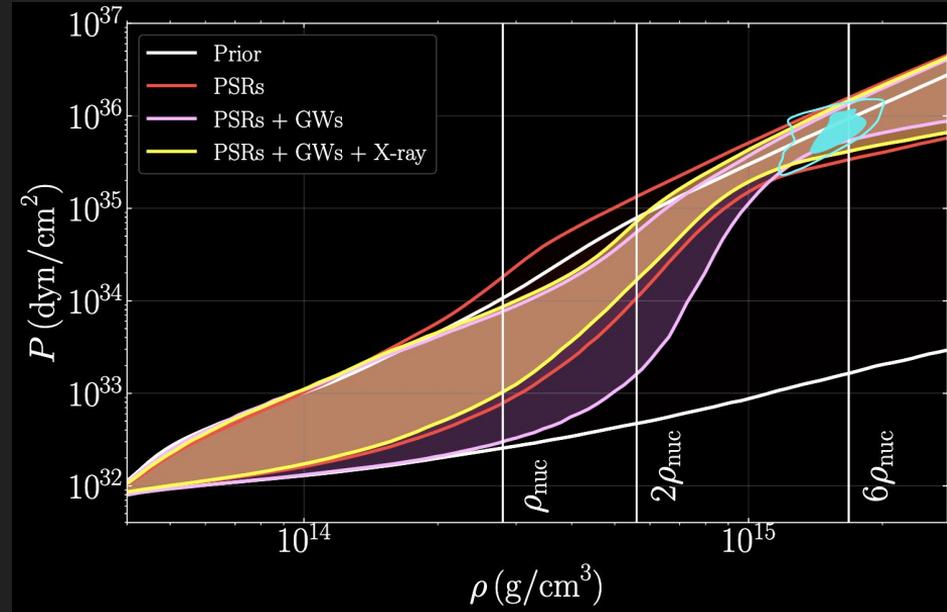
# Merger observations



# GW observations



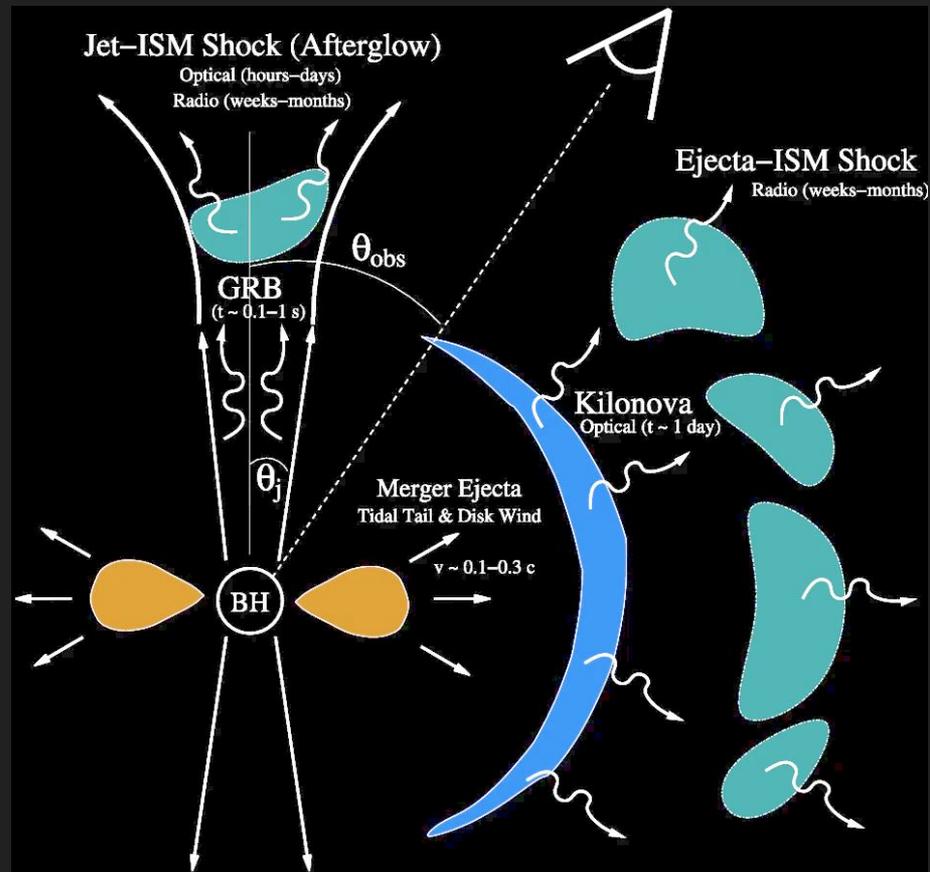
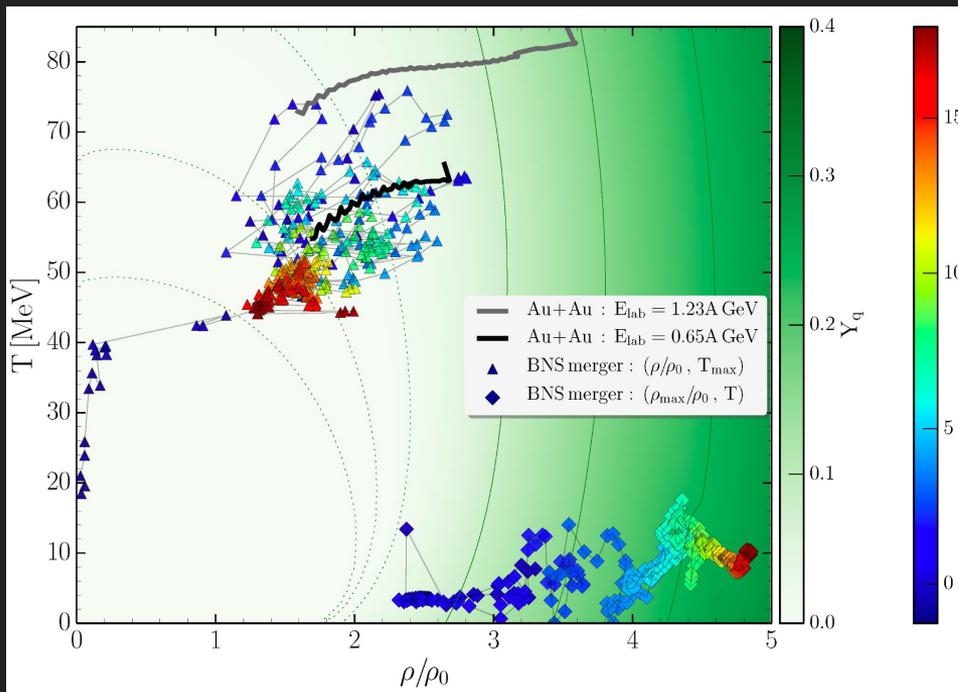
- direct constraints on masses and tidal deformability from observed inspiral
- constrain mass distribution and EOS (see right)
- Growing sample of NS
  - constraints on, e.g., hadron-to-quark phase transitions from a sample of deformability measurements (e.g., Chatziioannou & Han, Phys. Rev. D, 101, 044019).
- Multi-messenger constraints from combining GW and EM measurements (e.g., Dietrich et al., Science, 370, 1450).



*Legred et al Phys. Rev. D 104, 063003 (2021)*

# Postmerger, Kilonova, GRB

Connections to multi-messenger landscape



Metzger, Living Reviews in Relativity volume 23: 1  
(2020)