Multi-messenger Astronomy and the Physics of Hot and Dense Matter

Andrew W. Steiner

UTK/ORNL

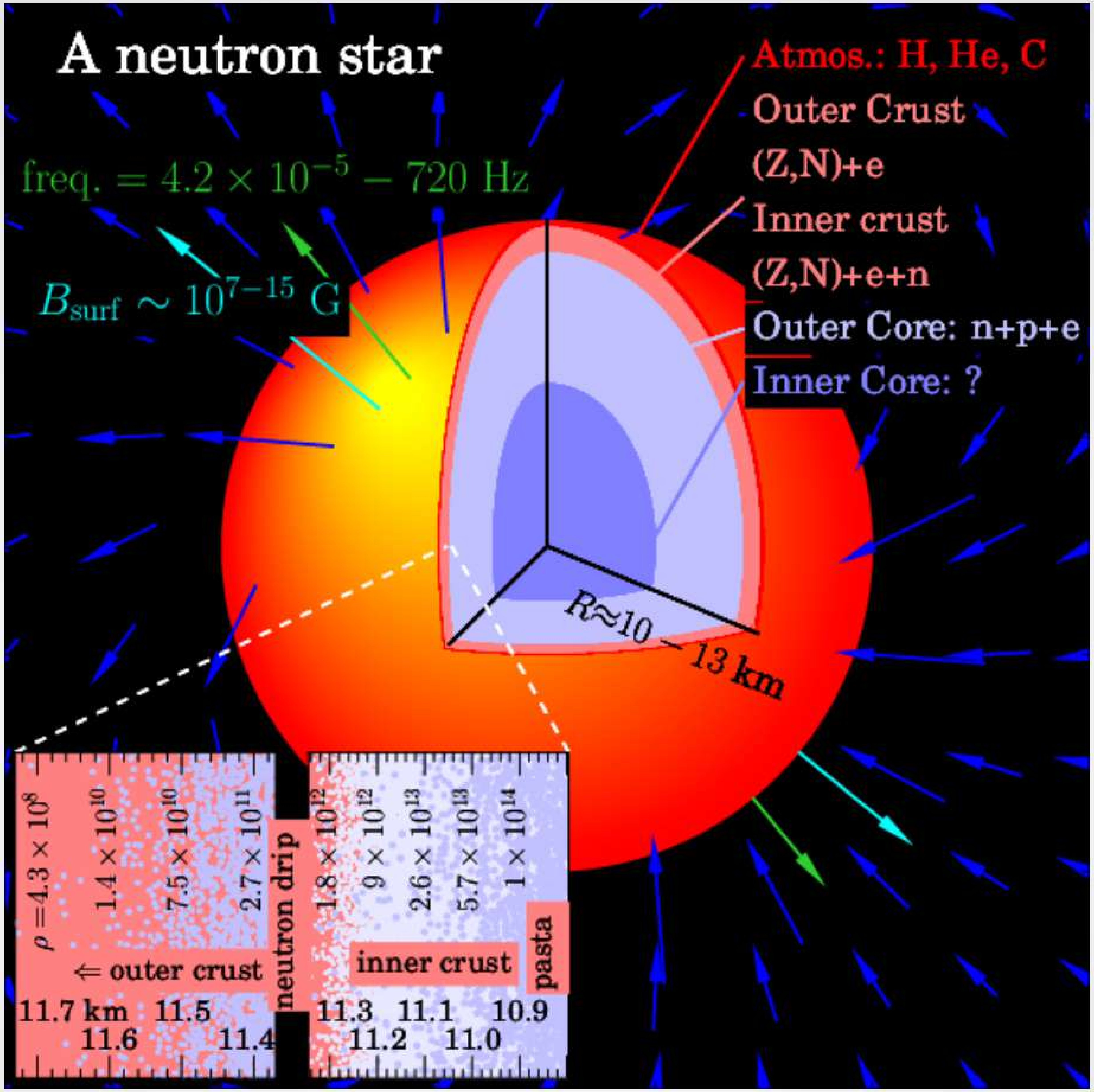
Oct. 27, 2021

Collaborators: **Mohammad Al-Mamun**, **Spencer Beloin**, **Xingfu Du**, Stefano Gandolfi, **Sophia Han**, **Anik Hasan**, Craig Heinke, Jeremy Holt, Jacob Lange, **Zidu Lin**, Joonas Nättilä, Khorgolkhuu Odbadrakh, Richard O'Shaughnessy, **Satyajit Roy**, Ingo Tews

Outline

- Neutron star introduction
- Somewhat myopic view of the last decade on the nature of hot and dense matter
- Nuclear physics input for neutron star mergers
- Putting it all together: NP3M

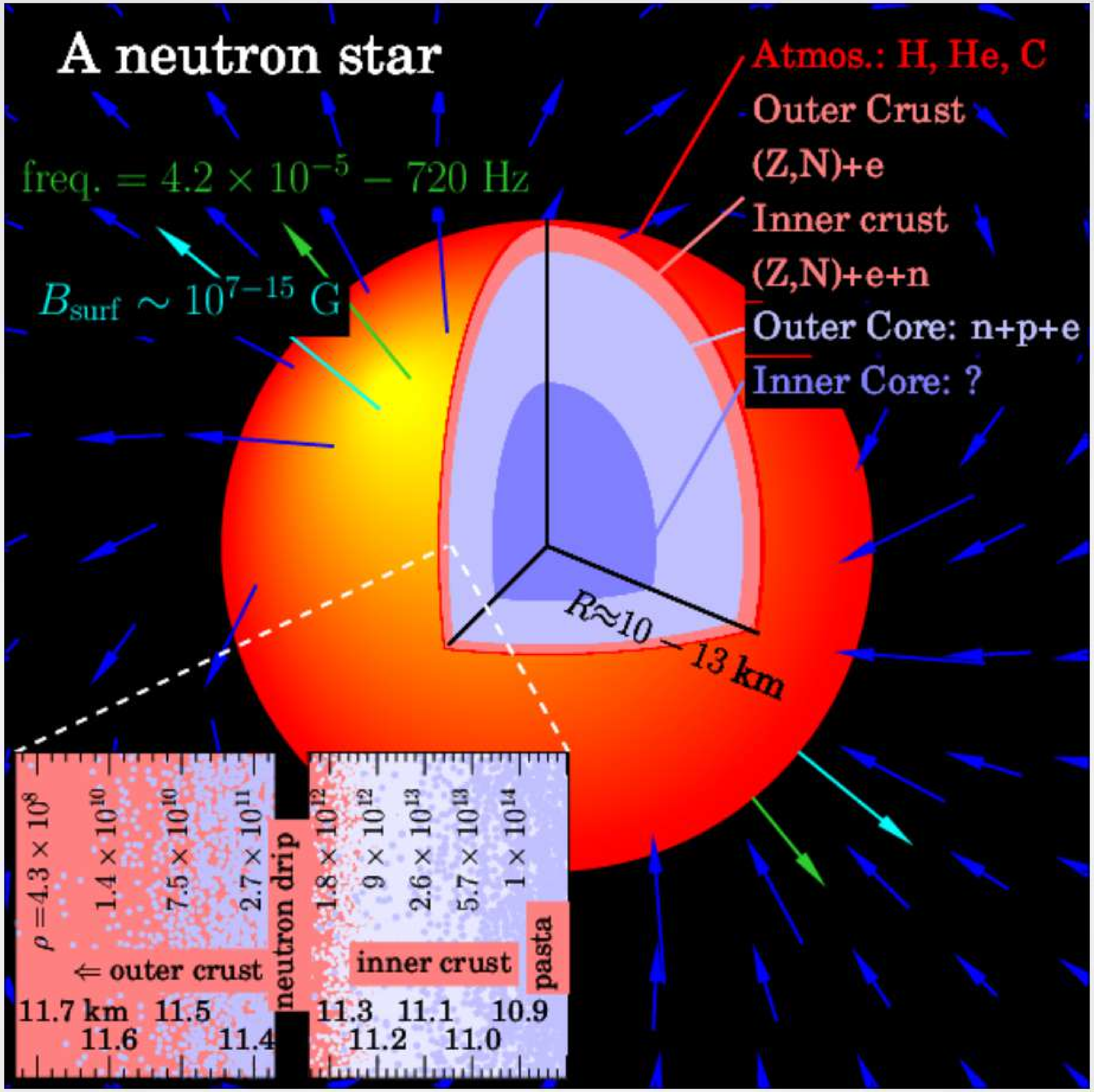
Neutron Stars



Plot inspired by Dany Page; open source

- The final state in the evolution of stars between 8 and 20 times $\mathrm{M}_\odot$

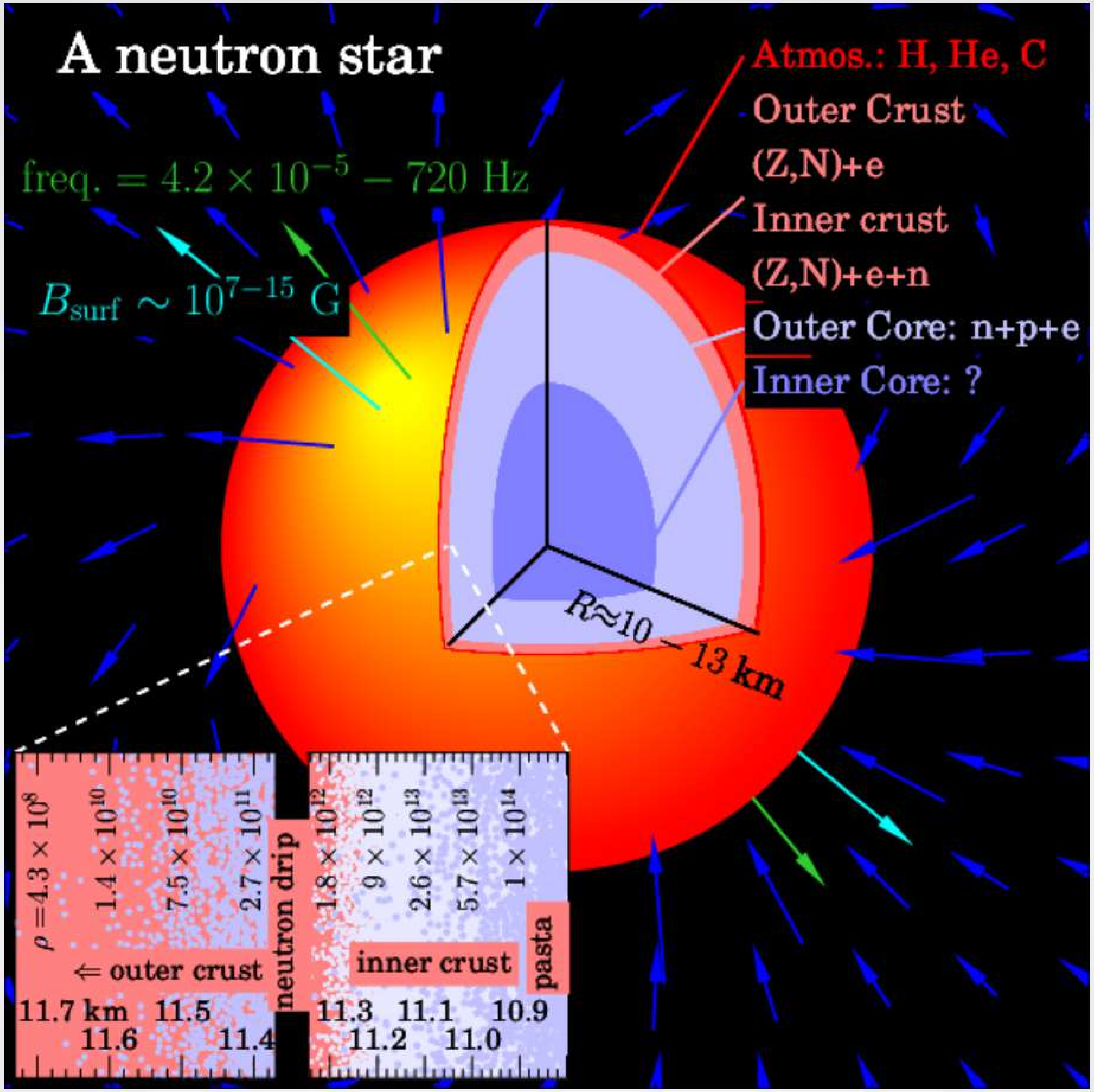
Neutron Stars



Plot inspired by Dany Page; open source

- The final state in the evolution of stars between 8 and 20 times $\mathrm{M}_\odot$
- Nuclei with $A \sim 10^{57}$ that provide information about QCD

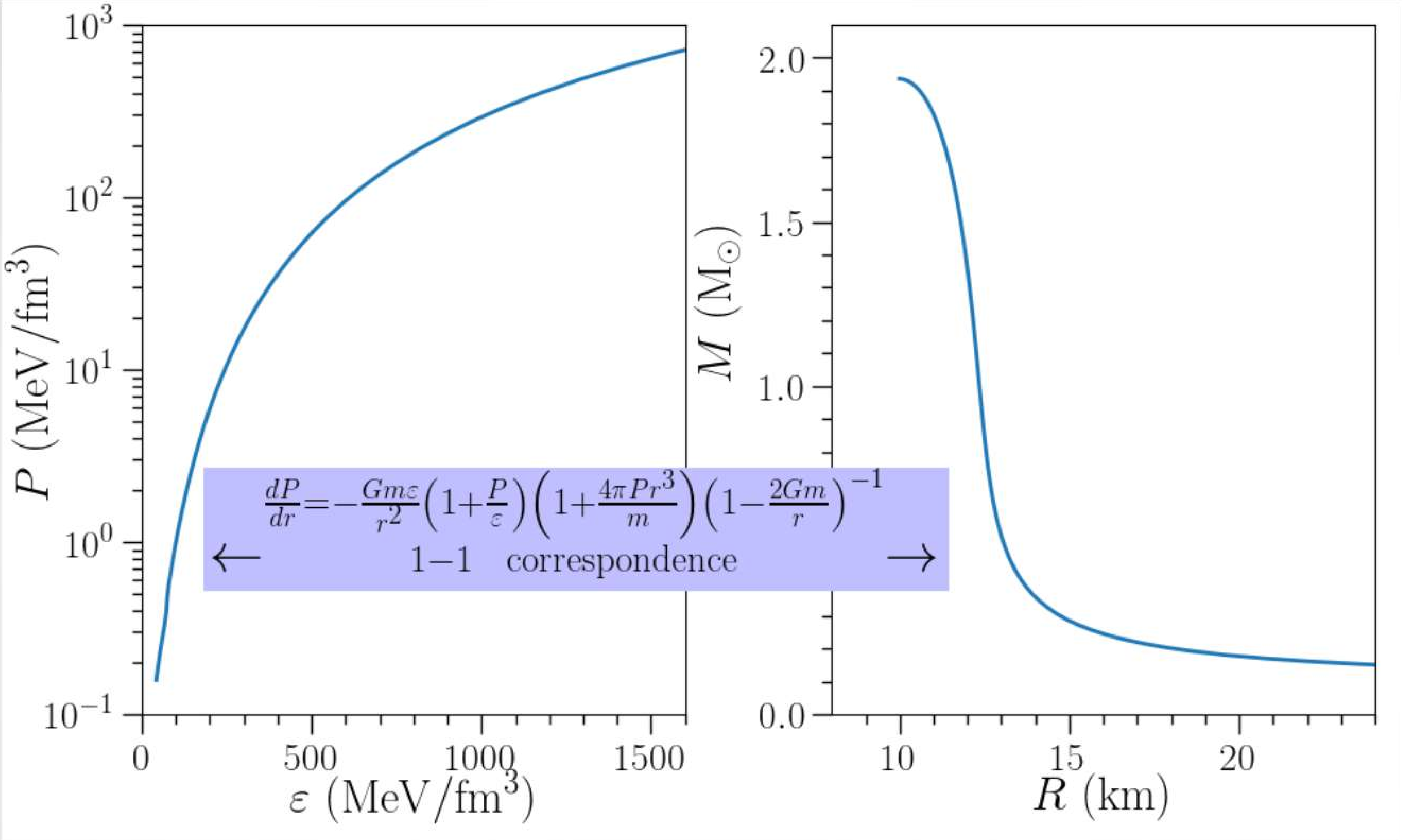
Neutron Stars



Plot inspired by Dany Page; open source

- The final state in the evolution of stars between 8 and 20 times $M_\odot$
- Nuclei with $A \sim 10^{57}$ that provide information about QCD
- Degenerate: $(\mu_{\rm min,core} \approx 20\ \text{MeV}) \gg T$

Equation of State of Dense Matter and the Neutron Star Mass-Radius Curve



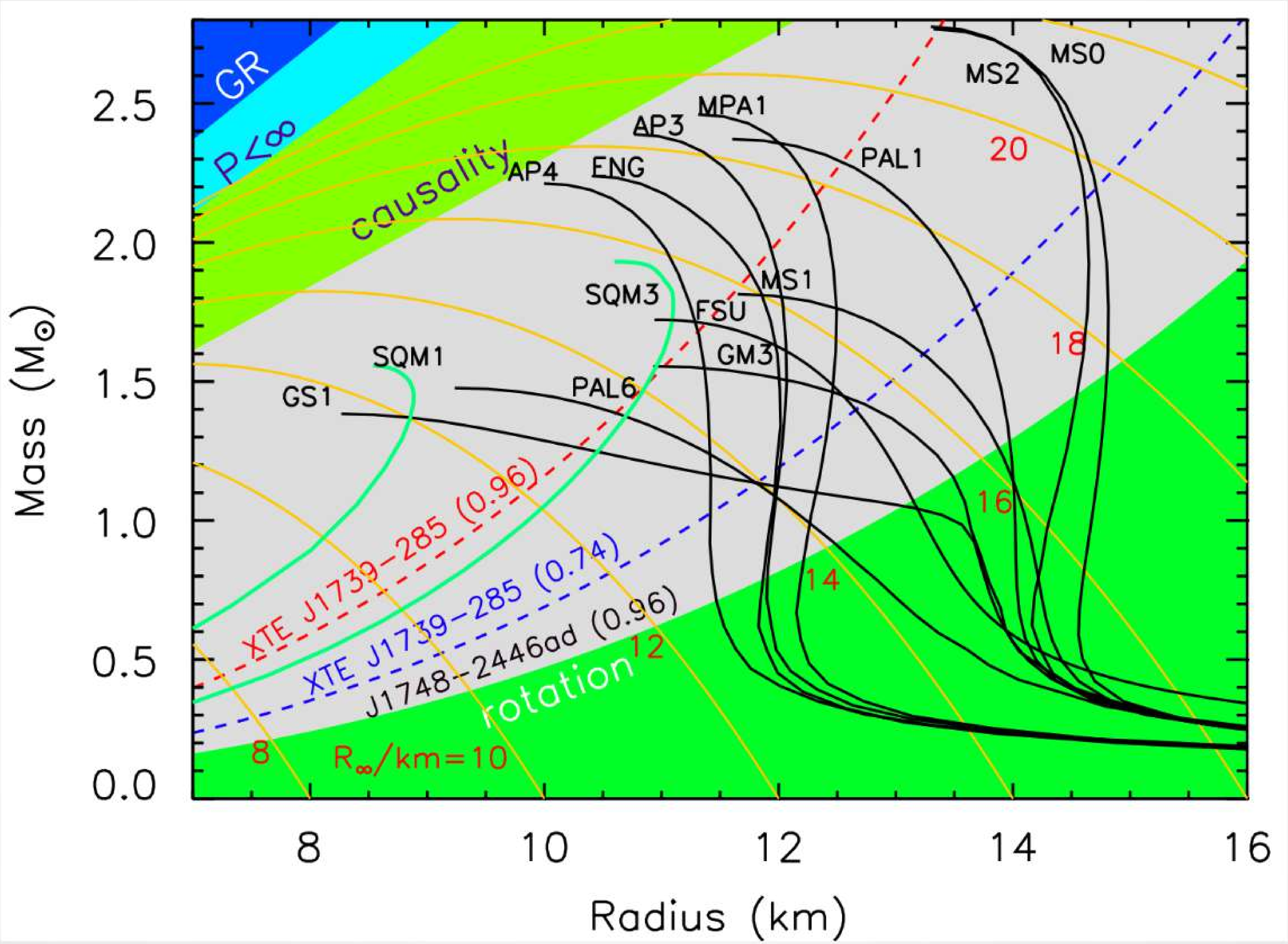
$$\frac{dP}{dr} = -\frac{Gm\varepsilon}{r^2}\left(1+\frac{P}{\varepsilon}\right)\left(1+\frac{4\pi P r^3}{m}\right)\left(1-\frac{2Gm}{r}\right)^{-1}$$

← 1−1 correspondence →

- There is a 1-1 correspondence between the (cold) equation of state and the neutron star mass-radius curve

- Attempts to make this connection go back to **Cameron (1959)**

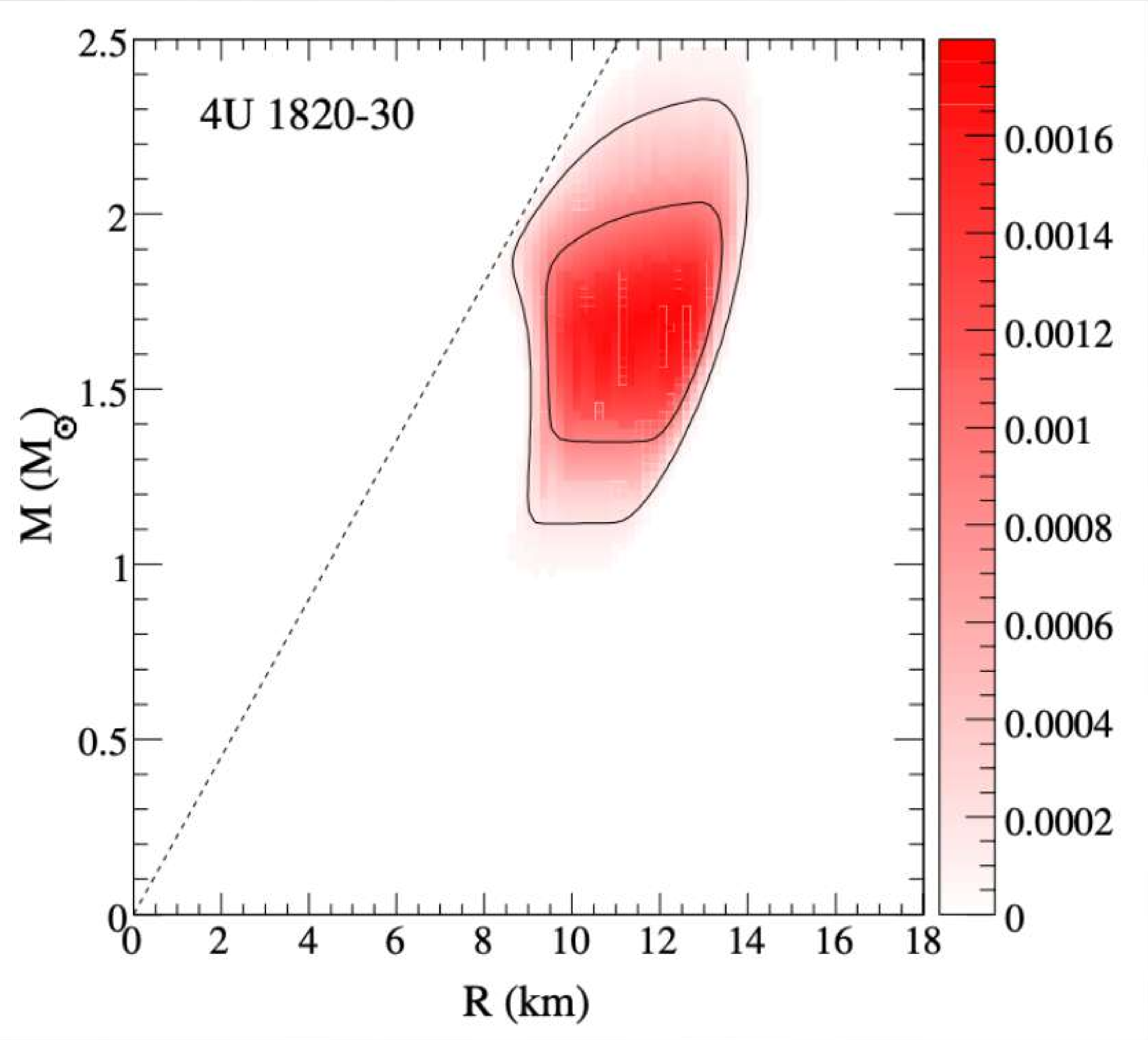
Neutron Star Mass-Radius Curves, 2007



Lattimer et al. (2007)

- A significant amount of uncertainty in the EOS across a range of densities
- Observational and theoretical constraints lead to the grey region

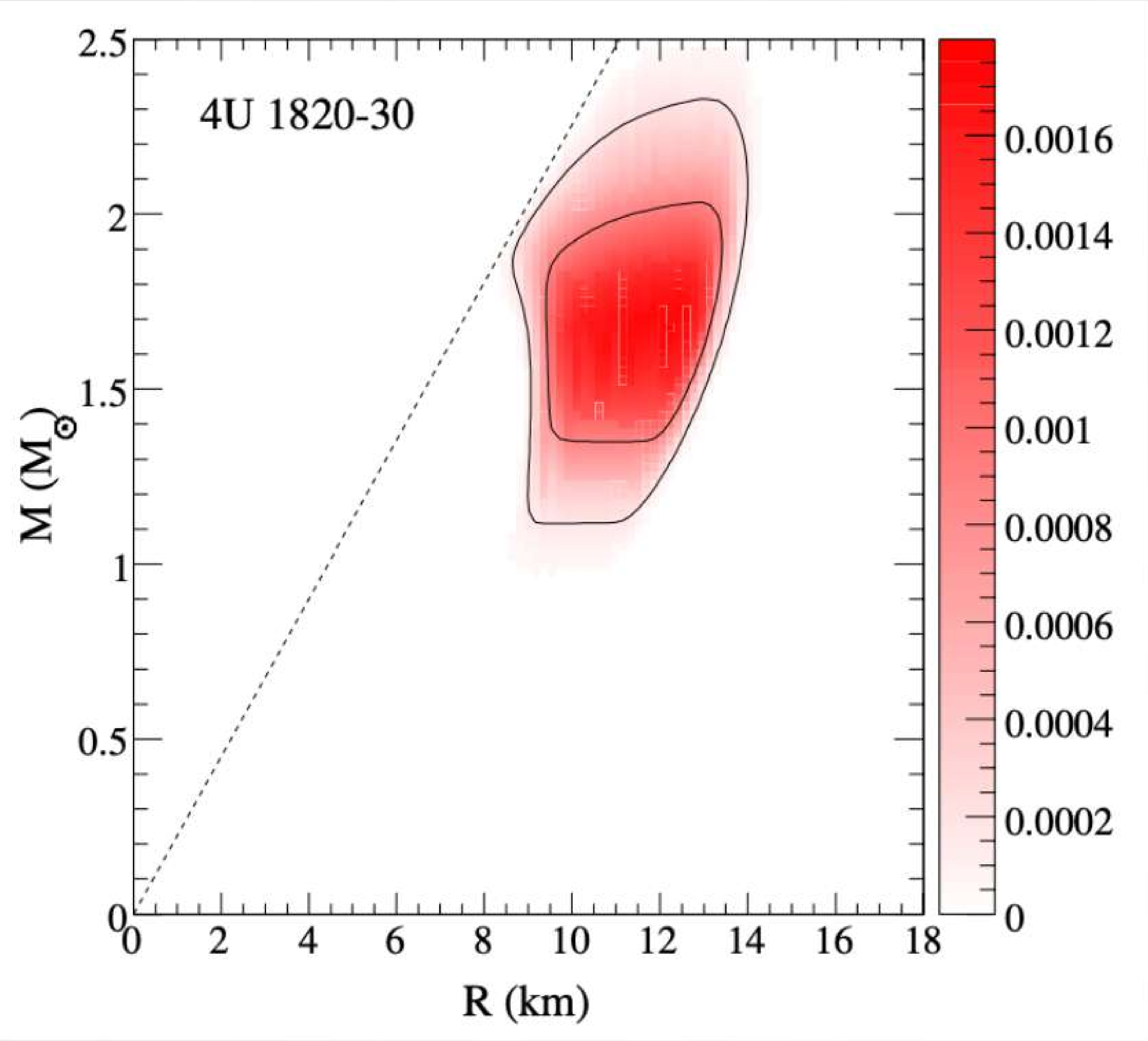
Neutron Star Mass-Radius Curves, 2010



Steiner et al. (2010) based on Chandra observations, work by Özel et al., etc.

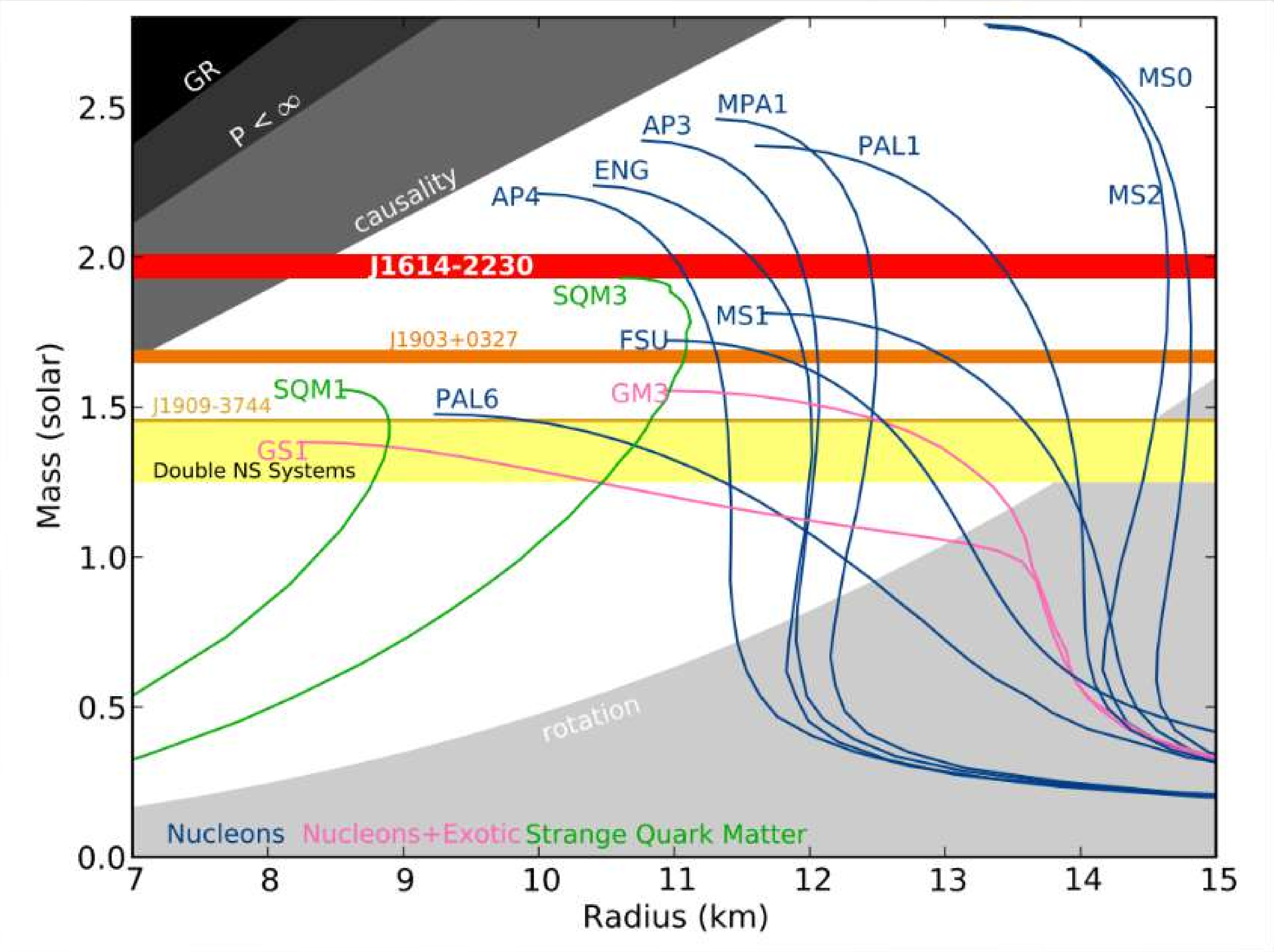
- Radius information for six stars
- Radii beteen 10.4 and 12.9 km

Neutron Star Mass-Radius Curves, 2010



Steiner et al. (2010) based on Chandra observations, work by Özel et al., etc.

- Radius information for six stars
- Radii beteen 10.4 and 12.9 km



Demorest et al. (2010)

- Observation of a two solar mass neutron star
- **New information on the equation of state!**

Constrain the Nucleon-Nucleon Interaction, 2012

- Normally nn-interaction ⇒ EOS ⇒ neutron star prediction

Constrain the Nucleon-Nucleon Interaction, 2012

- Normally nn-interaction ⇒ EOS ⇒ neutron star prediction
- Take advantage of Bayesian inference as "inverse probability"

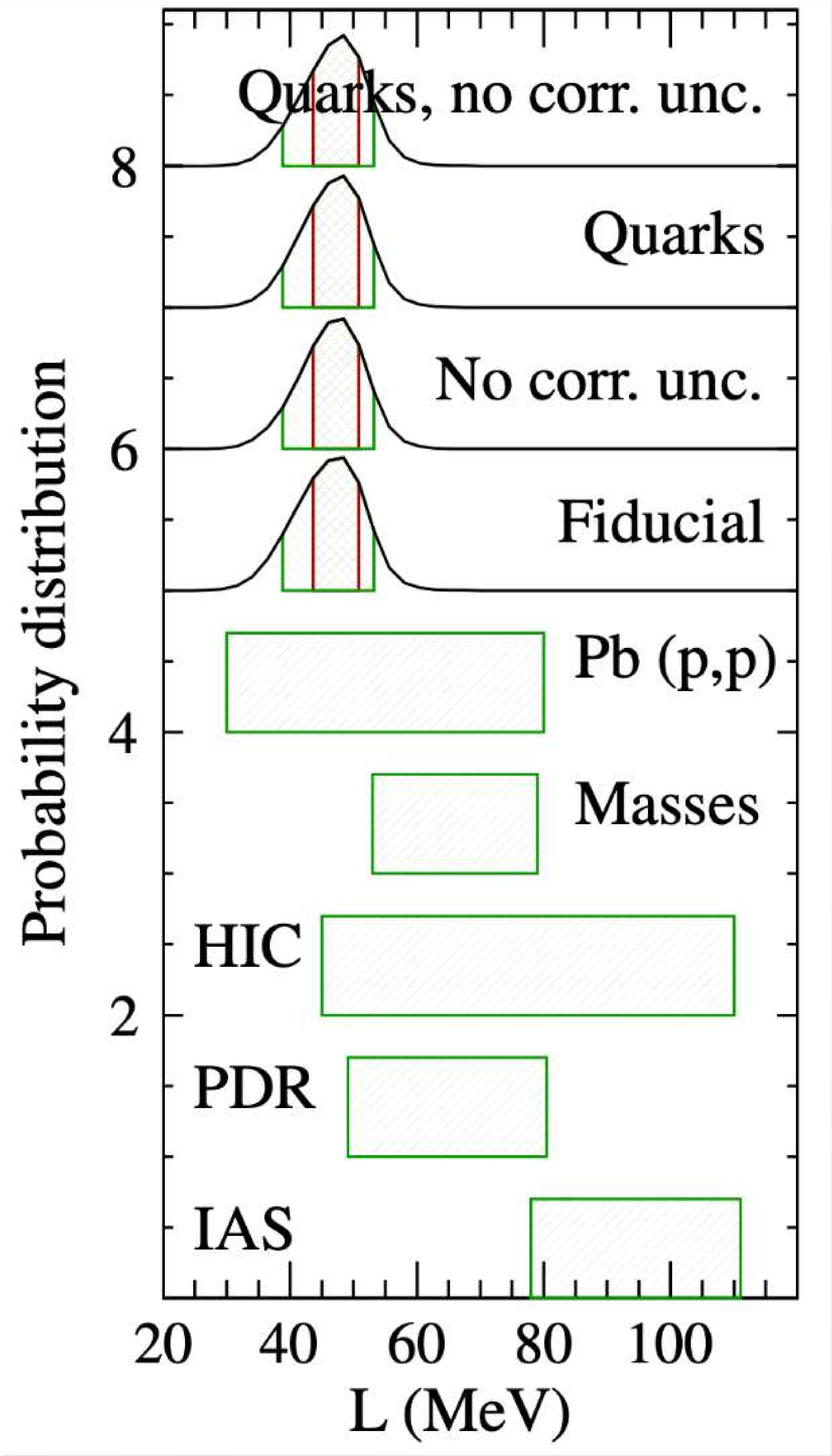
Constrain the Nucleon-Nucleon Interaction, 2012

- Normally nn-interaction ⇒ EOS ⇒ neutron star prediction
- Take advantage of Bayesian inference as "inverse probability"
- Neutron star observations constrain L, the density derivative of the nuclear symmetry energy

$$S(n_B) = E_{\mathrm{neut}}(n_B) - E_{\mathrm{nuc}}(n_B)$$
$$L = 3 n_B S'(n_B)$$

(from Steiner and Gandolfi 2012)

Constrain the Nucleon-Nucleon Interaction, 2012

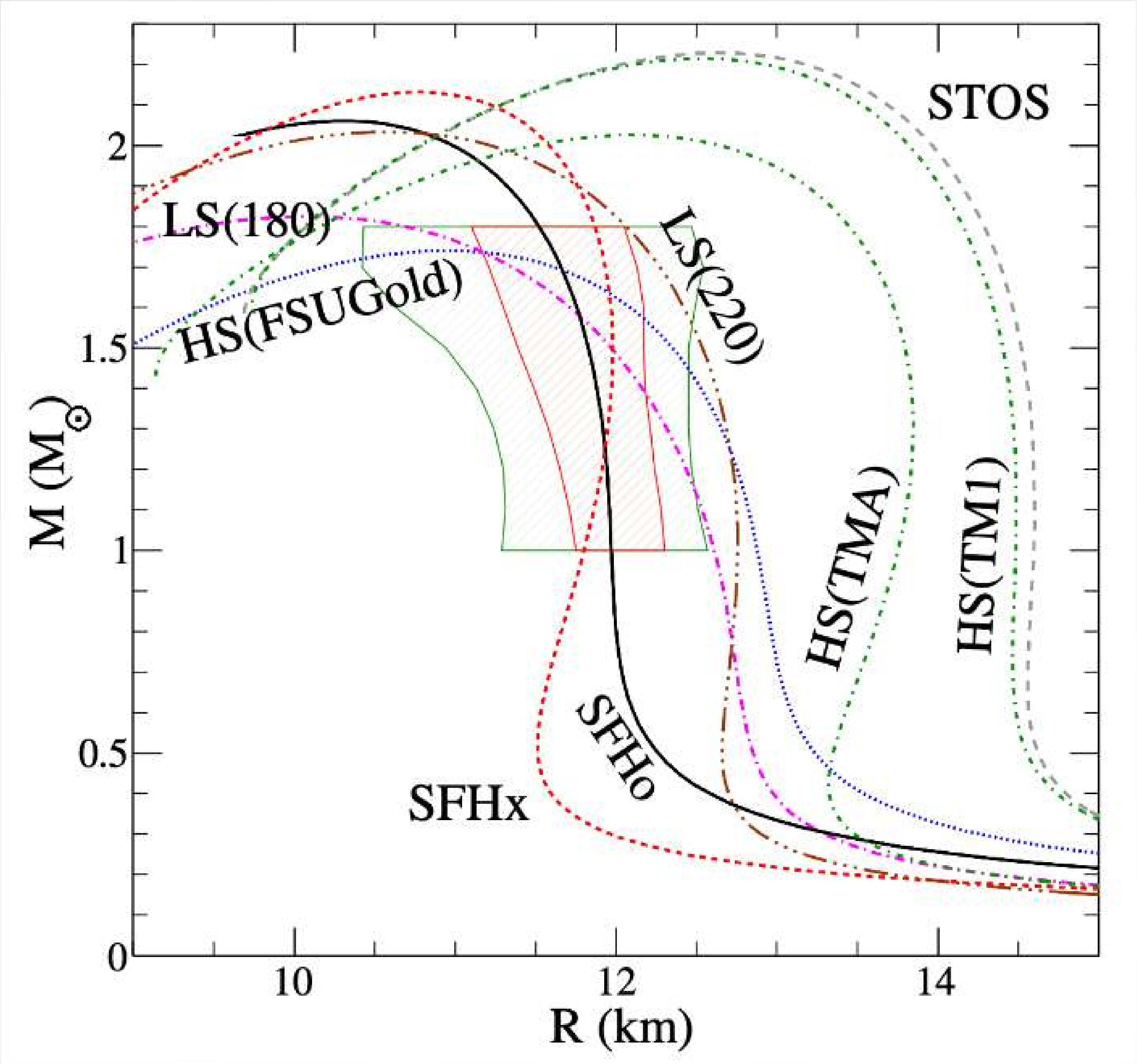


- Normally nn-interaction ⇒ EOS ⇒ neutron star prediction
- Take advantage of Bayesian inference as "inverse probability"
- Neutron star observations constrain L, the density derivative of the nuclear symmetry energy

$$S(n_B) = E_{\rm neut}(n_B) - E_{\rm nuc}(n_B)$$
$$L = 3 n_B S'(n_B)$$

(from Steiner and Gandolfi 2012)

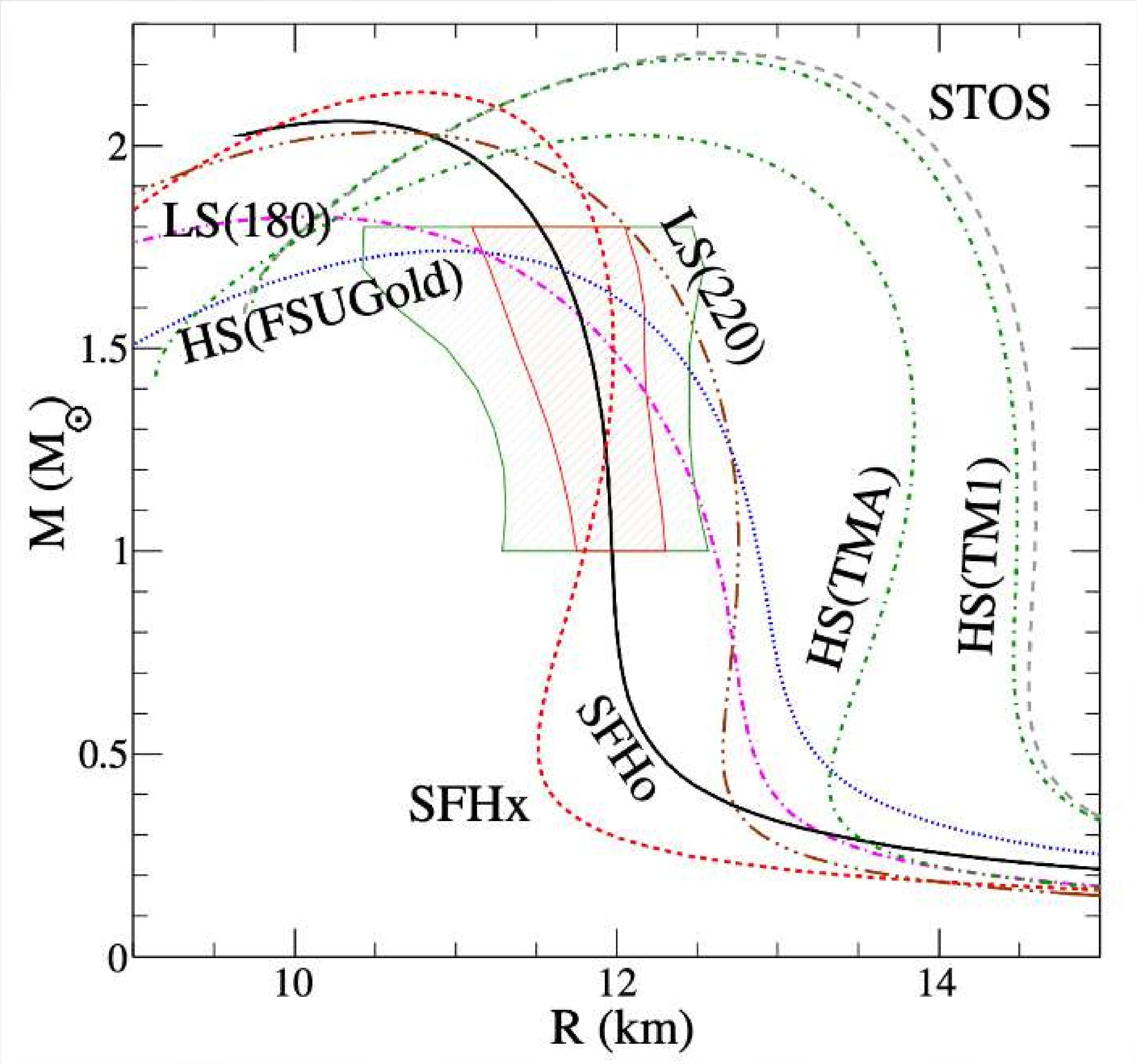
Implication for Core-Collapse Supernovae, 2013



Steiner et al. (2013)

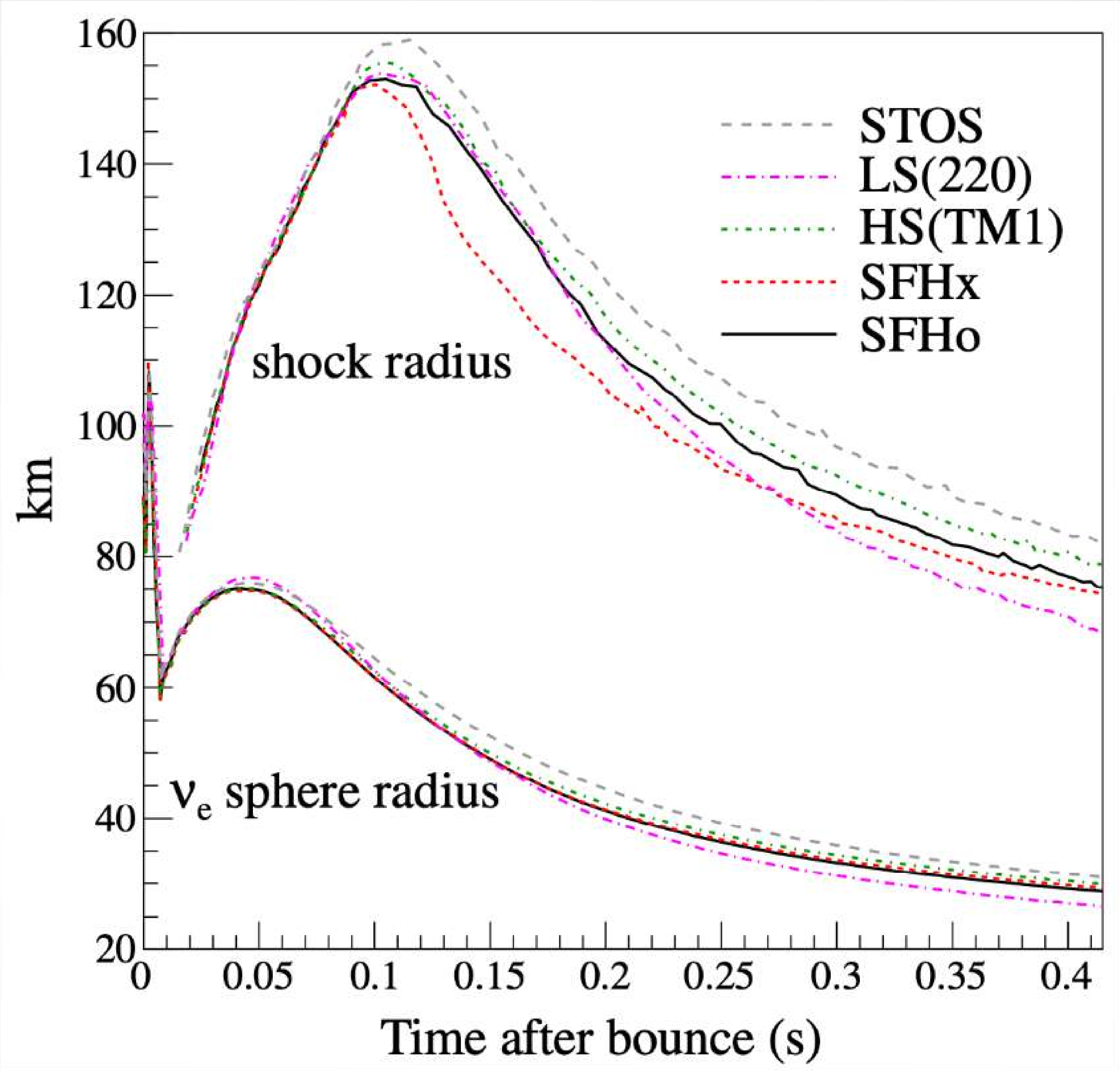
- Create a new equation of state for core-collapse supernovae
- Updated theory, observations and nuclear structure constraints

Implication for Core-Collapse Supernovae, 2013



Steiner et al. (2013)

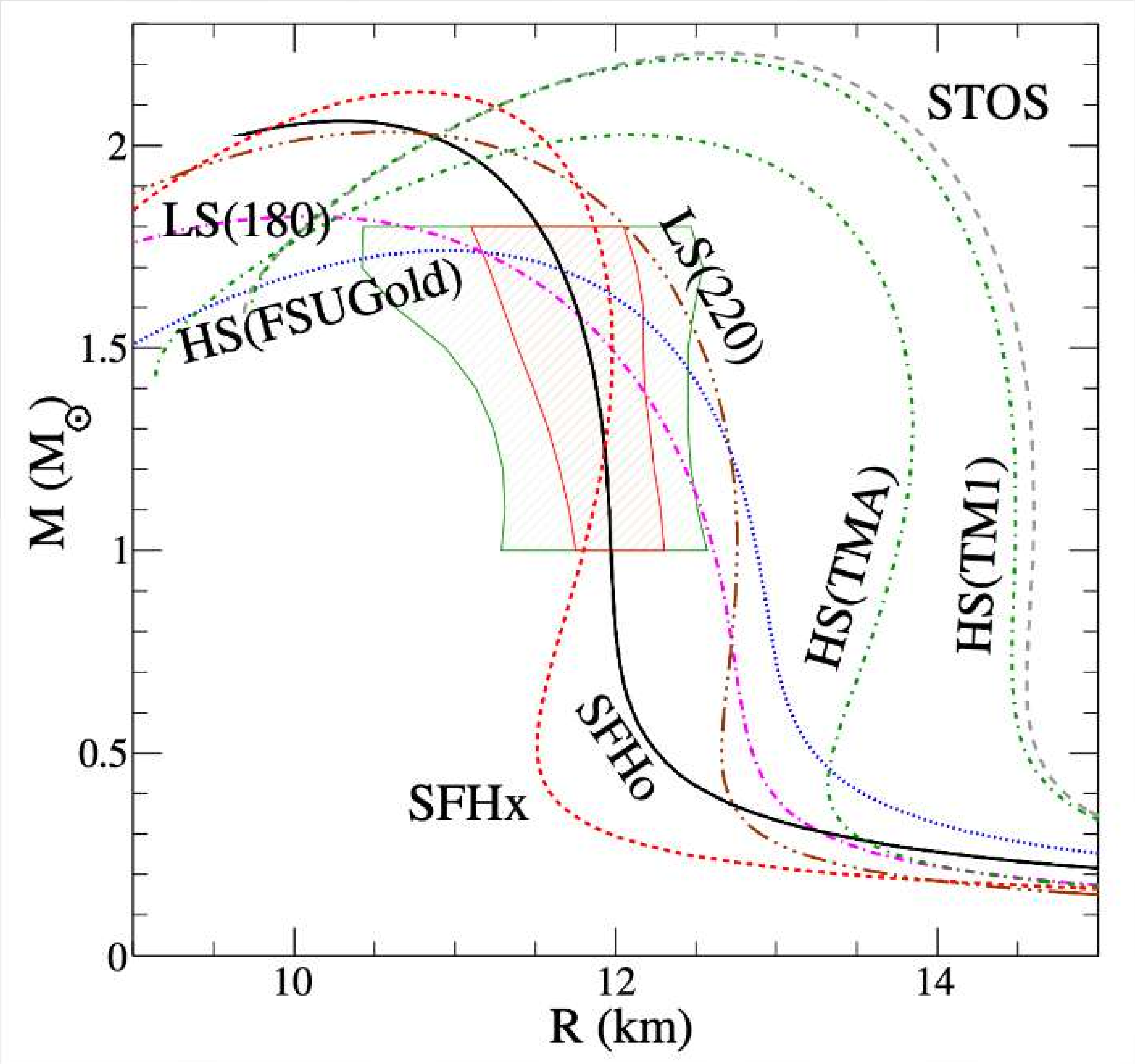
- Create a new equation of state for core-collapse supernovae
- Updated theory, observations and nuclear structure constraints



Steiner et al. (2013)

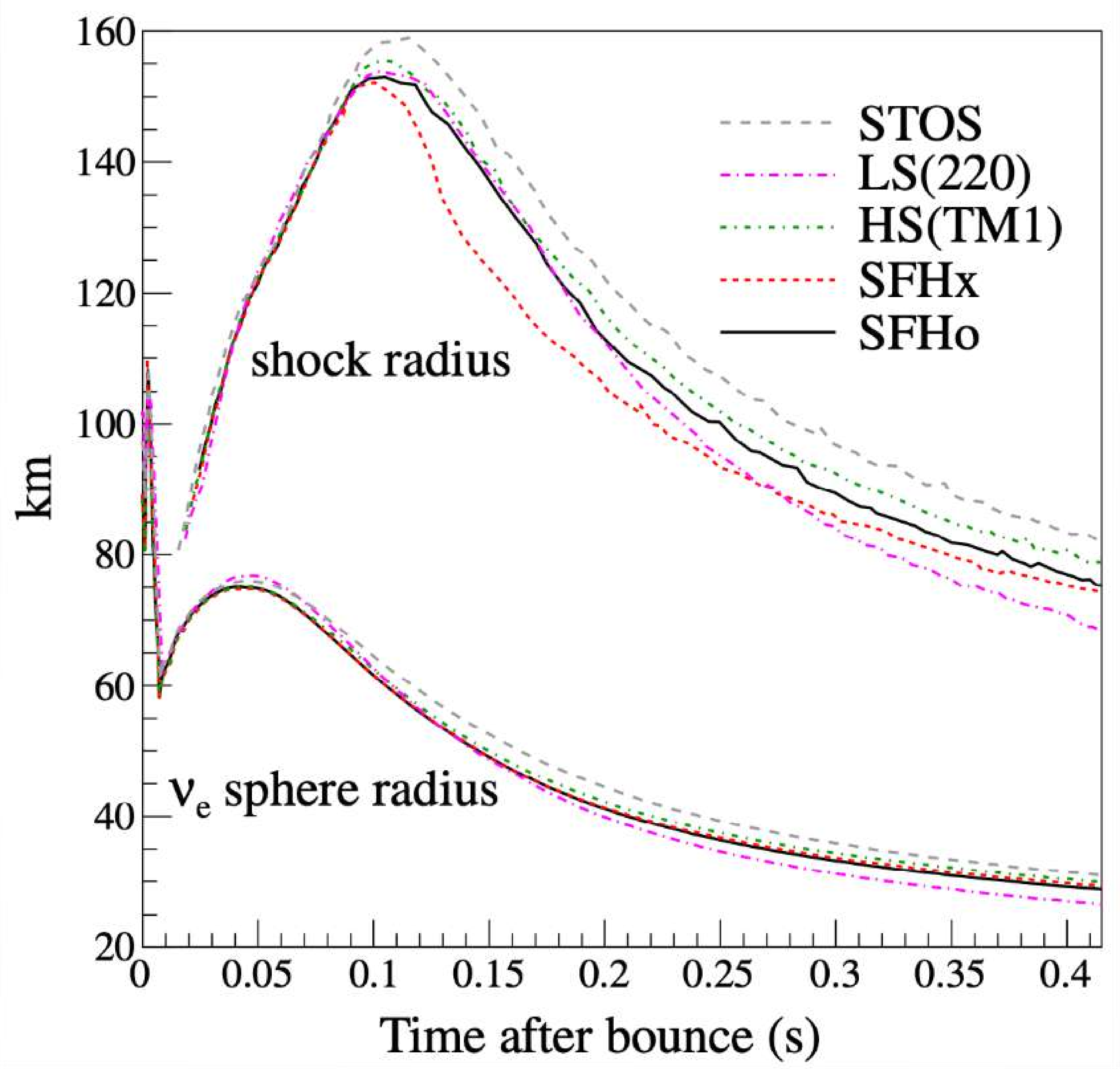
- **No** significant impact on core-collapse

Implication for Core-Collapse Supernovae, 2013



Steiner et al. (2013)

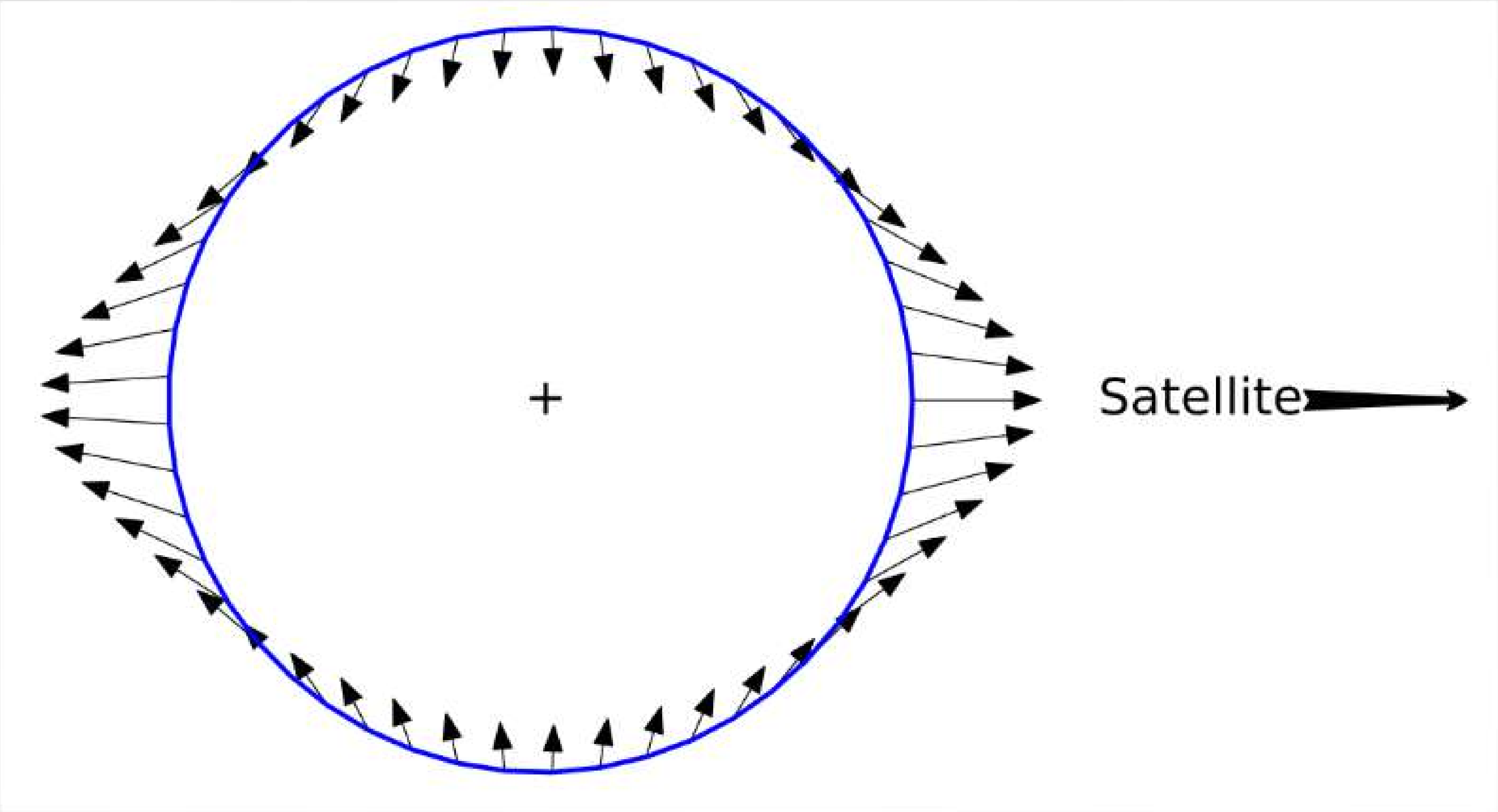
- Create a new equation of state for core-collapse supernovae
- Updated theory, observations and nuclear structure constraints



Steiner et al. (2013)

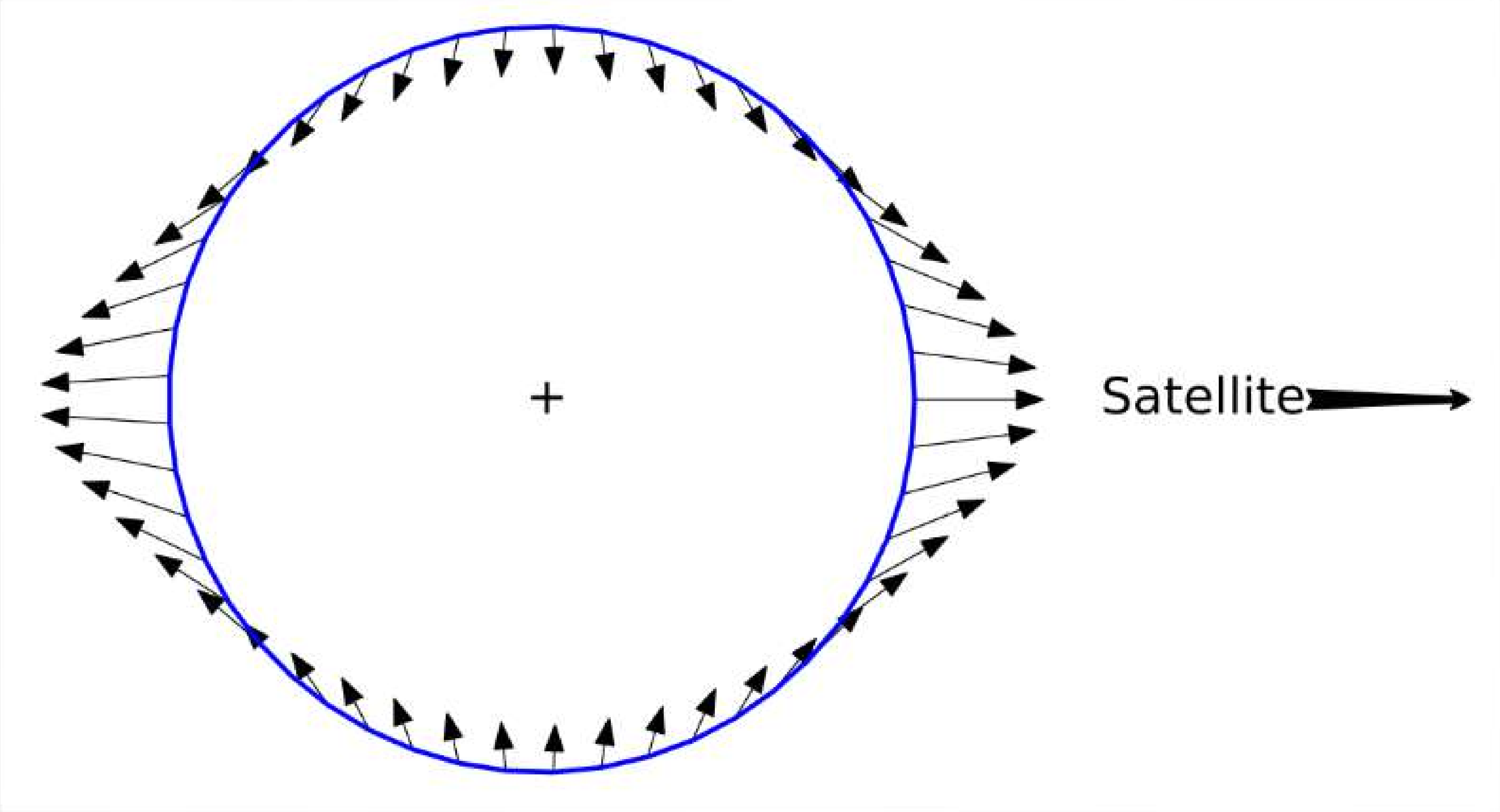
- **No** significant impact on core-collapse
- **But!** Hold that thought...

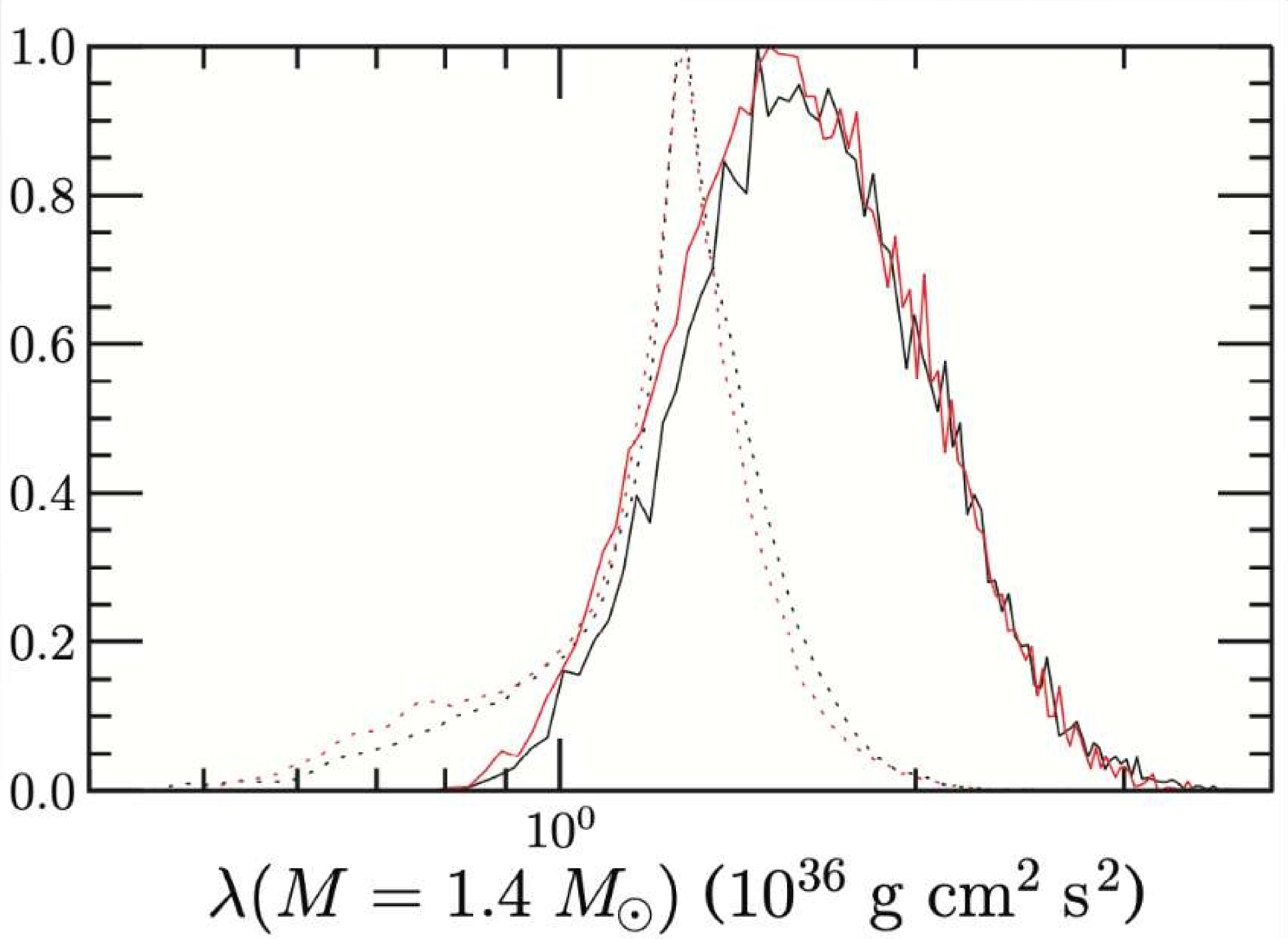
Neutron Star Mergers, pre-LIGO, 2015



- Nearby neutron star creates a tidal force
- LIGO measures "tidal deformability"
- Gravitational analog of nuclear electric polarizability
- Tidal deformability correlated with NS radius

Neutron Star Mergers, pre-LIGO, 2015





Steiner et al. (2015)

- Nearby neutron star creates a tidal force
- LIGO measures "tidal deformability"
- Gravitational analog of nuclear electric polarizability
- Tidal deformability correlated with NS radius

- New observations + modern theory + nuclear structure
- *Predict* tidal deformability

Neutron Star Mergers, pre-LIGO, Part II, 2015

- SFHo equation of state used in neutron star merger simulations

Neutron Star Mergers, pre-LIGO, Part II, 2015

- SFHo equation of state used in neutron star merger simulations
- Abundances are not strongly modified by equation of state changes

Neutron Star Mergers, pre-LIGO, Part II, 2015

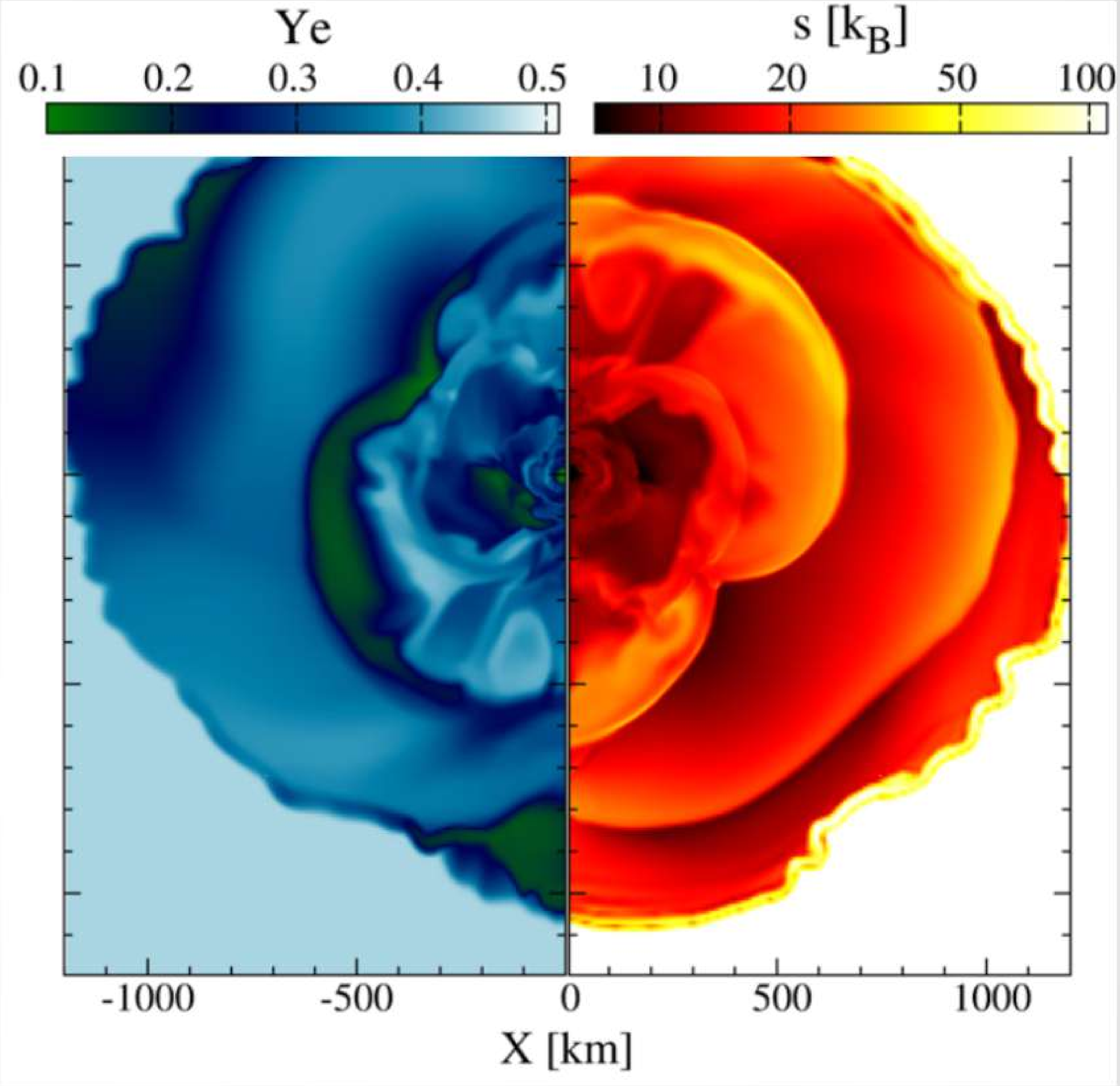
- SFHo equation of state used in neutron star merger simulations
- Abundances are not strongly modified by equation of state changes
- **However**, amount of mass ejected significantly increased:
  SFHo: $> 1.0 \times 10^{-2}\ \mathrm{M}_\odot$
  DD2: $< 2.1 \times 10^{-3}\ \mathrm{M}_\odot$
  TM1: $< 1.2 \times 10^{-3}\ \mathrm{M}_\odot$

Neutron Star Mergers, pre-LIGO, Part II, 2015

- SFHo equation of state used in neutron star merger simulations

- Abundances are not strongly modified by equation of state changes

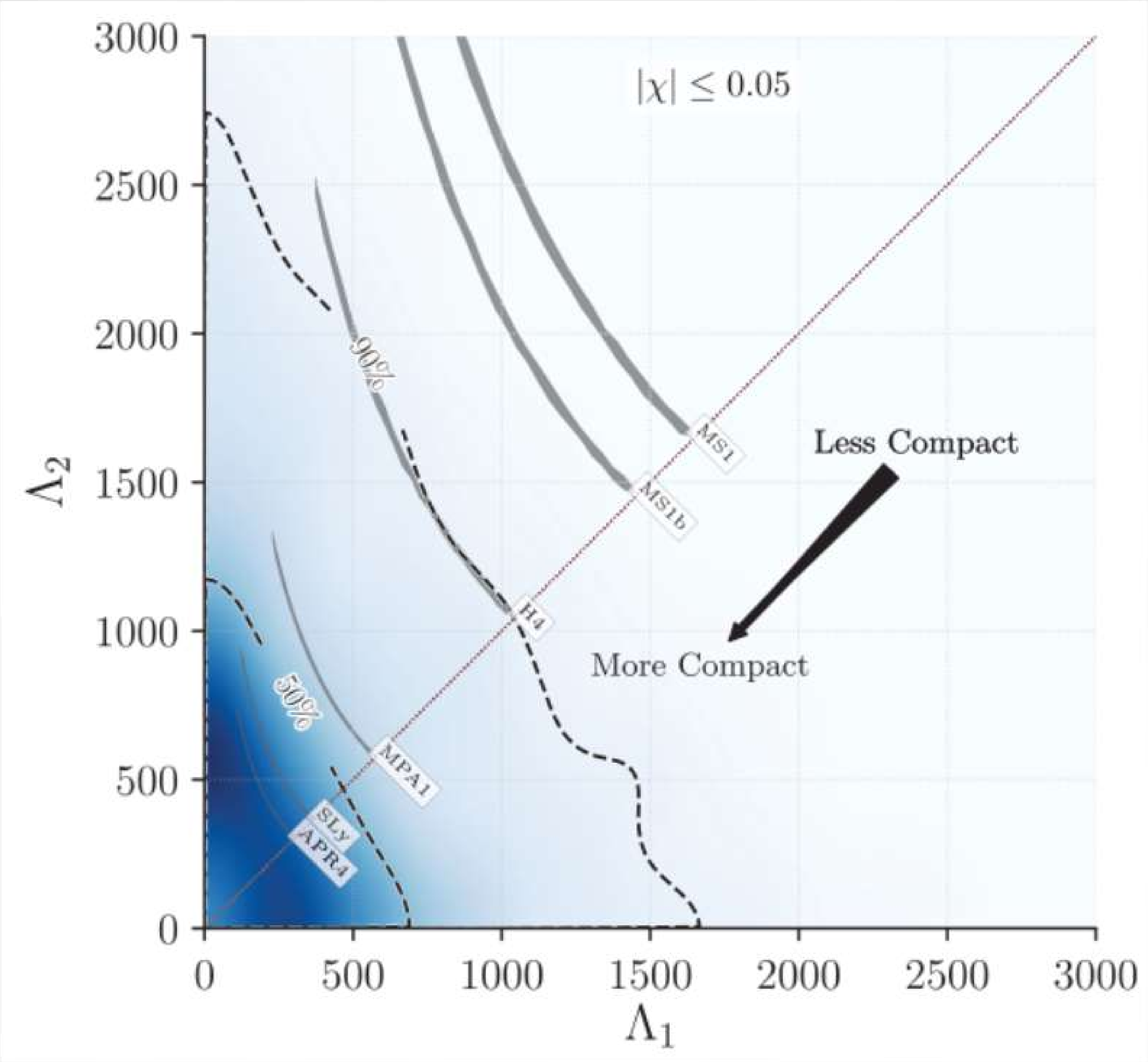
- **However**, amount of mass ejected significantly increased:
  SFHo: $> 1.0 \times 10^{-2}\ M_\odot$
  DD2: $< 2.1 \times 10^{-3}\ M_\odot$
  TM1: $< 1.2 \times 10^{-3}\ M_\odot$



Sekiguchi et al. (2015)

- Improves ability of mergers to produce r-process elements!

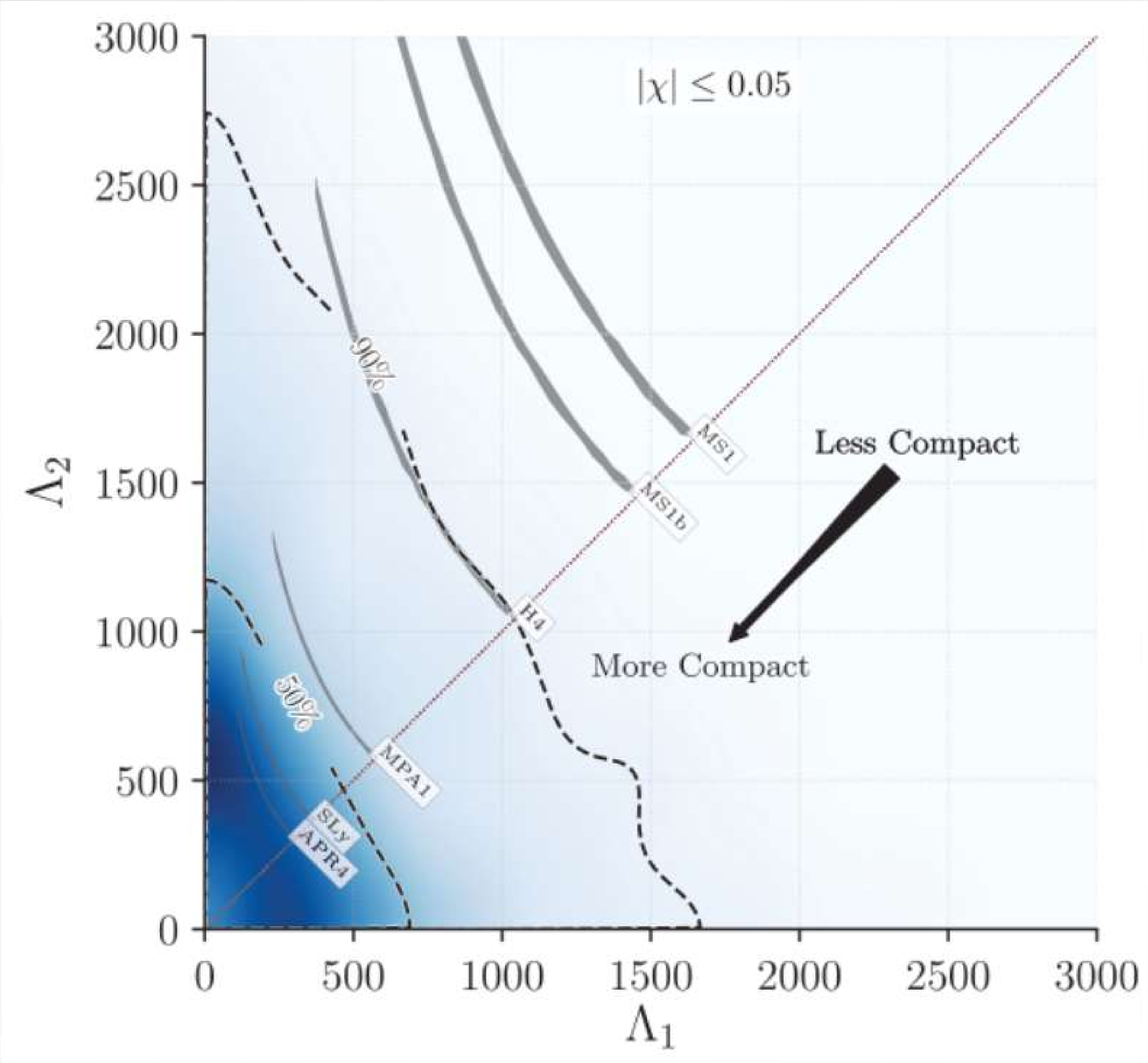
GW 170817 (2017)



- LIGO observes a double neutron star merger
- Measured $\tilde{\Lambda}$

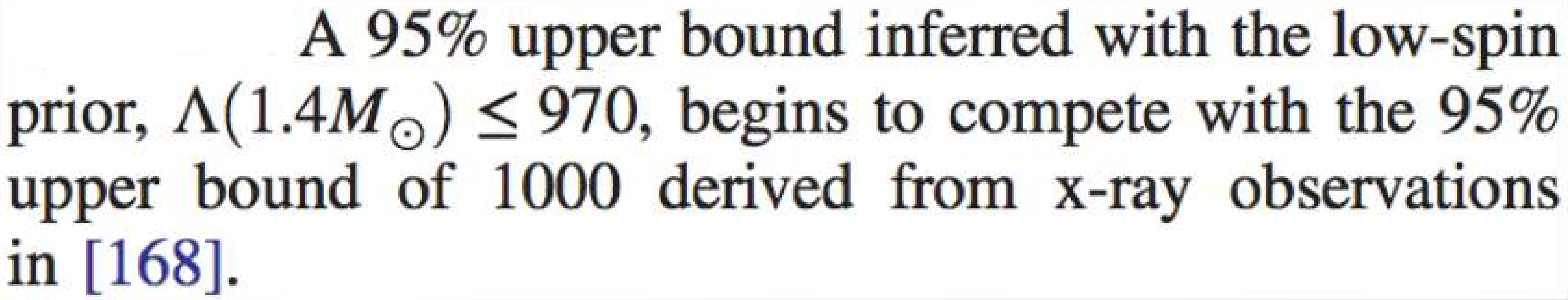
Abbott et al. (2017)

GW 170817 (2017)



Abbott et al. (2017)

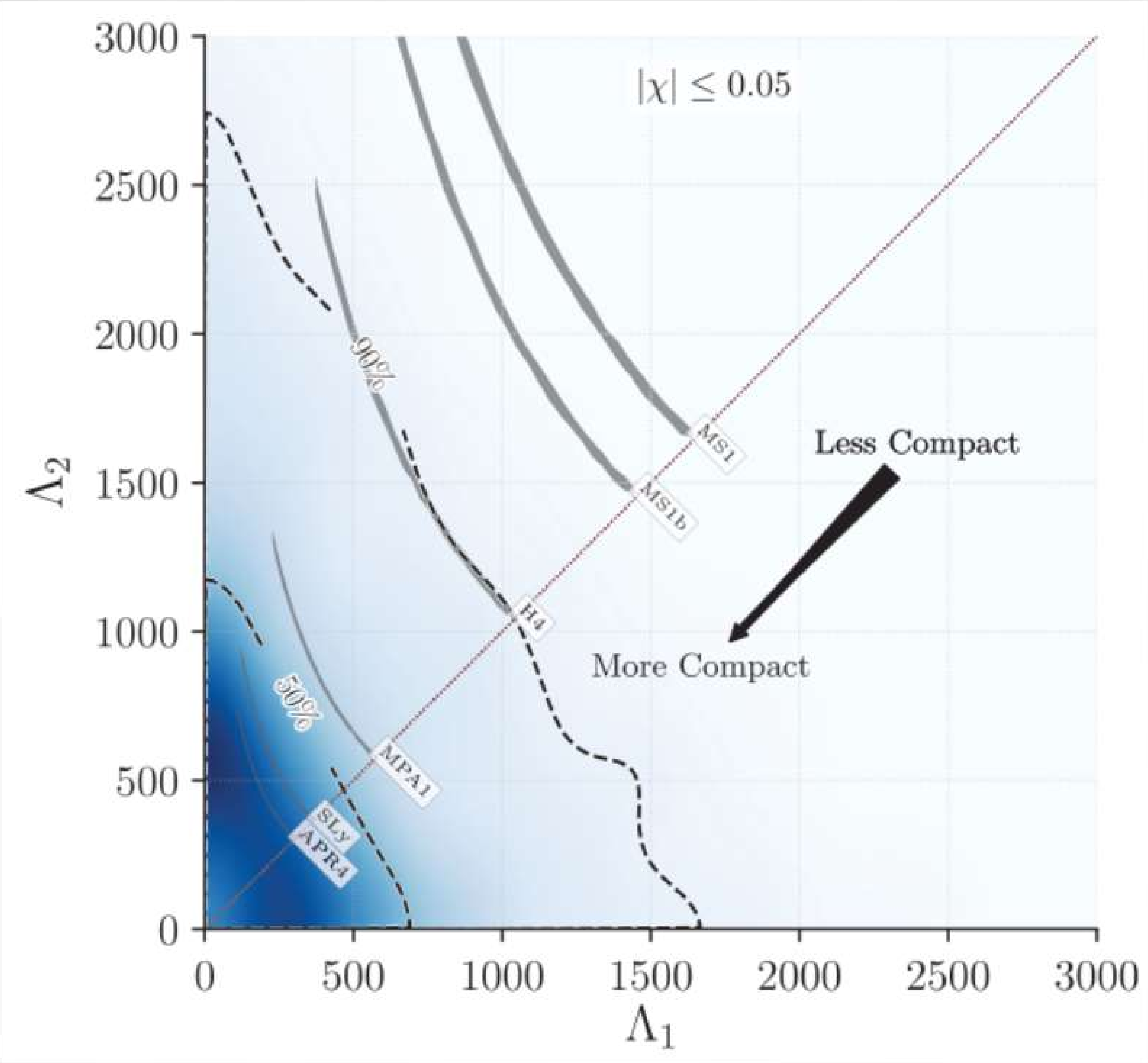
- LIGO observes a double neutron star merger
- Measured $\tilde{\Lambda}$


A 95% upper bound inferred with the low-spin prior, $\Lambda(1.4M_\odot) \leq 970$, begins to compete with the 95% upper bound of 1000 derived from x-ray observations in [168].

Abbott et al. (2017) citing Steiner et al. (2015)

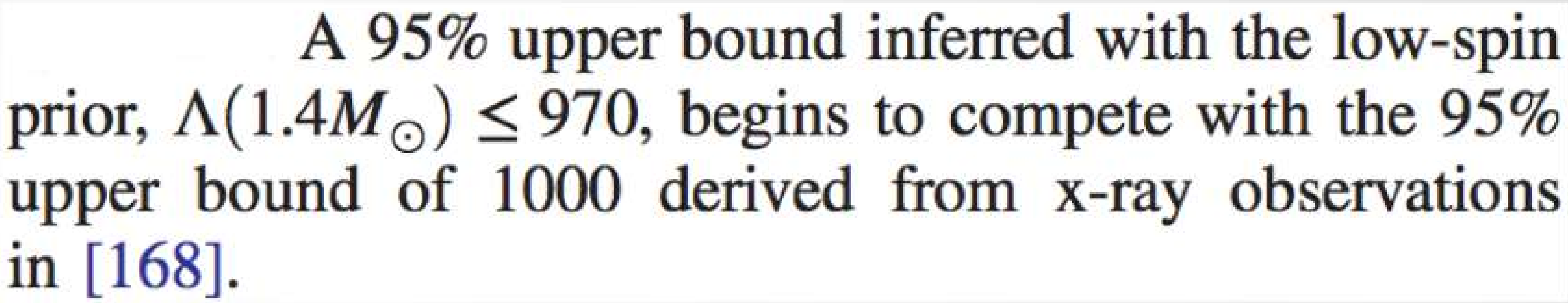
- Verified prediction!

GW 170817 (2017)



Abbott et al. (2017)

- LIGO observes a double neutron star merger
- Measured $\tilde{\Lambda}$

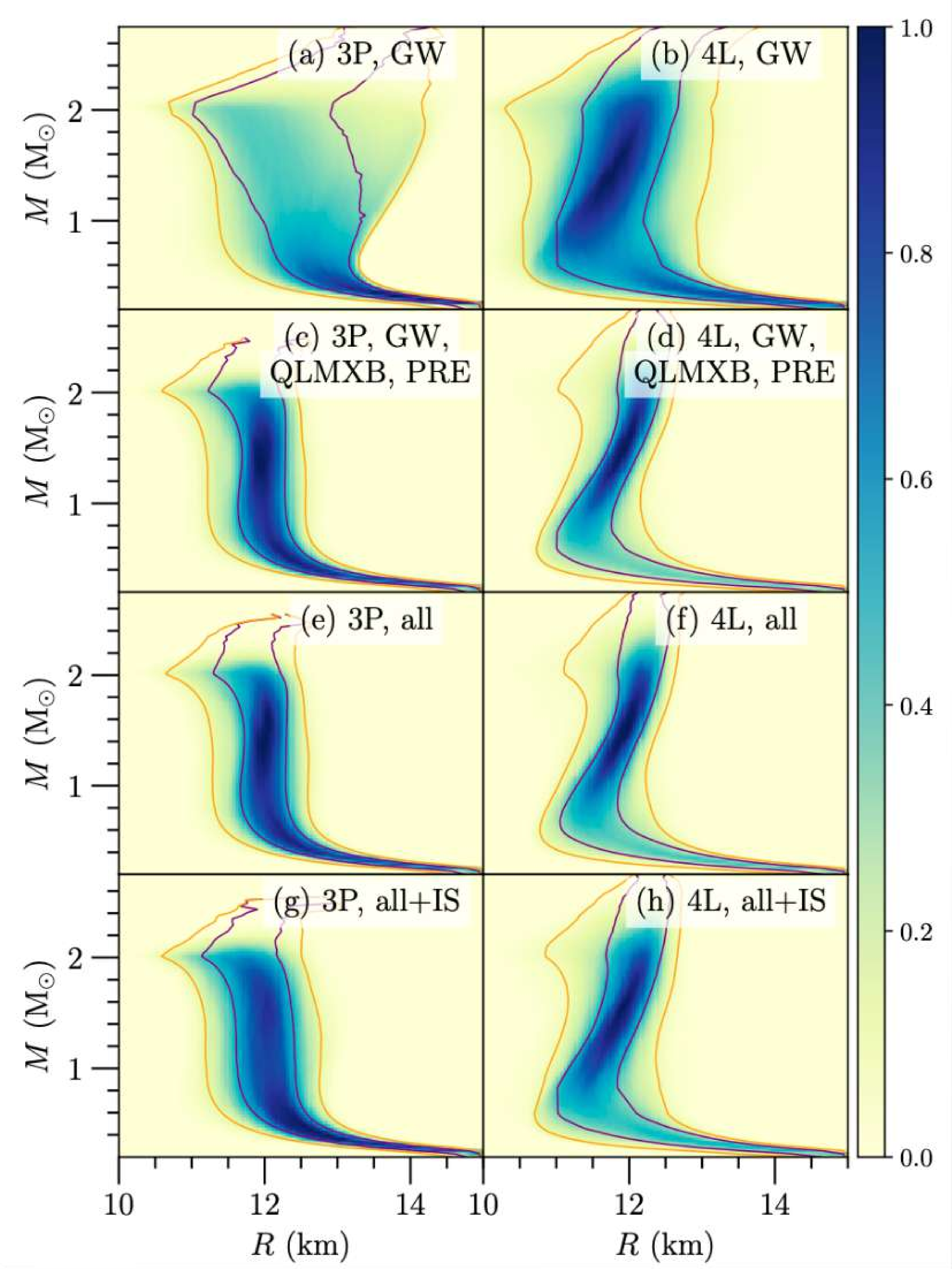


A 95% upper bound inferred with the low-spin prior, $\Lambda(1.4M_\odot) \leq 970$, begins to compete with the 95% upper bound of 1000 derived from x-ray observations in [168].

Abbott et al. (2017) citing Steiner et al. (2015)

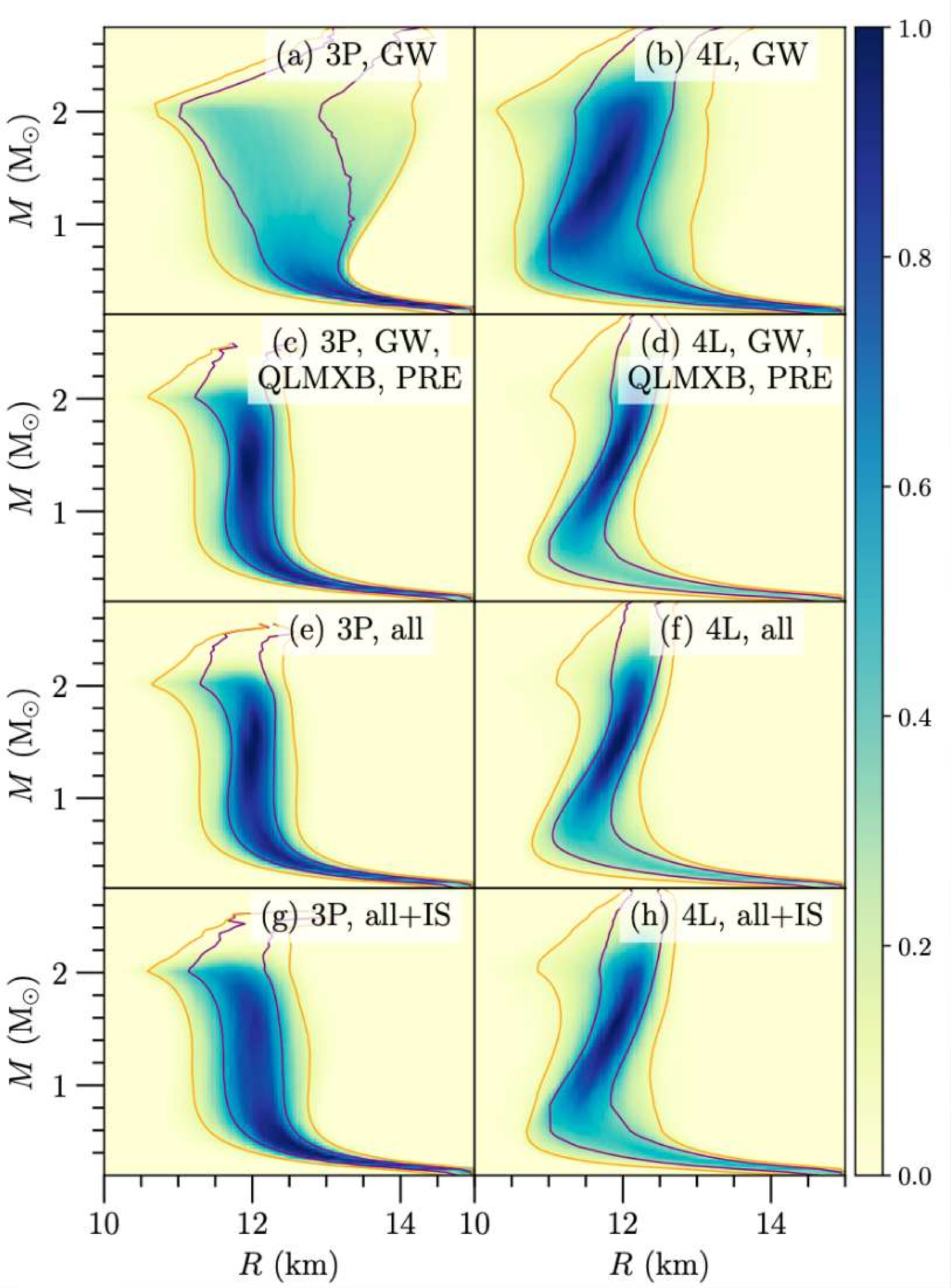
- Verified prediction!
- Not only that, but we get a kilonovae which offers some support for mergers as an r-process site!

Revised Results After GW 170817



Al-Mamun et al. (2021)

Revised Results After GW 170817



- Now LIGO + 11 EM observations, including NICER
- Better constraints on M-R curve and EOS
- Still **prior-dominated** in some regions of the M-R curve and across the EOS

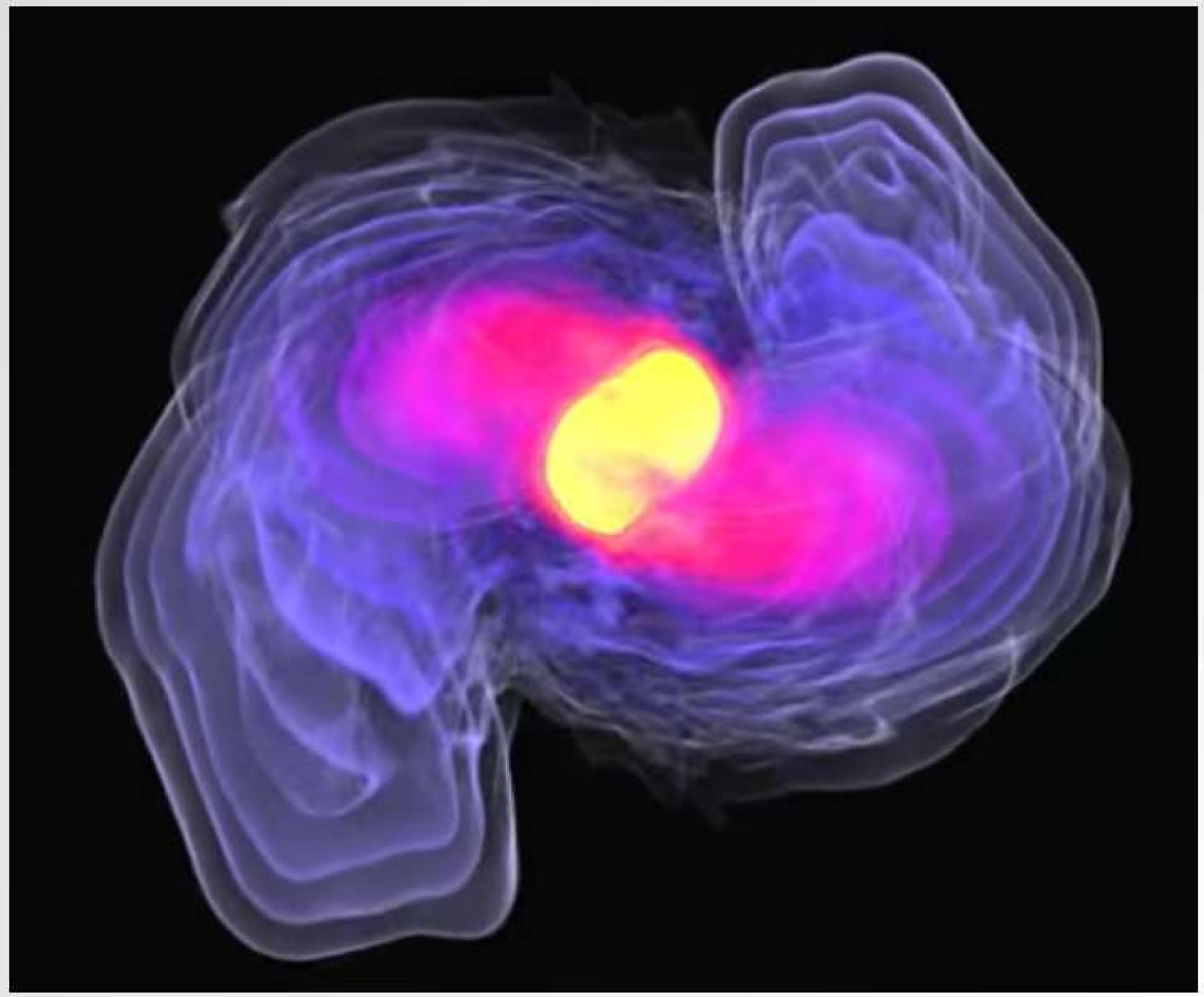
Al-Mamun et al. (2021)

We can use neutron star observations to learn about the nature of strongly-interacting matter at high densities!

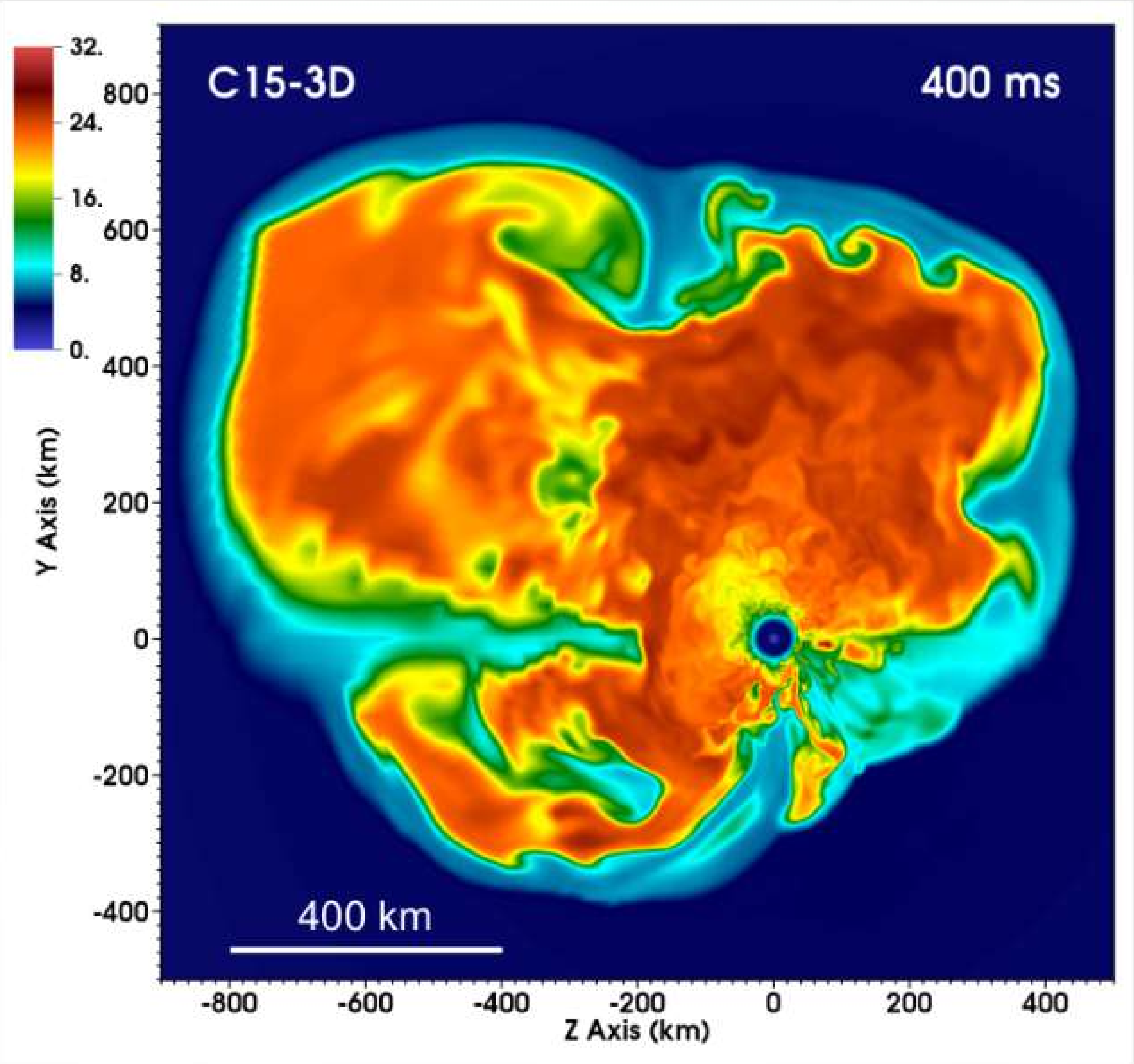
We can use neutron star observations to learn about the nature of strongly-interacting matter at high densities!

What about using neutron star mergers as a laboratory?

Astrophysical Processes Require Nuclear Physics Input

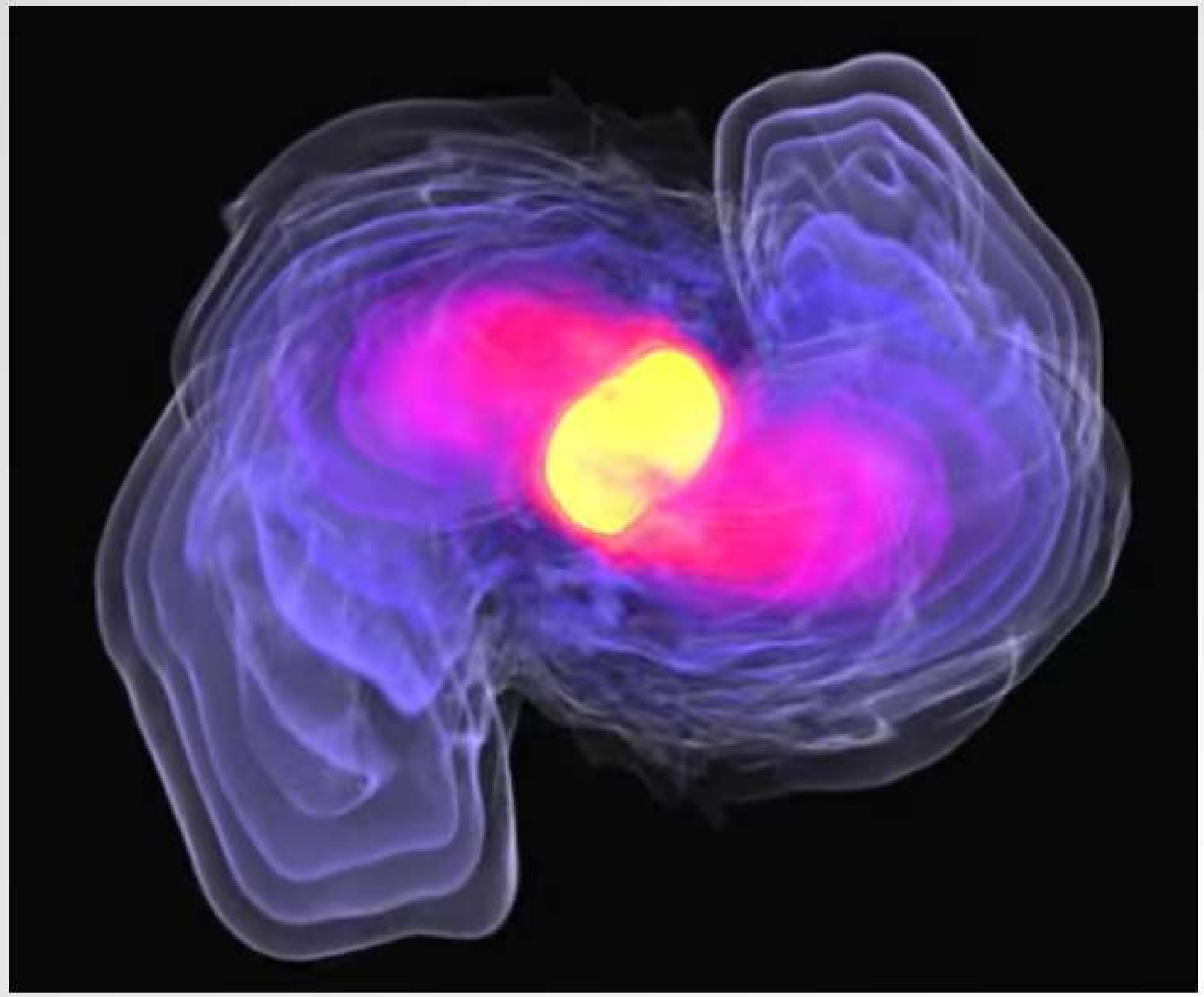


NS-NS merger simulation, Radice et al. (2016)

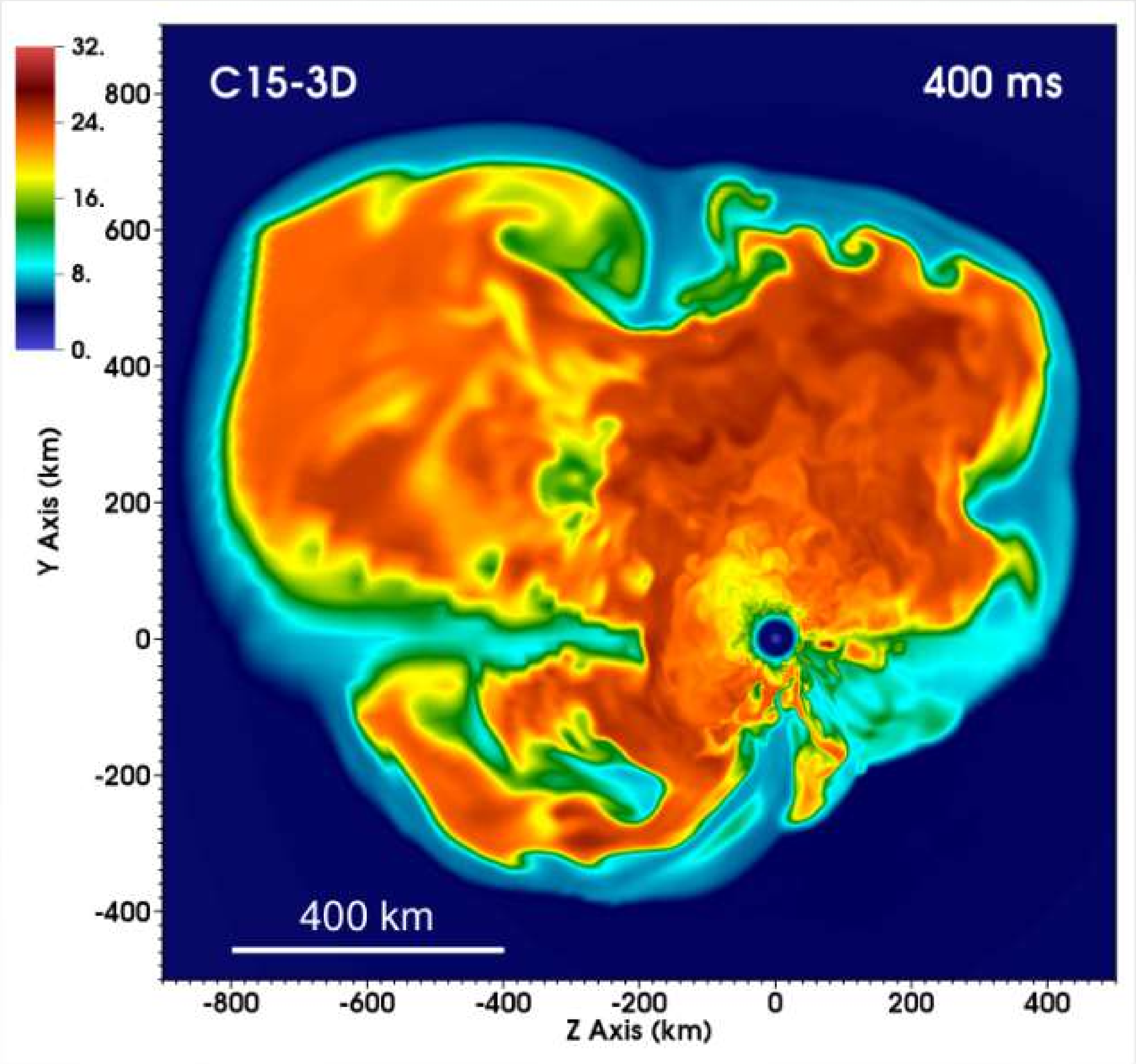


Core-collapse simulation, $15\ \mathrm{M}_\odot$ progenitor, Lentz et al. (2015)

Astrophysical Processes Require Nuclear Physics Input



NS-NS merger simulation, Radice et al. (2016)



Core-collapse simulation, $15\ M_\odot$ progenitor, Lentz et al. (2015)

- Requires: EOS, nuclear reactions, transport, and neutrino interactions with matter

The EOS challenge

- Three-dimensional space, $(n_B, Y_e \approx n_p/n_B, T)$

The EOS challenge

- Three-dimensional space, $(n_B, Y_e \approx n_p/n_B, T)$
- Different physical regimes:

The EOS challenge

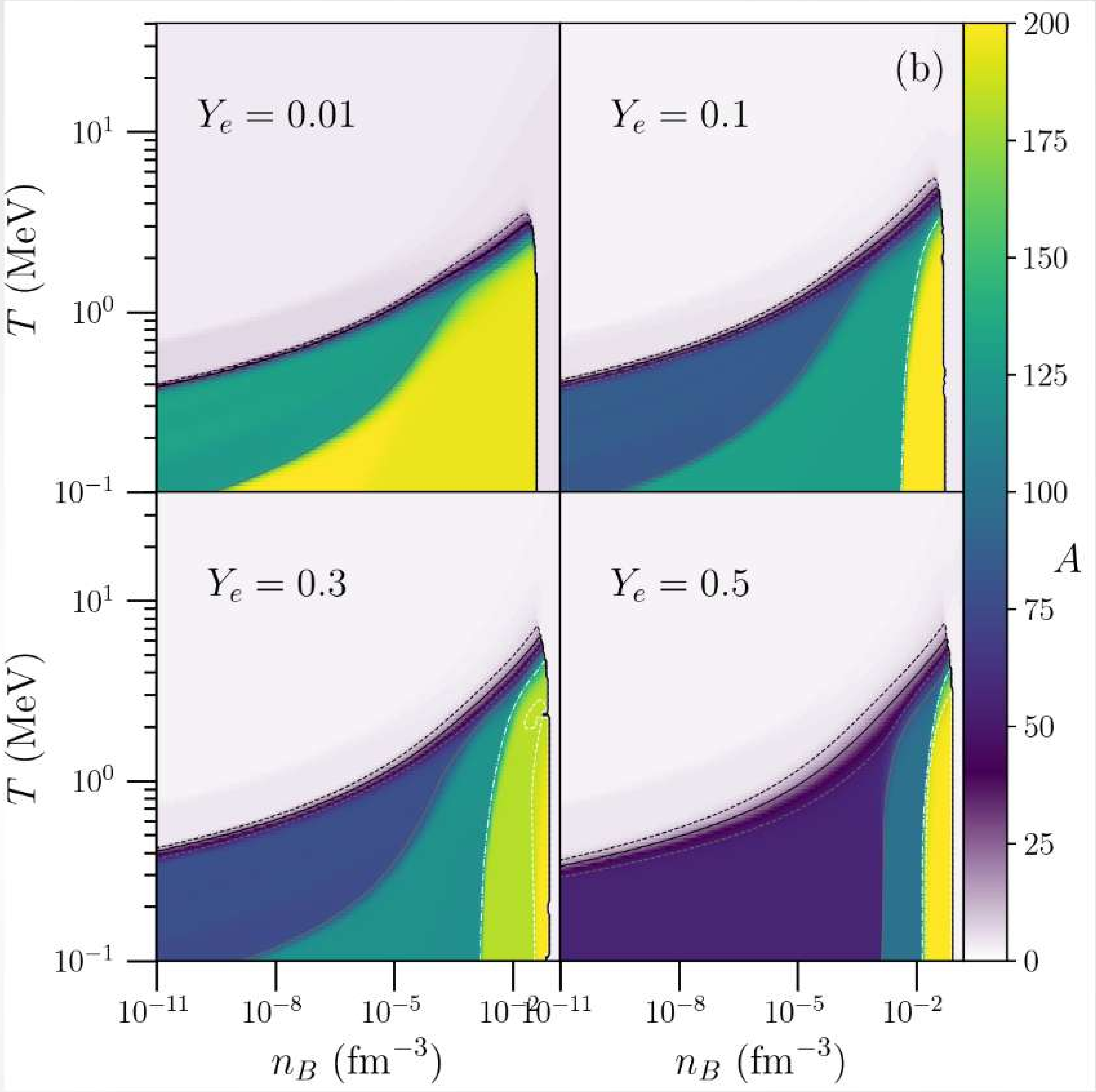
- Three-dimensional space, $(n_B, Y_e \approx n_p/n_B, T)$
- Different physical regimes:
    - Isospin-symmetric matter near saturation
      $n_B \approx n_0, Y_e \approx 1/2, T \approx 0$
    - Neutron-rich matter near saturation
      $n_B \approx n_0, Y_e \approx 0, T \approx 0$
    - Nearly non-degenerate matter
      n_B small or T large
    - Dense neutron-rich matter
      n_B large, $Y_e \approx 0, T \approx 0$
    - Hot matter near saturation
      $n_B \approx n_0, Y_e \approx 1/2, T \in [1 - 20]$ MeV

The EOS challenge

- Three-dimensional space, $(n_B, Y_e \approx n_p/n_B, T)$
- Different physical regimes:
  - Isospin-symmetric matter near saturation
    $n_B \approx n_0, Y_e \approx 1/2, T \approx 0$
  - Neutron-rich matter near saturation
    $n_B \approx n_0, Y_e \approx 0, T \approx 0$
  - Nearly non-degenerate matter
    n_B small or T large
  - Dense neutron-rich matter
    n_B large, $Y_e \approx 0, T \approx 0$
  - Hot matter near saturation
    $n_B \approx n_0, Y_e \approx 1/2, T \in [1 - 20]$ MeV
- Canonically, most EOS tables have focused on choosing one nucleon-nucleon interaction, and extrapolating

Quilting an EOS

- Require different interactions, different many-body techniques, and are constrained by different data
- Different physical regimes:

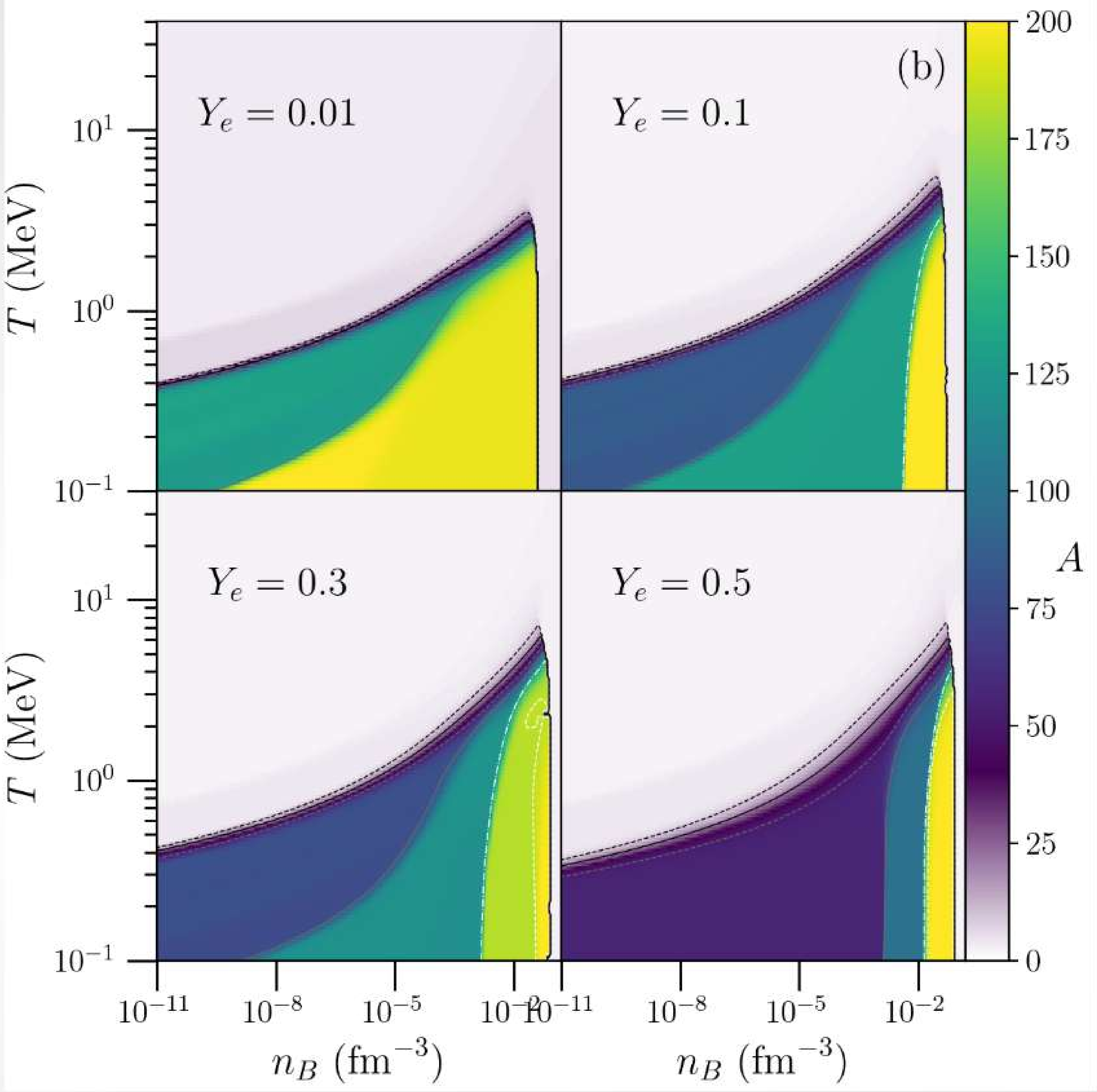


Du et al. (2021)

Quilting an EOS

- Require different interactions, different many-body techniques, and are constrained by different data
- Different physical regimes:
  - Isospin-symmetric matter near saturation

Laboratory nuclei; NUCLEI collaboration



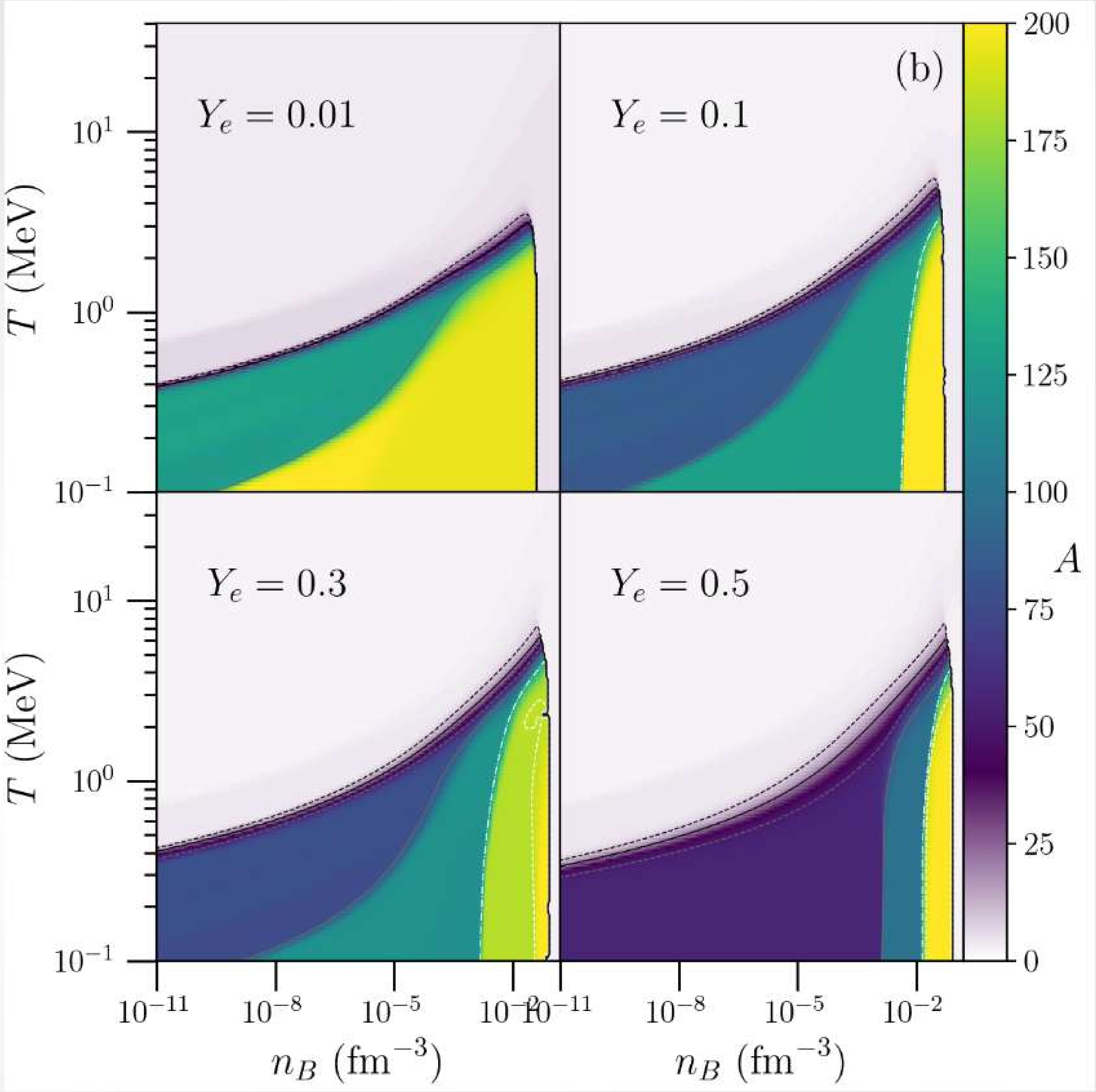
Du et al. (2021)

Quilting an EOS

- Require different interactions, different many-body techniques, and are constrained by different data
- Different physical regimes:
    - Isospin-symmetric matter near saturation

      Laboratory nuclei; NUCLEI collaboration
    - Neutron-rich matter near saturation

      Nuclear theory, e.g. Gandolfi et al. (2012)



Du et al. (2021)

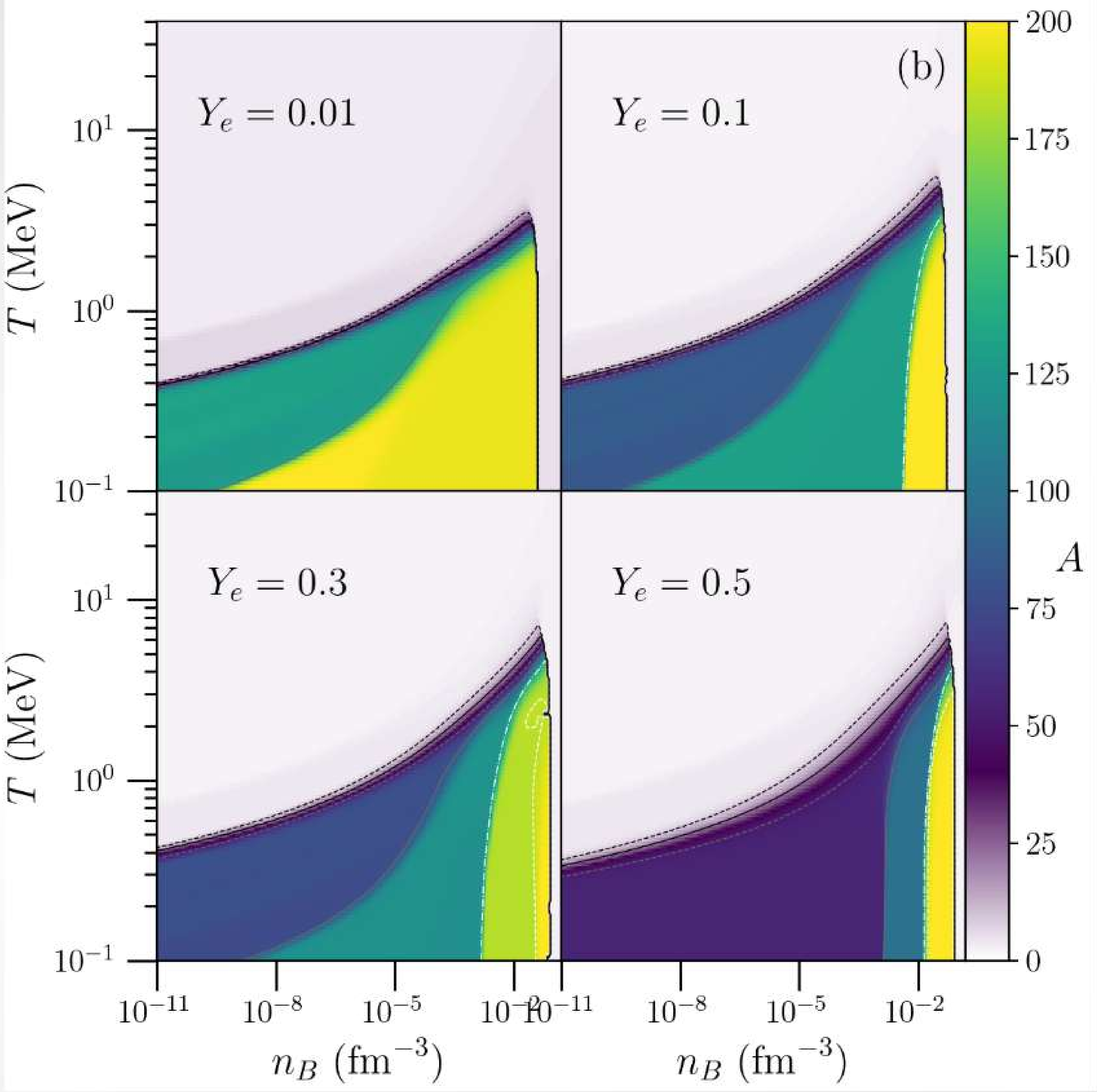
Quilting an EOS

- Require different interactions, different many-body techniques, and are constrained by different data
- Different physical regimes:
    - Isospin-symmetric matter near saturation

      Laboratory nuclei; NUCLEI collaboration
    - Neutron-rich matter near saturation

      Nuclear theory, e.g. Gandolfi et al. (2012)
    - Nearly non-degenerate matter

      Virial expansion, Horowitz et al. (2006)



Du et al. (2021)

Quilting an EOS

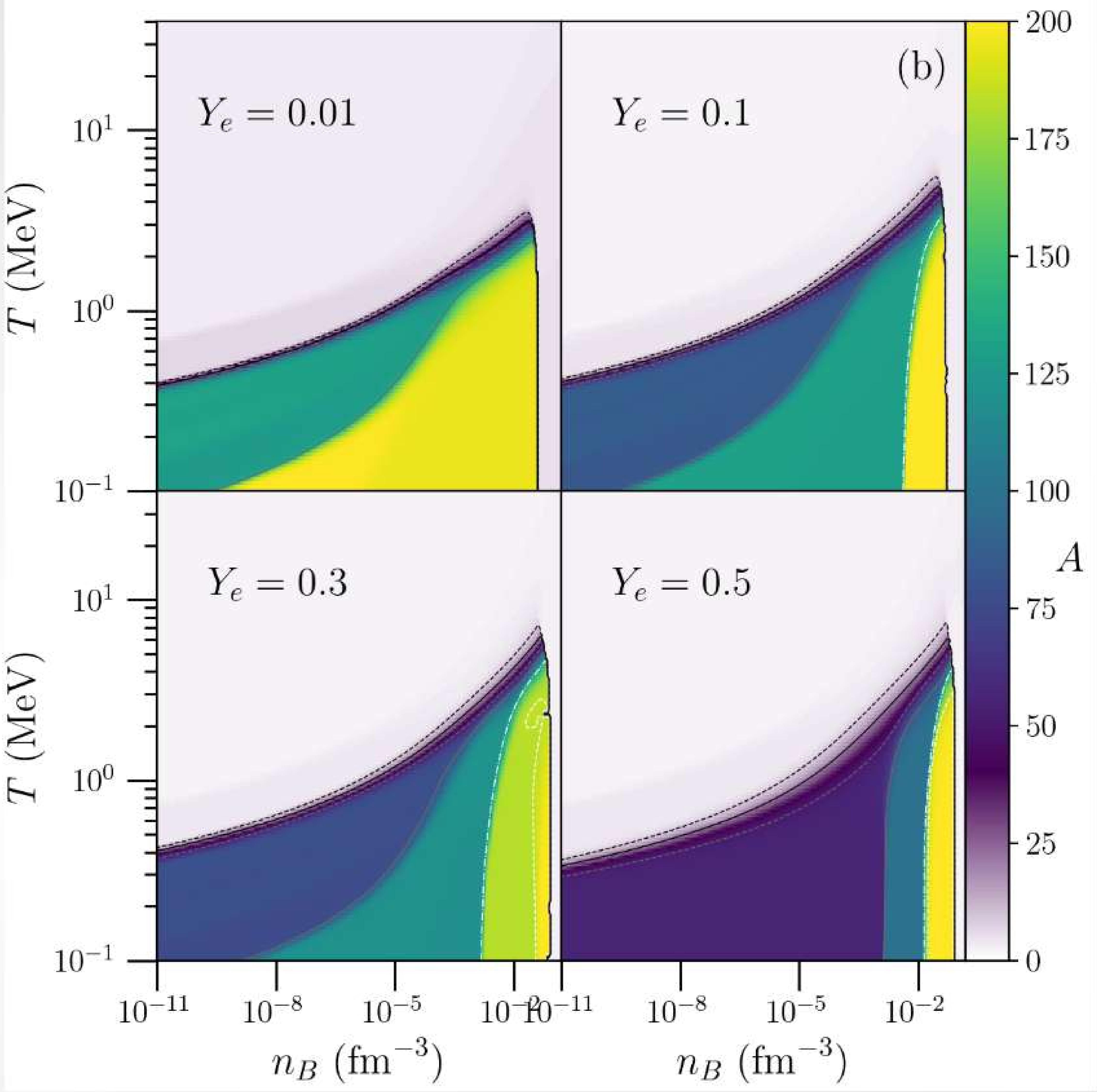
- Require different interactions, different many-body techniques, and are constrained by different data
- Different physical regimes:
  - Isospin-symmetric matter near saturation

    Laboratory nuclei; NUCLEI collaboration
  - Neutron-rich matter near saturation

    Nuclear theory, e.g. Gandolfi et al. (2012)
  - Nearly non-degenerate matter

    Virial expansion, Horowitz et al. (2006)
  - Dense neutron-rich matter

    Neutron star observations



Du et al. (2021)

Quilting an EOS

- Require different interactions, different many-body techniques, and are constrained by different data
- Different physical regimes:
  - Isospin-symmetric matter near saturation

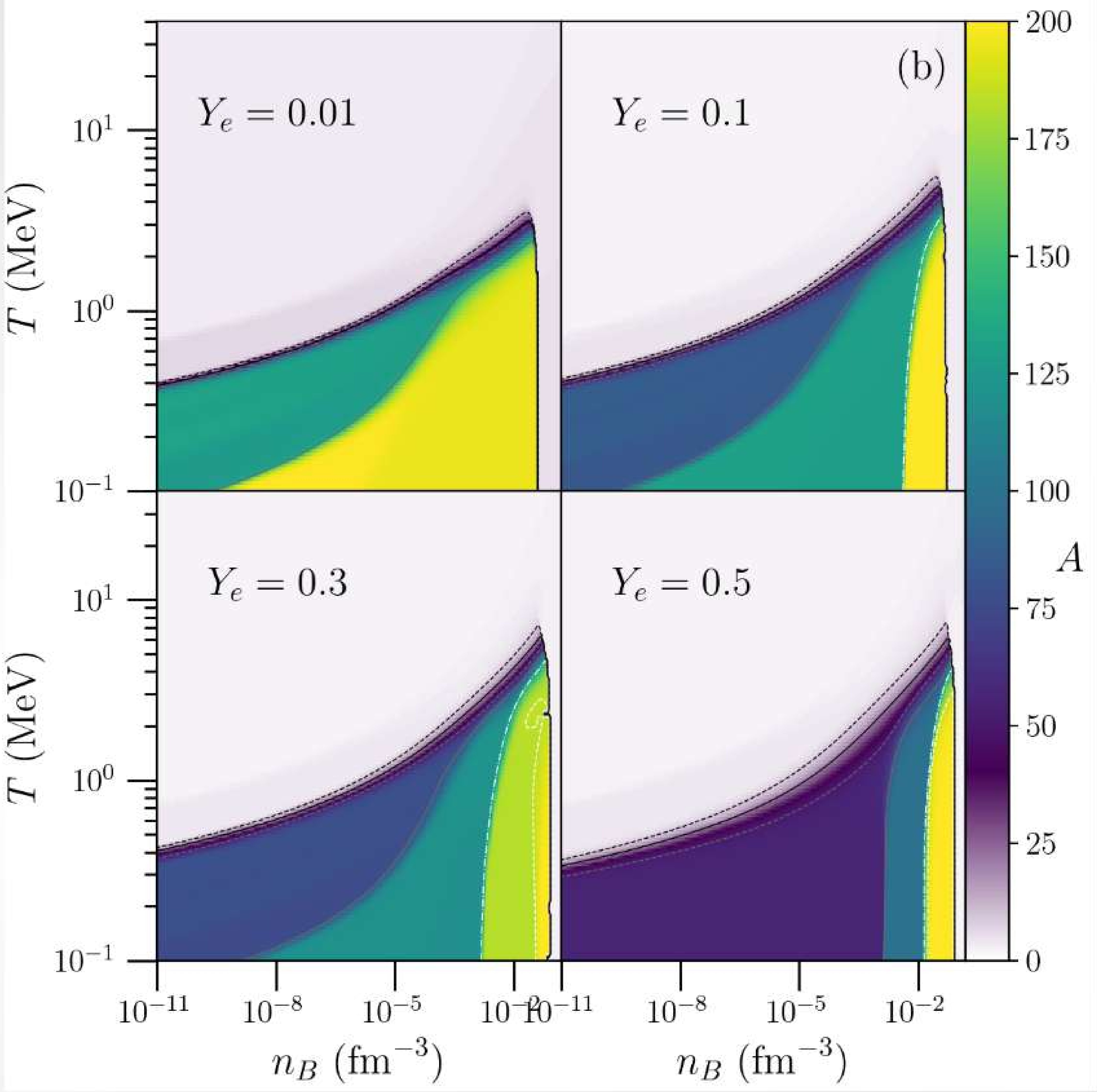
    Laboratory nuclei; NUCLEI collaboration
  - Neutron-rich matter near saturation

    Nuclear theory, e.g. Gandolfi et al. (2012)
  - Nearly non-degenerate matter

    Virial expansion, Horowitz et al. (2006)
  - Dense neutron-rich matter

    Neutron star observations
  - Hot matter near saturation

    Nuclear theory, but different than $T = 0$ techniques, Holt et al.



Du et al. (2021)

EOS as a Probability Distribution

- Probability distribution for EOS for simulations at $n_B > 3n_0$

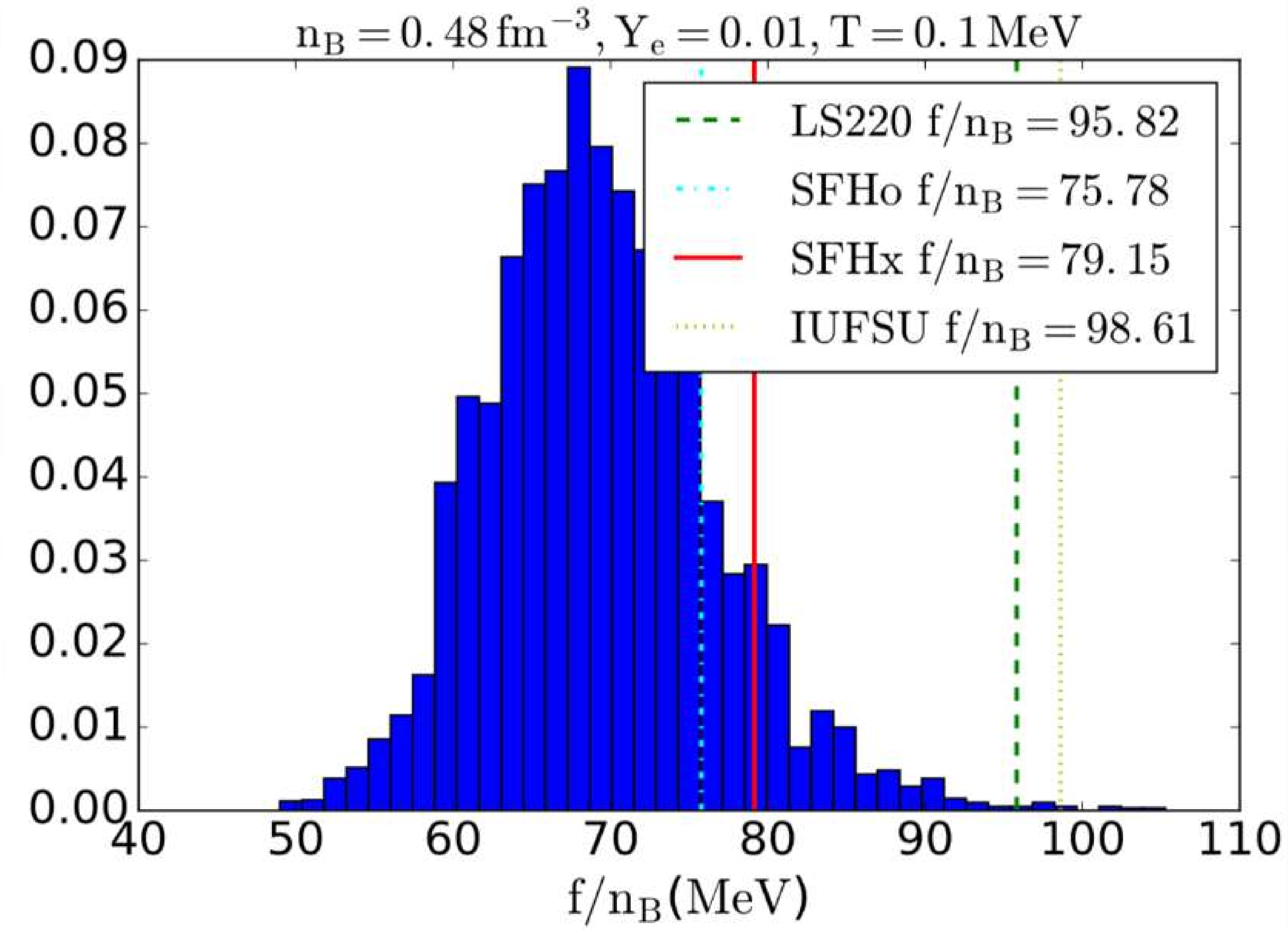


FIG. 6. The probability distribution for the free energy per baryon at $n_B = 0.48\ \mathrm{fm}^{-3}$, $Y_e = 0.10$, and $T = 0.1$ MeV.

Du et al. (2019)

EOS as a Probability Distribution

- Probability distribution for EOS for simulations at $n_B > 3n_0$
- Probability density peaks at lower values because of influence of NS radius observations

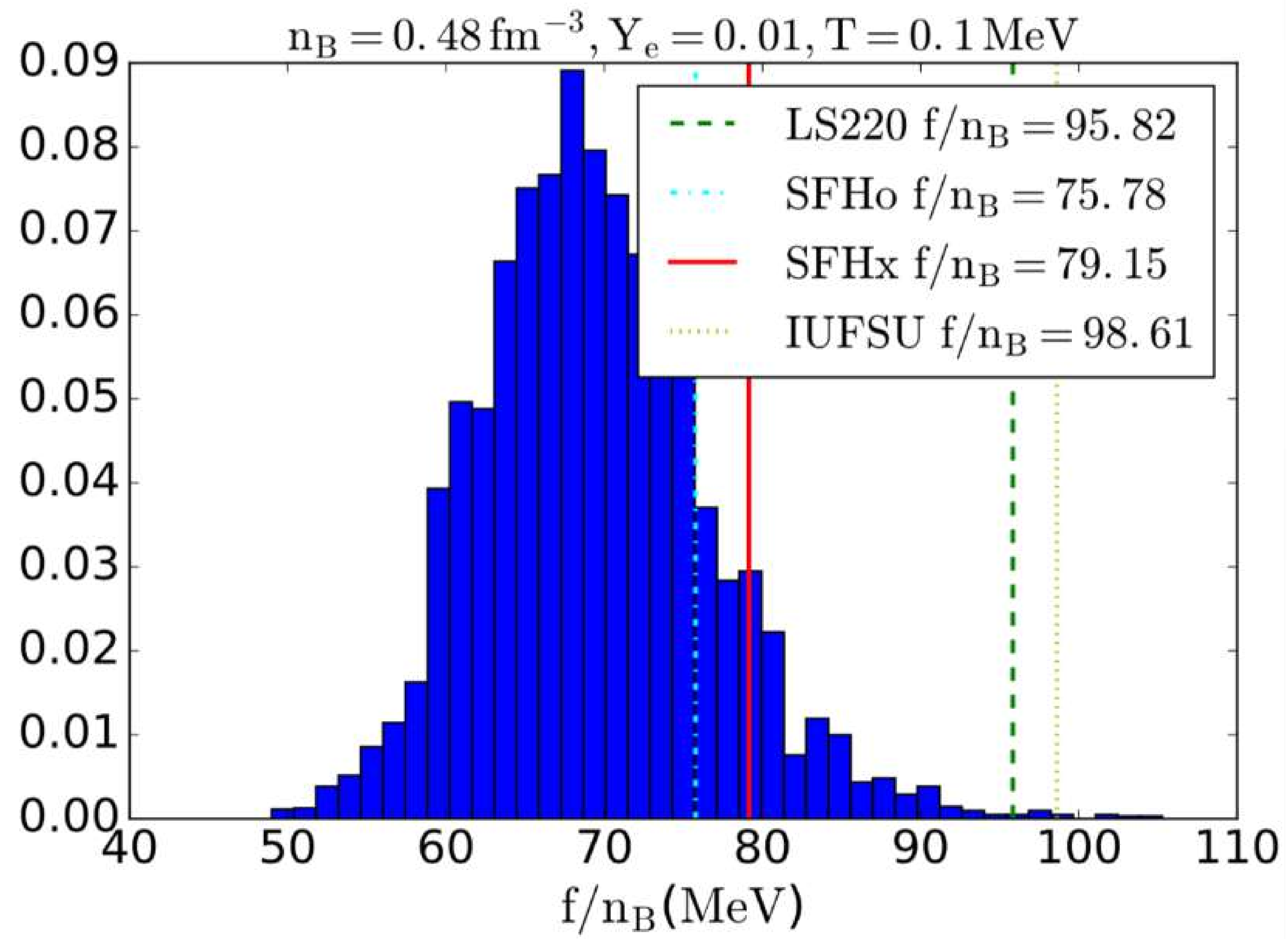


FIG. 6. The probability distribution for the free energy per baryon at $n_B = 0.48\,\mathrm{fm}^{-3}$, $Y_e = 0.10$, and $T = 0.1\,\mathrm{MeV}$.

Du et al. (2019)

EOS as a Probability Distribution

- Probability distribution for EOS for simulations at $n_B > 3n_0$
- Probability density peaks at lower values because of influence of NS radius observations
- Nine sample EOS tables available now!

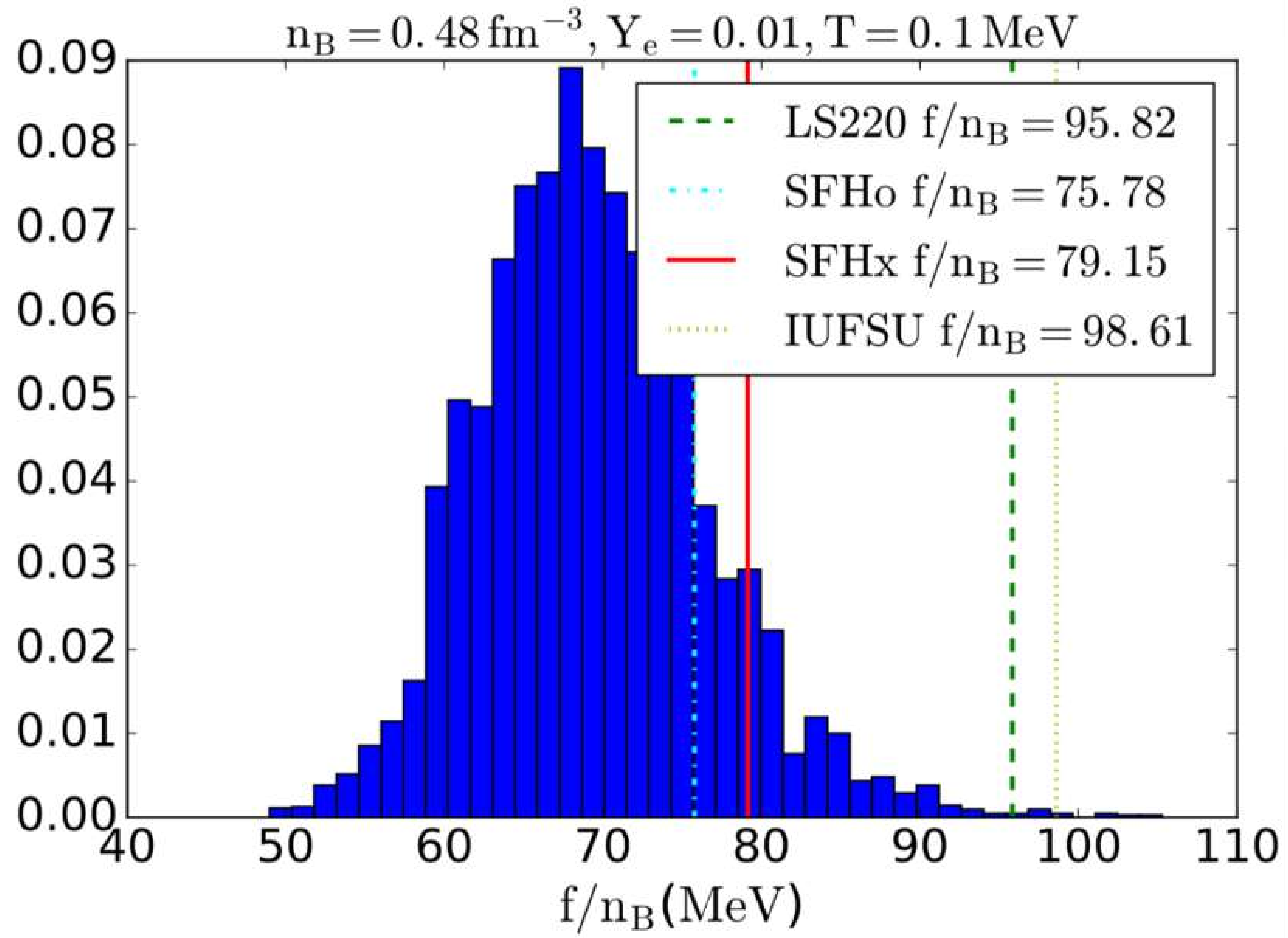


FIG. 6. The probability distribution for the free energy per baryon at $n_B = 0.48\,\mathrm{fm}^{-3}$, $Y_e = 0.10$, and $T = 0.1\,\mathrm{MeV}$.

Du et al. (2019)

EOS as a Probability Distribution

- Probability distribution for EOS for simulations at $n_B > 3n_0$
- Probability density peaks at lower values because of influence of NS radius observations
- Nine sample EOS tables available now!
- Implications for stellar evolution and r-process nucleosynthesis

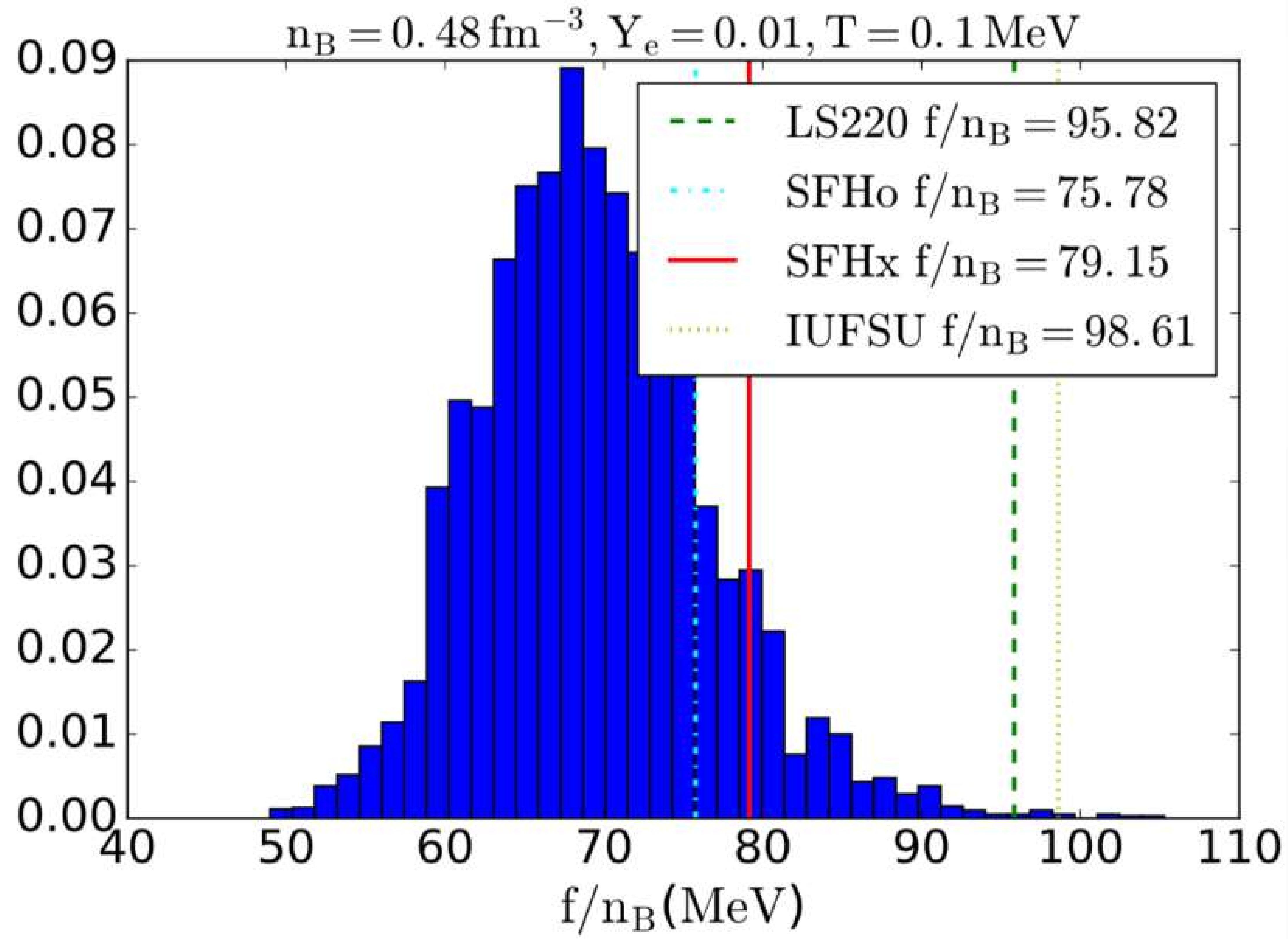


FIG. 6. The probability distribution for the free energy per baryon at $n_B = 0.48\ \mathrm{fm}^{-3}$, $Y_e = 0.10$, and $T = 0.1\ \mathrm{MeV}$.

Du et al. (2019)

EOS as a Probability Distribution

- Probability distribution for EOS for simulations at $n_B > 3n_0$
- Probability density peaks at lower values because of influence of NS radius observations
- Nine sample EOS tables available now!
- Implications for stellar evolution and r-process nucleosynthesis

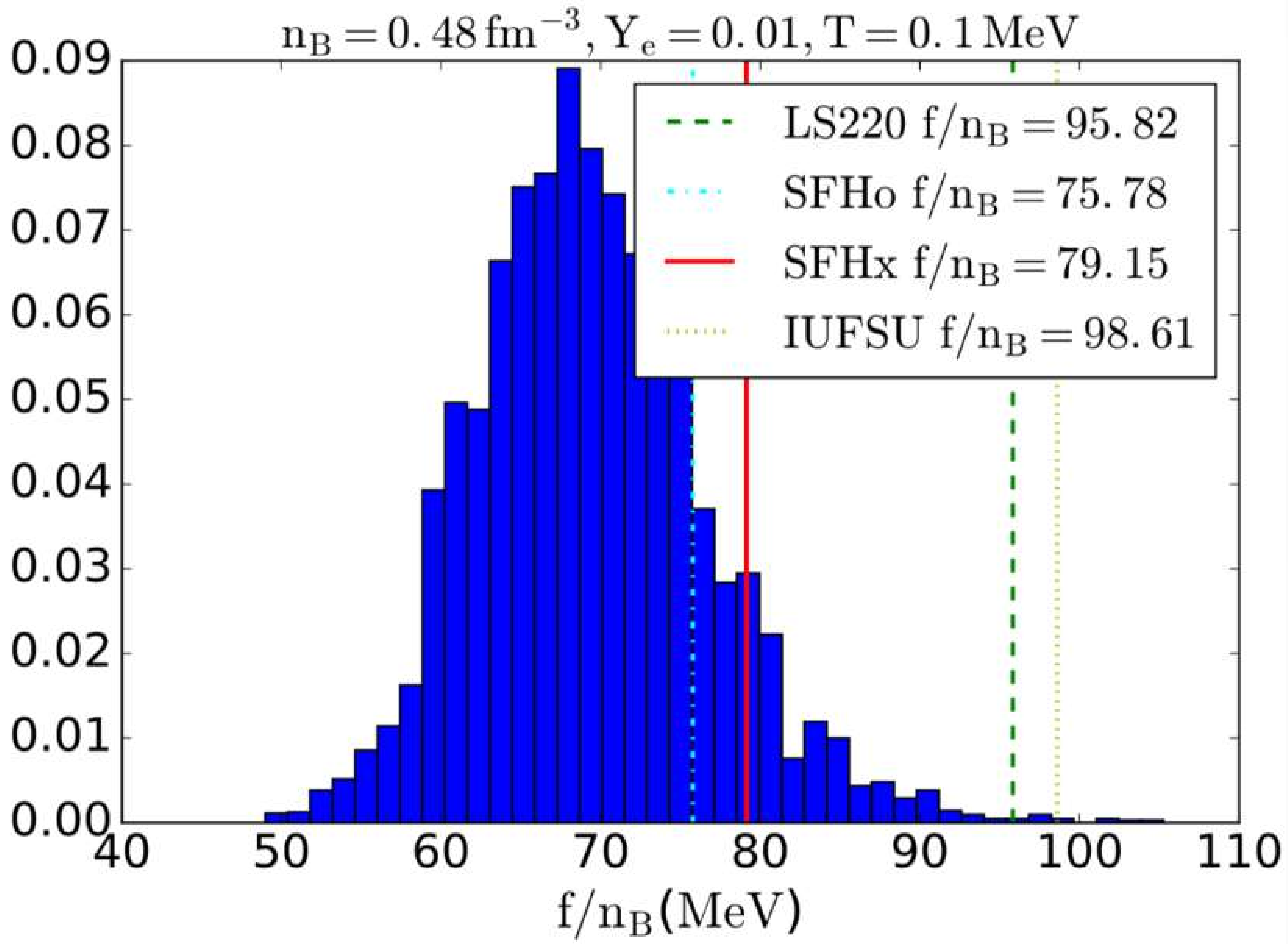


FIG. 6. The probability distribution for the free energy per baryon at $n_B = 0.48\ \mathrm{fm}^{-3}$, $Y_e = 0.10$, and $T = 0.1$ MeV.

Du et al. (2019)

- Propagating uncertainties through the neutrino opacities for charged and neutral current processes

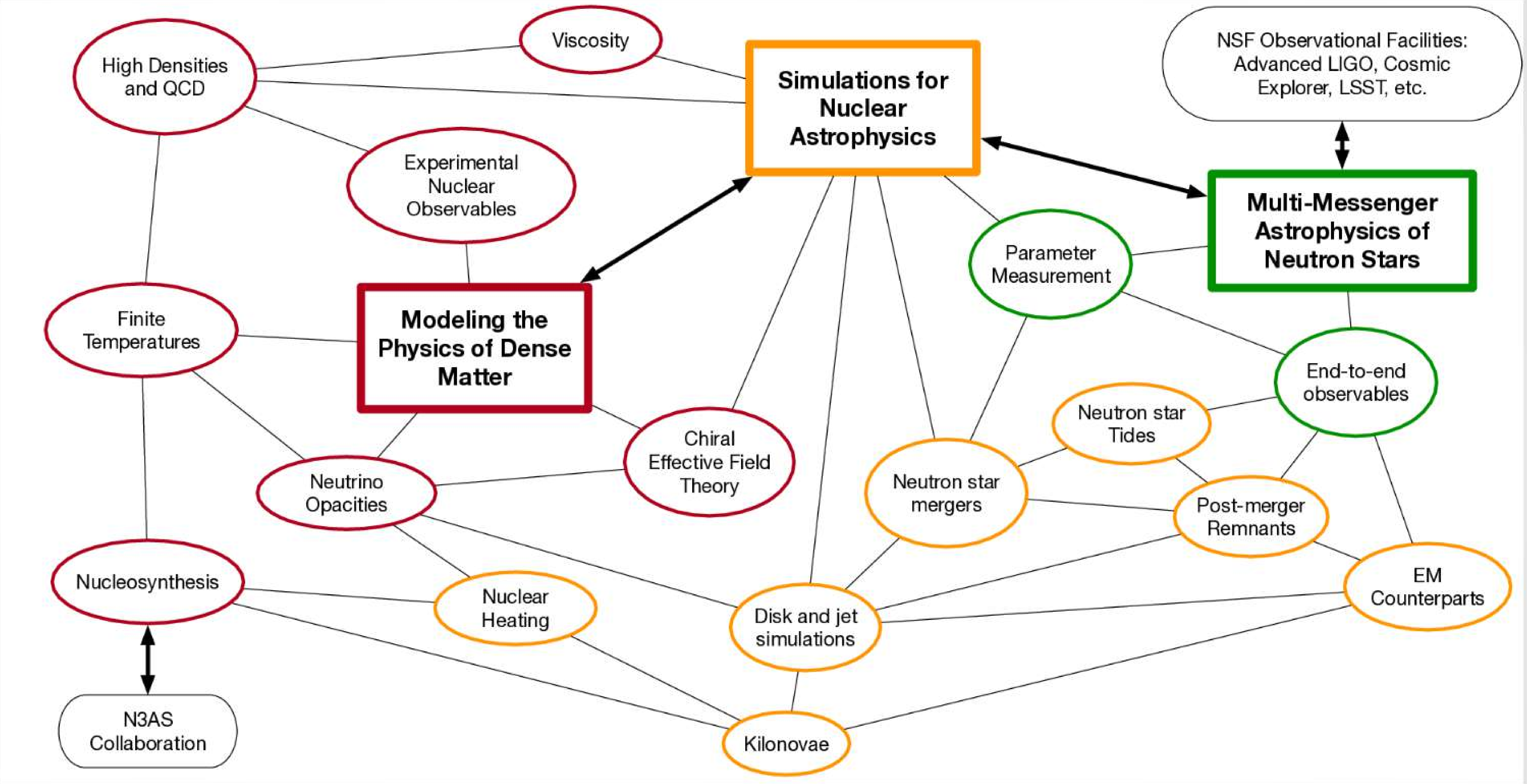
Lin et al., in prep.

Nuclear Physics of Multi-Messenger Mergers

- Understanding neutron star mergers will require a coordinated effort between many communities

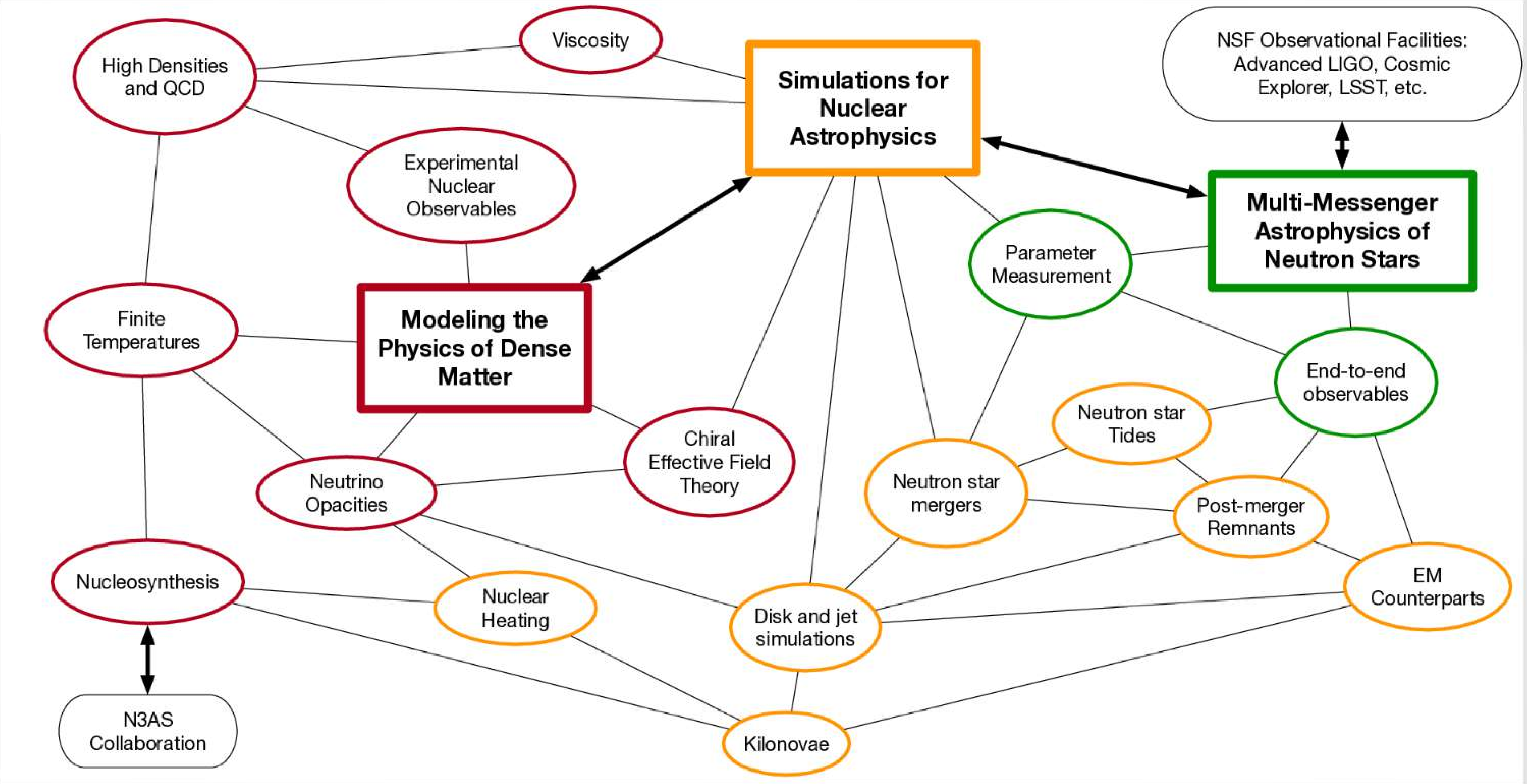
Nuclear Physics of Multi-Messenger Mergers

- Understanding neutron star mergers will require a coordinated effort between many communities



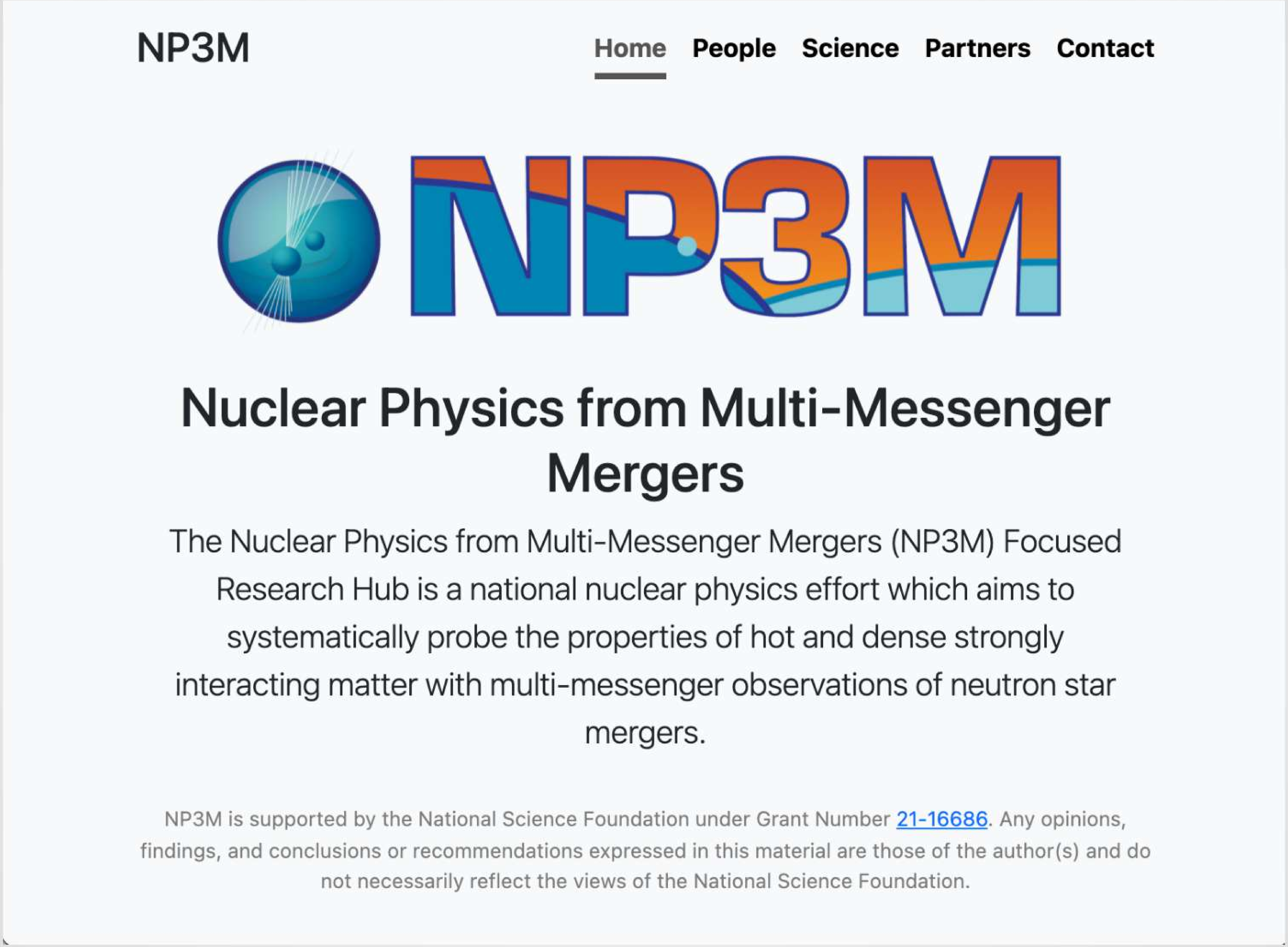
Nuclear Physics of Multi-Messenger Mergers

- Understanding neutron star mergers will require a coordinated effort between many communities



- Nuclear structure theory, low-energy nuclear theory, high-energy nuclear theory, nuclear experiment, astrophysics theory, astronomical observations, gravitational wave experiment

np3m.org

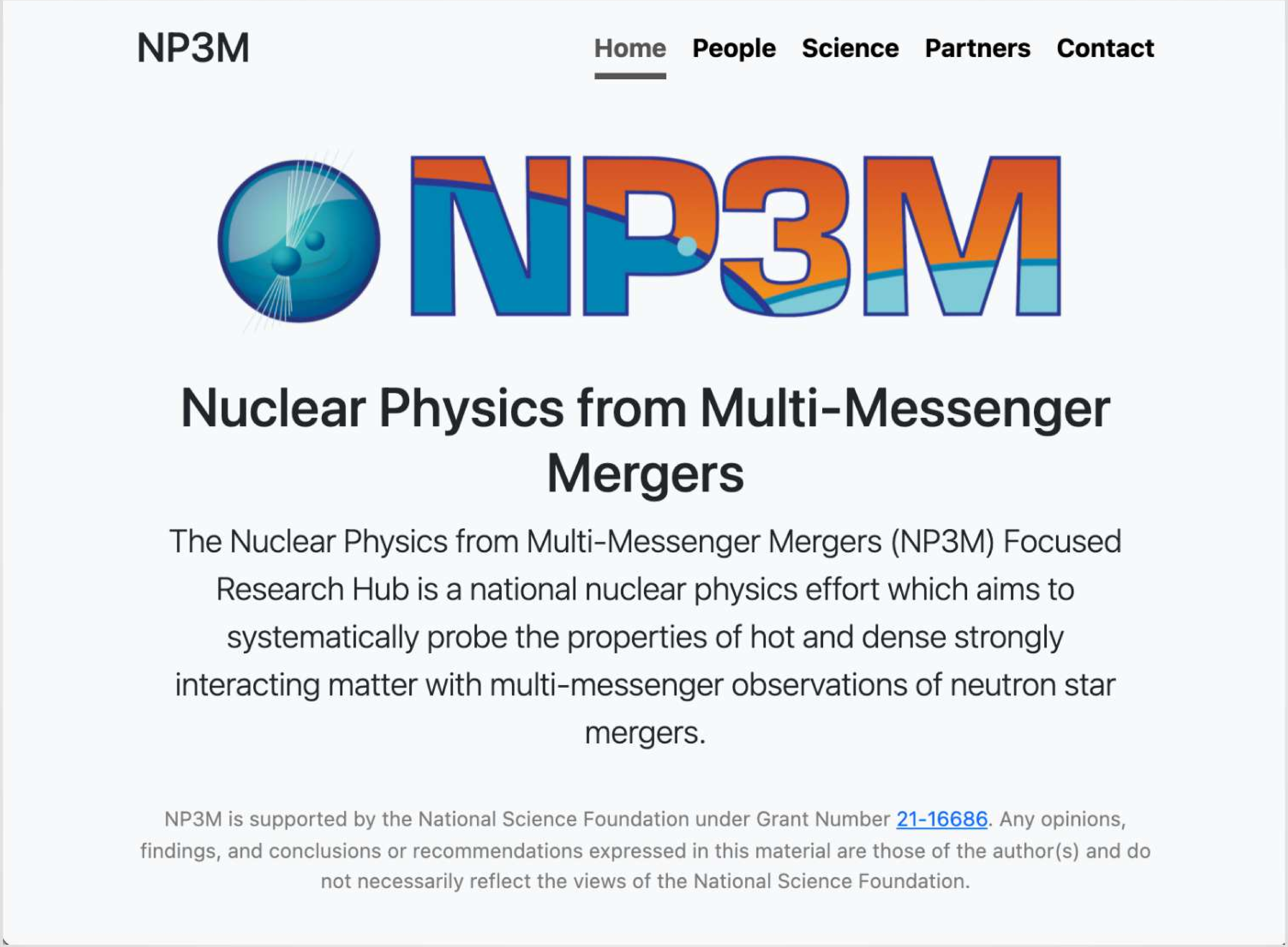


Nuclear Physics from Multi-Messenger Mergers

The Nuclear Physics from Multi-Messenger Mergers (NP3M) Focused Research Hub is a national nuclear physics effort which aims to systematically probe the properties of hot and dense strongly interacting matter with multi-messenger observations of neutron star mergers.

NP3M is supported by the National Science Foundation under Grant Number 21-16686. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

np3m.org



Nuclear Physics from Multi-Messenger Mergers

The Nuclear Physics from Multi-Messenger Mergers (NP3M) Focused Research Hub is a national nuclear physics effort which aims to systematically probe the properties of hot and dense strongly interacting matter with multi-messenger observations of neutron star mergers.

NP3M is supported by the National Science Foundation under Grant Number 21-16686. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

- Join Us!

Summary

- Future: leveraging experimental data, nuclear theory, and astronomical observations to determine the properties of strongly-interacting matter

Summary

- Future: leveraging experimental data, nuclear theory, and astronomical observations to determine the properties of strongly-interacting matter
- Determined the neutron star mass-radius curve and the equation of state of dense matter

Summary

- Future: leveraging experimental data, nuclear theory, and astronomical observations to determine the properties of strongly-interacting matter
- Determined the neutron star mass-radius curve and the equation of state of dense matter
- Predicted properties of the GW signal from GW 170817

Summary

- Future: leveraging experimental data, nuclear theory, and astronomical observations to determine the properties of strongly-interacting matter
- Determined the neutron star mass-radius curve and the equation of state of dense matter
- Predicted properties of the GW signal from GW 170817
- Moving to a new laboratory — neutron star mergers

Summary

- Future: leveraging experimental data, nuclear theory, and astronomical observations to determine the properties of strongly-interacting matter
- Determined the neutron star mass-radius curve and the equation of state of dense matter
- Predicted properties of the GW signal from GW 170817
- Moving to a new laboratory — neutron star mergers
- Begun propagating nuclear physics uncertainties through neutron star mergers

Summary

- Future: leveraging experimental data, nuclear theory, and astronomical observations to determine the properties of strongly-interacting matter
- Determined the neutron star mass-radius curve and the equation of state of dense matter
- Predicted properties of the GW signal from GW 170817
- Moving to a new laboratory — neutron star mergers
- Begun propagating nuclear physics uncertainties through neutron star mergers

Very exciting future! LIGO/VIRGO, CE, ET, FRIB, ARIEL, FAIR, SPIRAL2, NICER, Athena, eXTP, STROBE-X,...

There is a lot yet missing here:

There is a lot yet missing here:

there is a lot more to the nucleon-nucleon interaction than just the equation of state!

Composition

Composition

Superfluidity and superconductivity

Simplifying Composition and Superfluidity

- Even those two topics are too complicated for one research group

Simplifying Composition and Superfluidity

- Even those two topics are too complicated for one research group
- Begin by assuming that hot and dense matter contains only neutrons and protons

Simplifying Composition and Superfluidity

- Even those two topics are too complicated for one research group
- Begin by assuming that hot and dense matter contains only neutrons and protons
- For now, don't focus on singlet neutron superfluidity, where theory and experiment are providing guidance

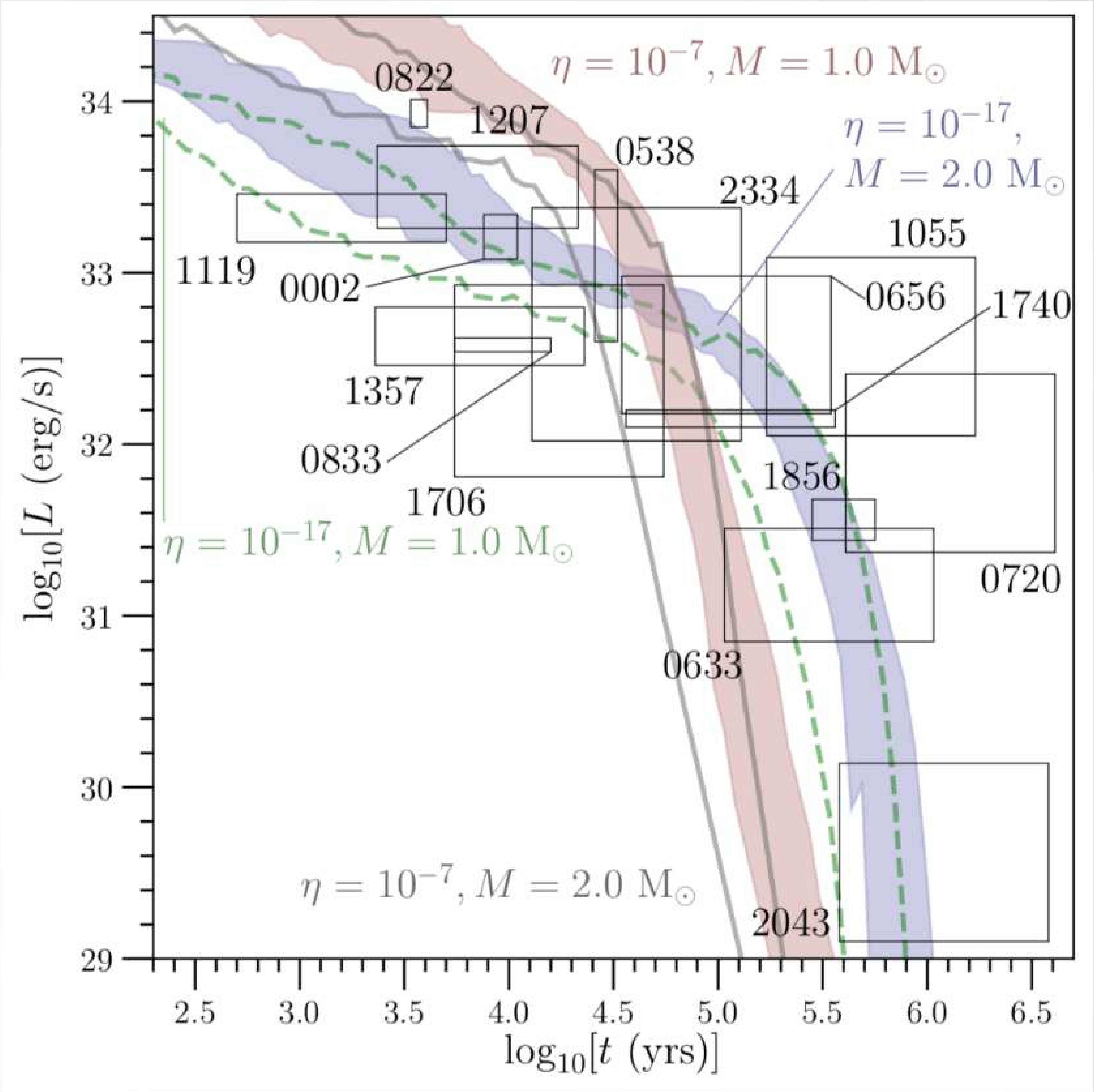
Simplifying Composition and Superfluidity

- Even those two topics are too complicated for one research group
- Begin by assuming that hot and dense matter contains only neutrons and protons
- For now, don't focus on singlet neutron superfluidity, where theory and experiment are providing guidance
- Use neutron star observations to tackle proton superconductivity and neutron triplet superfluidity in high-density matter

Thermal Emission from Isolated Neutron Stars

- After ~ 10 years, the neutron star is isothermal ⇒ one temperature = T

$$C_V \frac{dT}{dt} = L_\nu + L_\gamma$$



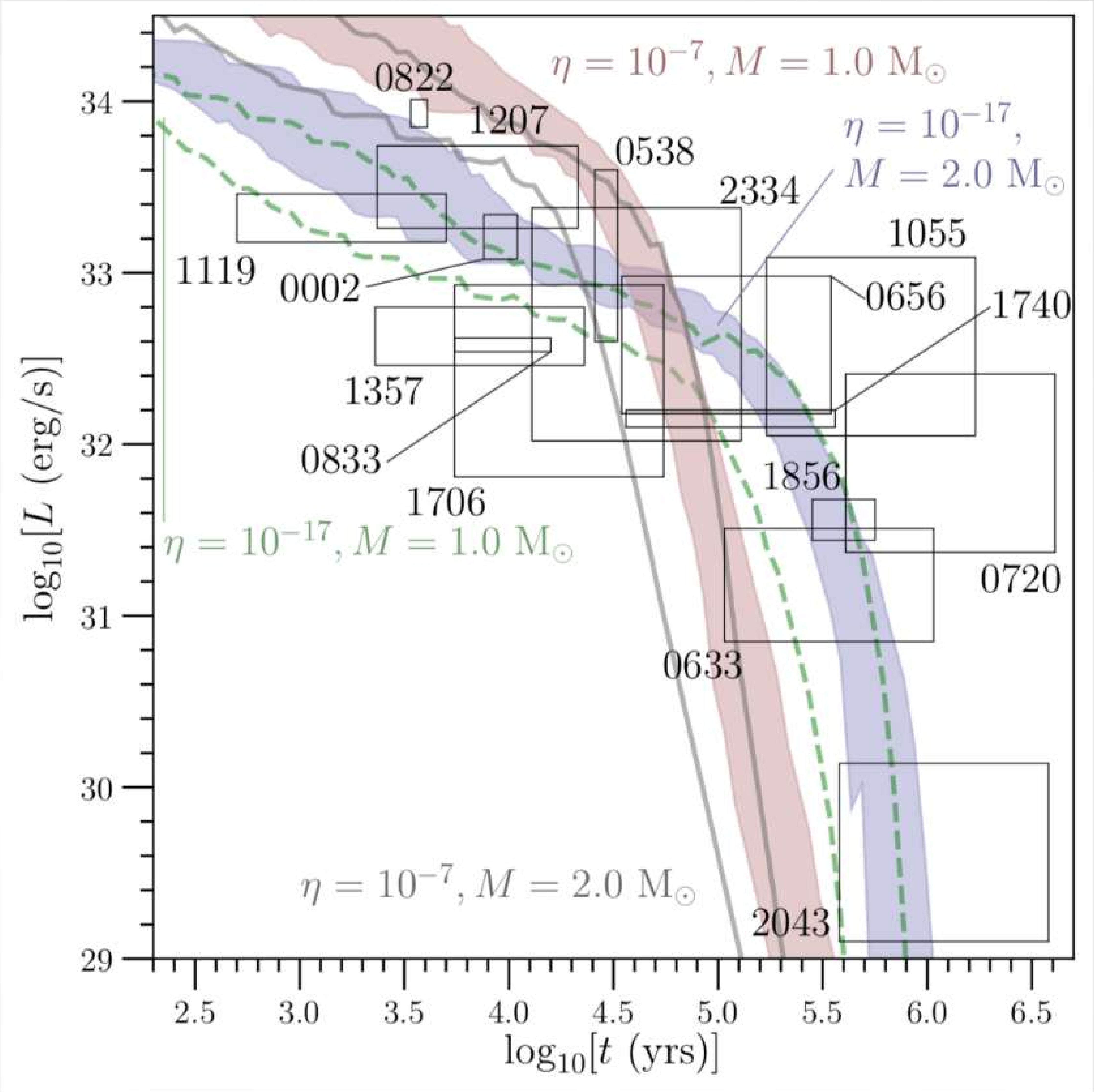
Beloin et al. (2019)

Thermal Emission from Isolated Neutron Stars

- After ~ 10 years, the neutron star is isothermal ⇒ one temperature = T

$$C_V \frac{dT}{dt} = L_\nu + L_\gamma$$

- Assume only neutrons and protons



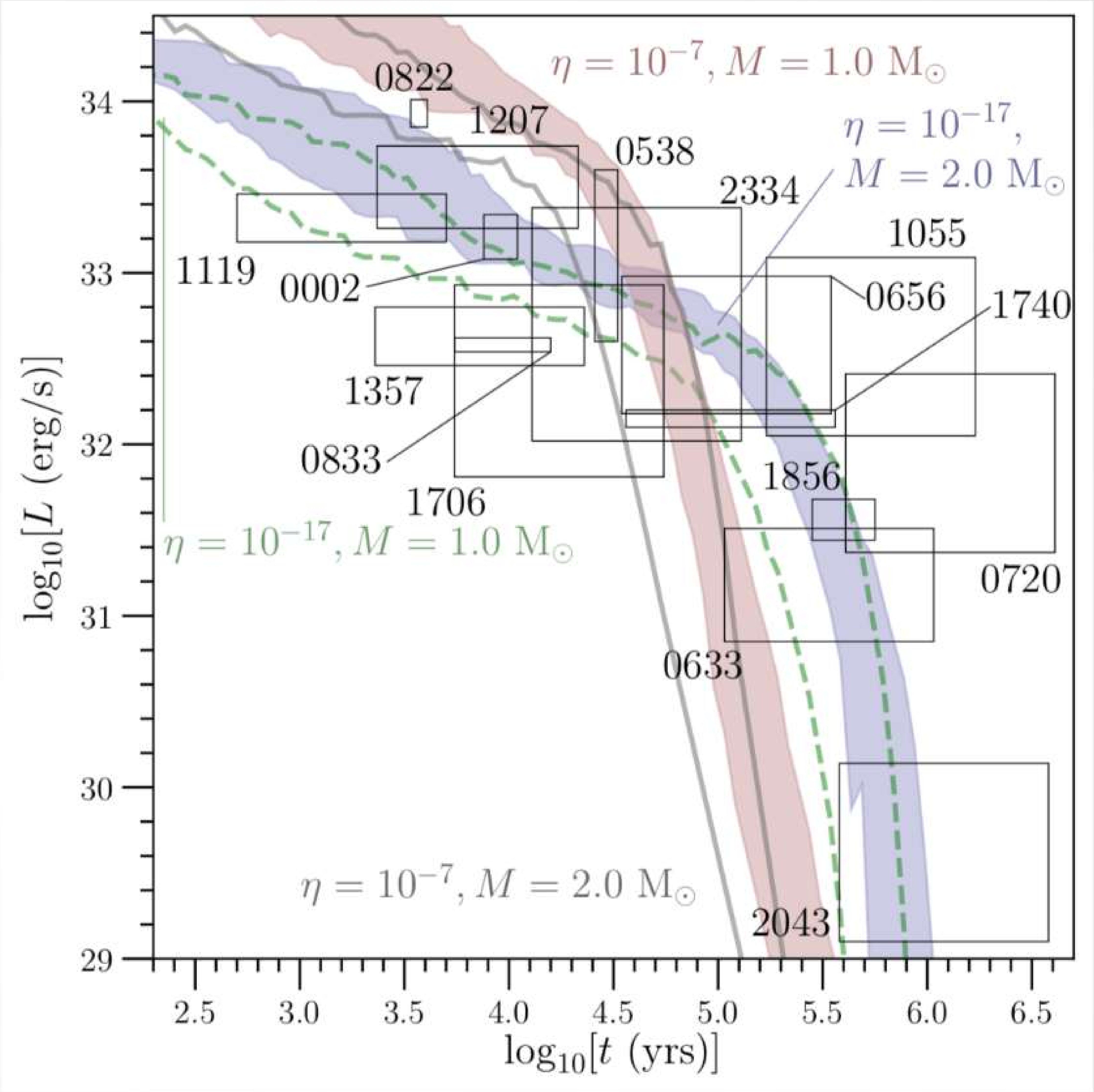
Beloin et al. (2019)

Thermal Emission from Isolated Neutron Stars

- After ~ 10 years, the neutron star is isothermal ⇒ one temperature = T

$$C_V \frac{dT}{dt} = L_\nu + L_\gamma$$

- Assume only neutrons and protons
- Age taken from, e.g., association with a supernova remnant



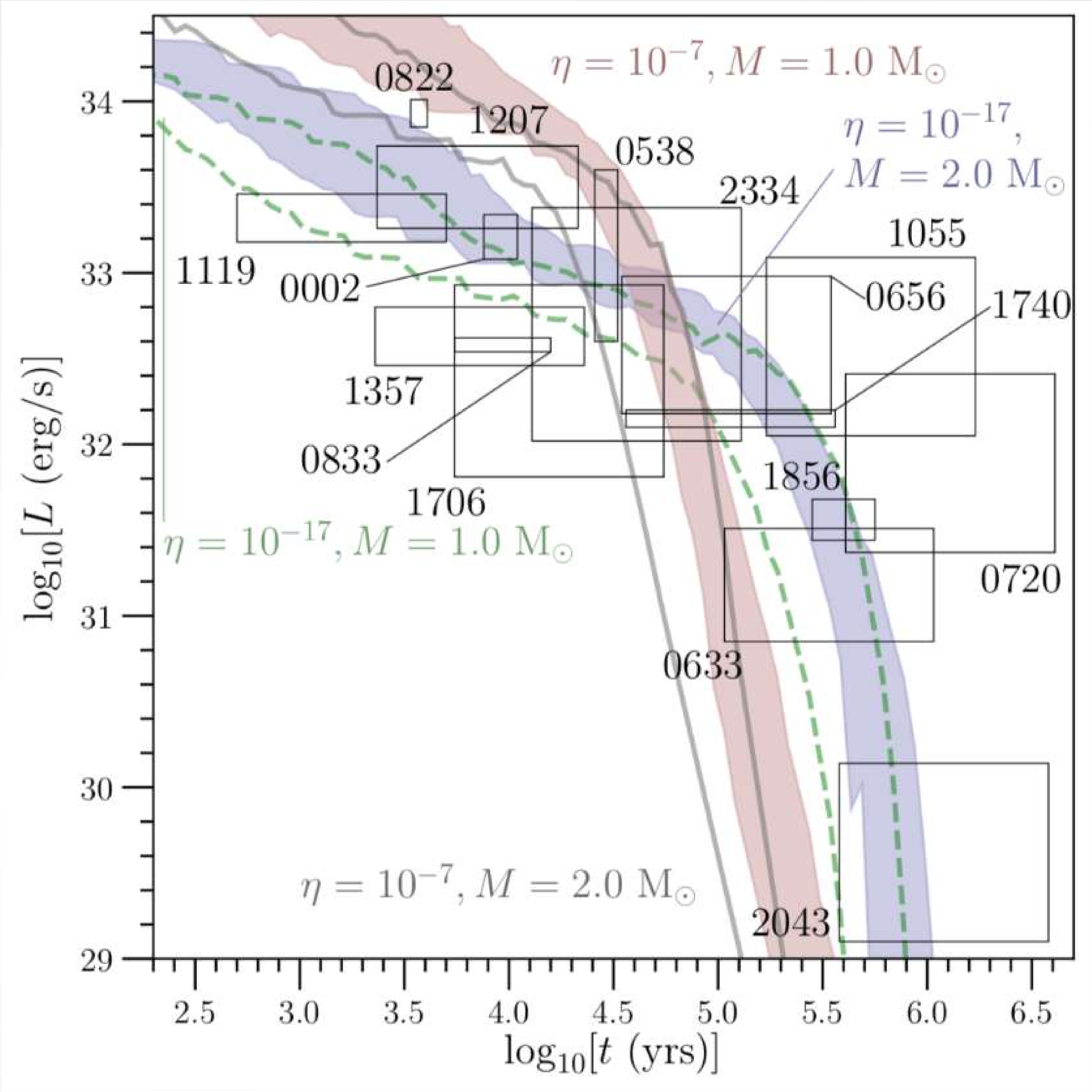
Beloin et al. (2019)

Thermal Emission from Isolated Neutron Stars

- After ~ 10 years, the neutron star is isothermal ⇒ one temperature = T

$$C_V \frac{dT}{dt} = L_\nu + L_\gamma$$

- Assume only neutrons and protons
- Age taken from, e.g., association with a supernova remnant



Beloin et al. (2019)

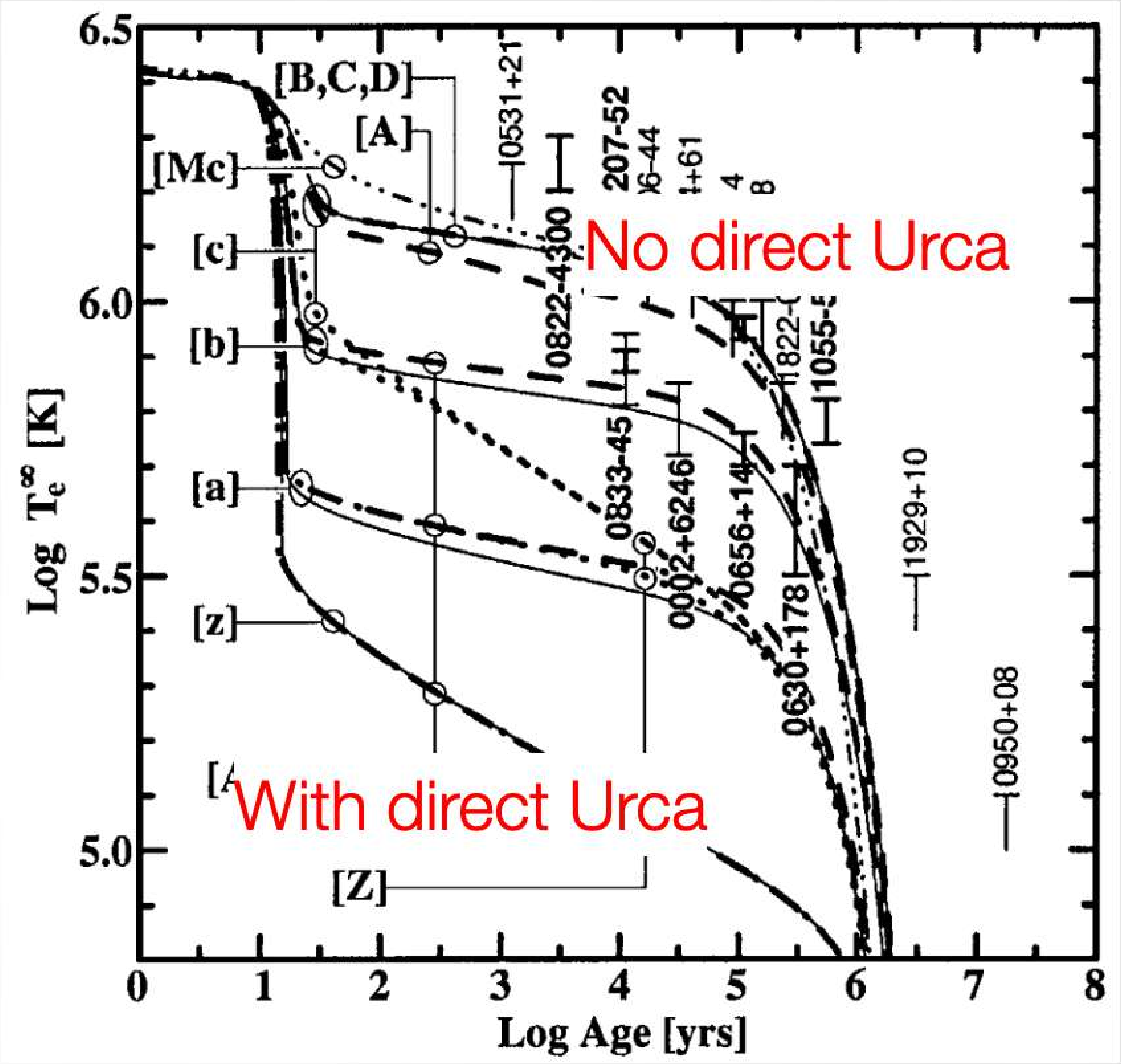
J0002-6216, i.e. the "cannonball pulsar"

(This star is not in our data set.)

Role of Composition

- Beta-decay ("direct Urca process") cools very quickly

$$n \rightarrow p + e + \bar{\nu}_e$$



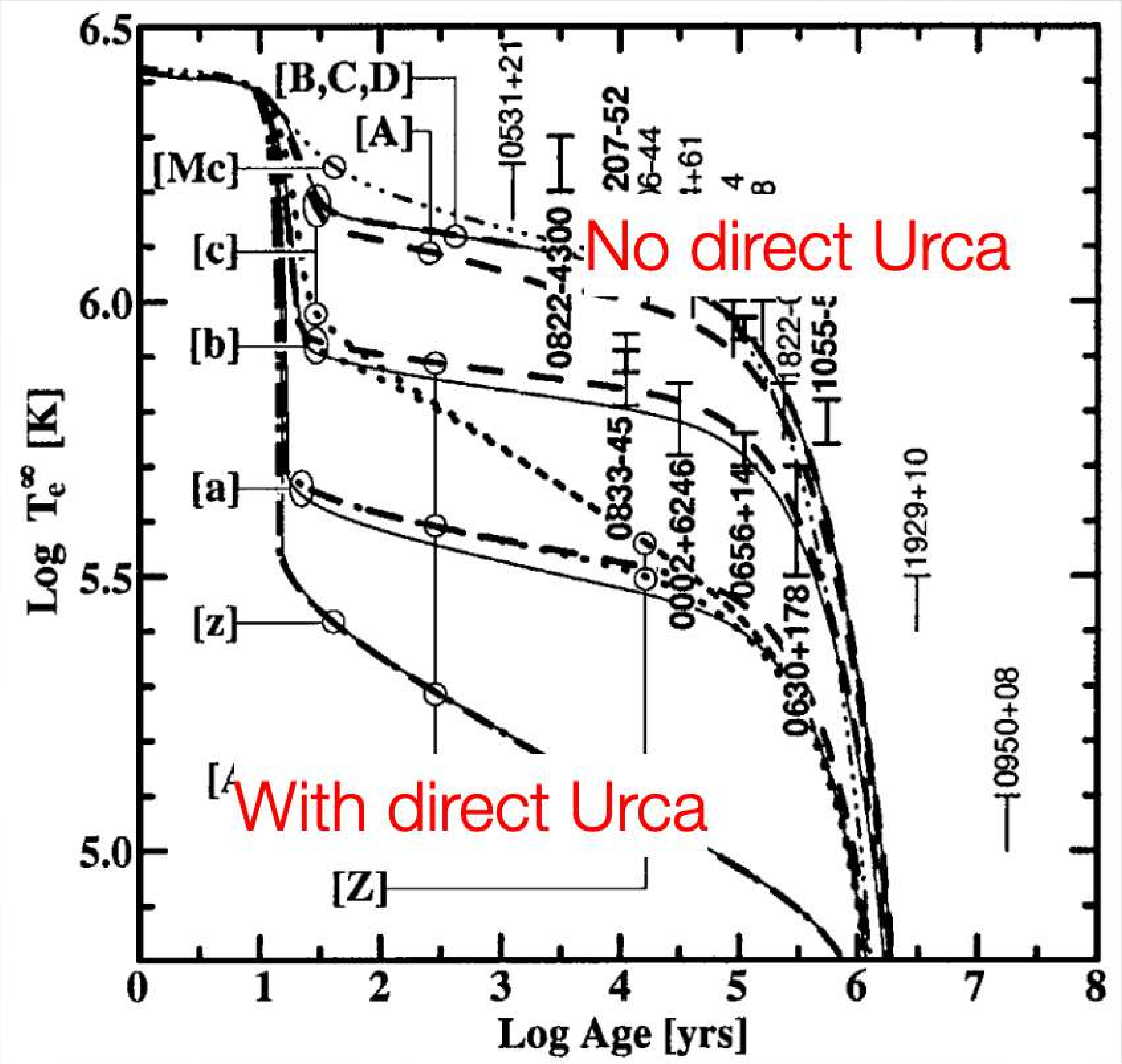
Page et al. (2000)

Role of Composition

- Beta-decay ("direct Urca process") cools very quickly

$$n \rightarrow p + e + \bar{\nu}_e$$

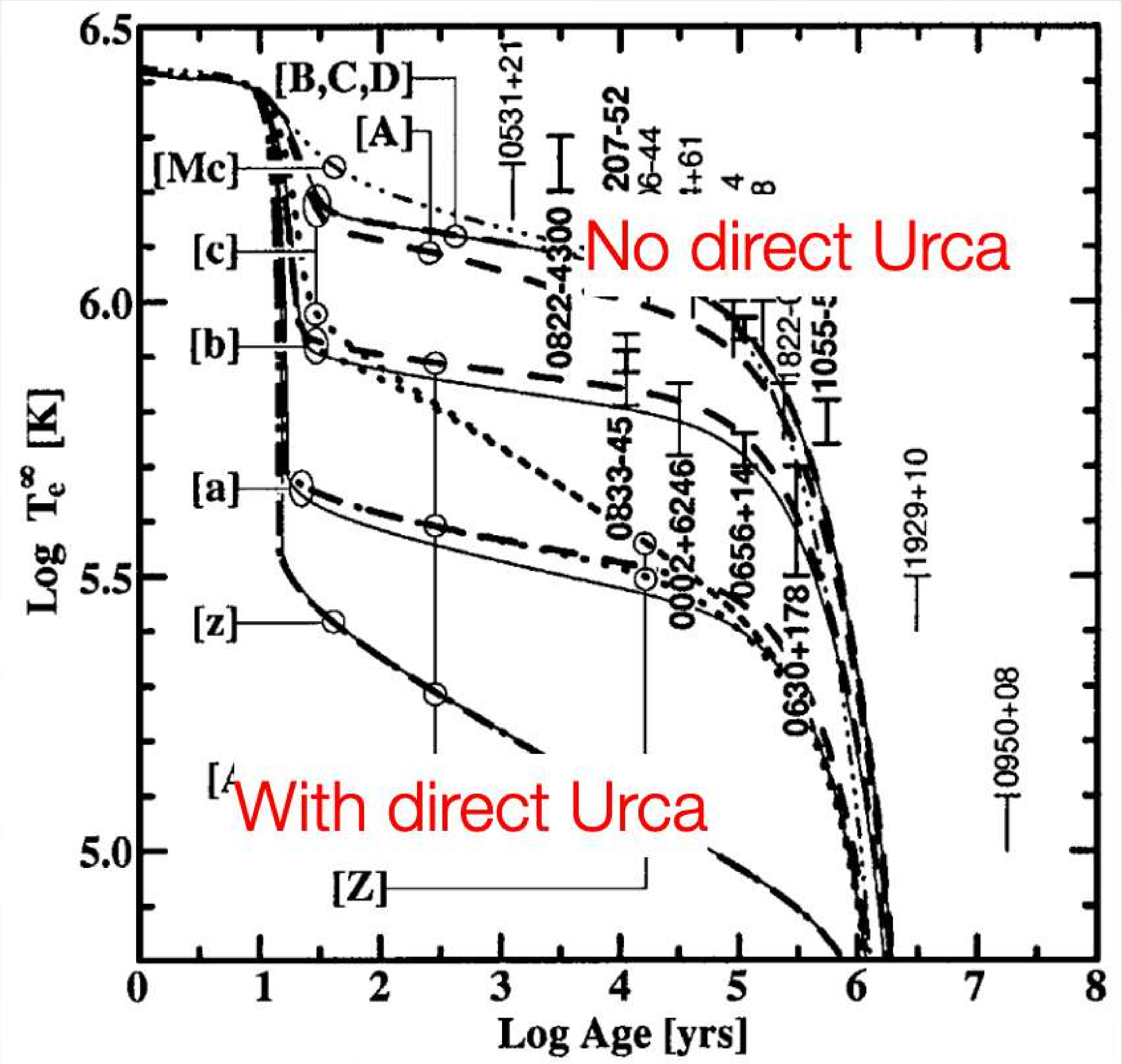
- Degenerate system + energy and momentum conservation means it is allowed only if $n_p/n_n > 11\%$



Page et al. (2000)

Role of Composition

- Beta-decay ("direct Urca process") cools very quickly
$$n \rightarrow p + e + \bar{\nu}_e$$
- Degenerate system + energy and momentum conservation means it is allowed only if $n_p/n_n > 11\%$
- Strong direct Urca process ruled by observations



Page et al. (2000)

Role of Composition

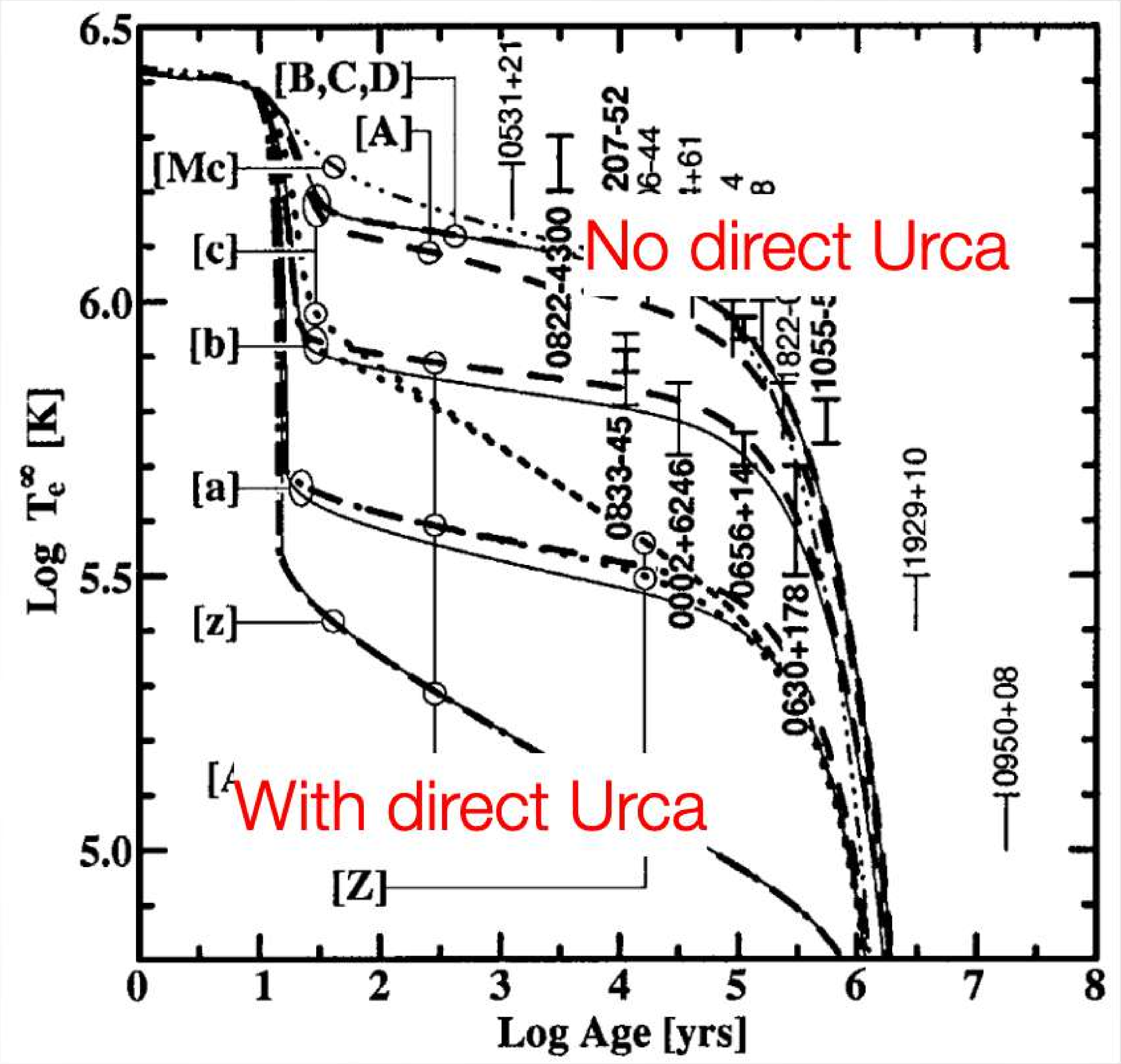
- Beta-decay ("direct Urca process") cools very quickly

$$n \rightarrow p + e + \bar{\nu}_e$$

- Degenerate system + energy and momentum conservation means it is allowed only if $n_p/n_n > 11\%$

- Strong direct Urca process ruled by observations

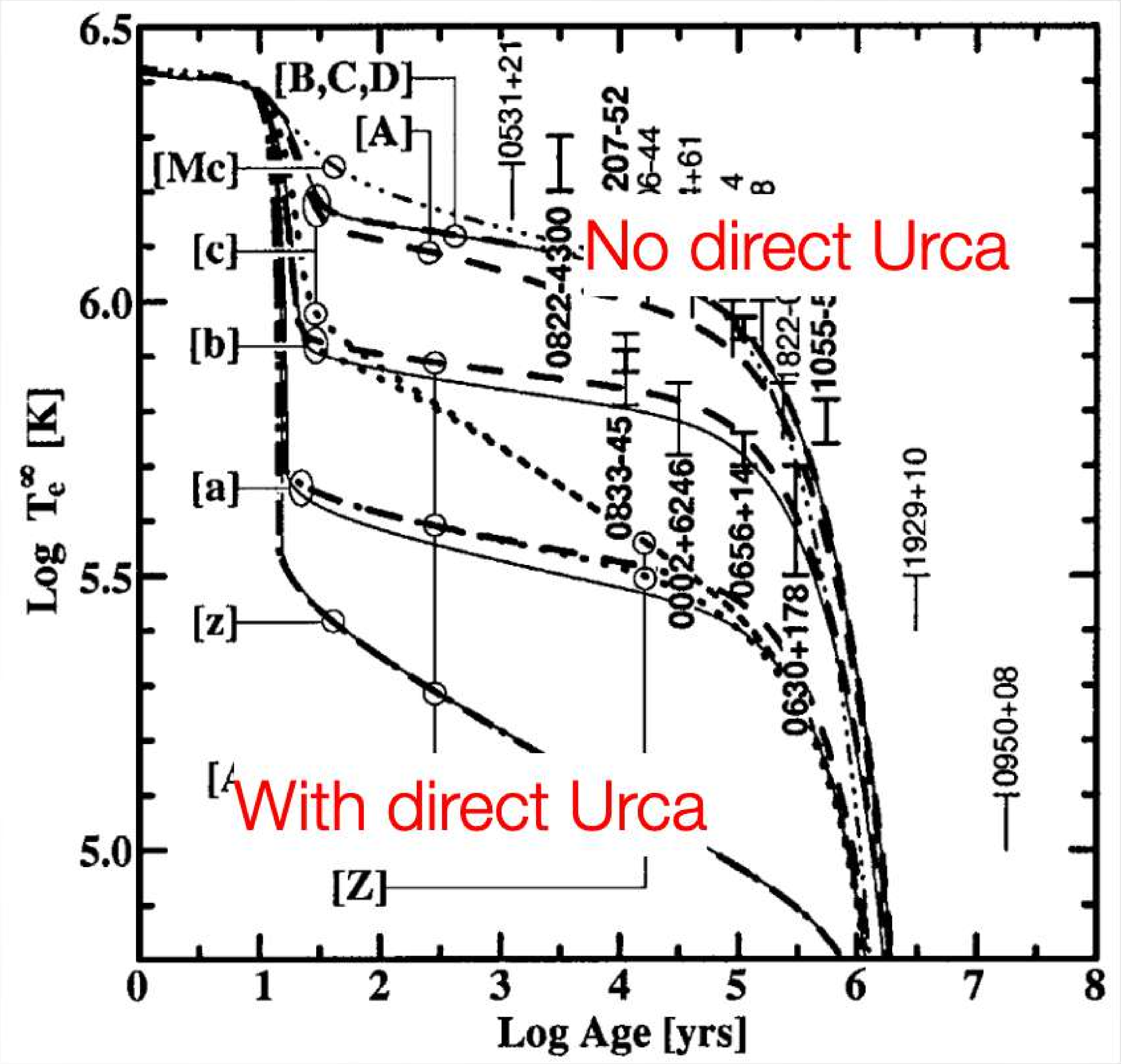
- Most theoretical models predict a direct Urca process for $M \sim 2\,\mathrm{M}_\odot$



Page et al. (2000)

Role of Composition

- Beta-decay ("direct Urca process") cools very quickly
$$n \to p + e + \bar{\nu}_e$$
- Degenerate system + energy and momentum conservation means it is allowed only if $n_p/n_n > 11\%$
- Strong direct Urca process ruled by observations
- Most theoretical models predict a direct Urca process for $M \sim 2\,\mathrm{M}_\odot$

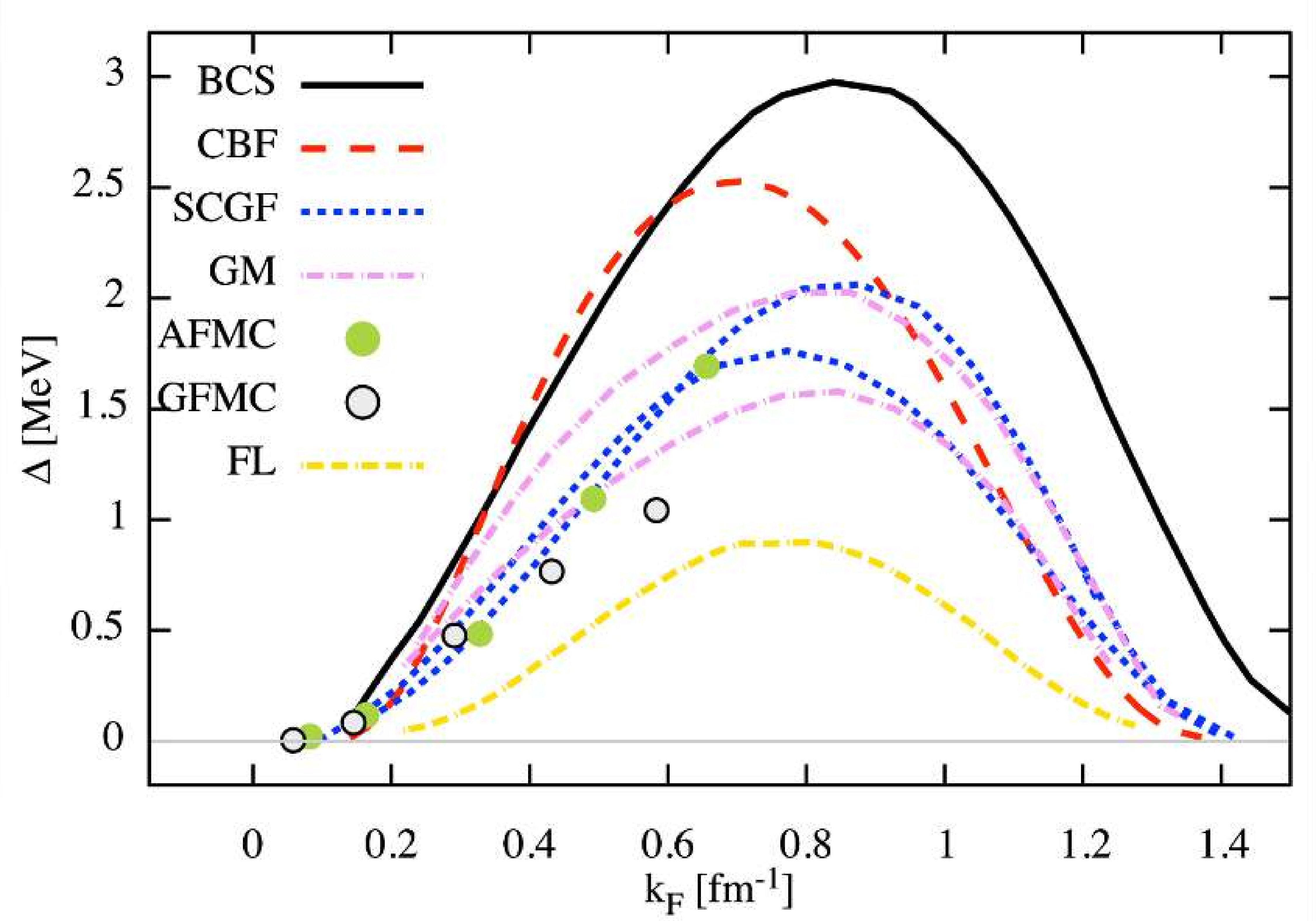


Page et al. (2000)

- Urca quandary: Why are there so few cold isolated neutron stars?

Superfluidity and Superconductivity

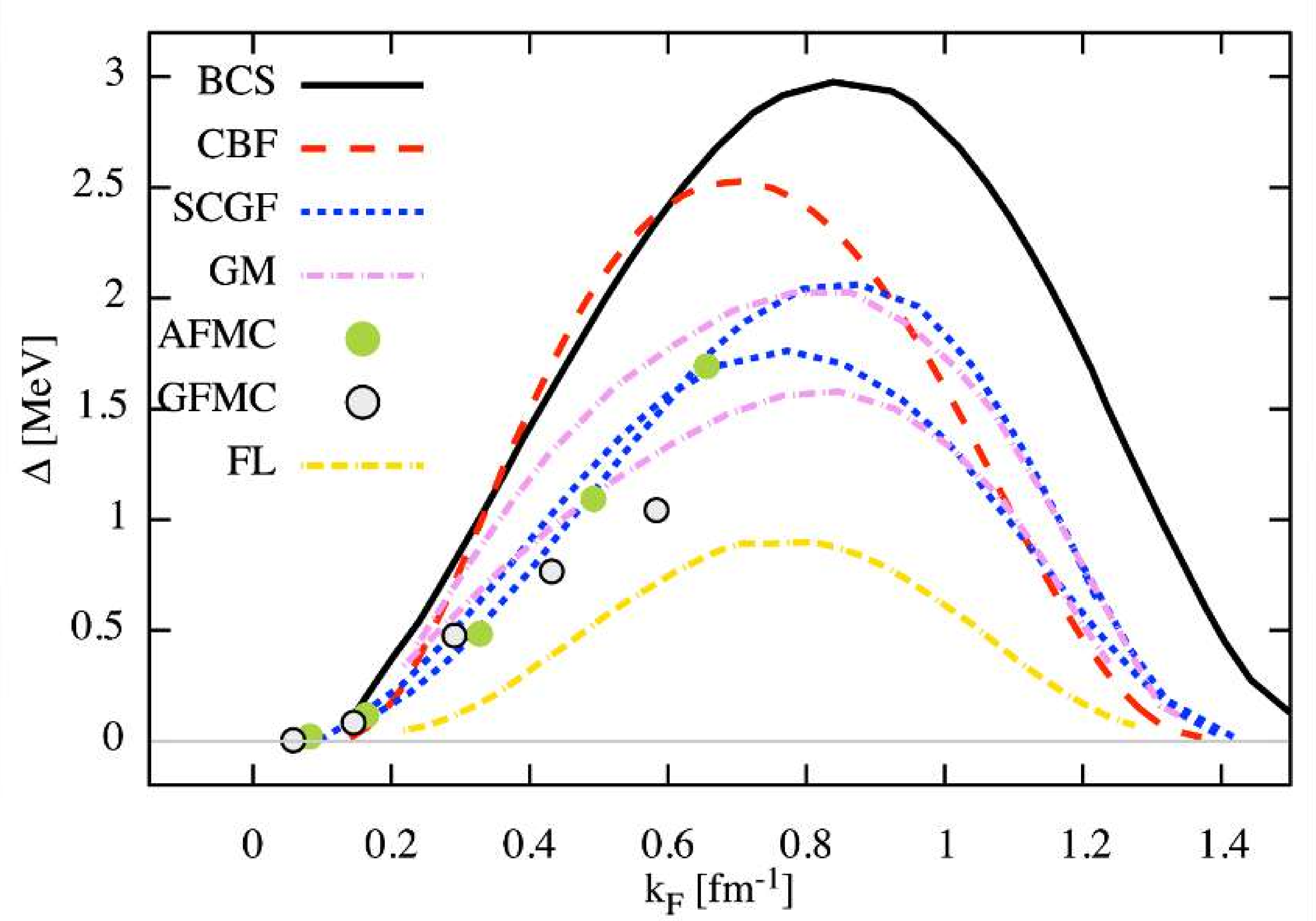
- Superfluid properties are particularly difficult to calculate



Sedrakian and Clark (2019), Review of recent theory results on $^1S_0$ neutron superfluidity

Superfluidity and Superconductivity

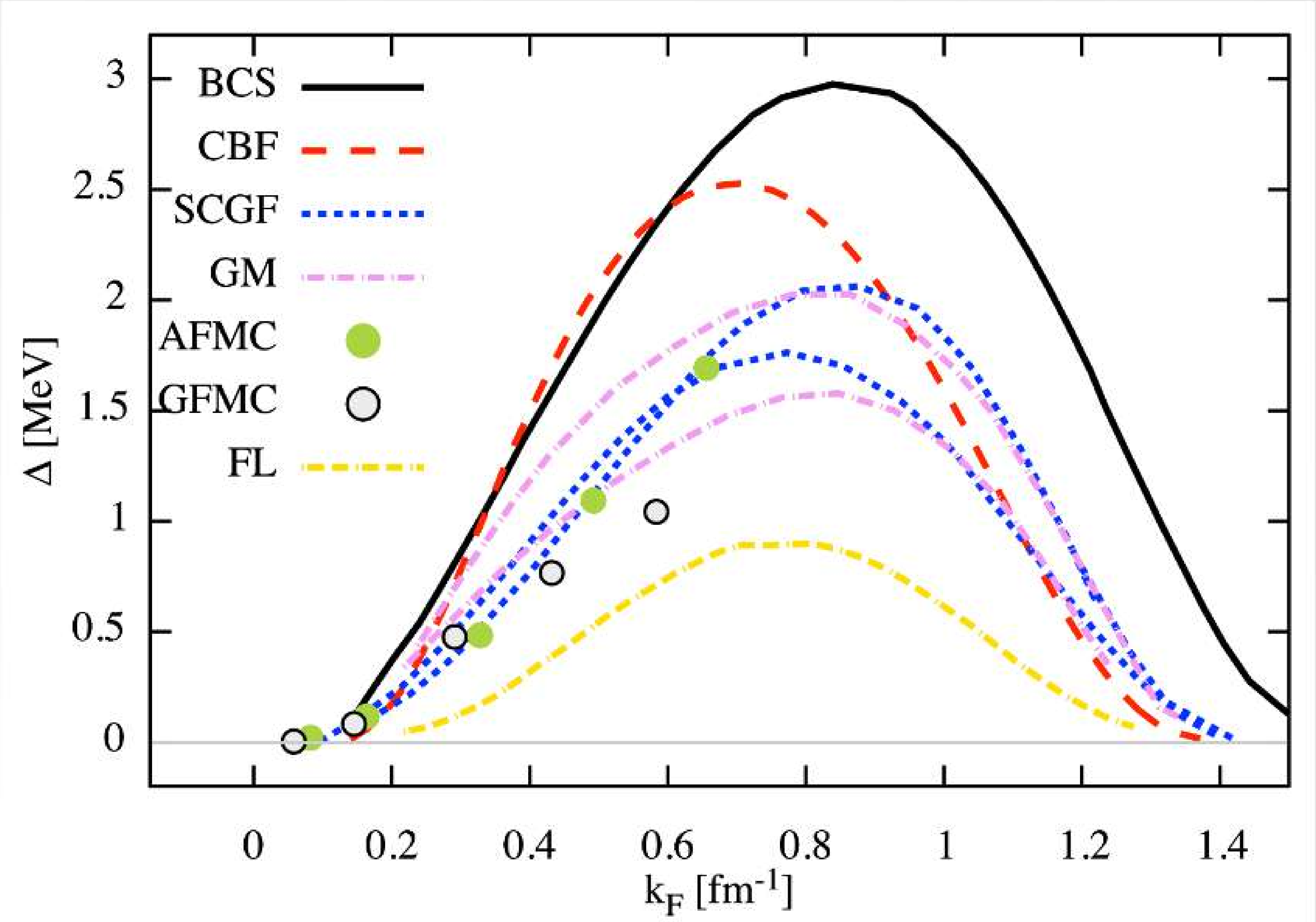
- Superfluid properties are particularly difficult to calculate
- Superfluidity prevents beta-decay because it breaks a neutron Cooper pair



Sedrakian and Clark (2019), Review of recent theory results on $^1S_0$ neutron superfluidity

Superfluidity and Superconductivity

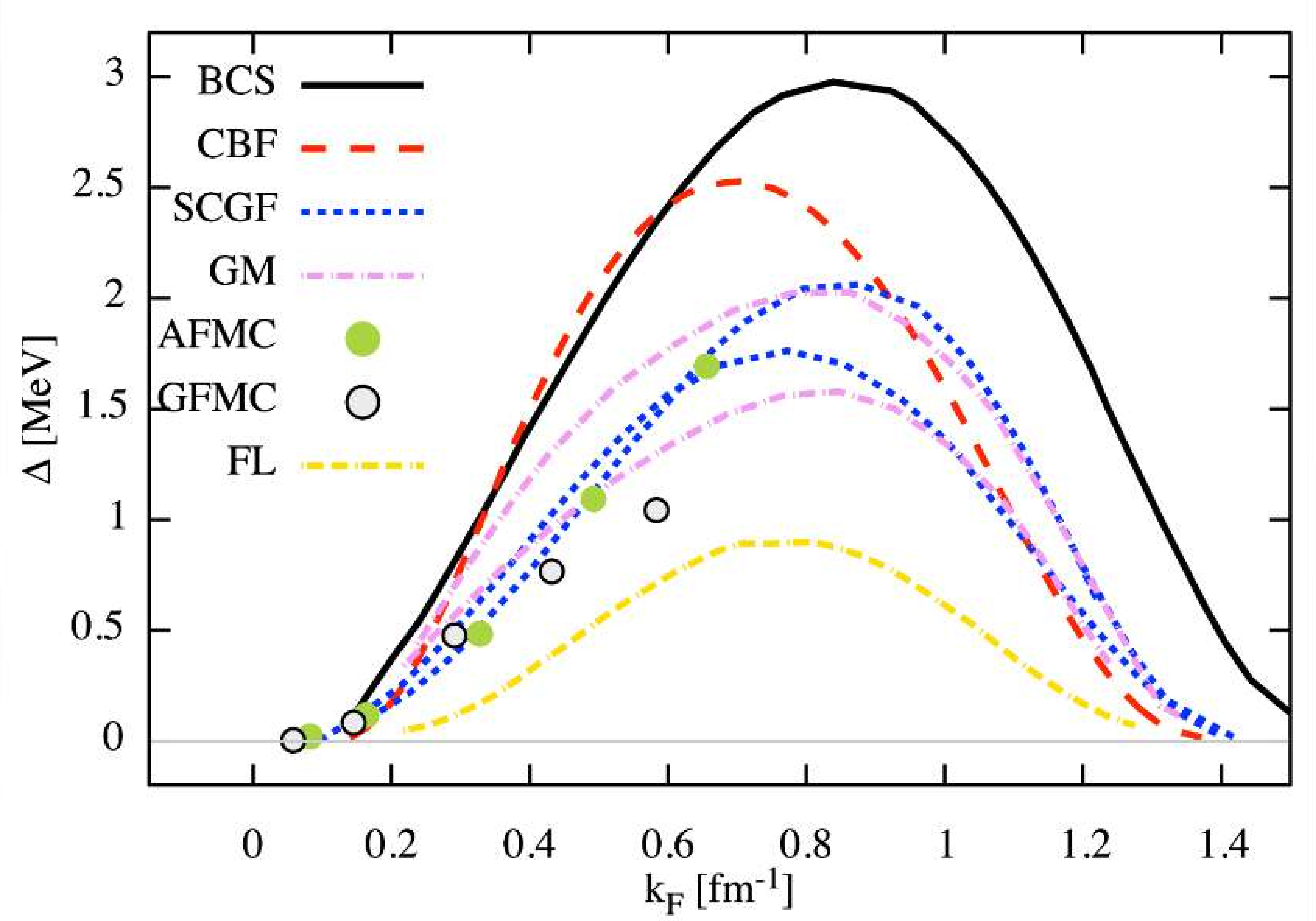
- Superfluid properties are particularly difficult to calculate
- Superfluidity prevents beta-decay because it breaks a neutron Cooper pair
- Parameterize neutron triplet and proton singlet critical temperature with simple Gaussian



Sedrakian and Clark (2019), Review of recent theory results on $^1S_0$ neutron superfluidity

Superfluidity and Superconductivity

- Superfluid properties are particularly difficult to calculate
- Superfluidity prevents beta-decay because it breaks a neutron Cooper pair
- Parameterize neutron triplet and proton singlet critical temperature with simple Gaussian

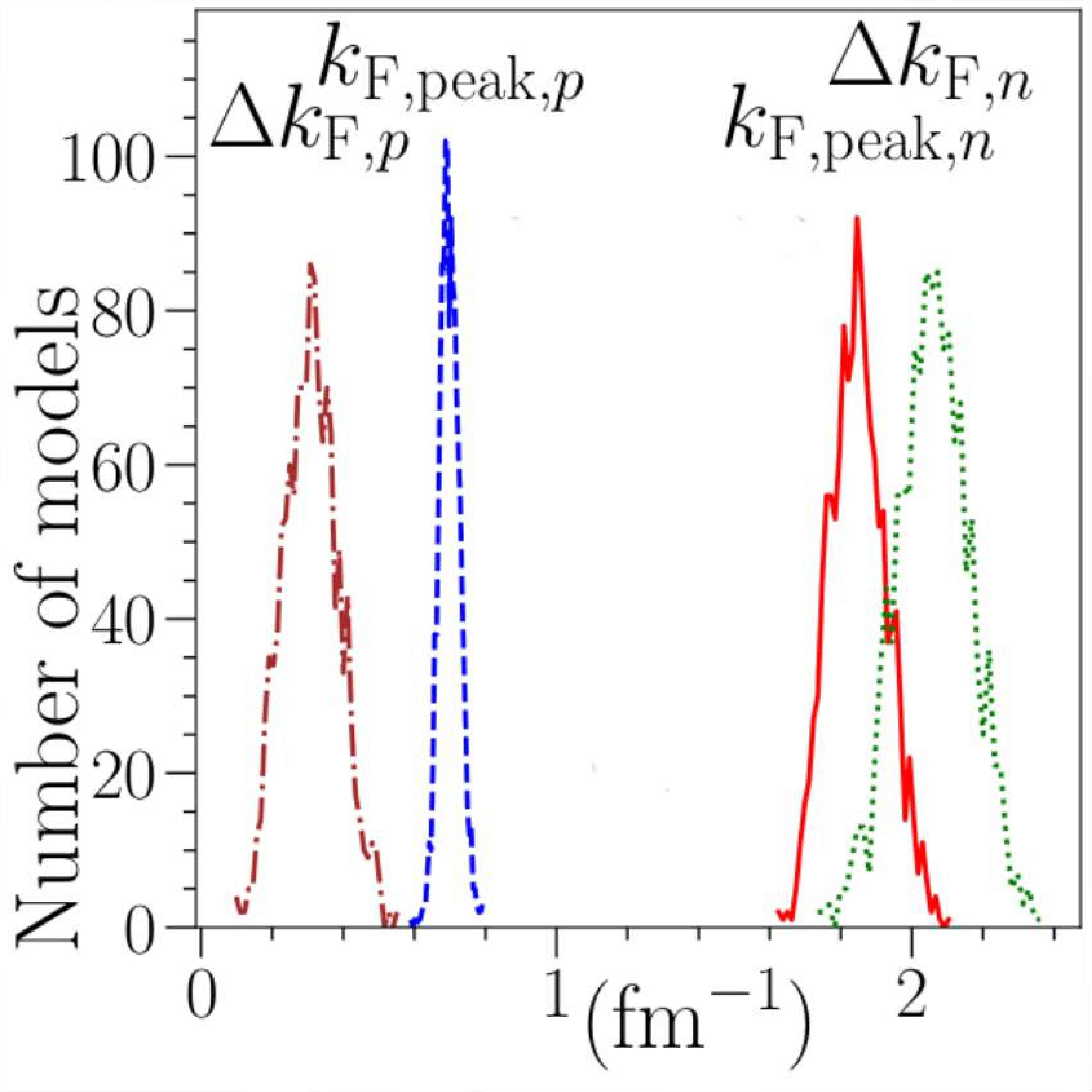


Sedrakian and Clark (2019), Review of recent theory results on $^1S_0$ neutron superfluidity

$$T_C(k_F) = T_{C,\max} \exp\left[-\left(\frac{k_{F,\mathrm{peak}} - k_F}{\Delta k_F}\right)^2\right]$$

Early Cooling Results

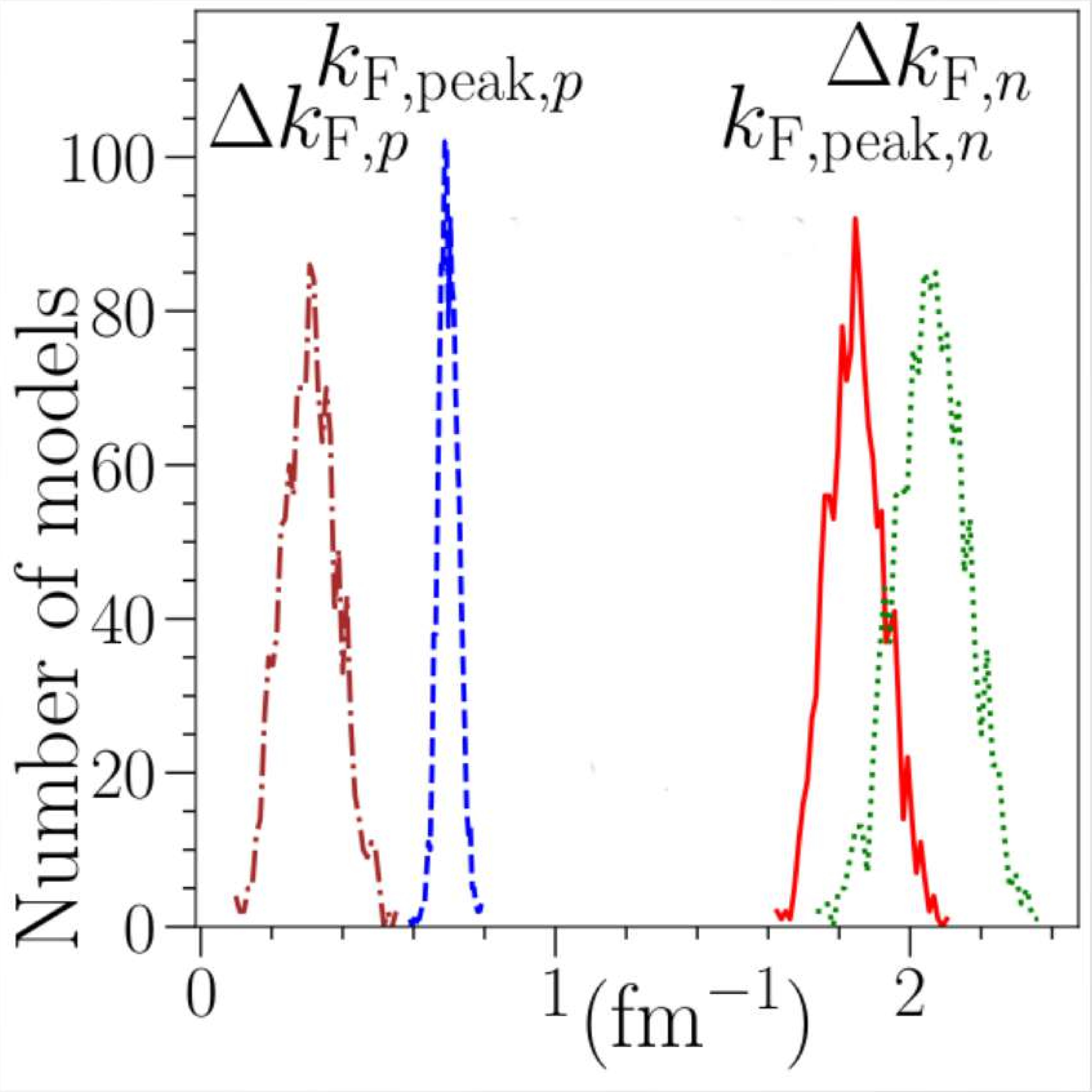
- Proton fraction typically large, allowing direct Urca for stars with masses $> 1.4 - 1.7\ \mathrm{M}_\odot$



Beloin et al. (2019)

Early Cooling Results

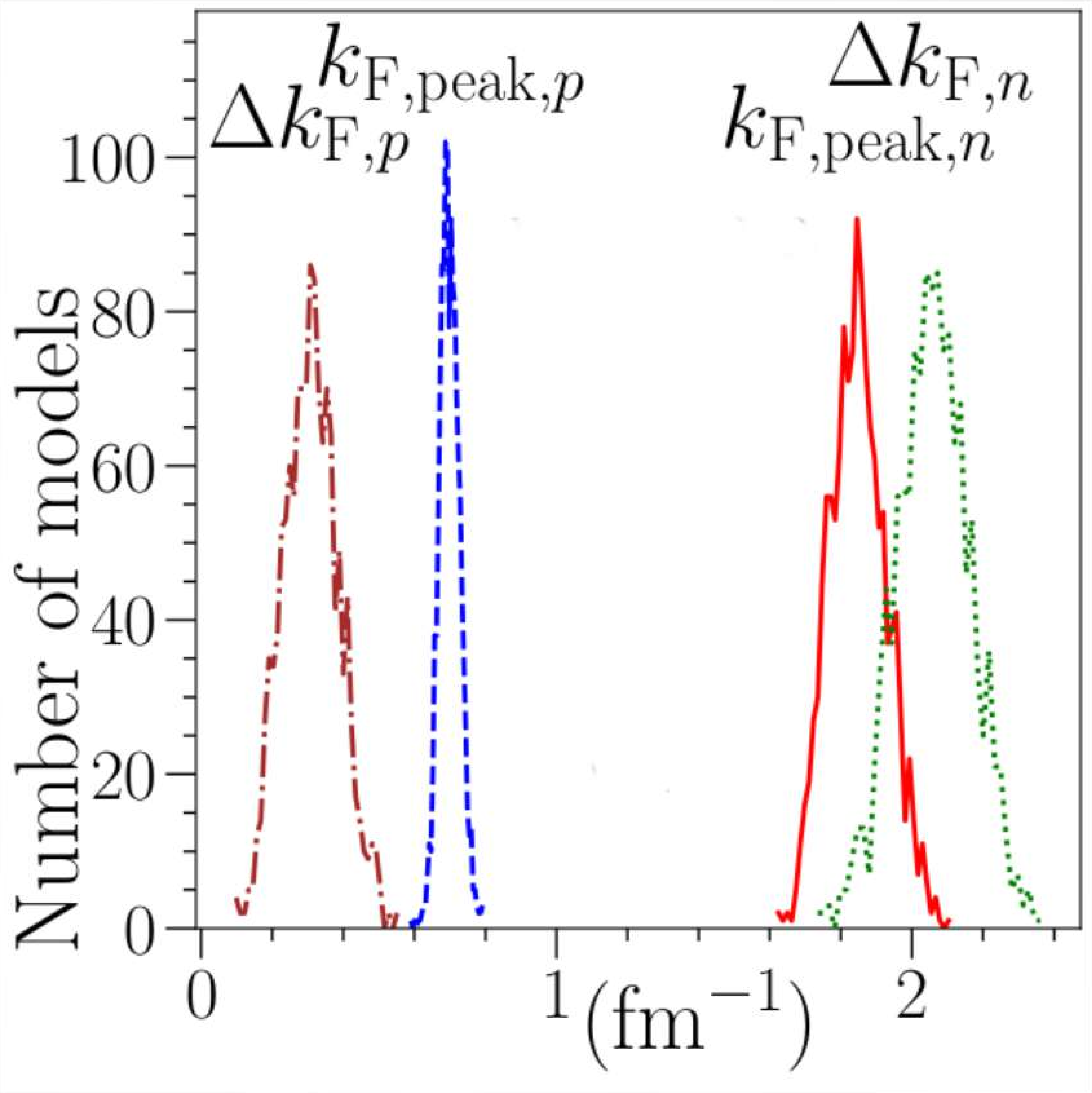
- Proton fraction typically large, allowing direct Urca for stars with masses $> 1.4 - 1.7\ \mathrm{M}_\odot$
- Neutron superfluidity pervades the star



Beloin et al. (2019)

Early Cooling Results

- Proton fraction typically large, allowing direct Urca for stars with masses $> 1.4 - 1.7\ \mathrm{M}_\odot$
- Neutron superfluidity pervades the star
- Thus, beta-decay is rarely allowed and superfluidity solves the Urca quandary.



Beloin et al. (2019)

Current Status: Large-Scale Bayesian Inference

- 30 isolated cooling neutron stars
- Steady-state luminosities for 6 accreting neutron stars
- 8 QLMXB or PRE radius observations
- 2 NICER observations
- PREX and nuclear structure constraints
- GW 170817

- EOS parameters
- Superfluidity/superconductivity parameters
- Atmosphere or envelope composition for many stars
- Mass of each star stars
- Age for cooling isolated neutron stars
- Average accretion rate for accreting neutron stars