Equation of State at finite temperature in the era of new nuclear physics and multi-messenger constraints

Chiranjib Mondal
https://chiranjibmondal.netlify.app/

ICCUB
Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

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Physics across scales

Nuclei and Neutron Star and Equation of state

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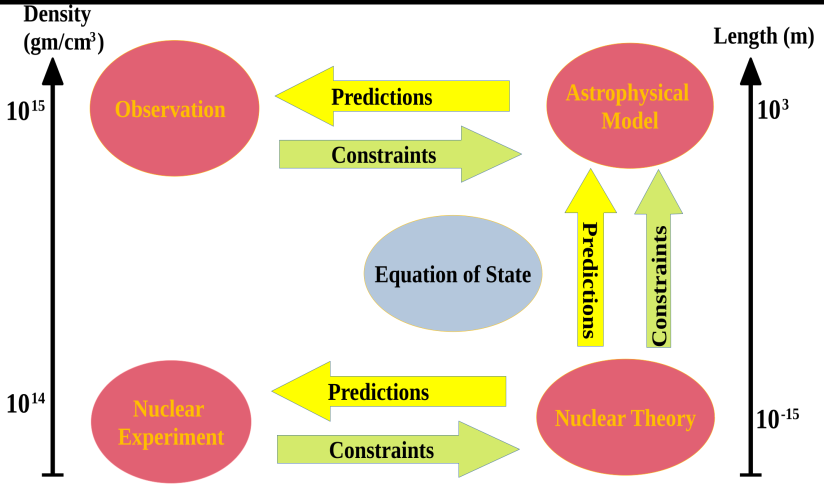
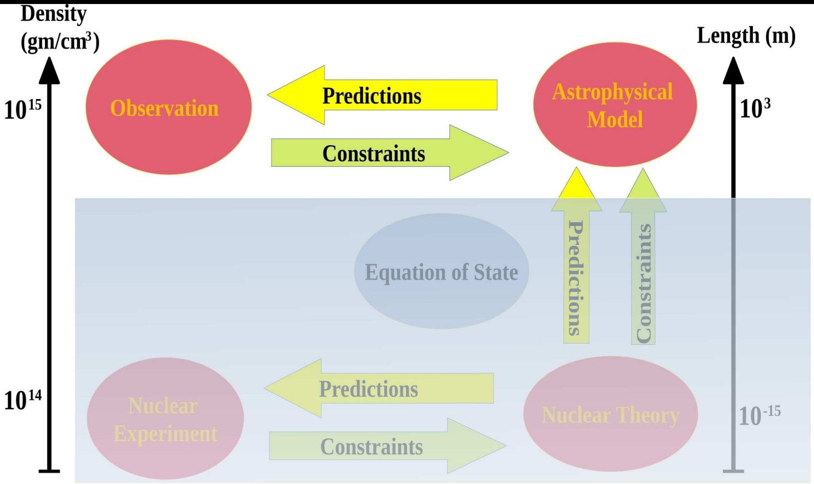


Physics across scales

Nuclei and Neutron Star and Equation of state



$$\mathcal{H}\psi = \mathrm{E}\psi \rightarrow < \psi|\mathcal{O}|\psi > \implies \mathrm{P}(\epsilon).$$

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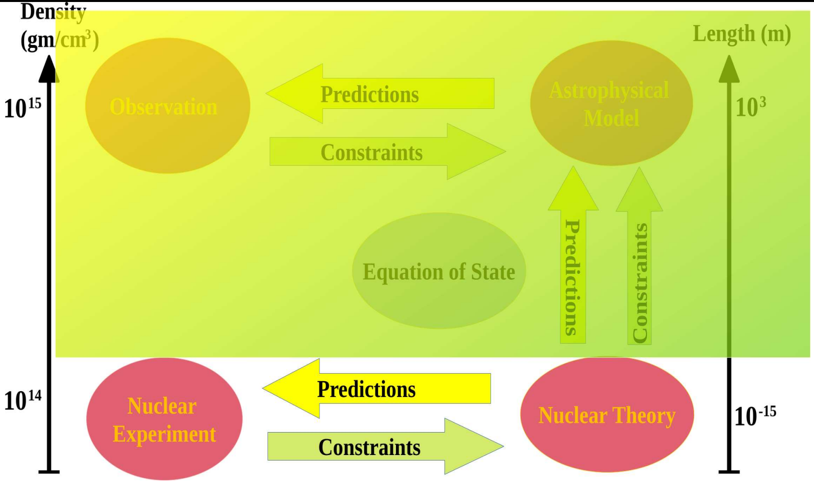
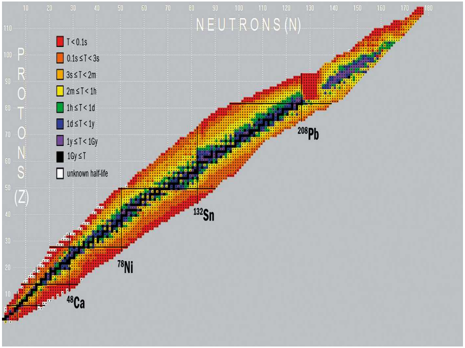


$$P(\epsilon) \rightarrow G_{\mu\nu} + \Lambda g_{\mu\nu} = \kappa T_{\mu\nu}.$$

Equation of State

Theory, Experiment, Observation

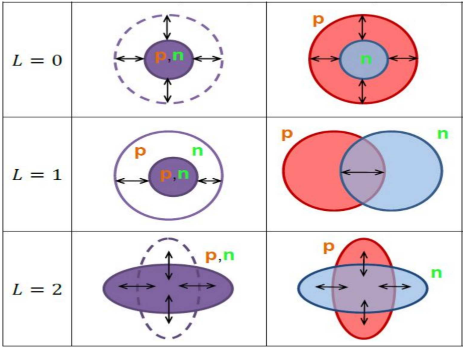


Experiment

- Nuclear masses

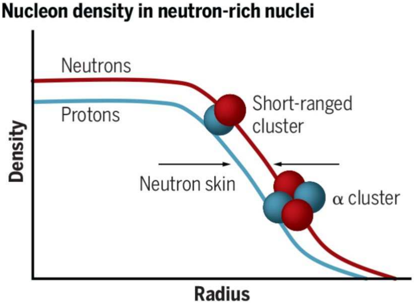
Equation of State

Theory, Experiment, Observation



Experiment

- Nuclear masses
- Nuclear Resonances



Experiment

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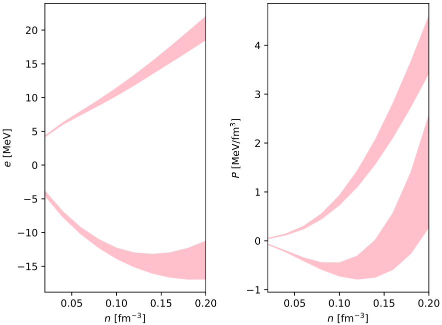

Drischler *et. al.*, PRC 93, 05431 (2016)

Experiment
Theory

- Nuclear masses
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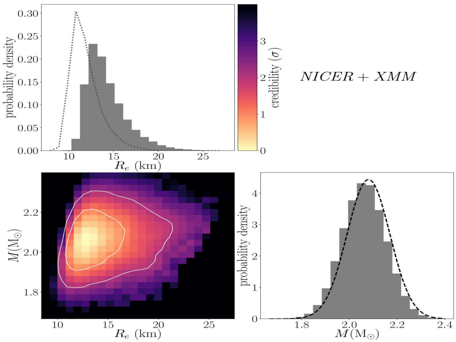
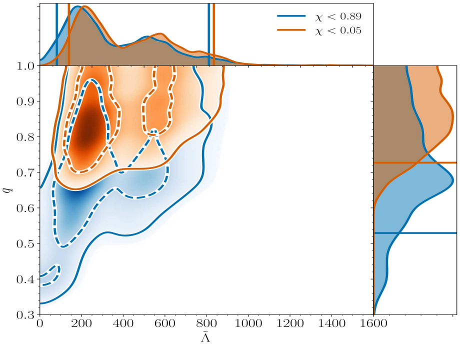
- χ-EFT prediction



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

Experiment
Theory
Observation

- Nuclear masses
- Nuclear Resonances
- Neutron skin
- χ-EFT prediction
- NICER observation



LVC, PRX 9, 011001 (2019)

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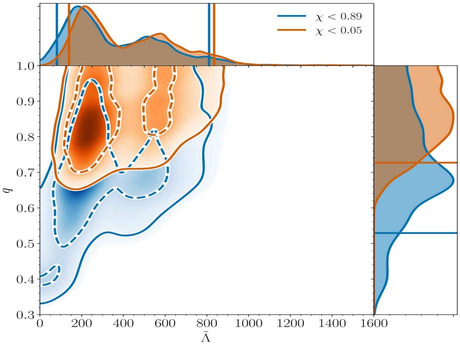

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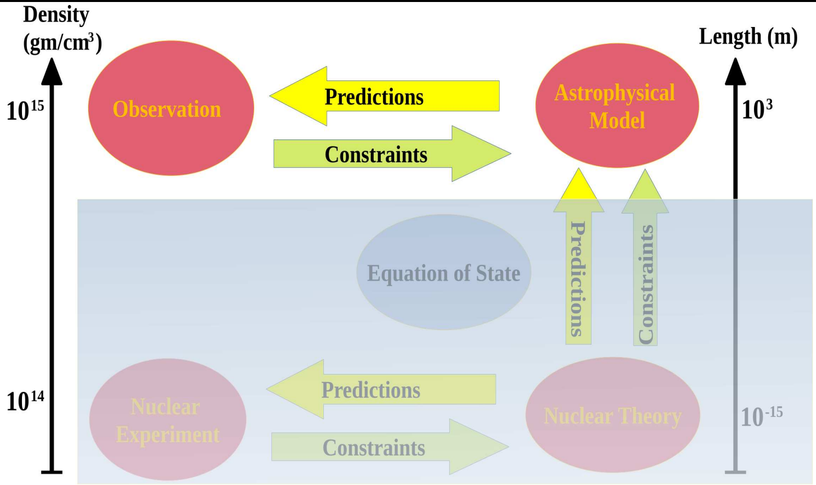
Nuclear models can be employed to construct Equation of state $\rightarrow$ P(ϵ).

Traditional nuclear models

Uncertainties in Theories



$$\mathcal{H}\psi = \mathrm{E}\psi \rightarrow < \psi|\mathcal{O}|\psi > \implies \mathrm{P}(\epsilon).$$

- In non-relativistic approach, at baryon density n, asymmetry $\delta \left(= \frac{\mathrm{n_n}-\mathrm{n_p}}{\mathrm{n}}\right)$

$$\mathcal{H} = \sum_{\mathrm{q}} \frac{\hbar^2}{2\mathrm{M}_{\mathrm{q}}^*}\tau_{\mathrm{q}} + \frac{1}{8}\mathrm{t}_0 \left\{3 - (2\mathrm{x}_0 + 1)\delta^2\right\} \mathrm{n}^2$$
$$+\frac{1}{48}\mathrm{t}_3 \left\{3 - (2\mathrm{x}_3 + 1)\delta^2\right\} \mathrm{n}^{\alpha+2}.$$

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- In relativistic approach, a typical Lagrangian is written as,

$$\begin{aligned}\mathcal{L} &= \overline{\psi}\big[i\gamma^\mu\left(\partial_\mu+i\mathrm{g}_\omega\omega_\mu\right)-\left(m-\mathrm{g}_\sigma\sigma\right)\big]\psi\\ &+\frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma-m_\sigma^2\sigma^2\right)-\frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu}+\frac{1}{2}m_\omega^2\omega_\mu\omega^\mu.\end{aligned}$$

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- $\mathcal{H}\psi = \mathrm{E}\psi \rightarrow <\psi|\mathcal{O}|\psi> \Longrightarrow \mathrm{P}(\epsilon(\mathrm{n},\delta))$. Typically optimize 15-20 parameters on experimental data. This can lead to uncertainties.

Features:

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Constraints in Bayesian studies:

χ-EFT, Finite nuclei, M_{max}, GW170817, NICER *etc.*

Dinh-Thi *et. al.* 2021, CM *et.al* 2022, 2023.

Relativistic Formalism:

Char *et. al.* 2023, 2025.

Exploration

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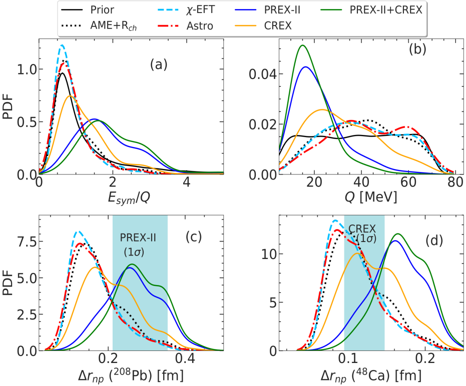
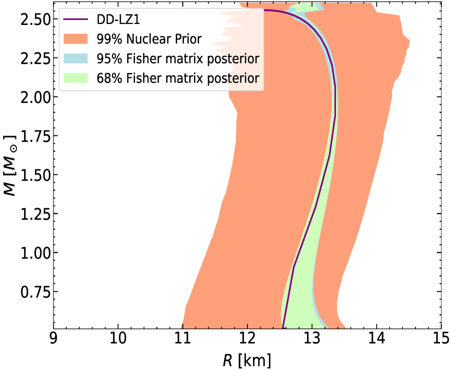


CM & Gulminelli, PRC 107, 015801 (2023)

- CREX-PREX puzzle!!

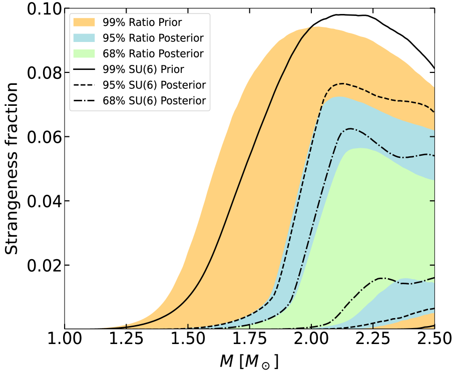
Exploration



ET CoBA study, Branchesi, CM et.al., JCAP 07, 068 (2023)

- Identify EoS from GW detection(s)

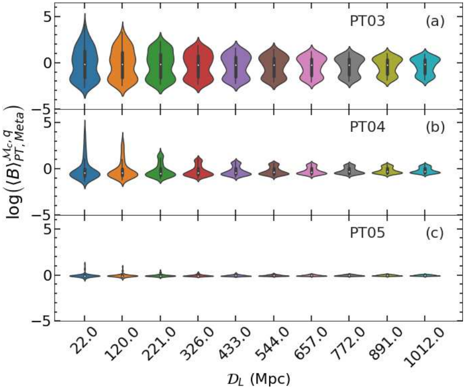
Exploration



- Hyperons??

Char, CM et. al., arXiv:2510.00997 (2025)

Exploration



- Hadron-Quark phase transition?

CM et.al., MNRAS 524, 3464 (2023)

What's next??

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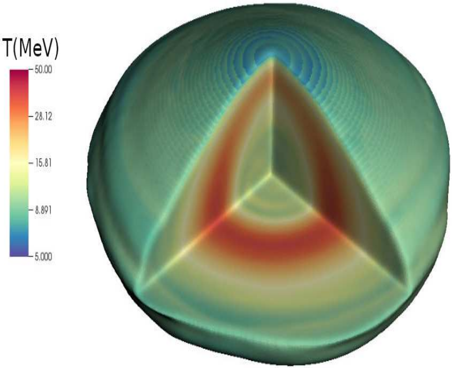

Perego *et. al.*, EPJA 55, 124 (2019)

- Neutron stars heat up and go beyond equilibrium. Typically up to $\sim$ 50 MeVs are reached during merger.

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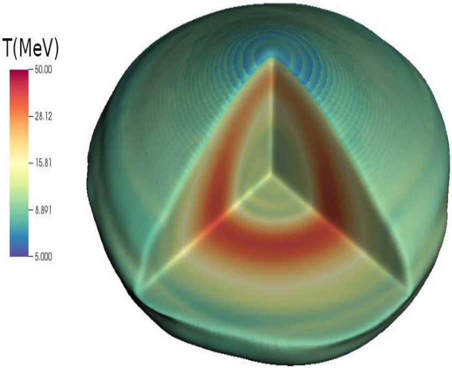

Perego *et. al.*, EPJA 55, 124 (2019)

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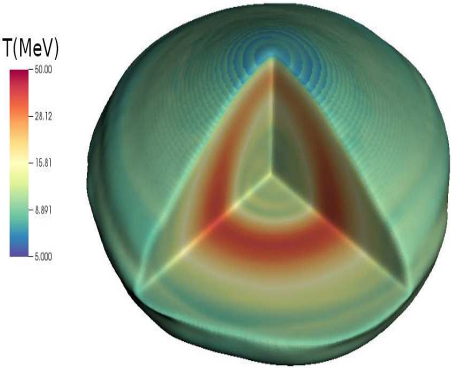

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- Neutron stars heat up and go beyond equilibrium. Typically up to $\sim$ 50 MeVs are reached during merger.
- We need $P(n, T, x_p)$.
- We need end-to-end dynamic simulations using physically sound EoS models.