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Equation of state in dense nuclear matter controlled by nuclear data

Flow data,
Giant Monopole Resonance.

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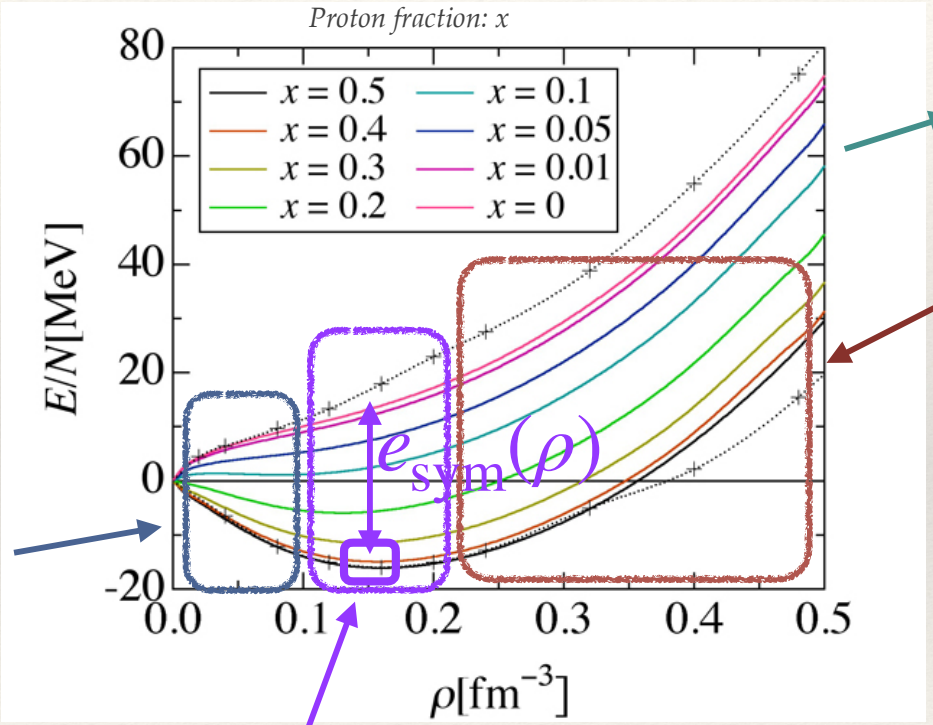
In collaboration with R. Kumar (post-doc), E. Khan (IJCLab),

and P. Danielewicz, W. Lynch, B. Tsang (FRIB).

Known and unknown of the nuclear EOS

From a prediction to a measurement:



pQCD

Predictions

Controlled by low density QCD modeling or nuclear physics

Nuclear empirical parameters (NEP):

$n_{\rm sat} = 0.155 \pm 0.005$ fm^{-3} $\quad E_{sym} = 32 \pm 2$ MeV

$E_{sat} = -15.8 \pm 0.4$ MeV $\quad L_{sym} = 60 \pm 15$ MeV

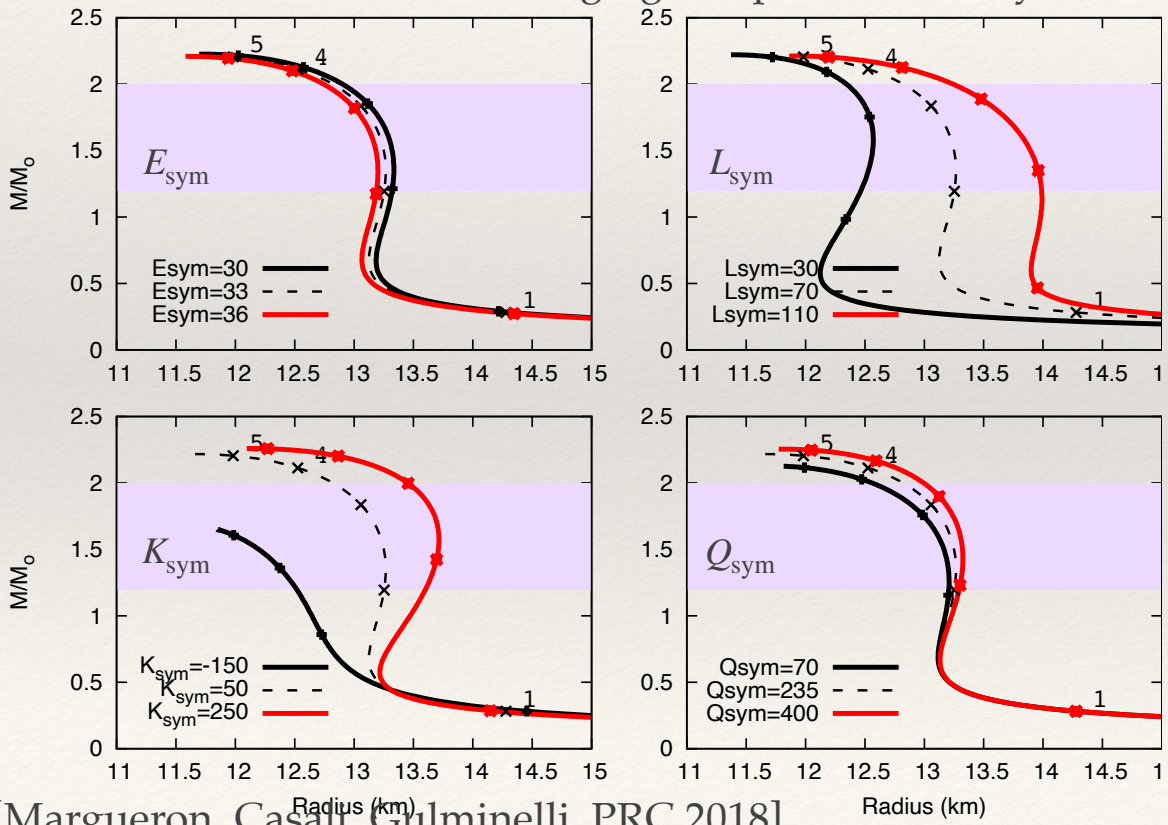
$K_{sat} = 240 \pm 20$ MeV

Saturation density n_{sat} & energy E_{sat}, E_{sym}, … → **Controlled by nuclear experiments.**

EoS and neutron stars observations

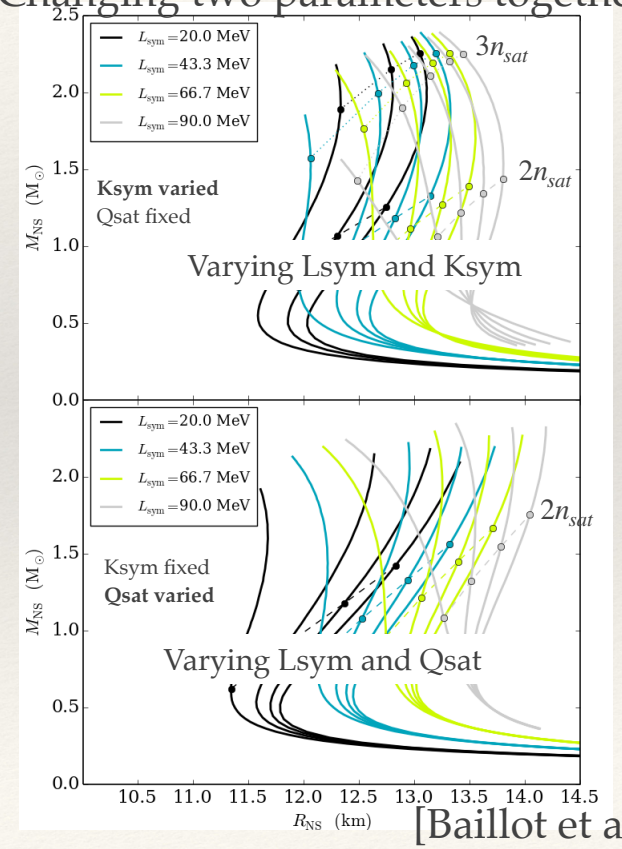
Impact of changing the NEP on the MR relation of neutron stars

Isovector channel Changing one parameter only



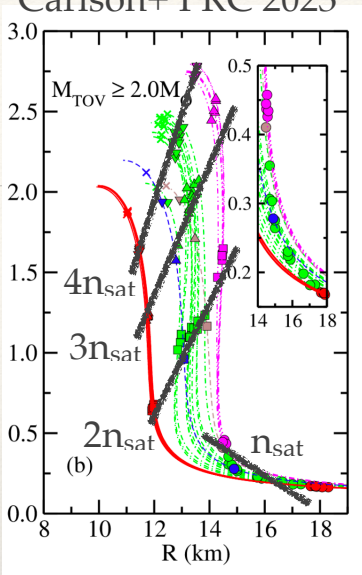
[Margueron, Casali, Gulminelli, PRC 2018]

Changing two parameters together



[Baillot et al., ApJ 2020]

Carlson+ PRC 2023



Questions:

- Neutron star crust contribution?
- Phase transition in the inner core?

A multi-physics approach based on Bayesian statistics

- Nuclear structure
- Heavy ion-collision

Bayesian approach

- Theory
- Experimental Data

Prediction for neutron stars

Nuclear heavy-ion collision

Overview of the dynamics for a Au+Au collision:

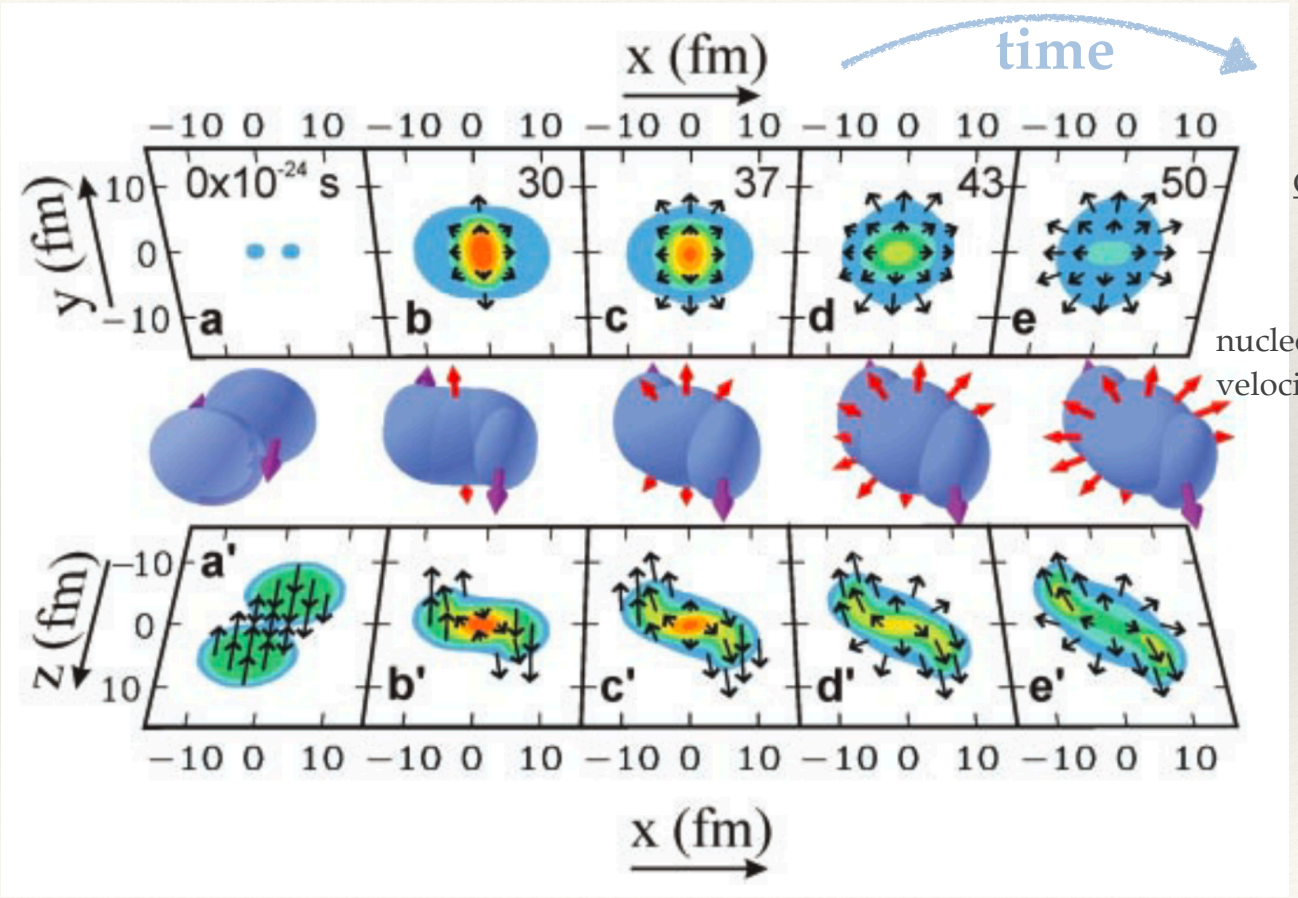
Initial condition:

Head-on collision (b=6 fm).

Particle distribution:

$$\frac{1}{v_0}\frac{dN}{u_t du_t dy_0 d\phi} = 1 + 2v_1 \cos\phi + 2v_2 \cos 2\phi + \ldots$$

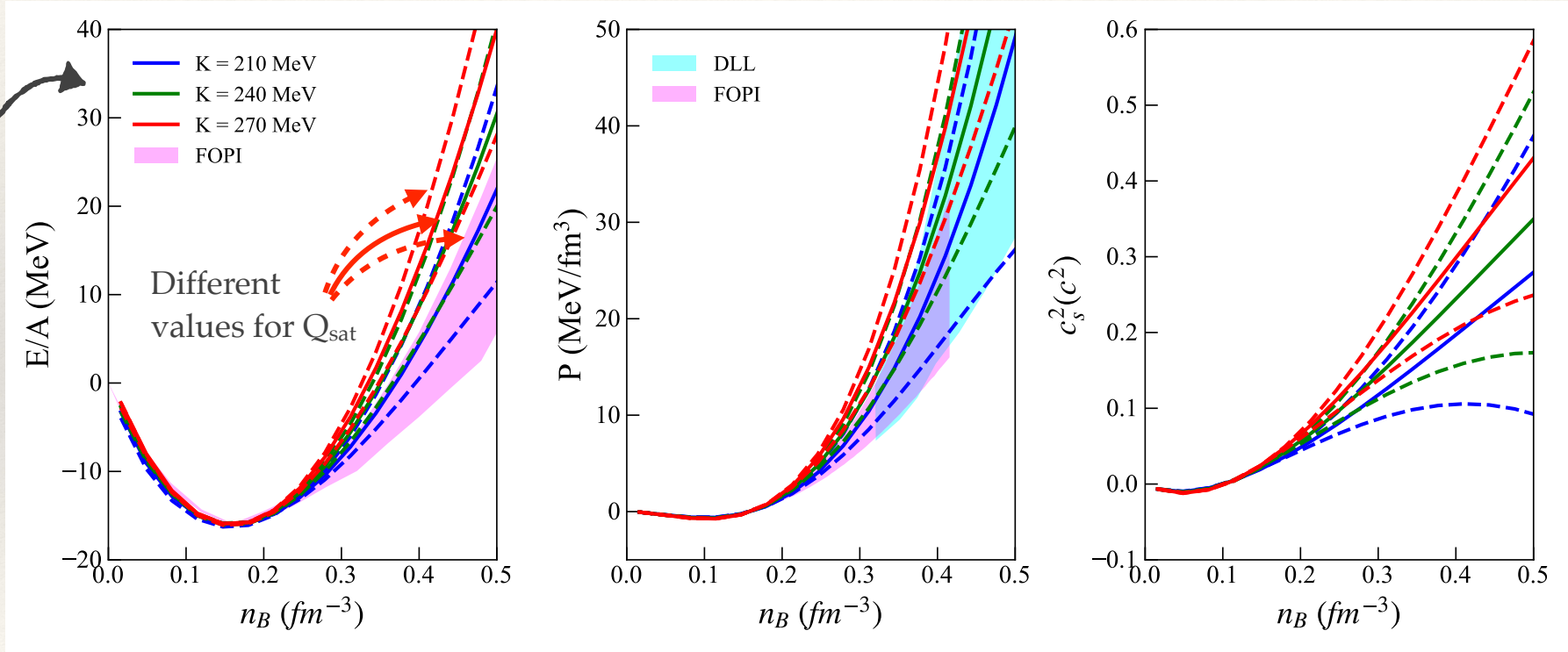
v_1: directed flow; v_2: elliptic flow



Danielewicz, Lacey, Lynch, Science 2002

Equation of state in symmetric matter

Controlled by n_{sat}, E_{sat}, K_{sat}, Q_{sat}.



K_{sat} is fixed by GMR results (prior).

$K_{sat} = 240 \pm 30$ MeV

→ 9 prior EoSs varying K_{sat} and Q_{sat}.

Bayesian approach

Model: IQMD [Aichelin, PR 1991; Hartnack, EPJA 1998]

Einc = 400-1500 MeV / u

Each EoS is assessed by its ability to reproduce experimental data:

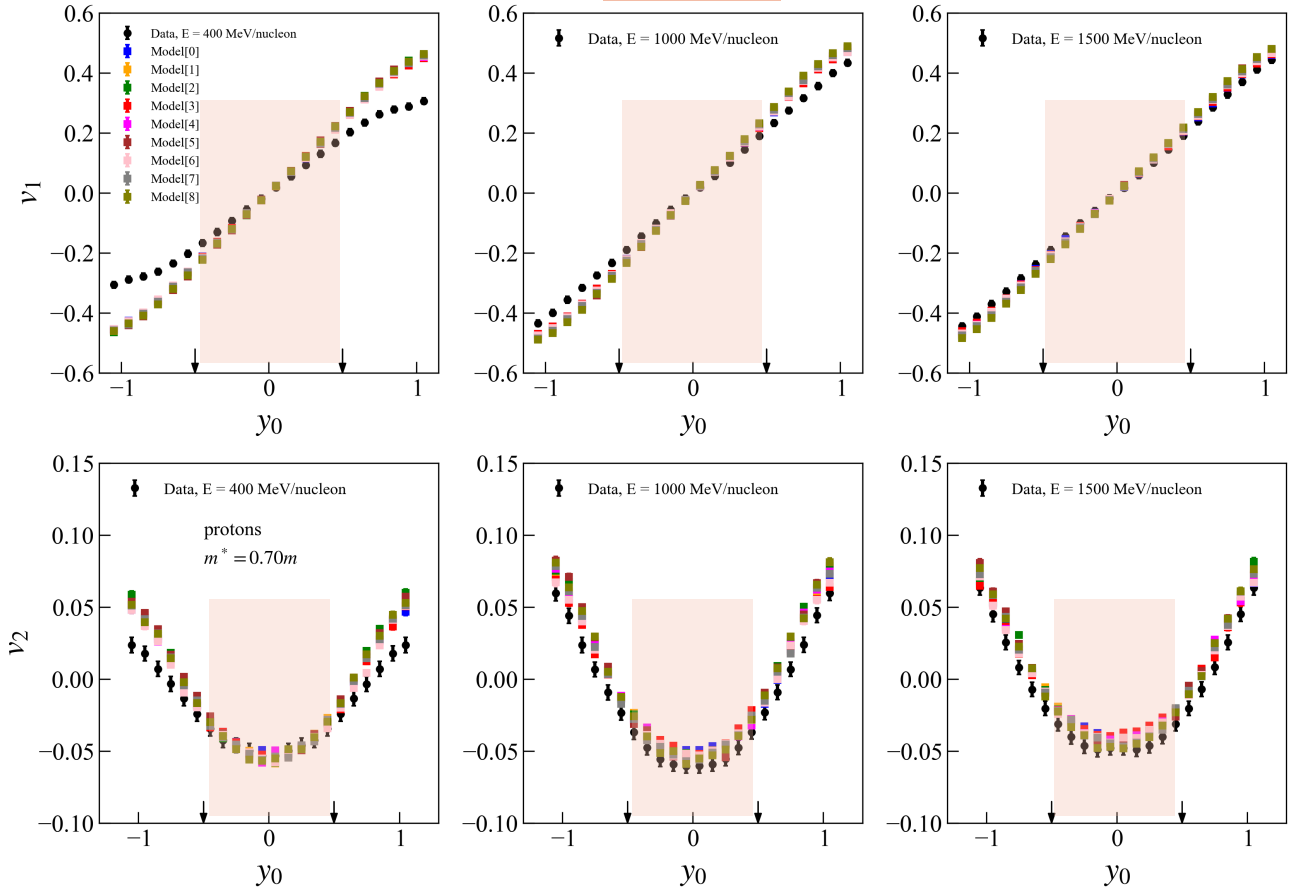
$$p_{EoS} \propto \exp\left(-\frac{1}{2}\chi^2\right)$$

with

$$\begin{cases} \chi^2 = \frac{1}{N_{dof}} \Delta^T_{exp/mod} \Sigma^{-1} \Delta_{exp/mod} \\ \Delta_{exp/mod} = O(exp) - O(model) \end{cases}$$

FOPI data

protons



[R. Kumar et al., in preparation]

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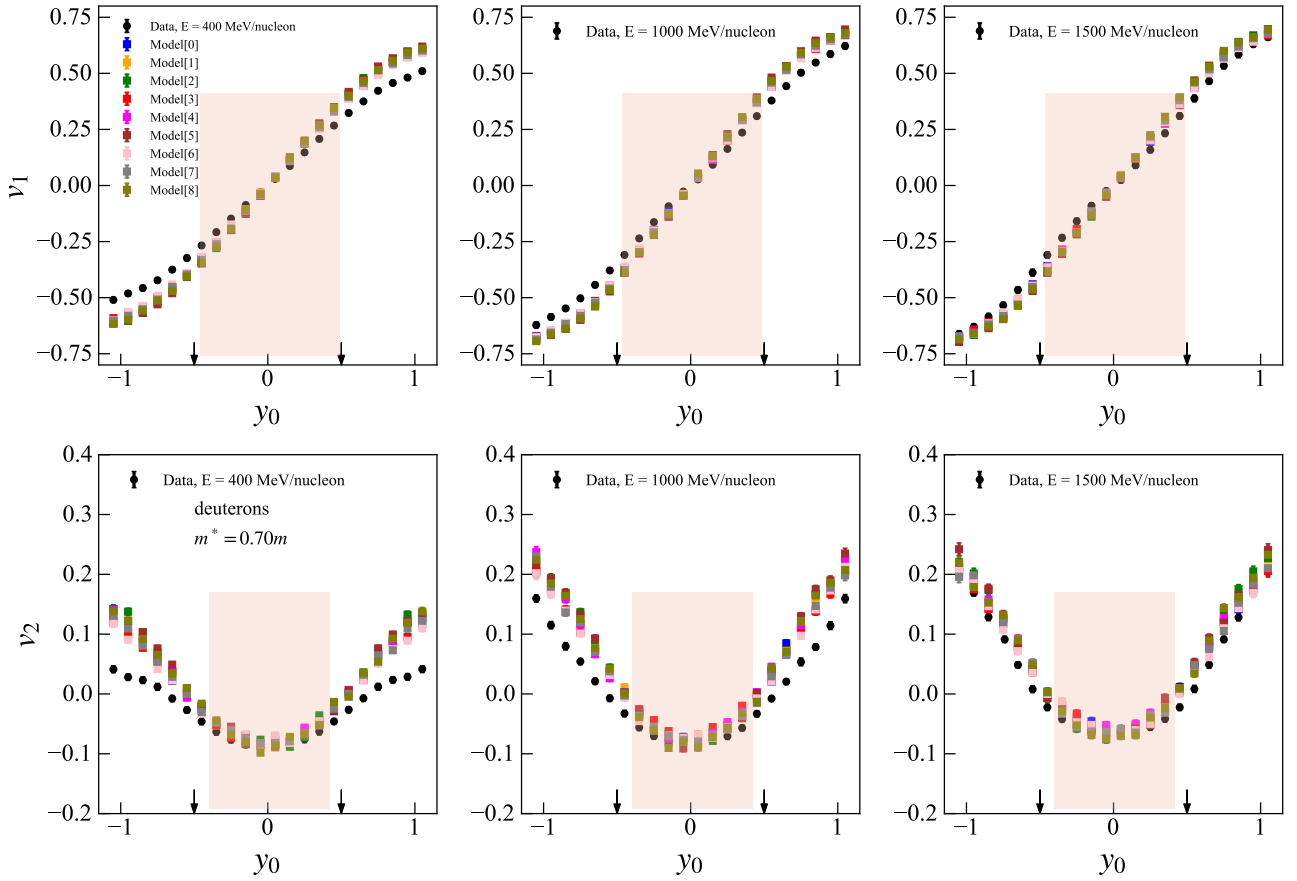
FOPI data

deuterons



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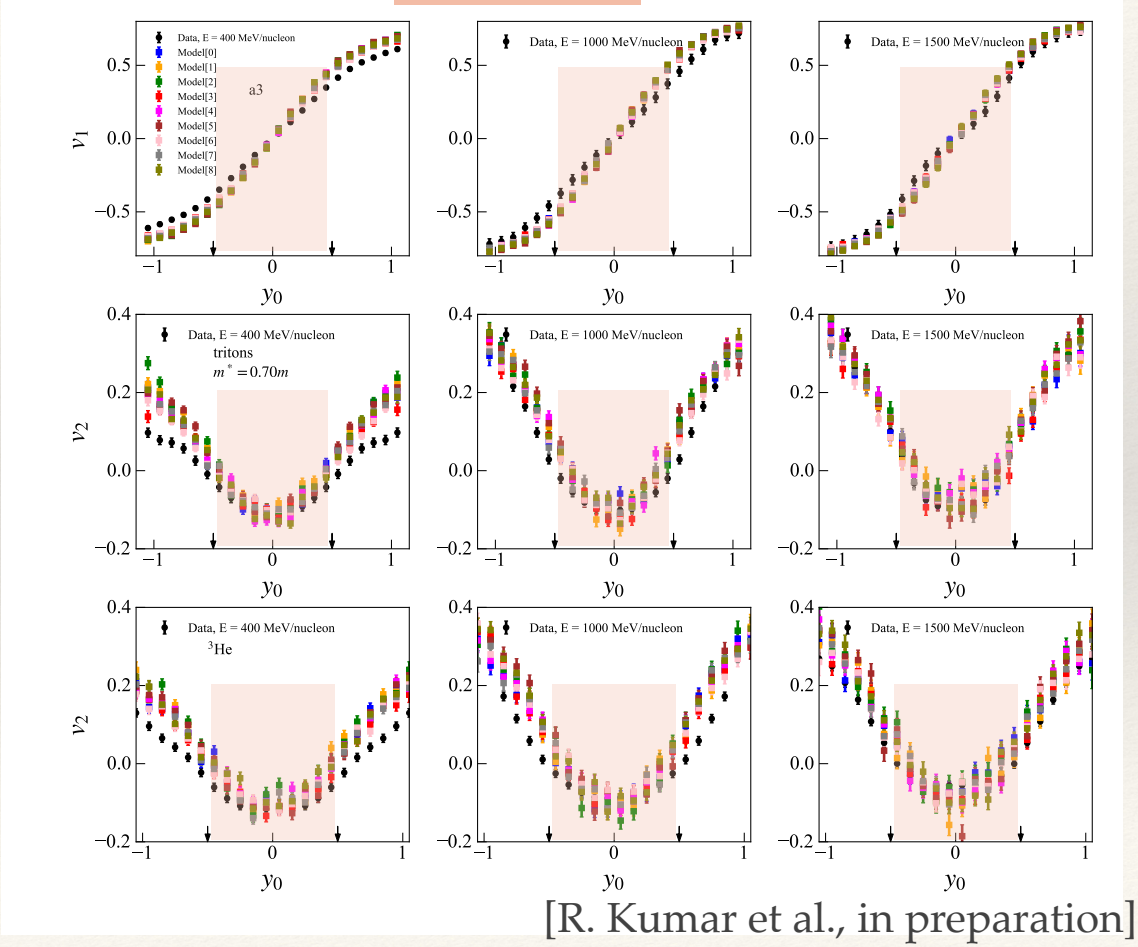
FOPI data

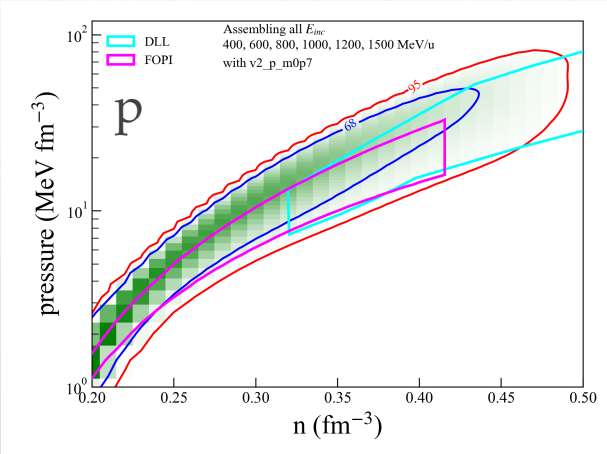
Triton, ^{3}He

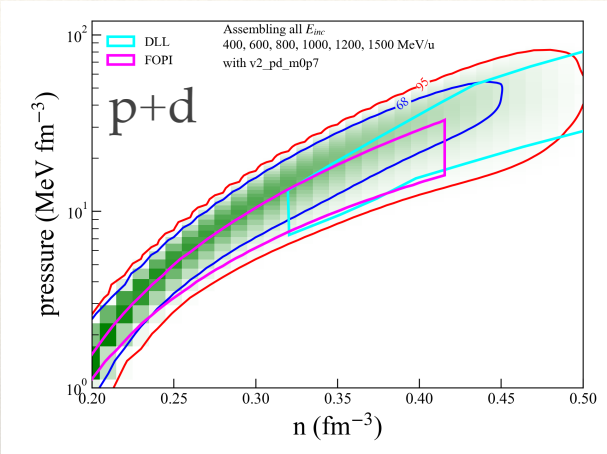


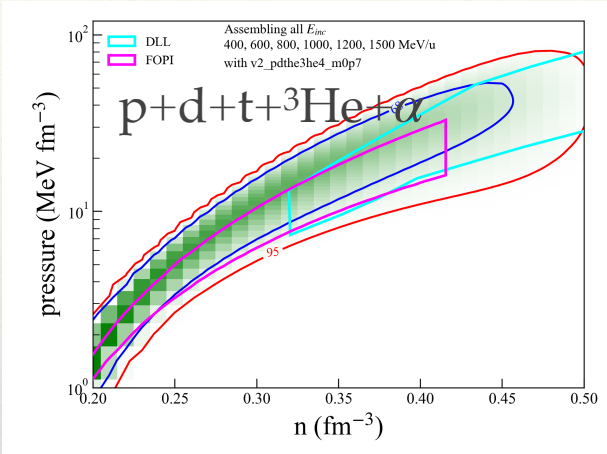
[R. Kumar et al., in preparation]

EoS prediction: P versus n

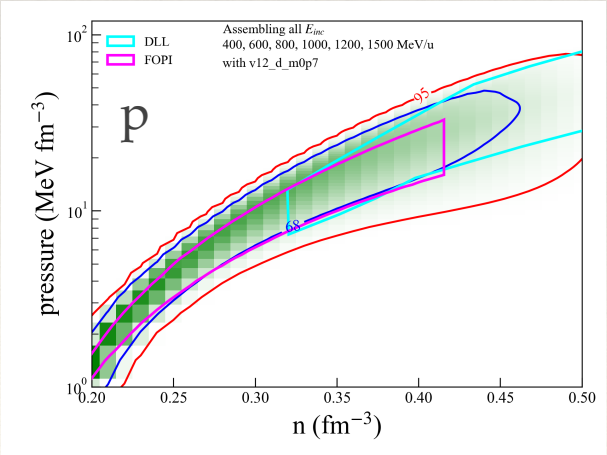
v_2 only

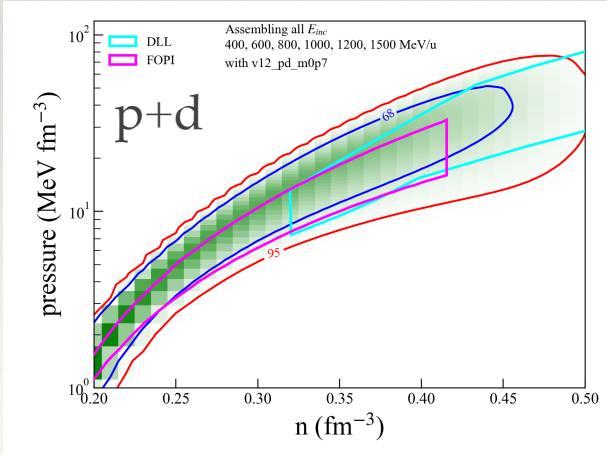


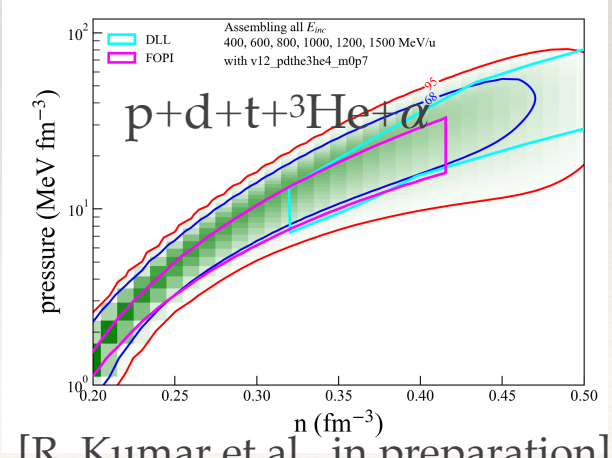




v_1 & v_2





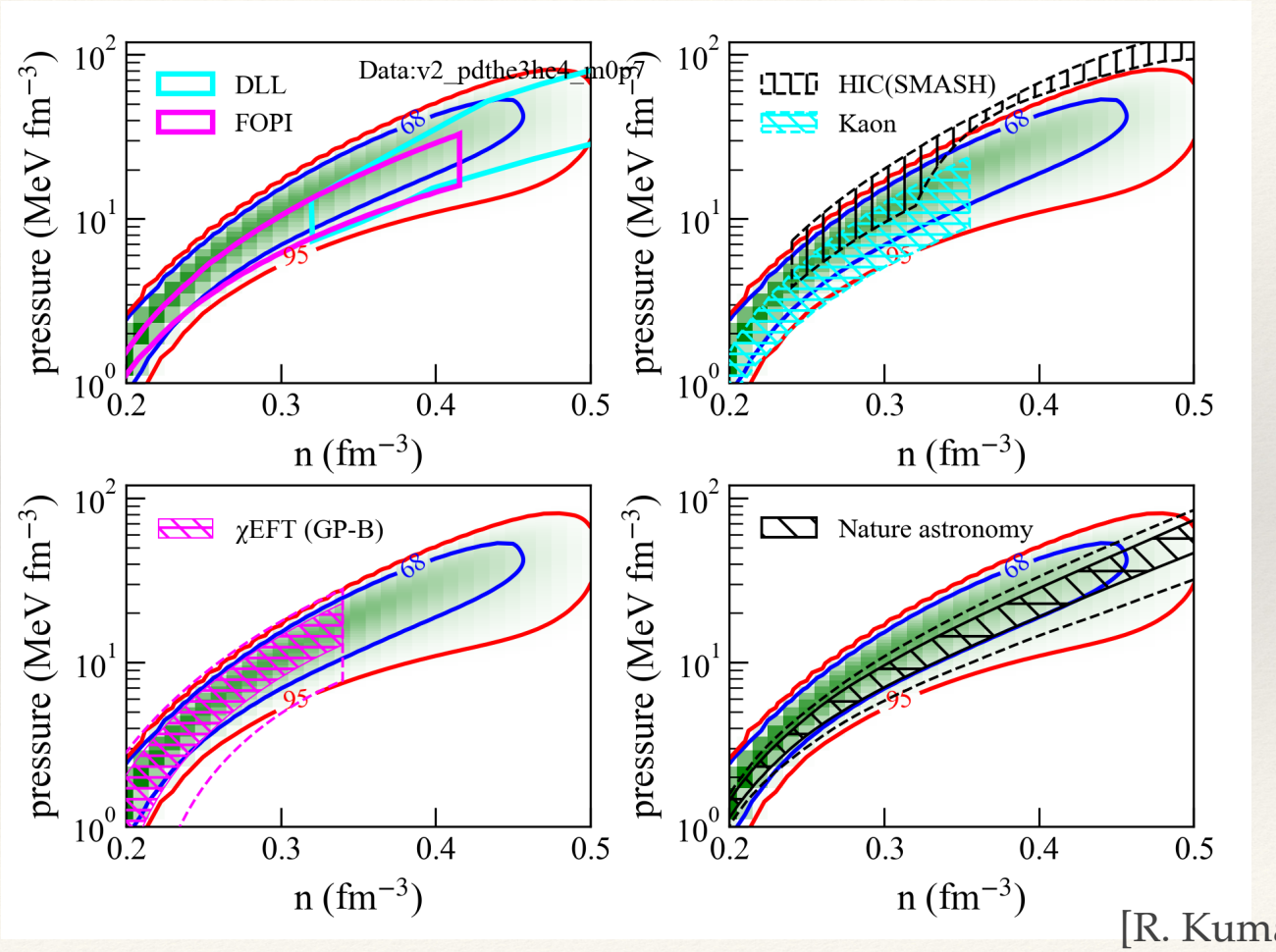


[R. Kumar et al., in preparation]

Comparison to other results

v_2 only

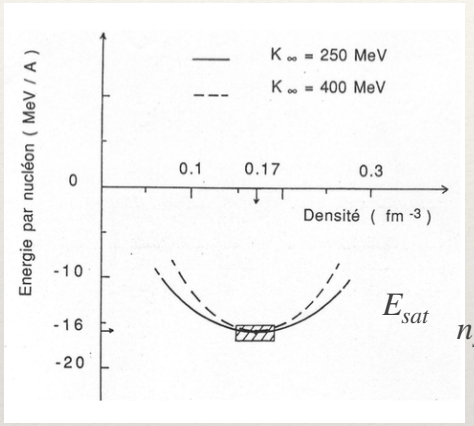
p+d+t+^{3}He+α



[R. Kumar et al., in preparation]

Analysis of Giant Monopole Resonances

Density dependence of the energy around n_{sat}

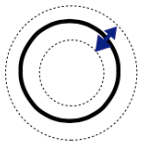


Compressible liquid-drop: $e(n) \approx e(n_{sat}) + \frac{1}{2}K_{sat}x^2 + \ldots$ with $x = (n - n_{sat})/(3n_{sat})$.

Incompressibility

How is incompressibility measured?

α scattering on nuclei
→ monopolar compression



Measured in different nuclei

Extracted

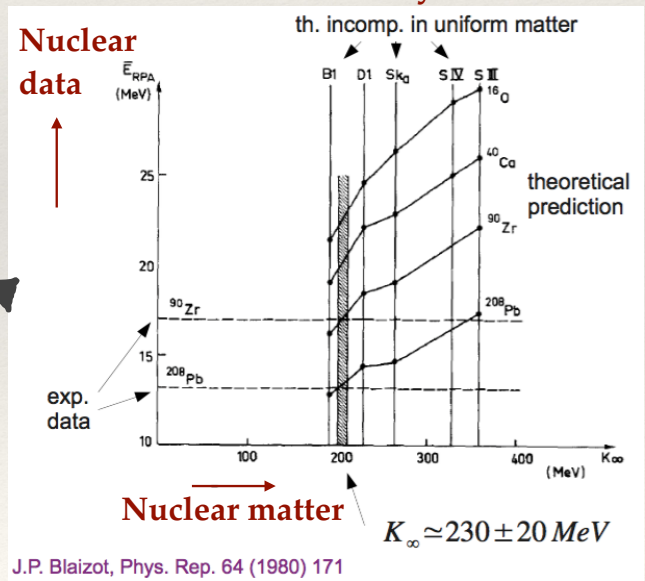
vibration frequency: $\hbar\omega = \hbar\sqrt{\frac{K_A}{mr_0^2}A^{-1/3}}$

$$K_A = K_{sat} + K_s A^{-1/3} + K_{sym}\left(\frac{N-Z}{N+Z}\right)^2 + K_{coul}\frac{Z^2}{A^{4/3}}$$

Uniform matter

Finite size effects

Correlation analysis



Present estimation:

$K_{sat} = 240 \pm 20$ MeV

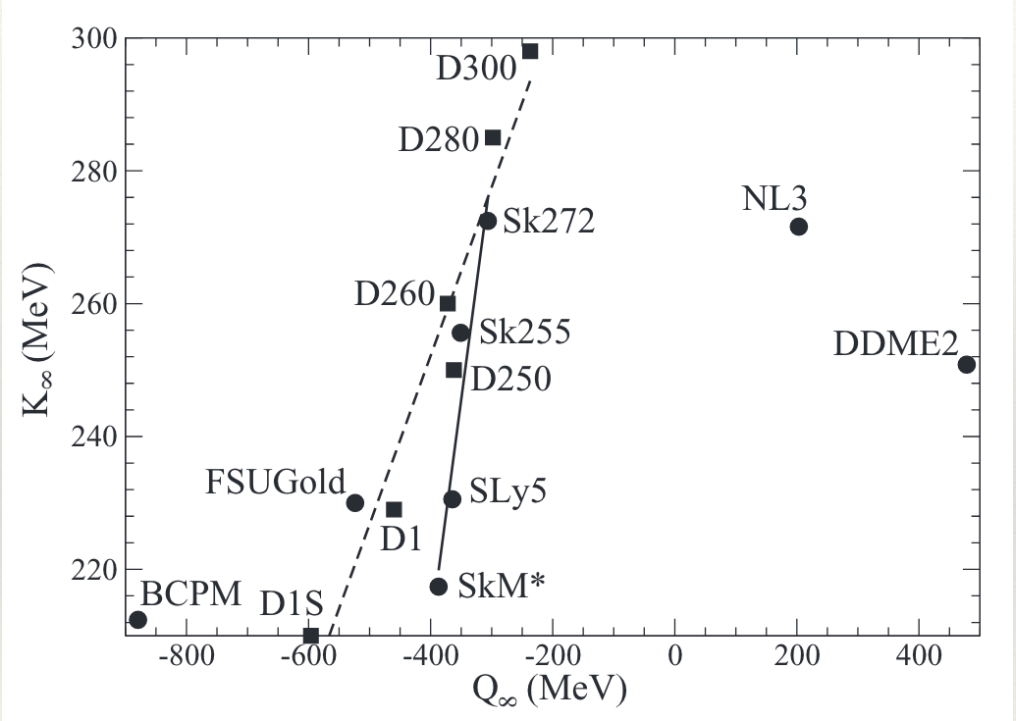
[Garg & Colo, 2018]

Model dependence? Underestimation of the uncertainty?

[Khan, JM, Vidaña PRL 2012, PRC 2013]

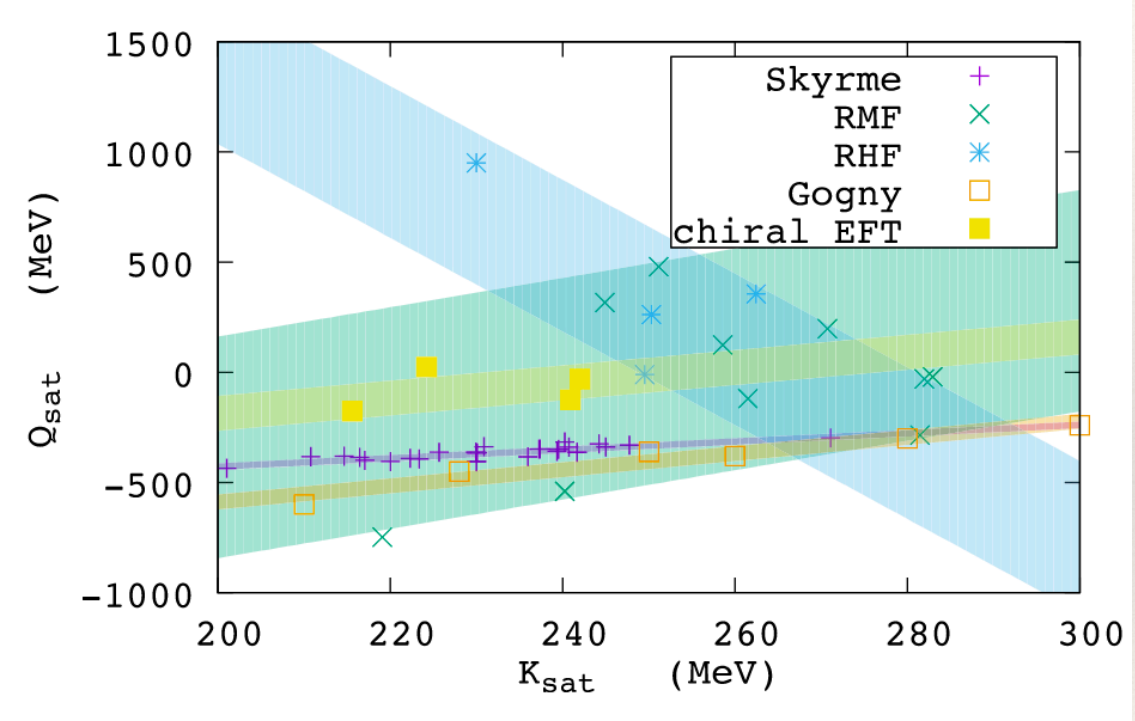
[Grams+ PRC 2022]

Exploration of the K_{sat}-Q_{sat} diagram



[Khan & Margueron, PRC 88 (2013)]

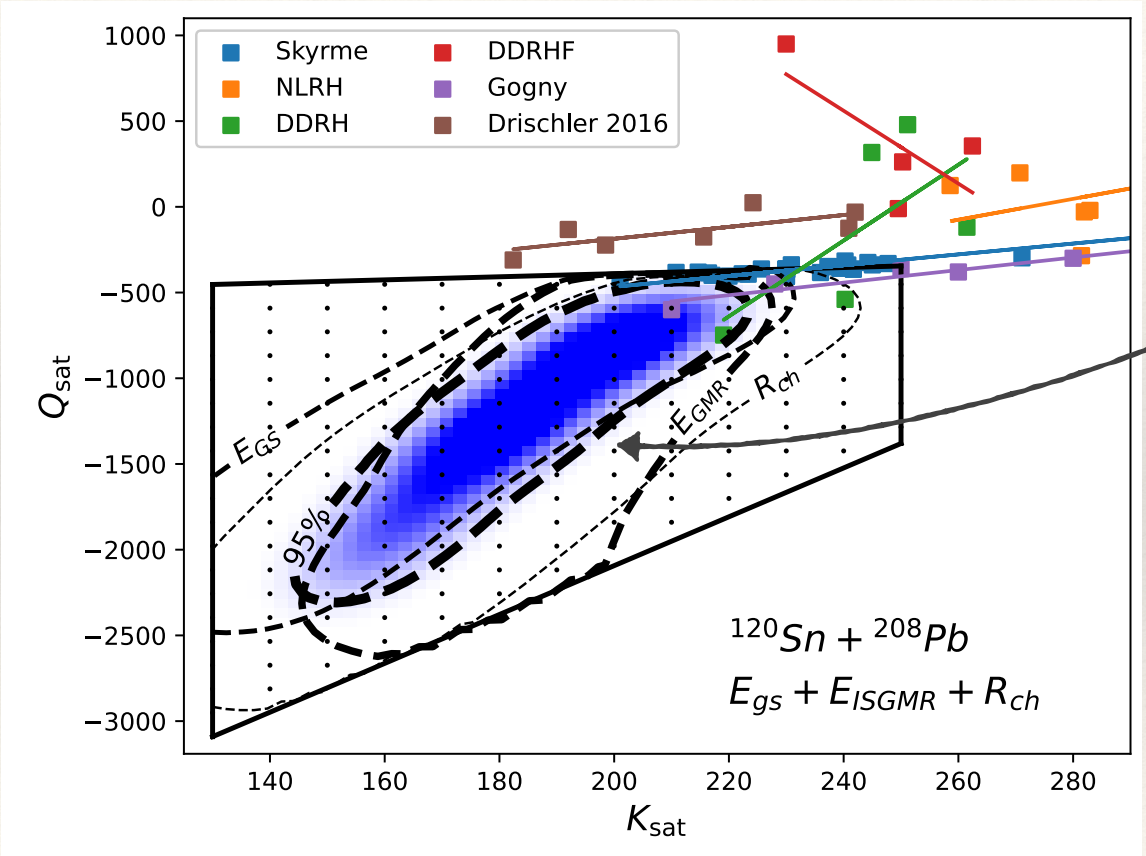
Artificial correlation between K_{sat} and Q_{sat}, due to the lake of flexibility of Skyrme EDF.



[Margueron, Casali, Gulminelli, PRC 97 (2018)]

Spurious correlations between K_{sat} and Q_{sat} exists also for other models.

Exploration of the K_{sat}-Q_{sat} diagram compatible with the GMR



This region of the parameter space is also compatible with GMR + ground state energy + charge radius.

—> The value of Ksat can be lower than 200 MeV, provided Qsat is reduced as well.

[Margueron & Khan, in preparation]

Conclusions

The nuclear incompressibility may be reproduced by EDF models with low values of K_{sat}, provided Q_{sat} is reduced.

HIC Flow Data (FOPI) may constrain the nuclear matter equation of state, especially K_{sat} and Q_{sat}.

Additional questions w.r.t. model dependencies should be explored more systematically.

The present analysis shows that the Bayesian approach could be applied to compare directly experimental data and model predictions to infer the EoS.

→ In the **future**, more data and more consistencies between different measurements shall be explored.