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Implications of Neutron Skin Measurements on Neutron Stars

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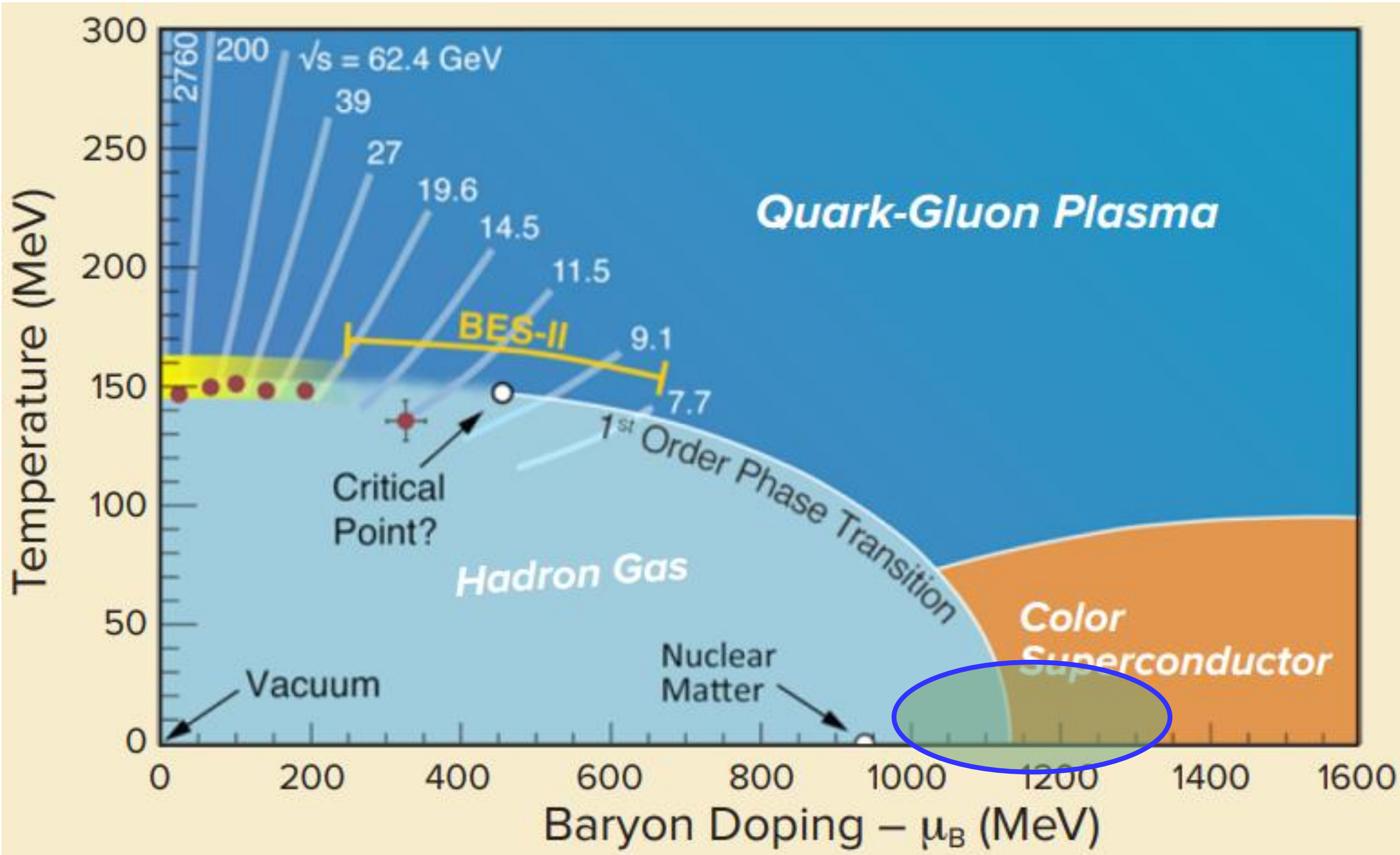
UNQP, MITP, Mainz, 2024.6

Contents

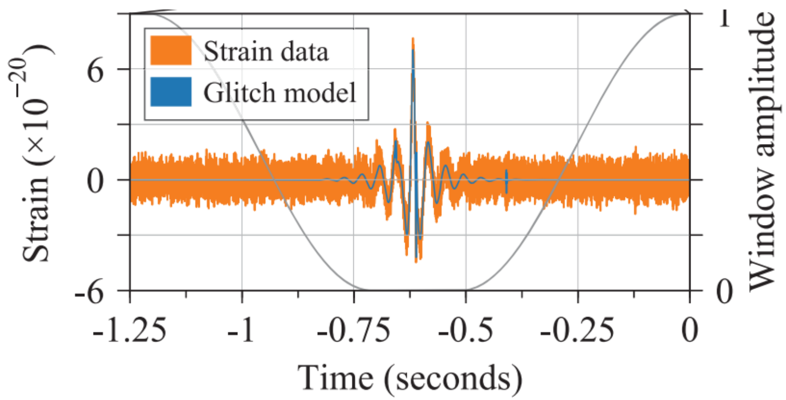
- Neutron skin relevant studies
- Implications on Skyrme EoS
- Constraints on speed of sound in neutron stars
- Bayesian evaluation of imperfect fission yields
- Perspectives

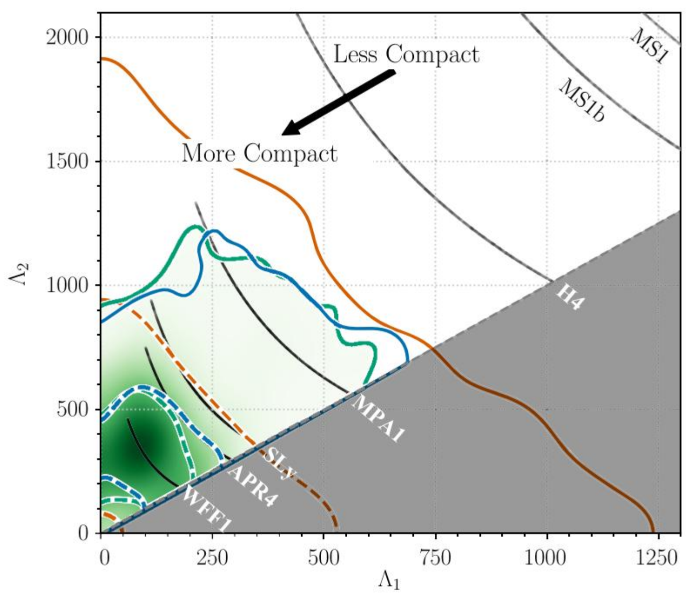
Understanding strong interacting matter



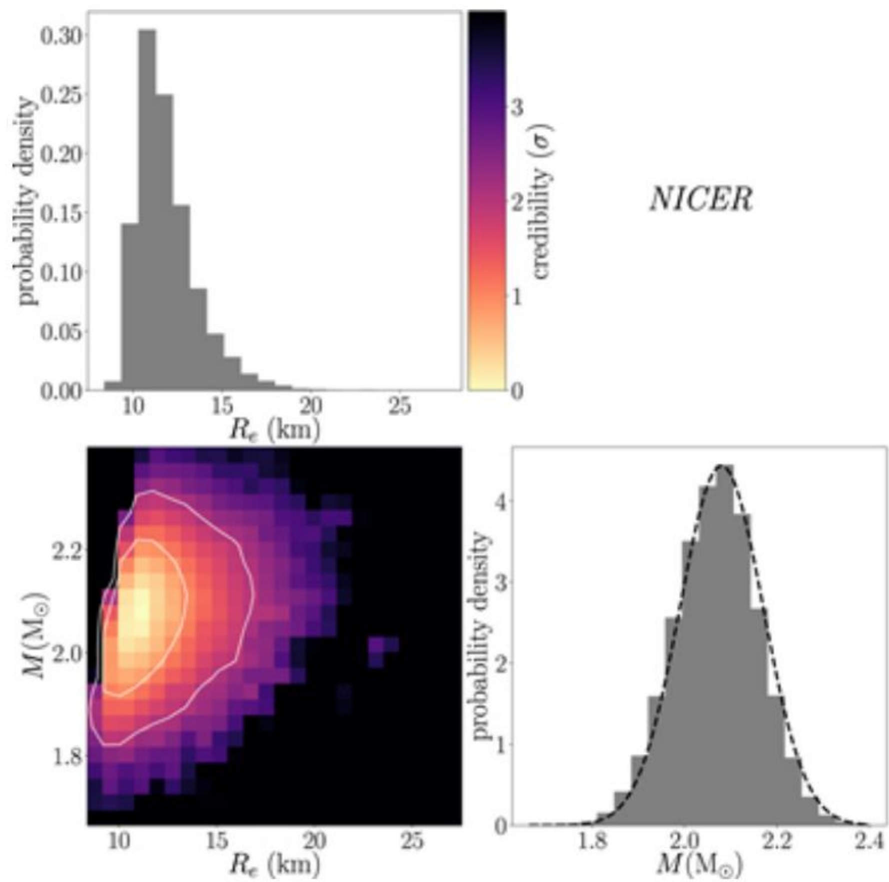
- The transition from nuclear matter to quark matter is quite complex
- Saturation density: finite nuclei
- Extremely high density >40 ρ_s : perturbative QCD

Observations of neutron stars



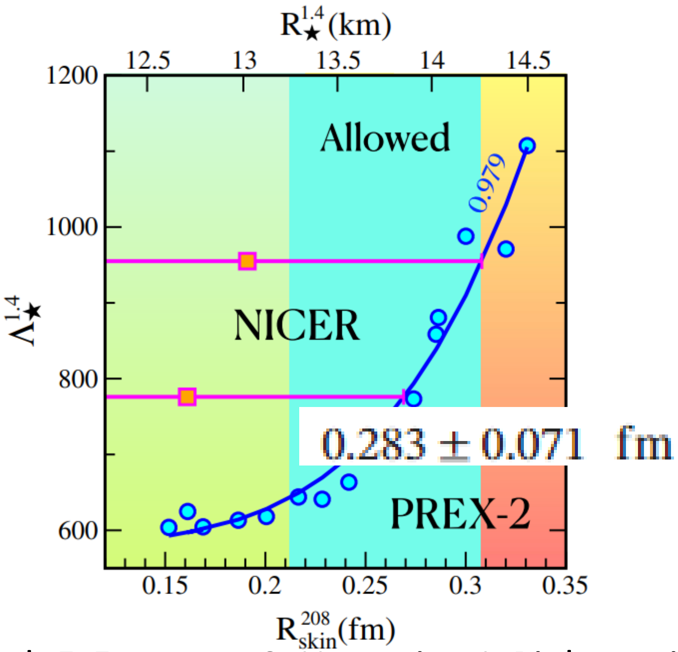


posterior for the tidal deformabilities of the two binary components of GW170817

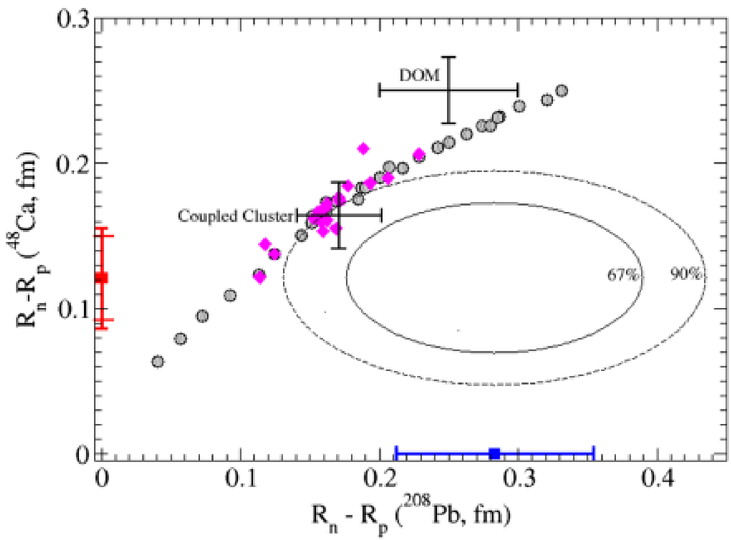


Mass and Radius of PSR J0740+6620

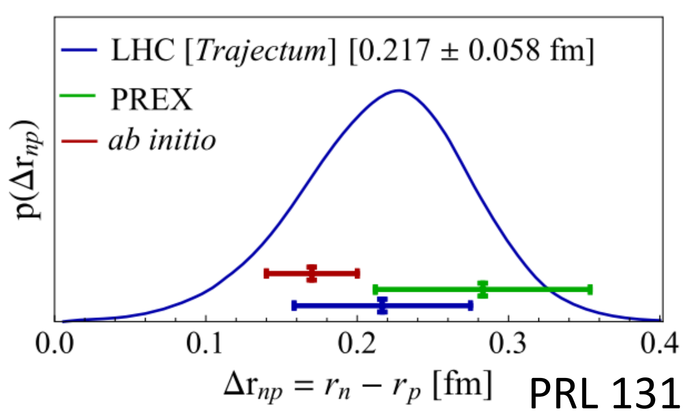
Neutron skin measurements



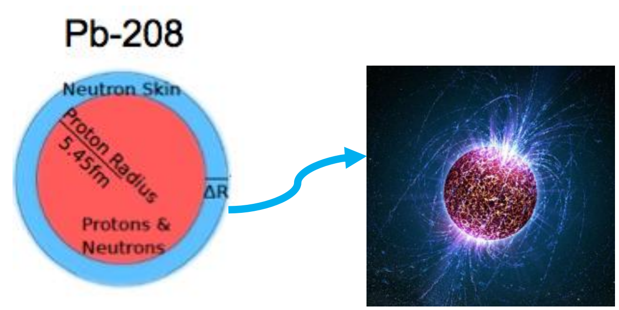
B. Reed, F. Fattoyev, C. Horowitz, J. Piekarewicz
Phys. Rev. Lett. 126, 172503 –2021



D. Adhikari et al. (CREX)
Phys. Rev. Lett. 129, 042501 –2022

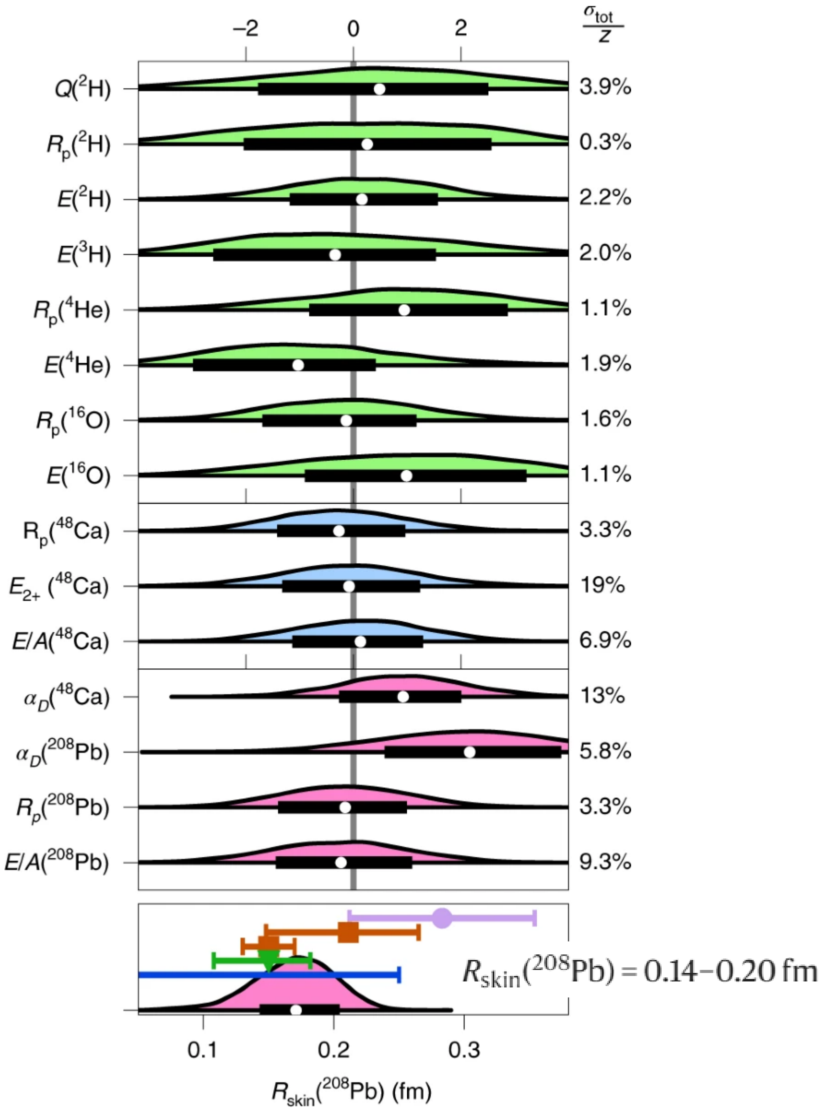


PRL 131, 202302 (2023)

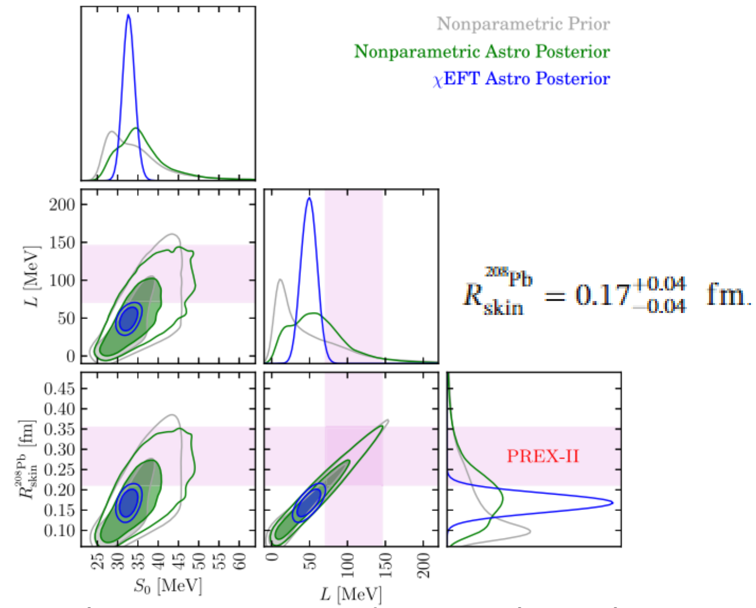


A major theoretical challenge!

Inference with uncertainties



B. Hu, W. Jiang, T. Miyagi, Z. Sun, et al.,
Nat. Phys. 18, 1196 (2022).



R. Essick, I. Tews, P. Landry, A. Schwenk
Phys. Rev. Lett. 127, 192701 –2021
P.-G.Reinhard, X. Roca-Maza,W. Nazarewicz
Phys. Rev. Lett. 129, 232501 –2022

Our motivation: how about if the neutron skin of 208Pb is indeed very thick? How to reconcile with other observables? Charge radii are underestimated by Ab initio calculations?

Fitting with neutron skin thickness

- Extended Skyrme functional with additional density dependence （why not in χEFT）

$$\chi^2 = \left(\frac{e_\infty + 16.0}{0.2}\right)^2 + \left(\frac{\rho_s - 0.16}{0.005}\right)^2 + \sum_i \left(\frac{E(i) - E^{\exp}(i)}{2.0}\right)^2 + \sum_i \left(\frac{\sqrt{<r^2>_{\rm ch}(i)} - \sqrt{<r^2>^{\exp}_{\rm ch}(i)}}{0.02}\right)^2 + w_1(R^{48}_{\rm skin} - 0.12)^2 + w_2(R^{208}_{\rm skin} - 0.28)^2.$$

$$v^{(3)}_{ijk} = \frac{1}{6}t_3(1 + x_3 P_\sigma)\rho(\boldsymbol{R})^\gamma \delta(\boldsymbol{r}_i - \boldsymbol{r}_j) + \frac{1}{6}t_{3E}(1 + x_{3E} P_\sigma)\rho(\boldsymbol{R})^{\gamma_E} \delta(\boldsymbol{r}_i - \boldsymbol{r}_j).$$

- Several parameterizations obtained by varying the fitting weights of neutron skins
  study implications of neutron skins in a consistent manner

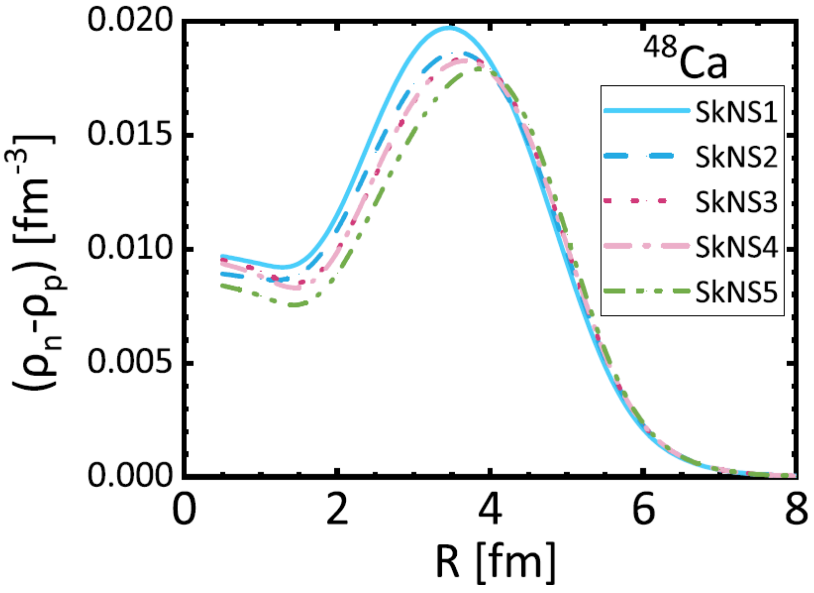
	SkNS1	SkNS2	SkNS3	SkNS4	SkNS5	Expt.
$R^{48}_{\rm skin}$	0.153	0.168	0.178	0.183	0.195	0.121±0.026
$R^{208}_{\rm skin}$	0.186	0.220	0.247	0.259	0.284	0.283±0.071
R^{48}_{ch}	3.55	3.54	3.53	3.52	3.51	3.48
R^{208}_{ch}	5.51	5.51	5.50	5.48	5.47	5.50

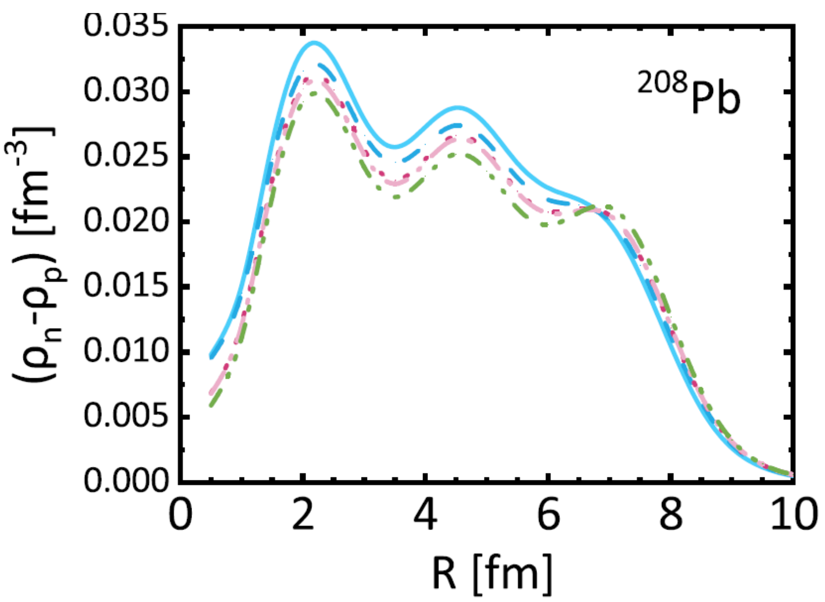
Parameters	SkNS1	SkNS2	SkNS3	SkNS4	SkNS5
t_0	−2381.22	−2340.20	−2287.31	−2195.17	−2339.41
t_1	451.24	455.64	475.35	475.96	472.89
t_2	−399.65	−399.65	−465.37	−465.37	−462.58
t_3	12115.30	11564.79	10955.19	9849.11	11709.66
t_{3E}	2477.62	2887.07	3217.65	3864.70	2620.65
x_0	0.431	2.41E-002	−0.303	−0.602	−0.649
x_1	−0.297	−0.309	−0.243	−0.243	−0.243
x_2	−0.729	−0.718	−0.763	−0.763	−0.763
x_3	0.640	−0.193	−0.874	−1.823	−1.414
x_{3E}	6.20E-003	1.100	1.586	2.793	1.935
b_4	67.46	68.16	97.38	96.20	96.11
b'_4	93.96	98.69	74.60	82.04	79.35
γ	1/6	1/6	1/6	1/6	1/6
γ_E	0.5	0.5	0.5	0.5	0.5
e_∞	−16.03	−16.03	−16.01	−16.02	−15.98
ρ_s	0.1592	0.1605	0.1597	0.1592	0.1603
K	232.68	239.00	238.64	240.79	233.39
$a_s^{0.16}$	32.941	35.614	34.624	36.468	36.964
$a_s^{0.11}$	26.860	26.405	26.635	27.048	25.880
L	29.732	46.653	60.077	60.543	81.659
w_1	1000	5000	10000	5000	1000
w_2	1000	5000	10000	10000	20000

L Strongly correlated with R_{skin}

Density distributions of neutron skins

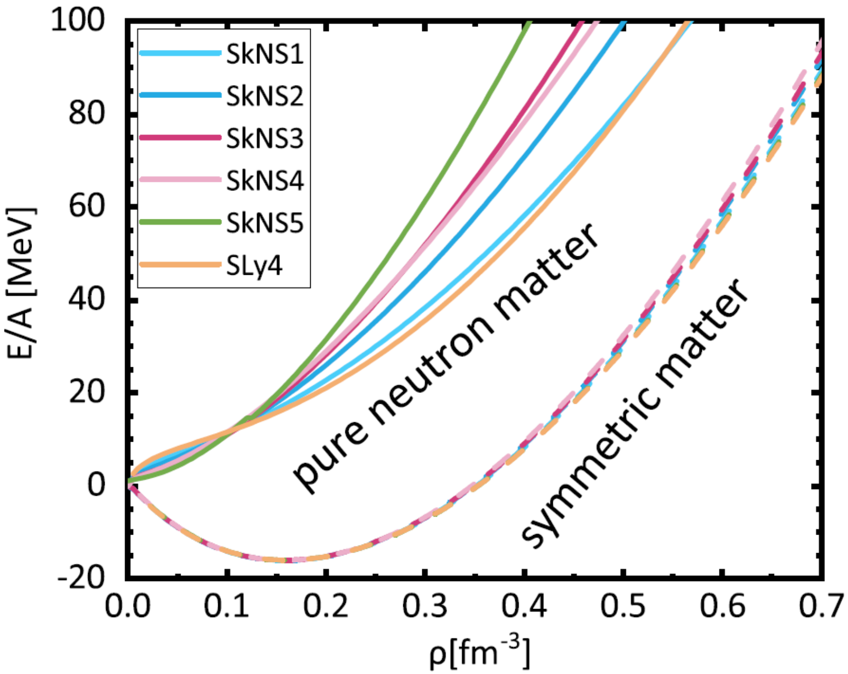
- Major differences in the inner part rather than the outside part, thick neutron skin→lower inner neutron density
- Role of symmetry energy at sub-saturation density

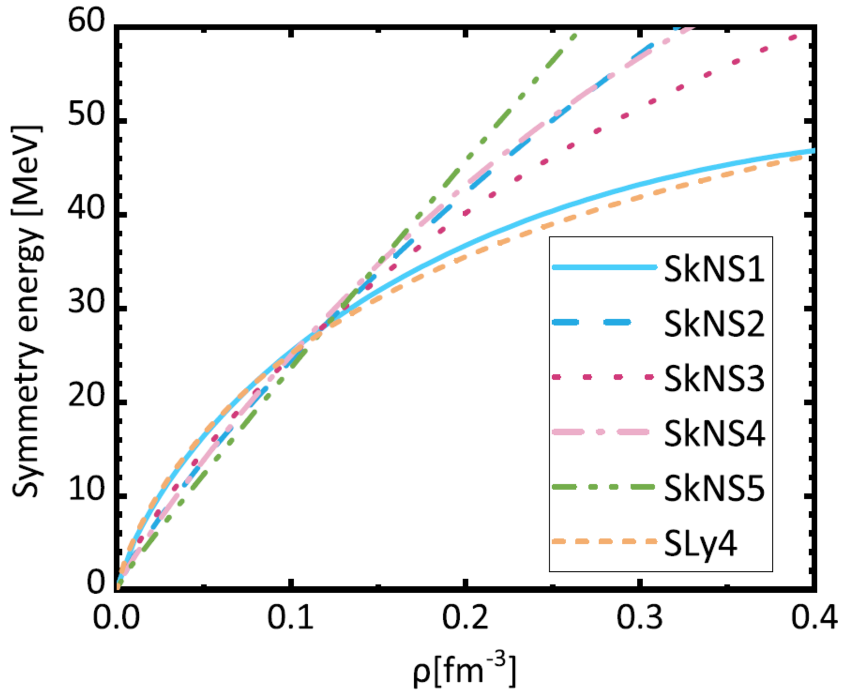




Equation of state

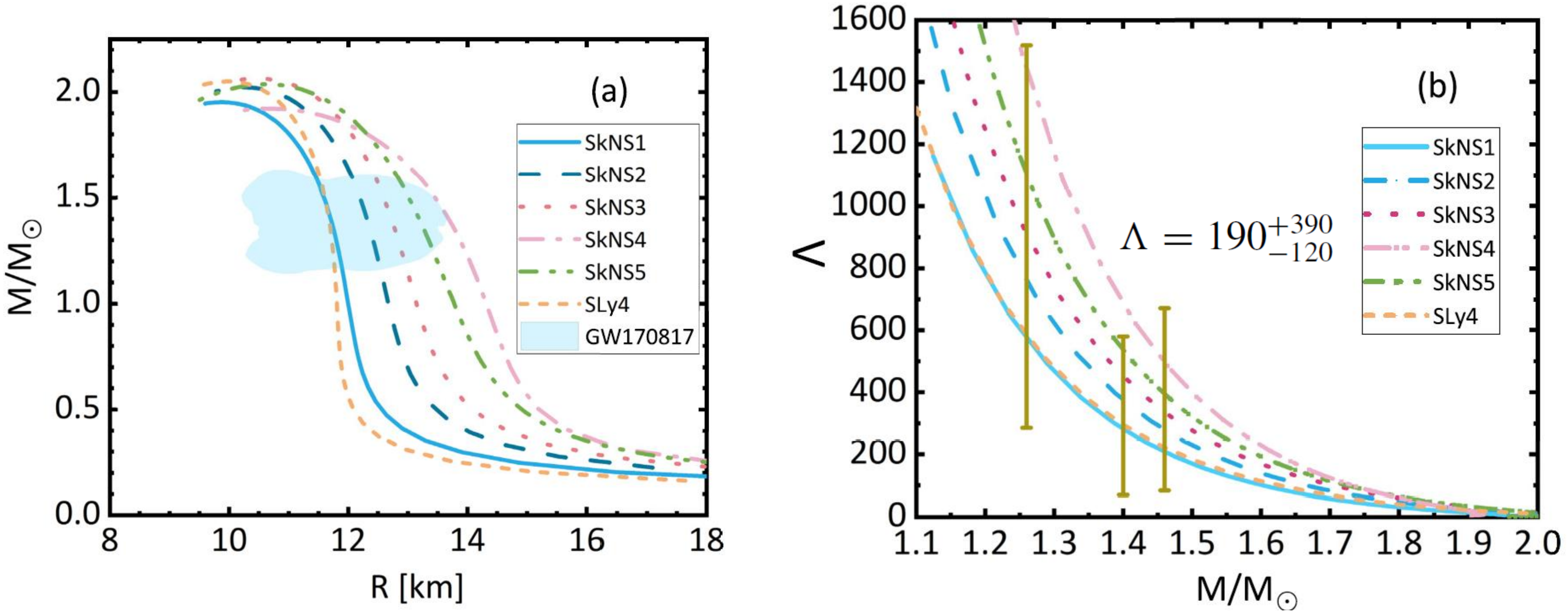
- Thick neutron skins -> higher energies of neutrons at high densities, lower energies at low densities
- Thick neutron skins -> larger symmetry energies at high densities, lower symmetry energies at low densities



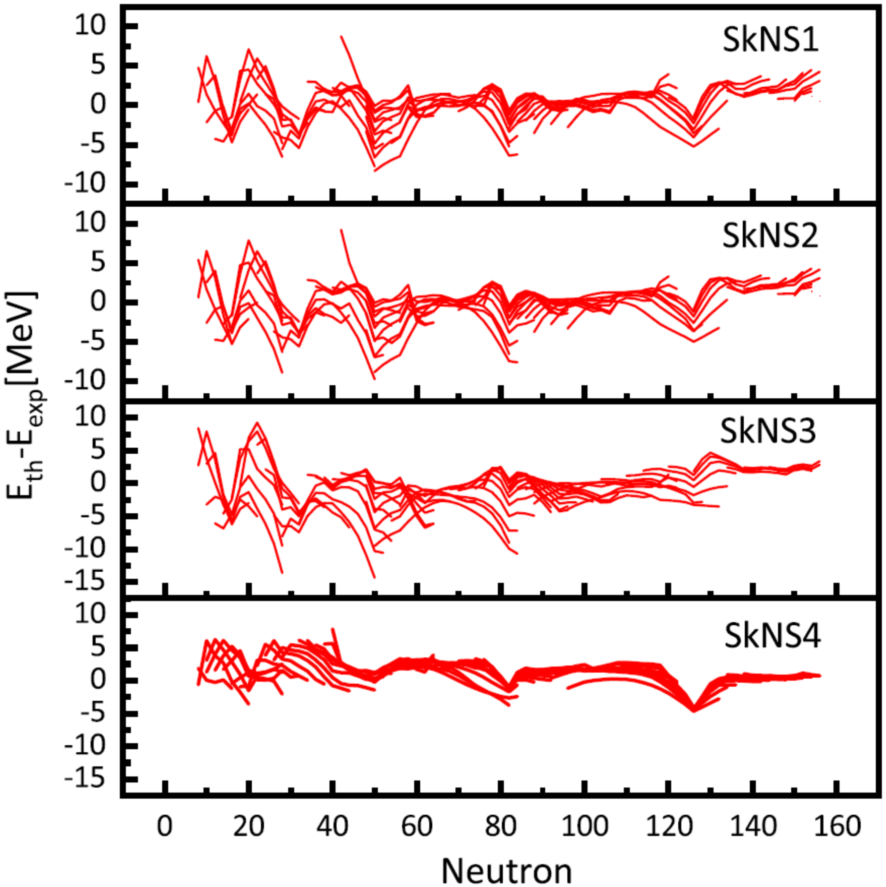


Neutron skins and neutron stars

- Thick neutron skins -> larger NS radius→ larger tidal deformability Λ (cause a tension with GW170817: $\Lambda_{up\text{-}limit}$~580 at 1.4 $M_{\odot}$)



Implications on finite nuclei



The implications from SkNS4 parameters: a larger parameter space maybe helpful to reconcile with other nuclear observables

Extended neutron drip-line locations

	SkNS1	SkNS2	SkNS3	SkNS4	SkNS5
Mg	32	32	32	32	34
Ca	50	54	56	56	58
Sn	124	124	126	124	132
Pb	186	186	190	188	202
U	206	204	224	216	240

Da Wei Guan, JP, Chong Ji Jiang,
Chin. Phys. C 48, 064105 (2024)

Possible clues

- Weak mixing angle dependence, which is a key parameter in electroweak theory, may be a clue to explaining this contradiction

s_W^2 can sensibly differ from the SM at low energies

$$s_W^{2\,\mathrm{SM}} = 0.23857 \pm 0.00005$$

$$\sin^2\theta_W (8 \lesssim Q \lesssim 78\ \mathrm{MeV}) = 0.228 \pm 0.008.$$

M. Atzori Corona, M. Cadeddu, N. Cargioli, P. Finelli, and M. Vorabbi,Phys. Rev. C 105, 055503 –2022

- the role of clustering is very small in magic nuclei

Nuclei	R_{skin} (fm)	L (MeV) no α cluster	P_α	L (MeV) with α cluster
^{208}Pb	0.283 ± 0.071	$75.2^{+24.3}_{-24.5}$	9.3×10^{-3}	$75.3^{+24.3}_{-24.6}$
^{48}Ca	0.121 ± 0.050	$13.2^{+25.4}_{-24.9}$	7.3×10^{-2}	$15.0^{+25.6}_{-25.0}$
*	0.071 (lower)	1.7		3.4
*	0.171 (upper)	24.8		26.8

S.Yang, R.Li, C. Xu
Phys. Rev. C 108, L021303-2023

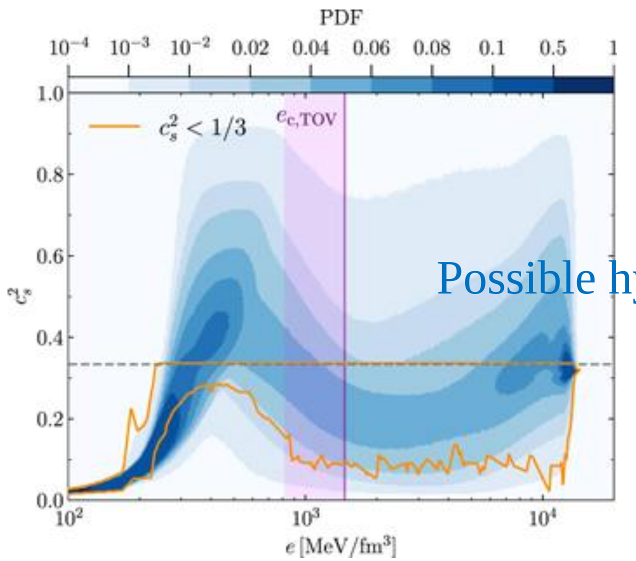
- A larger parameter space may be helpful to reconcile with other observables

indications from SkNS4 parameters

- Contribution from ground state correlations

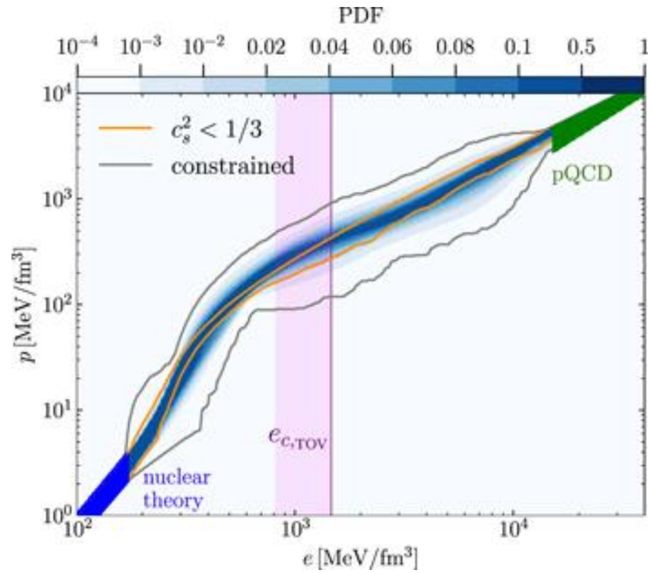
Speed of sound in neutron stars

More flexible than symmetry energy
exhaustive numerical searching of EOS



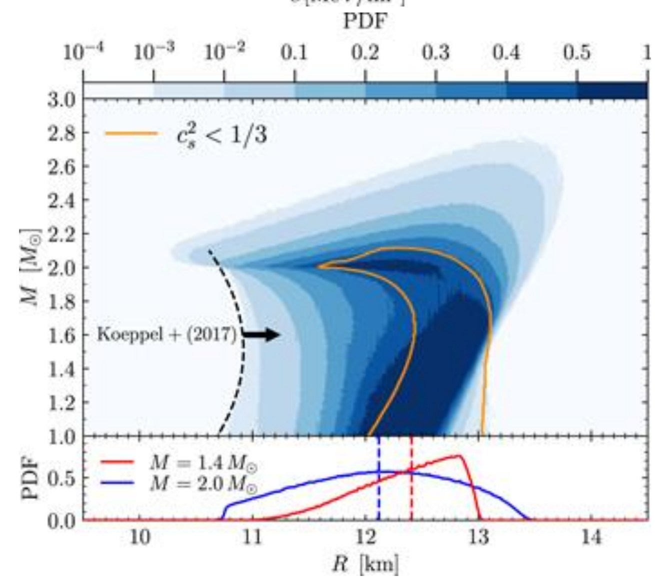
Possible hybrid stars

1/3



$$c_s^2 := \left(\frac{\partial p}{\partial e}\right)_s, \quad c_s^2(\mu) = \frac{(\mu_{i+1} - \mu)c_{s,i}^2 + (\mu - \mu_i)c_{s,i+1}^2}{\mu_{i+1} - \mu_i},$$

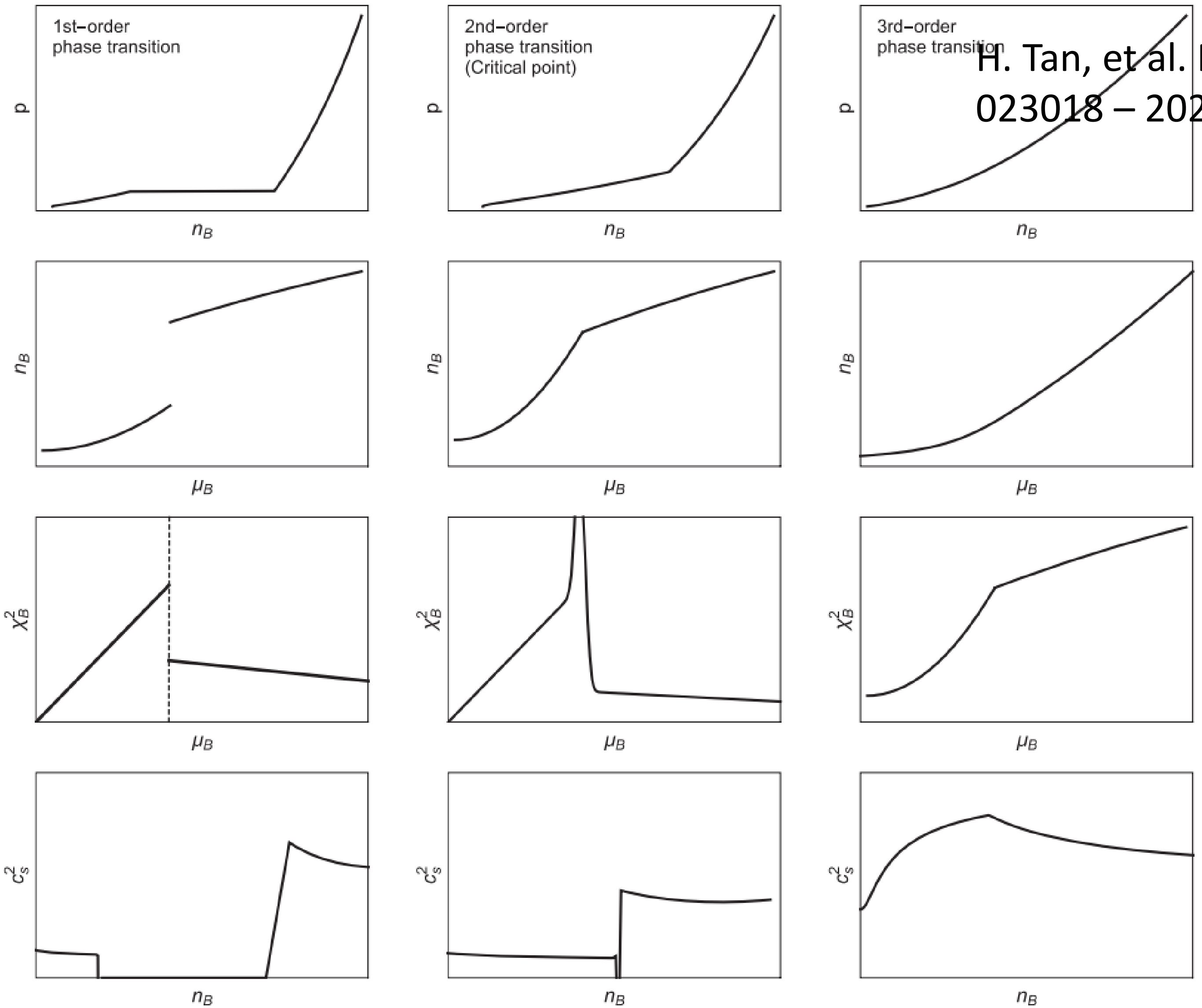
$$n(\mu) = n_1 \exp\left(\int_{\mu_1}^{\mu} \frac{d\mu'}{\mu' c_s^2(\mu')}\right), \quad p(\mu) = p_1 + \int_{\mu_1}^{\mu} d\mu' n(\mu'),$$



Large uncertainties below $2\rho_s$
Interpretation starts at $1.1\ \rho_s$

S. Altiparmak, C. Ecker, and L. Rezzolla, Astrophys. J. Lett. 939, L34 (2022).

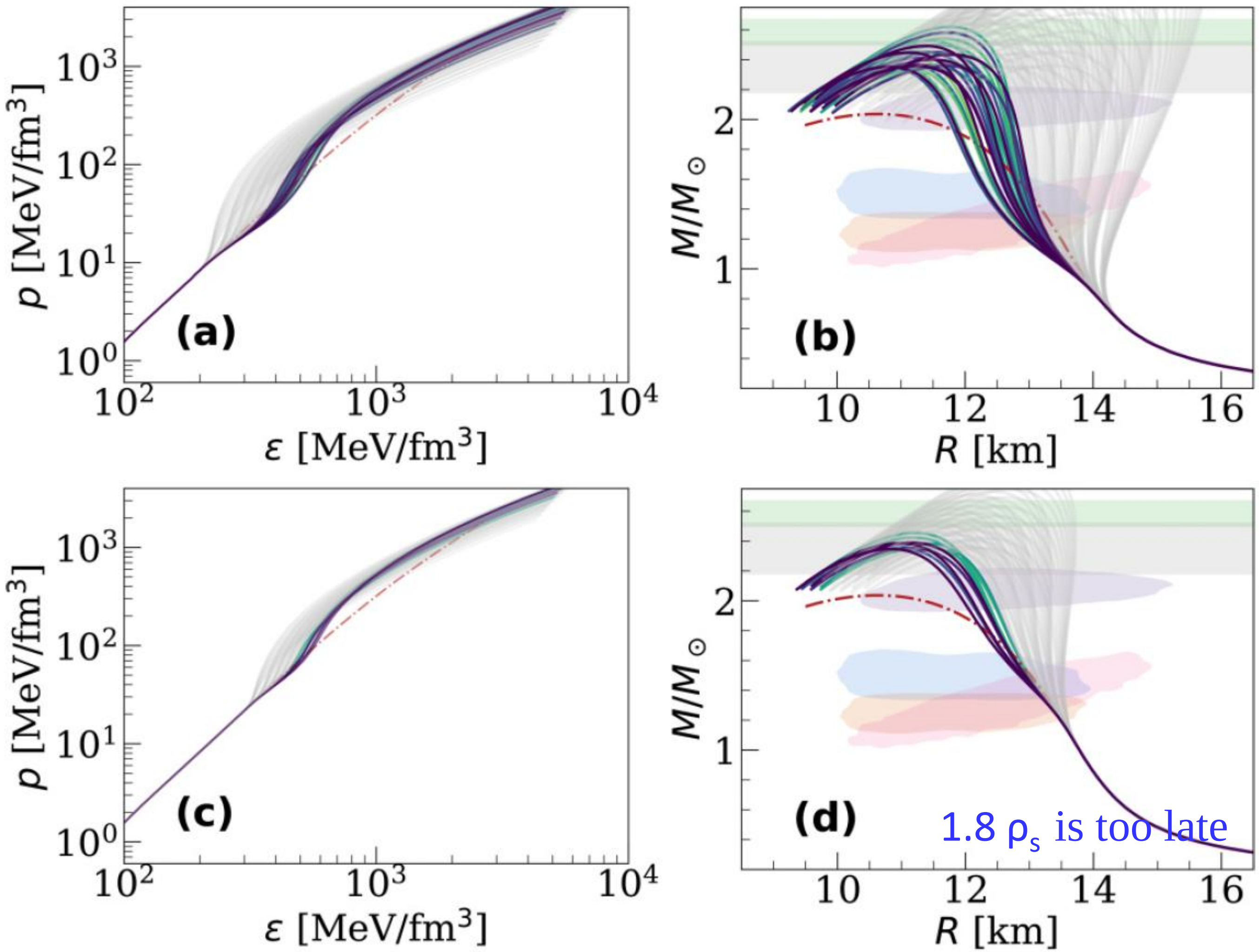
Phase transitions in nuclear matter



H. Tan, et al. Phys. Rev. D 105, 023018 – 2022

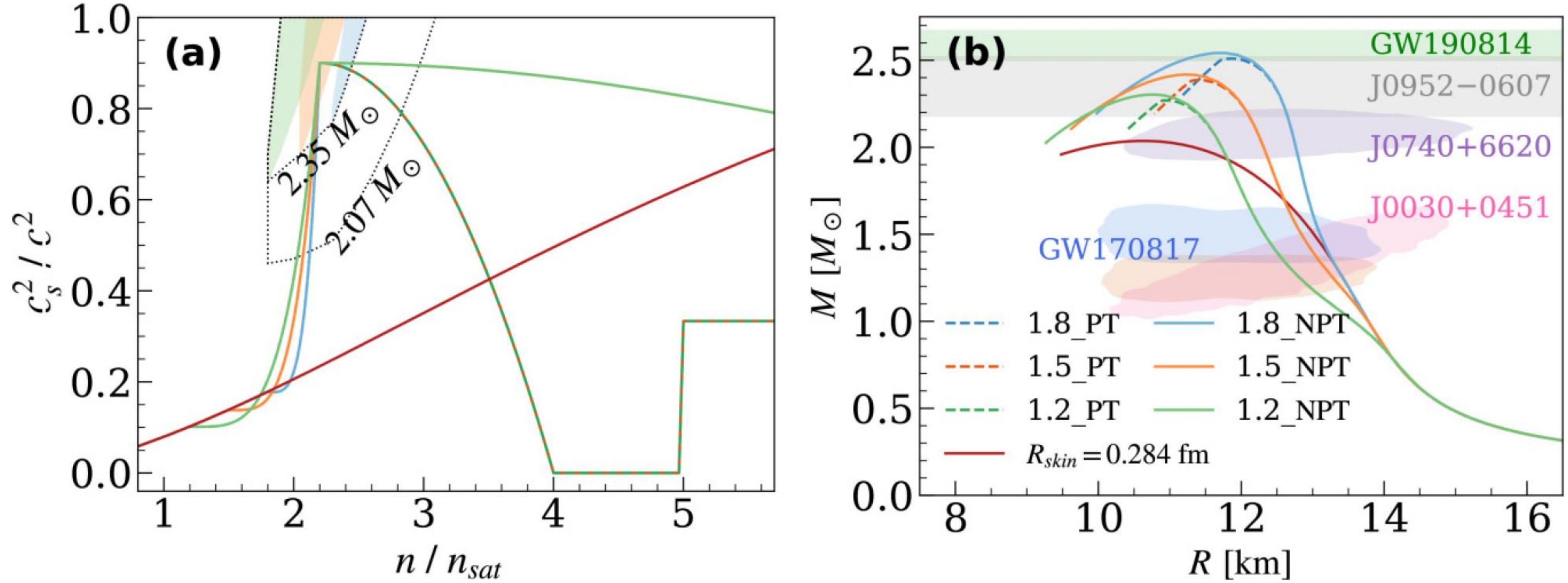
C_s : a good probe of phase transitions

Searching speed of sound with thick neutron skins



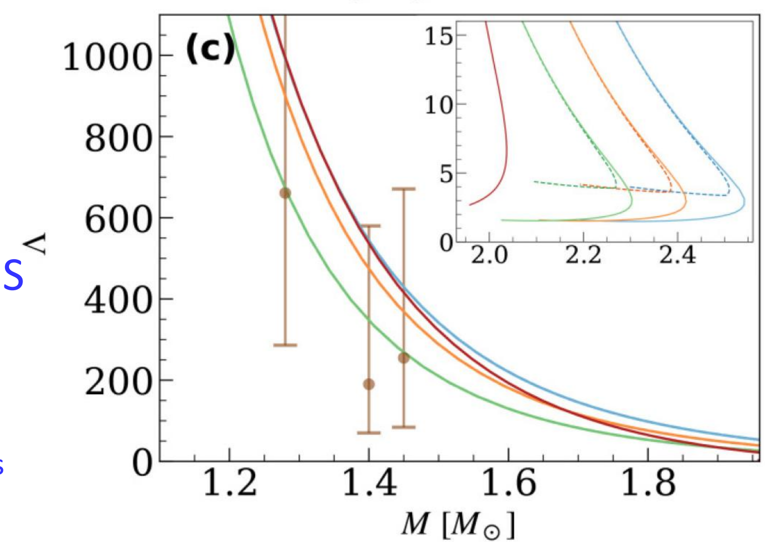
Matching the speed of sound at $1.2\rho_s$ and $1.8\ \rho_s$

Speed of sound with thick neutron skins



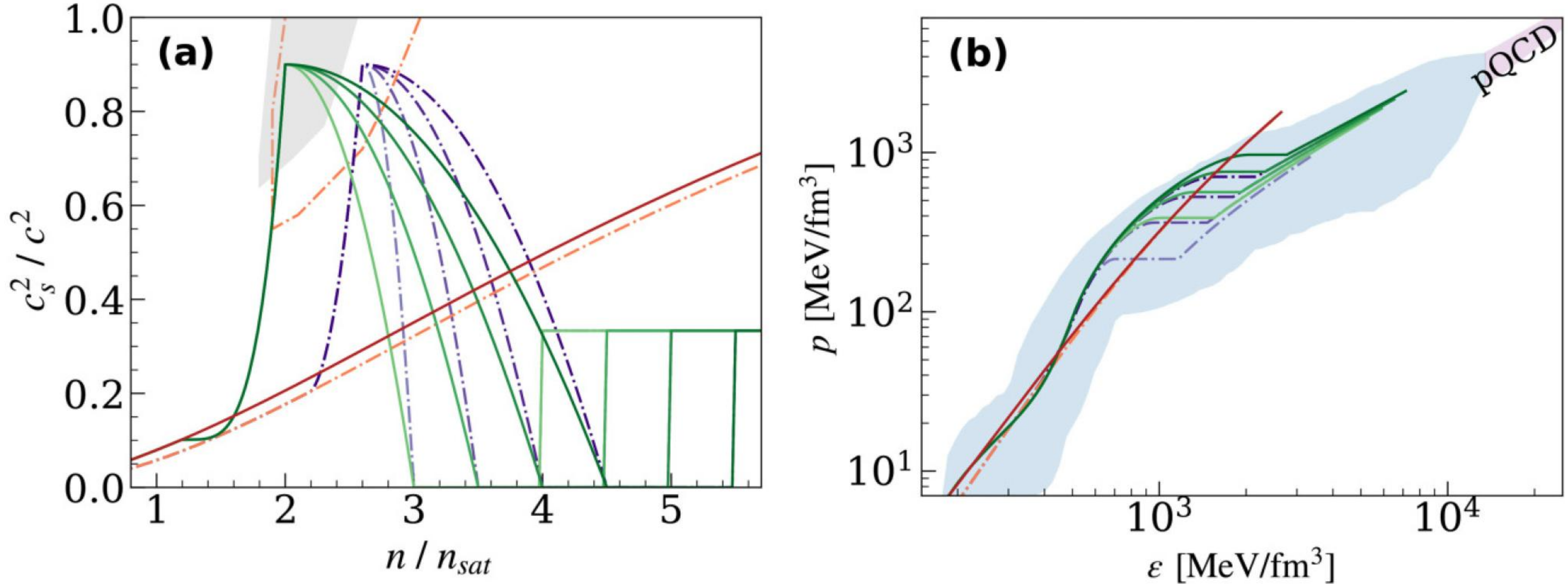
M. Chen, D. Guan, C. Jiang, JP,
Phys. Rev. C 108, 065806 –2023

- The peak is constrained around $2\rho_s$
- Soft C_s is needed to reconcile with GW170817
- Rapid increasing C_s is needed to reach massive NS
- Twin NS stars indication of phase transitions, difficult to detect
- Maximum masses not sensitive to EOS above $3\rho_s$

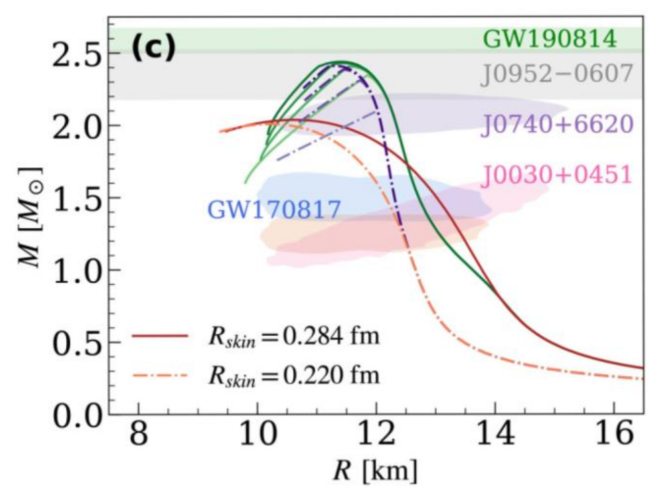


Speed of sound with thick neutron skins

- thick vs. thin neutron skins



Implications of thick neutron skins:
Early and strong first-order phase transition is comparatively favorable



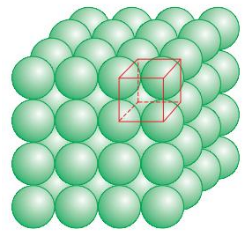
M. Chen, D. Guan, C. Jiang, J.Pei
Phys. Rev. C 108, 065806 –2023

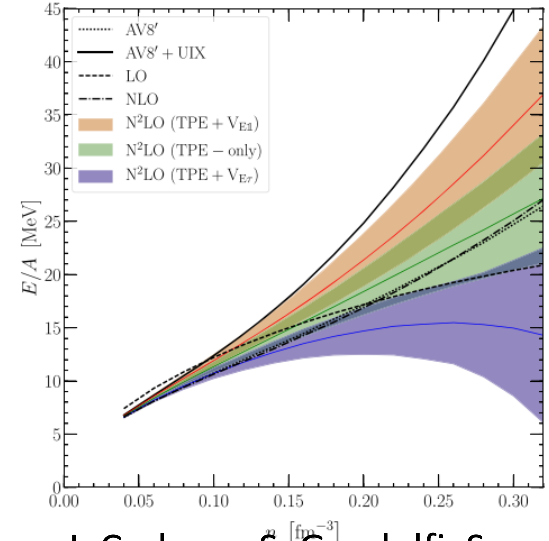
Discussions on exotic structures C_s^2

- Appearance of soft slope
  --mixing of hyperons
- Rapid rise of speed of sound
  --repulsive many-body forces

Brainwashed by Feynman?

Philip W. Anderson





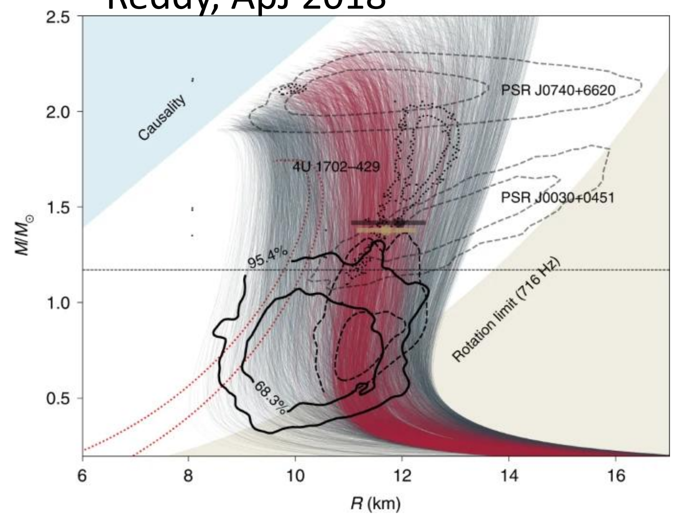
I.Tews, J. Carlson , S. Gandolfi, S. Reddy, ApJ 2018

- Overlap between nucleons：
  --dense cubic packing at $1.5\rho_s$
  large uncertainties at high densities
- A strange small neuron stars

$$M = 0.77^{+0.20}_{-0.17}\, M_{\odot} \text{ and } R = 10.4^{+0.86}_{-0.78} \text{ km}$$

Nature Astronomy 6, 1444 (2022)

--contrary to thick neutron skins

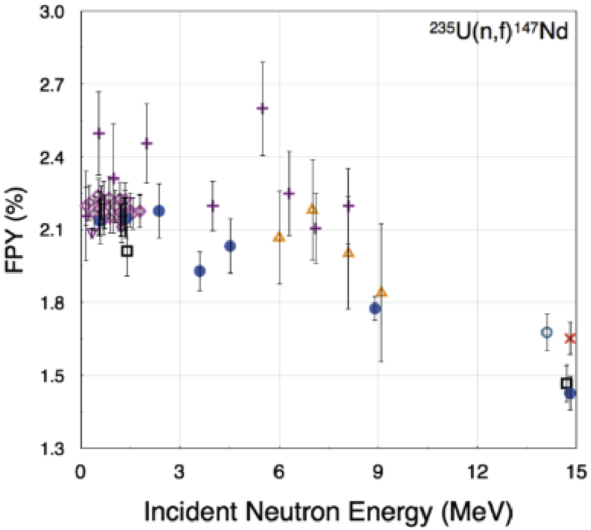


Bayesian evaluation of fission yields

- **Energy dependence**

Energy dependent fission data is a key need for fast-neutron reactors;
Most data at thermal energy, 14 MeV, but very sparse between them

How to interpolate the energy dependence



M.E. Gooden, et al., Nuclear Data Sheets 131, 319(2016)

- **Uncertainty quantification**

is a pressing issue in safety design;
Covariance matrix is widely used;
(first-order sensitivity propagation,
difficult to get complete covariance matrix)

$$\sigma_O^2 = \sum_{i,j} \mathrm{Cov}(x_i, x_j) \left[\frac{\partial O}{\partial x_i} \frac{\partial O}{\partial x_j} \right],$$

Evaluation methods of fission yields

- Evaluation is a combined inference based on experiments and modeling
- Multiple Gaussian approach for fission yields (5 Gaussians, 7 parameters, 1960s)

$$Y(A) = \frac{N_1}{\sigma_1\sqrt{2\pi}}\left[e^{-\left(\frac{(A-\bar{A}-D_1)^2}{2\sigma_1^2}\right)} + e^{-\left(\frac{(A-\bar{A}+D_1)^2}{2\sigma_1^2}\right)}\right] + \frac{N_2}{\sigma_2\sqrt{2\pi}}\left[e^{-\left(\frac{(A-\bar{A}-D_2)^2}{2\sigma_2^2}\right)} + e^{-\left(\frac{(A-\bar{A}+D_2)^2}{2\sigma_2^2}\right)}\right] + \frac{N_3}{\sigma_3\sqrt{2\pi}} e^{-\left(\frac{(A-\bar{A})^2}{2\sigma_3^2}\right)}$$

Key issues： energy dependence, uncertainty propagation

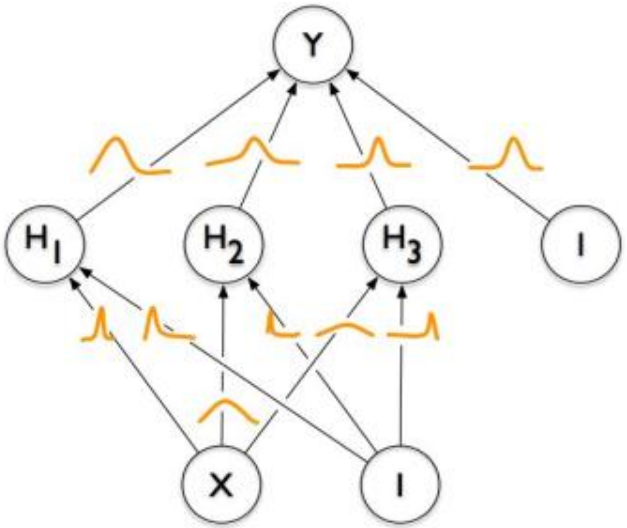
- Brosa model： multi-channels+random neck rupture(liquid-drop model+shell corrections) (Brosa, et al., Phys. Rep. 197, 167(1990))
- GEF model (~50 parameters, including physics inputs: barriers, level densities, fragment shells…..) (K.-H. Schmidt, et al. Nuclear Data Sheets 131, 107(2016))
- Evaluations of fission yields in major nuclear data libraries (ENDF, JENDL, JEFF, CENDL), with energies only available at thermal, 0.5, 14 MeV
- Conventional evaluations are not good at considering imperfect data information

Machine learning can be a new evaluation method…..

Bayesian machine learning for evaluation

- Machine learning is expected to provide new evaluations of nuclear data

* The combination of machine learning and nuclear data evaluation is a practical application.



Bayesian advantages:

is ideal for uncertainty quantification
is ideal to deal with imperfect data
enable physics-informed prior

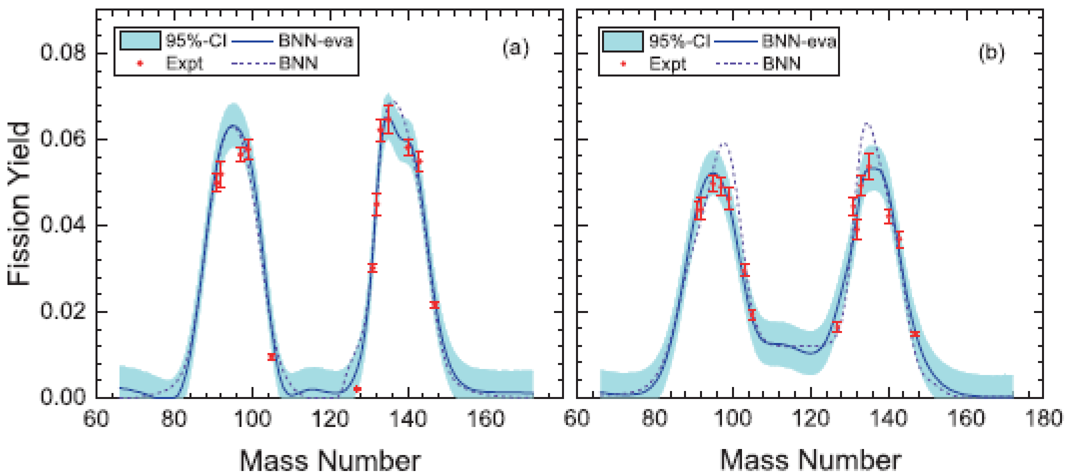
Bayesian neural network
y=f(x,ω)+σε

Build physics into priors

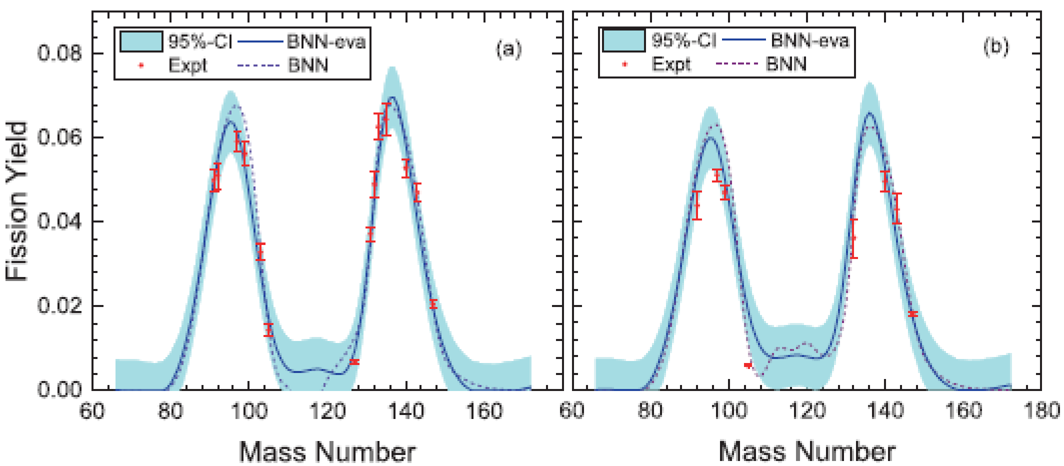
$$p(\mathbf{Q}|\mathbf{D}) \propto p(\mathbf{D}|\mathbf{Q},\mathbf{I})p(\mathbf{Q}|\mathbf{I})p(\mathbf{I}) \propto p(\mathbf{D}|\mathbf{Q})p(\mathbf{Q}|\mathbf{I})p(\mathbf{I}).$$

Bayesian evaluation of incomplete fission yields

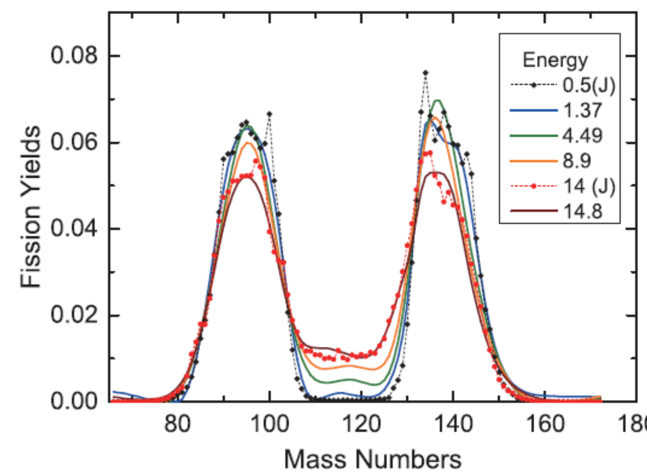
Evaluation at 1.37 and 14.8 MeV



Evaluation at 4.49 and 8.9 MeV

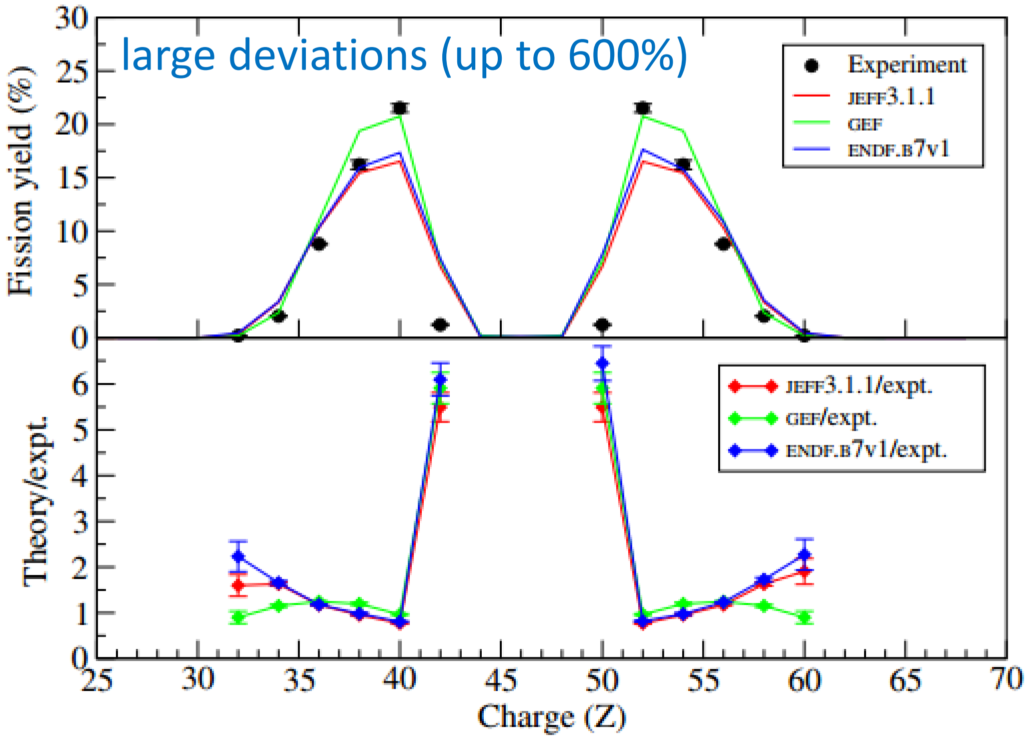


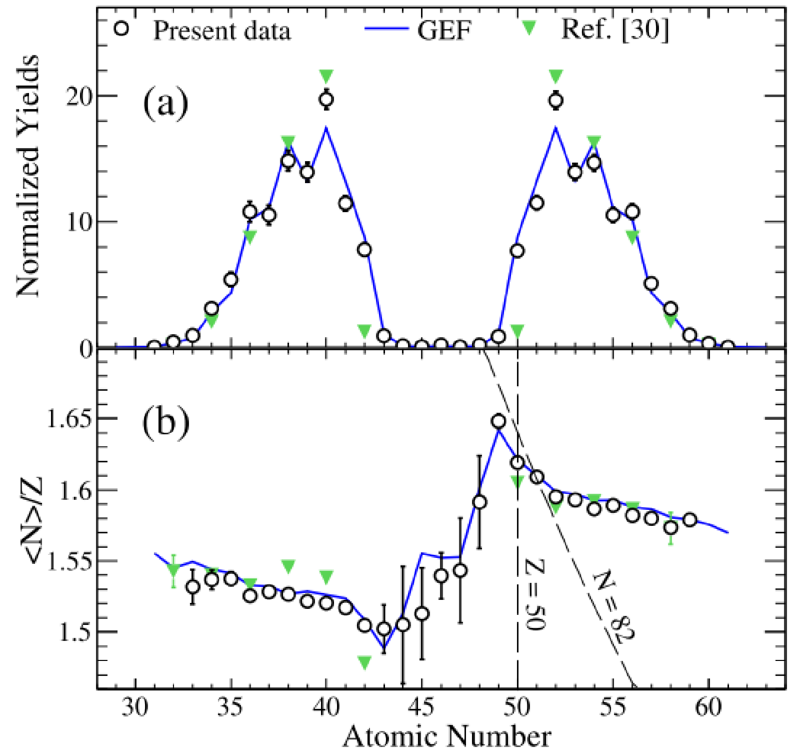
Symmetric fission increase as excitation energy increase, as shell effects fades in compound nuclei



Z.A. Wang, J.Pei, Y.Liu, Y.Qiang, PRL 123,122501 (2019)

Bayesian evaluations of charge yields





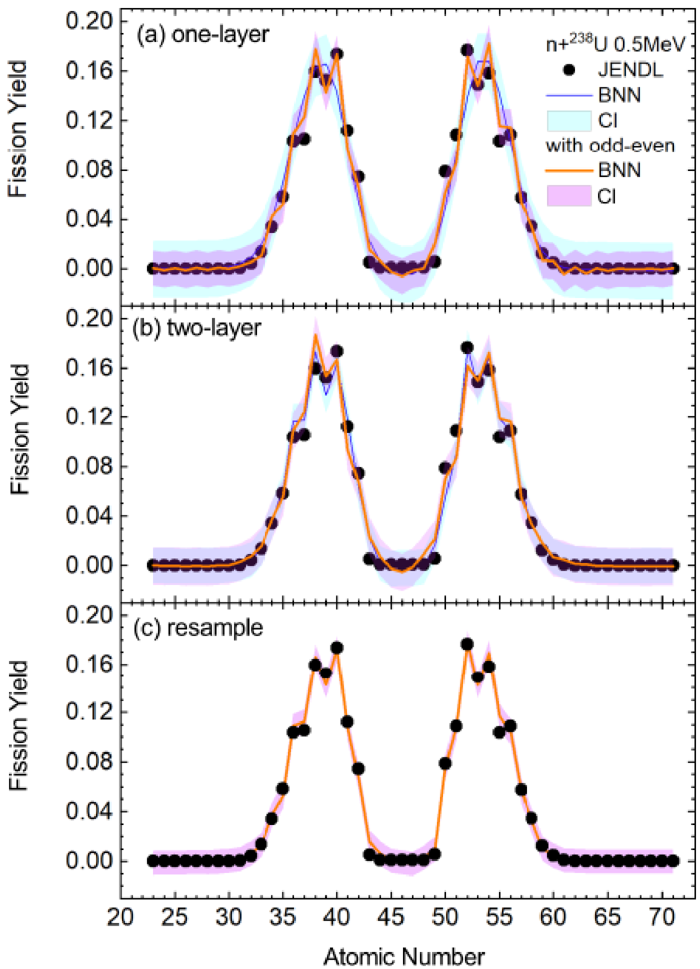
Two experiments have discrepancy in fission charge yields of 239U

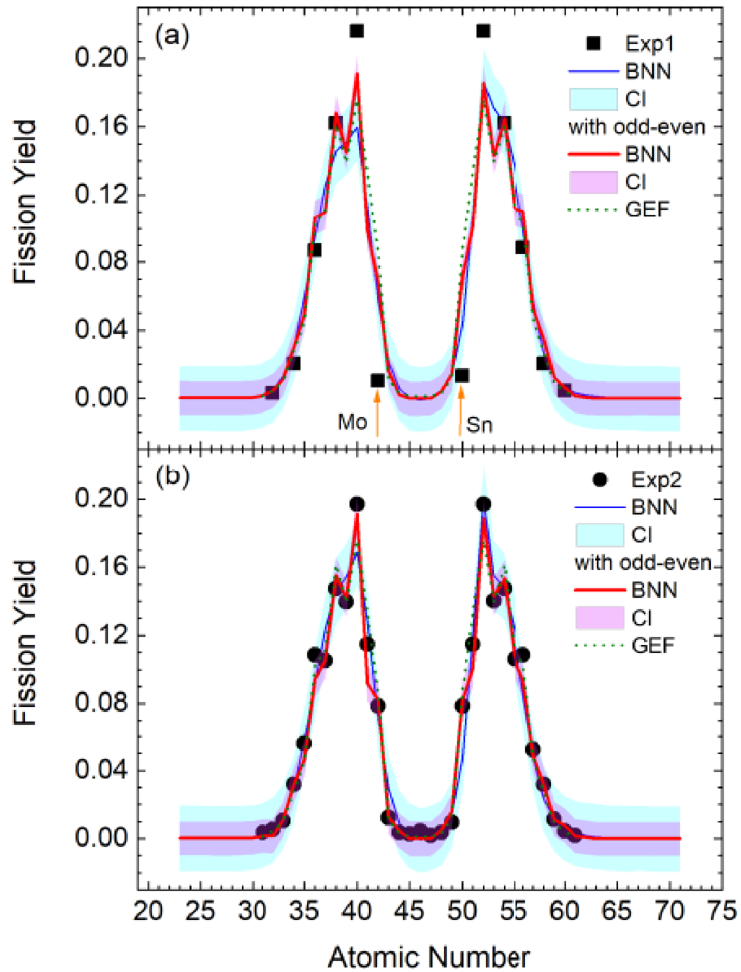
J. N. Wilson et al., Phys. Rev. Lett. 118, 222501(2017)

D. Ramos et al., Phys. Rev. Lett. 123, 092503(2019)

Large discrepancy at Mo, Sn charge yields

Bayesian evaluations of charge yields





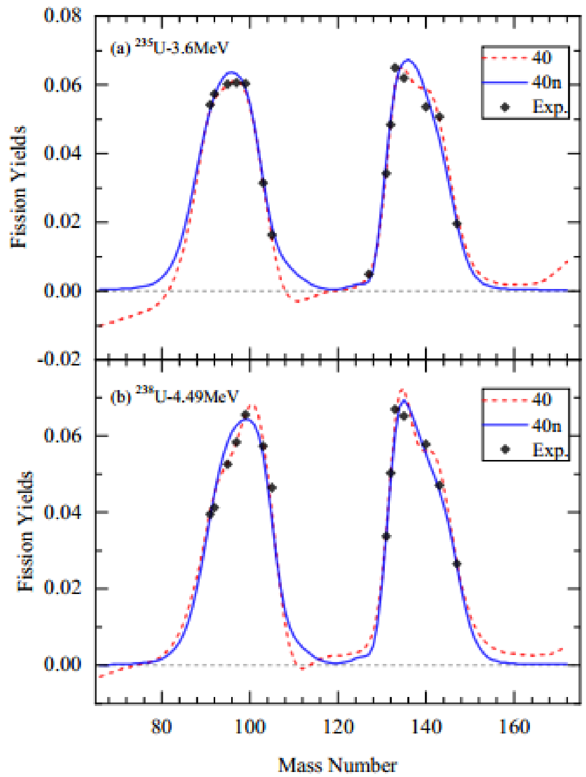
Input with odd-even effects

BNN evaluation is close to 2019 expt

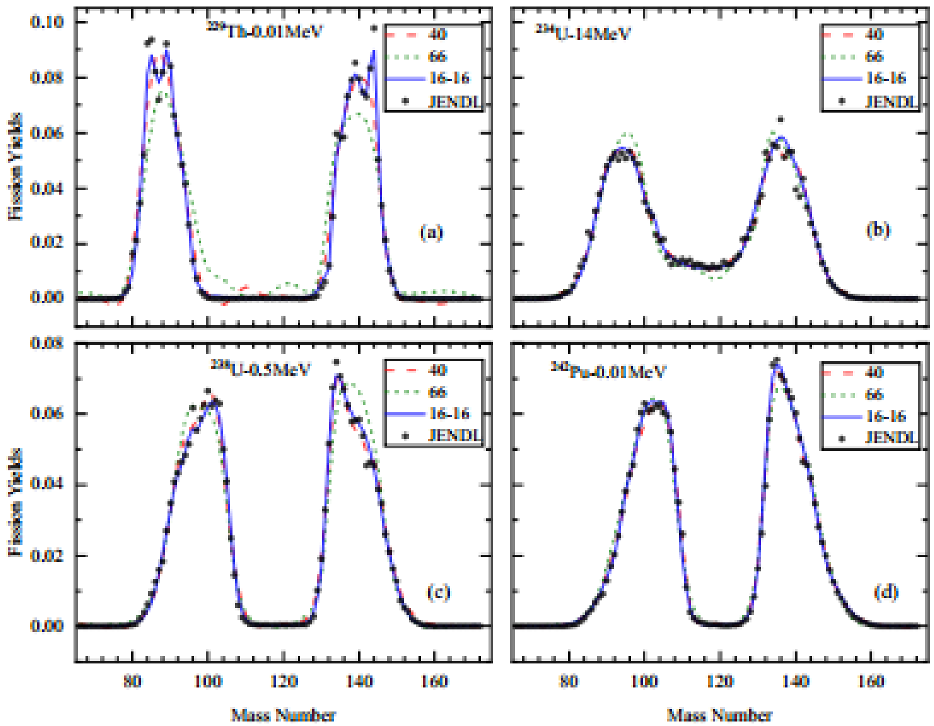
C. Y. Qiao, J. C. Pei, Z. A. Wang, Y. Qiang, Y. J. Chen, N. C. Shu, and Z. G. Ge， Phys. Rev. C 103, 034621 (2021)

Optimization of BNN

- Penalty on negative values testing for physics constraints



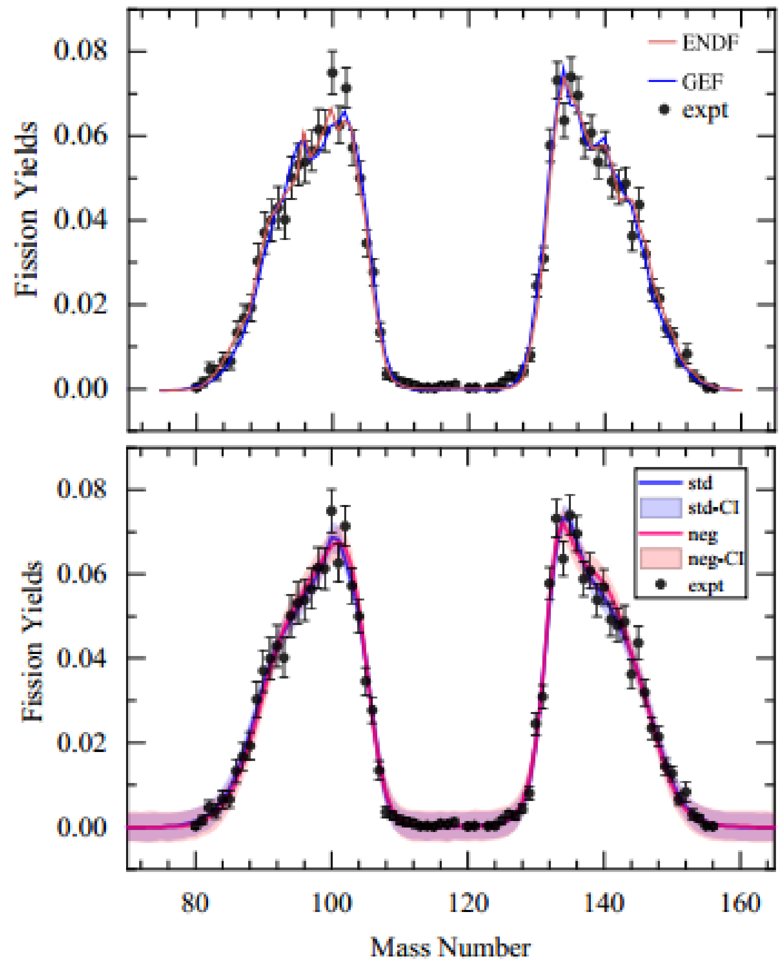
- Structures of network



Shallow or deeper neural networks?

66	16-16	11-12-12	9-10-10-10	9-9-8-8-9	8-8-8-8-7-7	7-7-7-7-7-7-8
4.35×10^{-6}	3.43×10^{-6}	4.07×10^{-6}	4.99×10^{-6}	4.64×10^{-6}	5.05×10^{-6}	4.94×10^{-6}

Optimization of BNN



Z.A. Wang, J.C.Pei, Phys. Rev. C 104, 064608 (2021)

Uncertainty propagation in BNN

- Uncertainty propagation is crucial for nuclear applications
- It is difficult to obtain covariance matrix experimentally, and difficult to combine them
- Most machine learning don’t treat uncertainty propagation and imperfect data
- Uncertainty propagation is a comprehensive effect, related to neighboring and also other data points, indicating complex uncertainty correlations inherent in BNN
- Bayesian machine learning uncertainty includes: background noise and data-sensitive uncertainty

Uncertainty propagation in BNN

Change expt. uncertainty

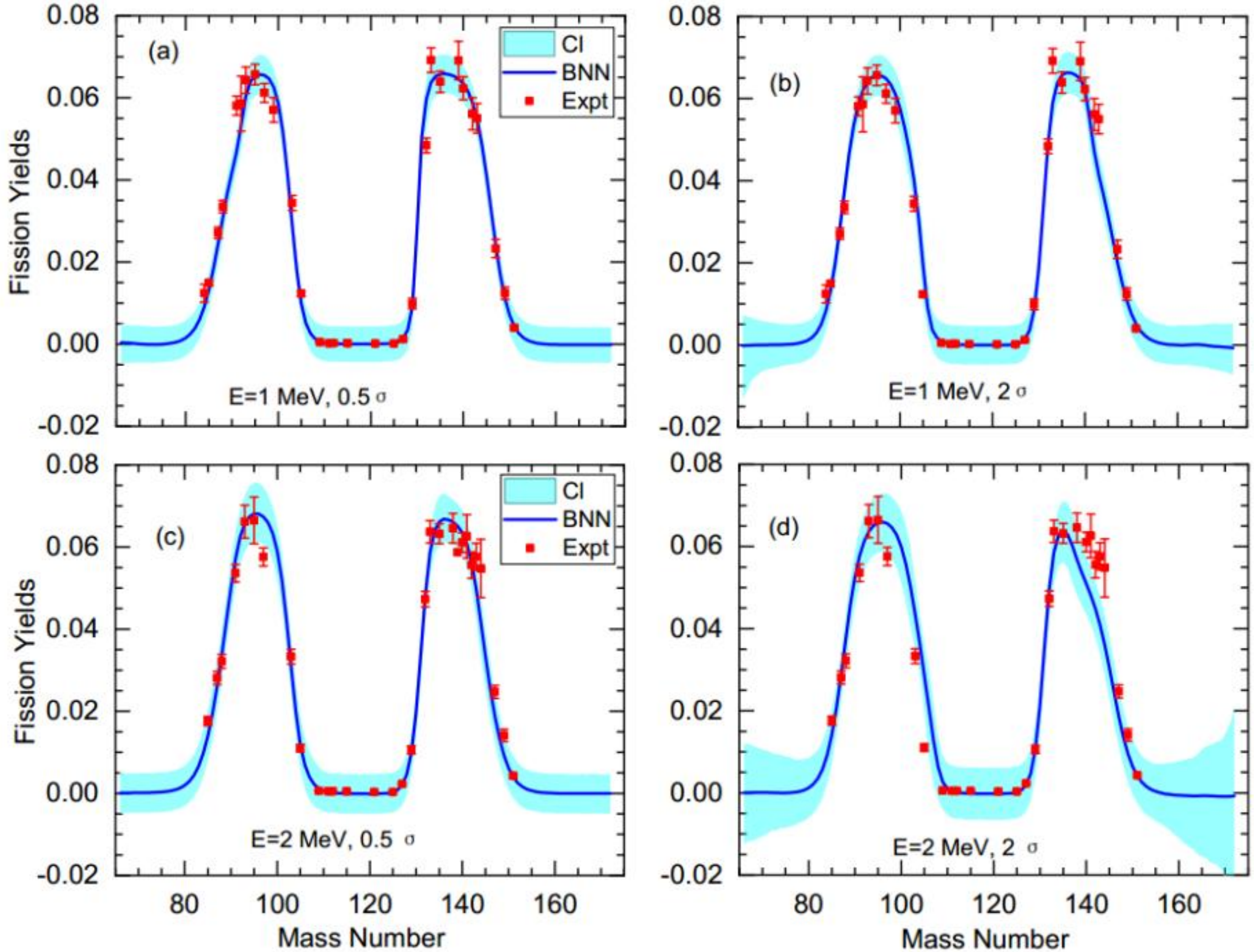


Figure 1: BNN evaluations of fission yields of n+^{235}U fission by taking into account the experimental uncertainties. (a) shows the evaluations with neutron incident energy E=1 MeV, but with reduced experimental uncertainties by a factor of 0.5. (b) shows the evaluations at E=1 MeV, but with a factor of 2.0. (c) shows the evaluations at E=2 MeV, but with a factor of 0.5. (d) shows the evaluations at E=2 MeV, but with a factor of 2.0. The shadow regions show the BNN uncertainties given by the confidential interval at 95%.

Uncertainty propagation in BNN

Discrepant data

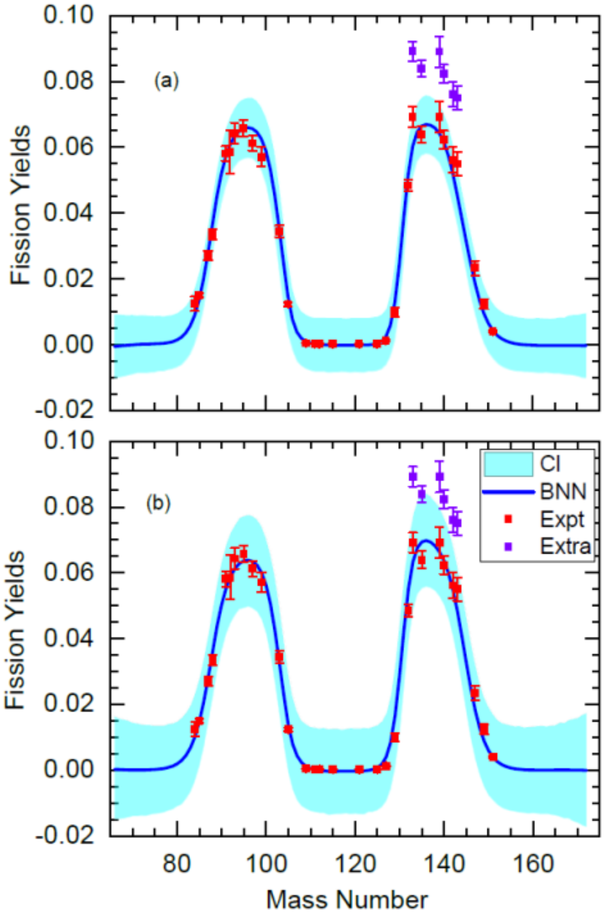


Figure 2: BNN evaluations of fission yields of n+^{235}U fission by taking into account the discrepant data. (a) shows the evaluations with extra data (purple color). (b) shows the evaluations with the same extra data, but the weights of these discrepant data are increased to be 4.

Missing data

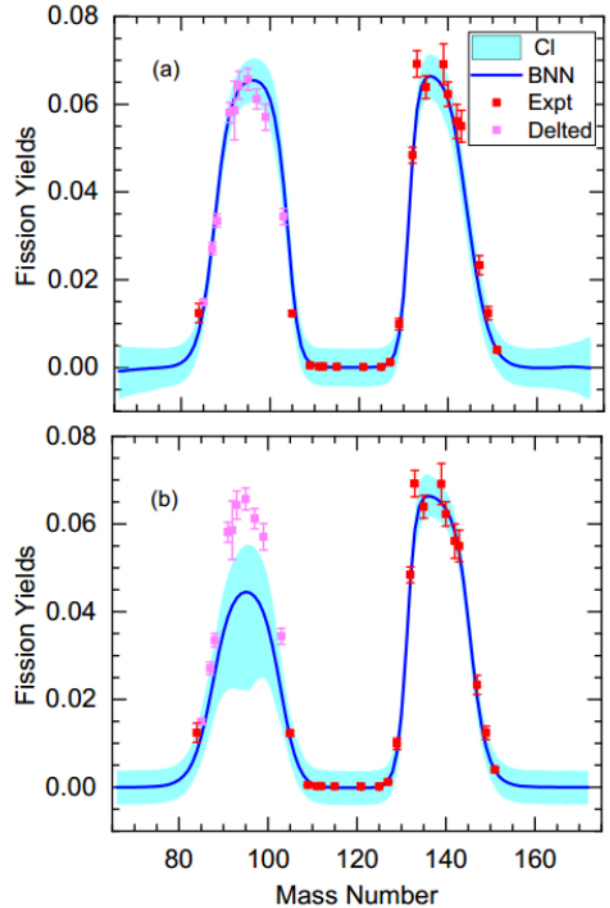
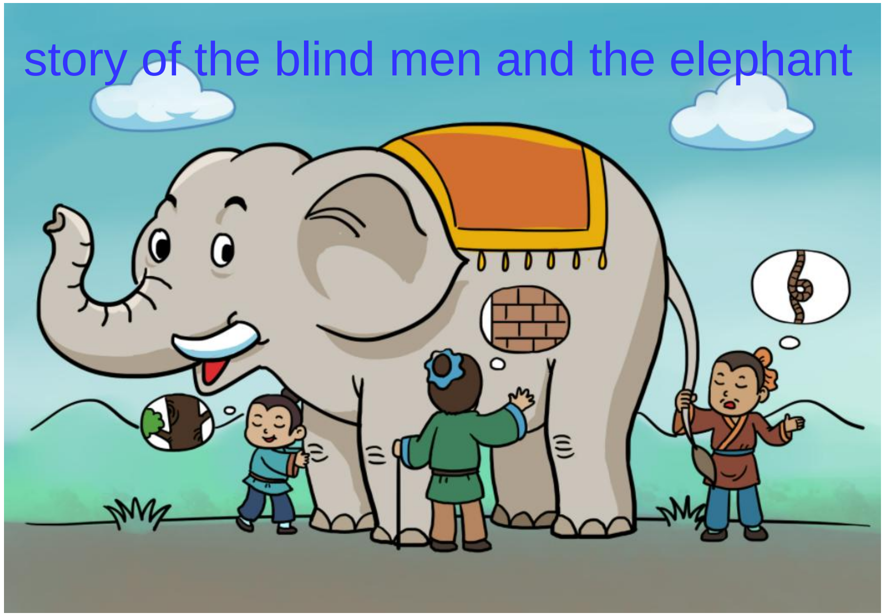


Figure 3: BNN evaluations of fission yields of n+^{235}U fission in case of incomplete data. (a) shows the evaluations by deleting experimental data and 14 MeV data at left peak (pink color). (b) shows the evaluations by deleting experimental data and thermal neutron data at left peak .

J.Yi, et al., Sci.Chin.Phys. 2022

Bayesian data fusion

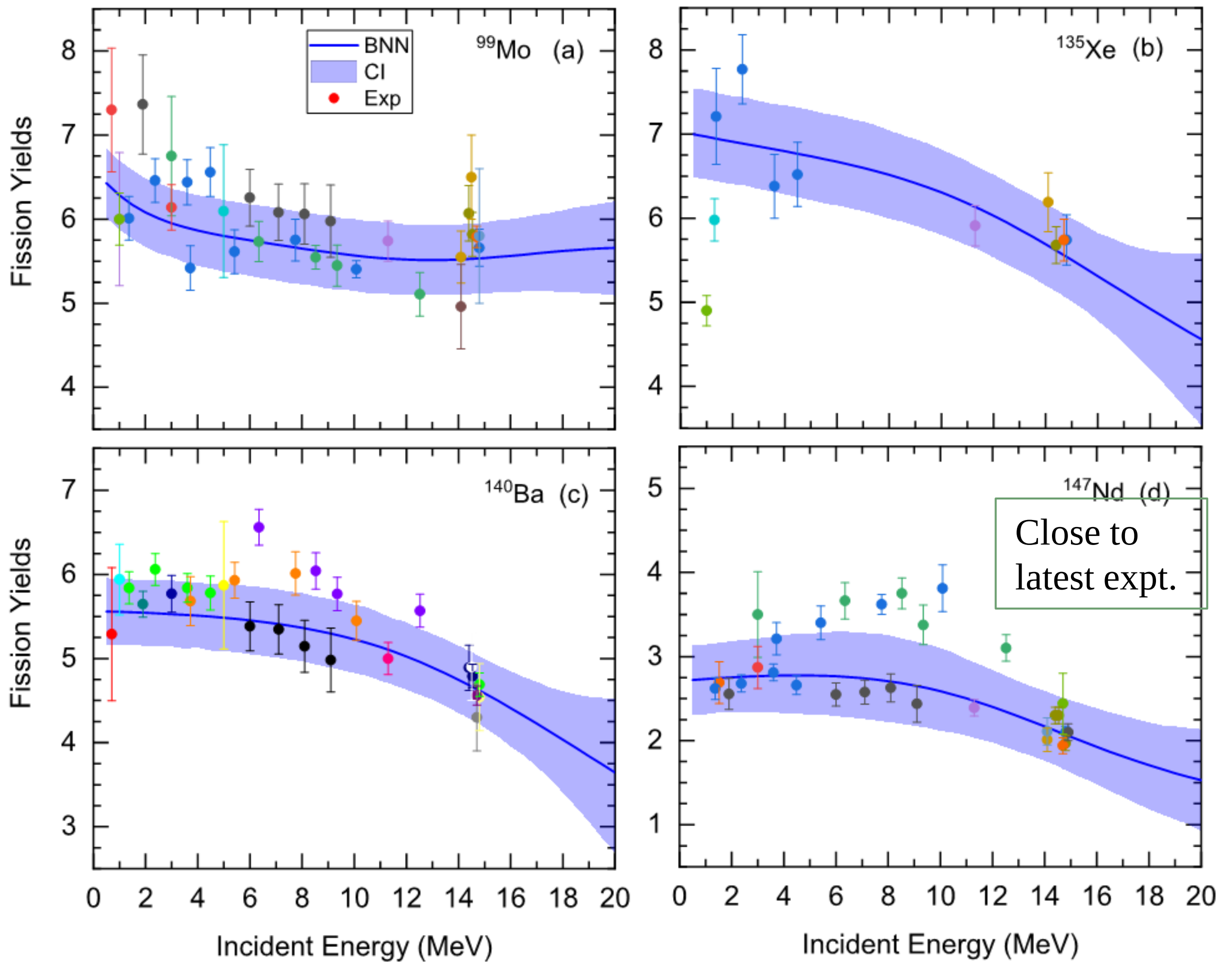
- Data fusion is the process of integrating multiple data sources to produce more consistent, accurate, and useful information than that provided by separated data sources.
- These data sources share a number of variables
- A prevalent way to deal with imperfect data： noisy, incomplete, discrepant
- To include underlying non-local and high-dimensional correlations, in analogy to long-range and many-body interactions
- Conception in some sense similar to model mixing



Bayesian data fusion for augmented evaluation

- Evaluation of cumulative fission yields by cross-experiment data fusion

- Lots of raw imperfect fission data in EXFOR library, need to exploit maximum values of them
- Applications needs yield-energy relations of some key fragments
- Data fusion can include underlying correlations
- Bayesian uncertainty include: background noise and data-dependent uncertainty

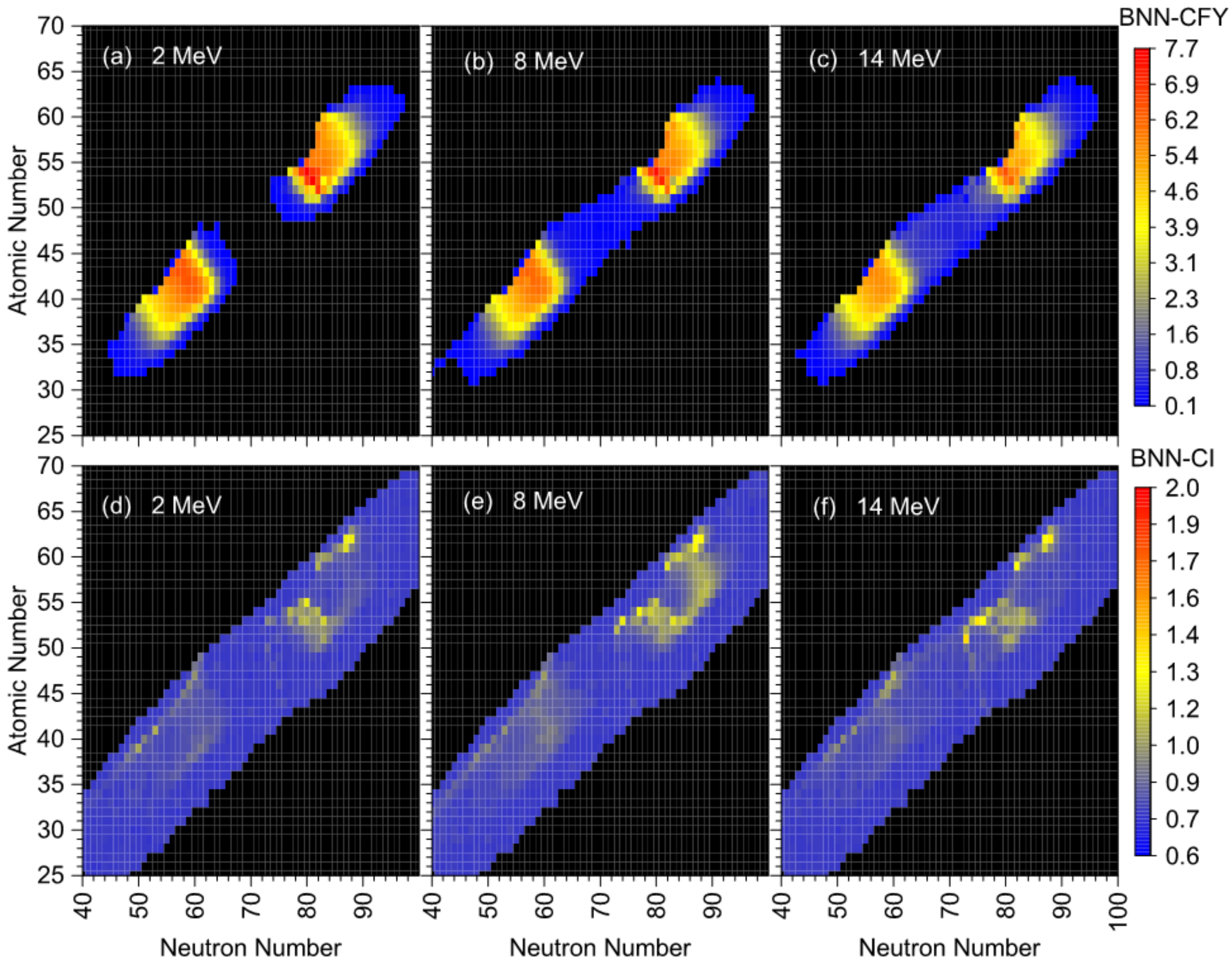


Z. A. Wang, J. C. Pei, et al., PRC106, L021304 (2022)

Bayesian data fusion for augmented evaluation

- Full two-dimensional energy dependent cumulative fission yields

  Expected to be useful for reactor simulations



Bayesian data fusion for augmented evaluation

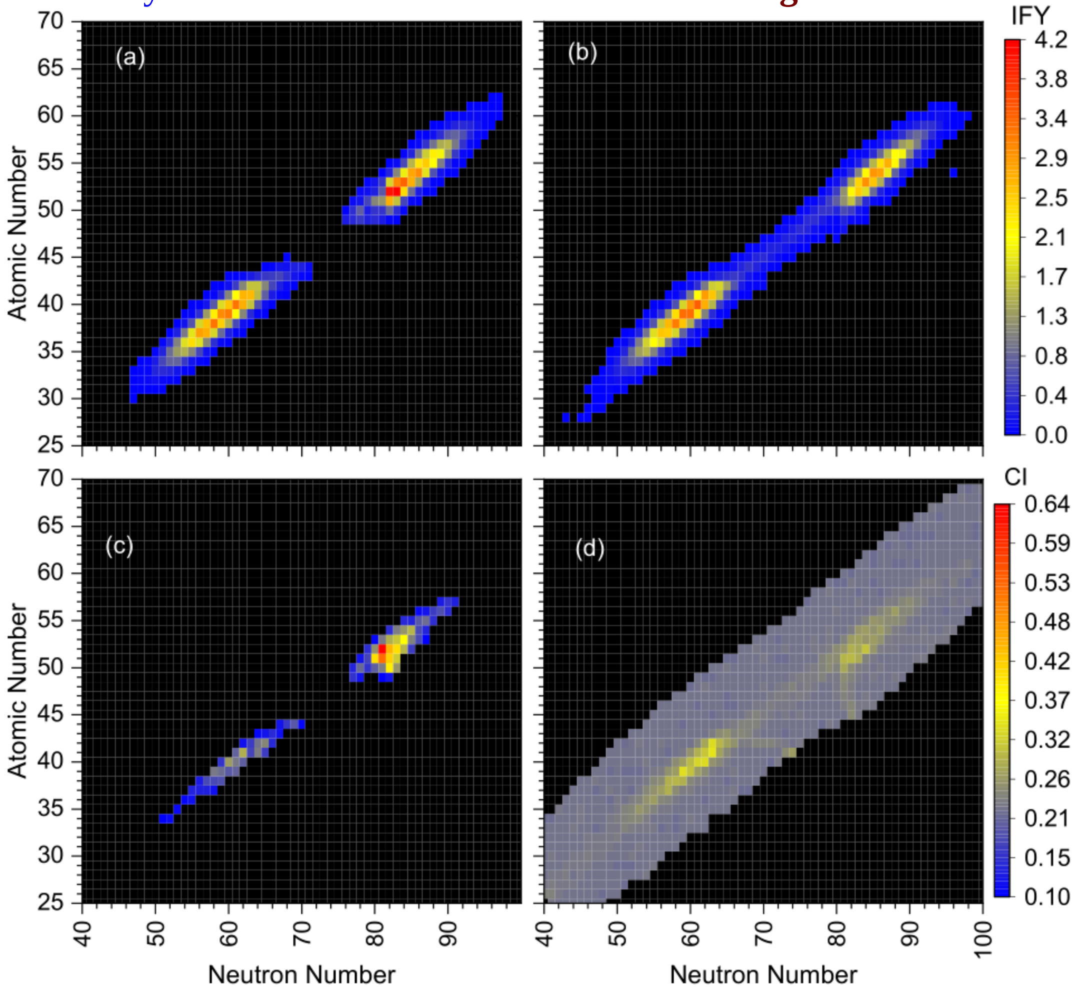
- Heterogeneous data fusion: independent fission yields, very few experimental data

*The inference would be less precise when data in some energies is sparse, however, its correlations with other data in other energies can be beneficial to improve the inference.

*heterogeneous data fusion is useful to understand correlations in multiple fission observables comprehensively

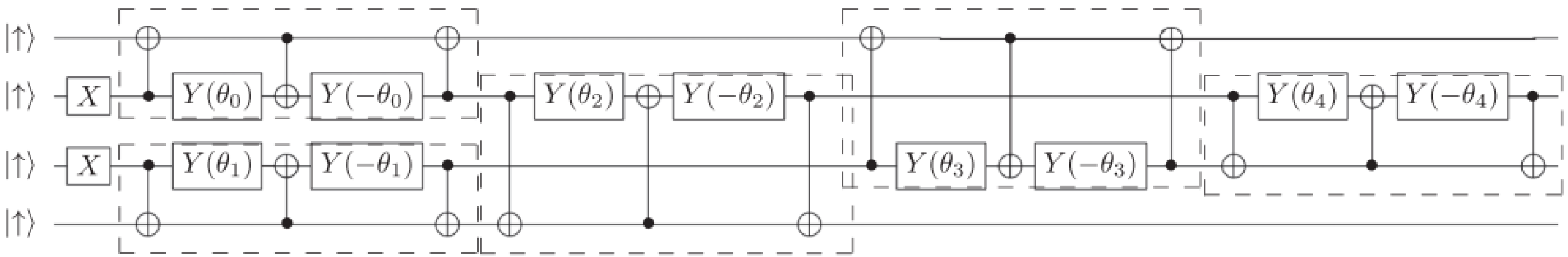
Only IFY at 8 MeV

IFY-CFY **heterogeneous data fusion**



Noise mitigation in quantum computing

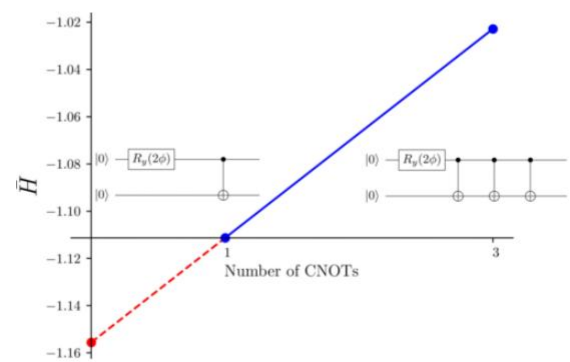
- Entangled noise in multi-qubits readout measurements
- Noise propagation via gates and operations
- How to get maximum information from correlated uncertainty?



A: Readout error mitigation:

$$S_k = \begin{pmatrix} P^k_{0,0} & P^k_{0,1} \\ P^k_{1,0} & P^k_{1,1} \end{pmatrix}.$$

B: noisy CNOT gate: zero noise extrapolation



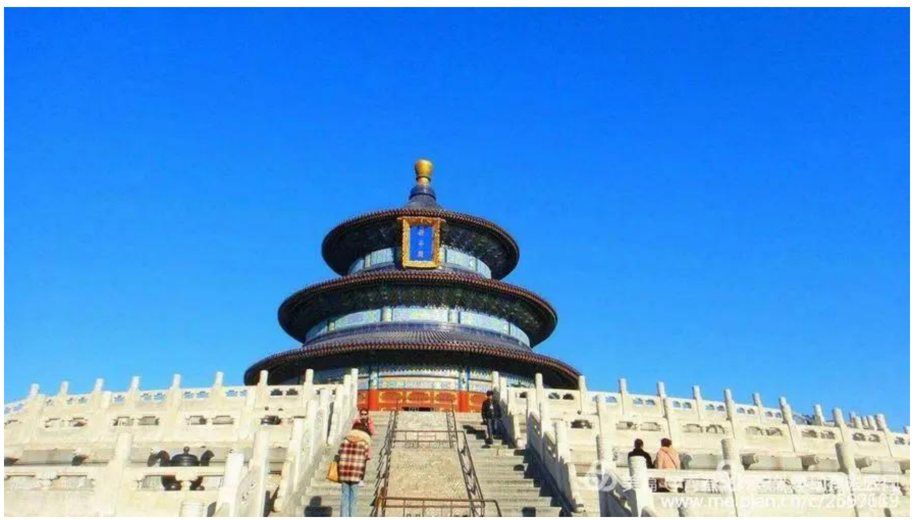
C.J.Jiang, JP, Phys.Rev.C 107, 044308 (2023)

Perspectives

- The reliable descriptions of nuclear matter at $2\rho_s$ is very needed, to exclude the exotic speed of sound: uncertainties due to repulsive many-body forces exploding towards higher densities and nucleons overlap begins at $1.5\rho_s$
- It may be not relevant to talk about symmetry energies at high densities due to other degrees of freedom while speed of sound is more flexible
- Larger parameter space is needed to describe competing observables
- More accurate neutron skin measurements are very needed
- Indication of missing physics by thick neutron skins: isovector part, ground state correlations
- Bayesian evaluation of imperfect fission data is useful but need physics informed learning
- How to get maximum information in quantum computing from correlated uncertainty?

https://napp.fudan.edu.cn/event/757/

Thank you!



Welcome to visit Peking University!