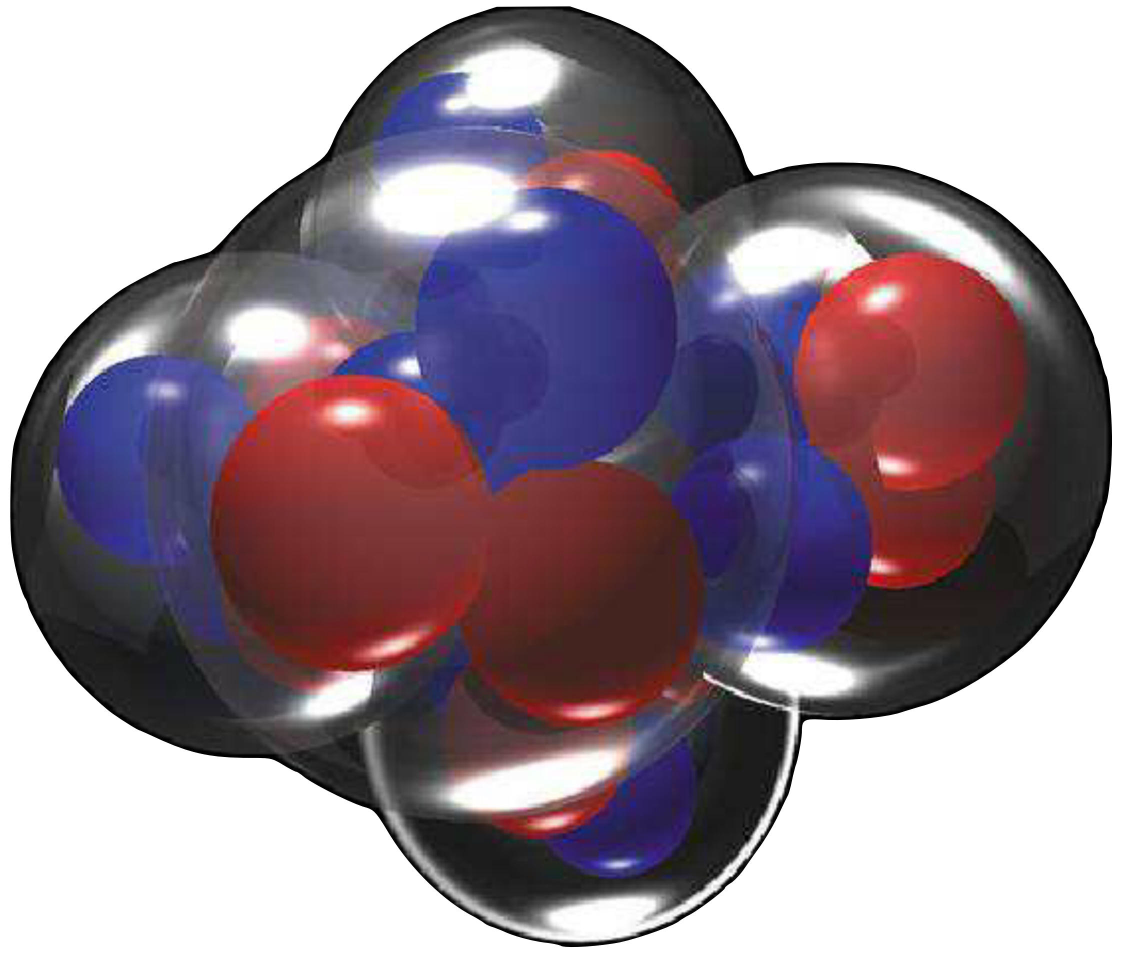
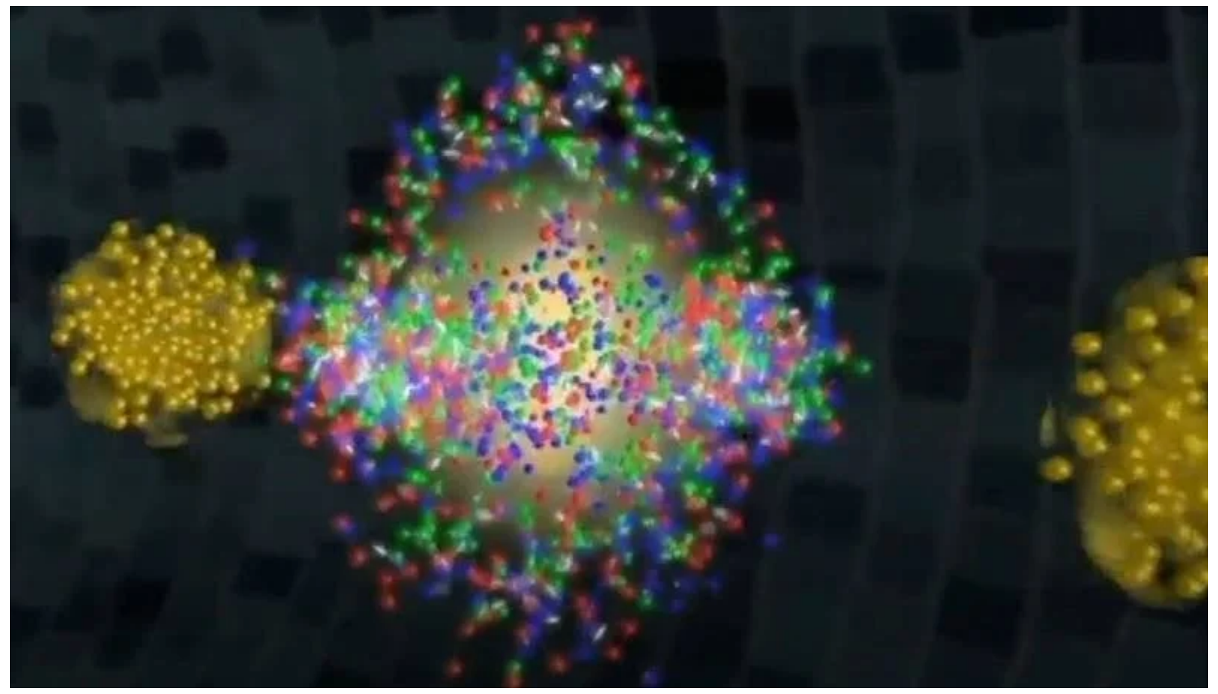
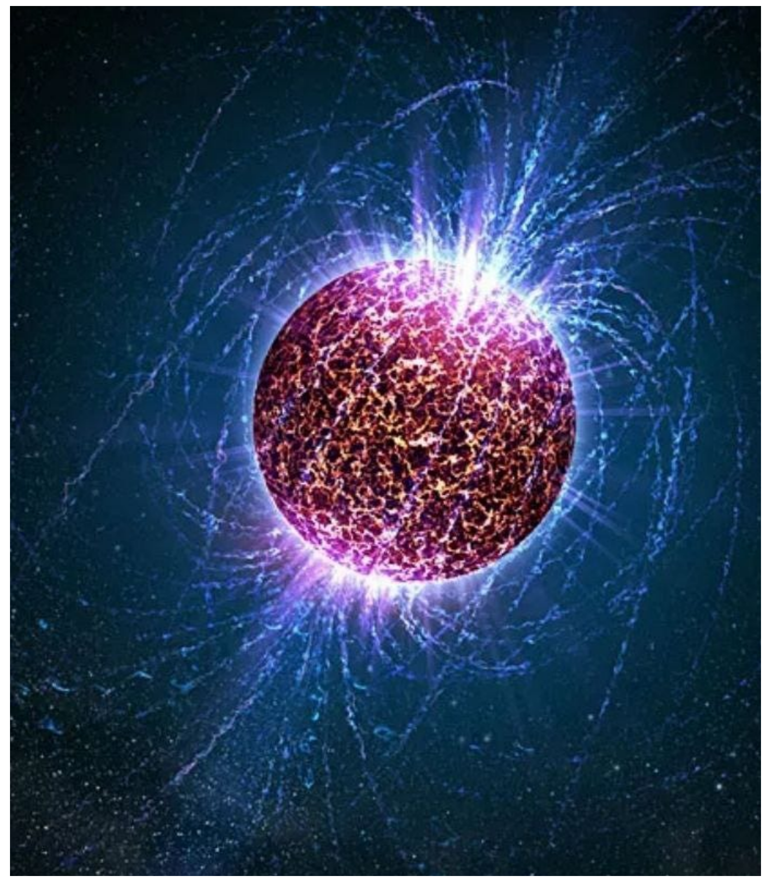
The equation of state from Neutron Stars to Heavy Ion Collisions

Jacquelyn Noronha-Hostler

CERN - 13th Nov, 2024







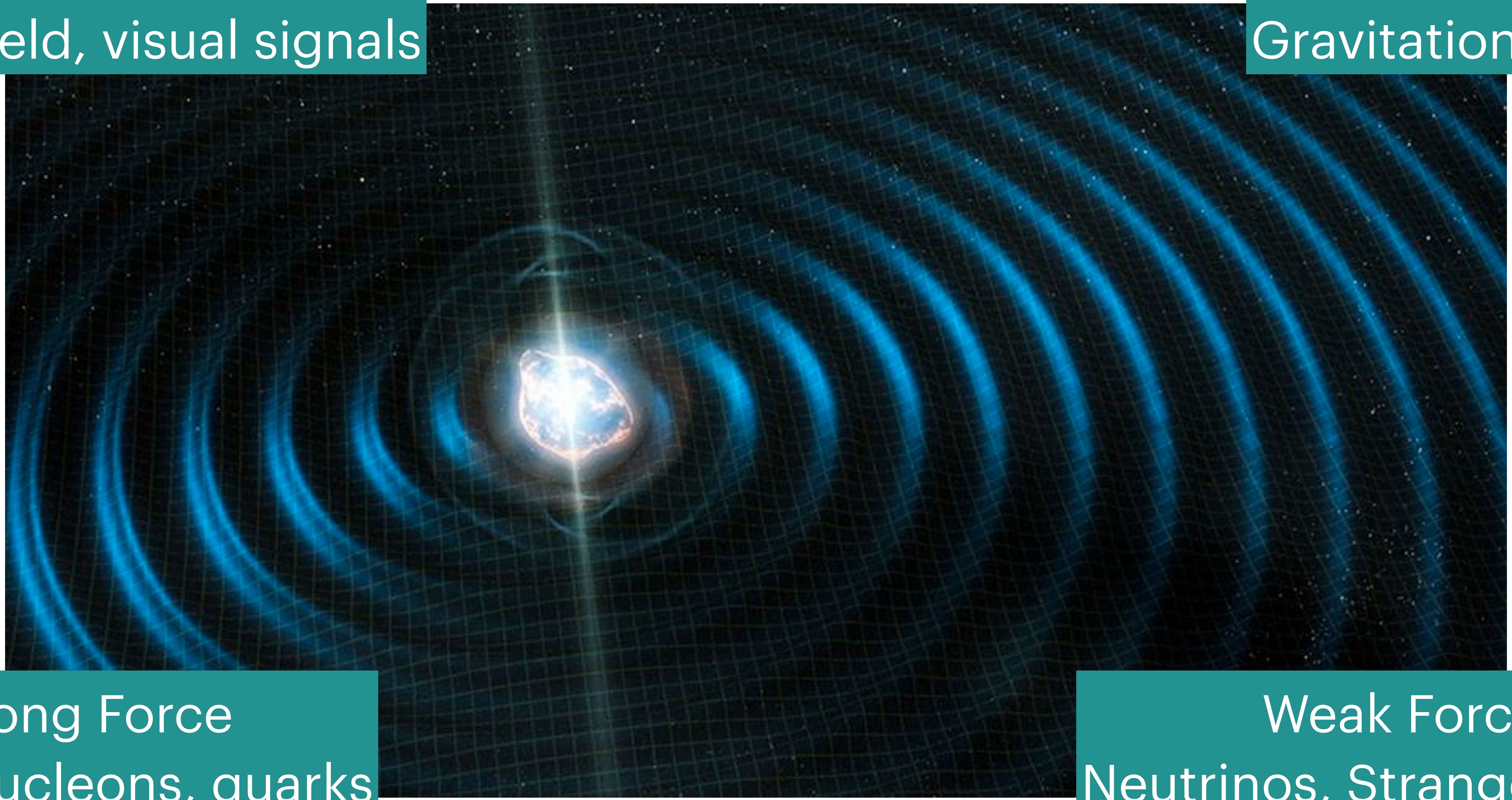

GW170817
Animation


GW170817
Animation

Neutron star mergers combine the fundamental forces

Electromagnetism
Large B field, visual signals

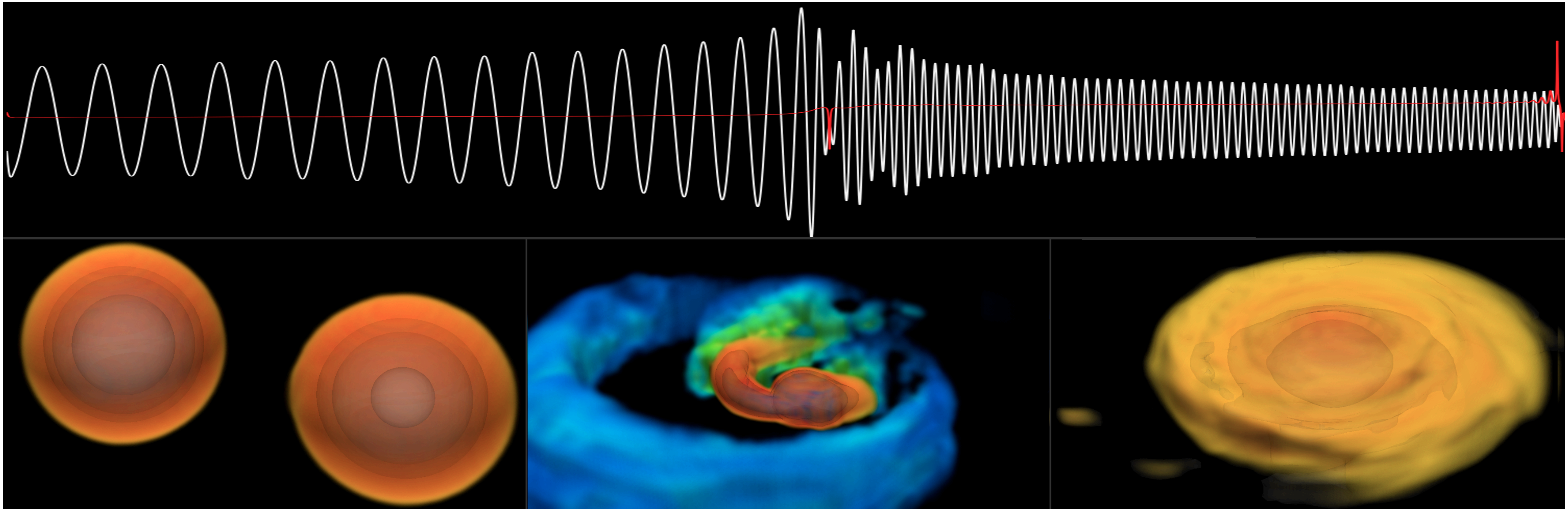
Gravity
Gravitational Waves



Strong Force
Nuclei, nucleons, quarks

Weak Force
Neutrinos, Strange decays

How hot is a neutron star during a merger?



Cold (inspiral)

$T \sim 10^6\ K$

$T \sim 10^{-5}\ MeV$

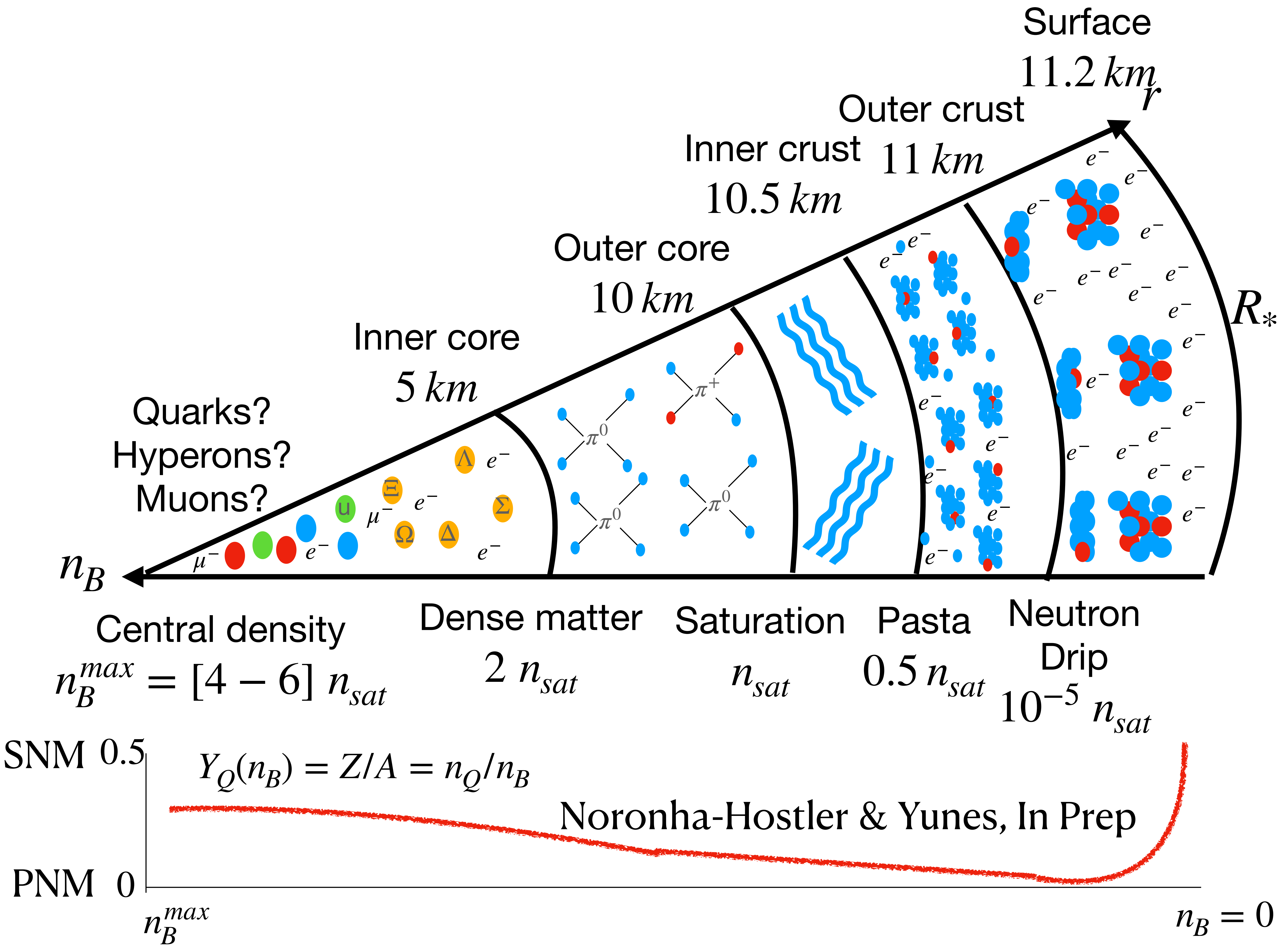
Hot (merger)

$T \sim 10^{12}\ K$

$T \sim 100\ MeV$

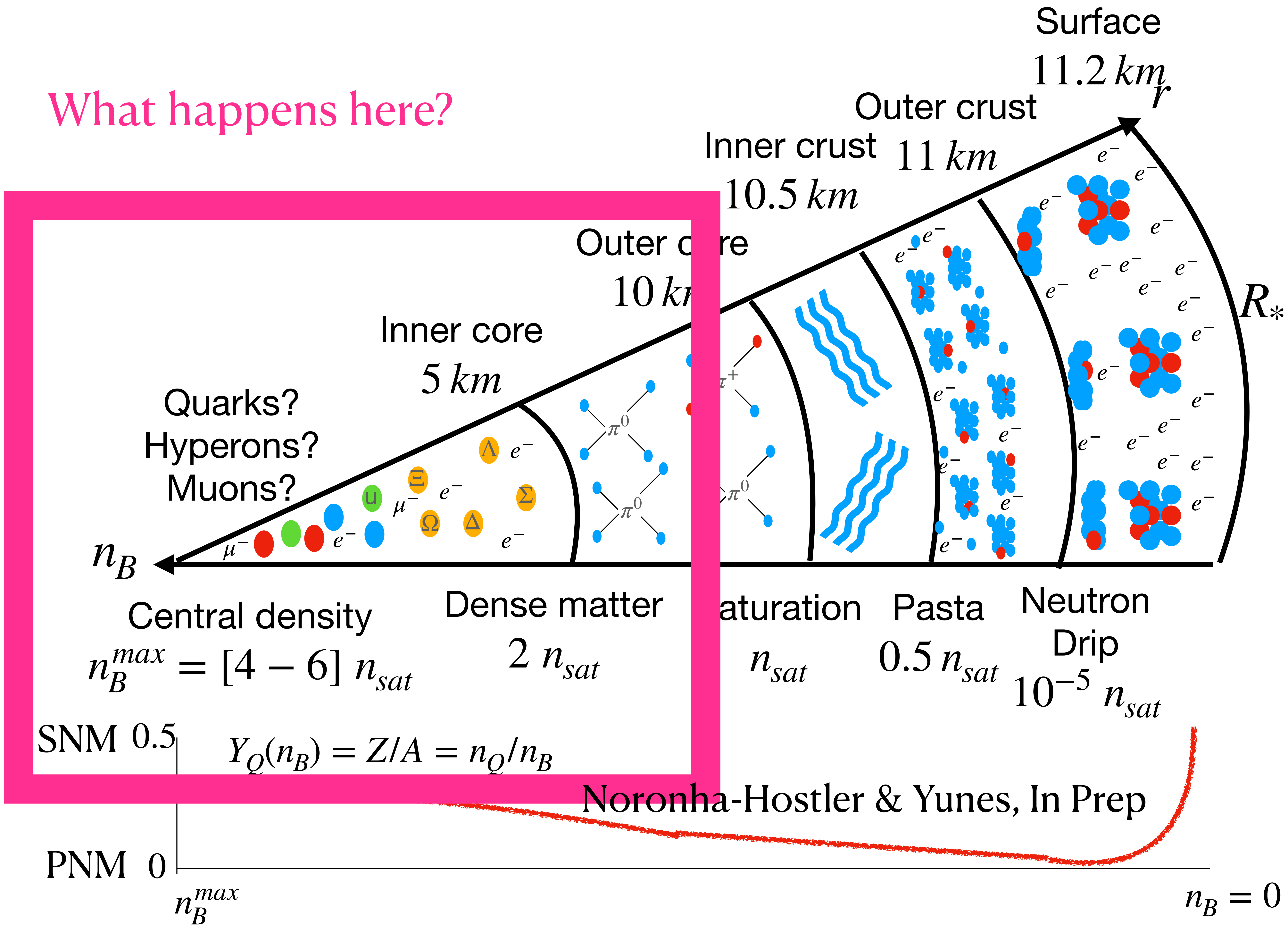
Currently have inspiral data, but hopefully future detectors will probe mergers

What is inside neutron stars?



Equation of State (EOS) encodes degrees of freedom, phases of matter, interactions into the pressure vs energy density relationship $p(\varepsilon)$

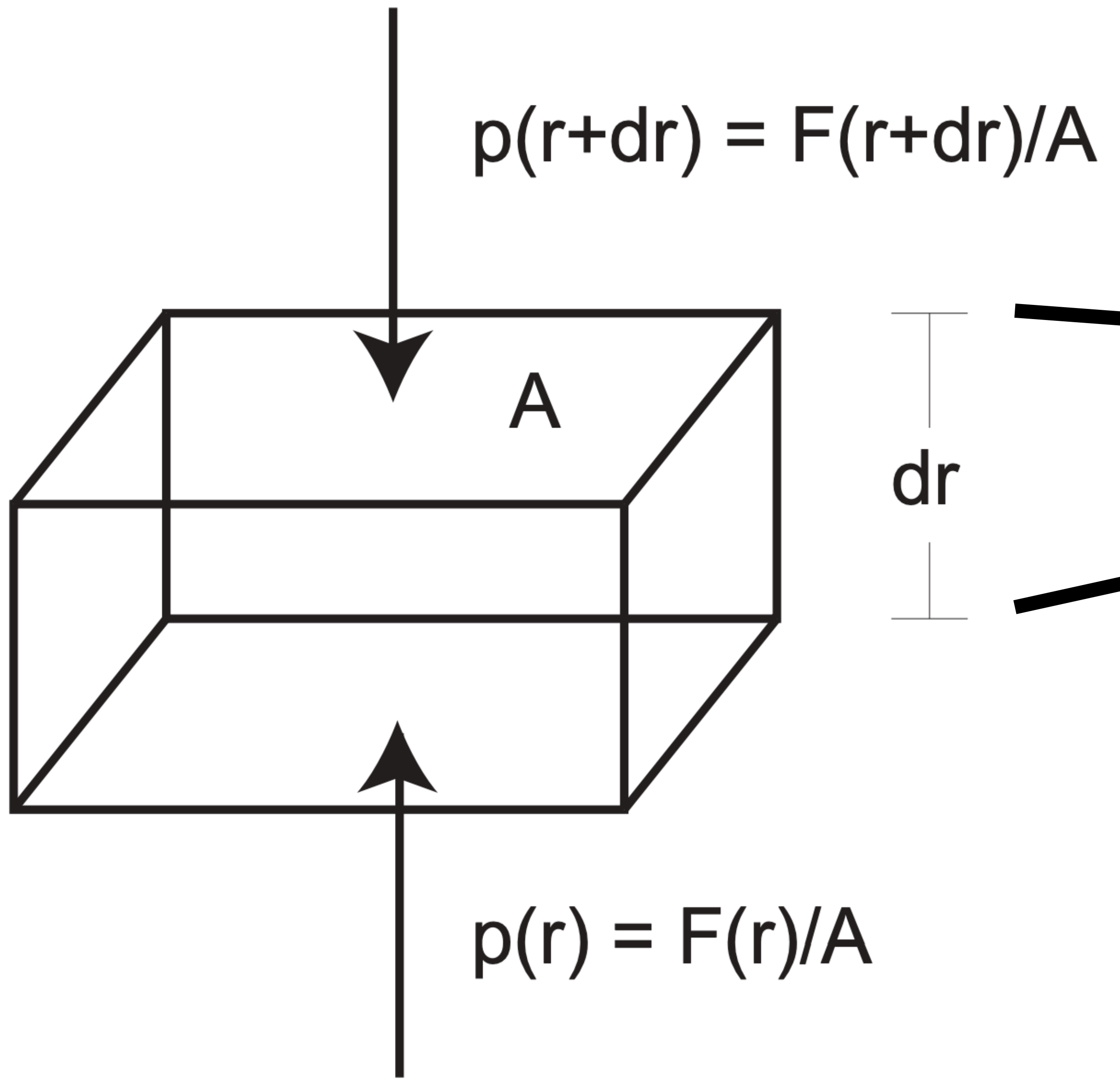
What is inside neutron stars?

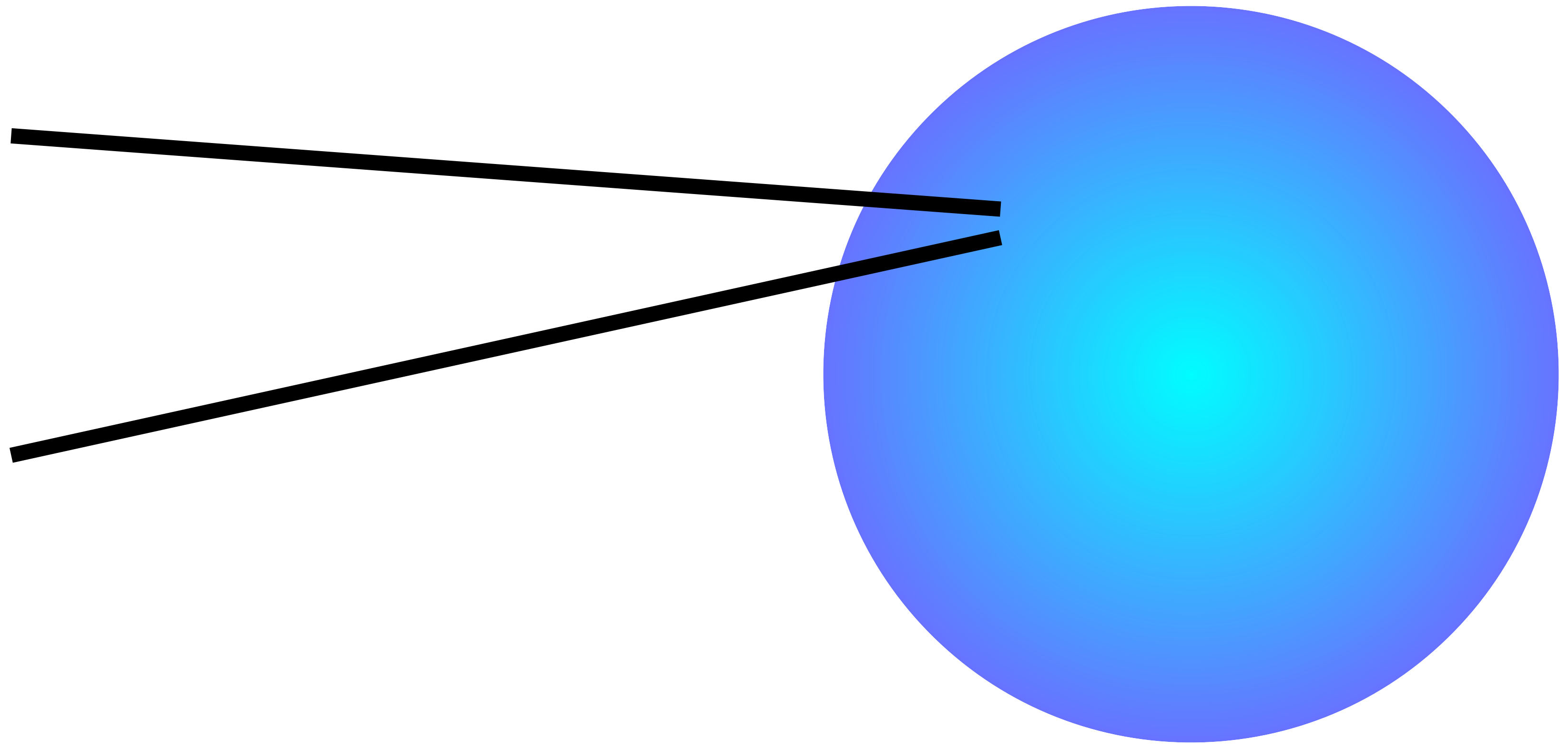


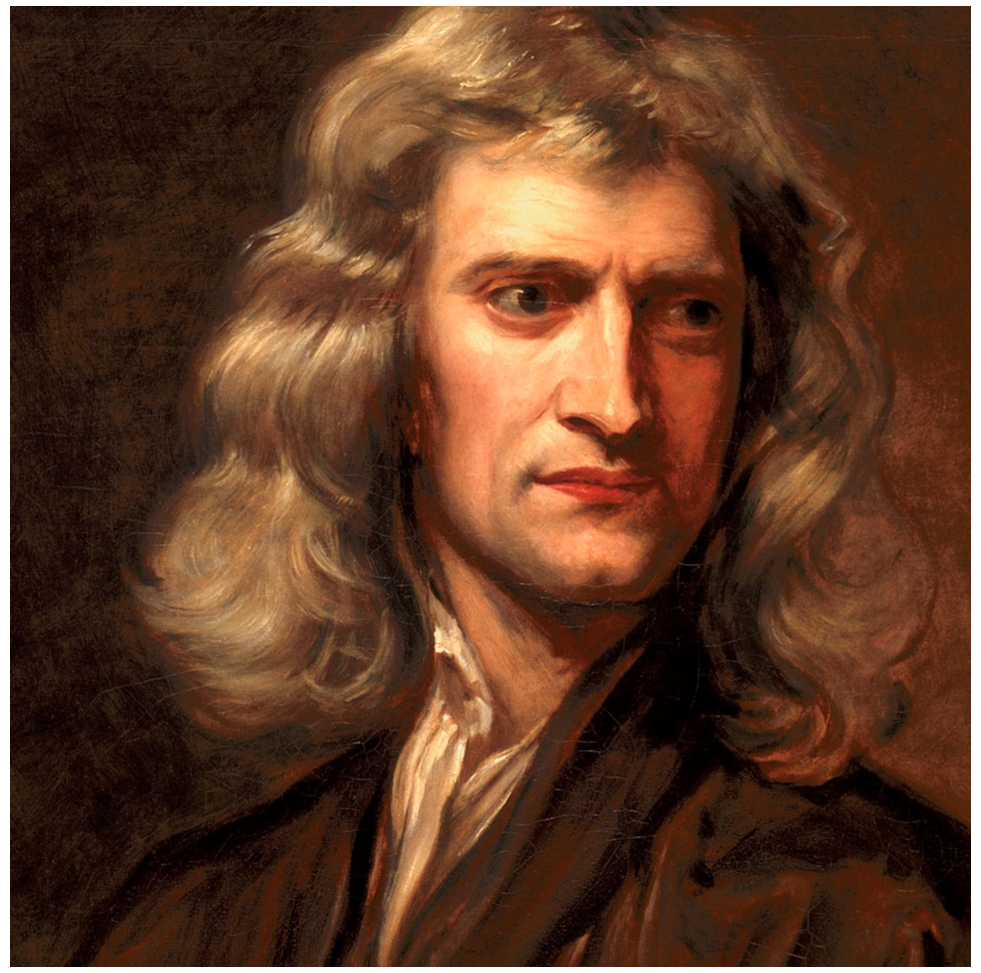
Equation of State (EOS) encodes degrees of freedom, phases of matter, interactions into the pressure vs energy density relationship $p(\varepsilon)$

Mass and Radius: ideal fluid, non-rotating

Newtonian Gravity







$$\frac{dp}{dr} = -\frac{G\rho(r)\mathcal{M}(r)}{r^2} = -\frac{G\epsilon(r)\mathcal{M}(r)}{c^2 r^2}$$

$$\frac{d\mathcal{M}}{dr} = 4\pi r^2 \rho(r) = \frac{4\pi r^2 \epsilon(r)}{c^2}$$

$$\mathcal{M}(r) = 4\pi \int_0^r r'^2 dr' \rho(r') = 4\pi \int_0^r r'^2 dr' \epsilon(r')/c^2$$

Total mass inside the sphere of radius r

Mass and Radius: ideal fluid, non-rotating

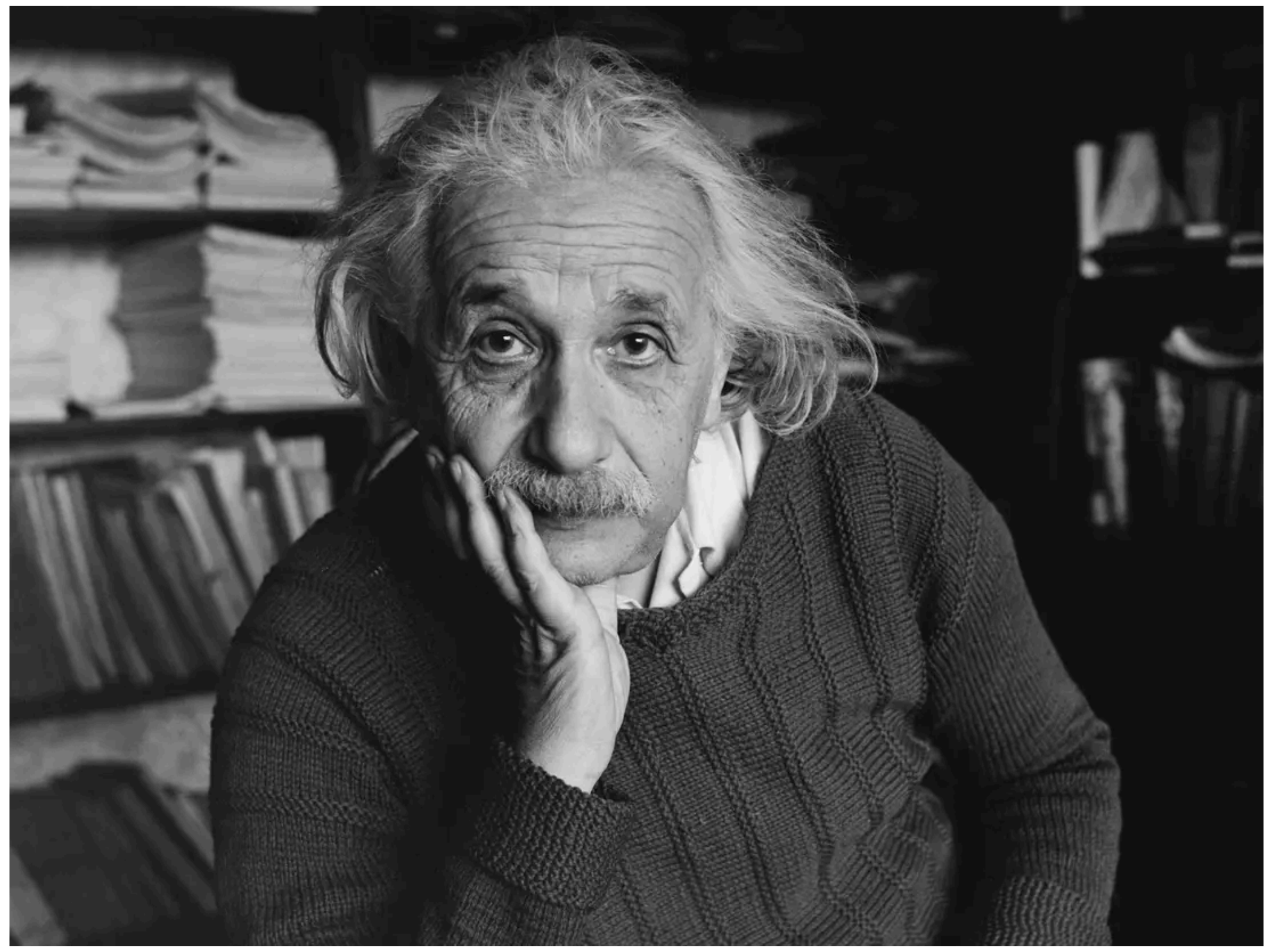
General Relativity: Tolman–Oppenheimer–Volkoff (TOV) equation

Input:
Equation of State $p(\varepsilon)$

Output:
$M(R)$ when P=0

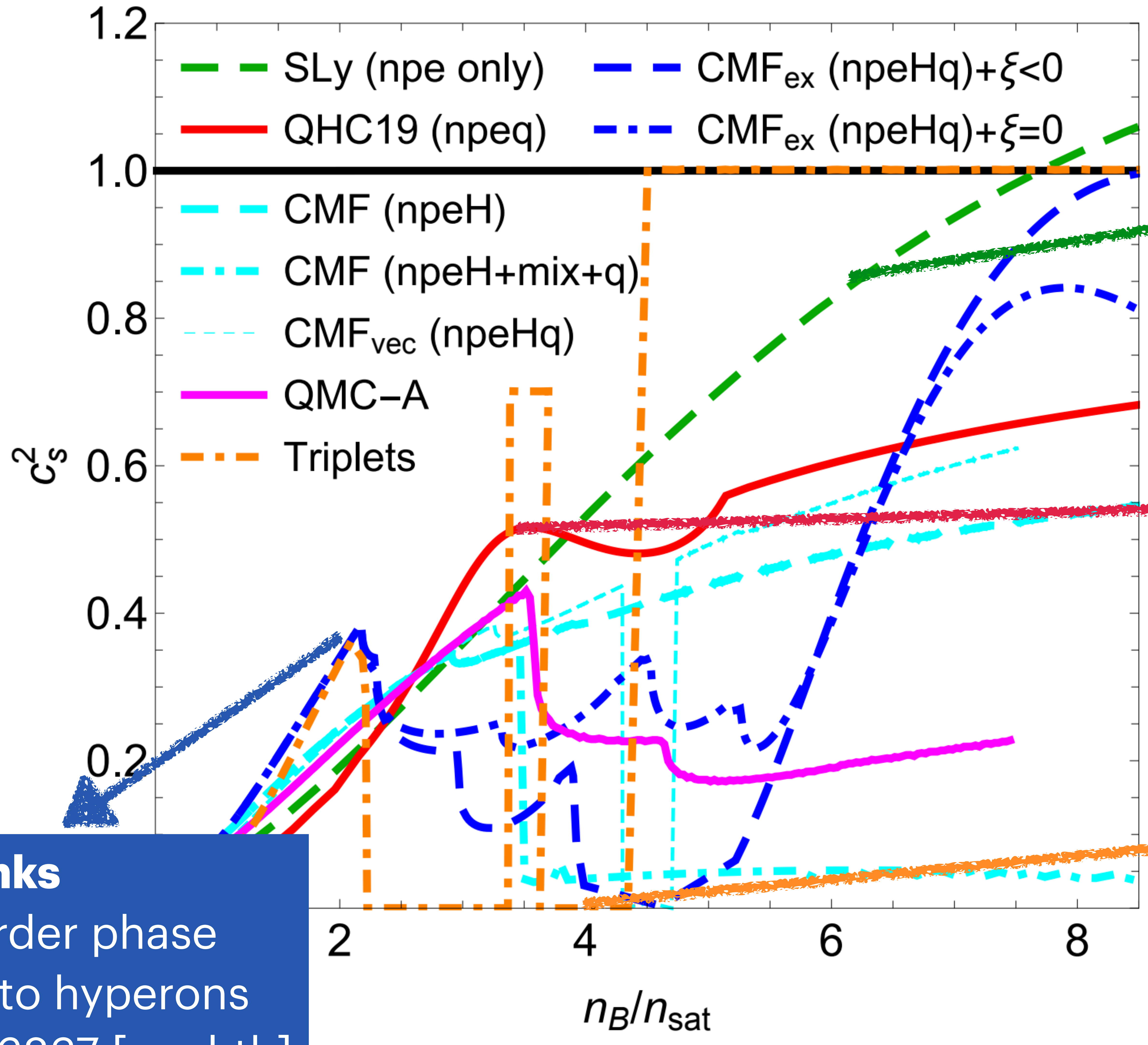
$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi r^3 P}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1}$$

$$M = m(R) = \int_0^R 4\pi r^2 \rho \, dr$$



Possible EOS: Insights from effective models

Looking for "bumps" in the night



Phys.Rev.D 105 (2022) 2, 023018+references within

$$c_s^2 = \frac{dp}{d\varepsilon}$$

Monotonic

Neutrons, protons, e^-

Astron.Astrophys. 380 (2001) 151

Bump

cross-over phase transition into quarks

Phys.Rev.Lett. 122 (2019) 12, 122701;

Astrophys.J. 885 (2019) 42

$c_s^2 \to 0$

1st-order phase transition (quarks or strange dominated)

Phys.Rev.D 88 (2013) 8, 083013

Kinks

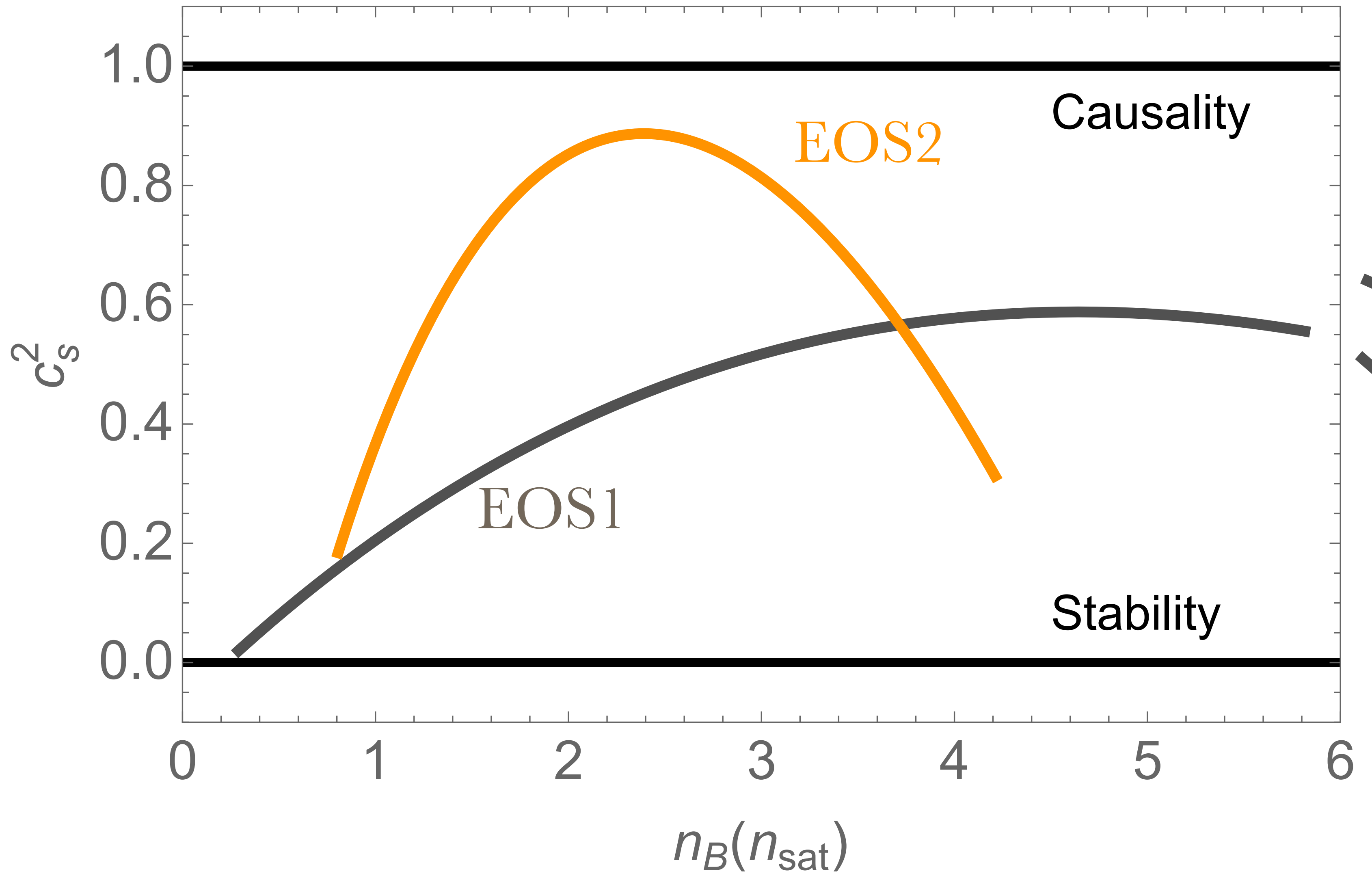
2nd/3rd-order phase transition into hyperons

[CMF] 2409.06837 [nucl-th]

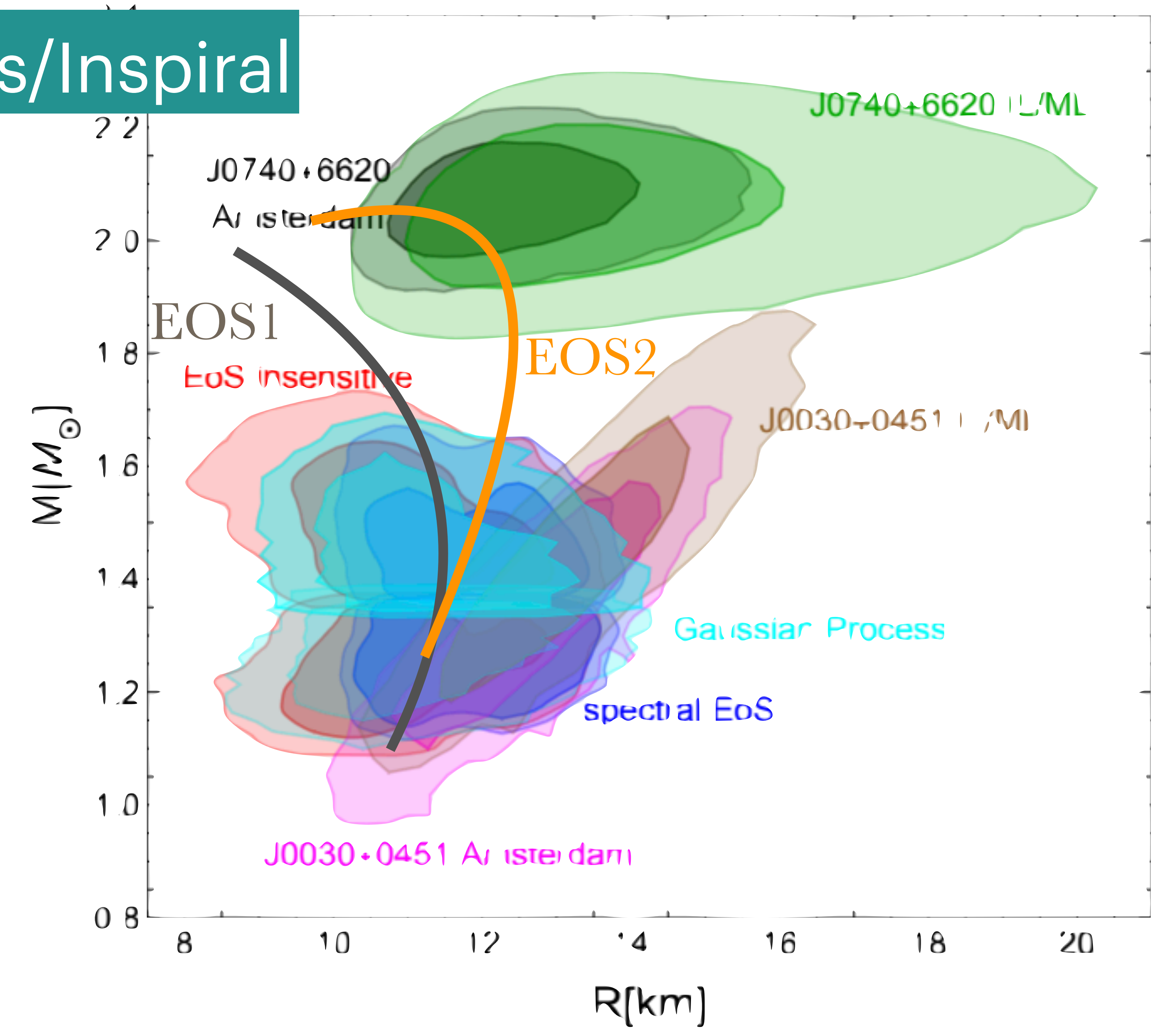
Equation of State from astrophysics observation?

Isolated, cold neutrons stars/Inspiral

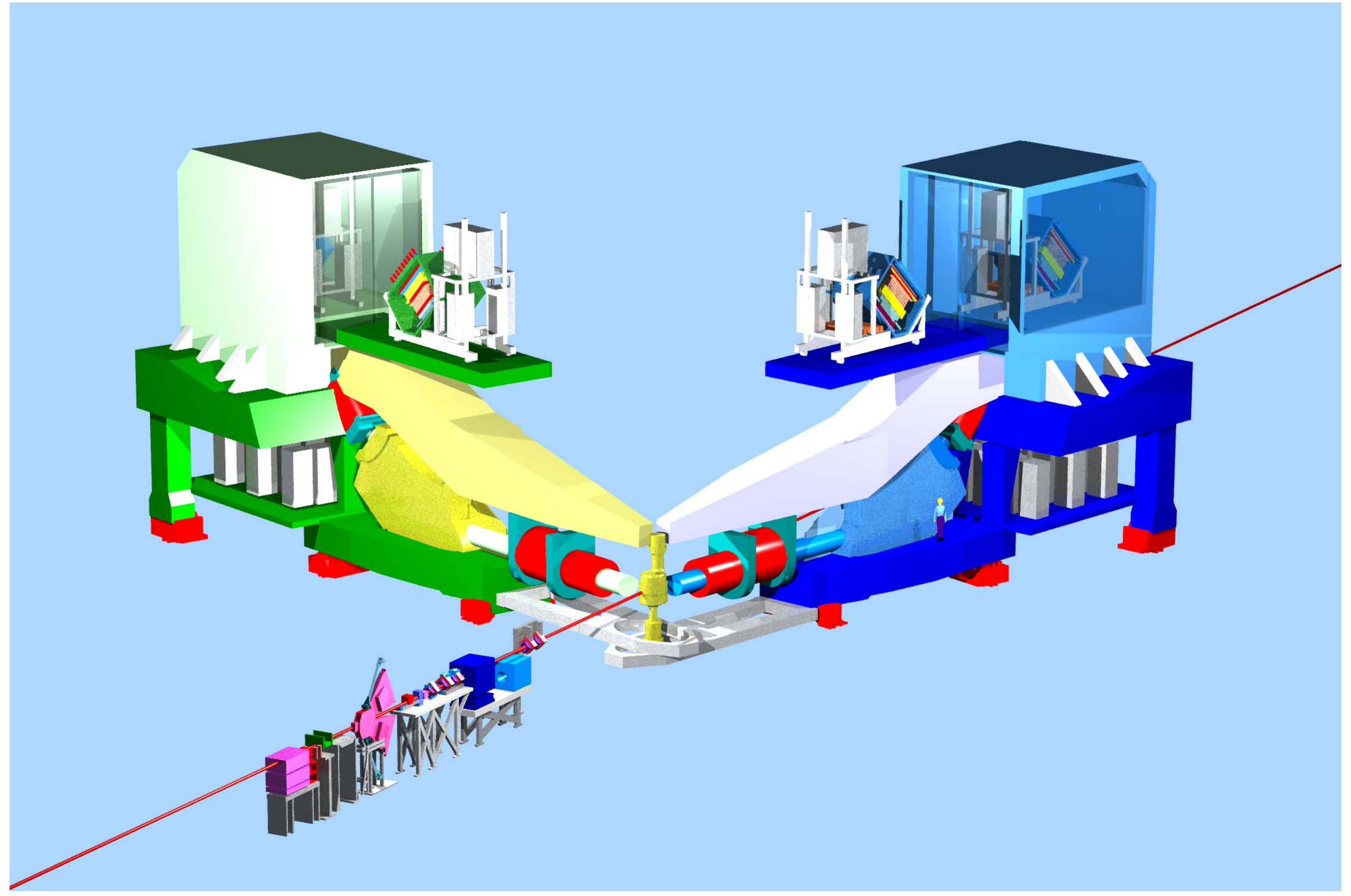
Build in desired features: particles, phase transitions, interactions etc



Astrophysical constraints



Nuclear experiments/saturation properties



Theory constraints

Assign a likelihood to each EOS

$$Posterior \propto Likelihood \times Prior$$

Independent measurements:

$$\mathscr{L} = \prod_{i=M,R,\ldots} \left[\prod_{j=1}^{j(i)} \mathscr{L}(i,j) \right]$$

Modified Gaussian Processes

Building in structure in c_s^2

Original Gaussian Process approach
R. Essick *Phys.Rev.D* 101 (2020) 6, 063007

- Model-agnostic approaches are common

→ Gaussian processes (GPs):

EoS modeled via: $\phi(x) = \log(1/c_s^2 - 1)$, **stable and causal**

$$\phi \sim \mathcal{N}(\mu_i, \Sigma_{ij})$$

Collection of functions, behavior specified by a mean and covariance kernel

Squared-exponential is a common choice:

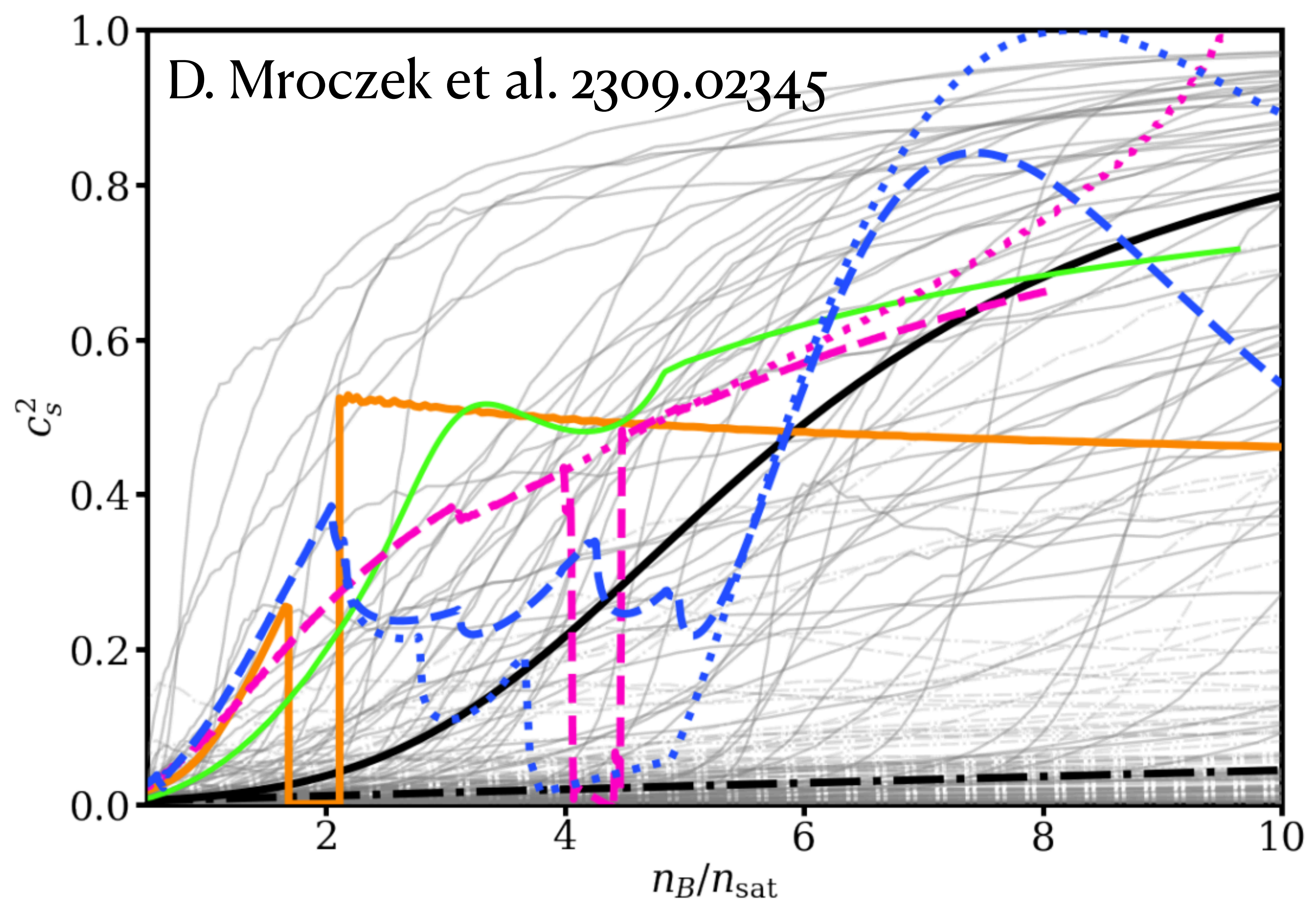
$$K_{se}\left(x_i, x_j\right) = \sigma^2 \exp\left[-\left(x_i - x_j\right)^2 / 2\ell^2\right]$$

ℓ: correlation length

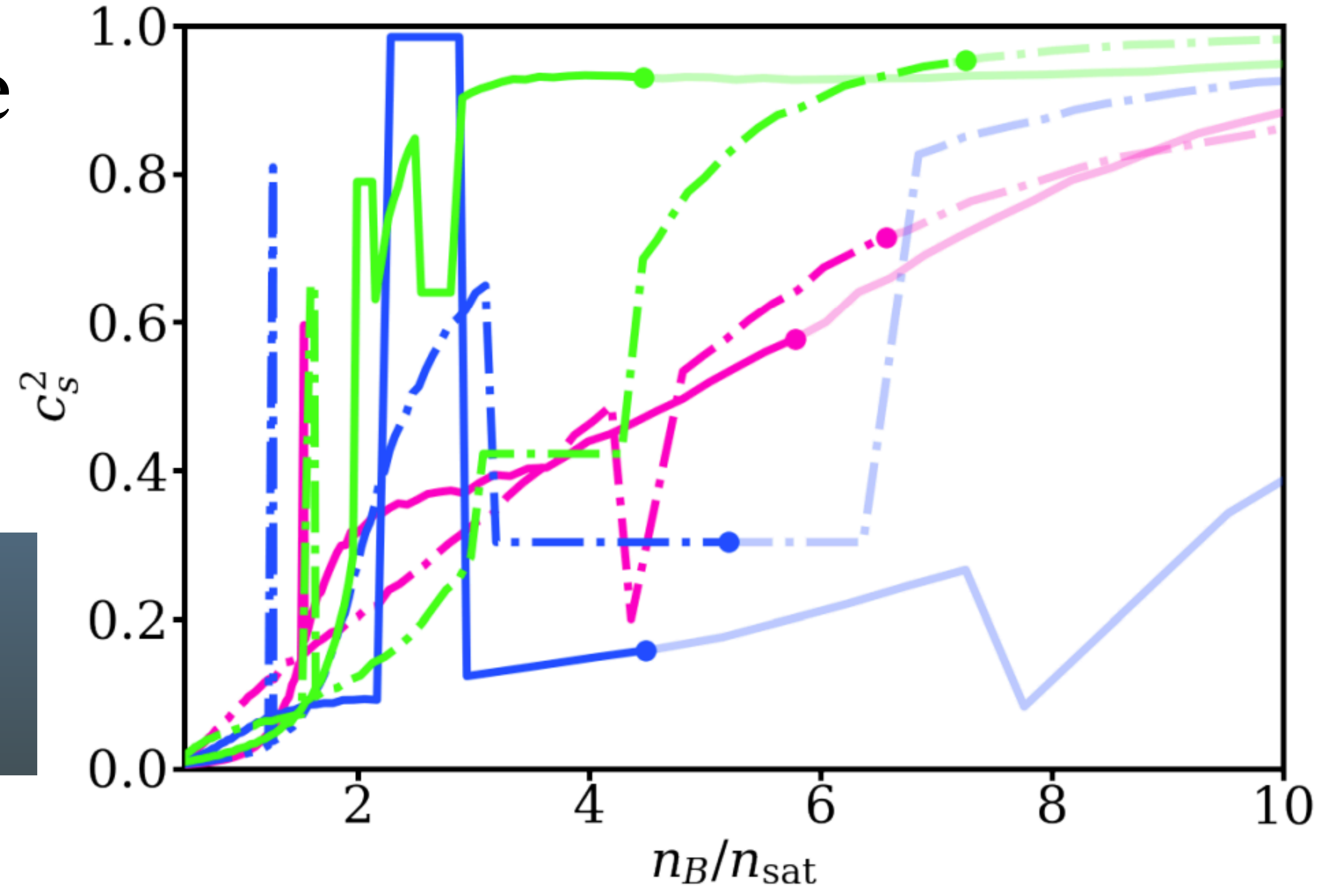
σ: correlation strength

Goal: Compare long range correlation (benchmark) versus multi-scale features

Gaussian Process (benchmark)

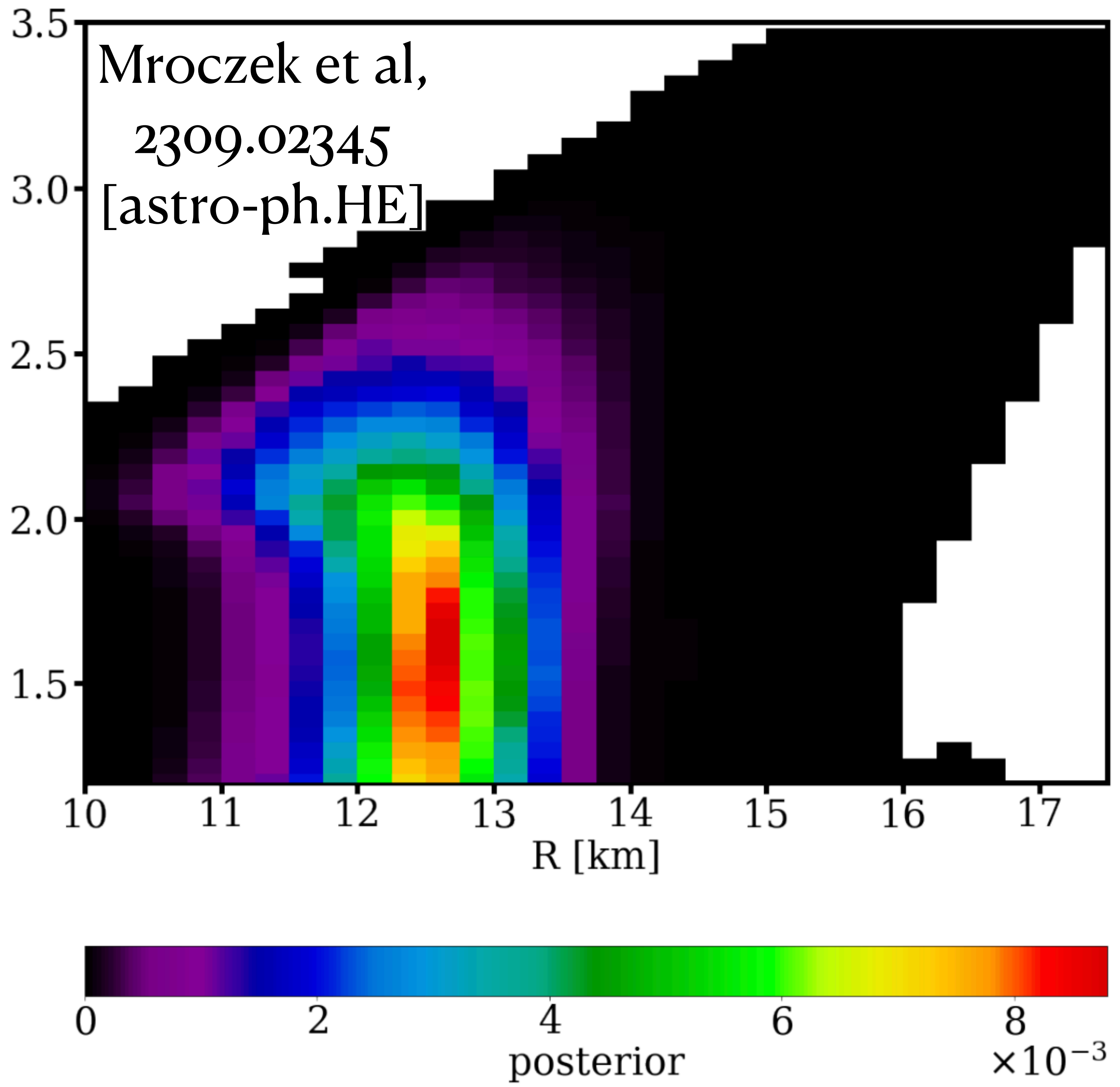


+ Structure

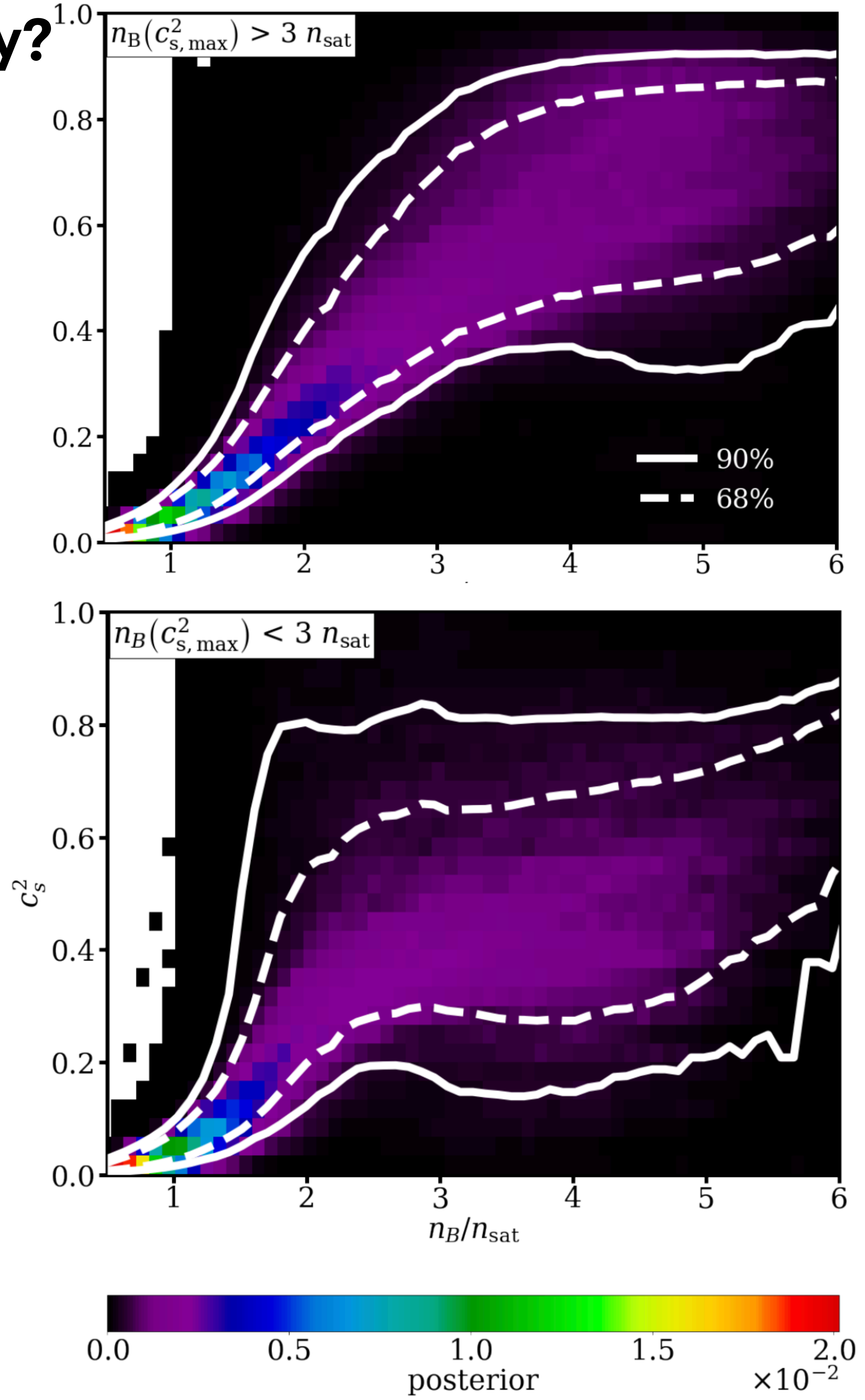


Posteriors of Mass, Radius, $c_s^2(n_B)$

What does current data tell us today?



Both a <u>monotonic</u> c_s^2 and one with a <u>bump</u> at $n_B = [2,3]\, n_{sat}$



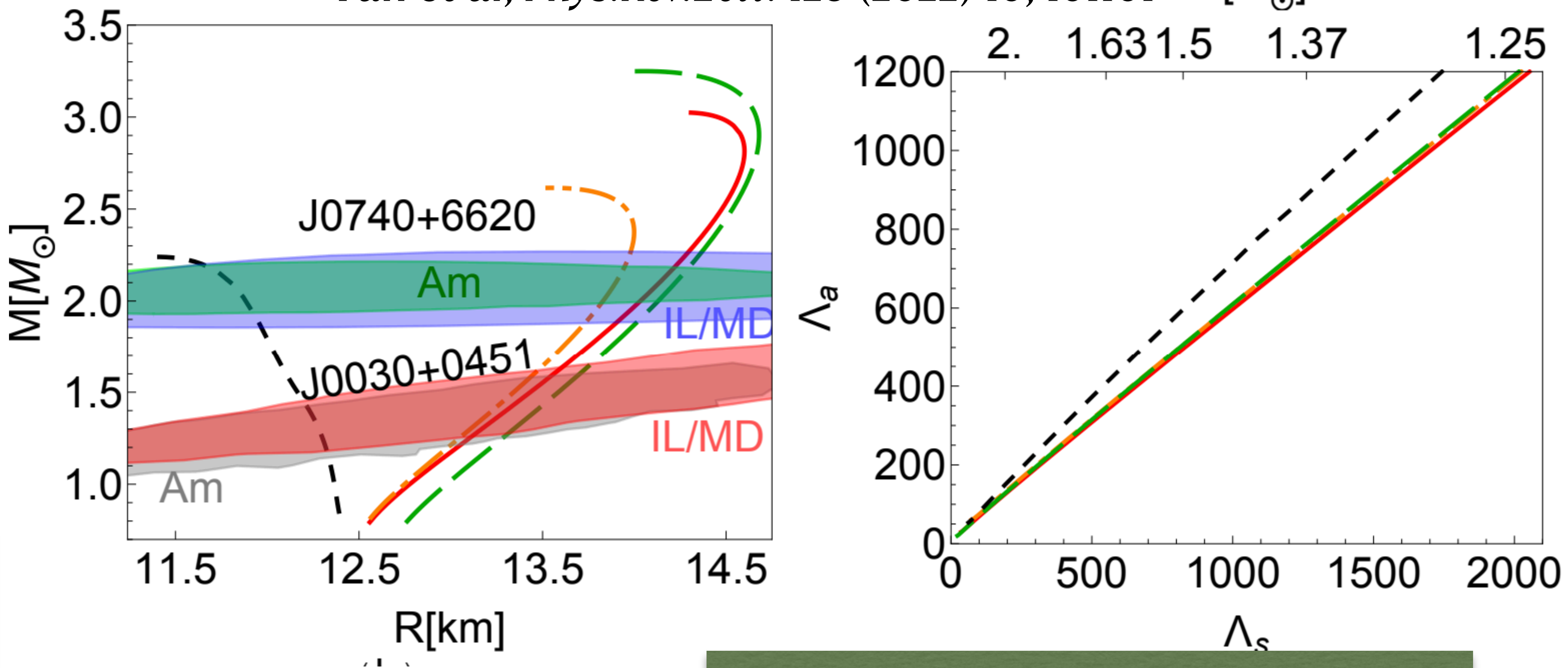
Current data is inconclusive, need more observations! Or new constraints!

More references on bump in c_s^2

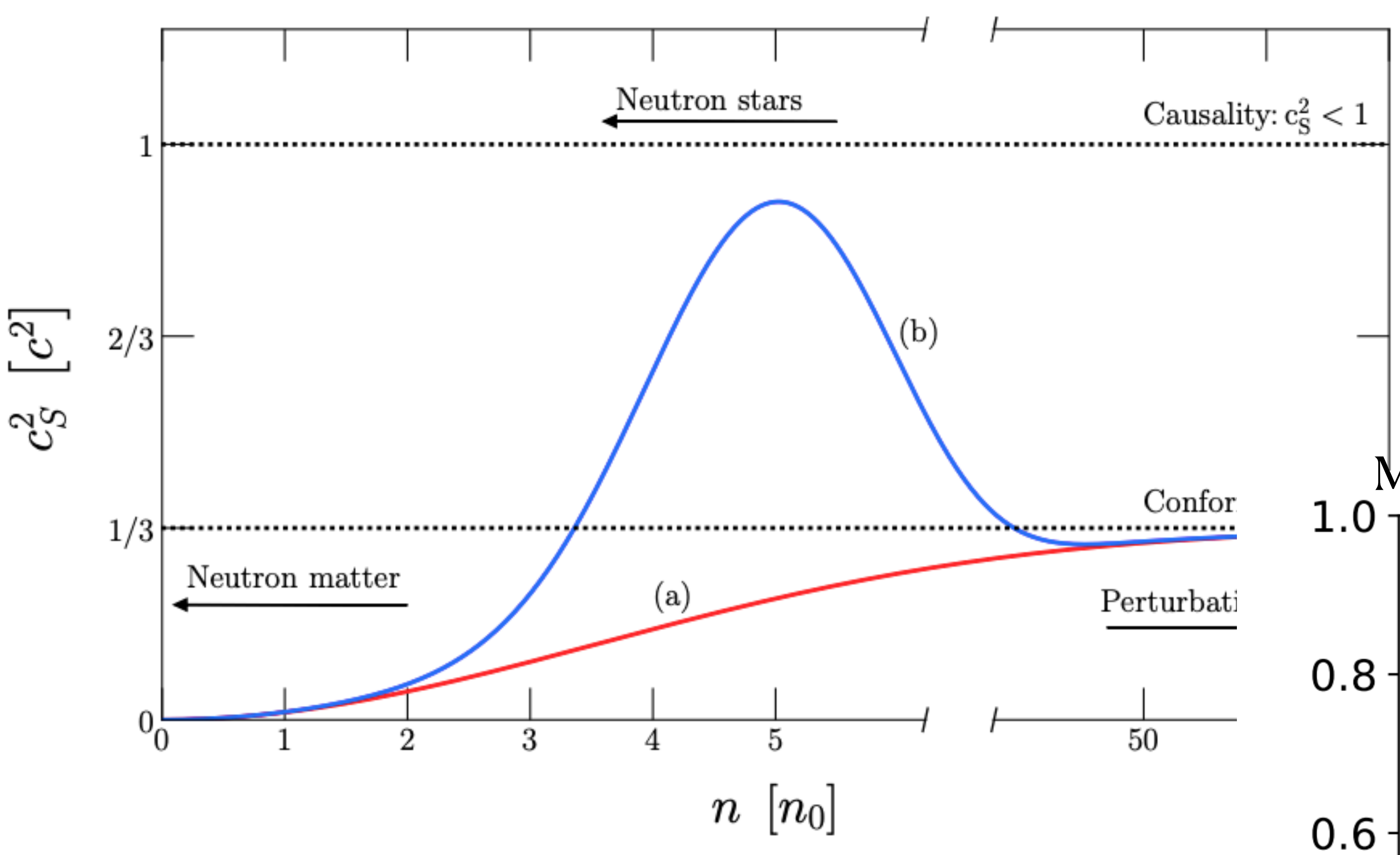
From various microscopic theories and Bayesian analyses

Measurements: breaking binary love relation

Tan et al, *Phys.Rev.Lett.* 128 (2022) 16, 161101



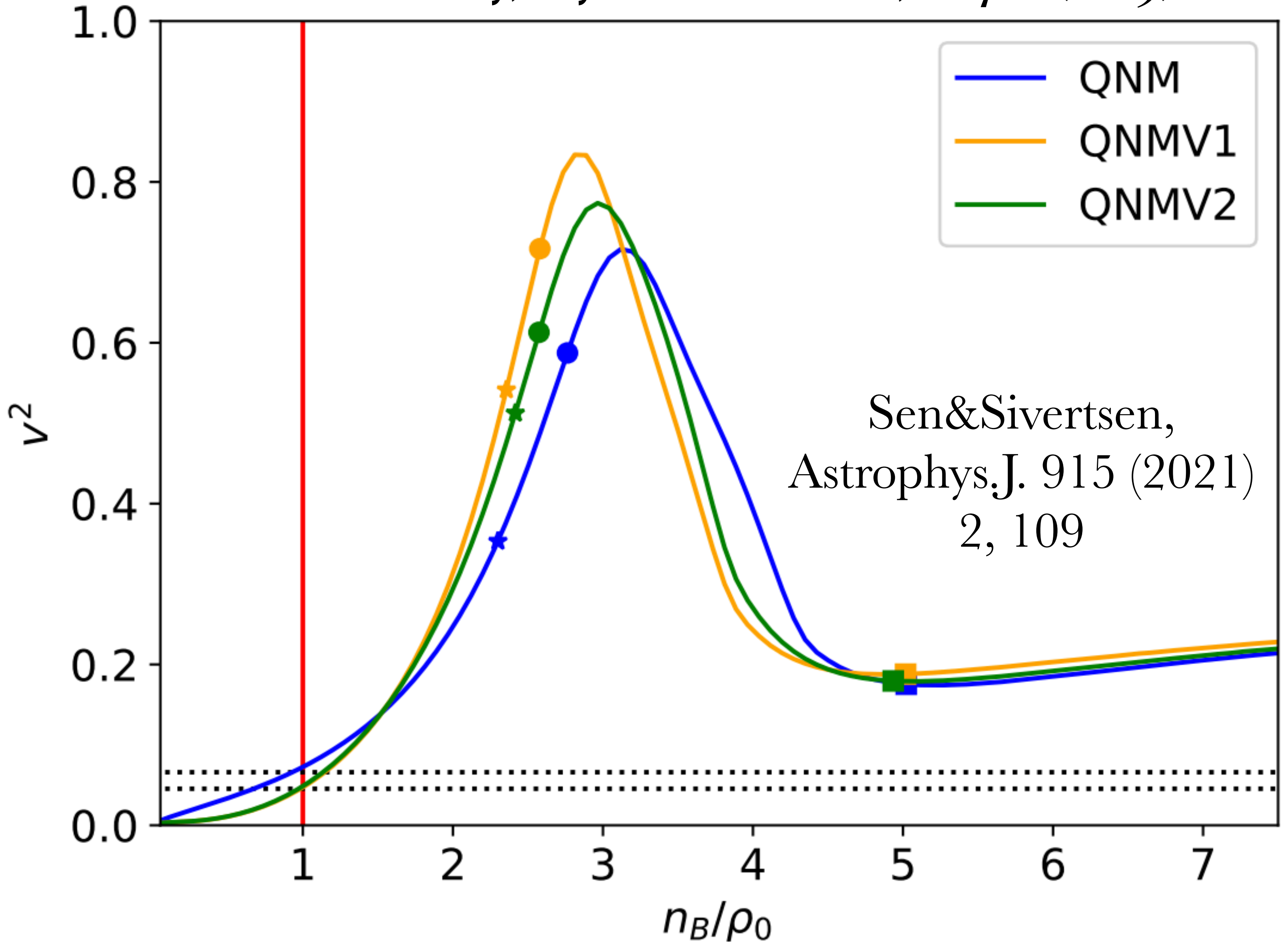
Steep rise in c_s^2 to reach $2M_\odot$



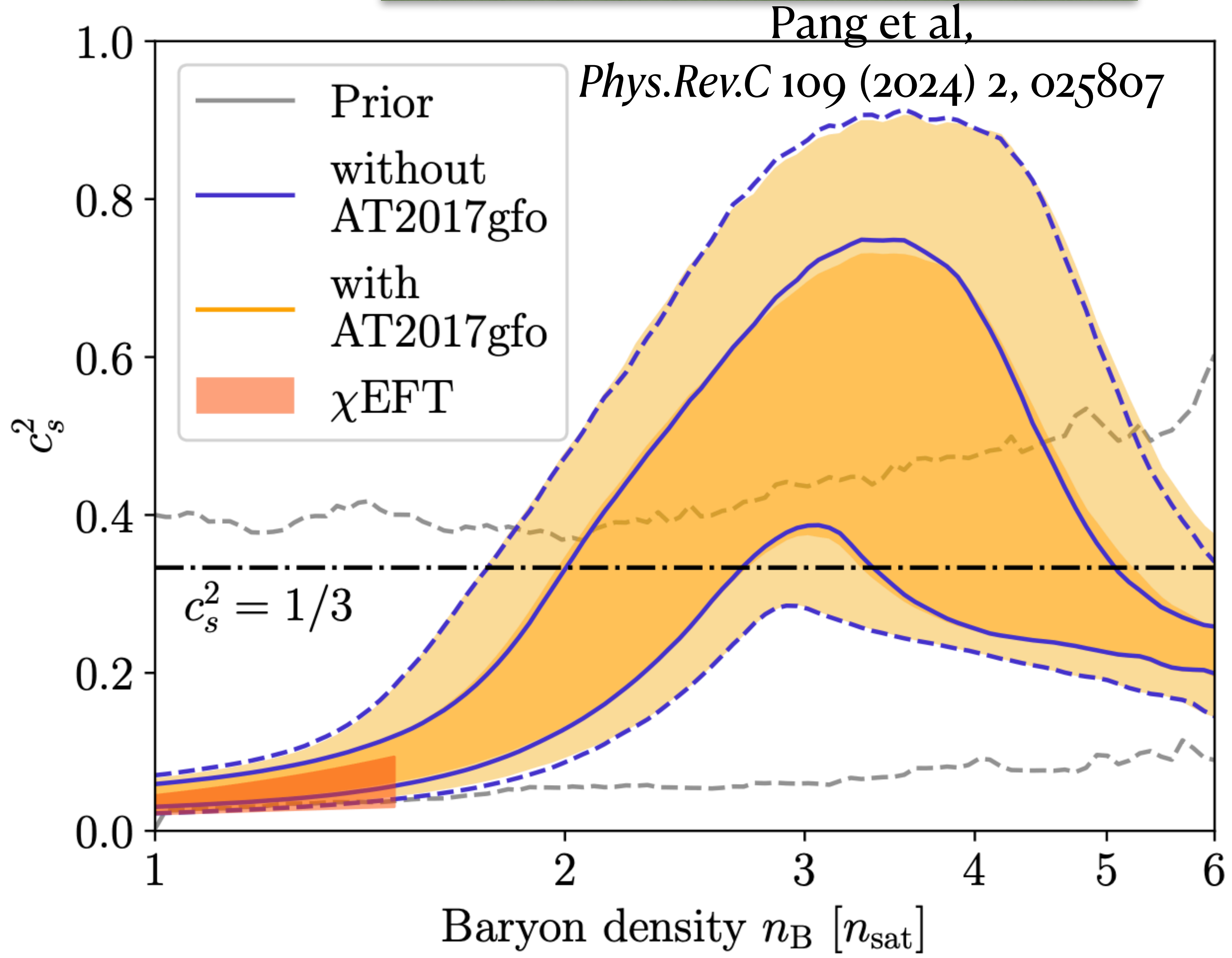
Bedaque & Steiner, Phys.Rev.Lett. 114 (2015) 3, 031103; Alford et al, Phys. Rev. D92, 083002 (2015), Ranea-Sandoval, et al, Phys. Rev. C93, 045812 I. Tews, et al, Phys. Rev. C98, 045804 (2018)

One physical mechanism: Quarkyonic Matter

McLerran&Reddy,Phys. Rev. Lett.122, 122701 (2019)

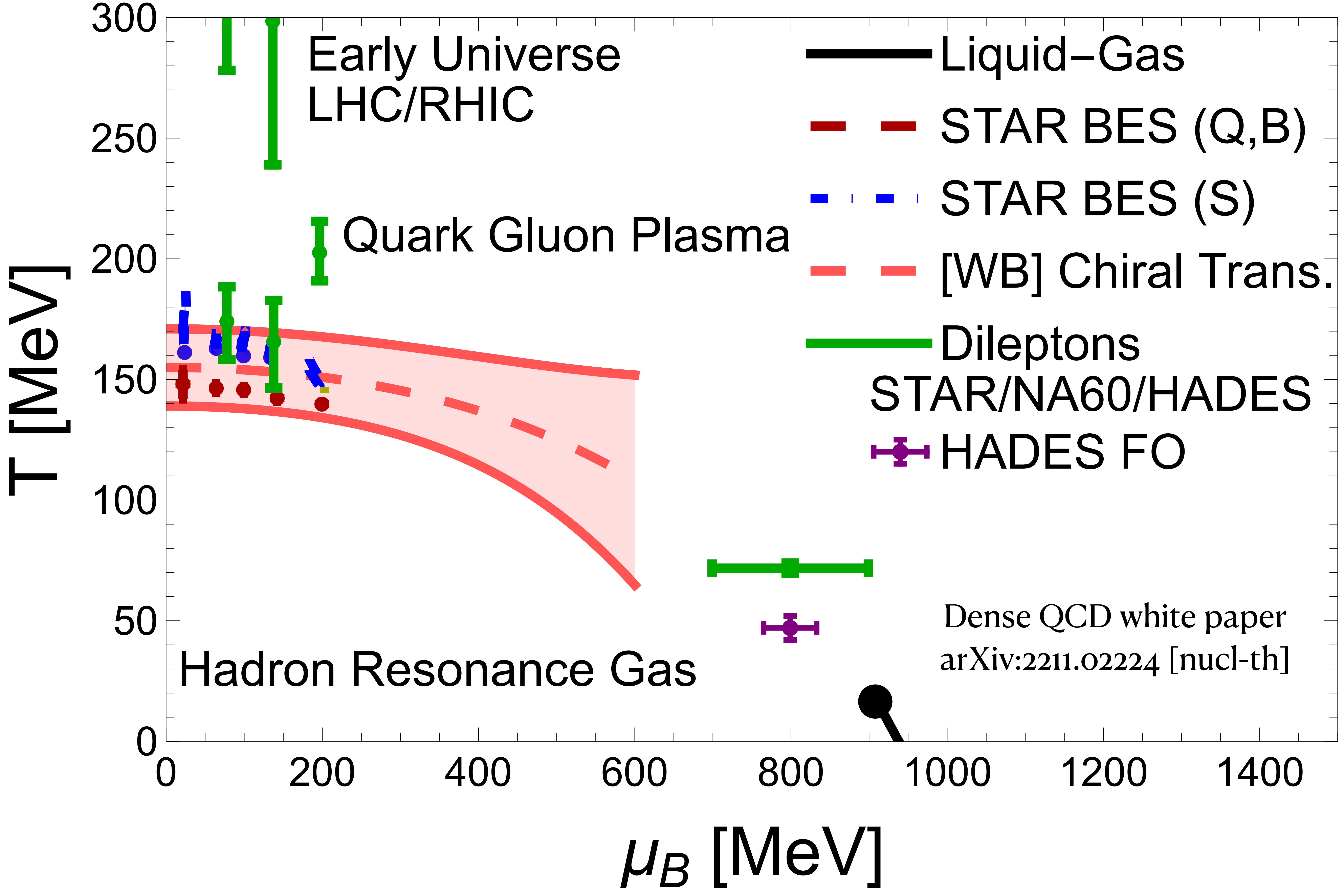


Bayesian analysis



Connecting heavy-ion collisions and neutron stars

QCD phase diagram



Hydro simulations from $\sqrt{s} = [3,7.7,27]\ GeV$
Shen&Schenke, Phys. Rev. C 105, 064905 (2022)

(T, μ_B) extracted from STAR net-(p,π,K), net-p, net-K fluctuations
Alba, et al, Phys. Rev. C 101, 054905 (2020)

Chiral transition from lattice QCD
[WB] Phys. Rev. Lett. 125, 052001 (2020)

Dilepton measurements from
[STAR] 2402.01998 [nucl-ex]
[HADES] Nature Phys. 15, 1040 (2019)
[NA60] Eur.Phys.J.C59:607-623,2009

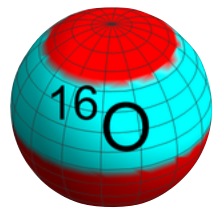
Statistical Hadronization Model
[HADES] Phys. Rev. C 102, 054903 (2020)

Liquid-gas phase transition location
Elliott, et al, Phys. Rev. C 87, 054622 (2013)
μ_B estimate Vovchenko, et al, Phys. Rev. Lett. 118, 182301 (2017)

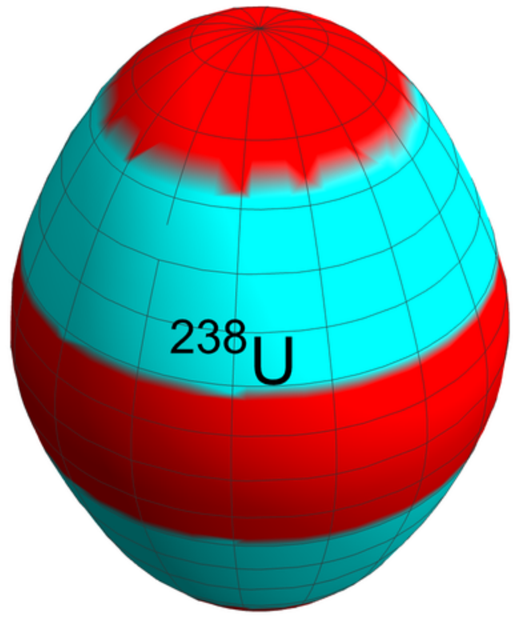
Charge fraction of ions

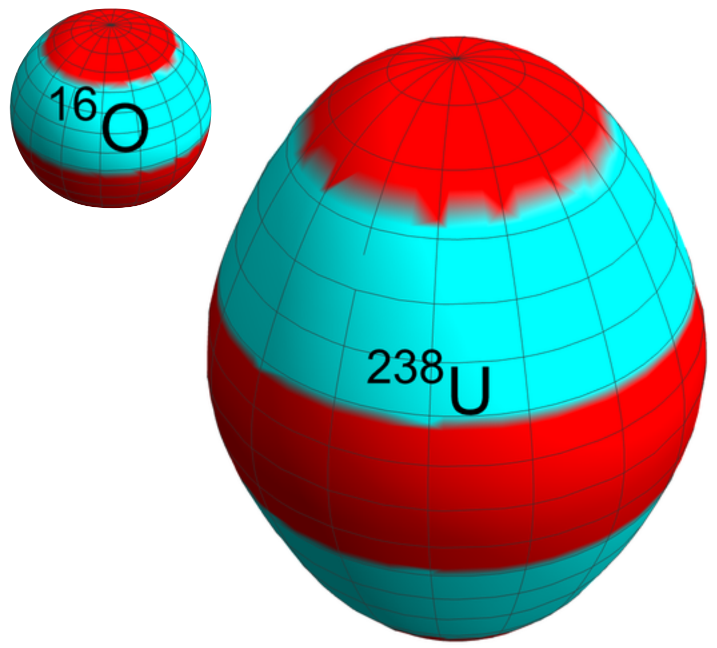
Isospin asymmetry

$$Y_Q = \frac{Z}{A} = \frac{n_Q}{n_B}$$



System	Z	A	Y_Q	Data?
O+O	8	16	0.5	some
Ne+Ne	10	20	0.5	no
Mg+Mg	12	24	0.5	no
Ca+Ca	20	40	0.5	no
Cu+Cu	29	63	0.46	yes
Ru+Ru	44	96	0.458	some
Ar+Ar	18	40	0.45	no
Xe+Xe	54	128	0.419	yes
Zr+Zr	40	96	0.417	some
Au+Au	79	198	0.399	yes
U+U	92	238	0.387	yes





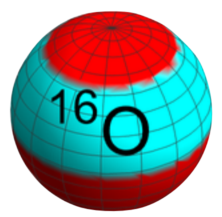
$Y_Q \lesssim 0.2$

Heavy-Ions and Neutron Stars are all on the same phase diagram, but very different Y_Q

Charge fraction of ions

Isospin asymmetry

$$Y_Q = \frac{Z}{A} = \frac{n_Q}{n_B}$$



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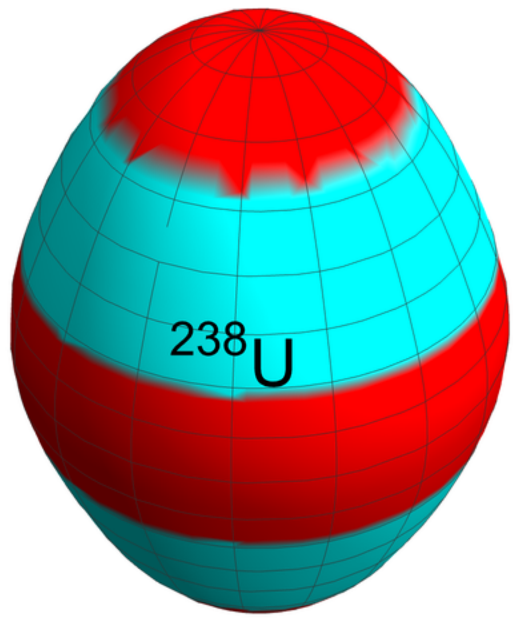
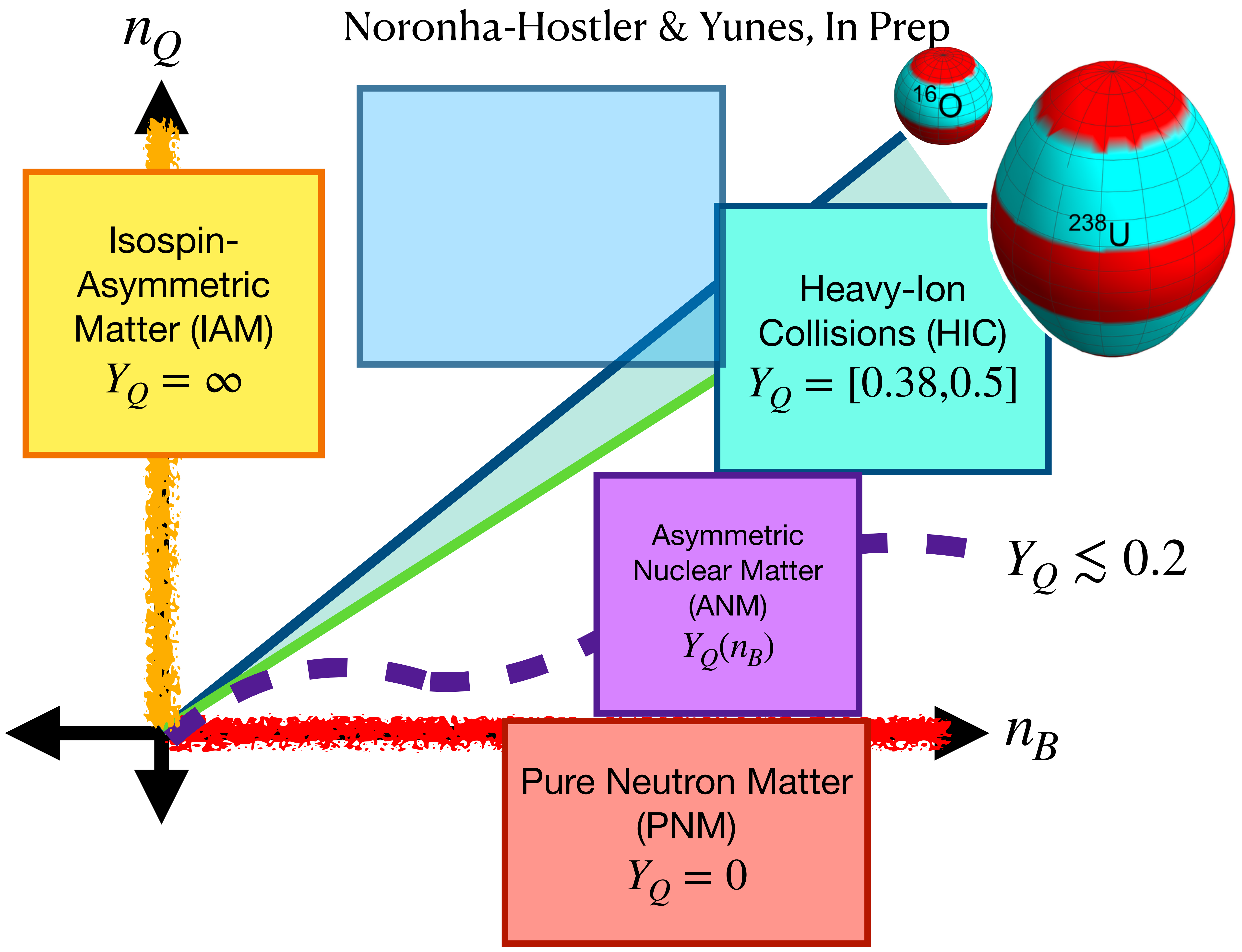
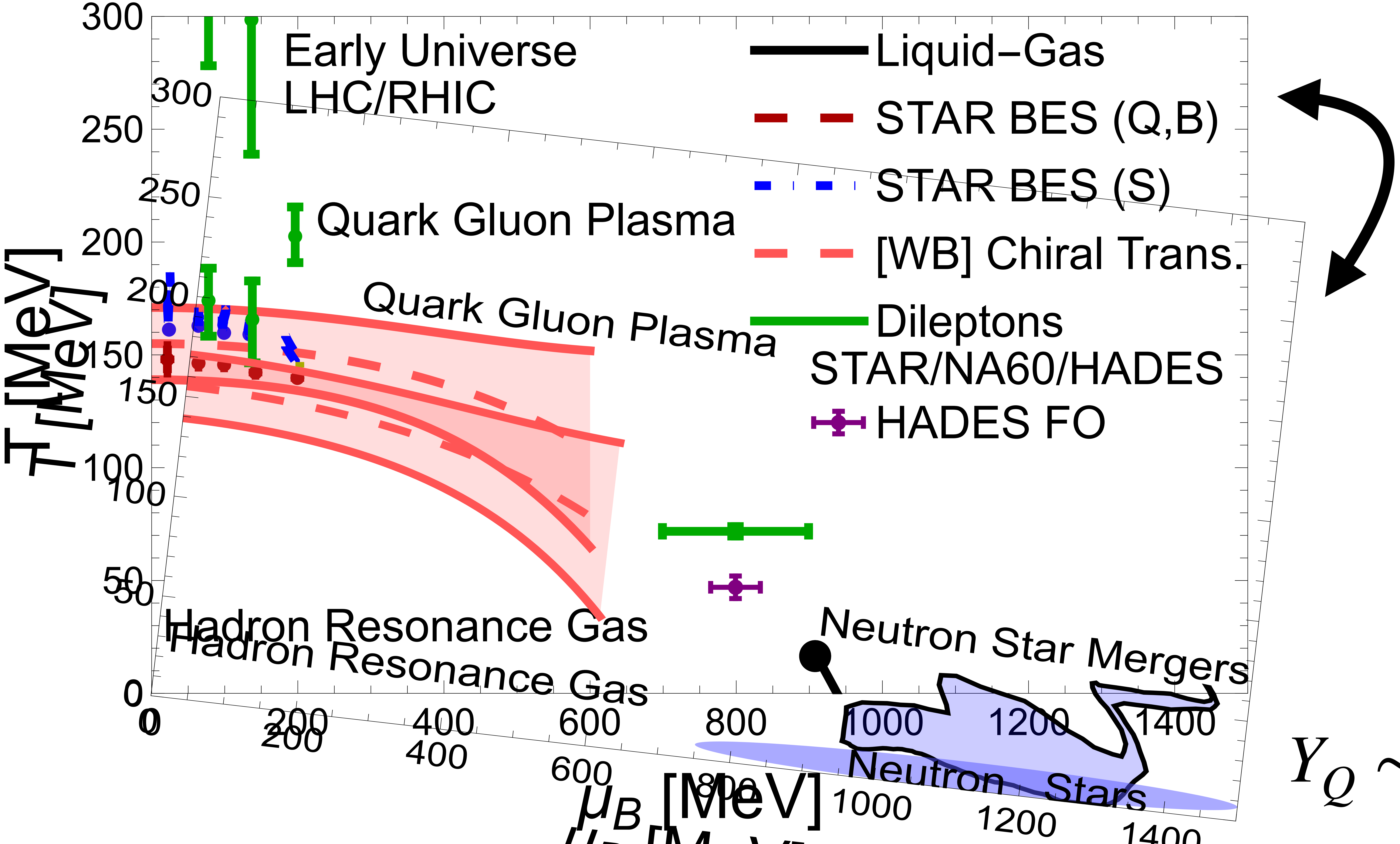




Heavy-Ions and Neutron Stars are all on the same phase diagram, but very different Y_Q

Connecting heavy-ion collisions and neutron stars

QCD phase diagram



How do we connect these regimes of the QCD phase diagram?

$Y_Q \sim [0.01, 0.2]$

First principle QCD constraints

Equation of State (EOS)

Summary of theory and experimental constraints [MUSES] Living Rev.Rel. 27 (2024) 1, 3

Resumed lattice QCD Lattice *Phys.Rev.Lett.* 126 (2021) 23, 232001; *Phys.Rev.D* 105 (2022) 11, 114504
Open-source code *Phys.Rev.D* 109 (2024) 9, 094046

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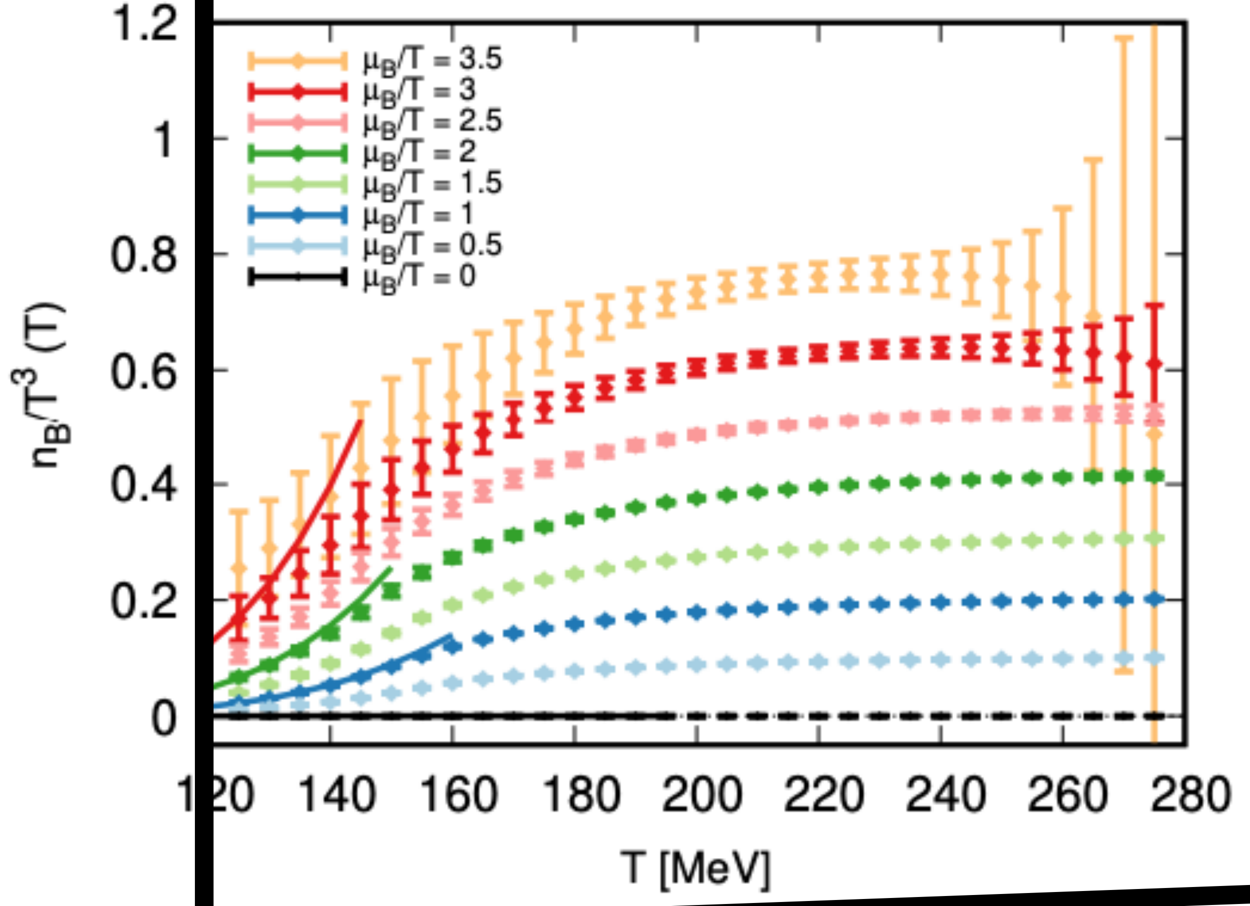
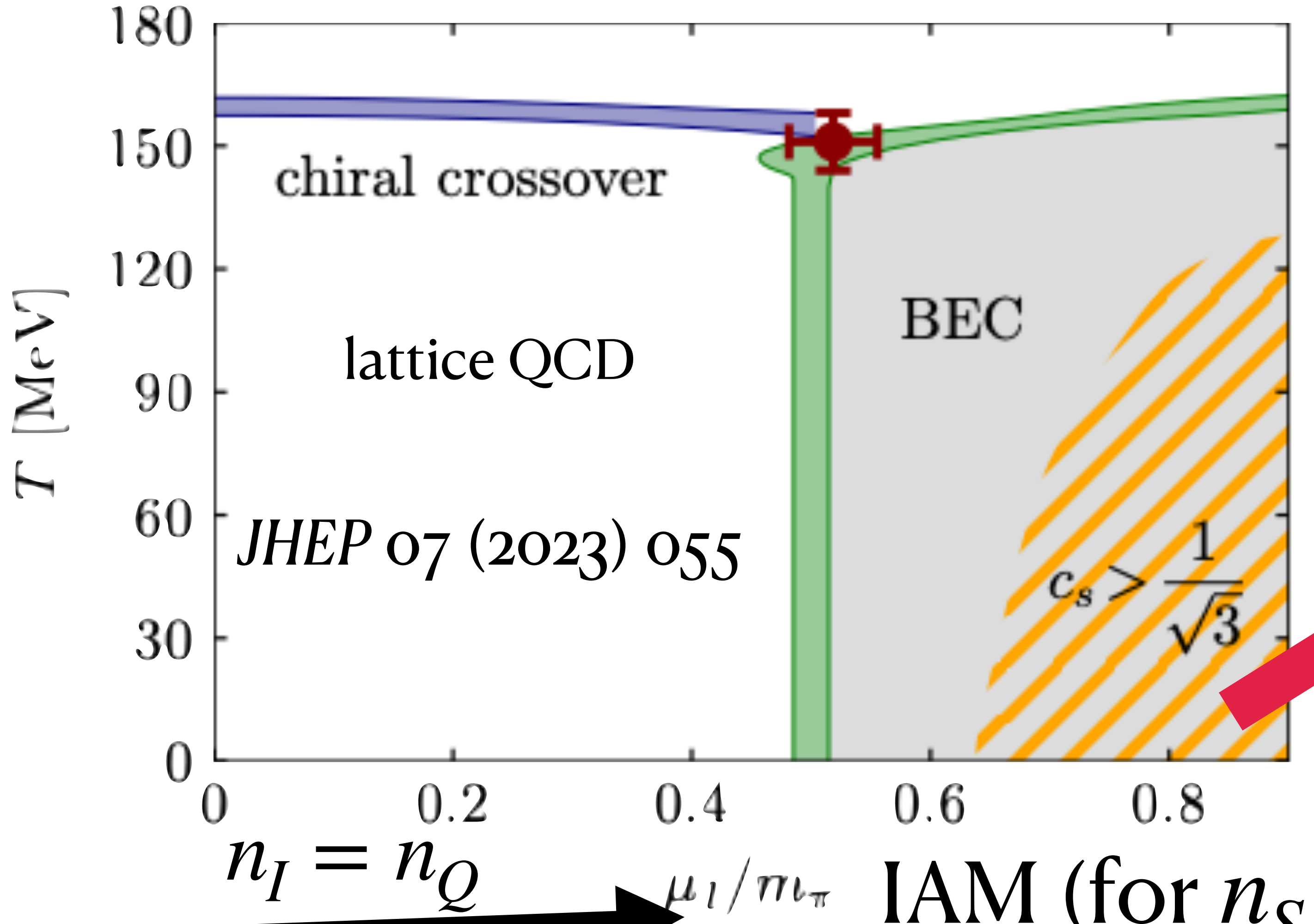
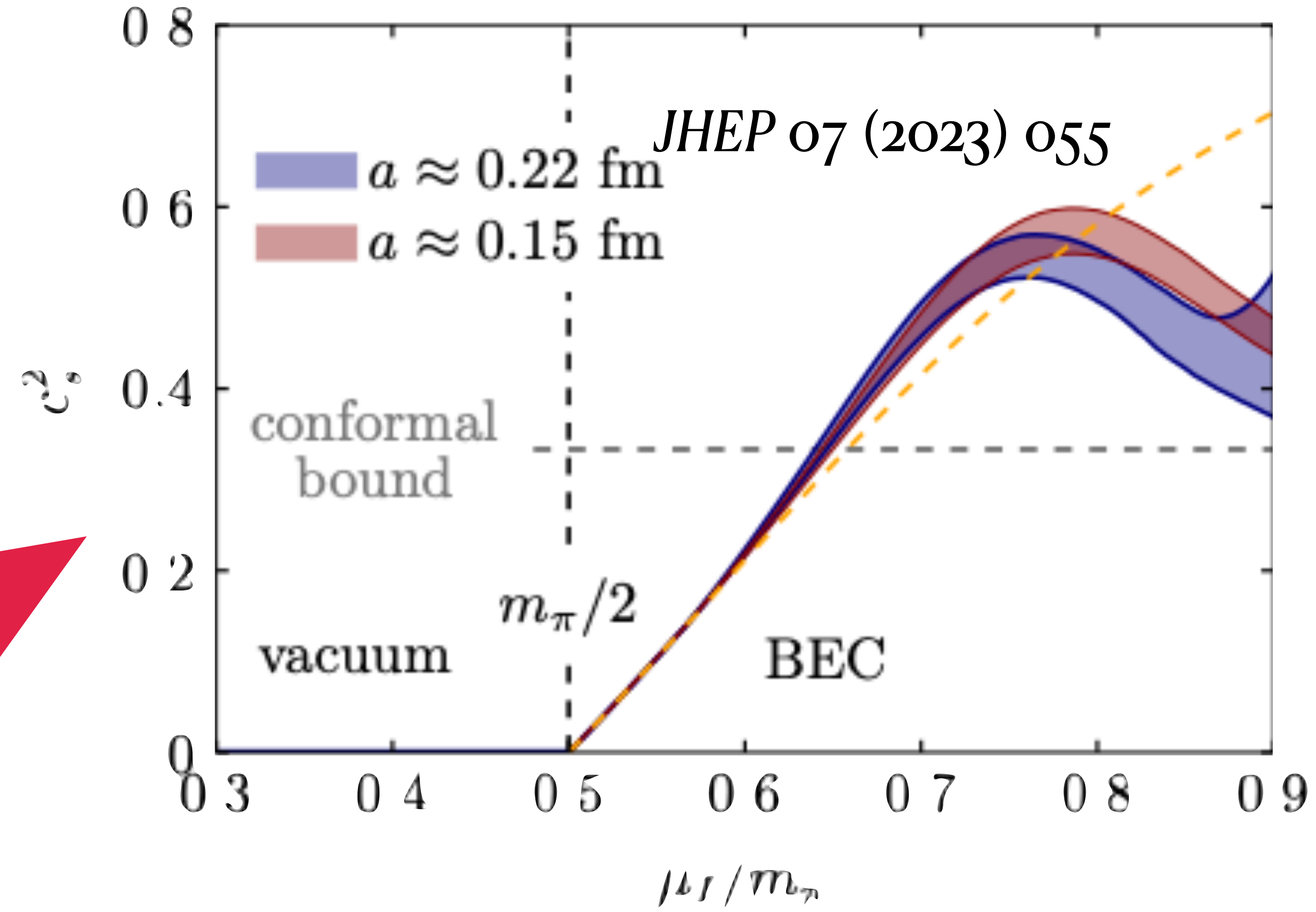
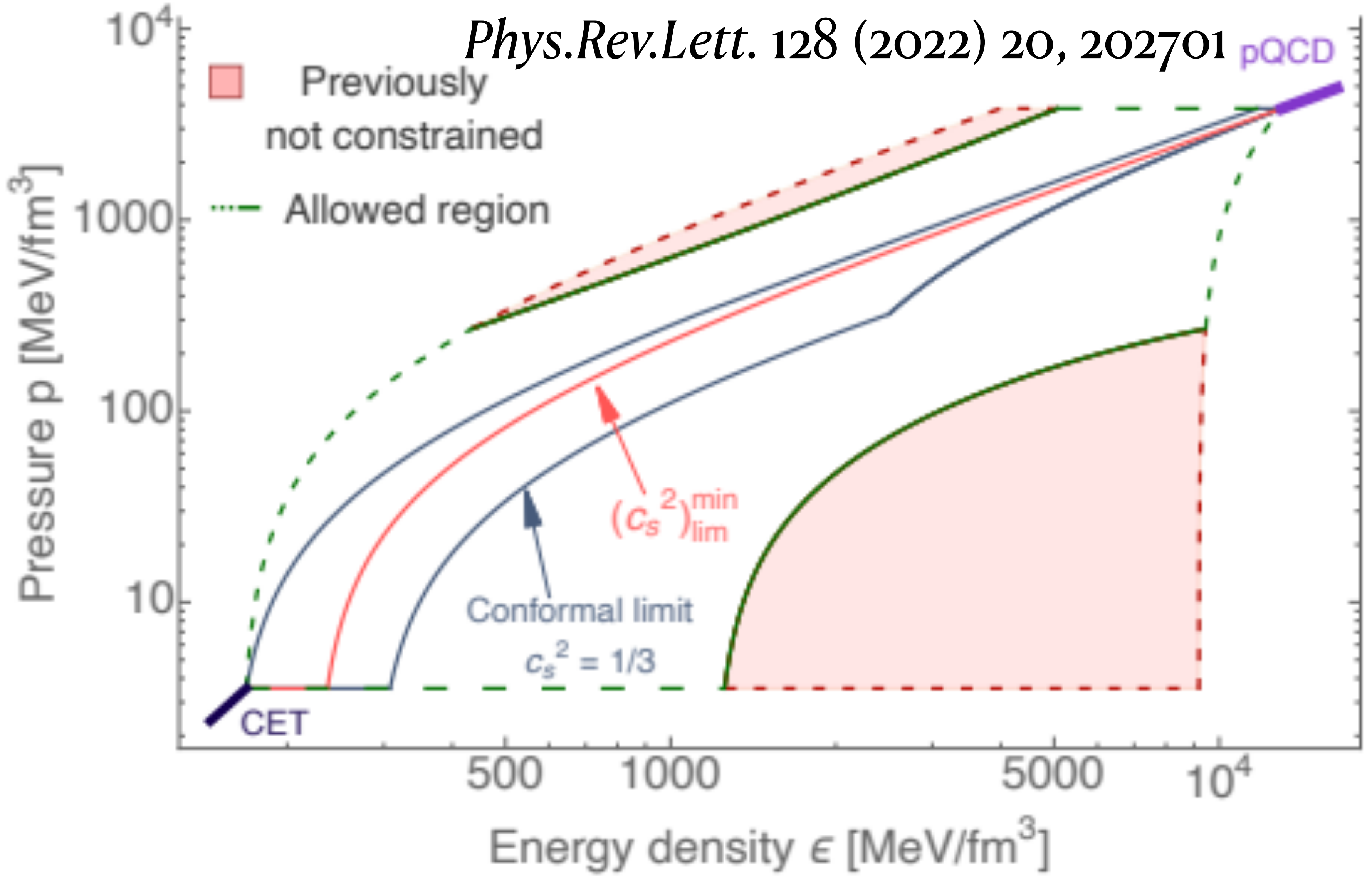






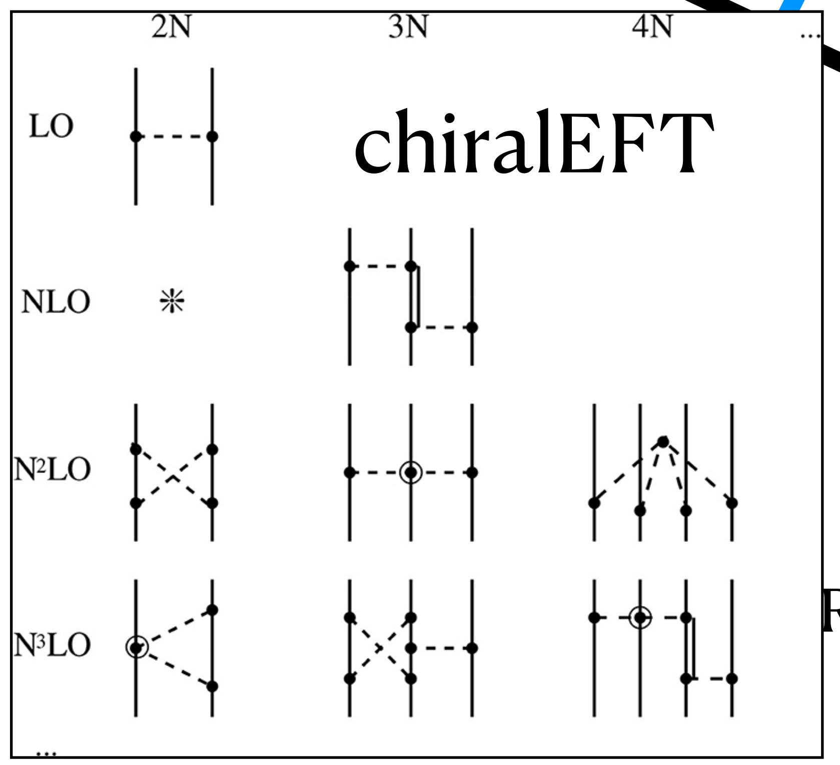
$n_I = n_Q$ IAM (for $n_S = n_B = 0$)

Perturbative QCD $n_B \gtrsim 40\, n_{sat}$



$\sim n_{sat}$

SNM $Y_Q = 0.5$ n_B



Review: *Phys.Rept.* 503 (2011) 1-75 + many, many works

n_B PNM $Y_Q = 0$

Filling gaps in our knowledge

Expansions: symmetry energy, finite T or μ, etc

Lattice QCD $\mu_B = 0$, then $p(T, \hat{\mu} = \vec{\mu}/T) = T^4 \sum_{i,j,k} \frac{1}{i!j!k!} \chi_{ijk}^{BQS} \hat{\mu}_B^i \hat{\mu}_S^j \hat{\mu}_Q^k$

Cold neutron stars $T = 0$, then $p(T, \vec{\mu}) = p_{T=0} + \frac{1}{2} \frac{\partial s}{\partial T}\Big|_{T=0,\vec{\mu}} T^2 + \mathcal{O}(T^3)$ 2404.01658 [astro-ph.HE]

Connect heavy-ions to neutron stars: $\frac{E_{ANM}}{N_B} = \frac{E_{SNM}}{N_B} + E_{sym}\delta^2 + \mathcal{O}(\delta^4)$ *& expansion around n_{sat}*

Caveat: breaks down outside of regime of validity, struggles with phase transitions

Effective Models: relativistic mean field, NJL, quarkyonic, etc

Qualitative features: bump in c_s^2, phase transitions, ...

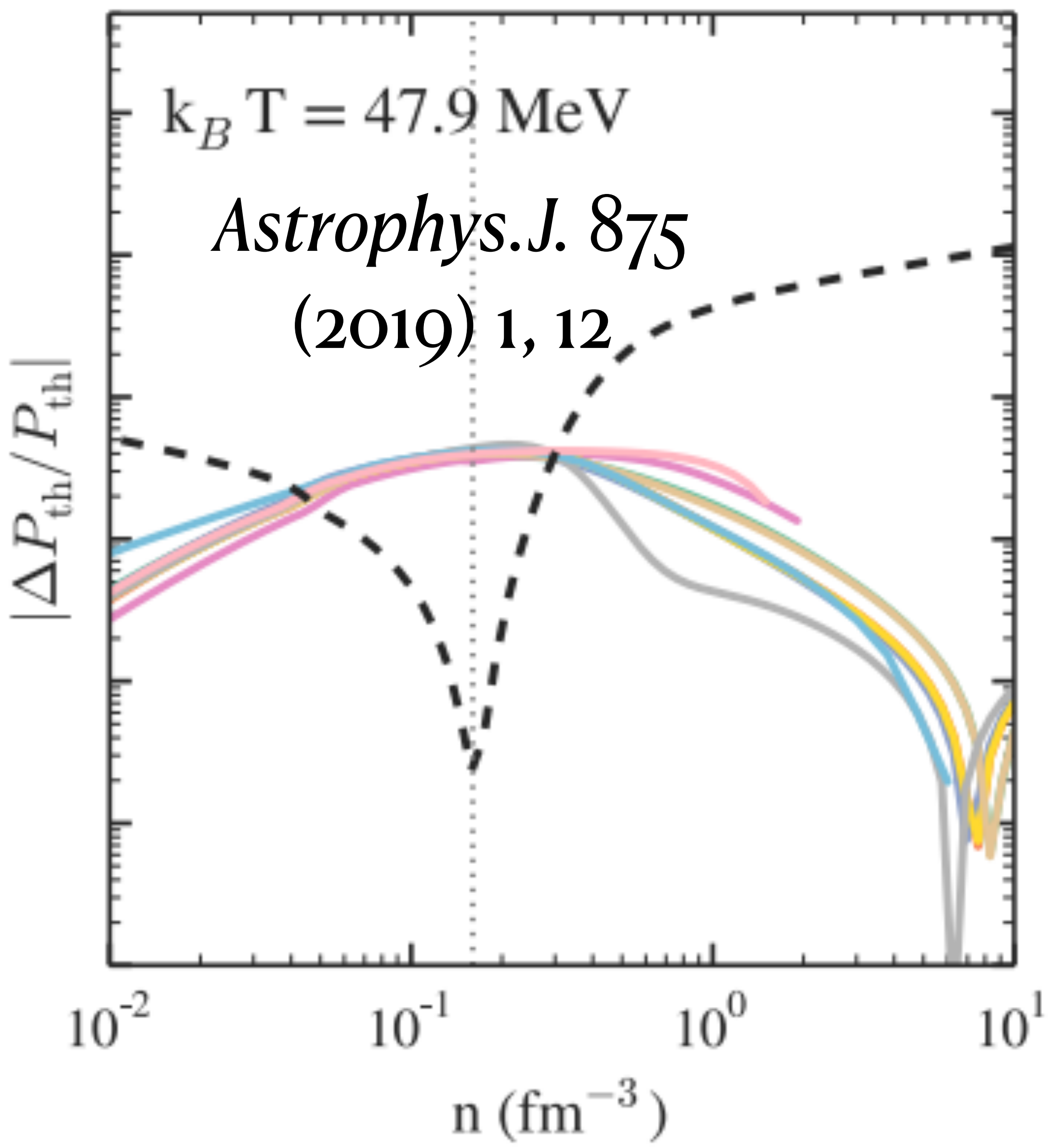
Constrain theory vs data; vary free parameters

Caveat: model assumptions and degrees of freedom

Minimalist models based on nuclear parameters

Effective Mass approach for neutron, proton, electron matter

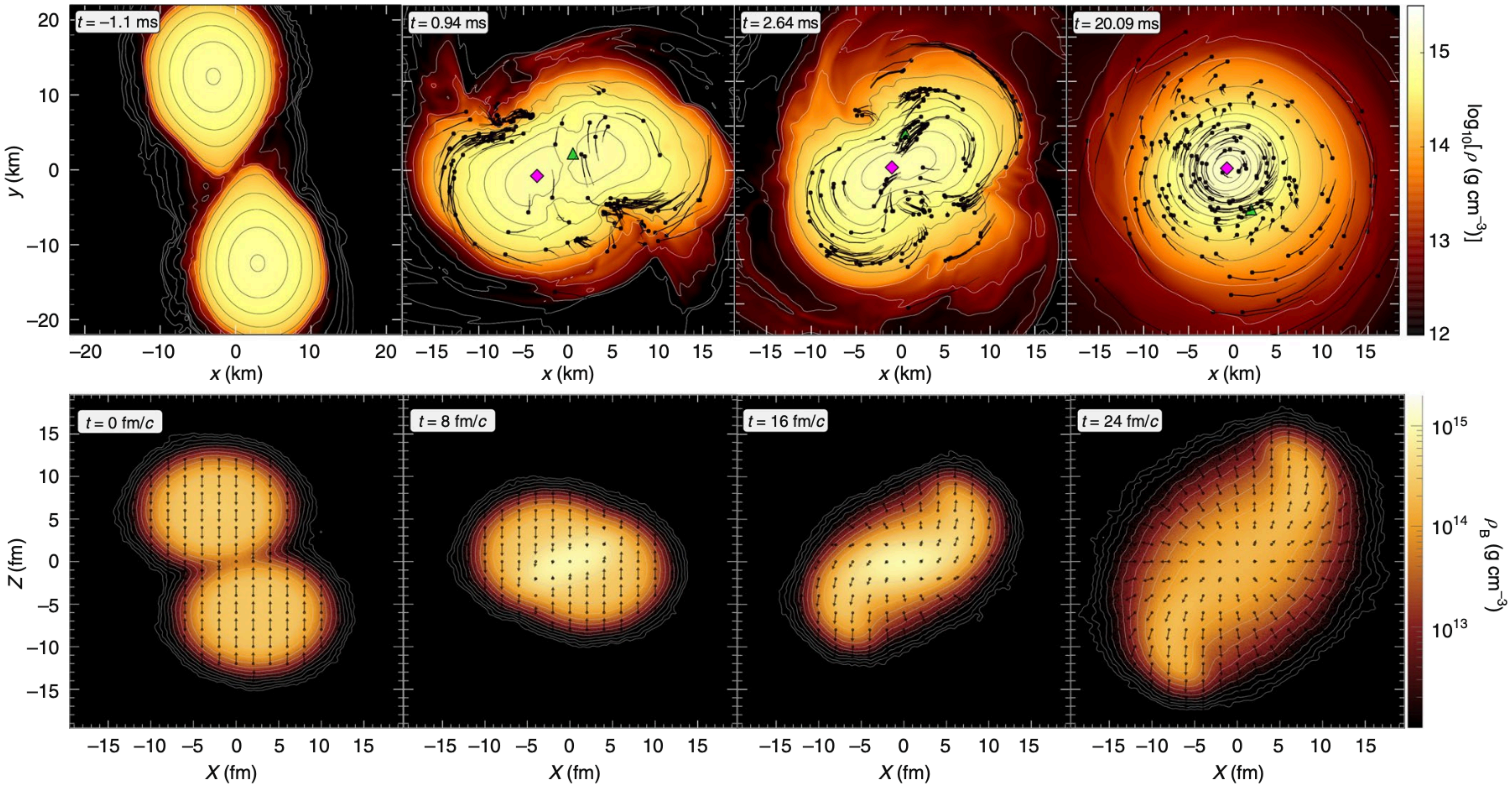
Caveat: breaks down outside of regime of validity, no phase transitions, hyperons etc



What new connections can be made to understand the core of a neutron star?

[HADES] Nature Phys. 15 (2019) 10, 1040-1045

Neutron Star Mergers (Numerical Relativity)

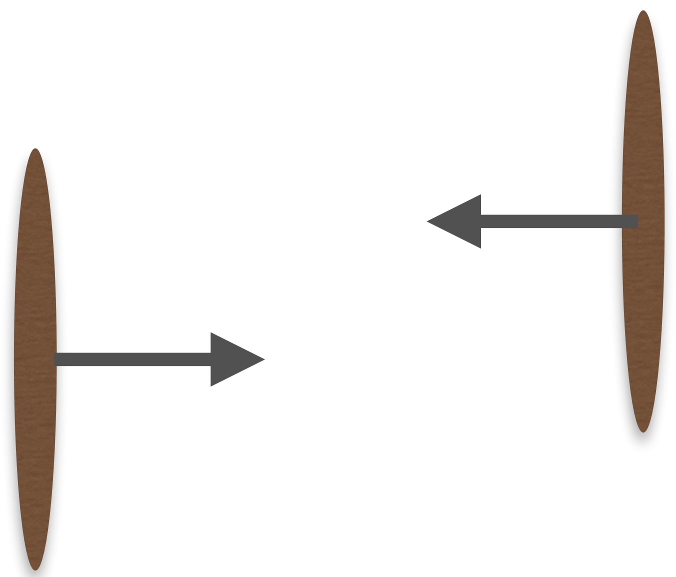


Low-energy Heavy-Ion Collisions (hadron transport)

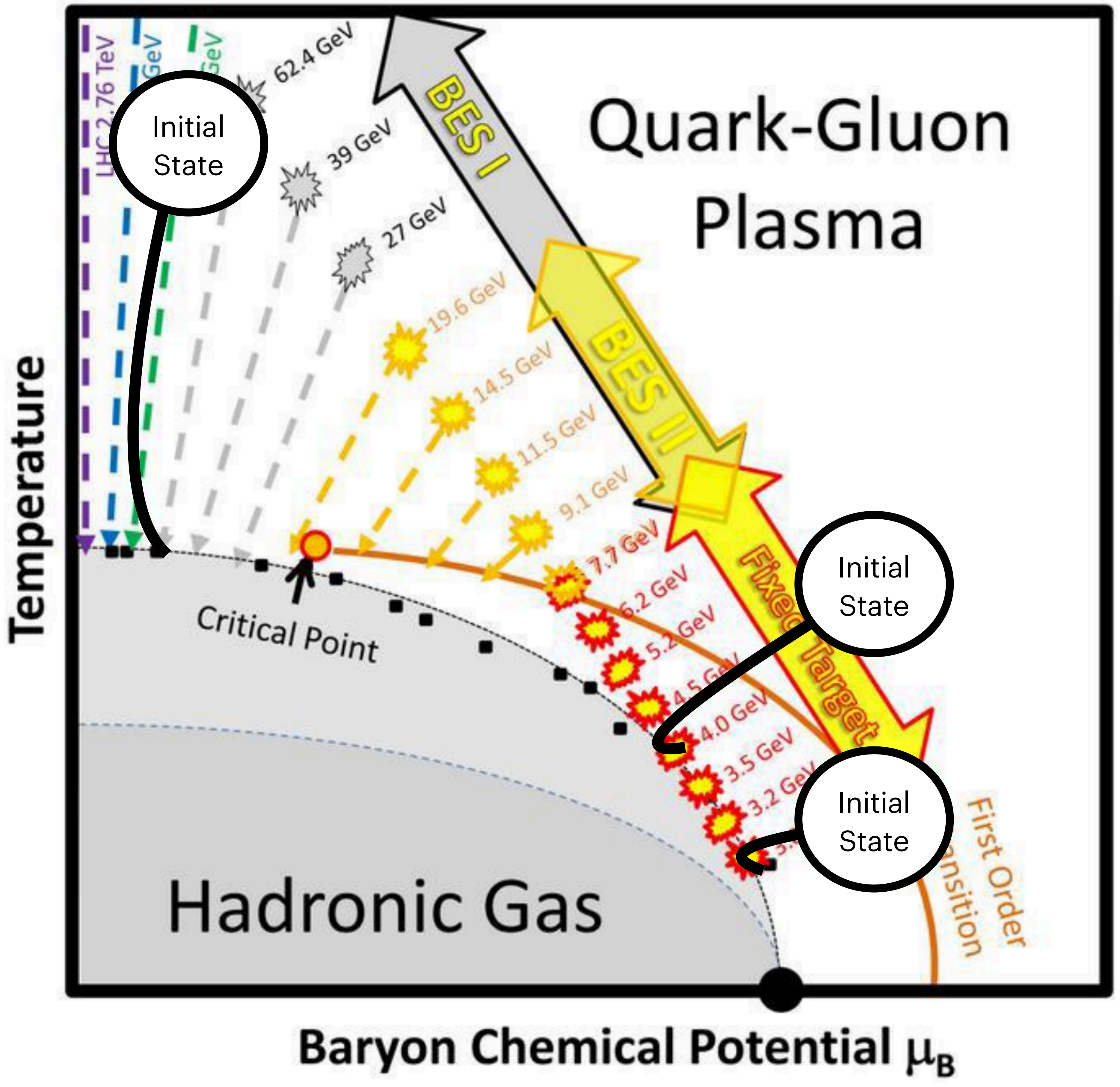
Differences as you lower $\sqrt{s}$ in HIC

Quark-gluon degrees of freedom may matter significantly less

Large $\sqrt{s_{NN}}$

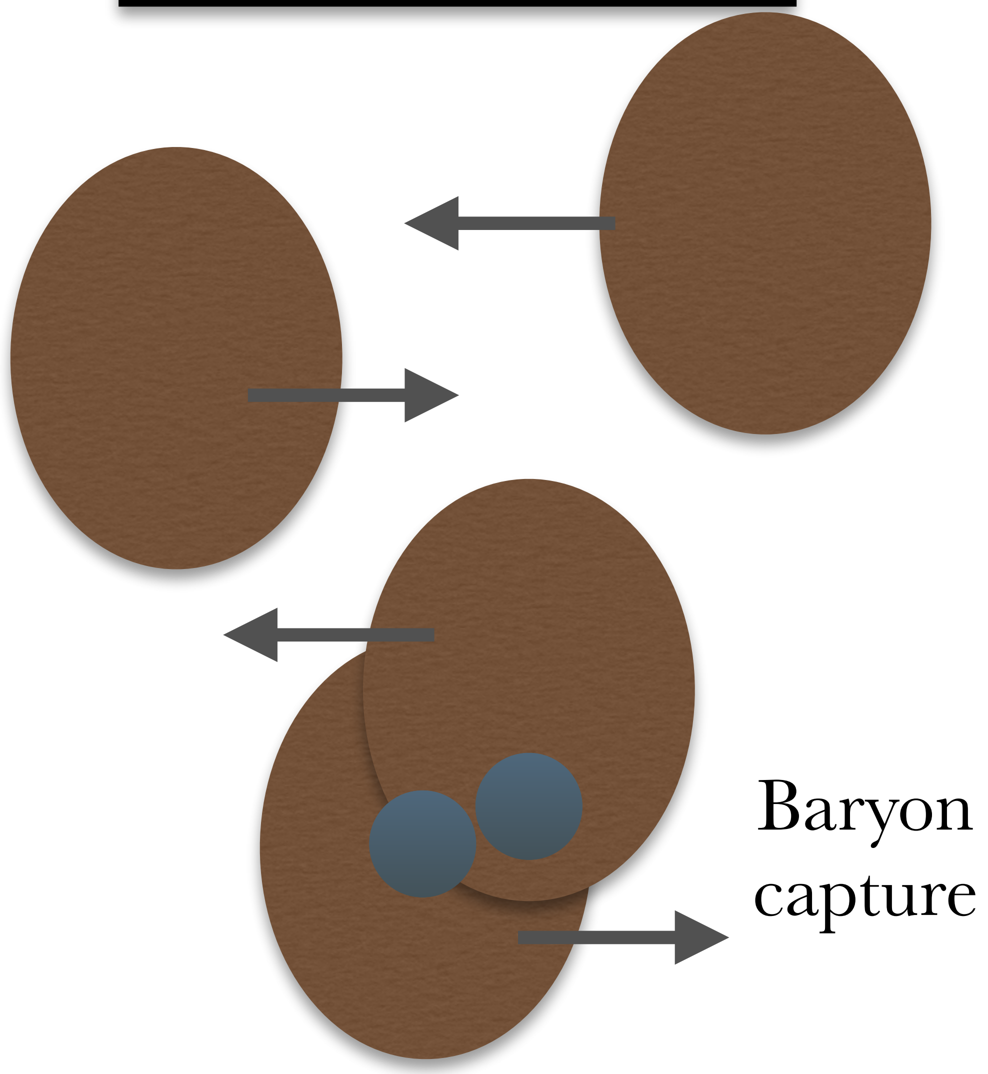


- Lorentz contracted (2D)
- Nuclei pass through instantaneously
- Too quick to capture baryons



Different $\sqrt{s}$ have different time spent in quark/gluon phase vs hadron phase

Small $\sqrt{s_{NN}}$



- 3D nuclei pass slowly
- Time to capture baryons

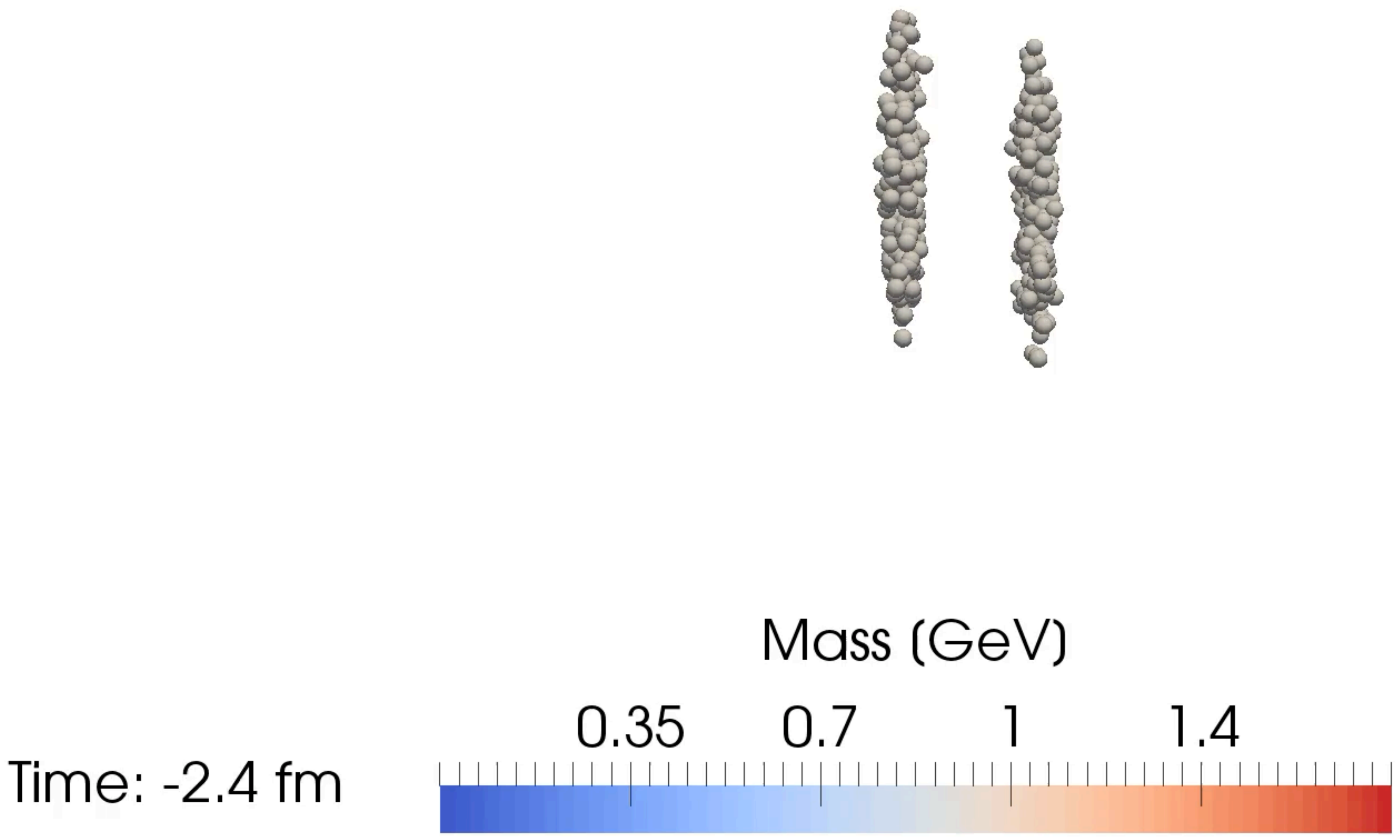
Low-energy heavy-ion collisions

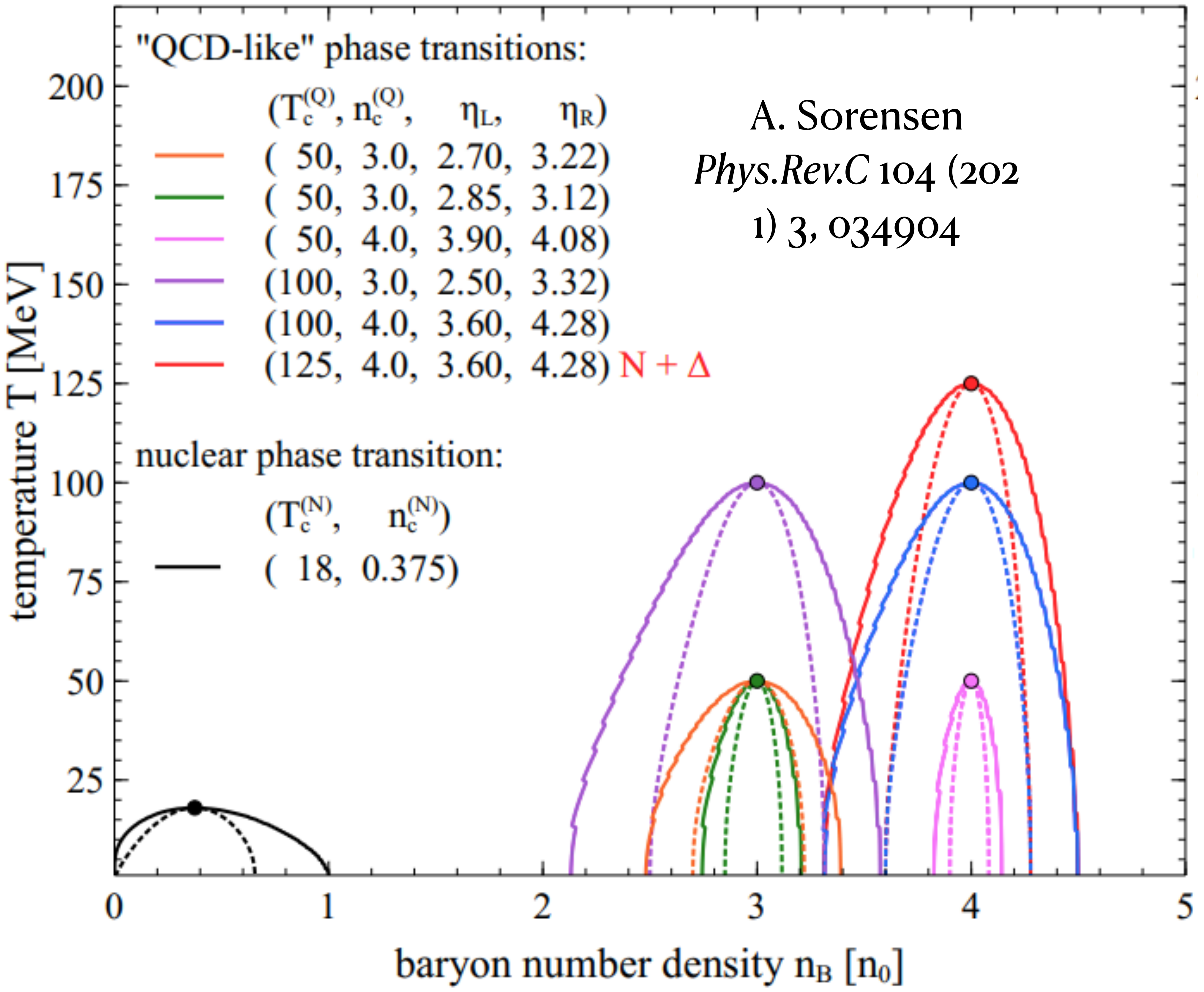
How do we interpret Heavy-ion (HIC) data?

$\sqrt{s} \leq 7.7\, GeV$ Fixed-target heavy-ion collisions

Open question: do quark-gluons d.o.f. matter?

One solution: build phase transitions into hadron transport





A. Sorensen
Phys.Rev.C 104 (2021) 3, 034904

Bayesian analysis with heavy-ion flow data found a peak in c_s^2 at $n_B^{peak} = [2,3]\, n_{sat}$ for SNM
Phys.Rev.C 108 (2023) 3, 034908

Systematic Hydro studies still needed

Low-energy heavy-ion collisions

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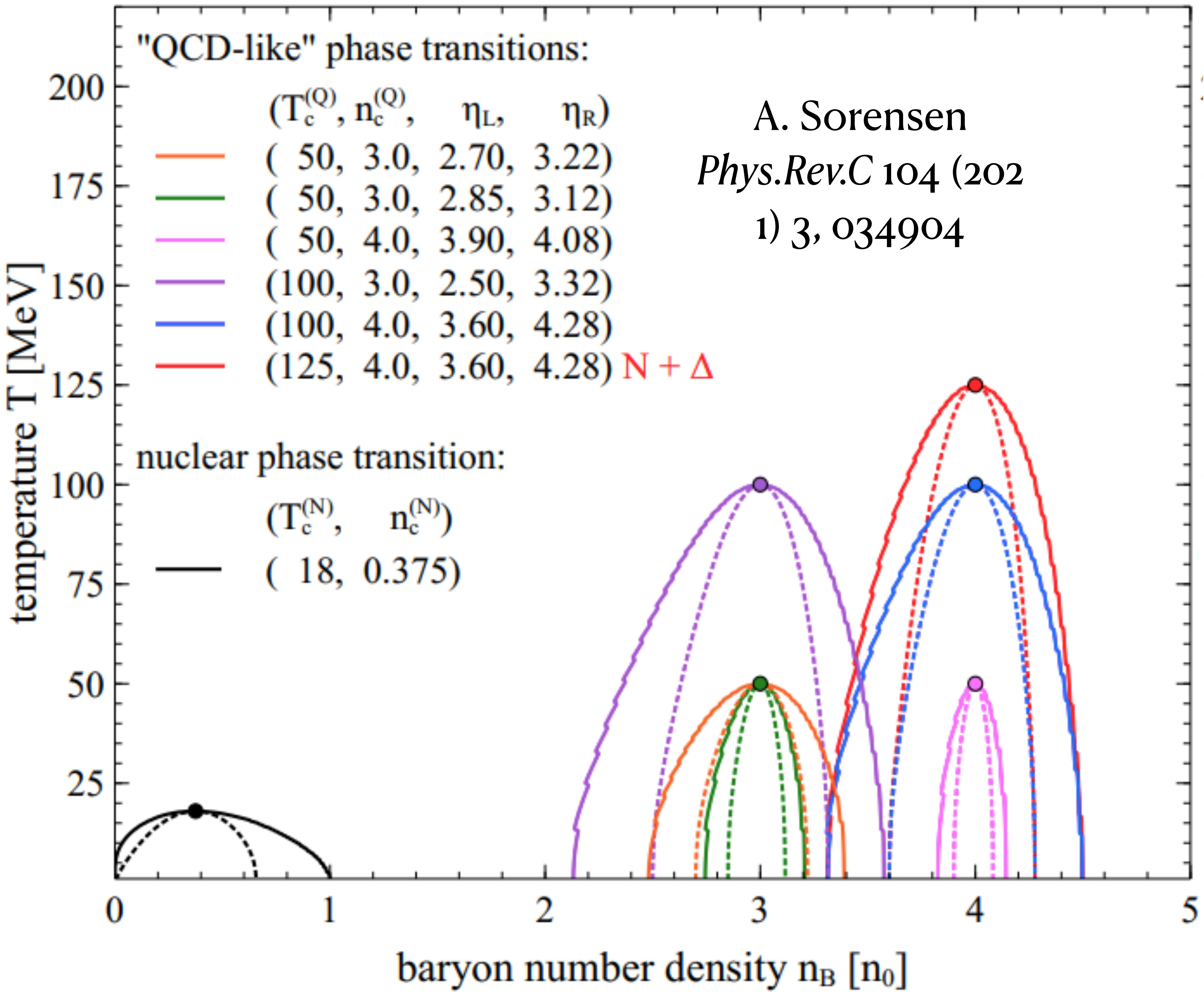

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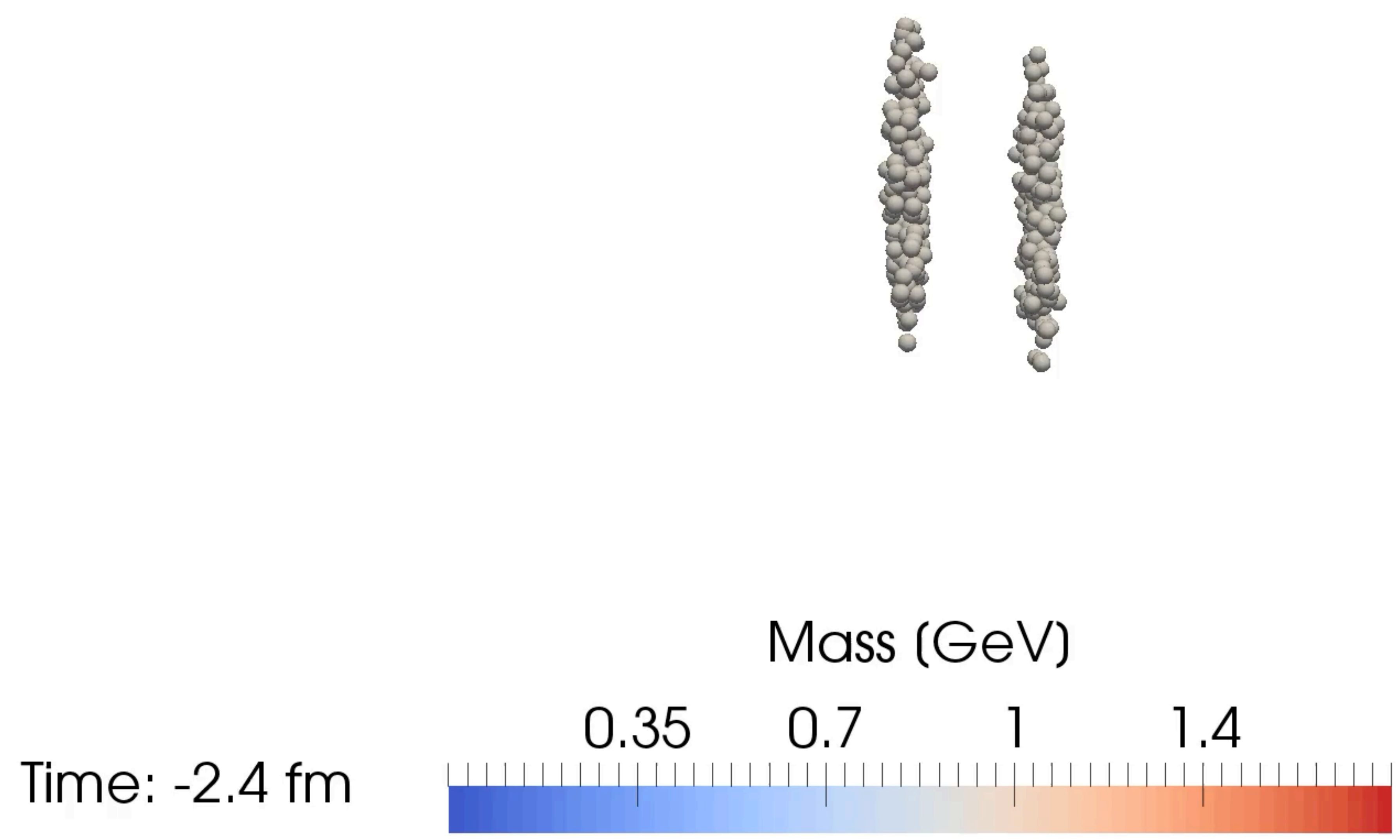

smash

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Phys.Rev.C 108 (2023) 3, 034908

Systematic Hydro studies still needed

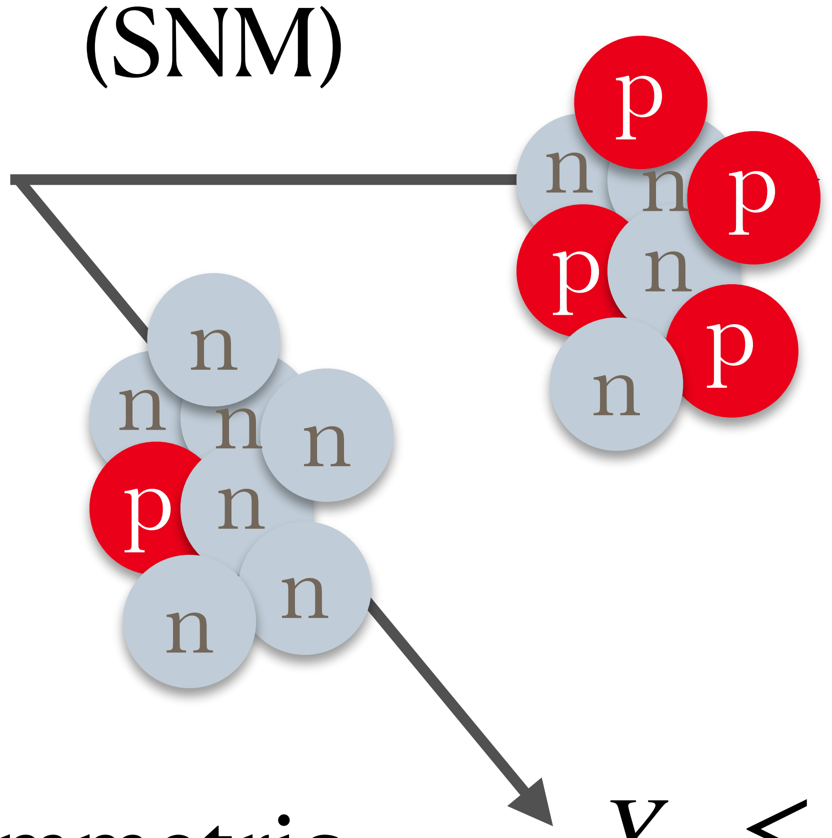
Isospin asymmetry/Symmetry Energy Expansion

Connecting NS to HIC across Y_Q

Original symmetry energy expansion from binding energies
Bombaci & Lombardo *Phys.Rev.C* 44 (1991) 1892-1900

Symmetric matter (SNM)

$Y_Q = 0.5$



Asymmetric matter (ANM)

$Y_Q \lesssim 0.1$

Isospin asymmetry $\delta = 1 - 2Y_Q$

where $\delta = 0$ for SNM and $\delta = 1$ for PNM

$$\frac{E_{ANM}}{N_B} = \frac{E_{SNM}}{N_B} + E_{sym,2}\delta^2 + \mathcal{O}(\delta^4)$$

Expand in δ where odd terms drop due to isospin symmetry

Convert EOS from NS to HIC, expand around n_{sat}

$$\varepsilon_{HIC} = \varepsilon_{NS} - 4n_B \left[E_{sym,sat} + \frac{L}{3}\left(\frac{n_B}{n_{sat}} - 1\right) + \frac{K}{18}\left(\frac{n_B}{n_{sat}} - 1\right)^2 + \frac{J}{162}\left(\frac{n_B}{n_{sat}} - 1\right)^3 \right] \left[\left(Y_Q^{HIC} - Y_{Q,NS}\right) + \left(Y_{Q,NS}^2 - \left(Y_Q^{HIC}\right)^2\right) \right]$$

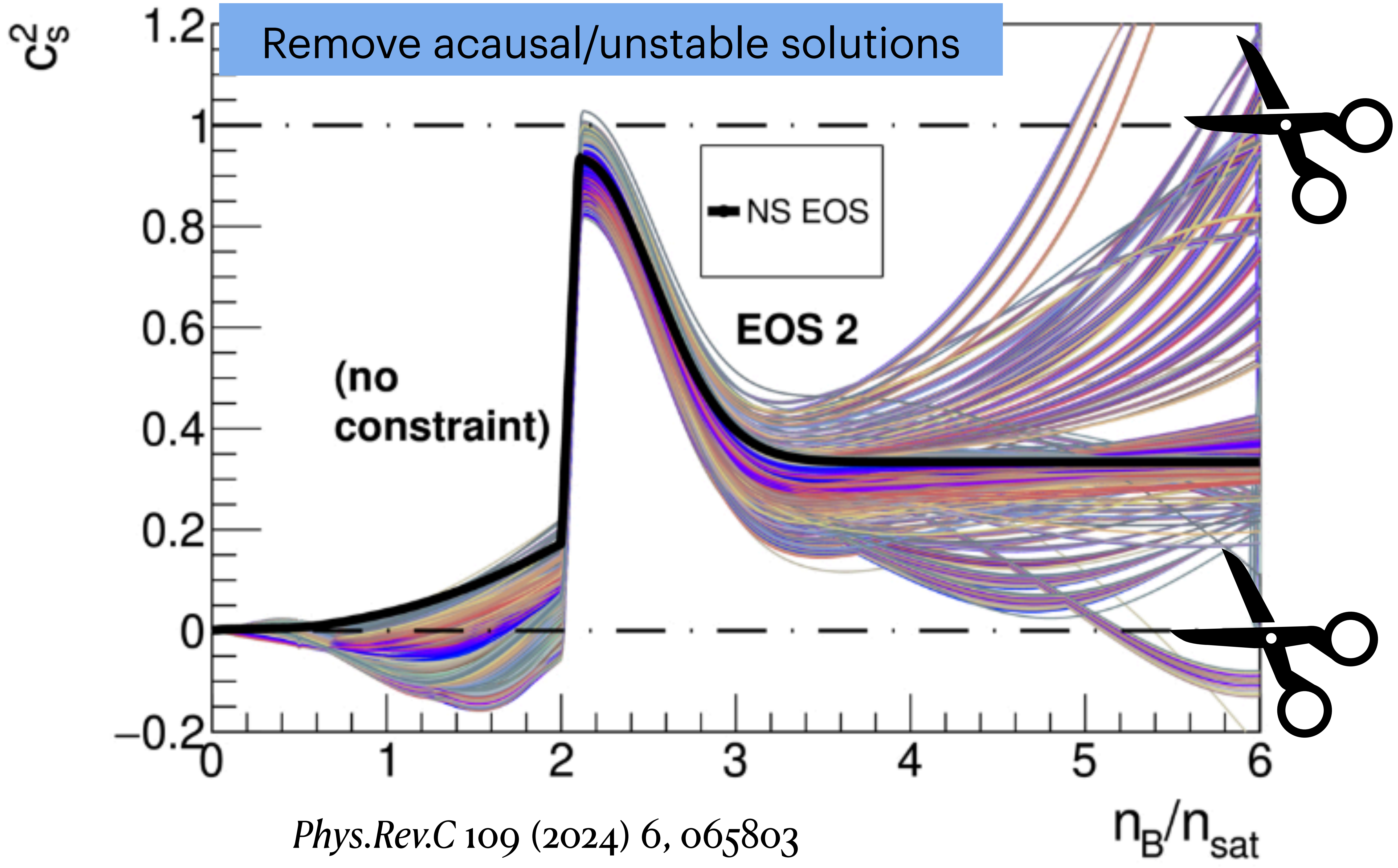
$E_{sym,2}(n_B)$ 4 unknowns

To varing Y_Q^{HIC}
Yao et al, *Phys.Rev.C* 109 (2024) 6, 065803

How do low-energy heavy-ion collisions at $T = 0$ connect to neutron stars?

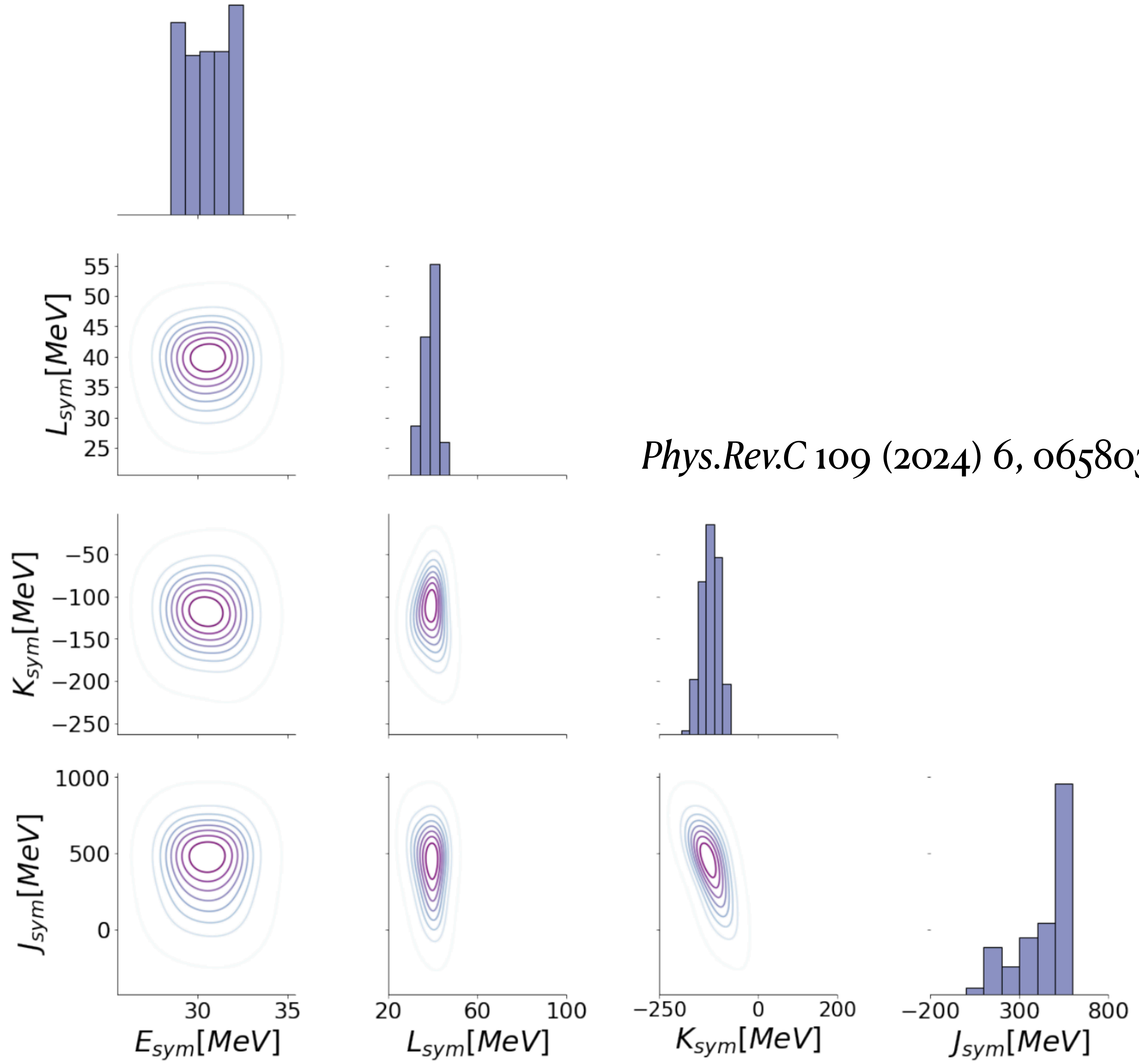
Symmetry energy expansion

Given neutron star equation of state → convert to HIC and can constrain by $0 \leq c_s^2 \leq 1$ and saturation properties.



Phys.Rev.C 109 (2024) 6, 065803

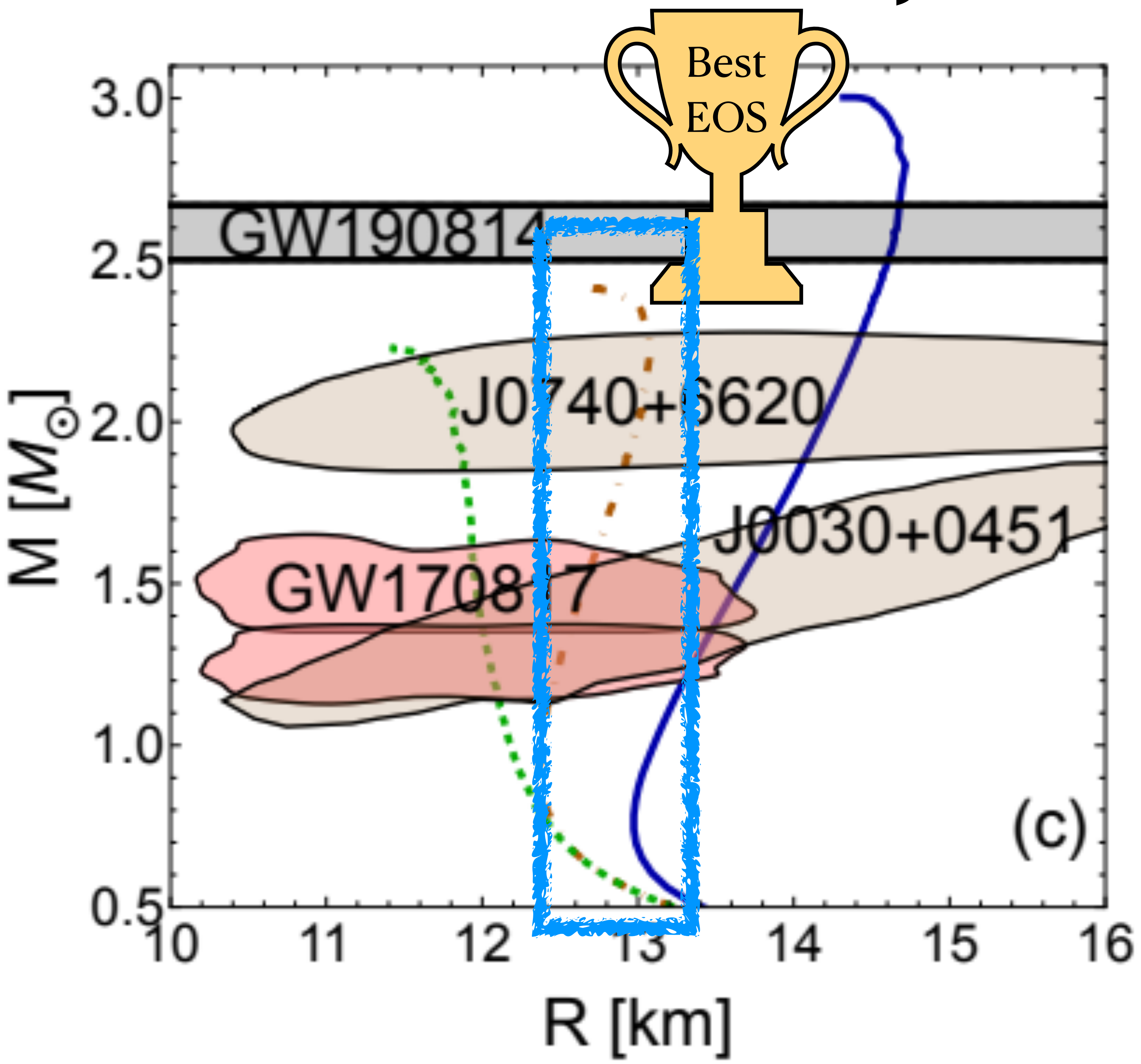
n_B

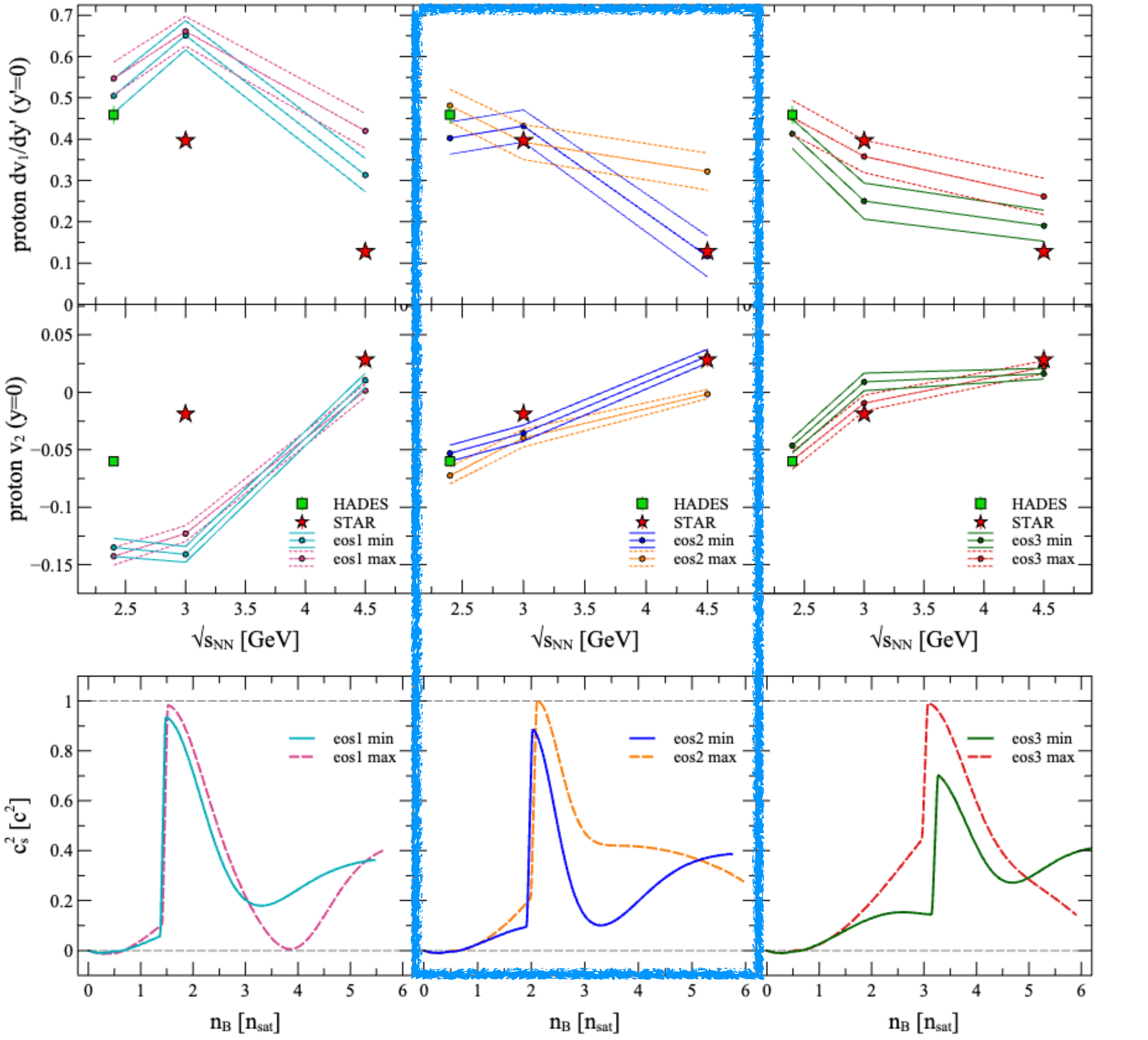


Phys.Rev.C 109 (2024) 6, 065803

Ultra heavy neutron star EOS works HIC

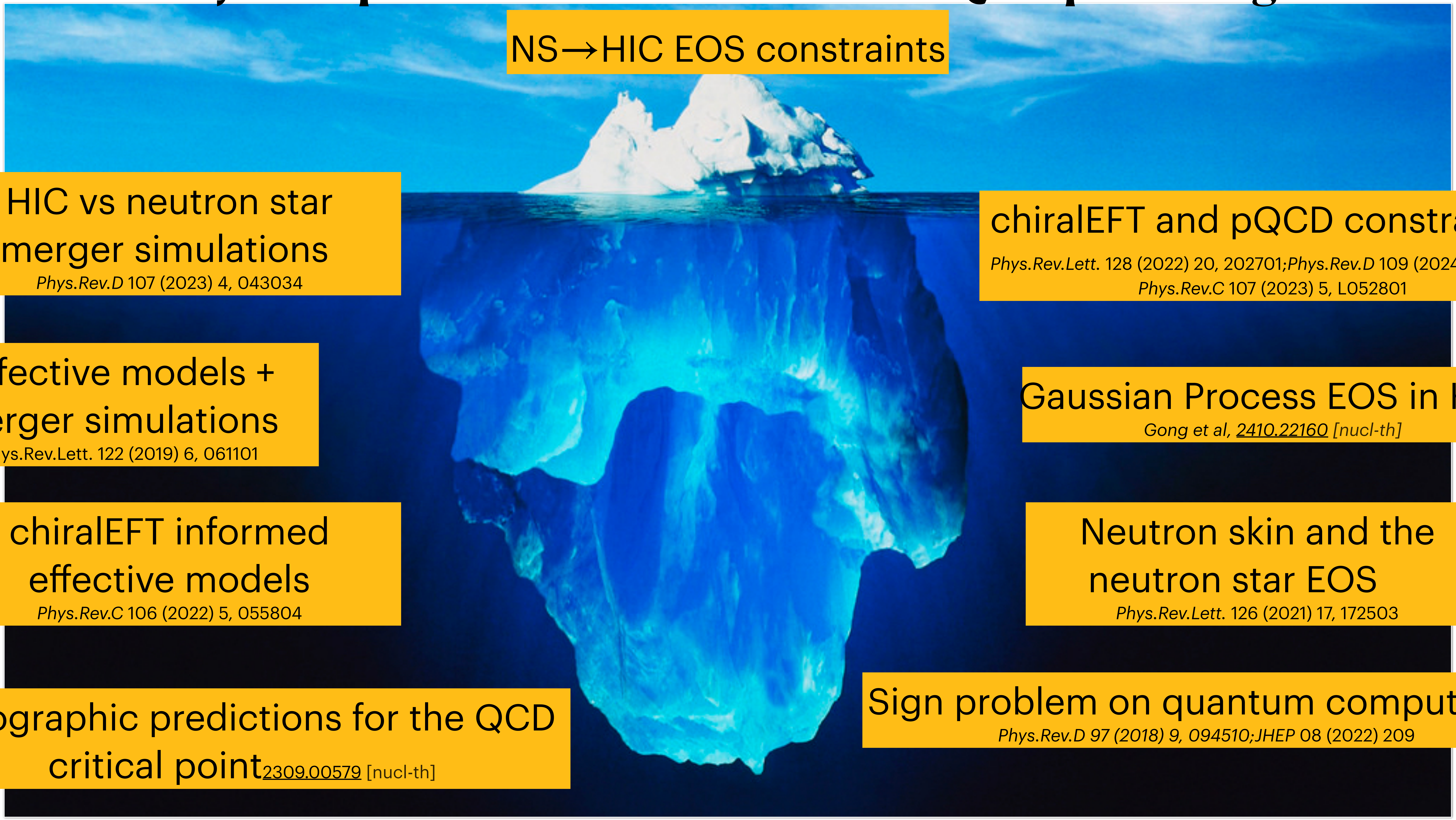
Phys.Rev.C 109 (2024) 6, 065803





Take extremes of the EOS band derived for heavy-ion collisions, run in hadron transport, and compare to heavy-ion collision flow data

Many more possible connections with the QCD phase diagram

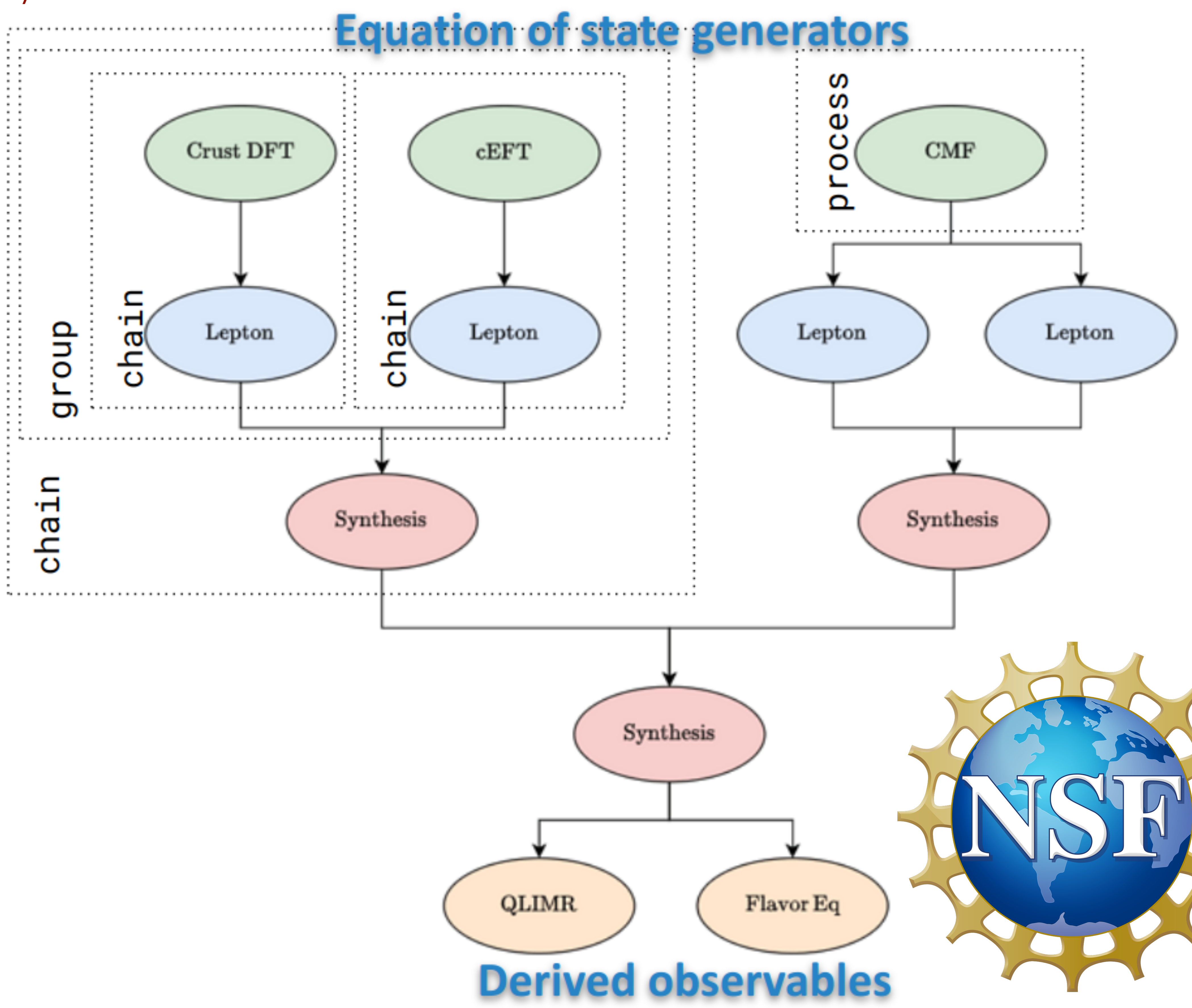


Open-source tools for more cross-disciplinary connections!

muses https://musesframework.io/

- 7 available equation of state (EOS) modules
- 3 available observable modules
- Both heavy-ion and neutron star EOS available
- α-release is out, being tested
- β-release soon. Possible to run crust to core of a neutron star+calculate mass, radius, tidal deformability etc
- Looking for new collaborators!

Software across the QCD phase diagram



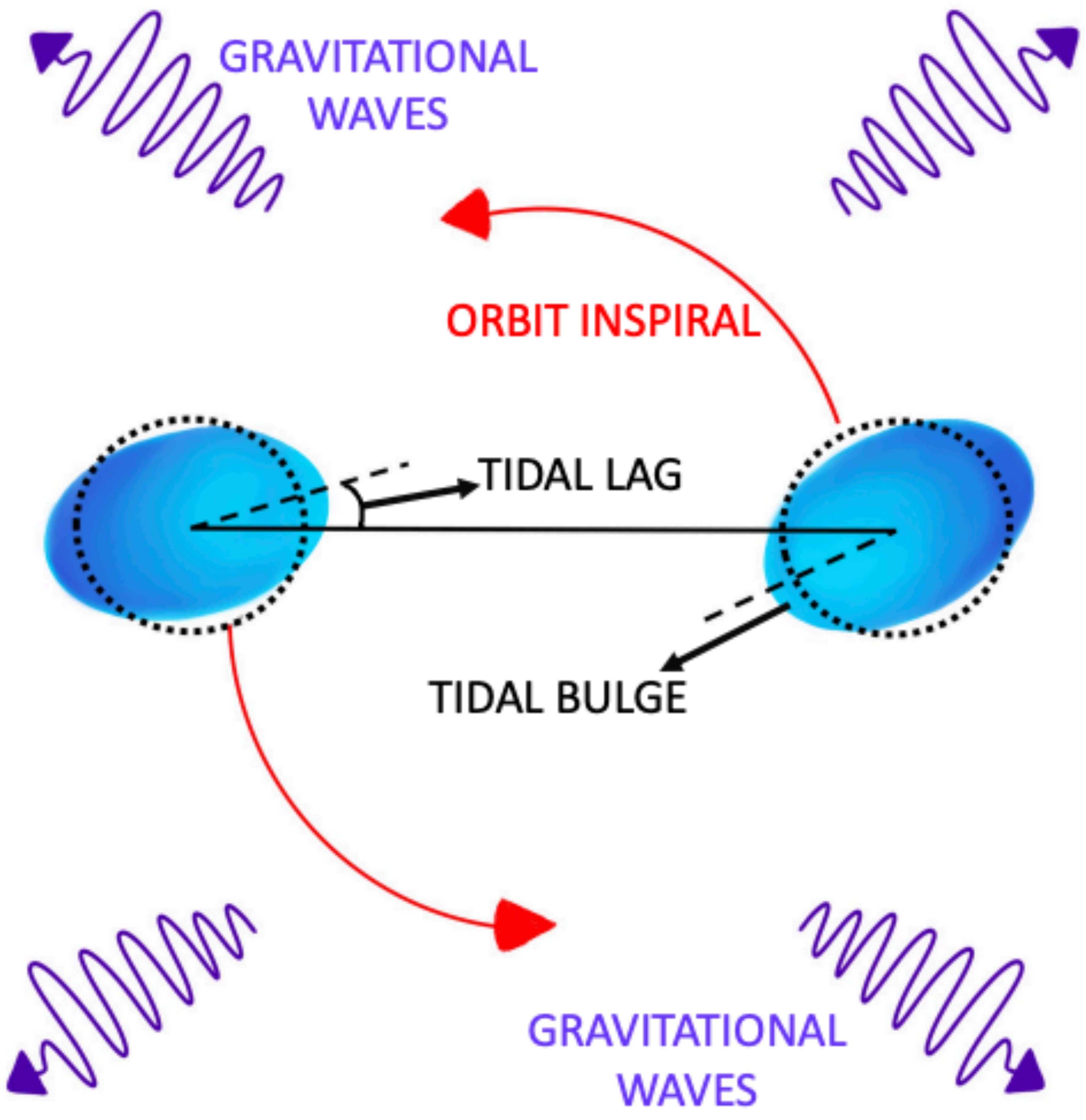
Later releases will connect heavy-ion and neutron star EOS across the entire phase diagram!

Viscous effects from neutron star mergers

Learning from heavy-ion collisions

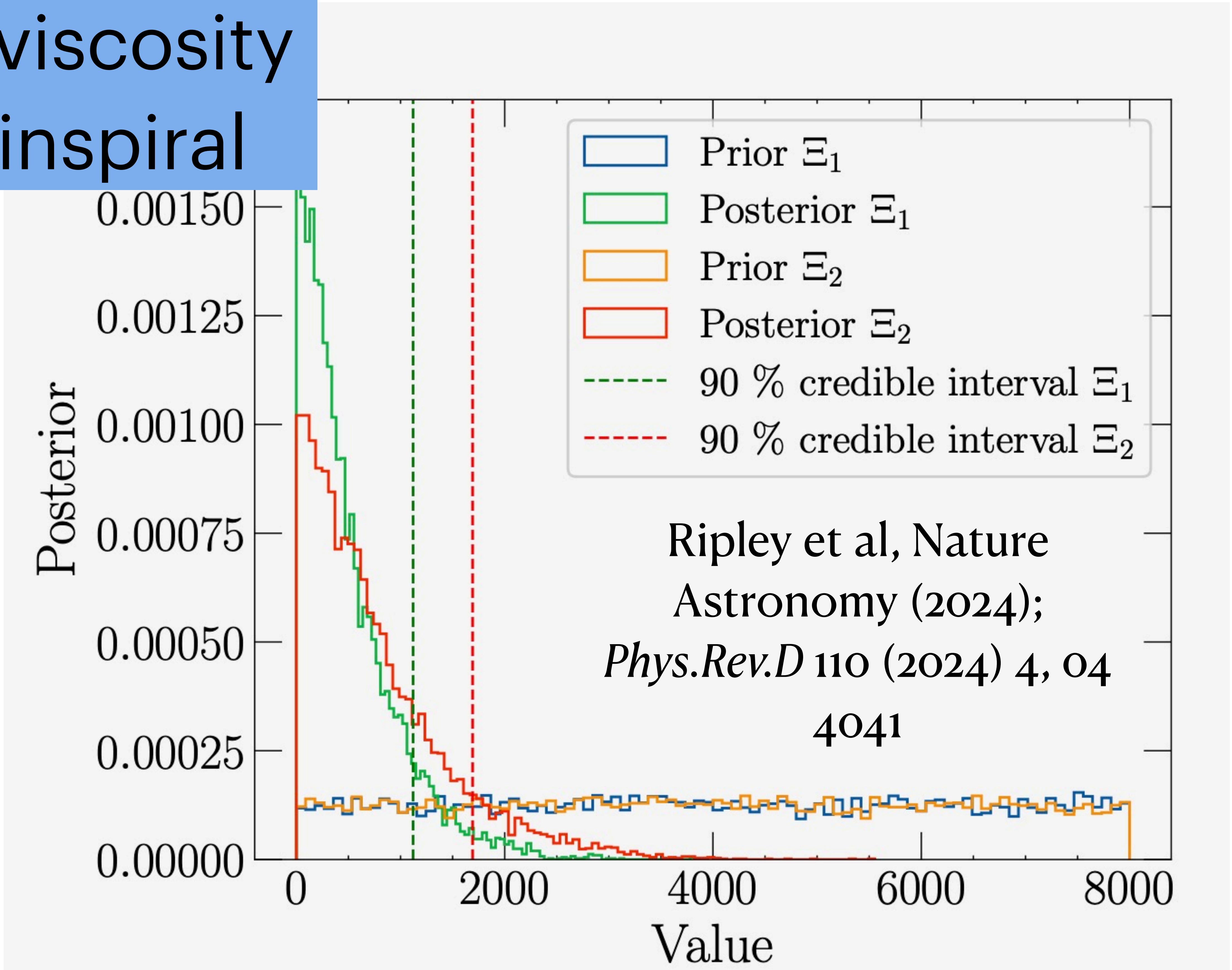
Out-of-equilibrium: misalignment of tidal bulge

First constraints on viscosity from gravitational wave data!



Ripley, Hegade, Chandramouli, Nature Astronomy (2024)

"Averaged" viscosity within the inspiral

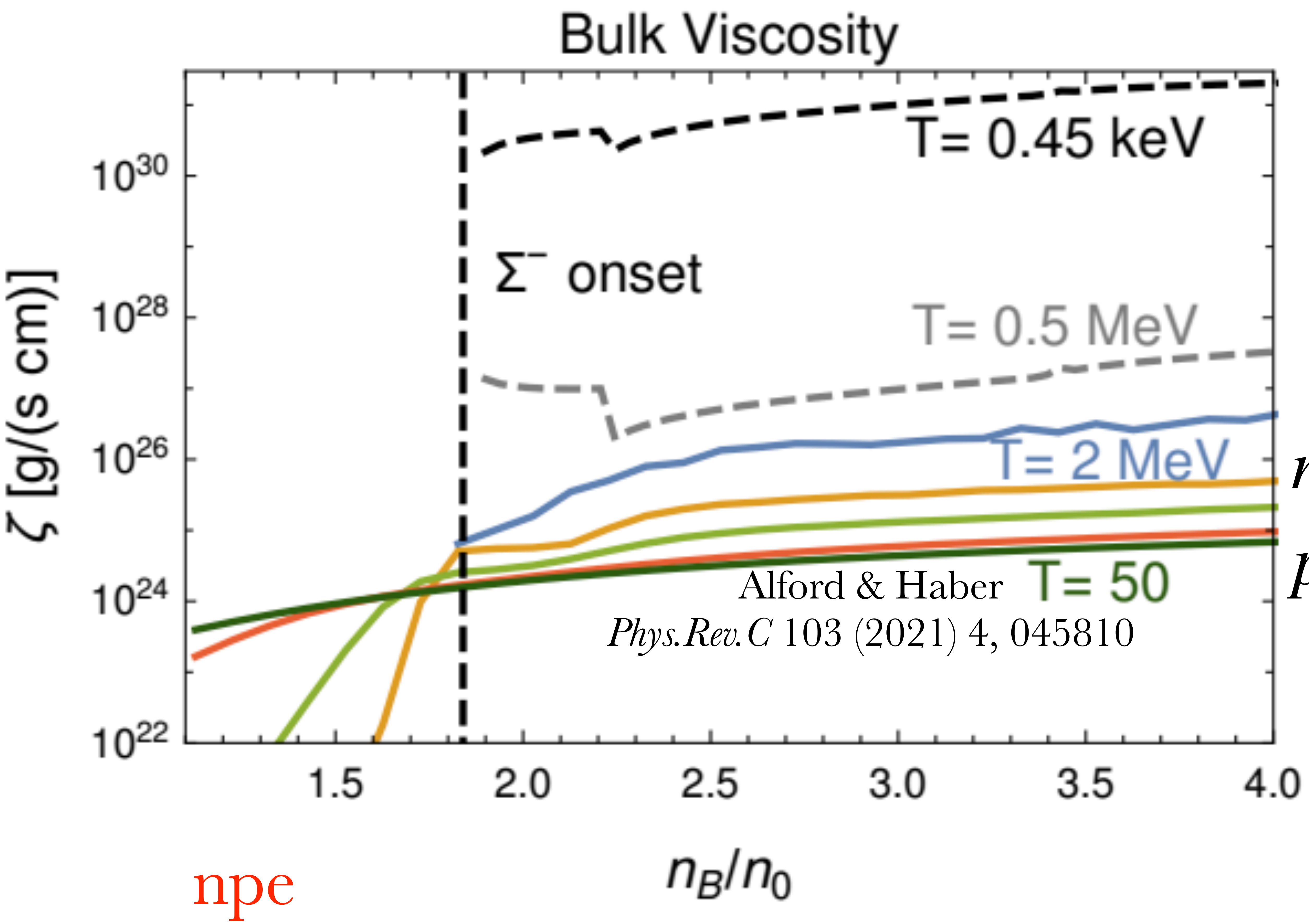


Ripley et al, Nature Astronomy (2024); *Phys.Rev.D* 110 (2024) 4, 04 4041

Out-of-equilibrium measurements provide new way to probe neutron star degrees-of-freedom!

Degrees-of-freedom and bulk viscosity

Depends on temperature, density, oscillations



npe

hyperons

quarks??

Delayed β-equilibrium in mergers

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

$$p + e^- \rightarrow n + \nu_e$$

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

$$p + e^- + X \rightarrow n + X + \nu_e$$

Bulk and Magnetic fields
2409.09423 [nucl-th]

Bulk viscosity can cause phase shift in post-merger
Astrophys.J.Lett. 967 (2024) 1, L14

Far-from-equilibrium and symmetry properties
Phys.Rev.C 109 (2024) 1, 015805

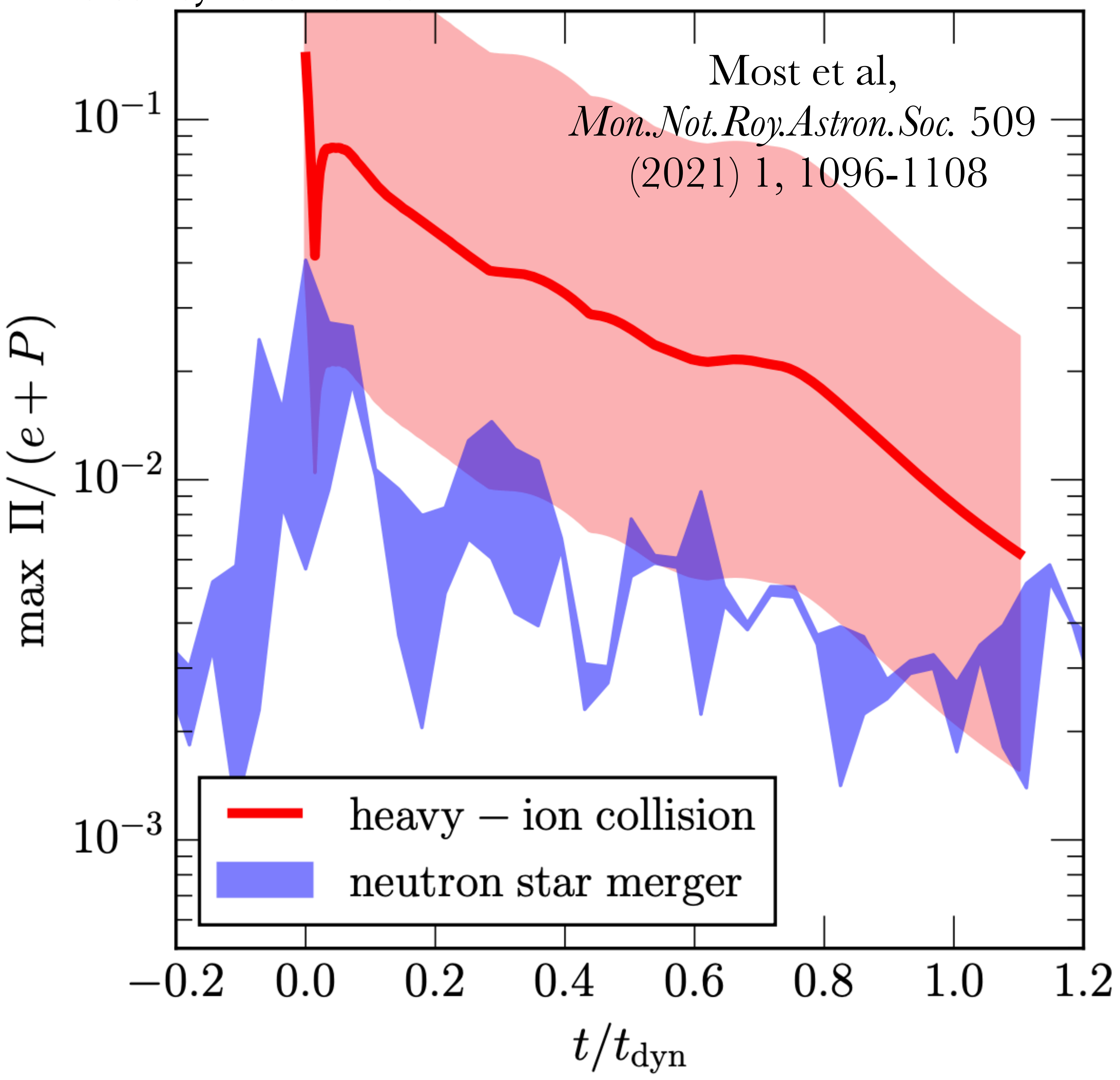
New approach to understand the microscopic degrees of freedom in neutron stars

Bulk viscosity: heavy-ions vs neutron stars

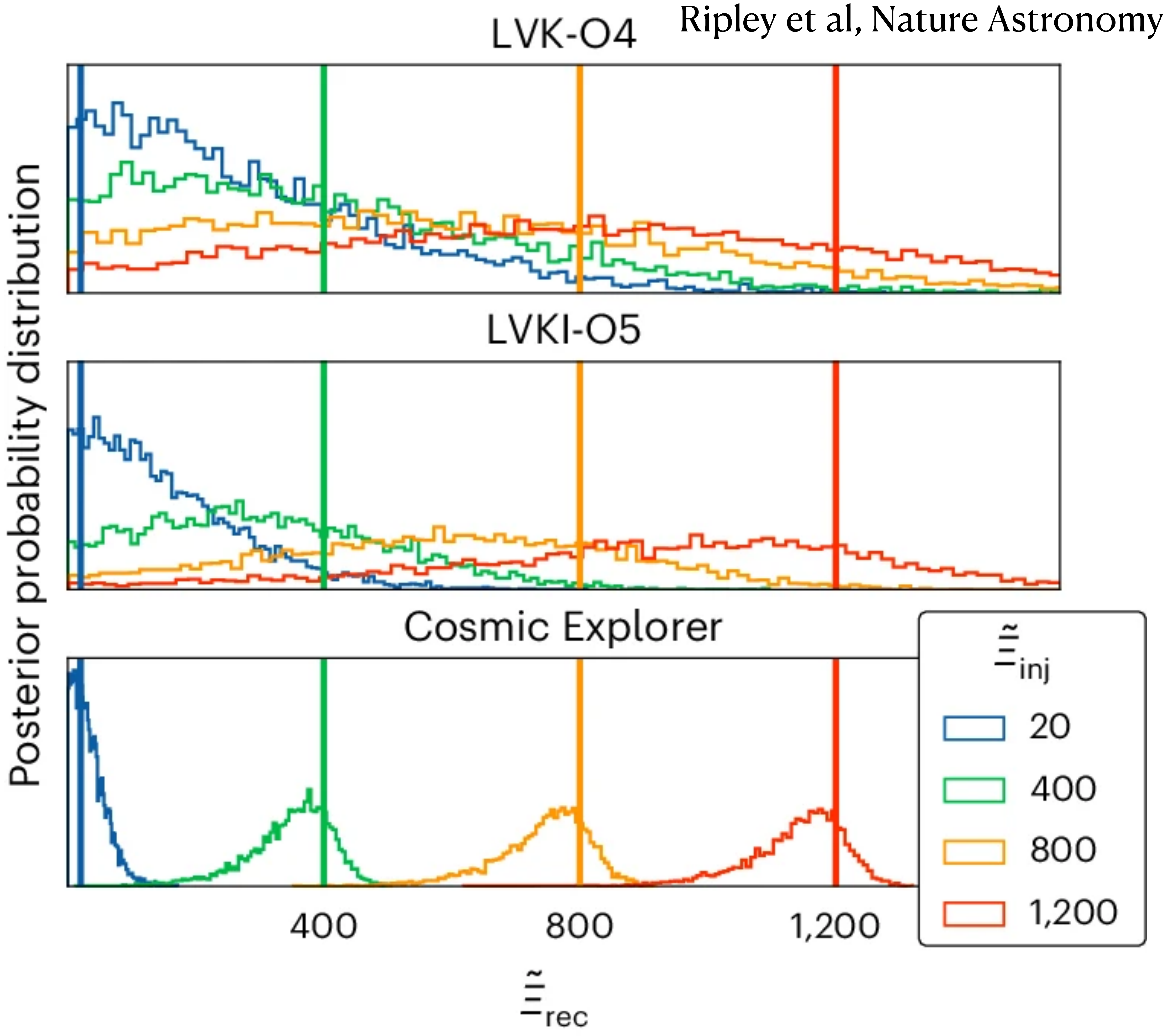
Comparisons of inverse Reynolds numbers

State-of-the-art heavy-ion collision simulations vs neutron star mergers find comparable effects from bulk viscosity

Inverse Reynolds number



Ripley et al, Nature Astronomy (2024)



Future detectors/runs able to better constrain the averaged viscosity in the inspiral. Potential for future collaborations!

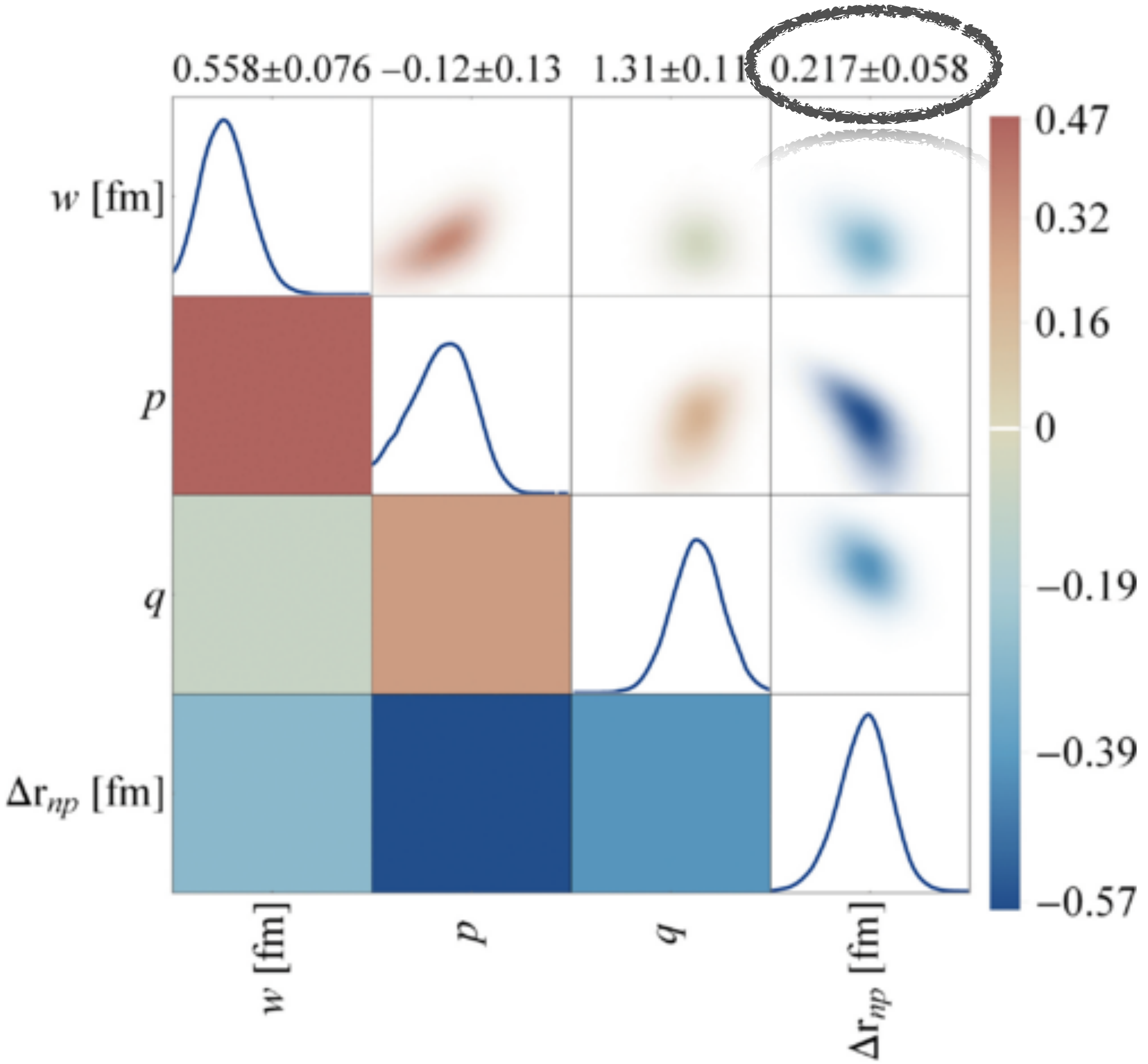
Other heavy-ion collision and neutron star connections

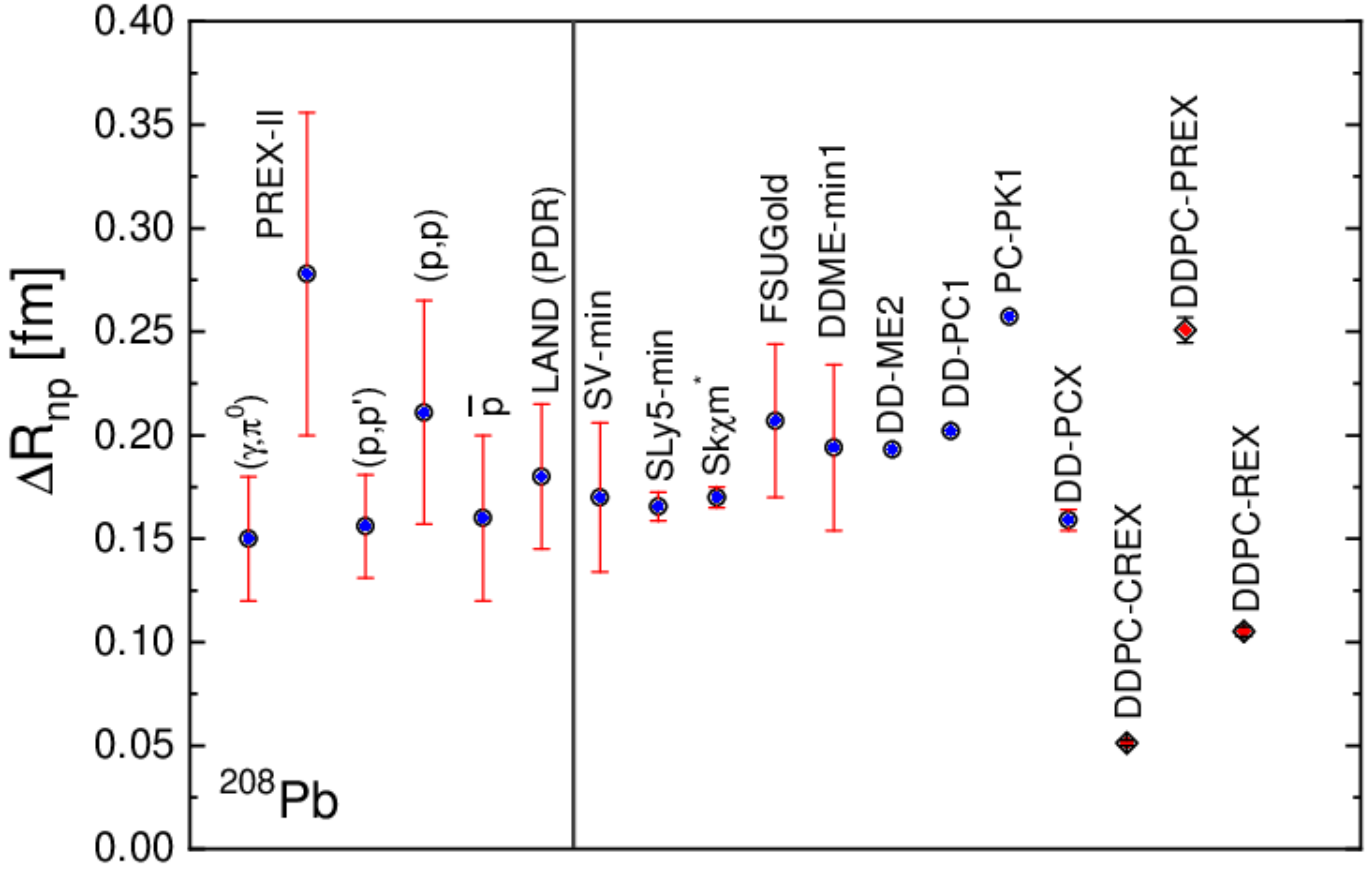
Extracting Neutron Skin from HIC data

Can be used to constrain symmetry energy coefficients

Extraction from Bayesian analysis

Giacalone et al, PRL (2023)131,202302





Extraction from Ultraperipheral heavy-ion collision data

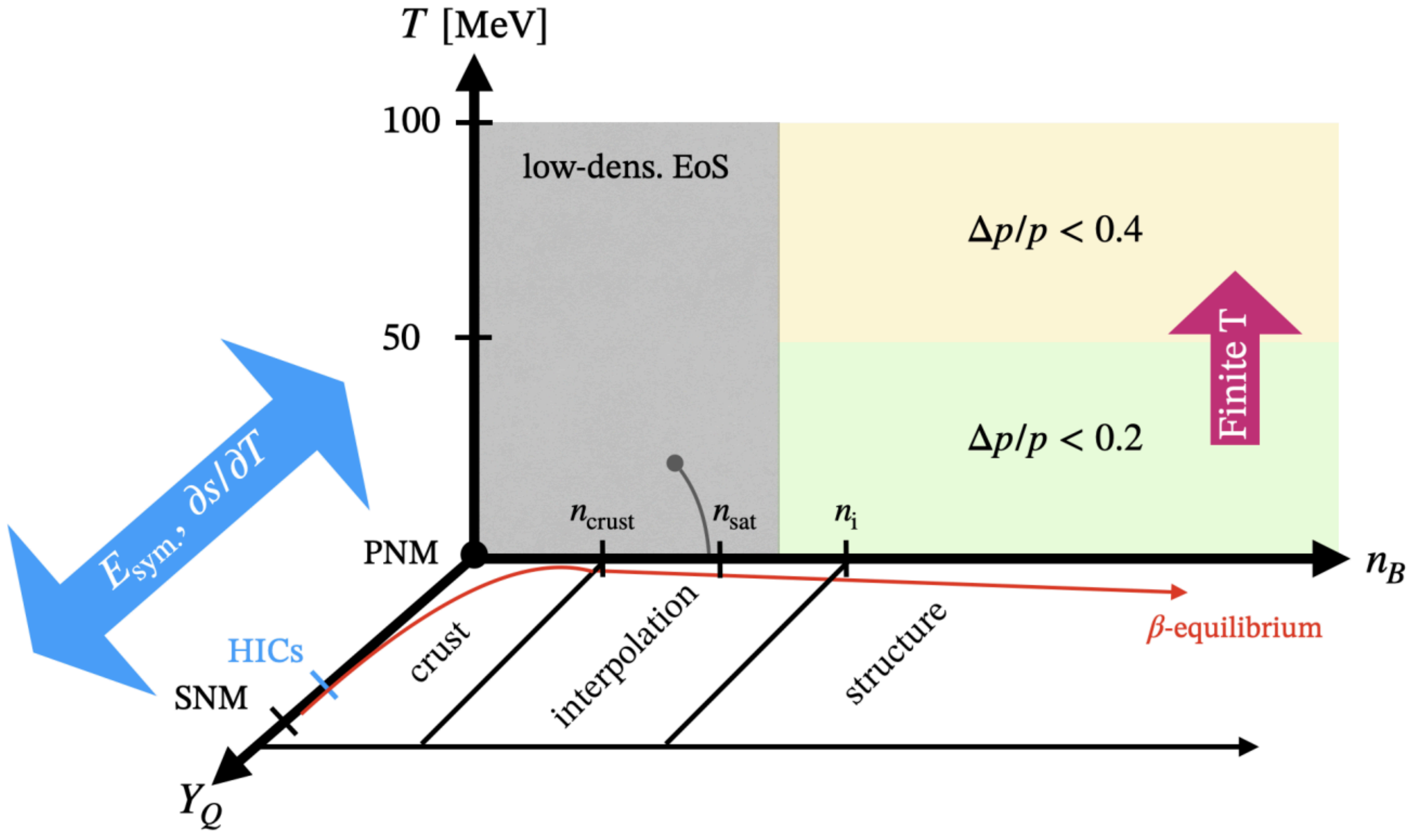
$$R_n - R_p = 0.17 \pm 0.03(stat) \pm 0.08(syst) \text{ for } {}^{197}Au$$

$$R_n - R_p = 0.44 \pm 0.05(stat) \pm 0.08(syst) \text{ for } {}^{238}U$$

[STAR] *Sci.Adv.* 9 (2023) 1, eabq3903

Yields across $\frac{Z}{A}$ and the neutron star equation of state

Mroczek, Yao et al, 2404.01658 [astro-ph.HE]

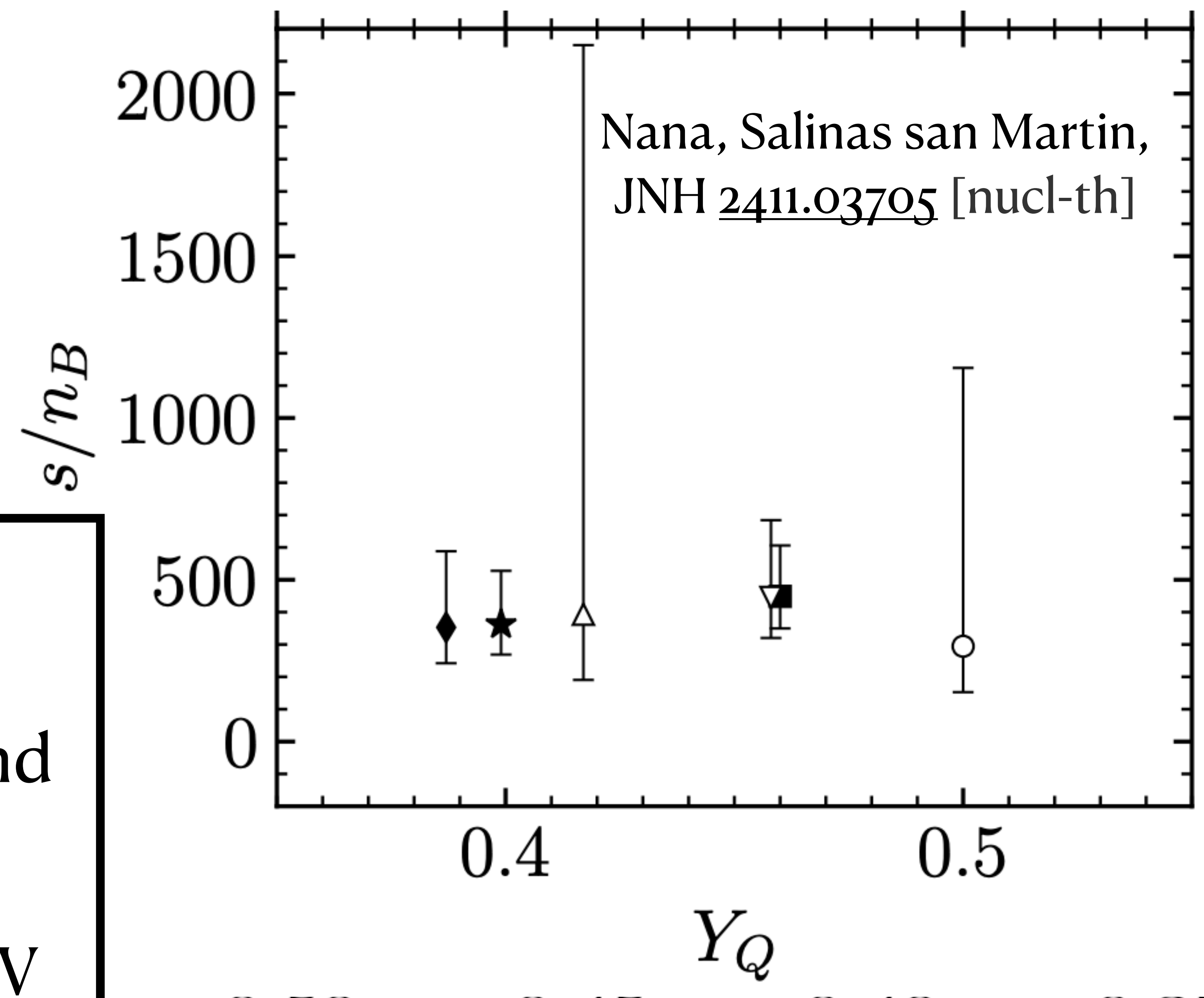


Repurposing isobars

How do we get this information?

Thermal models from heavy-ion collisions and varying Y_Q!

Proof-of-principle from RHIC $\sqrt{s} = 200$ GeV

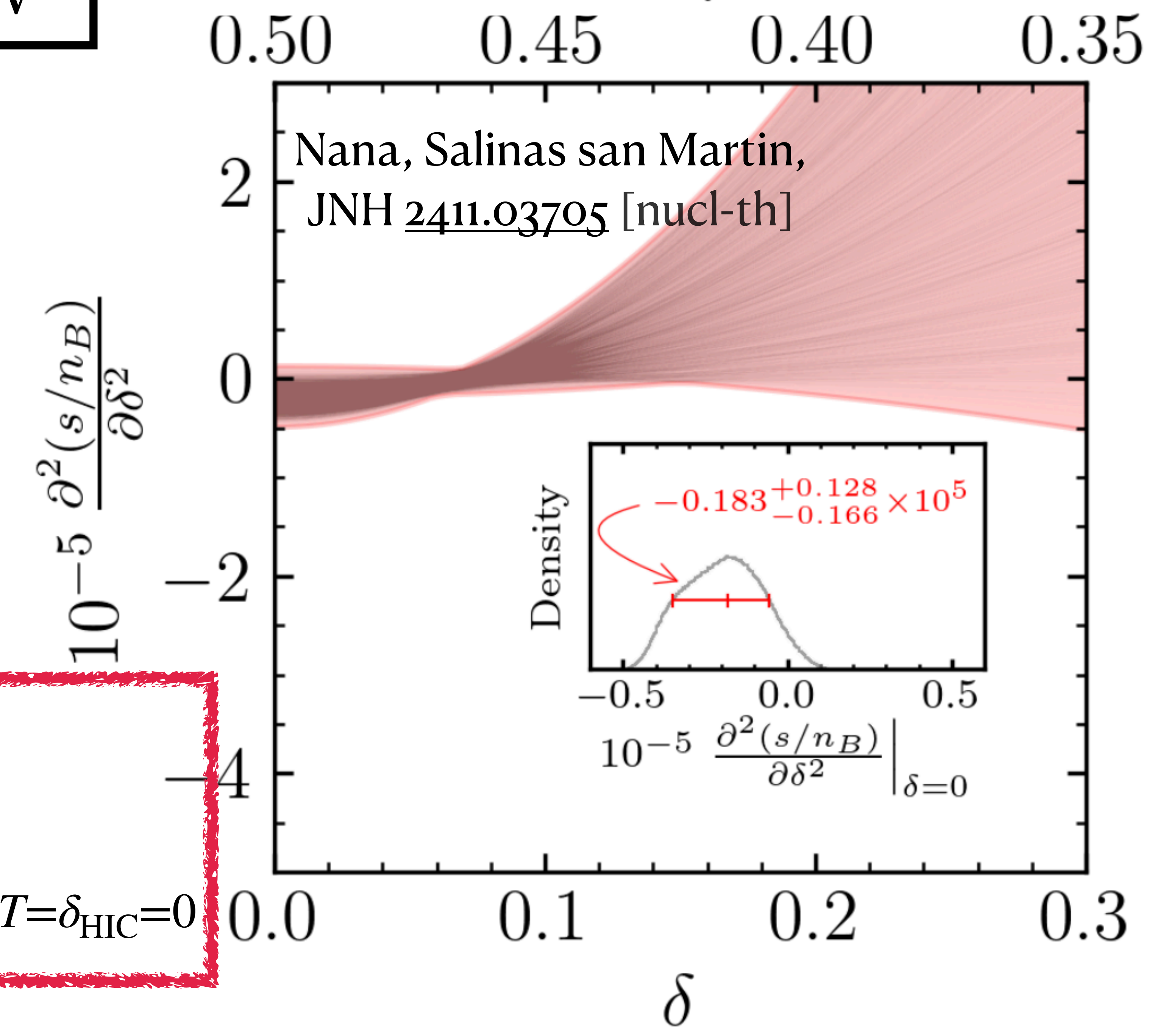


Expand from a cold, neutron star EOS

$$p(T, \vec{\mu}) = p_{T=0} + \frac{1}{2}\frac{\partial s}{\partial T}\Big|_{T=0,\vec{\mu}} T^2 + \mathcal{O}(T^3)$$

Need information about how $\partial s/\partial T$ varies with Y_Q

$$\frac{\partial s/n_B(T, n_B, Y_Q)}{\partial T}\Big|_{T=0} = \frac{1}{n_B}\frac{\partial s_{\mathrm{HIC}}(T, n_B, Y_Q)}{\partial T}\Big|_{T=\delta_{\mathrm{HIC}}=0} + \frac{1}{2}\left(1 - \frac{Y_Q}{Y_Q^{\mathrm{HIC}}}\right)^2 \frac{\partial^3 (s/n_B)_{\mathrm{HIC},2}(T, n_B, \delta_{\mathrm{HIC}})}{\partial T \partial \delta_{\mathrm{HIC}}^2}\Big|_{T=\delta_{\mathrm{HIC}}=0}$$



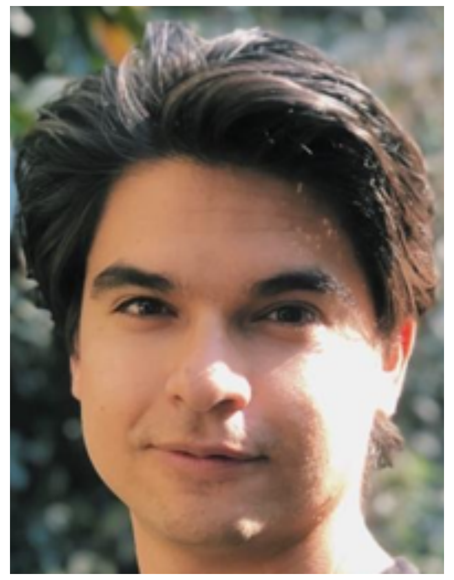
Summary and Outlook

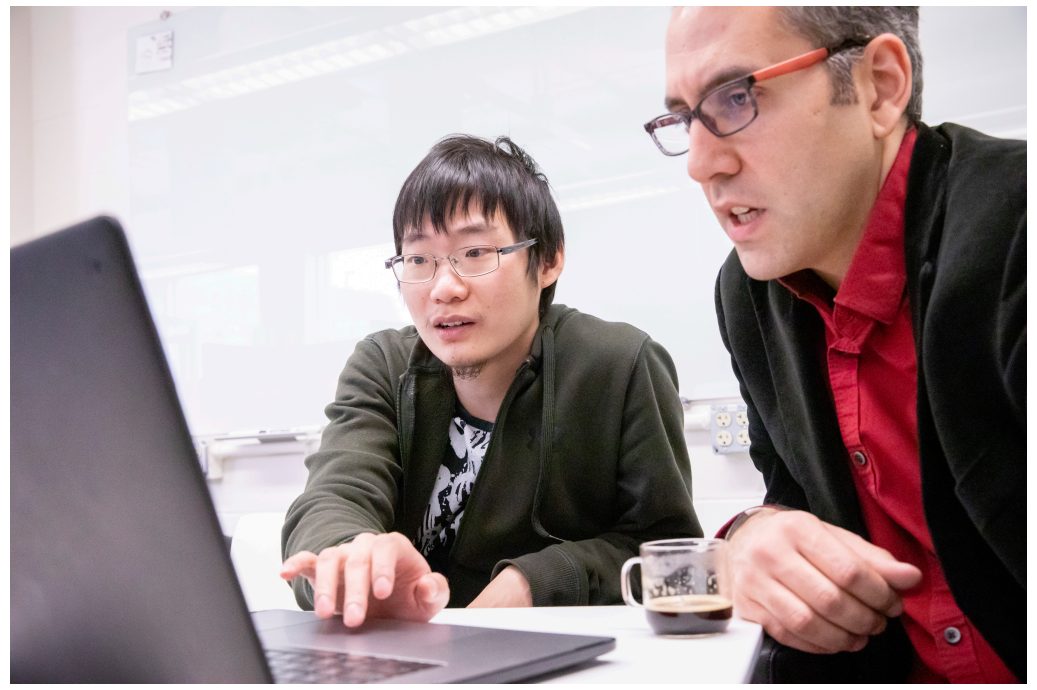
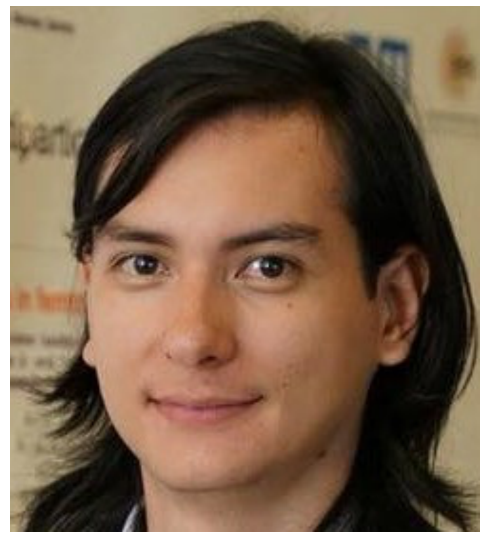
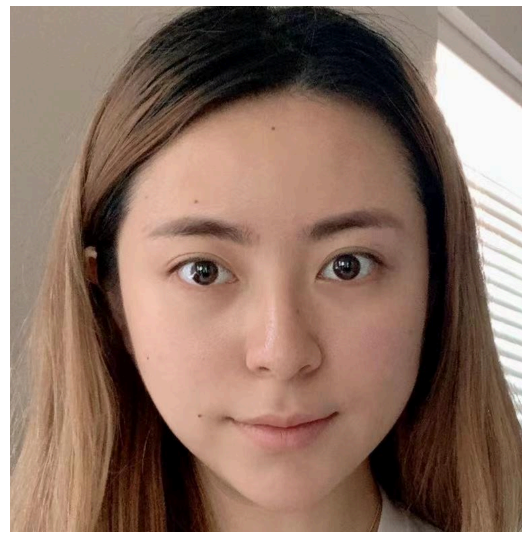
- The QCD phase diagram is inherently interdisciplinary and requires collaborations amongst subfield to fill in gaps
  - More data anticipated from LIGO/Virgo/Karga run 4 (now) & run 5 (2028+)
  - Waiting on STAR Fixed Target
- New fixed target heavy-ion detector: CMB at FAIR in Germany is being built to study the regime between heavy-ions and neutron stars → scans of Z/A
- Possibilities at other fixed target experiments? Here at CERN? AGS? FRIB400?
- (Bulk) Viscosity provides a new opportunity to learn about dense matter, opens up an interdisciplinary field of research
- Strange baryon interaction constraints from ALICE *Nature* 588, 232–238 (2020); *Phys.Lett.B* 844 (2023) 137223

Thank you!

To my group + collaborators







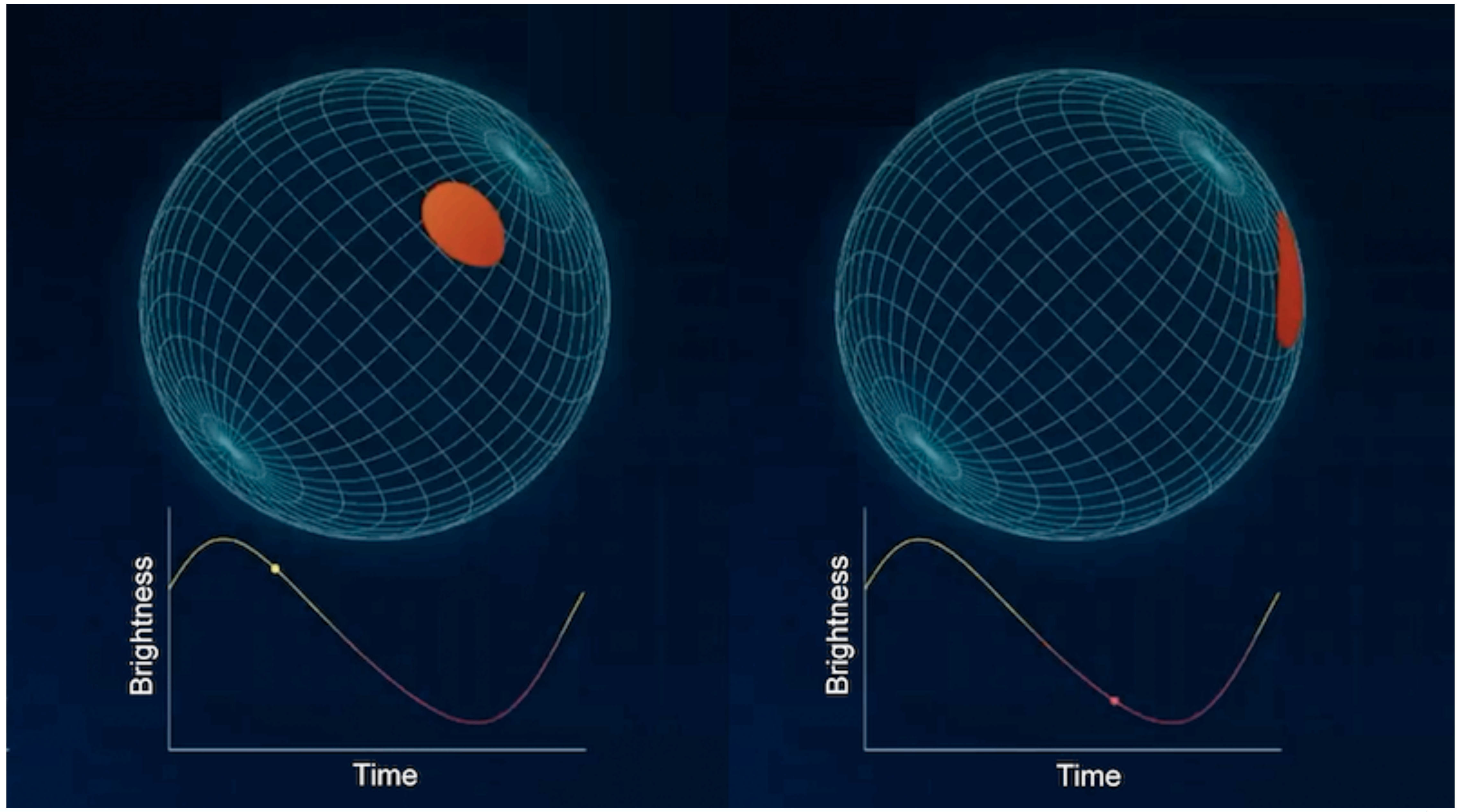

+Isaac Long,
Leonardo Pena,
David Olsen





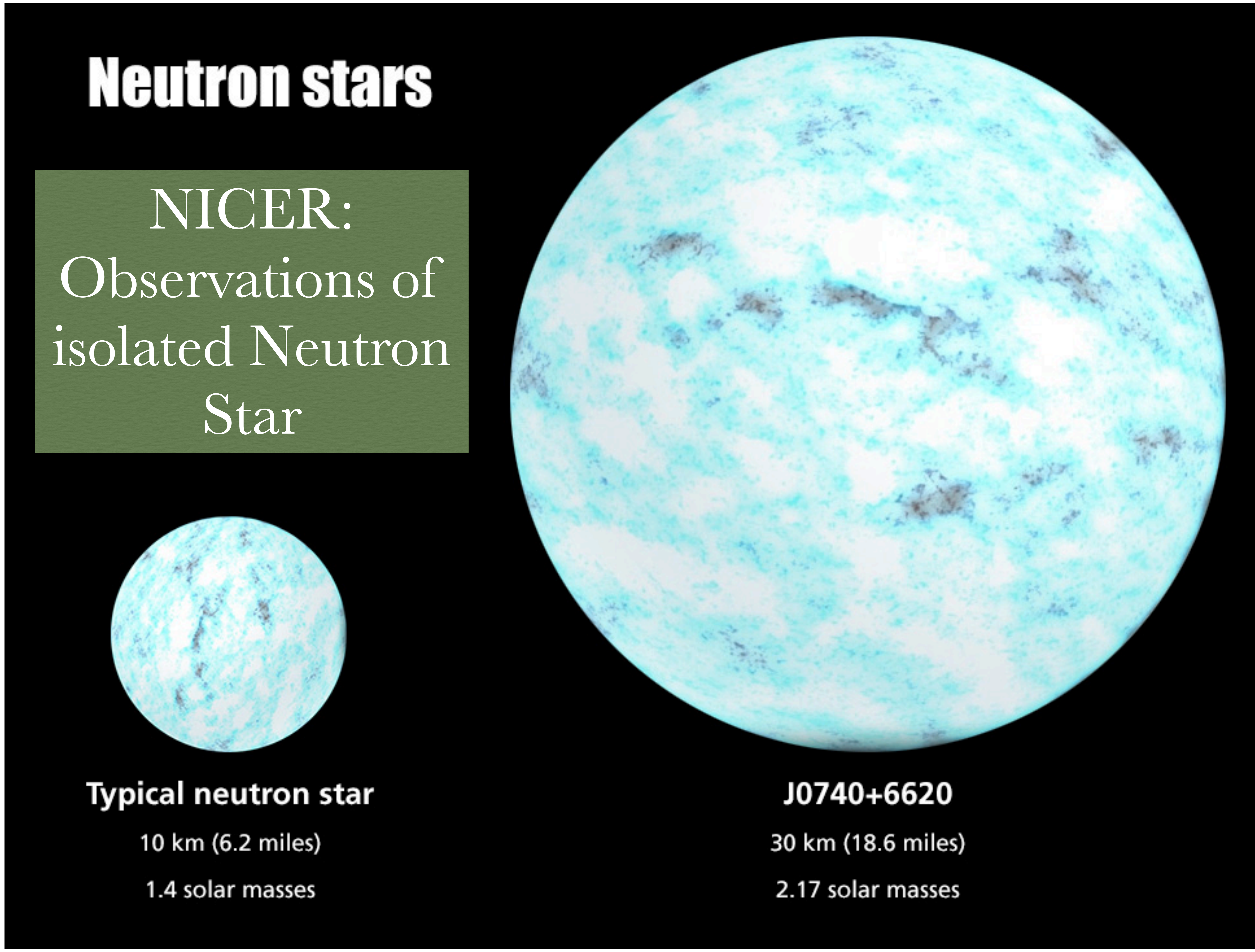
Mass-Radius of Isolated Neutron Stars

NICER collaboration



Heavier stars probe denser region of the EOS

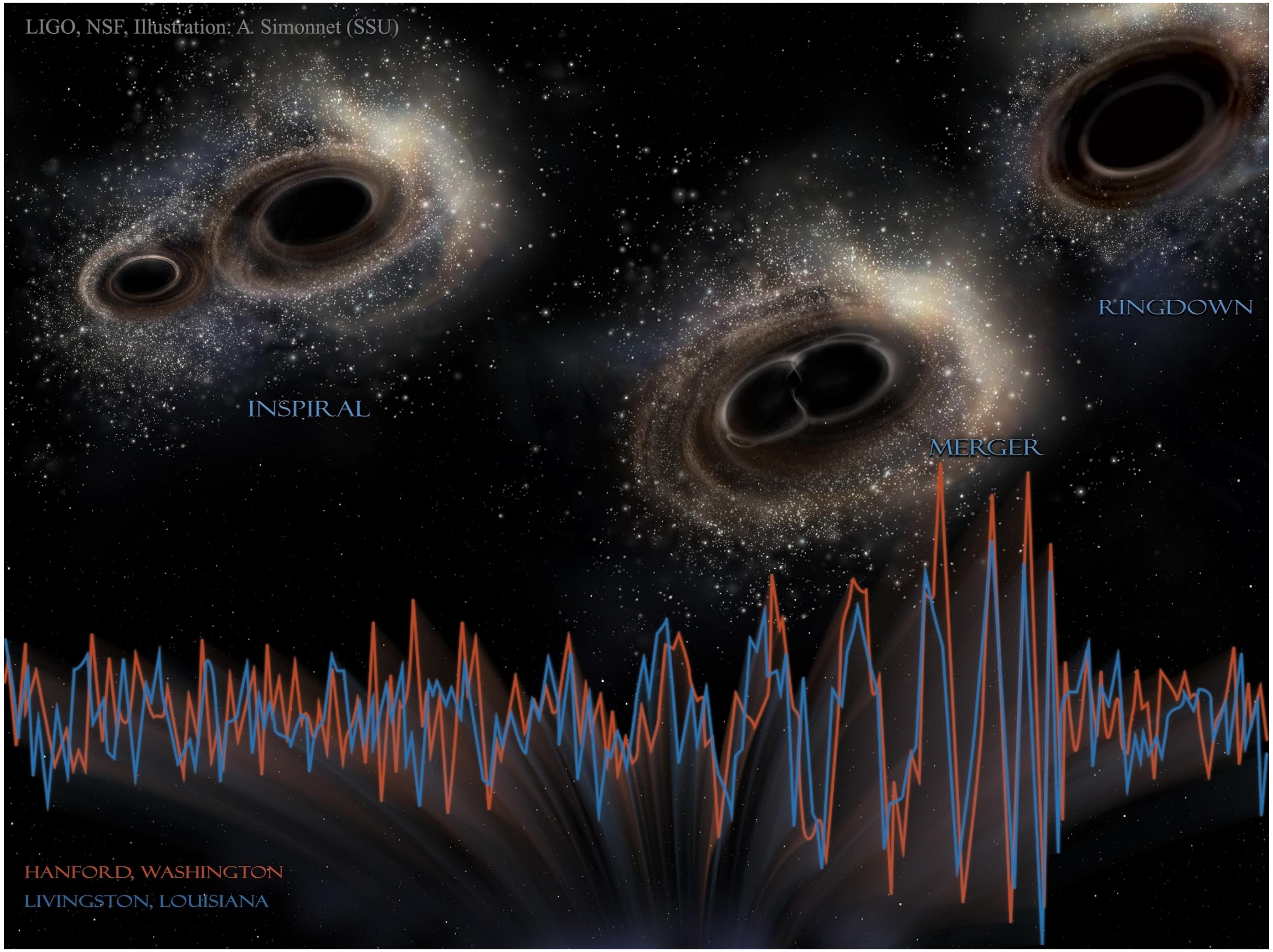
Miller, arXiv:2105.06979 [astro-ph.HE]; Astrophys.J.Lett. 887 (2019) 1, L24;
Raaijmakers, arXiv:2105.06981 [astro-ph.HE]; Astrophys.J.Lett. 887 (2019) 1, L22



NICER: Observations of isolated Neutron Star

Tidal deformability

EOS information from gravitational waves



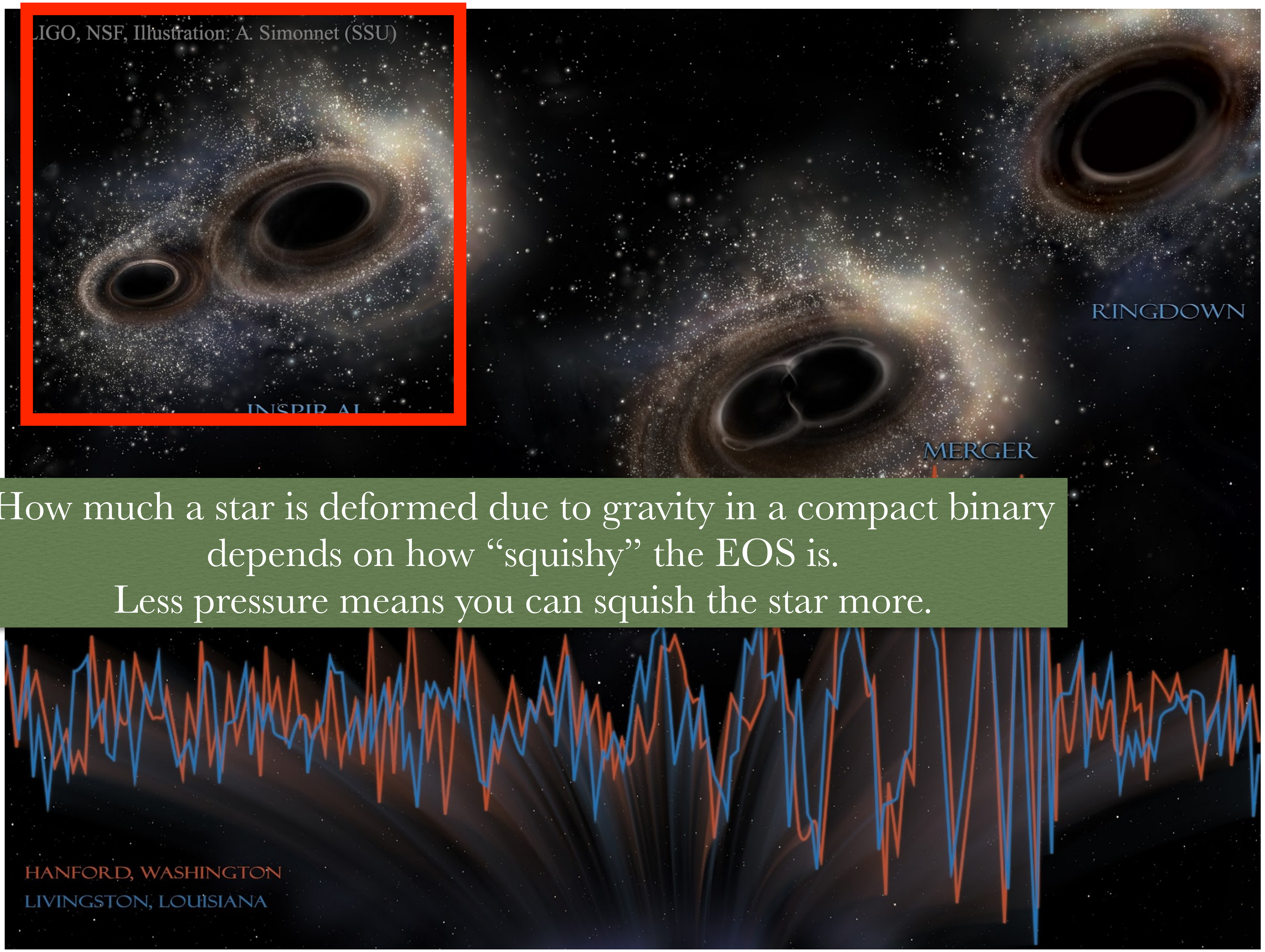
As the two objects approach, they are deformed (elongated)

The EOS dictates how much a neutron star can deform

- Black holes are not deformed $\Lambda = 0$
- Light neutron stars more deformed (large Λ)
- Heavy neutron stars less deformed (small Λ)

Tidal deformability

EOS information from gravitational waves



How much a star is deformed due to gravity in a compact binary depends on how "squishy" the EOS is.
Less pressure means you can squish the star more.

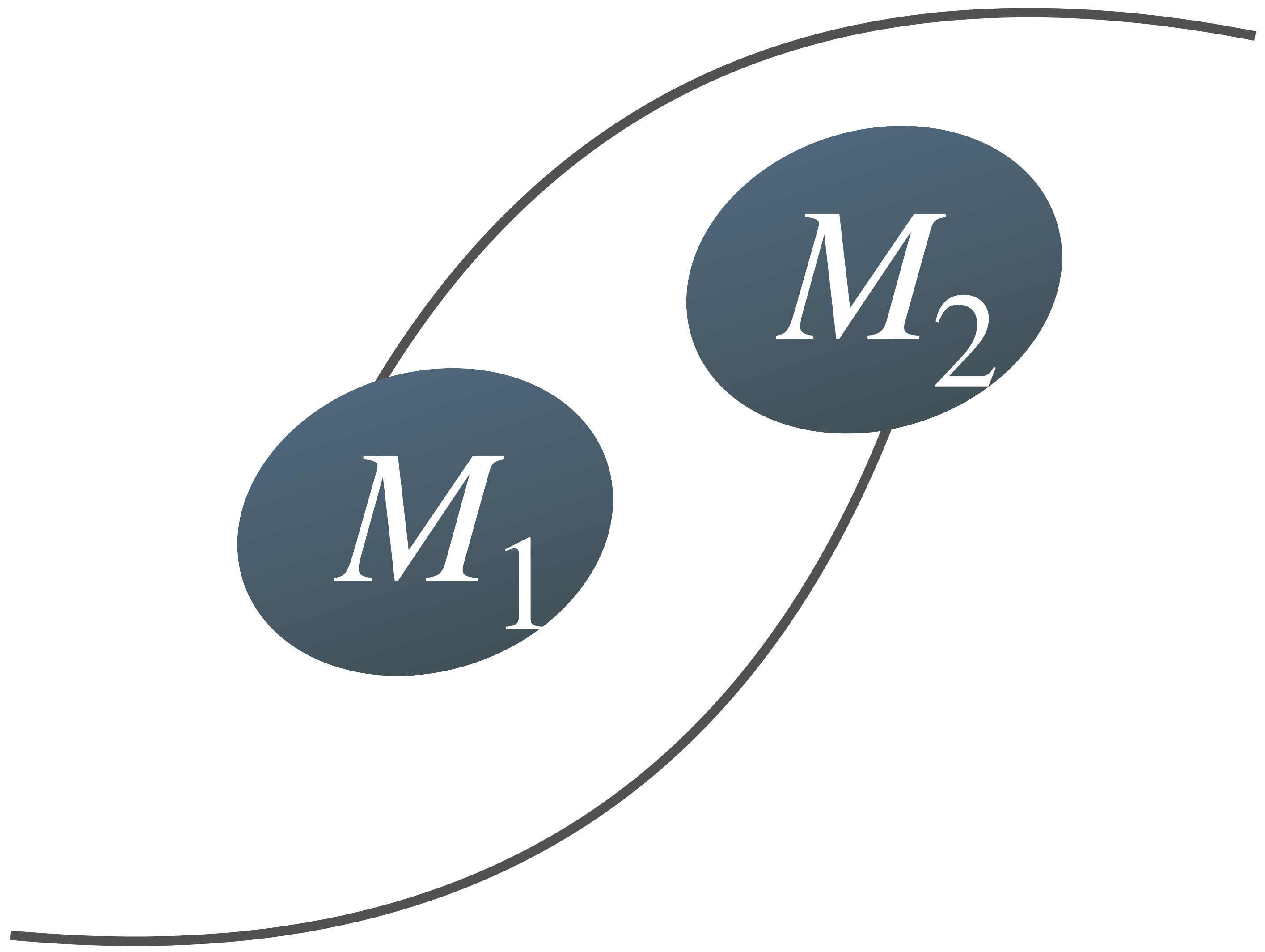
As the two objects approach, they are deformed (elongated)

The EOS dictates how much a neutron star can deform

- Black holes are not deformed $\Lambda = 0$
- Light neutron stars more deformed (large Λ)
- Heavy neutron stars less deformed (small Λ)

Breaking tidal deformability degeneracy

Binary love relation



We set m_1 to be the lighter mass and m_2 is the heavier star

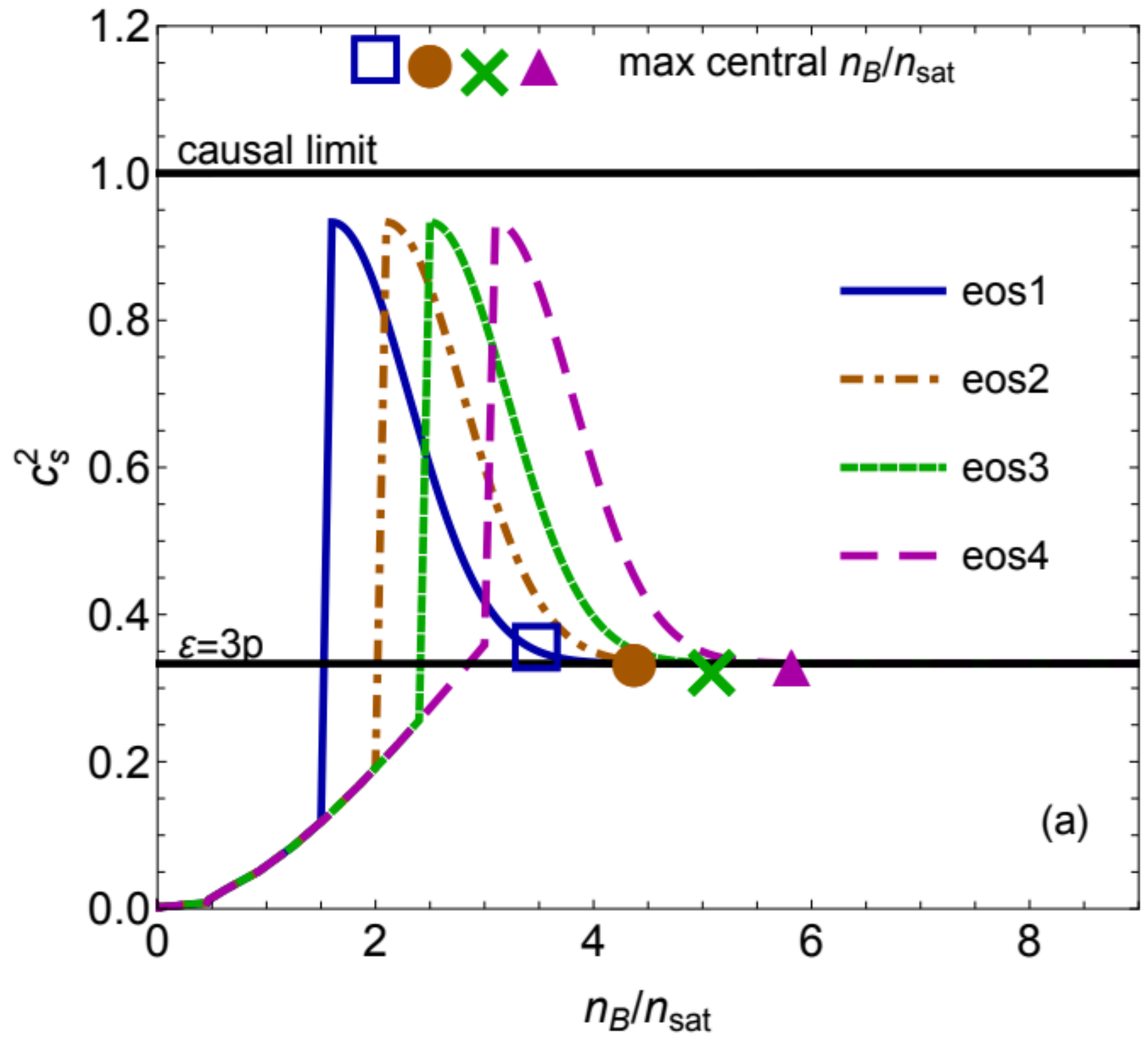
From gravitational waves, we obtain a combination of tidal deformabilities from each star

$$\tilde{\Lambda} \equiv \frac{16}{13}\frac{(M_1 + 12M_2)M_1^4\Lambda_1 + (M_1 + 12M_2)M_2^4\Lambda_2}{(M_1 + M_2)^5}$$

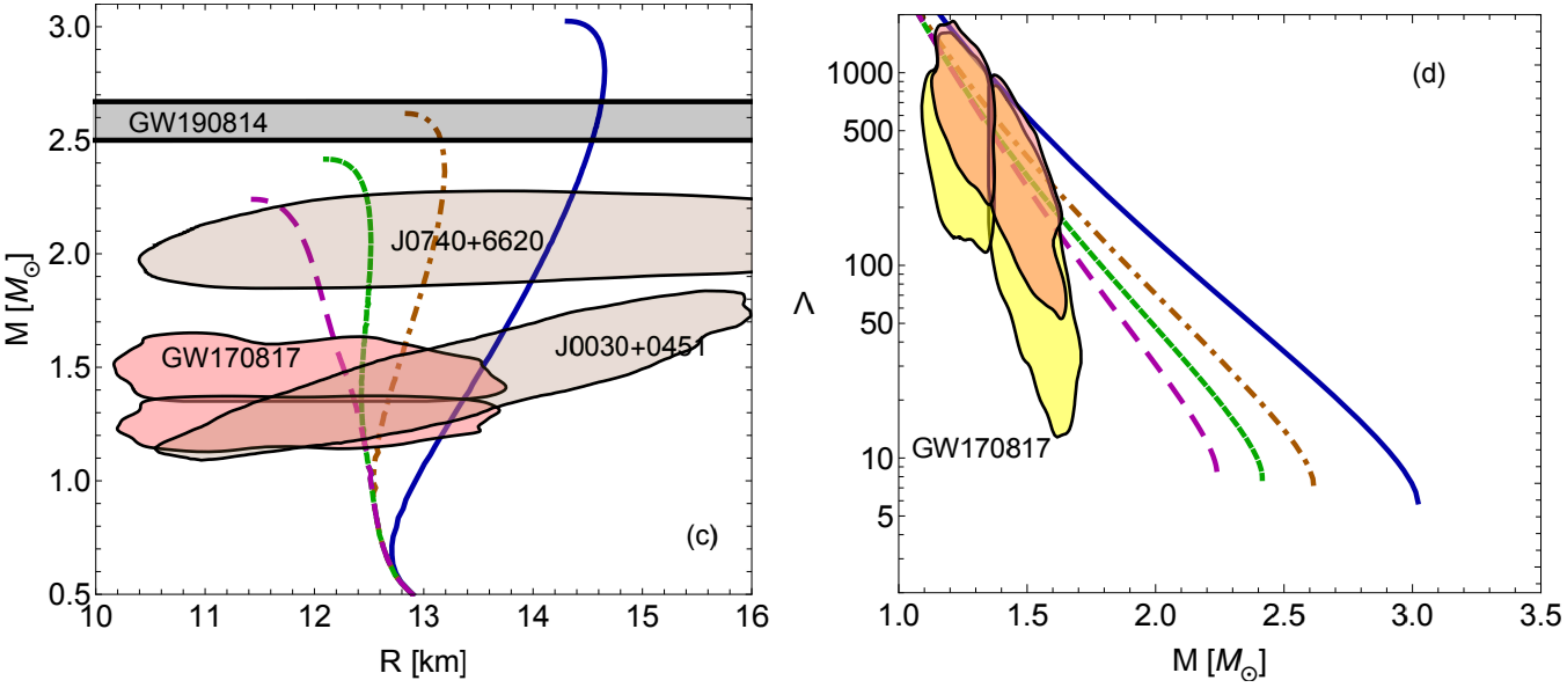
Need something to break the degeneracy between Λ_1 and Λ_2

Connecting an EOS to data

Need TOV and solve Einstein equations up to 2nd order in slow rotations



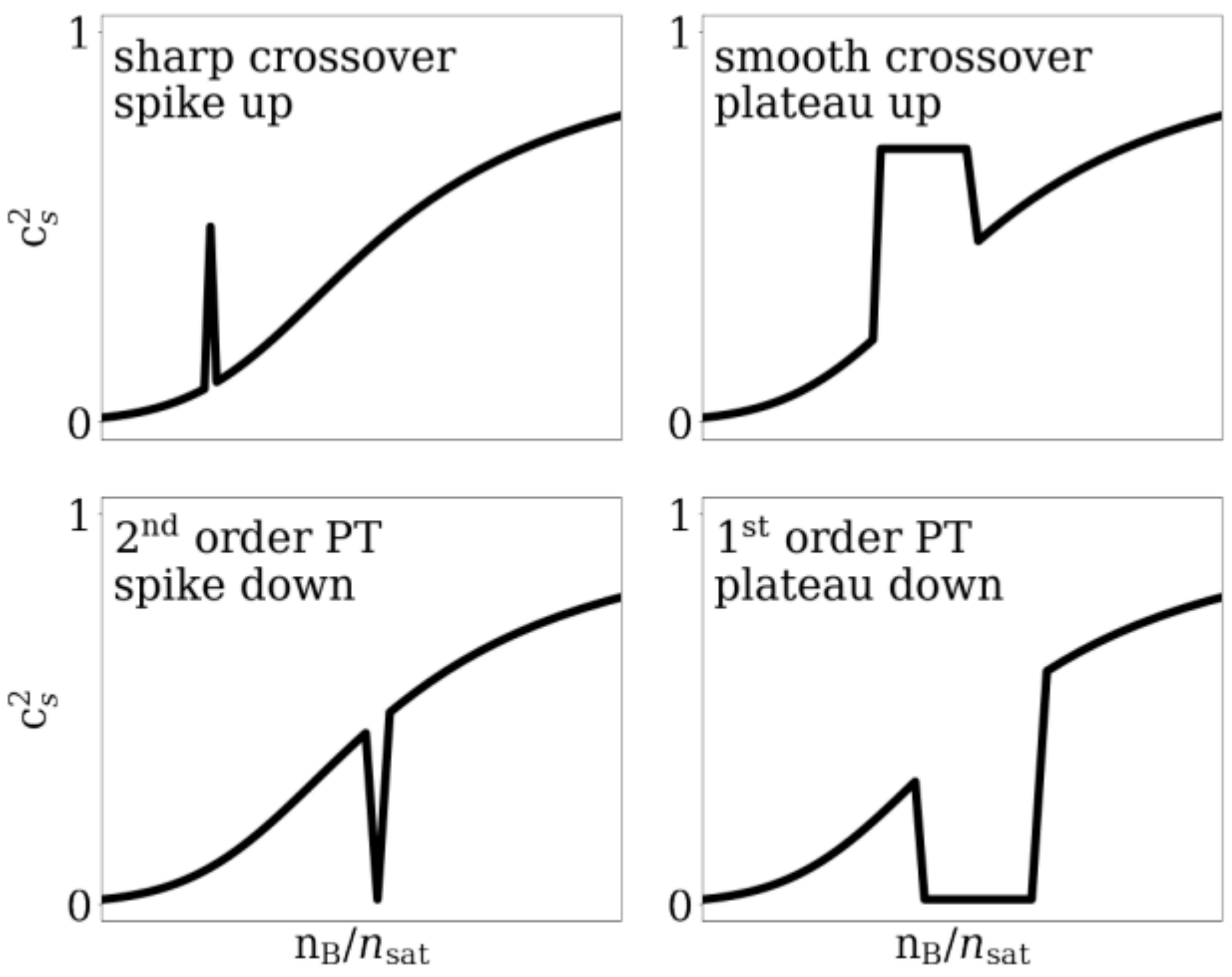
Given an EOS we can obtain a specific $M(R)$ and $\Lambda(M)$

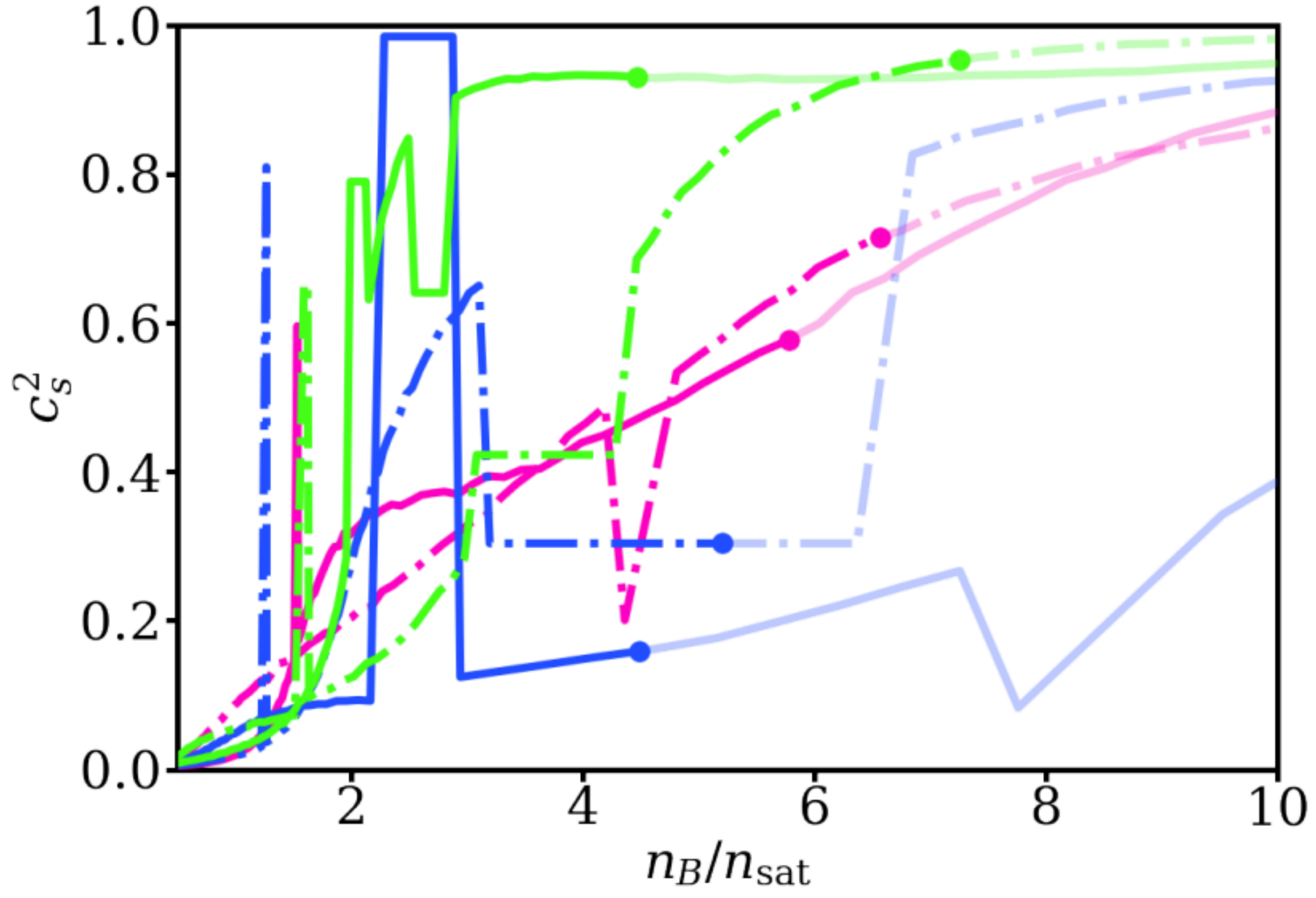


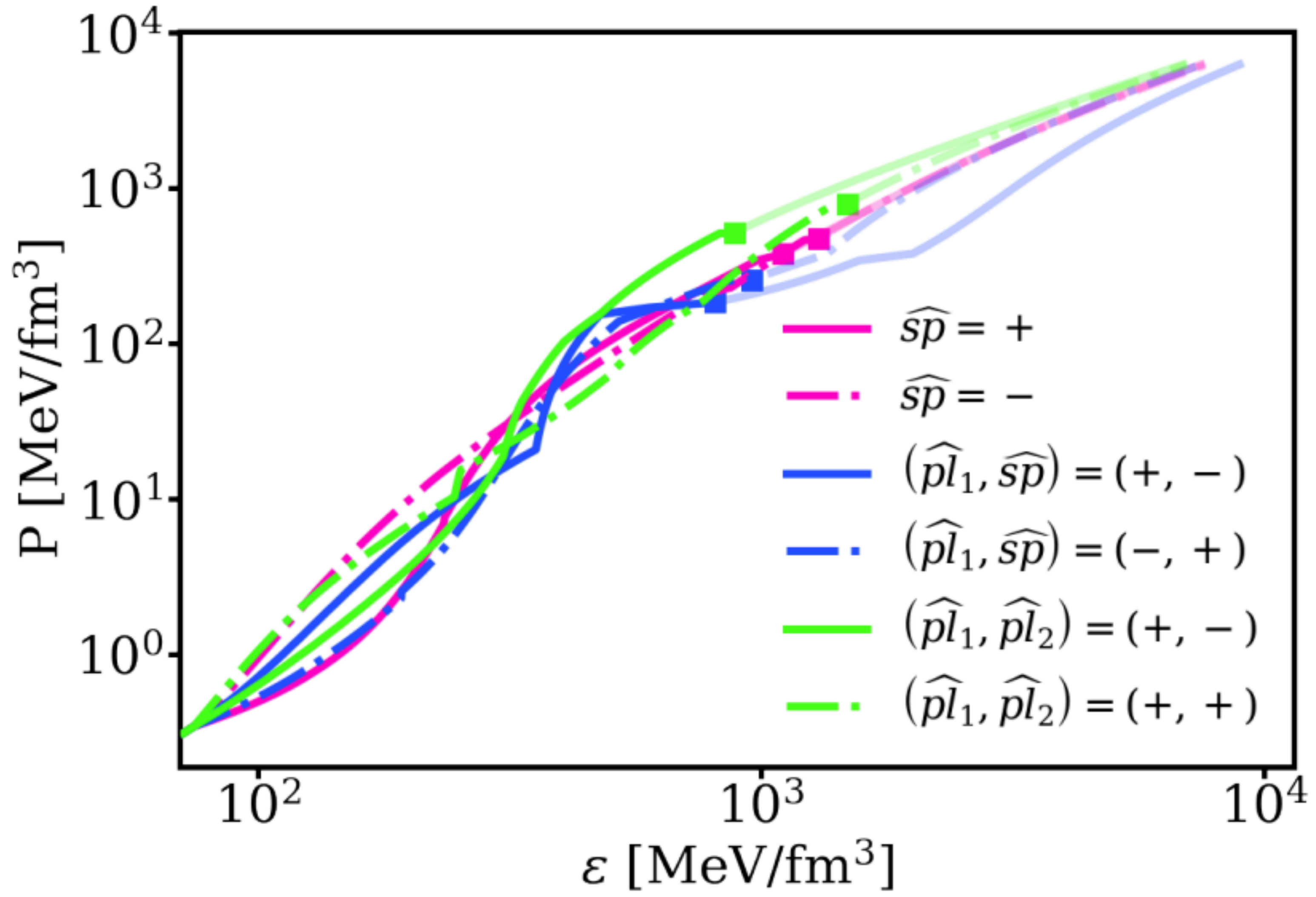
Neutron stars with structure in EOS

Functional forms

Mroczek et al, 2309.02345 [astro-ph.HE]





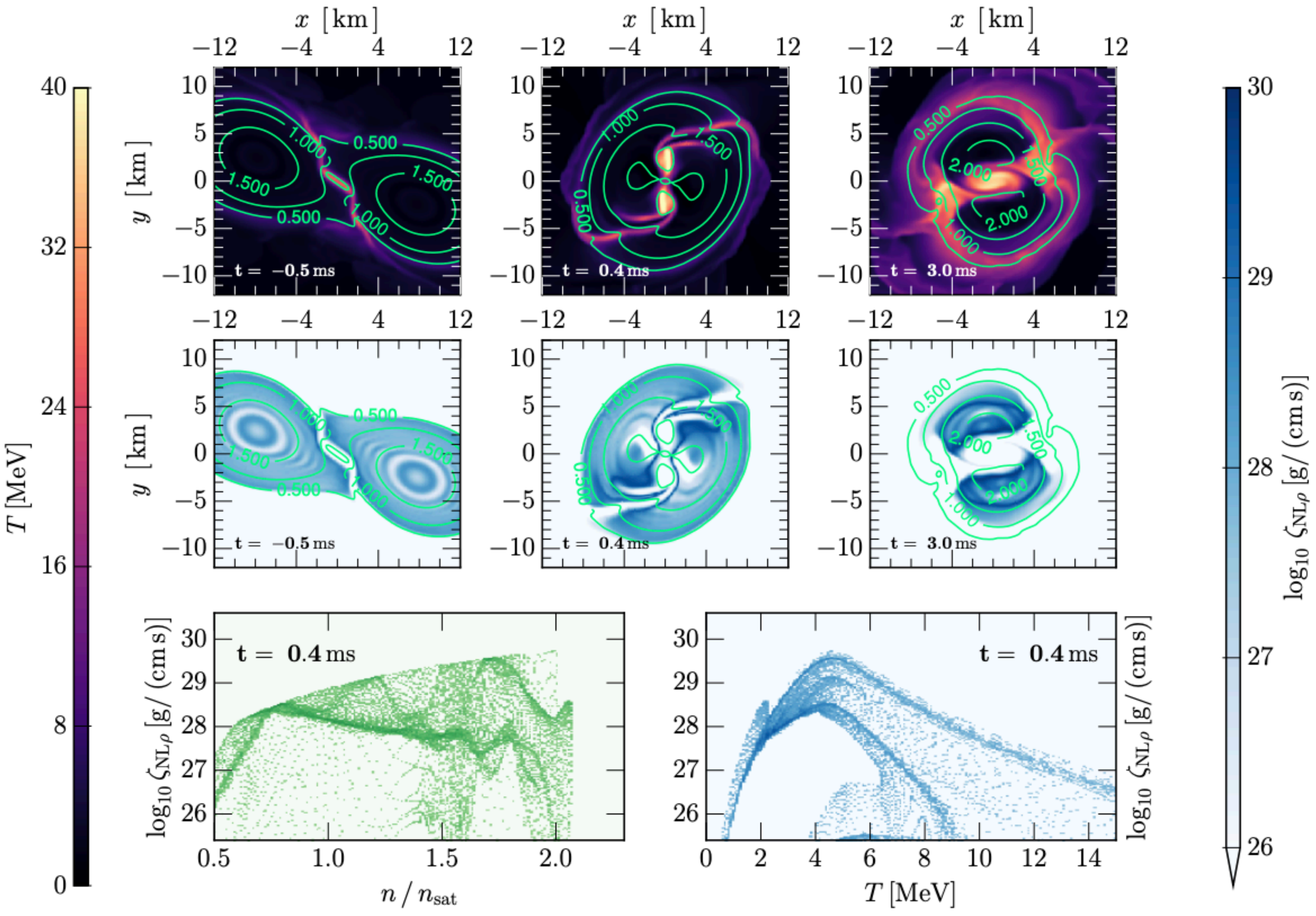


Features built into the EOS and example EOS using modified Gaussian Processes

Bulk viscosity: heavy-ions vs neutron stars

Post-merger influence of bulk viscosity

Most et al, *Mon.Not.Roy.Astron.Soc.* 509 (2021) 1, 1096-1108



Gaps in our knowledge

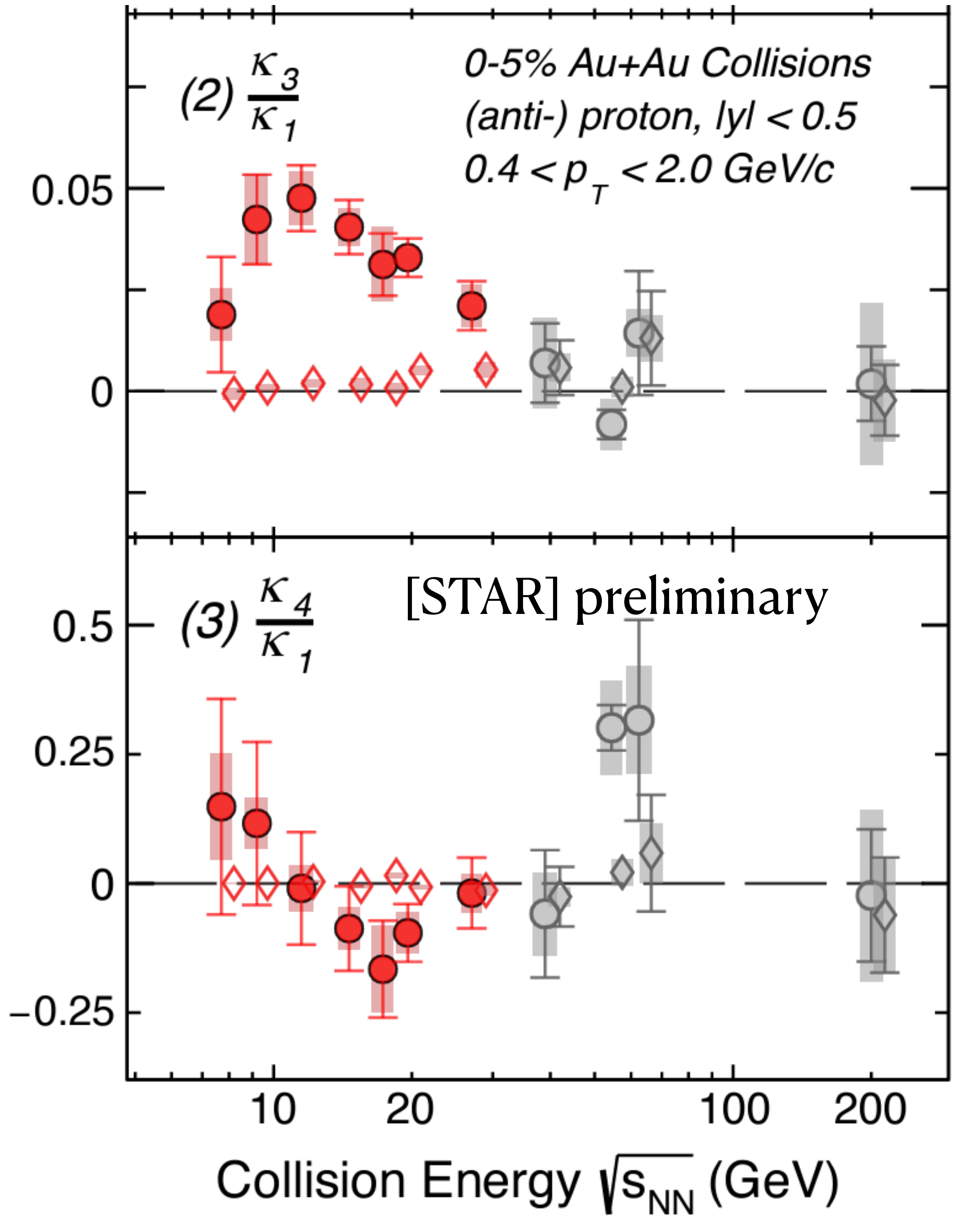
How do we interpret data?

Collider mode Heavy-ion collisions $\sqrt{s} \geq 7.7\,GeV$

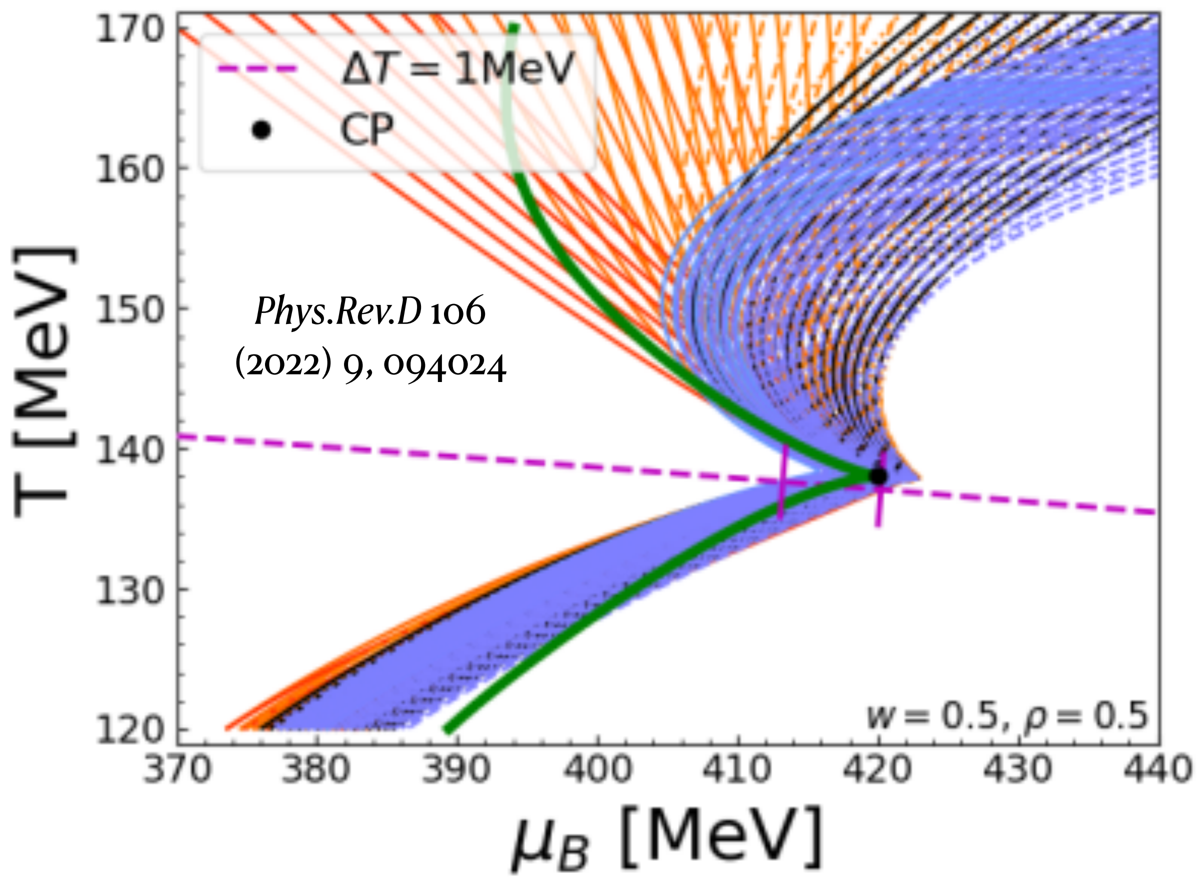
Exp. Observables: flow, multiplicity, fluctuations, HBT, … = Hundreds of data points!
Theory constraints: *thermodynamic* stability in 4D (Appendix E in 2409.06837 [nucl-th]),
out-of-equilibrium causality/stability (*Phys.Rev.Lett.* 126 (2021) 22, 222301, 2209.11210 [hep-th])

Model: Rel. viscous hydrodynamics+conserved charges, many unknowns in the initial state, EOS, transport coefficients etc

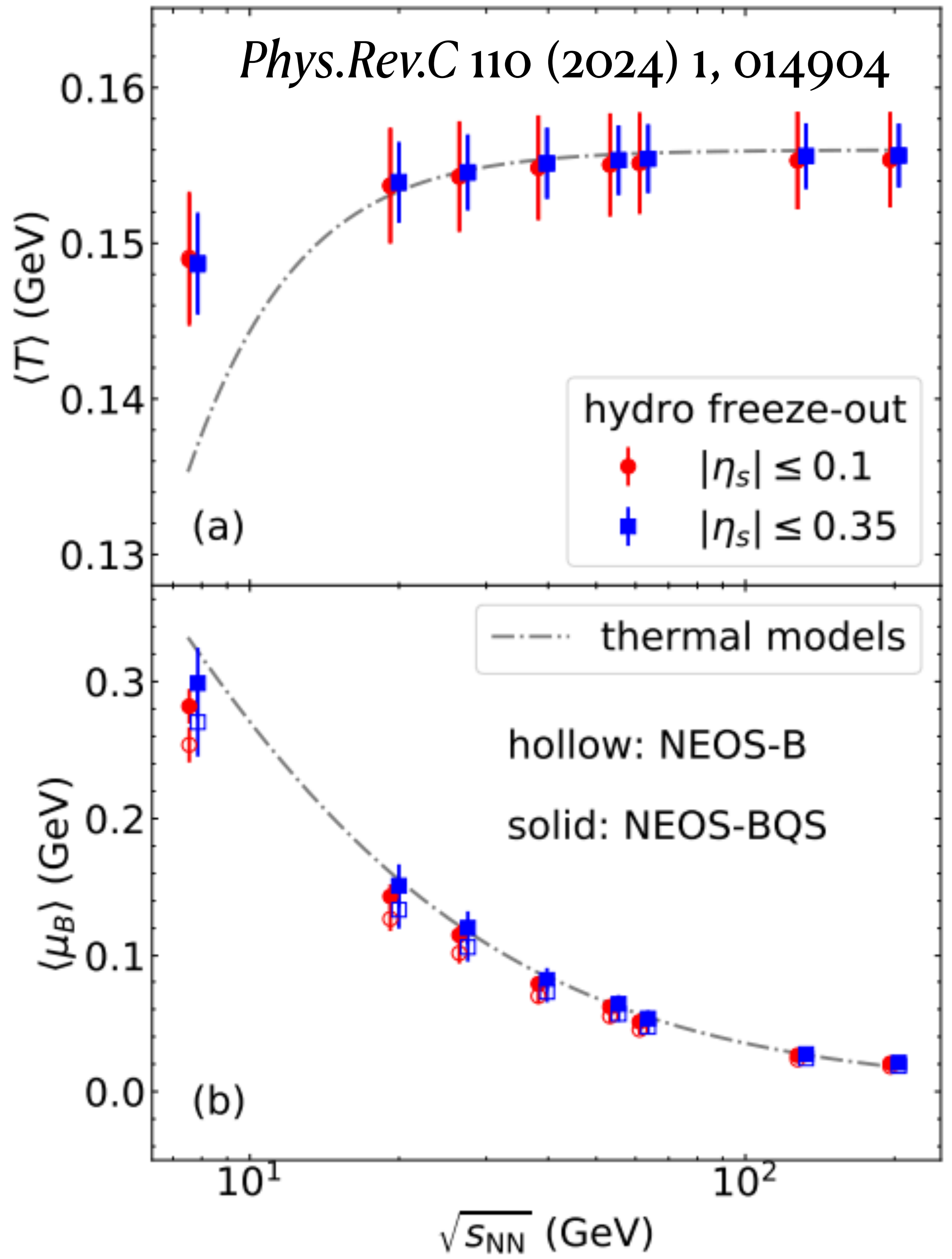
Desperately needed: collaboration to put together these tools and conduct a Bayesian analysis with the data!
Further details: 2211.02224 [nucl-th]; *Nucl.Phys.A* 1017 (2022) 122343



Hints of a critical point, but need full scale analysis of out-of-equilibrium effects



Out-of-equilibrium changes path through phase diagram



Head on collisions and deformations

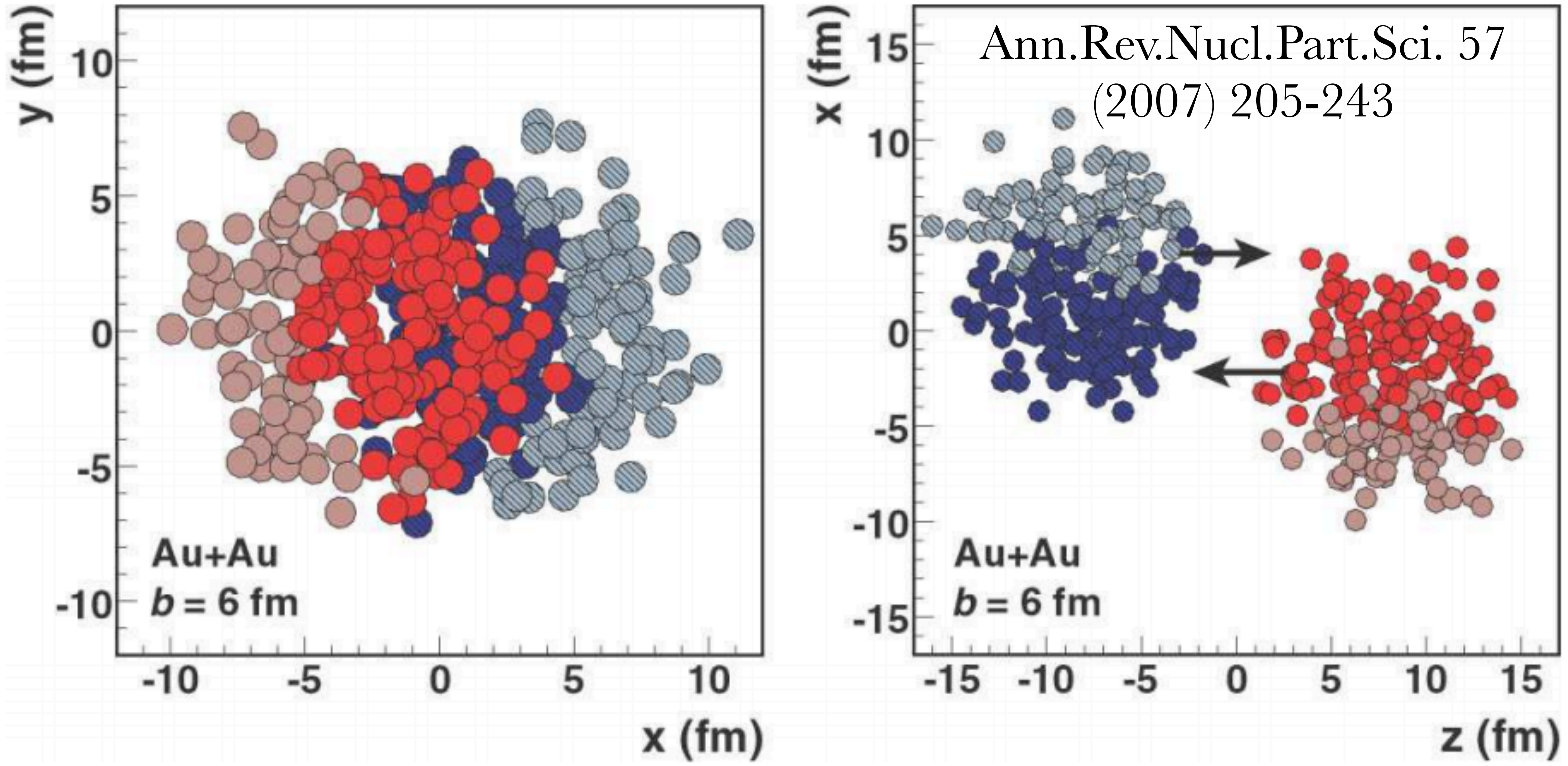
Centrality $\% = 0$ for head on collisions

Terminology:

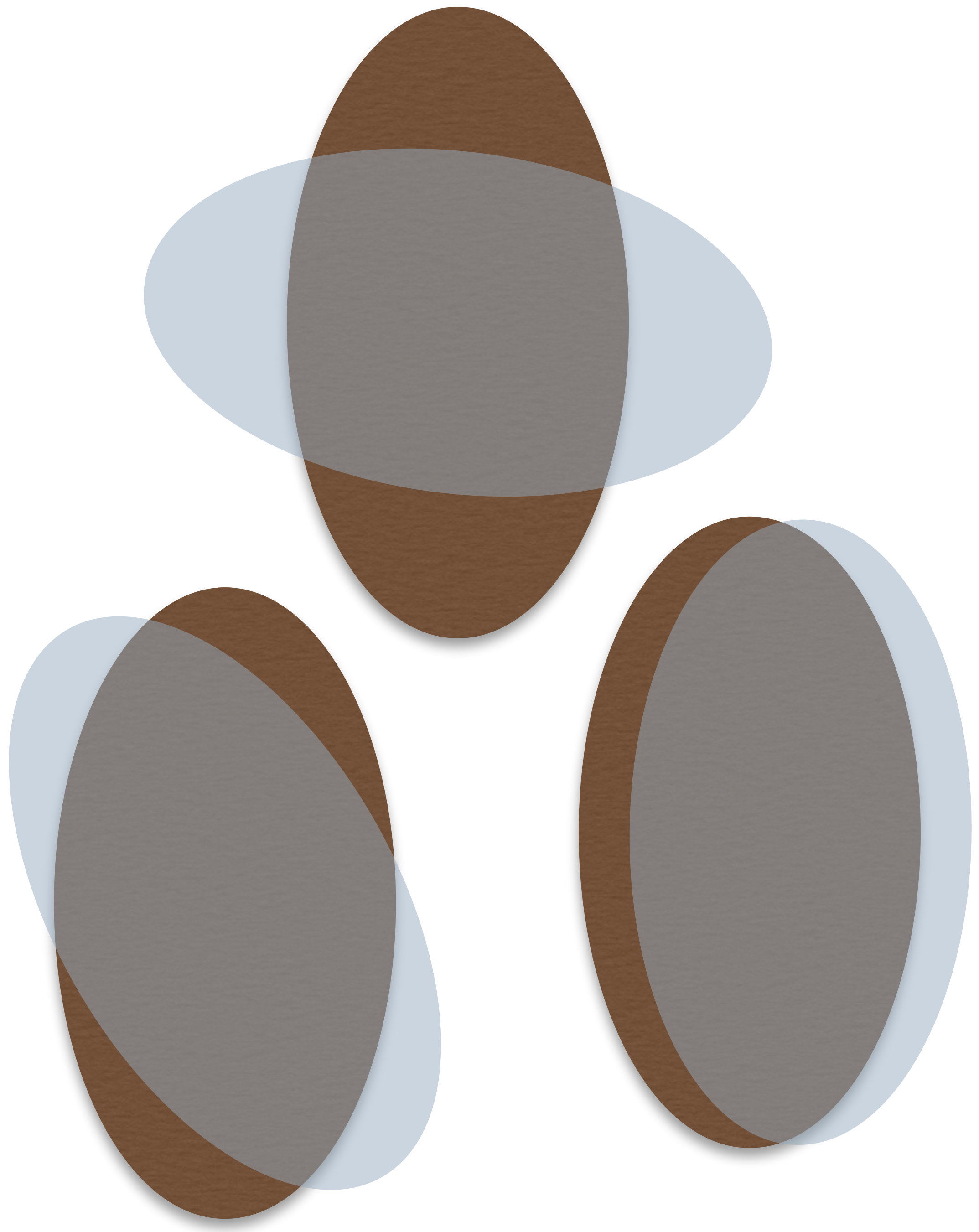
-participants (colliding nucleons)

-spectators (fly off to the detector)

All $b = 0$ impact parameters, very different shapes



Ann.Rev.Nucl.Part.Sci. 57 (2007) 205-243



Head-on collisions most sensitive to structure, but $b = 0$ does not necessarily mean ultra central!