



**I** | Illinois Center for Advanced Studies of the Universe



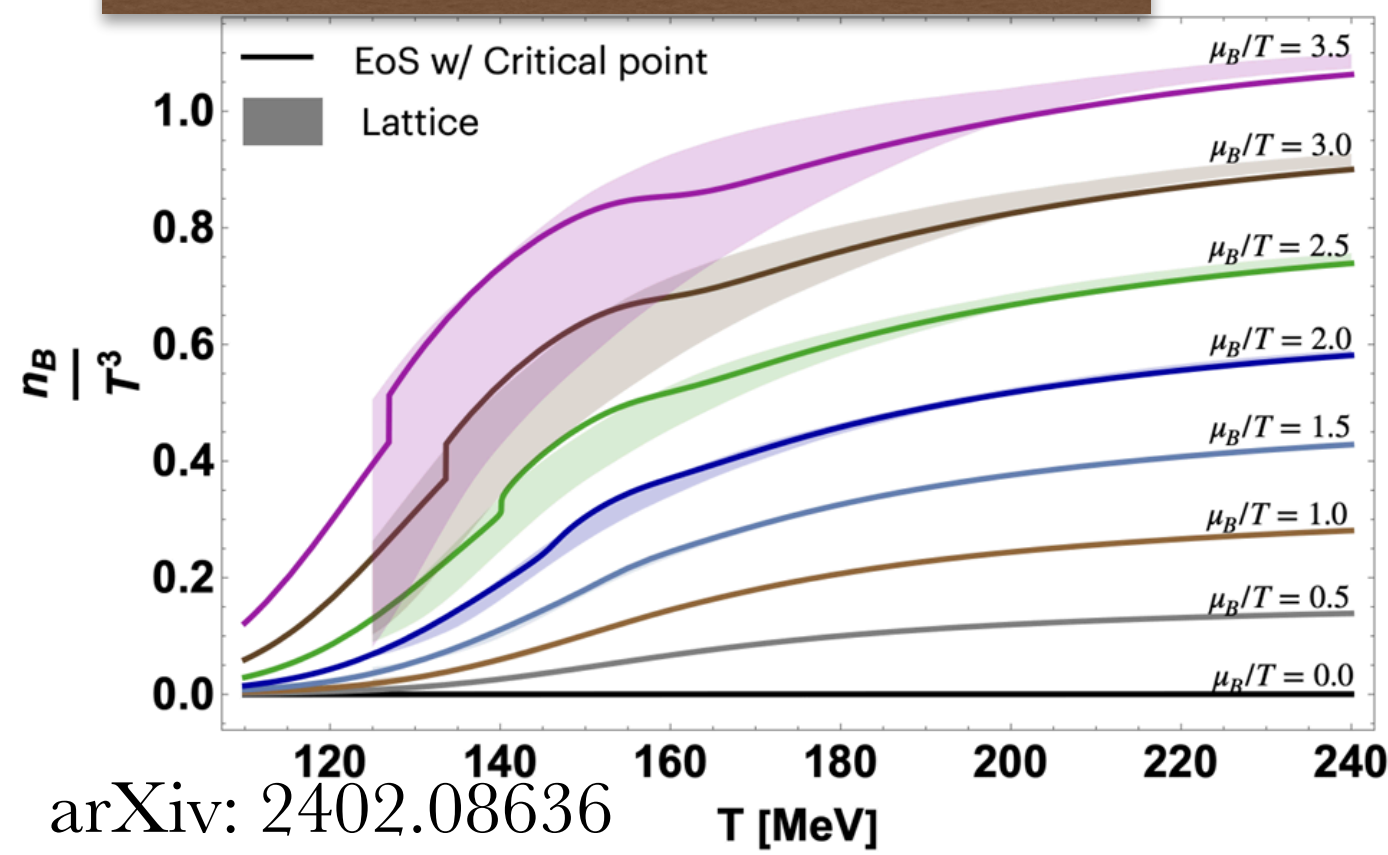
# Theory Overview/State-of-the-Art

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University of Illinois Urbana-Champaign

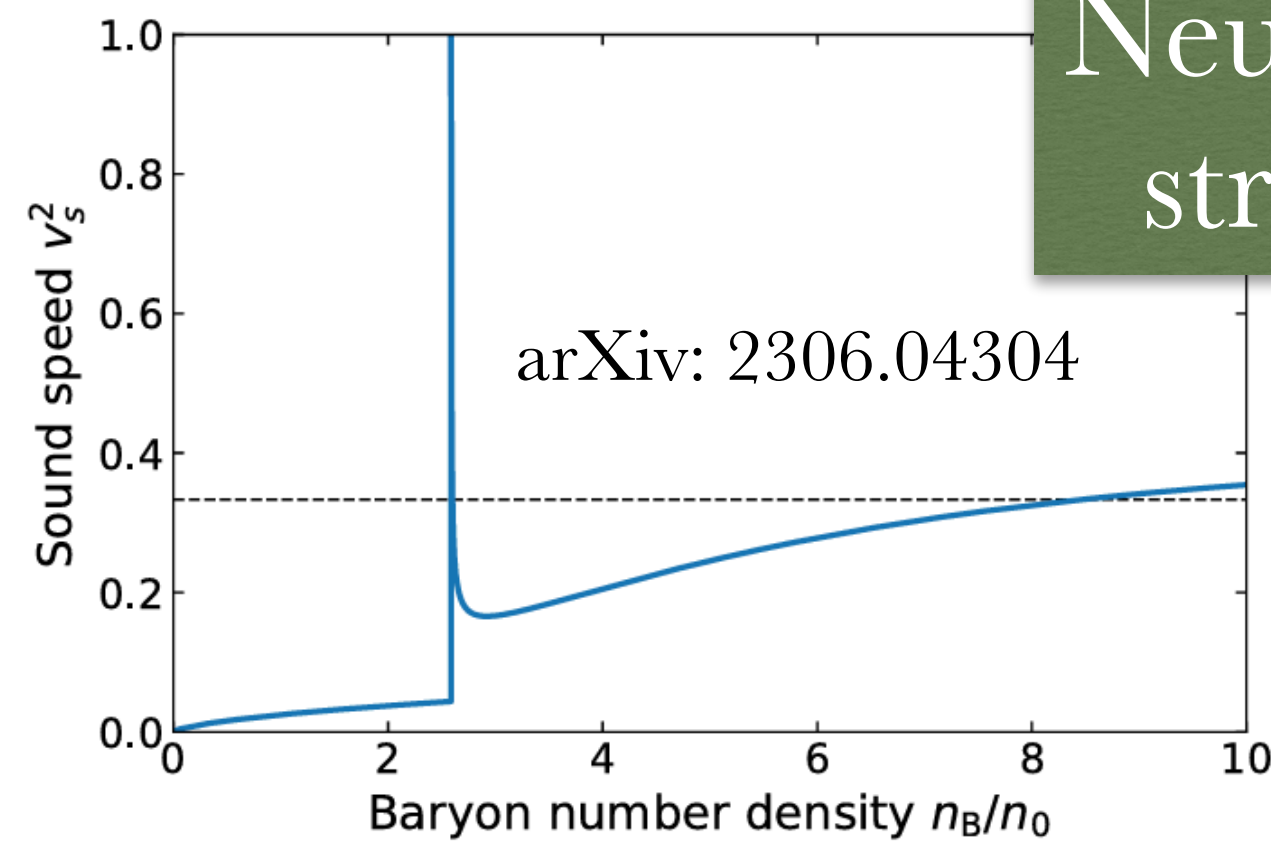
SQM2024: Strasbourg, May 2024

# Theory @ SQM24

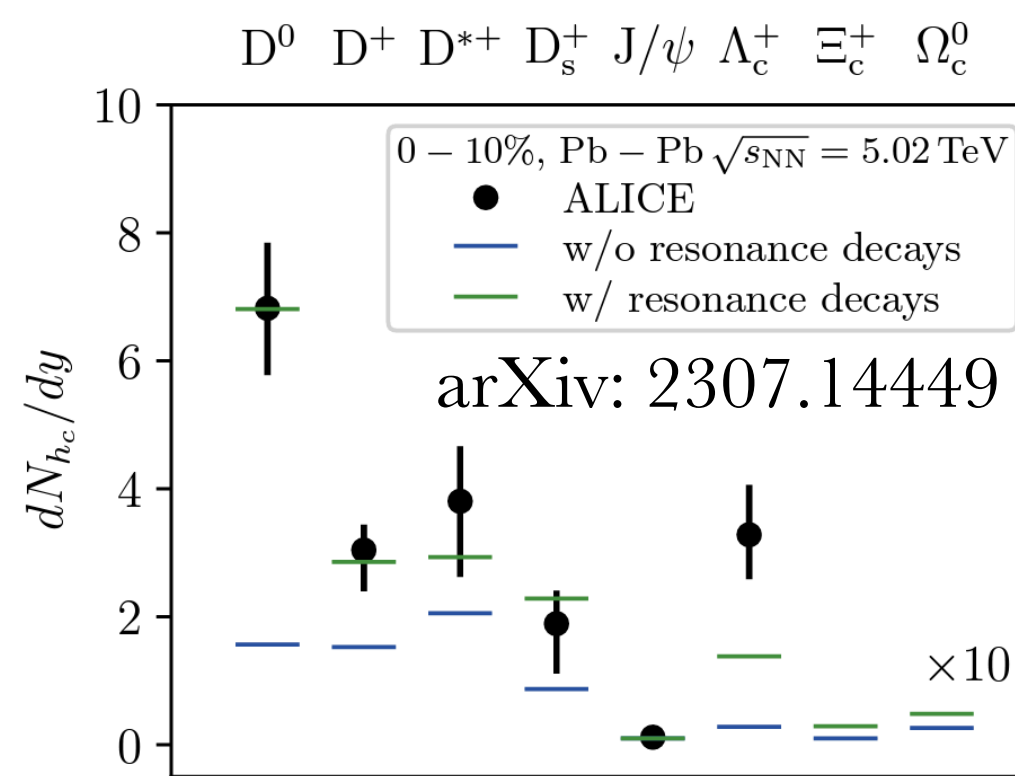
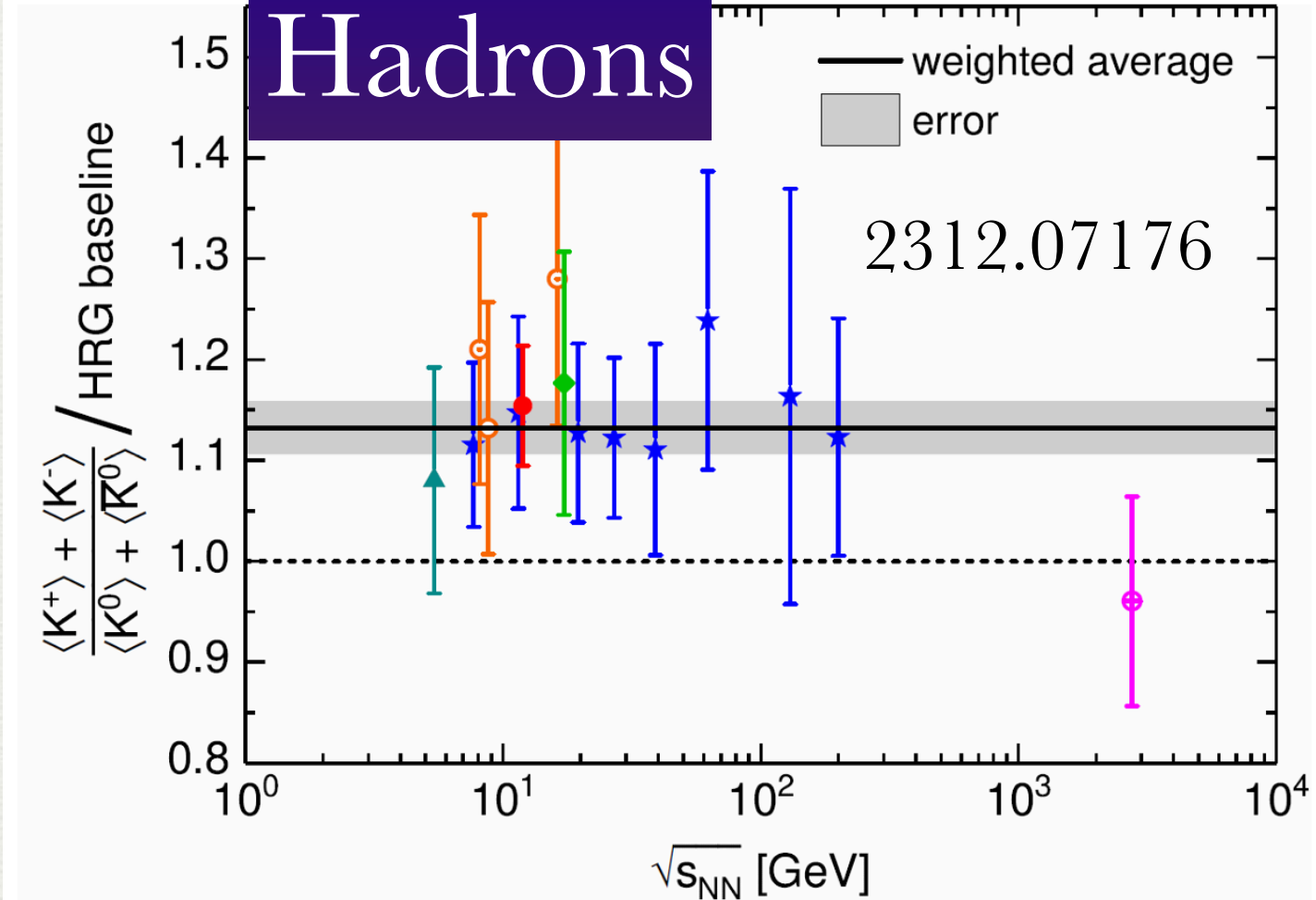
## QCD critical point



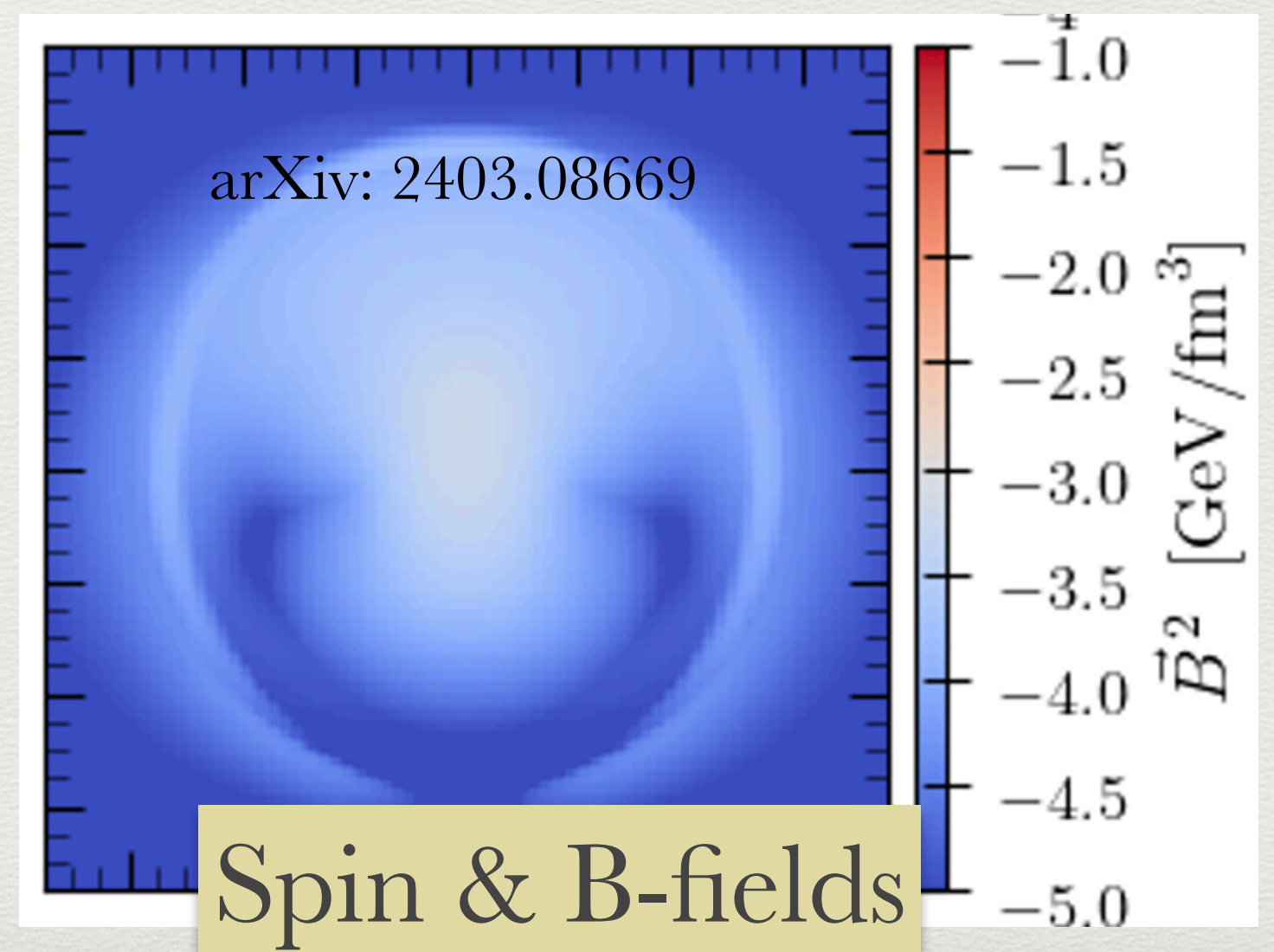
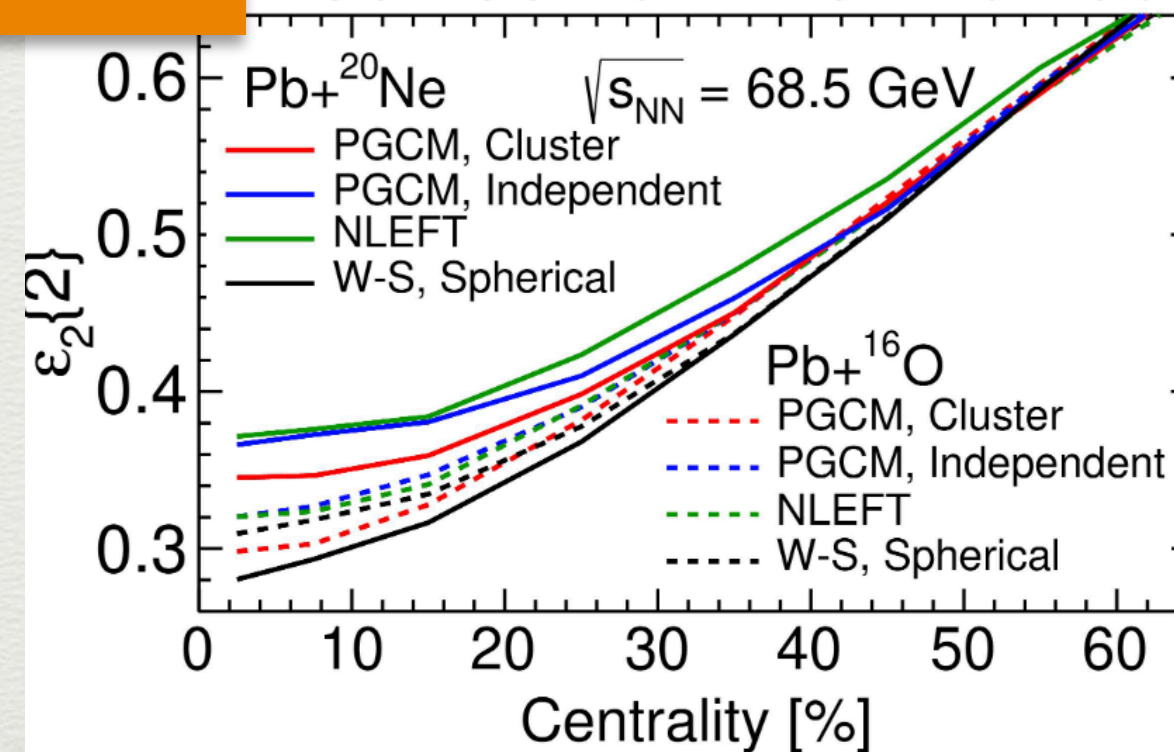
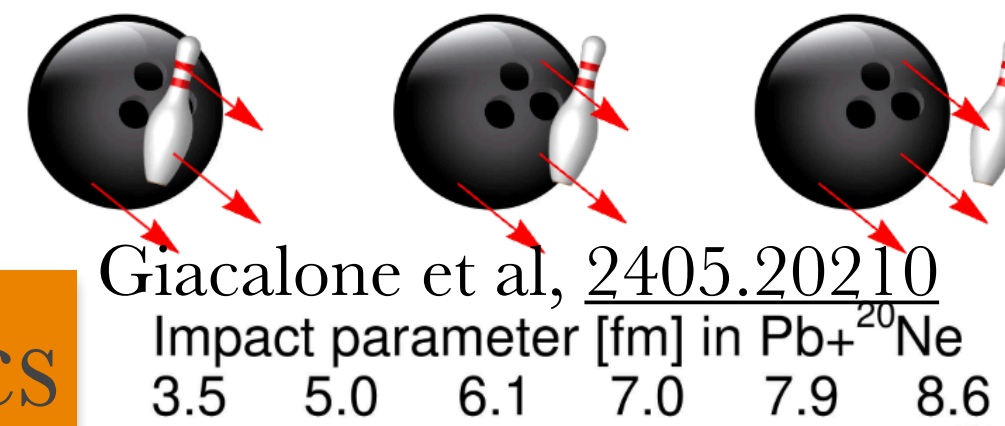
## Neutron stars+ strangeness?



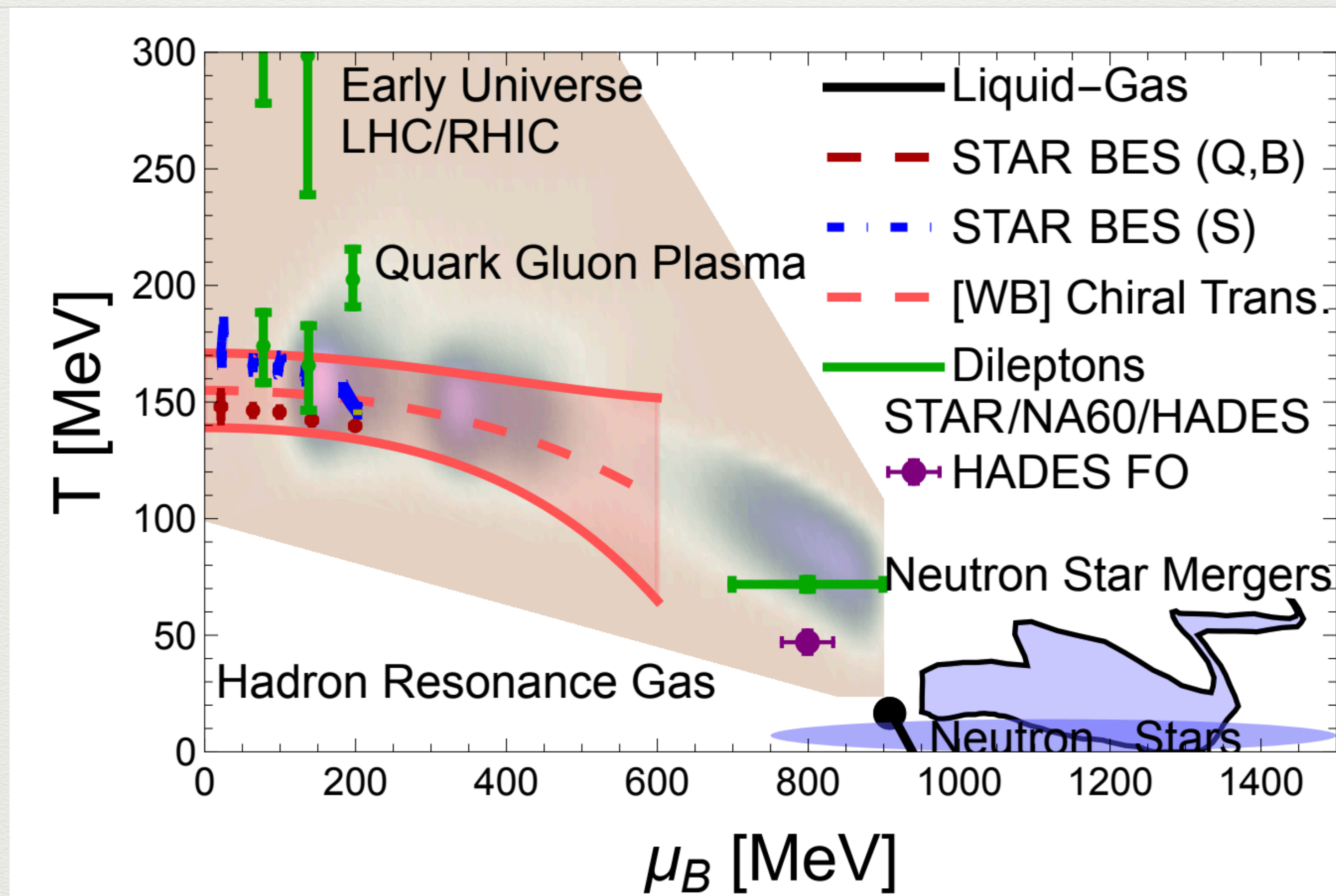
## Hadrons



## Bulk Dynamics



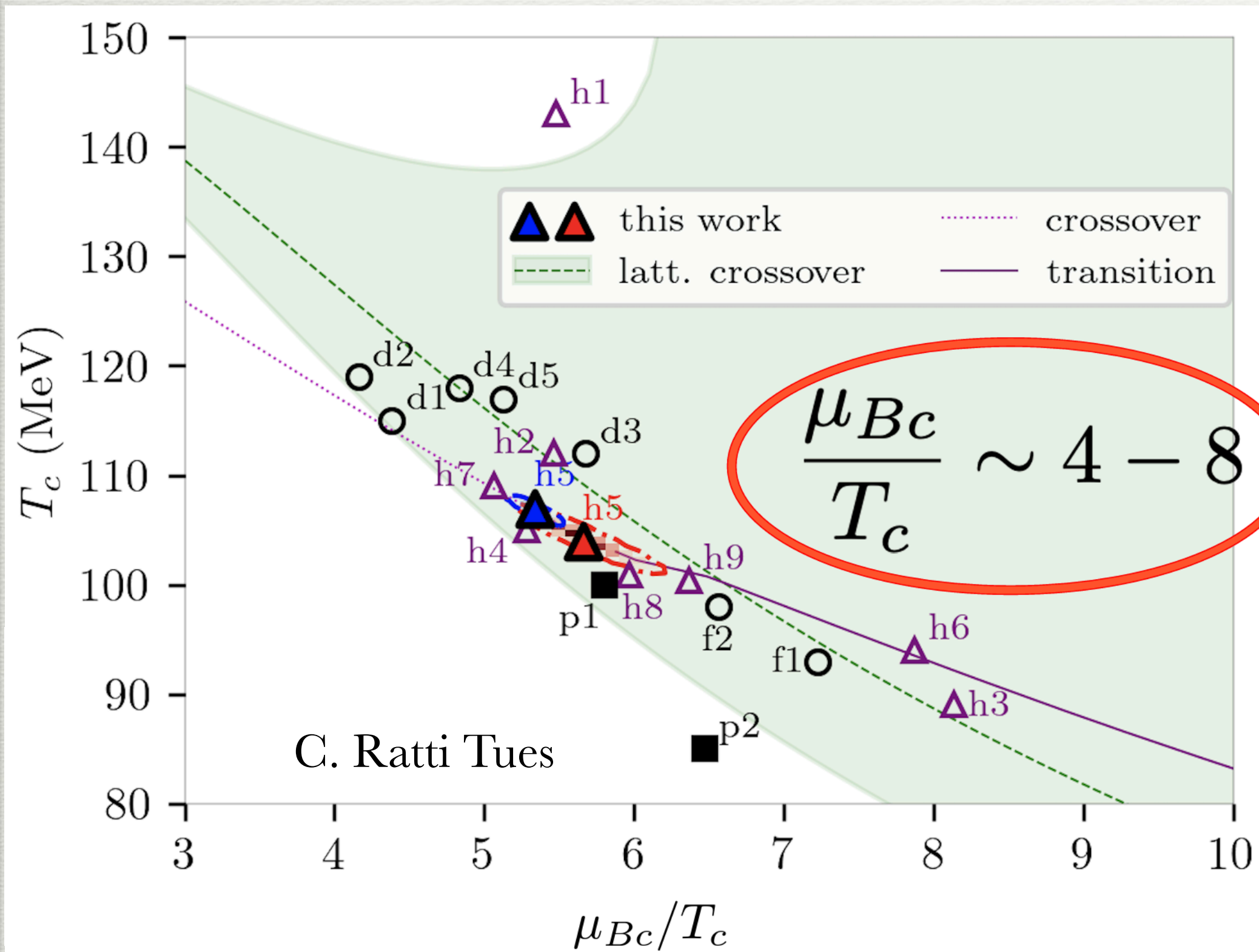
# QCD phase diagram from heavy-ions to neutron stars



Lovato et al, "Long Range Plan: Dense matter theory for heavy-ion collisions and neutron stars" 2211.02224 [nucl-th]

See references/discussion on data points

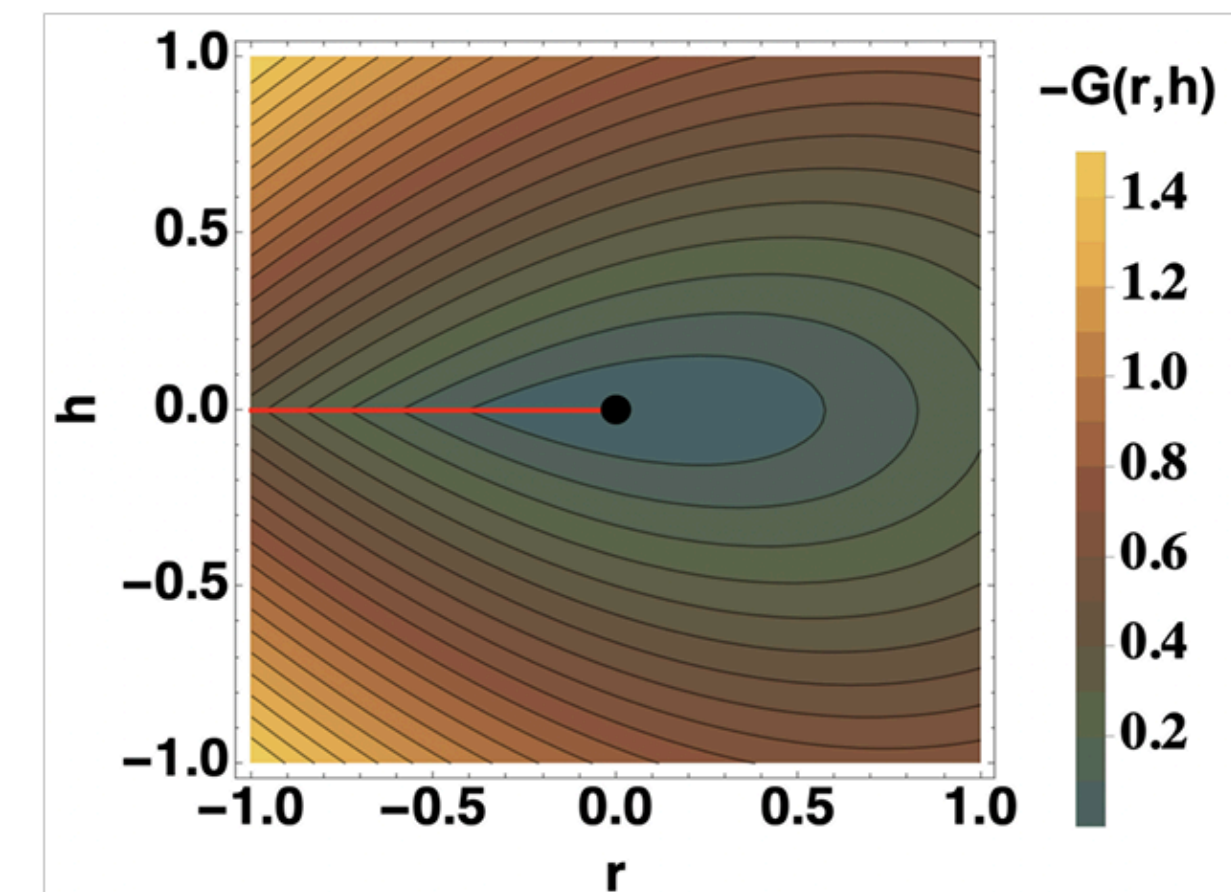
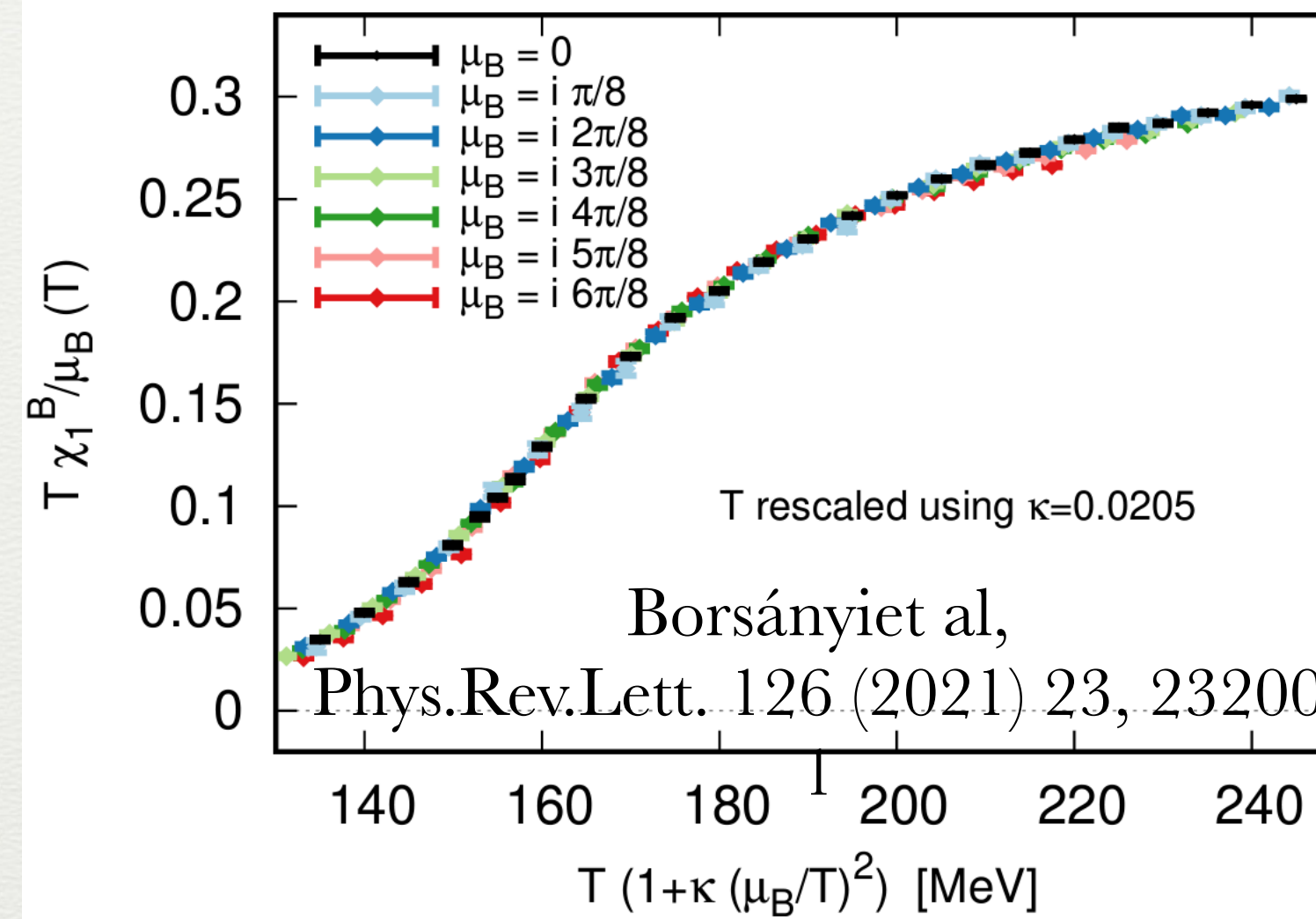
# EOS+CP: State-of-art



- |                                       |                                     |
|---------------------------------------|-------------------------------------|
| h1: Phys.Rev.D 83 (2011) 086005       | d1: Phys.Rev.D 90 (2014) 3, 034022  |
| h2: Phys.Lett.B 778 (2018) 419-425    | f1: Phys.Rev.D 102 (2020) 3, 034027 |
| h3: Phys.Rev.D 96 (2017) 9, 096026    | d2: Phys.Rev.D 104 (2021) 5, 054022 |
| h4: Phys.Rev.D 106 (2022) 12, L121902 | d3: Phys.Rev.D 104 (2021) 5, 054022 |
| h5: e-Print: 2309.00579 [nucl-th]     | d4: Phys.Rev.D 104 (2021) 5, 054022 |
| h6: Phys.Rev.D 109 (2024) 5, L051902  | d5: Phys.Rev.D 104 (2021) 5, 054022 |
| h7: e-Print: 2404.12109 [hep-ph]      | f2: e-Print: 2308.15508 [hep-ph]    |
| h8: e-Print: 2405.02394 [hep-th]      | p1: e-Print: 2312.06952 [hep-th]    |
| h9: e-Print: 2405.02394 [hep-th]      | p2: e-Print: 2401.08820 [hep-lat]   |

Alternative lattice  
QCD expansion

+ critical point

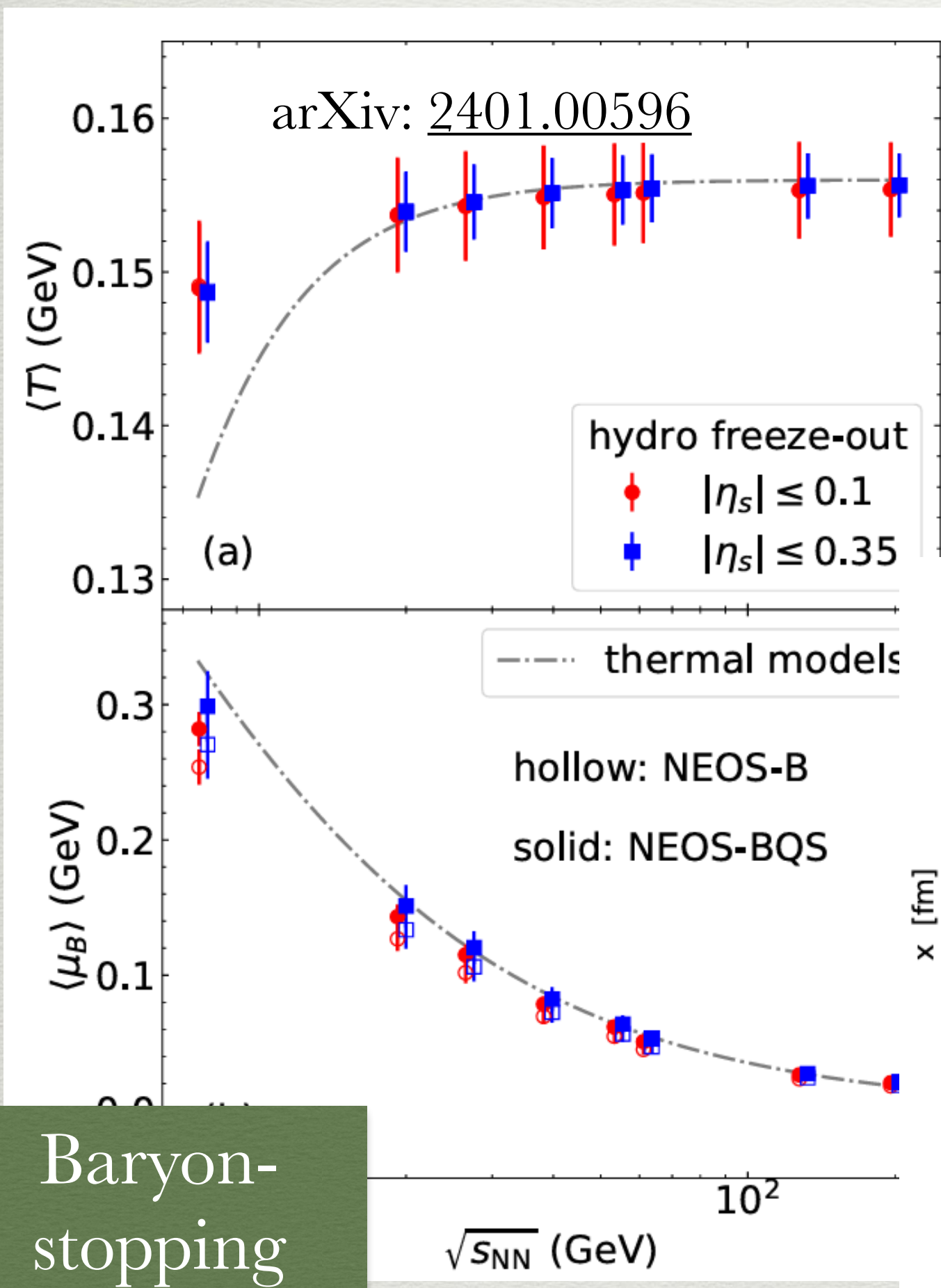


$\alpha$ -release coming soon!

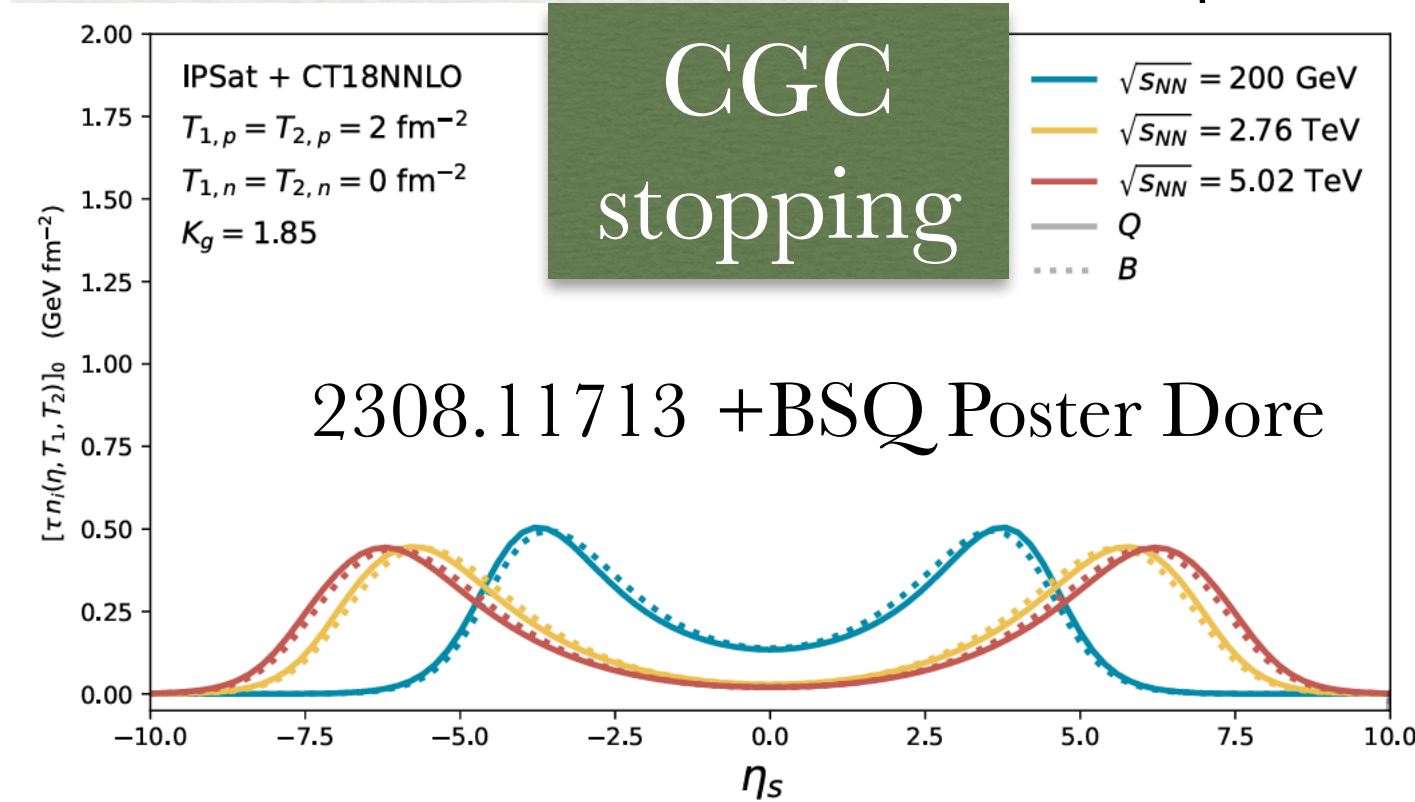
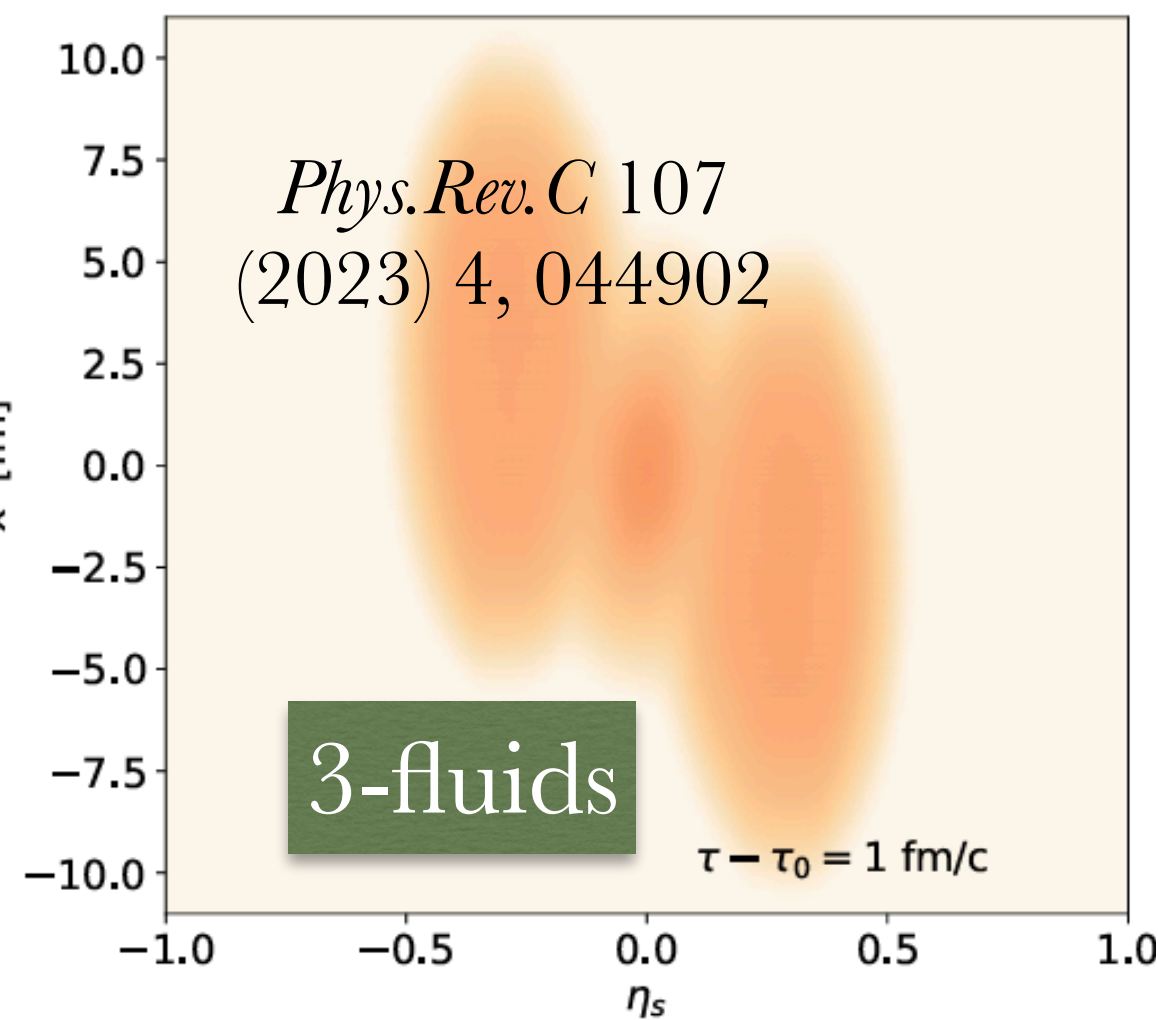
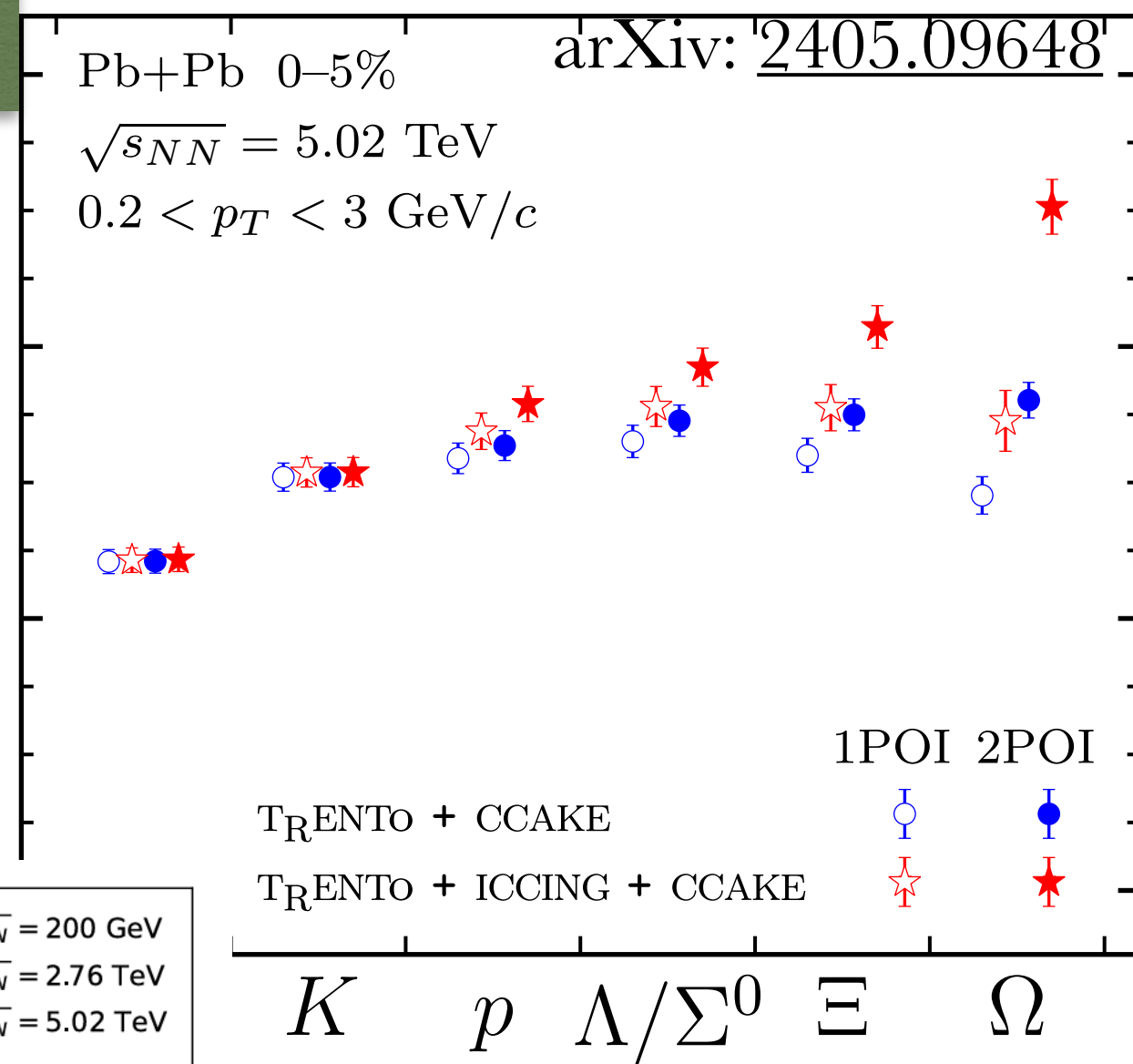
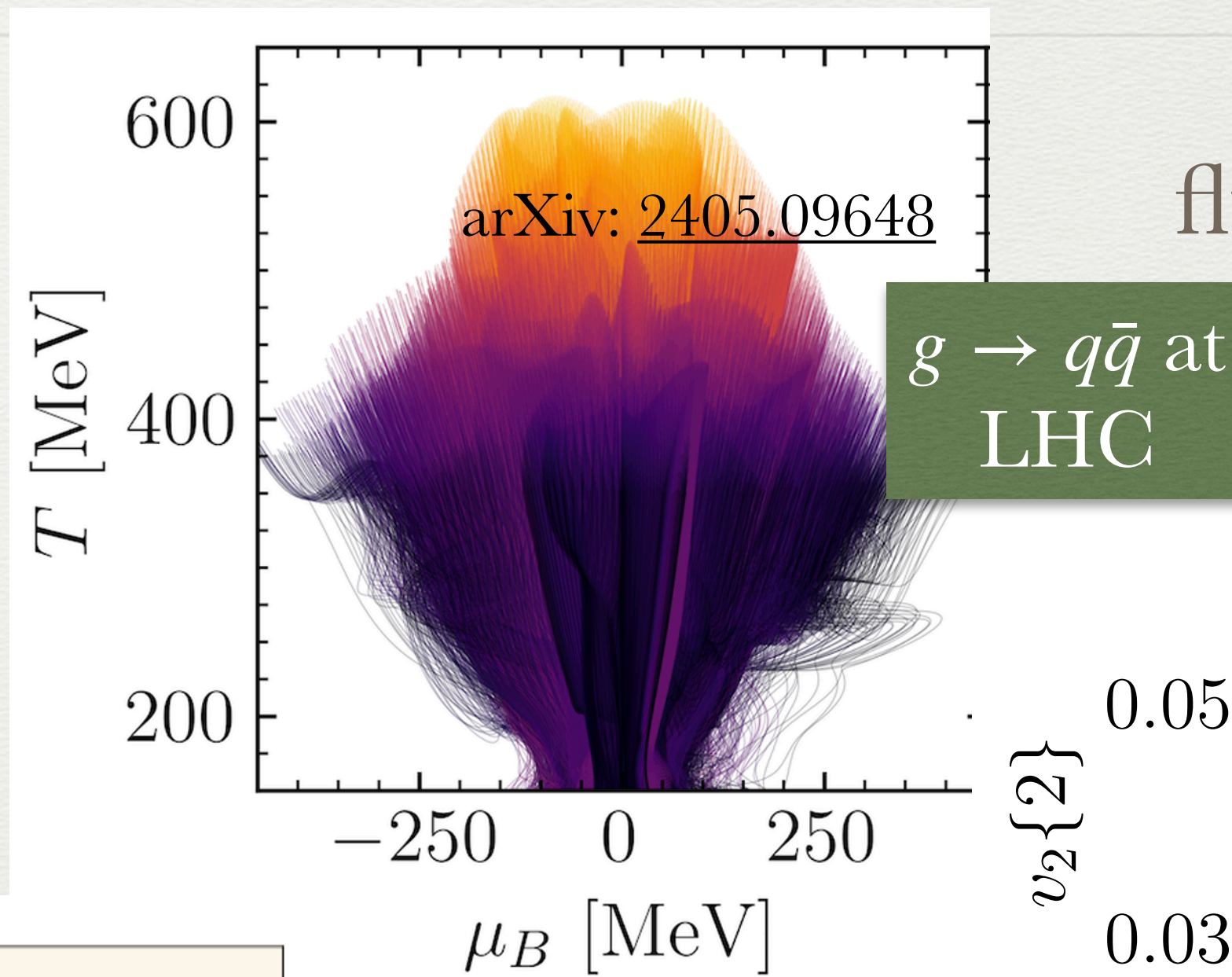
BSQ from lattice QCD, 4DTEoS, Holography,  
 $\chi$ EFT, CMF, Crust\_DFT, QLIMR, FlavorEquilibration

# EOS+CP: Key questions

How does QCD matter move at  $n_B \neq 0$ ?

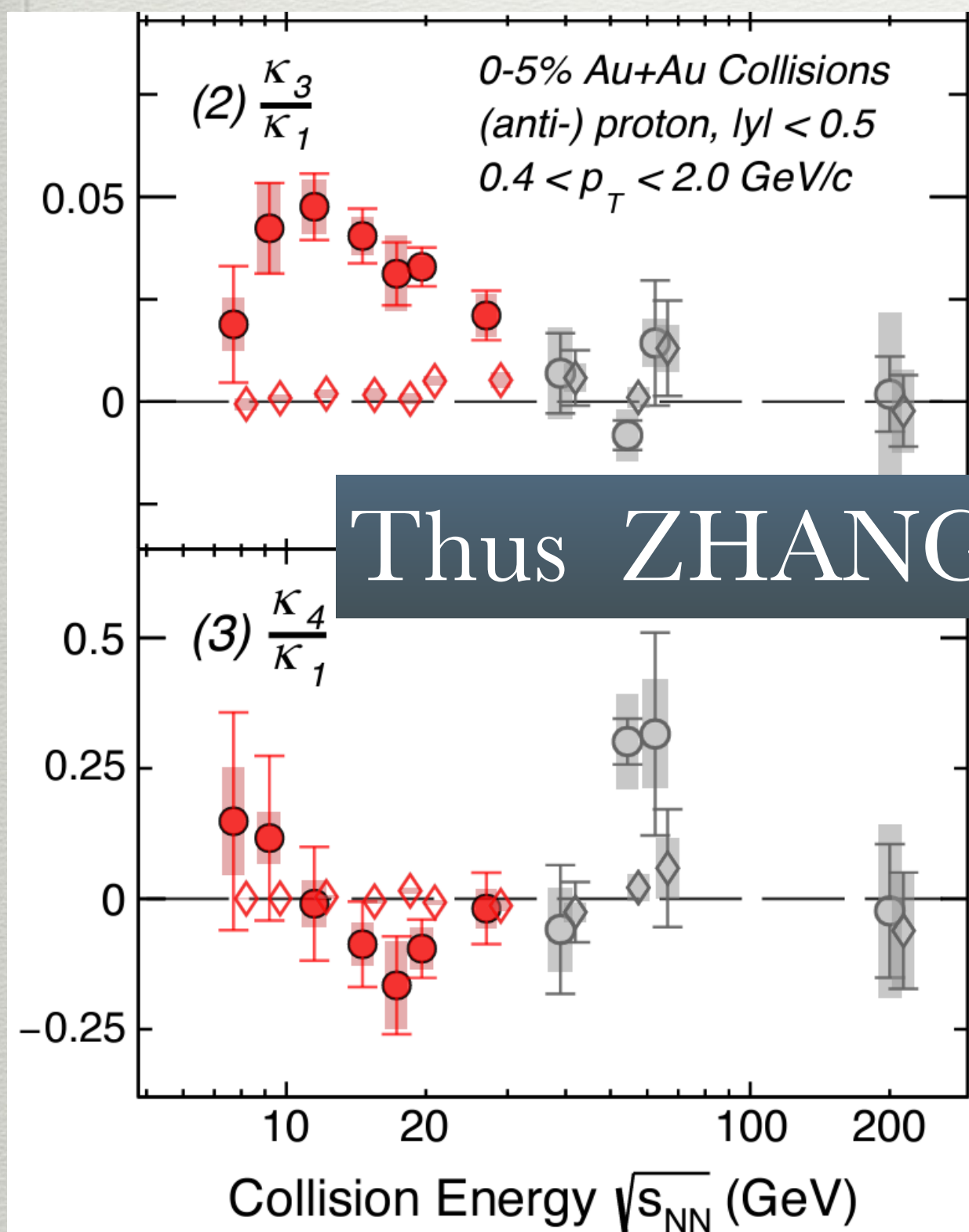


What role do BSQ fluctuations play at the LHC?

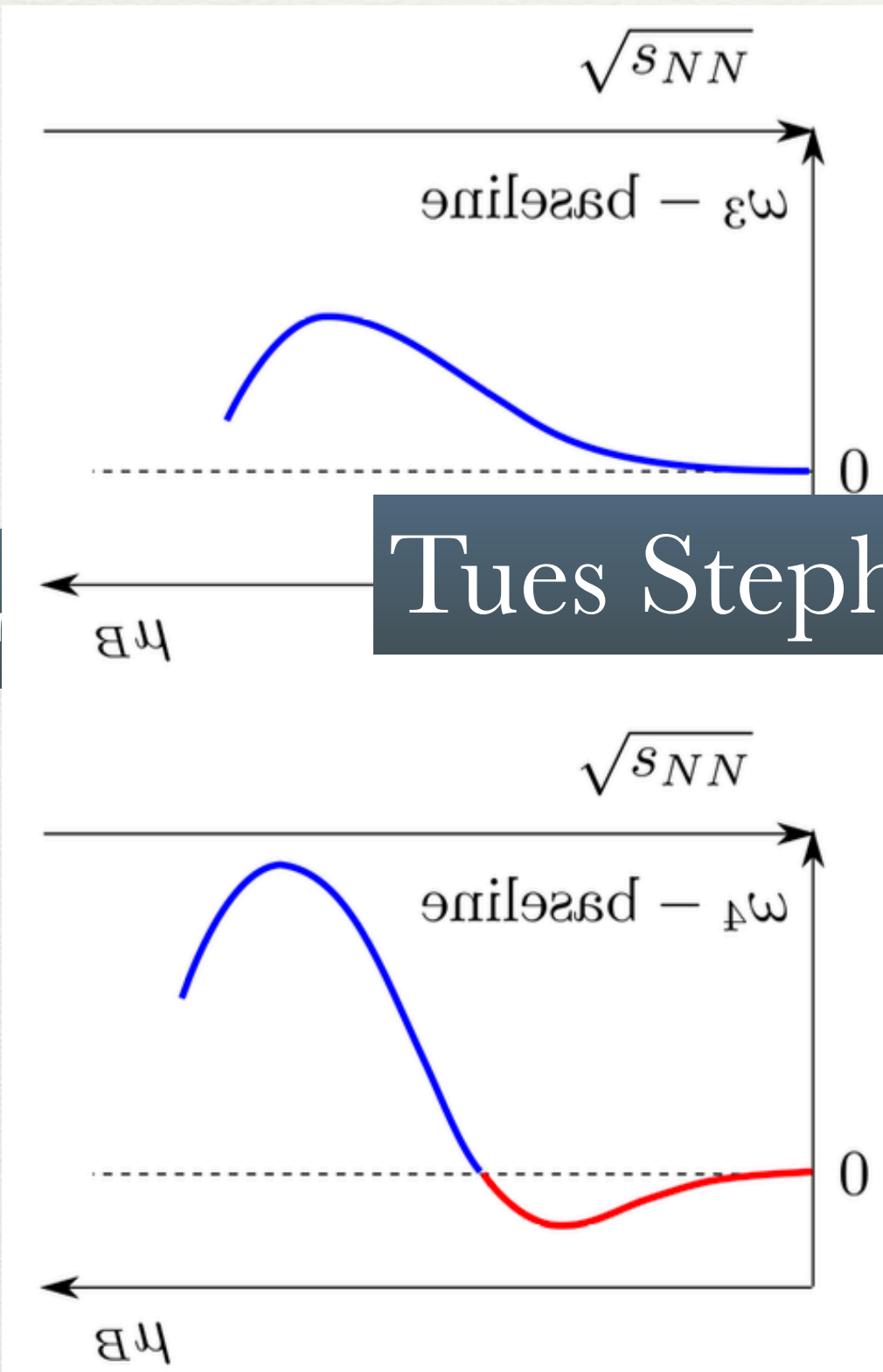


# EOS+CP: Key questions

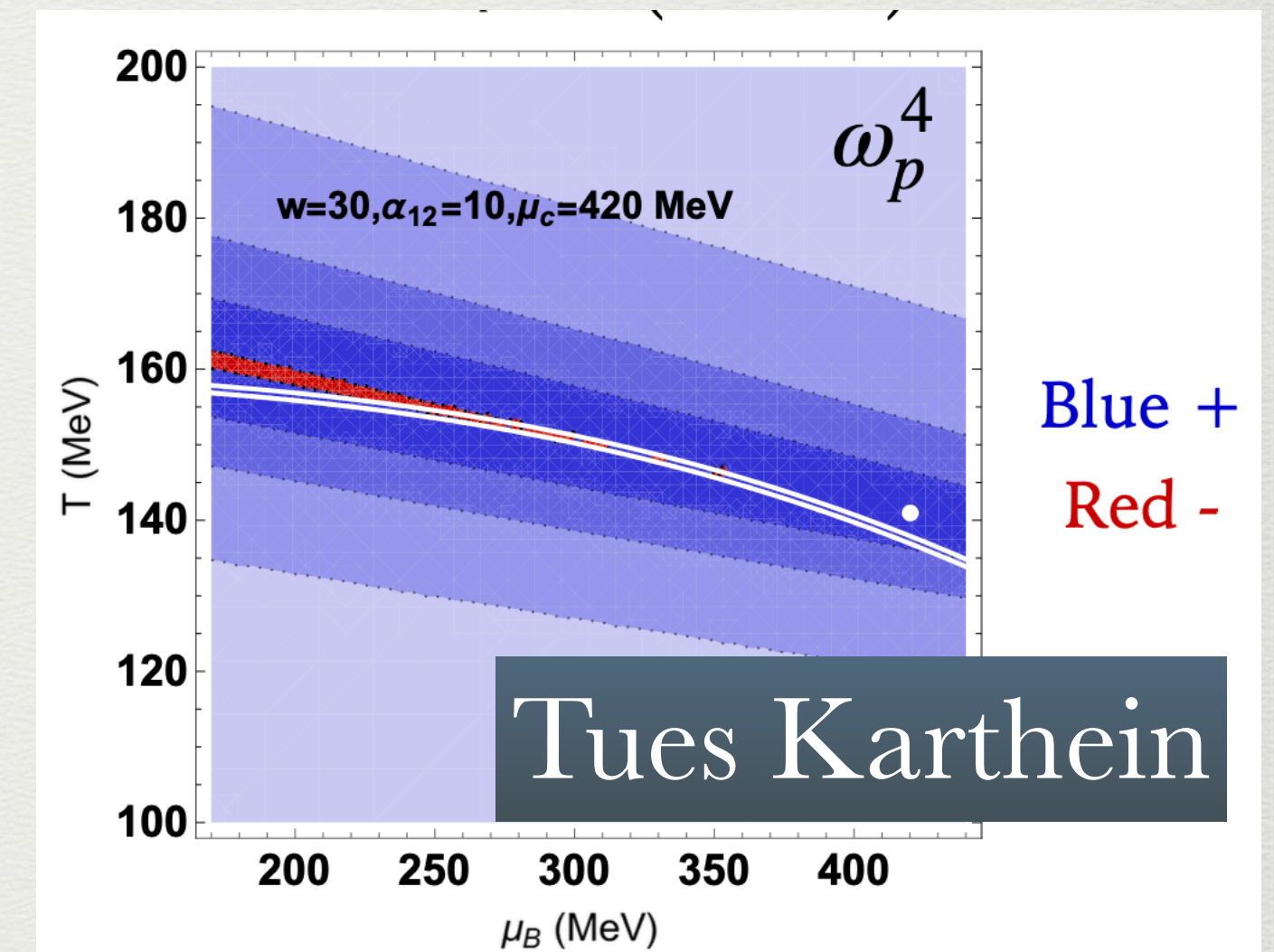
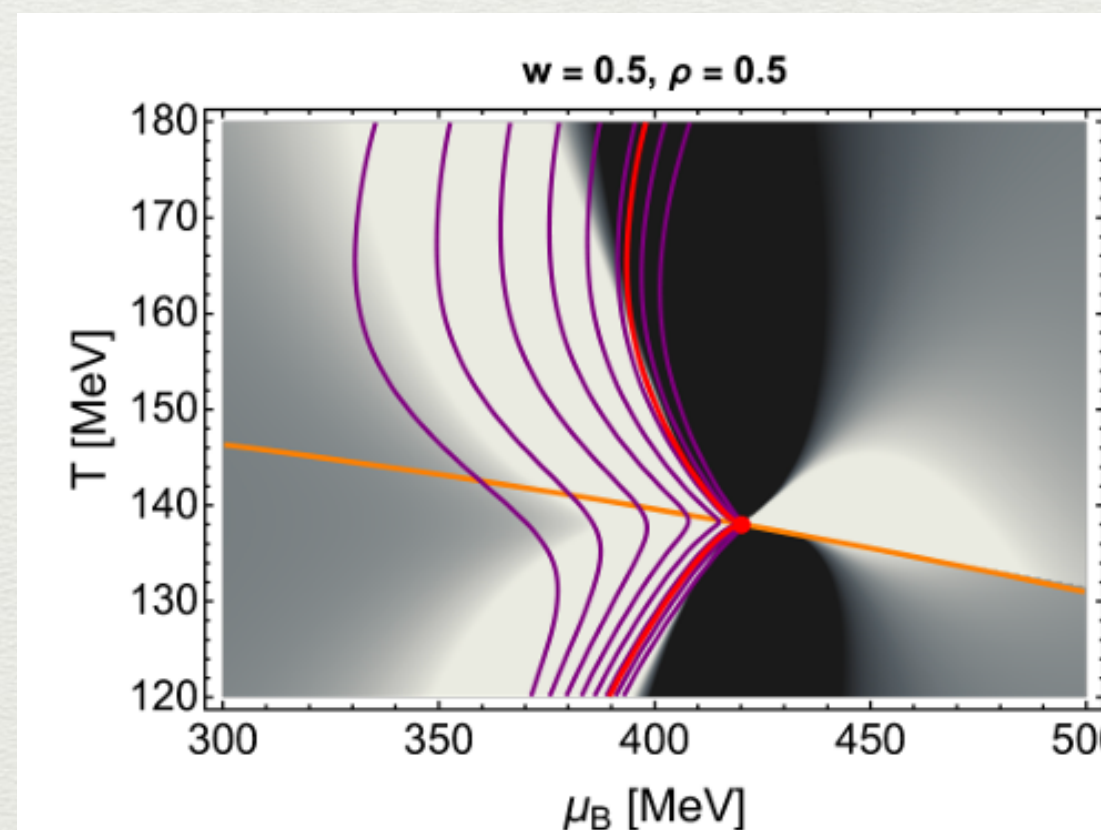
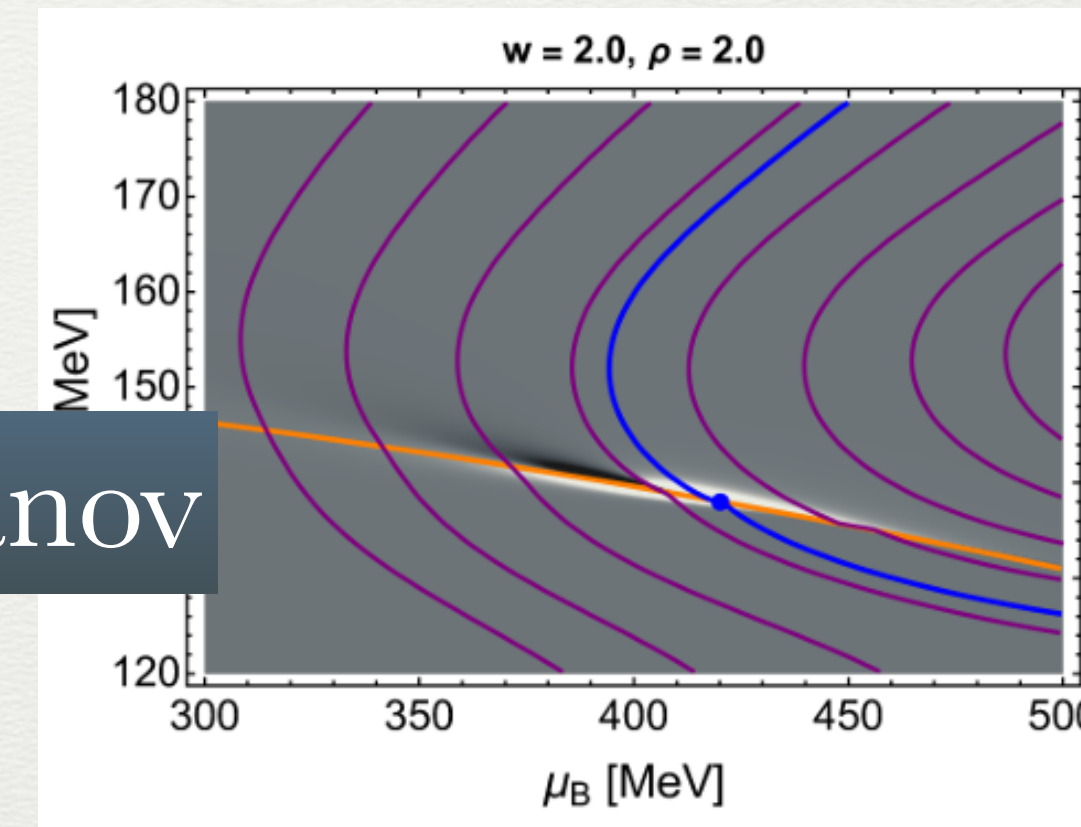
What can we learn from the new BES II data? Critical region & freeze-out  $T$  affect  $\kappa_4$



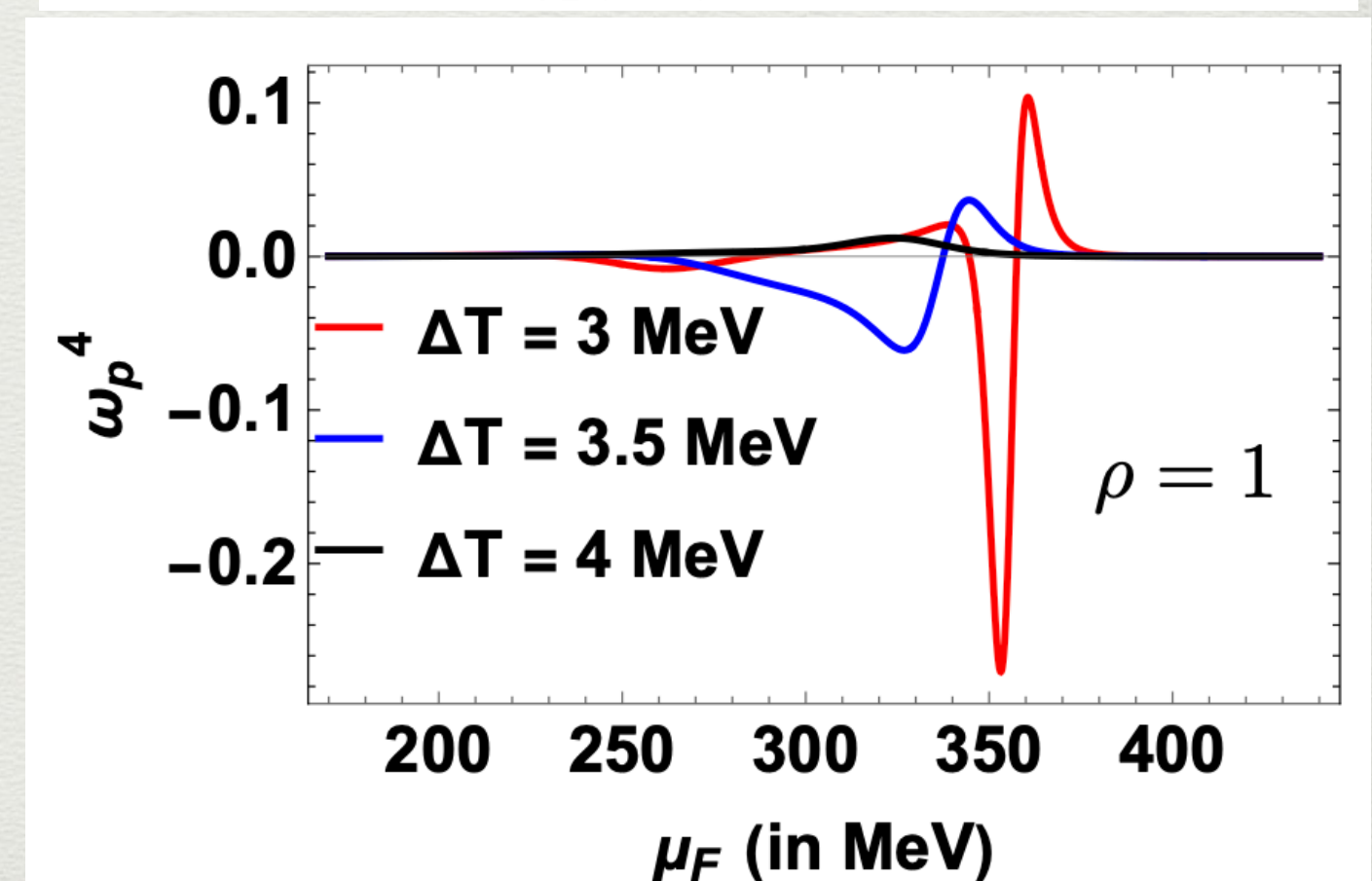
Thus ZHANG



Tues Stephanov



Tues Karthein



Expected for CP at  $\mu_B > 420$  [MeV]

# EOS+CP: Talks and Posters at SQM24

## Critical Point & fluctuations

Theoretical Tools for CP

Thurs Bzdak

CP & hydro

Tues Stephanov

Molecular dynamics

Tues Kuznietsov

Diffusion model G

Tues Grossi

Non-Gaussian CP Fluctuations

Tues Karthein

Renormalization of fluctuations

Poster Attieh

## Overview

Mon Endrodi

## Dynamics

BSQ initial state fluctuations

Poster Dore

Spinodal in fluid

Tues Singh

Non-equilibrium phase transitions

Poster Harhoff

Correlations in flow at large  $n_B$

Poster Reichert

## EOS development

4D lattice EOS+CP

Tues+Poster Jahan

Phases in Swinger model

Poster Shi

## Bayesian analyses

CP from holography

Tues Ratti

Low  $\sqrt{S}$

Tues Kuttan

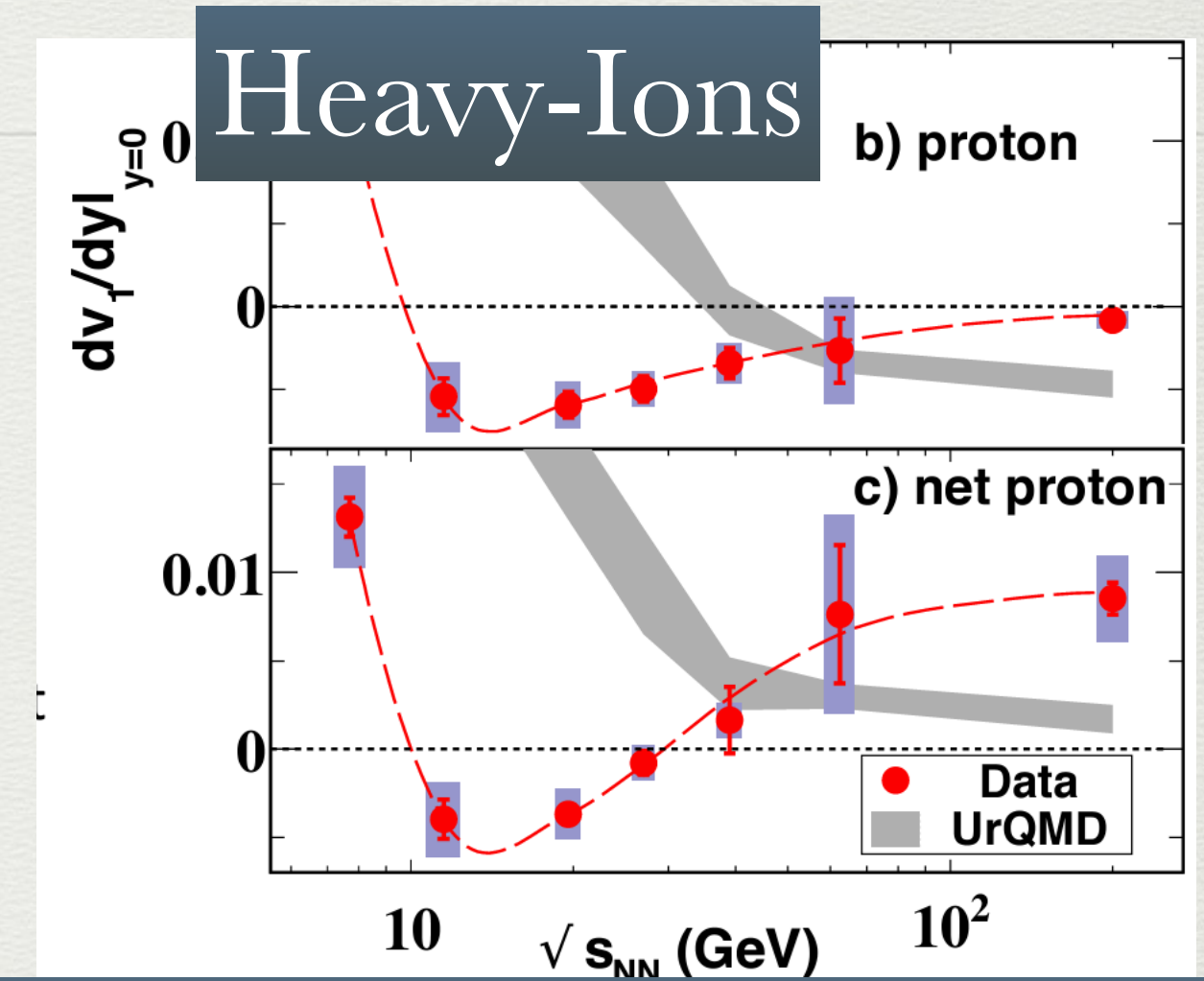
# Astrophysics: constraints

Theory constraints

$$c_s^2 \lesssim 0.8 \text{ arXiv: 2402.14085}$$

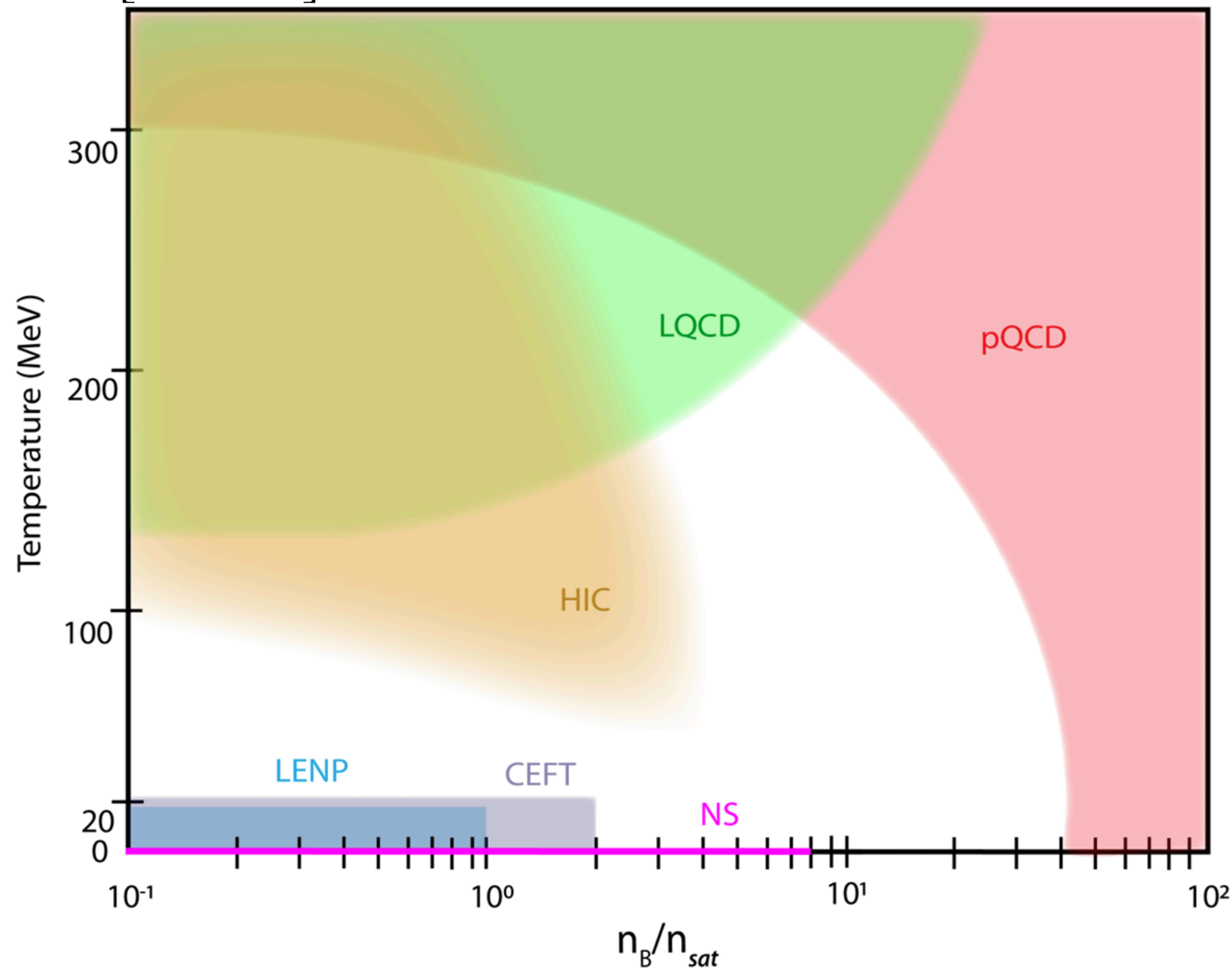
Hadrons: mass, interactions etc

[ALICE] Phys. Rev. Lett. 123, 112002 (2019)+many more

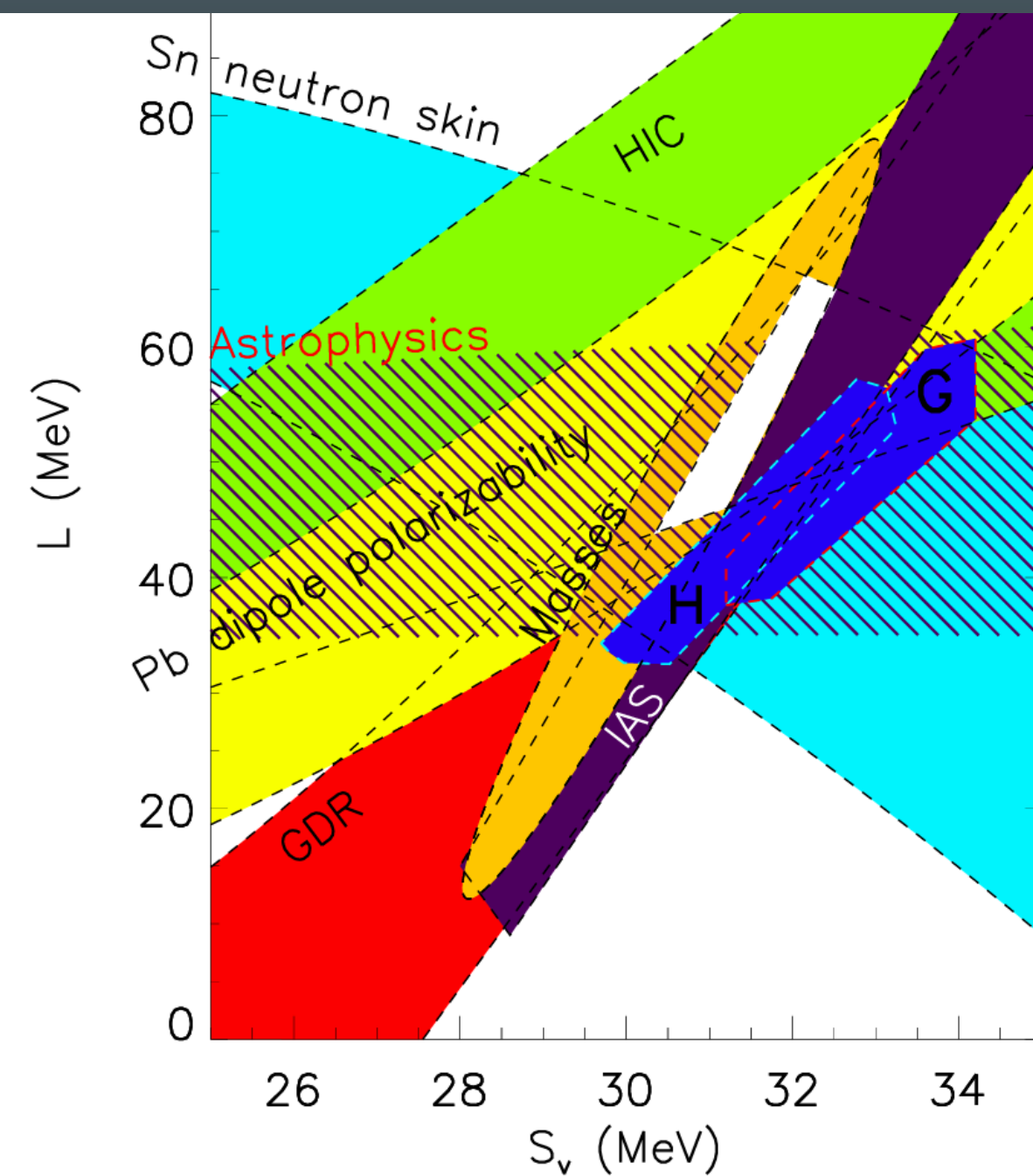


[MUSES] 2303.17021

muses

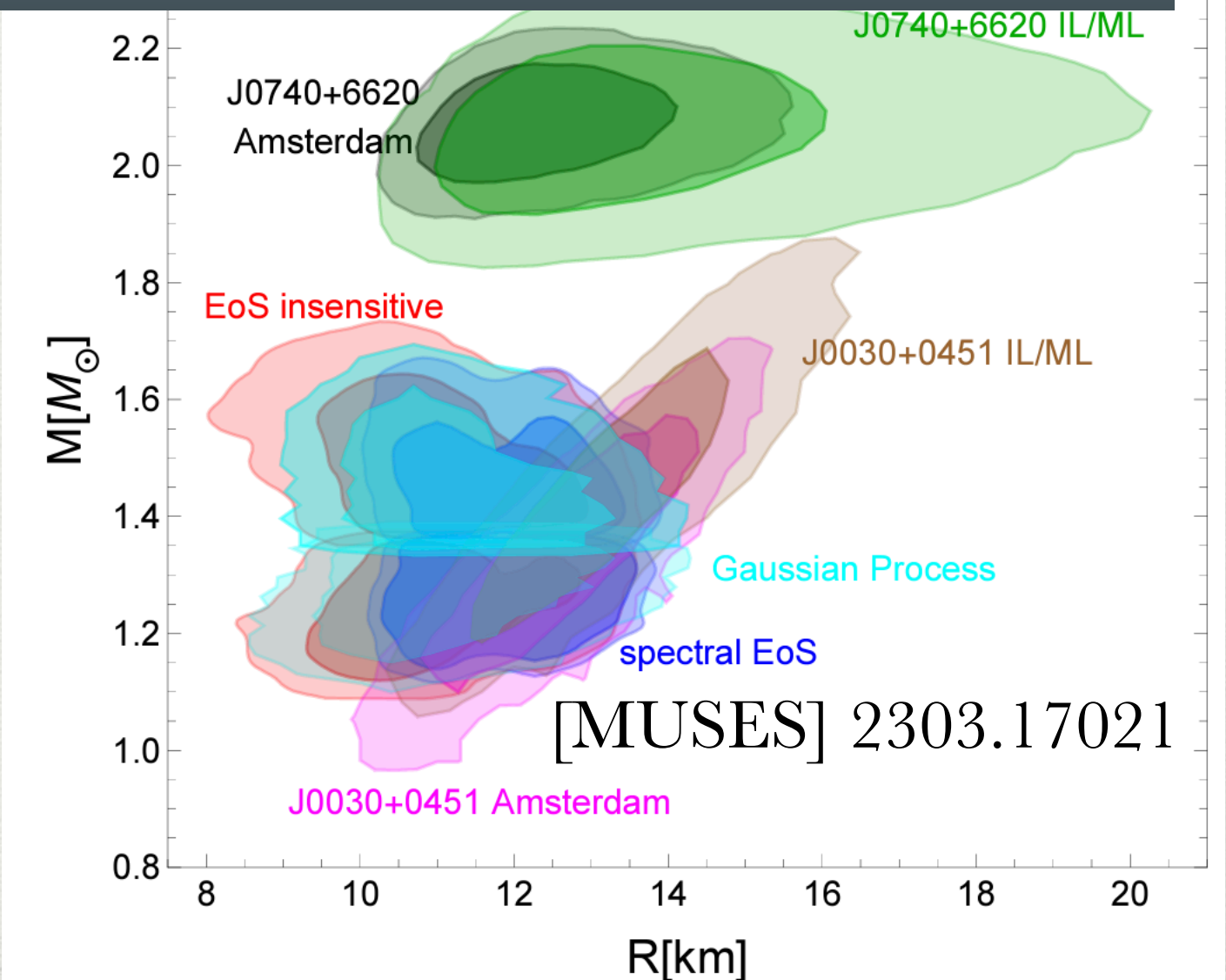


Low-energy constraints



Eur. Phys. J. A 50, 40 (2014)

NICER/Gravitational Waves



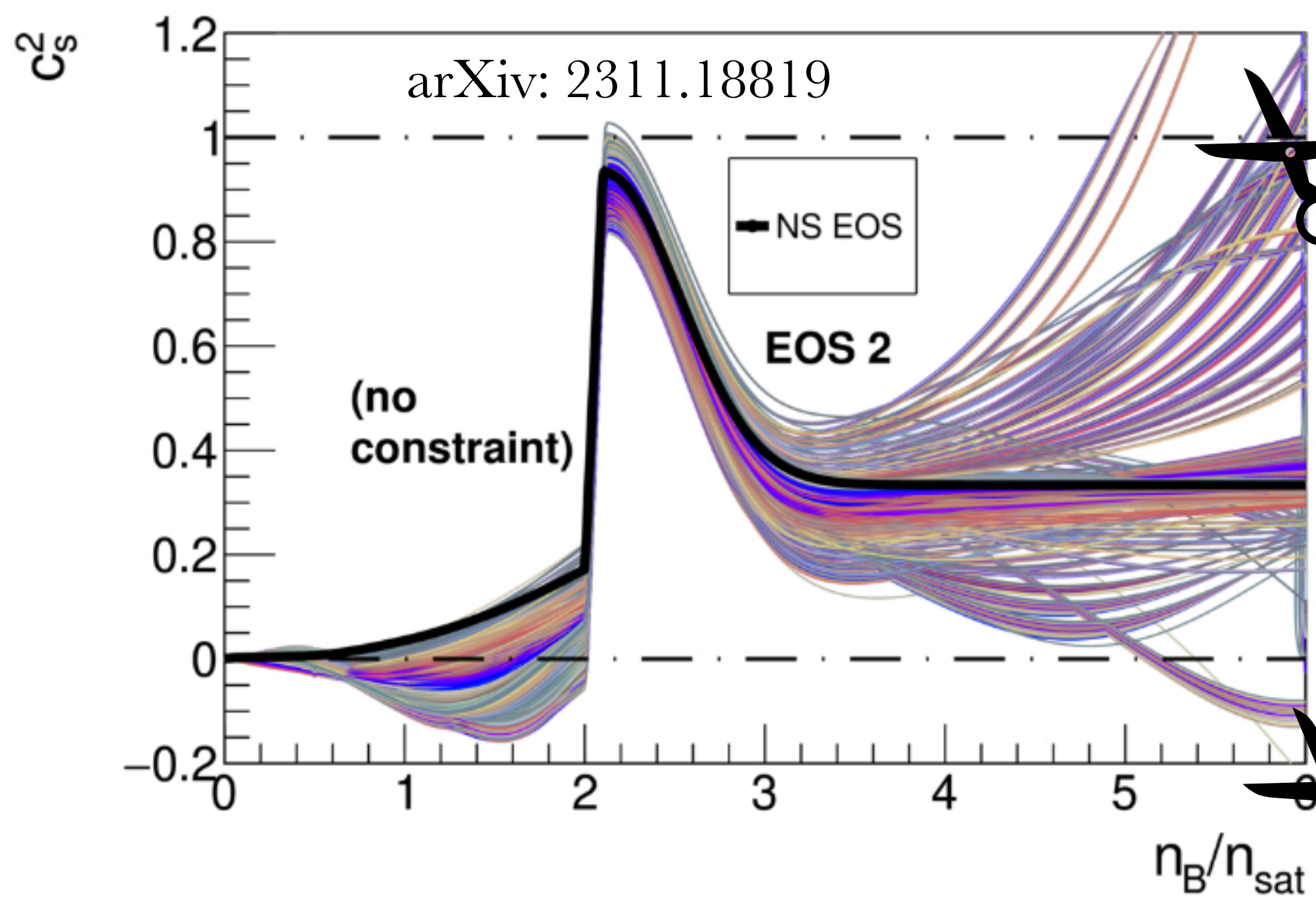
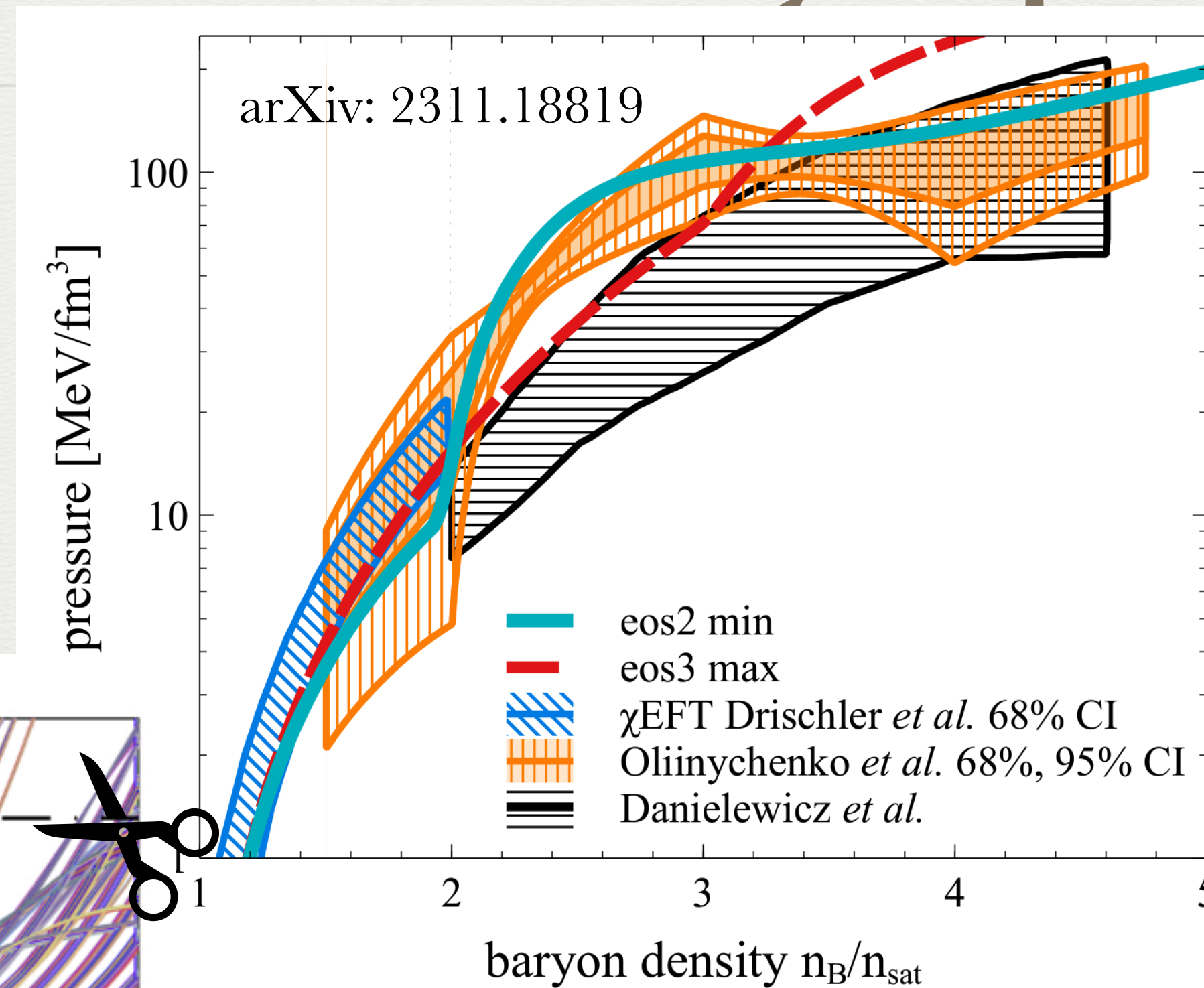


# NS+HIC: Key questions

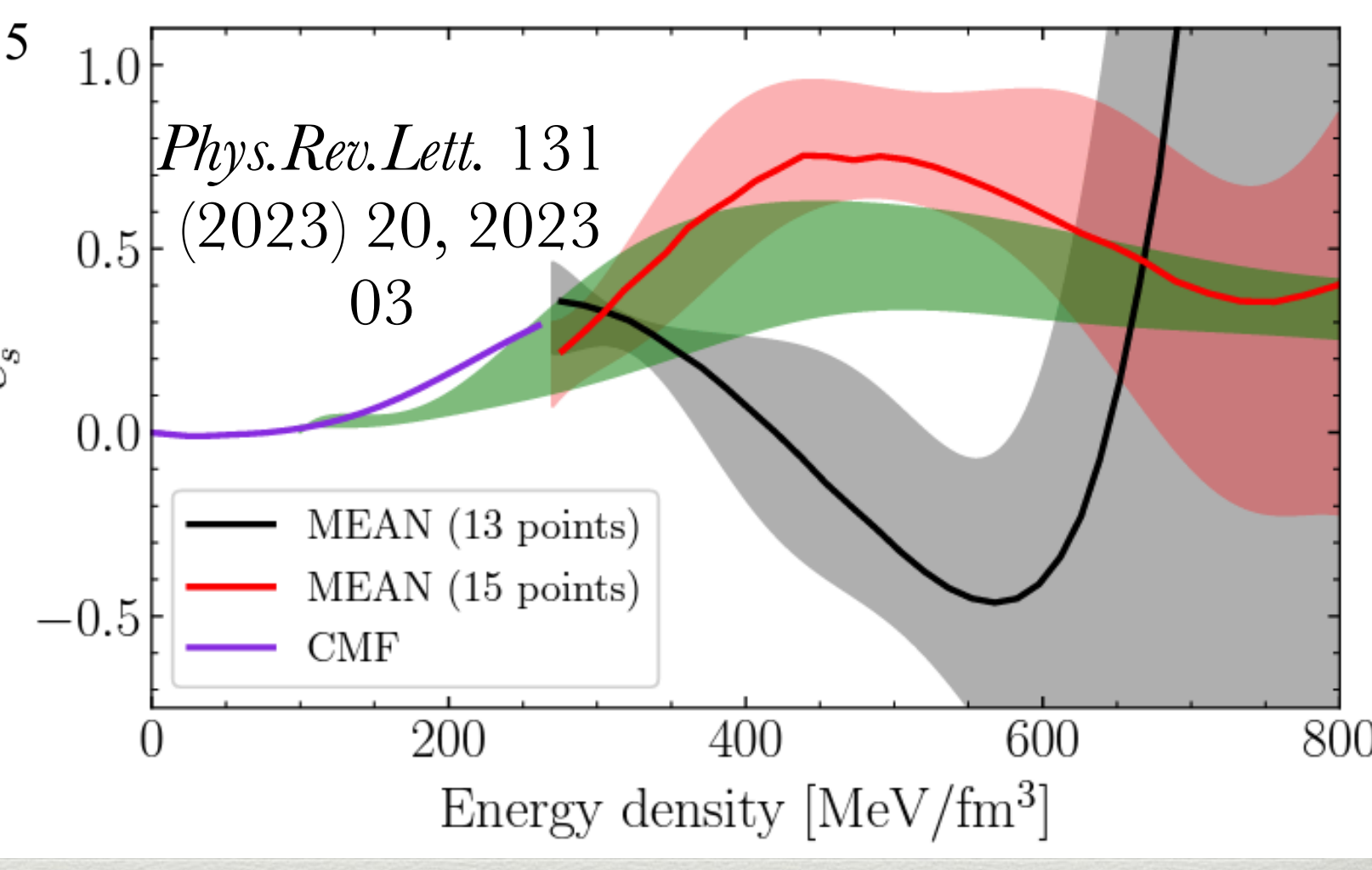
Constraints for neutron stars from HIC?

STAR fix-target flow data is crucial!

Building in structure into the EOS (quarks, hyperons etc)



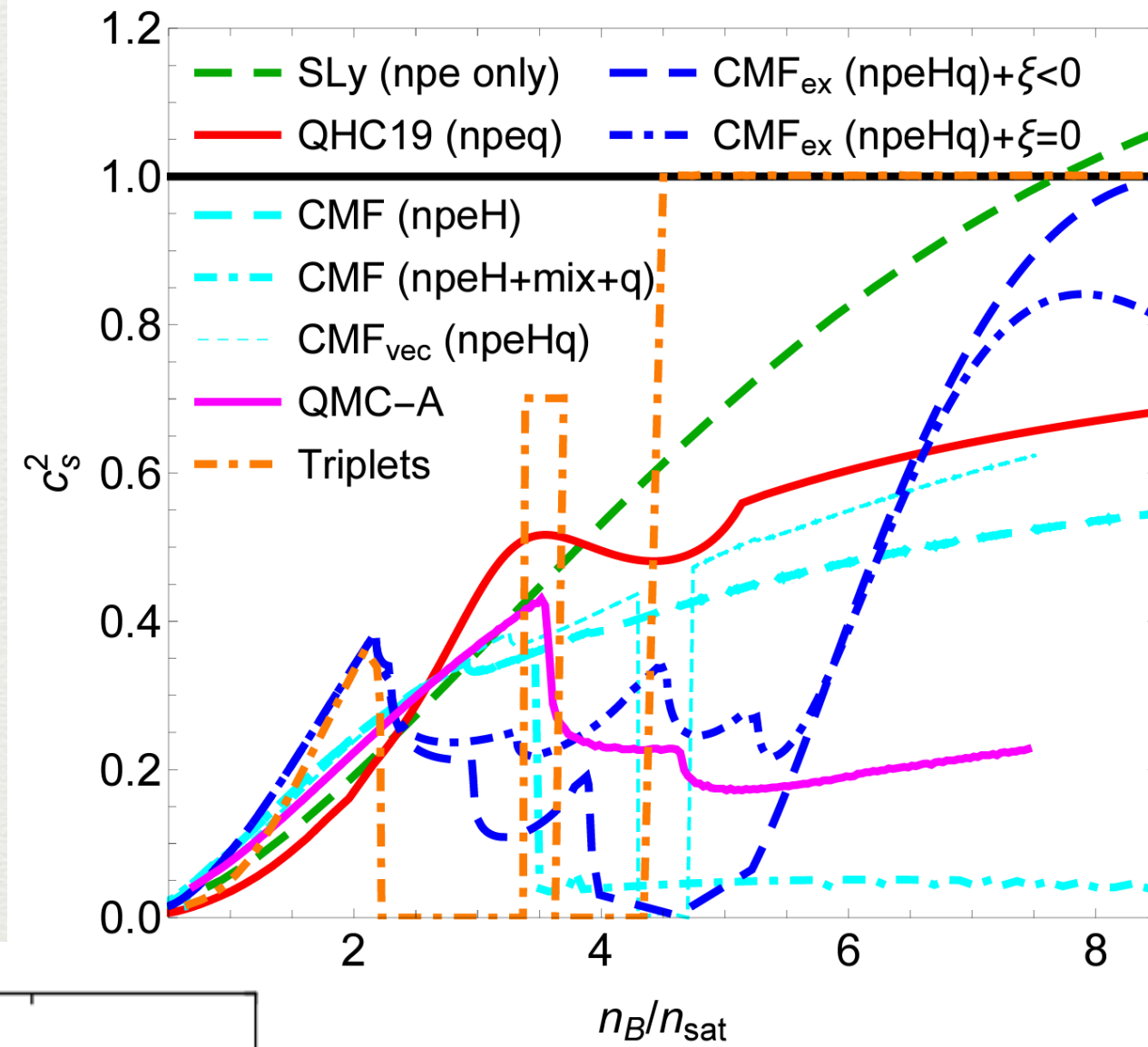
Uncertainty between NS to HIC



# Astrophysics: State-of-art

## Microphysical EOS

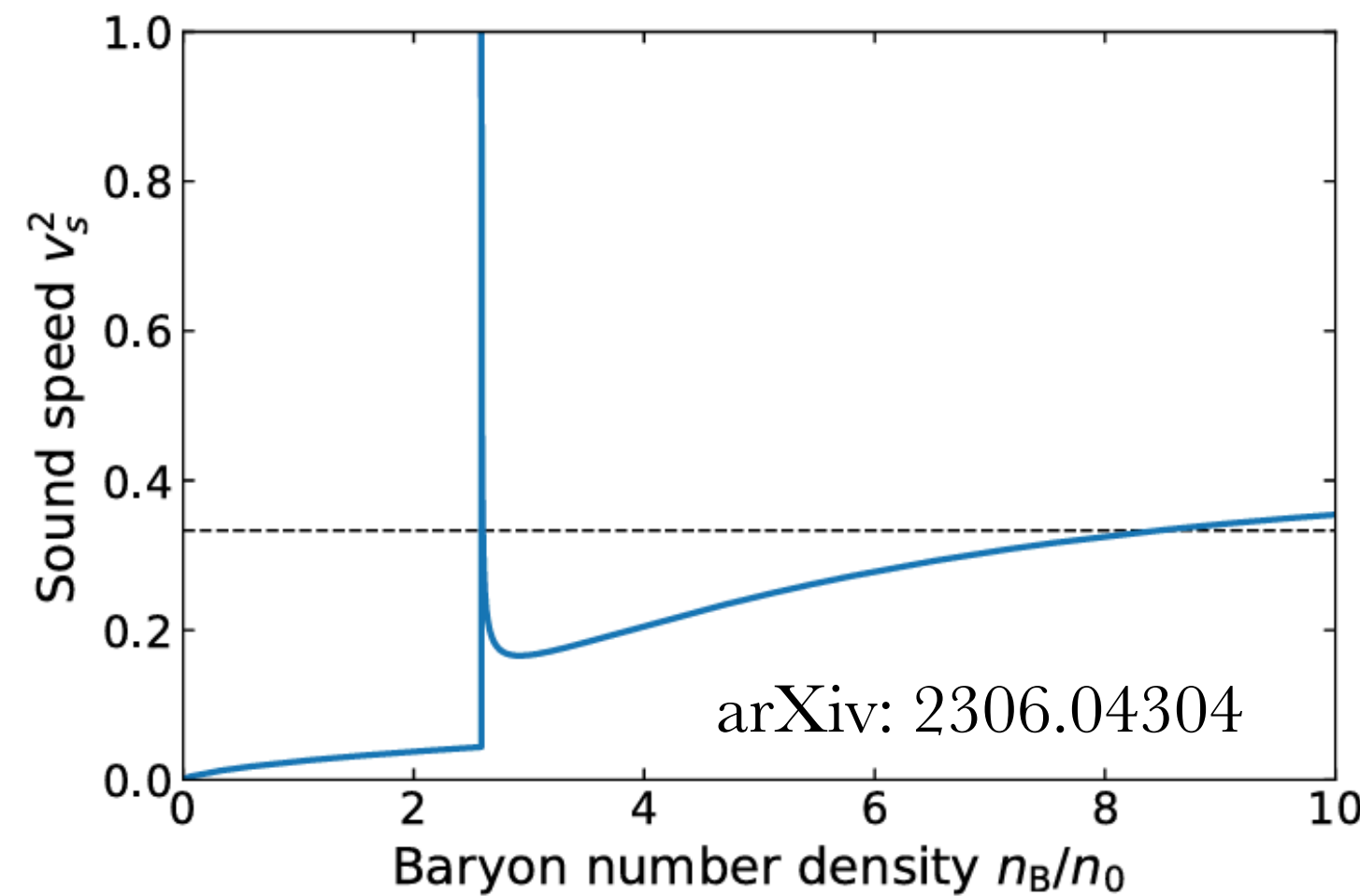
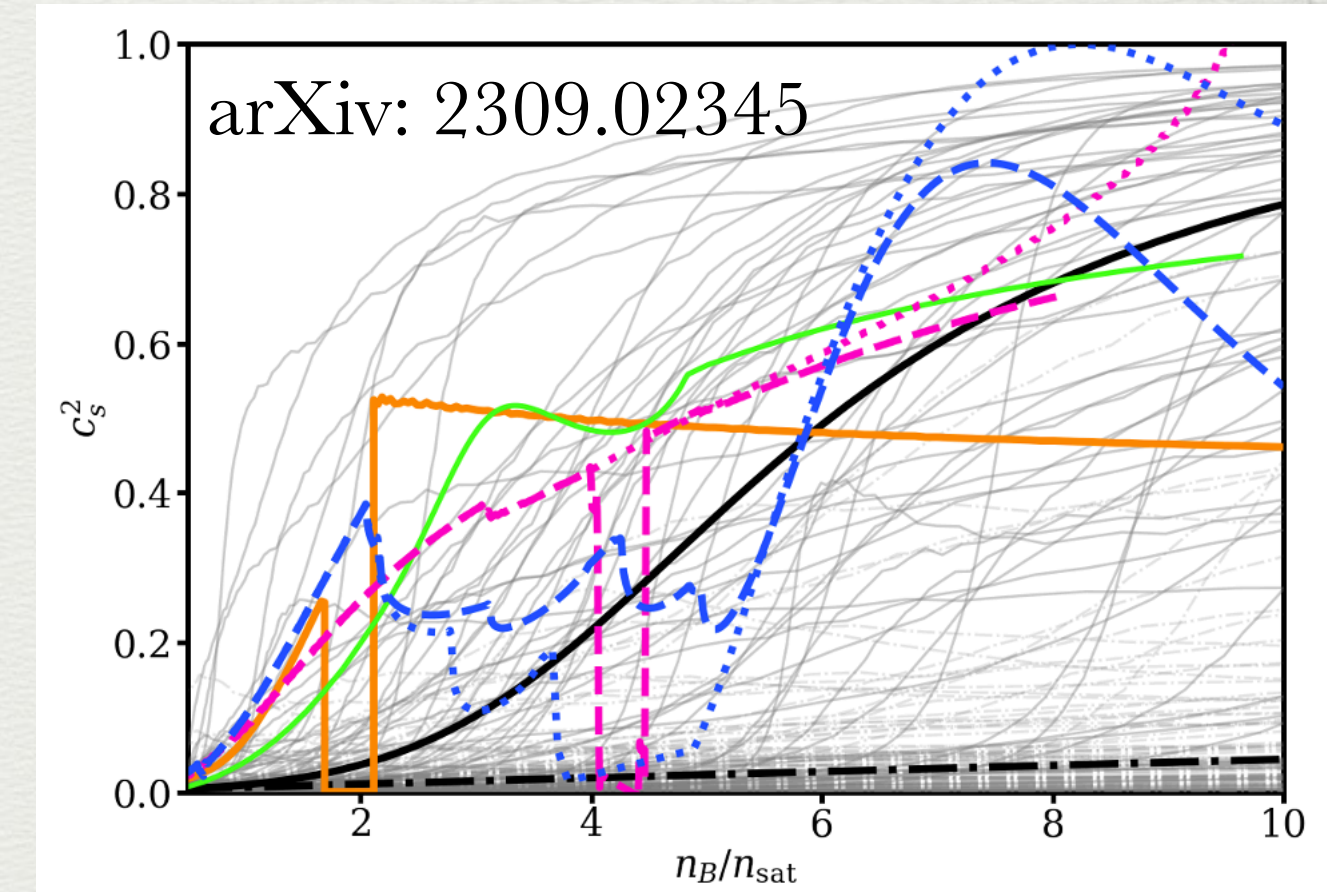
Tan et al, Phys.Rev.D 105 (2022) 2, 023018



Strange baryons and quarks add structure to  $c_s^2$

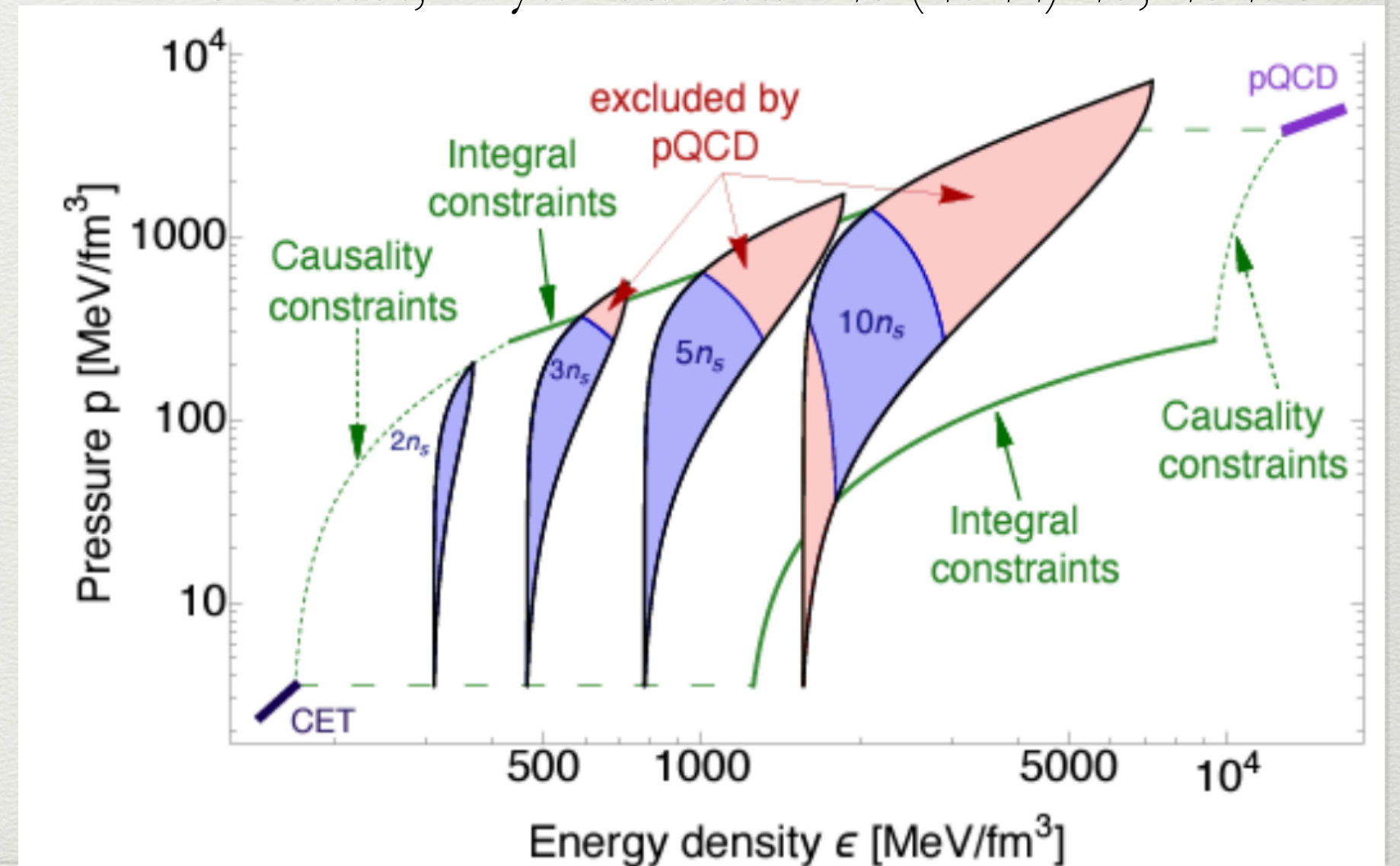
## Inference of EOS

QCD-informed approaches



Quarkyonic matter has large  $c_s^2 \rightarrow 1$ , leads to heavy neutron stars

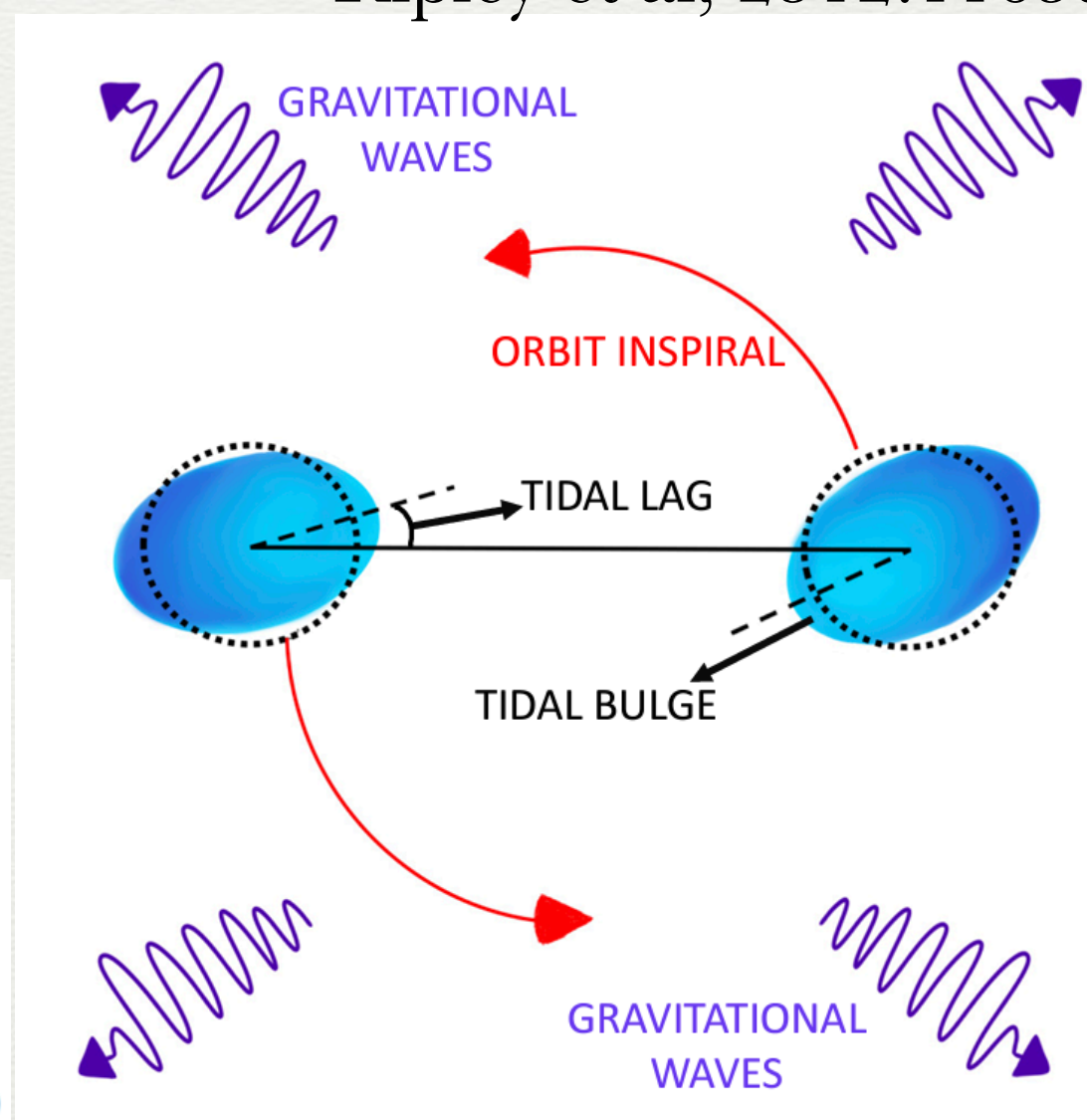
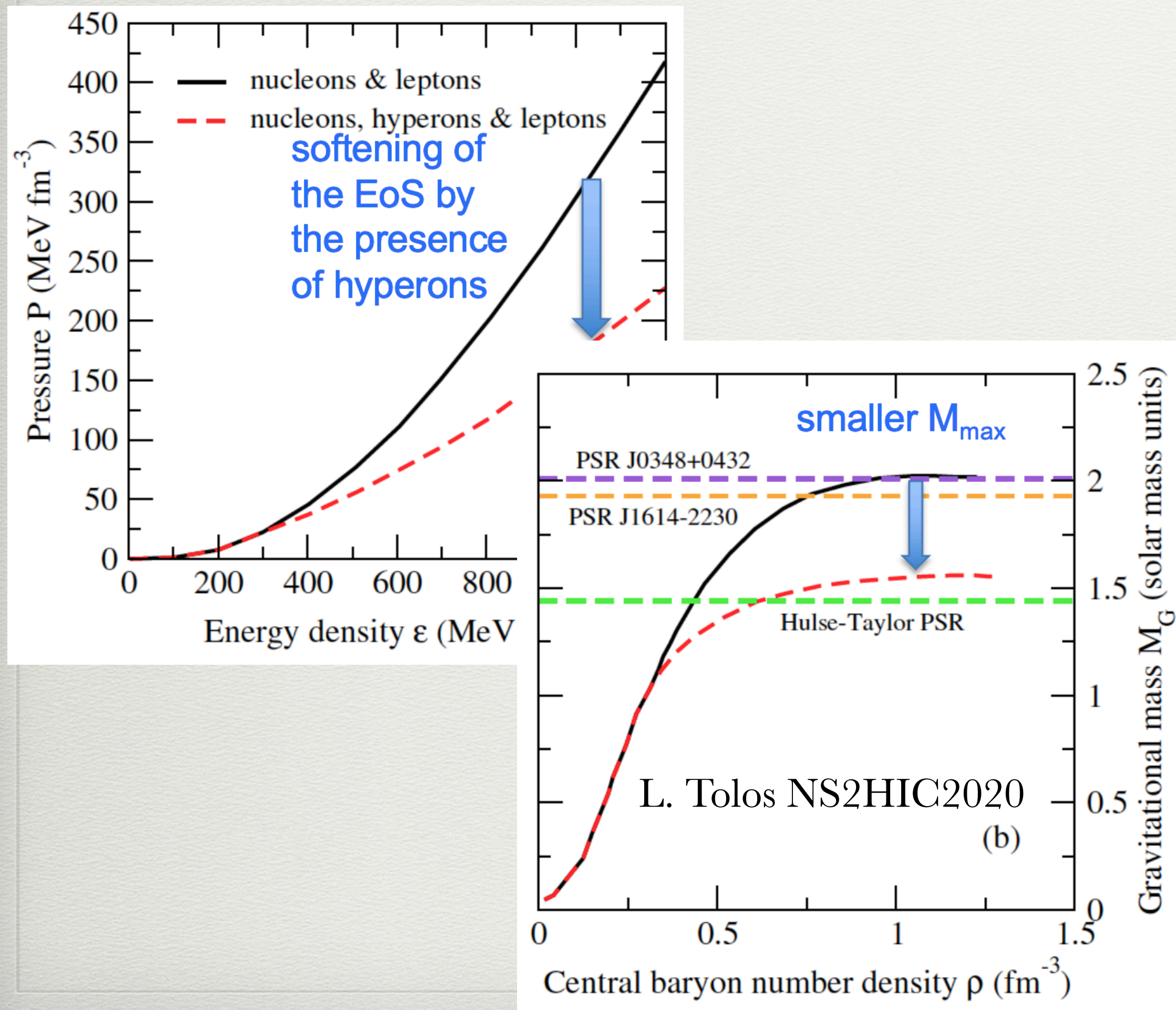
Komoltsev, Phys.Rev.Lett. 128 (2022) 20, 202701



# Astrophysics: Key questions

Can we reconcile strange baryons degrees of freedom inside neutron stars and  $M_{max} \geq 2M_{\odot}$ ?

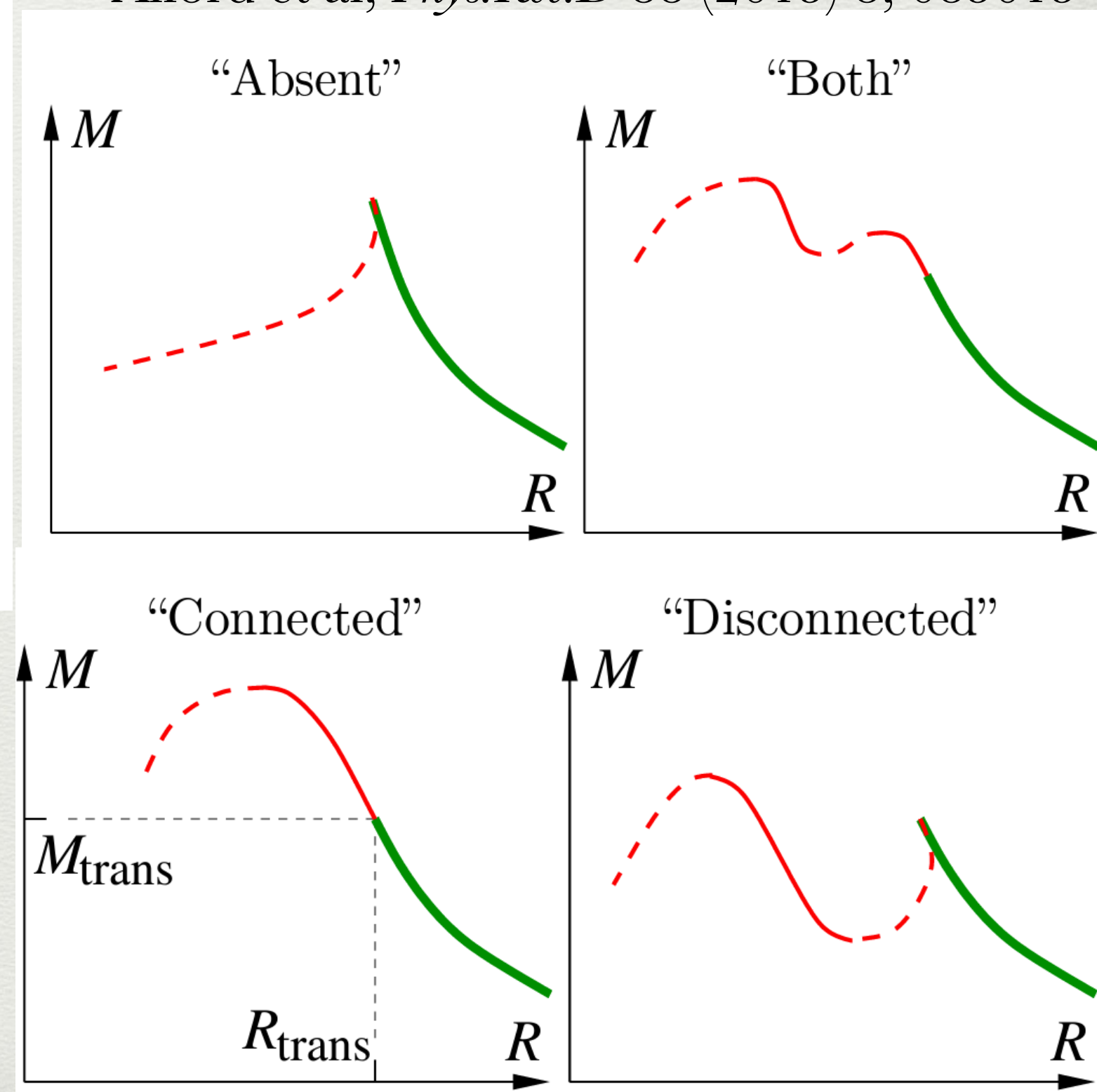
Ripley et al, 2312.11659



Can out-of-equilibrium effects shed new light on the interior of NS?

Can we find signatures of quarks within the core of neutron stars?

Alford et al, *Phys.Rev.D* 88 (2013) 8, 083013



# Astrophysics: Talks and Posters at SQM24

## Comparisons to astrophysics data

Bayesian uncertainty & pQCD  
Tues Mazeliauskas

Hybrid stars vs data  
Poster: Kumar

## Strangeness in Astrophysics

Strangeness in astrophysics  $\Lambda$  potential from  $v_1^\Lambda$   
Mon Tolos                      Poster Jinno

Strangeness & f-mode oscillations  
Poster: Banik

Strangeness in Cosmic Rays  
Poster: Singh

## Quarkyonic Matter

Quarkyonic Matter & Hyperons  
Tues Fujimoto

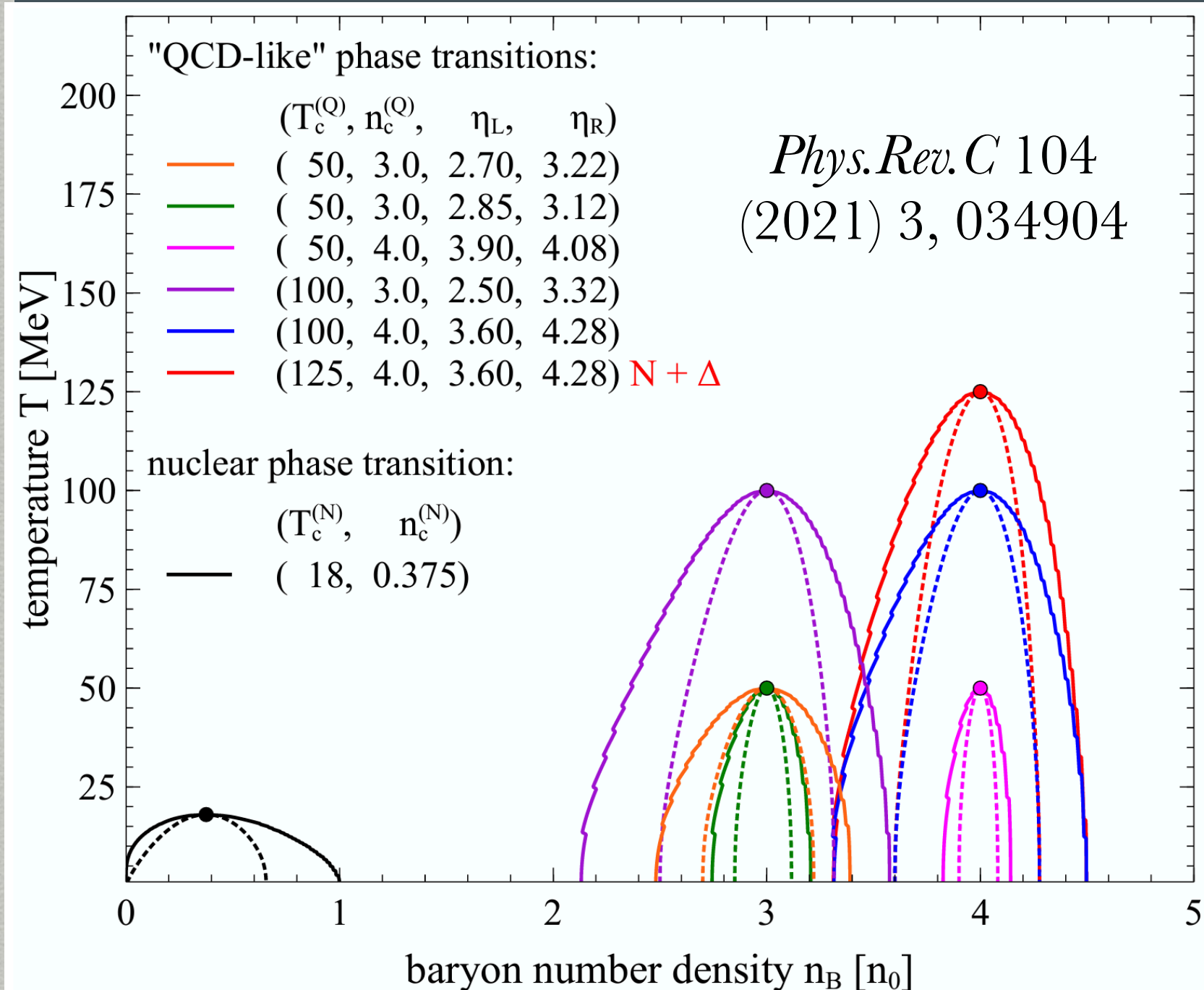
Strange quark nucleonation  
Tues Guerrini

Quarkyonic Matter & isospin asymmetry  
Poster: Moss

Quarkyonic: nuclear+quark matter  
Poster: Poberezhnyuk

# Hadrons: State-of-art

## Flexible potentials to hadron transport



Disoriented isospin condensates may explain anomalous kaon correlations *Phys.Rev.C 109 (2024) 3, L031902*

Interest in understanding charm-molecules/pentaquarks

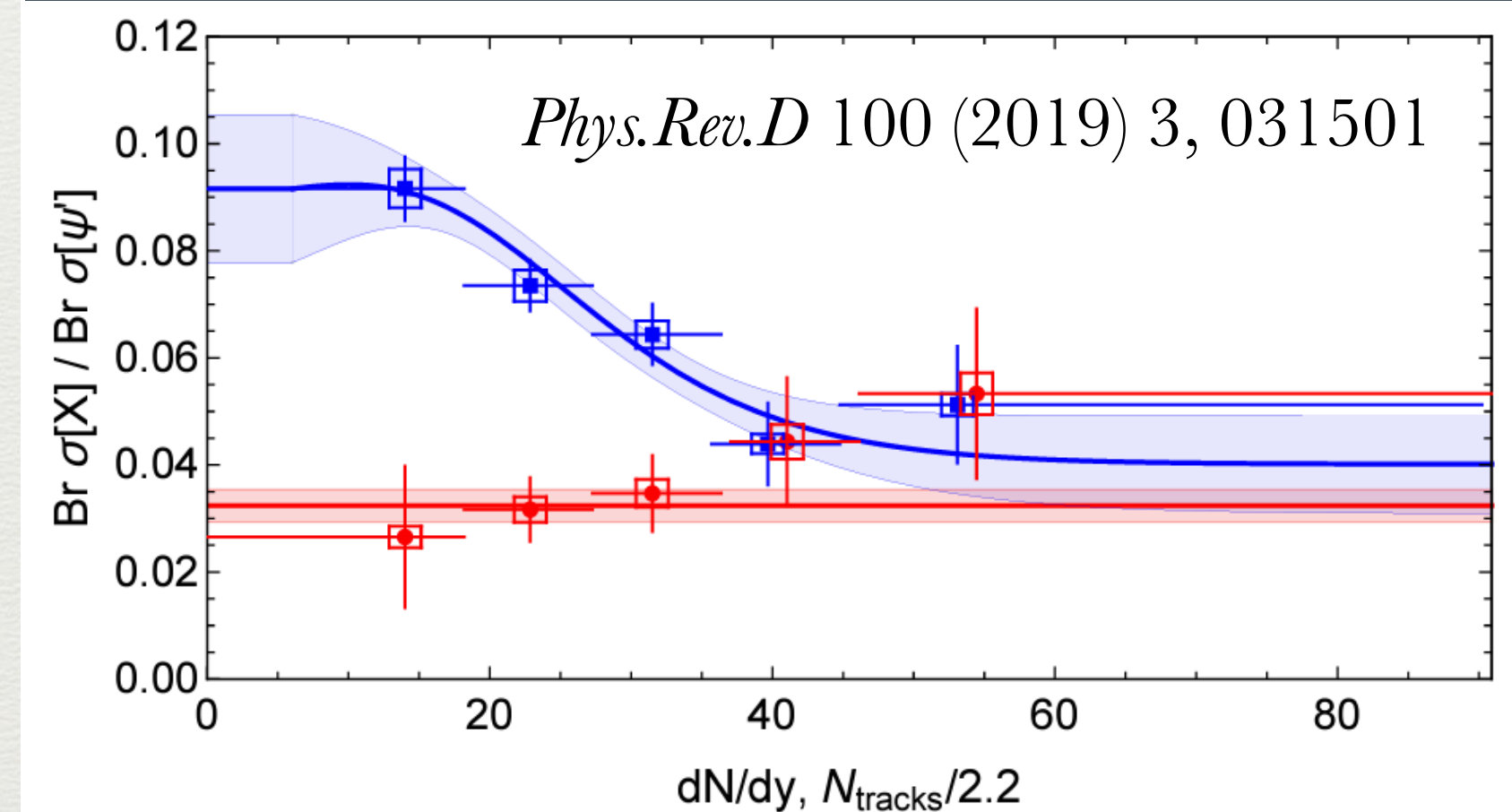
Extensions to the Hadron Resonance Gas (HRG) model

B-fields [arXiv: 2405.16306](https://arxiv.org/abs/2405.16306)

Surface Tension [Poster Zhrebtsova](#)

S-Matrix [Nucl. Phys. A 1010, 122176 \(2021\)](#)

New lists (PDG21+) [arXiv: 2309.01737](https://arxiv.org/abs/2309.01737)

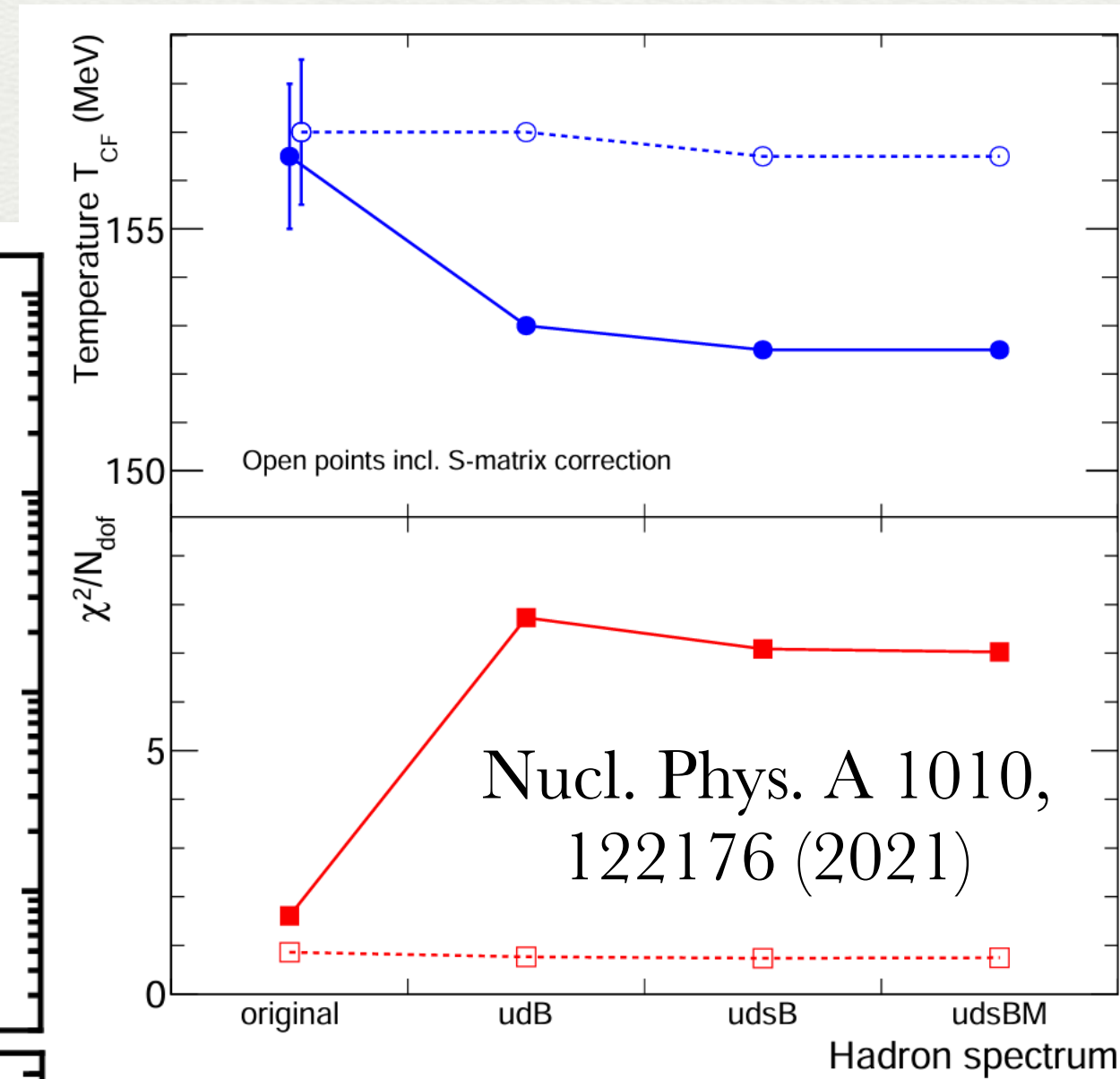
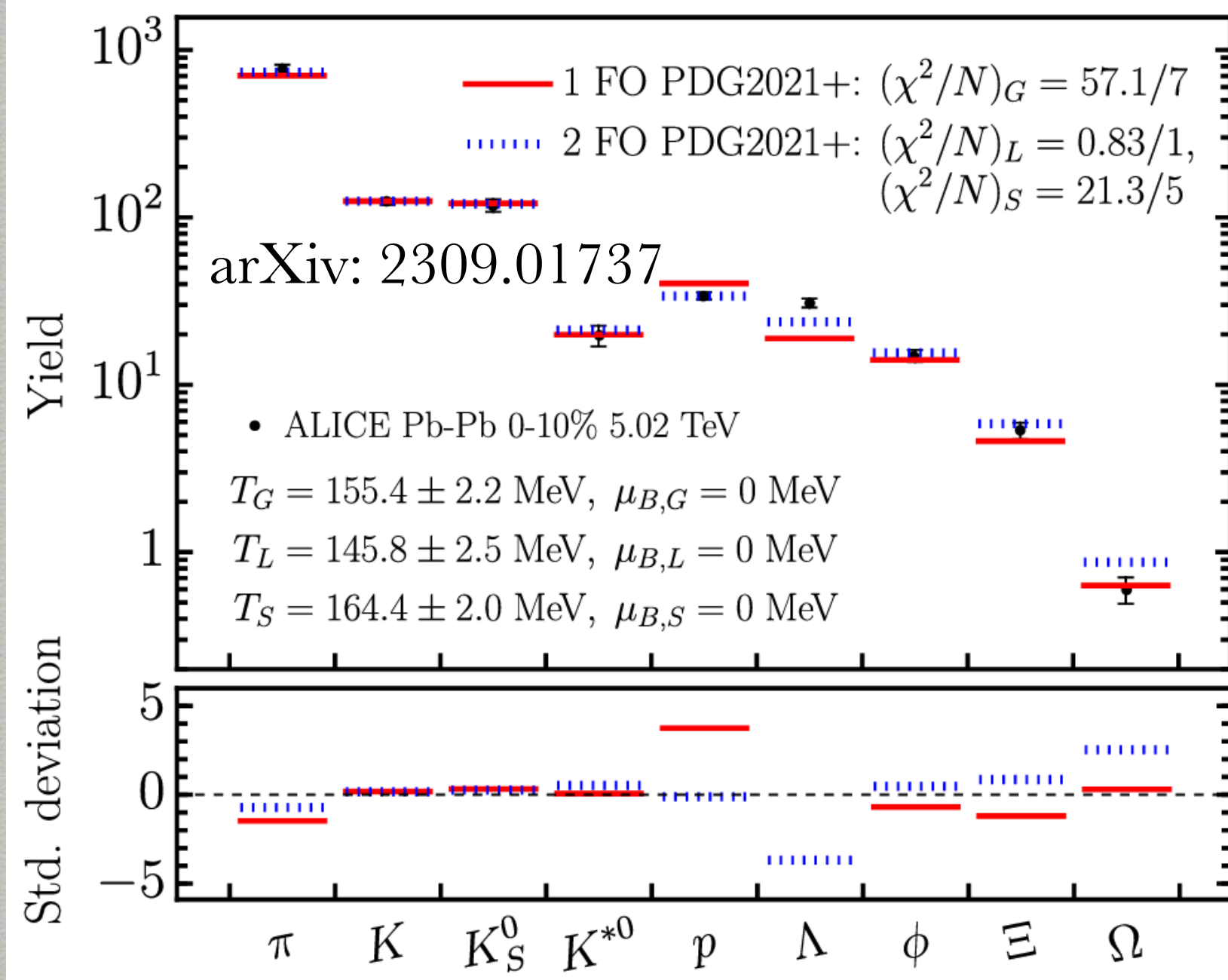


# Hadrons: Key questions

How and when is strangeness produced?

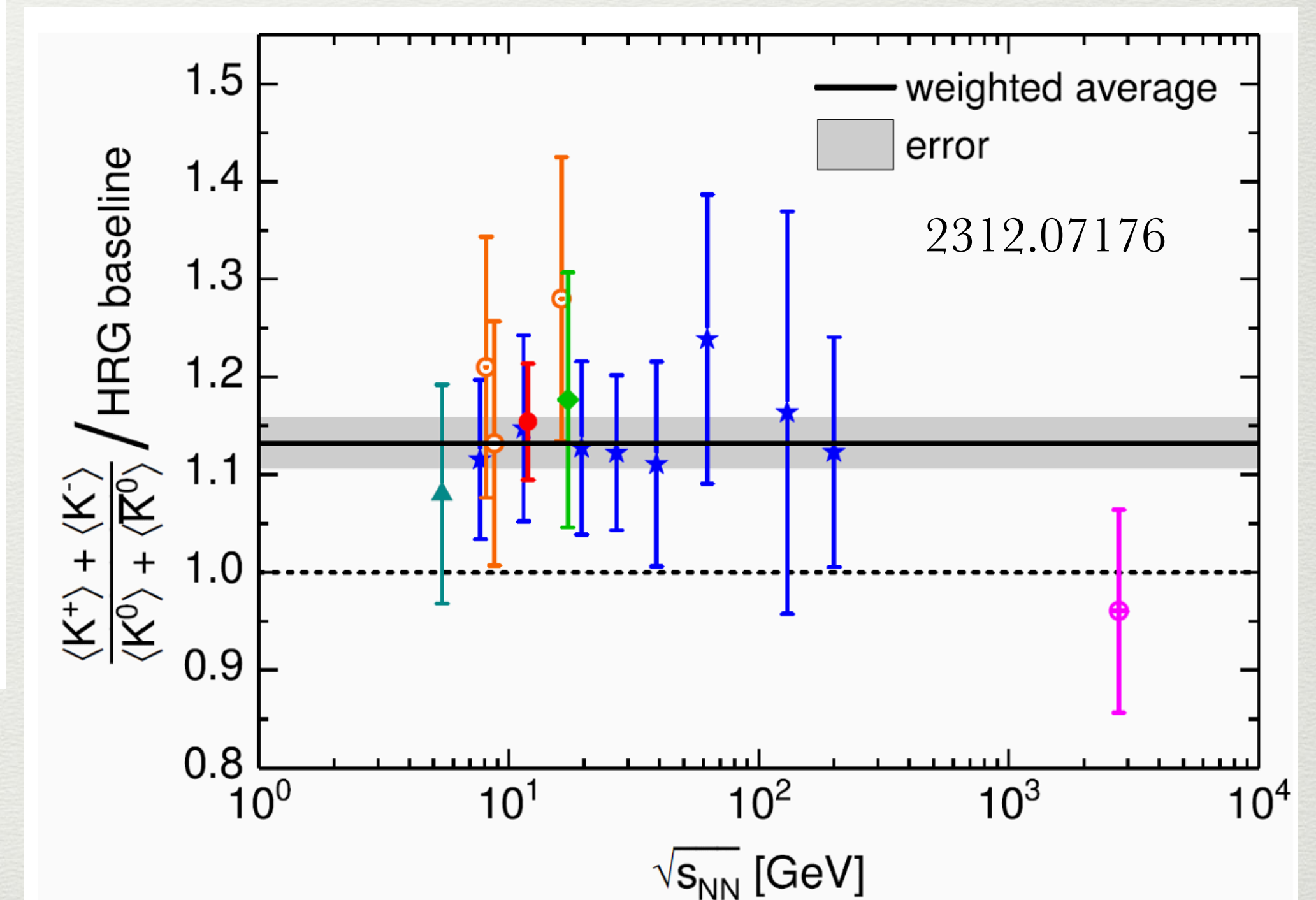
Hadron interactions in a dense environment-  
what do we understand, what are we missing?

PDG21+ signs of flavor hierarchy



S-matrix solution?

What leads to isospin breaking?



# Hadrons: Talks and Posters at SQM24

## New Developments

Disoriented Isospin Condensates  
Tues Singh

Clustering and the EOS  
Weds Bratkovskaya

$p$ - $\phi$  correlations  
Weds Kuroki

Vector mesons in medium  
Poster Liu

Tsalis Thermometer  
Poster Barnafoldi

Dynamical quasi-particle model  
Poster Grishmanovskii

Overview  
Mon Bass

## Nuclei/Exotica

⇓ triton in a kinetic approach  
Weds Sun

X(3872)  
Tues Escobedo Espinosa

## Strangeness

S production at low  $\sqrt{s}$   
Poster Piasecki  
Optimization of S Production  
Poster Rosenkvist

Light vs S quark freeze-out  
Poster Gordeev  
S in AMPT  
Poster Jalotra

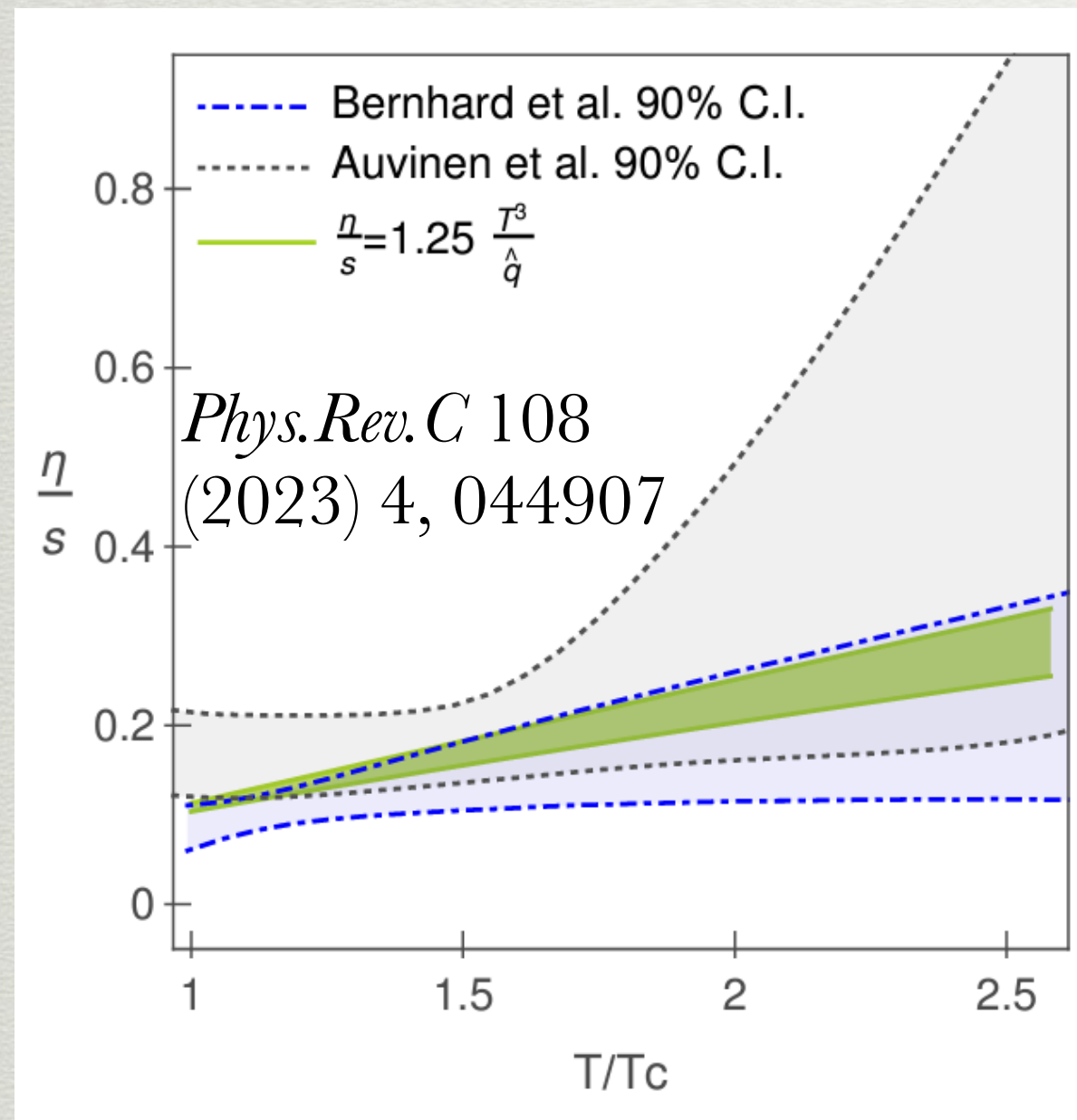
## HRG/Thermal model

Surface tension in HRG  
Poster Zherebtsova  
Thermal model:  $y$  vs net- $p$  cumulants  
Poster Li

# Dynamics: State-of-art for $\eta, \zeta, \dots$

## Bayesian analyses

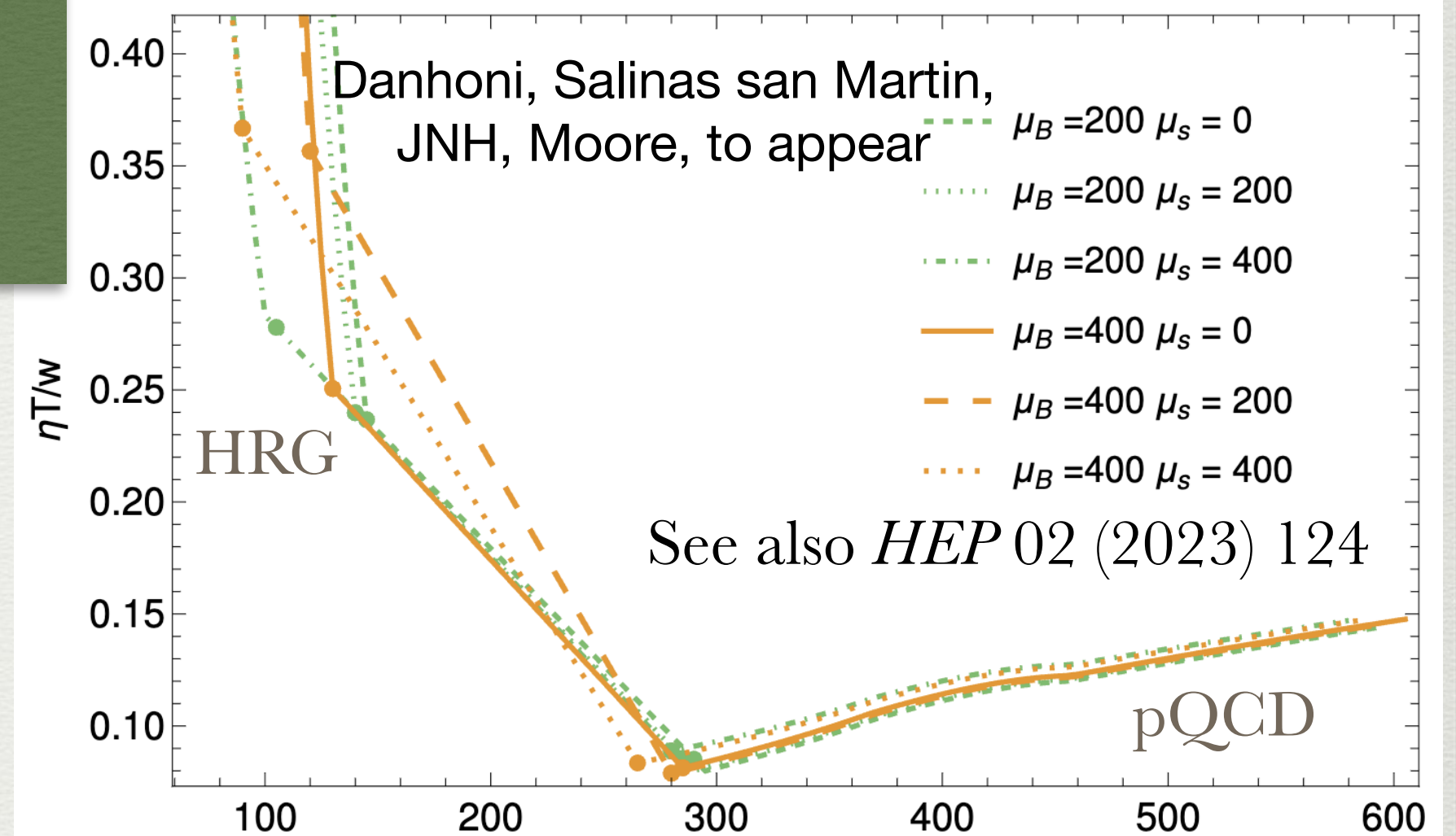
At vanishing  $n_B$  & from  $\hat{q}$



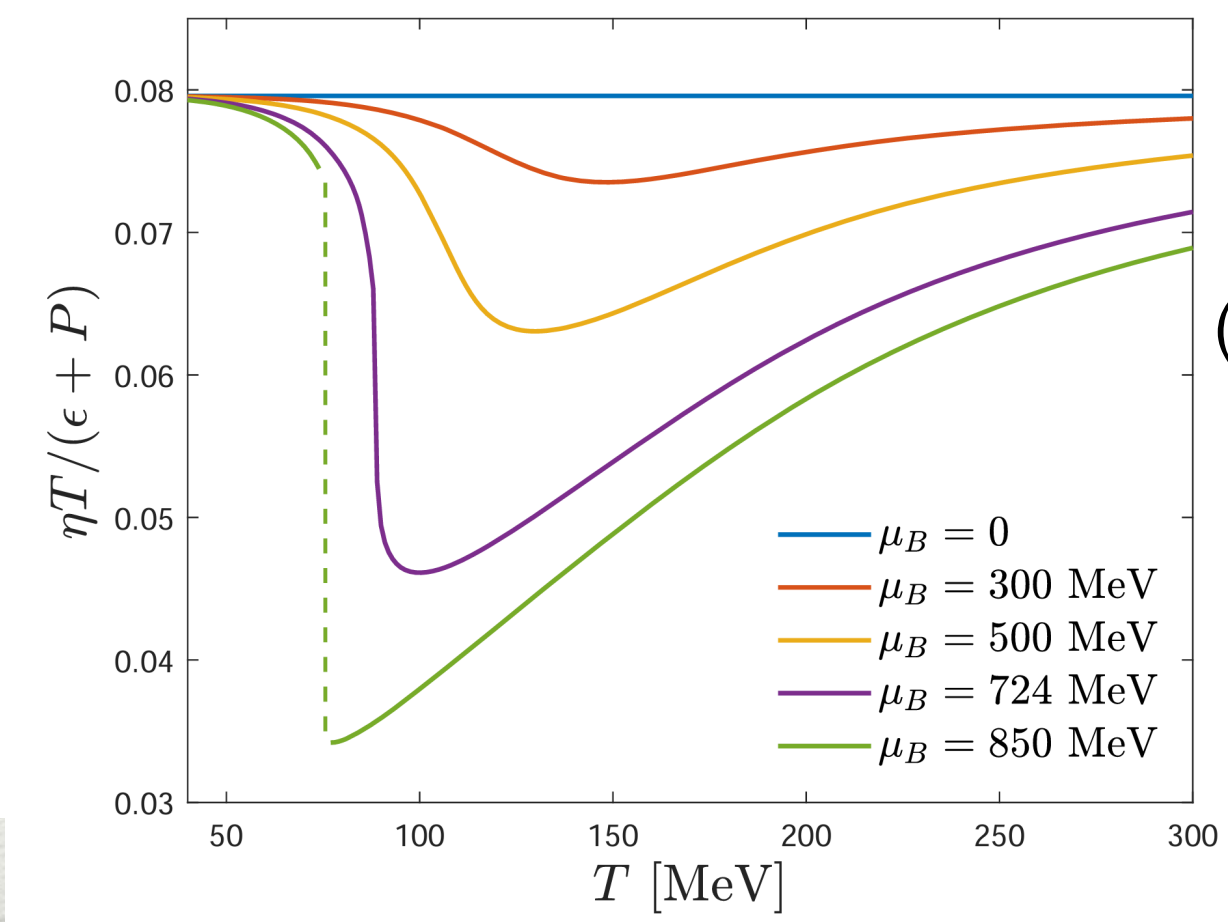
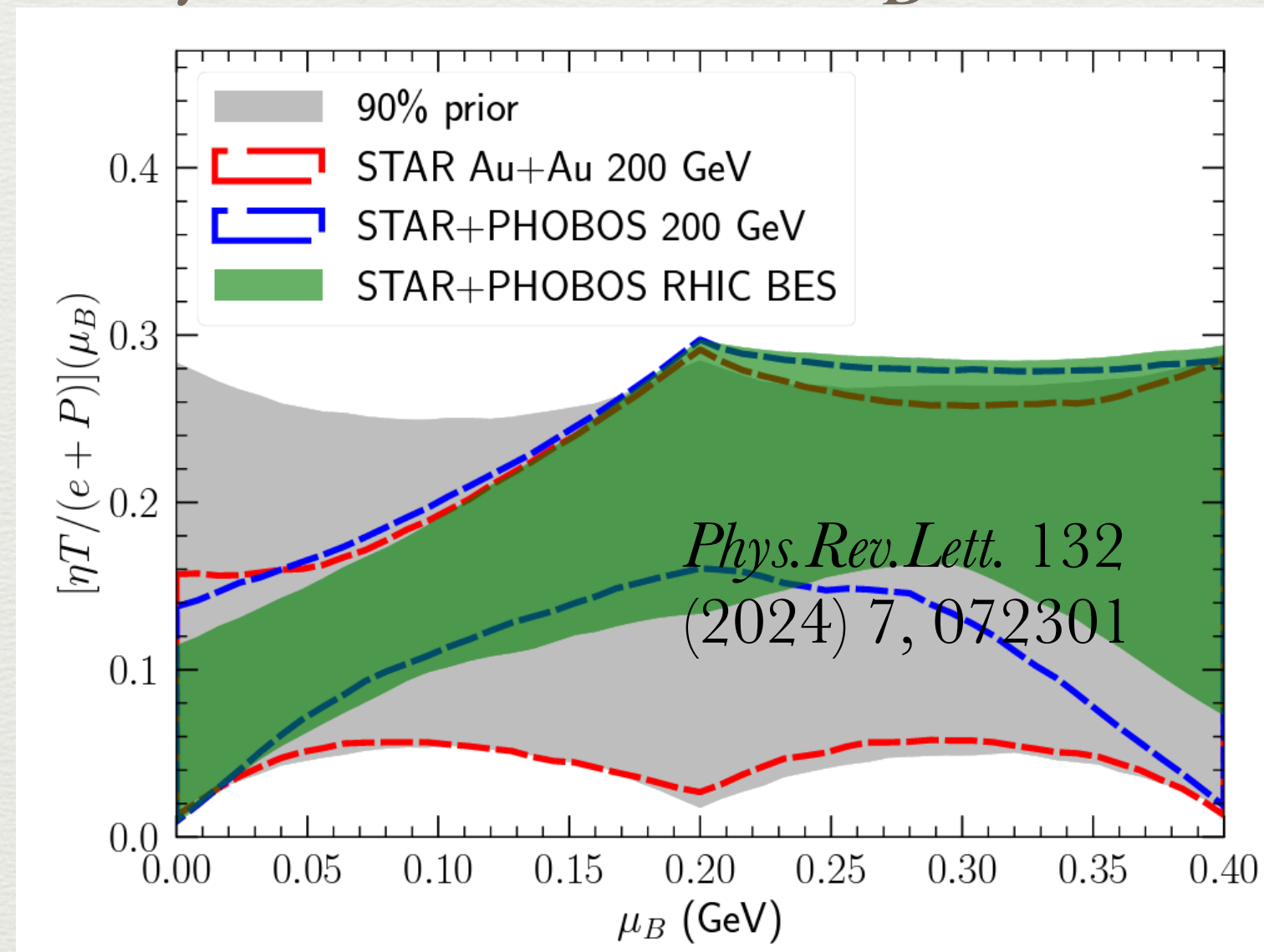
+JETSCAPE  
*Phys. Rev. Lett.* 126 (2021) 24, 242301  
 ; TRAJECTUM  
*Phys. Rev. C* 103 (2021) 5, 054909

## Microphysical developments at finite $\mu_B, \mu_S, \mu_Q$

pQCD results at finite  $\mu_B, \mu_S, \mu_Q$



## Bayesian at finite $n_B$



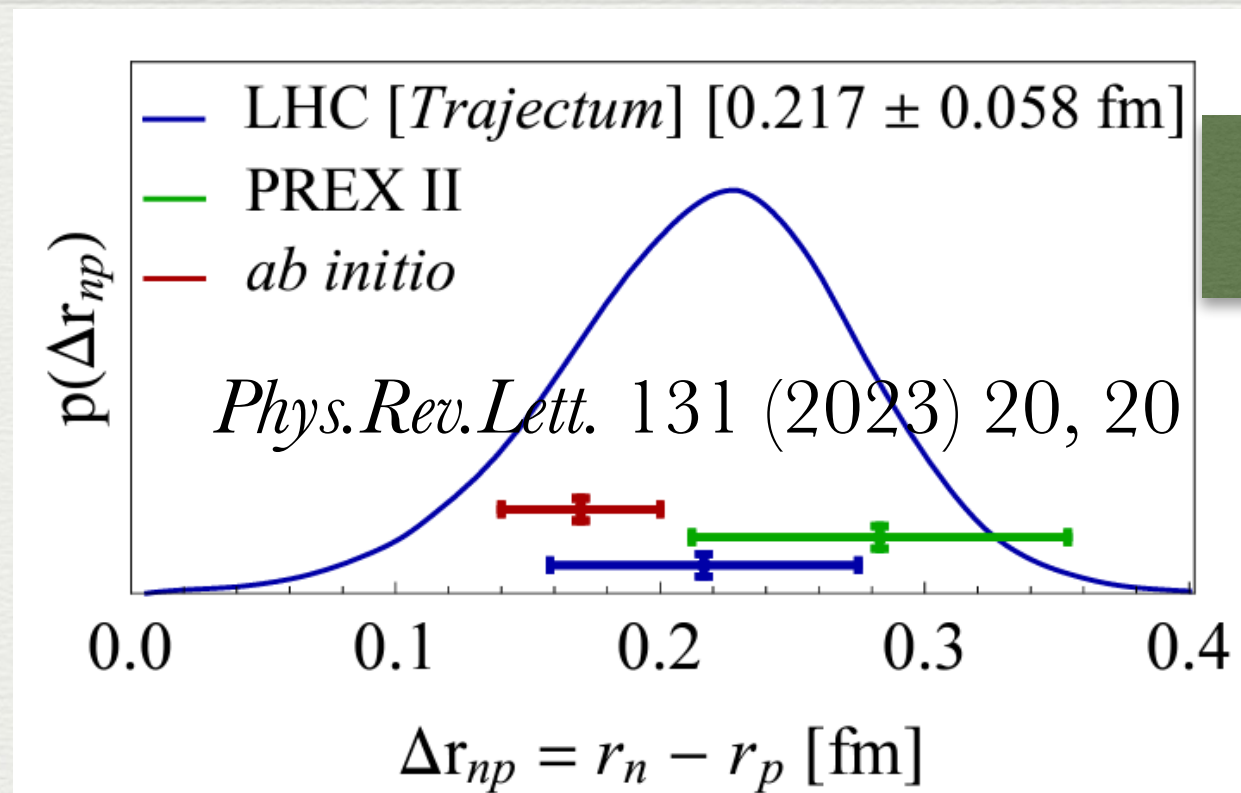
Holography,  
*Phys. Rev. D* 106 (2022) 3, 034024

See also PNJL,  
*Phys. Rev. C* 103 (2021) 5, 054901



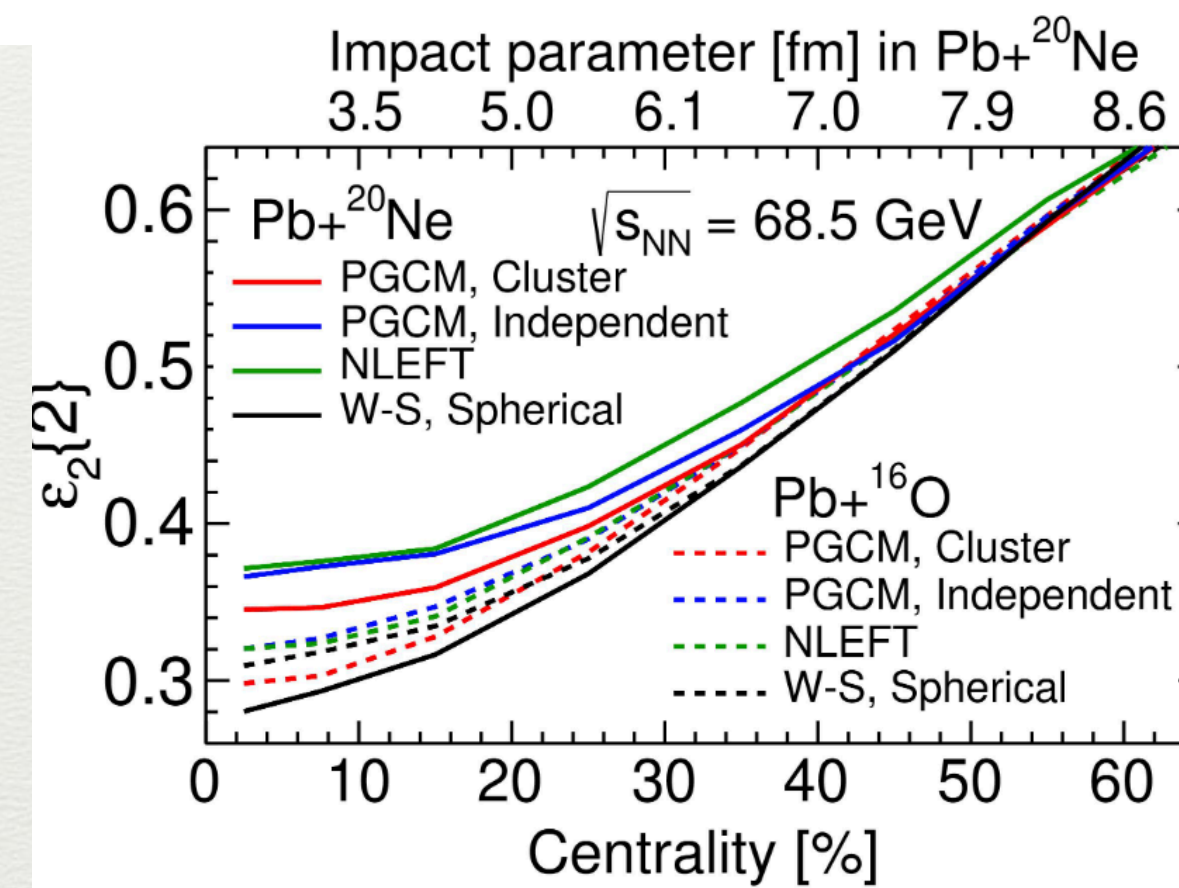
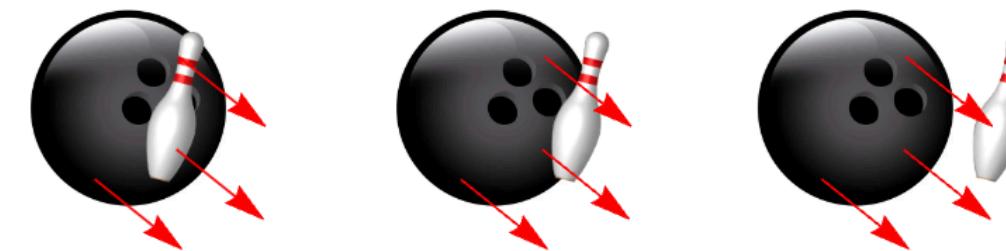
# Dynamics: State-of-art for limits of hydro

Neutron skin  $\rightarrow$   
insight into neutron  
star EOS



## Nuclear Structure

Giacalone et al, 2405.20210

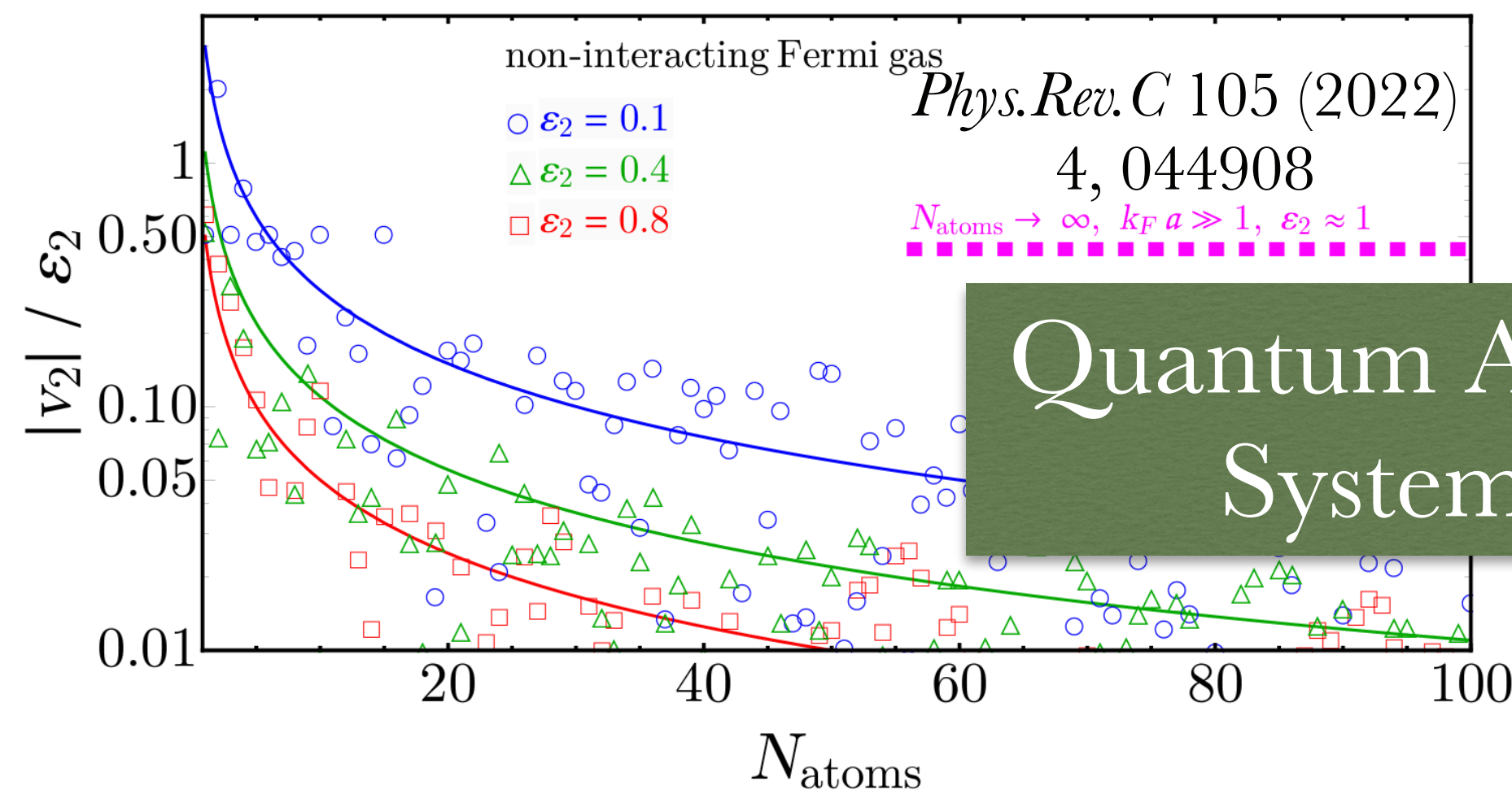


Proposal for LHCb

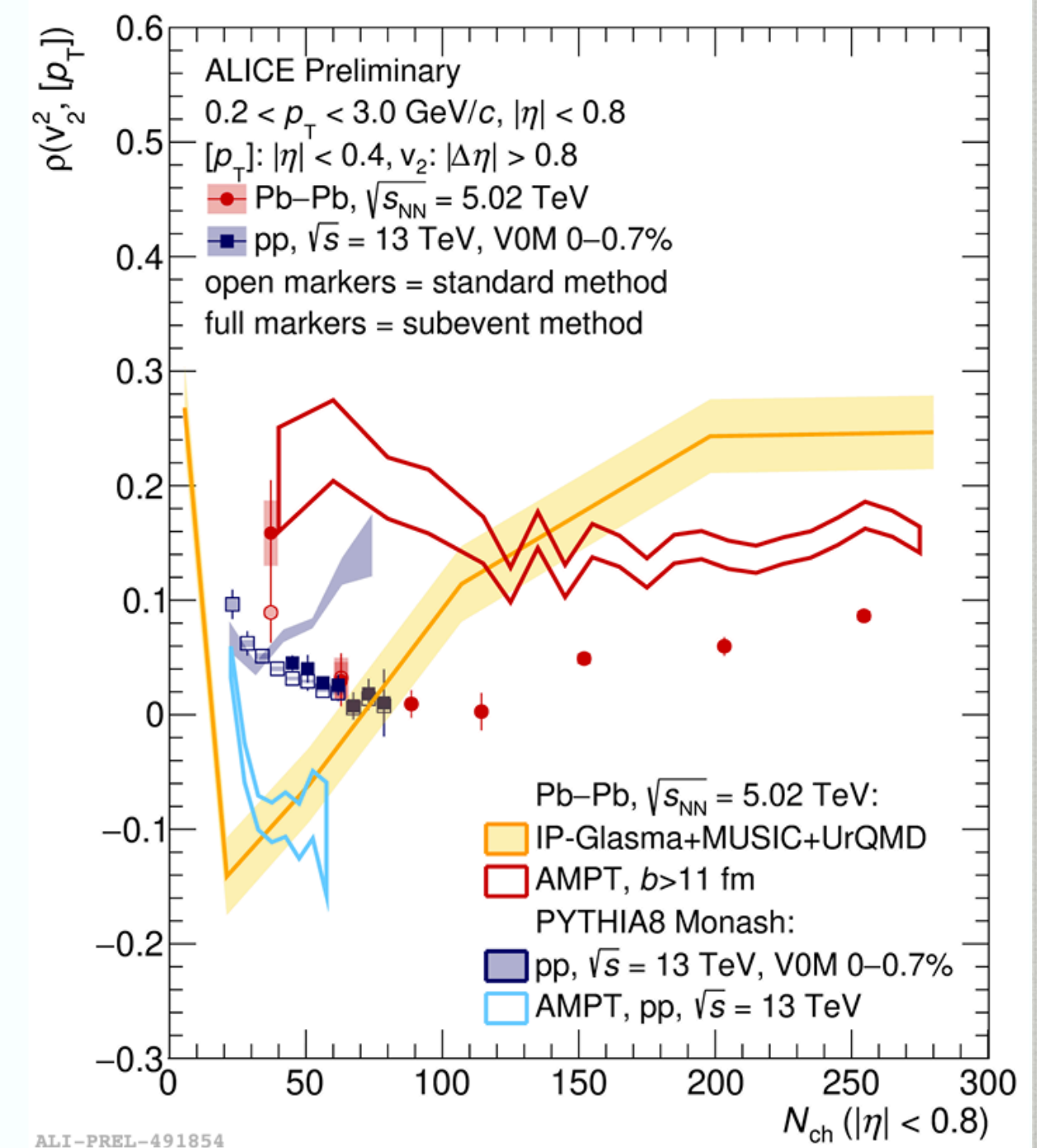
## Small systems

Remaining questions  
in small systems

Flow in small systems with cold atoms

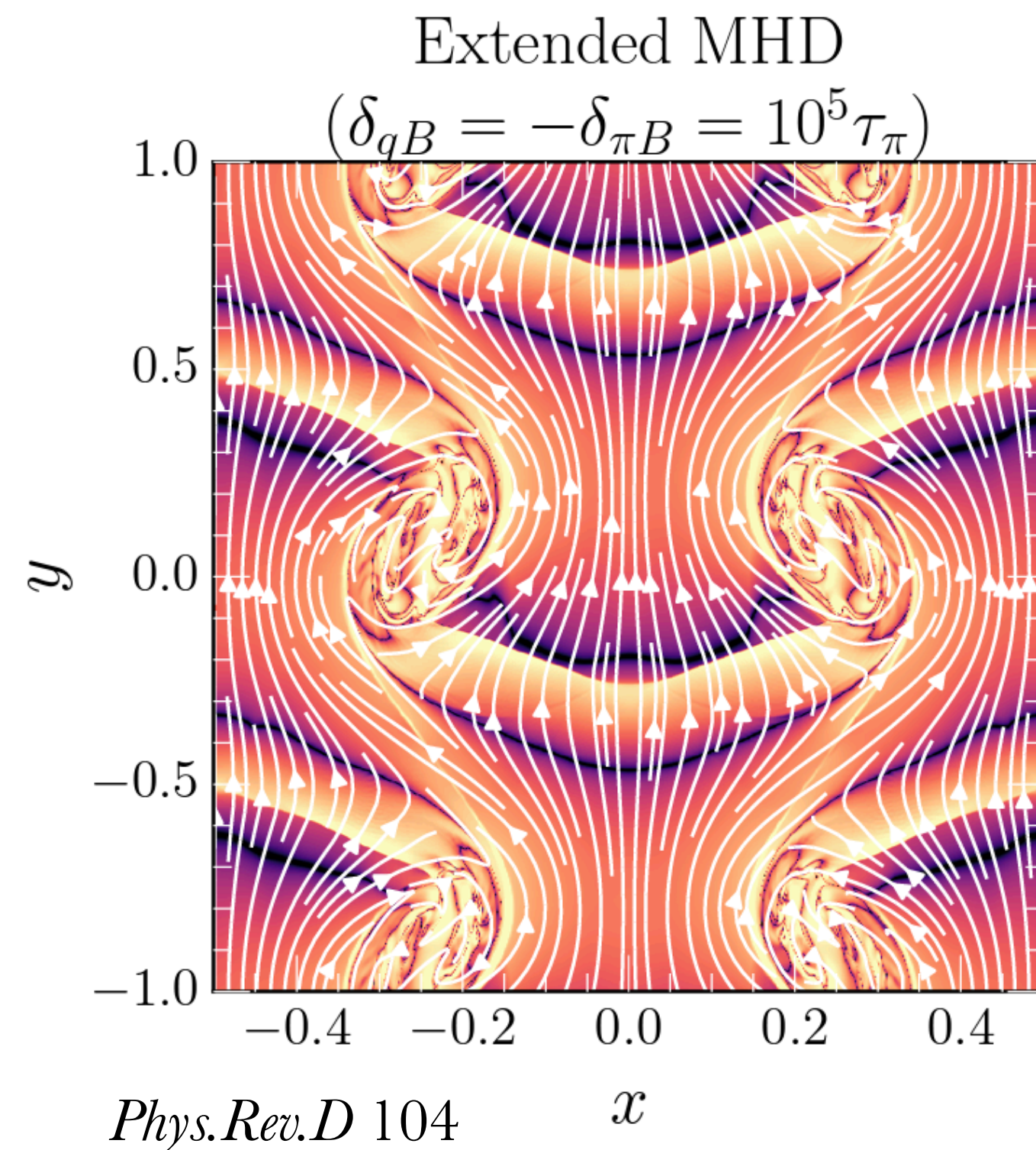
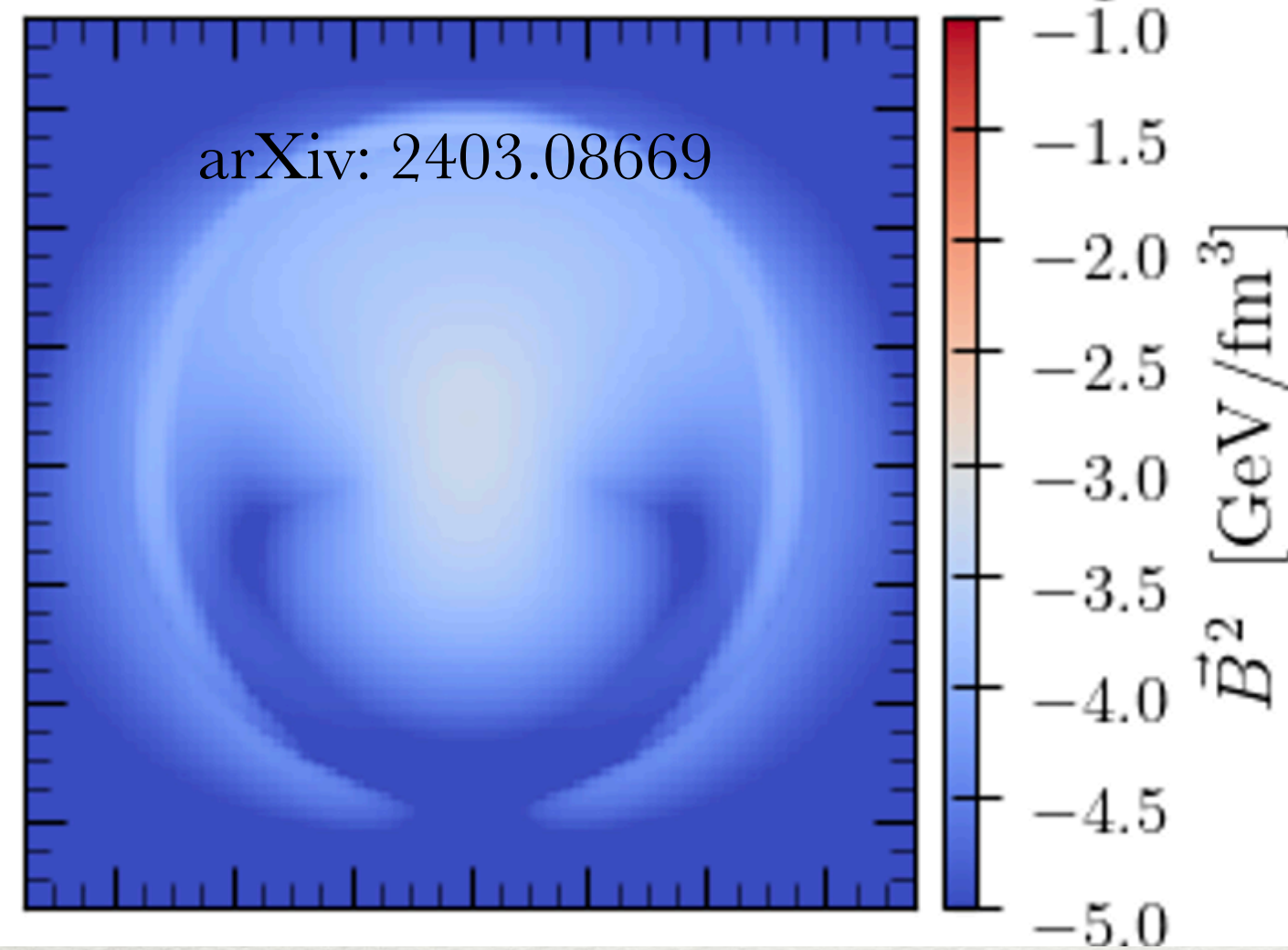


## Quantum Analog Systems

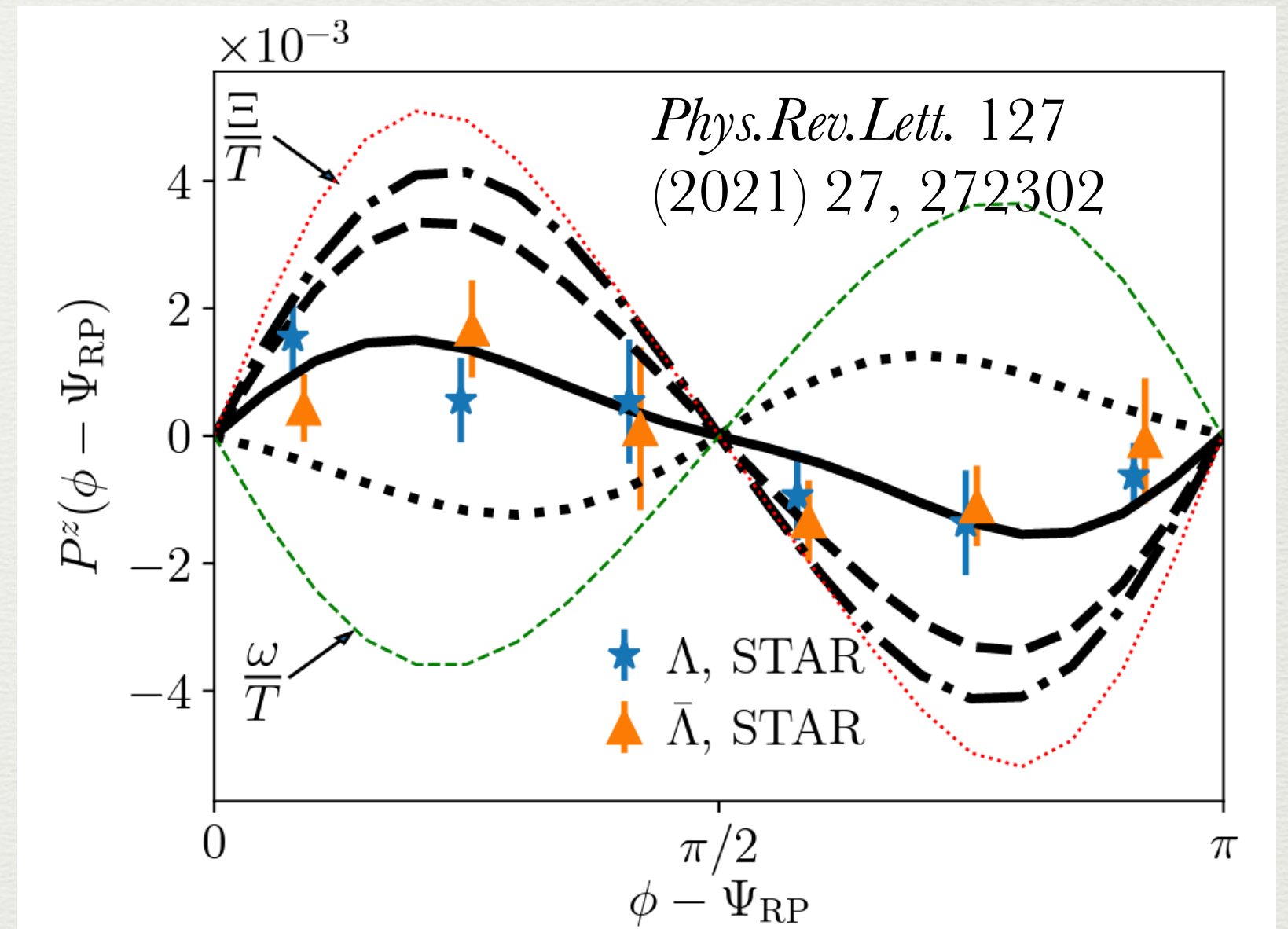


# Dynamics: State-of-the-art for Spin/B-fields

New ideal  
Magnetohydrodynamics  
framework for HIC



Comparisons to  $\Lambda$  polarization



Rel. viscous  
Magnetohydrodynamics  
for astro

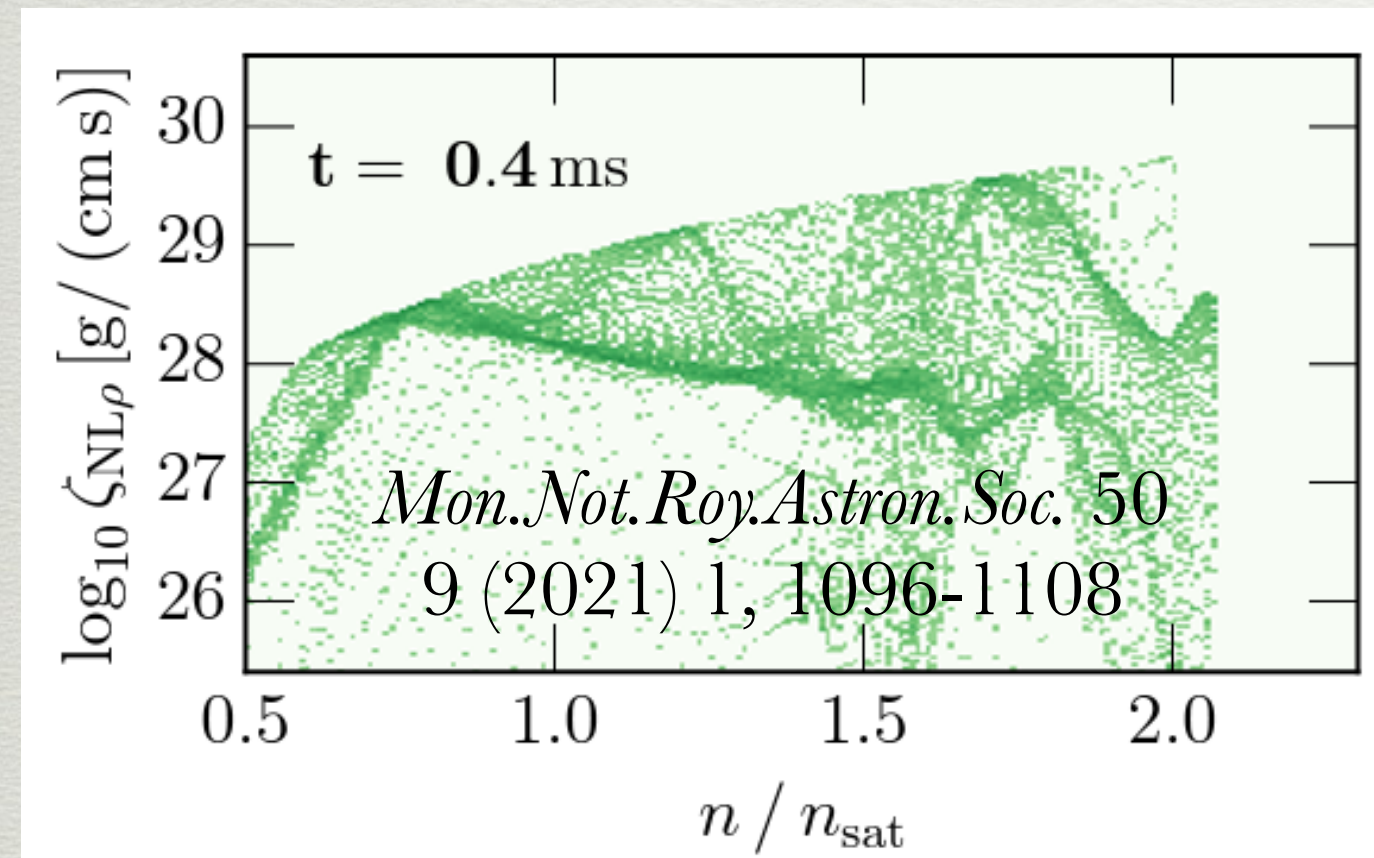
Significant work on spin hydro theory  
development

Speranza, Weickgenannt, Wagner, Florkowski, Becattini, Noronha,  
Karpenko, Grossi, Palermo, Rischke, Kaminski, Torrieri, Singh,  
Rybleski, Jaiswal, Elfner+ many others

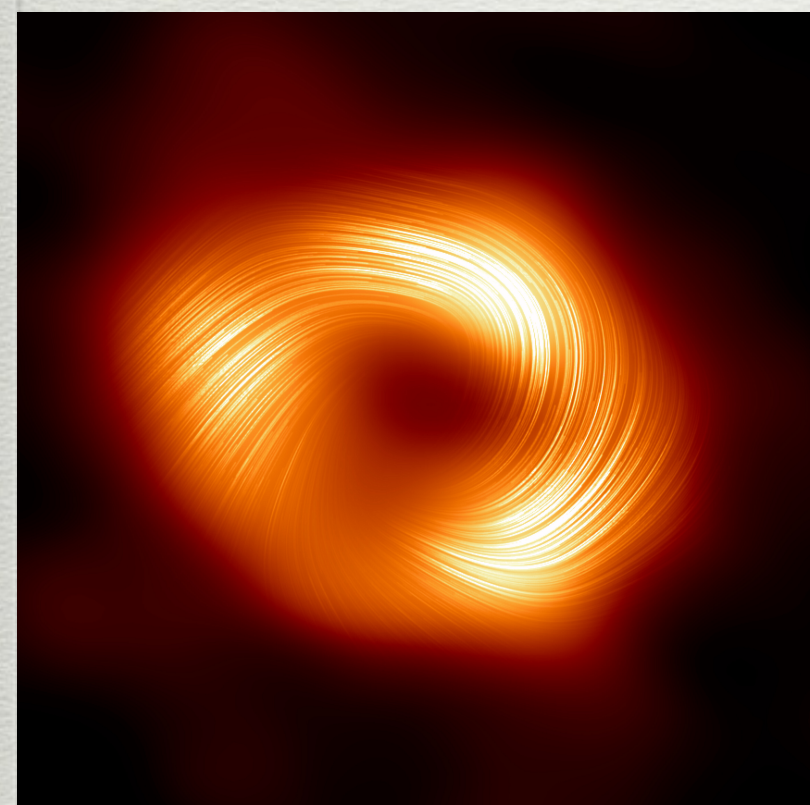
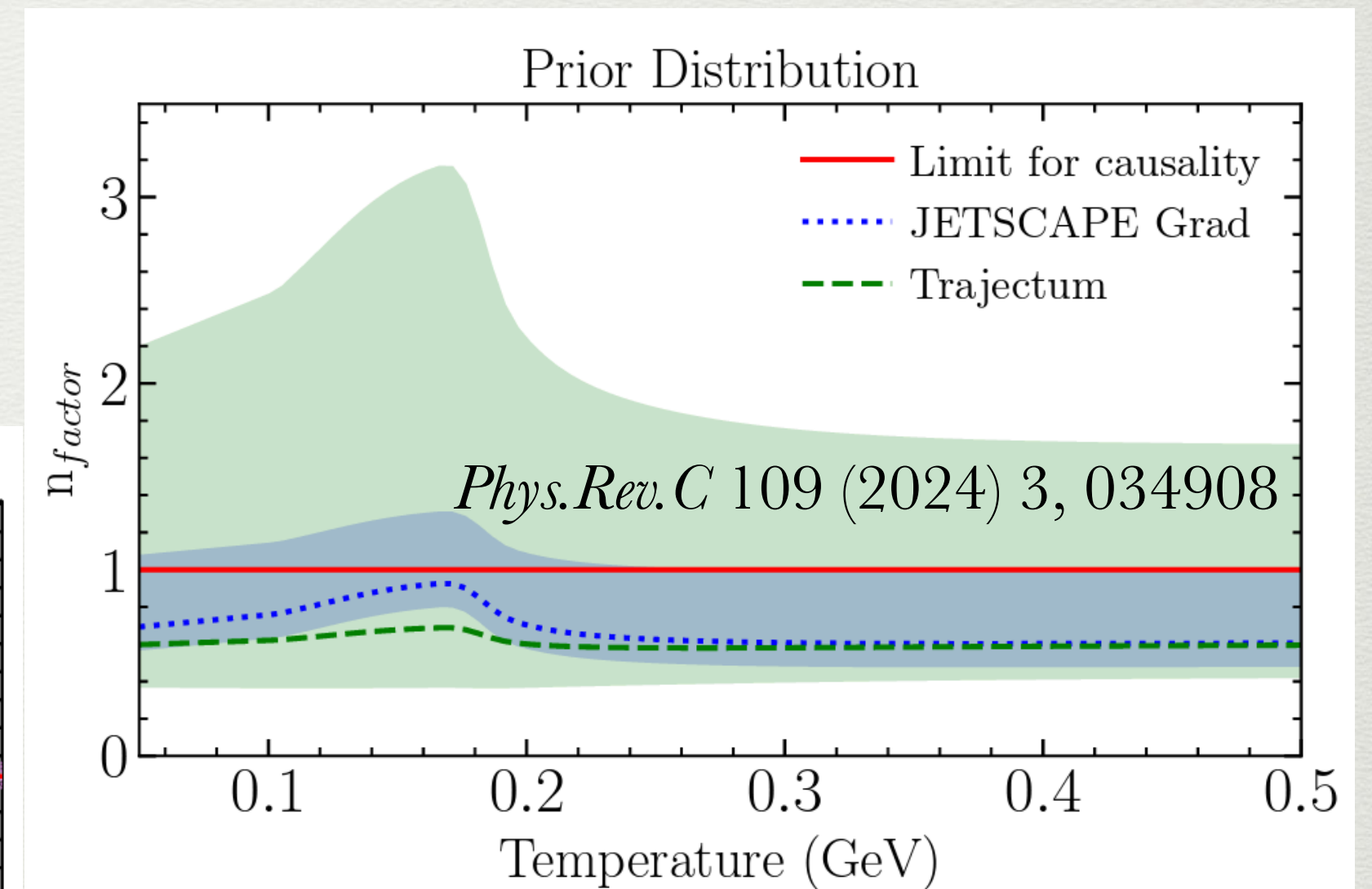
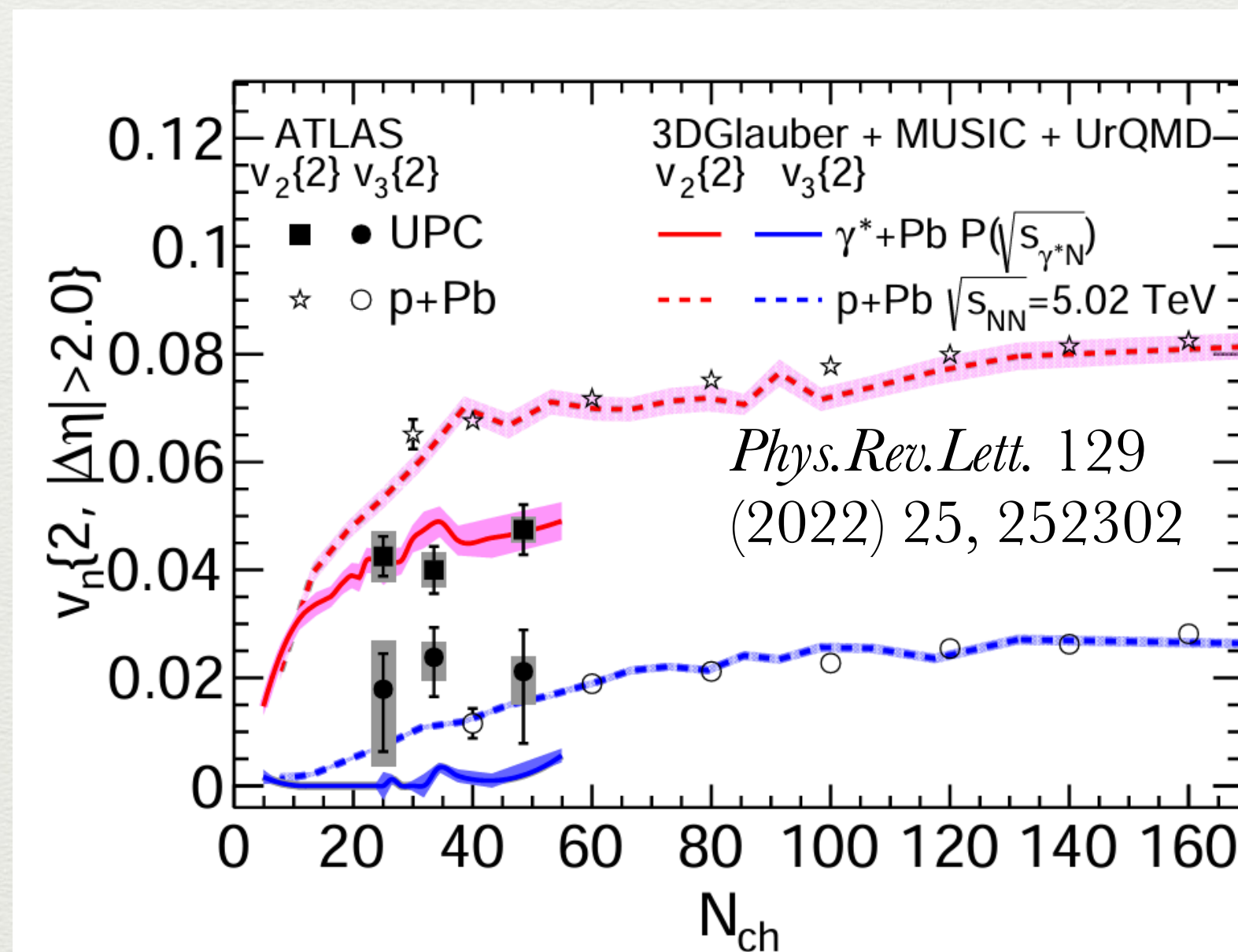
# Dynamics: Key questions

How does heavy-ion knowledge of rel. viscous fluids translate to other fields?

How will causality/stability constraints affect the Bayesian analyses?



Could hydrodynamics be relevant for the EIC?



Viscosity in neutron star mergers/accretion disks

Stability constraints for BSQ conserved charges

arXiv: 2209.11210

# Dynamics: Talks and Posters at SQM24

## Nuclear Structure

Nuclear radii

Thurs Giacalone

Breit-Wheeler & charge radius

Poster Wang

Uranium-238 deformation

Poster Xu

## Cold Atoms/Quantum Analog system

Flow & number of particles

Tues Heyen

## Dynamics

Deuteron flow

Poster Tomasik

Low  $p_T$  spectra & effective  $\mu_\pi$

Poster Vitiuk

Thermalization of Wigner function

Poster Chen

Deep learning to predict  $v_n$

Tues Barnafoldi

## Unifying soft/heavy/energy loss

Transport properties: high & low  $p_T$

Tues Djordjevic

Unified soft-heavy EPOSHQ

Tues Gossiaux

Soft-hard correlations: event-by-

event JEWEL

Poster Barreto Campos

# Spin/B-fields: Talks and Posters at SQM24

## Spin Hydro

Initial conditions and  $\zeta/s$  effects

Weds Palermo

Entropy and Dissipation in spin hydro

Weds Daher

Spin polarization of fermions at local equilibrium

Weds Sheng

Vorticity and Viscosity on  $\Lambda$  Polarization

Poster Singh

## Other approaches

$\Lambda$  polarization within Transport

Poster Vitiuk

Spin polarization in a blast wave model

Poster Bhadury

Spin alignment of vector mesons by glasma fields

Weds Yang

## Other considerations

B-field effects in HRG

Weds Vovchenko

Estimating B-Fields with  $\gamma$  & dileptons

Poster Wei

Spin alignment of  $K^*$

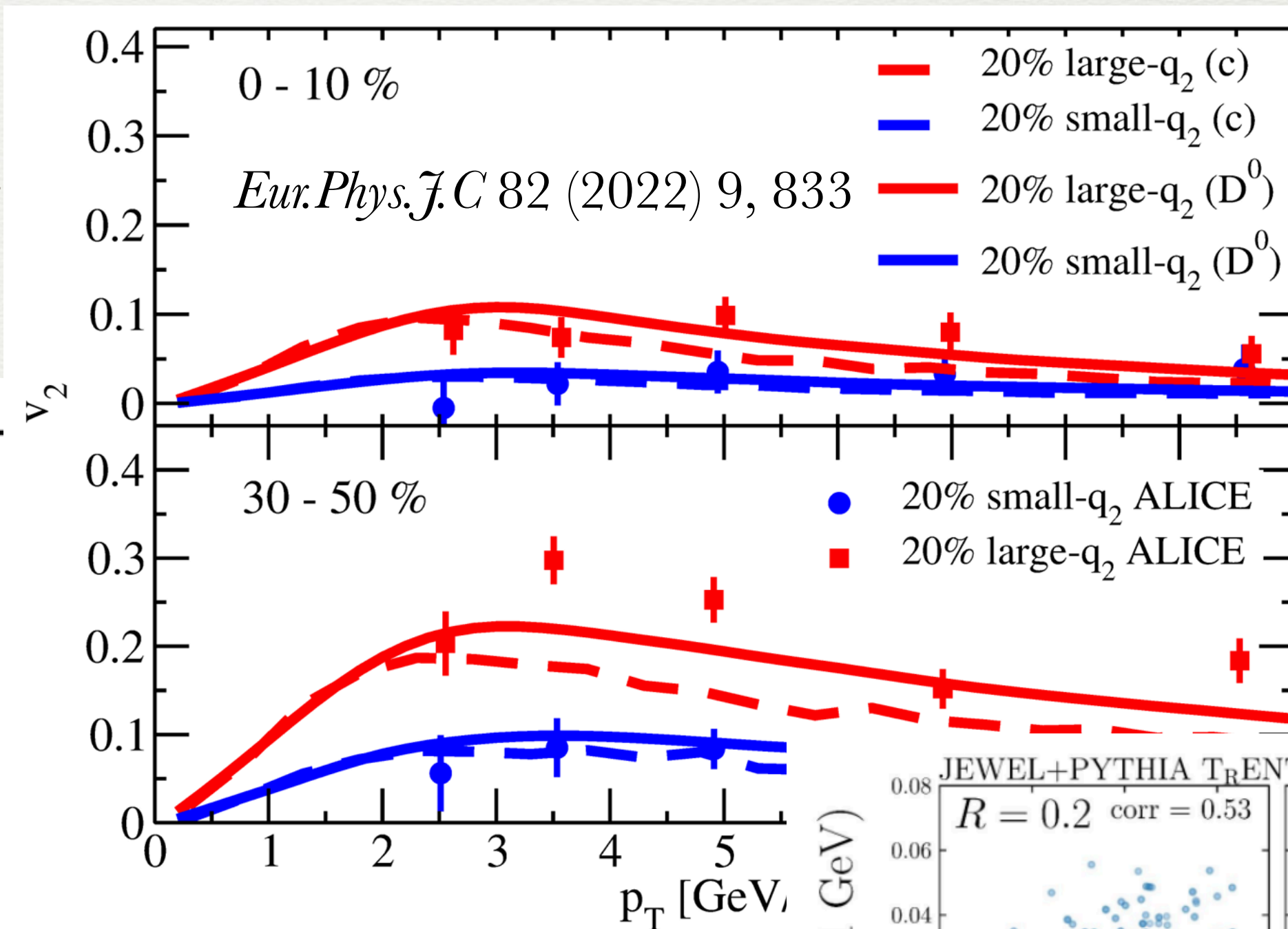
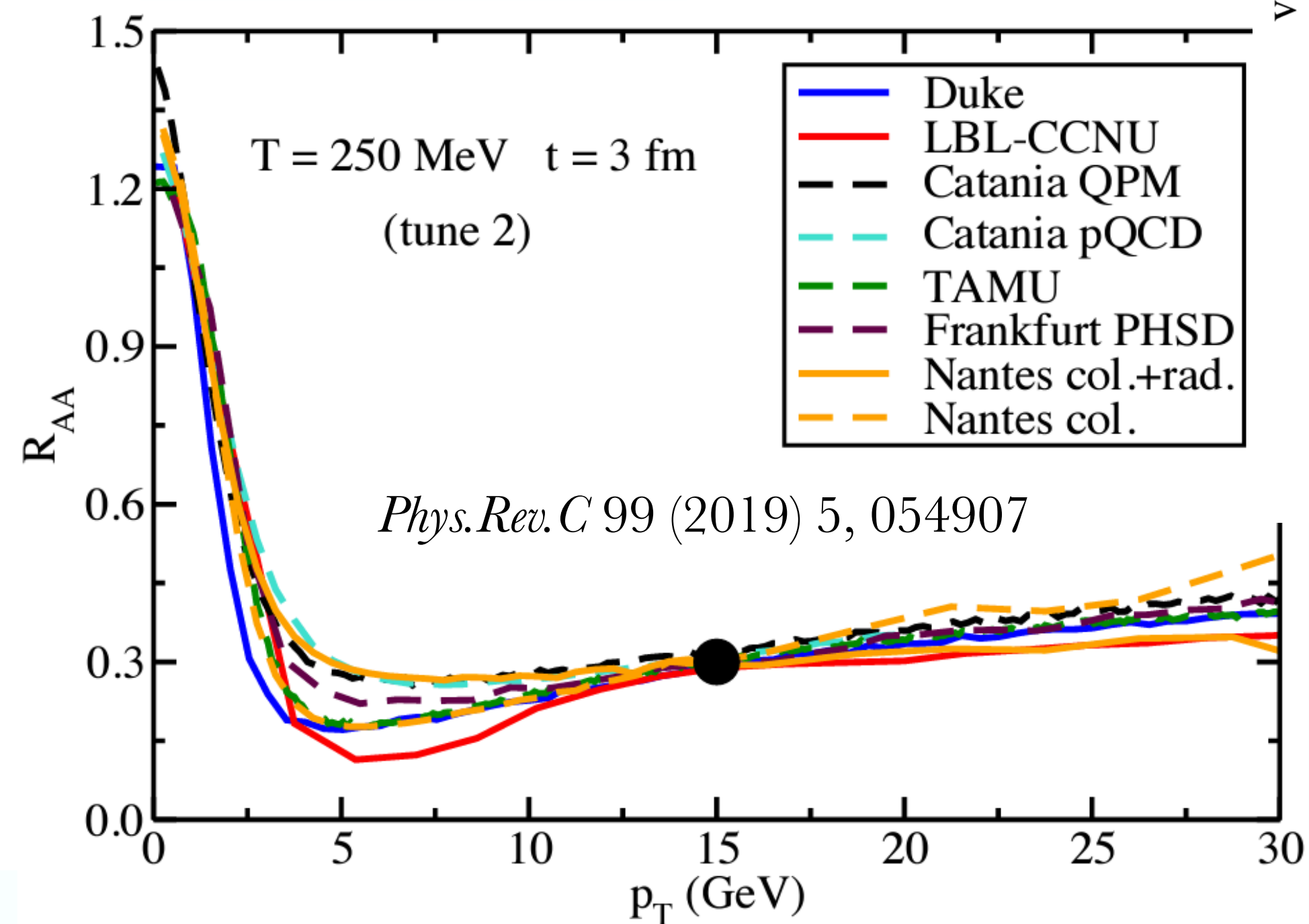
Poster Li

Chiral restoration and polarization

Poster Bhadury

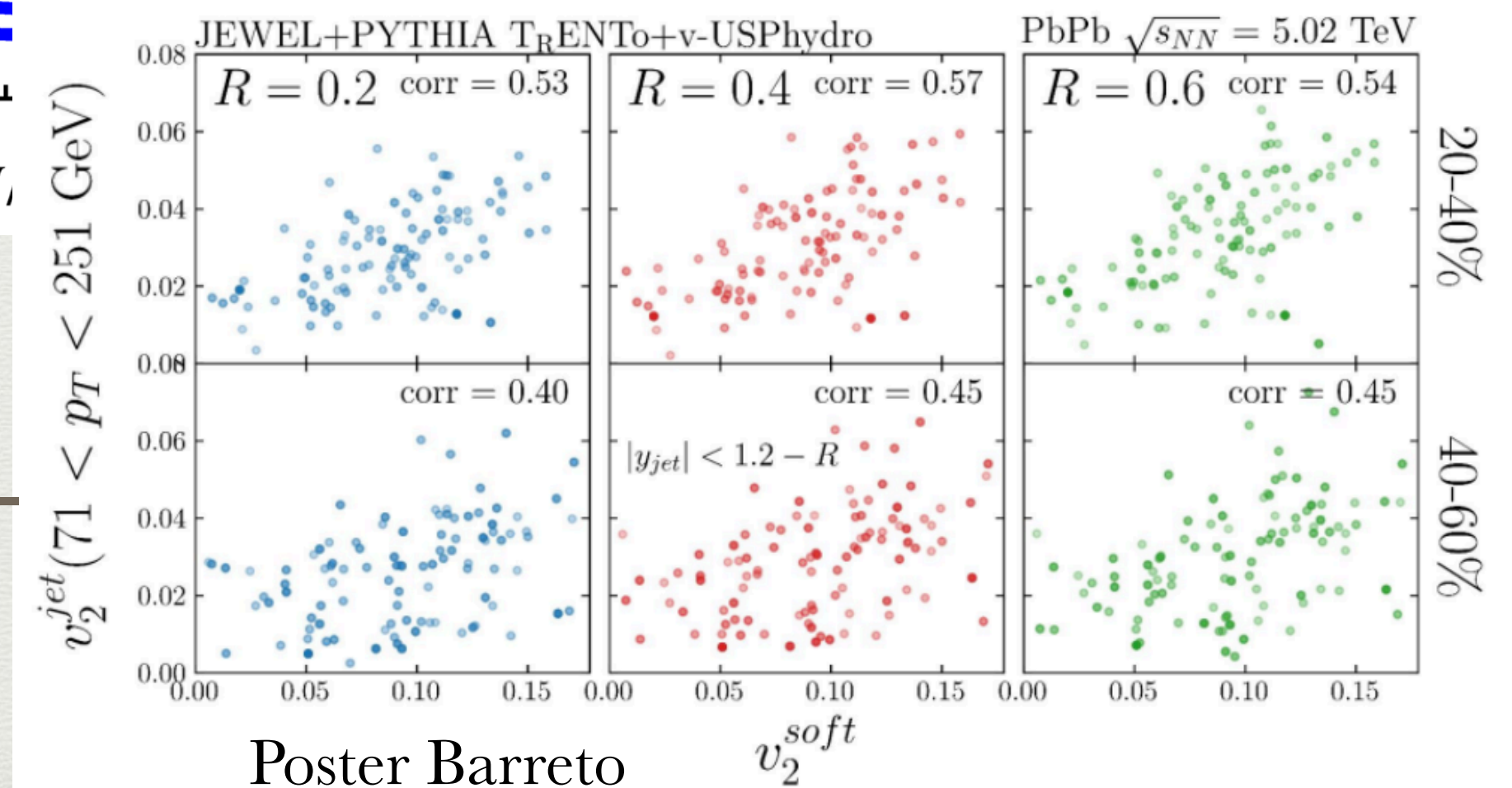
# HF/Jets: State-of-art

Unified medium evolution  
significant reduces uncertainty



Understanding  
of soft-heavy/  
hard correlations

Soft-hard  
correlations by Jet-  
radius



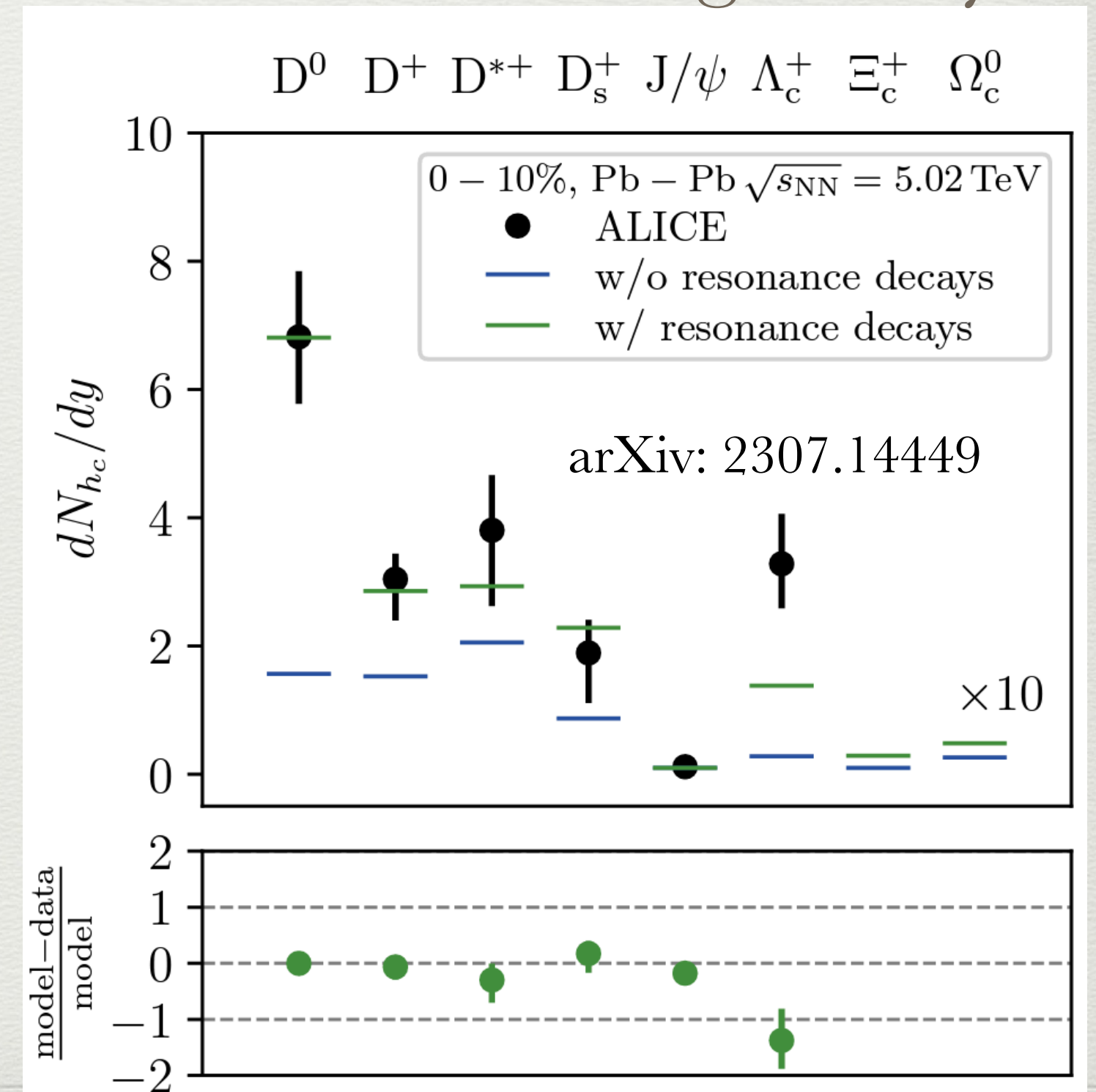
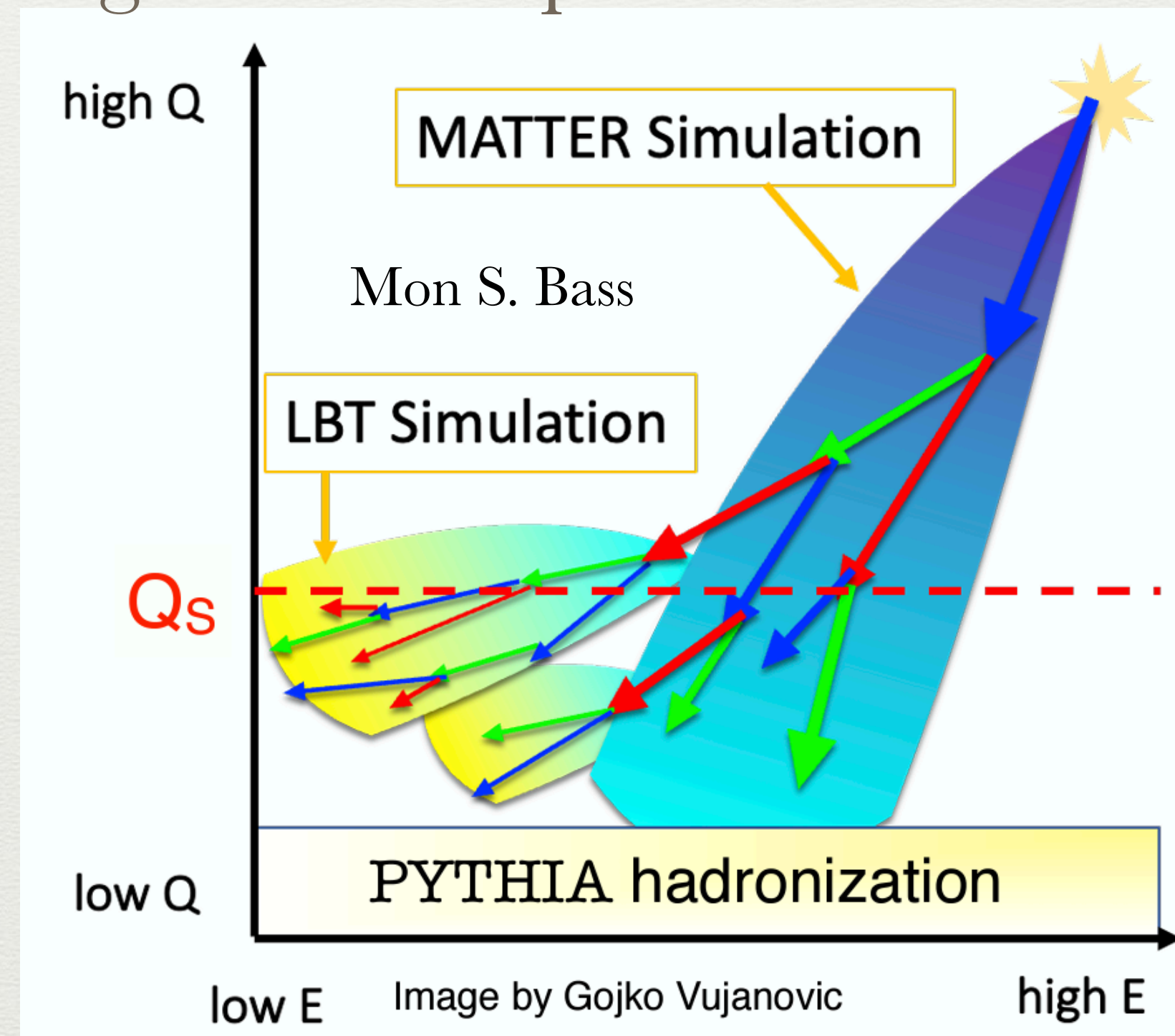
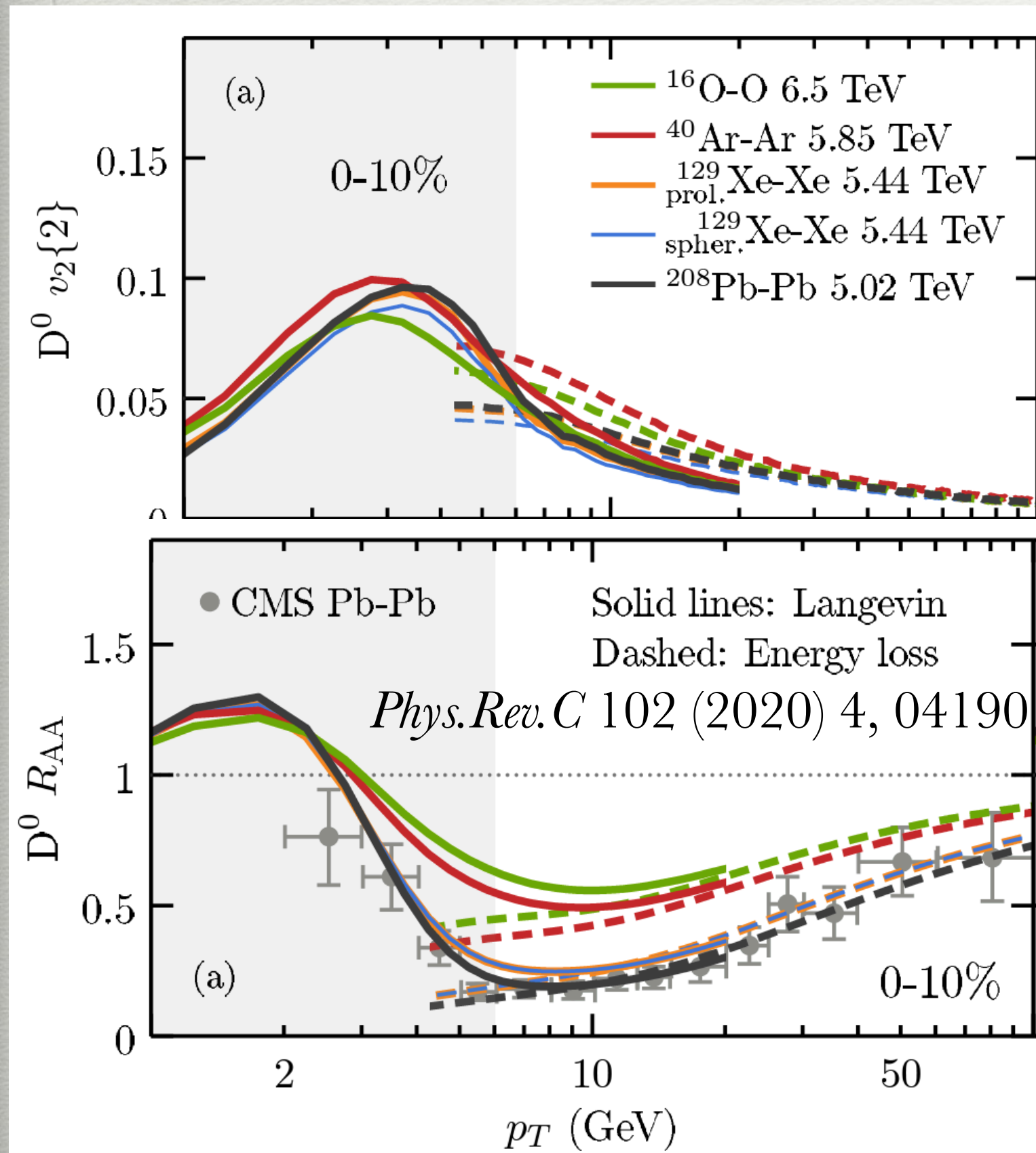
# HF/Jets: Key questions

Can we understand HF/  
energy-loss across system  
size?

Could charm quarks be thermalized in the medium?

Most HF approaches based on  
Langevin/transport/kinetic theory

New approach on charm as  
a conserved charge in hydro



# HF/Jets: Talks and Posters at SQM24

## Different theoretical approaches

Minijet quenching in non-equilibrium  
Poster Zhou

Charm melting in strings vs vdW  
Poster Goswami

Bayesian Flavor hierarchy of E-oss  
Tues Xing

B meson study of  $R_{AA}$  &  $v_n$   
Tues Lucia Sambataro

Mass hierarchy with E-loss  
Tues Dang

Quark-meson coupling  
Poster Mondal

Flow of charmonium  
Poster Cho

B-fields and HF  
Weds Chen

$\Upsilon$  production with Pythia  
Poster Mezhenska

Spin 1 quarkonia  
Poster Kim

Partonic Critical Opalescence  
Poster Wu

## Small Systems

Charmonia polarization in pp  
Poster Deb

HF in small and large systems  
Tues Faraday

AA to pp scan for D and B  
Tues Pulmari

Quarkonia in pp  
Poster Singh

$R_{AA}$  in OO  
Poster Behera

## Early Stages

Disassociation of  $q\bar{q}$  in plasma  
Poster Ruggieri

Production time of Charm  
Poster Gyulai

Diffusion in Early Stages  
Poster Pooja

## Coalescence and Hadrons

Realistic Coalescence Model  
Tues Horst

Rescattering of HF hadrons  
Poster Hirayama



# Thanks to the organizers!



The 21<sup>st</sup> International Conference on Strangeness in Quark Matter  
3-7 June 2024, Strasbourg, France

For offering child  
care!



Many wonderful talks and posters to see!