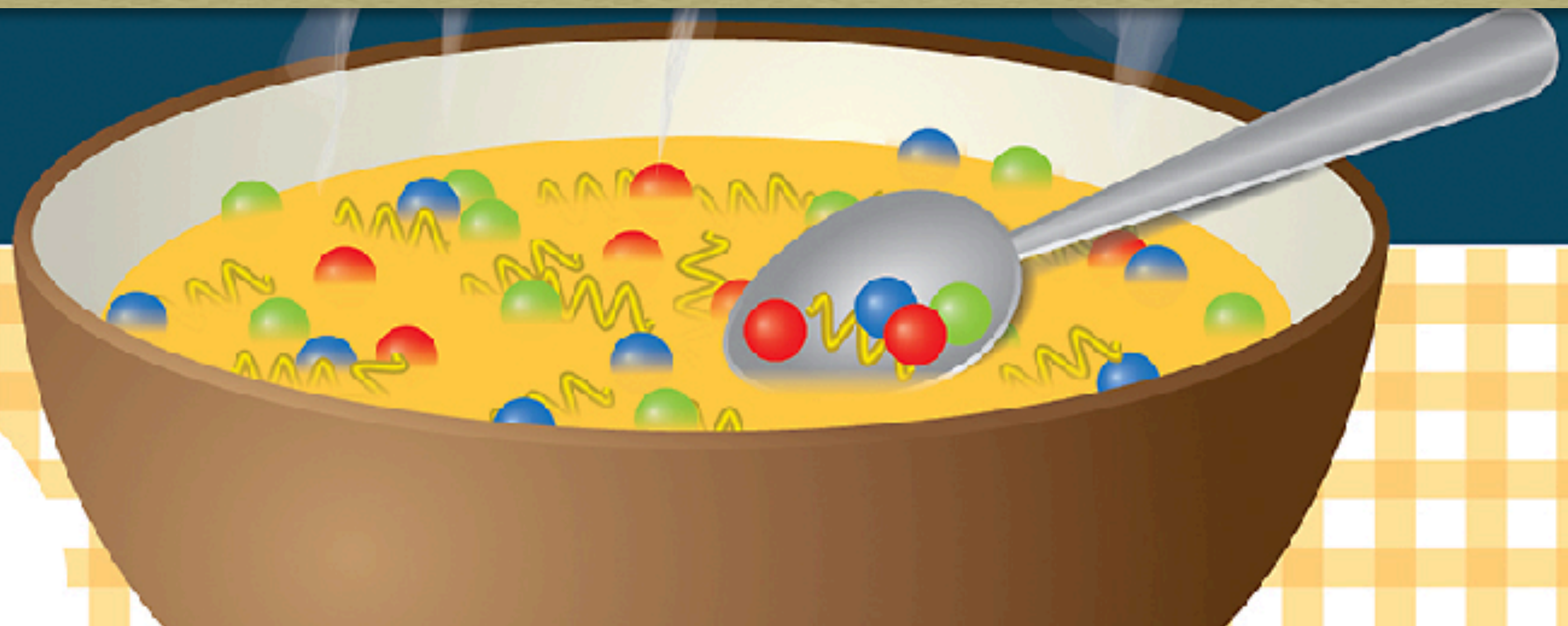
Illinois Center for Advanced Studies of the Universe

Studying $q\bar{q}$ pairs in the initial state as a background for the CME



Jacquelyn Noronha-Hostler
University of Illinois Urbana-Champaign

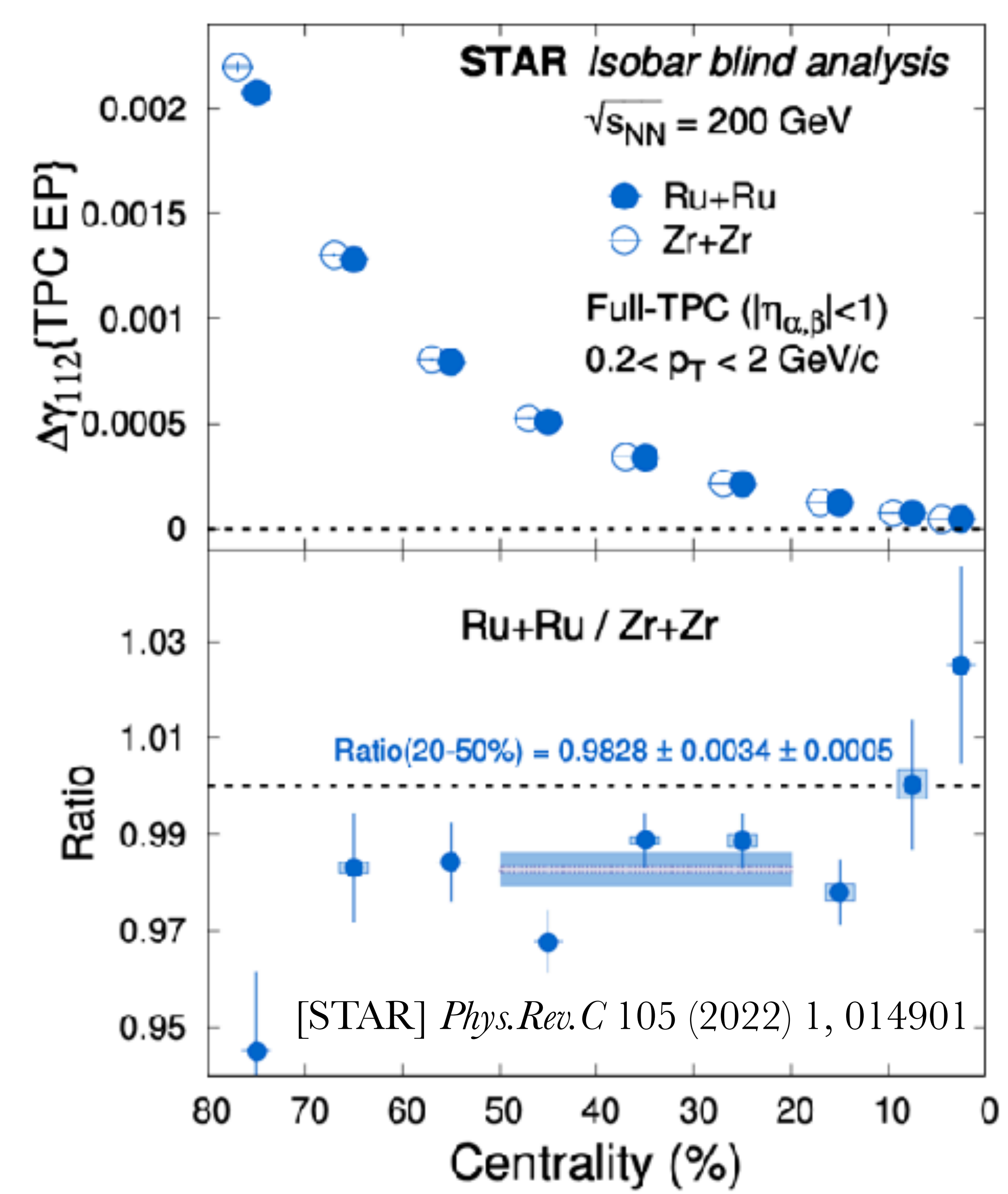
ECT* HOLOGRAPHIC PERSPECTIVES ON CHIRAL TRANSPORT

Charge effects in the isobar run

Charge correlates observables where α, β are particles of interest e.g. same-sign/opposite sign charges

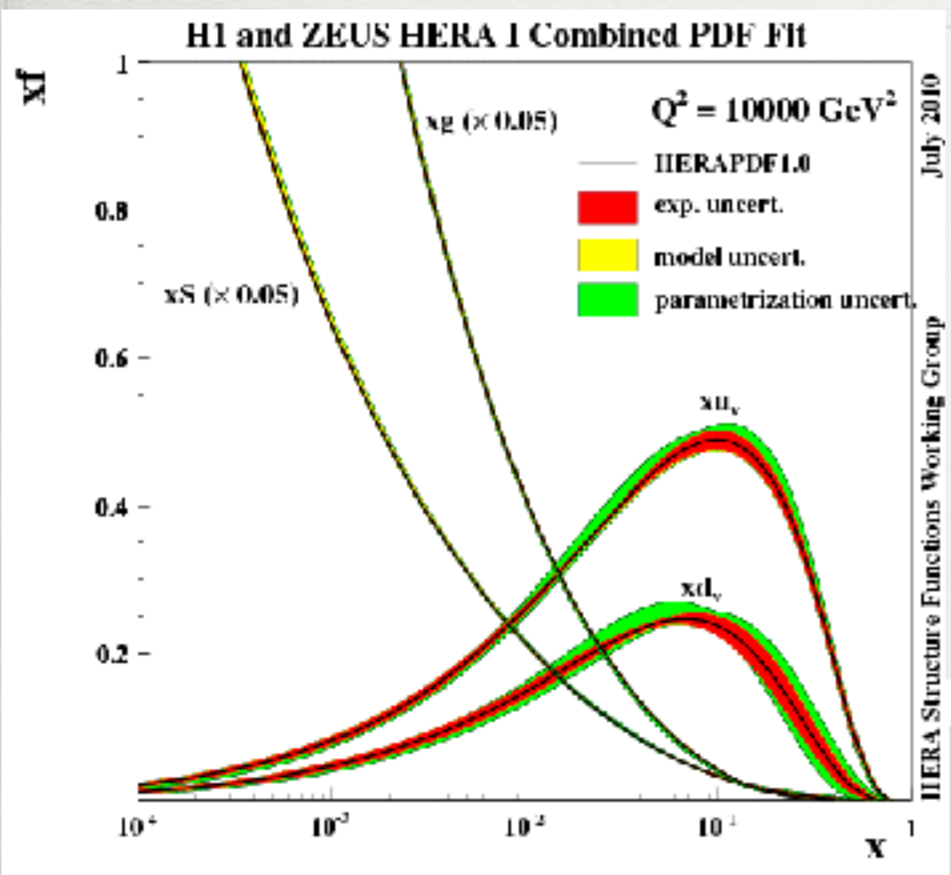
$$\gamma_{ijk} = \langle \cos\left(i\phi_\alpha + j\phi_\beta - k\Psi_k \right) \rangle$$

What role do charge fluctuations from $g \to q\bar{q}$ play?

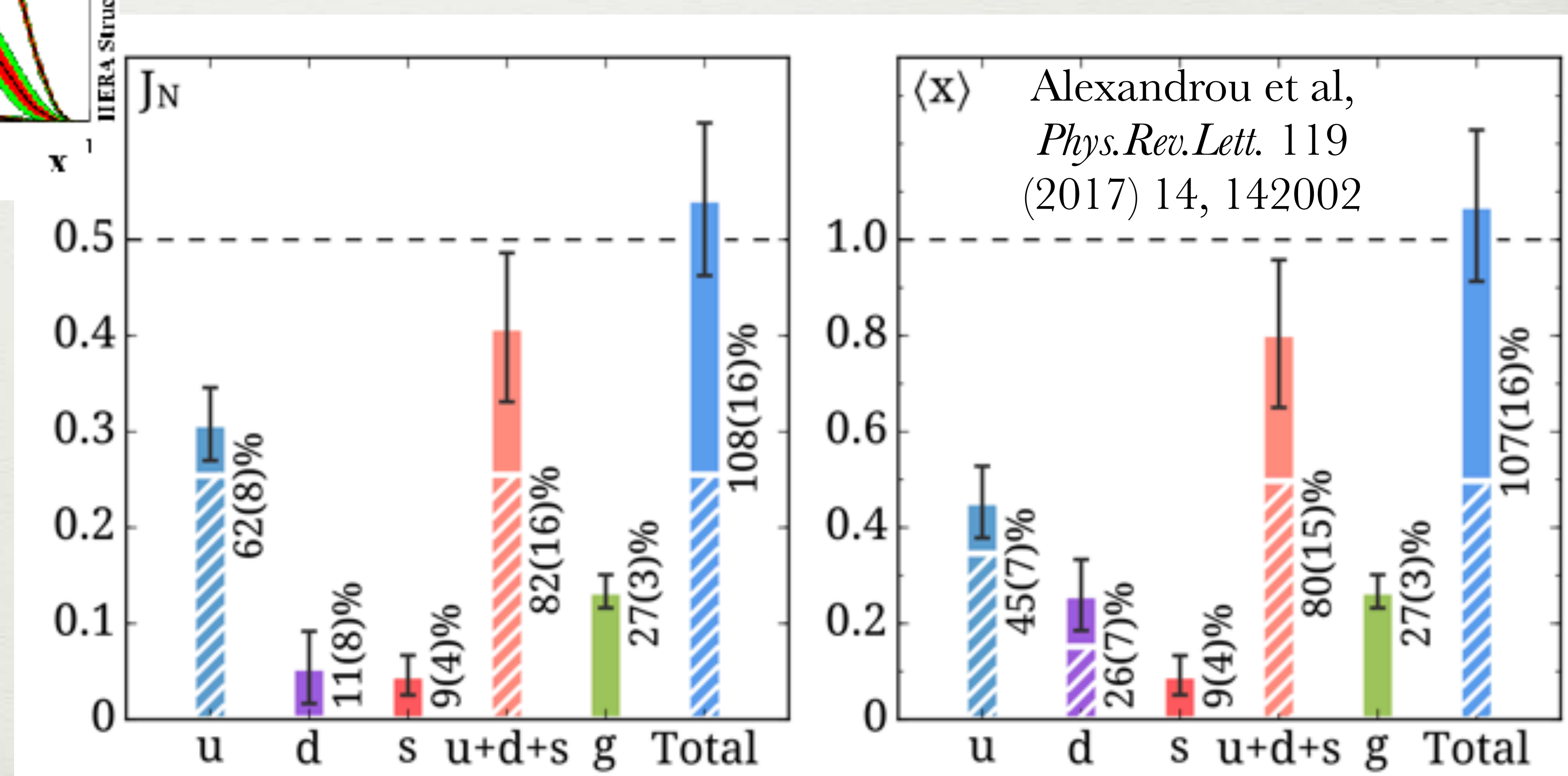


[STAR] *Phys.Rev.C* 105 (2022) 1, 014901

Motived by sea quarks and lattice QCD

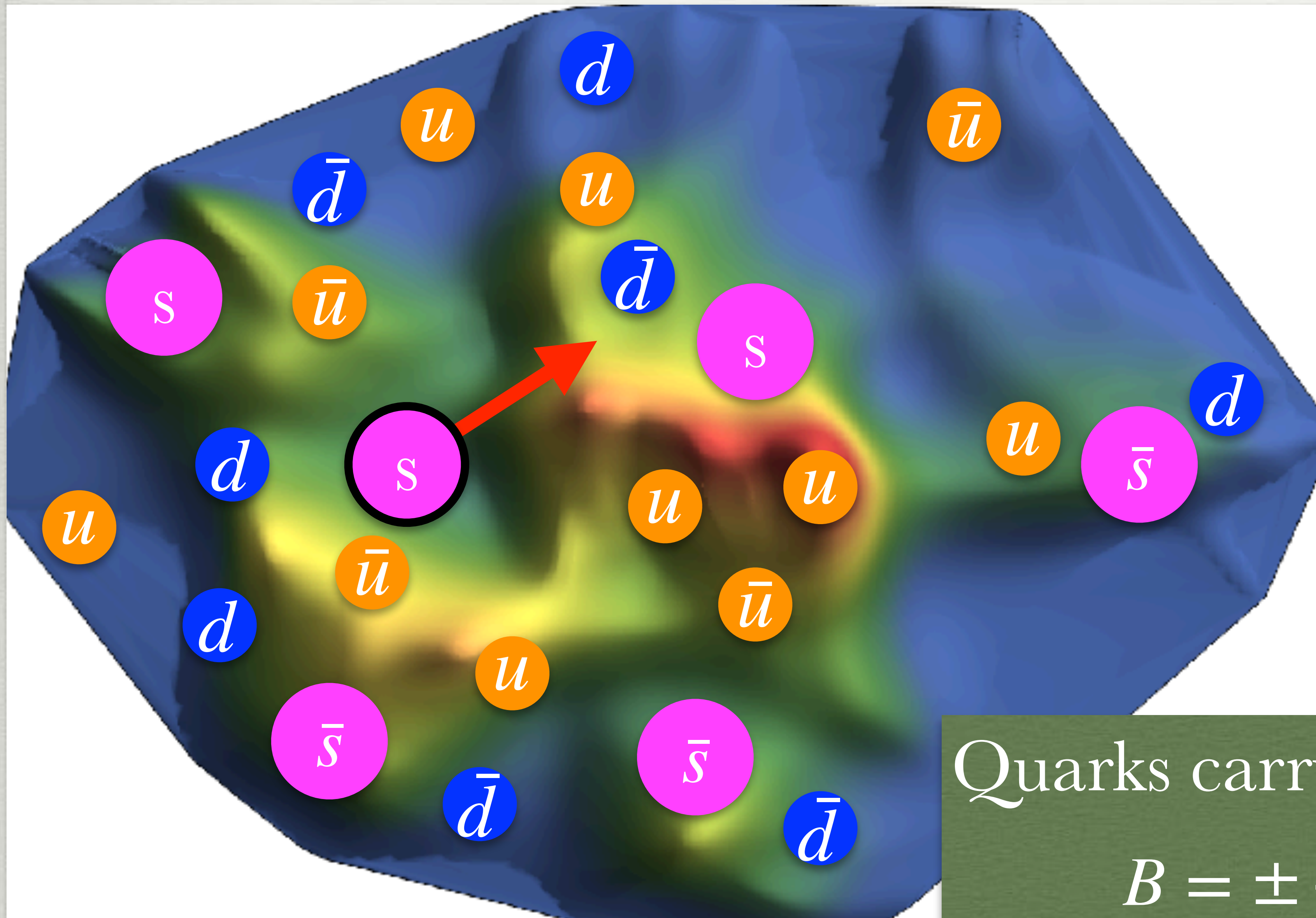


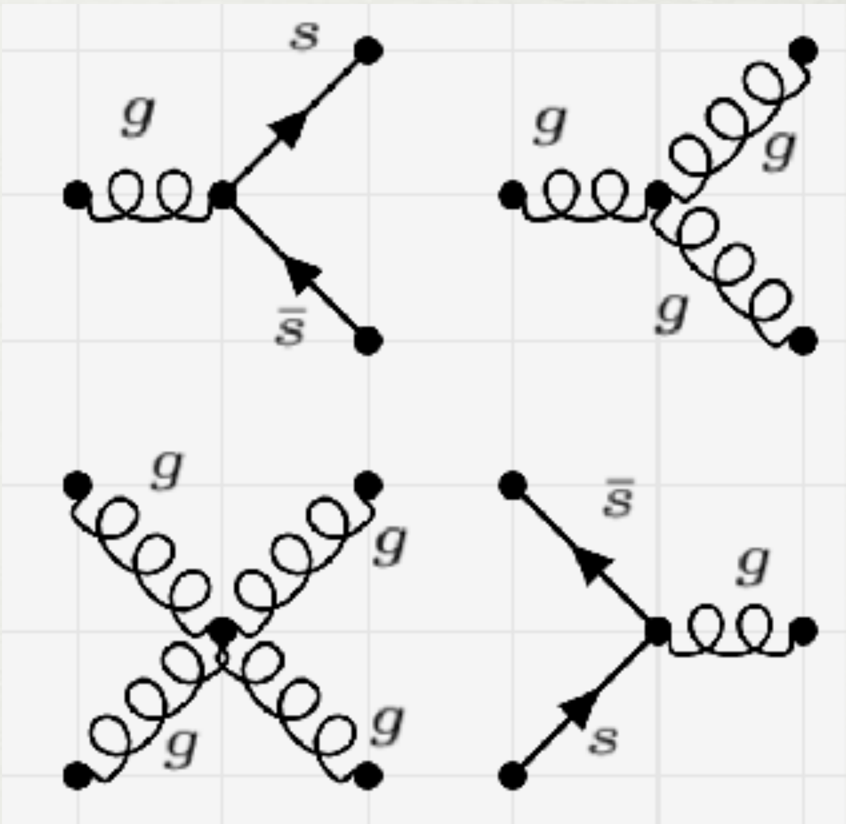
Strange quarks contribute nearly 10 % to the proton spin and momentum



Sea quarks contributions grow at low-x

Beyond simple (gluon) initial conditions: BSQ charges





Quarks carry ~3 conserved charges:

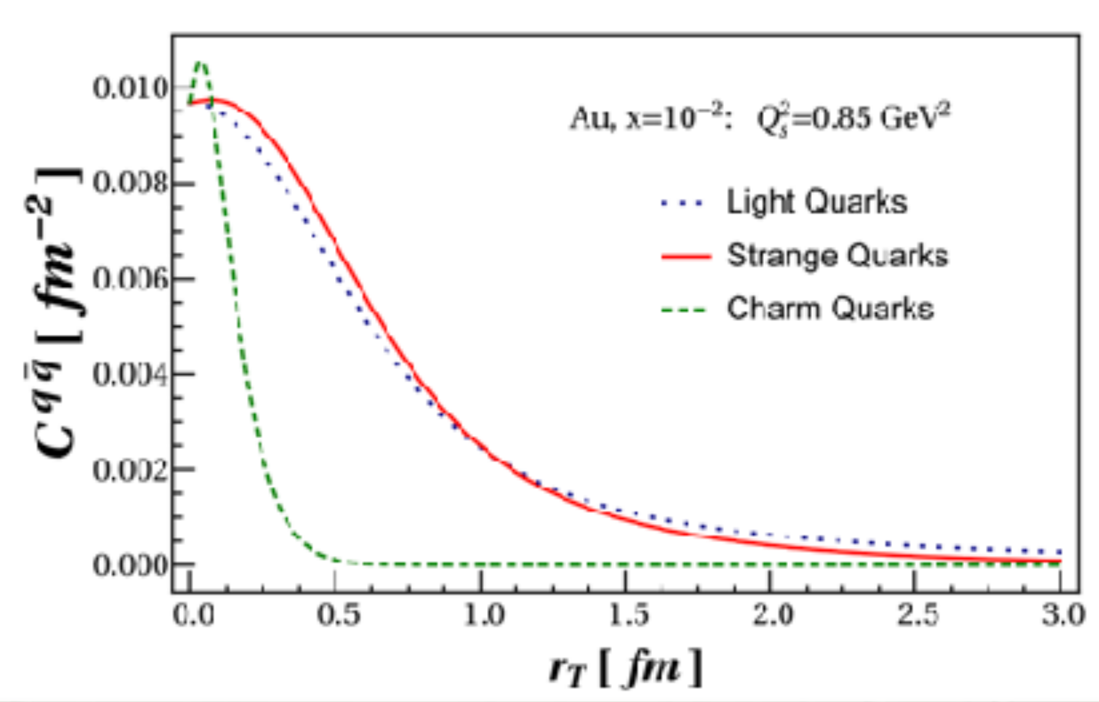
$$B = \pm\frac{1}{3} \text{ Baryon number}$$

$$S = \pm 1 \text{ Strangeness}$$

$$Q = \pm\frac{1}{3} \text{ (d,s) or } Q = \pm\frac{2}{3} \text{ (u)}$$

Splittings into $q\bar{q}$ pairs

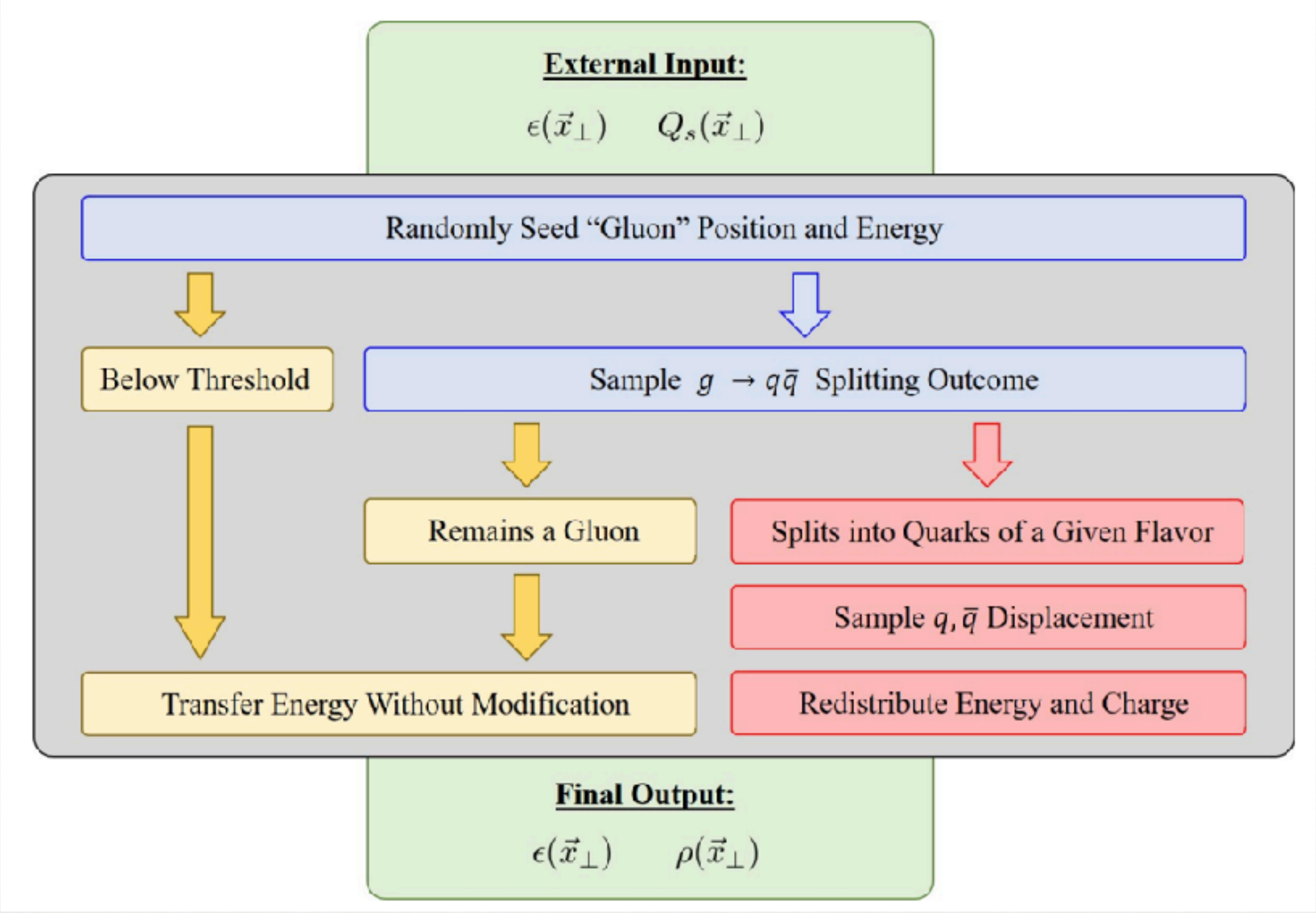
Martinez, Sievert, Wertepny JHEP 02 (2019) 024;JHEP 1807 (2018) 003



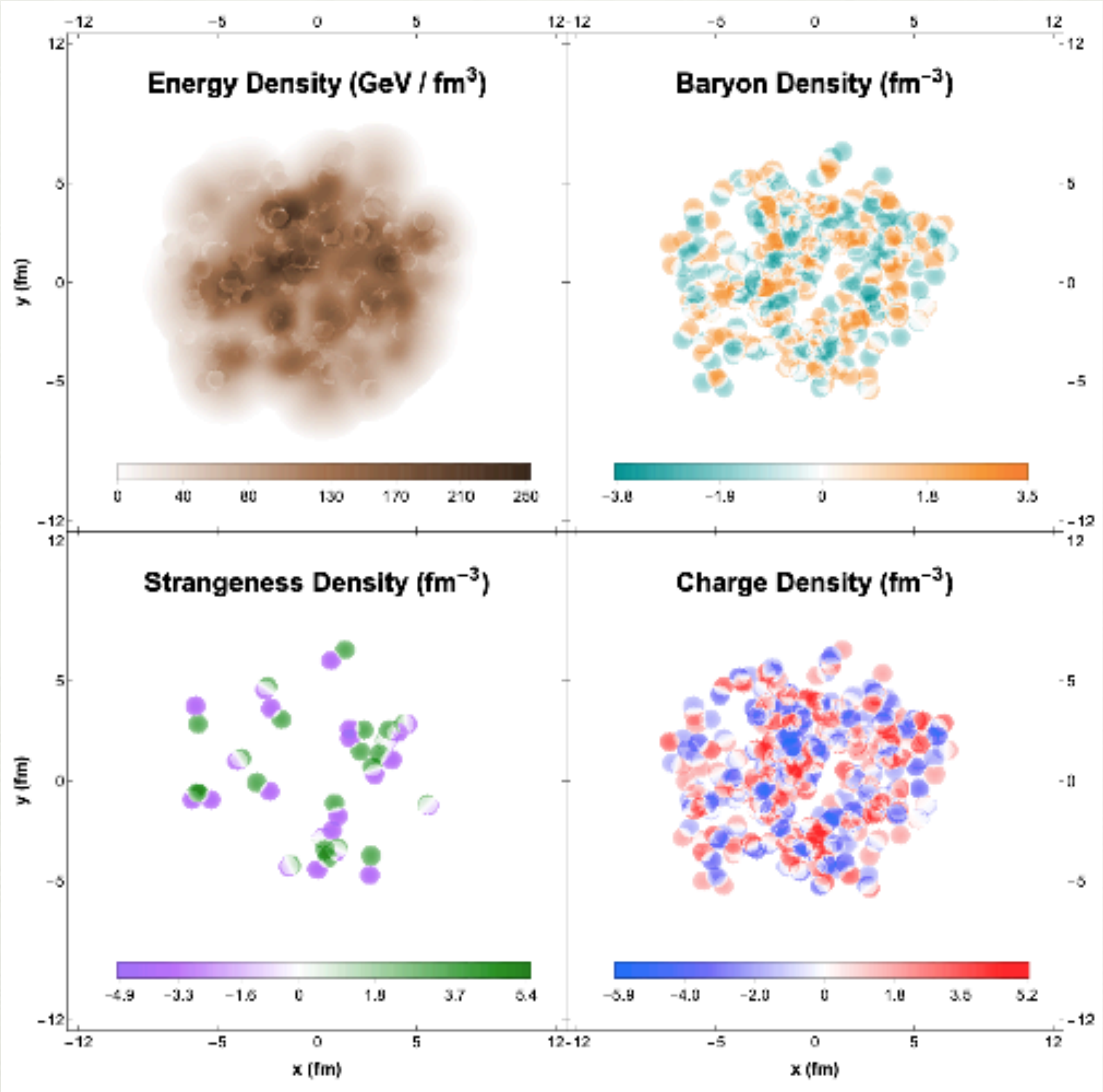
- $g \to q\bar{q}$ production from CGC (other methods possible, just need splitting probabilities)
- Spatial correlations calculated in dense-light limit
- Currently using single-pair production only (double pair production is possible, just not done yet in ICCING)

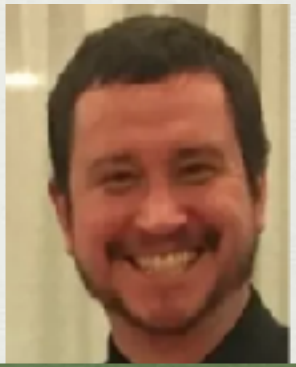
ICCING algorithm

Initial Conserved Charges in Nuclear Geometry

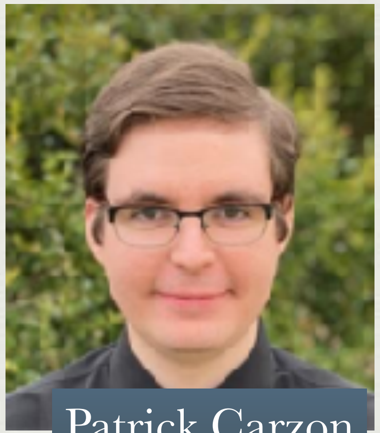


Example ICCING initial condition Trento for PbPb $\sqrt{s_{NN}} = 5.02$ TeV





Matt Sievert
Faculty NMSU
Former Postdoc

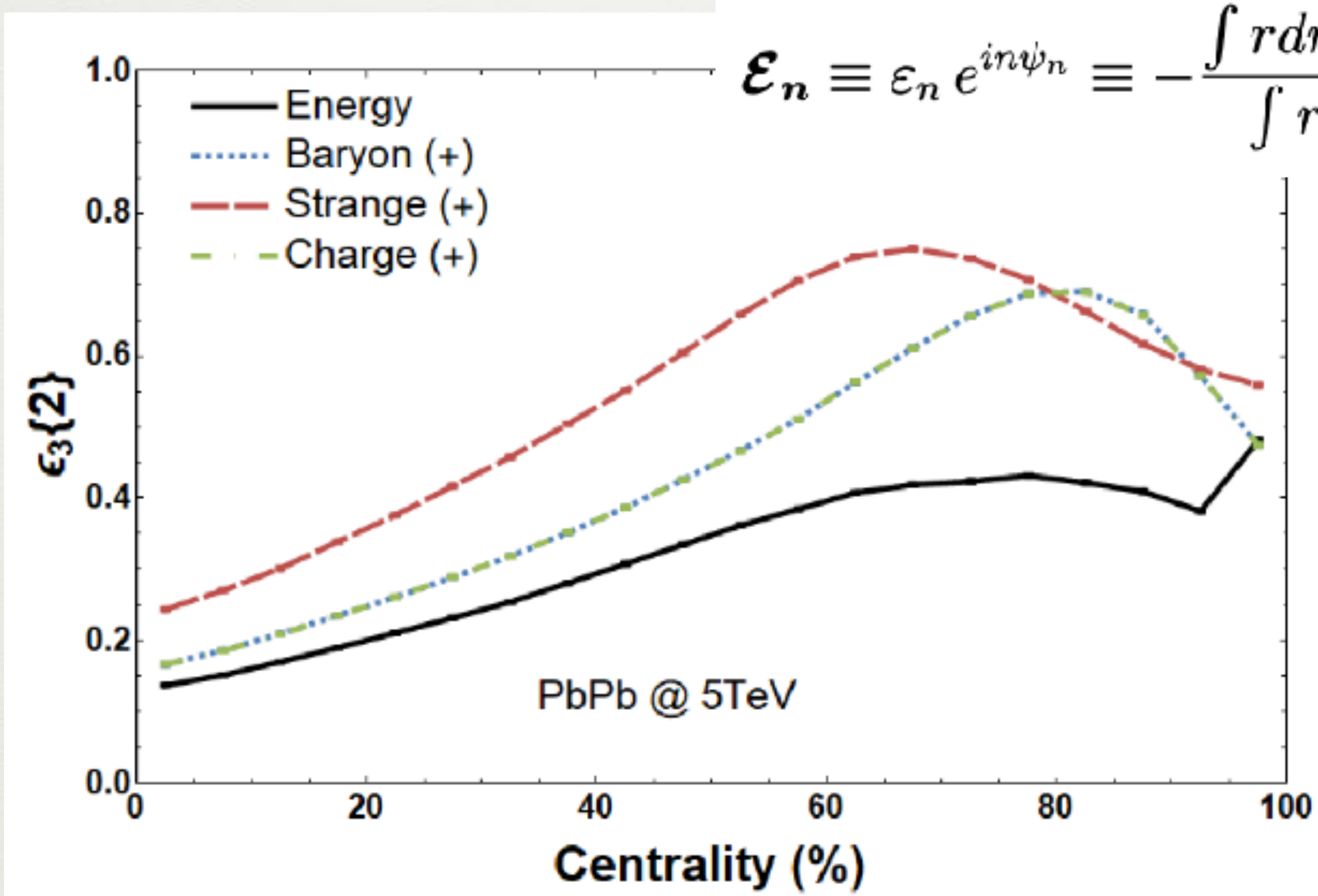


Patrick Carzon
PhD student

Carzon, (JNH) et al, *Phys.Rev.C* 105 (2022) 3, 034908; 1911.10272 [nucl-th]

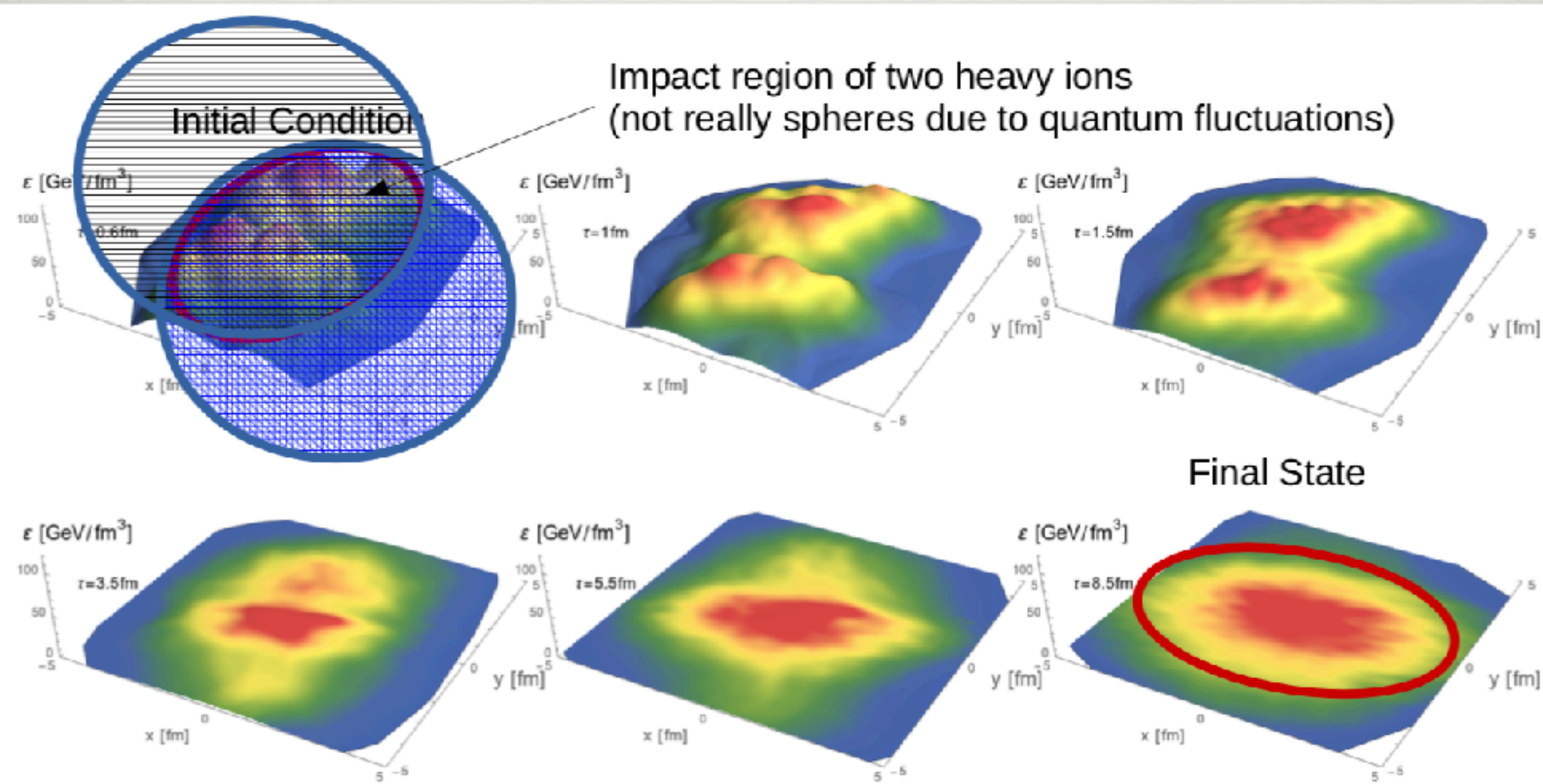
ICCING leads to distinct differences in initial state geometry

$$\mathcal{E}_n \equiv \varepsilon_n \, e^{in\psi_n} \equiv -\frac{\int r dr d\phi \, r^n e^{in\phi} \, f(r,\phi)}{\int r dr d\phi \, r^n \, f(r,\phi)}$$



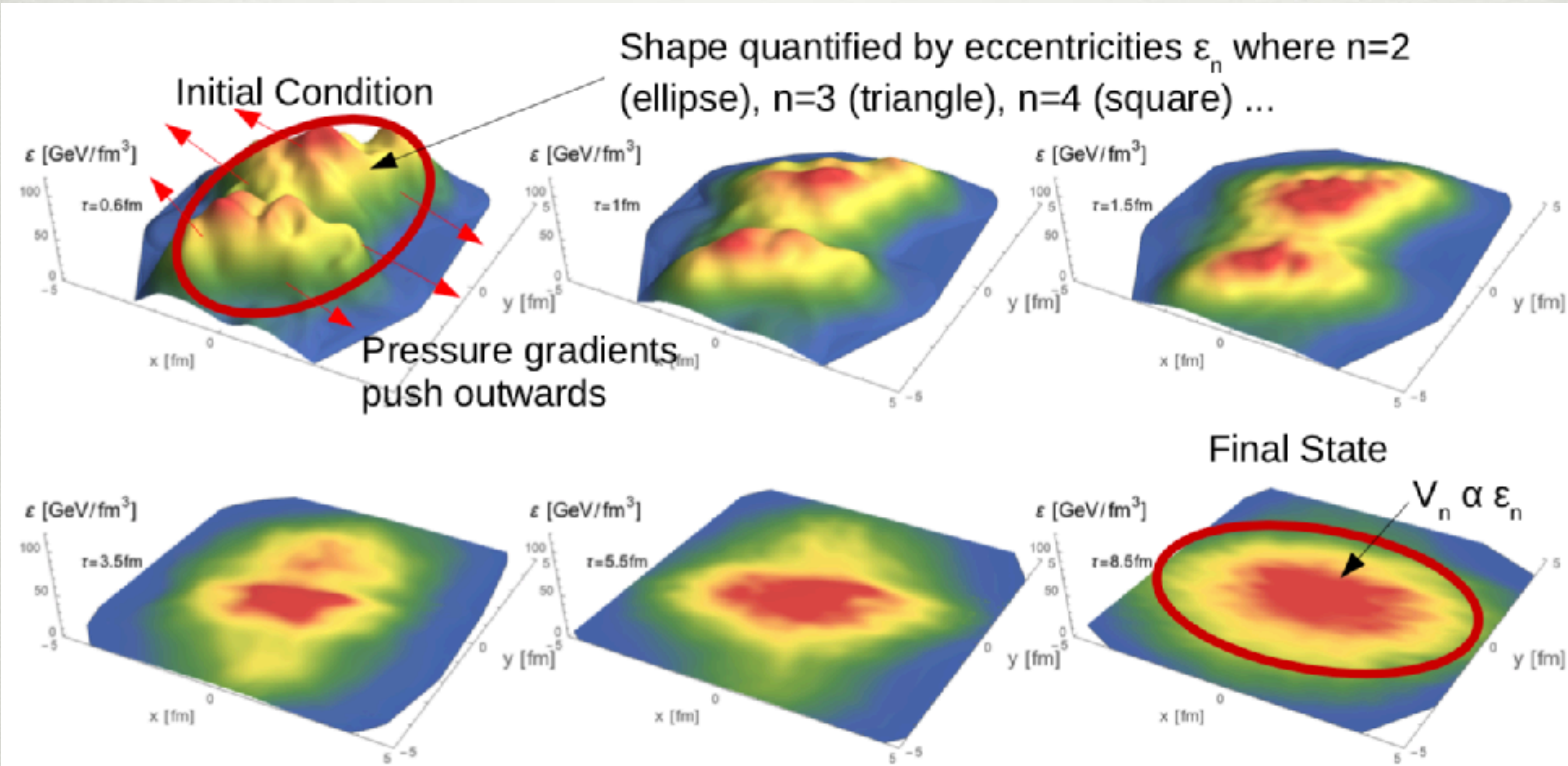
Here only positive charge is considered to calculate eccentricities. Eccentricities of BSQ charges ill-defined (working in progress)

How does $\mathscr{E}_n \to V_n$



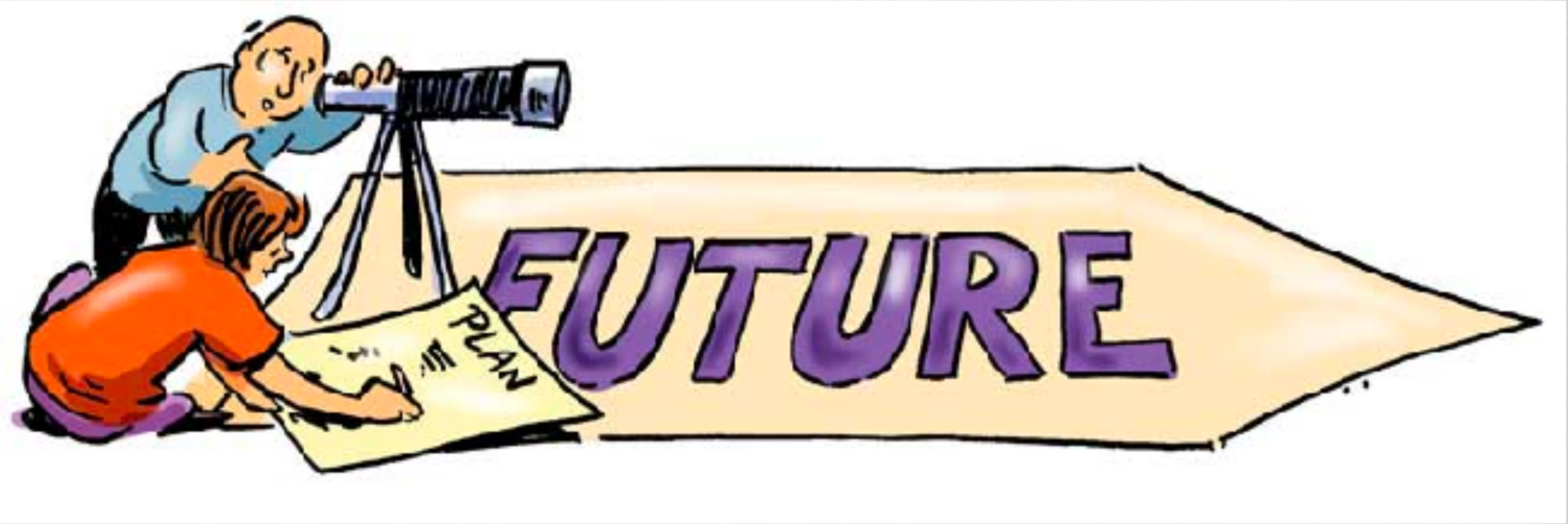
Eccentricities ε_2's are directly related to the final measured flow observables v_n's

How does $\mathcal{E}_n \rightarrow V_n$



Eccentricities ε_2's are directly related to the final measured flow observables v_n's

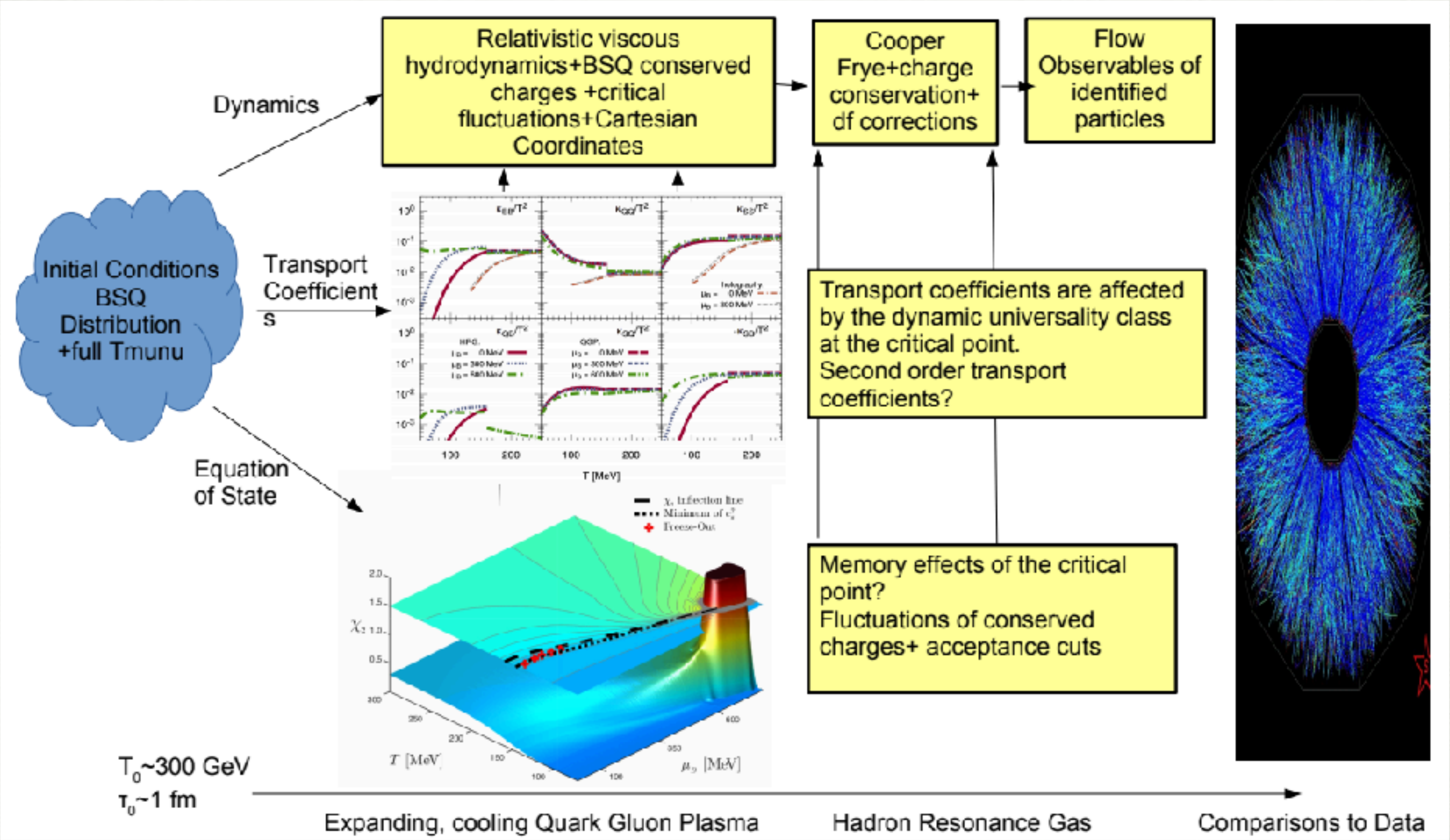
Future possibilities with ICCING



- Spin
- Full $T^{\mu\nu}$ and Q^{μ}
- Small systems
- Include double-pair production
- Finite net-densities?
- Inclusion of the chiral anomaly?

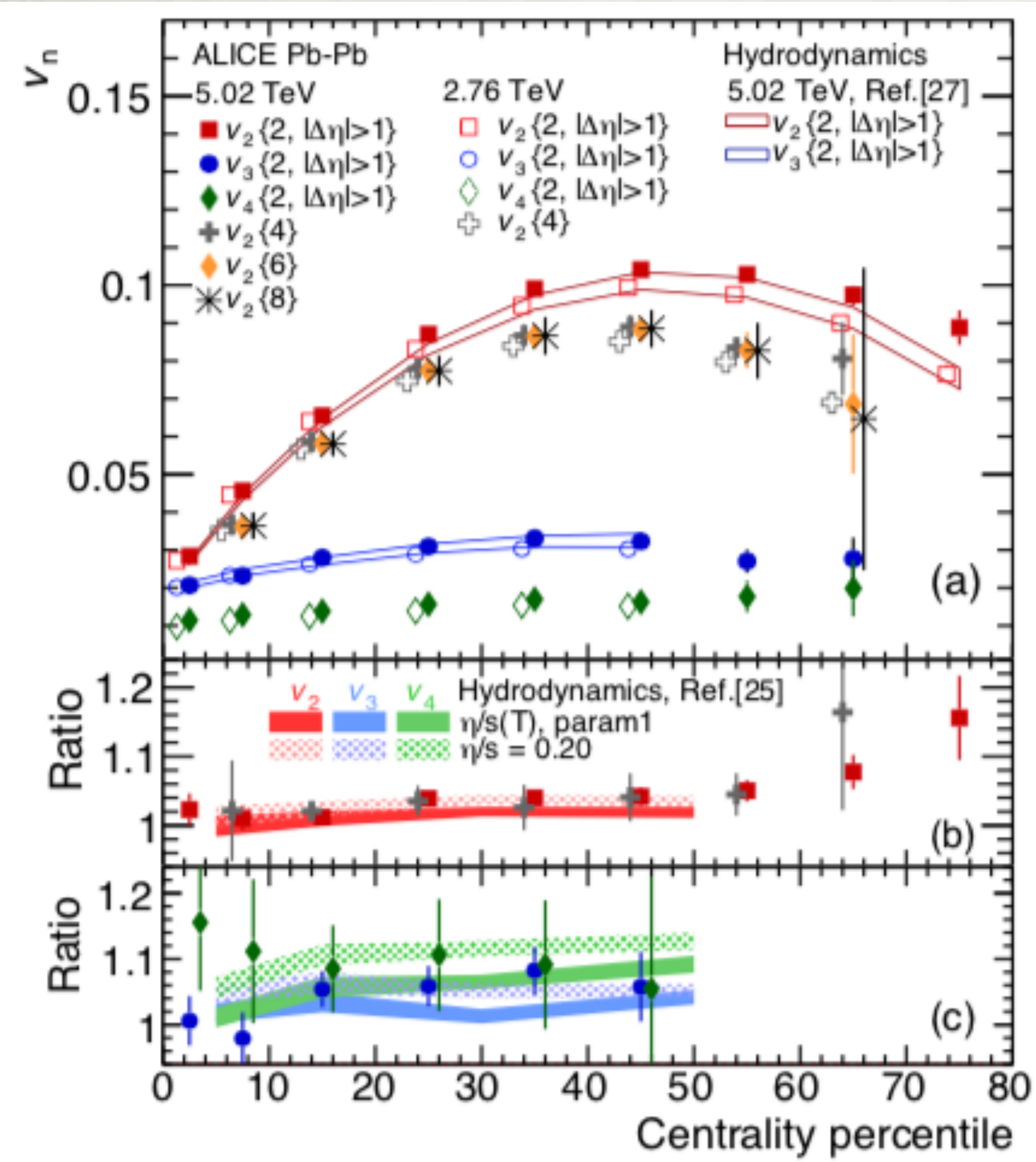
Need relativistic viscous hydrodynamics + 3 conserved charges (BSQ)

Review: Dexheimer, Noronha, JNH, Ratti, Yunes, *J.Phys.G* 48 (2021) 7, 073001



J. Noronha-Hostler

Converting v-USPhydro to include BSQ conserved charges



v-USPhydro used to make predictions at the ~1% level.

ALICE *Phys.Rev.Lett. 116 (2016) no.13, 132302*
v-USPhydro predictions*: JNH et al, Phys.Rev. C93 (2016) no.3, 034912*
EKRT predictions*: Niemi et al, Phys. Rev. C 93, 014912 (2016)*

Travis Dore
Postdoc Bielefeld

Equation of motion: BSQ diffusion in relativistic hydrodynamics

Almaalol, Dore, JNH [arXiv:2209.11210 [hep-th]]

Dekra Almaalol
Postdoc

Ensure only positive entropy production

$$\tau_\pi \dot{\pi}^{\mu\nu} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} + \frac{\tau_\pi \pi^{\mu\nu}}{2}\theta - \frac{\tau_\pi}{2\beta_\pi}\dot{\beta}_\pi \pi^{\mu\nu} - \frac{2\eta}{\beta}\left(\gamma_1^q \nabla^{\langle\mu} n_q^{\nu\rangle} + \frac{1}{2} n_q^{\langle\mu}\nabla^{\nu\rangle}\gamma_1^q\right)$$

Israel-Stewart DNMR

$$\tau_\Pi \dot{\Pi} + \Pi = -(\zeta + \frac{\tau_\Pi}{2}\Pi)\theta - \frac{\tau_\Pi}{2\beta_\Pi}\dot{\beta}_\Pi \Pi - \frac{\zeta}{\beta}\left(\gamma_0^q D_\mu n_q^\mu + \frac{1}{2} n_q^\mu \nabla_\mu \gamma_0^q\right)$$

$$\tau_{qq'}\dot{n}^\mu_{q'} + n^\mu_q = -\kappa_{qq'}\nabla^\mu \alpha_{q'} + \frac{\tau_{qq'}n^\mu_{q'}}{2}\theta - \frac{\tau_{qq'}}{2\beta_{qq'}}\dot{\beta}_{qq'}n^\mu_{qq'} - \frac{\kappa_{qq'}}{\beta}\left(\gamma_0^{qq'}\nabla^\mu \Pi - \frac{\Pi}{2}\nabla^\mu \gamma_0^{qq'}\right) - \frac{\kappa_{qq'}}{\beta}\left(\gamma_1^{qq'}\nabla_\nu \pi^{\mu\nu} + \frac{\pi^{\mu\nu}}{2}\nabla_\nu \gamma_1^{qq'}\right)$$

CCAKE: new hydrodynamic code with all BSQ coefficients

Linear thermodynamic stability constraints for BSQ hydro

Almaalol, Dore, JNH [arXiv:2209.11210 [hep-th]]

Following the method from [1]

(1) derive Lyapunov functional for S^μ in Landau frame

(2) generalize BSQ fluid

(3) extract the conditions for positive energy functional

7 stability conditions on both EOS and transport coefficients

Diffusion/$\pi^{\mu\nu}$ coupling

Diffusion matrix

$$\varepsilon + p \geq \frac{T\eta}{\tau_\pi}\lambda^2(\delta^q_{n\pi} + 1)^2 - \rho_q^2 \beta_n^{qq'}$$

[1] L. Gavassino, Class. Quant. Grav. 38 21LT02 (2021)

EoS: Moving beyond Lattice QCD

Taylor series provides cross-over Equation of State $\mu_B \lesssim 450$ MeV

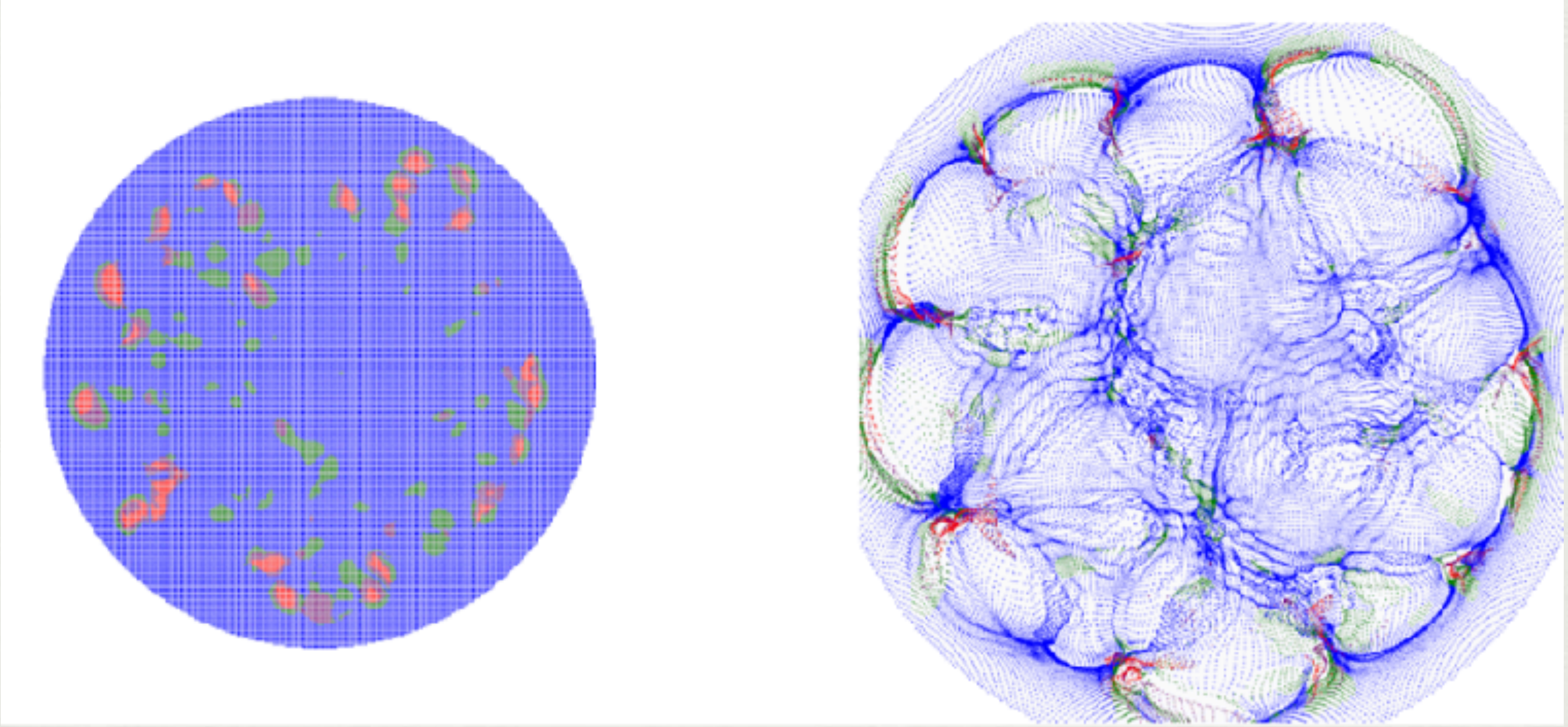
$$\frac{p(T,\mu_B,\mu_Q,\mu_S)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!} \chi_{ijk}^{BSQ} \left(\frac{\mu_B}{T}\right)^i \left(\frac{\mu_Q}{T}\right)^j \left(\frac{\mu_S}{T}\right)^k$$

JNH, Paolo Parotto, Claudia Ratti, Jamie Stafford Phys.Rev.C 100 (2019) 6, 064910

- Taylor series not suited for critical point analyses
- Other expansion series have issues far from the critical point: Critelli et al *Phys.Rev.D* 96 (2017) 9, 096026
- Currently only have Lattice QCD results for the full BSQ expansion up to $\mathcal{O}(\mu/T)^4$

Current lattice QCD EOS not enough

Almaalol, Carzon, Dore, Espino, Mroczek, Plumberg, Salinas San Martin, Spychalla, Sievert, JNH to appear soon

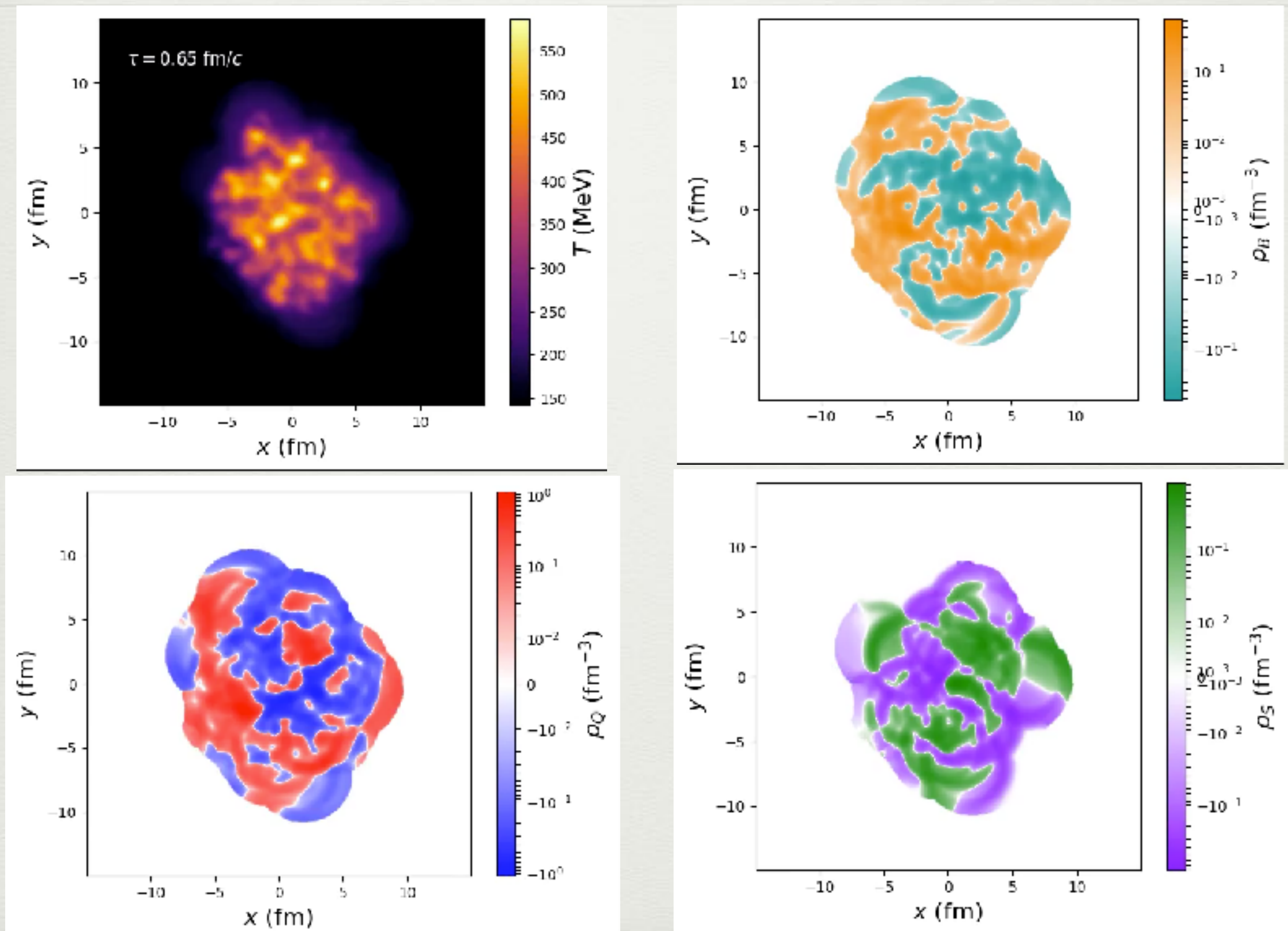


Blue lattice QCD
Green tanh non-conformal
Red conformal EOS

Lattice QCD EOS breaks down with μ_B/T so low T, high n_B hard to capture

Hydrodynamics with BSQ charges

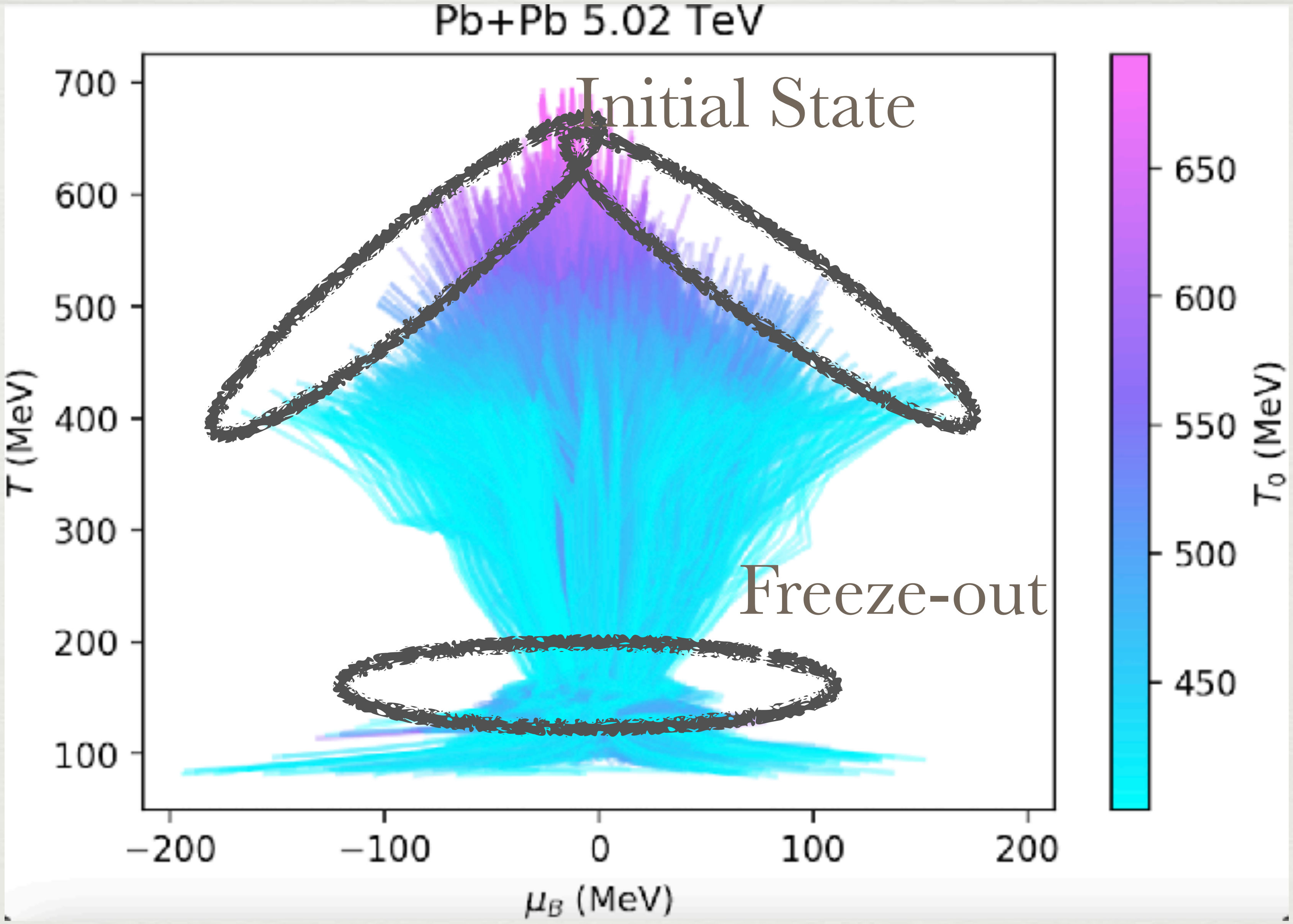
Almaalol, Carzon, Dore, Espino, Mroczek, Plumberg, Salinas San Martin, Spychalla, Sievert, JNH to appear soon

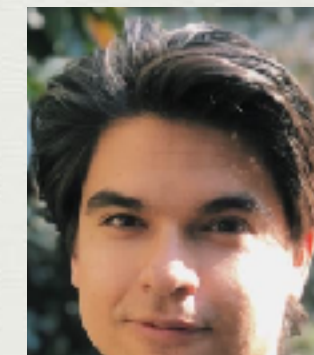


BSQ fluctuations large at the LHC

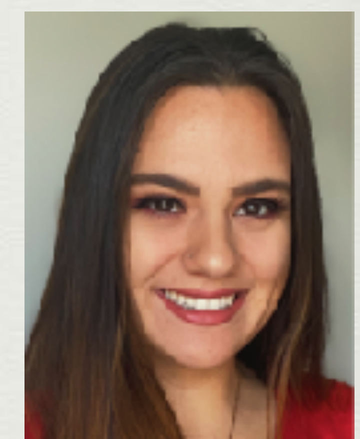
$\varepsilon + B + S + Q$

Christopher Plumberg
Pepperoni University





Jordi Salinas
San Martín
PhD student



Debora Mroczek
PhD Student

BSQ fluctuations just from $g \to q\bar{q}$.
net-B=0, local baryon number fluctuations large

Almaalol, Carzon, Dore, Espino, Mroczek, Plumberg, Salinas San Martin, Spychalla, Sievert, JNH to appear soon

End goal

Calculate γ_{ijk} charge correlations for all BSQ possibilities

Ideas for other quantities that are sensitive to this physics as well

Holography wish list

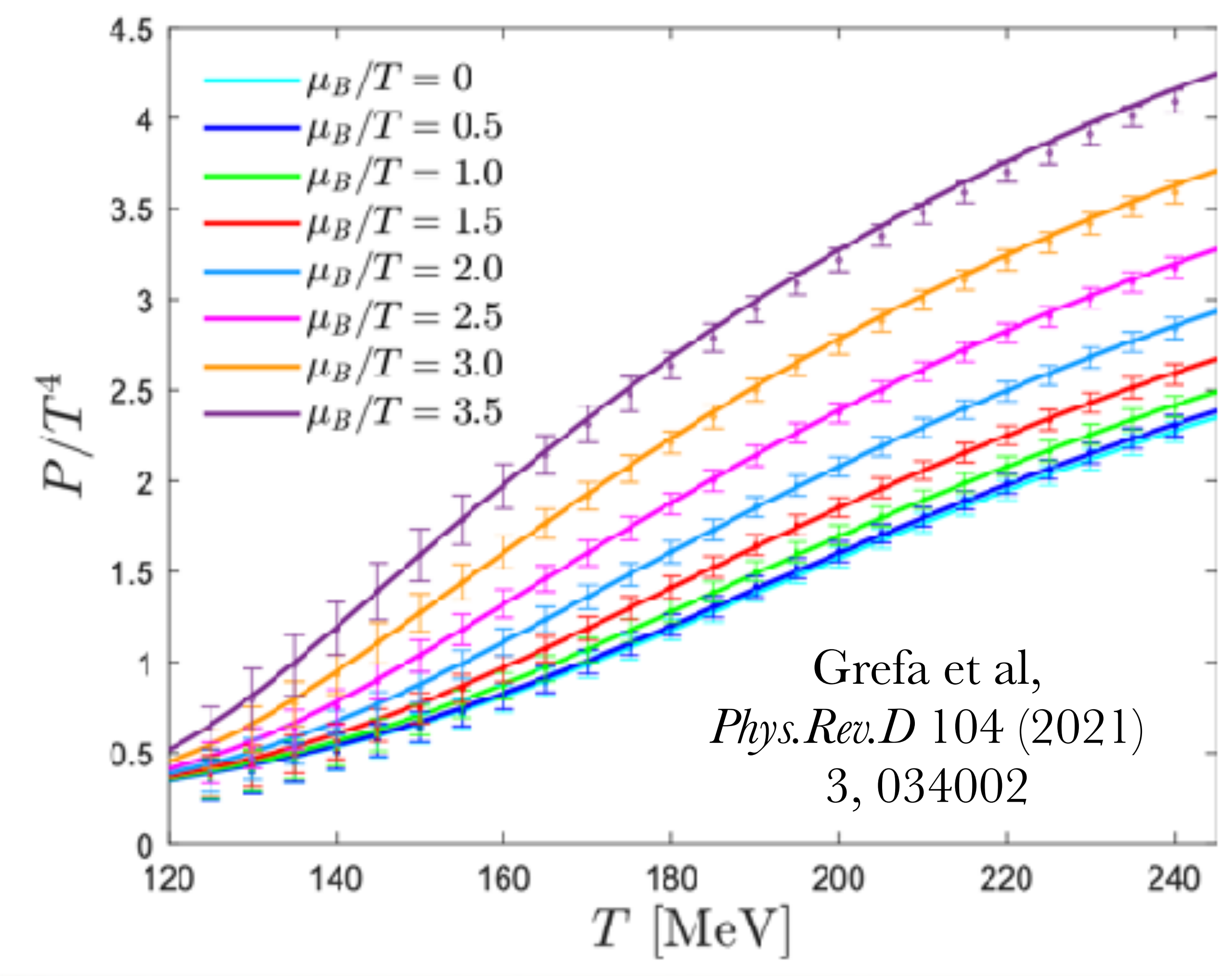
- Equation of state with BSQ conserved charges (looks like QCD)
- Transport coefficients with BSQ conserved charges: shear, bulk, diffusion matrix (6 independent terms)
- Initial state $T^{\mu\nu}$ and B^μ, S^μ, Q^μ for the 3 out-of-equilibrium currents

Summary

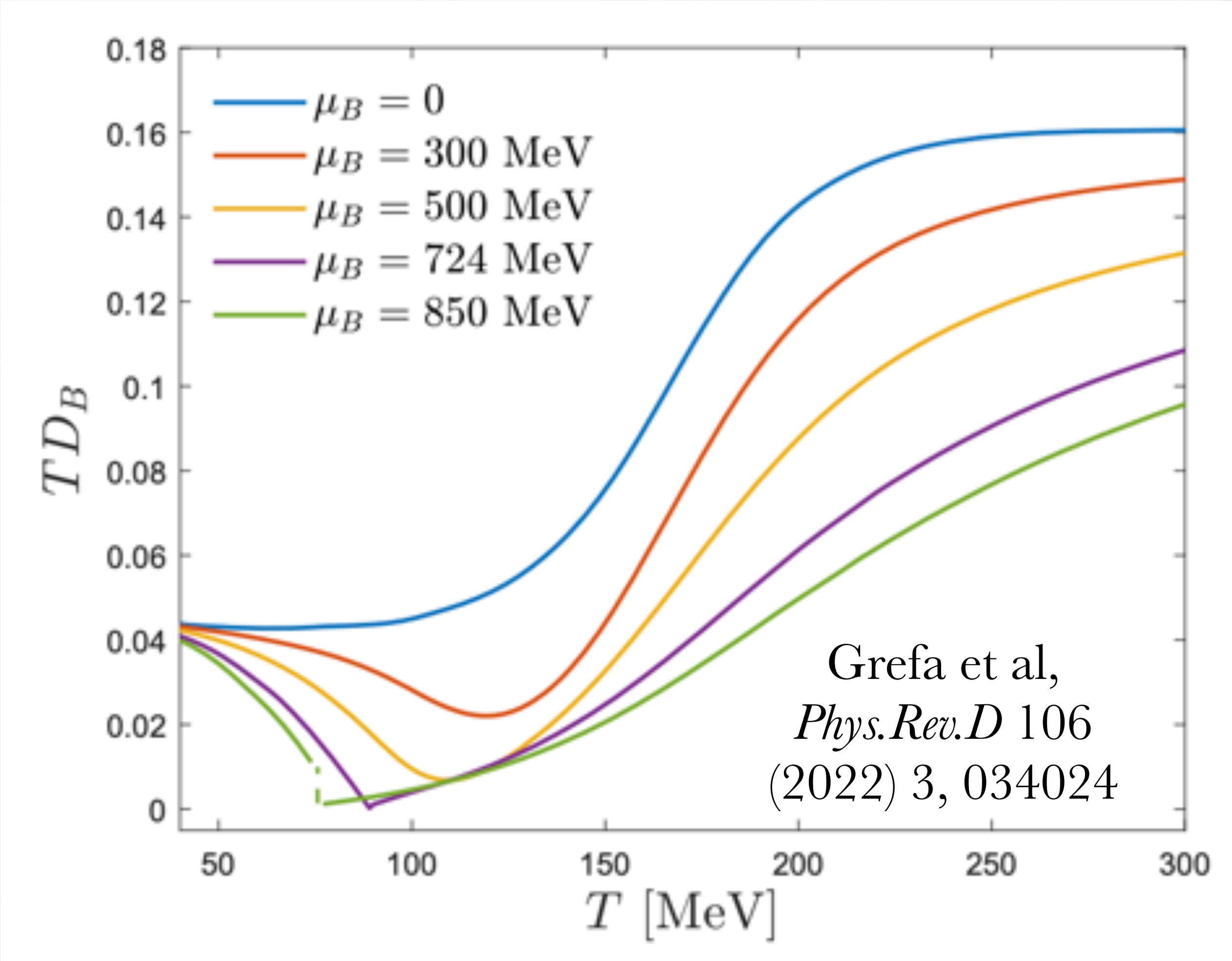
- ICCING can help to quantify background effects for the CME observables
- BSQ relativistic viscous hydrodynamics CCAKE allows for direct comparisons to data
- Preliminary results find consequences for flow
- Future: isobar study with ICCING+CCAKE

How can holography help?

Non-conformal EOS



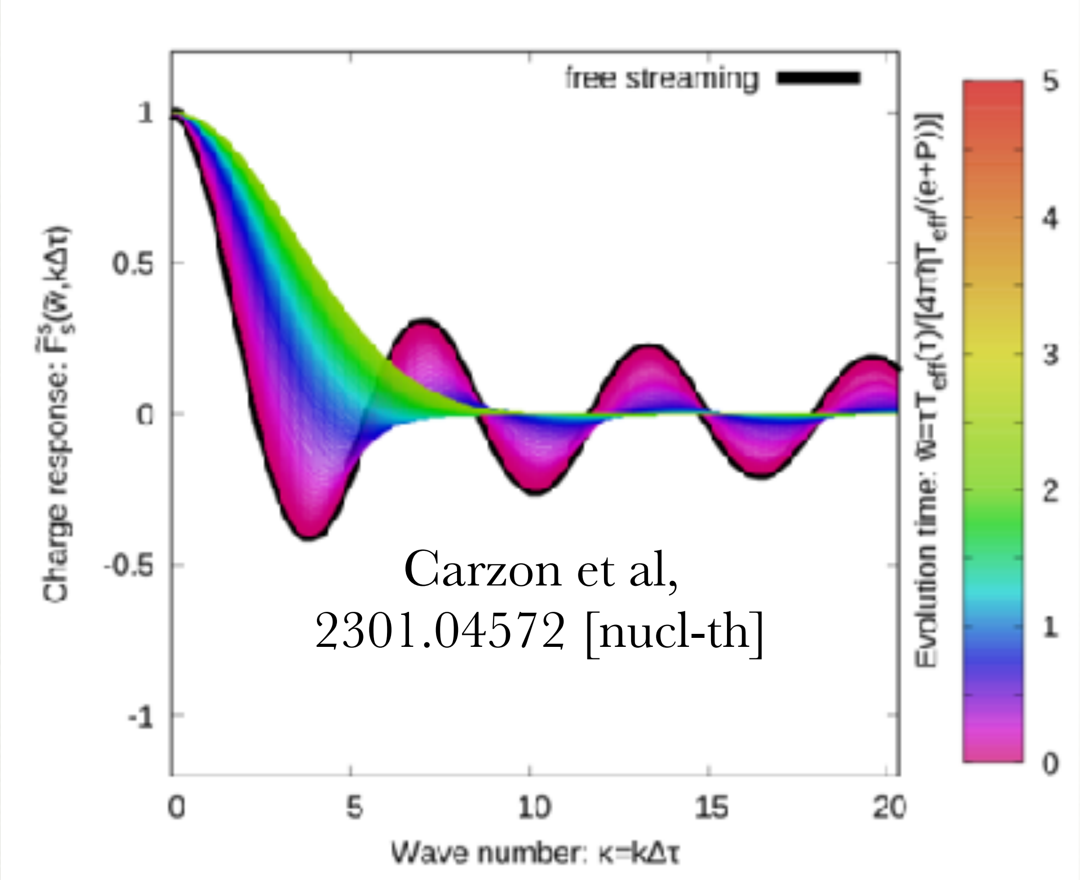
Transport coefficients at finite μ_B



However, need 3 conserved charges. Currently only includes 1

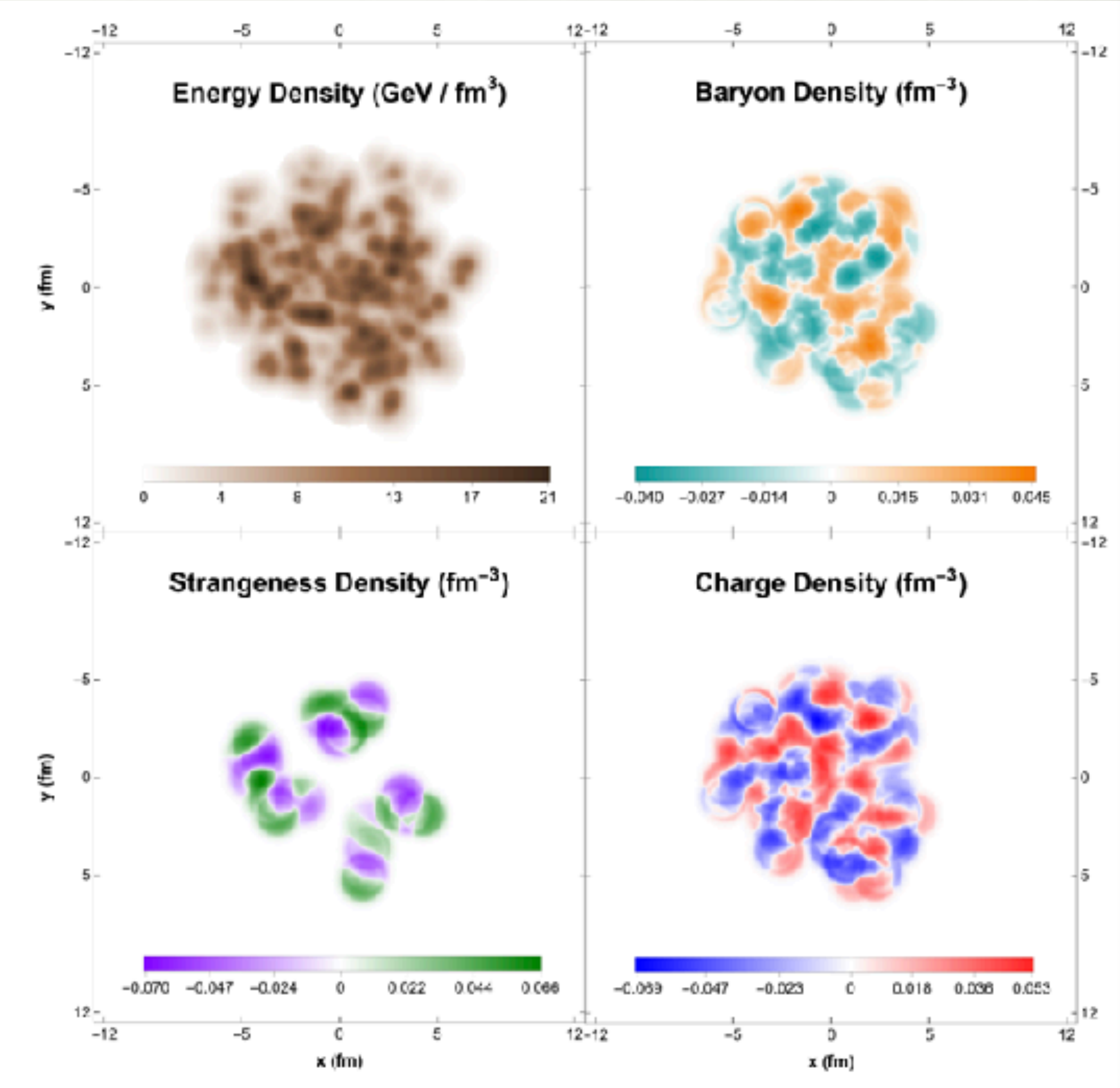
Pre-equilibrium expansion of BSQ charge

Energy and charge Green's functions

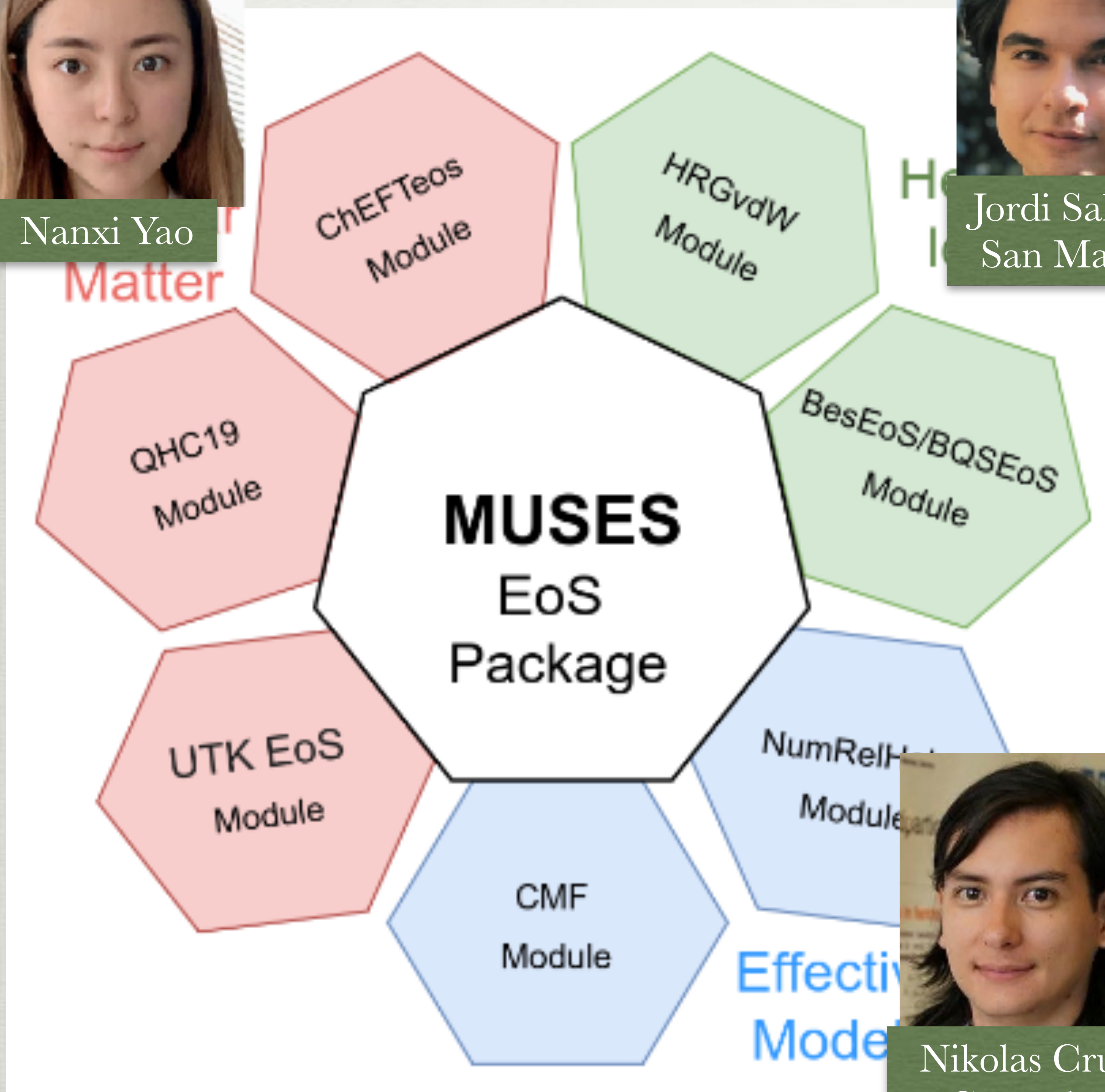


Relies on a perturbative approach, limits $q\bar{q}$ production

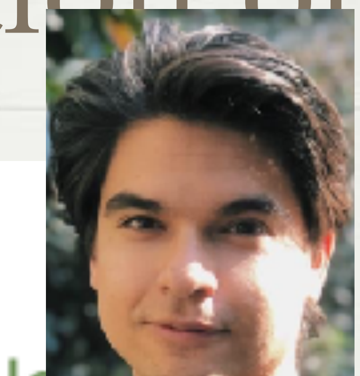
ICCING evolution after $\tau = 1\ fm$



MUSES: Modular Unified Solver of the Equation of State



Nanxi Yao



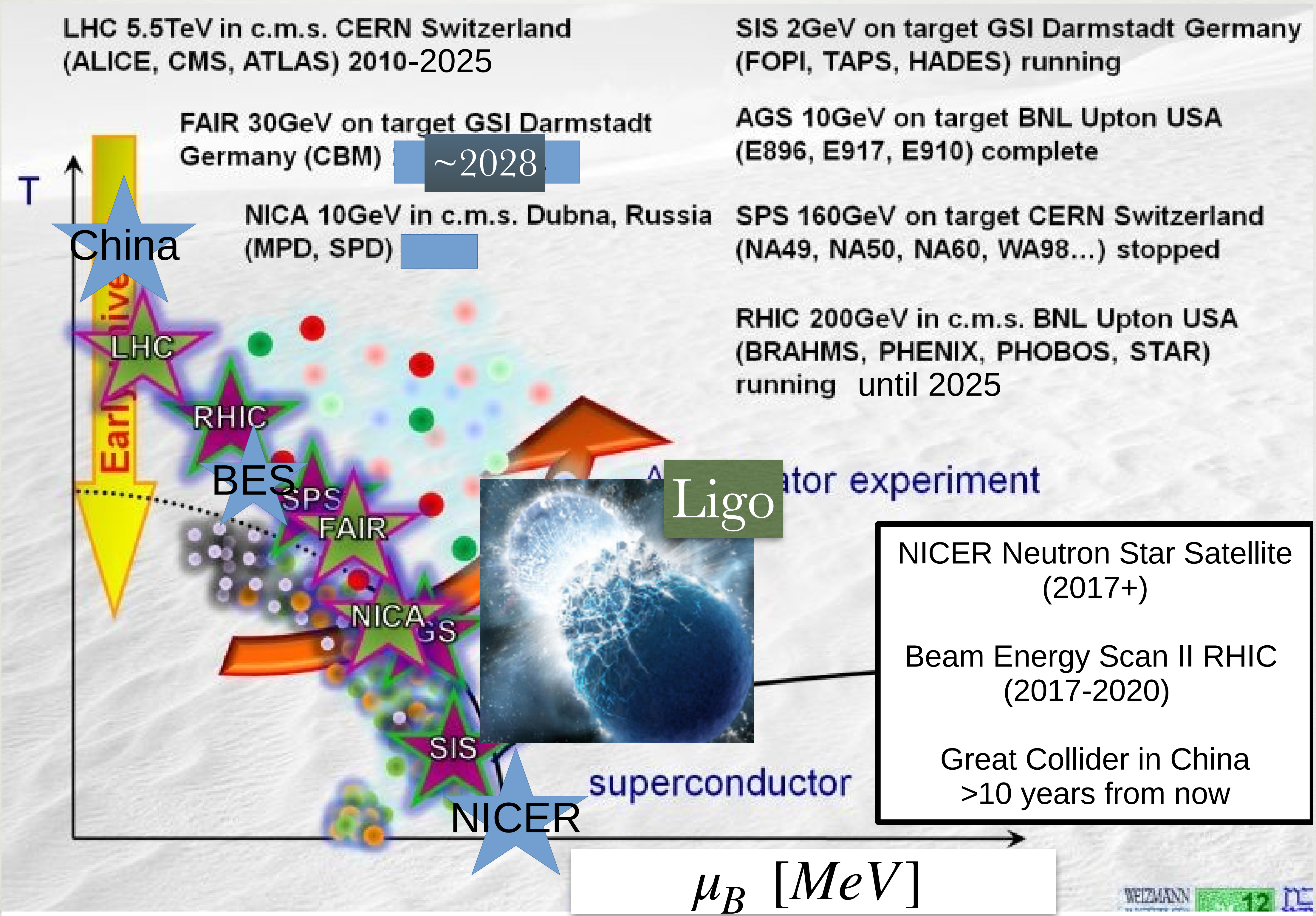
Jordi Salinas San Martín

Nikolas Cruz Camacho

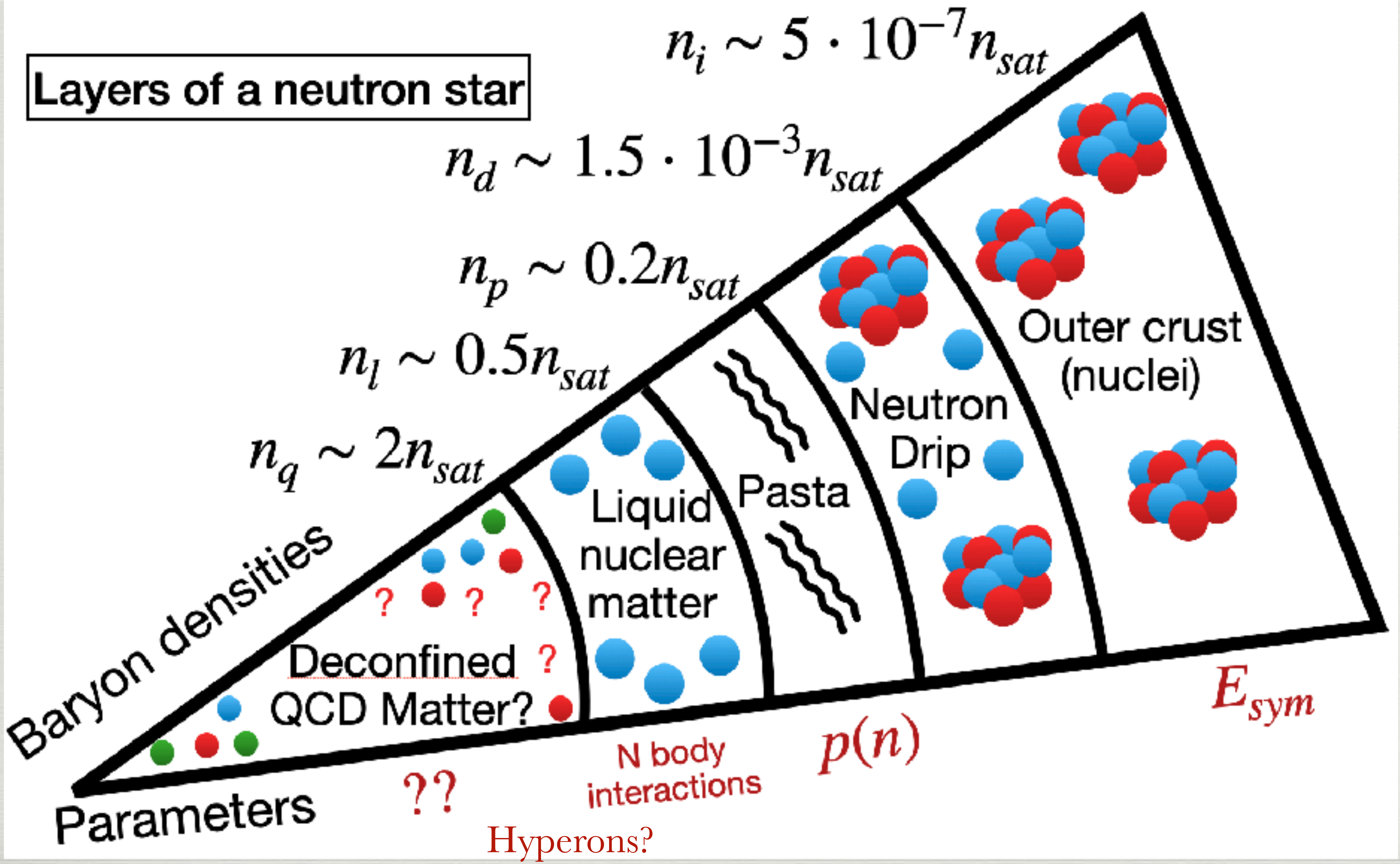
Started Fall 2021

16+ institutions, combines nuclear/computer science/ gravity/astro/particle

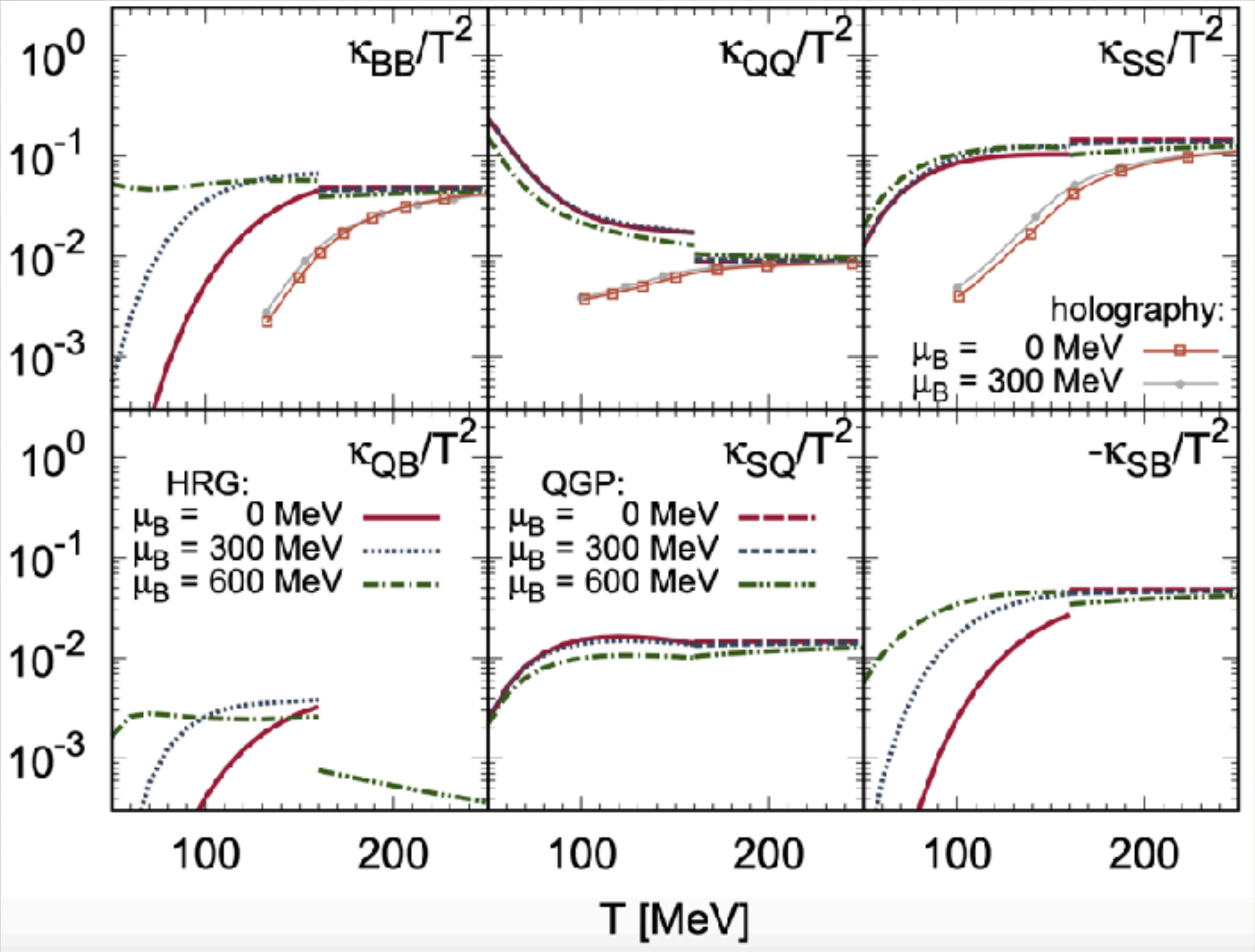
Mapping the QCD phase diagram



Degrees of freedom by density



Dynamics: BSQ Diffusion Matrix



Weakly Coupled

Greif, Fotakis, Denicol, Greiner Phys.Rev.Lett. 120 (2018) no.24, 242301

Very Strongly Coupled

Rougemont, Critelli, JNH, Noronha, Ratti Phys.Rev. D96 (2017) no.1, 014032