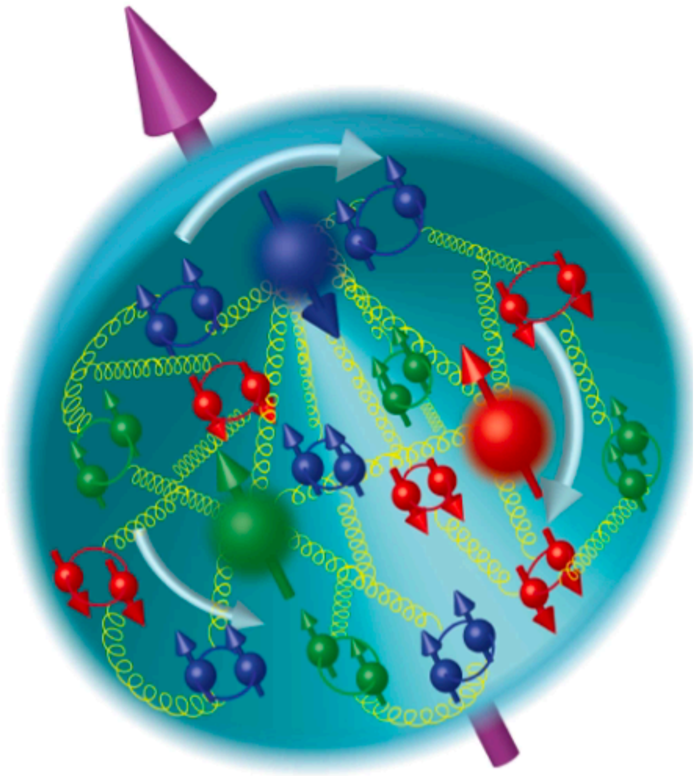
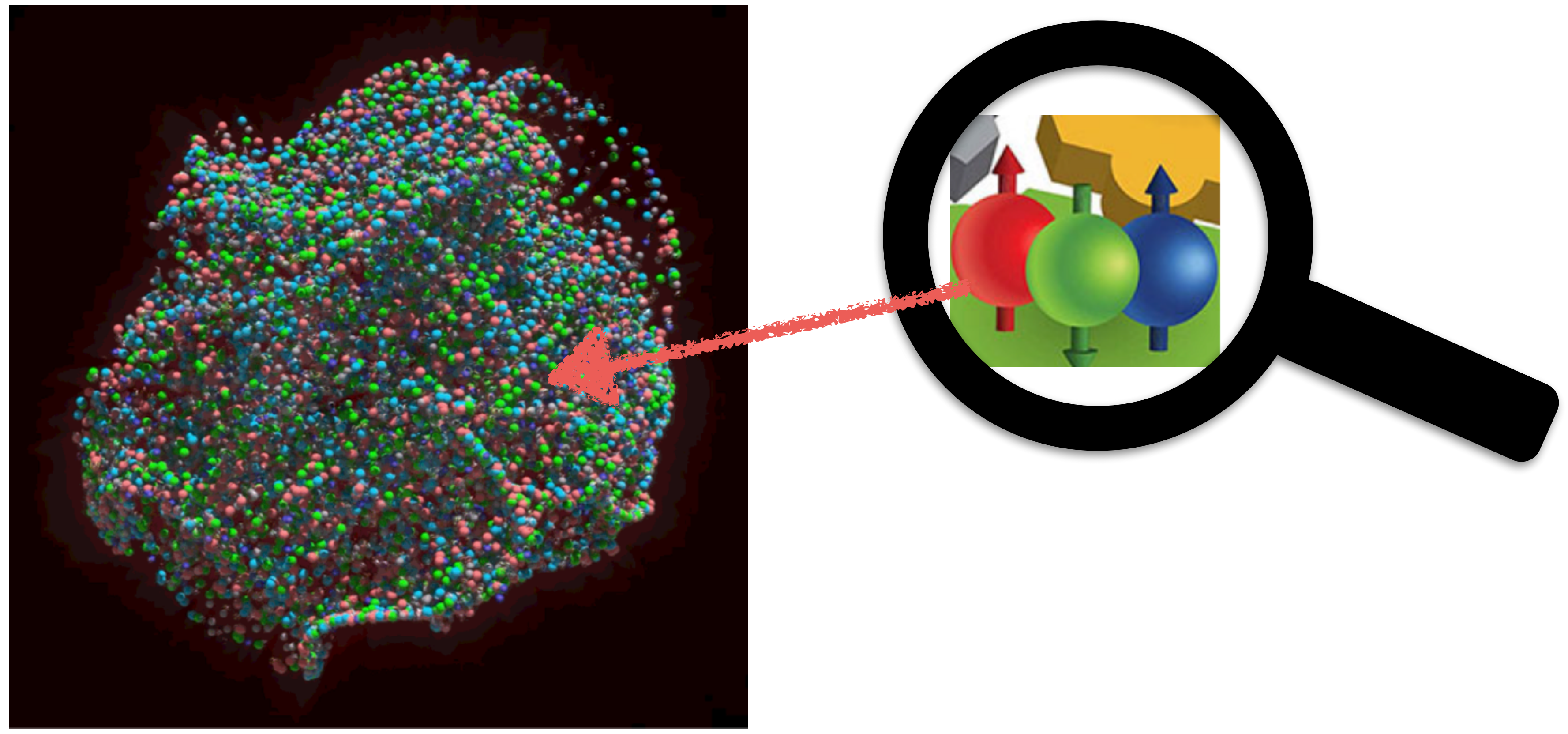
Spin and QCD Phase Structure





Temperature/density

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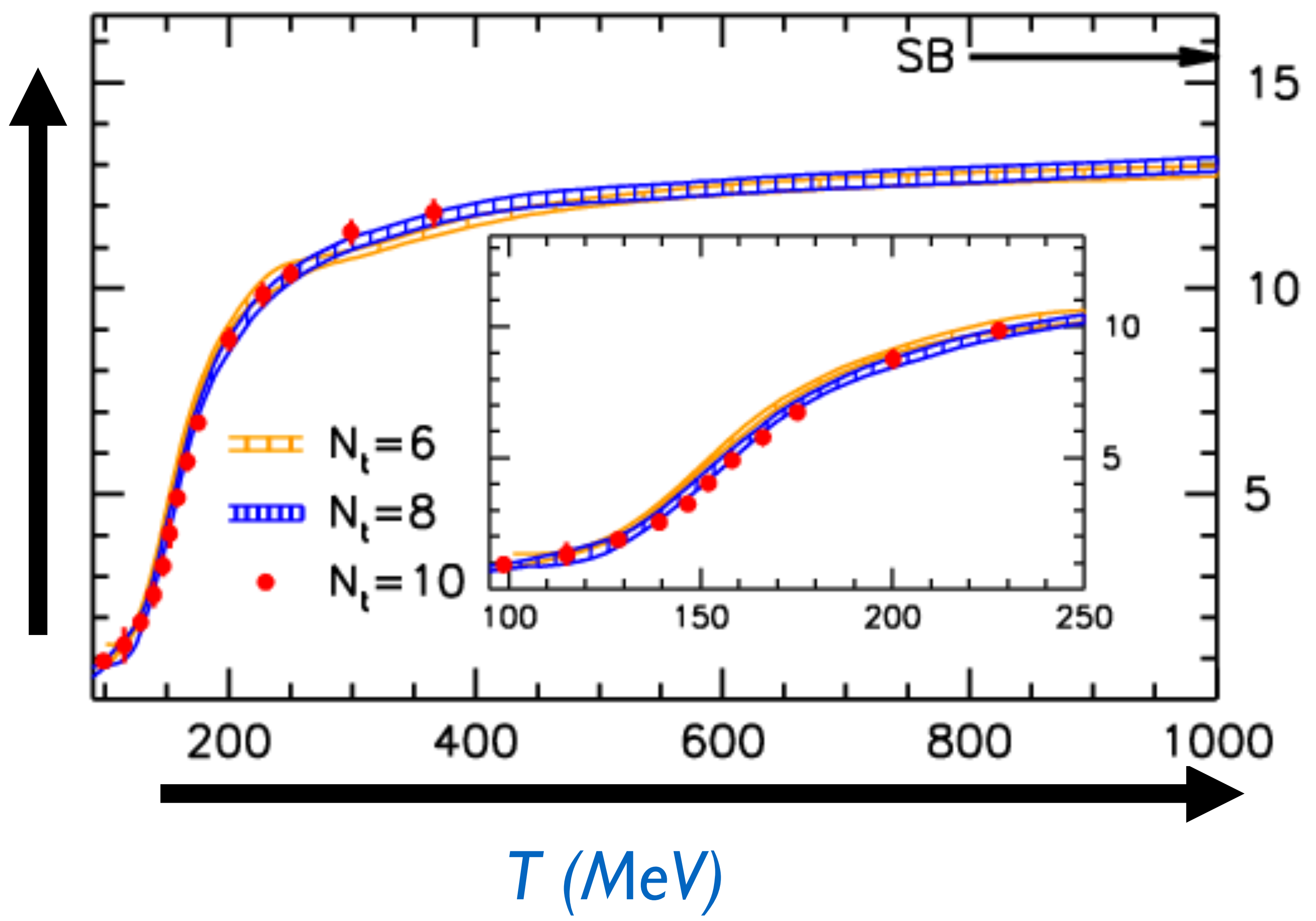
CPOD2024, May. 23rd, 2024

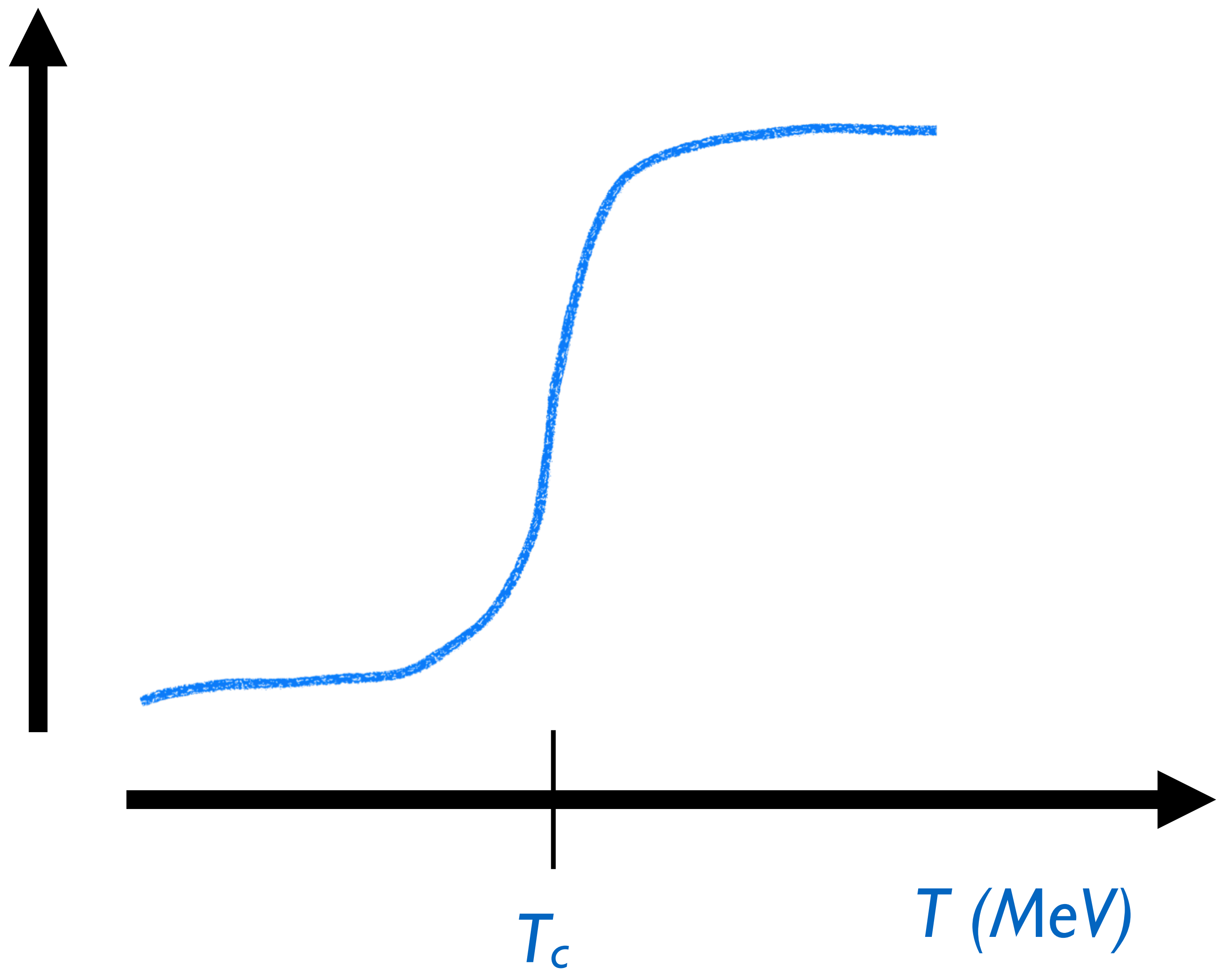
Outline

- Spin polarization generation: recent theoretical progress
- Phenomenological application
- Summary and outlook

Spin and Phase Structure



(Budapest-Marseille-Wuppertal Collaboration, JHEP'10)



- Spin carriers change dramatically near transition temperature
- Λ spin polarization/vector meson spin alignment measurement in heavy-ion collisions open a new frontier to study the properties of QCD matter

STAR Nature 2017, 2023

Polarization Generation in HIC

- Vorticity/rotation effect describes the trends of momentum-averaged (global) Λ polarization; was considered as the main mechanism for generating polarization

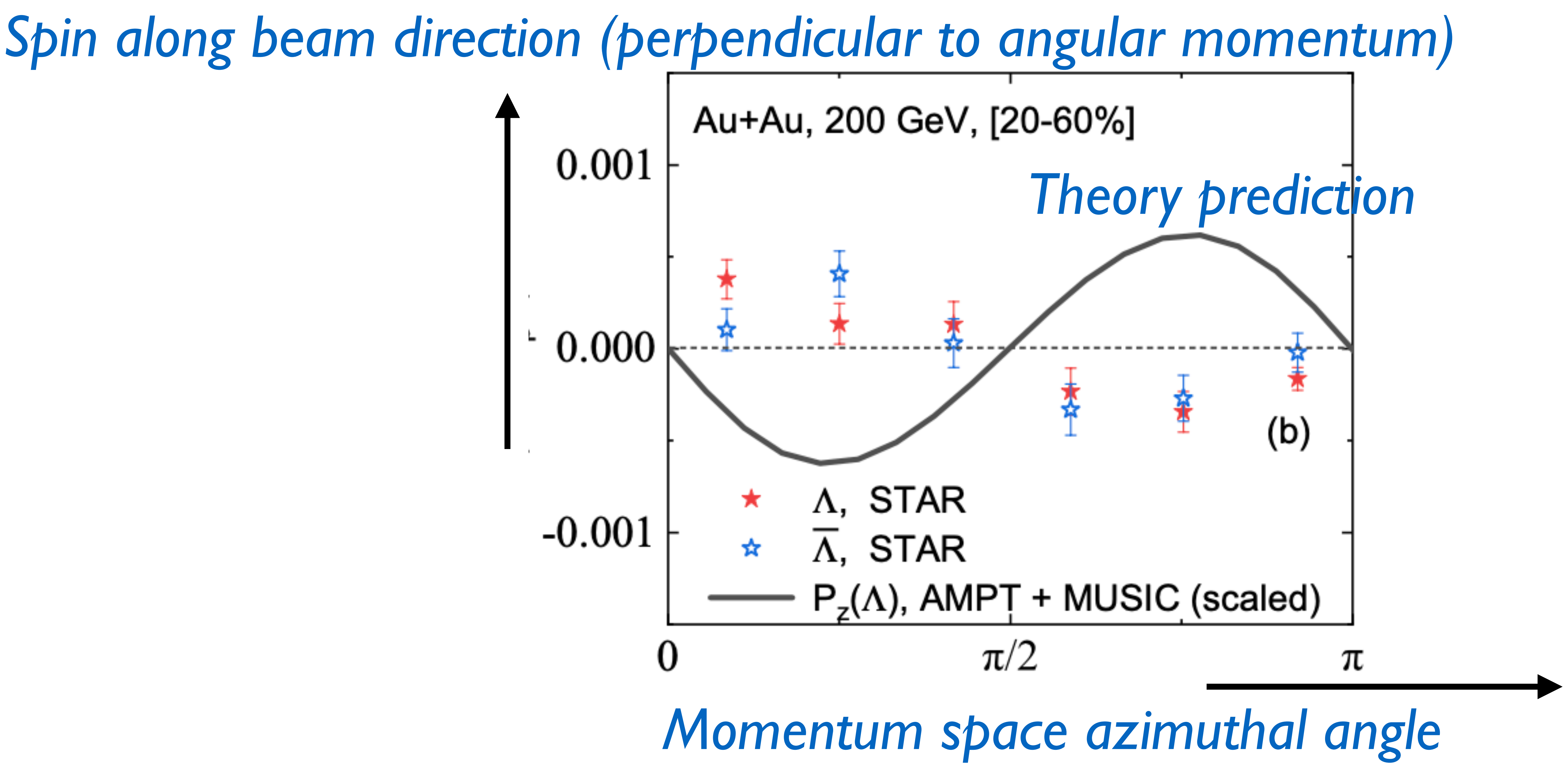
$$\hat{s} \parallel \overrightarrow{\Omega}$$

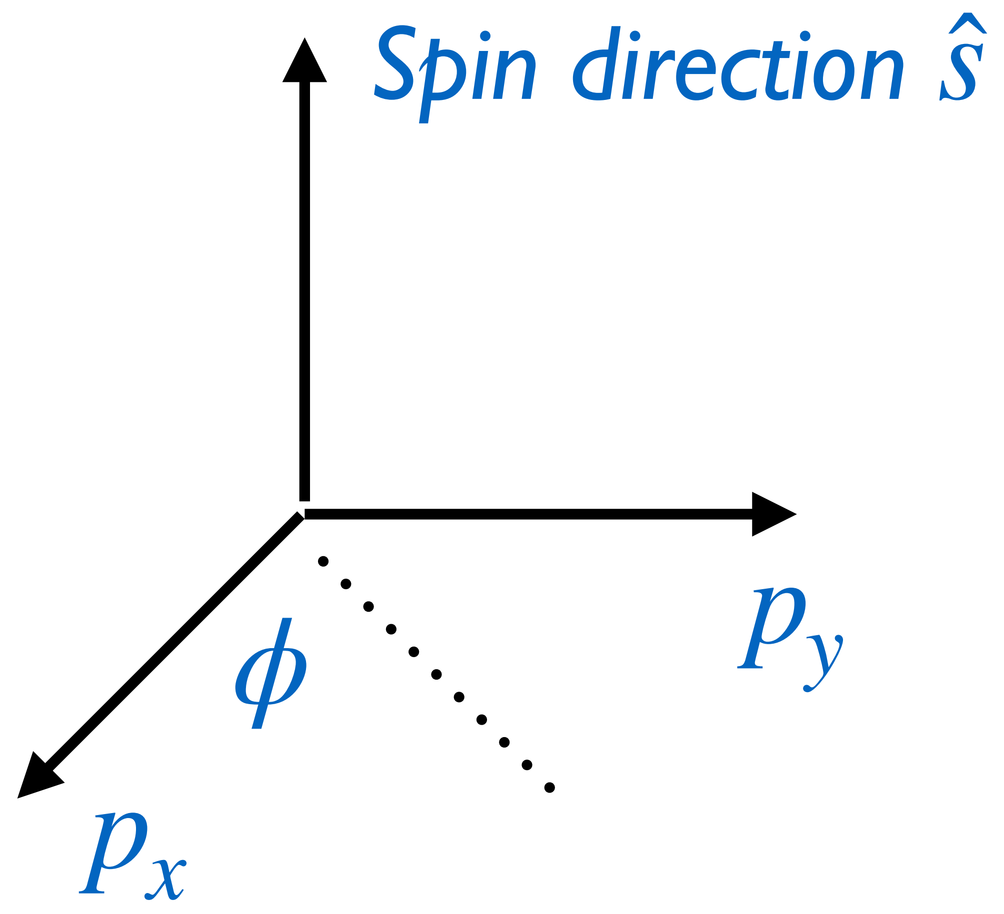
Xin-Nian Wang, Zuo-Tang Liang, PRL 05';
Becattini et al, Annals Phys 13'

- Since 2021', significant progress revealing rich spin effects
- Is instructive to revisit spin "sign puzzle" for differential polarization

Differential Spin Polarization

STAR Collaboration PRL 19

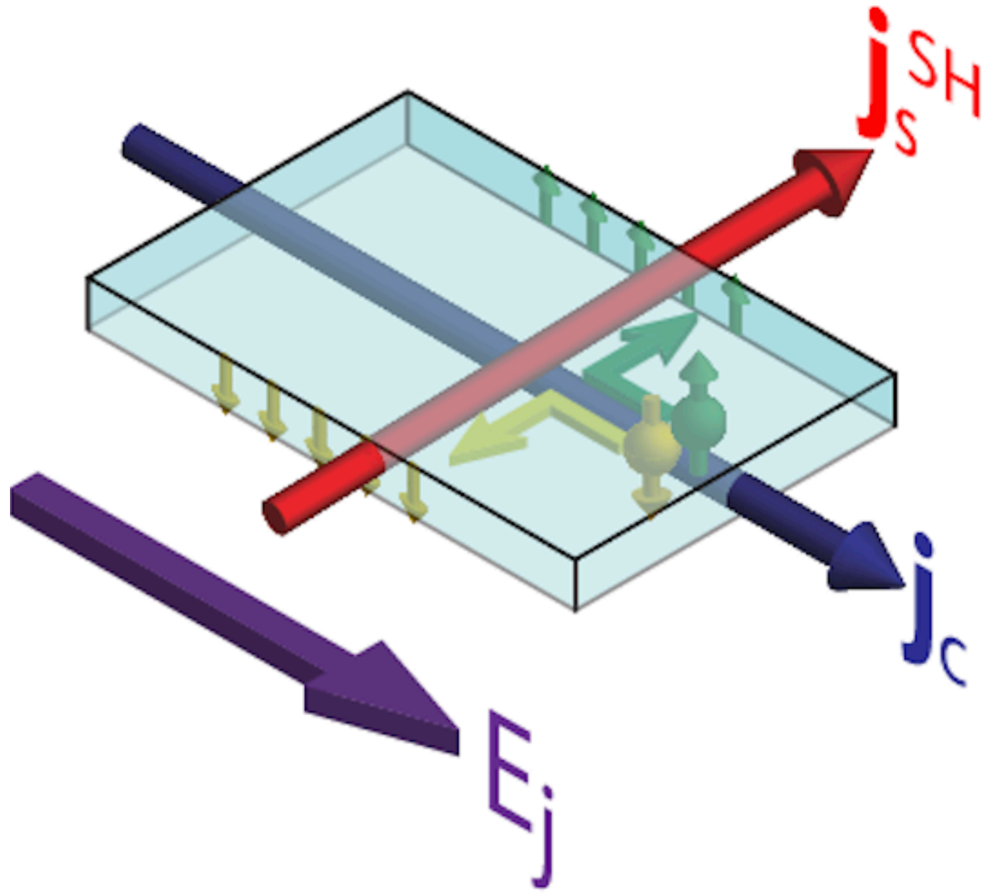




- Data indicates non-trivial spin-motion correlation, yet its origin is puzzling

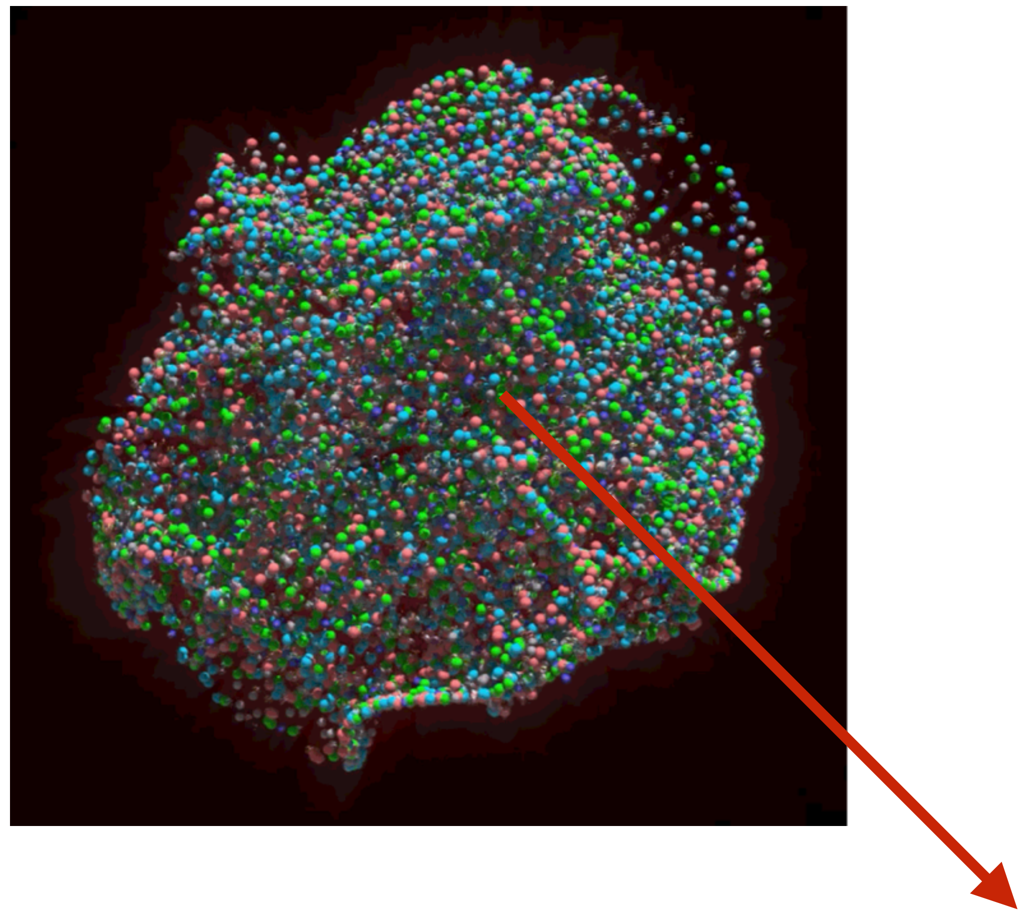
A class of models based on vorticity effect predict qualitatively different behavior ("sign puzzle")

Spin Hall Effect



Meyer et al, Nature material 17

$$\hat{s} \propto \vec{v} \times \vec{E}$$



Direction of gradient

$$\hat{s} \propto \vec{v} \times \vec{\partial}$$

- Electric force generates spin-motion correlation
- The gradient of density (e.g. momentum, energy/charge density) in QGP acts as generalized force that polarizes spin; can be analyzed systematically by extending usual gradient expansion to spin observables

Uncovering New Effects

Shuai Liu-YY JHEP 21
Also Becattini et al, PLB 21

Spin in phase space

$$s^i(t,\vec{x},\vec{v}) = c_\omega \omega^i + c_T \epsilon^{ijk} v_j \partial_k T + c_\sigma \epsilon^{ikj} \hat{v}_j \hat{v}_l \sigma^l{}_k$$

Vorticity effect — *T-gradient* — *Shear-induced polarization*

$$\vec{\omega} = \nabla \times \vec{u}$$

$$\sigma_{ij} = (\partial_i u_j + \partial_j u_i)$$

- Shear-induced polarization (SIP): allowed by symmetry, was never considered before
- One-loop calculation and quantum kinetic theory confirm the existence of SIP: $c_\omega \sim c_\sigma \propto$ density of spin carriers
- Baryon density gradient also polarizes spin

Shuai Liu and YY, PRD 20; Fu et al, 2022

$$\vec{s} \propto \vec{v} \times \vec{\partial}\mu_B$$

An Emerging New Field

- Rapid progress in relativistic quantum kinetic theory, spin hydrodynamics

Works by many

- Dissipative or not: shear effect is typically dissipative but spin is inherently quantum.

Shear-induced polarization examplifies a new class of emergent phenomena that the system is off-equilibrium, yet the transport is non-dissipative

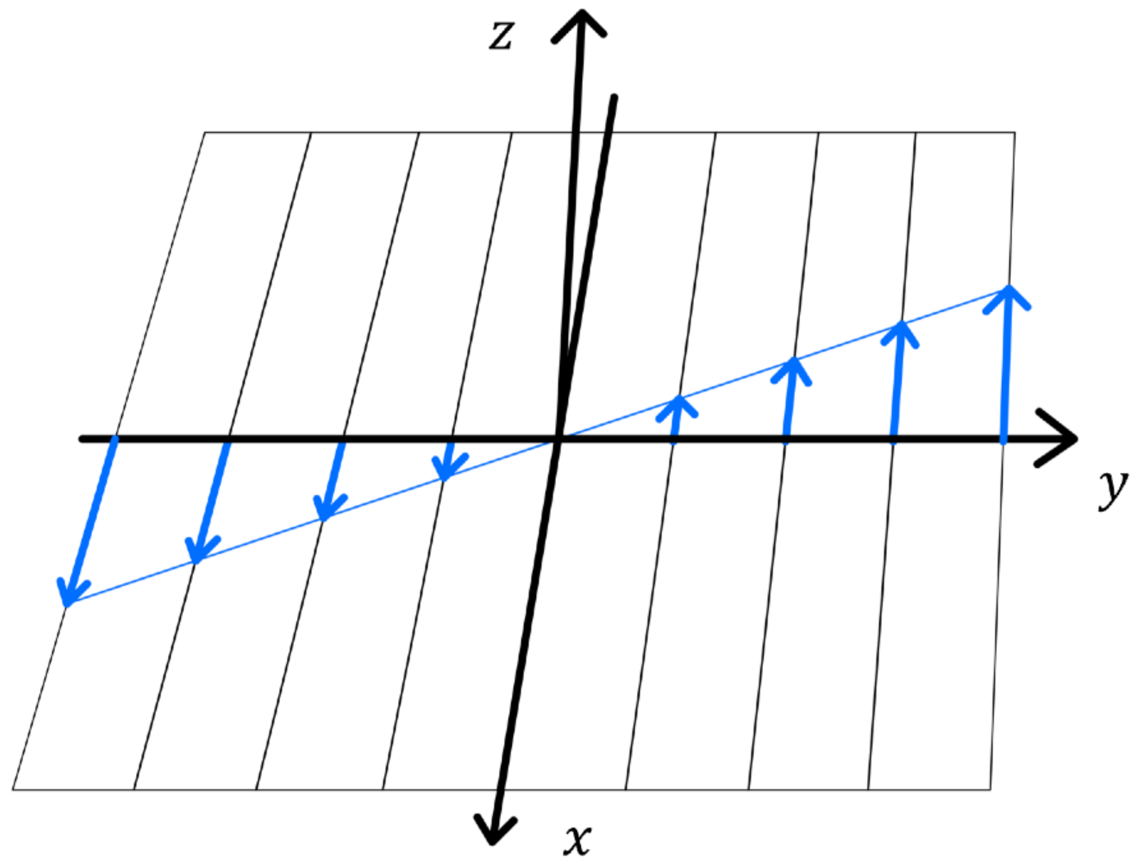
Becattini and YY, in preparation.

Phenomenological Implications

Particle distribution: ϵ, u^μ + gradient corrections

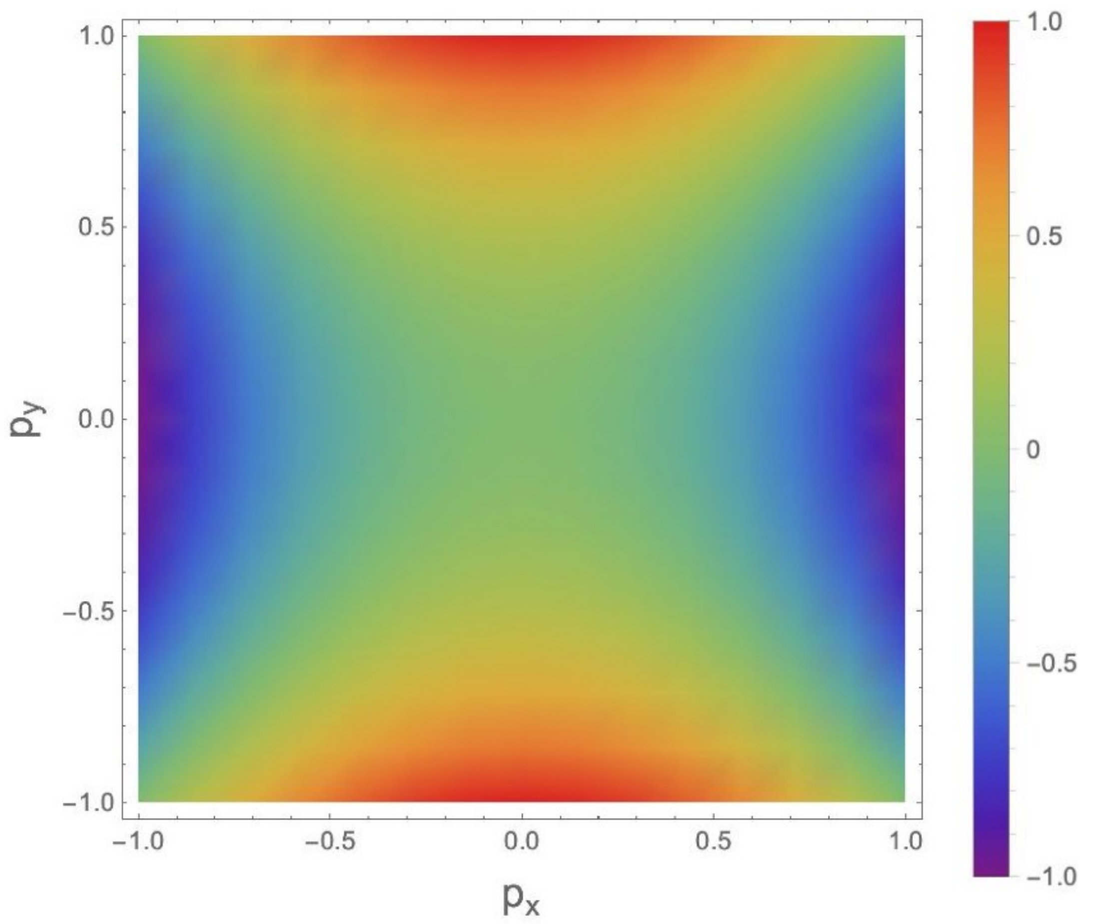
Polarization distribution $\propto$ gradient; sensitive to initial condition, transport coefficients, etc

How Shear Induces Polarization



A standard shear flow profile:
$\omega^z \neq 0\,,\sigma^{xy} \neq 0$

$$s^i \propto \epsilon^{ikj}\hat{v}_j\hat{v}_l\sigma^l{}_k$$

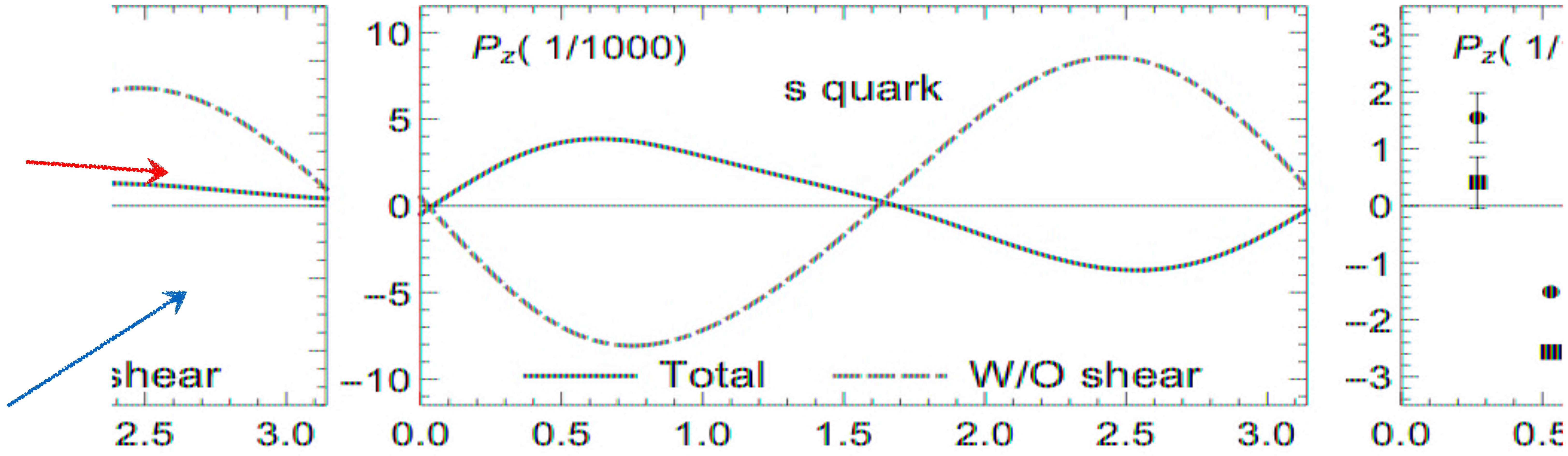


Distribution of s^z in $v_x - v_y$ plane due to SIP; vorticity does not induce any momentum distribution

Differential Polarization and SIP

Baochi Fu, Shuai Liu, Longgang Pang, Huichao Song, YY, PRL 21
also confirmed in Becattini et al PRL 21

With SIP



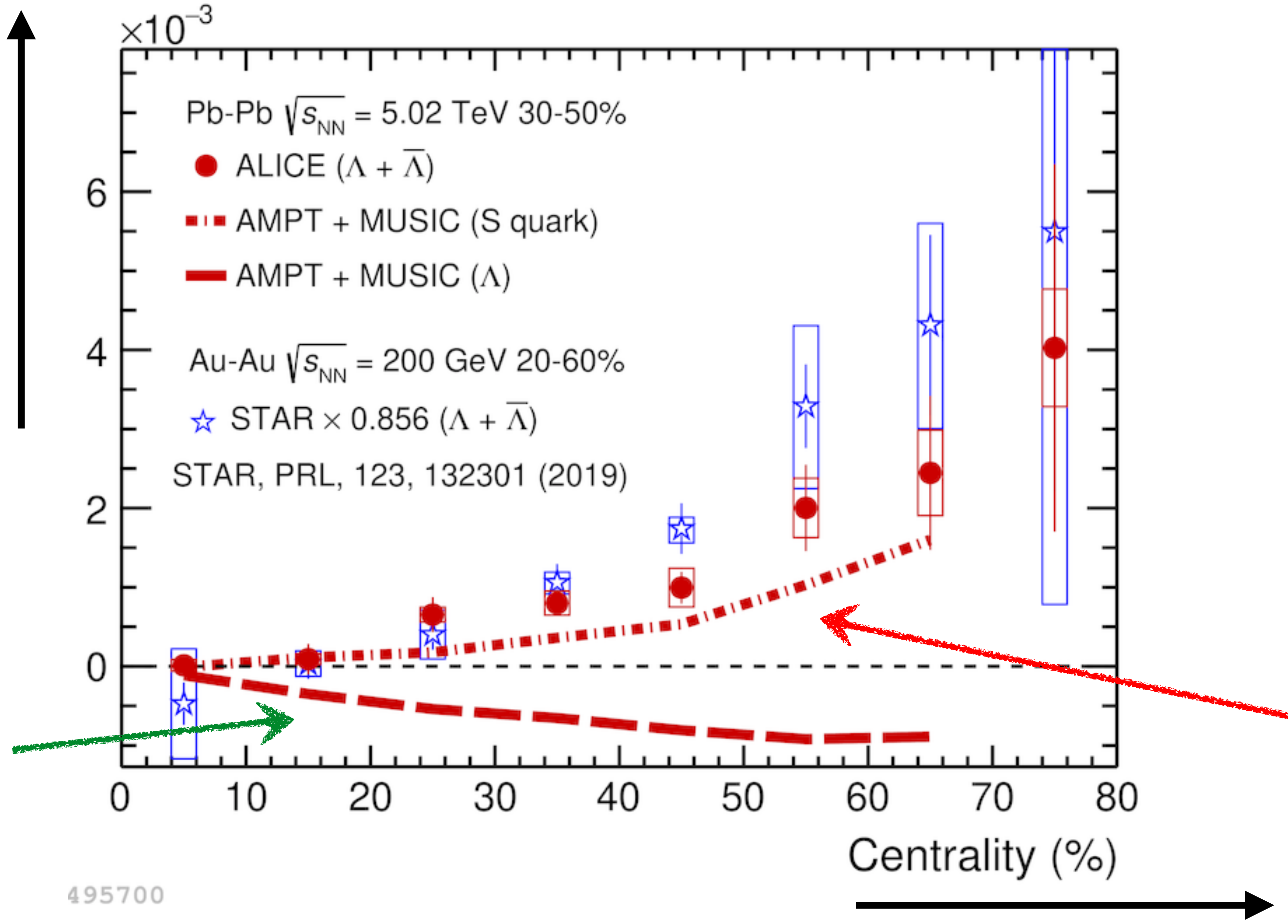
Without SIP

vs transverse azimuthal angle ϕ_p

- Shear-induced polarization (SIP) contribution qualitatively agrees with the data

Coefficient of $\sin(2\phi)$ modulation

LHC results from ALICE collaboration PRL 22



Suppressing shear effect

Including shear effect

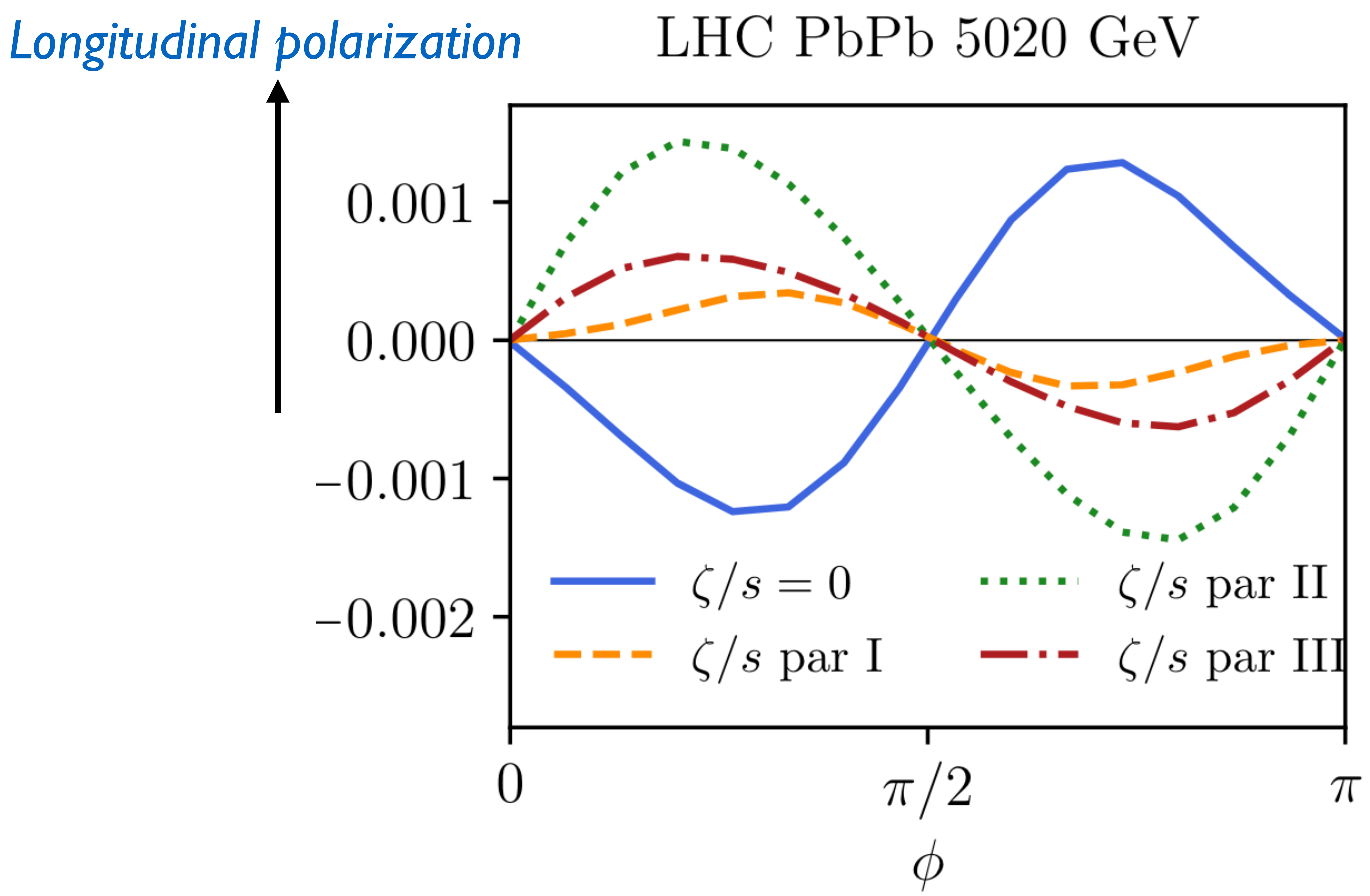
Stronger shear stress

- Tantalizing evidence for SIP: data can no be understood without including shear effects. More efforts are needed to claim discovery

Shear effects on other spin observables: STAR PRL 23

Sensitivity to Transport Coefficient

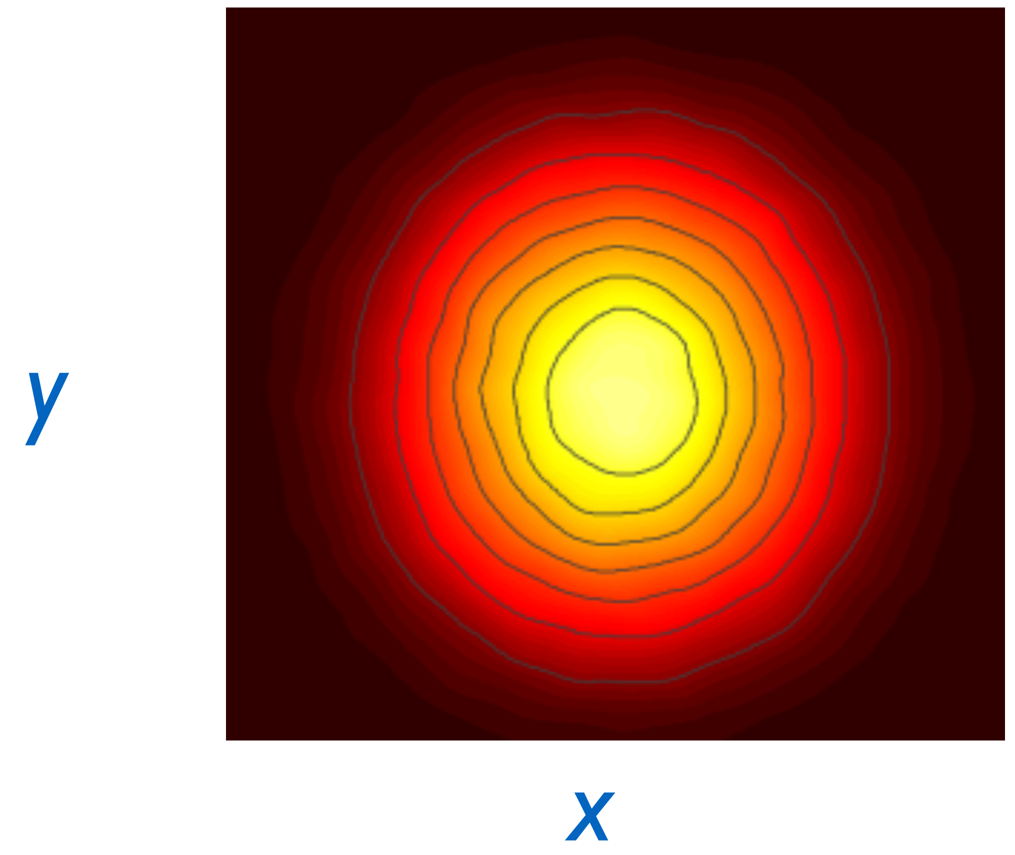
Palermo et al:, arXiv: 2404.14295



- Extension to BESII data can help constraining transport properties of Baryon-rich QGP

Baryonic Spin Hall Effect

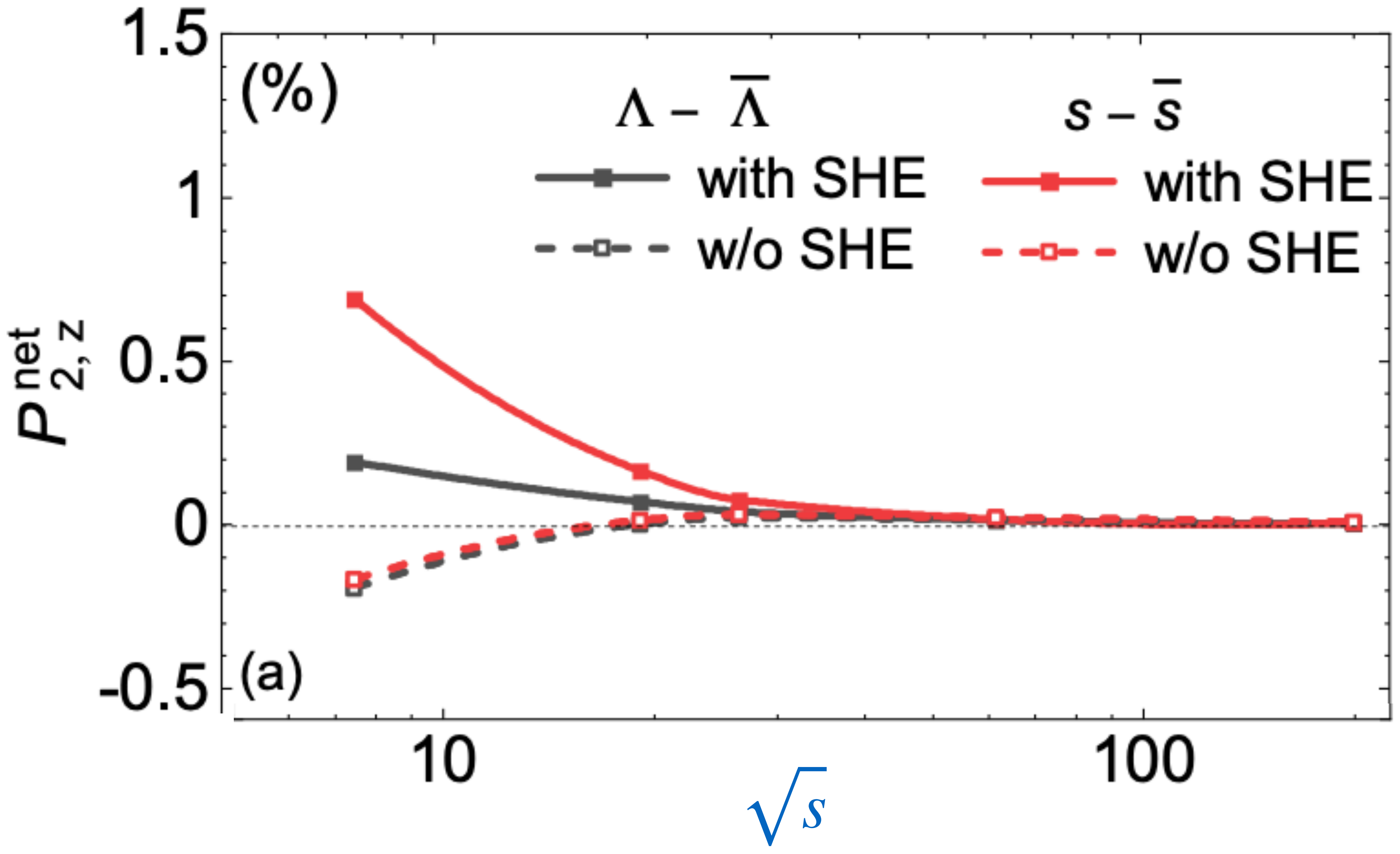
Baochi Fu, Longgang Pang, Huichao Song, YY, 2201.12970



Initial n_B profile at $\sqrt{s} = 7.7\ \mathrm{GeV}$ from AMPT

$$\vec{s} \propto \vec{v} \times \vec{\partial}\mu_B$$

Coefficient of $\sin(2\phi)$ modulation: $\Lambda - \bar{\Lambda}$



- Sensitive to EoS, diffusive constant and initial baryon stopping

A similarly effect induces neutrino current in supernovea *Di-Lun Yang, Naoki Yamamoto PRD 24*

Vector Meson Spin Alignment

- measures the difference between the occupation of transverse and longitudinal spin states

$$\delta\rho_{00} = \rho_{00}(\hat{n}) - \frac{1}{3} \propto \text{long. mode density - trans. mode density}$$

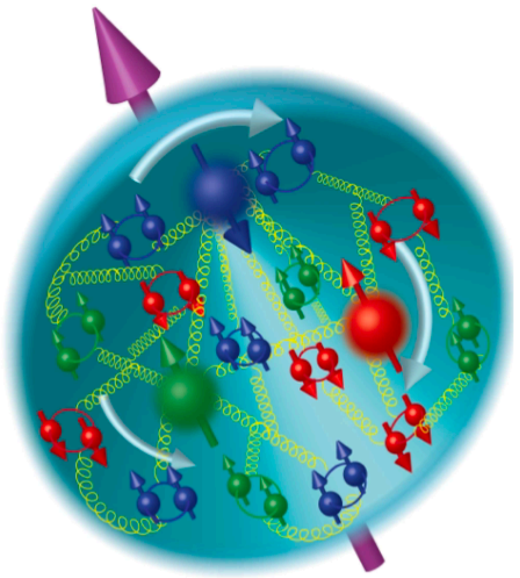
- shows non-trivial dependence on the species of mesons, centrality and $\sqrt{s}$ in both sign and magnitude; the underlying mechanism is under debate

e.g. Xin-Li Shen et al, PRL 23

- can be used to constrain in-medium properties of vector mesons

$$\delta\rho_{00}^{(0)} \propto E_L(p) - E_T(p)$$

Outlook: QCD Spin Structure



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

Xiangdong Ji et al, Nature Review, 20

orbital ang. momen.

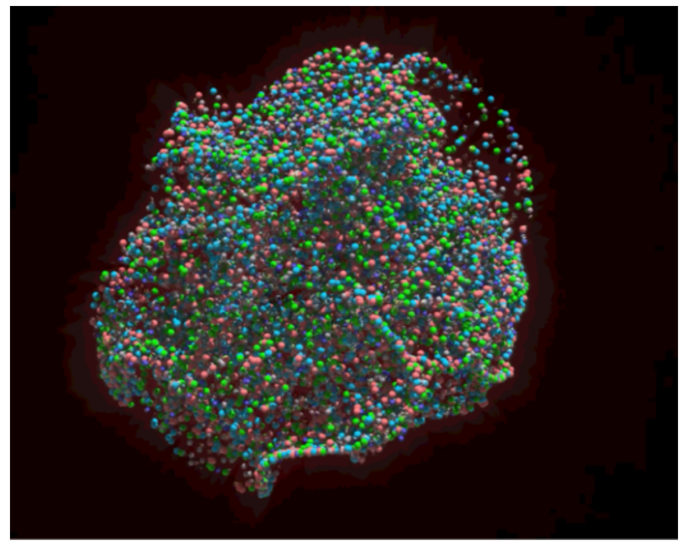
quark spin (only $\approx 20\,\%$)

gluon spin (up to $50\,\%$)

- Is the complex spin structure specific to confinement? Or a generic feature of non-perturbative quark-gluon interaction?
- Need to examine deconfined but strongly-coupled quark matter

Spin Structure of Quark Matter

Total angular momentum
$\hat{J} \neq 0$



$$J = \frac{1}{2}\Delta\Sigma + \Delta G + L$$

gluon spin? *orbital ang. mom.?*

- Consider rotating hot/dense quark matter

Quark spin: $\frac{1}{2}\frac{\Delta\Sigma}{\Omega} = \frac{1}{12}T^2 + c_0 g^2$

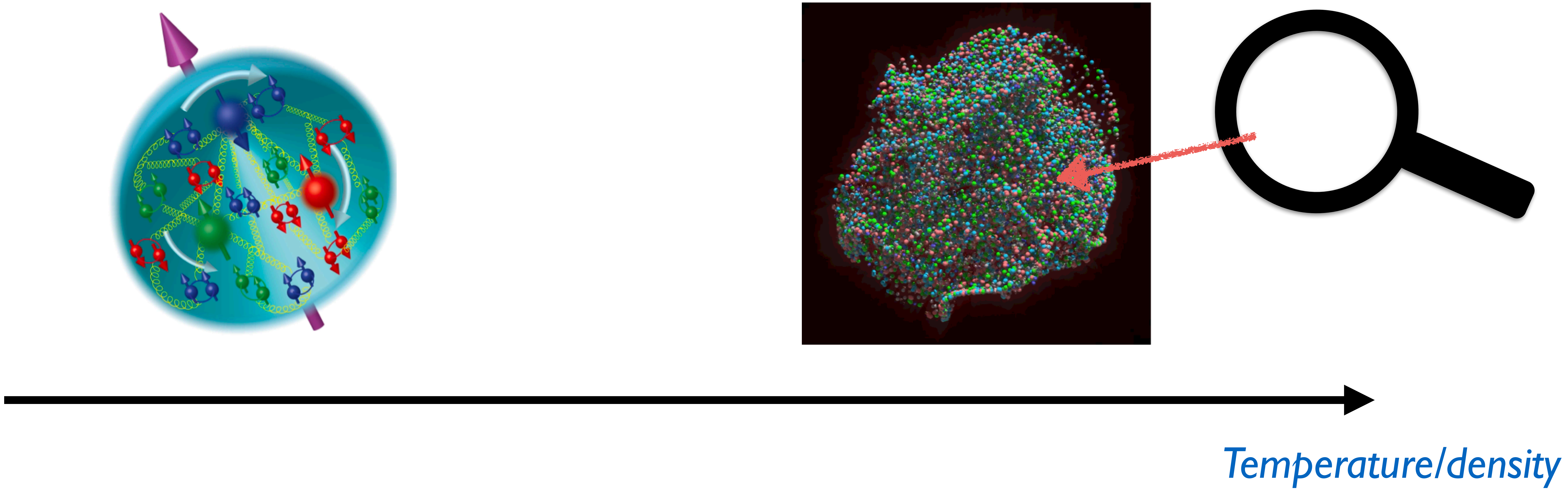
Two-loop, De-fu Hou et al 2013

Related to Chiral Vortical Effect coefficients

$$\frac{\Delta G, L}{\Omega} = ?$$

Analyzing and comparing spin structure will deepen the understanding of confinement/deconfinement transition

Summary



- Recent theoretical progress allows for utilizing spin observables to constraint the properties of QGP at different energies
- Outlook: spin structure monitors QCD phase transition

Back-up

Spin, Quantum Matter and QCD

- Broad context: spin effects reveal quantum behavior of many-body systems

- QCD employs a sophisticated way to build up proton spin

- Λ spin polarization/vector meson spin alignment measurement in heavy-ion collisions open a new frontier to study the properties of QCD matter

  STAR Nature 2017, 2023

(Modern view: quantum effects are important in characterizing and understanding phases)

Spin Dynamics

- Baryon density gradient also polarizes spin; the experimental investigation is under way *Shuai Liu and YY, PRD 20; Fu et al, 2022*

A similarly effect induces neutrino current in supernovea *Di-Lun Yang, Naoki Yamamoto PRD 24*

- Rapid progress in relativistic quantum kinetic theory, spin hydrodynamics

Works by many, e.g. Jianhua Gao, Xu-Guang Huang, Koichi Hattori, Defu Hou, Shu Lin, Shi Pu, Qun Wang, Pengfei Zhuang, Shuzhe Shi

- Dissipative or not: shear effect is typically dissipative but spin is inherently quantum. Calling for a deeper understanding *Becattini and YY, in progress.*

Gradient Expansion

- Observables are expressible in terms of conserved densities, e.g., energy and momentum density (or flow velocity u^μ) for slow varying gradient $\partial \sim k,\ k\, l_{\text{mfp}} \ll 1$

In a collision, $kl_{\text{mfp}} \sim 0.1$

$$O = (\partial^0) + (\partial^1) + \dots$$

- All possible terms allowed by symmetry should be included with expansion coefficients computed from microscopic calculations

Reminiscent of effective field theory

Constitutive relation in hydro: $T^{ij} = p\,\delta^{ij} + \eta\sigma^{ij} + \dots$

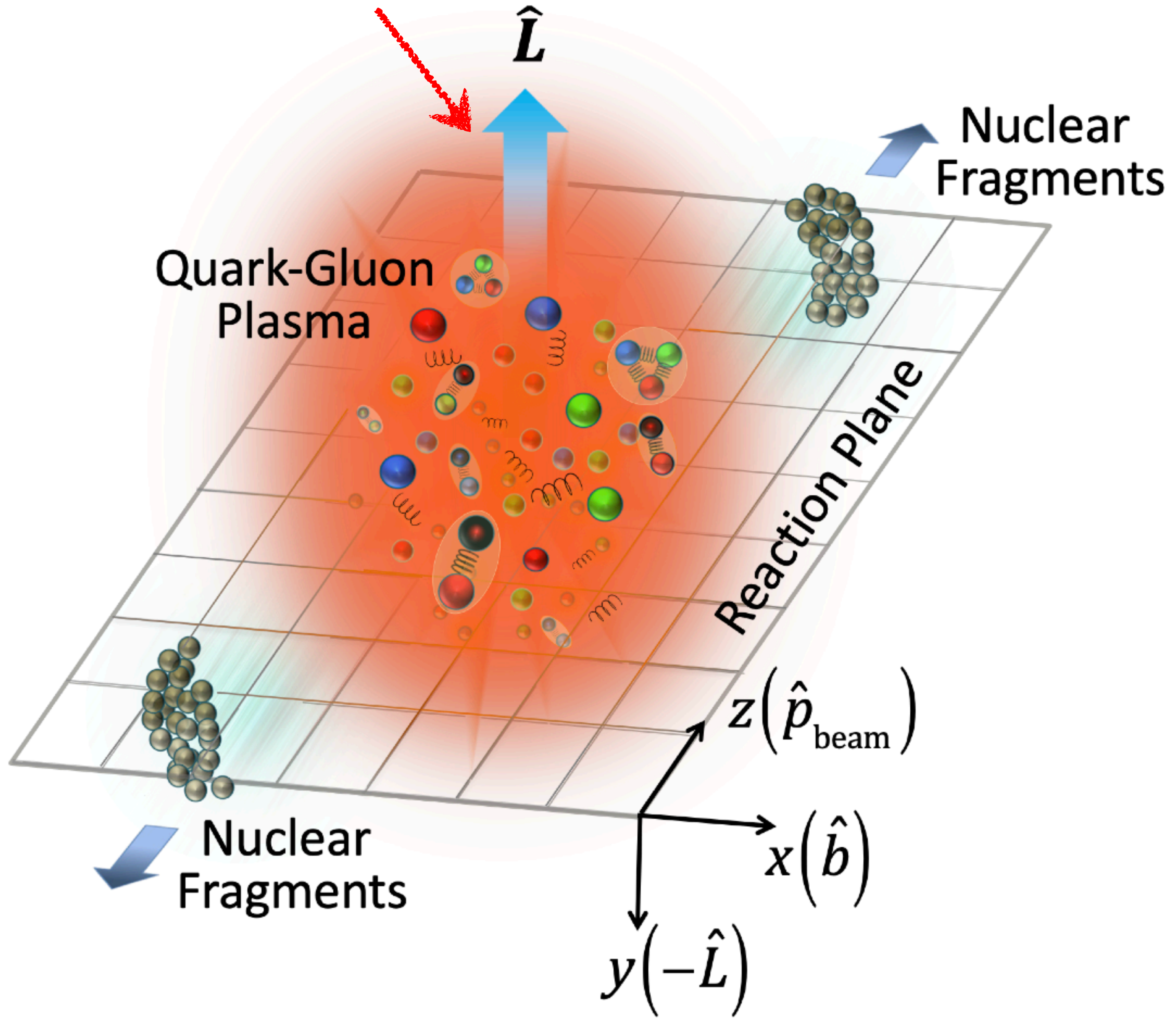
shear stress

- Applying the same method to spin observables

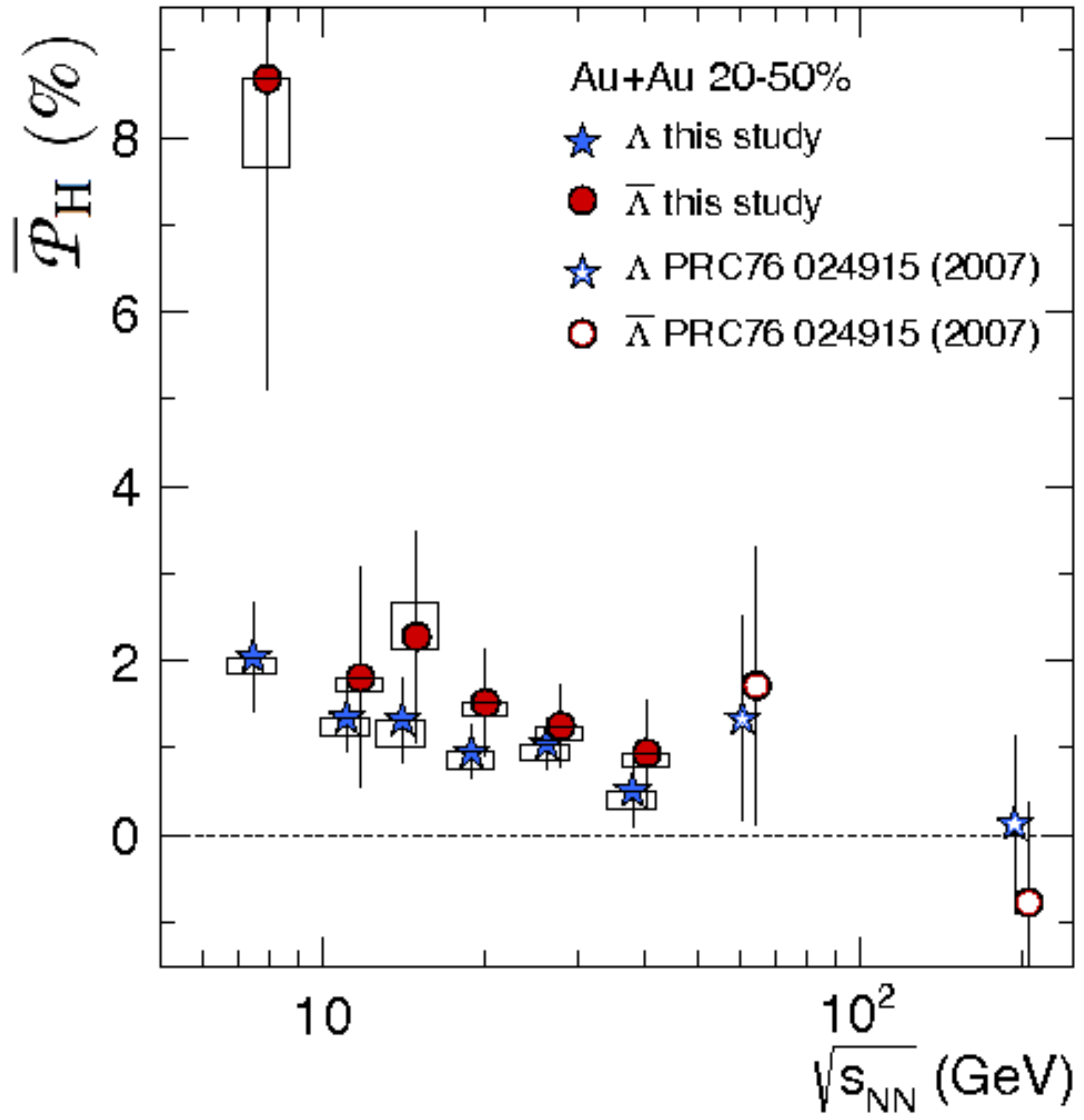
Λ Hyperon Polarization at RHIC

STAR Collaboration Nature 17

Direction of angular momentum



Rotating quark matter



Λ polarization (momentum-averaged) along the direction of angular momentum vs collision energy

Vorticity effect describes the trends of momentum-averaged Λ polarization (spin parallels to angular velocity)