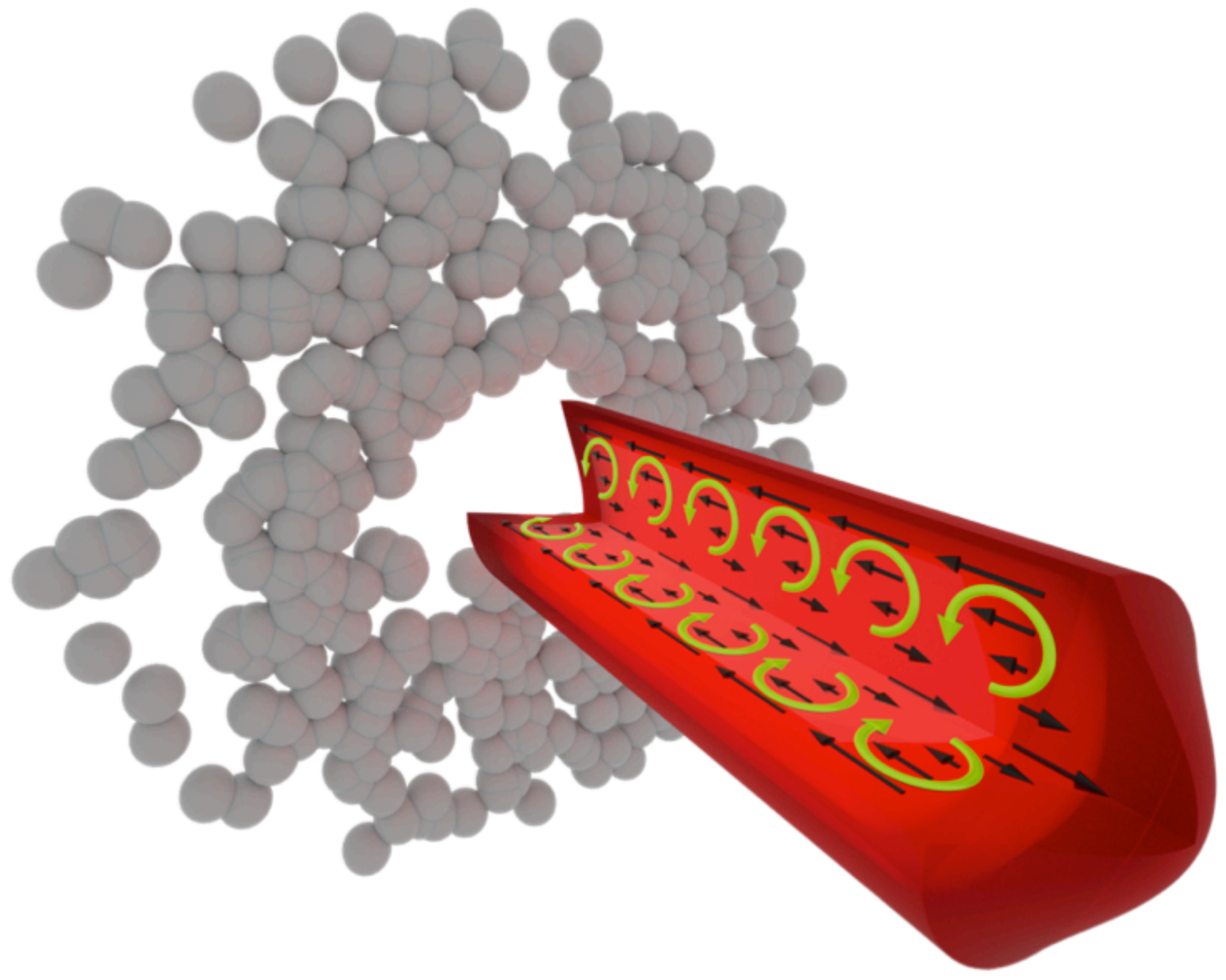
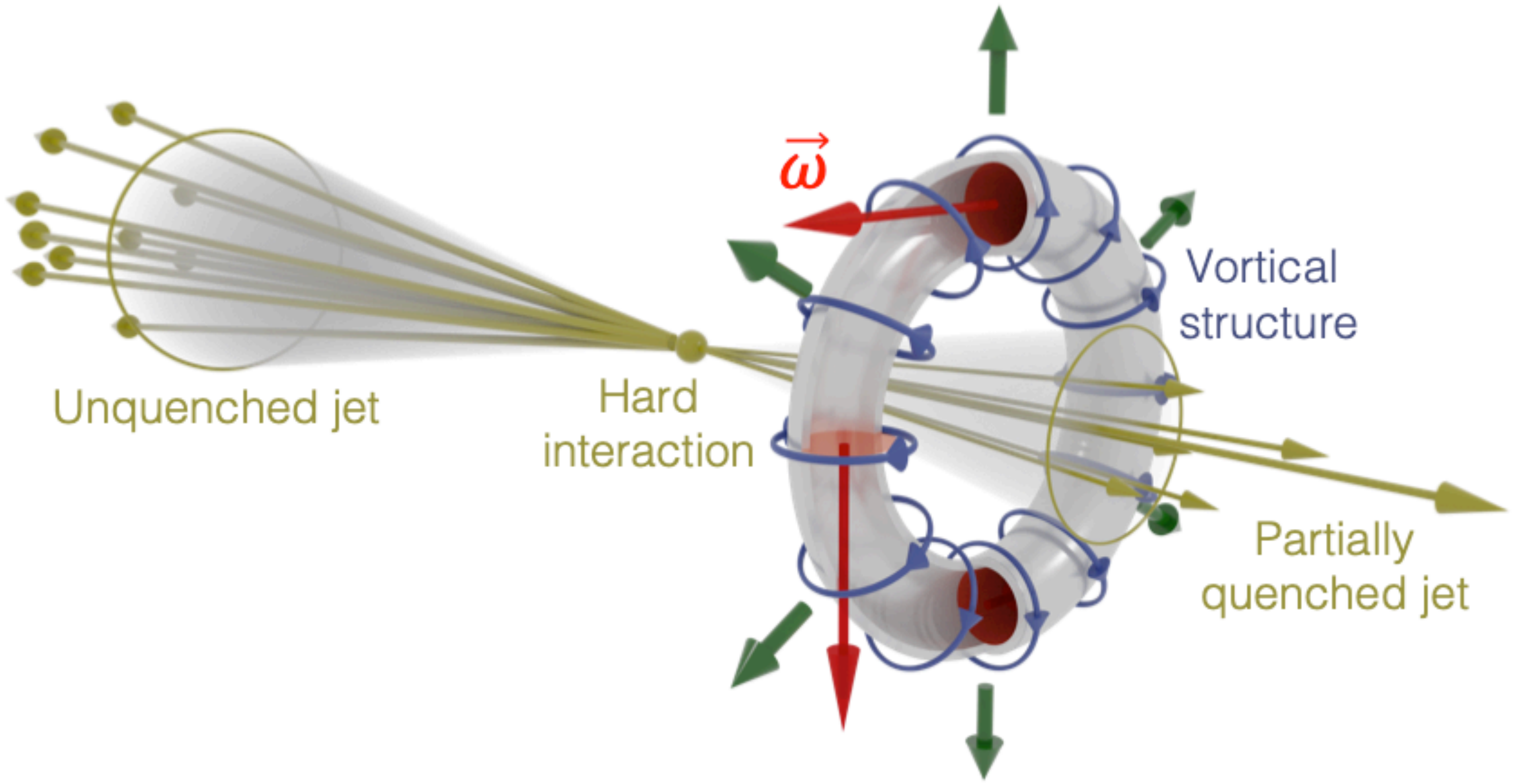
LOCAL POLARIZATION FROM HYDRODYNAMICS

CHUN SHEN





The 6th International Conference on Chirality, Vorticity, and Magnetic Field in Heavy Ion Collisions

Nov. 2, 2021

ROTATIONAL STRUCTURE IN NON-CENTRAL HIC

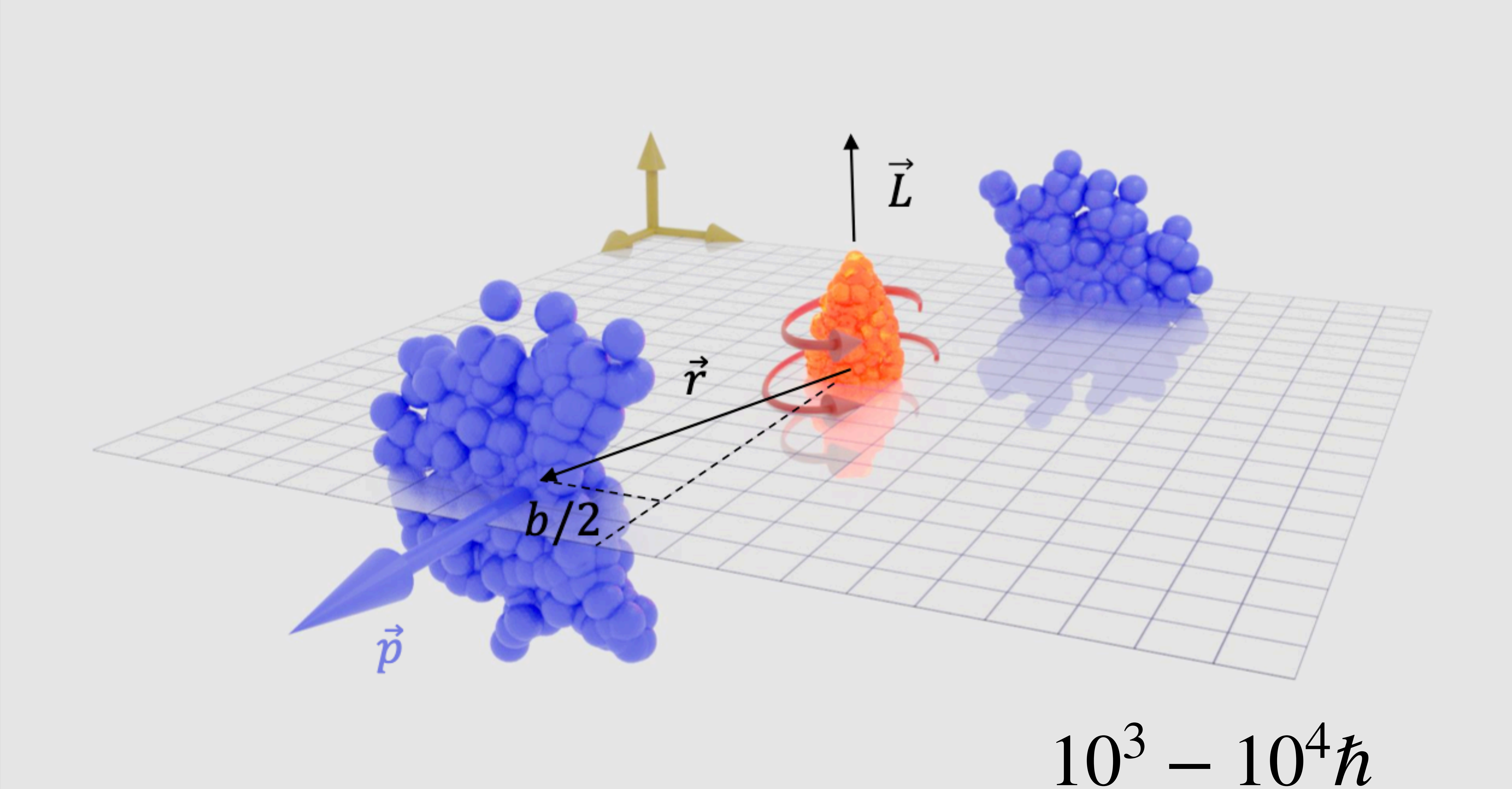
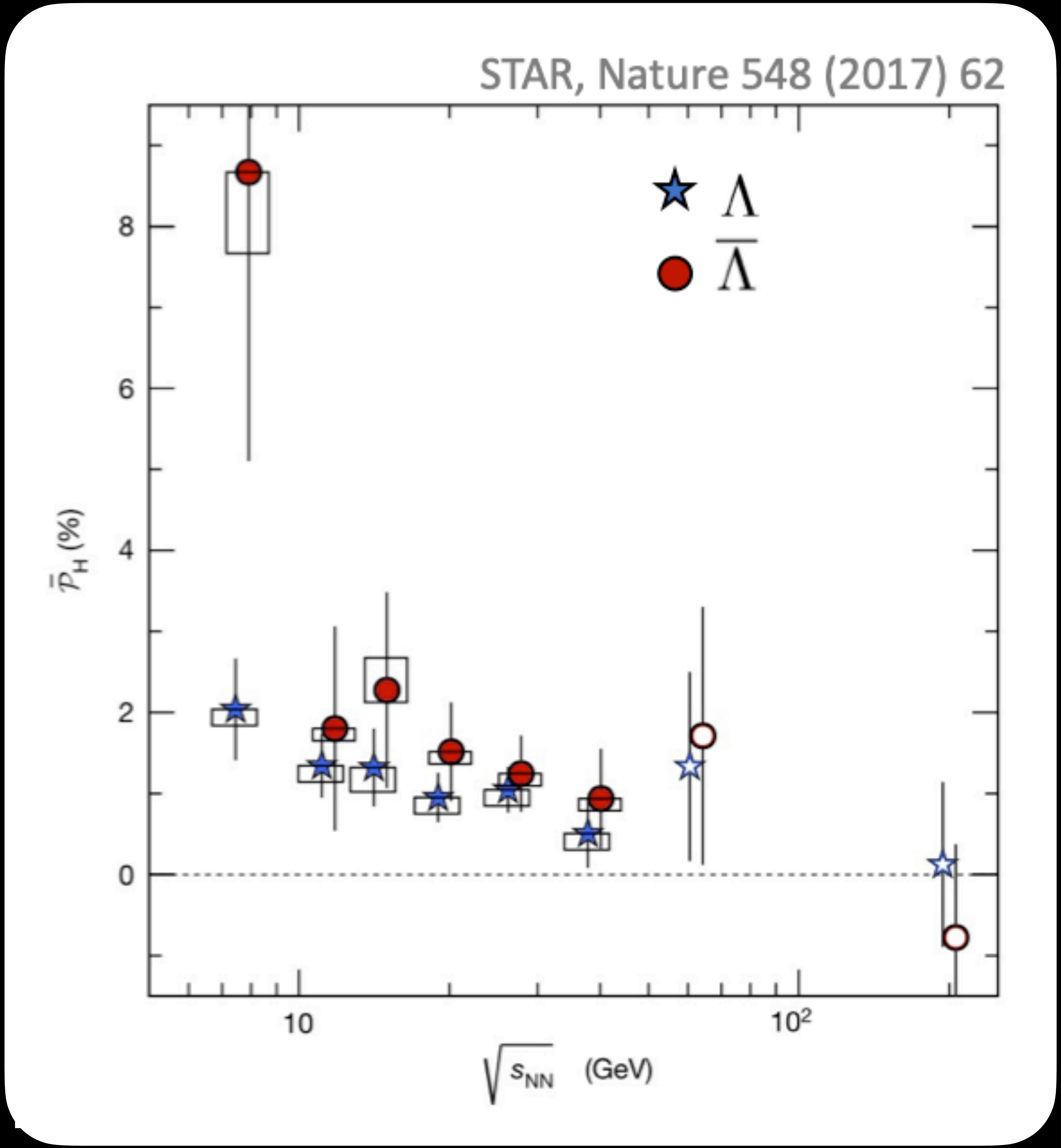
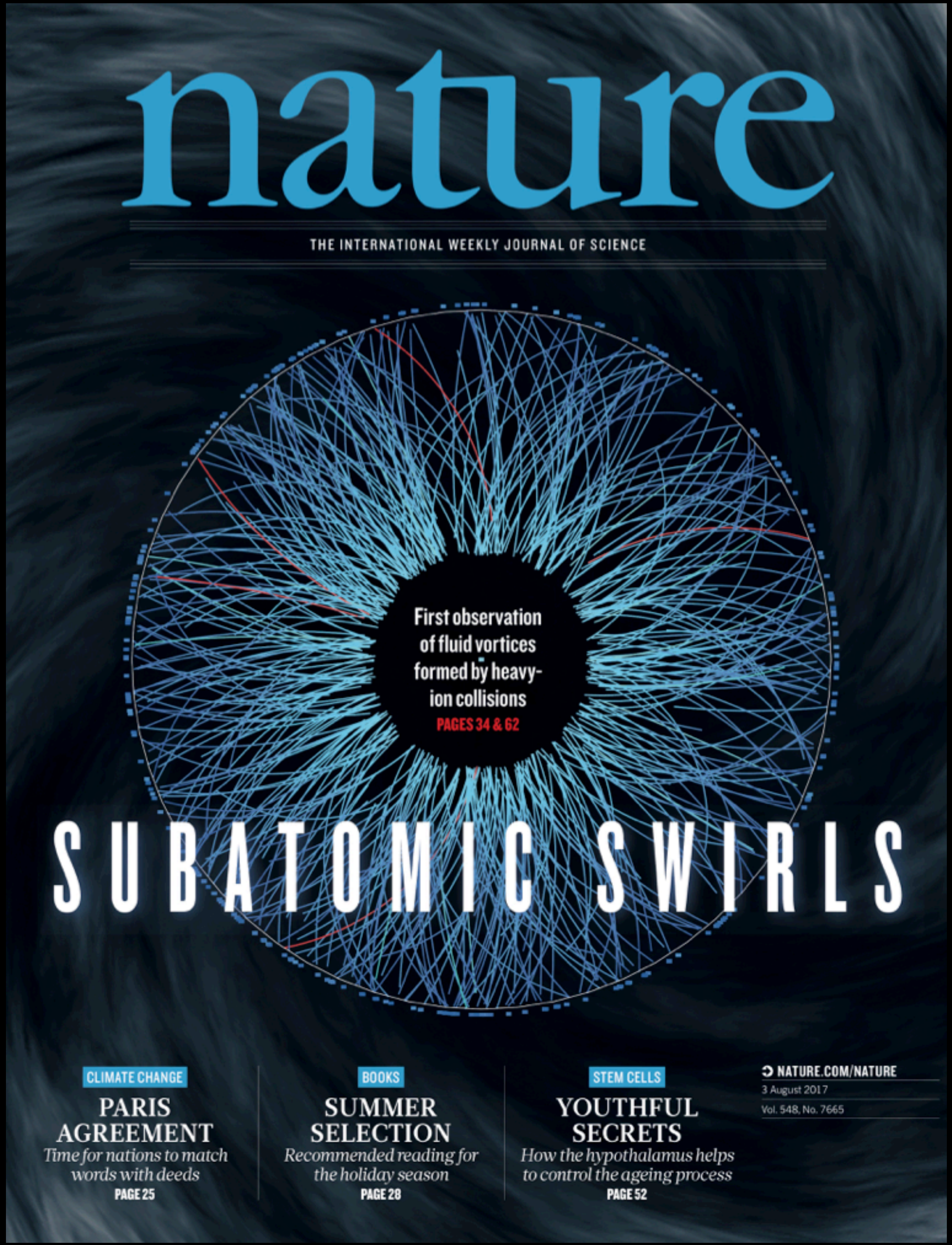


Figure by David D. Chinellato

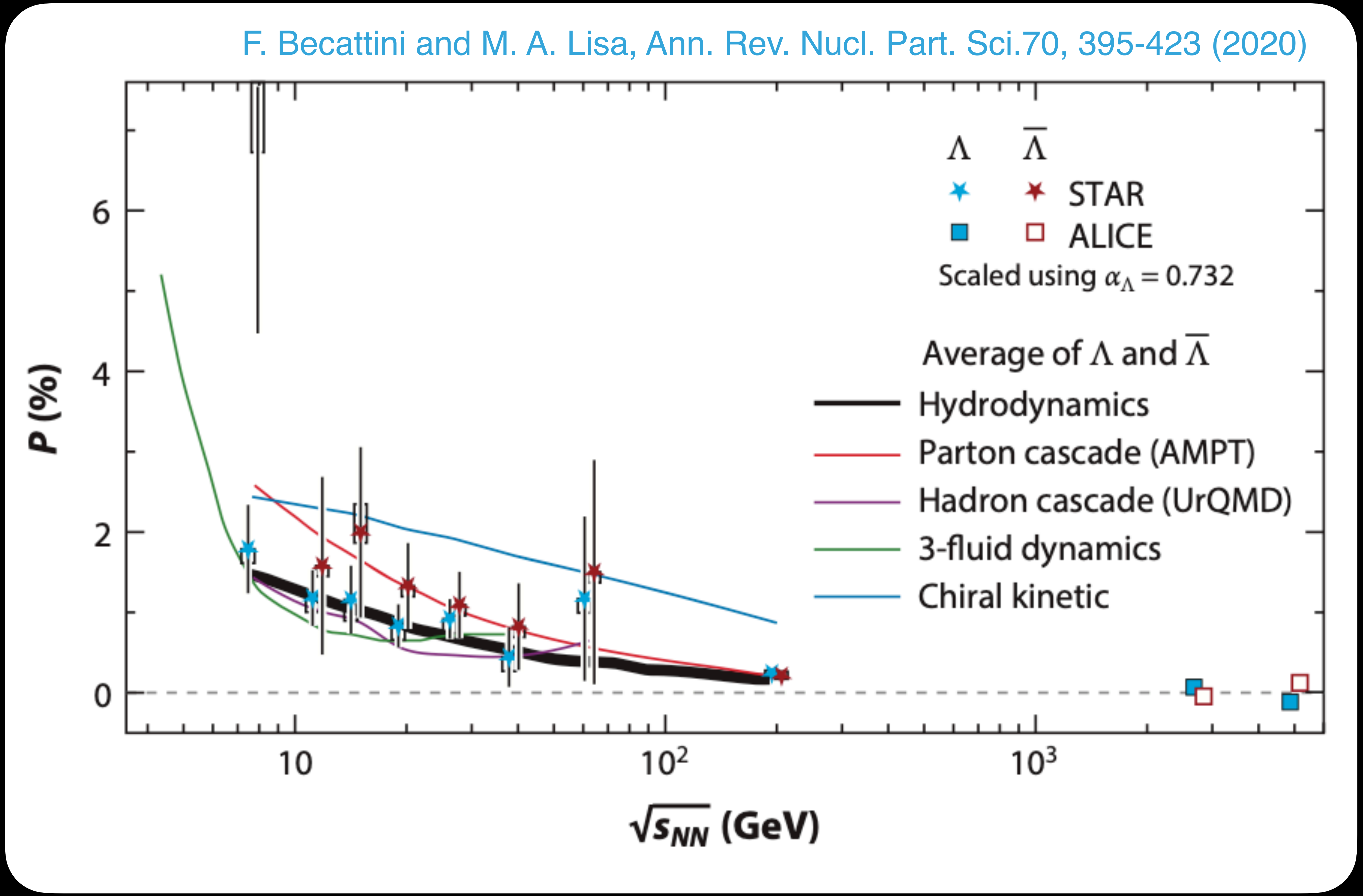
- Non-central heavy-ion collisions create QGP carrying large angular momentum

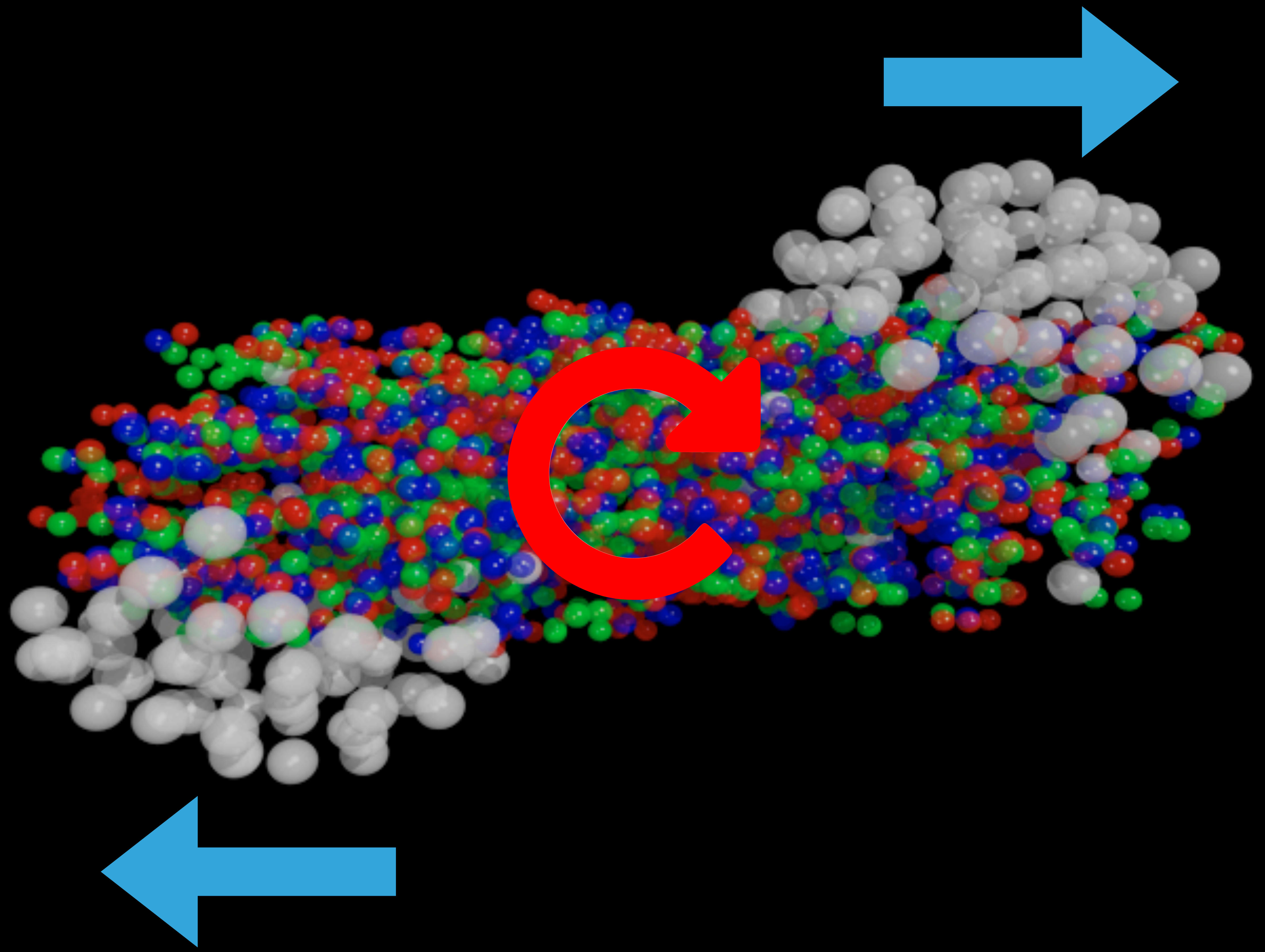
THE MOST VORTICAL FLUID IN NATURE





SUCCESSFUL THEORETICAL PREDICTIONS





- Dynamical models gave quantitative prediction of the global polarization as a function of collision energy

AN OAM-VORTICITY-SPIN PARADIGM

Assuming the spin degrees of freedom reach local thermal equilibrium,

- Initial orbital angular momentum (OAM) from the collision geometry
- Evolution of local fluid vorticity
- Map the fluid vorticity to hyperon's spin polarization

FOR THEORETICAL DEVELOPMENTS OF SPIN HYDRODYNAMICS, SEE BECATTINI TUE 10:50 & HUANG WED 09:40

AN OAM-VORTICITY-SPIN PARADIGM

Assuming the spin degrees of freedom reach local thermal equilibrium,

- Initial orbital angular momentum (OAM) from the collision geometry
- Evolution of local fluid vorticity
- Map the fluid vorticity to hyperon's spin polarization

We want to learn how hyperon's polarization can provide information about the dynamics of heavy-ion collisions, especially at the early-stage

- Early-time longitudinal dynamics

  S. Ryu, V. Jupic and C. Shen, arXiv:2106.08125 [nucl-th]
  M. Lisa, *et. al.*, Phys. Rev. C104, 011901 (2021)

- Jet-medium interactions

  W. Serenone, *et. al.*, Phys. Lett. B 820 (2021) 136500

HYPERON'S SPIN POLARIZATION AT FREEZE-OUT

F. Becattini, I. Karpenko, M. Lisa, I. Upsal and S. Voloshin, Phys. Rev. C95, 054902 (2017)
Y. Hidaka, S. Pu and D. L. Yang, Phys. Rev. D97, 016004 (2018)
S. Liu and Y. Yin, Phys. Rev. D104, 054043 (2021); JHEP07, 188 (2021)
F. Becattini, M. Buzzegoli, A. Palermo, G. Inghirami, Phys. Lett. B820, 136519 (2021)
C. Yi, S. Pu and D. L. Yang, arXiv:2106.00238 [hep-ph]
Y. C. Liu and X. G. Huang, arXiv:2109.15301 [nucl-th]
M. Buzzegoli, arXiv:2109.12084 [nucl-th]

BECATTINI TUE 10:50

The spin polarization of Λ hyperons can be computed as,

$$P^\mu(p) = \frac{1}{2m} \frac{\int d\Sigma_\alpha p^\alpha A^\mu(p)}{\int d\Sigma_\alpha p^\alpha f_0(p)}$$

$$A^\mu(p) = f_0(1 - f_0)\left[\omega_{\rm th}^{\mu\nu} p_\nu - \frac{b_i}{E}\epsilon^{\mu\nu\alpha\lambda} u_\nu p_\alpha \partial_\lambda(\beta\mu_B) + \frac{\beta}{E}\epsilon^{\mu\nu\alpha\lambda} u_\nu p_\alpha p^\beta \sigma_{\beta\lambda}\right]$$

Thermal vorticity — Gradients of μ_B/T — Shear velocity tensor

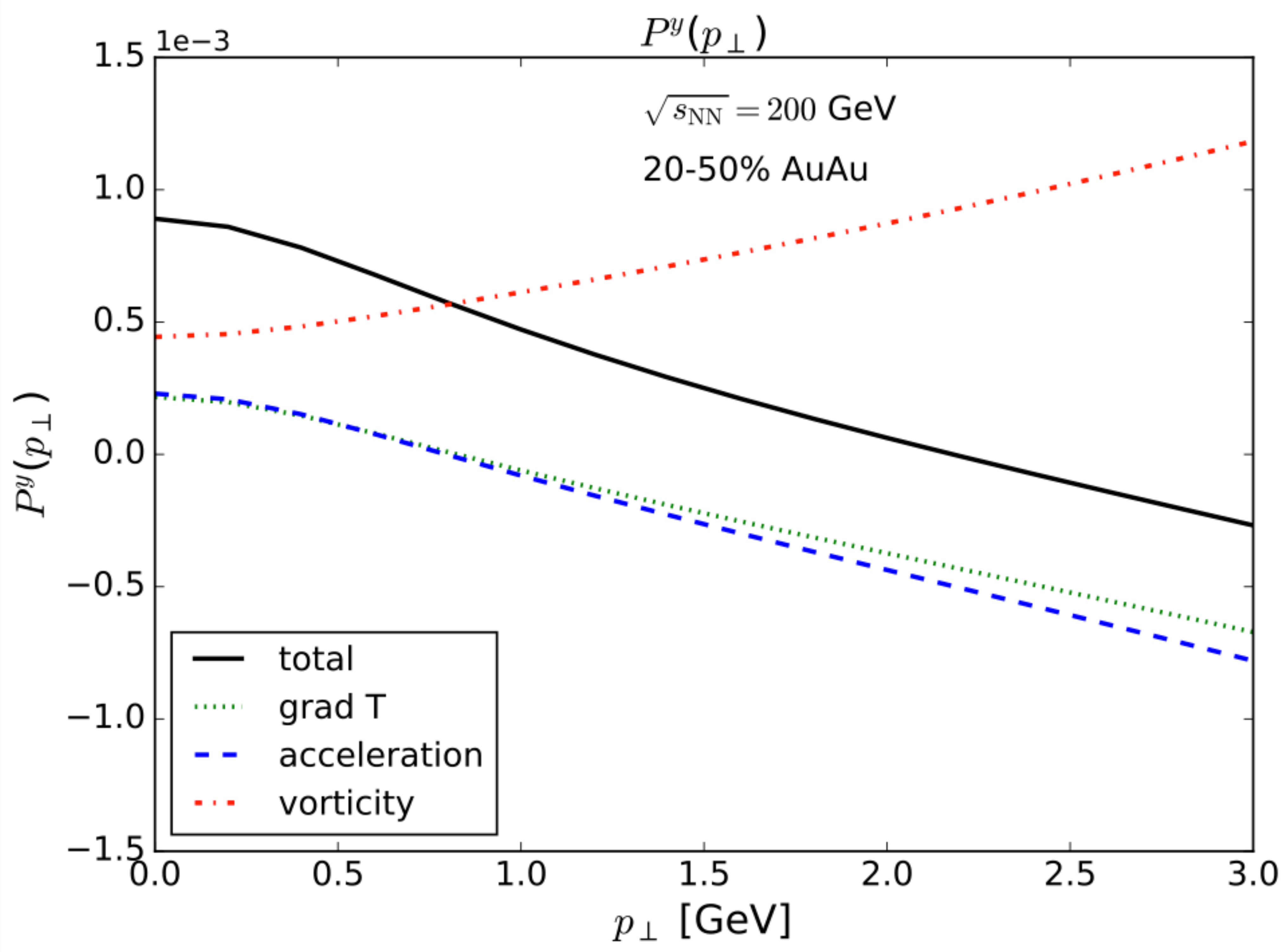
- The polarization observables carry gradient information from hydrodynamics

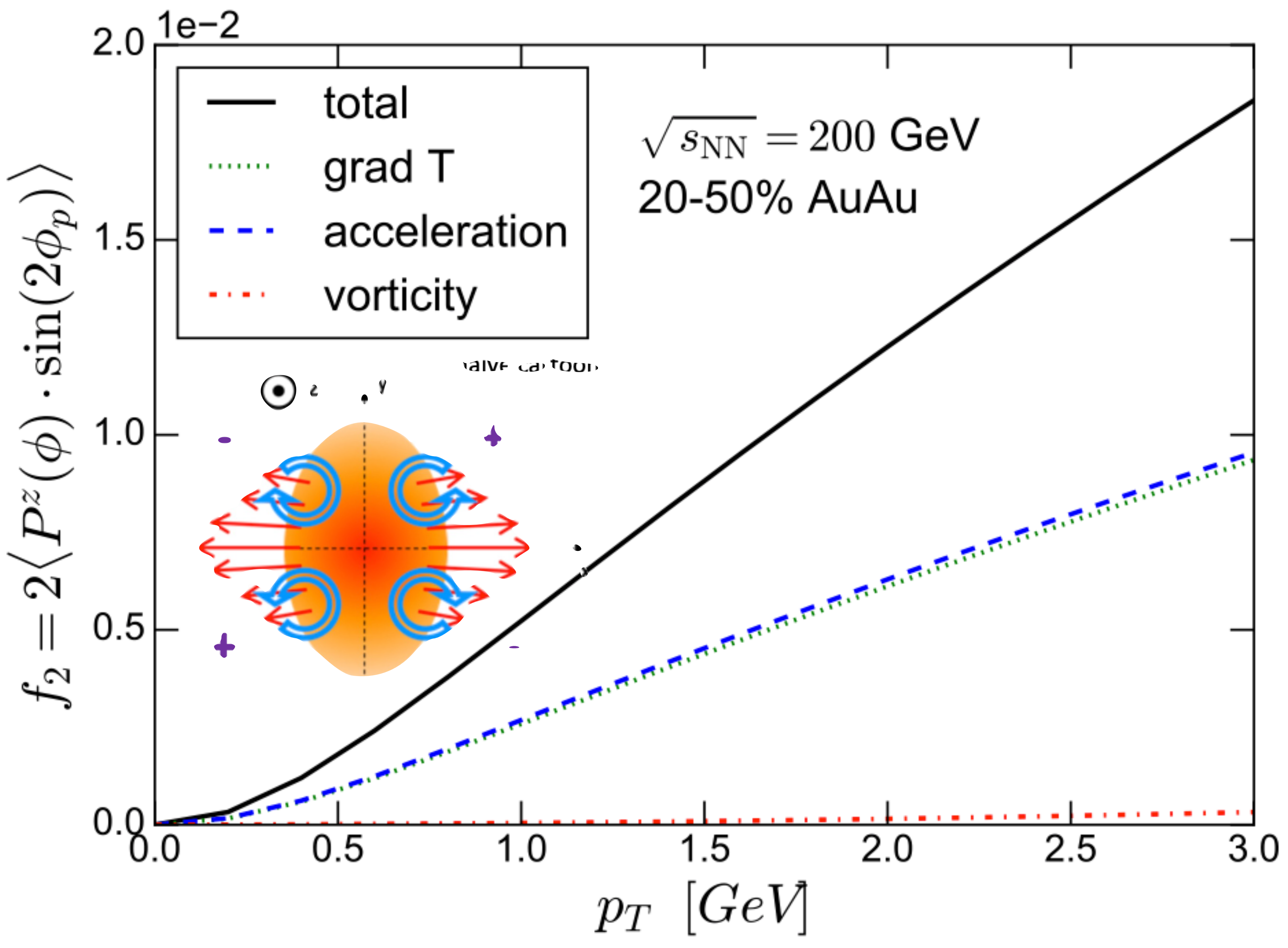
PROBING HYDRODYNAMIC GRADIENTS

$$\omega^{\mu\nu}_{\rm th} = \frac{1}{2T}\left[(\nabla^\nu u^\mu - \nabla^\mu u^\nu) + (u^\nu D u^\mu - u^\mu D u^\nu) - \frac{1}{T}(u^\mu \partial^\nu T - u^\nu \partial^\mu T)\right]$$

flow vorticity | acceleration | temperature grad.

I. Karpenko and F. Becattini, Nucl. Phys. A 982, 519-522 (2019)





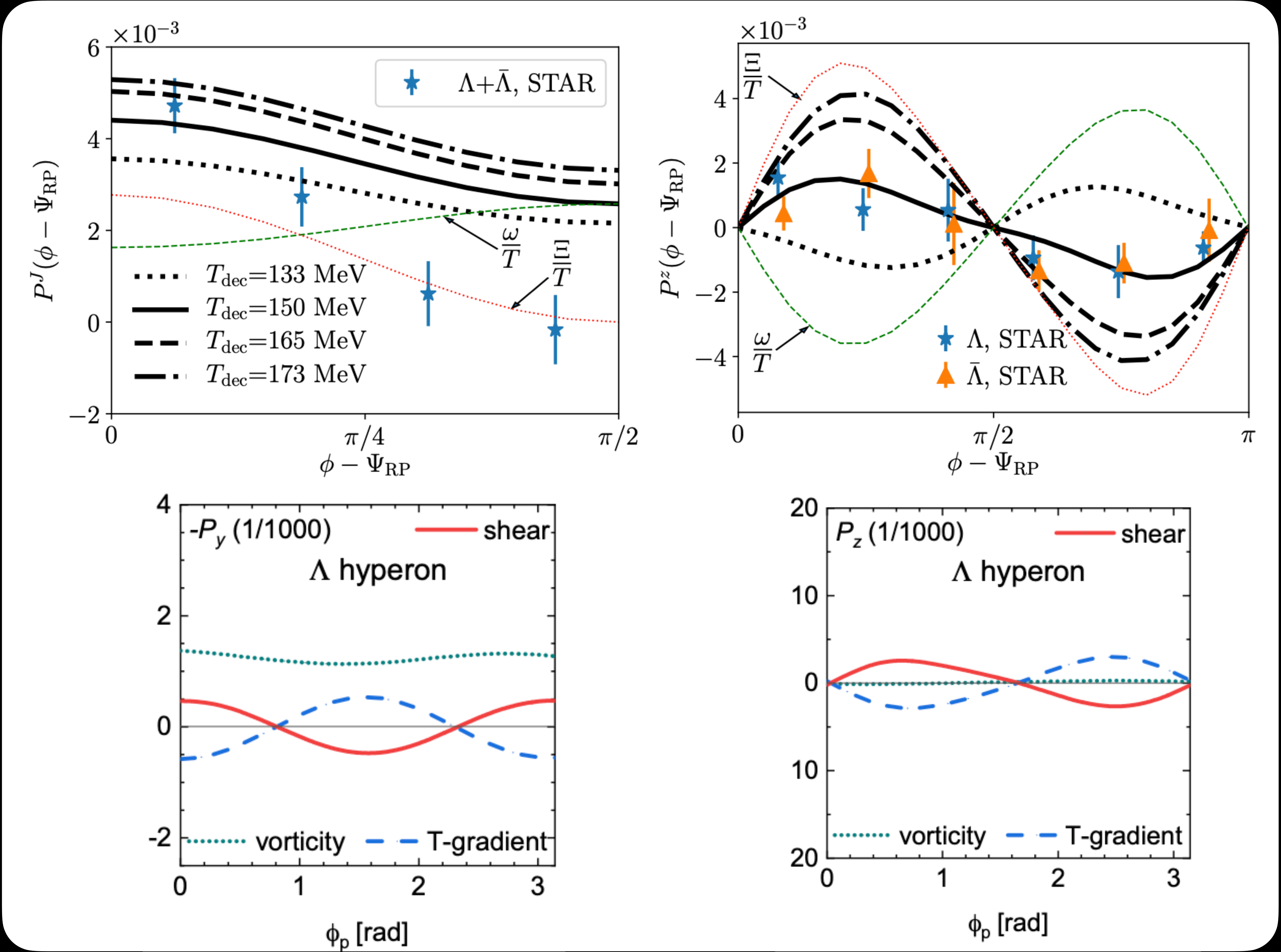
PROBING HYDRODYNAMIC GRADIENTS

F. Becattini, M. Buzzegoli, A. Palermo, G. Inghirami and I. Karpenko, arXiv:2103.14621 [nucl-th]

B. Fu, S. Y. F. Liu, L. Pang, H. Song and Y. Yin, Phys. Rev. Lett. 127, 142301 (2021)

$$(\nabla^\nu u^\mu - \nabla^\mu u^\nu)p_\nu$$
$$+(u^\nu D u^\mu - u^\mu D u^\nu)p_\nu$$
$$-\frac{1}{T}(u^\mu \partial^\nu T - u^\nu \partial^\mu T)p_\nu$$
$$+\frac{\beta}{E}\epsilon^{\mu\nu\alpha\lambda}u_\nu p_\alpha p^\beta \sigma_{\beta\lambda}$$

- The shear term gives significantly to the azimuthal dependence



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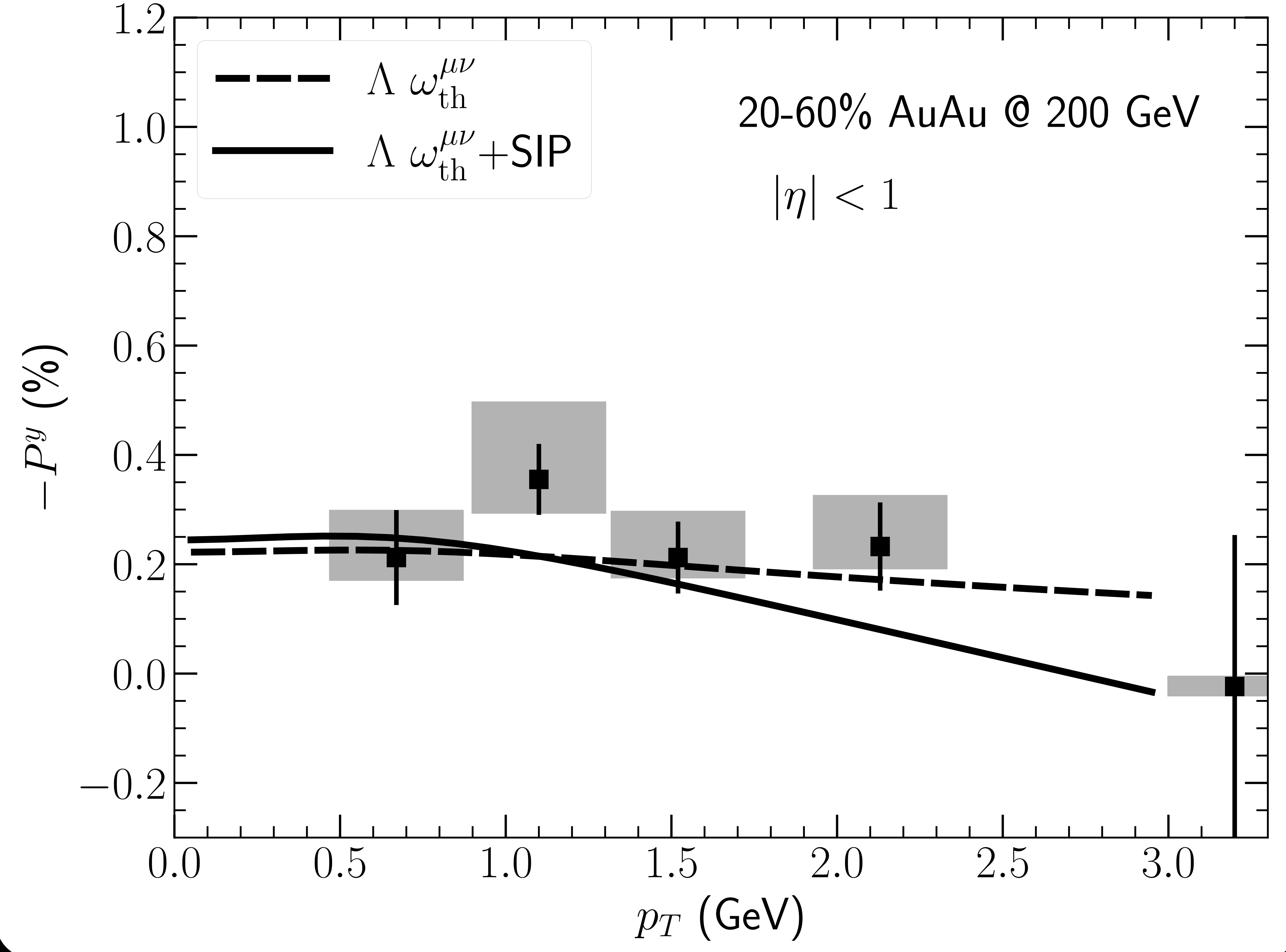
S. Ryu, V. Jupic and C. Shen, arXiv:2106.08125 [nucl-th]



- The shear term grows quadratically with p_T
- Measurements of P^y_Λ at high p_T can provide crucial constraints

PROBING HYDRODYNAMIC GRADIENTS

S. Liu and Y. Yin, Phys. Rev. D104, 054043 (2021); JHEP07, 188 (2021)
C. Yi, S. Pu and D. L. Yang, arXiv:2106.00238 [hep-ph]
Y. C. Liu and X. G. Huang, arXiv:2109.15301 [nucl-th]

$$-\frac{b_i}{E}\epsilon^{\mu\nu\alpha\lambda}u_\nu p_\alpha \partial_\lambda(\beta\mu_B)$$

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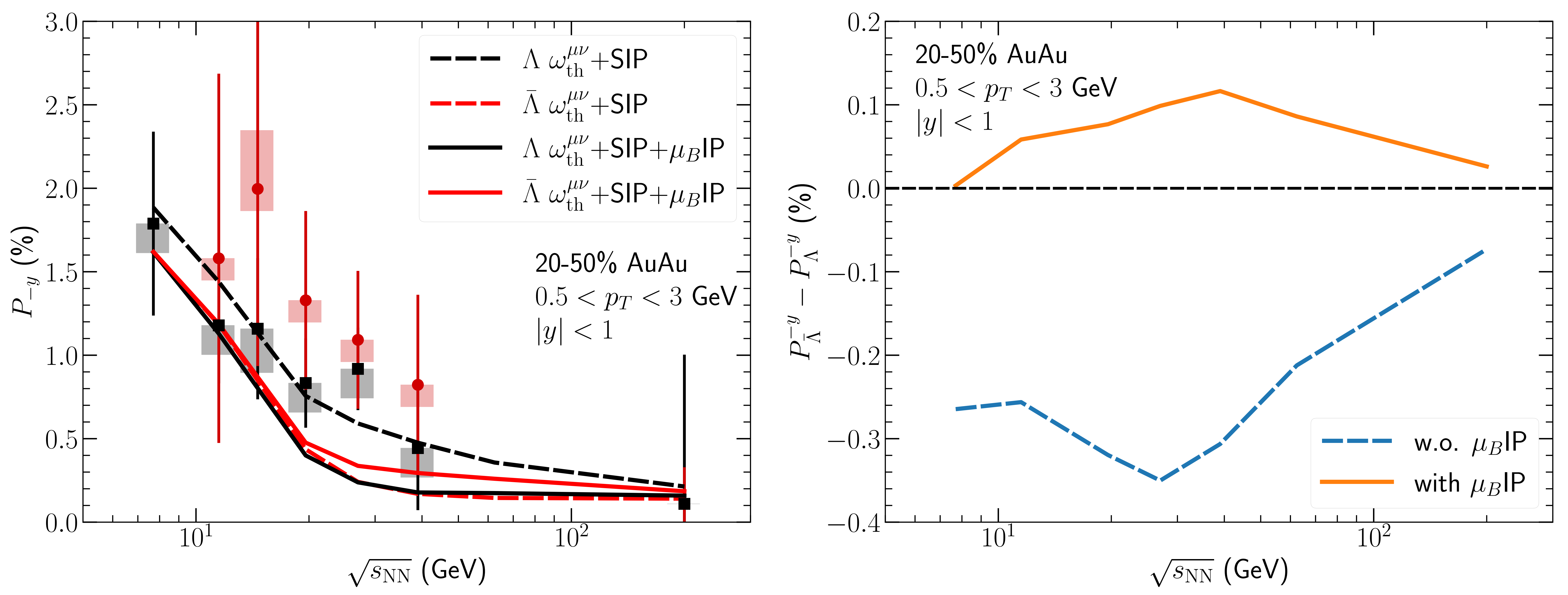
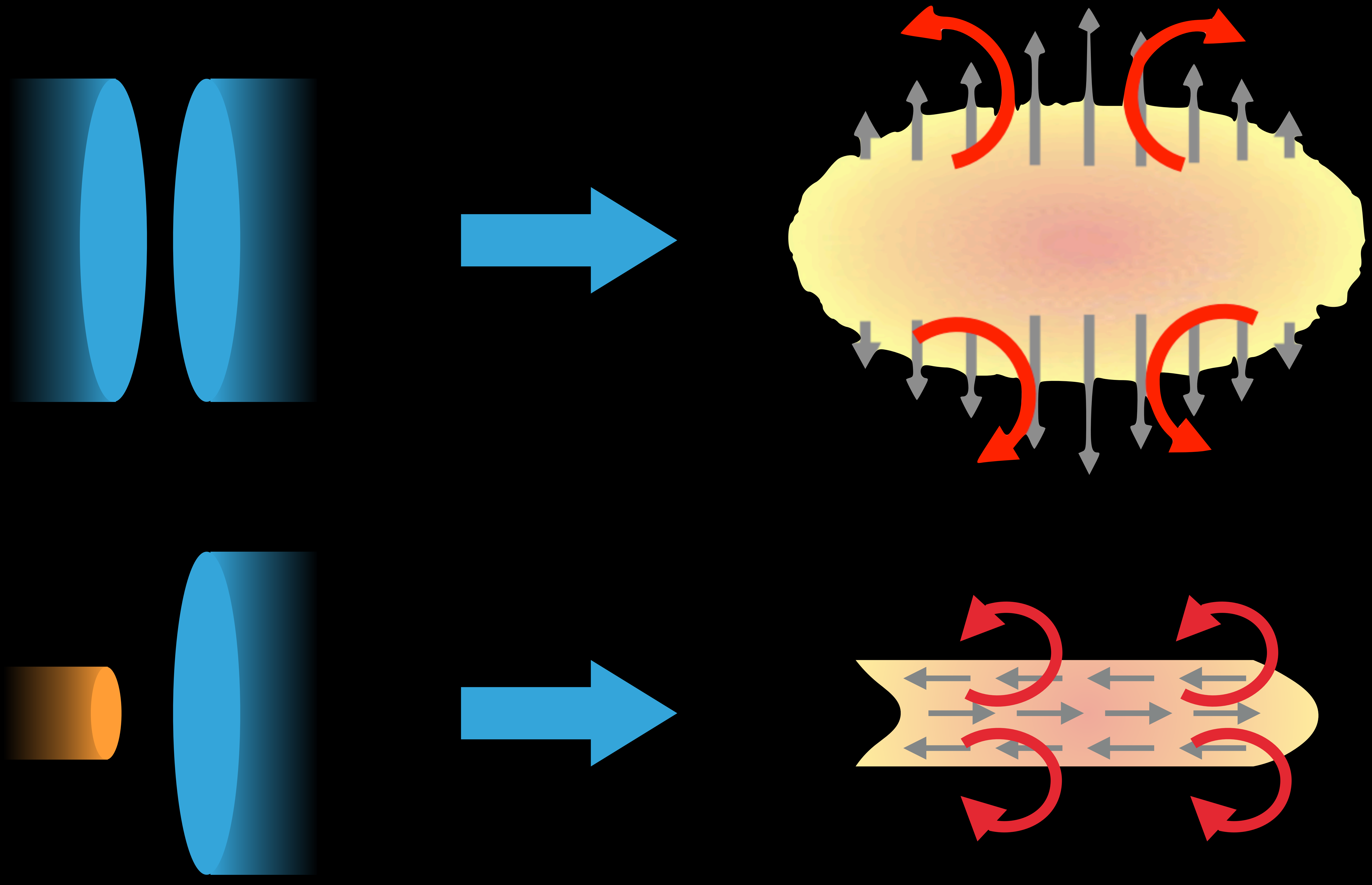
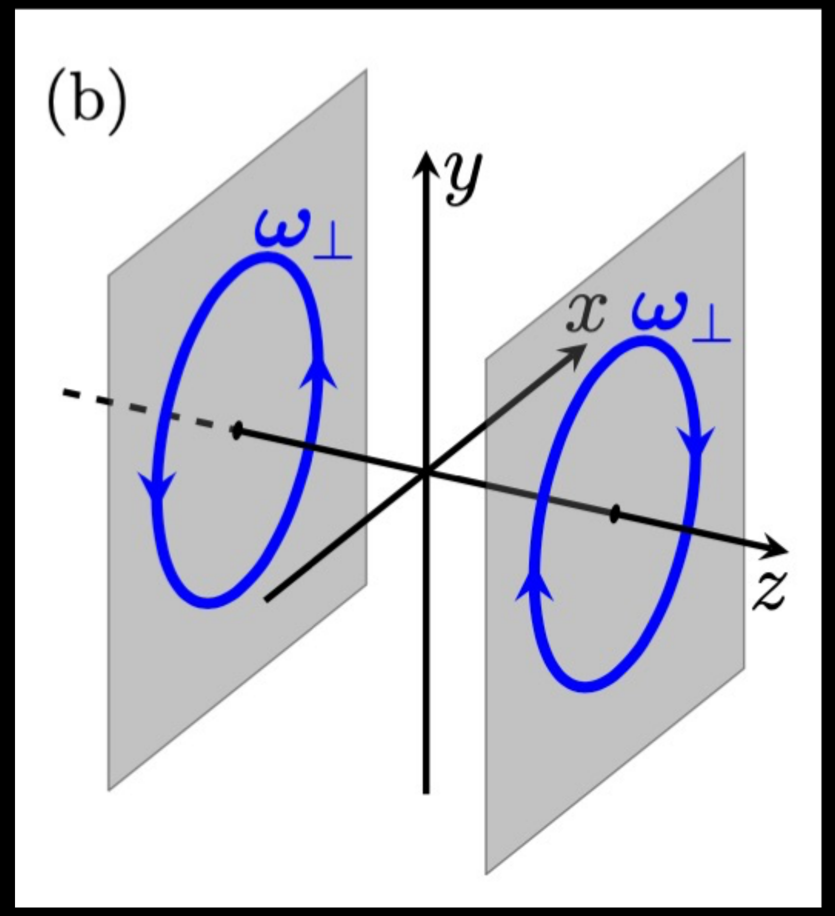


- The μ_B gradient induced polarization flips the difference between P^y_Λ and $p^y_{\bar\Lambda}$, competing with the magnetic field's splitting effects

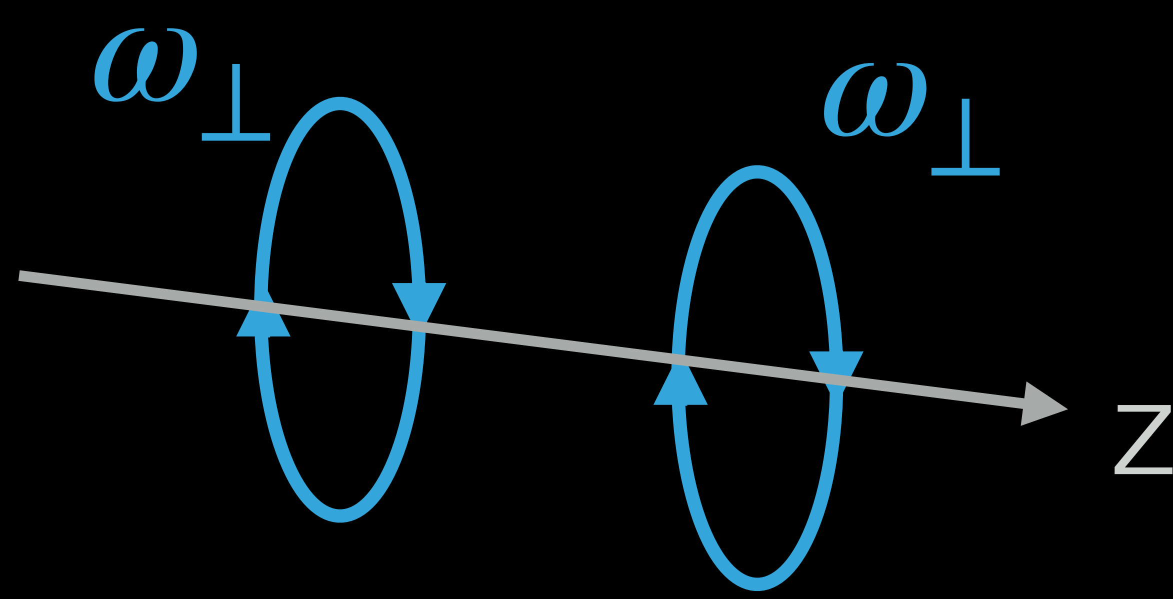
LOOKING FOR NEW VORTICAL STRUCTURES

Xia, Li, Tang, Wang PRC 98, 024905 (2018)





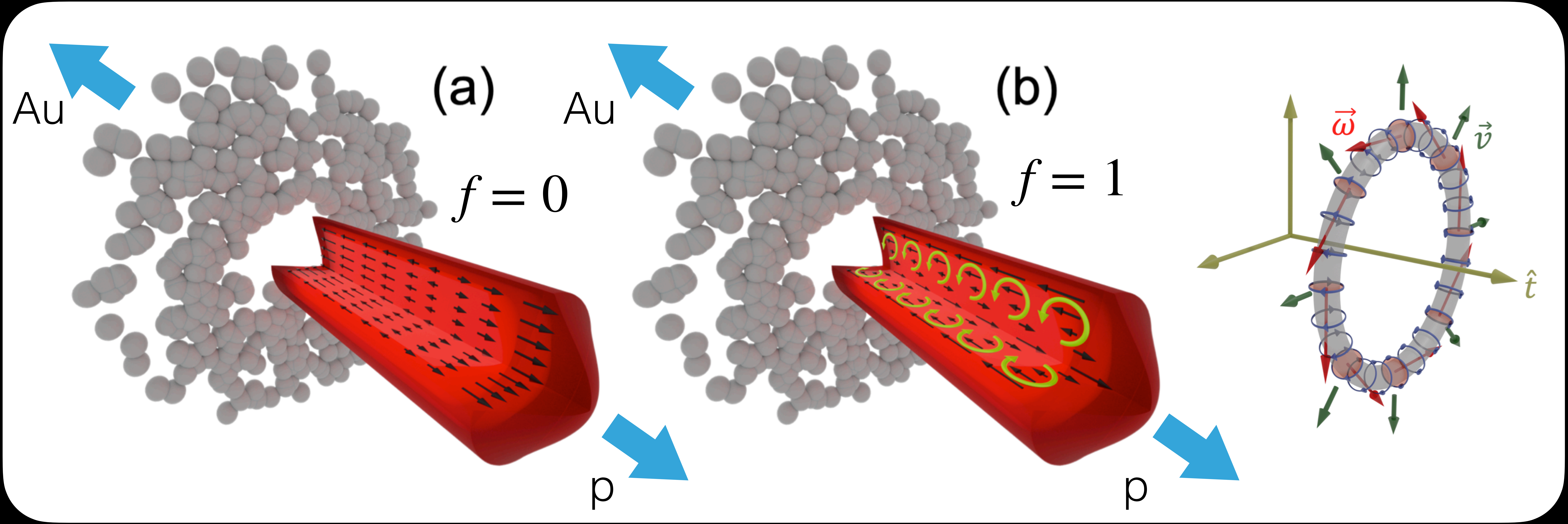
Rapidity odd



Rapidity even

LOOKING FORWARD IN SMALL SYSTEMS

M. Lisa, J. Barbon, D. Chinellato, W. Serenone, C. Shen, J. Takahashi and G. Torrieri, Phys. Rev. C104, 011901 (2021)



- As a proton drills through the Au nucleus, a vortical ring of vorticity distribution could be present at early-time

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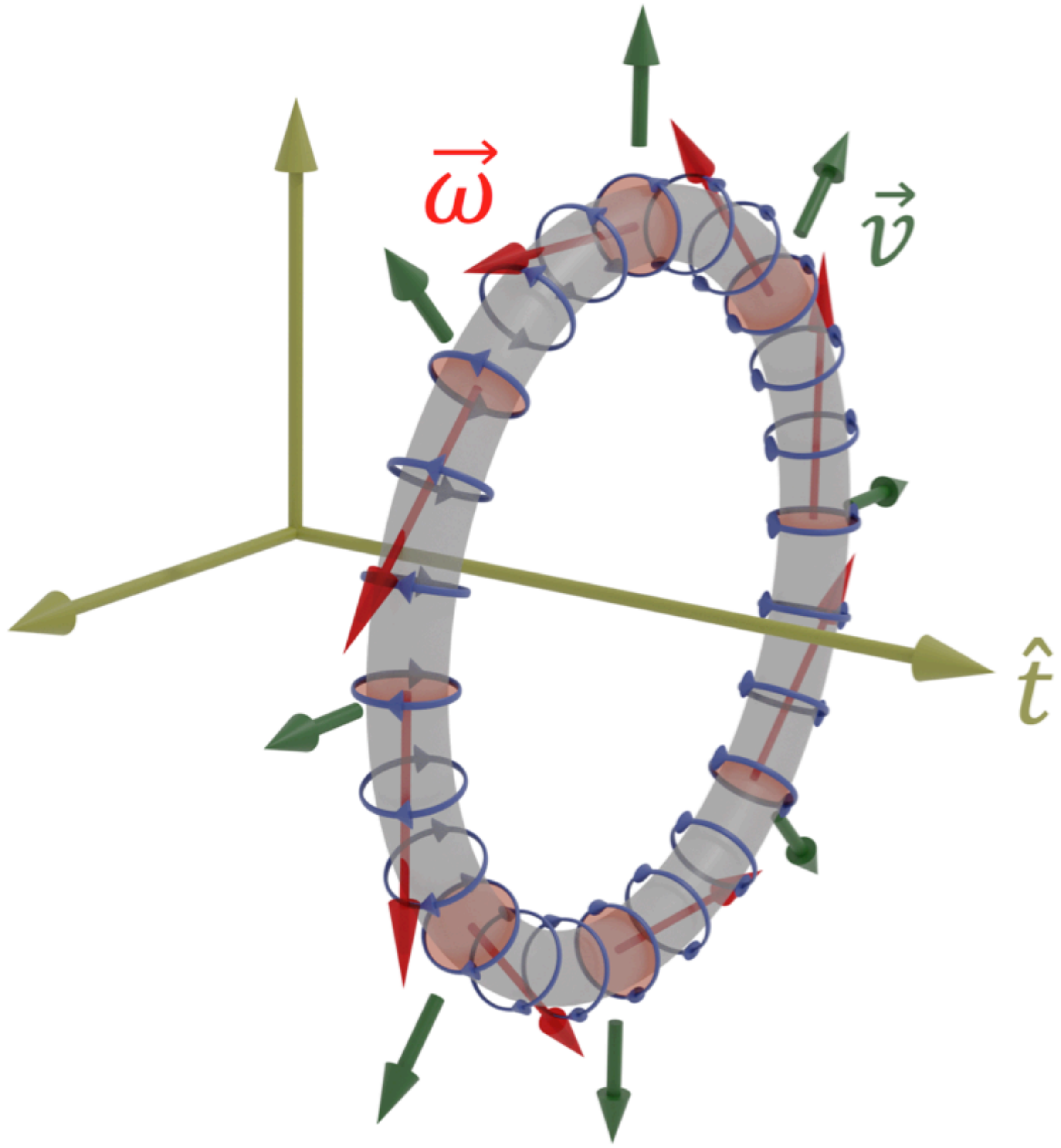

The vortex ring structure can be characterized by a triple-product scalar,

$$R^{\hat{z}}_{\rm fluid} = \left\langle \frac{\vec{\omega} \cdot (\hat{z} \times \vec{v})}{\hat{z} \times \vec{v}} \right\rangle_{\phi}$$

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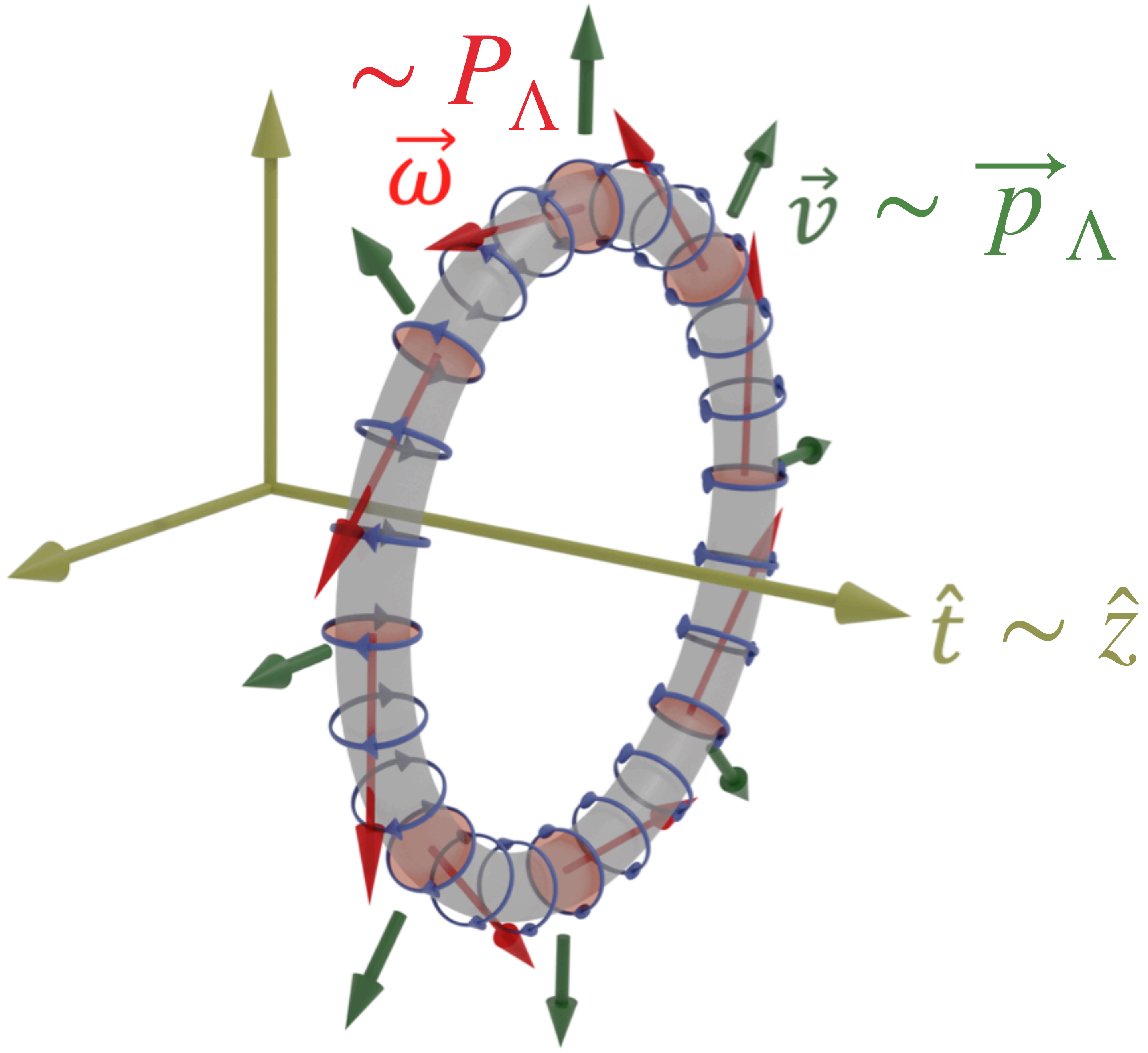

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$$R^{\hat{z}}_{\Lambda} = \left\langle \frac{P_\Lambda \cdot (\hat{z} \times \overrightarrow{p}_\Lambda)}{\hat{z} \times \overrightarrow{p}_\Lambda} \right\rangle_\phi$$

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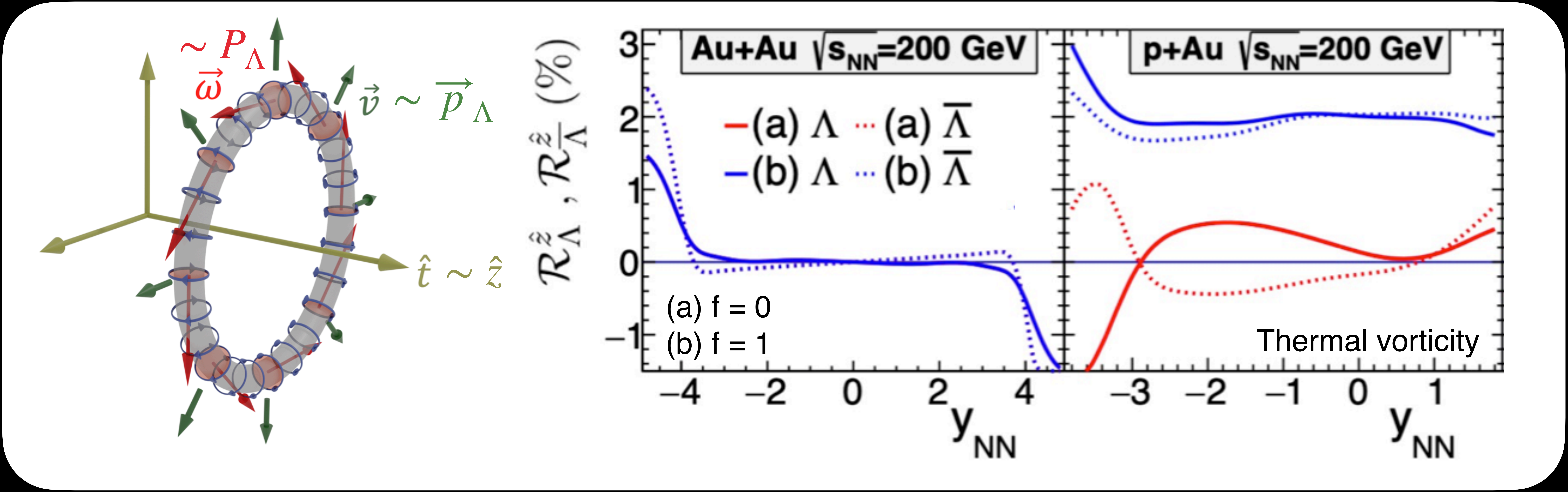
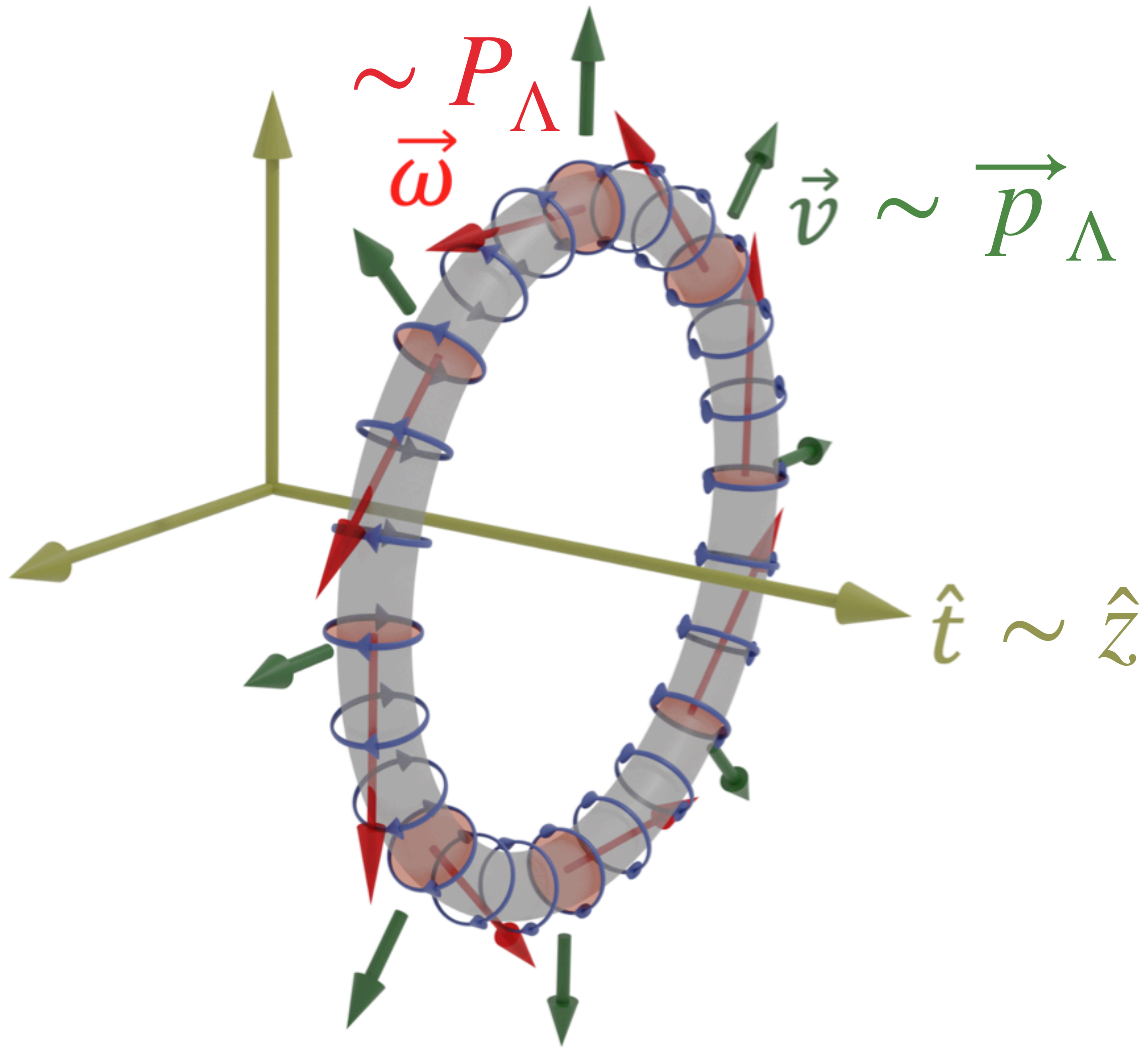


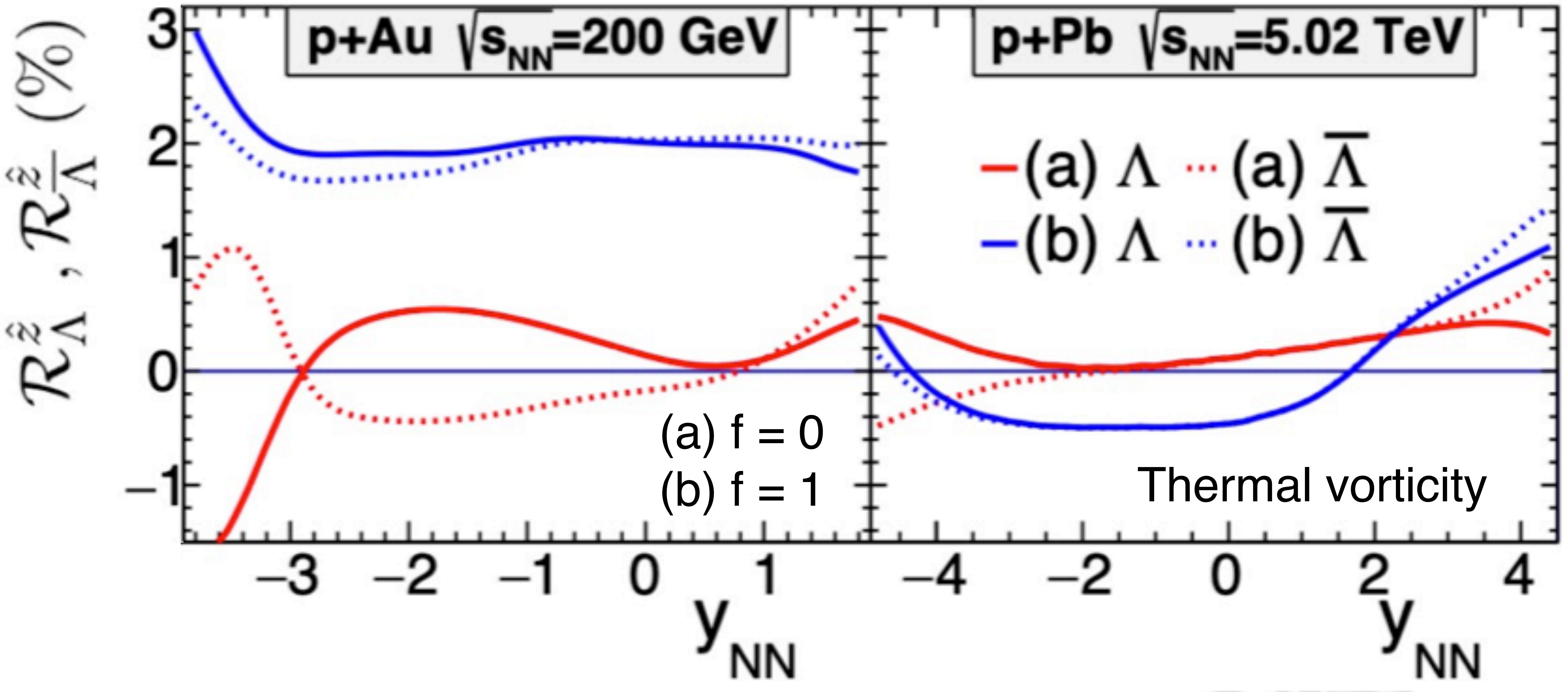
$$R^{\hat{z}}_\Lambda = \left\langle \frac{P_\Lambda \cdot (\hat{z} \times \vec{p}_\Lambda)}{\hat{z} \times \vec{p}_\Lambda} \right\rangle_\phi$$

- A strong longitudinal flow at early-time leads to a positive $R^{\hat{z}}_\Lambda$ in p+Au collisions at RHIC
- $R^{\hat{z}}_\Lambda$ is mainly driven by the flow vorticity

LOOKING FORWARD IN SMALL SYSTEMS

M. Lisa, J. Barbon, D. Chinellato, W. Serenone, C. Shen, J. Takahashi and G. Torrieri, Phys. Rev. C104, 011901 (2021)



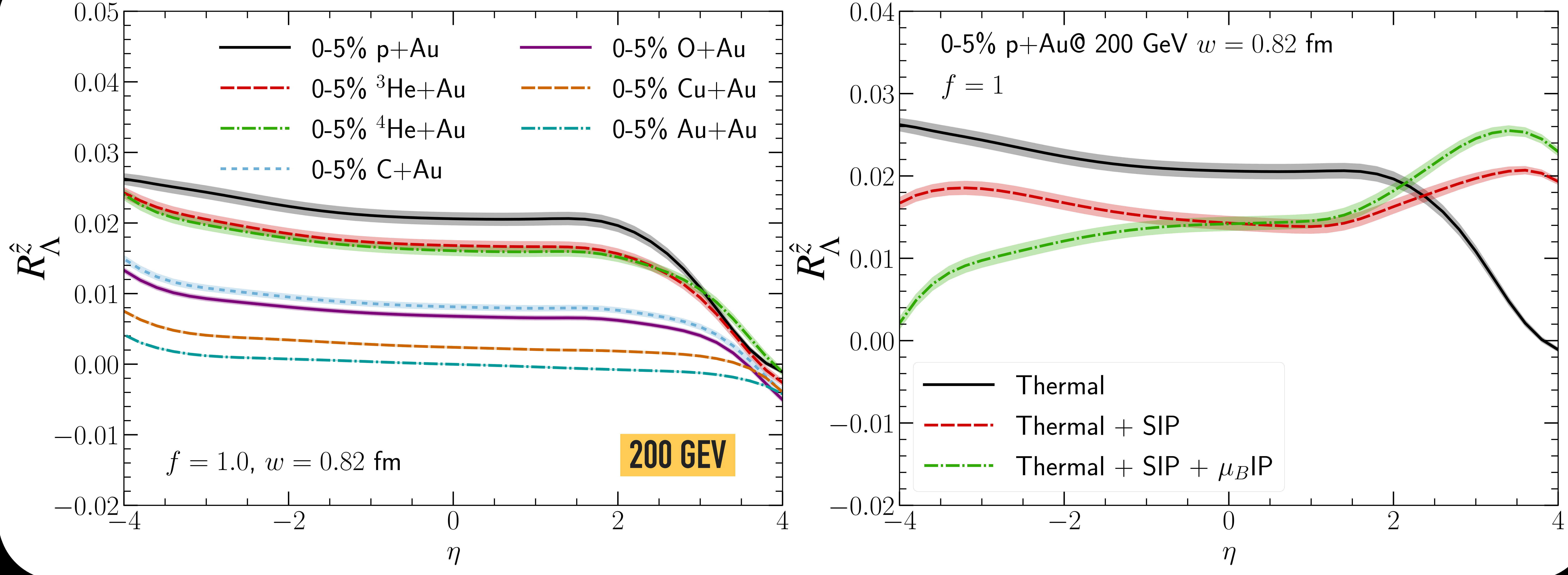


$$R^{\hat{z}}_{\Lambda} = \left\langle \frac{P_\Lambda \cdot (\hat{z} \times \overrightarrow{p}_\Lambda)}{\hat{z} \times \overrightarrow{p}_\Lambda} \right\rangle_\phi$$

- A strong transverse expansion in p+Pb collisions at LHC reverse the hydrodynamic vortex structure

LOOKING FORWARD IN SMALL SYSTEMS

J. Barbon, D. Chinellato, M. Lisa, W. Serenone, C. Shen, J. Takahashi and G. Torrieri, in preparation



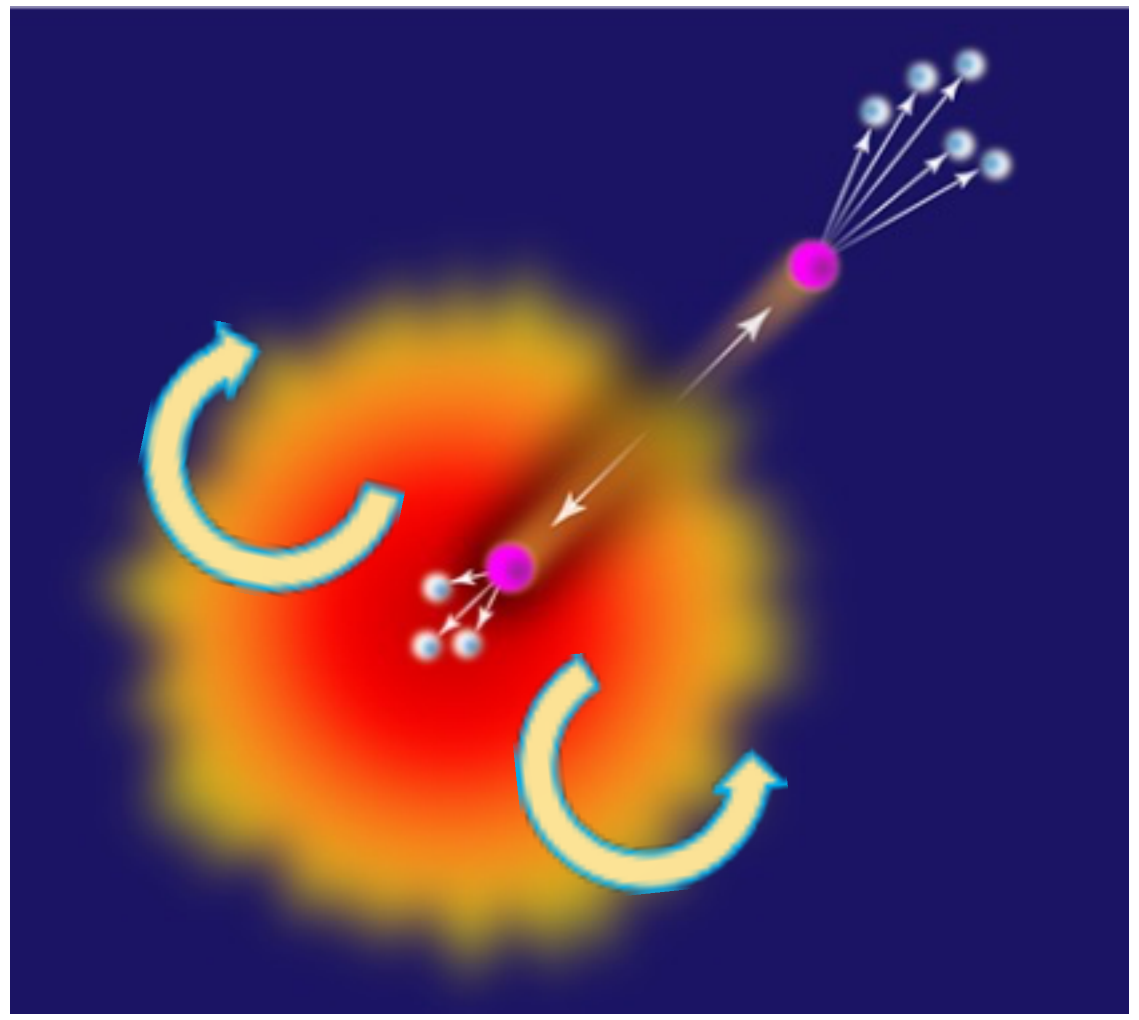
$$R_\Lambda^{\hat{z}} = \left\langle \frac{P_\Lambda \cdot (\hat{z} \times \overrightarrow{p}_\Lambda)}{\hat{z} \times \overrightarrow{p}_\Lambda} \right\rangle_\phi$$

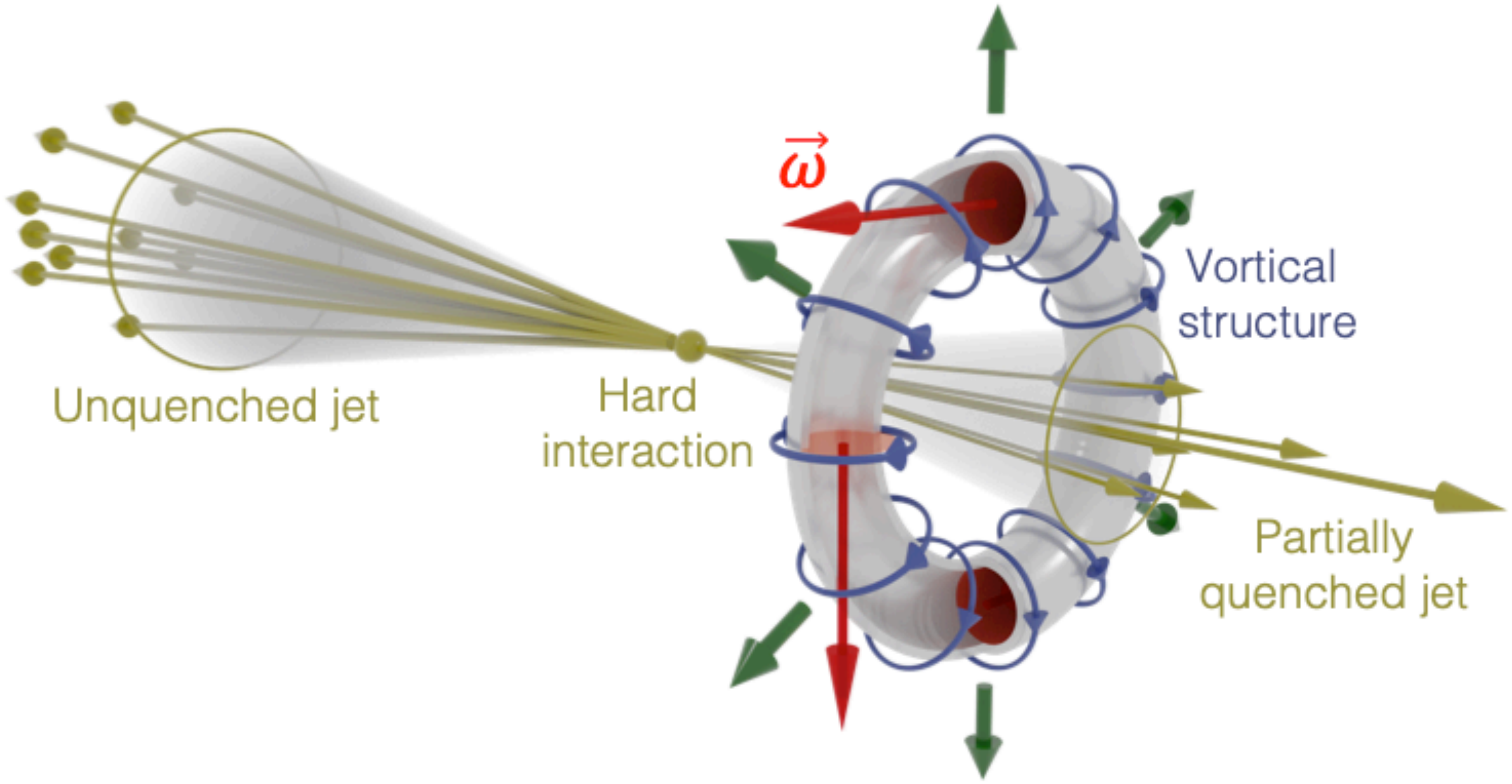
- A system-size study of $R_\Lambda^{\hat{z}}$ in asymmetric event-by-event collisions at RHIC is under way
- Thermal vorticity gives the main contribution to $R_\Lambda^{\hat{z}}$ at mid-rapidity

VORTEX RING EXCITED BY A QCD JET

Y. Tachibana and T. Hirano, Nucl. Phys. A 904-905, 1023c-1026c (2013)

W. Serenone, J. Barbon, D. Chinellato, M. Lisa, C. Shen, J. Takahashi, G. Torrieri, Phys. Lett. B 820 (2021) 136500

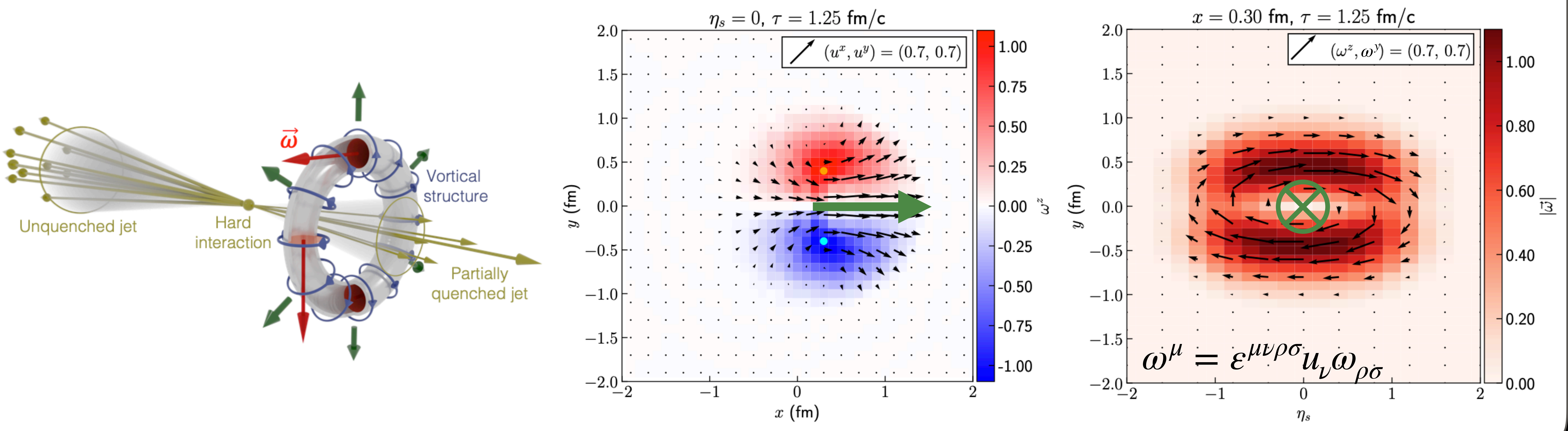




- The (partially) quenched jet deposits energy-momentum into medium and excites vortical flow pattern along its trajectory

VORTEX RING EXCITED BY A QCD JET

W. Serenone, J. Barbon, D. Chinellato, M. Lisa, C. Shen, J. Takahashi, G. Torrieri, Phys. Lett. B 820 (2021) 136500



- The deposited energy-momentum current from a jet traveling along the +x direction induce a vortex-ring distribution for the fluid vorticity vector
- This velocity distribution is tagged by Λ's polarization

VORTEX RING EXCITED BY A QCD JET

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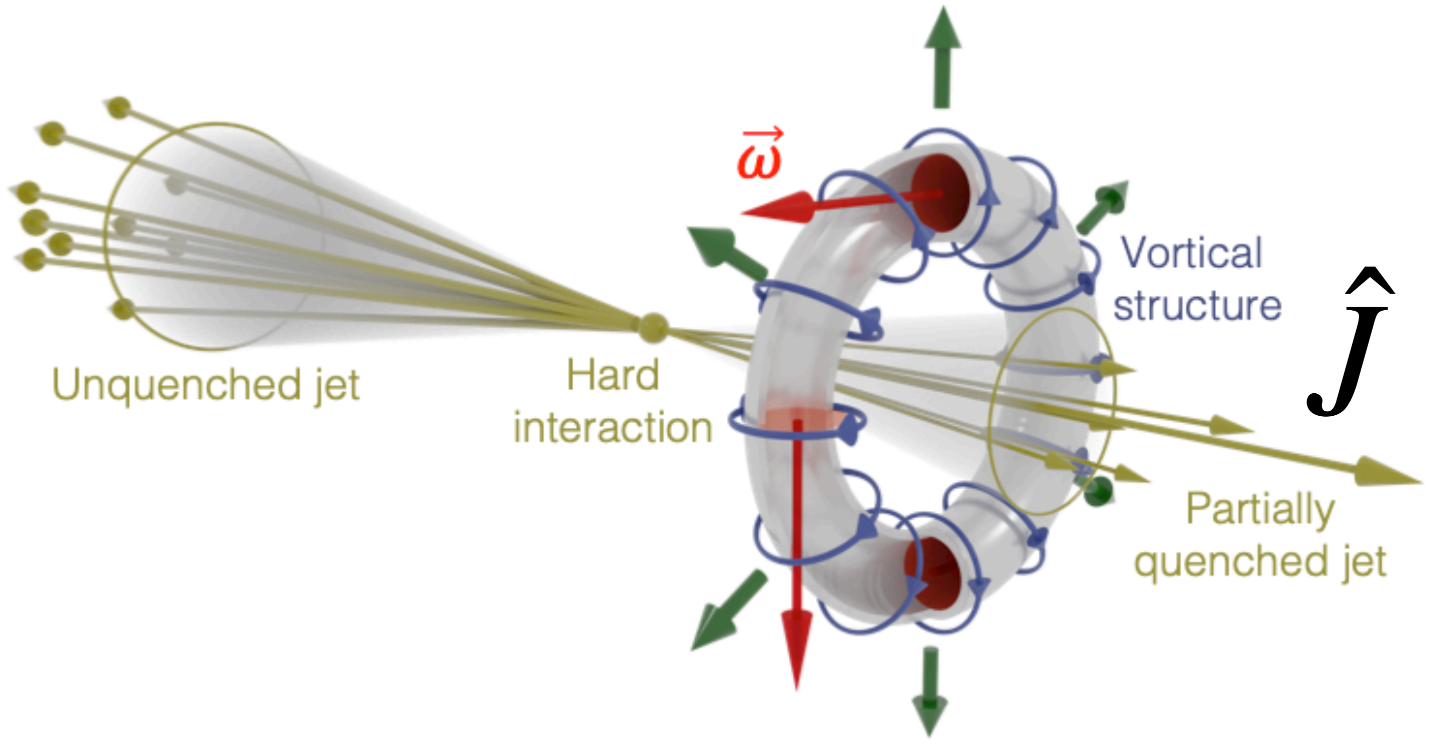

$$R_\Lambda^{\hat{J}} = \left\langle \frac{P_\Lambda \cdot (\hat{J} \times \overrightarrow{p}_\Lambda)}{\hat{J} \times \overrightarrow{p}_\Lambda} \right\rangle_\phi$$

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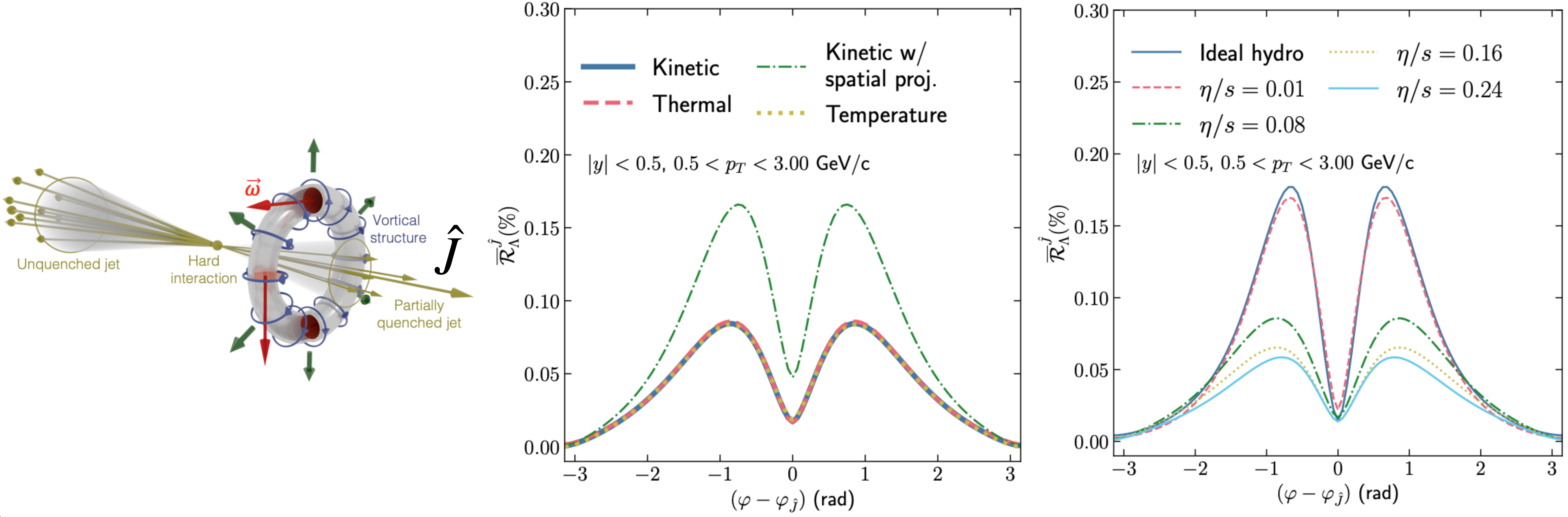

$$R_\Lambda^{\hat{J}} = \left\langle \frac{P_\Lambda \cdot (\hat{J} \times \vec{p}_\Lambda)}{\hat{J} \times \vec{p}_\Lambda} \right\rangle_\phi$$

- The $R_\Lambda^{\hat{J}}$ is mainly driven by flow vorticity and acceleration
- $R_\Lambda^{\hat{J}}$ shows a strong sensitivity to the medium viscosity

SUMMARY

- Polarization measurements have pushed heavy-ion phenomenology to a full 3D era; They provide valuable information about the fluid gradients and role of orbital angular momentum
- The newly proposed vortex-ring structure of polarization vectors can probe **early-stage longitudinal dynamics** as well as **jet-medium interactions**
- The vortical flow pattern is present in a variety of forms in the simulations of heavy-ion collisions; Studying multiple observables together will verify the OAM-vorticity-spin paradigm and offer constraints on the QGP properties

➡ RBRC Workshop **"Physics opportunities from the RHIC Isobar run"** Jan 25-28, 2022

Organizers: Jiangyong Jia (Stony Brook), Chun Shen (Wayne State/RBRC), Derek Teaney (Stony Brook), and Zhangbu Xu (BNL)