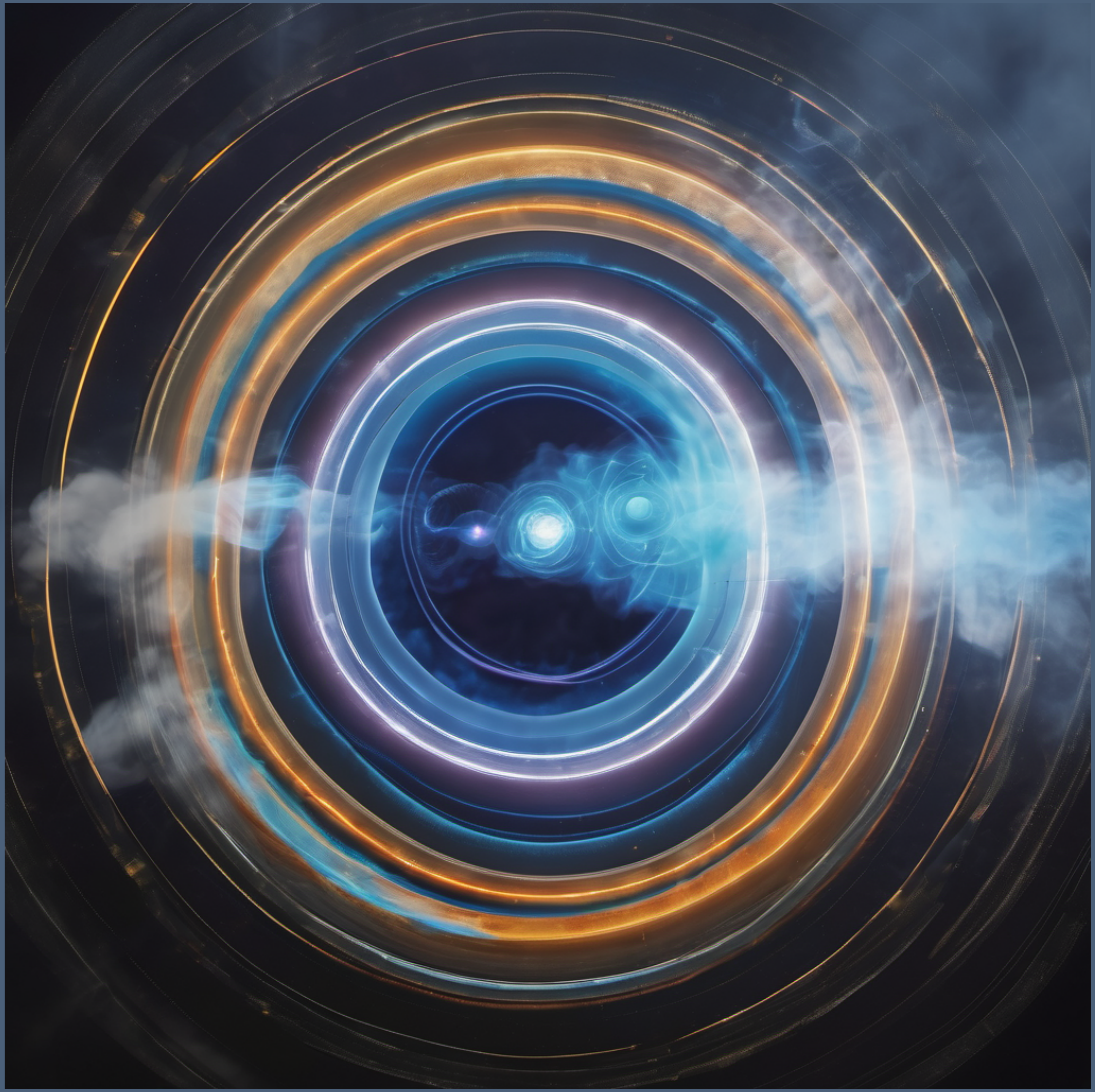
INSTITUTE for NUCLEAR THEORY

Heavy Ion Physics in the EIC Era

Toroidal Vorticity

Smoke rings of nuclear matter



Maria Stefaniak

The Ohio State University

Already enjoyed some "local" activities

Olympic National Park

Already enjoyed some
“local” activities

Olympic National Park

But now, it is time to move to physics!

Motivation

Presence of collectivity in "smaller" systems: pA ?

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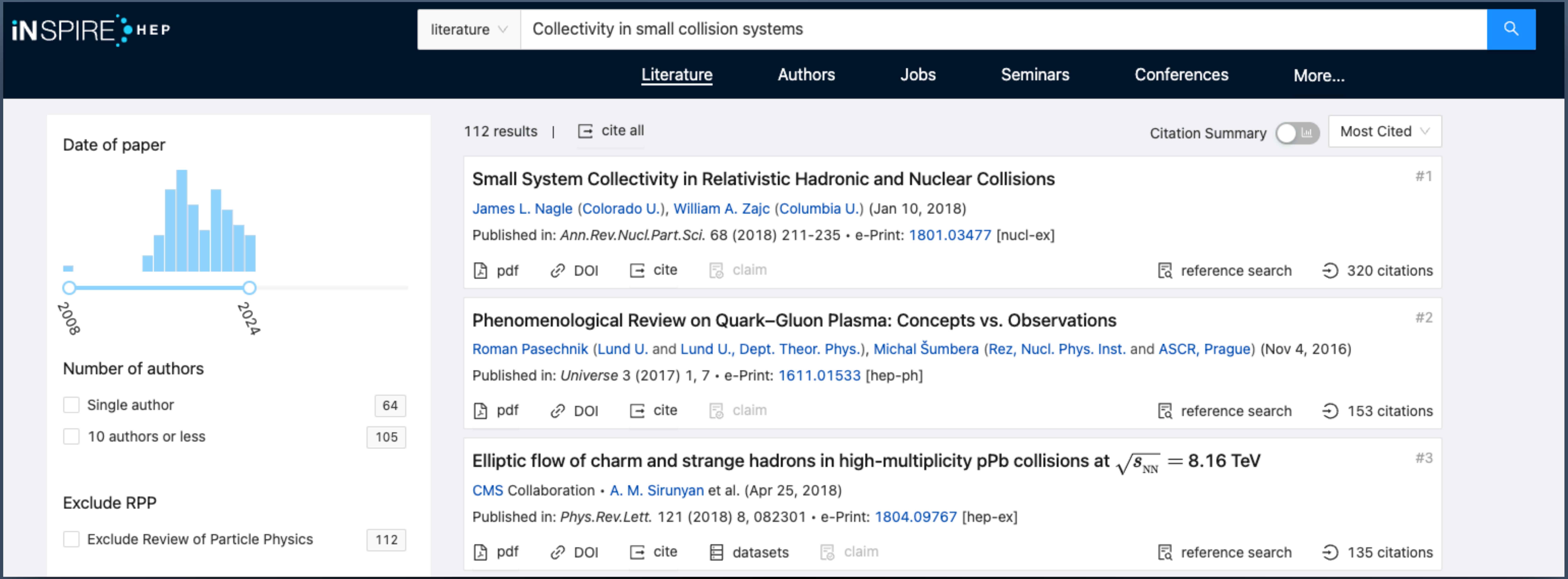

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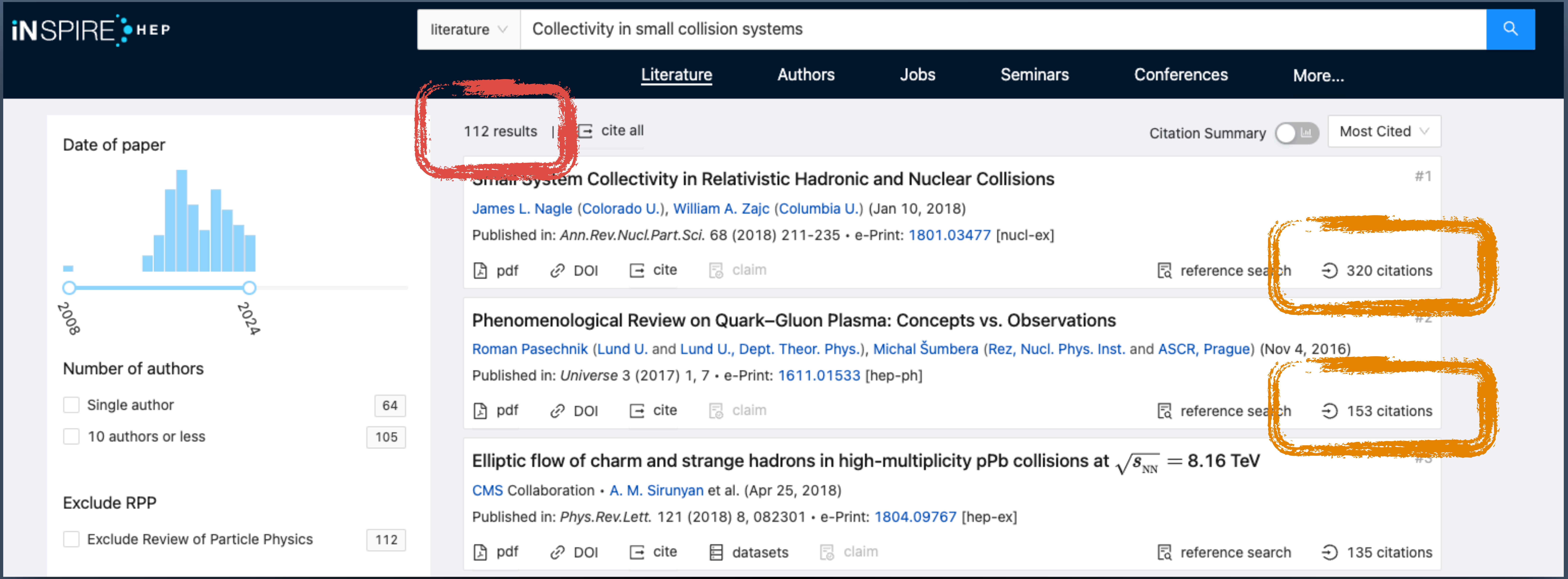
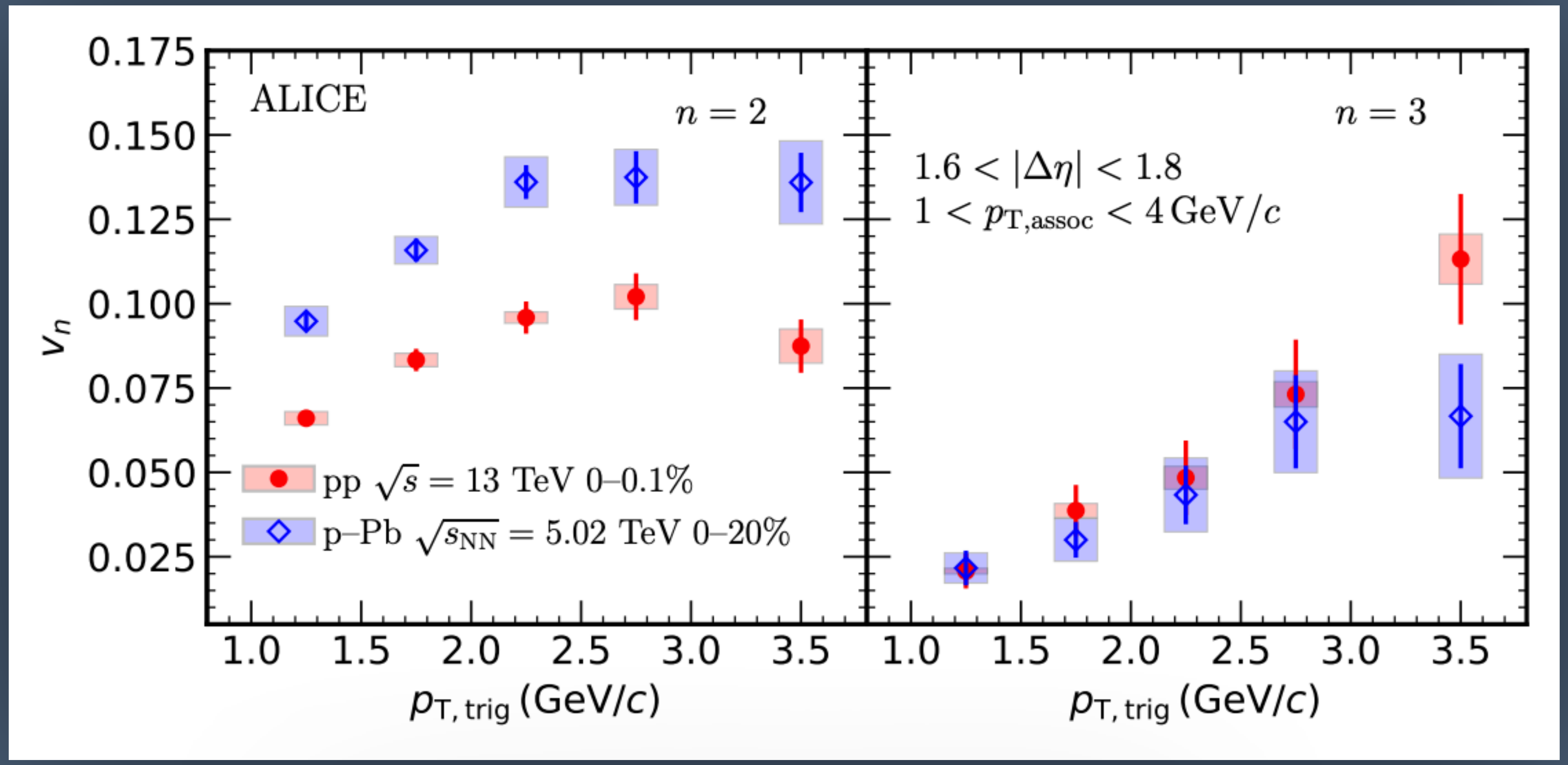


Motivation

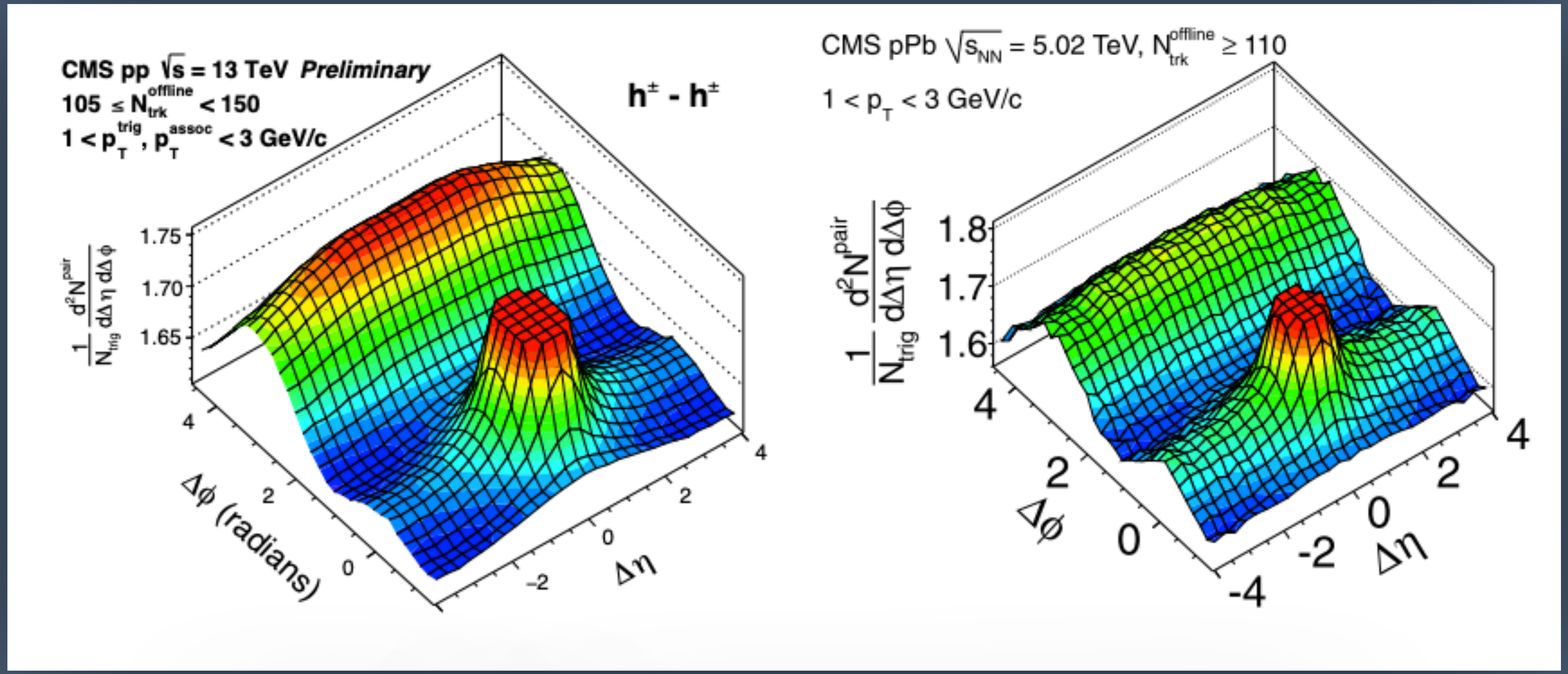
Presence of collectivity in "smaller" systems: pA ?

Non-zero v_n in p+Pb collisions



ALICE: JHEP 2403 (2024) 092

"Ridge structure" in pp and pPb collisions



CMS Collaboration, Phys.Lett. B718, 795 (2013)
CMS Collaboration, Phys. Rev. Lett. 116, 172302 (2016)
CMS Collaboration, Eur. Phys. J. C72, 2012 (2012)

Motivation

Presence of collectivity in “smaller” systems: pA ?

Hydrodynamic flow in small systems

or: “How the heck is it possible that a system emitting only a dozen particles can be described by fluid dynamics?”

Ulrich Heinz[1a], in collaboration with J. Scott Moreland[b]
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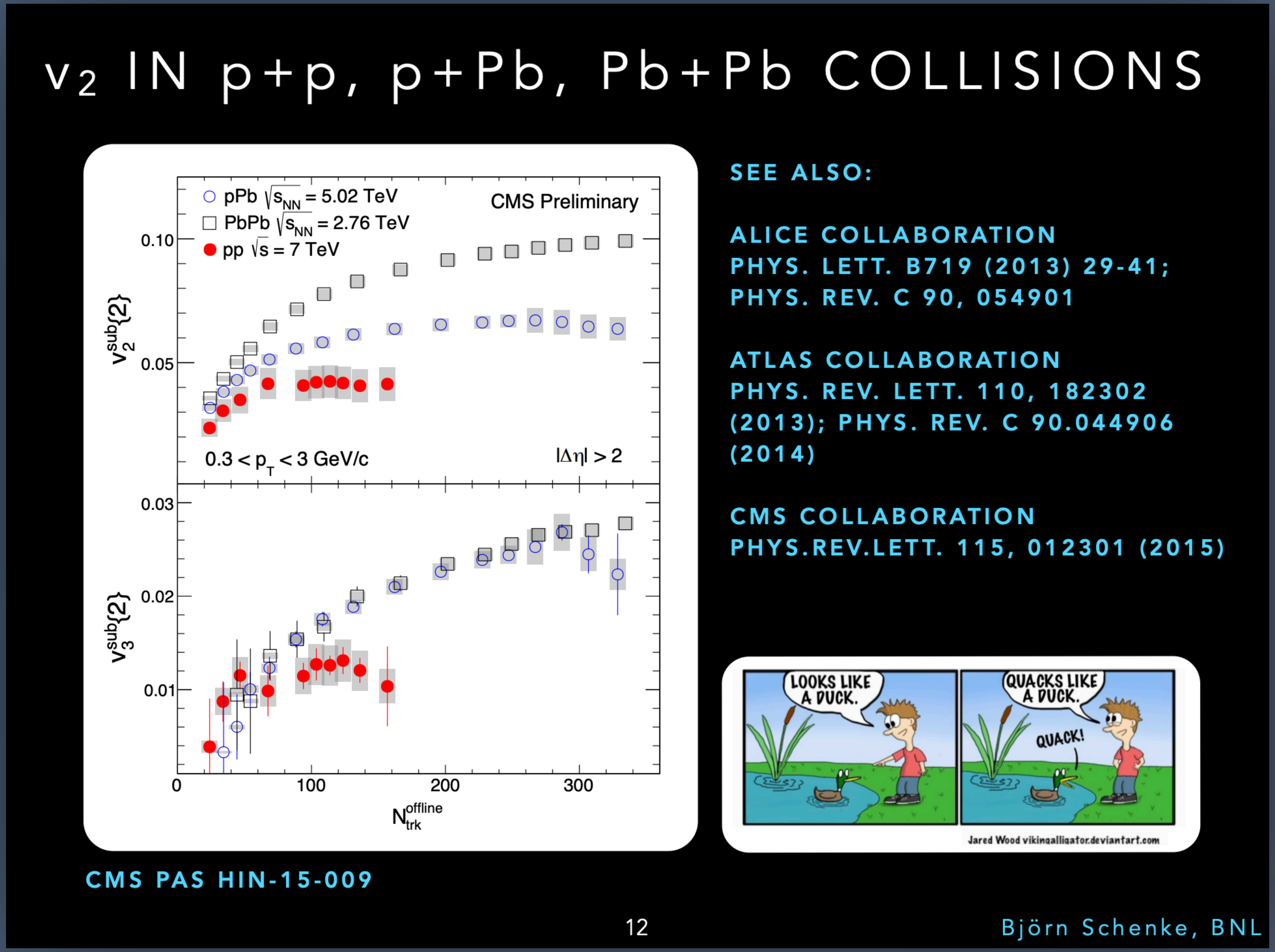
E-mail: heinz.9@osu.edu

IOP Conf. Series: Journal of Physics: Conf. Series 1271 (2019) 012018



LHCP 2018

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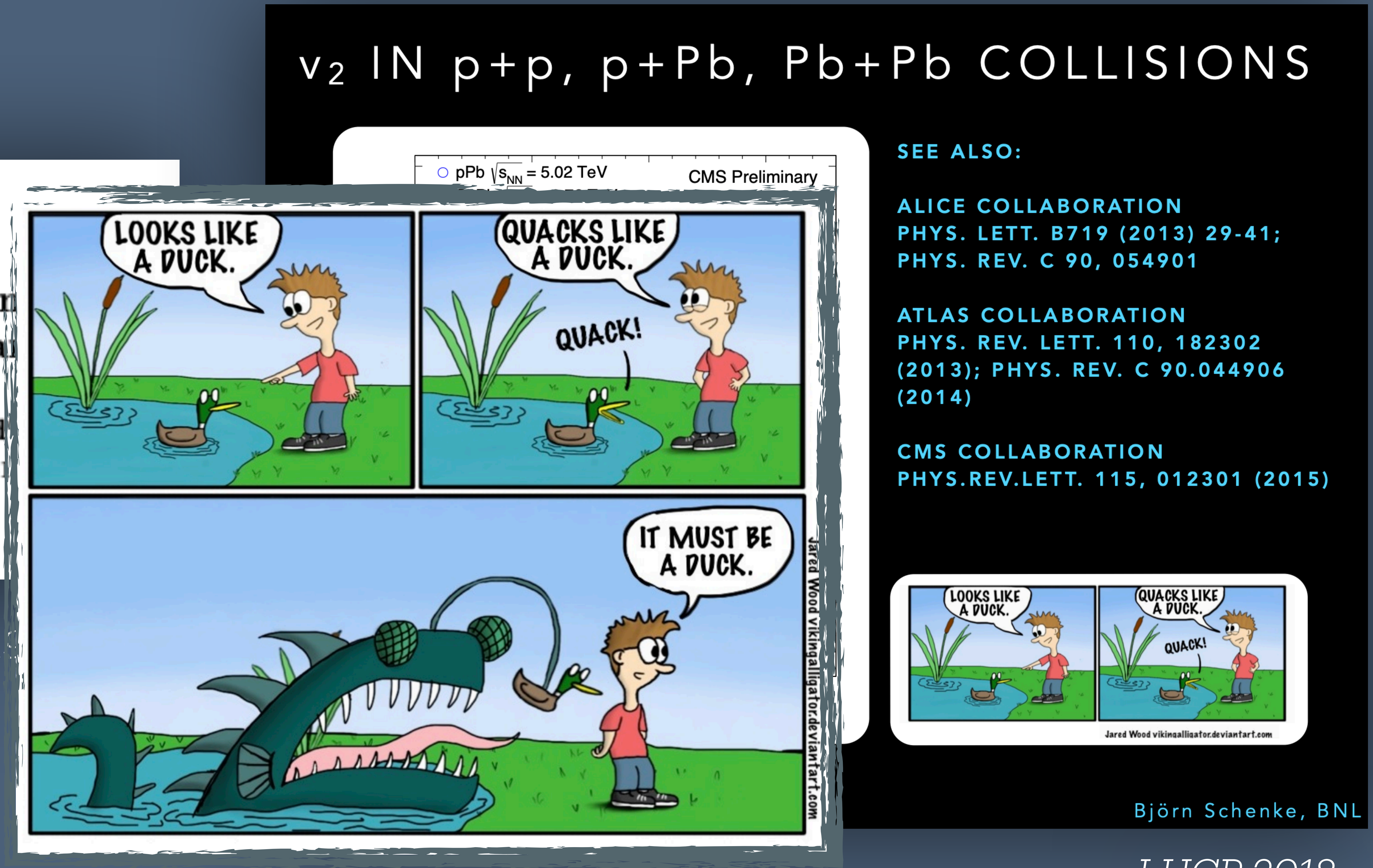
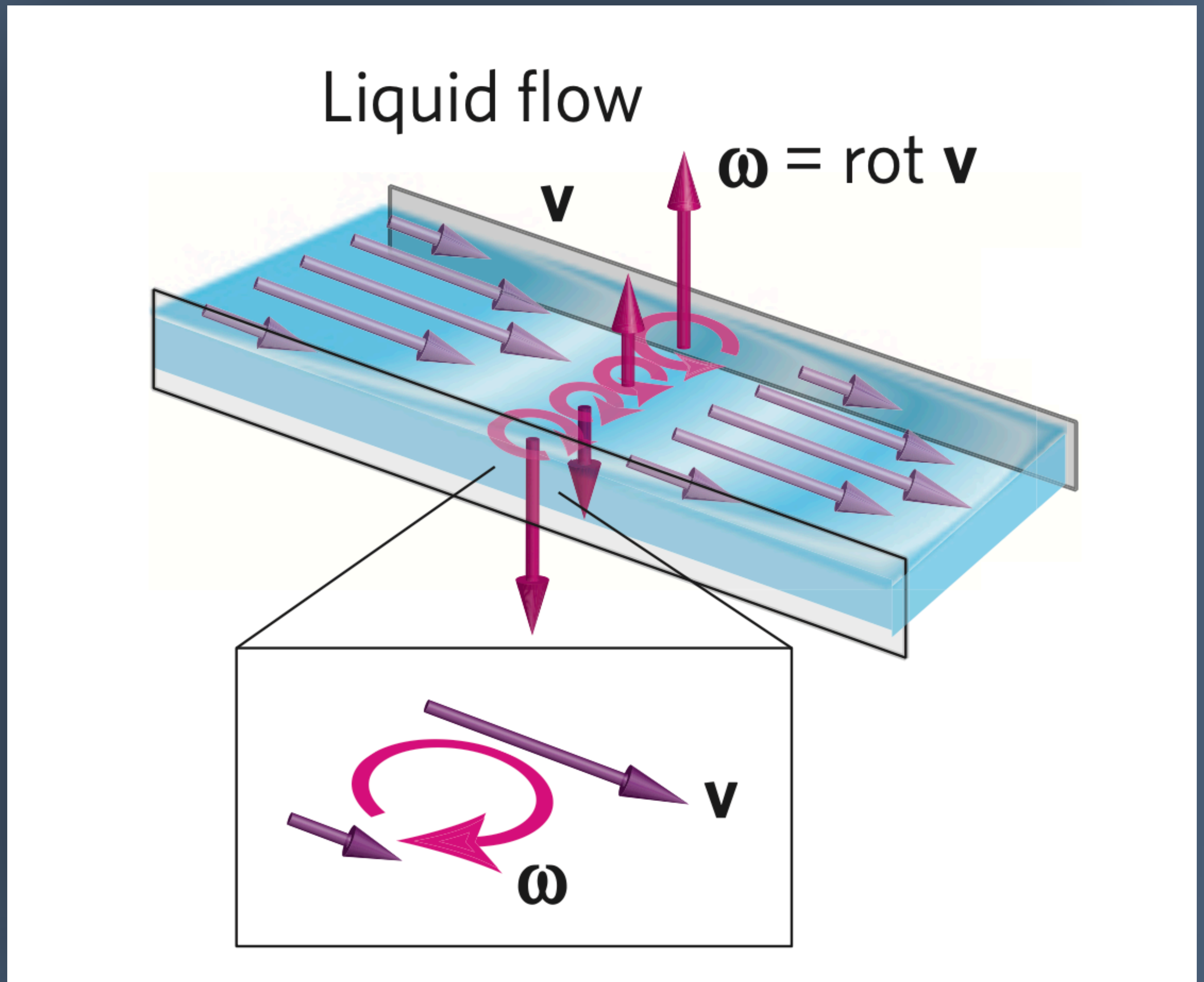


LHCP 2018

Another way to probe a fluid:

Vorticity



Takahashi: Nature Physics 12, 52-56 (2016)

- **Vorticity** represents local mechanical rotation of fluid

$$\vec{\omega}_{NR} = \frac{1}{2}\vec{\nabla} \times \vec{v}$$

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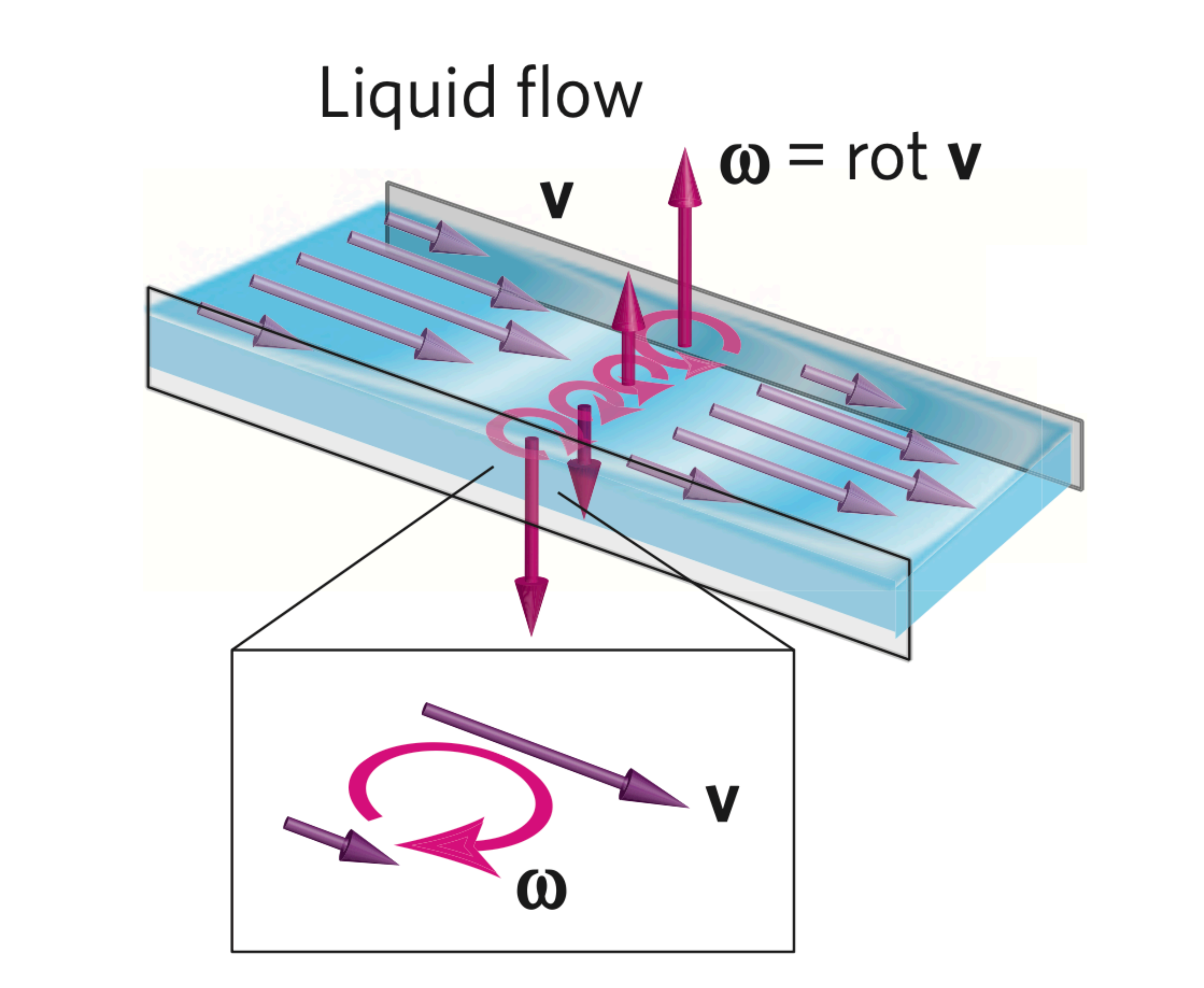


Takahashi: Nature Physics 12, 52-56 (2016)

- **Vorticity** represents local mechanical rotation of fluid

$$\vec{\omega}_{NR} = \frac{1}{2}\vec{\nabla} \times \vec{v}$$

- **Vorticity** is a spin-current source.

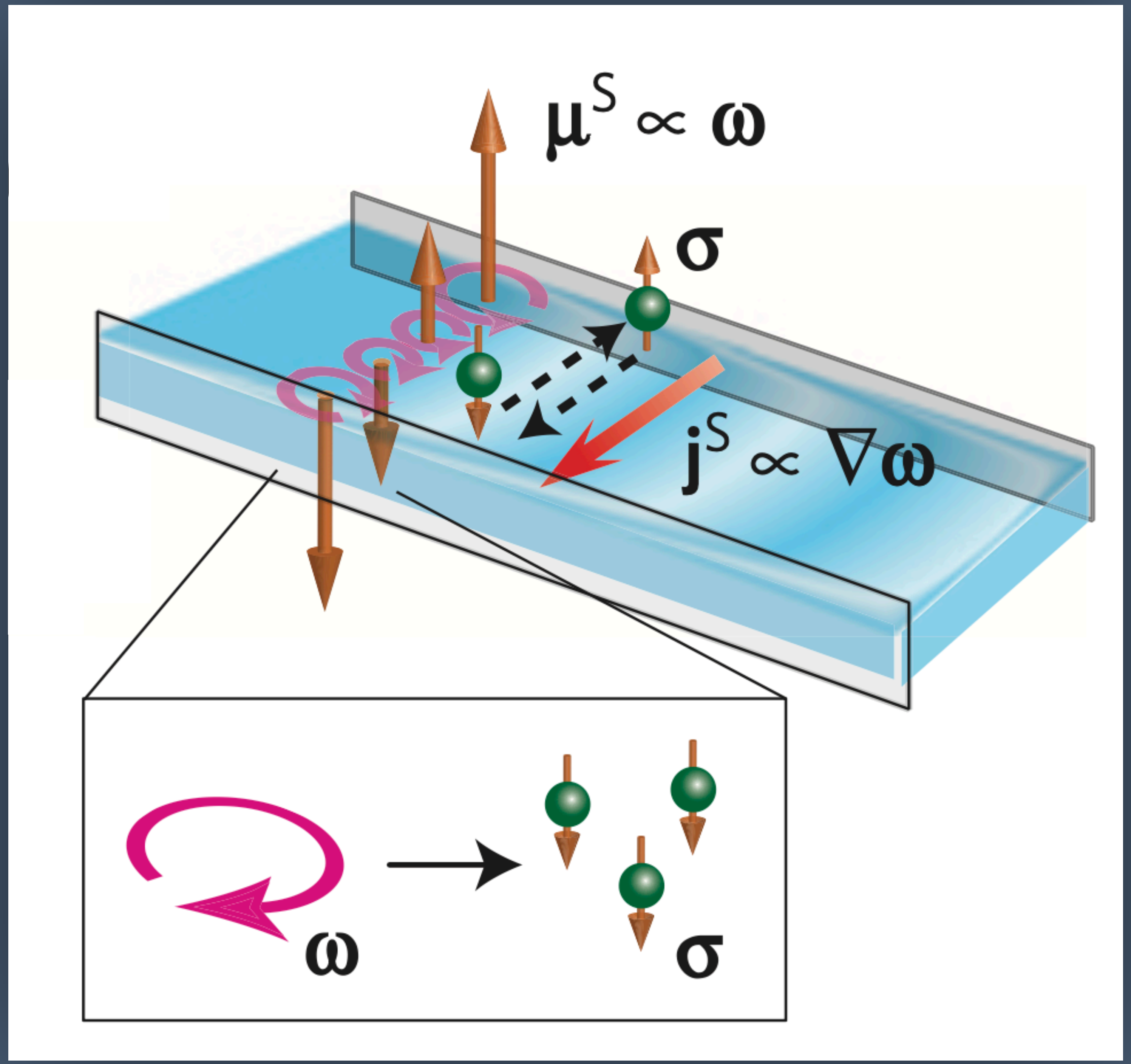
$$\nabla^2 \mu^s = \frac{1}{\lambda}\mu^s - \frac{4e^2}{\sigma_0 \hbar}\xi\omega$$

μ^s - spin voltage

λ - spin-diffusion lenght

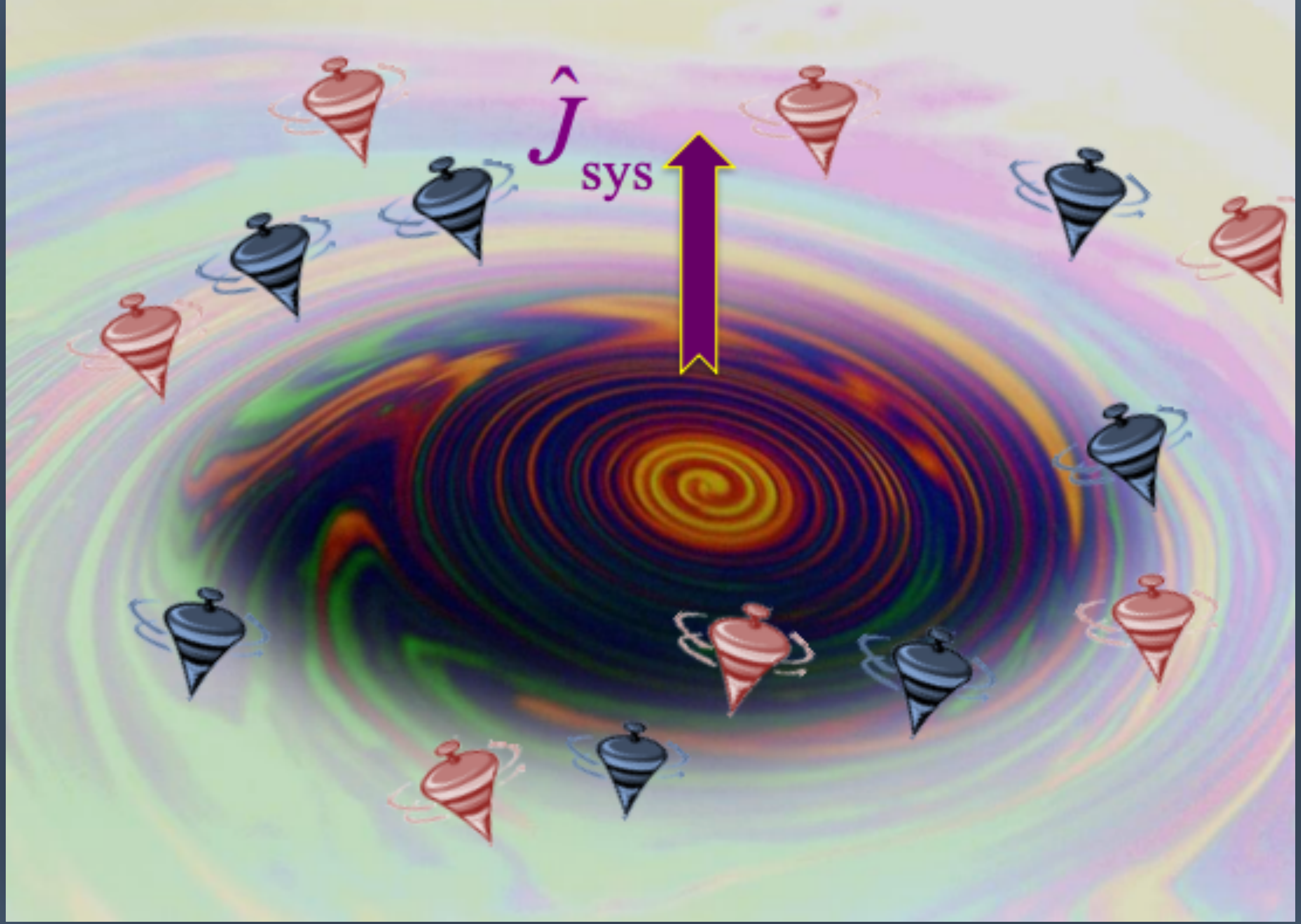
σ_0 - electric conductivity

ξ- related to fluid viscosity caused by angular-momentum tranfser



Vorticity

Fig by Mike Lisa



Possible to measure via polarization!

Vorticity

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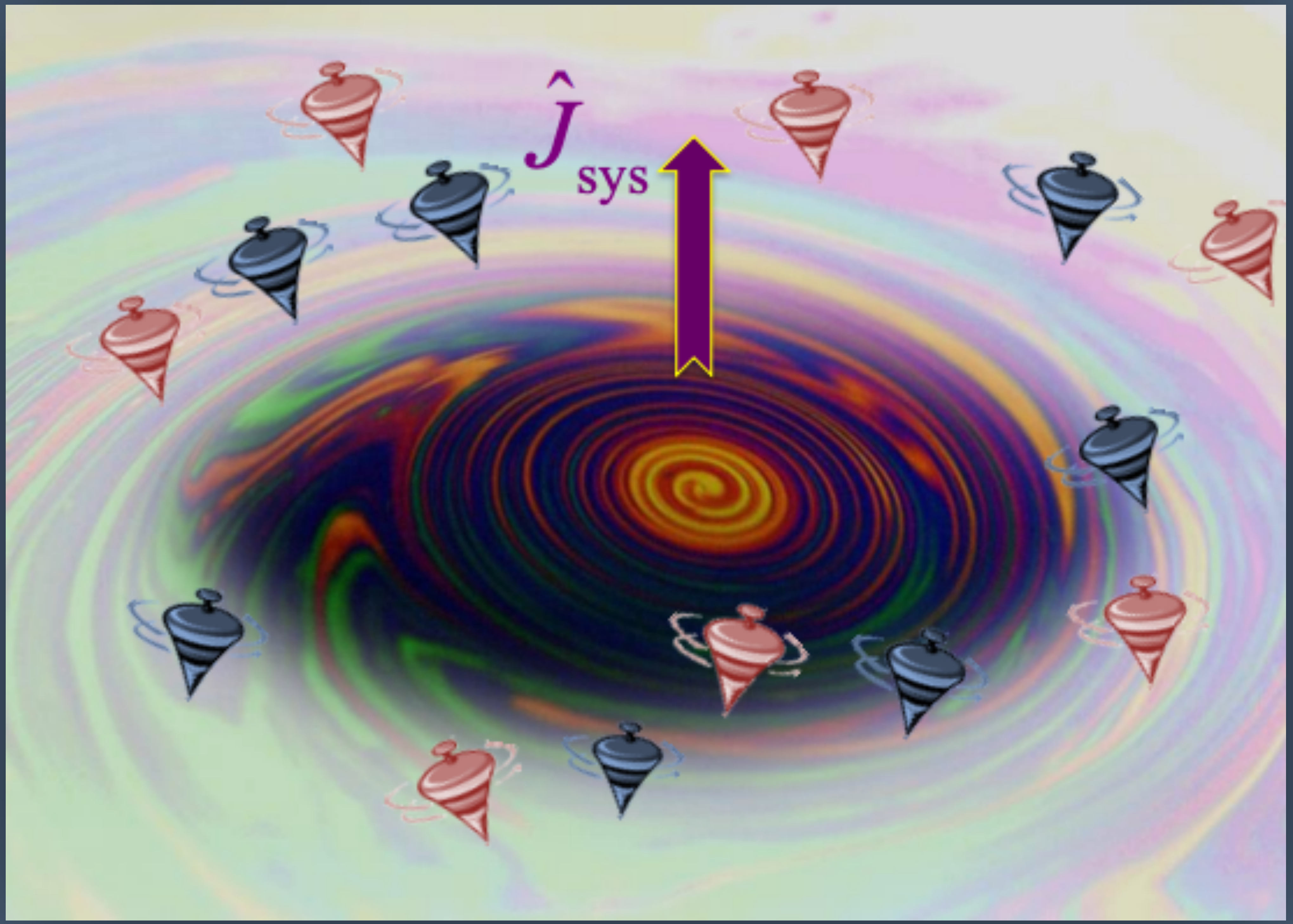

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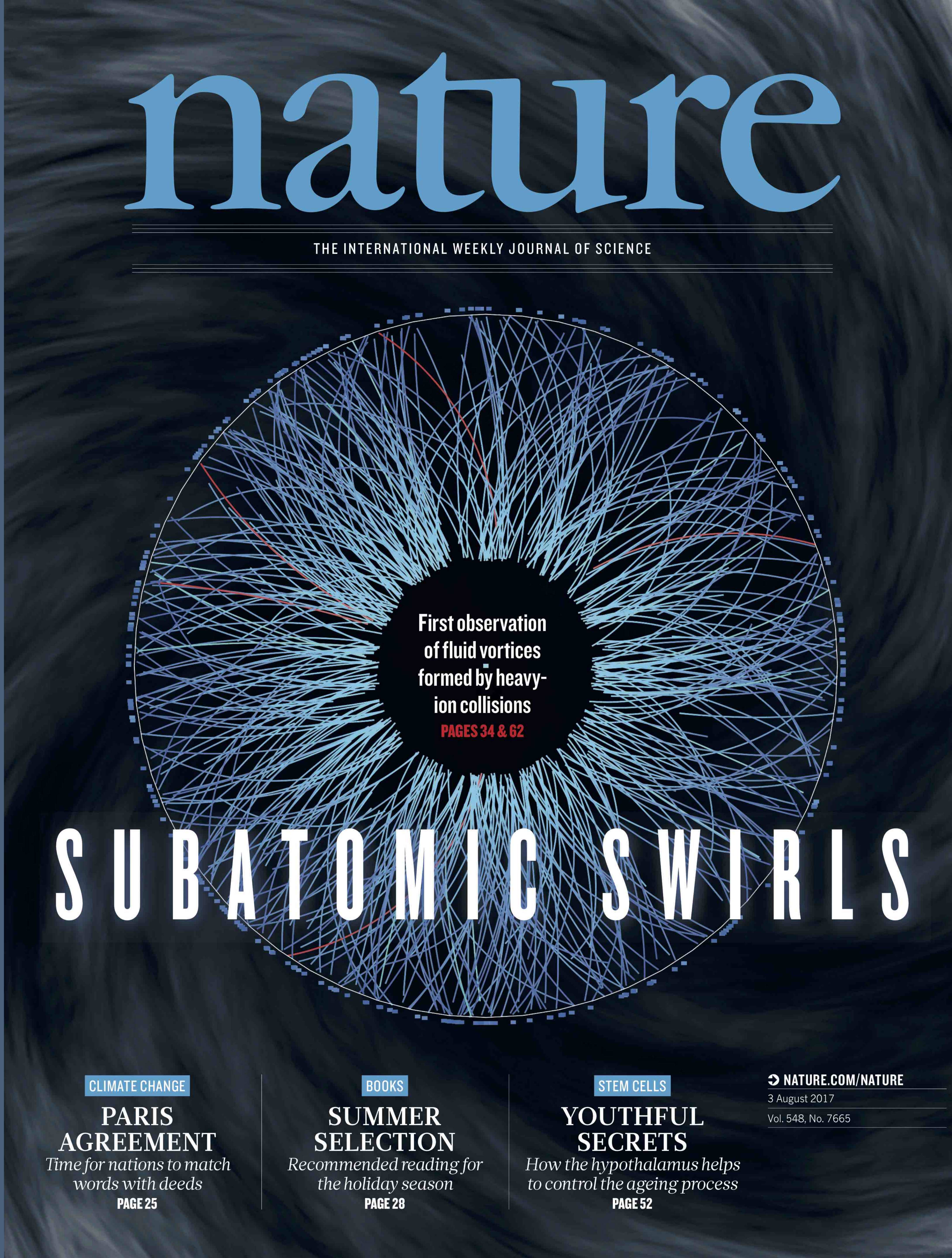
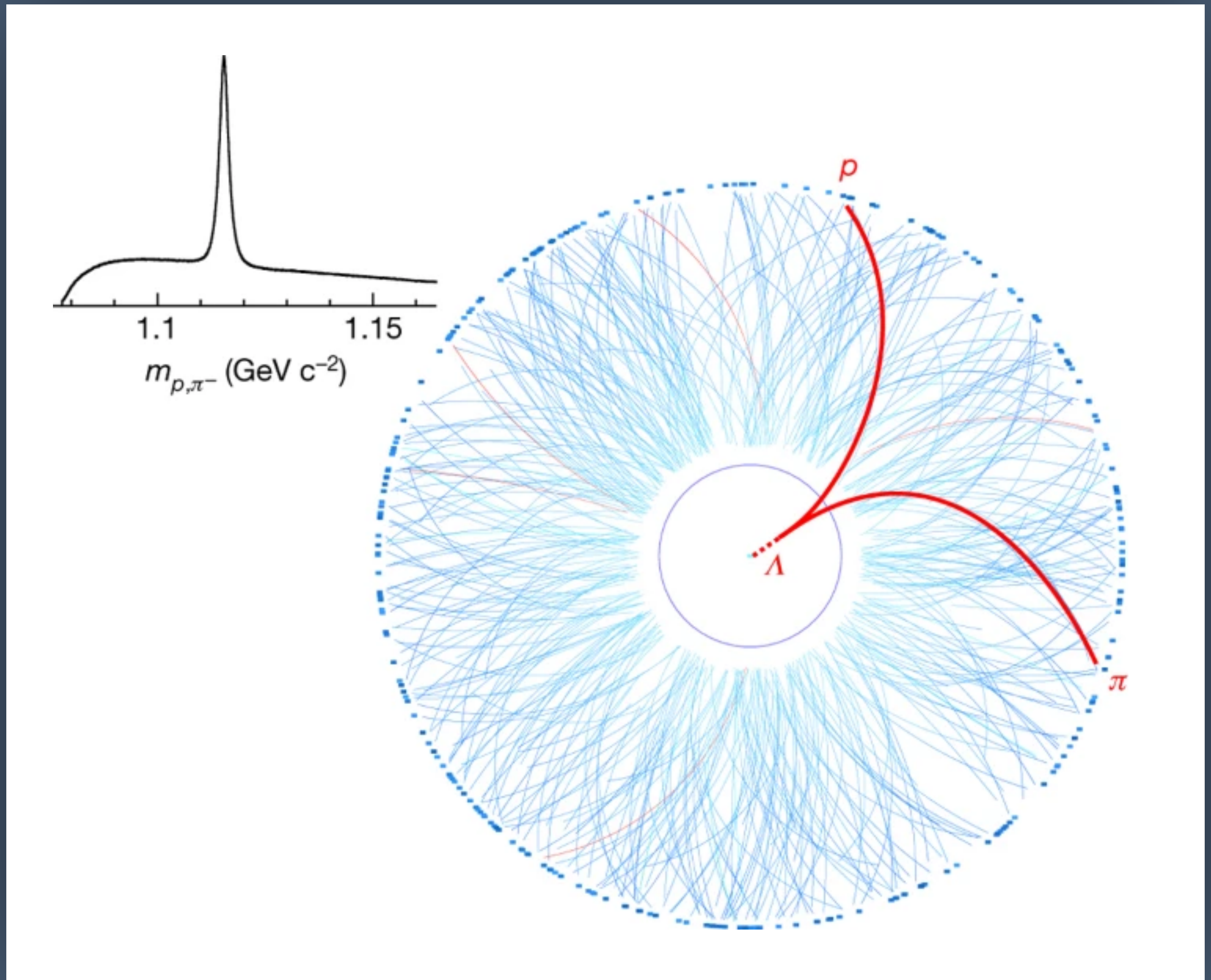
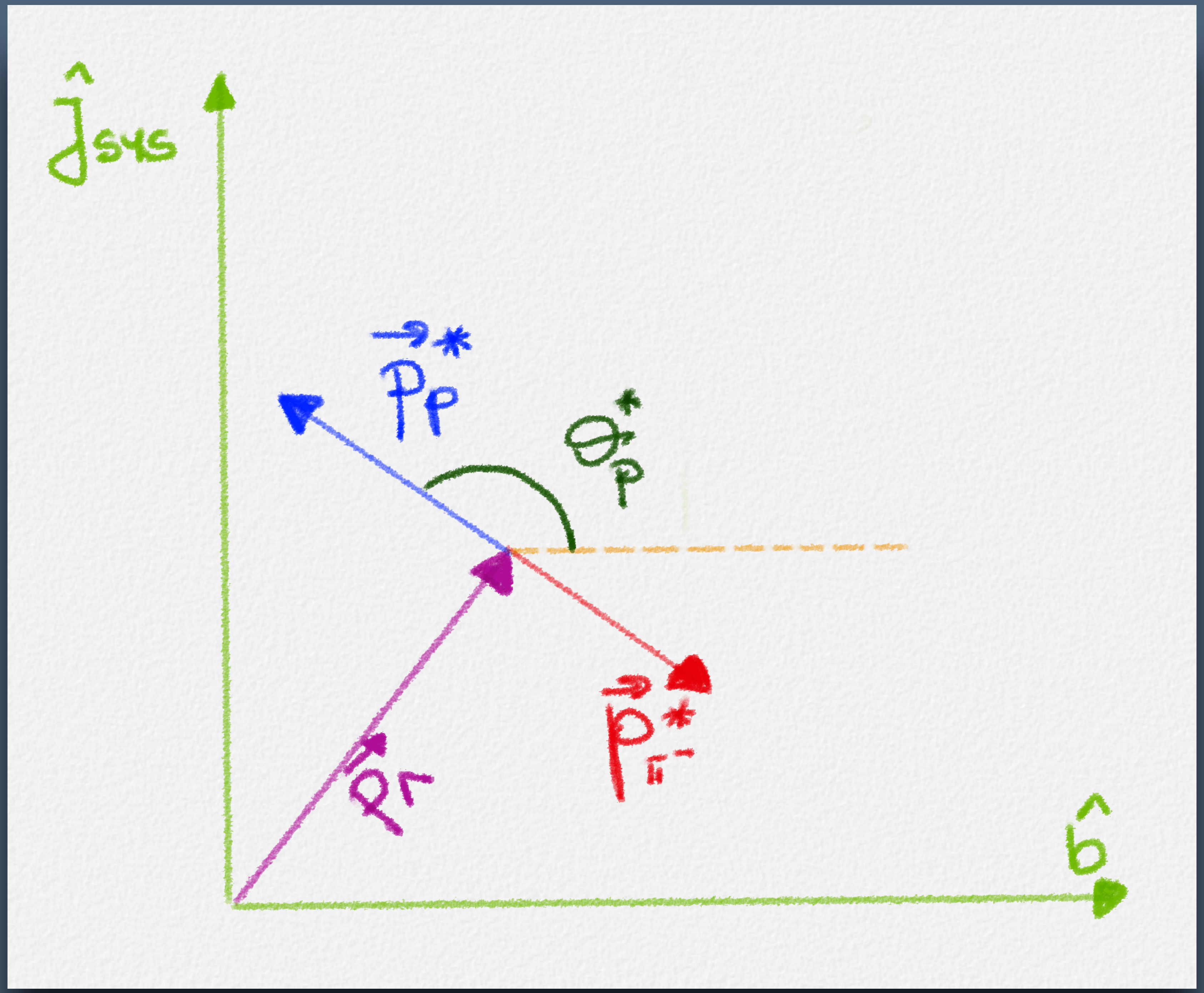


Vorticity

Polarization via self-analyzing decay of $\Lambda \rightarrow p + \pi^-$





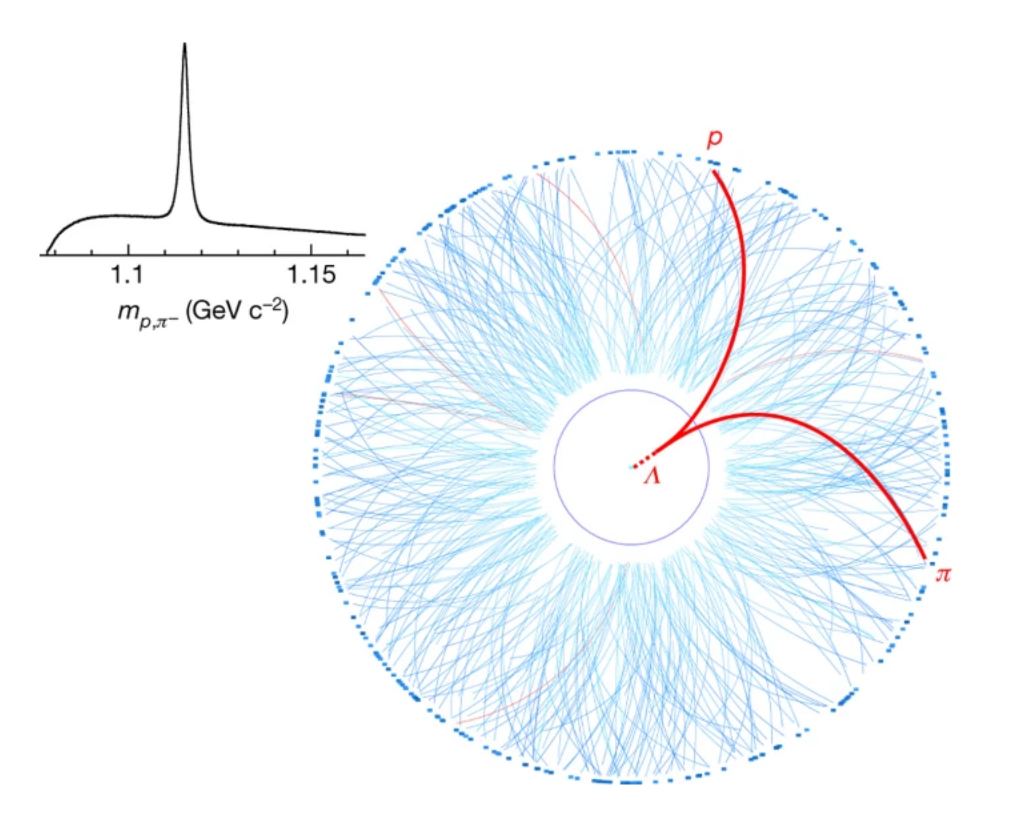
$$\frac{dN}{d\cos(\theta)*} = \frac{1}{2}\left(1 + \alpha_H |\overrightarrow{P_H}| \cos\theta*\right)$$

- If $P_H = 0$ then $\theta*$ of proton momentum in Λ frame distribution uniform

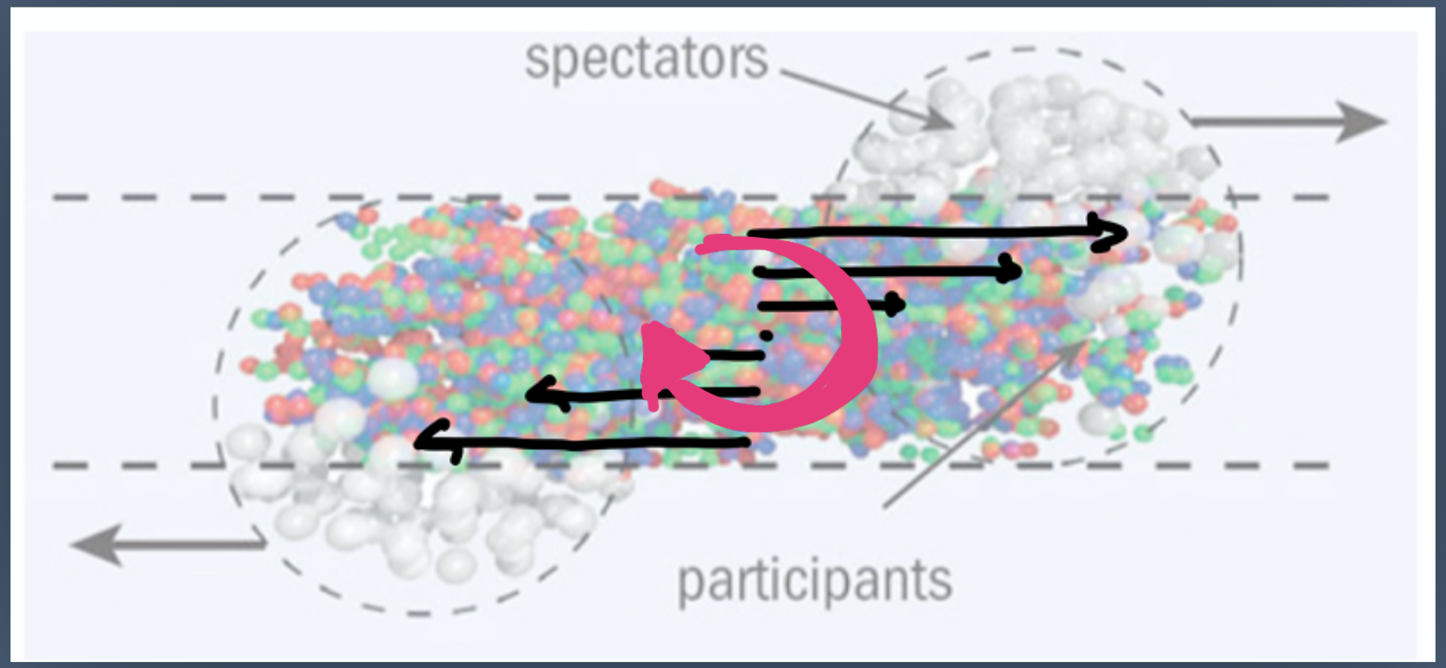
Vorticity

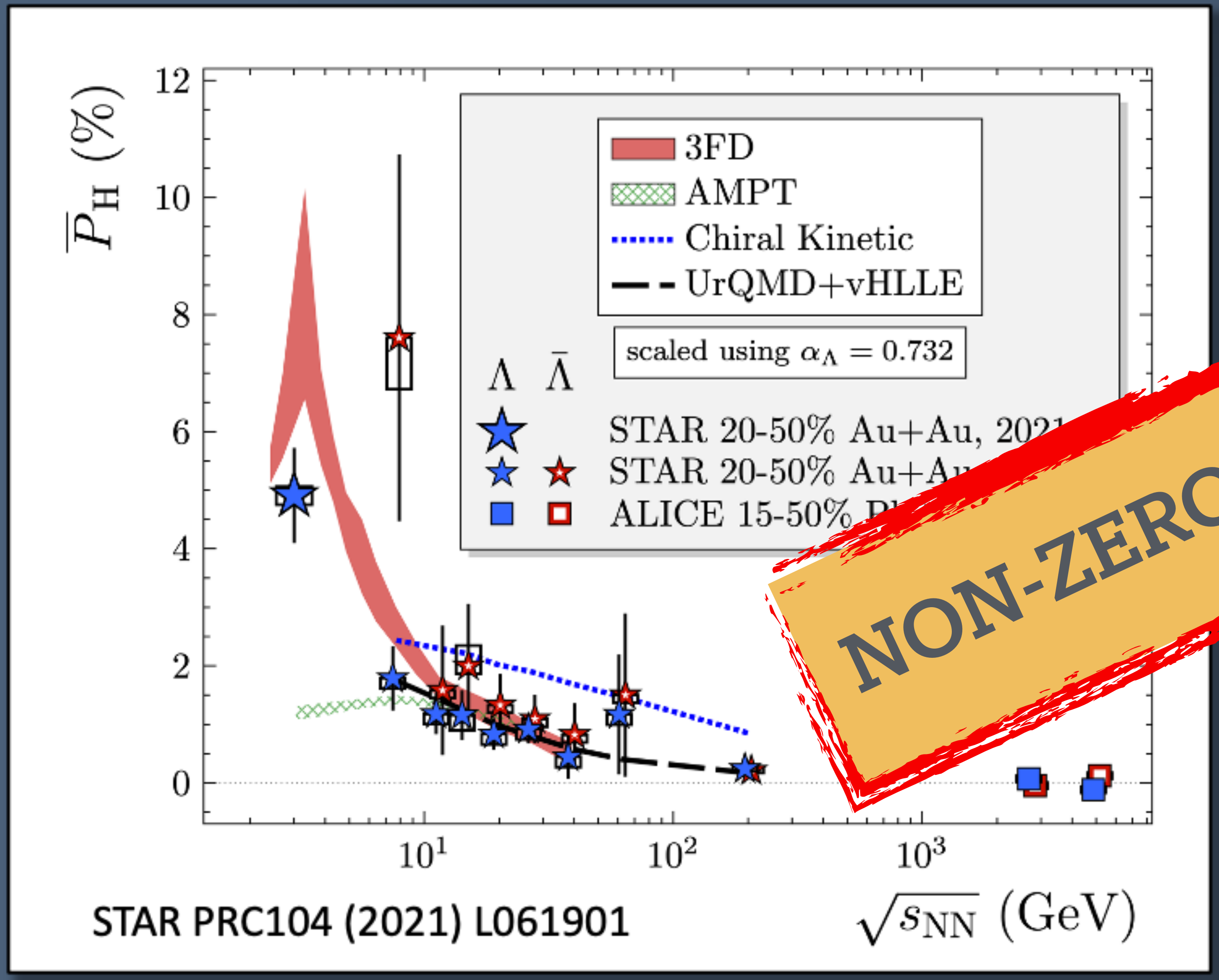
Polarization via self-analyzing decay of $\Lambda \rightarrow p + \pi^-$

$$\frac{dN}{d\cos(\theta)*} = \frac{1}{2}\left(1 + \alpha_H |\overrightarrow{P_H}| \cos\theta*\right)$$



GLOBAL



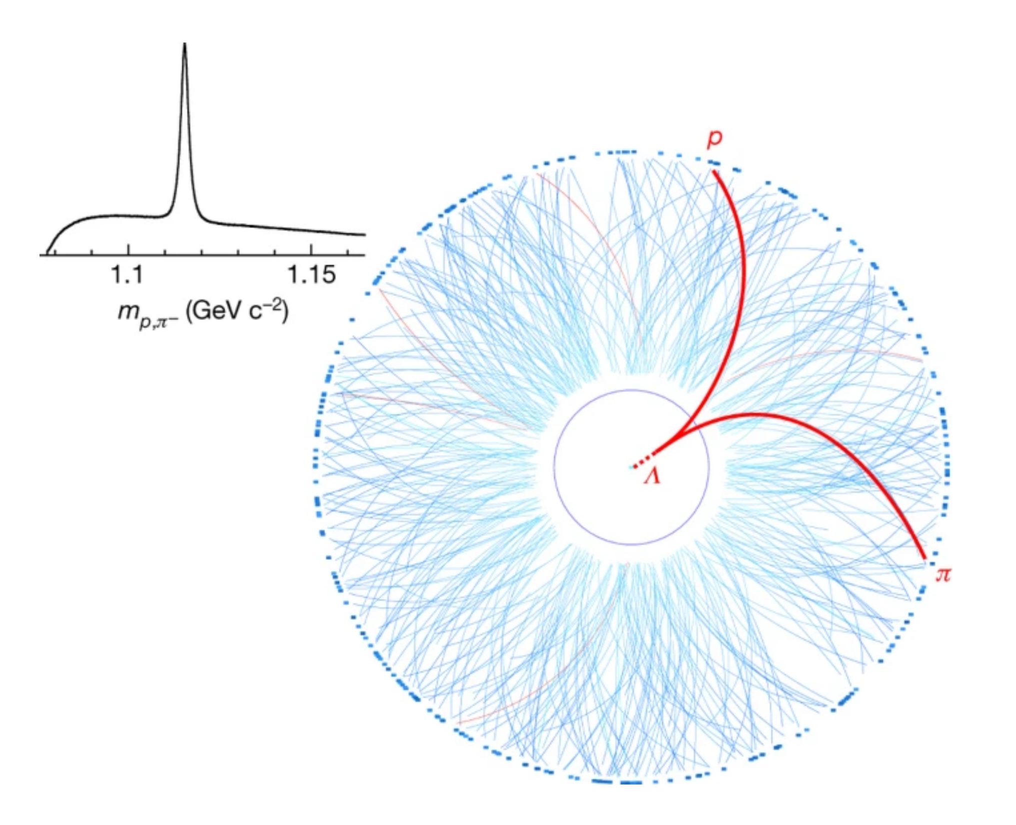


NON-ZERO at lower $\sqrt{s_{NN}}$!!

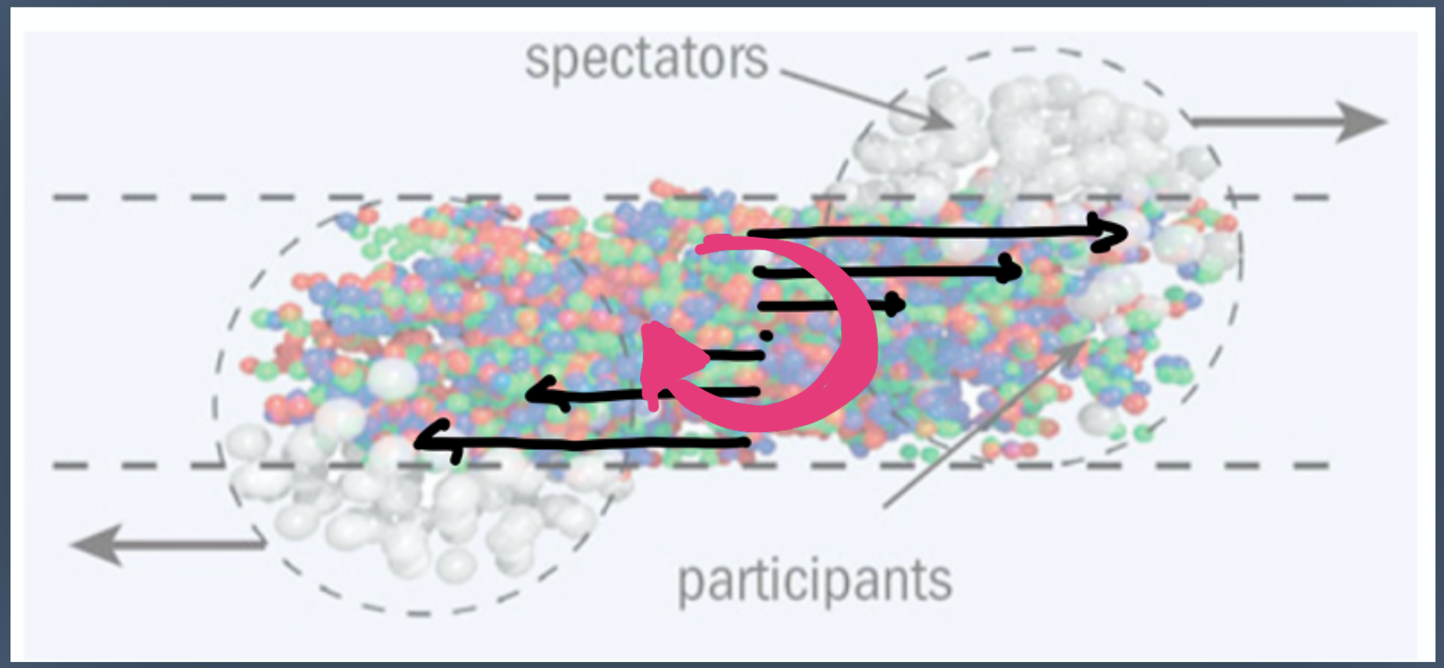
Vorticity

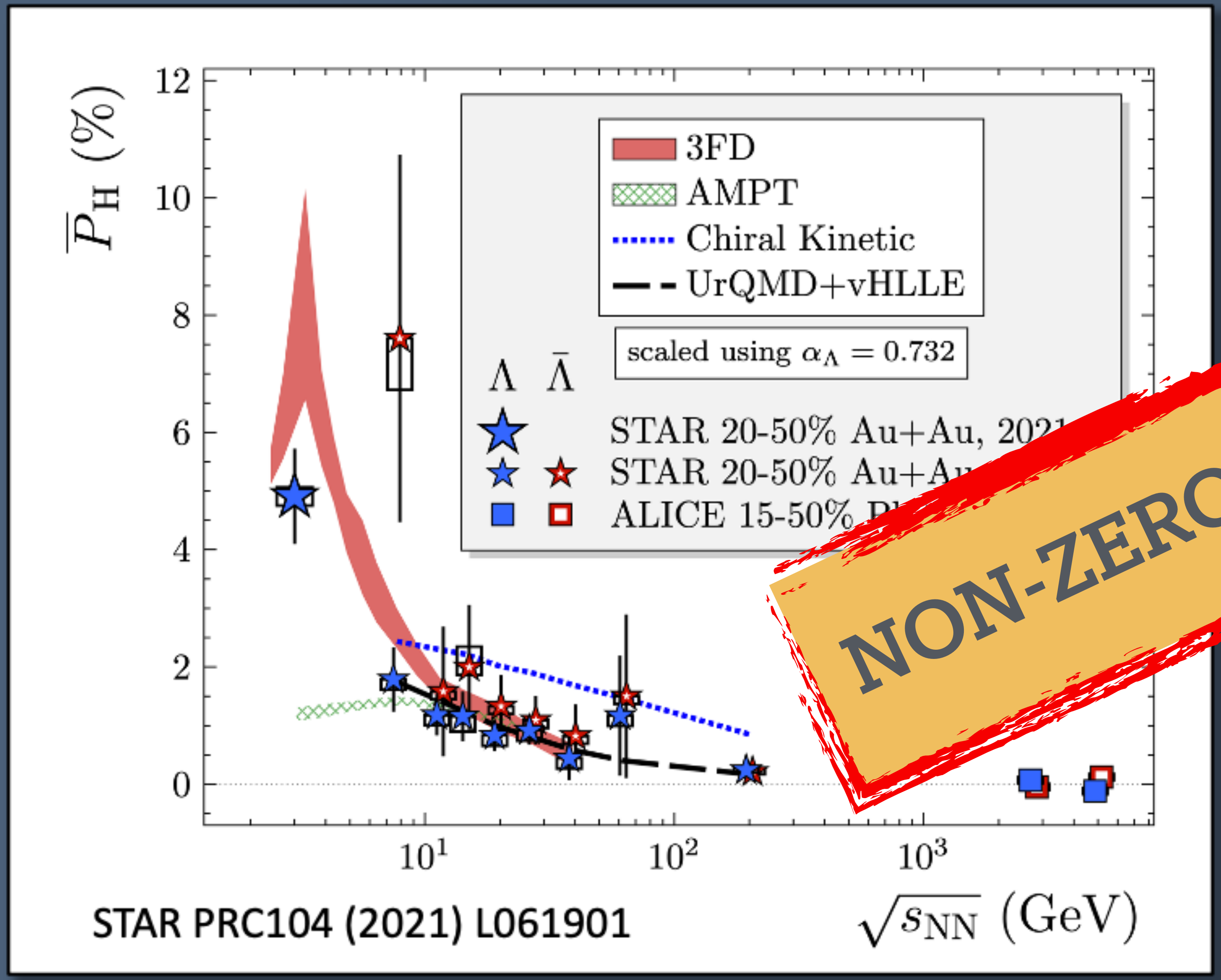
Polarization via self-analyzing decay of $\Lambda \rightarrow p + \pi^-$

$$\frac{dN}{d\cos(\theta)^*} = \frac{1}{2}\left(1 + \alpha_H |\overrightarrow{P_H}| \cos\theta^*\right)$$



GLOBAL

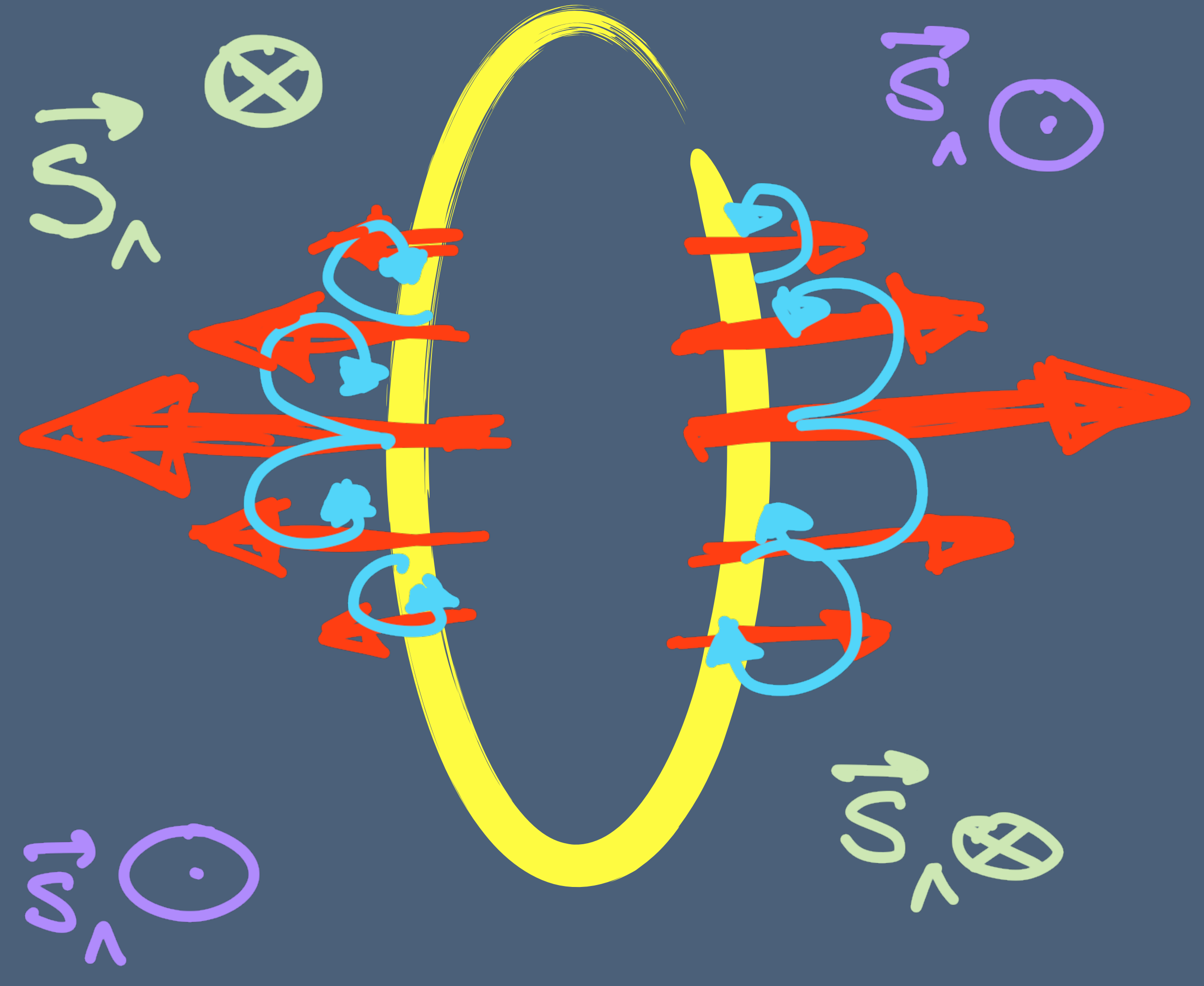




NON-ZERO at lower $\sqrt{s_{NN}}$!!

LOCAL

Effect of elliptic flow



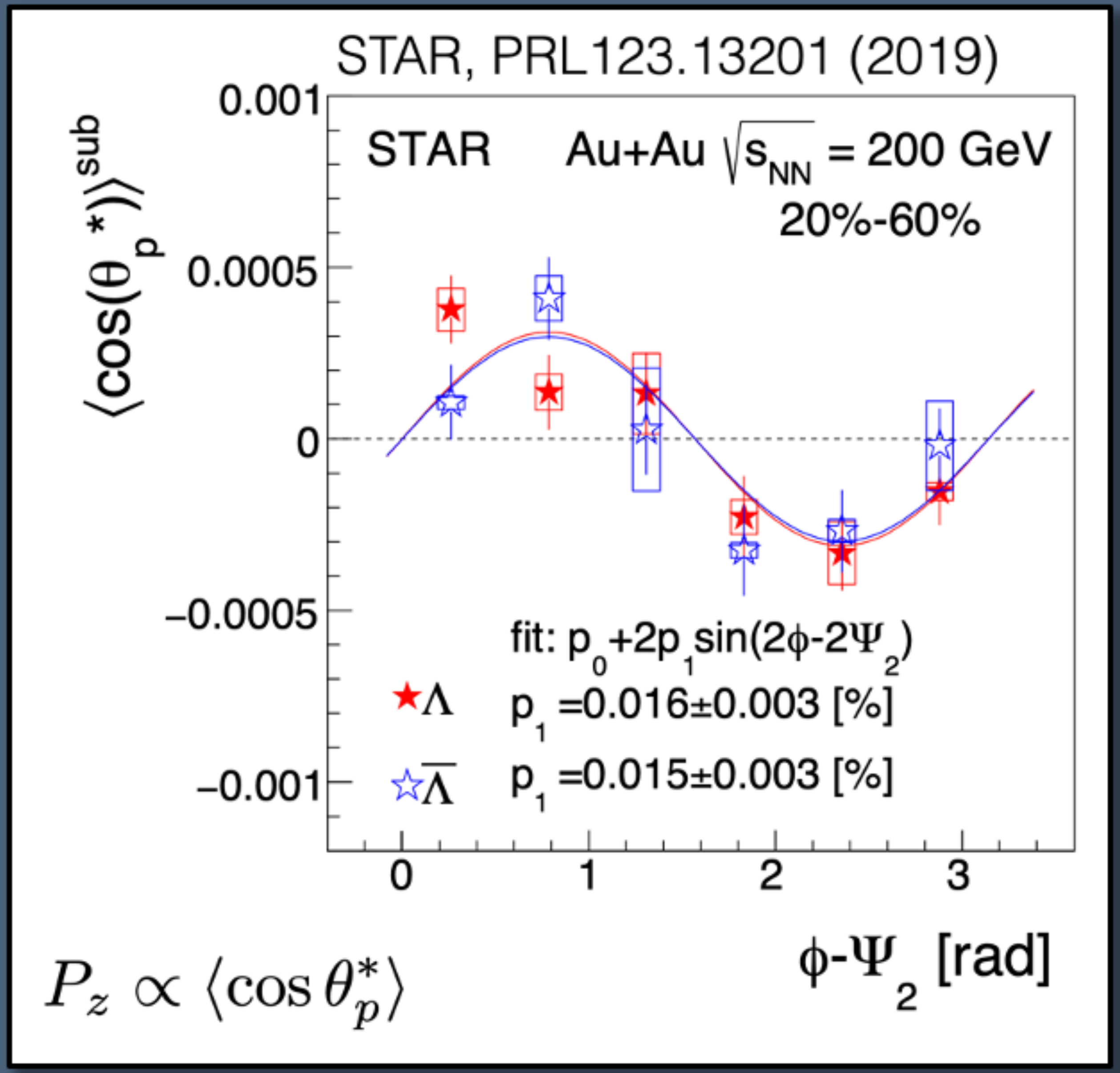
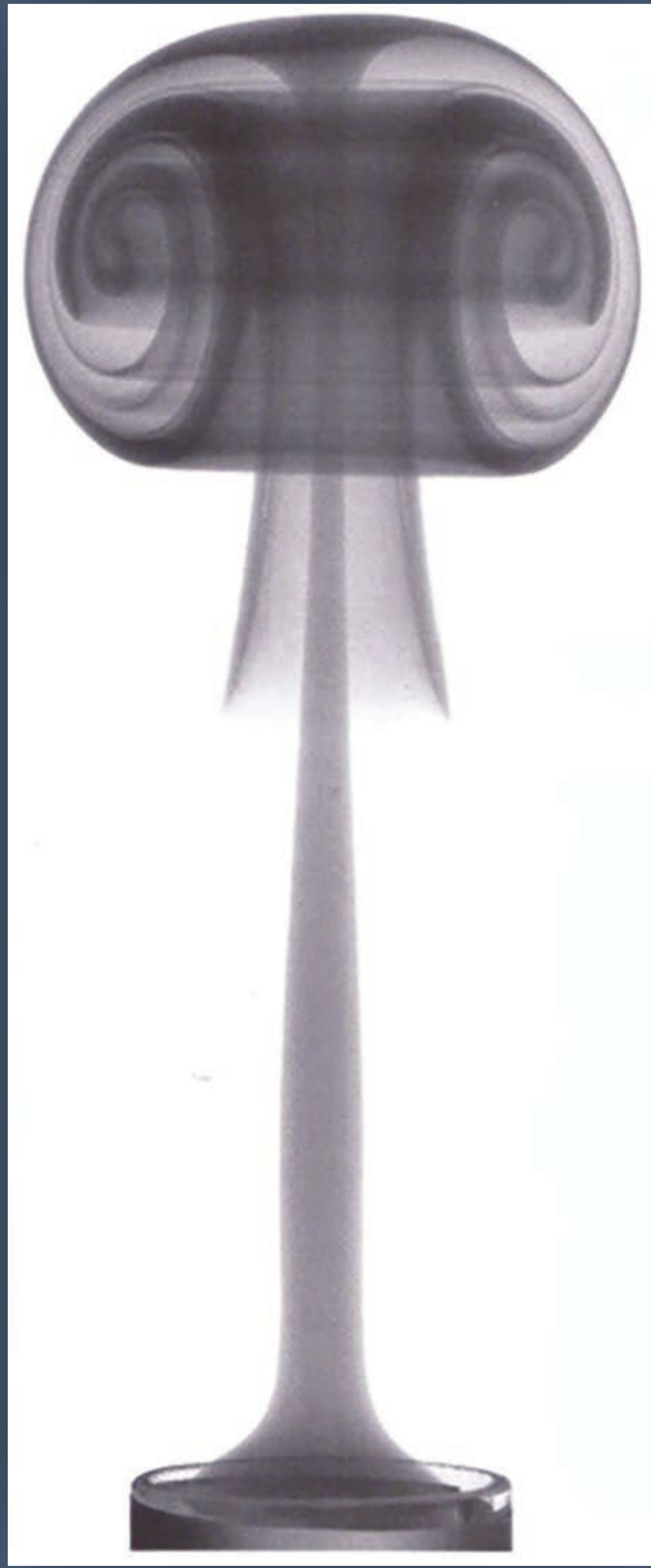


Photo: Andreas Wilkens, Institute of Flow Sciences, Herrischried, Germany
Figures from book: Subtle Agroecologies

Vorticity: Toroidal (smoke rings)

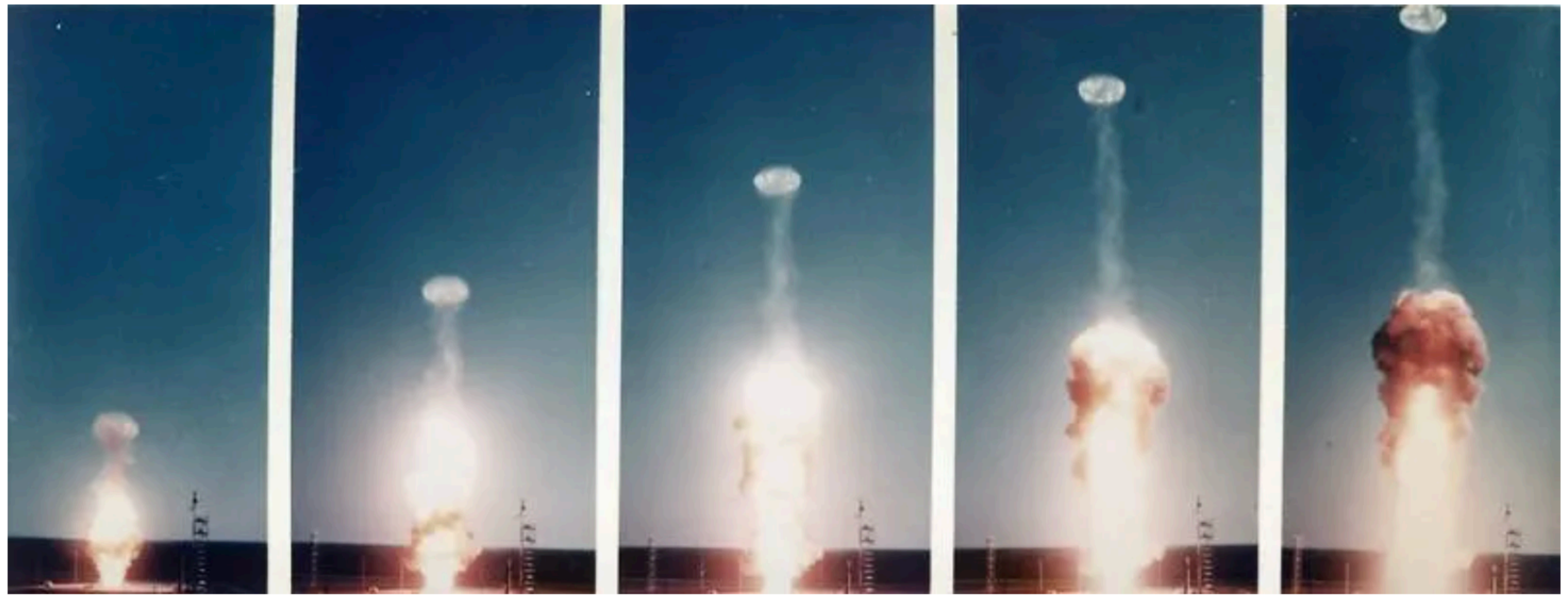
Present (in physics) for ages.



On Integrals of the Hydrodynamic Equations That Correspond to Vortex Motions

Helmholtz (1858)

Persistent vortical toroids (smoke rings) are quintessential fluid behavior



Since the first *Minuteman* launches from Cape Canaveral in 1961, nearly every missile has generated a perfect ring of smoke.

https://www.smithsonianmag.com/air-space-magazine/minuteman-missile-blows-smoke-rings-180958003/

Photo: Andreas Wilkens, Institute of Flow Sciences, Herrischried, Germany

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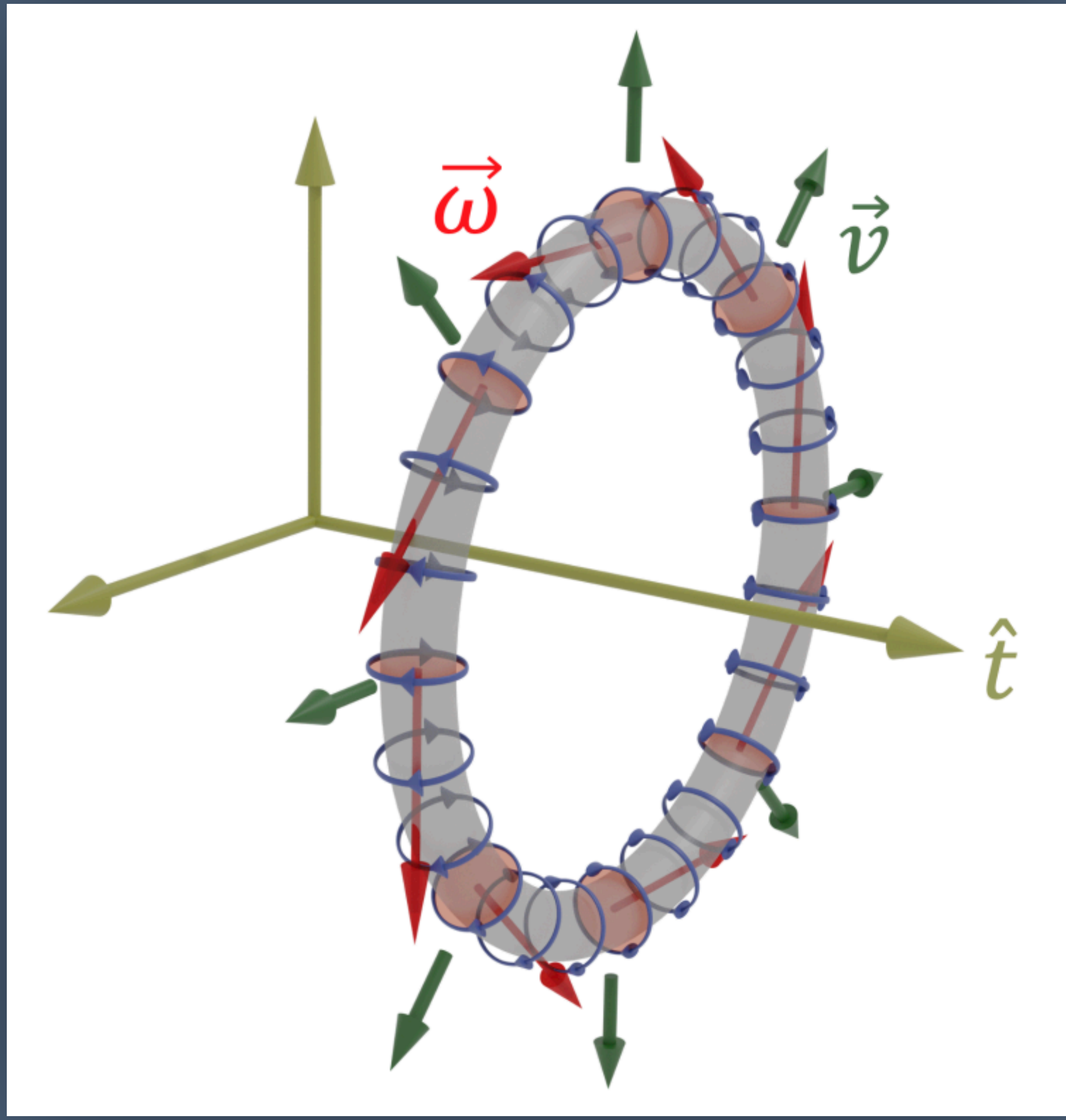


Expanding smoke ring can be quantified by:

non-relativistic

$$\bar{R}^{\hat{t}}_{NR} = \left\langle \frac{\vec{\omega}_{NR} \cdot (\hat{t} \times \vec{v}_{cell})}{|\hat{t} \times \vec{v}_{cell}|} \right\rangle_{\phi}$$

Curl of flow velocity $\vec{v}$:

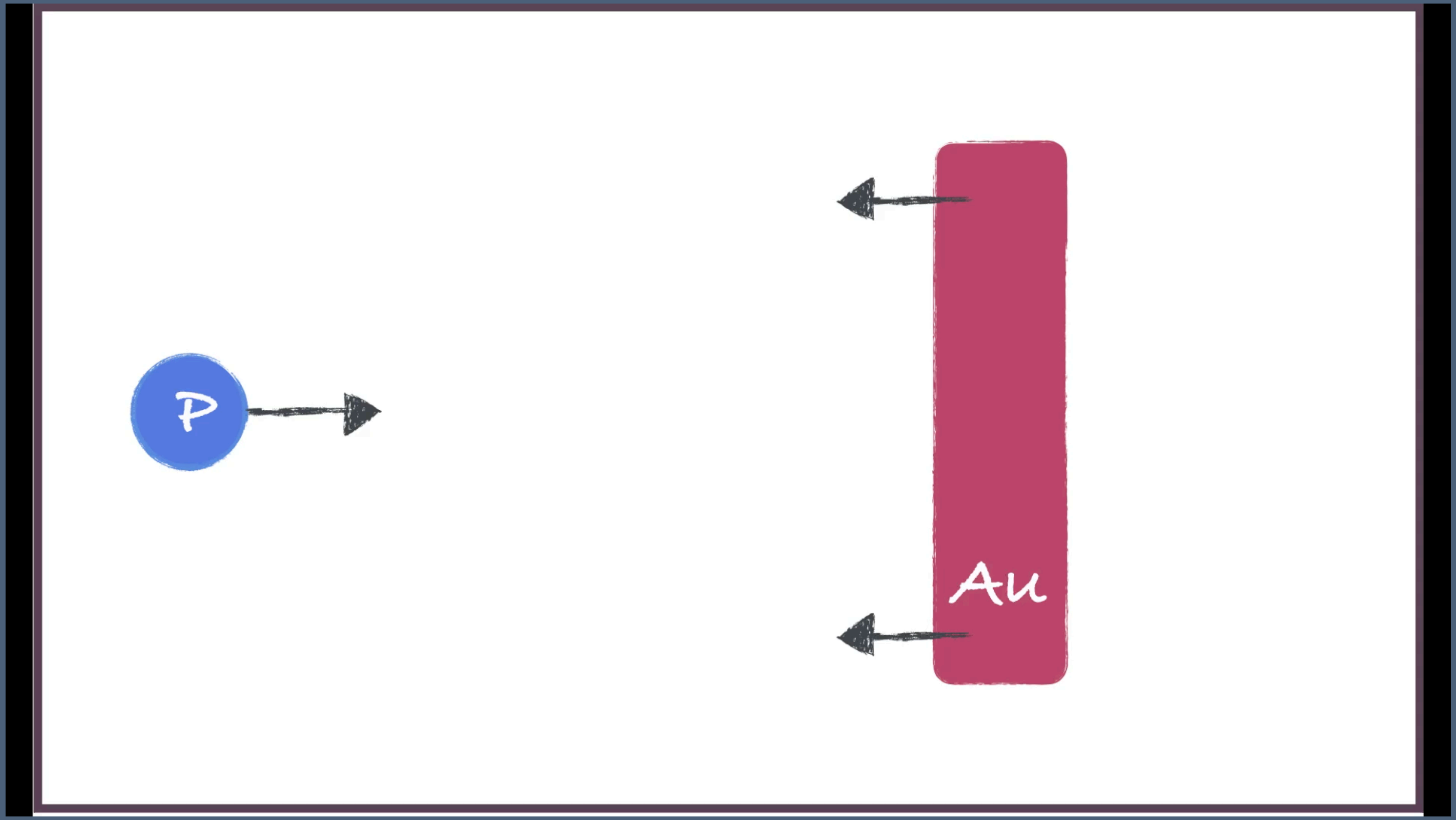
$$\vec{\omega}_{NR} = \frac{1}{2} \vec{\nabla} \times \vec{v}$$

$\hat{t}$ - thrust vector

[1] M Lisa, et al: Phys. Rev. C 104, 011901 (2021)

Vorticity: Toroidal (smoke rings)

animation: M. Stefaniak



- Surface friction with "wall" decreases velocity of the fluid
- Higher $\vec{v}$ in the center of the "tube"
- Differences of $\vec{v}$ induce an azimuthally oriented vorticity structure
- The strength and sense of created vortex toroid structures:

$$R^{\hat{t}}_{fluid} = \frac{\epsilon^{\mu\nu\rho\sigma}\Omega_\mu n_\nu \hat{t}_\rho u_\sigma}{|\epsilon^{\mu\nu\rho\sigma} n_\nu \hat{t}_\rho u_\sigma|}$$

Ω_μ - proxy for vorticity

$\epsilon^{\mu\nu\rho\sigma}$ - Levi-Civvita tensor, fully asymetric in four dimentions

n_ν - normal vector of the fluid cell

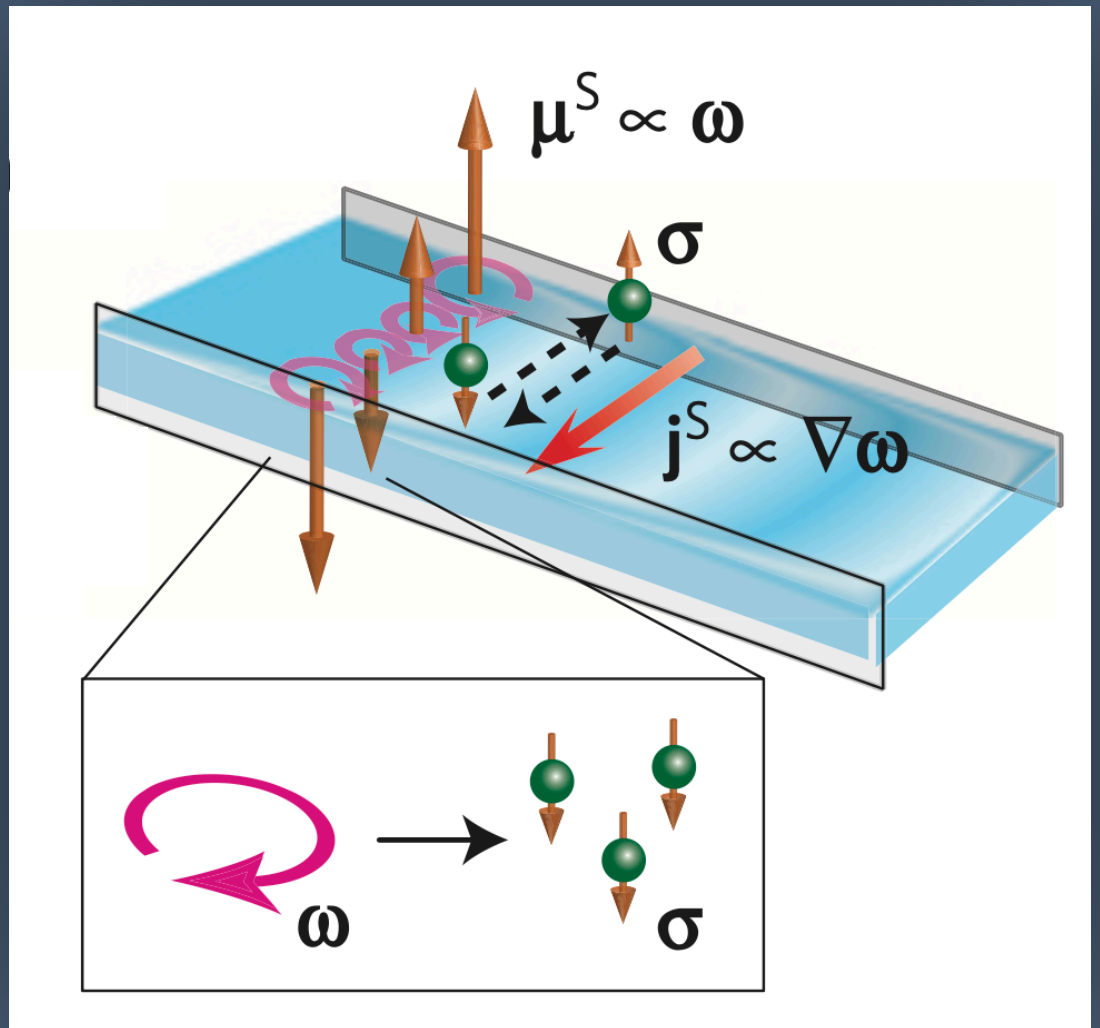
[1] M Lisa, et al: Phys. Rev. C 104, 011901 (2021)

Vorticity: Toroidal (smoke rings)

- Spin-orbit coupling produces polarization proportional to the local fluid vorticity ω

- In relativistic treatment vorticity (thermal):

$$\omega_{th}^{\mu\nu} = \frac{1}{2}[\partial^{\nu}(u^{\mu}/T) - \partial^{\mu}(u^{\nu}/T)]$$



- Measured hadrons are not part of evolving fluid, but they are created in process of hadronization

- The hyperon polarization is dictated by the fluid vorticity distribution on "freeze-out" hyper-surface Σ:

$$S^{\mu}(p) = -\frac{1}{8m}\epsilon^{\mu\rho\sigma\tau}p_{\tau}\frac{\int d\Sigma_{\lambda}p^{\lambda}n_F(1-n_F)\omega_{\rho\sigma}}{\int d\Sigma_{\lambda}p^{\lambda}n_F}$$

n_F -Fermi-Dirac distribution

more details: F. Becattini, et al: Annals Phys. 338, 32 (2013)

[1] M Lisa, et al: Phys. Rev. C 104, 011901 (2021)

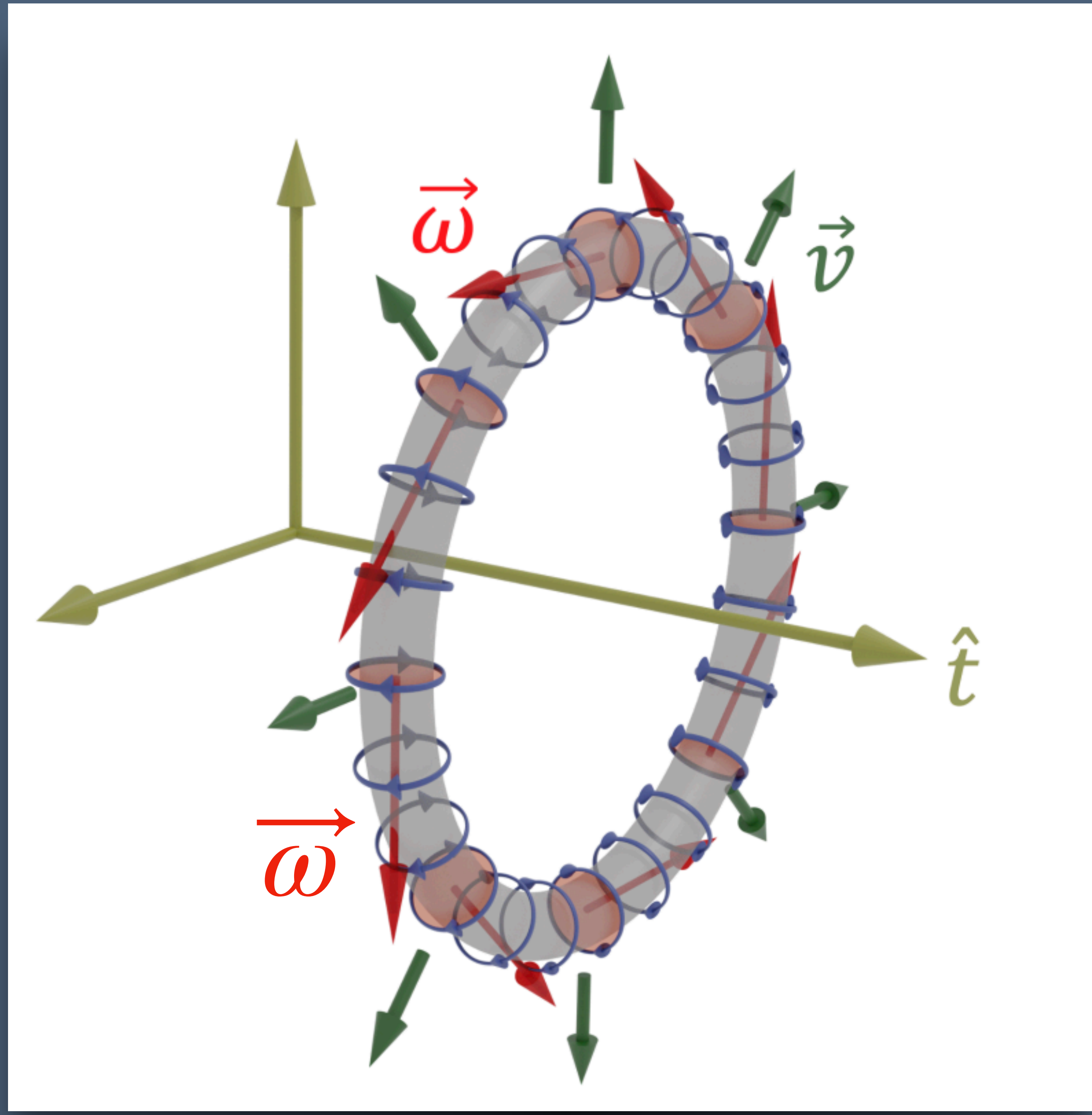
Vorticity: Toroidal (smoke rings)

- In [1] authors use the Cooper-Fry procedure to switch from hydro paradigm to hadrons

S_μ - Λ spin four-vector

p_σ - Λ momentum four-vector

$$R^{\hat{t}}_{fluid} = \frac{\epsilon^{\mu\nu\rho\sigma}\Omega_\mu n_\nu \hat{t}_\rho u_\sigma}{|\epsilon^{\mu\nu\rho\sigma} n_\nu \hat{t}_\rho u_\sigma|} \xrightarrow{\text{HADRONIZATION}} R^{\hat{t}}_{\Lambda} = \frac{\epsilon^{\mu\nu\rho\sigma} S_\mu n_\nu \hat{t}_\rho p_\sigma}{|S||\epsilon^{\mu\nu\rho\sigma} n_\nu \hat{t}_\rho p_\sigma|}$$



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HADRONIZATION

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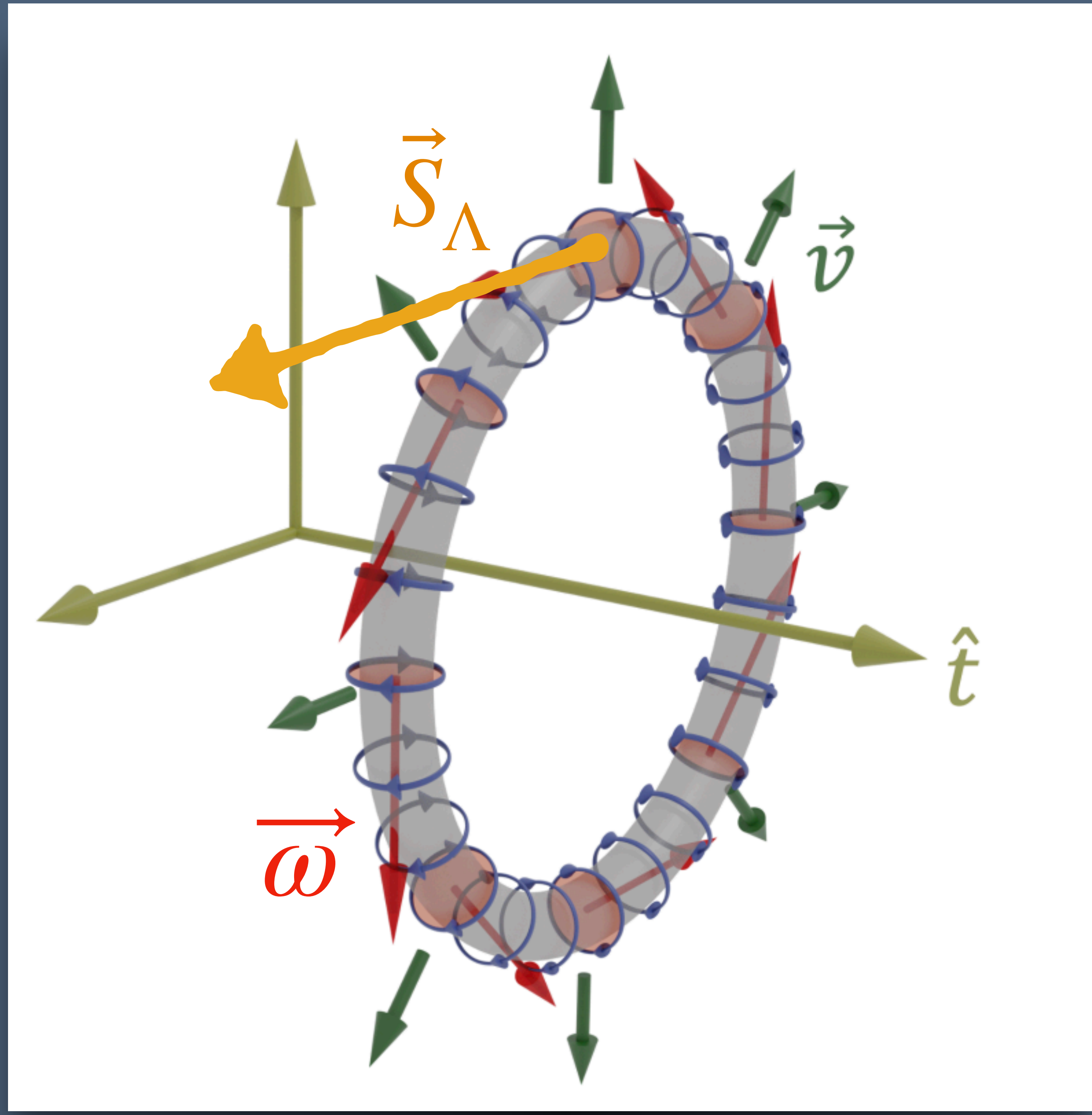

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(′) - three-vectors in NN frame

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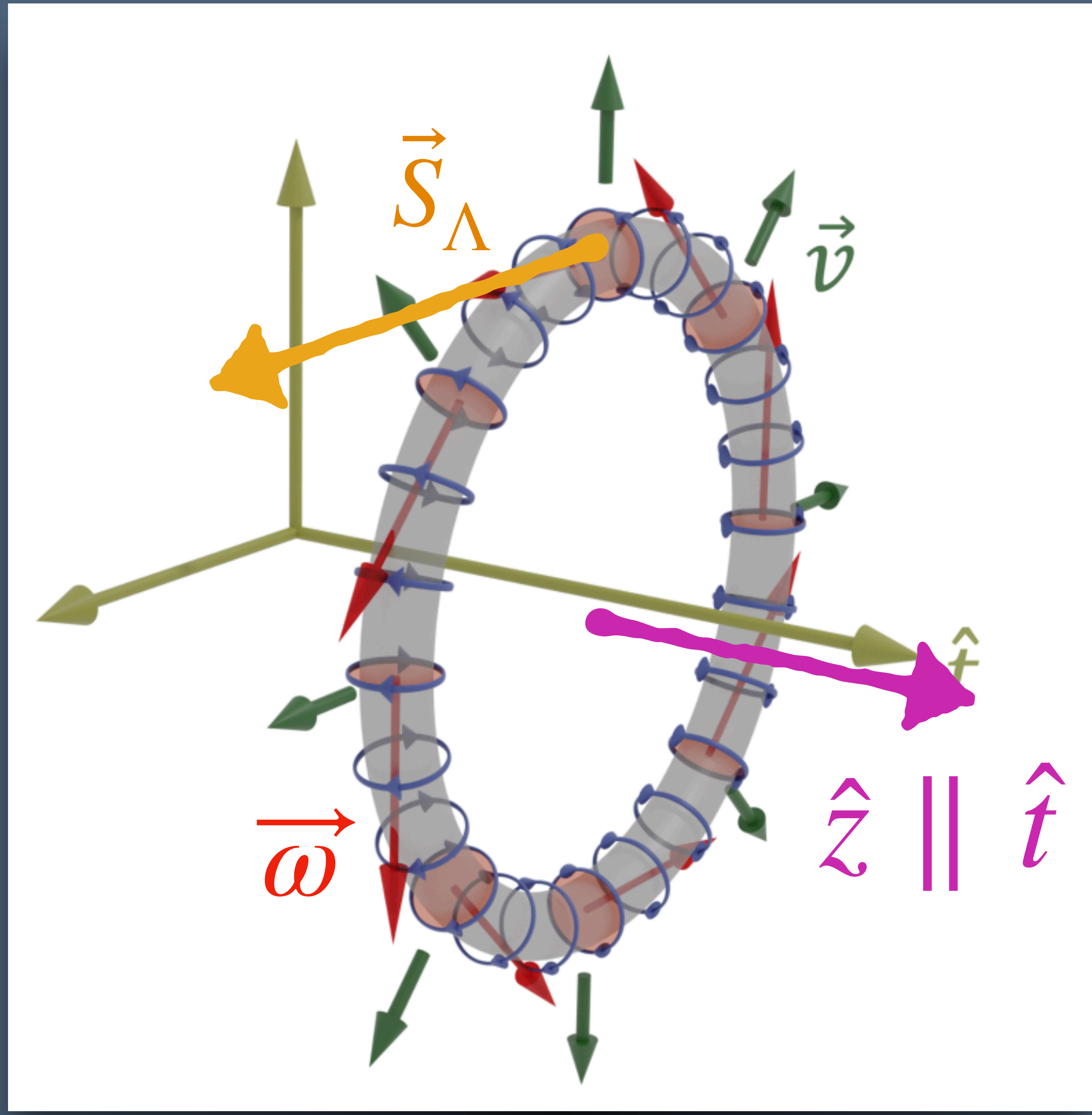

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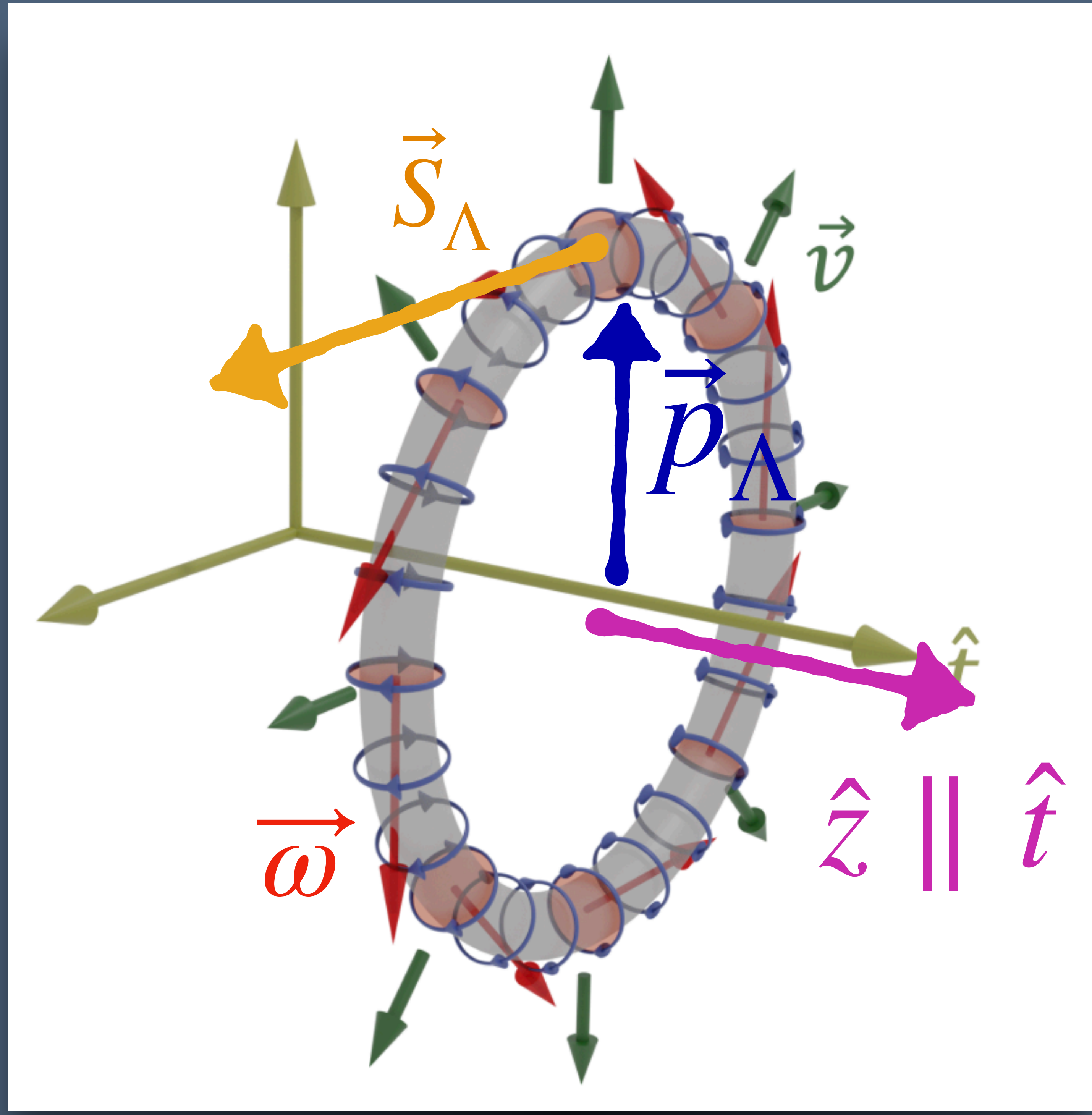

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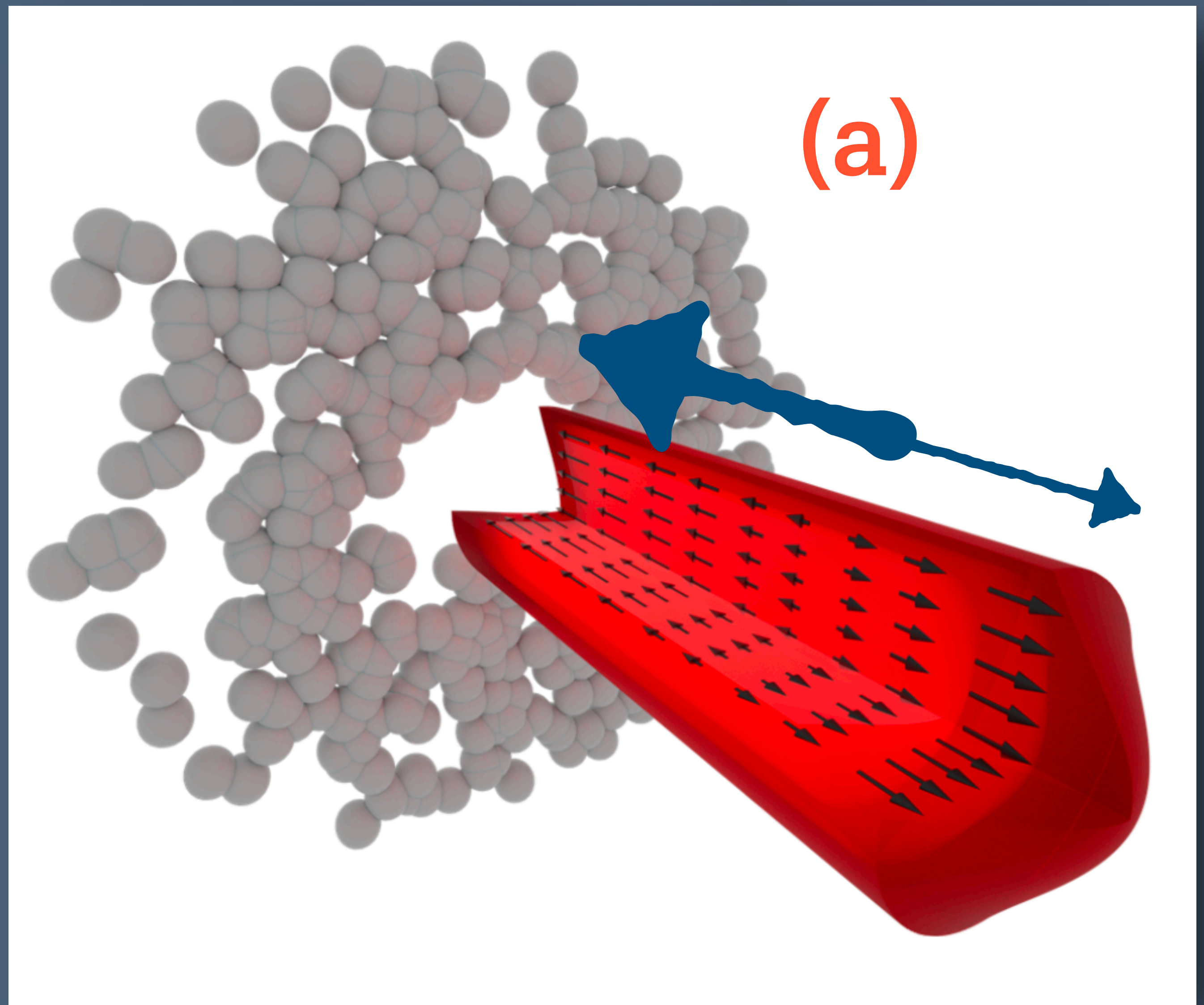
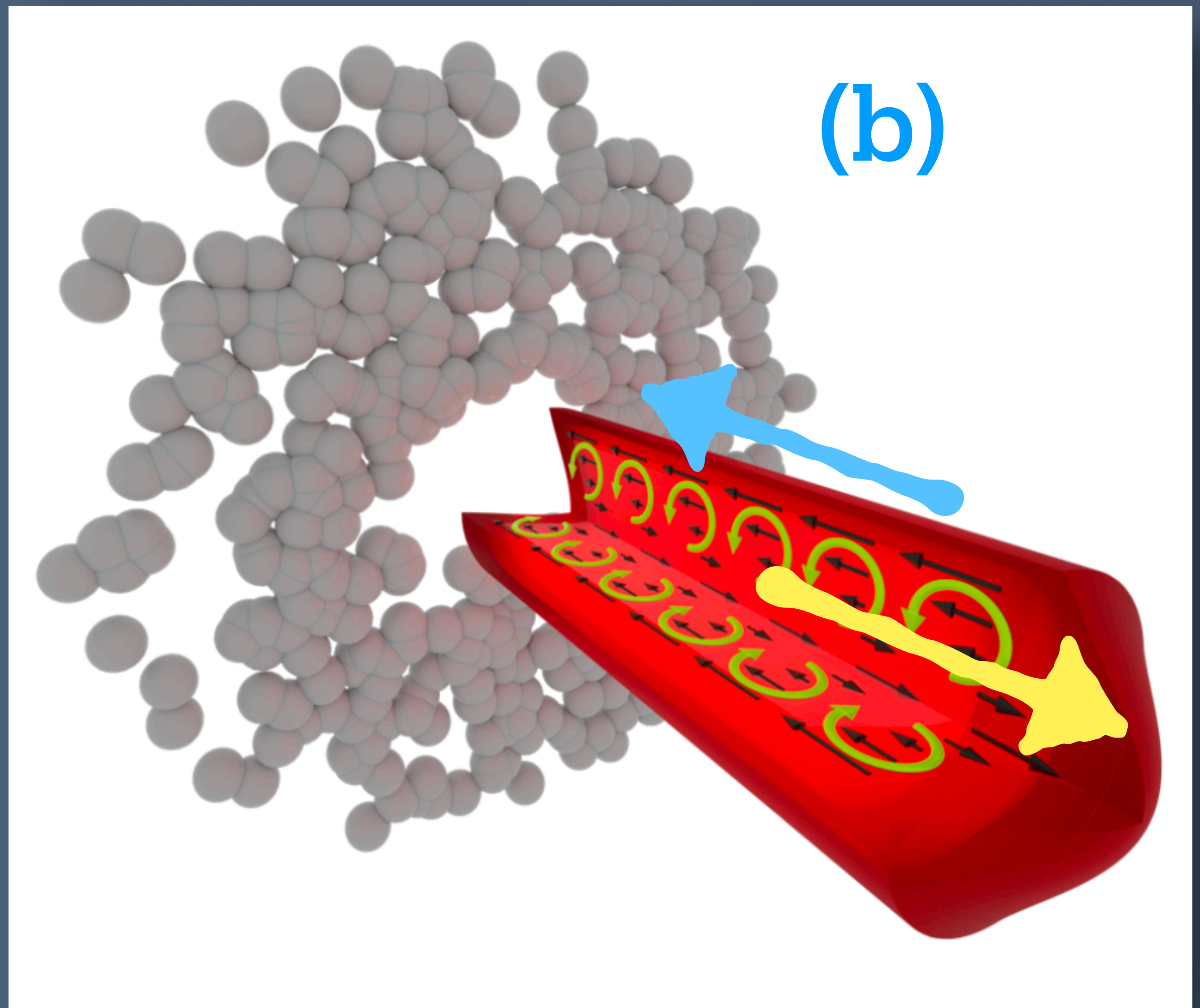




Proton drilling a nuclei:

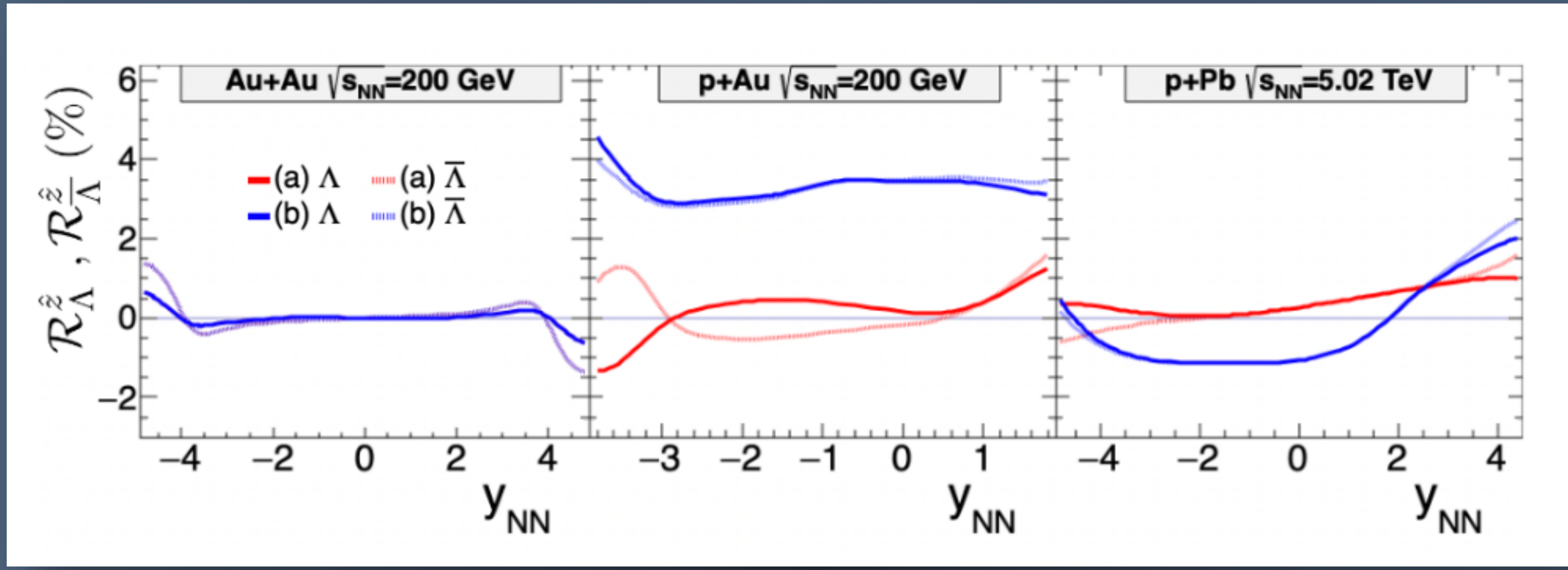
a) A boost-invariant flow distribution with more matter in the nuclei-going direction.

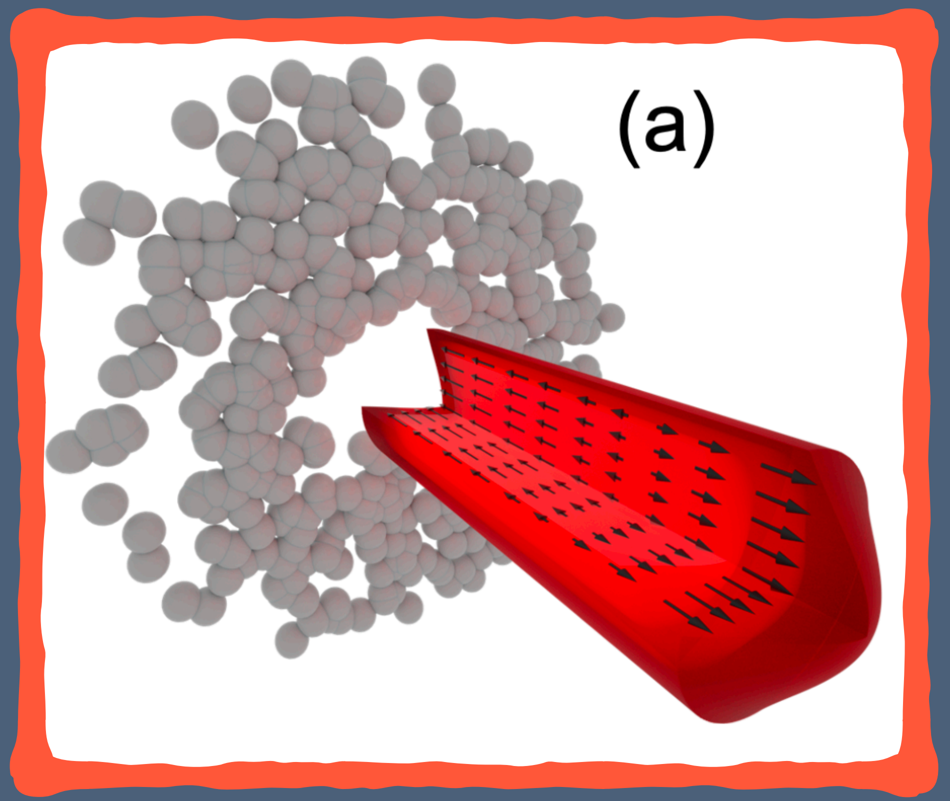
b) The edges of the cylinder flow more in the nuclei-going direction than fluid cells at the center of the cylinder.

[1] M Lisa, et al: Phys. Rev. C 104, 011901 (2021)

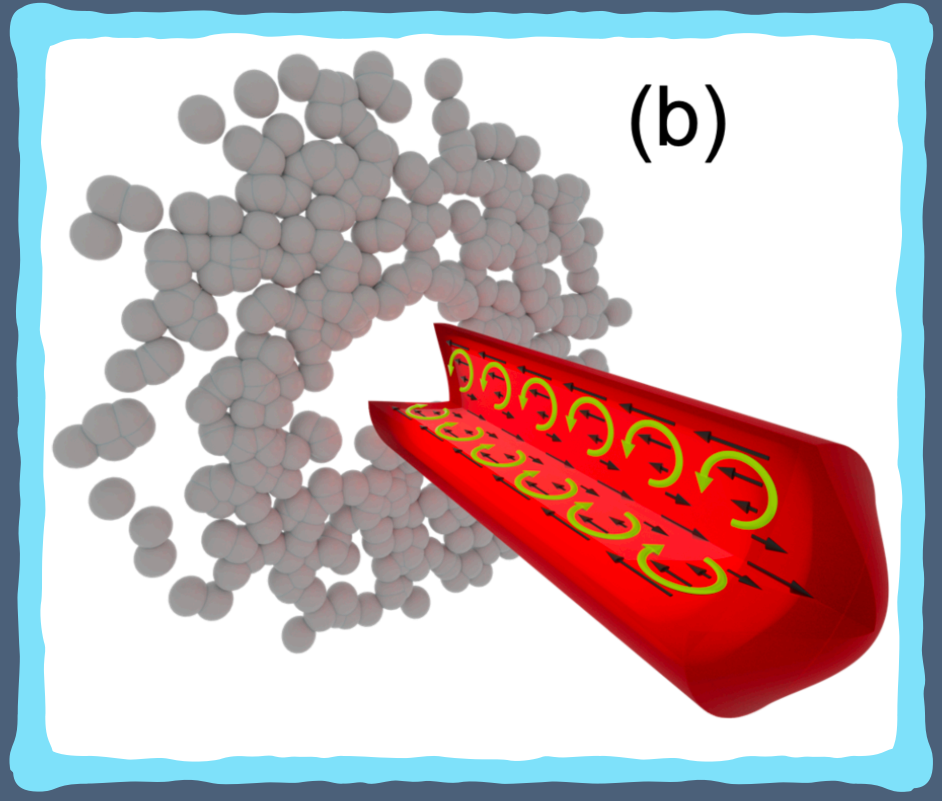
Vorticity: Toroidal (smoke rings)

Simulations with MUSIC [1] :

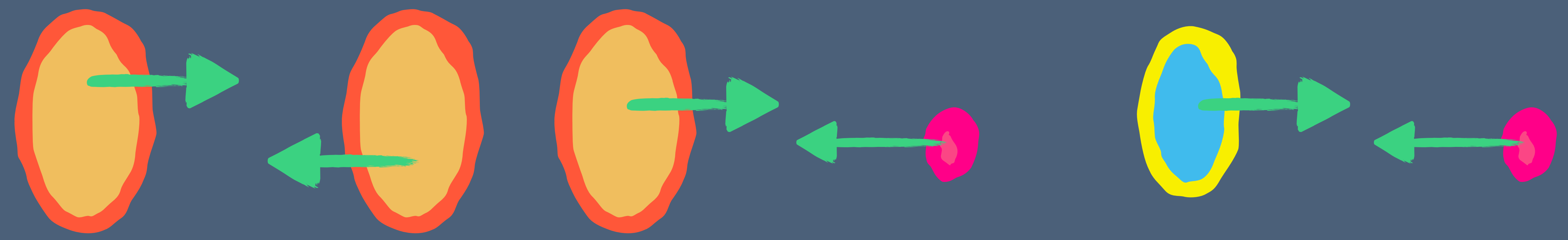




No TV



With TV



According to [1]:

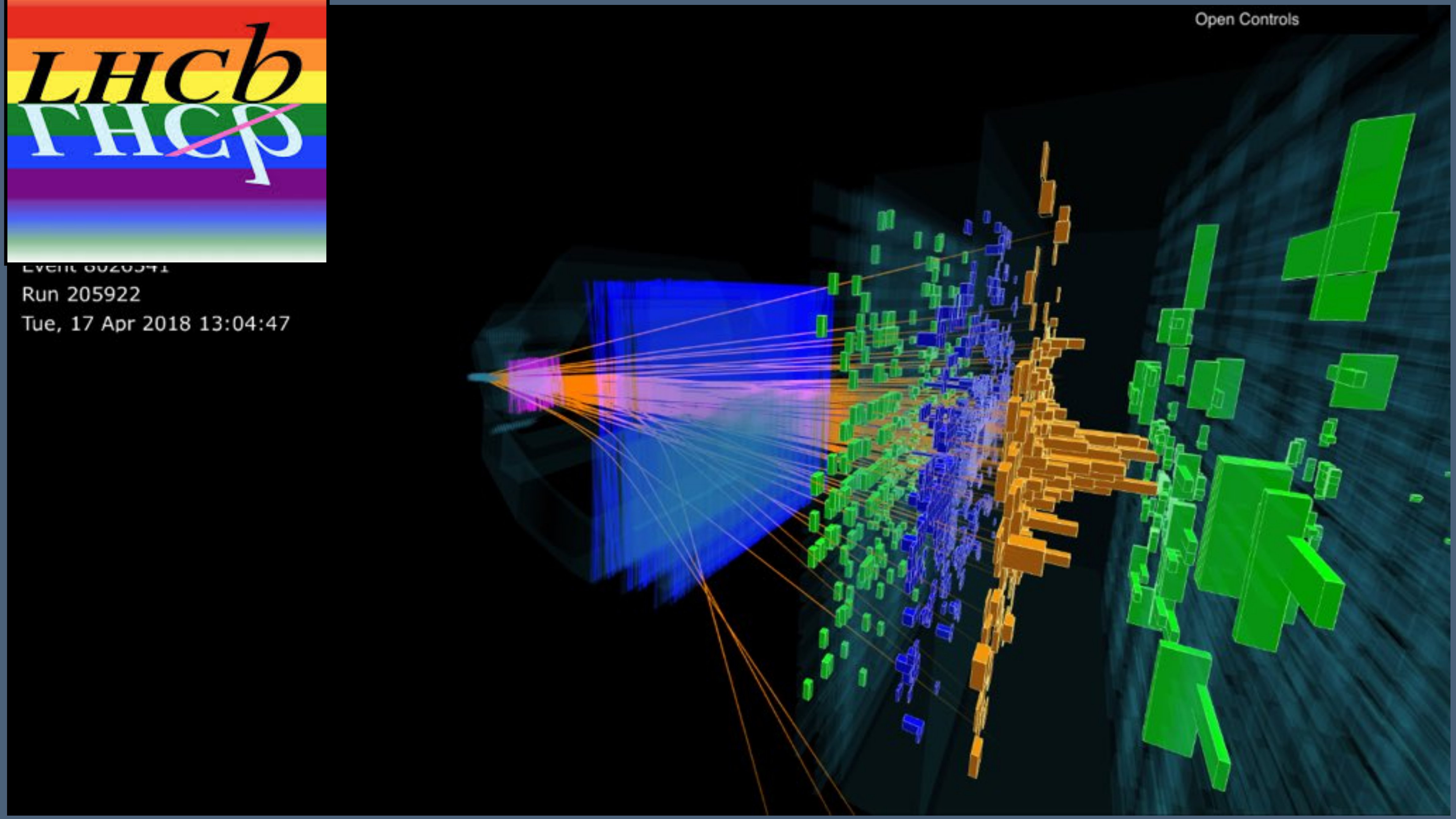
- Dependent of $\sqrt{s_{NN}}$
- No need to measure Event Plane!
- Signal present also for AntiLambdas!

As opposed to the known hadronic high-x production-plane polarization effect

[1] M Lisa, et al: Phys. Rev. C 104, 011901 (2021)

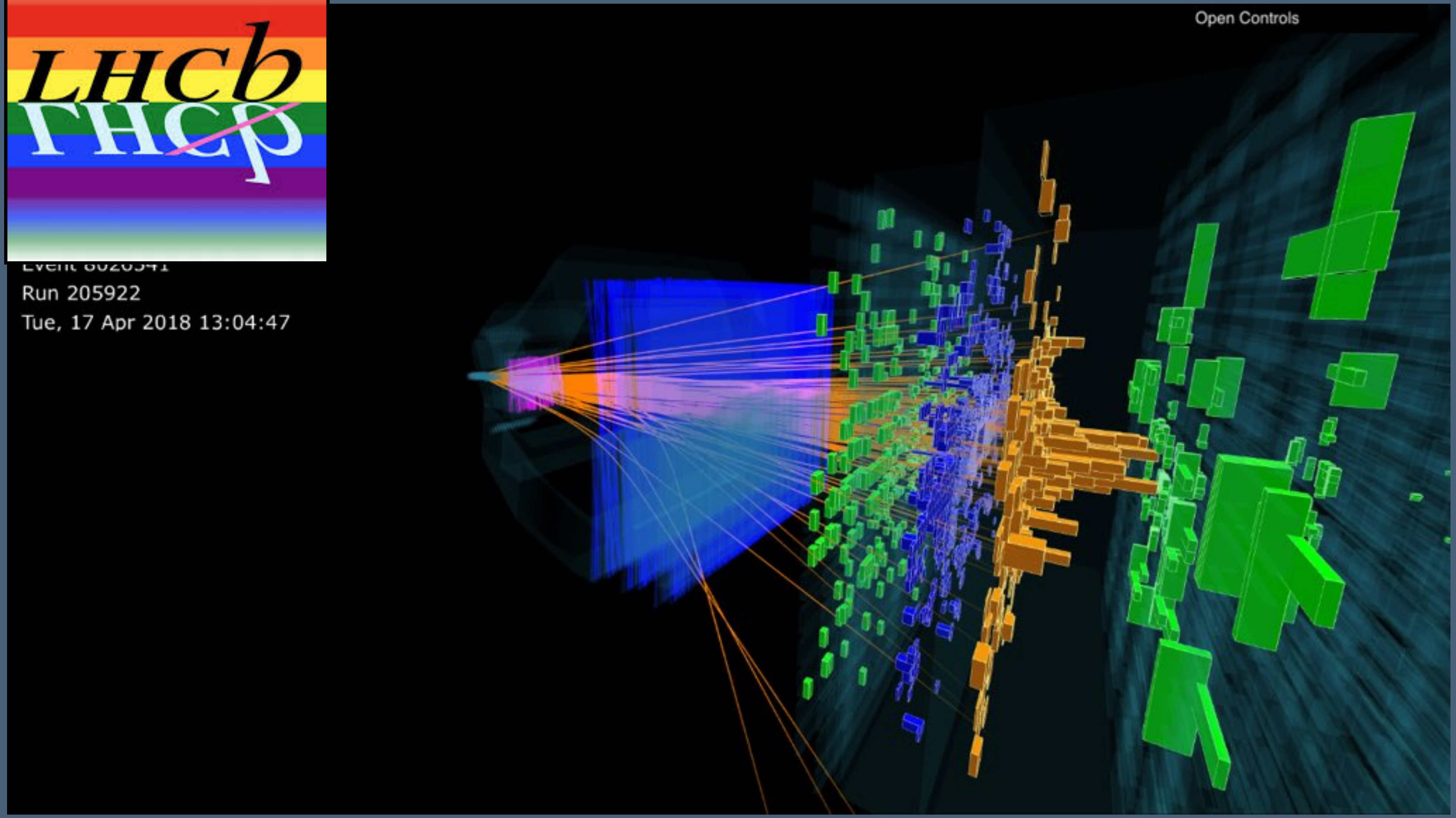
Smoking rings at LHC

- High precision of Λ identification
- Forward rapidity coverage
- Multiple p+A (+PbNe) collision systems ready to be studied with incredible statistics

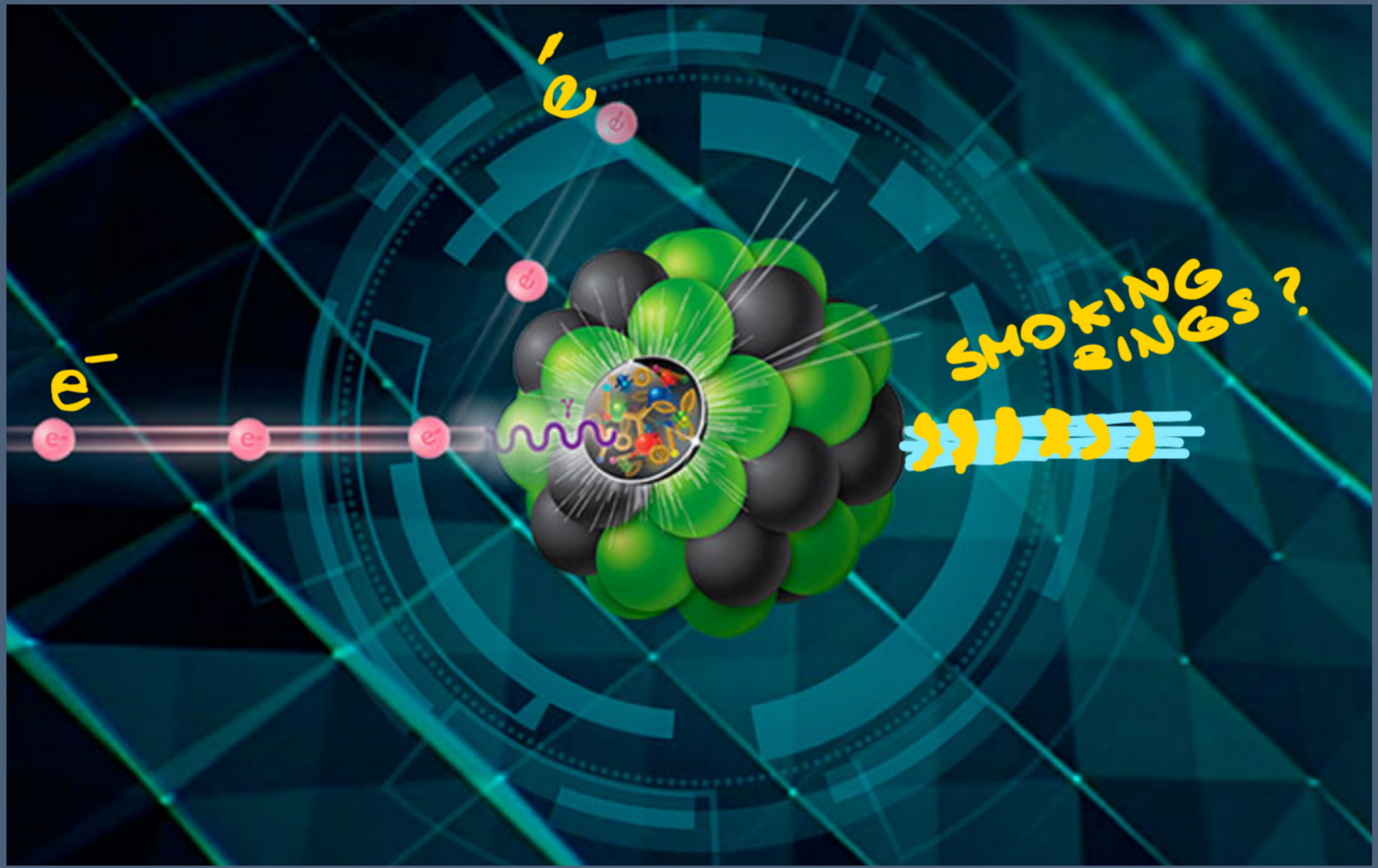


Smoking rings at LHC and EIC

- High precision of Λ identification
- Forward rapidity coverage
- Multiple p+A (+PbNe) collision systems ready to be studied with incredible statistics



- Toroidal vortexes in e+A collisions?



Questions

1. What is "a small system" ?
2. If we see non-zero R, is it definitely fluid or can be described by sth else?
3. How we can encourage "hydro" people to look on vorticity ?
4. Can any fluid behavior be observed at EIC collisions?

Thank you!