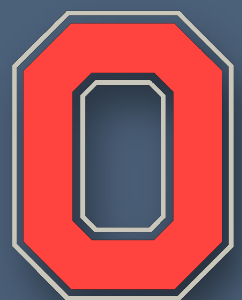


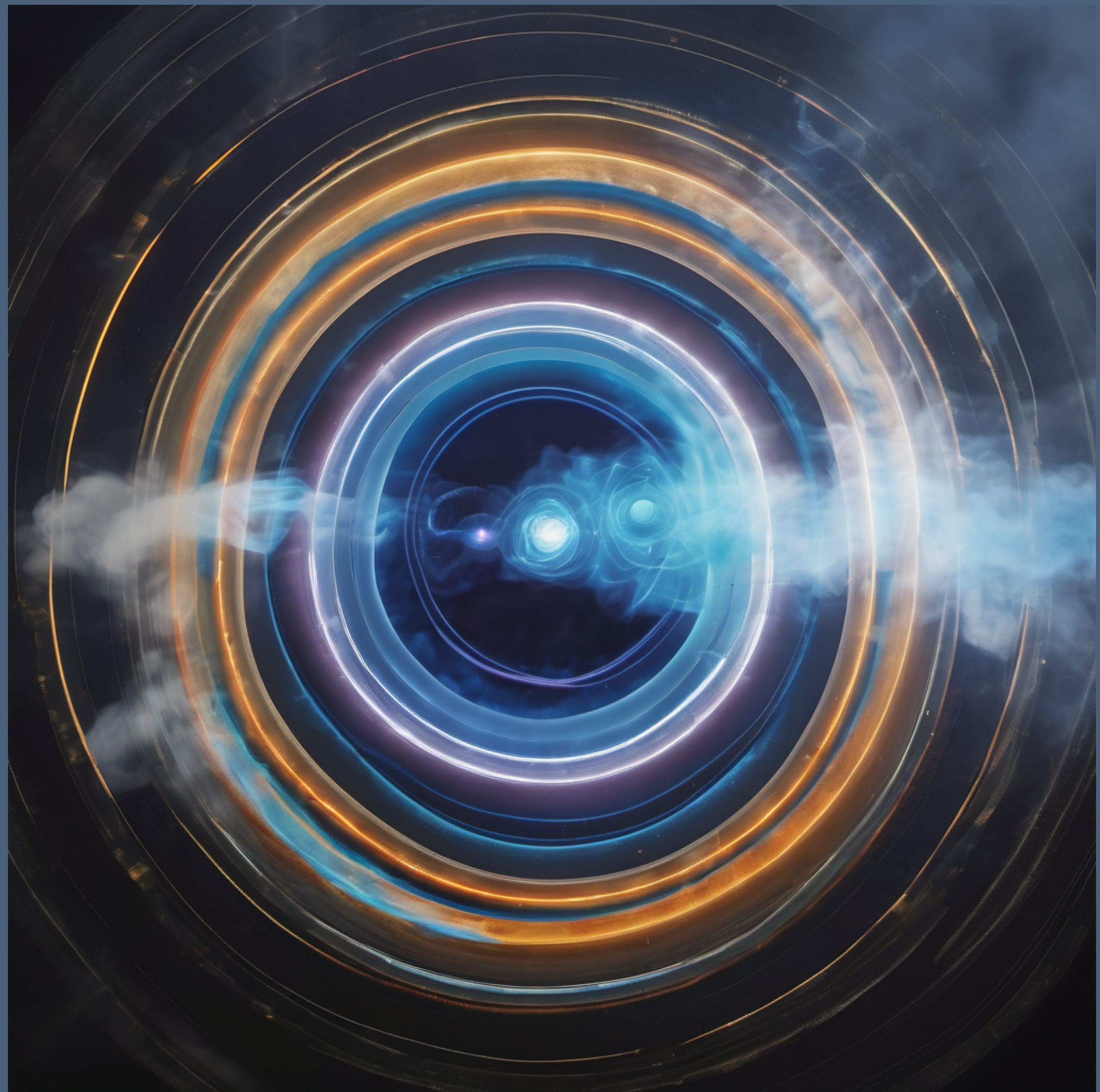
# Toroidal Vorticity @ LHC and EIC

*Maria Stefaniak-Theohares*

with Mike Lisa



THE OHIO STATE UNIVERSITY



# Motivation

Presence of collectivity in “smaller” systems: pA ?

# Motivation

## Presence of collectivity in “smaller” systems: pA ?

The screenshot shows the INSPIRE HEP search results page for the query "Collectivity in small collision systems". The page features a navigation bar with "Literature" selected, and a search bar containing the query. On the left, there is a sidebar with a histogram titled "Date of paper" showing a distribution from 2008 to 2024, and filter options for "Number of authors" (Single author: 64, 10 authors or less: 105) and "Exclude RPP" (Exclude Review of Particle Physics: 112). The main content area displays 112 results, with the top three results shown. Each result includes the title, authors, publication information, and citation count.

INSPIRE HEP literature

Literature Authors Jobs Seminars Conferences More...

112 results |  Citation Summary

**Small System Collectivity in Relativistic Hadronic and Nuclear Collisions** #1  
James L. Nagle (Colorado U.), William A. Zajc (Columbia U.) (Jan 10, 2018)  
Published in: *Ann.Rev.Nucl.Part.Sci.* 68 (2018) 211-235 • e-Print: [1801.03477](#) [nucl-ex]

**Phenomenological Review on Quark–Gluon Plasma: Concepts vs. Observations** #2  
Roman Pasechnik (Lund U. and Lund U., Dept. Theor. Phys.), Michal Šumbera (Rez, Nucl. Phys. Inst. and ASCR, Prague) (Nov 4, 2016)  
Published in: *Universe* 3 (2017) 1, 7 • e-Print: [1611.01533](#) [hep-ph]

**Elliptic flow of charm and strange hadrons in high-multiplicity pPb collisions at  $\sqrt{s_{NN}} = 8.16$  TeV** #3  
CMS Collaboration • A. M. Sirunyan et al. (Apr 25, 2018)  
Published in: *Phys.Rev.Lett.* 121 (2018) 8, 082301 • e-Print: [1804.09767](#) [hep-ex]

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The screenshot shows the INSPIRE HEP search results page for the query "Collectivity in small collision systems". The page features a navigation bar with "Literature", "Authors", "Jobs", "Seminars", "Conferences", and "More...". The search results are displayed in a list format, with the top three results highlighted by orange boxes. The first result, "Small System Collectivity in Relativistic Hadronic and Nuclear Collisions" by James L. Nagle and William A. Zajc, is circled in red. The second and third results are also circled in orange. The left sidebar contains a histogram of paper dates and filter options for the number of authors and RPP exclusion.

INSPIRE HEP literature

Literature Authors Jobs Seminars Conferences More...

112 results |  Citation Summary  Most Cited

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**Date of paper**  
  
2008 2024

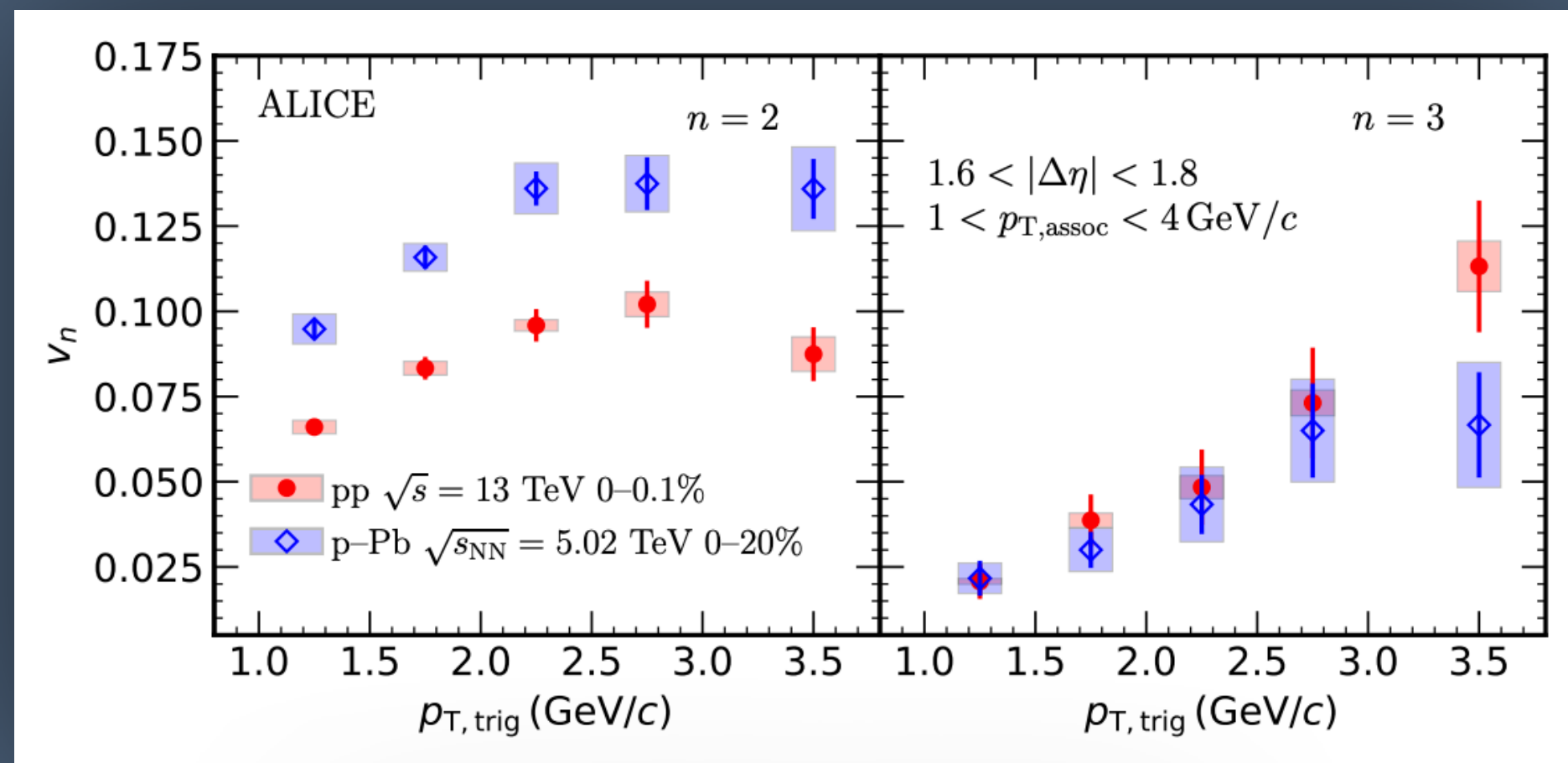
**Number of authors**  
 Single author   
 10 authors or less

**Exclude RPP**  
 Exclude Review of Particle Physics

# Motivation

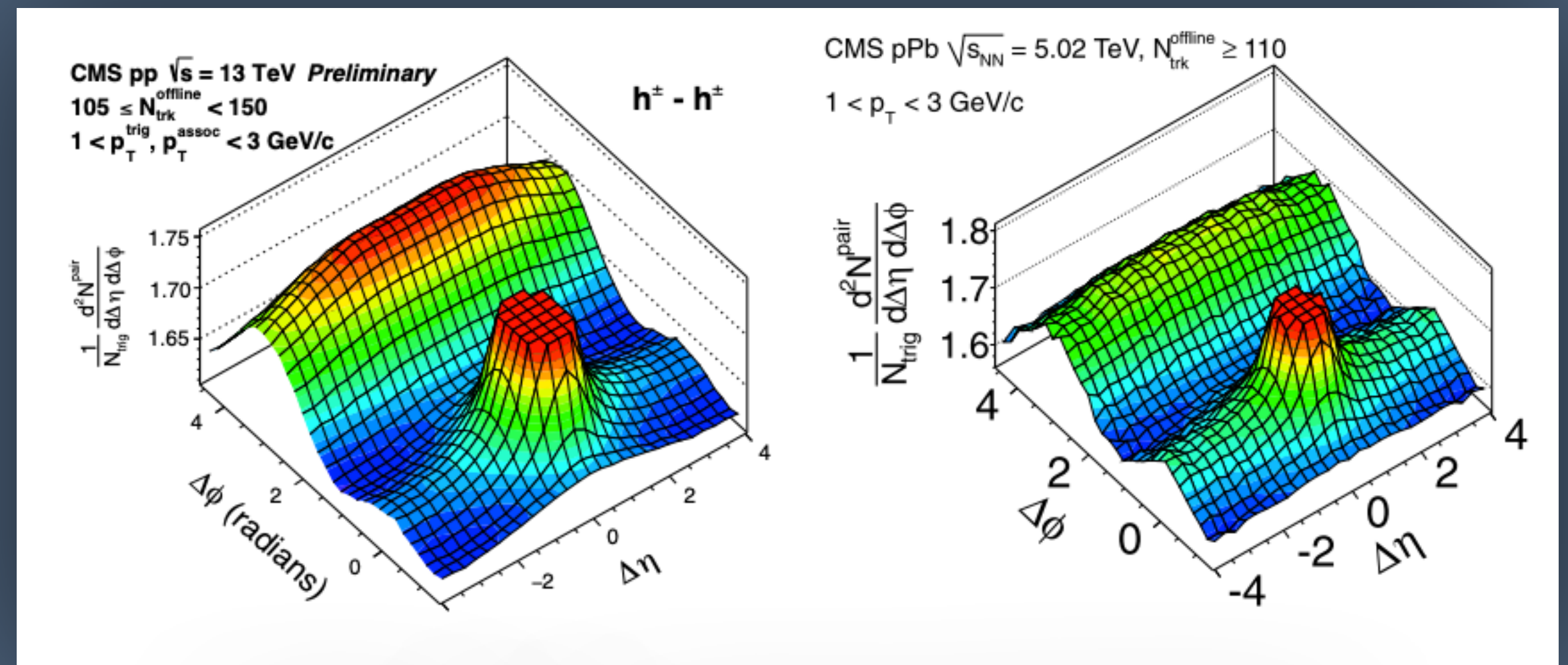
Presence of collectivity in “smaller” systems: pA ?

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<sup>1a</sup>, in collaboration with J. Scott Moreland<sup>b</sup>

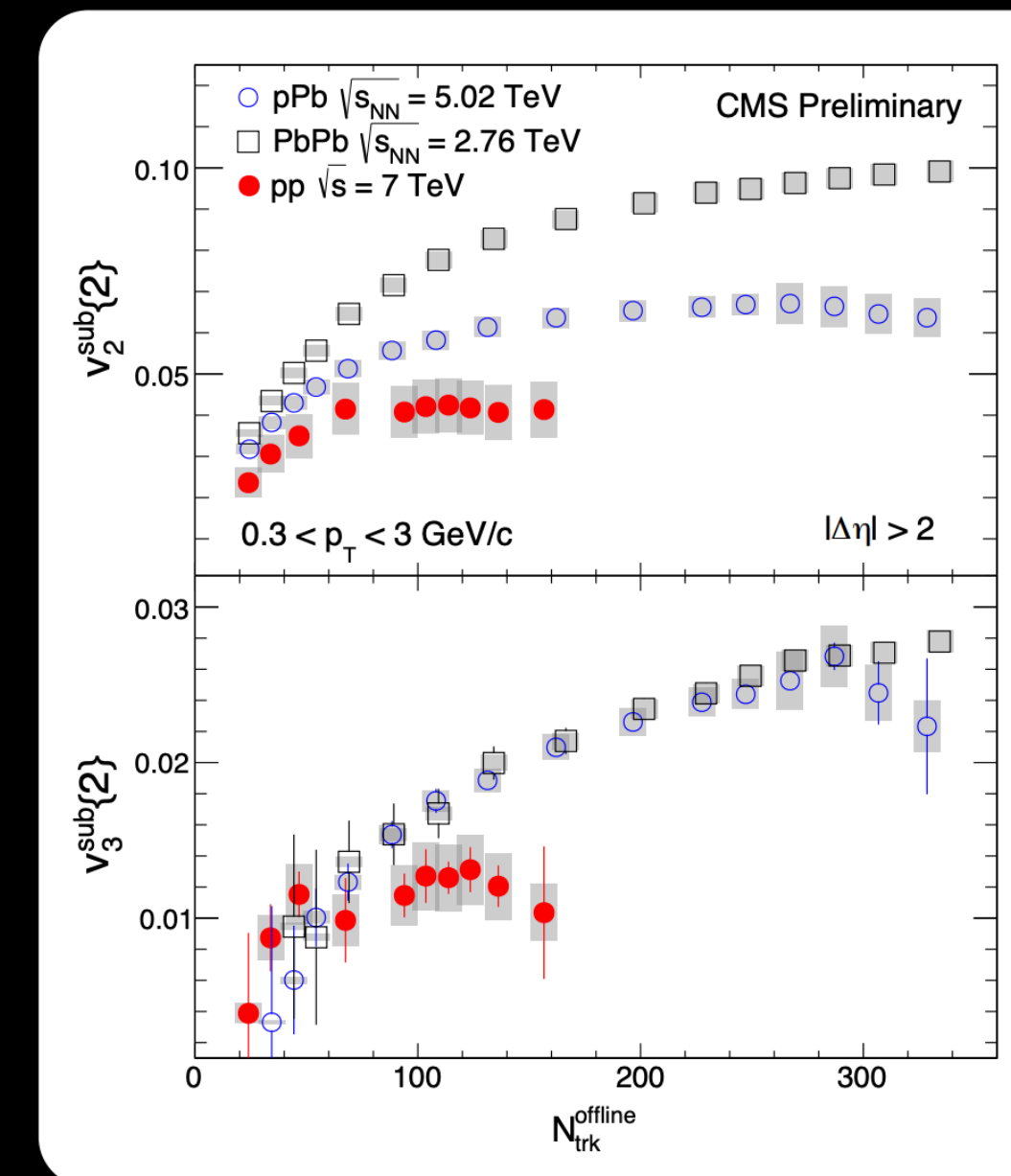
<sup>a</sup>Department of Physics, The Ohio State University, Columbus, OH 43210-1117, USA

<sup>b</sup>Department of Physics, Duke University, Durham, NC 27708-0305, USA

E-mail: heinz.9@osu.edu

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

## $v_2$ IN p+p, p+Pb, Pb+Pb COLLISIONS



SEE ALSO:

ALICE COLLABORATION  
PHYS. LETT. B719 (2013) 29-41;  
PHYS. REV. C 90, 054901

ATLAS COLLABORATION  
PHYS. REV. LETT. 110, 182302  
(2013); PHYS. REV. C 90.044906  
(2014)

CMS COLLABORATION  
PHYS.REV.LETT. 115, 012301 (2015)



CMS PAS HIN-15-009

12

Björn Schenke, BNL

LHCP 2018

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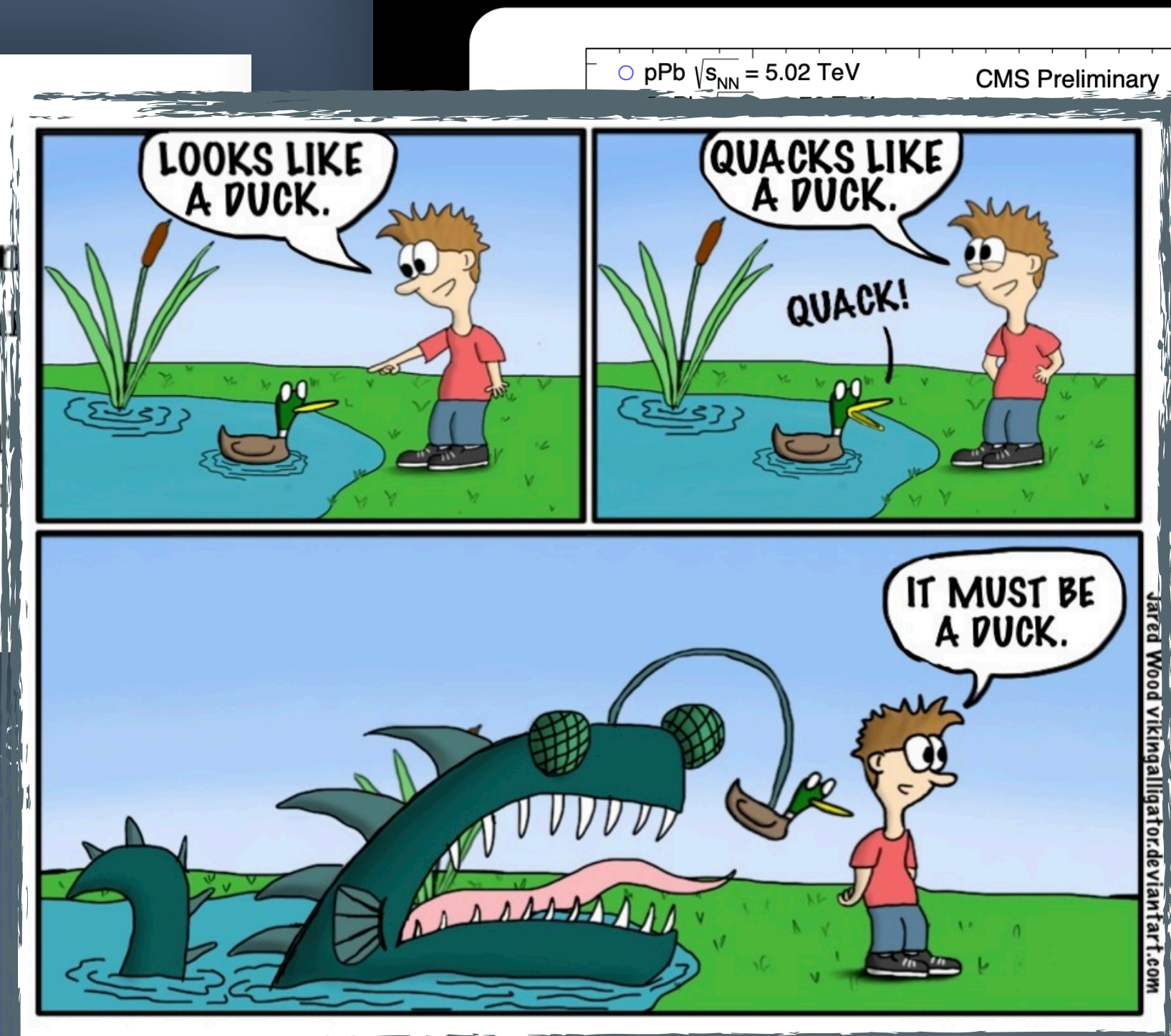
Ulrich Heinz<sup>1a</sup>, in collaboration with J. Scott Moreland

<sup>a</sup>Department of Physics, The Ohio State University, Columbus, OH 43210-1321

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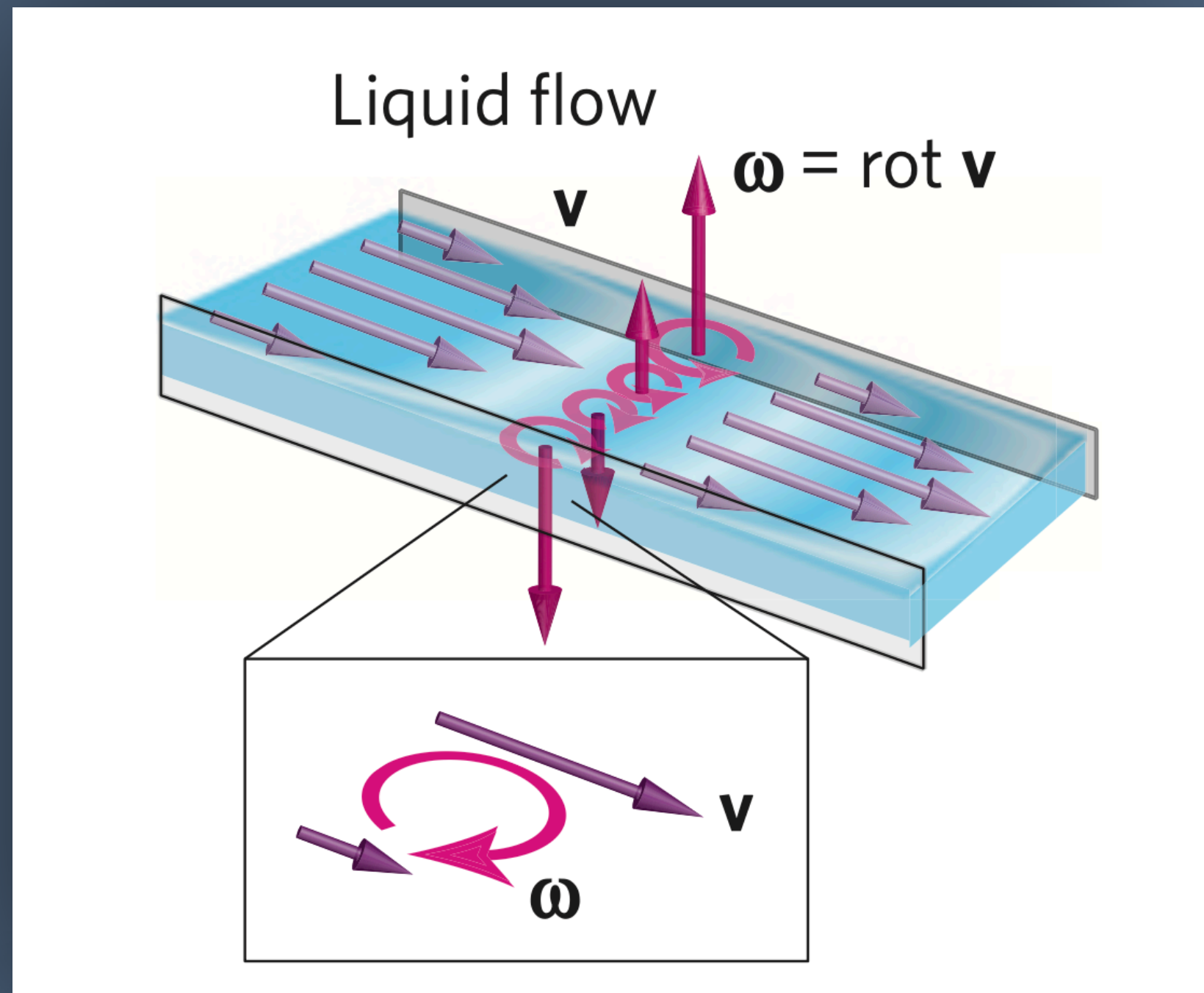


Björn Schenke, BNL

LHCP 2018

Another way to probe fluid:

# Vorticity



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

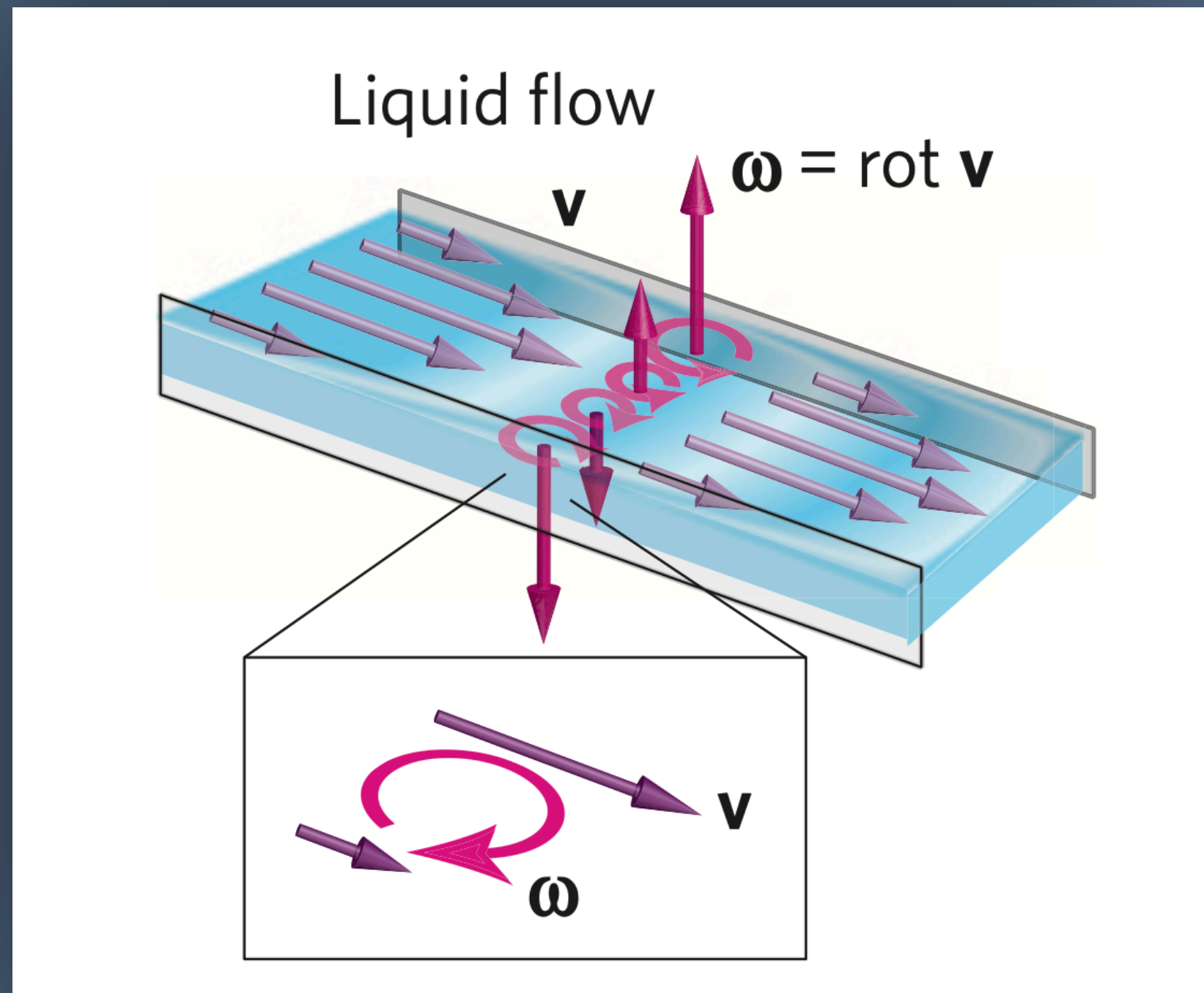
$$\vec{\omega}_{NR} = \frac{1}{2} \vec{\nabla} \times \vec{v}$$

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



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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.

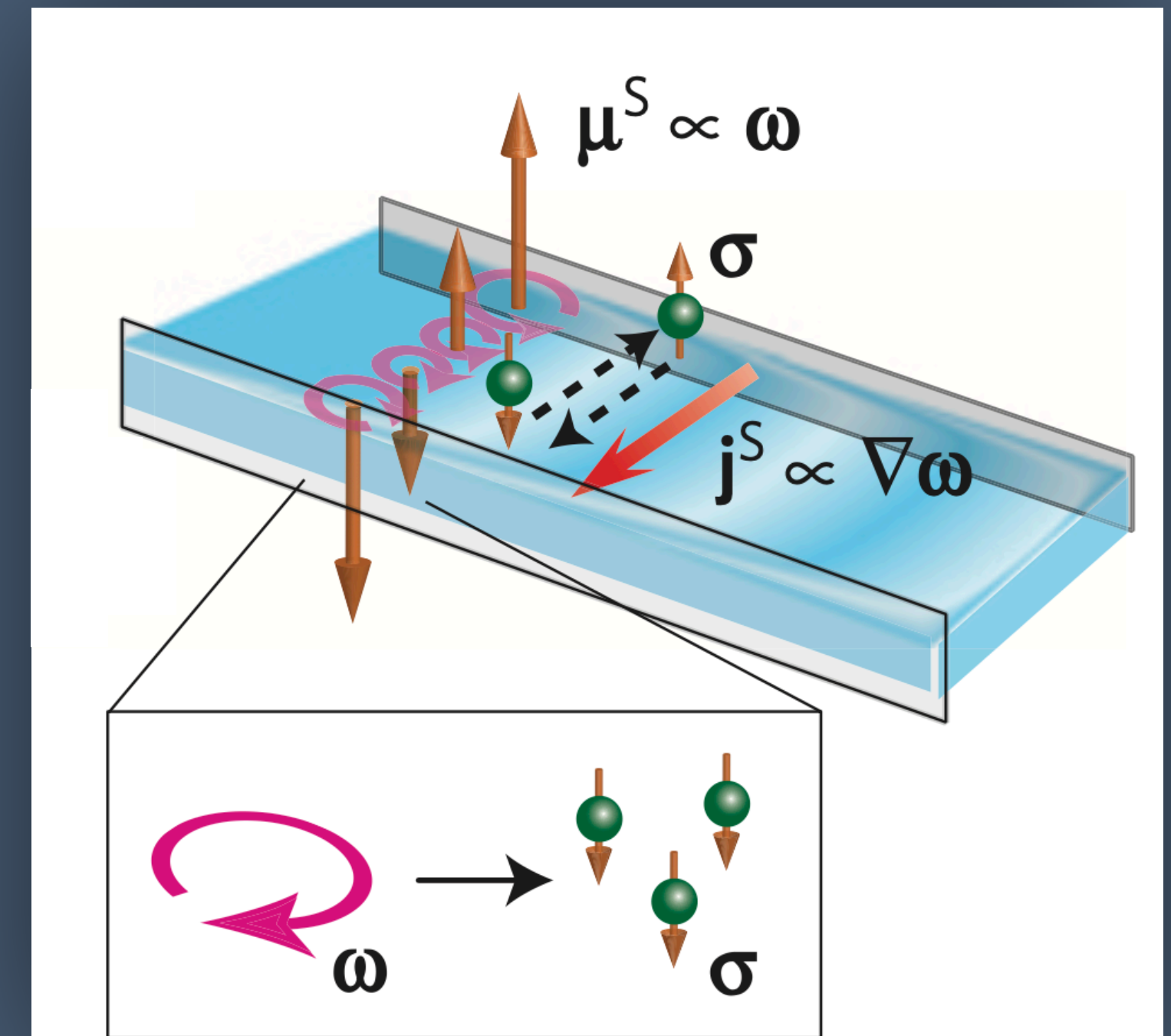
$$\nabla^2 \mu^s = \frac{1}{\lambda} \mu^s - \frac{4e^2}{\sigma_0 \hbar} \xi \omega$$

$\mu^s$  - spin voltage

$\lambda$  - spin-diffusion length

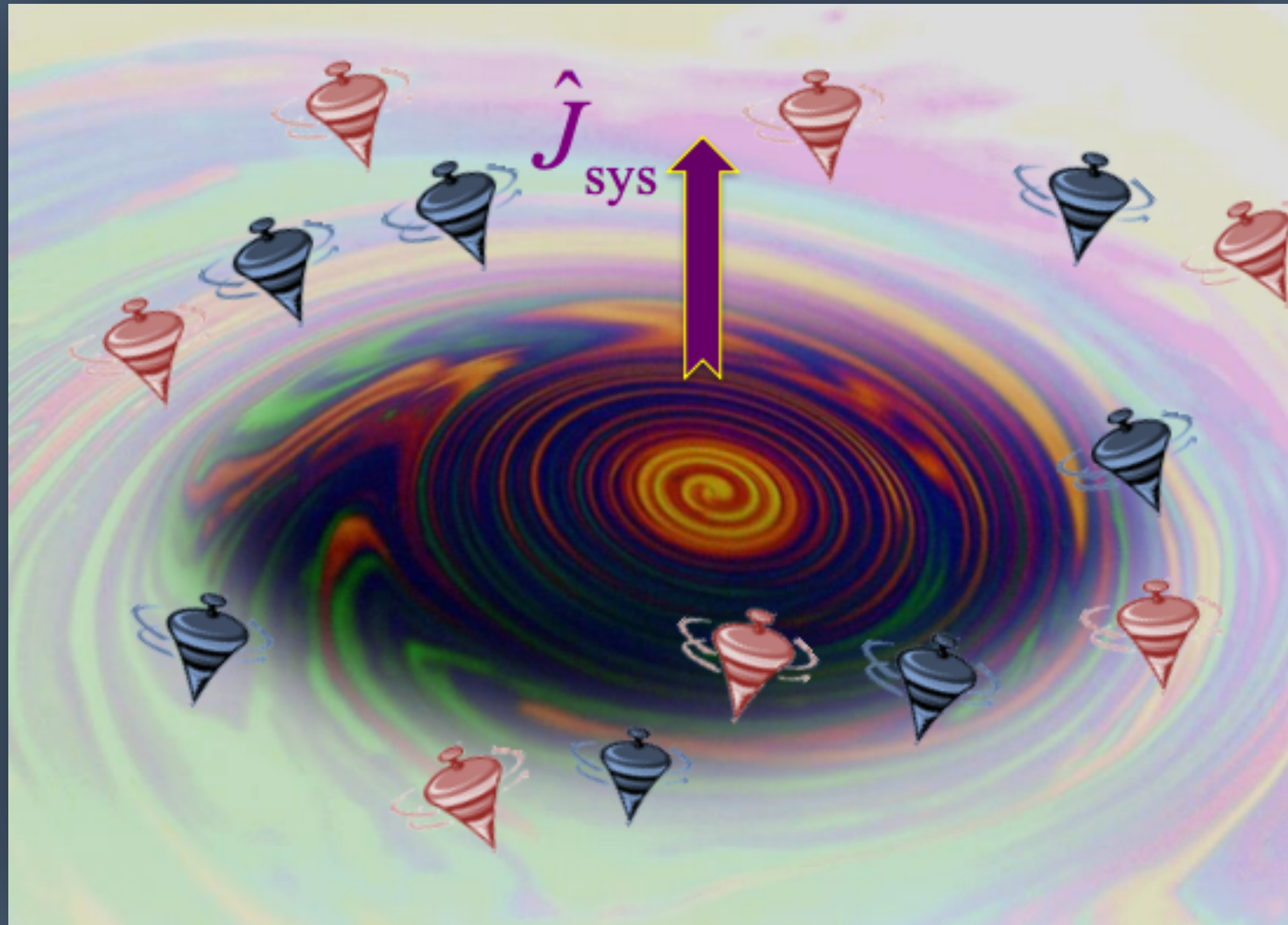
$\sigma_0$  - electric conductivity

$\xi$  - related to fluid viscosity caused by angular-momentum transfer



# Vorticity

Fig by Mike Lisa

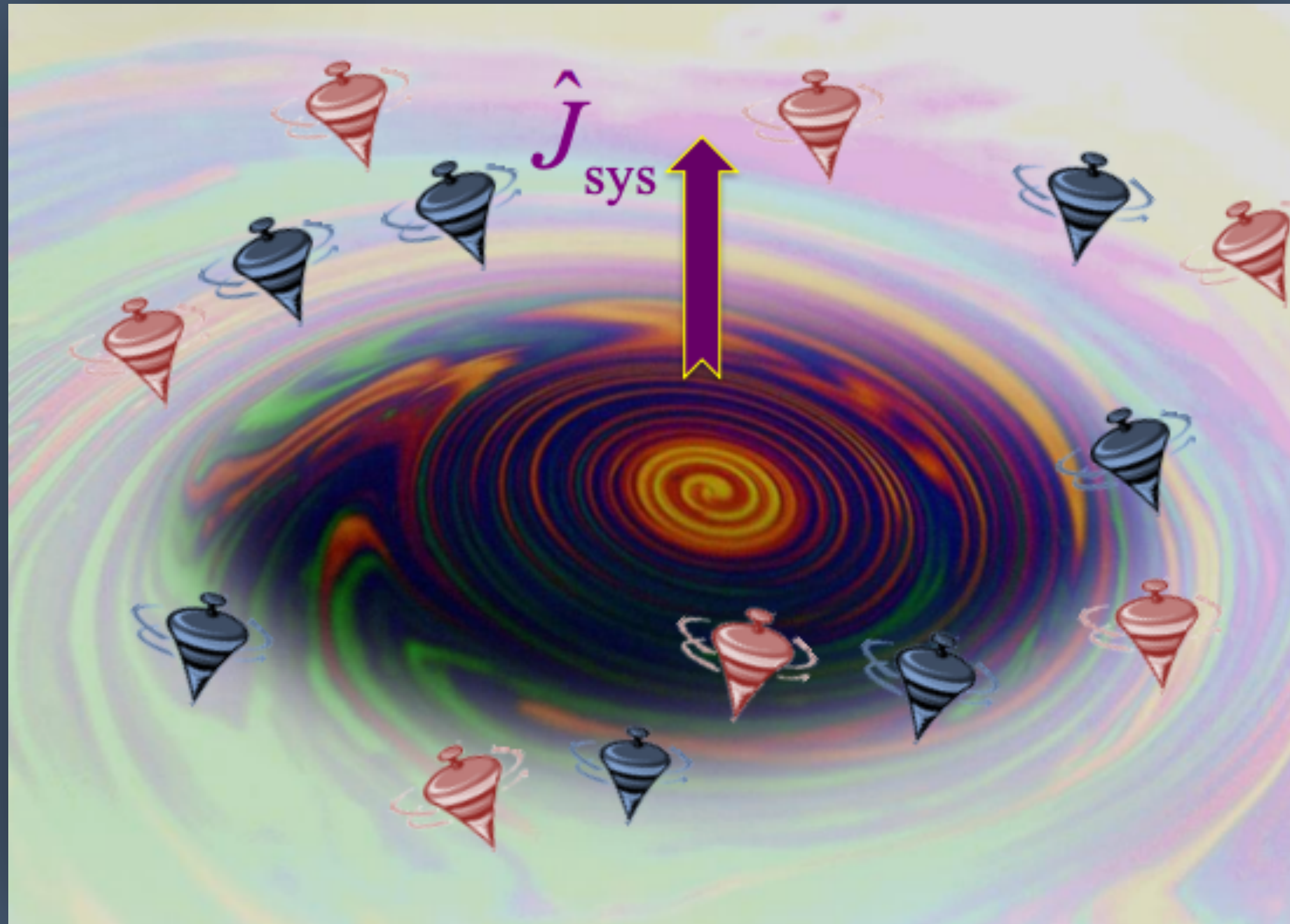


Possible to measure via polarization:

*Spin-orbit coupling produces an observable electron polarization proportional to the local fluid vorticity*

# Vorticity

Fig by Mike Lisa



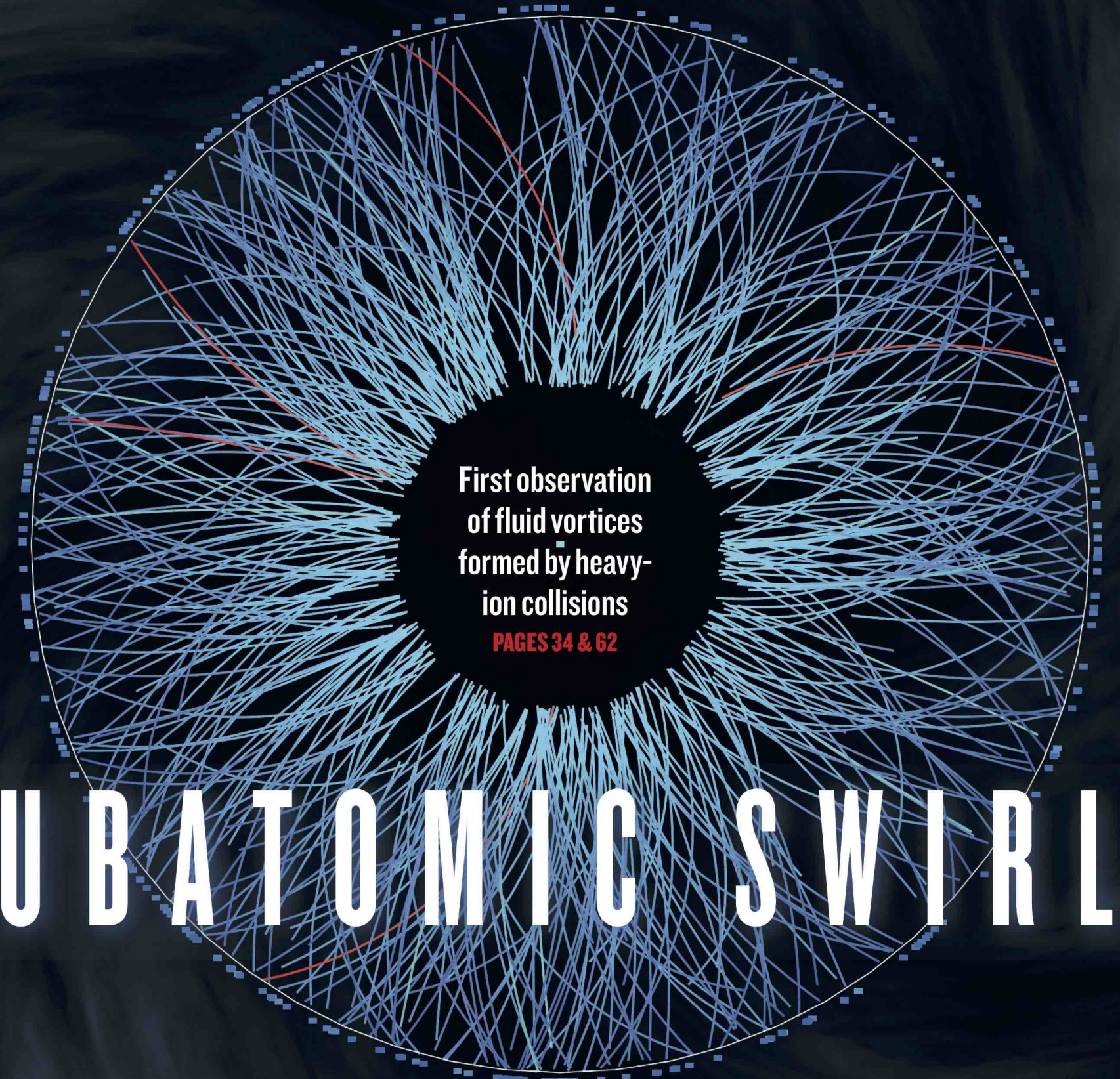
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*M. Stefaniak-Theohares: Physics with high-luminosity proton-nucleus collisions*

# nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE



## SUBATOMIC SWIRLS

CLIMATE CHANGE

**PARIS AGREEMENT**  
Time for nations to match words with deeds  
PAGE 25

BOOKS

**SUMMER SELECTION**  
Recommended reading for the holiday season  
PAGE 28

STEM CELLS

**YOUTHFUL SECRETS**  
How the hypothalamus helps to control the ageing process  
PAGE 52

NATURE.COM/NATURE

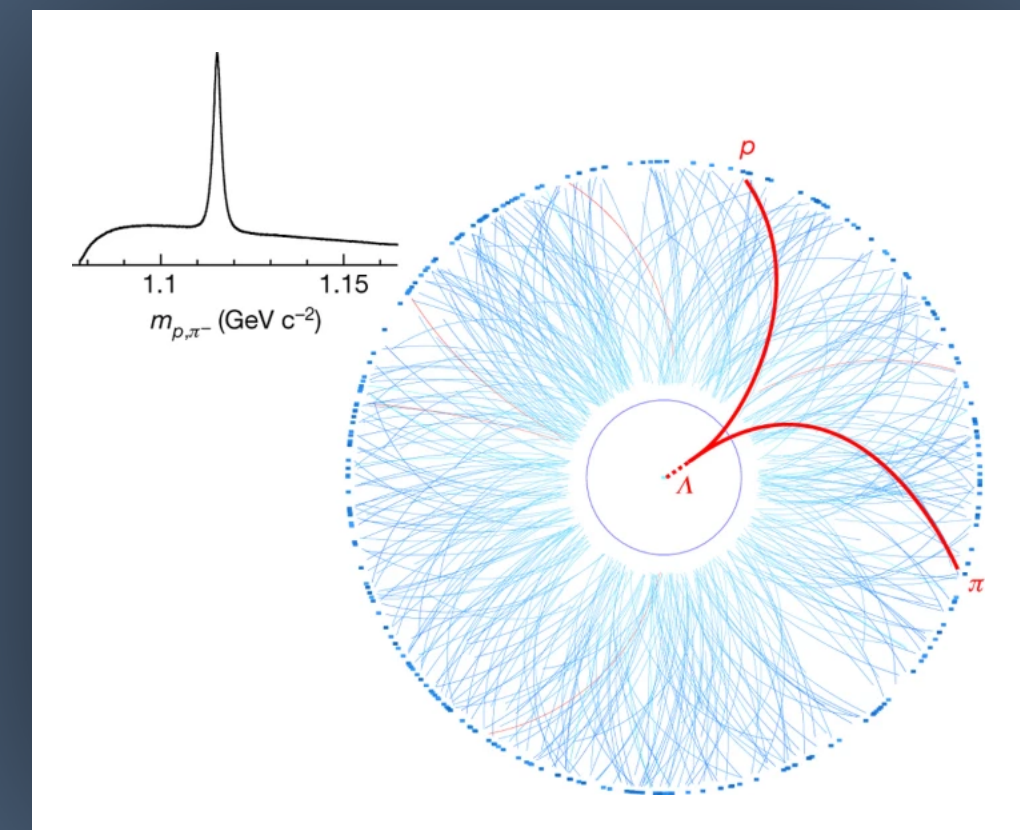
3 August 2017

Vol. 548, No. 7665

# Vorticity

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

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

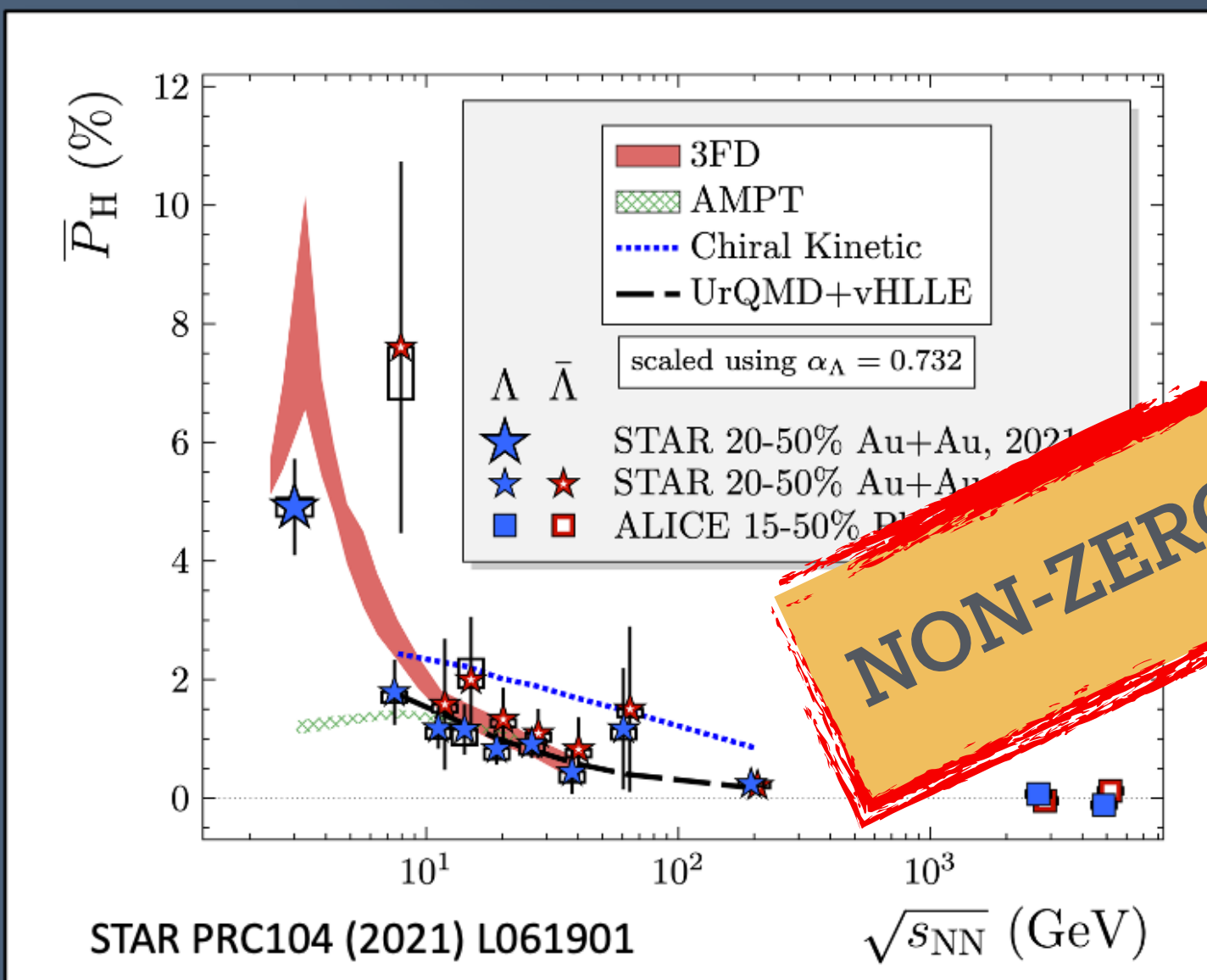
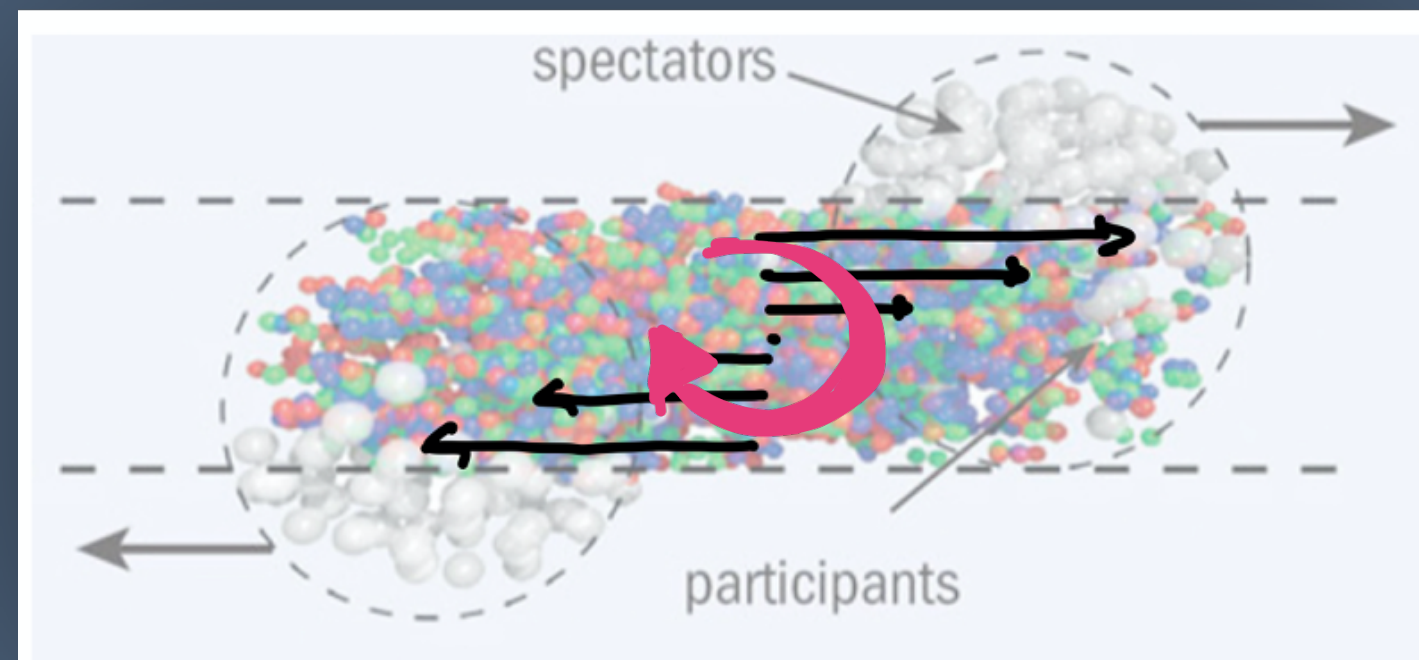
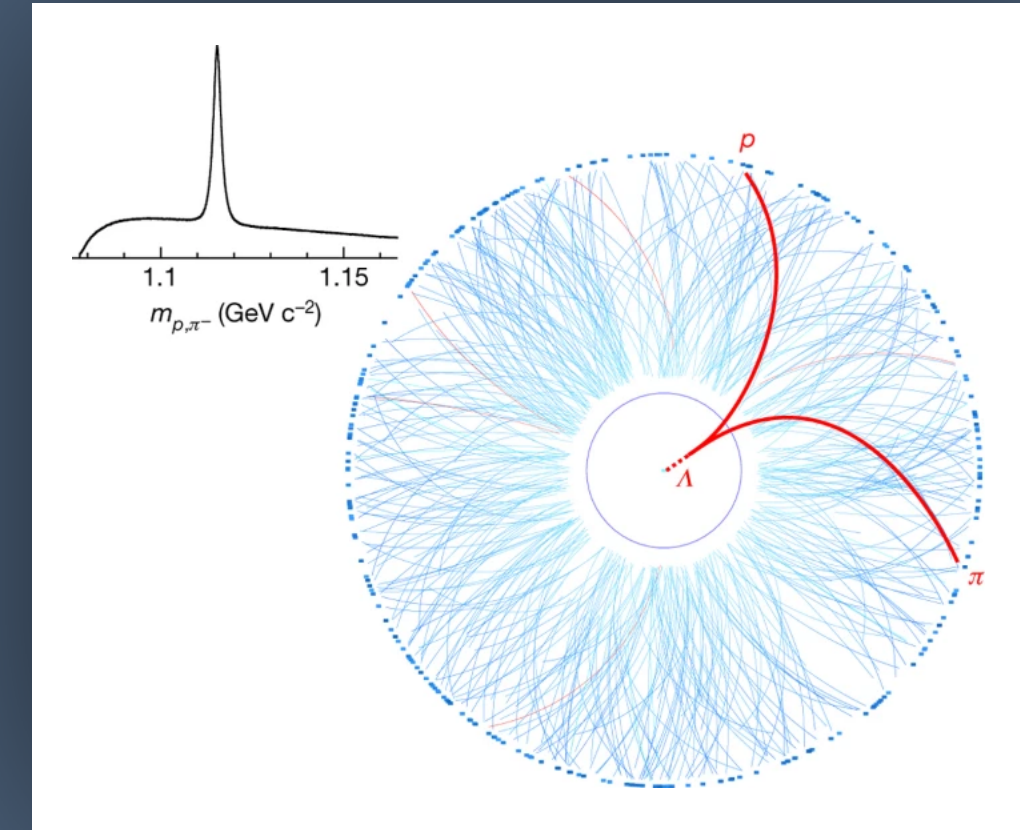


# Vorticity

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

## GLOBAL

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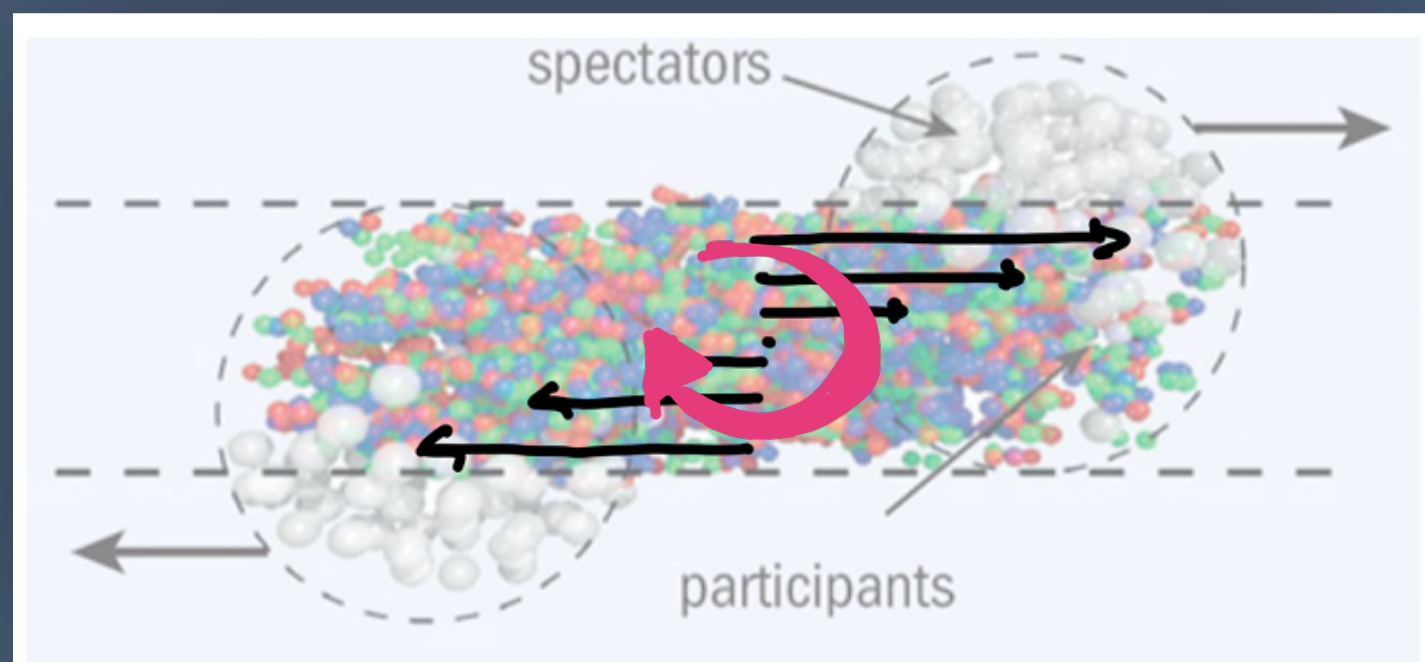
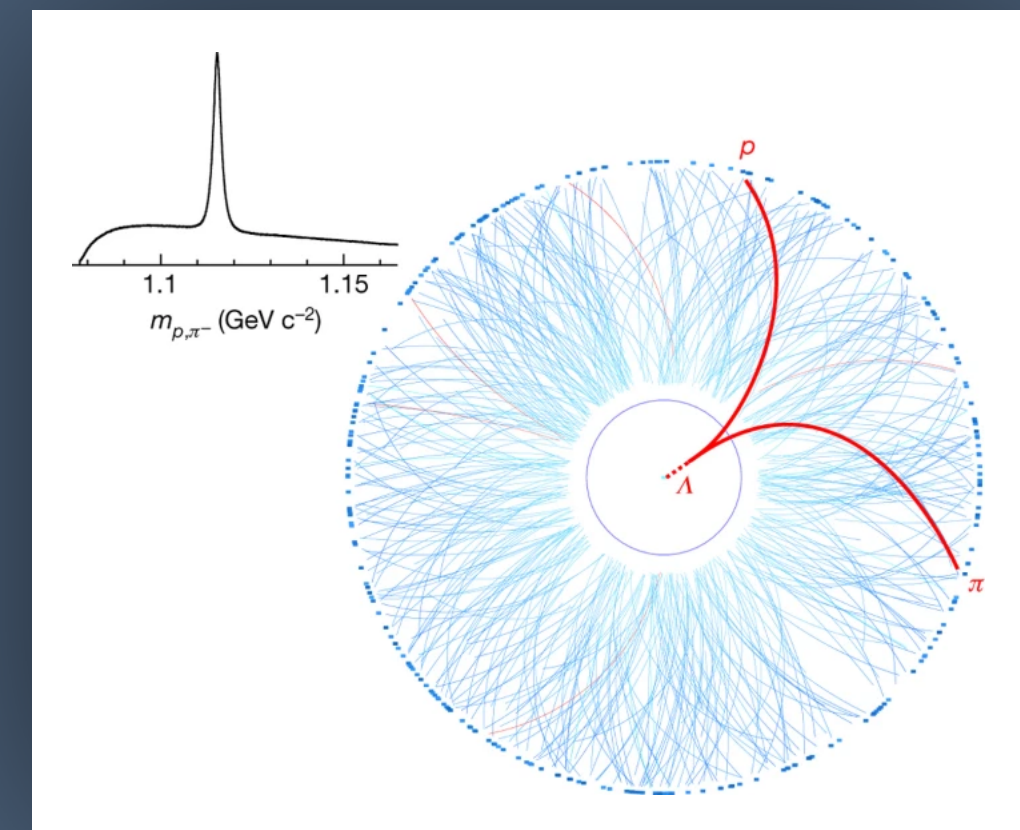
**NON-ZERO at lower  $\sqrt{s_{NN}}$  !!**

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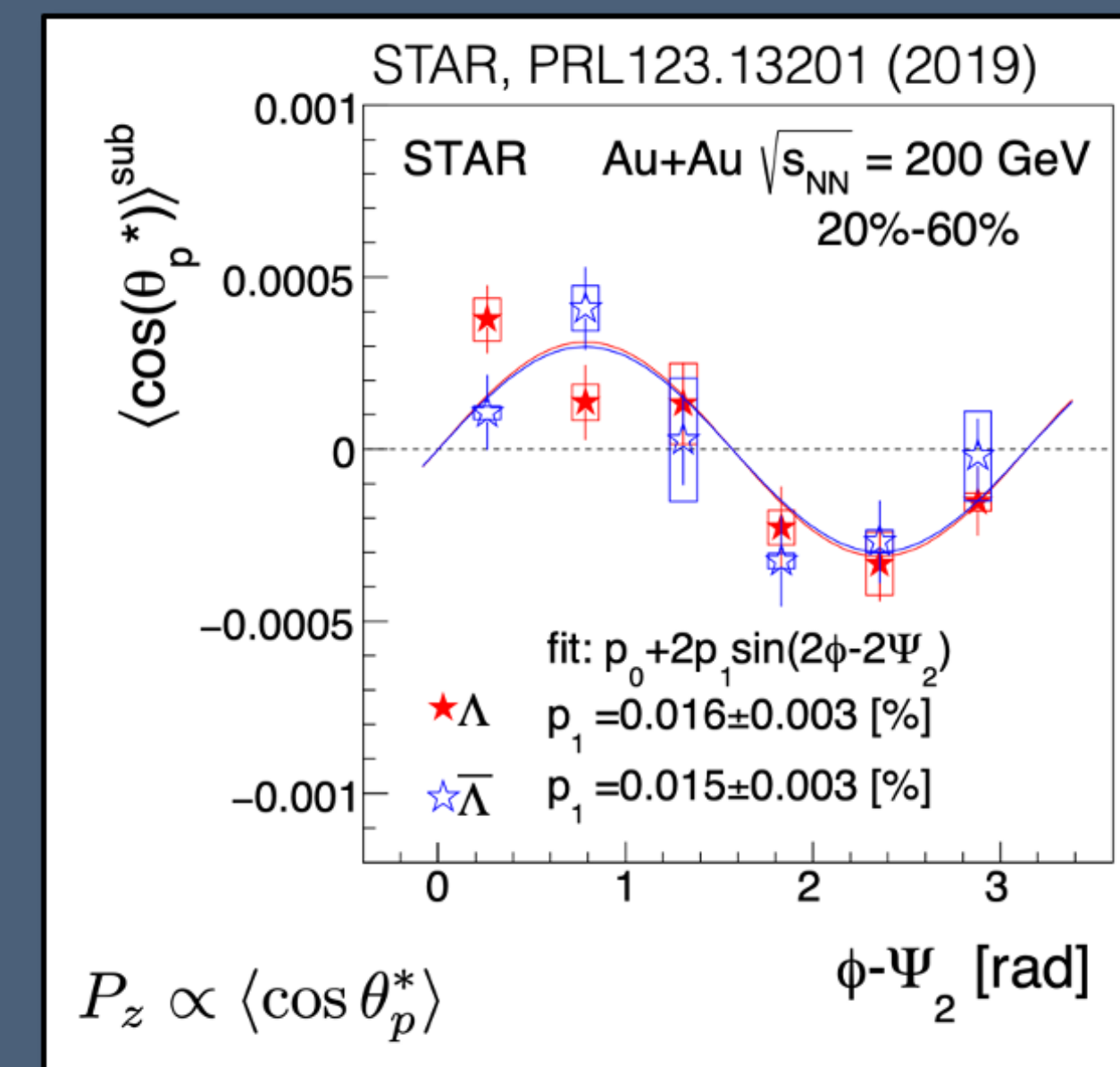
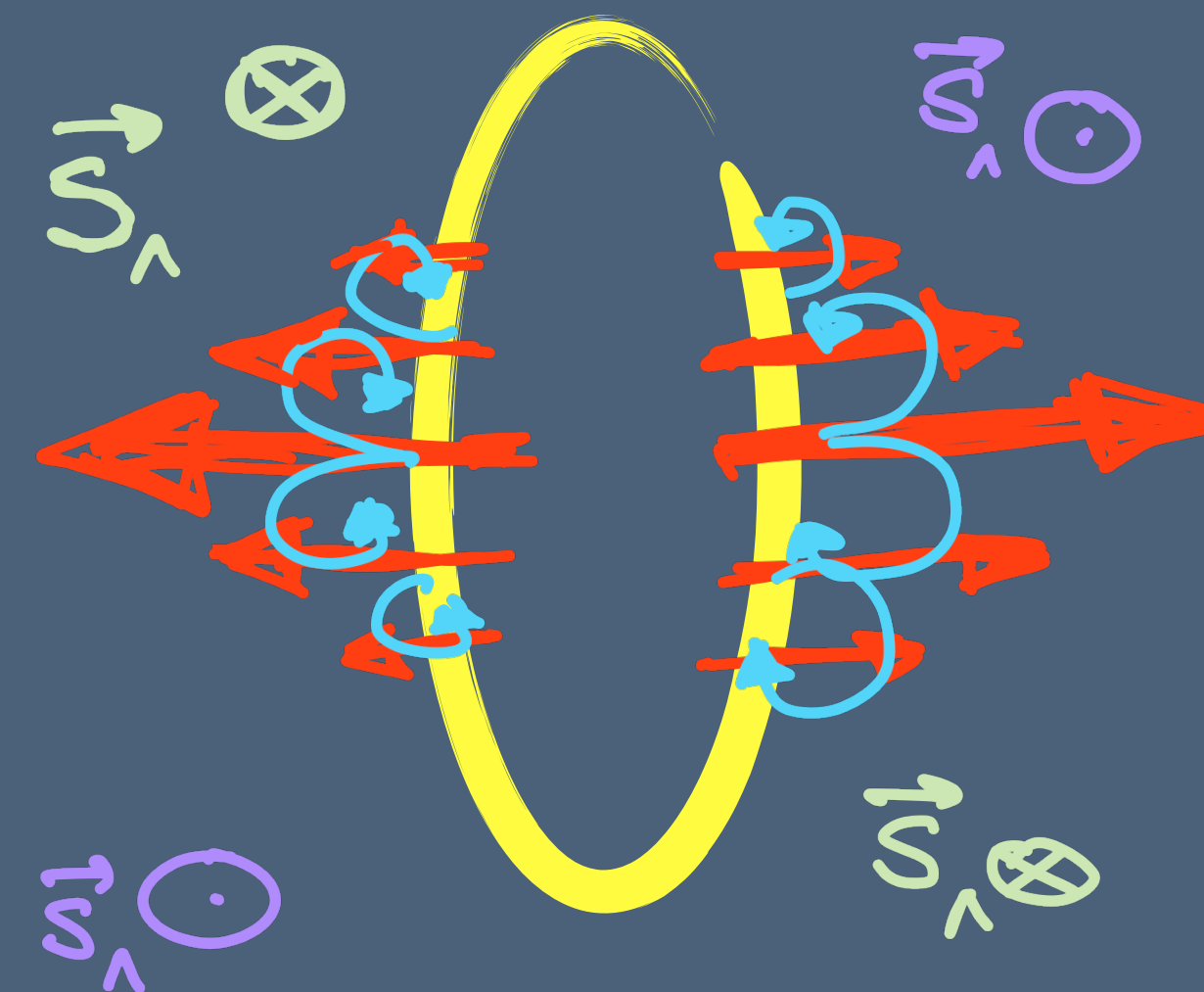
## GLOBAL

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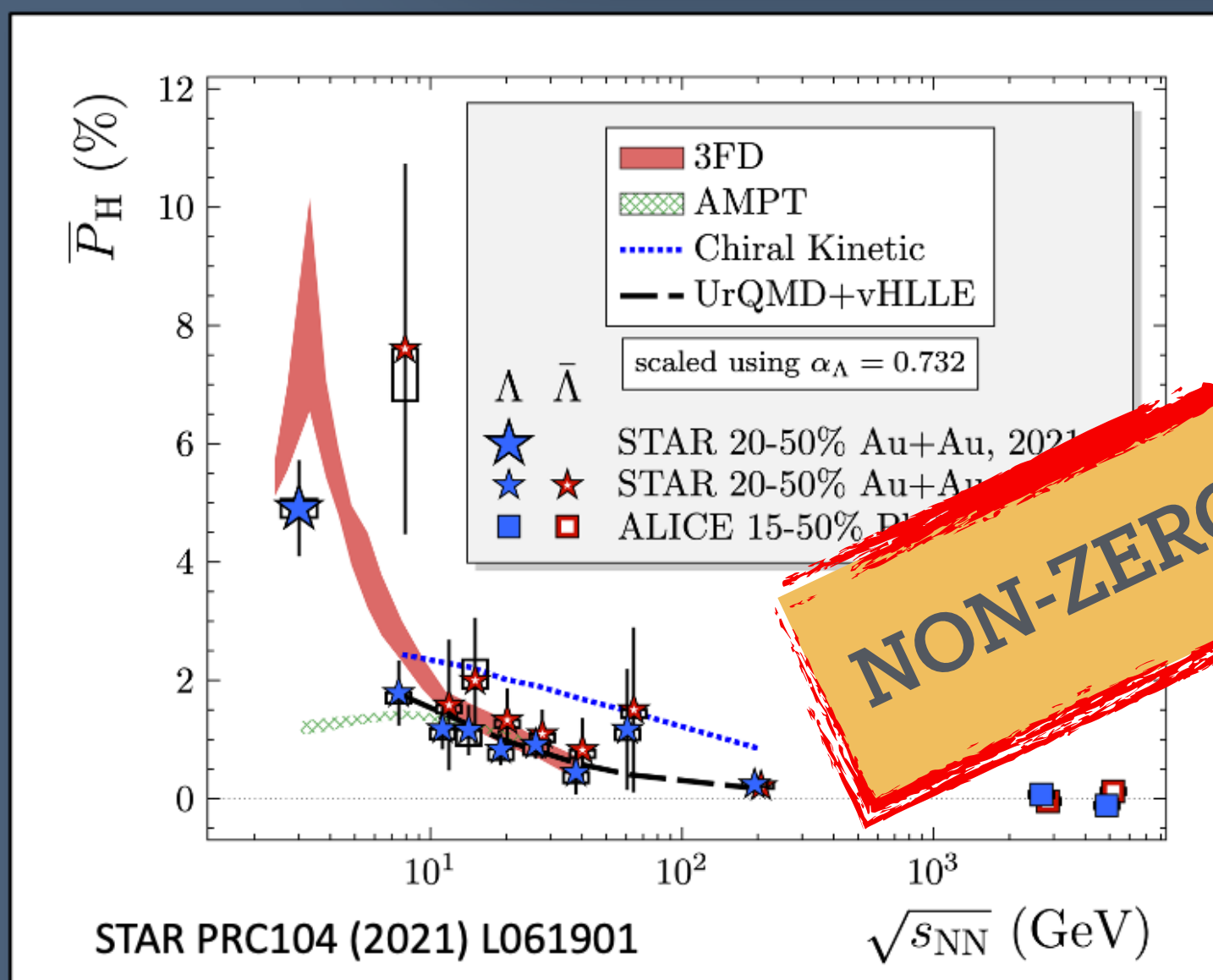


## LOCAL

Effect of elliptic flow



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



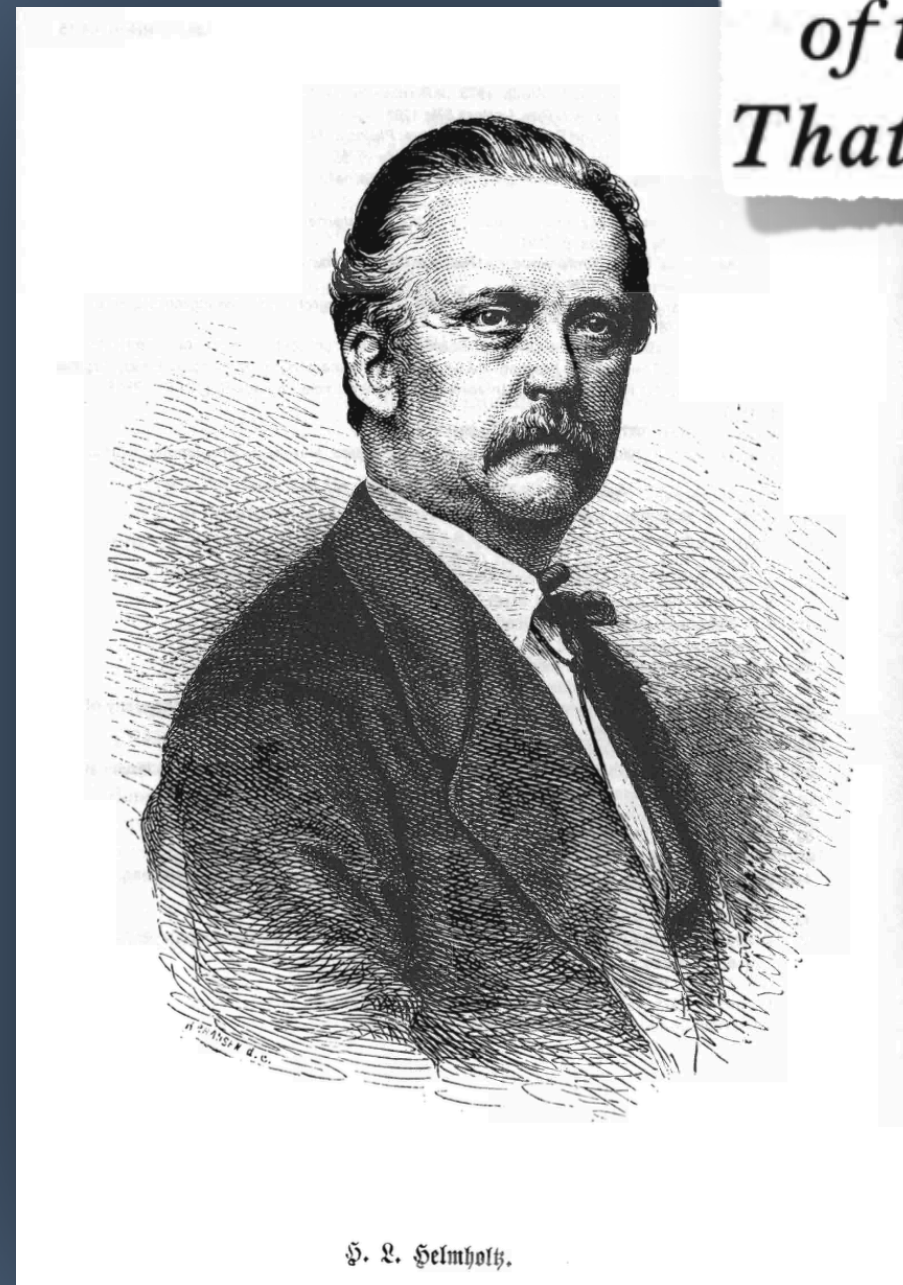
# Vorticity: Toroidal (smoke rings)

Present (in physics) for ages.

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

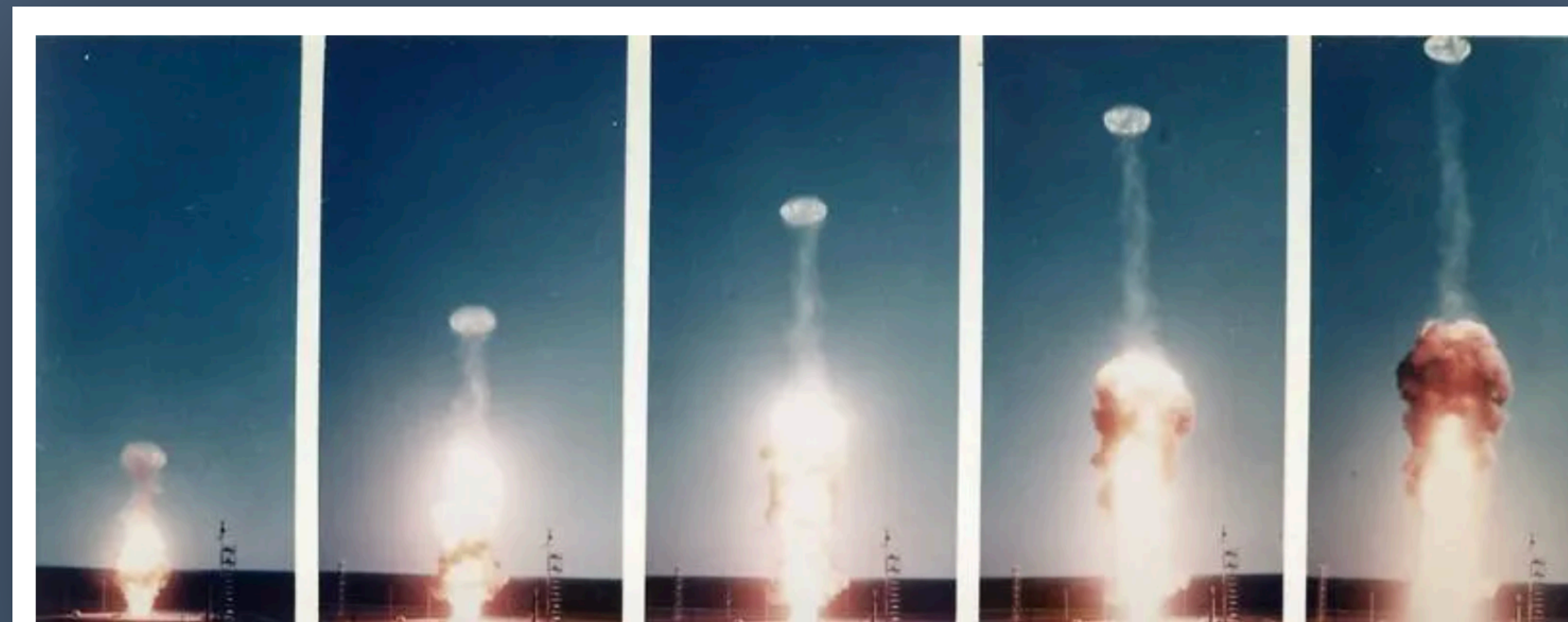
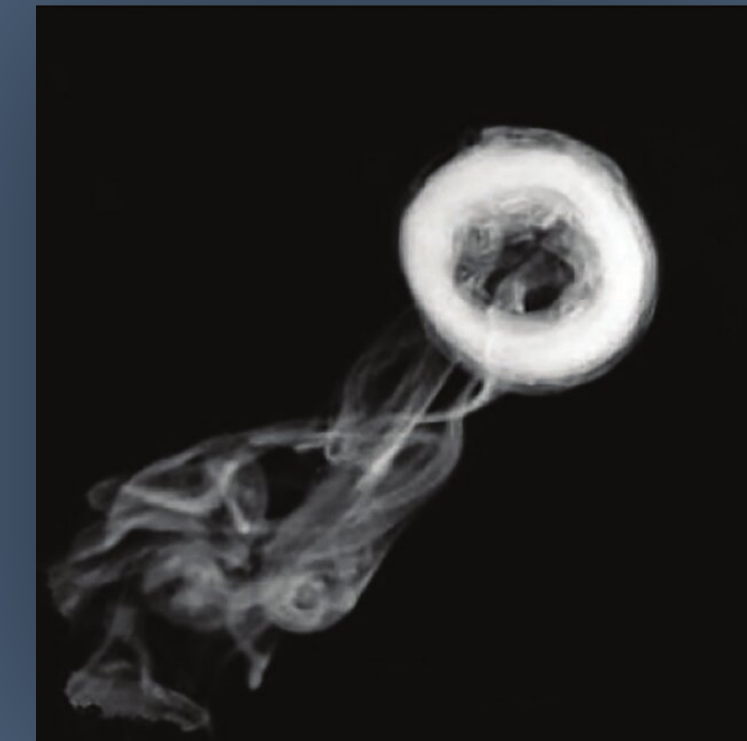
Figures from book: *Subtle Agroecologies*

*On Integrals  
of the Hydrodynamic Equations  
That Correspond to Vortex Motions*



Helmholtz (1858)

*Persistent vortical toroids (smoke rings) are  
quintessential fluid behavior*

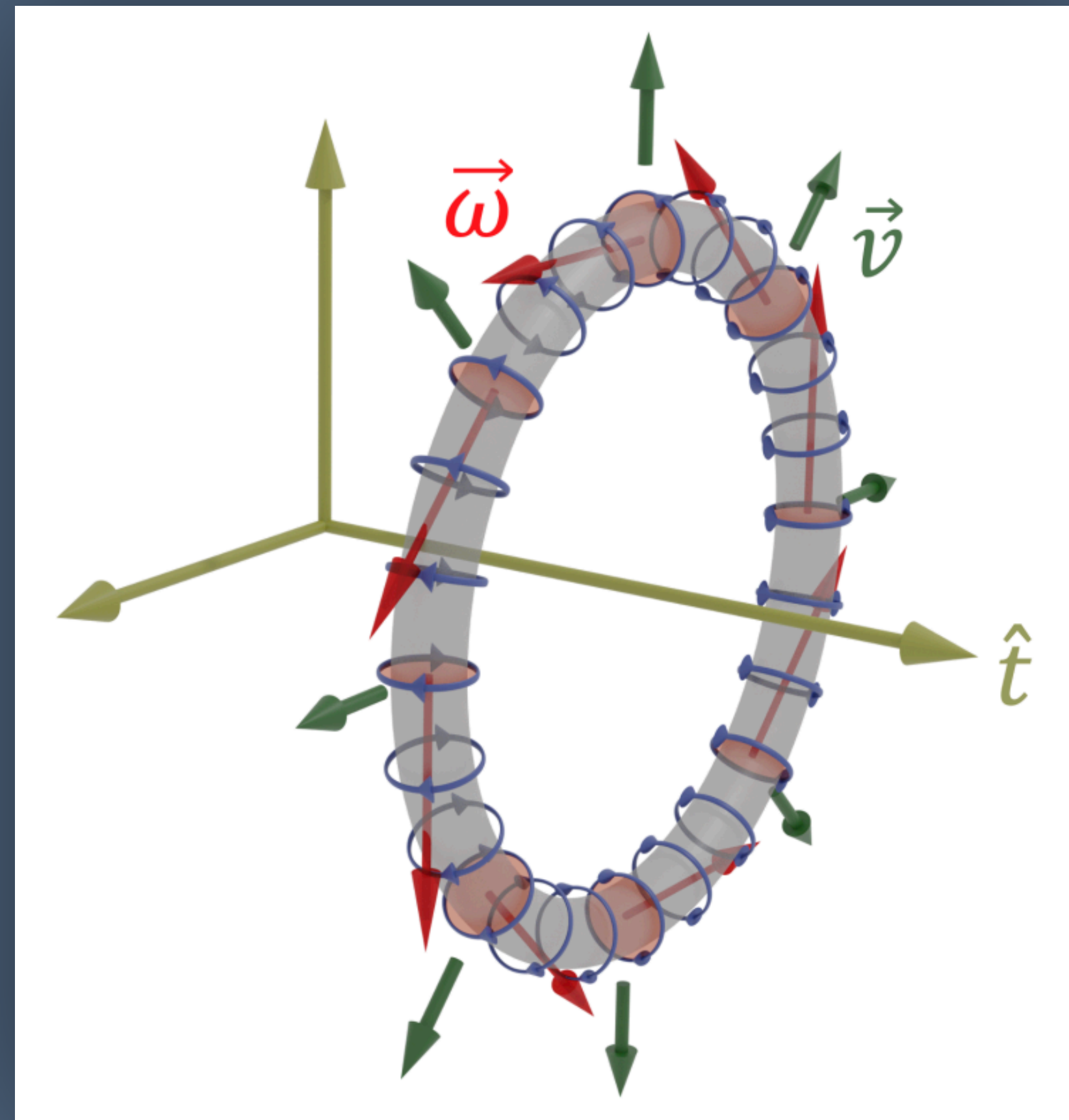


Since the first *Minuteman* launches from Cape Canaveral in 1961, nearly every missile has generated a perfect ring of smoke.



# Vorticity: Toroidal (smoke rings)

Present (in physics) for ages.



Expanding smoke ring can be quantified by:

non-relativistic

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

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

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

$\hat{t}$  - thrust vector

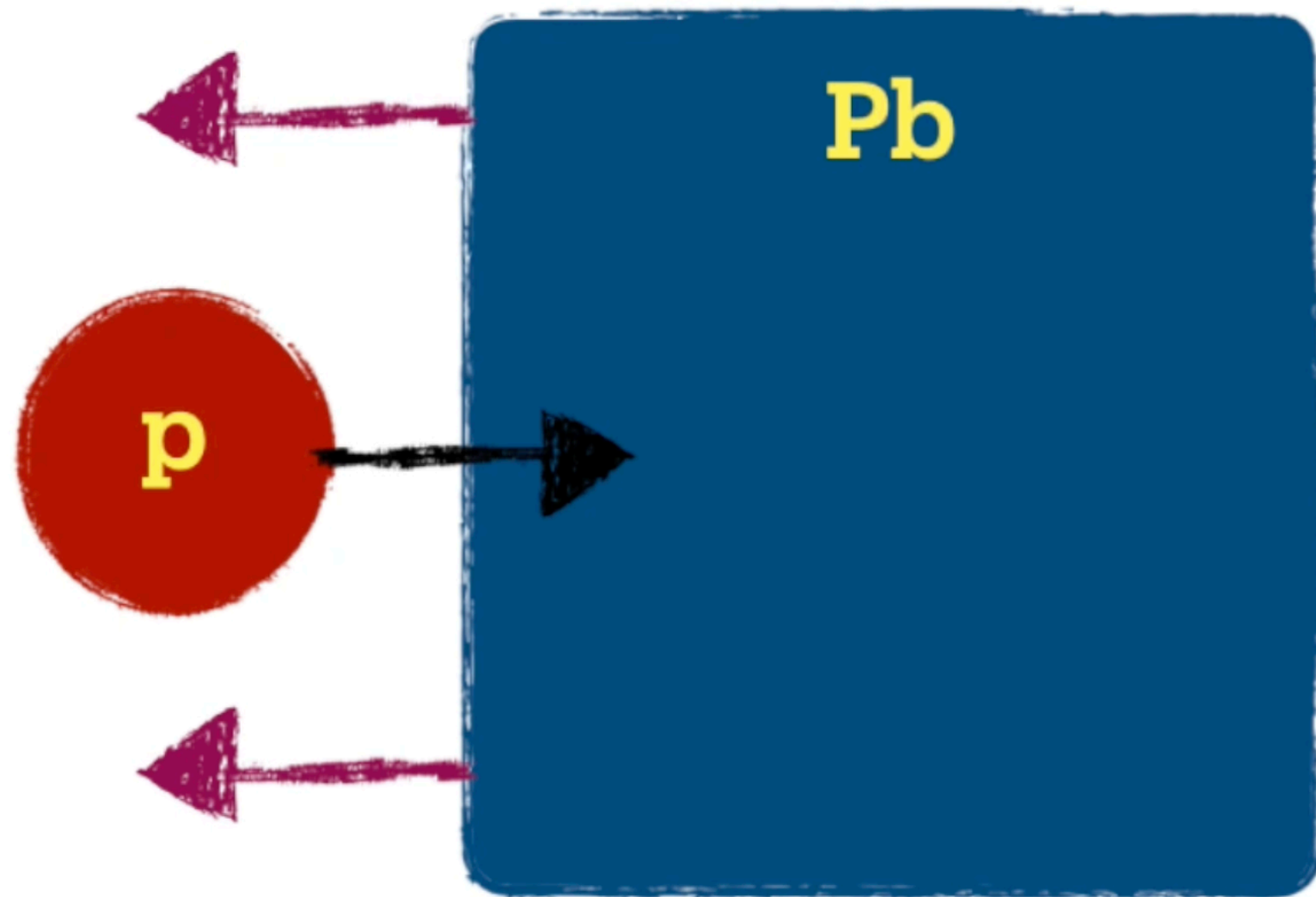




# Vorticity: Toroidal (smoke rings)

animation: M. Stefaniak

Black arrows - velocity of fluid cell



- 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:

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

$\Omega_{\mu}$  - proxy for vorticity

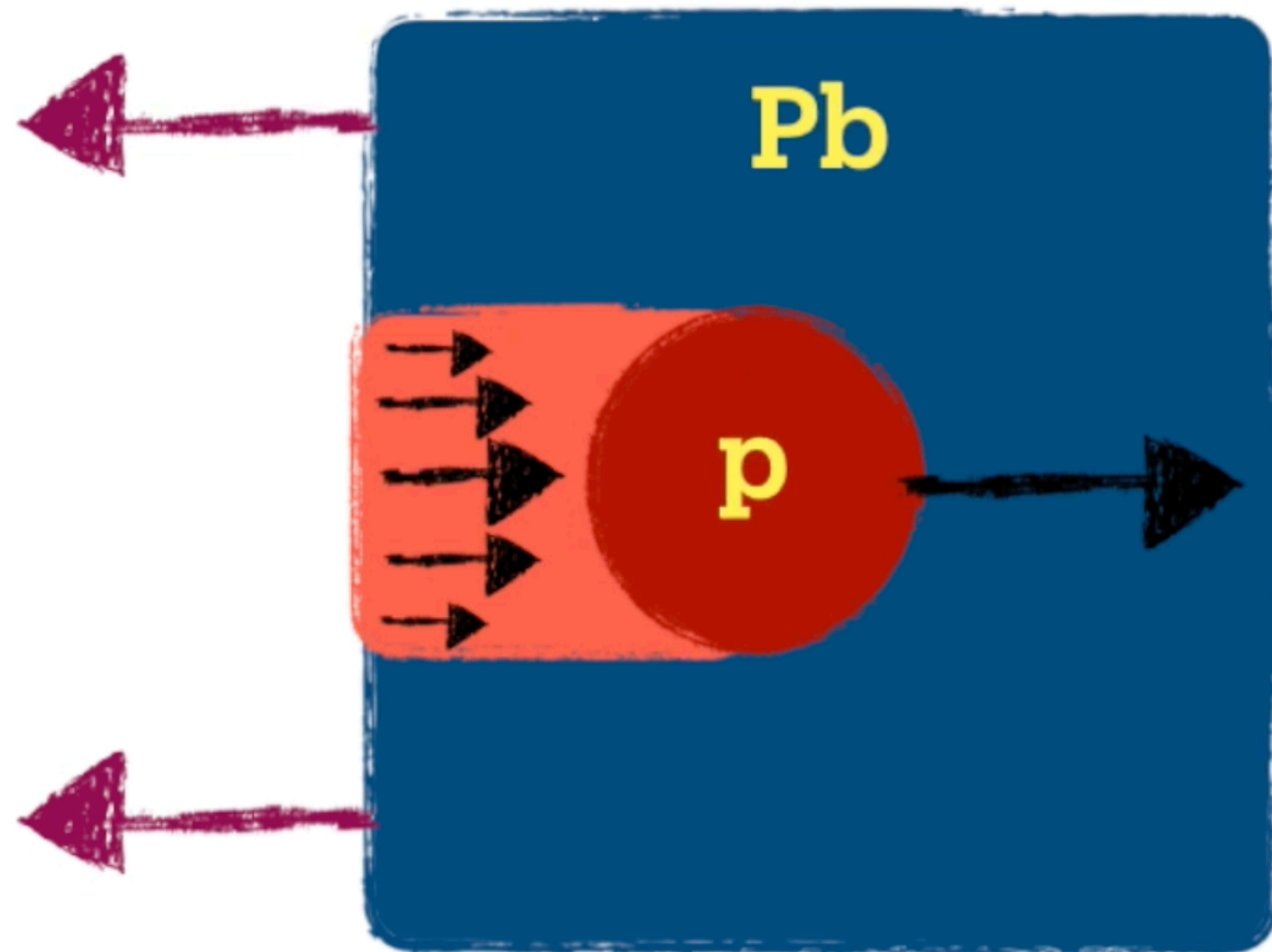
$\epsilon^{\mu\nu\rho\sigma}$  - Levi-Civita tensor, fully asymmetric in four dimensions

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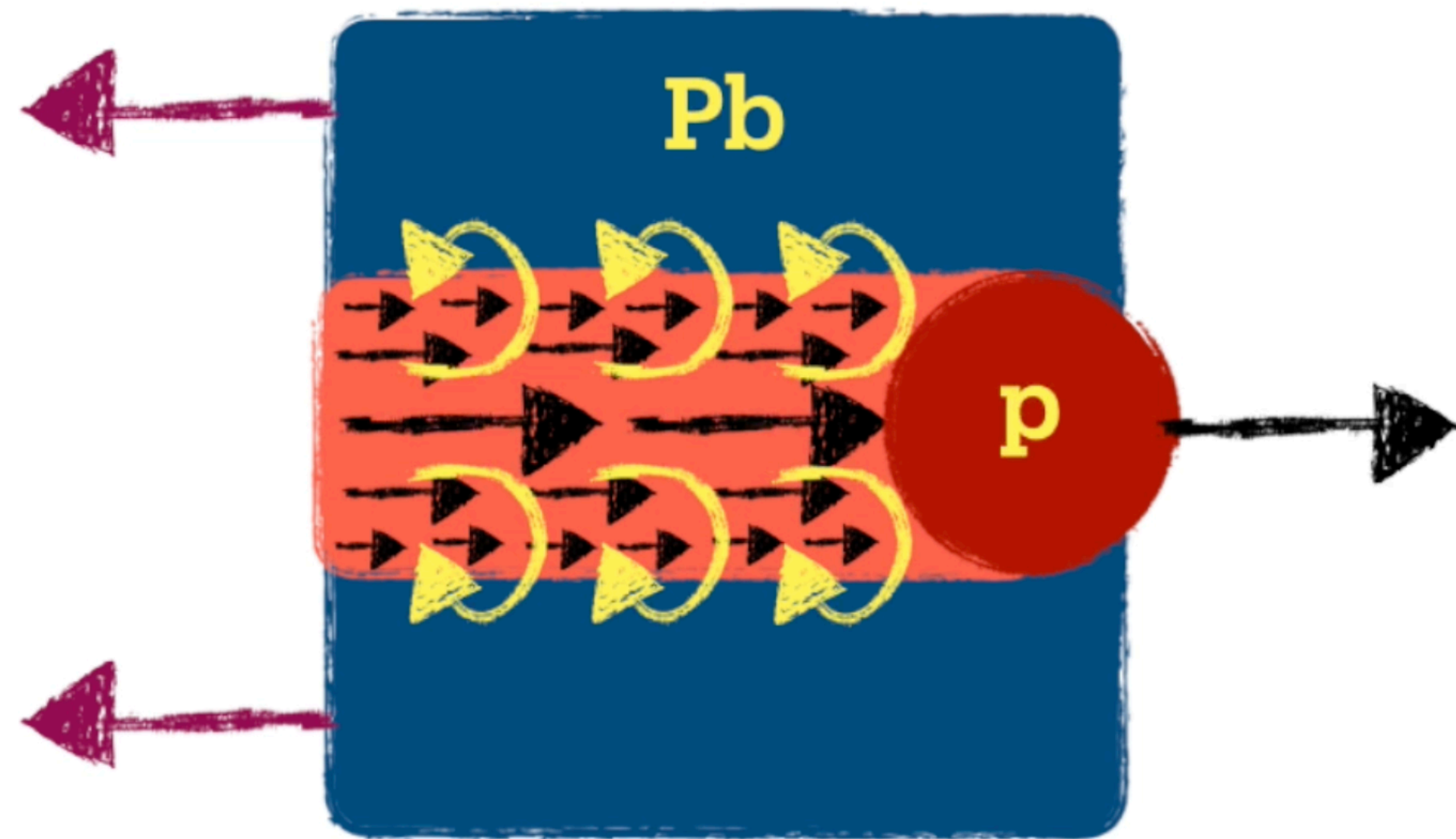
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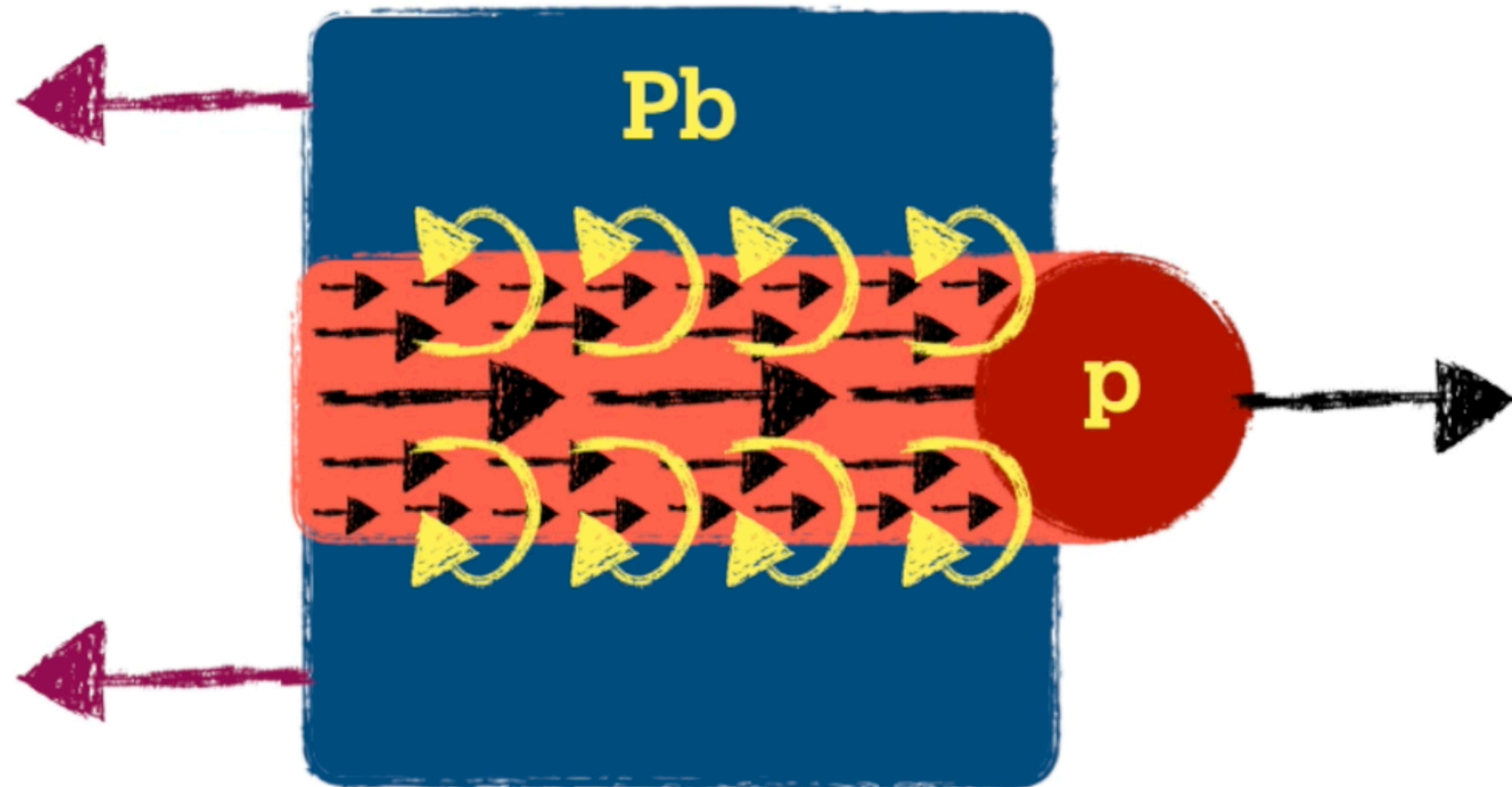
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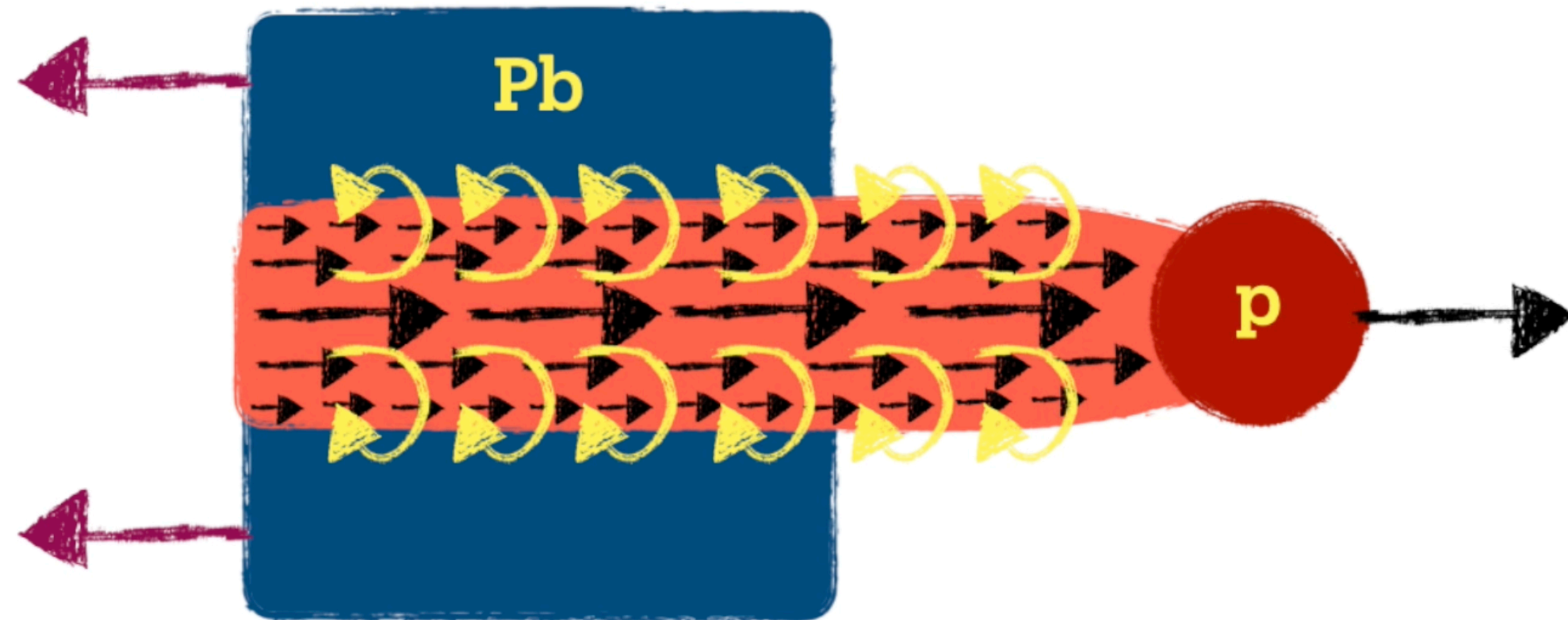
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# Vorticity: Toroidal (smoke rings)

- Spin-orbit coupling produces polarization proportional to the local fluid vorticity  $\omega$

- In relativistic treatment vorticity (thermal):

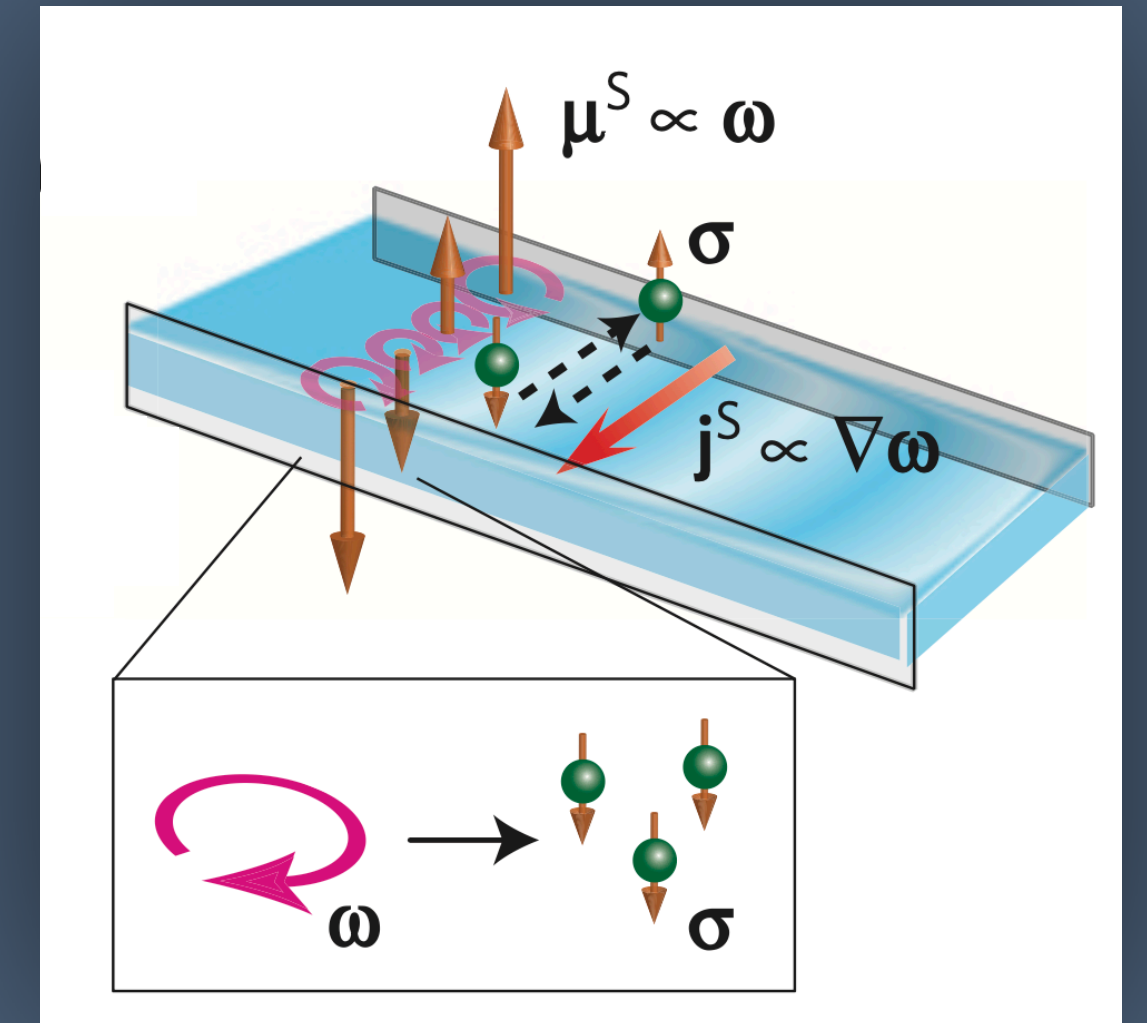
$$\omega_{th}^{\mu\nu} = \frac{1}{2}[\partial^\nu(u^\mu/T) - \partial^\mu(u^\nu/T)]$$

- 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” hypersurface  $\Sigma$ :

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

$n_F$  -Fermi-Dirac distribution

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

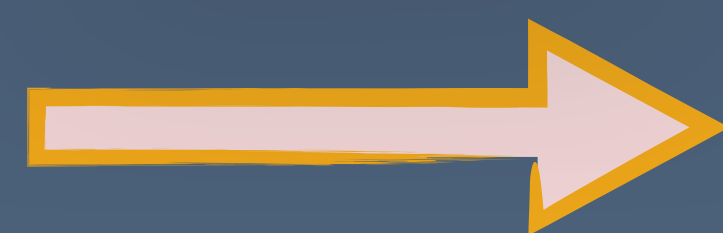


# Vorticity: Toroidal (smoke rings)

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

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

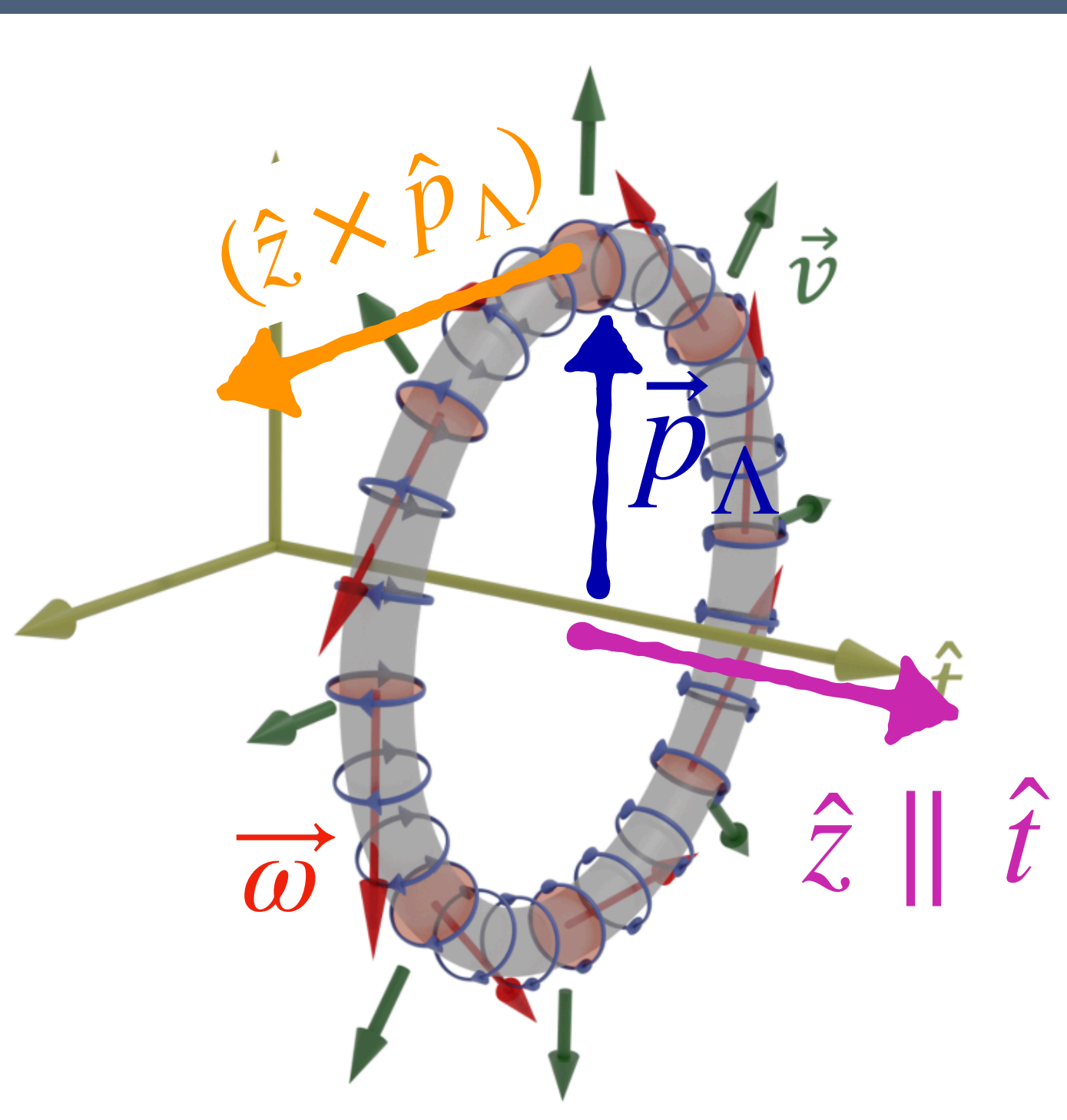
HADRONIZATION



$$R_{\Lambda}^{\hat{t}} = \frac{\epsilon^{\mu\nu\rho\sigma} S_{\mu} n_{\nu} \hat{t}_{\rho} p_{\sigma}}{|S| |\epsilon^{\mu\nu\rho\sigma} n_{\nu} \hat{t}_{\rho} p_{\sigma}|}$$

$S_{\mu}$  -  $\Lambda$  spin four-vector

$p_{\sigma}$  -  $\Lambda$  momentum four-vector



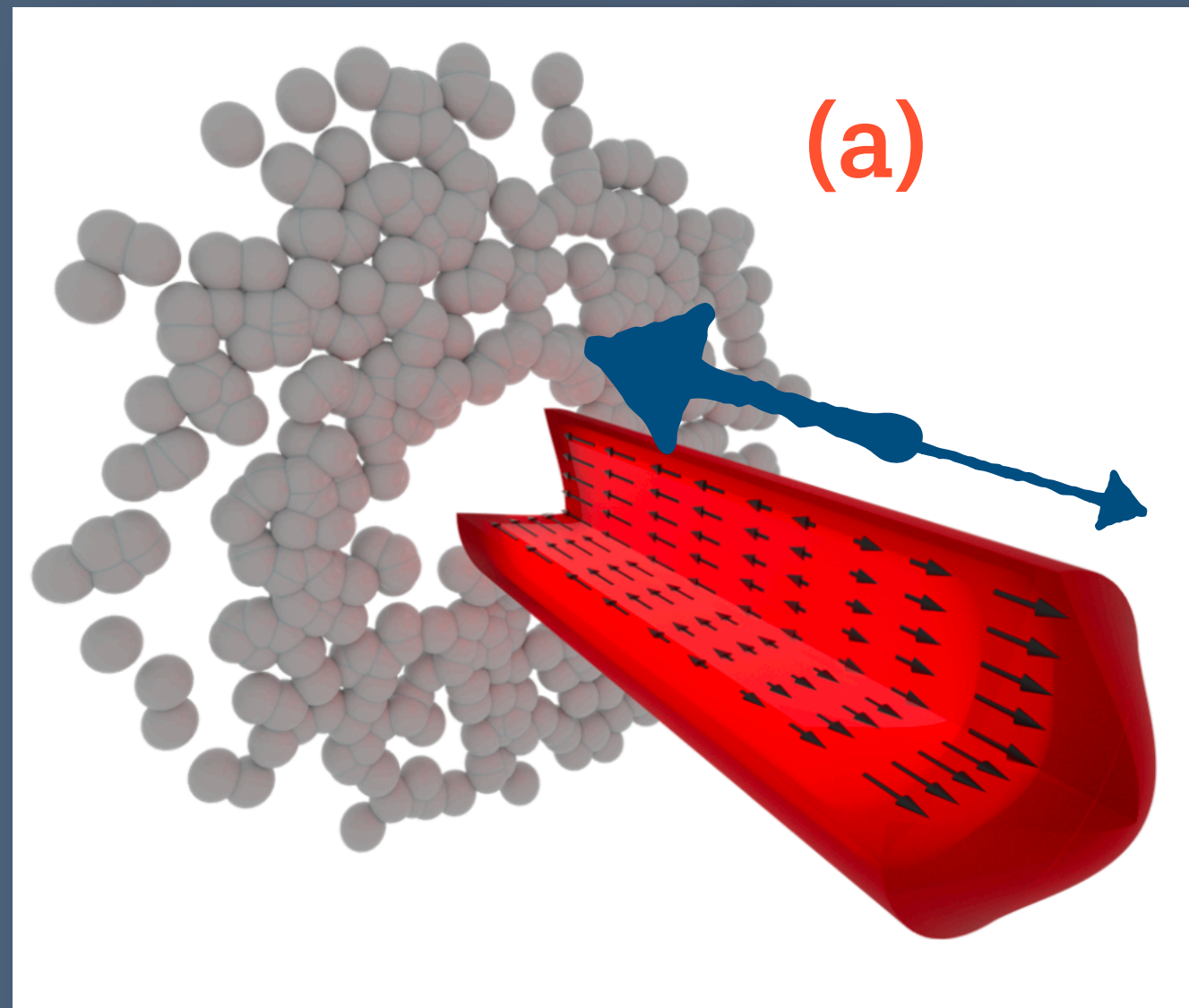
$$\bar{R}_{NR}^{\hat{t}} = \left\langle \frac{\vec{\omega}_{NR} \cdot (\hat{t} \times \vec{v}_{cell})}{|\hat{t} \times \vec{v}_{cell}|} \right\rangle_{\phi}$$

Proposition of Toroidal vorticity probe in HIC:

$$\bar{R}_{\Lambda}^{\hat{z}} = 2 \left\langle \frac{\vec{S}'_{\Lambda} \cdot (\hat{z}' \times \vec{p}'_{\Lambda})}{|\hat{z}' \times \vec{p}'_{\Lambda}|} \right\rangle_{\phi}$$

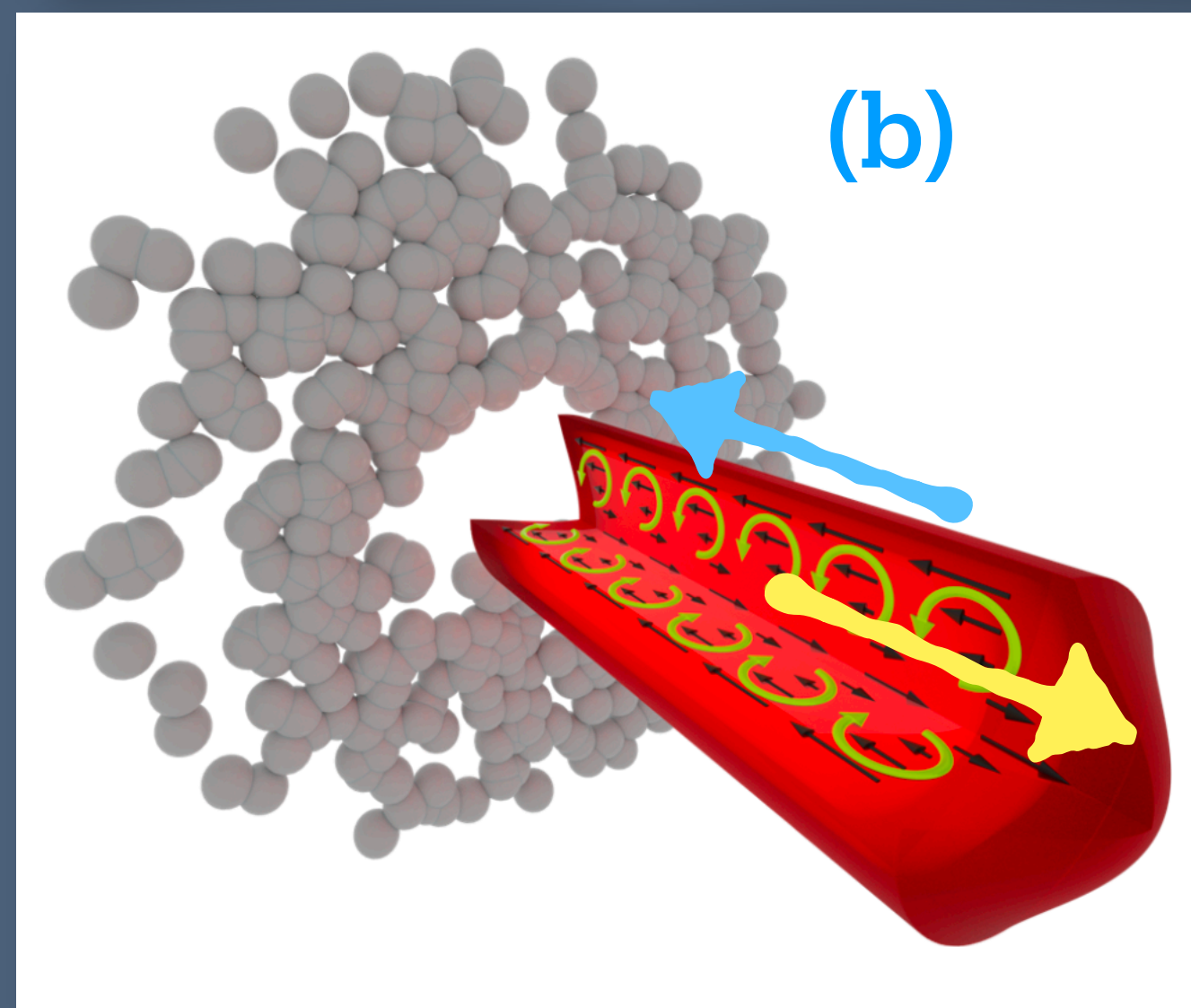
( $\wedge$ ) - three-vectors in NN frame

# Vorticity: **Toroidal** (smoke rings)



Proton drilling a nuclei:

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

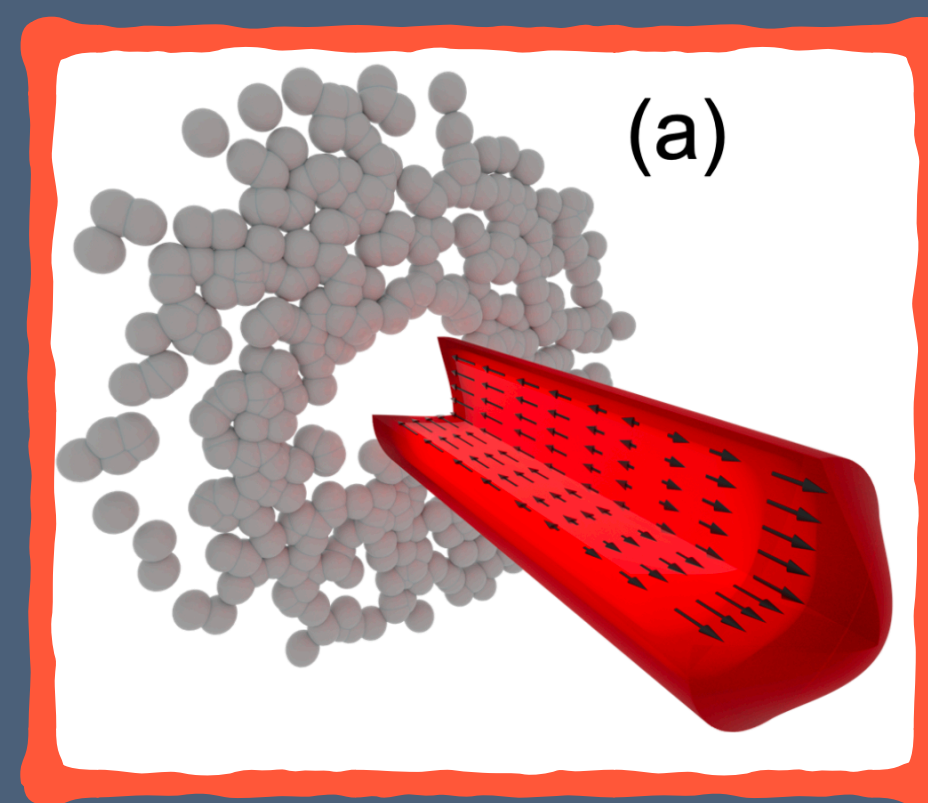


b) The edges of the cylinder flow more in the nuclei-going direction than fluid cells at the center of the cylinder.

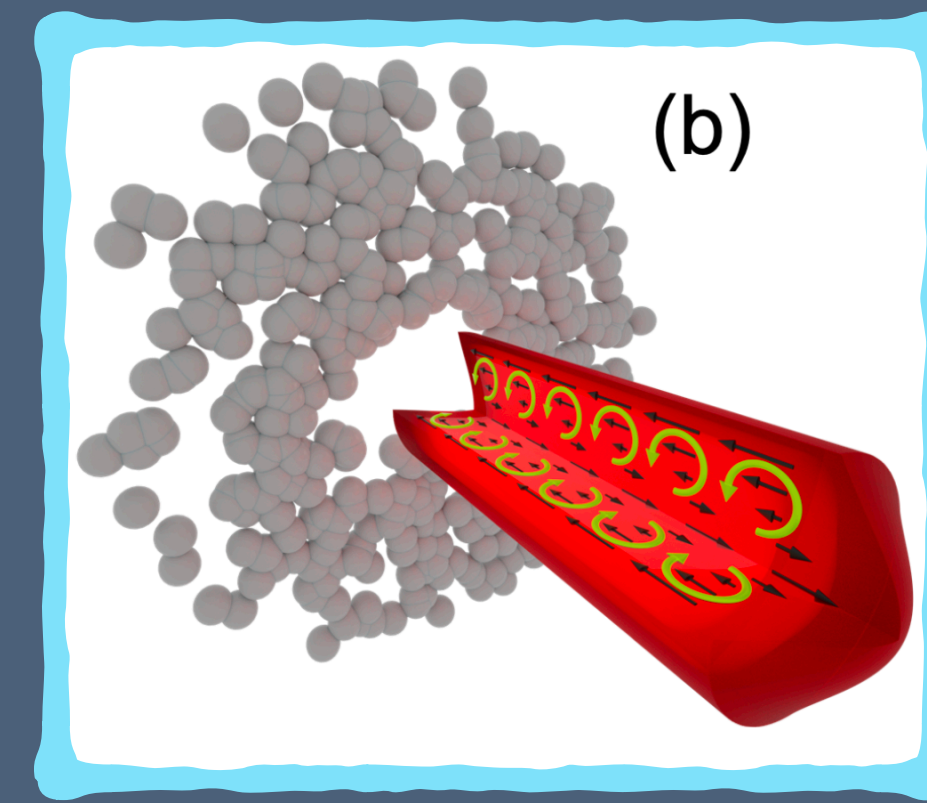


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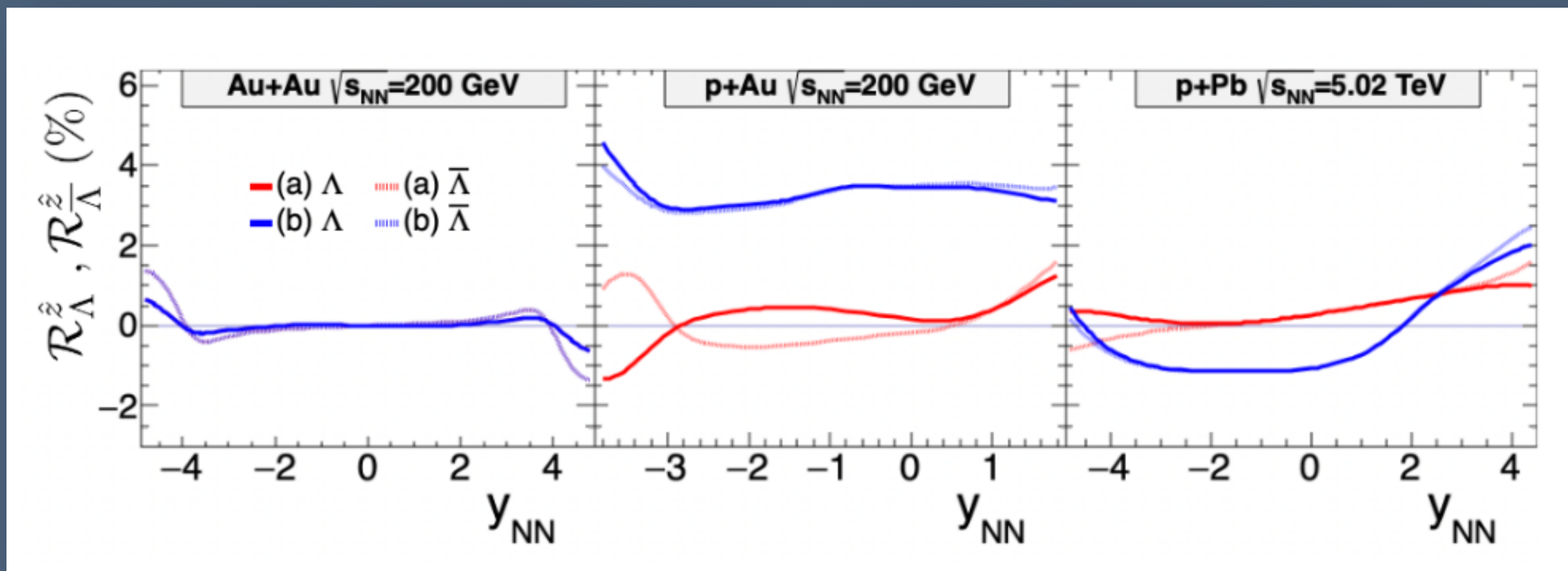
Simulations with MUSIC [1]:



No TV



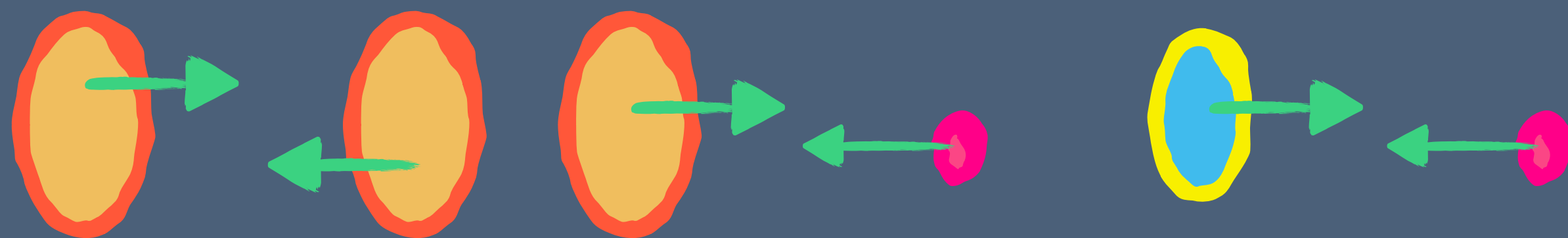
With TV



According to [1]:

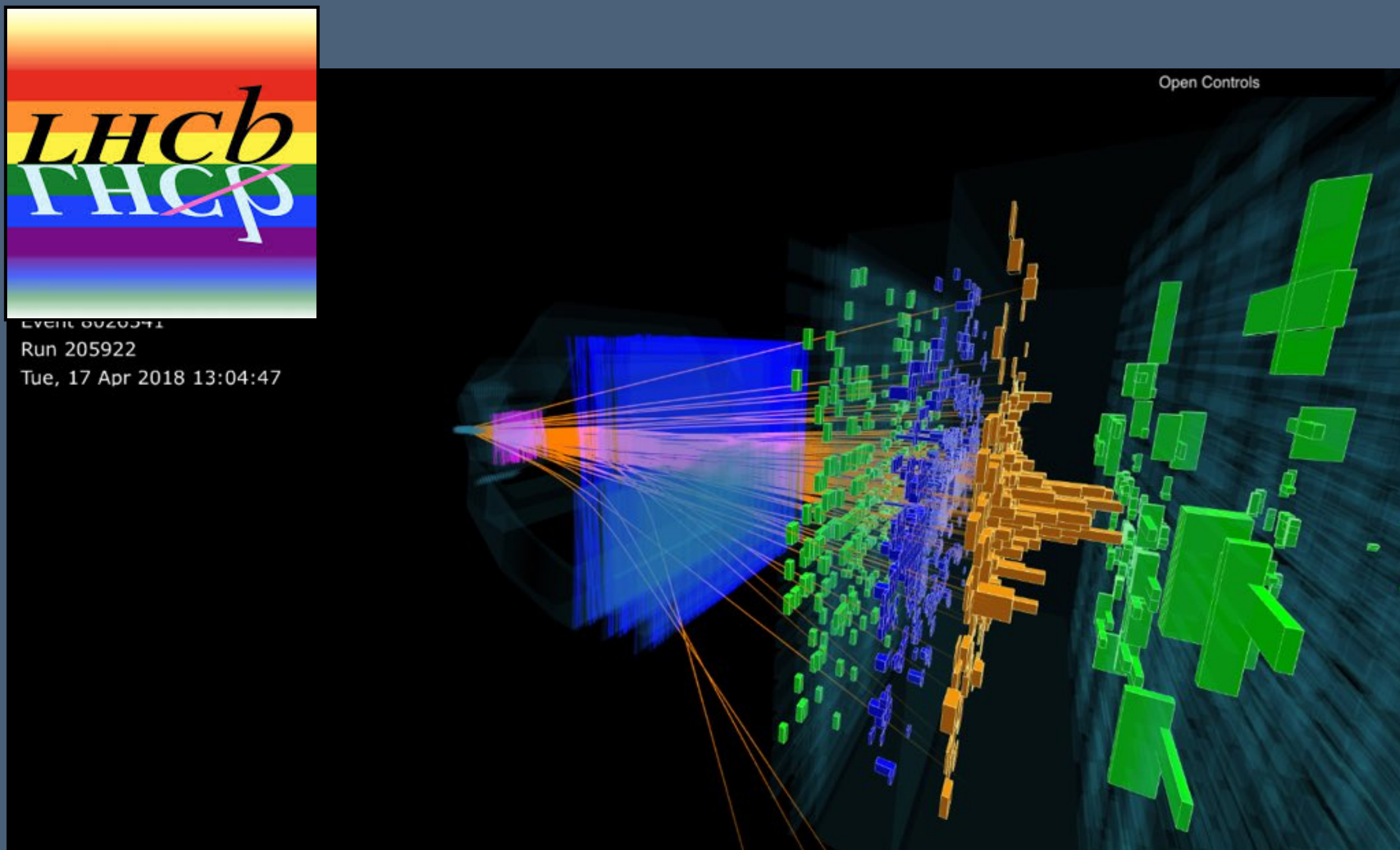
- Dependent of  $\sqrt{s_{NN}}$
- No need to measure Event Plane!
- Signal present also for **Anti**Lambdas!

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



# Smoking rings at LHC

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



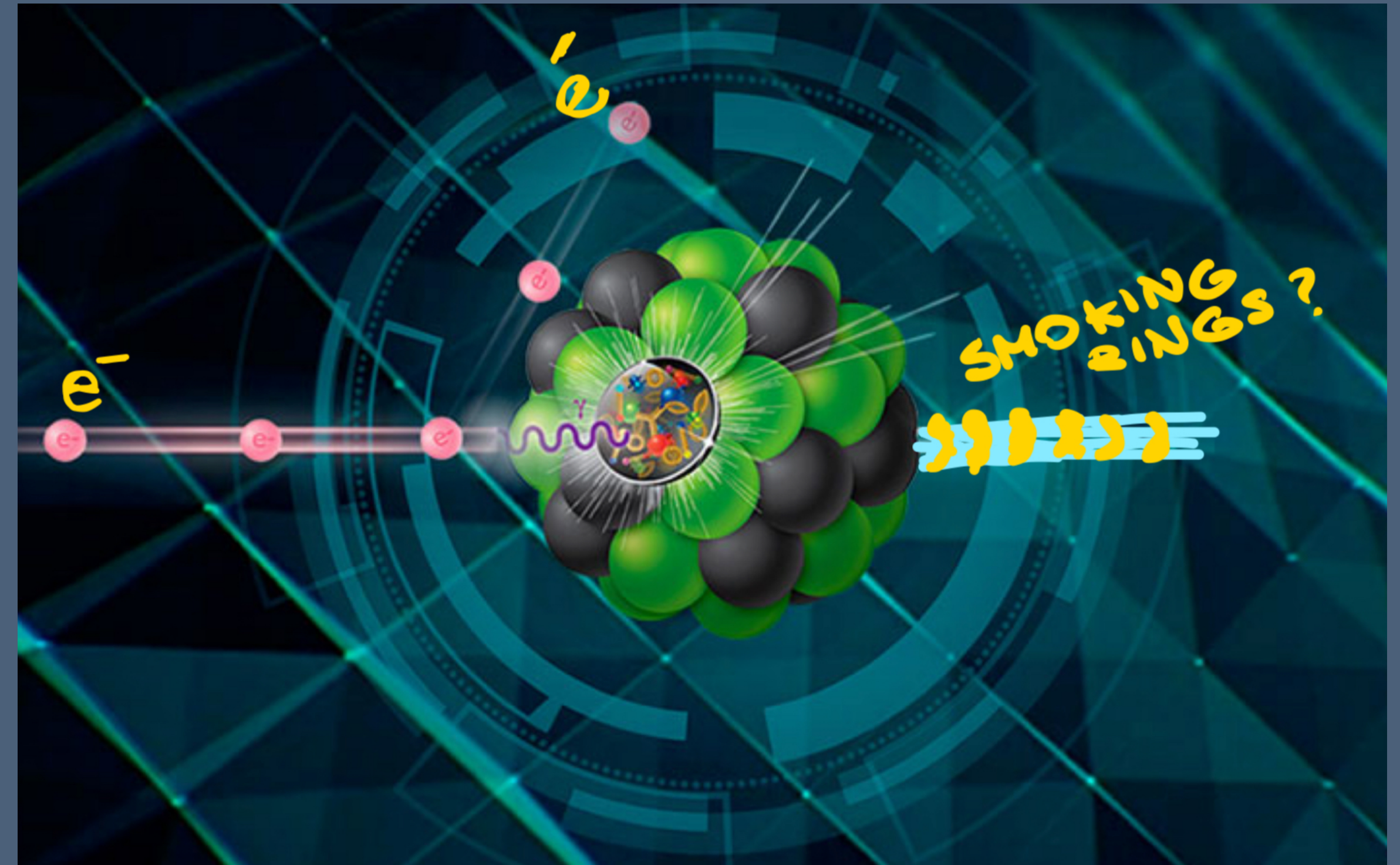
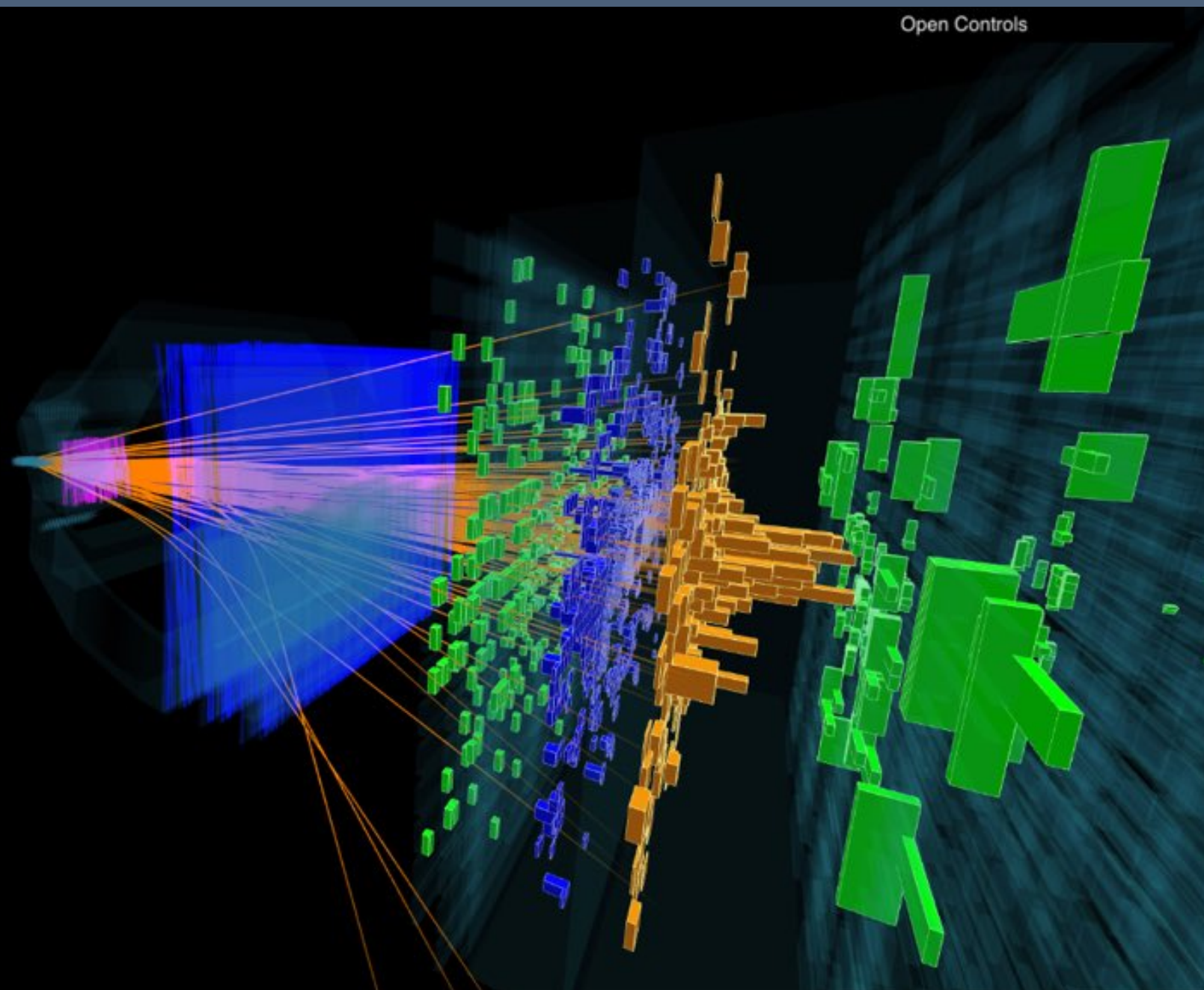
# Smoking rings at LHC and EIC

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

- Toroidal vortexes in e+A collisions?



Event 0020541  
Run 205922  
Tue, 17 Apr 2018 13:04:47



Thank you!