

INSTITUTE for NUCLEAR THEORY

Heavy Ion Physics in the EIC Era

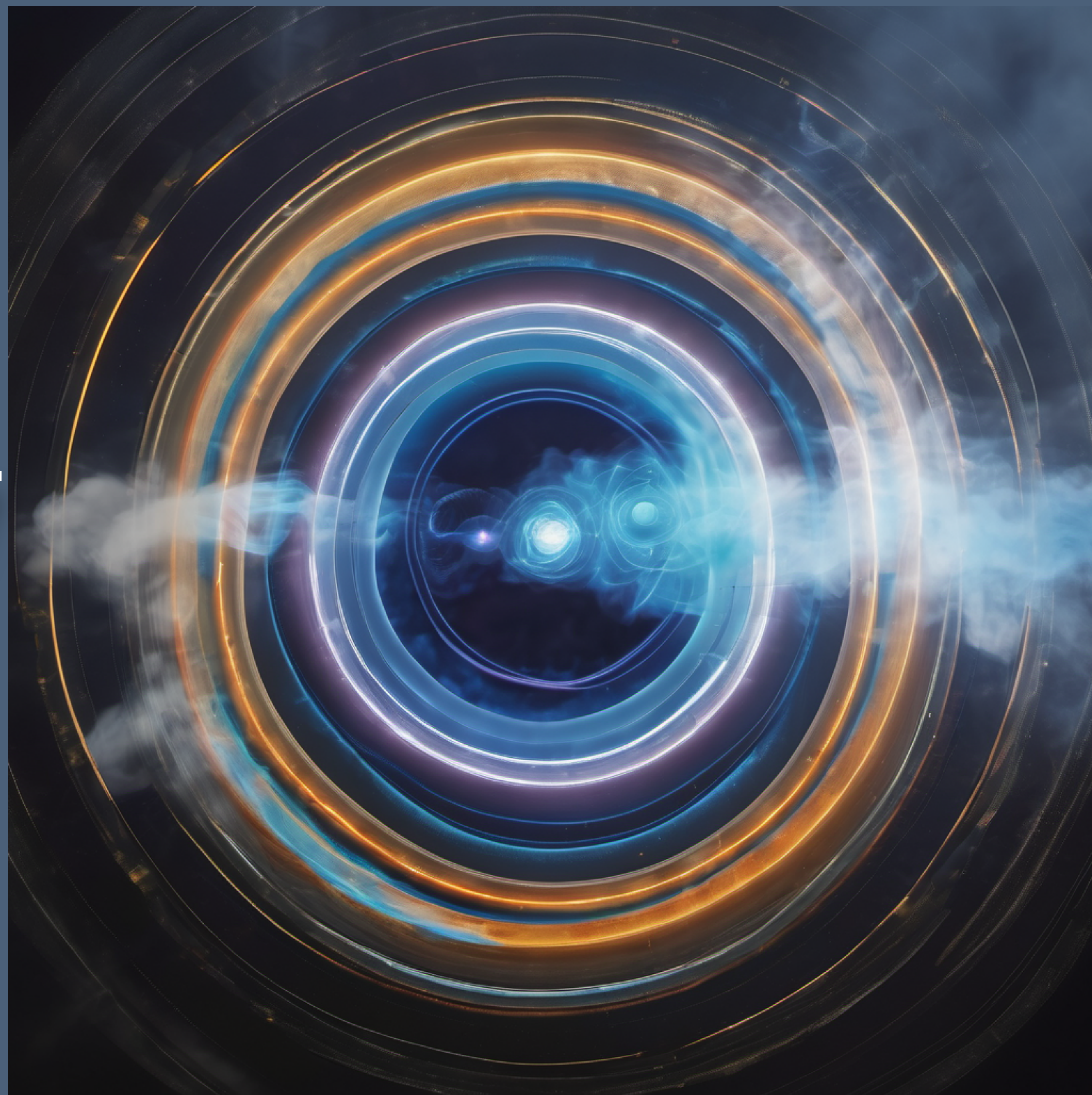
Toroidal Vorticity

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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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.

literature

Literature Authors Jobs Seminars Conferences More...

112 results | Citation Summary Most Cited

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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INSPIRE HEP literature

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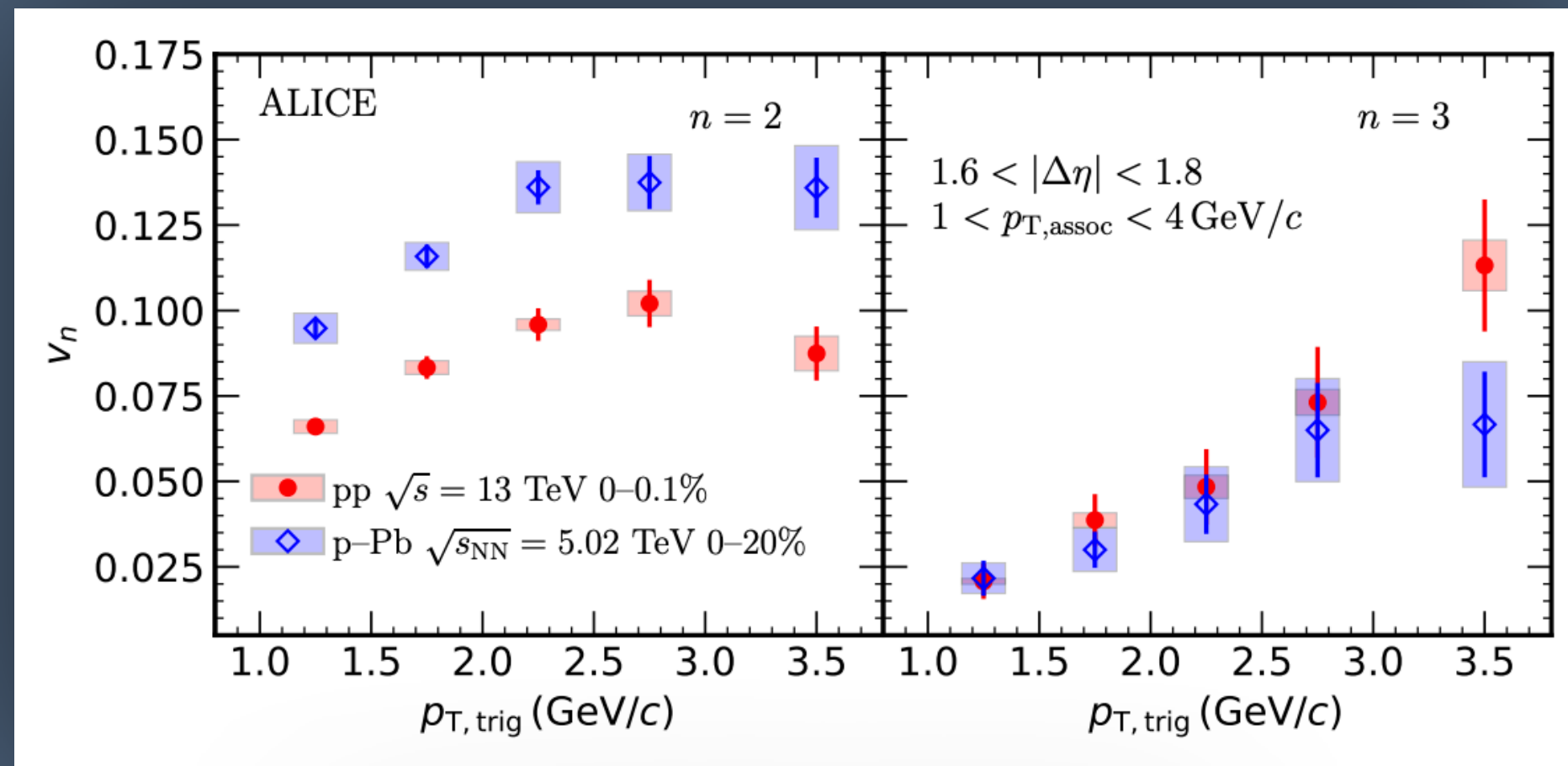
Number of authors
 Single author
 10 authors or less

Exclude RPP
 Exclude Review of Particle Physics

Motivation

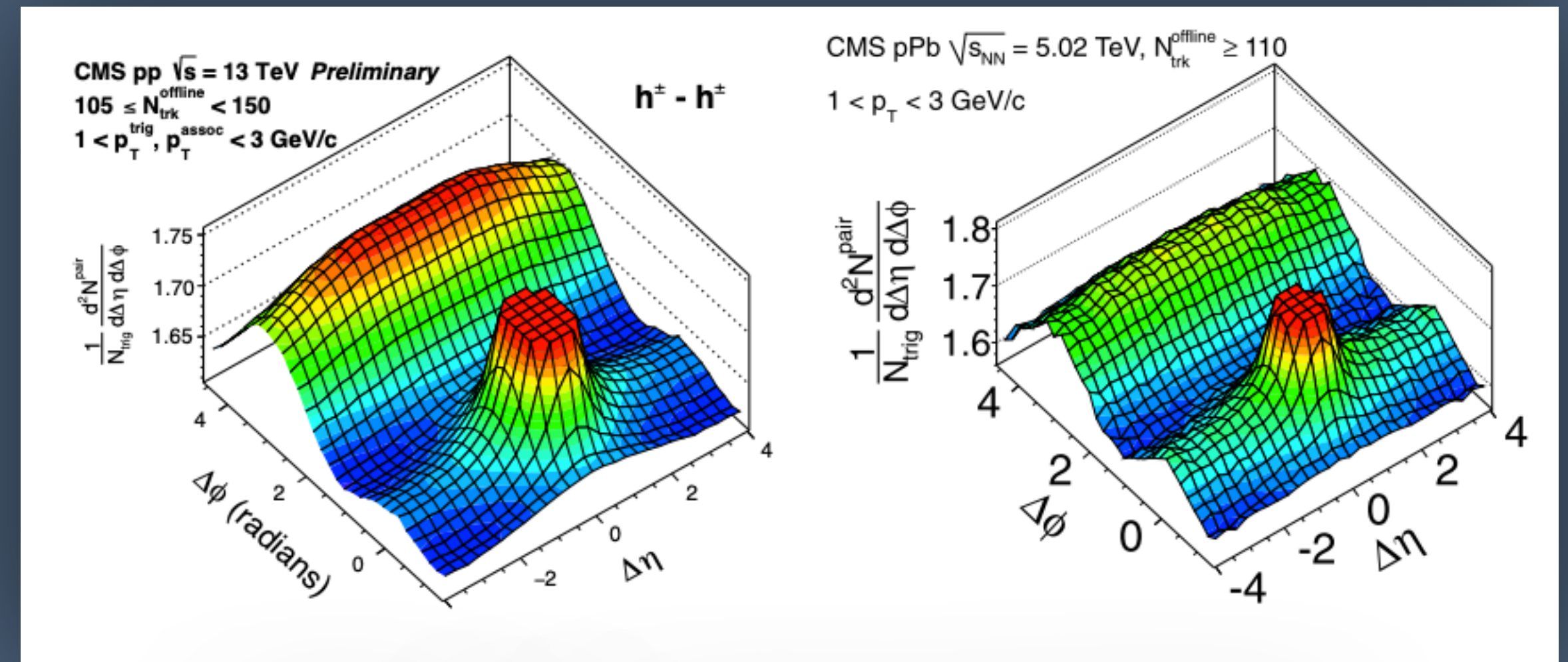
Presence of collectivity in “smaller” systems: pA ?

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^{1a}, in collaboration with J. Scott Moreland^b

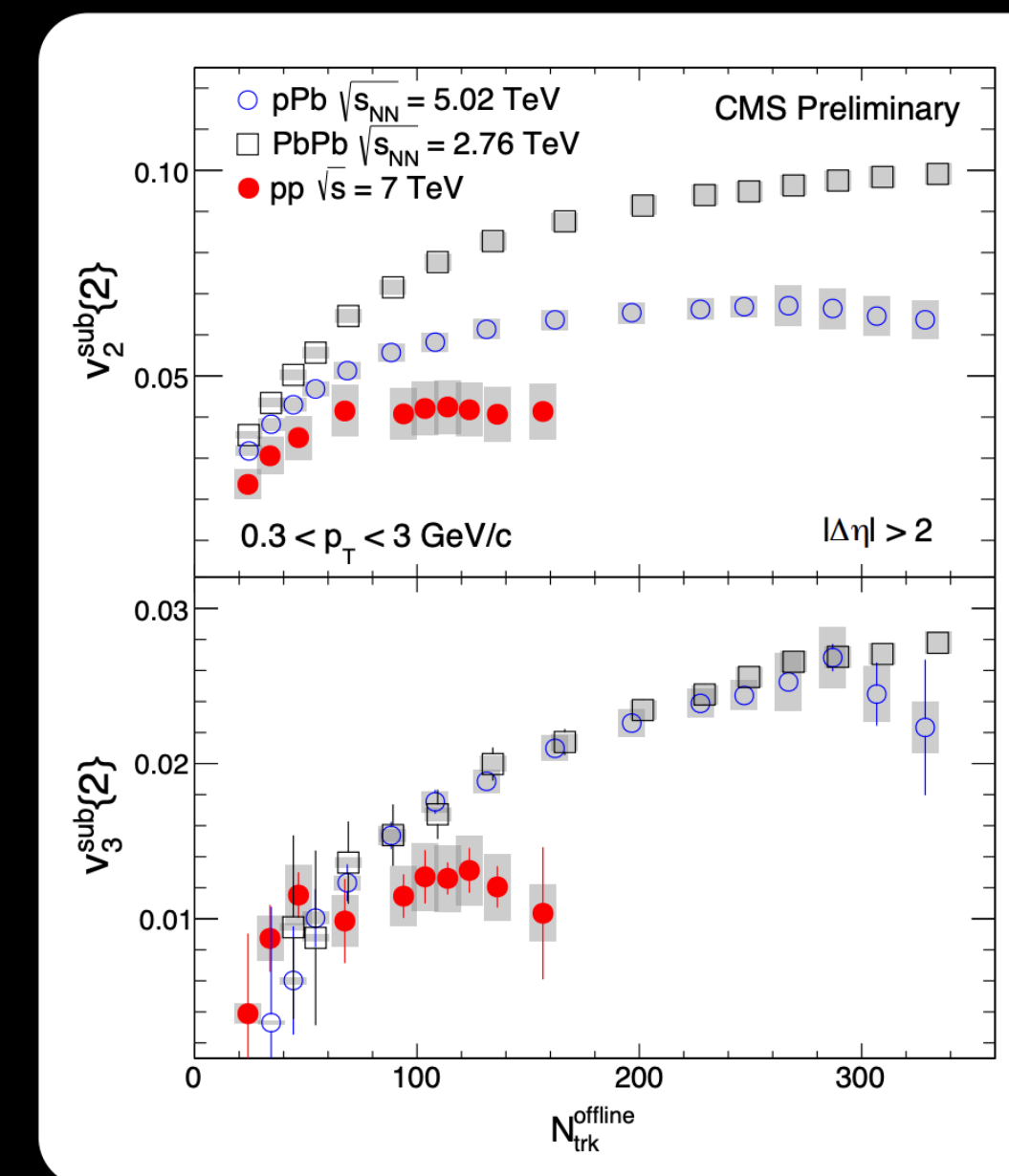
^aDepartment of Physics, The Ohio State University, Columbus, OH 43210-1117, USA

^bDepartment 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



CMS PAS HIN-15-009

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)



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Björn Schenke, BNL

LHCP 2018

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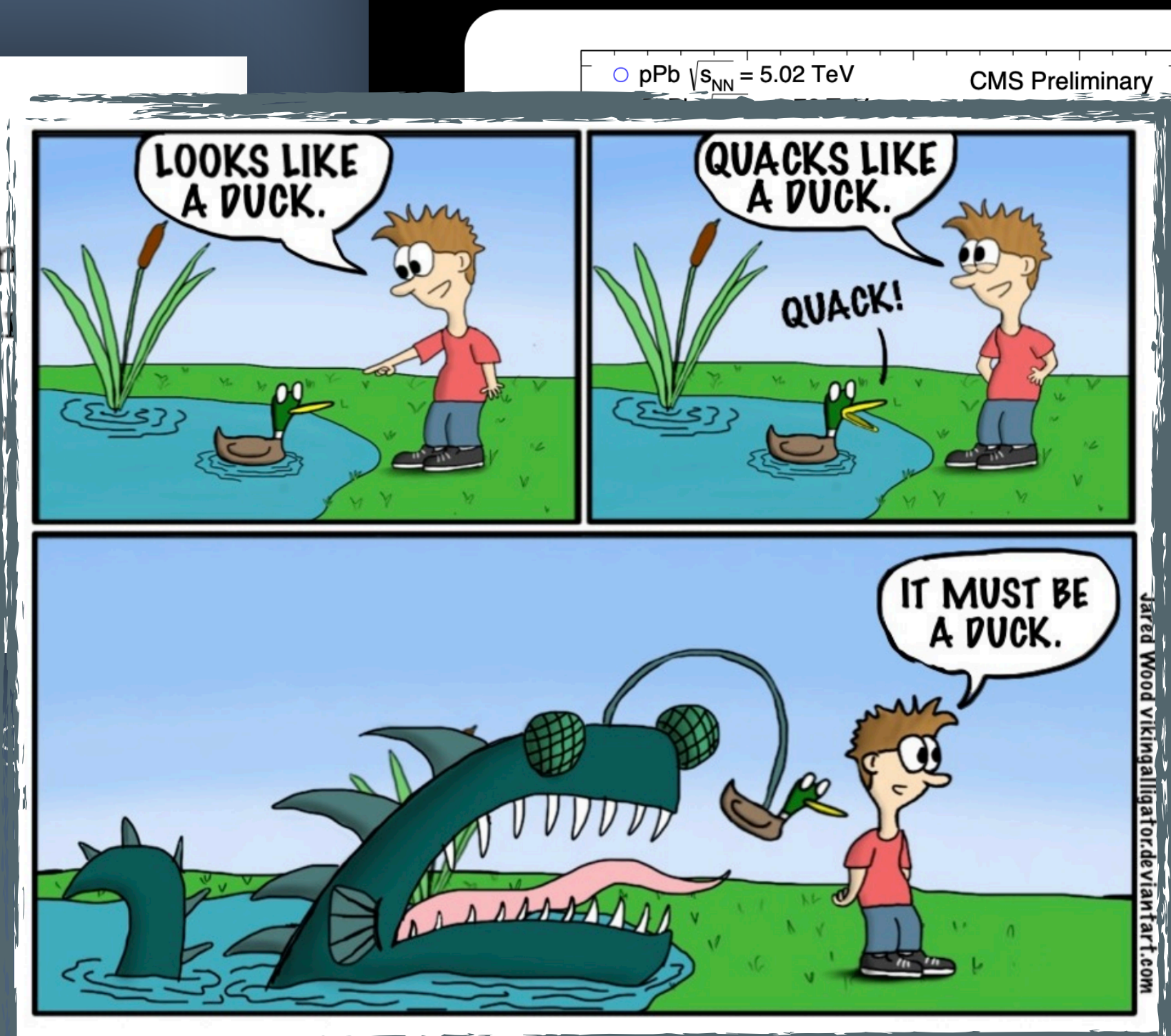
Ulrich Heinz^{1a}, in collaboration with J. Scott Moreland

^aDepartment of Physics, The Ohio State University, Columbus, OH 43210-1325

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IOP Conf. Series: Journal of Physics: Conf. Series 1271 (2015) 012001

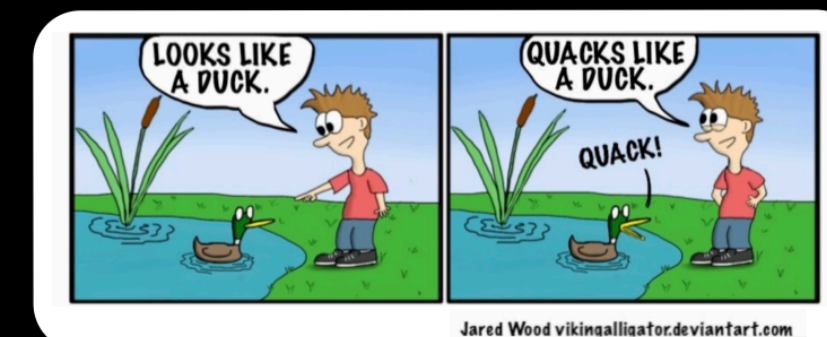


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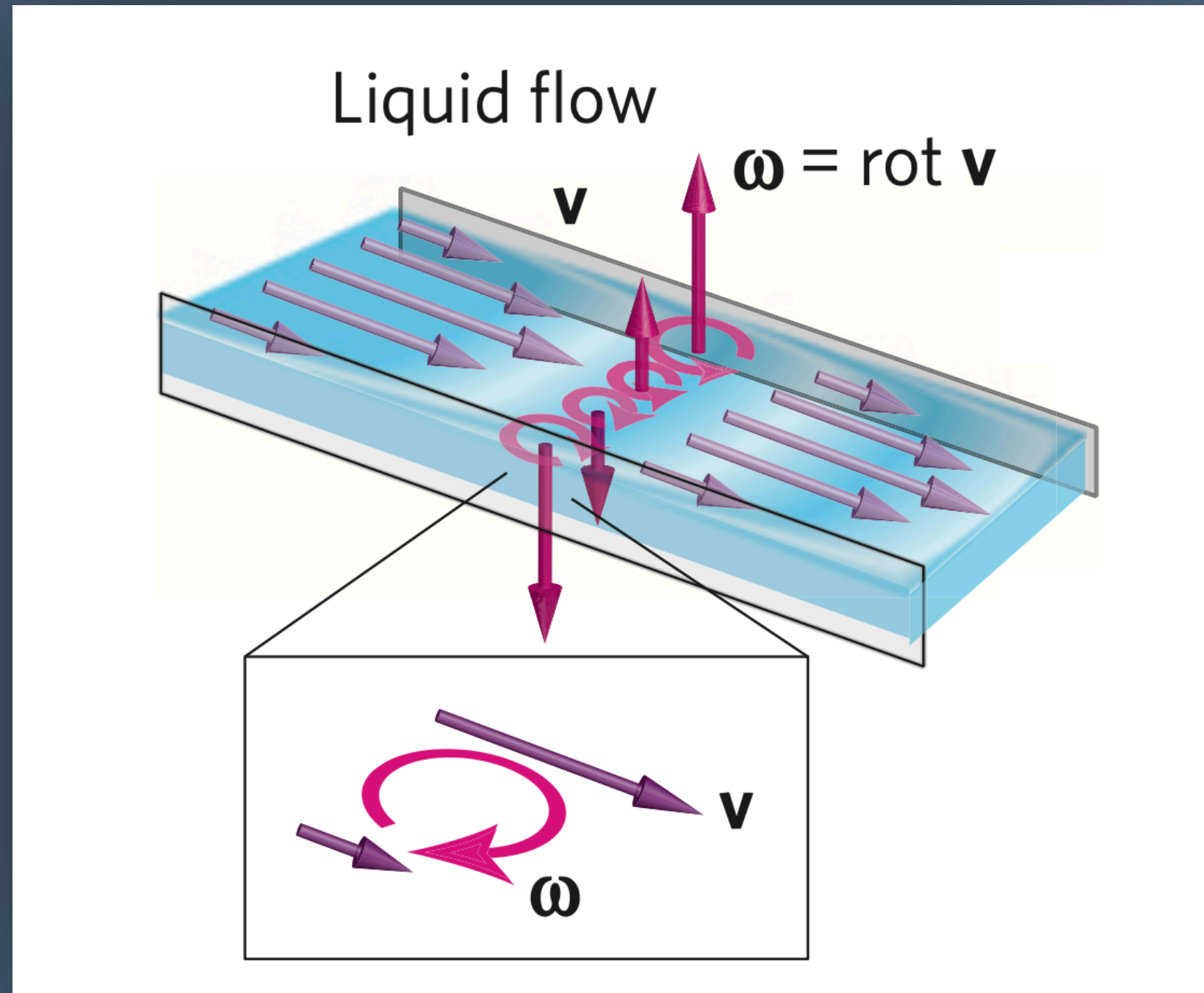


Björn Schenke, BNL

LHCP 2018

Another way to probe a fluid:

Vorticity



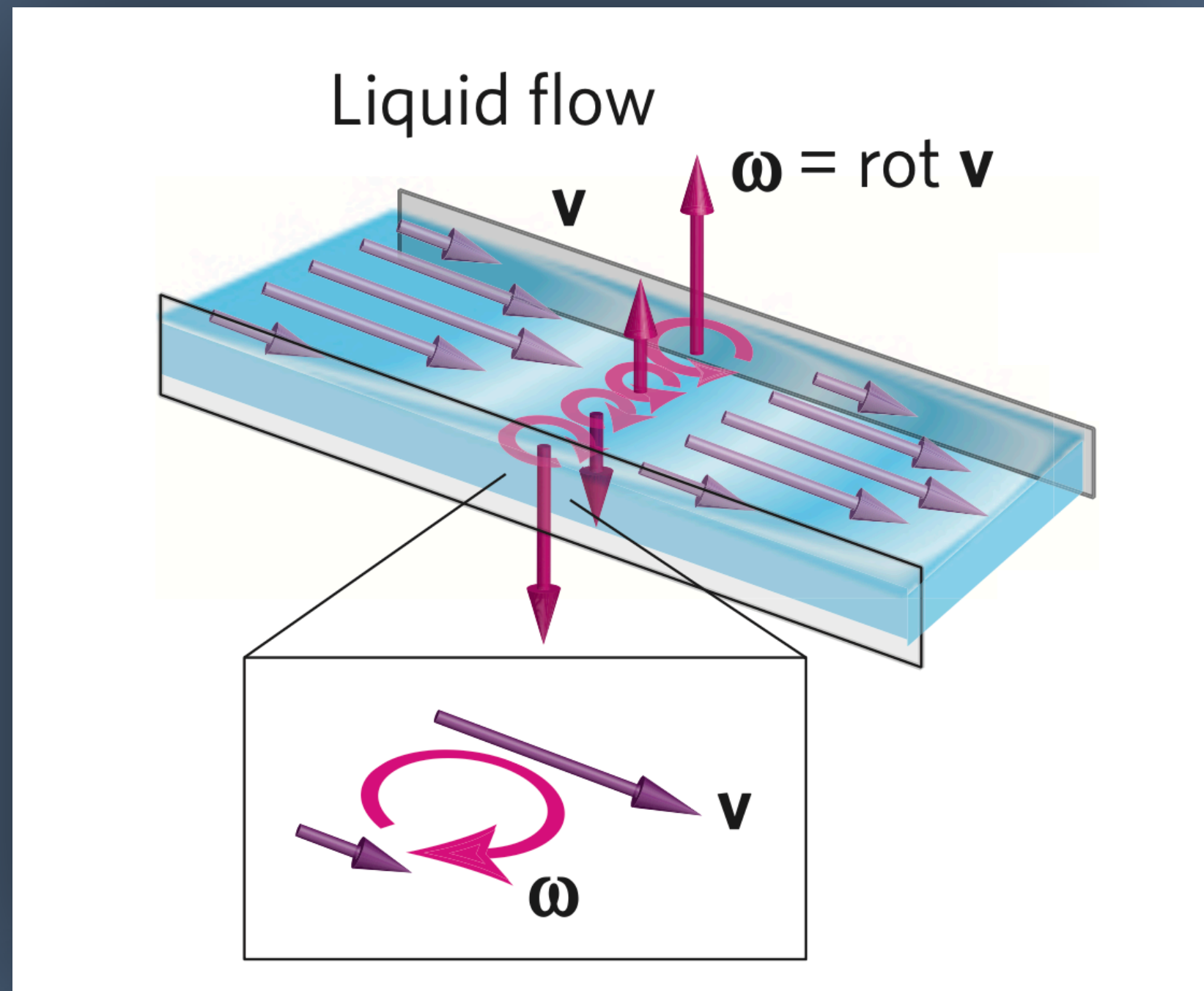
- **Vorticity** represents local mechanical rotation of fluid

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

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

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

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

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

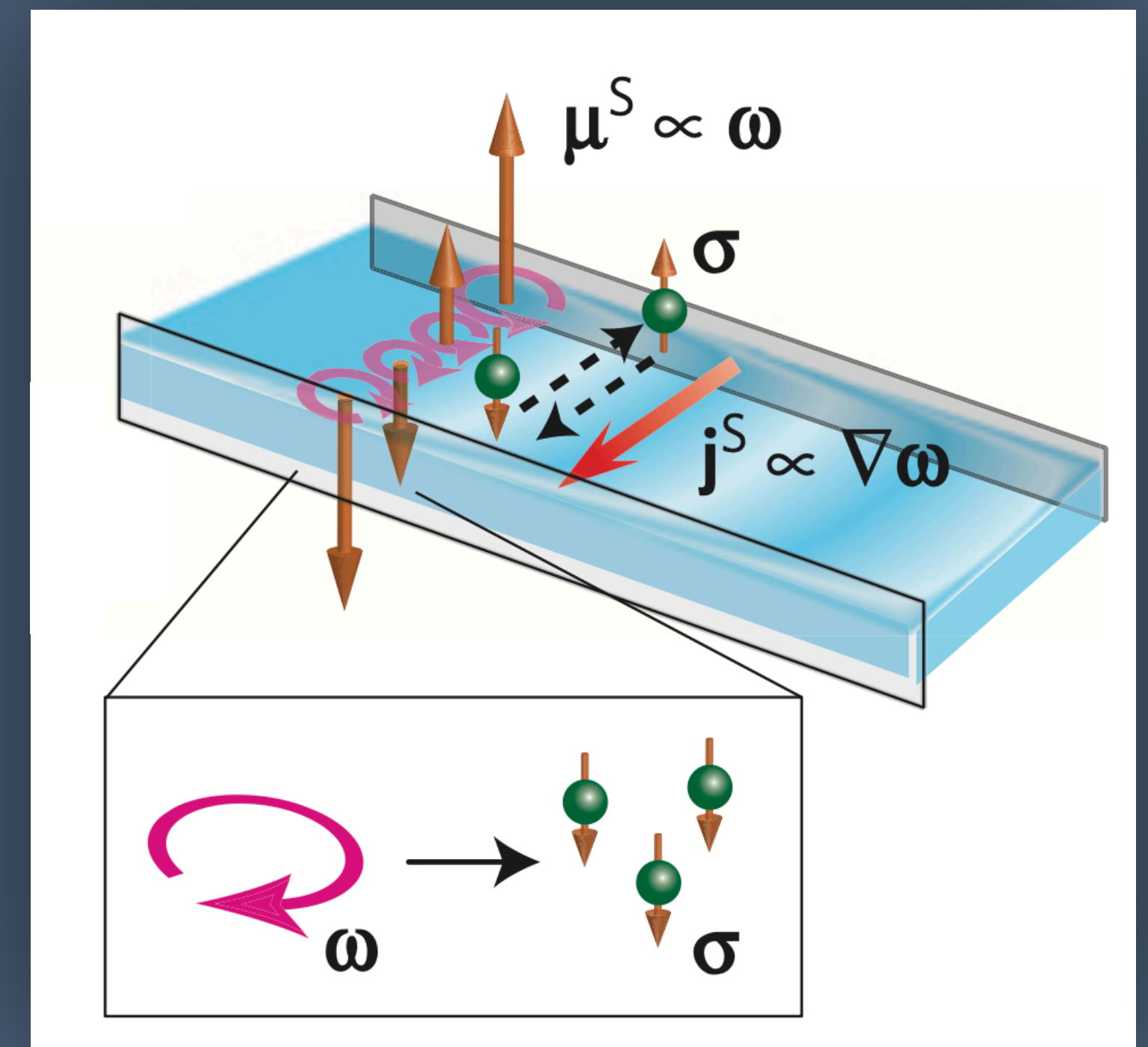
$$\nabla^2 \mu^s = \frac{1}{\lambda} \mu^s - \frac{4e^2}{\sigma_0 \hbar} \xi \omega$$

μ^s - spin voltage

λ - spin-diffusion length

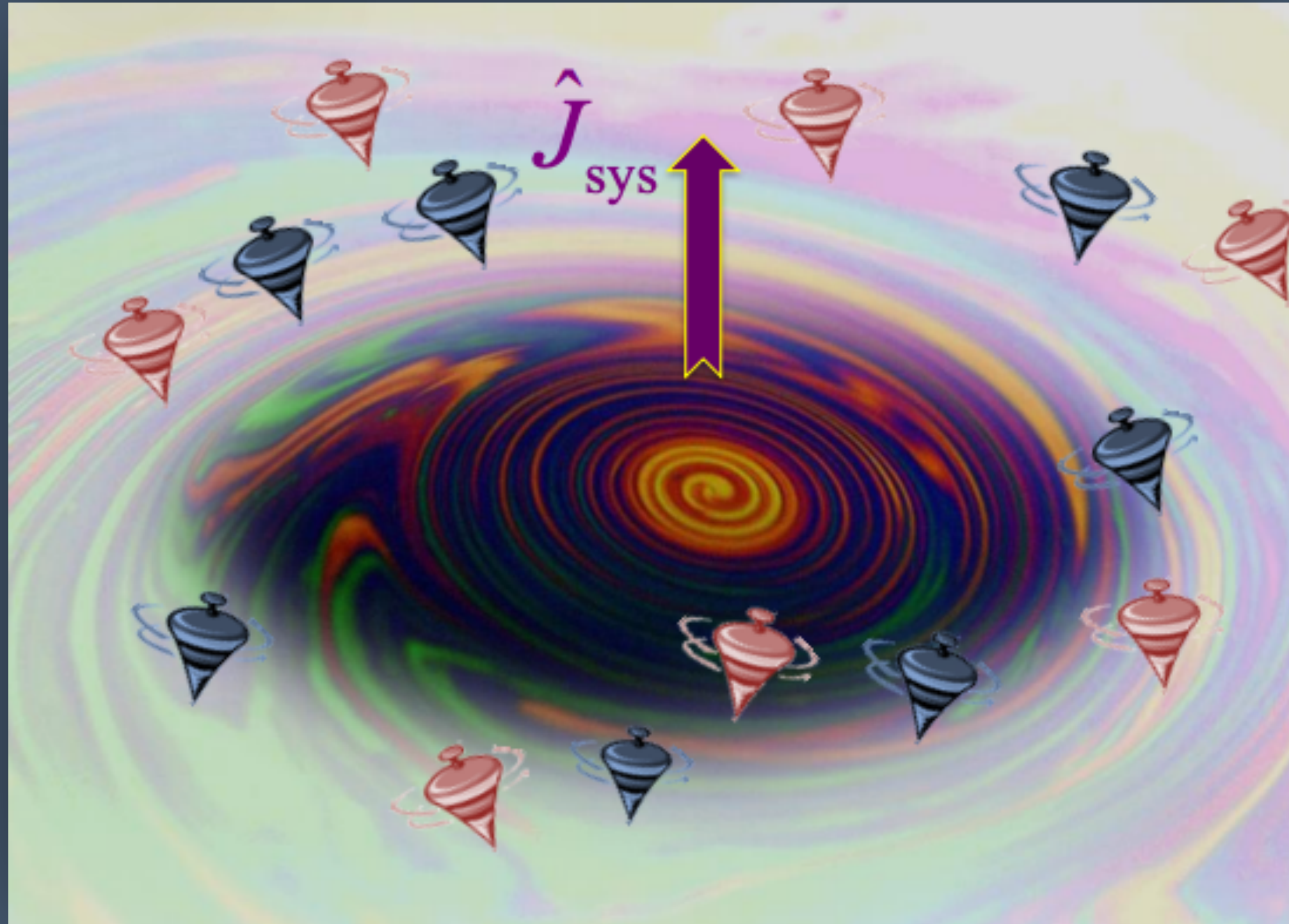
σ_0 - electric conductivity

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



Vorticity

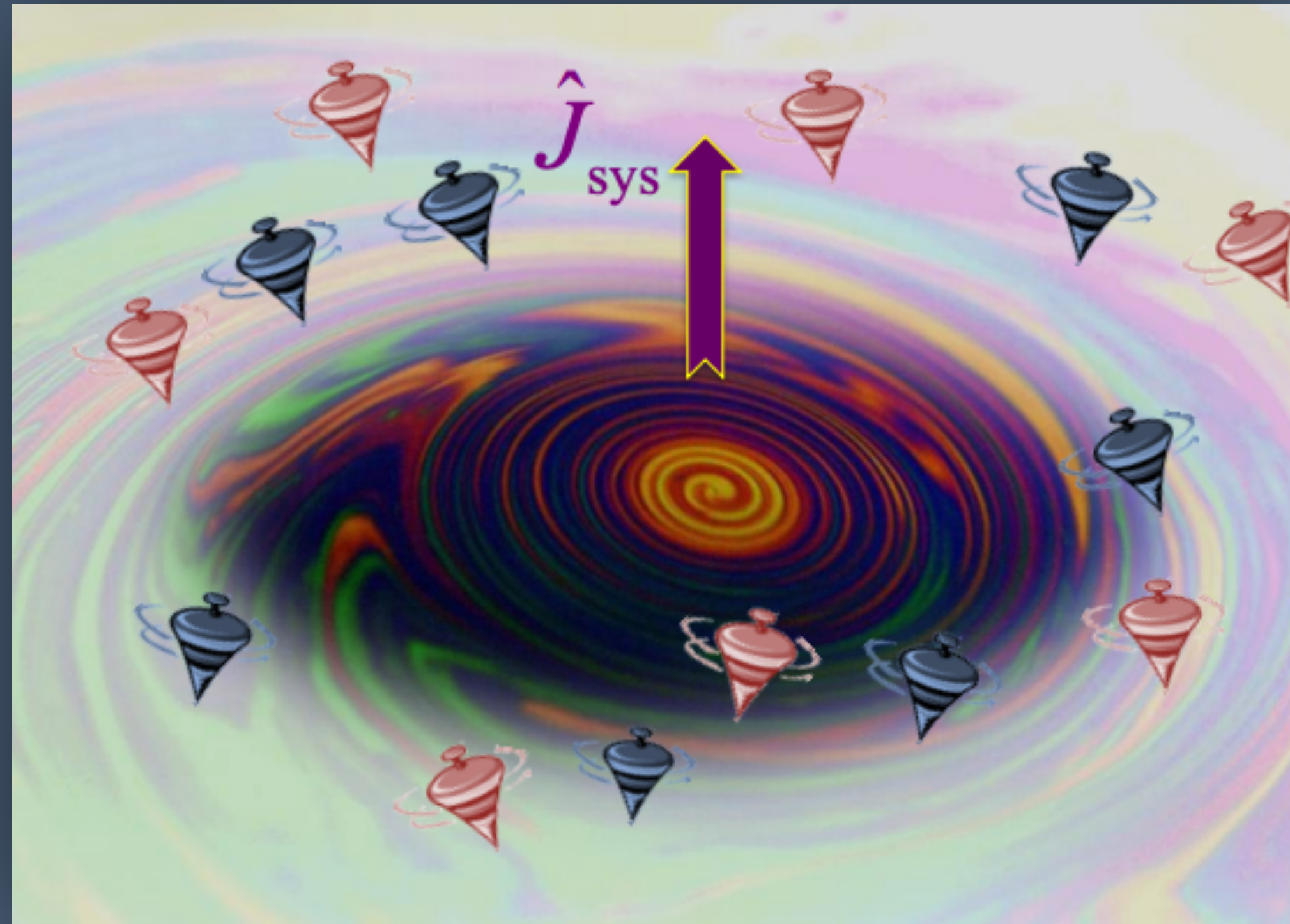
Fig by Mike Lisa



Possible to measure via polarization!

Vorticity

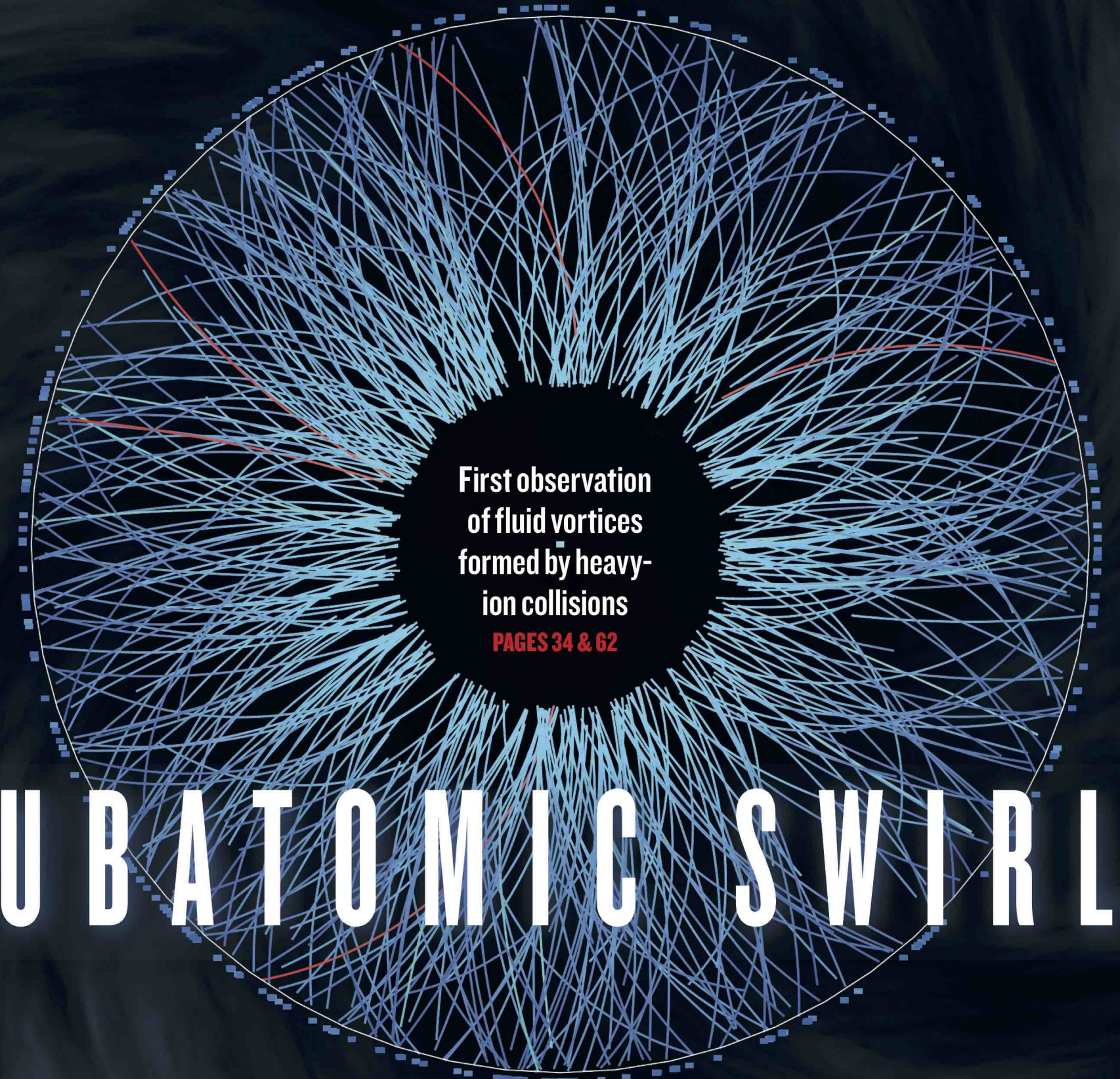
Fig by Mike Lisa



Possible to measure via polarization!

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

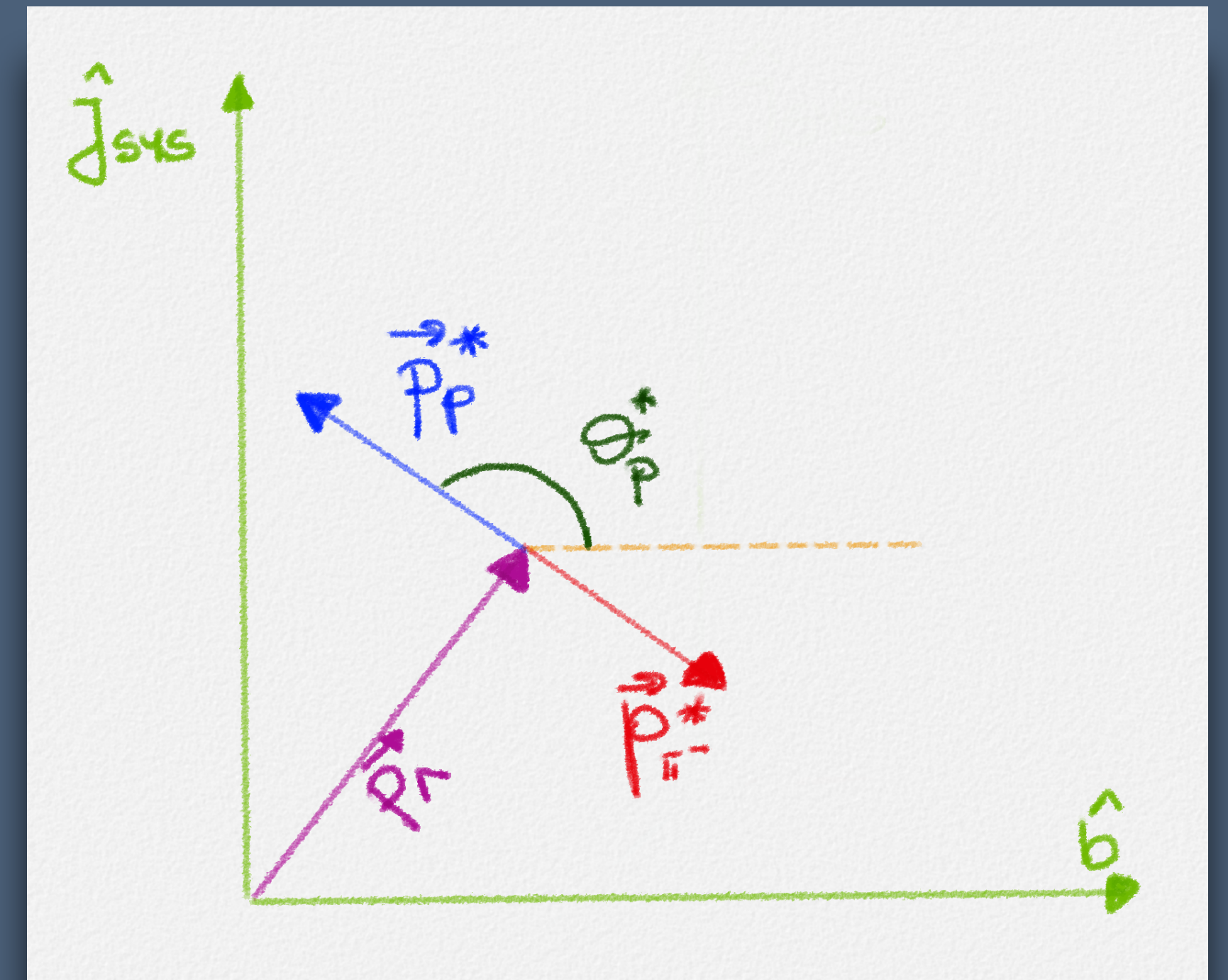
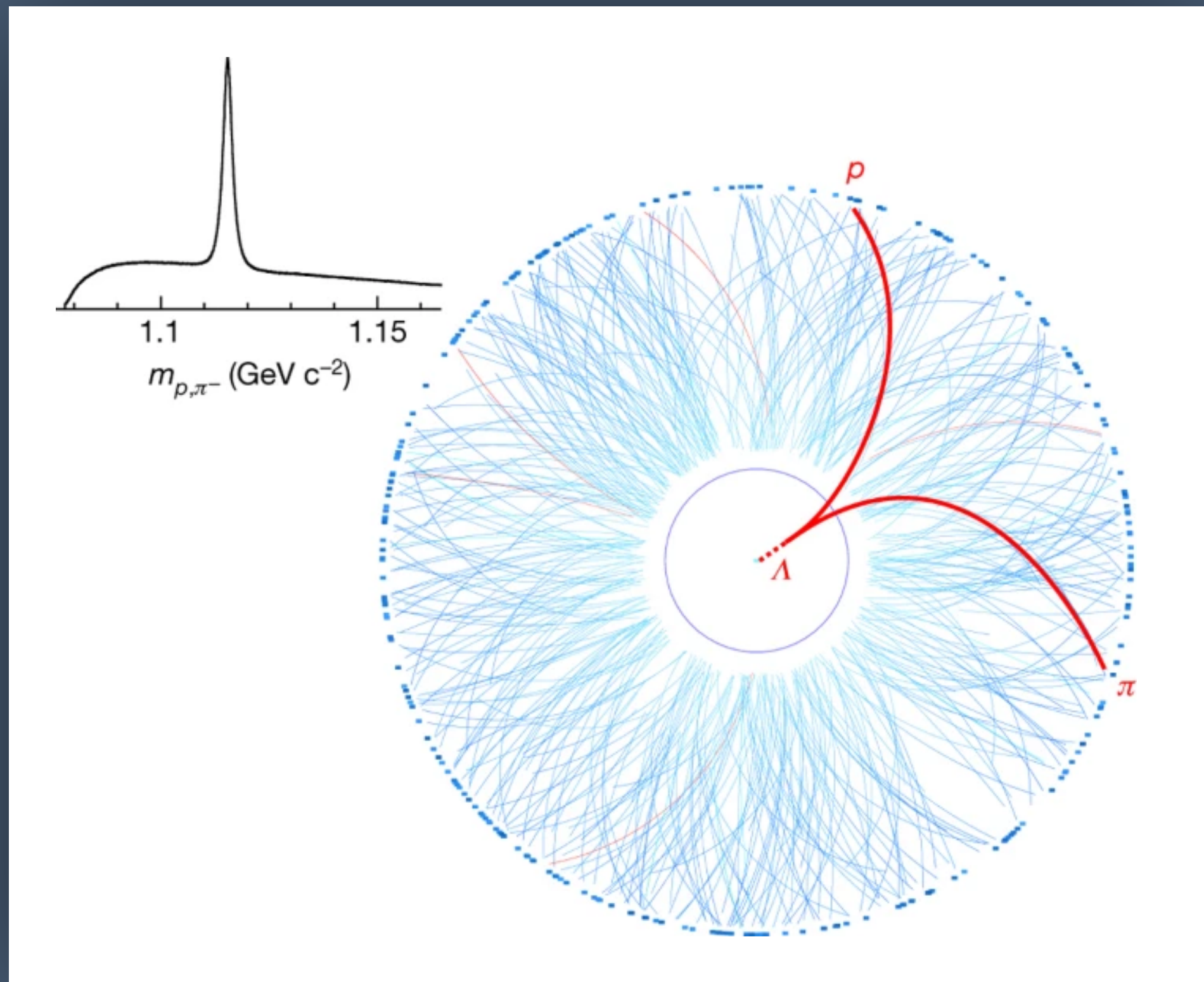
NATURE.COM/NATURE

3 August 2017

Vol. 548, No. 7665

Vorticity

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



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

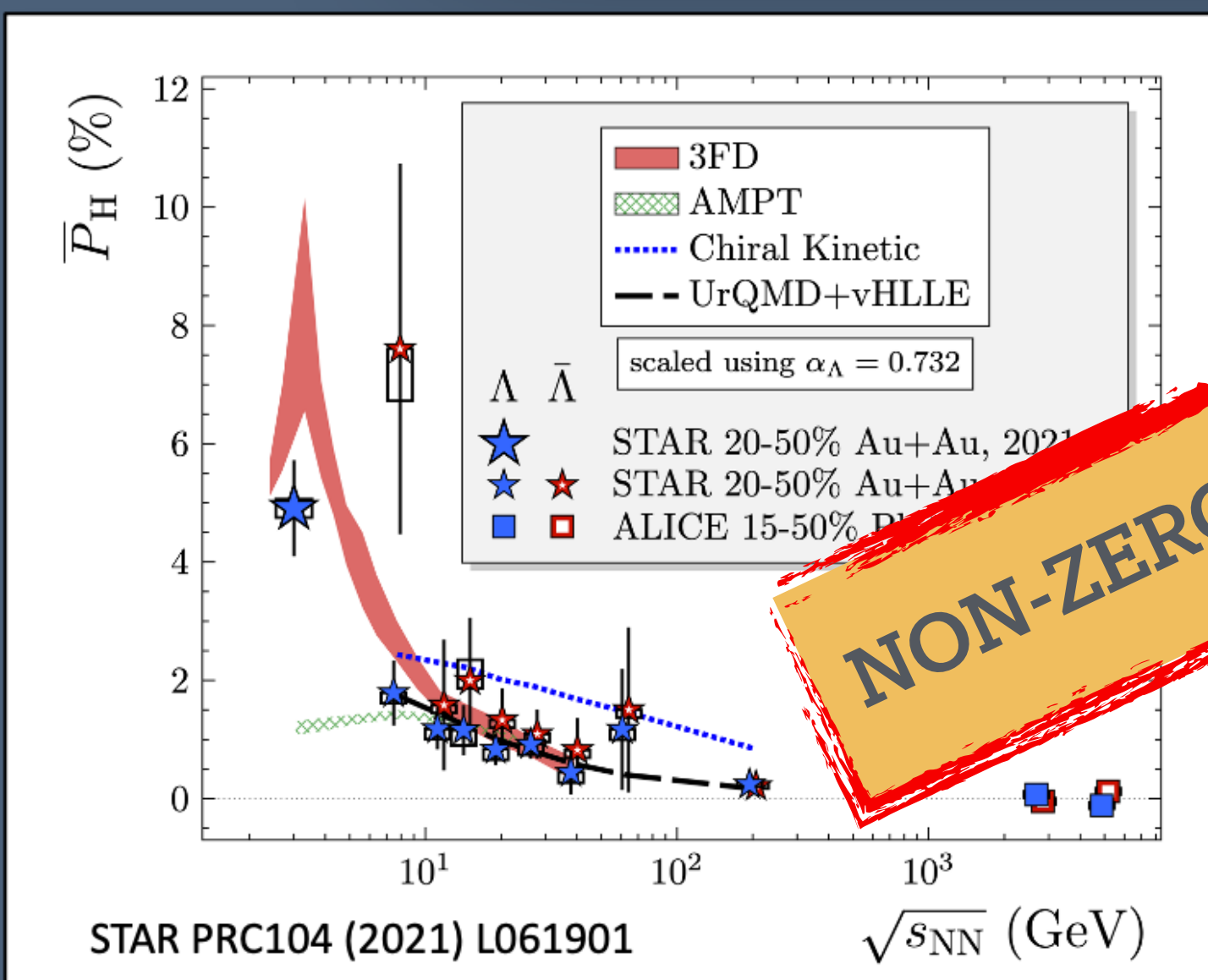
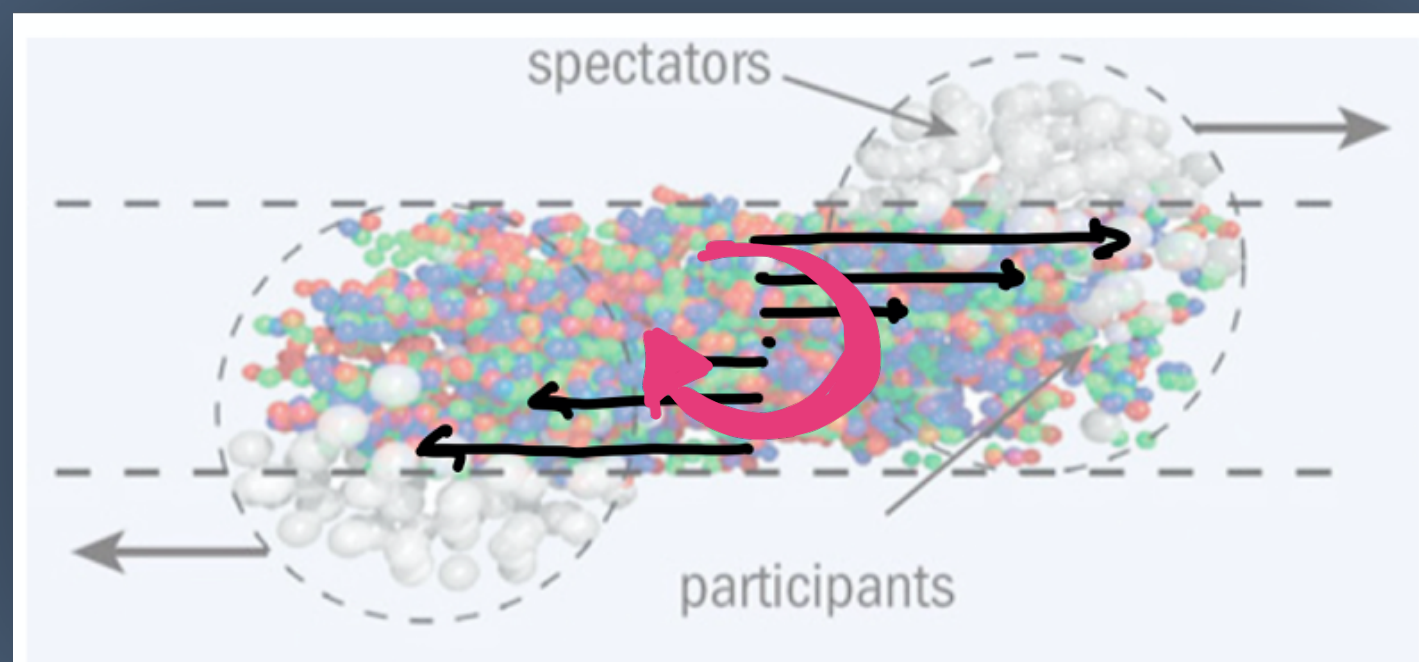
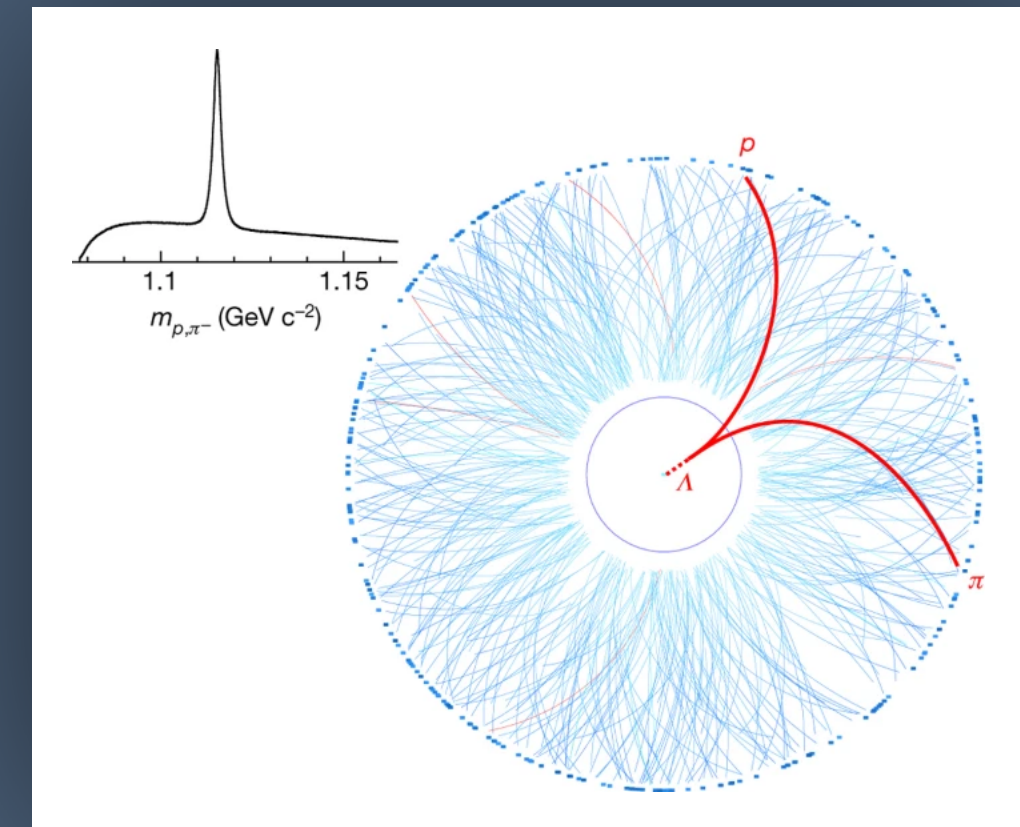
- If $P_H = 0$ then θ^* of proton momentum in Λ frame distribution uniform

Vorticity

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

GLOBAL

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

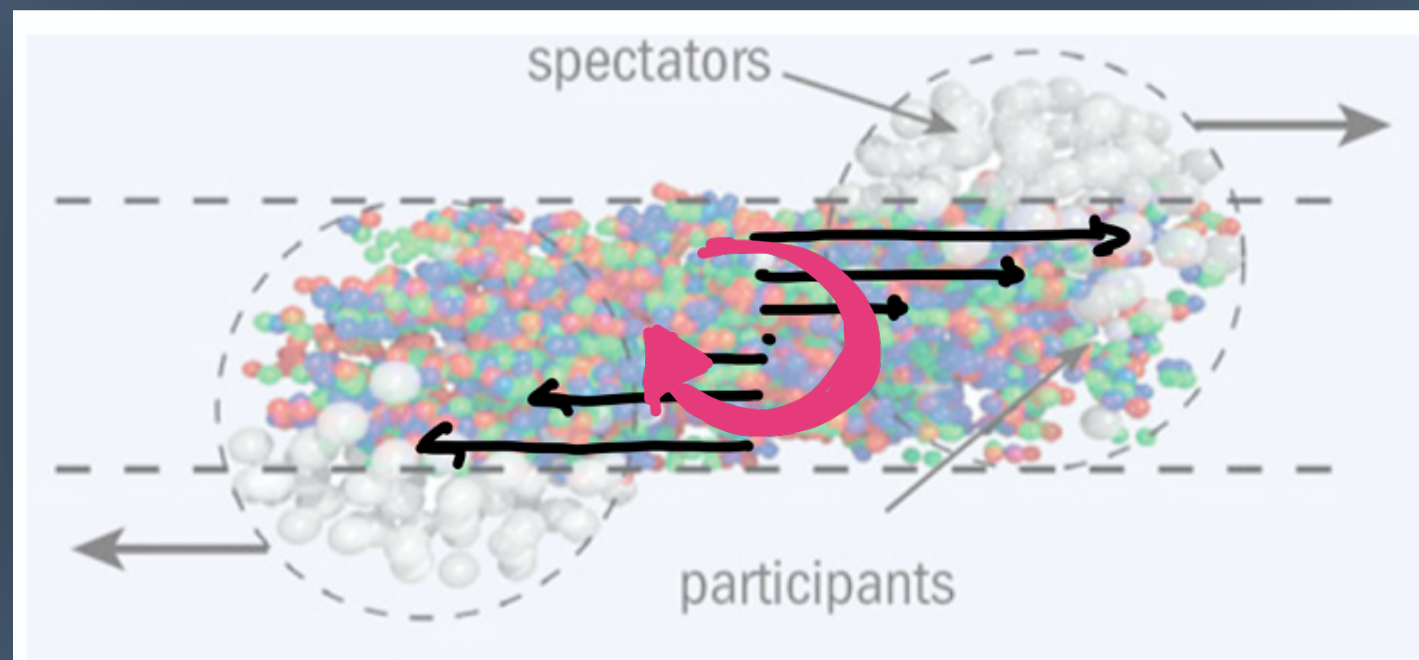
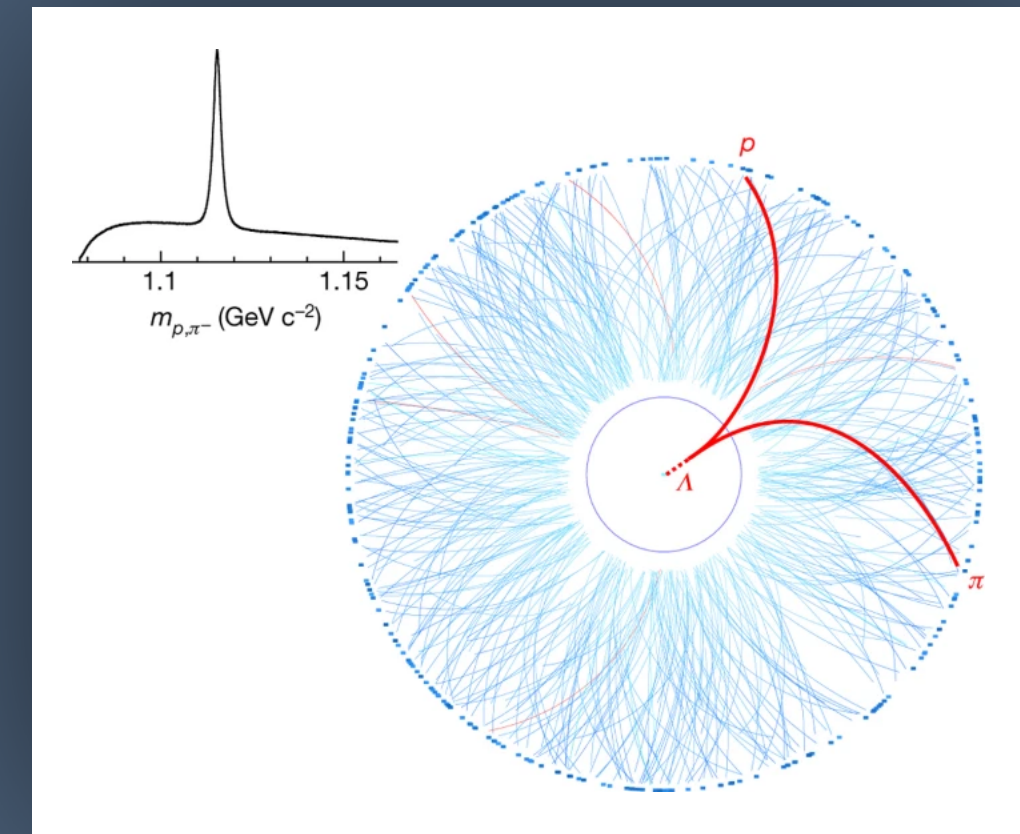


Vorticity

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

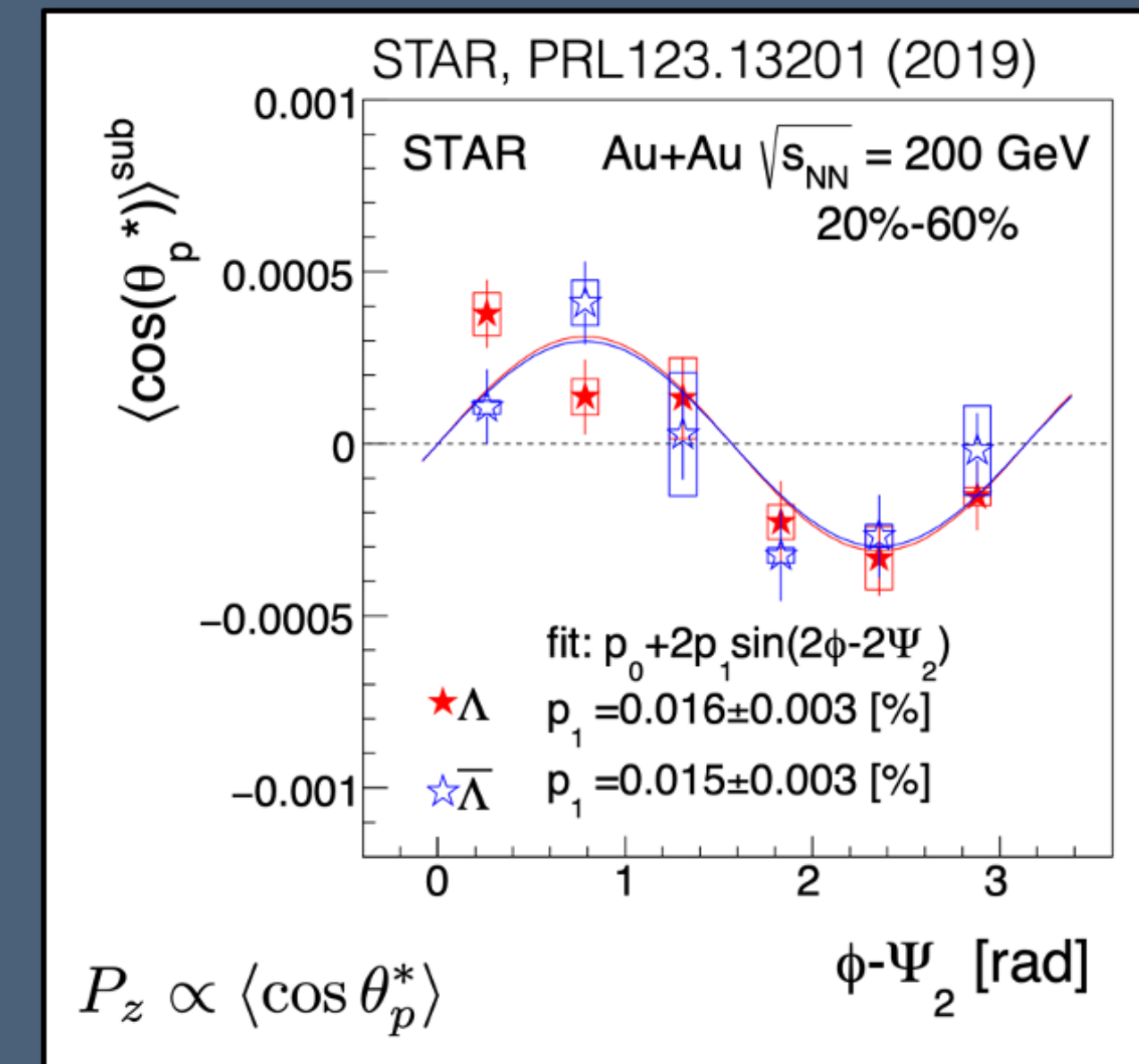
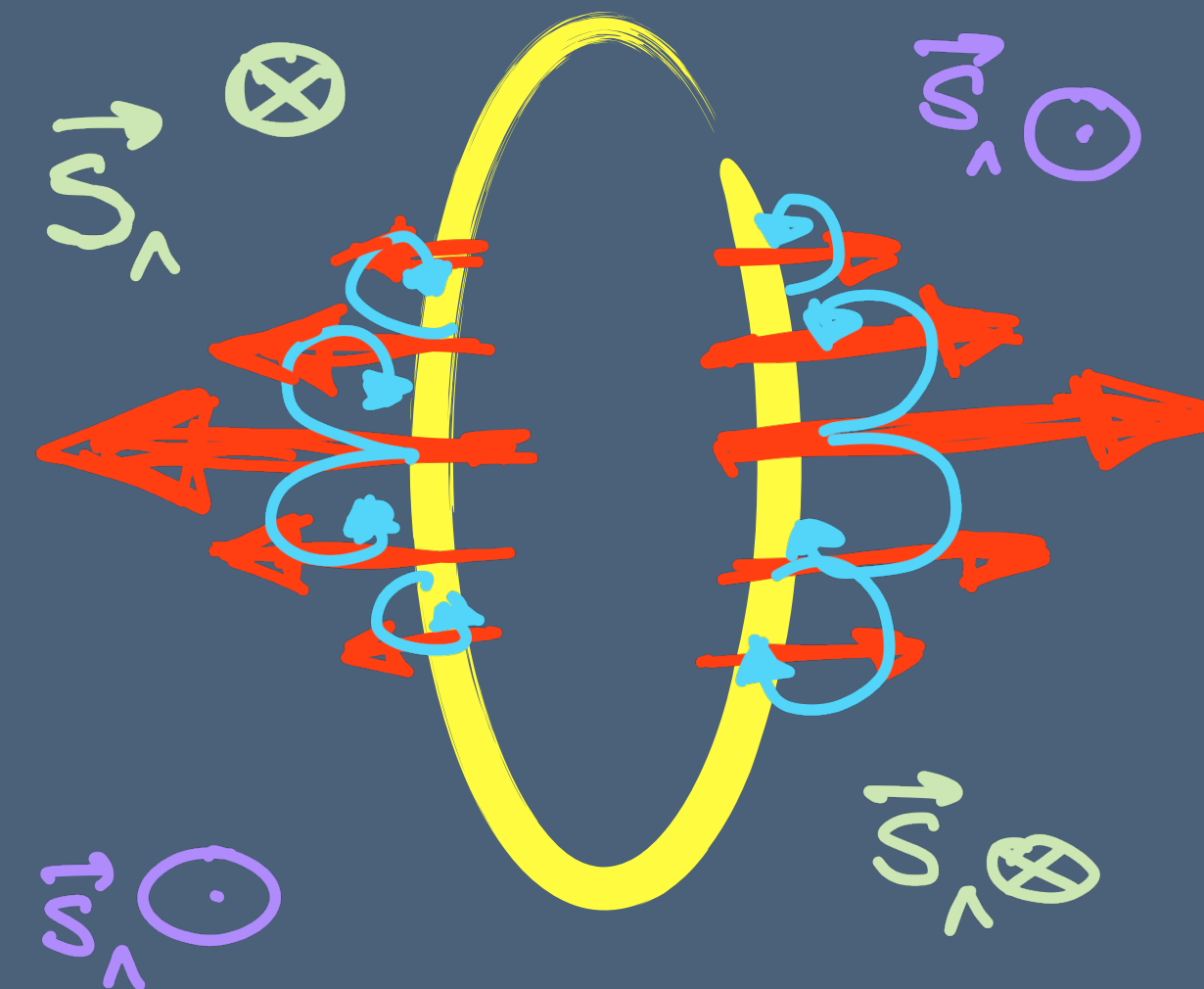
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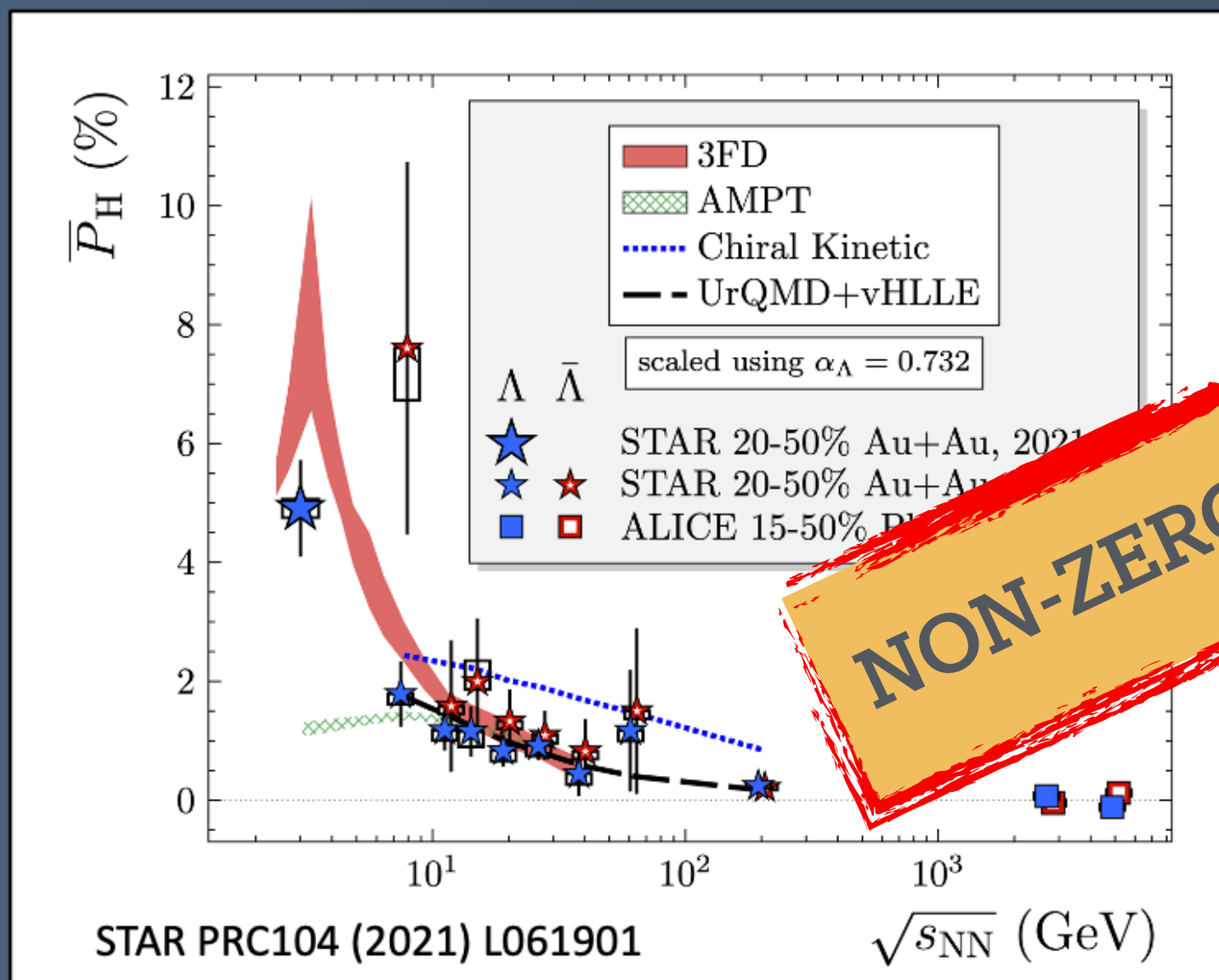


LOCAL

Effect of elliptic flow



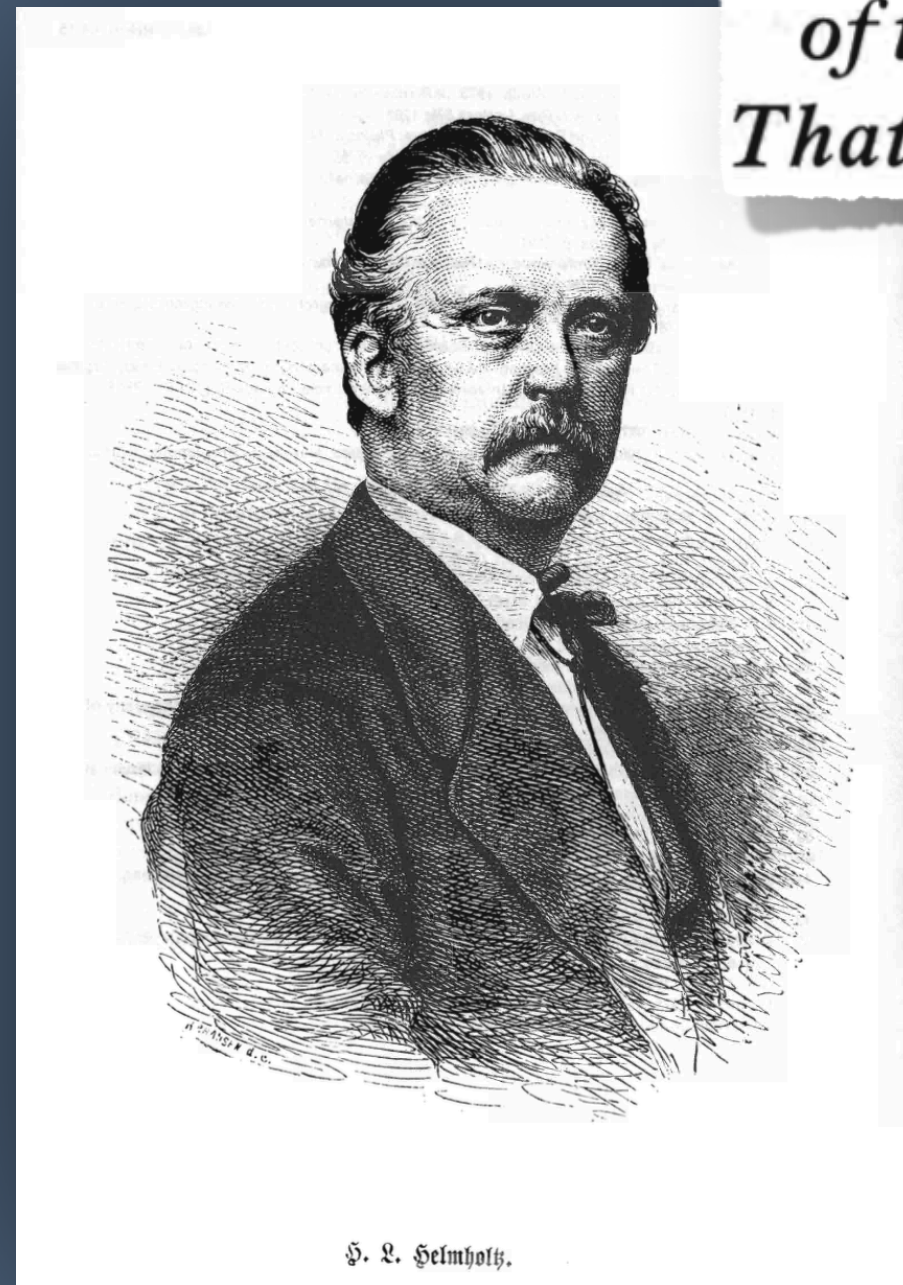
NON-ZERO at lower $\sqrt{s_{NN}}$!!



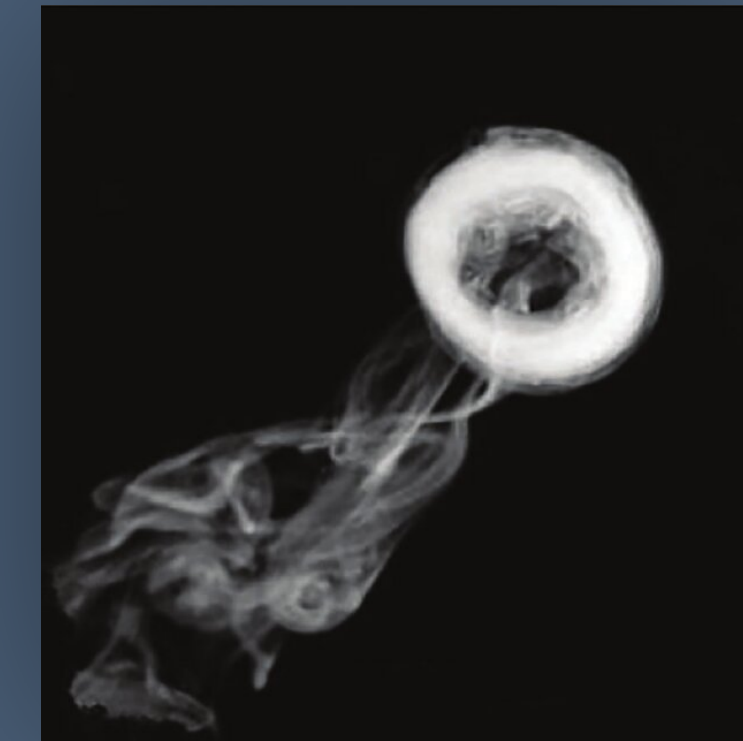
Vorticity: Toroidal (smoke rings)

Present (in physics) for ages.

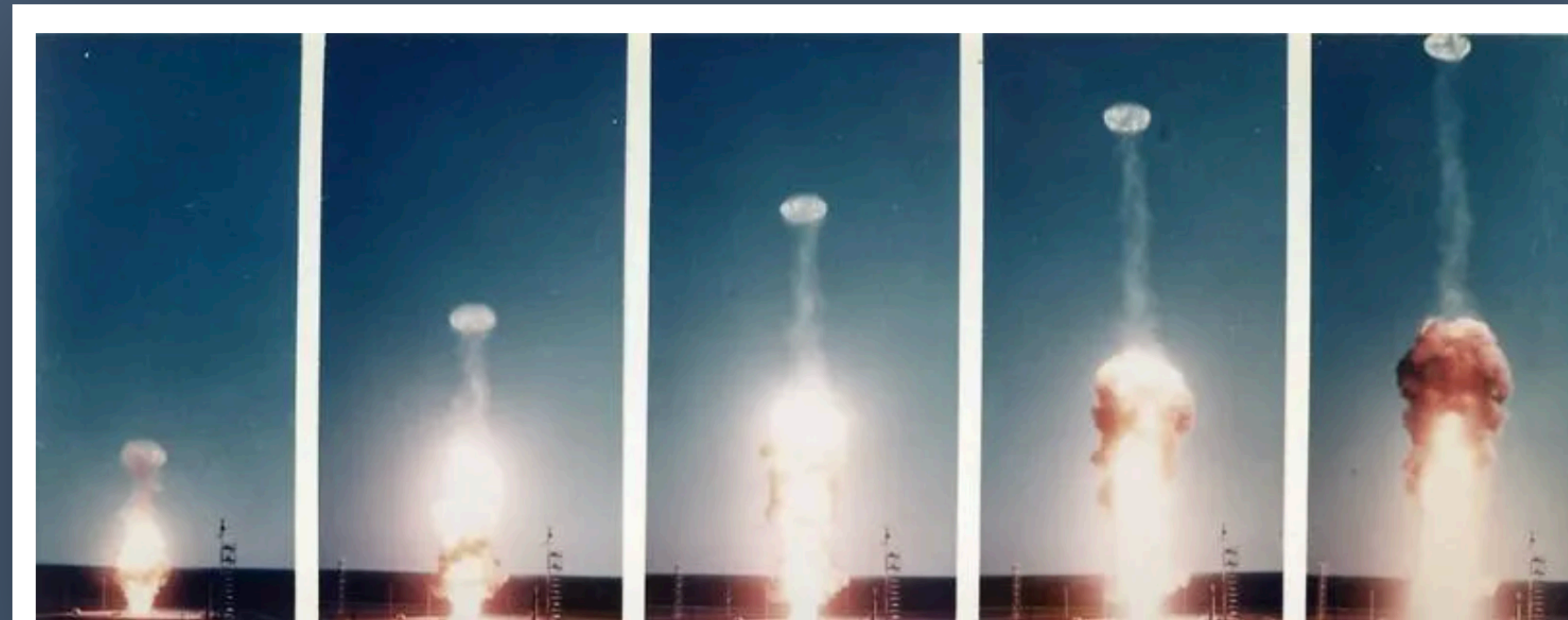
*On Integrals
of the Hydrodynamic Equations
That Correspond to Vortex Motions*



Helmholtz (1858)



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

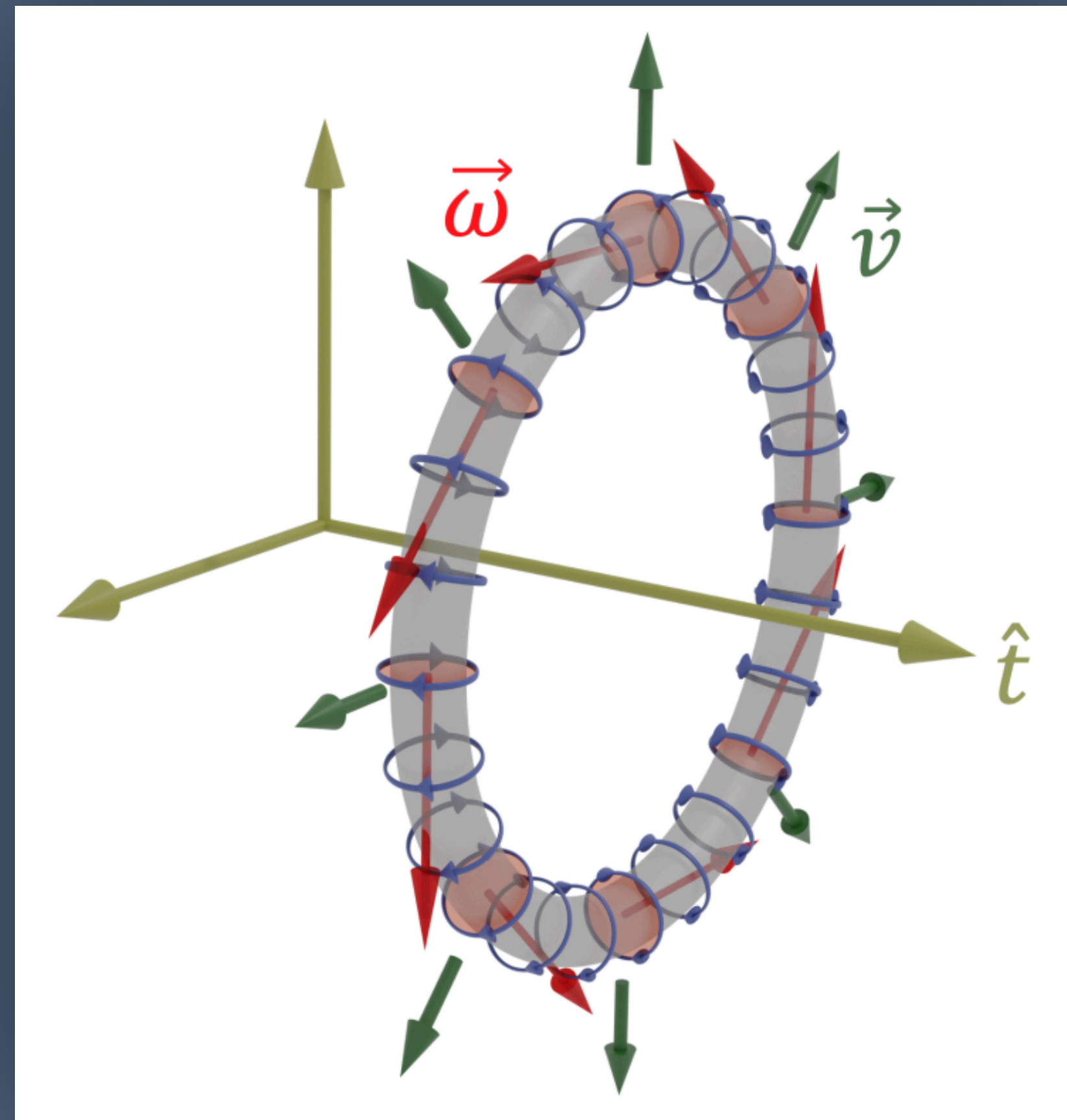


Since the first *Minuteman* launches from Cape Canaveral in 1961, nearly every missile has generated a perfect ring of smoke.



Vorticity: Toroidal (smoke rings)

Present (in physics) for ages.



Expanding smoke ring can be quantified by:

non-relativistic

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

Curl of flow velocity \vec{v} :

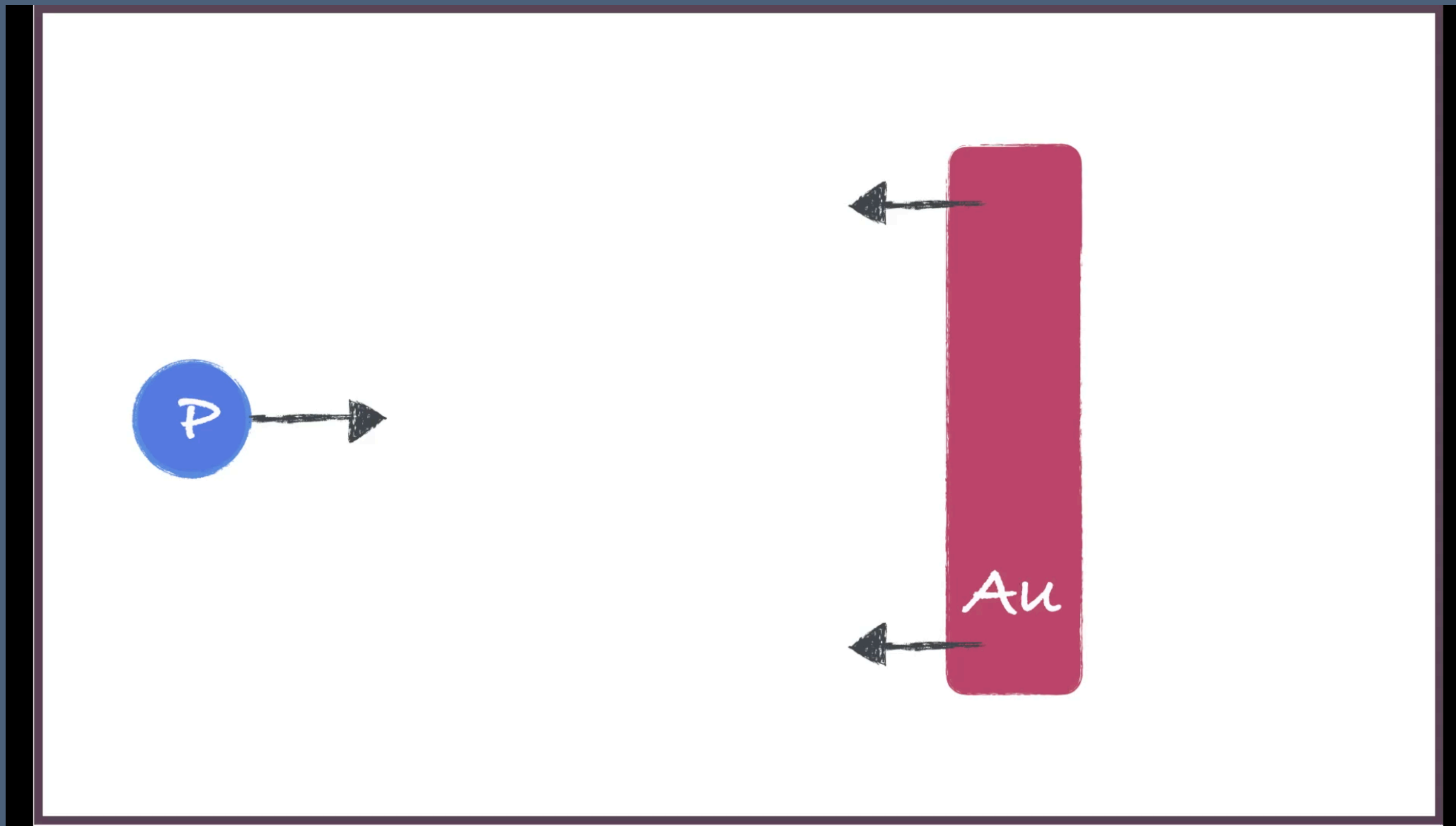
$$\vec{\omega}_{NR} = \frac{1}{2} \vec{\nabla} \times \vec{v}$$

\hat{t} - thrust vector



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:

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

Ω_{μ} - proxy for vorticity

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

n_{ν} - normal vector of the fluid cell

Vorticity: Toroidal (smoke rings)

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

- In relativistic treatment vorticity (thermal):

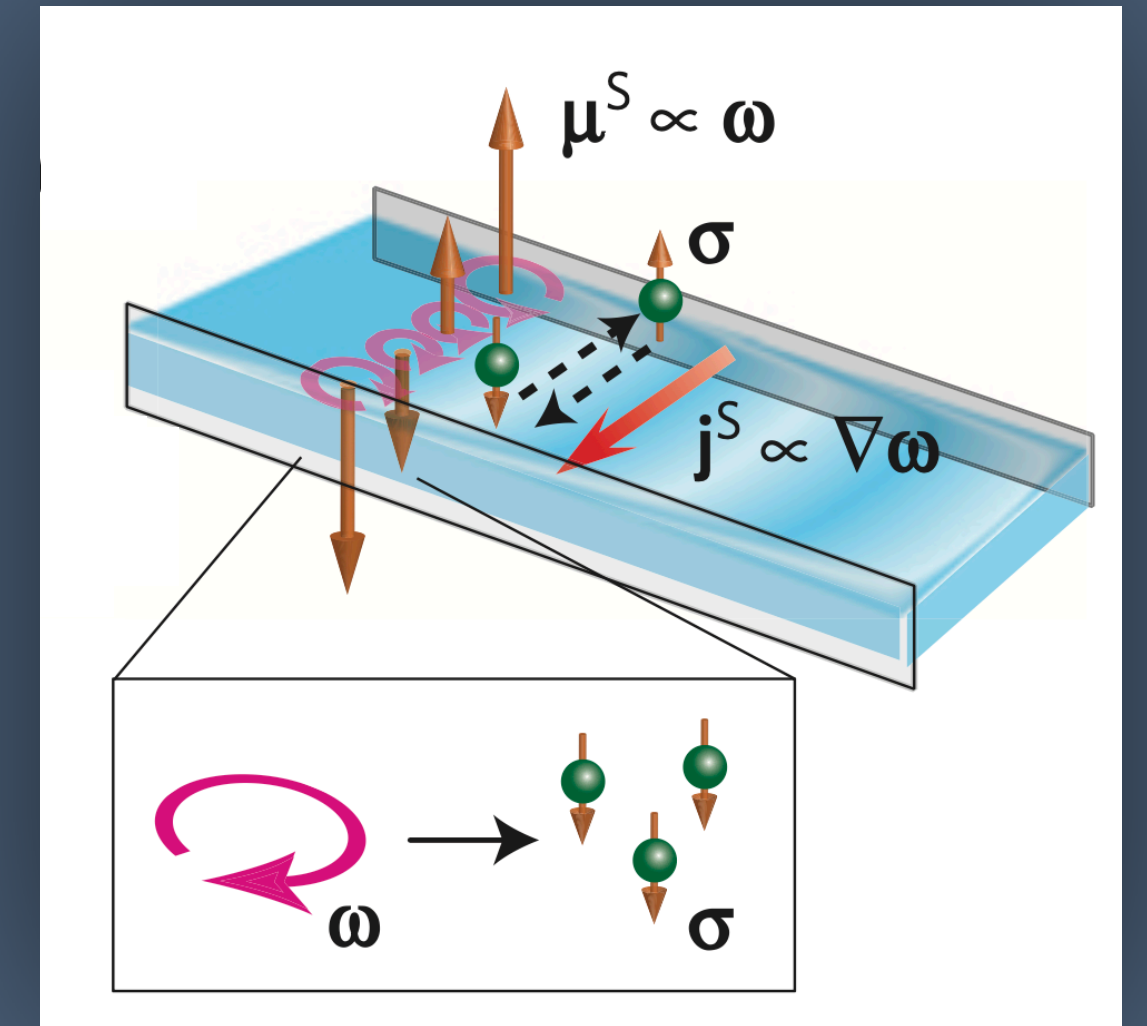
$$\omega_{th}^{\mu\nu} = \frac{1}{2}[\partial^\nu(u^\mu/T) - \partial^\mu(u^\nu/T)]$$

- 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” hypersurface 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)

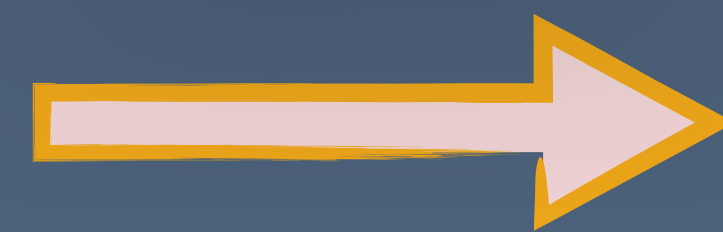


Vorticity: Toroidal (smoke rings)

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

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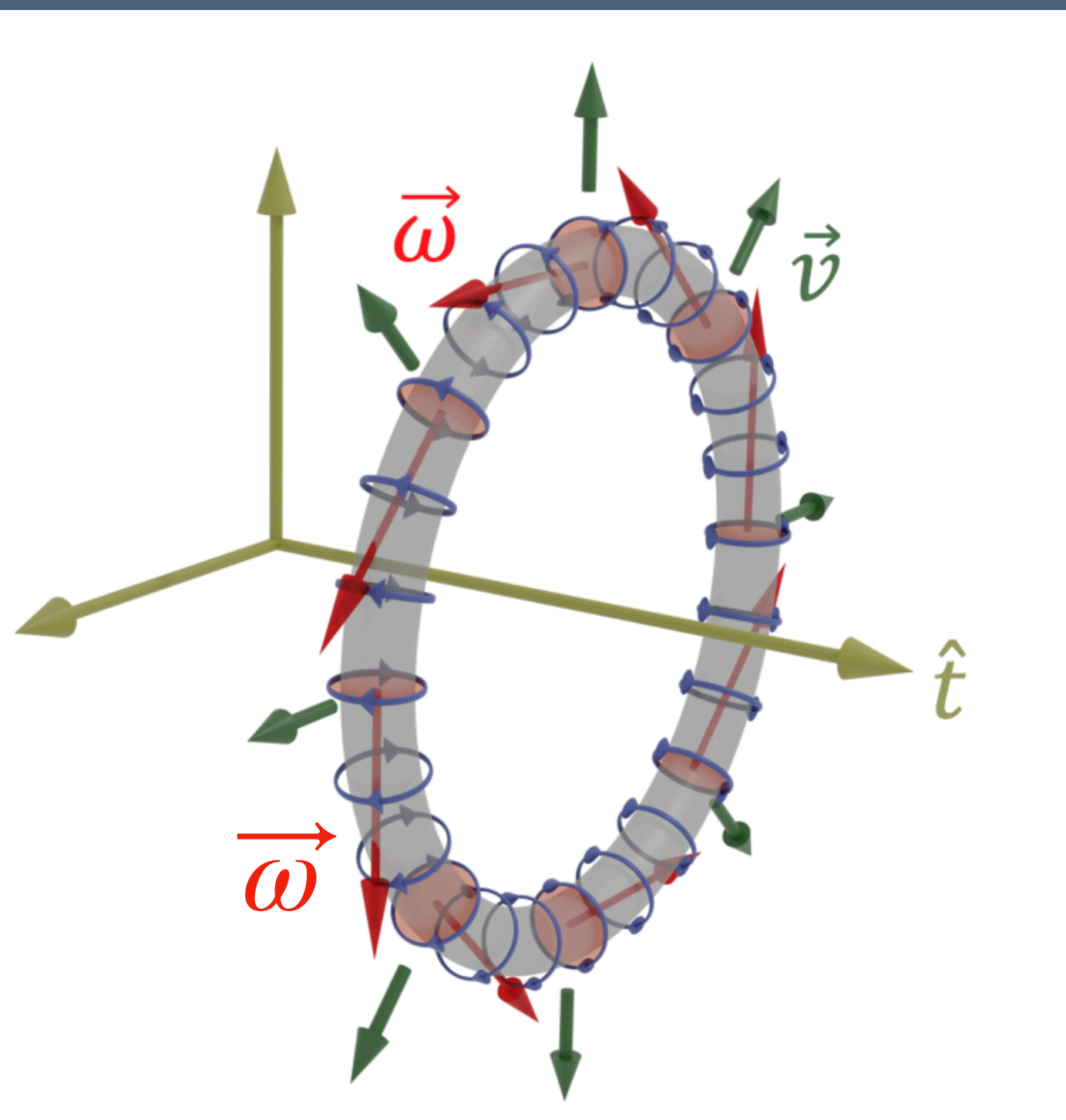
HADRONIZATION



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

S_{μ} - Λ spin four-vector

p_{σ} - Λ momentum four-vector

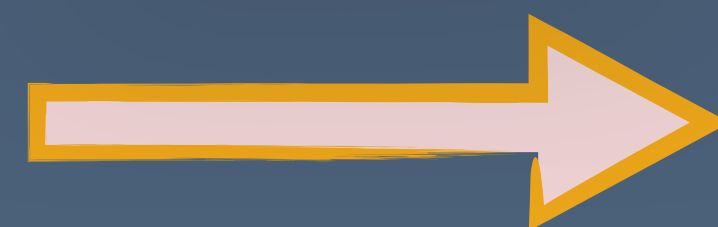


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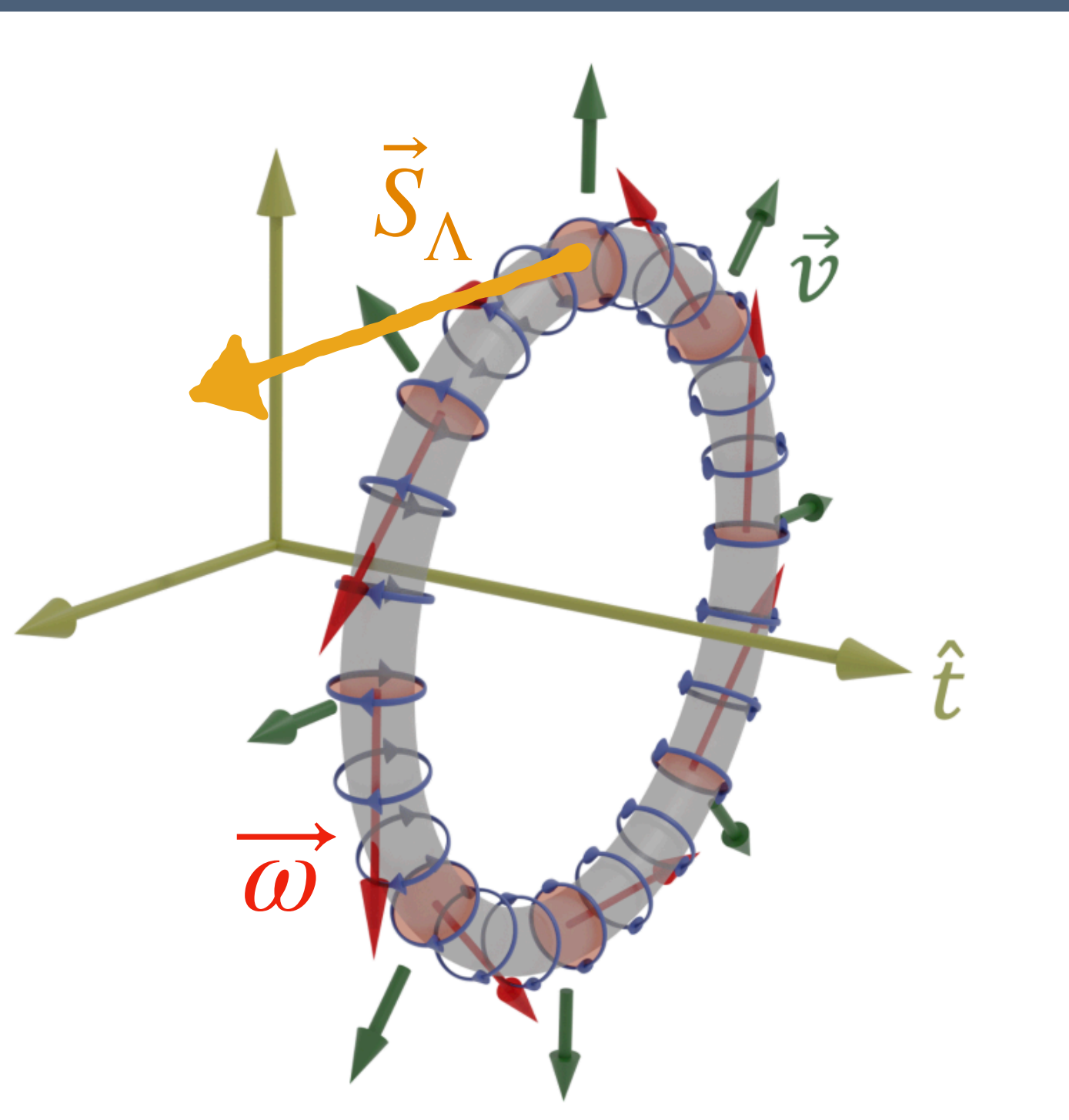
HADRONIZATION



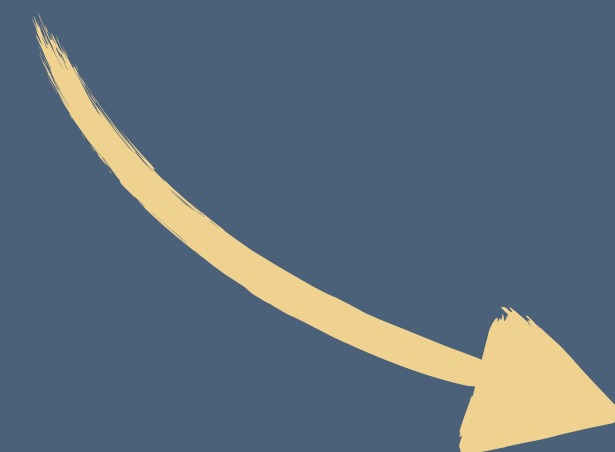
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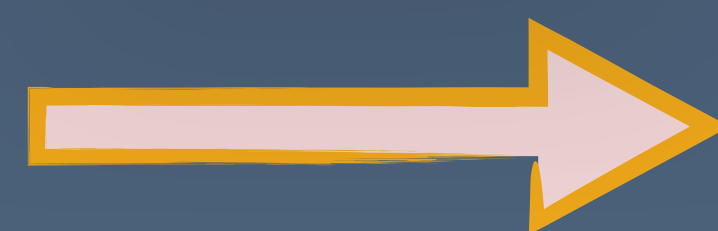
($\hat{\cdot}$) - three-vectors in NN frame

Vorticity: Toroidal (smoke rings)

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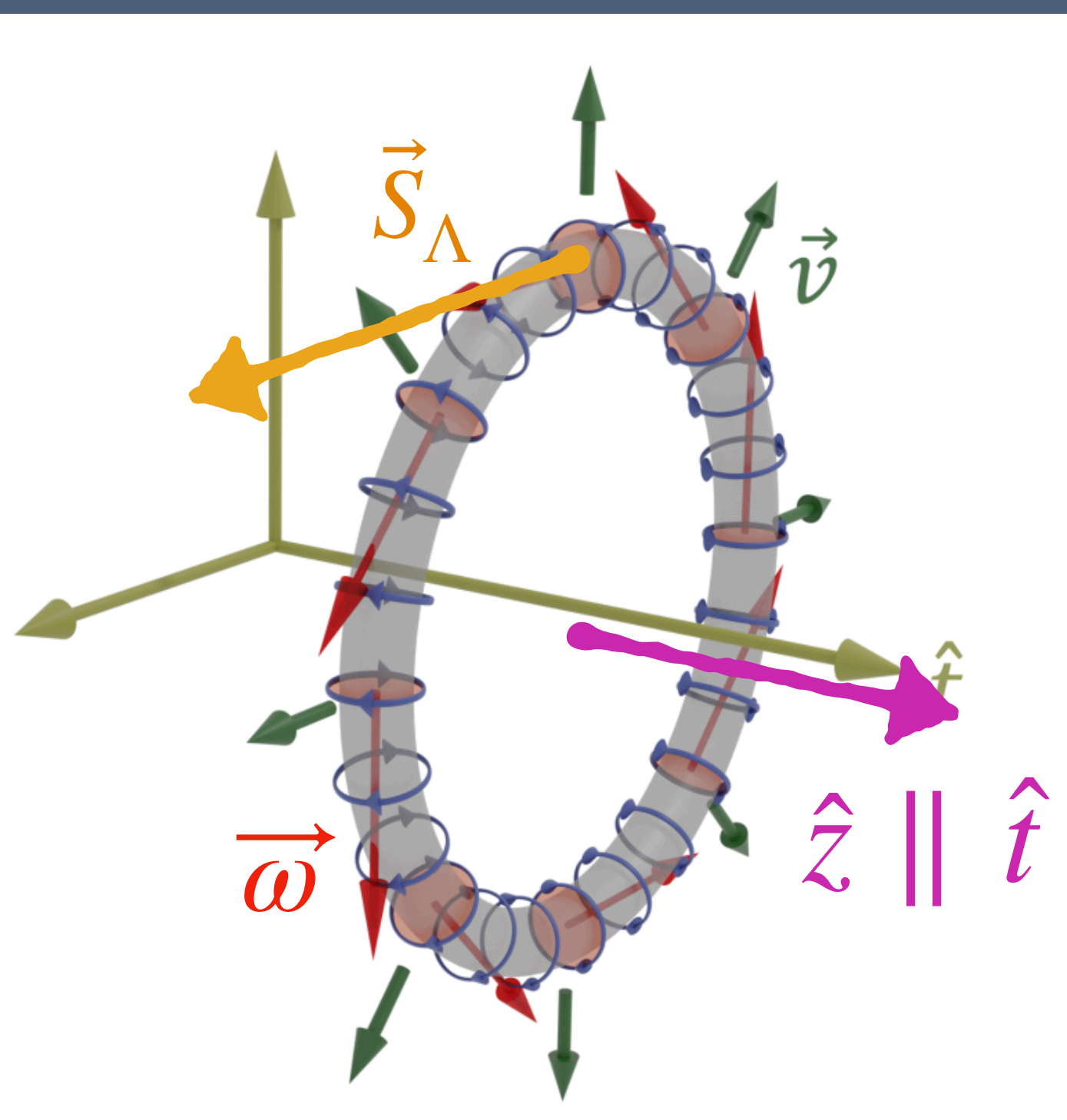
HADRONIZATION



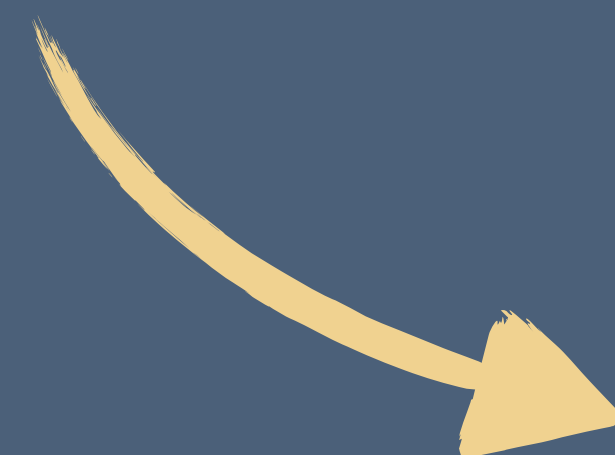
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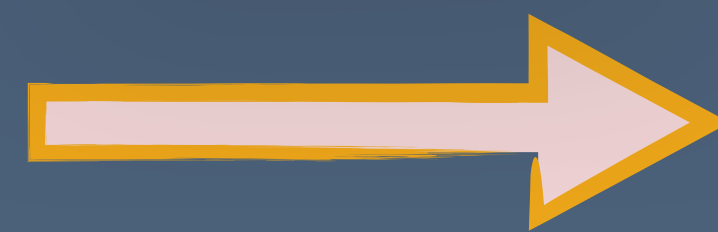
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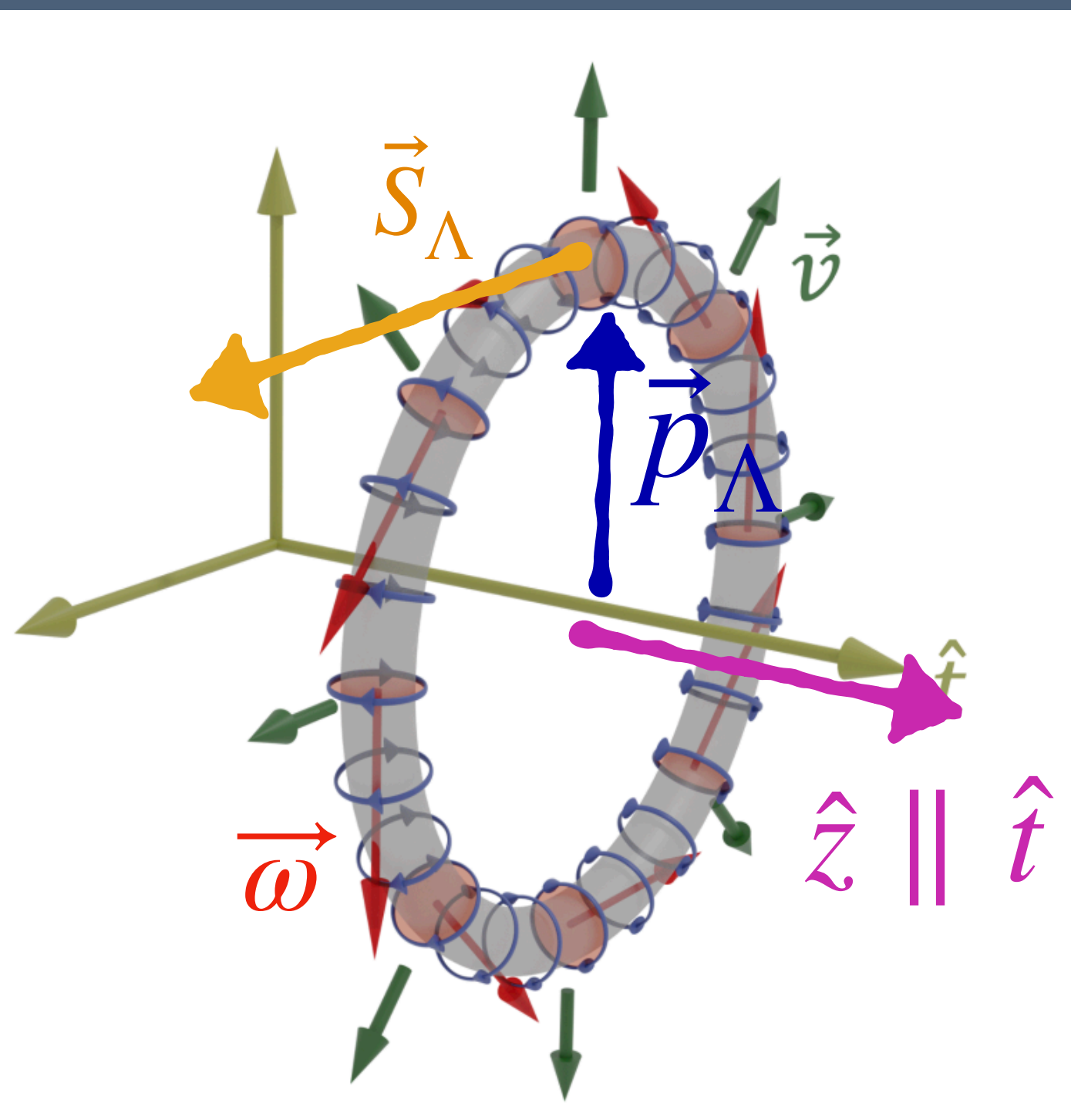
HADRONIZATION



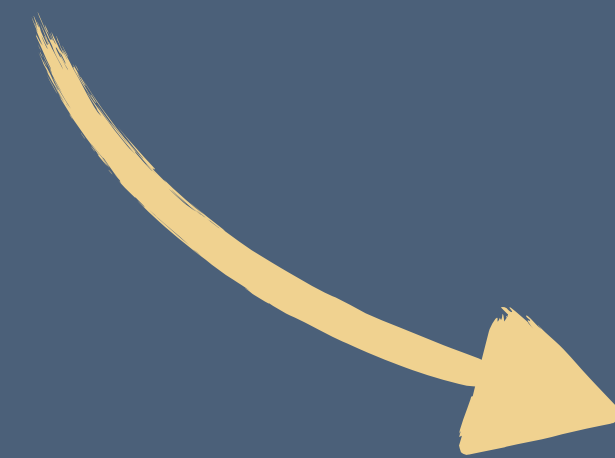
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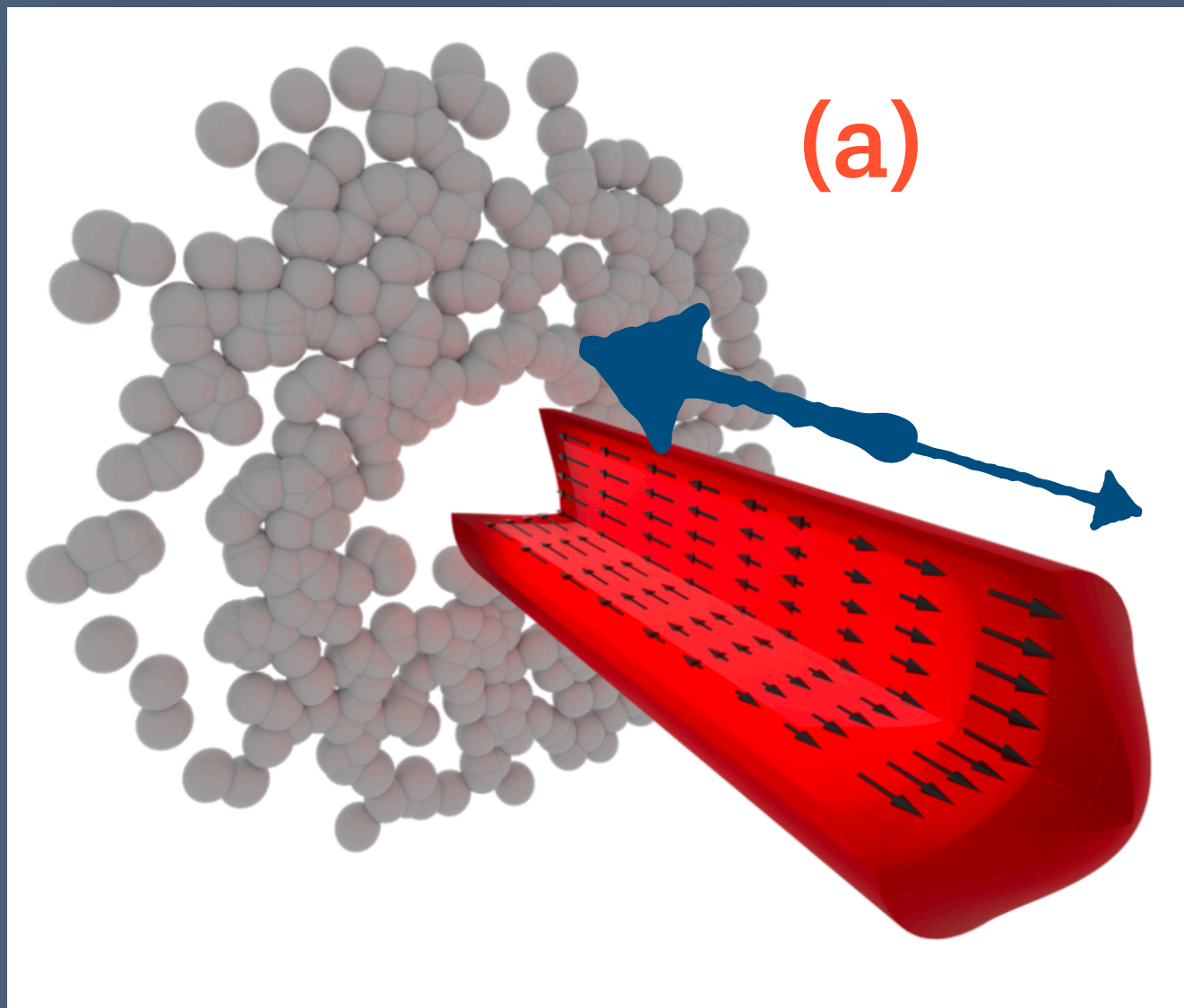
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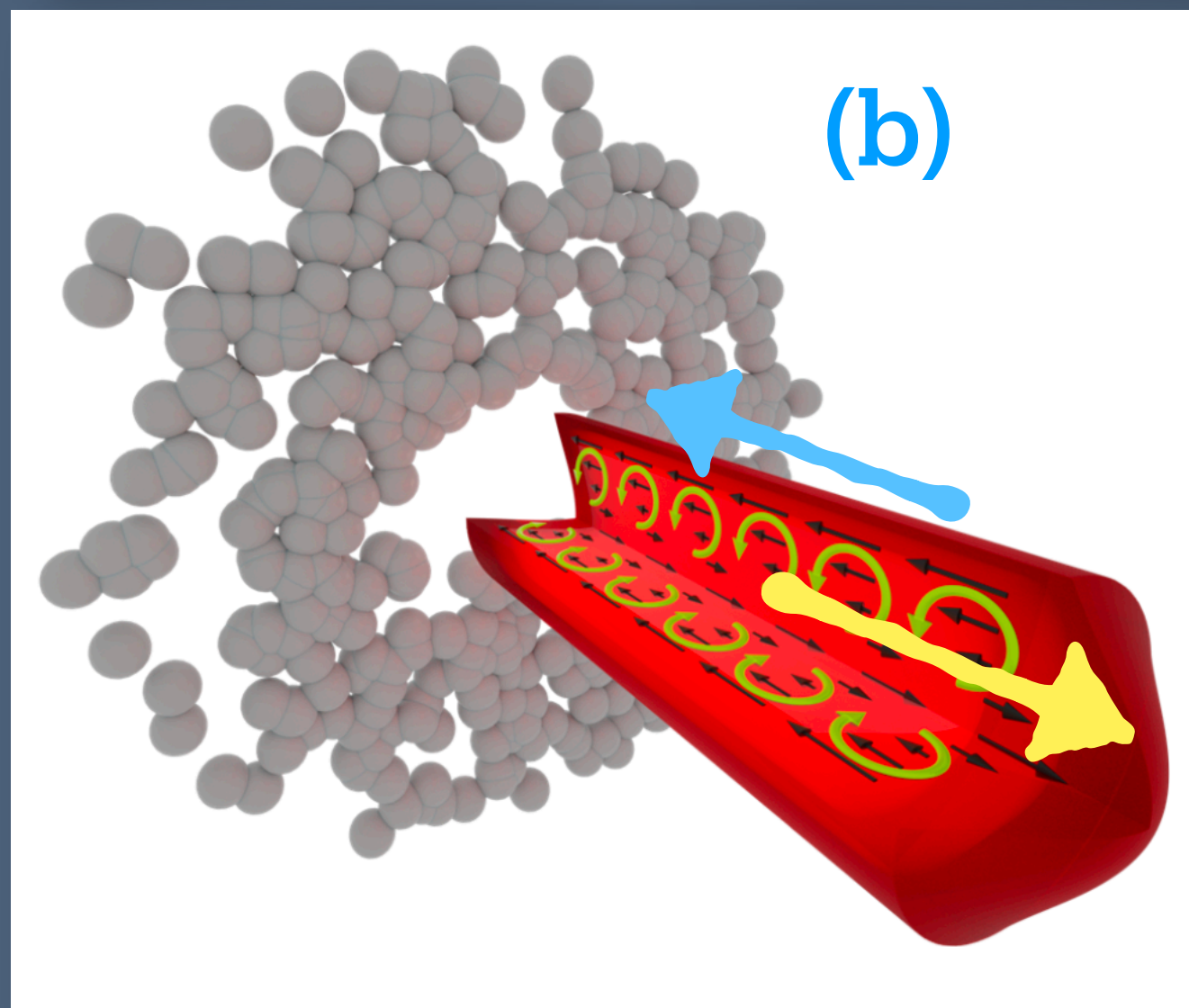
($\hat{\cdot}$) - three-vectors in NN frame

Vorticity: Toroidal (smoke rings)



Proton drilling a nuclei:

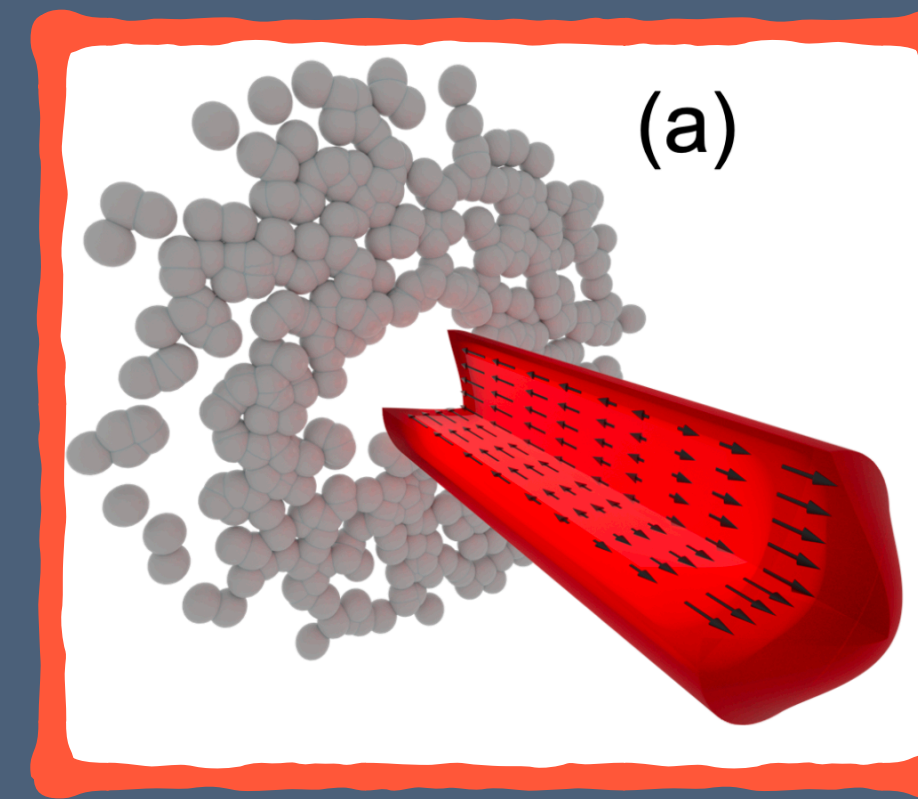
a) A boost-invariant flow distribution with more matter in the nuclei-going direction.



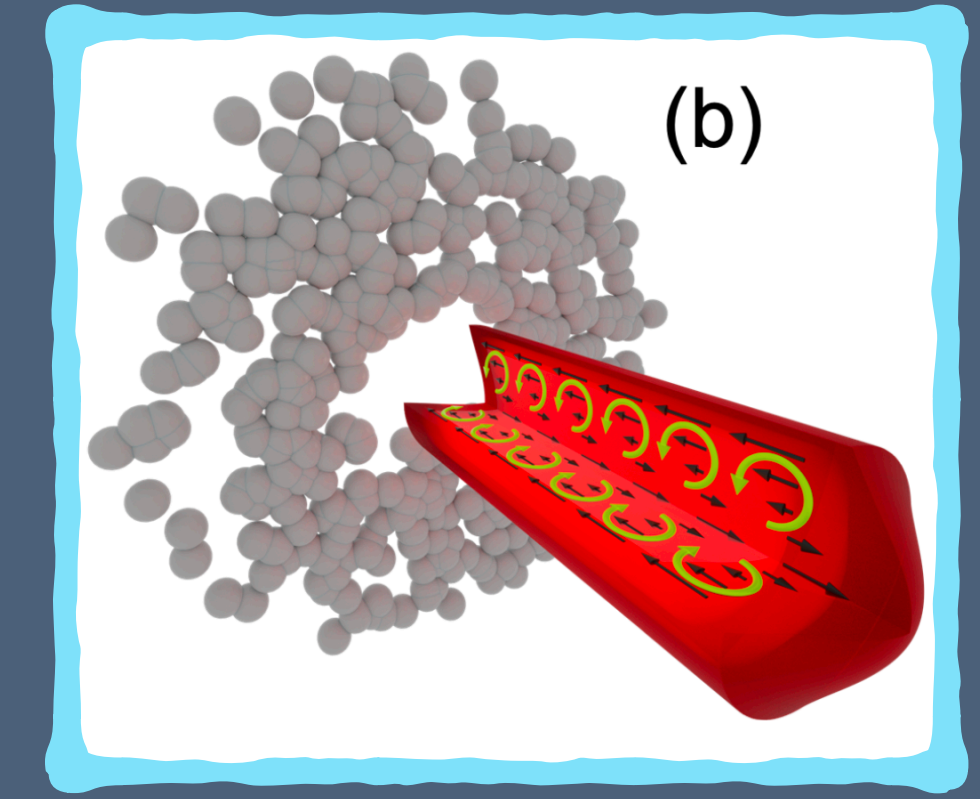
b) The edges of the cylinder flow more in the nuclei-going direction than fluid cells at the center of the cylinder.

Vorticity: Toroidal (smoke rings)

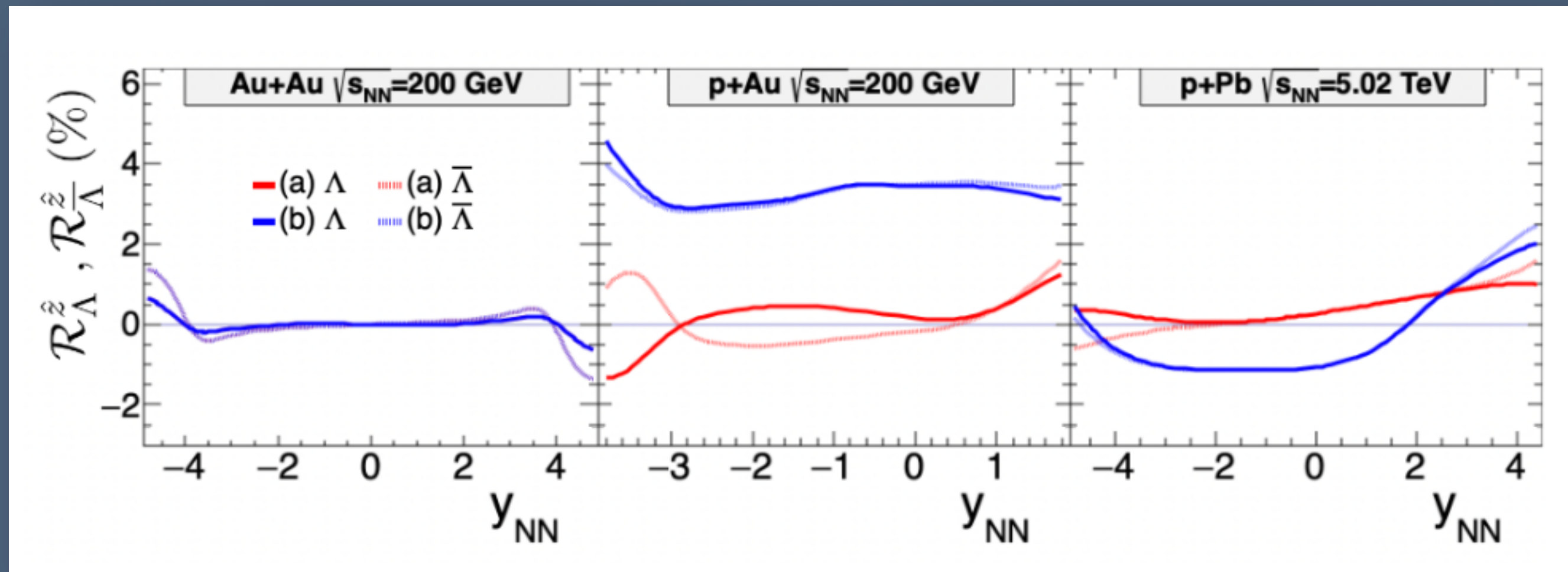
Simulations with MUSIC [1]:



No TV



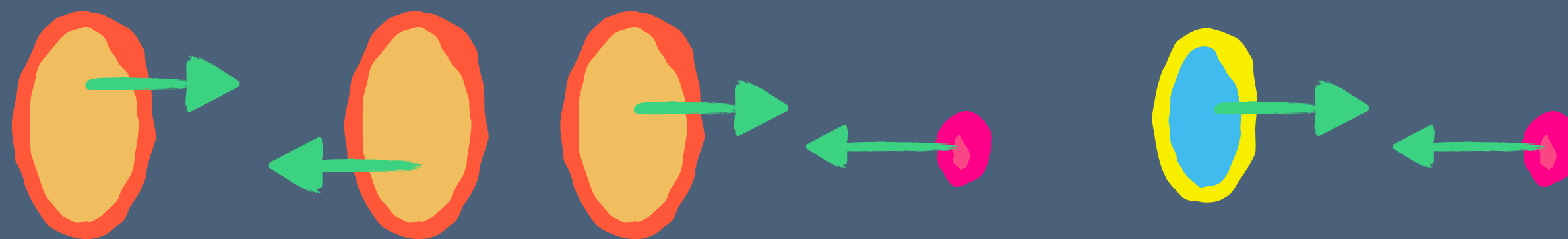
With TV



According to [1]:

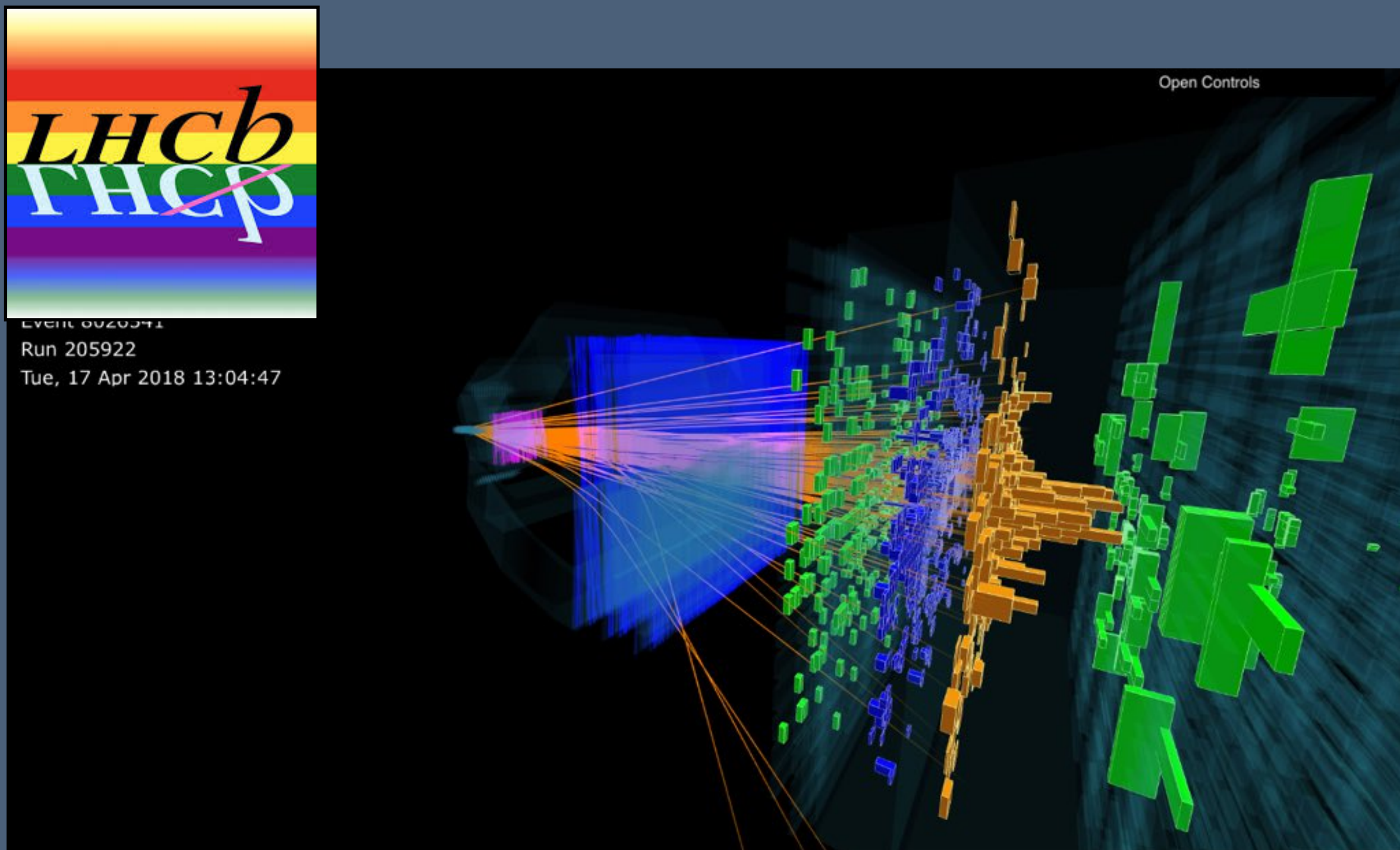
- Dependent of $\sqrt{s_{NN}}$
- No need to measure Event Plane!
- Signal present also for **Anti**Lambdas!

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



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



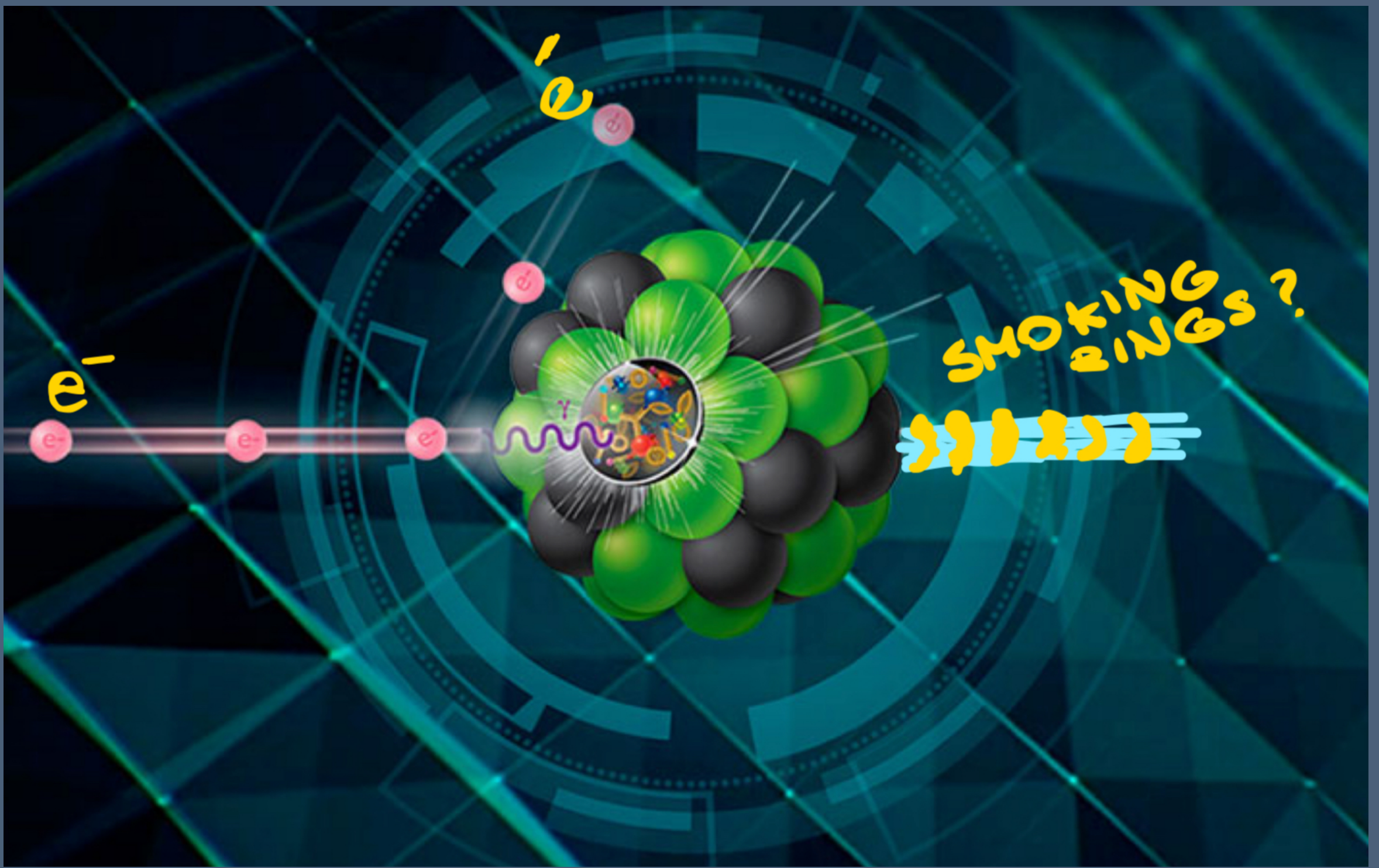
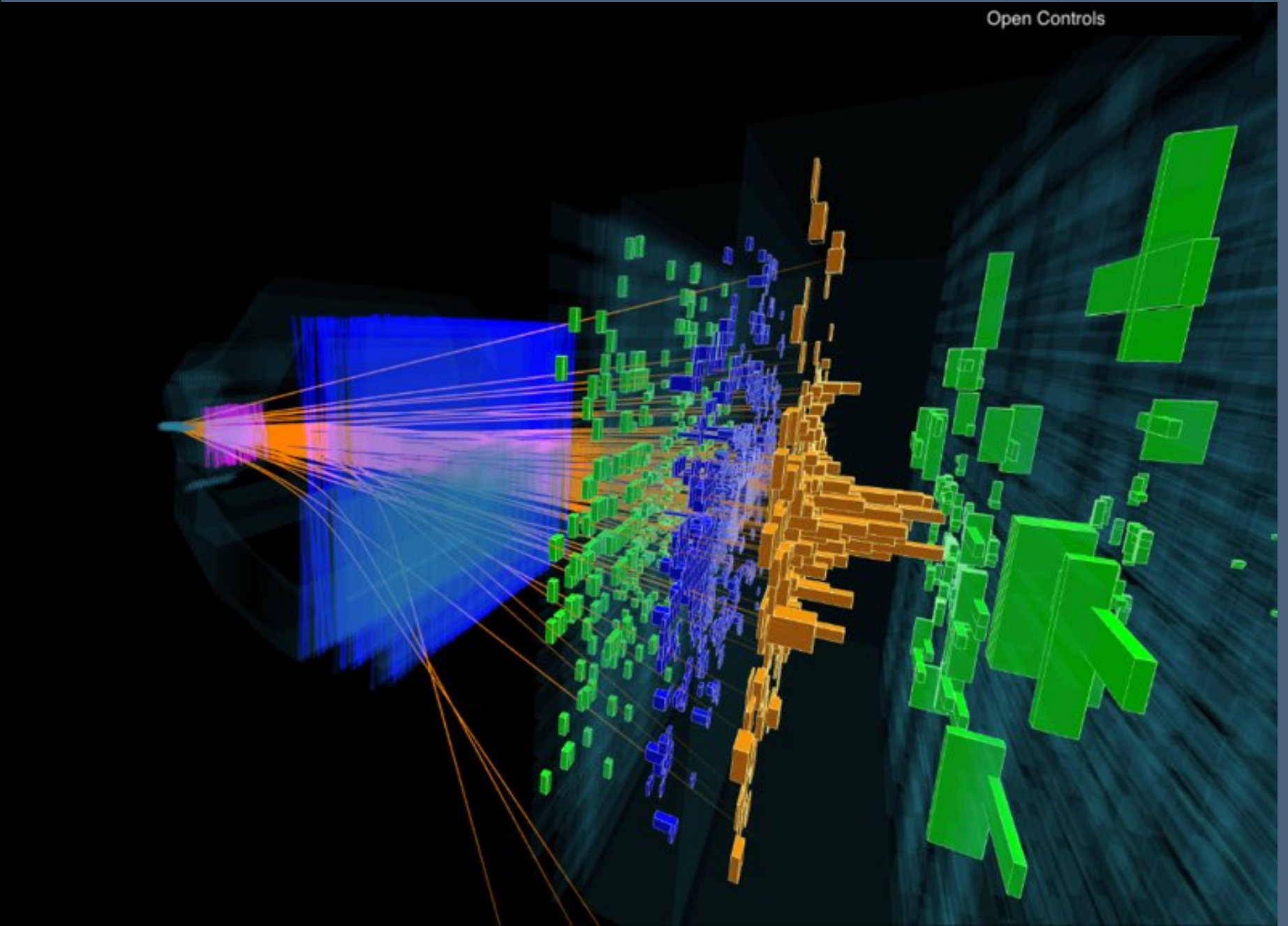
Smoking rings at LHC and EIC

- 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?



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



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!