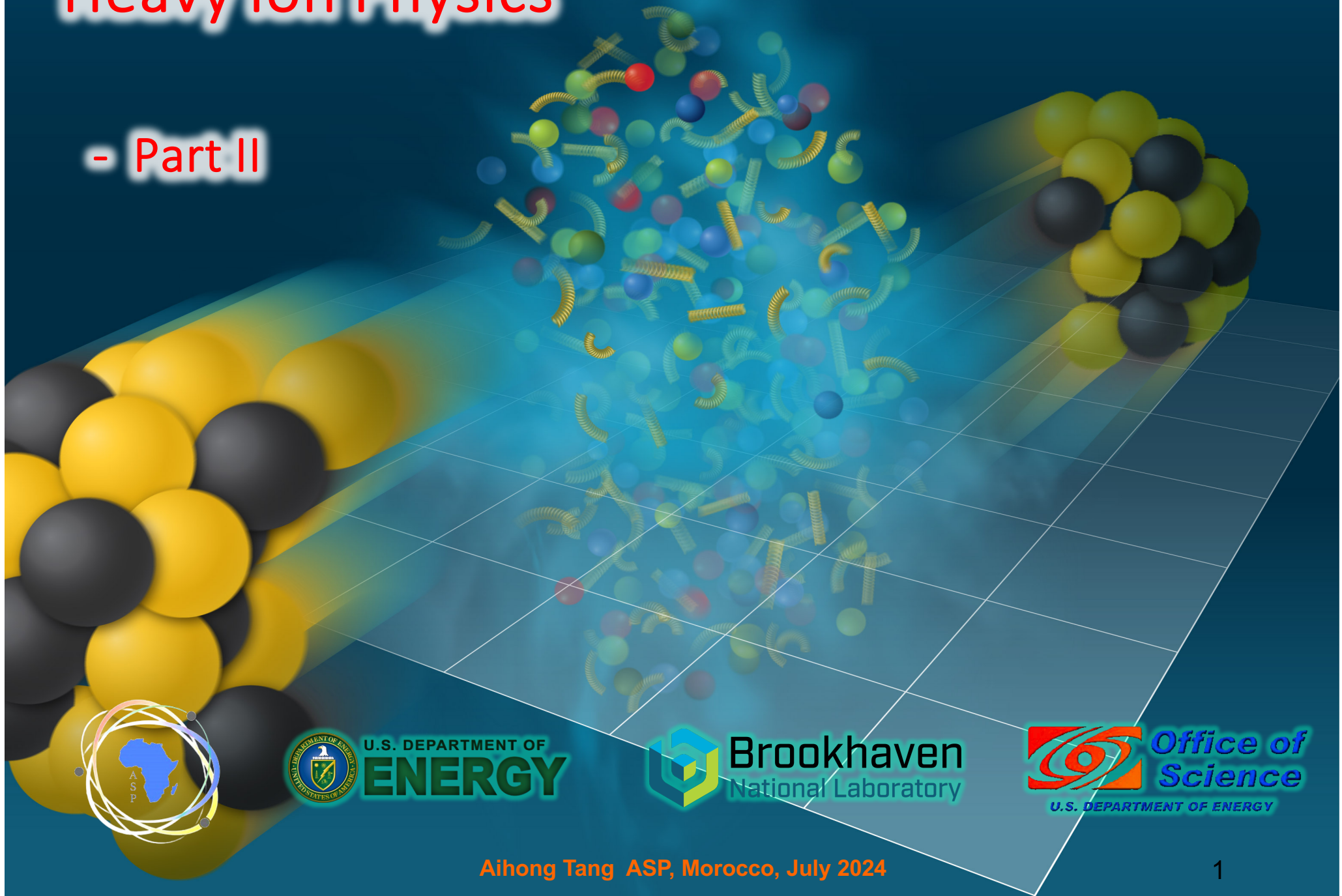


# Heavy Ion Physics

## - Part II



U.S. DEPARTMENT OF  
**ENERGY**



**Brookhaven**  
National Laboratory



**Office of  
Science**

U.S. DEPARTMENT OF ENERGY

Aihong Tang ASP, Morocco, July 2024

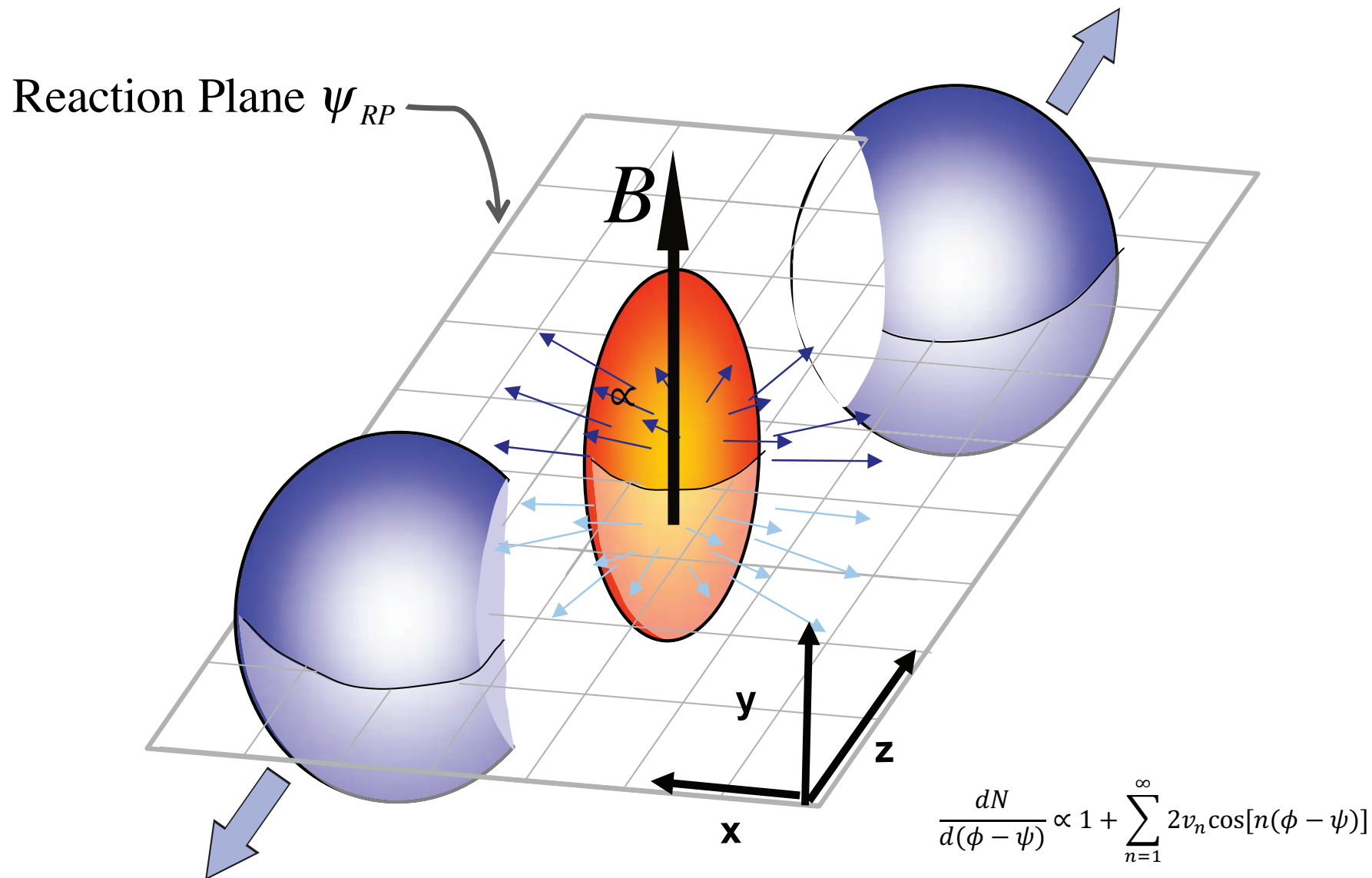
---

## **Part II : In-depth discussion on two selected topics (flow dynamics and antimatter)**

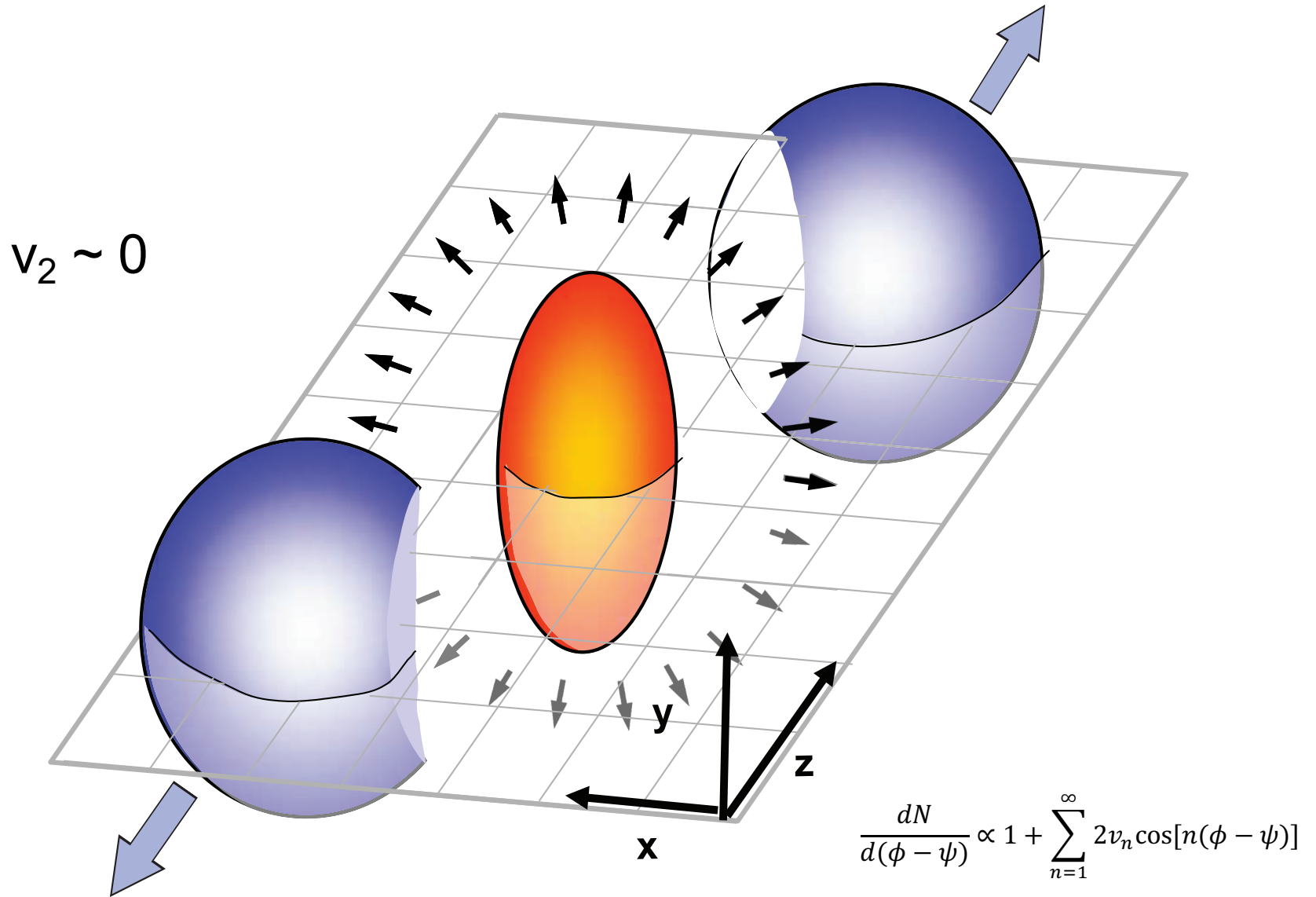
**Topic 1 :**  
**Flow Dynamics**



# Recap : the Reaction Plane

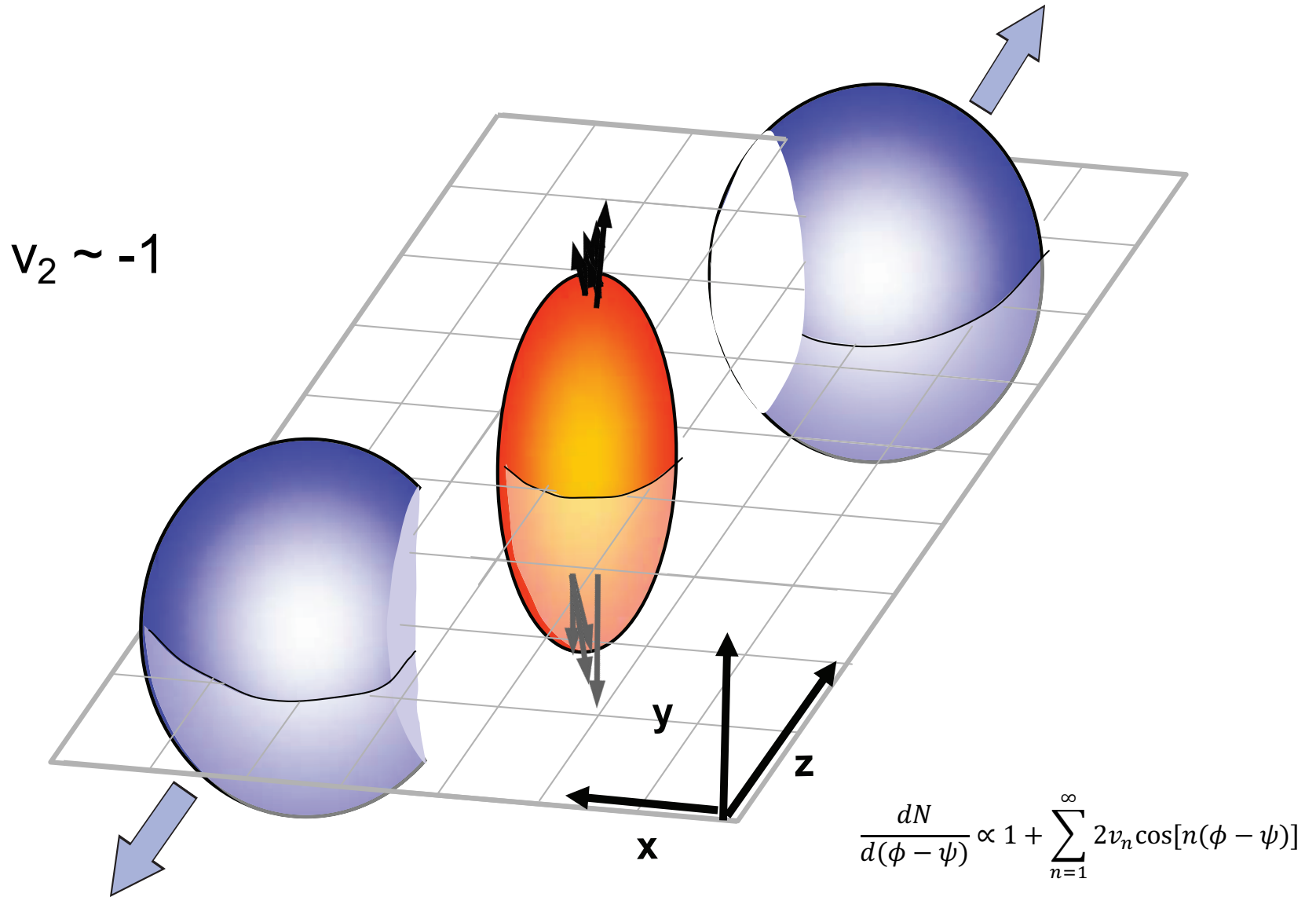


$V_2$



$v_2$  describes how well particles converge towards reaction plane

$V_2$

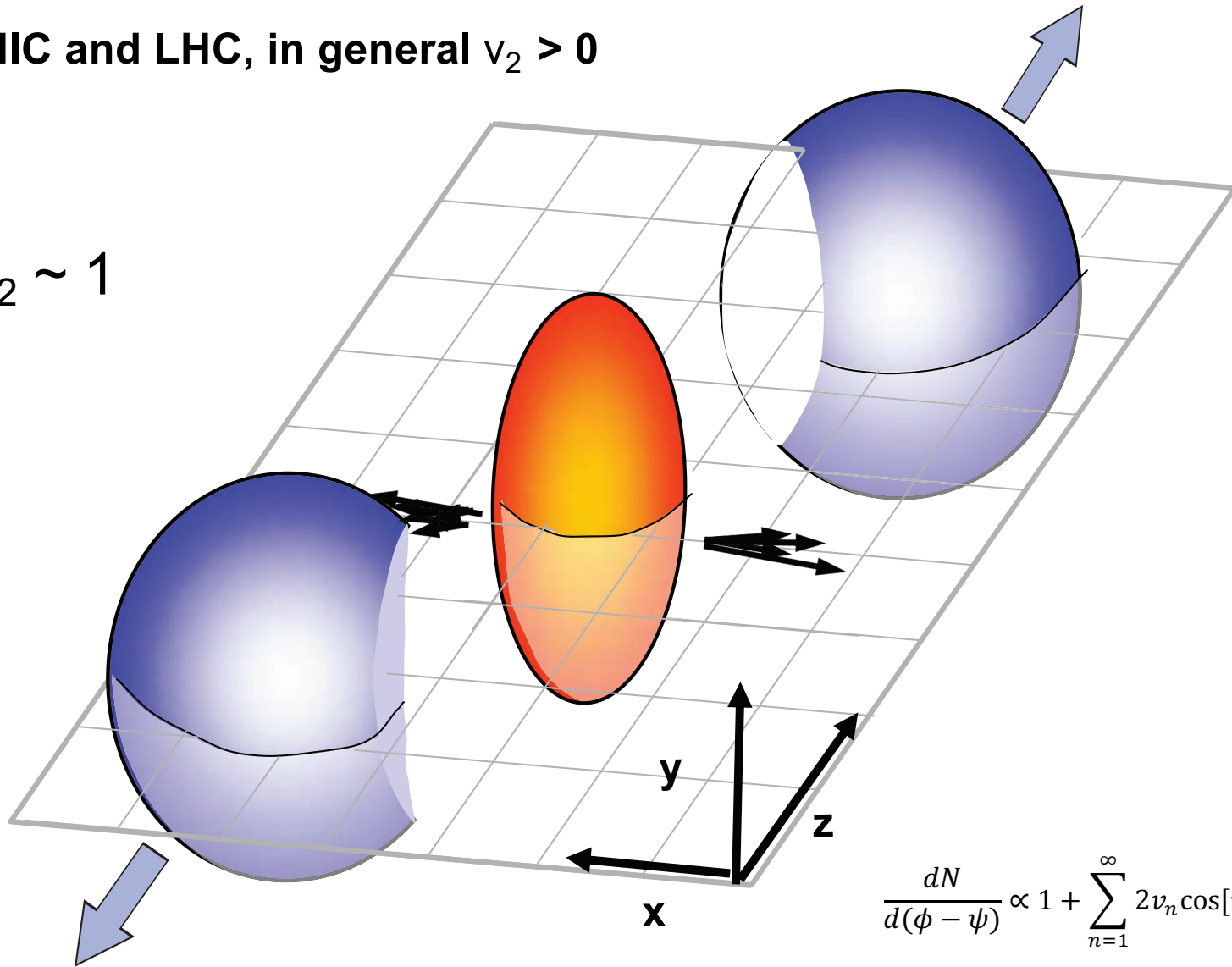


$v_2$  describes how well particles converge towards reaction plane

$V_2$

At RHIC and LHC, in general  $v_2 > 0$

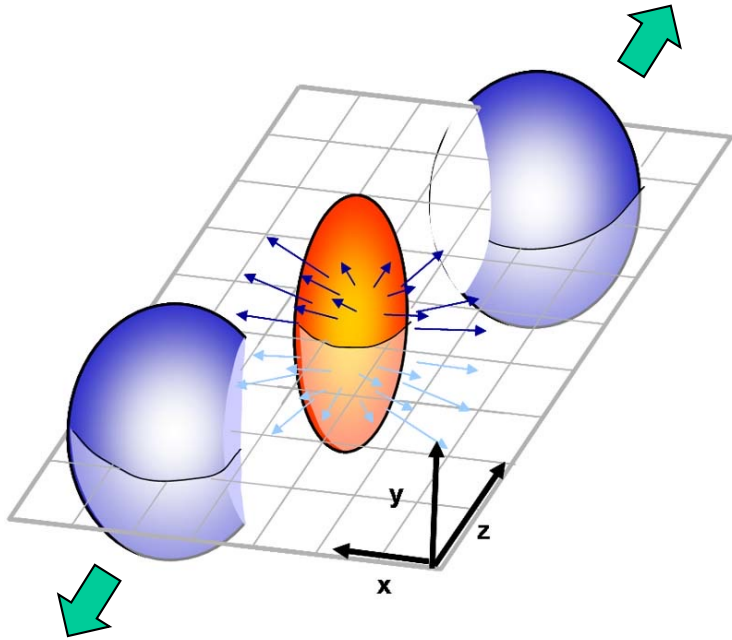
$v_2 \sim 1$



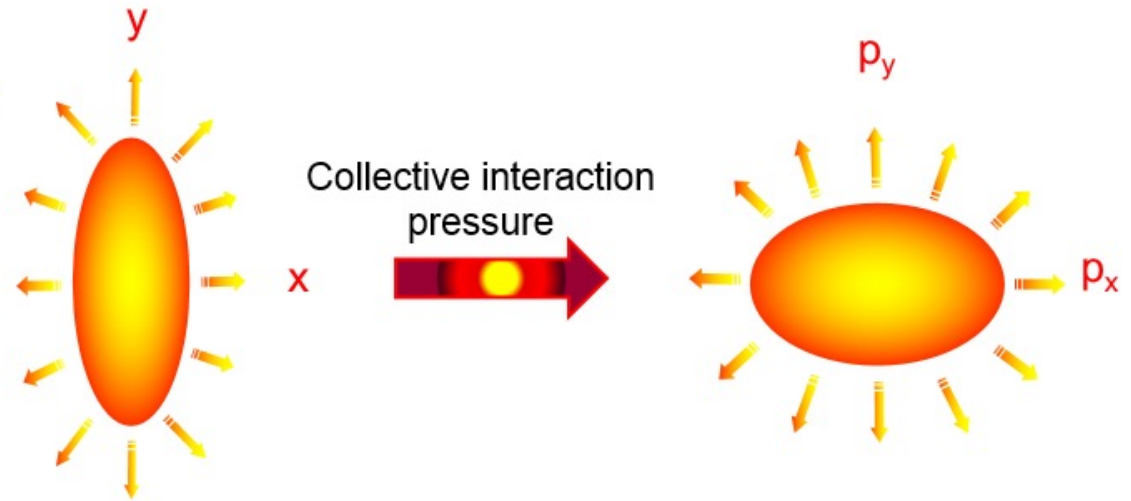
$$\frac{dN}{d(\phi - \psi)} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \psi)]$$

$v_2$  describes how well particles converge towards reaction plane

# Recap : Flow Driven by Pressure



**Reaction plane  $\psi$**  : Defined by the beam and the line connecting two colliding nuclei



Coordinate space :  
initial asymmetry

$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Momentum space:  
final asymmetry

$$v_2 = \left\langle \frac{p_y^2 - p_x^2}{p_y^2 + p_x^2} \right\rangle$$

$$\begin{aligned} &= \langle \cos^2(\phi - \psi) - \sin^2(\phi - \psi) \rangle \\ &= \langle \cos 2(\phi - \psi) \rangle \end{aligned}$$

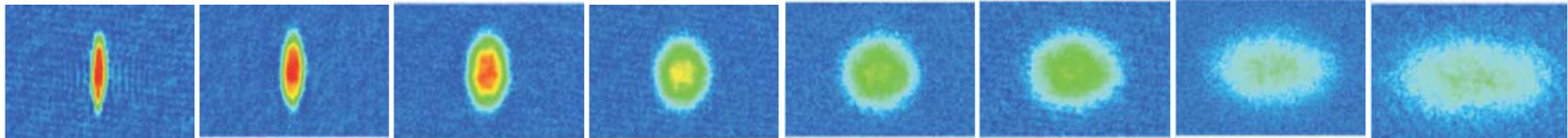
$v_n$  : flow measurements

$$\frac{dN}{d(\phi - \psi)} = \frac{1}{2\pi} \left( 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \psi)] \right)$$



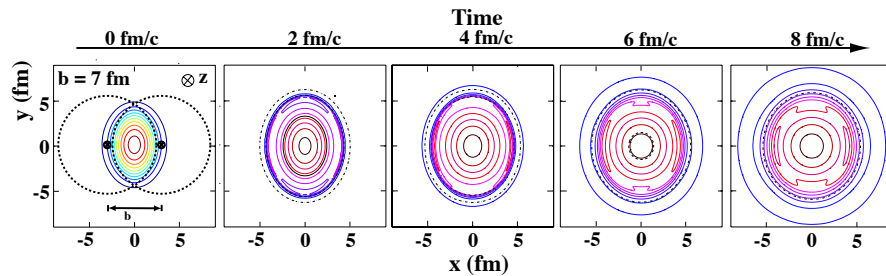
# Pressure-driven Expansion

## Atomic gas cloud



J. Thomas, Physics Today. 63 34-37 (2010)

## Relativistic heavy ion collision ( $E_T$ density)

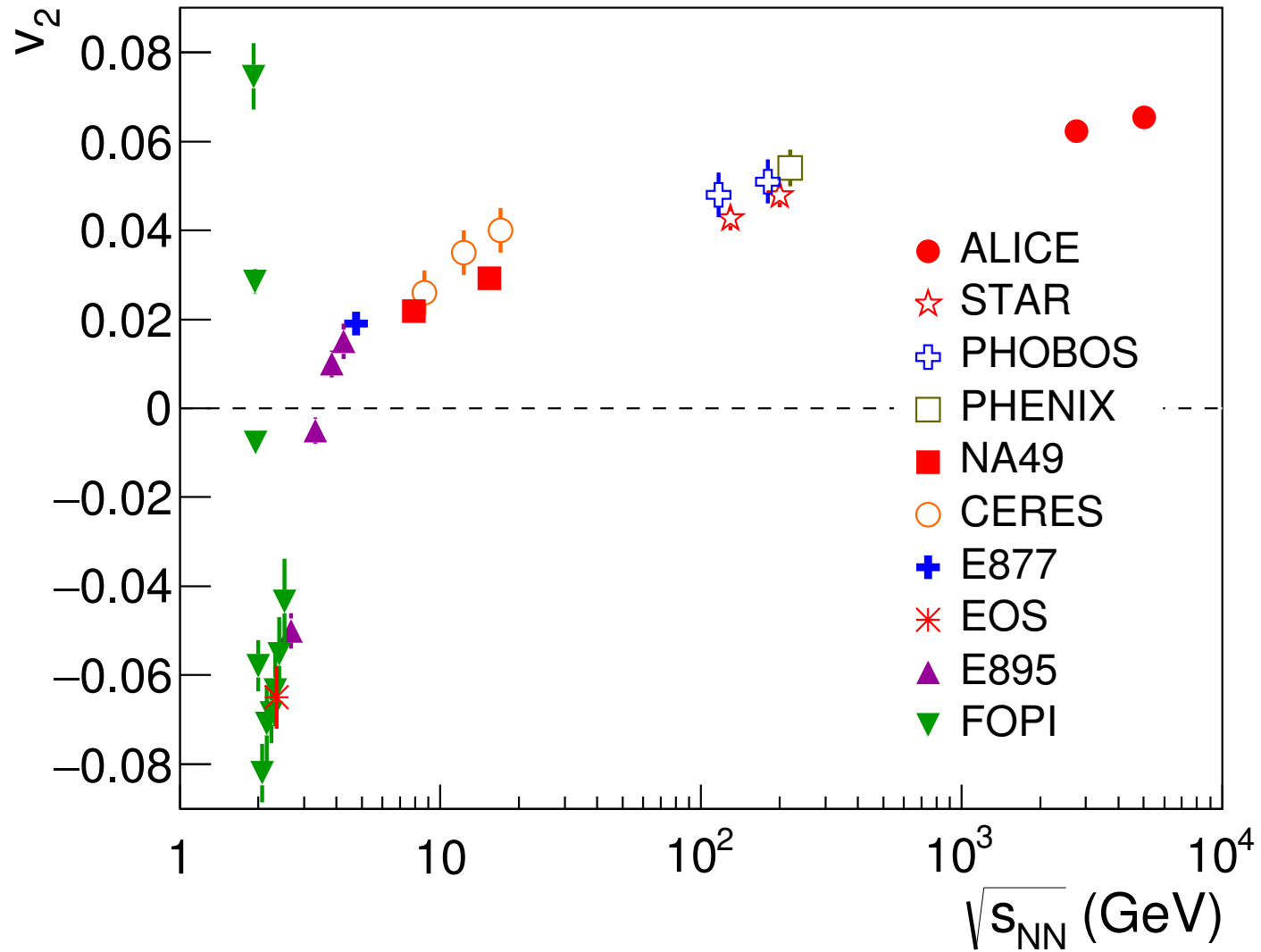


P.F. Kolb, UW.Heinz, in Hua, R.C. (ed.) et al: Quark Gluon Plasma 634-714

In both cases, expansion along the short axis.

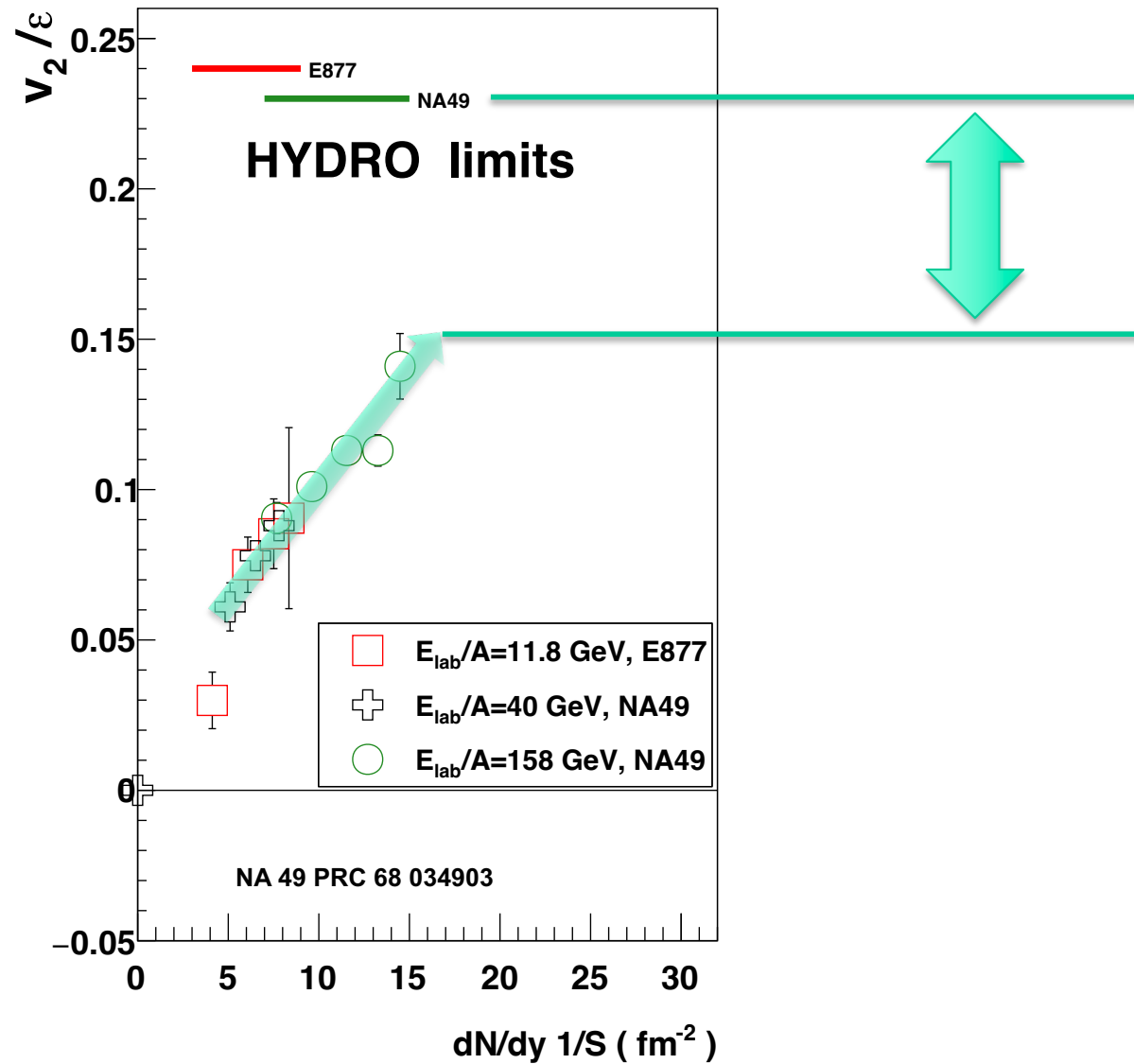
Can only be explained if the droplet is a fluid, not a collection of independent particles.

# $v_2$ vs Energy



Alice, arXiv:2211.04384

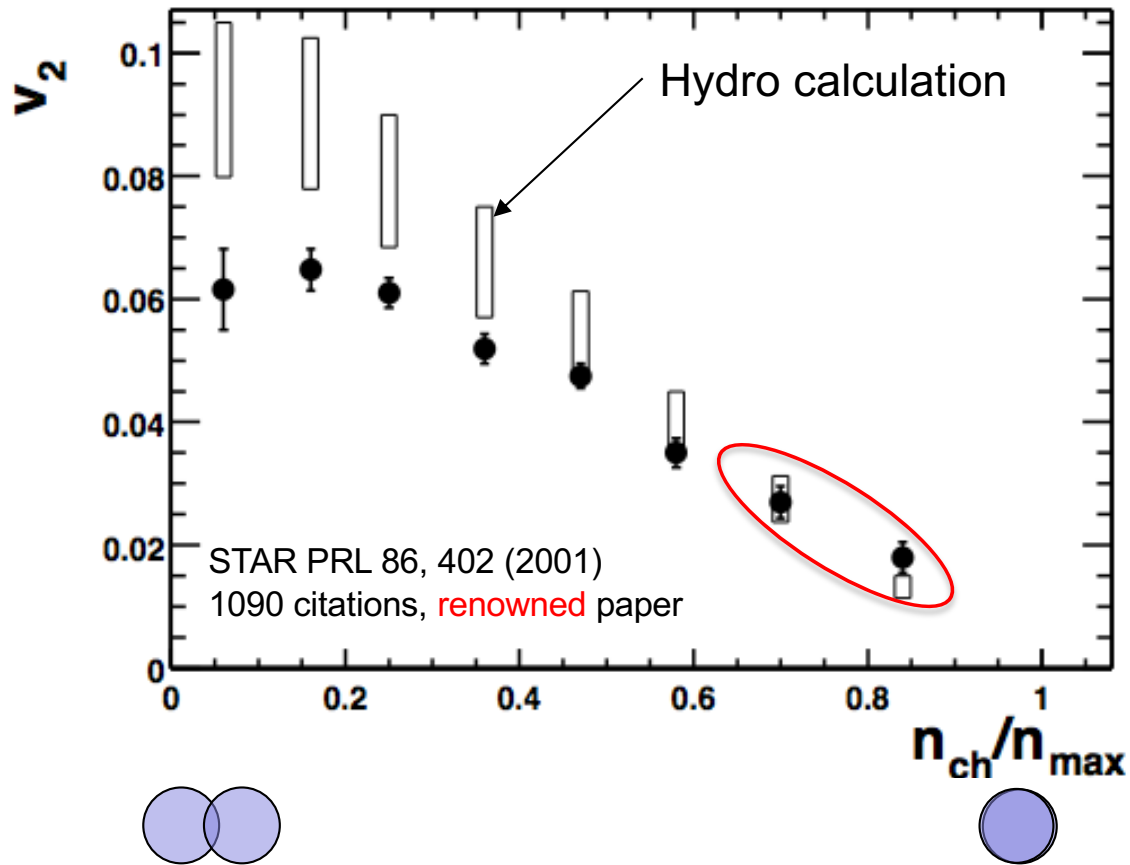
# The March to Hydro



# The March to Hydro

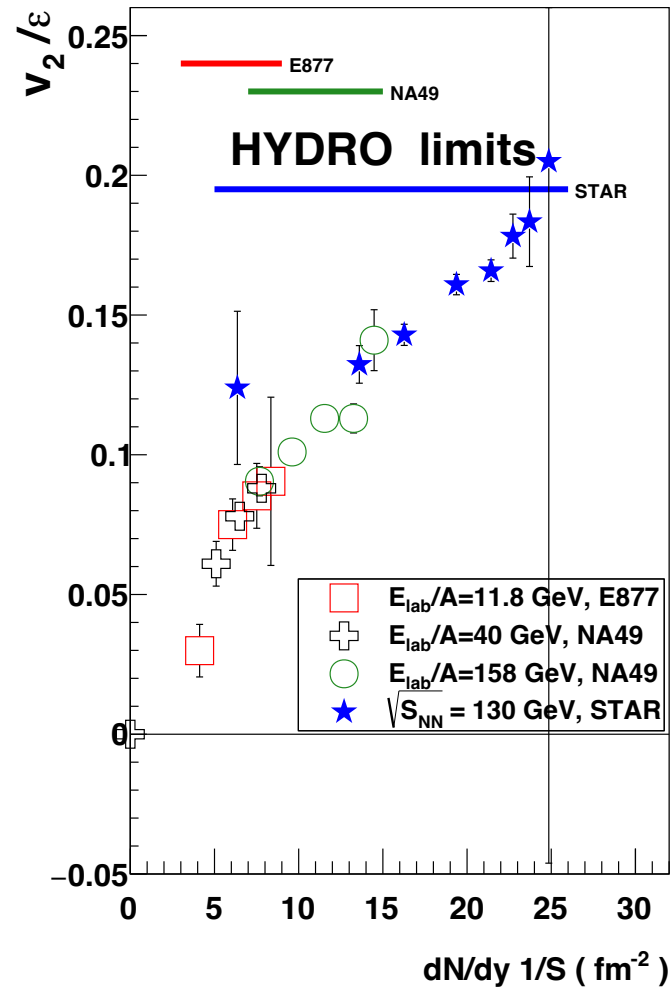


# The First Sign of Hydro Flow



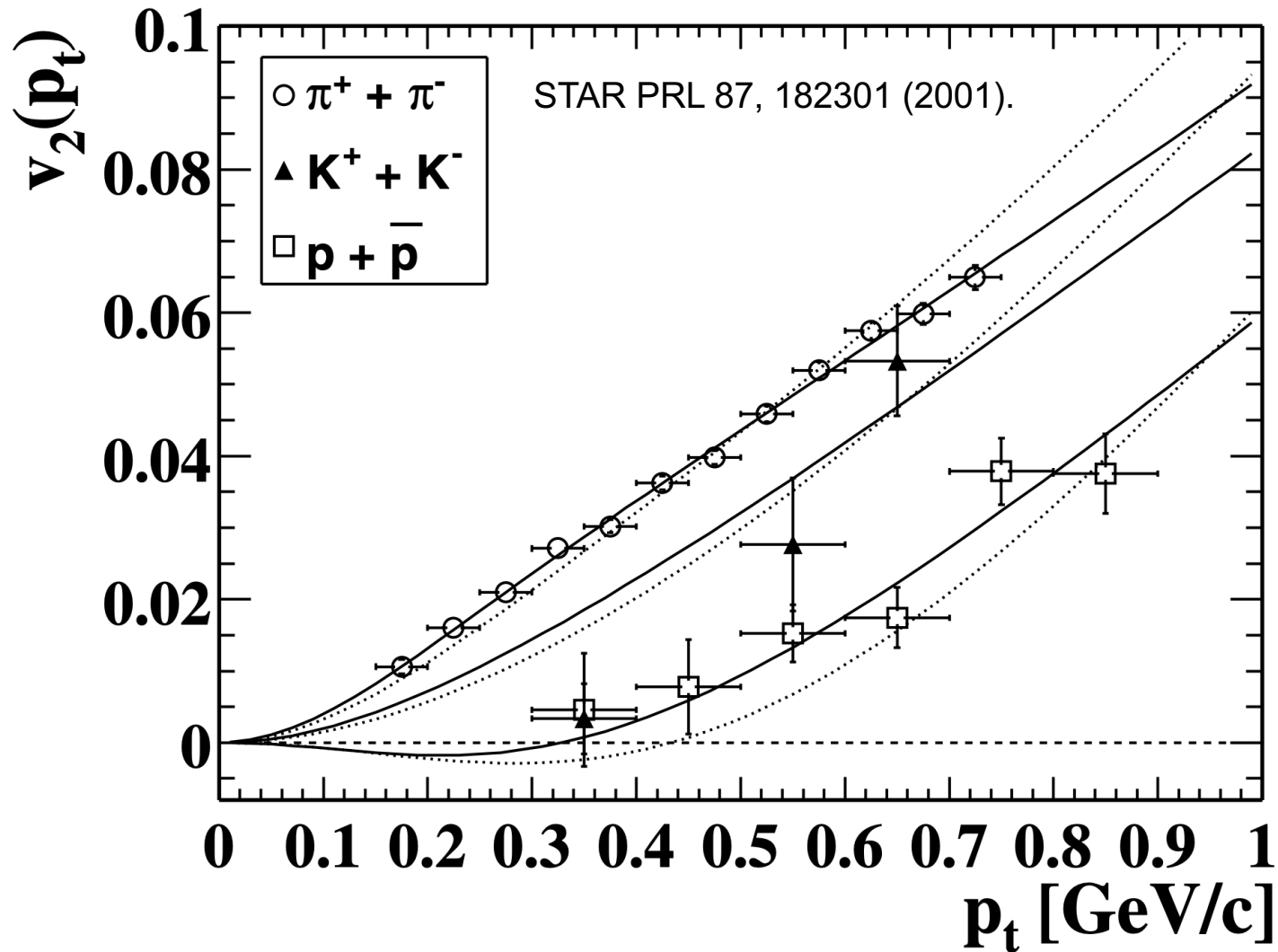
Approaching Hydro for central collisions

# The March to Hydro



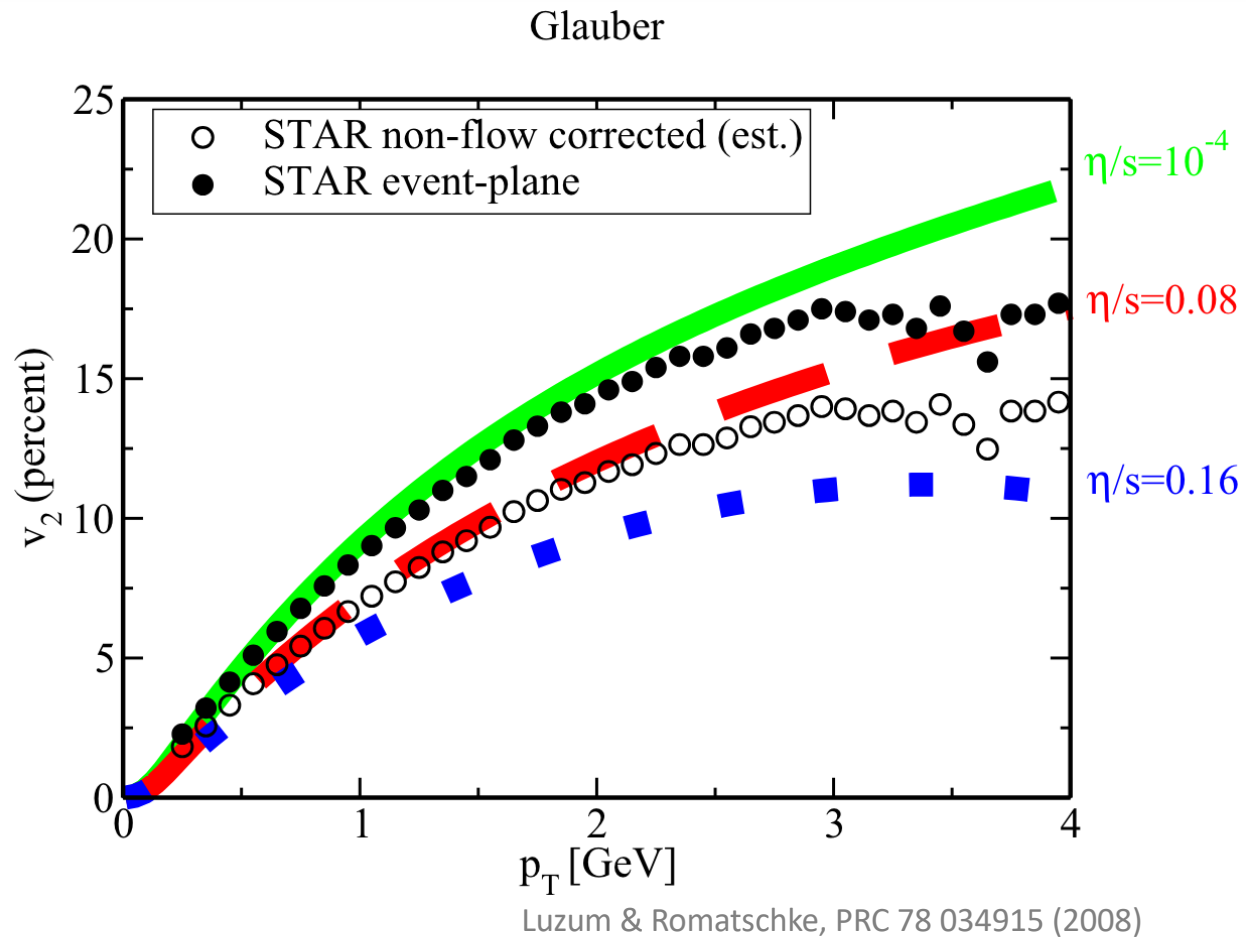
STAR PRC 66 034904 (2002)

# Identified Particle $v_2$



Mass splitting consistent with collective flow

# Viscosity



$\eta/s$  close to  $\sim 1/(4\pi)$ ,  
the Ads/CFT limit

The lowest viscosity/entropy density possible



# Perfect Liquid

The Washington Post  
Democracy Dies in Darkness

## Universe May Have Begun as Liquid, Not Gas

By Associated Press  
April 18, 2005 at 8:00 p.m. EDT

Share Save

New results from a particle collider suggest the universe behaved like a liquid in its earliest moments, rather than the fiery gas that was thought to have pervaded the first microseconds of existence.

### Early Universe was a liquid

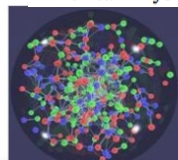
[Mark Peplow](#)

[Nature](#) (2005) | [Cite this article](#)

707 Accesses | 29 Altmetric | [Metrics](#)

### Quark-gluon blob surprises particle physicists.

The Universe consisted of a perfect liquid in its first moments, according to results from an atom-smashing experiment.



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More Science :: News :: April 18, 2005 :: Email :: Print

## New State of Matter Is 'Nearly Perfect' Liquid

By Sarah Graham

Physicists working at Brookhaven National Laboratory announced today that they have created what appears to be a new state of matter out of the building blocks of atomic nuclei, quarks and gluons. The researchers unveiled their findings--which could provide new insight into the composition of the universe just moments after the big bang--today in Florida at a meeting of the American Physical Society.

Image: BNL



**BBC NEWS** Watch One-Minute World News

Last Updated: Tuesday, 19 April, 2005, 16:26 GMT 17:26 UK

E-mail this to a friend Printable version

### Early Universe was 'liquid-like'

Physicists say they have created a new state of hot, dense matter by crashing together the nuclei of gold atoms.

The high-energy collisions prised open the nuclei to reveal their most basic particles, known as quarks and gluons.

The impression is of matter that is more strongly interacting than predicted

News Front Page

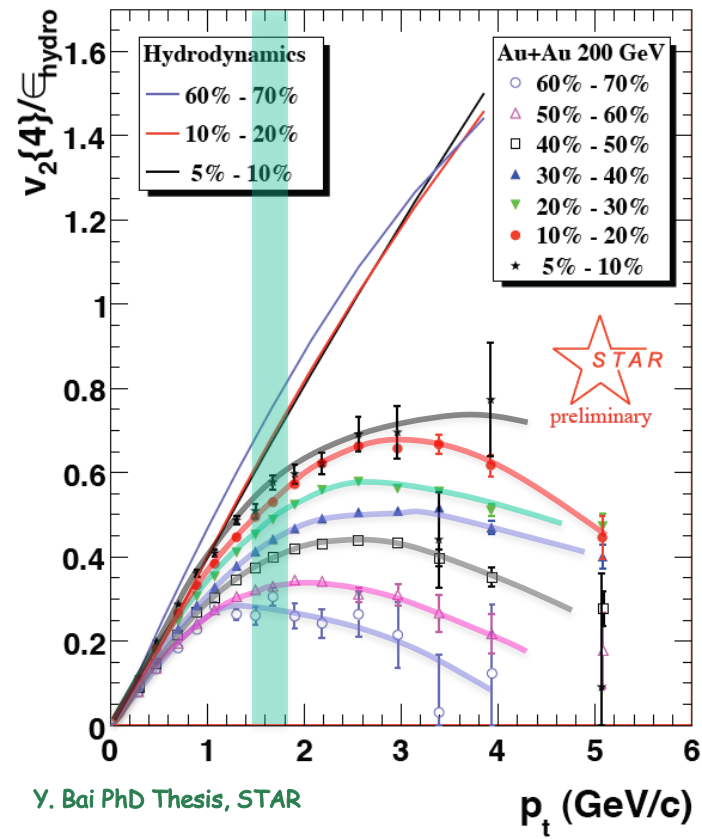
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- Also in the news

Video and Audio

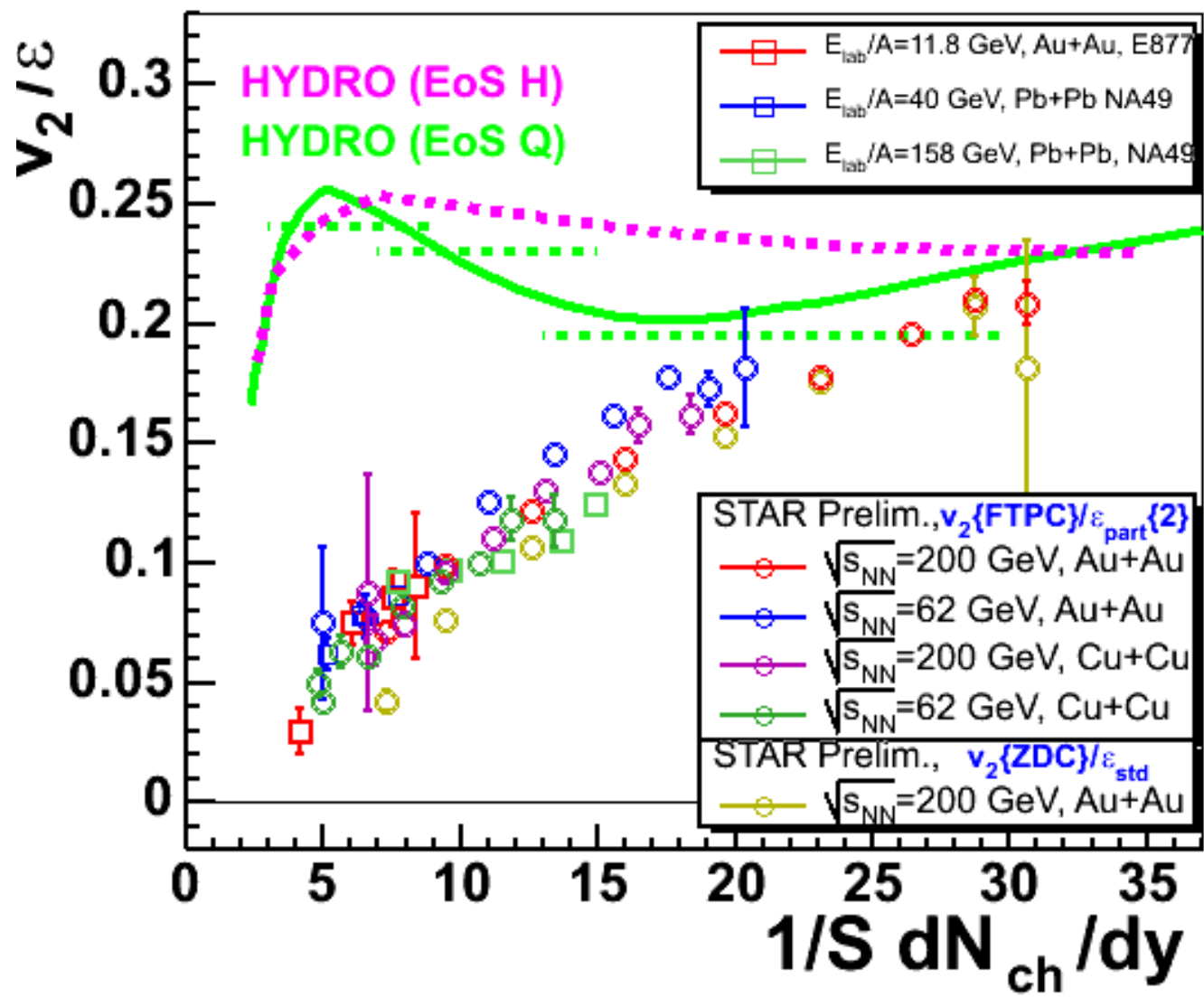
A 3D digital rendering of the Statue of Liberty, colored in a vibrant purple. The statue is positioned in the center-right of the frame, appearing to be in a dark, stormy environment. Heavy rain is falling vertically across the entire scene, creating a sense of intense weather. A bright purple lightning bolt strikes the crown of the statue from the upper left. The background is a dark, textured sky with a grainy, digital appearance. The overall mood is dramatic and ominous.

Are we saturated ?

# Are we saturated ?

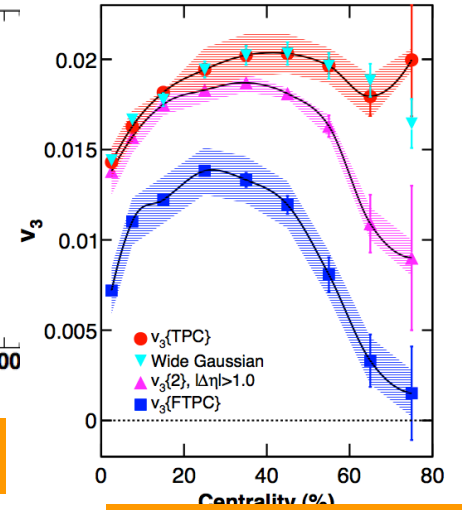
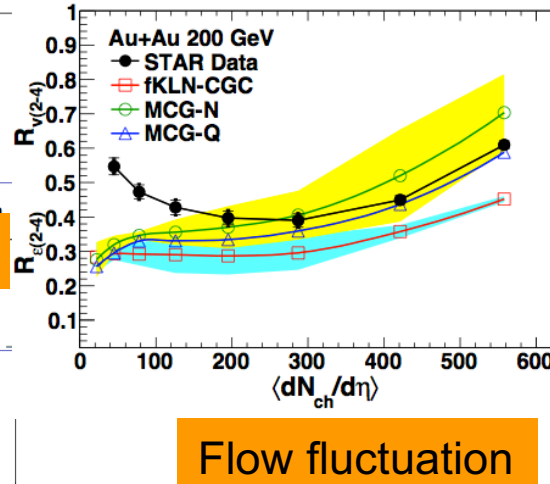
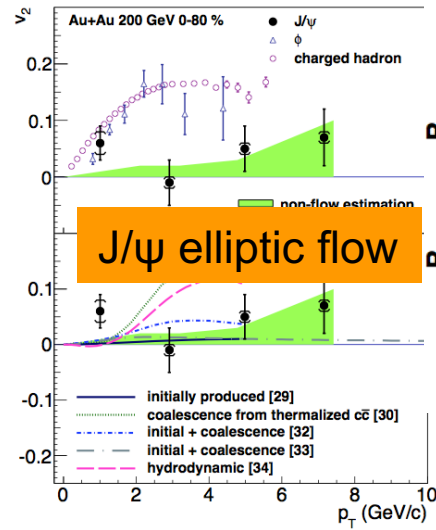
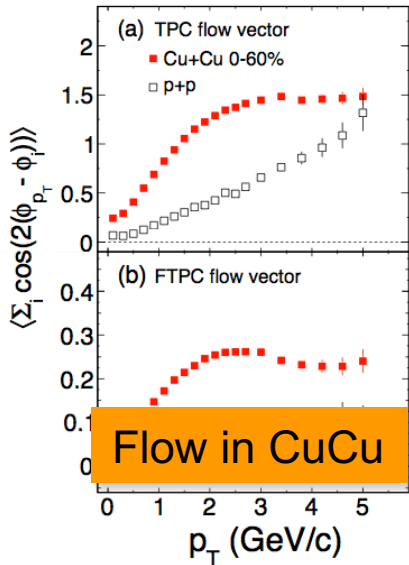


# Are we saturated ?

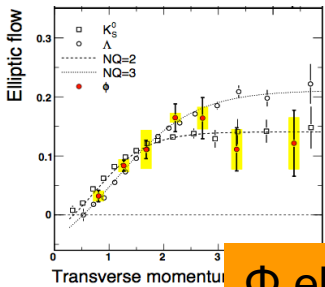
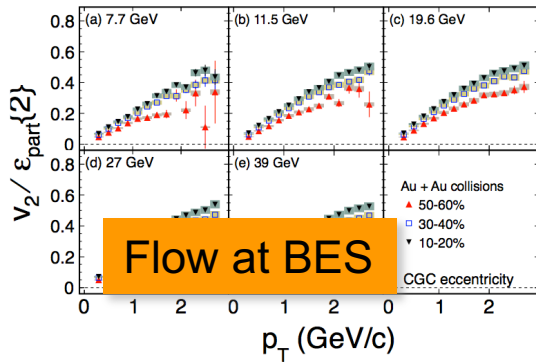


Voloshin QM06

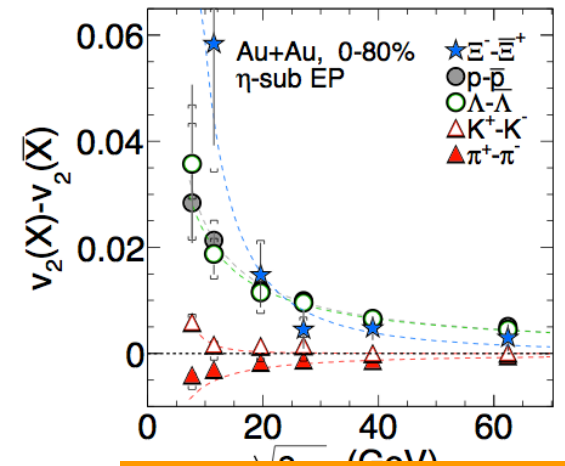
# Keep Flowing



3rd harmonic flow

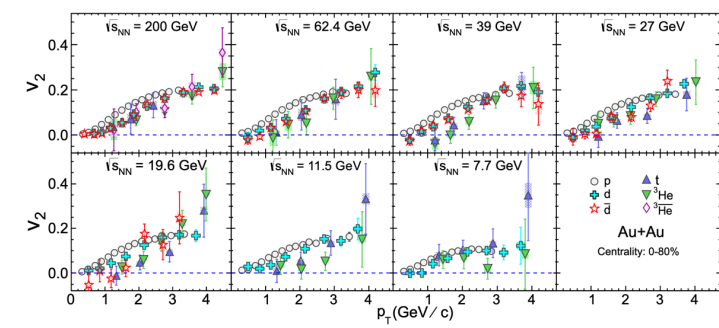
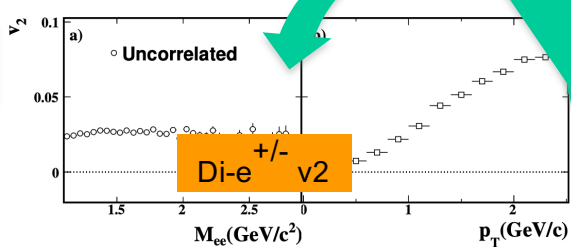
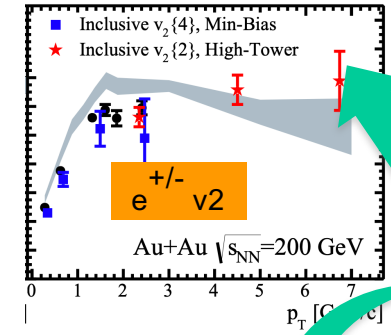
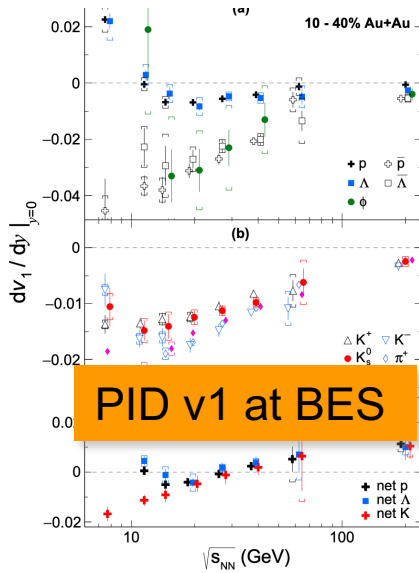
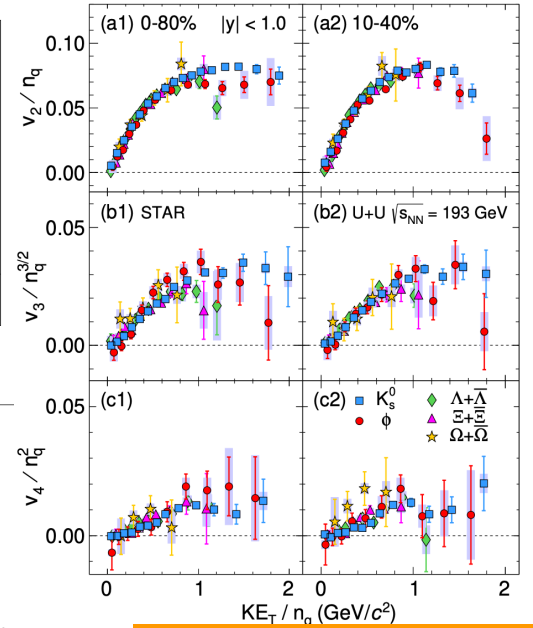
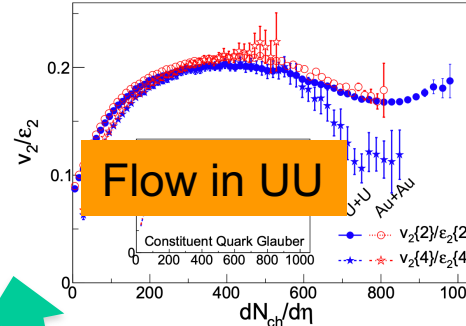
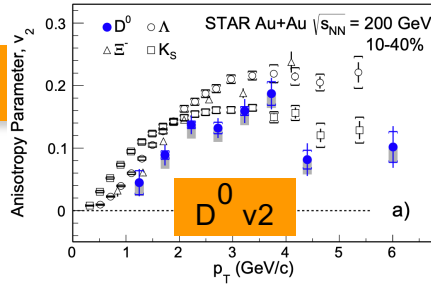
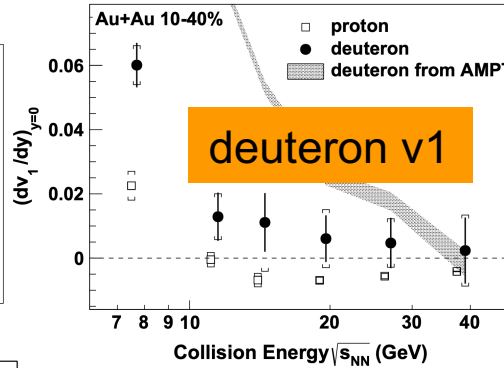
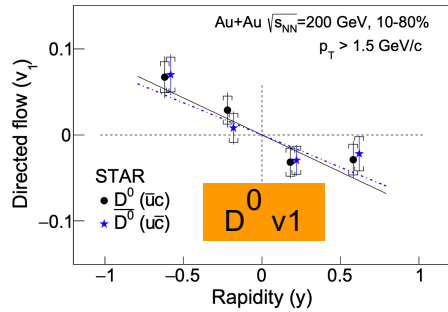
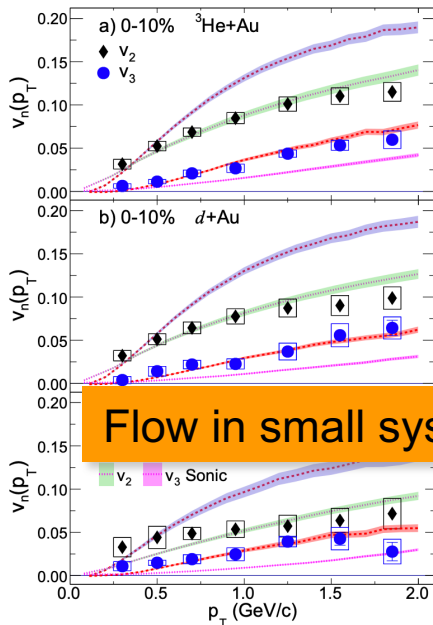


$\Phi$  elliptic Flow



particle and antiparticle

# Keep Flowing



Light nuclei flow

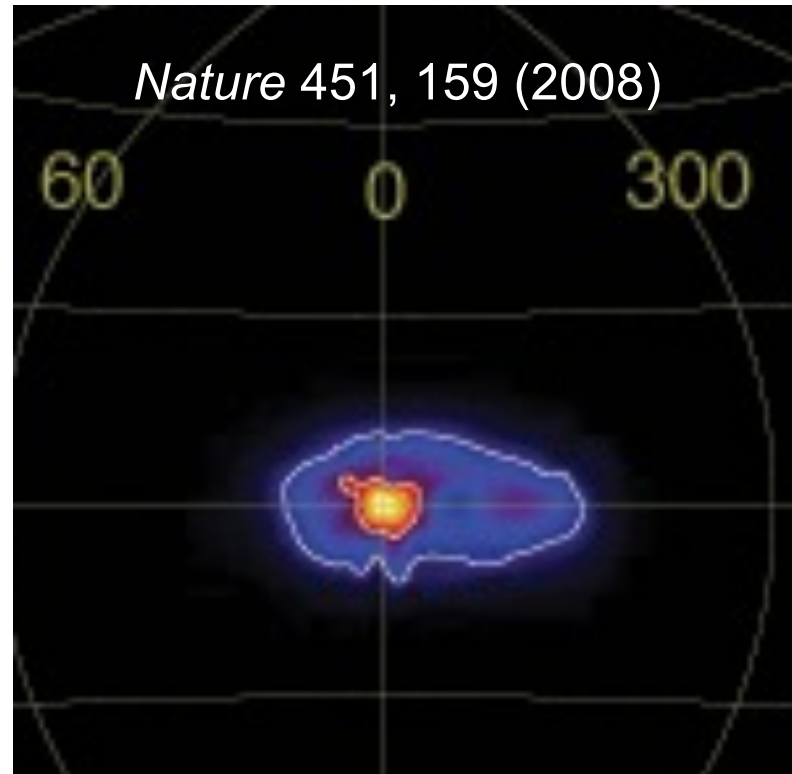
**Topic 2 :**  
**Discovery of anti- $\alpha$**

RHIC



# Why Antimatter ?

---



Nature 451, 159 (2008)

Clue to the matter anti-matter asymmetry

**Antimatter matters !**



# Why Antihelium 4 (anti- $\alpha$ ) ?

---

BESS

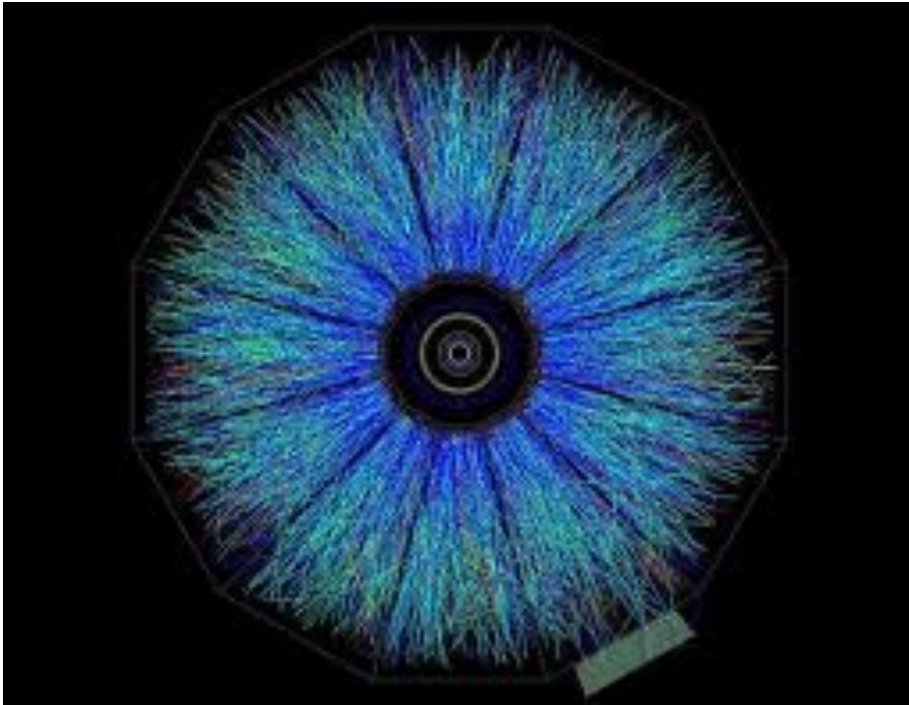


PaMela

Fingerprint of anti-star !

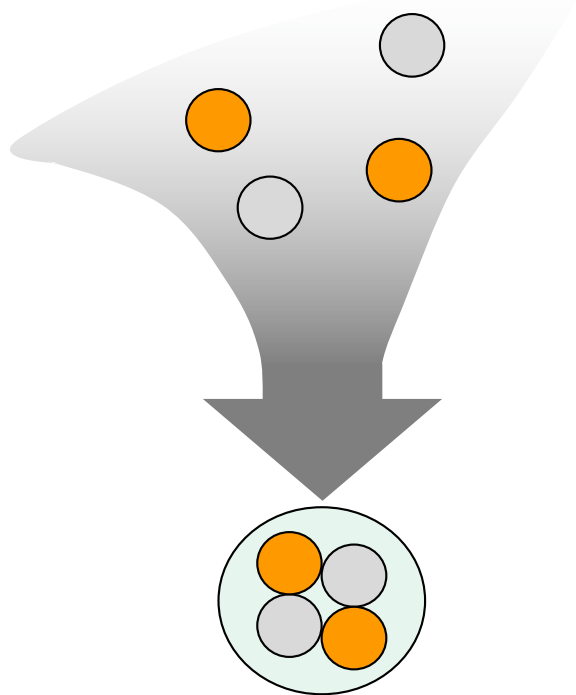
# Why in High-energy Nuclear Collisions ?

---



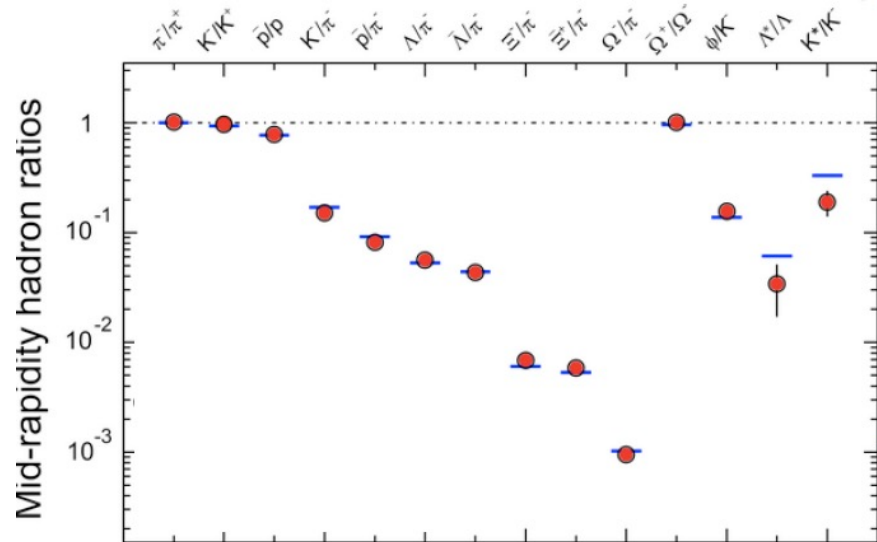
- Sweet spot between elementary particle collisions and Big Bang for anti-nuclei production.
- Controlled, repeatable “little bangs”. Active production instead of “passive” searches.
- Prove the existence (if any), provide a point of reference for future observations in cosmic radiation

# Production Mechanisms



## Coalescence

- Relativistic Heavy Ion collisions :
  - ✓ High antibaryon density
  - ✓ High temperature
- Favorable environment for both production mechanisms

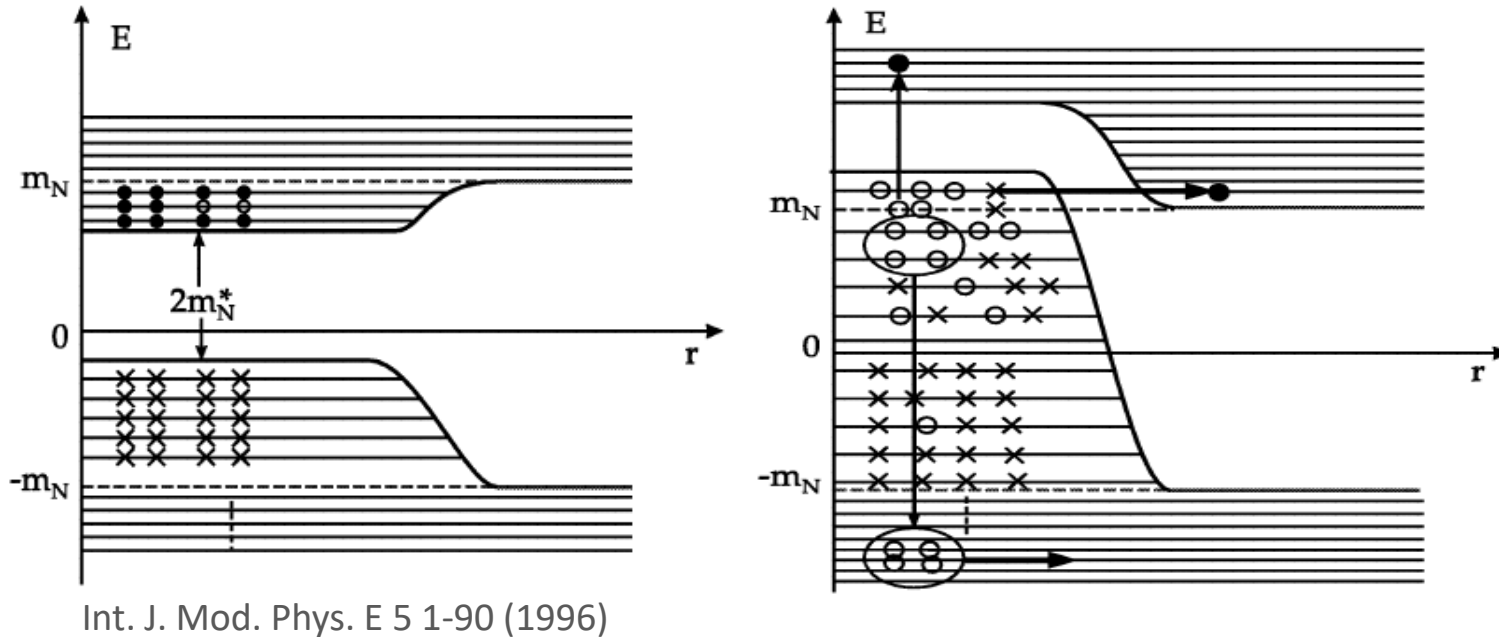


200 GeV  $^{197}\text{Au} + ^{197}\text{Au}$  central collision  
STAR whitepaper, NPA757(2005)

$$N_i = V g_i \int \frac{d^3 p}{(2\pi)^3} \exp\left(-\frac{E_i}{T} + \frac{\mu_i}{T}\right)$$

## Thermal production

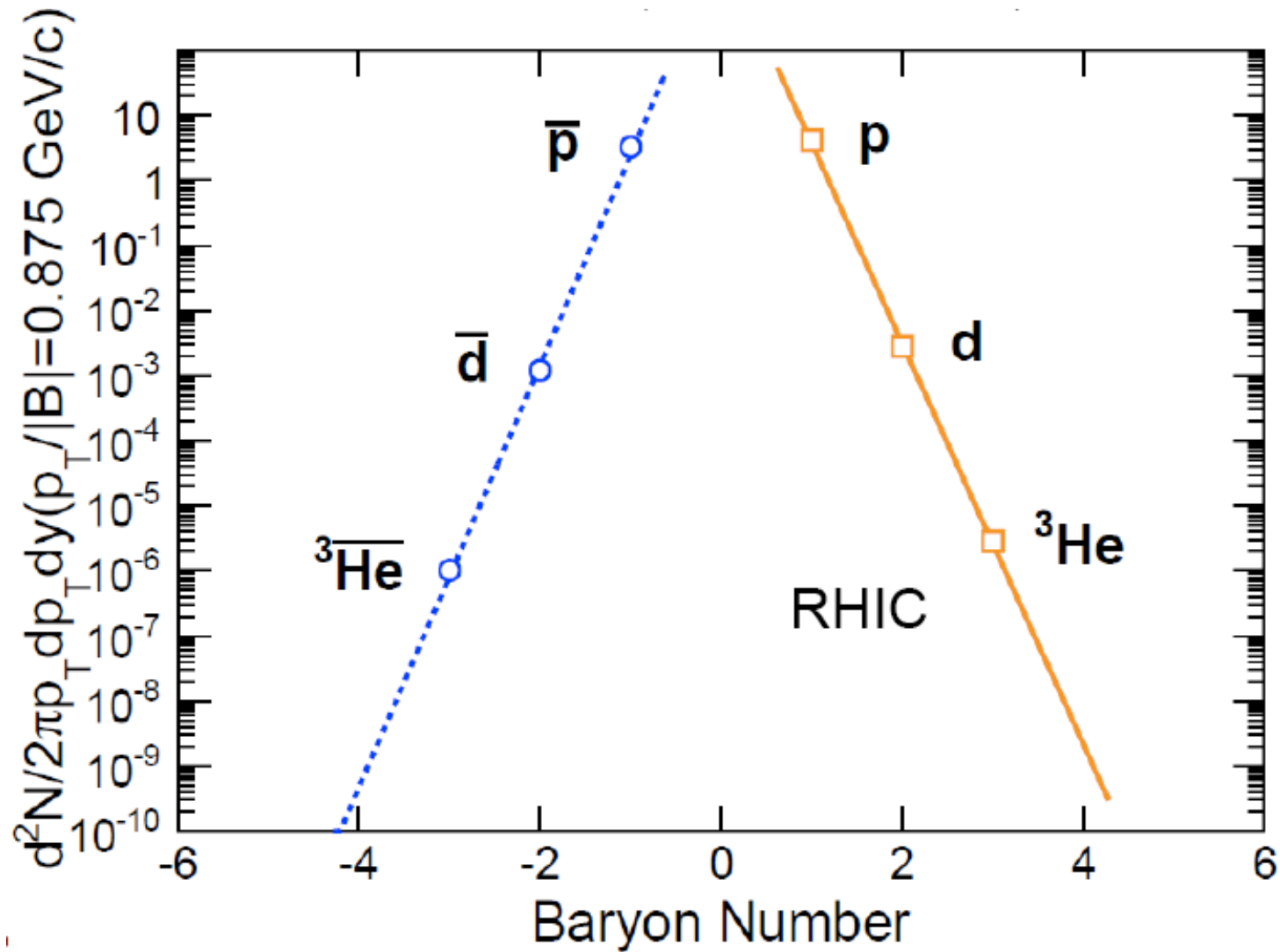
# Production Mechanisms



Idea from Walter Greiner: correlations are present in vacuum, allowing antinucleus like anti- $\alpha$  to be directly excited from the vacuum. Rate could be much larger than low value predicted by statistical coalescence.

**Could be exciting but no evidence so far.**

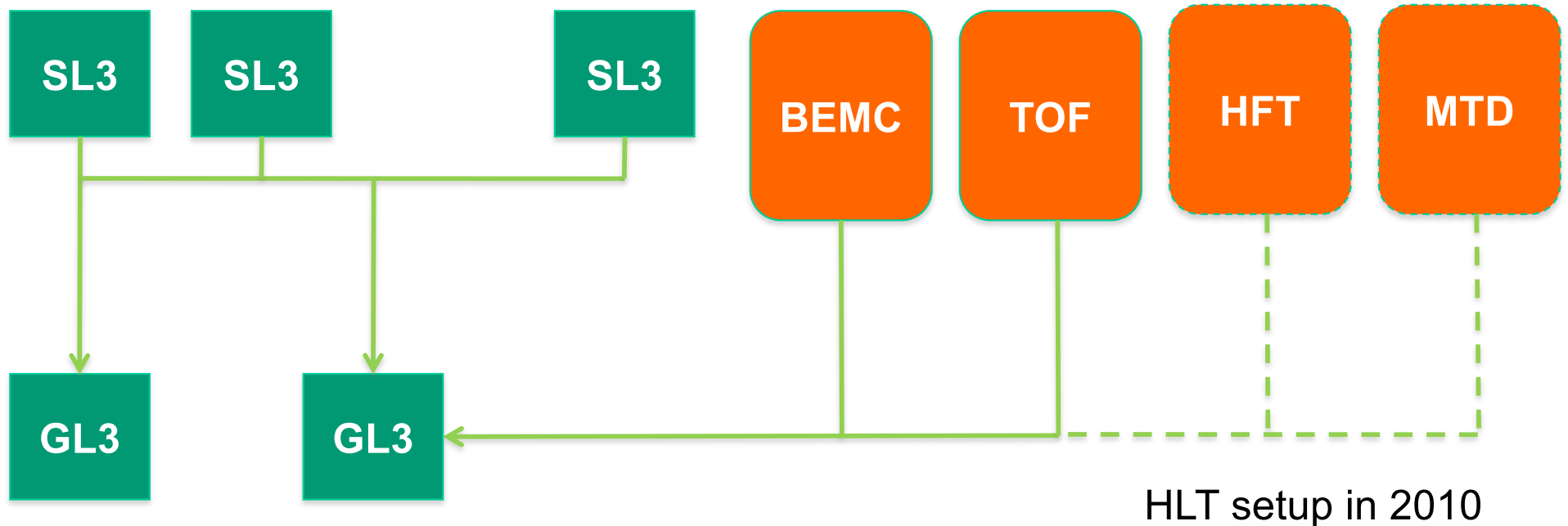
# The Reduction Factor



It is a challenging job !

# High Level Tracking Trigger (HLT)

---



- Sector tracking (SL3) in DAQ machines (24 in total, each for a TPC sector).
- Information from subsystems (SL3 and others) are sent to Global L3 machines (GL3) where an event is assembled and a trigger decision is made.

Fast physics output with HLT

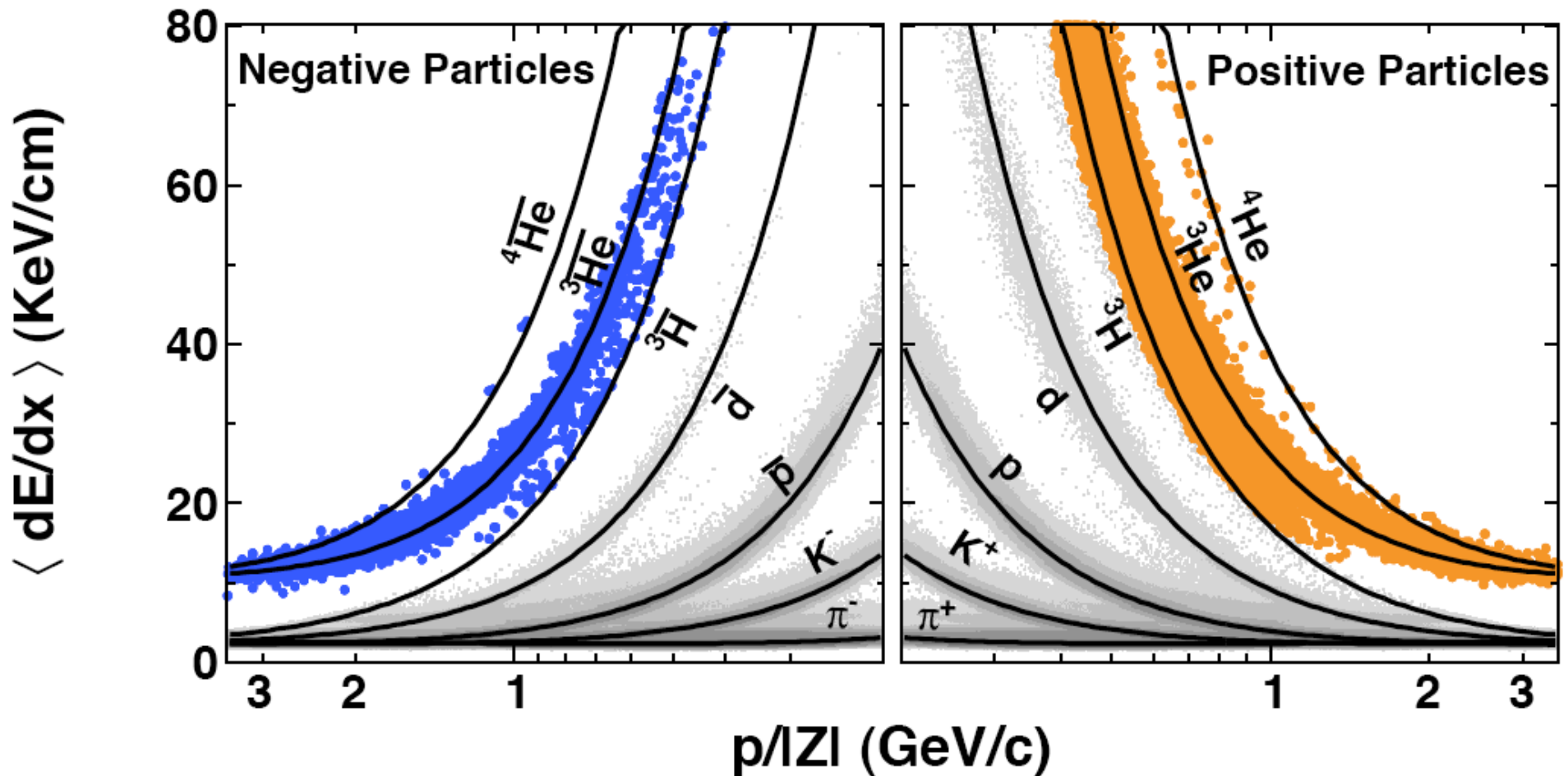
# Data Sample

---

- 360 million minimum bias (MB) collisions, 270 million central collisions and 170 million high tower calorimeter events at 200 GeV in 2010.
- 70 million MB events at 200 GeV in 2007.
- 170 million MB events at 62 GeV in 2010.

In total one billion AuAu events sampled

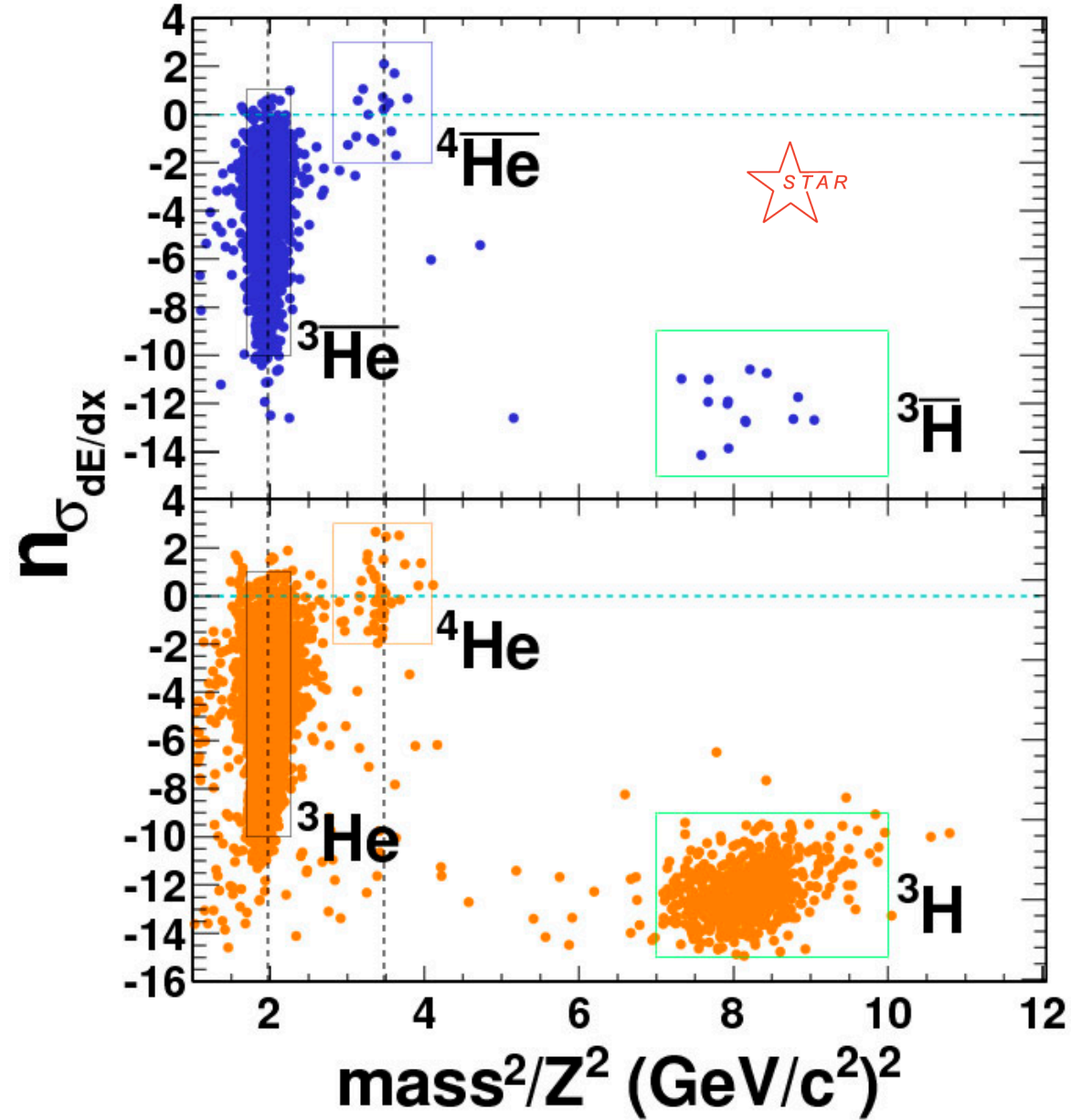
# dE/dx



HLT has processing power to do rudimentary event reconstruction in real time, allowing events with a  $|Z| = 2$  track to be tagged and fast-tracked via the normal offline calibration & reconstruction chain.

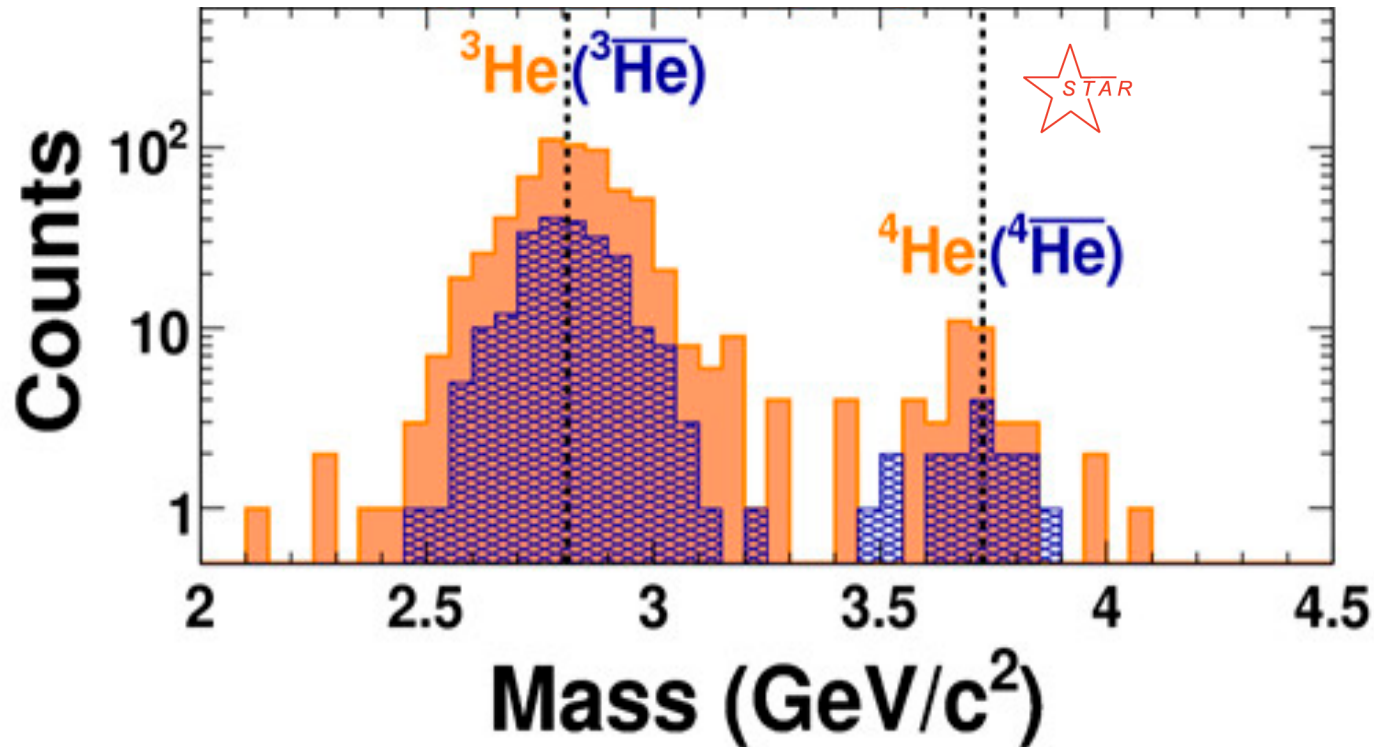


# Combined PID (TPC+TOF)



## Combined PID (TPC+TOF)

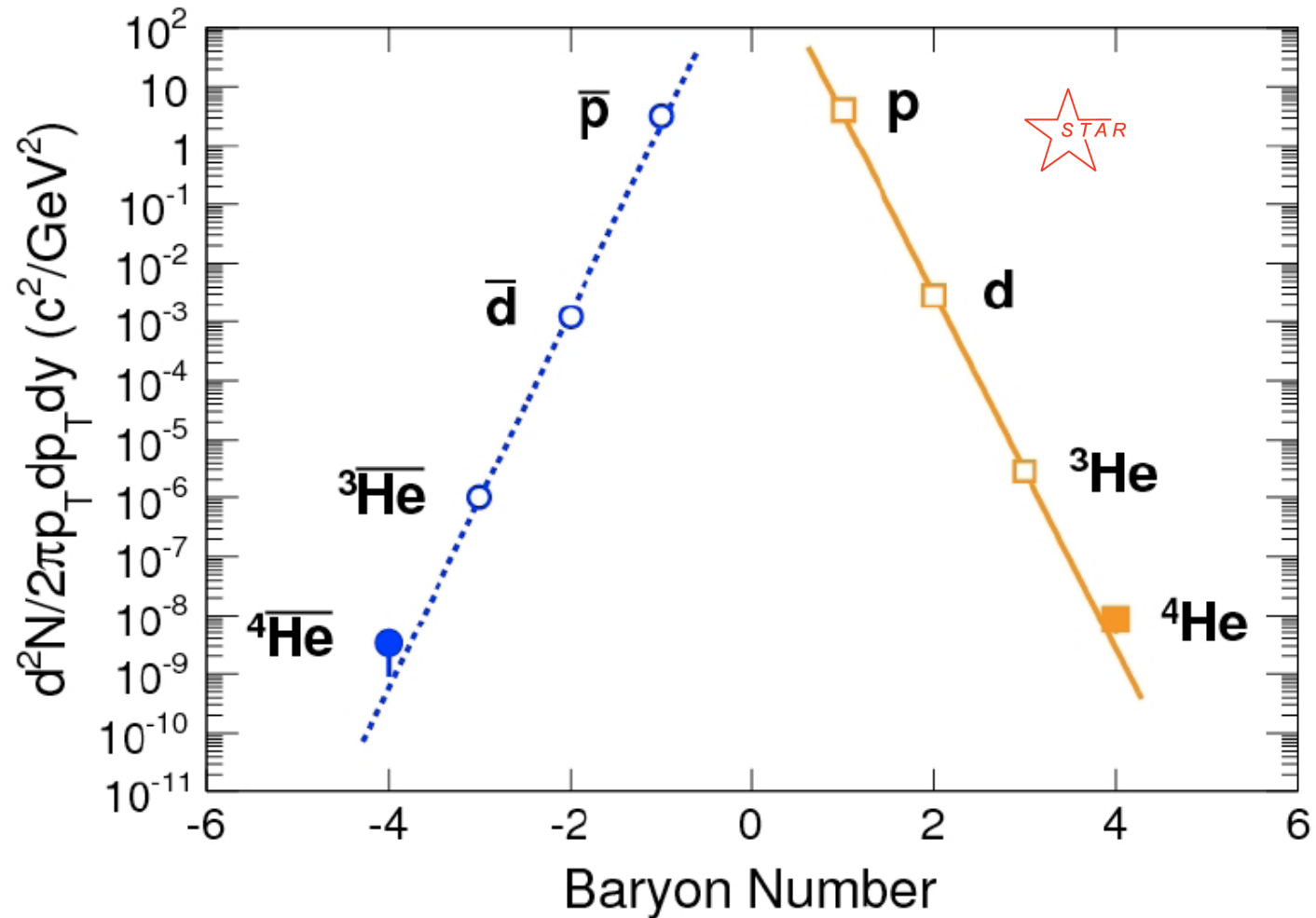
---



Very clean identification after search of > half-trillion tracks from almost one billion gold-gold collisions.

**In total 18 counts observed.**

# Reduction Factor



- Production rate reduces by a factor of  $1.6 \times 10^3$  ( $1.1 \times 10^3$ ) for each additional antinucleon (nucleon) added to the antinucleus

# Race for the Heaviest

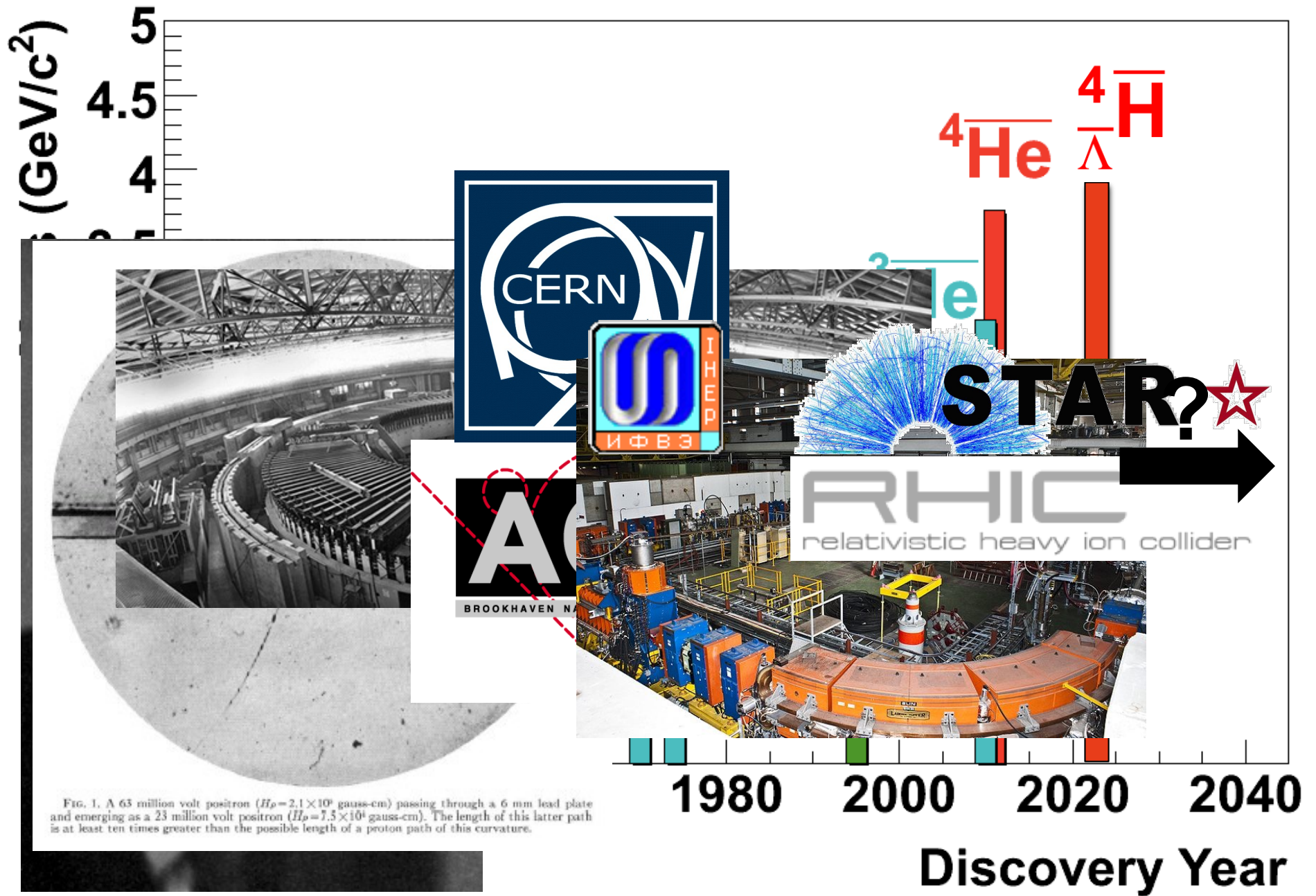
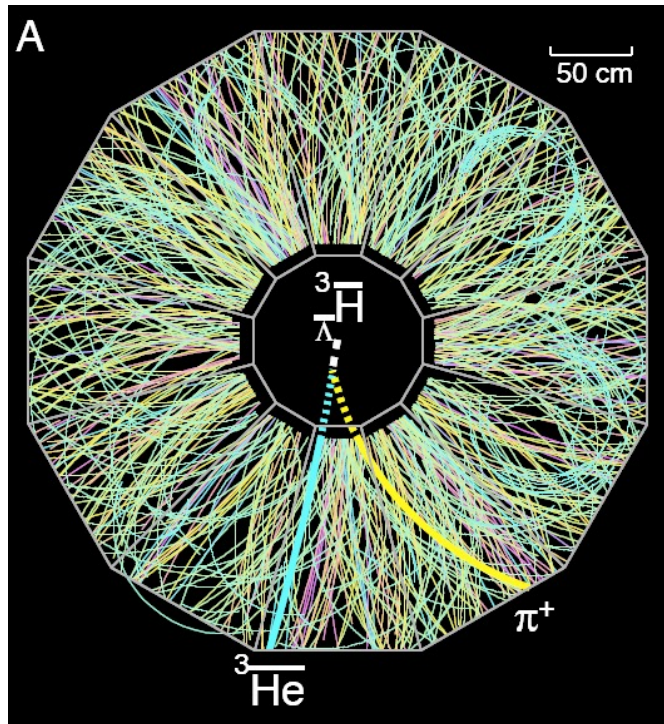


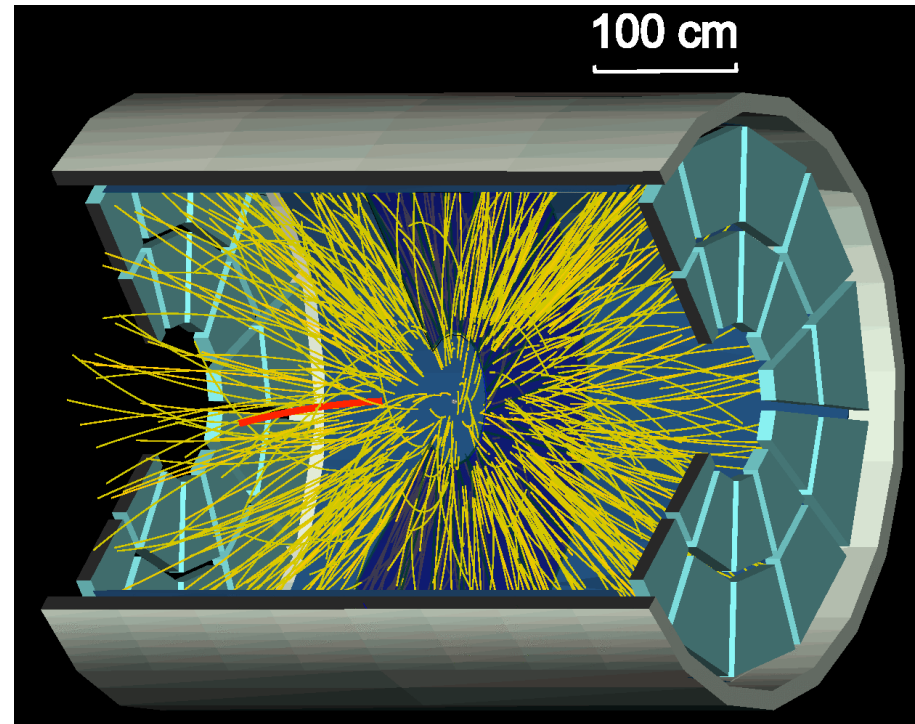
FIG. 1. A 63 million volt positron ( $H_p = 2.1 \times 10^9$  gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ( $H_p = 7.5 \times 10^8$  gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

# HIC as Exotic/Antimatter Machine



Science

Science 328, 58 (2010)



nature

Nature 473 353 (2011)

# News Coverage

IOP A website from the Institute of Physics

## physicsworld.com

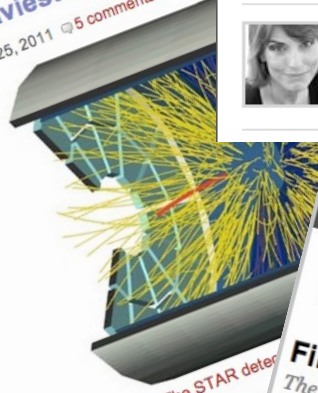
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### Heaviest ever antimatter

Mar 25, 2011 5 comments



The STAR detector

Physicists at the Relativistic Heavy Ion Collider (RHIC) have produced several nuclei of the heaviest antimatter yet.

宇宙探秘

## 宇宙探秘

yuzhoutanmi.cn

宇宙天体 宇宙物质 时间空间 UFO 科幻 智能模糊搜索 百度搜索

相对论重离子对撞机中产生最重反物质

时间：2011年03月25日

美国布鲁克海文国家实验室相对论重离子对撞机国际团队科学家观察到的最重反物质。

TAGs: 反物质 相对论重离子对撞机

## Discovery News

... has gone fishing.

EARTH | SPACE | TECH | ANIMALS | DINOSAURS | ARCHAEOLOGY | HISTORY | HUMAN

Discovery News > Space News > Antimatter

### ANTIMATTER GETS



Analysis by Jennifer Ouellette  
Wed Mar 30, 2011 01:03 PM EST

#### technology review

Published by MIT

### The Physics arXiv Blog

#### First Observation of the creation of 18 nuclei of energy physics.

RFC 03/21/2011 4 COMMENTS

## SCIENTIFIC AMERICAN

### Antimatter of Fact: Collider Generates Most Massive Antinucleus Yet

The Relativistic Heavy Ion Collider has produced several nuclei of the antimatter counterpart to helium 4

By John Matson | March 24, 2011 | 32

## guardian.co.uk

News | Sport | Comment | Culture | Business | Money | Life & style

### US scientists get glimpse of antihelium

Heaviest particles of antimatter seen in a lab survive for about 10 billionths of a second before crashing into collider's detector

Ian Sample, science correspondent  
guardian.co.uk, Sunday 24 April 2011 17.59 BST

## Antimatter's posterous

Antimatter's posterous

## Science News

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### Antihelium-4 nucleus, antinucleus yet

30 in Physics & Chemistry

Brookhaven national laboratory in

Anti-Money Laundering

Like Sign Up to see what your friends like.

March 21st, 2011, 09:12 GMT | By Tudor Vieru

Ads by Google

Helium | Balloons Met Helium | Location D Helium | Anti Acne | Anti Envelhecimento

A group of high-energy physics experts in the United States announces the production of 18 antinuclei of helium-4, the antimatter opposite of the common chemical element. This is a tremendous achievement and breakthrough in this branch of physics, analysts say.

Using data obtained from in-depth analysis of these nuclei could allow experts to understand why normal matter prevailed over antimatter shortly after the Big Bang, and why the Universe exists.

Among things

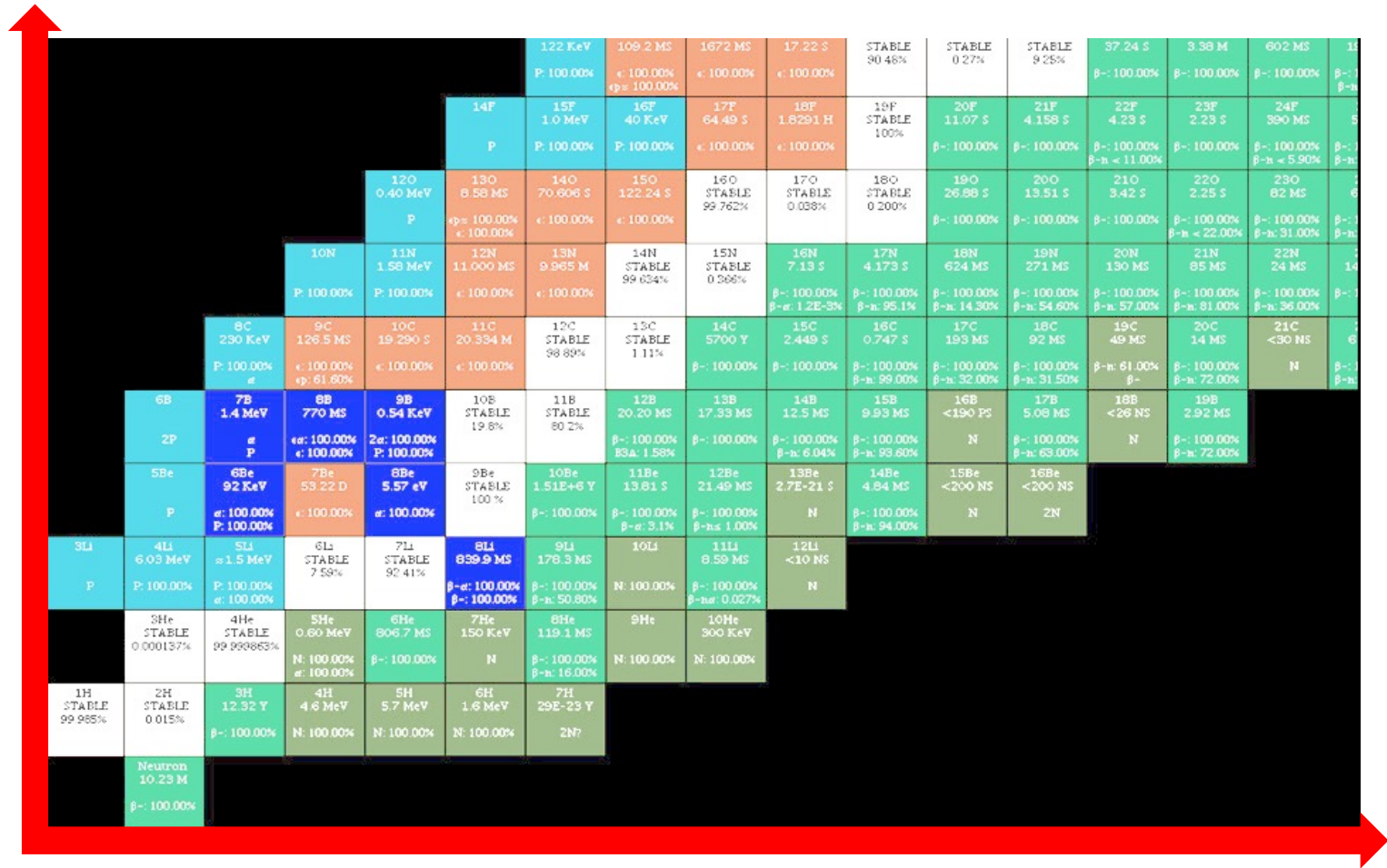
# The Search Continues

---



# 3-D Chart of the Nuclides

Protons (Z)

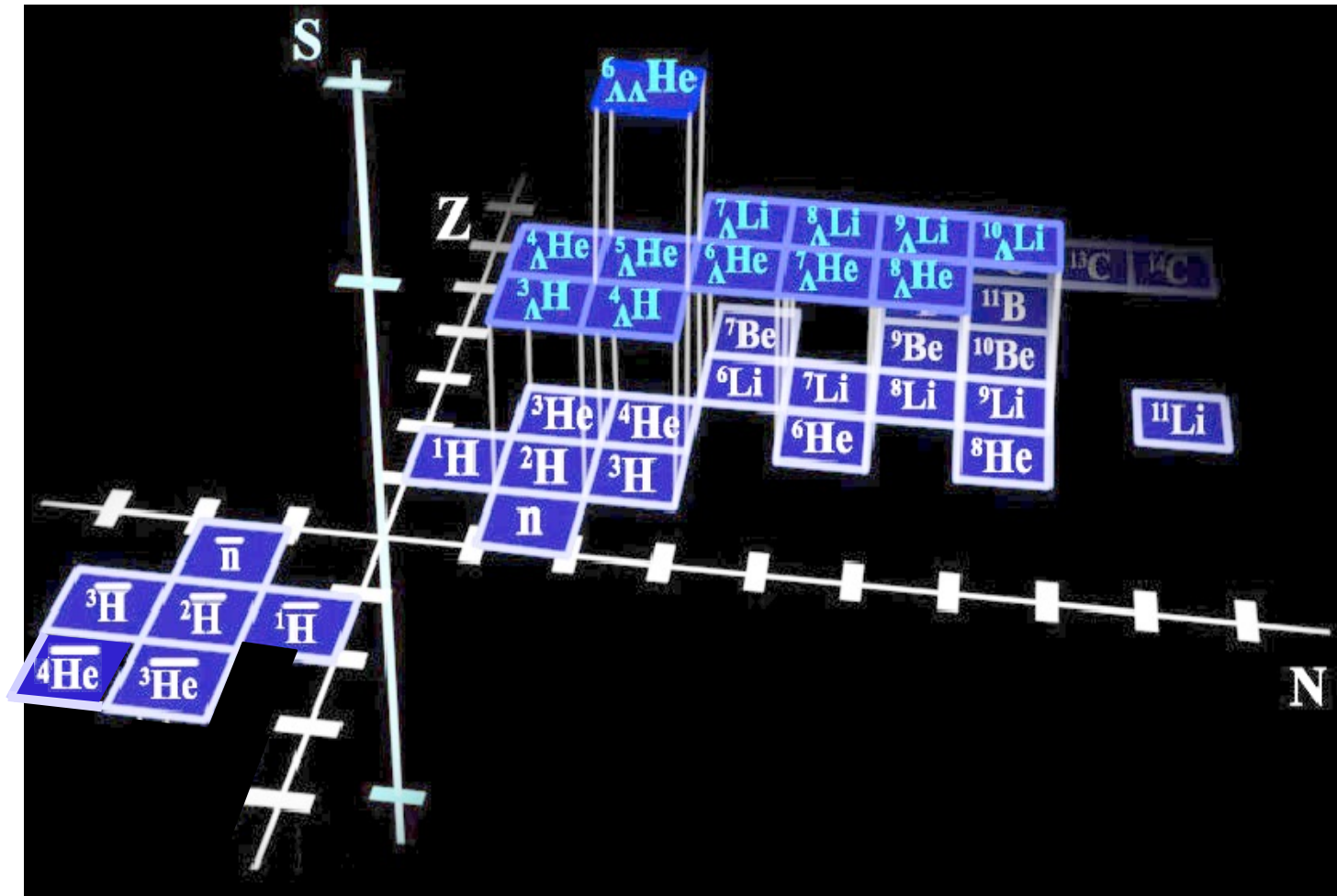


Neutrons (N)

Antinuclei  $\Rightarrow$  extend chart to negative Z and negative N  
 Hypernuclei  $\Rightarrow$  add 3<sup>rd</sup> axis for strangeness S  
 Antihypernuclei  $\Rightarrow$  S axis also flips sign



# 3-D Chart of the Nuclides



Antinuclei  $\Rightarrow$  extend chart to negative Z and negative N  
Hypernuclei  $\Rightarrow$  add 3<sup>rd</sup> axis for strangeness S  
Antihypernuclei  $\Rightarrow$  S axis also flips sign

# Implications

---

- **Proved that anti- $\alpha$  exists.**
- **Provides the point of reference for various searches for new phenomena in the cosmos.**

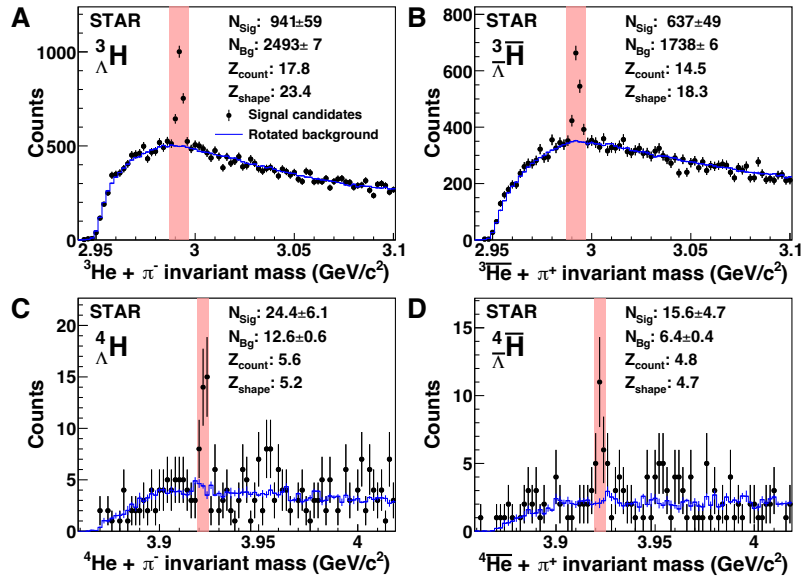
The production rate of antihelium4 in nuclear collisions is consistent with thermodynamic and coalescent nucleosynthesis models.

If anti- $\alpha$  in the cosmos were from coalescence, the ratio of anti- $\alpha/\alpha$  would be  $10^{-16}$ . With a sensitivity of  $10^{-9}$ , even a single anti- $\alpha$  count seen by the AMS experiment would be a strong evidence of anti-star.

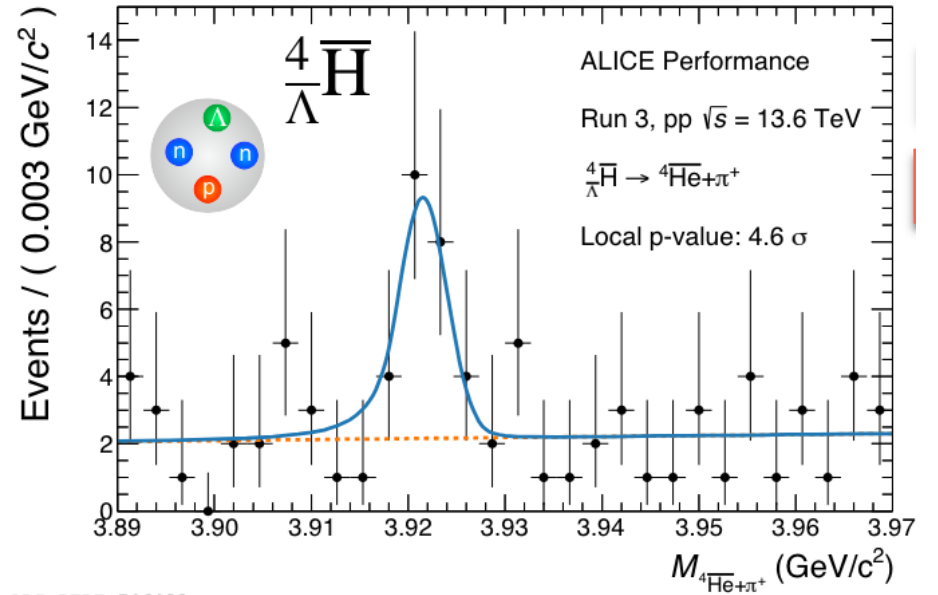
- **Unless accelerator technology has major break through, our record for the heaviest stable antimatter will stand for the foreseeable future.**

---

# Backup Slides



STAR, arXiv:2310.12674 (2023)



ALI-PERF-546499

ALICE, QM 2023