Heavy Ion Physics

- Part II

U.S. DEPARTMENT OF ENERGY

Brookhaven National Laboratory

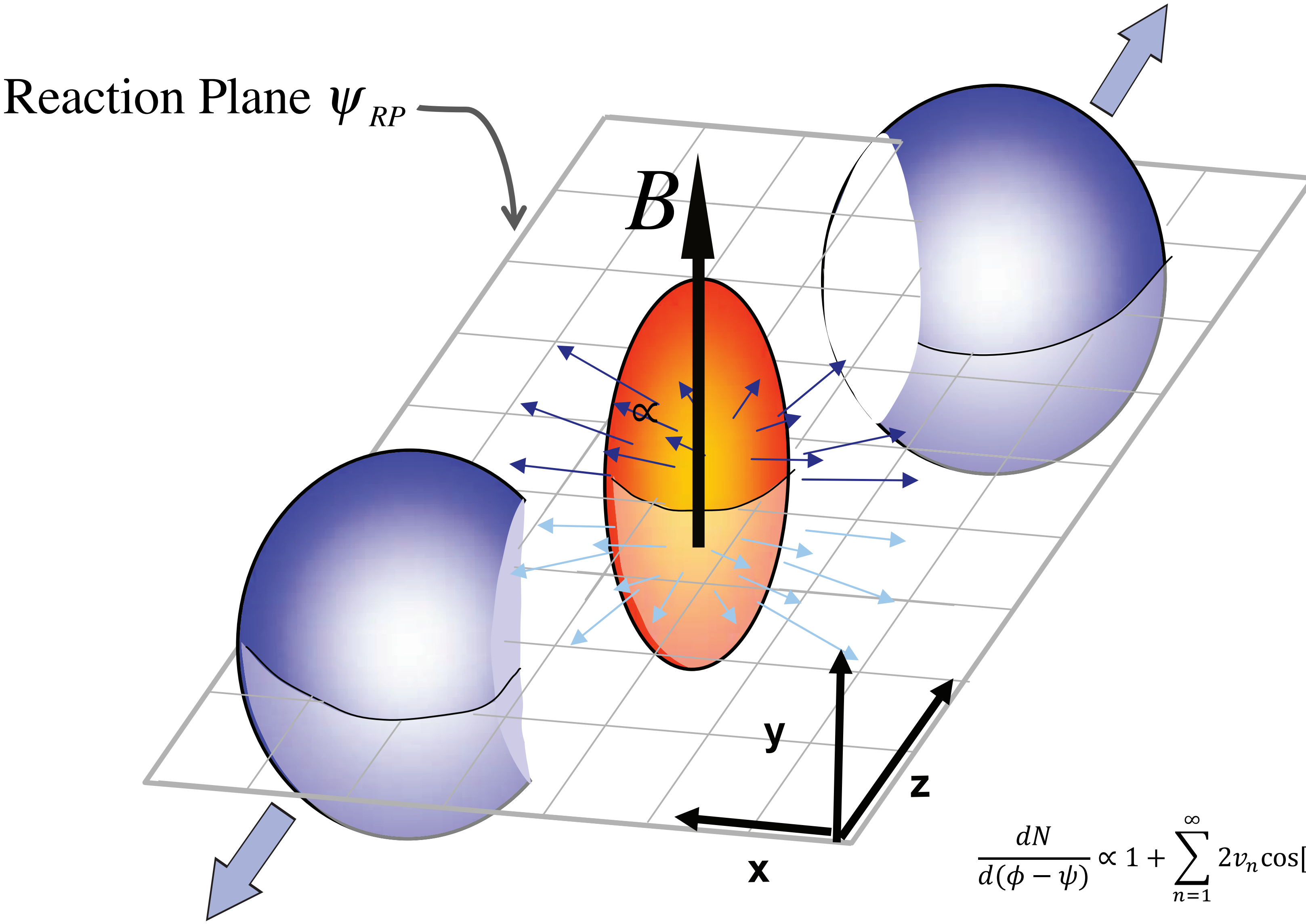
Office of Science
U.S. DEPARTMENT OF ENERGY

Aihong Tang ASP, Morocco, July 2024

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

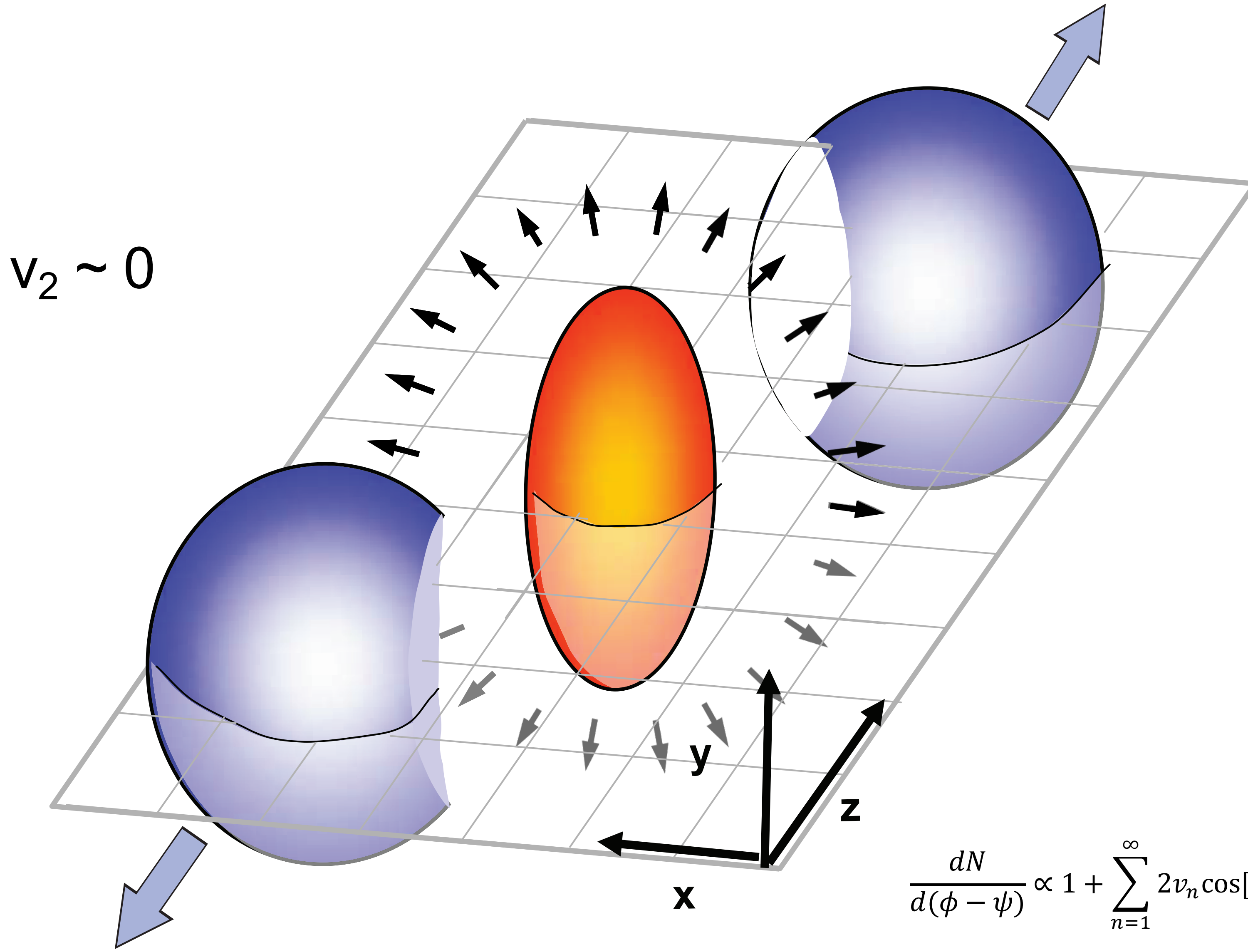
Topic 1 :
Flow Dynamics

Recap : the Reaction Plane



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

v_2

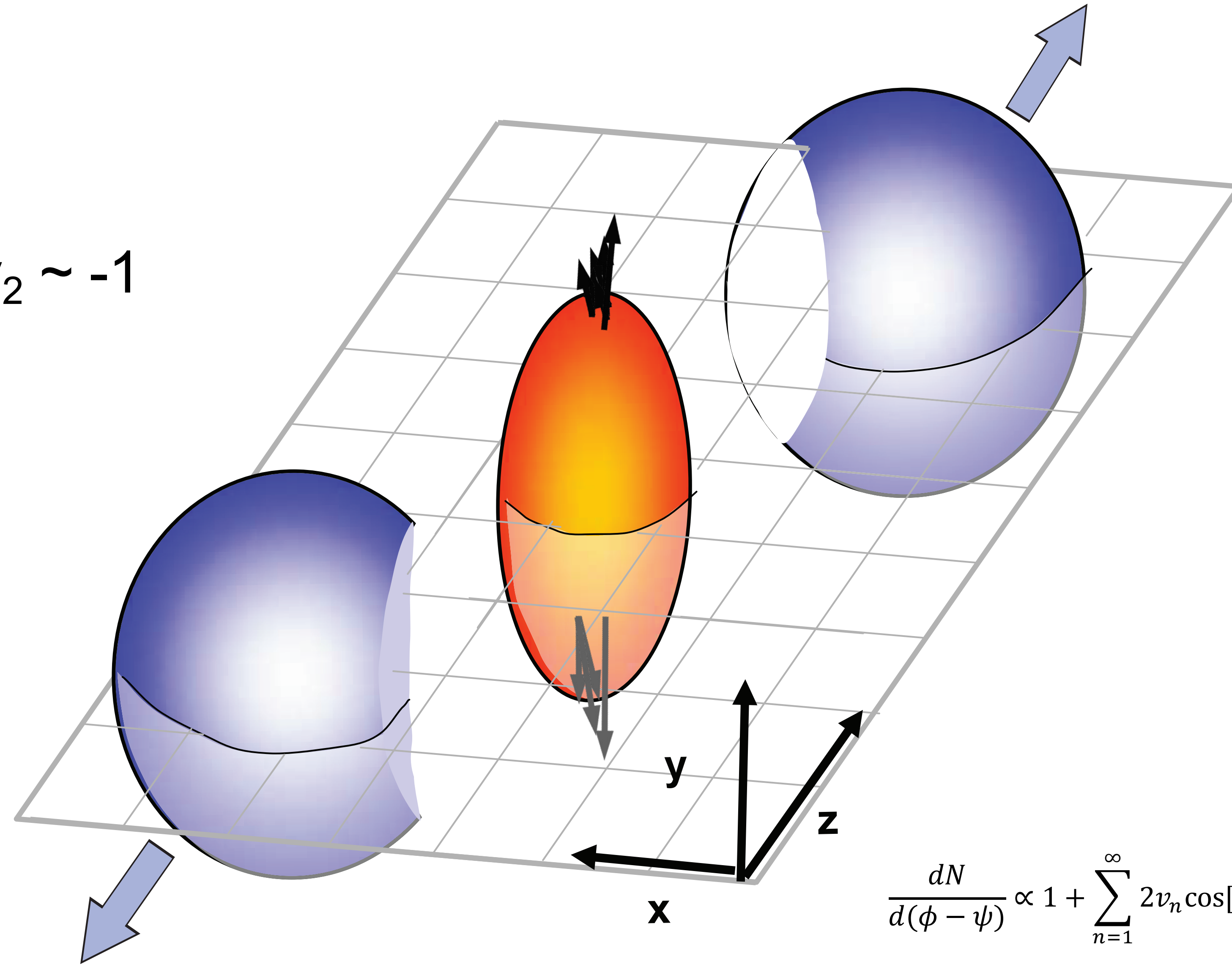


$$\frac{dN}{d(\phi-\psi)} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi-\psi)]$$

v_2 describes how well particles converge towards reaction plane

v_2

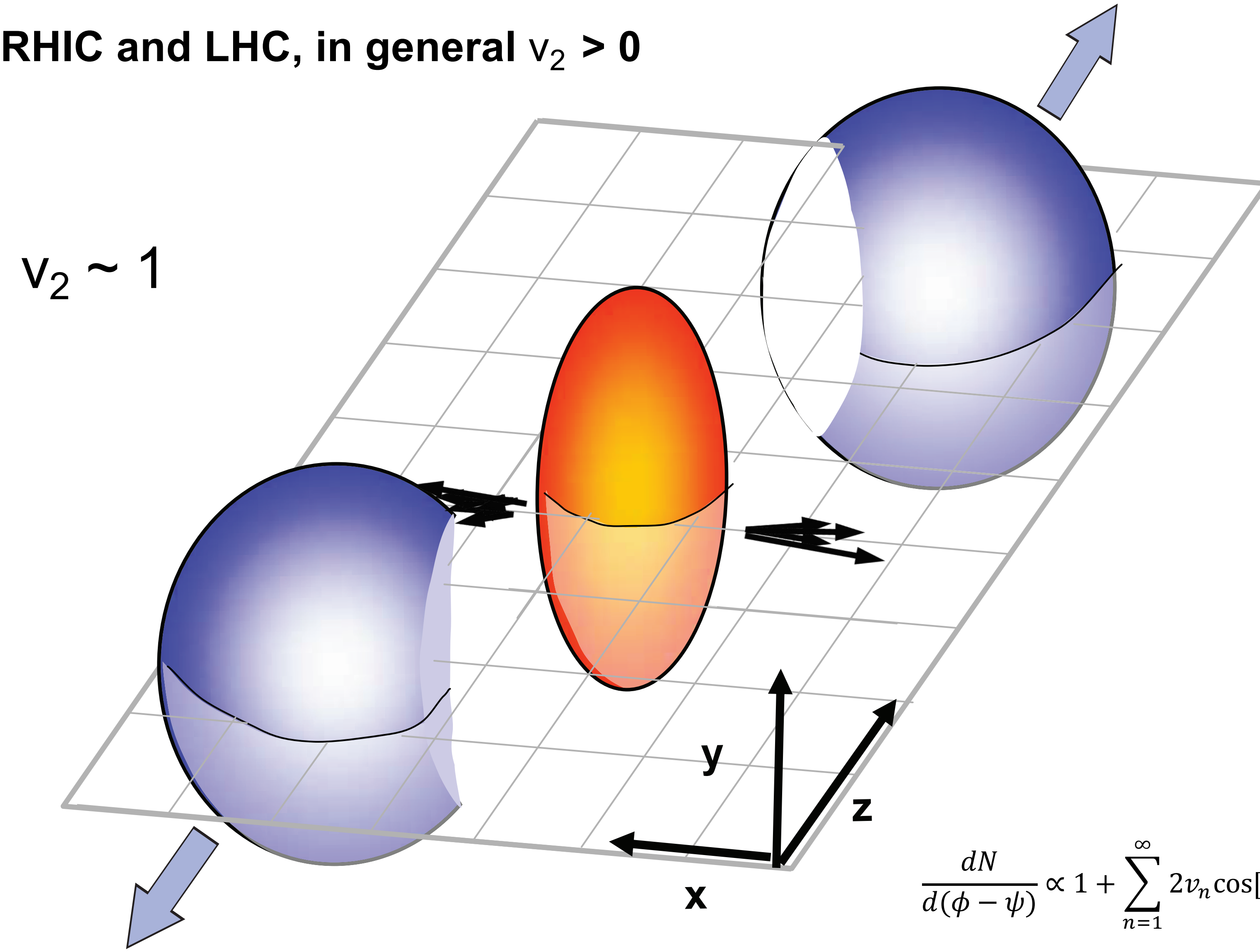
$v_2 \sim -1$



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

v_2 describes how well particles converge towards reaction plane

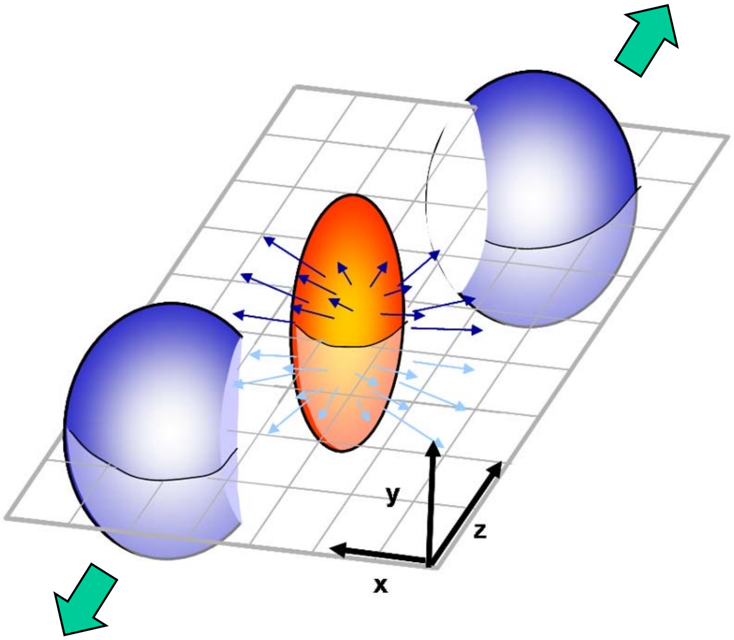
At RHIC and LHC, in general v_2 > 0

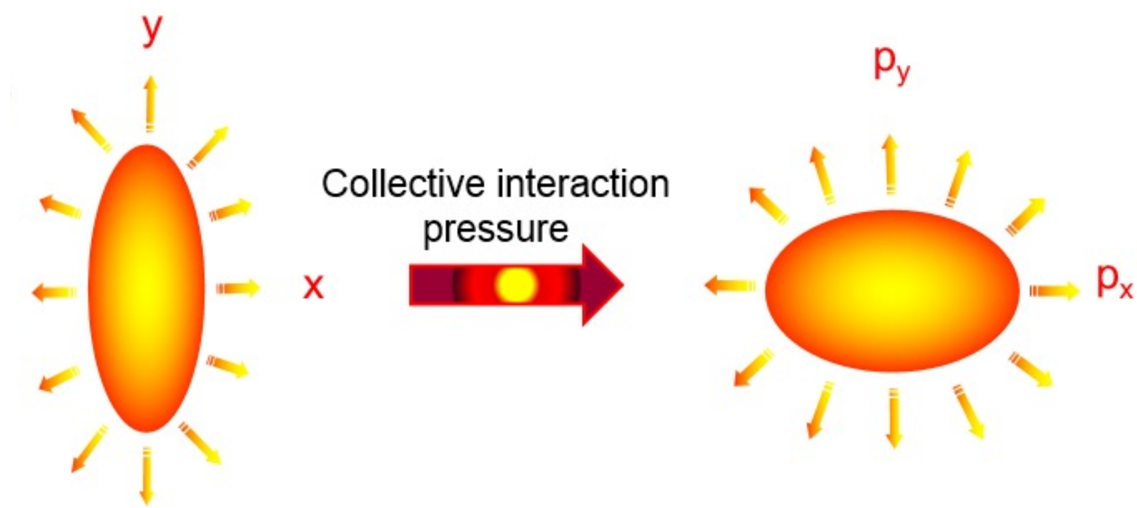


$$\frac{dN}{d(\phi - \psi)} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \psi)]$$

v_2 describes how well particles converge towards reaction plane

Recap : Flow Driven by Pressure





Reaction plane ψ : 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

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

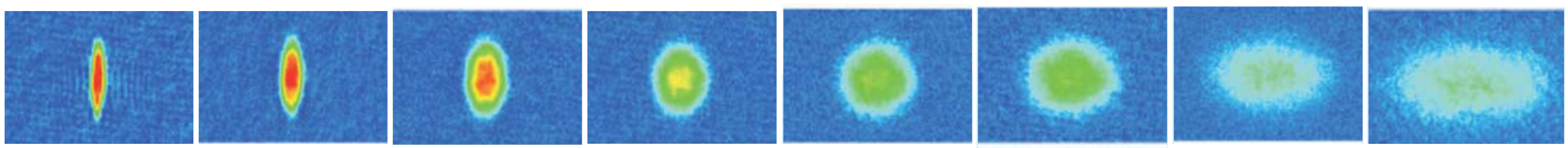
$$= \langle \cos^2(\phi - \psi) - \sin^2(\phi - \psi) \rangle$$
$$= \langle \cos 2(\phi - \psi) \rangle$$

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

v_n : flow measurements

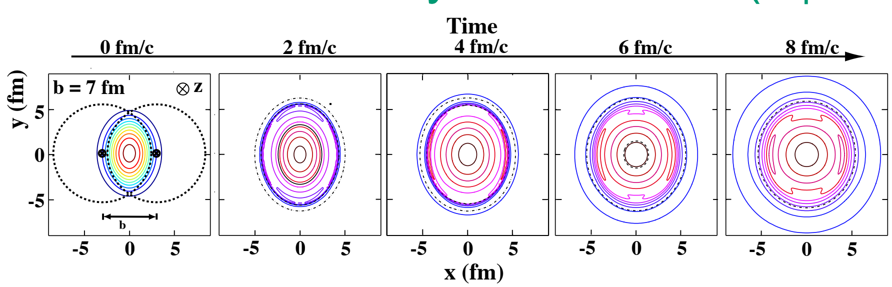
Pressure-driven Expansion

Atomic gas cloud



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

Relativistic heavy ion collision (E_T density)

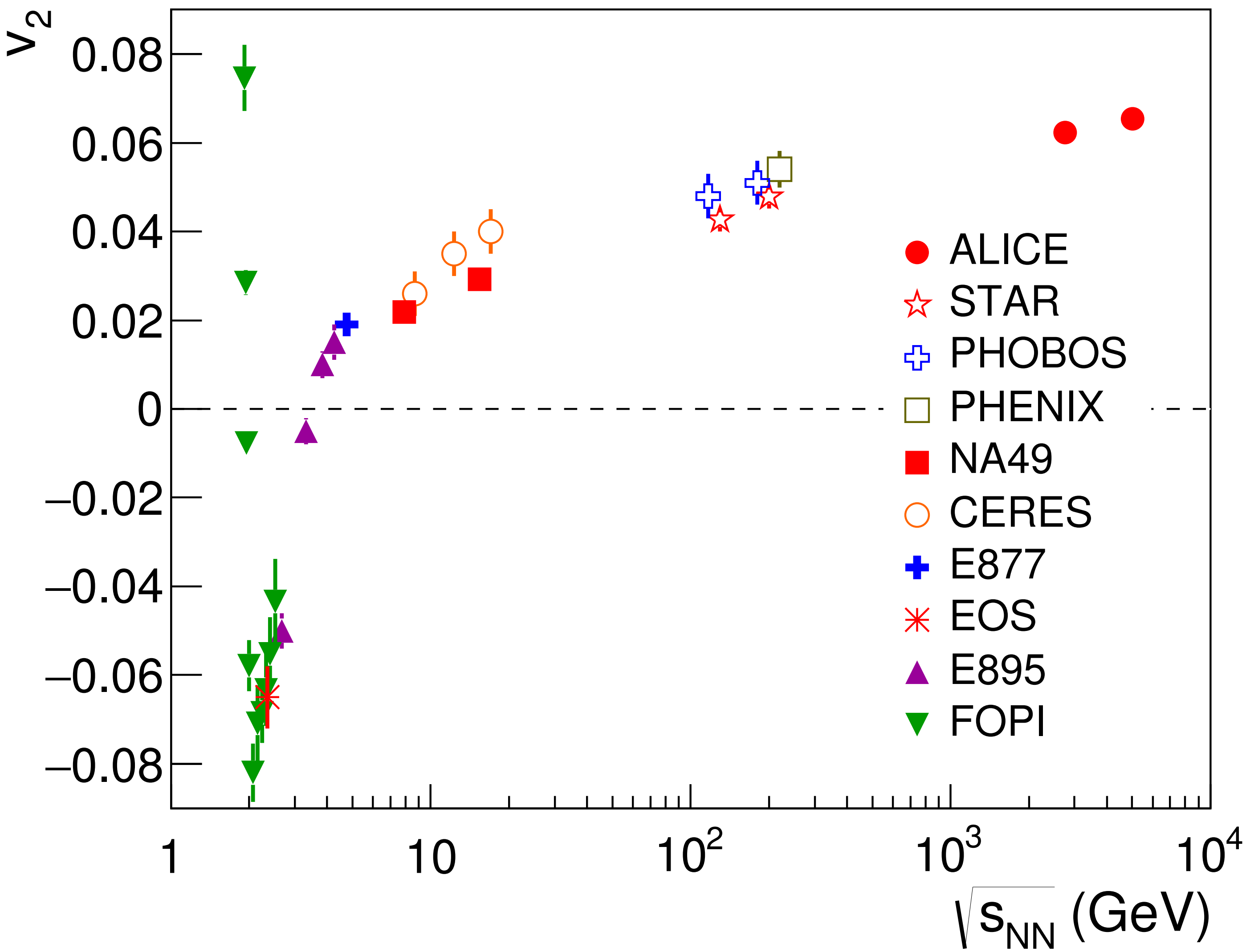


P.F. Kolb, UW.Heinz, in Hua, R.C. (ed.) et al: Quark Gluon Plasma 634-714

In both cases, expansion along the short axis.

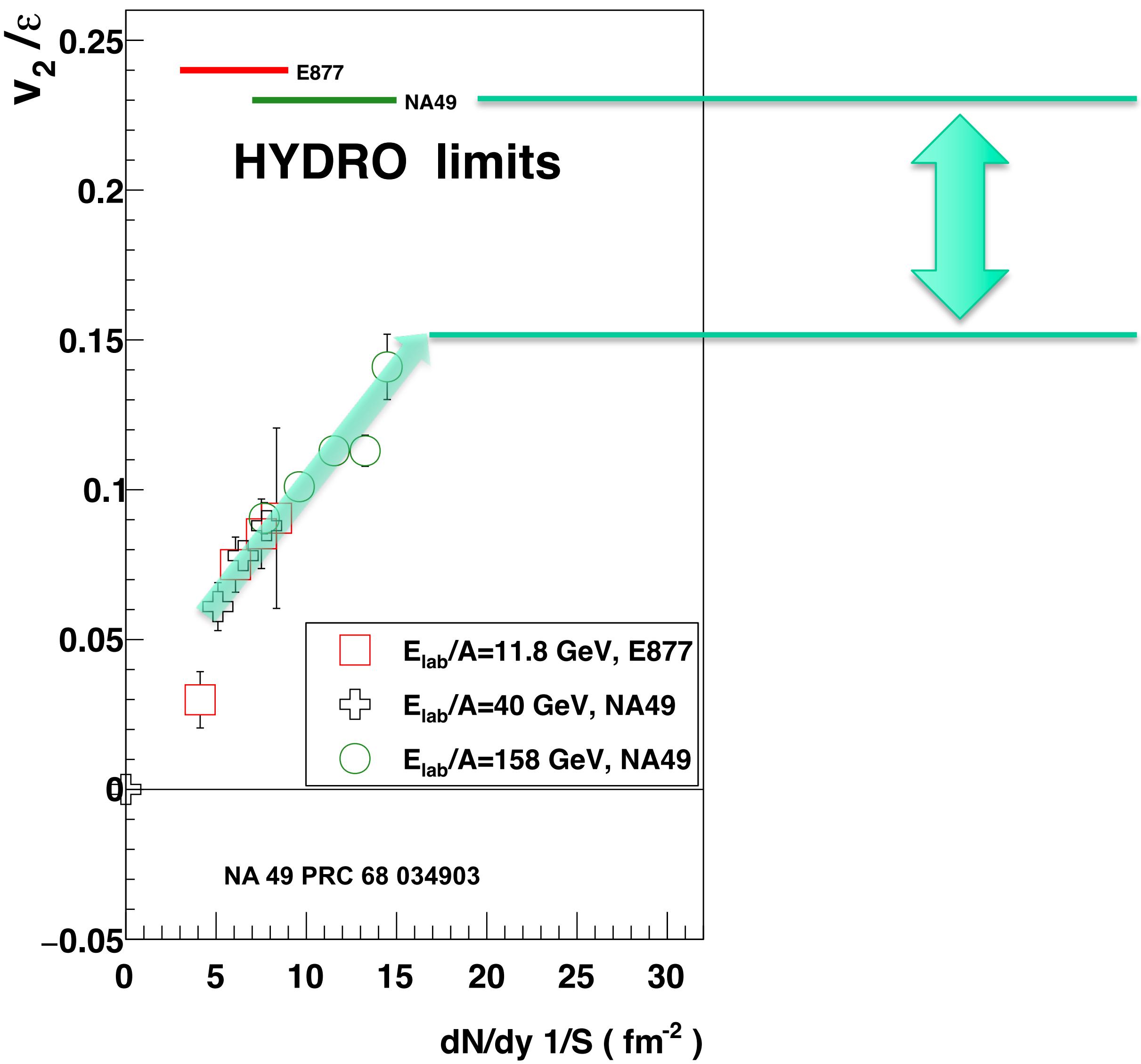
Can only be explained if the droplet is a fluid, not a collection of independent particles.

v_2 vs Energy



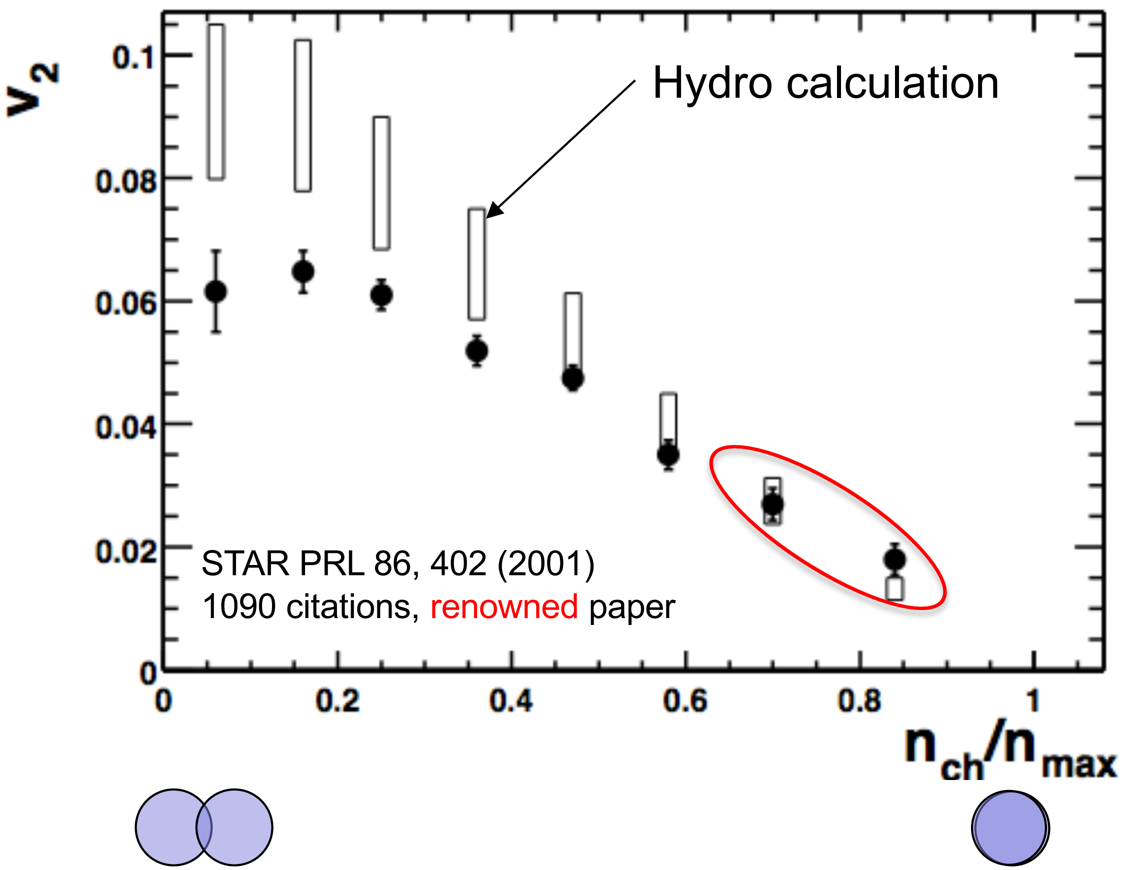
Alice, arXiv:2211.04384

The March to Hydro



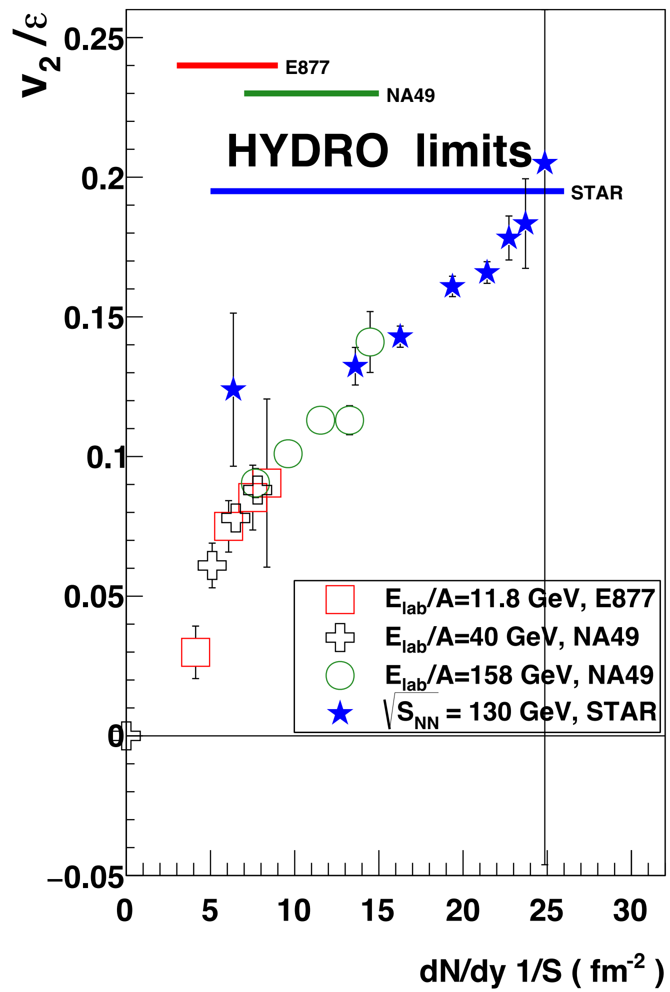

The March to Hydro

The First Sign of Hydro Flow



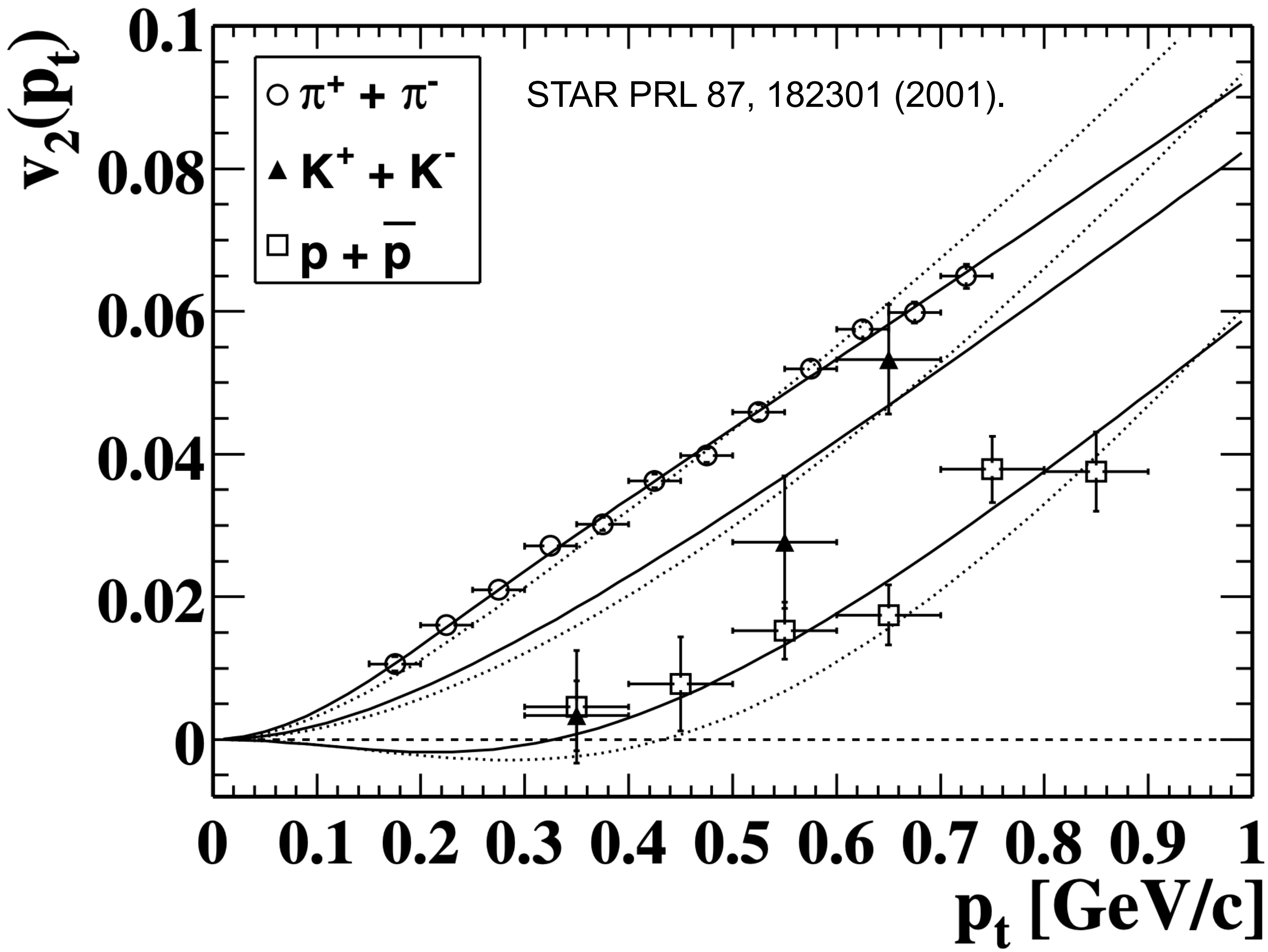
Approaching Hydro for central collisions

The March to Hydro



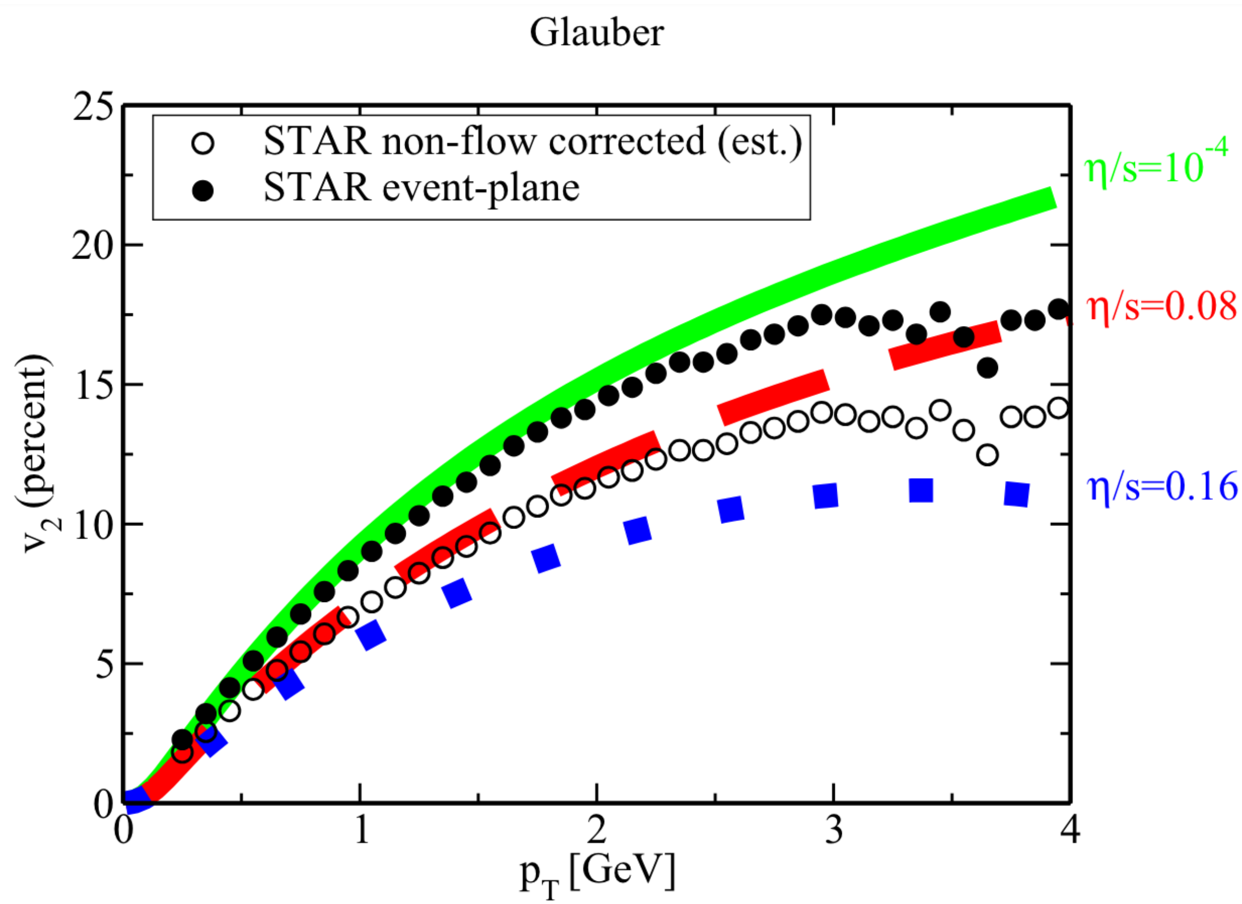
STAR PRC 66 034904 (2002)

Identified Particle v_2



Mass splitting consistent with collective flow

Viscosity



Luzum & Romatschke, PRC 78 034915 (2008)

η/s close to ~ 1/(4π), 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 sugges universe behaved like a liquid in its earlies the fiery gas that was thought to have perv microseconds of existence.

Early Universe was a liquid

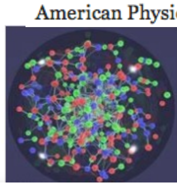
Mark Peplow

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.



SCIENTIFIC AMERICAN™

Sign In / Register

Search ScientificAmerican.com

Subscribe | News & Features | Topics | Blogs | Videos & Podcasts | Education | Ci

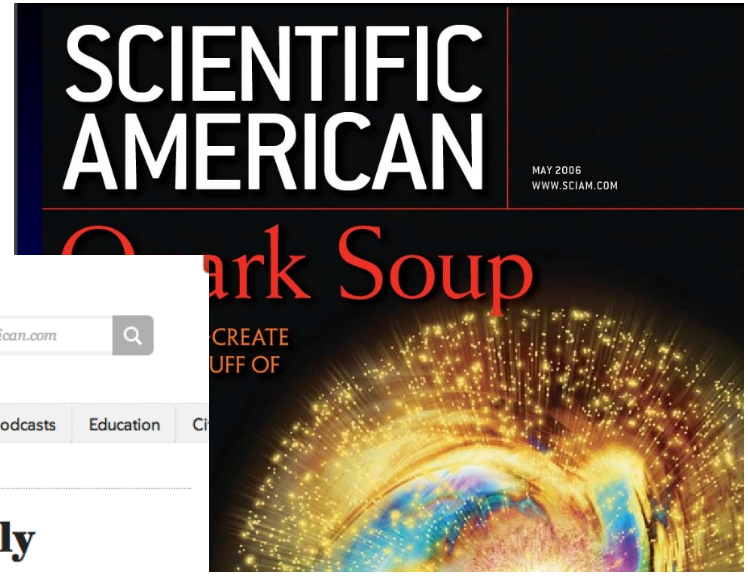
More Science :: News :: April 18, 2005 :: Email :: Print

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

News Front Page

Africa
Americas
Asia-Pacific
Europe
Middle East
South Asia
UK
Business
Health
Science & Environment
Technology
Entertainment
Also in the news

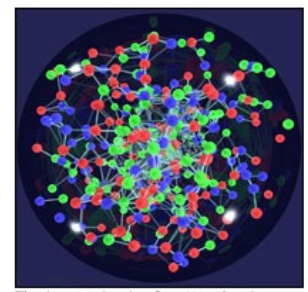
Video and Audio

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.

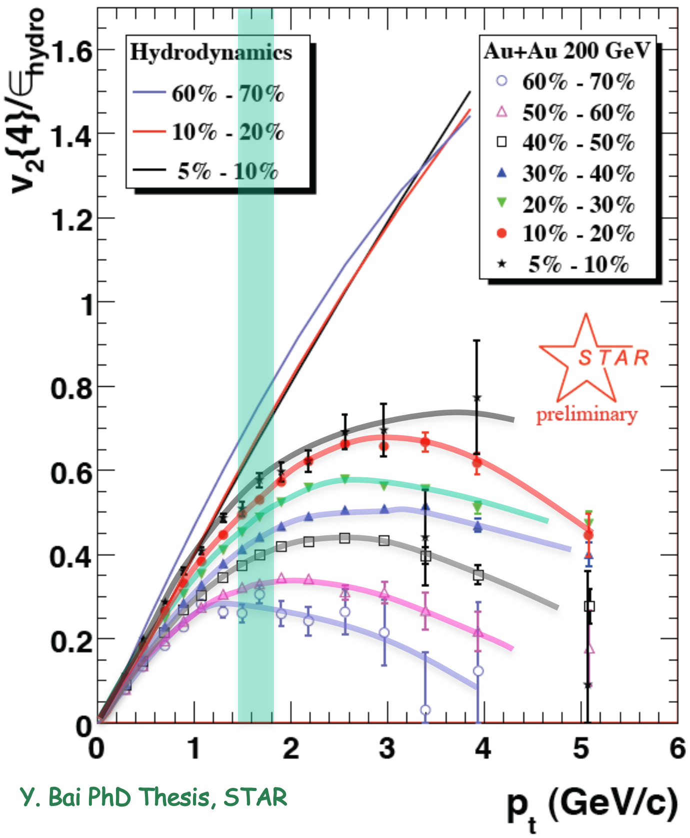


The impression is of matter that is more strongly interacting than predicted

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

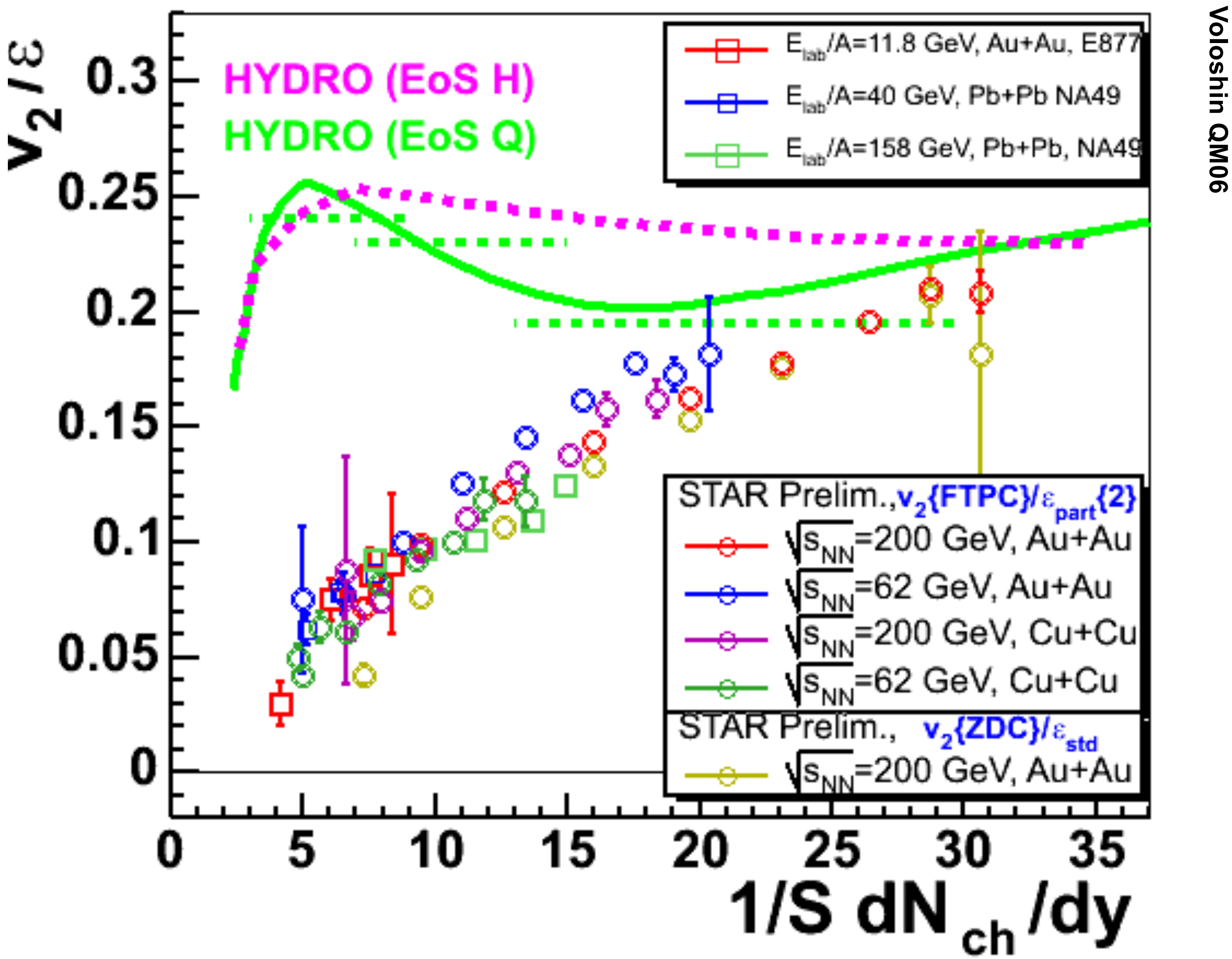

Are we saturated ?

Are we saturated ?

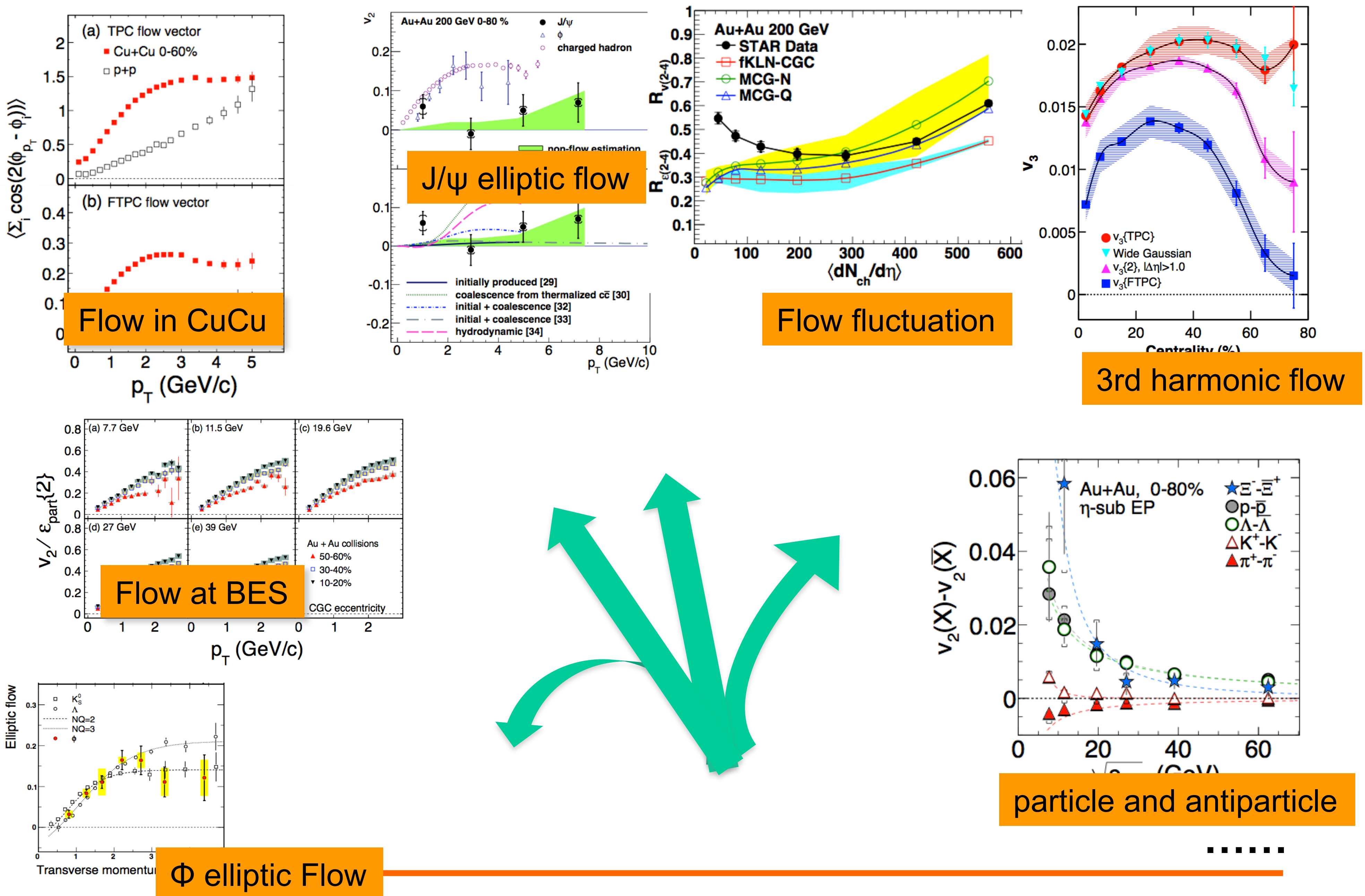


Y. Bai PhD Thesis, STAR

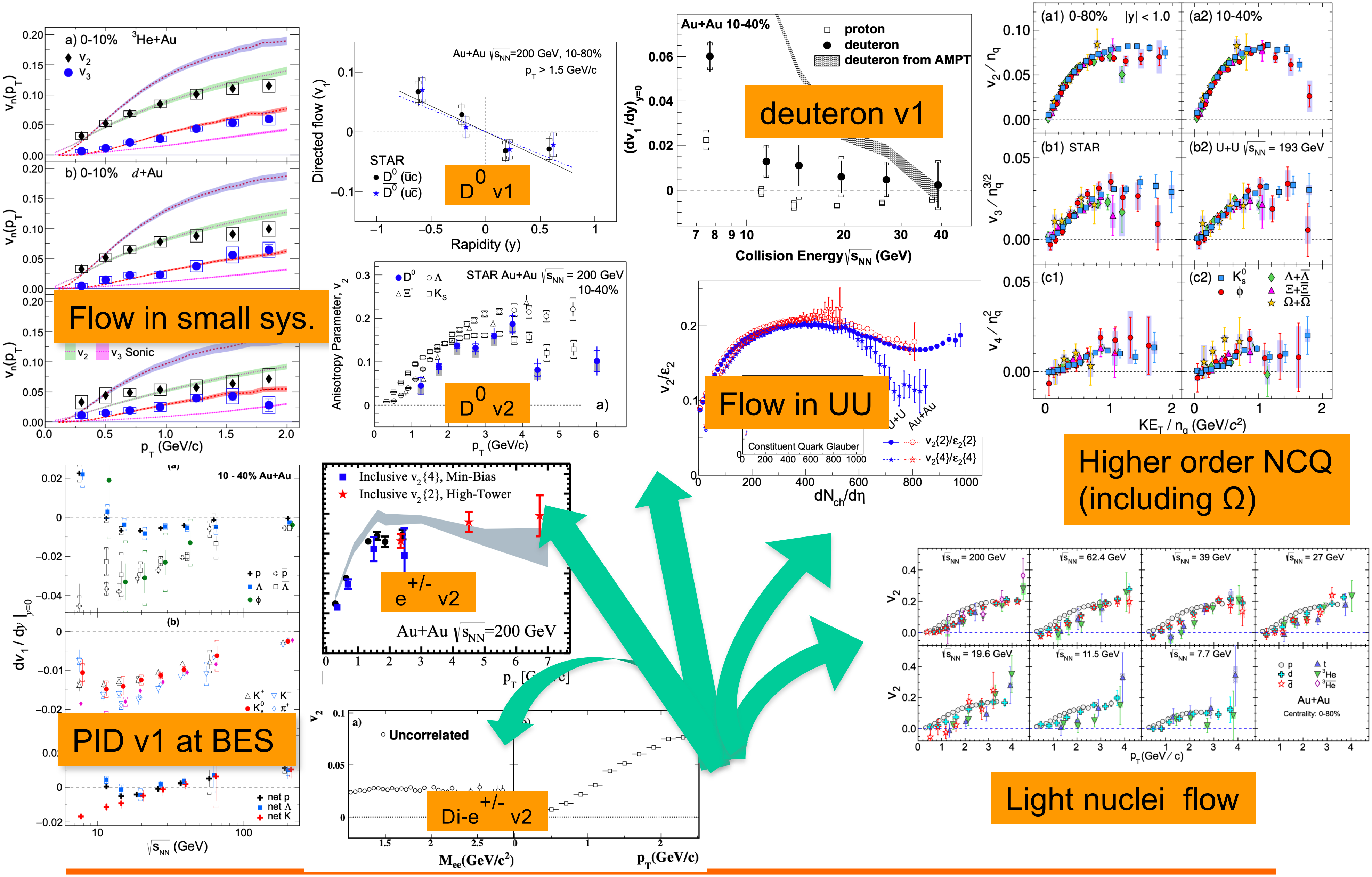
Are we saturated ?



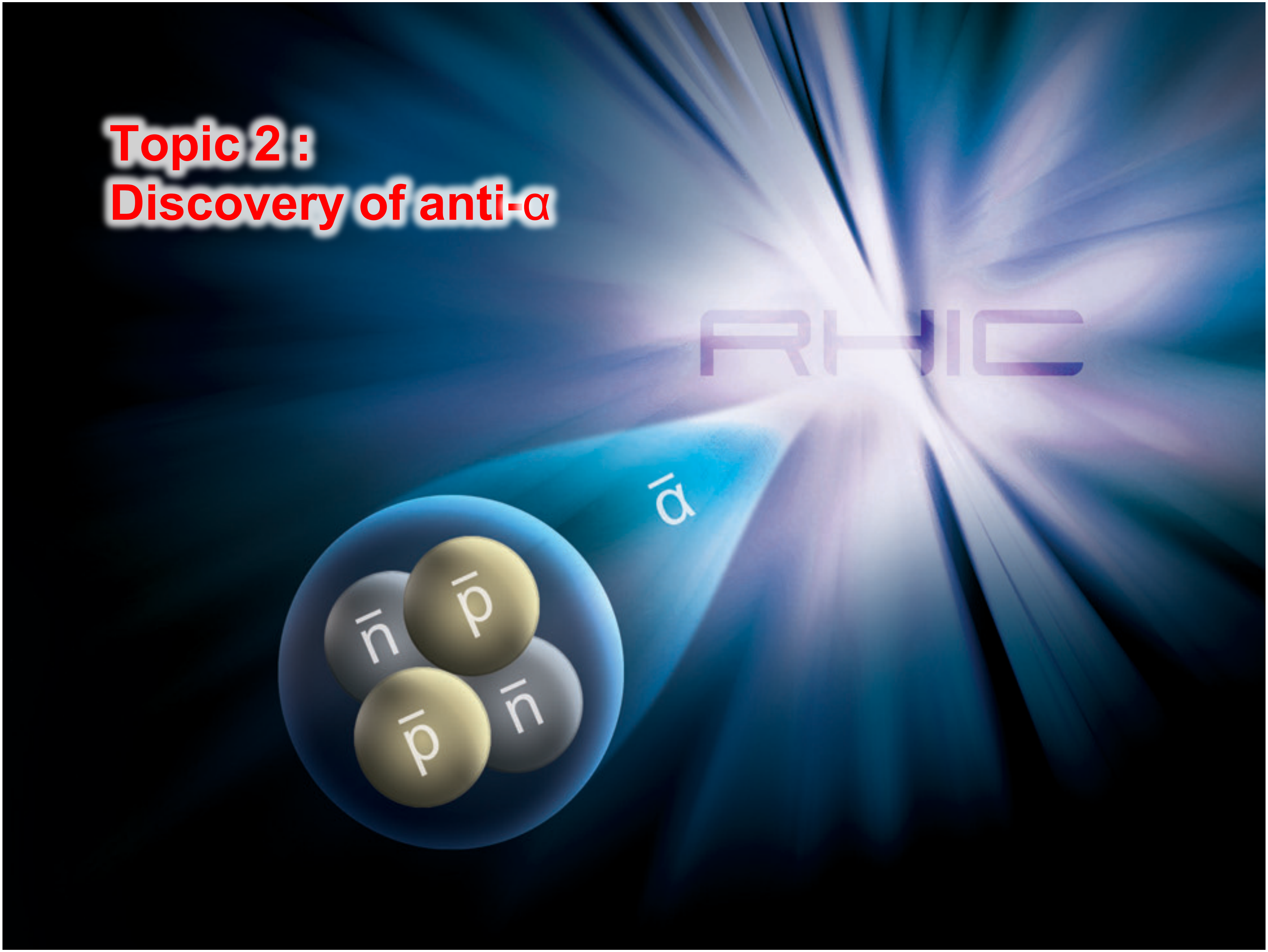
Keep Flowing



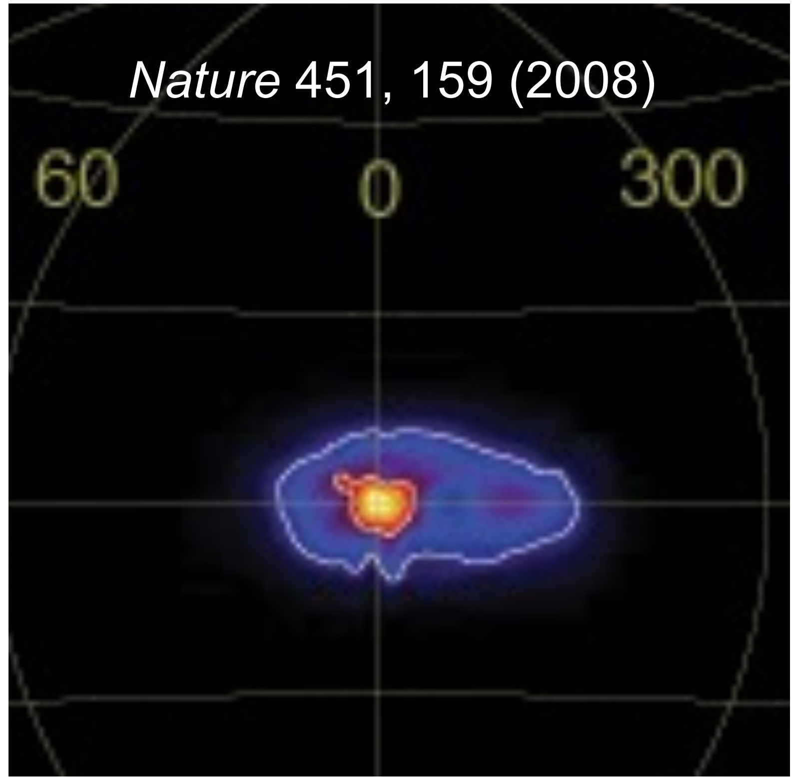
Keep Flowing



Topic 2 : Discovery of anti-α



Why Antimatter ?



Nature 451, 159 (2008)

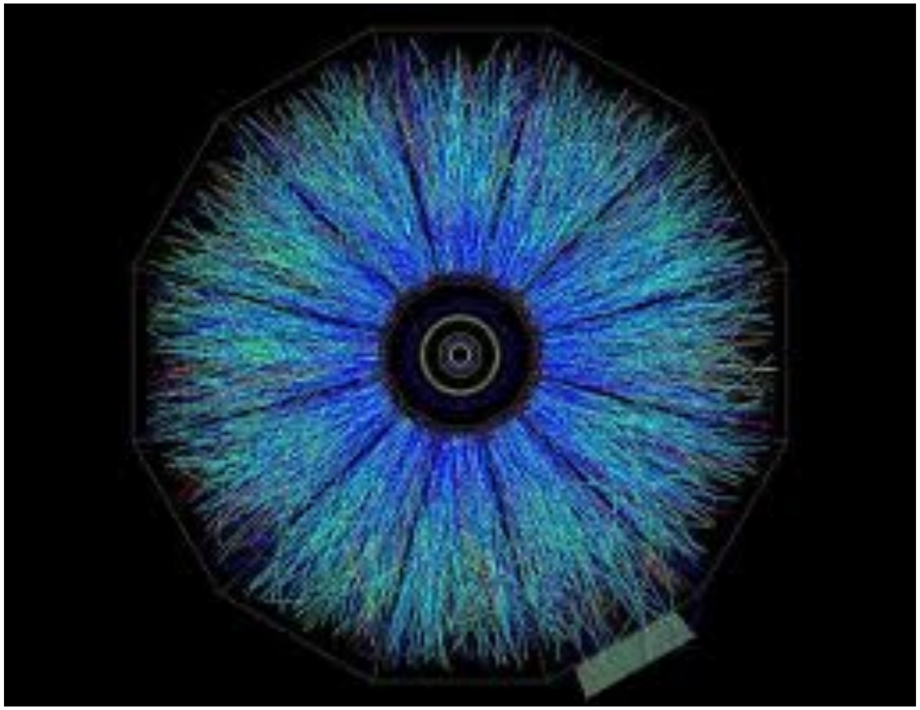
Clue to the matter anti-matter asymmetry

Antimatter matters !

Why Antihelium 4 (anti-α) ?

Fingerprint of anti-star !

Why in High-energy Nuclear Collisions ?

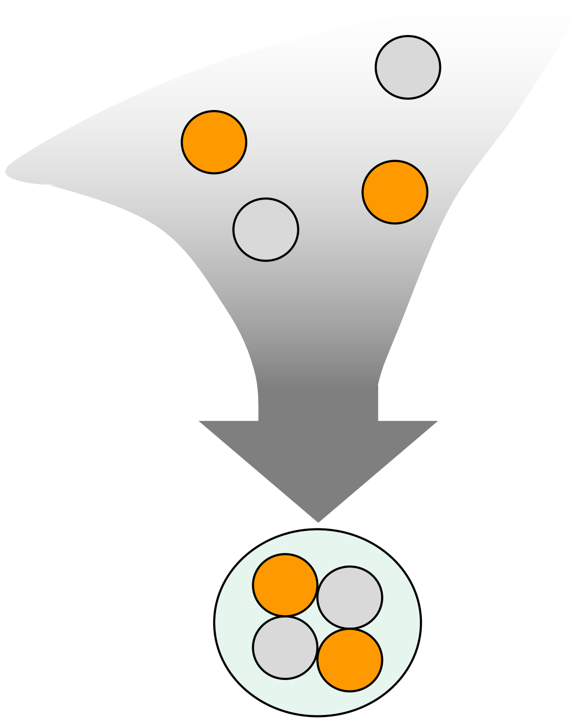


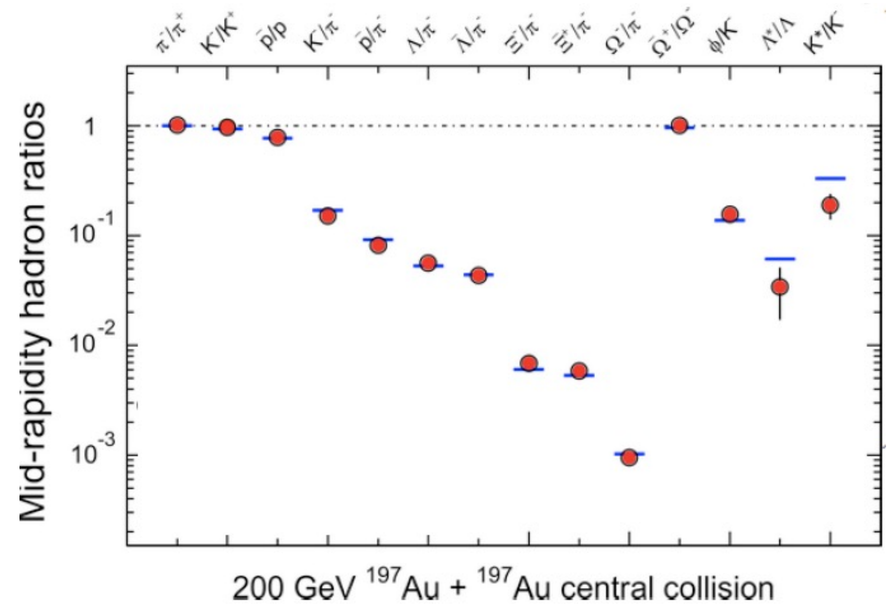
•Sweet spot between elementary particle collisions and Big Bang for anti-nuclei production.

• 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





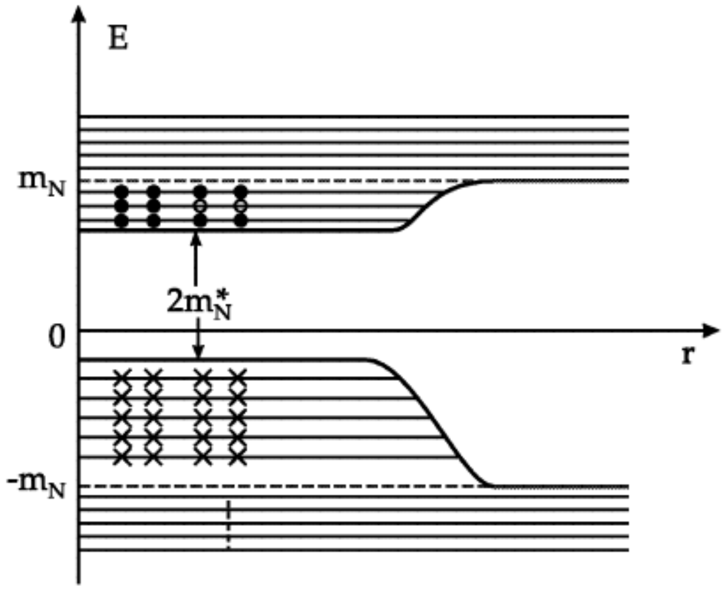
STAR whitepaper, NPA757(2005)

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

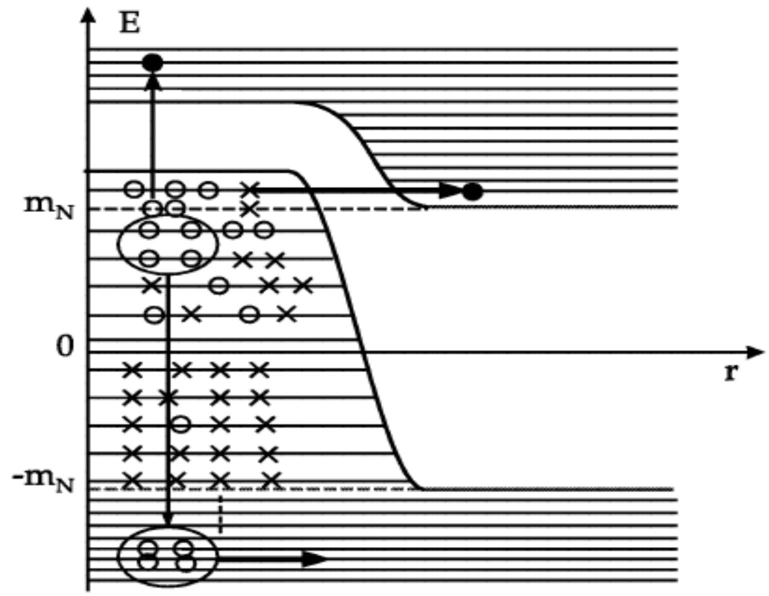
Coalescence **Thermal production**

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

Production Mechanisms



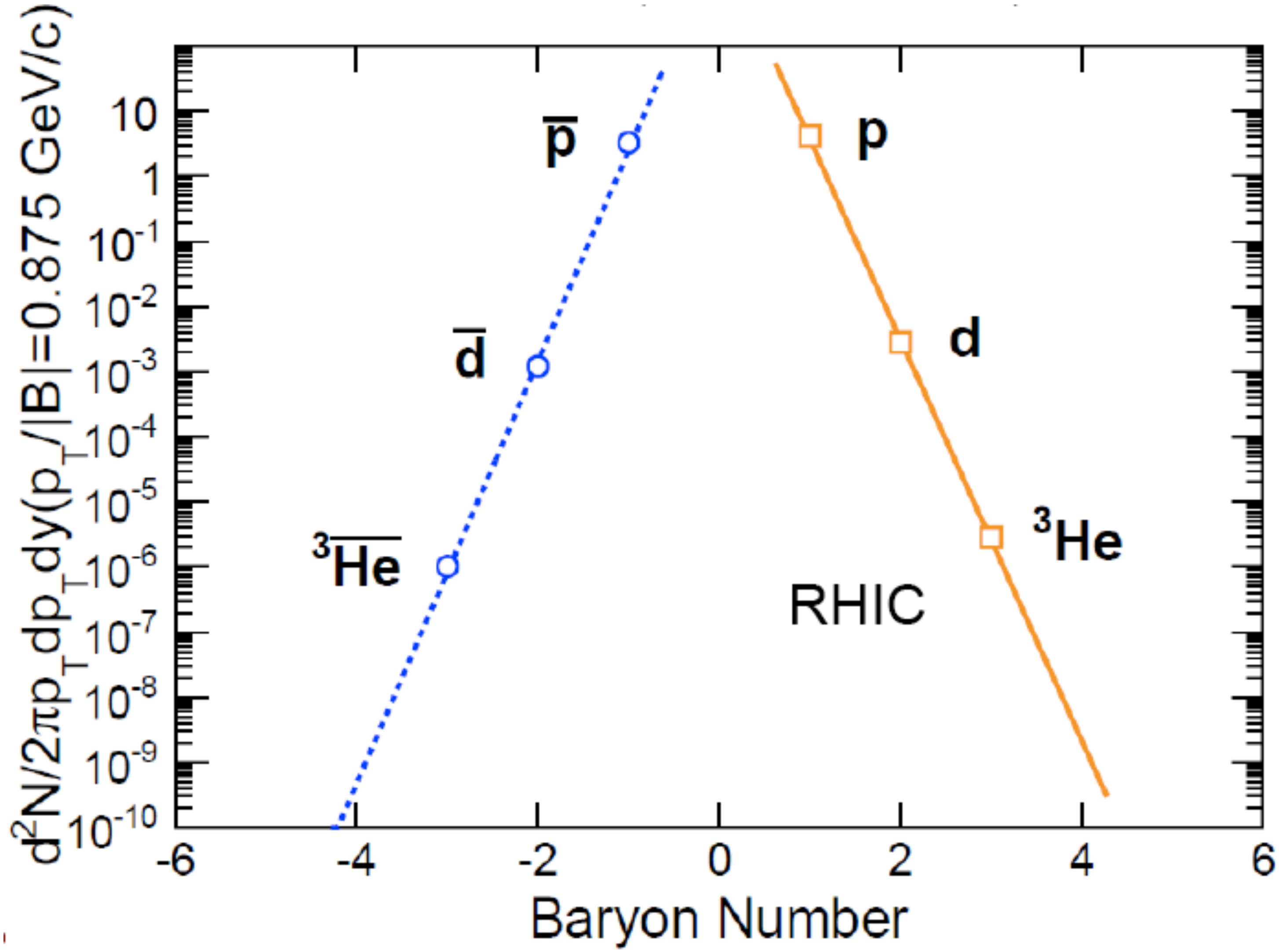
Int. J. Mod. Phys. E 5 1-90 (1996)



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

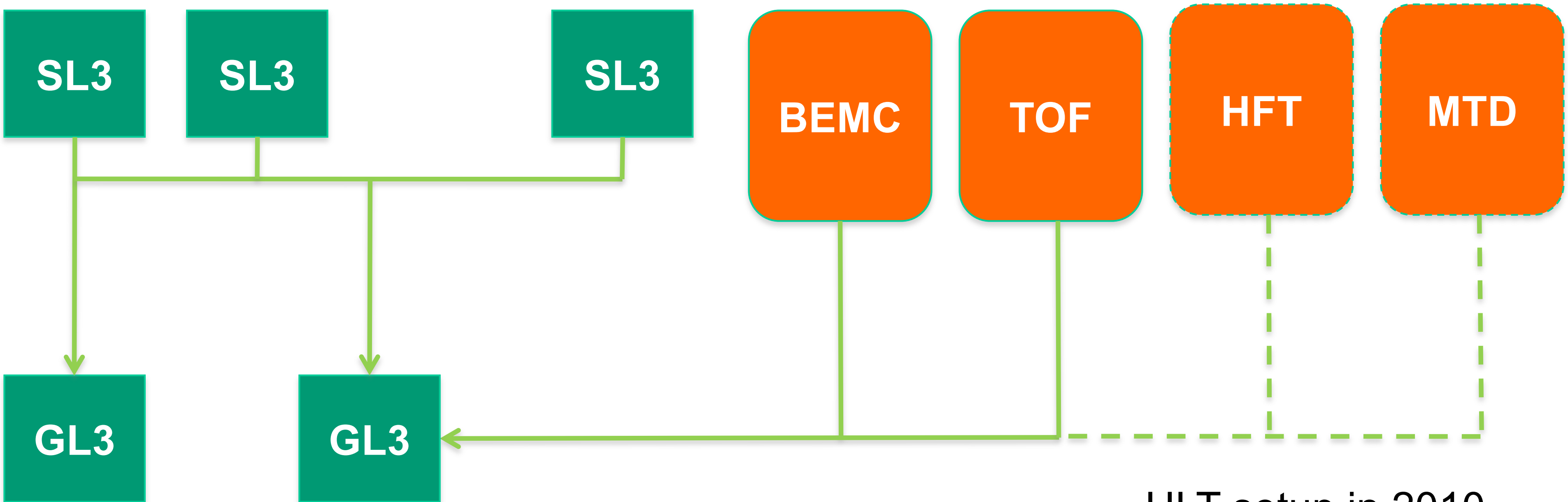
Could be exciting but no evidence so far.

The Reduction Factor



It is a challenging job !

High Level Tracking Trigger (HLT)



HLT setup in 2010

- 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

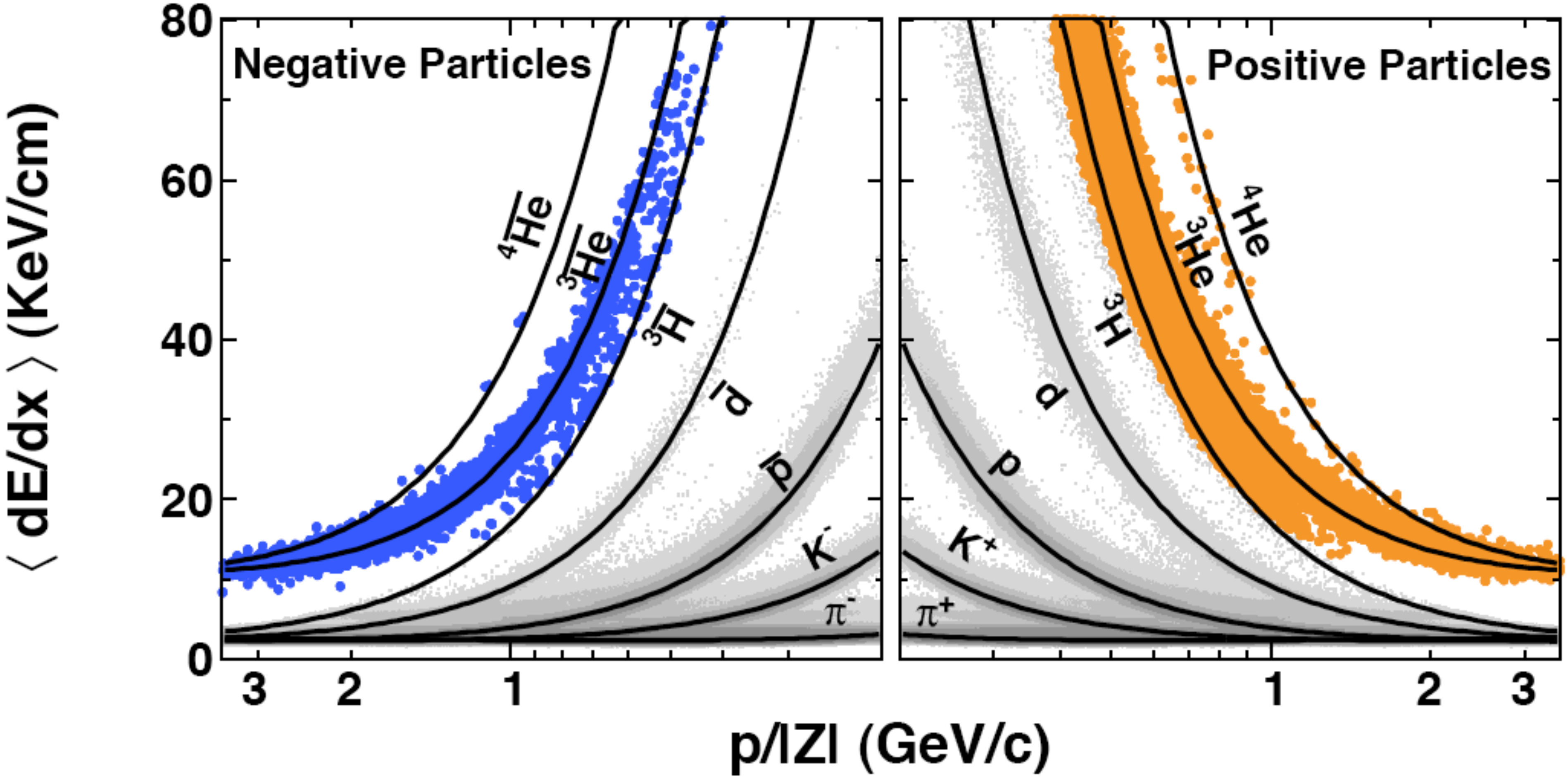
• 360 million minimum bias (MB) collisions, 270 million central collisions and 170 million high tower calorimeter events at 200 GeV in 2010.

• 70 million MB events at 200 GeV in 2007.

• 170 million MB events at 62 GeV in 2010.

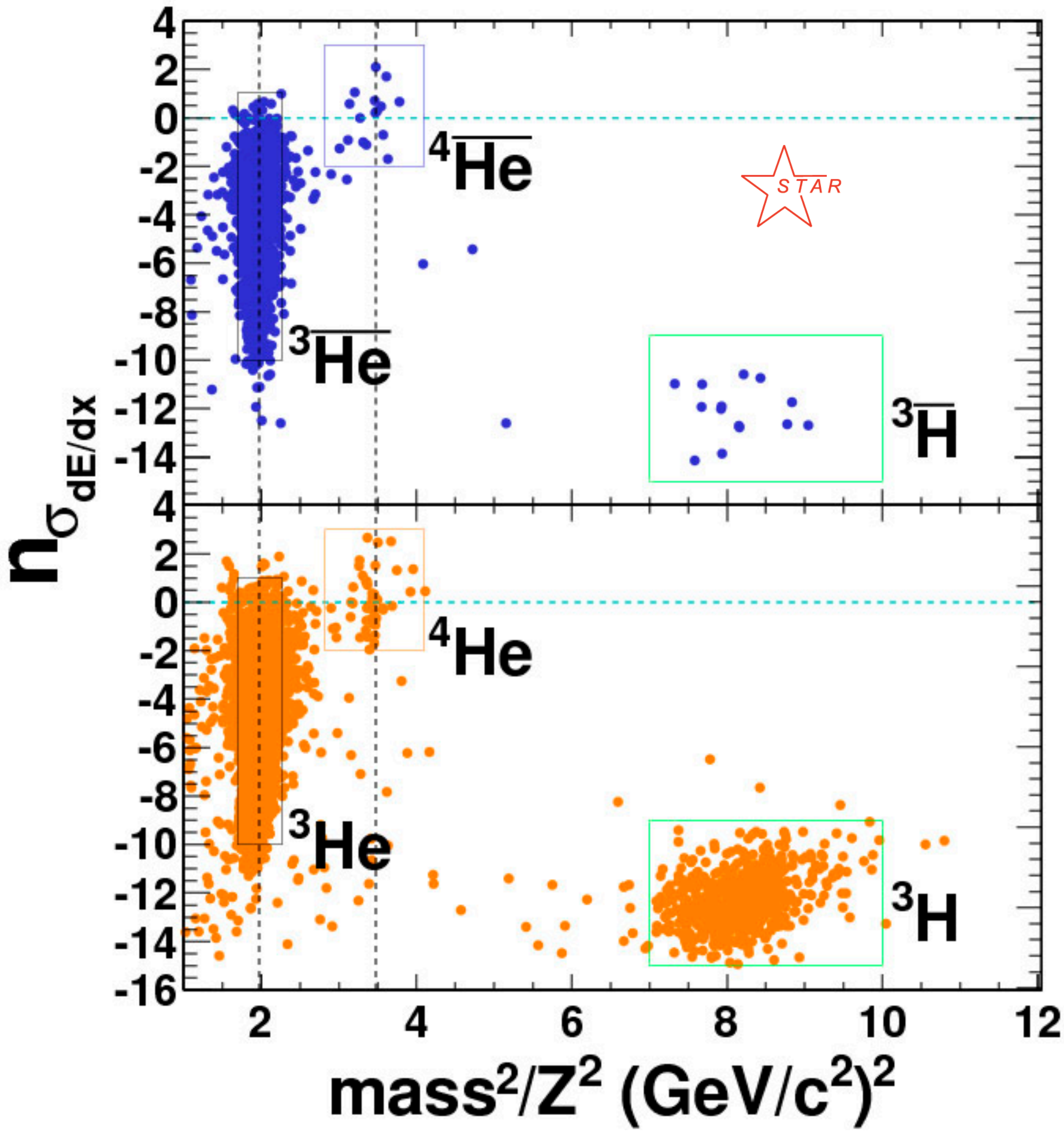
In total one billion AuAu events sampled

dE/dx

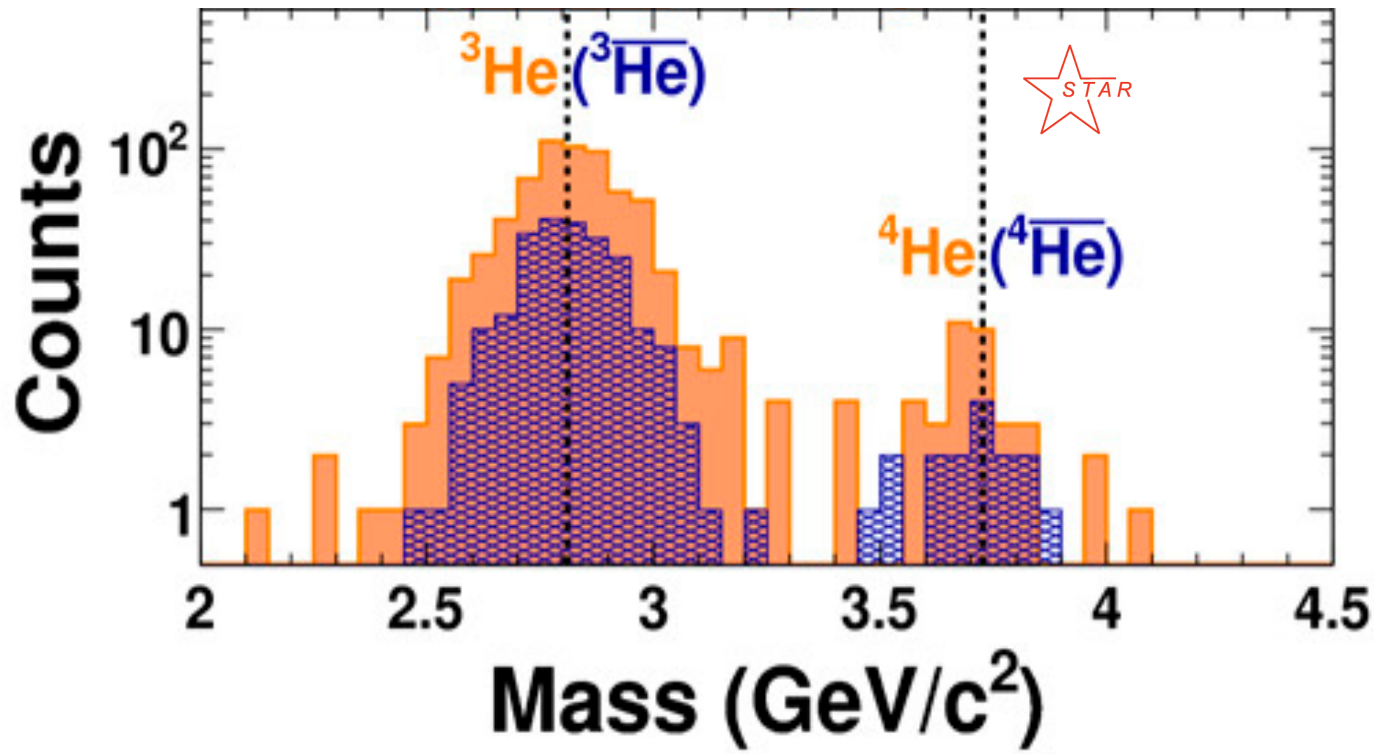


HLT has processing power to do rudimentary event reconstruction in real time, allowing events with a $|Z| = 2$ track to be tagged and fast-tracked via the normal offline calibration & reconstruction chain.

Combined PID (TPC+TOF)



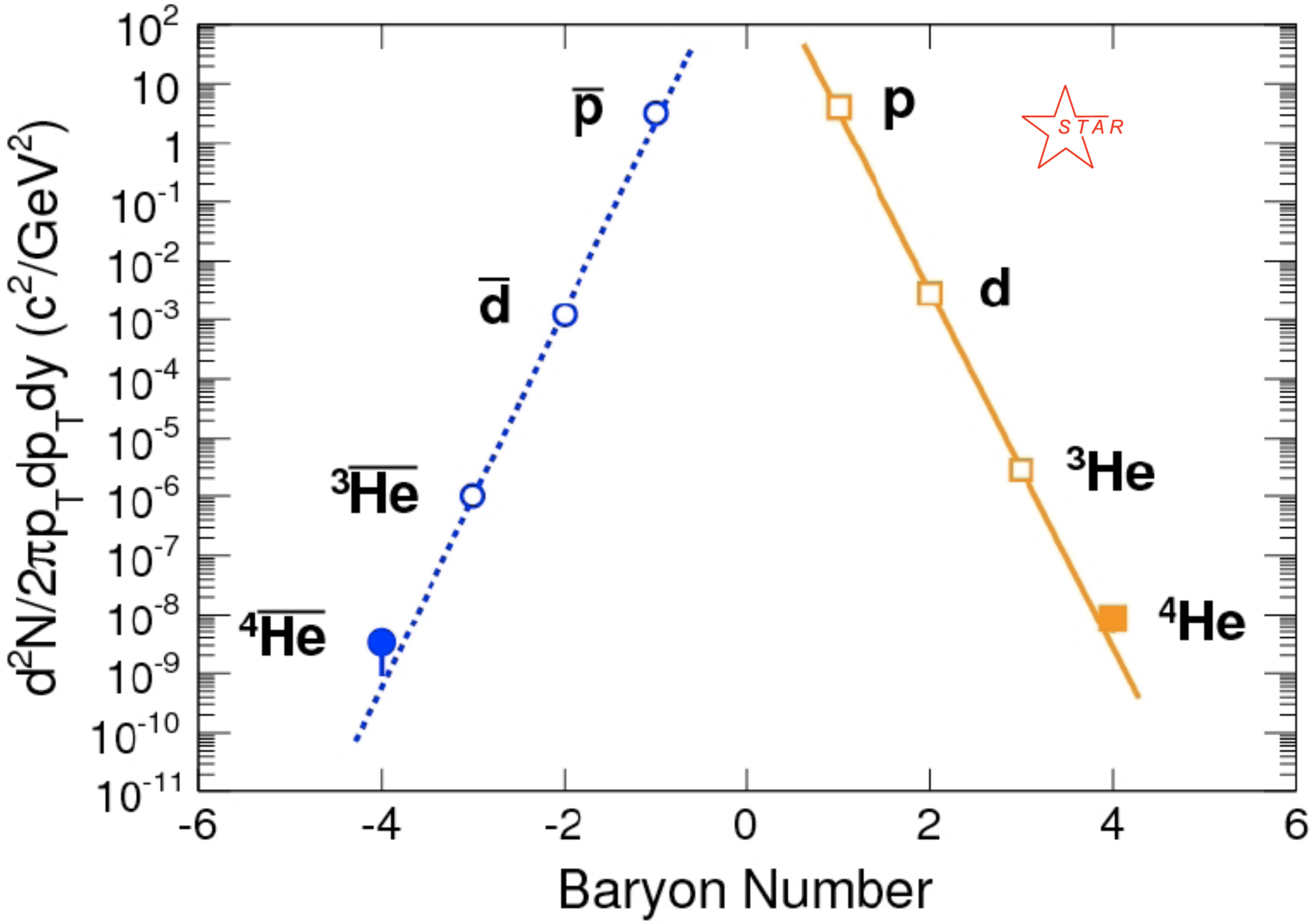
Combined PID (TPC+TOF)



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

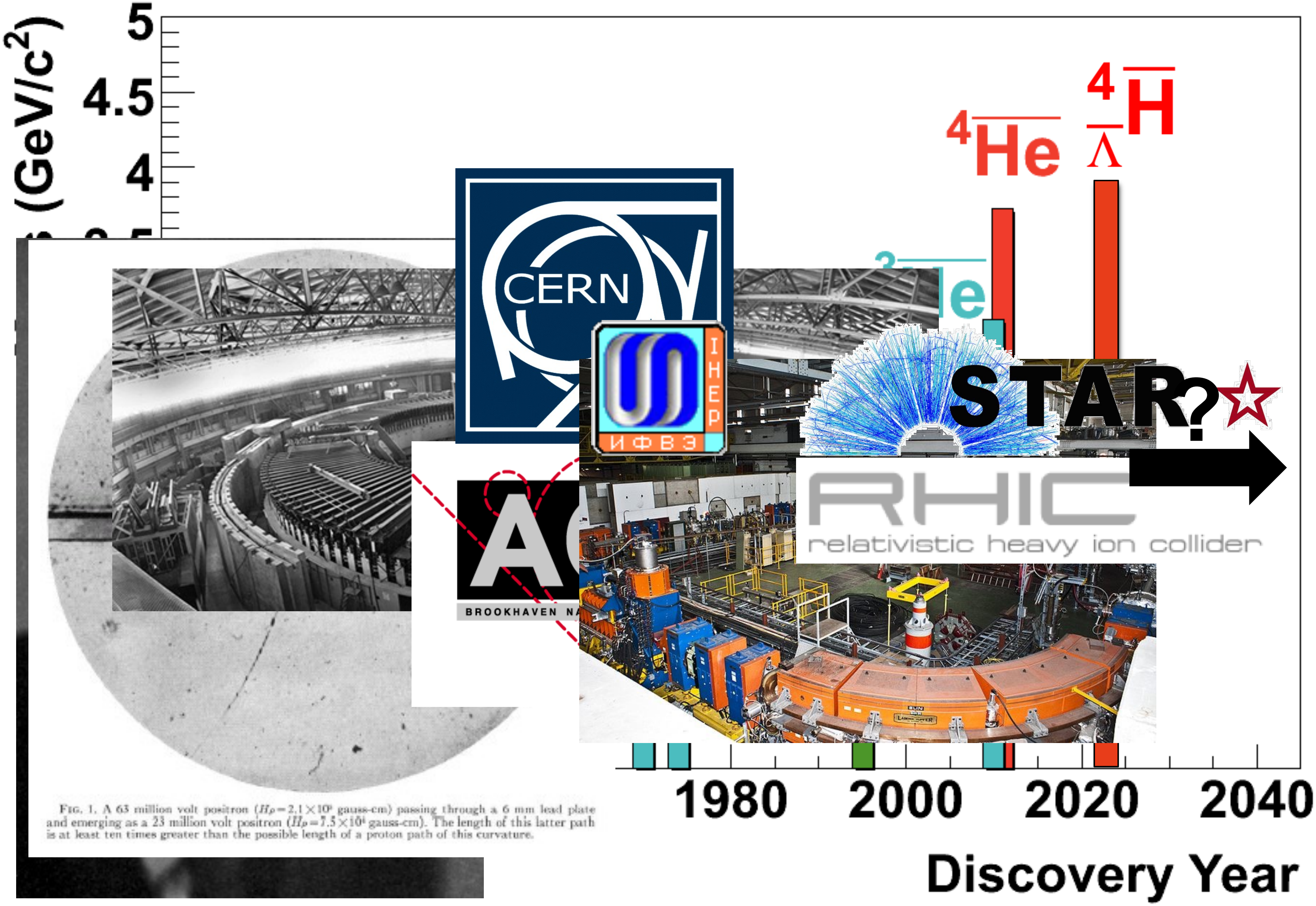
In total 18 counts observed.

Reduction Factor

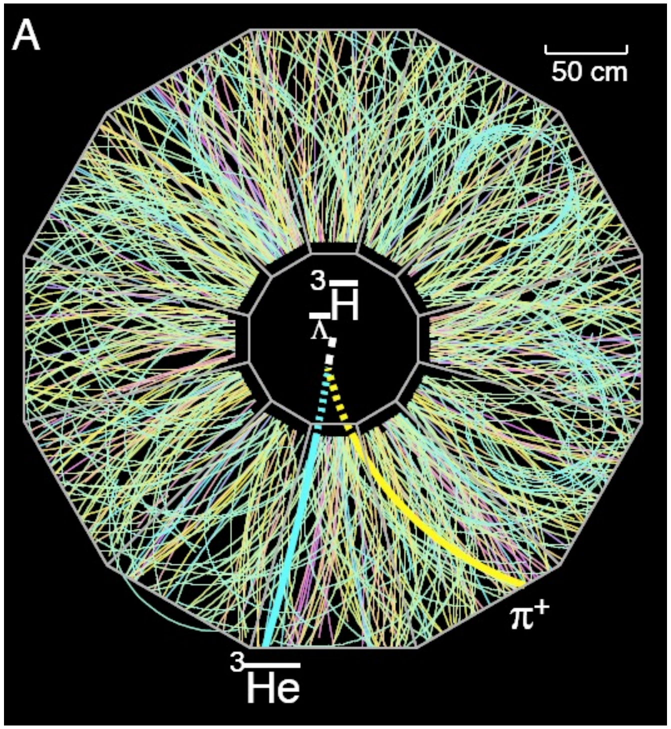


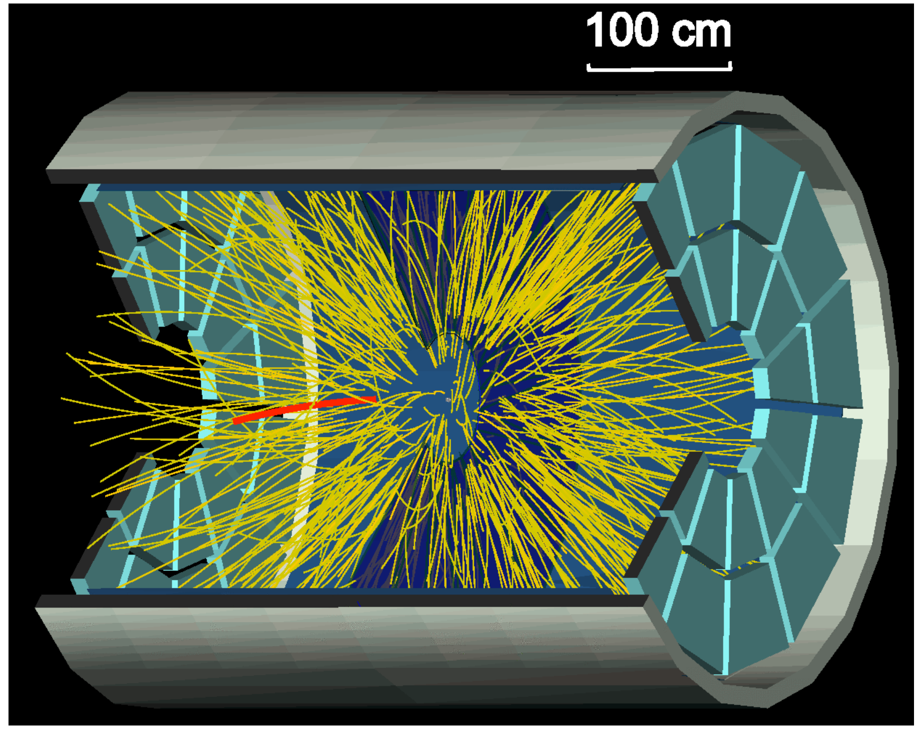
• Production rate reduces by a factor of 1.6×10^3 (1.1×10^3) for each additional antinucleon (nucleon) added to the antinucleus

Race for the Heaviest



HIC as Exotic/Antimatter Machine





Science 328, 58 (2010)

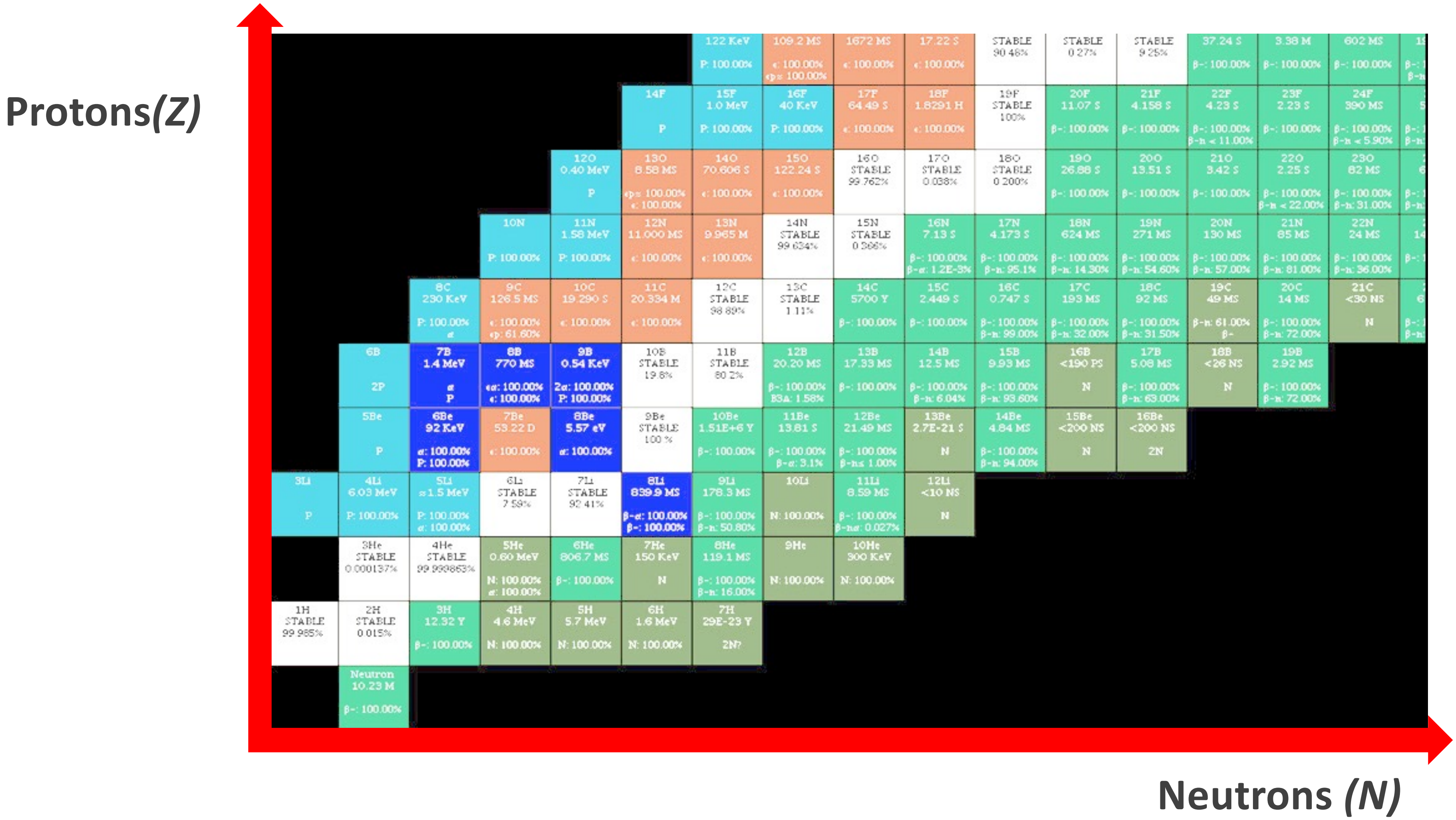
Nature 473 353 (2011)

News Coverage

Among Ta

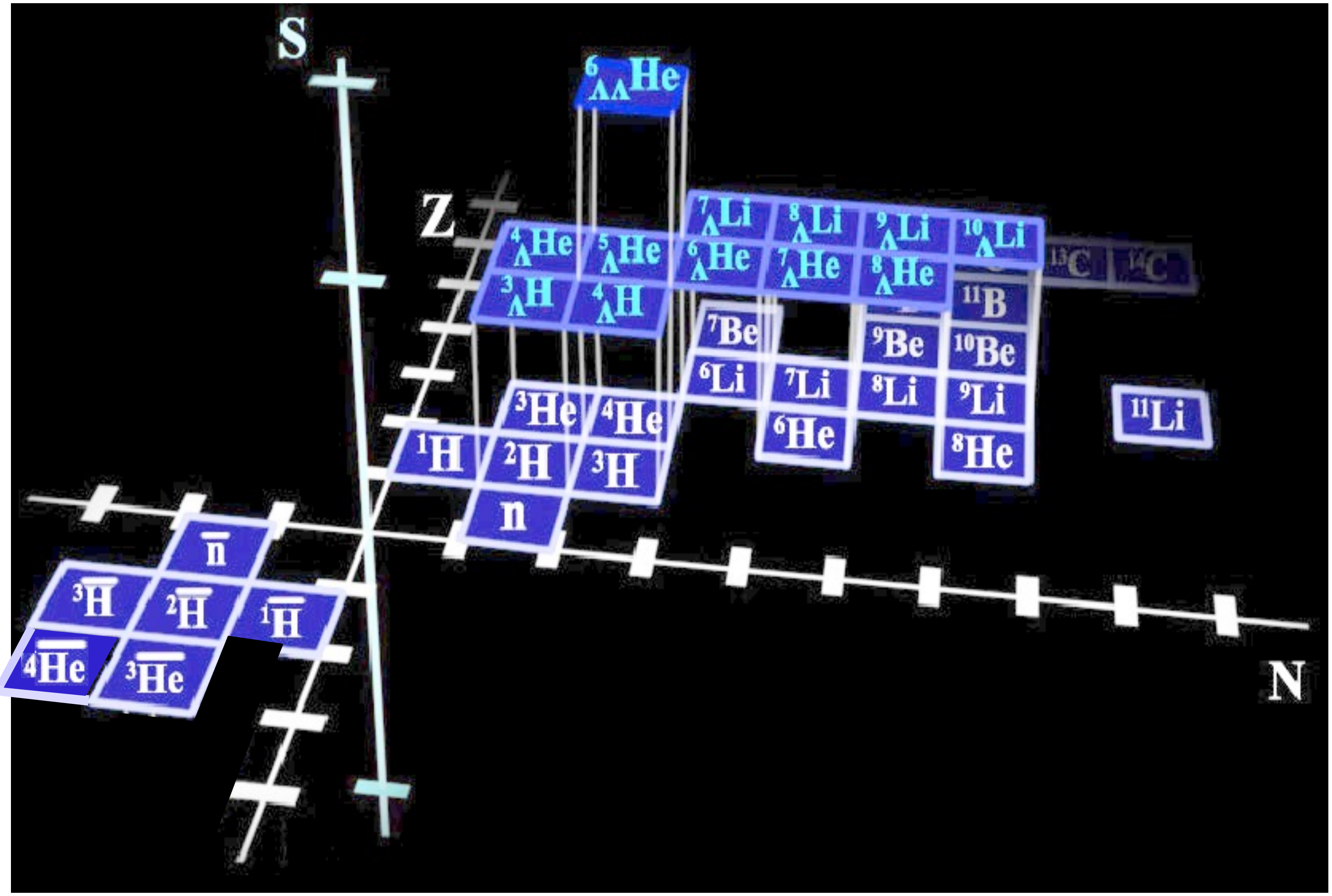
The Search Continues

3-D Chart of the Nuclides



Antinuclei ⇒ extend chart to negative Z and negative N
Hypernuclei ⇒ add 3rd axis for strangeness S
Antihypernuclei ⇒ S axis also flips sign

3-D Chart of the Nuclides



Antinuclei ⇒ extend chart to negative Z and negative N
Hypernuclei ⇒ add 3rd axis for strangeness S
Antihypernuclei ⇒ S axis also flips sign

Implications

•**Proved that anti-**α exists.

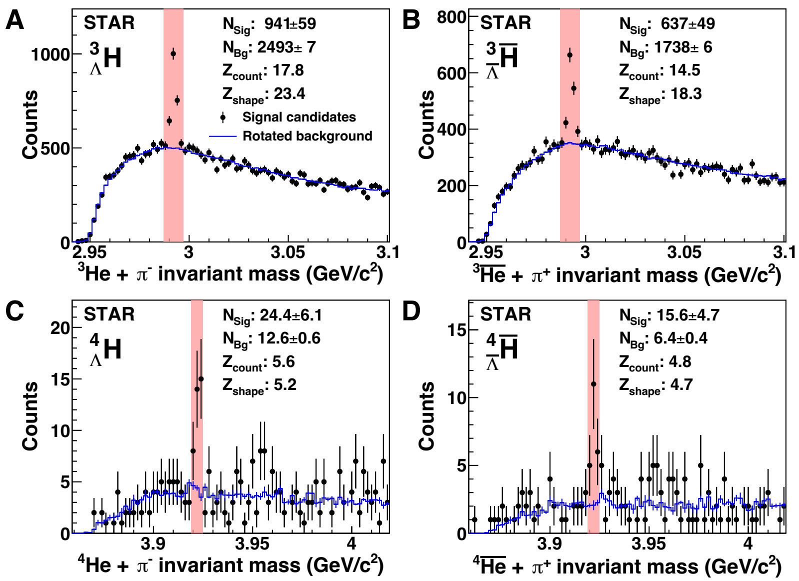
•**Provides the point of reference for various searches for new phenomena in the cosmos.**

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

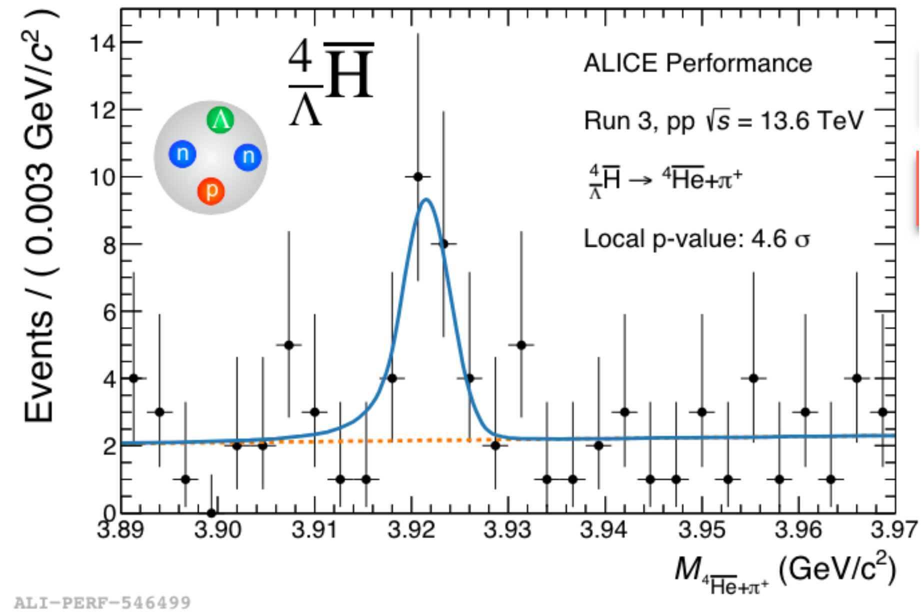
If anti-α in the cosmos were from coalescence, the ratio of anti-α/α would be 10^{-16}. With a sensitivity of 10^{-9}, even a single anti-α count seen by the AMS experiment would be a strong evidence of anti-star.

• **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)



ALICE, QM 2023