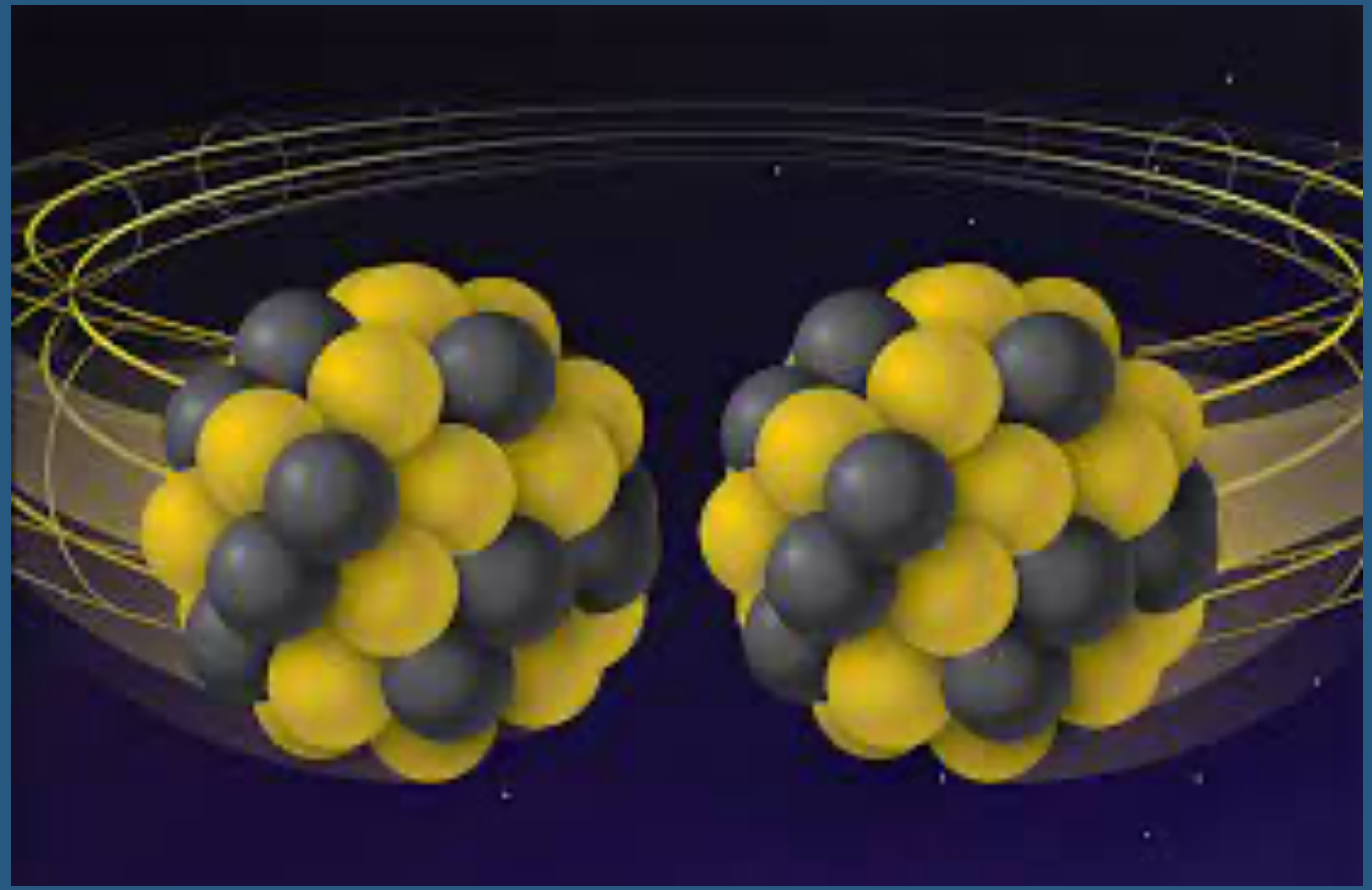


Studying hot and dense nuclear matter in heavy-ion collisions

Agnieszka Sorensen

University of Washington

INSTITUTE for NUCLEAR THEORY

July 19th, 2023

Studying hot and dense nuclear matter in heavy-ion collisions (HICs)

What is “dense”?

Number density in the cores of heavy nuclei: $n_0 \approx 0.160 \ \text{fm}^{-3}$ $\Rightarrow$ $\rho_0 = 2.5 \times 10^{17} \ \dfrac{\text{kg}}{\text{m}^3}$

(250 trillion times the density of water)

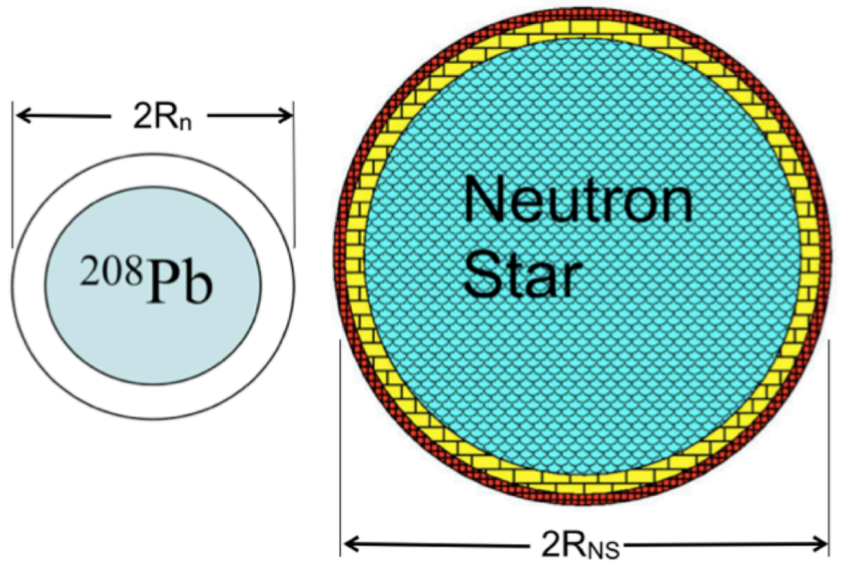
Back-of-the-envelope calculation:

proton radius: $r_p \approx 0.84 \ \text{fm}$

volume occupied by a nucleon: $V_N \approx 2.5 \ \text{fm}^3$ $\Rightarrow$ $n_N \equiv \dfrac{1}{V_N} \approx 0.4 \ \text{fm}^{-3}$

percentage of all volume occupied by hard spheres $\approx 75\,\%$ $\Rightarrow$ $n_{\text{max}} \equiv 0.75 \times n_N = 0.3 \ \text{fm}^{-3} \approx 2n_0$

$\Rightarrow$ there’s room to squeeze nuclei more! nucleons are not hard spheres etc.



How can we squeeze nuclear matter?

1) Gravitational force: density in neutron stars likely reaches several times n_0 (asymmetric matter)
2) Collide heavy nuclei (gold, lead, etc.) at relativistic speeds = relativistic HICs: up to several times n_0

Studying hot and dense nuclear matter in heavy-ion collisions (HICs)

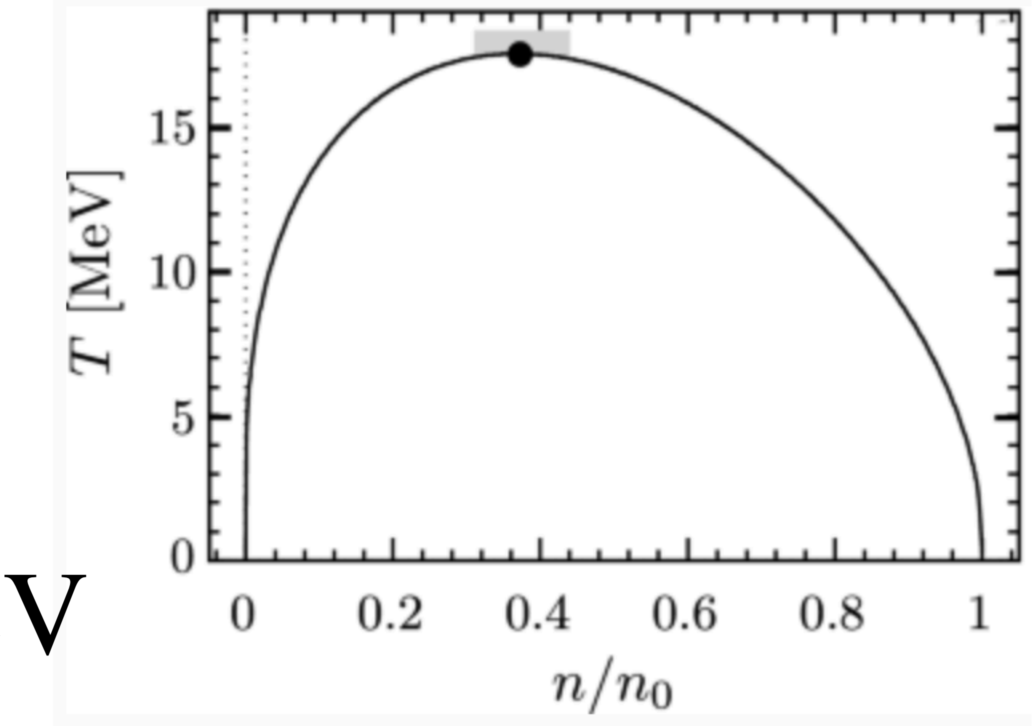
What is "hot"? Always depends on what you're comparing to.

(surface of the Sun: ~5,800 K)

"Cold" neutron stars on average have a temperature of about $\approx 2 \times 10^6$ K ≈ 170 eV $\approx 2 \times 10^{-4}$ MeV

Neutron mass: $m_N \approx 938$ MeV Kinetic energy at n_0: $E\Big|_{n_B=n_0} \approx 994$ MeV $\Rightarrow$ $\mathrm{E_{kin}} \approx 56$ MeV

$\Rightarrow$ the available thermal energy is comparatively small $\Rightarrow$ one can just as well say that $T = 0$



Binding energy of nuclear matter at saturation density: $B_0 \approx -16$ MeV

At $T = 0$, coexistence with vacuum ~ a nuclear liquid drop in empty space

At higher temperatures, some of the nuclear matter coexists with nucleon gas

Critical temperature of the nuclear liquid-gas phase transition: $T_c \in (15,\ 20)$ MeV

$\Rightarrow$ thermal energy is comparable to relevant energies $\Rightarrow$ for nuclear matter, tens of MeV matter

How can we heat nuclear matter? Squeeze it!

1) Neutron star mergers reach up to ≈ 50 to 100 MeV (asymmetric matter)

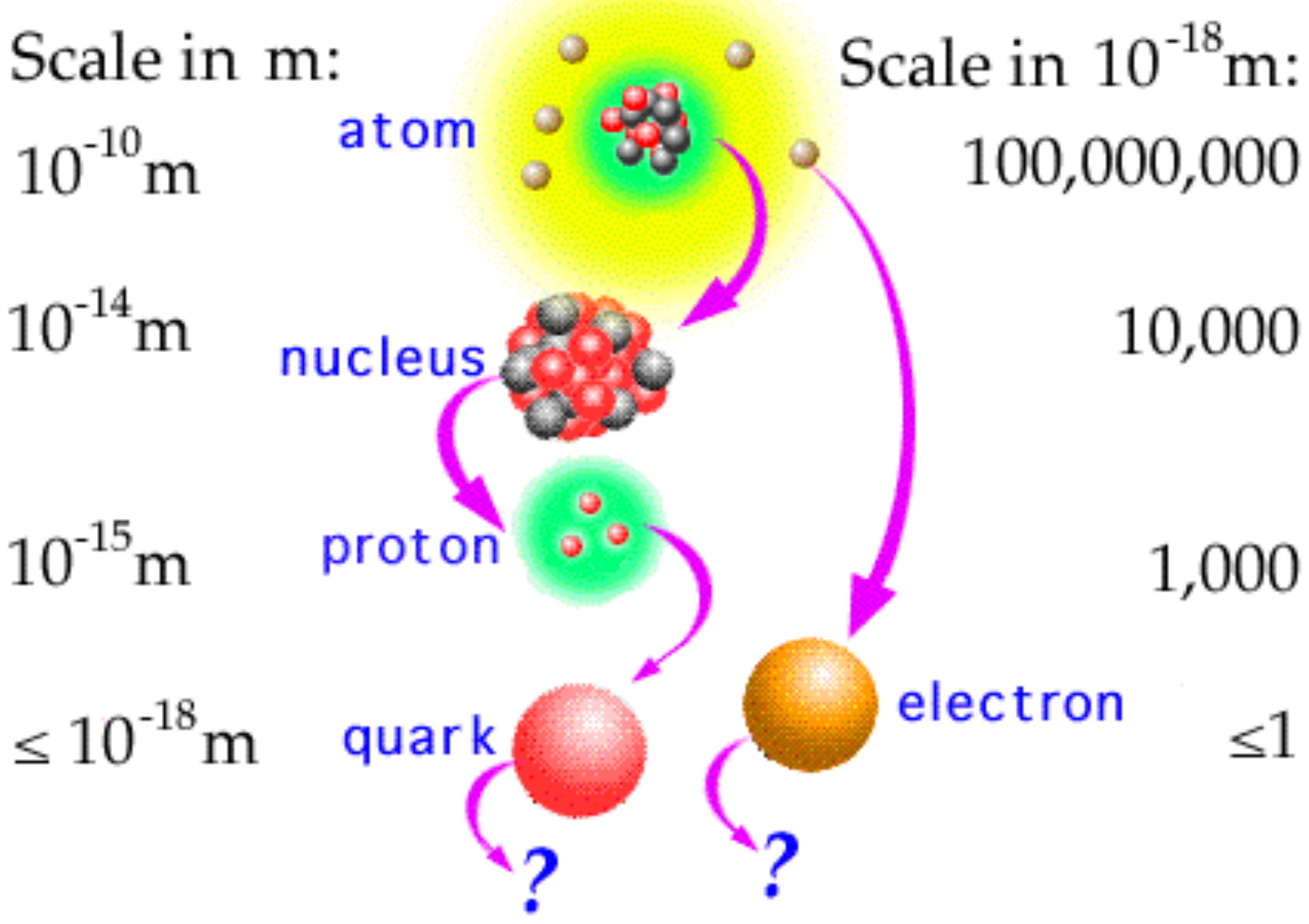
2) Collide heavy nuclei (gold, lead, etc.) at relativistic speeds = relativistic HICs: up to *hundreds* of MeV!

The key mission of RHIC (HICs from the early 2000s): QGP

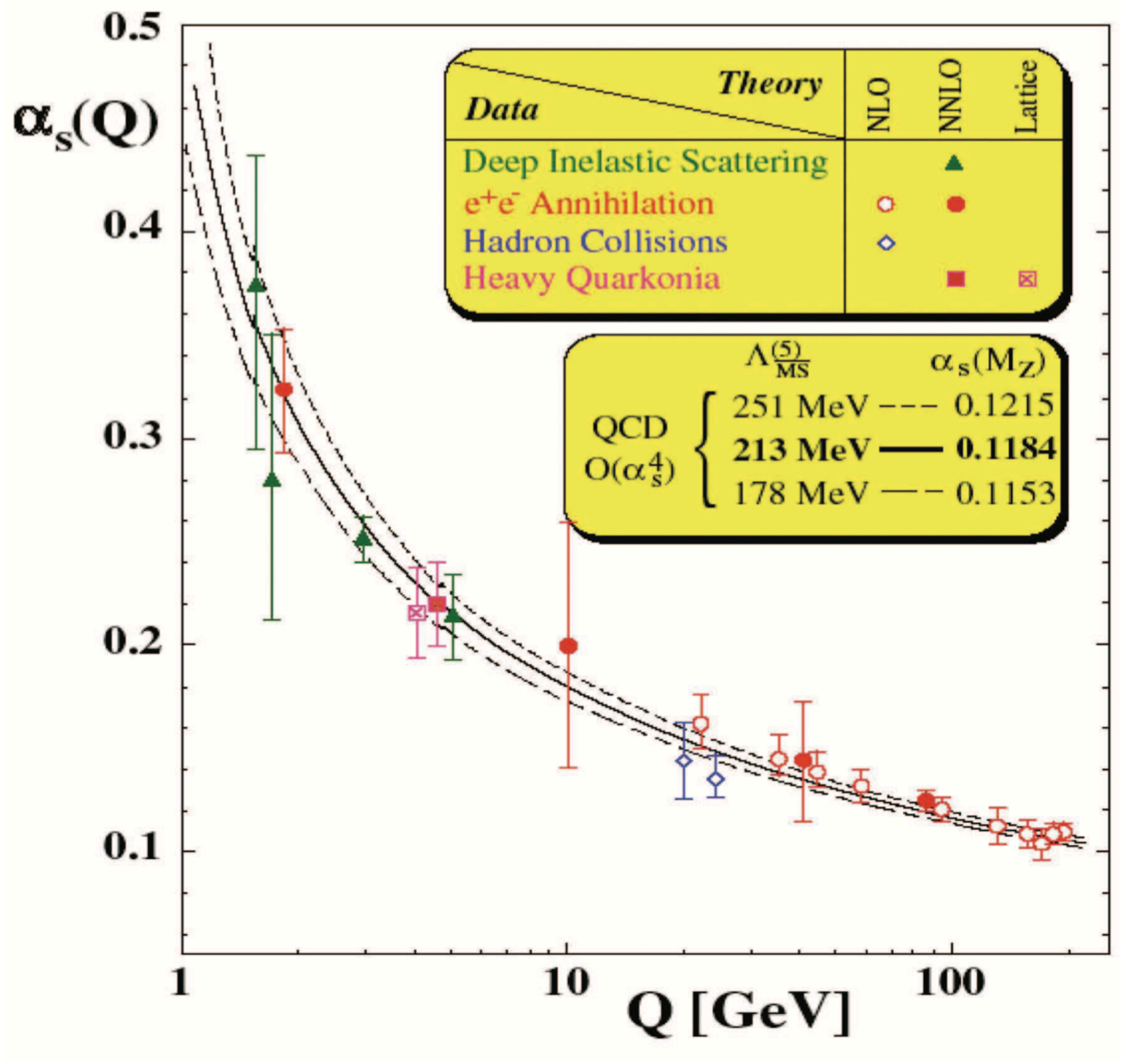
What happens to nuclei when they are heated up to *hundreds* of MeV?

We know that at $T \gtrsim 20$ MeV, nucleons are a homogeneous fluid.
We also know that nucleons are made out of quarks and gluons.

At what temperature = energy scale does it start to matter that nucleons are made out of quarks and gluons?



The QCD coupling constant changes with energy:



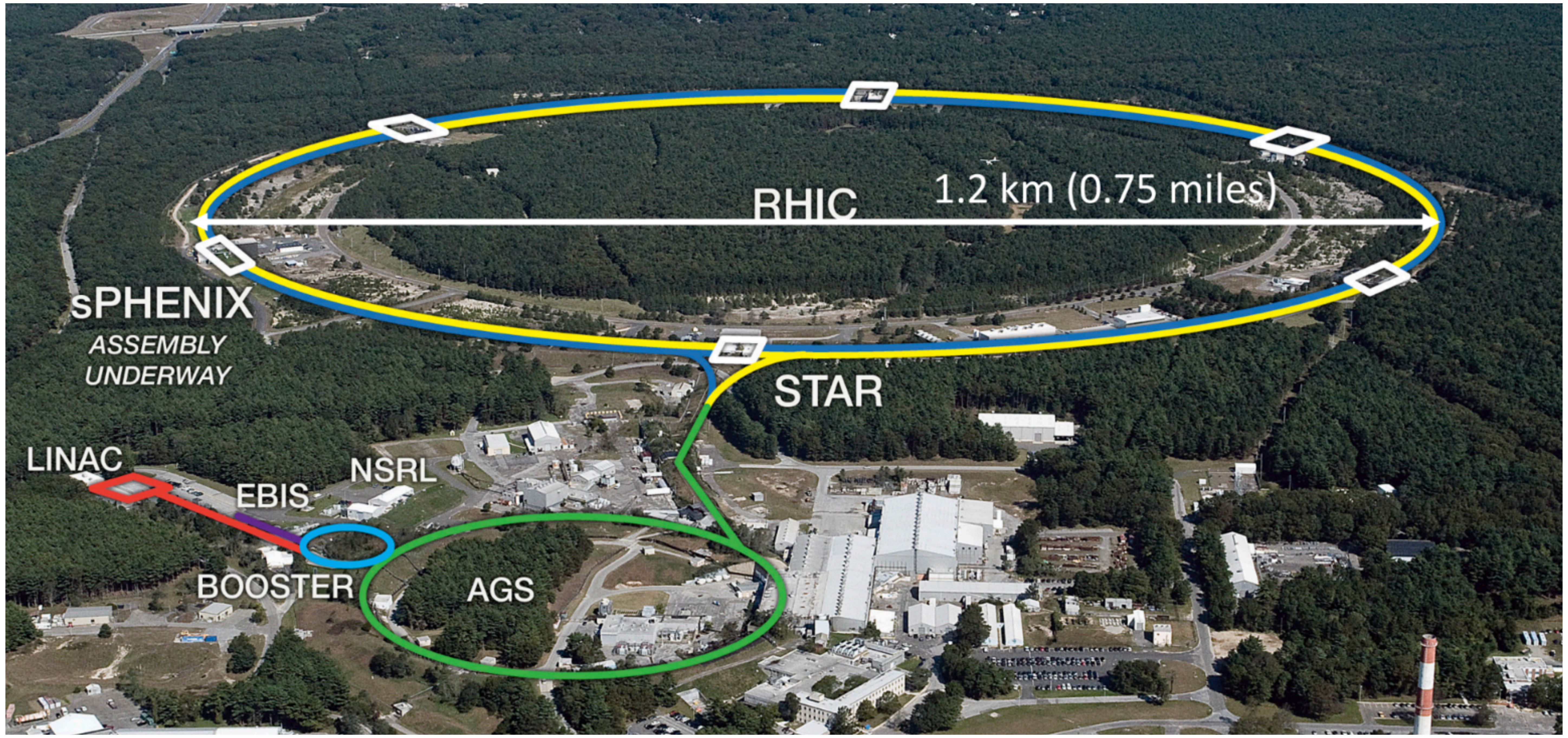
F. Wilczek, “Asymptotic Freedom: From Paradox to Paradigm”,
https://frankwilczek.com/Wilczek_Easy_Pieces/373_Asymptotic_Freedom.pdf

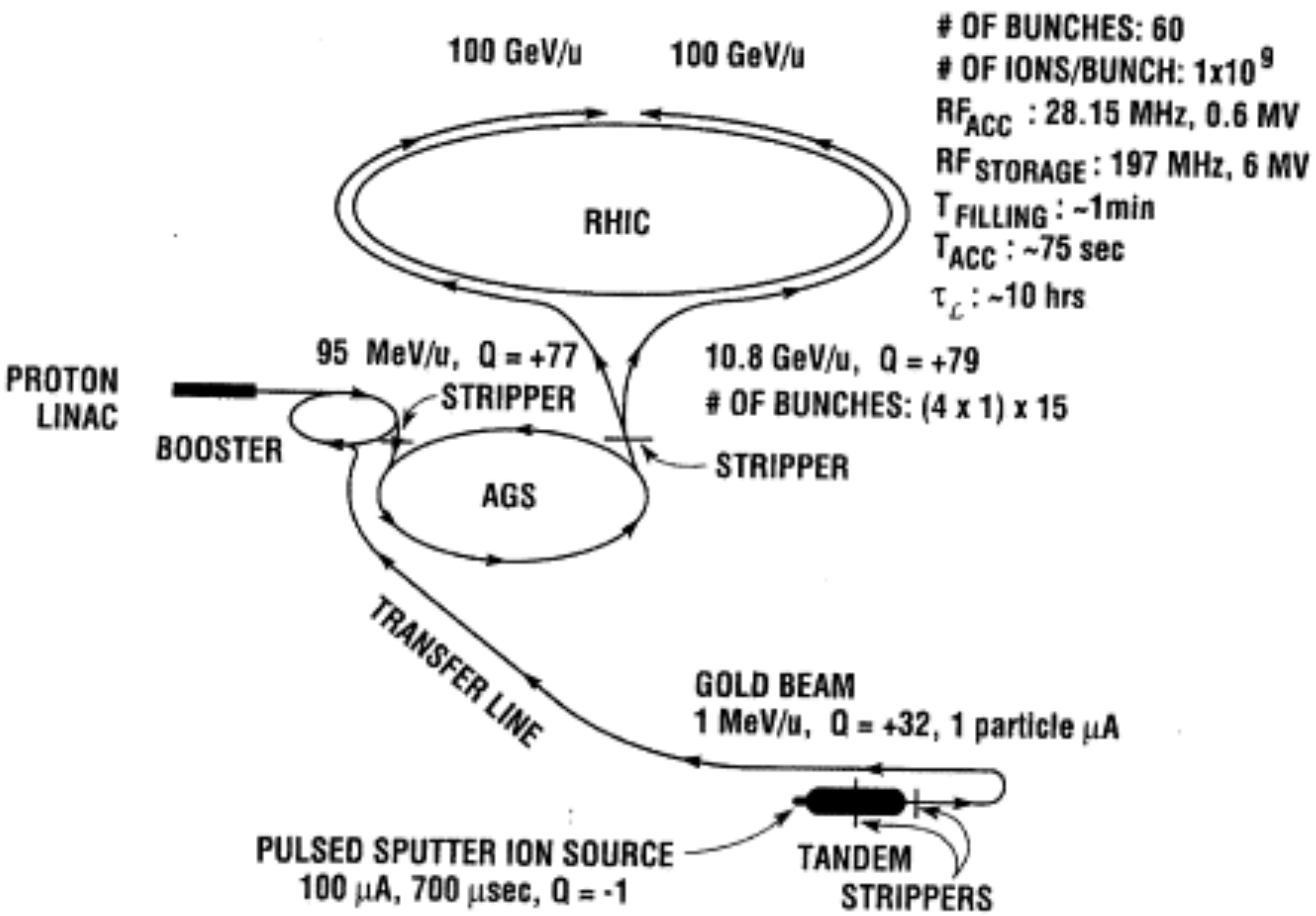
Energy where non-perturbative effects (i.e., confinement) start/stop being important:

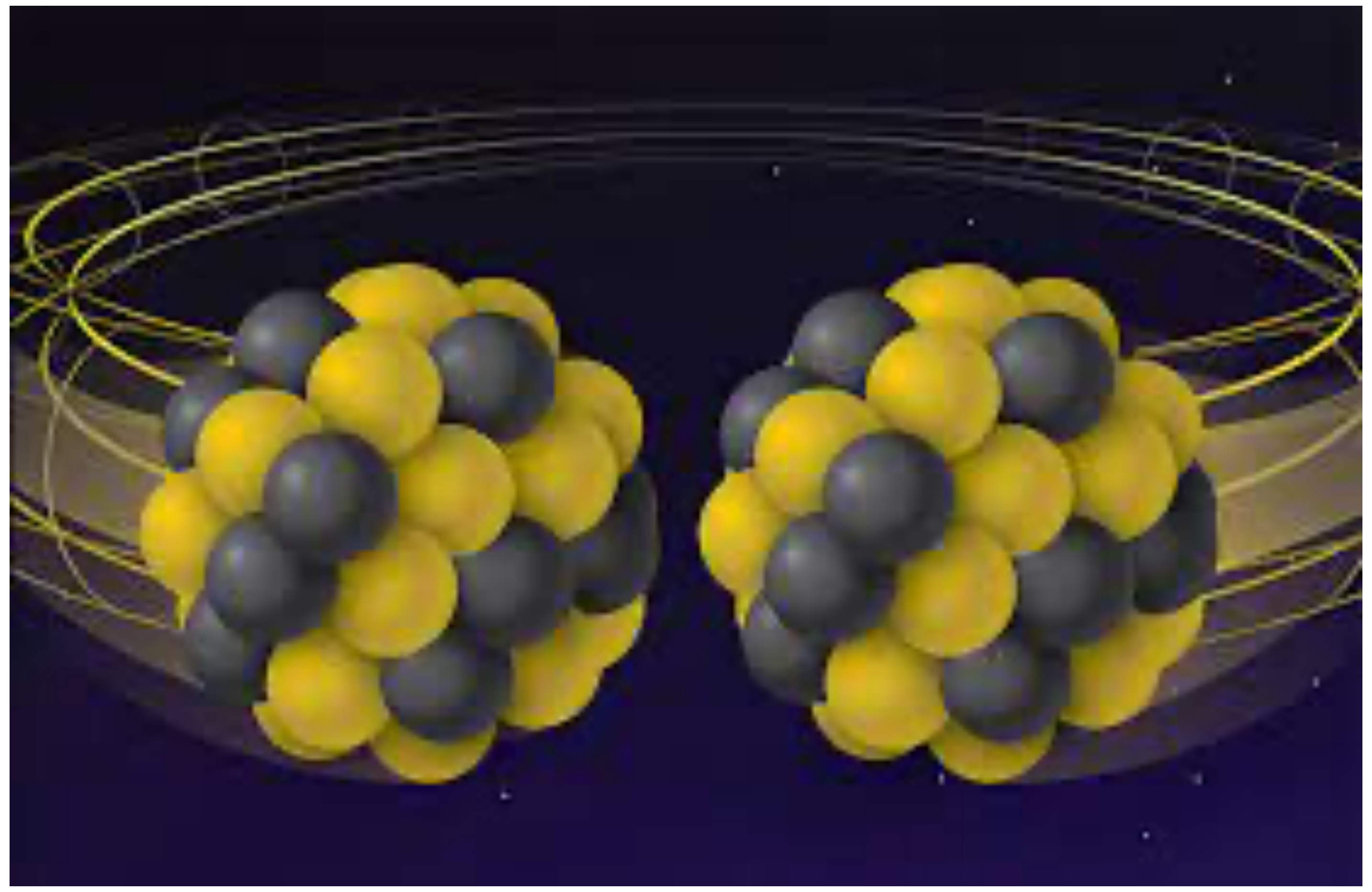
$\Lambda_{\mathrm{QCD}} \approx 200$ MeV

Since HICs lead to high temperatures, can one probe free quarks and gluons in HICs?

RHIC = Relativistic Heavy Ion Collider, Brookhaven National Lab, NY

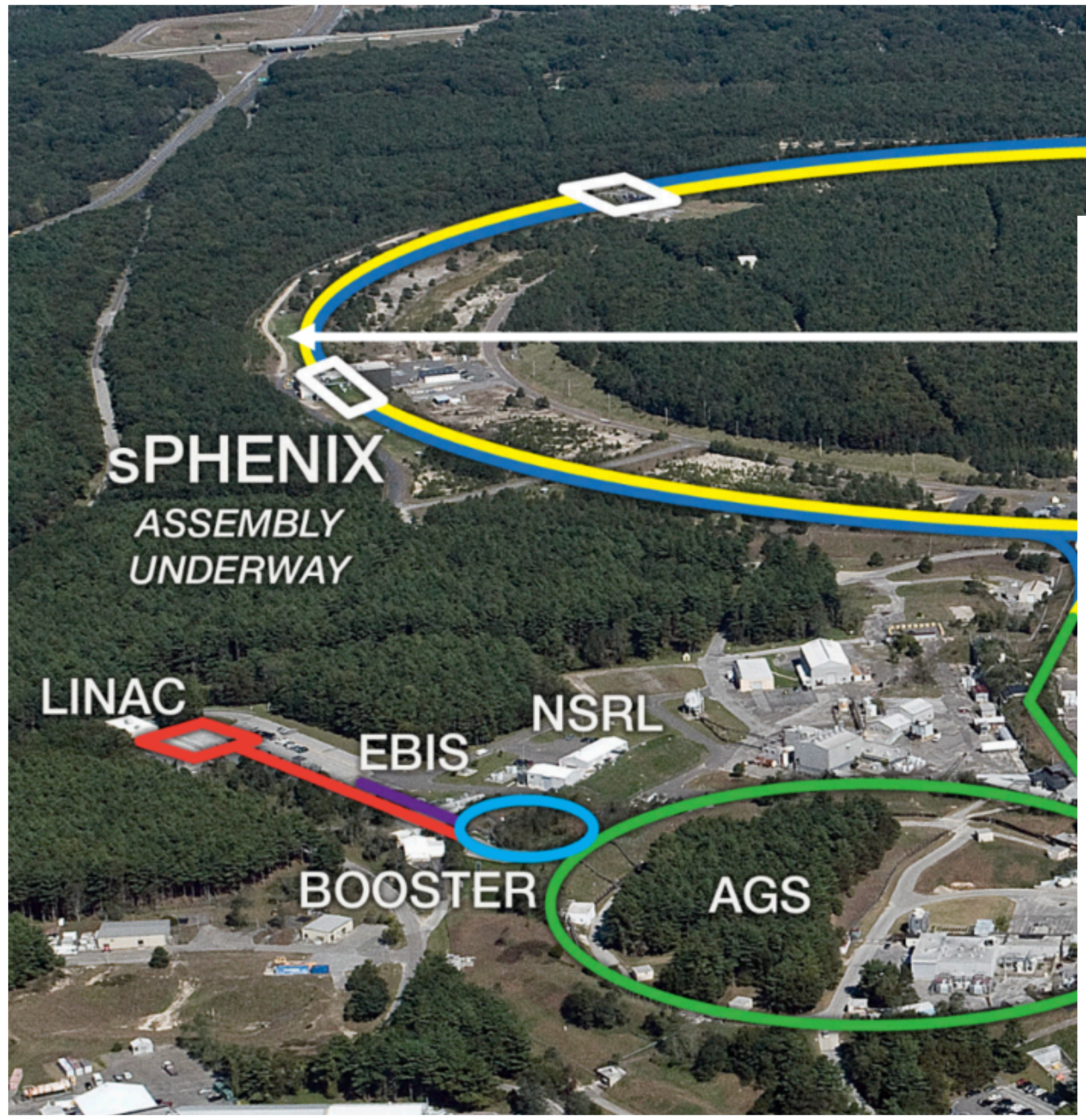


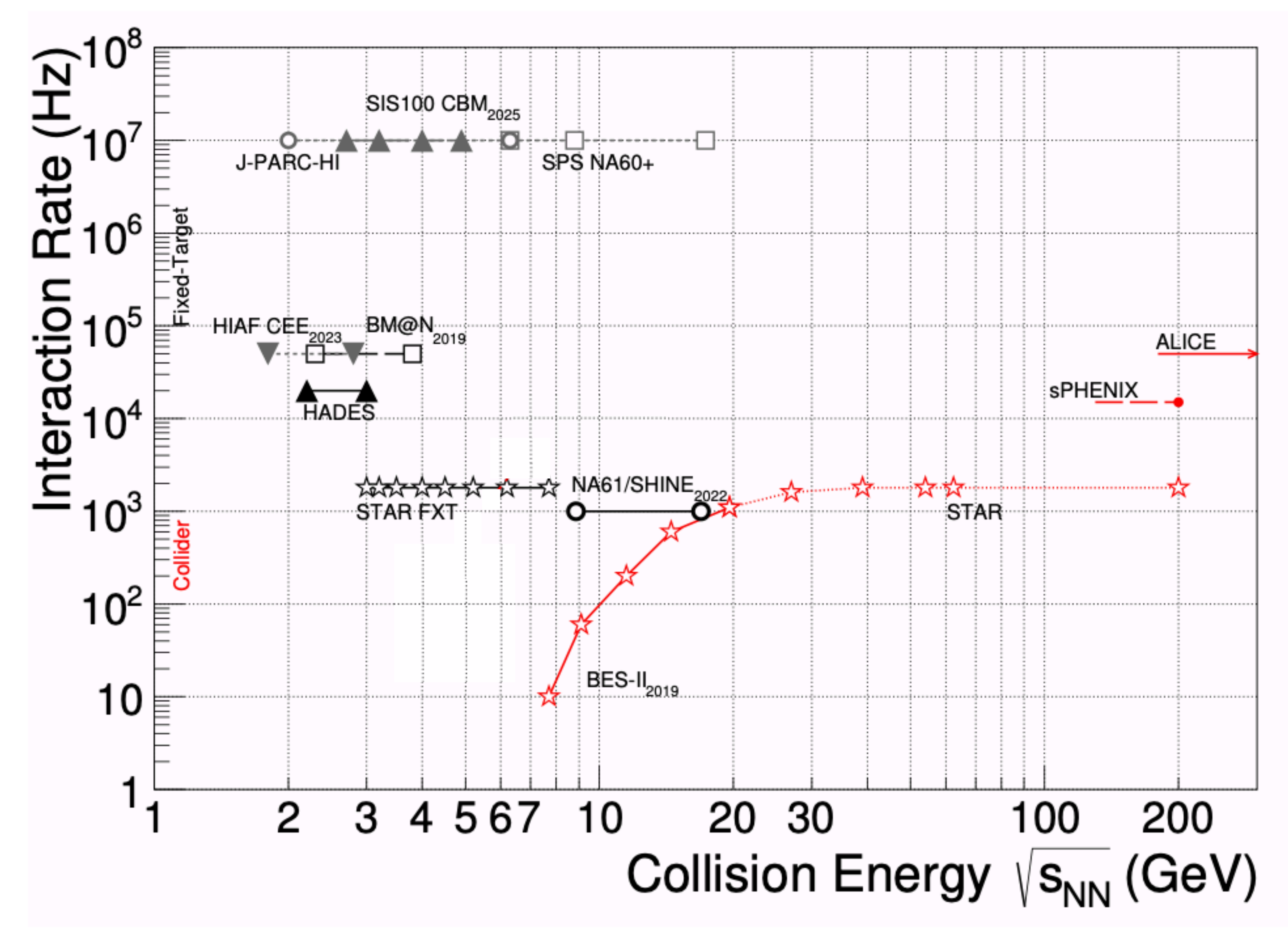


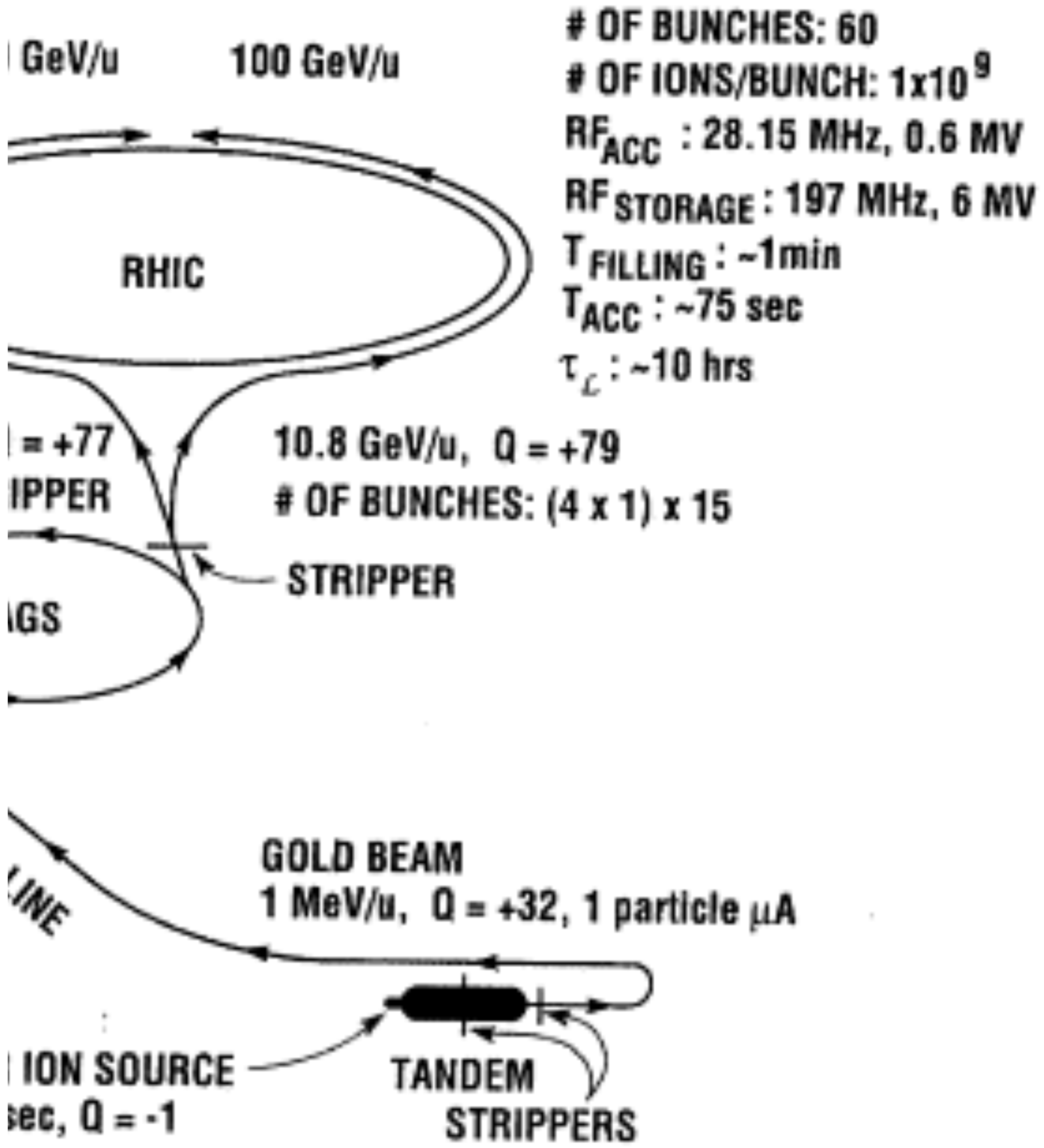


$$\sqrt{s_{\mathrm{NN}}} = 200\ \mathrm{GeV} \quad \Rightarrow \quad E_{\mathrm{lab}} \approx 21{,}000\ \mathrm{GeV}$$

RHIC = Relativistic Heavy Ion Collider, Brookhaven National Lab, NY

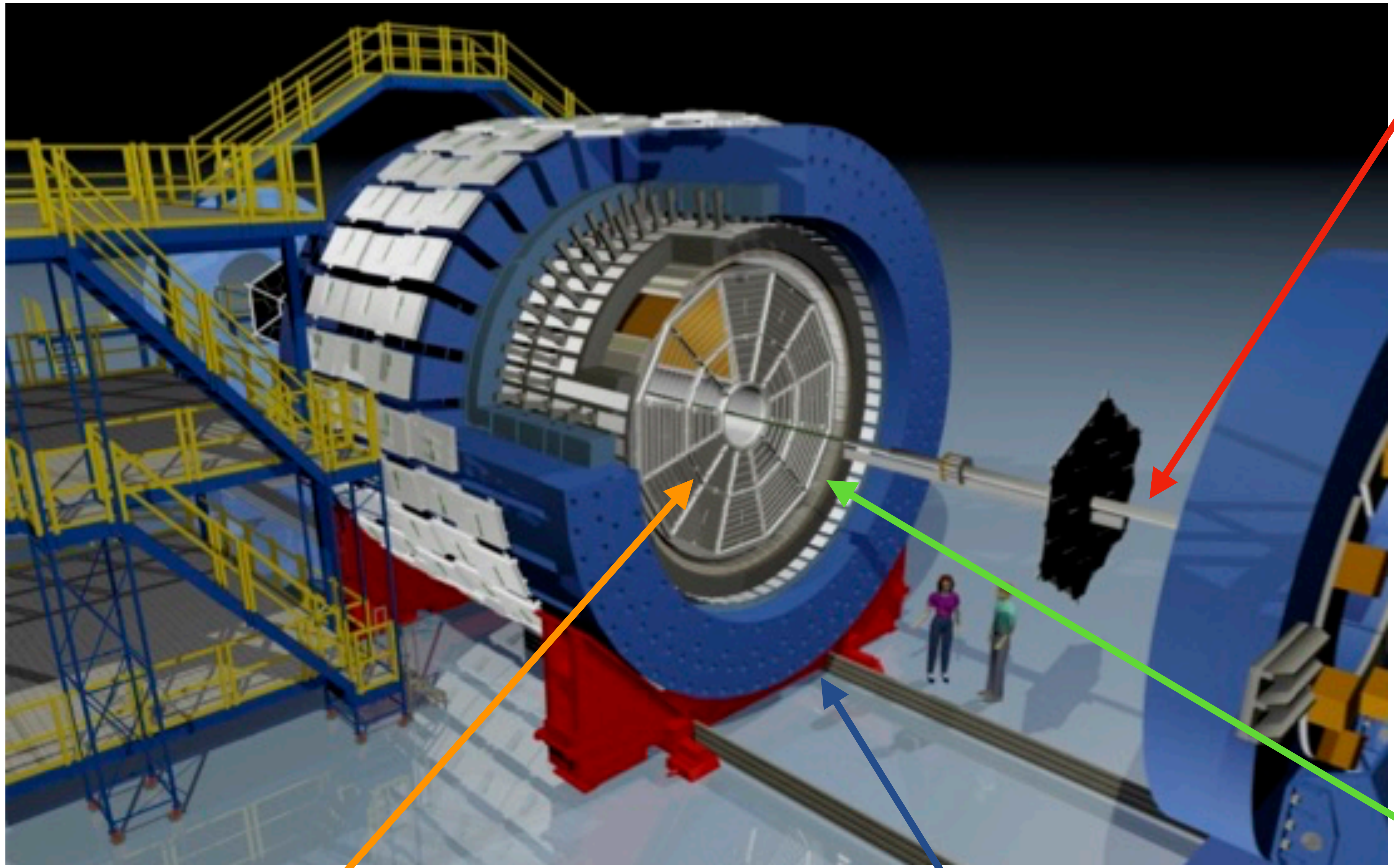




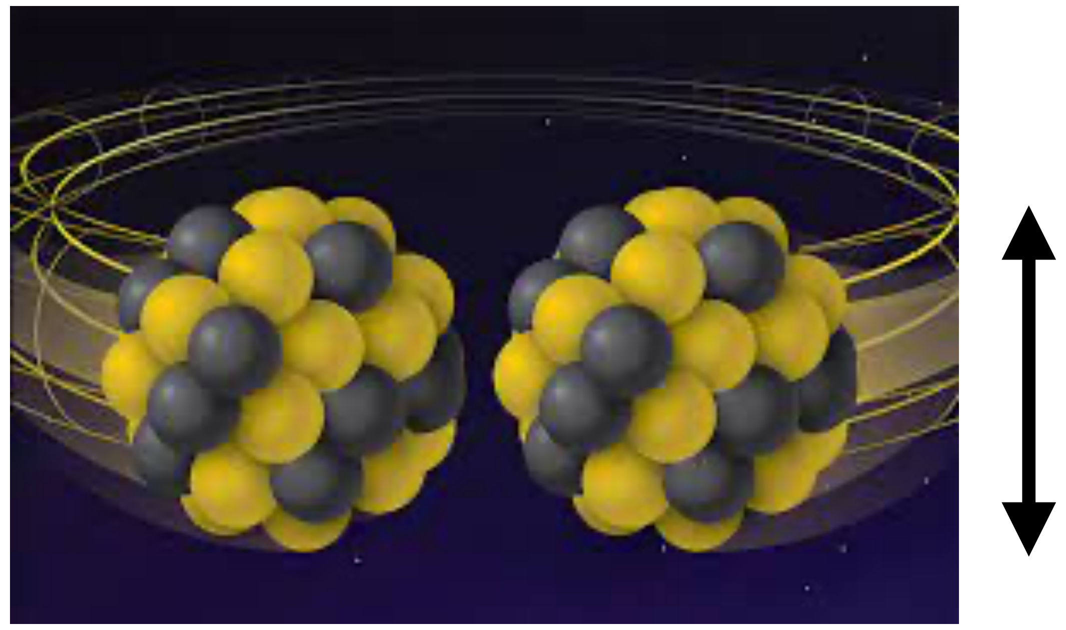


$$\sqrt{s_{\mathrm{NN}}} = 200\ \mathrm{GeV} \quad \Rightarrow \quad E_{\mathrm{lab}} \approx 21{,}000\ \mathrm{GeV}$$

STAR detector



beam pipe: radius ~ 3 cm (diameter of a Coke can)



Au: ~15 fm

collision region: ~15 fm
collision duration: ~100 fm/c
[strongly depends on energy]
size when interactions cease: ~100 fm

time projection chamber (TPC):
measures paths of particles
inner radius ~ 0.5 m
outer radius ~ 1.9 m
length ~ 4 m

magnet: curves paths of charged particles

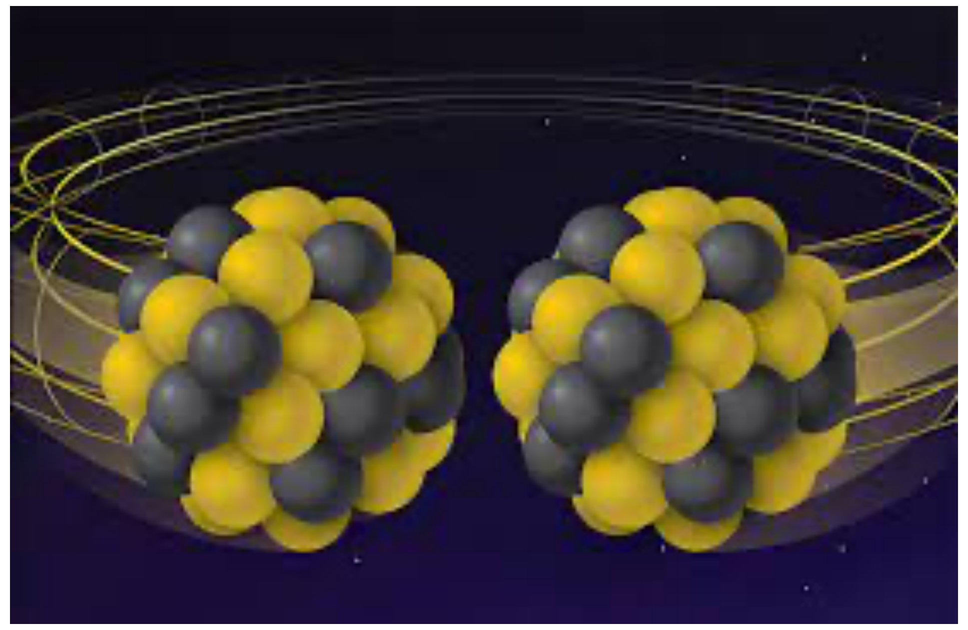
time of flight (TOF):
measures velocities of particles

particle momenta → particle mass = particle species identification (ID)

STAR detector

beam pipe: radius ~ 3 cm (diameter of a Coke can)

Detectors only measure *final momenta*;
particle *positions* during collisions unknown



Au: ~15 fm

collision region: ~15 fm

collision duration: ~100 fm/*c*
[strongly depends on energy]

size when interactions cease: ~100 fm

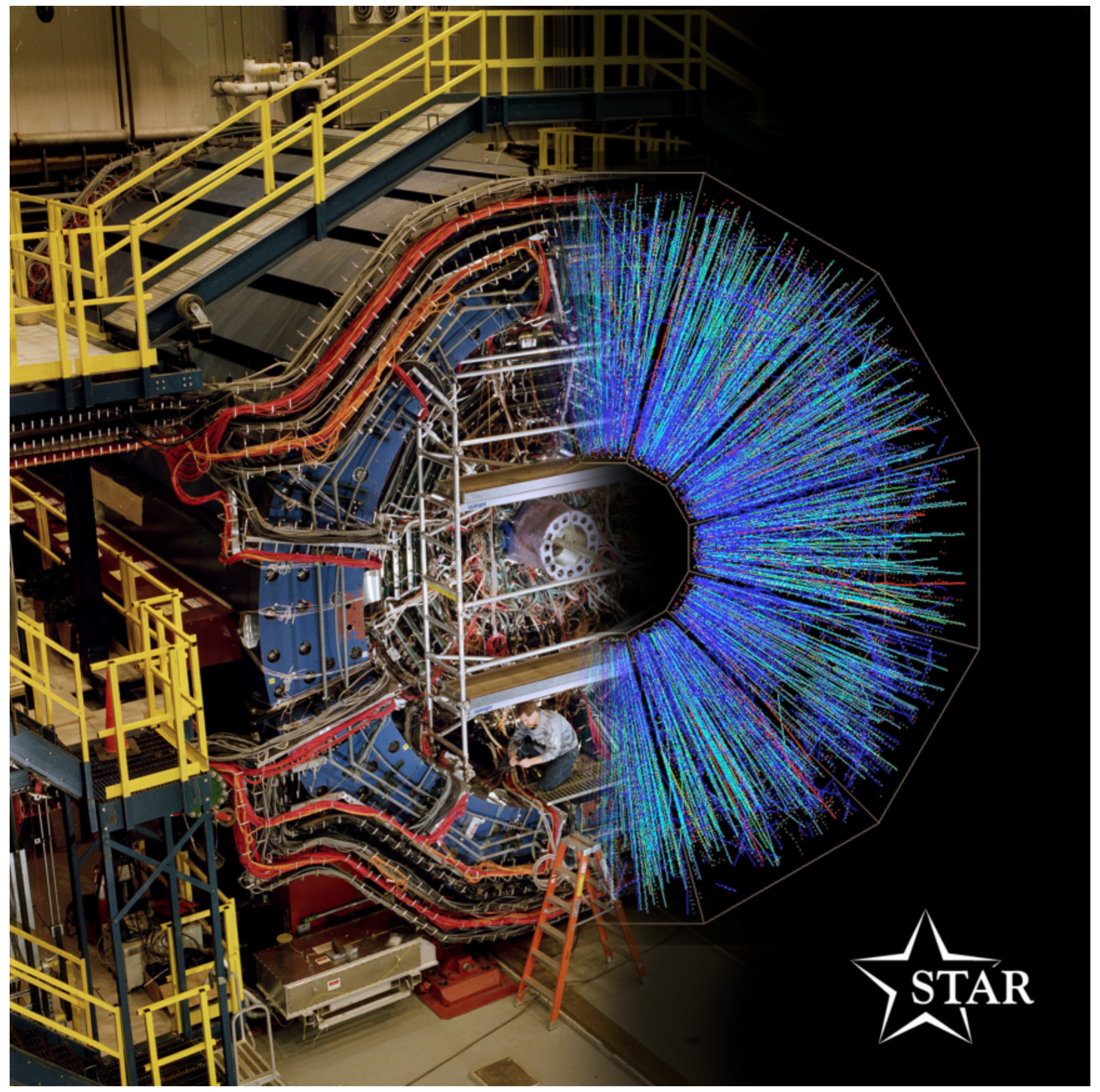
time projection chamber (TPC):
measures paths of particles
inner radius ~ 0.5 m
outer radius ~ 1.9 m
length ~ 4 m

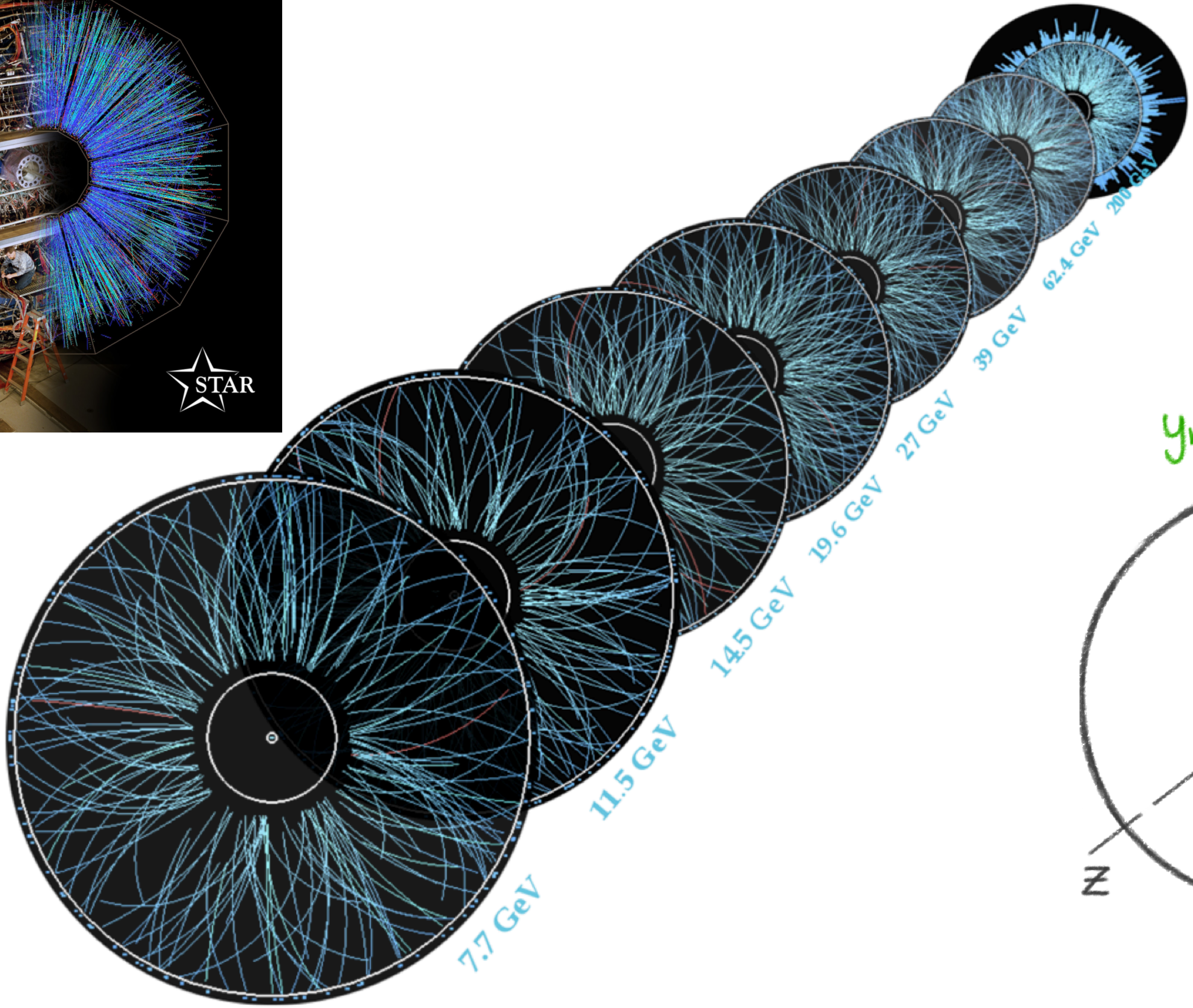
magnet: curves paths
of charged particles

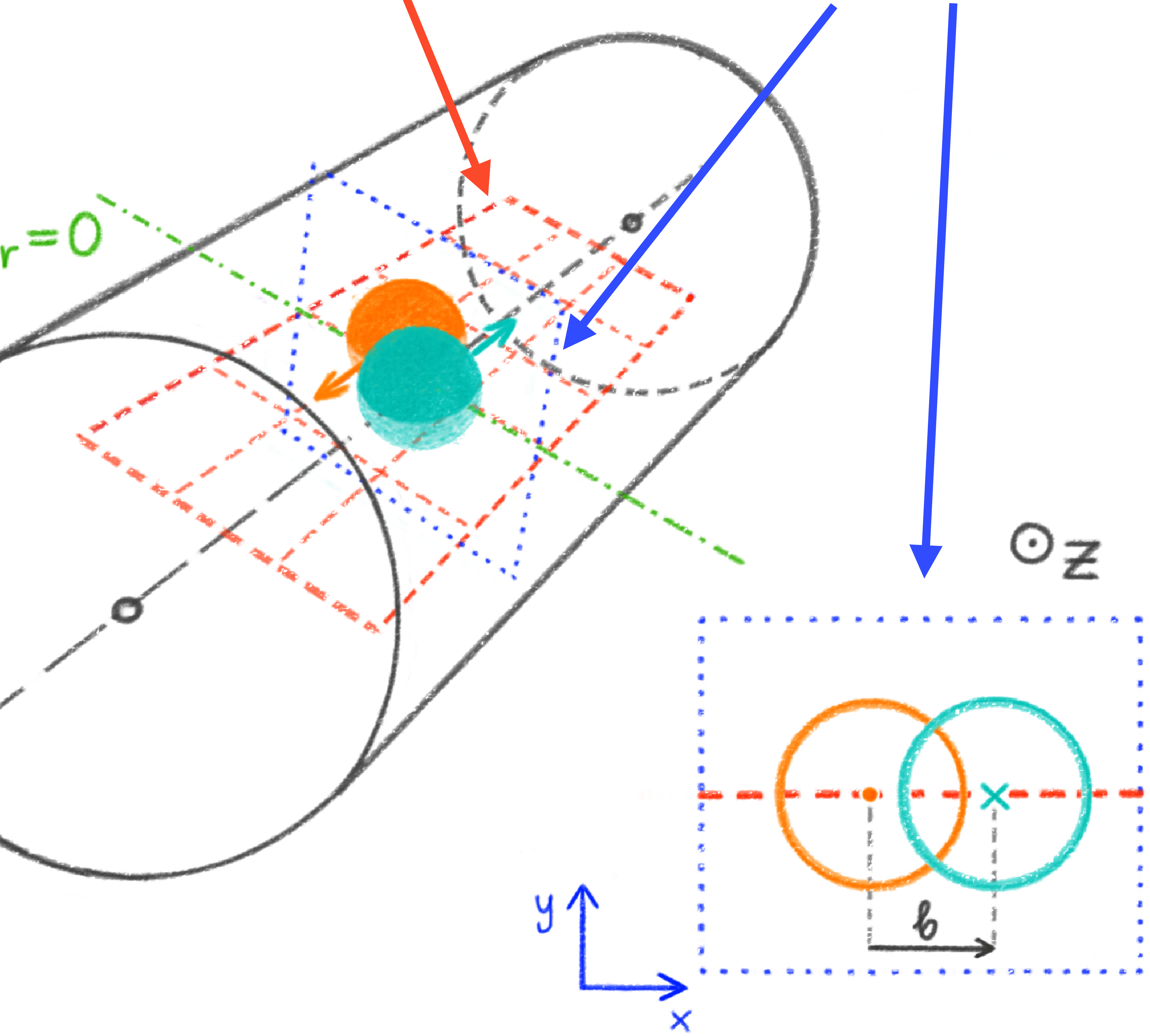
time of flight (TOF):
measures velocities of particles

particle momenta → particle mass = particle species identification (ID)

STAR event display







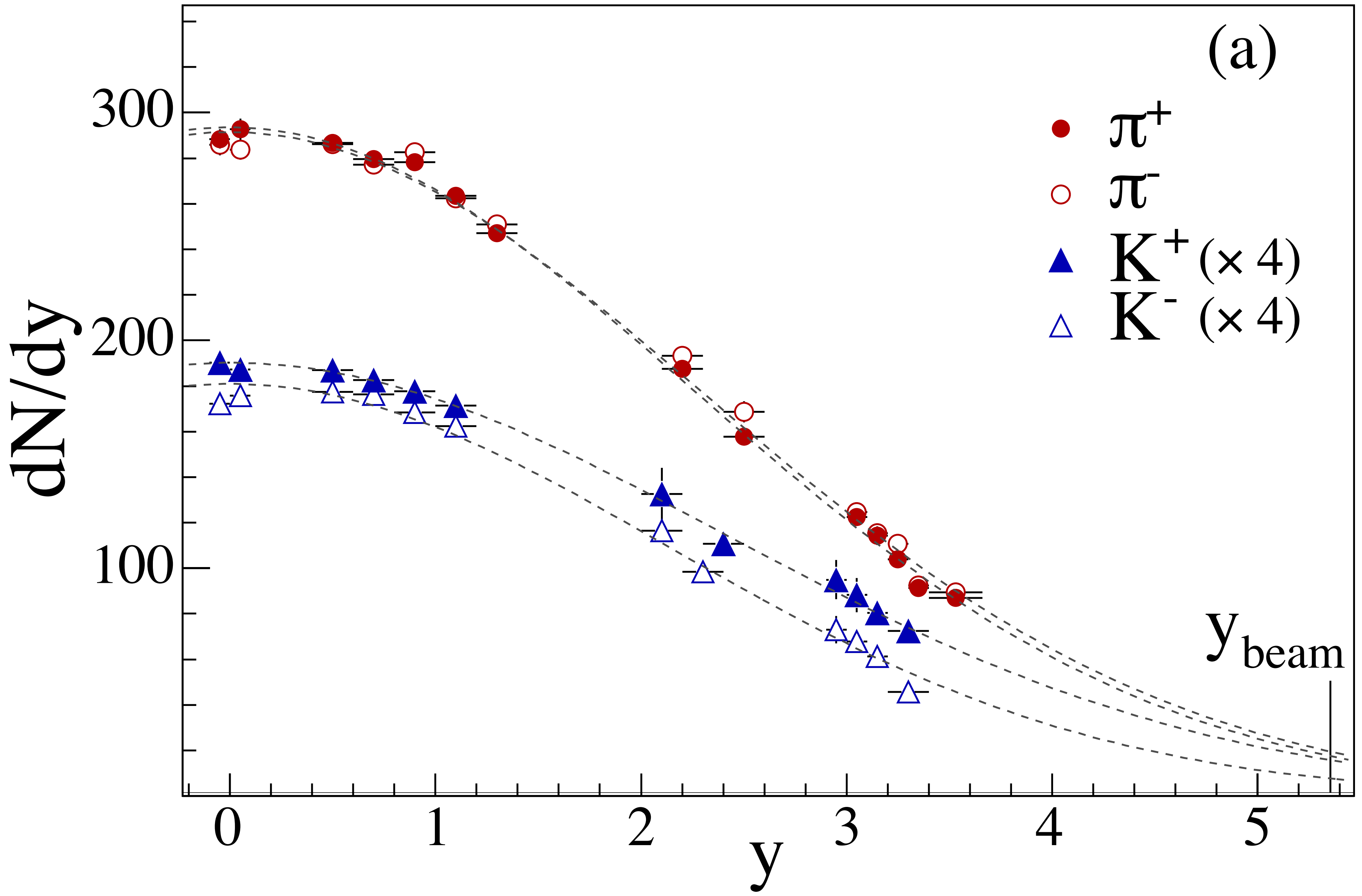
reaction plane

transverse plane

HIC observables

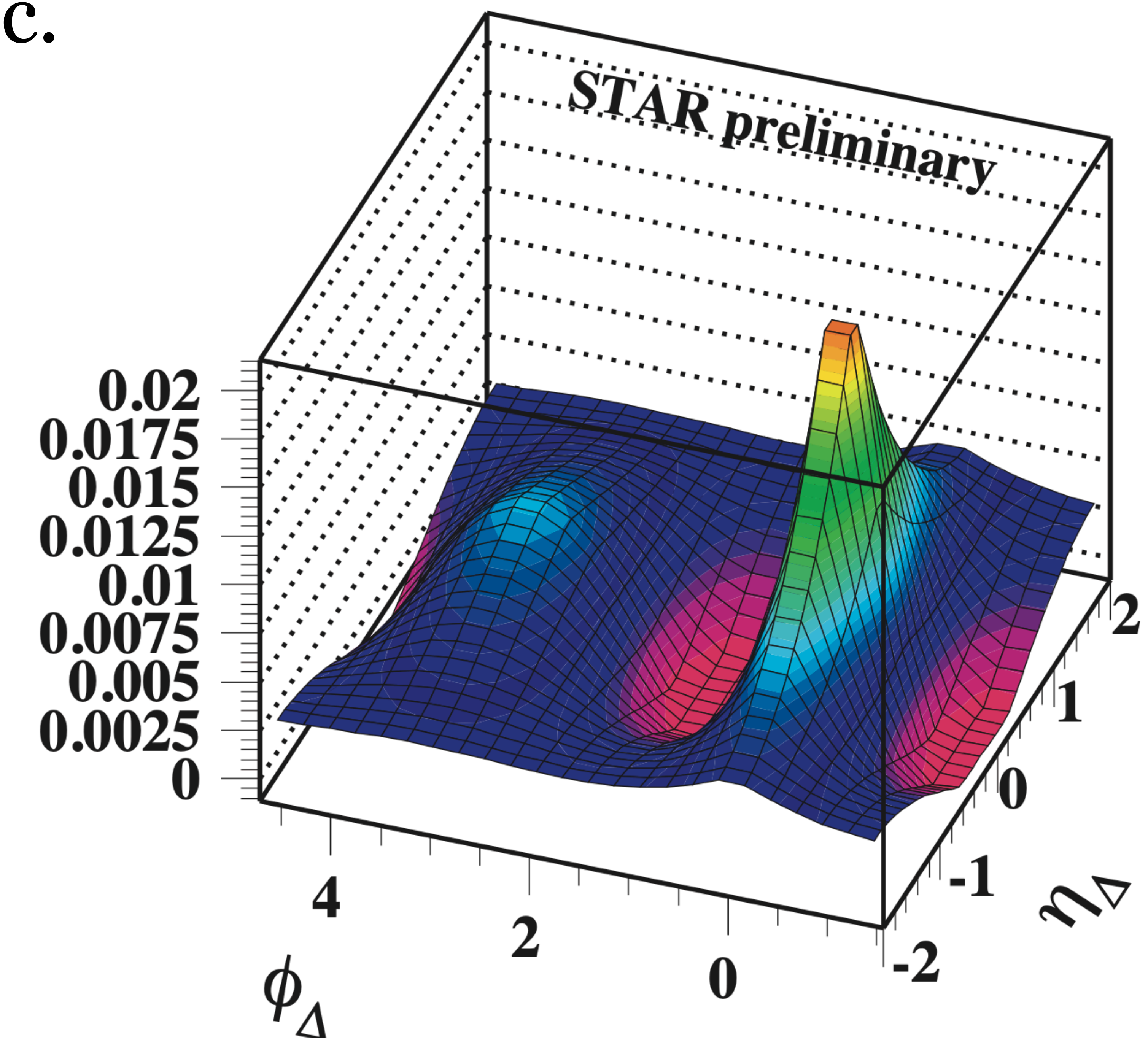
What can we measure? Particle species and momenta:

- single-particle observable: particle yields
  - as a function of rapidity y
  - as a function of transverse momentum p_T
  - etc.



BRAHMS Collaboration, "Charged meson rapidity distributions in central Au+Au collisions at s(NN)**(1/2) = 200GeV", Phys. Rev. Lett. 94, 162301 (2005) arXiv:nucl-ex/0403050

- many-particle observables: e.g., two-particle correlations,
  - as a function of rapidity y
  - as a function of transverse momentum p_T
  - etc.

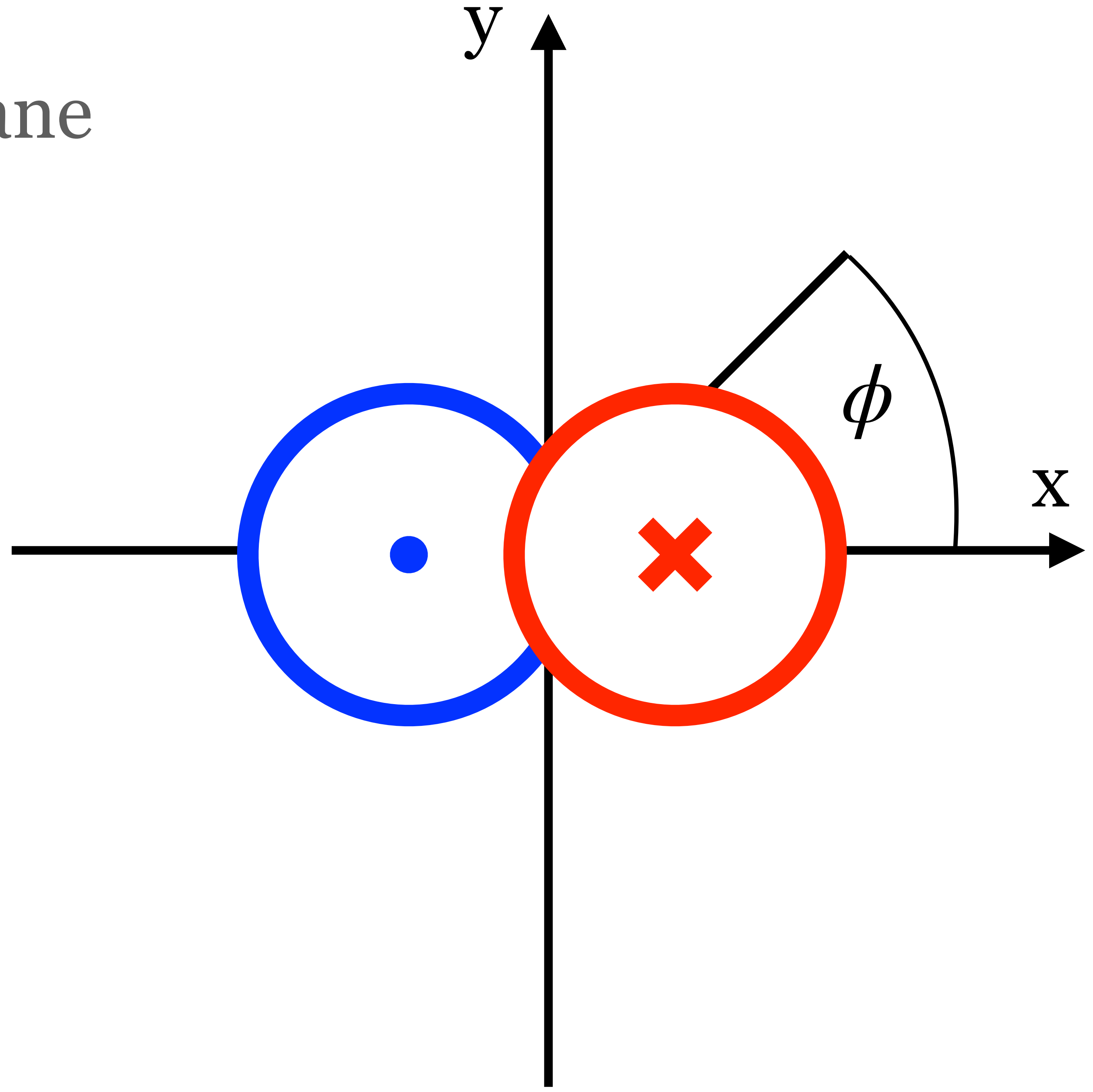


P. Sorensen, "Searching for Superhorizon Fluctuations in Heavy-Ion Collisions", 24th Winter Workshop on Nuclear Dynamics, arXiv:0808.0503

Flow observables in HICs

Flow $v_n \equiv \langle \cos(n\phi) \rangle$

transverse plane



$\cos(\phi) = 0$
$\cos(2\phi) = -1$

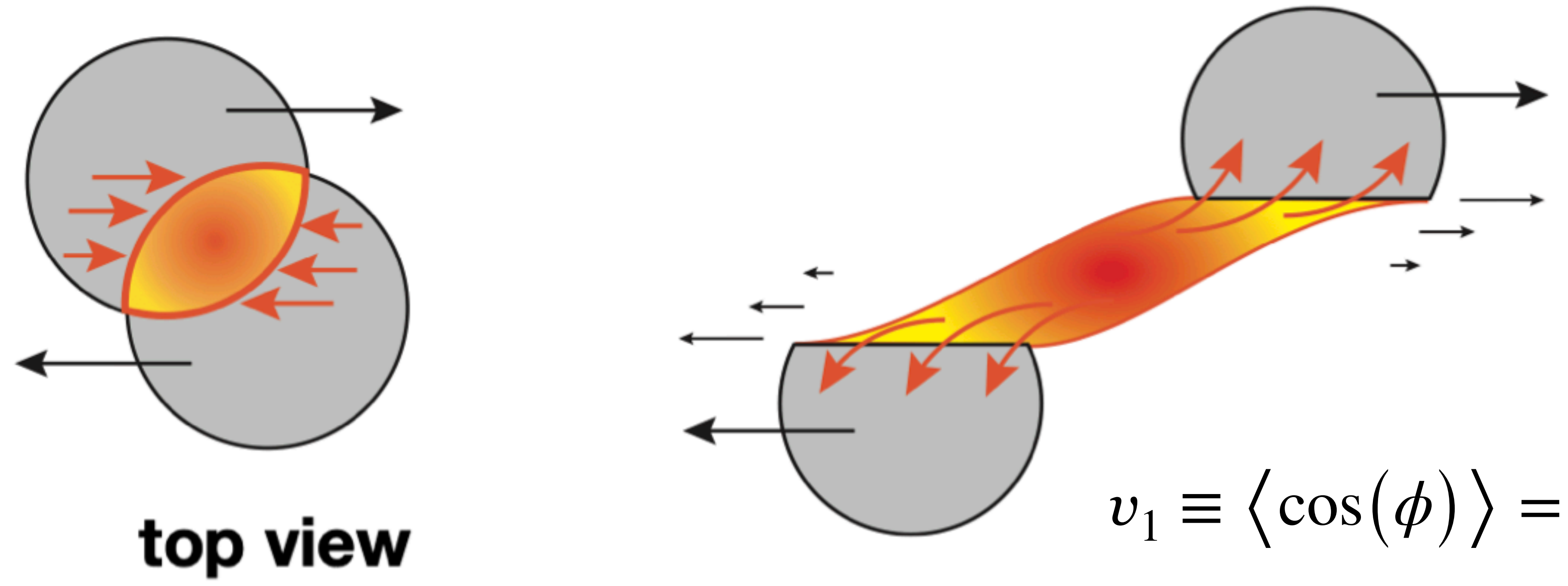
$\cos(\phi) = -1$
$\cos(2\phi) = +1$

$\cos(\phi) = +1$
$\cos(2\phi) = +1$

$\cos(\phi) = 0$
$\cos(2\phi) = -1$

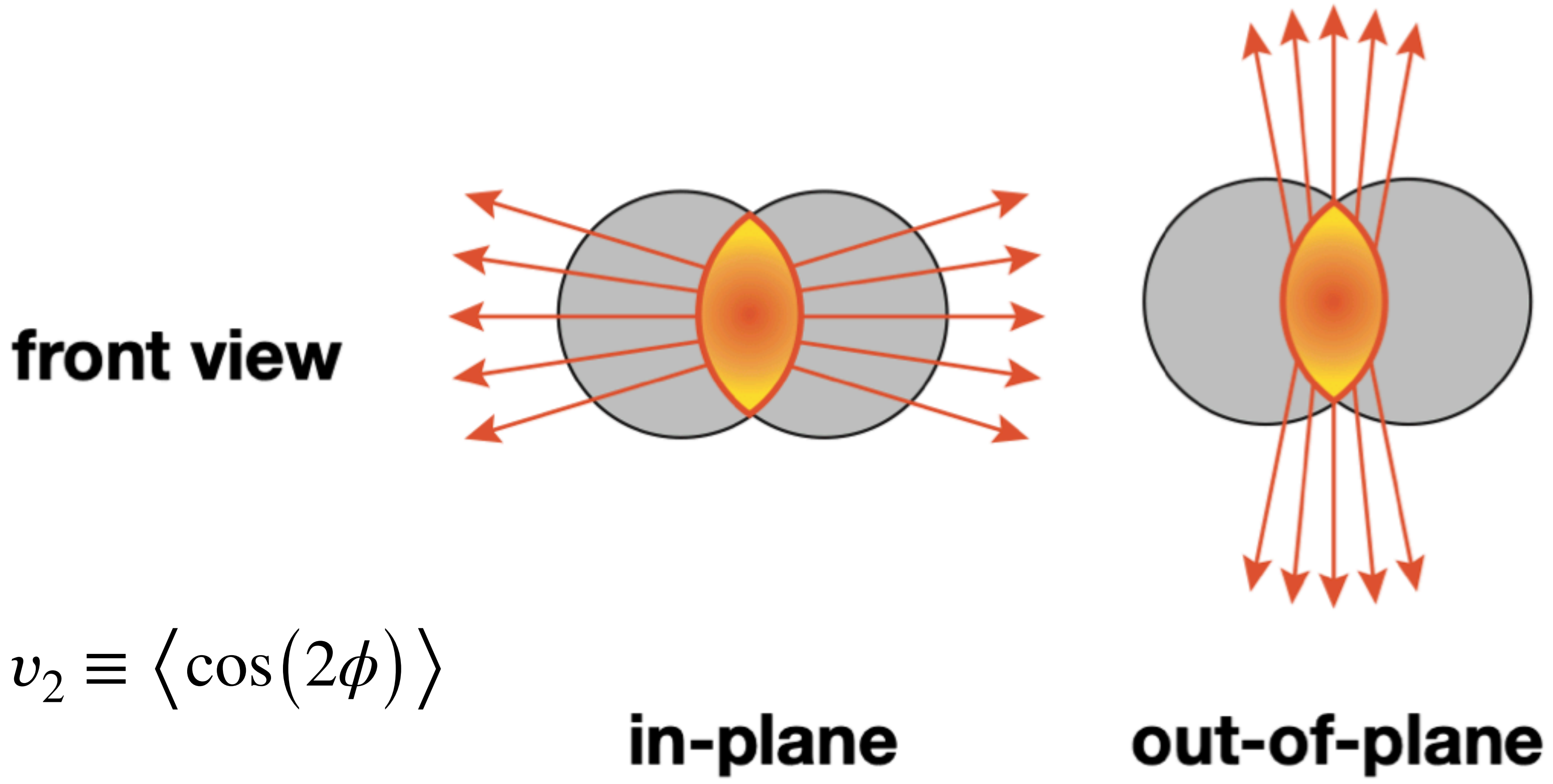
These observables are extremely sensitive to the EOS

directed flow v_1 (dv_1/dy ~ longitudinal expansion)



$v_1 \equiv \langle \cos(\phi) \rangle = \langle \frac{p_x}{p_T} \rangle$

elliptic flow v_2 ($v_2(y \approx 0)$ ~ midrapidity)



$v_2 \equiv \langle \cos(2\phi) \rangle$

illustrations from a presentation by B. Kardan (HADES)

Evidence for production of QGP in ultra-relativistic HICs

If quarks and gluons are deconfined in high-energy HICs, how would we know?

We only measure final momenta of produced hadrons!

How are hadrons produced from quarks? Consider two proposed processes:

1. Fragmentation: as the system expands (becomes more dilute), distances between quarks increase = quark-quark potential increases ⇒ new quark pairs are produced ⇒ eventually the produced pairs stay intact
   Note: final mesons and baryons have a *fraction* of the original quark momentum
2. Coalescence: two or three quarks very close in position and momentum space combine to form a meson or a baryon
   Note: final mesons and baryons have a *sum* of the original quark momentum

Consequently: fragmentation leads to statistically lower momenta of measured particles,
while coalescence leads to statistically higher momenta of measured particles

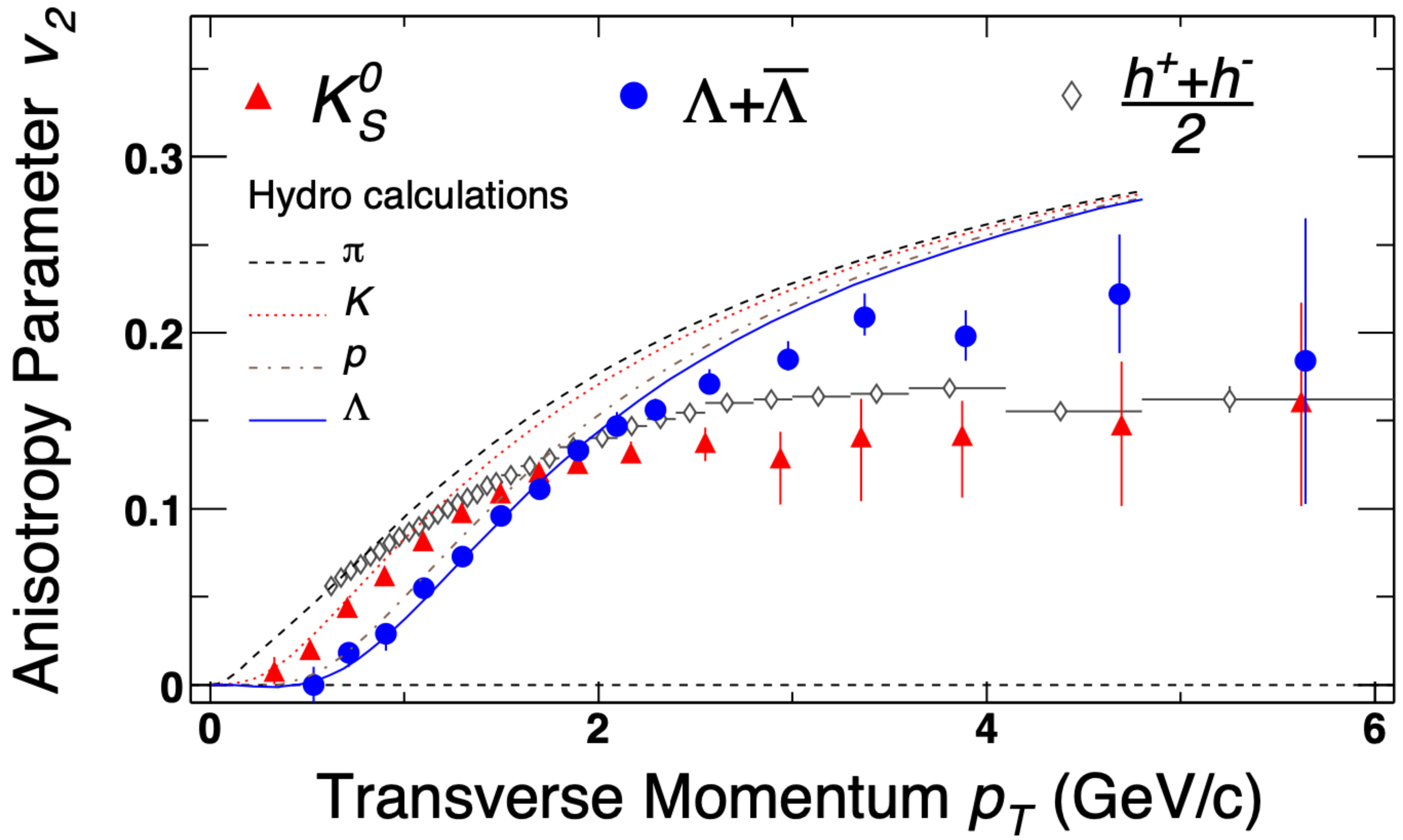
Fragmentation: probability to produce a particle ∝ quark density

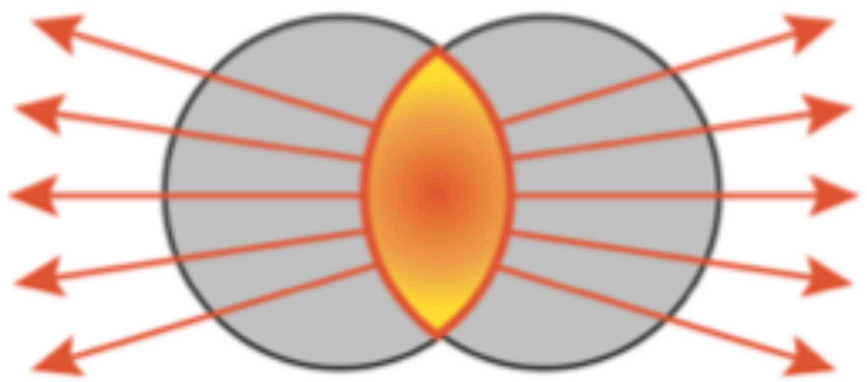
Coalescence: probability to produce a particle ∝ (quark density)^2 [mesons] or (quark density)^3 [baryons]

Evidence for production of QGP in ultra-relativistic HICs from flow

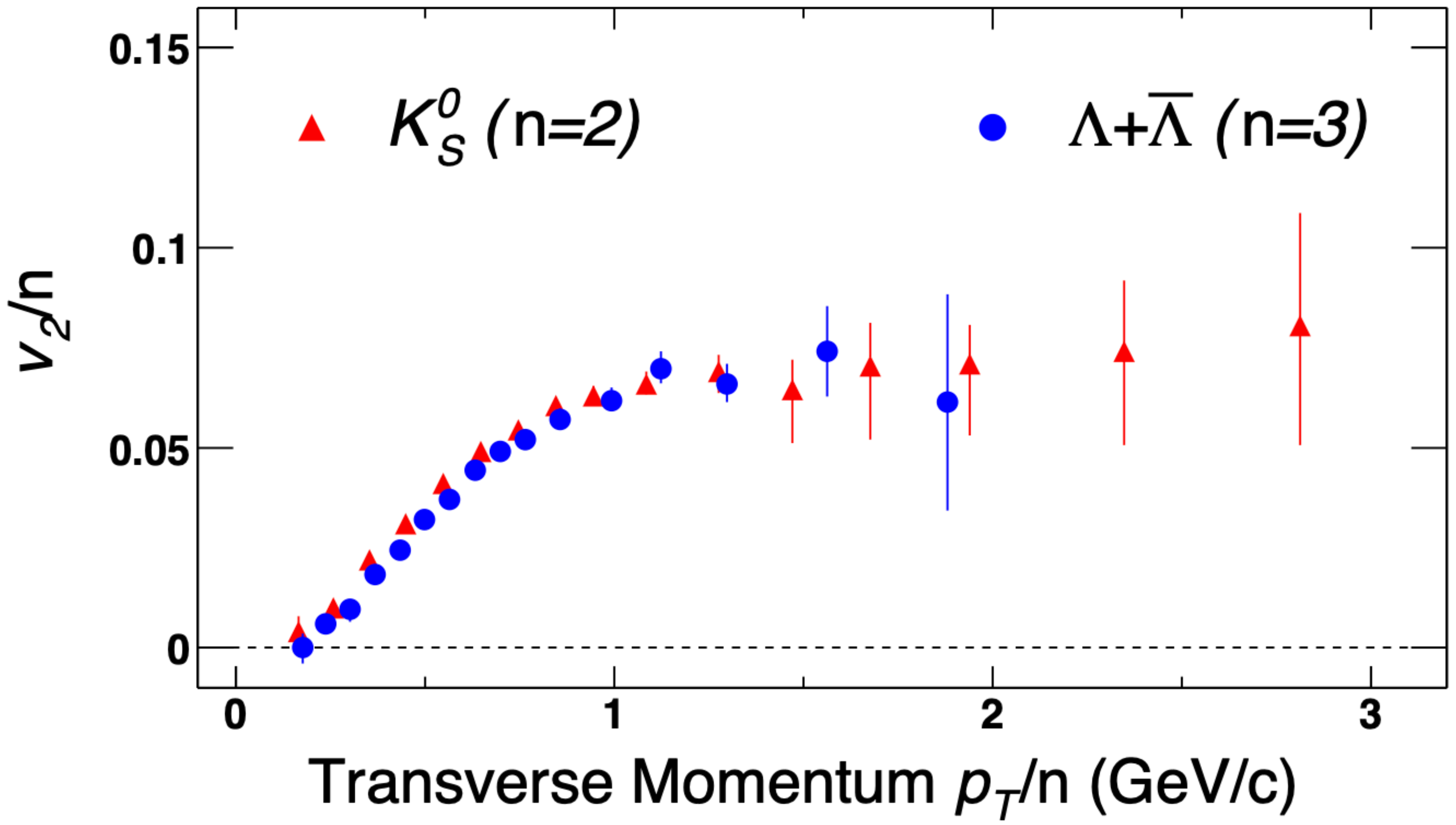
Fragmentation: statistically lower momenta of measured particles,
probability to produce a particle ∝ quark density

Coalescence: statistically higher momenta of measured particles ,
probability to produce a particle ∝ (quark density)^2 [mesons] or (quark density)^3 [baryons]





Flow of baryons from coalescence
enhanced w.r.t.
flow of mesons from coalescence



STAR Collaboration, “Particle type dependence of azimuthal anisotropy and nuclear modification of particle production in Au + Au collisions at s(NN)**(1/2) = 200 GeV”,
Phys. Rev. Lett. 92, 052302 (2004)
arXiv:nucl-ex/0306007