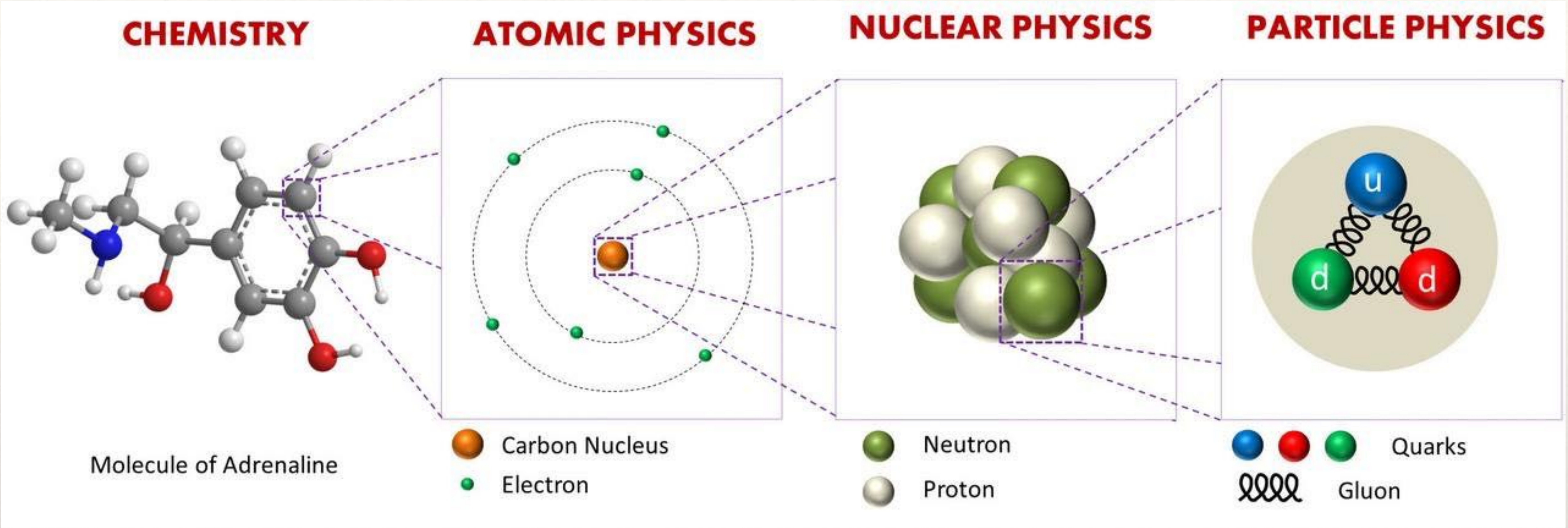
Strongly Interacting Matter at 5 Trillion Degrees

Shanshan Cao

Building blocks of the universe and their interactions

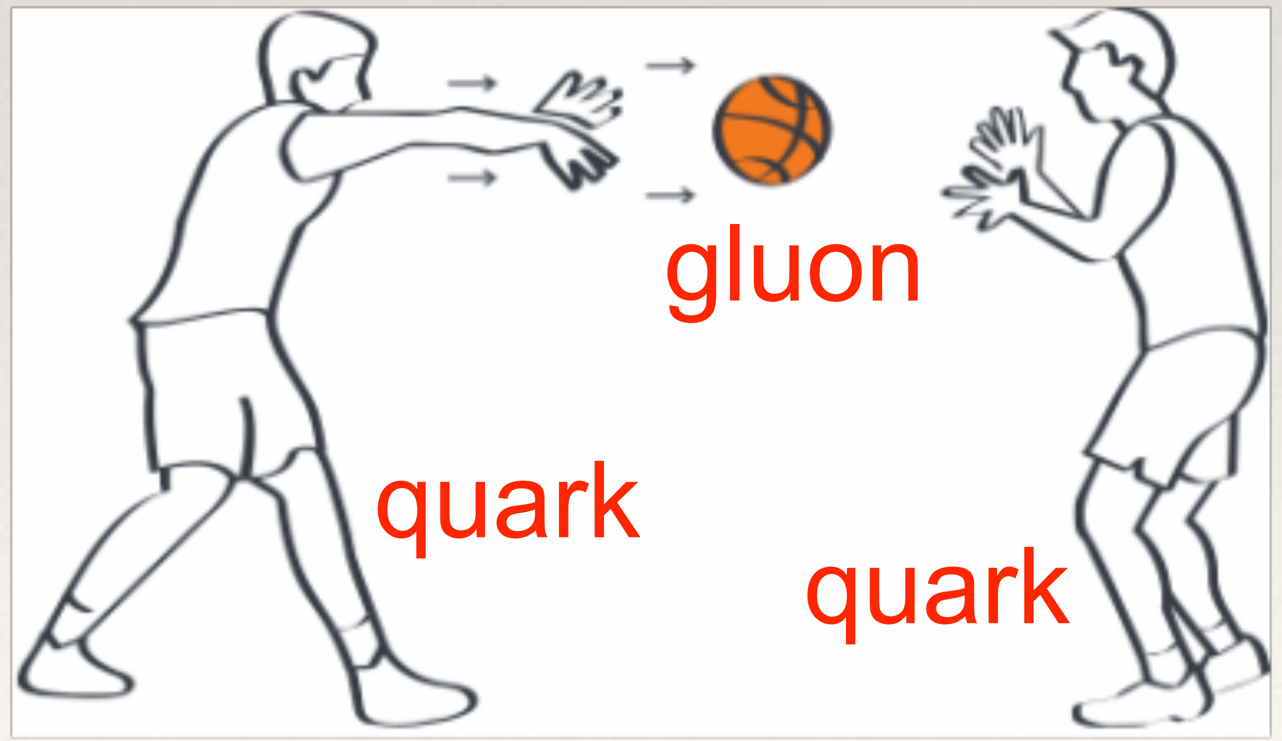


Building blocks (elementary particles):

quarks, gluons ; electrons, photons …

strong interaction

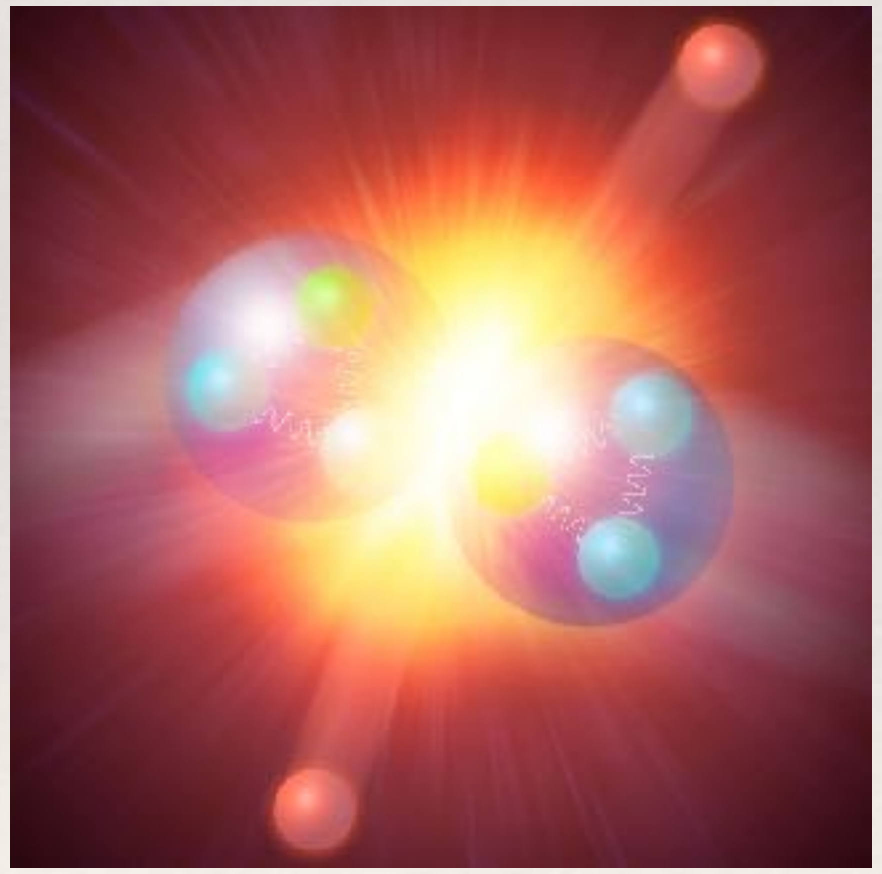
electromagnetic interaction



Four fundamental forces

Gravitational force

Electromagnetic force



Strong force

Weak force

One of the most precise theories

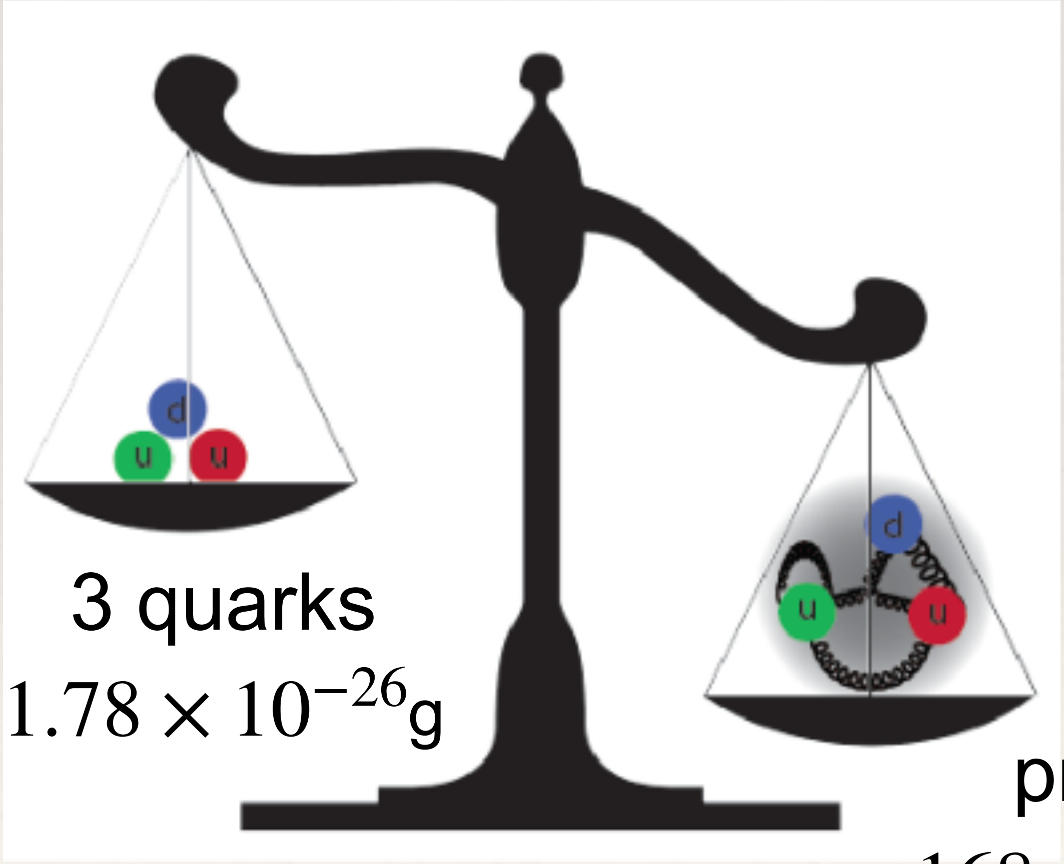
12-digit theory-experiment match

Electroweak force

Spontaneous symmetry breaking

$\rightarrow$ Higgs boson (origin of mass)

But Higgs only contributes 1%



proton

168×10^{-26}g

strong force 99%

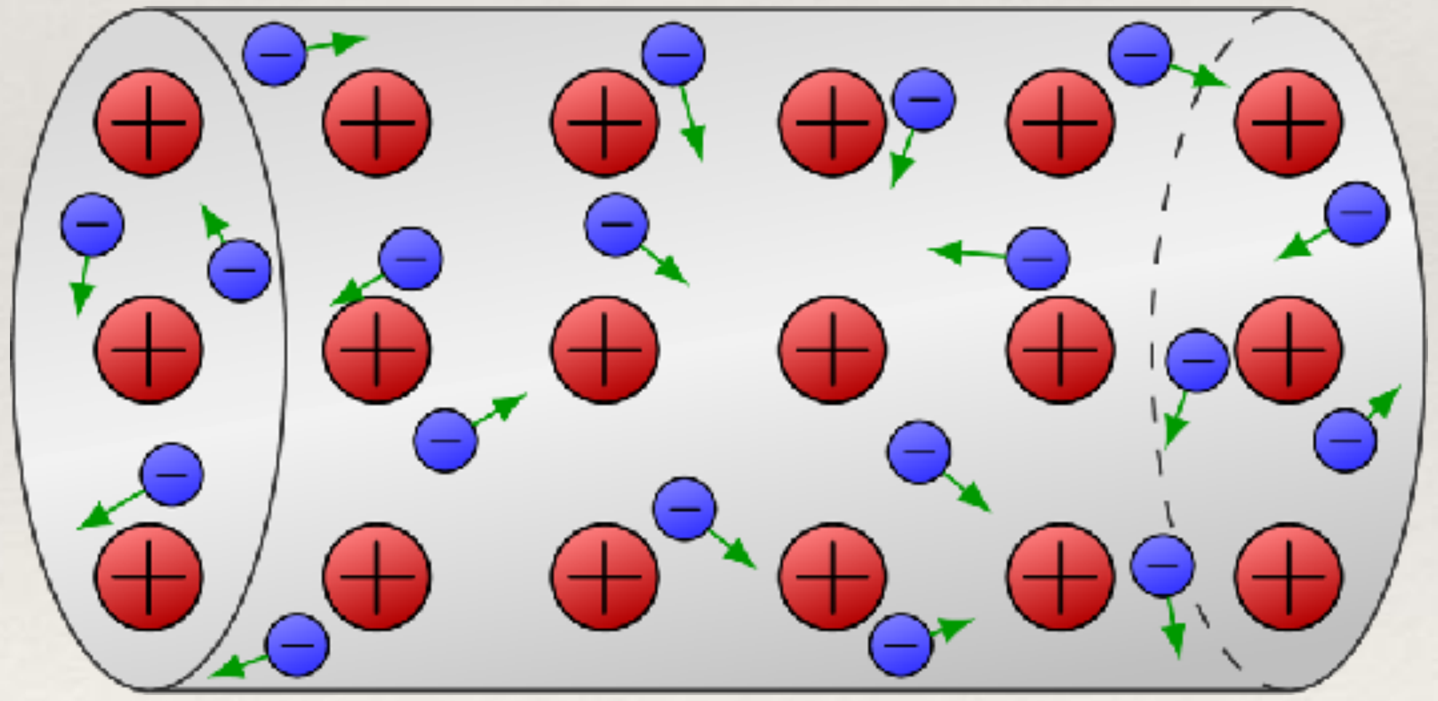
Quark confinement of strong interaction

- Electromagnetic force (QED):

$$\mathscr{L}_{\text{QED}} = \bar{\psi}_e i\gamma^\mu \left[\partial_\mu + ieA_\mu\right] \psi_e - m_e \bar{\psi}\psi_e - \frac{1}{4} F_{\mu\nu}F^{\mu\nu}$$

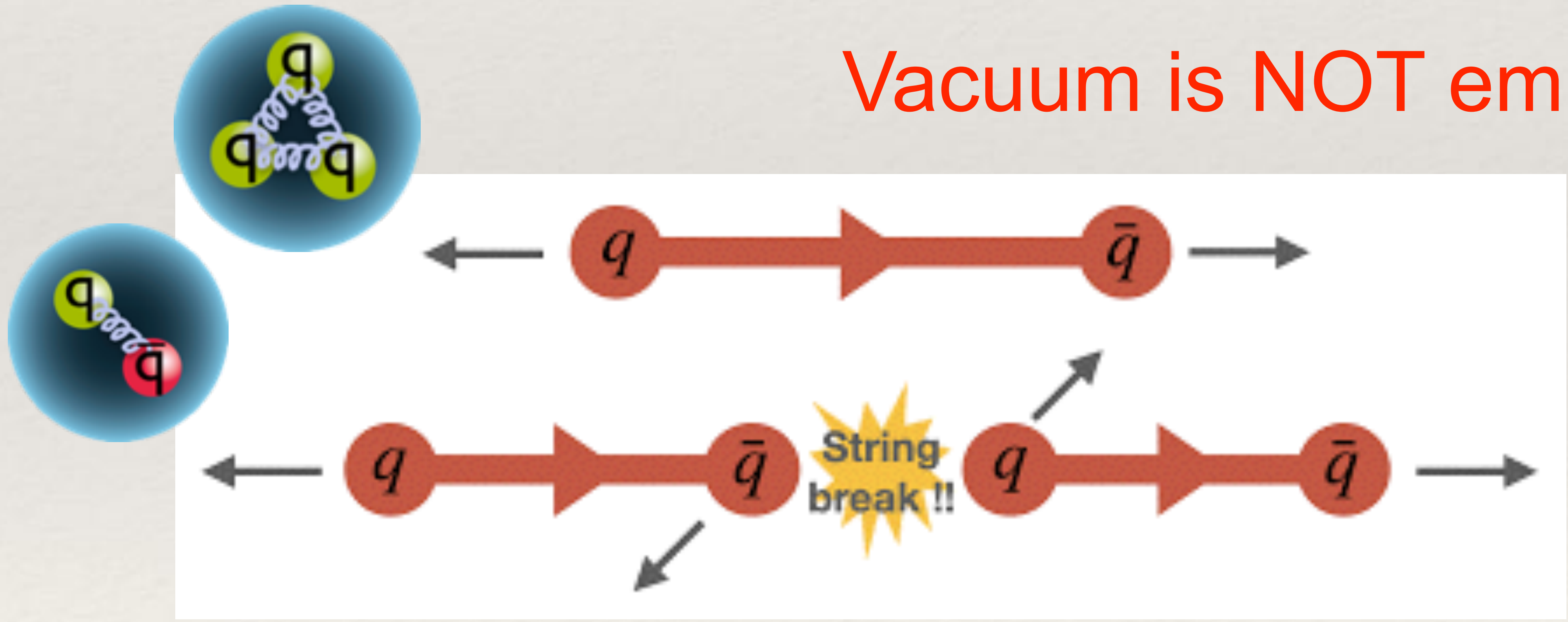
- Strong force (QCD):

$$\mathscr{L}_{\text{QCD}} = \sum_q \left\{ \bar{\psi}_{qi} i\gamma^\mu \left[\delta_{ij}\partial_\mu + ig\left(G^a_\mu t_a\right)_{ij}\right] \psi_{qj} - m_q \bar{\psi}_{qi}\psi_{qi} \right\} - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$



Free electrons allowed

Vacuum is NOT empty!



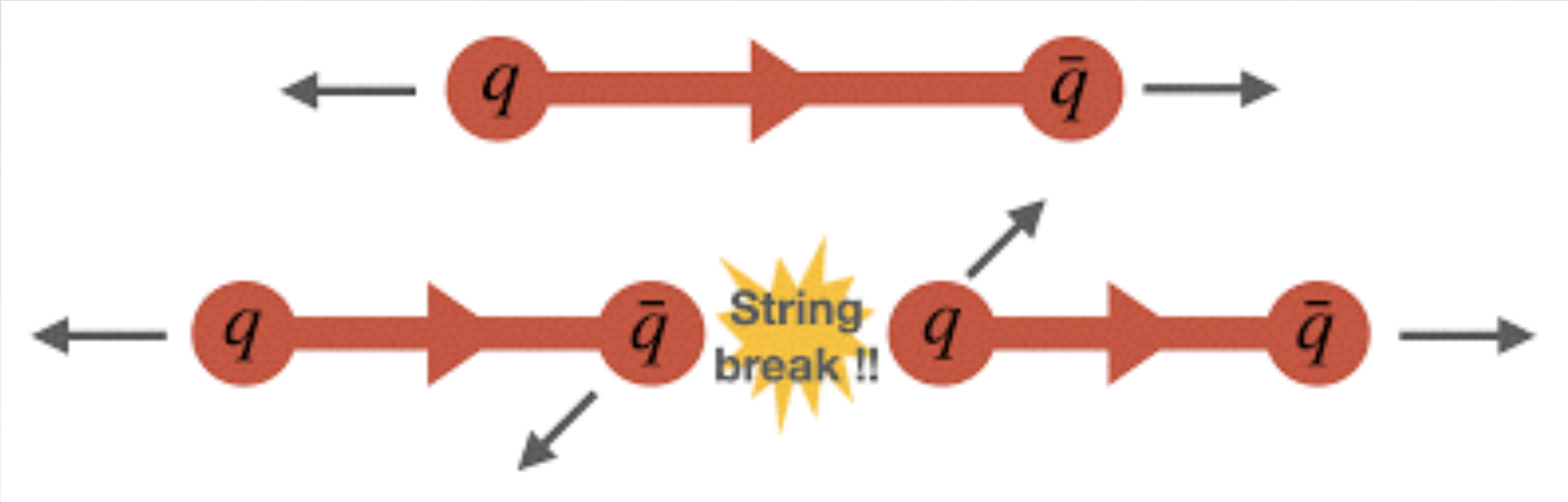
Quarks confined in hadrons

Quark confinement

A ballroom filled with people

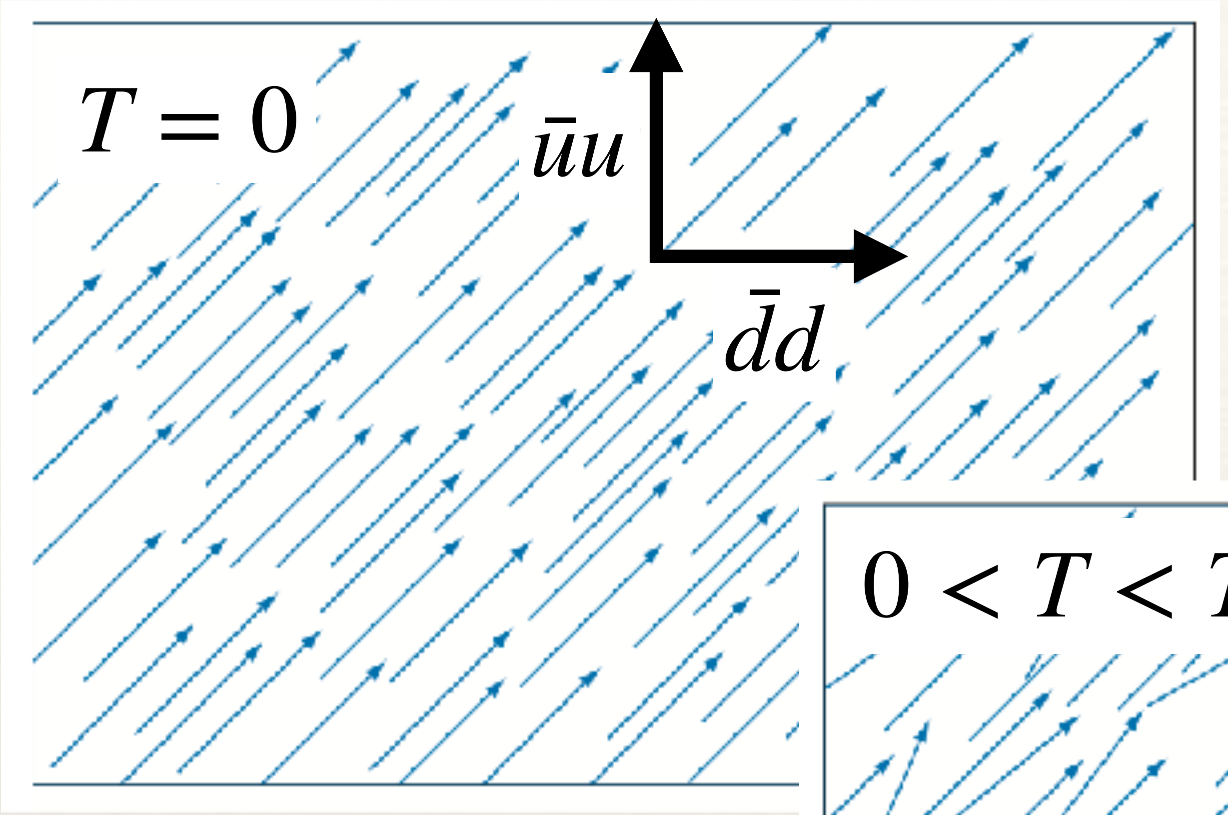
A superstar walks in

Get trapped in the room

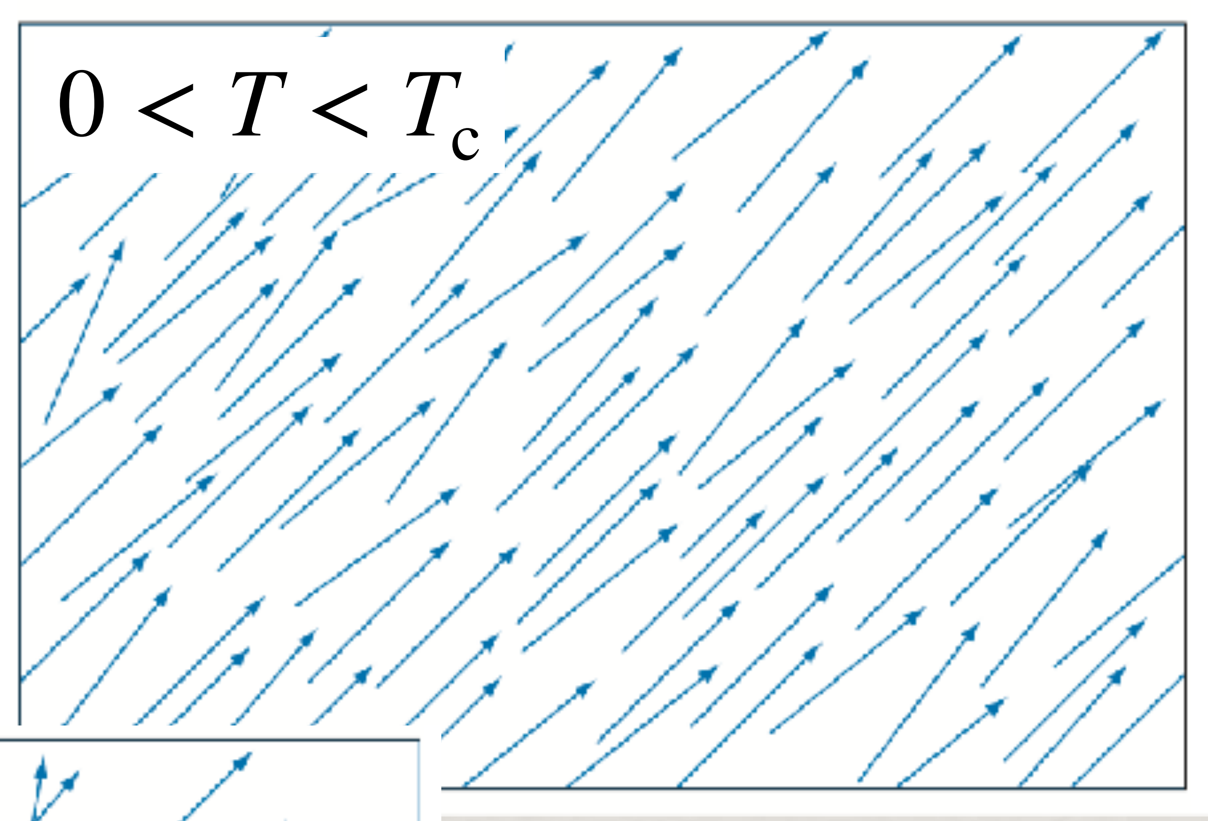


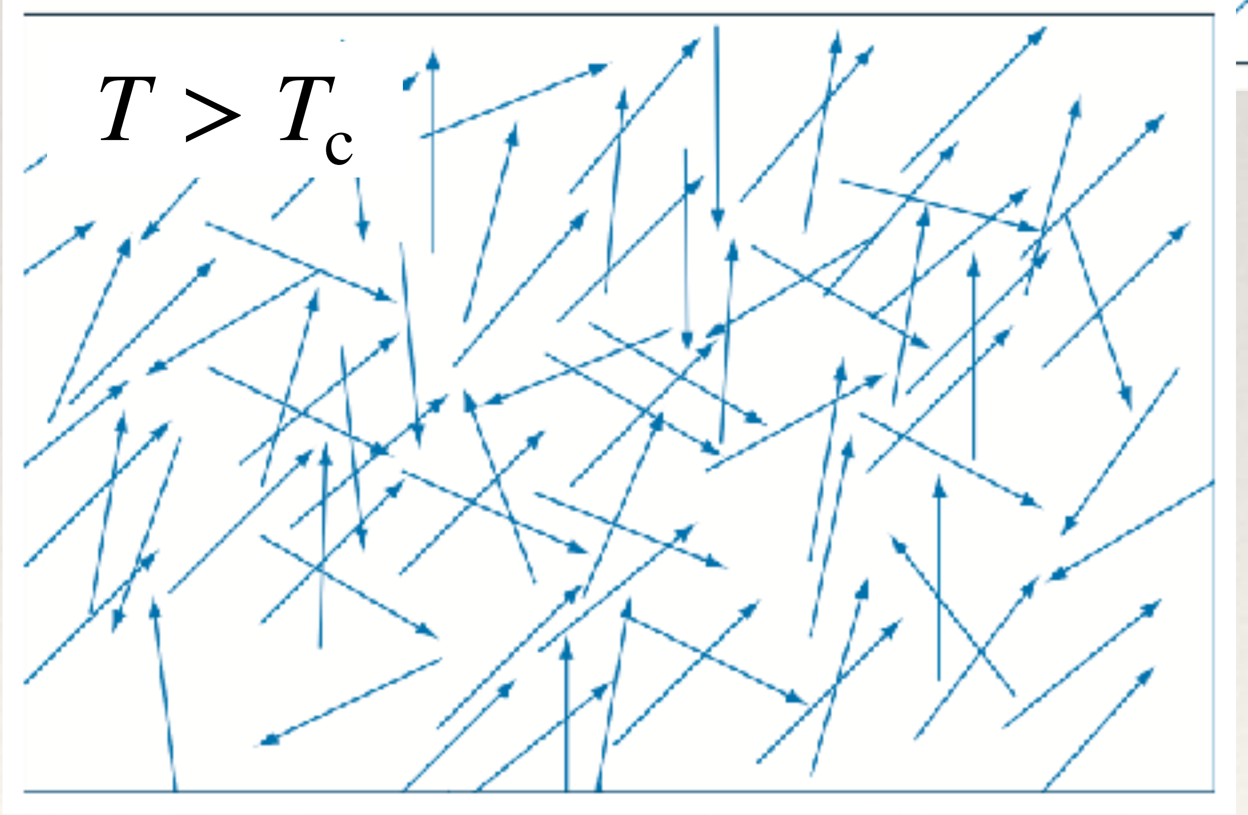
How to break the confinement?

Free the quarks with high temperature



quark
condensate



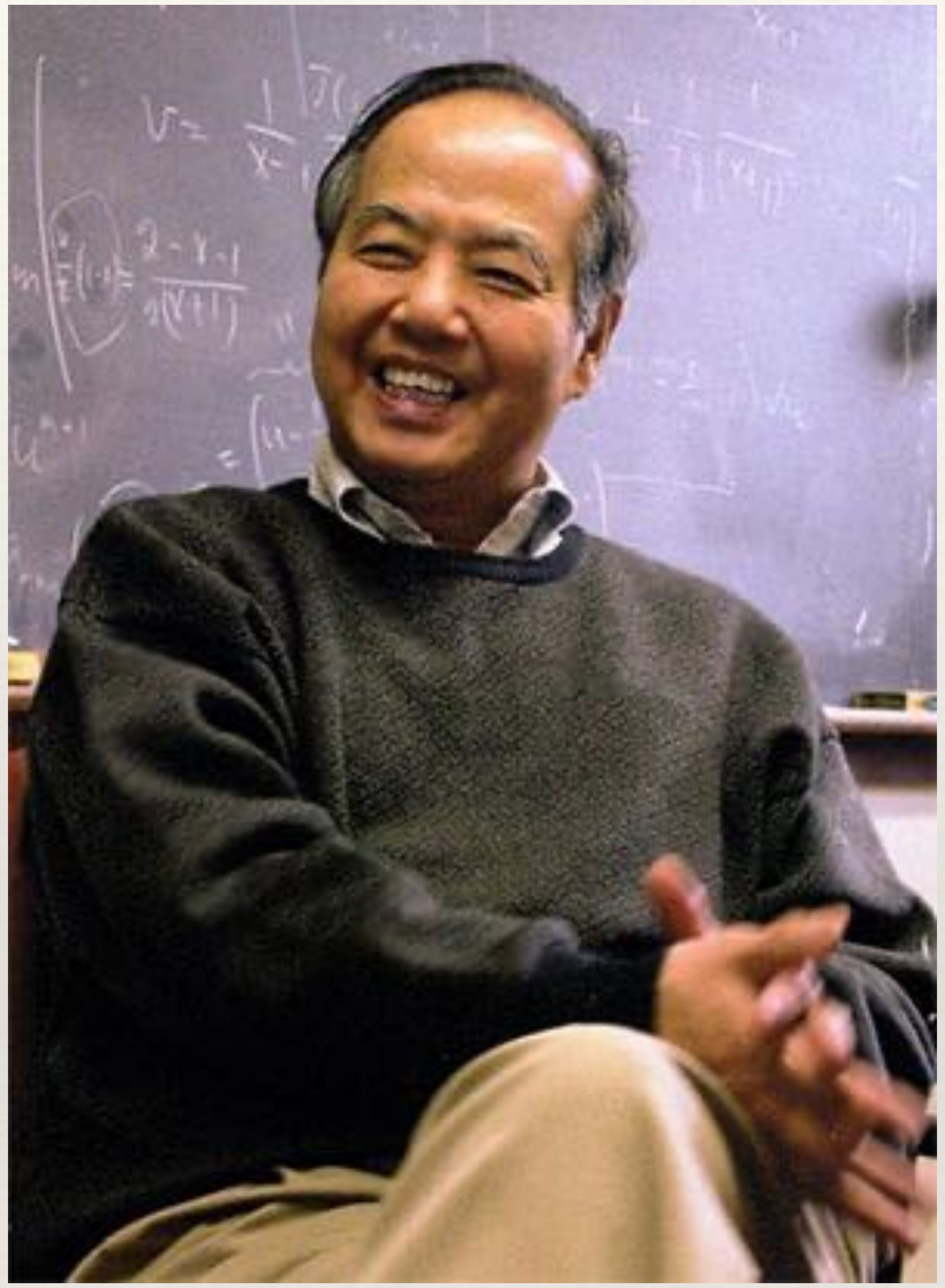


quark
condensate
broken

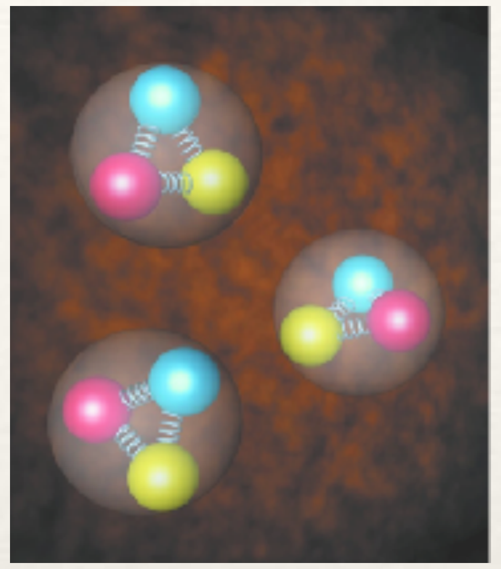
$T_c \sim 2 \times 10^{12}$ K

300 million times of the surface temperature of the sun (~ 6000 K)

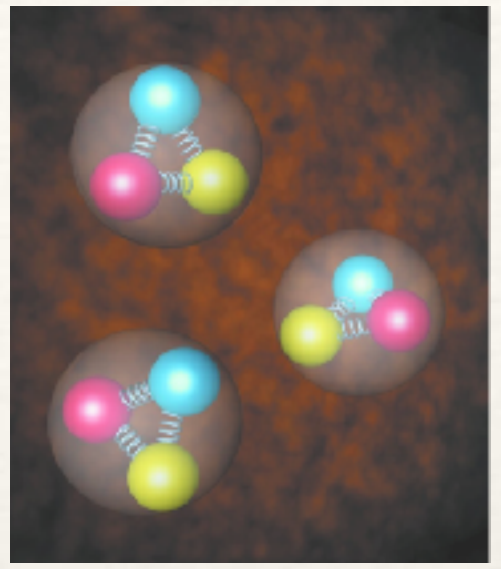
Relativistic heavy-ion collisions



T. D. Li (李政道), a leading pioneer in proposing relativistic heavy-ion collision programs since 1974

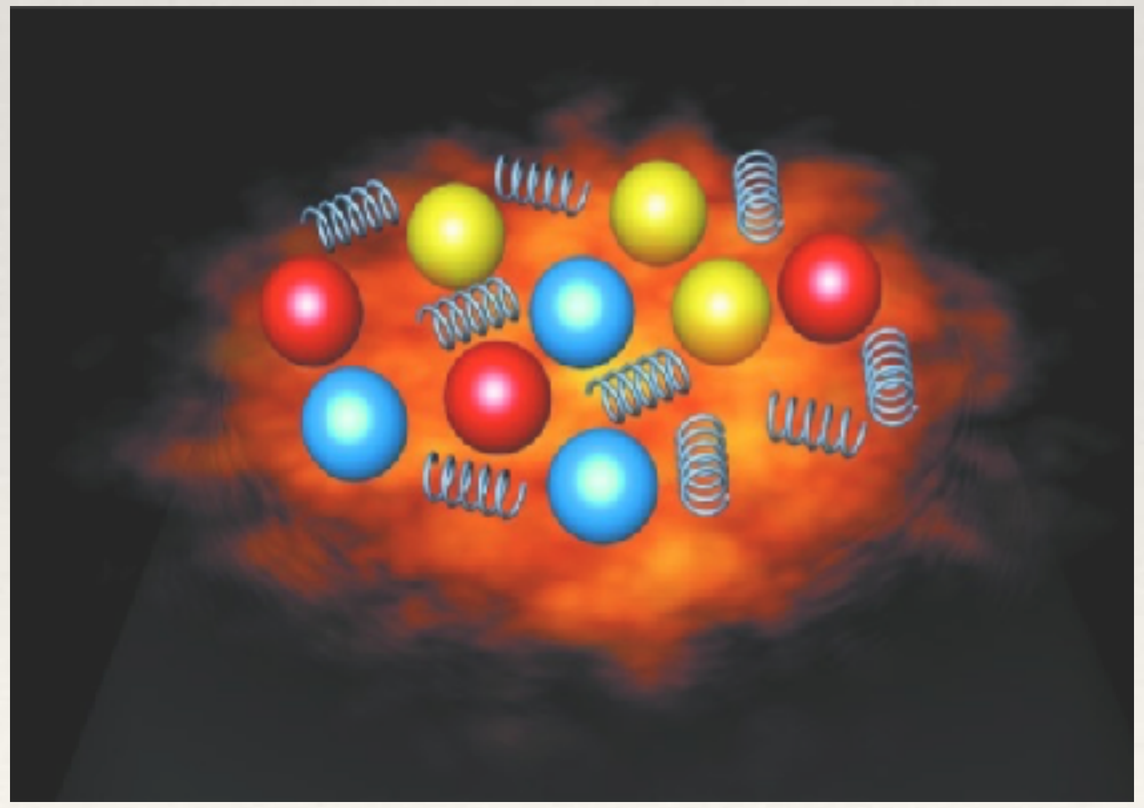


Hadrons



Hadrons

Ke-Ran Li
李可染, 1986

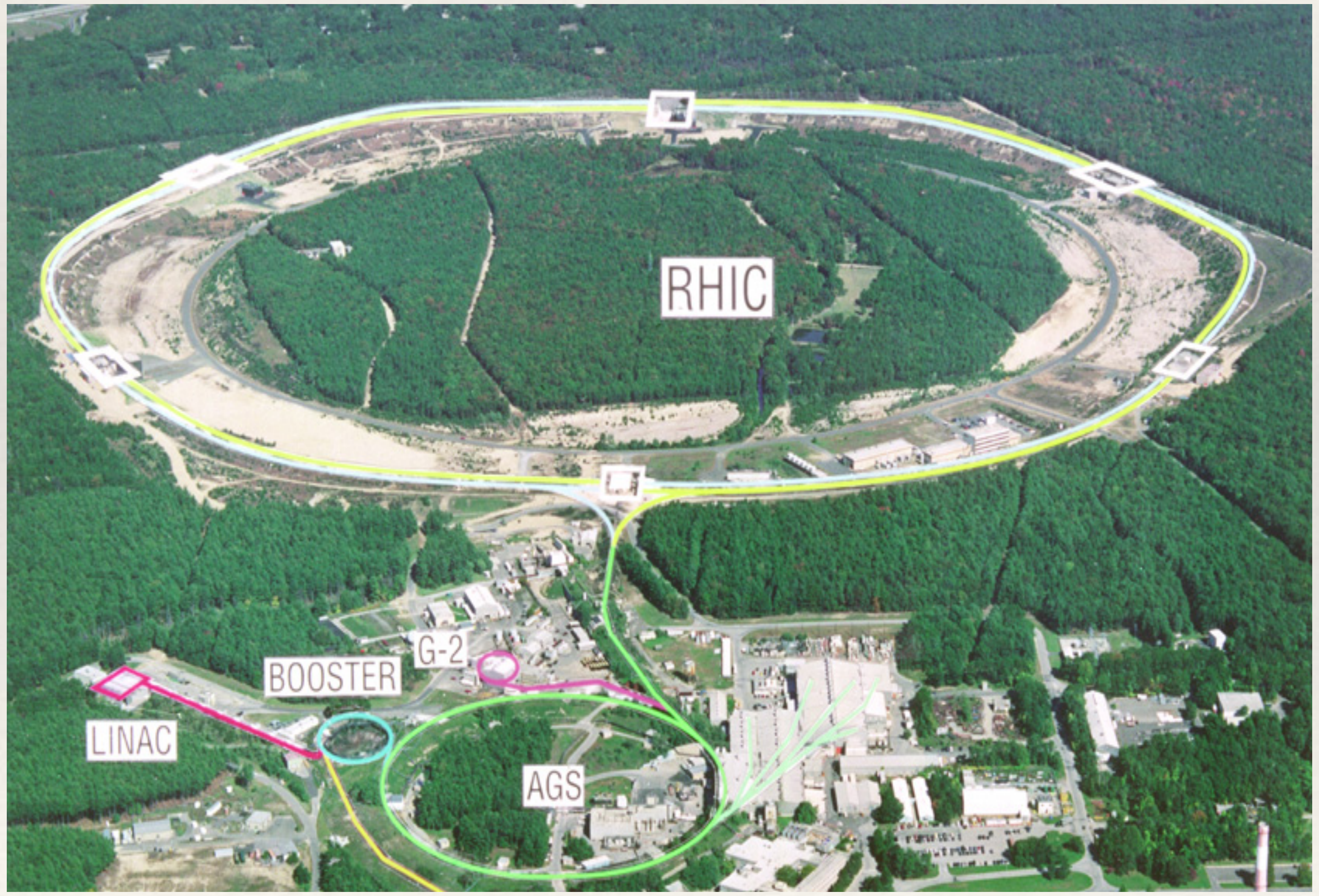


Quark-Gluon Plasma
(QGP)

Creation of QGP in laboratories

Relativistic Heavy Ion Collider (RHIC) at BNL (3.8 km), since 2000:

Collide Au/Cu/U/… nuclei at 0.99995*c*



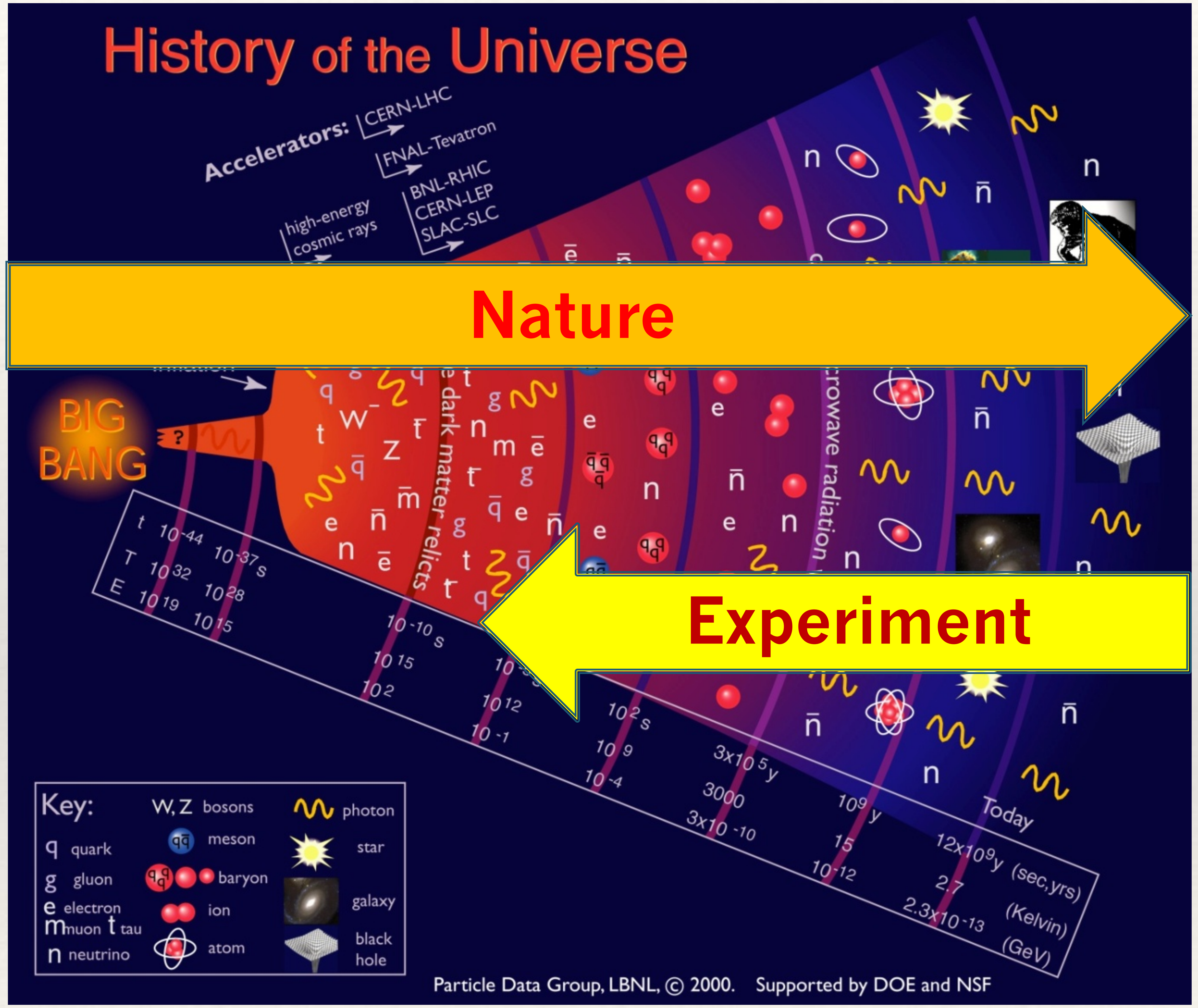
Large Hadron Collider (LHC) at CERN (27 km), since 2010:

Collide Pb/Xe/… nuclei at 0.99999992*c*

QGP and the early universe

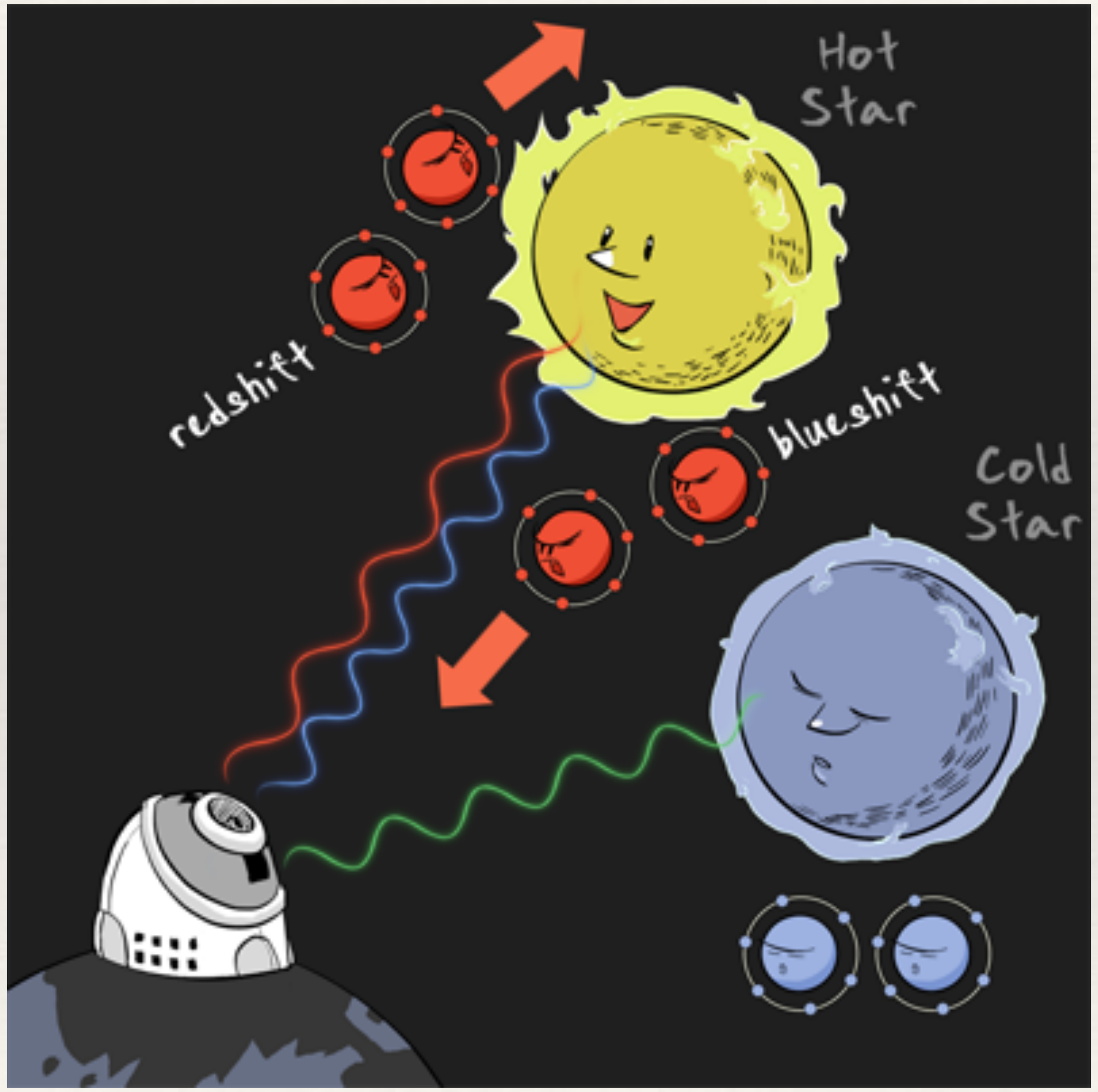
- A few microseconds after the Big Bang, the entire universe was in the QGP phase

- Collide beams of ultra-relativistic heavy ions **(little bang)** to create QGP in laboratories



Methodologies of indirect observations

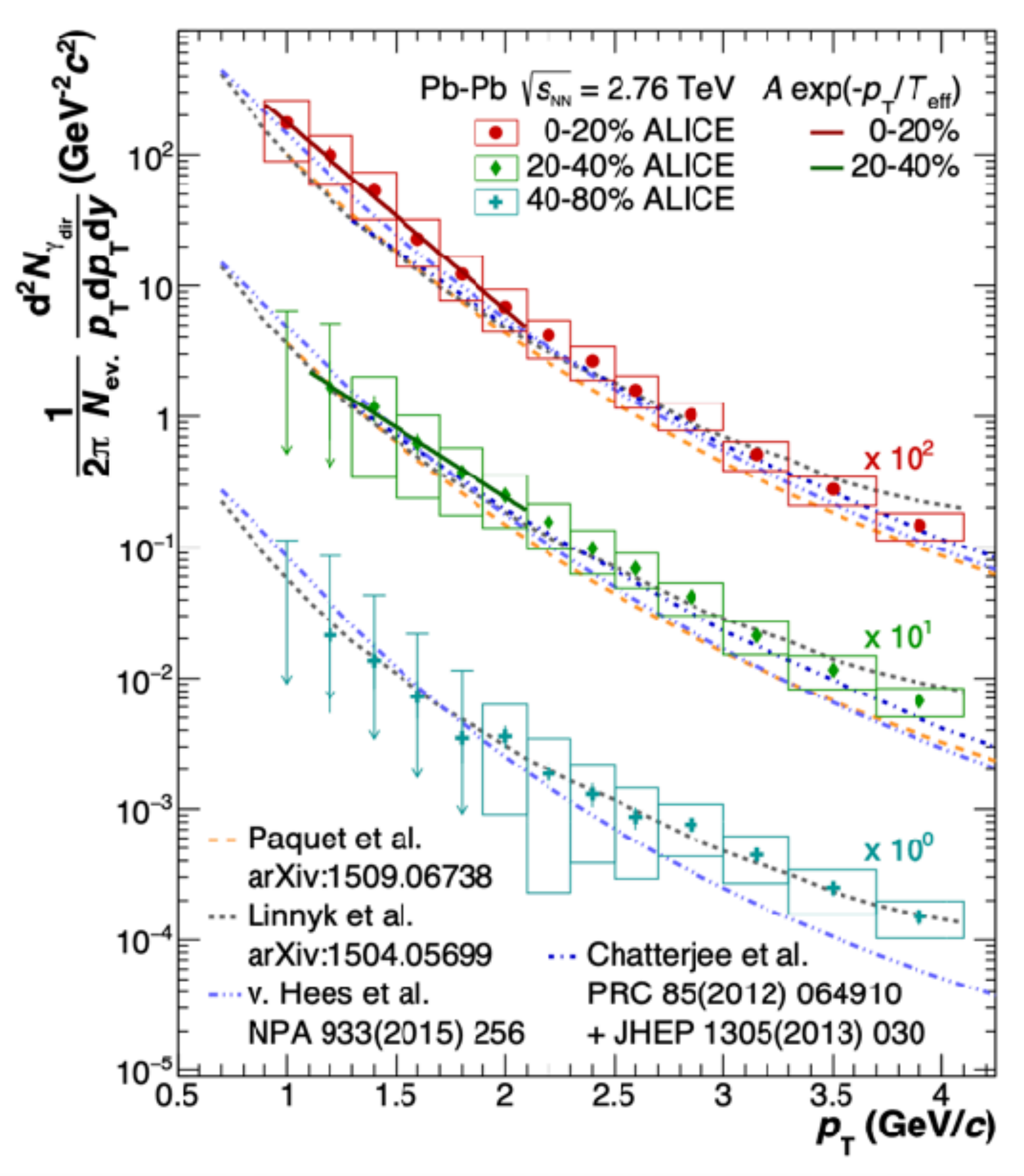
- Thermal (**soft**) particle emission



- Energetic (**hard**) particle tomography

Photon spectra and QGP temperature

Real photon spectra

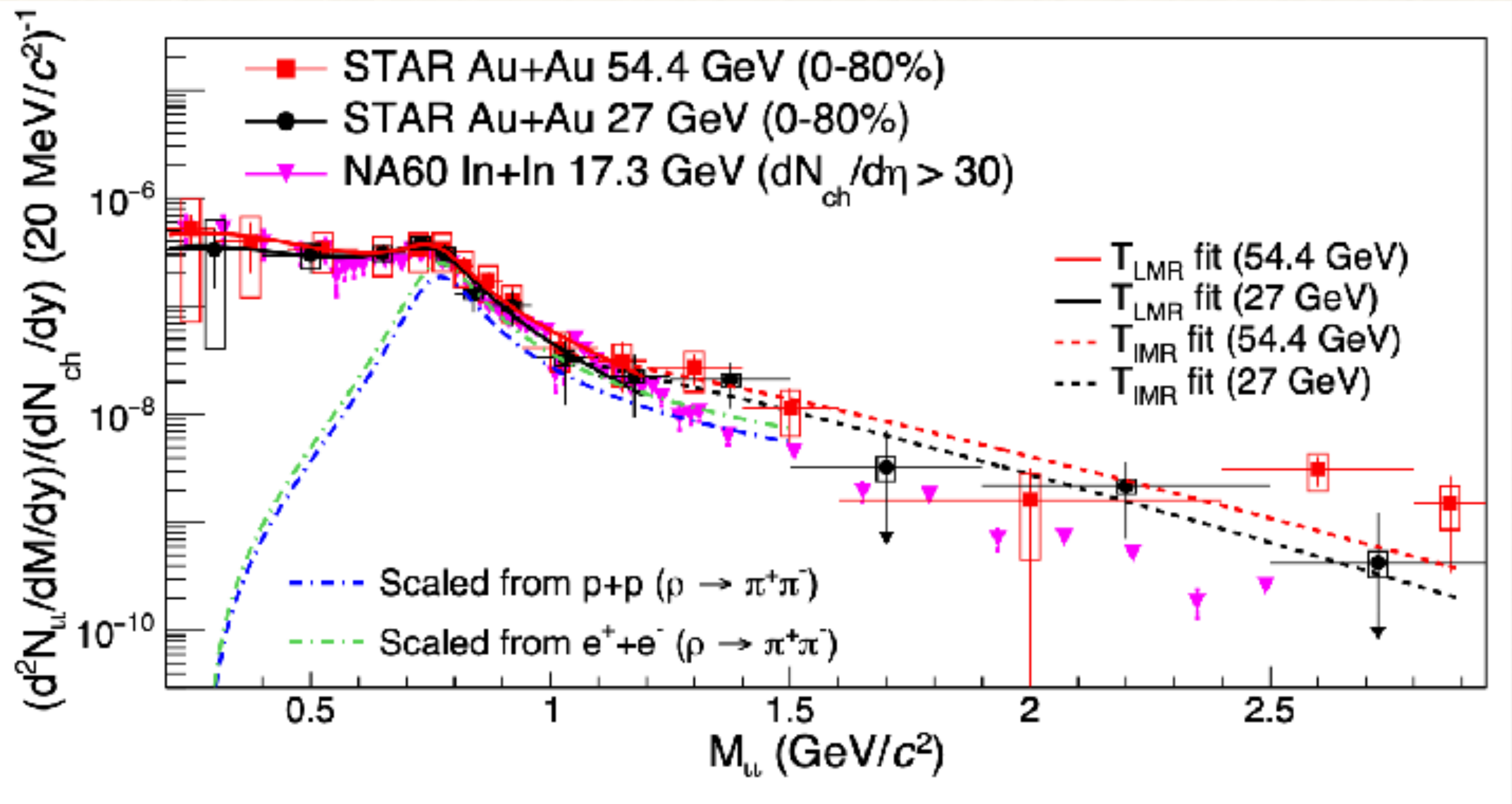


ALICE, Phys. Lett. B 754 (2016) 235-248

fit with

$\sim e^{-E/T}$

Virtual photon ($\gamma \to e^+e^-$) spectra



STAR, Nature Commun. 16 (2025) 9098

Lorentz invariant

Highest artificial temperature

https://www.guinnessworldrecords.com/world-records/highest-man-made-temperature

Who

CERN, LARGE HADRON COLLIDER

What

5X10^12 DEGREE(S) KELVIN

Where

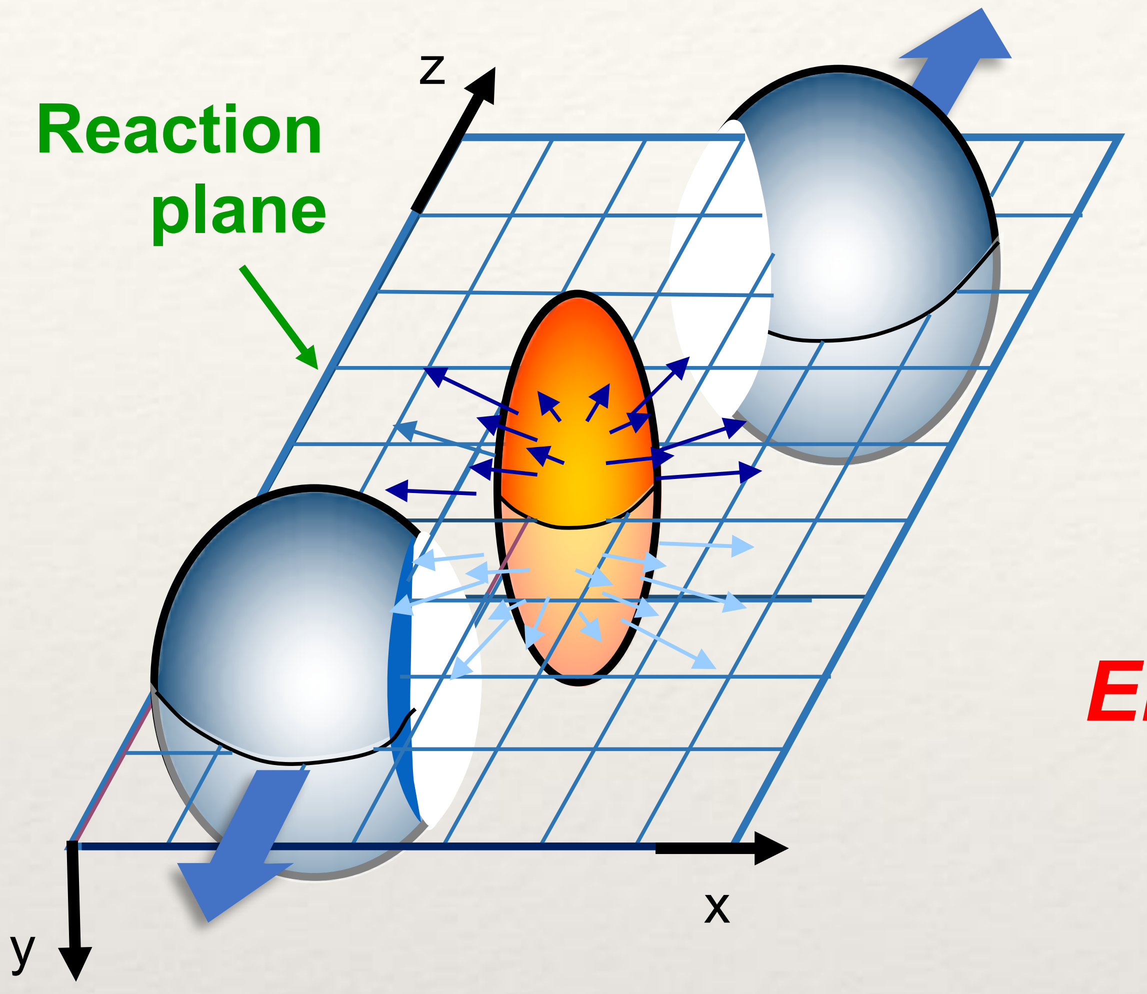
SWITZERLAND ()

When

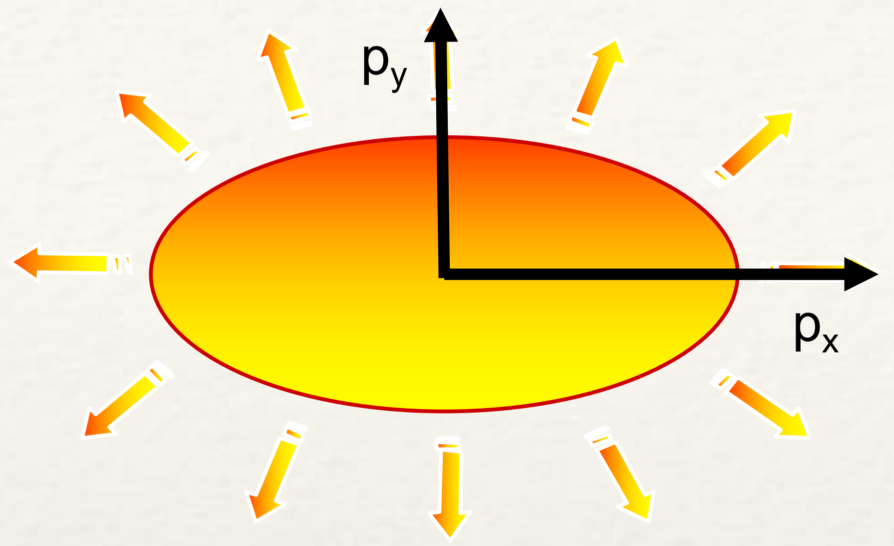
13 AUGUST 2012

On 13 August 2012 scientists at CERN's Large Hadron Collider, Geneva, Switzerland, announced that they had achieved temperatures of over 5 trillion K and perhaps as high as 5.5 trillion K. The team had been using the ALICE experiment to smash together lead ions at 99% of the speed of light to create a quark gluon plasma – an exotic state of matter believed to have filled the universe just after the Big Bang.

Collective flows and viscosity



Geometric anisotropy

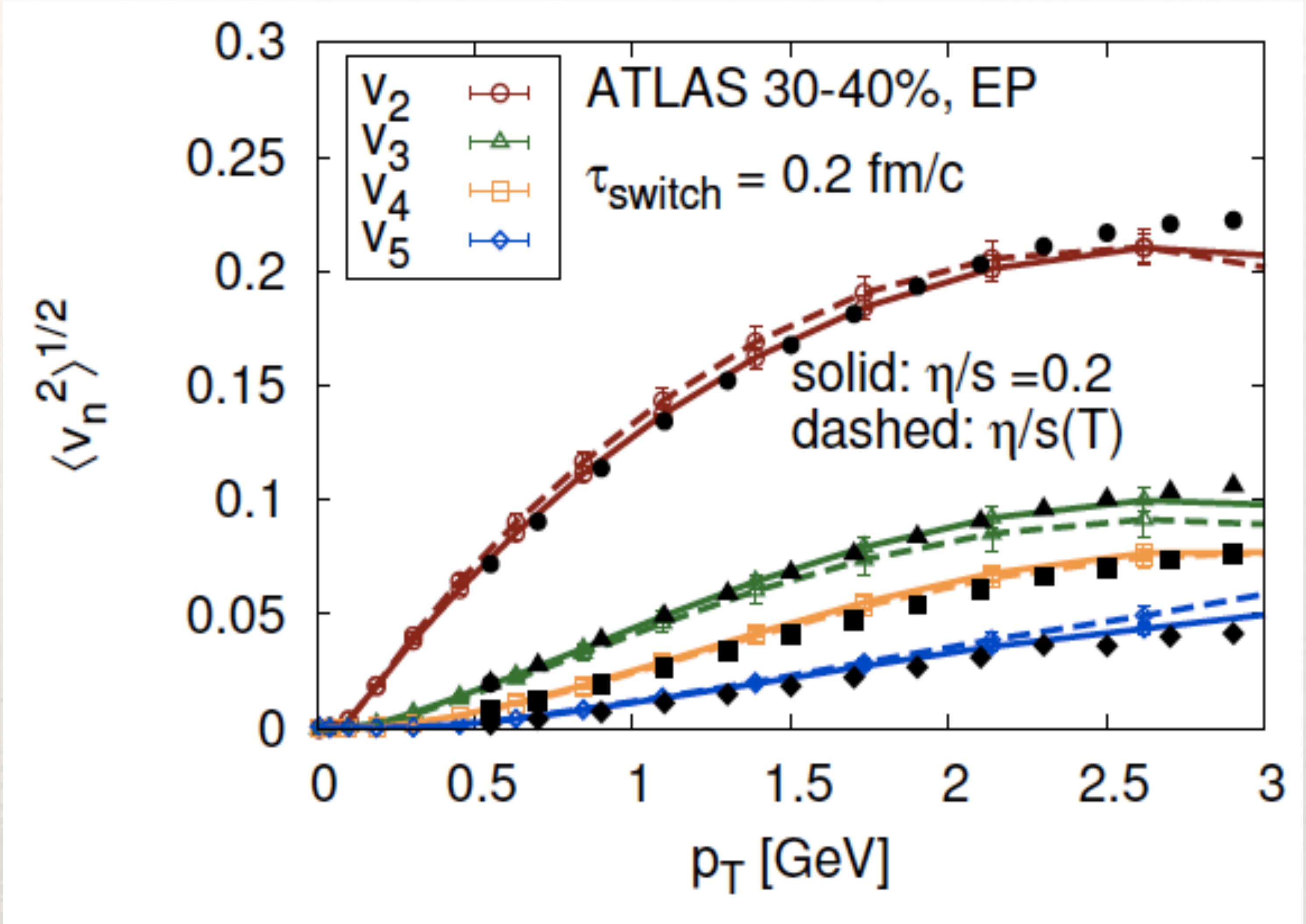


Elliptic flow:

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

Momentum space anisotropy

Expansion depends on transport properties, e.g., viscosity



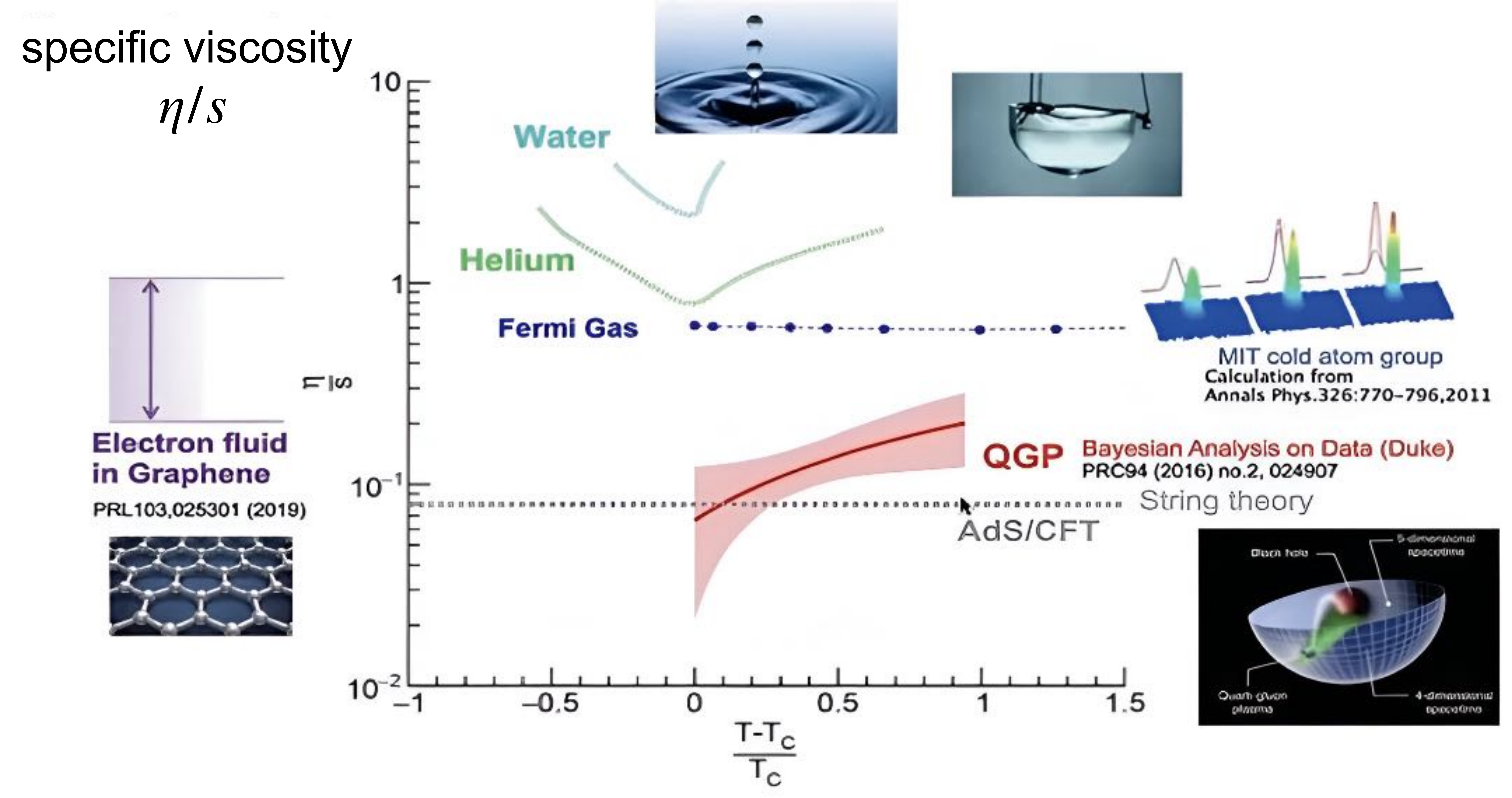
Gale *et al.*, Phys. Rev. Lett. 110 (2013) 012302

Collective flow coefficients:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left\{1 + \sum_n 2v_n \cos\left[n\left(\varphi - \Phi_n\right)\right]\right\}$$

Very small specific viscosity extracted from model-to-data comparison

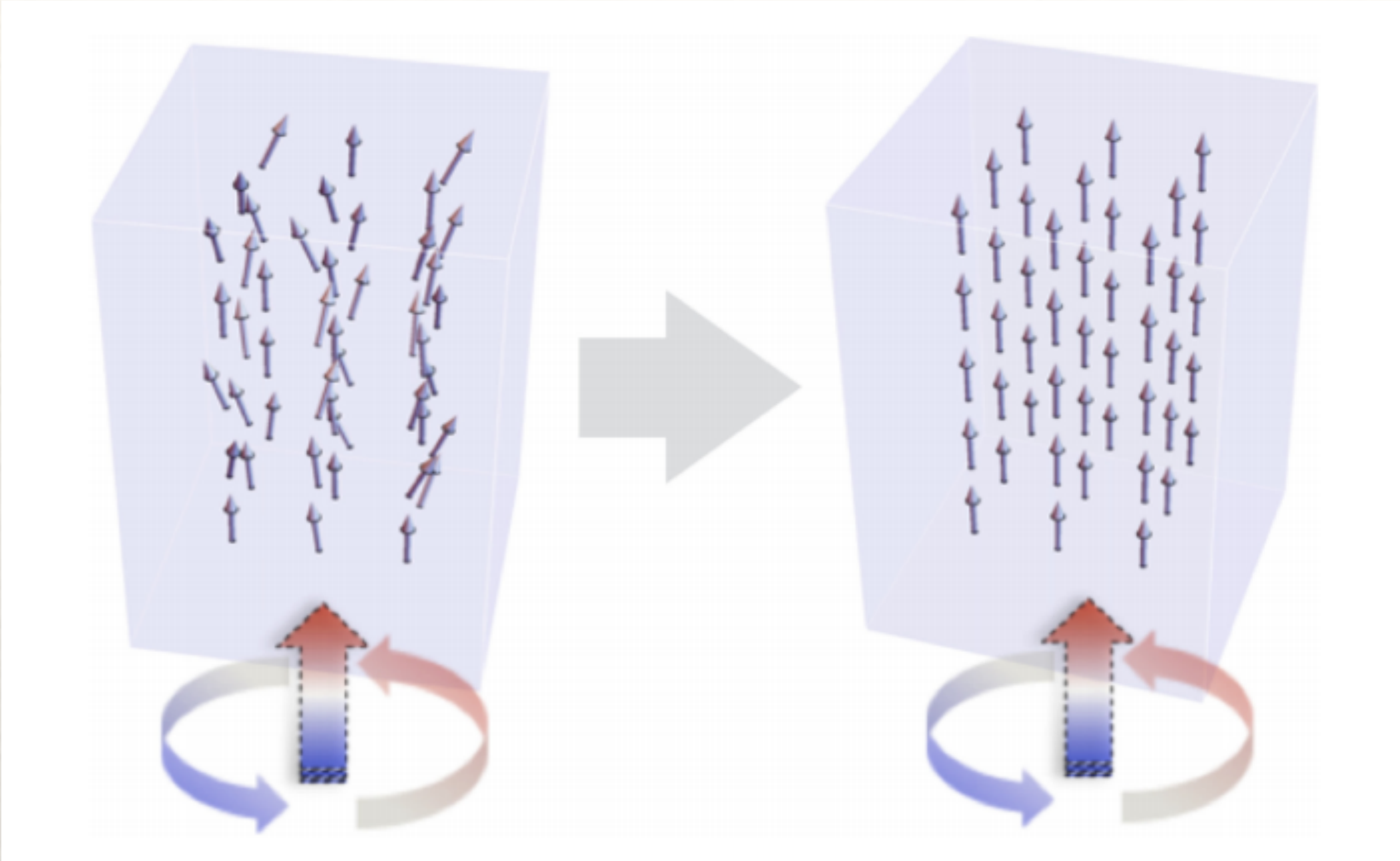
Smallest specific viscosity we know



The most perfect drop of liquid close to the string theory limit.

Spin-orbital coupling and hyperon polarization

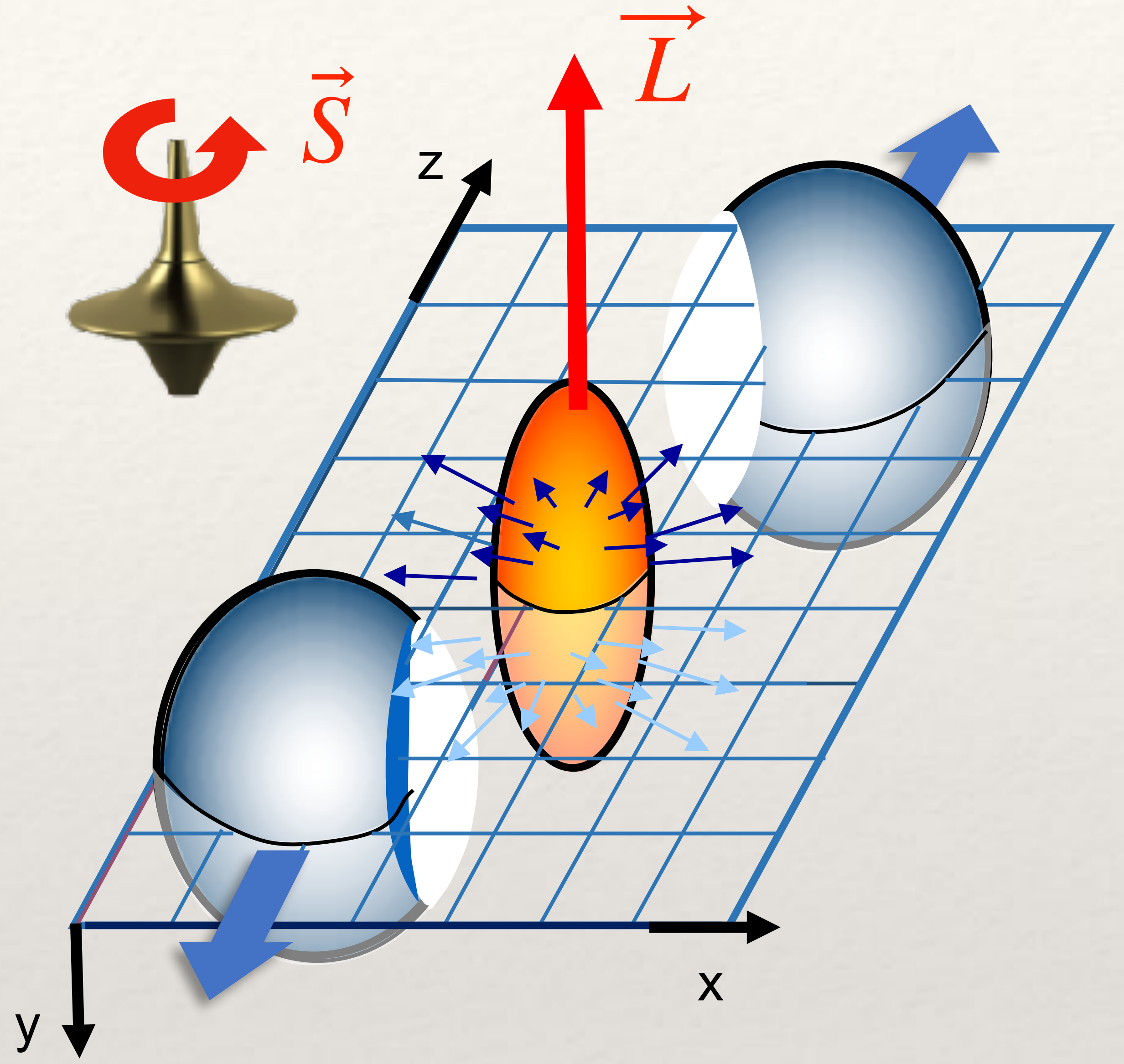
Coupling between orbital angular momentum and spin: $\hat{H} \sim \hat{\vec{L}} \cdot \hat{\vec{S}}$



Barnett effect:

rotation causes spin alignment (magnetization)

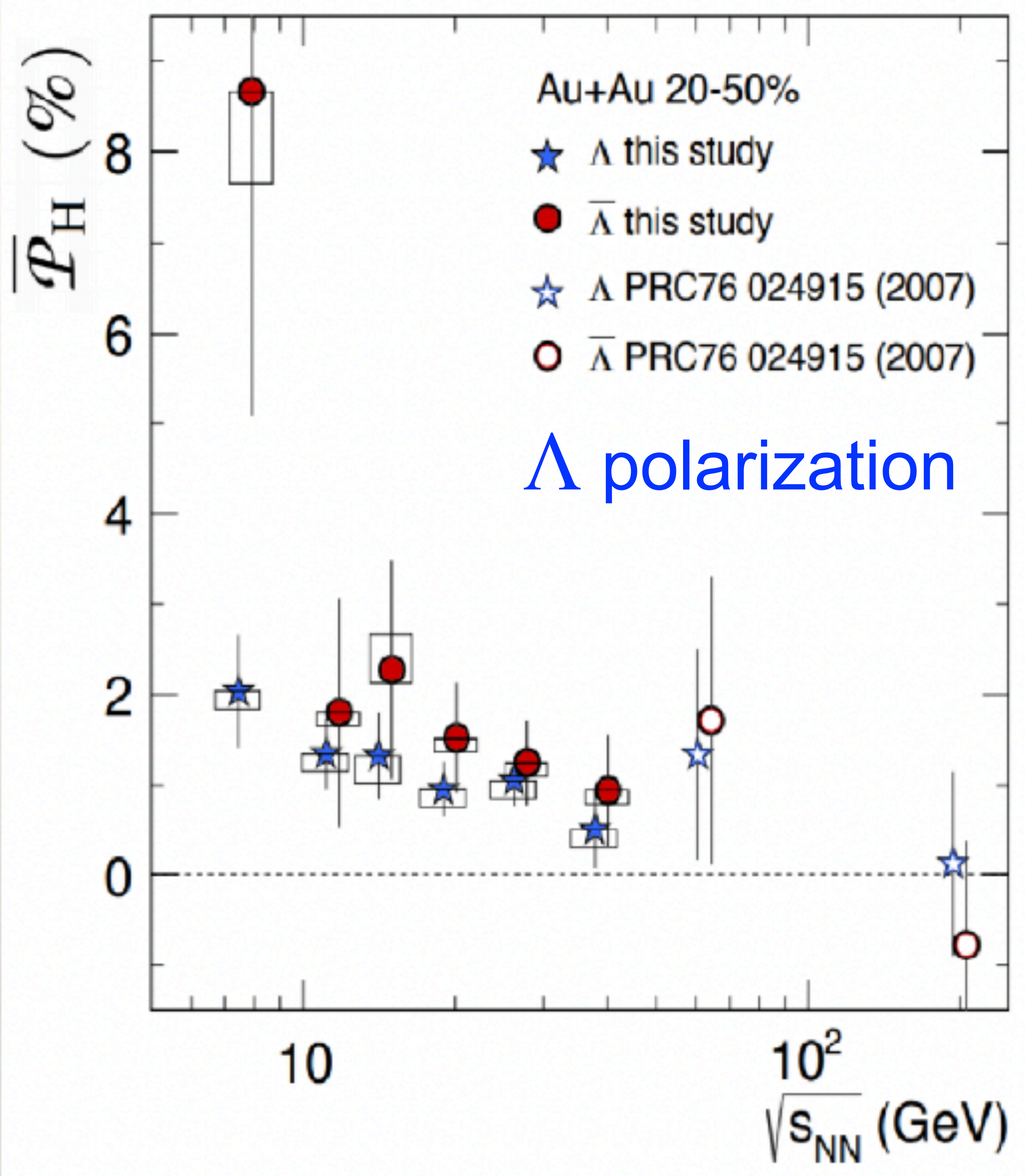
Electromagnetic force

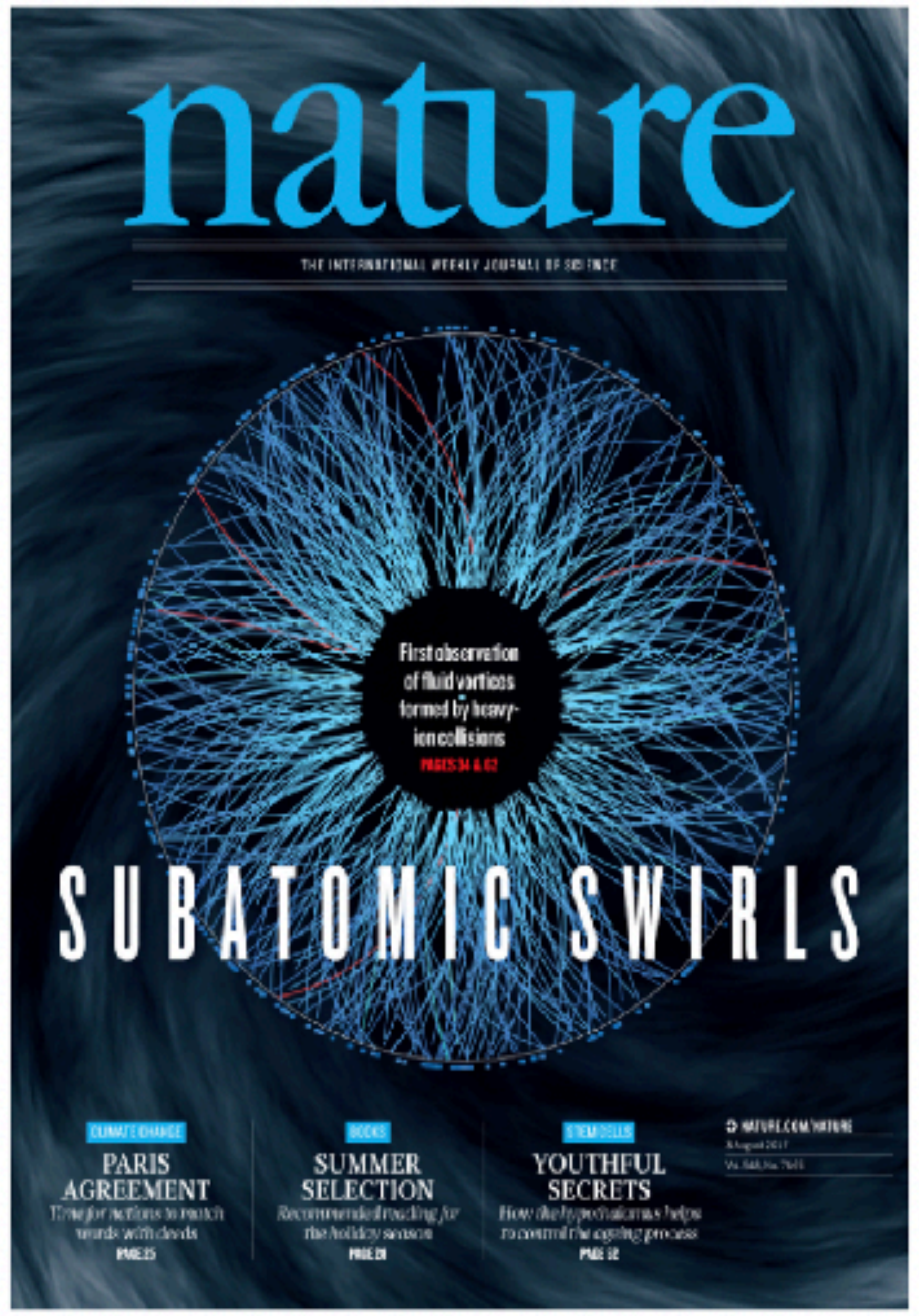


Huge orbital angular momentum → spin polarization of Λ hyperons emitted from the QGP

Strong force

The most vortical matter we know

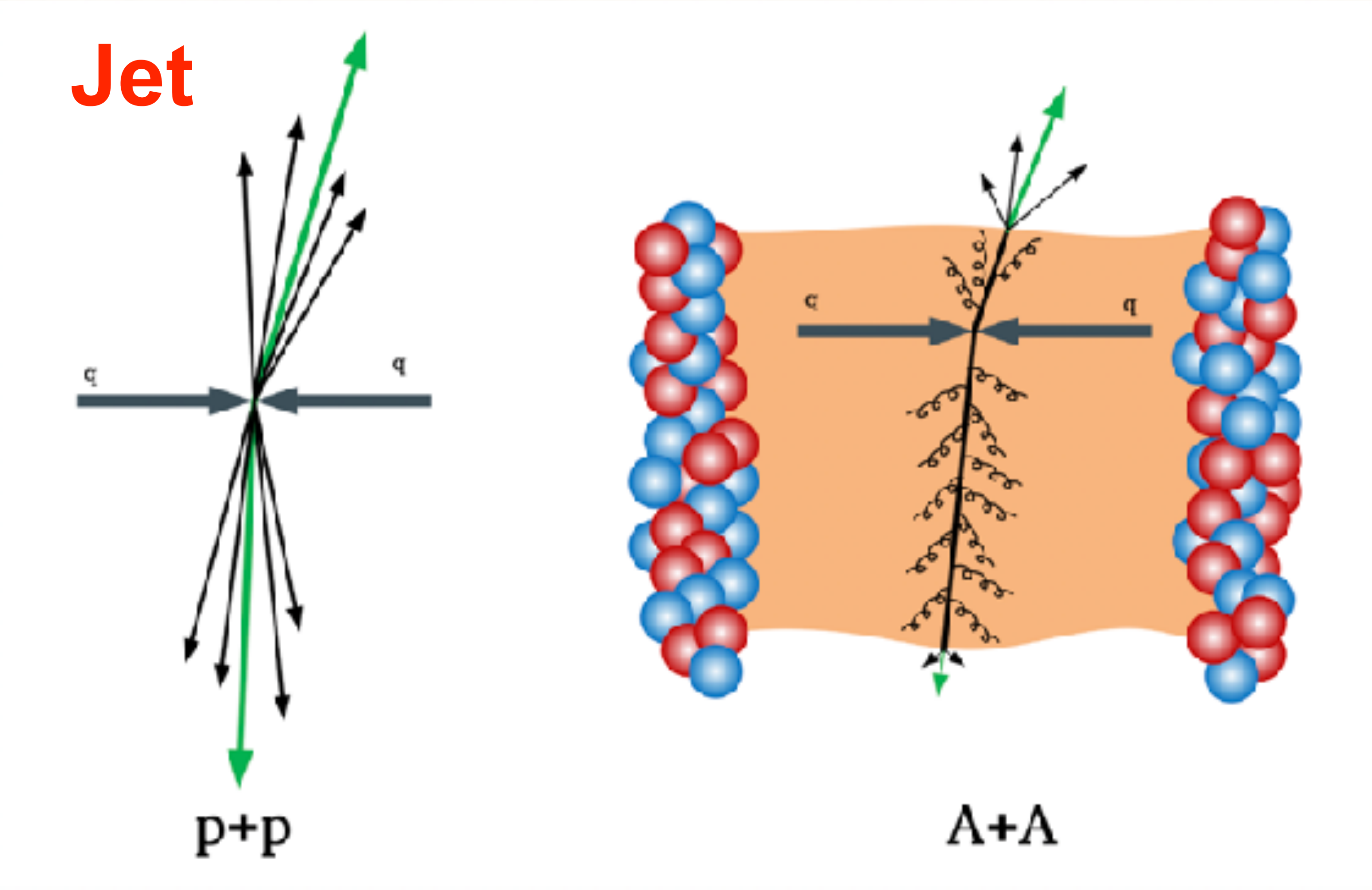




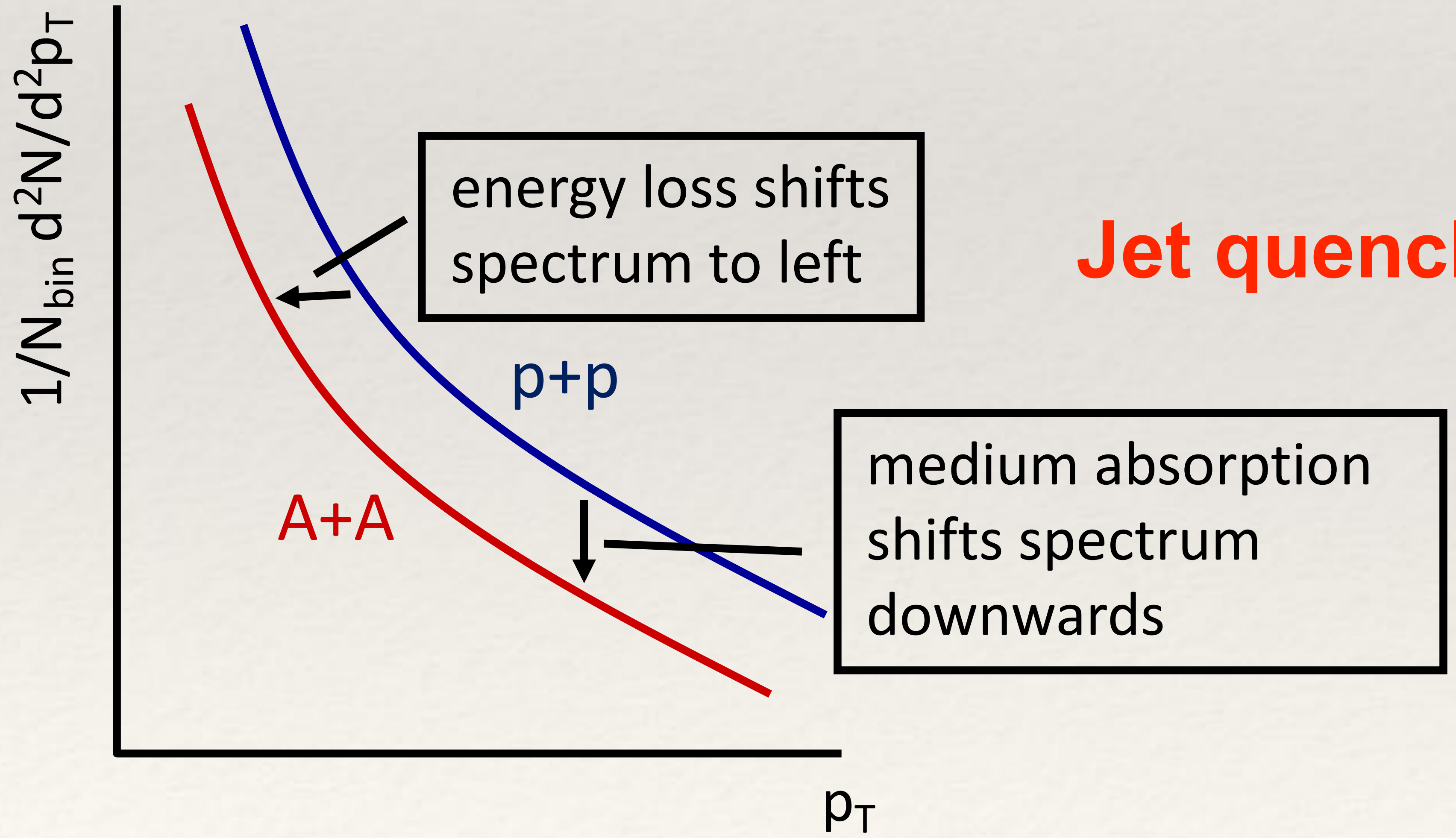
STAR, Nature 548 (2017) 62-65

$$\omega \sim (P_\Lambda + P_{\bar{\Lambda}})\, k_B T/\hbar \sim 10^{22}\,\mathrm{s}^{-1} \quad \sim 10^{21}$$ revolutions per second

Nuclear modification of high-energy particles



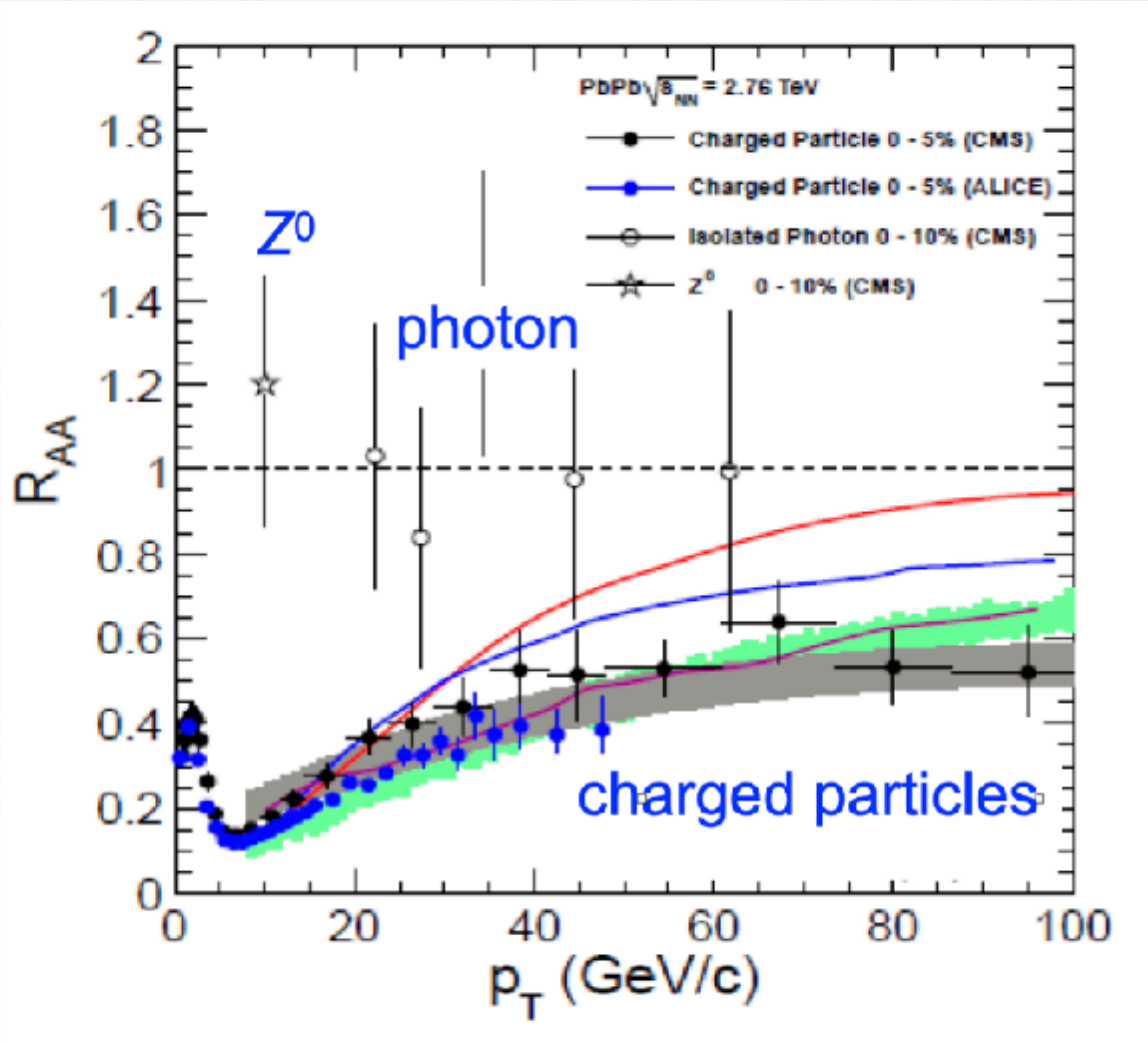
by M. Rybar / ATLAS



Jet quenching

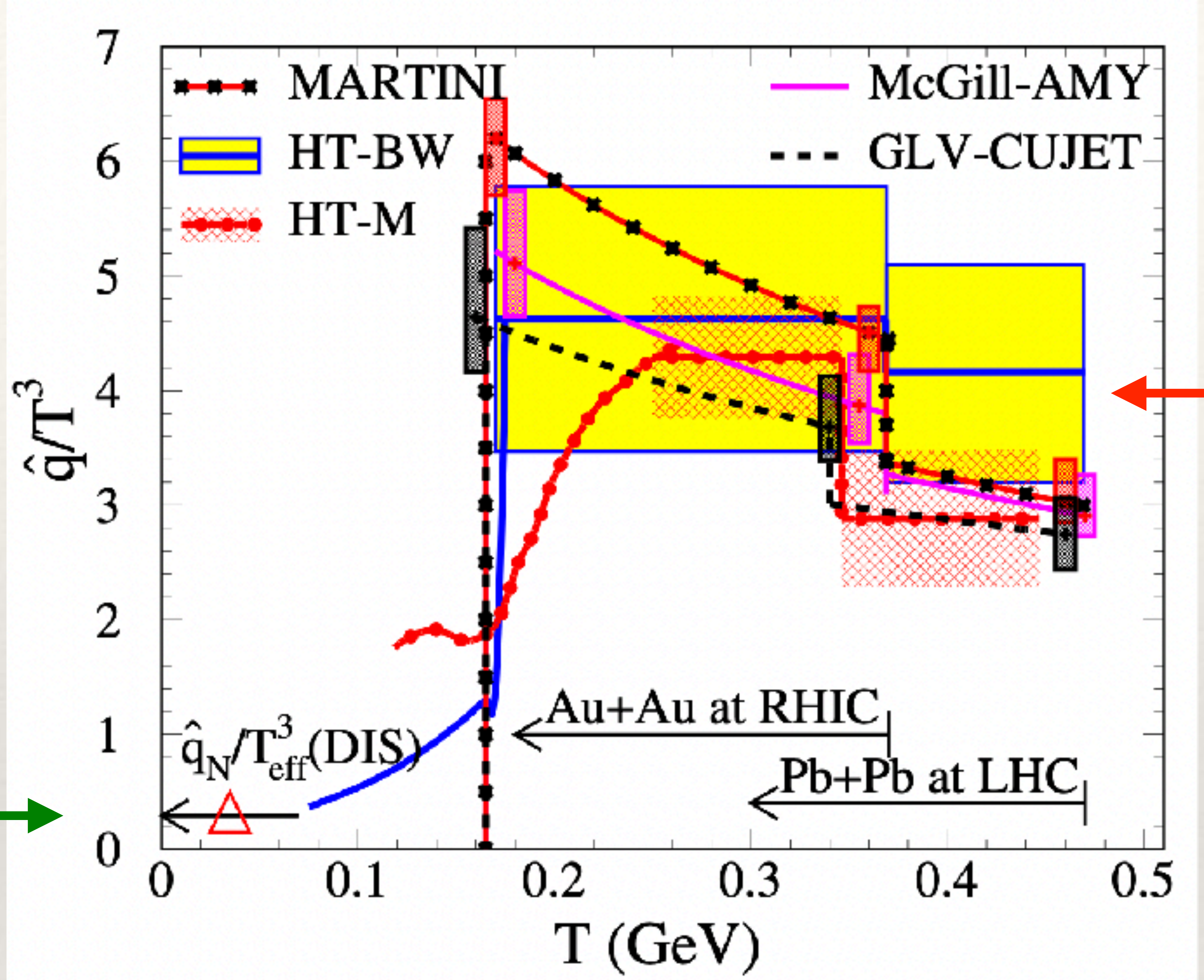
Nuclear modification factor

$$R_{AA} \equiv \frac{d^2N^{AA}/dydp_\perp}{d^2N^{pp}/dydp_\perp \times \langle N_{coll}^{AA} \rangle}$$



Mueller *et al.*, Ann. Rev. Nucl. Part. Sci. 62, 361 (2012)

The most opaque medium to energetic particles



cold nucleus

QGP

JET, Phys. Rev. C 90 (2014) 1, 014909

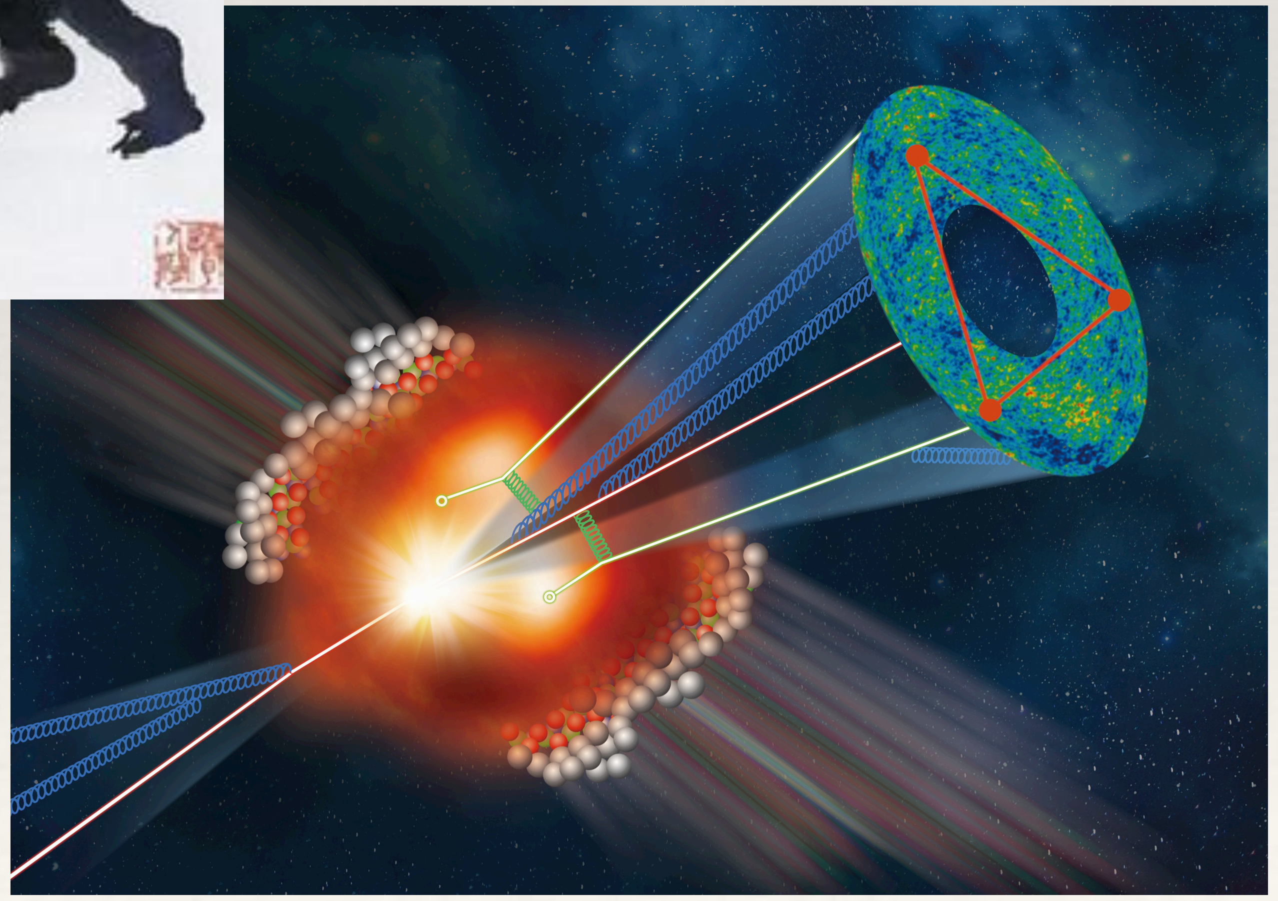
- Jet transport coefficient: $\hat{q} \equiv d\langle k_\perp^2 \rangle / dt$ (deflection by the medium per unit time)
- QGP is over 10 times more opaque to jets than regular (cold nuclear) matter

Summary: nuclear matter with extreme properties

Highest temperature

Smallest viscosity

Largest vorticity



Greatest opacity