Observation of the antimatter hypernucleus ${}^{4}_{\bar{\Lambda}}\bar{H}$ at STAR

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Road map

Hypernuclei

The Universe through time (mysterious antimatter)

QCD Phase Diagram

RHIC and STAR experiment

Major discoveries

- antimatter particles
- PID and signal detection
- antihypernuclei's lifetimes
- particles ratios and coalescence scenario

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What do we know from Wikipedia?

Hypernucleus

文A 16 languages

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From Wikipedia, the free encyclopedia

A **hypernucleus** is similar to a conventional atomic nucleus, but contains at least one hyperon in addition to the normal protons and neutrons. Hyperons are a category of baryon particles that carry non-zero strangeness quantum number, which is conserved by the strong and electromagnetic interactions.

A variety of reactions give access to depositing one or more units of strangeness in a nucleus. Hypernuclei containing the lightest hyperon, the lambda (Λ), tend to be more tightly bound than normal nuclei, though they can decay via the weak force with a mean lifetime of around 200 ps. Sigma (Σ) hypernuclei have been sought, as have doubly-strange nuclei containing xi baryons (Ξ) or two Λ's.

Nomenclature [edit]

Hypernuclei are named in terms of their atomic number and baryon number, as in normal nuclei, plus the hyperon(s) which are listed in a left subscript of the symbol, with the caveat that atomic number is interpreted as the total charge of the hypernucleus, including charged hyperons such as the xi minus (Ξ^-) as well as protons. For example, the hypernucleus $^{16}_{\Lambda}O$ contains 8 protons, 7 neutrons, and one Λ (which carries no charge).[1]

History [edit]

The first was discovered by Marian Danysz and Jerzy Pniewski in 1952 using a nuclear emulsion plate exposed to cosmic rays, based on their energetic but delayed decay. This event was inferred to be due to a nuclear fragment containing a Λ baryon.[2] Experiments until the 1970s would continue to study hypernuclei produced in emulsions using cosmic rays, and later using pion (π) and kaon (K) beams from particle accelerators.[1]

Since the 1980s, more efficient production methods using pion and kaon beams have allowed further investigation at various accelerator facilities, including CERN, Brookhaven National Laboratory, KEK, DAϕNE, and JPARC.[3][4] In the 2010s, heavy ion experiments such as ALICE and STAR first allowed the production and measurement of light hypernuclei formed through hadronization from quark–gluon plasma.[5]

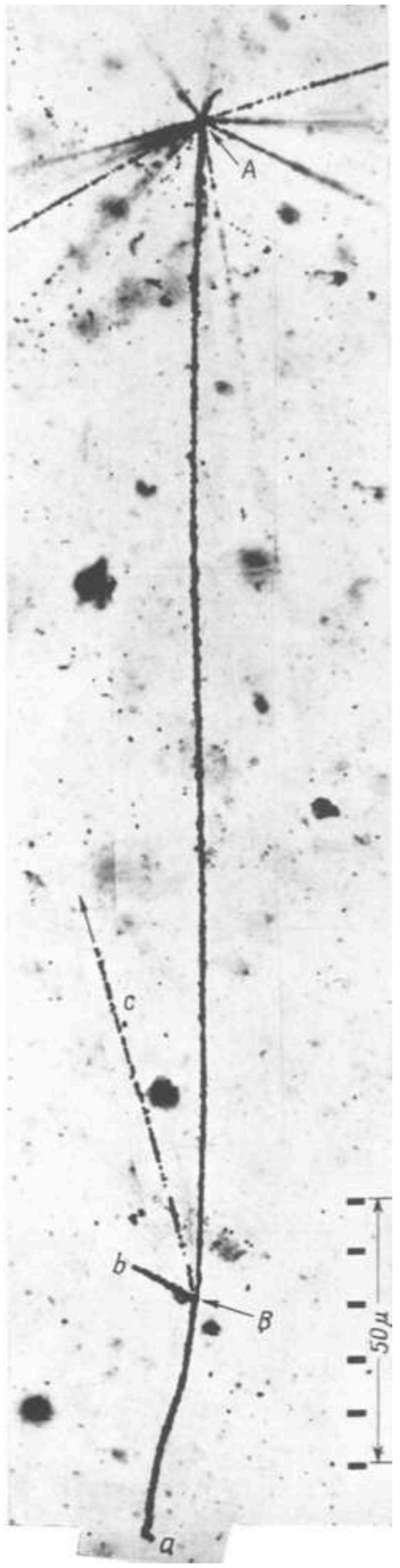
Discovery of the first hypernucleus

The first hypernucleus
was discovered in September 1952
by Marian Danysz and Jerzy Pniewski
in the University of Warsaw
physics laboratory at Hoża 69

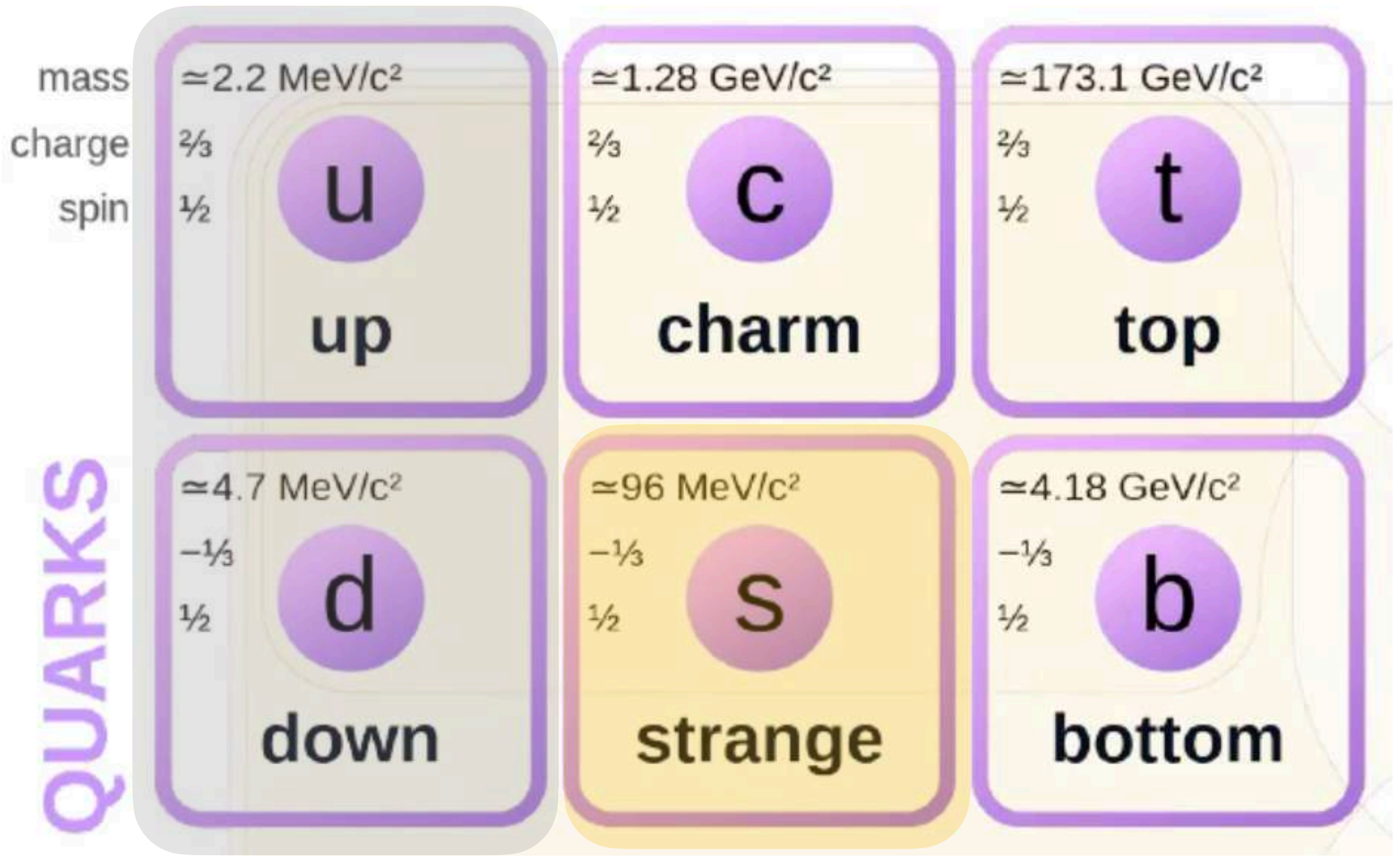
It happened during the time of confusion
concerning the newly discovered
heavy unstable particles.
The study of hypernuclei was of
considerable help in understanding
the properties of strange particles.

V particles discovered in 1947 had unusual properties

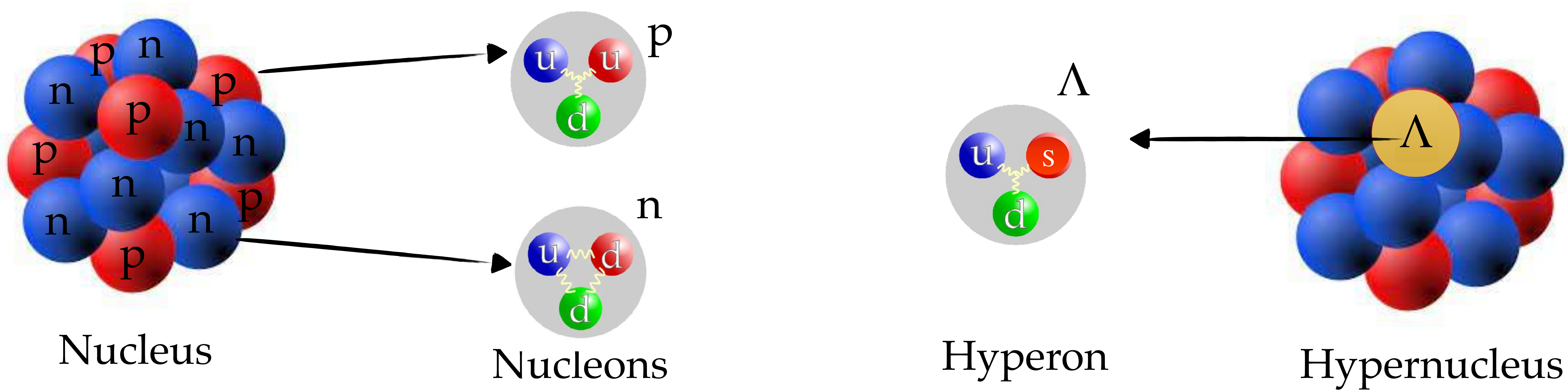
- They were copiously produced in high energy collisions (with cross section of a few percent of that for π production)
- Thus, if the same mechanism was responsible for their production and decay, their lifetime should be of the order of 10^{-21} s
- The observed lifetime was $\geq 10^{-10}$ s



Blocks of matter

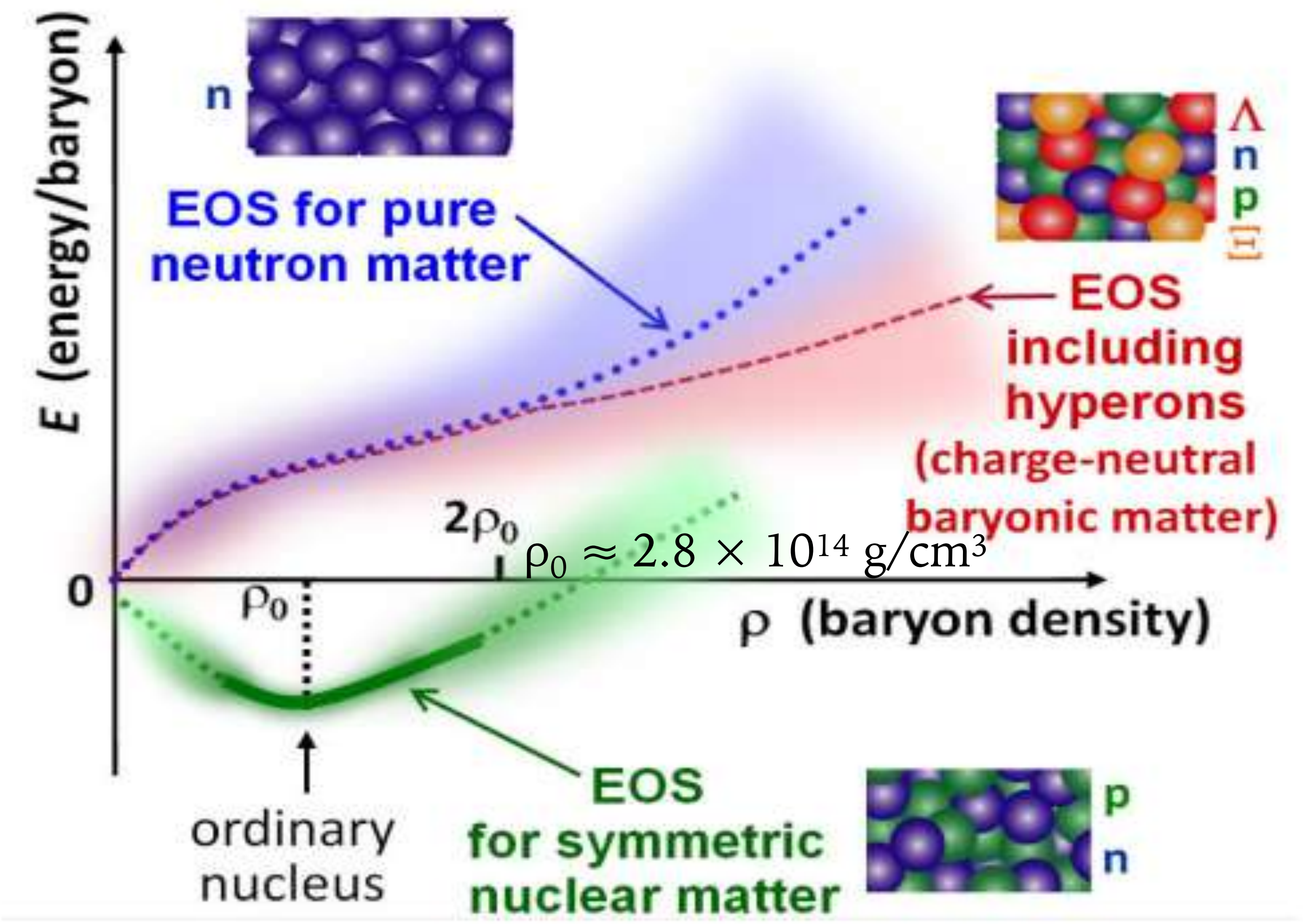


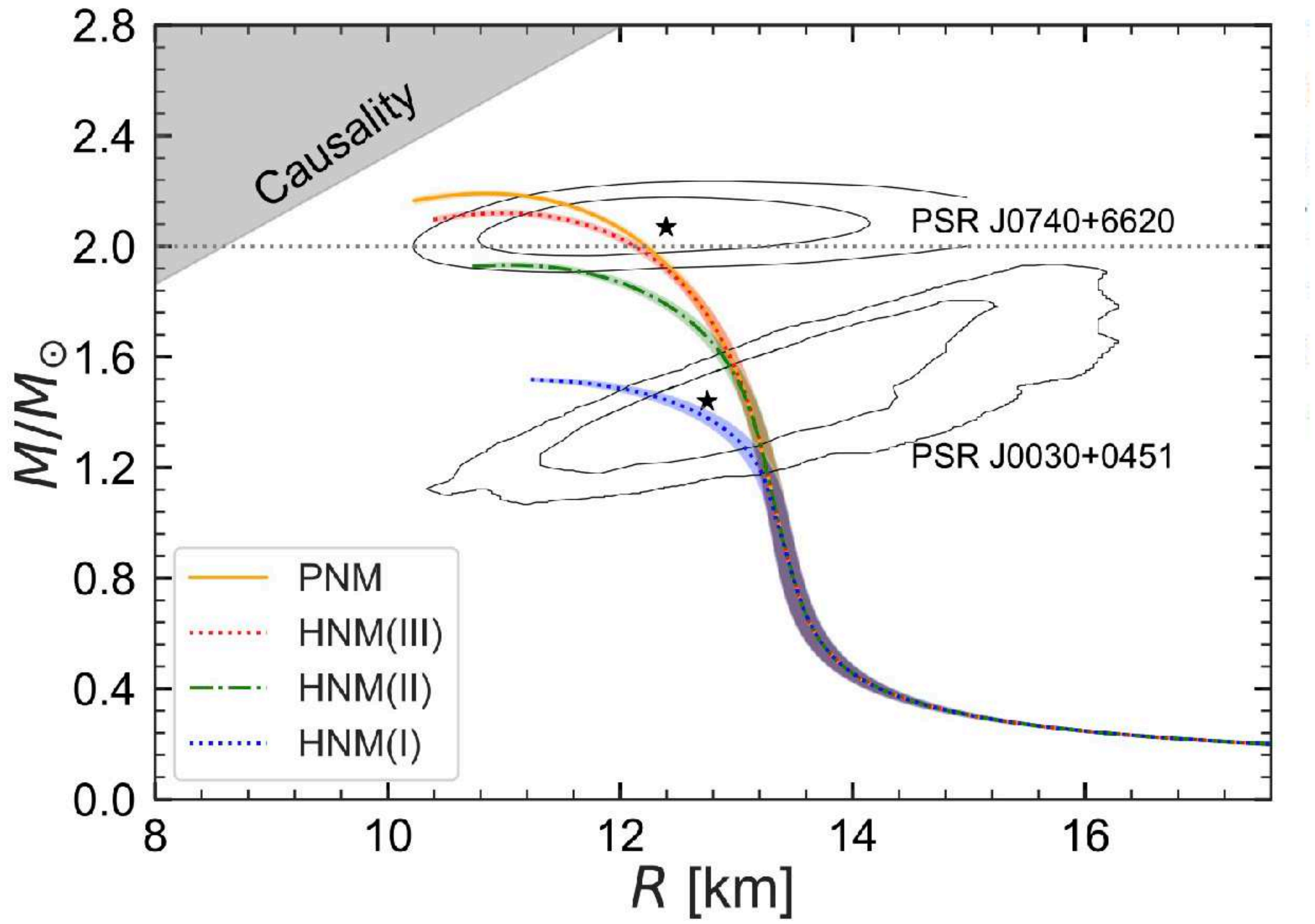
- **Six** flavours of quarks.
- The lightest ***up*** and ***down*** quarks constitute nucleons.
- The ***strange*** quark is the third lightest quark.
- Particles with strange quarks tend to **decay** (due to weak interaction).
- A baryon containing at least one strange quark - a **hyperon**.
- Nucleons form an atomic nucleus, hyperons and nuclei can also constitute a bound state - **hypernucleus**.



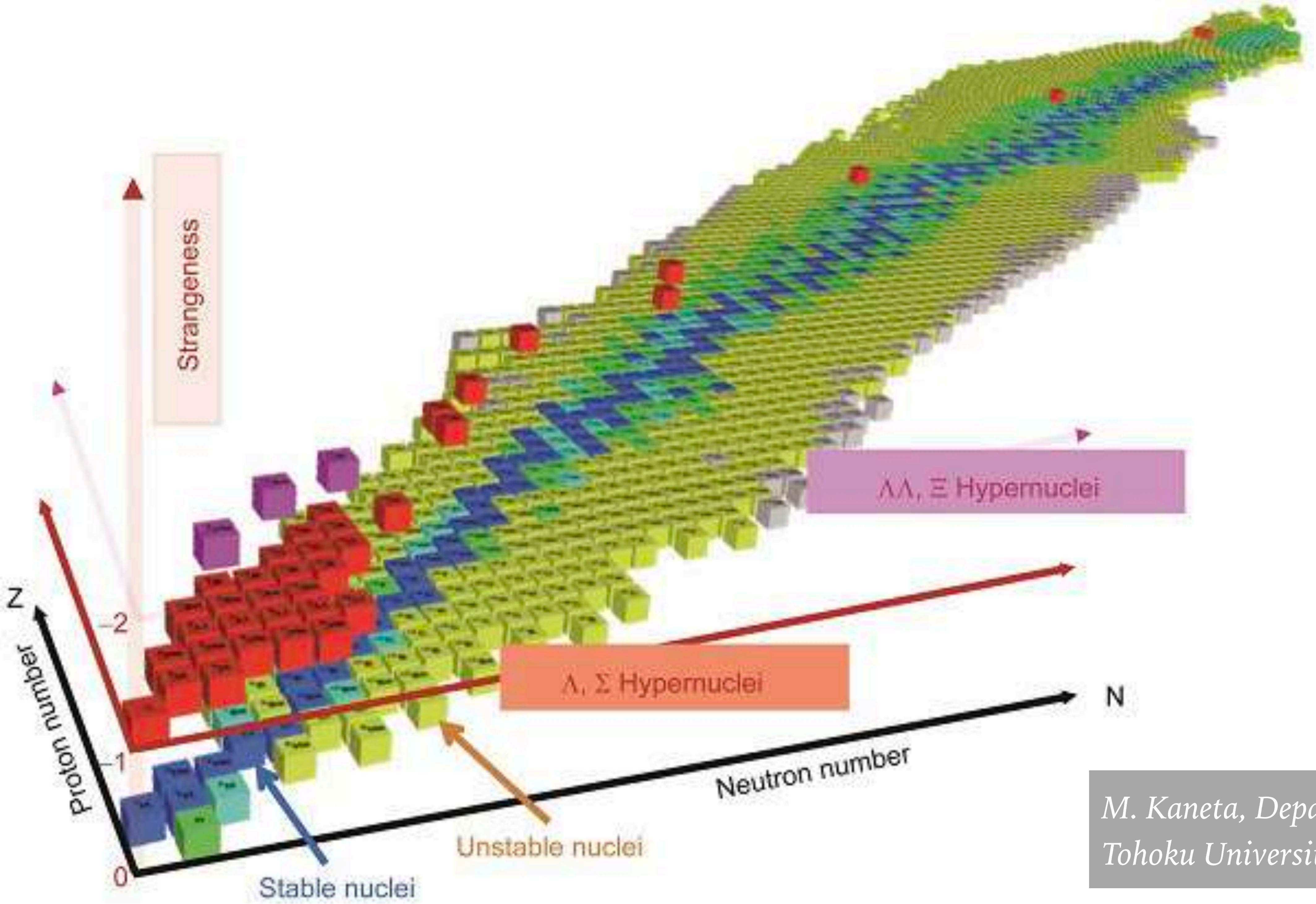
Neutron star (NS) puzzle

H.Tamura, JPS Conf. Proc. , 011003 (2014)





„To establish the EoS applicable to the neutron star has been one of the most important subjects in nuclear physics for a long time but has not been achieved yet." T. Hamura



M. Kaneta, Department of Physics, Tohoku University, Japan

Hypernuclei are pivotal for the EoS of the NS

- How do nuclei and hypernuclei form?
- What are their characteristics?
- How do nuclei (N) and hyperons (Y) interact?

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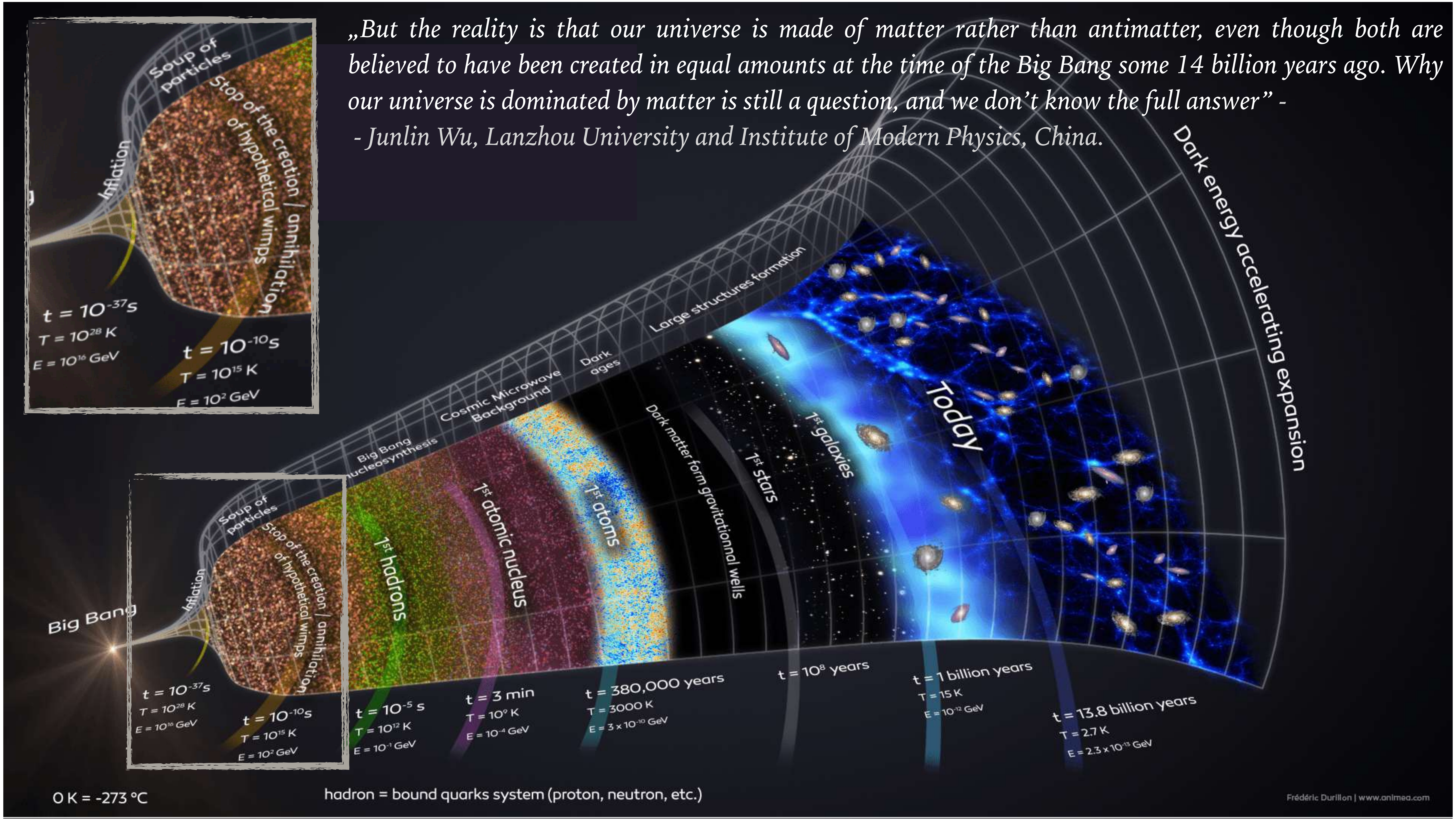
Universe evolution

Fot: BBC repository

Starting from Big Bang

„But the reality is that our universe is made of matter rather than antimatter, even though both are believed to have been created in equal amounts at the time of the Big Bang some 14 billion years ago. Why our universe is dominated by matter is still a question, and we don't know the full answer" -

- Junlin Wu, Lanzhou University and Institute of Modern Physics, China.



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- The Universe through time (mysterious antimatter)
- **QCD Phase Diagram**
- RHIC and STAR experiment
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  - PID and signal detection
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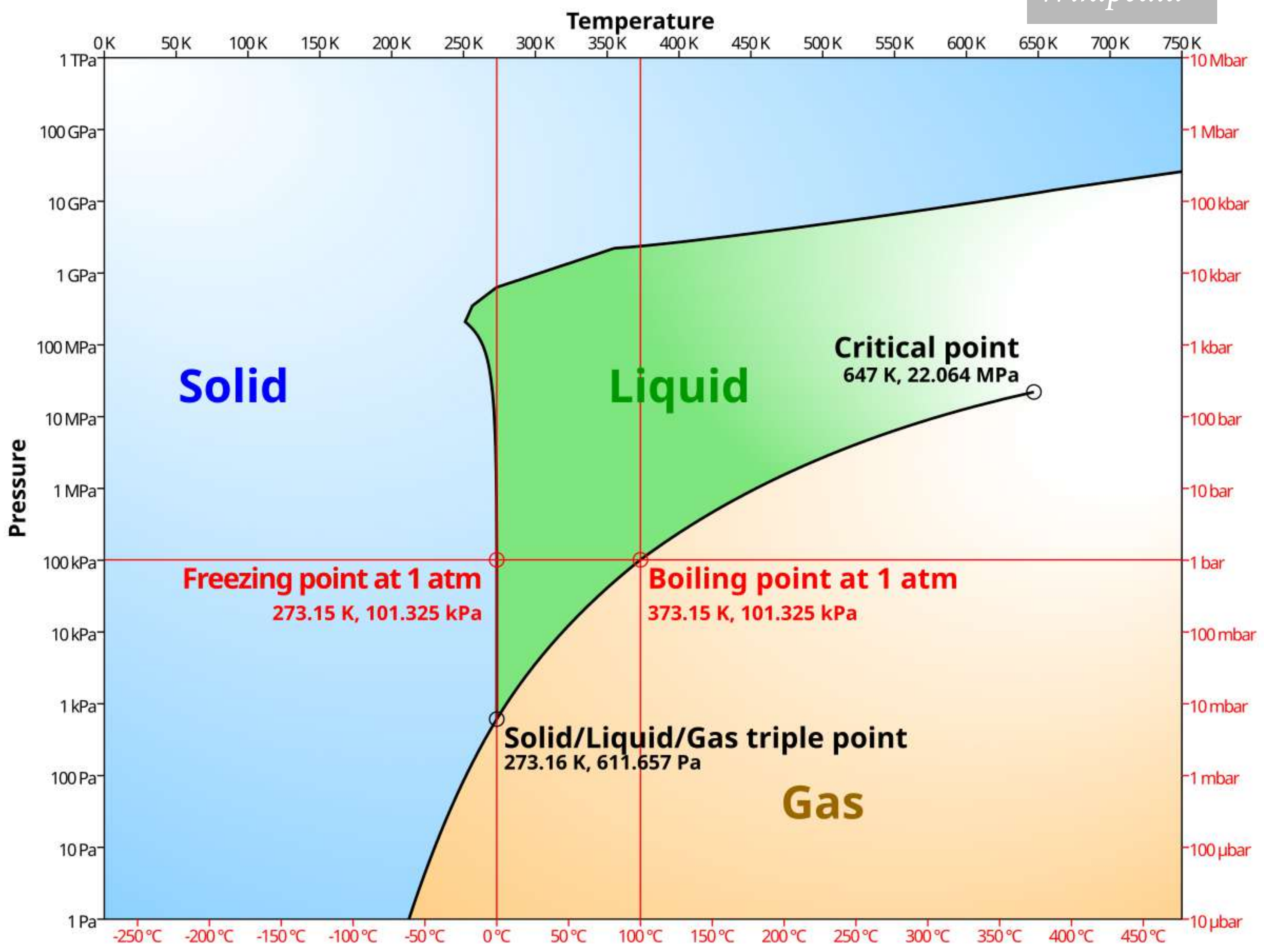
Water phase diagram

A **phase diagram** in physical chemistry, engineering, mineralogy, and materials science exhibits conditions (pressure, temperature, etc.) of phases coexisting at equilibrium.

Phase boundaries: multiple phases coexist together

Phase transitions along phase boundaries

Wikipedia



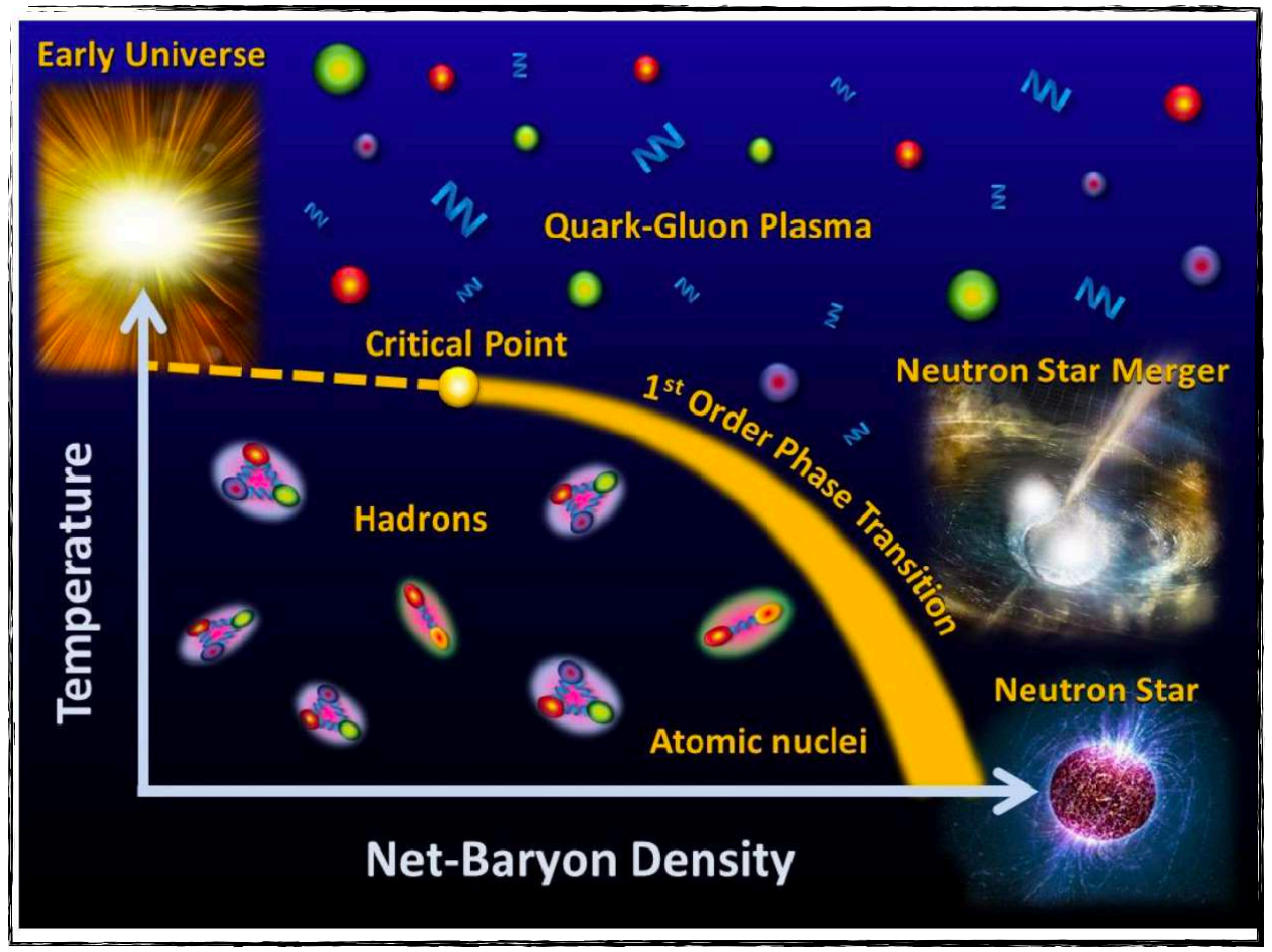
QCD **phase diagram**

Collisions of heavy-ions at various $\sqrt{s_{NN}}$ probe different areas of the QCD diagram.

- early Universe
- critical point, first order phase transition
- **neutron star merger, neutron star**

$\sqrt{s_{NN}}$

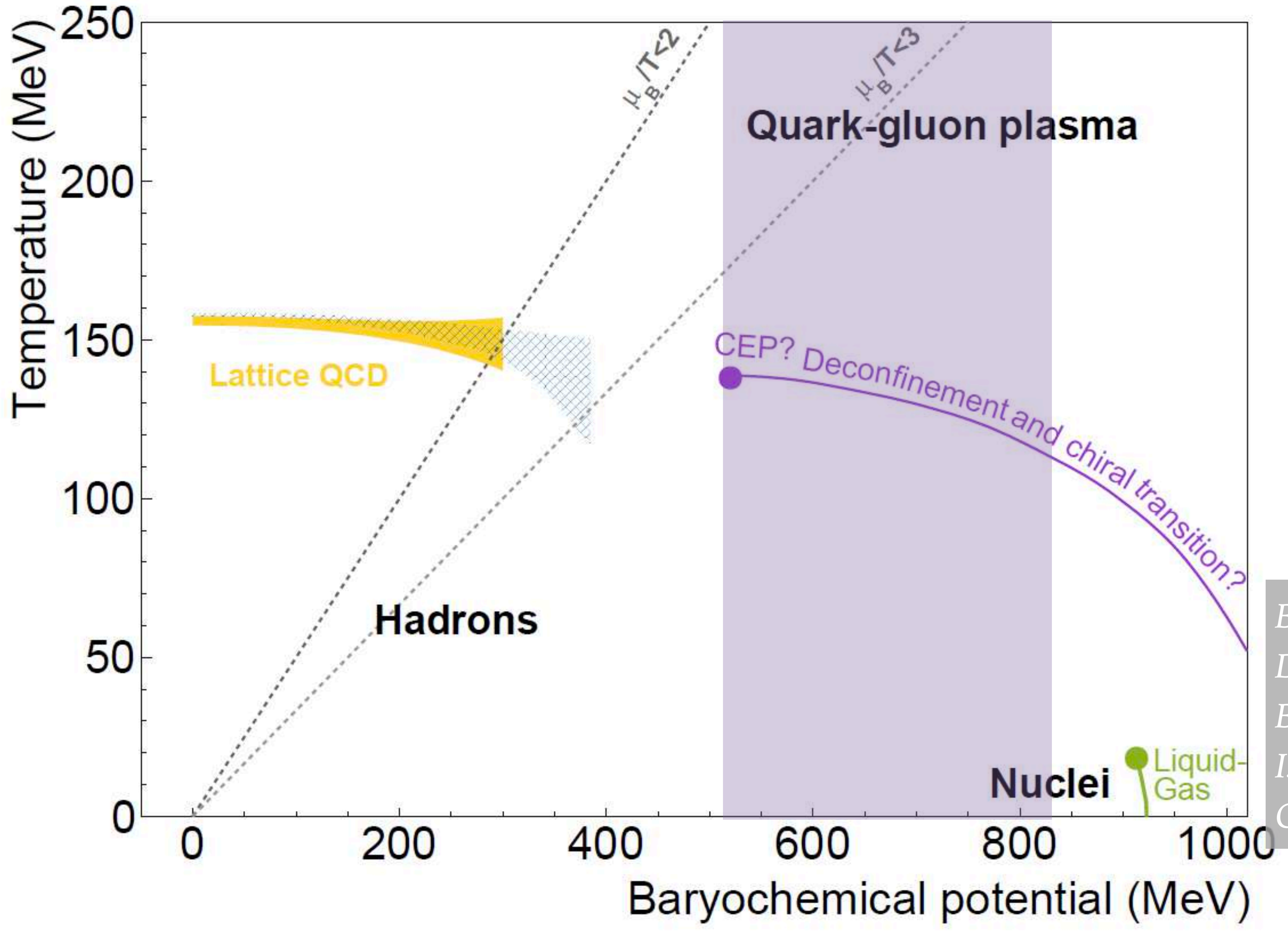
Nucl. Phys. News 2018, 28, 23



QCD Phase Diagram

Low μ_B, hight T:

- **Cross-over** transition from hadronic to quark matter - comprehensive studies of **QGP** properties
- No **critical point** anticipated for $\mu_B/T < 3$ (LQCD)

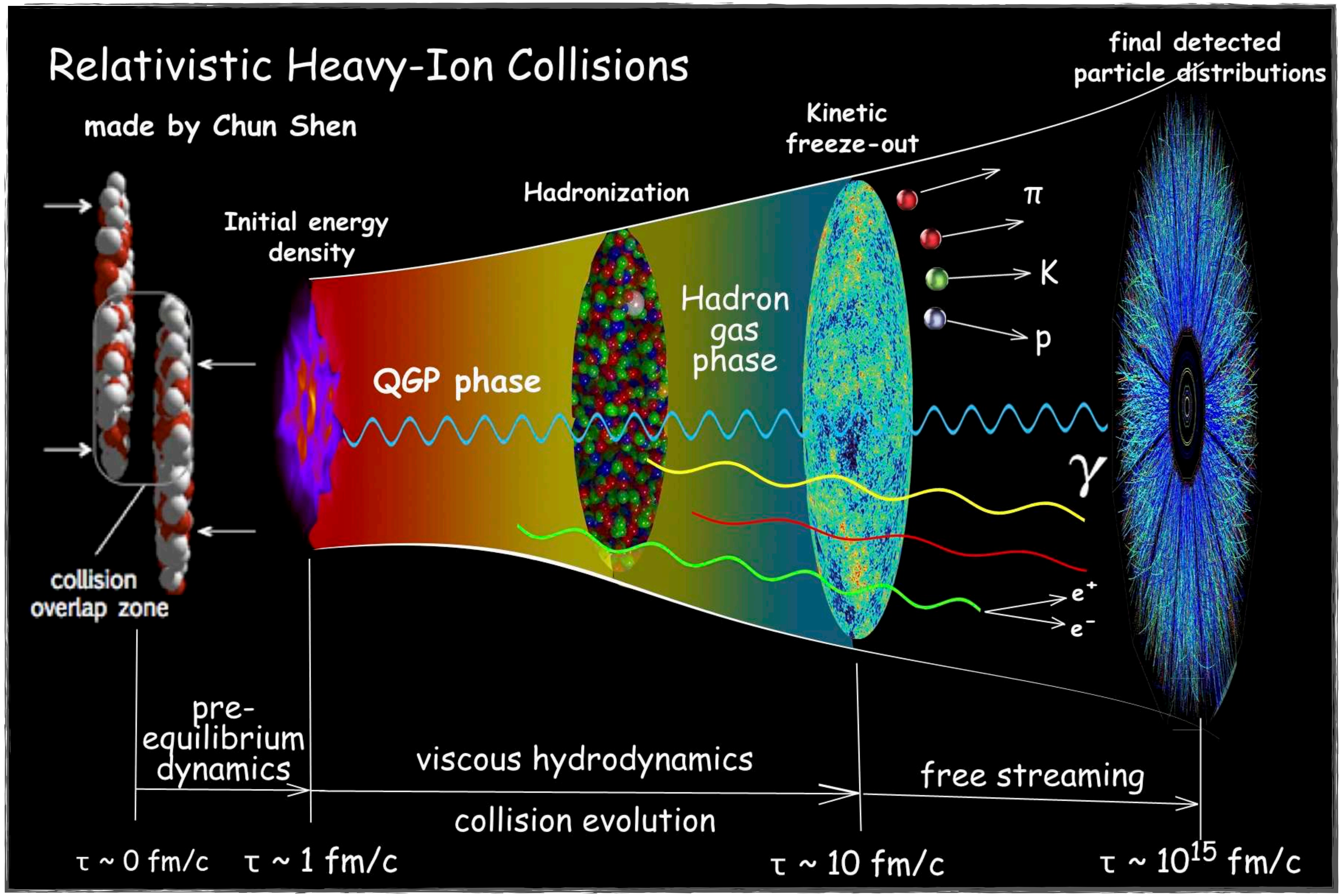


Bazavovet al.[HotQCD], PLB 795 (2019) 15-21
Dinget al., [HotQCD], PRL 123 (2019) 6, 062002
Borsanyiet al., PRL125(2020)5,052001
Isserstedt et al. PRD 100 (2019) 074011
Gao, Pawlowski, PLB 820 (2021) 136584

High μ_B, low T:

- Unknown **phase structure** (first-order phase transition, critical point possible, mixed phases, new phases, …)
- Properties of matter to determine
- Characteristics of hadrons
- Equation of State (**EoS**) to establish
- Neutron Star (**NS**)

Heavy-ion collisions at the highest collision energies



- Antimatter annihilates with matter.
- It is difficult to observe antimatter particles.
- Relativistic heavy-ion collisions can create the quark–gluon plasma with nearly equal amounts of matter and antimatter.
- The collision system expands and cools rapidly, allowing some antimatter to decouple from matter.
- Heavy-ion collisions are an effective tool to create and study antimatter nuclei or hypernuclei.

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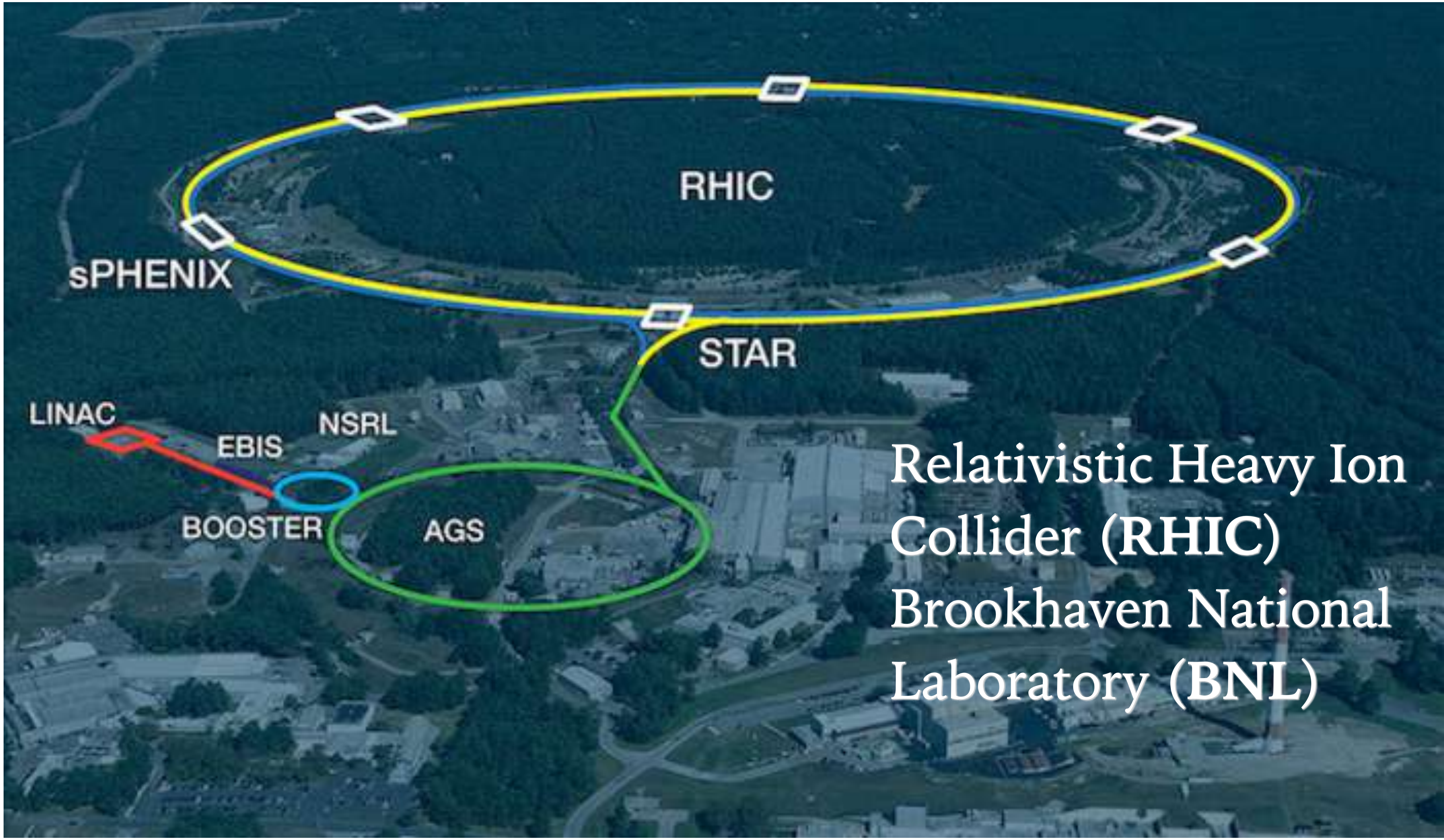
Relativistic Heavy Ion Collider

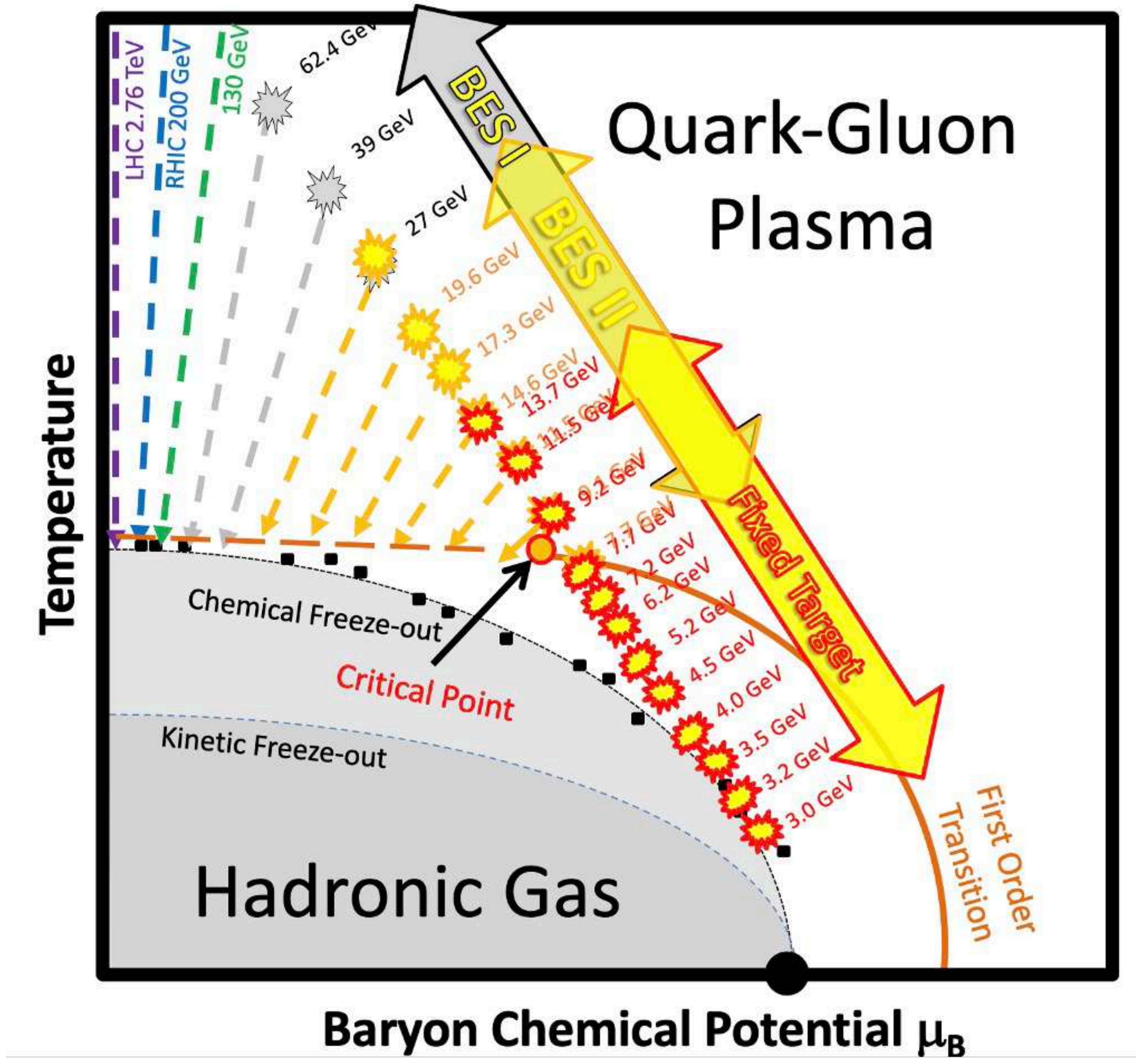
- 3.83 km circumference
- Two independent rings
- Collides so far:
  - Au+Au, p+p, d+Au, Cu+Cu, U+U, Cu+Au, ^{3}He+Au, p+Au Zr+Zr, Ru+Ru
- Top Center-of-Mass Energy
  - 510 GeV for p-p
  - 200 GeV/nucl. for Au-Au

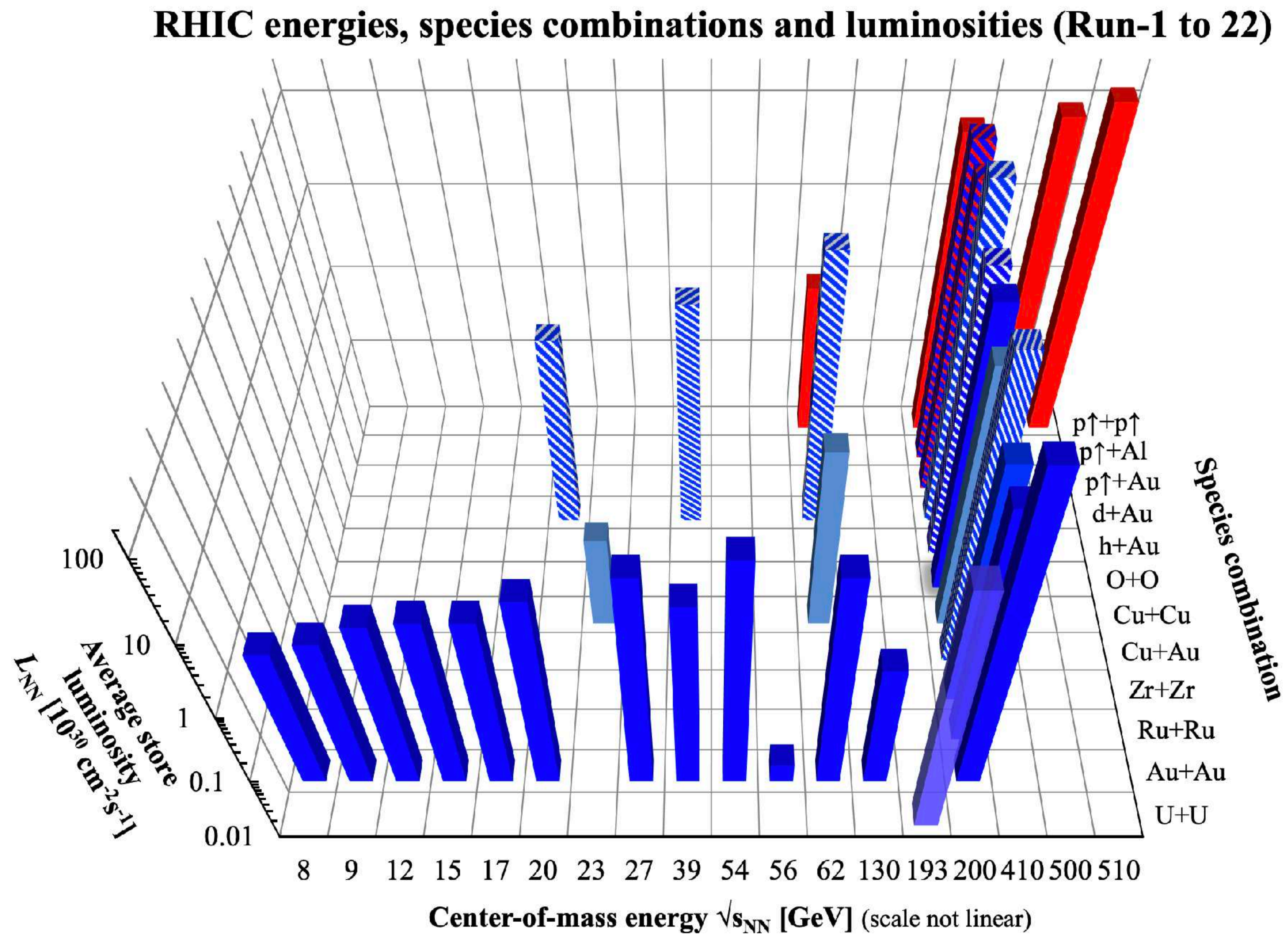


Solenoidal Tracker At RHIC

Versatile experiment + Many detector subsystems →
Varied and interesting program to better understand Quantum Chromodynamics

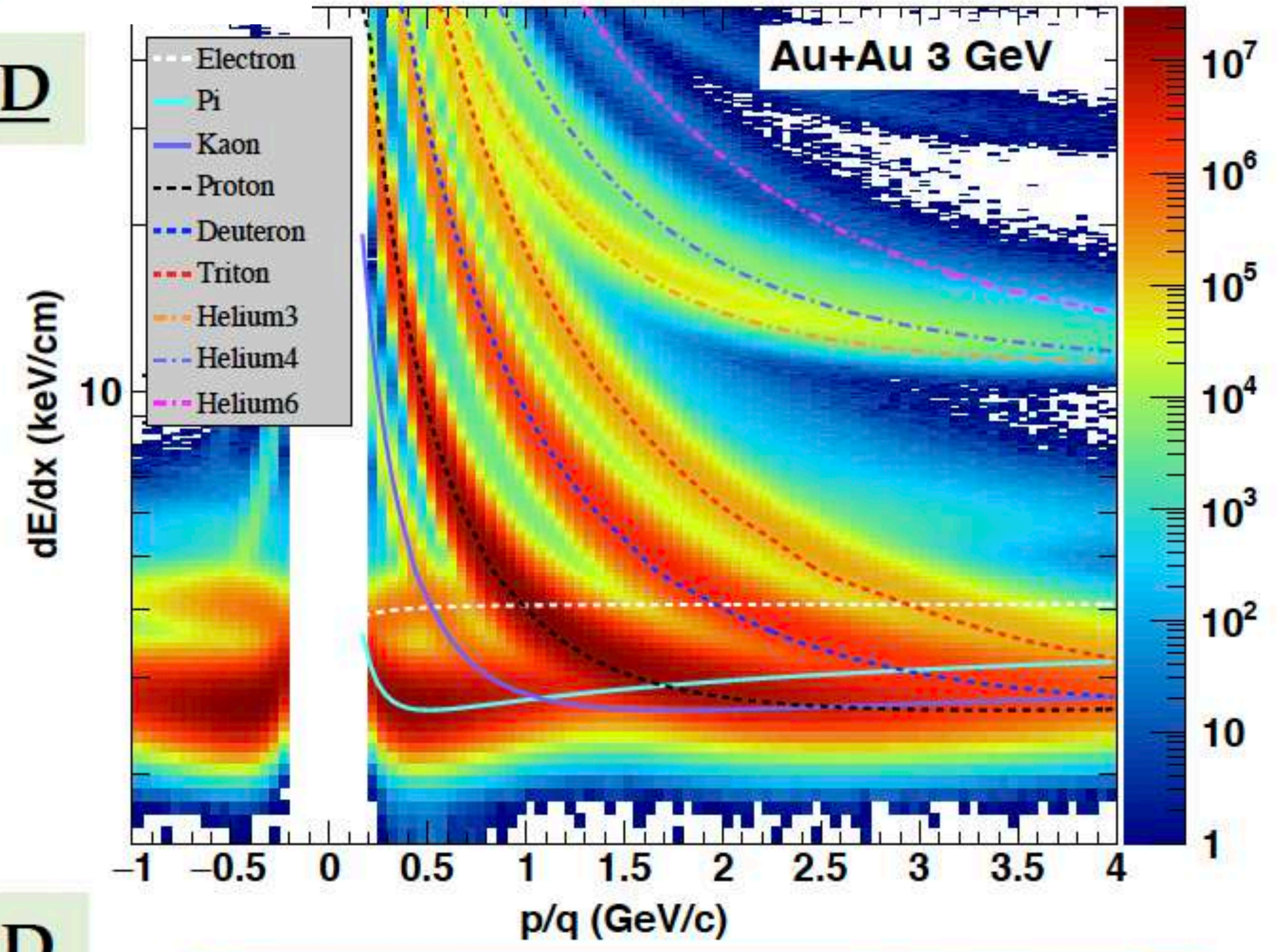
- Beam Energy Scan
- System Size at top RHIC Energy
- Exploring QGP Dynamical Structure
- Electro-Magnetic Probes
- Hard Probes
- Understanding QCD and Nucleons



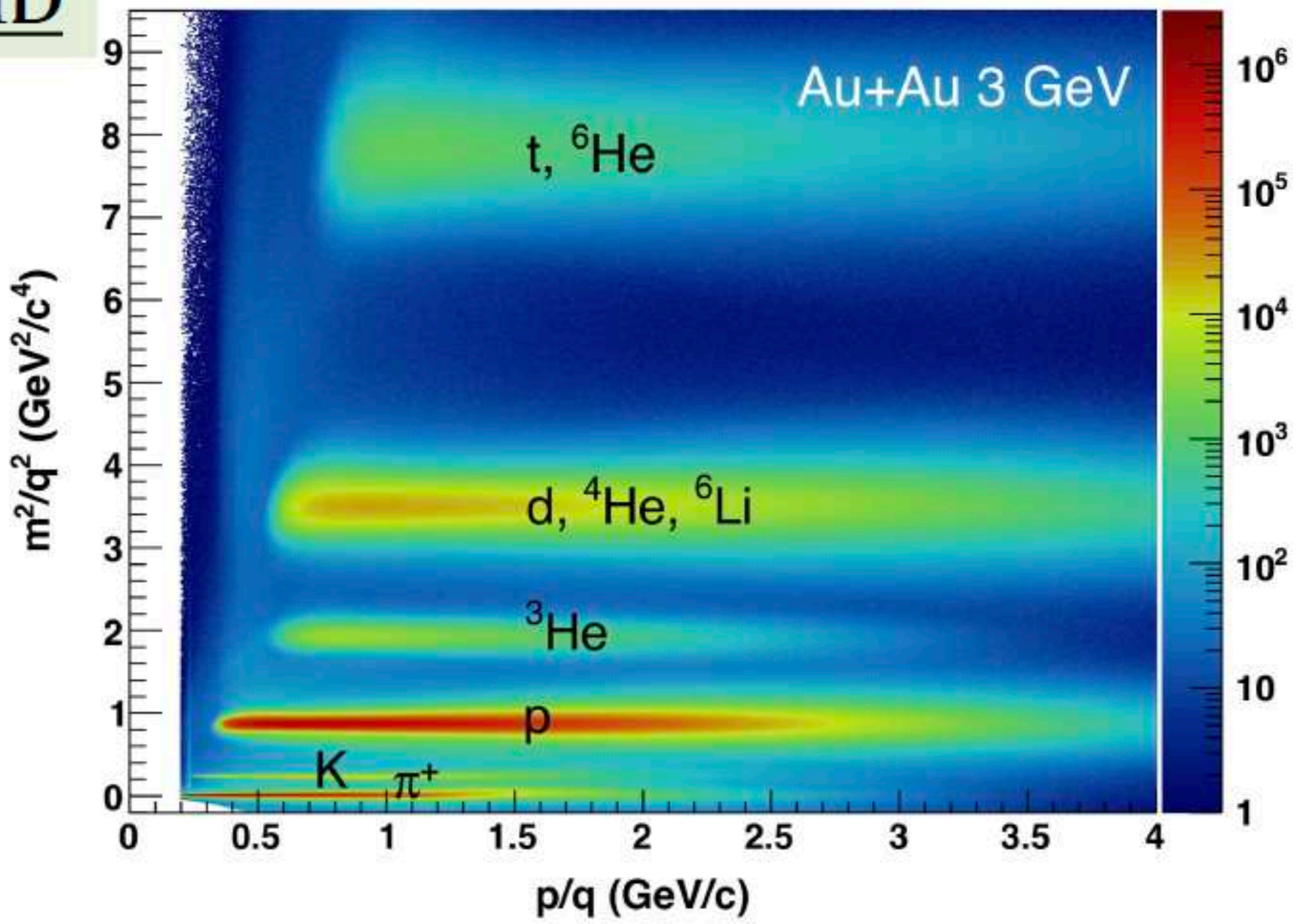


Particle identification at STAR

TPC PID



TOF PID



Excellent particle identification due to combined information from Time Projection Chamber and Time of Flight detectors.

Unique *mass/dEdx* separation for
$\pi, K, p, d, t, {}^{3}He, {}^{4}He, {}^{6}He, {}^{6}Li$.

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Article | Published: 21 August 2024

Observation of the antimatter hypernucleus ${}^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$

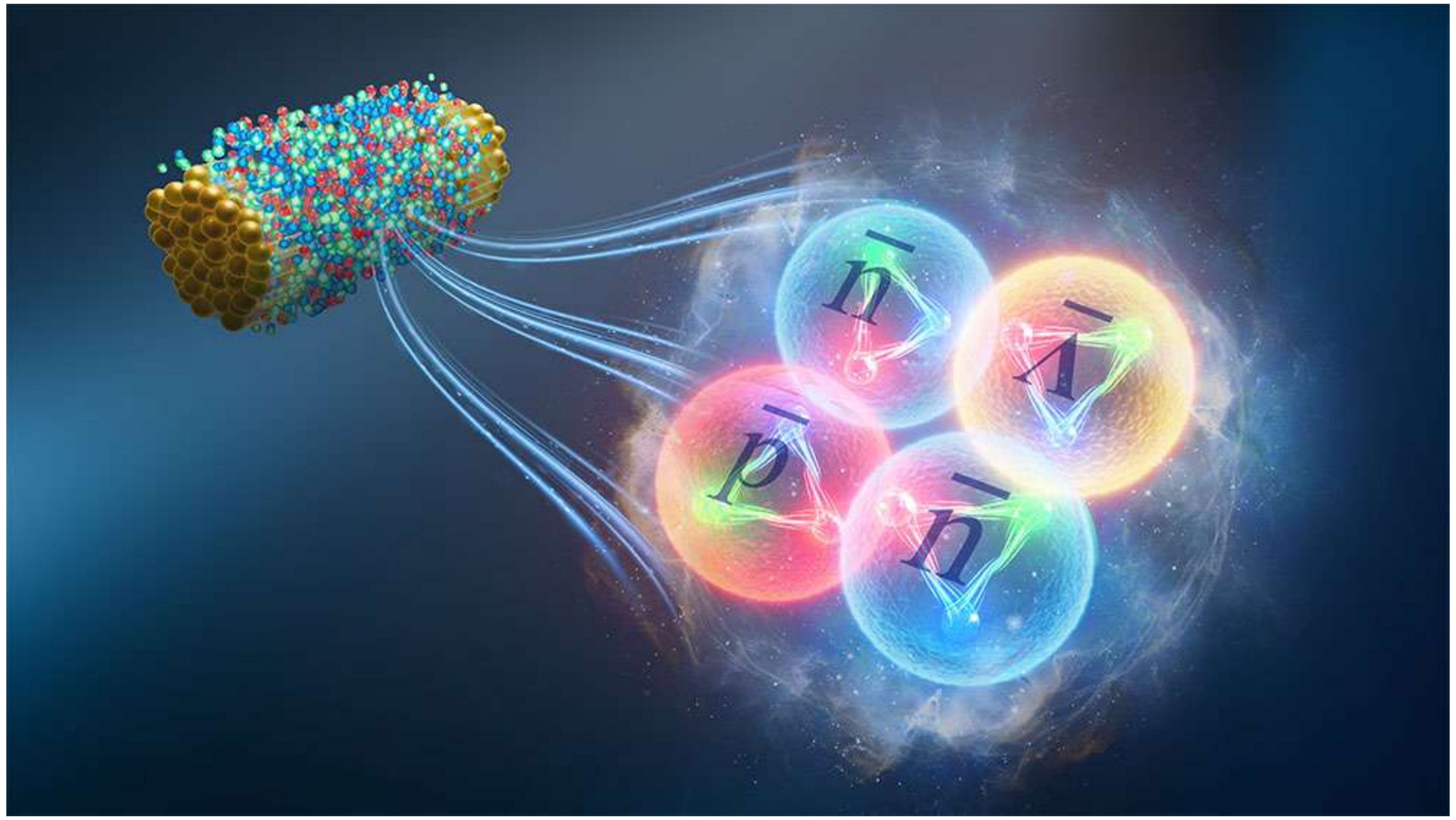
STAR Collaboration

Nature **632**, 1026–1031 (2024) | Cite this article

Abstract

At the origin of the Universe, an asymmetry between the amount of created matter and antimatter led to the matter-dominated Universe as we know it today. The origins of this asymmetry remain unknown so far. High-energy nuclear collisions create conditions similar to the Universe microseconds after the Big Bang, with comparable amounts of matter and antimatter[1,2,3,4,5,6]. Much of the created antimatter escapes the rapidly expanding fireball without annihilating, making such collisions an effective experimental tool to create heavy antimatter nuclear objects and to study their properties[7,8,9,10,11,12,13,14], hoping to shed some light on the existing questions on the asymmetry between matter and antimatter. Here we report the observation of the antimatter hypernucleus ${}^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$, composed of a $\bar{\Lambda}$, an antiproton and two antineutrons. The discovery was made through its two-body decay after production in ultrarelativistic heavy-ion collisions by the STAR experiment at the Relativistic Heavy Ion Collider[15,16]. In total, 15.6 candidate ${}^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$ antimatter hypernuclei are obtained with an estimated background count of 6.4. The lifetimes of the antihypernuclei ${}^{3}_{\bar{\Lambda}}\bar{\mathrm{H}}$ and ${}^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$ are measured and compared with the lifetimes of their corresponding hypernuclei, testing the symmetry between matter and antimatter. Various production yield ratios among (anti)hypernuclei (hypernuclei and/or antihypernuclei) and (anti)nuclei (nuclei and/or antinuclei) are also measured and compared with theoretical model predictions, shedding light on their production mechanisms.

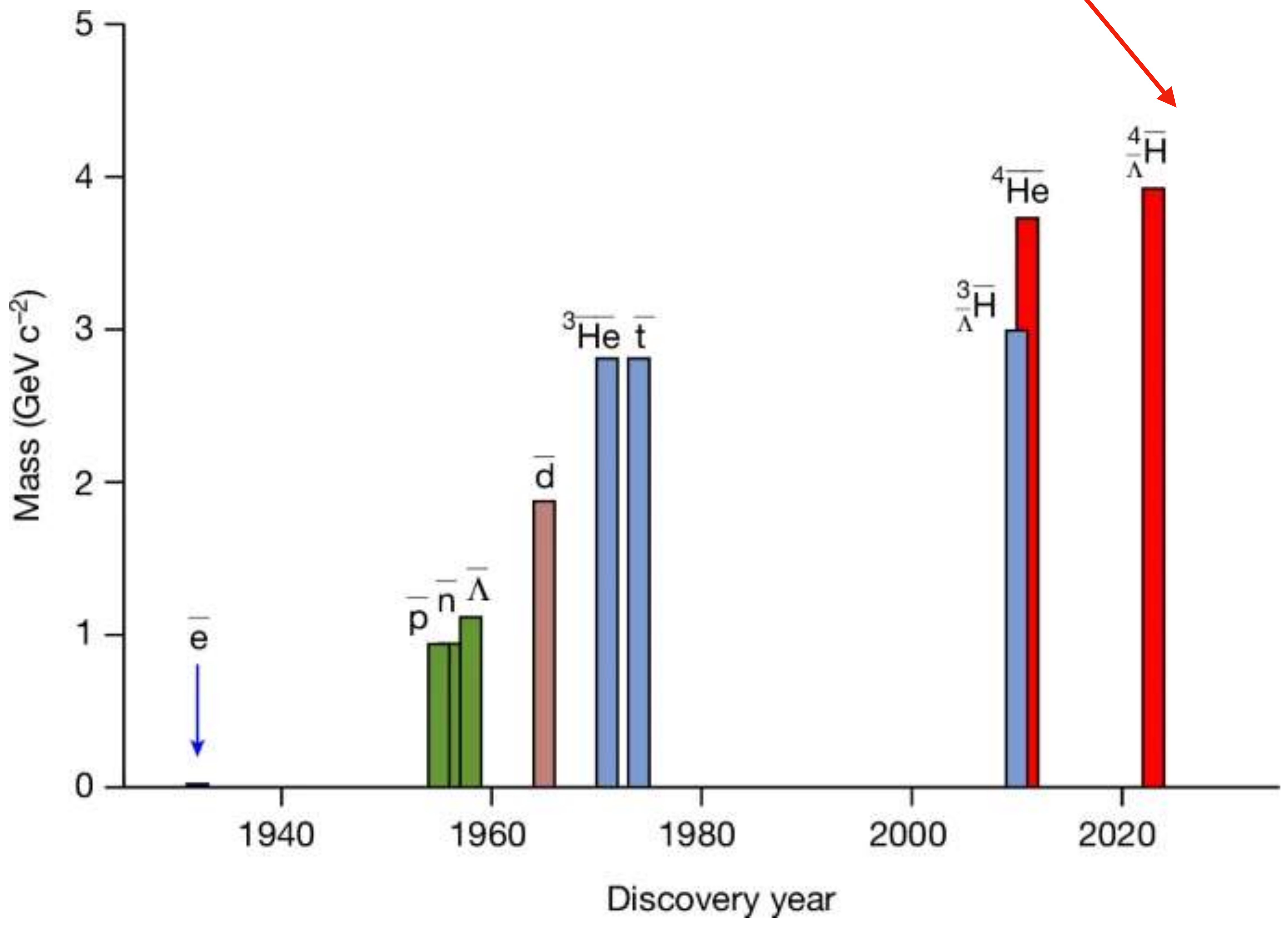
Recent STAR findings



Courtesy of Institute of Modern Physics, China

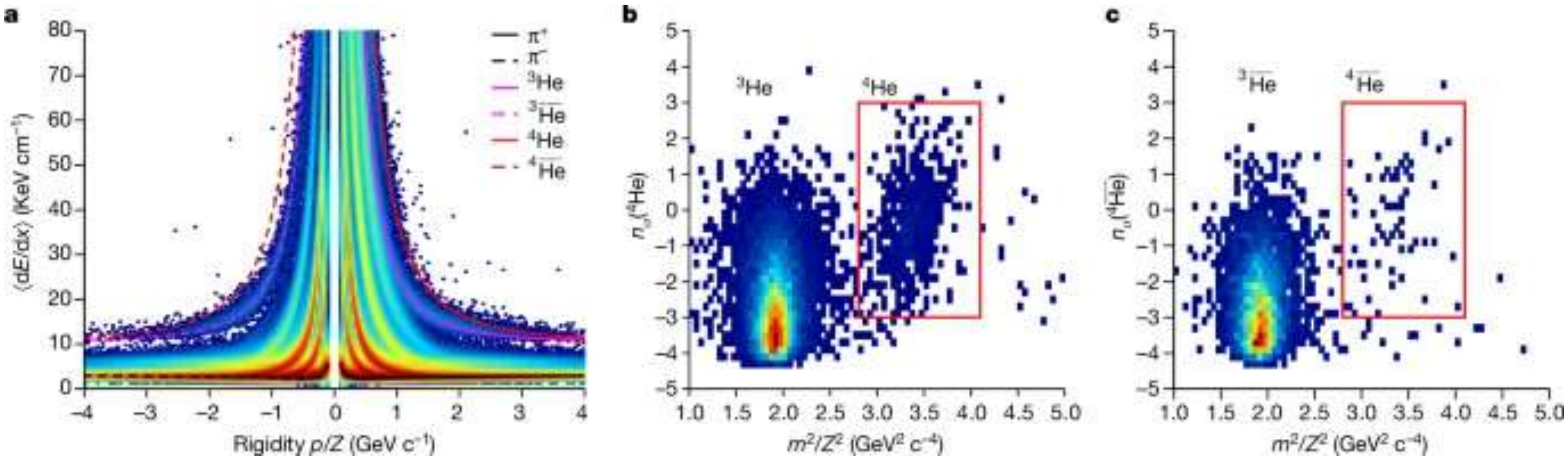
Discoveries of antimatter particles

The heaviest antimatter hypernuclear cluster observed until now



- 1928: Paul Dirac found possible solutions with positive and **negative energies** to his equation (describes the **relativistic quantum behaviour of the electron**).
- The negative-energy solution indicates **a new particle with the same mass** as an electron, but with opposite charge.
- 1932: Carl Anderson discovered in cosmic rays new particle - **positron**
- Theoretical framework and the experimental foundation for the study of **antimatter** established.
- New, heavier and more complicated **antimatter particles** are discovered and their properties are studied.

Particle identification



- Particle **identification**: $dE/dx(p/Z)$ and m^2/Z^2 (TPC and ToF)
  6.4 billion U + U, Au + Au, Ru + Ru and Zr + Zr collisions

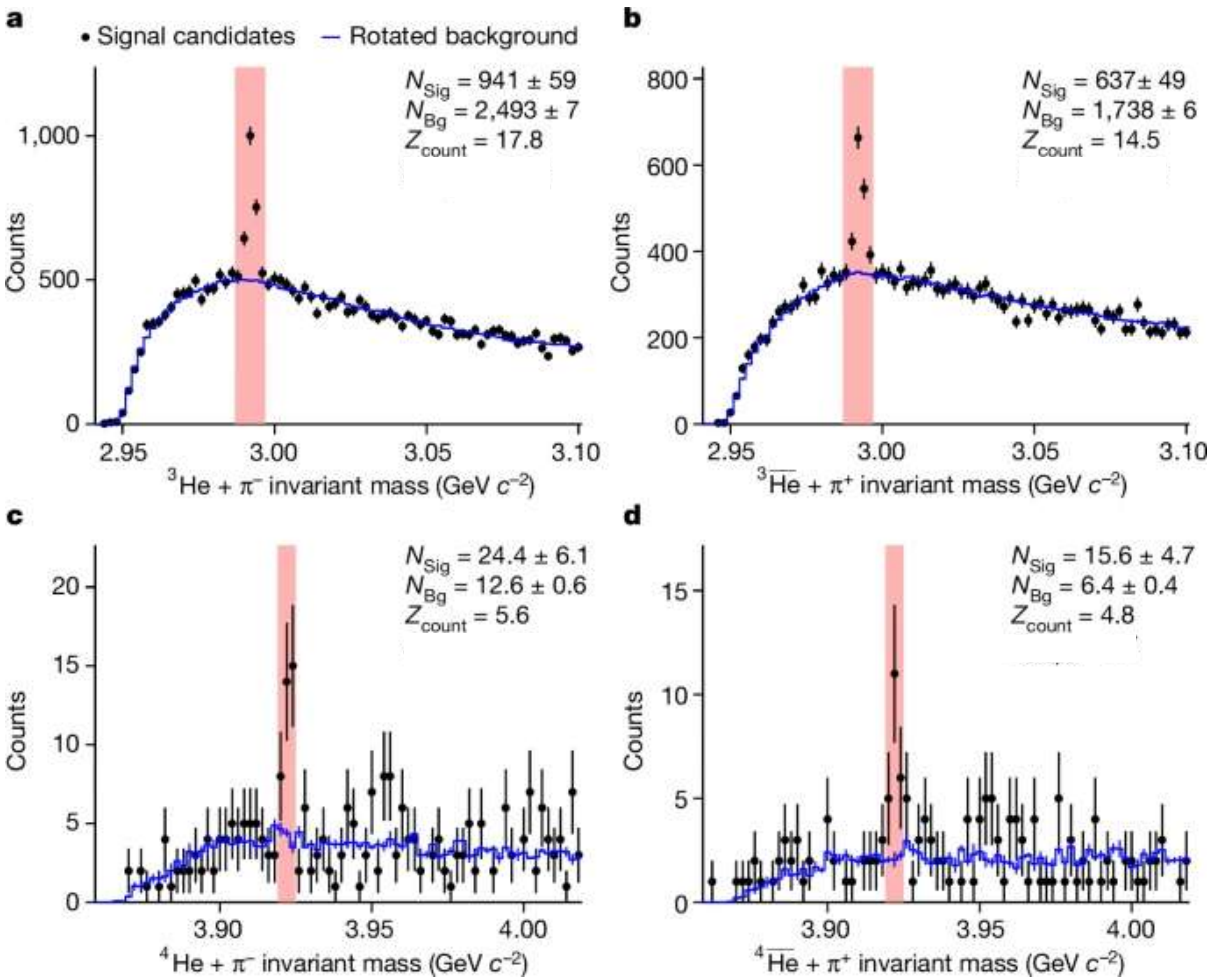
- Once created (anti)hypernuclei - fly ∼ few cm, then decay
- (anti)hypernucleus **reconstructed** by tracing back the daughter tracks to the decay point.

$$^3_\Lambda H \rightarrow ^3 He + \pi^- \qquad ^4_\Lambda H \rightarrow ^4 He + \pi^-$$
$$^3_\Lambda \bar{H} \rightarrow ^3 \bar{H}e + \pi^+ \qquad ^4_\Lambda \bar{H} \rightarrow ^4 \bar{H}e + \pi^+$$

$$n_\sigma = ln(\frac{< dE/dx >}{< dE/dx >_{th}})/\sigma_{dE/dx}$$

Signals detection

$$m_{inv} = \sqrt{(E_{He} + E_{\pi})^2 - (\mathbf{p_{He}} + \mathbf{p}_{\pi})^2}$$



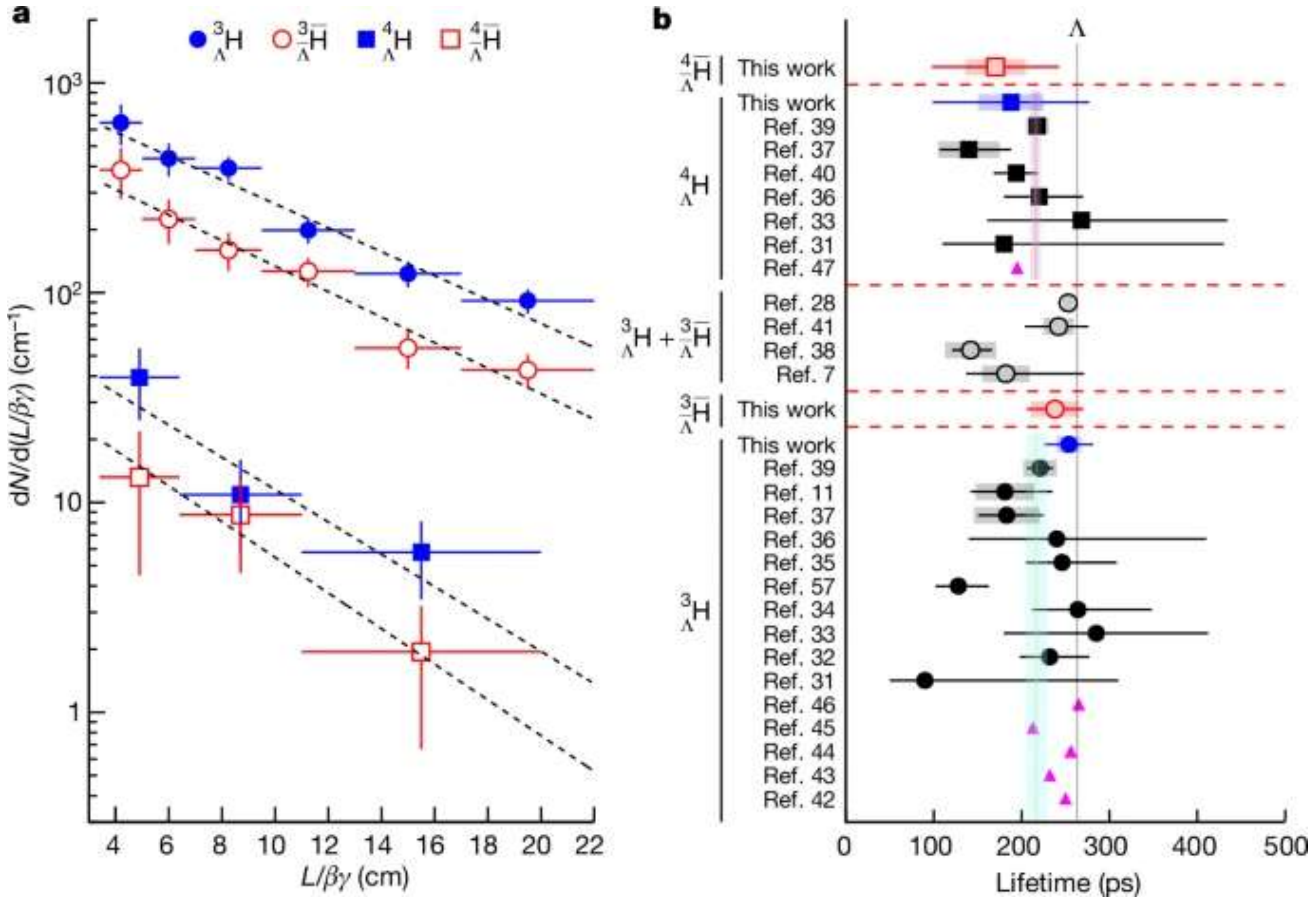
$$Z_{count} = \sqrt{2[(N_{sig} + N_{bck})ln(1 + \frac{N_{sig}}{N_{bck}}) - N_{sig}]}$$

- m_{inv} of the daughters - equal to the parent mass.
- The background reproduced with a rotation method: (anti)helium nucleus track randomly rotated around the beamline, the decay kinematics of the real candidate destroyed and randomized as background.
- The final signal extracted by subtracting combinatorial background from signal-candidate distribution.
- $^3_\Lambda H$: 941 ± 59 $\quad ^4_\Lambda H$: 24.4 ± 6.1
  $^3_\Lambda \bar{H}$: 637 ± 49 $\quad ^4_\Lambda \bar{H}$: 15.6 ± 4.7

Significance: 5.6 ($^4_\Lambda H$) and 4.8 ($^4_\Lambda \bar{H}$) of σ

the signal significance calculated by the likelihood ratios between the hypothesis of pure B and that of S+B

Hypernuclei's lifetime



- Matter and antimatter particles: the same properties *(CPT theorem, physical laws should remain unchanged under the combined operation of charge conjugation C, parity transformation P and time reversal T)*.
- Comparing the properties: mass, lifetime of a particle and antiparticle *(important test of the CPT symmetry)*
- Search for mechanisms responsible for **matter and antimatter asymmetry** in the Universe.
- Important for interaction studies (NS, etc..)

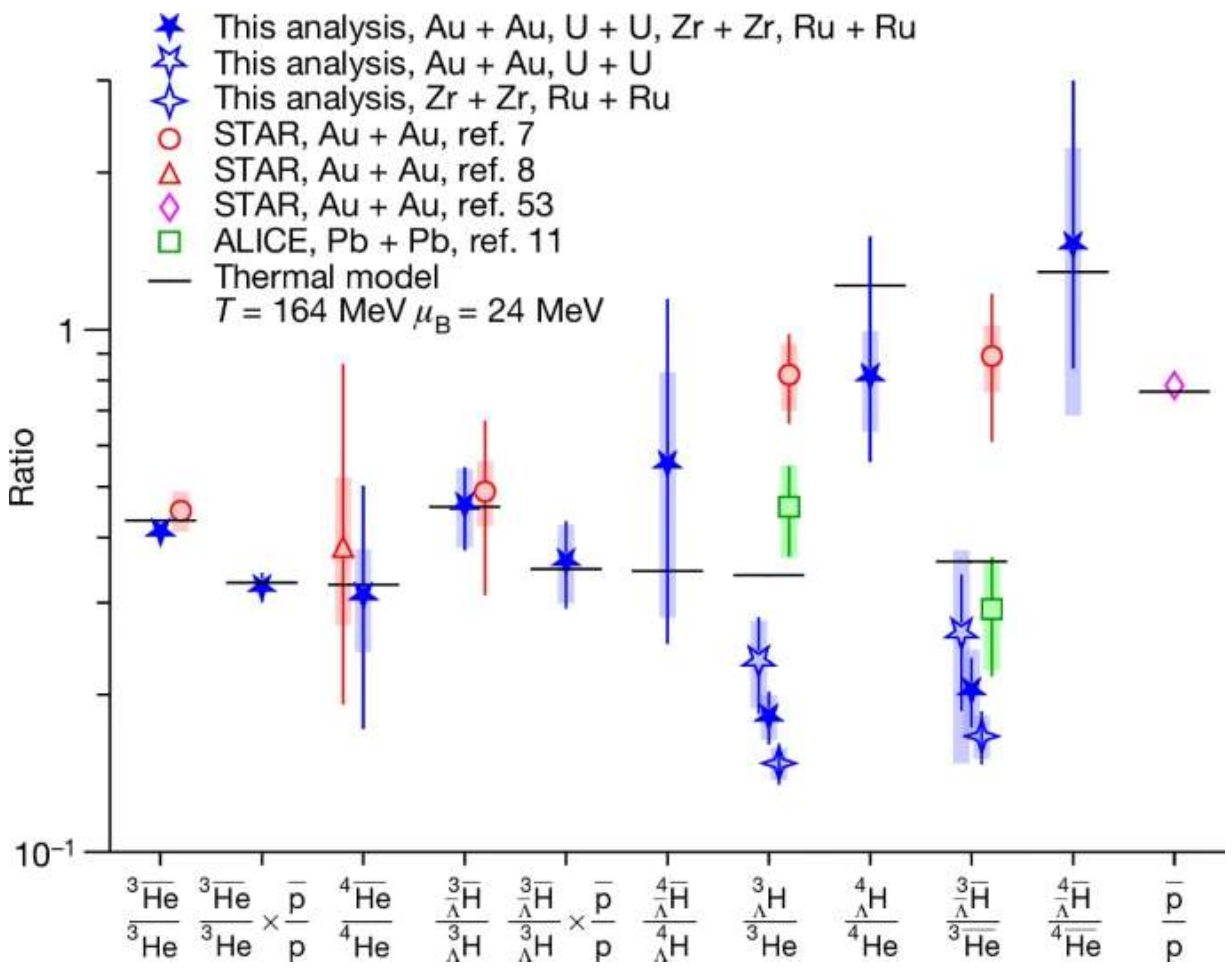
- Lifetime differences consistent with 0 ($^3_\Lambda H$ - $^3_\Lambda \bar{H}$ and $^4_\Lambda H$ - $^4_\Lambda \bar{H}$)

$$\tau(^3_\Lambda H) = 254 \pm 28(stat.) \pm 14(sys.) \text{ ps}$$
$$\tau(^3_\Lambda \bar{H}) = 238 \pm 33(stat.) \pm 28(sys.) \text{ ps}$$
$$\tau(^4_\Lambda H) = 188 \pm 89(stat.) \pm 37(sys.) \text{ ps}$$
$$\tau(^4_\Lambda \bar{H}) = 170 \pm 72(stat.) \pm 34(sys.) \text{ ps}$$

- Hypernuclei $dN/d(L/\beta\gamma = ct)$.
- $N(t) = N_0 exp(-t/\tau) = N_o exp(-(L/\beta\gamma)/c\tau)$

$$\tau(^3_\Lambda H) - \tau(^3_\Lambda \bar{H}) = 16 \pm 43(stat.) \pm 20(sys.) \text{ ps}$$
$$\tau(^4_\Lambda H) - \tau(^4_\Lambda \bar{H}) = 18 \pm 115(stat.) \pm 46(sys.) \text{ ps}$$

Particles' ratios

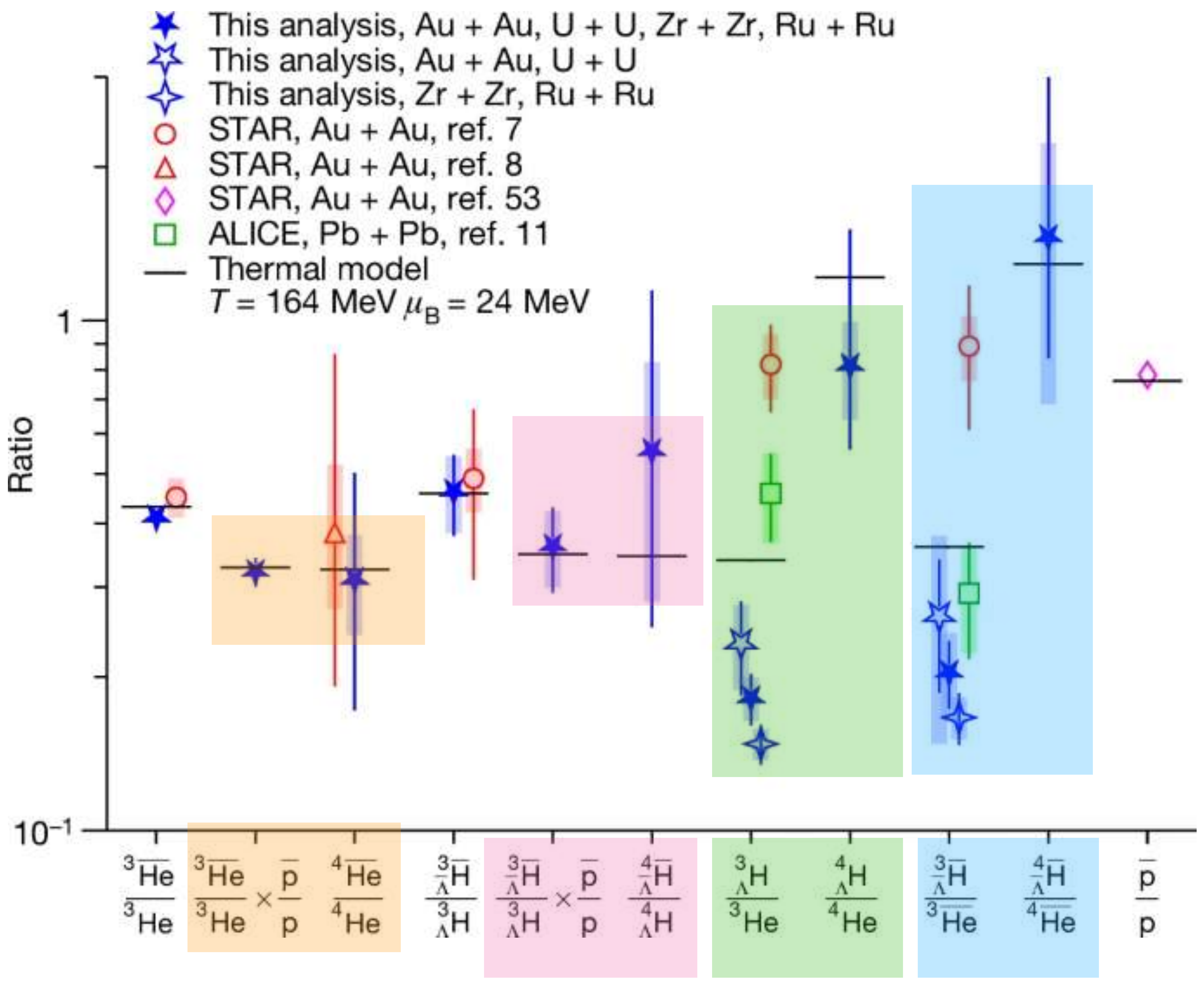


Antimatter /matter particle yield ratios below unity

(colliding heavy-ions carry positive baryon numbers, the collision system has $\mu_B > 0$)

- Goal: to learn about **production mechanisms** in HIC
  At RHIC T~several hundred MeV (~10^{12}K) (and typical binding energies ~several MeV / (anti)baryon).
- (anti)hypernuclei production mechanism: **coalescence** during last stage of HIC *(the probability of coalescence decreases by 2-3 orders of magnitude with each additional (anti)baryon)*.
- Λ is heavier than p/n, takes more energy to create it, fewer Λ than p/n created in HIC.
- (Anti)hypernucleus yields usually lower than (anti)nuclei with the same baryon number.
- Baryon / strangeness numbers of particle **production yields** described by the **statistical thermal models** *(assumes all particles in thermal and chemical equilibrium)*.
- The parameters of the statistical thermal model (T, μ_B) obtained by a **simultaneous fit** to existing particle yields.

Coalescence scenario



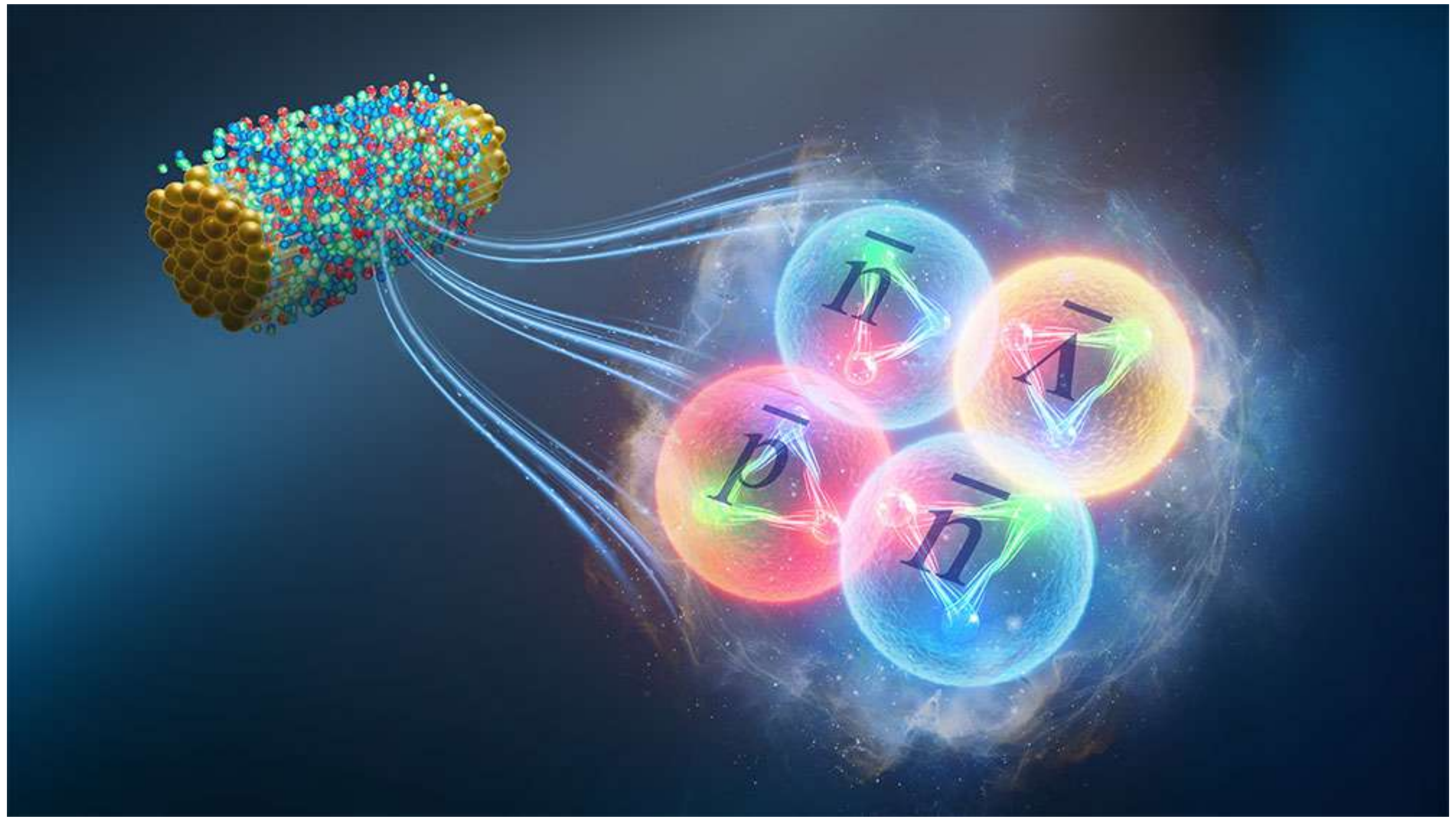
Antimatter /matter particle yield ratios below unity (colliding heavy-ions carry positive baryon numbers, the collision system has $\mu_B > 0$

- $\frac{^4\bar{He}}{^4He} \simeq \frac{^3\bar{He}}{^3He} \times \frac{\bar{p}}{p}$
- $\frac{^4_\Lambda\bar{H}}{^4_\Lambda H} \simeq \frac{^3_\Lambda\bar{H}}{^3_\Lambda H} \times \frac{\bar{p}}{p}$
- $\frac{^4_\Lambda H}{^4He} \simeq 4 \times \frac{^3_\Lambda H}{^3He}$
- $\frac{^4_\Lambda\bar{H}}{^4\bar{He}} \simeq 4 \times \frac{^3_\Lambda\bar{H}}{^3\bar{He}}$
- Factor 4: spin-0 and spin-1 states of $^4_\Lambda H$ have enough binding energy (no energetically allowed strong decay channels exist for them, therefore spin 1-state with a spin degeneracy of 3, will decay electromagnetically to the spin-0 ground state).
- This enhances the total measured $^4_\Lambda H$ and $^4_\Lambda\bar{H}$ production yield by a factor of 4, compared with ^4He and $^4\bar{He}$, which have only a spin-0 state.

Considering this spin-degeneracy effect, the statistical-thermal-model predictions also match our measurements, except that the measured ratio $^3_\Lambda H/^3He$ is slightly lower than the statistical-thermal-model prediction. This difference may be explained by the very small binding energy of $^3_\Lambda H$.

Summary

- First observation of the antimatter hypernucleus ${}^{4}_{\bar{\Lambda}}H$.
- The discovery made through two-body decay registered by STAR at RHIC.
- In total, 15.6 candidates of ${}^{4}_{\bar{\Lambda}}H$.
- The lifetimes of the antihypernuclei measured and compared with lifetimes of their corresponding hypernuclei, tested the symmetry between matter and antimatter.
- Various production yield ratios measured and compared with theoretical predictions, shedding light on their production mechanisms.



Courtesy of Institute of Modern Physics, China

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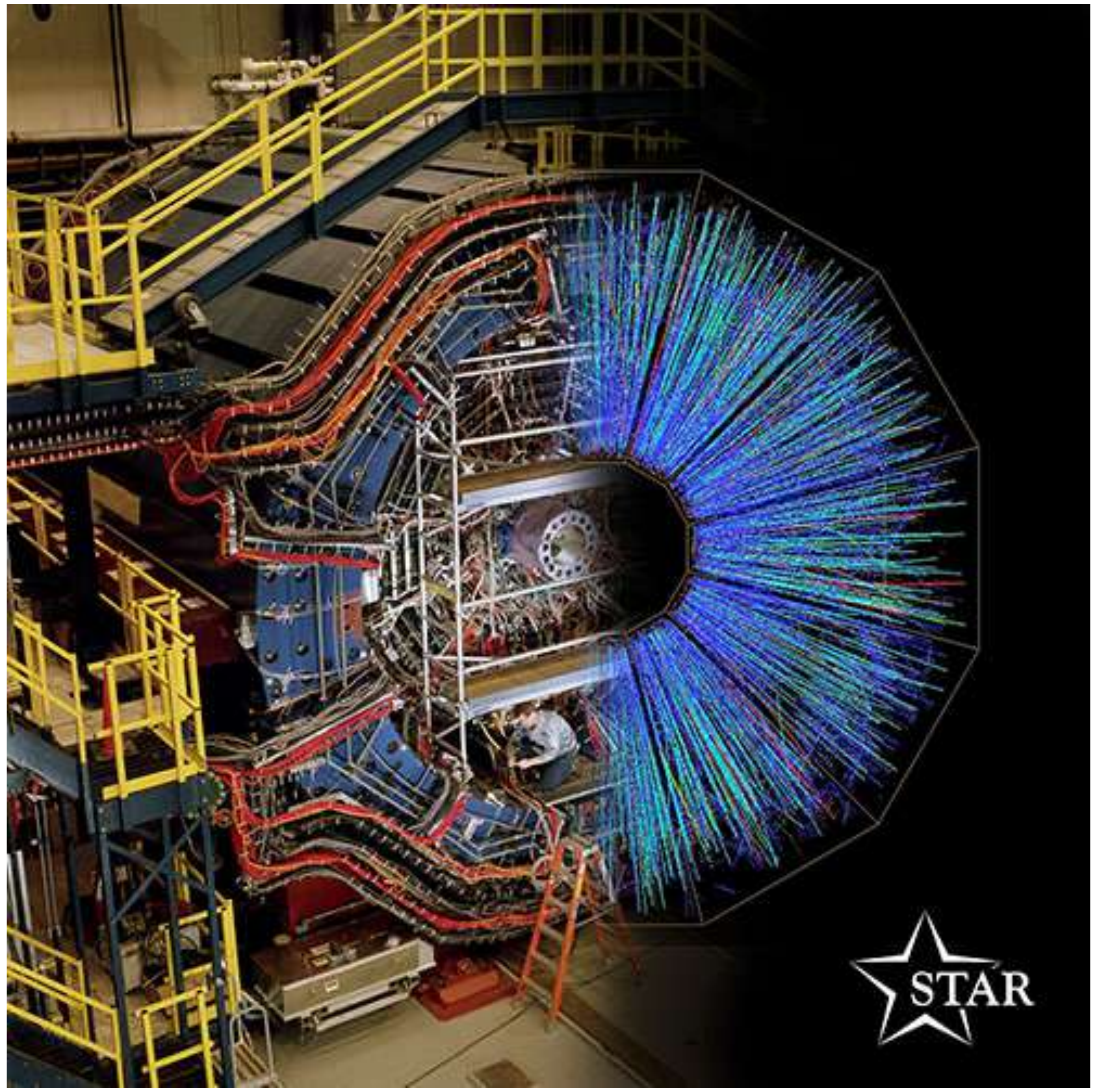


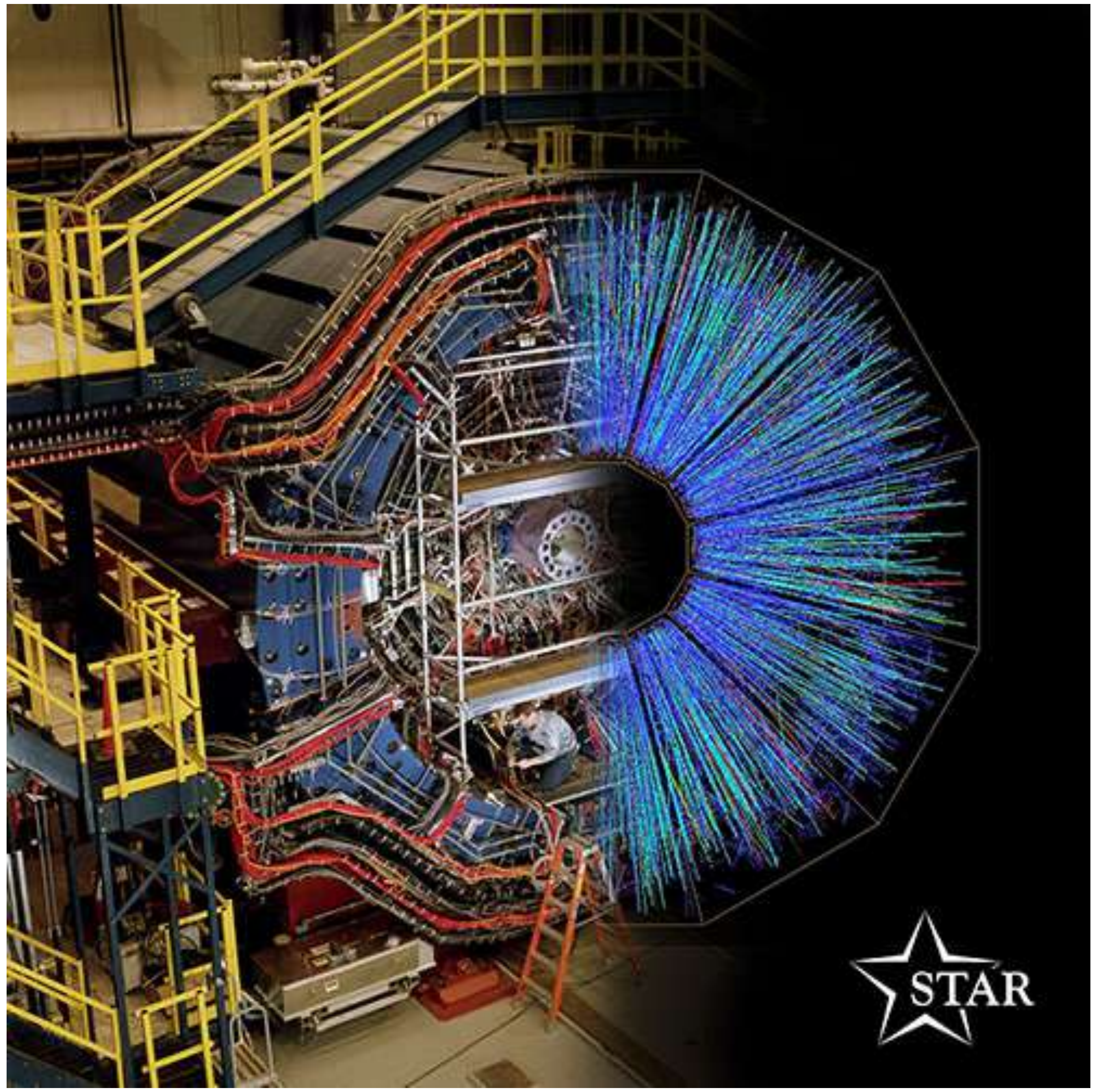
Joe Rubino and Jen Abramowitz/BNL

„Our physics knowledge about matter and antimatter is that, except for having opposite electric charges, antimatter has the same properties as matter - same mass, same lifetime before decaying, and same interactions" said STAR collaborator Junlin Wu, Joint Department for Nuclear Physics, Lanzhou University and Institute of Modern Physics, China. *„But the reality is that our universe is made of matter rather than antimatter, even though both are believed to have been created in equal amounts at the time of the Big Bang some 14 billion years ago. Why our universe is dominated by matter is still a question, and we don't know the full answer"*

"To study the matter-antimatter asymmetry, the first step is to discover new antimatter particles" said Hao Qiu, Wu's advisor at IMP.
"That's the basic logic behind this study."

***"It is only by chance that you have these four constituent particles emerge from the RHIC collisions close enough together that they can combine to form this antihypernucleus"* said Brookhaven Lab physicist Lijuan Ruan, one of two co-spokespersons for the STAR Collaboration**

Recent STAR findings



Joe Rubino and Jen Abramowitz/BNL

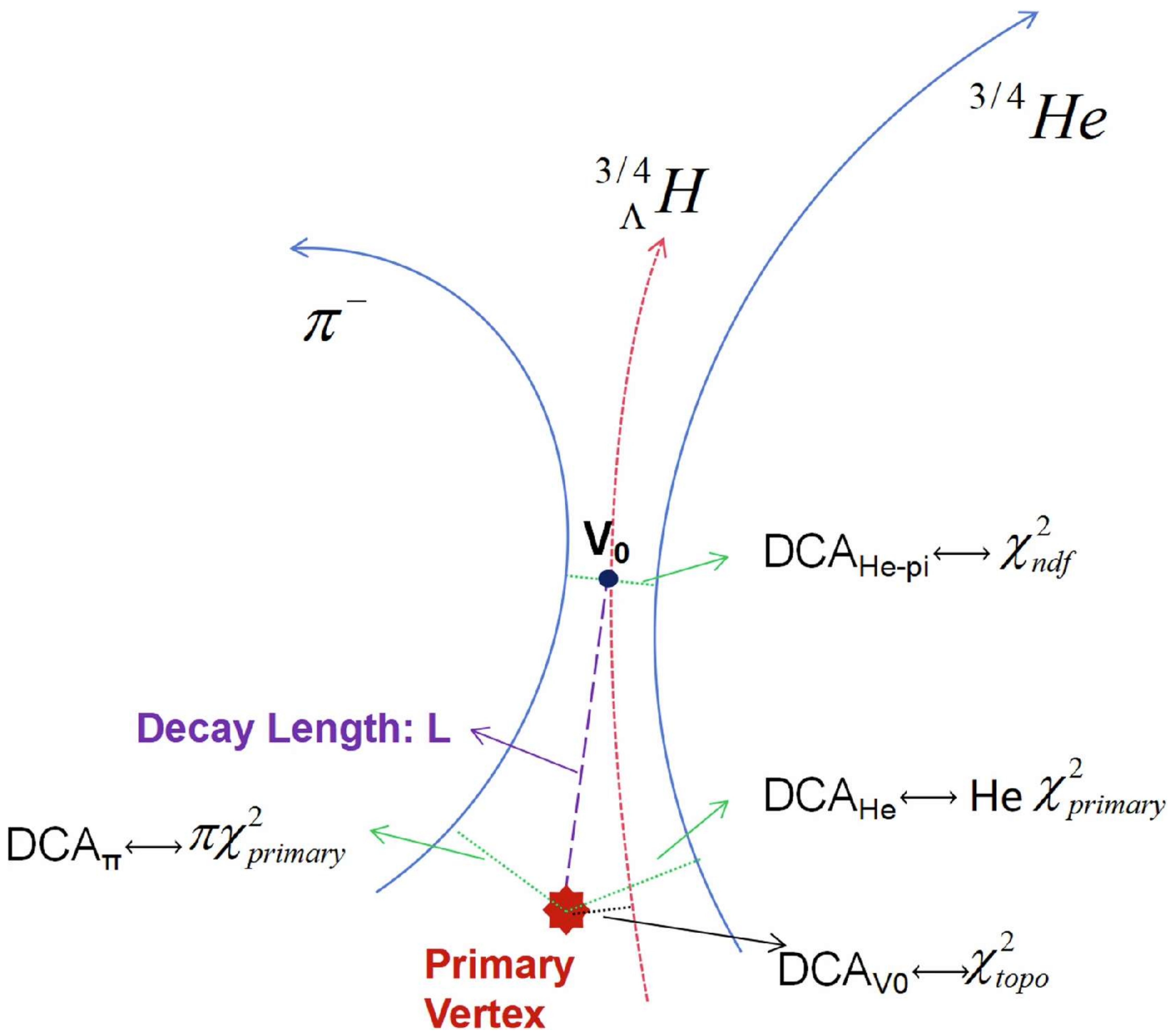
„Our … except for
havi… as matter
- sar… ions" said
STA… r Physics,
Lanz… the reality
is th… en though
both … of the Big
Bang … matter is
still …

"To st… cover new
antim…
"That…

"It is only by chance that you have these four constituent particles emerge from the RHIC collisions close enough together that they can combine to form this antihypernucleus" ***said Brookhaven Lab physicist Lijuan Ruan, one of two co-spokespersons for the STAR Collaboration***

Bonus slides

Details of analysis



Reconstructed via decay daughters by the **Kalman Filter Particle Finder** package:

- χ^2_{topo} *(the deviation of the reconstructed path of the mother particle from the primary vertex),*
- χ^2_{ndf} *(the deviation between the two daughter tracks at the decay vertex),*
  $\chi^2_{primary}$ *(the deviation of the decay daughter track from the primary vertex),*
- L *(the decay length),*
- L/dL *(L over its uncertainty).*

Particles	χ^2_{topo}	χ^2_{NDF}	π $\chi^2_{primary}$	He $\chi^2_{primary}$	L(cm)	L/dL
$^3_\Lambda$H, $^4_\Lambda$H	< 2	< 5	> 10	< 2000	> 3.5	> 3.4
$^3_\Lambda\overline{\text{H}}$, $^4_\Lambda\overline{\text{H}}$	< 3	< 5	> 10	< 2000	> 3.5	> 3.4

Systematic uncertainties

4 sources of systematic uncertainties evaluated for the (anti)hypernucleus-lifetime and the yield-ratio measurements:

(1) **track-reconstruction efficiency**, evaluated by varying the minimal number of measured points on the tracks;

(2) **(anti)hypernucleus reconstruction efficiency** due to topological selections, evaluated by varying the topological-selection variables;

(3) **(anti)hypernucleus signal-yield extraction from the invariant-mass spectra**, evaluated by enlarging the invariant-mass ranges for signal-yield integration, and from the pT-spectrum shapes, evaluated by narrowing the pT-spectrum fit ranges;

(4) **(anti)helium yields**, evaluated by varying the minimal number of measured points for $\langle dE/dx \rangle$ calculation and the cut on the helium-track DCA to primary vertex.

The total systematic uncertainty calculated as the quadratic sum of the four contributions above, the correlations of systematic uncertainties from the same sources have been considered and cancelled.

Details of analysis

- A corrections for the **detector acceptance** and **reconstruction efficiency** in the **lifetime** and **yield-ratio** measurements.
- The **acceptance** and **efficiency** are obtained with an embedding Monte Carlo technique. (Anti)hypernucleus decay and the paths of their daughters are simulated using GEANT3 and GEANT4, taking into account the geometry and materials of the STAR detectors. The responses of the detectors and read-out electronics are also simulated, and the final simulated data are embedded into real-data events, which are sampled from different data-taking runs to have a good representation of the whole data set used in the analysis.
- The number of Monte Carlo (anti)hypernuclei embedded is 5% of the multiplicity of the real-data events. The embedded events are processed through the same reconstruction procedures as real data, the same track and topological requirements as for the real data are applied.
- The final reconstruction efficiency ϵ is calculated as the ratio of the number of reconstructed Monte Carlo (anti)hypernuclei to the number of input Monte Carlo (anti)hypernuclei.
- This efficiency ϵ includes particle interaction with materials, detector acceptance, tracking efficiency and selection efficiency. This correction is less than 3% for nuclei and less than 5% for antinuclei. The fraction of (anti)hypernuclei absorbed by the beam pipe and insulation gas are estimated to be minimal and can be neglected.