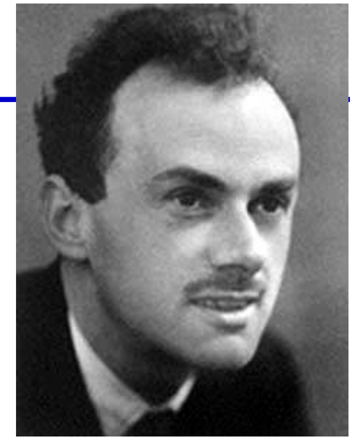
Antimatter and Hypernuclei at RHIC

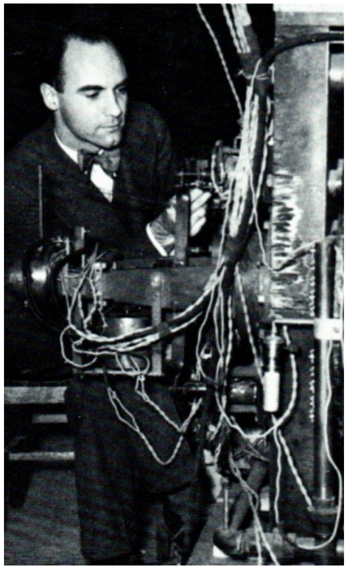
Zhangbu Xu
(for the STAR Collaboration)

- Heavy and Exotic Antimatter
- What has RHIC discovered?
  - $^{3}_{\Lambda}H$ and $^{3}_{\bar{\Lambda}}\bar{H}$ signal (for discovery)
  - How Anti-Helium-4 was discovered
- What can we do with the discovery?
  - Production Rates for antimatter
  - Even Heavier antimatter?
- Outlook

History of Antimatter

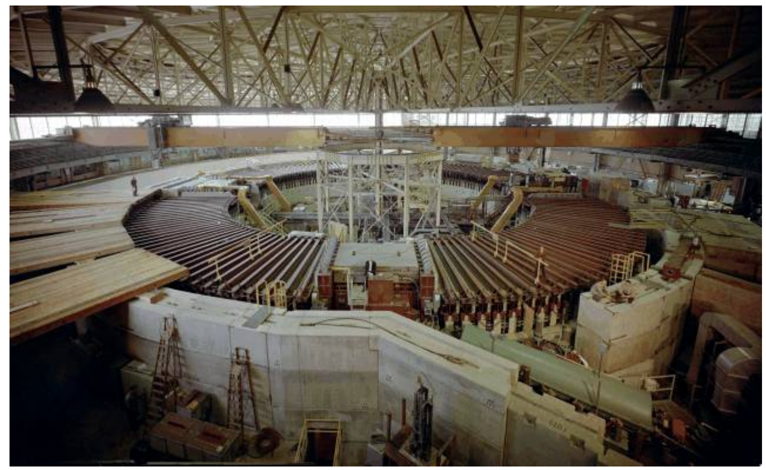


In 1928, Paul Dirac theorized possibility of antimatter as one of his equations for quantum mechanics had two "solutions" (regular matter and antimatter)

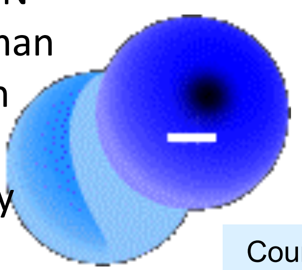


In 1932, Carl Anderson discovered positrons while studying cosmic rays

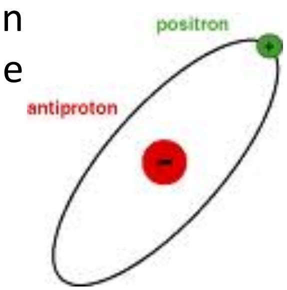
Two teams working at the Bevatron in Lawrence Berkeley National Lab discovered antiprotons and antineutrons in 1955 and 1956



In 1965, Antoni Zichichi of CERN and Leon Lederman of Brookhaven National Lab simultaneously discovered antideuteron

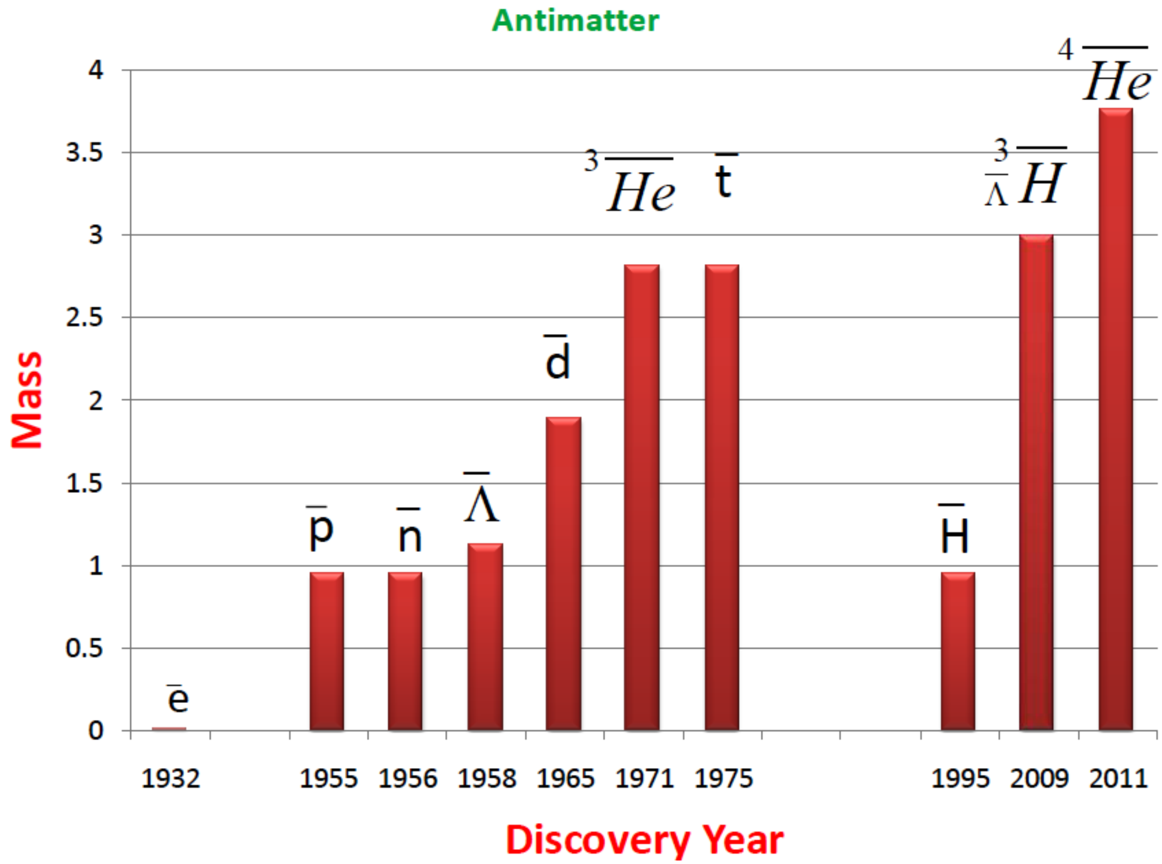


In 1995, CERN created antihydrogen atoms at the LEAR by slowing the antiprotons and attaching positrons



Courtesy of Will Pascucci, Choate Rosemary Hall; Wallingford, CT
2010 Summer High-School Student

What is Antimatter?



"Those who say that antihydrogen is antimatter should realize that we are not made of hydrogen and we drink water, not liquid hydrogen"
-- Dirac
Quoted from A. Zichichi (2008)
Antiparticles and antimatter: the basic difference

1. Annihilate with normal matter
   π^+,π^- are each other's antiparticle
2. Nuclear force
3. Relatively long lifetime

Science AAAS

Observation of an Antimatter Hypernucleus
The STAR Collaboration, *et al.*
Science **328**, 58 (2010);
DOI: 10.1126/science.1183980

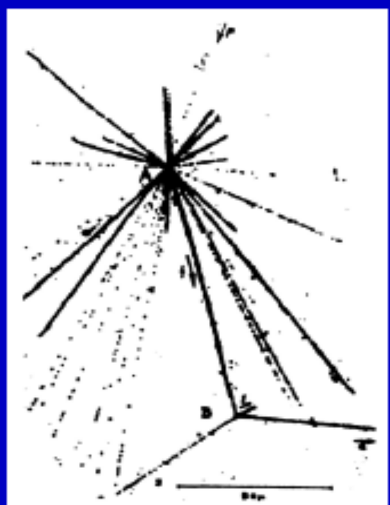
LETTER nature doi:10.1038/nature10079

Observation of the antimatter helium-4 nucleus

The STAR Collaboration*

What are Hypernuclei ?

Nucleus which contains at least one hyperon in addition to nucleons.

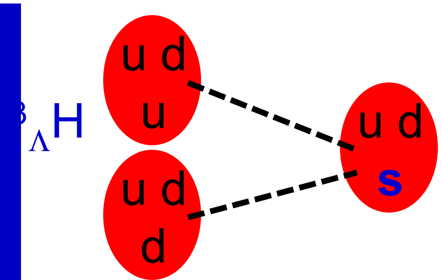


The first hypernucleus was discovered by Danysz and Pniewski in 1952. It was formed in a cosmic ray interaction in a balloon-flown emulsion plate.

M. Danysz and J. Pniewski, Phil. Mag. 44 (1953) 348

No one has ever observed **any** antihypernucleus before RHIC

Hypernuclei of lowest A

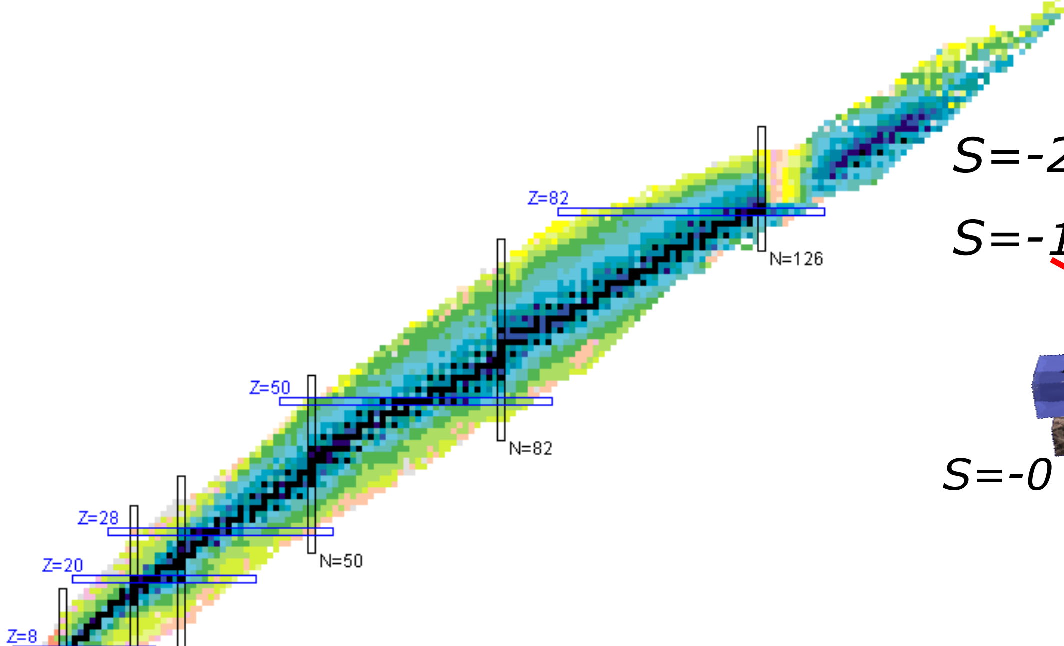


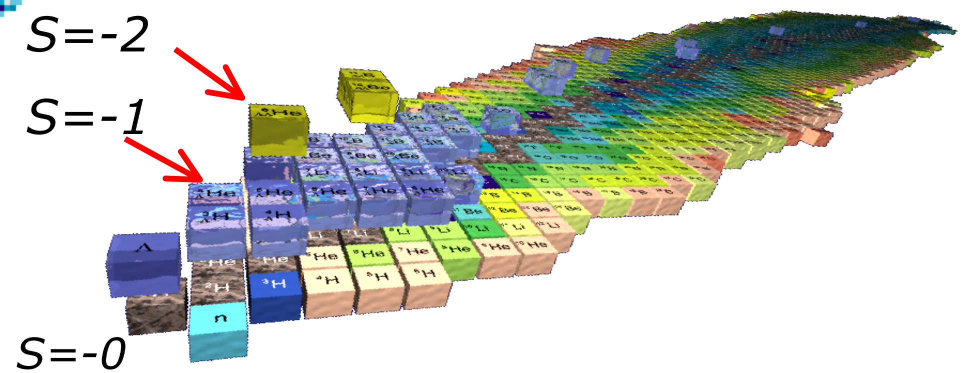
$$^{3}_{\Lambda}H(n+p+\Lambda)$$

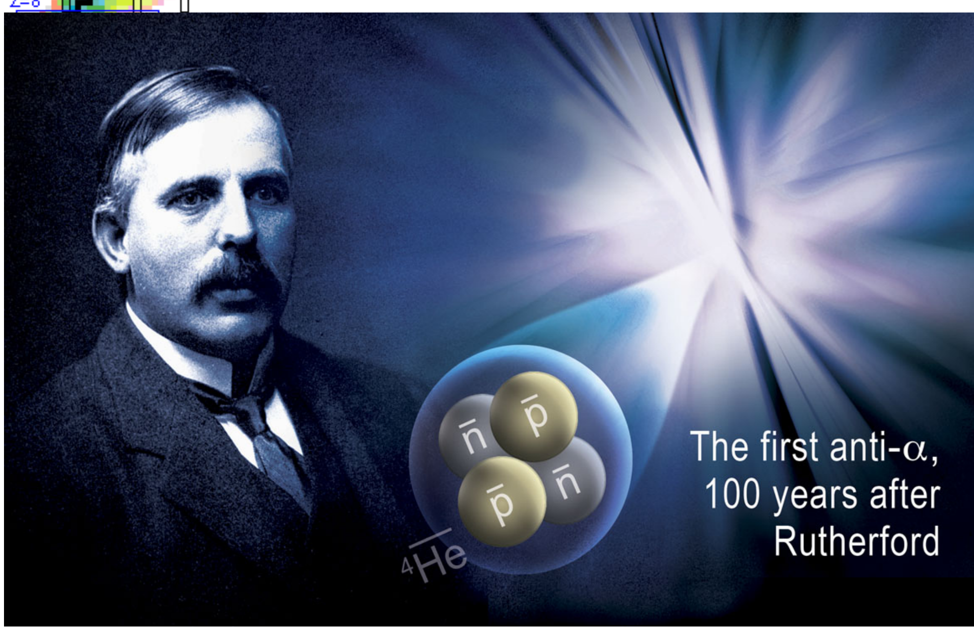
$$^{3}_{\bar{\Lambda}}\overline{H}(\bar{n}+\bar{p}+\bar{\Lambda})$$

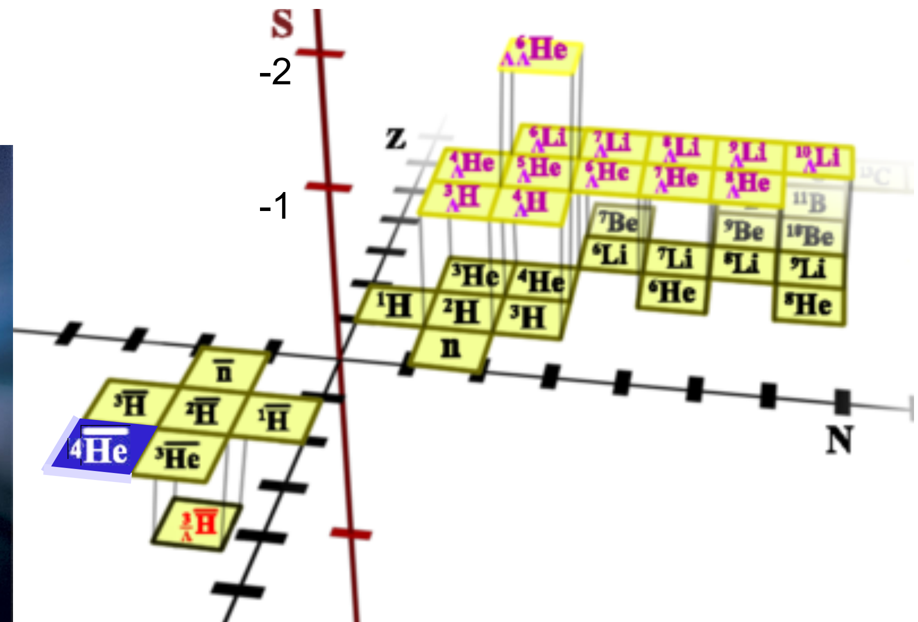
- Y-N interaction: a good window to understand the baryon potential
- Binding energy and lifetime are very sensitive to Y-N interactions
- Hypertriton: **ΔB=130±50 KeV; r~10fm**
- Production rate via coalescence at RHIC depends on overlapping wave functions of **n+p+Λ** in final state
- Important first step for searching for other exotic hypernuclei (double-Λ)

3-D Chart of Nuclides

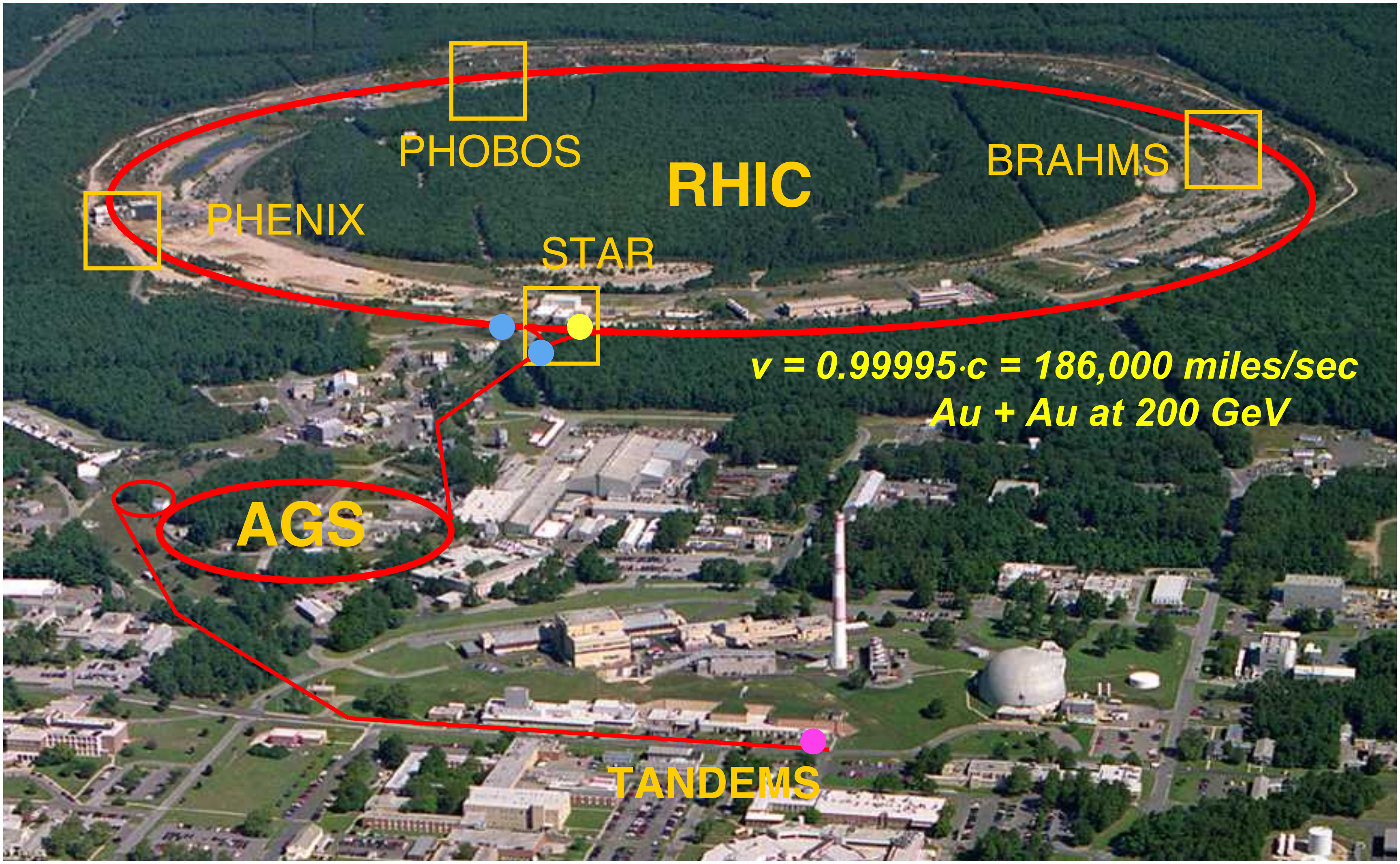




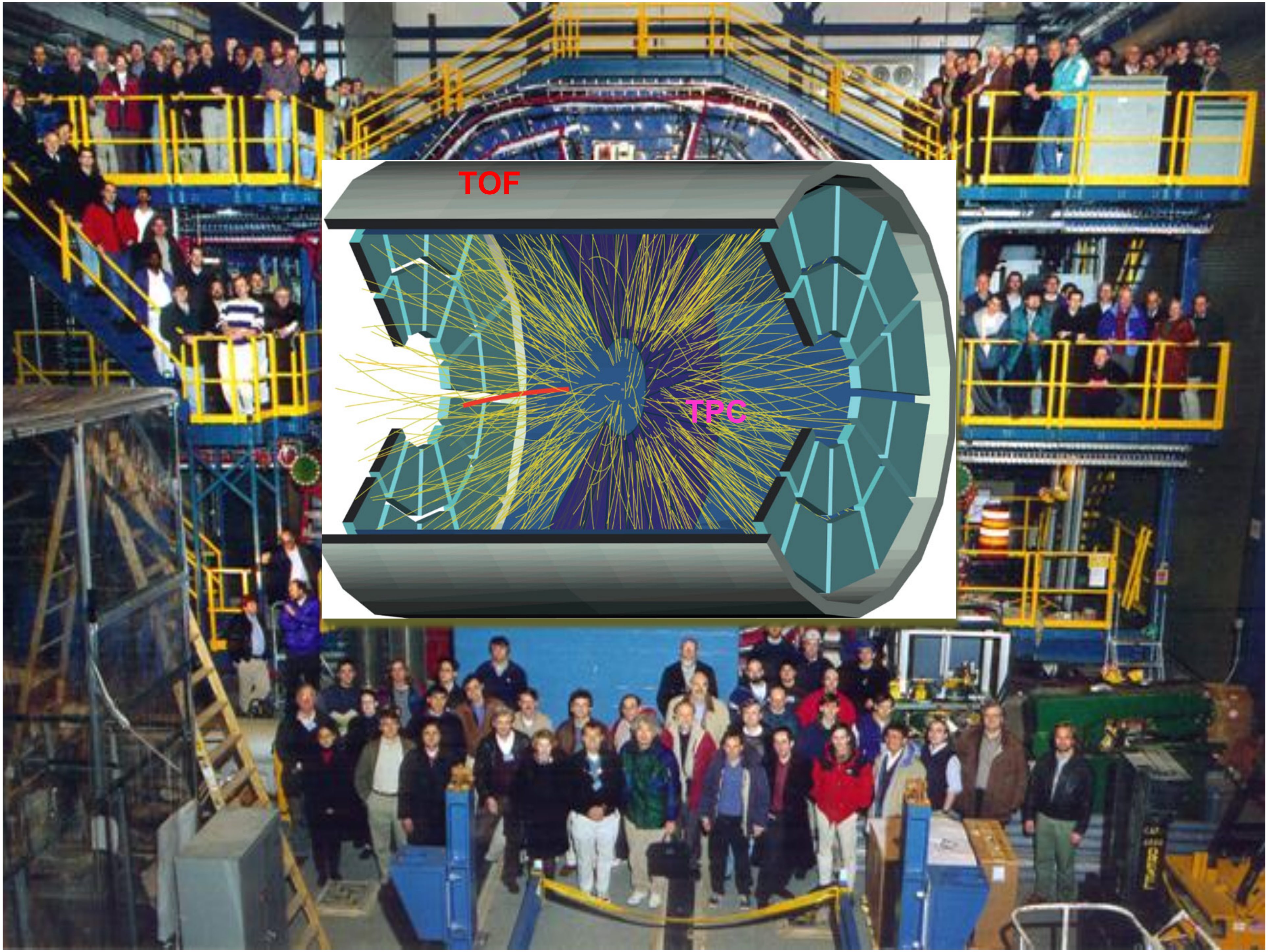




Relativistic Heavy Ion Collider (RHIC)

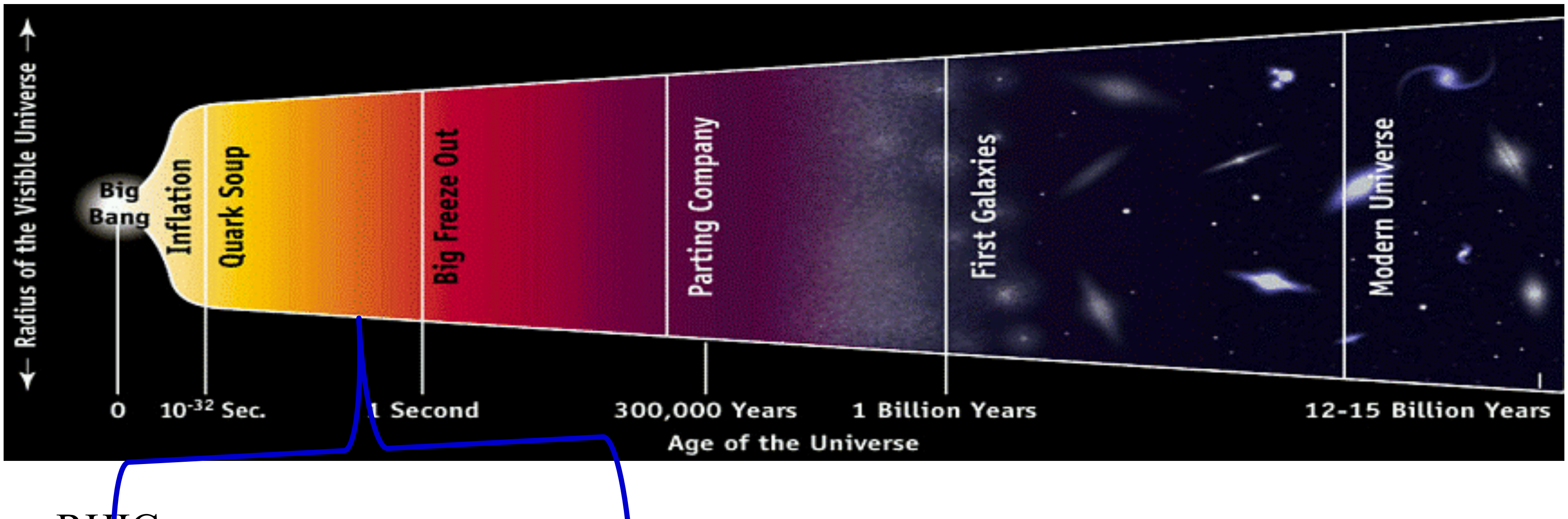


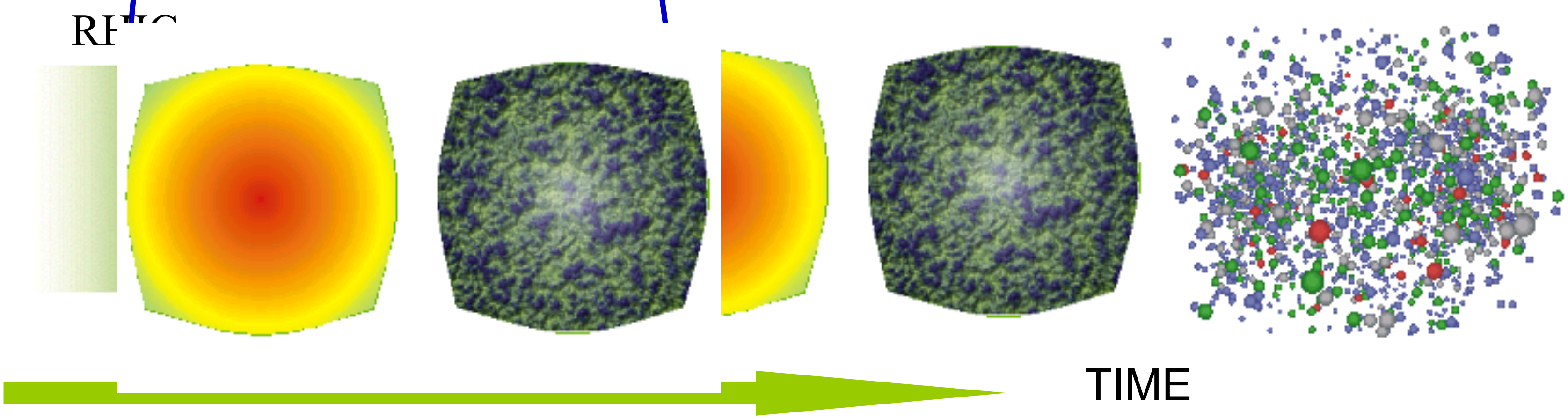
Animation M. Lisa


TOF
TPC

Little Big Bang

BIG; All 4 forces at work; Gravitation dominates; QGP@10^{-6}s; Slow expansion; Antimatter-matter annihilate





Little; Strong force at work; QGP@10^{-23}s; Fast expansion; Antimatter-matter decouple; repeat trillion times

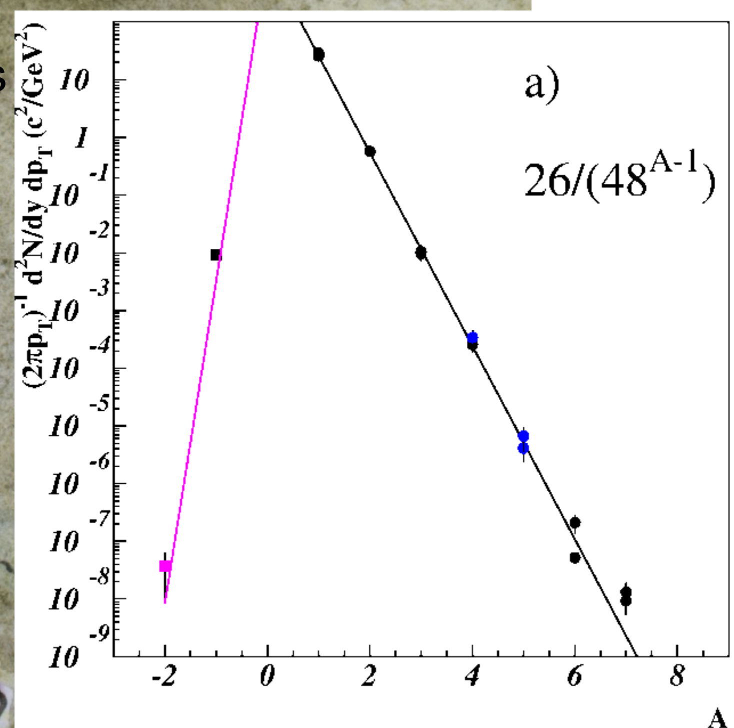
Can we observe hypernuclei at RHIC?

- Low energy and cosmic ray experiments (wikipedia):

  hypernucleus production via
  - Λ or K capture by nuclei
  - the direct strangeness exchange reaction

  hypernuclei observed
  - energetic but delayed decay,
  - measure momentum of the K and π mesons

- In high energy heavy-ion collisions:
  - nucleus production by coalescence, characterized by penalty factor. 聚并
  - AGS data[1] indicated that hypernucleus production will be further suppressed.
  - What's the case at RHIC?

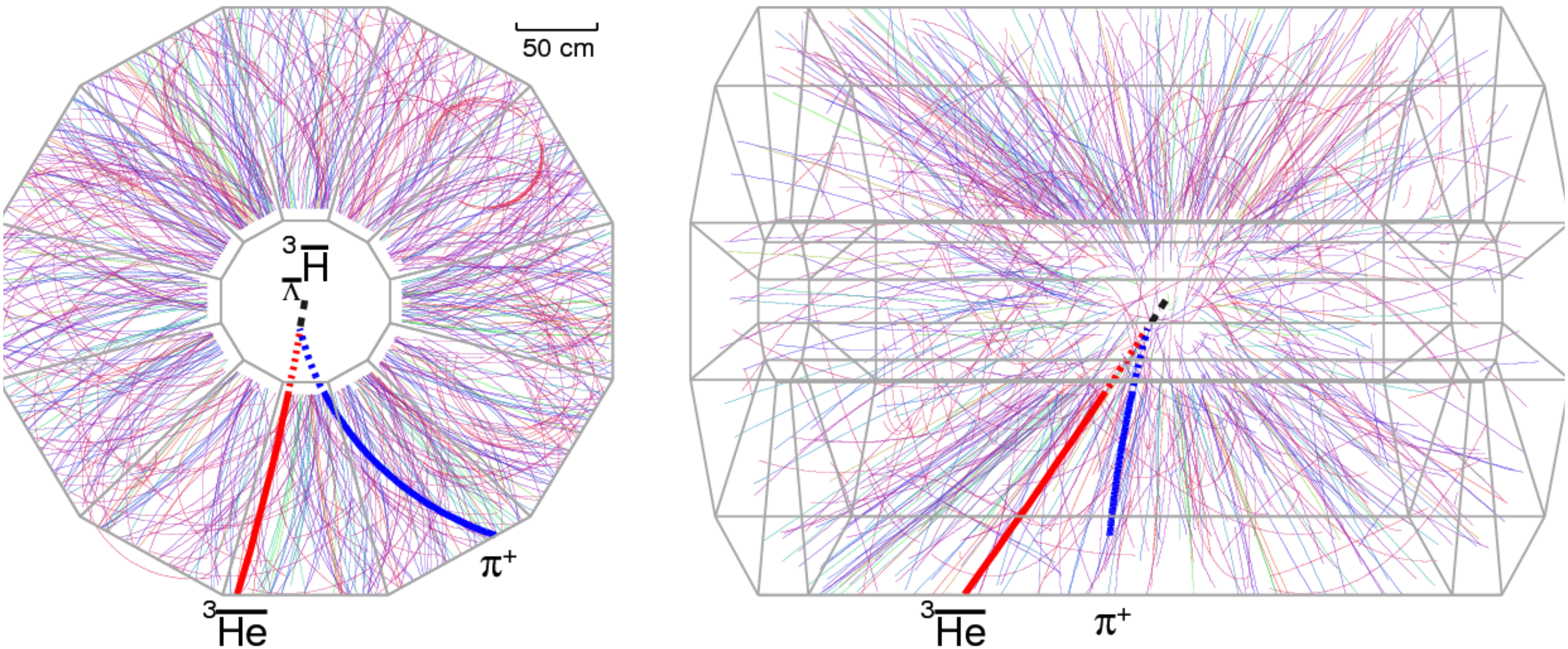


[1] AGS-E864, Phys. Rev. C70,024902 (2004)

Jesi, 2011

A candidate event at STAR

Run4 (2004)
200 GeV Au+Au collision



Observation of an Antimatter Hypernucleus
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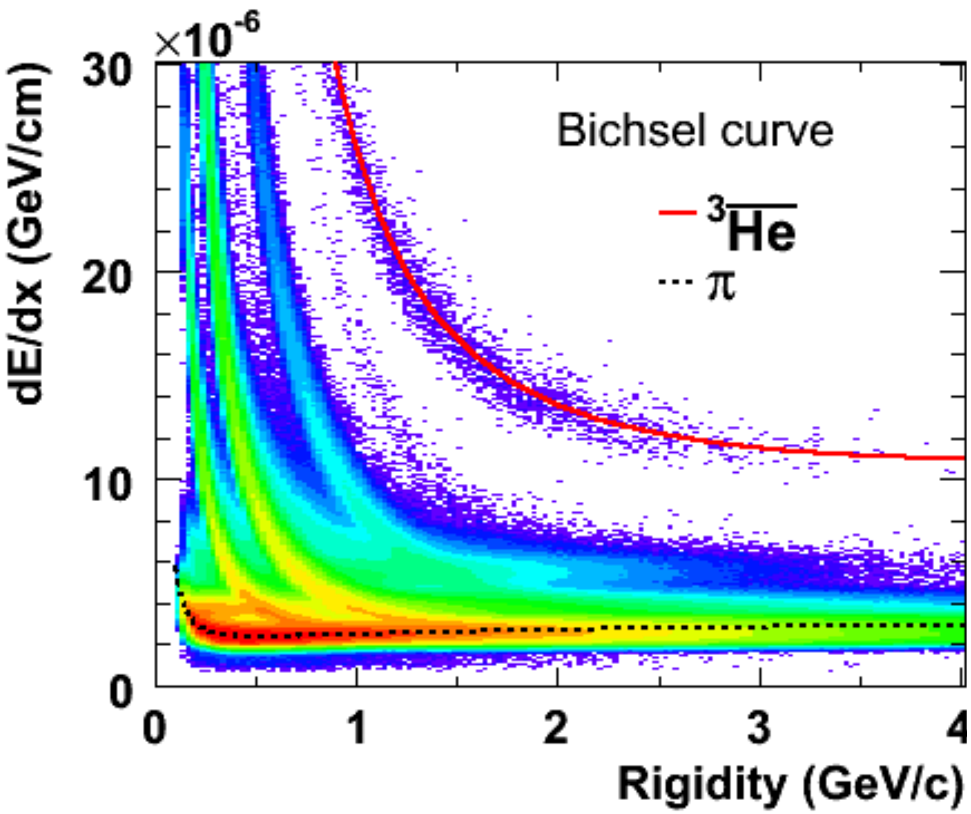
^{3}He & anti-^{3}He selection



Science

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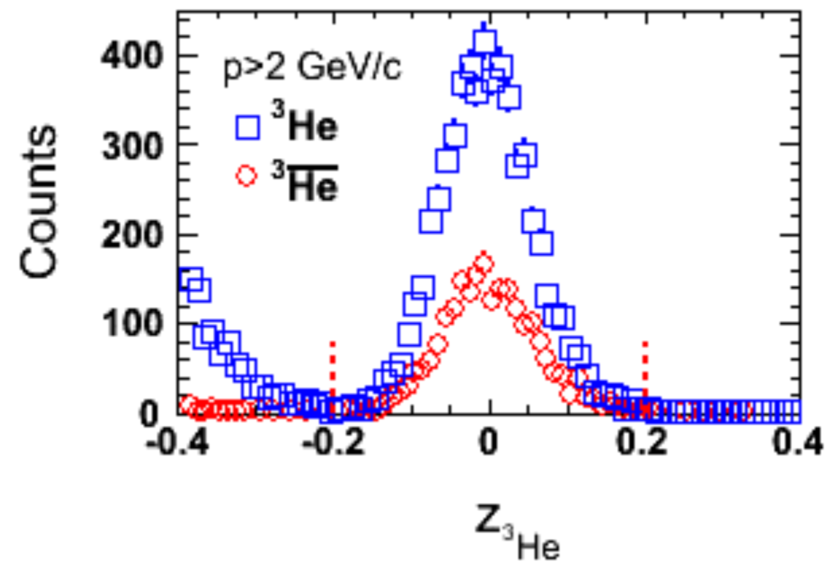


$$Z = \ln\left(\frac{\langle dE/dx \rangle}{\langle dE/dx \rangle^{Bichsel}}\right)$$

Select pure ^{3}He sample: -0.2<Z<0.2 & dca <1.0cm & p >2 GeV

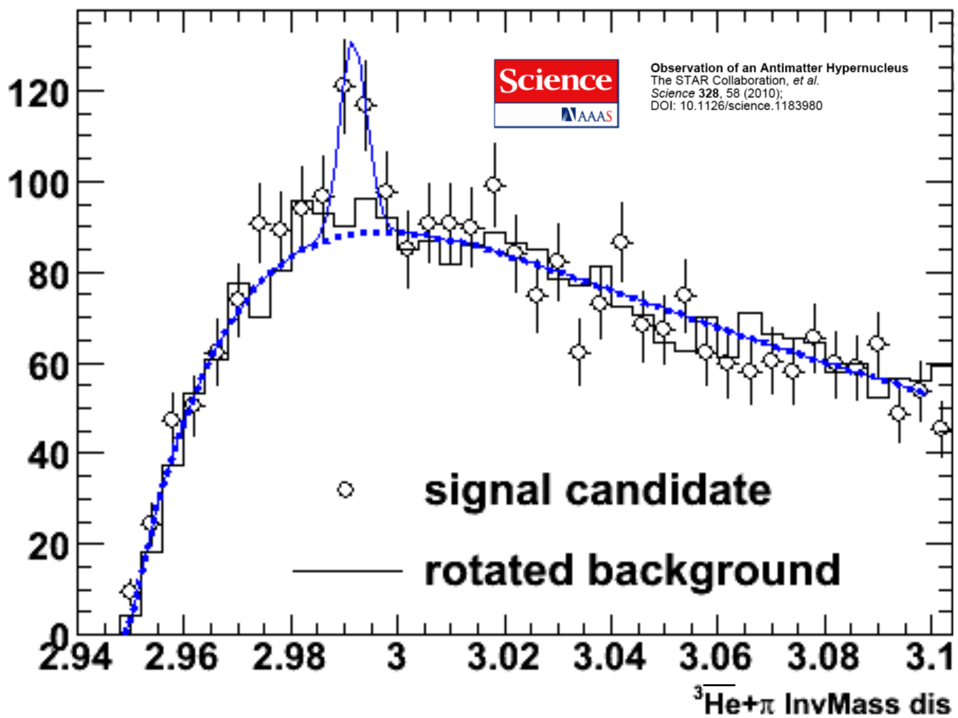
^{3}He: 2931(MB07) + 2008(central04) + 871(MB04) = 5810

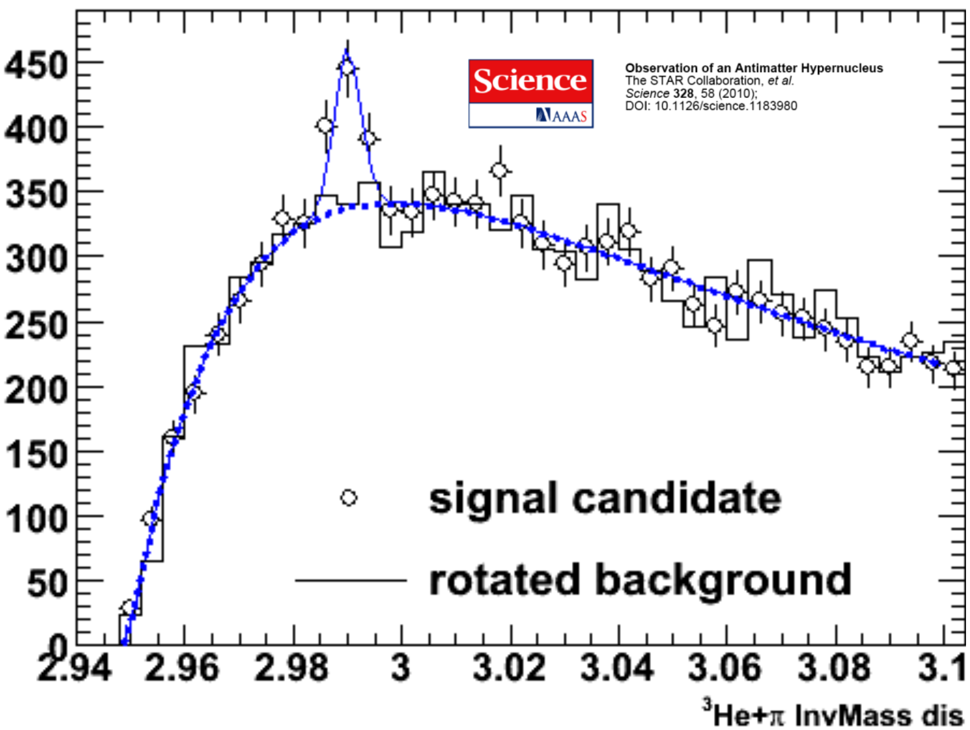
Anti-^{3}He: 1105(MB07) + 735(central04) + 328(MB04) = 2168

${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$ and Combined signals

${}^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$

Combine hypertriton and antihypertriton signal:
225±35



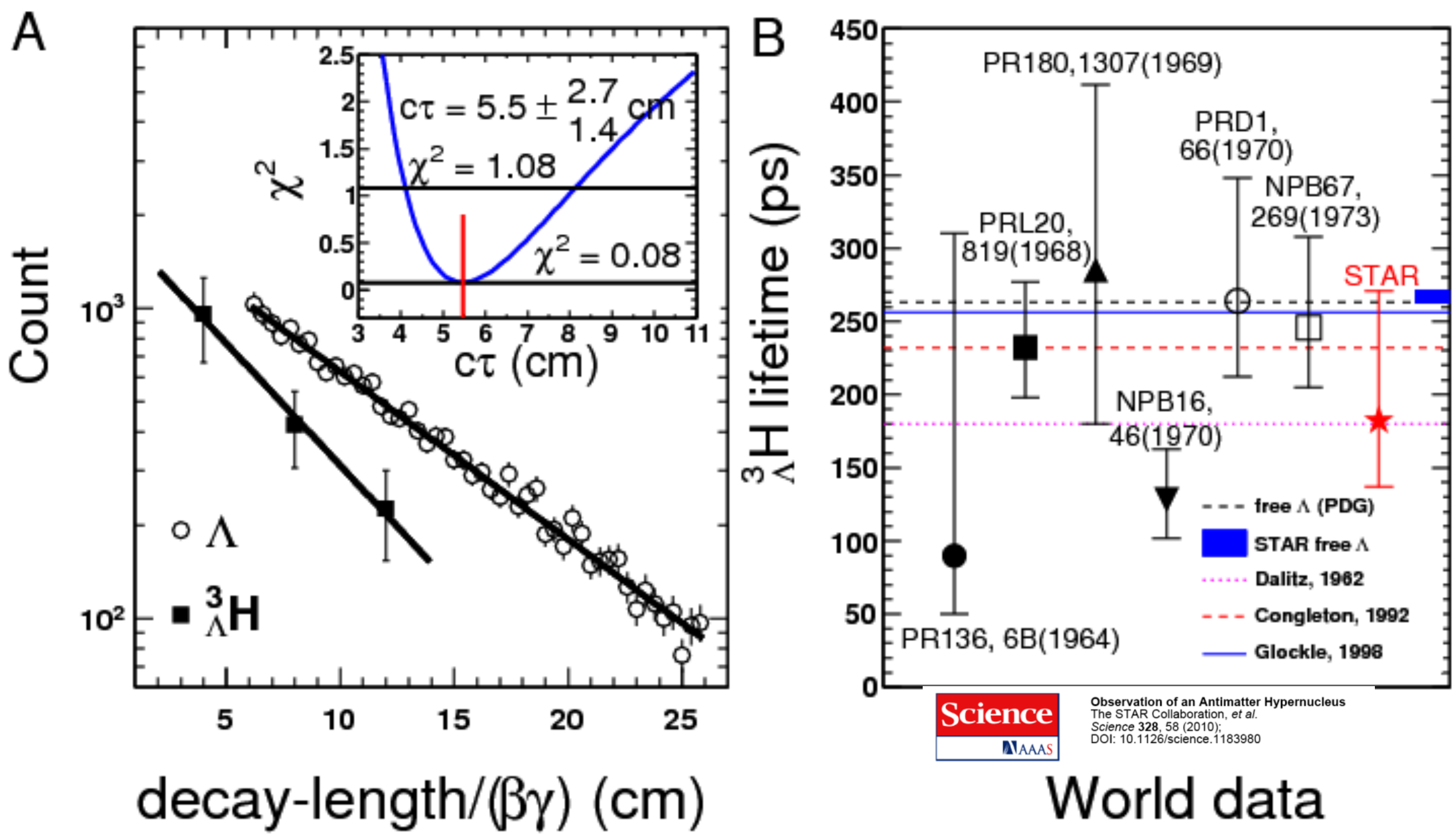


- Signal observed from the data (bin-by-bin counting): **70±17**;

Mass: 2.991±0.001 GeV; Width (fixed): 0.0025 GeV;

This provides a >6σ signal for discovery

Lifetime of a hypertriton



- Lifetime related to binding energy
- Theory input: the Λ is lightly bound in the hypertriton

[1] R. H. Dalitz, *Nuclear Interactions of the Hyperons* (Oxford Uni. Press, London, 1965).

[2] R.H. Dalitz and G. Rajasekharan, Phys. Letts. 1, 58 (1962).

[3] H. Kamada, W. Glockle at al., Phys. Rev. C 57, 1595(1998).

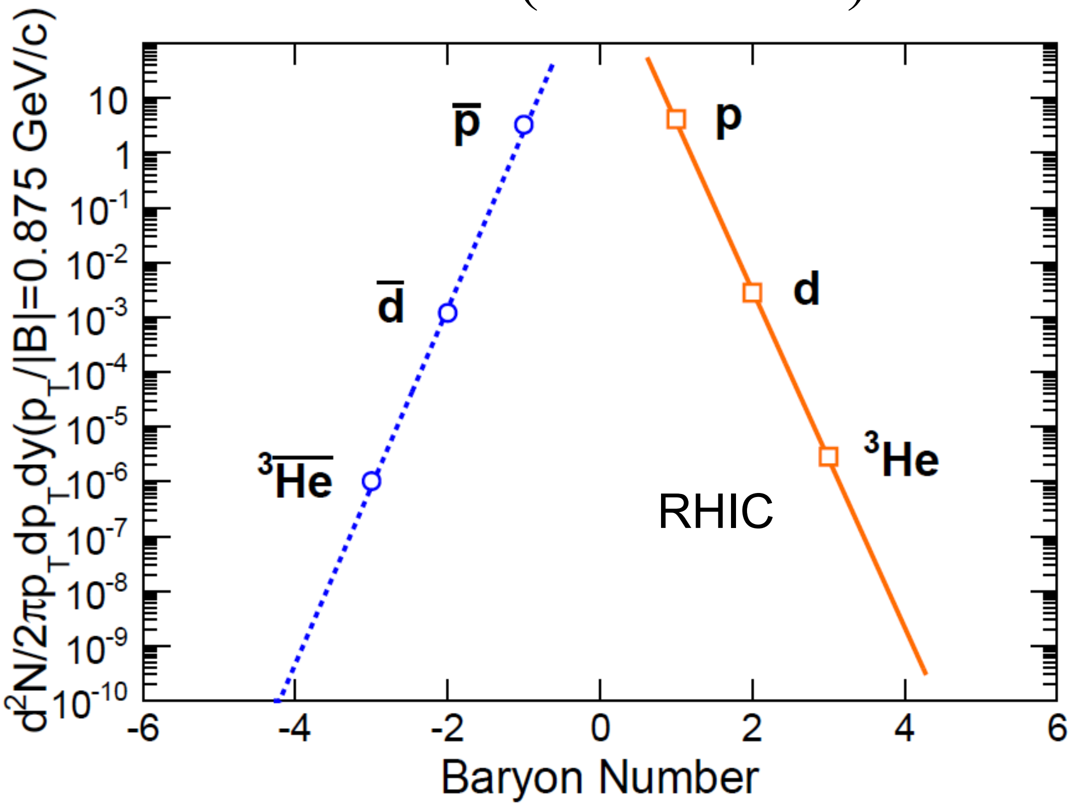
Matter and antimatter are not created equal

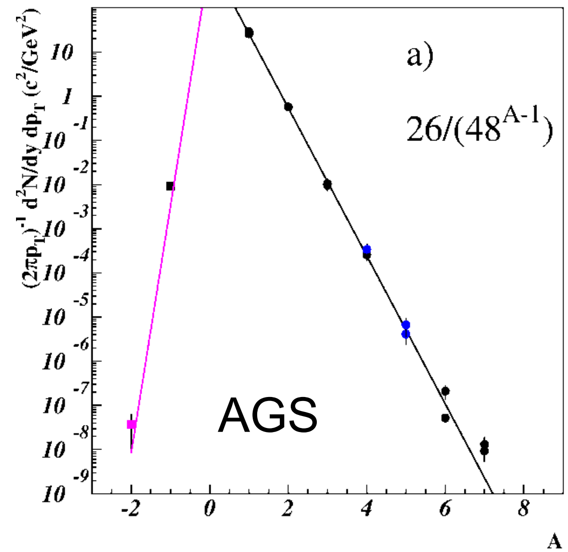
But we are getting there !

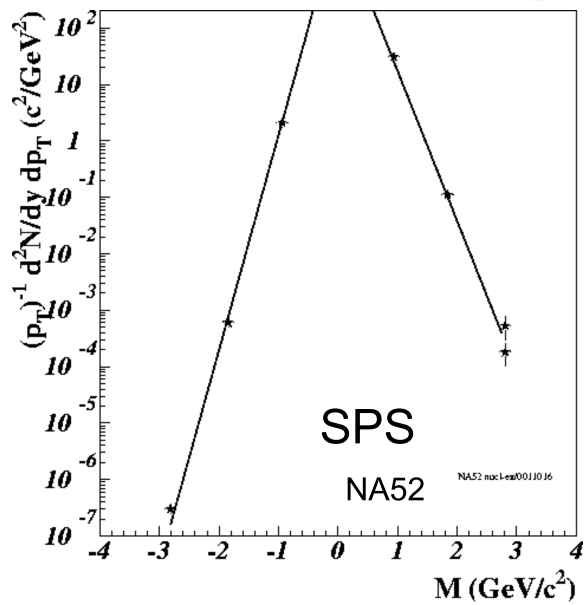
$$^3\overline{He}/^3He \approx 10^{-11}$$ (AGS,Cosmic)

$$^3\overline{He}/^3He \approx 10^{-3}(SPS/CERN)$$

$$^3\overline{He}/^3He \approx 0.5(RHIC/BNL)$$



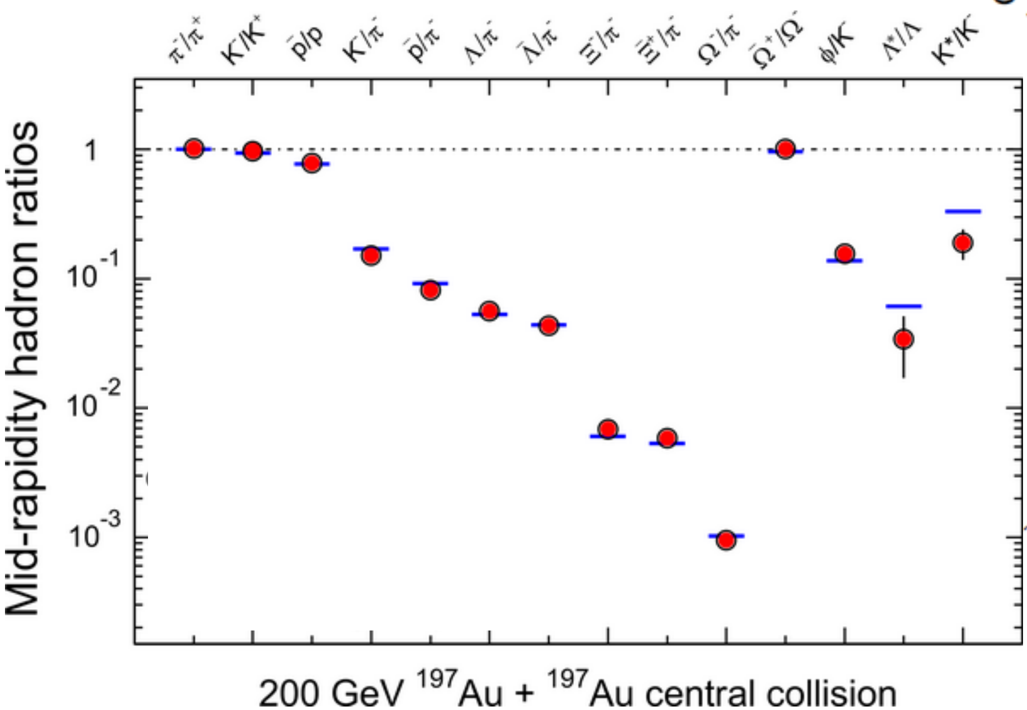




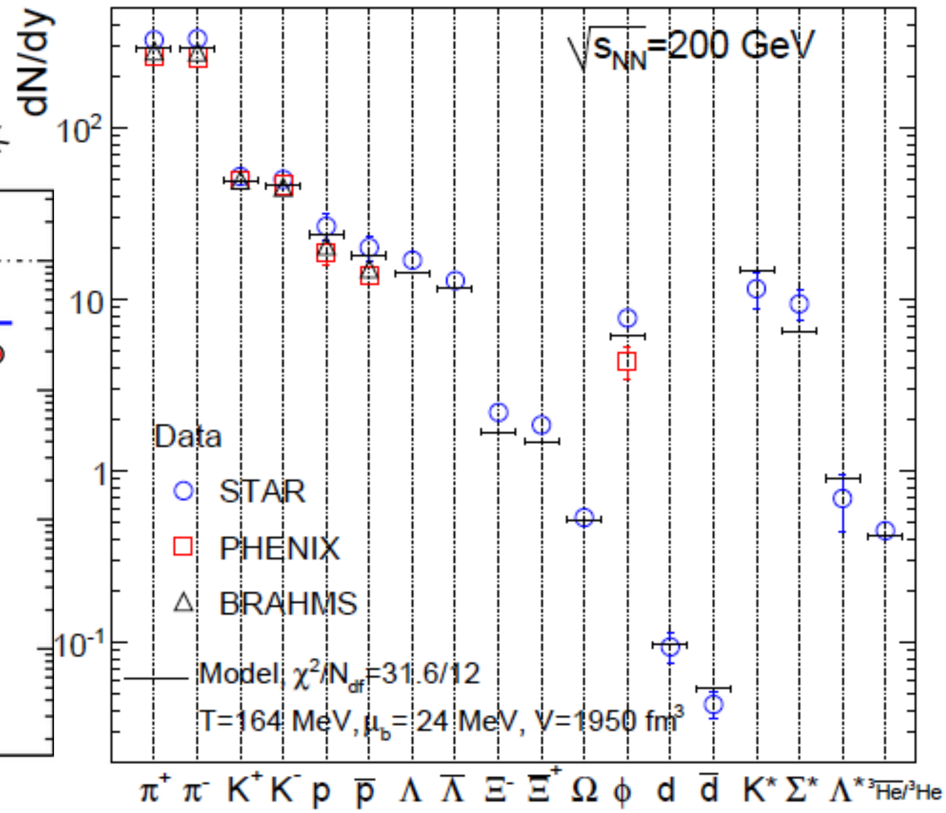
Flavors (u,d, s) are not created equal

except in possible QGP

J. Rafelski and B. Muller, Phys.Rev.Lett.48:1066,1982



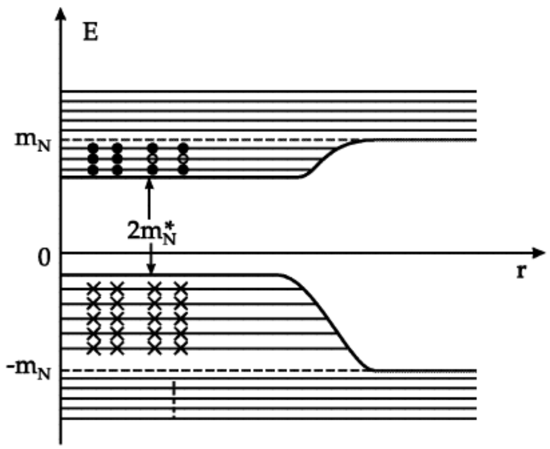
STAR whitepaper, NPA757(2005)

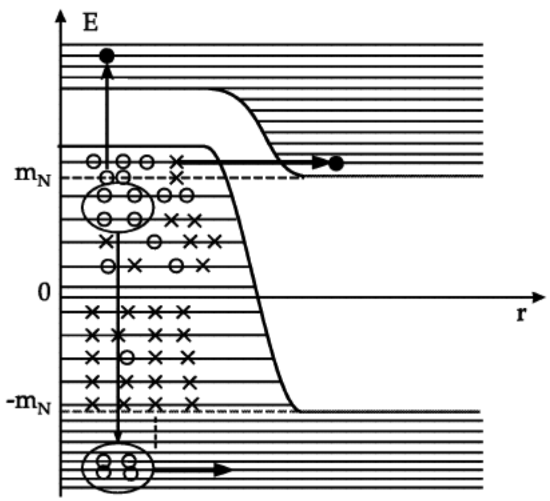


A. Andronic, P.Braun-Munzinger, J.Stachel, Phys. Lett. B 673 (2009) 142

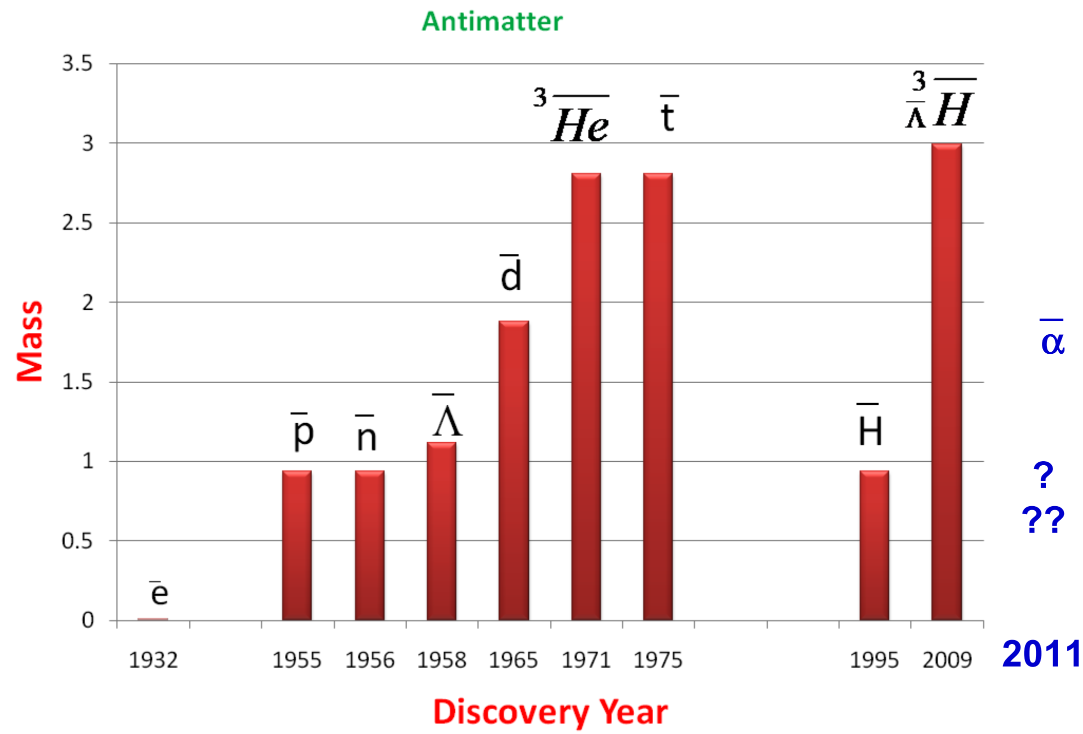
A. Andronic, P.Braun-Munzinger, K.Redlich, J.Stachel, Phys. Lett. B 652 (2007) 259; B 678 (2009) 350; arXiv:1002.4441

Antimatter Project: 40 years per step





- Pull $\bar{\alpha}$ from vacuum (Dirac Sea)



The extension of the periodic system into the sectors of hypermatter (strangeness) and antimatter is of general and astrophysical importance. … The ideas proposed here, the verification of which will need the **commitment for 2-4 decades of research, could be such a vision with considerable** attraction for the best young physicists… I can already see the enthusiasm in the eyes of young scientists, when I unfold these ideas to them — similarly as it was 30 years ago,…

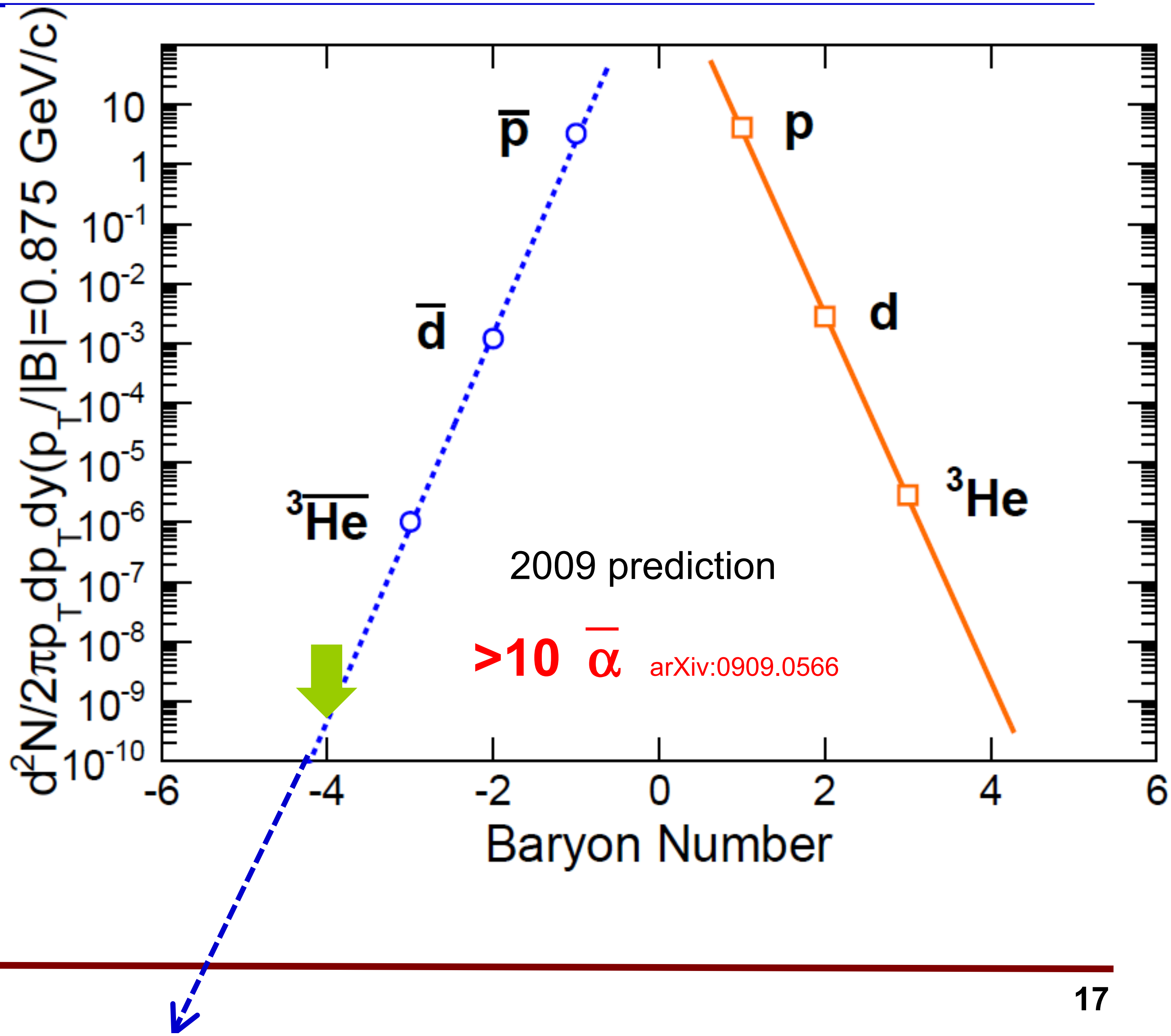
---- Walter Greiner (2001)

Projected Discovery of antimatter Helium-4 nucleus from STAR

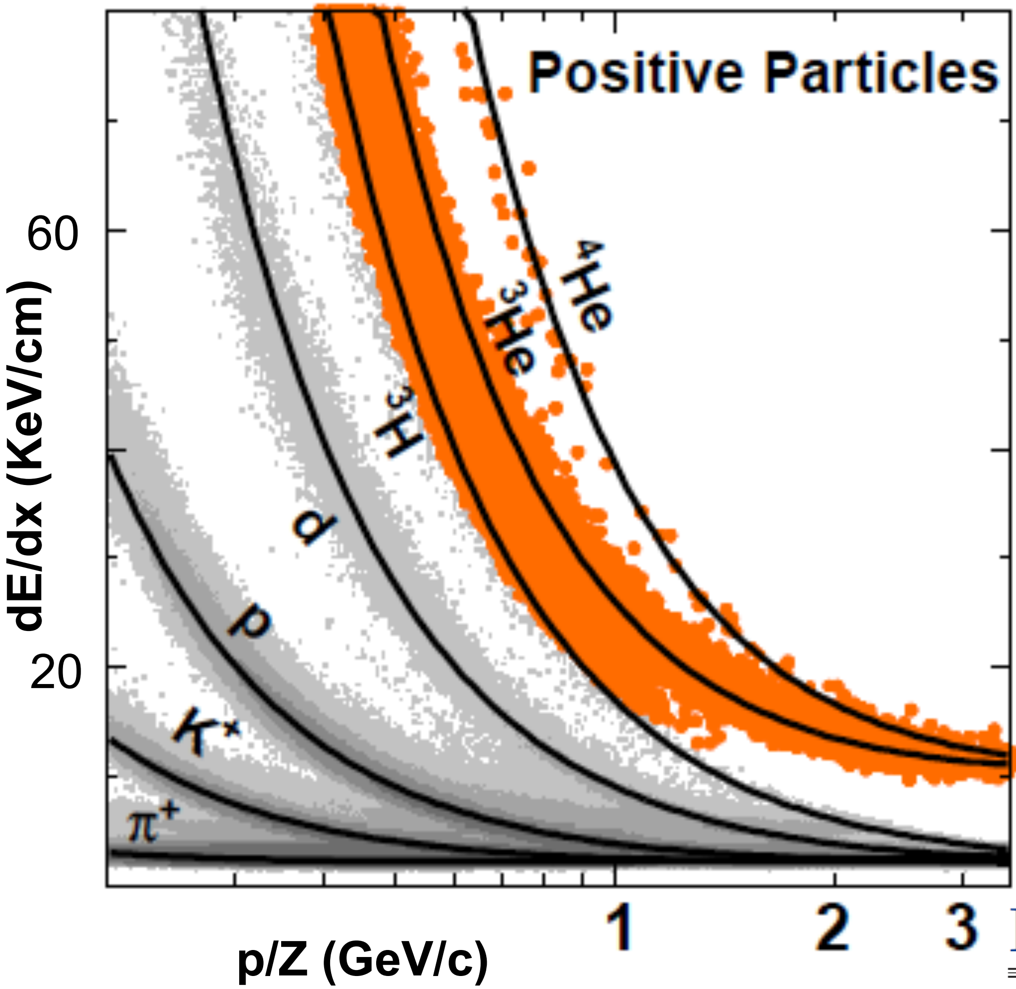
Can we get to antimatter ^{6}He, ^{6}Li?

Production rate
1 million times lower
than anti-Helium-4

Unless technology or production mechanism change dramatically, **NO**!



How to identify Helium-4



dE/dx in Time Projection Chamber

Separation at low pT
Merged with Helium-3 at p>3.5GeV/c
Most of the statistics at that range

Need a different detector

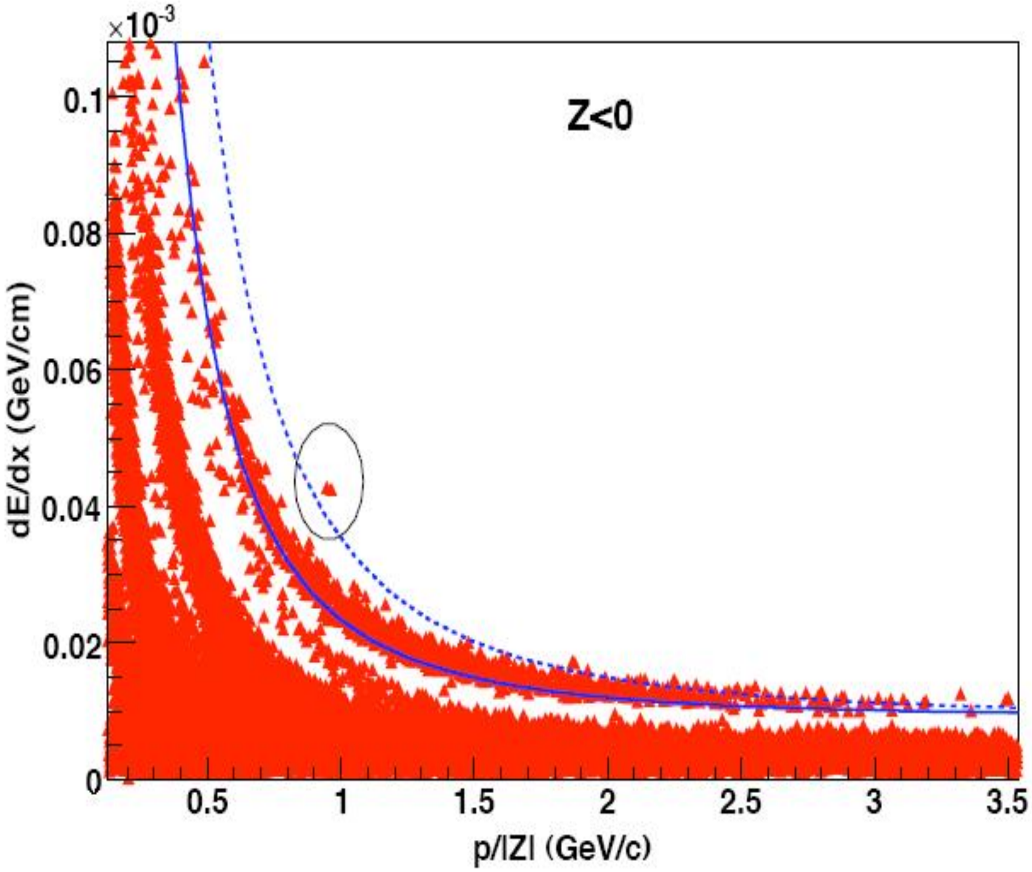
Nature Letters:
Received 14 March; accepted 4 April 2011.
Published online 24 April 2011.

LETTER nature doi:10.1038/nature10079

Observation of the antimatter helium-4 nucleus

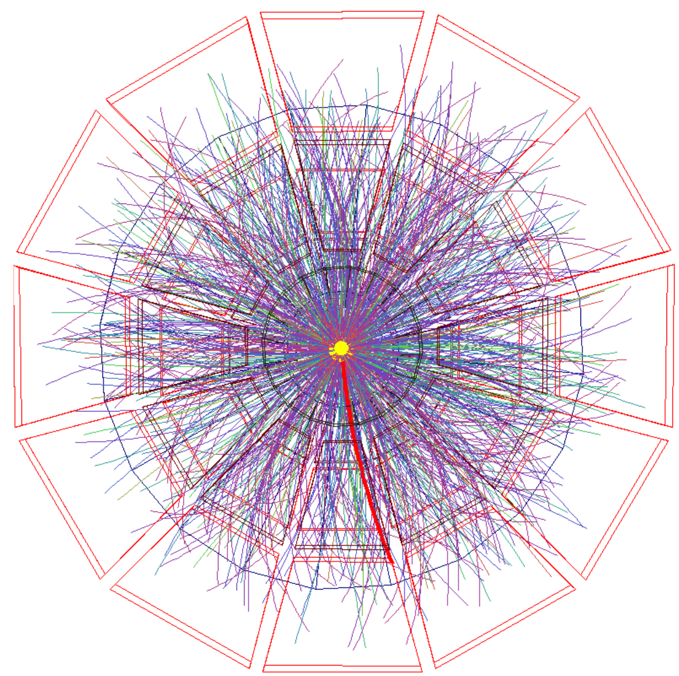
The STAR Collaboration*

Candidates identified by TPC (2007)



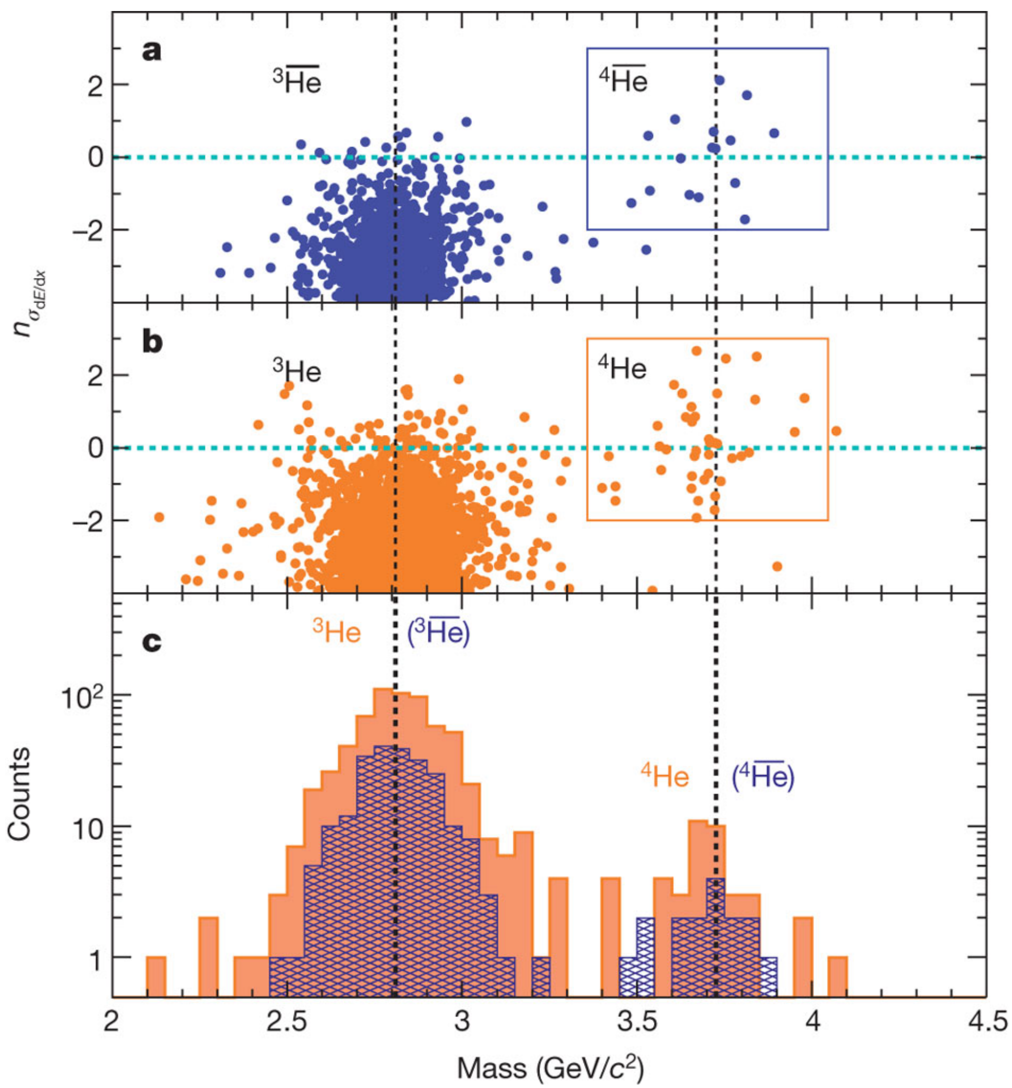
Two candidates;
Clean separation;

To claim the discovery:
need more statistics and
confirmation using new detector



Jianhang Zhou (Rice) PHD thesis 2009
Light (Anti-)Nuclei Production in the STAR Experiment at RHIC

STAR The Power of Time-of-Flight Detector



$$m^2 = p^2(1/\beta^2 - 1)$$

Two detectors confirm each other
With different methods:
dE/dx vs mass
18 count of antimatter Helium-4
Clean separation of Helium isotopes

1. Data Acquisition 10→100→1000Hz
2. TOF 100% installed in 2009:
   A US-China joint Project for STAR
3. High-Level Trigger for express output
4. Collider performance and Luminosity

More details on Sunday in talk by Hao Qiu (H7.00007)

STAR

[1103.3312] Observation of the antimatter helium

http://arxiv.org/abs/1103.3312

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[1103.3312] Observation of the antimatter helium

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Nuclear Experiment

Observation of the anti

STAR Collaboration

(Submitted on 16 Mar 2011 (v1), last revised 2

High-energy nuclear collisions create a
antimatter are formed with comparable
quickly from matter, and avoid annihila
antimatter. The antimatter helium-4 nu
antineutrons (baryon number B=-4). It
and is present in cosmic radiation at th
accelerators, where the rate of antinuc
present the observation of the antimatt
STAR experiment at RHIC in 10^9 re
yield is consistent with expectations fro

Comments: 19 pages, 4 figures. Submitted t
Subjects: **Nuclear Experiment (nucl-ex)**
Cite as: arXiv:1103.3312v2 **[nucl-ex]**

Submission history

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Observation of the antimatter helium-4 nucleus

The STAR Collaboration

Affiliations | Contributions

Nature (2011) | doi:10.1038/nature10079

Received 14 March 2011 | Accepted 04 April 2011 | Published online 24 April 2011

High-energy nuclear collisions create an energy density similar to that of the Universe microseconds after the Big Bang[1]; in both cases, matter and antimatter are formed with comparable abundance. However, the relatively short-lived expansion in nuclear collisions allows antimatter to decouple quickly from matter, and avoid annihilation. Thus, a high-energy accelerator of heavy nuclei provides an efficient means of producing and studying antimatter. The antimatter helium-4 nucleus ($^4\overline{\mathrm{He}}$), also known as the anti-α ($\overline{\alpha}$), consists of two antiprotons and two antineutrons (baryon number $B = -4$). It has not been observed previously, although the α-particle was identified a century ago by Rutherford and is present in cosmic radiation at the ten per cent level[2]. Antimatter nuclei with $B < -1$ have been observed only as rare products of interactions at particle accelerators, where the rate of antinucleus production in high-energy collisions decreases by a factor of about 1,000 with each additional antinucleon[3, 4, 5]. Here we report the observation of $^4\overline{\mathrm{He}}$, the heaviest observed antinucleus to date. In total, 18 $^4\overline{\mathrm{He}}$ counts were detected at the STAR experiment at the Relativistic Heavy Ion Collider (RHIC; ref. 6) in 10^9 recorded gold-on-gold (Au+Au) collisions at centre-of-mass energies of 200 GeV and 62 GeV per nucleon–nucleon pair. The yield is consistent with expectations from thermodynamic[7] and coalescent nucleosynthesis[8] models, providing an indication of the production rate of even heavier antimatter nuclei and a benchmark for possible future observations of $^4\overline{\mathrm{He}}$ in cosmic radiation.

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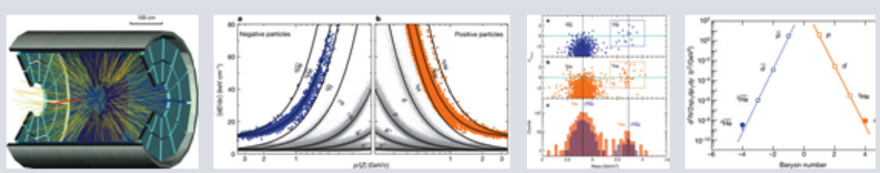
Figures at a glance



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Existence is no surprise

It's still unclear whether finding the antihypertriton will have practical implications for physics, said Frank Close, a physicist at the University of Oxford and author of the book *Antimatter*. "One way of saying it is it's **stamp collecting**. Some stamps are more exciting than others," he said. "The fact that this particle has been found **confirms our general belief** that antimatter should exist just as much as matter exists," Close added. --- February 2011, National Geographic

"It is an enormous technical achievement that they can extract these rarely produced objects," says Tom Cohen, a nuclear physicist at the University of Maryland, College Park. "But everybody believed—I should almost say knew— that anti-alpha particles could exist." Cohen compares the feat with climbing the world's tallest mountain: "It's really impressive that you can do it, but the fact that there's **a summit to Mount Everest is not a big surprise**."

"It's really, really very impressive that they're able to do that, to see these rare events and convincingly isolate them," he says. "What they've found is that **there is no shock**; it's where it's predicted to be."

"Some of my colleagues take it for granted that there obviously has to be an anti-alpha. My view, and I am a theorist, is that it **is just an idea** – of course a good idea - **until it is actually seen**. The fact that you encountered the antihypertriton - no one's obvious choice - on the way, is a sign that probing the attainable structure of antimatter is a real scientific adventure."

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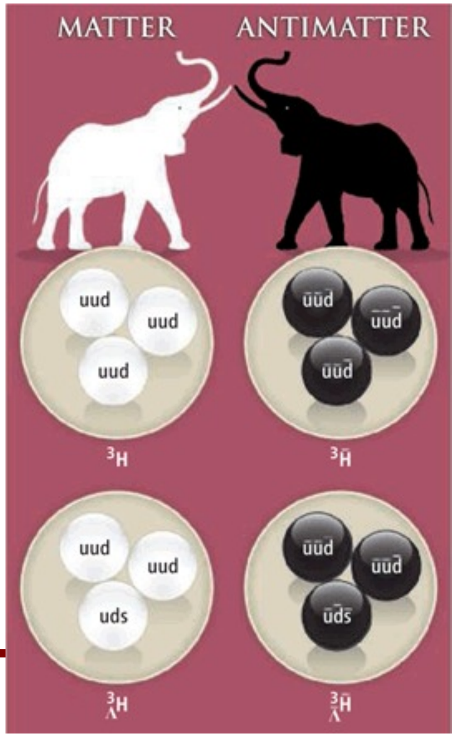


Predictability is a shock

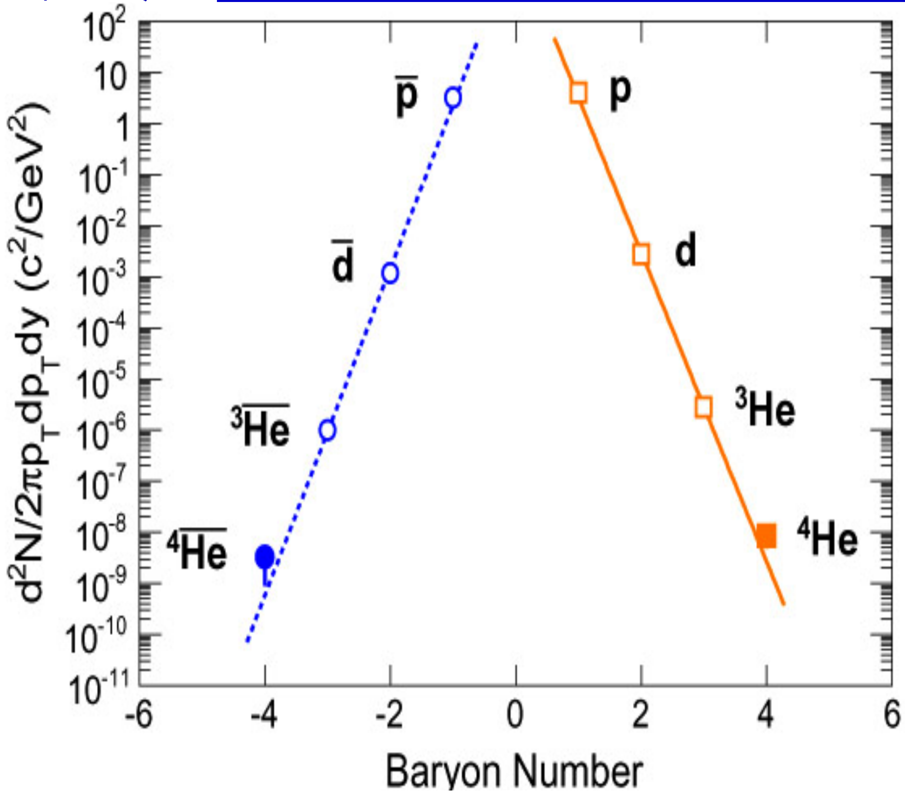
If I told you that:

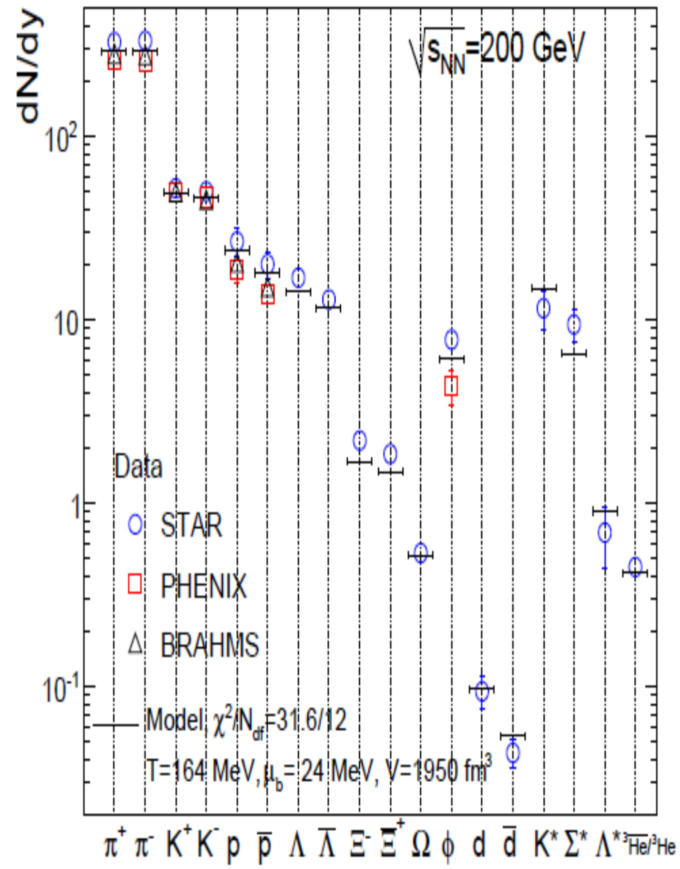
1.create a state of matter at 4×10^{12} degrees
out of a few thousands of particles
2.Matter and antimatter do not annihilate at
energy density 100 times the normal nuclear density
3.Anti-nuclei and nuclei with weak binding energy
carry information from the QGP phase transition
(Temperature = 160MeV)
4.All particles maintain statistical equilibrium
(no sign of annihilation but coalescence)
5.Models that assume thermal equilibrium correctly account for
yields spanning 11 orders of magnitude.
(1000 π, 10^{-8} ^{4}He)
±0.0000000001

How many of you would say that "I expect that!"?

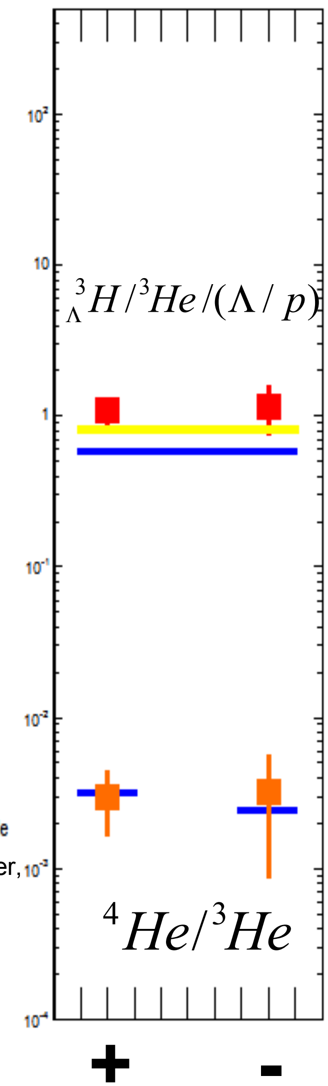
That is what we did when we found all these
Heavy antimatter nuclei!

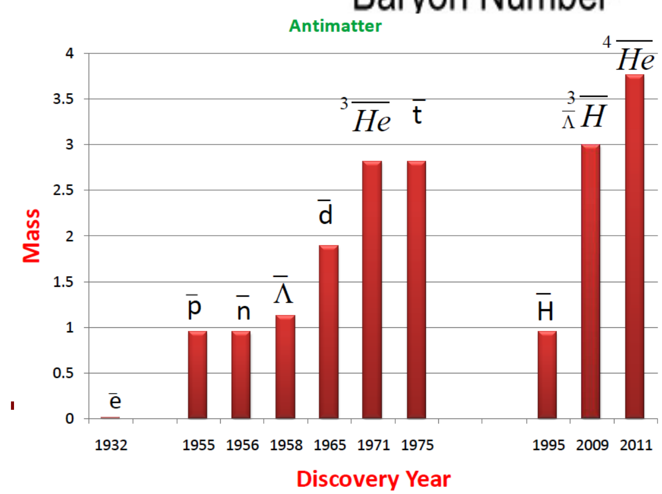
Predictable Production Rate





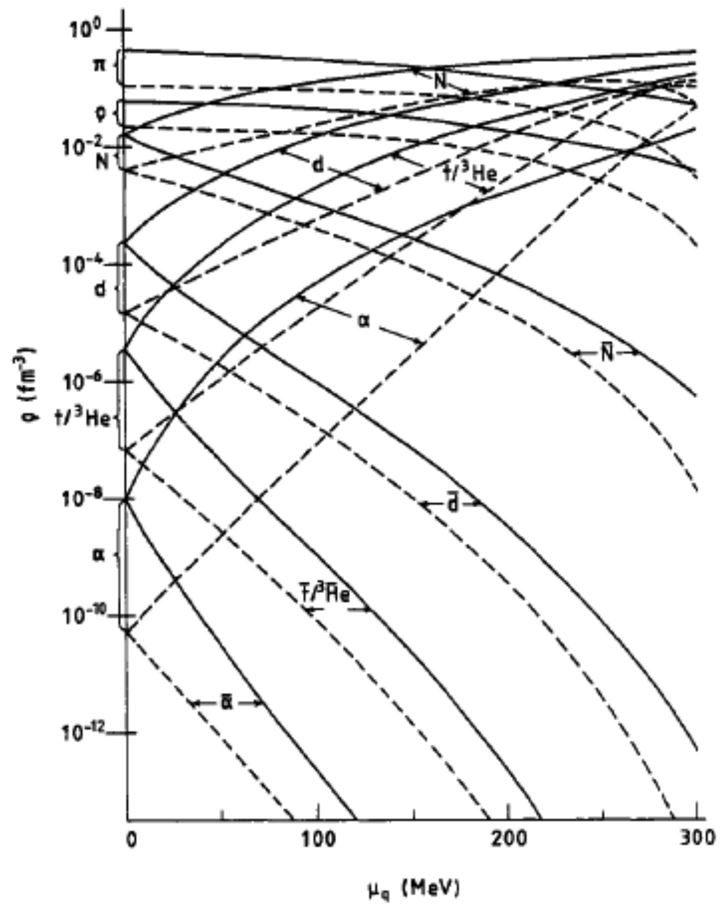
A. Andronic, P. Braun-Munzinger, J. Stachel, and H. Stocker, Phys.Lett.B697:203-207,2011

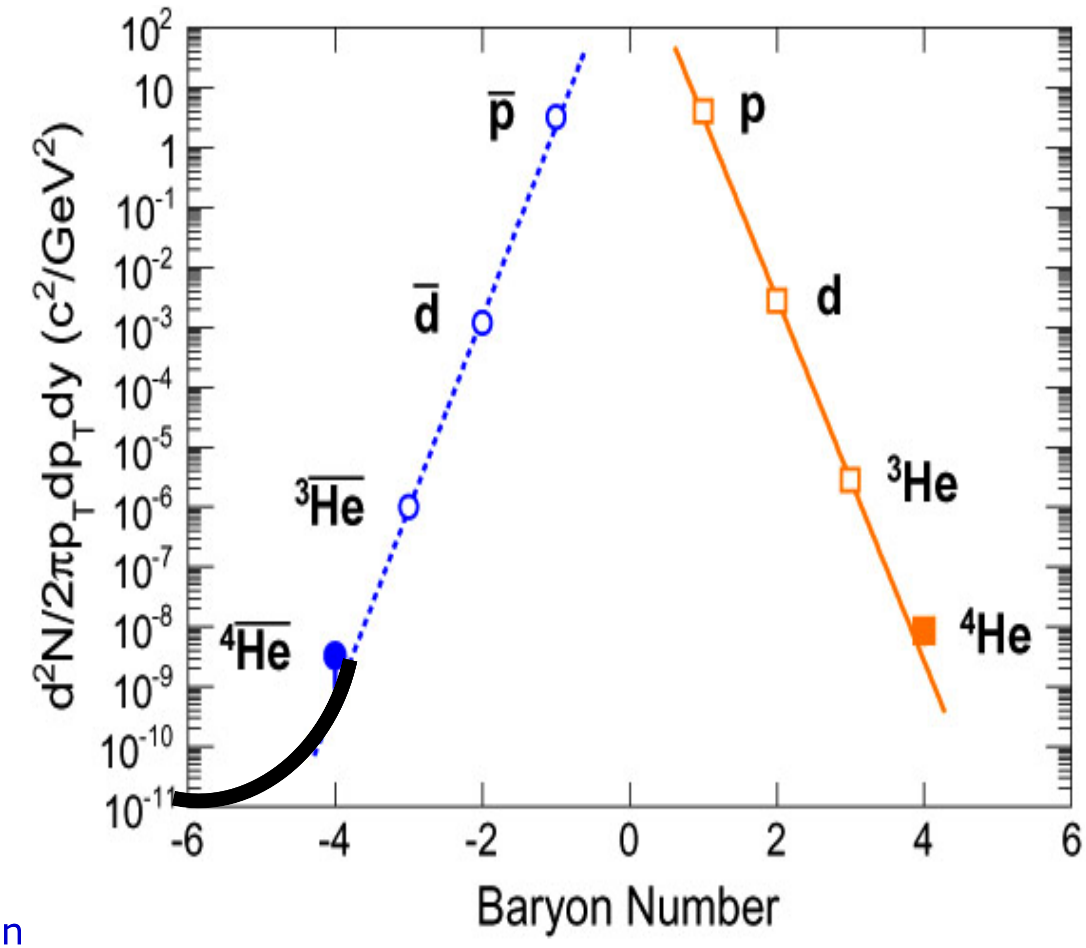




Why is it so predictable?
T=164MeV?

Even Heavier Antimatter





- Formation of antimatter clusters in the hadronisation phase transition: U. Heinz et al. JPG: 12 (1986) 1237
- Pull $\overline{\alpha}$ from vacuum (Dirac Sea): W. Greiner, IJMPE 5 (1995) 1

LETTER nature

doi:10.1038/nature10079

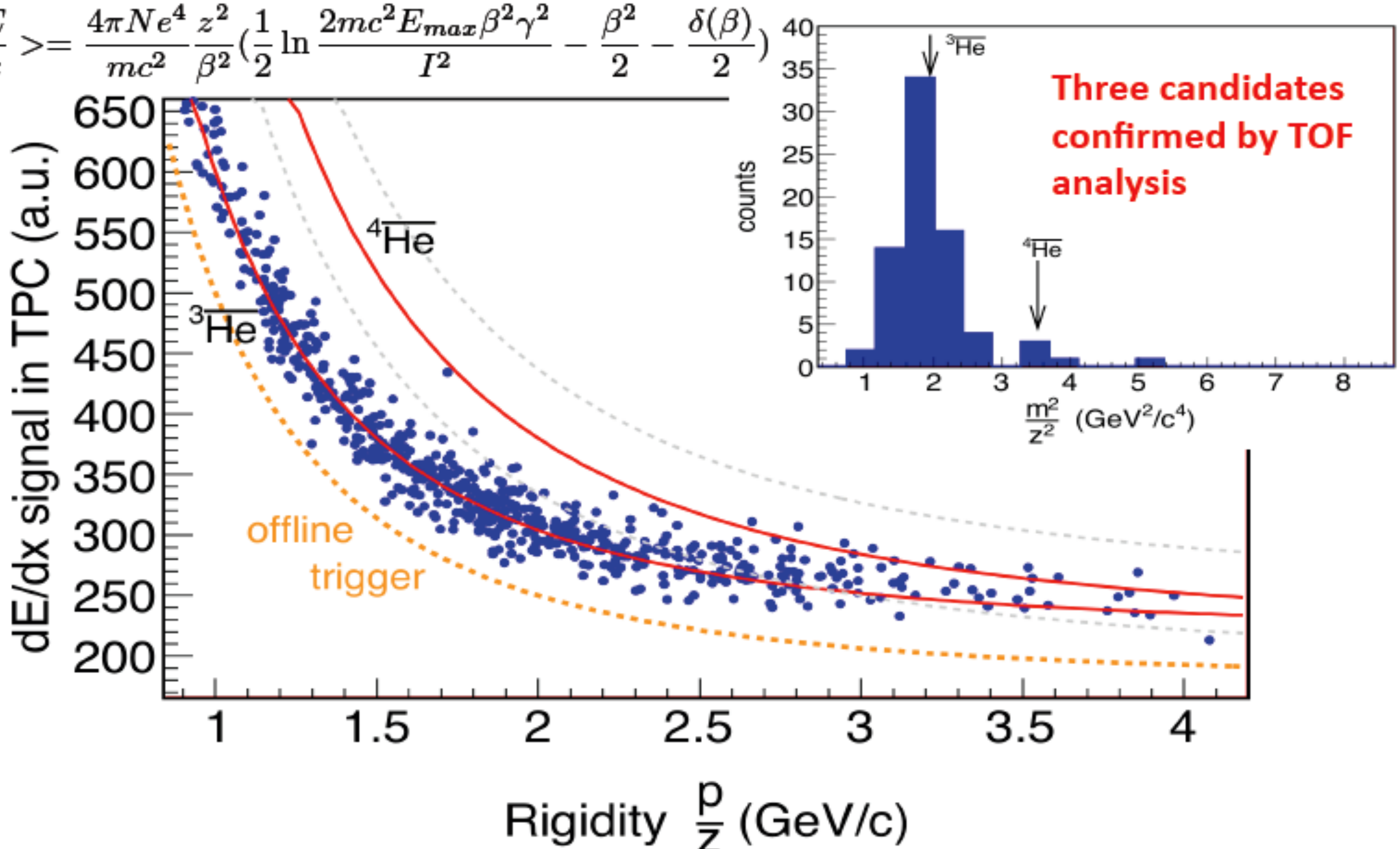
Observation of the antimatter helium-4 nucleus

The STAR Collaboration*

Anti-Alpha candidates in Pb-Pb

Time of flight (sensitive to m/z-ratio): $m = \frac{z \cdot R}{\sqrt{\gamma^2 - 1}}$

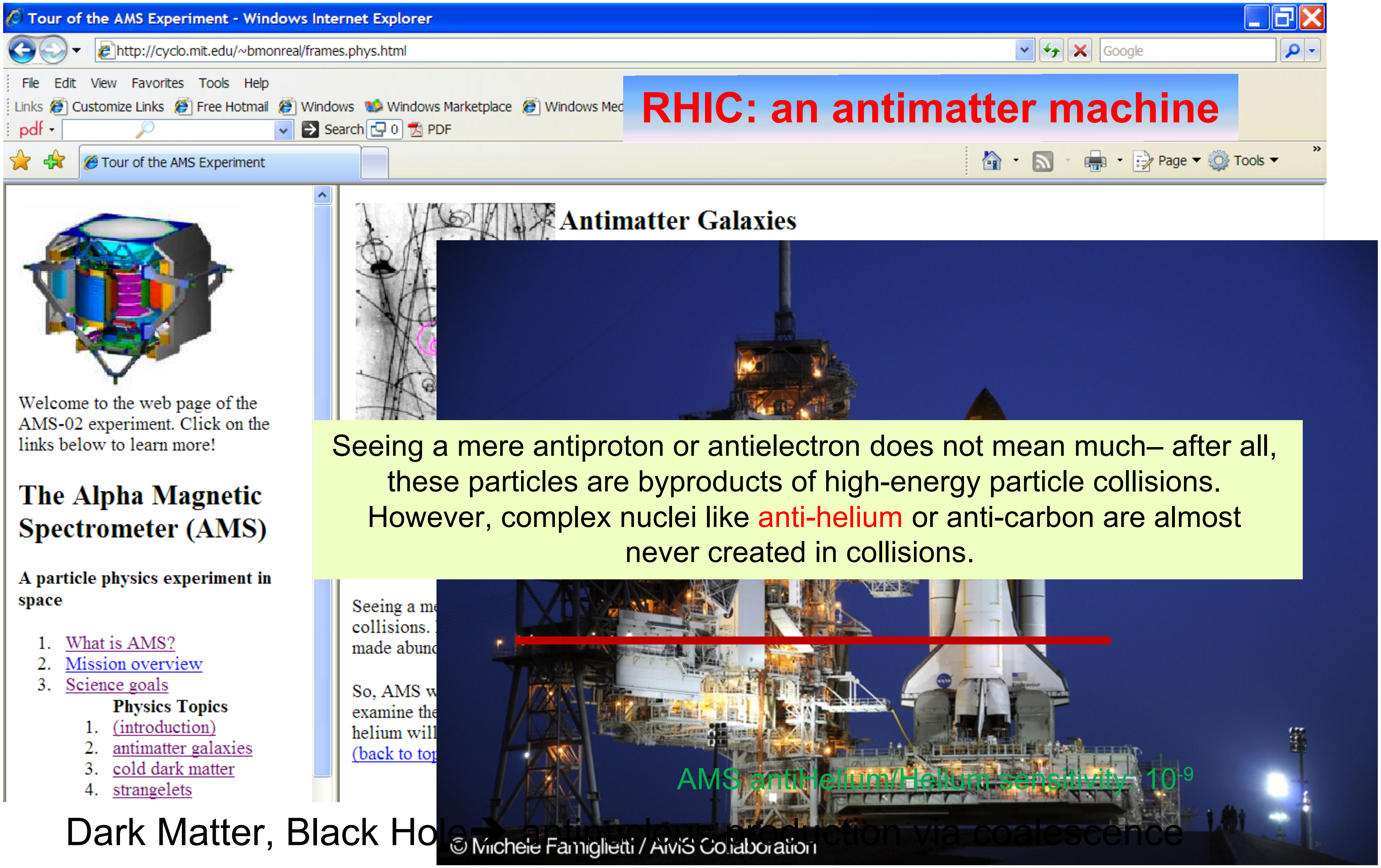
$$< \frac{dE}{dx} >= \frac{4\pi N e^4}{mc^2} \frac{z^2}{\beta^2} (\frac{1}{2} \ln \frac{2mc^2 E_{max} \beta^2 \gamma^2}{I^2} - \frac{\beta^2}{2} - \frac{\delta(\beta)}{2})$$



"ALICE came second but it's amazing to see how fast the results came," exclaims Paolo Giubellino, the experiment's spokesperson. – CERN Bulletin

Antinuclei in nature (new physics)

To appreciate just how rare nature produces antimatter (strange antimatter)



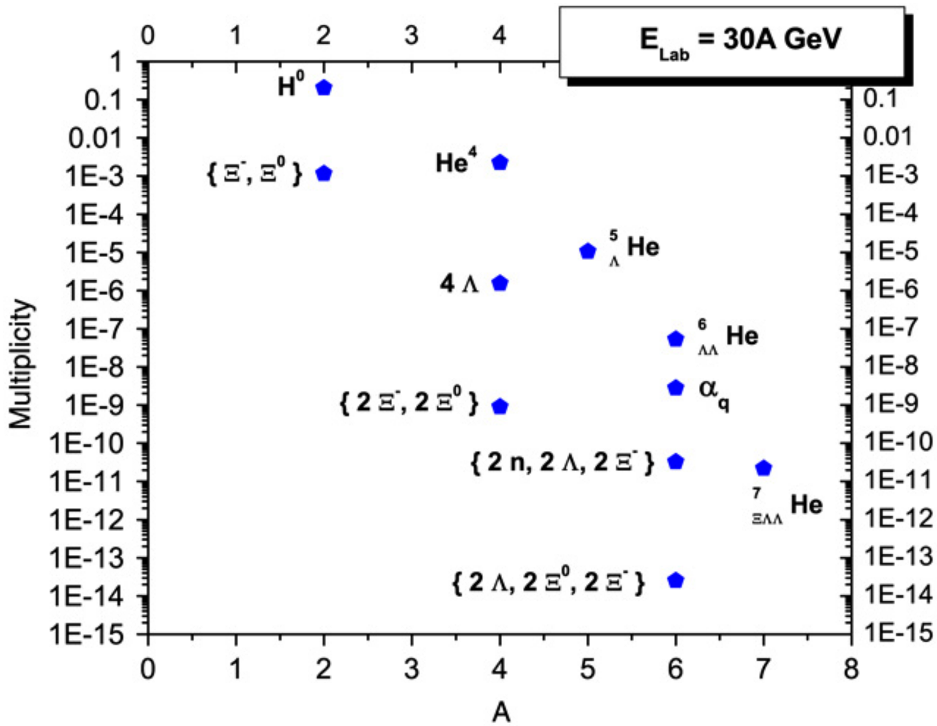
RHIC: an antimatter machine

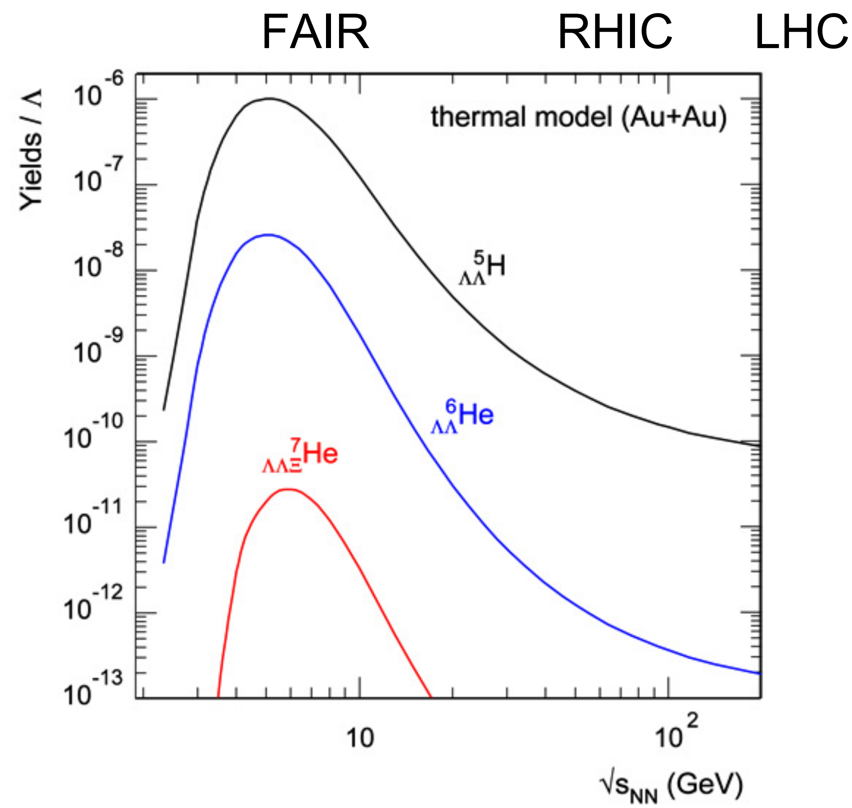
Seeing a mere antiproton or antielectron does not mean much– after all, these particles are byproducts of high-energy particle collisions. However, complex nuclei like anti-helium or anti-carbon are almost never created in collisions.

AMS antiHelium/Helium sensitivity: 10^{-9}

Dark Matter, Black Hole → antinucleus production via coalescence

Exotic Hypernuclei



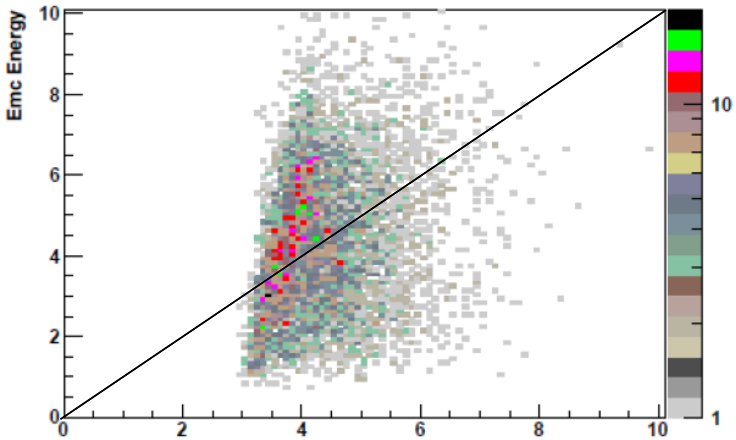


A. Andronic, P. Braun-Munzinger, J. Stachel, Nucl. Phys. A 772 (2006) 167.
P. Braun-Munzinger, J. Stachel, J. Phys. G 21 (1995) L17
A. Andronic: SQM09

More details on Sunday in talk by Neha Shah (H7.00001)

Other antimatter searches at RHIC

Unstable Antimatter Nuclei



Anti-He3 energy deposit in calorimeter

$^4Li \rightarrow {}^3He+p$

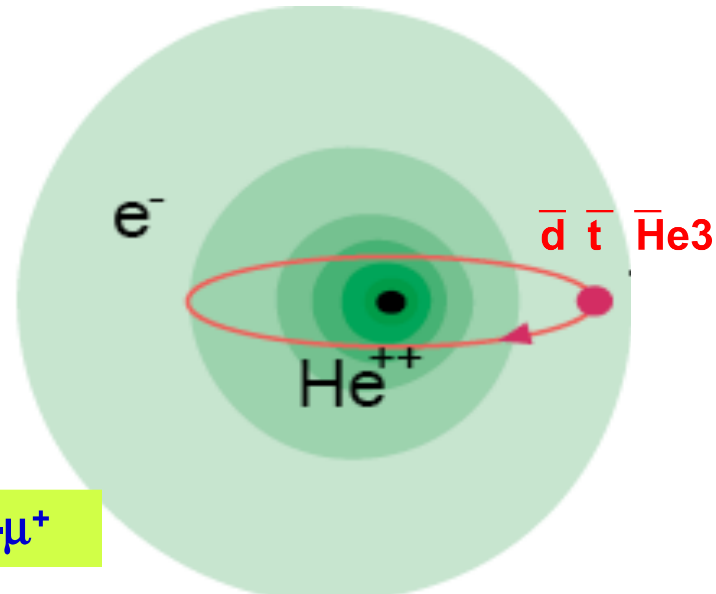
$^4He^* \rightarrow d+d,\ t+p$

$^5Li \rightarrow {}^4He+p$

$^4_\Lambda H \rightarrow {}^4He+\pi$

Antinuclei Atomcules

Metastable antiproton-helium atom discovered at KEK:
Iwasaki, **PRL** 67 (1991); **nature** 361 (1993) 238
Mass difference: p-pbar < 2×10^{-9}; Hori, **PRL** 96 (2006);
measurement of baryon mass and magnetic moment
for CPT test at LEAR/CERN
http://asacusa.web.cern.ch/ASACUSA/index-e.html



Antimatter mounic hydrogen: $\bar{p}$-μ^+

$$\frac{dN_{\rm atom}}{dy d^2 p_{\perp,\rm atom}} = 8\pi^2 \zeta(3) \alpha^3 m^2_{\rm red} \frac{dN_h}{dy d^2 p_{\perp,h}} \frac{dN_l}{dy d^2 p_{\perp,l}}. \quad (1)$$

>1000 candidates in 500M central events

Production of muon-meson atoms in Ulrearelativistic heavy-ion collisioins:
G. Baym et al., PRD 48(1993)
Hydrogenlike atoms from ultrarelativistic nuclear collisions:
J. Kapusta and A. Mocsy, PRC 59 (1999)
Measurement of the rate of formation of π-μ atoms in K_L^0 decay:
S.H. Aronson et al., PRL 48 (1982)

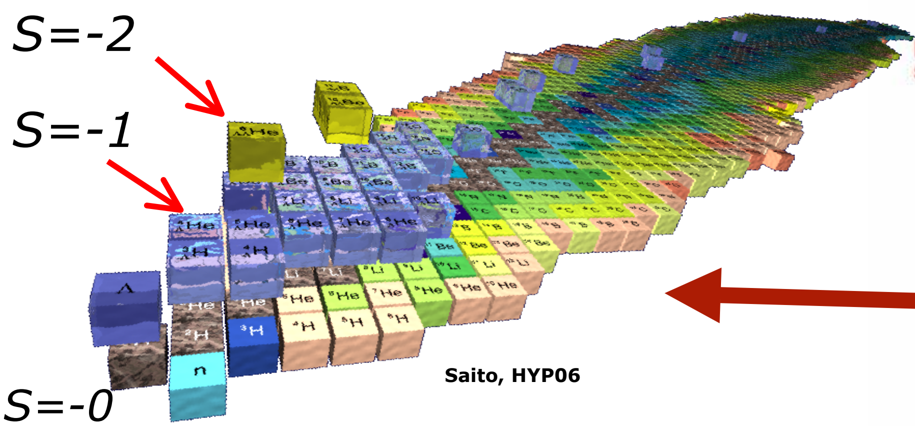
Conclusion and Outlook

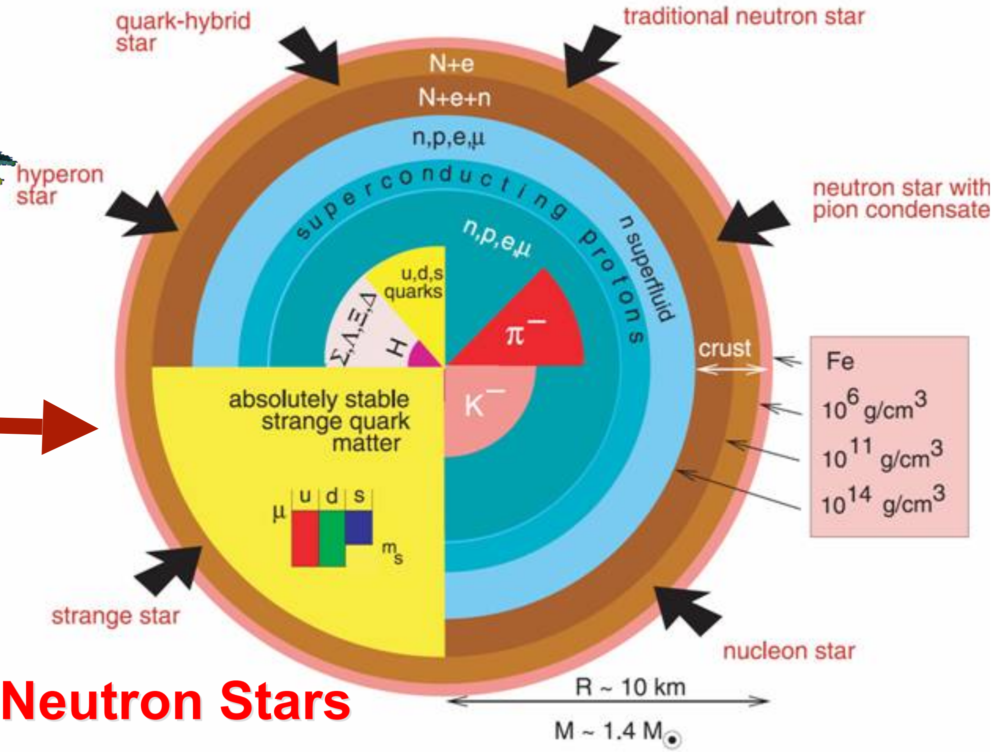
- $^{3}_{\bar{\mathrm{E}}}\overline{\mathrm{H}}$ has been observed for 1st time
- Discovery of antimatter Helium-4

- **$_{\Lambda}^{3}H \rightarrow$ *d*+*p*+π channel measurement: *d* and $\bar{d}$ via ToF.**
- **Search for other hypernucleus: $^{4}_{\Lambda}H$, double Λ-hypernucleus.**
- **heavier antinuclei, antinucleus atomcules, muonic hydrogen**
- **RHIC: best antimatter machine**

from Hypernuclei to Neutron Stars

hypernuclei ← Λ-B Interaction → Neutron Stars



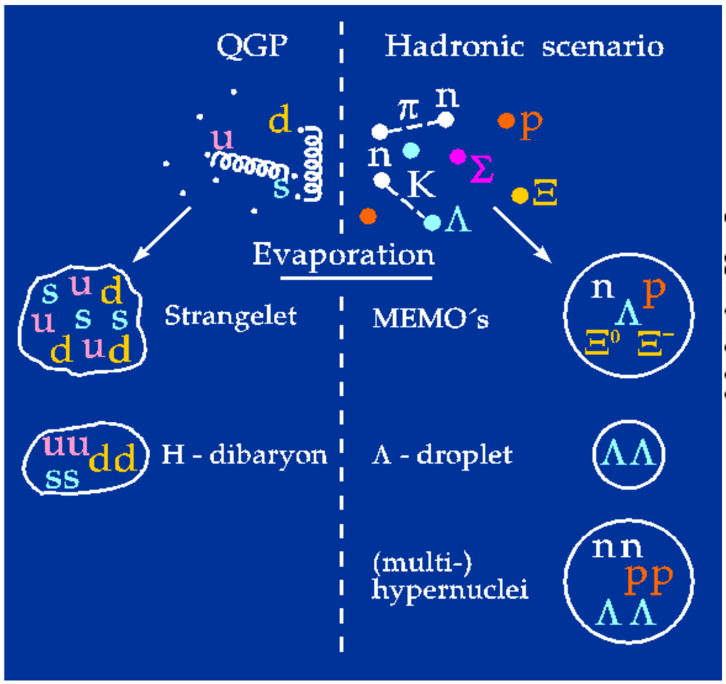


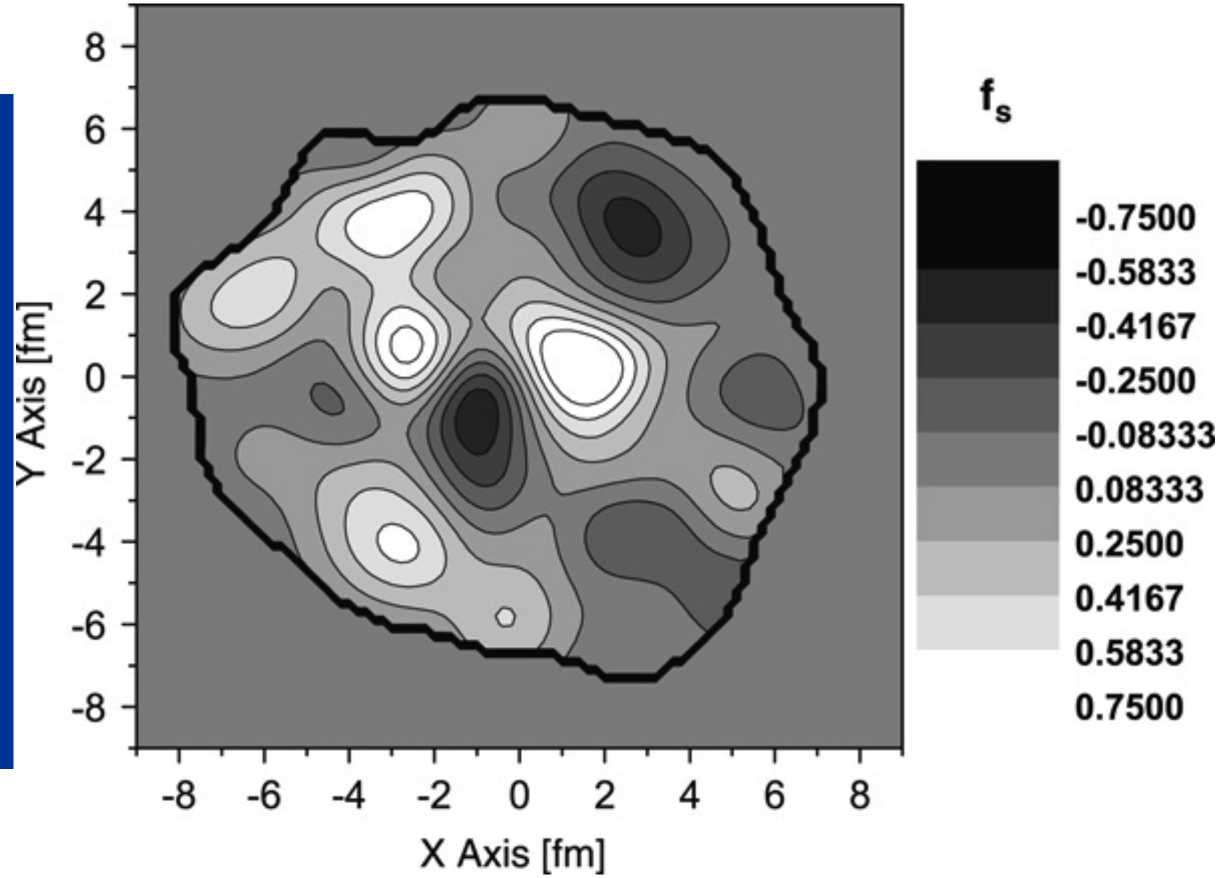
Several possible configurations of Neutron Stars
- **Kaon condensate, hyperons, strange quark matter**

J.M. Lattimer and M. Prakash, "The Physics of Neutron Stars", Science 304, 536 (2004)
J. Schaffner and I. Mishustin, *Phys. Rev. C* 53 (1996): Hyperon-rich matter in neutron stars

***Single* and *double* hypernuclei in the laboratory:**
- **study the strange sector of the baryon-baryon interaction**
- **provide info on EOS of neutron stars**

Strangeness Fluctuation

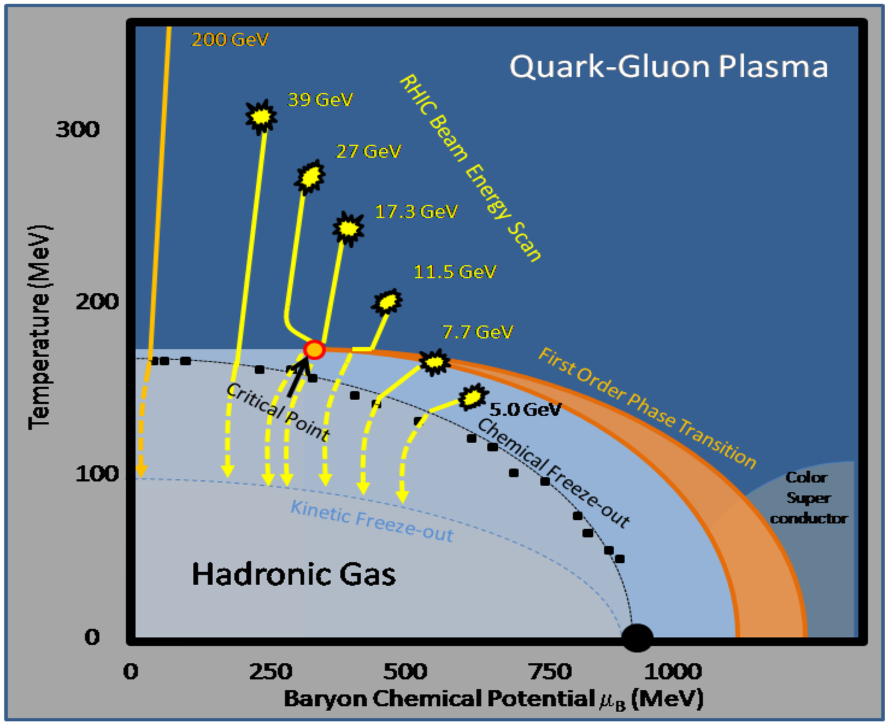


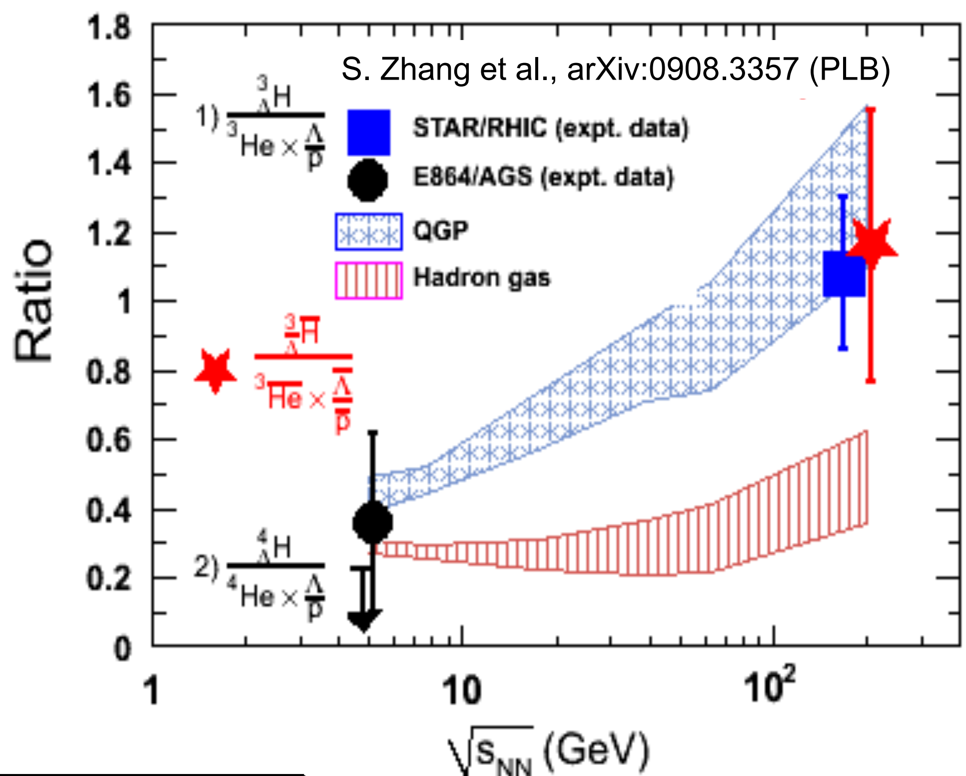


UrQMD E-by-E Distribution of the strangeness to baryon fraction in the transverse plane (z=0 fm).

Jan Steinheimer , Horst Stoecker, Ingo Augustin, Anton Andronic, Takehiko Saito,Peter Senger,
Progress in Particle and Nuclear Physics 62 (2009) 313317
J. Steinheimer: SQM09

Energy scan to establish the trend



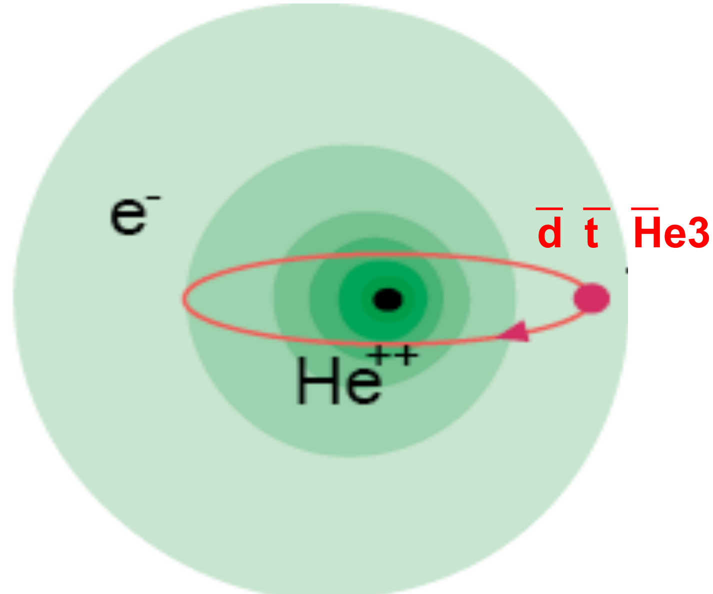


Beam energy	200(30—200) GeV	~17 (10—30)GeV	~5 (5-10) GeV
Minbias events# (5σ)	300M	**~10—100M**	**~1—10M**
Penalty factor	1448	368	48
^{3}He invariant yields	1.6x10^{-6}	2x10^{-4}	0.01
$^3_\Lambda$H/^{3}He assumed	1.0	0.3	0.05

Hypertriton only
STAR: DAQ1000+TOF

Creating first Antinucleus Atomcules

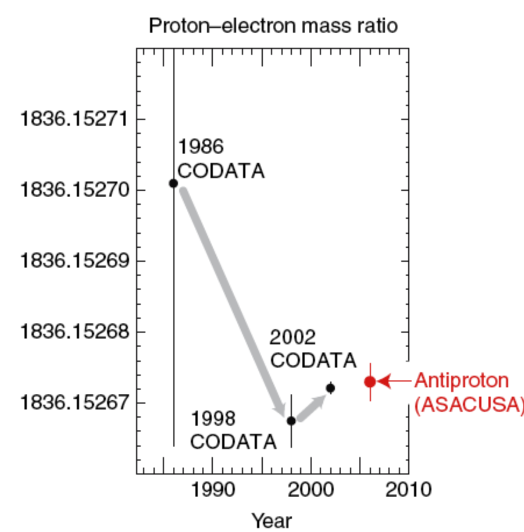
Metastable antiproton-helium atom discovered at KEK:
Iwasaki, **PRL** 67 (1991); **nature** 361 (1993) 238
Mass difference: p-pbar < $2\text{x}10^{-9}$; Hori, **PRL** 96 (2006);
measurement of baryon mass and magnetic moment
for CPT test at LEAR/CERN
http://asacusa.web.cern.ch/ASACUSA/index-e.html



What happens if we replace antiproton
with **antideuteron, antitriton or antiHelium3**

Atomic structure should be the same
for antideuteron and antitriton (-1 charge)
Reduced mass M* will be different.

Only RHIC can answer this question with
enough antimatter nuclei for such study



Possible Physics Topics:

- Measure antinucleus mass and magnetic moment for CPT test,
- Study the antinucleus annihilation process (sequence)
- antinucleus-nucleus Annihilation
  (what do they create? Hot or cold matter)
- Maybe even antiAlpha Atomcule