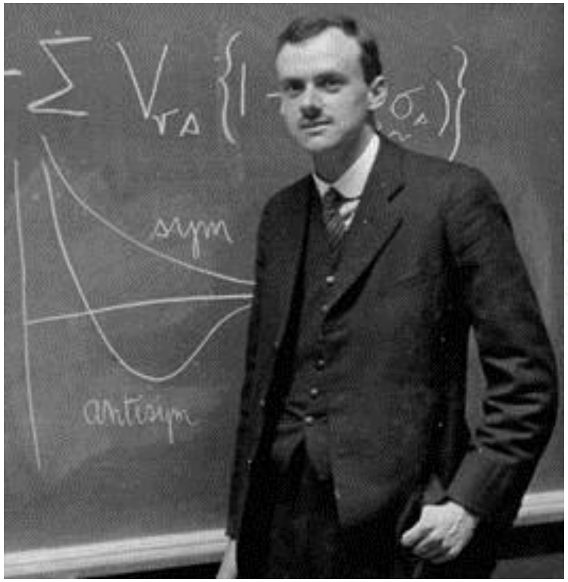
Antinucleus Production at STAR

- 2001 data: better statistics for anti-^{3}He
- 2007 data: discovery of anti-hypertriton
- 2010 data: discovery of anti-α
- new data: what's next?

Declan Keane
Kent State University

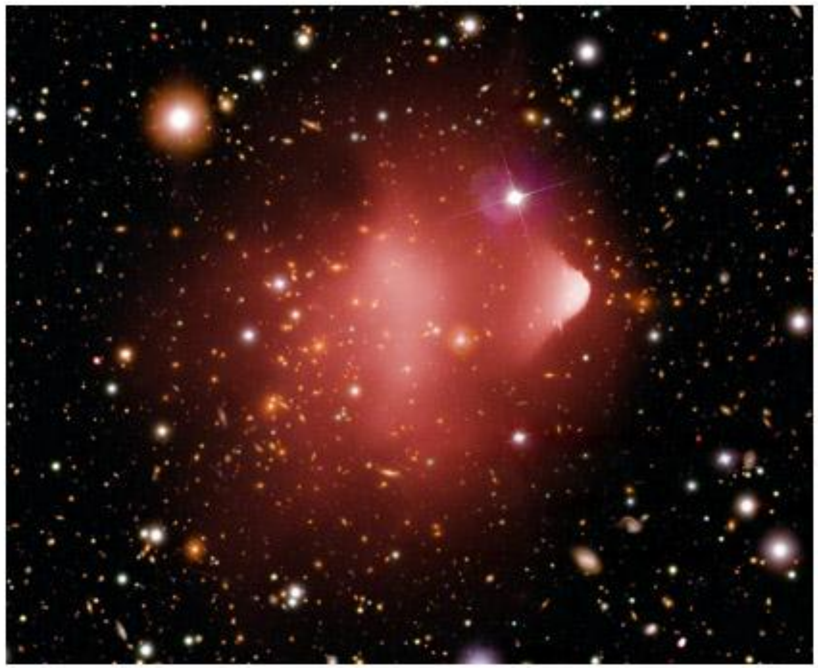
Antimatter 101

STAR



The Dirac equation (1928) predicted the existence of antimatter. It was confirmed 4 years later by Anderson's discovery of the positron.

THE BULLET CLUSTER:
SEARCHING FOR PRIMORDIAL ANTIMATTER

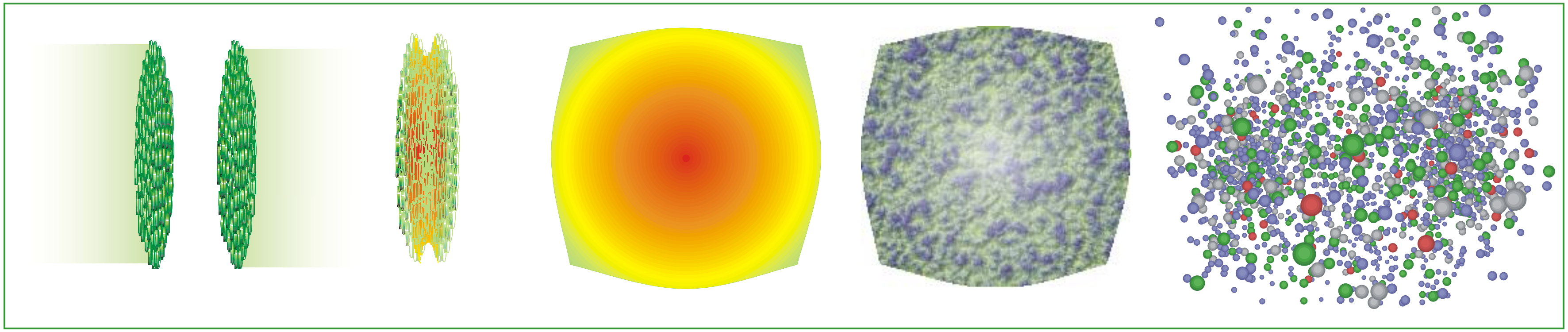


Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.

This view of the Bullet Cluster, located about 3.8 billion light years from Earth, combines an image from NASA's Chandra X-ray Observatory with optical data from the Hubble Space Telescope and the Magellan telescope in Chile.

Big Bang initially produced matter & antimatter in equal abundance – so does any primordial antimatter still persist in isolated regions of the cosmos?

Collisions at RHIC



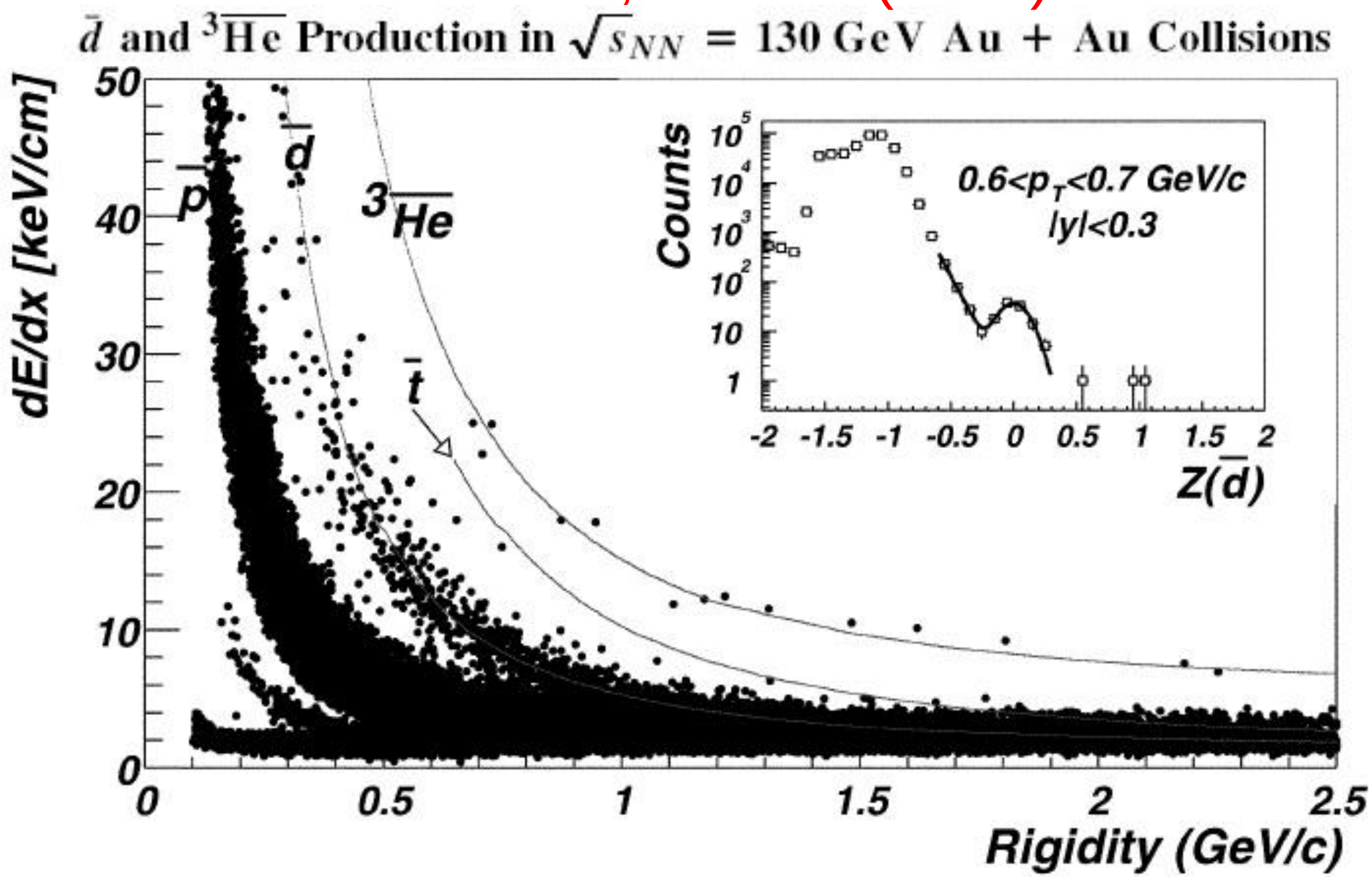
Hadronization & freeze-out

RHIC generates hot and dense matter,
where matter & antimatter decouple quickly:

Ideal factory for antinuclei

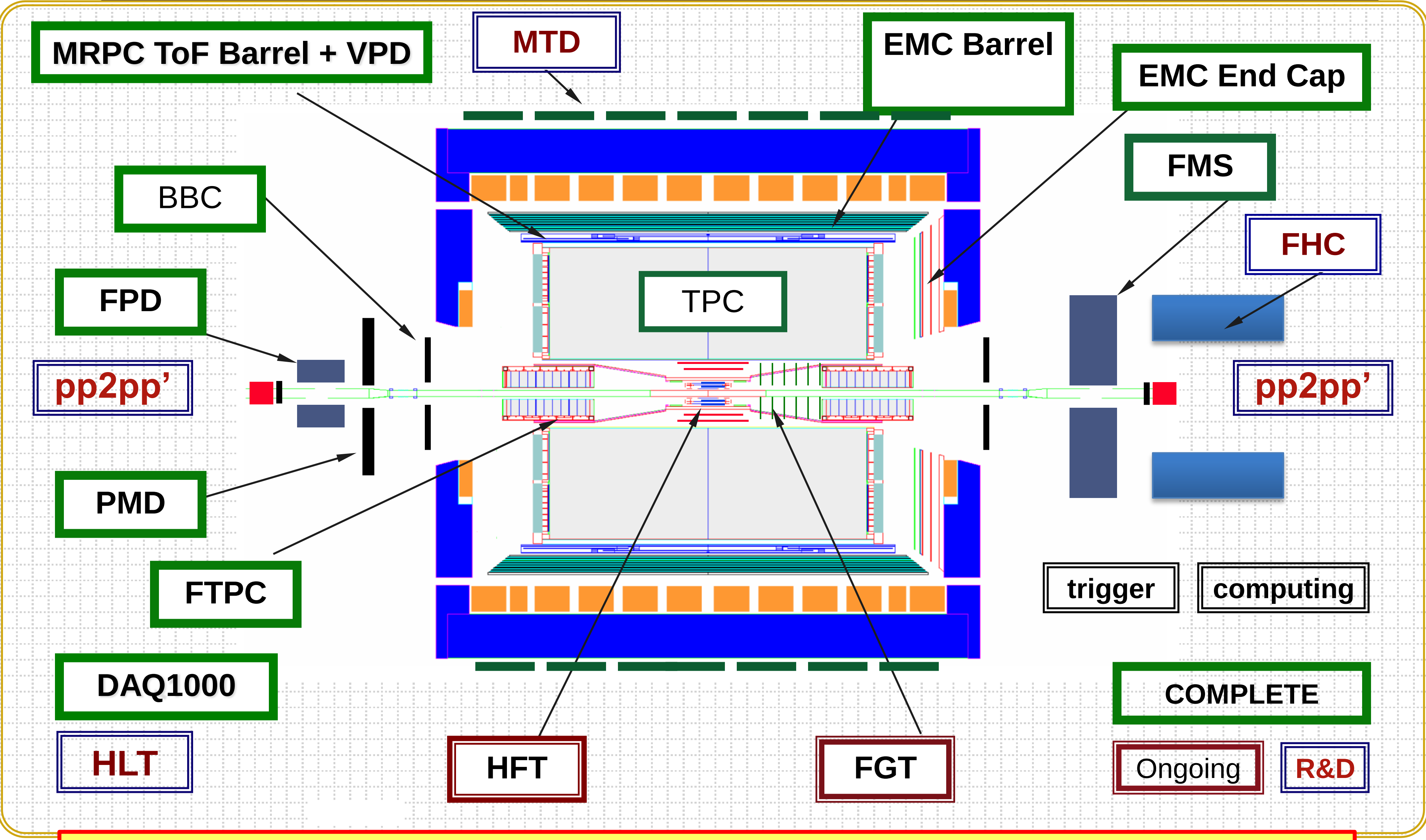
First STAR results for antinuclei

PRL 87, 262301 (2001)



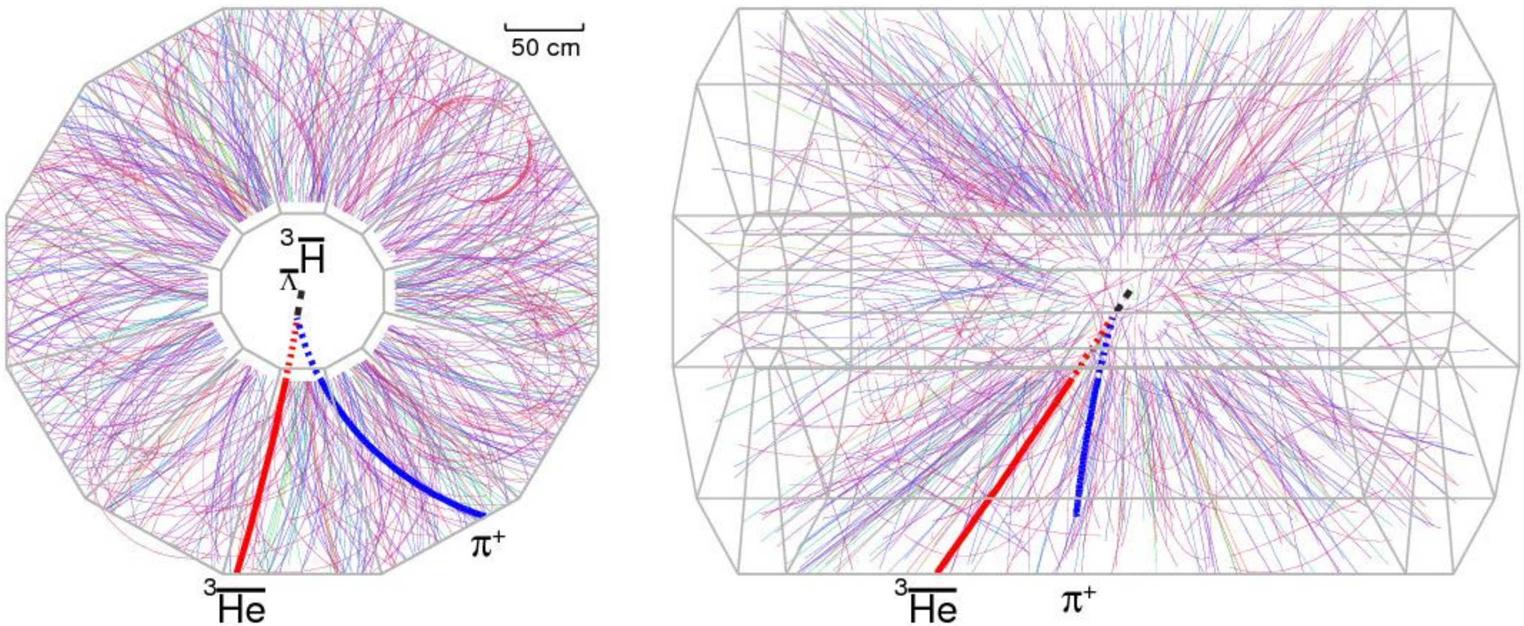
★ 14 anti-^{3}He based on 0.6M central AuAu at 130 GeV

STAR Subsystem Status – 2010



2010 run provided ~ a billion events with greatly enhanced PID

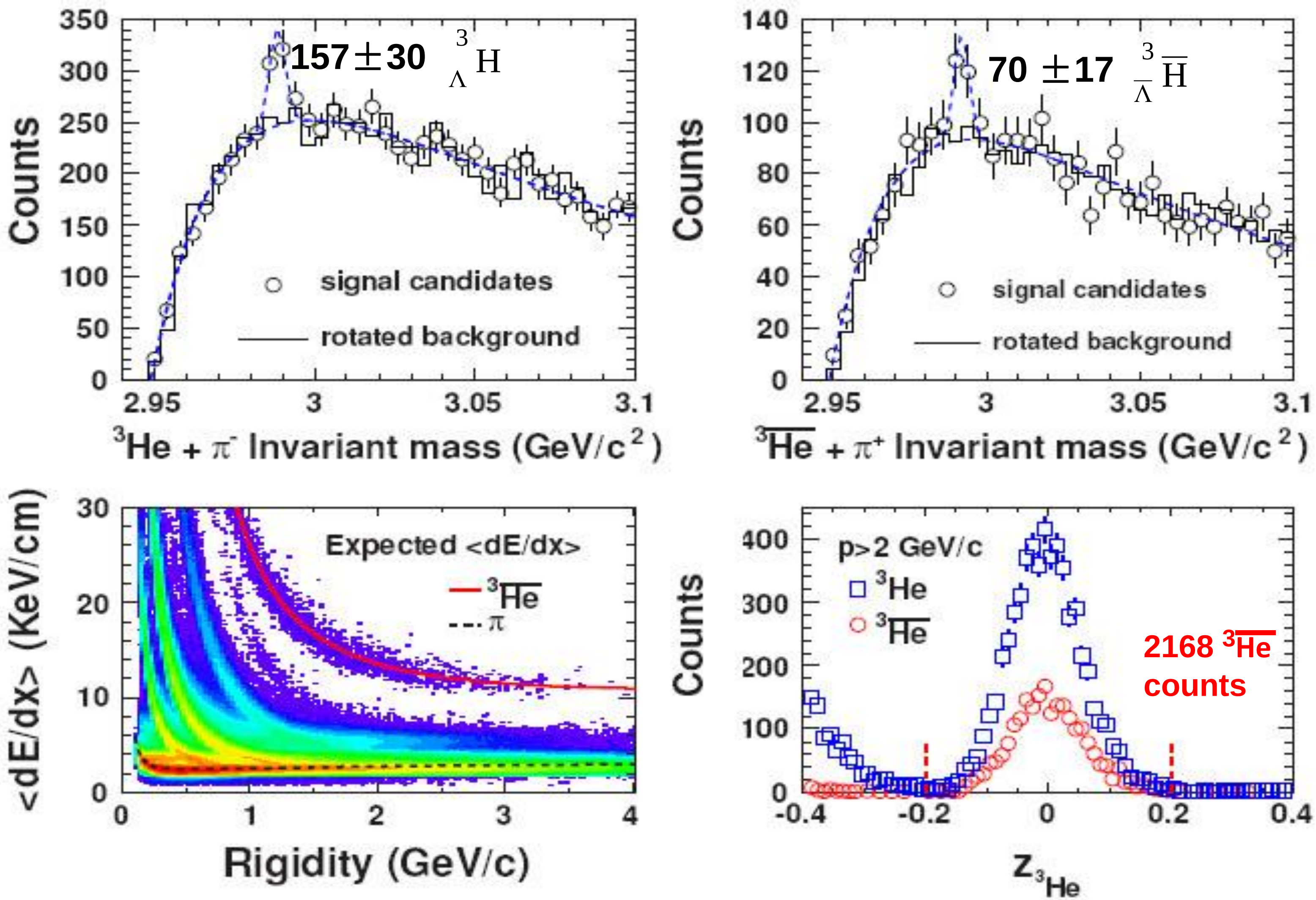
Results from Data up to 2007



- Anti-hypertriton: anti-proton, anti-neutron & anti-Λ – the first antinucleus with strangeness, and the heaviest antinucleus so far.
- After searching >100 million AuAu collisions, found 70 anti-hypertritons.
- Published in *Science* in March 2010; much favorable PR for STAR & RHIC. News stories in *Nature*, *Scientific American*, *National Geographic*, many news outlets worldwide.

STAR Collaboration, *Science* **328**, 58 (2010)

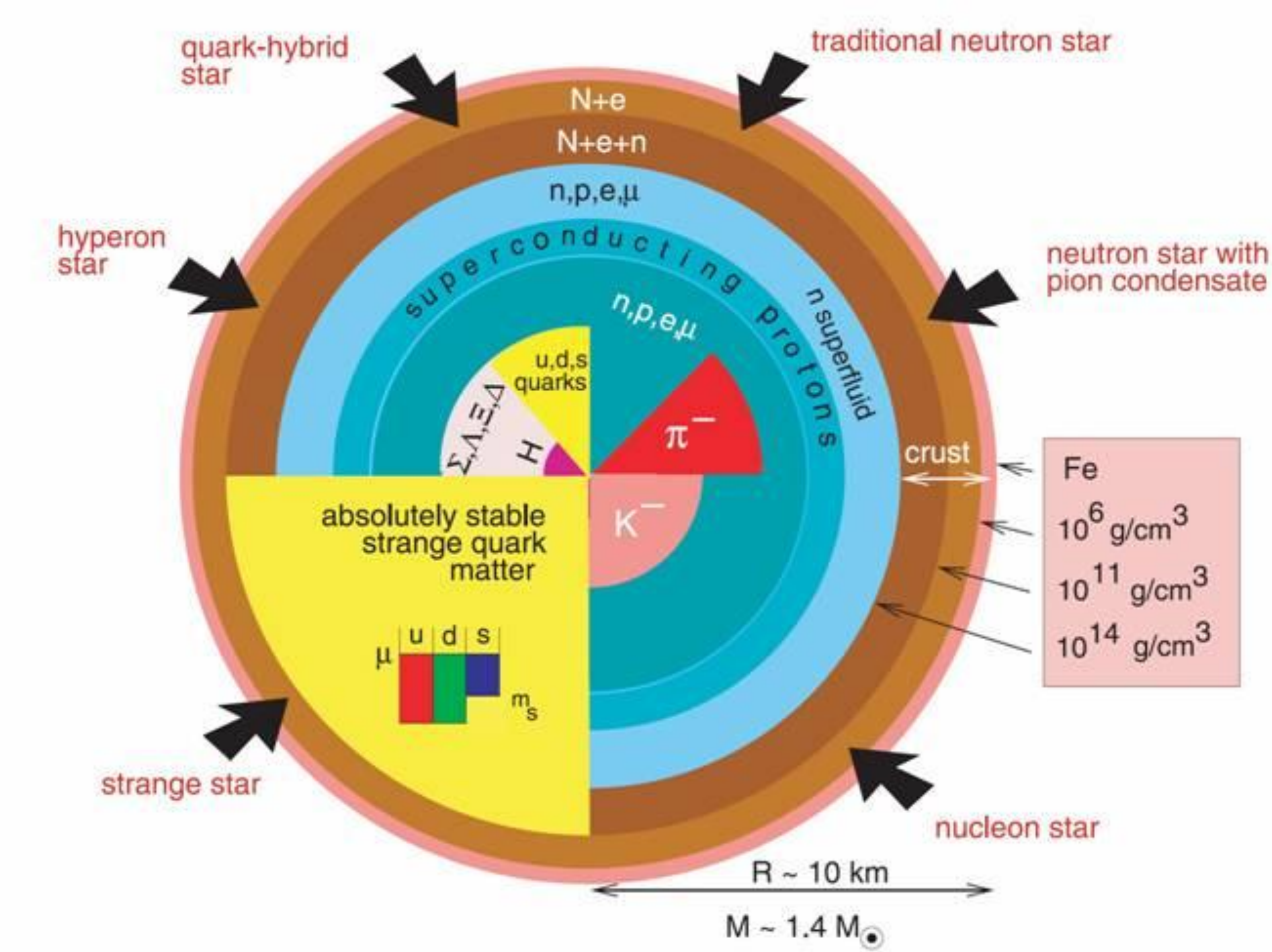
Signal & Background



Hypertriton signal is 5.2σ while anti-hypertriton signal is 4.1σ

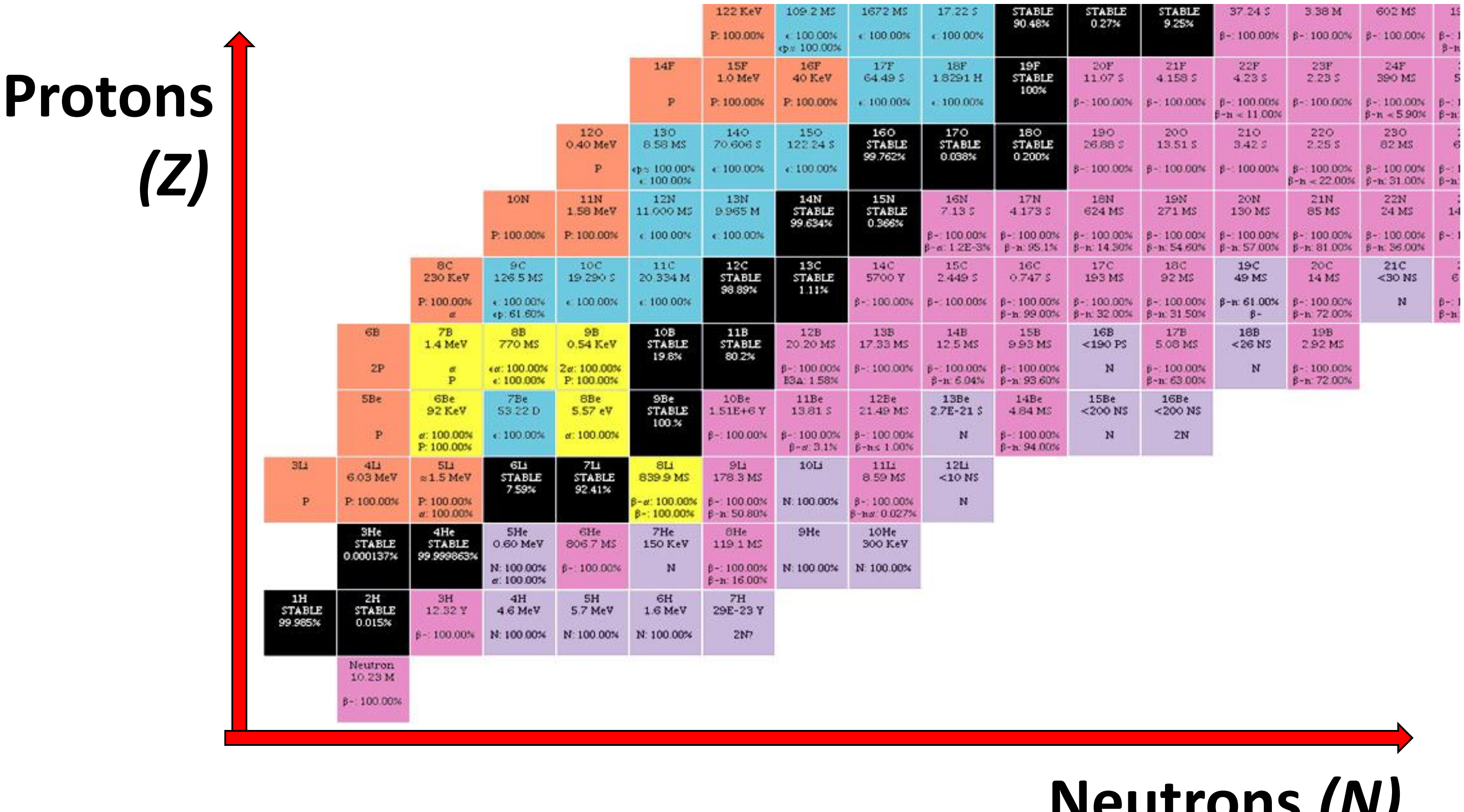
STAR Collaboration, *Science* **328**, 58 (2010)

Competing Neutron Star Models



Better Y-N interaction constraints (combining lifetime measurements from anti-hypernuclei and hypernuclei) should help distinguish among models

Chart of the Nuclides

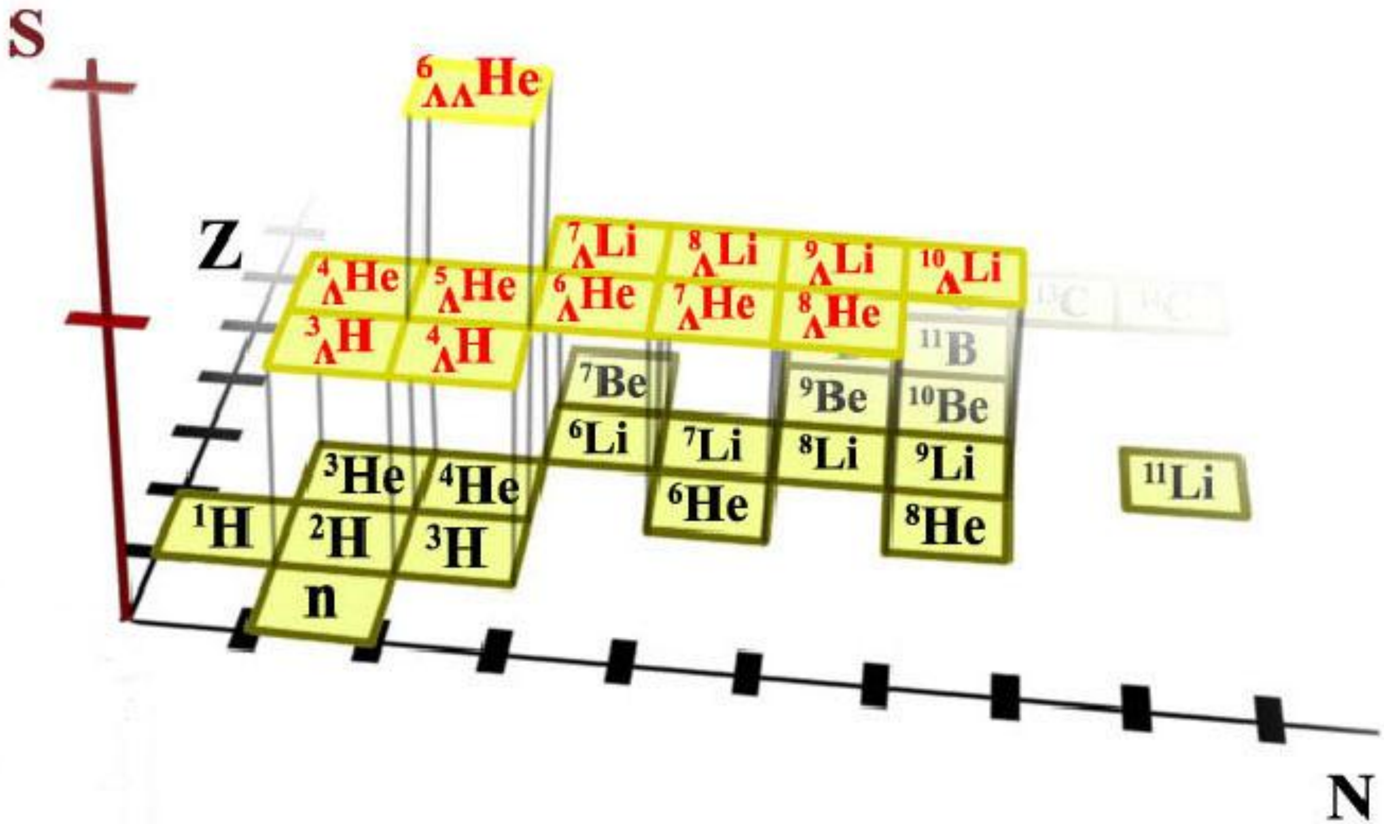


★ Antinuclei → extend chart to negative *Z* & negative *N*

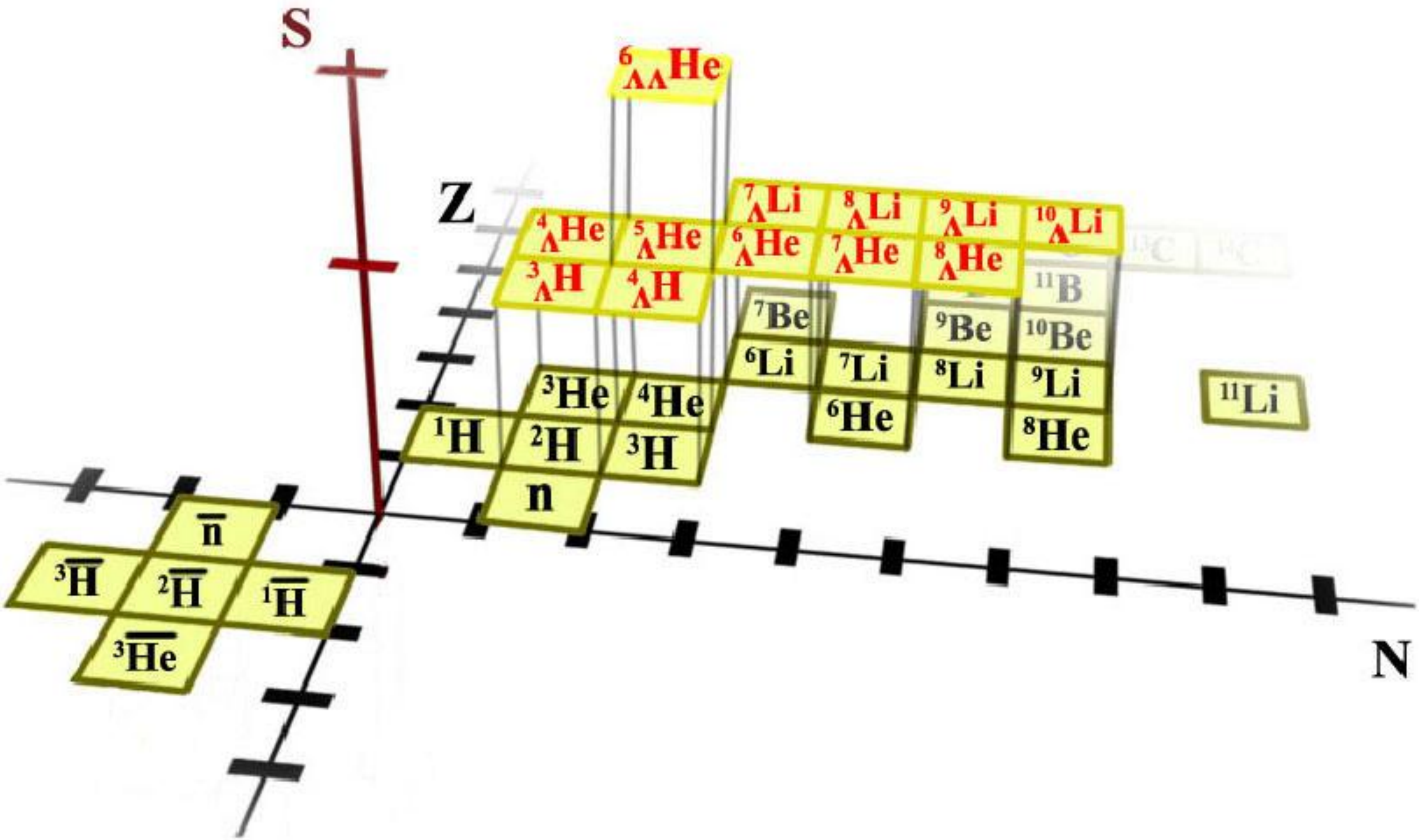
★ Hypernuclei → add 3rd axis for strangeness *S*

★ Antihypernuclei → *S* axis also flips sign

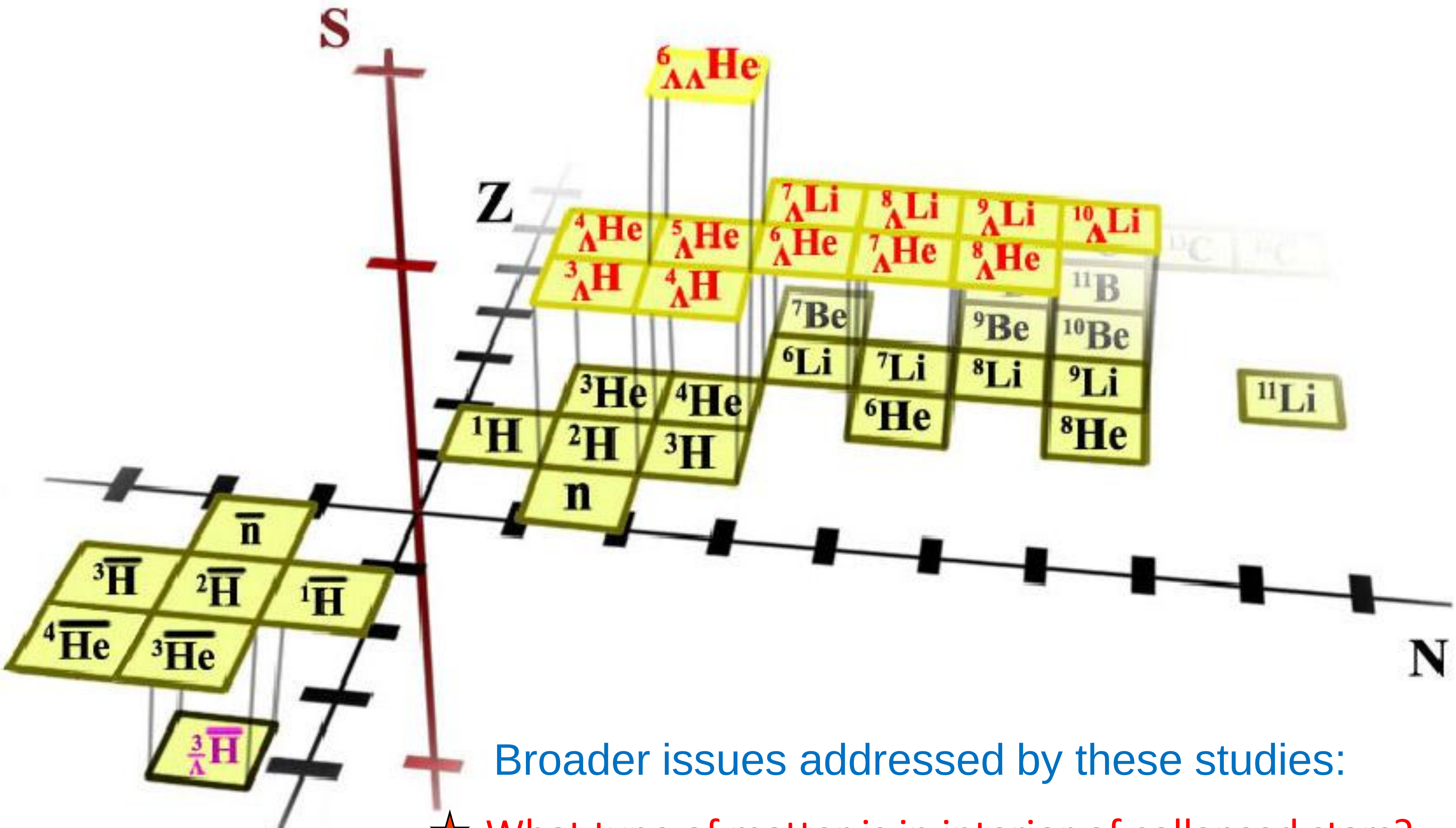
3-D Chart of the Nuclides



3-D Chart of the Nuclides



3-D Chart of the Nuclides



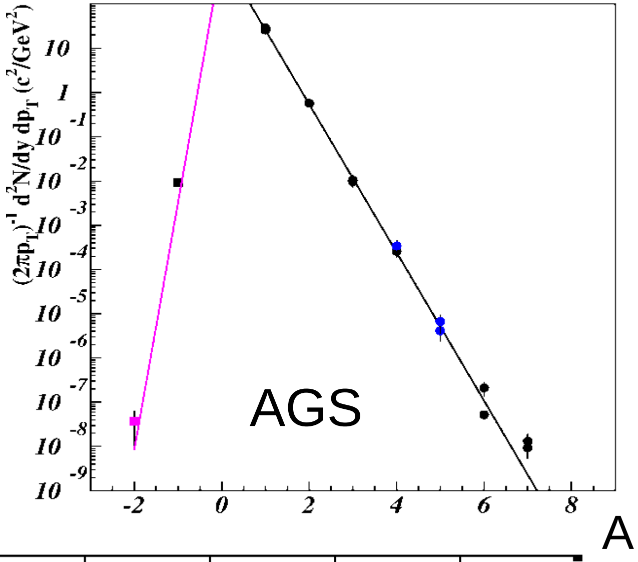
Broader issues addressed by these studies:

- What type of matter is in interior of collapsed stars?
- What happened to antimatter created in the Big Bang?
- Implications for cosmic ray searches for new physics.

Production Rate for Antinuclei

So far, production rates for (anti)nuclei of mass # *A* are consistent with [(anti)nucleon density]^A i.e., consistent with statistical coalescence

At AGS (and in cosmic rays):
$\bar{p} / p \approx 2 \times 10^{-4}$
$^3\overline{\mathrm{He}}/^3\mathrm{He} \approx 10^{-11}$ etc.

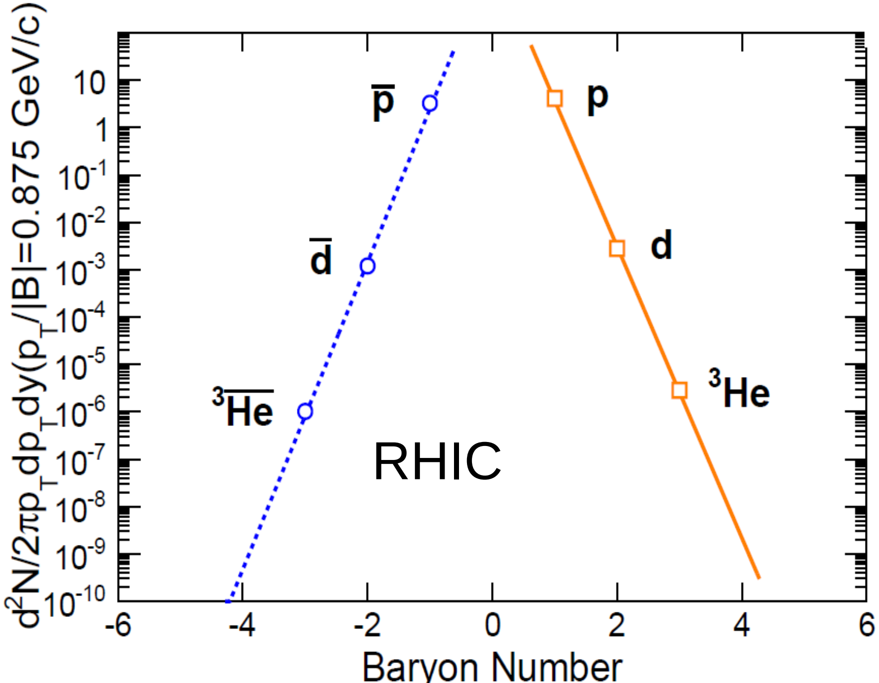


At max RHIC energy, already close to high energy limit:

$^3\overline{\mathrm{He}}/^3\mathrm{He} \approx 10^{-3}$: SPS
$^3\overline{\mathrm{He}}/^3\mathrm{He} \approx 0.5$: RHIC

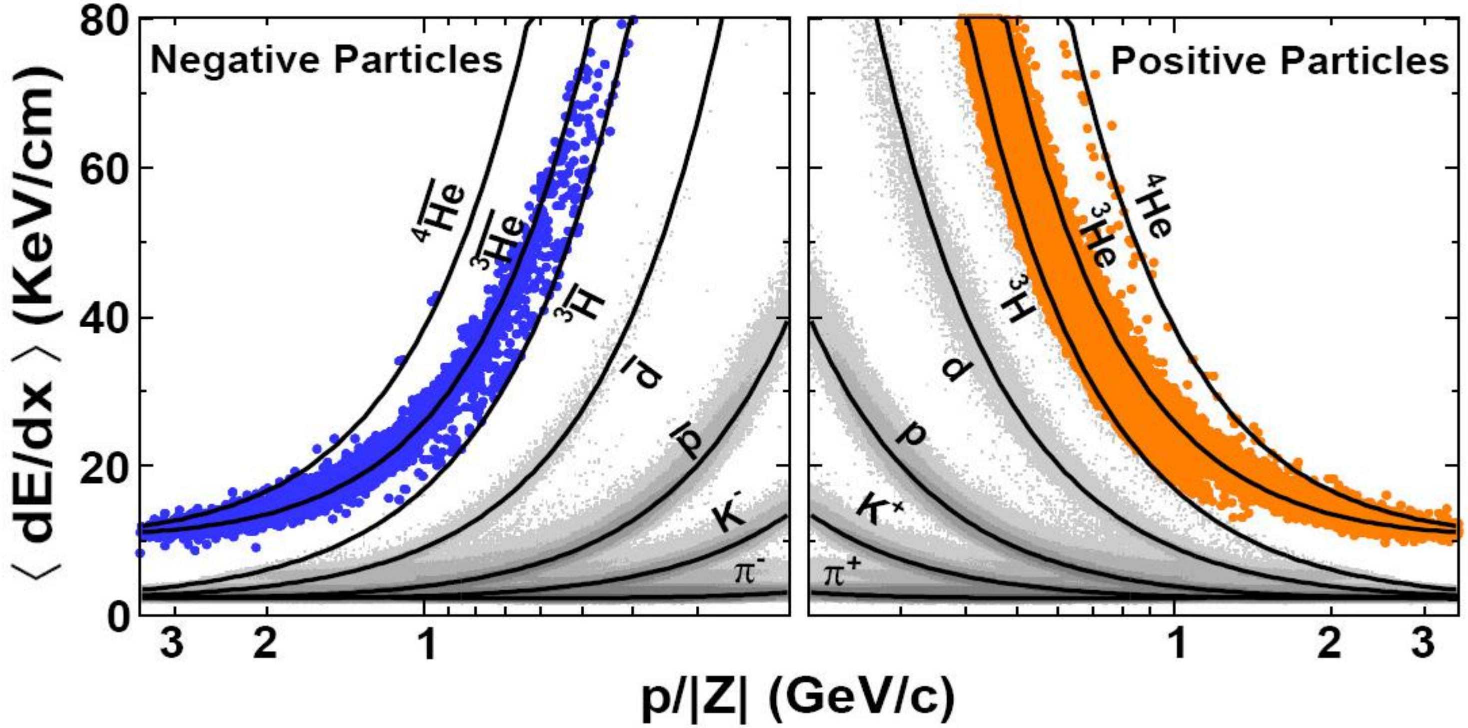
100M events (up to 2007) yielded 2.2K anti-^{3}He. 2010 run contains ~a billion AuAu events & upgraded PID. Thus

we expect >10 $\bar{\alpha}$. Biggest challenge: reconstruction of > 0.5 trillion tracks.



High Level Trigger & Anti-α Search

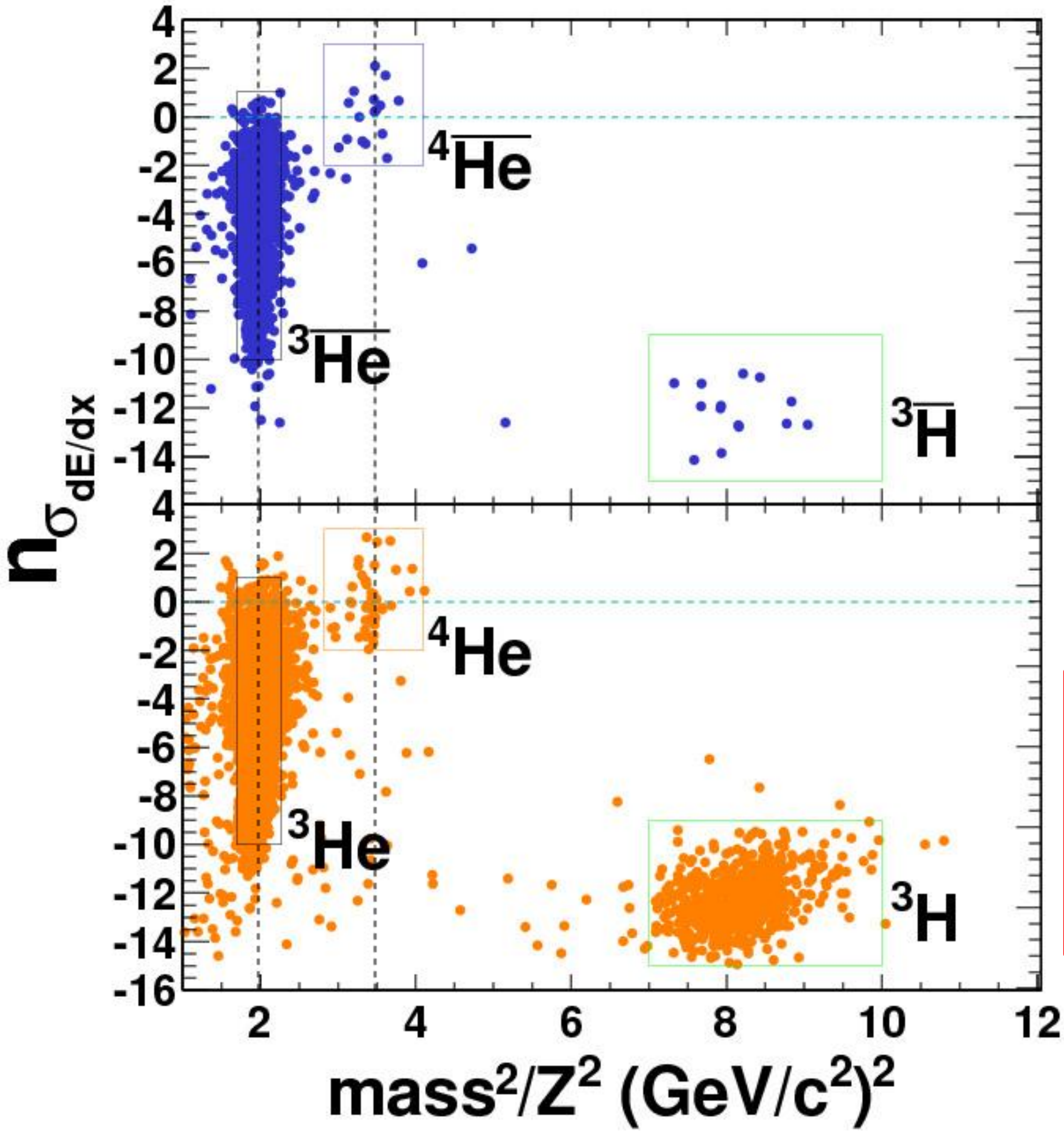
HLT has processing power to do rudimentary event reconstruction in real time, allowing events with a $|Z| = 2$ track to be tagged and fast-tracked via the normal offline calibration & reconstruction chain.



H. Agakishiev *et al*. (STAR collaboration) Nature **473**, 353 (2011); arXiv:1103.3312

Many anti-αs lie where <dE/dx> band merges with anti-^{3}He, so TOF is needed

Anti-α PID from <dE/dx>, *p* & TOF



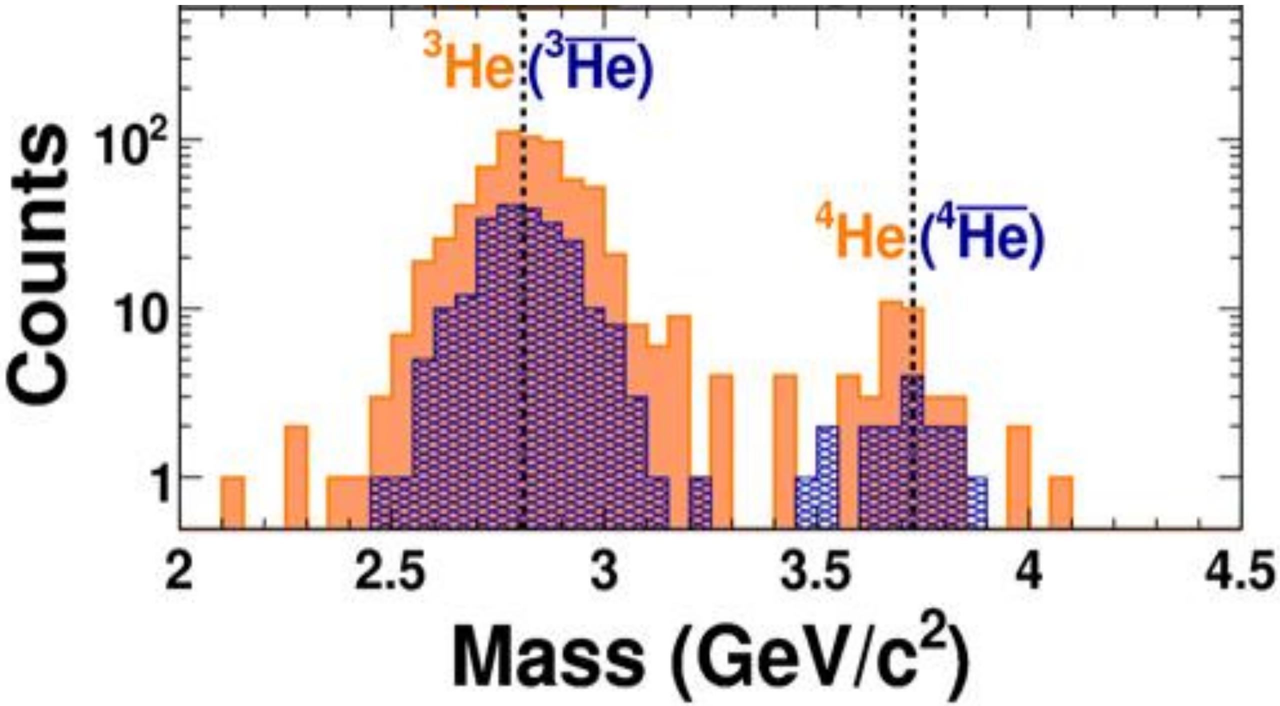
Combining measured magnetic rigidity & time-of-flight, we can determine **mass/Z**

~1.4 background counts within anti-α signal cuts; misident. prob. ~ 10^{-11}

Anti-α PID from <dE/dx>, *p* & TOF

STAR

Projecting to mass axis, we find 16+2 anti-αs:

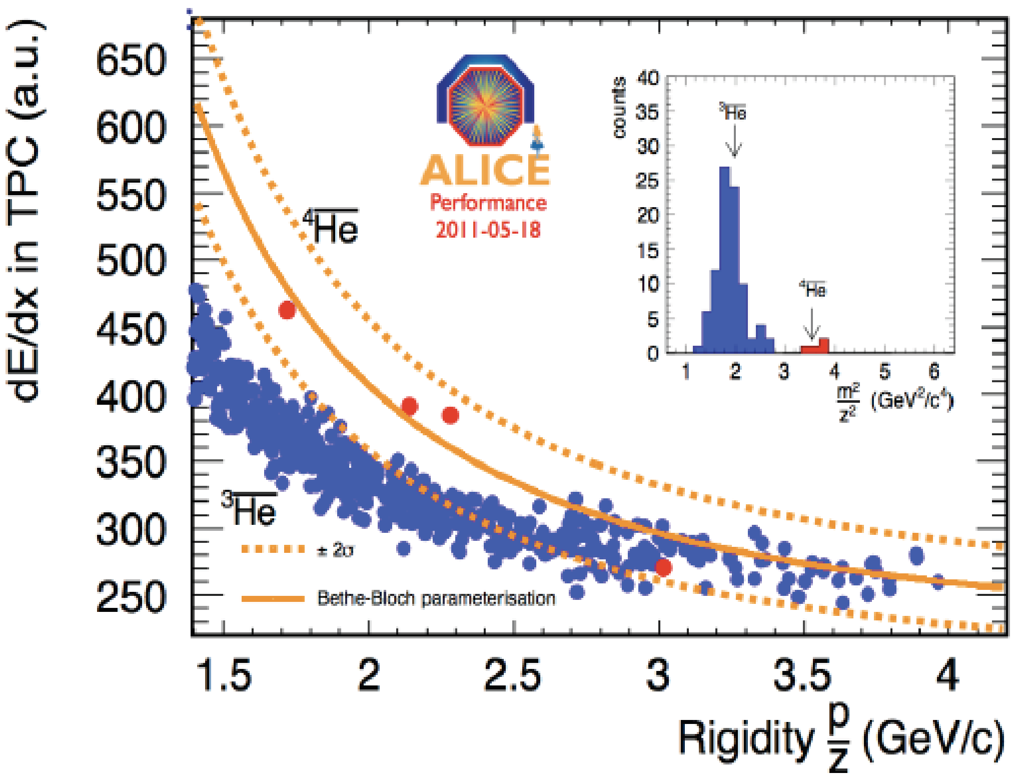


H. Agakishiev *et al*. (STAR collaboration) Nature **473**, 353 (2011); arXiv:1103.3312

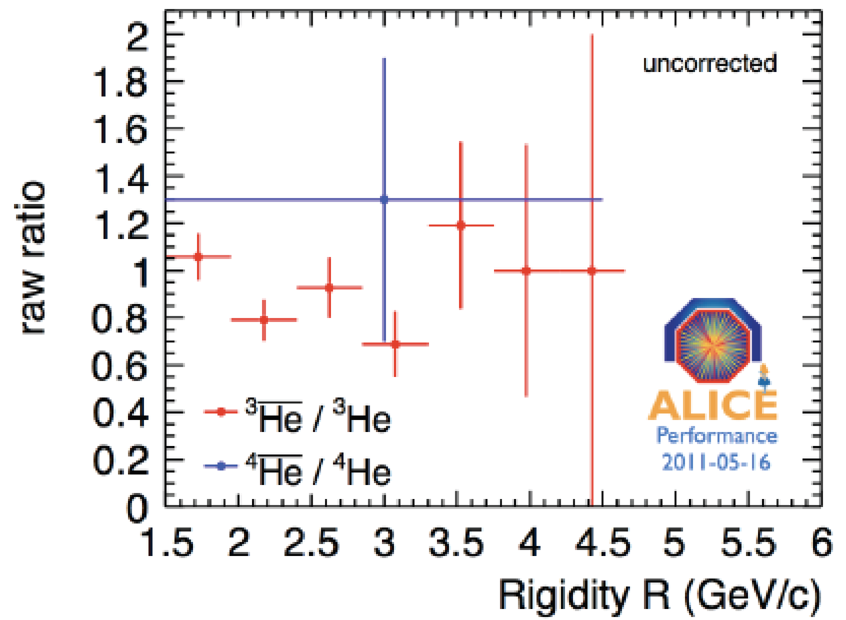
Very clean identification after search of > half-trillion tracks from about one billion gold-gold collisions

Anti-alpha and nuclei-ratio

Anti-alpha identification :



Ratios of anti-nuclei to nuclei :



✓ Four candidates of $^4\overline{He}$ are found in the PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV (red points).

A. Kalweit for the ALICE Collaboration, J. Phys. G **38**,124073 (2011) .

What's in the Pipeline?

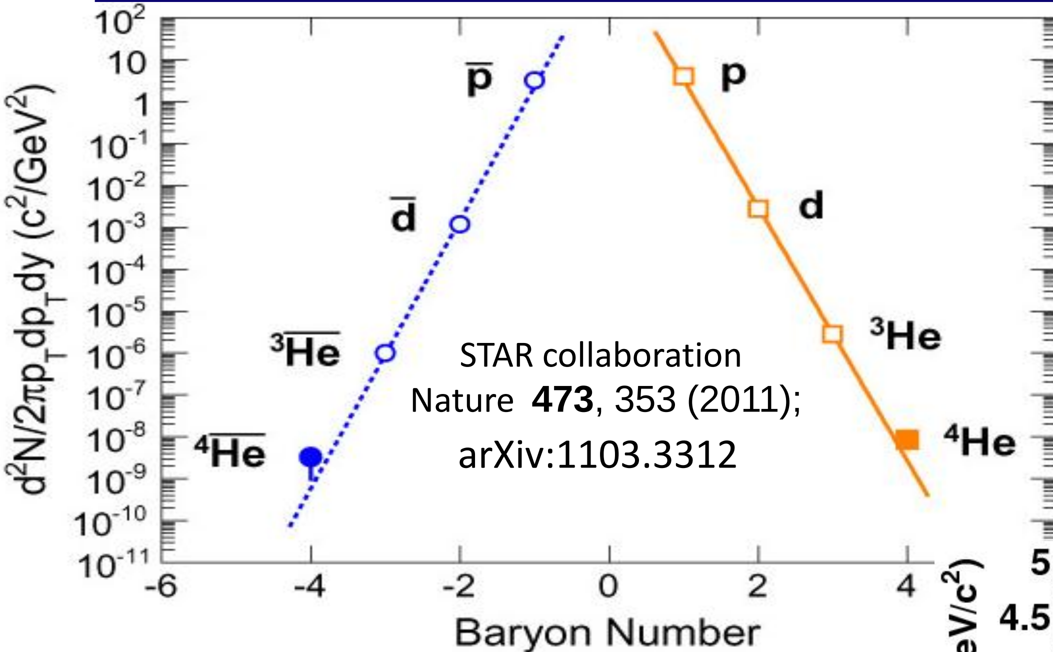
- $^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}, ^{3}_{\Lambda}\mathrm{H}$ published analysis is based on ~100M events.

- Current statistics include ~1000M events for 200 GeV AuAu, & a further 210M at lower energies where signal/background is still strong. Plus, new TOF barrel further improves PID.

- New results for $^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}, ^{3}_{\Lambda}\mathrm{H}$ based on $^{3}\mathrm{He} + \pi$ decays will be reported by Yuhui Zhu at Quark Matter (Aug 2012).

- Three-body decays with higher branching fractions are also forthcoming.

Prospects for $A > 4$ Antinuclei?

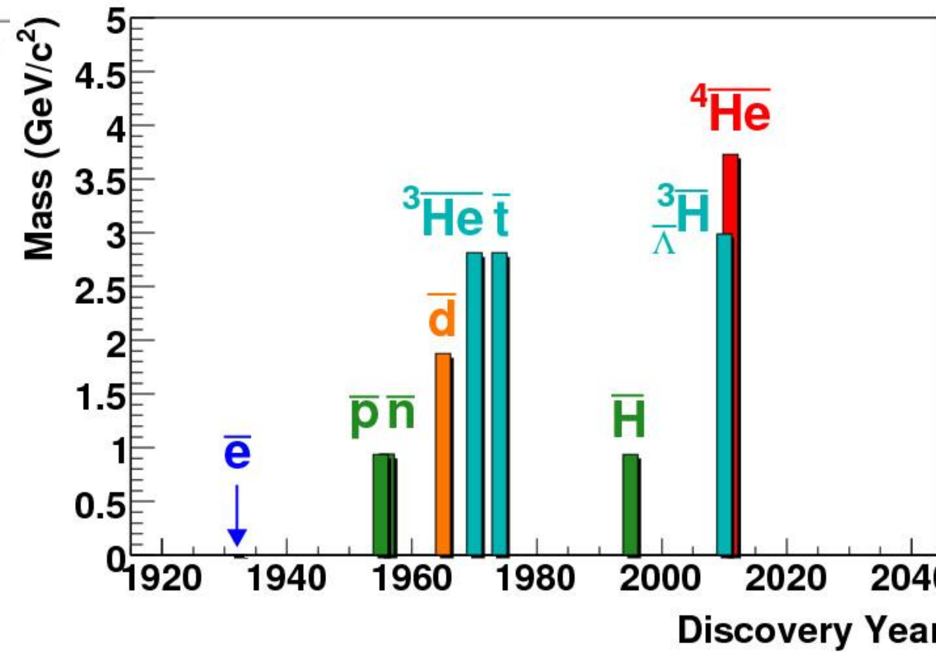


Anti-α yields continue to follow, within errors, exponential predicted by both thermal model and statistical coalescence.

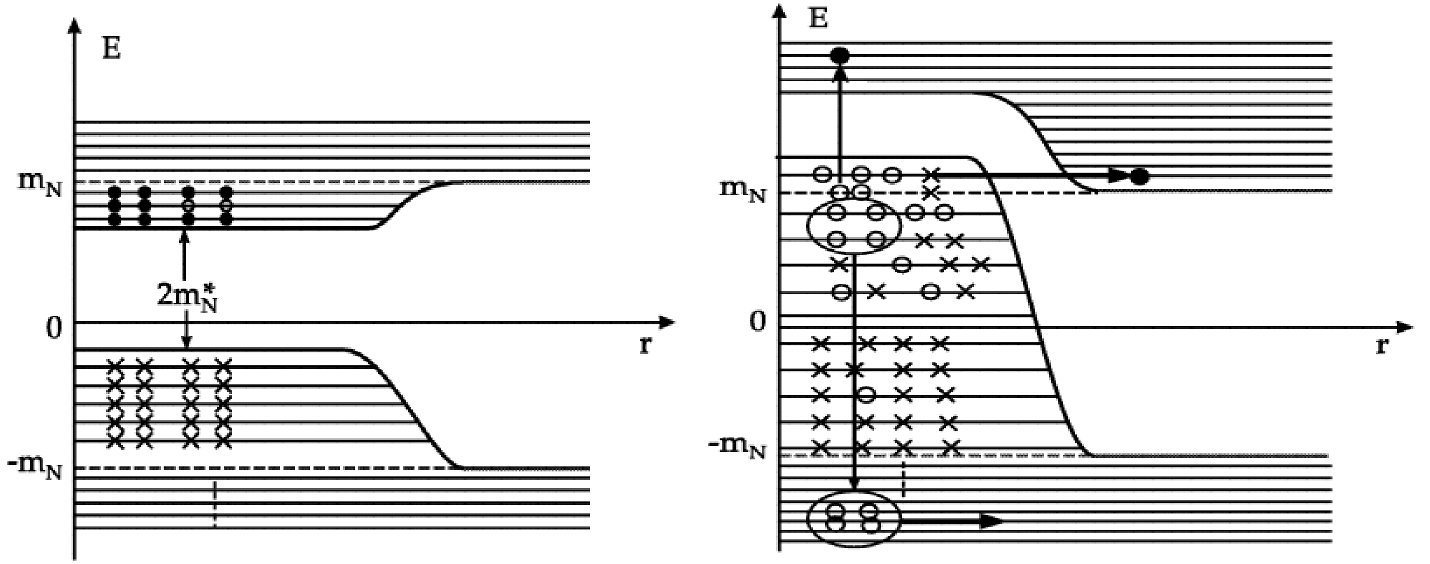
If we add one extra antinucleon, production rate drops ~ 1/1600 (called the "penalty factor")

Prospects beyond $A = 4$?

Next stable antinucleus has $A = 6$;
(penalty factor)^2 ~ $(1600)^2$
– out of reach for foreseeable future,
unless.....



Correlations in the Vacuum

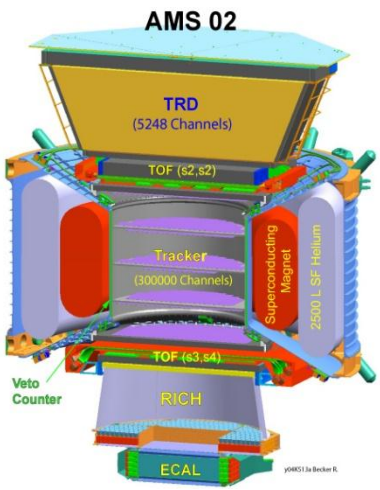


Idea from Walter Greiner*: correlations are present in vacuum, allowing antinucleus like anti-α to be directly excited from the vacuum. Rate for such antinuclei could be much larger than low value predicted by statistical coalescence.

No evidence so far.

* Int. J. Mod. Phys. E **5**, 1–90 (1996).

Search for Antinuclei in Space

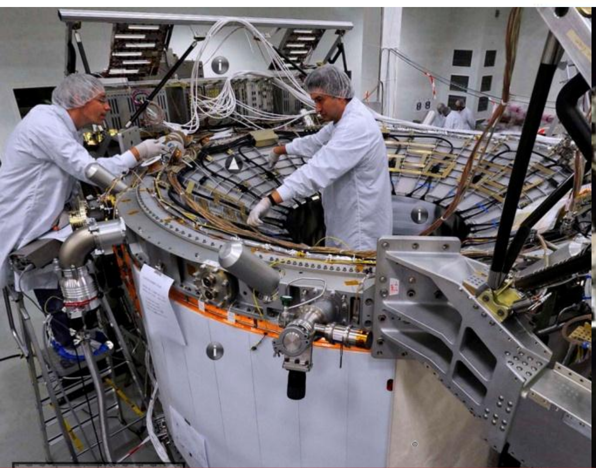


HAPPY FIRST YEAR IN SPACE TO AMS!

May 19th, 2012

One year ago AMS-02 began the data taking operations from the ISS.

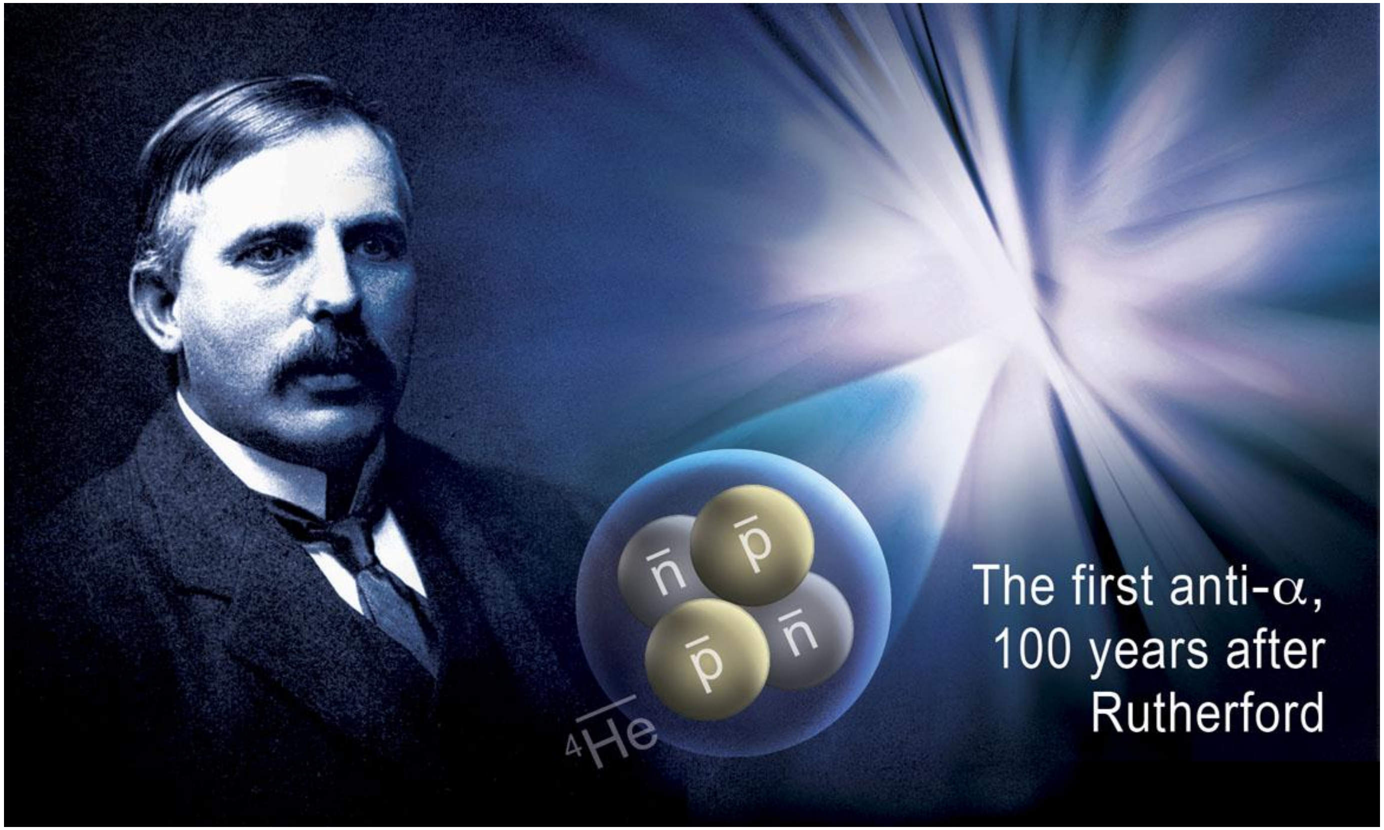
The **Alpha Magnetic Spectrometer** (AMS-02) is a state-of-the-art particle physics detector designed to operate as an external module on the International Space Station. It will use the unique environment of space to study the universe and its origin by searching for antimatter, dark matter while performing precision measurements of cosmic rays composition and flux. The AMS-02 observations will help answering fundamental questions, such as **"What makes up the universe's invisible mass?"** or **"What did happen to the primordial antimatter?"**



INSIDE THE C-5M SUPER GALAXY

If there is bulk antimatter in the cosmos, AMS could detect anti-α; rate from matter-matter collisions in space is too low

From Physics to Aesthetics…..



Proposed cover art for print version of *Nature*

(Synergy with centennial of use of α + gold to discover the nucleus)

"Illustrations should be selected more for their aesthetic appeal than for their scientific content"
– guidance from editors

Summary & Outlook – I

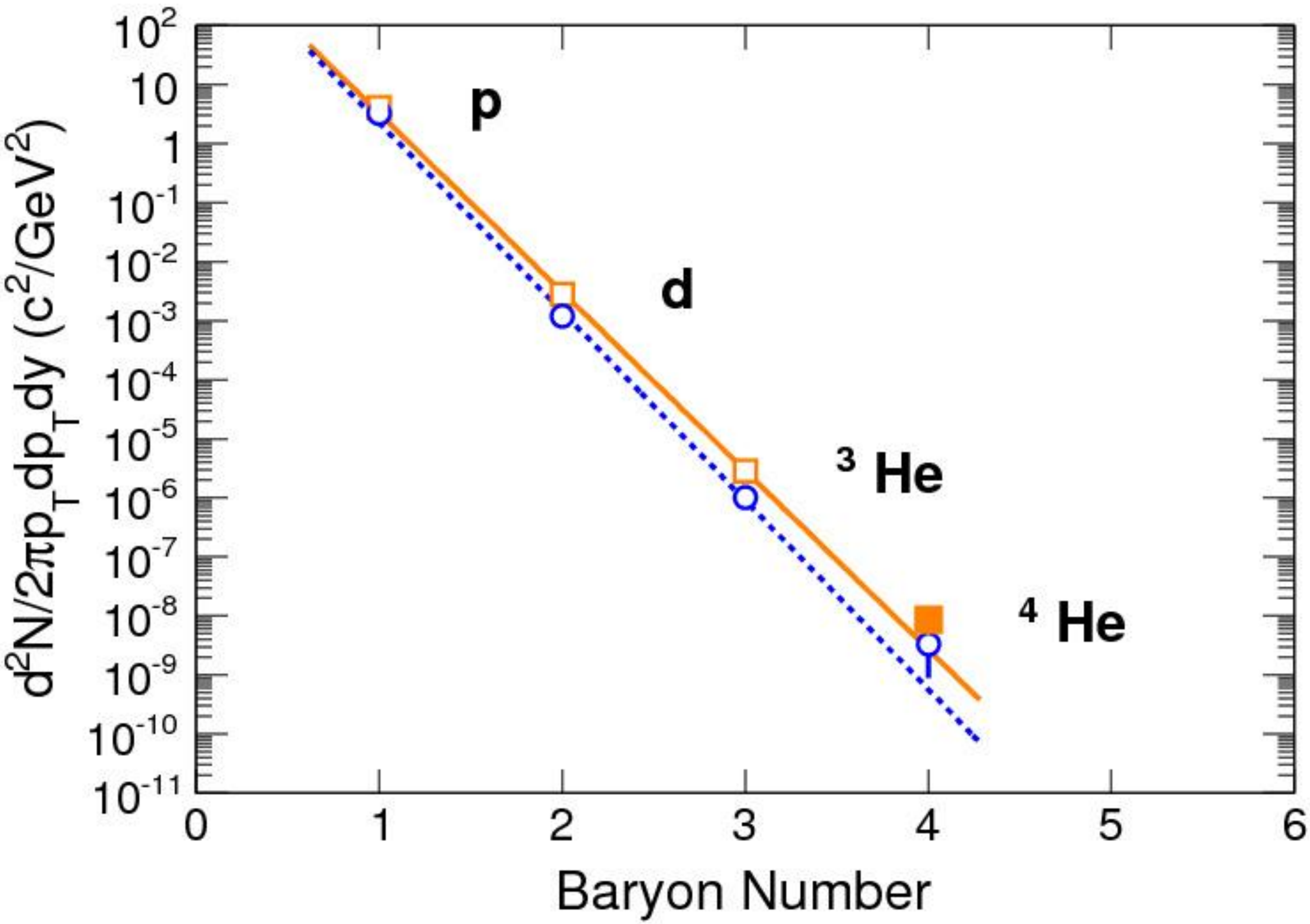
- $^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}$ has been published in 2010; 70 candidates based on data up to 2007, with significance ~4σ.
- Consistency check has been done on $^{3}_{\Lambda}\mathrm{H}$ analysis; 157 candidates, with significance better than 5σ.
- The measured lifetime is $\tau = 182 \pm^{89}_{45} \pm 27$ ps, shorter than the free Λ lifetime (263 ps) but consistent with it.
- $^{3}_{\bar{\Lambda}}\overline{\mathrm{H}}, {}^{3}_{\Lambda}\mathrm{H}$ analysis nearing release with >10x statistics, better PID, & more decay modes.
- High Level Trigger has allowed fast-track search for anti-α among >0.5 trillion tracks of 2010 data; 18 anti-αs found, with mis-ID probability ~ 10^{-11}. Published in *Nature* in 2011.

Summary & Outlook – II

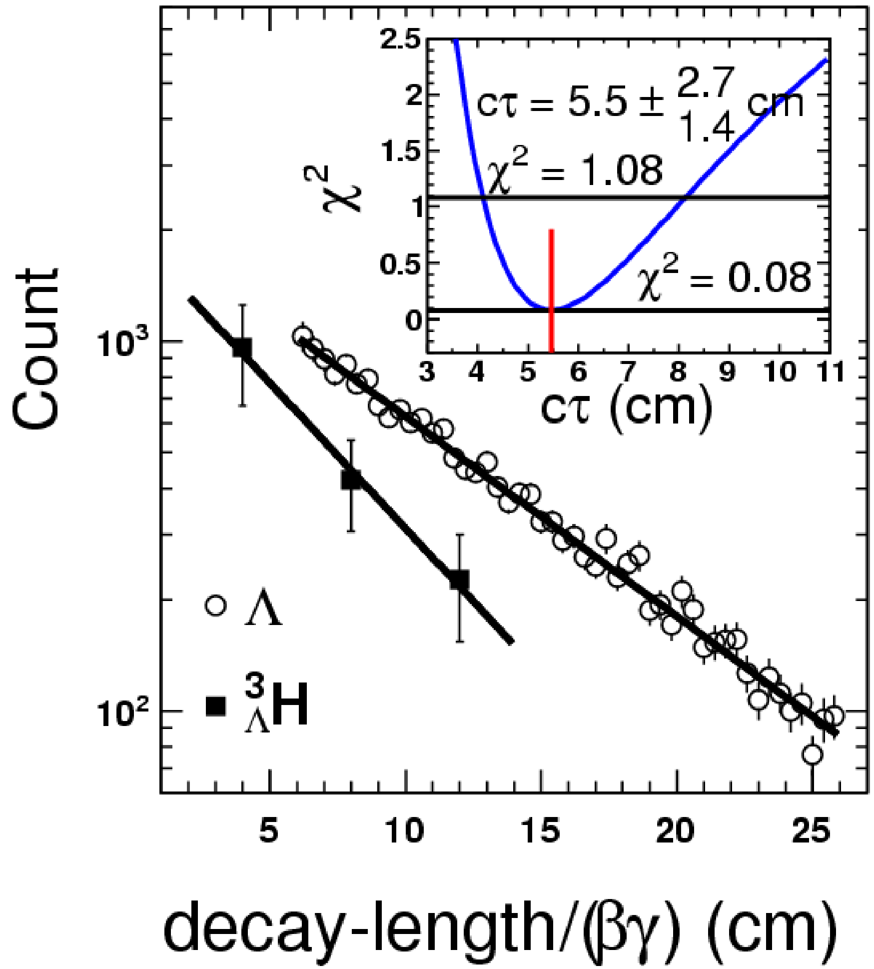
- Antinucleus yields up to *A* = 4 remain consistent within errors with thermal & statistical coalescence models. This has important implications for the AMS experiment & for other searches for new phenomena in the cosmos.
- The next stable antinucleus after anti-α has *A* = 6. Penalty factor > 2 million means new record for heaviest stable antinucleus is likely to stand for a very long time.

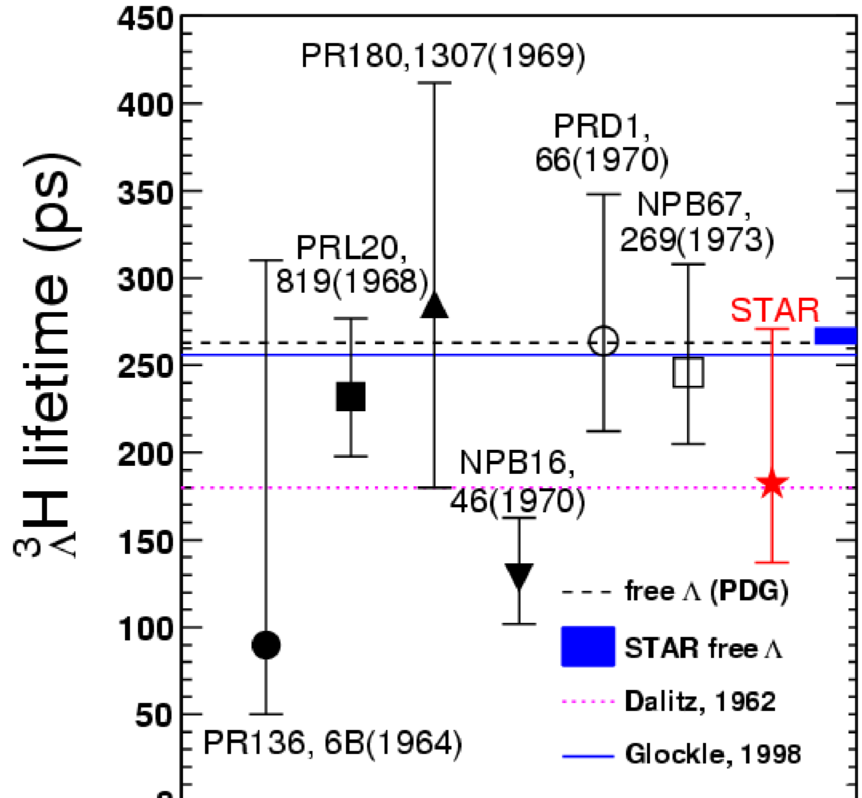
EXTRA SLIDES

Yields: Nuclei & Antinuclei Compared



Lifetime Measurement





2010 data (~10 times statistics) coming

World data

$$\tau = 182 \pm^{89}_{45} \pm 27 \text{ ps}$$

We measure τ_Λ = 267 ± 5 ps
PDG value τ_Λ = 263 ± 2 ps

STAR Collaboration, *Science* **328**, 58 (2010)

Predictability is a shock

From a talk by Zhangbu Xu

If I told you that:

1. create a state of matter at $4x10^{12}$ 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)
   ±0.00000000001

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

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