The surprising agreement of hypertriton yields in high energy HICs with thermal model

Hypertriton puzzle in relativistic heavy-ion collisions

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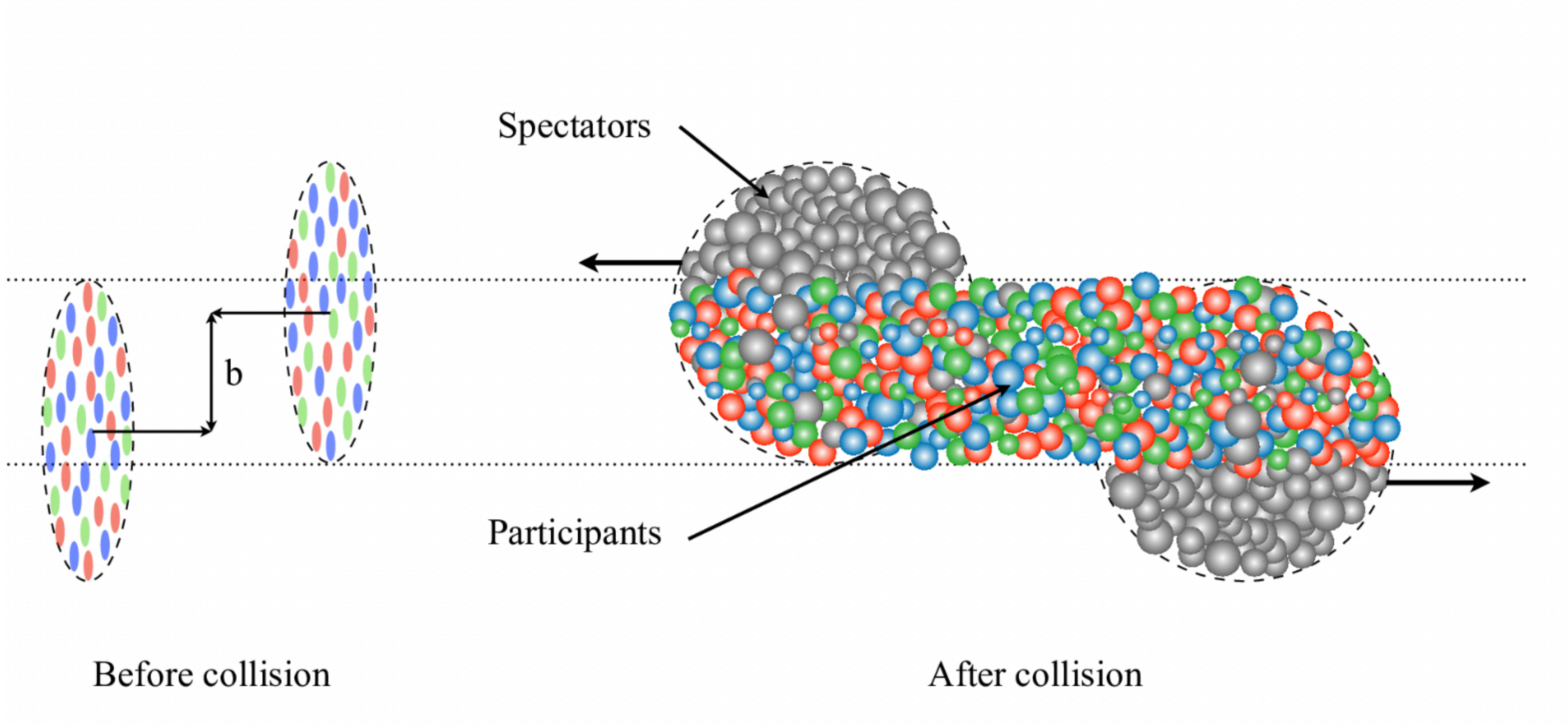
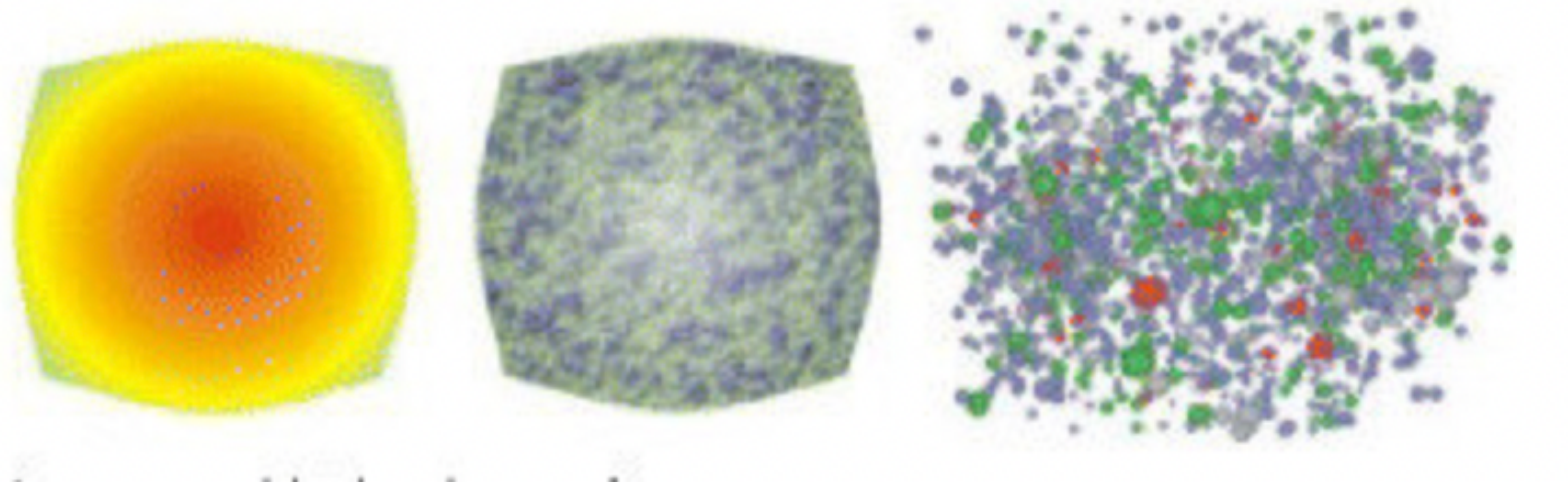
Heavy-Ion Collisions

CERN Website



Initial State **Time (t) = 0**



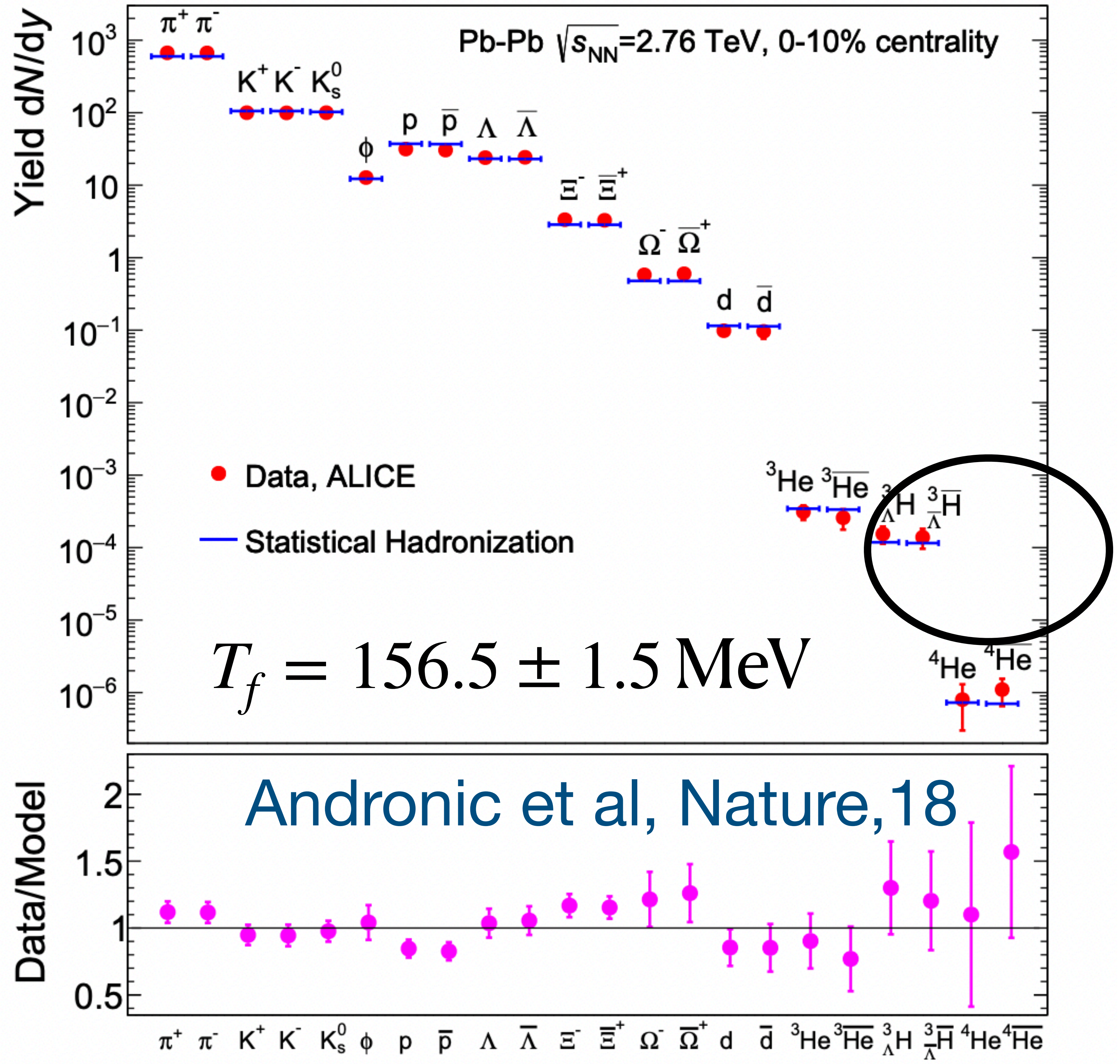
Hydrodynamic Evolution : Expansion and Cooling

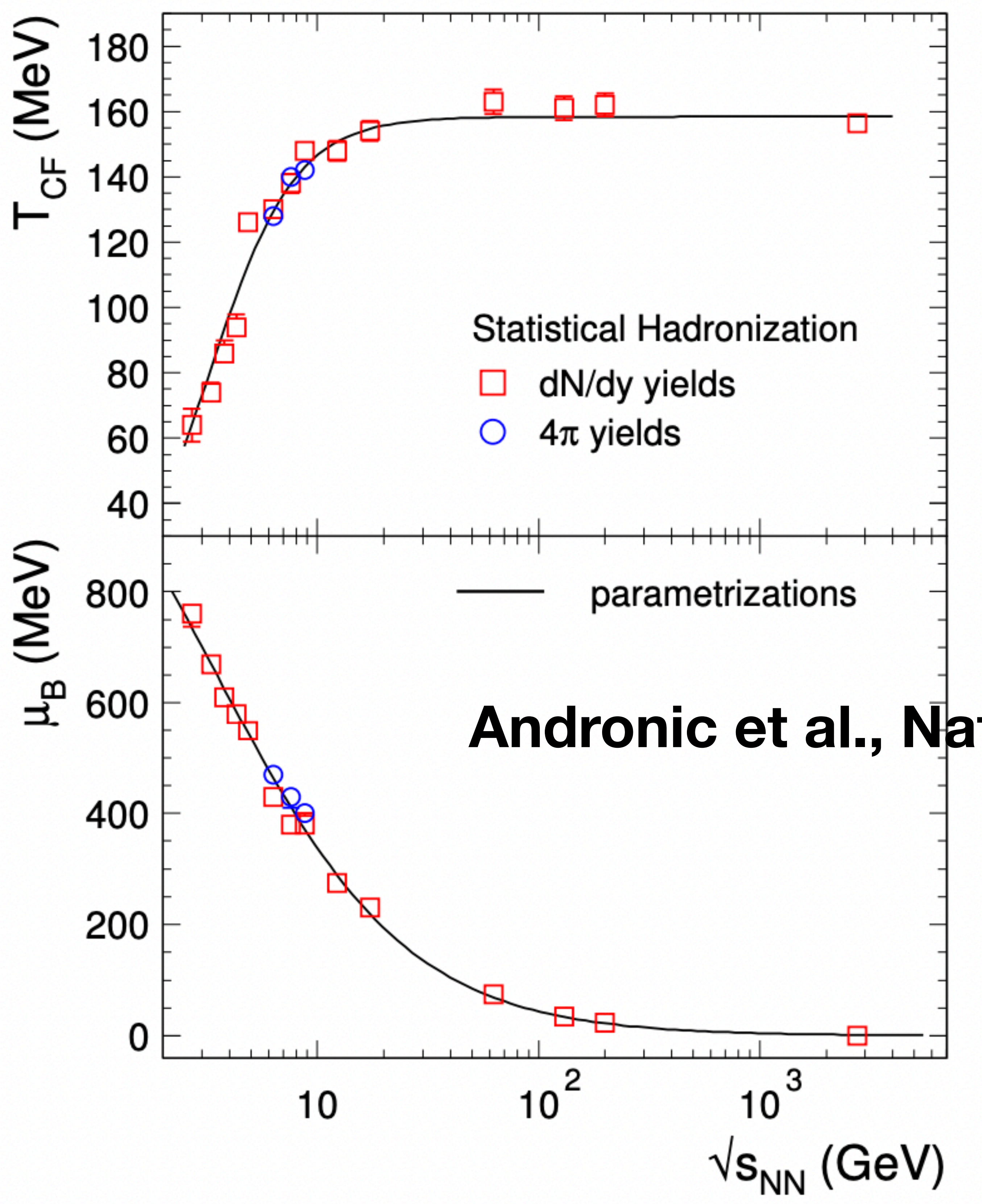
Freeze-out

Figure by S.A.Bass

- QGP thermalizes in a relatively short amount of time ~ 1fm/c ~ 10^{-23} s
- Freeze-out at about 10 fm/c ~10^{-22}s
- The event by event distribution of the particle multiplicities are frozen at freeze-out and are measured at the detectors.

Statistical Hadronization Model at freeze-out





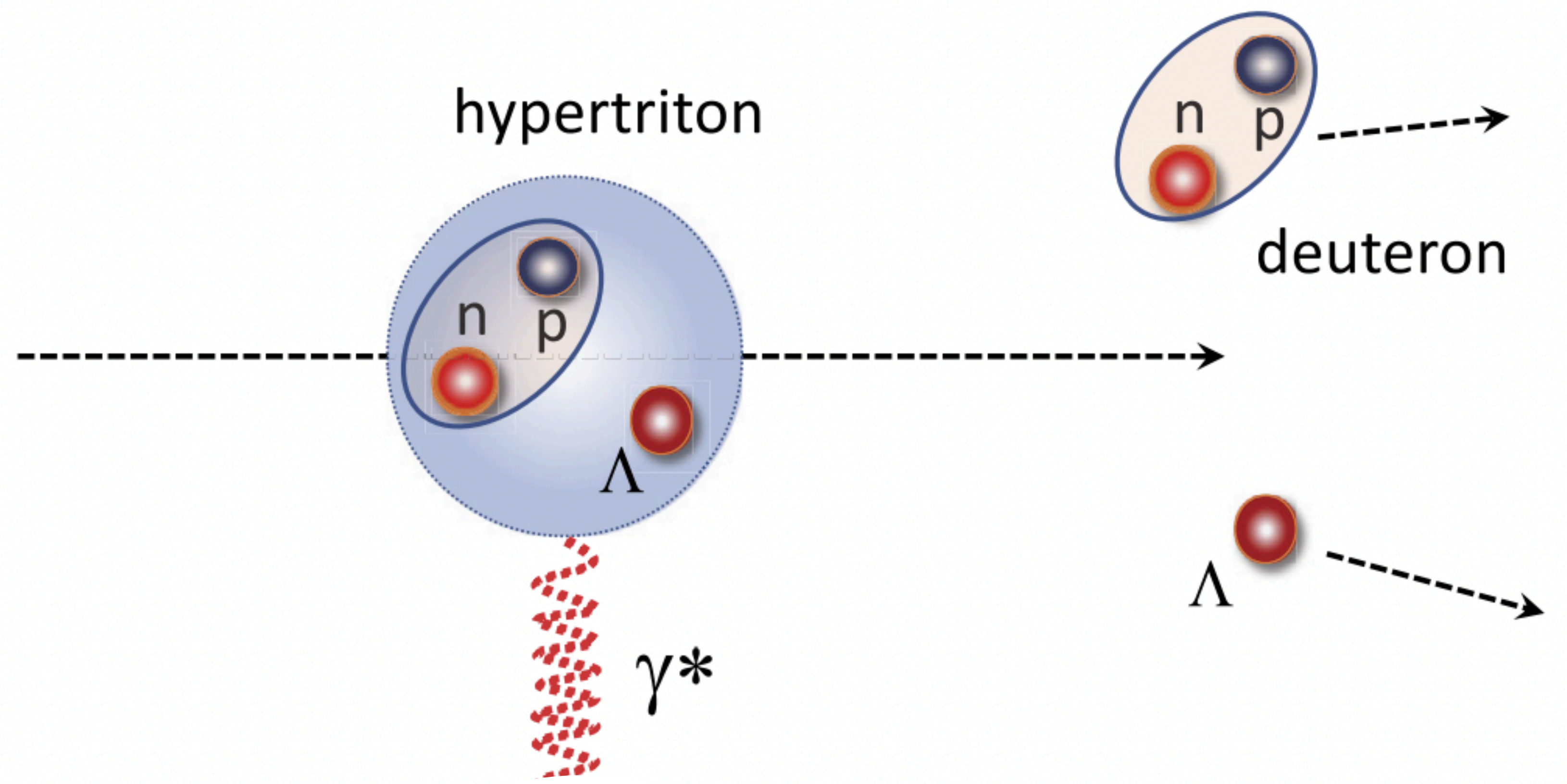
Andronic et al., Nature, 2018

- Mid-rapidity yields consistent with a Statistical Hadron Resonance Gas model across a broad range of collision energies
- Model assumes: chemical freeze-out → yields fixed by an ideal gas of hadrons & nuclei (free-space masses) in equilibrium.
- Stunning phenomenological success: spans nine orders of magnitude in abundances including light (hyper) nuclei.

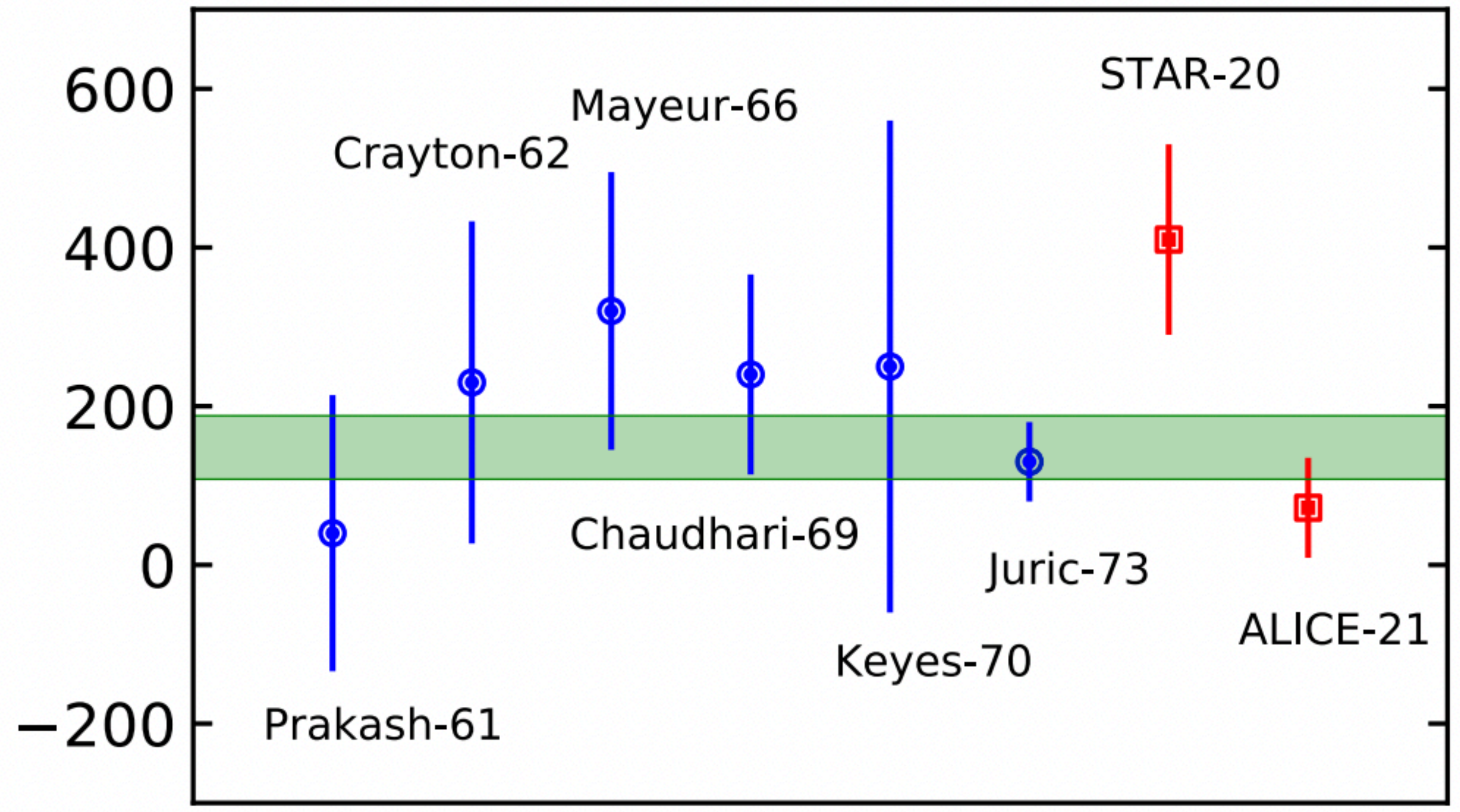
Physical picture at freeze-out

- There is a gas of almost non-interacting hadrons and light nuclei in thermal equilibrium at 156 MeV at freeze-out within the confines of the fireball boundary
- Particles are well localized
- Binding energy of light nuclei , typically few MeV or keV << 156 MeV
- Still plausible, if the gas is dilute enough

Hypertritons in HICs - "Snowballs in hell"



$$\mathrm{B.E} \sim 148 \pm 40\,\mathrm{keV} \ll 156\,\mathrm{MeV}$$



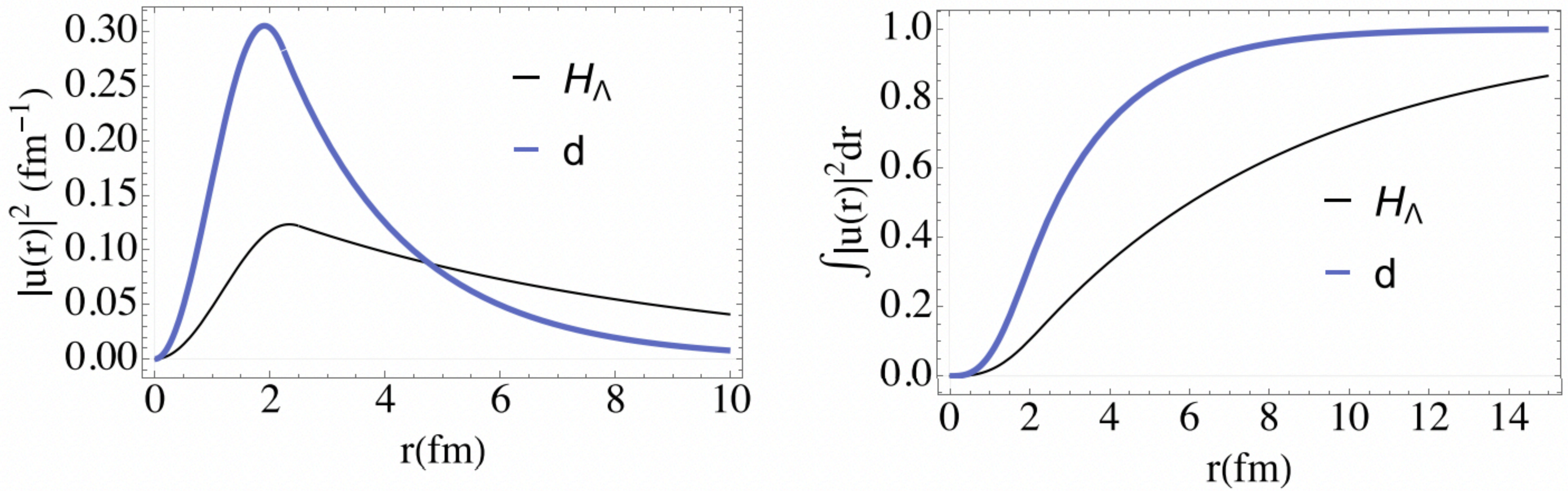
Bertulani, 22

- Weakly bound state of deuteron and Lambda baryon
- A single thermal pion can dissociate H_Λ by quasi-free scattering / resonant process ~ short lifetimes of a few fm
- Root mean-squared radius $\sim$ 10 fm ~ Size of the fireball?

$$\langle r^2 \rangle \sim \frac{\hbar^2}{4\mu B}$$

Quantum mechanical hypertriton comes in all sizes!

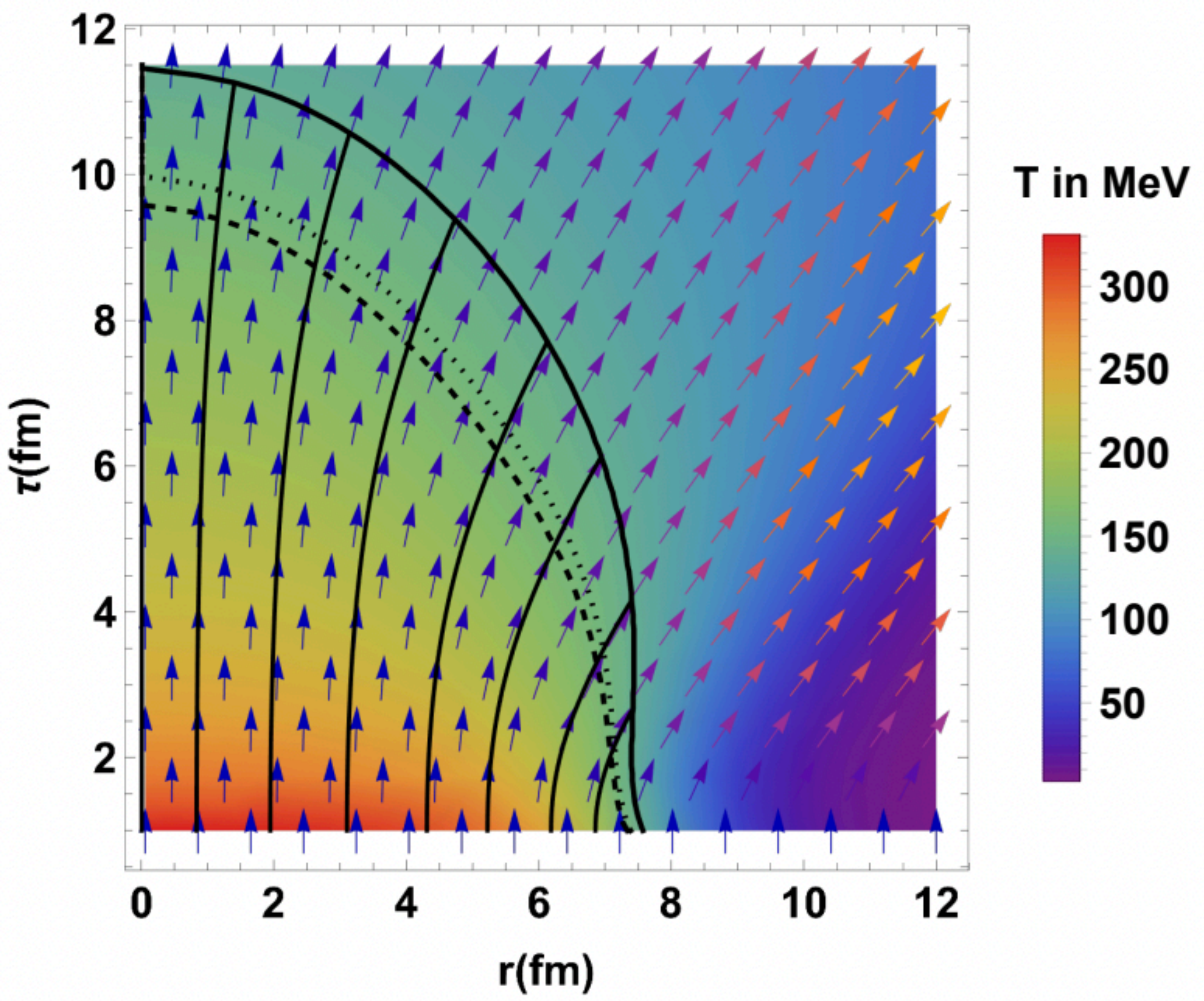
$$V(r) = \begin{cases} -V_0, & r < a, \\ 0, & r \geq a, \end{cases}$$

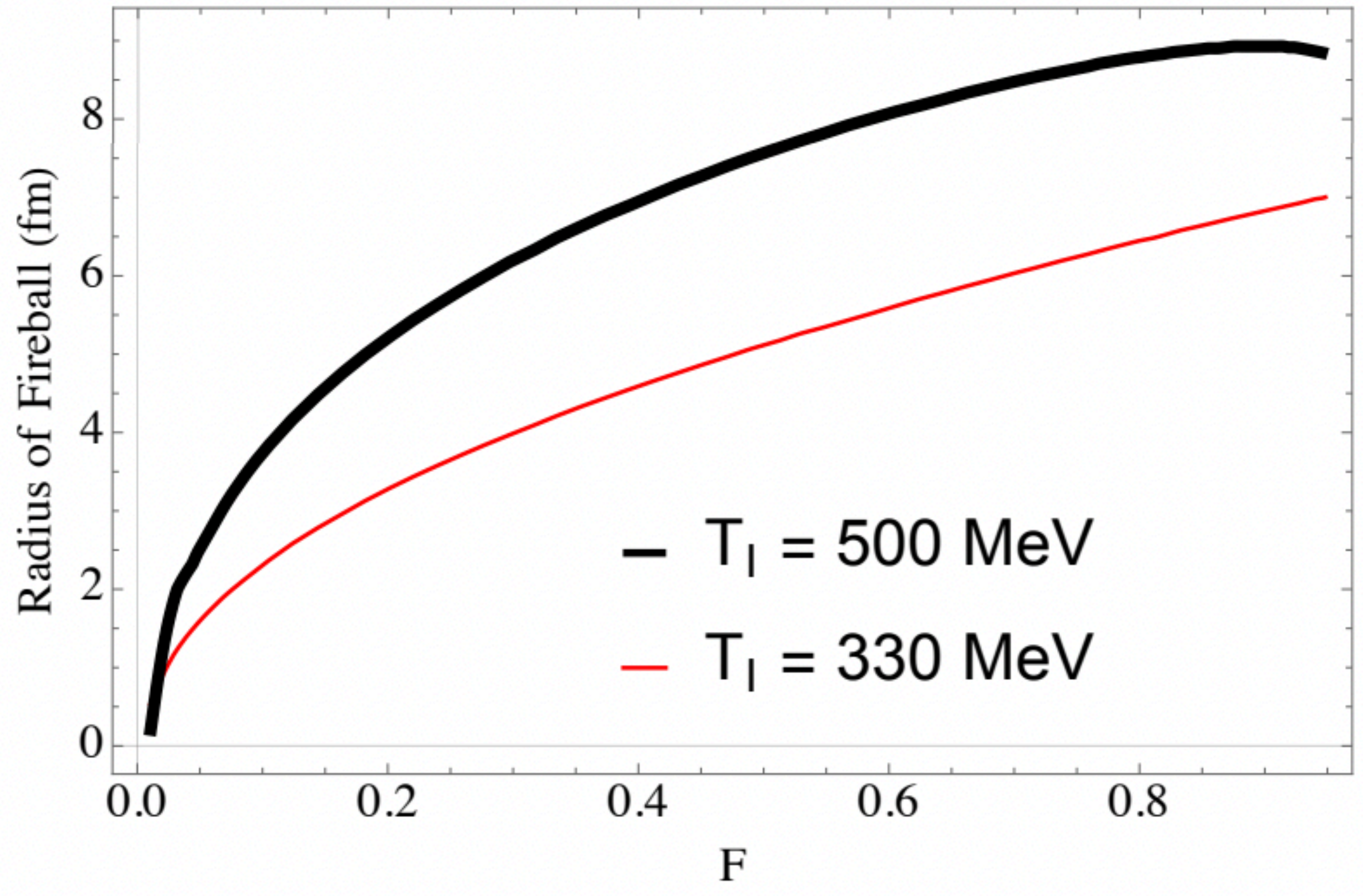


- Probability distribution for the radial separation between Λ and d has a long ranged tail
- Magnitude of the short distance part of the H_Λ wave function is non-negligible, even though small due to large binding energy
- Deuteron itself has a root mean-squared radius of 8.1 fm and a weak B.E of 2.24 MeV
- We model both H_Λ and d by finite square well potential specified by the depth of the potential and finite radial extent

Fireball radius decreases as the system cools with time

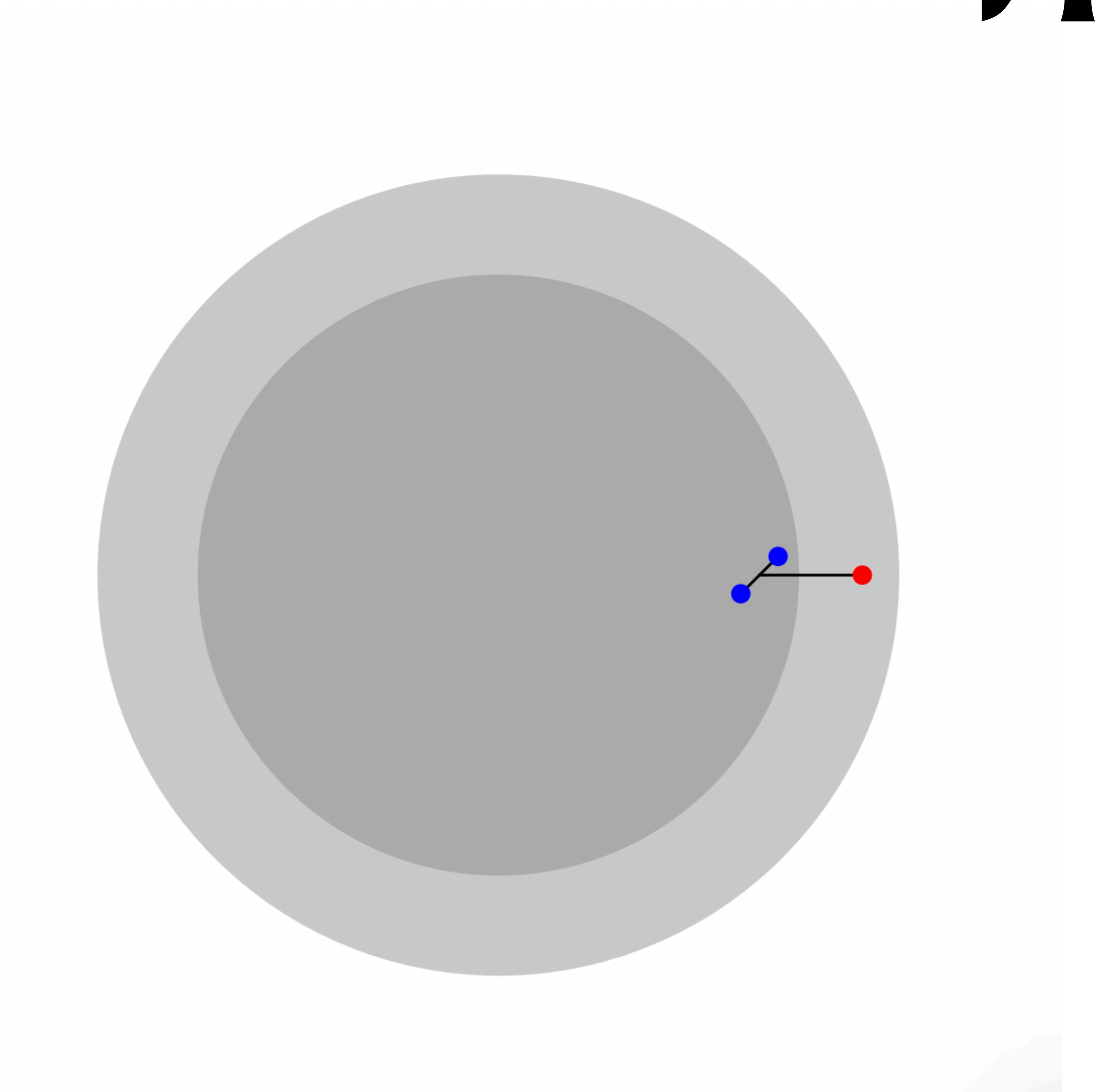
$T_f = 156.5 \pm 1.5$ MeV



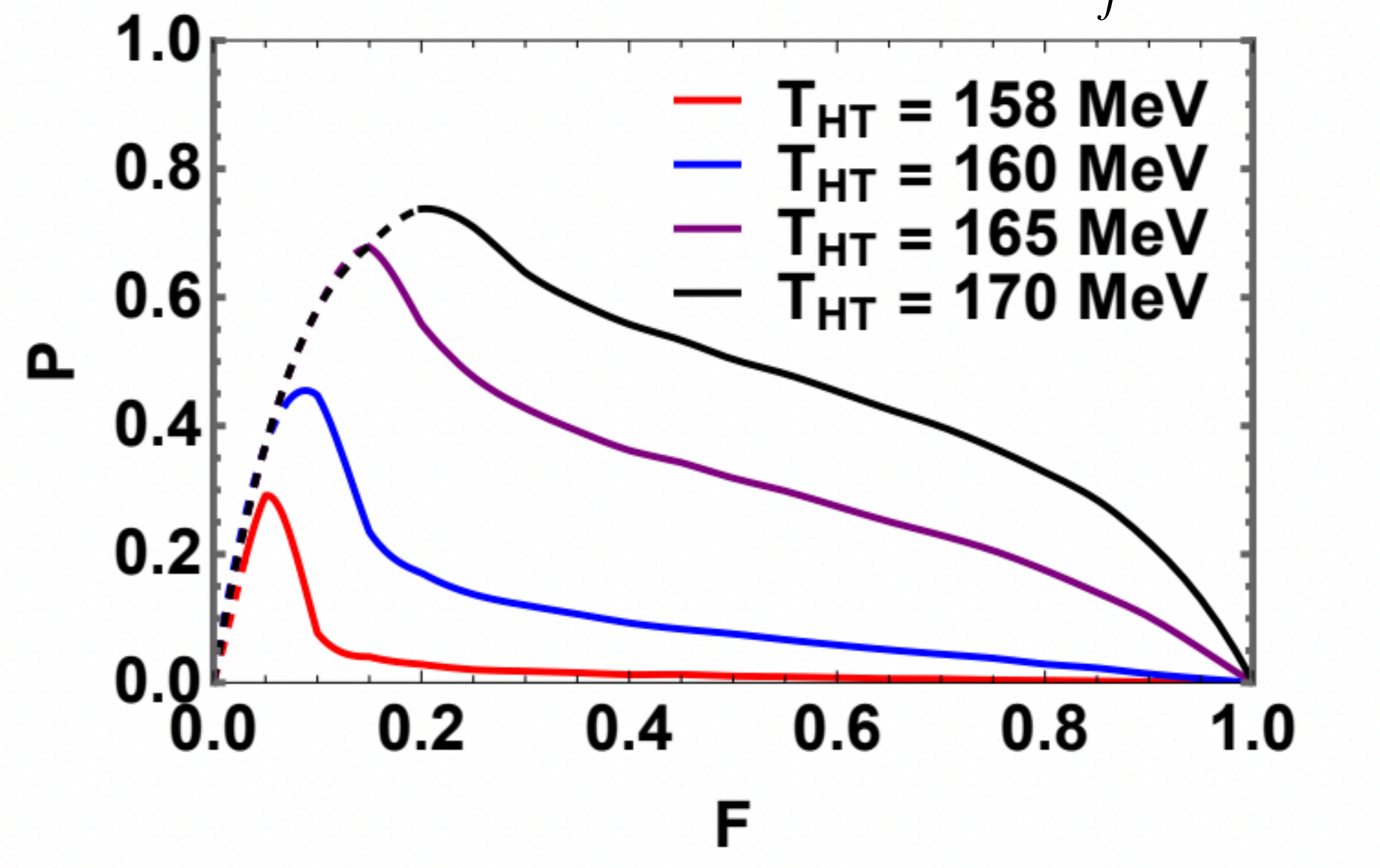


- The radius of the remaining fireball decreases as the fraction of energy density remaining in the fireball decreases

Will the hypertriton fit inside the fireball?



$T_f = 156.5 \pm 1.5\,\mathrm{MeV}$



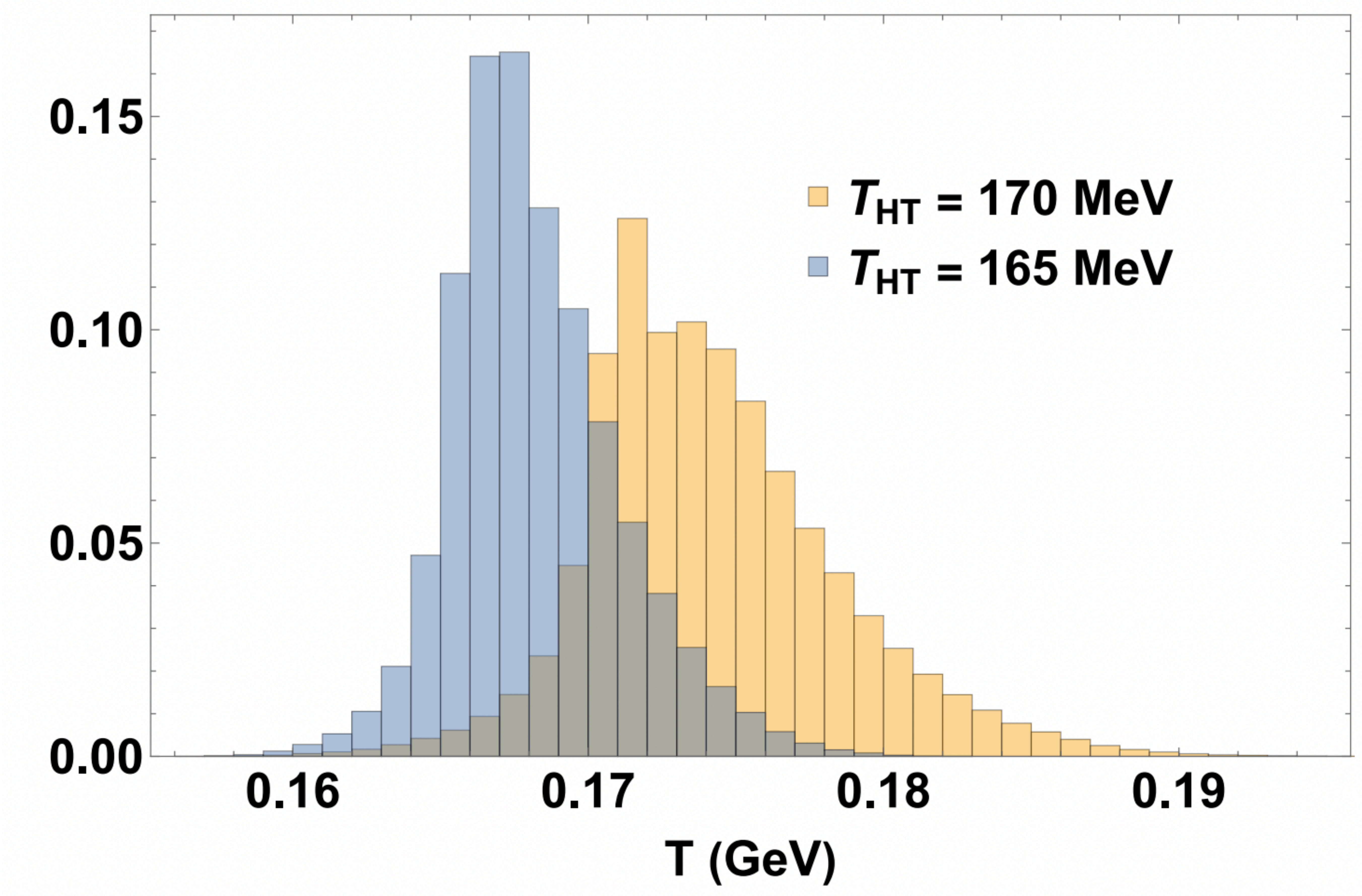
Suppose the center of mass of the H_Λ is at a temperature T_{HT} , what is the probability of the proton, neutron and Λ being inside the fireball when fraction of the initial energy density, F is remaining?

$$P_{\mathrm{IN}} < 30\,\%\text{ for } T_{\mathrm{HT}} = 170\,\mathrm{MeV},\; P_{\mathrm{IN}} < 10\,\%\text{ for } T_{\mathrm{HT}} = 160\,\mathrm{MeV}$$

Temperature gradients across the size of hypertriton

Distribution of maximum of the temperature at the location of its constituents

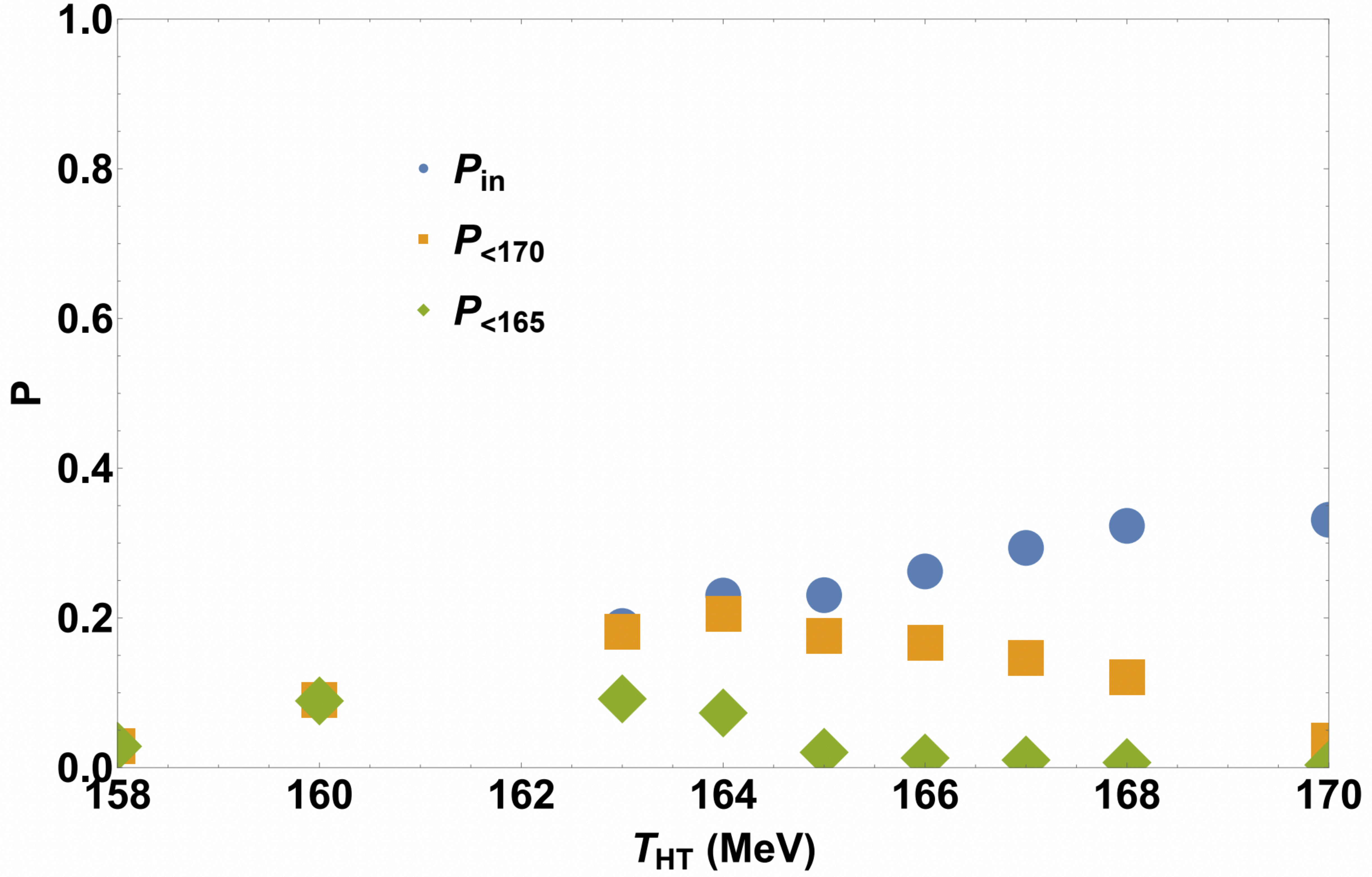
$T_f = 156.5 \pm 1.5\,\mathrm{MeV}$



- Temperature variations across the size of the hypertriton is huge
- $R_T = \langle N \rangle_T / \langle N \rangle_{156.5}$
- $R_{170} = 5.2$
- $R_{165} = 2.9$
- $R_{160} = 1.6$

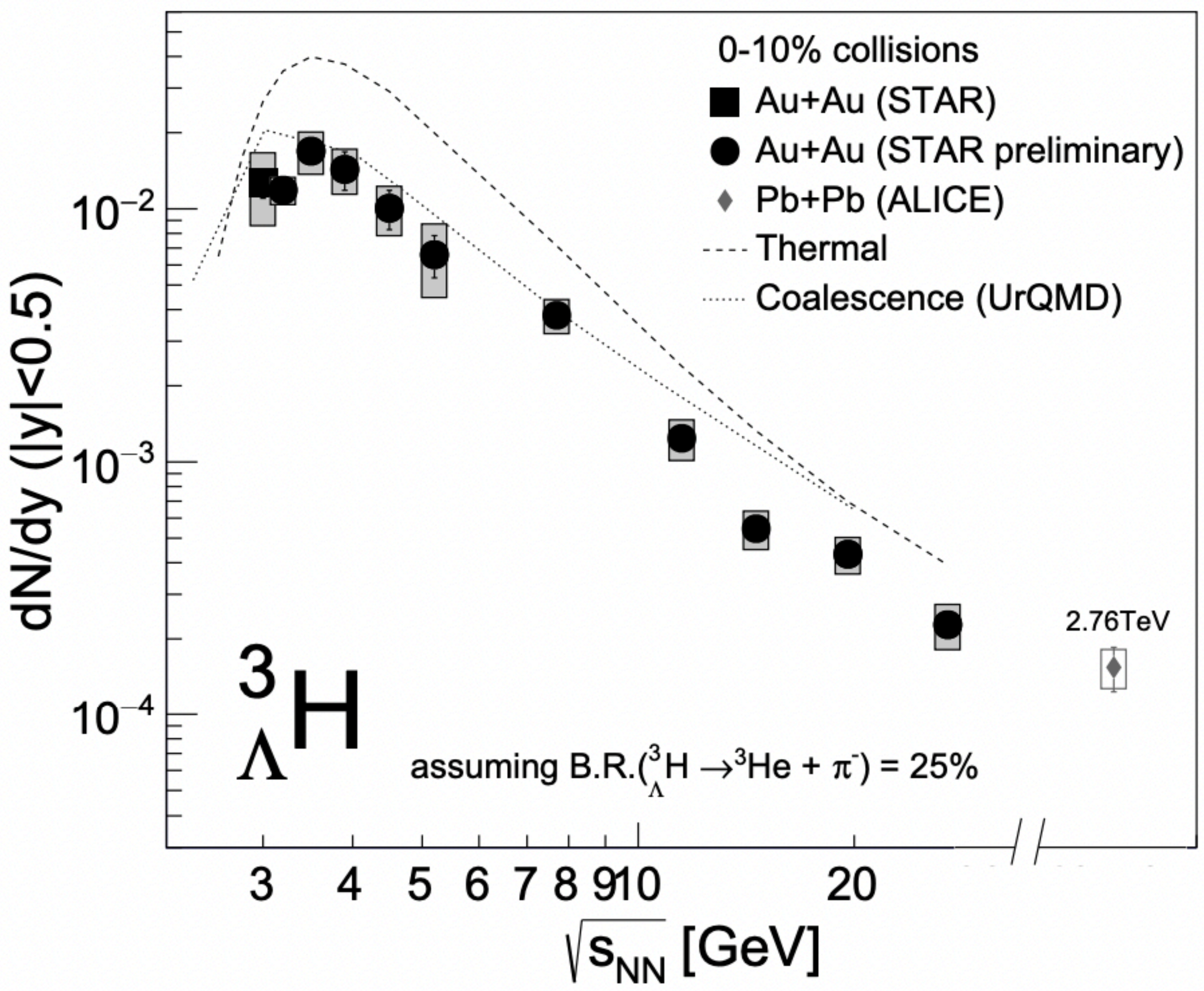
The hypertriton puzzle

$T_f = 156.5 \pm 1.5\,\text{MeV}$



Consistency with data and quantum mechanics demands the hypertriton reside in regions below 160 MeV, where the likelihood of all constituents fitting is under **10%.**

Thermal agreement of hypertriton production as a function of collision energy



- Discrepancies between experiment and thermal model increase at lower energies
- Coalescence models — more parameters and features can also explain
- Hypertriton production is maximized at energies which can probed at NICA
- Event by event fluctuation measurements with large statistics

Summary

- The weakly bound hypertriton demands a quantum treatment on length scales comparable to the fireball at freeze-out.
- A simple quantum model yields a conservative $\lesssim 10\%$ bound on the probability that a thermally produced hypertriton stays inside the freeze-out shell.
- Refinements to the quantum mechanical descriptions is likely to only decrease this estimate as binding energy decreases in medium.
- Hypertriton production remains a puzzle, and NICA offers an opportunity to investigate it further.

Thank you!

Additional Slides

Hypertriton inside a fireball