“Snowballs in hell”:
light nuclei production in heavy ion collisions

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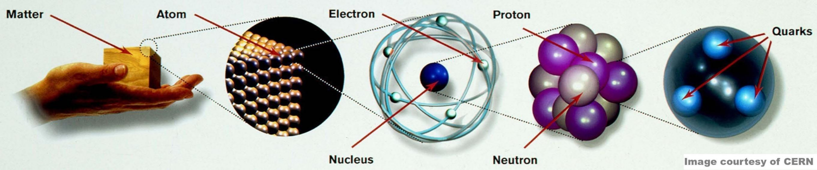
MSU

Main question in heavy ion collisions



What happens to nuclear matter under heating and compression?

How to get hot/dense nuclear matter?

normal nuclear density is $\rho_0 = 2.7 \cdot 10^{17}\ \mathrm{kg/m^3}$

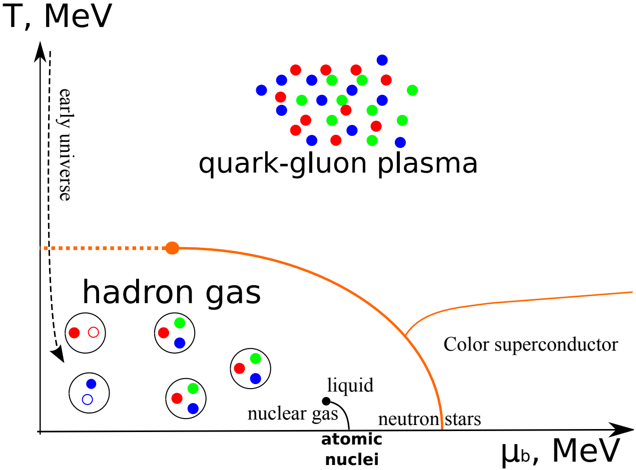
- High density: collapse of supernovae, neutron star mergers
- High temperature: early universe

  10^{-5} s after Big Bang: temperatures $T \sim 10^{12}$ K $\approx 10^2$ MeV
- Heavy ion collisions

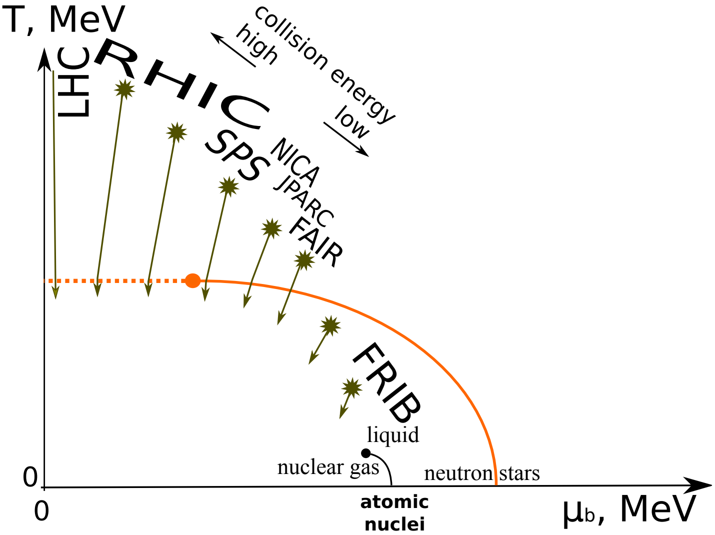
Nuclear matter in equilibrium: phase diagram

Equation of state? Properties of the quark-gluon plasma?

Does phase transition/critical point exist? (T^{cr}, μ_b^{cr})?



Heavy ion collisions: experiments



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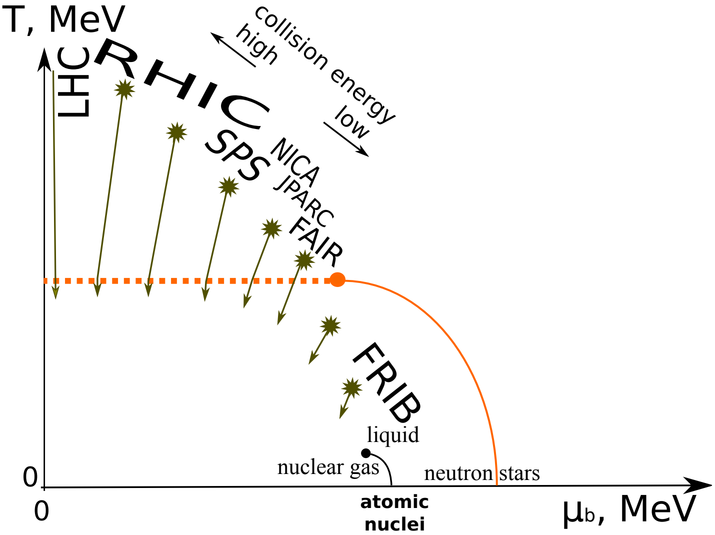
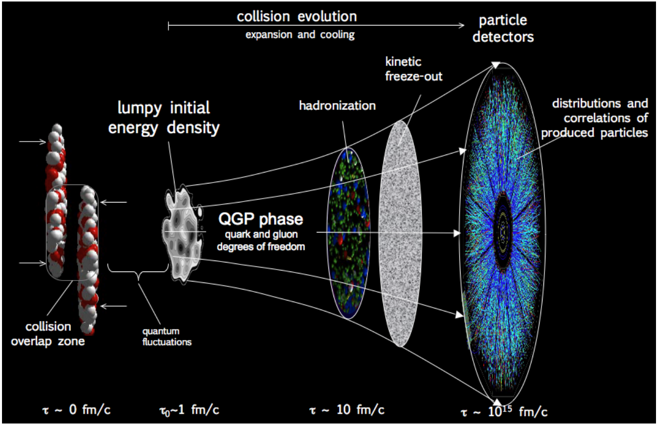


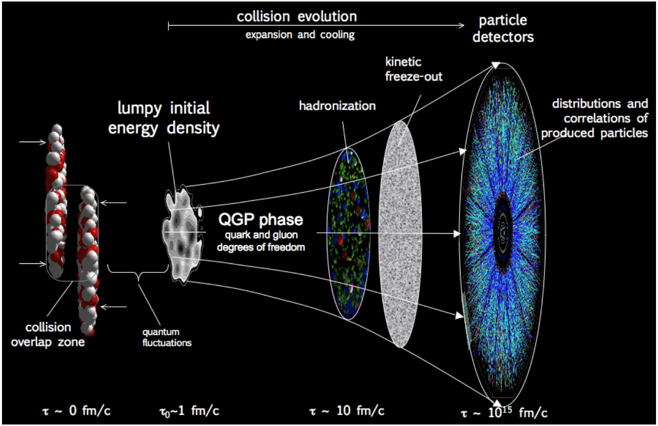
How to learn about earlier stages of heavy ion collisions?



Only final particles are measured by detectors.

Need reliable simulations to interpret experimental data

How to learn about earlier stages of heavy ion collisions?



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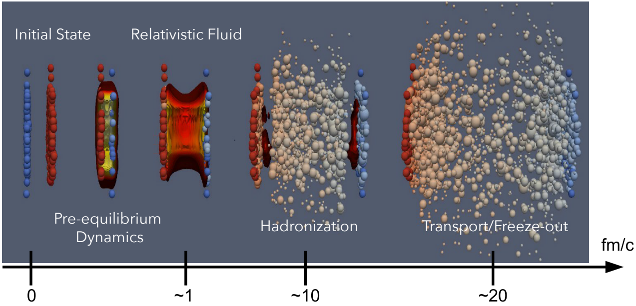
Need reliable simulations to interpret experimental data

Me: simulating heavy ion collisions with hydrodynamic and transport approaches

Ultra-relativistic heavy ion collisions: standard model



- Hydrodynamics: local thermal equilibrium, $\partial_\mu T^{\mu\nu} = 0$, $\partial_\mu j^\mu = 0$, EoS, boundary conditions

  Applicability: mean free path $\ll$ system size $\Longrightarrow$ high density

- Transport: Monte-Carlo solution of Boltzmann equations

  Applicability: mean free path $\gg \lambda_{Compton}$ $\Longrightarrow$ low density

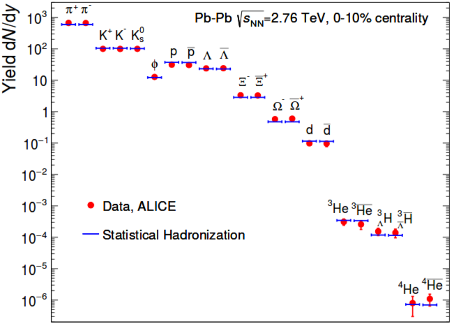
- Hybrid: hydro at high density + transport at low density

Hadron yields in heavy ion collisions

Assume rapid chemical freeze-out at
temperature T, volume V, baryon chemical potential μ_B
Thermalized mixture of all hadrons and resonances

$$N_i^{th} = \frac{g_i V}{(2\pi)^3} e^{\frac{\mu_B B_i + \mu_S S_i + \mu_{I3} I_{3i}}{T}} \int d^3p \, e^{-\frac{\sqrt{p^2+m^2}}{T}}$$

$$N_i = N_i^{th} + \sum_j N_j^{th} \, br(j \to i)$$



Andronic, Braun-Munzinger, Redlich, Stachel, Nature 561 (2018) no.7723, 321-3305

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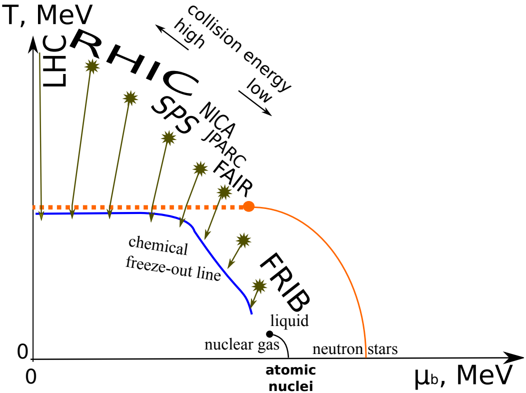


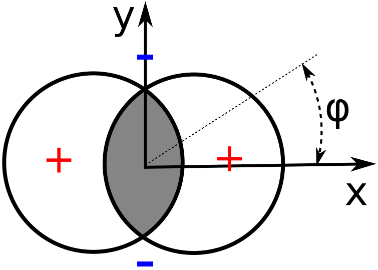
Viscosity of the quark-gluon plasma and v_2

$\tan\varphi = \frac{p_y}{p_x}$, "elliptic flow" $v_2 = \langle \cos 2\varphi \rangle$

Physical meaning: measure of interaction,

spatial anisotropy → momentum anisotropy

No interaction – $v_2 = 0$



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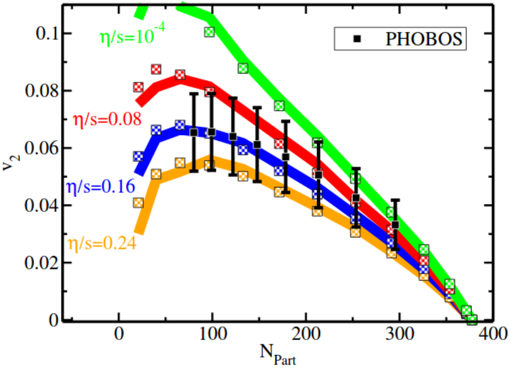
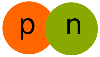


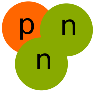
Quark-gluon plasma — fluid with lowest known kinematic viscosity,

$$\eta/s = 0.08 - 0.16$$

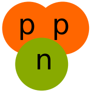
Light nuclei in heavy ion collisions



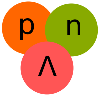
Deuteron (d)



Tritium (t)

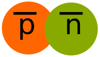


Helium-3 (^{3}He)

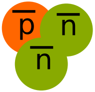


Hypertriton ($^{3}_{\Lambda}$H)

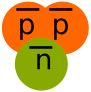
Anti-



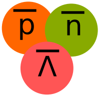
Deuteron ($\bar{d}$)



Tritium ($\bar{t}$)



Helium-3 ($^{3}\overline{\mathrm{He}}$)



Hypertriton ($^{3}_{\Lambda}\bar{\mathrm{H}}$)

These and other nuclei are created in heavy ion collisions

Anti-helium by Alpha-Magnetic Spectrometer

The First Five Years of the Alpha Magnetic Spectrometer
on the International Space Station:

Unlocking the Secrets of the Cosmos

December 8, 2016

S. Ting

- Few events (compatible with) $^3\overline{\mathrm{He}}$, $^4\overline{\mathrm{He}}$

  Caveats: hard measurement, 1 event/year, not published

- Where do they come from?

  Antimatter clouds? Dark matter annihilations? pp collisions?

Understanding anti-helium measurement by AMS

- K. Blum, K. C. Y. Ng, R. Sato and M. Takimoto,
  "Cosmic rays, antihelium, and an old navy spotlight,", PRD 96, no. 10, 103021 (2017)

  Conclusion: $\overline{\mathrm{He}}$ production compatible with *pp*

  Use coalescence model for $pp \to \overline{\mathrm{He}} + X$

- V. Poulin, P. Salati, I. Cholis, M. Kamionkowski and J. Silk,
  "Where do the AMS-02 antihelium events come from?", PRD 99, no. 2, 023016 (2019)

  Conclusion: *pp* cannot produce that much $\overline{\mathrm{He}}$

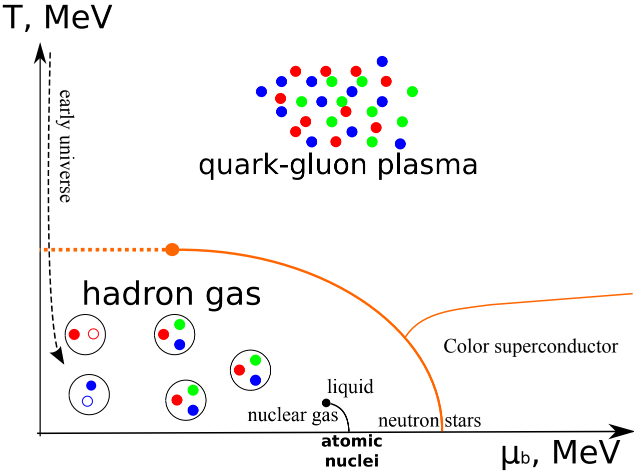
  advocate presence of anti-clouds in our Galaxy

  Use coalescence model for $pp \to \overline{\mathrm{He}} + X$

Both use *pp* collisions data from ALICE to calibrate models

Extrapolation from $pp \to \bar{d}$ to $pp \to \overline{\mathrm{He}} + X$, $pA \to \overline{\mathrm{He}} + X$, $AA \to \overline{\mathrm{He}} + X$, from high to low energies, from midrapidity to forward rapidity involved

Light nuclei and critical fluctuations



Generic critical point feature: **spatial** fluctuations increase

Nucleon density fluctuations in coordinate space

Kaijia Sun et al., Phys. Lett. B 774, 103 (2017)
Kaijia Sun et al., Phys. Lett. B 781 (2018) 499-504

Proton and neutron density:

$$\rho_n(x) = \langle \rho_n \rangle + \delta\rho_n(x)$$

$$\rho_p(x) = \langle \rho_p \rangle + \delta\rho_p(x)$$

Correlations and fluctuations:

$$C_{np} \equiv \langle \delta\rho_n(x)\delta\rho_p(x) \rangle \,/\, (\langle \rho_n \rangle \langle \rho_p \rangle)$$

$$\Delta\rho_n \equiv \left\langle \delta\rho_n(x)^2 \right\rangle / \left\langle \rho_n^2 \right\rangle$$

From a simple coalescence model

$$N_d \approx \frac{3}{2^{1/2}} \left(\frac{2\pi}{mT}\right)^{3/2} \int d^3x\, \rho_p(x)\rho_n(x) \sim \langle \rho_n \rangle N_p (1 + C_{np})$$

$$N_t \approx \frac{3^{1/2}}{4} \left(\frac{2\pi}{mT}\right)^{3} \int d^3x\, \rho_p(x)\rho_n^2(x) \sim \langle \rho_n \rangle^2 N_p (1 + 2C_{np} + \Delta\rho_n)$$

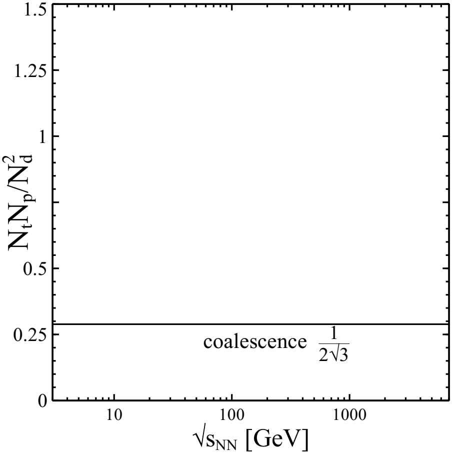
$$\frac{N_t N_p}{N_d^2} = \frac{1}{2\sqrt{3}} \frac{1 + 2C_{np} + \Delta\rho_n}{(1 + C_{np})^2}$$

Thermal ratio $\frac{g_t g_p}{g_d^2} \left(\frac{3m \cdot m}{(2m)^2}\right)^{3/2} = \frac{1}{2\sqrt{3}}$ Fluctuations and correlations

Light nuclei are sensitive to spatial density fluctuations

Comparing the *p*-*d*-*t* ratio to NA49, STAR, and ALICE data

Data: NA49 [Anticic:2010mp,Blume:2007kw,Anticic:2016ckv], STAR [Adam:2019wnb,Zhang:2019wun], ALICE [Adam:2015vda]; model JAM + coalescence [Liu:2019nii]



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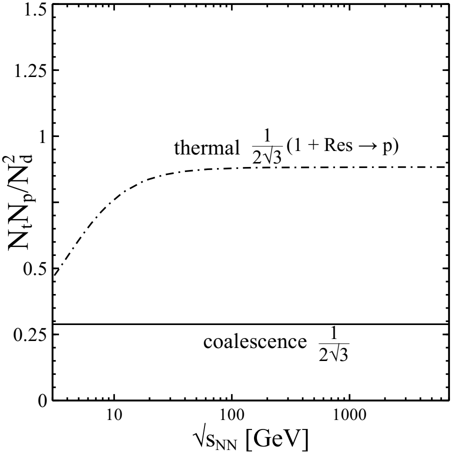

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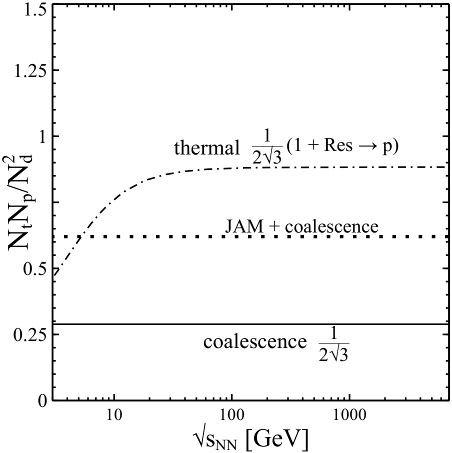

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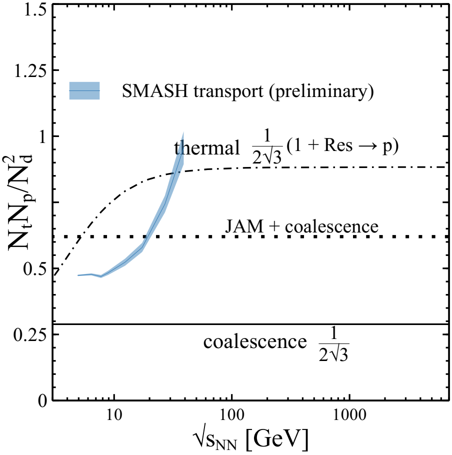

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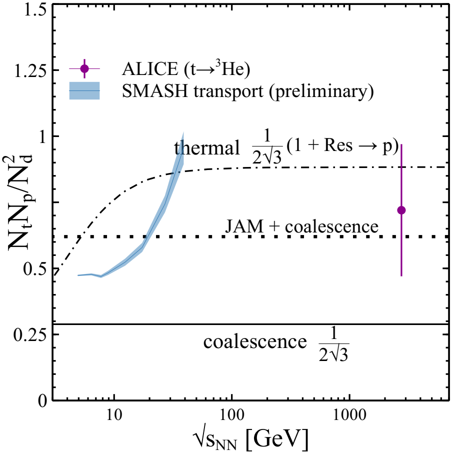

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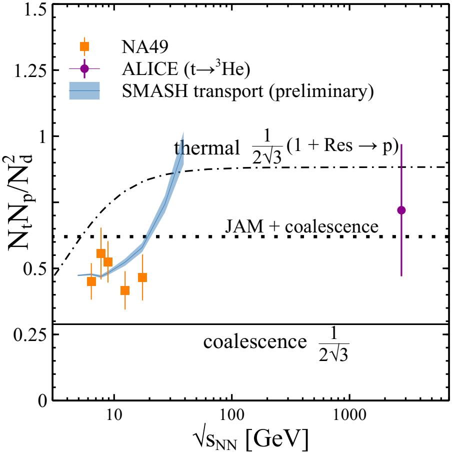

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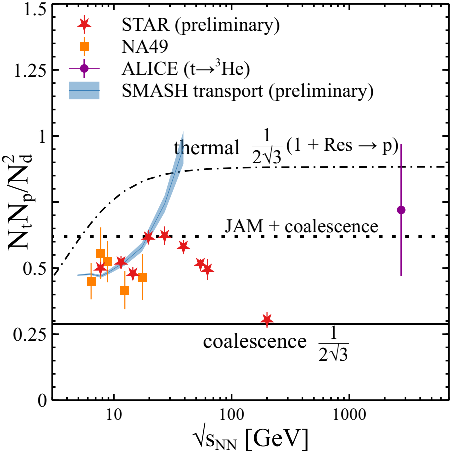

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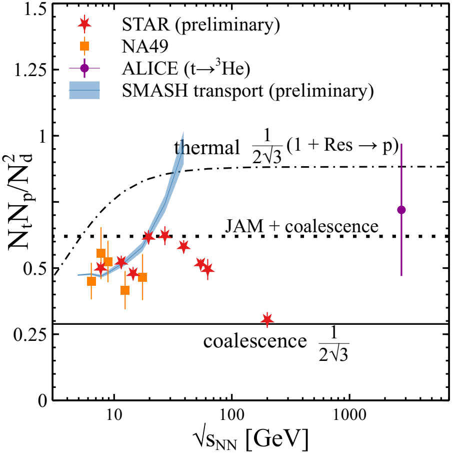


Models do not agree with each other and with the data.

Are the bumps related to fluctuations?

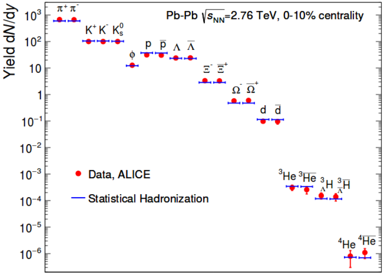
Thermal model and “snowballs in hell” puzzle

- Nuclei formed early — at hadronic freeze-out

$$N_A \approx g_A V \left(\pi T m_A/2\right)^{3/2} e^{(A\mu_B - m_A)/T}$$

- ALICE fit of yields, Pb+Pb, $\sqrt{s_{NN}} = 2.76$ TeV: $T = 155$ MeV
- Nuclei momentum spectra: $T_{kin} \simeq 110$ MeV
- How can they survive from chemical to kinetic freeze-out?
- Binding energies: d, $^3\mathrm{He}$, $^3_\Lambda\mathrm{H}$, $^4\mathrm{He}$ – 2.2, 7.7, 0.13, 8.5 MeV

Snowballs in hell.

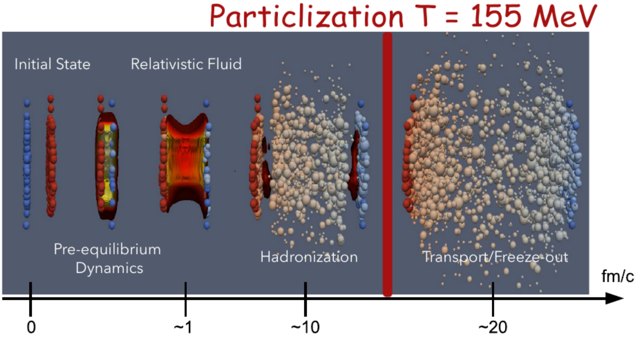


Andronic, Braun-Munzinger, Redlich, Stachel, Nature 561 (2018) no.7723, 321-3305

Light nuclei: rapid chemical freeze-out at 155 MeV, like hadrons?

Purely dynamical model

DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907
DO, Pang, Elfner, Koch, MDPI Proc. 10 (2019) no.1, 6



- CLVisc hydro L. G. Pang, H. Petersen and X. N. Wang, arXiv:1802.04449 [nucl-th]
- SMASH hadronic afterburner J. Weil *et al.*, PRC 94, no. 5, 054905 (2016)
- Treat deuteron as a single particle
  - implement deuteron + X cross-sections explicitly

SMASH transport model J. Weil et al., Phys.Rev. C94 (2016) no.5, 054905

- Monte-Carlo solver of relativistic Boltzmann equation

  BUU type approach, testparticles ansatz: $N \to N \cdot N_{test}$, $\sigma \to \sigma / N_{test}$

- Degrees of freedom
  - most of established hadrons from PDG up to mass 3 GeV
  - mesons: 44 non-strange mesons, 12 strange mesons
  - baryons: 17 N, 8 Δ, 14 Λ, 10 Σ, 6 Ξ, 2 Ω
  - strings via Pythia 8
- Interactions: $2 \leftrightarrow 2$ and $2 \to 1$ collisions, decays, potentials
- Initial conditions:
  - "collider" - elementary or AA reactions, $E_{beam} \gtrsim 0.5\ A$ GeV
  - "box" - infinite matter simulations

    detailed balance tests, computing transport coefficients, thermodynamics of hadron gas
  - "sphere" - expanding system

    comparison to analytical solution of Boltzmann equation,
    Tindall et al., Phys.Lett. B770 (2017) 532-538
  - "list" - hadronic afterburner after hydrodynamics

Interactions in SMASH

- Resonance formation and decay

  Ex. $\pi\pi \to \rho \to \pi\pi$, quasielastic scattering
  $\pi\pi \to f_2 \to \rho\rho \to \pi\pi\pi\pi$

- (In-)elastic $2 \to 2$ scattering

  Ex. $NN \to NN$, $NN \to N\Delta$, $NN \to \Delta\Delta$, $KN \to \Lambda\pi$
  parametrized cross-sections $\sigma(\sqrt{s}, t)$ or
  isospin-dependent matrix elements $|M|^2(\sqrt{s}, I)$

- String formation/fragmentation

  Via Pythia 8

- Potentials

  only change equations of motion

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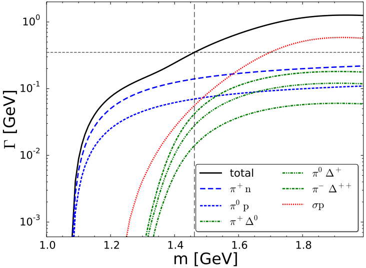
$N(1440)^+$



For every resonance:

- Breit-Wigner spectral function $\mathcal{A}(m) = \frac{2\mathcal{N}}{\pi}\frac{m^2\Gamma(m)}{(m^2-M_0^2)^2+m^2\Gamma(m)^2}$
- Mass dependent partial widths $\Gamma_i(m)$

  Manley formalism for off-shell width Manley and Saleski, Phys. Rev. D 45, 4002 (1992)
  Total width $\Gamma(m) = \sum_i \Gamma_i(m)$

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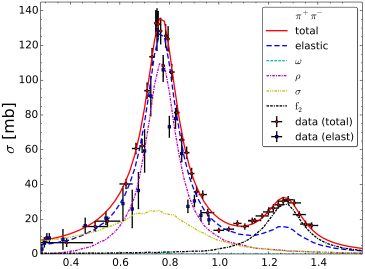

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- $2 \rightarrow 1$ cross-sections from detailed balance relations

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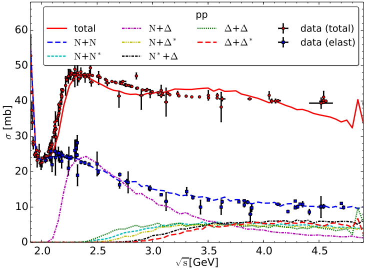


- Potentials

  only change equations of motion

  - $NN \to NN^*$, $NN \to N\Delta^*$, $NN \to \Delta\Delta$, $NN \to \Delta N^*$, $NN \to \Delta\Delta^*$

    angular dependencies of $NN \to XX$ cross-sections implemented

  - Strangeness exchange $KN \to K\Delta$, $KN \to \Lambda\pi$, $KN \to \Sigma\pi$

Interactions in SMASH

- Resonance formation and decay

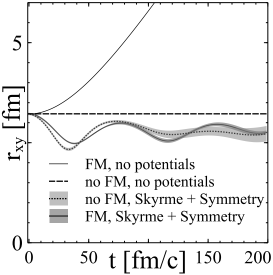
  Ex. $\pi\pi \to \rho \to \pi\pi$, quasielastic scattering
  $\pi\pi \to f_2 \to \rho\rho \to \pi\pi\pi\pi$
- (In-)elastic $2 \to 2$ scattering

  Ex. $NN \to NN$, $NN \to N\Delta$, $NN \to \Delta\Delta$, $KN \to \Lambda\pi$
  parametrized cross-sections $\sigma(\sqrt{s}, t)$ or
  isospin-dependent matrix elements $|M|^2(\sqrt{s}, I)$
- String formation/fragmentation

  Via Pythia 8
- Potentials

  only change equations of motion

Transverse radius of Cu nucleus.

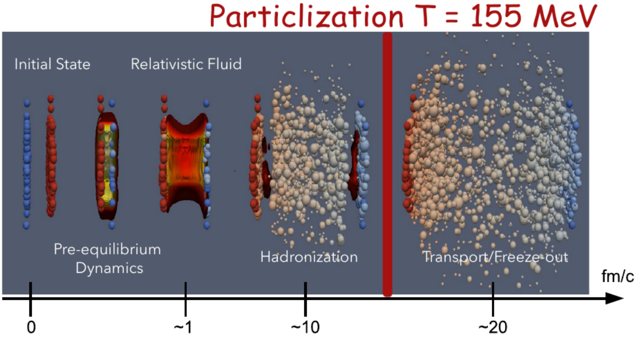


- Skyrme and symmetry potential
- $U = a(\rho/\rho_0) + b(\rho/\rho_0)^\tau \pm 2S_{\text{pot}}\frac{\rho_{I3}}{\rho_0}$

  ρ - Eckart rest frame baryon density
  ρ_{I3} - Eckart rest frame density of I_3/I
  $a = -209.2$ MeV, $b = 156.4$ MeV, $\tau = 1.35$, $S_{\text{pot}} = 18$ MeV
  corresponds to incompressibility $K = 240$ MeV
  assures stability of a nucleus with Fermi motion

Back to the simulation

DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907
DO, Pang, Elfner, Koch, MDPI Proc. 10 (2019) no.1, 6

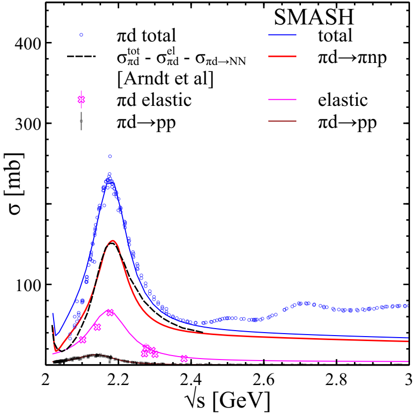


- CLVisc hydro L. G. Pang, H. Petersen and X. N. Wang, arXiv:1802.04449 [nucl-th]
- SMASH hadronic afterburner J. Weil *et al.*, PRC 94, no. 5, 054905 (2016)
- Treat deuteron as a single particle
  - implement deuteron + X cross-sections explicitly

Light nuclei production by pion catalysis

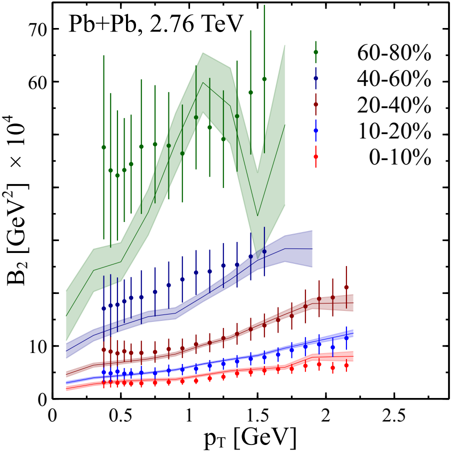
- $\pi d \leftrightarrow \pi np$, $\pi t \leftrightarrow \pi nnp$, $\pi^3\mathrm{He} \leftrightarrow \pi npp$
- all are tested to obey detailed balance within 1% precision
- large disintegration cross sections → large reverse rates

DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



$B_2(p_T)$ for different centralities

DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907

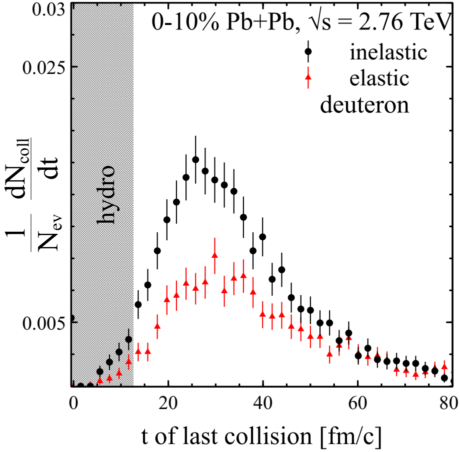


$$B_2(p_T) = \frac{\frac{1}{2\pi}\frac{d^3N_d}{p_T dp_T dy}\Big|_{p_T^d = 2p_T^p}}{\left(\frac{1}{2\pi}\frac{d^3N_p}{p_T dp_T dy}\right)^2}$$

No free parameters. Works well for all centralities.

Does deuteron freeze out at 155 MeV?

Only less than 1% of final deuterons originate from hydrodynamics

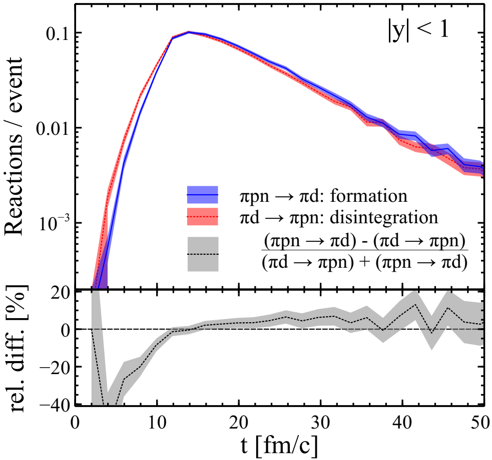


Deuteron freezes out at late time

Its chemical and kinetic freeze-outs roughly coincide

Is $\pi d \leftrightarrow \pi np$ reaction equilibrated

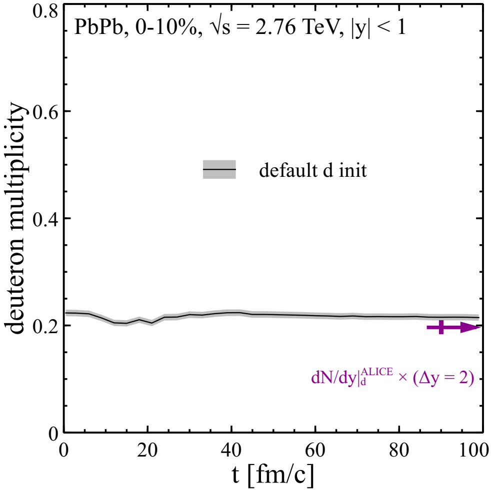
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



After about 12-15 fm/c within 5% $\pi d \leftrightarrow \pi np$ is equilibrated

Deuteron yield

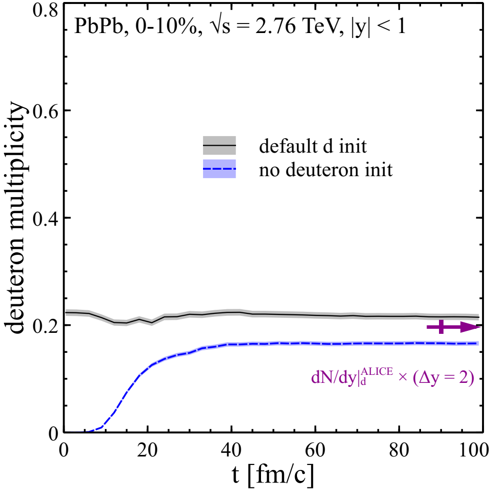
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



The yield is almost constant. Why? Does afterburner really play any role?

Deuteron yield

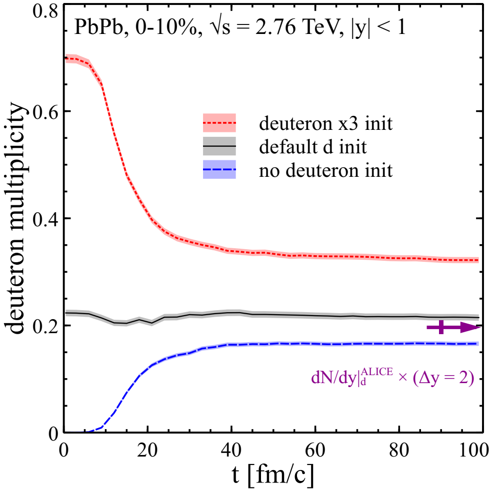
DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



No deuterons at particlization: also possible. Here **all** deuterons are from afterburner.

Deuteron yield

DO, Pang, Elfner, Koch, PRC99 (2019) no.4, 044907



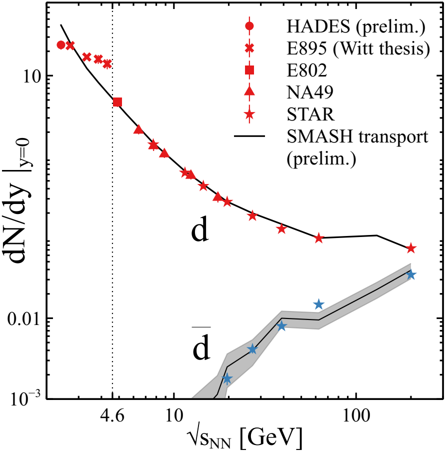
No deuterons at particlization: also possible. Here **all** deuterons are from afterburner.

Why thermal model describes light nuclei yields at LHC

- Stable hadron yields (π, K, N, Λ, $\ldots$) comprising resonances are fixed at chemical freeze-out
- Nuclei are kept in partial (relative) equilibrium by huge cross-sections of $A + h \leftrightarrow A \times N + h$ until kinetic freeze-out
  - Therefore nuclei yields stay constant from hadron chemical freeze-out to kinetic
  - This picture works for all measured nuclei at LHC
    Xu, Rapp, Eur. Phys. J. A55 (2019) no.5, 68
    Vovchenko et al, arXiv:1903.10024
  - It works even if no nuclei are produced at chemical freeze-out
    DO, Pang, Elfner, Koch, Phys.Rev. C99 (2019) no.4, 044907
    DO, Pang, Elfner, Koch, MDPI Proc. 10 (2019) no.1, 6

Exactly the same mechanism, lower energies

Data: Alt:2006dk, Anticic:2010mp, Adams:2003xp, Adamczyk:2017iwn, Abelev:2009bw, Adcox:2003nr, Klay:2001tf, Ahle:1999in

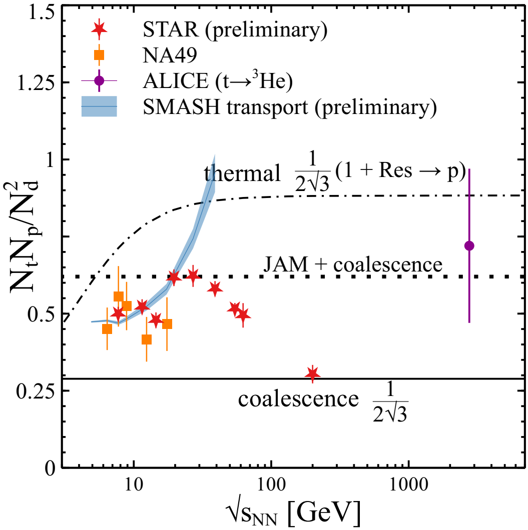


Still works for deuteron!

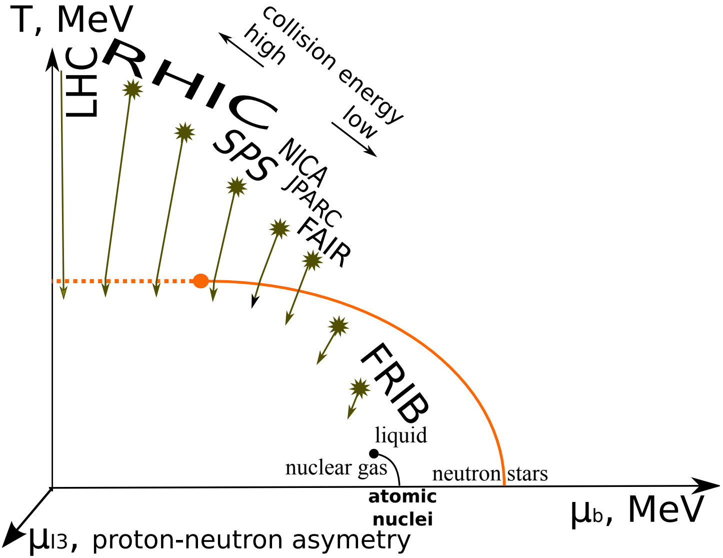
Summary so far

- Benefits of understanding light nuclei production better
  - Estimation of background for antimatter in space.
    May lead to discovery of antimatter clouds in the Universe
  - Possible detection of critical point from density fluctuations
    $\Longrightarrow \frac{N_t N_p}{N_d^2}$
- "Snowballs in hell": light nuclei "survive" temperatures of 150 MeV, because they are continuously created and disintegrated at similar rates
- $\pi d \leftrightarrow \pi pn$ — pion catalysis mechanism of deuteron production

Summary so far



Heavy ion collisions at FRIB



Symmetry energy

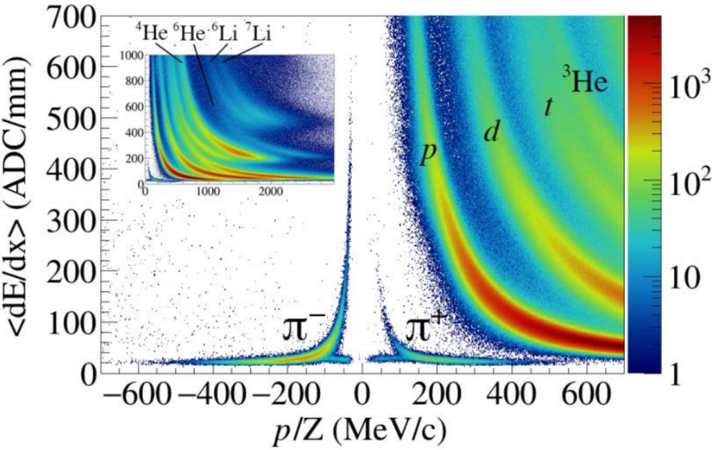
Baryon density: $\rho_B = \rho_n + \rho_p$
Isospin asymetry: $\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$
Symmetry energy $S(\rho_B)$: $\epsilon(\rho_B, \delta) = \epsilon(\rho_B, 0) + S(\rho_B)\delta^2 + O(\delta^4)$
Pressure from symmetry energy: $p_{sym} = \rho_B^2 \frac{dS}{d\rho_B}$

Sensitivity to $S(\rho_B)$:

- Neutron stars, mergers
  - Mass-radius relation
  - Tidal deformability
  - Cooling rates from $n \to p + e^- + \bar{\nu}_e$
- Low energy heavy ion collisions (FRIB, TAMU, GSI)
  - SπRIT experiment at FRIB
    $^{112}\mathrm{Sn} + {}^{108}\mathrm{Sn}$ ($N/Z = 1.2$) versus $^{132}\mathrm{Sn} + {}^{124}\mathrm{Sn}$ ($N/Z = 1.56$)
    $E_{kin}/A = 270$ MeV

Need combined analysis of constraints → Bayesian analysis

Connection to light nuclei production



π^-/π^+ is used to constrain symmetry energy

$t/^3\mathrm{He}$ can be used too

Ongoing studies and outlook

- Strategy: Fit parameters of the transport code (including symmetry energy) to match experimental observables
- Challenges:
  - Physics missing in transport codes
  - Most codes only describe selected observables well
  - Constraints from one code differs from another

Transport code comparison project → fix physics
Bayesian analysis → perform global fit of available data to constrain symmetry energy

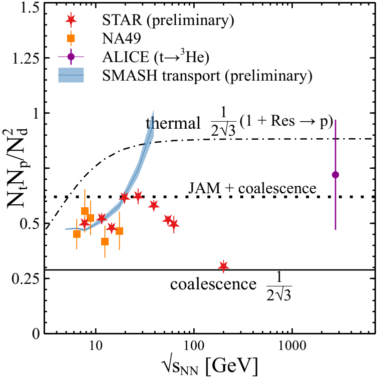
Takeaway: light nuclei in heavy ion collisions

High energy

- "Snowballs in hell"
- Search for critical point
- Anti-nuclei in space

Low energy

- Equation of state (EoS) at few ρ_0
- EoS dependence on μ_{I3}
- Connections to neutron star properties, neutron star mergers



Backup

Simple analytical coalescence framework

- Nucleons bind into nuclei if they are close in phase space

$$E_A \frac{dN_A}{d^3P_A} = B_A \left(E_{\mathrm{p}} \frac{dN_{\mathrm{p}}}{d^3P_{\mathrm{p}}}\right)^Z \left(E_{\mathrm{n}} \frac{dN_{\mathrm{n}}}{d^3P_{\mathrm{n}}}\right)^N \Bigg|_{P_{\mathrm{p}}=P_{\mathrm{n}}=P_A/A}$$

- Expectations from a "simple analytical coalescence":
    - $B_A \sim V_{HBT}^{-(A-1)}, \quad B_{A=2} \sim 1/V_{HBT}, \quad B_{A=3} \sim 1/V_{HBT}^2$
    - $B_A(p_T)$ grows with p_T in AA, $B_A(p_T) \approx const$ in pp
    - B_A decreases with larger multiplicity

Qualitatively these expectations are fulfilled

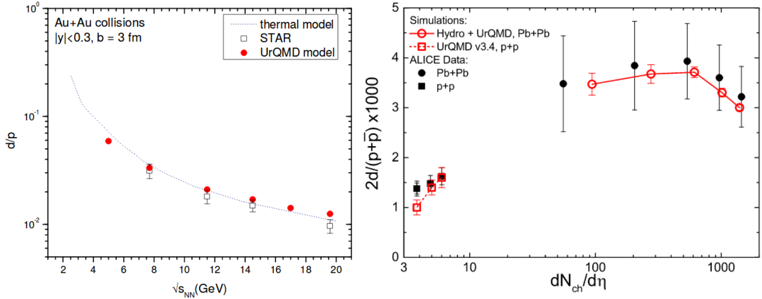
- Attempts to get more precision:
    - More realistic proton phase space distribution from dynamical models
    - Advanced coalescence: account for nuclei wavefunction

Example of [hydro +] transport + coalescence

Recipe to make a deuteron:

1. Take nucleon pair at $t =$ maximum of last interaction times
2. Boost to their rest frame
3. Bind $|\Delta p| < 0.28$ GeV and $|\Delta x| < 3.5$ fm
4. Take isospin factor into account

UrQMD — Sombun et al, Phys.Rev. C99 (2019) no.1, 014901



Good description from low to high energies with 2 parameters