# Flavored Freezeout

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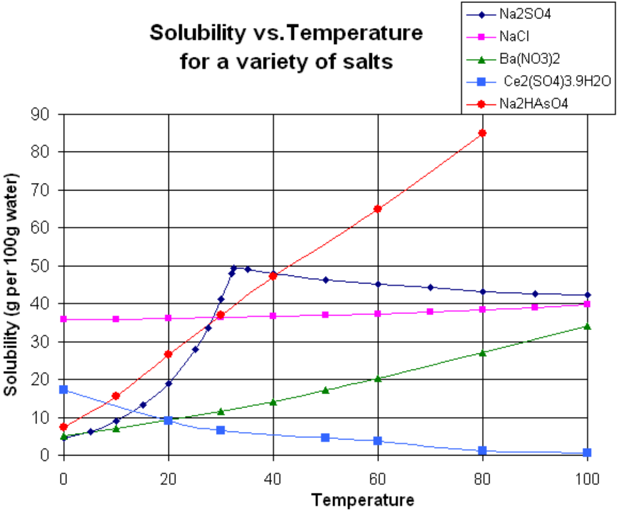
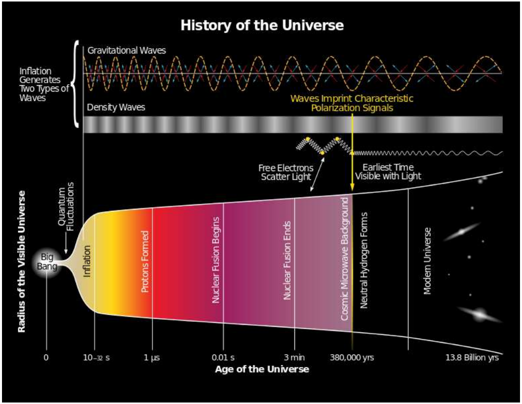
27-30 January, 2015

# Multiple Freezeout on your table top: Salt mixture in water



# Multiple Freezeout in the Early Universe




Hypothetical Q: A more rapid expansion $\rightarrow$ sudden single freezeout a la HIC ?

# Freezeout in HIC

- Freezeout is a result of competition between 2 effects: constituent interactions and fireball expansion- Cross section vs Dilution
- In the late stage of a heavy ion collision (HIC), the rate of collisions between the constituents can no longer cope with the expansion rate. As a result, hadrons start freezing out.
- Simple assumption: All strong interaction rates are same. Hence single chemical freezeout (1CFO).

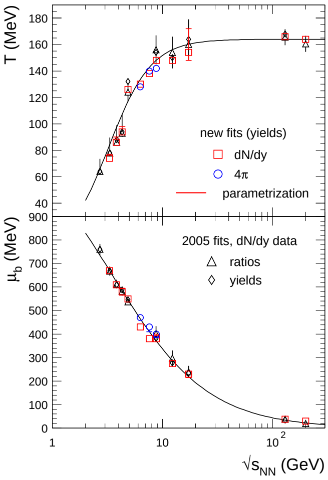
# Single Chemical Freezeout: 1CFO

Standard practice:

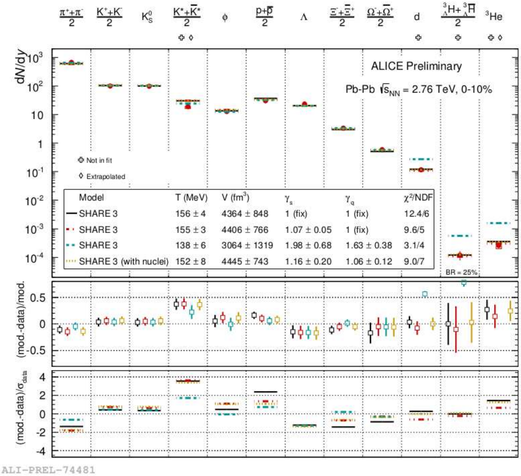
All the hadrons CFO at the same $(T, \mu_B)$ surface.

This provides an overall good qualitative picture of CFO at $\sqrt{s_{\rm NN}} \sim 2 - 200$ GeV with $\sim 4$ params.

Andronic et al: 0812. 1186



# 1CFO at LHC

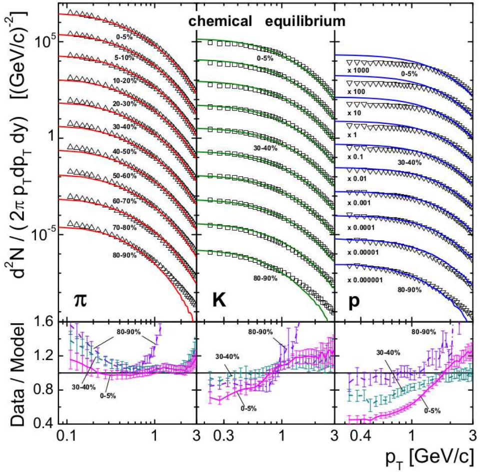



| Model | T (MeV) | V (fm$^3$) | $\gamma_s$ | $\gamma_q$ | $\chi^2$/NDF |
|---|---|---|---|---|---|
| SHARE 3 | 156 ± 4 | 4364 ± 848 | 1 (fix) | 1 (fix) | 12.4/6 |
| SHARE 3 | 155 ± 3 | 4406 ± 766 | 1.07 ± 0.05 | 1 (fix) | 9.6/5 |
| SHARE 3 | 138 ± 6 | 3064 ± 1319 | 1.98 ± 0.68 | 1.63 ± 0.38 | 3.1/4 |
| SHARE 3 (with nuclei) | 152 ± 8 | 4445 ± 743 | 1.16 ± 0.20 | 1.06 ± 0.12 | 9.0/7 |

no. of parameters 4+1($\mu_B$ set to 0 by hand.)

Floris: 1408.6403

# 1CFO at LHC




Begun et al: 1405.7252

# Revisitng our 1CFO assumption: When does chemistry freeze out?

Basic observables are the spectra of identified particles; from this one gets yields. Relative yields of hadrons is the outcome of "chemistry".

At early times, fireball is a reactive fluid. Reaction rates depend on local densities as well as rates of mixing.

Kinetic equations more complicated: need numerical treatment, but many parameters fed into the code.

# When does isospin freeze out?

- The rates for processes $p + \pi^- \leftrightarrow n + \pi^0$, remain high at $\simeq 150$ MeV, because $m_n - m_p$ is small and the yield of pions is large. So the chemical freezeout of baryon isospin can be delayed. The $p \leftrightarrow n$ reaction may proceed without suppression right up to kinetic freezeout
Asakawa, Kitazawa, 2011

# Can the K and $\pi$ freeze separately?

- Indirect transmutations of $K$ and $\pi$ involve strange baryons in reactions such as $\Omega^- + K^+ \leftrightarrow \Xi^0 + \pi^0$. These have very high activation thresholds. There is no physics forcing $K$ and $\pi$ to freezeout together. But $K$ and $\phi$ are resonantly coupled, so freeze out together.
  SC, Godbole, Gupta, 2013

# Double Chemical Freezeout: 2CFO

- 'Isospin changing' reactions are last to freezeout $(p + \pi^0 \leftrightarrow n + \pi^+)$ (Asakawa, Kitazawa 2011)
  - low activation energy
  - high pion density
- 'Strangeness changing' reactions can freezeout earlier $(\Omega^- + K^+ \leftrightarrow \Xi^0 + \pi^0)$
  - High activation energy
  - $\Omega$ and $K$ densities much less compared to that of $\pi$; $\Omega^- + K^+$ reactions much suppressed
- Motivates to propose separate CFO for (strange+hidden strangeness) and non strange hadrons: 2CFO
- $T_s$, $V_s$, $\mu_{B_s}$ characterise the strange surface
- $T_{ns}$, $V_{ns}$, $\mu_{B_{ns}}$ characterise the non-strange surface

# Hadron Yields in Thermal Model

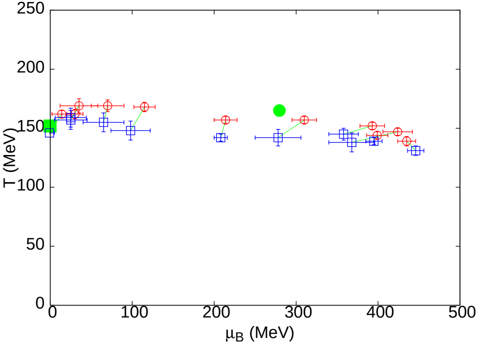
- The ideal hadron resonance gas (HRG) partition function $Z$ in the grand canonical ensemble at the time of CFO at a particular beam energy $\sqrt{s_{\mathrm{NN}}}$ is given as

$$\log\left[Z\left(\sqrt{s_{\mathrm{NN}}}\right)\right] = \sum_i \log\left[Z_i\left(T_i\left(\sqrt{s_{\mathrm{NN}}}\right), \mu_i\left(\sqrt{s_{\mathrm{NN}}}\right), V_i\left(\sqrt{s_{\mathrm{NN}}}\right)\right)\right]$$

-

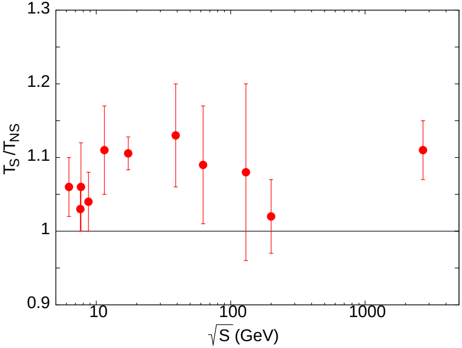
$$\begin{aligned} N_i^{\mathrm{p}} &= \frac{\partial}{\partial\left(\frac{\mu_i}{T_i}\right)} \log\left[Z\right] \\ &= \frac{V_i T_i}{\pi^2} g_i m_i^2 \sum_{l=1}^{\infty} (-a)^{l+1}\, l^{-1} K_2\left(l m_i / T_i\right) \times \\ &\quad \exp\left(l\left(B_i \mu_{B\,i} + Q_i \mu_{Q\,i} + S_i \mu_{S\,i}\right) / T_i\right) \end{aligned}$$

# 2CFO Freezeout Parameters




SC, Godbole, Gupta: 1306.2006

# 2CFO Freezeout Parameters




SC, Godbole, Gupta: 1306.2006

# Nuclei Yields in Thermal Model

- Treat the nuclei on the same footing as other hadrons
- Thus the Boltzmann factor decides the nuclei yield:
  Braun-Munzinger et al, 1996

# Nuclei Yields in Simple Coalescence

- Nuclei formed by coalescence of hadrons near the KFO surface

$$E_A \frac{d^3 N_A}{d^3 P_A} = B_A \left( E_p \frac{d^3 N_p}{d^3 P_p} \right)^Z \left( E_n \frac{d^3 N_n}{d^3 P_n} \right)^{A-Z}$$

- At the level of yields

$$N_A = C_A \, (N_p)^Z \, (N_n)^{A-Z}$$

- For ratios of nuclei, for eg. anti-nuclei to nuclei

$$\begin{aligned} \frac{\overline{N_A}}{N_A} &= C_{\overline{A}A} \, (N_{\bar{p}}/N_p)^Z \, (N_{\bar{n}}/N_n)^{(A-Z)} \\ &\sim C_{\overline{A}A} \, (N_{\bar{p}}/N_p)^A \end{aligned}$$

# Nuclei Yields in Simple Coalescence

- Nuclei production within the coalescence model is a combination of two distinct physics issues:
  - The physics of $C_{\overline{A}A}$. This is related to the correlation effects in the phase space that exist between the constituent hadrons at the time of the KFO
  - The abundances of the constituent hadrons at the time of KFO which is already fixed at the CFO surface obtained from fits to the hadron yields.
- Here we are interested in the role played by the latter physics in determining the nuclei yields. Hence take $C_{\overline{A}A} = 1$. Sufficient for our purpose to demonstrate the dependence of the nuclei production on the CFO scheme.

# Ratios

- Unlike Flavor Ratio ($R^{\mathrm{UF}}$):

$$\left(N_s^{\mathrm{t}}/N_{ns}^{\mathrm{t}}\right)^{\mathrm{th}} = \exp\left(S\mu_S/T_s\right)\frac{g_s V_s}{g_{ns}V_{ns}}\left(\frac{T_s m_s}{T_{ns}m_{ns}}\right)^{3/2} \times \exp\left(m_{ns}/T_{ns} - m_s/T_s\right) \times \exp\left(\mu_{B\,s}/T_s - \mu_{B\,ns}/T_{ns}\right)$$

- Hence,

$$R_{\mathrm{2CFO}}^{\mathrm{UF}} \sim \left(\frac{T_s}{T_{ns}}\right)^{3/2}\left(\frac{V_s}{V_{ns}}\right)R_{\mathrm{1CFO}}^{\mathrm{UF}}$$

# Ratios

- Like Flavor Ratio ($R^{\text{LF}}$):

$$N_i^t / N_j^t = \left(\frac{g_i}{g_j}\right)\left(\frac{m_i}{m_j}\right)^{3/2} \times \exp\left(\left((m_j - m_i) + (B_i - B_j)\,\mu_B\right)/T\right)$$

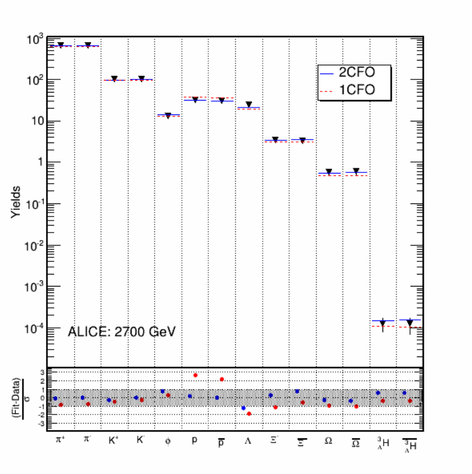
- Hence,

$$R^{\text{LF}}_{\text{2CFO}} \sim R^{\text{LF}}_{\text{1CFO}}$$

- Anti-particle to particle ratios simplifies even further.

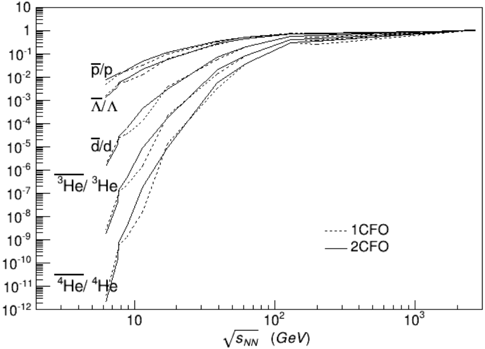
$$\left(\overline{N_i^t}/N_i^t\right)^{\text{th}} = \exp\left(-2\left(B_i\mu_{B\,i} + Q_i\mu_{Q\,i} + S_i\mu_{S\,i}\right)/T\right)$$

# 2CFO at LHC



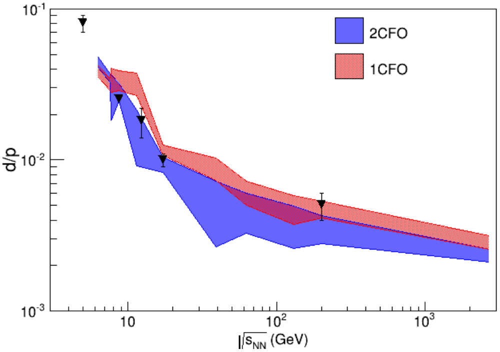

SC, Mohanty: 1405.2632

# Antiparticle to Particle Ratio




SC, Mohanty: 1405.2632

# Like Flavor Ratio

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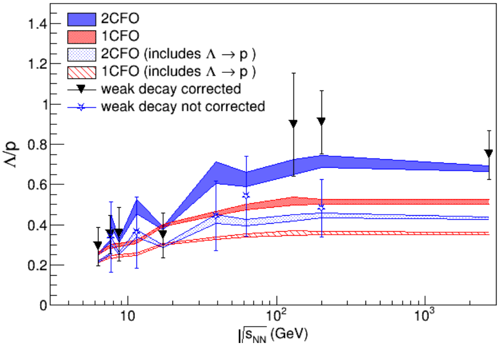


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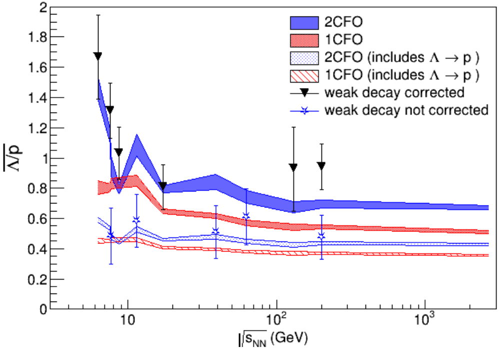
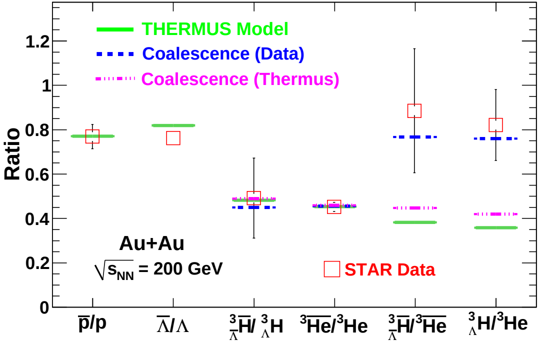


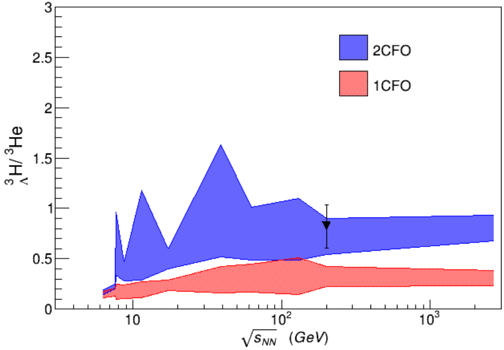

SC, Mohanty: 1405.2632

# Unlike Flavor Ratio: Nuclei




Andronic et al 2011, Cleymans et al 2011, Pal et al 2013

# Unlike Flavor Ratio

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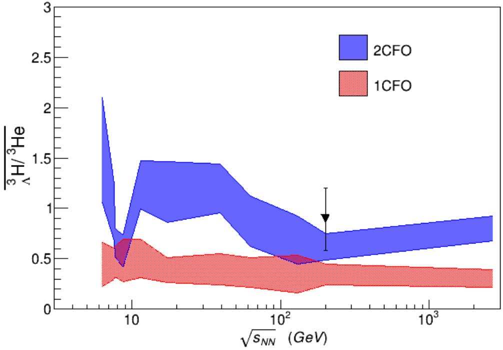



SC, Mohanty: 1405.2632

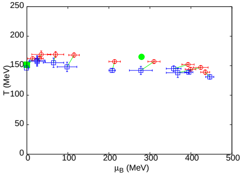
# Other approaches

- Post 1CFO employ hadronic afterburner: Microscopic Transport Approach (UrQMD Model). Baryon-antibaryon annihilation main source of correction. Systematics ?- Steinheimer et al, 2013
- Introduce additional light and strange chemical non-equilibrium fugacity factors- Petran et al, 2013

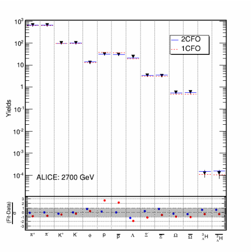
# Summarising..

- Multiple freezeout is a common occurence in nature: from a cooling salt mixture in water to the cooling early universe. A multi-component system naturally freezes over a range in the relevant parameter space.
- Freezeout in the cooling fireball in HIC- Is the freezeout gradual enough to leave an imprint on the data ?
- 1CFO provides an overall good description of the hadrons(nuclei) yields across a wide range of $\sqrt{s_{\rm NN}}$
- Does closer/careful inspection of the data reveal details in freezeout ? Which observables are most sensitive?
- Strange to non strange hadron/nuclei ratios are most sensitive to flavor dynamics at freezeout
- Anomaly with data of $\Lambda/p$ at LHC, ${}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}$ at top RHIC have a common origin: flavor dynamics at freezeout
- Influence of additional resonances ?- they will affect the above strange to non strange ratios. On including them, can the above anomalies with data be addressed within 1CFO ? Need to check- require input on their branching ratios
- Data from FAIR, BES-II can throw more light

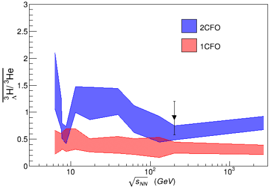
# Take home



T (MeV)
$\mu_B$ (MeV)

2CFO
1CFO
Yields
ALICE: 2700 GeV
(Fit-Data)/σ

2CFO
1CFO
$^3_\Lambda H/^3He$
$\sqrt{s_{NN}}$ (GeV)