# Freeze-out dynamics in Big Bang and Little Bangs

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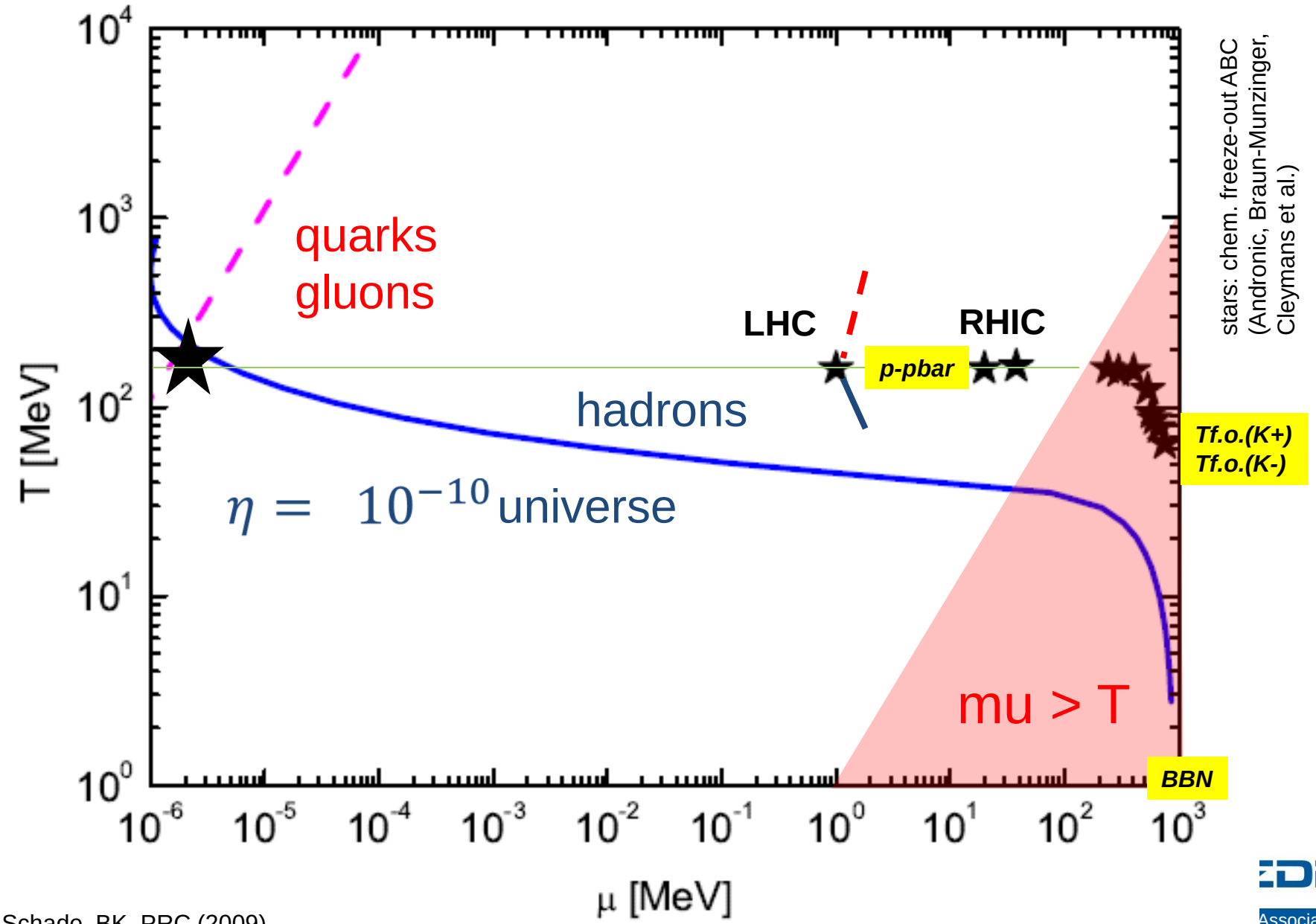
# Cosmic Swing: from estimates to precision



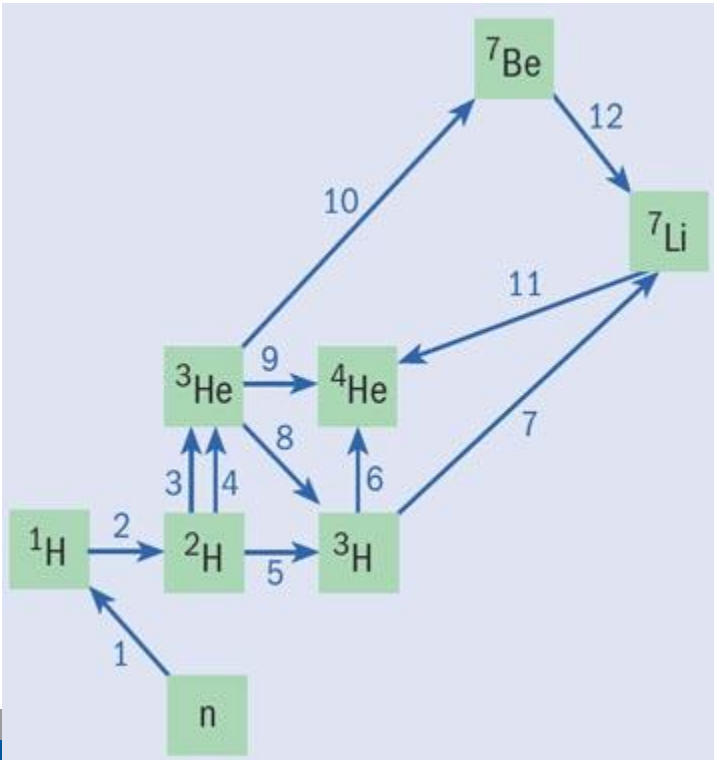

Schade, BK, PRC (2009)

# Example 1: nuclear isotopes in BBN

$$\dot{Y}_i = \sum_{kl,x} Y_k Y_l < \sigma v >^{(T)}_{kl \to ix} - \sum_{k,jx} Y_i Y_k < \sigma v >^{(T)}_{ik \to jx}$$

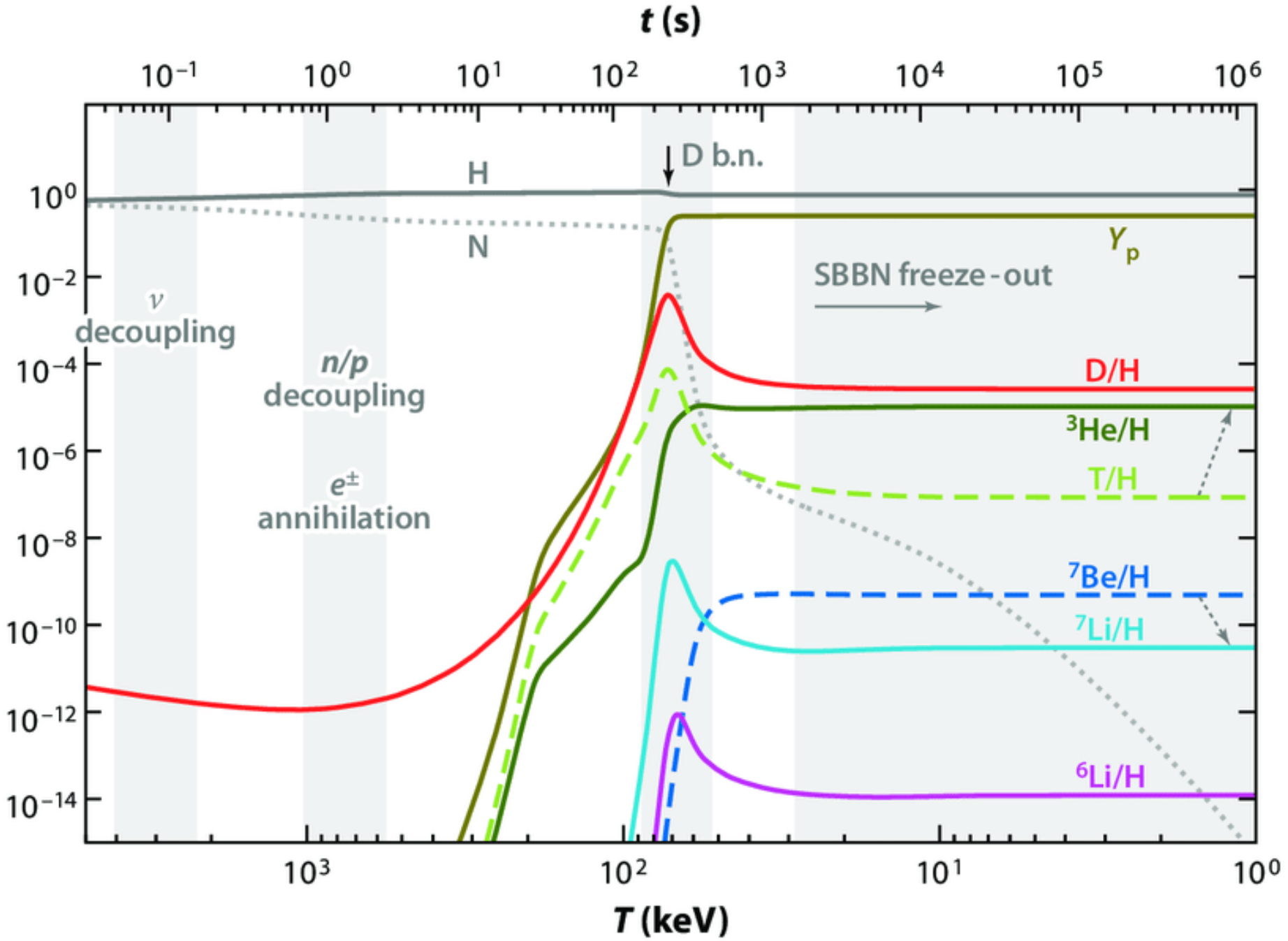
**rates**

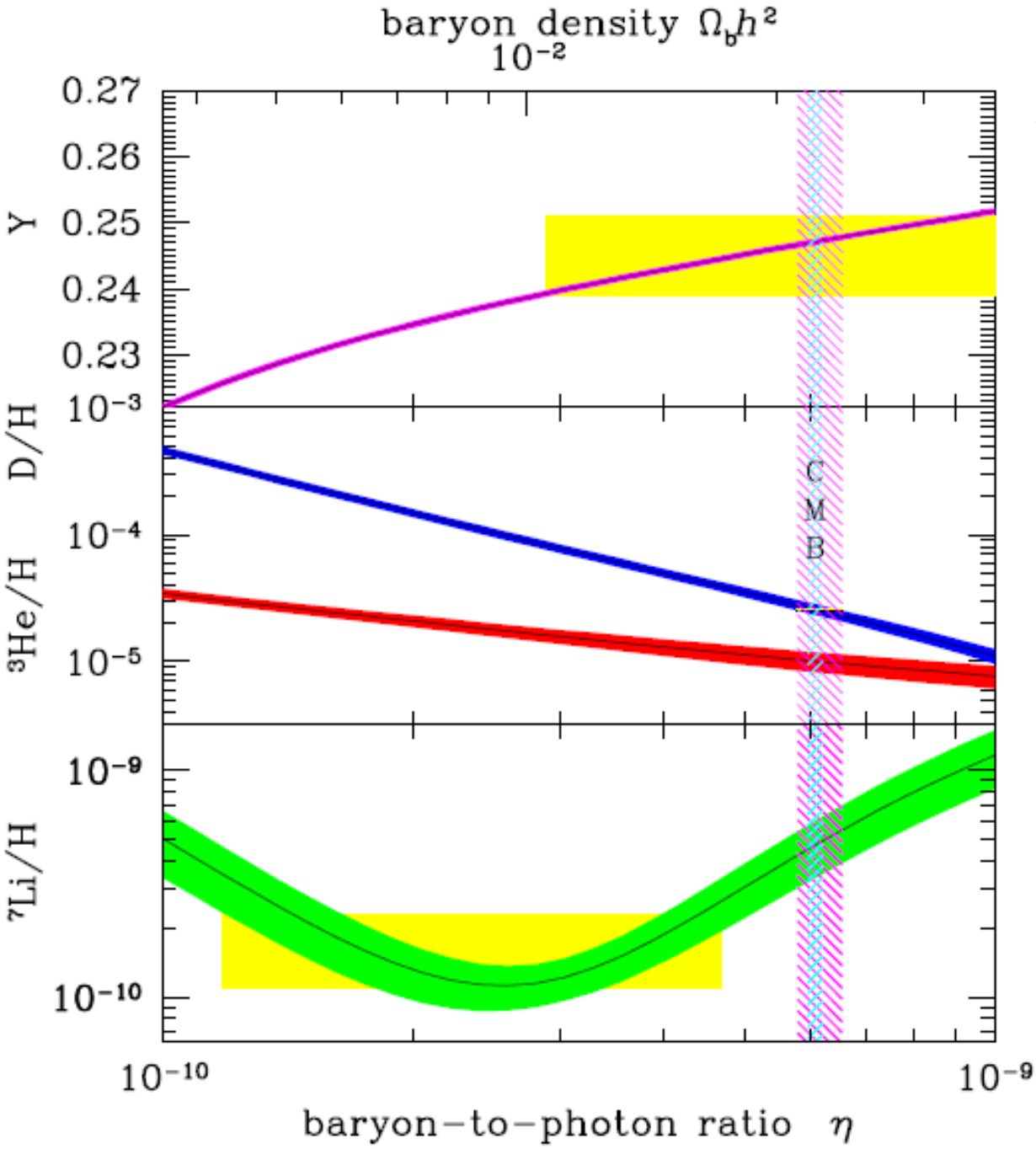
Friedmann eqs. → T(t)




1 $n \rightarrow {}^{1}H + e^{-} + \bar{\nu}$
2 ${}^{1}H + n \rightarrow {}^{2}H + \gamma$
3 ${}^{2}H + {}^{1}H \rightarrow {}^{3}He + \gamma$
4 ${}^{2}H + {}^{2}H \rightarrow {}^{3}He + n$
5 ${}^{2}H + {}^{2}H \rightarrow {}^{3}H + {}^{1}H$
6 ${}^{2}H + {}^{3}H \rightarrow {}^{4}He + n$
7 ${}^{3}H + {}^{4}He \rightarrow {}^{7}Li + \gamma$
8 ${}^{3}He + n \rightarrow {}^{3}H + {}^{1}H$
9 ${}^{3}He + {}^{2}H \rightarrow {}^{4}He + {}^{1}H$
10 ${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$
11 ${}^{7}Li + {}^{1}H \rightarrow {}^{4}He + {}^{4}He$
12 ${}^{7}Be + n \rightarrow {}^{7}Li + {}^{1}H$

$$T_{[MeV]} = \frac{1.55}{\sqrt{t_{[s]}\sqrt{N(T)}}}$$


t (s)
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
D b.n.
H
N
10^0
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
Y_p
SBBN freeze-out
ν decoupling
n/p decoupling
e± annihilation
D/H
3He/H
T/H
7Be/H
7Li/H
6Li/H
10^3
10^2
10^1
10^0
T (keV)




sensible dependence on
- nuclear reaction rates (10%)
- N_eff → T(t) (3%)

concordance !

concordance ?

→ observed isotopic ratios are off-equilibrium freeze-out values

$$Y_i\,(\mathrm{t}) \neq Y_i^{eq}\,(T(t))$$

slow and cool

depends on history and $Y_j$ and cross sections

mystery: $Y_i = Y_i^{eq}\,(T)$

fast and hot

at LHC, RHIC, SPS, AGS, SIS18

survival of weakly bound nuclei
from 155 MeV → 100 MeV
„snowballs in hell“

[Oliinchychenko, Pang, Elfner, Koch, PRC(2019)]
[Vovchenko, Gallmeister, Schaffner-B, Greiner, 1903.10024]
[Sun, Ko, Donigus,PLB(2019)]
[Zhang, Ko, PLB(2019)]
[Xu, Rapp, EPJA(2019)]

[Cai, Cohen, Gelman, Yamauchi, 1905.02753]

# Example 2: p - pbar

momentum integrated Boltzmann eqs. for $Y_i = n_i / s$, $x = m_N / T$

$$\frac{dY_+}{dx} = -\frac{\Lambda_{(\xi)}}{x^\xi}\left(Y_+(Y_+ - \eta) - Y_{eq}^2\right)$$

$$\frac{dY_-}{dx} = -\frac{\Lambda_{(\xi)}}{x^\xi}\left(Y_-(Y_- + \eta) - Y_{eq}^2\right)$$

collision term vanishes for

$$Y_{eq} = \frac{45}{4\pi^4}\frac{2}{h_{eff}}x^2 K_2(x)$$

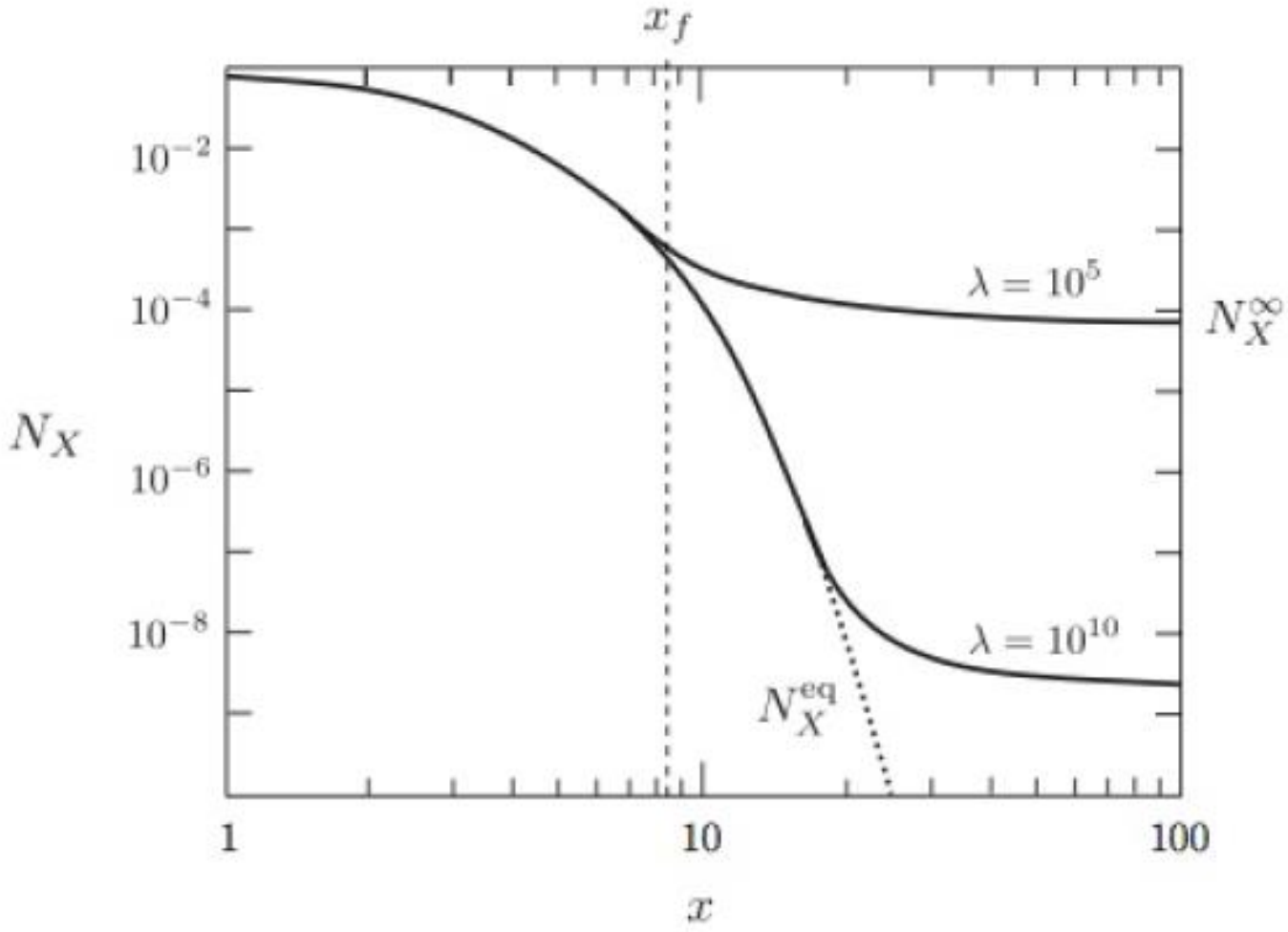
Big Bang: $\Lambda_{(2)} = \langle\sigma v\rangle\, g_*^{1/2}\, M_{Pl}\, m_N \sqrt{\frac{\pi}{45}}$ ~ $10^{21}$

Little Bang:

$$\Lambda_{(4)} = 3\langle\sigma v\rangle \bar{\tau} m_N^3 \frac{2\pi^2}{45} h_{eff}\left(1 + \tau\frac{\dot{h}_{eff}}{h_{eff}}\right)^{-1} \sim 10^4$$

$$\langle\sigma v\rangle = \frac{\int_{2x}^\infty d\xi \xi^2(\xi^2 - 4x^2)K_1(\xi)\sigma(p_{lab})}{4x^4 K_2^2(x)}$$

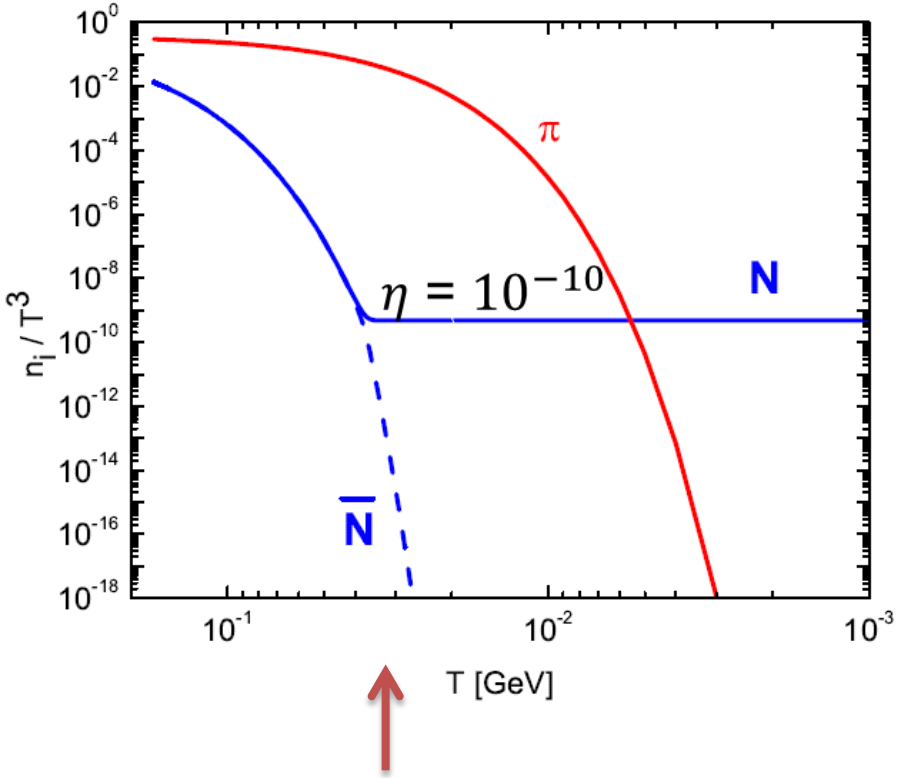
textbook freeze-out $$\frac{dN_X}{dx} = -\frac{\lambda}{x^2}\left[N_X^2 - (N_X^{eq})^2\right]$$

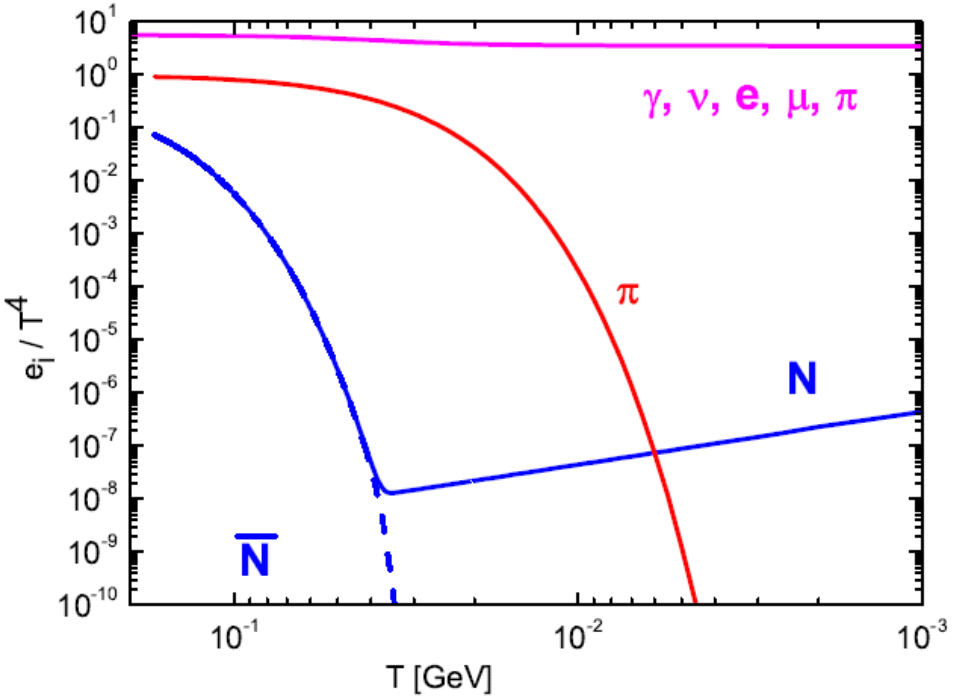


# Big Bang dynamics: large $\Lambda$ → late freeze-out

$$T > 1 \text{ MeV}, \; Y_{\pm} \approx Y_{\pm}^{eq}$$

no anti-matter is left

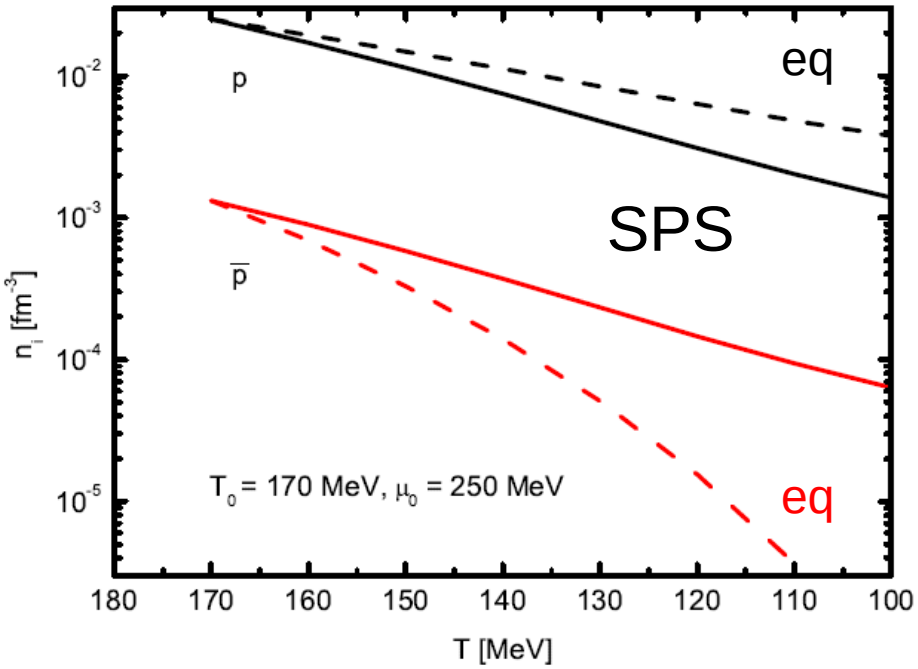


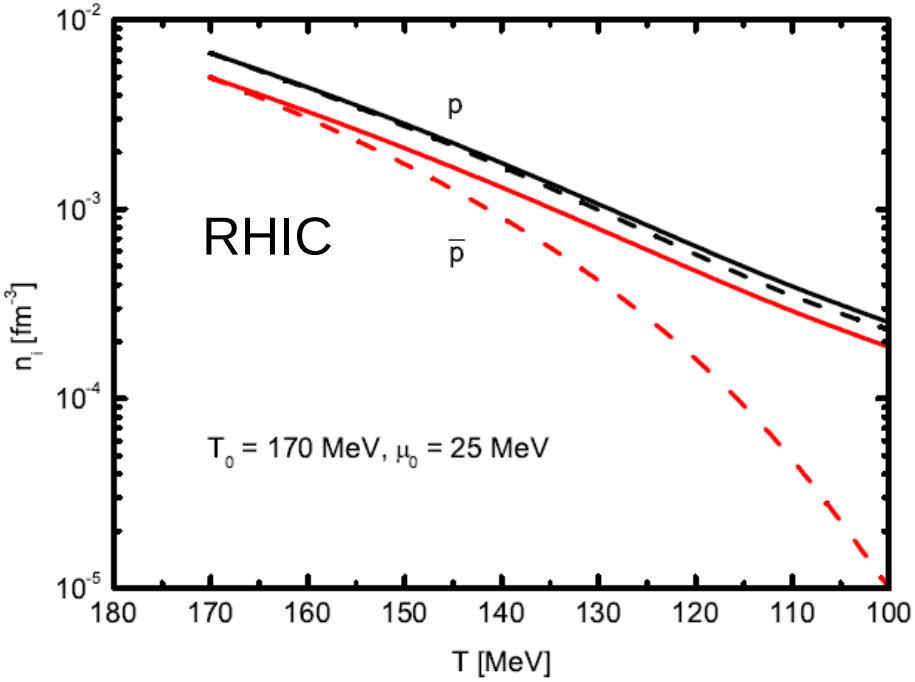




cosmic swing from small to large $\mu$

# Little Bang dynamics: smaller Λ

[Bleicher et al., PLB(2000)]
[Rapp, PRC(2002)]
[Huovinen, Kapusta, PRC(2004)]
[Pan, Pratt 1210.15779]
[Seifert, Cassing, PRC(2018)]




dashed: fiducial equilibrium values

rapid expansion (→ off-equilibrium) & regeneration
prevent strong pbar annihilation → no pbar puzzle

key: two-meson doorway model $p + \bar{p} \leftrightarrow X + \bar{X}$ [Weise, NPA(1993)]

# Example 3: Kaon freeze-out at SIS18

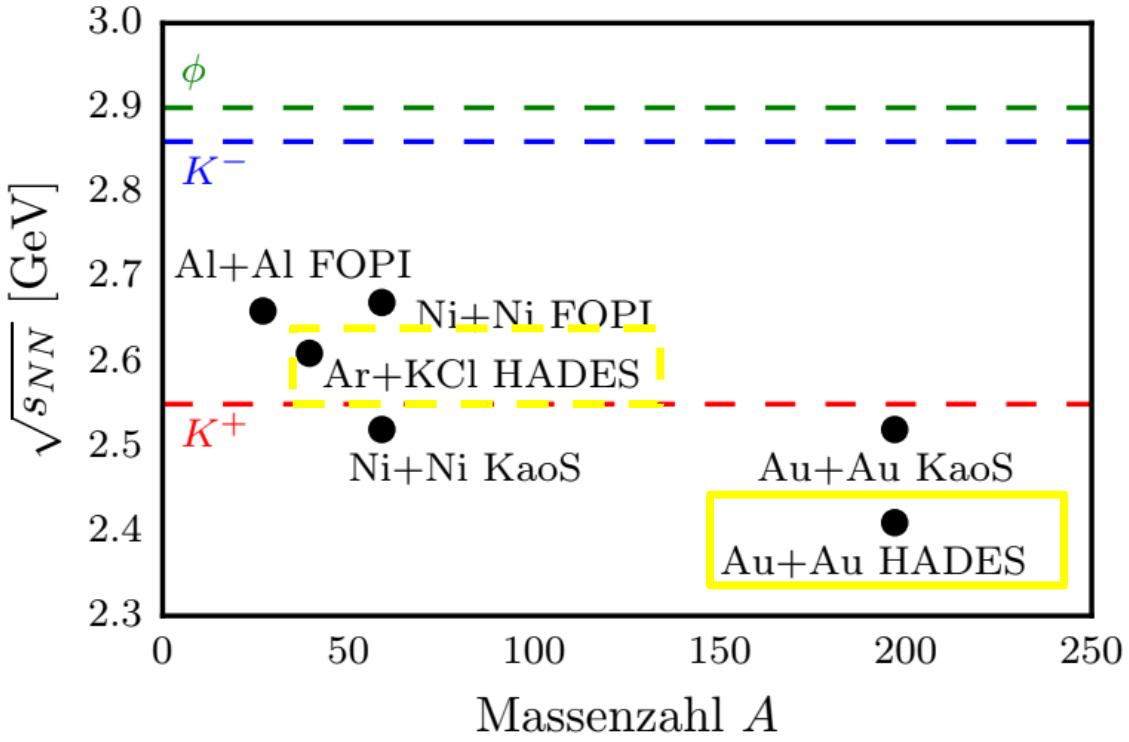
KaoS (2003): $T_{kin}$ (K-) < $T_{kin}$ (K+) due to later freeze-out of K-

HADES (2018): $T_{kin}$ (K-, direct) ~ $T_{kin}$ (K+) with strong feeding from
$\phi \rightarrow K + K- \rightarrow$ cools K- spectra
since $T_{kin}$ (K- from $\phi$) < $T_{kin}$ (K-, direct)

Kotte, BK (2002)

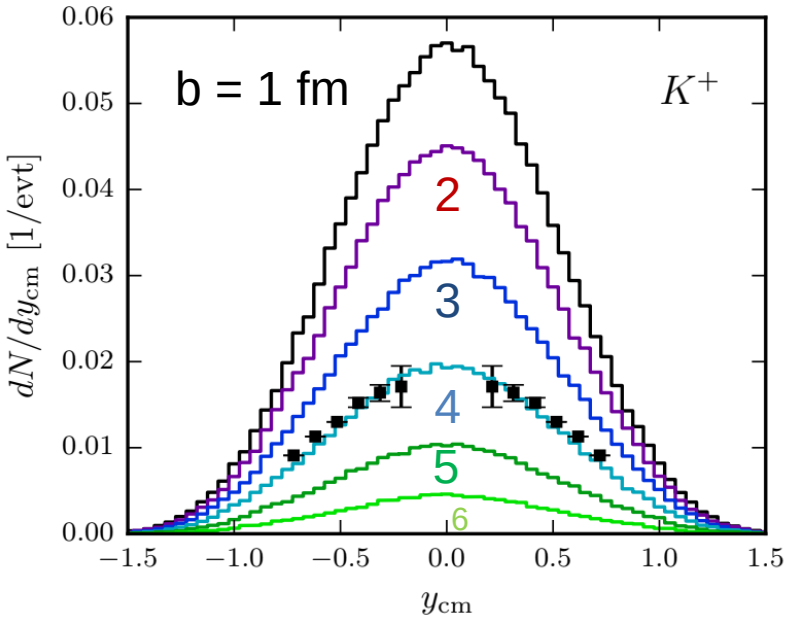
key: many $\phi$

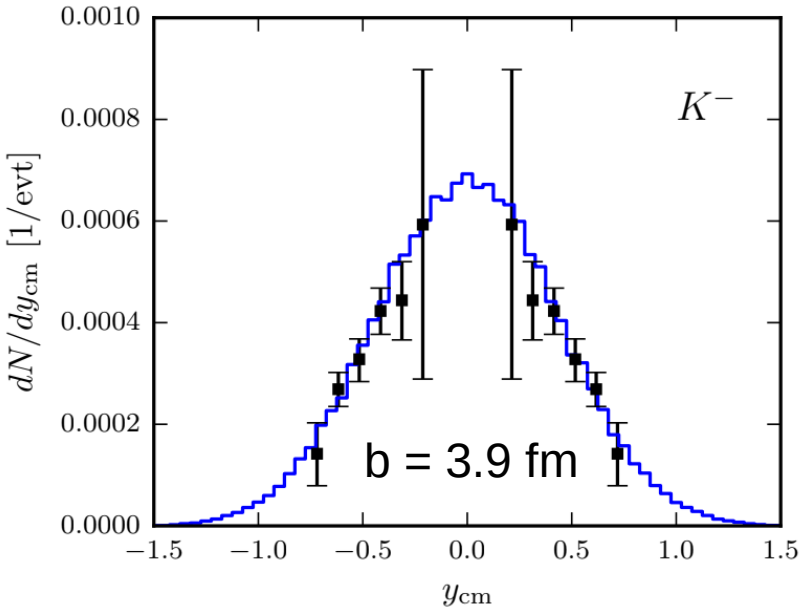
[BK, Kotte, Hartnack, Aichelin JPhys(2002)]

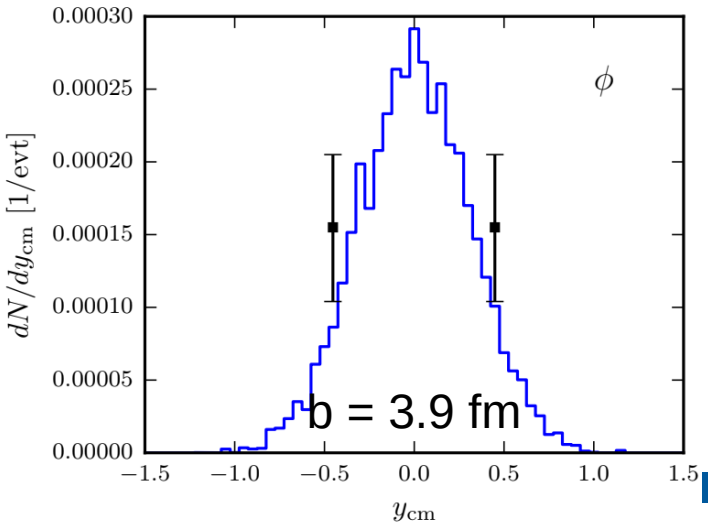


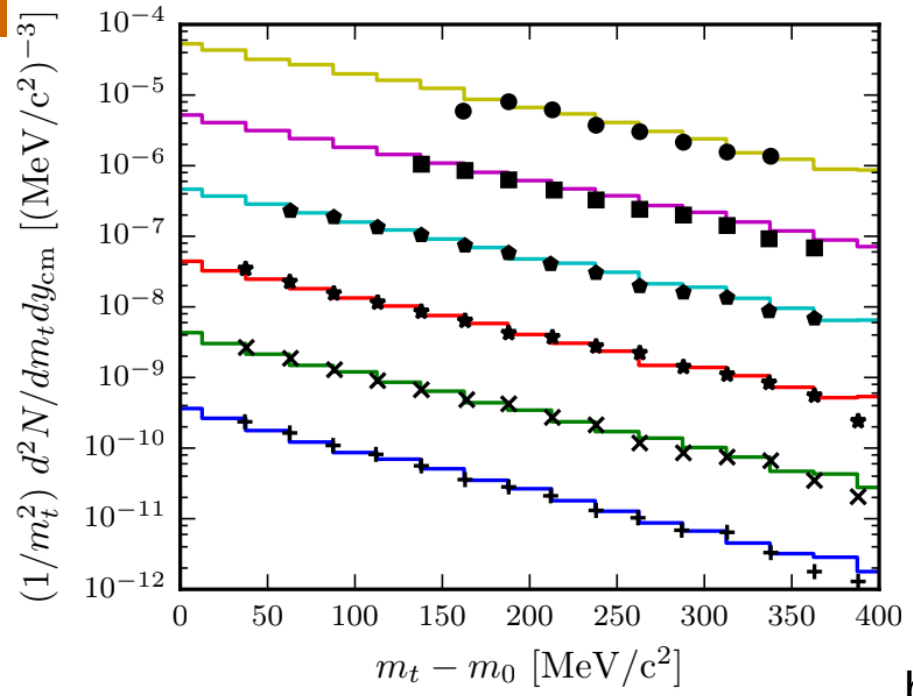
# benchmarking the BR BUU code: Ar(1.756 AGeV) + KCl

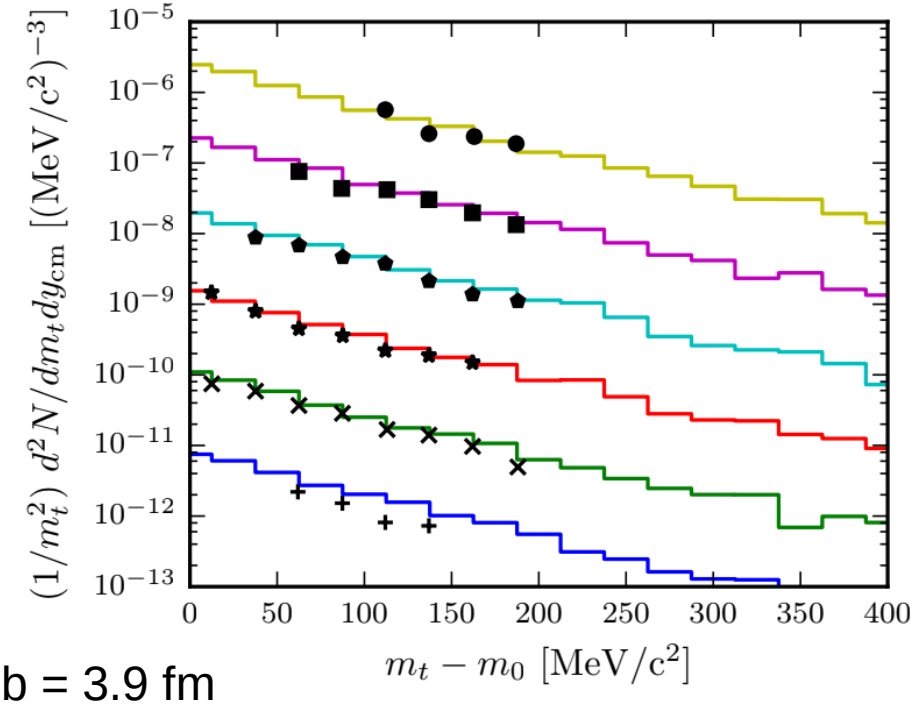
Schade, BK [PRC(2010)] HADES data [PRC(2009)]



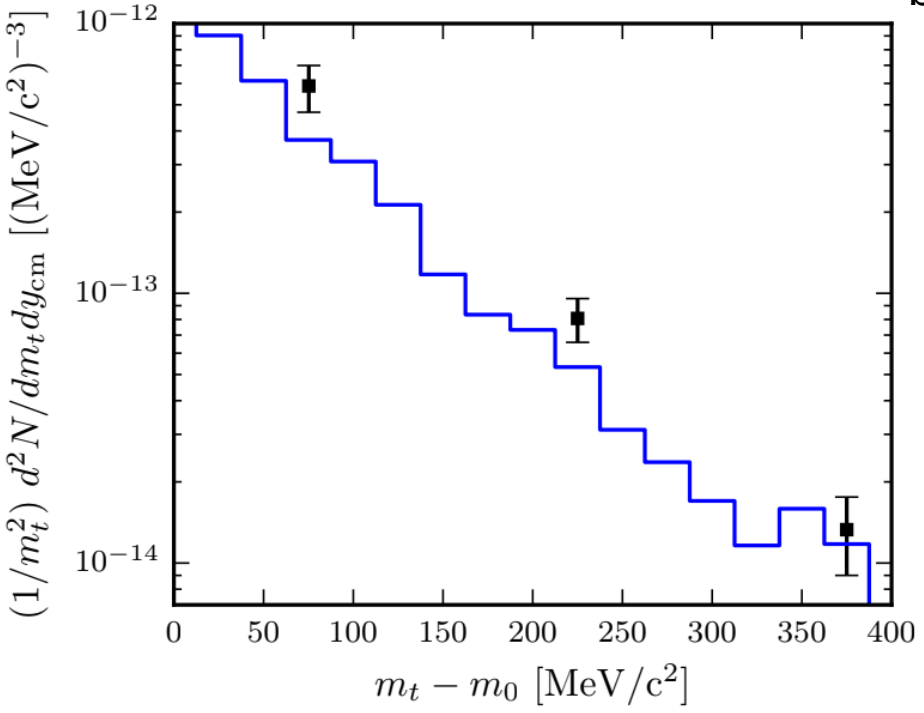



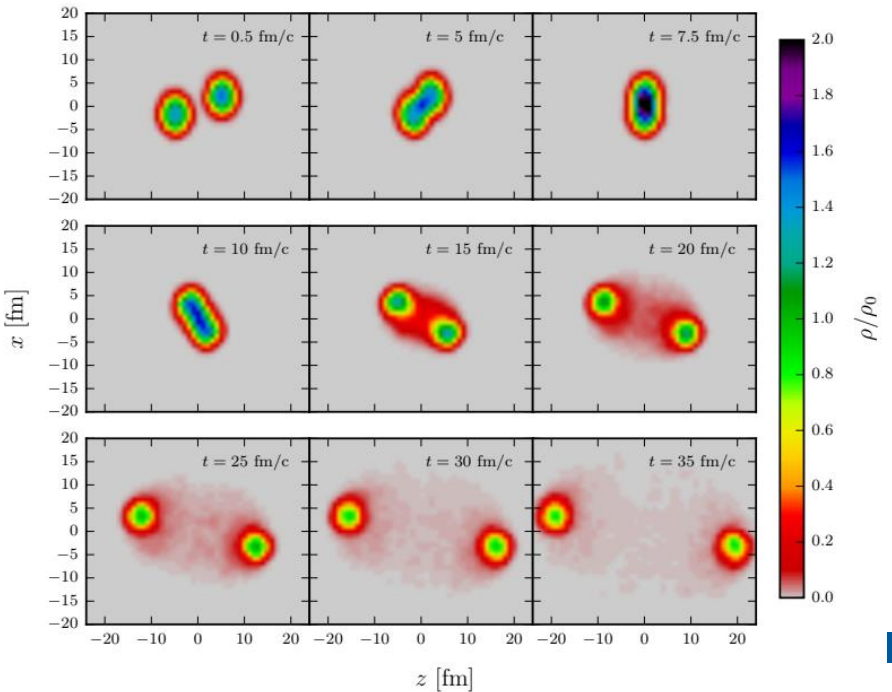




$(1/m_t^2)\ d^2N/dm_t dy_{cm}\ [(MeV/c^2)^{-3}]$
$m_t - m_0\ [MeV/c^2]$


$(1/m_t^2)\ d^2N/dm_t dy_{cm}\ [(MeV/c^2)^{-3}]$
$m_t - m_0\ [MeV/c^2]$

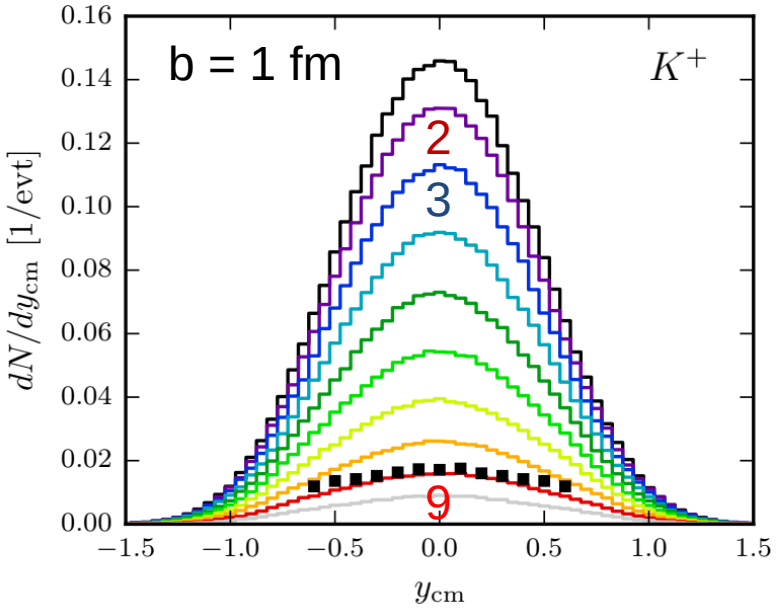
b = 3.9 fm

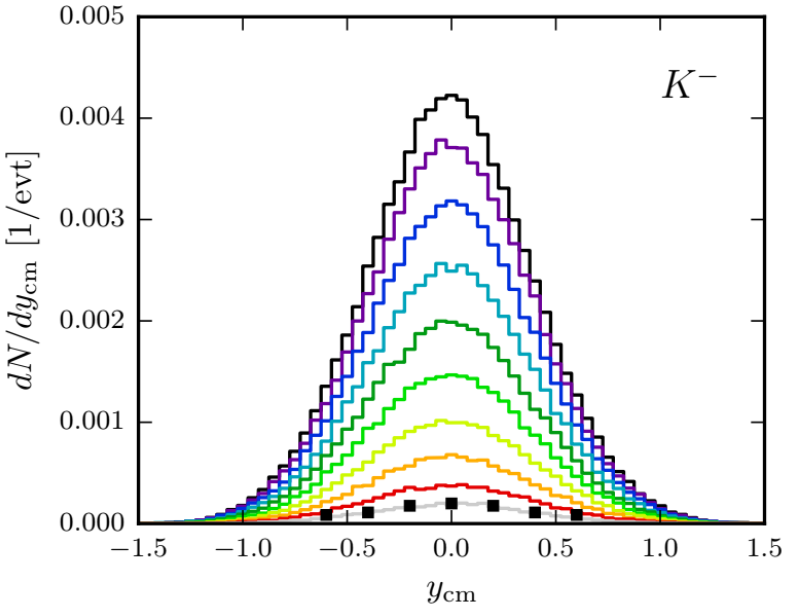

$(1/m_t^2)\ d^2N/dm_t dy_{cm}\ [(MeV/c^2)^{-3}]$
$m_t - m_0\ [MeV/c^2]$

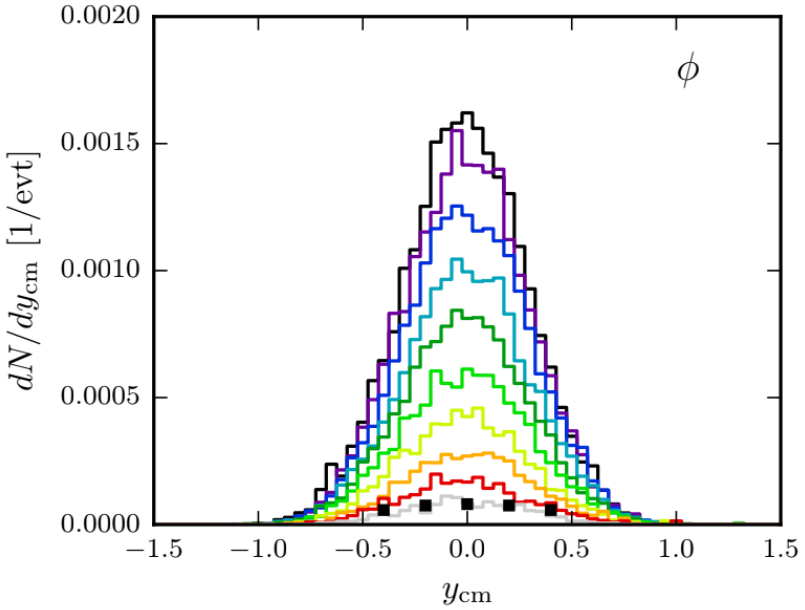

t = 0.5 fm/c
t = 5 fm/c
t = 7.5 fm/c
t = 10 fm/c
t = 15 fm/c
t = 20 fm/c
t = 25 fm/c
t = 30 fm/c
t = 35 fm/c
x [fm]
z [fm]
$\rho/\rho_0$

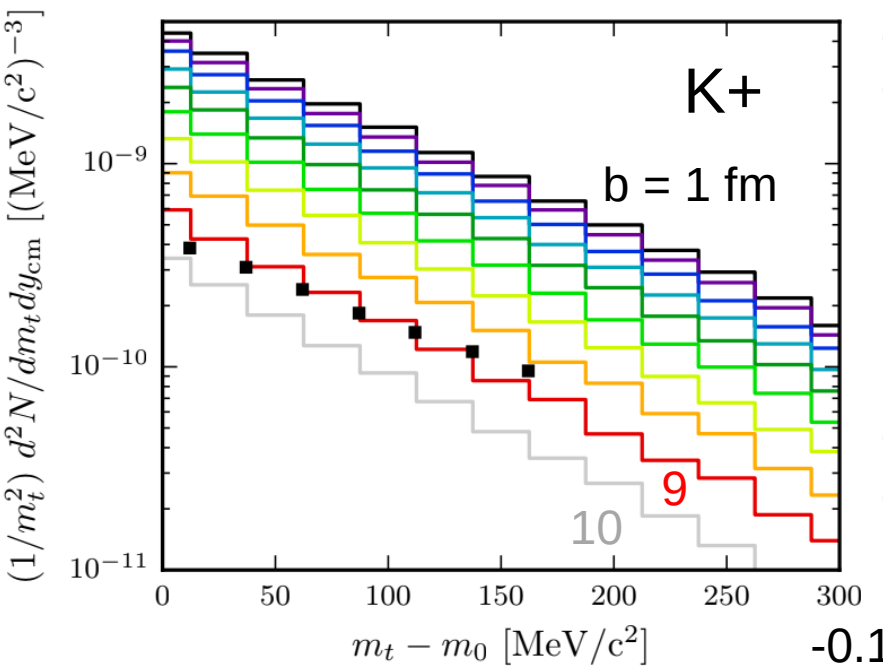
# applying the same code to Au(1.23 AGeV) + Au

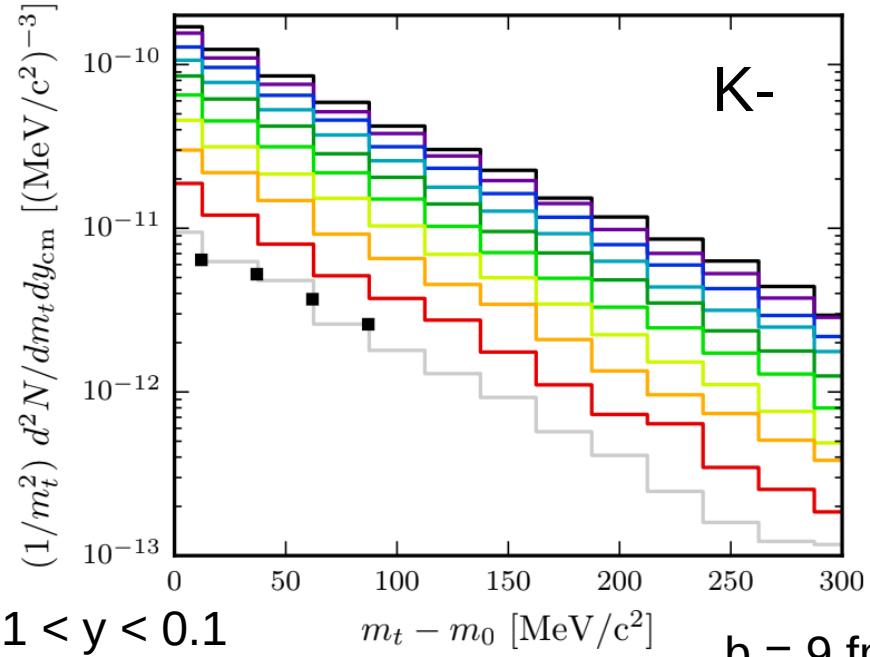
HADES data [PLB(2018)]



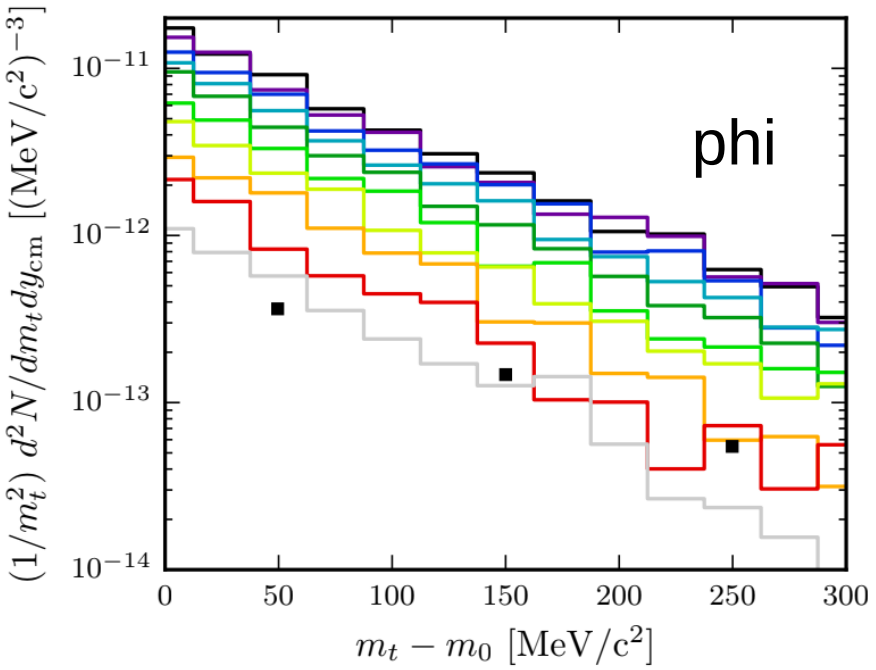



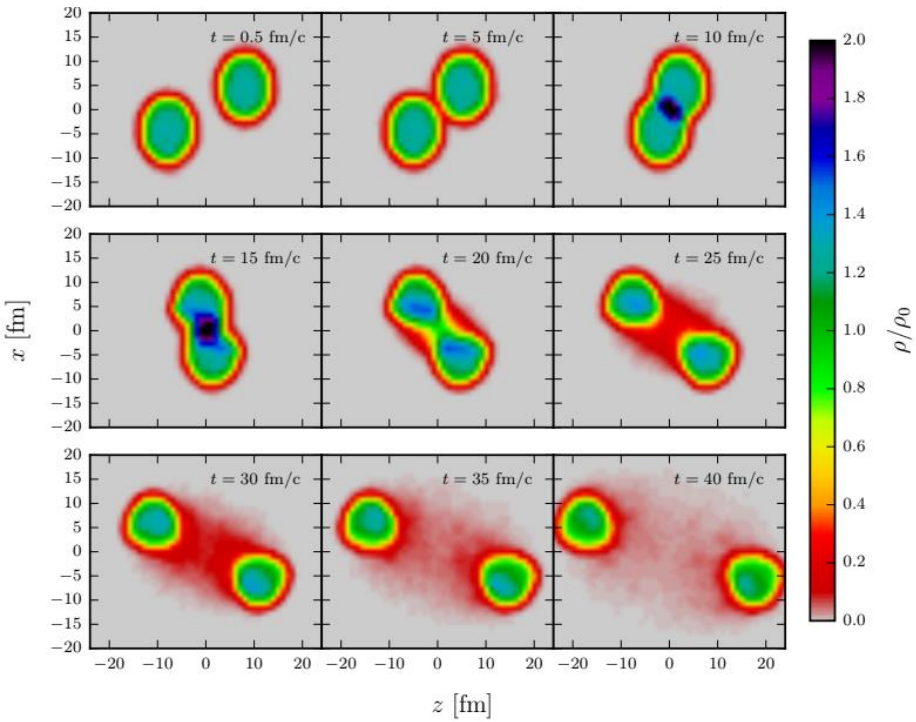

K+
b = 1 fm
9
10
$(1/m_t^2)\ d^2N/dm_t dy_{cm}\ [(MeV/c^2)^{-3}]$
$m_t - m_0\ [MeV/c^2]$


K-
$(1/m_t^2)\ d^2N/dm_t dy_{cm}\ [(MeV/c^2)^{-3}]$
$m_t - m_0\ [MeV/c^2]$

-0.1 < y < 0.1


phi
$(1/m_t^2)\ d^2N/dm_t dy_{cm}\ [(MeV/c^2)^{-3}]$
$m_t - m_0\ [MeV/c^2]$

b = 9 fm

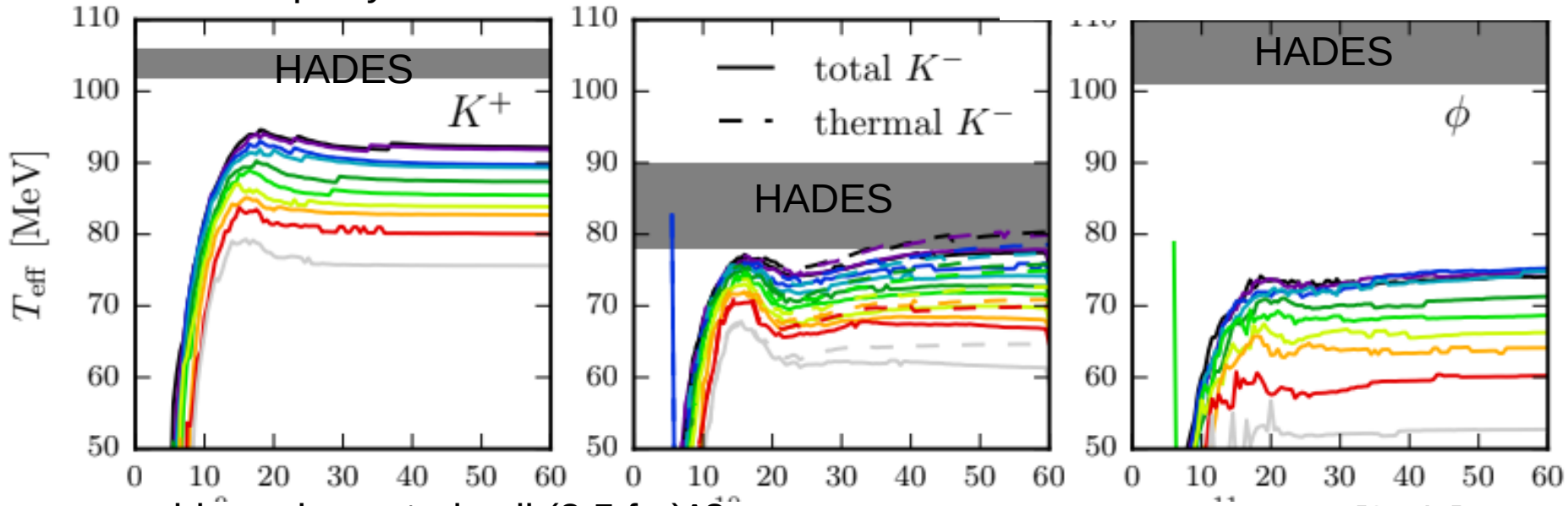

t = 0.5 fm/c
t = 5 fm/c
t = 10 fm/c
t = 15 fm/c
t = 20 fm/c
t = 25 fm/c
t = 30 fm/c
t = 35 fm/c
t = 40 fm/c
x [fm]
z [fm]
ρ/ρ0

# time evolution & freeze-out

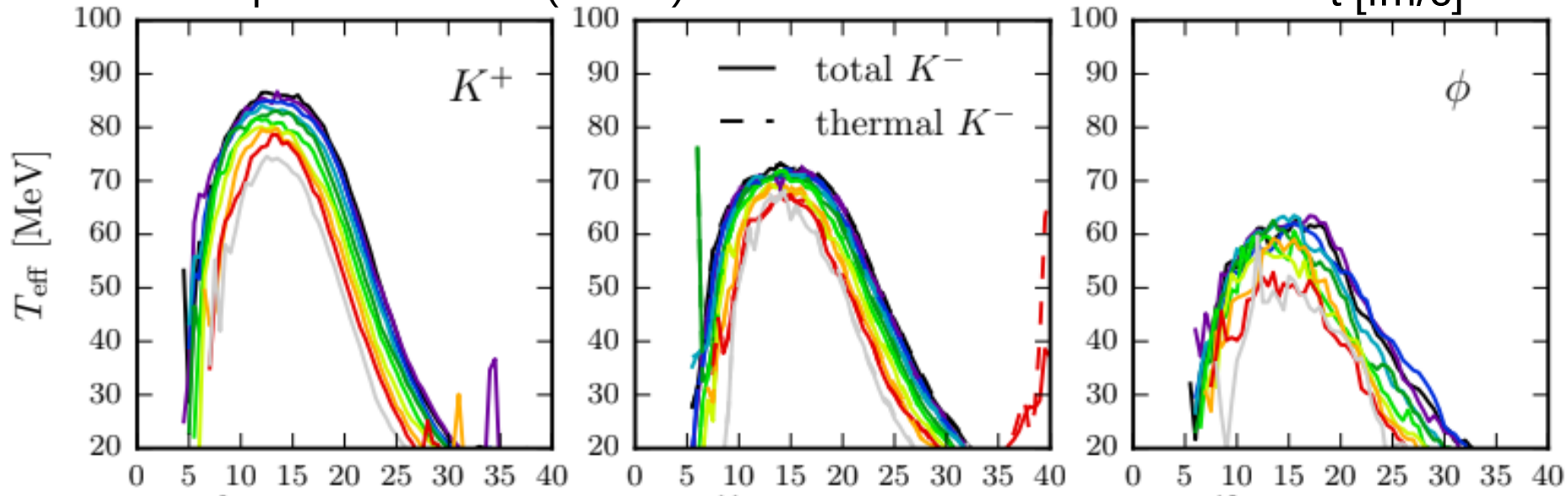
$$T_{eff} = T_B \cosh(y_{cm})$$

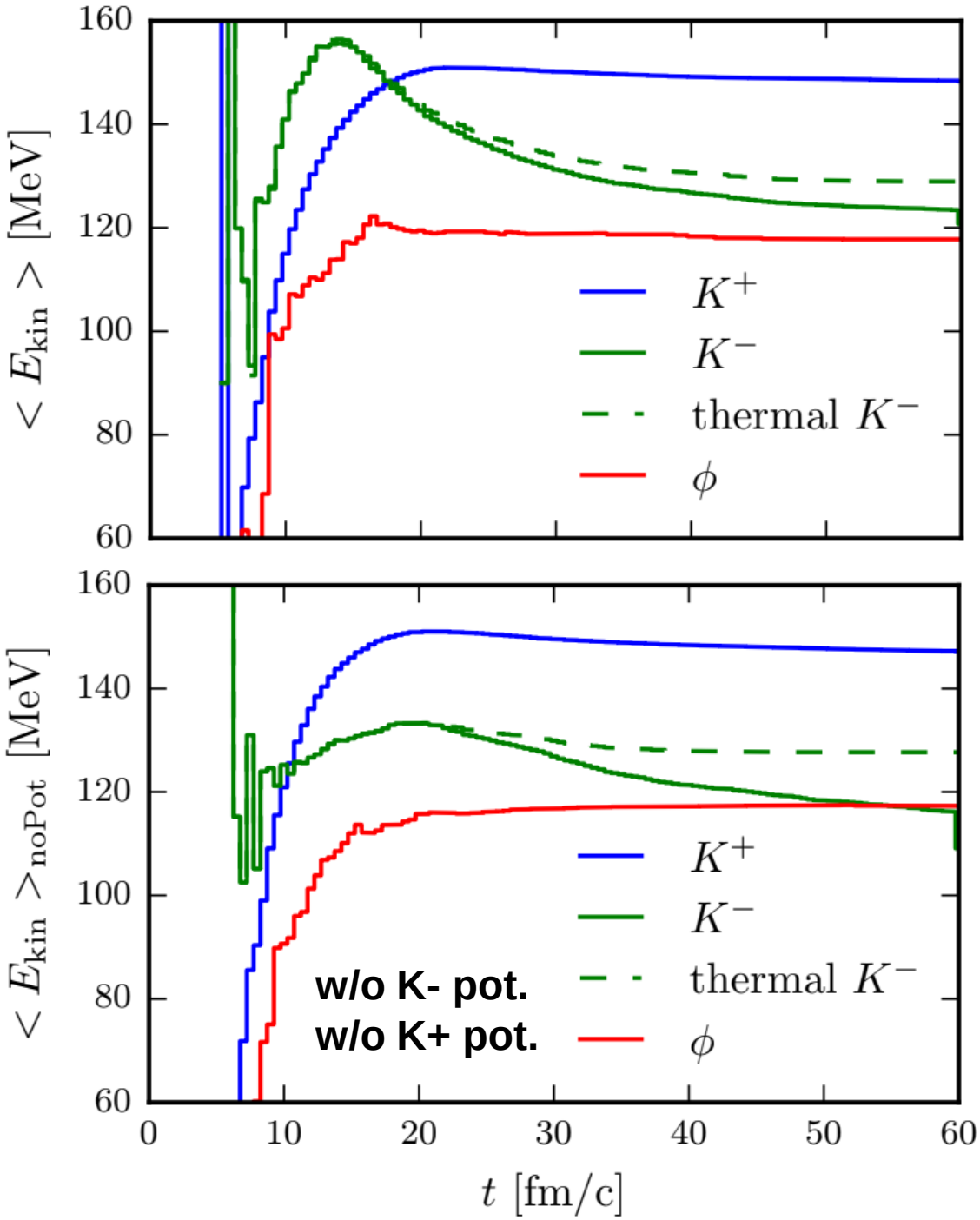
$$\frac{1}{m_t^2}\frac{d^2N}{dm_t dy_{cm}} = C(y_{cm}) \exp\left(-\frac{(m_t - m_0)}{T_B(y_{cm})}\right)$$

all midrapidity hadrons




mid.rap. in central cell (2.5 fm)^3






using Ekin instead of T
(b = 9 fm)

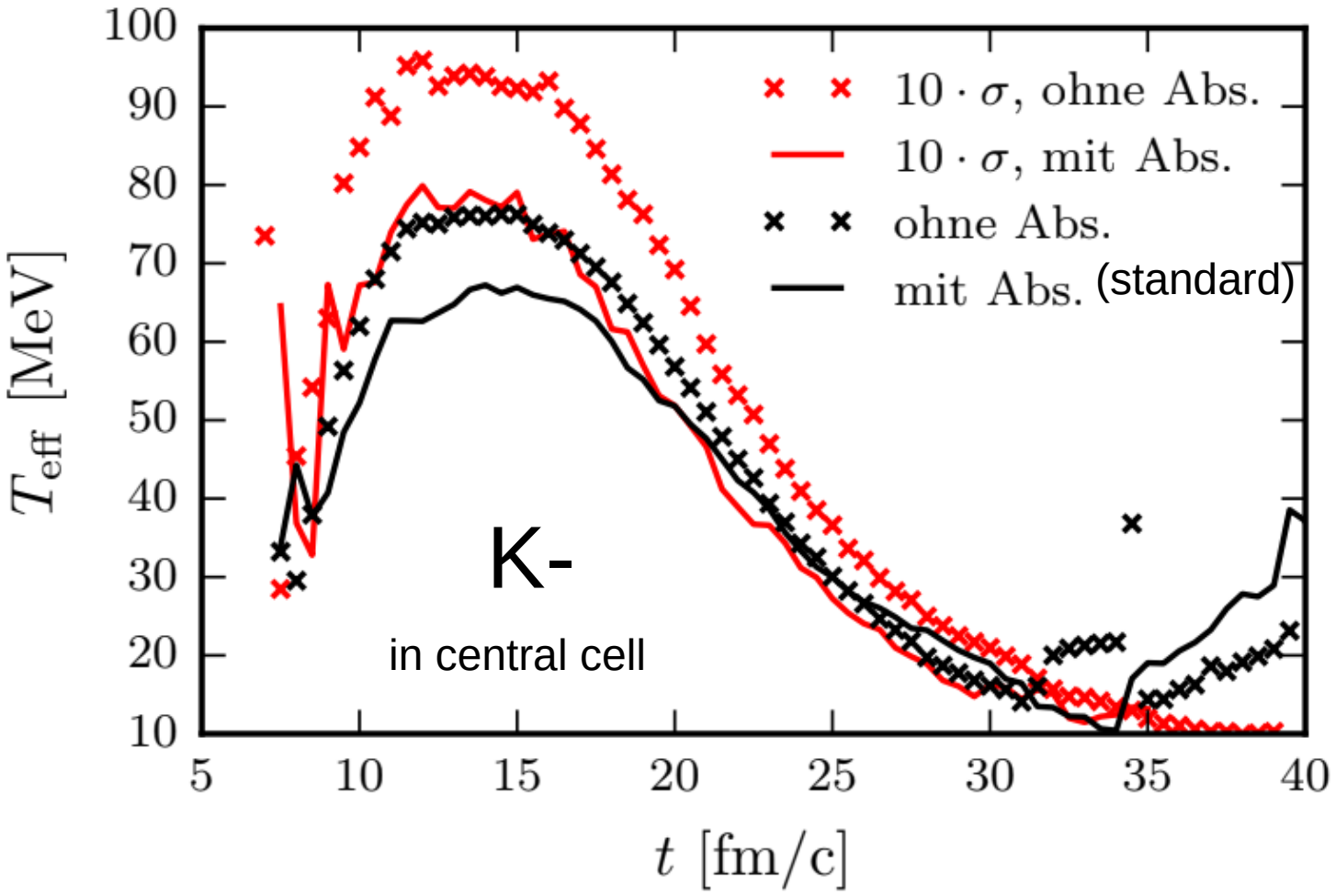
Ekin = E – m*

K- potential matters

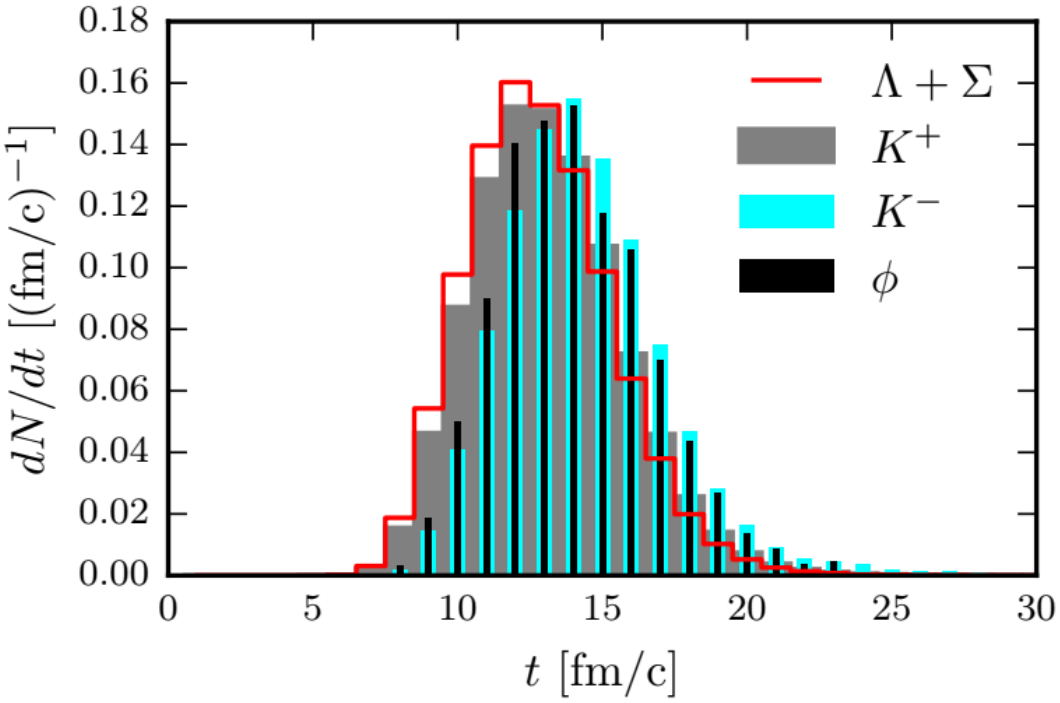
⬅ w/ phi contribution

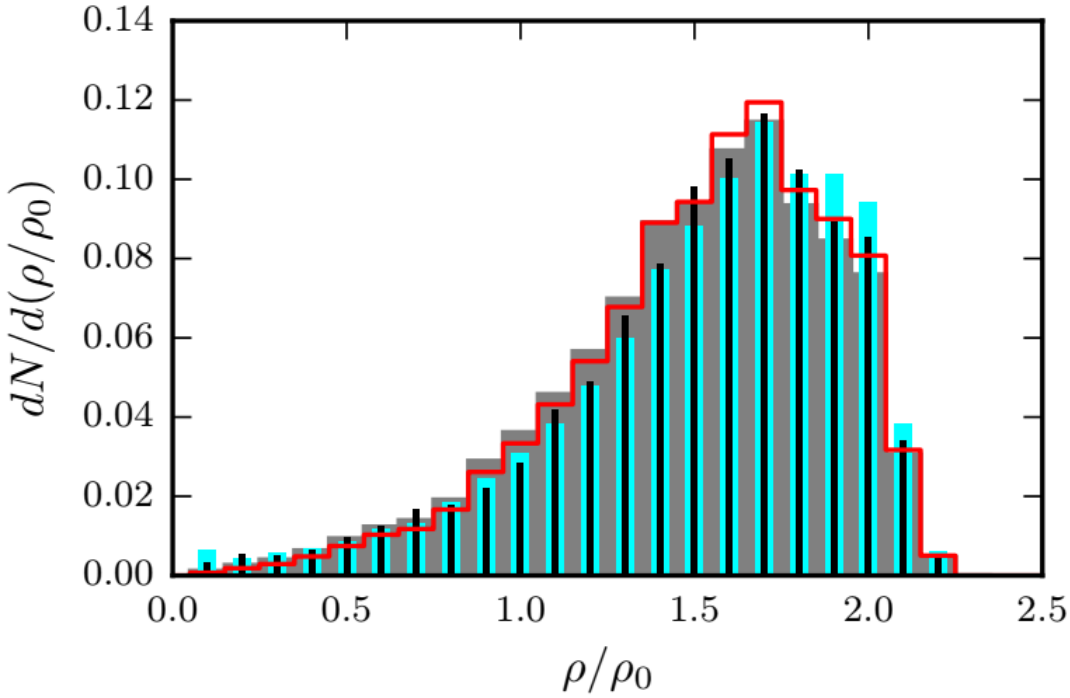
# impact of cross sections

b = 9 fm



# hadron production (normalized rates)

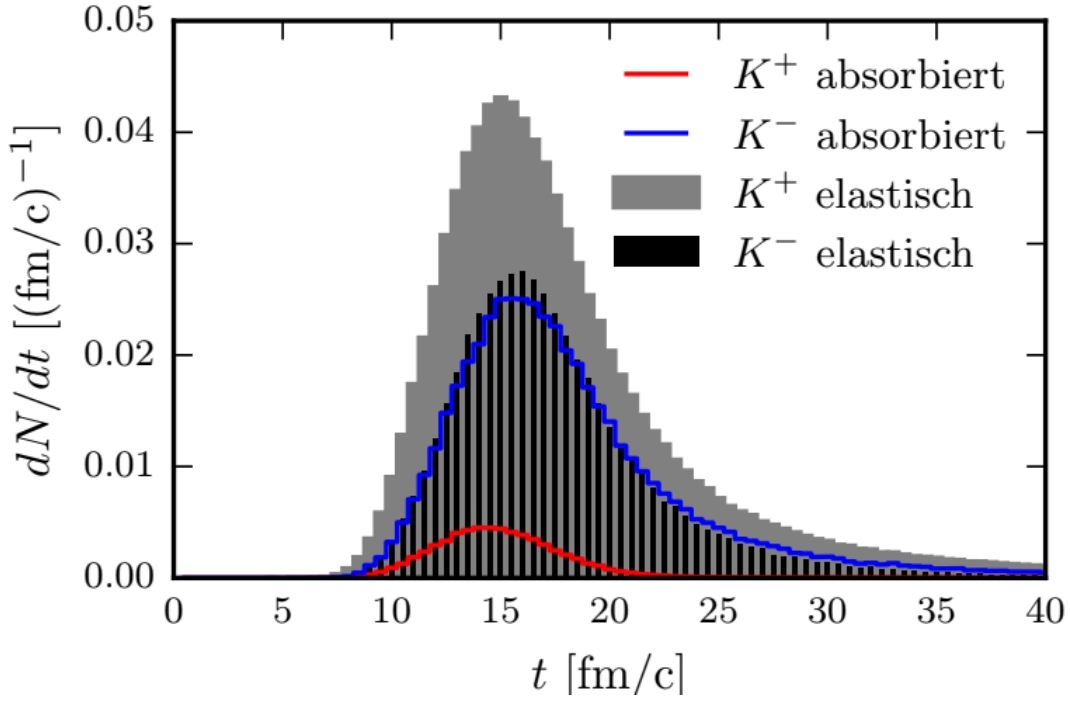


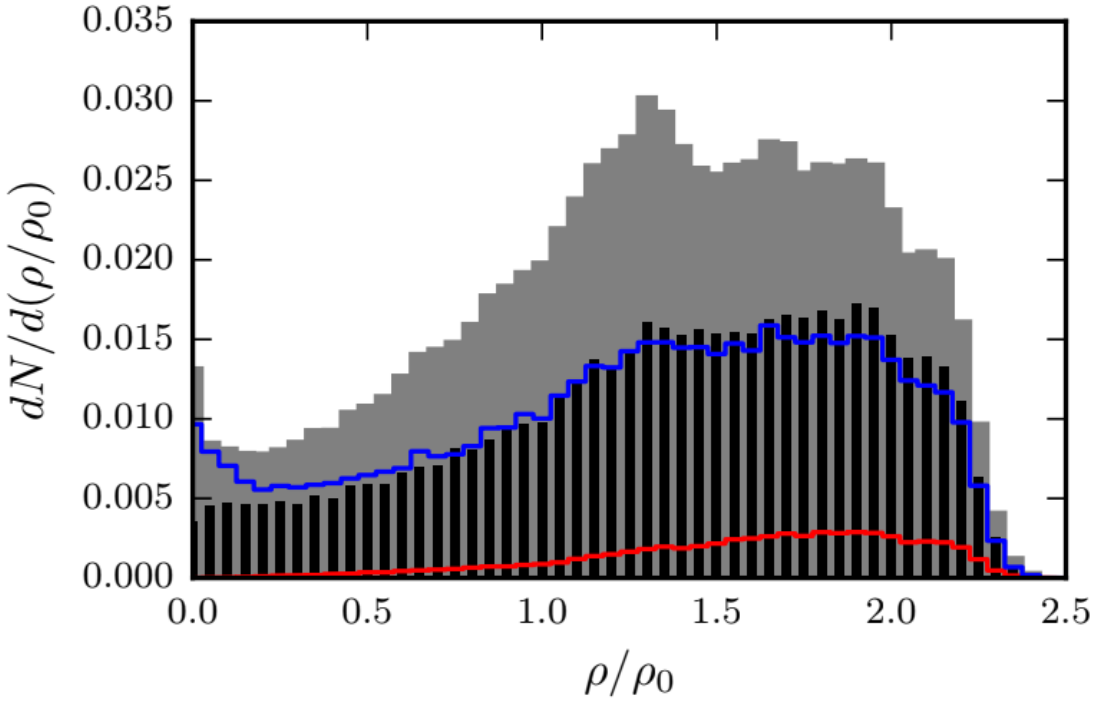



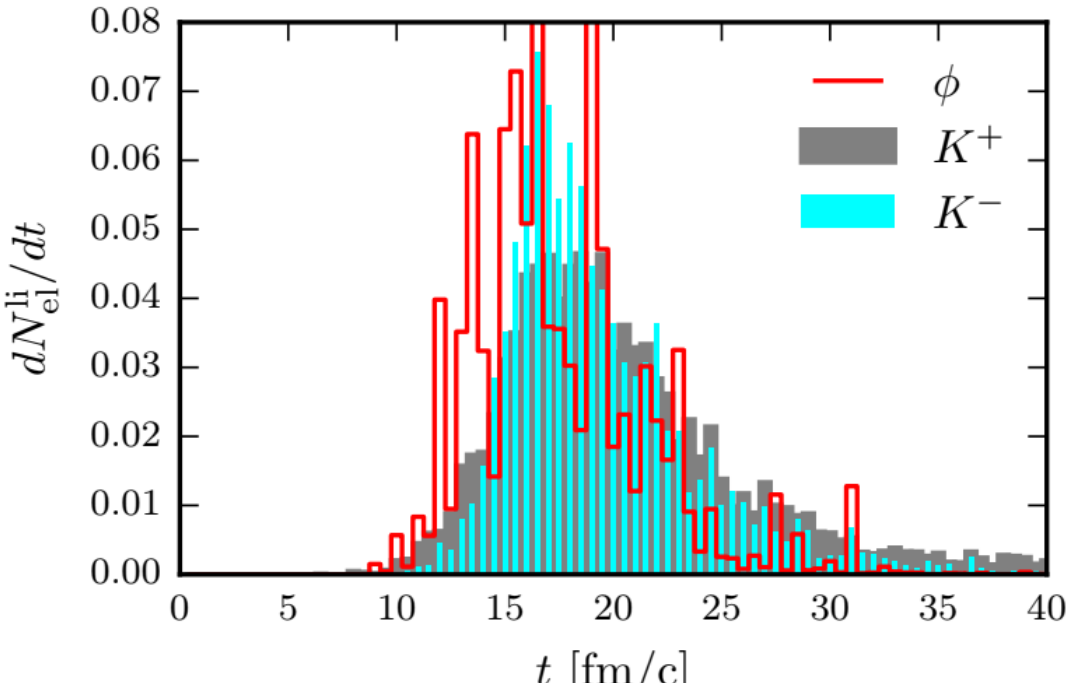

analog to Hartnack, Oeschler, Leifels, Bratkovskaya, Aichelin [PR(2012)]

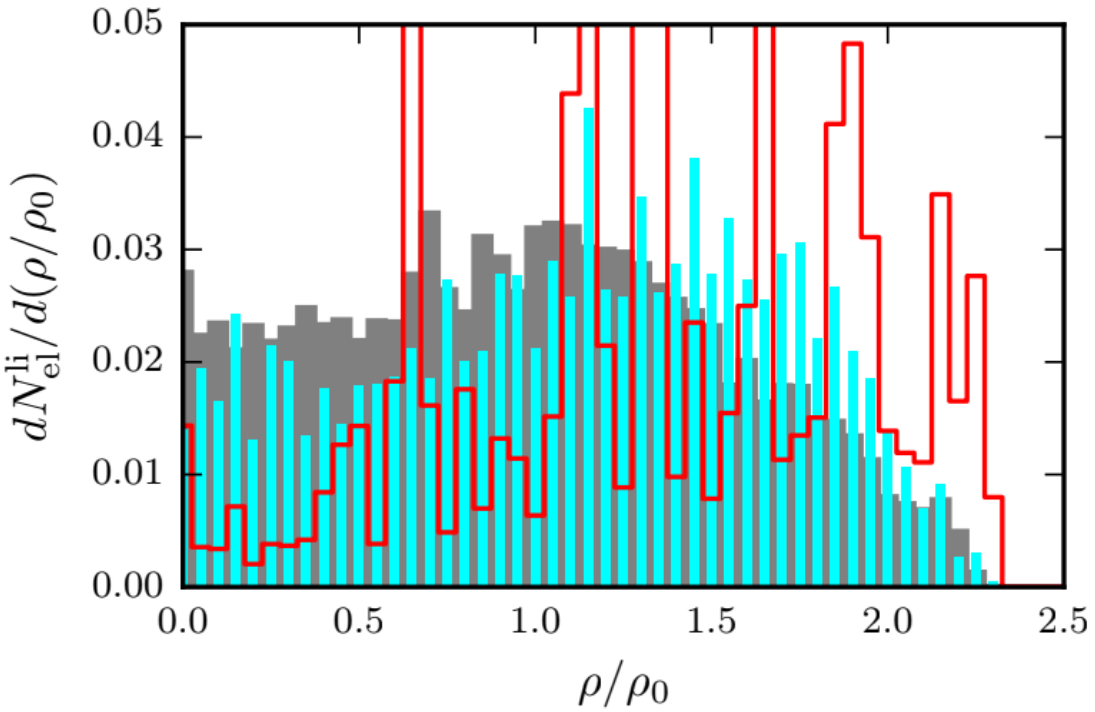
delayed K- production

# collision rate K-N (normalized)





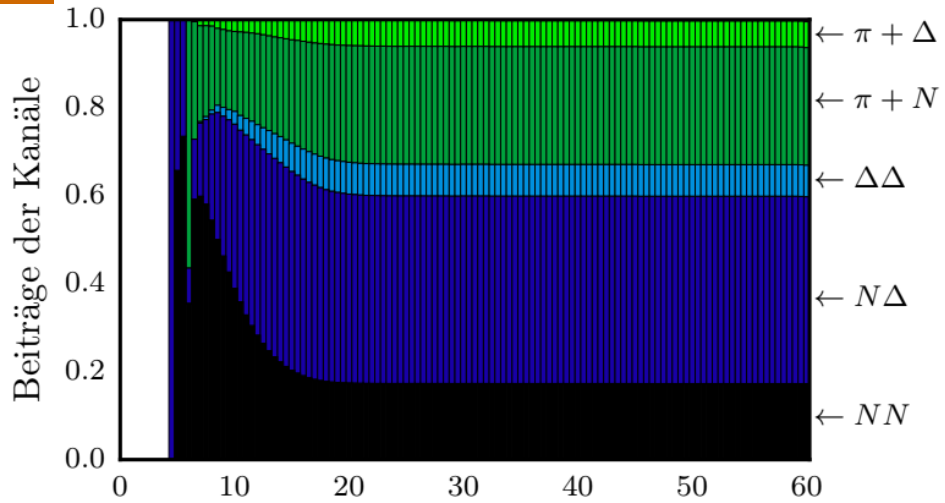




normalized
last elastic interaction
= freeze-out ?

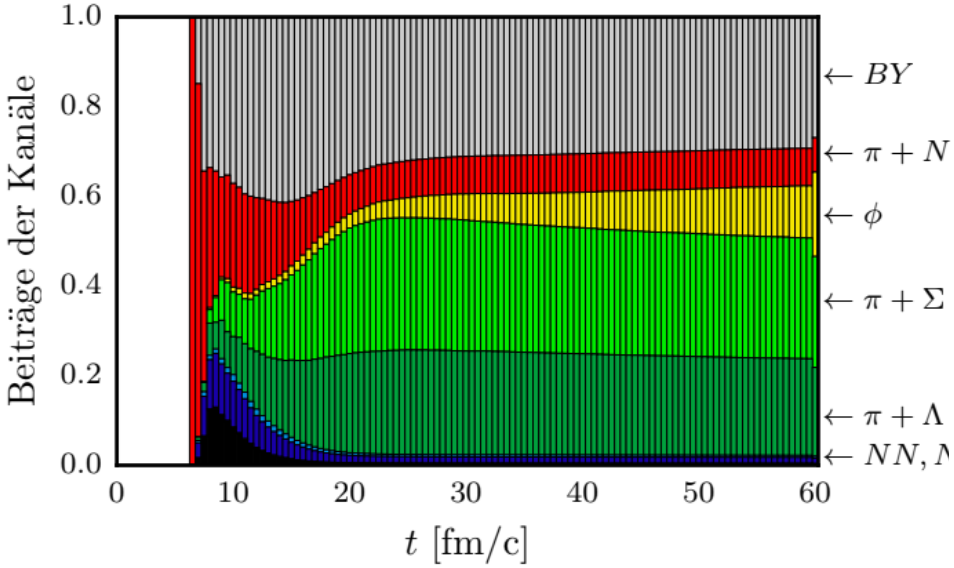
no delayed K- freeze-out

# channel distributions

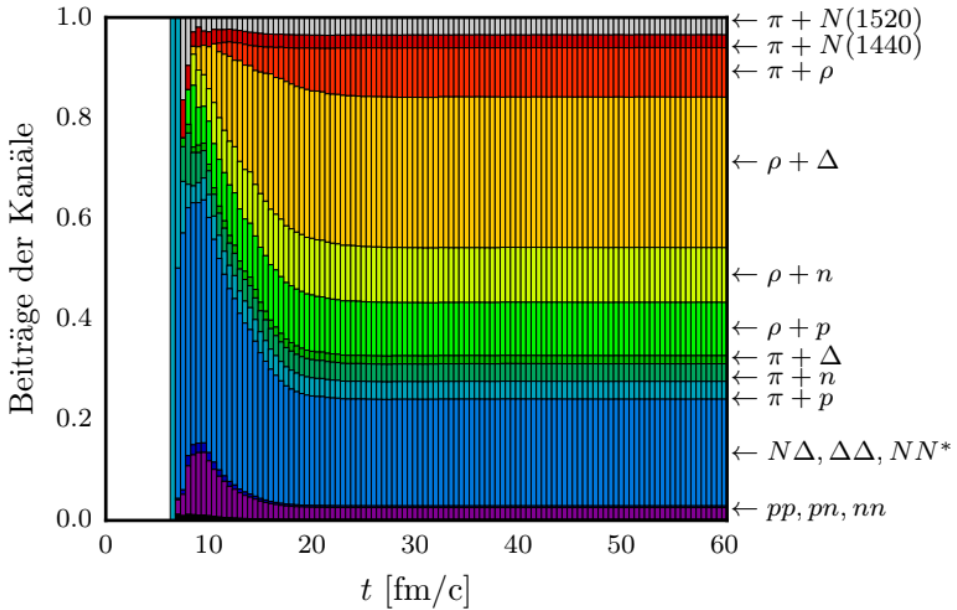
K+




K-




phi

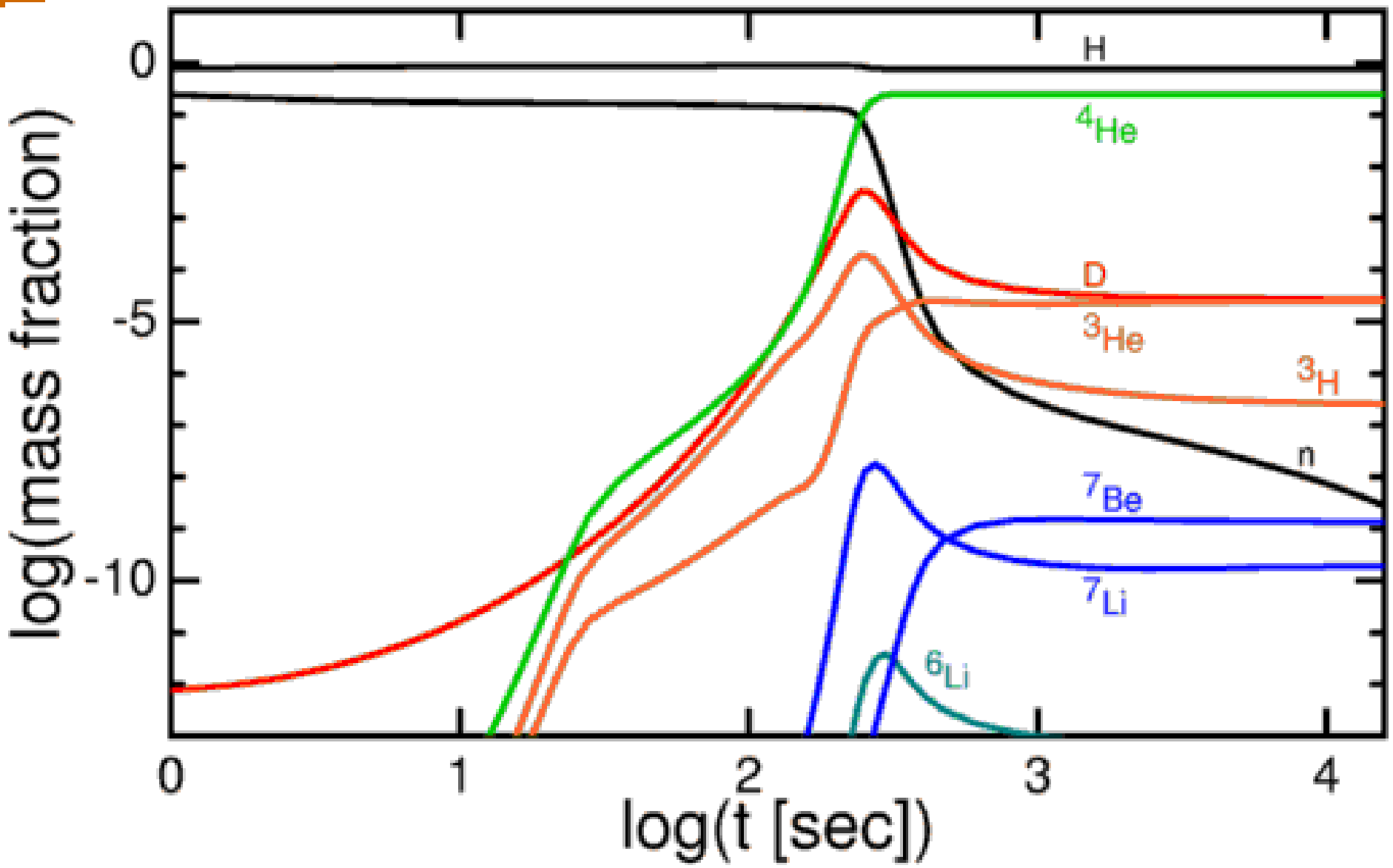


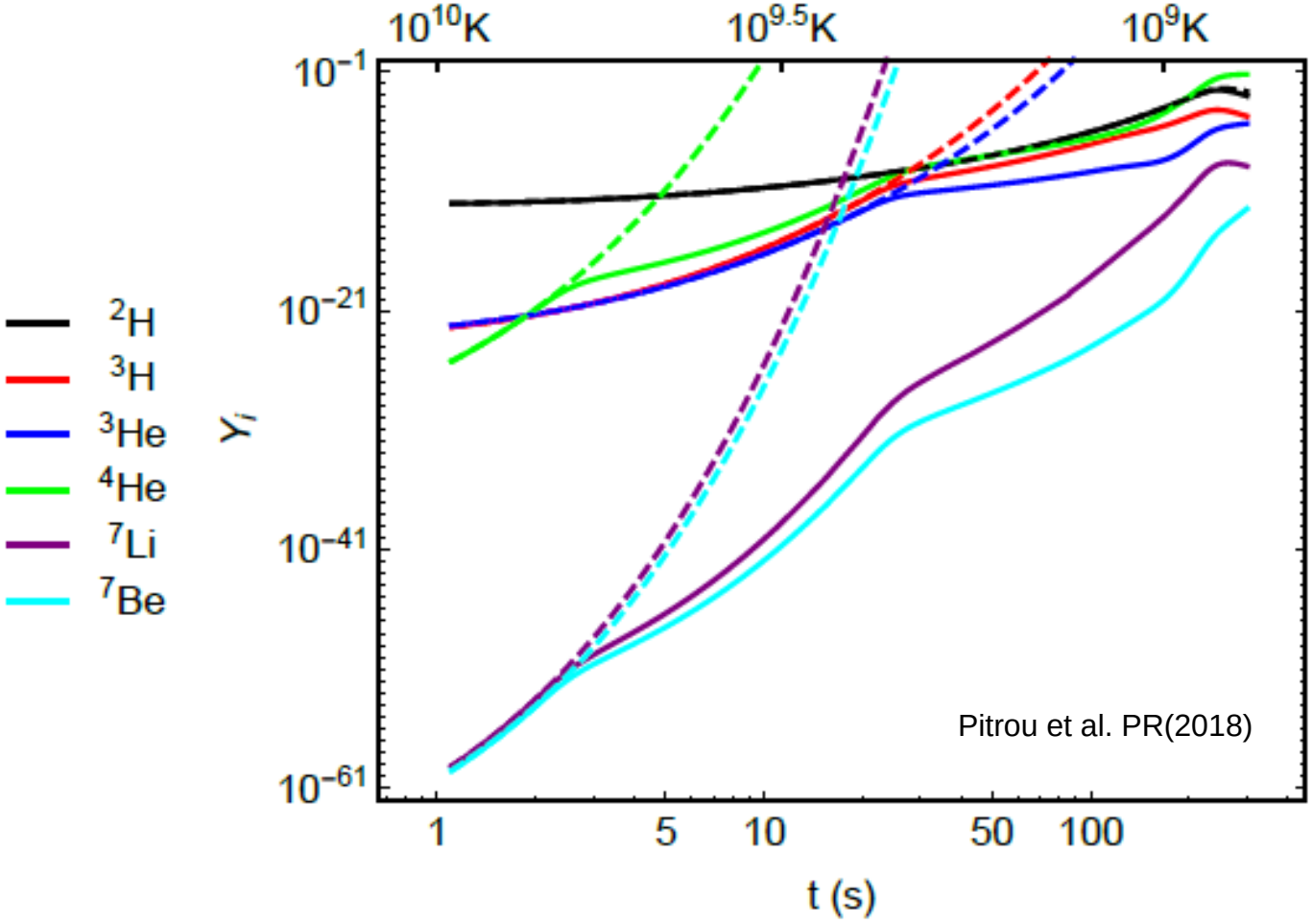
# Summary

1. BBN: isotope abundances depend on cross sections
   → dynamical freeze-out

2. pbar annihilation: n = n_eq in Big Bang
   difference of n and n_eq in Little Bangs

3. No temporal change of midrapidity pT distributions after 20 fm/c in Little Bangs → dynamical freeze-out
   → no sequential freeze-out of K+ and K-
   seen in this observable
   (K- are intrinsically cooler)


0
-5
-10
log(mass fraction)
H
4He
D
3He
3H
n
7Be
7Li
6Li
0
1
2
3
4
log(t [sec])




rates (solid) vs. NSE/Saha (dashed)

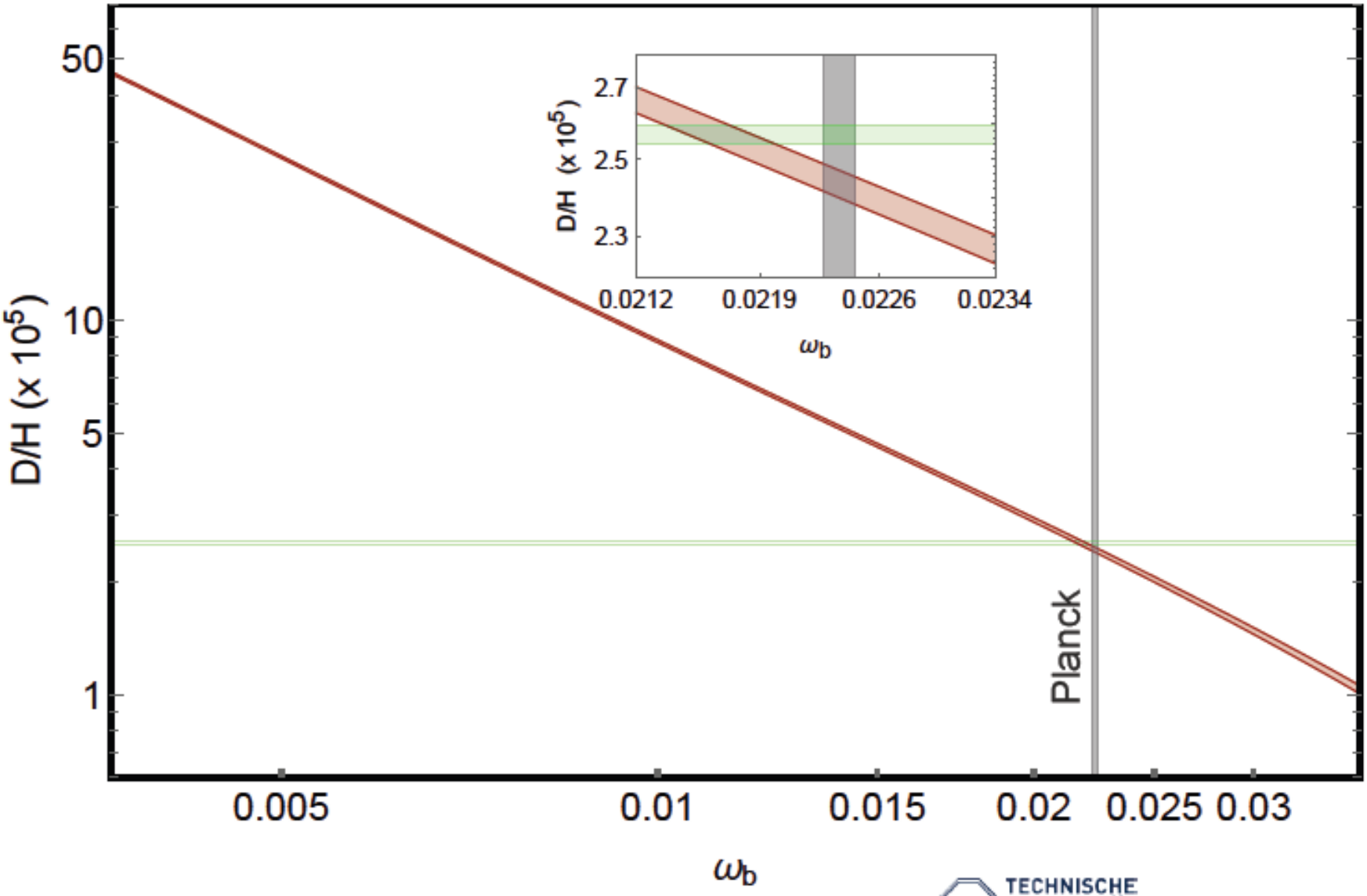
FIG. 31 Evolution of the first elements abundances in solid lines, together with the nuclear statistical equilibrium values in dashed lines. The deuterium abundance stays very close to its NSE value until the time it is more efficiently destroyed than formed around $t \simeq 200\,\mathrm{s}$.

- Abundance evolution:

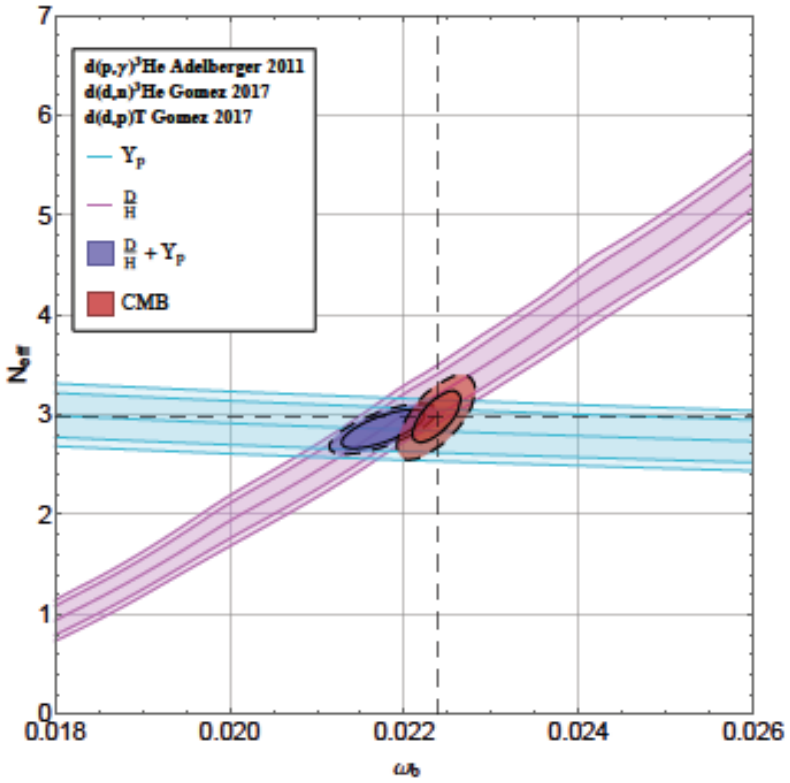
$$\frac{dY_i}{dt} = \sum_{jkl} N_i \left( \Gamma_{kl\to ij} \frac{Y_l^{N_l} Y_k^{N_k}}{N_l! N_k!} - \Gamma_{ij\to kl} \frac{Y_i^{N_i} Y_j^{N_j}}{N_i! N_j!} \right)$$

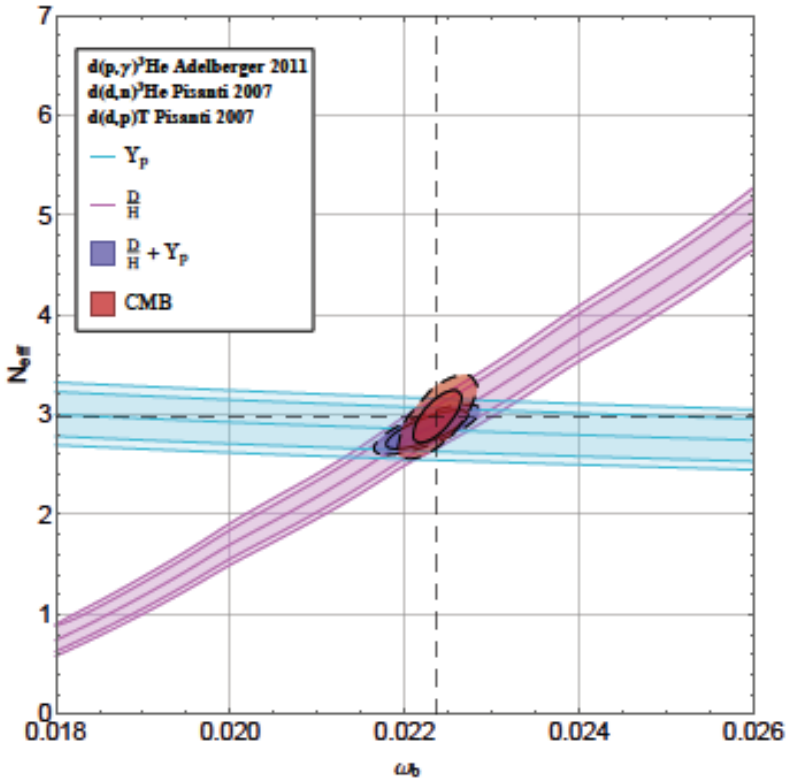
- abundances: $Y_i = \frac{n_i}{n_\mathrm{b}}$
- reaction rates: $\Gamma_{ij} \propto \langle \sigma v \rangle = \sqrt{\frac{8}{T^3 \pi \mu_{ij}}} \int_0^\infty dE\, E \underbrace{\sigma(E)}_{\text{Felsenkeller}} e^{-\frac{E}{T}}$

# Concordance Plot: D/H



# Two Parameter Variations: $N_{eff}(\omega_b)$




- dpg: Adelberger 2011
- ddn: Gomez 2017 / Pisanti 2007
- ddp: Gomez 2017 / Pisanti 2007