Asymmetry Dependence of the Nuclear Caloric Curve

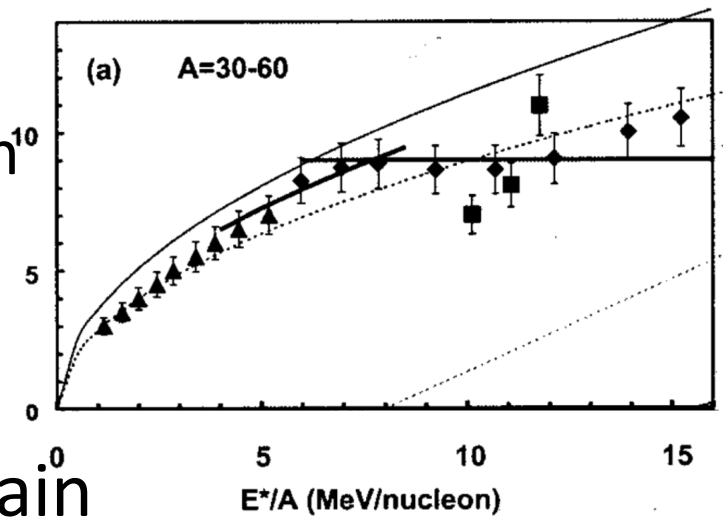
- Nuclear Caloric Curve: Background & Motivation
- The Measurement: Reconstructing Highly Excited Nuclei & Extracting Their Temperatures
- Result: Temperature Decreases Linearly with Increasing Asymmetry
- Summary

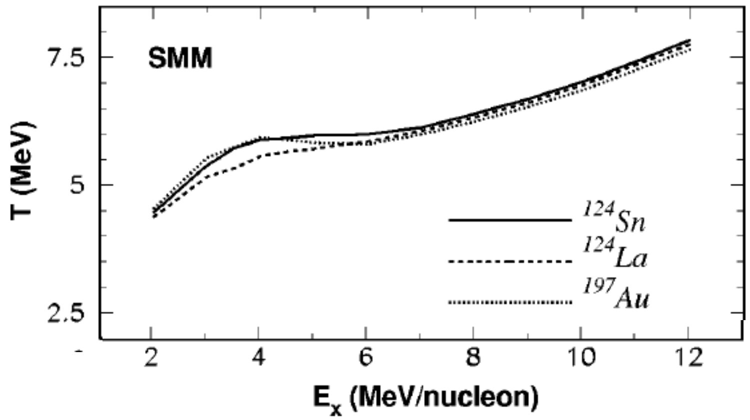
A.B. McIntosh, A. Bonasera, Z. Kohley, S. Galanopoulos, K. Hagel, L.W. May, P. Marini, D.V. Shetty, W.B. Smith, S.N. Soisson, G.A. Souliotis, B.C. Stein, R. Tripathi, S. Wuenschel, S.J. Yennello

Department of Energy & Robert A Welch Foundation

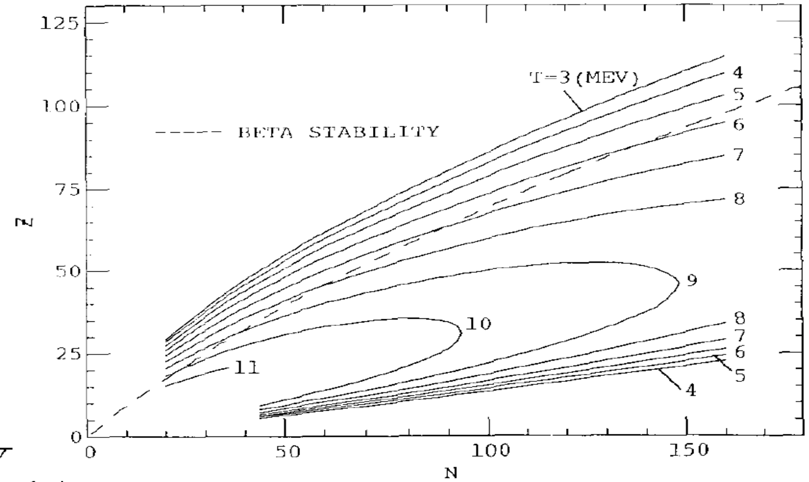
The Nuclear Caloric Curve

- Essential Piece of Nuclear Equation of State: T vs E*/A
- Search for & Study of "Phase" Transition
  - Evaporation to Multifragmentation
- Mass Dependence
  - Natowitz et al., Phys.Rev.Lett. **64**, 034618 (2002)
- Asymmetry Dependence Uncertain
  - Conflicting Theoretical Predictions
  - Very Limited Experimental Data

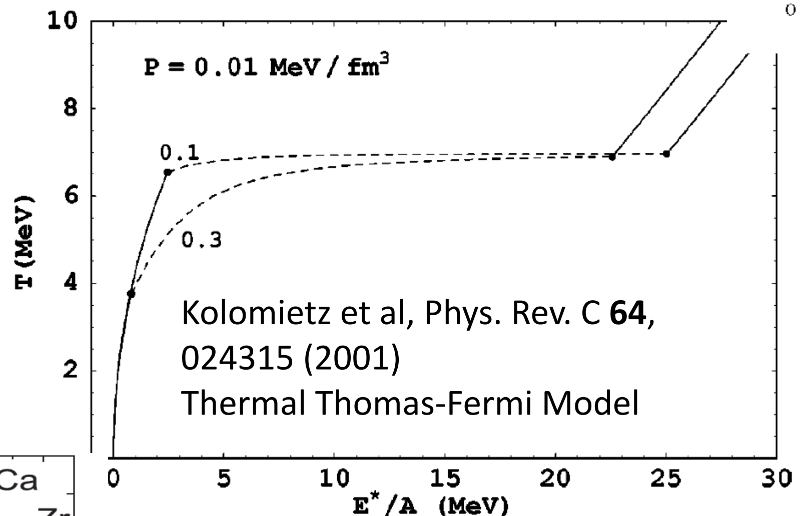




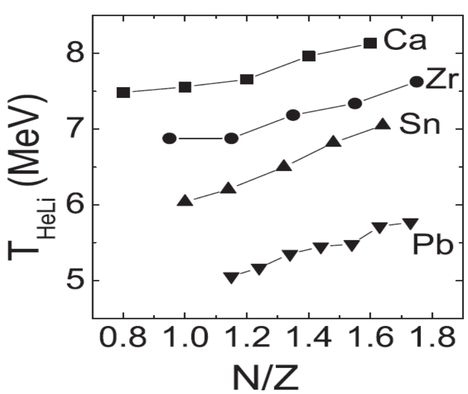
Ogul & Botvina, Phys. Rev. C **66**, 051601 (2002)
Statistical Multifragmentation Model



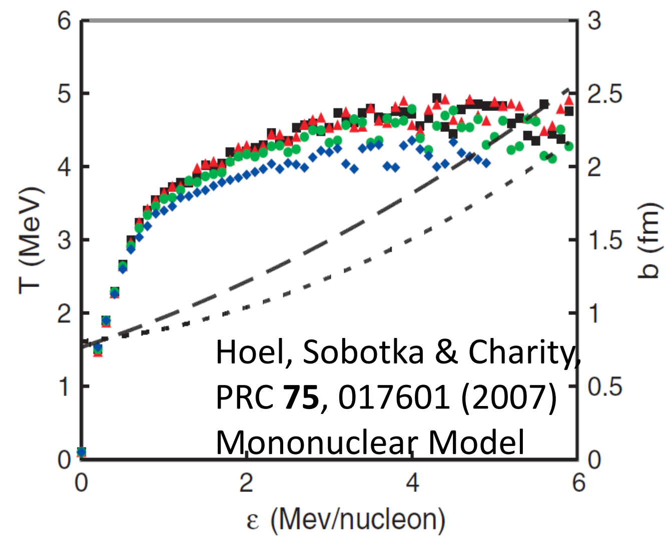
Besprosvany & Levit Phys. Lett B **217**, 1 (1989)
Hot Liquid Drop Model



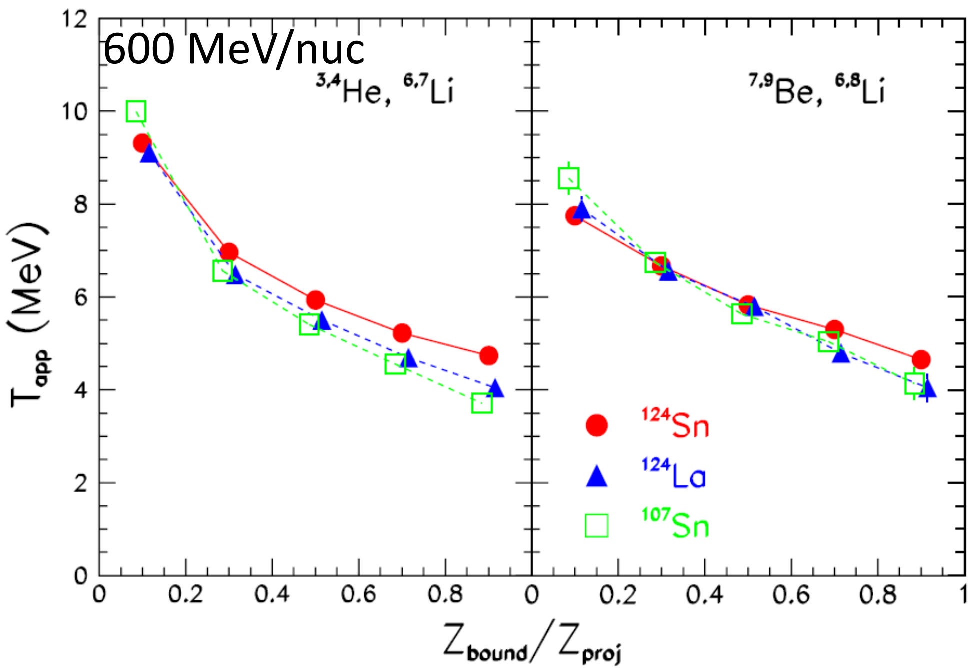
Kolomietz et al, Phys. Rev. C **64**, 024315 (2001)
Thermal Thomas-Fermi Model



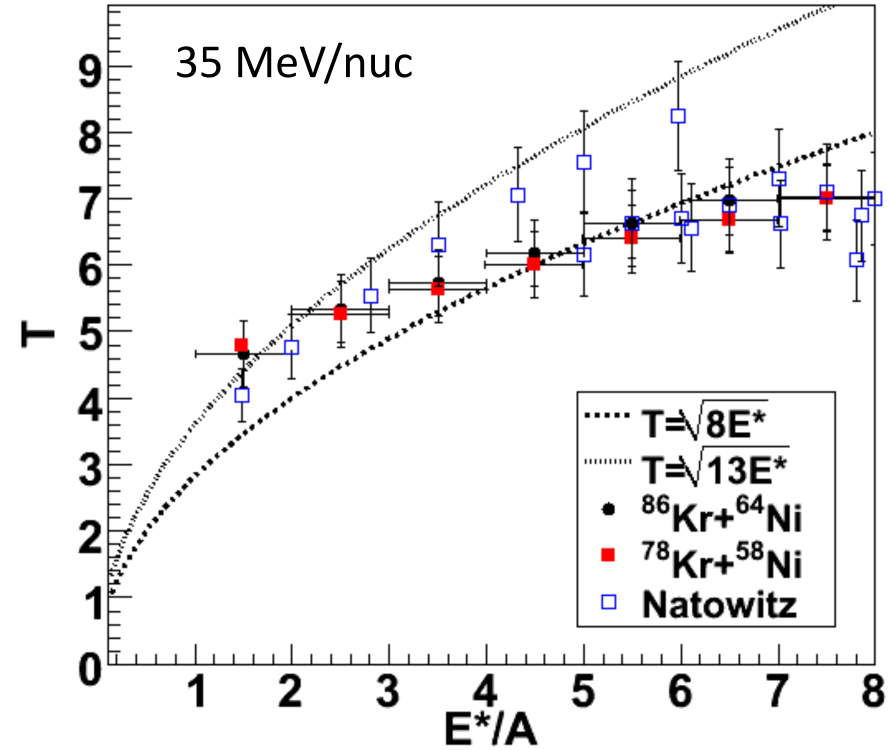
Su & Zhang, Phys. Rev. C **84**, 037601 (2011)
Isospin-Dependent Quantum Molecular Dynamics



Hoel, Sobotka & Charity, PRC **75**, 017601 (2007)
Mononuclear Model



Sfienti et al., PRL **102**, 152701 (2009)

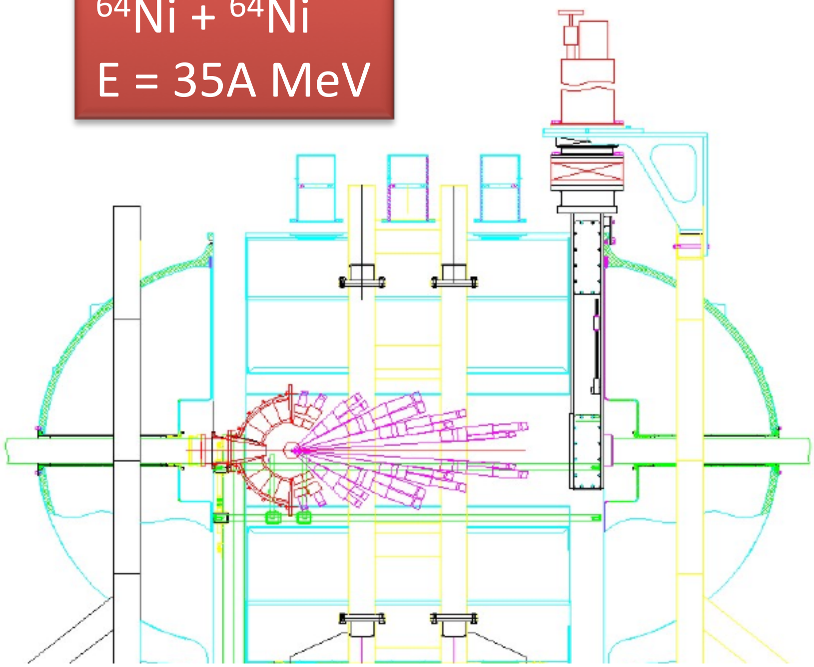


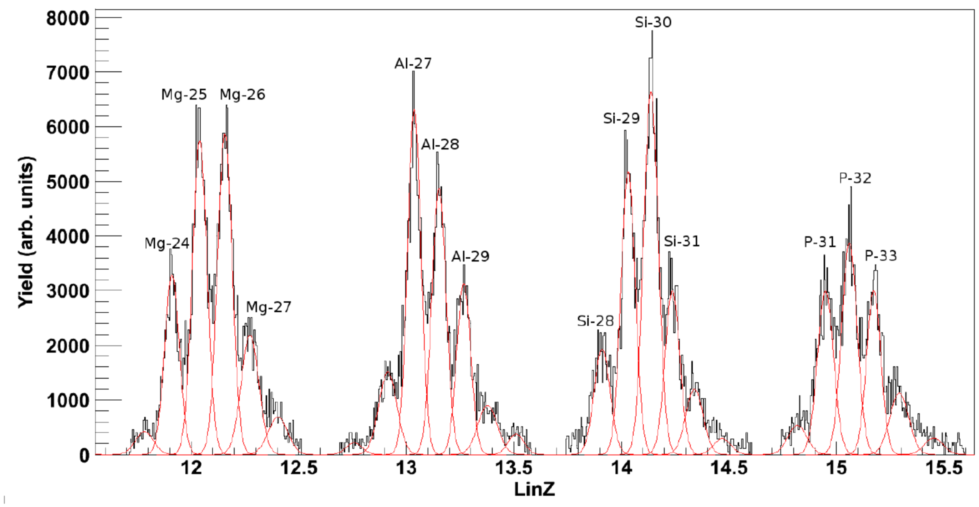
S. Wuenschel, PhD thesis,2009

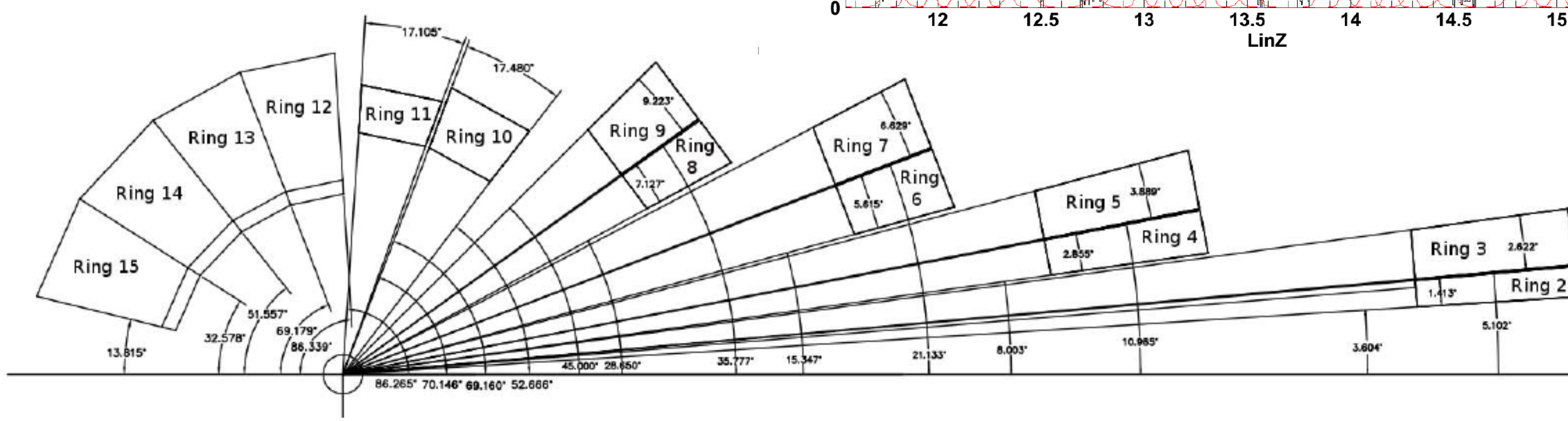
$^{70}Zn + ^{70}Zn$
$^{64}Zn + ^{64}Zn$
$^{64}Ni + ^{64}Ni$
E = 35A MeV

NIMROD-ISiS Array

- Full Silicon Coverage (4π)
- Isotopic Resolution to Z=17
- Elemental Resolution to $Z_{projectile}$
- Neutron Ball (4π)







Event Selection & QP definition

Remove particles that clearly do not belong (on average) to a statistically emitting projectile-like source

$$Z = 1: \quad 0.35 \le {}^{v_z}/_{v_{z,PLF}} \le 1.65$$

$$Z = 2: \quad 0.40 \le {}^{v_z}/_{v_{z,PLF}} \le 1.60$$

$$Z \ge 3: \quad 0.55 \le {}^{v_z}/_{v_{z,PLF}} \le 1.45$$

Select events with a well-measured QP:

$$48 \le \sum_i^{CP} A_i + M_n \le 52$$

Select events with near-zero average momentum quadrupole.

$$-0.3 \le \log Q \le 0.3$$

$$Q = \frac{\sum p_{z,i}{}^2}{\frac{1}{2}\sum p_{T,i}{}^2}$$

Identity $$Z_{QP} = \sum_i^{CP} Z_i \qquad A_{QP} = \sum_i^{CP} A_i + M_n$$

Reference Frame $$\vec{v}_{QP} m_{QP} = \sum_i^{CP} \vec{v}_i m_i$$

Excitation $$E^*_{QP} = \sum_i^{CP} \tfrac{3}{2} K_{\perp,i} + M_n \langle K_n \rangle - Q$$

Strength of the Measurement

- Excellent isotopic resolution
- 4π charged particle detection
- Neutron multiplicity measurement
- Excellent energy resolution

→ **Well defined quasi-projectile source**

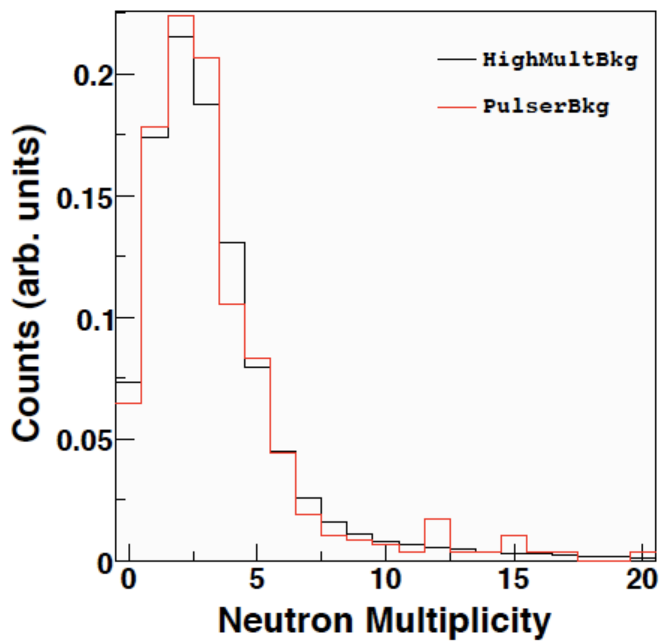
S. Wuenschel et al., PRC**79**, 061602 (2009)
J.C. Steckmeyer et al., NPA**686**, 537 (2001)

Free Neutrons

- Used HIPSE-SIMONE[1] to link M_{exp} to M_{QP}

$$Mult_{QP} = \frac{Mult_{exp} - Mult_{bkg}}{(Eff_{QP} + \frac{N_T}{N_P} Eff_{QT})(.7/.6)}$$

- $Mult_{exp}$ = neutrons in experimental signal gate
- $Mult_{bkg}$ = neutrons in experimental background gate
- Eff_{QP} = fraction of QP source neutrons detected
- Eff_{QT} = fraction of QT source neutrons detected



1- D. Lacroix et al. PRC 69, 054604 (2004)

Nuclear Thermometers

<u>Momentum Quadrupole Fluctuation Temperature</u>

The quadrupole momentum distribution

$$Q_{xy} = {p_x}^2 - {p_y}^2$$

Contains information on the temperature through its fluctuations

$$ {\sigma_{xy}}^2 = \int d^3p \left({p_x}^2 - {p_y}^2\right)^2 f(p)$$

If f(p) is a Maxwell-Boltzmann distribution

$$ {\sigma_{xy}}^2 = 4m^2T^2$$

H. Zheng & A. Bonasera, PLB **696**, 178 (2011)

<u>Albergo Yield Ratio Temperature</u>

$$R = \frac{Y(d)/Y(t)}{Y(^3He)/Y(\alpha)}$$

Account for binding energy differences and spin-degeneracies

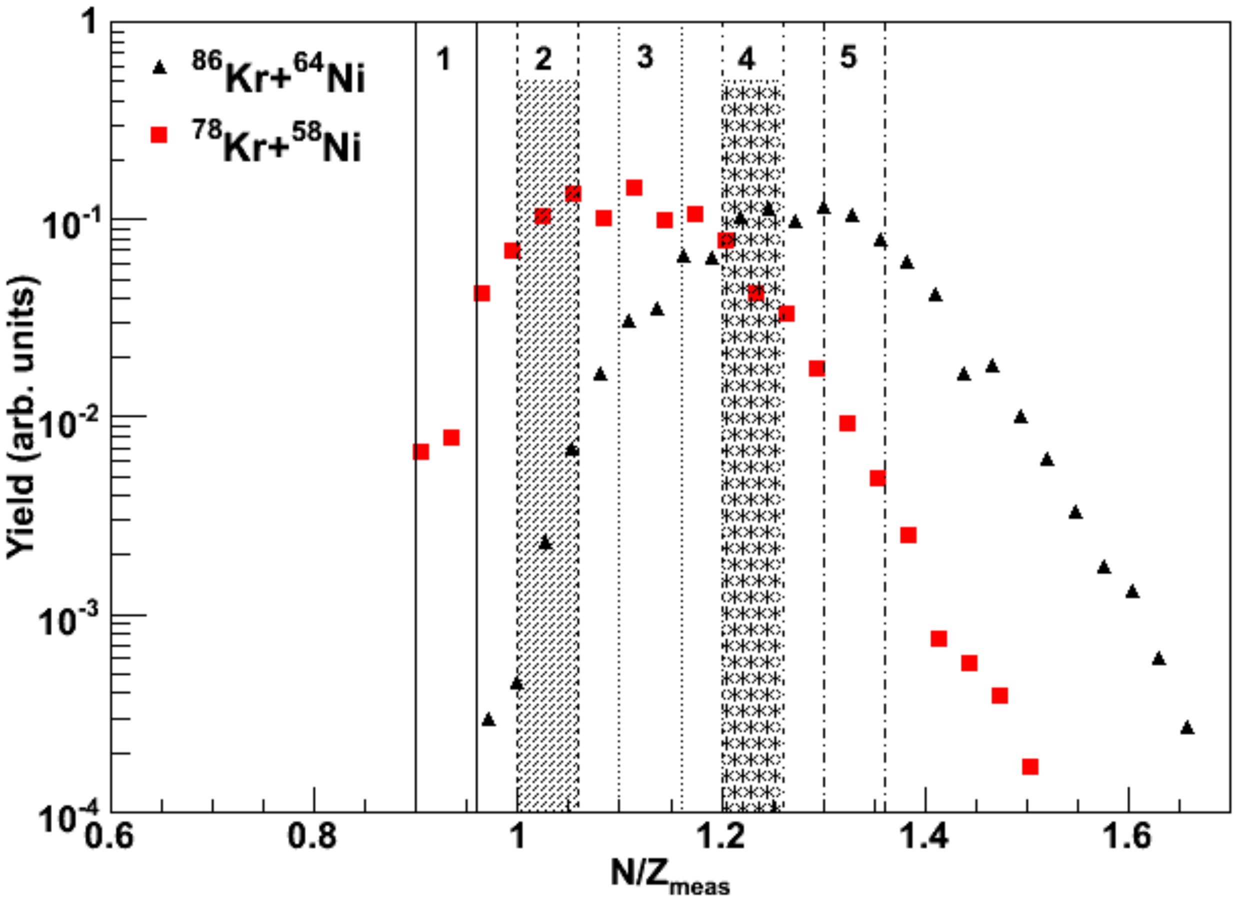
$$T_{raw} = \frac{14.3MeV}{\ln(1.59R)}$$

~3% correction
for secondary decay

$$T = \frac{1}{\frac{1}{T_{raw}} - 0.0097}$$

S. Albergo et al., Il Nuovo Cimento **89**, 1 (1985)

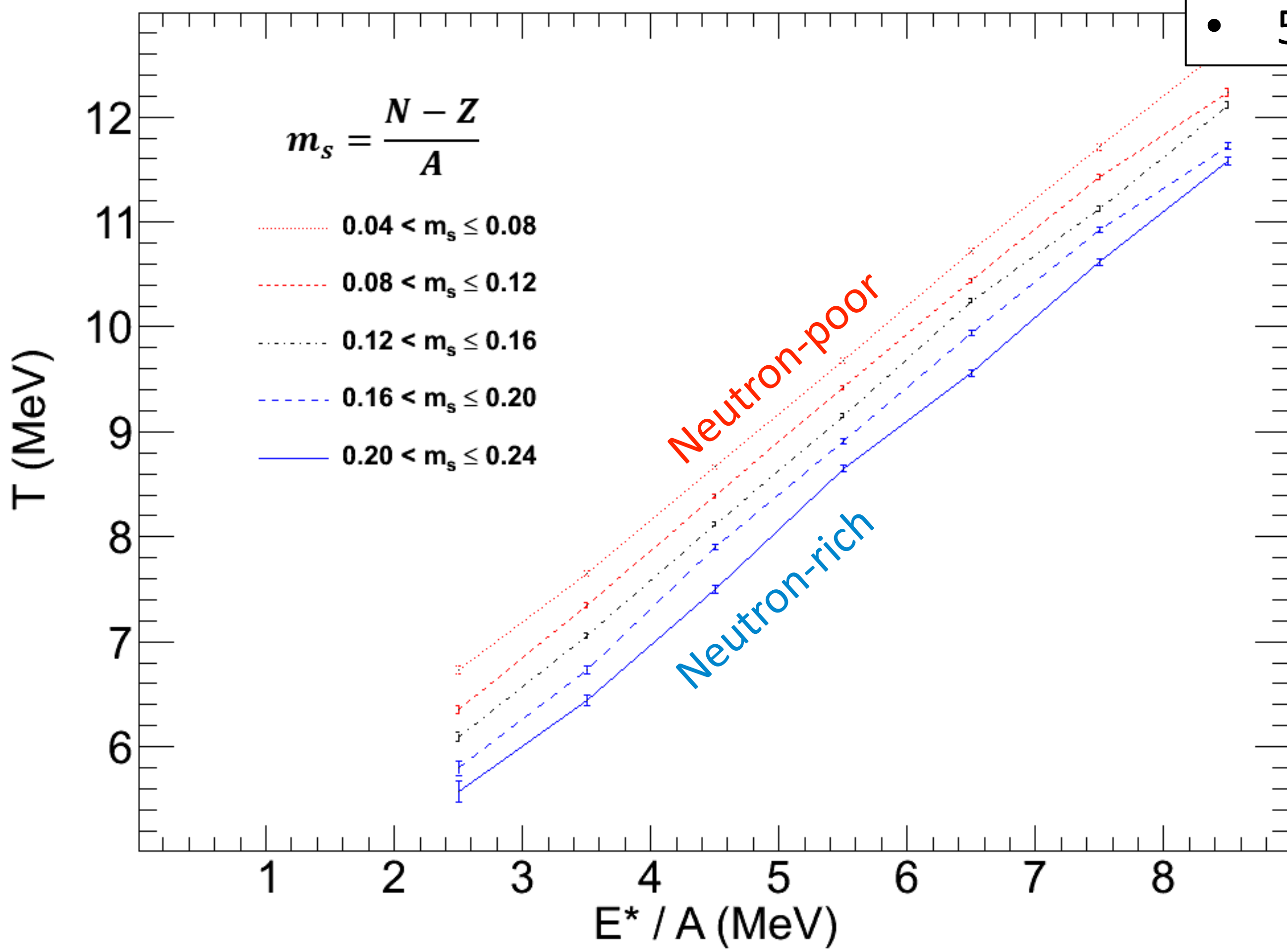
$$\frac{N}{Z}_{meas} = \frac{\sum_i^{M_{cp}} N_i + M_n}{\sum_i^{M_{cp}} Z_i}$$



S. Wuenschel, Phys Rev C 79, 061602(R) (2009).

Fluctuation Temperature

- $48 \le A_{QP} \le 52$
- 5 narrow asymmetry bins



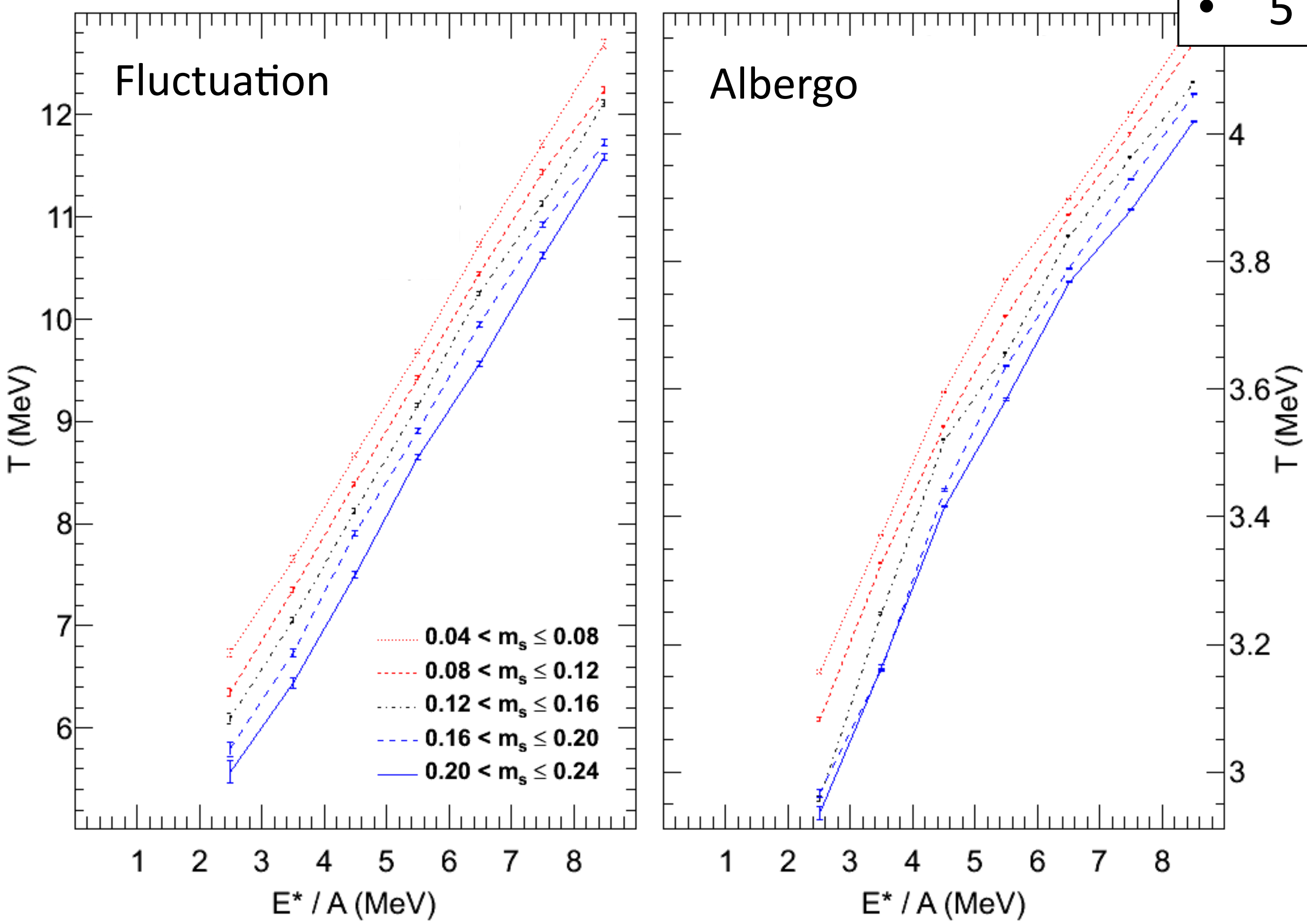
Larger Asymmetry
→ Lower Temperature

> 1 MeV shift!

Evenly Spaced

Fluctuation & Albergo Temperatures

- $48 \leq A_{QP} \leq 52$
- 5 narrow asymmetry bins



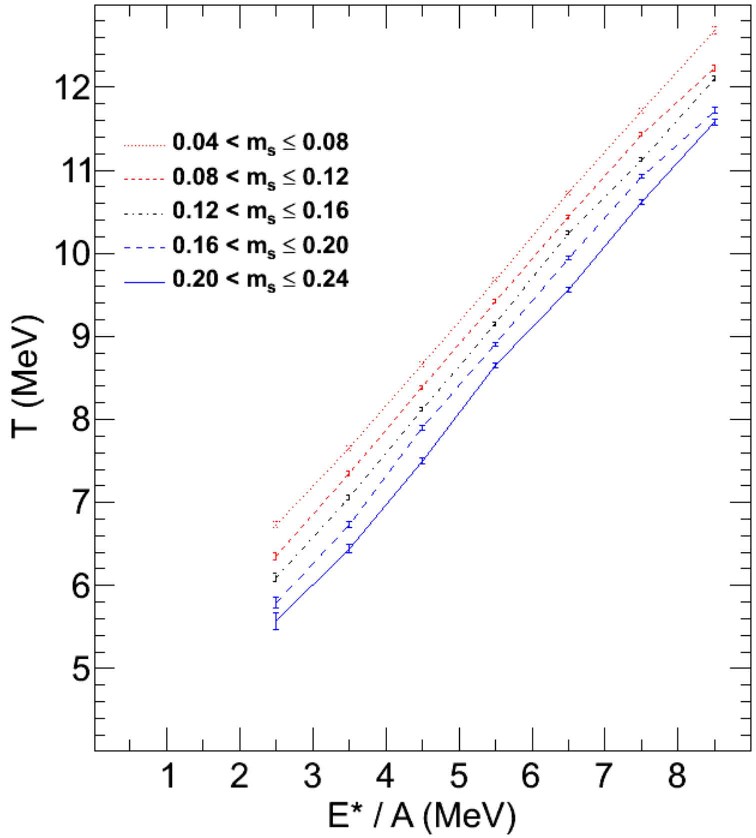
<u>Both Thermometers:</u>

Larger Asymmetry
→ Lower Temperature

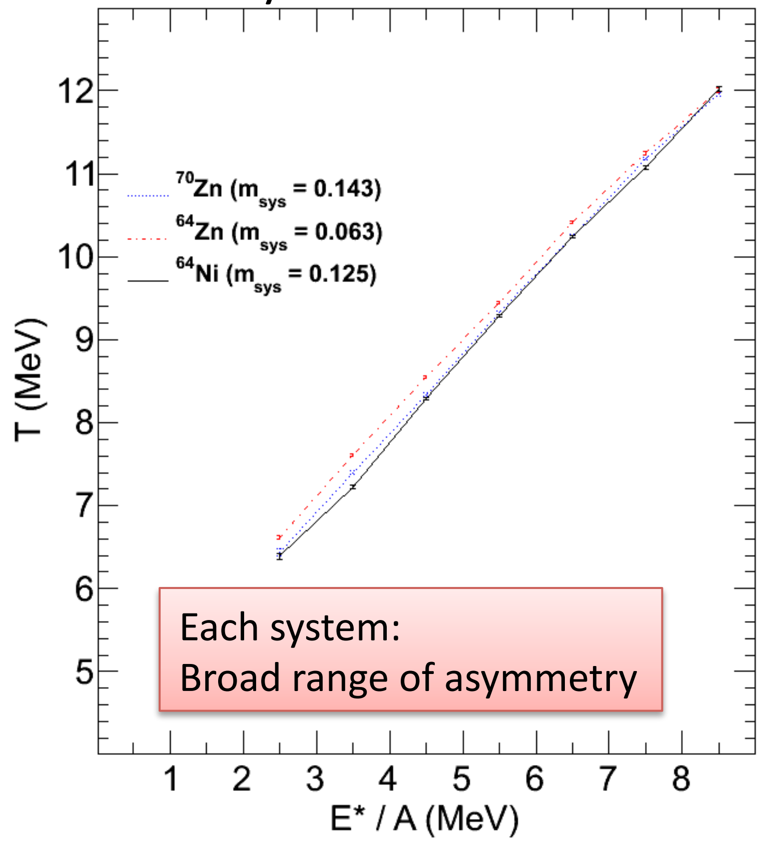
Evenly Spaced

Importance of Reconstruction

Asymmetry of Isotopically Reconstructed Source



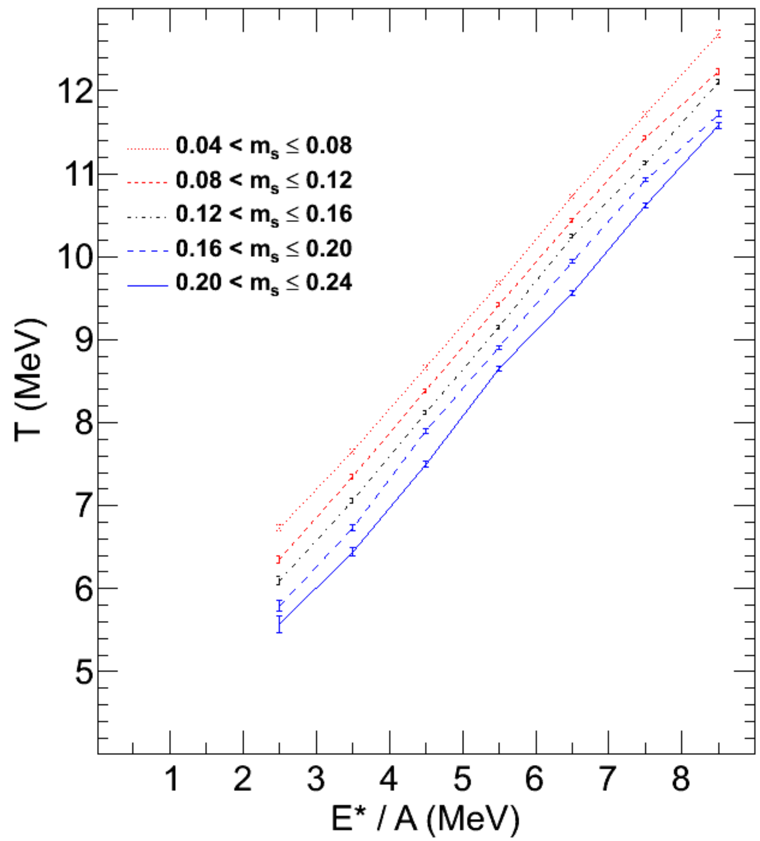
Asymmetry of Initial System

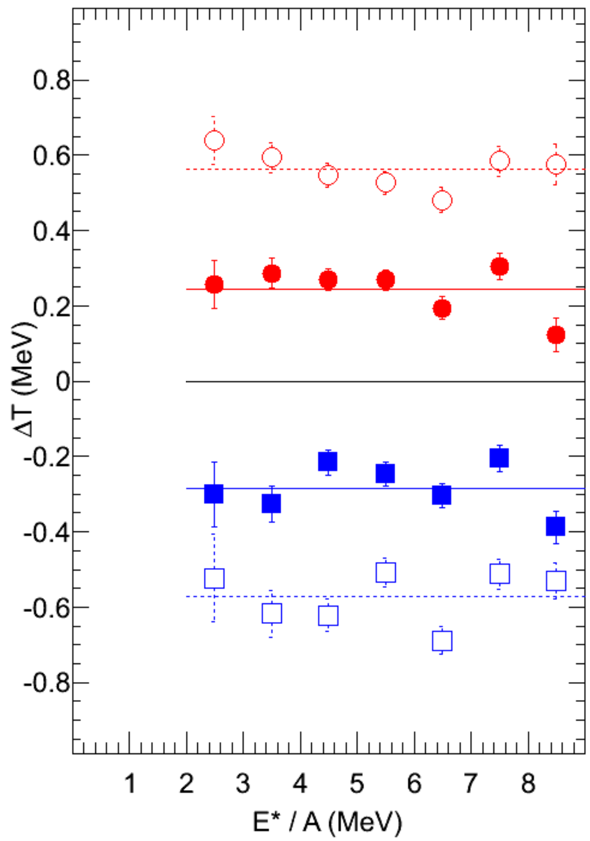


Larger Asymmetry
→ Lower Temperature
Observed either way, but…

Much more pronounced for selection on ***source*** composition

Excitation Independence



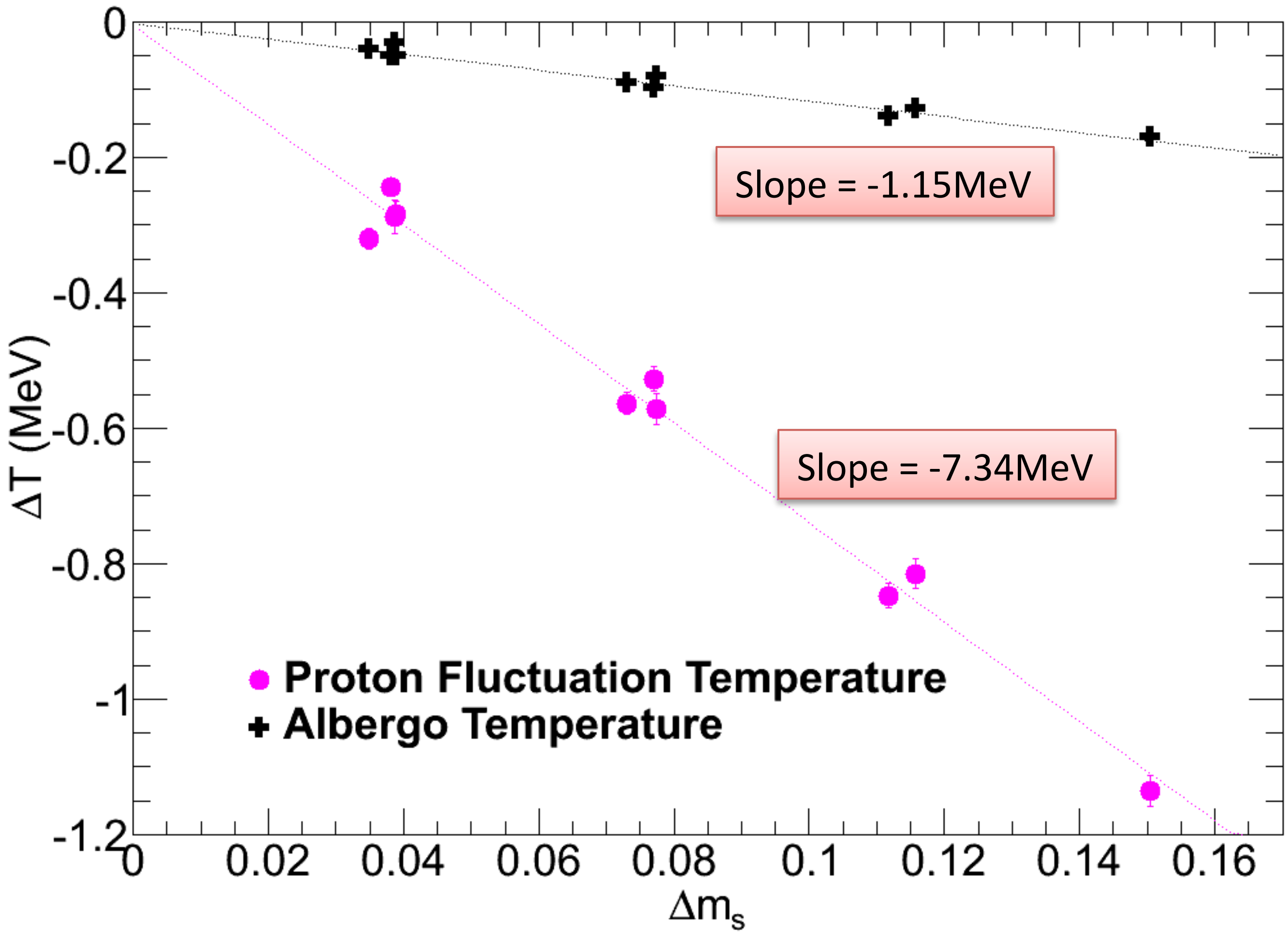


Larger Asymmetry
→ Lower Temperature

Temperature shift does not show a trend with excitation.

ave

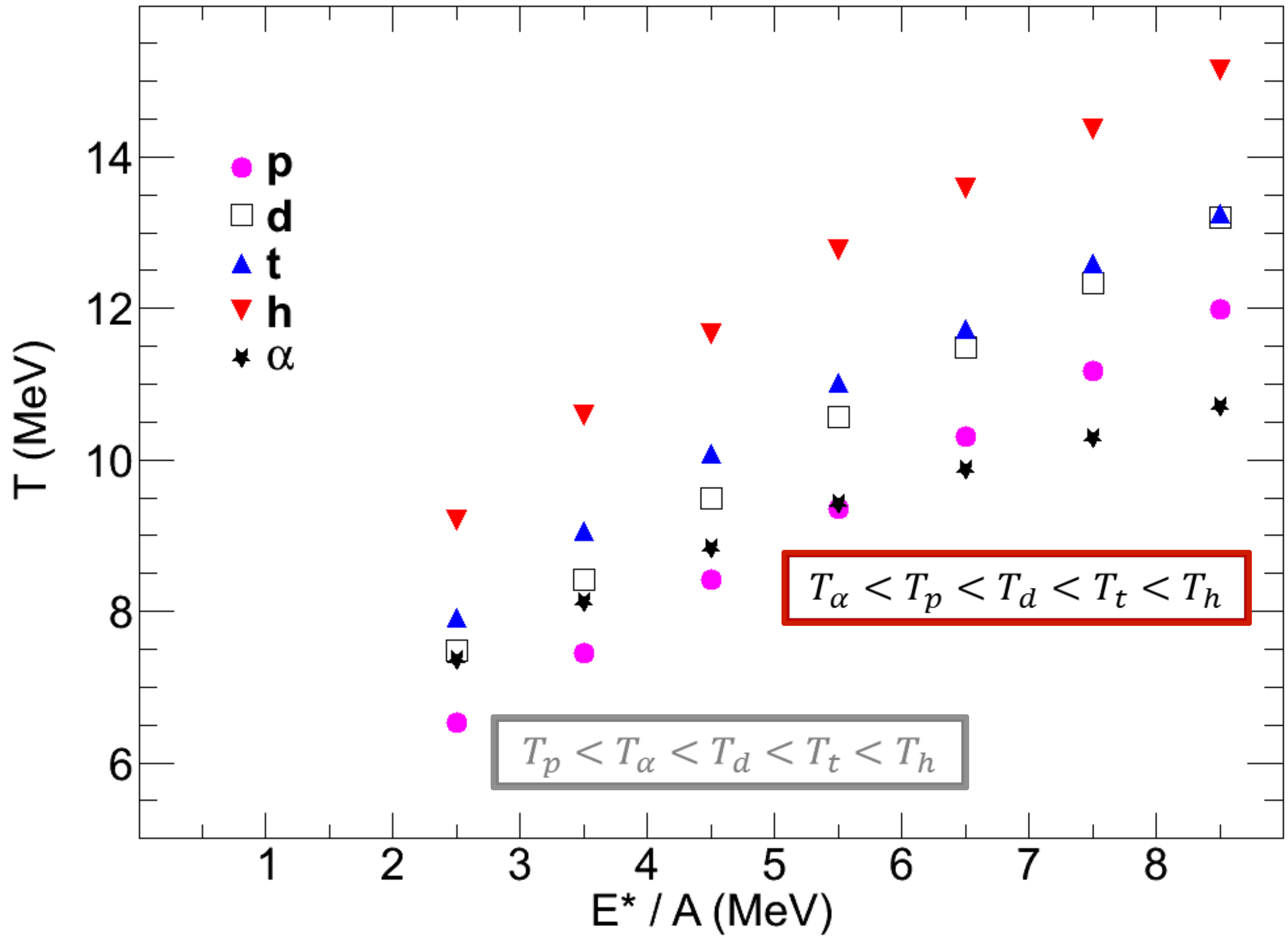
Asymmetry Dependence of Temperature



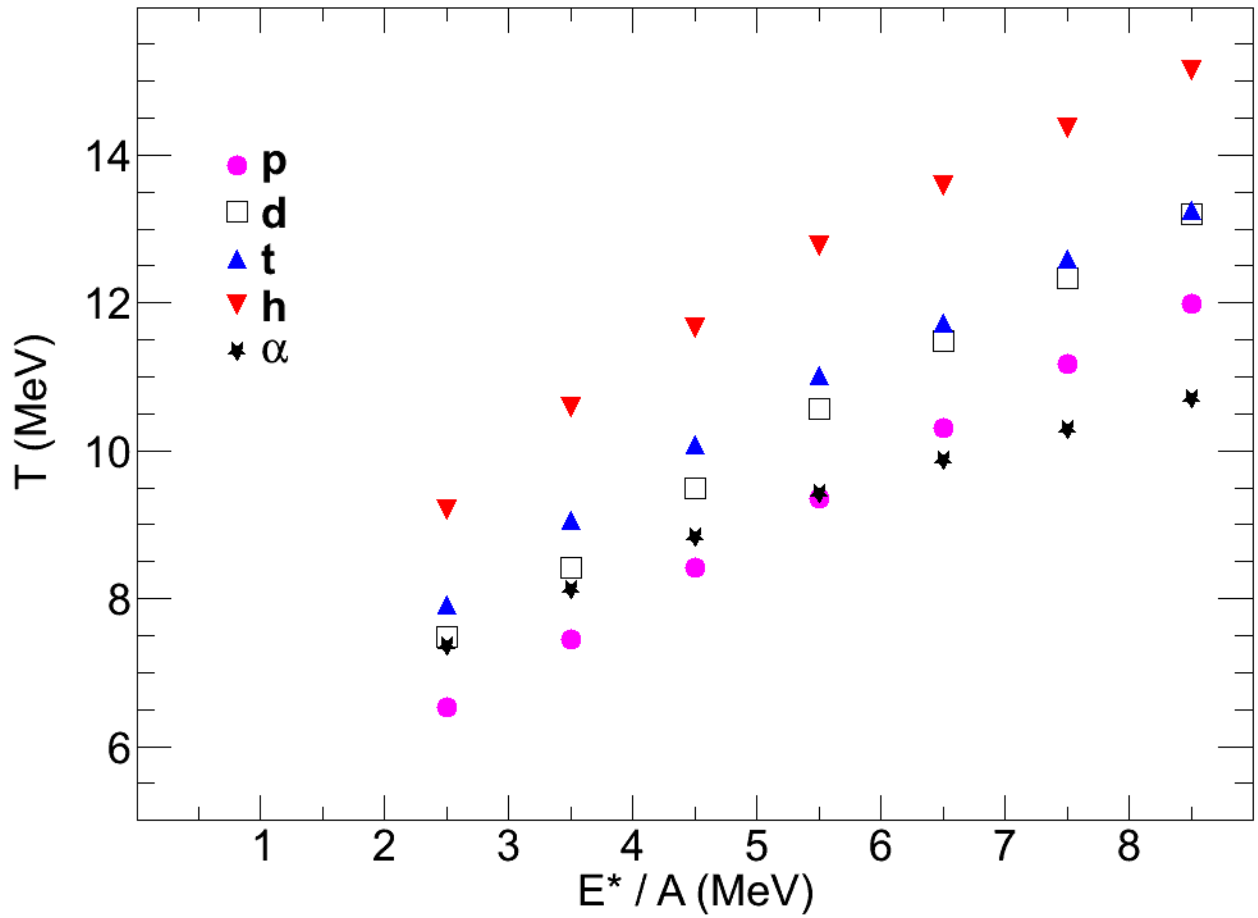
T_Albergo:
→ ΔT = -0.2MeV

T_Fluctuation:
→ ΔT = -1.2MeV

Caloric Curves for Light Charged Particles



Caloric Curves for Light Charged Particles



Ordering of Temperatures

$$T_\alpha < T_p < T_d < T_t < T_h$$

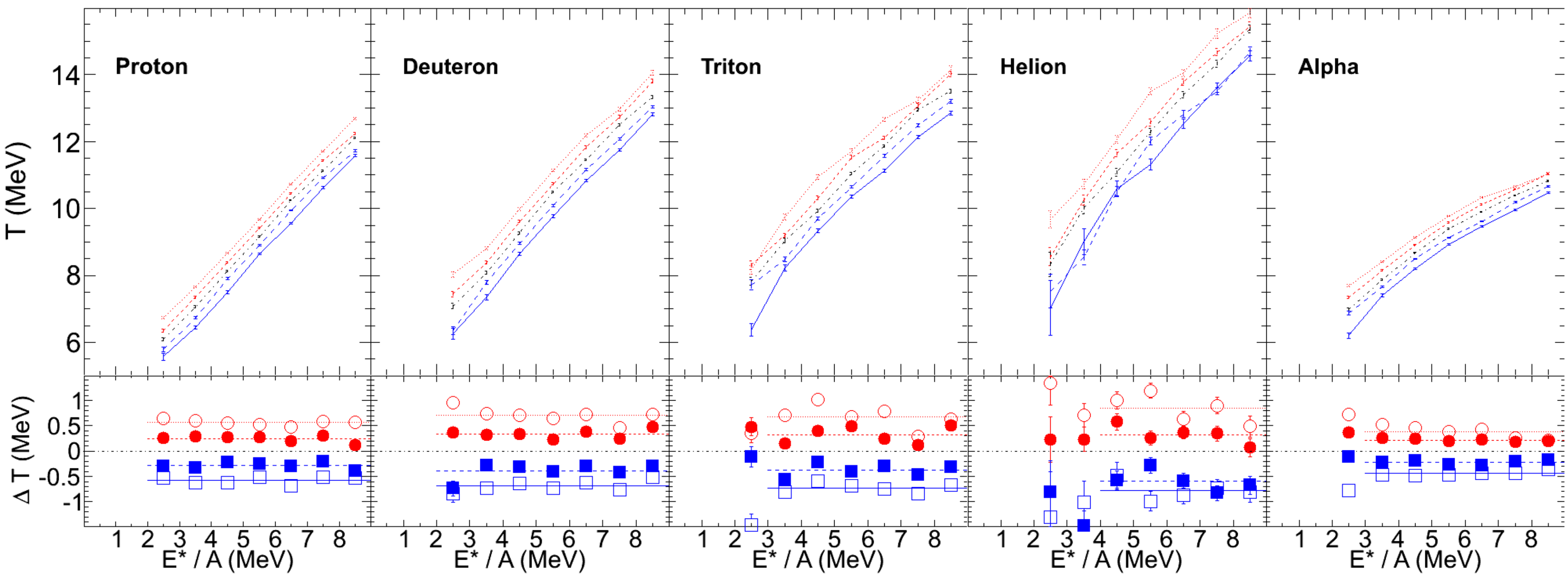
Expensive Particles:
Early times
Highest temperature

Q-value for emission:
~10MeV for proton, alpha
~20MeV for triton, helion

Different particles may also probe regions with different average density.

Emission Order:
S. Hudan et al., arXiv 0308031 (2003)
L. Chen et al., Nucl. Phys. A 729, 809 (2003)
R. Ghetti et al., Nucl. Phys. A 765, 307 (2006)
Z. Kohley et al., Manuscript Submitted to PRC (2012)

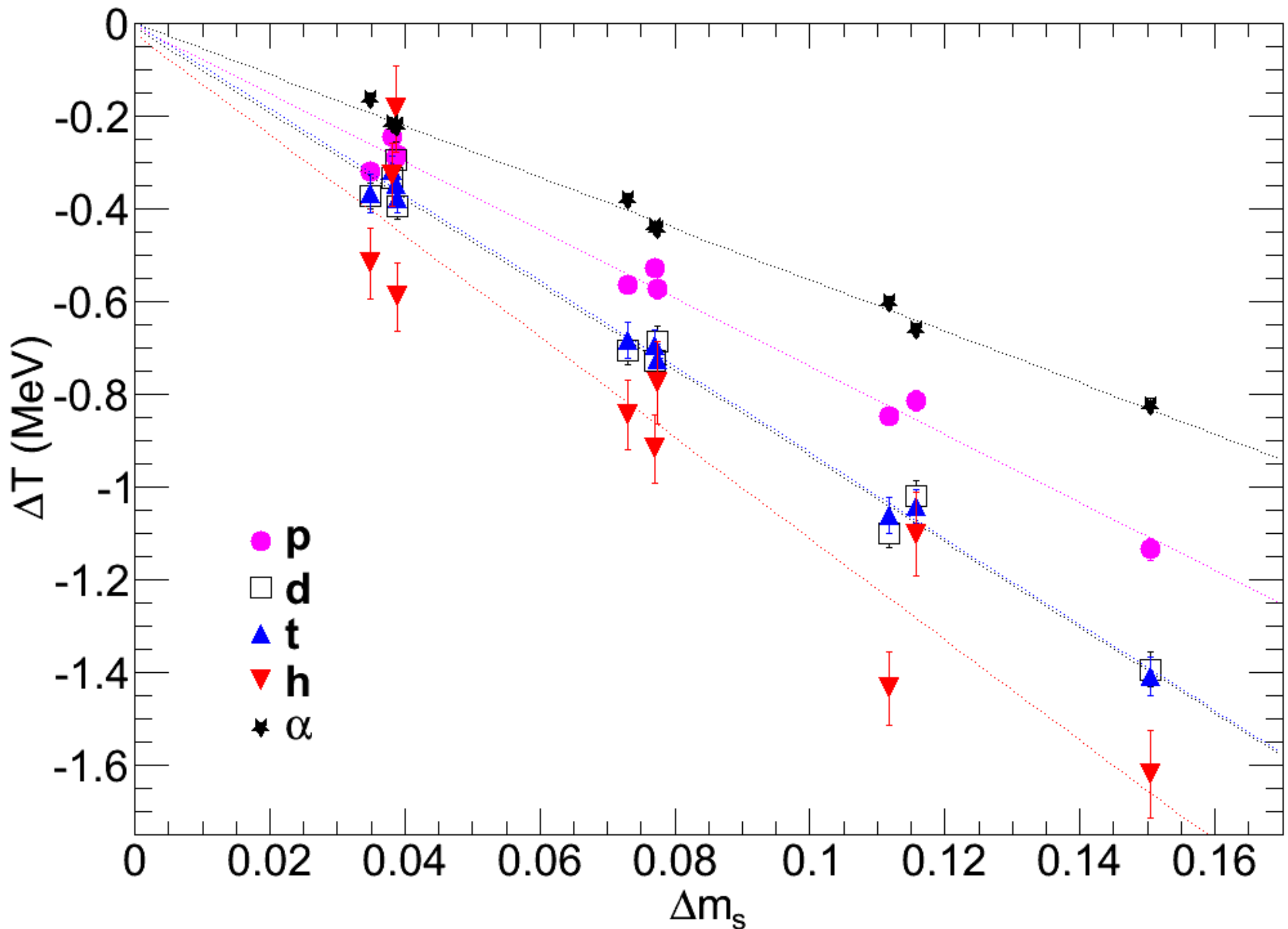
Caloric Curves for LCPs: Dependence on Composition



For All LCPs:
Larger Asymmetry
→ Lower Temperature

Temperature shift does not show a trend with excitation.

Asymmetry Dependence of Temperature



$\underline{\Delta T / \Delta m_s}$
α: -5.5
p: -7.3
d: -9.2
t: -9.3
h: -10.9

Same ordering as for temperature:

$$T_\alpha < T_p < T_d < T_t < T_h$$

Strength of correlation:
Source composition may evolve with time

Summary

- Nuclear temperature depends on asymmetry
  - (↑Neutron content) ➔ (↓Temperature)
  - Linear correlation
  - Seen for 2 thermometers
  - Seen for all light charged particles
- *Source* composition matters, not initial system
  - Intermediate energy
- Excitation: no influence on asymmetry dependence ($2.5 < E^*/A < 8.5$ MeV)
- Temperature ordering of LCPs
  - Consistent with emission time ordering
  - Impact of local density?