How much cooler would it be with some more neutrons?

The Influence of Neutron–Proton Asymmetry on Nuclear Temperature

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Texas A&M University

International Workshop on Nuclear Dynamics and Thermodynamics in Honor of Joe Natowitz

Thank you, Joe

for advancing nuclear chemistry as a field

for advancing nuclear chemistry at TAMU

for cultivating a great environment to work in

How much cooler would it be with some more neutrons?

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

Nuclear Equation of State and Nuclear Phase Diagram

Temperature
Density
Pressure
Excitation Energy
Asymmetry

★ Heavy Ion Collisions at All Energies
★ Nuclear Structure (e.g. Resonances)
★ Supernovae, Nucleosynthesis
★ Neutron Stars (Crust to Core)
➡ n-p Asymmetry Crucial

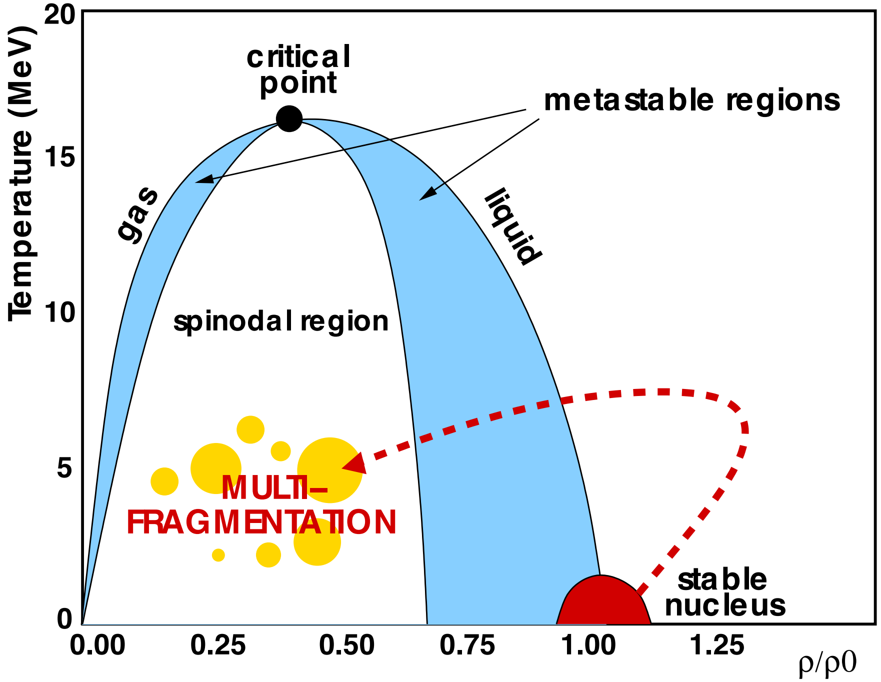
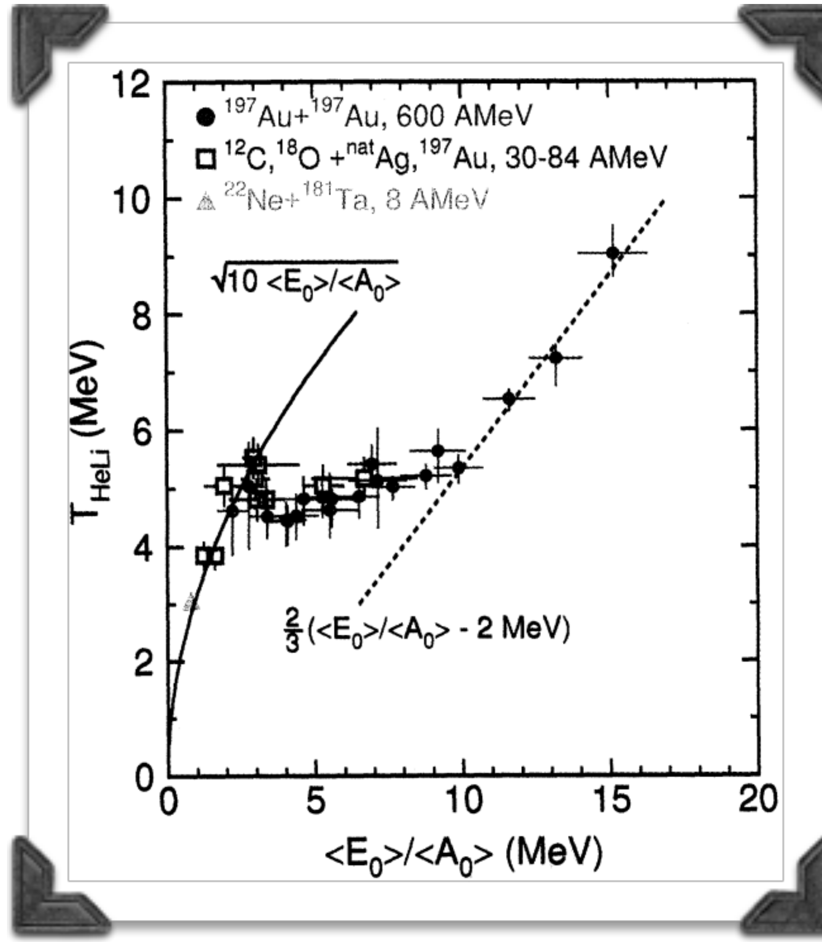


Figure: Ketel Turzo, Ph.D. Thesis, Universite Lyon (2002)

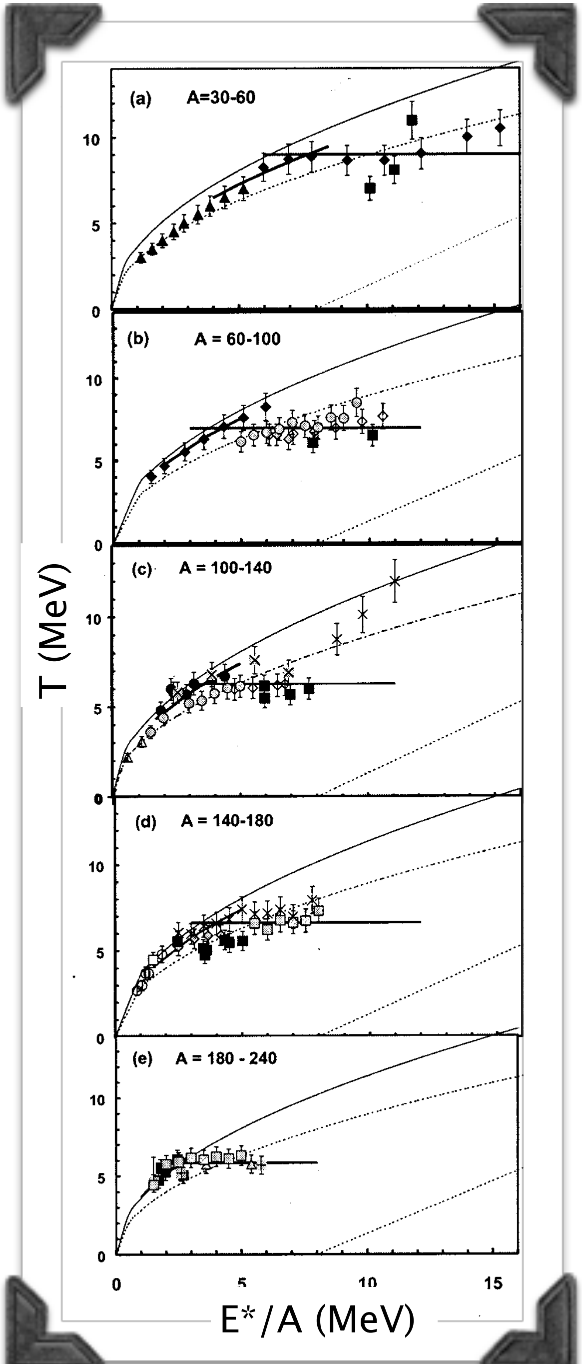
Nuclear Caloric Curve

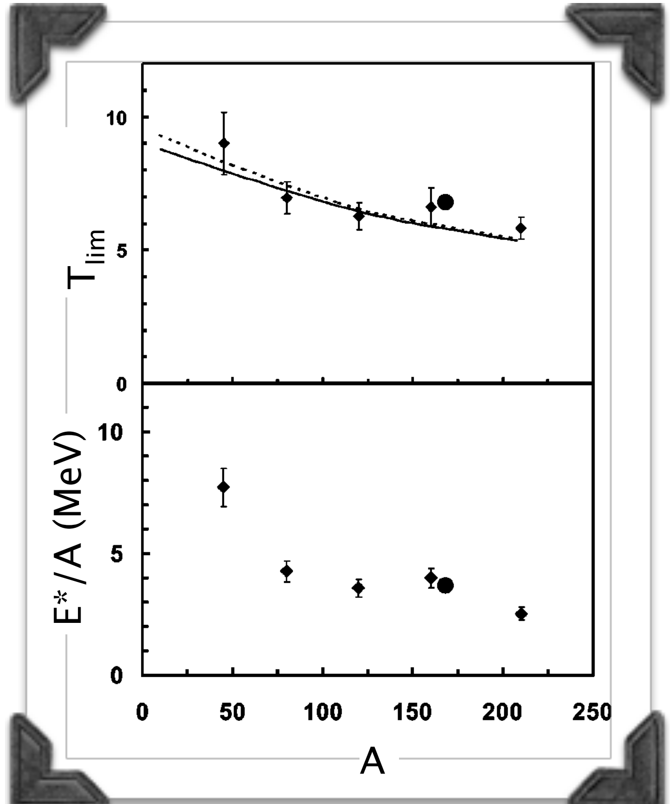
- Essential Piece of Nuclear Equation of State: T vs E*/A
- Search for & Study of Phase Transition
  - Liquid to Vapor
  - Evaporation to Multifragmentation



Pochodzalla et al. PRL 75, 1040 (1995)

Nuclear Caloric Curve: Mass Dependence





With increasing mass:

- Limiting temperature decreases
- Onset of T_{lim} moves to lower Excitation energy

Natowitz et al., PRC 65, 034618 (2002)

Caloric Curve: Asymmetry Dependence?

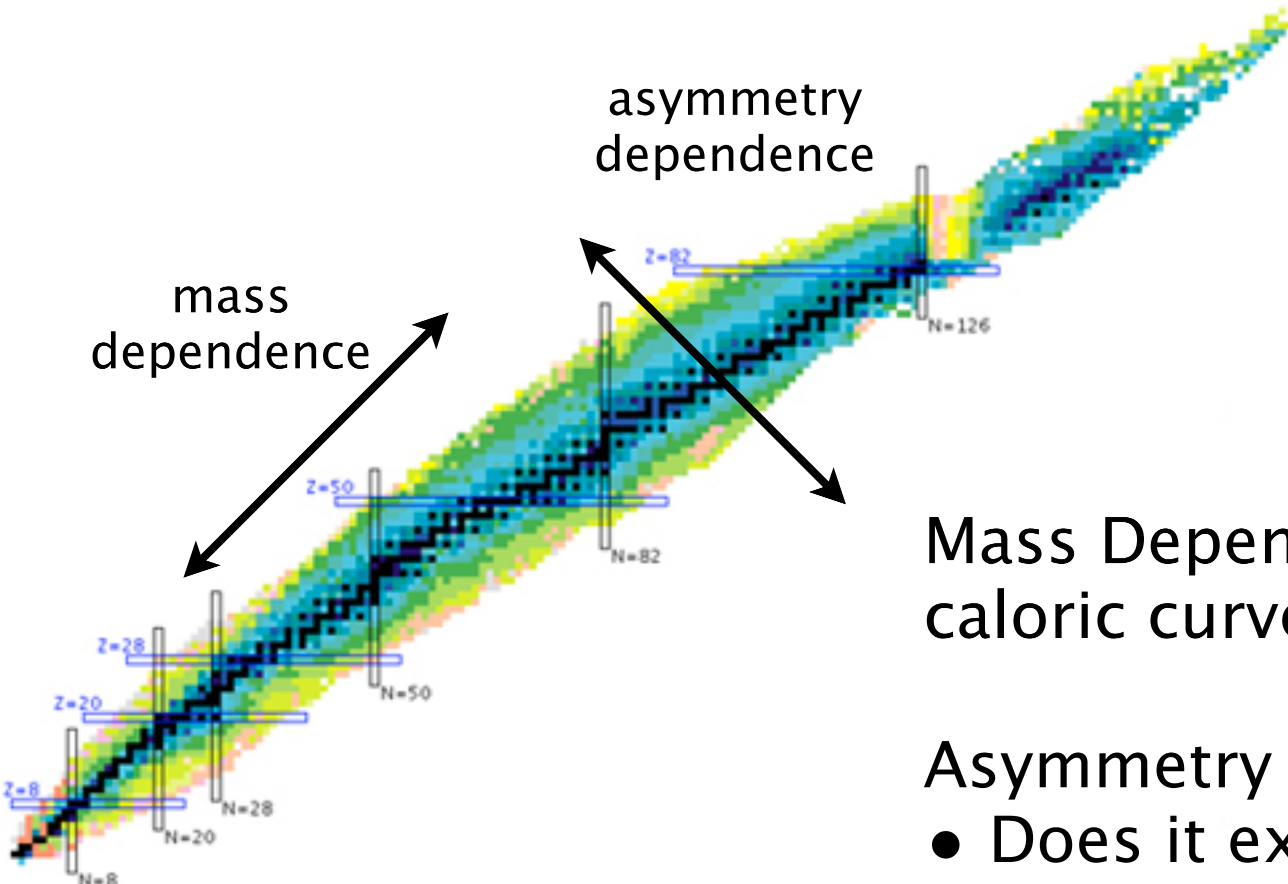


Figure: BNL

Mass Dependence of the caloric curve is measured.

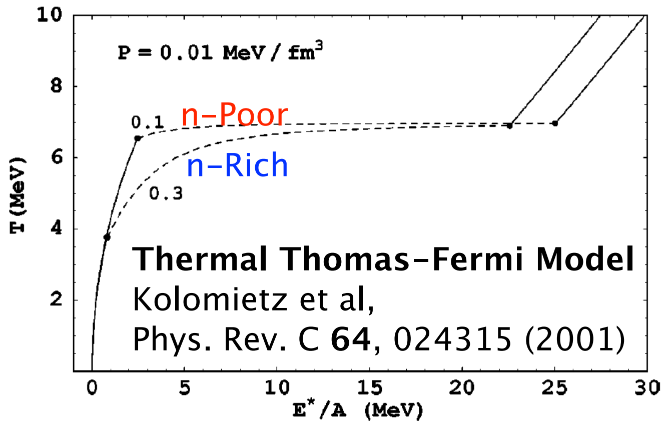
Asymmetry Dependence:
- Does it exist?
- Which way does it go?
- How strong is it?

Caloric Curve: Asymmetry Dependence?

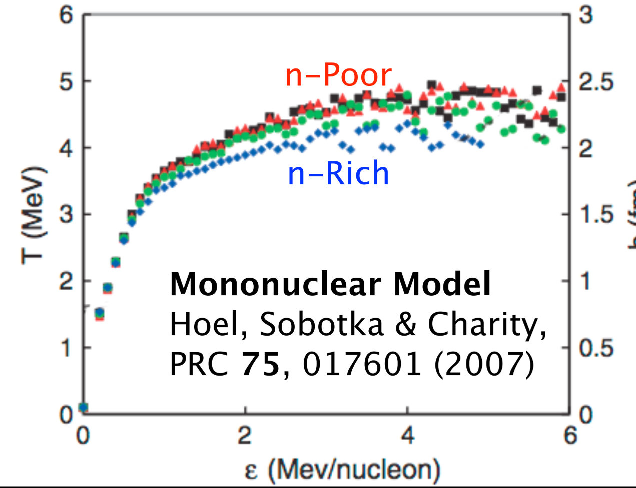
Theory

Different models make very different predictions about how the caloric curve depends on neutron-proton asymmetry

Neutron-rich
→ Lower T

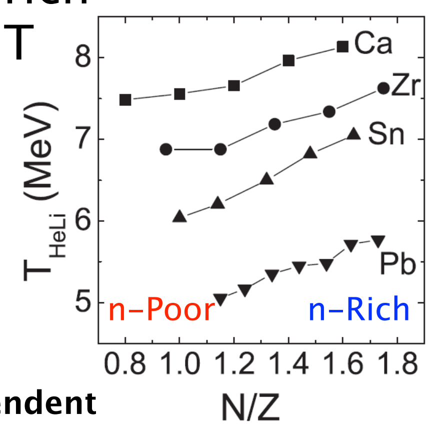


Thermal Thomas-Fermi Model
Kolomietz et al,
Phys. Rev. C **64**, 024315 (2001)

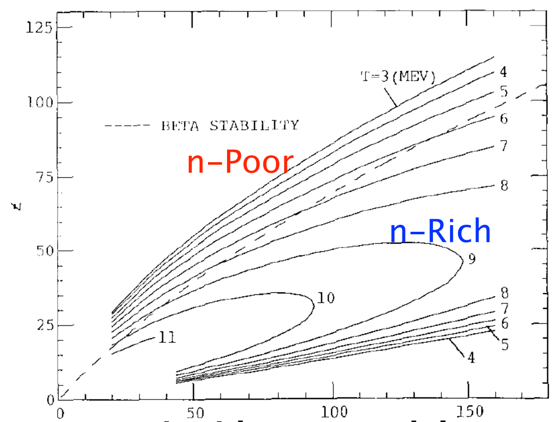


Mononuclear Model
Hoel, Sobotka & Charity,
PRC **75**, 017601 (2007)

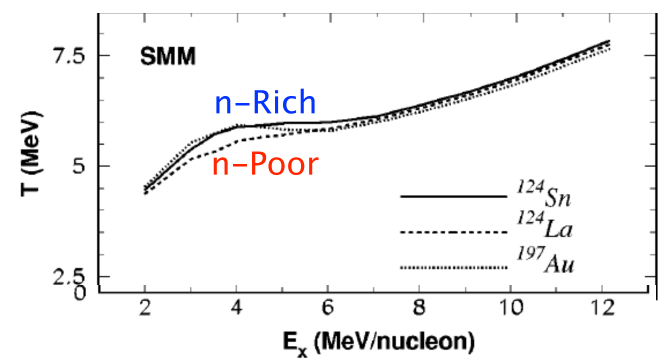
Neutron-rich
→Higher T



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



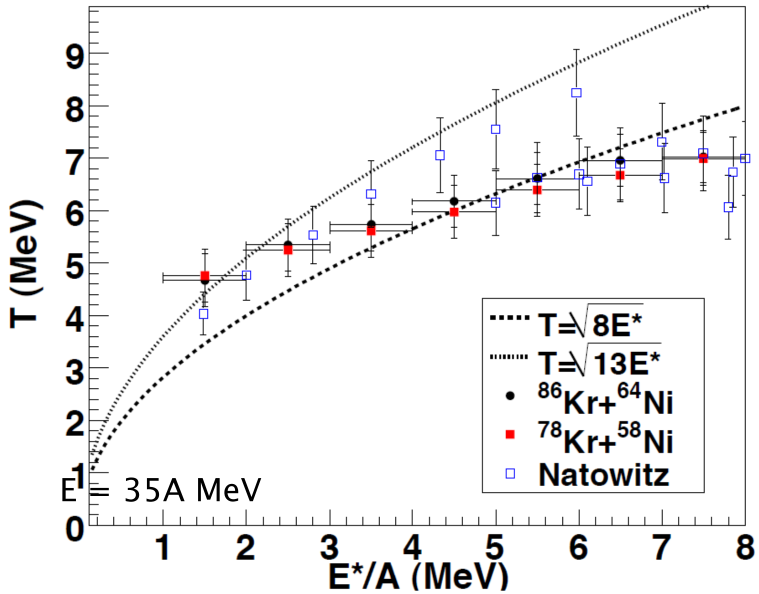
Hot Liquid Drop Model
Besprosvany & Levit
Phys. Lett B **217**, 1 (1989)



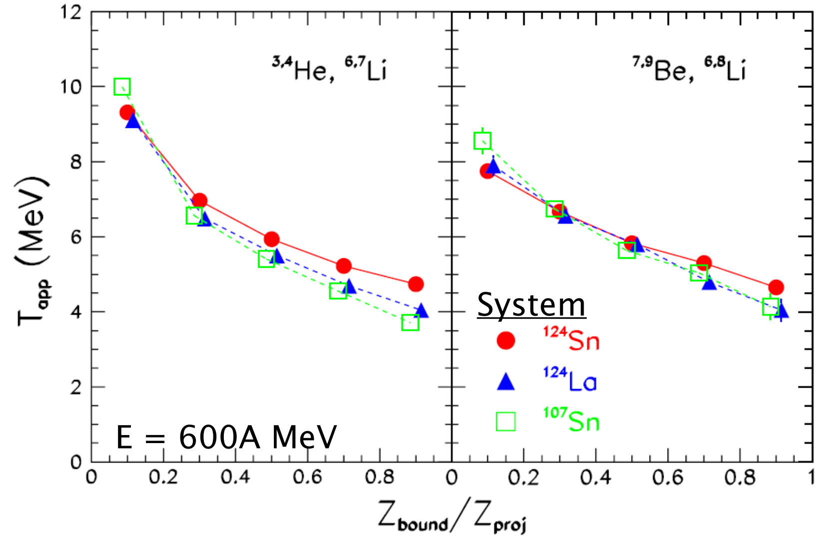
Statistical Multifragmentation Model
Ogul & Botvina, Phys. Rev. C **66**, 051601 (2002)

Caloric Curve: Asymmetry Dependence?

Experiment



S. Wuenschel, Ph.D. Thesis, 2009



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

Slight offset of neutron-rich system, but not statistically significant

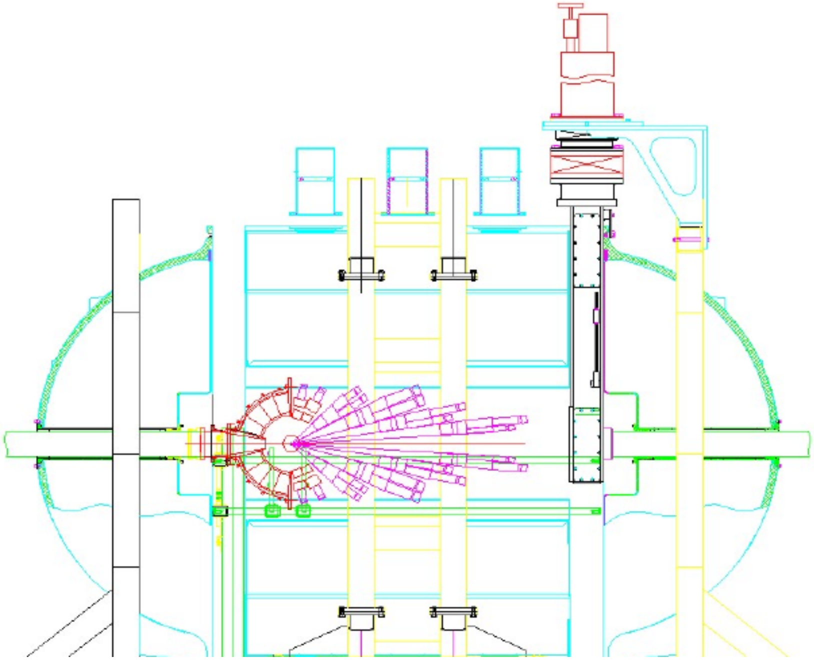
Possible dependence on asymmetry, but not for all impact parameters.

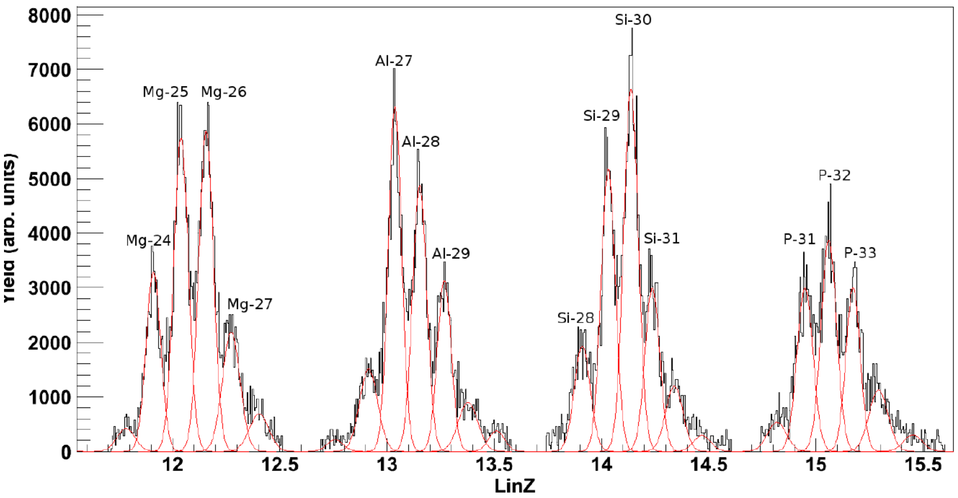
Selection was on system composition.
Should use **reconstructed-source composition.**

NIMROD-ISiS Array

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

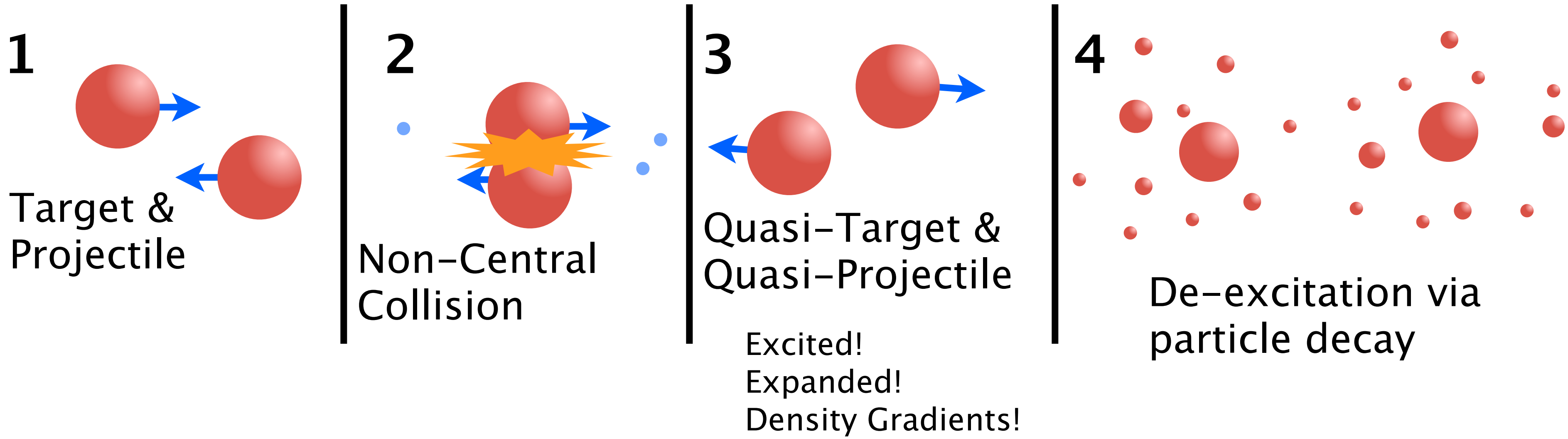
$^{70}Zn + ^{70}Zn$
$^{64}Zn + ^{64}Zn$
$^{64}Ni + ^{64}Ni$
E = 35A MeV





S. Wuenschel et al., Nucl. Instrum. Methods. A604, 578–583 (2009)
Z. Kohley, Ph.D Thesis, TAMU (2010)

Exciting Nuclear Matter



The QP (quasi-projectile) is the primary excited fragment that exists momentarily after the nuclear collision

- We want to study the decay of excited nuclear material (the QP)
- We use heavy ion collisions to create excited nuclear material
- From the reaction products, we reconstruct the QP

QP Reconstruction

Goal: select events with an equilibrated source

1. **Select particles** that may comprise the QP
   - ✦ Velocity selection
   - ✦ Charged particles & free neutrons
   - ✦ Calculate Z, A, p, E* & asymmetry=m_s=(N-Z)/A

2. **Select mass** (range) of QP

3. **Select on-average spherical events**

QP Reconstruction

Cut 1/3: Velocity

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

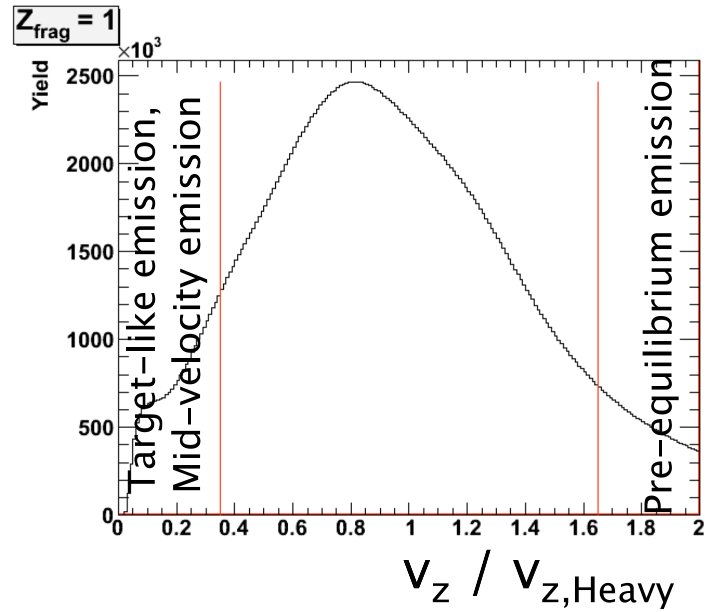
Compare laboratory parallel velocity of each particle to that of the heaviest charged particle measured in the event.

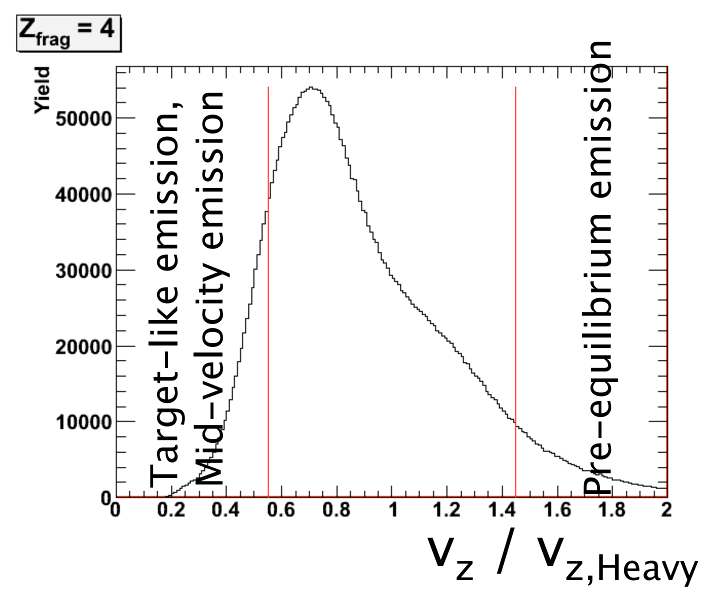
$$\mathbf{Z = 1: \quad 0.35 \leq \frac{v_z}{v_{z,PLF}} \leq 1.65}$$

$$\mathbf{Z = 2: \quad 0.40 \leq \frac{v_z}{v_{z,PLF}} \leq 1.60}$$

$$\mathbf{Z \geq 3: \quad 0.55 \leq \frac{v_z}{v_{z,PLF}} \leq 1.45}$$

Steckmeyer et al., NPA **686**, 537 (2001)





QP Reconstruction

Mass Selection Considerations

- Mass close to beam – well defined system
- Not too close to beam: significant E*, overlap of target and projectile
- Sufficient statistics

$$\mathbf{48 \leq A_{QP} \leq 52} \qquad \mathbf{m_{source} = \frac{N_{QP} - Z_{QP}}{A_{QP}}}$$

Largest uncertainty in A_{QP}: free neutron multiplicity

- Uncertainty in excitation
  - relatively small (compared to results)
- Uncertainty in asymmetry (N–Z)/A
  - relatively small (compared to results)

Marini et al., NIMA **707**, 80 (2013)

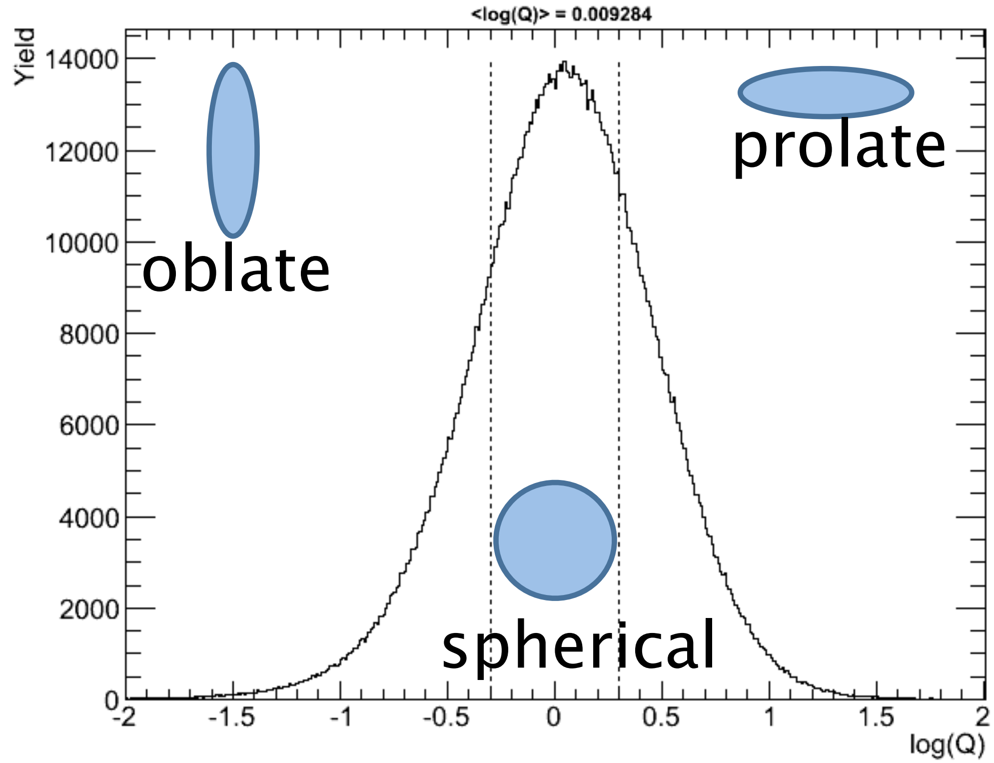
QP Reconstruction

Cut 3/3: Sphericity

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

$$-0.3 \leq \log Q \leq 0.3$$

Select events with near-zero average momentum quadrupole.



(Velocity cut and Mass cut imposed)

Concept to select thermally equilibrated events:
Shape equilibration is slow relative to thermal equilibration.

S. Wuenschel, NPA 843, 1 (2010)
S. Wuenschel, Ph.D. Thesis, Texas A&M University, (2009)

Neutron Measurement

$$\mathbf{M_{meas}} = (\epsilon_{\mathbf{QP}}\mathbf{M_{QP}} + \epsilon_{\mathbf{QT}}\mathbf{M_{QT}})\left(\frac{\epsilon_{\mathbf{lab}}}{\epsilon_{\mathbf{sim}}}\right) + \mathbf{M_{bkg}}$$

Efficiency ε_{lab} measured with a calibrated Cf source.

Simulations to determine efficiency ε_{QP}, ε_{QT}, ε_{sim}.

Efficiencies are model-independent (CoMD, HIPSE-SIMON).

Efficiencies are system-independent.

$$\mathbf{M_n} = \frac{\mathbf{M_{meas}} - \mathbf{M_{bkg}}}{\left(\epsilon_{\mathbf{QP}} + \frac{\mathbf{N_T}}{\mathbf{N_P}}\epsilon_{\mathbf{QT}}\right)\left(\frac{\epsilon_{\mathbf{lab}}}{\epsilon_{\mathbf{sim}}}\right)}$$

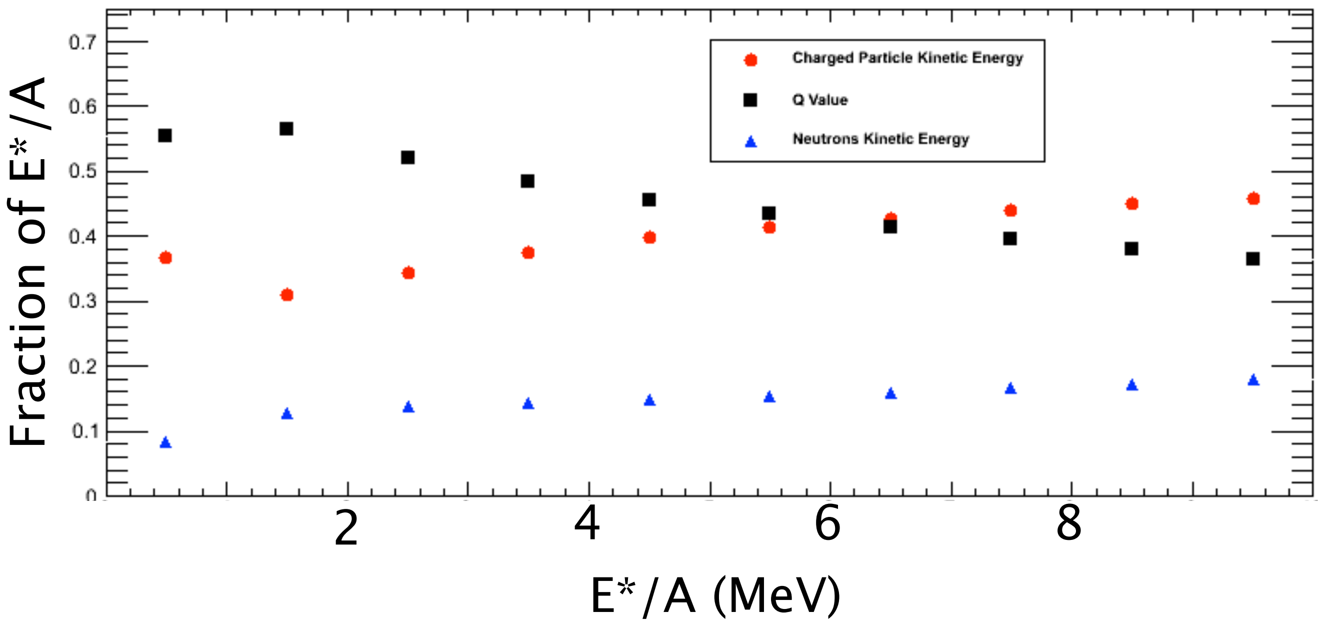
Marini et al., NIMA **707**, 80 (2013)
Wada et al., PRC 69, 044610 (2004)

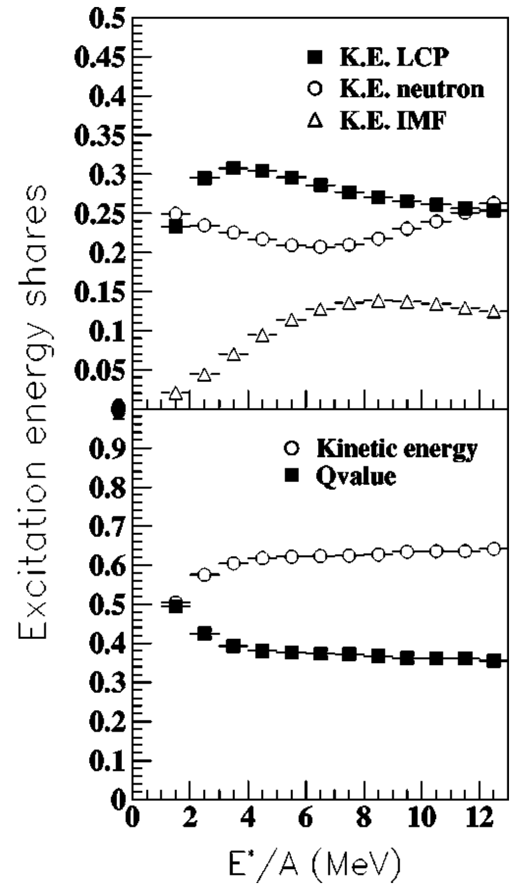
QP Identity

$$Z_{QP} = \sum_{i}^{CP} Z_i \qquad A_{QP} = \sum_{i}^{CP} A_i + M_n \qquad \vec{v}_{QP} m_{QP} = \sum_{i}^{CP} \vec{v}_i m_i \qquad E_{QP}^{*} = \sum_{i}^{CP} \tfrac{3}{2} K_{\perp,i} + M_n \langle K_n \rangle - Q$$

QP Identity

$$Z_{QP} = \sum_{i}^{CP} Z_i \qquad A_{QP} = \sum_{i}^{CP} A_i + M_n \qquad \vec{v}_{QP} m_{QP} = \sum_{i}^{CP} \vec{v}_i m_i \qquad E^*_{QP} = \sum_{i}^{CP} \tfrac{3}{2} K_{\perp,i} + M_n \langle K_n \rangle - Q$$

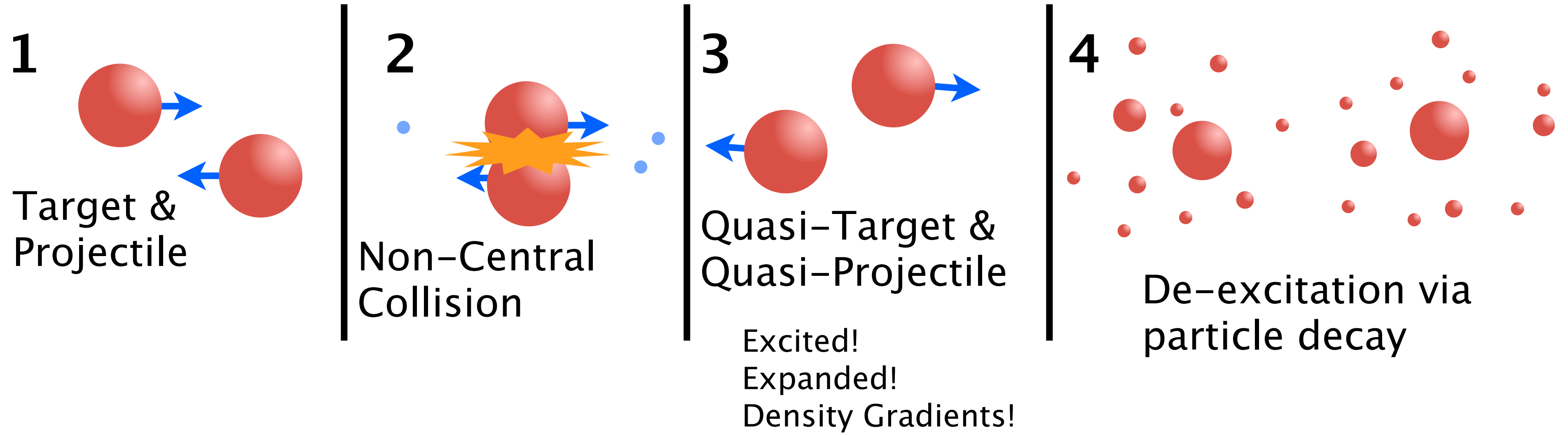




Excitation energy sharing is in reasonable agreement with previously published data:
~ 40% Charged particle KE
~ 40% Q value
~ 20% Neutrons

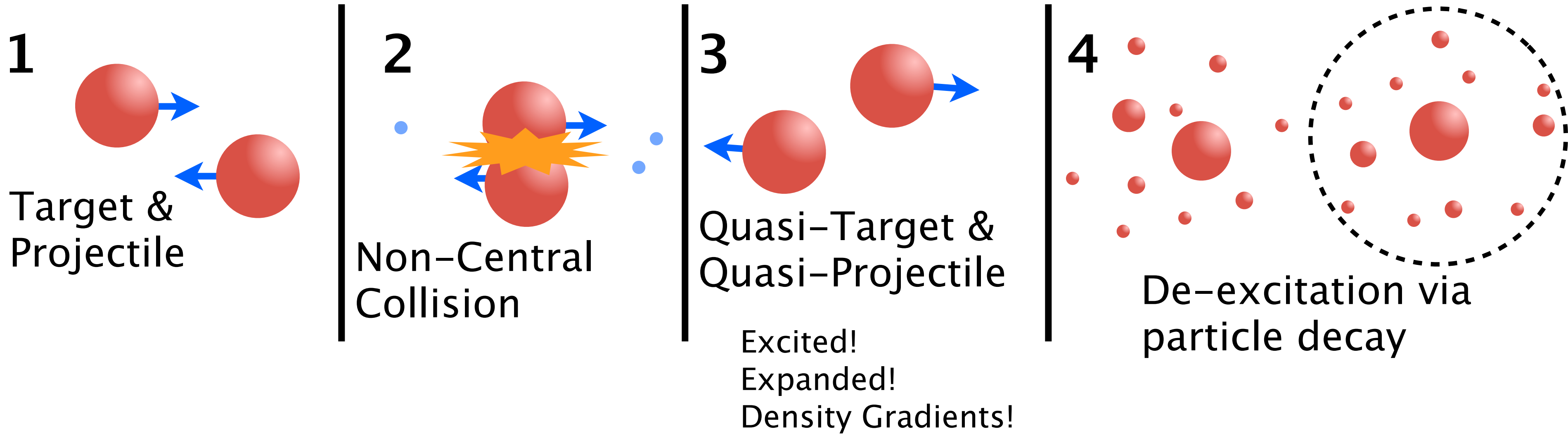
Lefort et al. PRC 64, 064603 (2001)
5-15 GeV/c Hadrons on Au

Reconstructed QP



- We have reconstructed the QP
  - E*/A, Asymmetry (n-p)
- We have thermometers to measure its temperature
- What can we learn?

Reconstructed QP



- We have reconstructed the QP
  - E*/A, Asymmetry (n-p)
- We have thermometers to measure its temperature
- What can we learn?

Thermometer: MQF

Momentum Quadrupole Fluctuation Temperature

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

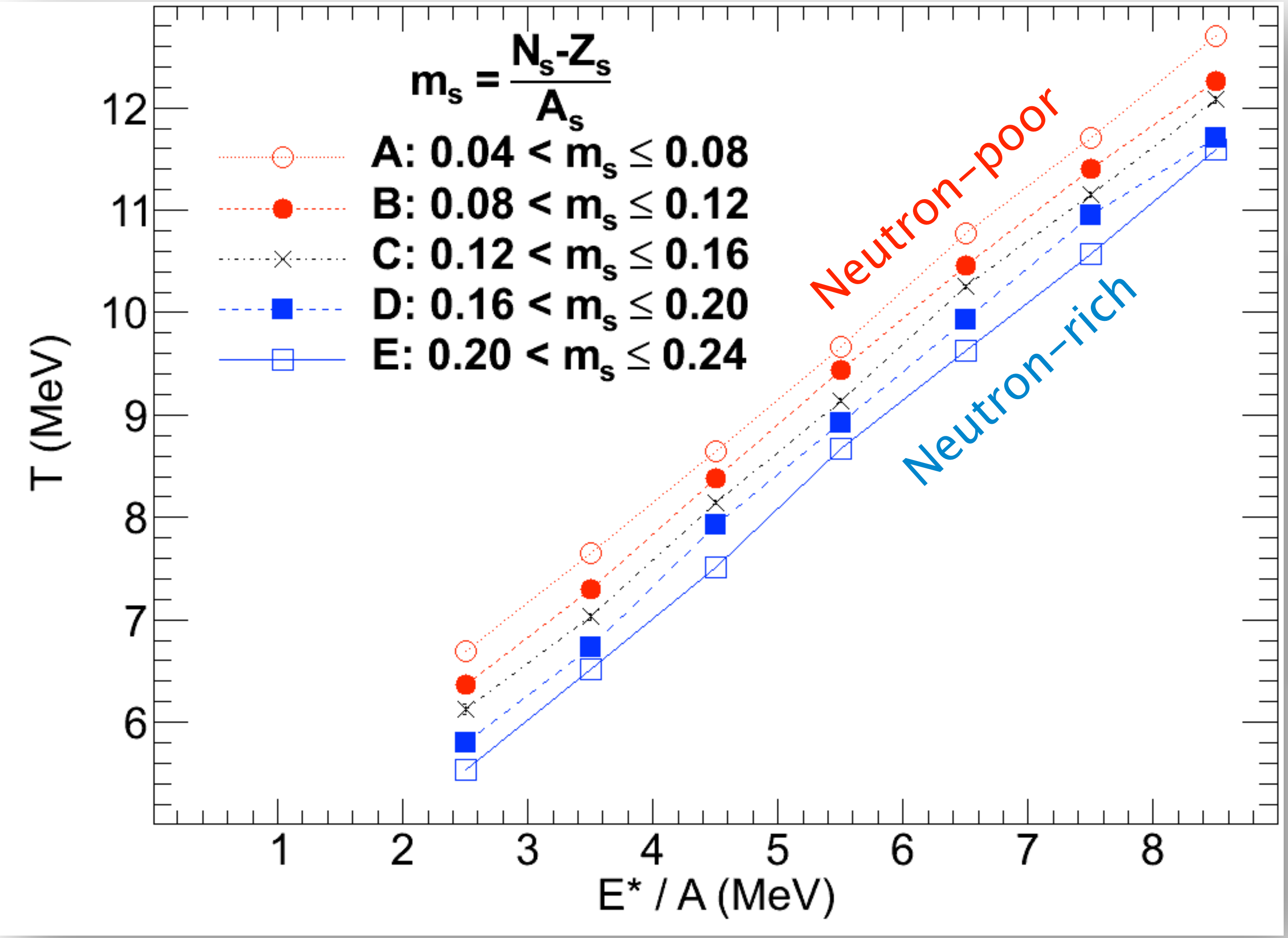
$$\sigma_{xy}{}^2 = 4m^2T^2$$

H. Zheng & A. Bonasera, PLB **696**, 178 (2011)
S. Wuenschel, NPA 843, 1 (2010)
S. Wuenschel Ph.D. Thesis, TAMU (2009)

Asymmetry Dependent Temperature

MQF Thermometer, Protons as Probe

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



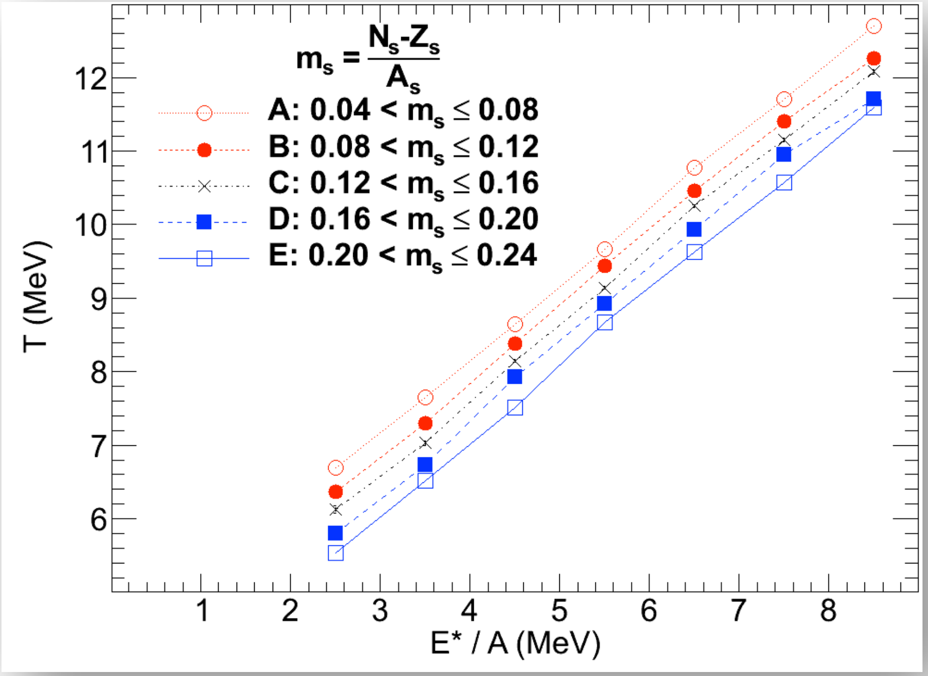
Larger Asymmetry
→ Lower Temperature

> 1 MeV shift!

Evenly Spaced

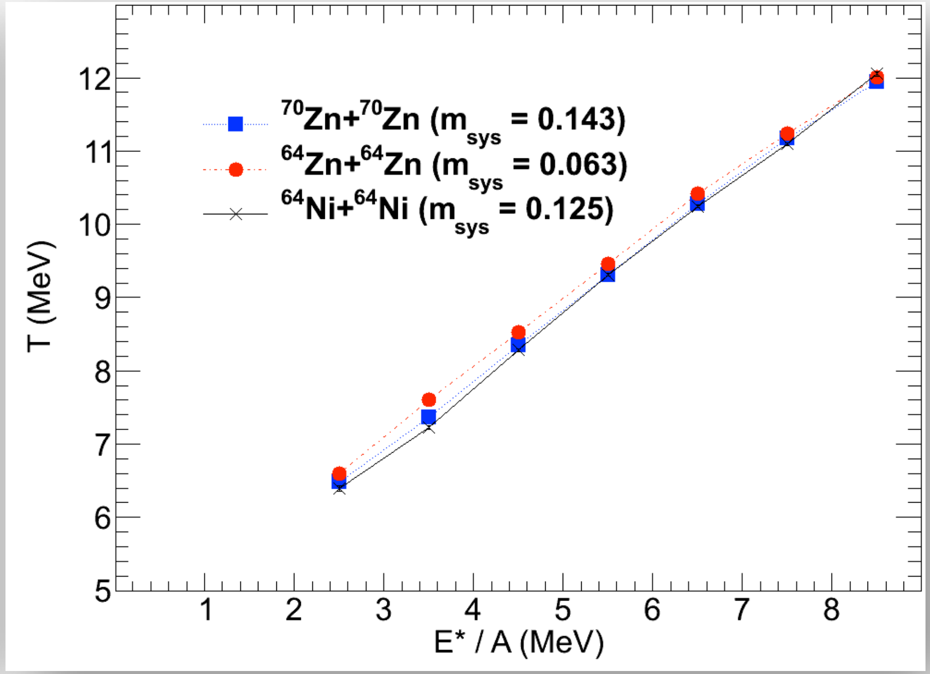
Importance of Reconstruction

Asymmetry of Isotopically Reconstructed Source



Asymmetry of Initial System

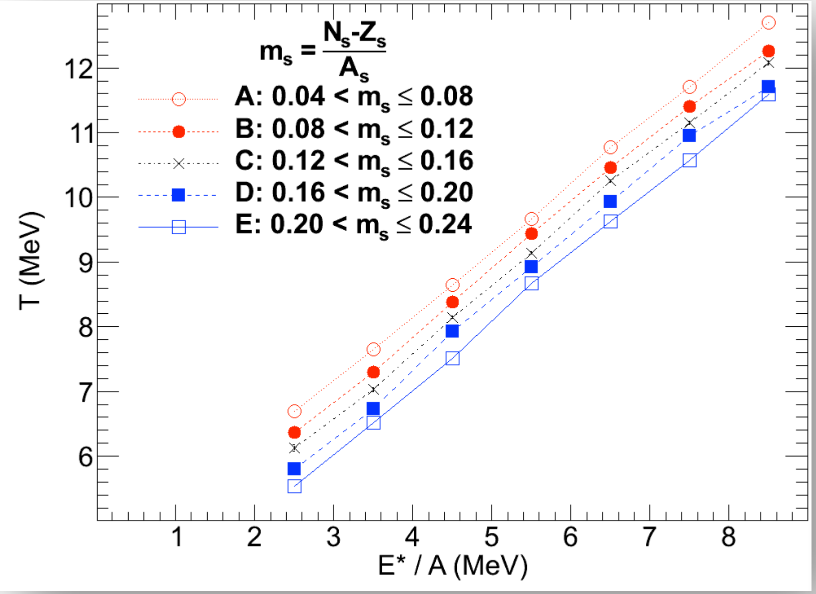
Each system:
Broad range of asymmetry

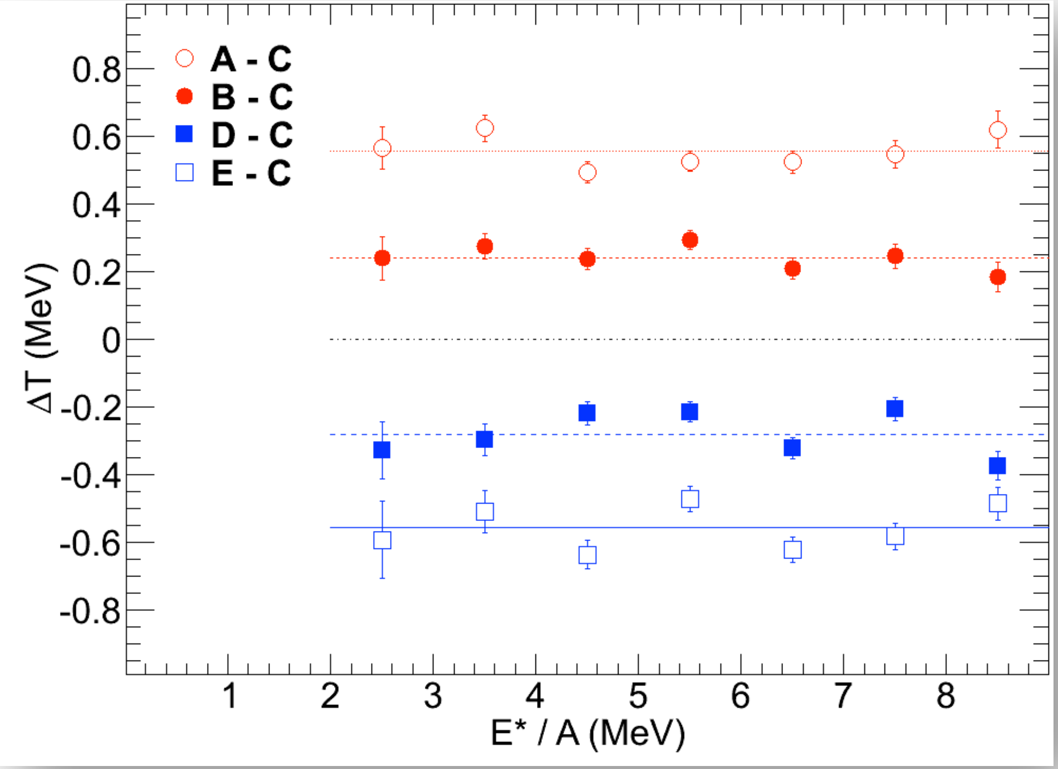


Larger Asymmetry
→ Lower Temperature
Observed either way, but…

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

Excitation Independence





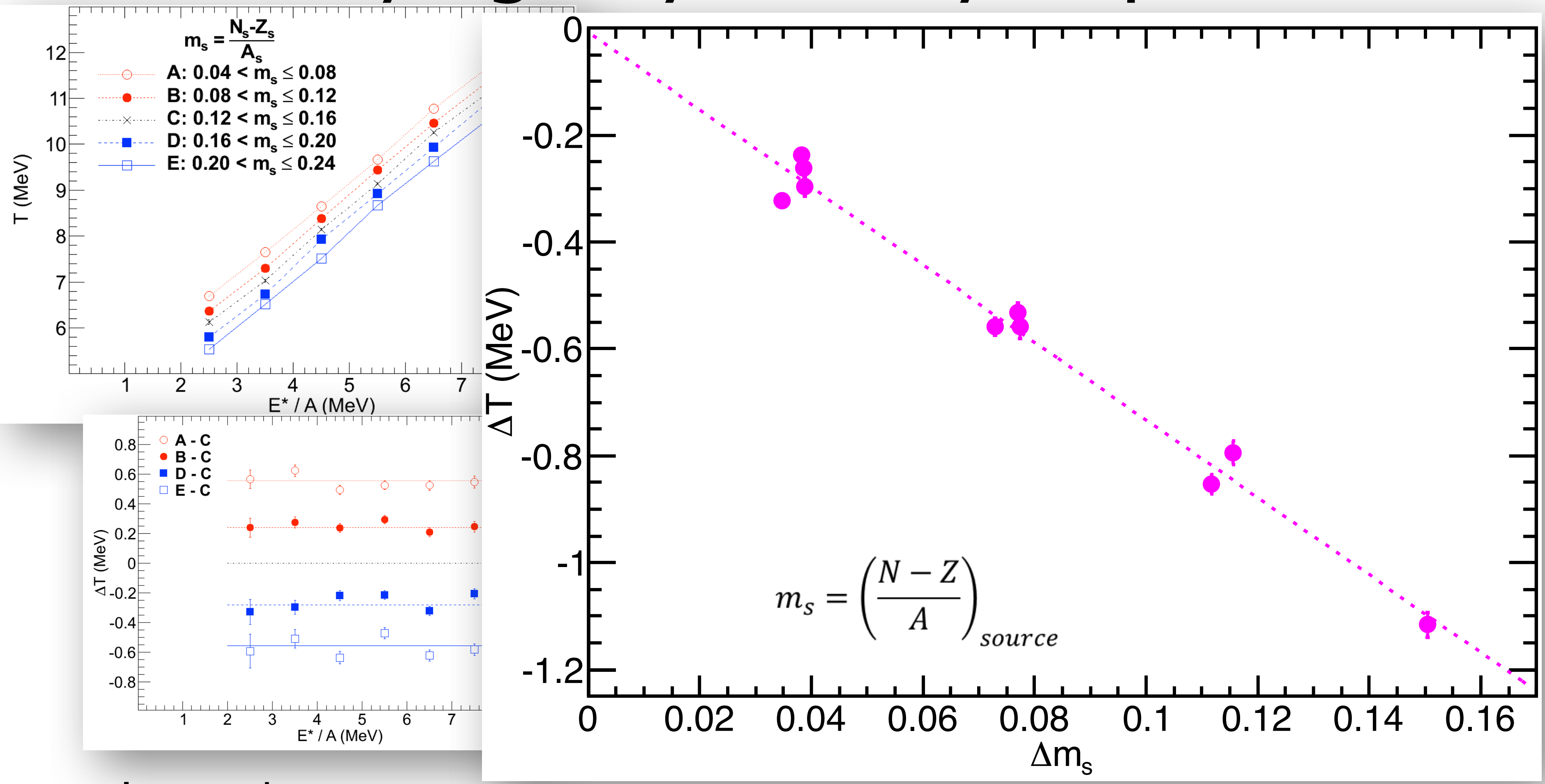
Larger Asymmetry
→ Lower Temperature

Temperature shift does not show a trend with excitation.

Horizontal lines indicate averages

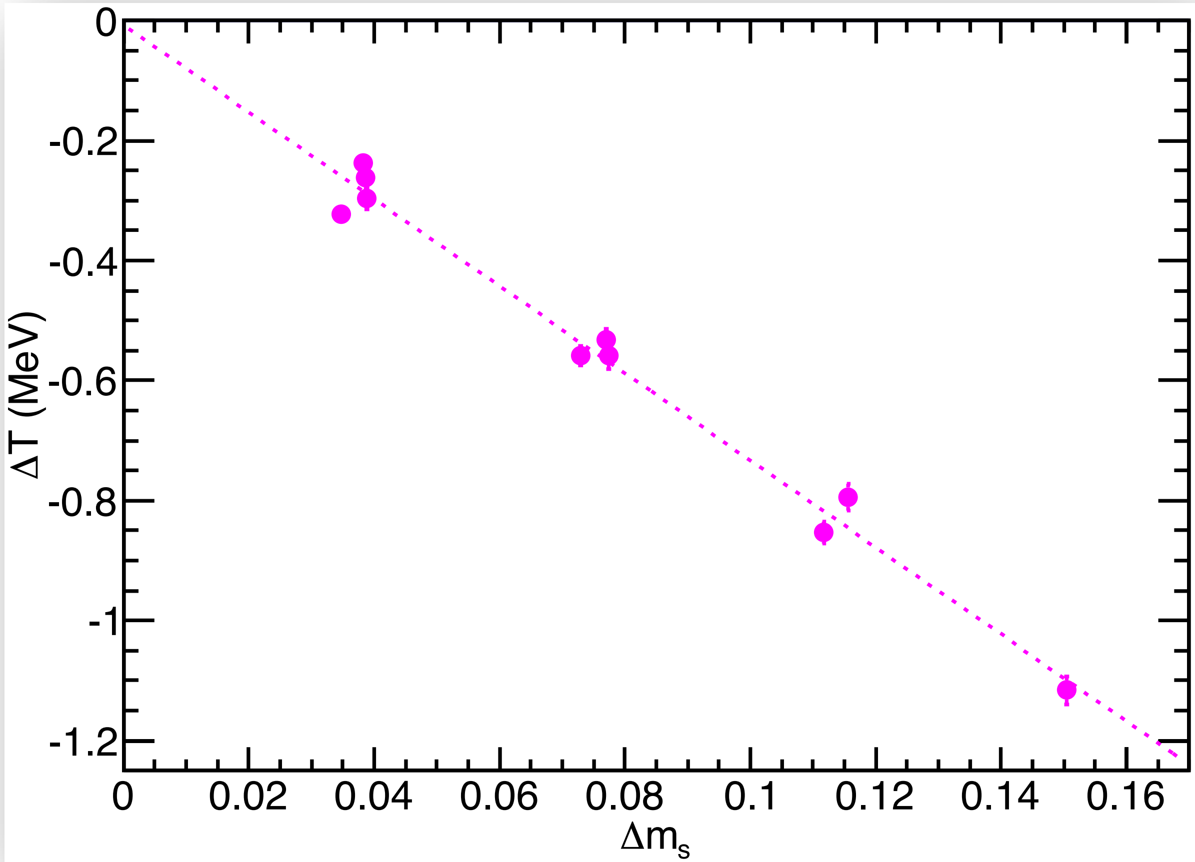
4 of 10 pairwise differences shown

Quantifying Asymmetry Dependence



- Increasing ms
  → lower temperature
- Linear relationship
- Quantitative: change of 0.15 units of ms corresponds to a temperature decreased by 1.1 MeV

Robust Asymmetry Dependence



We vary the neutron kinetic energy to physically unrealistic extremes:

- Neutron KE to 50%: slope ΔT/Δms decreases only to 75%
- Neutron KE to 150%: slope ΔT/Δms increases only to 125%

➡ Some uncertainty in magnitude of the correlation, but not in its existence

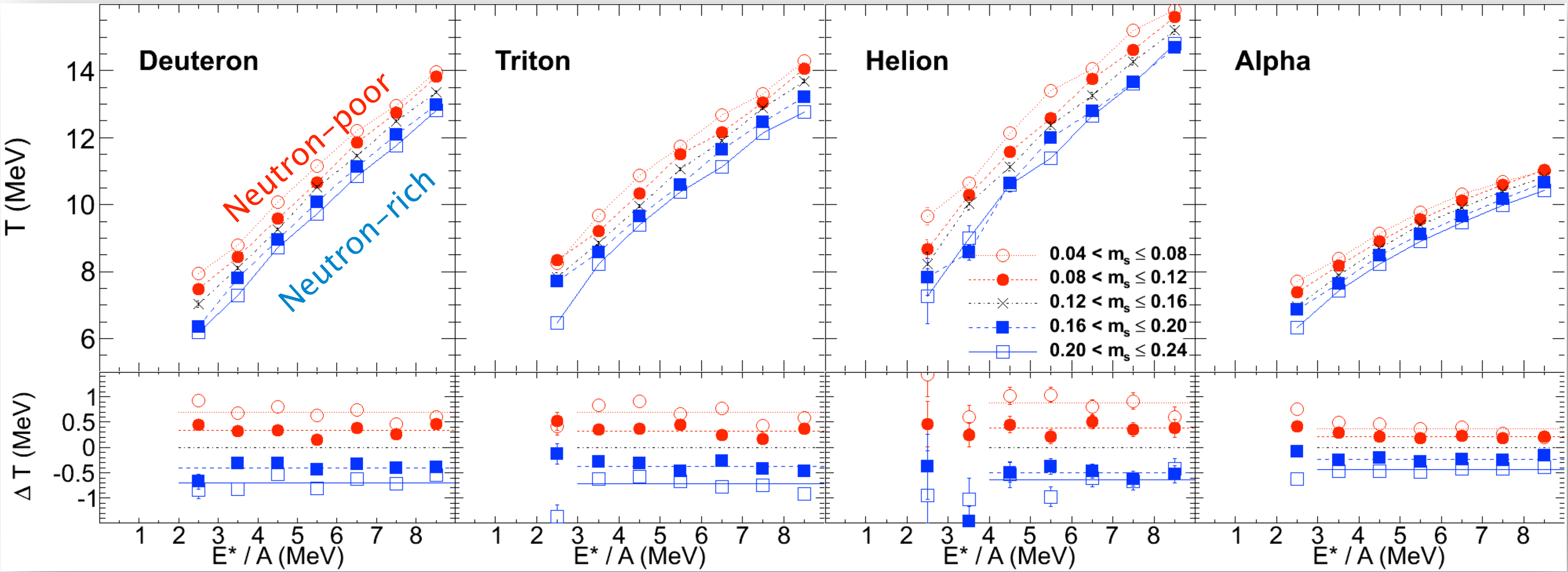
Asymmetry Depenence

☑ MQF Protons

Do other probes of the temperature measure an asymmetry dependence?

Caloric Curves for LCPs: Dependence on Asymmetry

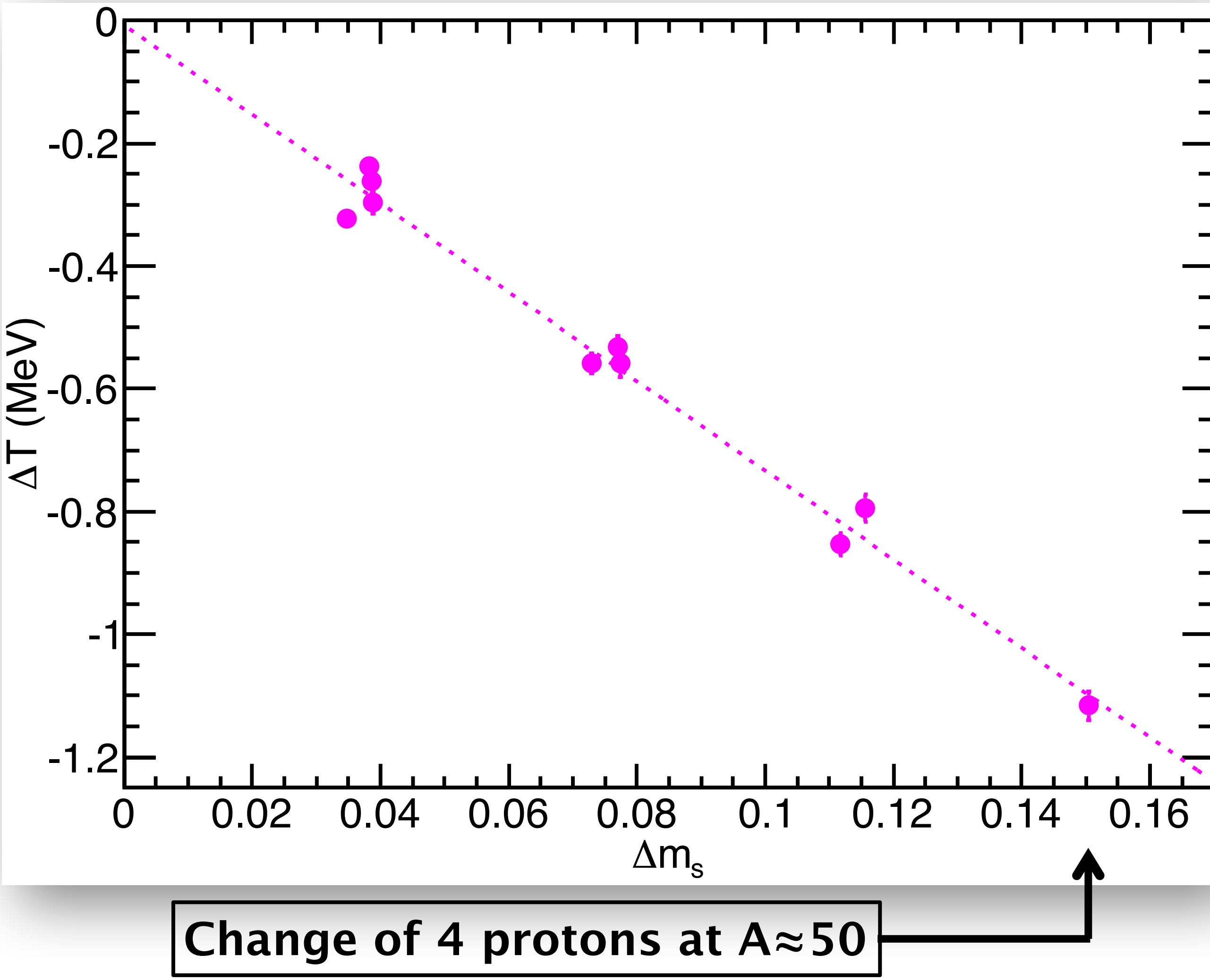
$$\sigma_{xy}{}^2 = 4m^2T^2$$



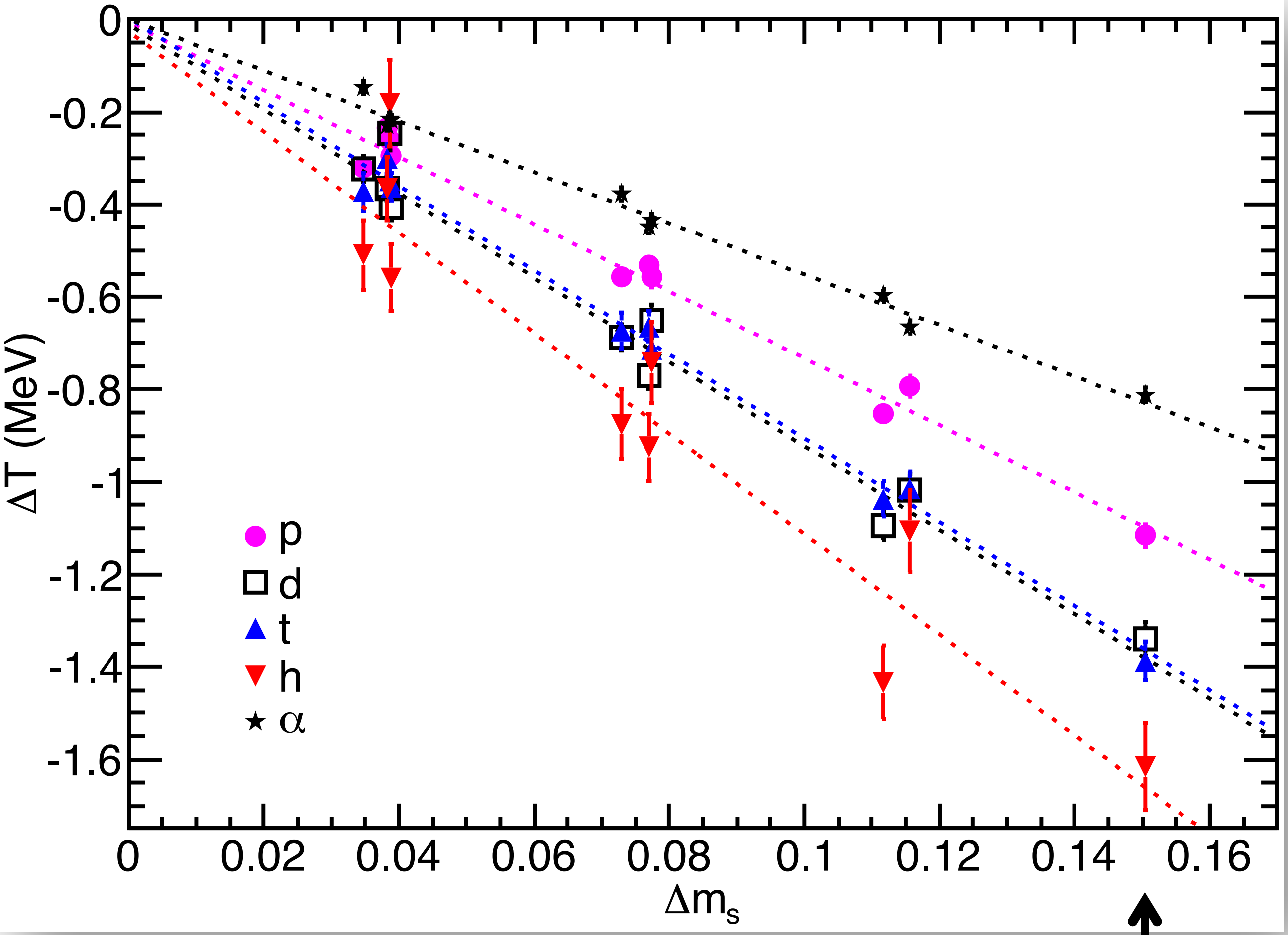
For All LCPs:
Larger Asymmetry
→ Lower Temperature

Temperature shift does not show a trend with excitation

Asymmetry Dependence of Temperature



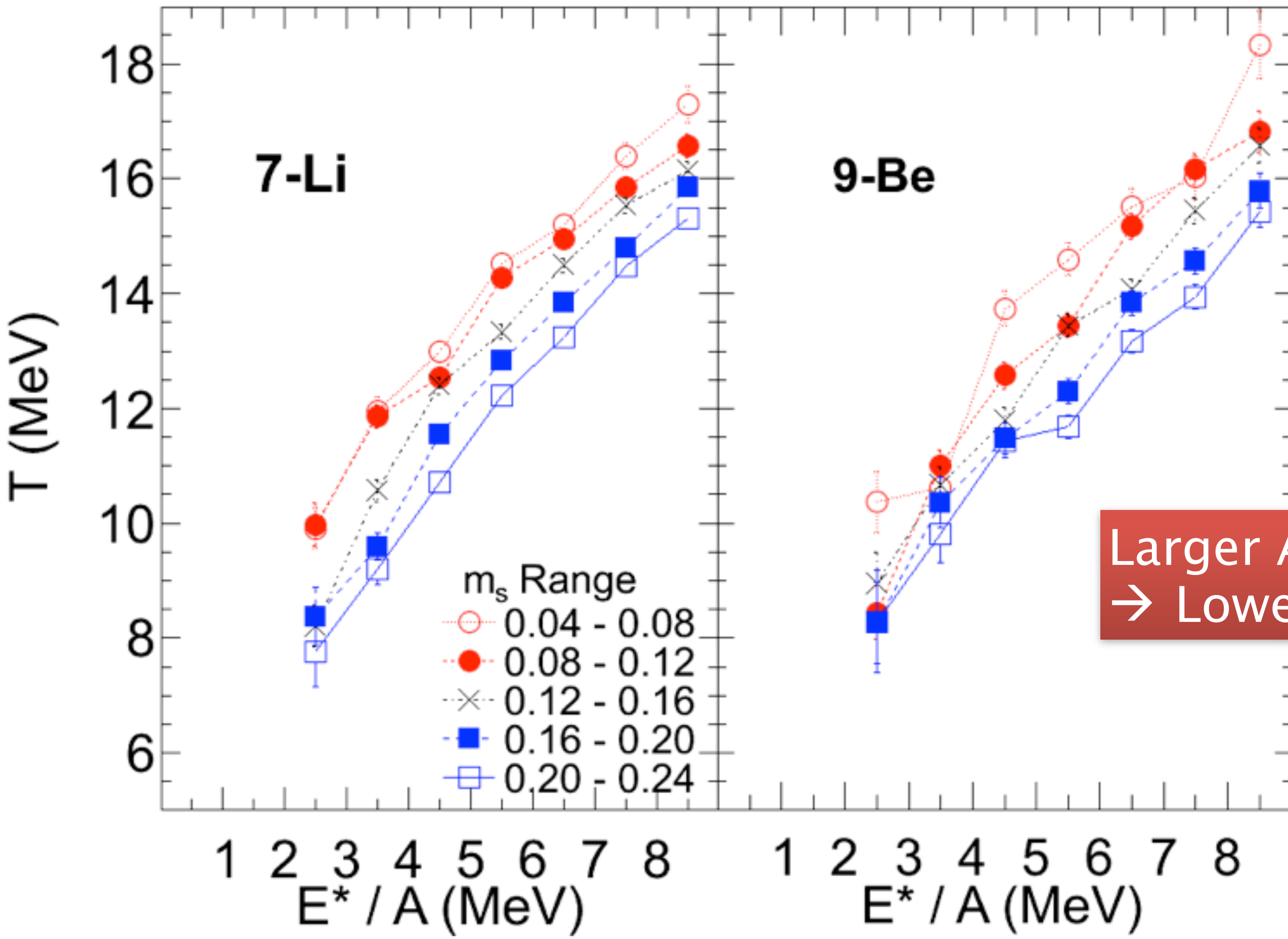
Asymmetry Dependence of Temperature



ΔT / Δm_s	
α:	−5.5
p:	−7.3
d:	−9.2
t:	−9.3
h:	−10.9

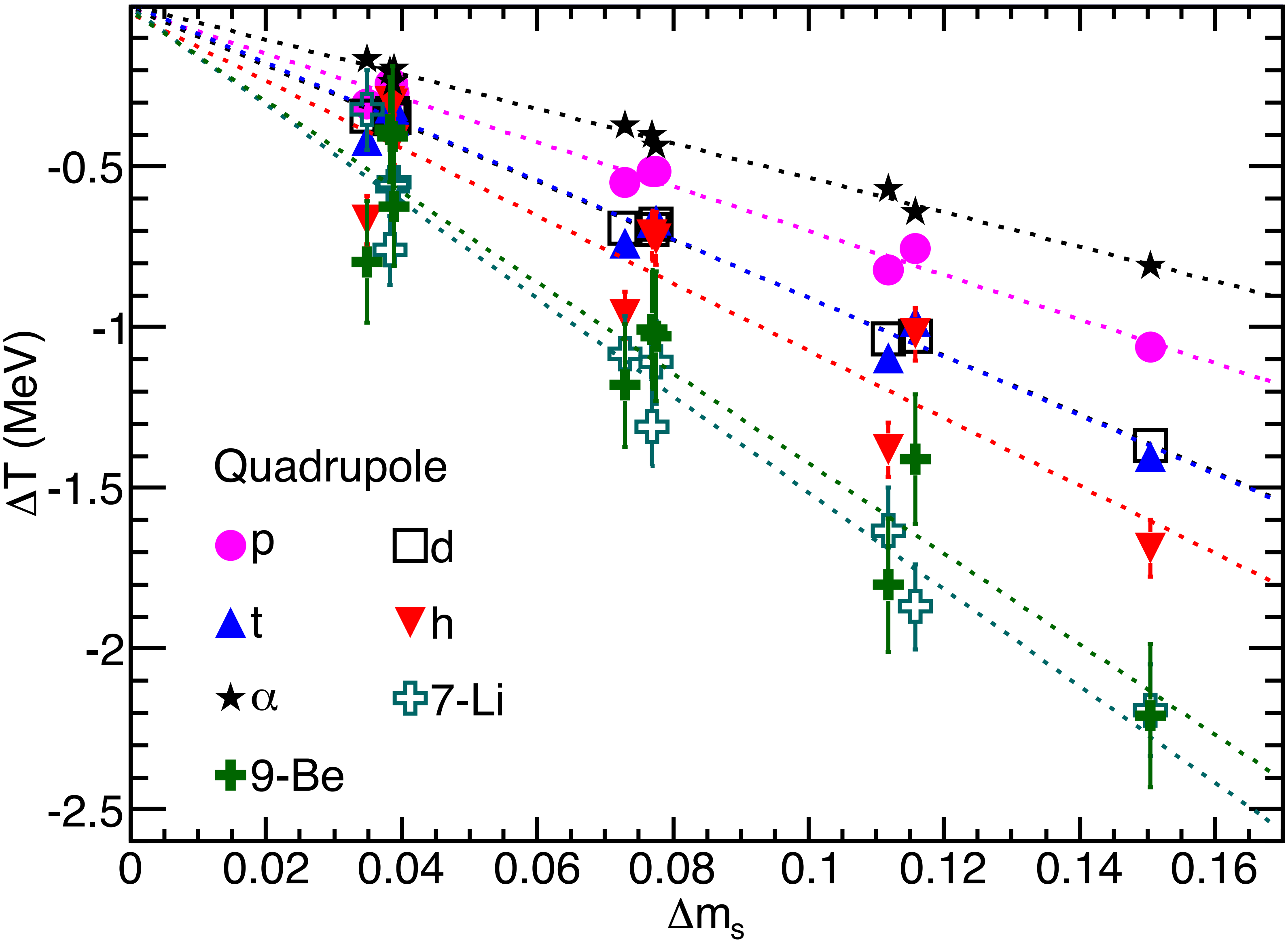
Change of 4 protons at A≈50

Temperatures Using Heavier Probes



Larger Asymmetry
→ Lower Temperature

Asymmetry Dependence of Temperature



Asymmetry Dependence

- ☑ MQF Protons
- ☑ MQF Deuterons
- ☑ MQF Tritons
- ☑ MQF Helion
- ☑ MQF Alphas
- ☑ MQF 7-Li
- ☑ MQF 9-Be

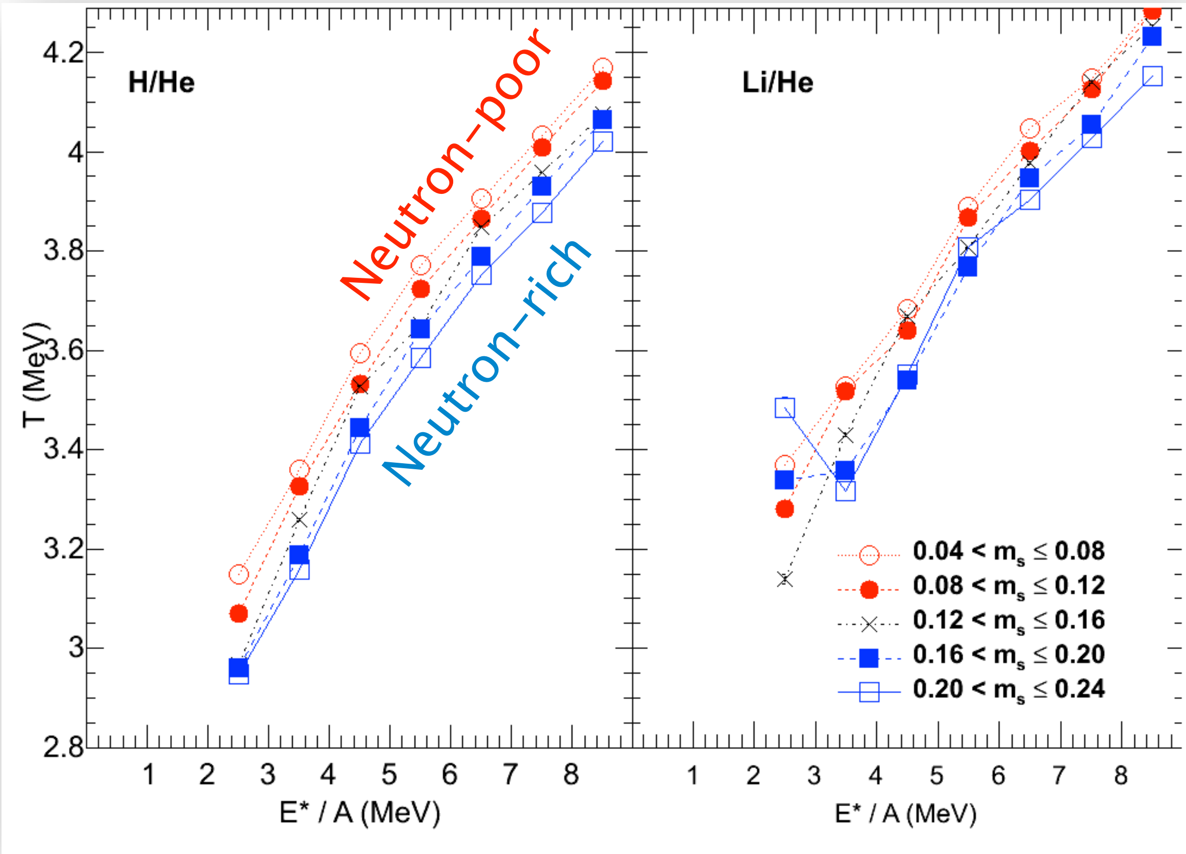
Do other thermometers measure an asymmetry dependence?

Albergo Thermometer

	H/He	Li/He
Double yield ratio	$$\mathbf{R} = \frac{\mathbf{Y(d)/Y(t)}}{\mathbf{Y(h)/Y(\alpha)}}$$	$$\mathbf{R} = \frac{\mathbf{Y(^6Li)/Y(^7Li)}}{\mathbf{Y(h)/Y(\alpha)}}$$
Account for binding energy differences and spin-degeneracies	$$\mathbf{T_{raw}} = \frac{\mathbf{14.3MeV}}{\mathbf{\ln(1.59R)}}$$	$$\mathbf{T_{raw}} = \frac{\mathbf{13.3MeV}}{\mathbf{\ln(2.18R)}}$$
~3% correction for secondary decay	$$\mathbf{T} = \frac{\mathbf{1}}{\frac{\mathbf{1}}{\mathbf{T_{raw}}} - \mathbf{0.0097}}$$	$$\mathbf{T} = \frac{\mathbf{1}}{\frac{\mathbf{1}}{\mathbf{T_{raw}}} + \mathbf{0.0051}}$$

Albergo et al., Il Nuovo Cimento **89**, 1 (1985)
Xi et al. PRC **59**, 1567 (1999)

Albergo Temperature: Asymmetry Dependent



Temperature is smaller than for MQF.
(Chemical vs Kinetic)

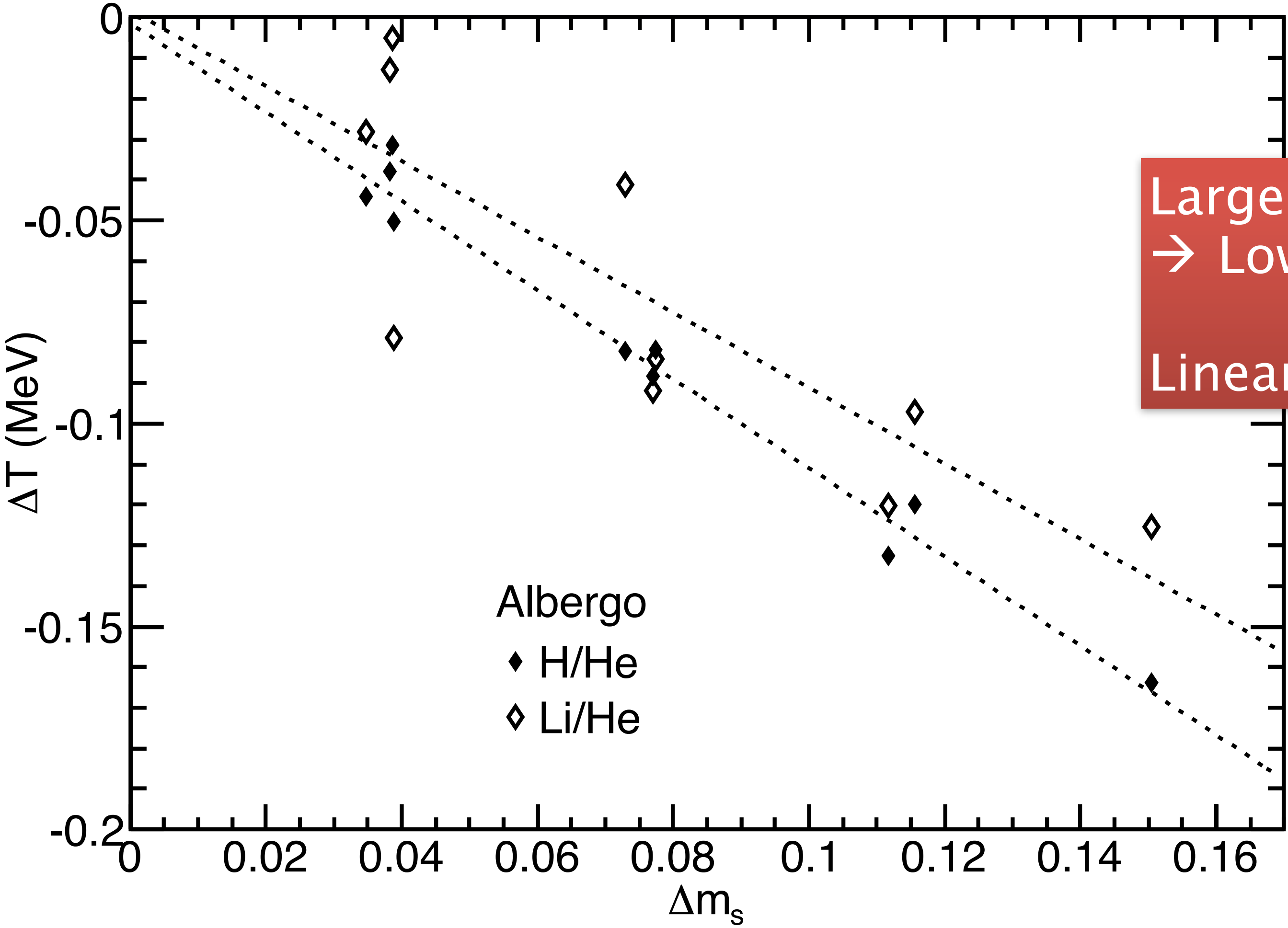
Asymmetry dependence is smaller than MQF.
(Lower Temperatures)

Key point:
Asymmetry dependence is clearly observed

Larger Asymmetry
→ Lower Temperature

Albergo: Asymmetry Dependence of T

Stronger dependence for MQF than for Albergo
- Smaller value of temperature for Albergo than MQF
- Different methods (chemical vs kinetic)



Larger Asymmetry
→ Lower Temperature

Linear Relation

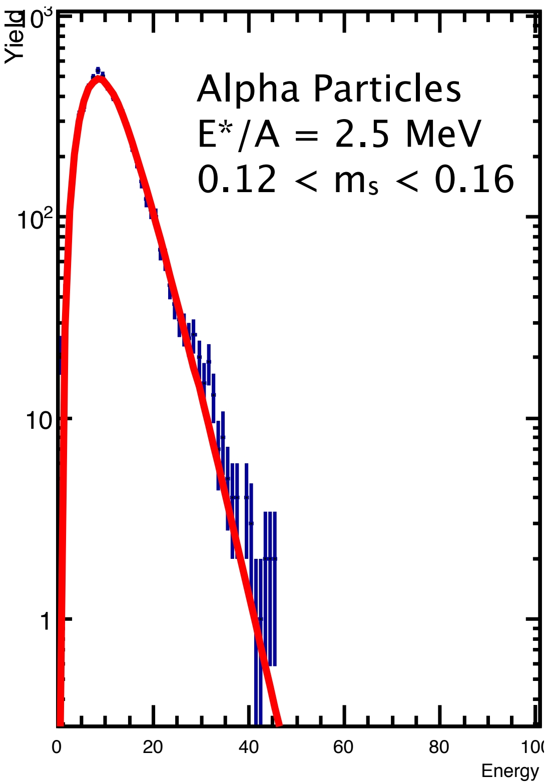
Asymmetry Dependence

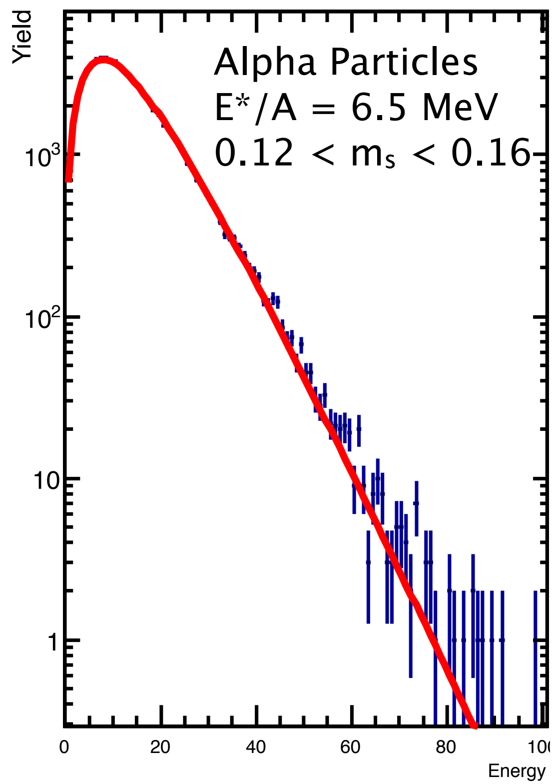
- ☑ MQF Protons
- ☑ MQF Deuterons
- ☑ MQF Tritons
- ☑ MQF Helion
- ☑ MQF Alphas
- ☑ MQF 7–Li
- ☑ MQF 9–Be
- ☑ Albergo H/He
- ☑ Albergo Li/He

Do any other thermometers measure an asymmetry dependence?

Slope Temperatures

Kinetic Energies in the QP frame
$\theta < 90$ degrees





Maxwell-Boltzmann with Diffuse Barrier

$$Y(E) \propto (E-B)\exp\left(-\frac{E}{T}\right); \quad E \geq B+T$$

$$Y(E) \propto C'(E-B')^D \exp\left(-\frac{E}{T}\right) \quad B' < E < B+T$$

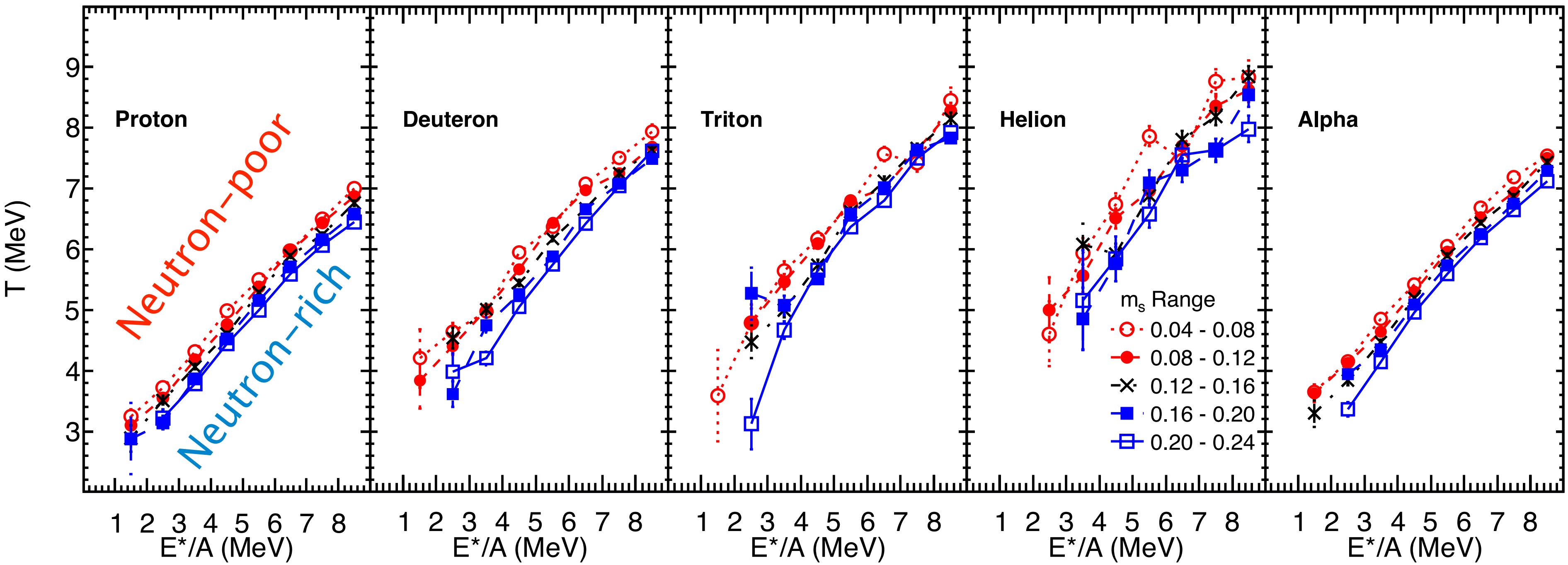
$$Y(E) = 0 \quad E \leq B'$$

$$C' = \frac{T}{(DT)^D} \qquad B' = (1-D)T + B$$

B: barrier parameter
D: diffuseness parameter

Yanez, Phys. Rev. C 68, 011602(R) (2003)

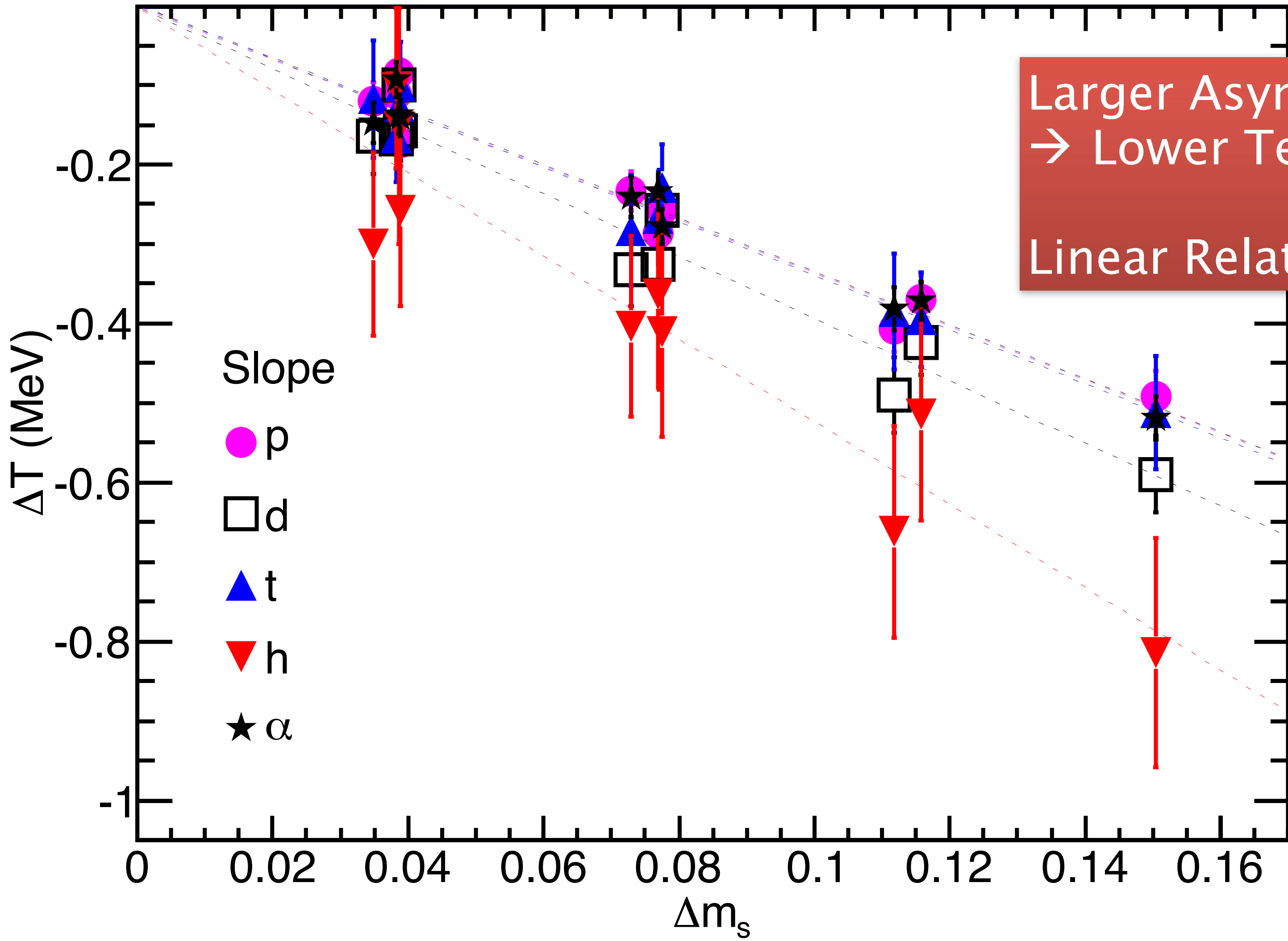
Slope Temperature: Asymmetry Dependent



Key point:
Asymmetry dependence is clearly observed

Larger Asymmetry
→ Lower Temperature

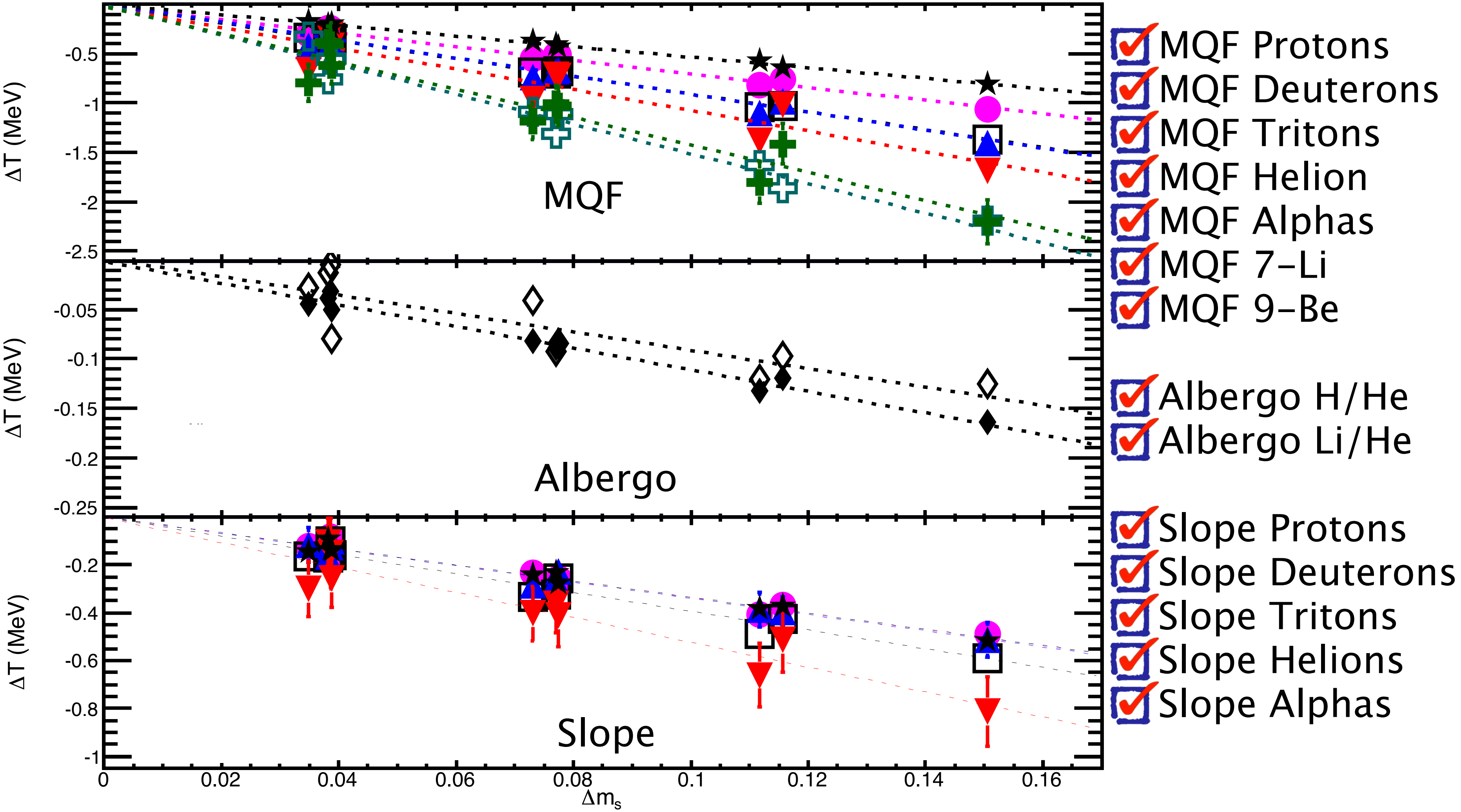
Asymmetry Dependence of Slope Temperature



Larger Asymmetry
→ Lower Temperature

Linear Relation

Q: How Much Cooler Would It Be With Some More Neutrons?



A.B. McIntosh et al. PLB 719, 337 (2013)
A.B. McIntosh et al. PRC 87, 034617 (2013)
A.B. McIntosh et al. EPJA special issue

A: Depends on the thermometer, but it would be cooler.

SUMMARY & OUTLOOK

- Isotopically reconstructed QP sources
- Three methods, multiple probes
  → 14 ways total to extract temperature
- All 14 temperature probes show a dependence of the caloric curve on the asymmetry
- **Neutron Rich → Lower Temperature**
  - **Linear relationship**
- Source composition matters, not system

- High-statistics CoMD calculation underway
- 3 equations of state (asy-soft, -stiff, -superstiff)
- Investigate sensitivity of the caloric curve to the EOS in the model calculations.

Acknowledgements

Collaborators

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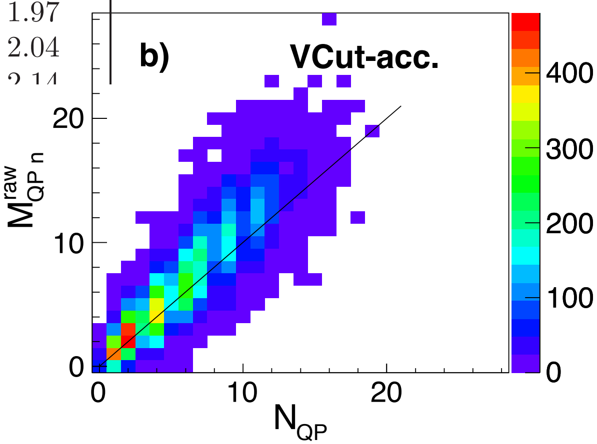
Neutron Uncertainty

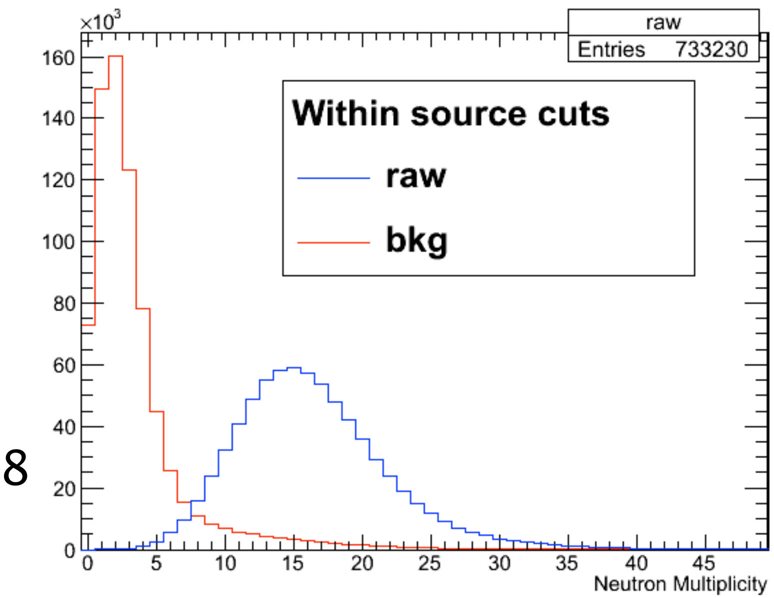
$$\sigma^2_{\mathbf{raw}} = \sigma^2_{\mathbf{true}} + \sigma^2_{\mathbf{eff}} + \sigma^2_{\mathbf{bkg}}$$

N_{QP}	$\langle M^{raw}_{QP_n} \rangle$	$\sigma(M^{raw}_{QP_n})$
	HIPSE	
0	1.46	1.10
1	2.13	1.21
2	3.02	1.64
3	3.67	1.68
4	4.06	1.75
5	4.72	1.88
6	5.28	1.97
7	5.94	2.04
8	6.59	2.14

raw width: 5.36
width due to efficiency: < 2.1 (worst case)
efficiency: 9% effect



raw width: 5.36
width due to background: 1.8
efficiency: 6% effect



Net effect: we know the QP neutron multiplicity to within 11% (1σ).

Marini et al., NIMA 707, 80 (2013)

Calculation of Neutron Uncertainty

We know the QP neutron multiplicity to within 11% (1σ).
How big is this?

excitation

For a source of 50 nucleons where 5 become free neutrons, the free neutrons contribute 0.97 MeV/nucleon to the excitation energy.

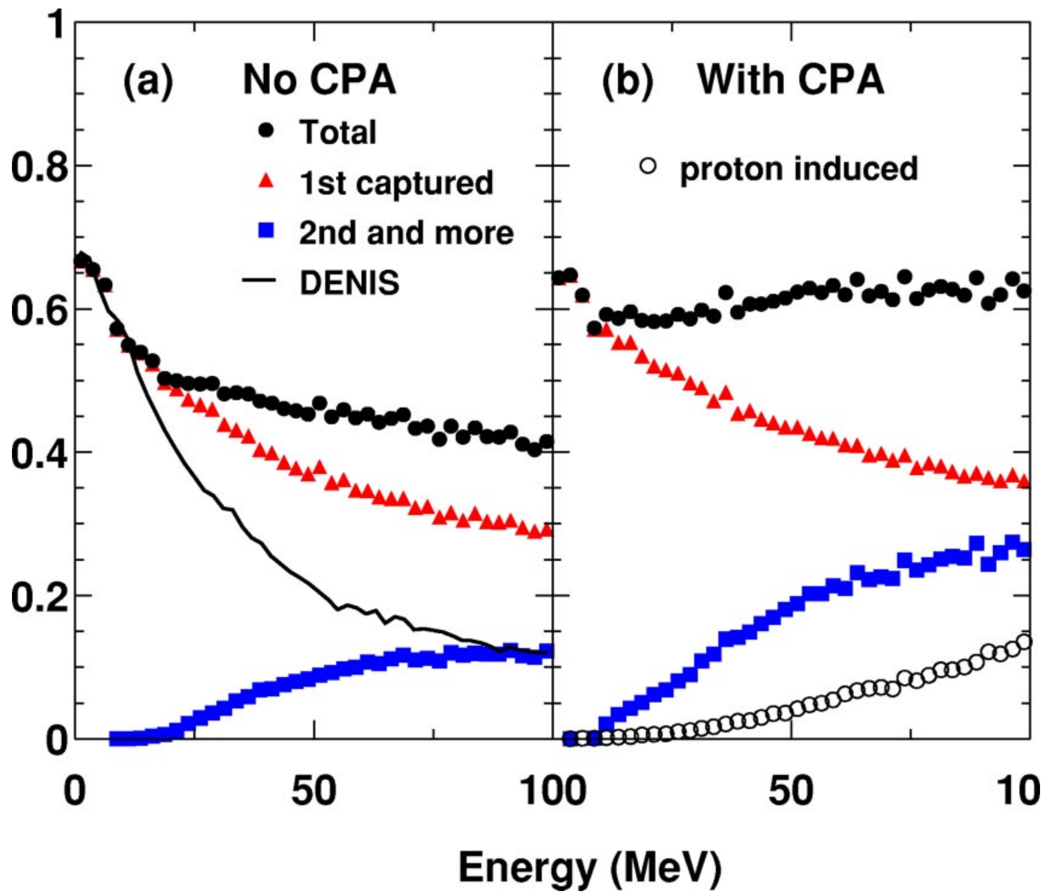
An uncertainty of 11% on the free neutron multiplicity corresponds to an uncertainty of 0.11 MeV/nucleon.

This uncertainty of 0.11 MeV/nucleon is significantly smaller than the spacing between even the closest caloric curves.

asymmetry

For a source of 50 nucleons where 5 become free neutrons, an error of 1 neutron corresponds to a 2σ variation. It would require an error of 4σ to shift from one asymmetry bin to another.

Neutron Ball Efficiency



Wada et al., PRC 69, 044610 (2004)