How Much Cooler Would It Be With Some More Neutrons?

Asymmetry Dependence of the Nuclear Caloric Curve

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Asymmetry Dependence of the Nuclear Caloric Curve

- 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

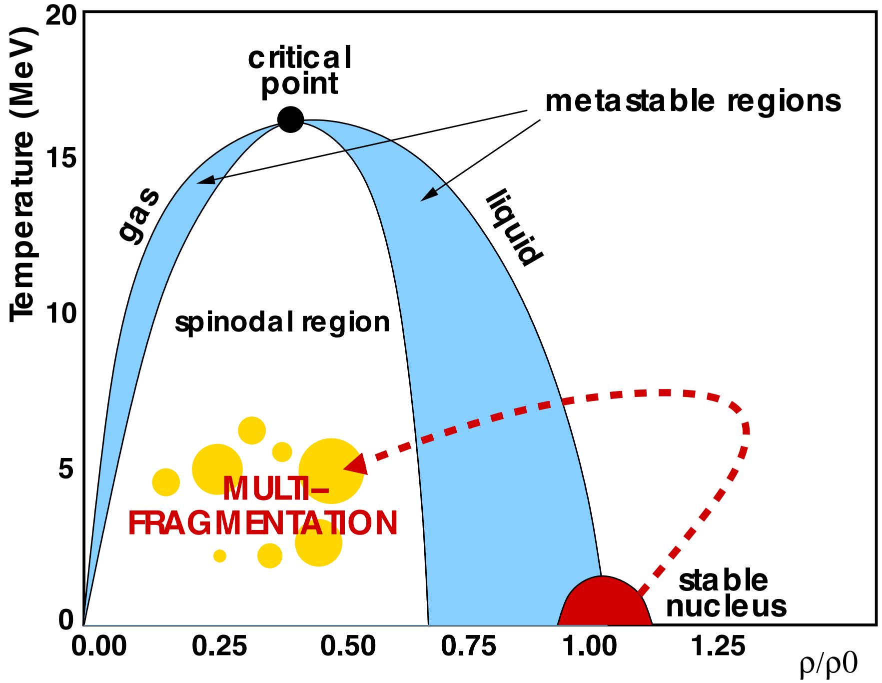
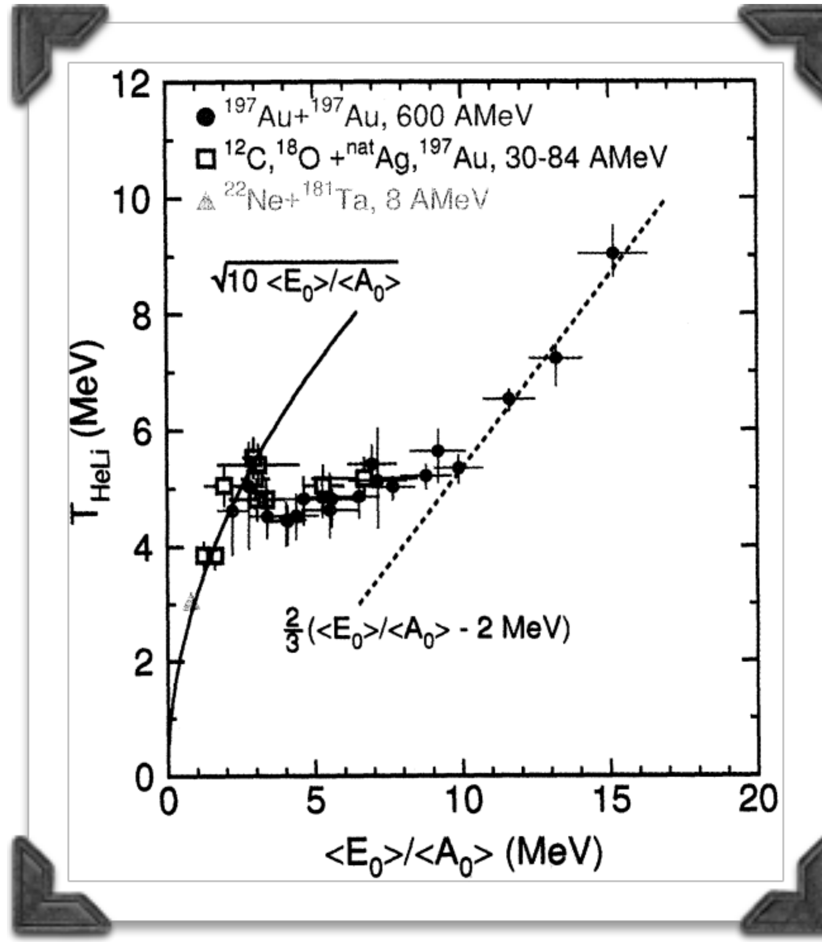


Figure: Ketel Turzo, Ph.D. Thesis, Universite Lyon (2002)

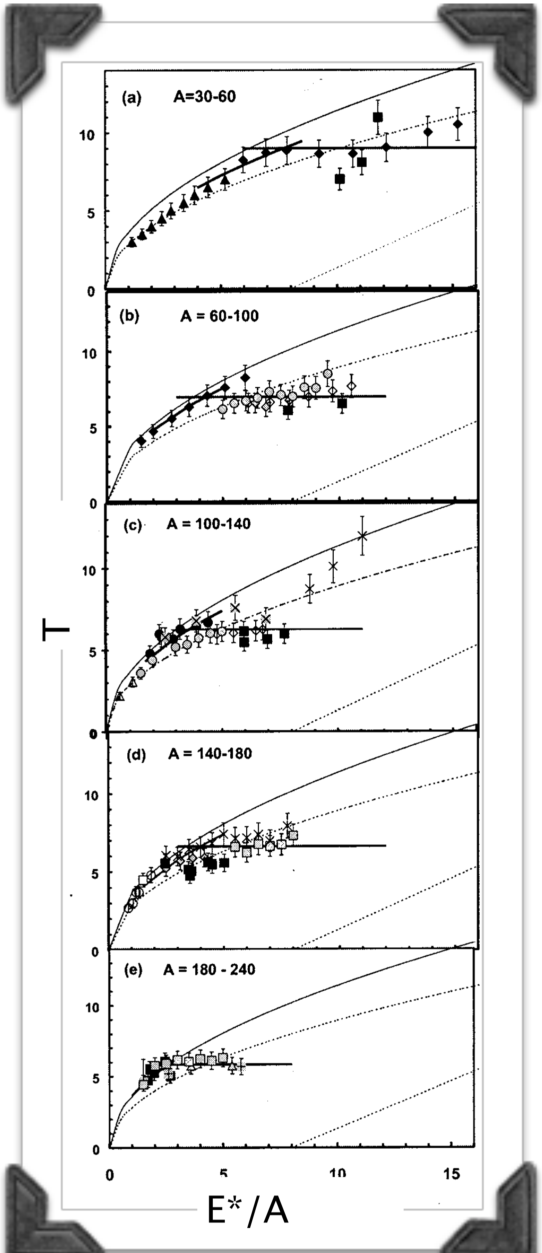
Nuclear Caloric Curve

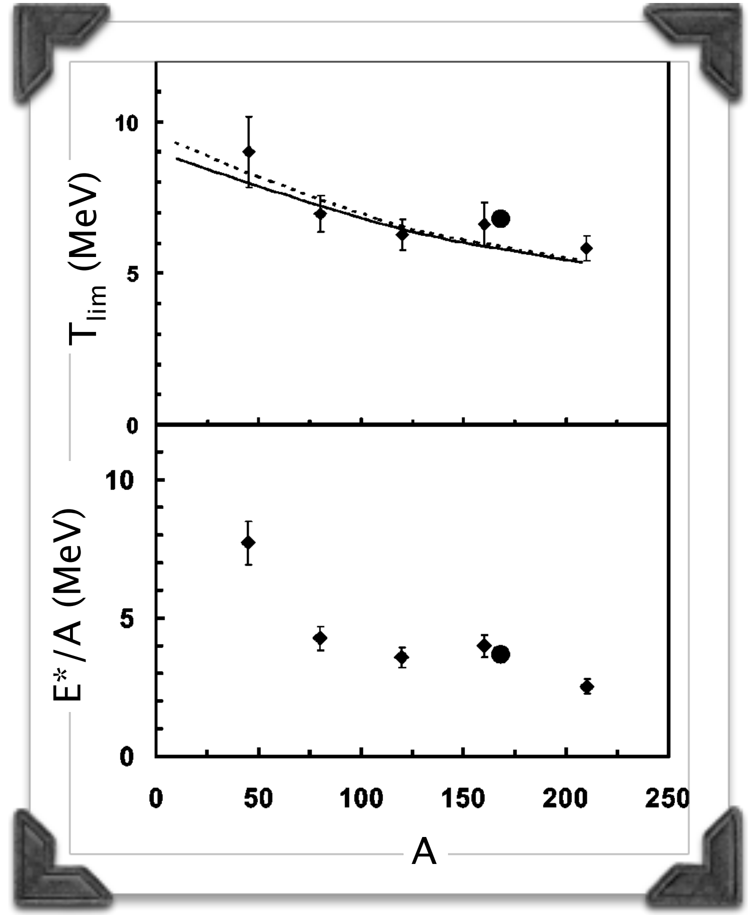
- Essential Piece of Nuclear Equation of State: T vs E*/A
- Search for & Study of Phase Transition
  - Liquid to Vapor
  - Evaporation to Multifragmentation



Pochodzalla et al. PRL 75, 1040 (1995)

Nuclear Caloric Curve: Mass Dependence





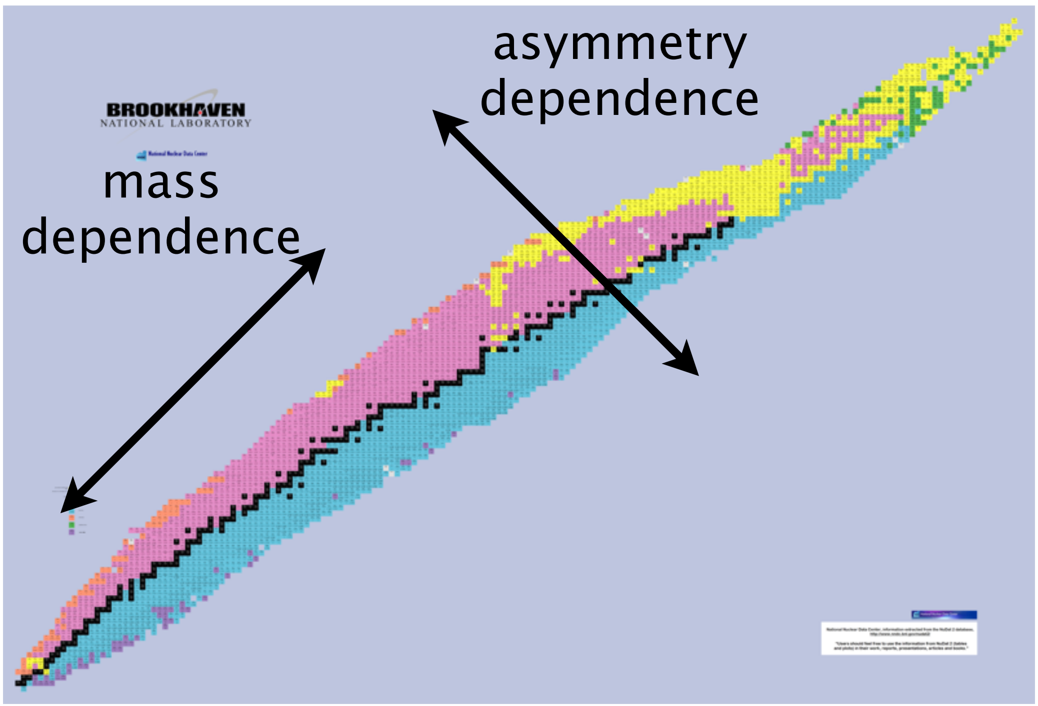
With increasing mass:

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

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

McIntosh, NuSym13

Caloric Curve: Asymmetry Dependence?



Mass Dependence of the caloric curve is measured.

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

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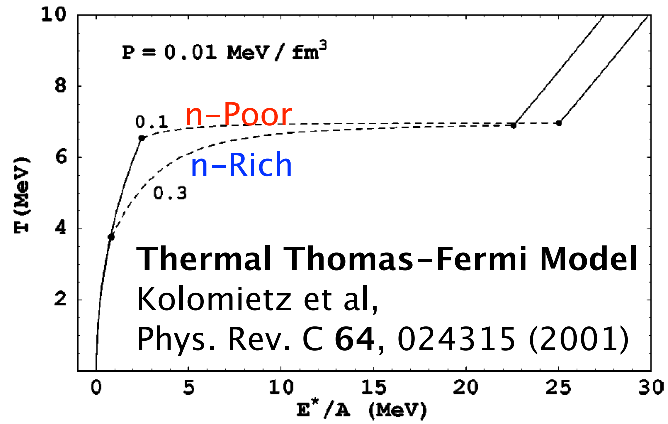
http://en.wikipedia.org/wiki/File:NuclideMap_stitched_small_preview.png

Caloric Curve: Asymmetry Dependence?

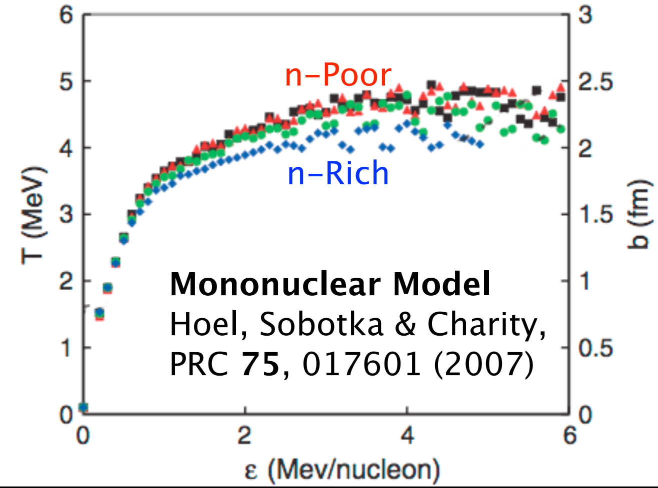
Theory

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

Neutron-rich
→ Lower T

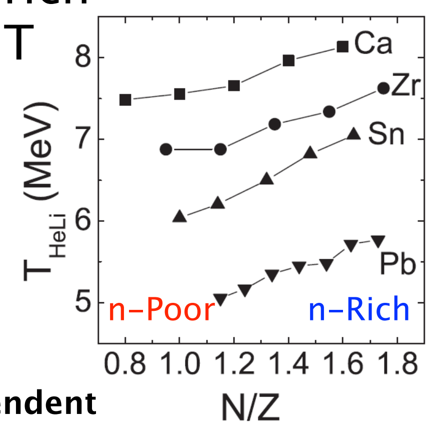


Thermal Thomas-Fermi Model
Kolomietz et al,
Phys. Rev. C **64**, 024315 (2001)

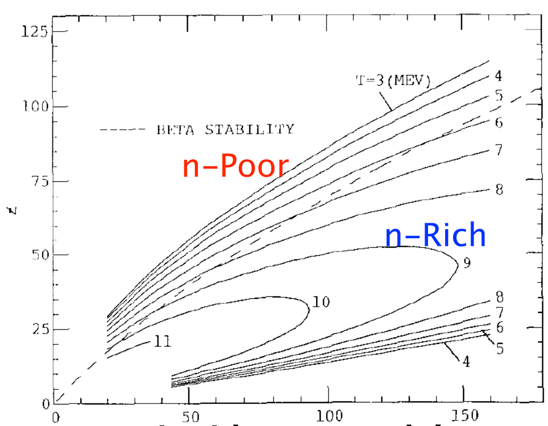


Mononuclear Model
Hoel, Sobotka & Charity,
PRC **75**, 017601 (2007)

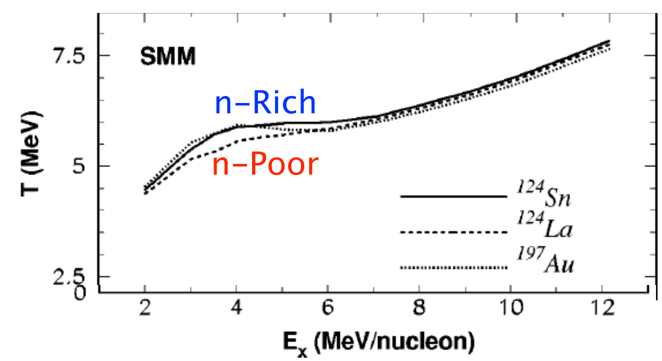
Neutron-rich
→Higher T



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



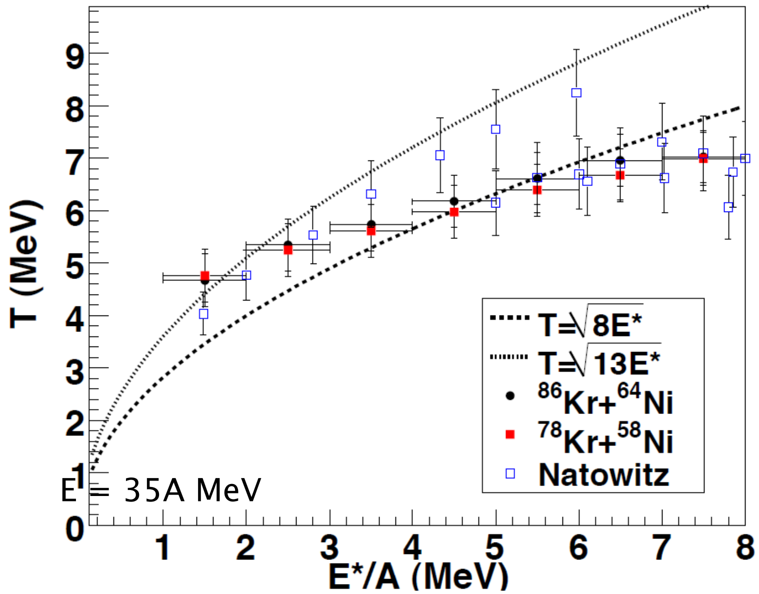
Hot Liquid Drop Model
Besprosvany & Levit
Phys. Lett B **217**, 1 (1989)



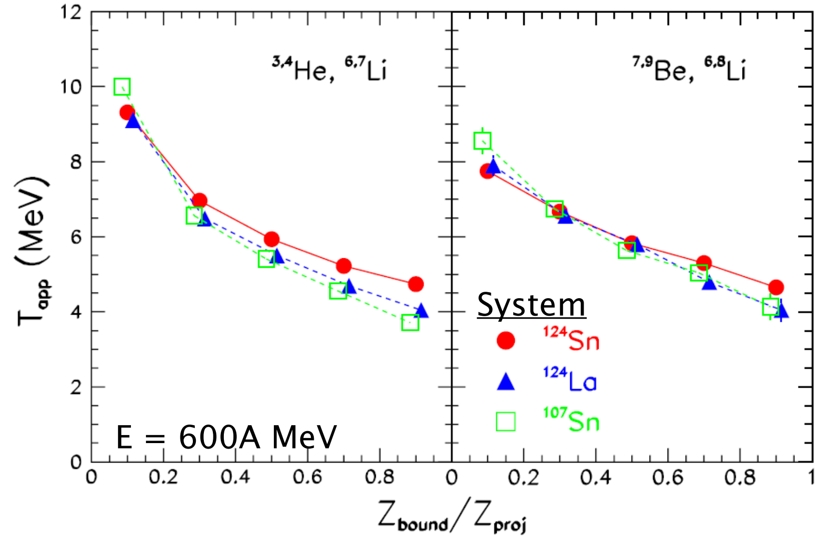
Statistical Multifragmentation Model
Ogul & Botvina, Phys. Rev. C **66**, 051601 (2002)

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

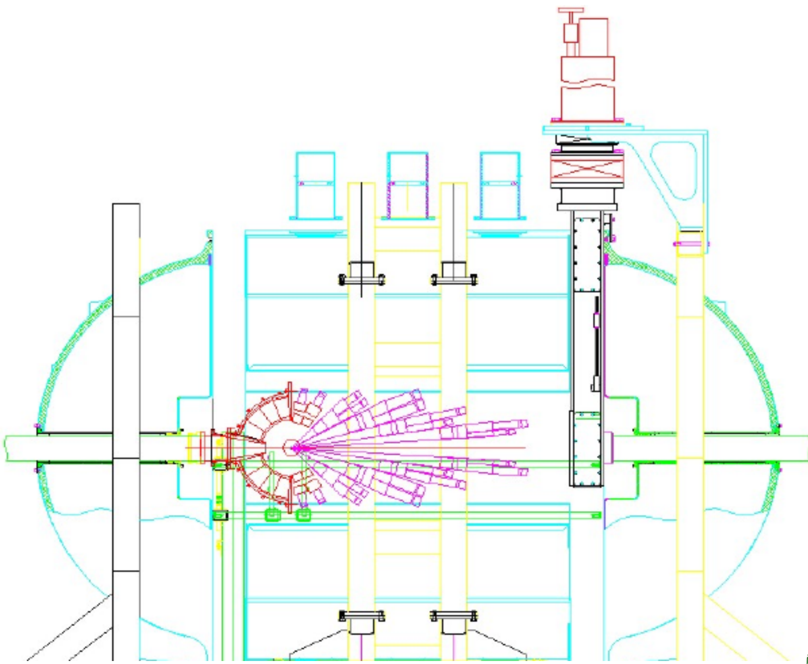
Possible dependence on asymmetry, but not for all impact parameters.

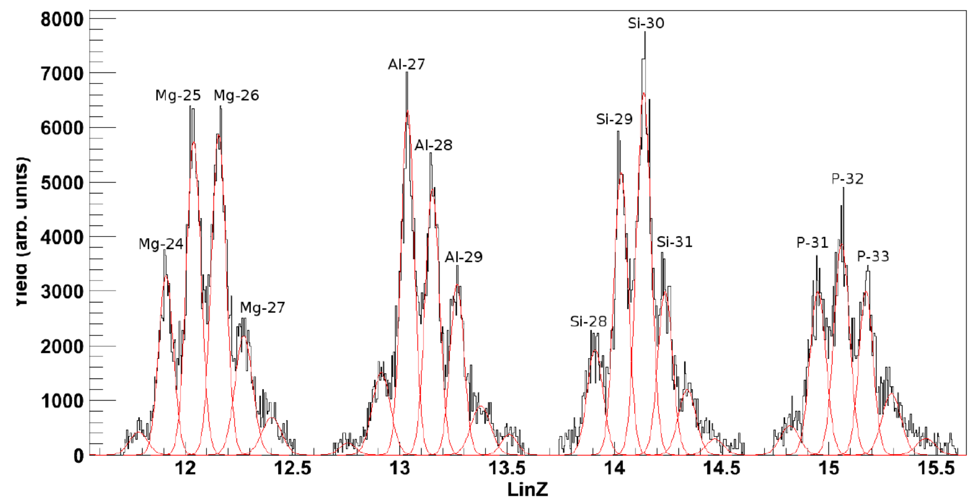
Non-observation:
Selection was on system composition.
Should use **reconstructed-source composition.**

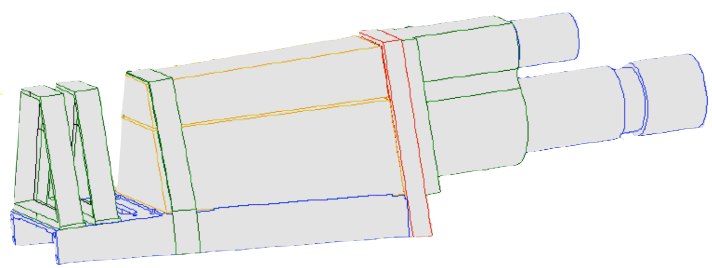
NIMROD-ISiS Array

- 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



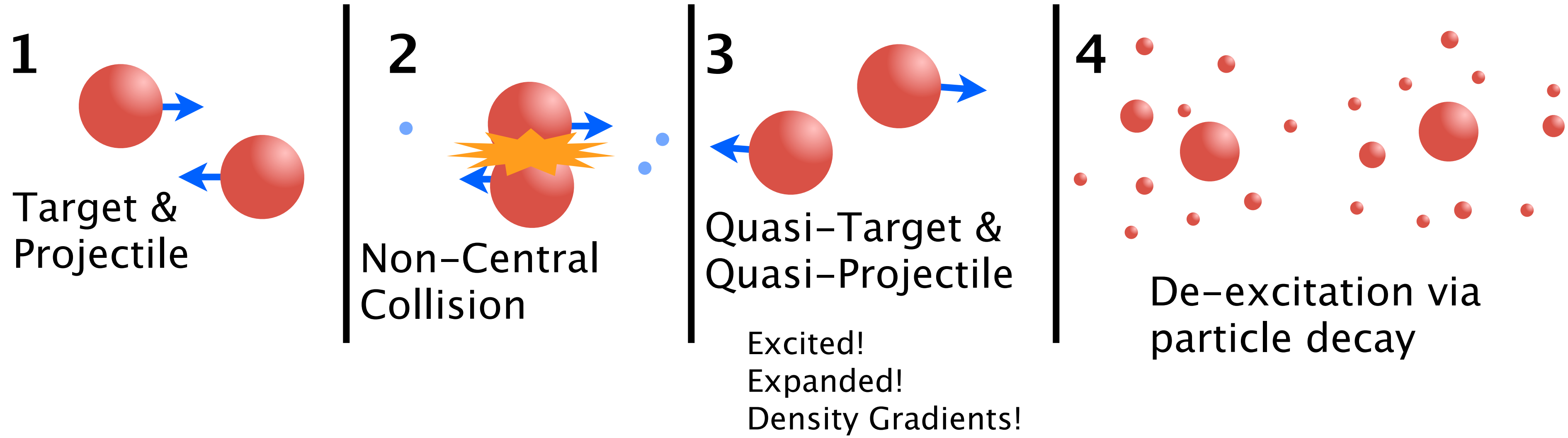




S. Wuenschel et al., Nucl. Instrum. Methods. A604, 578–583 (2009)

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

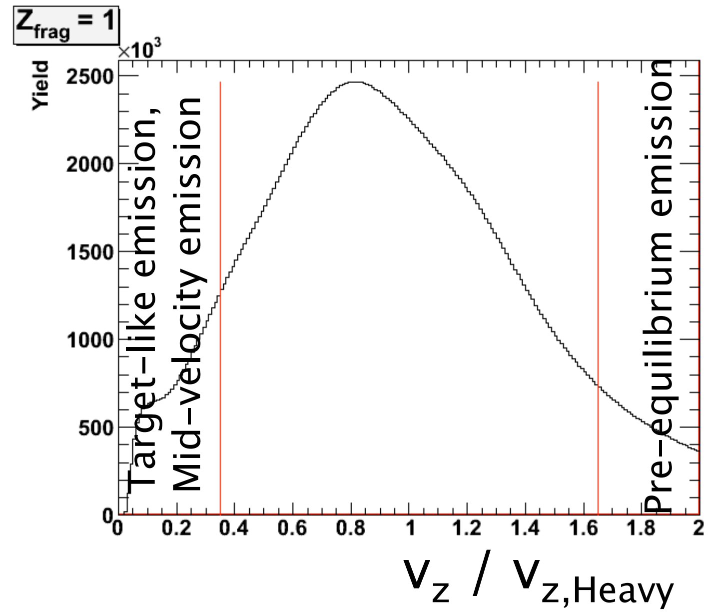
3. **Select on-average spherical events**

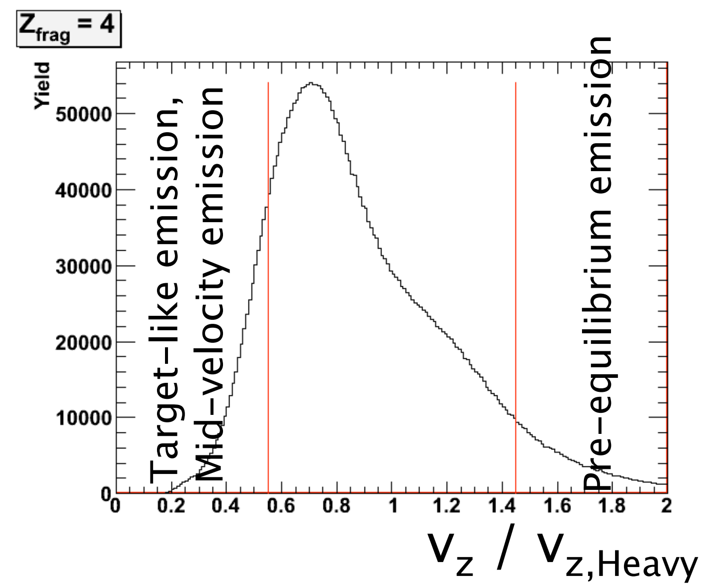
QP Reconstruction

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

$$\mathbf{48 \leq A_{QP} \leq 52}$$

$$\mathbf{m_{source} = \frac{N_{QP} - Z_{QP}}{A_{QP}}}$$

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)

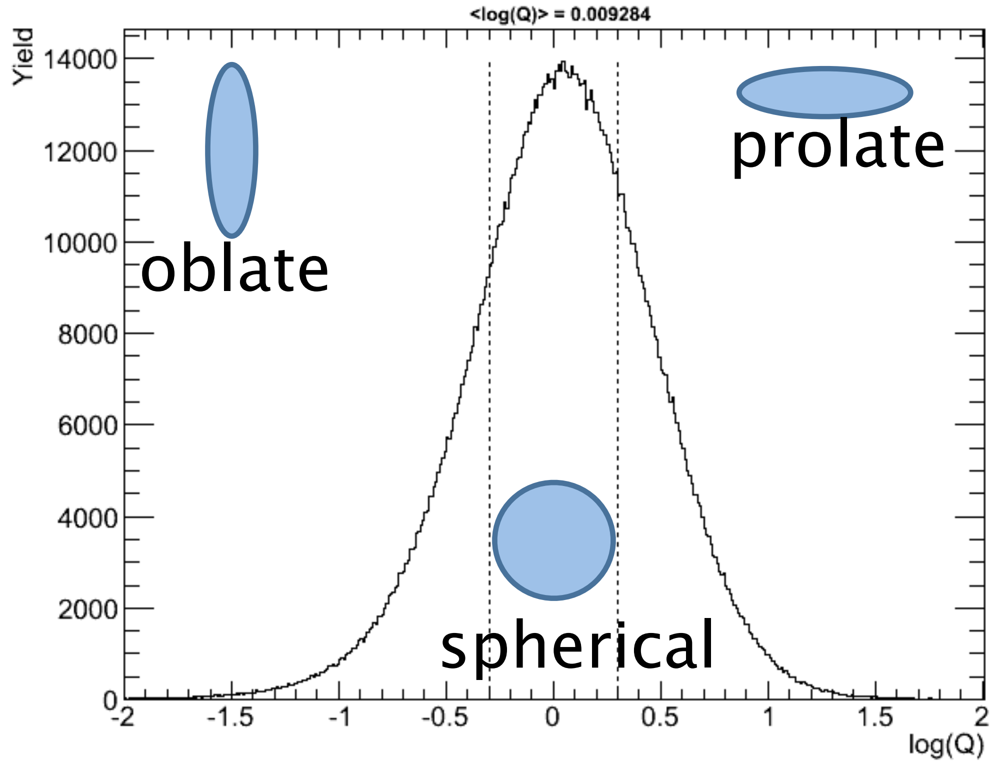
Marini et al., NIMA **707**, 80 (2013)

QP Reconstruction

Cut 3/3: Sphericity

$$\boxed{\begin{gathered} Q = \frac{\sum p_{z,i}{}^2}{\frac{1}{2}\sum p_{T,i}{}^2} \\ -0.3 \leq \log Q \leq 0.3 \end{gathered}}$$

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.

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

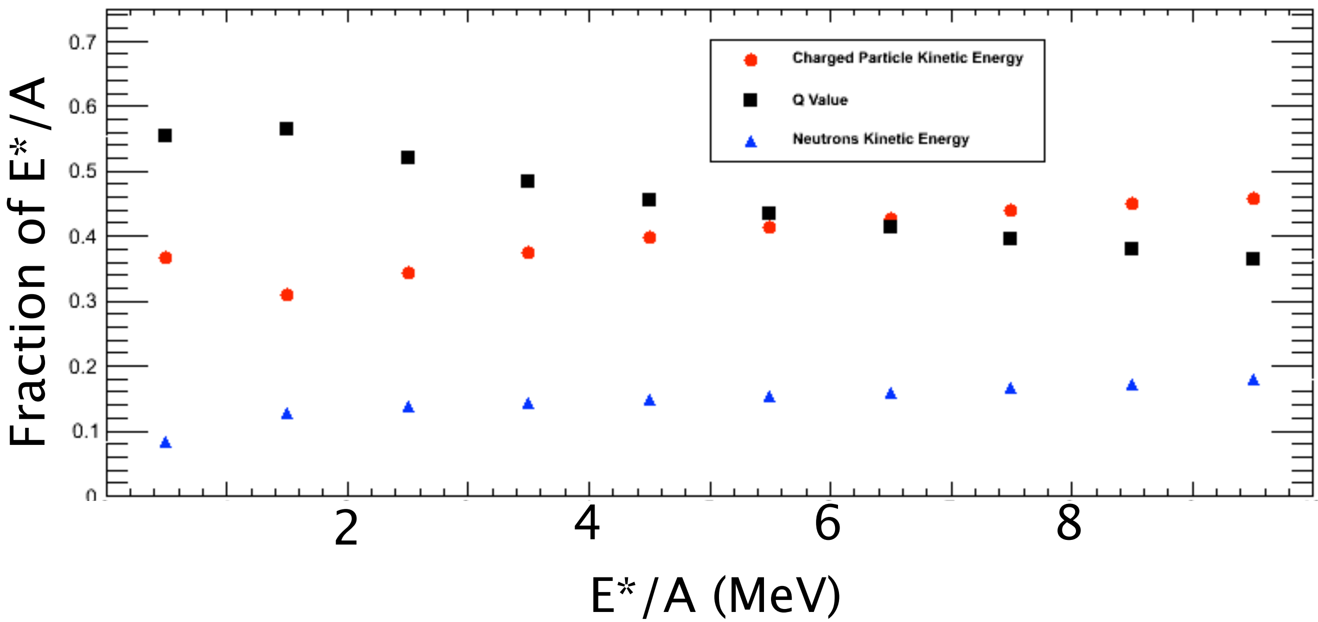
Marini et al., NIMA **707**, 80 (2013)
Wada et al., PRC 69, 044610 (2004)

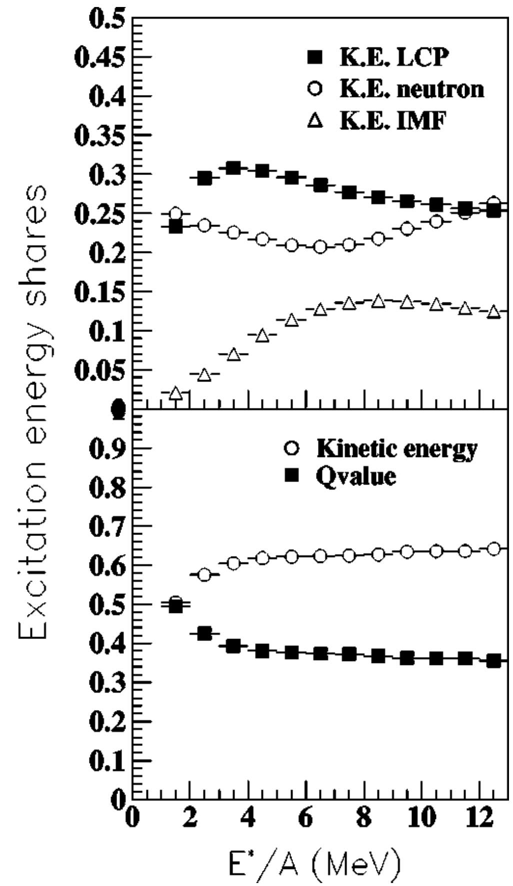
QP Identity

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

QP Identity

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

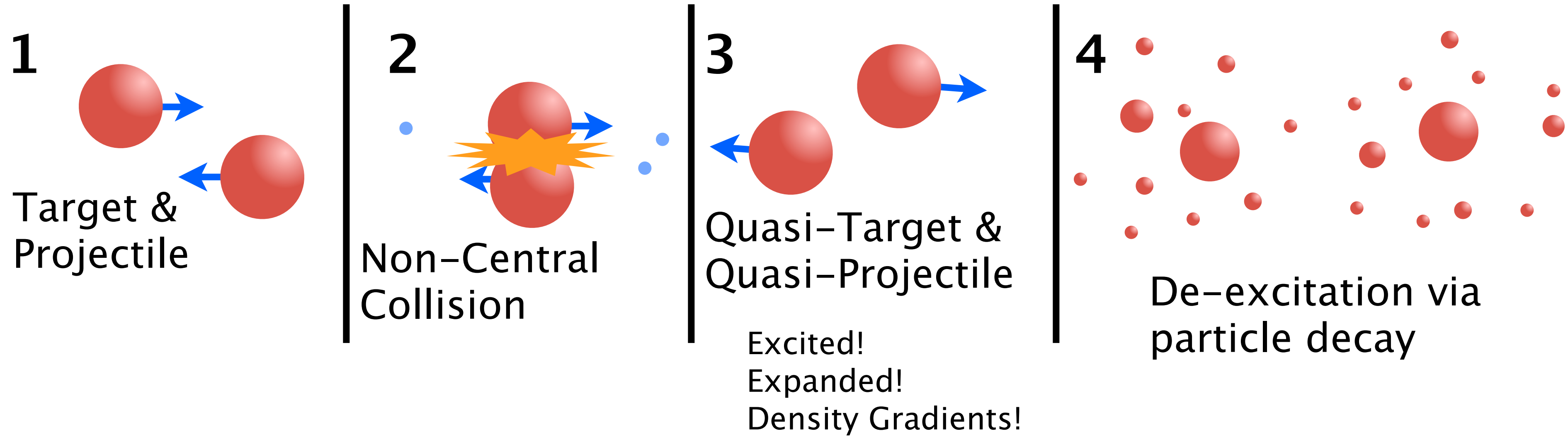




Excitation energy sharing is in reasonable agreement with previously published data:
~ 40% Charged particle KE
~ 40% Q value
~ 20% Neutrons

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?

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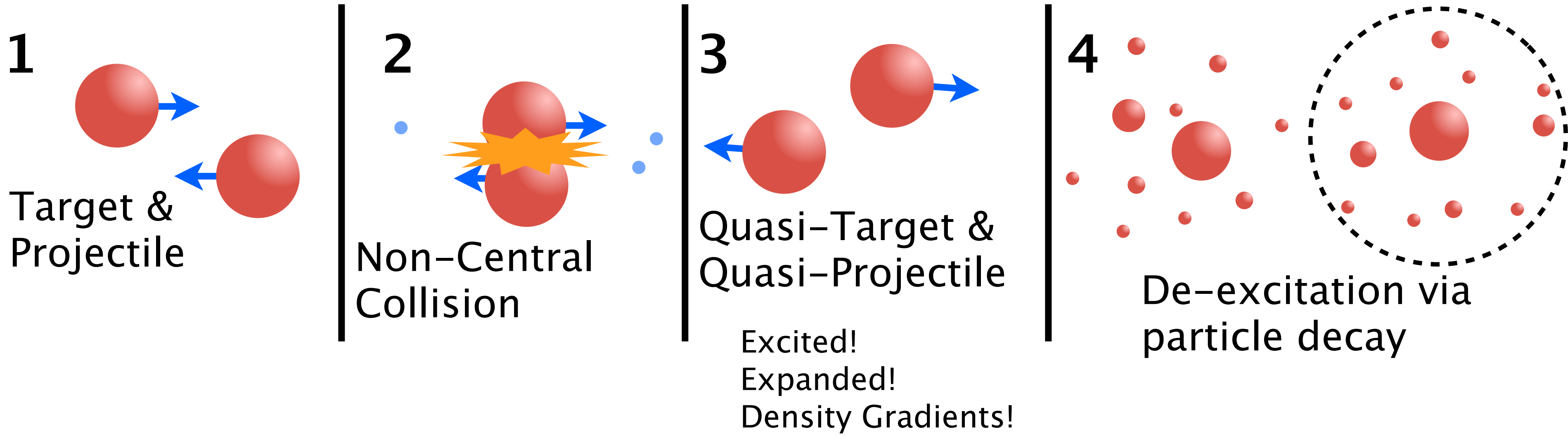
Reconstructed QP



- We have reconstructed the QP
  - E*/A, Asymmetry (n-p)
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Thermometer: MQF

Momentum Quadrupole Fluctuation Temperature

The quadrupole momentum distribution

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

Contains information on the temperature through its fluctuations

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

If f(p) is a Maxwell-Boltzmann distribution

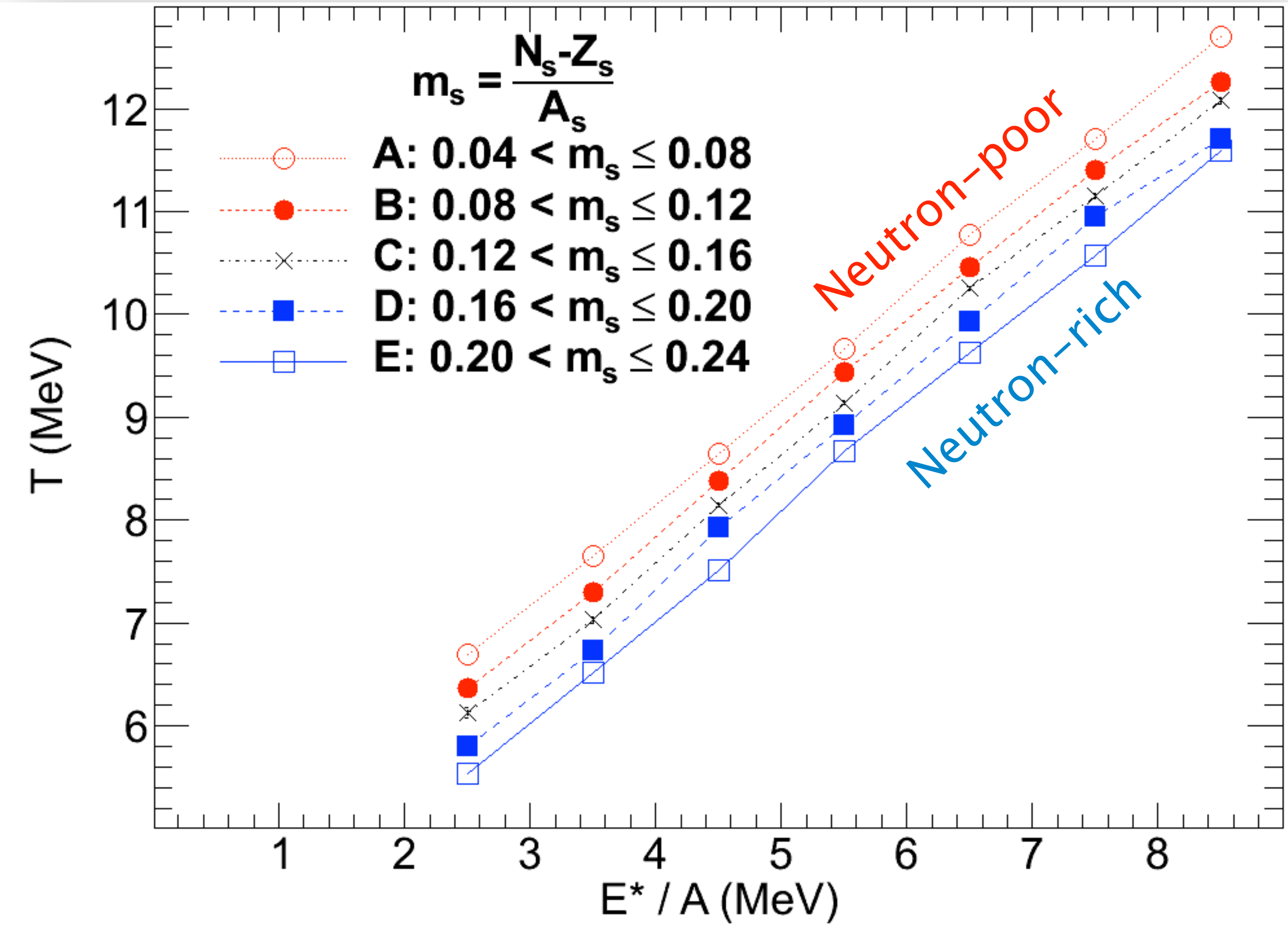
$$\boxed{{\sigma_{xy}}^2 = 4m^2T^2}$$

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

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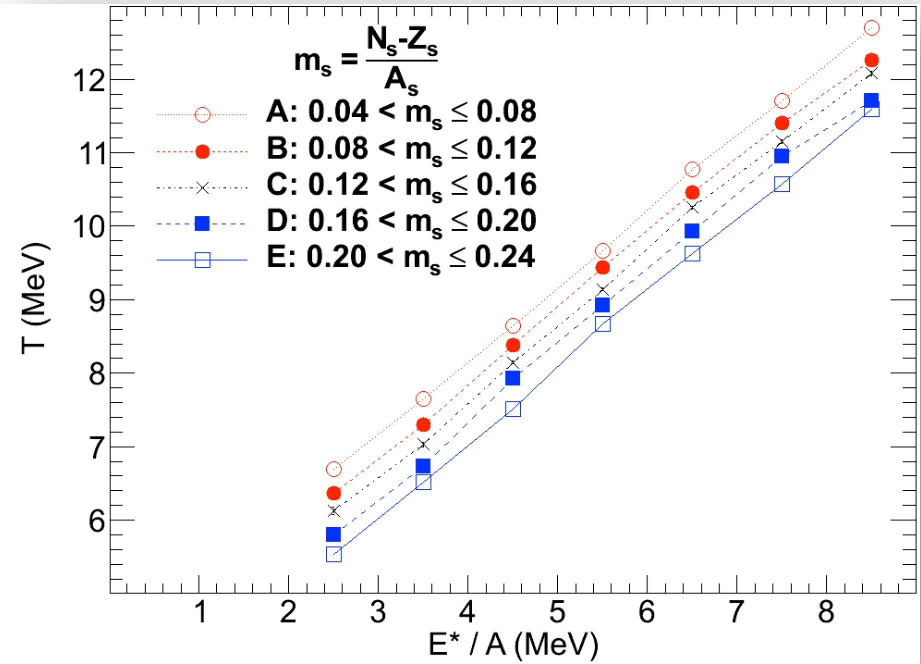
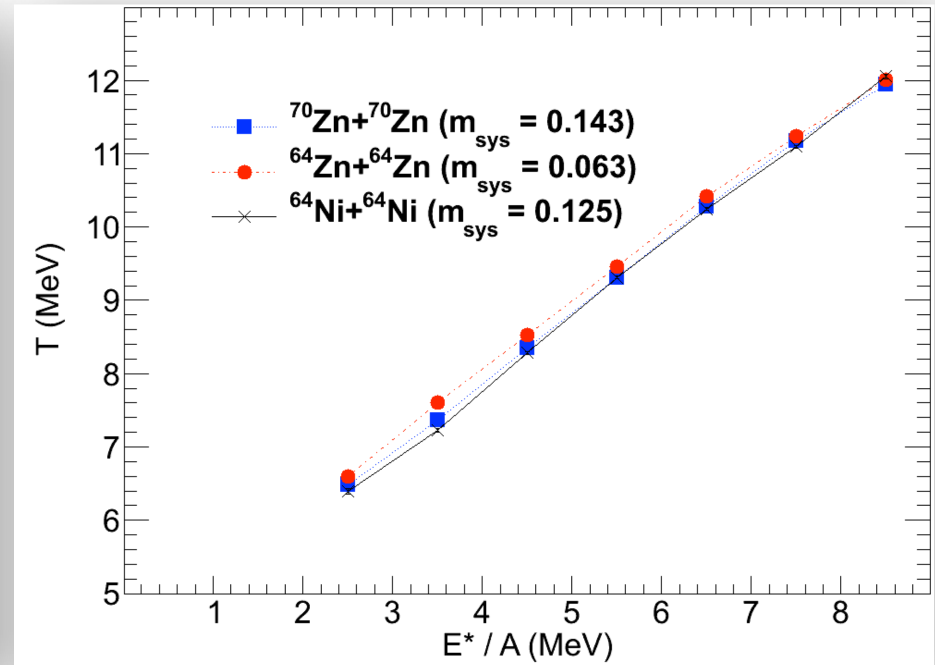
Importance of Reconstruction

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**

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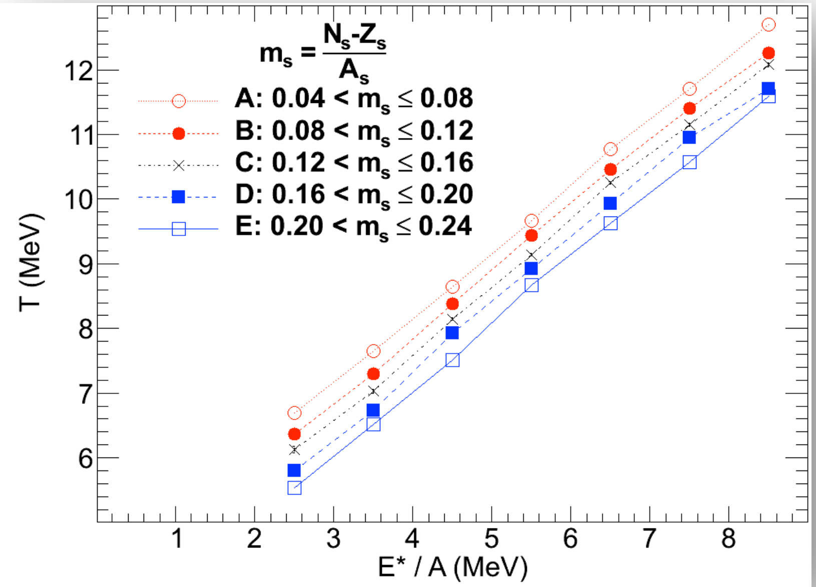
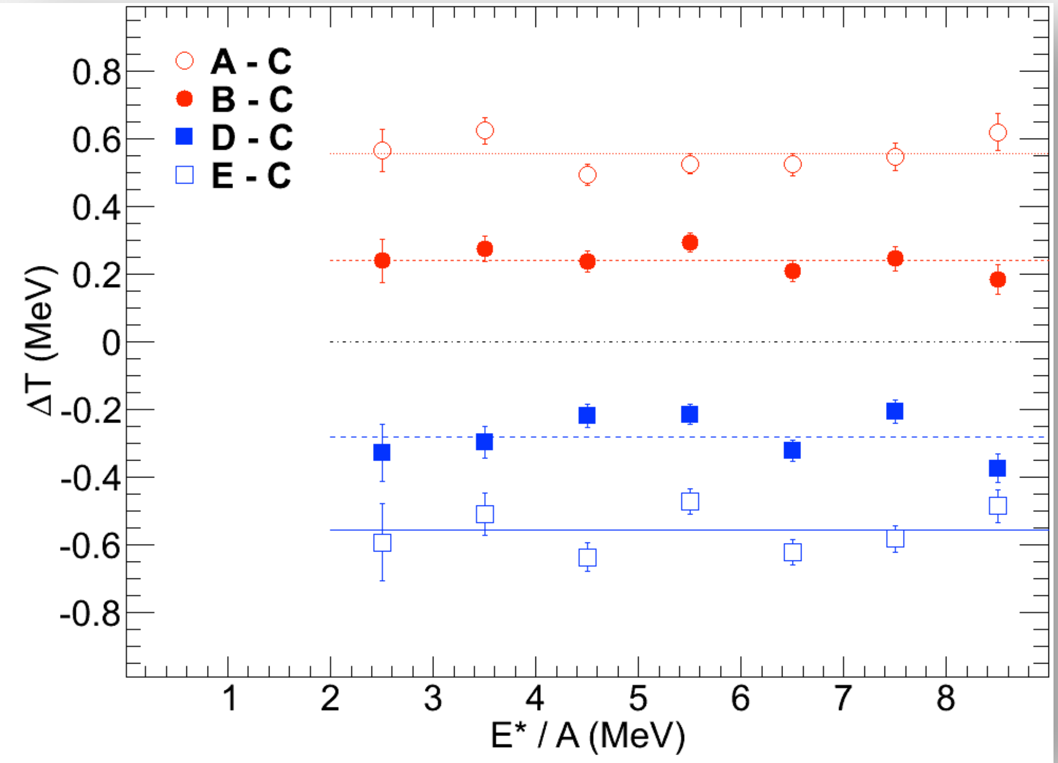
Excitation Independence





Larger Asymmetry
→ Lower Temperature

Temperature shift does not show a trend with excitation.

Horizontal lines indicate averages

4 of 10 pairwise differences shown

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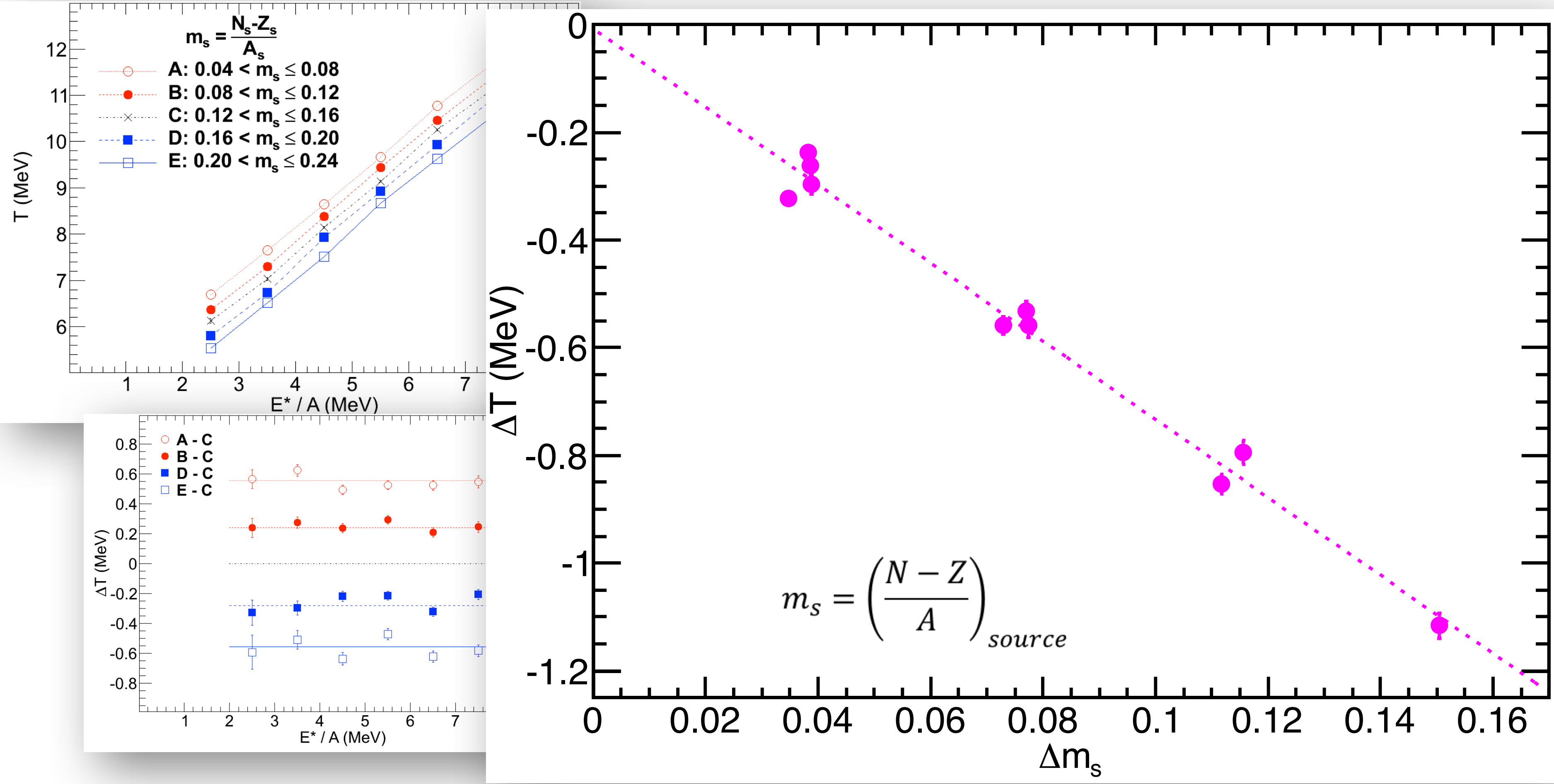
Quantifying Asymmetry Dependence



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

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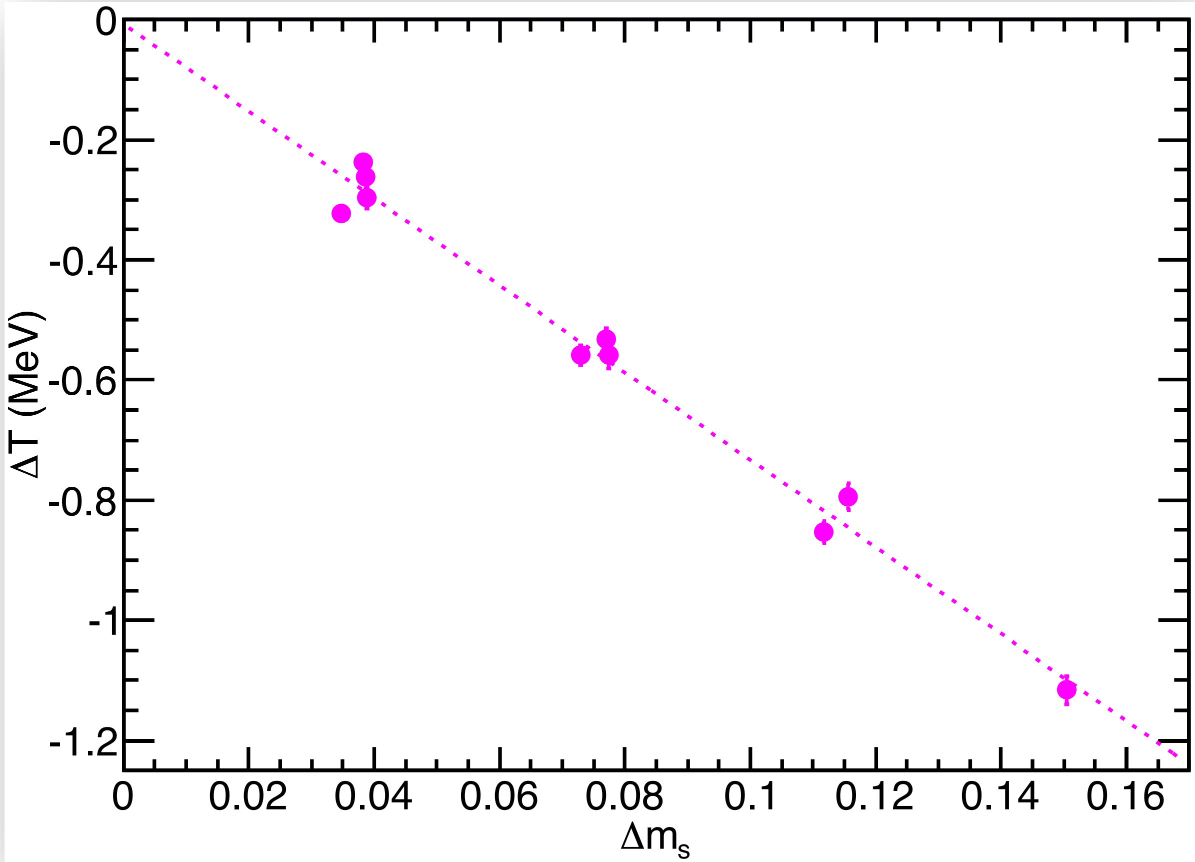
Robust Asymmetry Dependence



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

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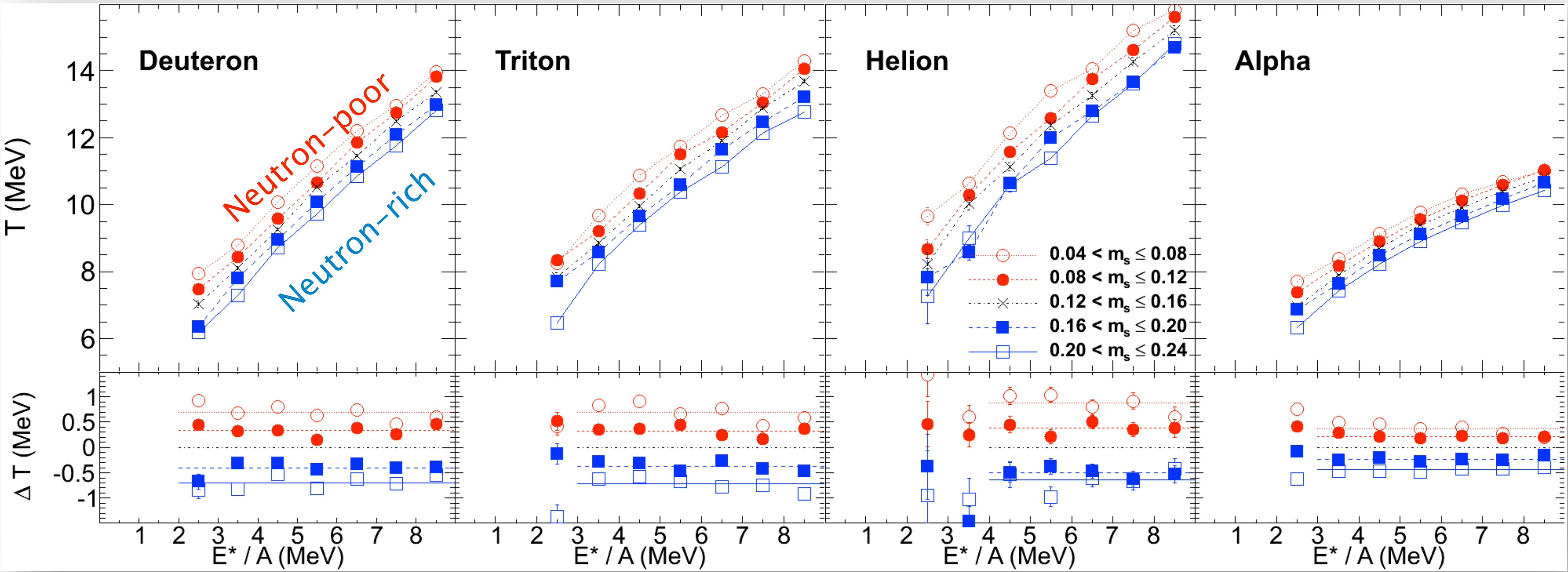
Asymmetry Depenence

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

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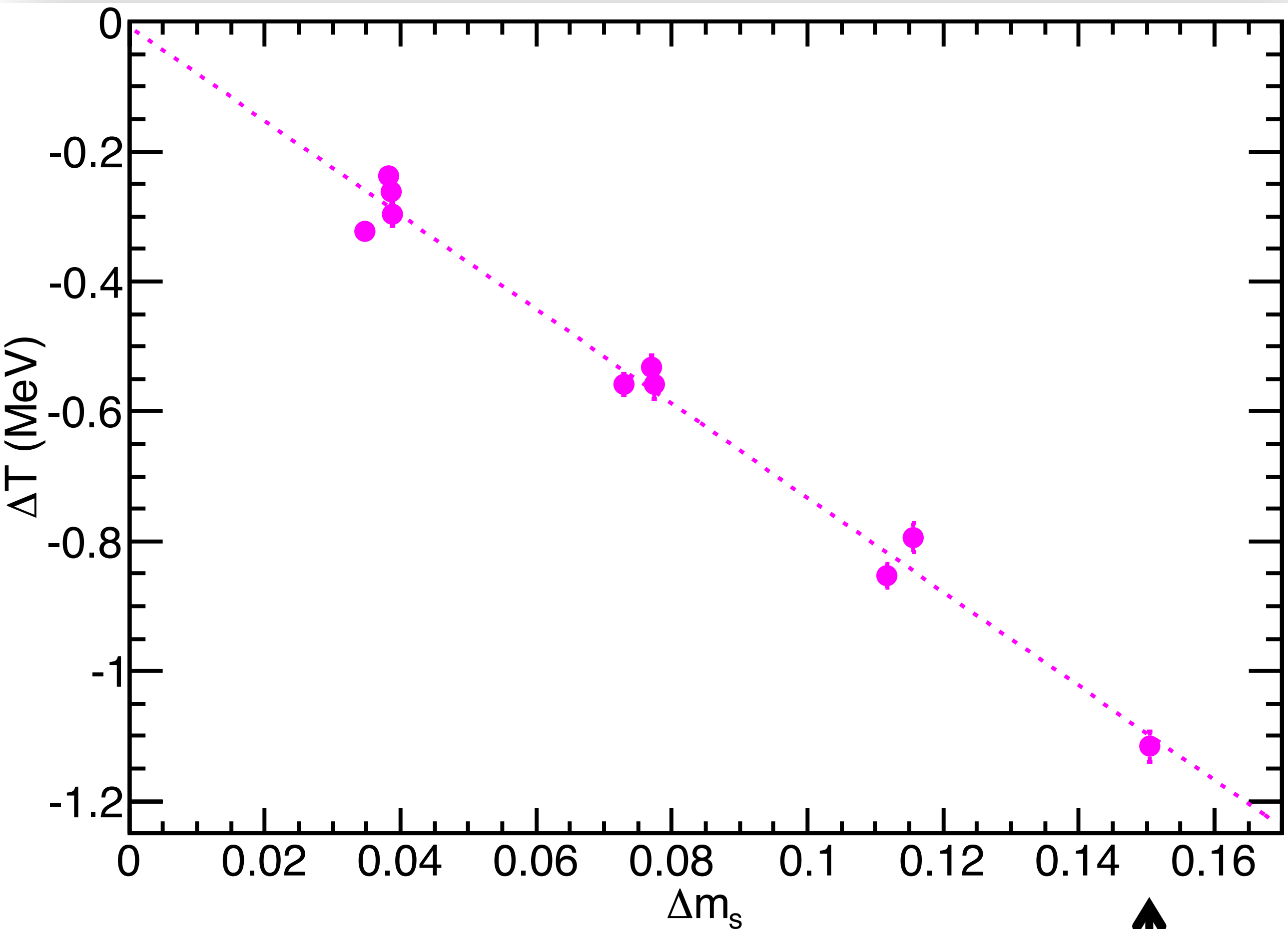
Asymmetry Dependence of Temperature



Change of 4 protons at A≈50

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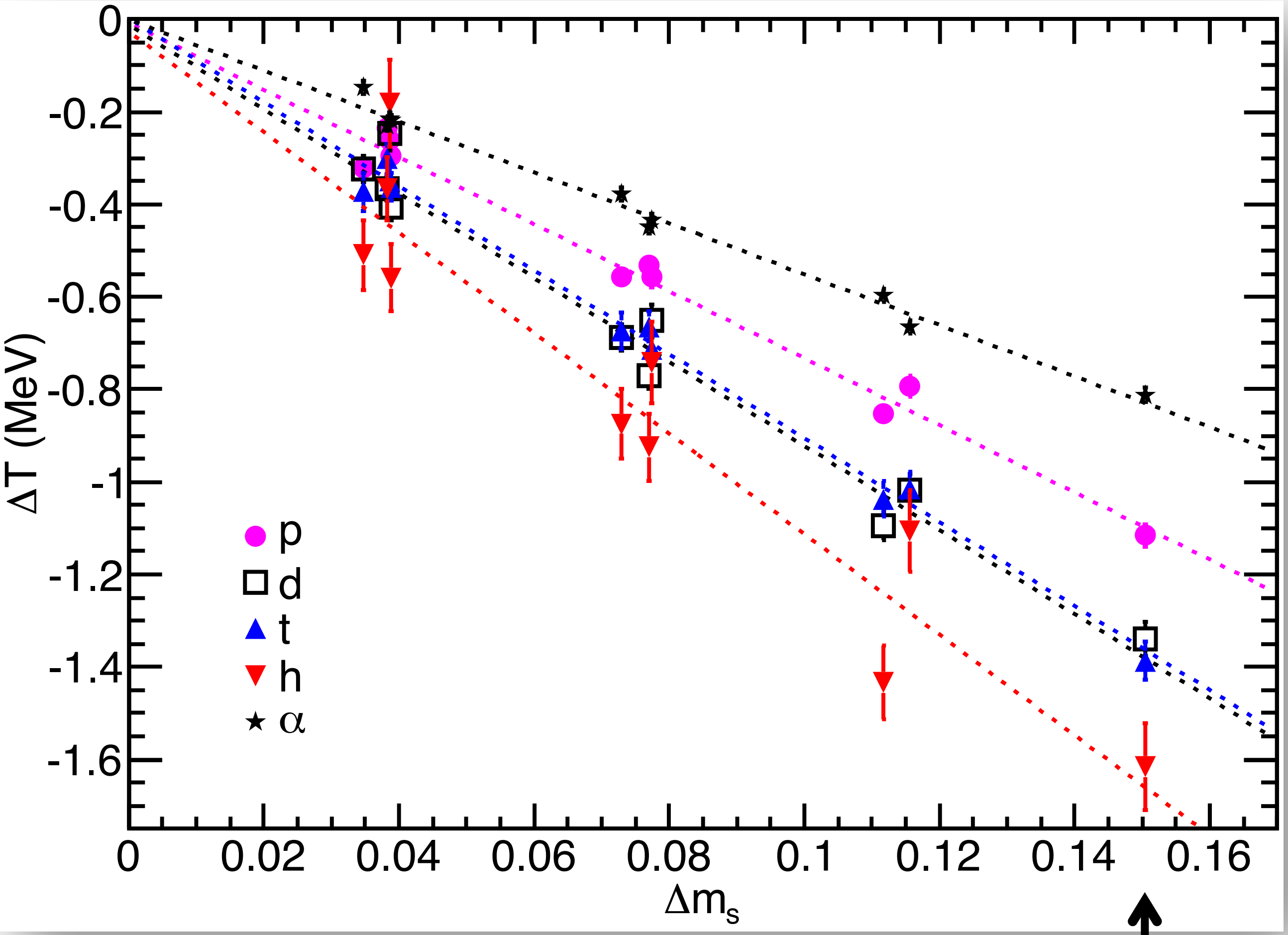
Asymmetry Dependence of Temperature



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

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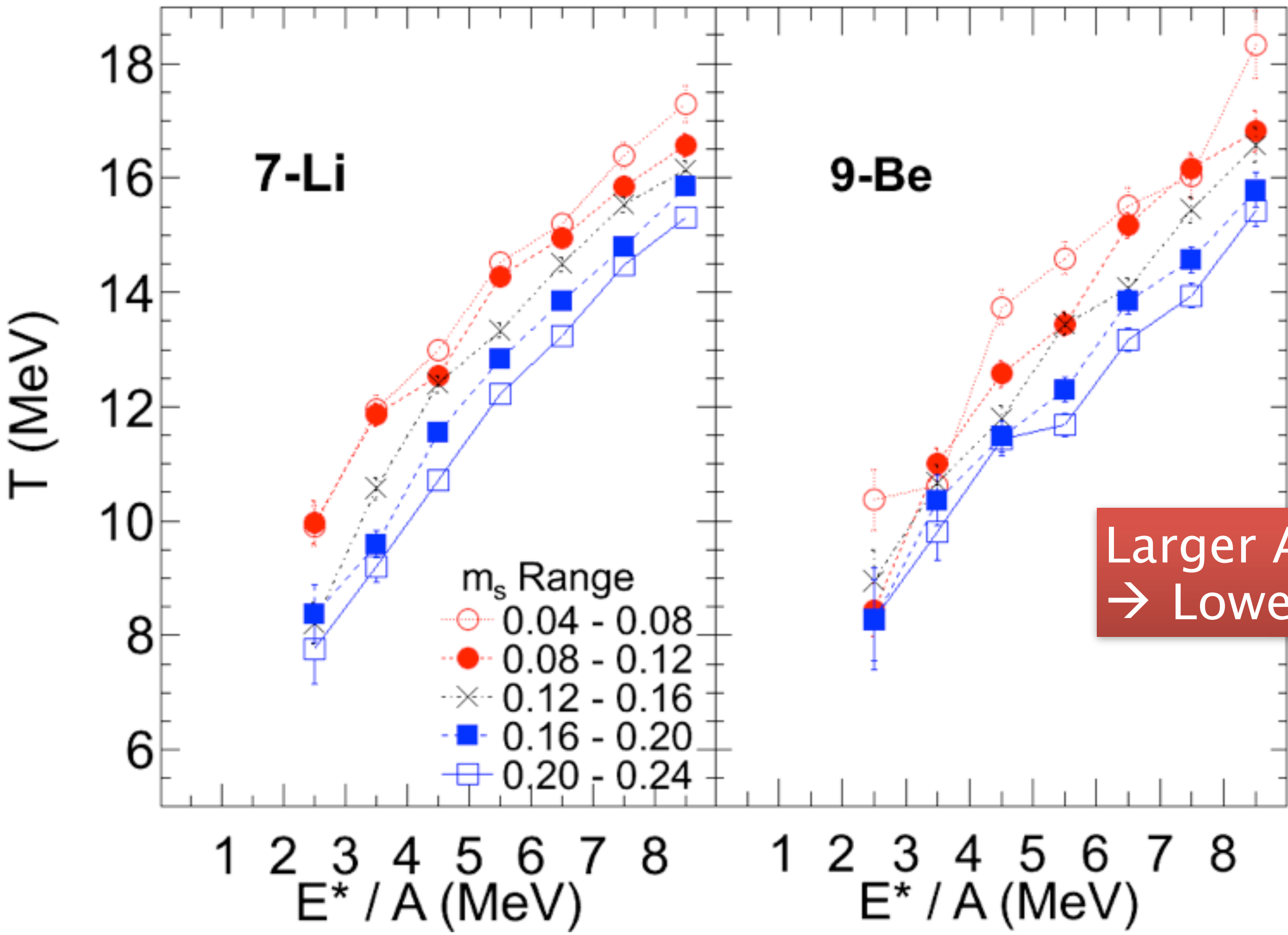
Temperatures Using Heavier Probes



Larger Asymmetry
→ Lower Temperature

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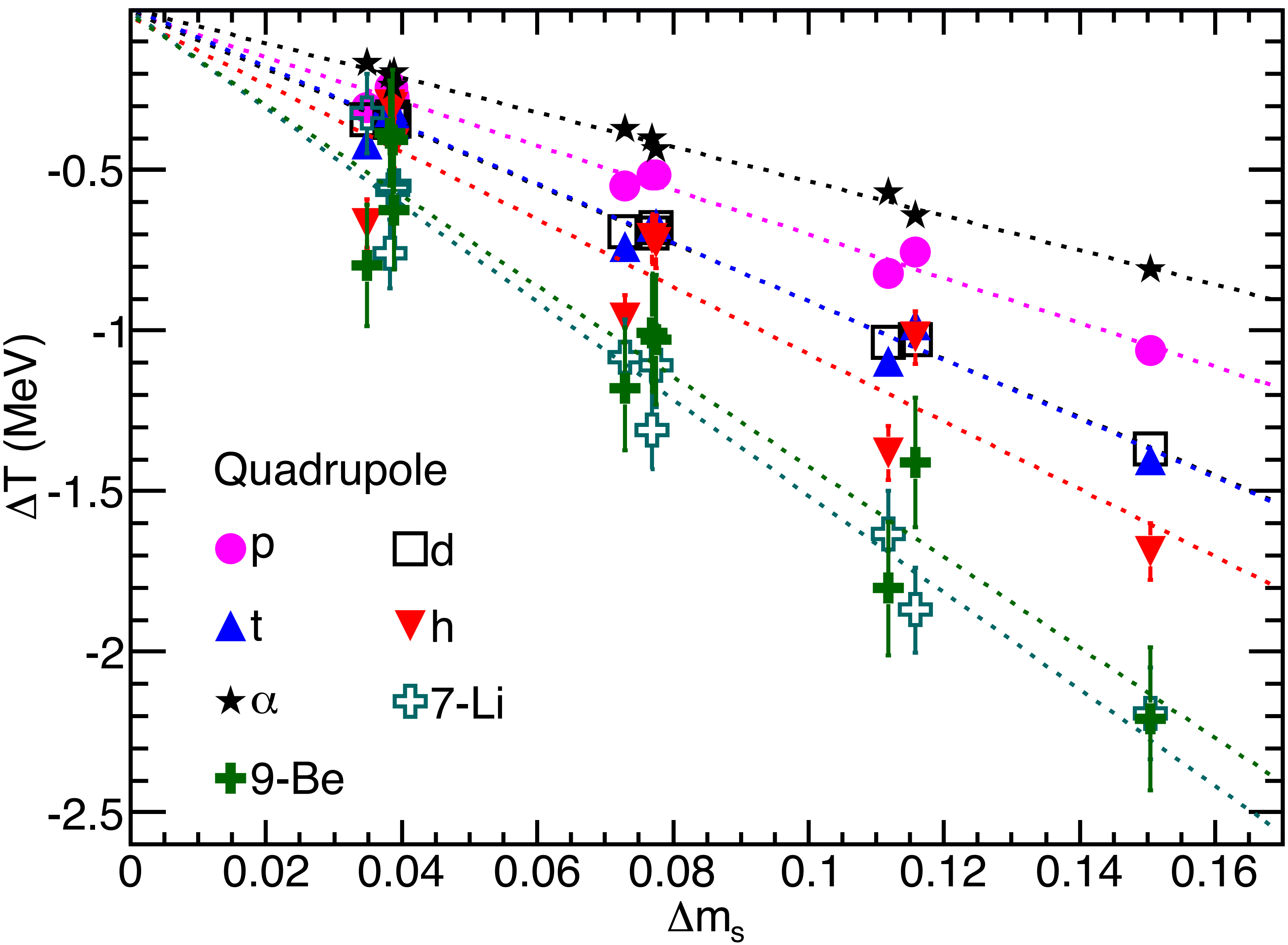
Asymmetry Dependence of Temperature



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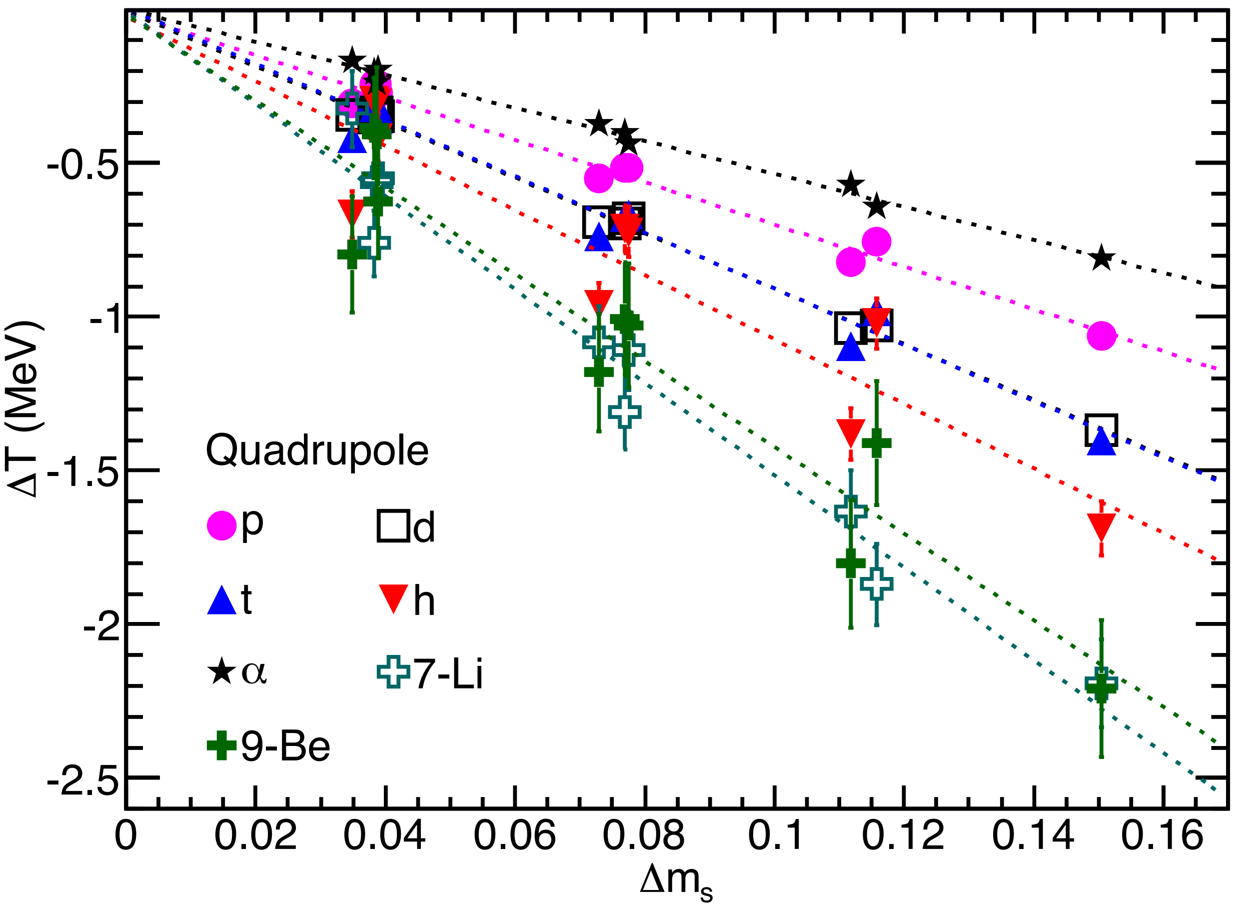
Asymmetry Dependence of Temperature



$m_s(^{112}Sn) = 0.107$
$m_s(^{124}Sn) = 0.194$
$\Delta m_s(Sn) = 0.087$
-> $\Delta T = 0.5\text{–}1.5$ MeV

$$\alpha = \frac{4C_{sym}(\rho)}{T}\left[\left(\frac{Z}{A}\right)_1^2 - \left(\frac{Z}{A}\right)_2^2\right]$$

Access to C_{sym} through isoscaling: what is T?

In the interpretation of isoscaling, understanding the asymmetry dependence of nuclear temperatures should be another consideration in addition to secondary decay, and definition of Δ.

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Asymmetry Dependence

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

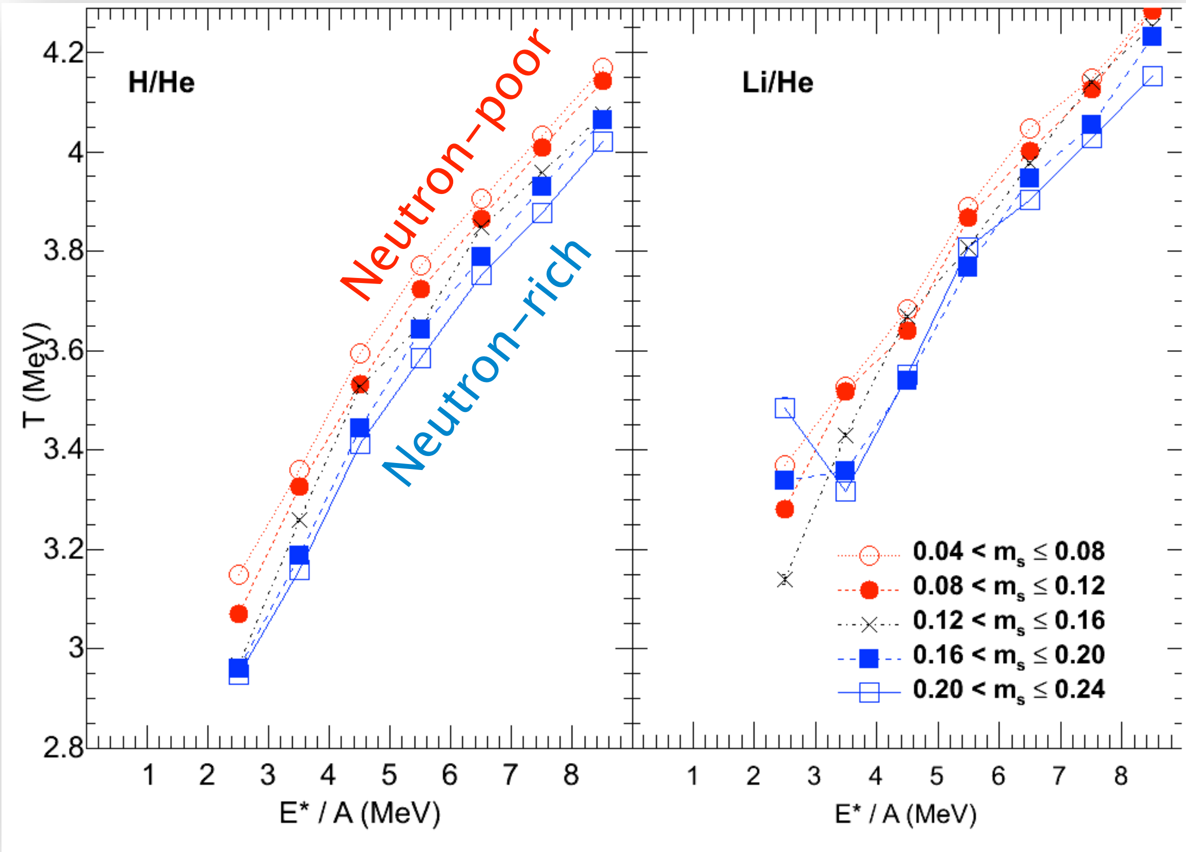
Do other thermometers measure an asymmetry dependence?

Albergo Thermometer

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

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

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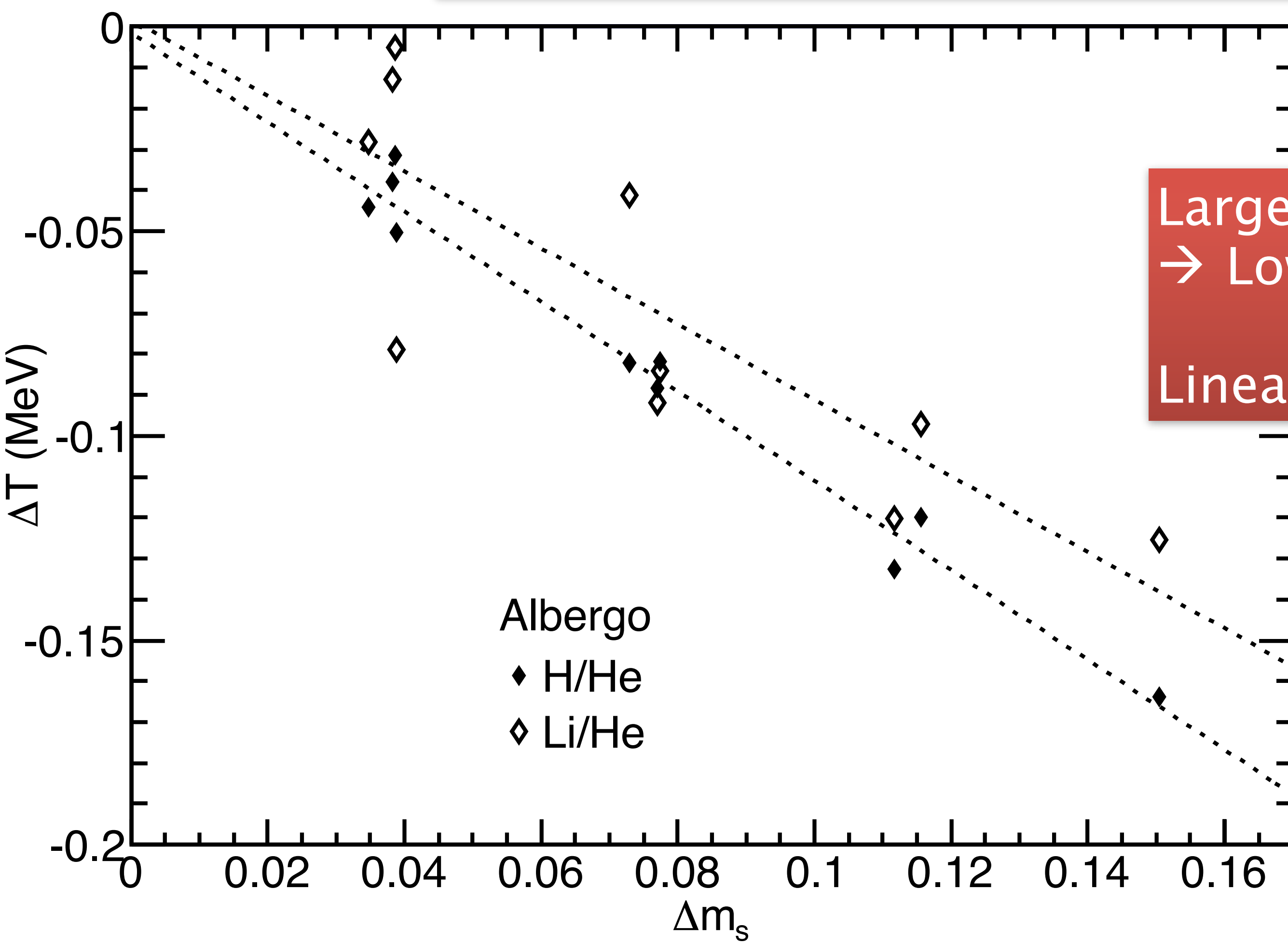
Albergo: Asymmetry Dependence of T

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

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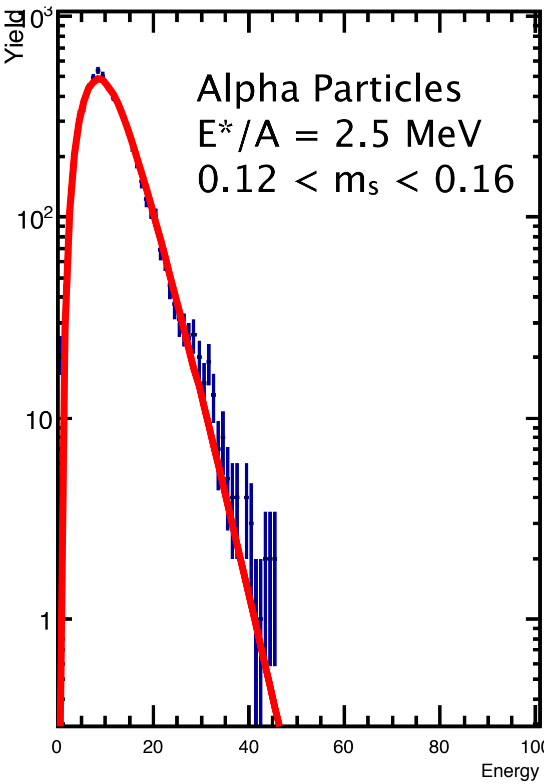
<u>Asymmetry Dependence</u>

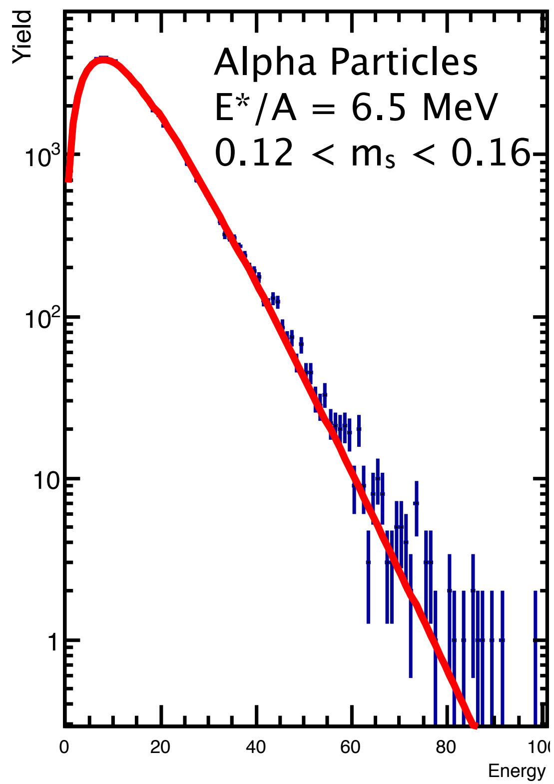
- ☑ MQF Protons
- ☑ MQF Deuterons
- ☑ MQF Tritons
- ☑ MQF Helion
- ☑ MQF Alphas
- ☑ MQF 7-Li
- ☑ MQF 9-Be
- ☑ Albergo H/He
- ☑ Albergo Li/He

Do any other thermometers measure an asymmetry dependence?

Slope Temperatures

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





Maxwell-Boltzmann with Diffuse Barrier

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

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

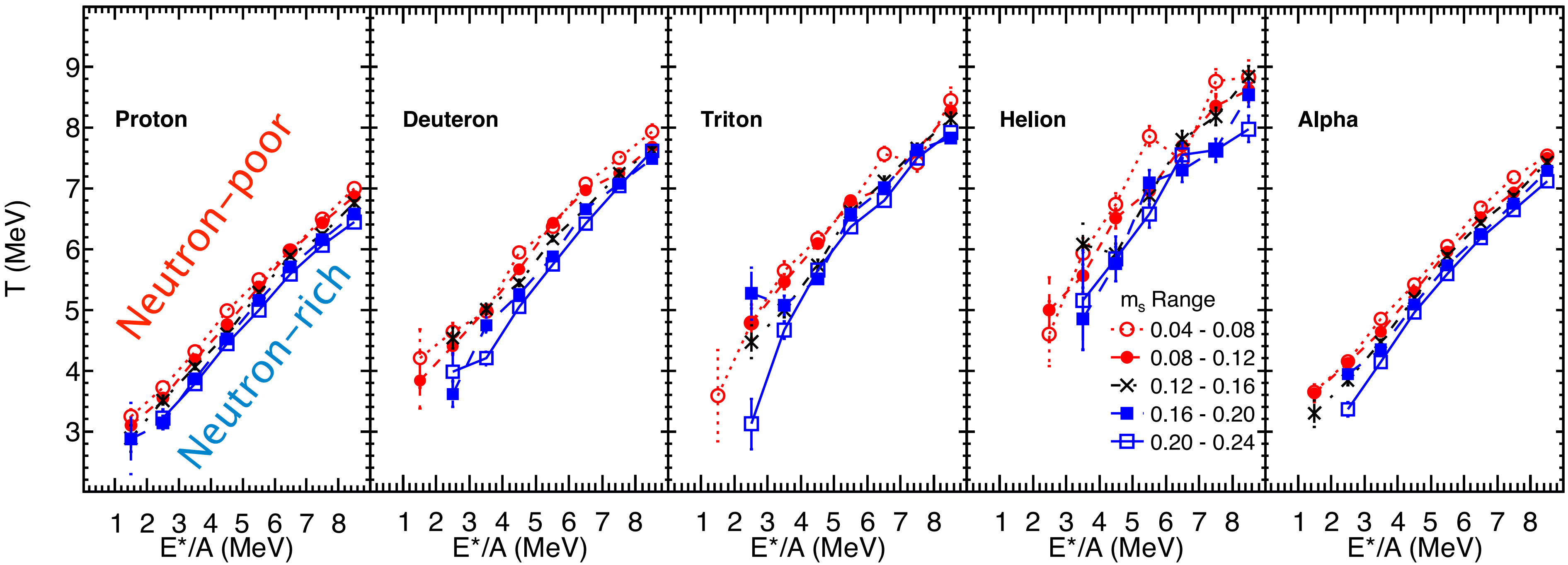
$$Y(E) = 0 \quad E \leq B'$$

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

B: barrier parameter
D: diffuseness parameter

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

Slope Temperature: Asymmetry Dependent

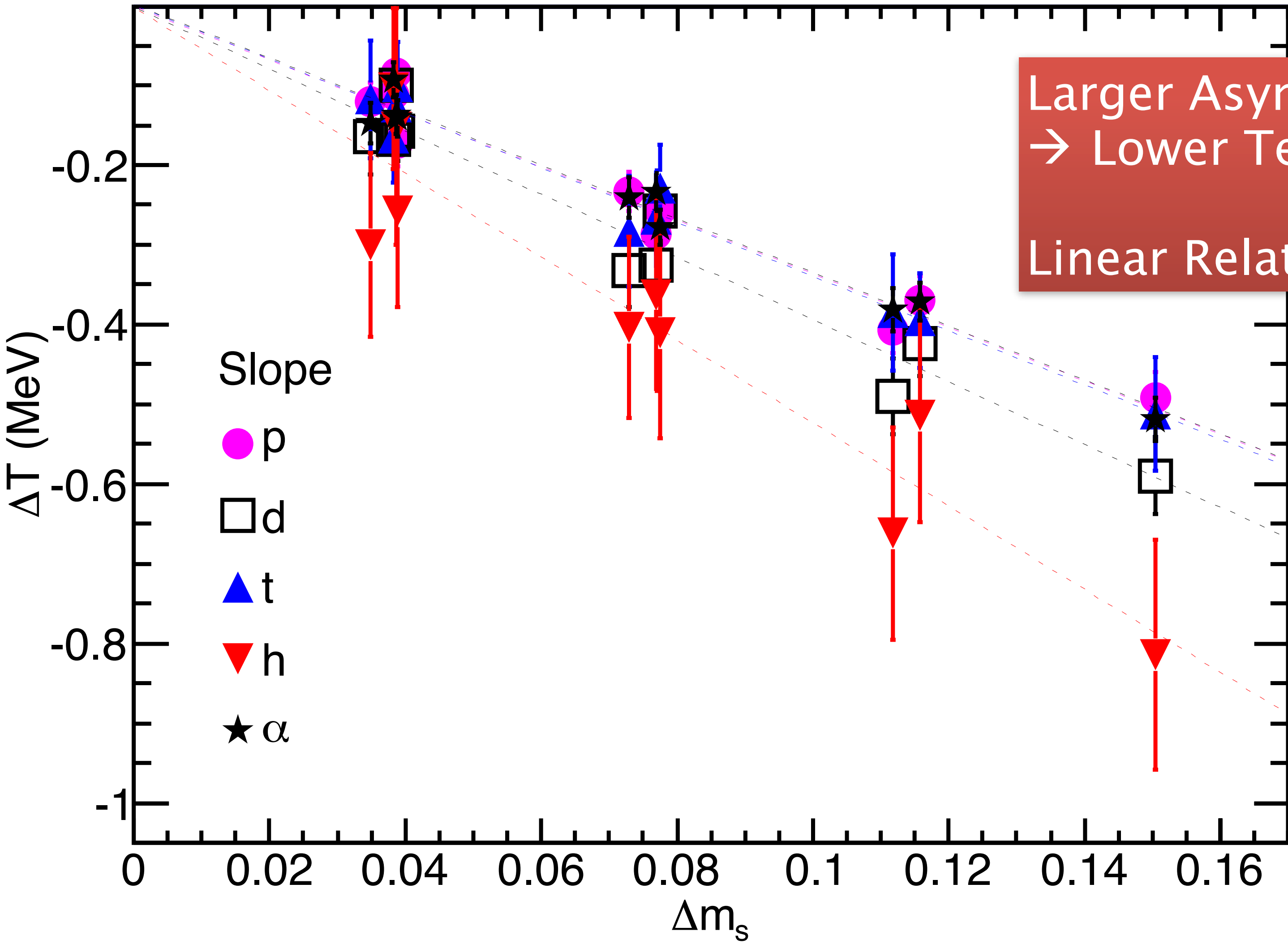


Key point:
Asymmetry dependence is clearly observed

Larger Asymmetry
→ Lower Temperature

McIntosh, NuSym13

Asymmetry Dependence of Slope Temperature

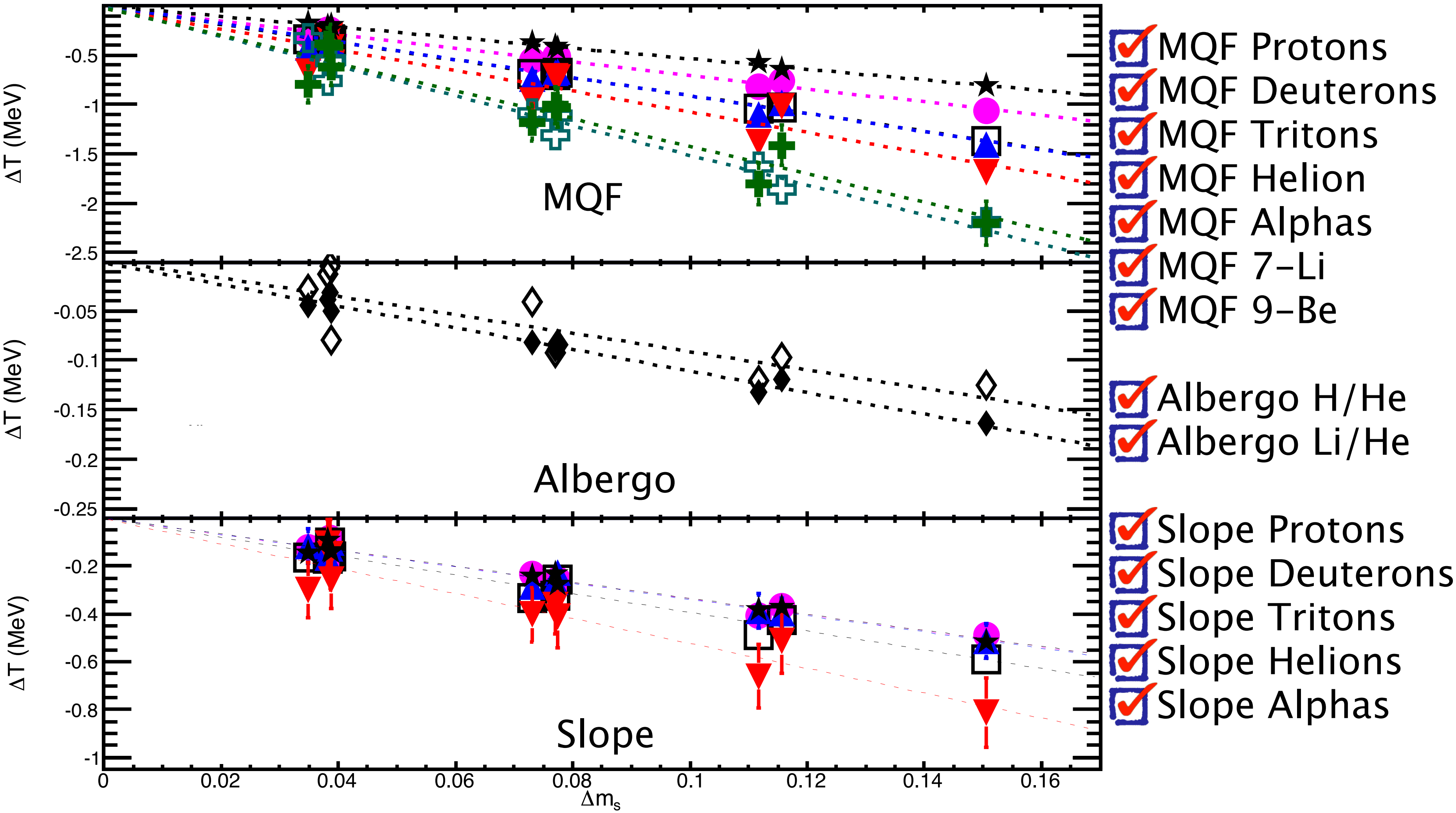


Larger Asymmetry
→ Lower Temperature

Linear Relation

McIntosh, NuSym13

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



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

McIntosh, NuSym13

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.

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Collaborators

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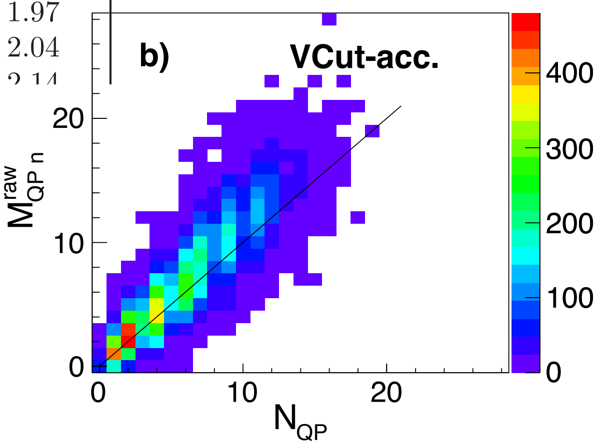
Neutron Uncertainty

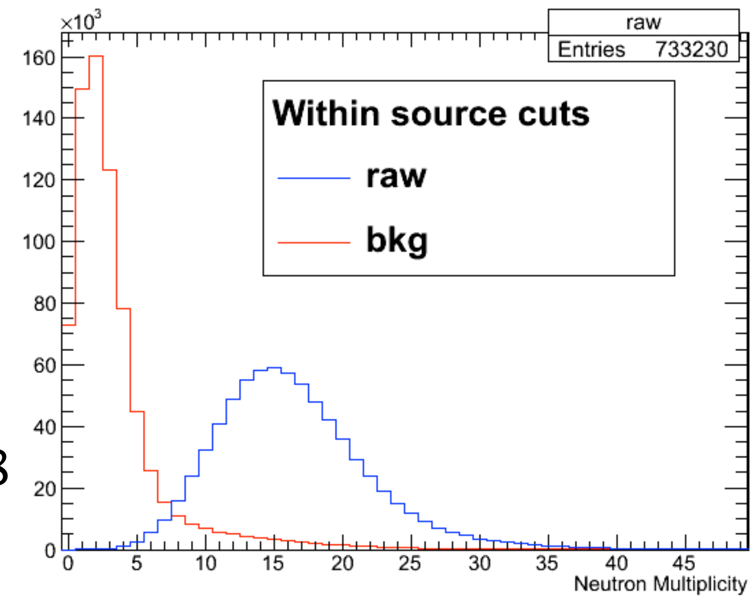
$$\sigma^2_{\mathbf{raw}} = \sigma^2_{\mathbf{true}} + \sigma^2_{\mathbf{eff}} + \sigma^2_{\mathbf{bkg}}$$

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	6.50	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.