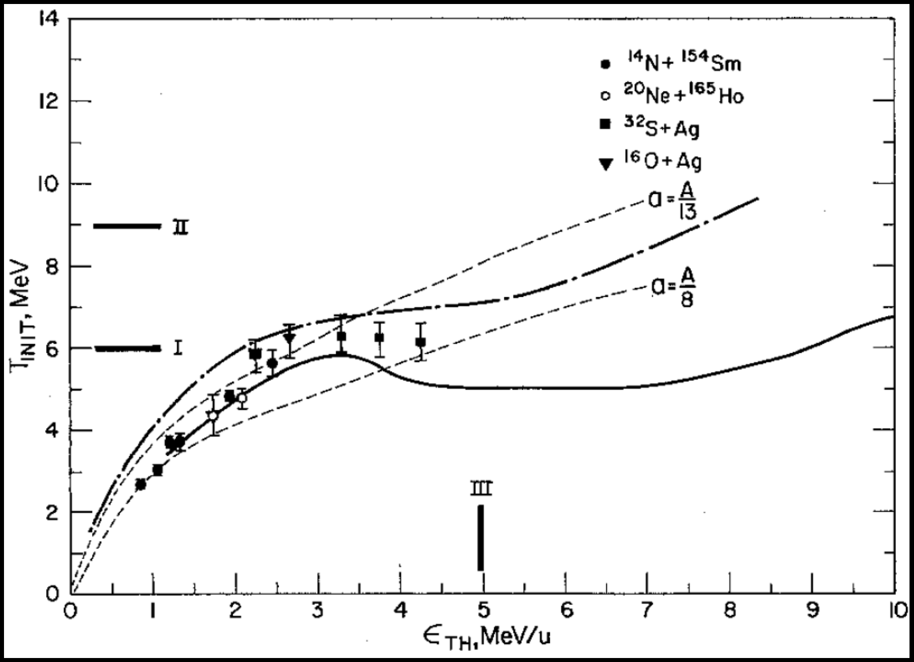
Kr+C Reactions to Explore the Asymmetry Dependence of the Nuclear Caloric Curve

Alan McIntosh
Texas A&M University
DNP 2018 Kona

Nuclear Equation of State: T, ρ, P, E*, I

- ❖ Heavy Ion Collisions at All Energies
- ❖ Nuclear Structure (e.g. Resonances)
- ❖ Supernovae (nucleosynthesis
- ❖ Neutron Stars (Crust to Core)
- ➢ n-p Asymmetry Crucial

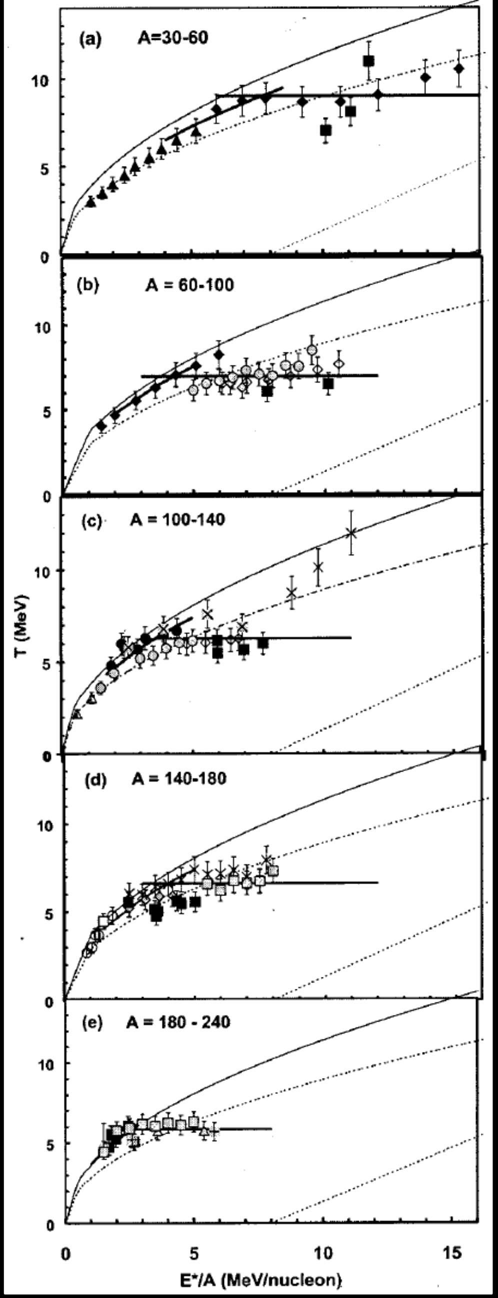


D. Fabris et al., Phys. Lett. B 196 (1987) 429

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

Nuclear Caloric Curve

Temperature (MeV)



E*/A (MeV)

MASS DEPENDENCE!

With increasing mass:

- Limiting Temperature decreases
- Onset of plateau at lower excitation

ASYMMETRY DEPENDENCE?

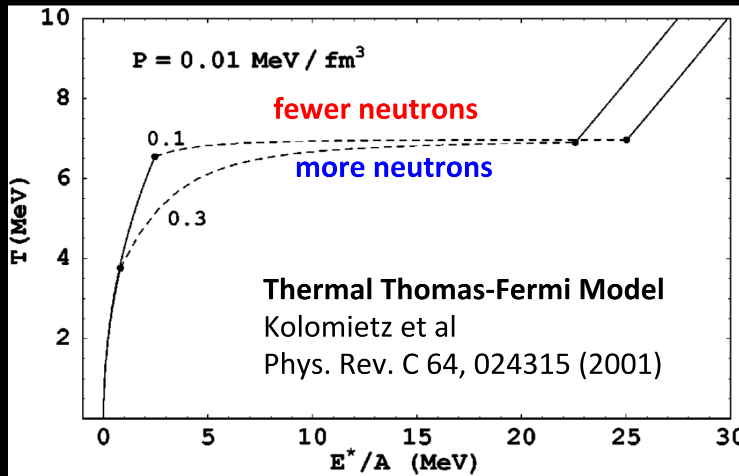
- Does an n-p Asymmetry Dependence Exist?
- Which way does it go?
- How strong is it?

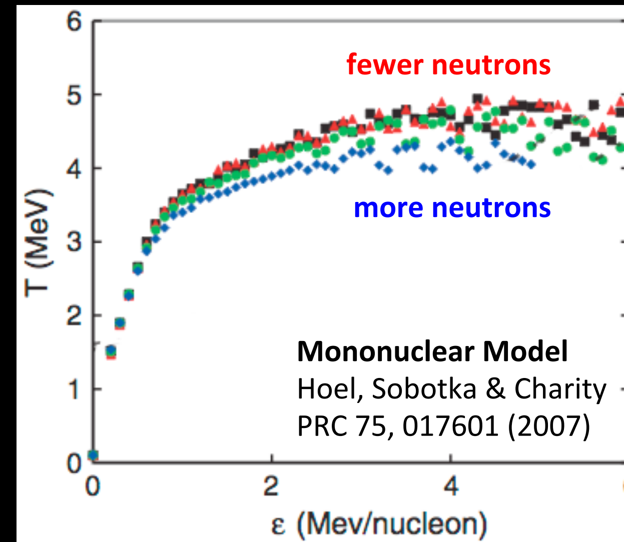
Natowitz et al. PRC, 034618 (2002)

Theory

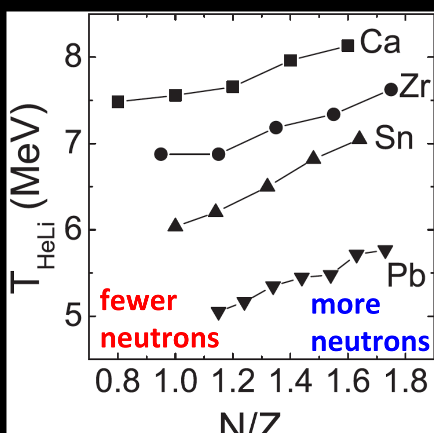
Different models make very different predictions about how the caloric curve may depend on n-p asymmetry.

Neutron Rich → Lower T

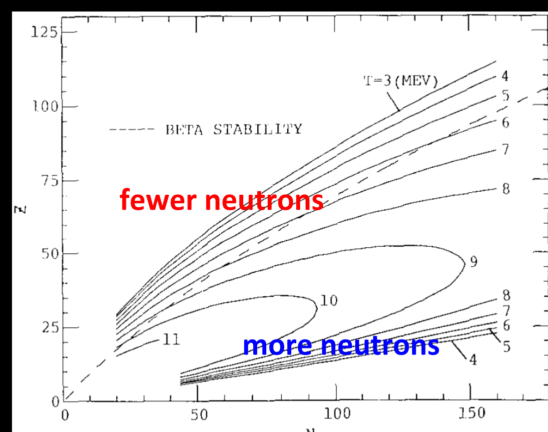




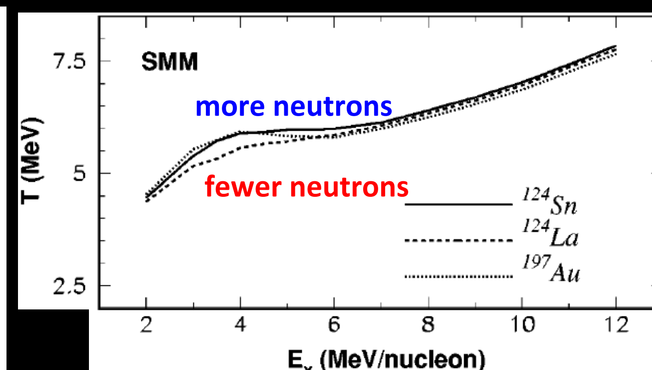
Neutron Rich → Higher T



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

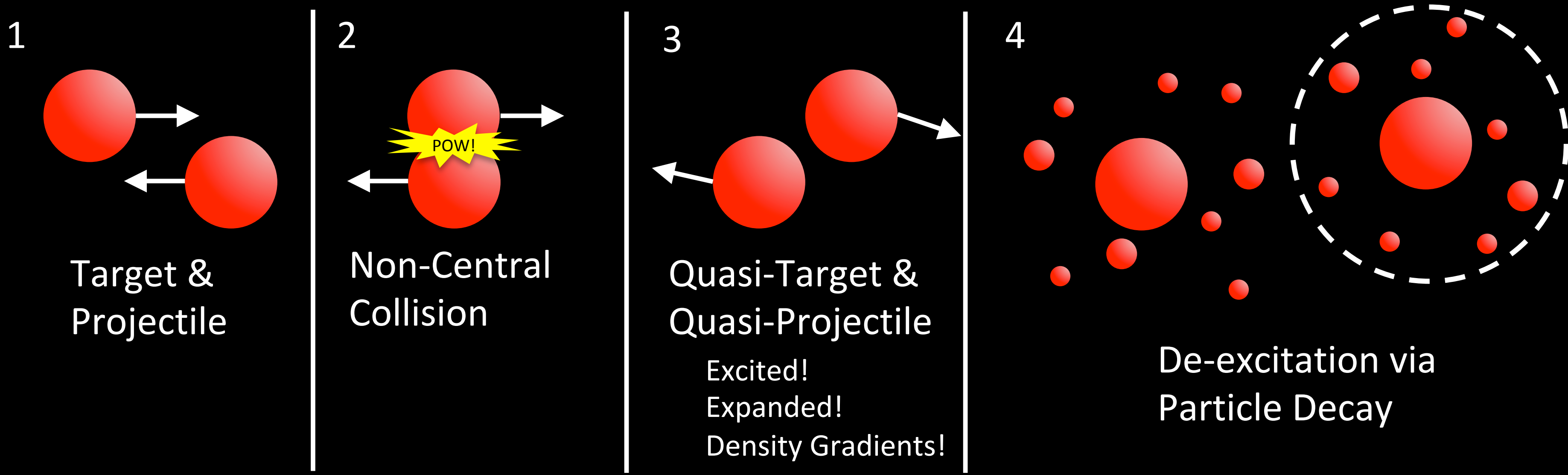


Hot Liquid Drop Model
Besprosvany & Levit
Phys. Lett B 217, 1 (1989)



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

Exciting Nuclear Matter!



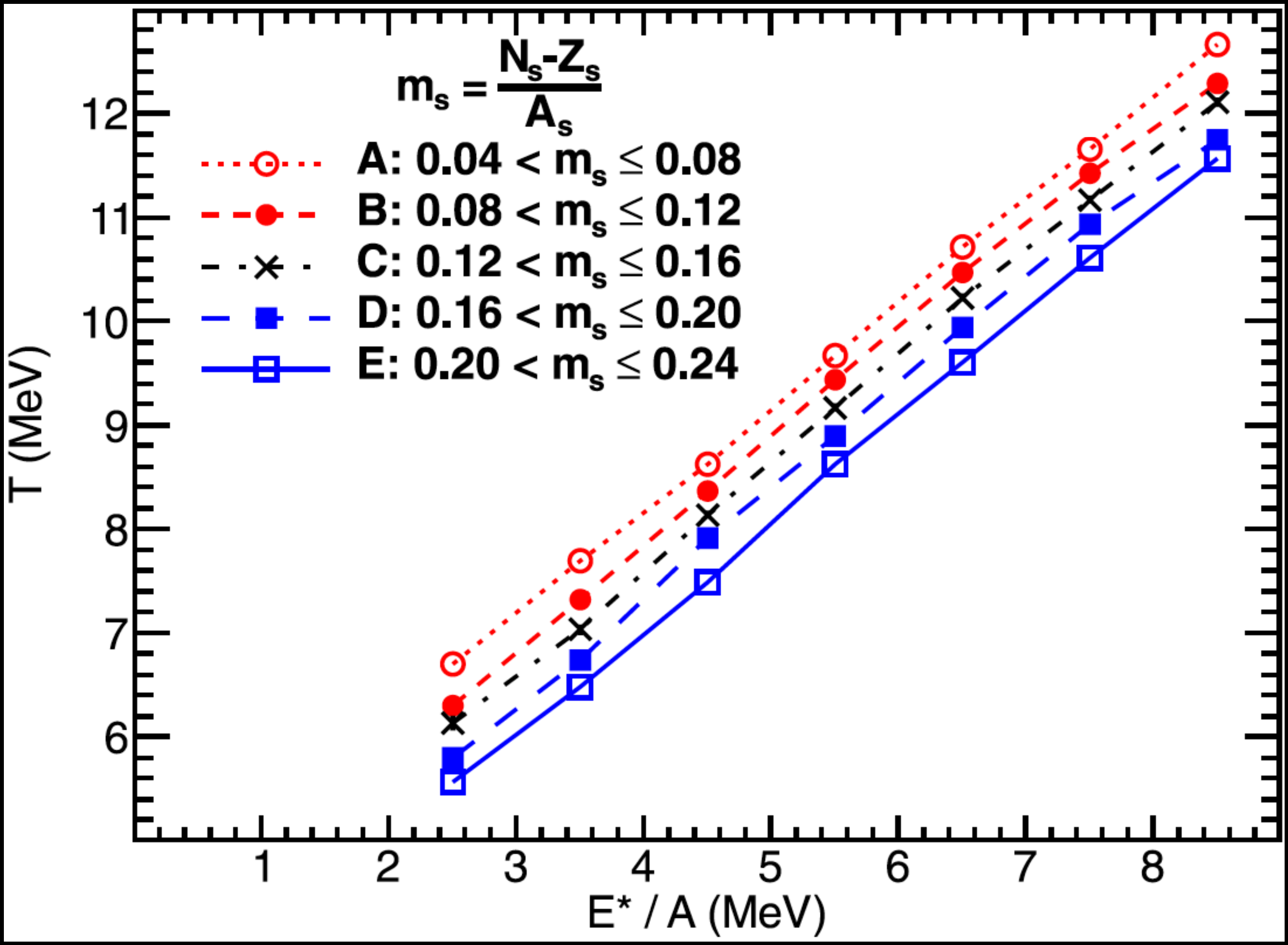
The QP (quasi-projectile) is the primary excited fragment that exists momentarily after the nuclear collision

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

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

Asymmetry Dependent Temperature

Physics Letters B 719 (2013) 337–340

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Asymmetry dependence of the nuclear caloric curve

A.B. McIntosh[a,*], A. Bonasera[a,b], P. Cammarata[a,c], K. Hagel[a], L. Heilborn[a,c], Z. Kohley[a,c,1], J. Mabiala[a], L.W. May[a,c], P. Marini[a,2], A. Raphelt[a,c], G.A. Souliotis[a,d], S. Wuenschel[a,c], A. Zarrella[a,c], S.J. Yennello[a,c]

PHYSICAL REVIEW C **87**, 034617 (2013)

Using light charged particles to probe the asymmetry dependence of the nuclear caloric curve

A. B. McIntosh,[1,*] A. Bonasera,[1,2] Z. Kohley,[1,3,†] P. J. Cammarata,[1,3] K. Hagel,[1] L. Heilborn,[1,3] J. Mabiala,[1] L. W. May,[1,3] P. Marini,[1,‡] A. Raphelt,[1,3] G. A. Souliotis,[1,4] S. Wuenschel,[1,3] A. Zarrella,[1,3] and S. J. Yennello[1,3]

Eur. Phys. J. A (2014) **50**: 35
DOI 10.1140/epja/i2014-14035-8

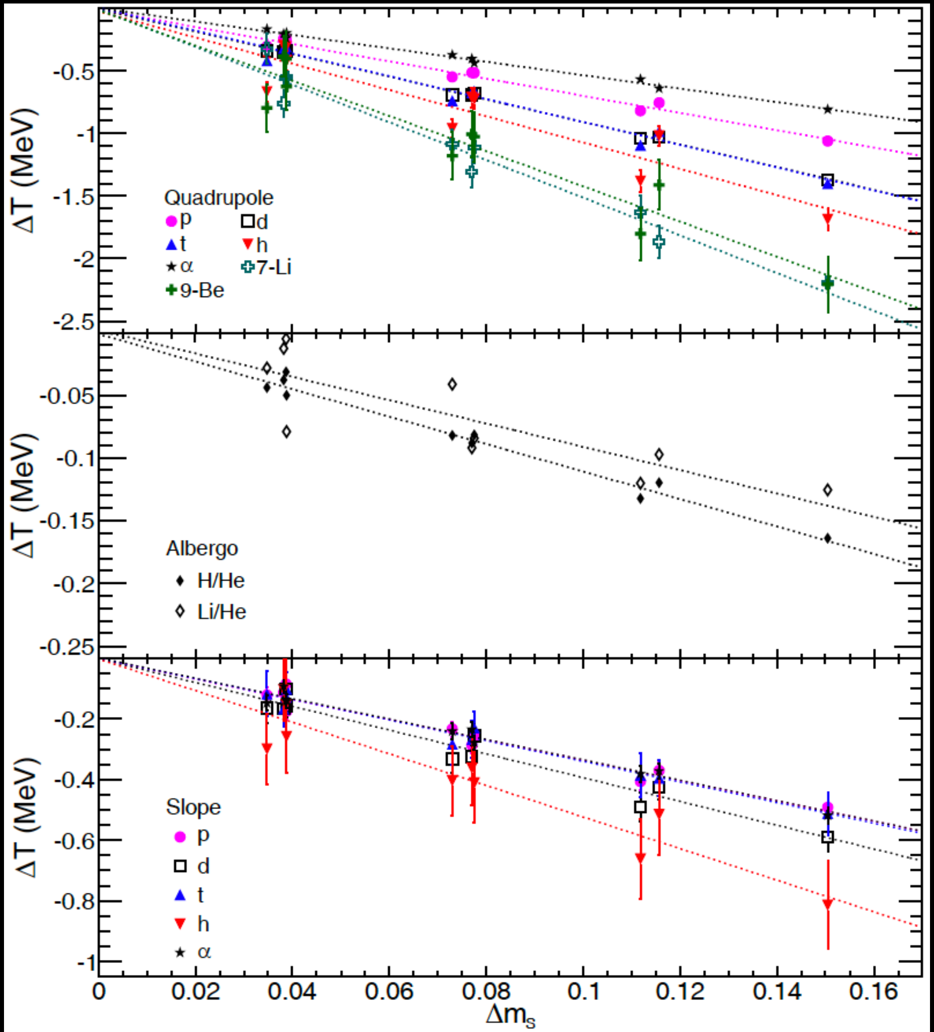
THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

How much cooler would it be with some more neutrons?*

Exploring the asymmetry dependence of the nuclear caloric curve and the liquid-gas phase transition

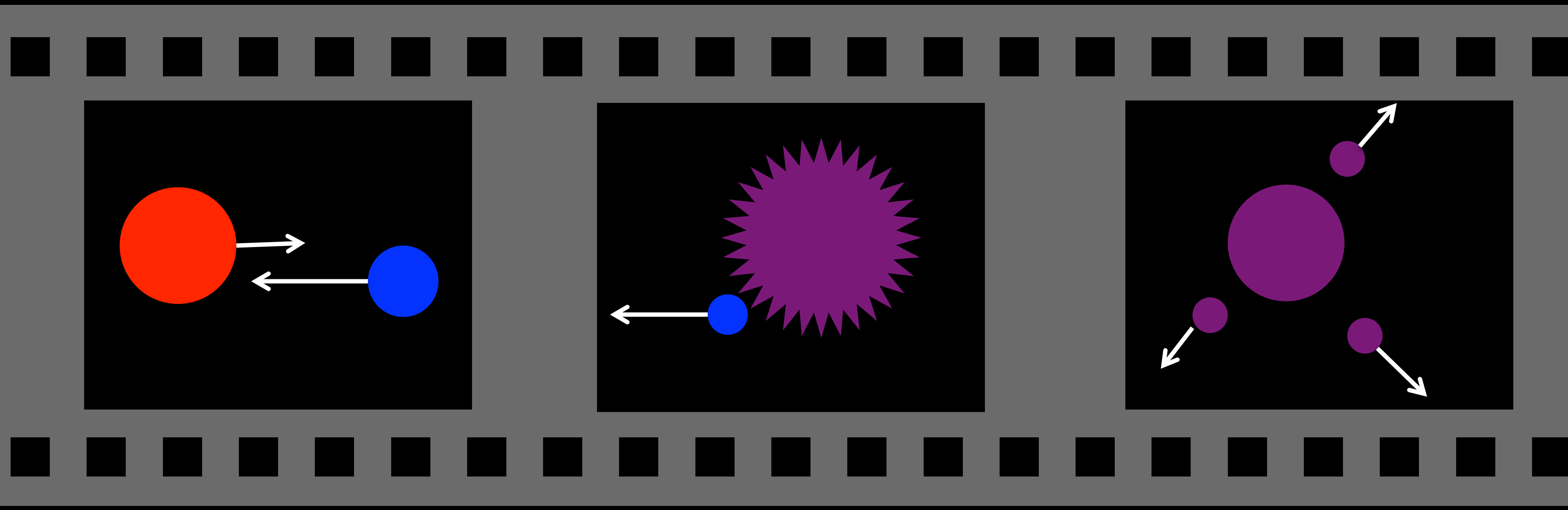
A.B. McIntosh[1,a], J. Mabiala[1], A. Bonasera[1,2], P. Cammarata[1,3], K. Hagel[1], Z. Kohley[1,3,4], L. Heilborn[1,3], L.W. May[1,3], P. Marini[1,5], A. Raphelt[1,3], G.A. Souliotis[1,6], S. Wuenschel[1,3], A. Zarrella[1,3], H. Zheng[1,7], and S.J. Yennello[1,3]



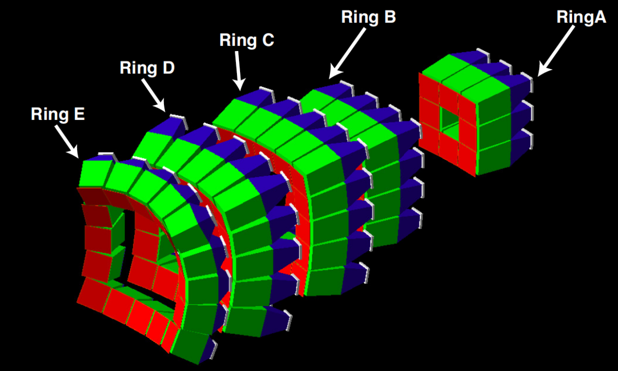
The Fusion Reactions

$^{78}Kr + ^{12}C$
$^{86}Kr + ^{12}C$

E/A = 15, 25, 35 MeV



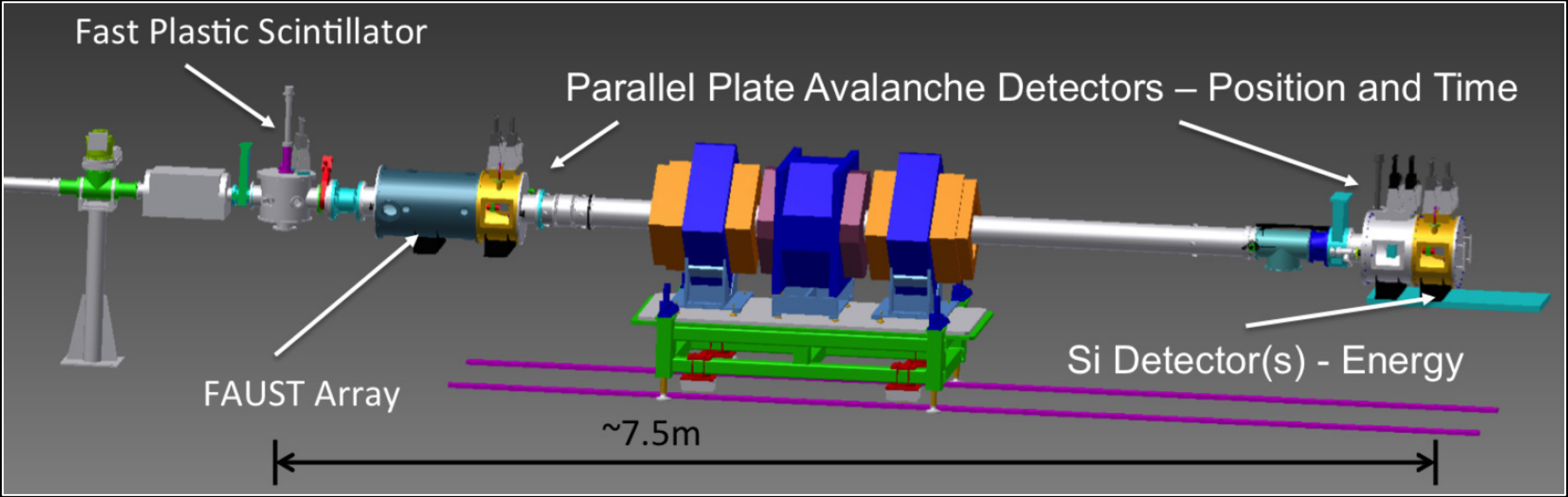
Experimental Configuration



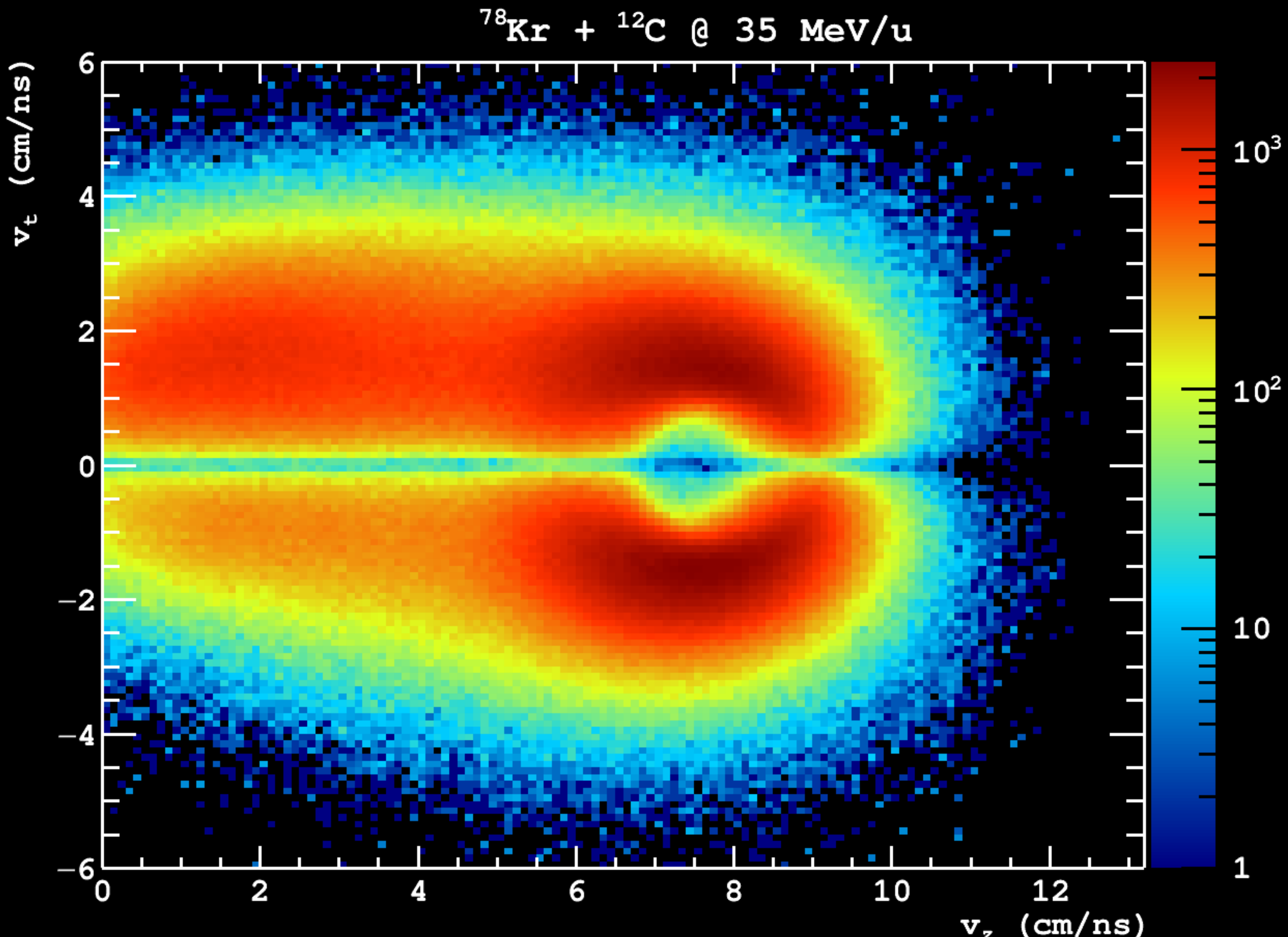
FAUST
Measure Light Charged Particles
Position-Sensitive
ΔE, E → Z, A, Energy
$1.6° \leq \theta \leq 45°$

Quadrupole Triplet Spectrometer
Measure Fusion-Evaporation Residues
Time-Of-Flight, ΔE, E → Velocity, Energy, Z, A
$0.9° \leq \theta \leq 2.3°$

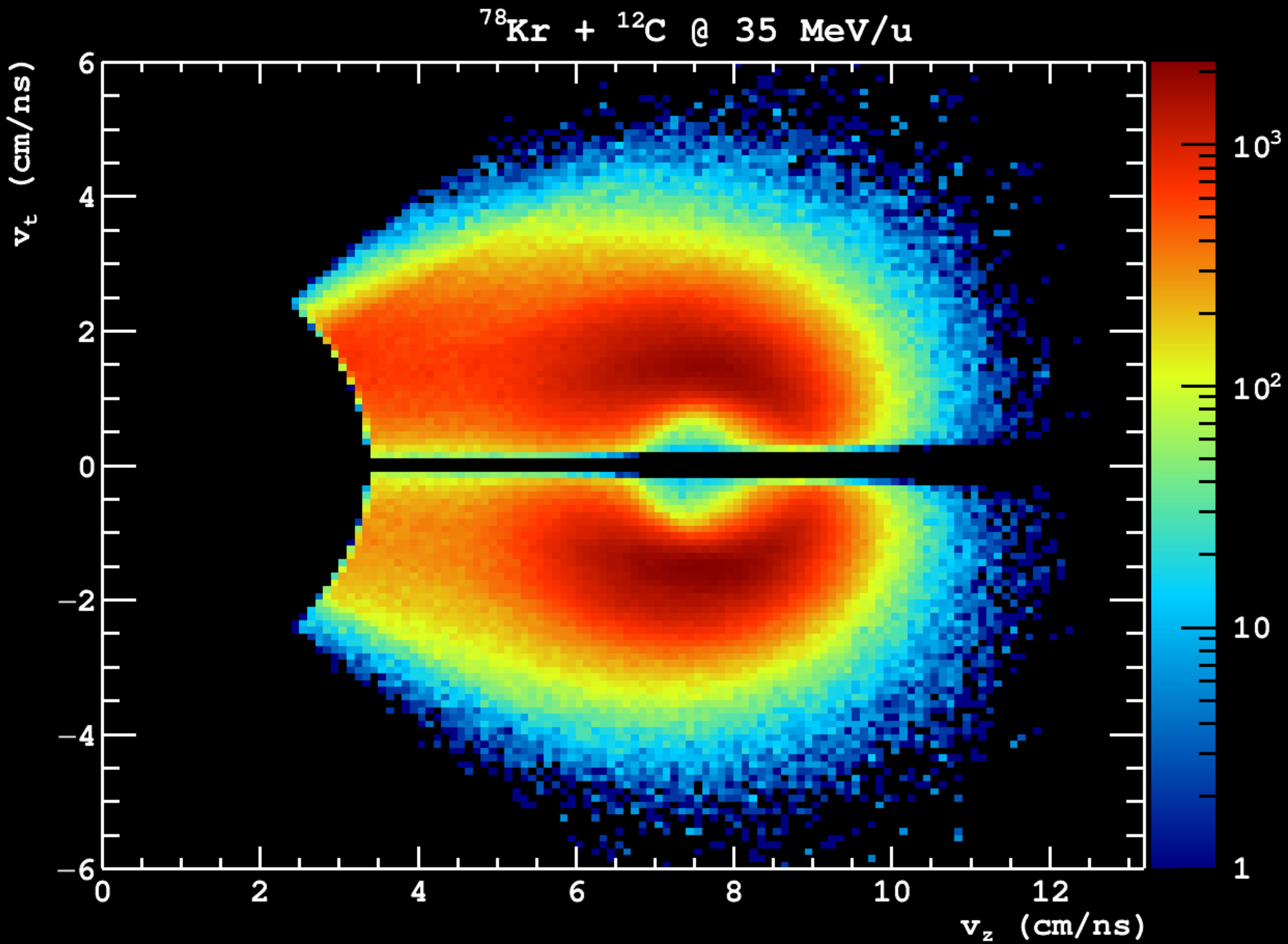
P. Cammarata et al., NIMA 792, 61 (2015)
L.A. Heilborn et al., article in preparation
A.B. McIntosh et al., article in preparation



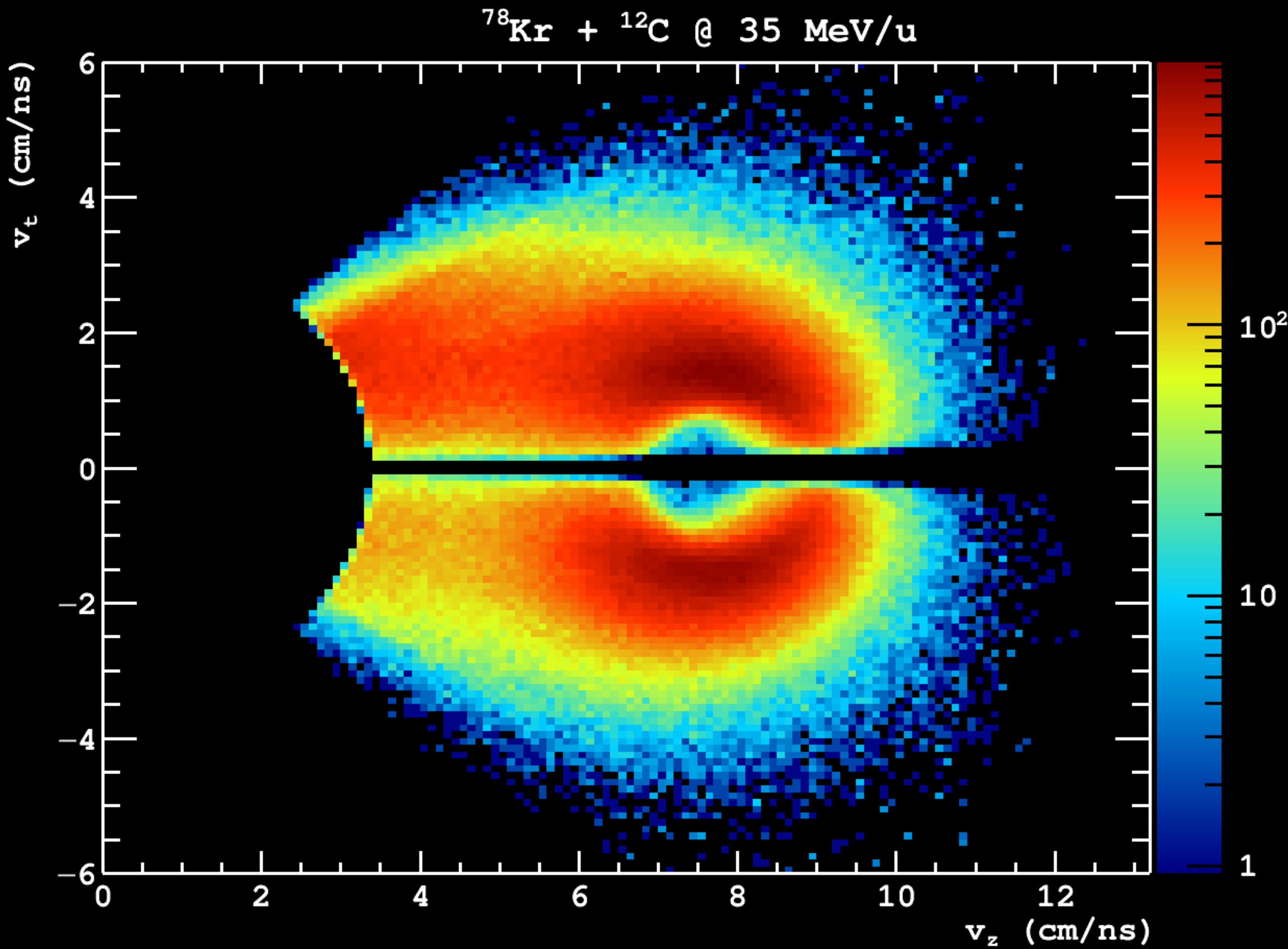
HIPSE (PRC 69 (2004) 054604) unfiltered



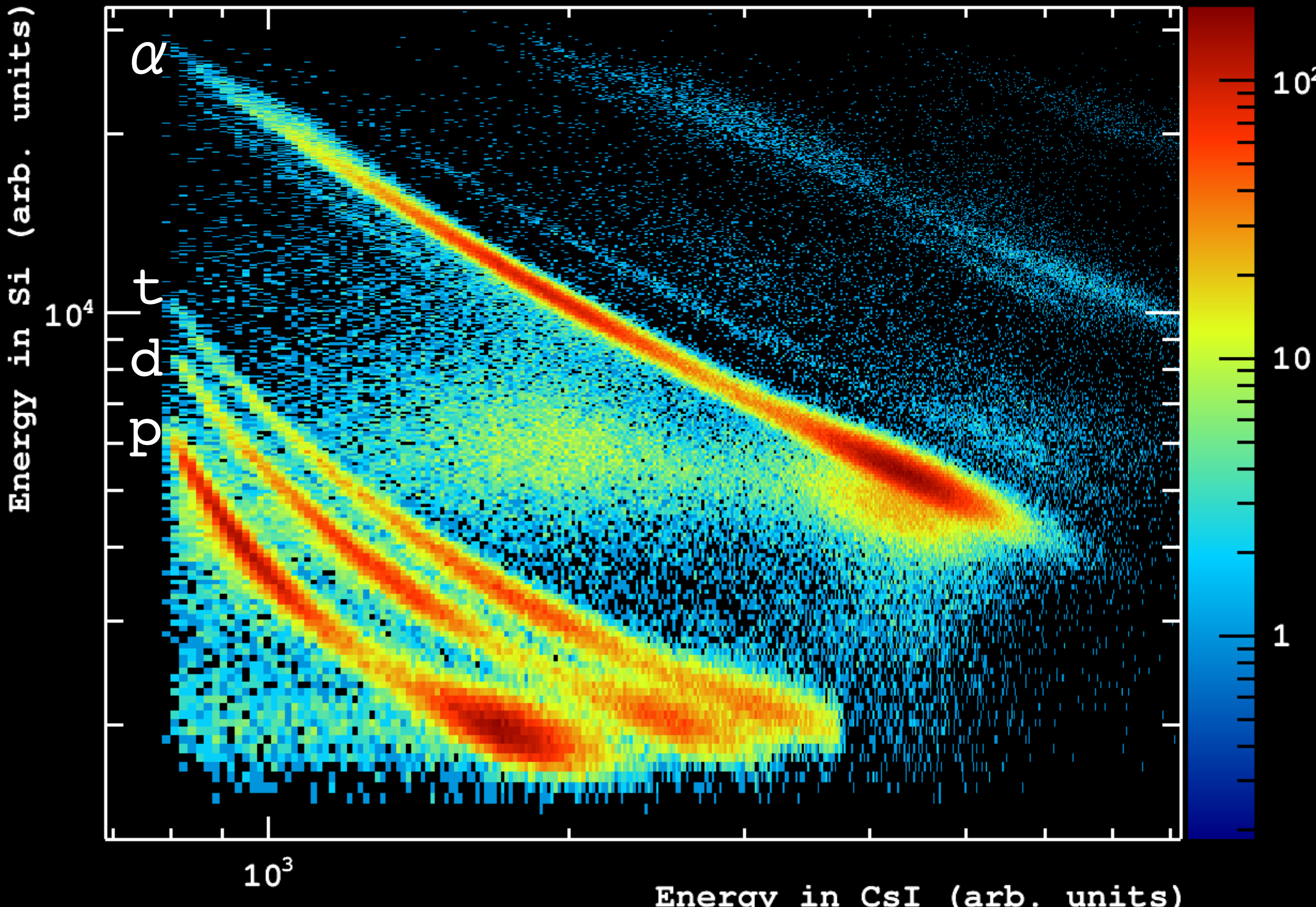
HIPSE filtered: (geom. & energy thresh.)



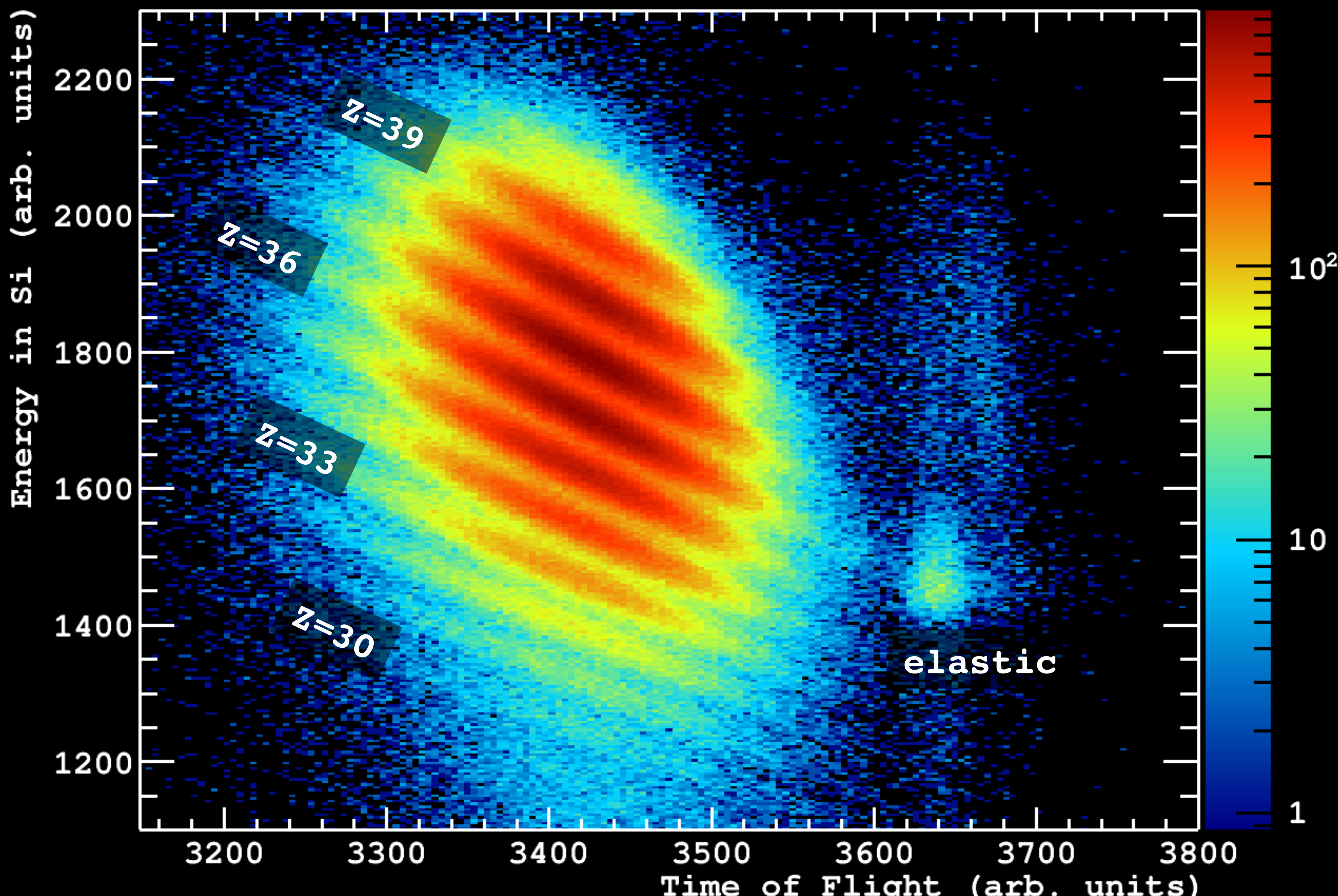
HIPSE filtered, coincident residue



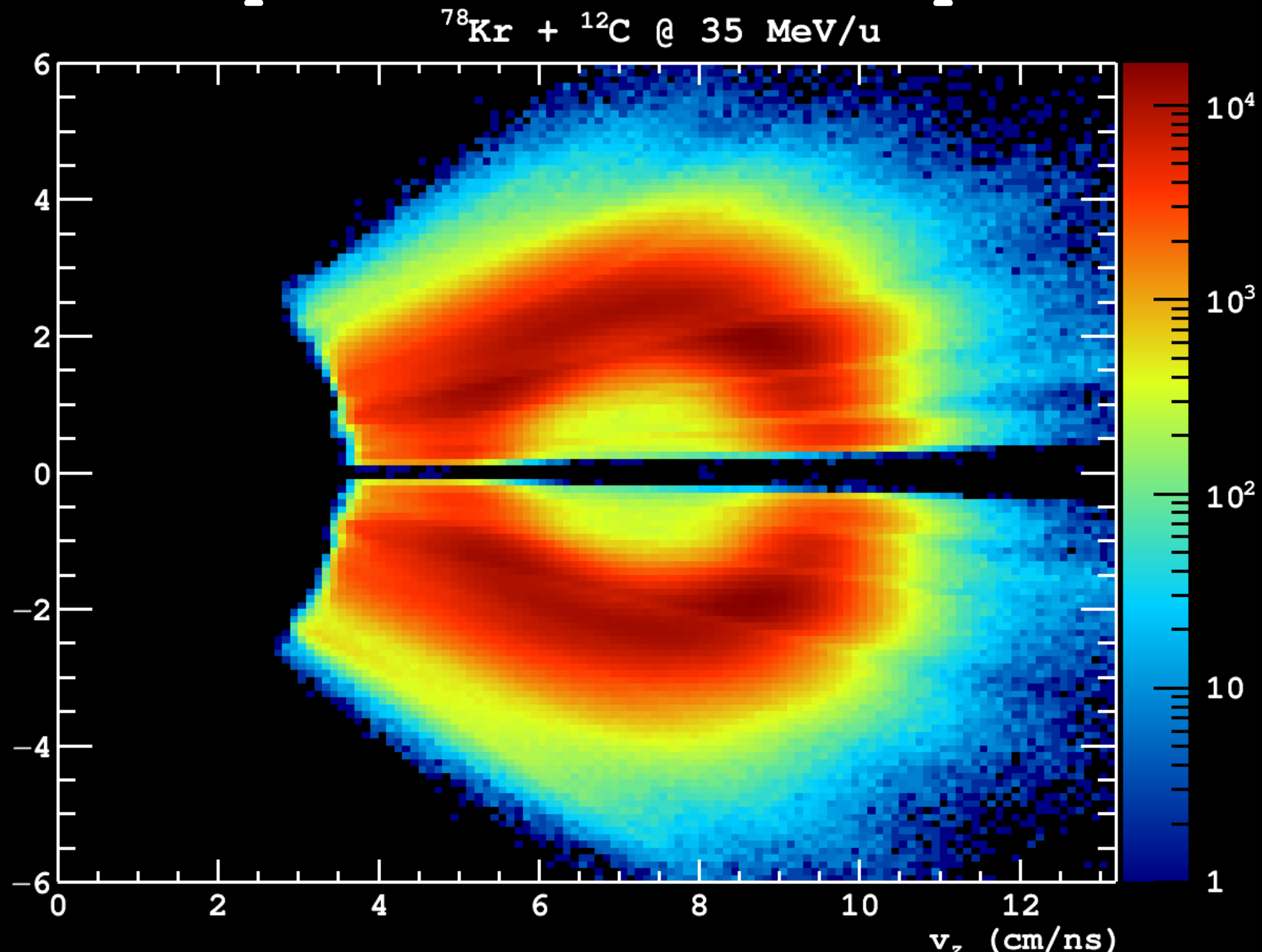
Raw FAUST Data



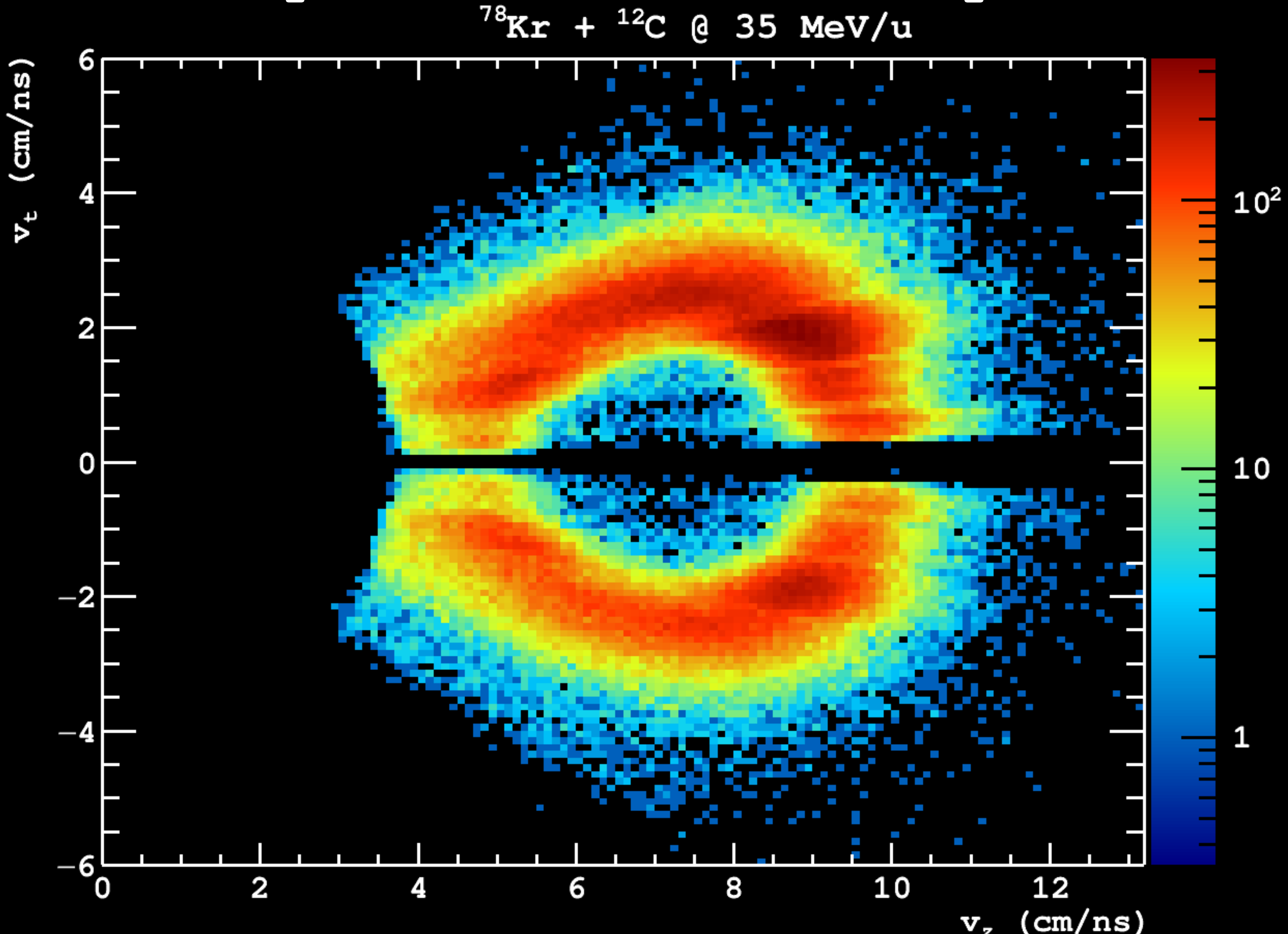
Raw QTS (Spectrometer) Data



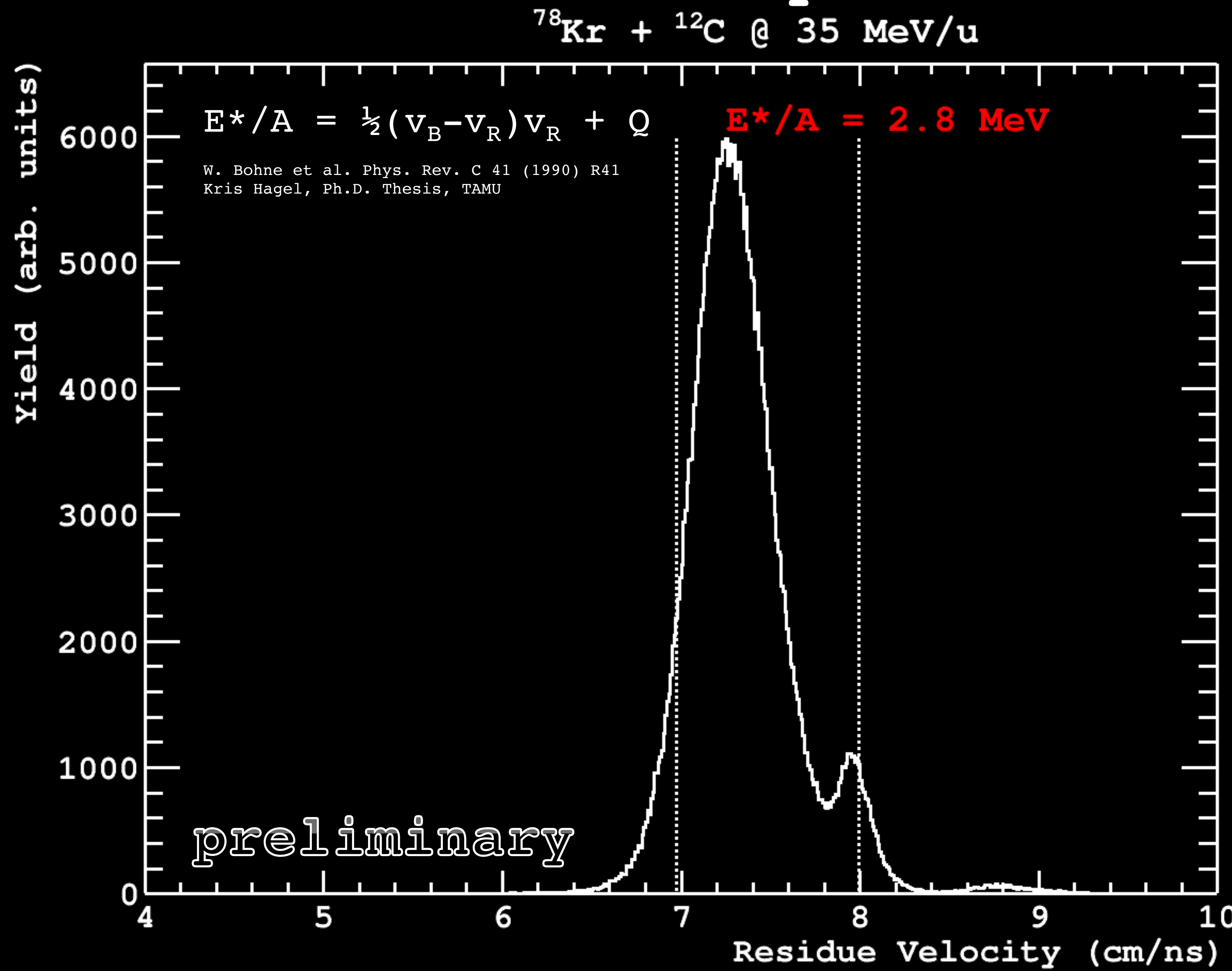
Measured Alpha-Particle Velocity



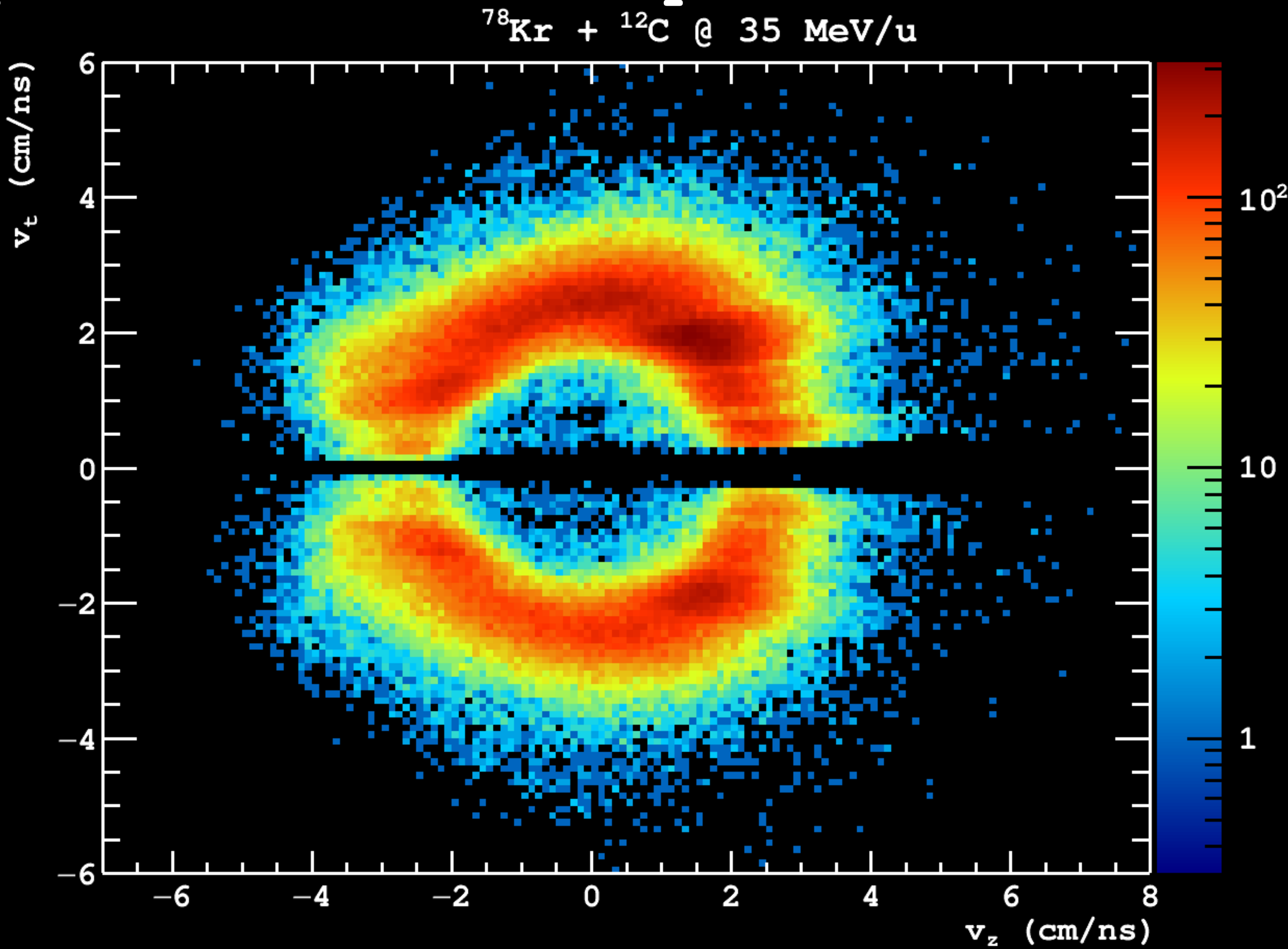
Measured Alpha-Particle Velocity



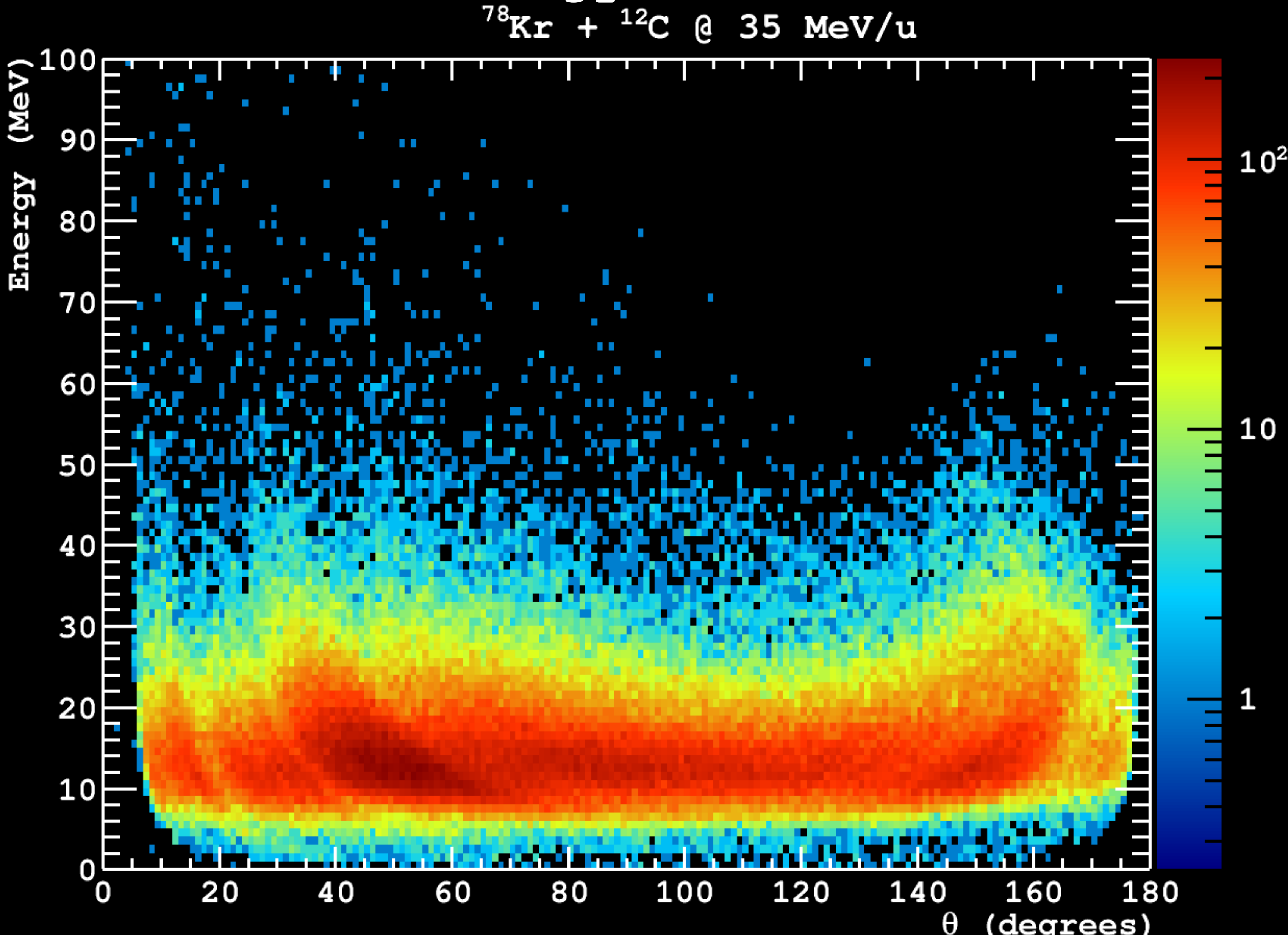
Measured Residue Velocity



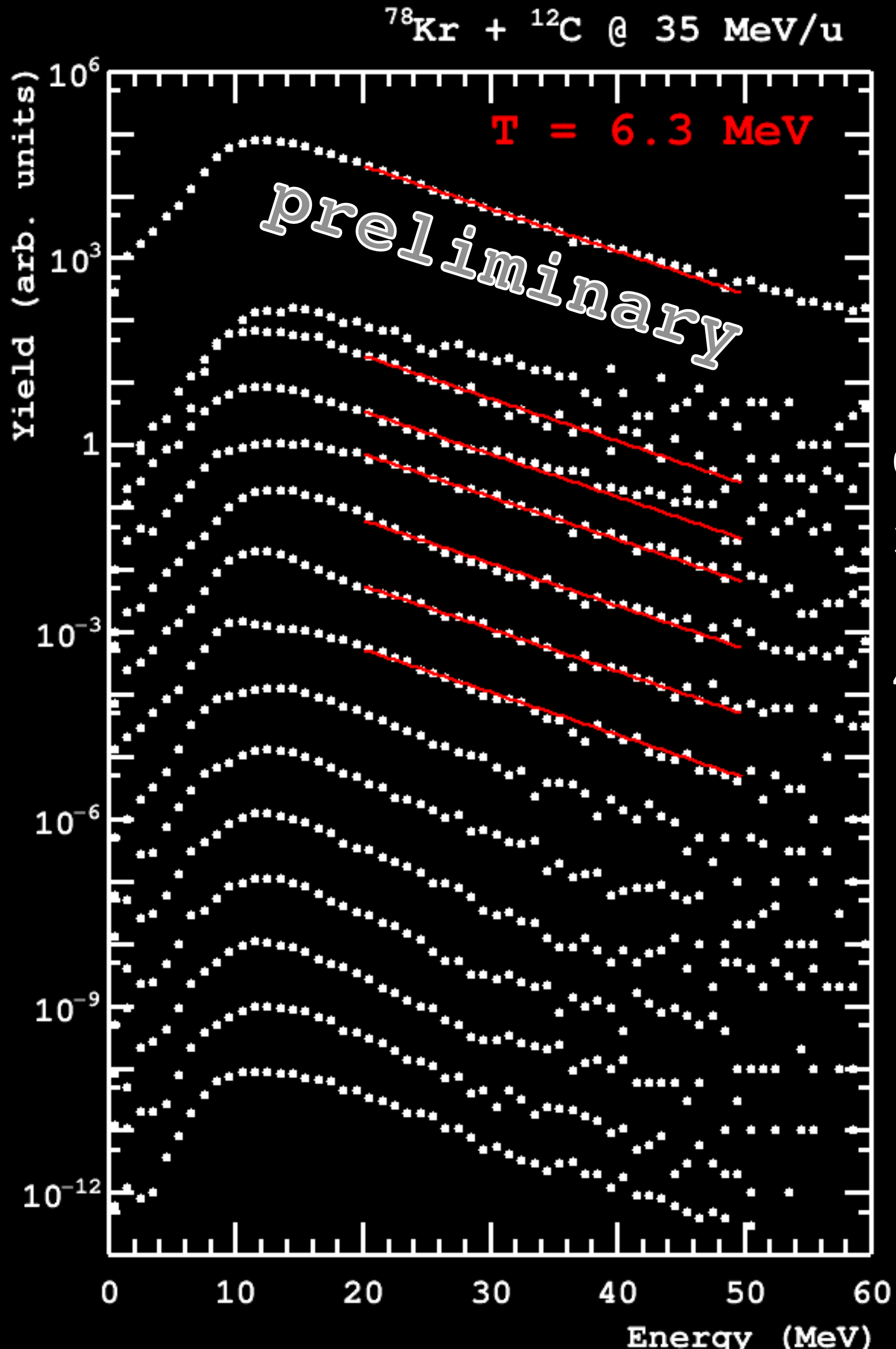
Alpha-Particle Velocity – Residue Frame



Alpha-Particle Energy



Alpha-Particle Energy



Fit: $Y(E) = A*\exp[-E/T]$
$20<E<50$ MeV
$10° < \theta < 70°$

$0° < \theta < 10°$

$10° < \theta < 20°$

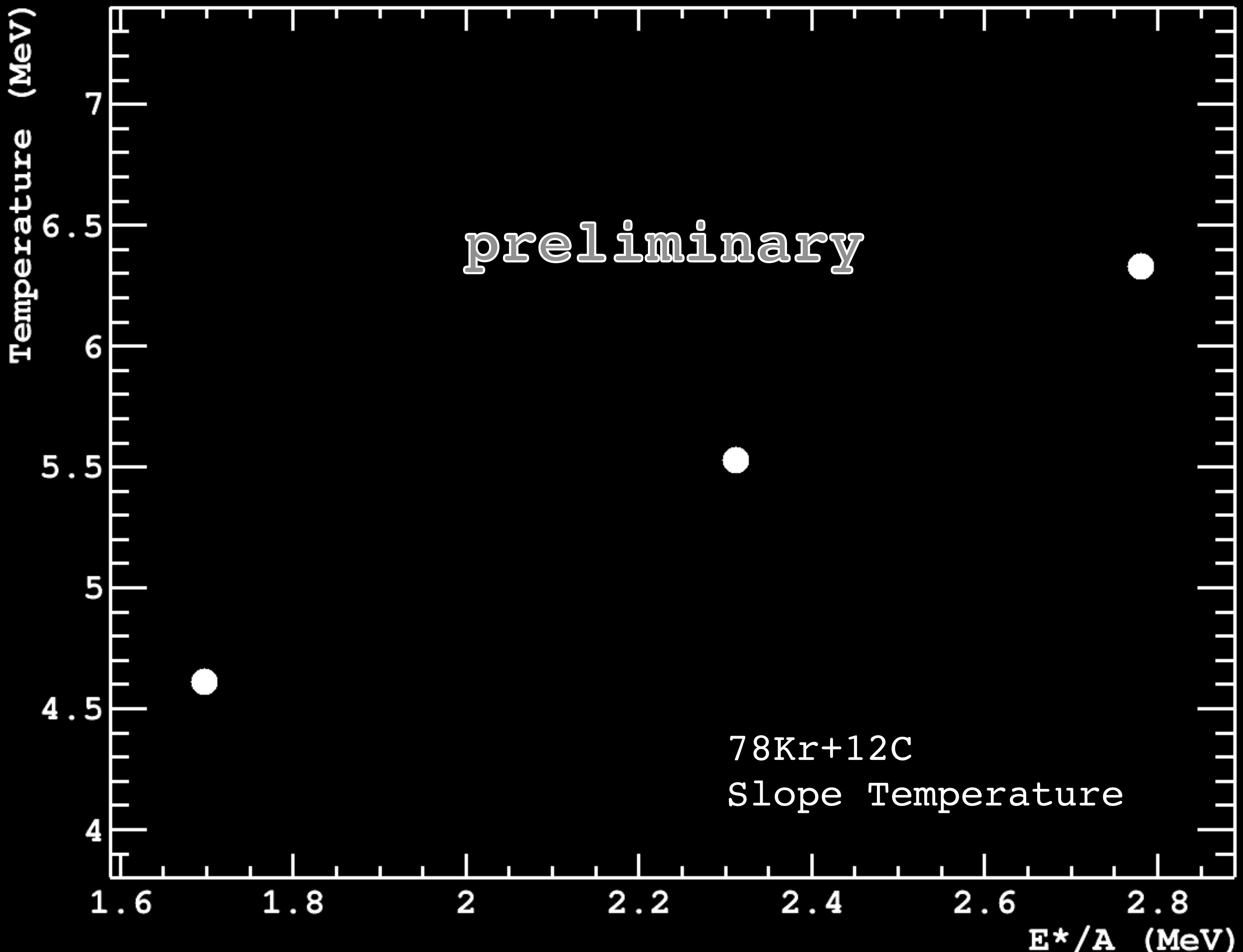
$40° < \theta < 50°$

$70° < \theta < 80°$

$100° < \theta < 110°$

$130° < \theta < 140°$

Data Along the Caloric Curve



Nuclear Caloric Curve

Mass Dependence

compilation of data

Asymmetry Dependence

Reconstructed Quasi-Projectiles in HI Collisions

Fusion Rections (78,86Kr+C @ 15,25,35 MeV/u)

Residue → E*

Light Particles → T

Preliminary E* and T Extracted Using α Particles

Rich Data Set – More to come

Acknowledgements

Yennello Research Group

A.B. McIntosh, L. Heilborn, P. Cammarata, M. Chapman, J. Gauthier, K. Hagel, M. Huang, A. Jedele, A. Keeler, Y.W. Lui, L.W. May, E. McCleskey, A. Rodriguez Manso, R. Wada, A. Wakhle, M.D. Youngs, A. Zarrella, S.J. Yennello

U.S. Department of Energy

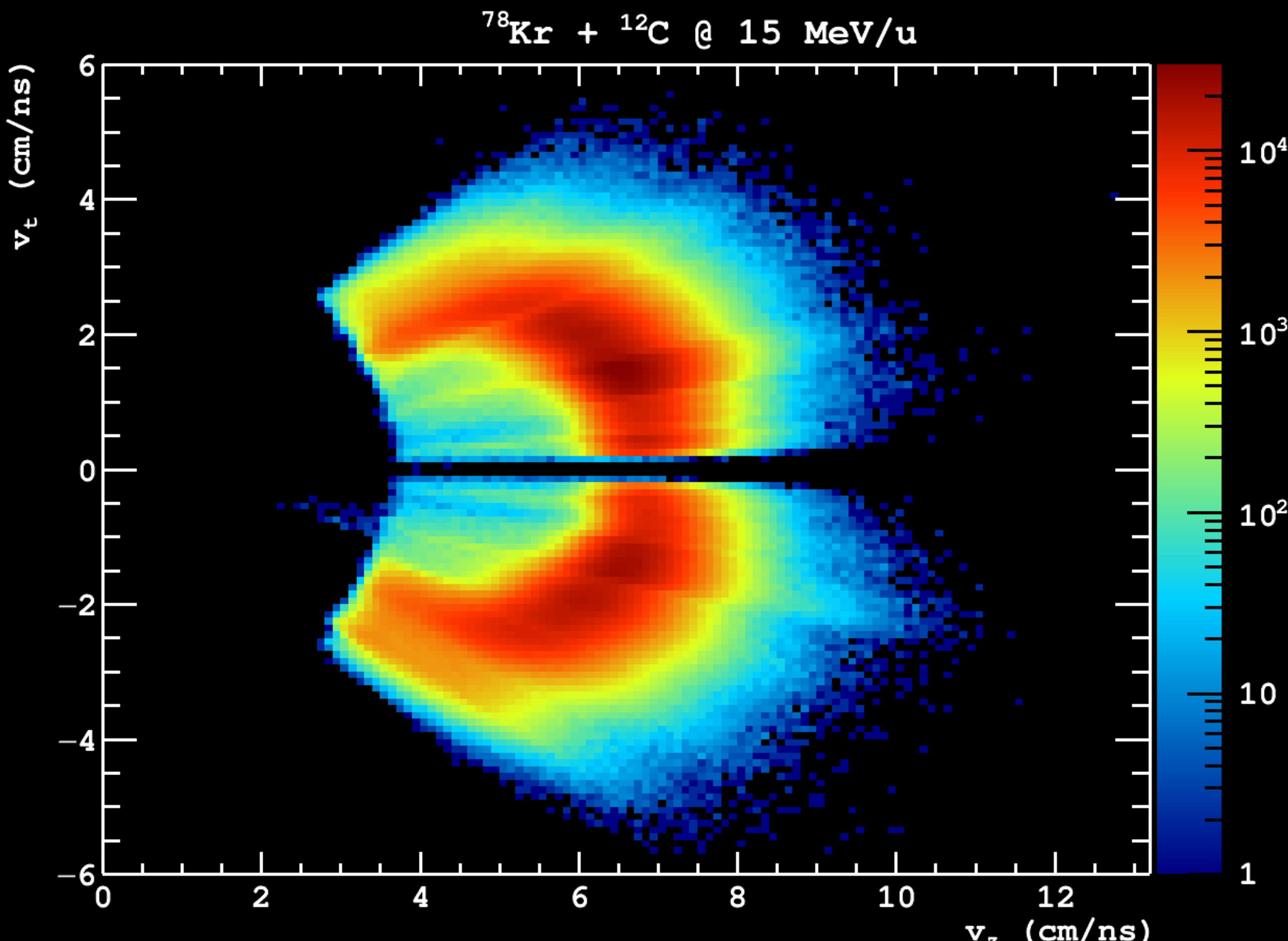
DE-FG03-93ER40773

Welch Foundation

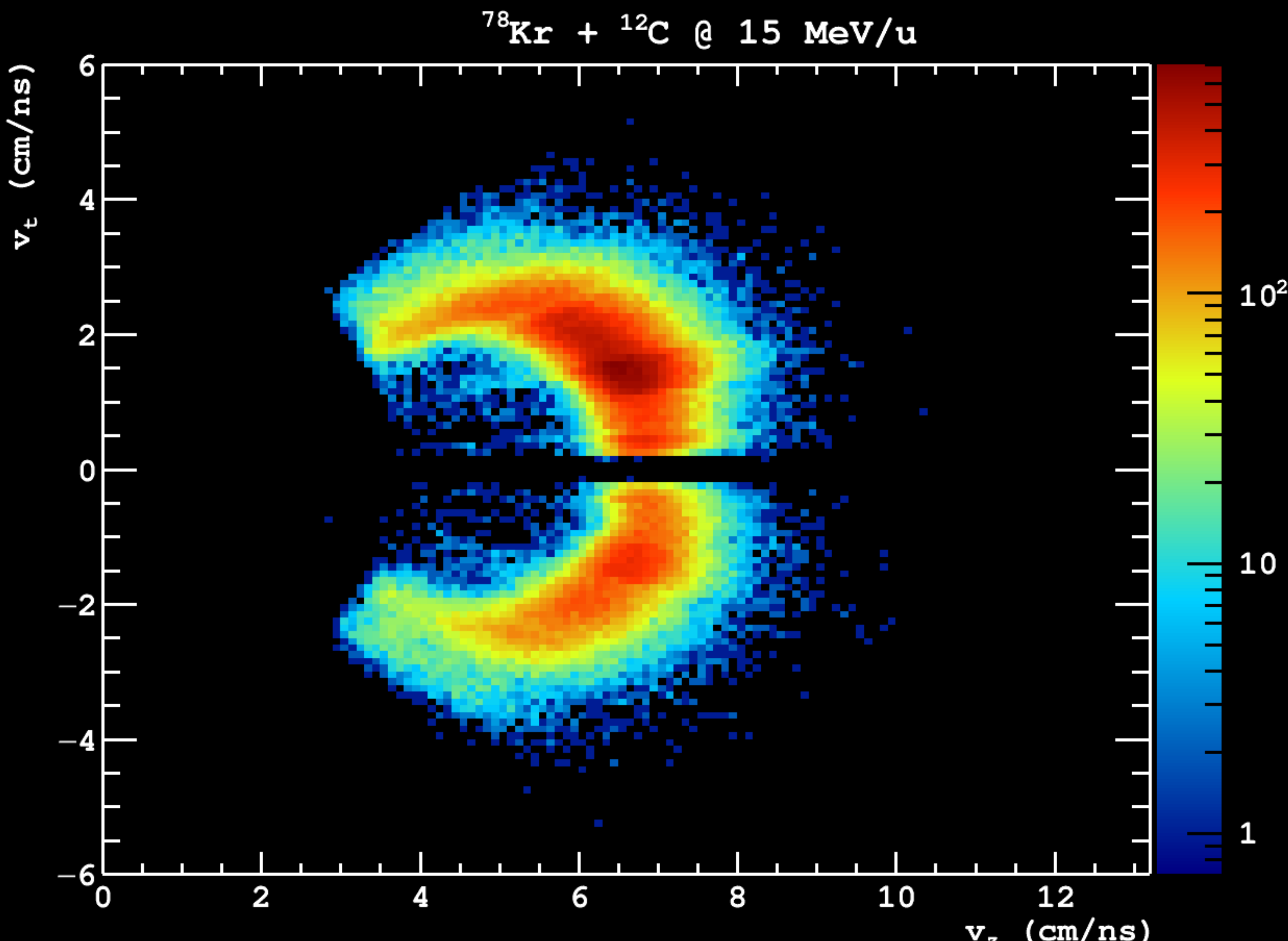
A-1266

Supplementary Material

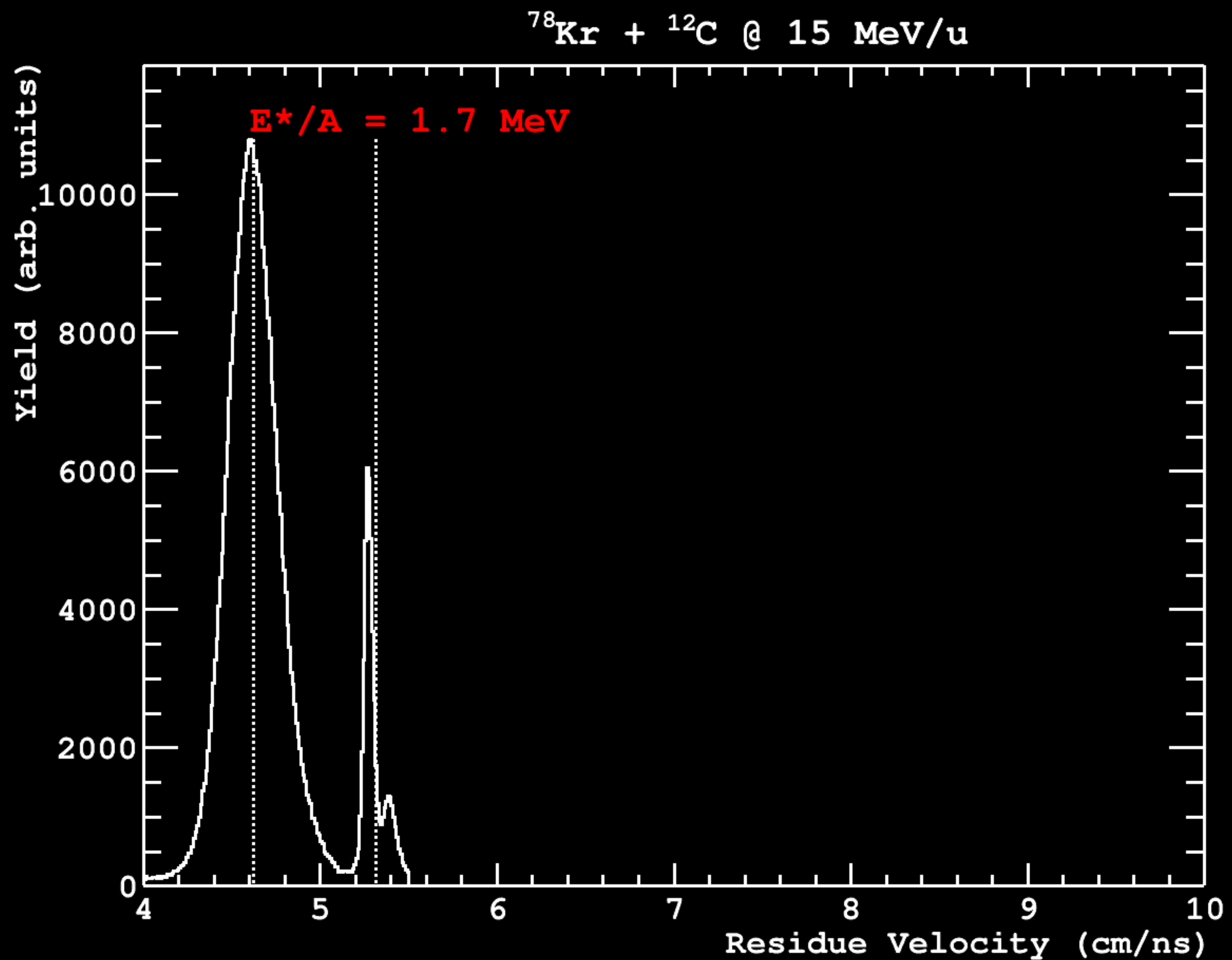
Data
78Kr + C @ 15 MeV/u



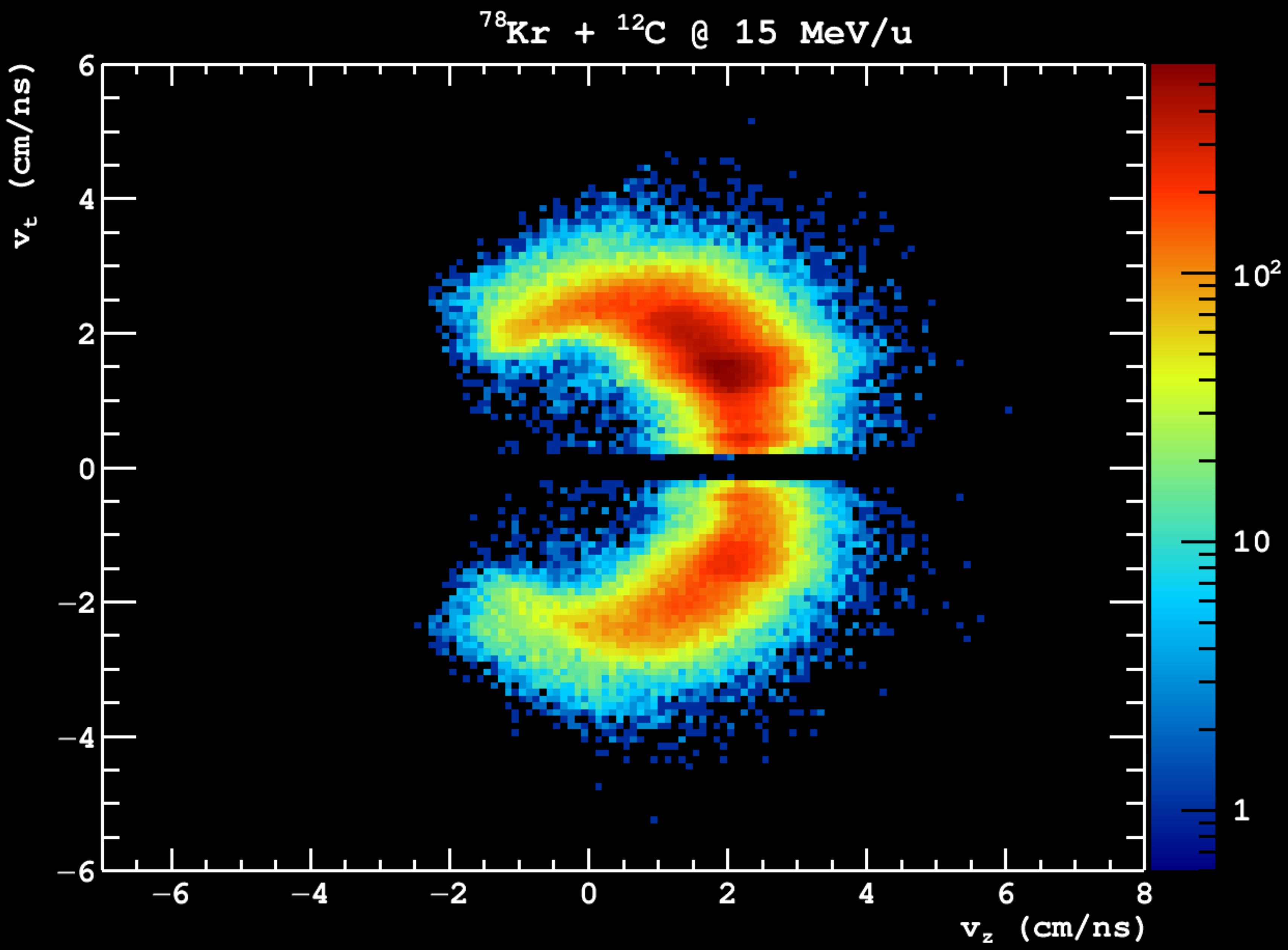
78Kr + 12C @ 15 MeV/u
vt (cm/ns)
vz (cm/ns)
6
4
2
0
−2
−4
−6
0
2
4
6
8
10
12
10^4
10^3
10^2
10
1

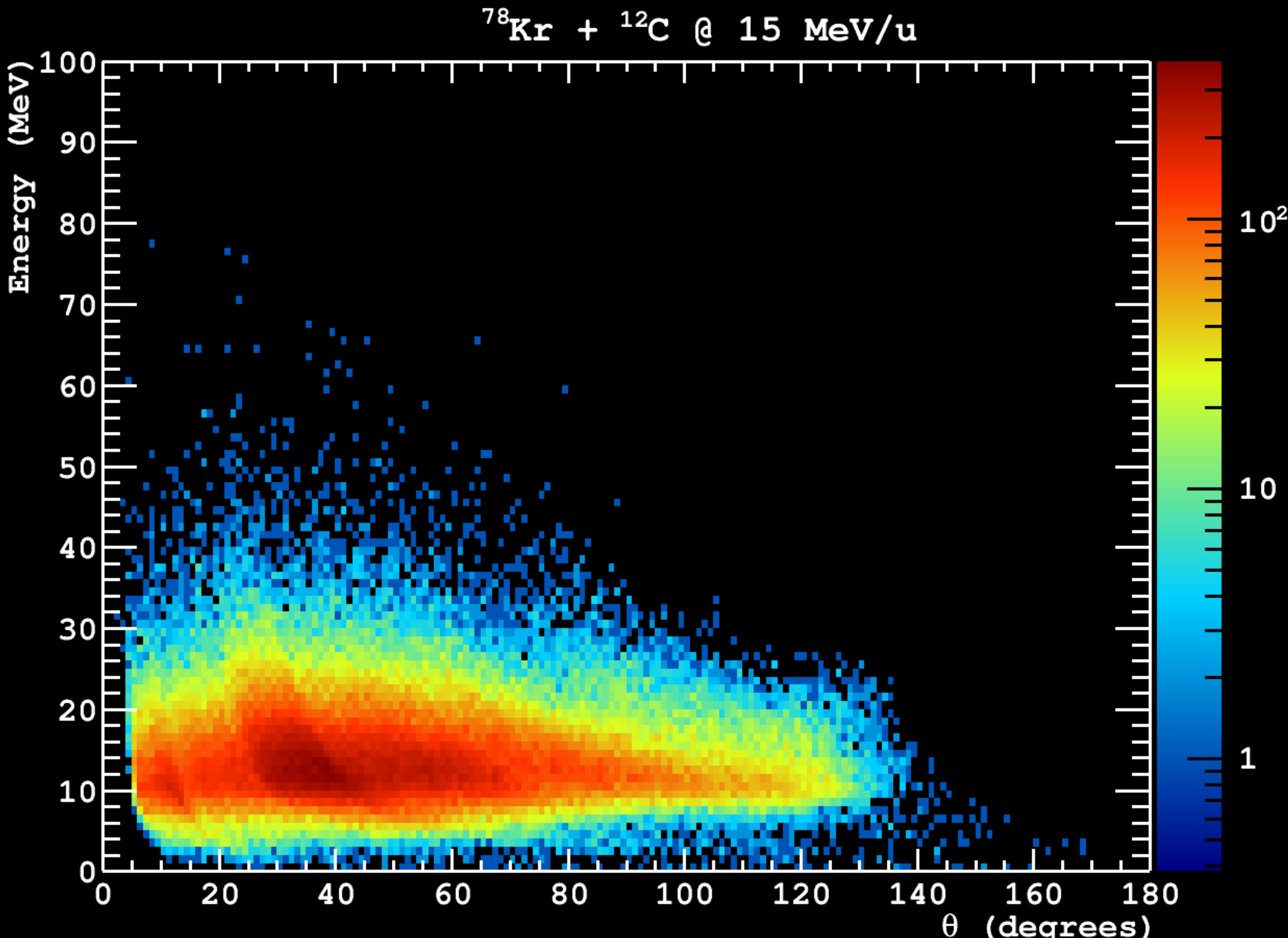


^{78}Kr + ^{12}C @ 15 MeV/u
v_t (cm/ns)
v_z (cm/ns)
6
4
2
0
−2
−4
−6
0
2
4
6
8
10
12
10^2
10
1

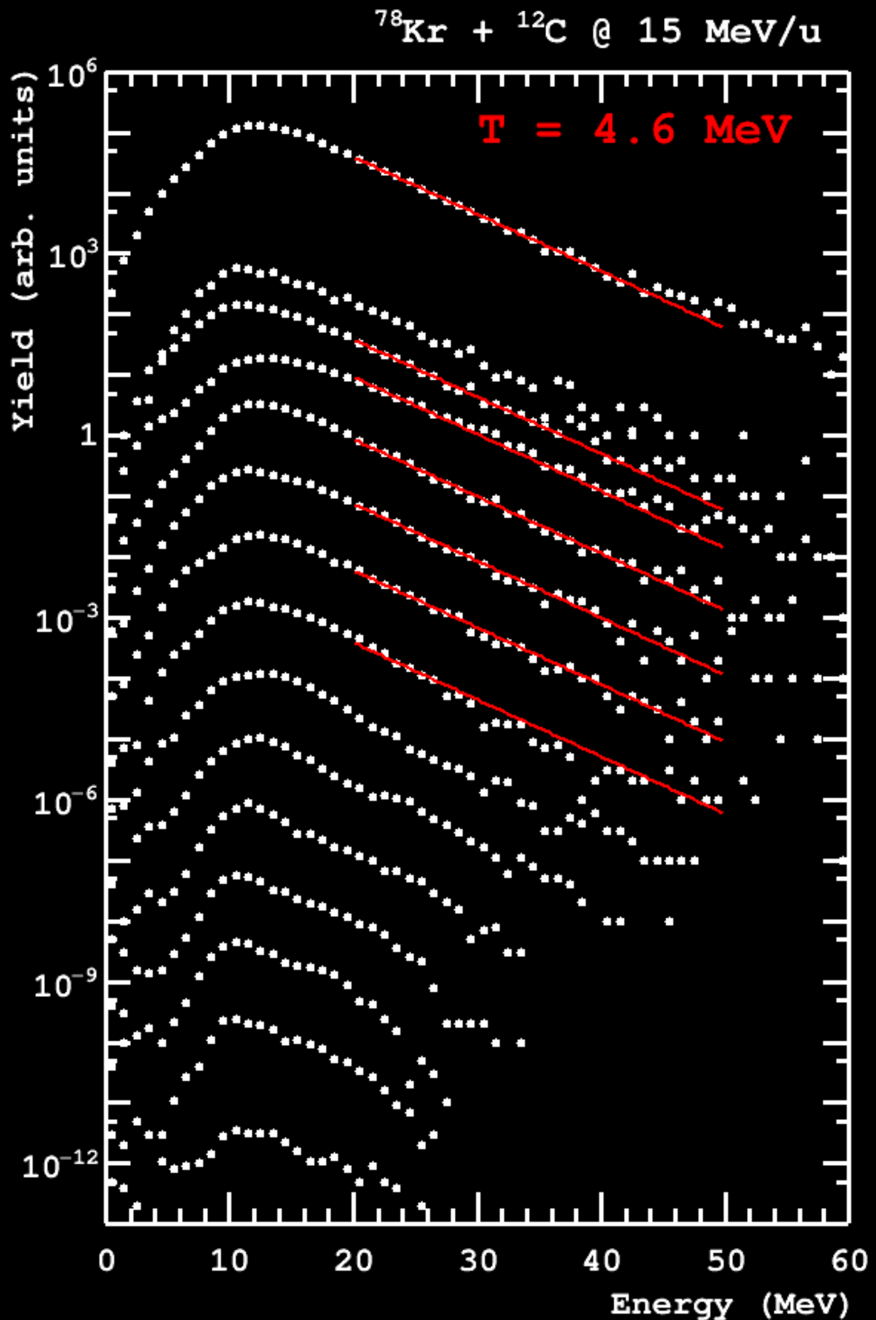


^{78}Kr + ^{12}C @ 15 MeV/u
E*/A = 1.7 MeV
Yield (arb. units)
0
2000
4000
6000
8000
10000
4
5
6
7
8
9
10
Residue Velocity (cm/ns)


^{78}Kr + ^{12}C @ 15 MeV/u
v_t (cm/ns)
v_z (cm/ns)
6
4
2
0
−2
−4
−6
8
1
10
10^2

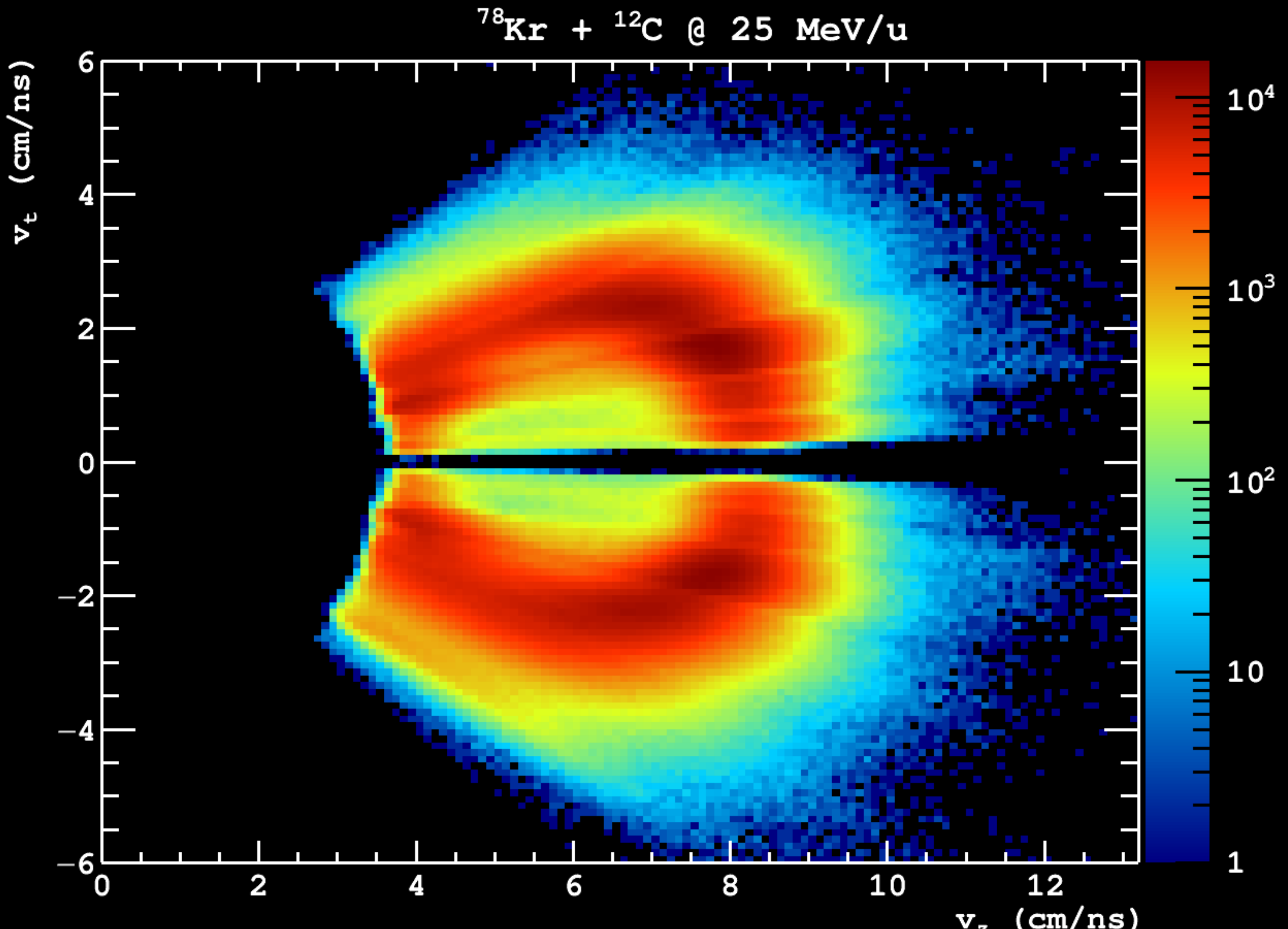


^{78}Kr + ^{12}C @ 15 MeV/u
Energy (MeV)
θ (degrees)
0
10
20
30
40
50
60
70
80
90
100
0
20
40
60
80
100
120
140
160
180
1
10
10^2

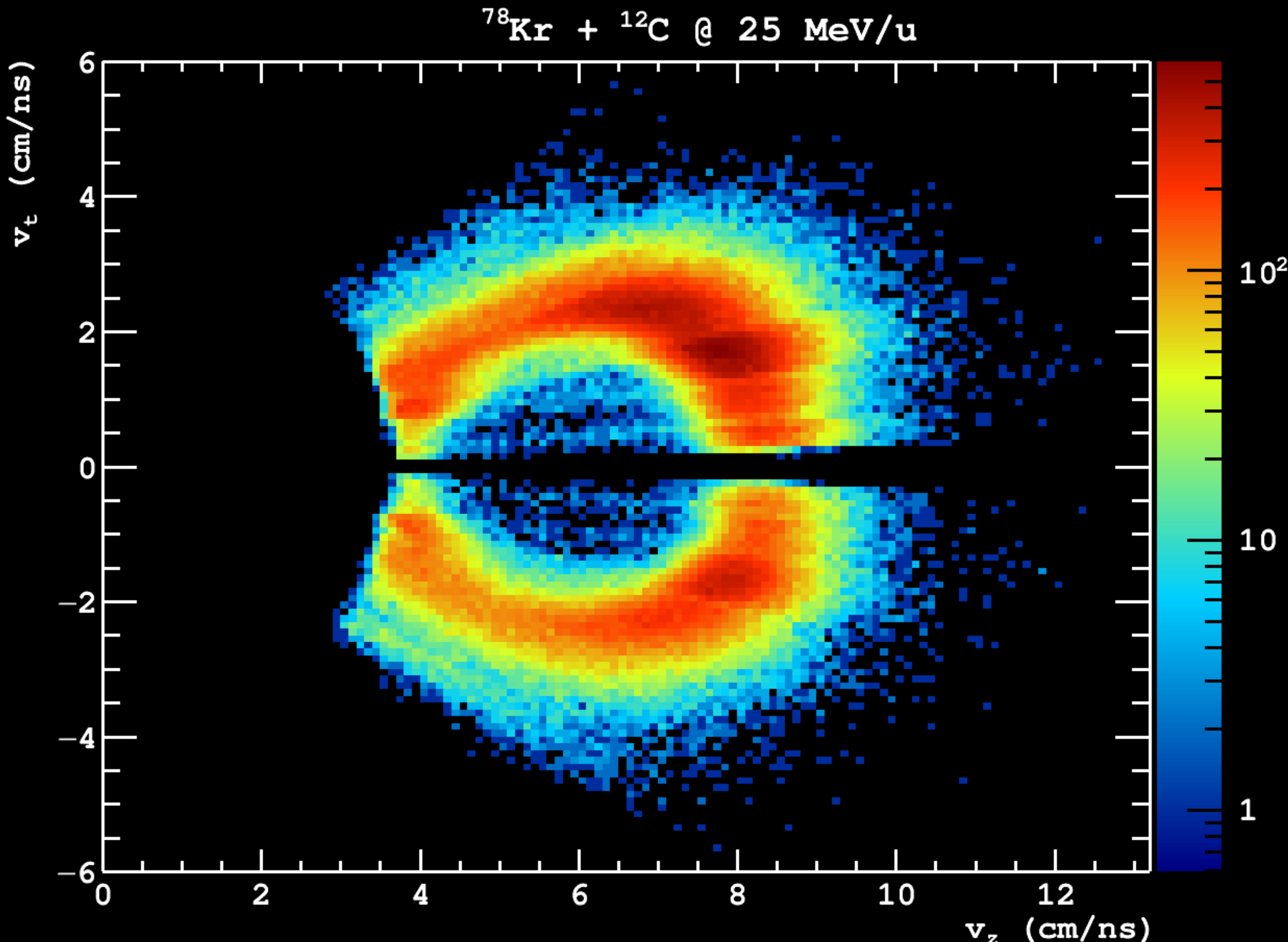


$^{78}Kr + ^{12}C$ @ 15 MeV/u
T = 4.6 MeV
Yield (arb. units)
Energy (MeV)
10^6
10^3
1
10^{-3}
10^{-6}
10^{-9}
10^{-12}
0
10
20
30
40
50
60

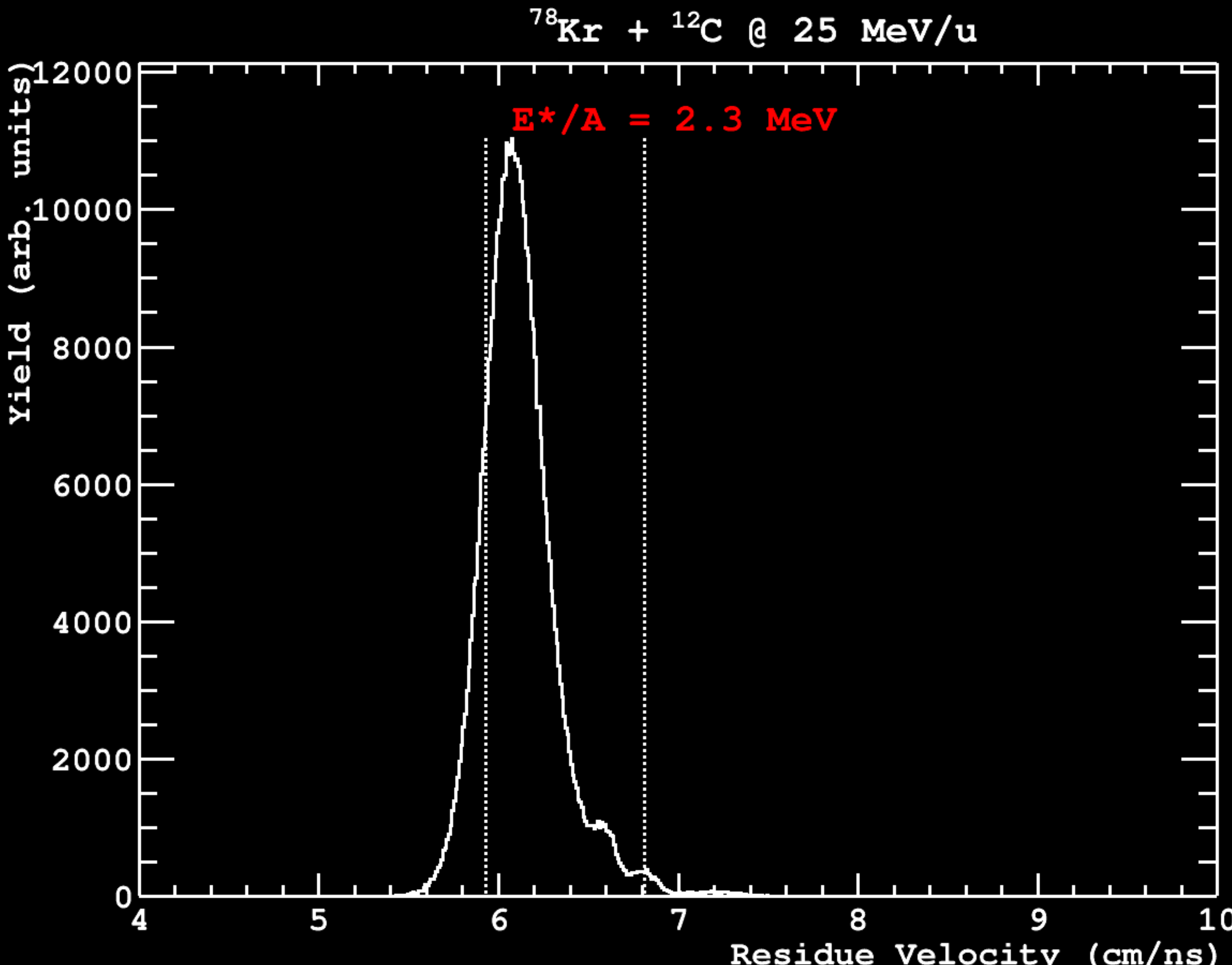
Data
78Kr + C @ 25 MeV/u



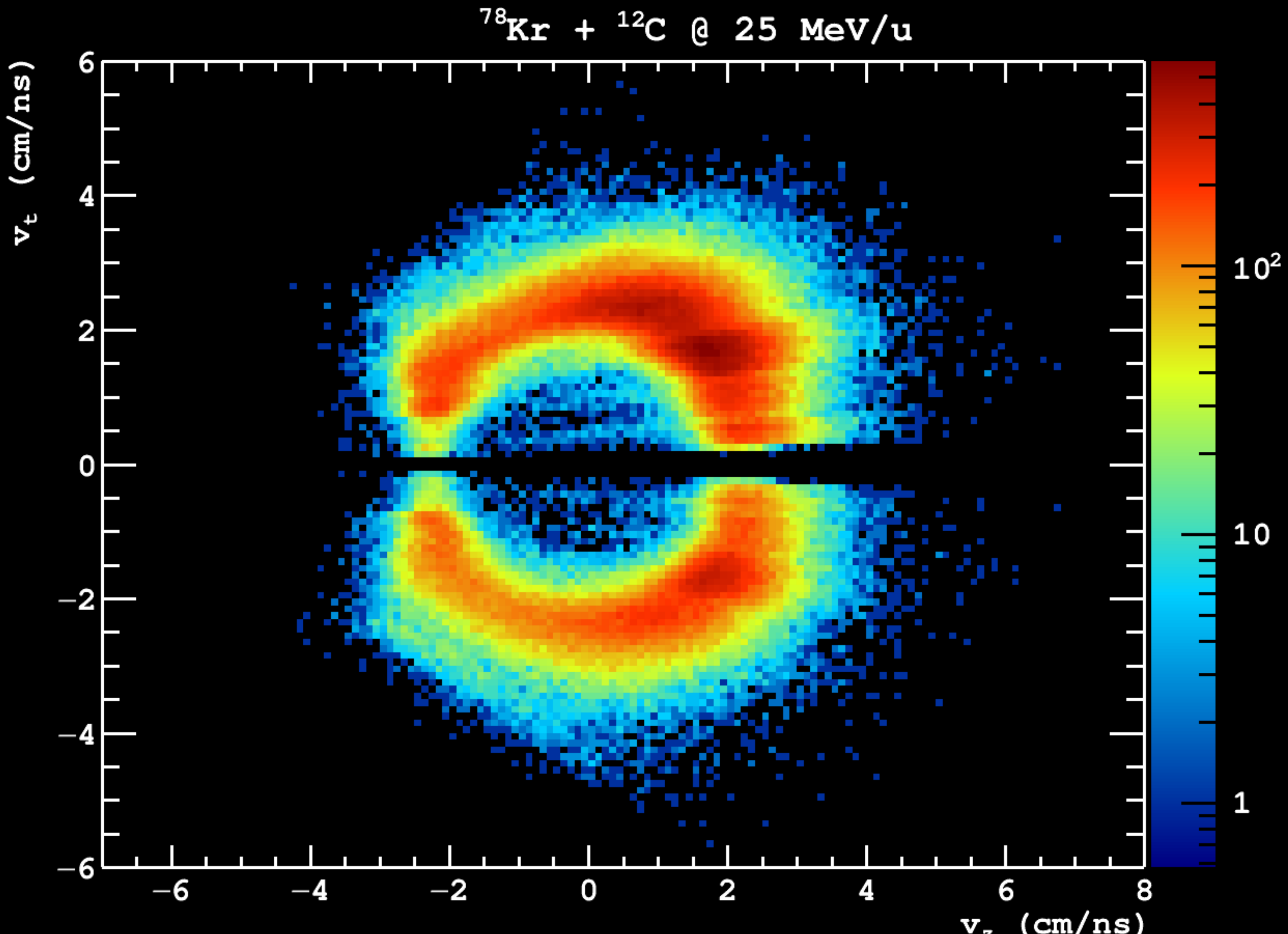
$^{78}Kr + ^{12}C$ @ 25 MeV/u
v_t (cm/ns)
v_z (cm/ns)
6
4
2
0
−2
−4
−6
0
2
4
6
8
10
12
10^4
10^3
10^2
10
1



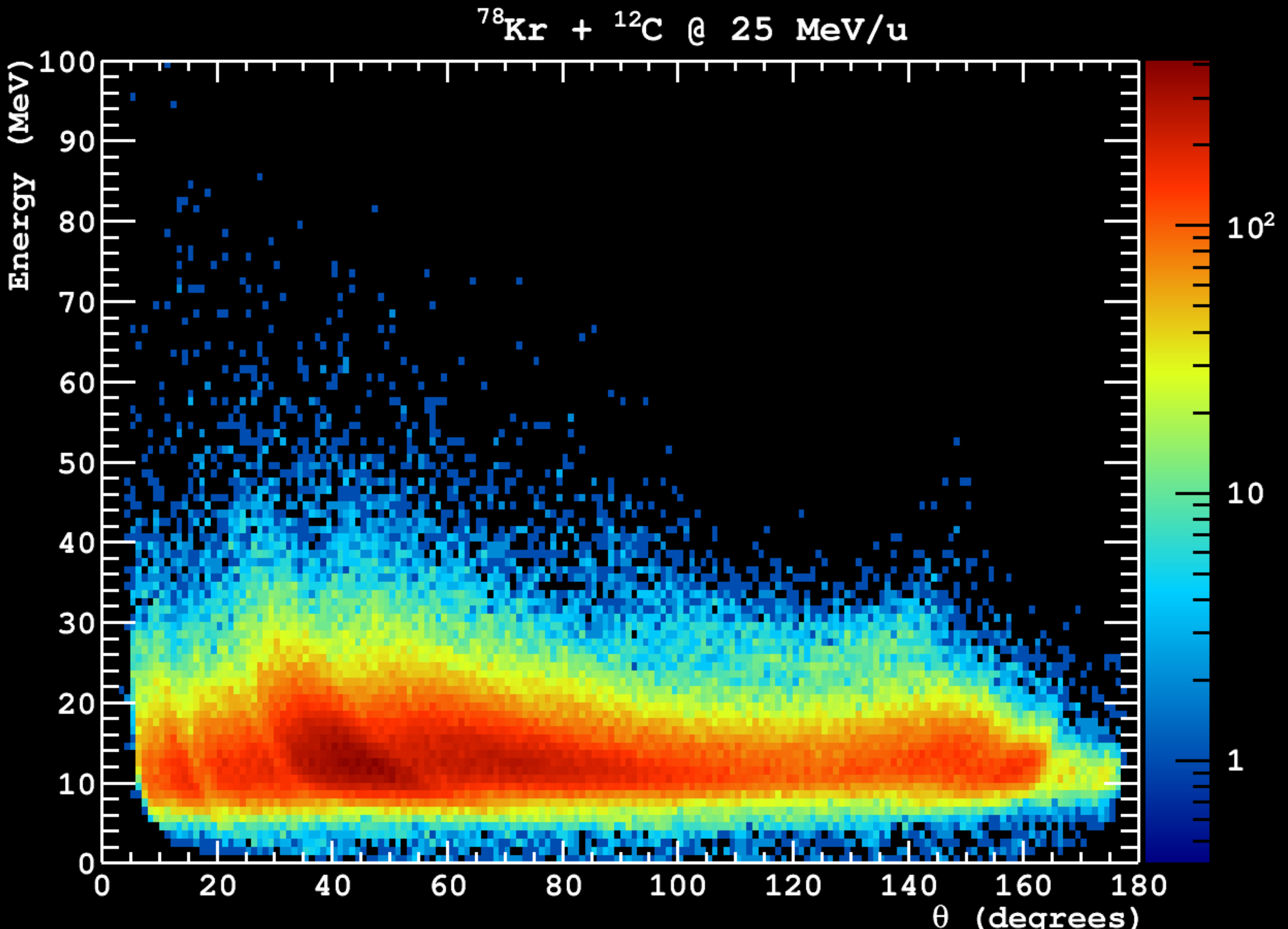
^{78}Kr + ^{12}C @ 25 MeV/u
v_t (cm/ns)
v_z (cm/ns)
6
4
2
0
−2
−4
−6
0
2
4
6
8
10
12
10^2
10
1



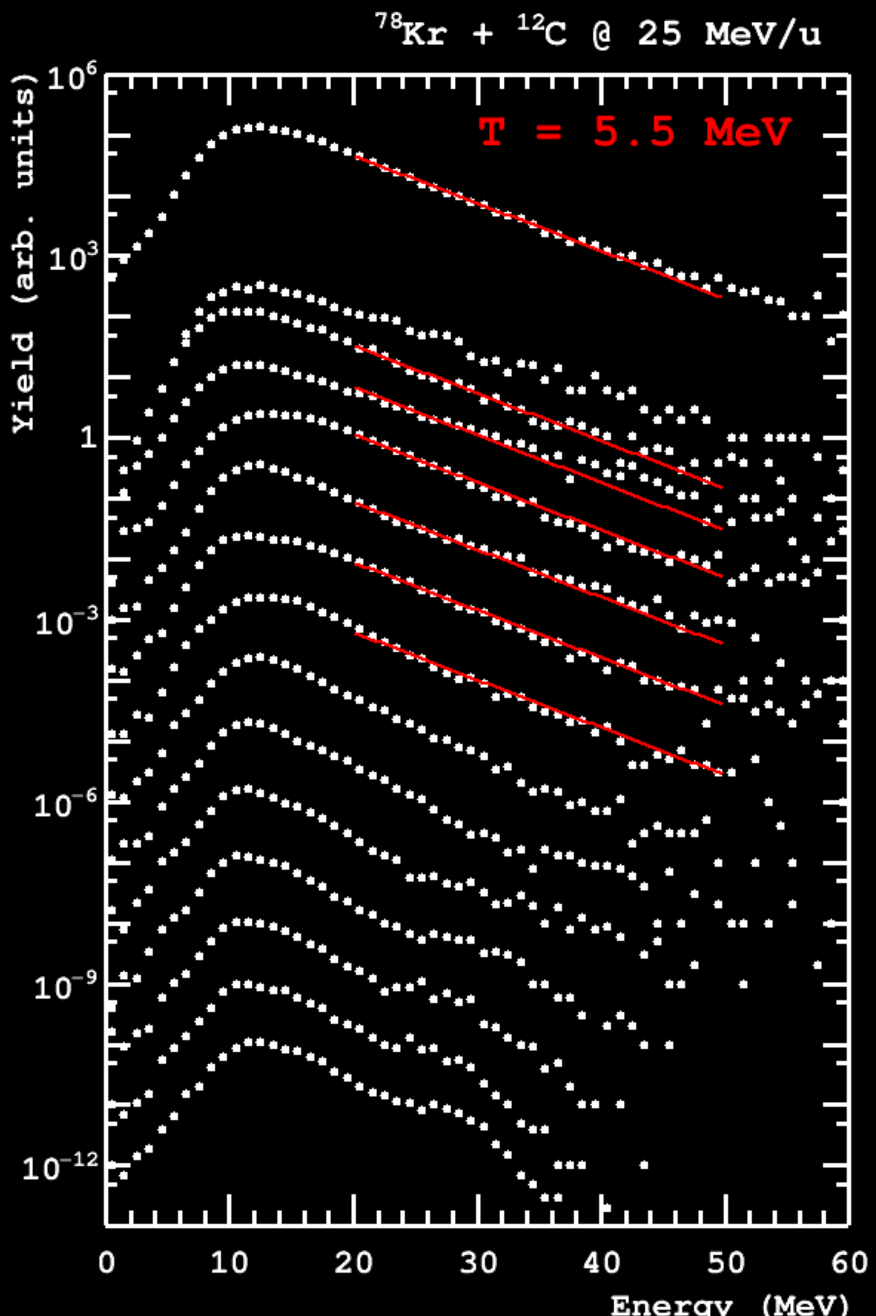
^{78}Kr + ^{12}C @ 25 MeV/u
E*/A = 2.3 MeV
Yield (arb. units)
12000
10000
8000
6000
4000
2000
0
4
5
6
7
8
9
10
Residue Velocity (cm/ns)



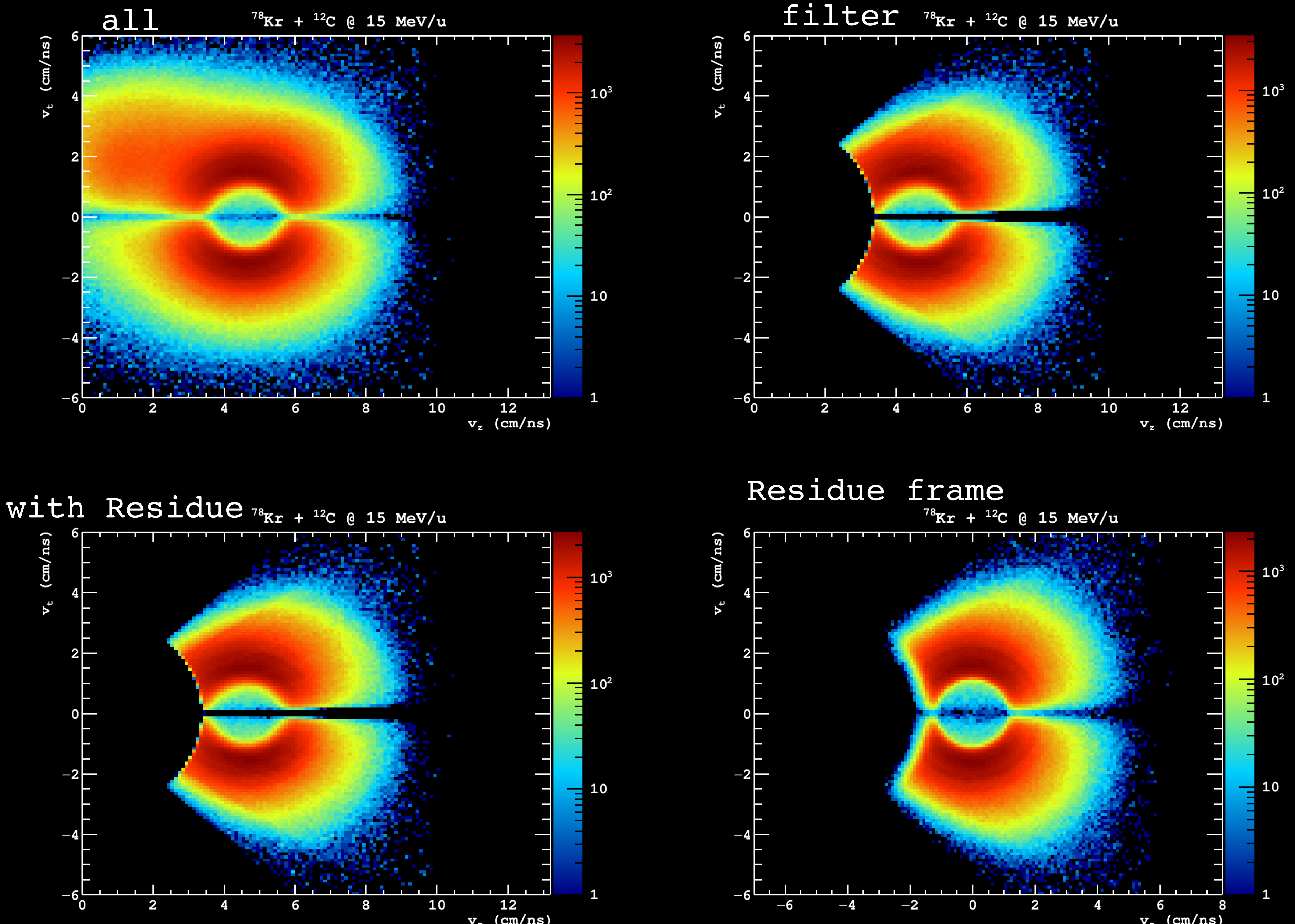
78Kr + 12C @ 25 MeV/u
vt (cm/ns)
vz (cm/ns)
6
4
2
0
−2
−4
−6
−6
−4
−2
0
2
4
6
8
10²
10
1

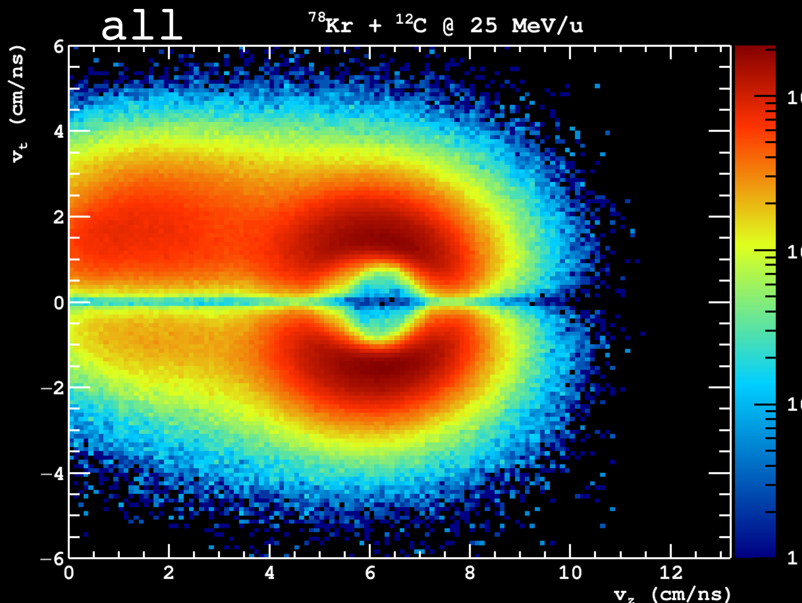


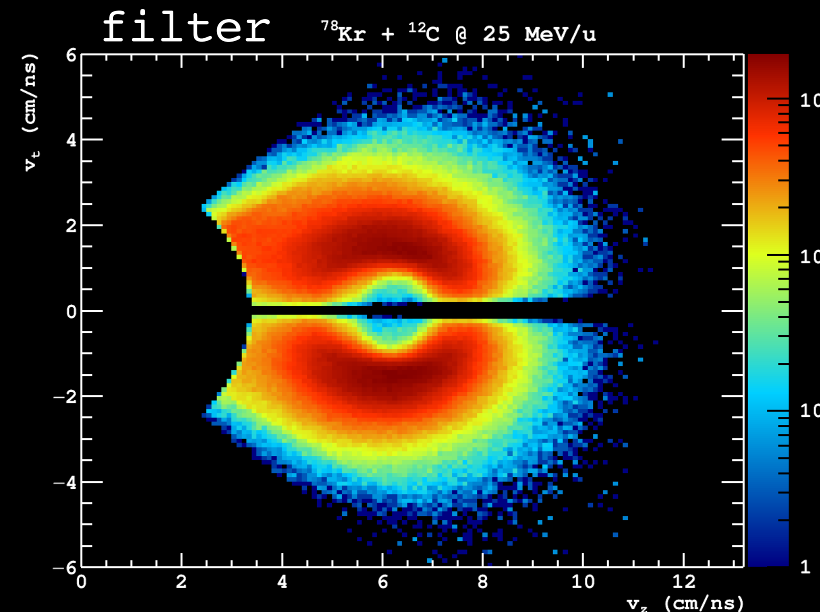
^{78}Kr + ^{12}C @ 25 MeV/u
Energy (MeV)
θ (degrees)
0
20
40
60
80
100
120
140
160
180
10
30
50
70
90
10^2
1

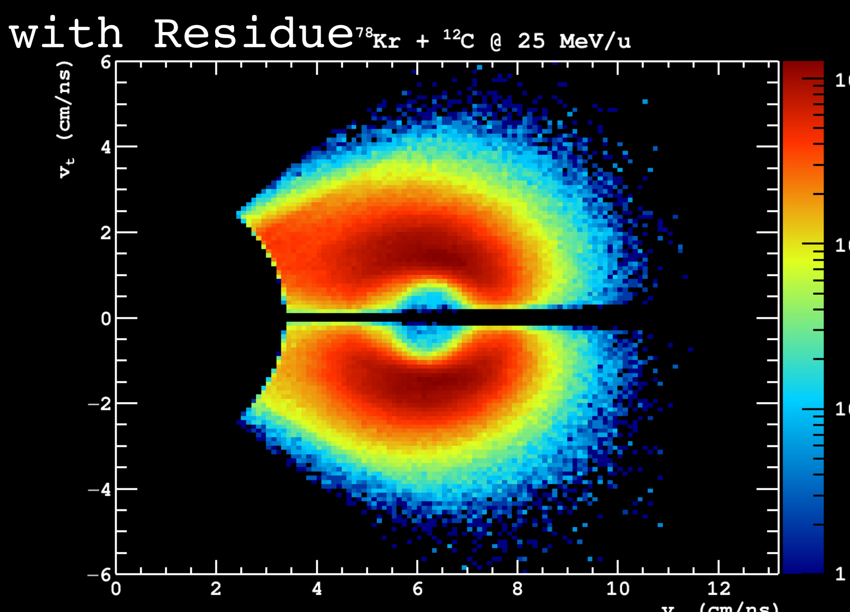

^{78}Kr + ^{12}C @ 25 MeV/u
T = 5.5 MeV
Yield (arb. units)
10^6
10^3
1
10^{-3}
10^{-6}
10^{-9}
10^{-12}
0
10
20
30
40
50
60
Energy (MeV)

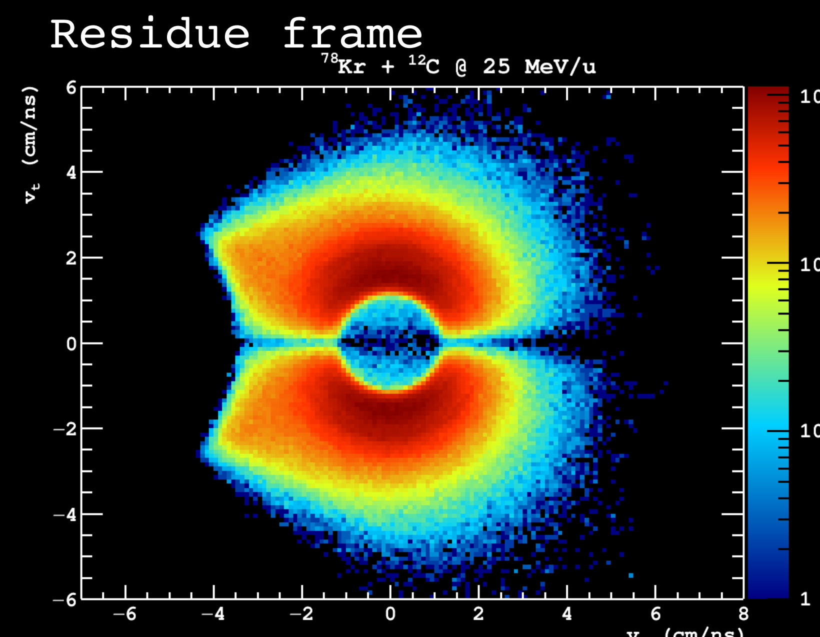
HIPSE

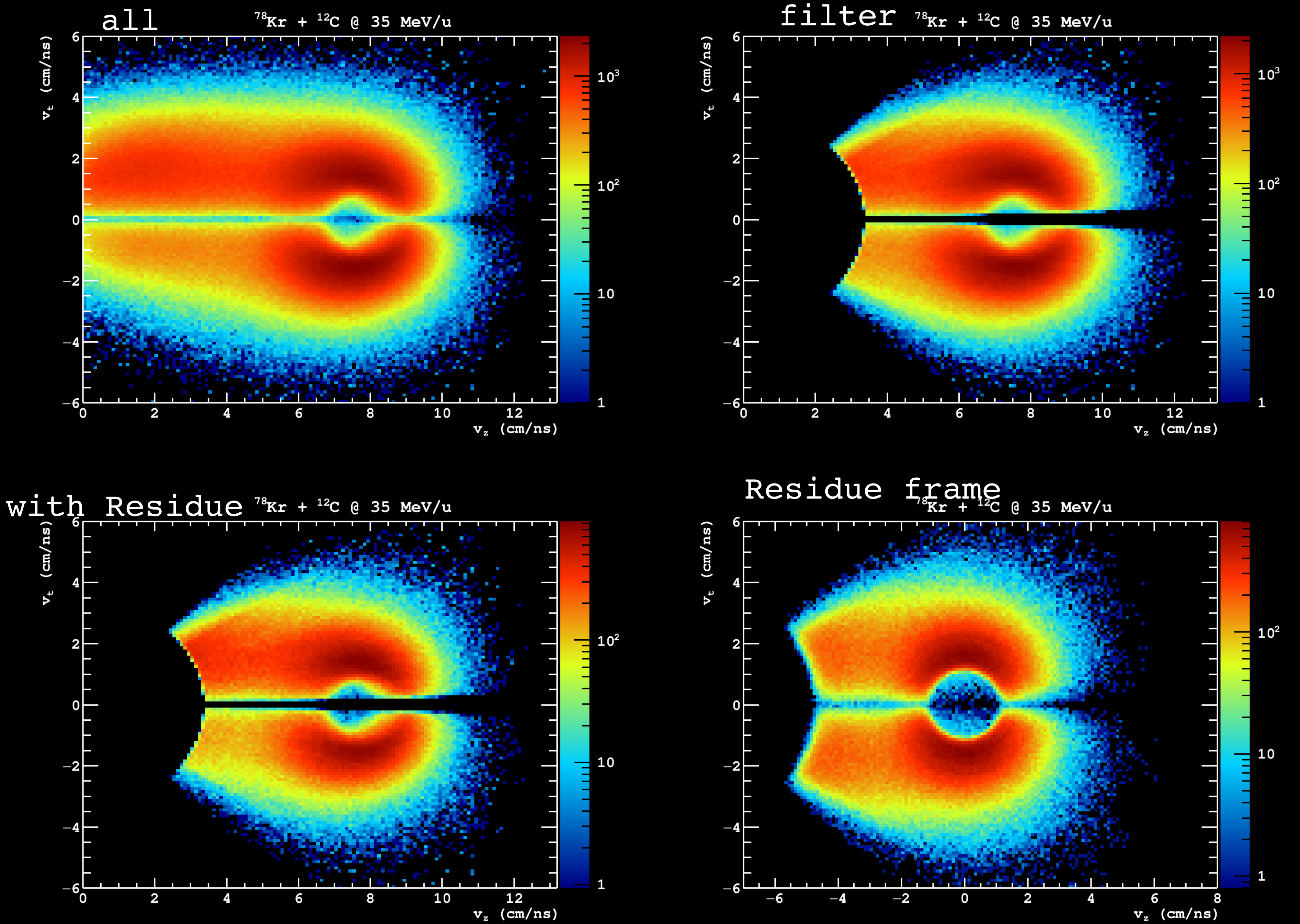

all
filter
with Residue
Residue frame
78Kr + 12C @ 15 MeV/u
v_t (cm/ns)
v_z (cm/ns)


all
78Kr + 12C @ 25 MeV/u
vt (cm/ns)
vz (cm/ns)
10^3
10^2
10
1


filter
78Kr + 12C @ 25 MeV/u
vt (cm/ns)
vz (cm/ns)
10^3
10^2
10
1

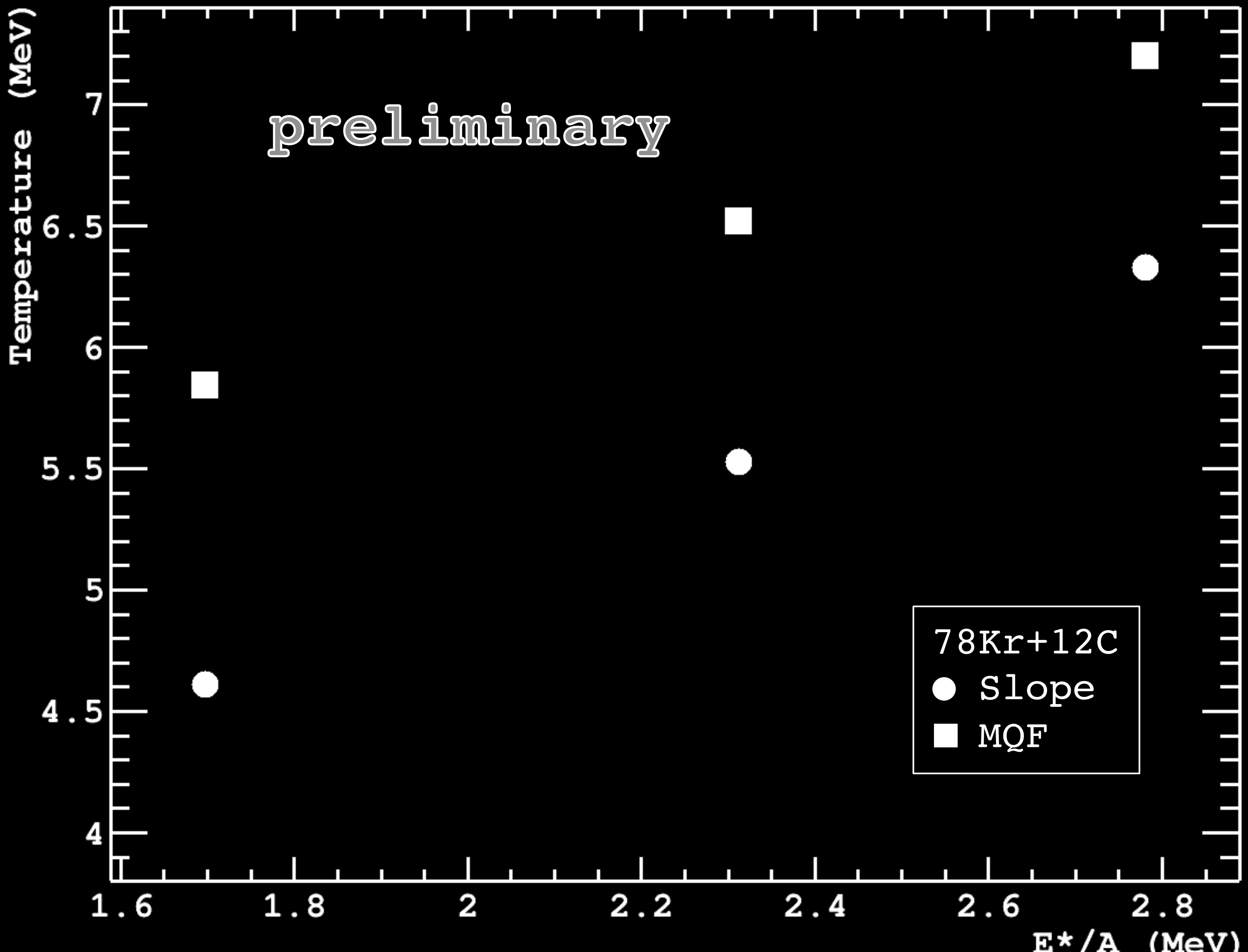

with Residue
78Kr + 12C @ 25 MeV/u
vt (cm/ns)
vz (cm/ns)
10^3
10^2
10
1


Residue frame
78Kr + 12C @ 25 MeV/u
vt (cm/ns)
vz (cm/ns)
10^3
10^2
10
1



all
78Kr + 12C @ 35 MeV/u
filter
78Kr + 12C @ 35 MeV/u
with Residue
78Kr + 12C @ 35 MeV/u
Residue frame
78Kr + 12C @ 35 MeV/u
vt (cm/ns)
vz (cm/ns)

Data Along the Caloric Curve

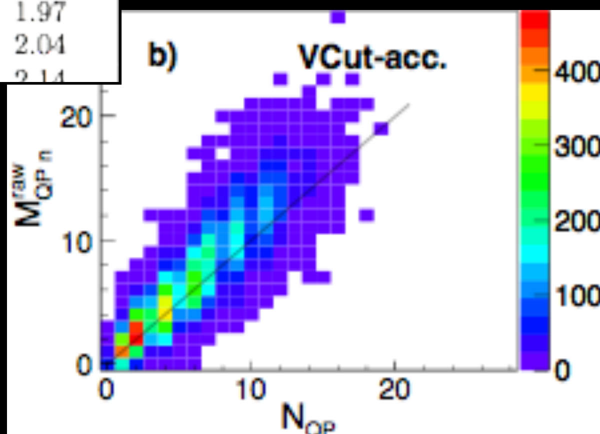


Neutron Uncertainty

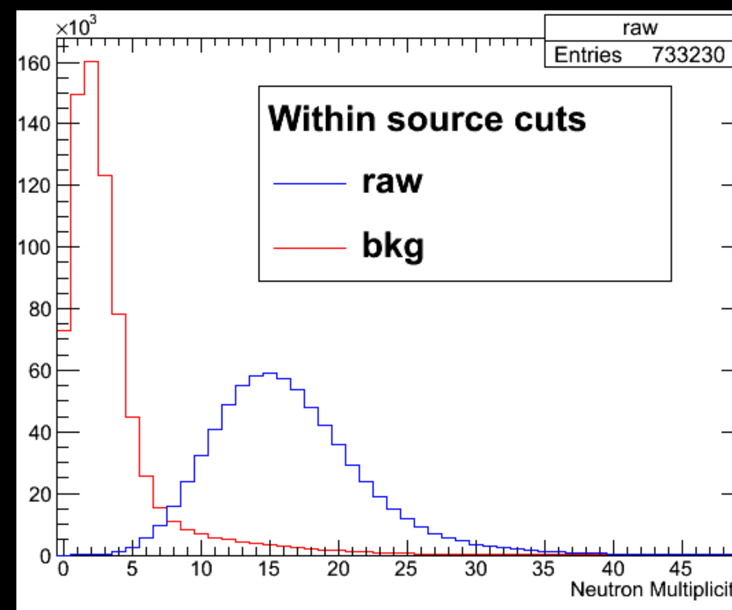
$$\sigma^2_{\mathbf{raw}} = \sigma^2_{\mathbf{true}} + \sigma^2_{\mathbf{eff}} + \sigma^2_{\mathbf{bkg}}$$

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



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

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

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.