Consequences of Sub-Zeptosecond Lifetimes in Near-Barrier Reaction Dynamics

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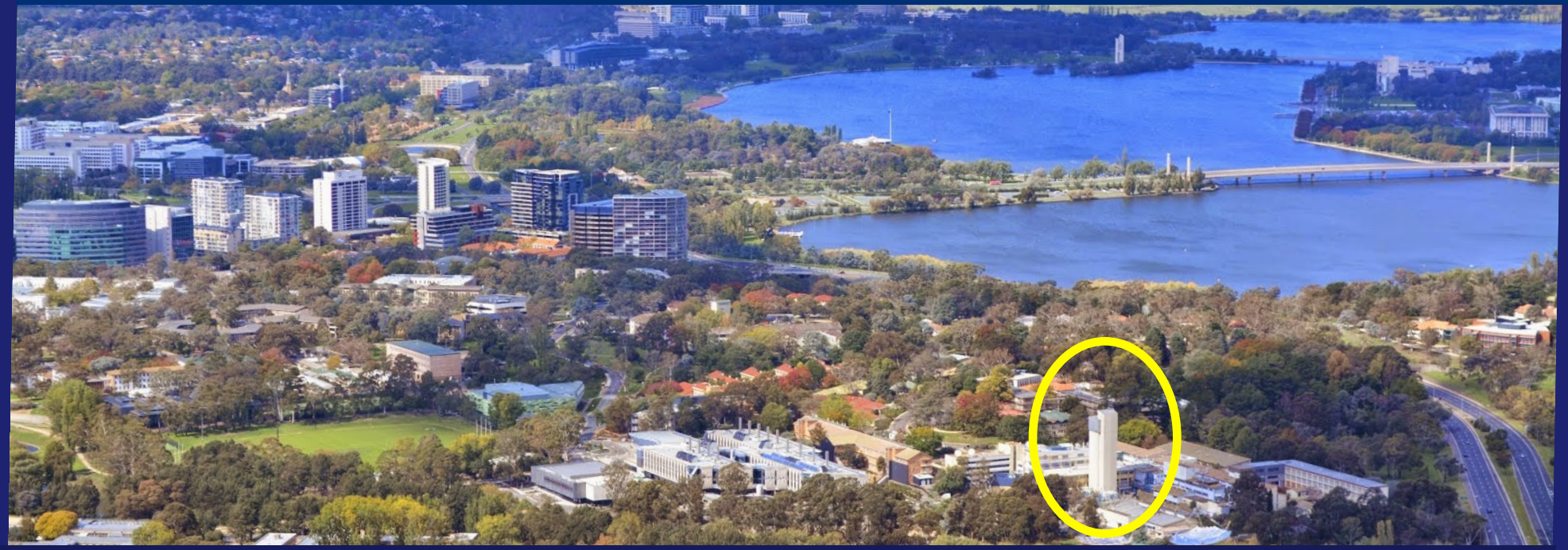
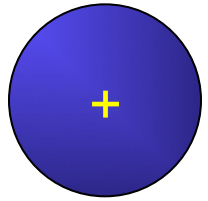
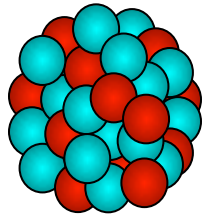


With: K. J. Cook, D.J. Hinde, S. D. Kalkal, D. H. Luong, E.C. Simpson, E. Williams

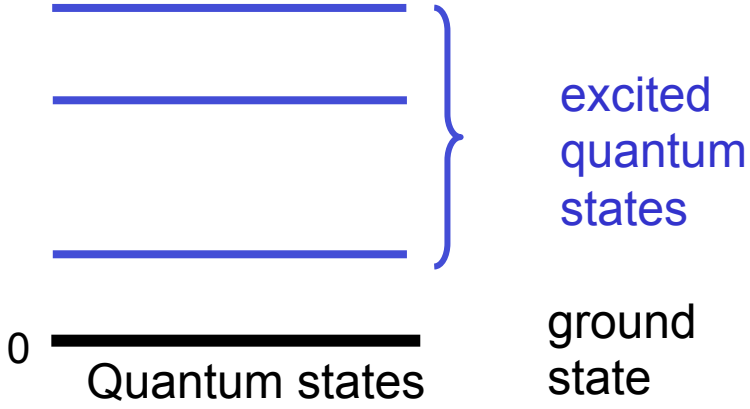
Collaboration: A. Diaz Torres (Italy), L. Gasques (Brazil), P.R.S. Gomes (Brazil)



Not an “elementary” particle

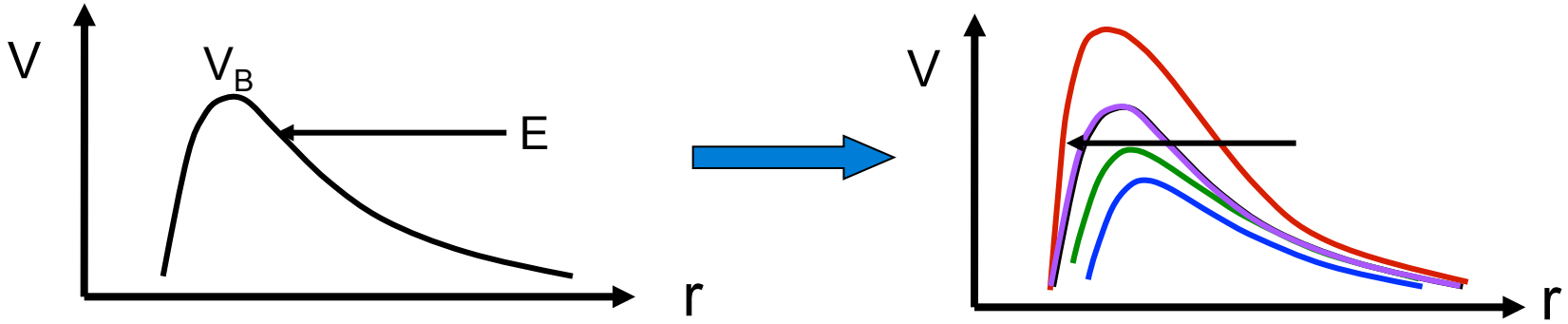


Many body quantum system



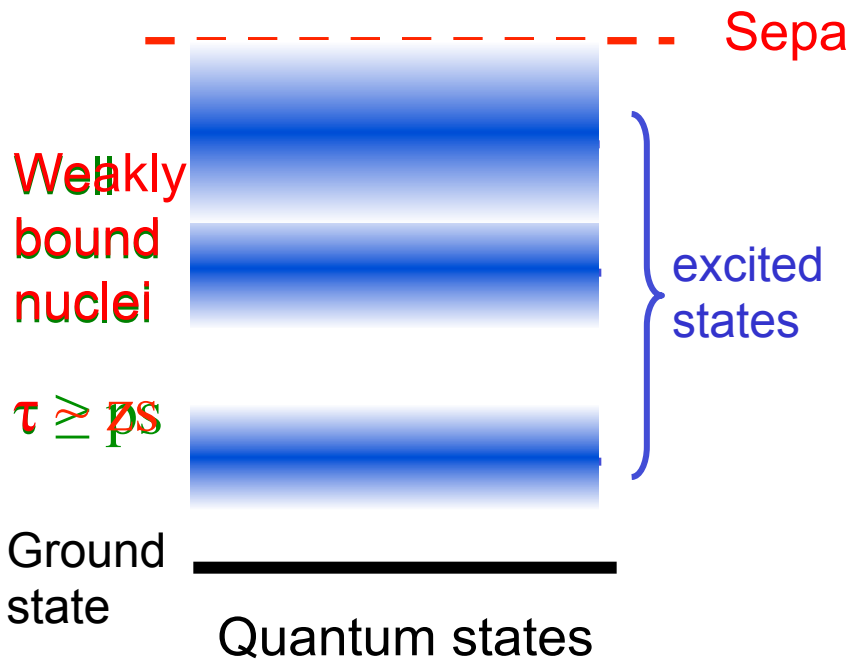
- Colliding nuclei in a superposition of quantum states
  → Distribution of fusion barrier energies

Fusion enhanced for $E<V_B$

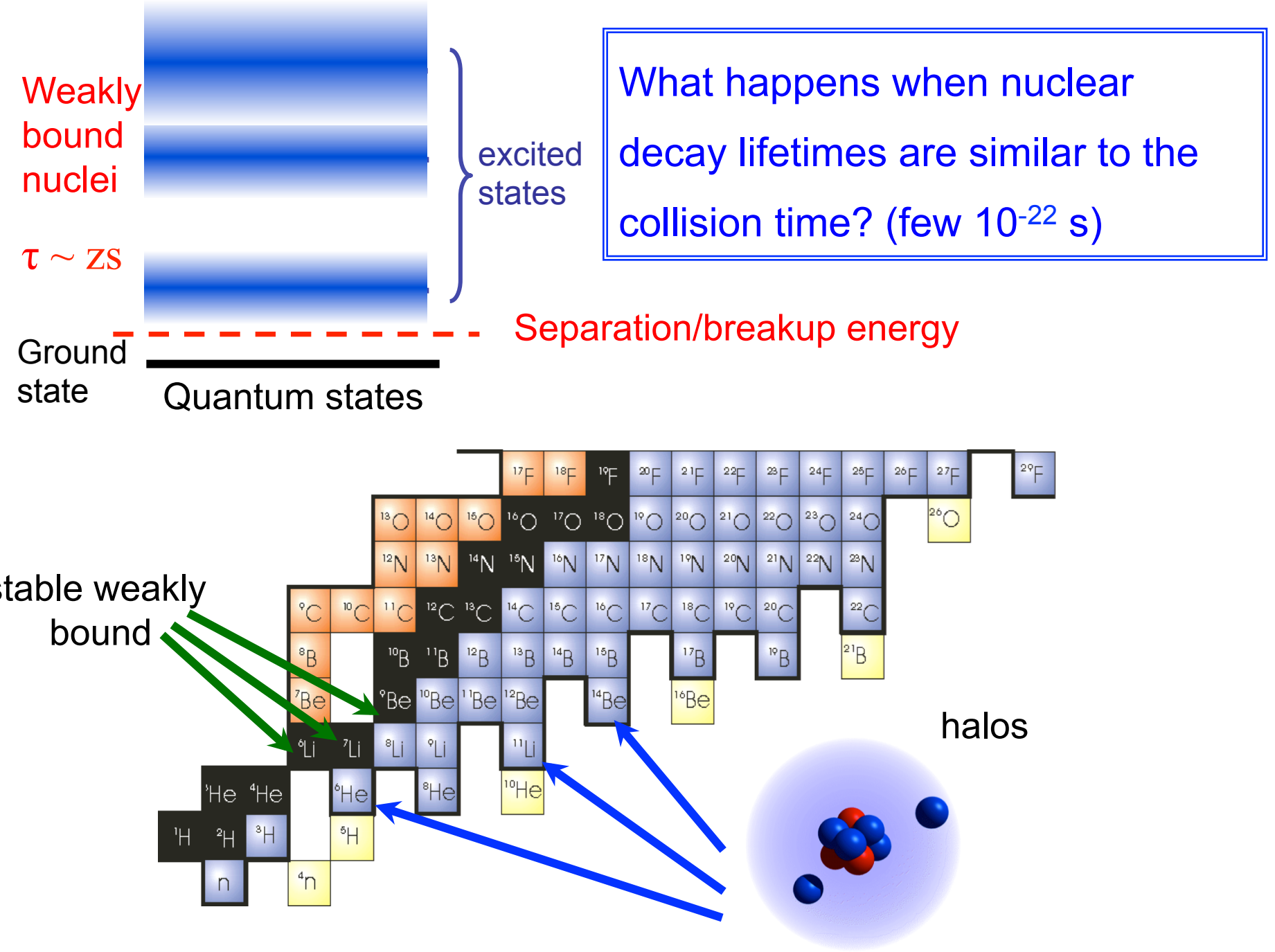


Dasso et al., Nucl. Phys. A 405 (1983) 221

Rowley et al., Phys. Lett. B, 254, 25 (1991)



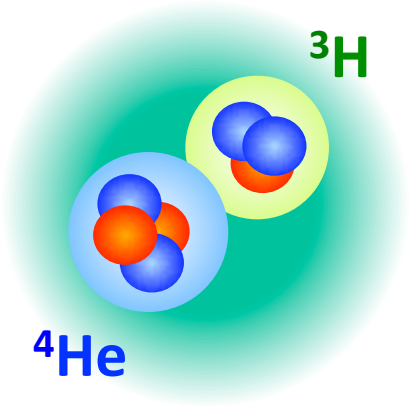
What happens when nuclear decay lifetimes are similar to the collision time? (few 10^{-22} s)


Weakly bound nuclei
τ ~ zs
excited states
Separation/breakup energy
Ground state
Quantum states
What happens when nuclear decay lifetimes are similar to the collision time? (few 10-22 s)
stable weakly bound
halos

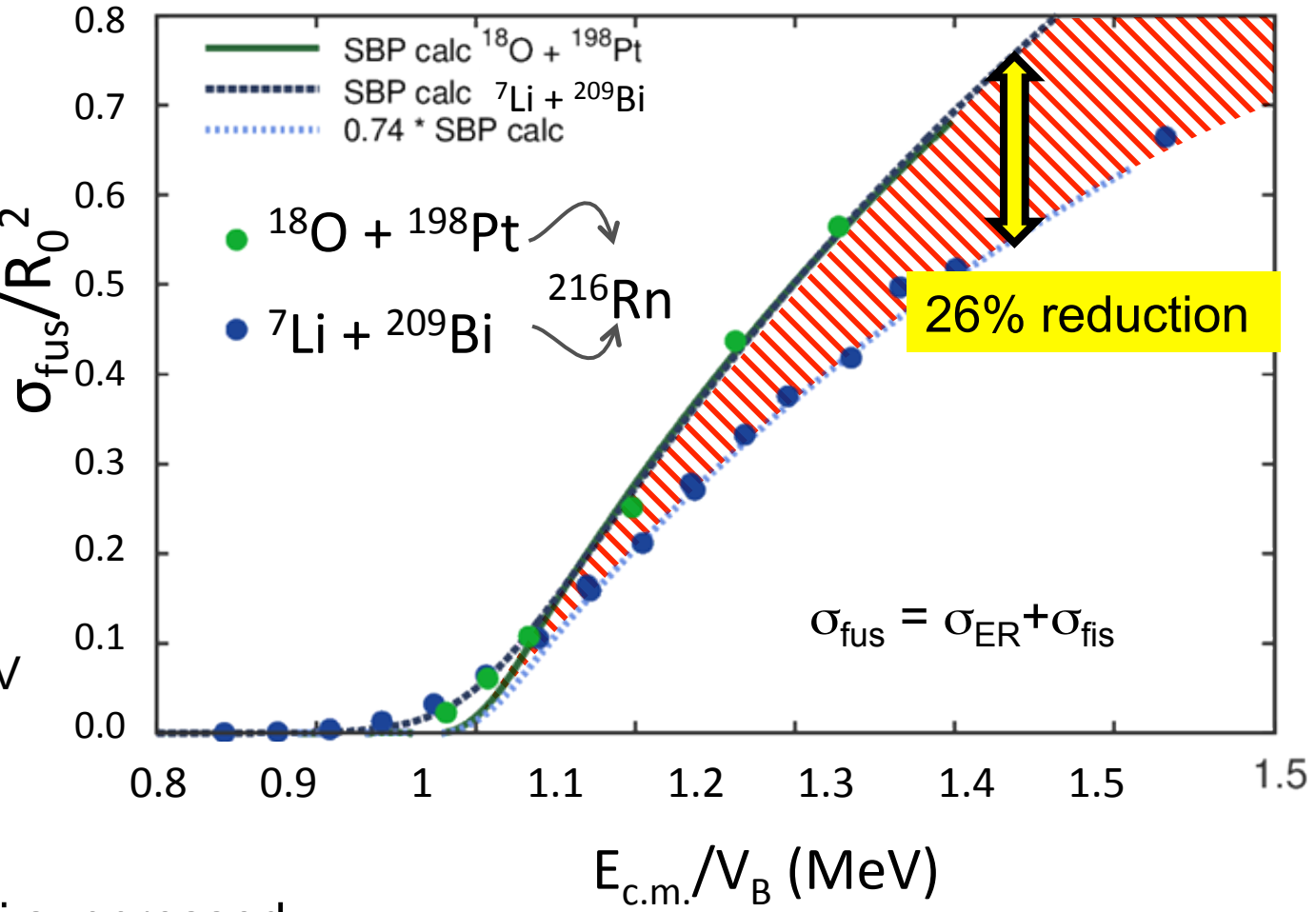
Fusion suppression at above barrier energies

^{7}Li

Weakly-bound



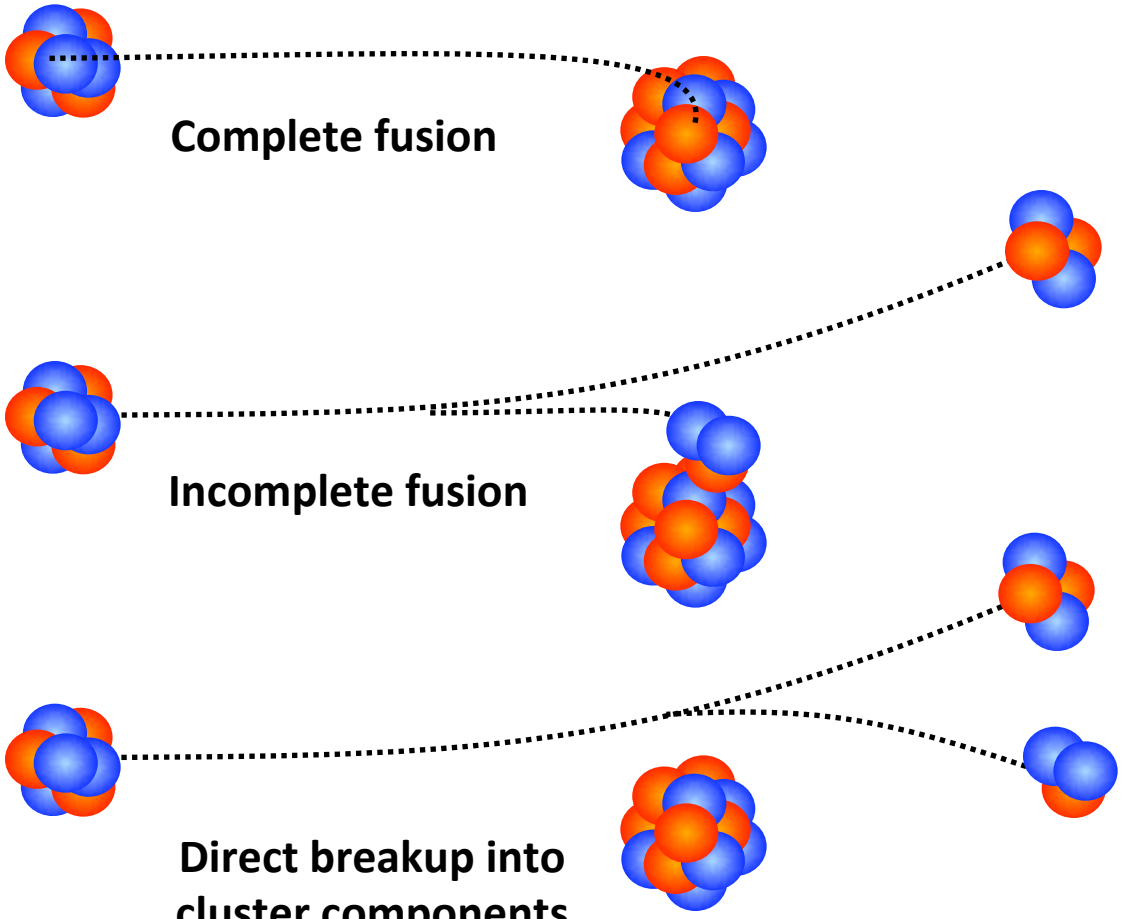
Q (→α+t) = -2.467 MeV



Fusion of ^{7}Li+^{209}Bi suppressed relative to single-barrier calculation – unlike ^{18}O+^{198}Pt

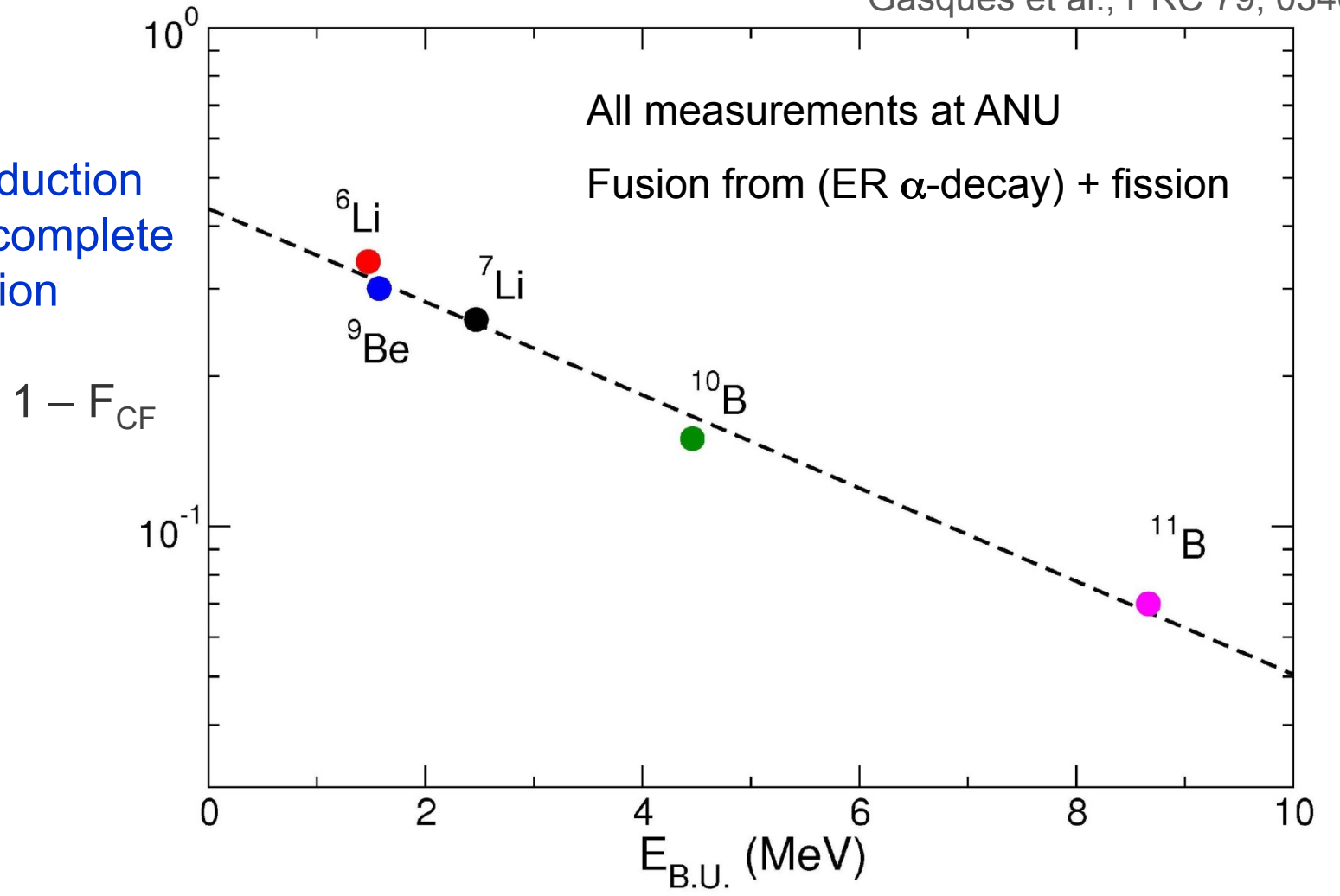
Dasgupta *et al.*, PRL 82, 1395 (1999)
Dasgupta *et al.*, PRC 70, 024606 (2004)

Complete fusion and breakup



Gasques et al., PRC 79, 034605 (2009)

Reduction of complete fusion

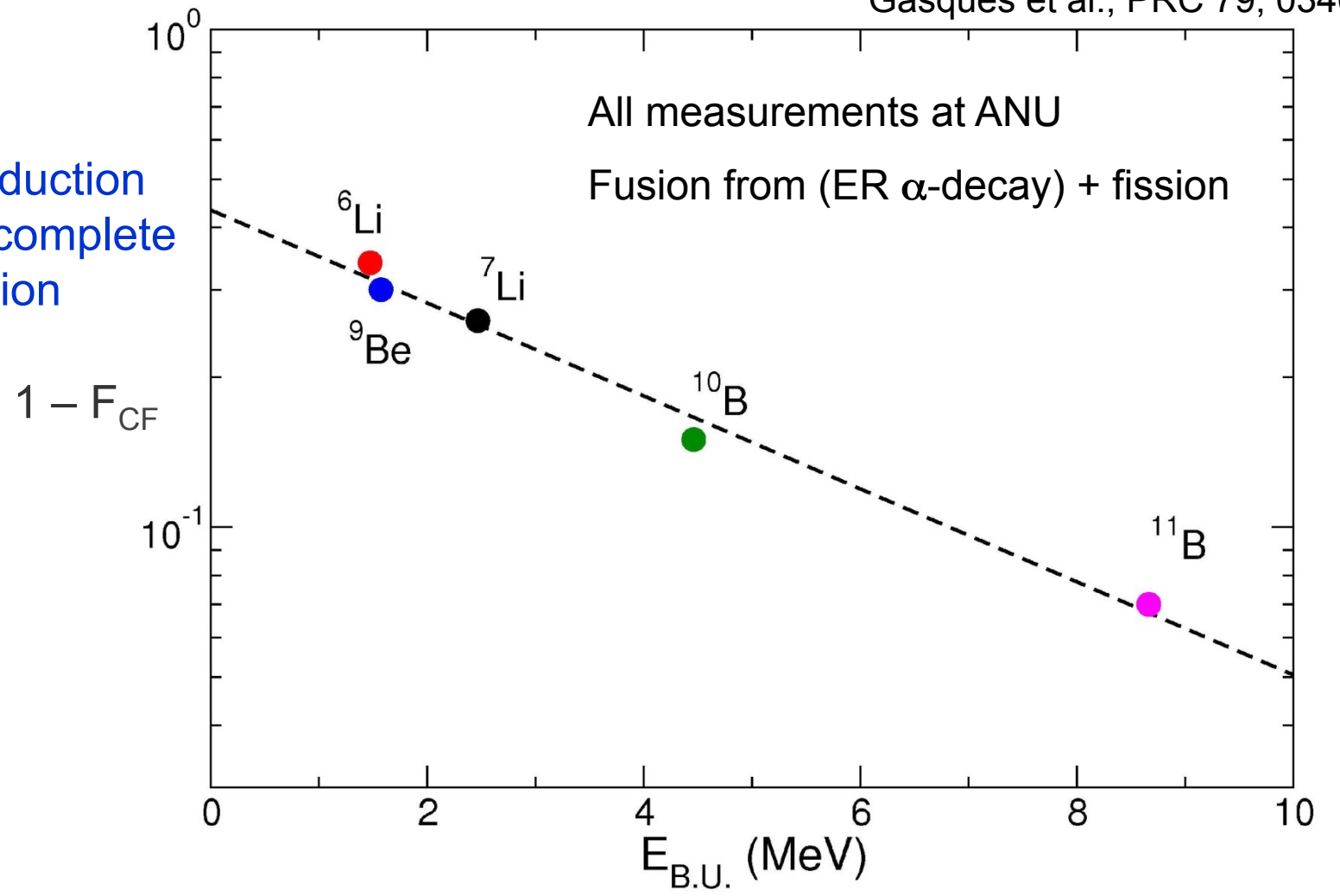


Signorini et. al., EPJ A5, 7 (1999)
Tripathi et al., PRL88,172701 (2002)
Wu et al., PRC68, 044605 (2003)
Dasgupta et al., PRC70 (2004) 024606
Mukherjee et al., PLB636, 91 (2006)

Gomes et al.,PRC73,064606 (2006)
Rath et al., PRC 79, 051601 (2009)
Gasques et al., PRC 79, 034605 (2009)
Dasgupta et al., PRC81, 024608 (2010)
RIB review: Keeley et al., Prog. Part. Nucl. Phys. Rep. 424, 1 (2007)

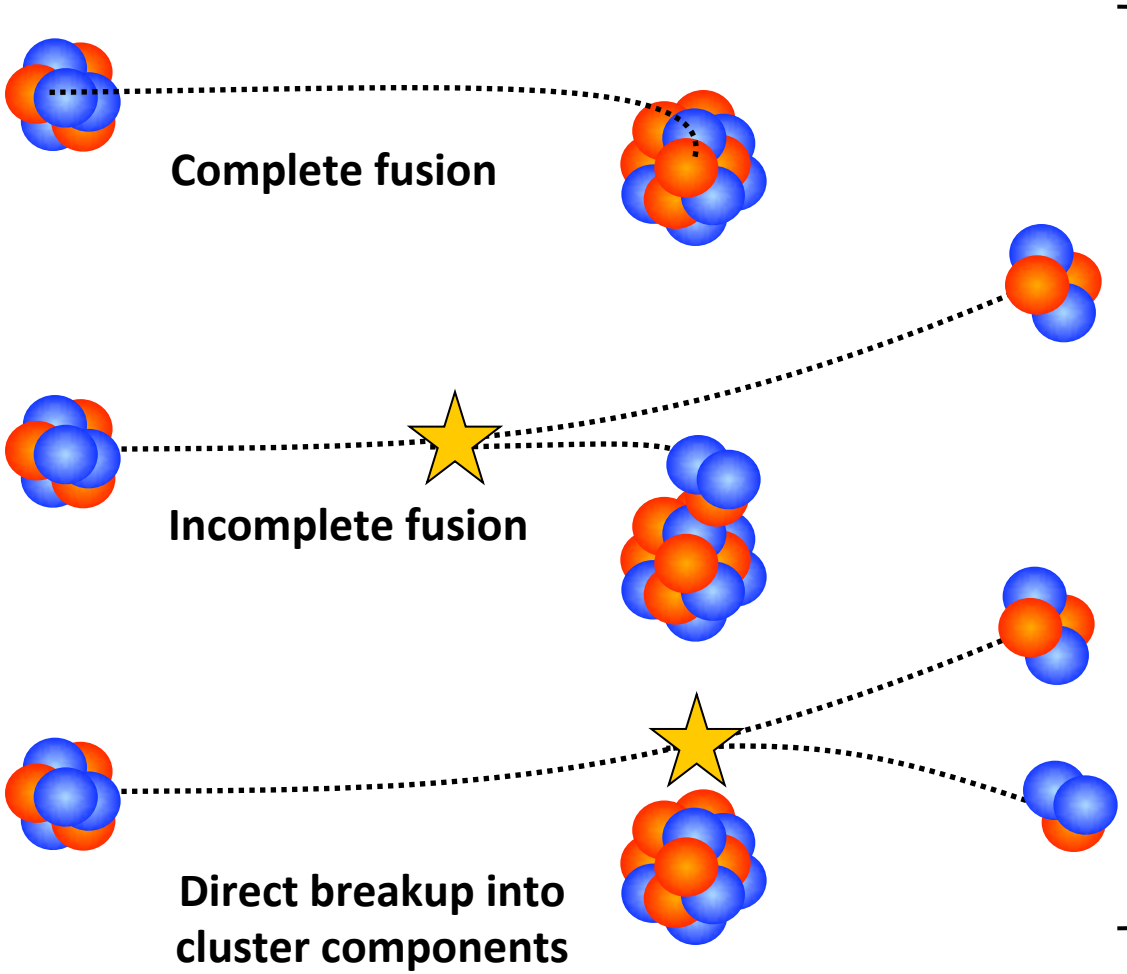
Gasques et al., PRC 79, 034605 (2009)

Reduction of complete fusion



Is the projectile breakup threshold all that matters?

Investigating mechanisms causing breakup



Is this the complete picture?

What processes can cause breakup?

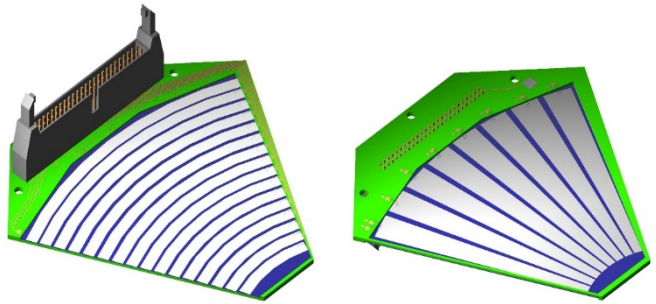
Where does breakup occur?

Measurements at sub-barrier energies: minimizes absorption

Measuring coincident charged fragments

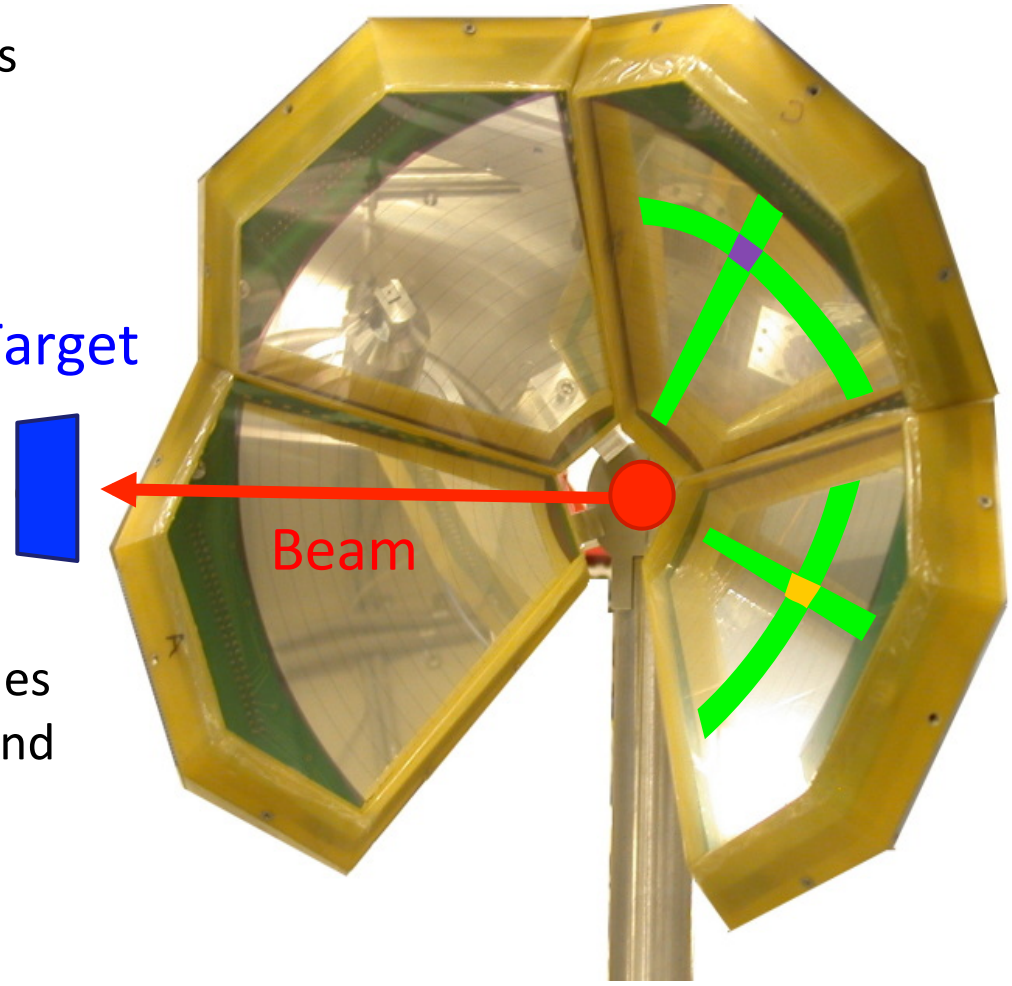
BALiN array

Micron Semiconductor
Double-Sided Silicon Strip Detectors



Front

Back



"lampshade" configuration: back angles
"front-back" configuration: forward and backward angles

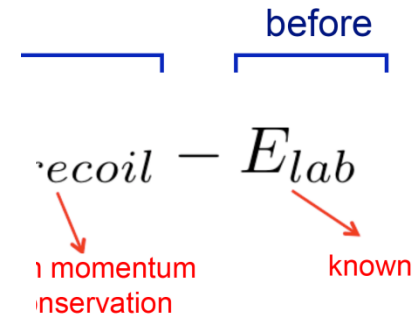
$115° < \theta < 170°$
$30° < \phi < 330°$

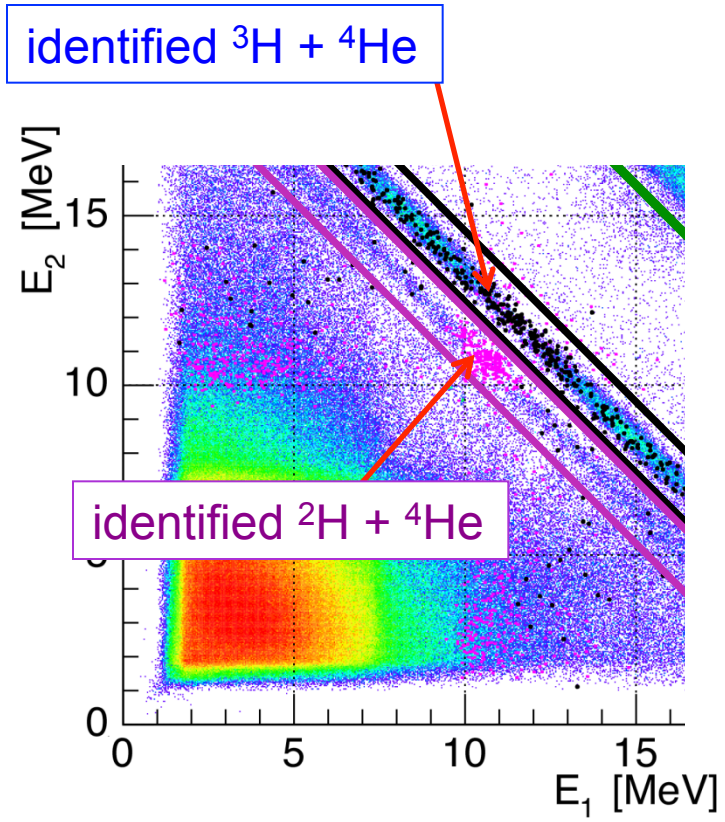
Detector telescope giving p,d,t identification

Experimental Results: 2-D plots of coincident fragment energies E_1 vs. E_2

$^{7}Li + {}^{208}Pb$

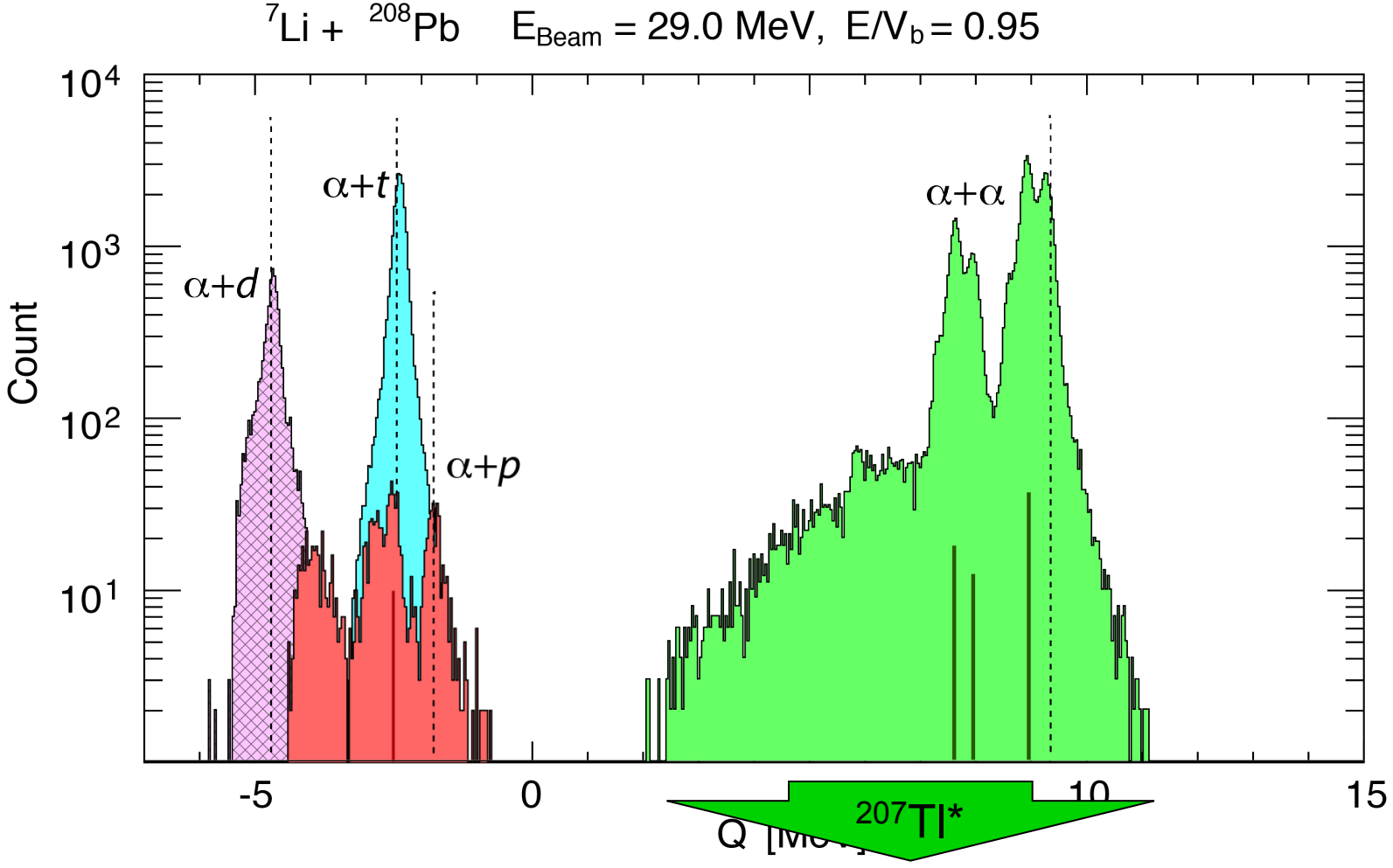
Reaction Q-value





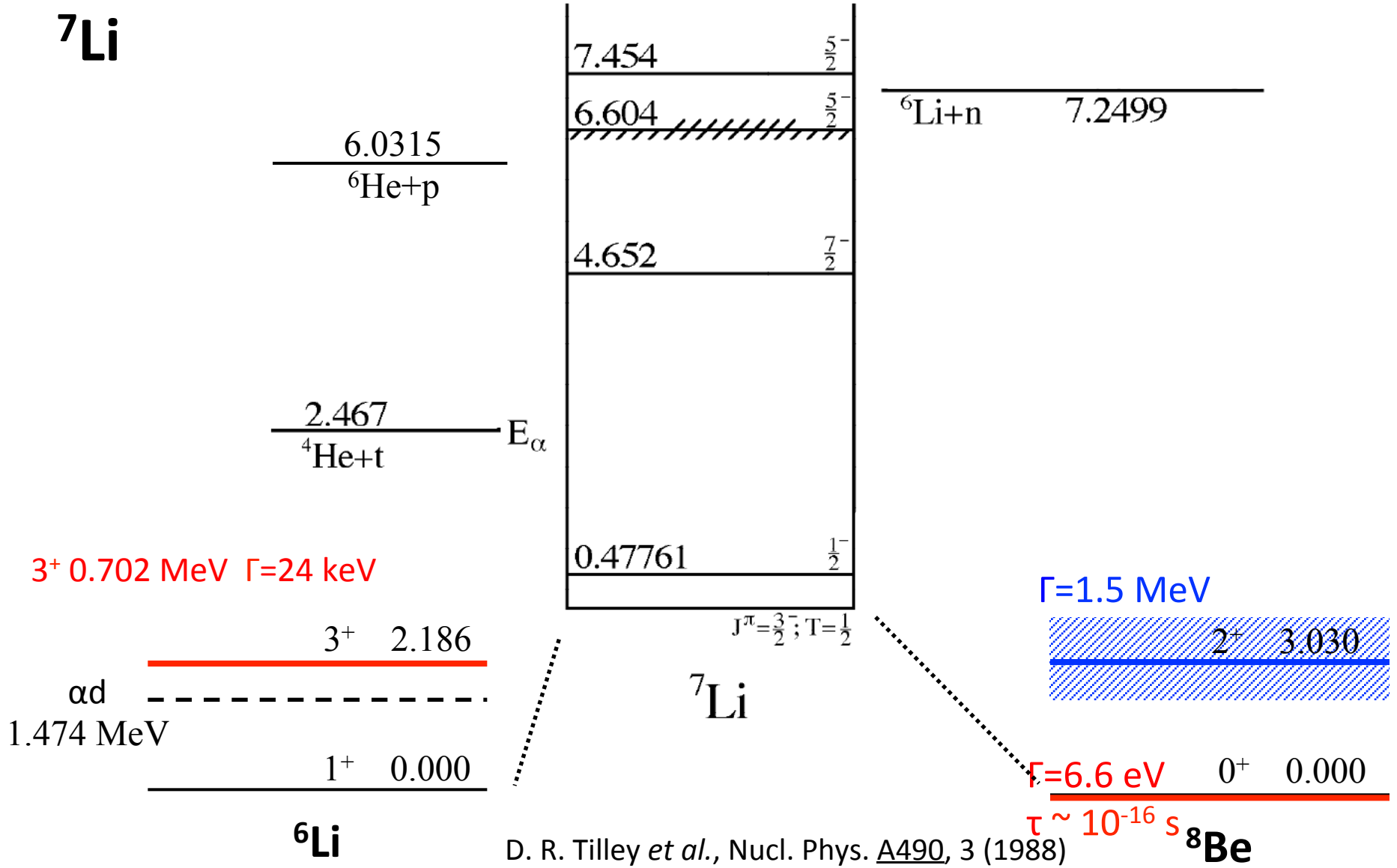
D.H. Luong, ANU PhD Thesis

Q-value spectrum – transfer-triggered breakup



Luong *et al.*, PRC **88**, 034609 (2013)

Structure and thresholds



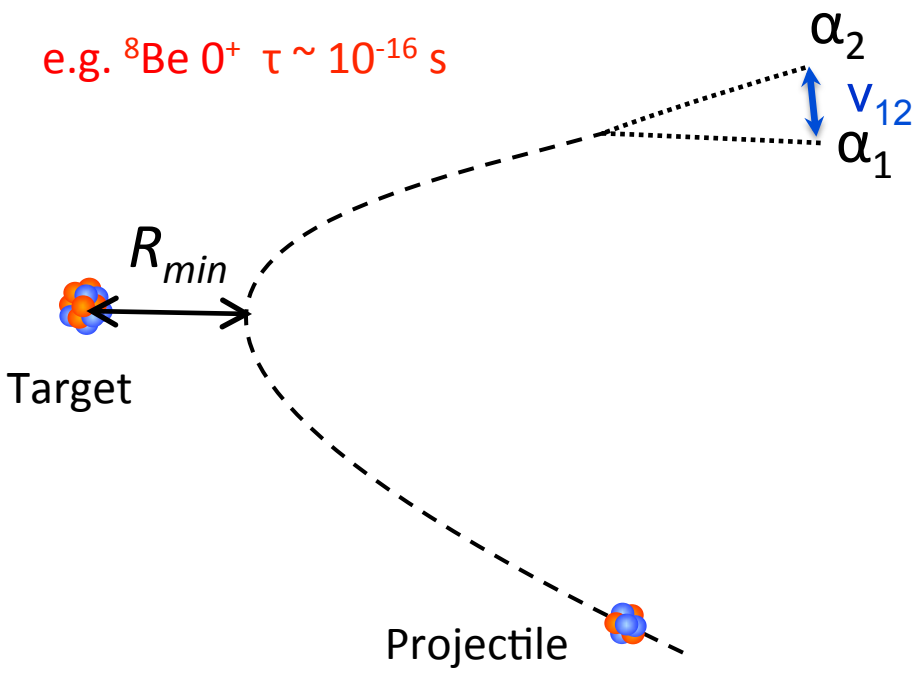
D. R. Tilley *et al.*, Nucl. Phys. A490, 3 (1988)

Long-lived and prompt breakup

Delayed Breakup

Disintegration far from the target following the population of a long-lived resonance state.

e.g. ^{8}Be 0^{+} $\tau \sim 10^{-16}$ s

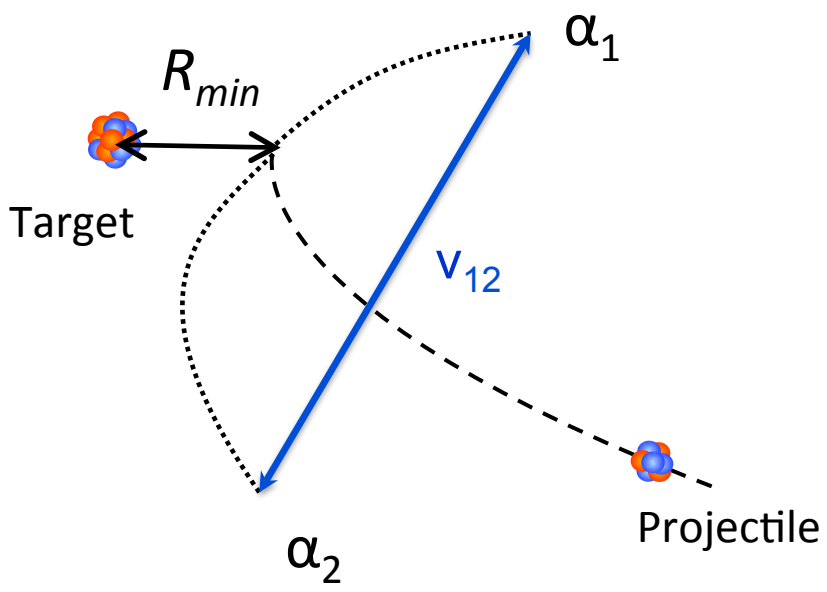


Delayed ≡ Asymptotic

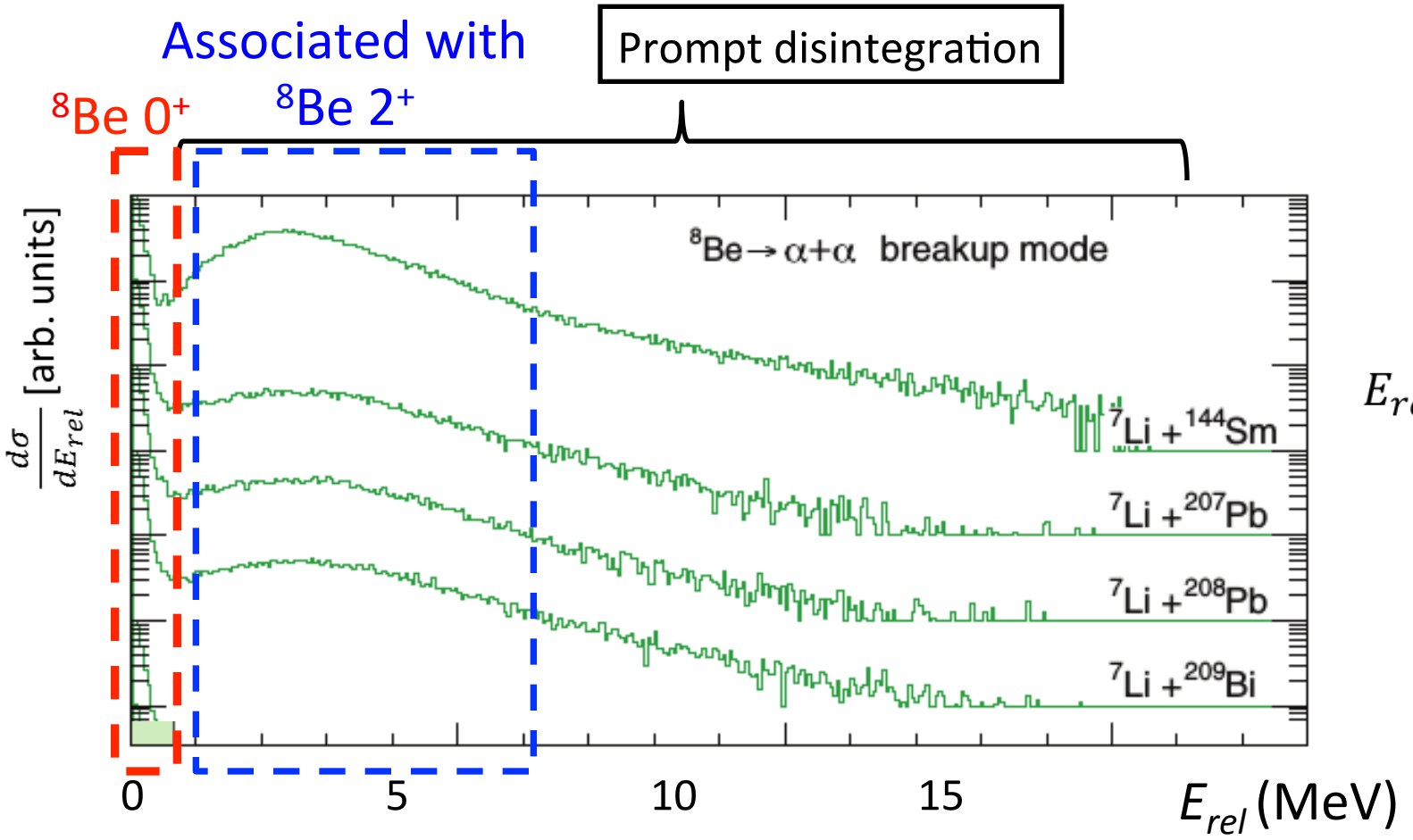
Prompt breakup

Disintegration near the distance of closest approach. Different interaction between each fragment and the target.

$$E_{rel} = \frac{1}{2}\mu v_{12}^2$$



Relative energy distributions

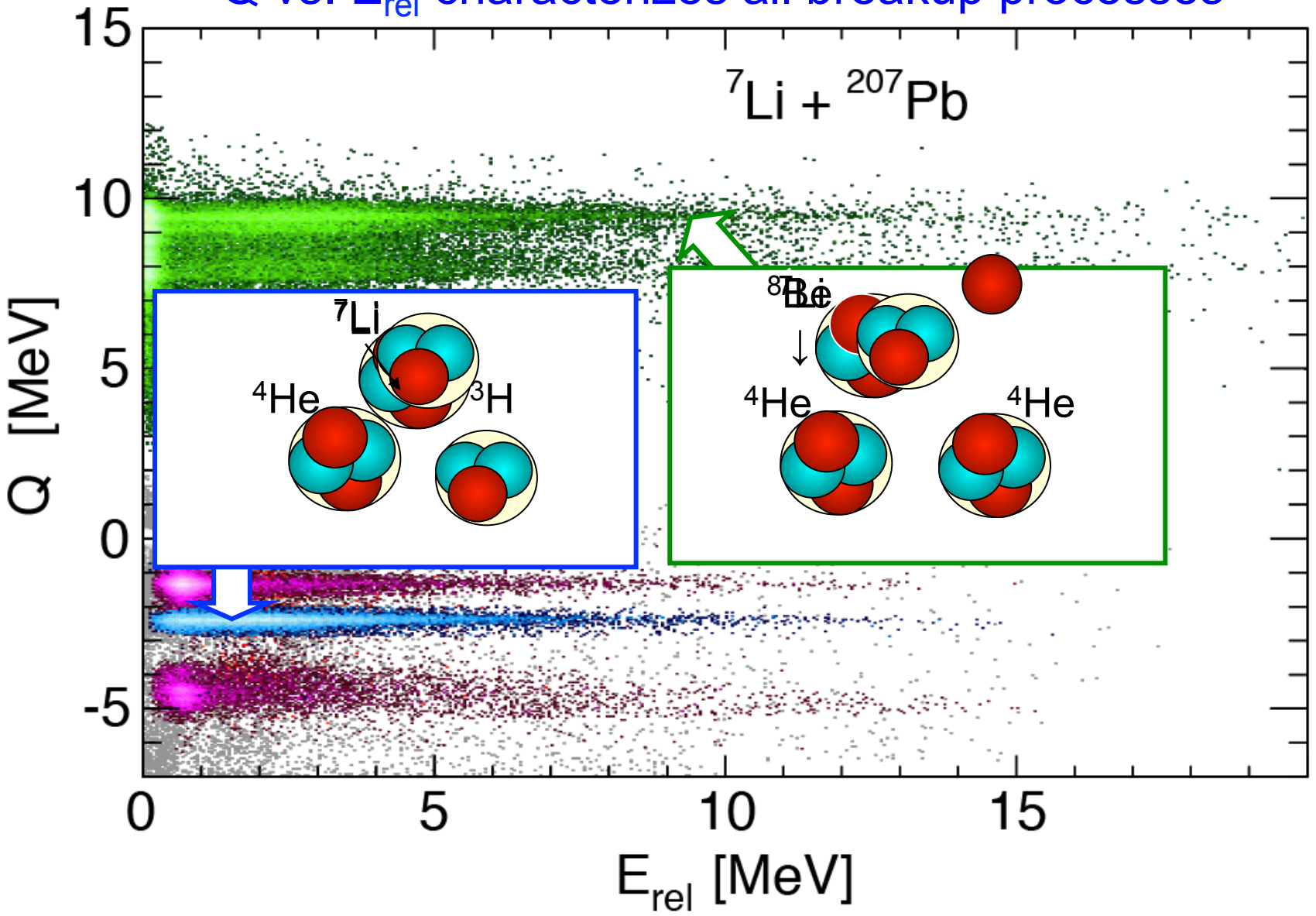


$$E_{rel} = \frac{1}{2}\mu v_{12}^2$$

- Narrow resonances cannot affect fusion – long-lifetime
- Assumed that prompt breakup is 50% incoming and 50% outgoing

Luong *et al.*, PLB 695, 105 (2011); PRC 88, 034609 (2013)

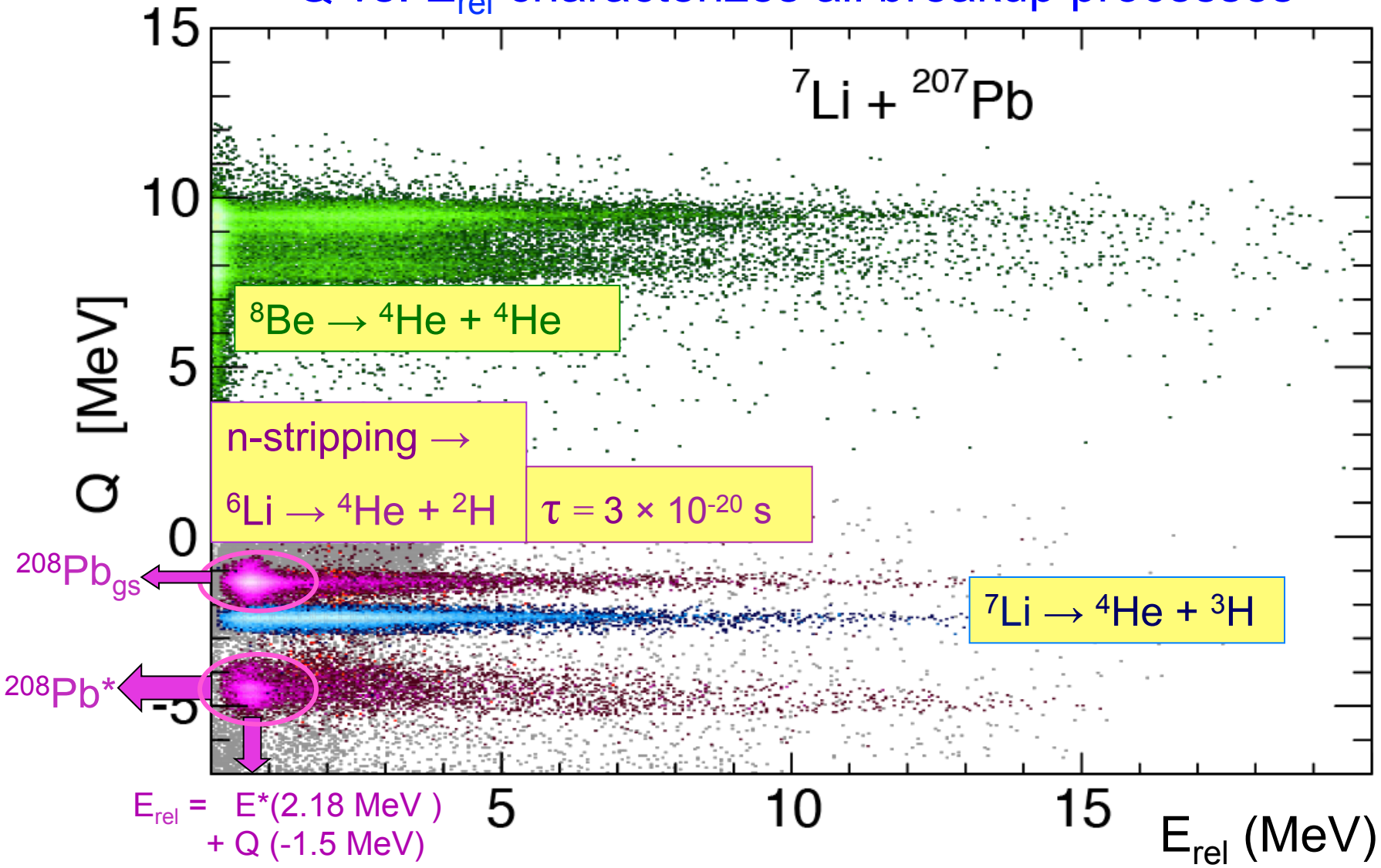
Q vs. E_{rel} characterizes all breakup processes



D.H. Luong *et al.*, Phys. Lett. B695, 105 (2011)

88, 034609 (2013)

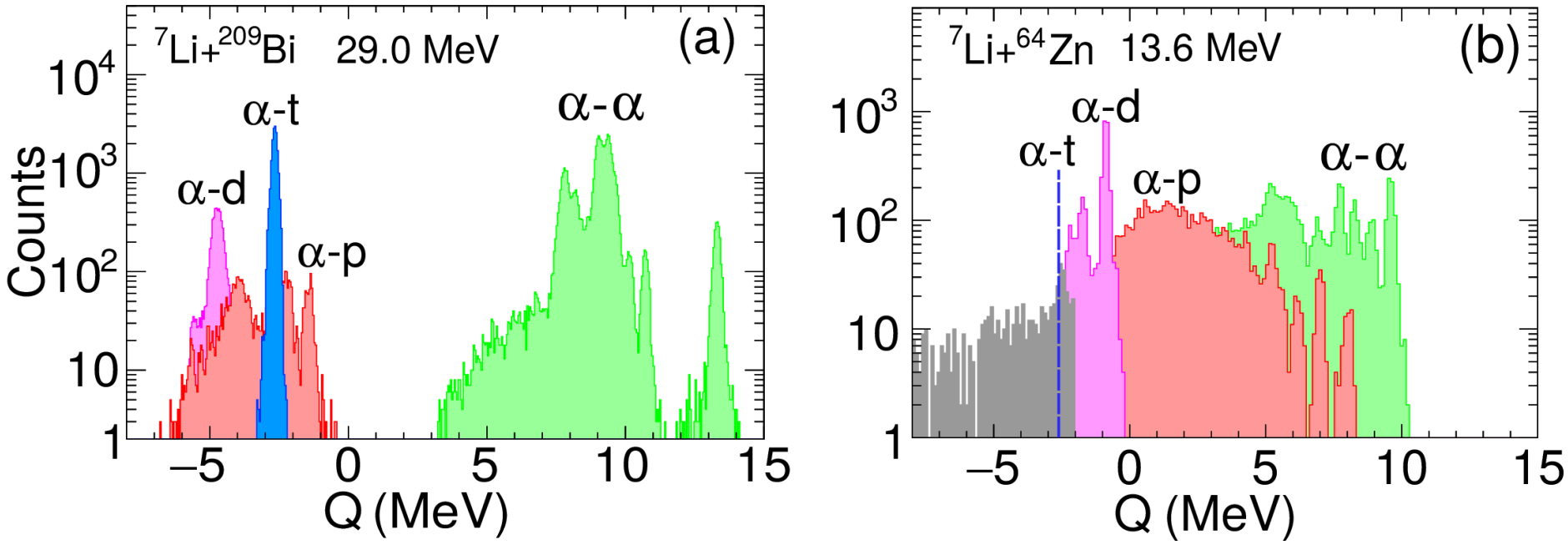
Q vs. E_{rel} characterizes all breakup processes



✓ α-d pairs - Q, E_{rel} consistent with n-transfer followed by breakup mostly from ^{6}Li excited state at 2.18 MeV

Luong et al., Phys. Lett. 695, 105 (2011)

Breakup for ^{7}Li incident on medium-mass target nuclei



- *p*-transfer forming ^{8}Be dominates (driven by stability of α; Q ≥ +9 MeV)
- **No direct breakup** (^{7}Li → α + t) seen for medium mass targets

Sunil Kalkal et al, in preparation

Sunil Kalkal et al, Phys. Rev. C 93, 044605 (2016)

Where does prompt breakup occur?

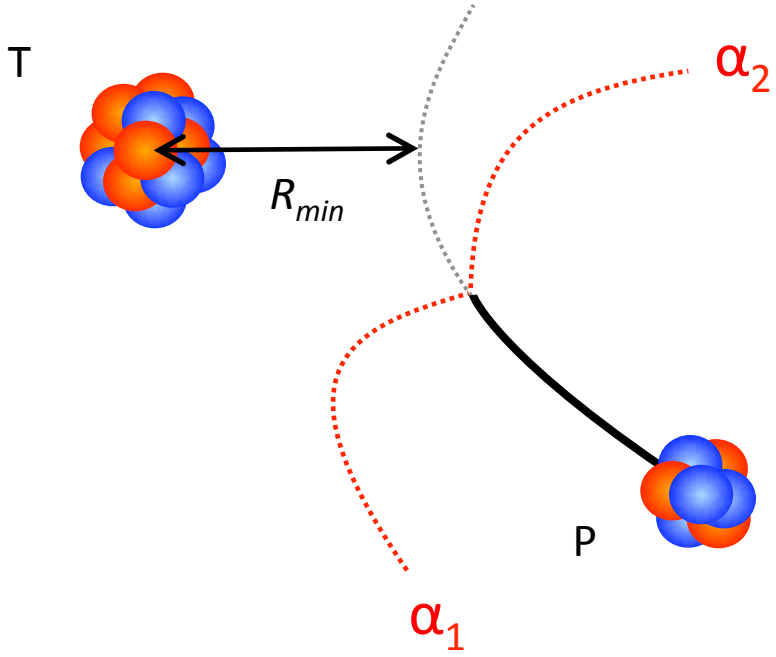
Incoming trajectory

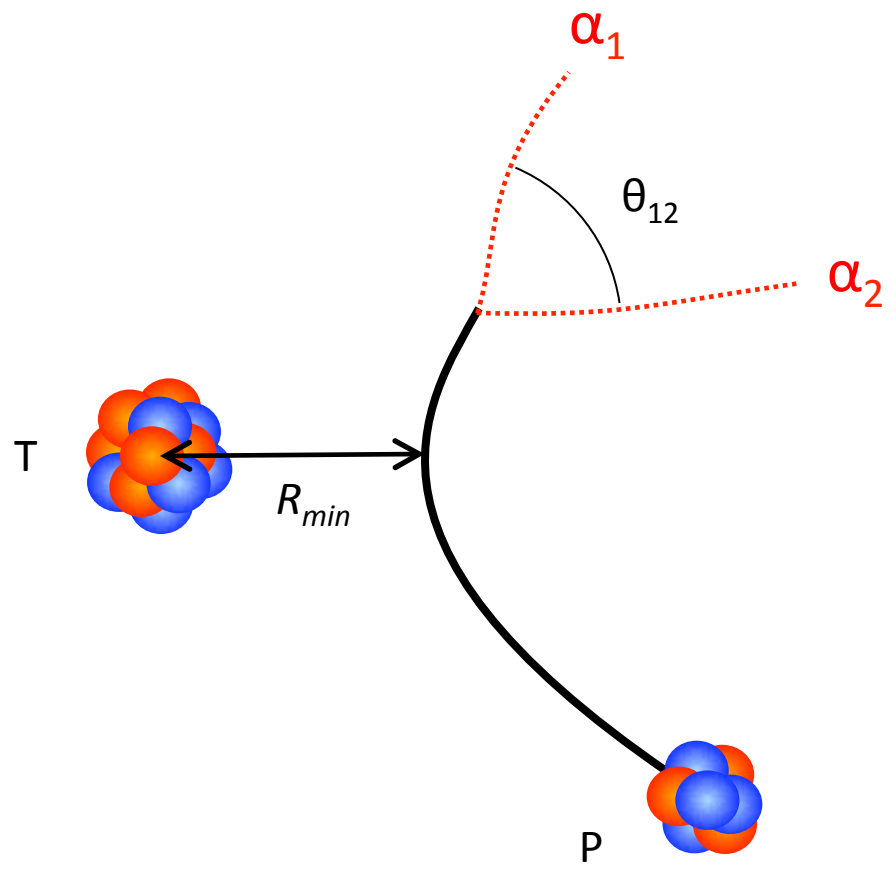
Can influence fusion

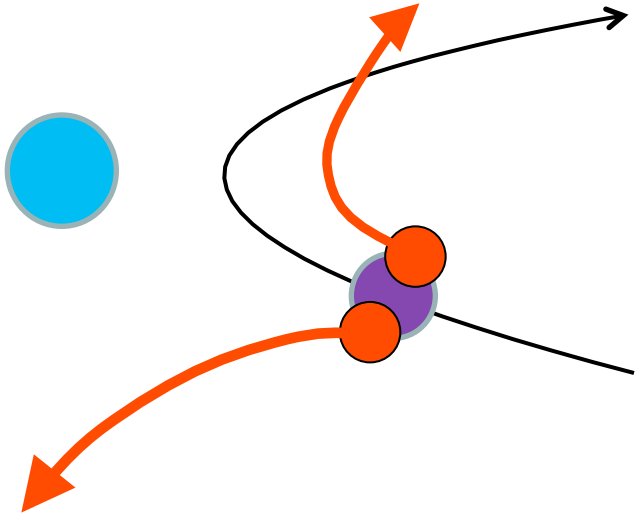
Outgoing trajectory

after reaching the fusion barrier)

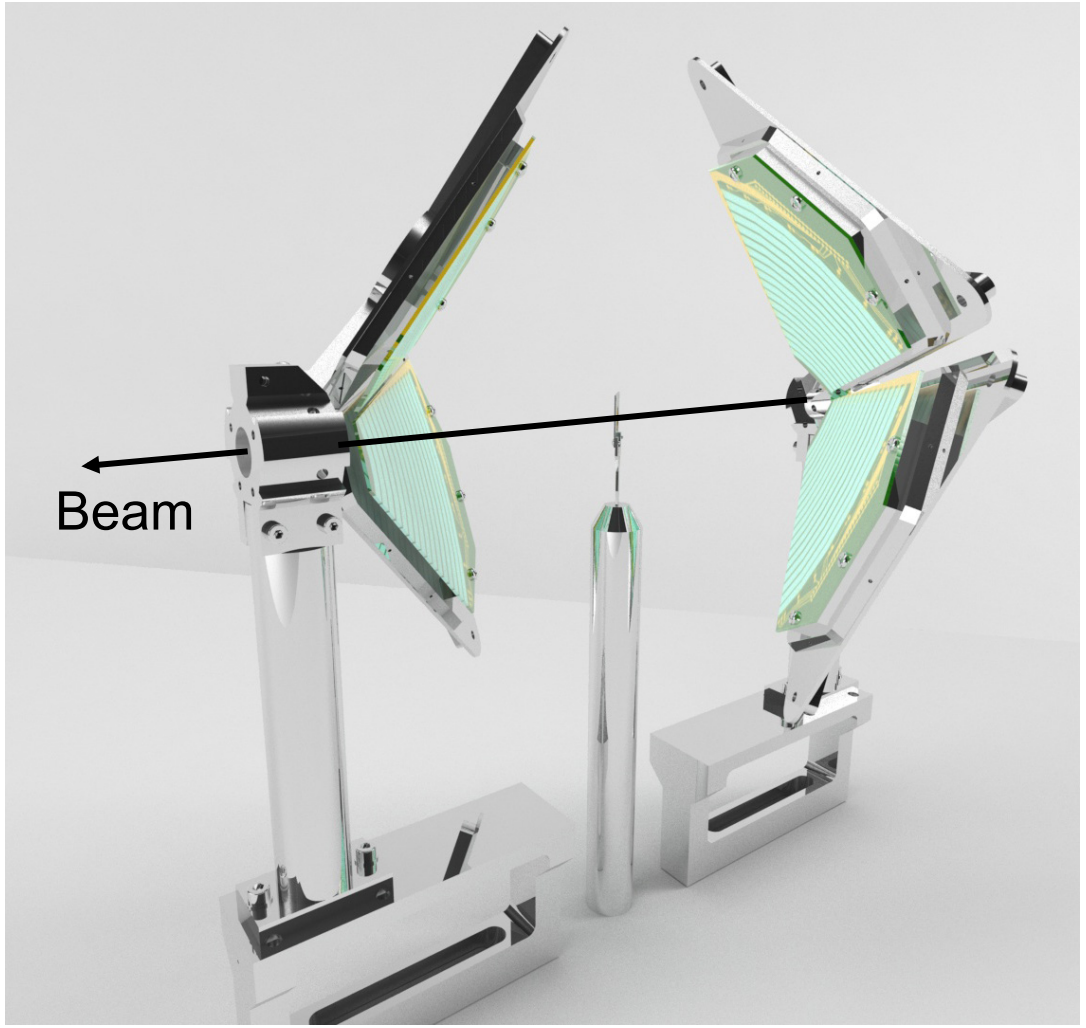
$$E_{rel} = \frac{1}{2}\mu v_{12}^2$$



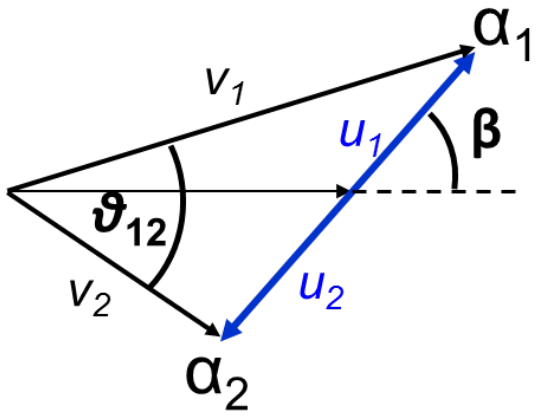




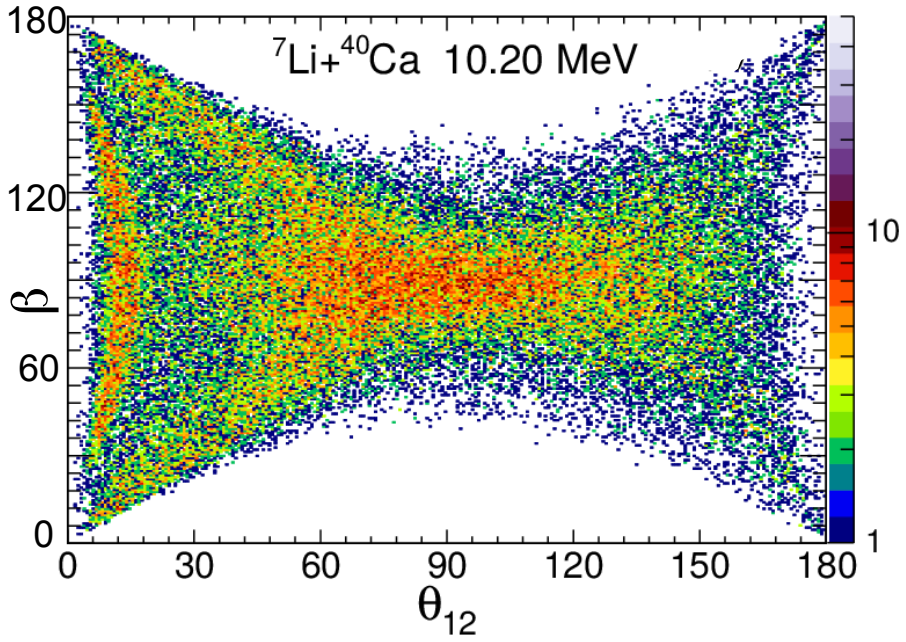
Front-back angle detector configuration sensitive to disintegration before R_{min}



Breakup location from experimental observables

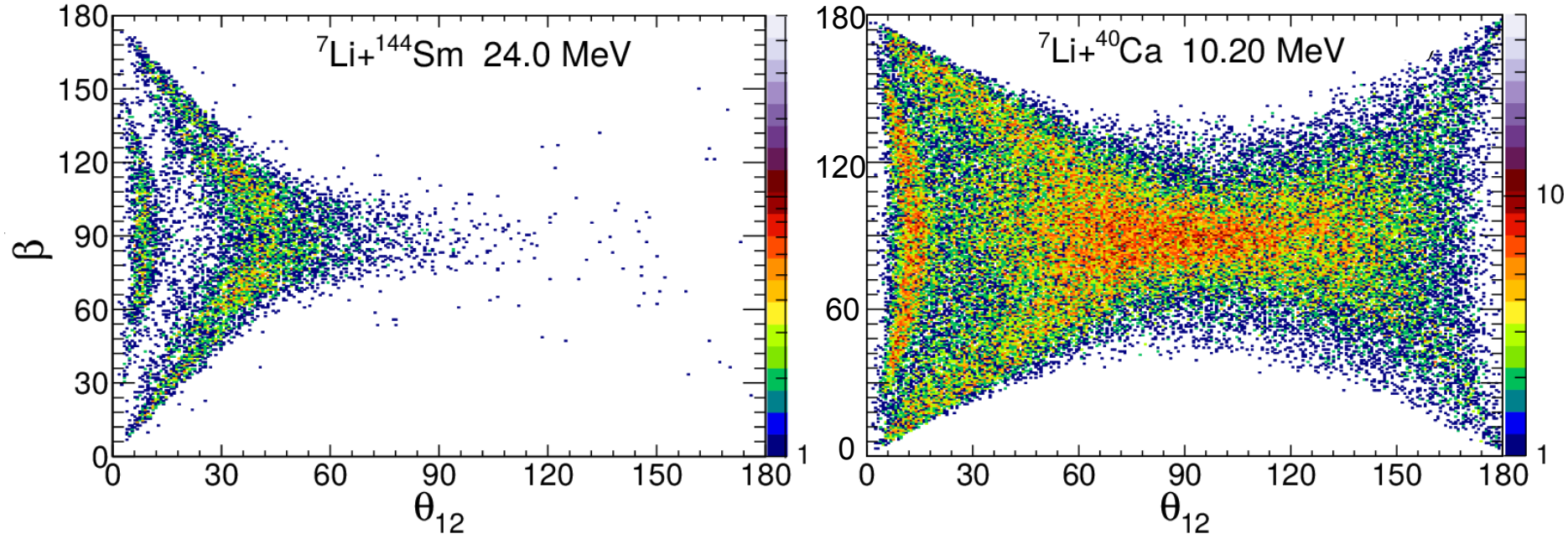


E.C. Simpson et al., Phys. Rev. C **93**, 024605 (2016)



Ed Simpson, Talk later in this session

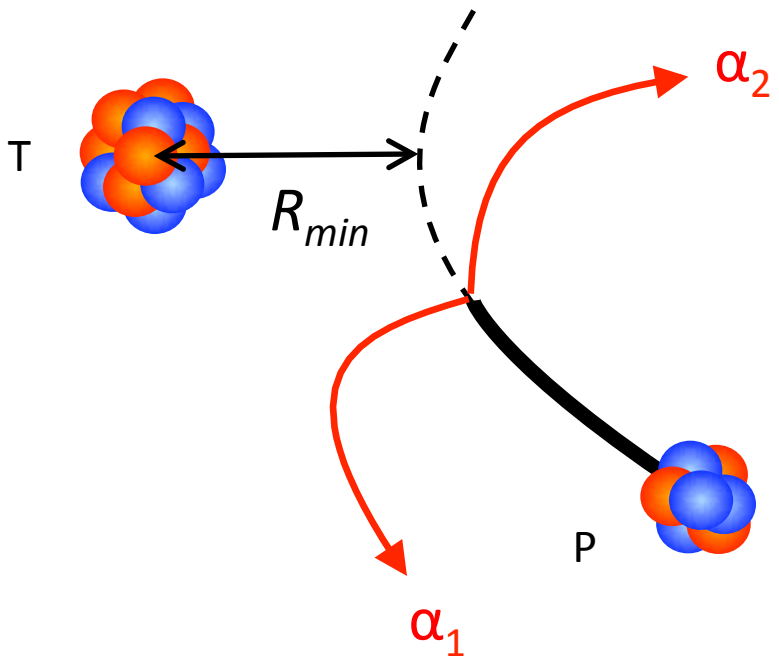
Breakup location from experimental observables



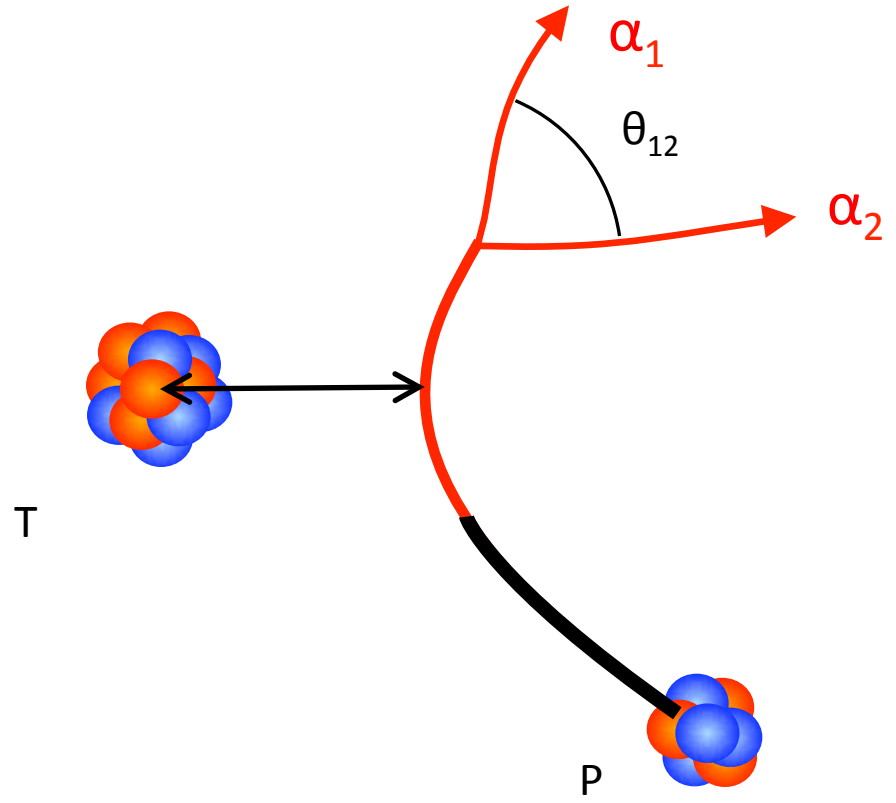
, recent work, unpublished (2016)

Effect of lifetime in prompt breakup location: Sub-barrier breakup measurements

Unbound state populated
Immediate breakup



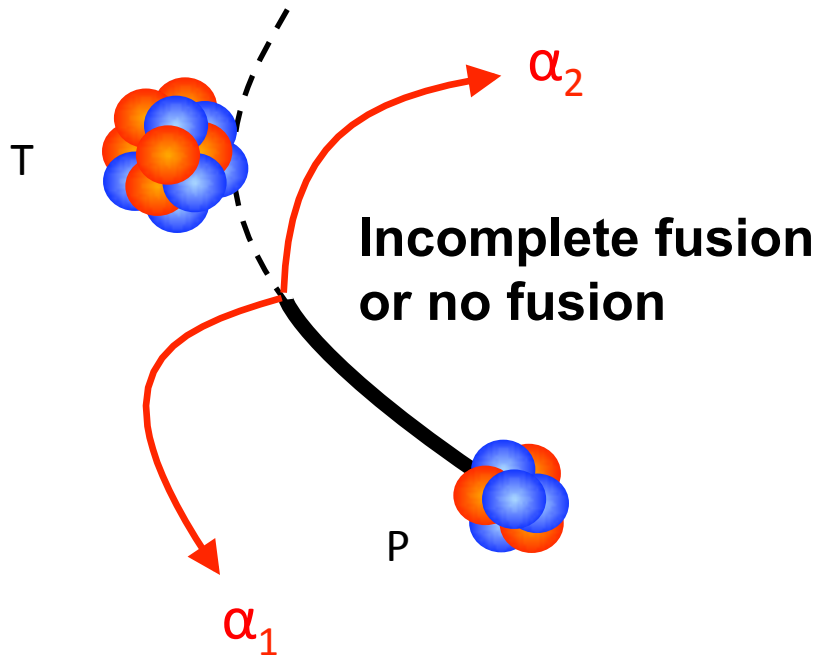
Unbound state populated
Lifetime delays breakup



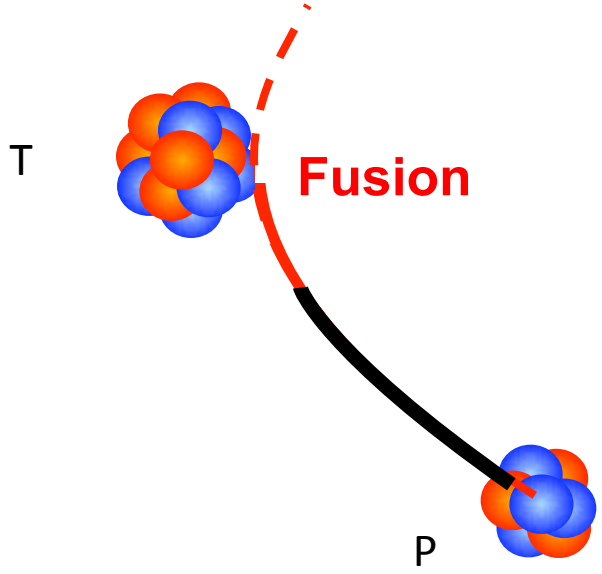
Expect differences in opening angle θ_{12} and relative energy E_{rel}.
Large E_{rel} correspond to earlier disintegration

Effect of lifetime in prompt breakup location: Above-barrier fusion suppression

Unbound state populated
Immediate breakup



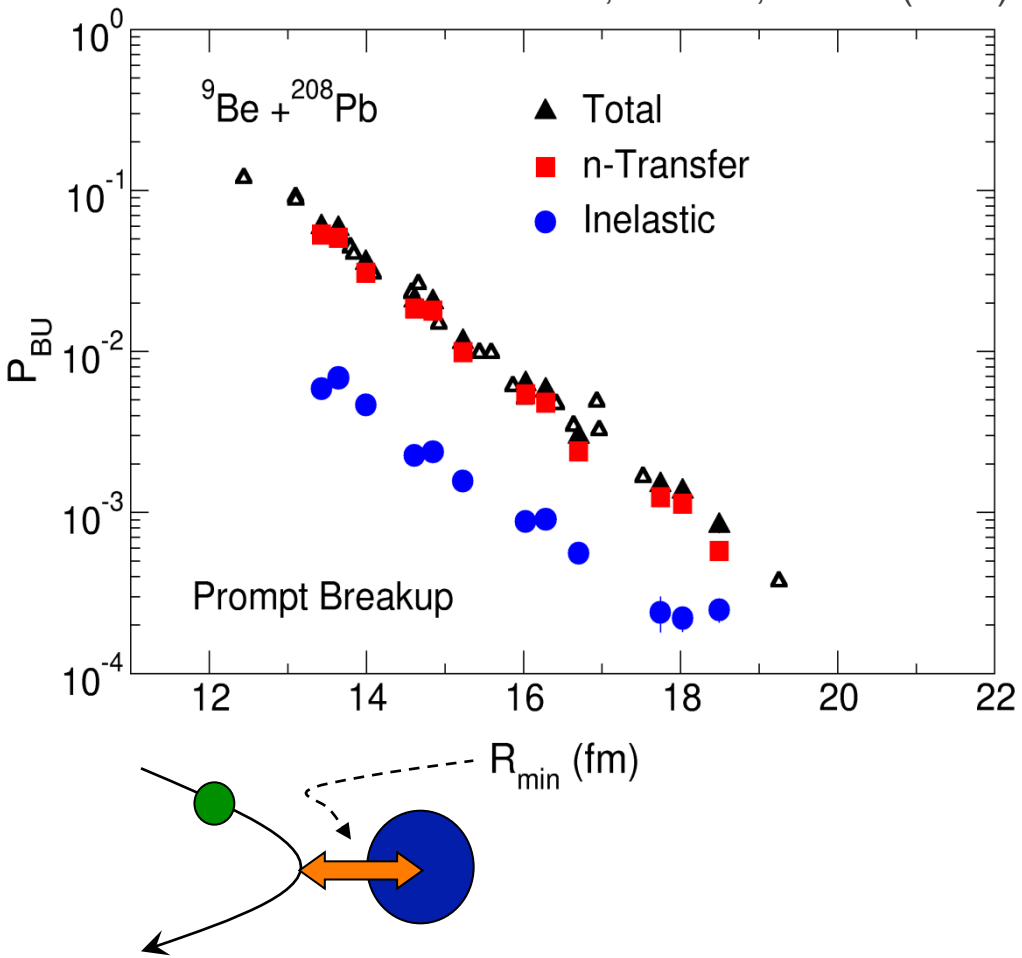
Unbound state populated
Lifetime delays breakup



Absolute breakup probabilities

- Breakup measurements made at a range of energies
- Probability as a function of distance of closest approach

Rafiei et al., PRC 81, 024601(2010)



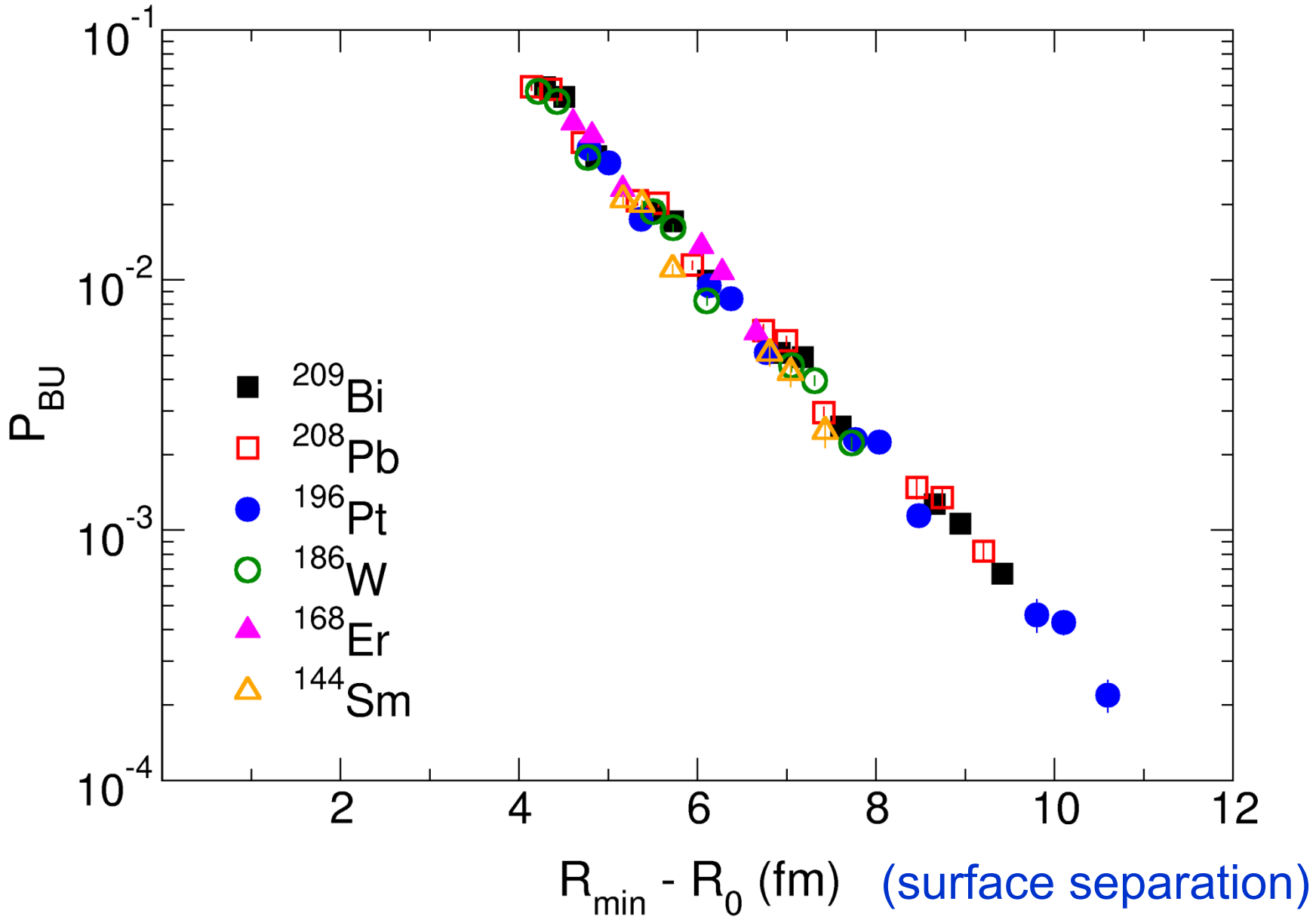
Prompt breakup probabilities at the fusion barrier

Predict above-barrier complete and incomplete fusion

D.J. Hinde et al., PRL 89 (2002) 272701

A. Diaz-Torres et al, PRL 98, 152701 (2007)

Experimental results demand advances in models

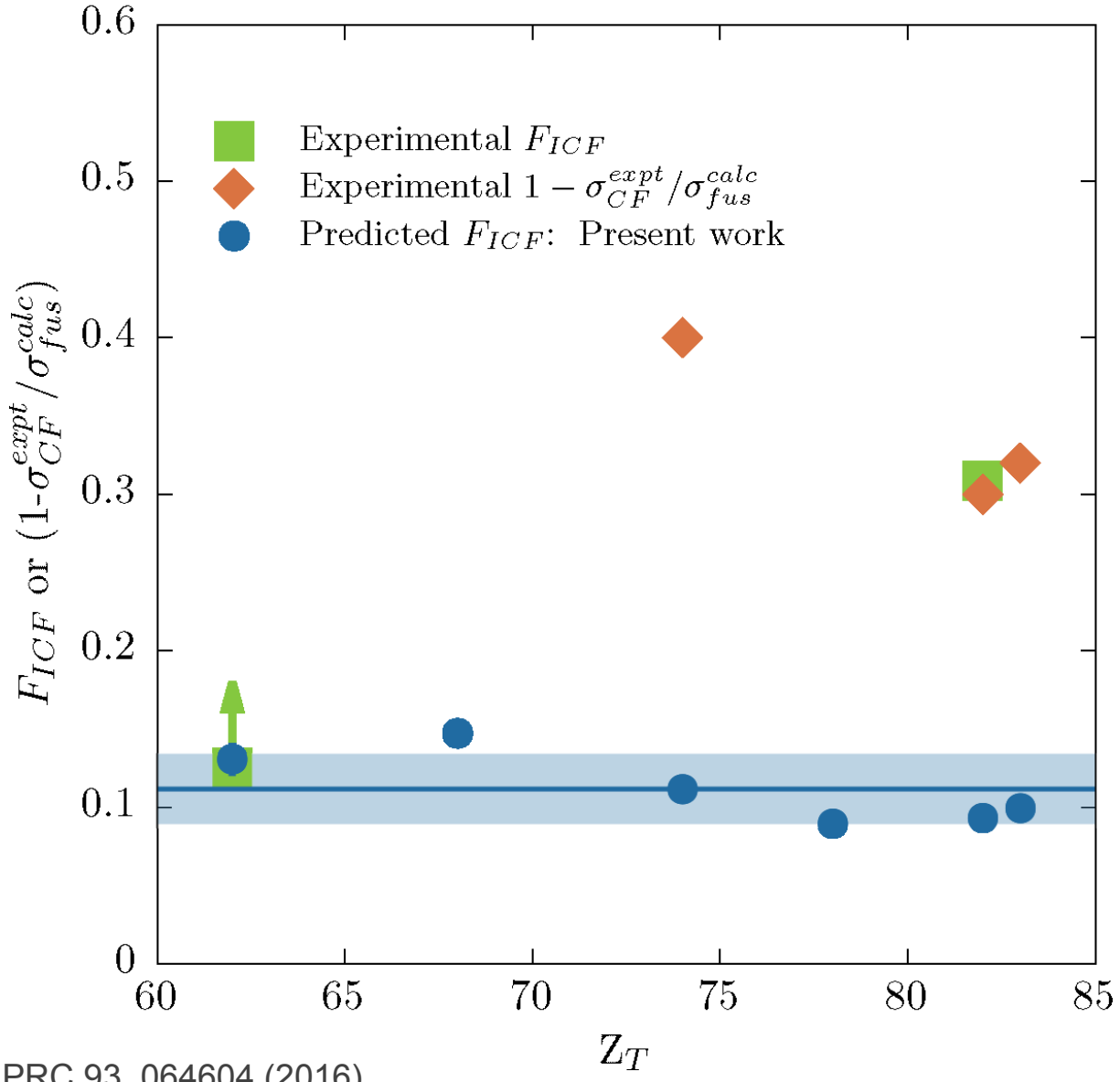


R. Rafiei et al., PRC 81, 024601 (2010)

K. Cook et al., PRC 93, 064604 (2016)

Breakup lifetime and complete fusion suppression

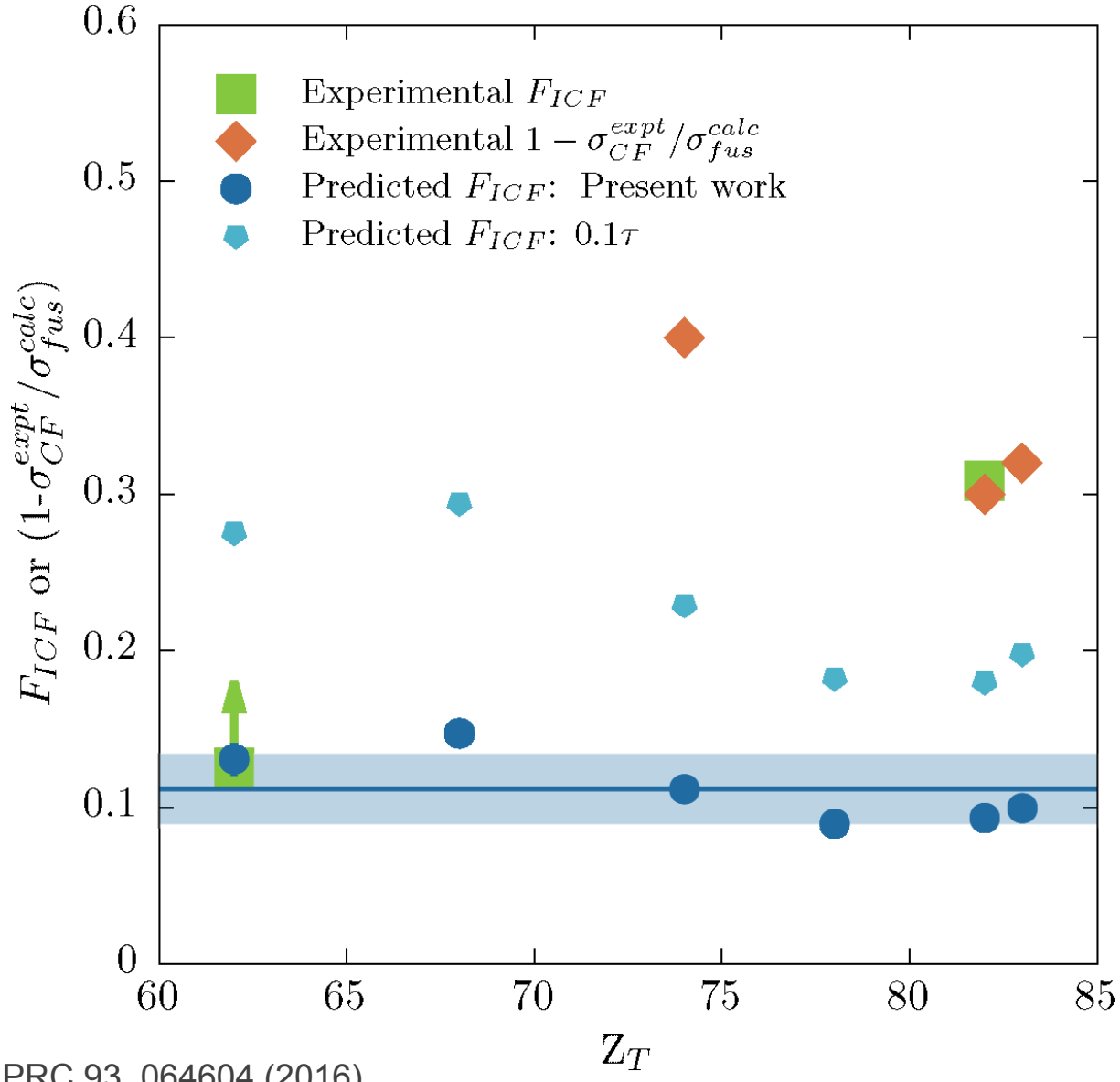
Reduction of complete fusion



K. Cook et al., PRC 93, 064604 (2016)

Breakup lifetime and complete fusion suppression

Reduction of complete fusion



K. Cook et al., PRC 93, 064604 (2016)

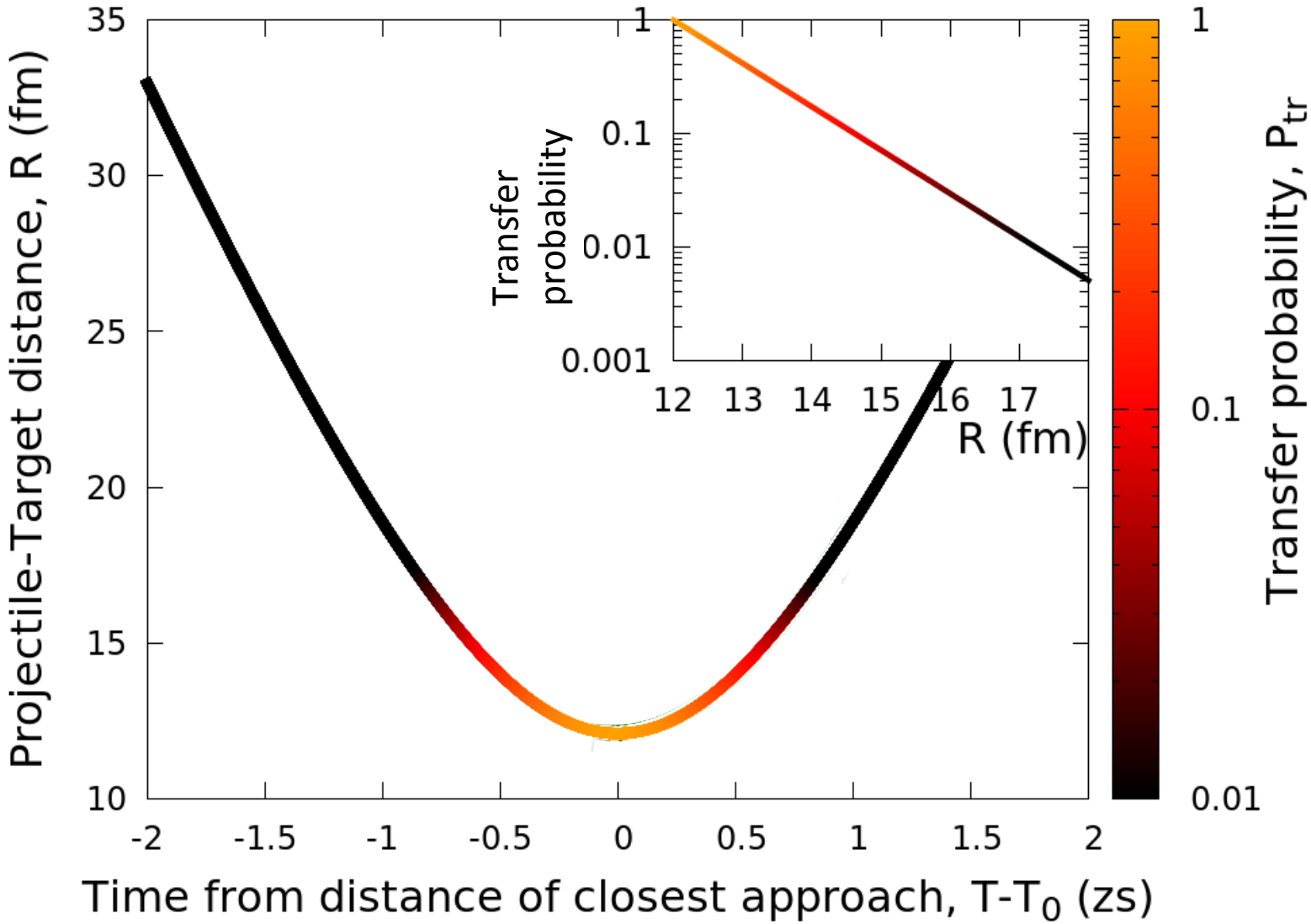
Summary and outlook

- What causes suppression of complete fusion?
  - thought to be due to breakup of weakly bound projectile

Direct breakup into cluster components	Breakup of projectile-like nucleus following transfer is most probable
Only significant for high Z_T	Low Z_T: all breakup follows transfer

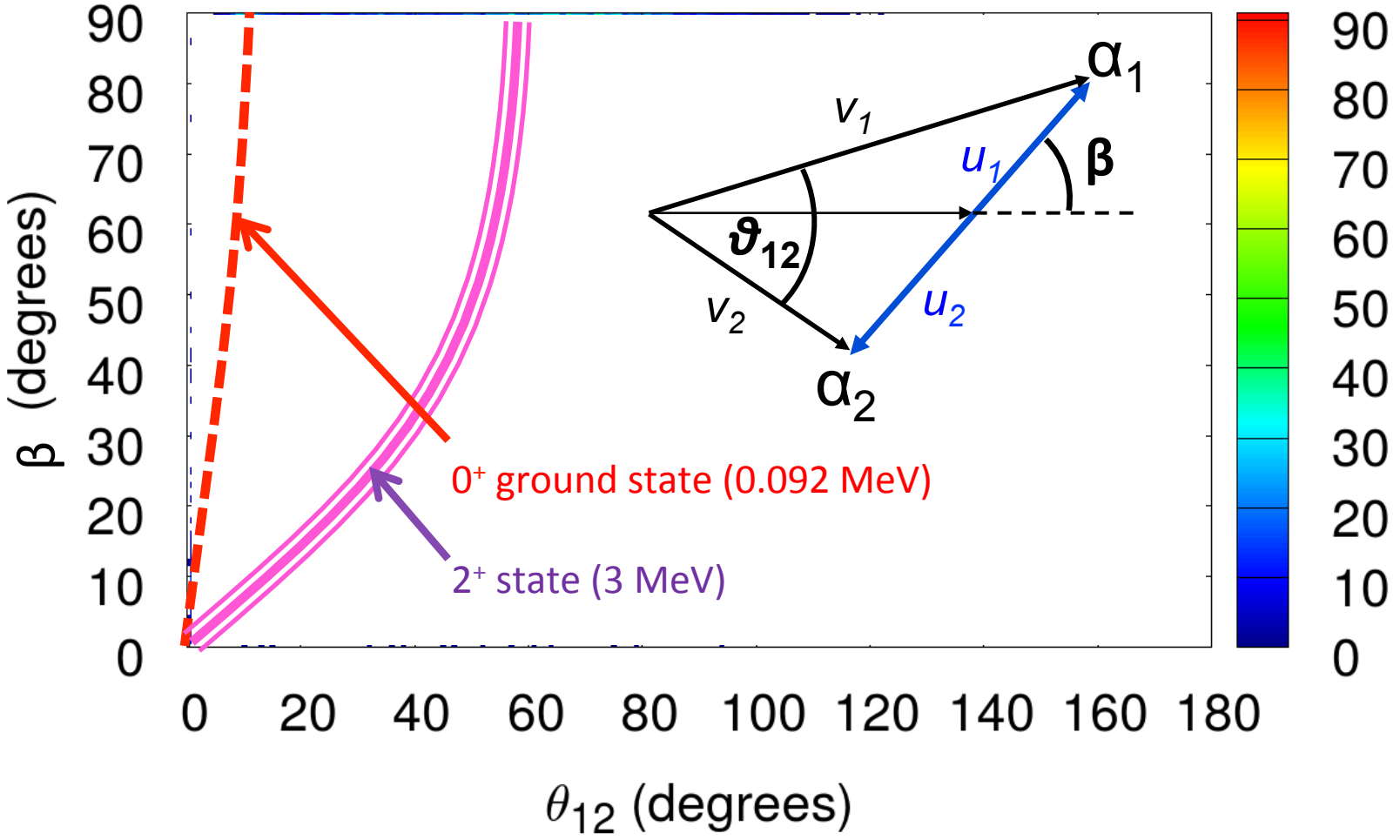
- Only breakup before the fusion barrier affects above-barrier fusion
  - suppression only if breakup occurs at short timescales ($\leq 10^{-21}$s)
  - new observables can provide information on breakup location
  - fusion suppression not fully explained
- Quantum model needed to match latest experiments that are extremely sensitive to breakup modes and location
  - Lifetime of resonances (even if < zeptosecond) important
  - Are lifetimes affected by proximity to target nucleus?
  - Final goal – model to understand complete and incomplete fusion

Projectile trajectory



β vs θ_{12}: asymptotic calculation

^{7}Li+^{58}Ni ➡ α+α **Curves show correlation for asymptotic breakup**



Observed prompt breakup modes

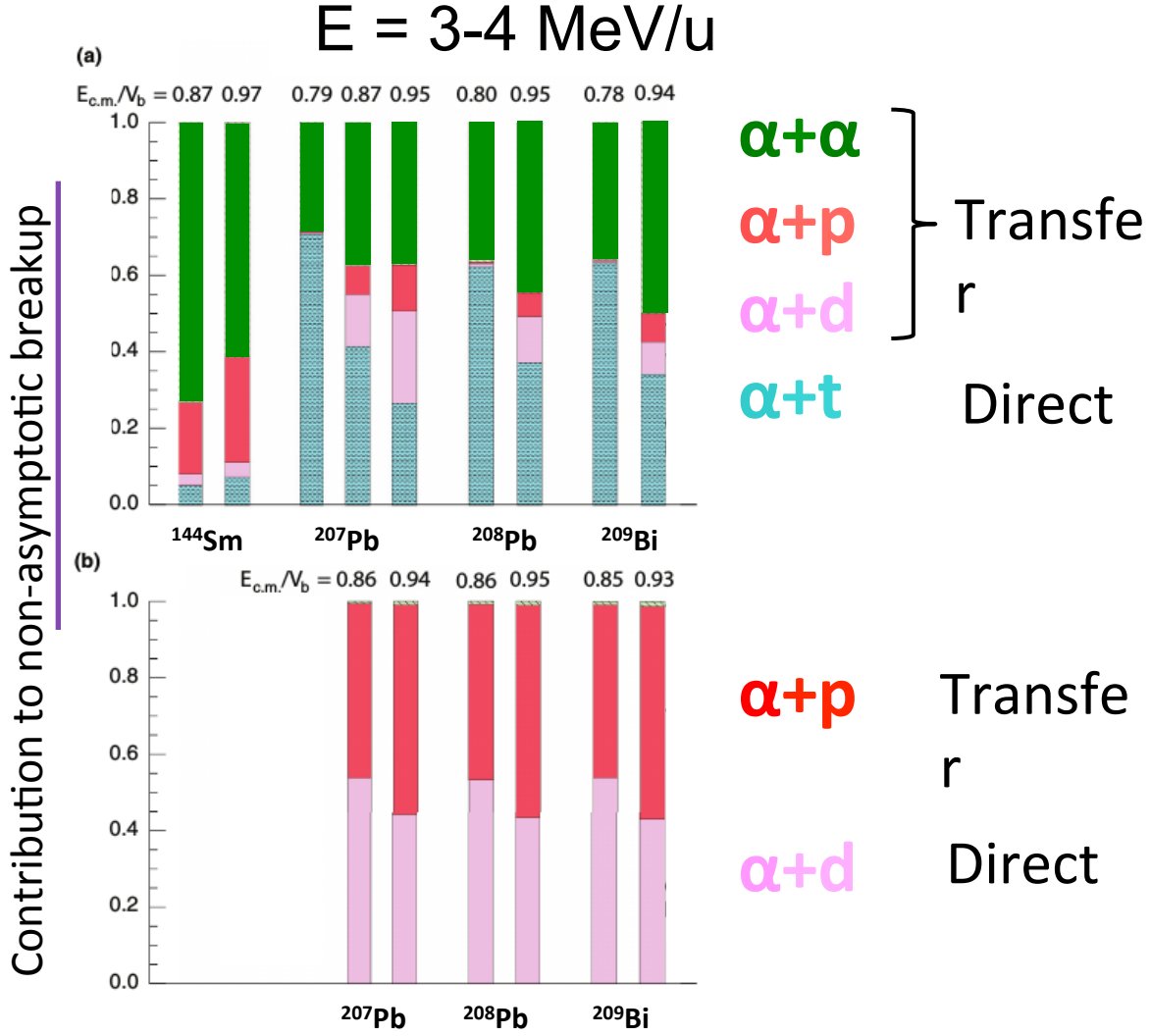
Transfer followed by breakup - a major contributor to prompt breakup

(Excludes long-lived resonances)

^{7}Li

^{6}Li

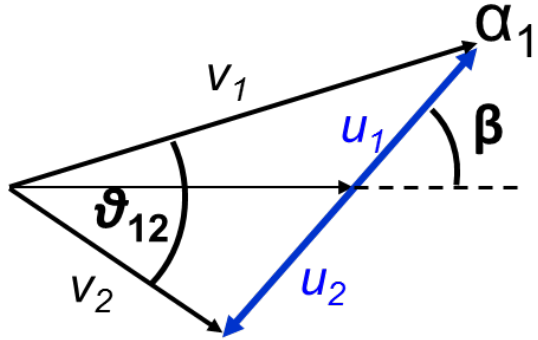
Breakup modes depend on the combination of projectile and target nuclei

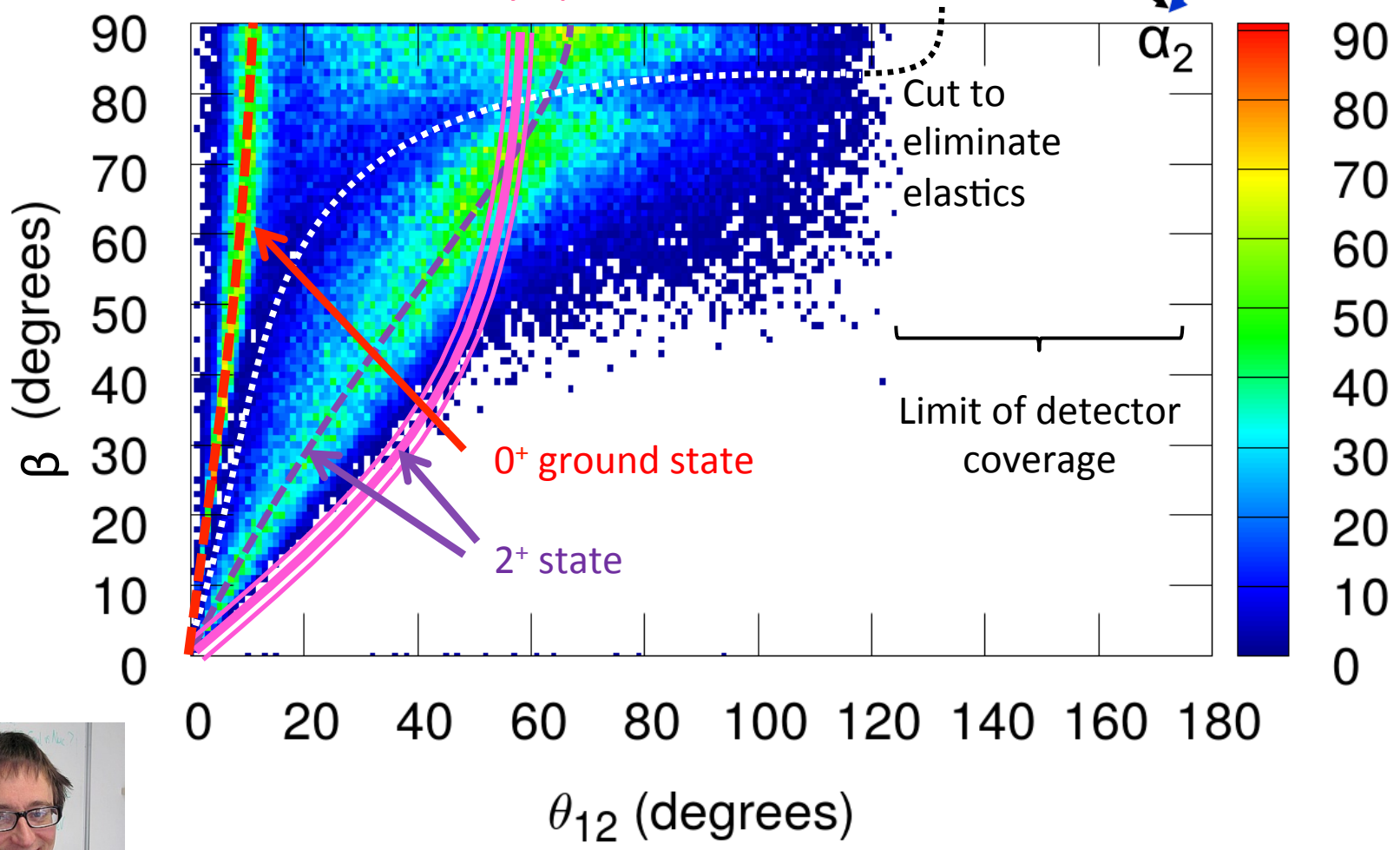


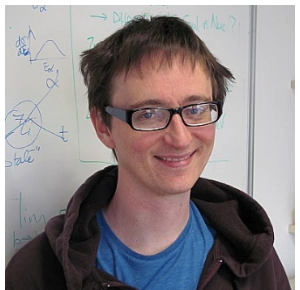
D.H. Luong *et al.*, PRC 88, 034609 (2013)

Experimentally obtained β vs θ_{12}

$^{7}Li+^{58}Ni \rightarrow \alpha+\alpha$





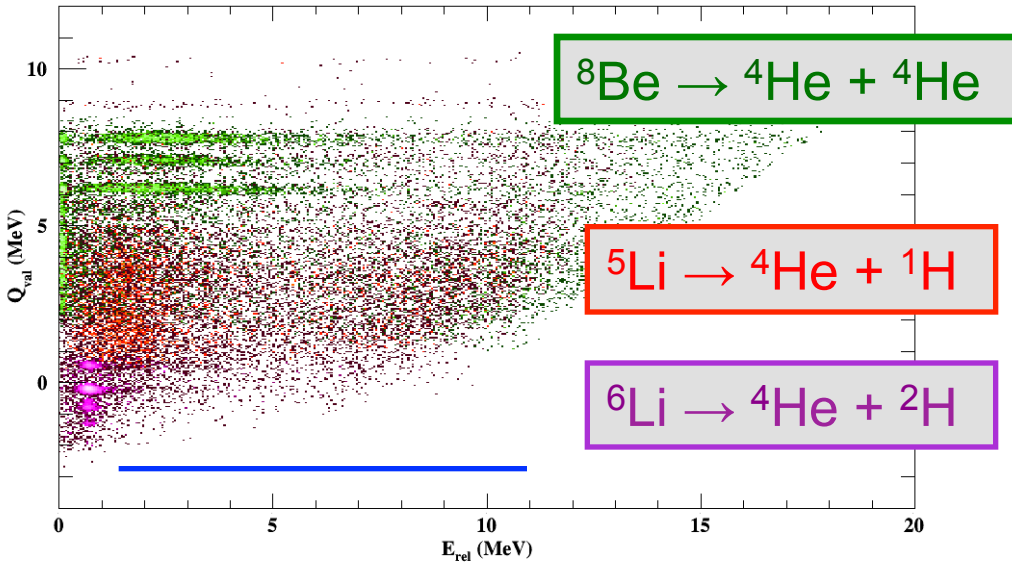


Ed Simpson

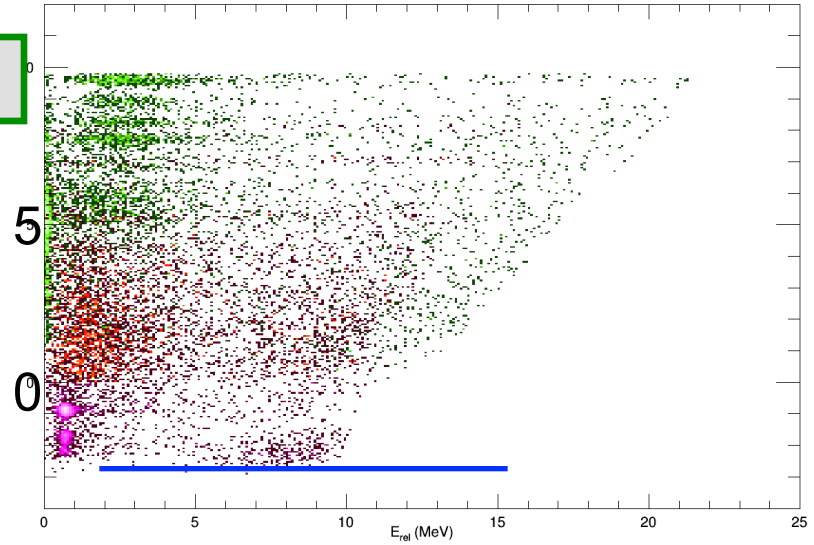
E.C. Simpson et al., Phys. Rev. C **93**, 024605 (2016)

Breakup for ^{7}Li incident on medium-mass target nuclei
Particle identification by t.o.f. over 11 cm (Z=1,2)

^{7}Li + ^{50}Cr, E_{beam} =11.7 MeV



^{7}Li + ^{64}Zn, E_{beam} =13.6 MeV



- *p*-transfer forming ^{8}Be dominates (driven by stability of α; Q ≥ +9 MeV)
- **No direct breakup** (^{7}Li → α + t) seen for medium mass targets

Sunil Kalkal

Open questions

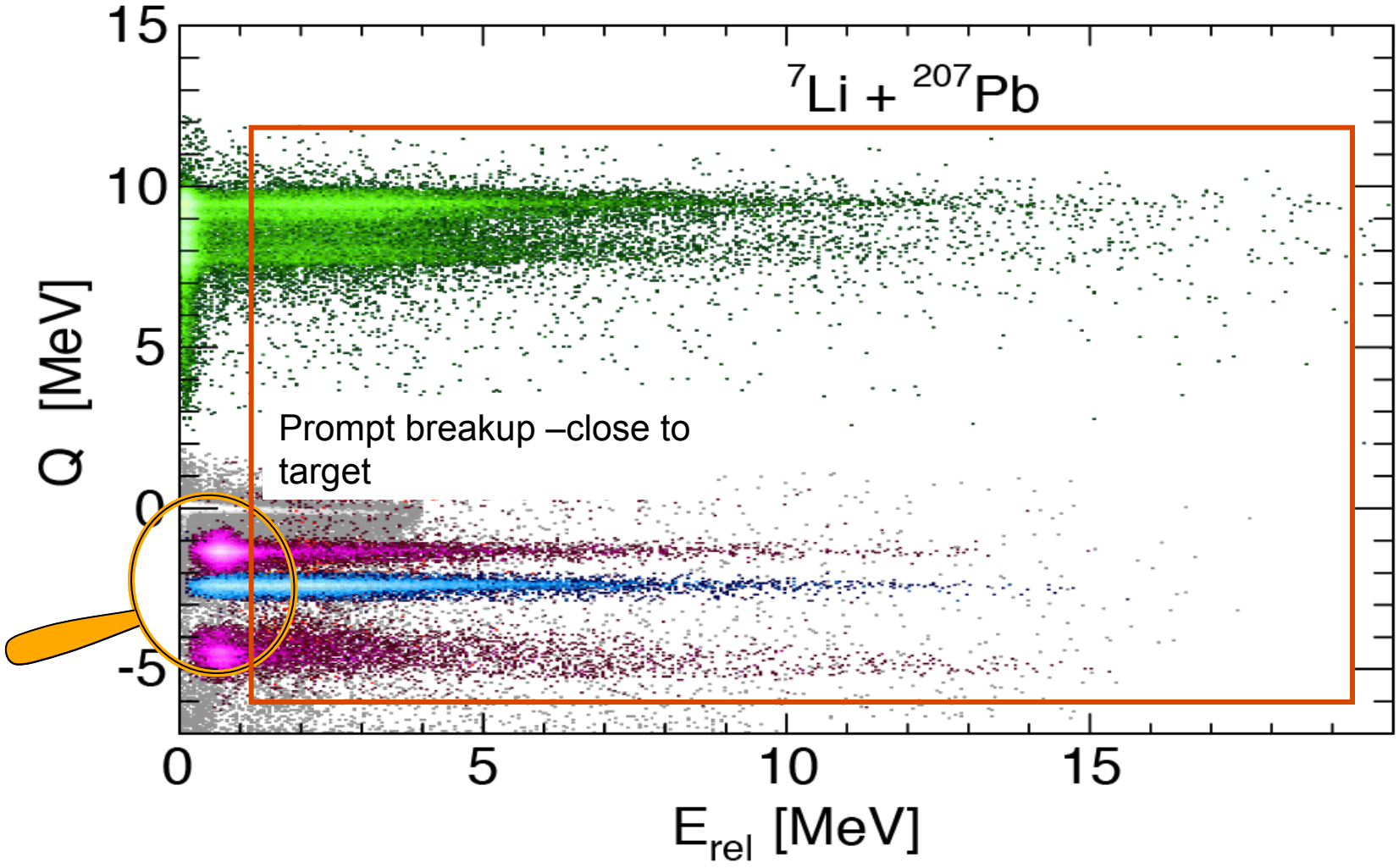
Limitations of a classical model of breakup?

Are resonance widths correct close to a heavy nucleus?

Mapping from below-barrier breakup to above-barrier fusion and incomplete fusion:

Need absolute breakup probabilities

Detector system efficiency



Transfer-triggered breakup

Focus on breakup close to target

} Key insights to develop predictive models