Locations of breakup in reactions near the fusion barrier

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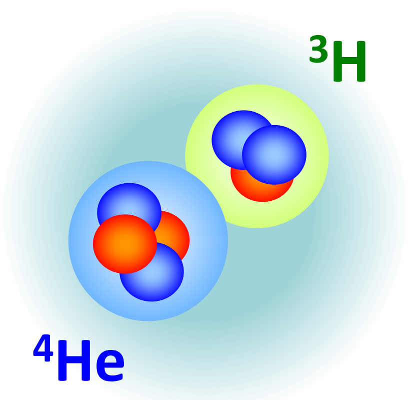
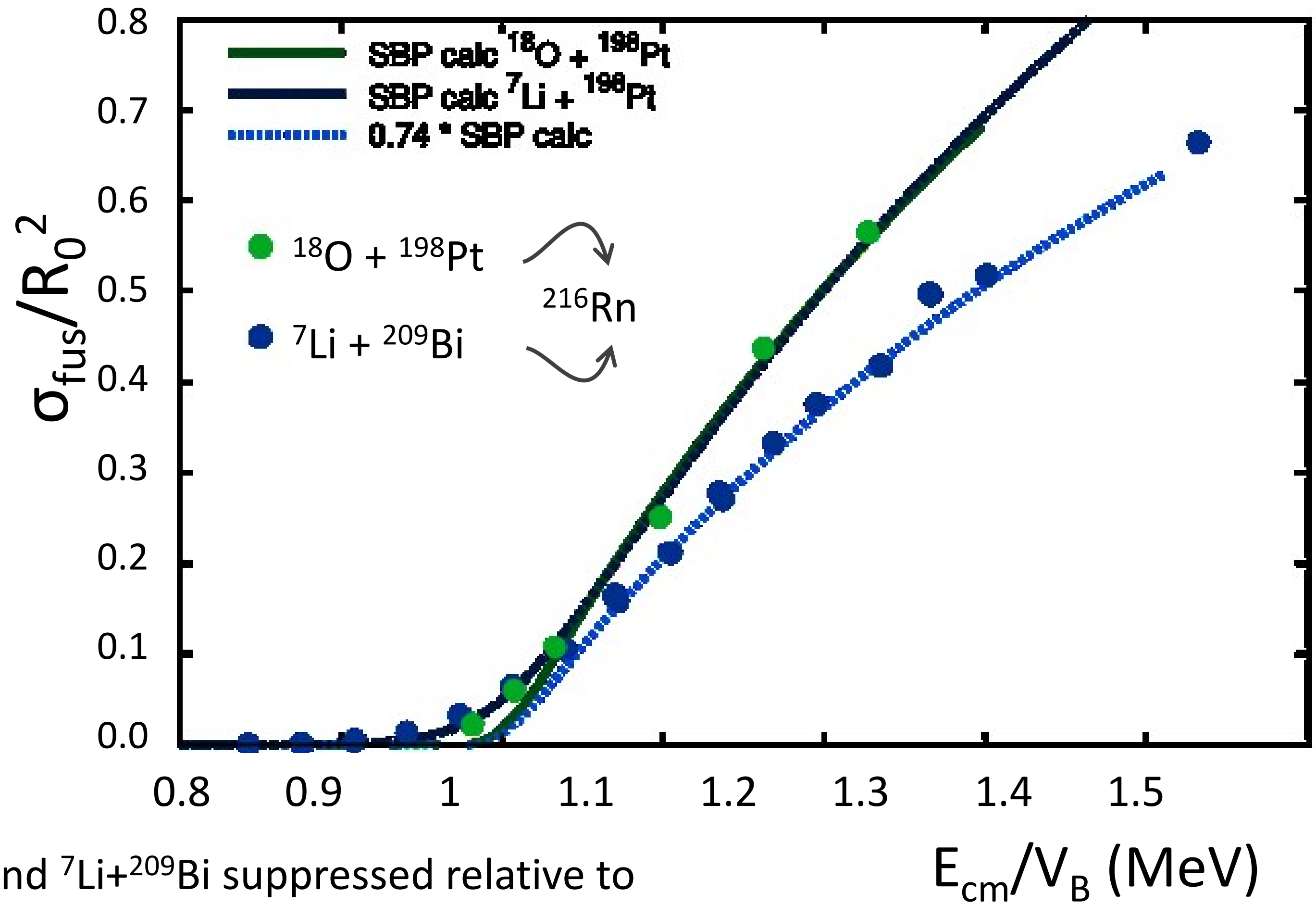
Above barrier fusion suppression

^{7}Li

Weakly-bound elastic breakup thought likely



S_{BU} = 2.467 MeV



Fusion of weakly bound ^{7}Li+^{209}Bi suppressed relative to single-barrier calculation in contrast to ^{18}O+^{198}Pt

Also ^{6}Li, ^{9}Be, many heavy targets

Dasgupta *et al.*, PRC 66, 041602(R) (2002); PRC 70, 024606 (2004); Wu *et al.*, PRC 68 044605 (2004)

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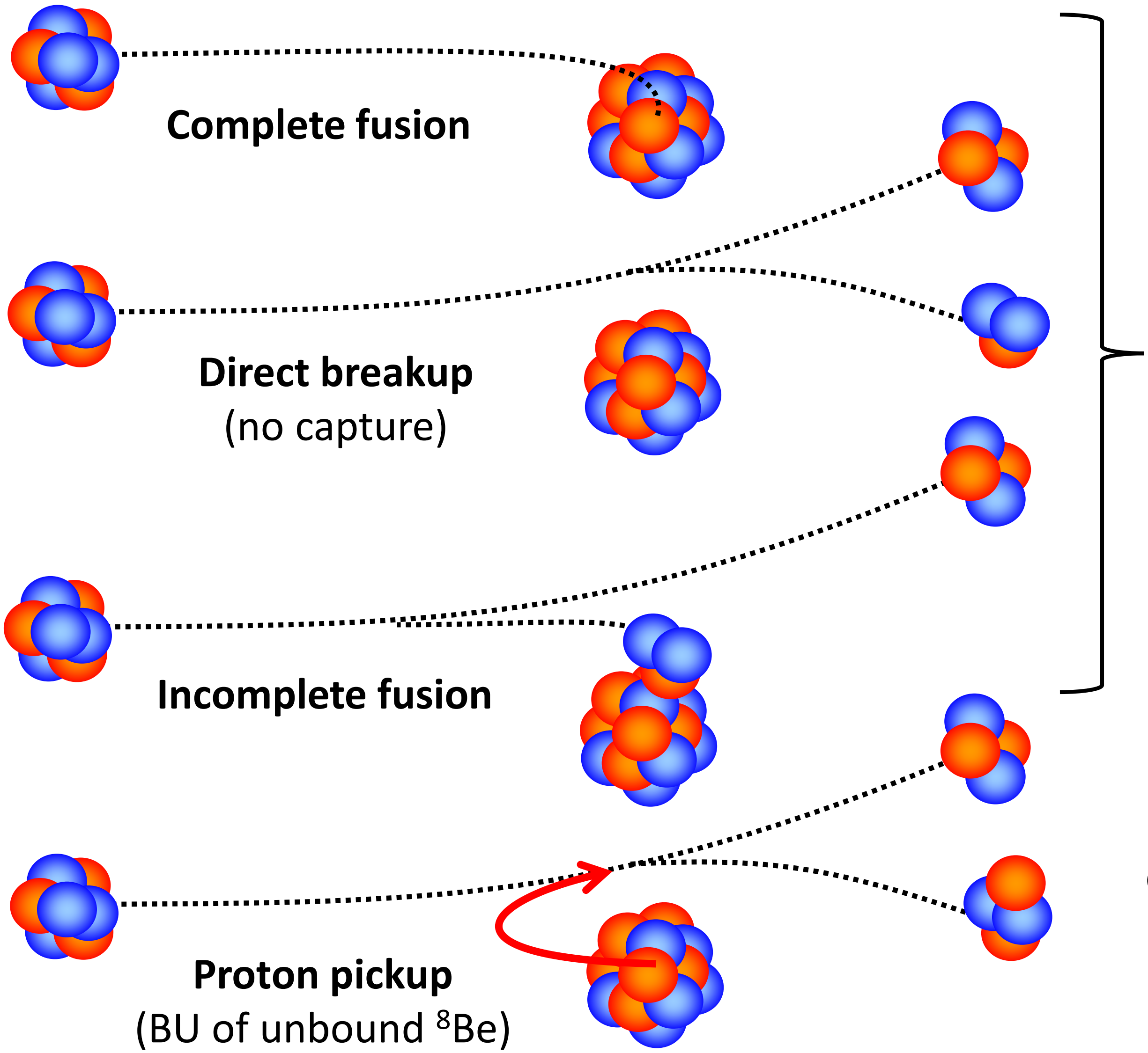
Reactions above barrier



Is this the complete picture? Do other processes cause breakup?

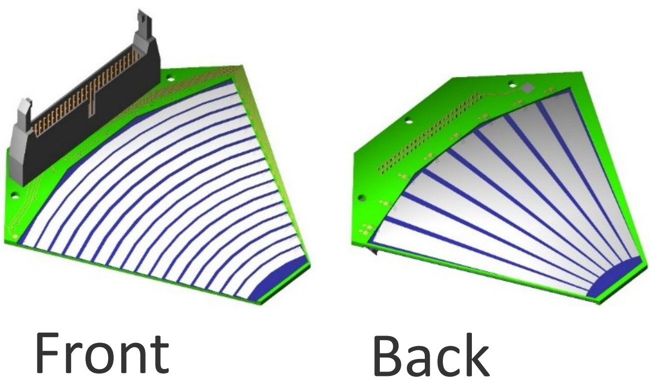
Where does breakup occur?

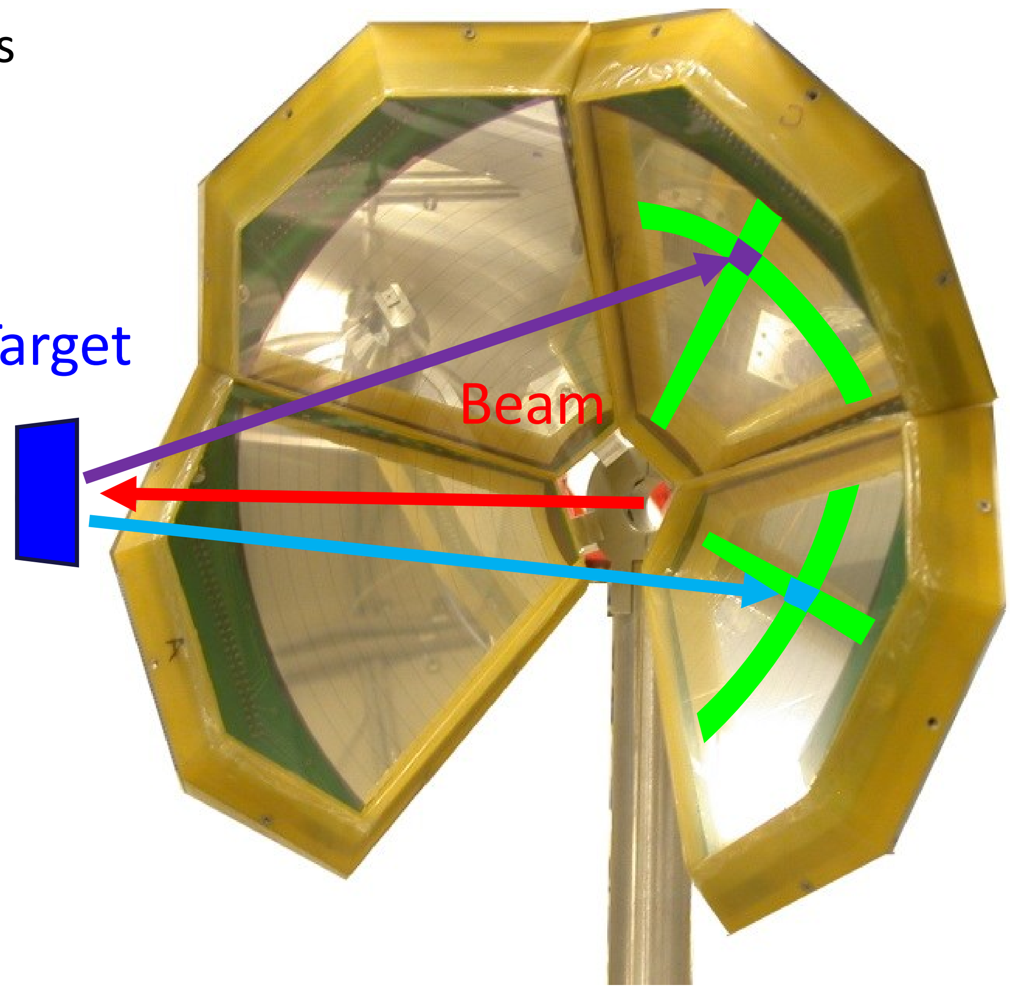
By measuring at **below barrier energies** we can test our understanding of which processes lead to breakup.

Experiment: Fragment Detection

BALiN array

Double-Sided Silicon Strip Detectors





In this “lampshade” configuration sensitive only to backward angles

115° < θ < 170°
30° < ϕ < 330°

See D. H. Luong, ANU PhD Thesis (2012)

Determined breakup modes

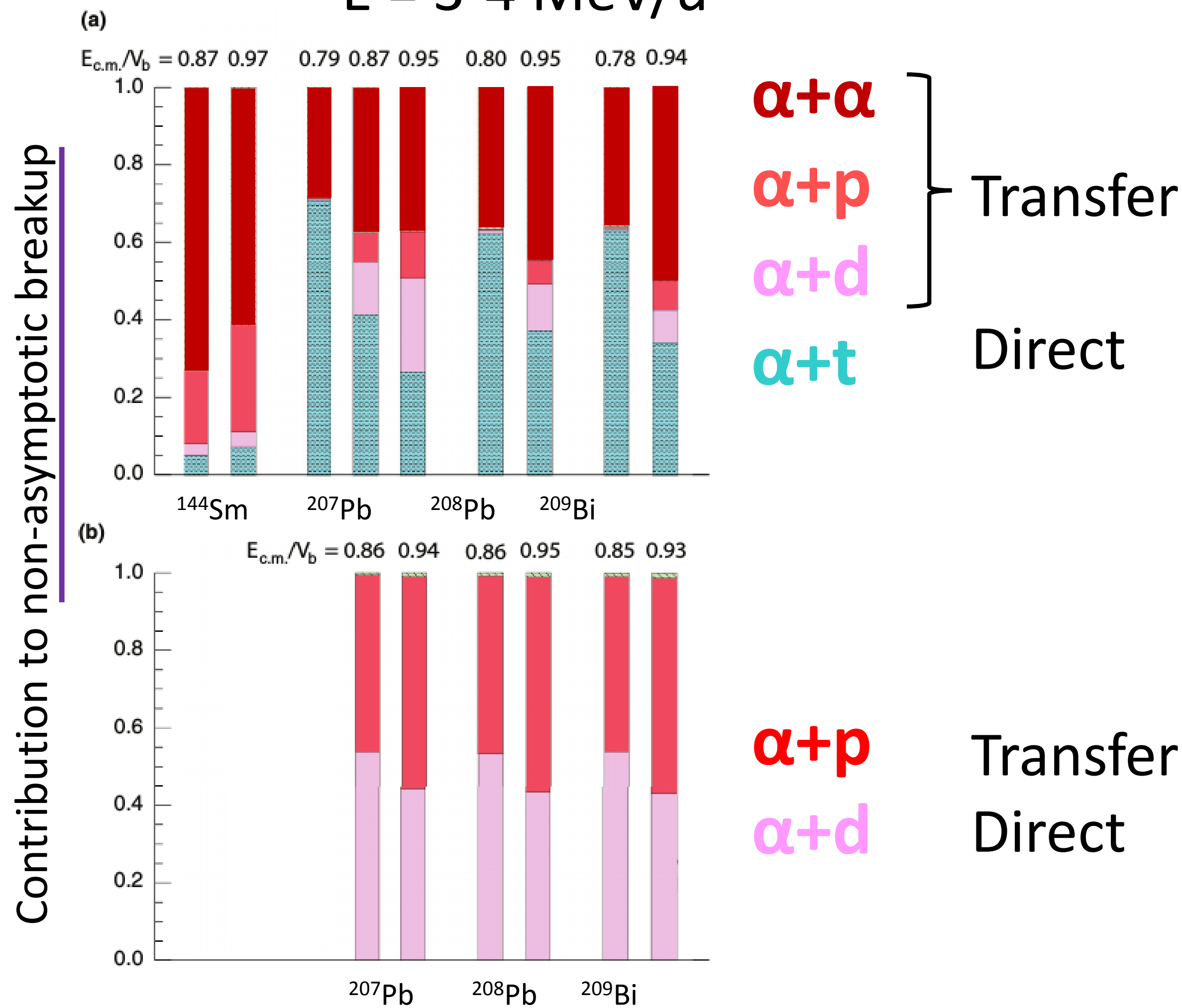
Breakup mode depends on the projectile

Excludes narrow resonances

E = 3-4 MeV/u

^{7}Li

^{6}Li



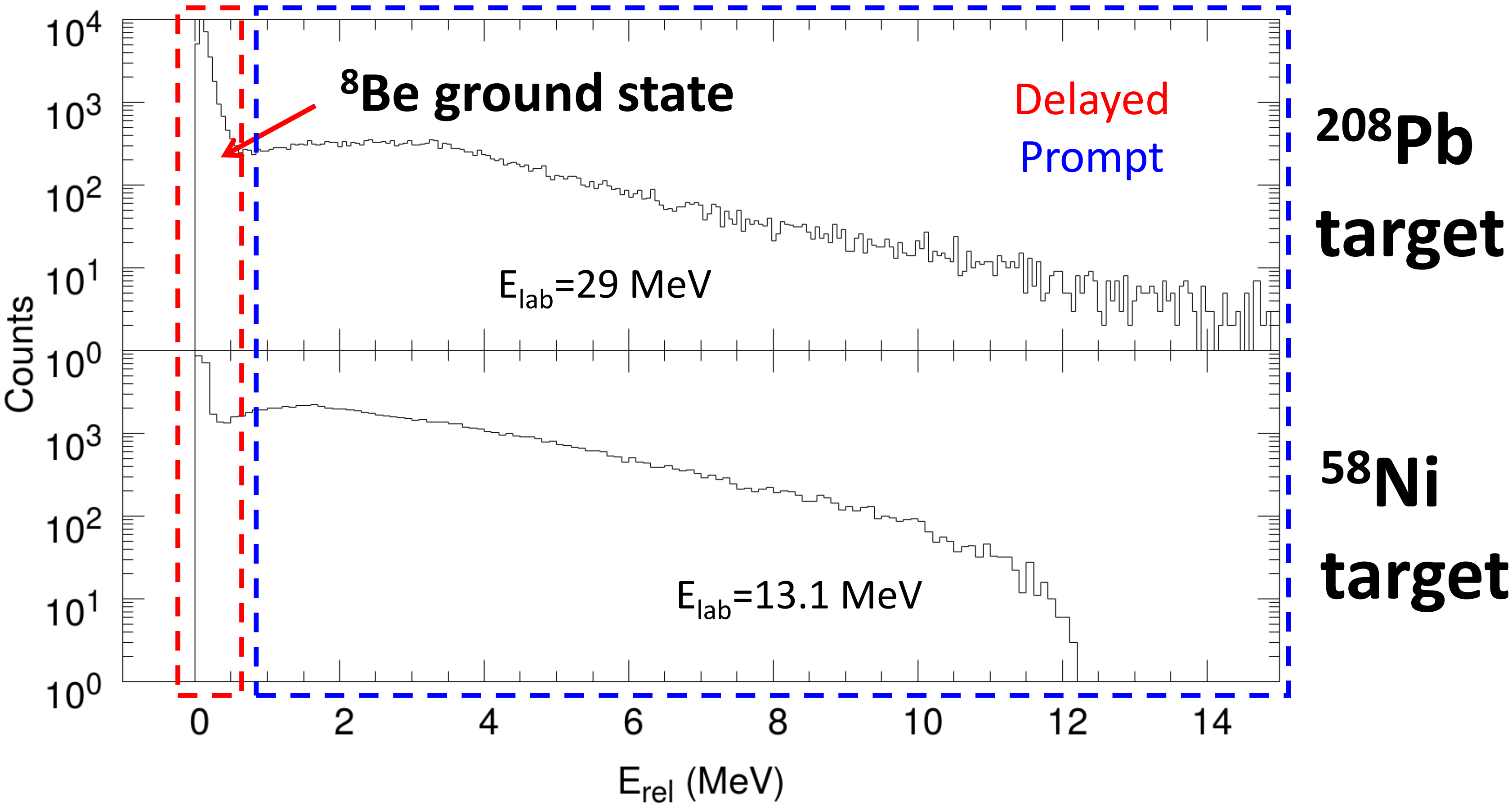
For ^{7}Li, transfer BU is dominant for non-asymptotic

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

Relative energy distribution

$^{7}Li \longrightarrow {}^{8}Be \longrightarrow \alpha + \alpha$

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



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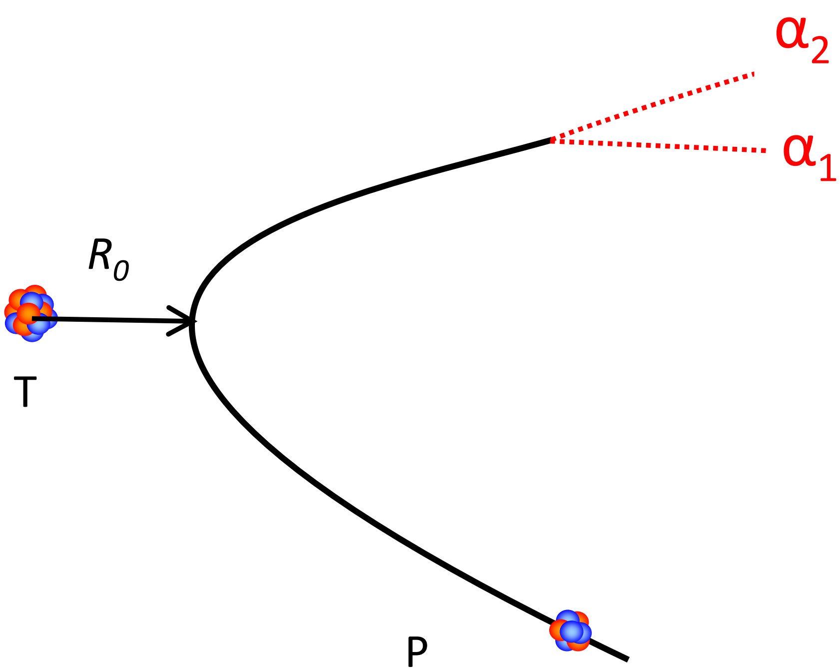
Delayed and prompt breakup

Delayed Breakup

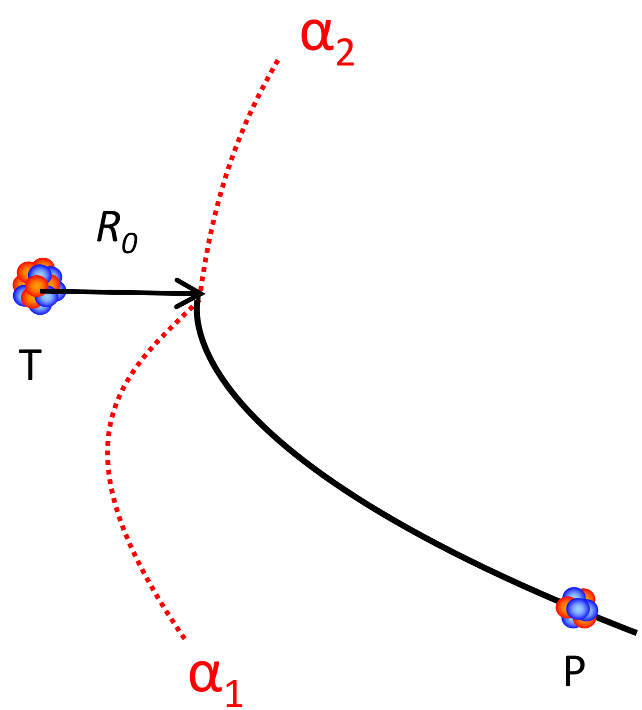
Disintegration far from the target following the population of a long-lived resonance state.



Delayed ≡ Asymptotic

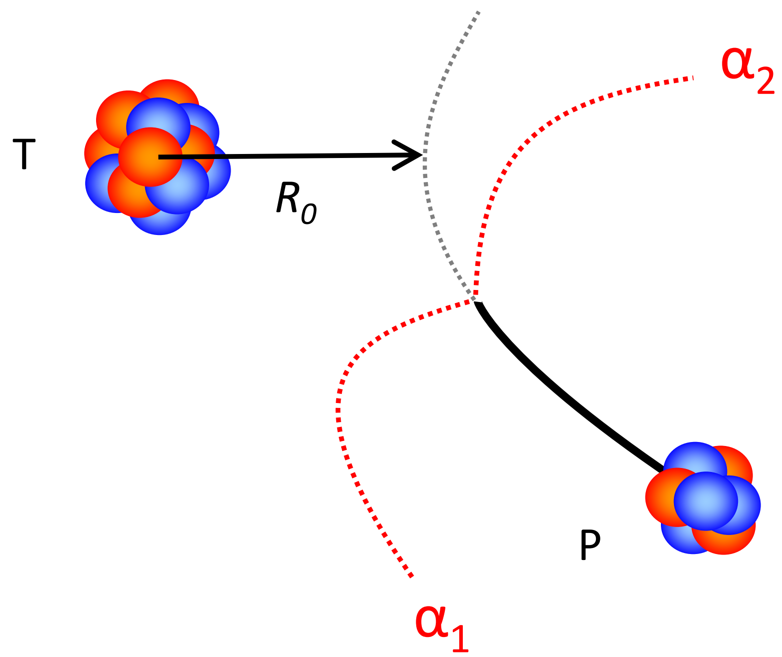
Prompt breakup

Disintegration near to the distance of closest approach. Large interaction between fragments and target.



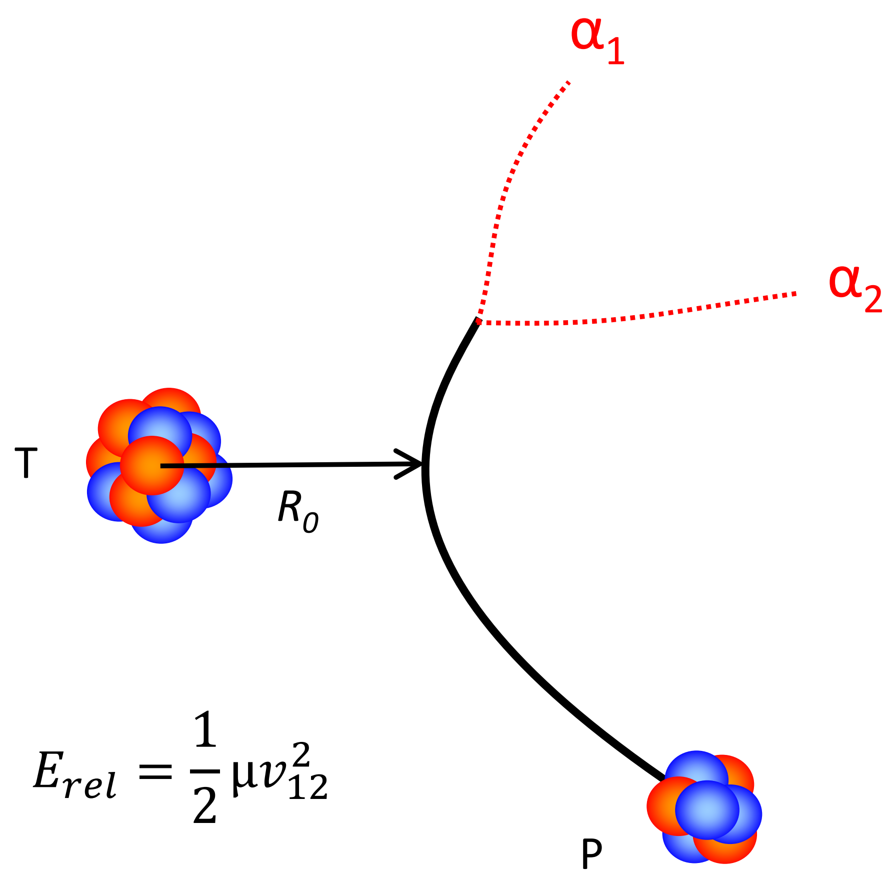
Prompt breakup

Incoming trajectory



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

Outgoing trajectory



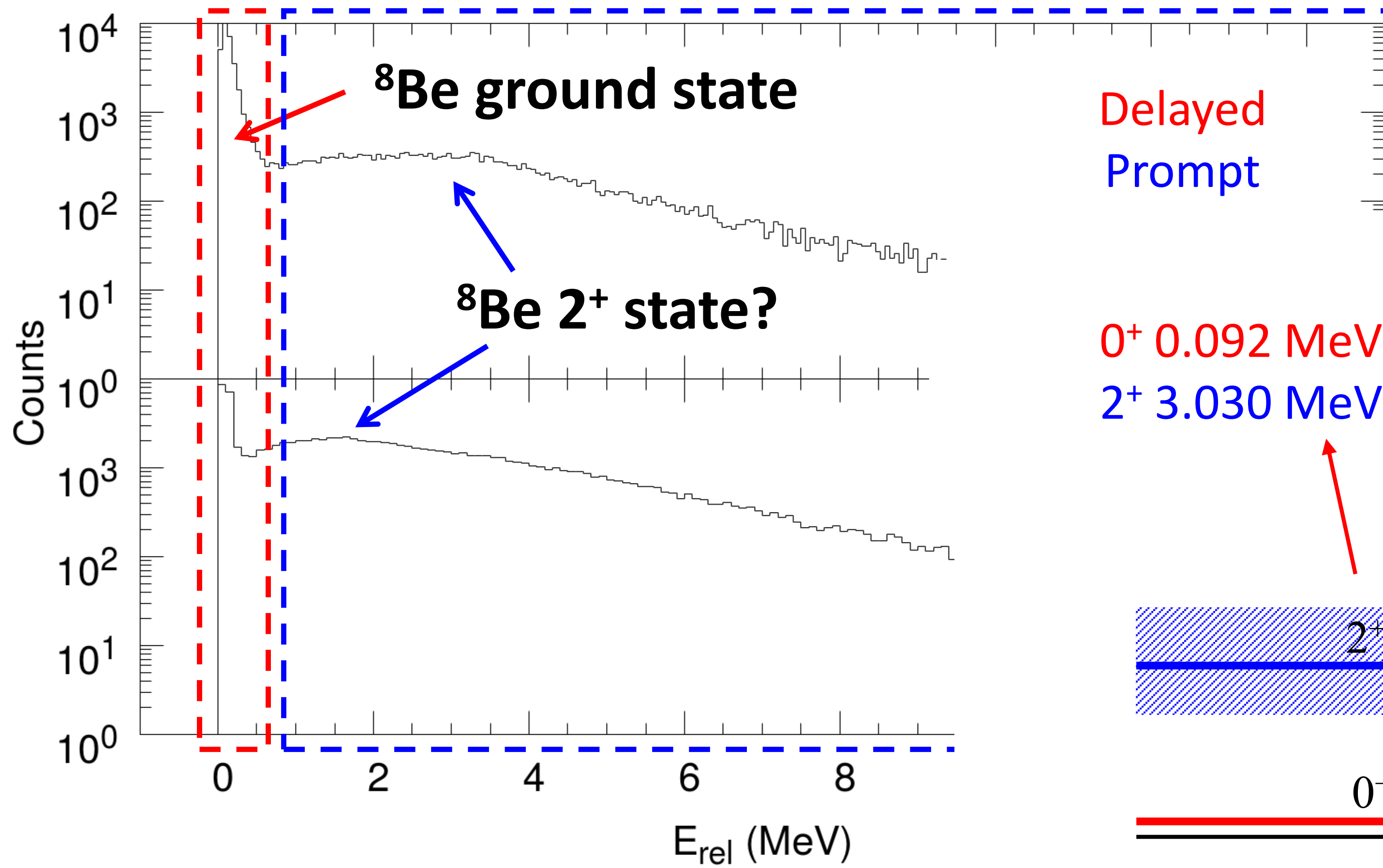
$$E_{rel} = \frac{1}{2}\mu v_{12}^2$$

Plus, asymptotic ≡ very long-lived states

Relative energy distribution

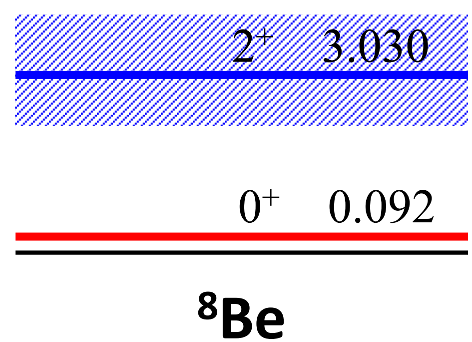
$^{7}Li \longrightarrow {}^{8}Be \longrightarrow \alpha + \alpha$

Can we understand the prompt breakup component?



0^{+} 0.092 MeV Γ=6.6 eV

2^{+} 3.030 MeV Γ=1.5 MeV

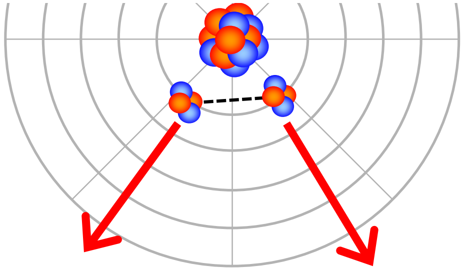


Post breakup acceleration

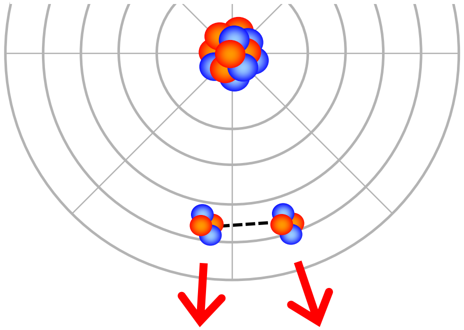
Suppose prompt breakup originates in the 2^+ resonance, with well defined initial E_x:

Sensitivity to target proximity

- Near target gives greater acceleration
- Larger changes in final E_{rel} w.r.t E_x



- Further from target, weaker acceleration
- Final E_{rel} closer to of E_x

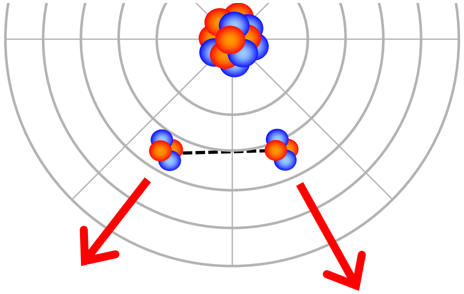


Post breakup acceleration

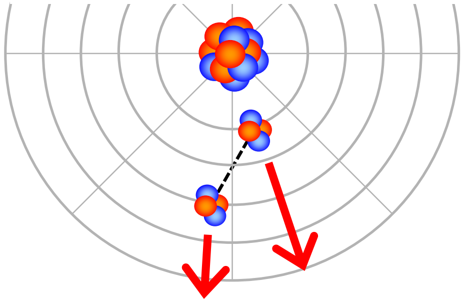
Suppose prompt breakup originates in the 2^+ resonance, with well defined initial E_x:

Sensitivity to orientation

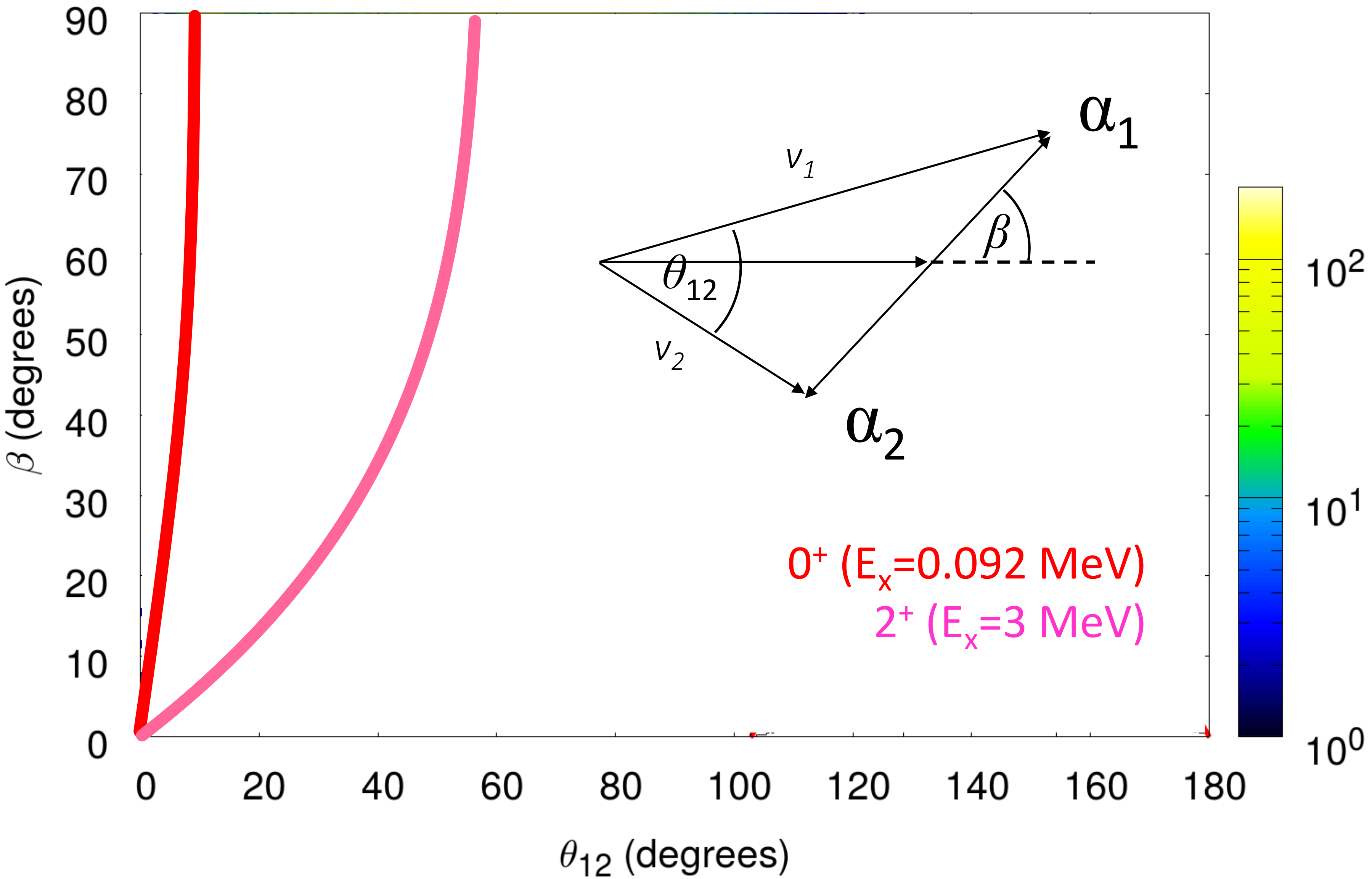
- Aligned perpendicular to the target field, leads to larger E_{rel}



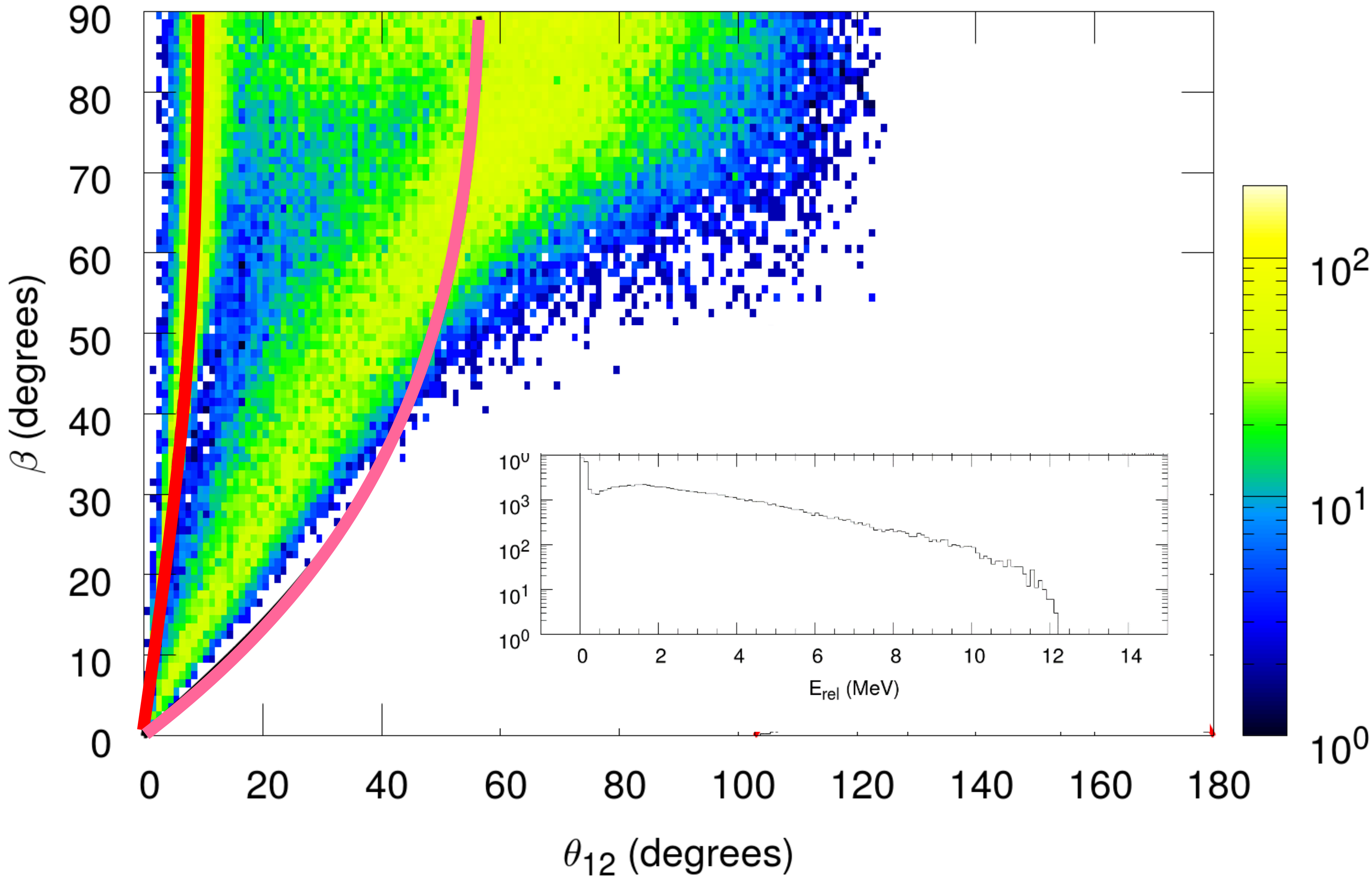
- Aligned parallel to the target field, acceleration tells to reduce the final relative energy E_{rel}



$^{7}Li+^{58}Ni$: β vs θ_{12}

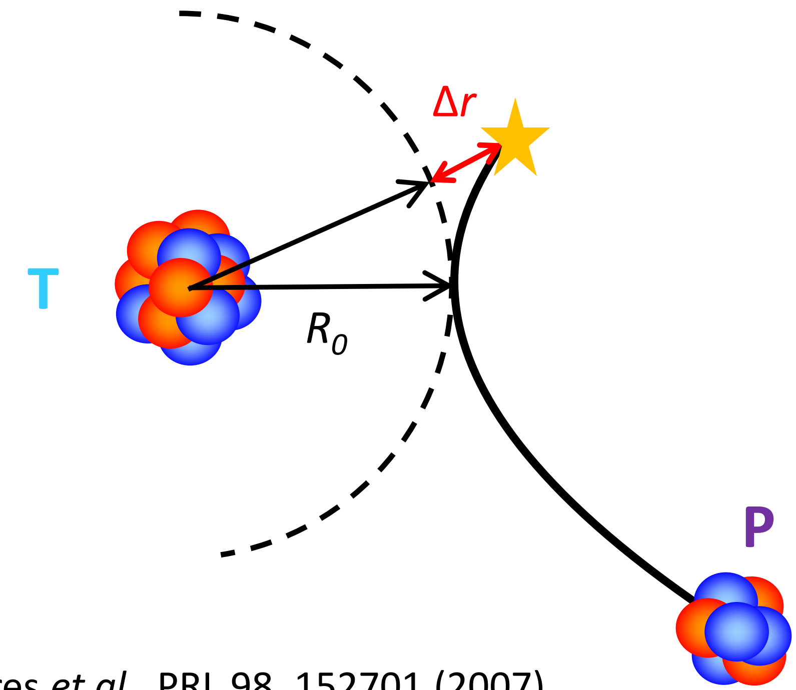


$^{7}Li+^{58}Ni$: β vs $θ_{12}$



Monte Carlo simulations

Assume a fixed E_x and R_{BU} and study how β vs. θ_{12} correlation changes.



Real nuclear interactions from Sao Paulo potential, though sensitivity low due to sub-barrier energy.

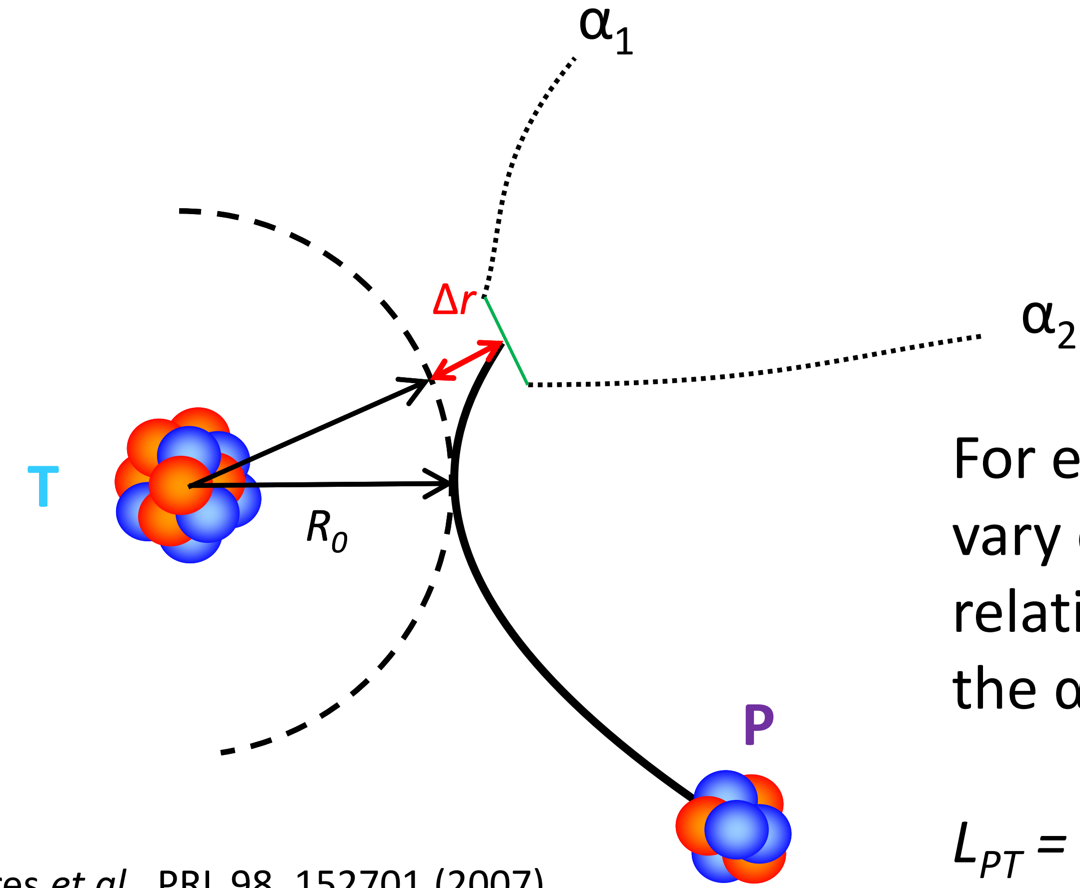
Uses a modified version of the PLATYPUS code to track target, projectile and fragment trajectories.

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

A. Diaz-Torres, CPC 182, 1100 (2011)

Sensitivity to target proximity

Assume a fixed E_x and R_{BU} and study how β vs. θ_{12} correlation changes.

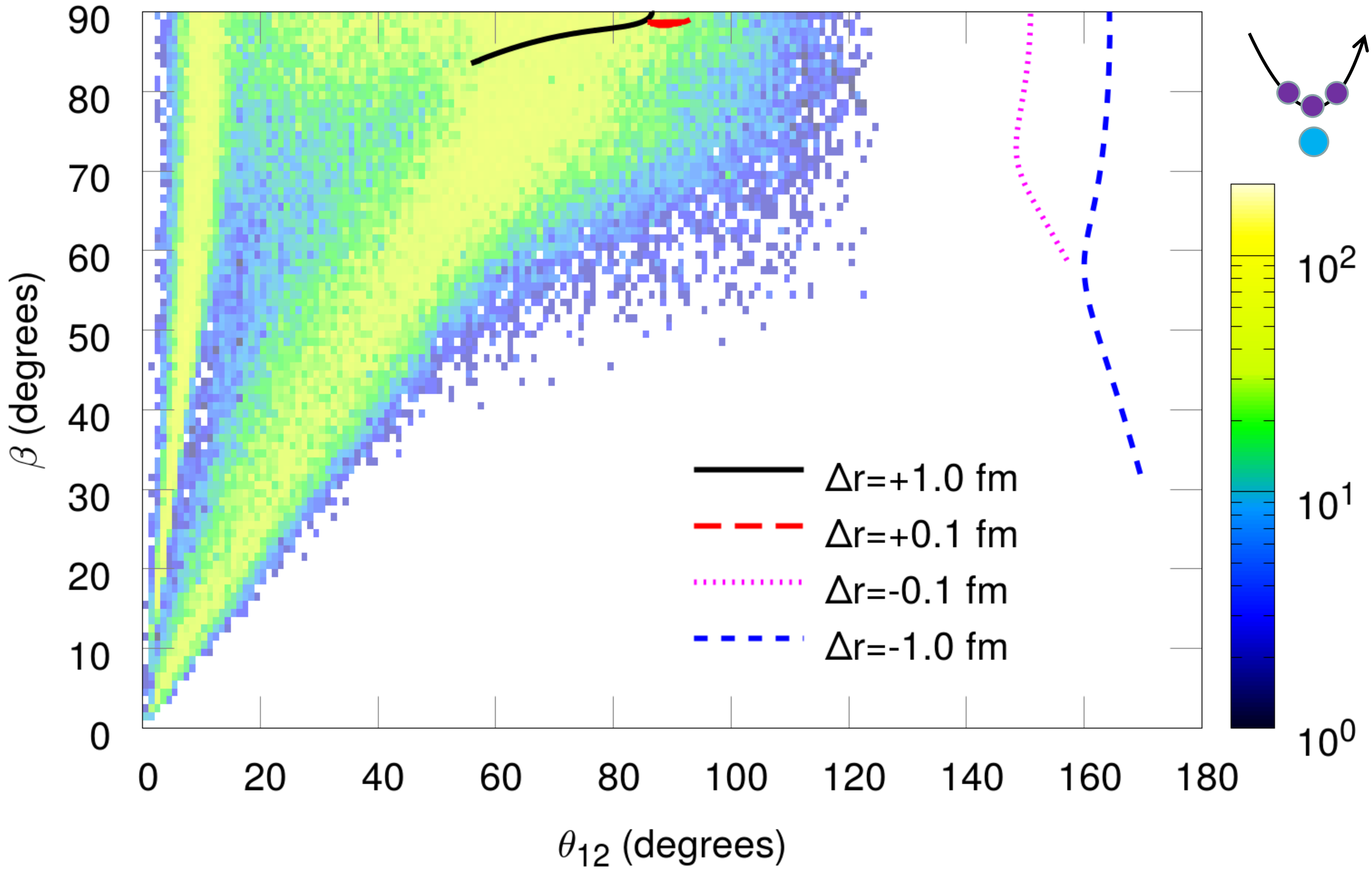


For each point $R_{BU}=R_0+\Delta r$ vary orientation initial relative momentum of the α-particles

$L_{PT} = 0$ (central collision)

A. Diaz-Torres *et al.*, PRL 98, 152701 (2007)
A. Diaz-Torres, CPC 182, 1100 (2011)

Near target breakup



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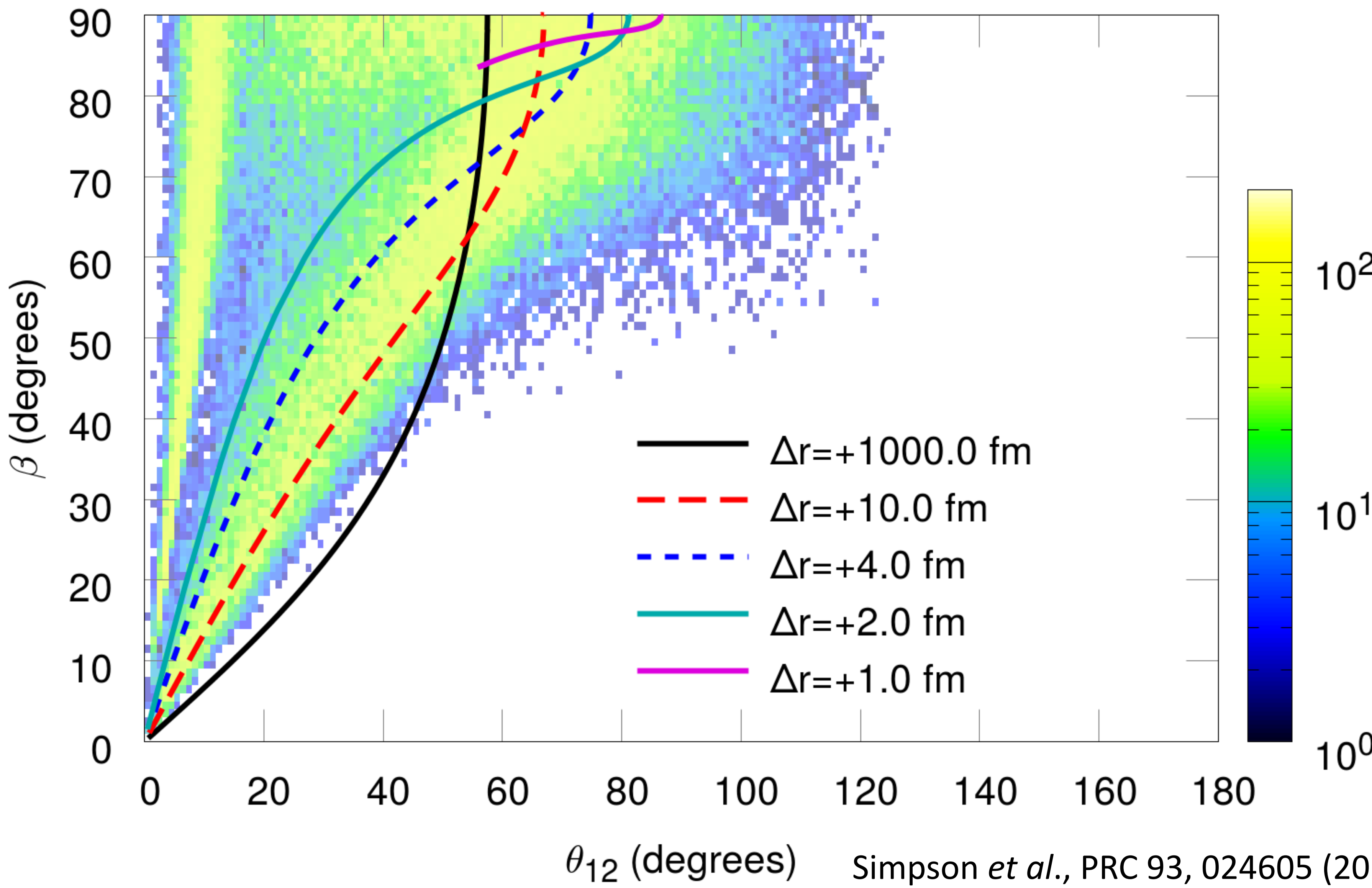
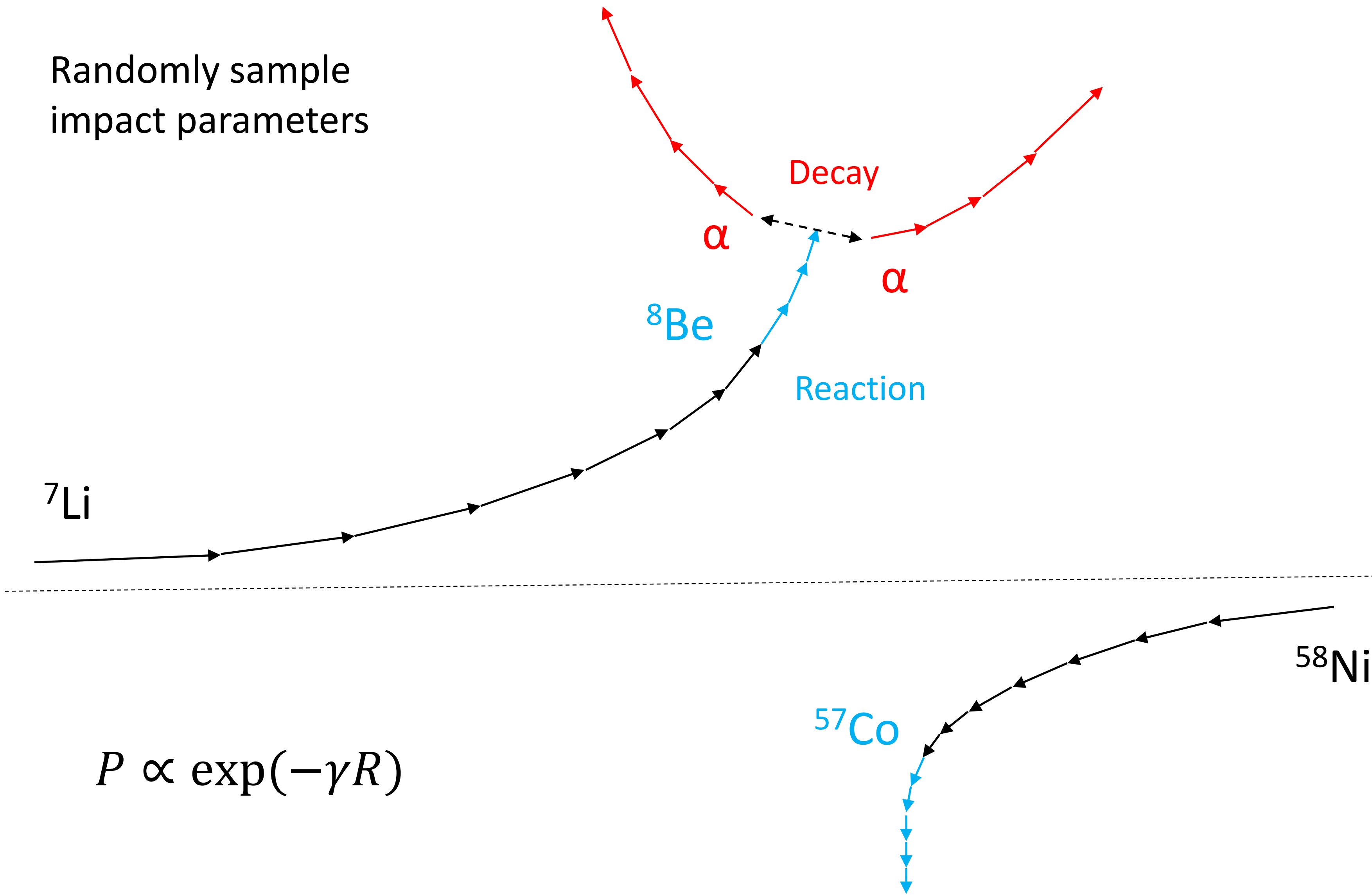
Breakup distances



Simpson *et al.*, PRC 93, 024605 (2016)

Full Monte Carlo simulations

Randomly sample impact parameters



$$P \propto \exp(-\gamma R)$$

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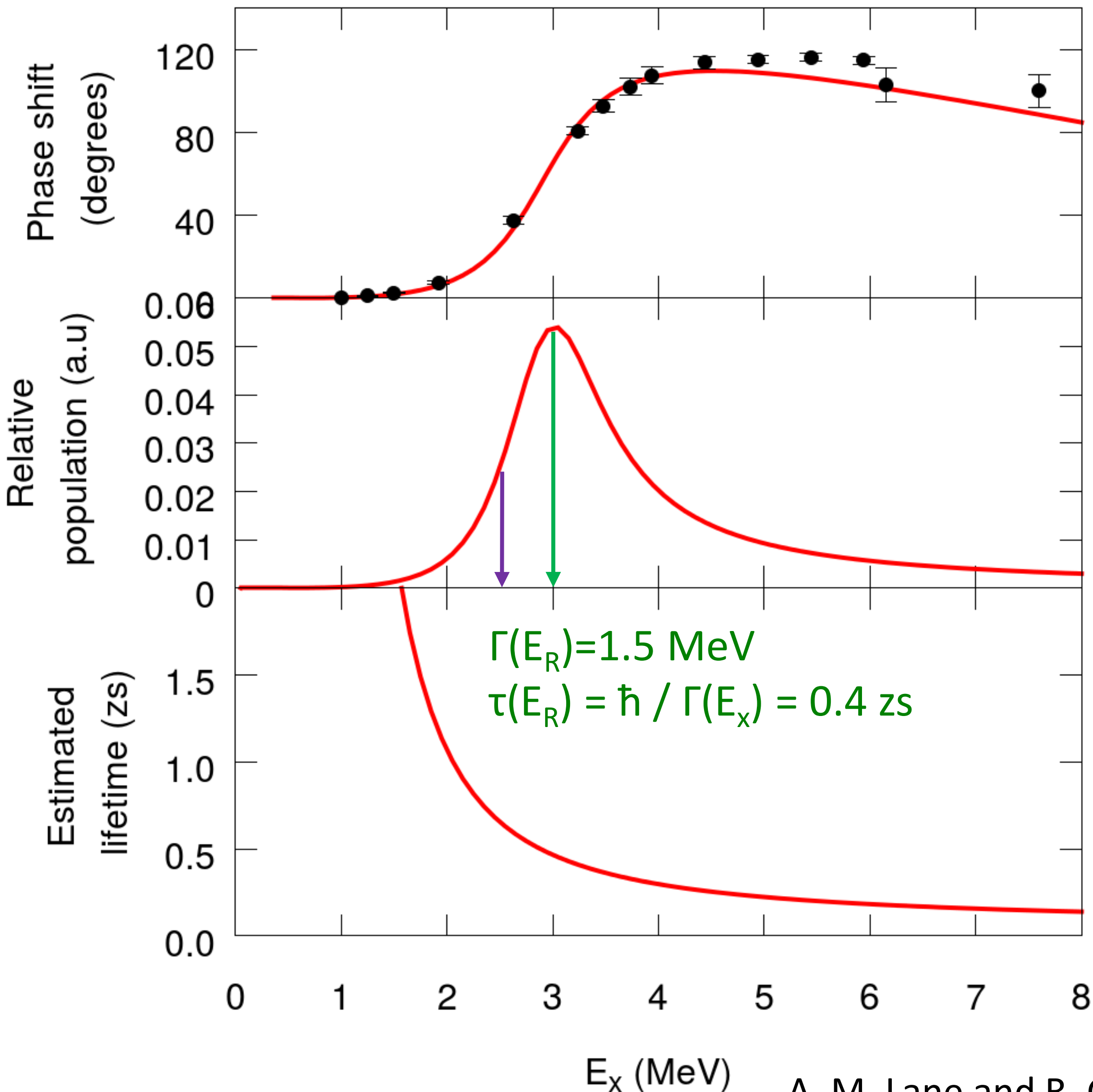
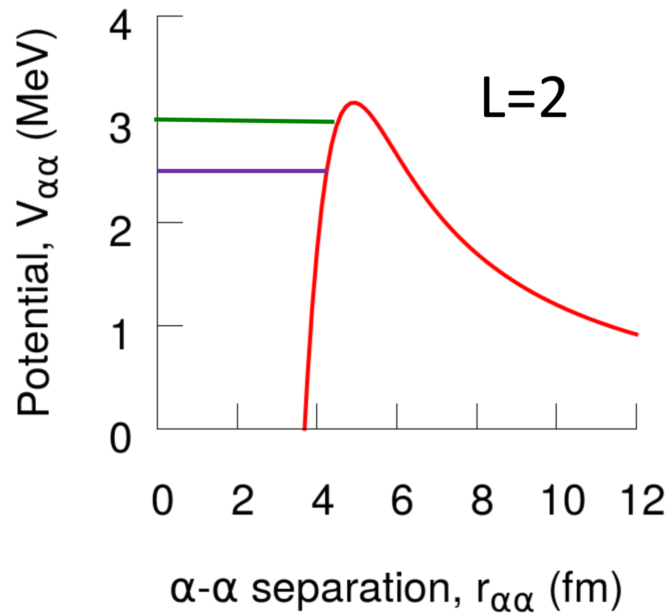
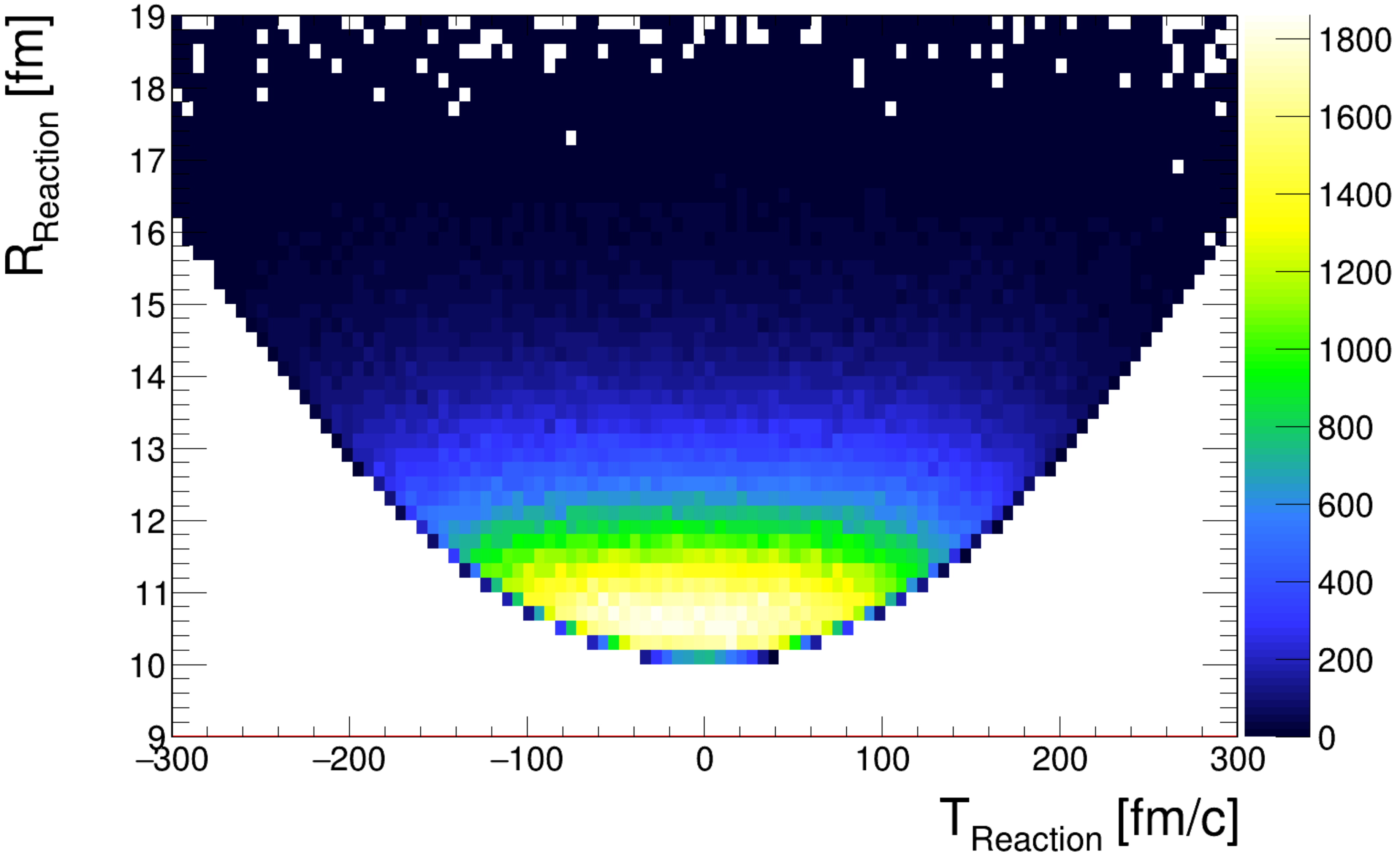
$^{8}Be\ 2^{+}$ resonance



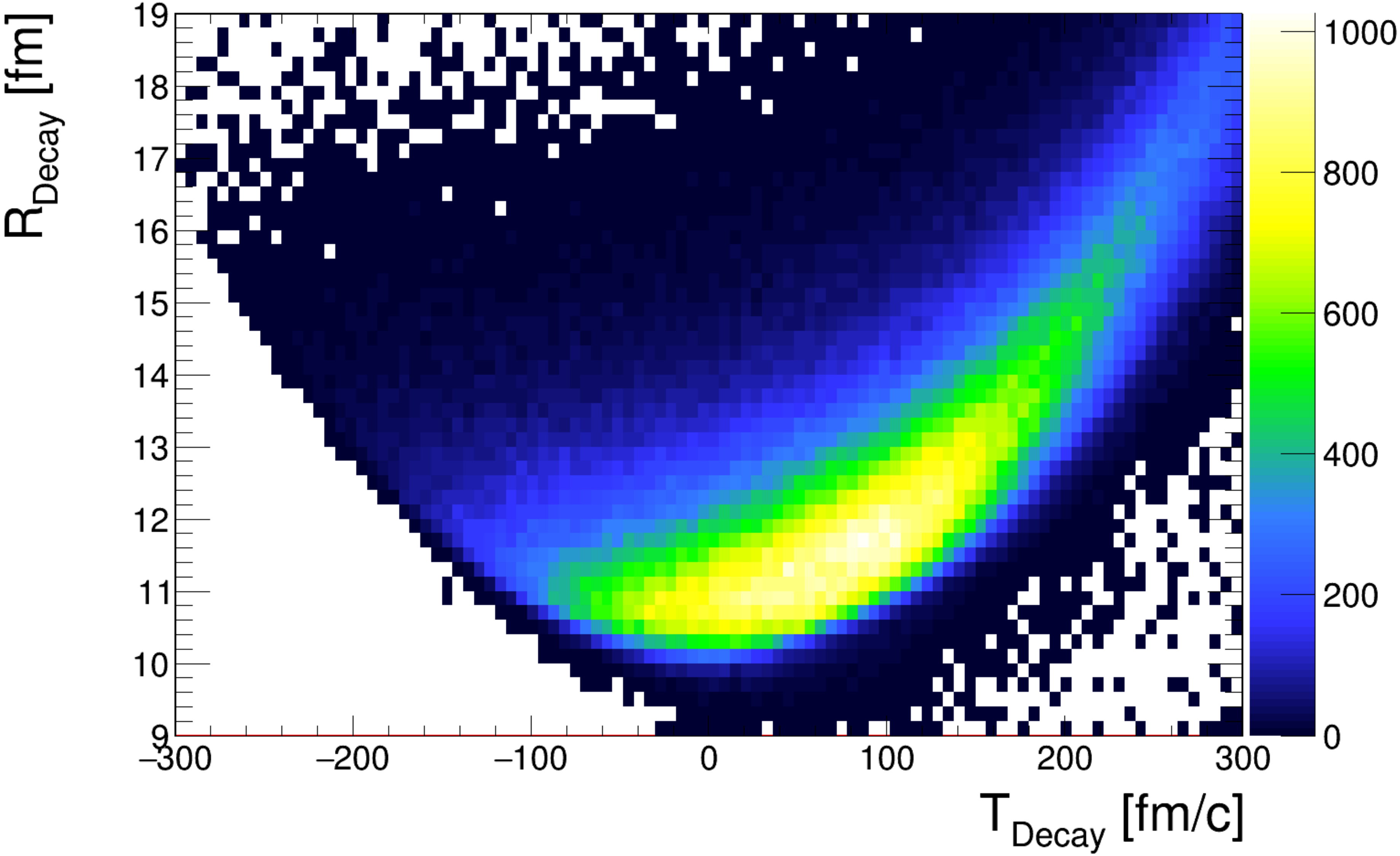


F. C. Barker, Aust. J. Phys 41, 743 (1988)
A. M. Lane and R. G. Thomas, Rev. Mod. Phys. 30, 257 (1958)

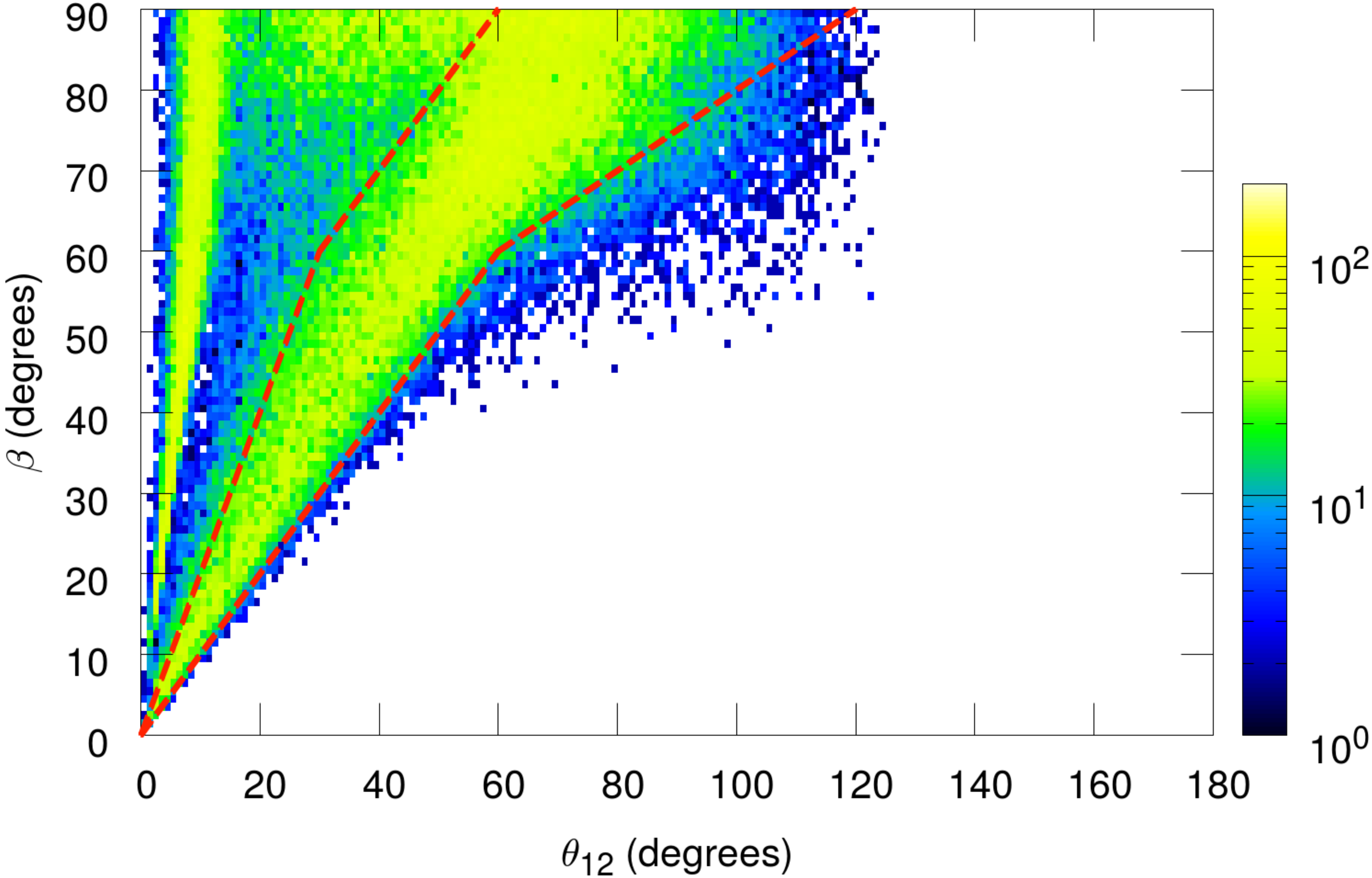
Reaction point



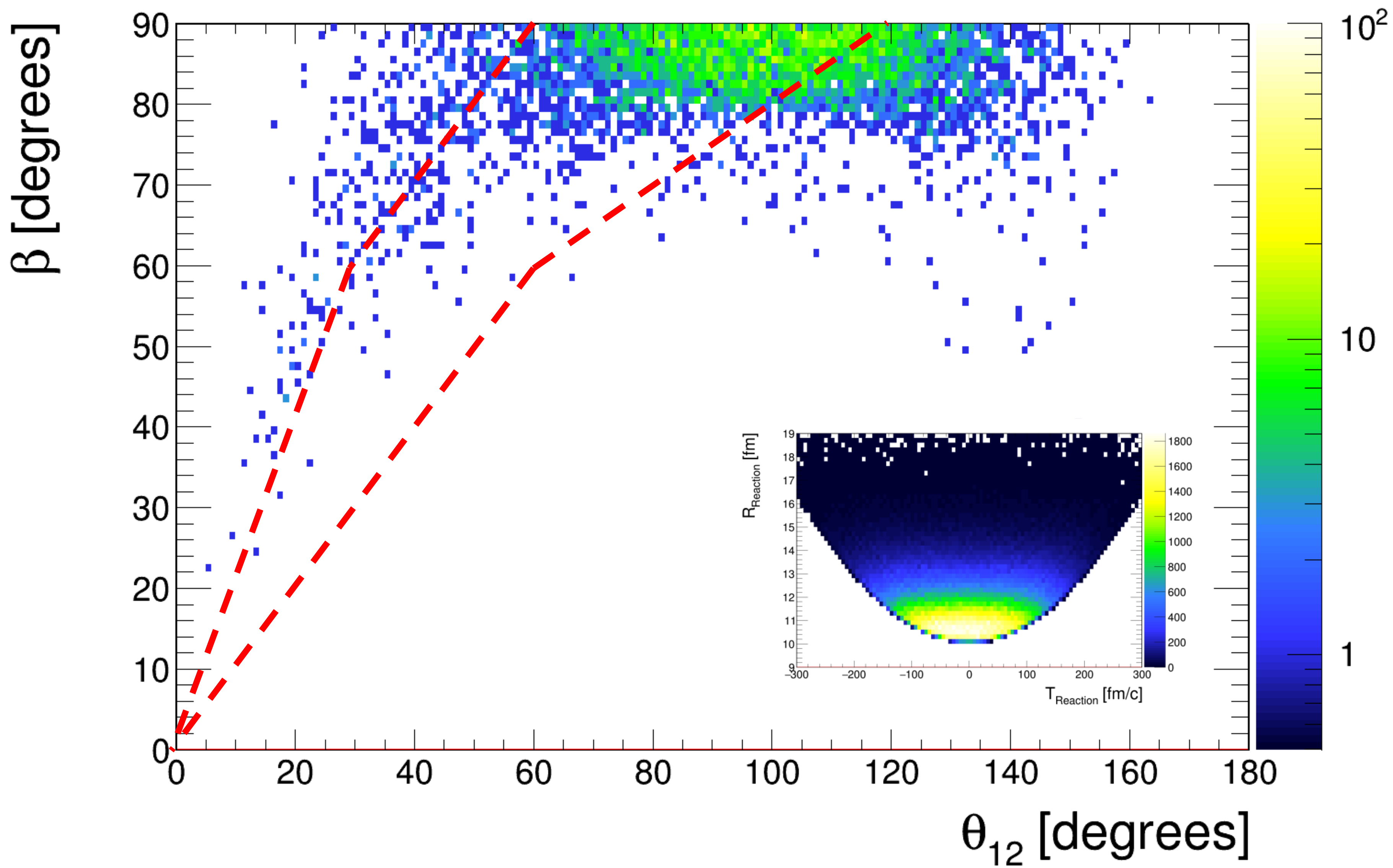
^{8}Be decay point



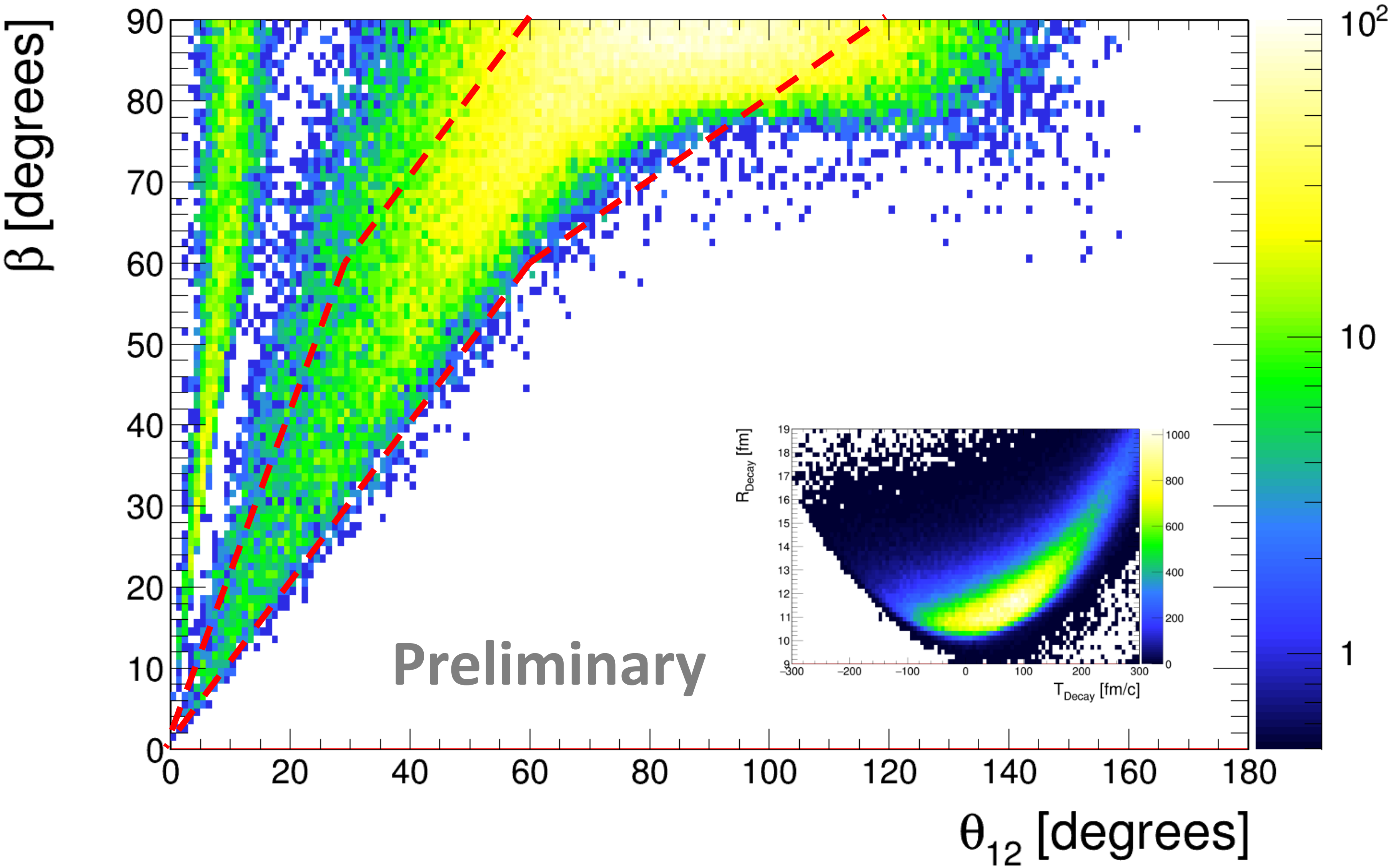
Experimental data



Simulation assuming instant decay



Simulation incorporating lifetime



Summary and further work

Summary

- Sub-barrier breakup tells us that lifetimes of short-lived states play a role in determining where breakup occurs
- This has consequences for fusion – can the break up happen fast enough to cause fusion suppression, contribute to ICF?
- Not all break up modes are the same

Fusion and incomplete fusion

- With an immutable ^{8}Be, the delayed breakup will clearly affect incomplete fusion - how important are tidal forces?
- Can we systematically understand sub-barrier breakup for other light projectiles such as ^{6}Li and ^{9}Be?
- Predictions for complete and incomplete fusion at above barrier energies

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