Near Barrier Reactions – many-body quantum dynamics in action

Part IV –Time scales in break-up and in quasi-fission

Mahananda Dasgupta

Department of Nuclear Physics

Australian National University, Canberra

Australian National University

- Studies using weakly bound stable beams

^{6}Li, ^{7}Li, ^{9}Be - weakly bound (breakup threshold 1.5, 2.5, 1.6 MeV)

- charged clusters (α-d, α-t, α-α-n) → detection easier

- accurate measurements possible (beam intensity)

- average fusion barrier can be determined experimentally

- no halo

⇒ First definitive demonstration of suppression of complete fusion at above barrier energies

Dasgupta et al., PRL 82 (1999) 1395

Many groups working in this area – Posters: Palshetkar, Pradhan, Rath, Thakur

Reference calculations – what causes the largest uncertainties?

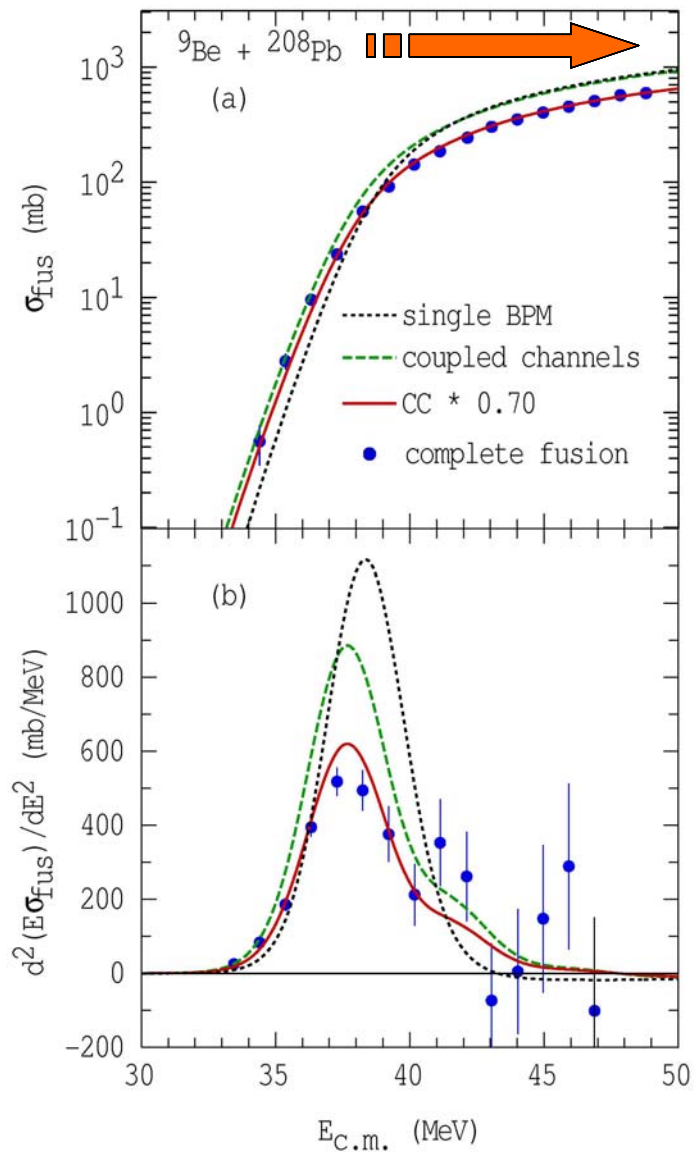
- Nuclear Potential → Barrier energy

  Solution: Get centroid of barrier distribution

- Couplings

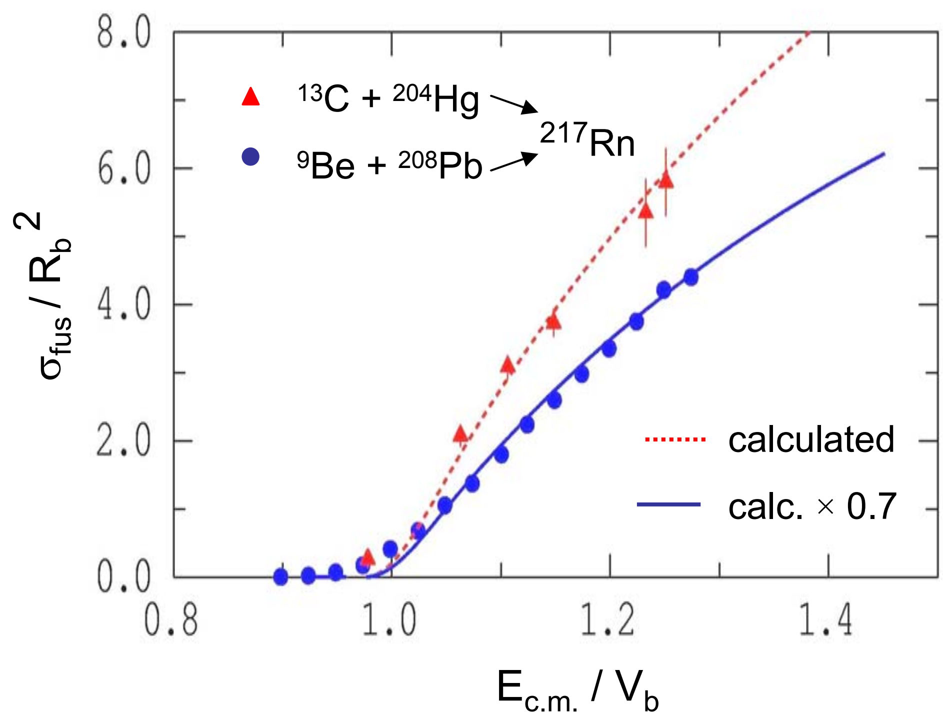
  Solution: make above barrier comparison

Suppression of complete fusion at $E>V_b$



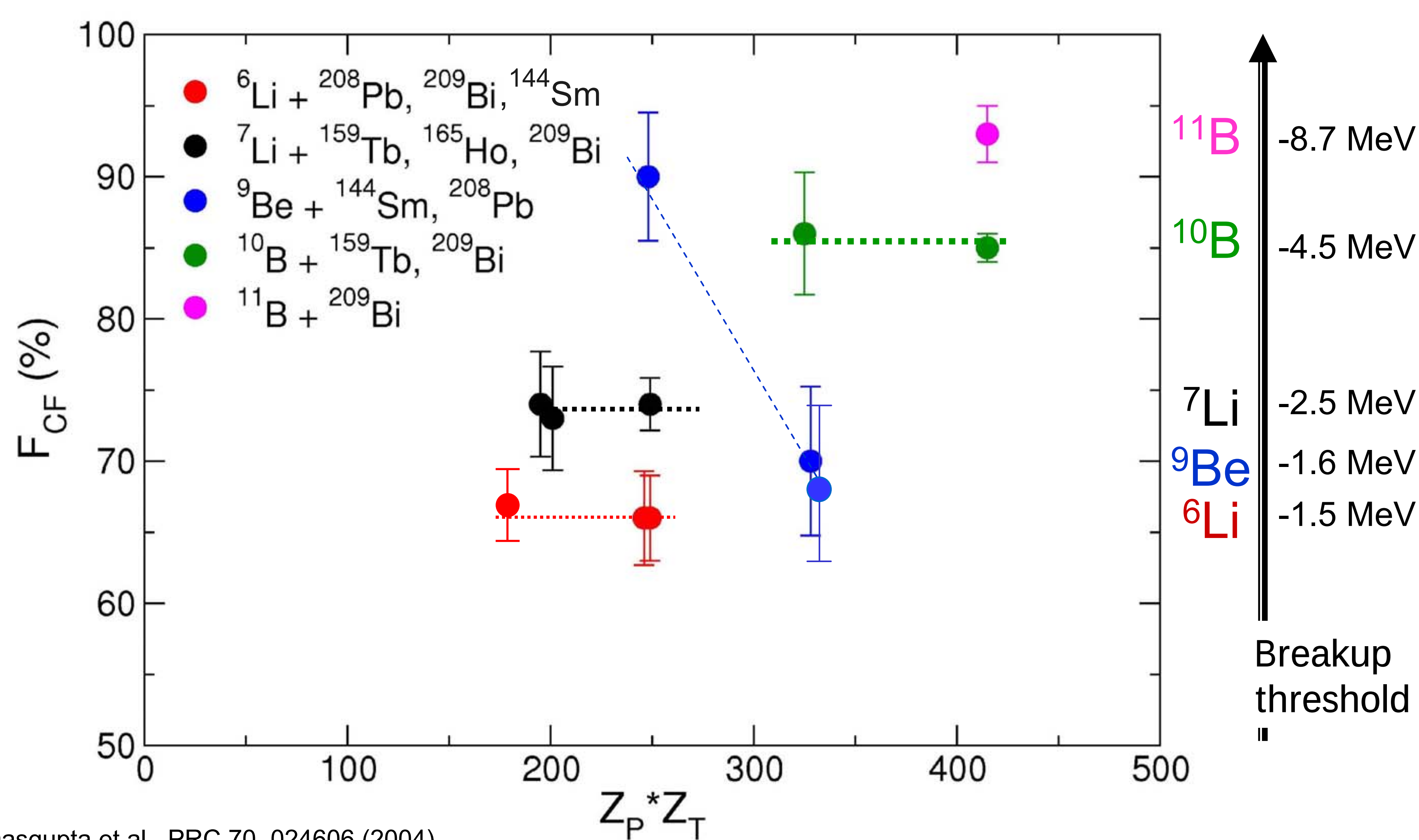
Dasgupta et al., PRL 82 (1999) 1395

- $^{9}Be + ^{208}Pb$ measurements
- Expt. Determination of average barrier
- Comparison with reaction with well-bound nuclei forming the same CN



$^{6,7}Li$, ^{9}Be: Dasgupta et al., PRC 70 (2004) 024606

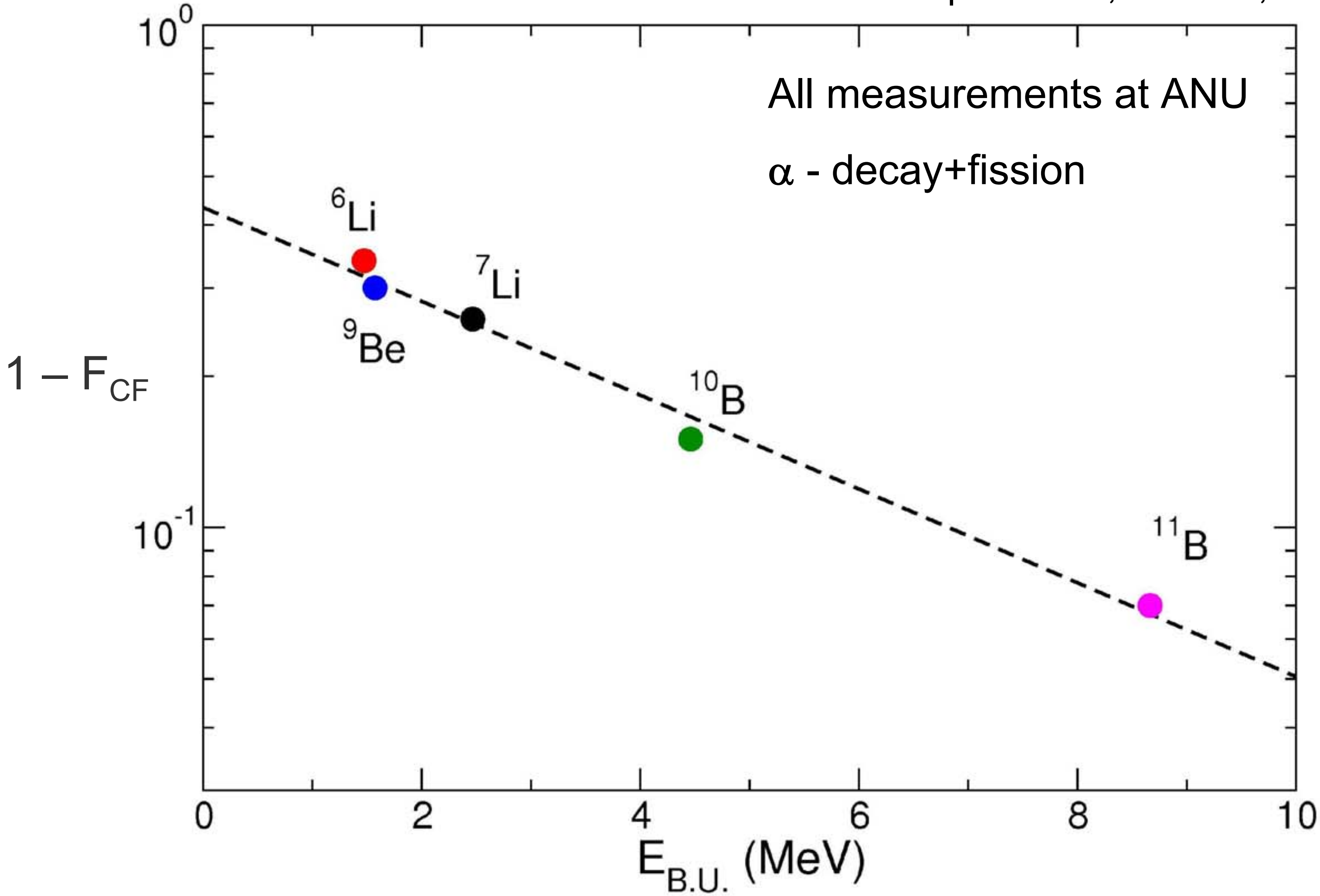
Weakly bound stable nuclei- complete fusion systematics



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

Dasgupta et al., PRC 70, 024606 (2004)
Wu et al., PRC68, 044605 (2003)
Mukherjee et al., PLB636, 91 (2006)
Tripathi et al., PRL88,172701 (2002)
Gomes et al.,PRC73,064606 (2006)
Rath et al., PRC 79, 051601 (2009)
Dasgupta et al., PRC81, 024608 (2010)

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



Is it this simple?

Expectations: $^{6}Li \rightarrow \alpha + d$ (Q= -1.475 MeV)

$^{7}Li \rightarrow \alpha + t$ (Q= -2.467 MeV)

Observations:

- ^{6}Li, ^{7}Li incident on ^{58}Ni, ^{118}Sn - low numbers of d and t compared to α

  Pfeiffer et al., NP A206, 545 (1973)

- ^{7}Li + ^{65}Cu: yield of α-d > α - t Shrivastava et al., PLB633, 463 (2006)

- ^{7}Li + ^{144}Sm – breakup following n-transfer forming ^{6}Li

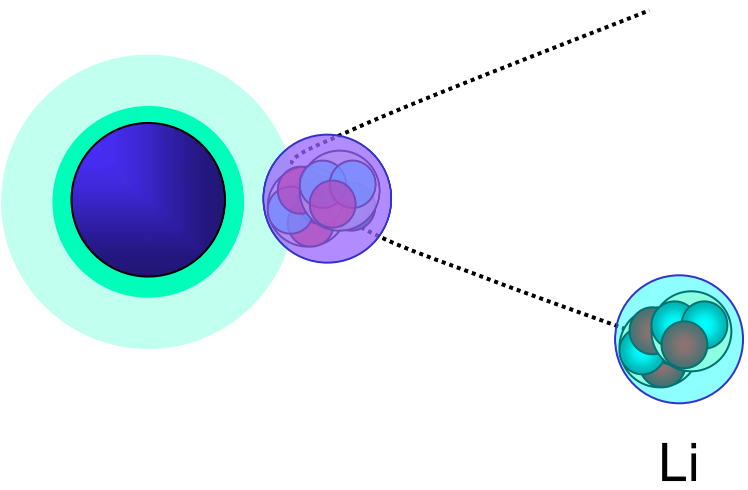
  D. Heimann Martinez et al., FUSION08, 275 (2008)

Is n-transfer the dominant trigger for breakup?

Relationship between observed breakup and fusion?

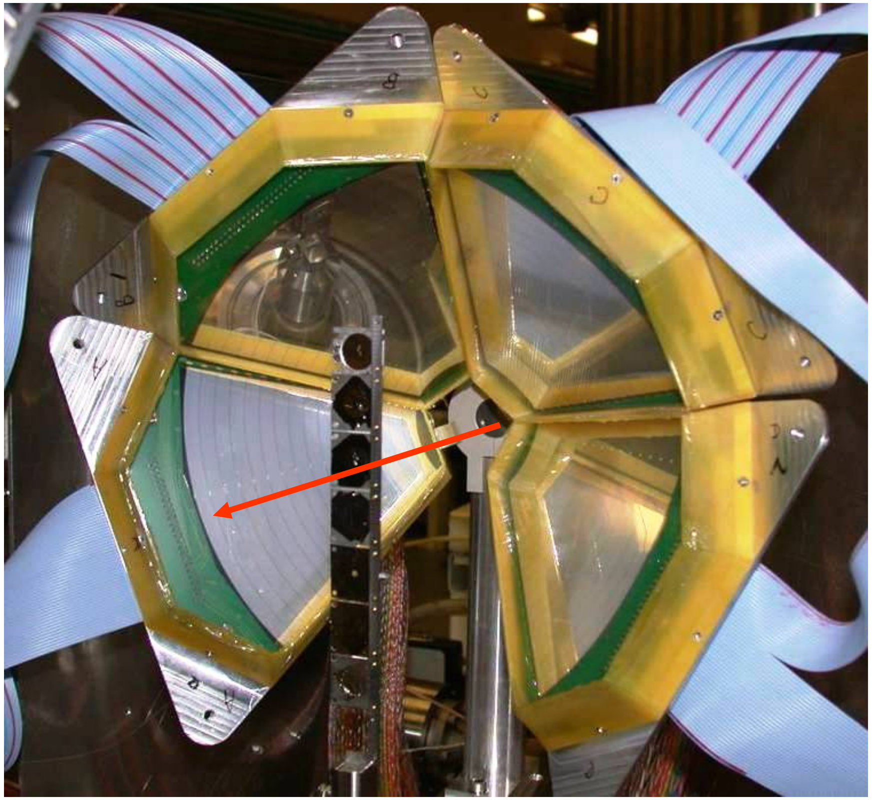
Breakup measurements at sub-barrier energies eliminates fragment absorption

→ least confusion



High efficiency array

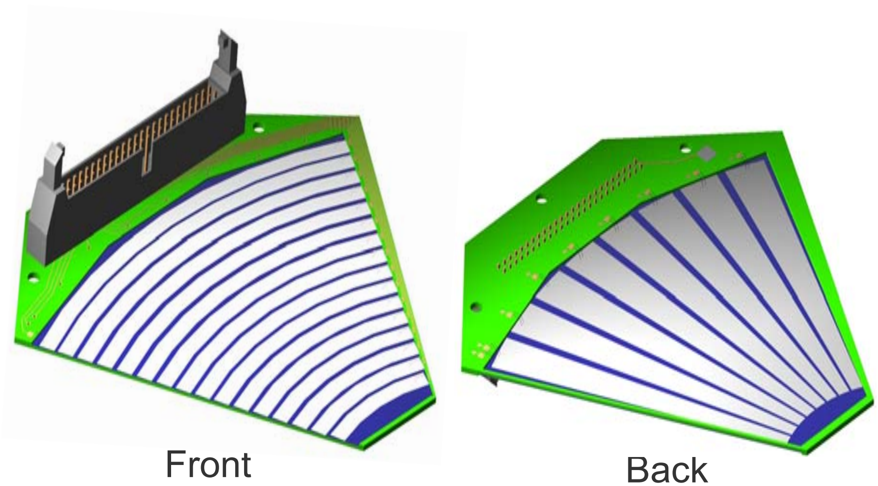
- pixellated detectors

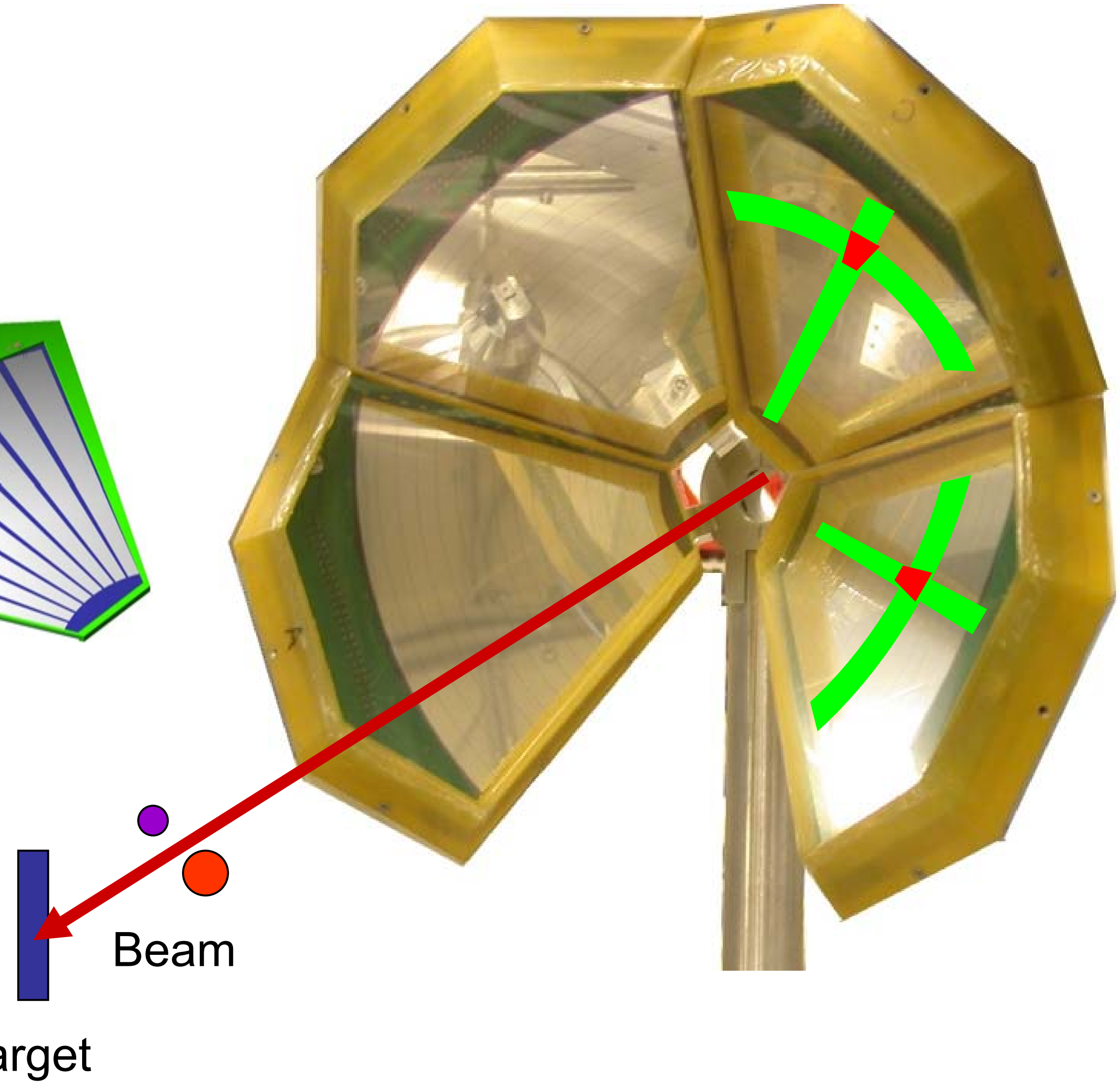


60º wedge detectors: Micron semiconductor Ltd.

Reality TV for physicists : spying on the participants isolated from outside world

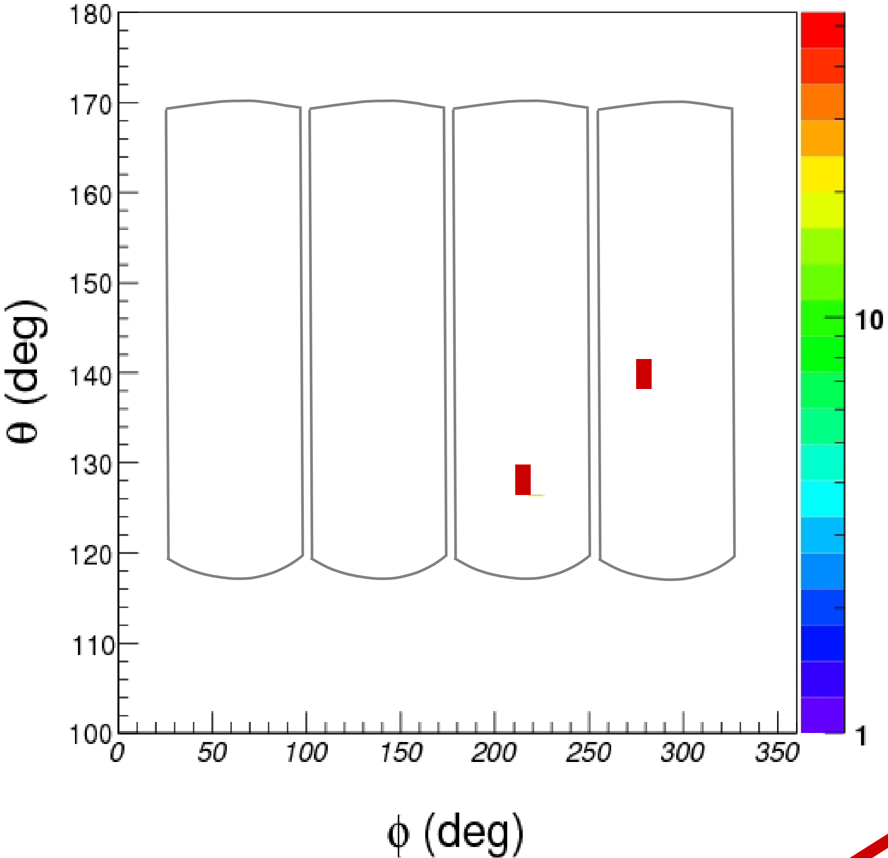
Measurements - Fragment energy, positions → Kinematic reconstruction



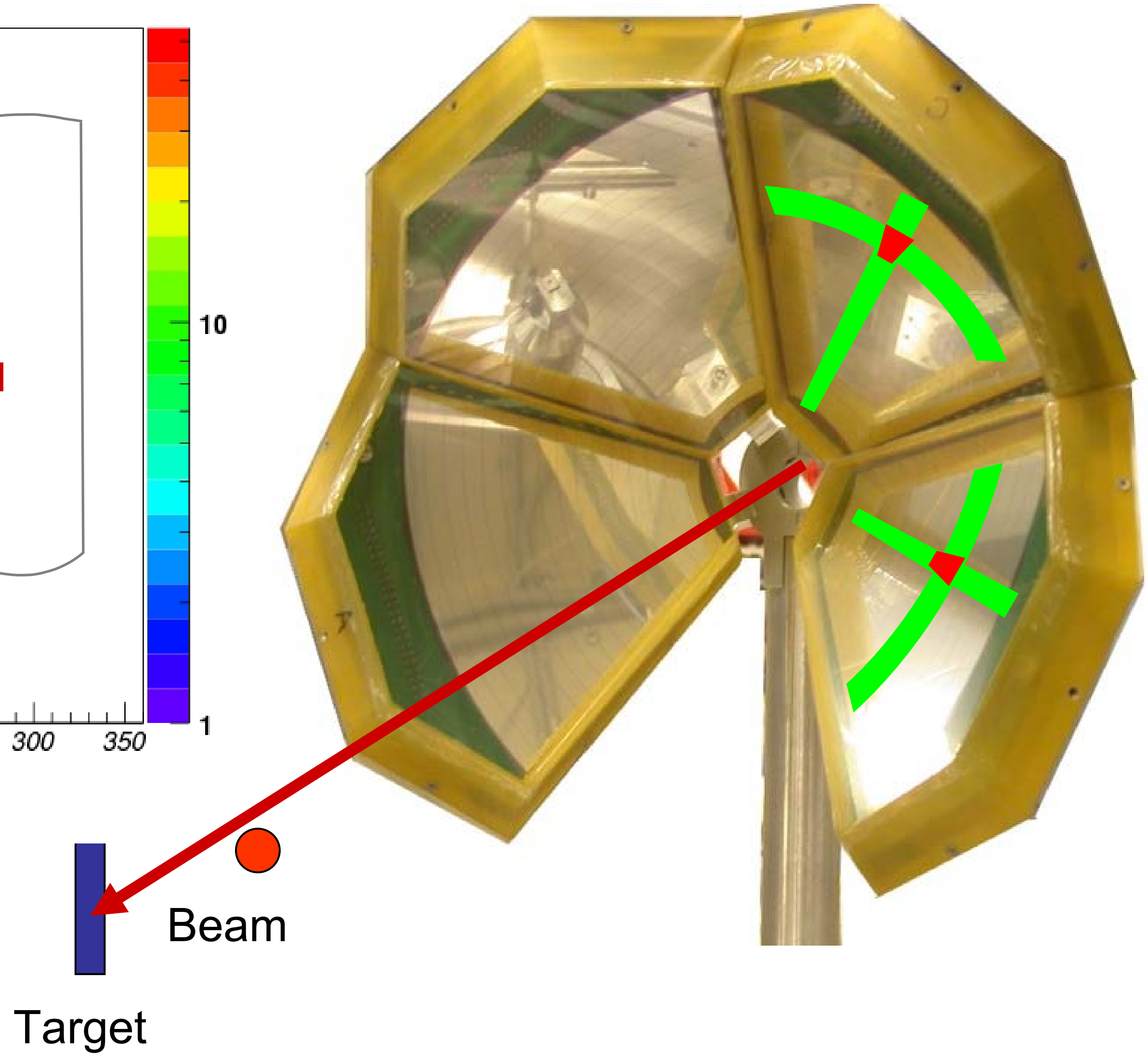


- 0.83π sr coverage

Measurements - Fragment energy, positions → Kinematic reconstruction



- 0.83π sr coverage



- Q-value determination → information about states in target-like nucleus
  → no information on excited state of proj-like nucleus

⇓

- Relative energy of the fragments can provide this information

Relative energies of the breakup fragment → $Q + E^*_{proj\_like}$

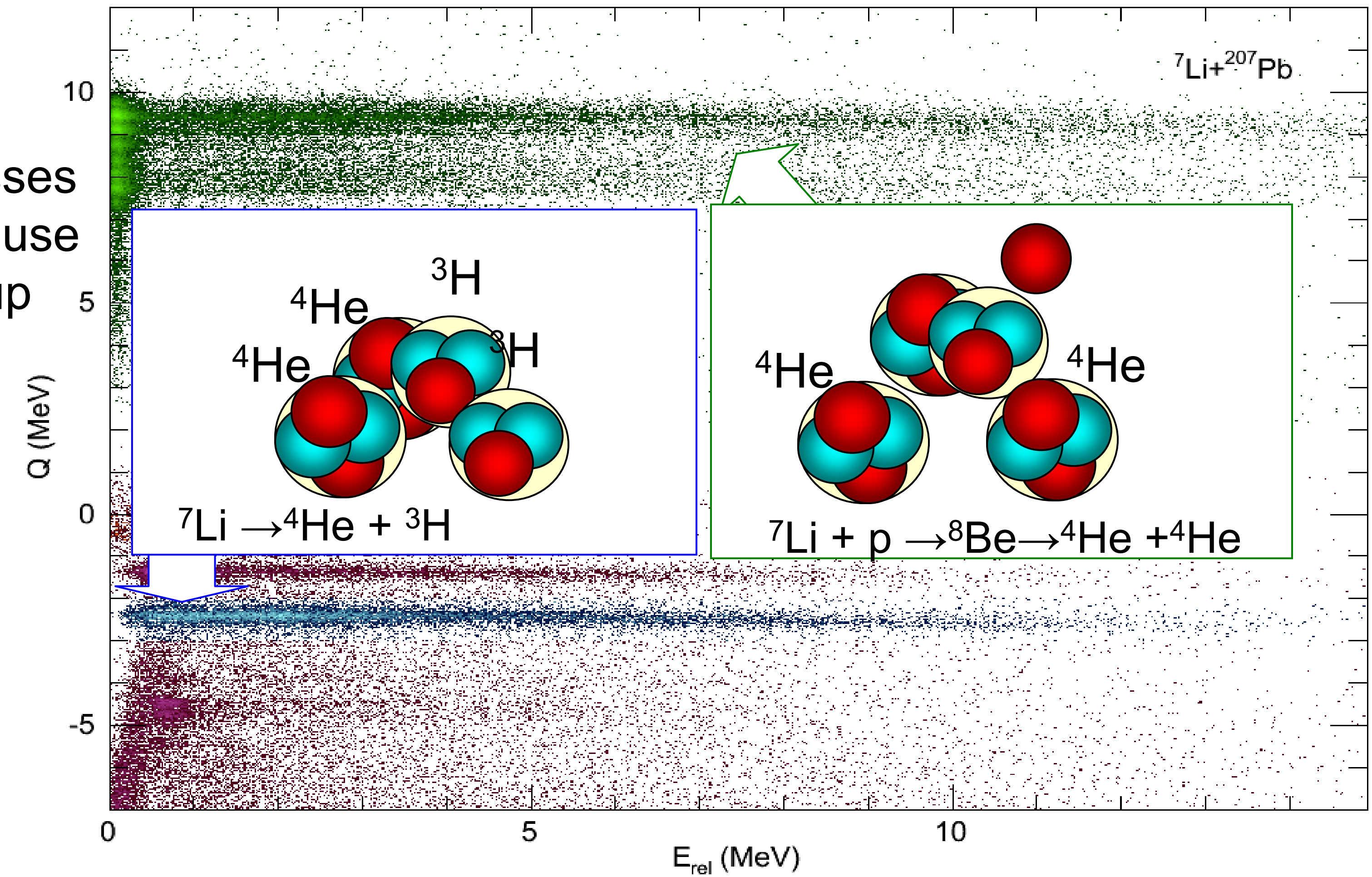
- Q and E_{rel} from energy and momentum conservation

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

^{7}Li + ^{207}Pb

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

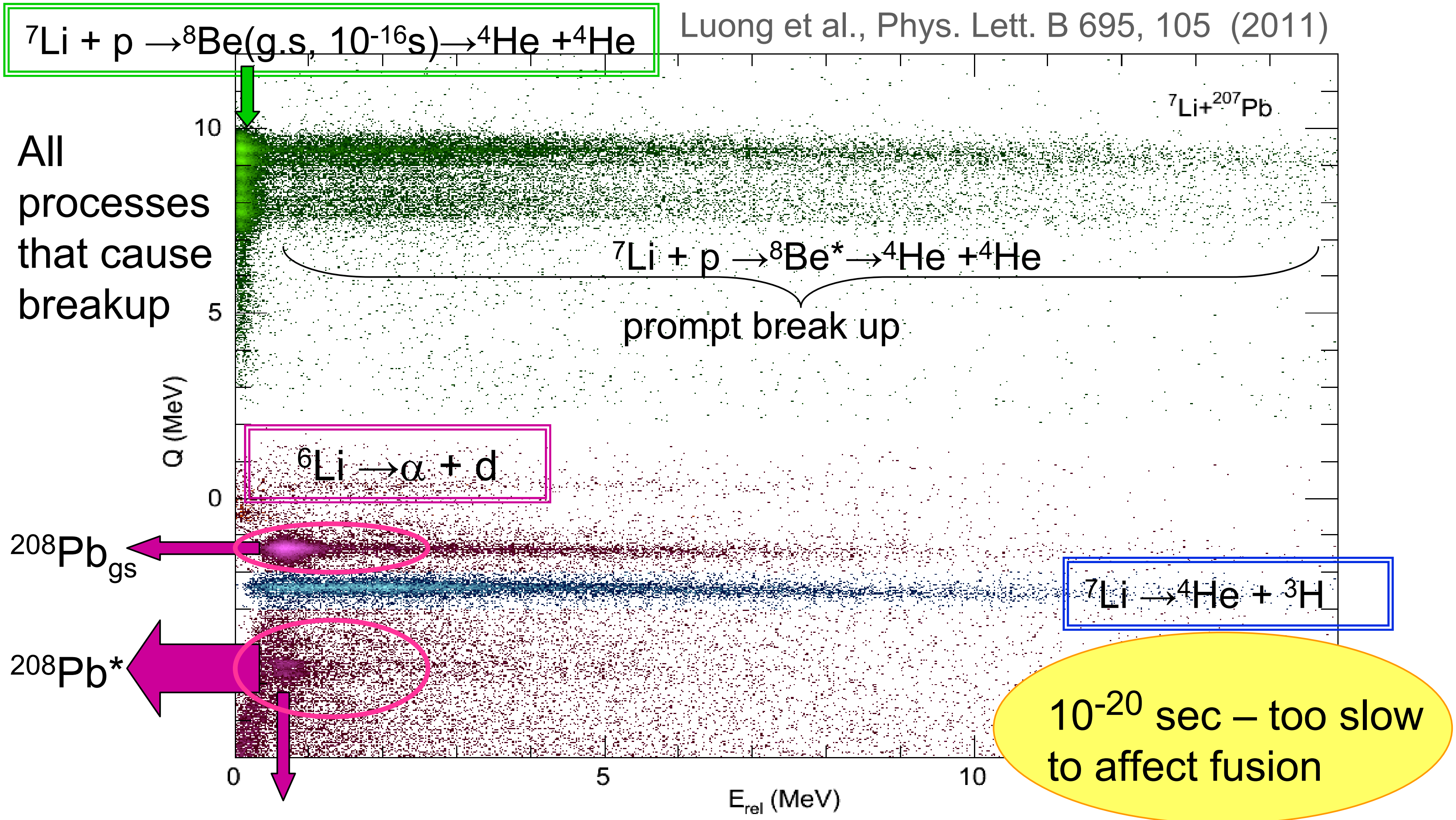
All processes that cause breakup



Time-scale

$^{7}Li + ^{207}Pb$

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

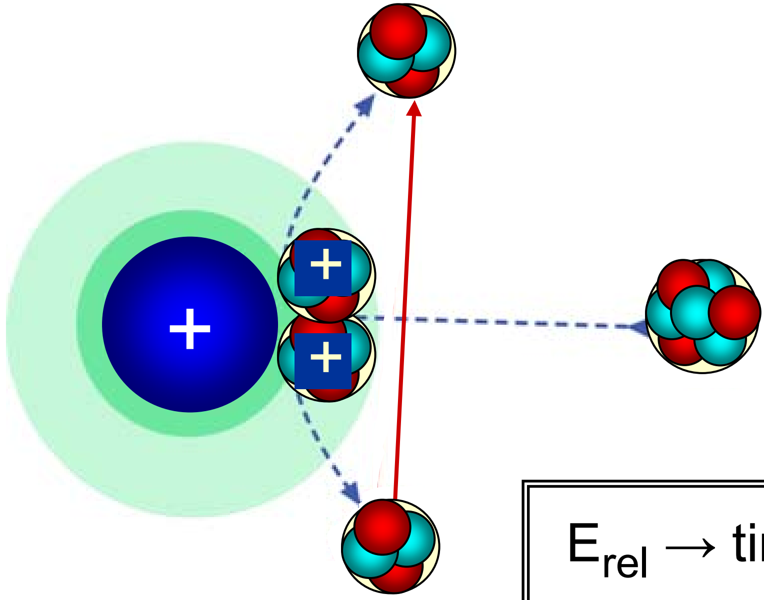


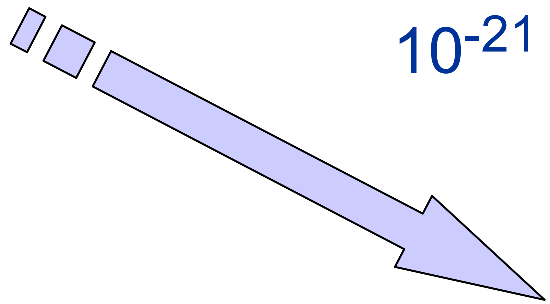
E_{rel} = E*(2.18 MeV) + Q (-1.5 MeV)

✓ α-d pairs - as observed by others – Q, E_{rel} consistent with n-transfer followed by breakup from ^{6}Li excited (2.18 MeV)

❖ ^{6}Li $\tau = 3 \times 10^{-20}$ s – too slow to breakup prior to fusion - cannot result in ICF

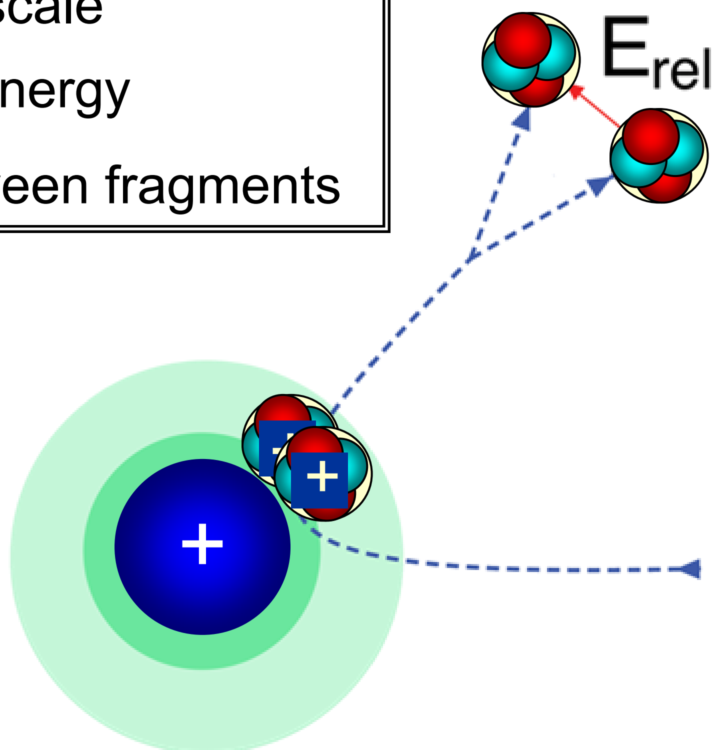
Time difference few 10^{-21} seconds!



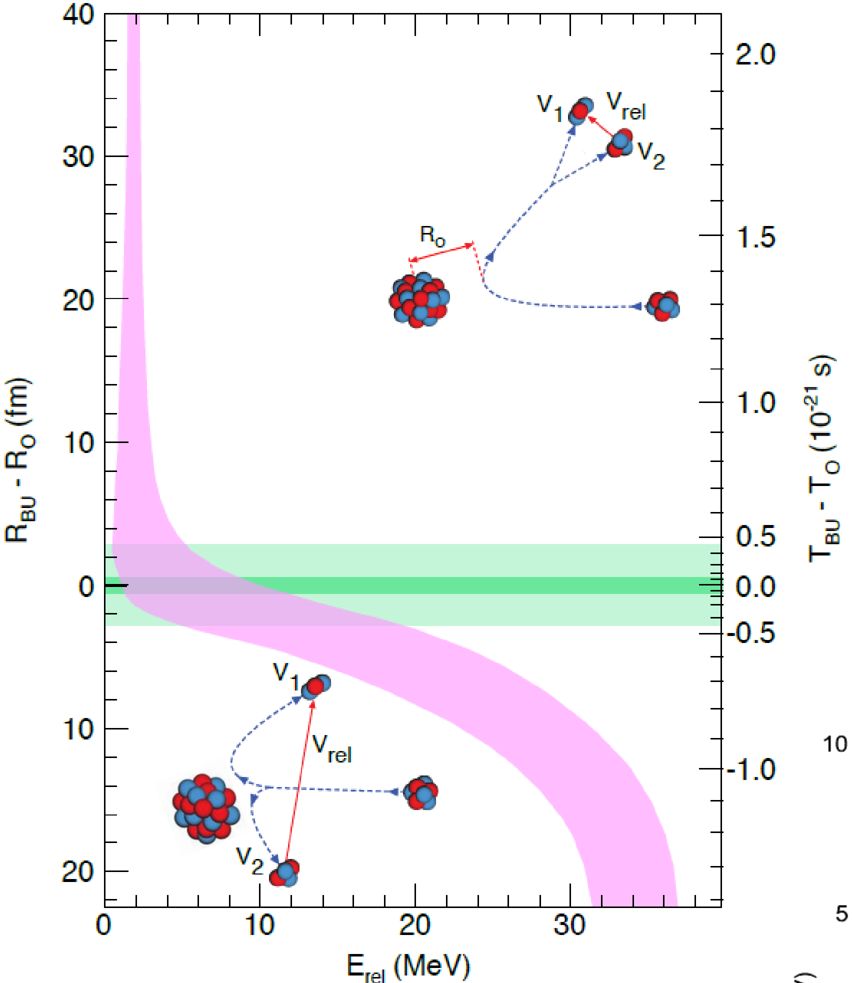


$E_{rel} \rightarrow$ time scale

- fragment energy
- angle between fragments

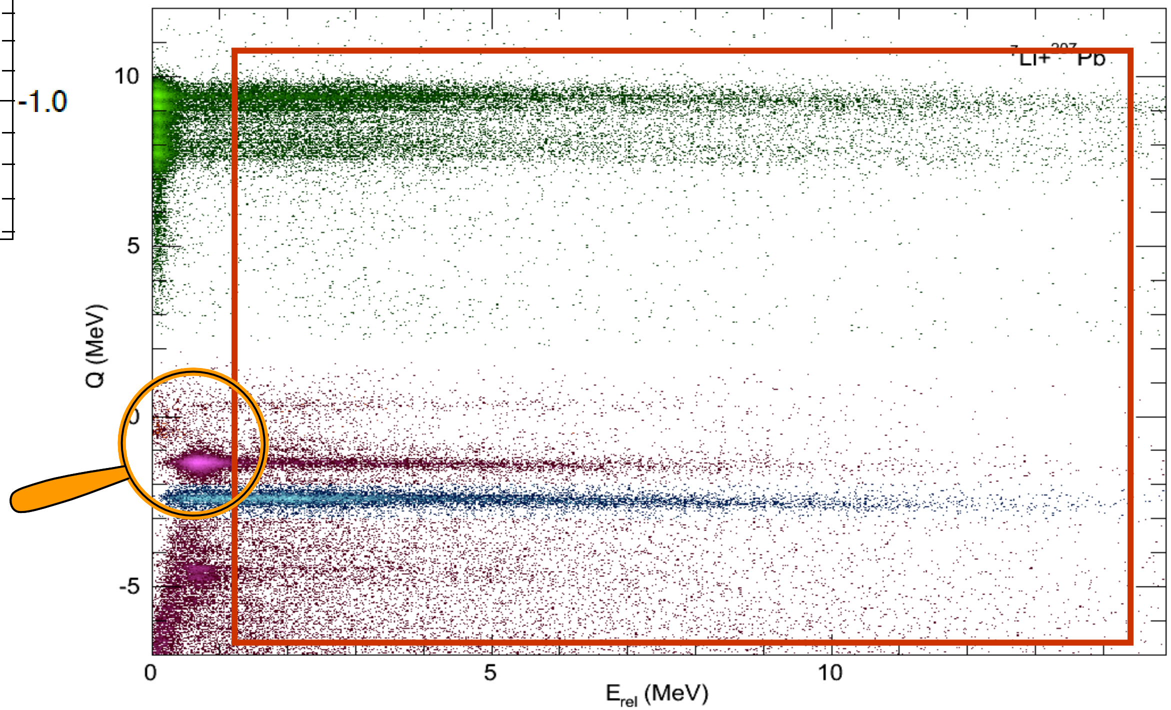


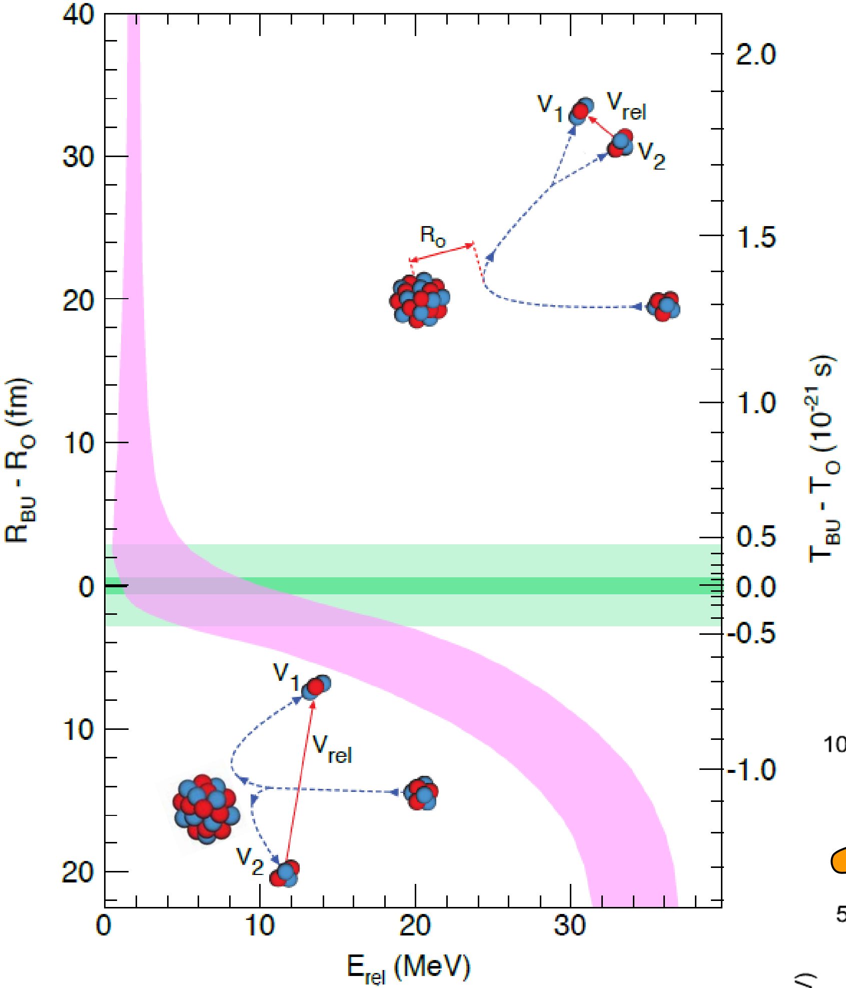
Diaz-Torres et al, Phys. Rev. Lett. 98, 152701 (2007)



Key insights to develop predictive models → new facilities & applications

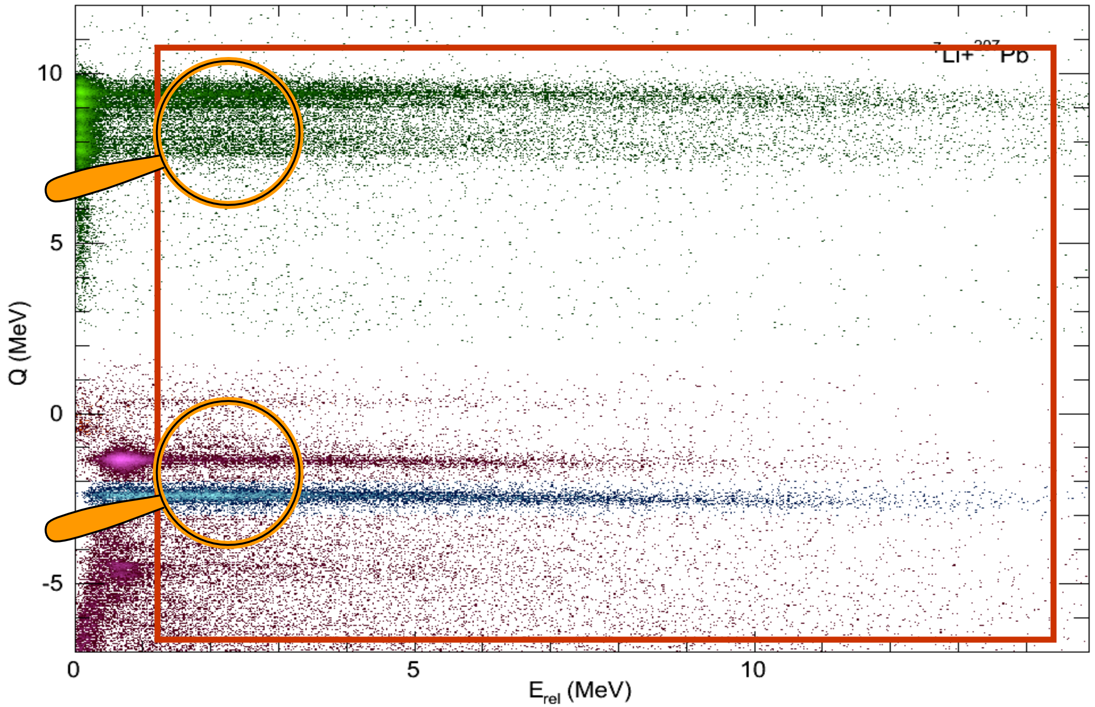
Luong et al., Phys. Lett. B 695, 105 (2011)



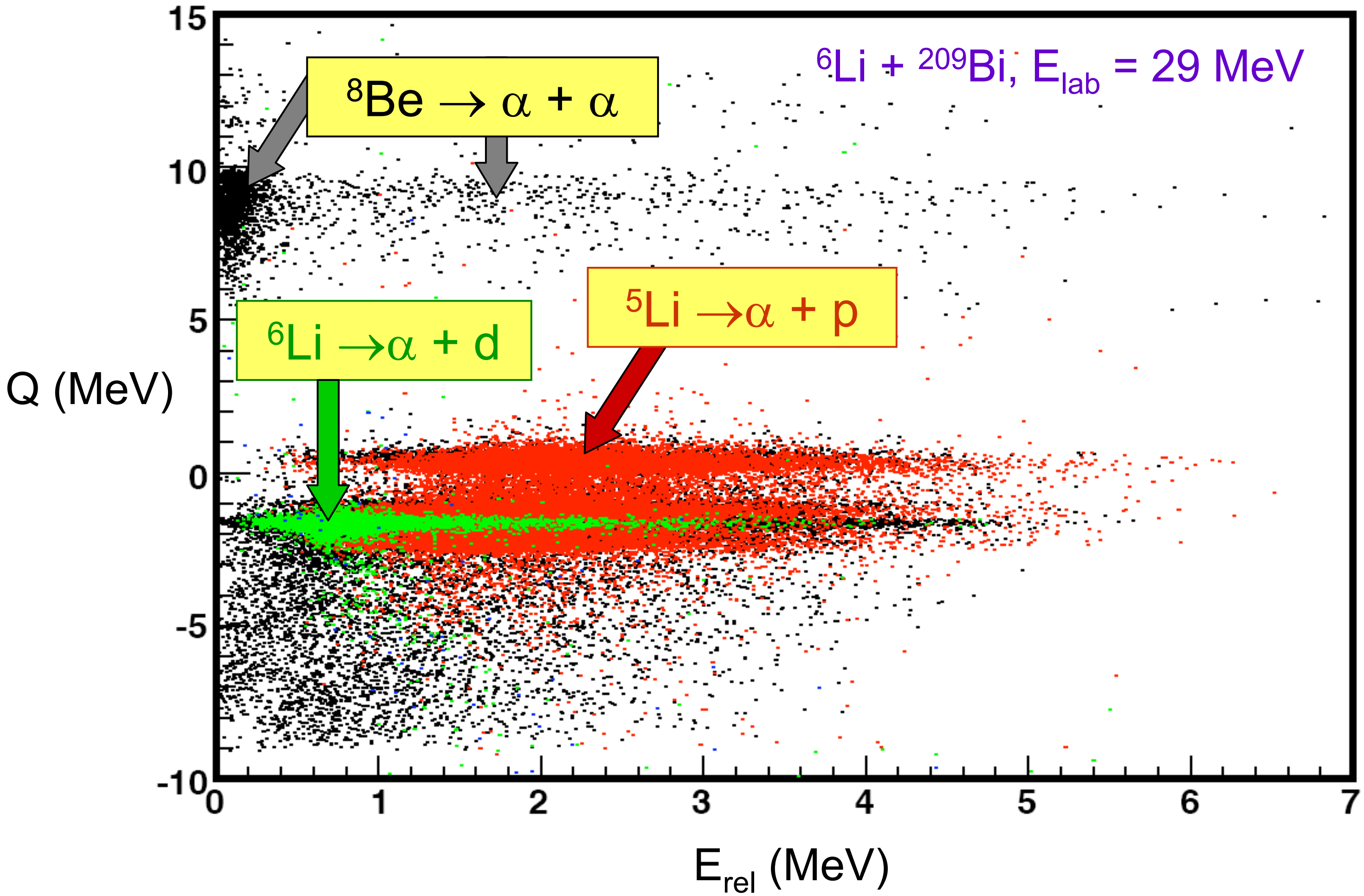


Key insights to develop predictive models → new facilities & applications

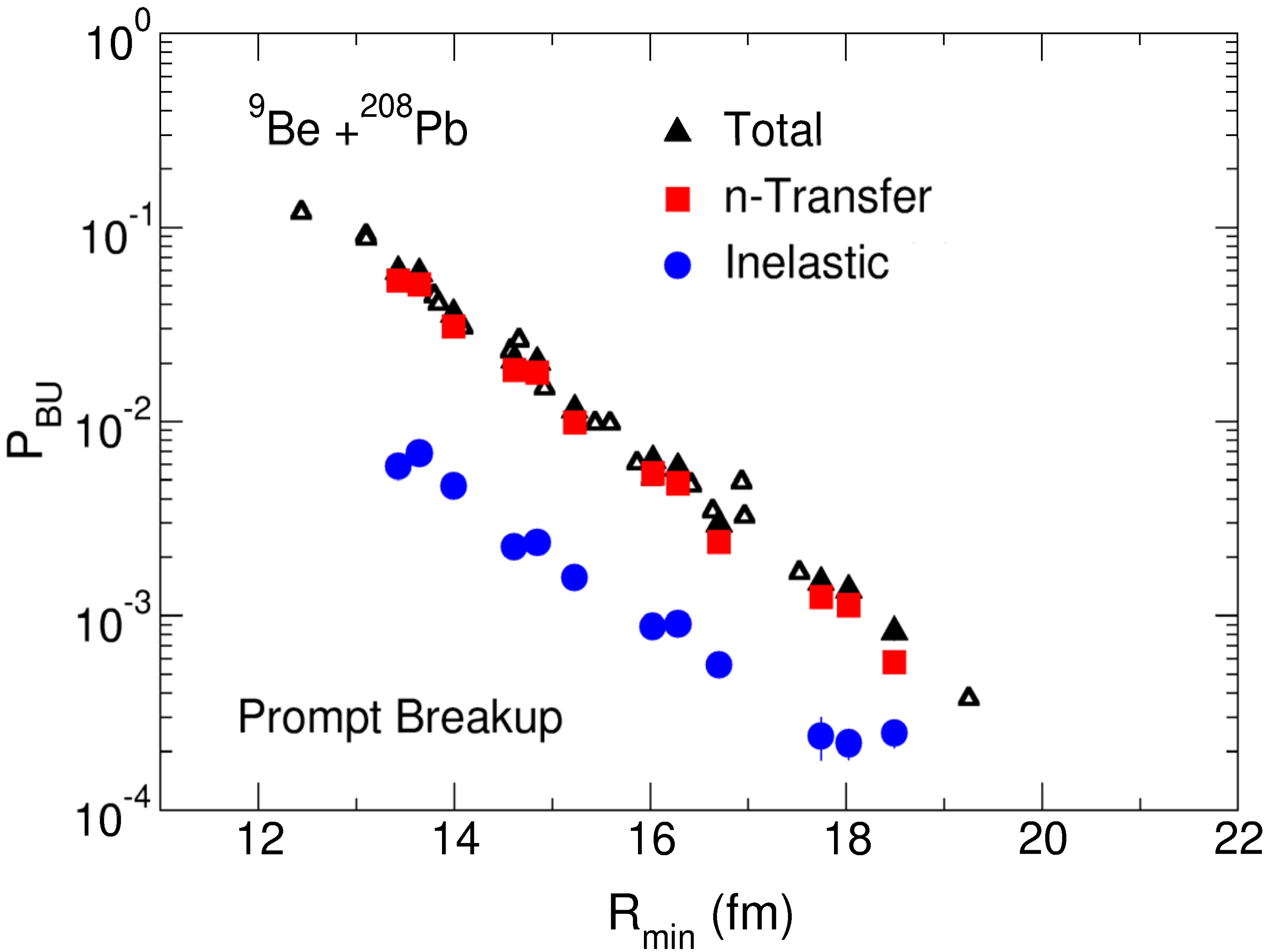
Luong et al., Phys. Lett. B 695, 105 (2011)



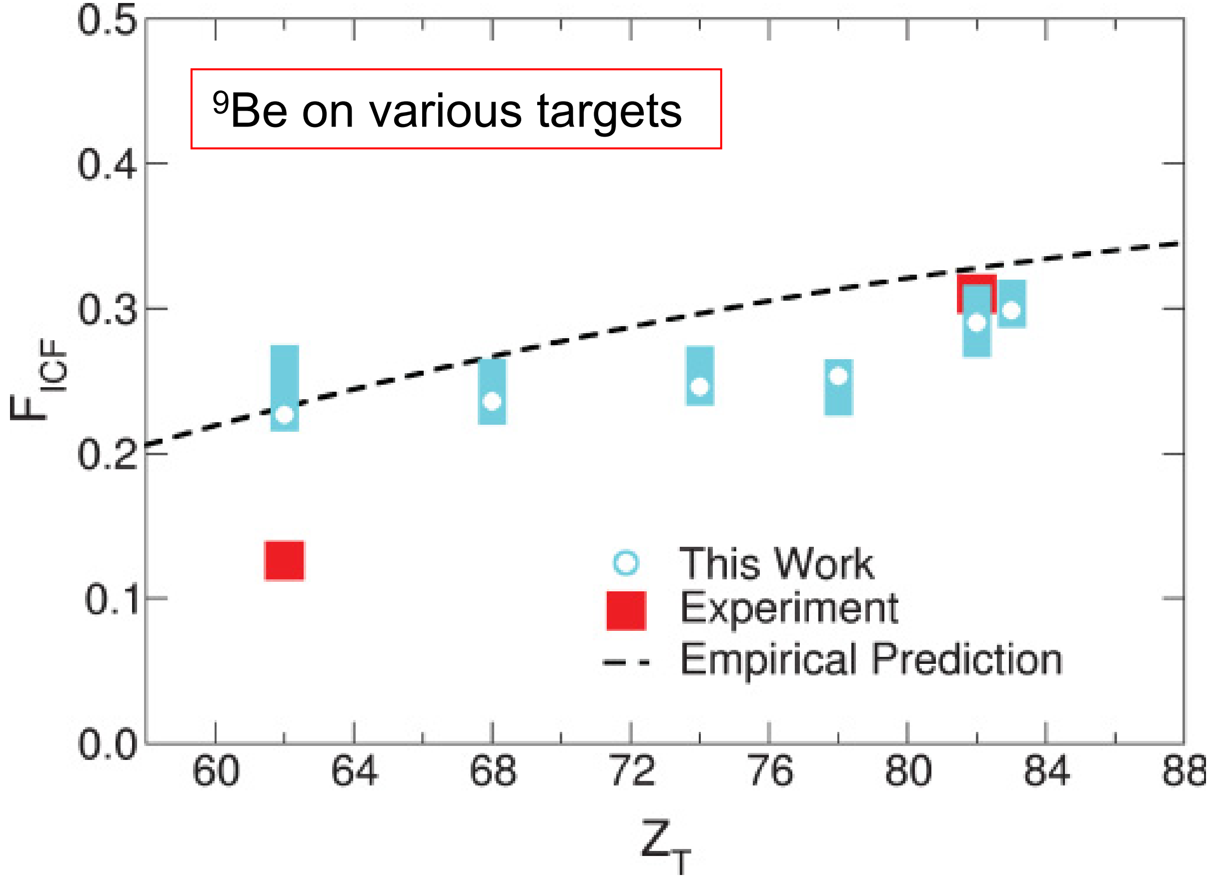
Luong et al., Phys. Lett. 695, 105 (2011)



- α -d – E_{rel} tight as well as wide distributions
- Predominantly α - p (from ^5Li formed following n transfer) - wide E_{rel}
- Large +Q events – d pickup forming ^8Be



Rafiei et al., PRC 81, 024601(2010) $^9Be + ^{209}Bi, ^{208}Pb, ^{196}Pt, ^{186}W, ^{168}Er, ^{144}Sm$



Model: Diaz-Torres et al, Phys. Rev. Lett. 98, 152701 (2007)

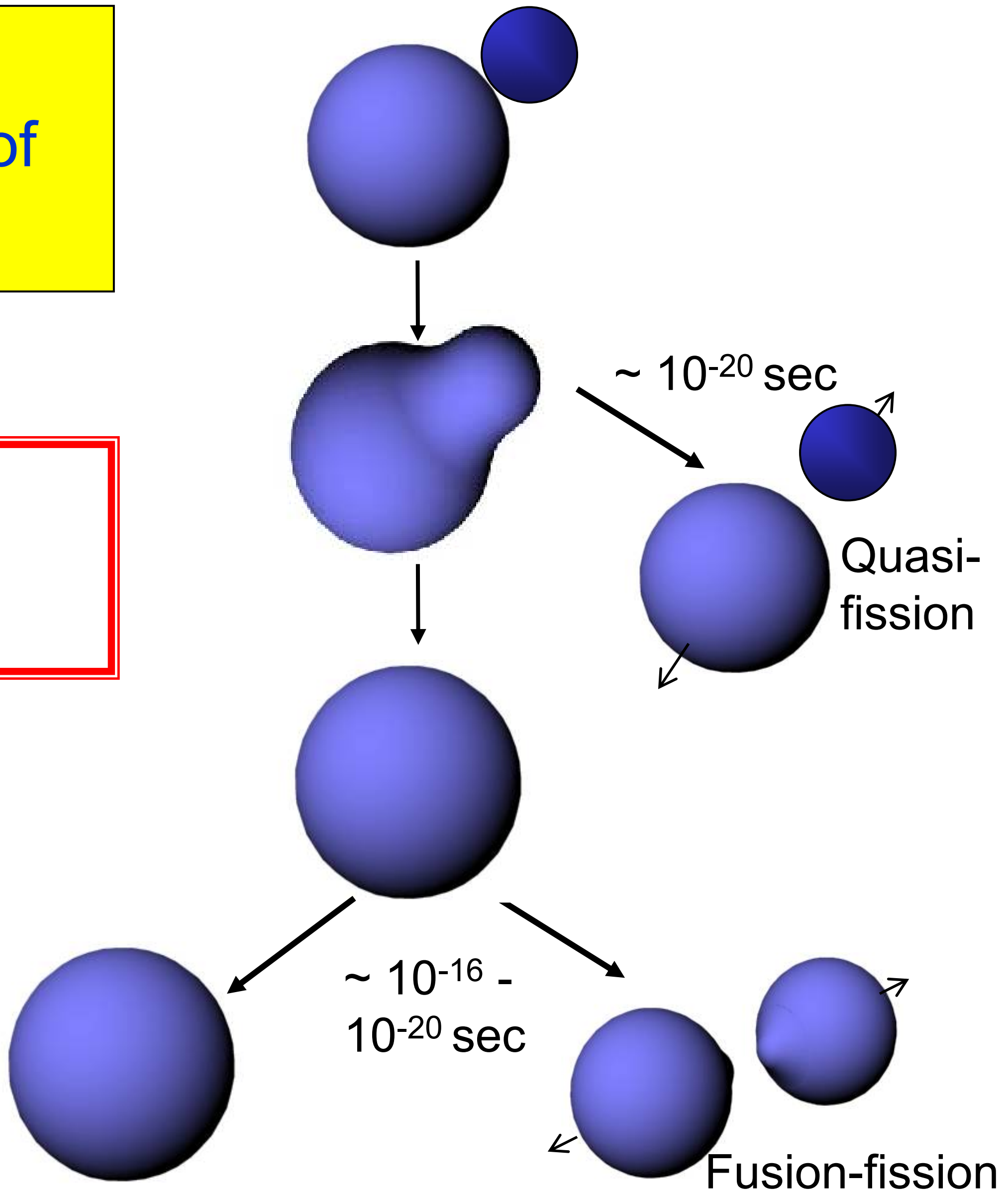
Rafiei et al., PRC 81, 024601(2010)

Important questions

Lecture series until now:

- What influences capture of two nuclei?

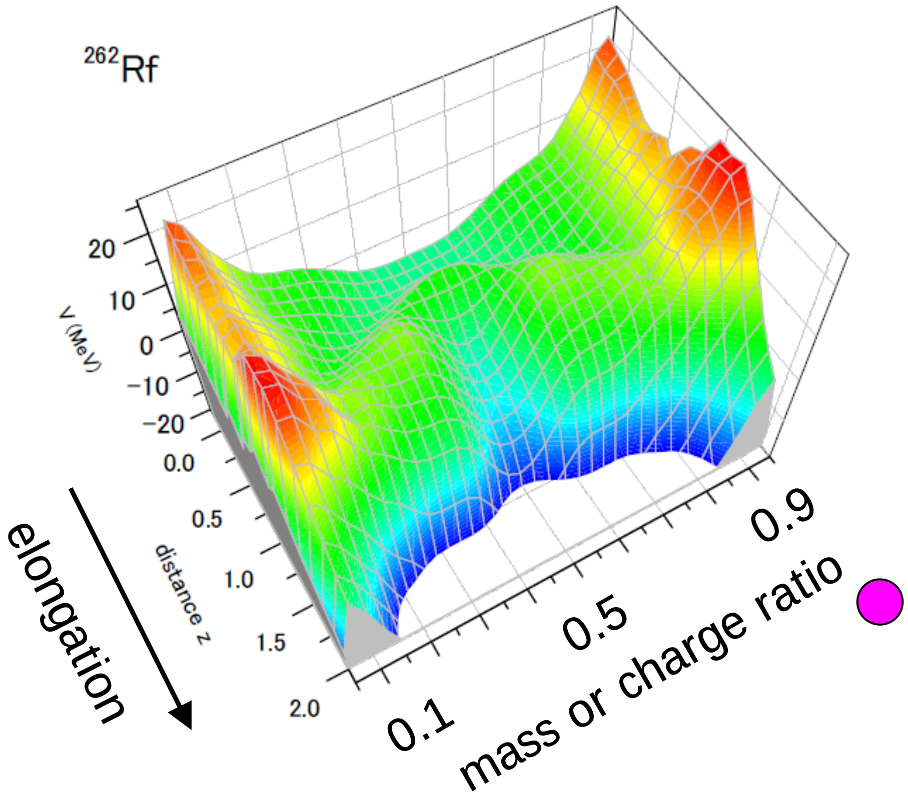
- What influences the subsequent evolution?



Effects of Nuclear Structure in Heavy Element Formation Dynamics

Heavy element formation - dynamical evolution of a complex quantum system

Diffusion of collective co-ordinates over multi-dimensional potential energy surface



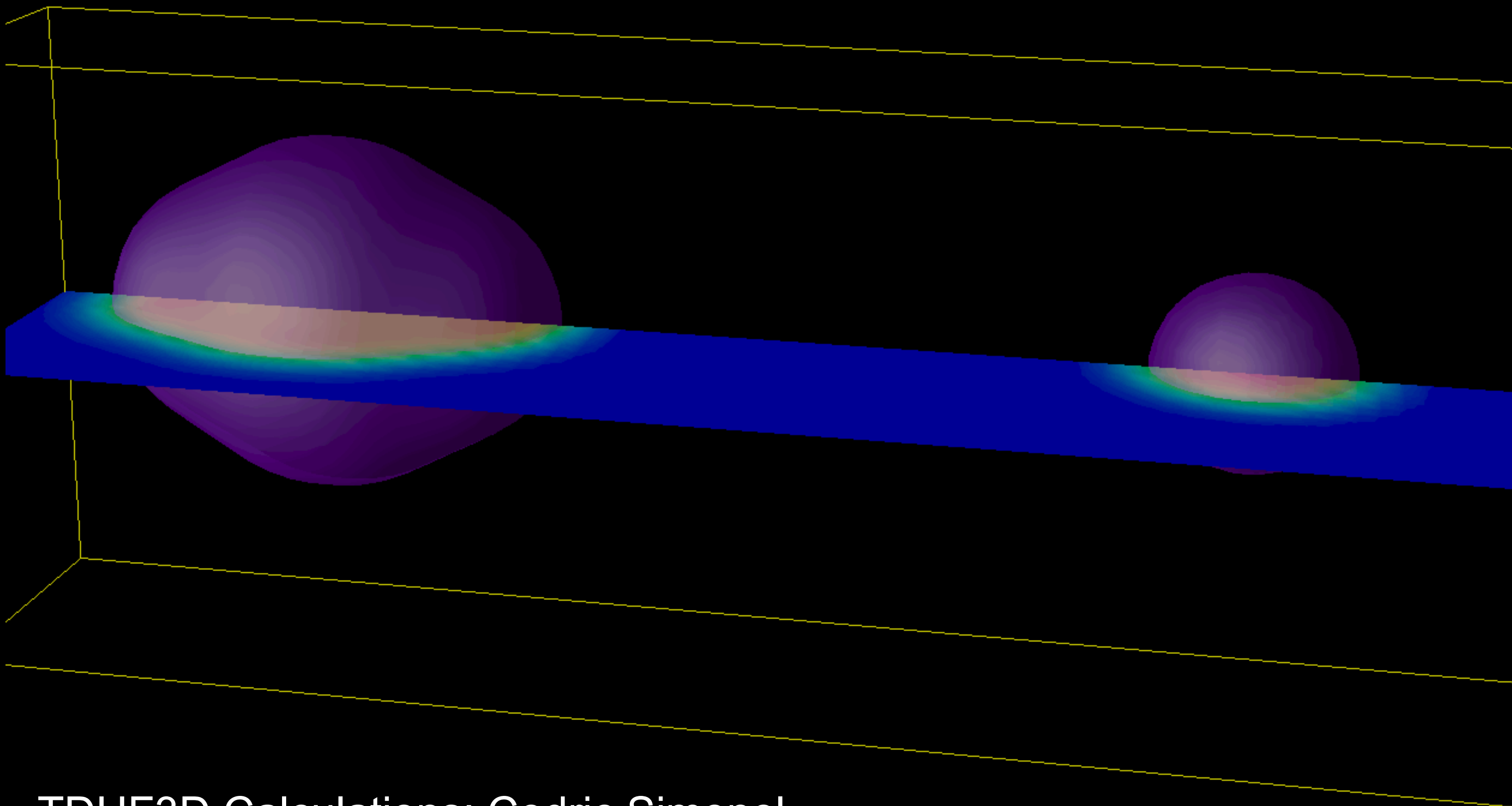
Outcomes depend on:

- **Potential energy surface**
- o C.N. fissility $Z_{C.N.}^2/A_{C.N.}^{1/3}$
- o Shell structure of combined system
- **"Entry point"**
- o Dissipation of initial relative energy
- o Deformation in entrance channel
- **Dependence of dynamics on structure**
- o Shell gaps – level spacing
- o Damping of shell effects with E_X

Slide from D.J. Hinde, ANU

ER and Quasi-fission Movies

by Y. Hinde



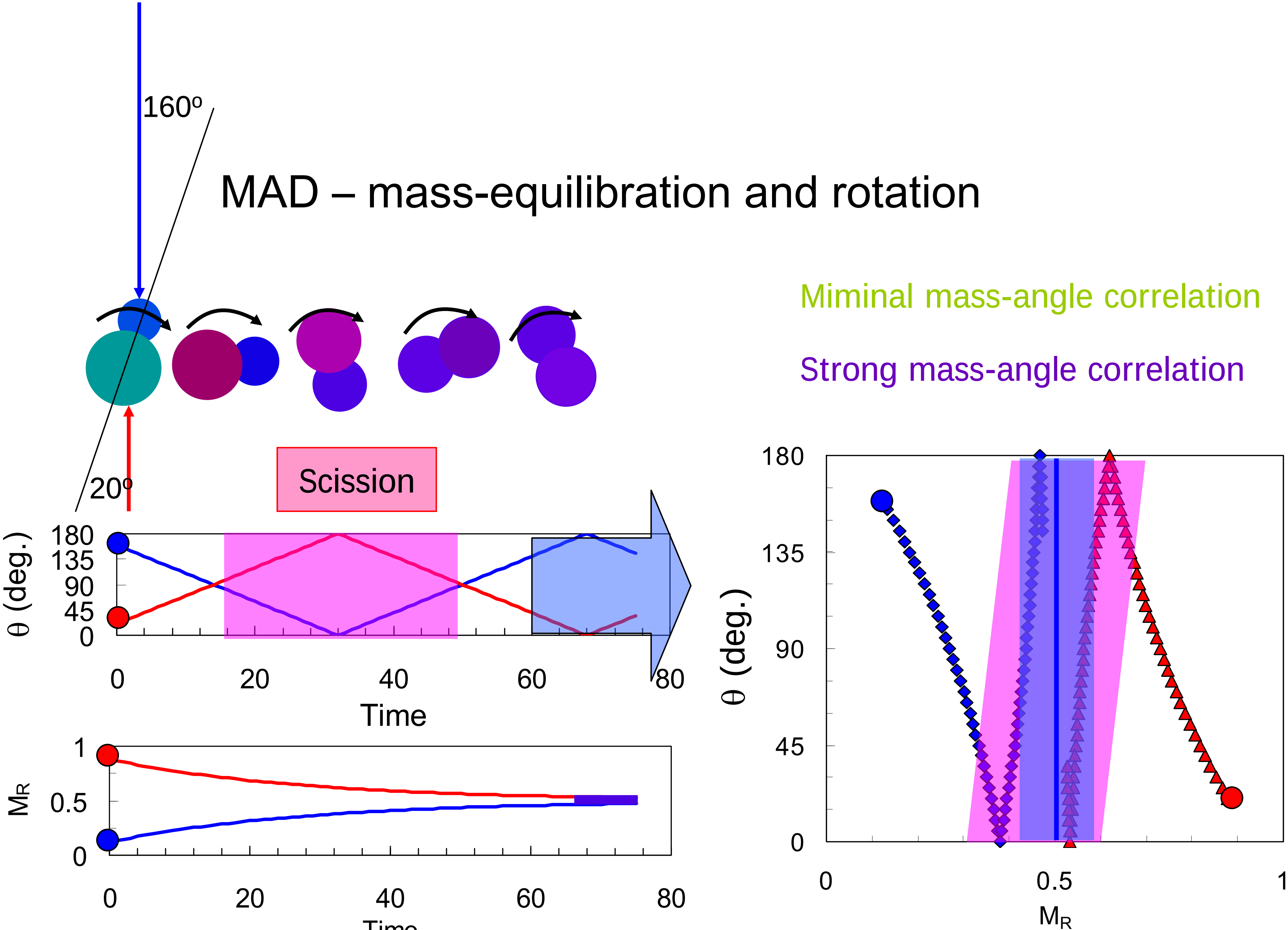
TDHF3D Calculations: Cedric Simenel

C. Golabek, C. Simenel, PRL 2009

D. Kadziora, C. Simenel, PRC 2010

Wakle, Simenel et al, to be published

MAD – mass-equilibration and rotation



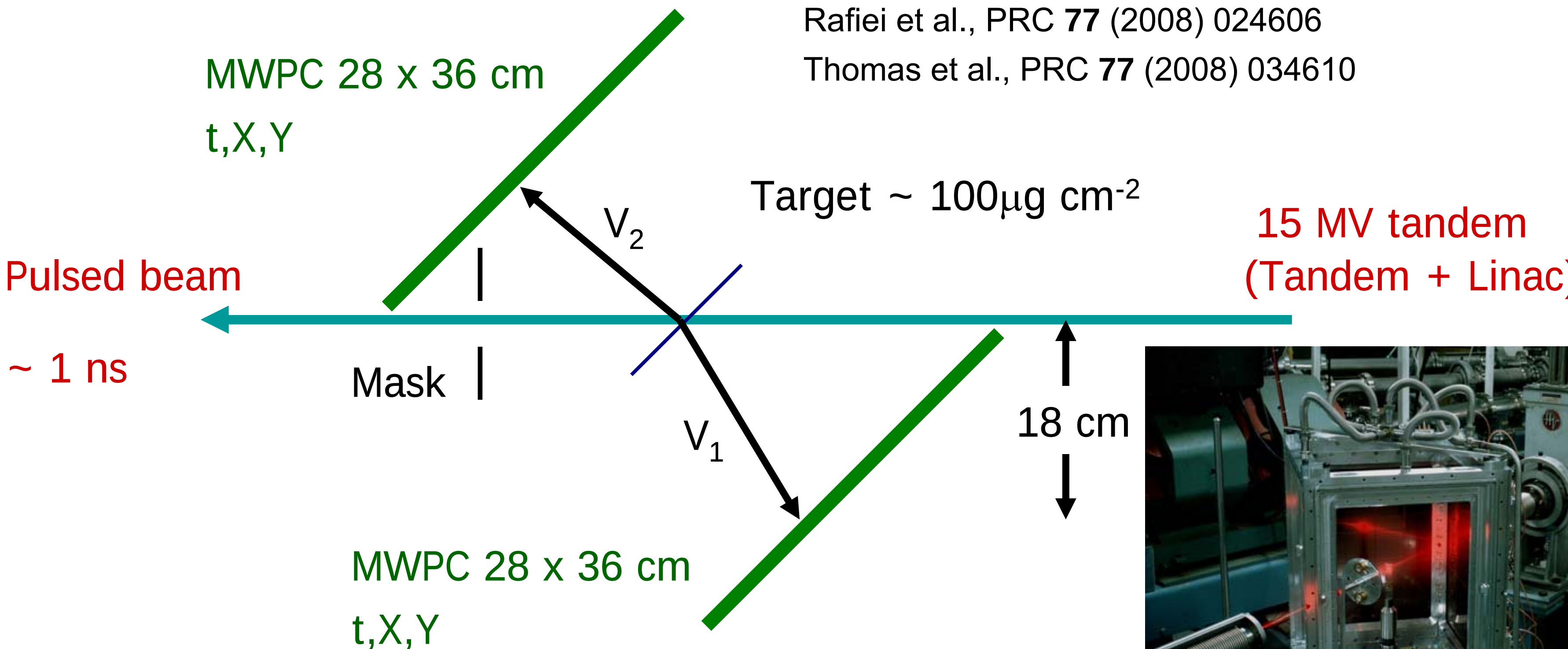
Slide from D.J. Hinde, ANU

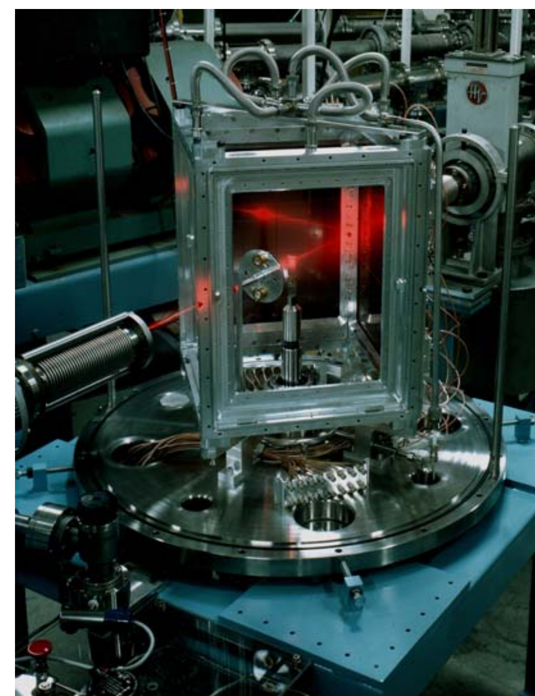
ANU MWPC detector configuration

Hinde et al., PRC **53** (1996) 1290

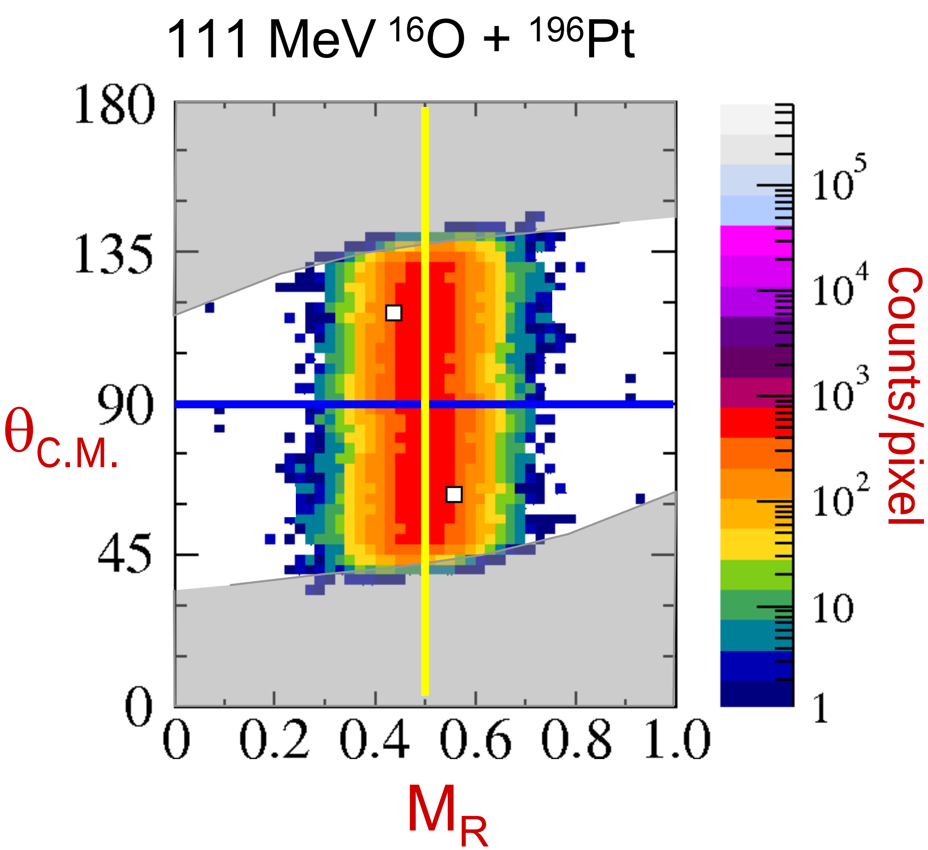
Rafiei et al., PRC **77** (2008) 024606

Thomas et al., PRC **77** (2008) 034610





Mass-angle distribution – MAD



Kinematic coincidence

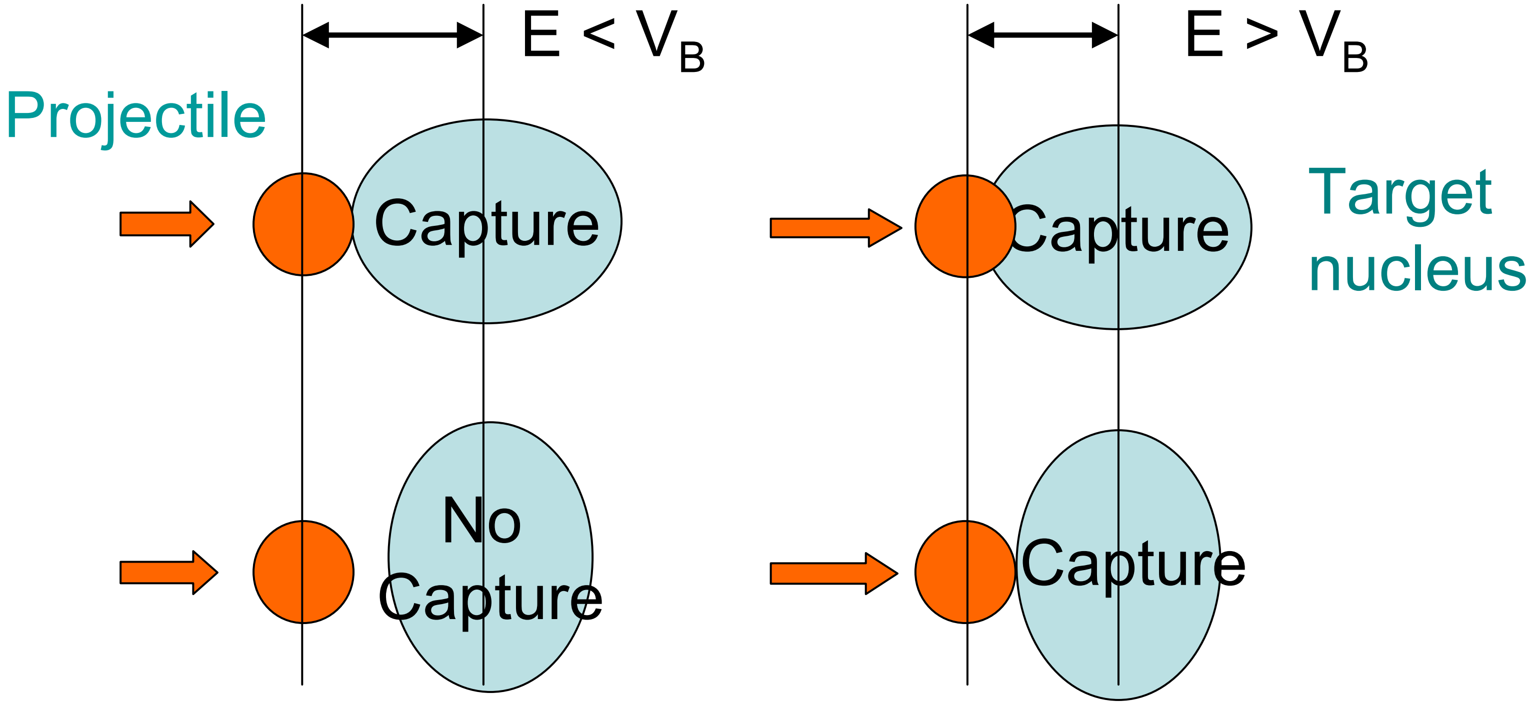
Detector angular acceptance

- Detect both fragments
- Populate matrix at M_R,θ_{CM}
- Also at $(1-M_R)$, $(\pi-\theta_{CM})$

Fusion-fission

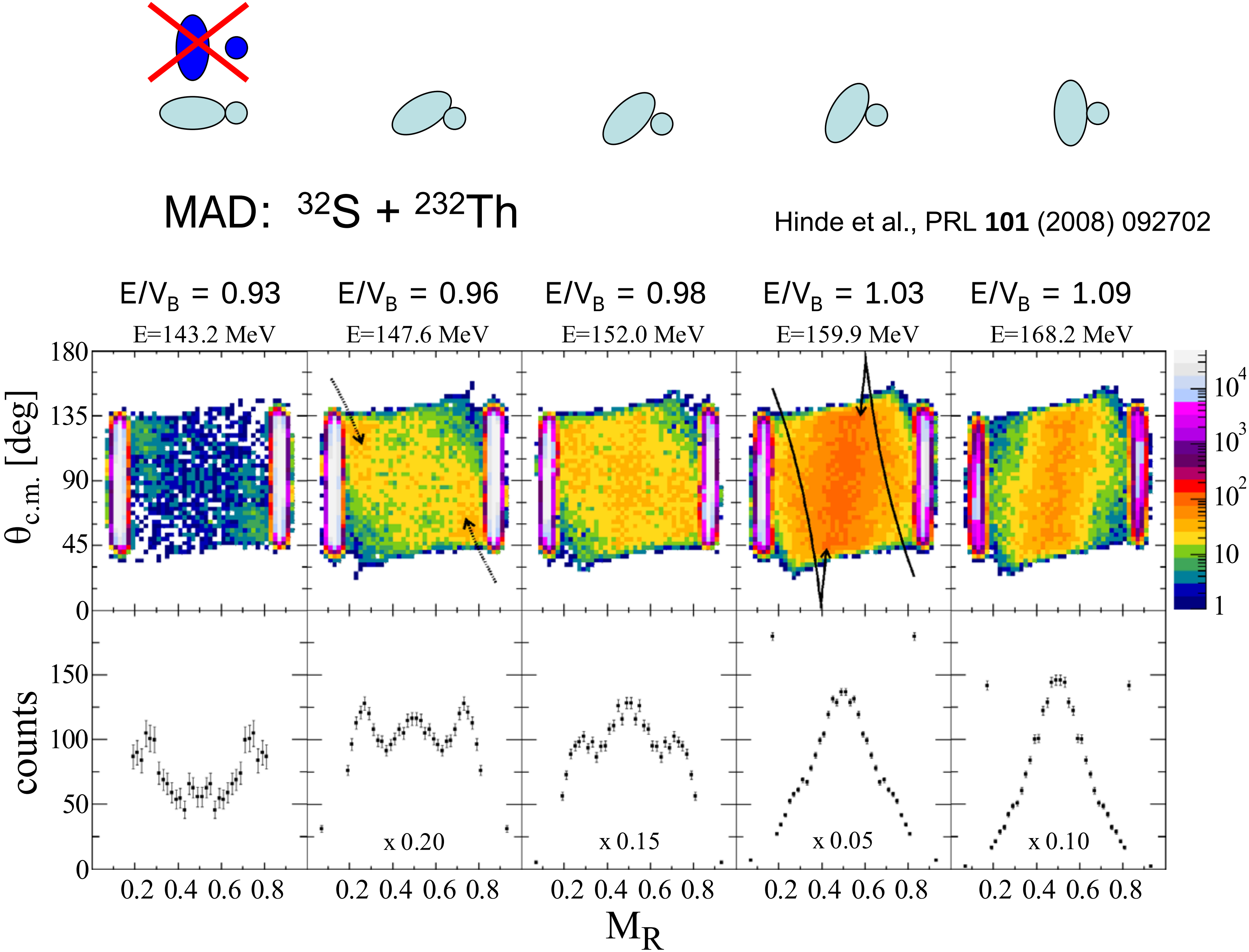
- symmetric about $M_R = 0.5$
- <u>and</u> symmetric about $\theta_{CM} = 90^o$

Capture probability and deformation alignment



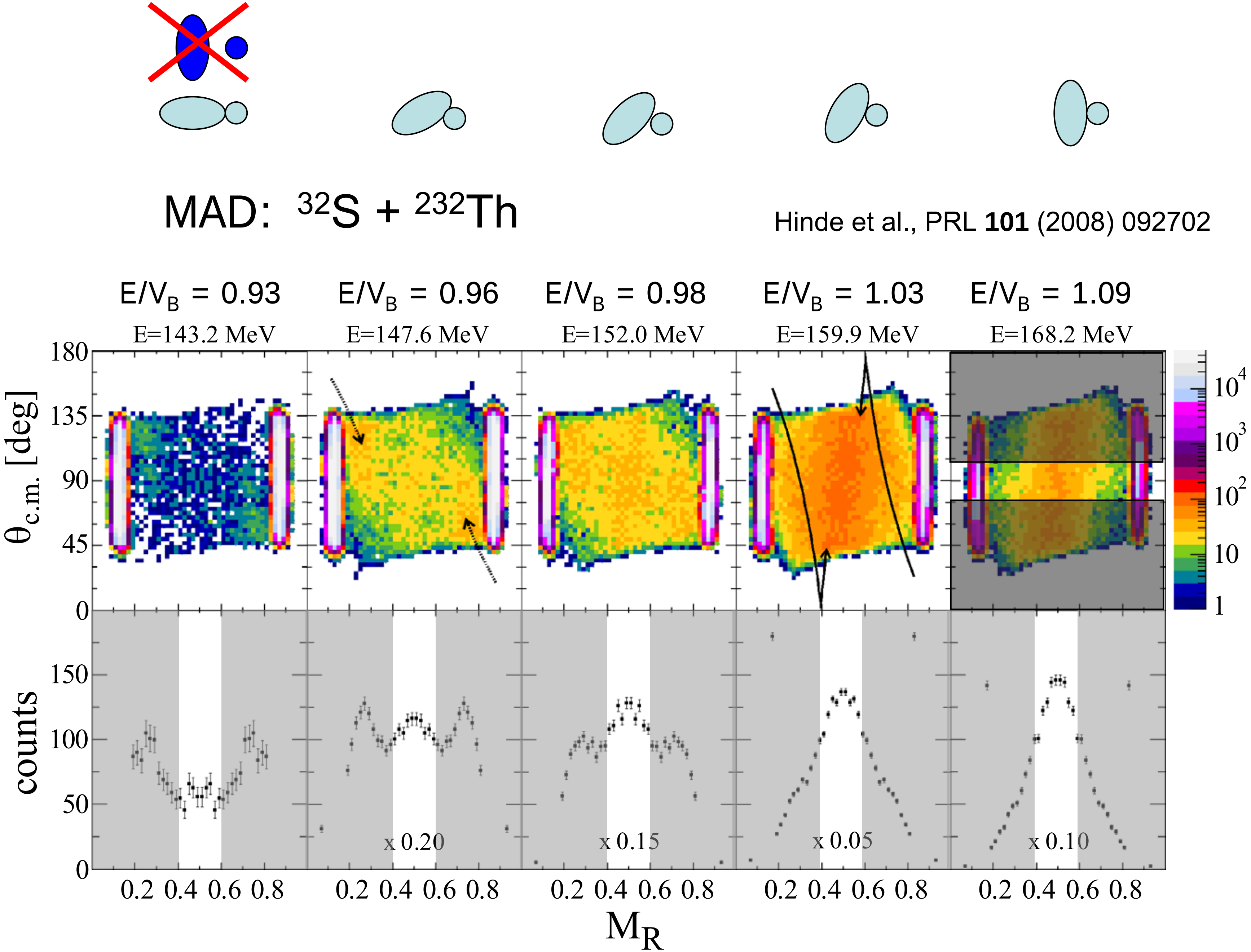
MAD: $^{32}S + ^{232}Th$

Hinde et al., PRL **101** (2008) 092702



MAD: $^{32}S + ^{232}Th$

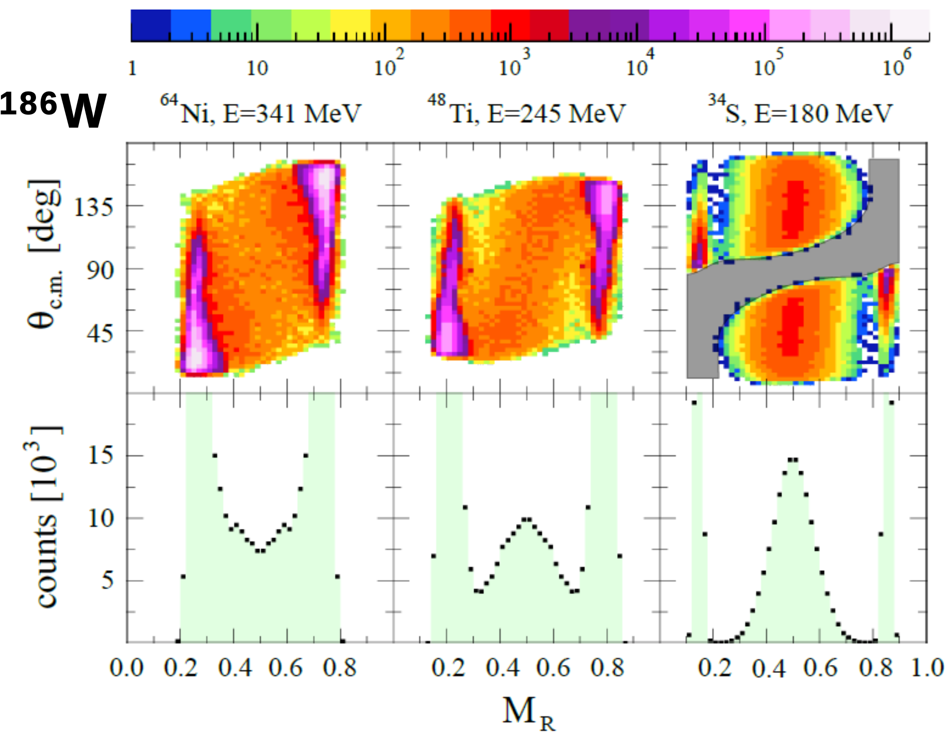
Hinde et al., PRL **101** (2008) 092702



MAD at ANU

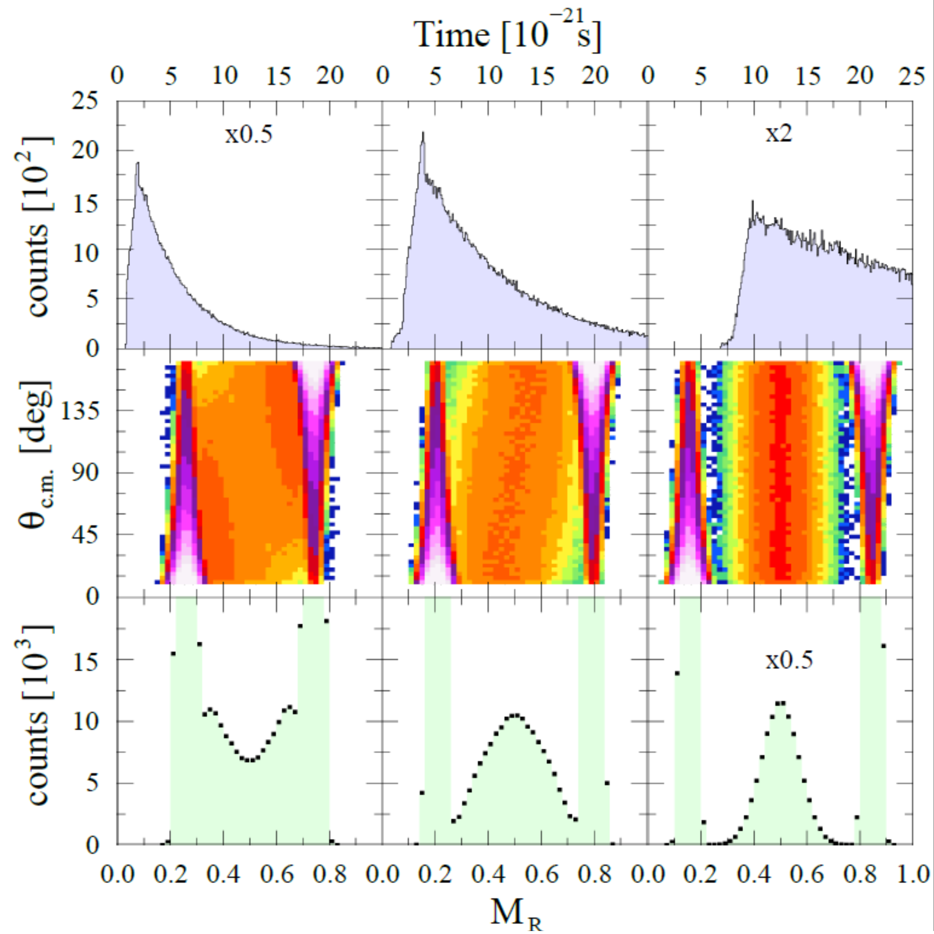
- Complete picture of evolution of the combined system in the first 10^{-20} sec
- Controversy: Fission time scales 10^{-18} sec, increasing with increasing Z

Anderson et al, PRL99, 162502 (2007)
Morjean et al, PRL101, 072701 (2008)



Simulations

$<\tau>$ 5x10^{-21}s $<\tau>$ 10x10^{-21}s $<\tau>$ >> 10x10^{-21}s



R. du Rietz et al. PRL 106(2011)052701

Time scale decreases with increasing mass of the combined system

Summary

- Frontiers of nuclear reaction dynamics
  - Experimental and theoretical challenge
  - Fundamental quantum mechanics

- Development of unique detection systems – an important role
  - Data of unmatched precision
  - Reveal new aspects of interacting many-body quantum systems

- Decreased tunnelling in complex systems - fusion – new approach needed
  - Standard modelling of environmental interactions not applicable
  - Collaborations with quantum theorists

- Techniques to probe time scales of breakup and quasi-fission
  - Key role in understanding dynamics, model developments

Additional material

Reconstruction – Q-value

non-relativistic implementation

Details: Rafiei et al., PRC 81, 024601(2010)
Luong et al., Phys. Lett. 695, 105 (2011)

1. momentum conservation (assume 3-body BU):

$$\vec{P}_{beam} = \vec{P}_1 + \vec{P}_2 + \vec{P}_{recoil}$$

$$E_{recoil} = \frac{\left\|\vec{P}_{recoil}\right\|^2}{2m_{recoil}}$$

2. energy conservation:

$$Q = (E_1 + E_2 + E_{reoil}) - E_{beam}$$

Reconstruction – Relative Energy

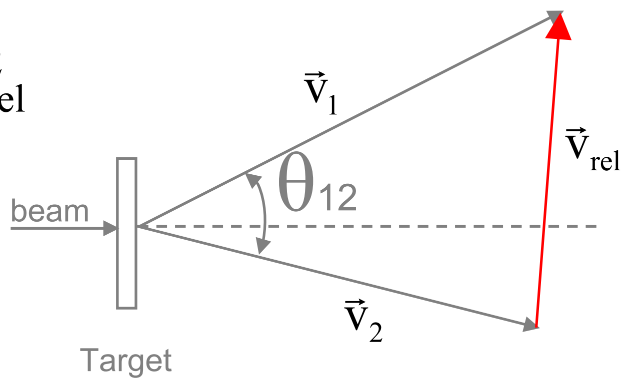
Details: Rafiei et al., PRC 81, 024601(2010)

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

- reminder: in CM frame the two fragments are emitted back-to-back:

$$m_1\vec{v}_1' + m_2\vec{v}_2' = 0$$

$$E_{rel} = \frac{1}{2}m_1(v_1')^2 + \frac{1}{2}m_2(v_2')^2 = \frac{1}{2}\mu v_{rel}^2$$



- CM → LAB : application of cosine rule to velocity diagram

$$E_{rel} = \frac{1}{m_1 + m_2}\left(m_1 E_2 + m_2 E_1 - 2\sqrt{m_1 m_2 E_1 E_2}\cos(\theta_{12})\right)$$

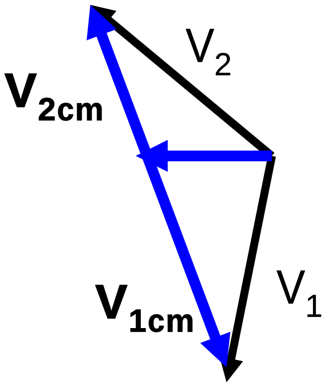
- measure E, θ, Ø of breakup fragments → reconstruct breakup E_{rel}

Binary fission kinematics

Hinde et al., PRC **53** (1996) 1290

Rafiei et al., PRC **77** (2008) 024606

Thomas et al., PRC **77** (2008) 034610



Kinematic coincidence:

Determine (binary) mass-ratio $M_{R1} = A_{F1}/(A_{F1}+A_{F2}) = V_{2cm}/(V_{1cm}+V_{2cm})$