ALEXIS DIAZ-TORRES

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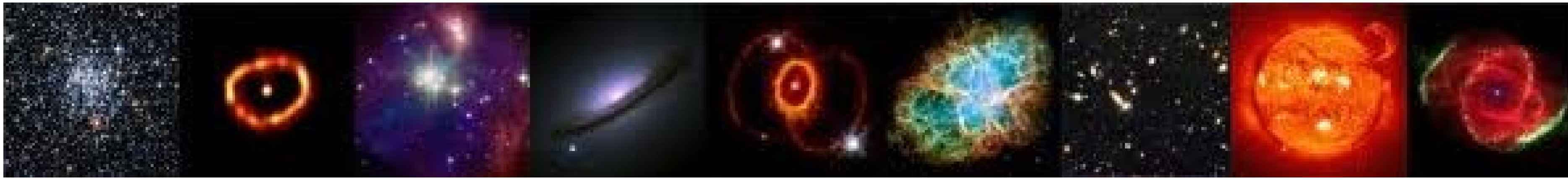
Why am I interested in the physics of nuclear reactions?



- **The physics of low-energy nuclear reactions** is crucial for understanding **energy production** and **nucleosynthesis** in the Universe

- **Nuclear reactions** are the **primary probe** of the **New Physics**

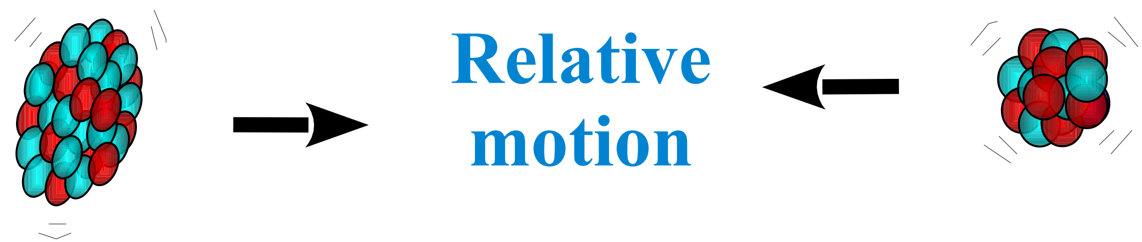
Quantifying low-energy fusion dynamics of weakly bound nuclei

- A Time Dependent Perspective -

What I will tell you next

- Issue & Important Concepts
- **Classical & Quantum Dynamical Models**
- Summary & Outlook

What's the issue I'd like to understand and quantify?

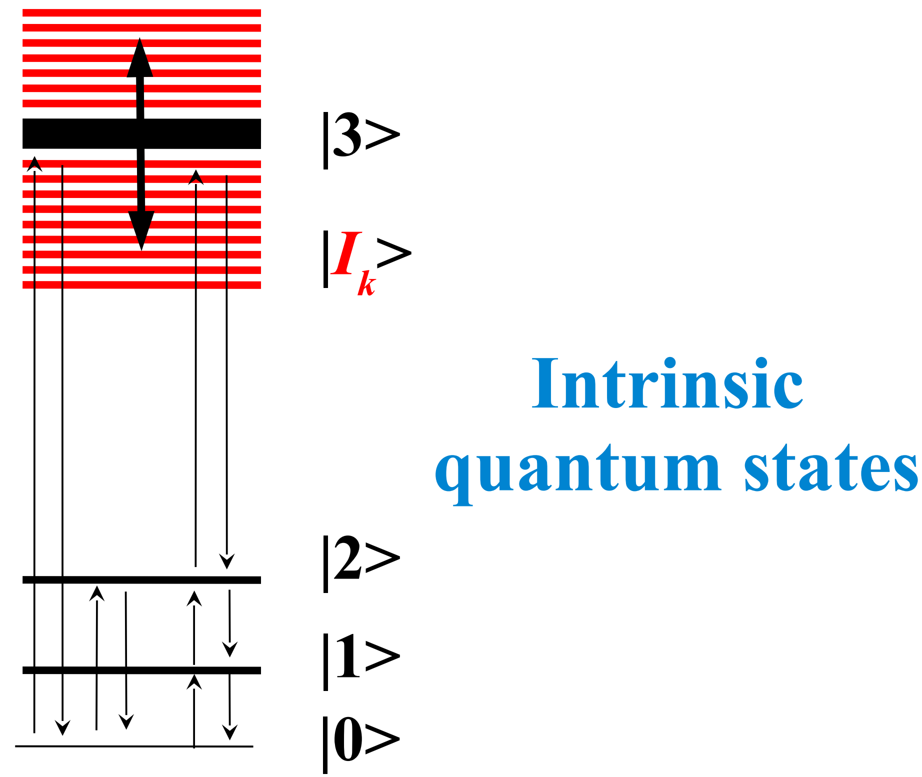


SCALES

Energy: MeV = 10^6 eV

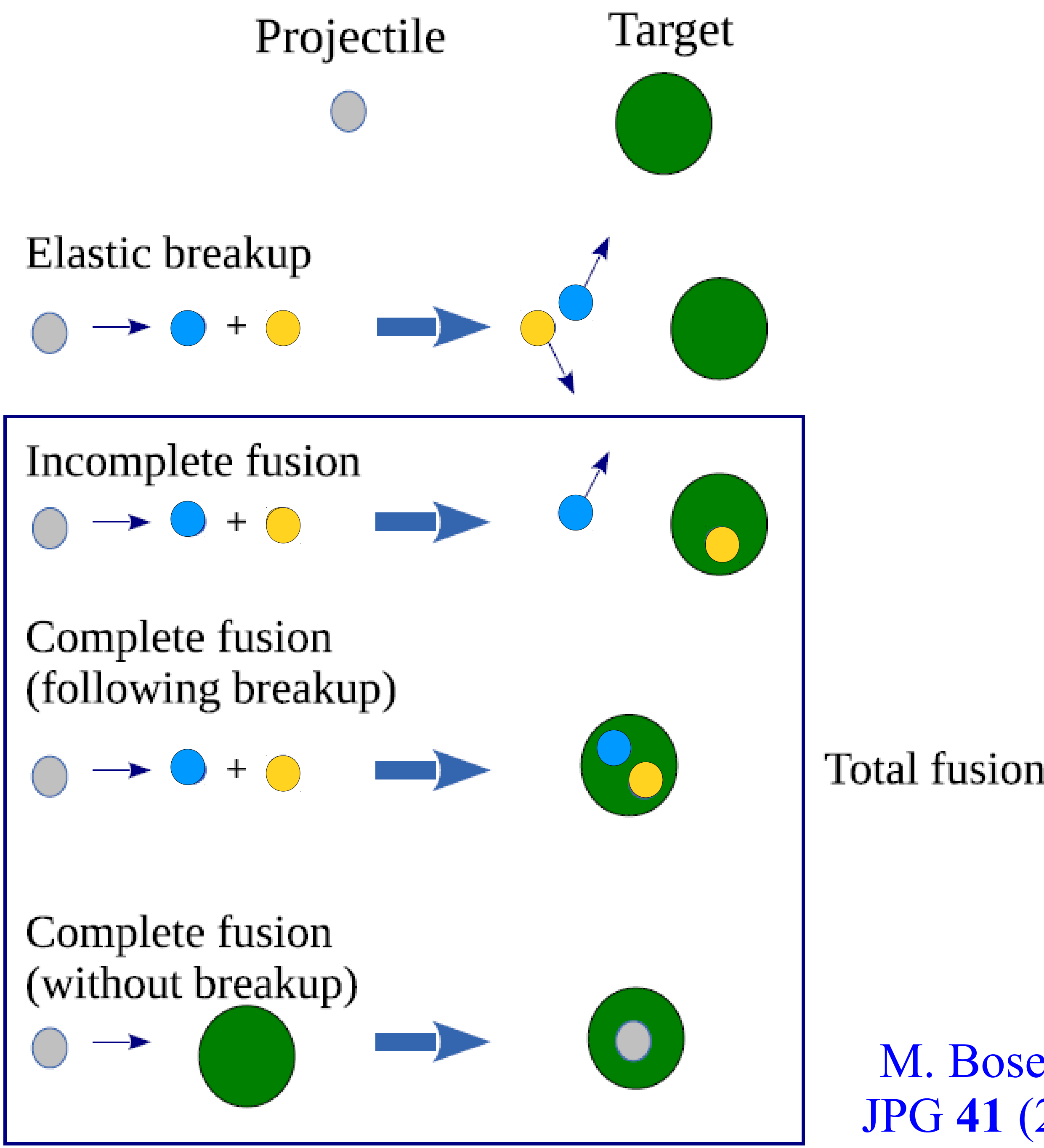
Length: fm = 10^{-15} m

Collision Time: 10^{-20}-10^{-22} s



Strong interplay of **nuclear structure** and **reaction dynamics** determines reaction outcomes (**cross sections**)

Unified description of low-energy reaction processes?



M. Boselli & AD-T,
JPG **41** (2014) 094001

Some examples of low-energy models in the last 15 years

Classical

AD-T, Hinde, Tostevin, Dasgupta & Gasques, PRL **98** (2007) 152701

Hagino, Dasgupta & Hinde, NPA **738** (2004) 475c

Mixed Quantum-Classical

Marta, Canto & Donangelo, PRC **89** (2014) 034625; PRC **73** (2005) 034608

Baye, Capel & Melezhik, NPA **722** (2003) 328c

Esbensen & Bertsch, NPA **706** (2002) 383

Yokimoto, Typel *et al.*, PRC **63** (2001) 035801

Quantum Mechanical

Descouvemont, Druet, Canto & Hussein, PRC **91** (2015) 024606

Lubian, Correa, Canto, Gomez-Camacho, Gomes *et al.*, PRC **79** (2009) 285

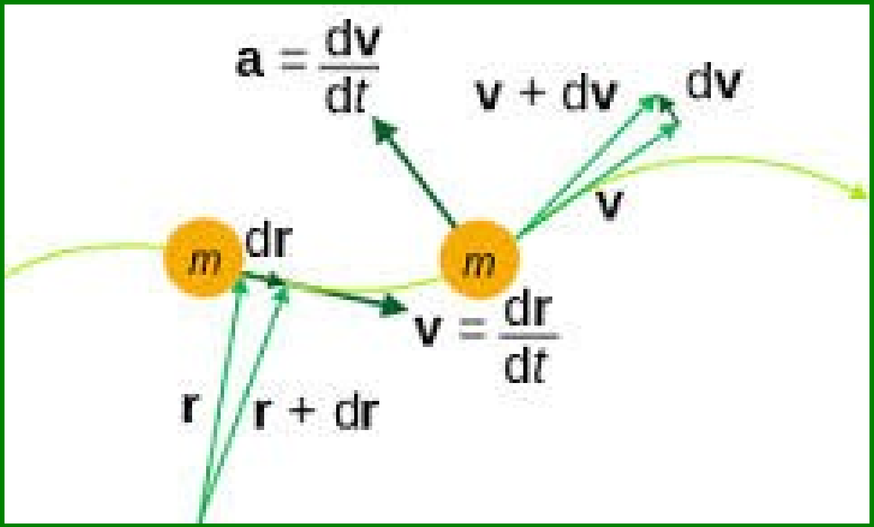
Rodriguez-Gallardo, Moro *et al.*, PRC **80** (2009) 051601

Ito, Yabana, Nakatsukasa & Ueda, PLB **637** (2006) 53

AD-T, Thompson & Beck, PRC **68** (2003) 044607; PRC **65** (2002) 024606

Tostevin, Nunes & Thompson, PRC **63** (2001) 024617

Hagino, Vitturi, Dasso & Lenzi, PRC **61** (2000) 037602



Classical Trajectory Monte Carlo Method

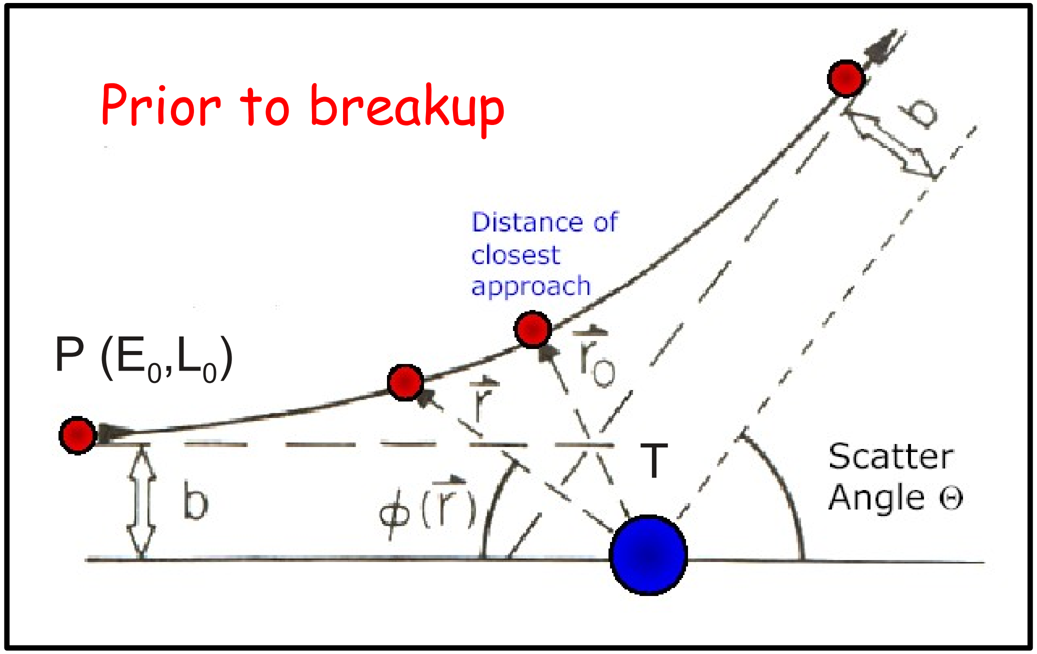
- After breakup, interaction among fragments is crucial
- Useful for interpreting particle-gamma coincidence data
- Breakup triggered by transfer enriches the fusion scenario

See e.g., R. E. Olson, CTMC techniques, in Springer Handbook of Atomic, Molecular & Optical Physics (2006) pp. 869-874

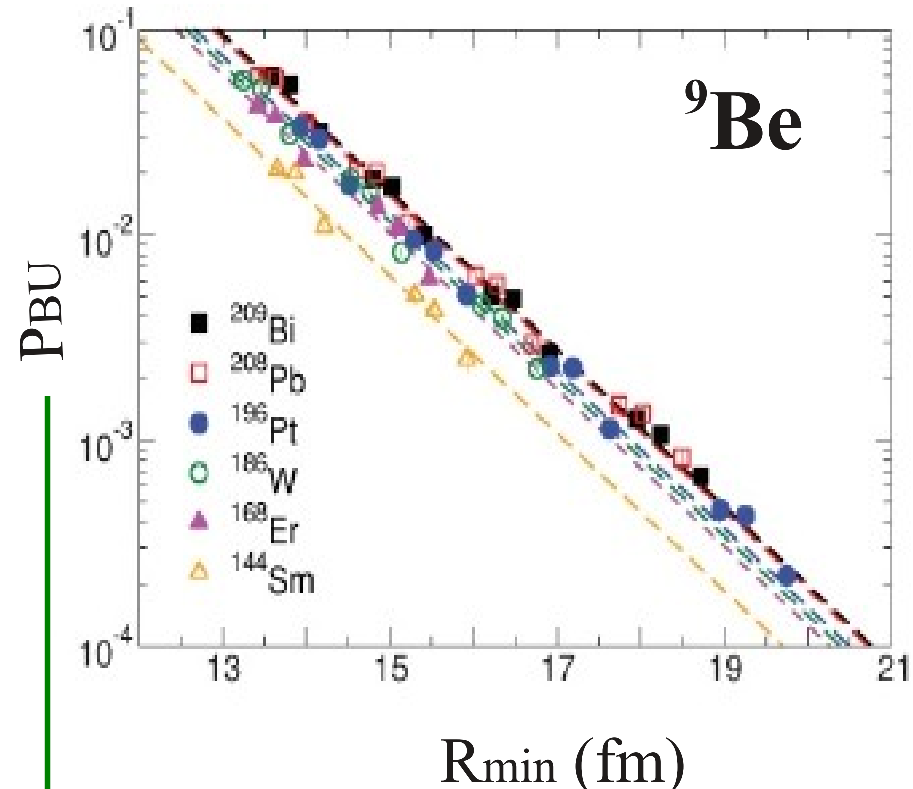
Classical Dynamical Model

AD-T, Hinde, Tostevin, Dasgupta & Gasques, PRL **98** (2007) 152701

AD-T, CPC **182** (2011) 1100 (**PLATYPUS** code)



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

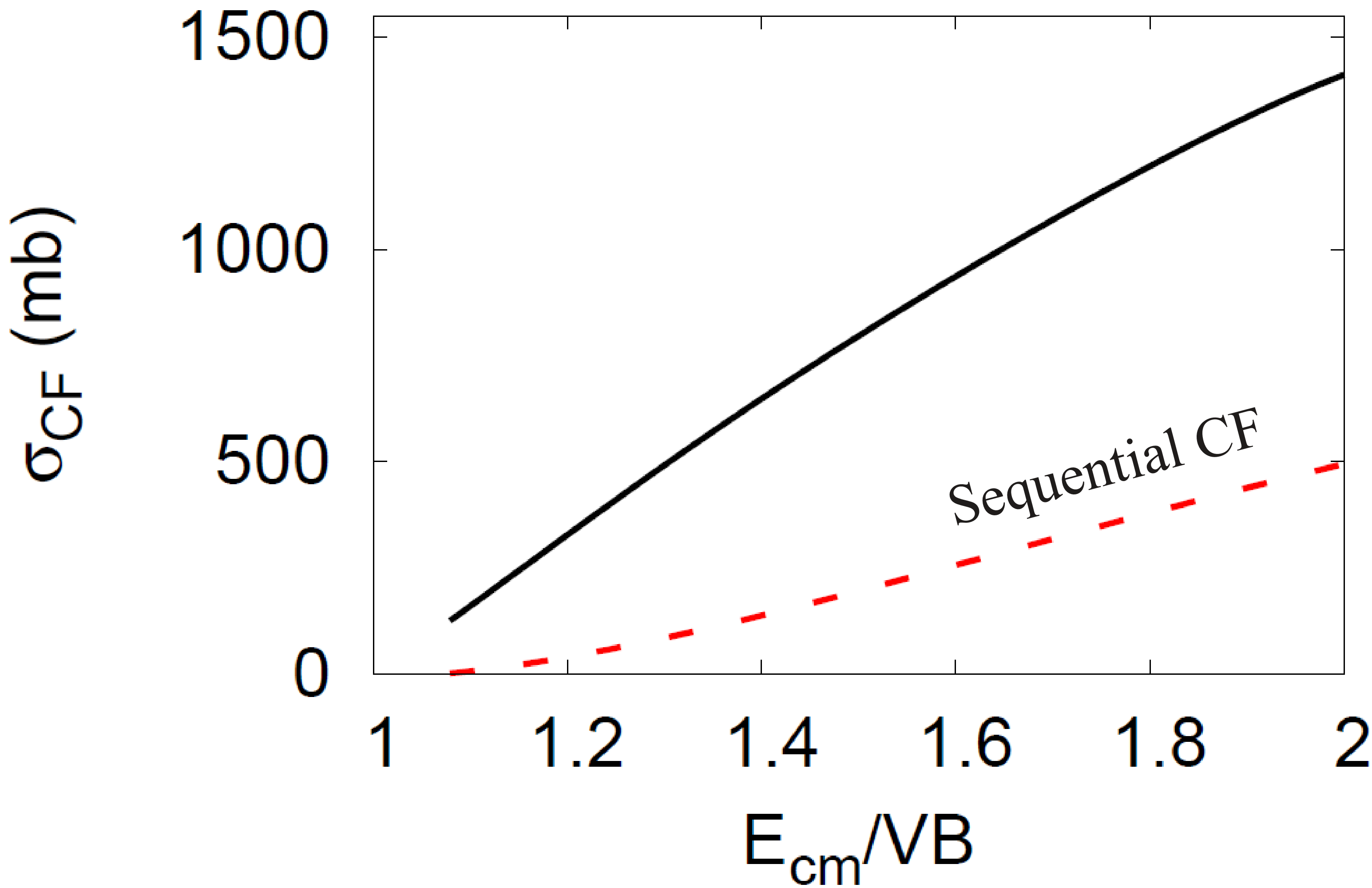


Main Ingredient :

$P^{L}_{BU}(R)dR$ *probability of breakup on the interval* $R + dR$

$$P_{BU}(R_{min}) = 2\int_{R_{min}}^{\infty} P^{L}_{BU}(R)dR = A exp(-\alpha R_{min})$$

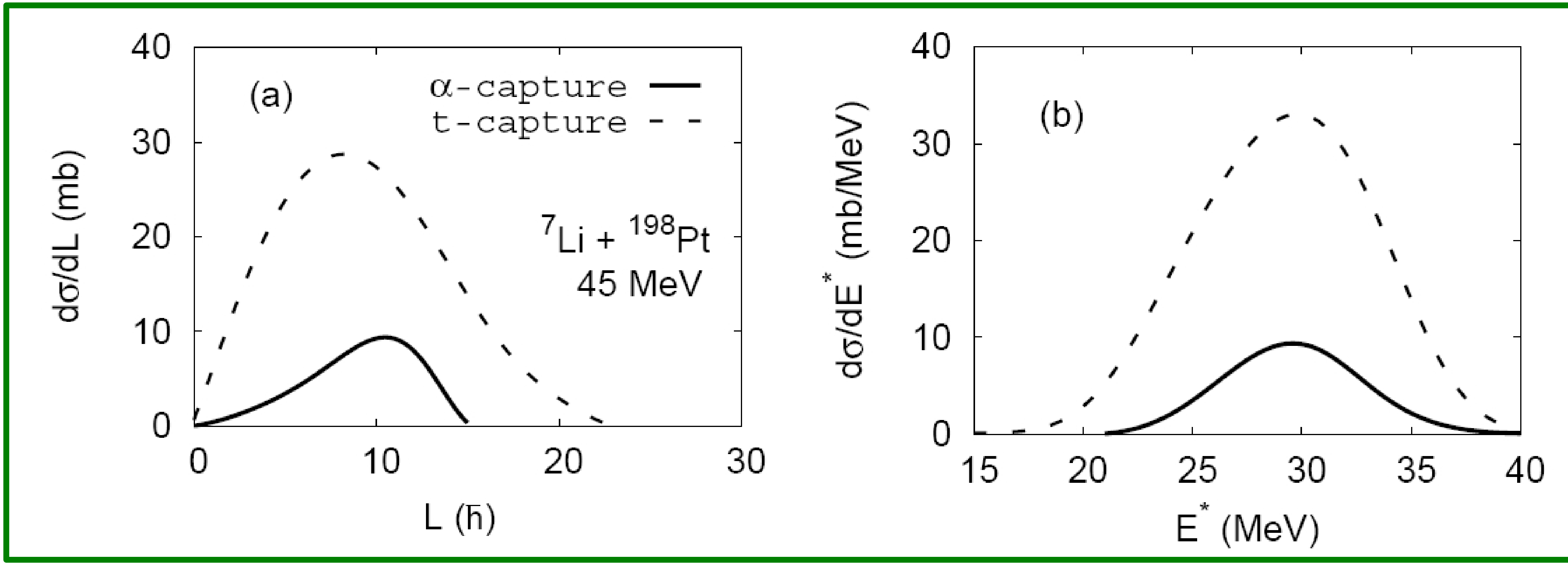
Complete fusion of ^{7}Li + ^{198}Pt at above-barrier energy

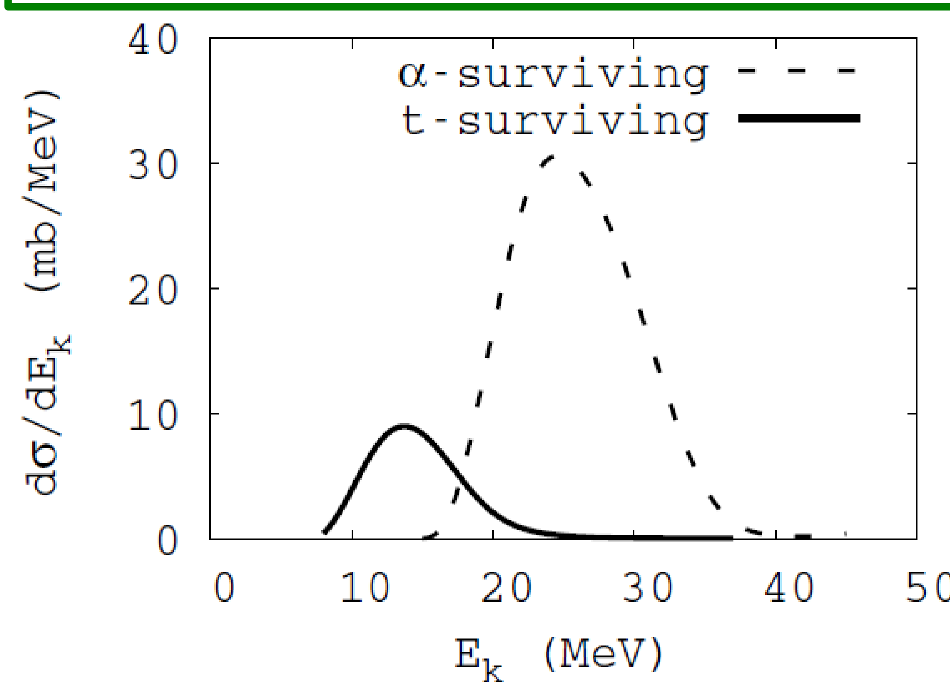


Sequential CF becomes substantial as energy increases

See e.g., Dasgupta *et al.*, PRC **66** (2002) 041602 (R), for ^{6,7}Li + ^{209}Bi

Incomplete fusion of $^{7}Li + ^{198}Pt$ at above-barrier energy





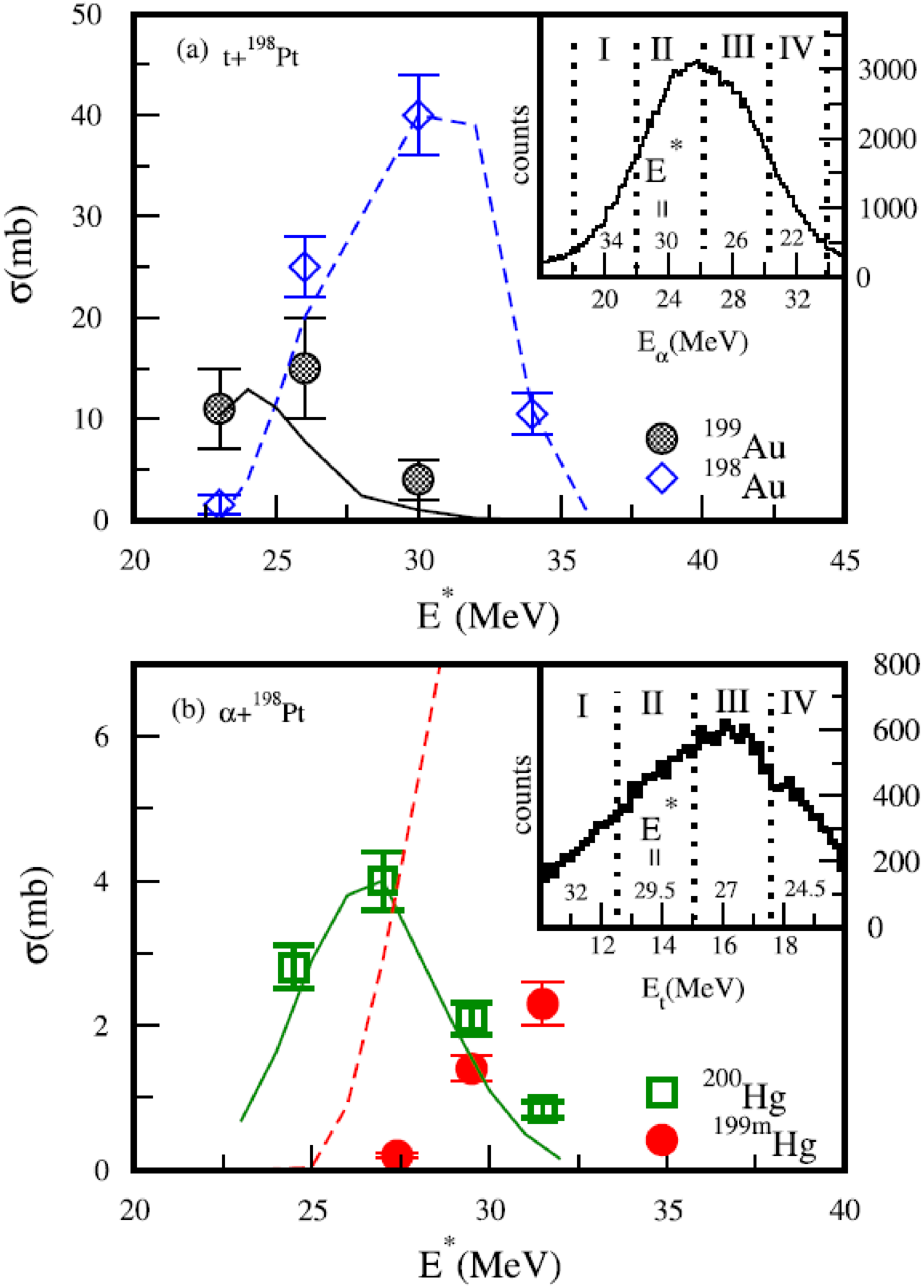
PLATYPUS code

AD-T, CPC **182** (2011) 1100

Useful for planning & interpreting particle-gamma-coincidence measurements

Incomplete fusion measurements vs. **Platypus+PACE** calculations:

E* and spin distribution from **Platypus** fed to evaporation code **PACE**



^{7}Li + ^{198}Pt @ 45 MeV

triton - fusion

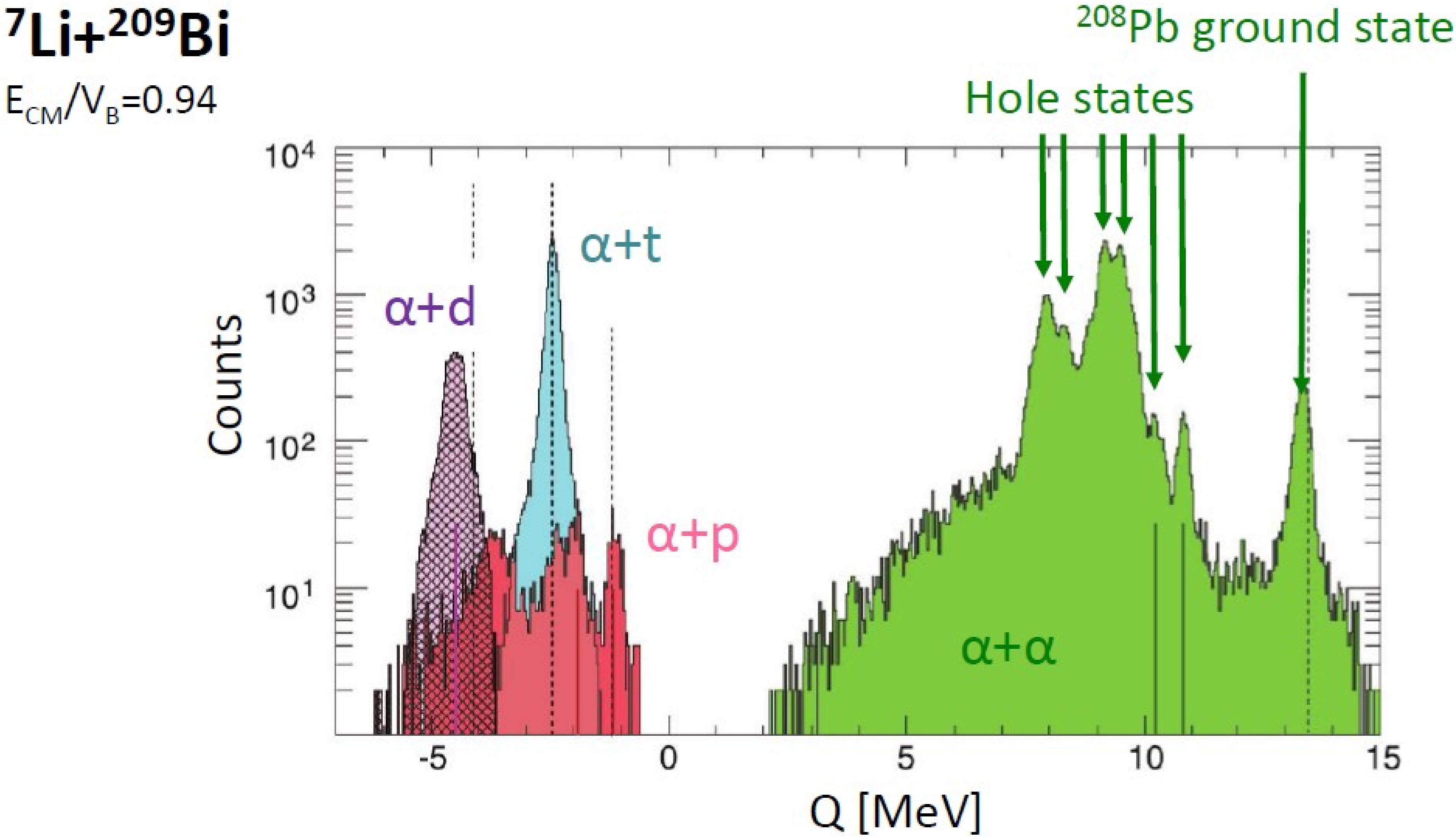
α gated γ spectra t + ^{198}Pt : ^{201}Au*

α - fusion

t gated γ spectra α + ^{198}Pt : ^{202}Hg*

Shrivastava, Navin, AD-T *et al.*,
PLB **718** (2013) 931

Q-value spectrum in sub-barrier breakup of ^{7}Li on ^{209}Bi



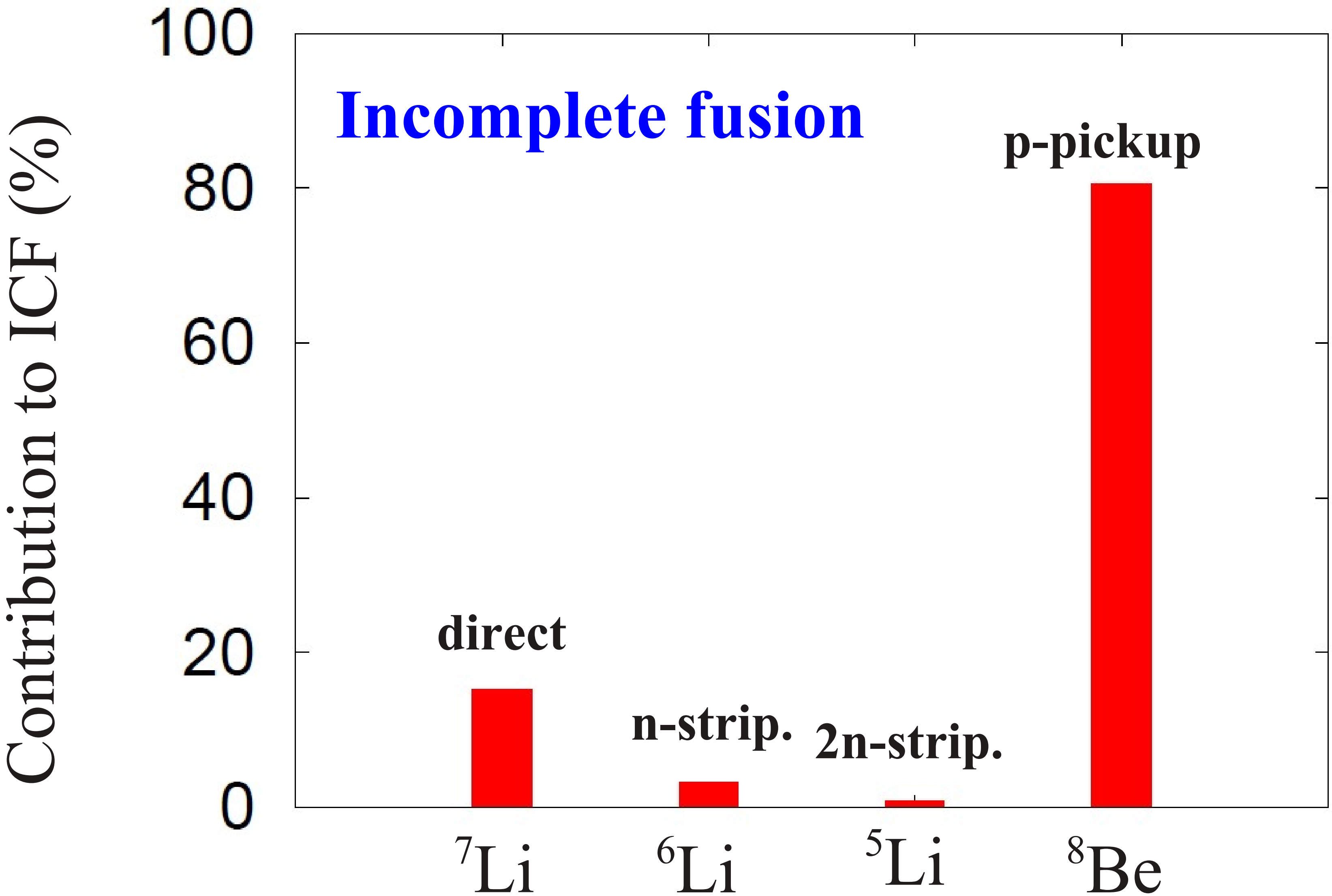
Luong *et al.*, Phys. Rev. C 88, 034609 (2013)

Courtesy of Ed Simpson (ANU)

Breakup triggered by transfer affects above-barrier fusion

Example: $^{7}Li + {}^{209}Bi$ @ Ecm/VB = 1.2

PRELIMINARY RESULTS FROM **PLATYPUS**



In collaboration with H. Luong

Time-Dependent Wave-Packet Dynamics

Useful for understanding sub-Coulomb fusion data

In collaboration with Maddalena Boselli,

PhD student at the ECT*

Time-Dependent Wave-Packet Dynamics

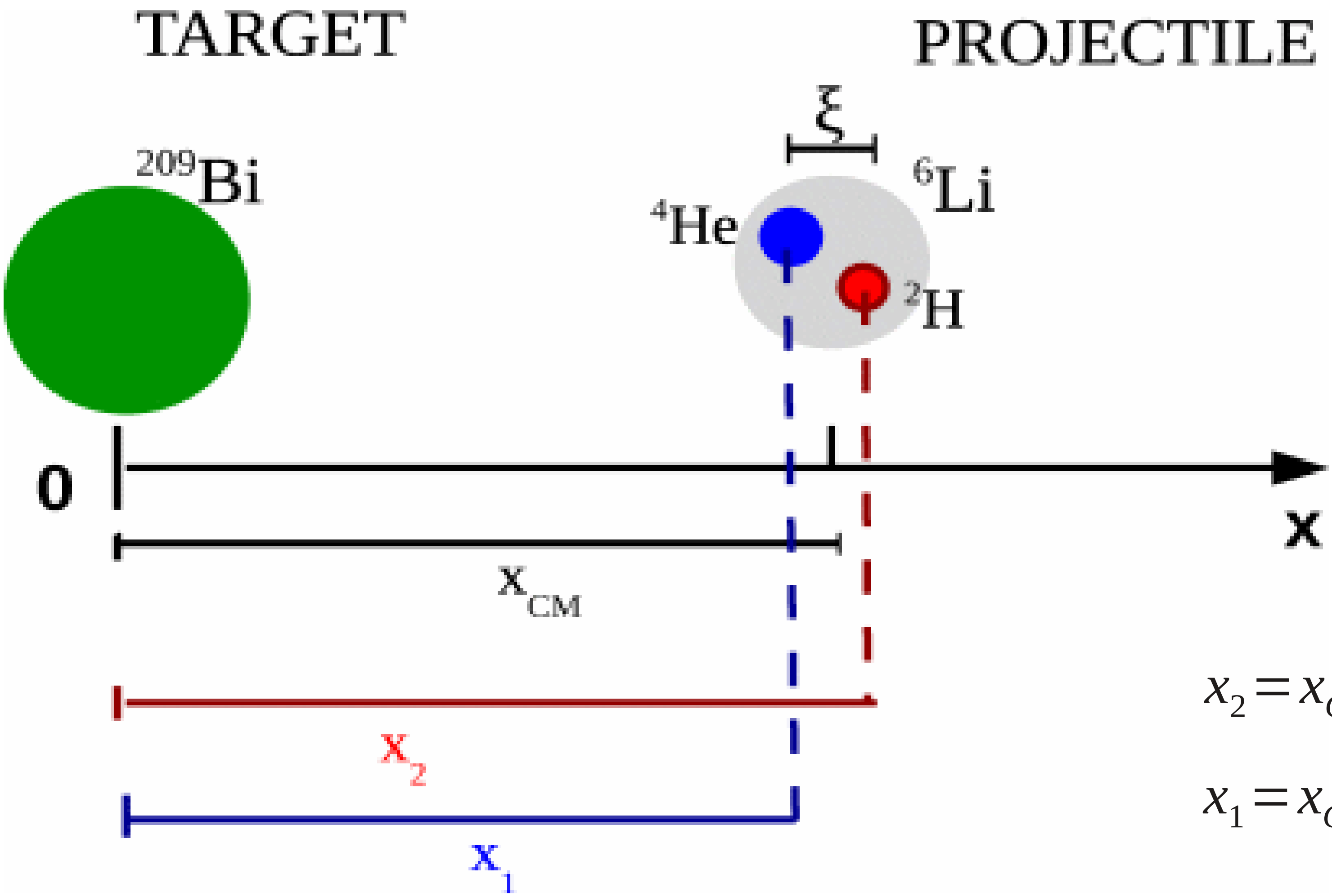
D.J. Tannor, *Quantum Mechanics in a Time-Dependent Perspective*, USB, 2007
Yabana, Prog. Theor. Phys. **97** (1997) 437
Schneider & Wolter, Z. Phys. A **339** (1991) 177

- **Preparation** of the initial state $\Psi(t=0)$.

- **Time propagation**, $\Psi(0) \rightarrow \Psi(t)$, guided by the evolution operator, $exp(-i\,\hat{H}\,t/\hbar)$, where $\hat{H}$ is the total Hamiltonian.

- **Analysis:** calculation of **cross sections** from the time-dependent wave function.

One-Dimensional Toy Model



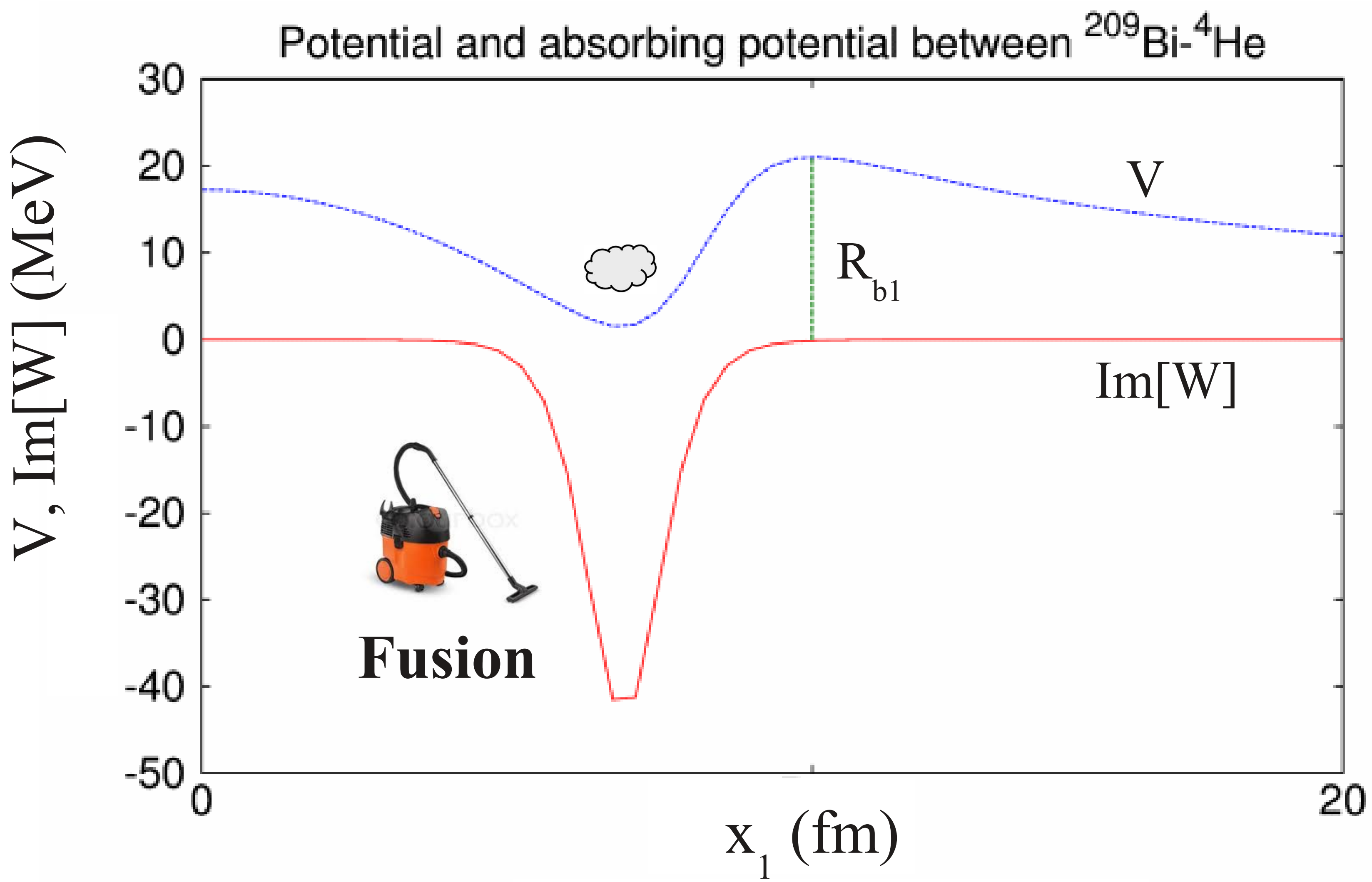
$$x_2 = x_{CM} + b\,\xi$$

$$x_1 = x_{CM} - a\,\xi$$

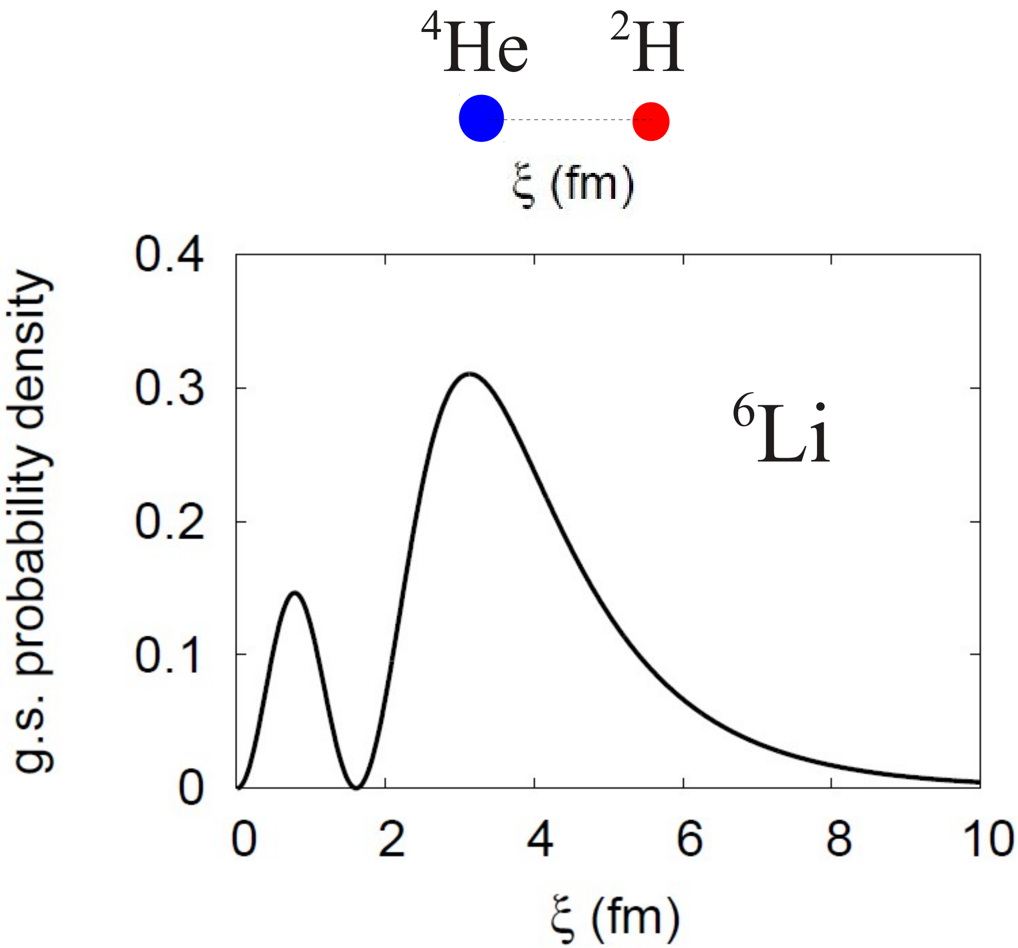
$$H = \frac{P_{x_{CM}}^2}{2M_{T12}} + \frac{P_\xi^{\;2}}{2m_{12}} + U_{12}(\xi) + V_{T1}(x_{CM} - a\,\xi) + V_{T2}(x_{CM} + b\,\xi)$$

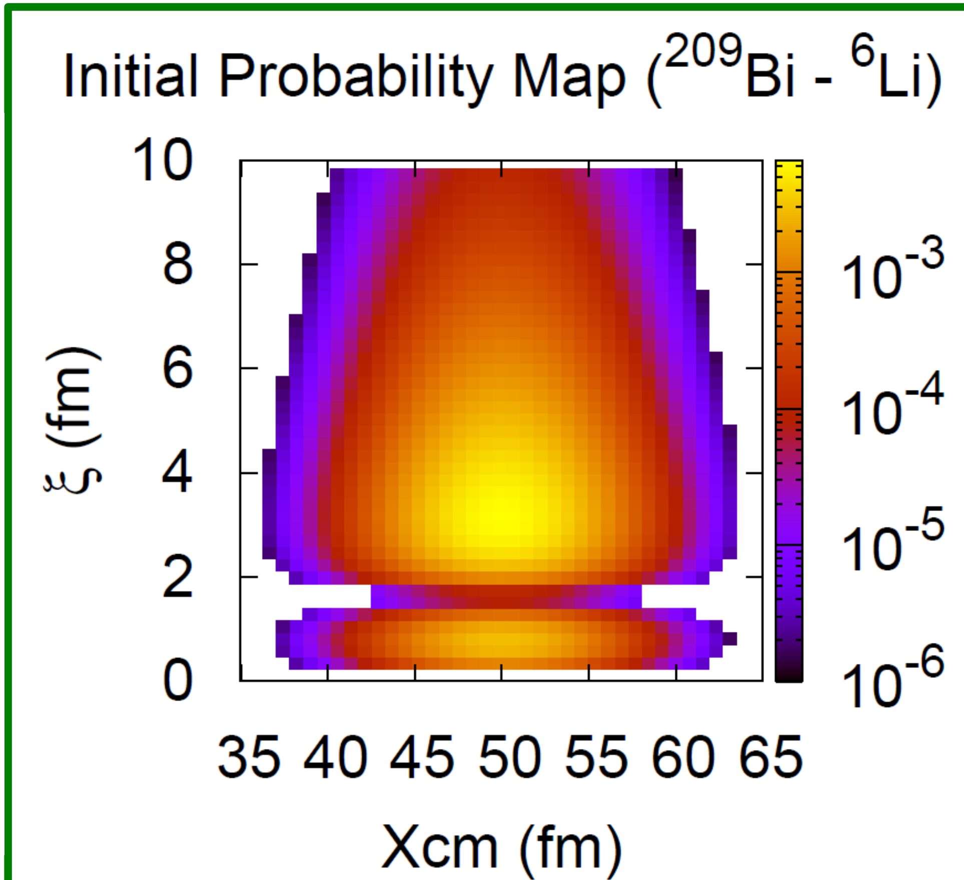
Describing Fusion

- To simulate fusion (**irreversibility**): acting inside the Coulomb barrier $-iW_{T1}(x_1)$ & $-iW_{T2}(x_2)$



Preparing the Initial State





Time Propagation

R. Kosloff, Ann. Rev. Phys. Chem. **45** (1994) 145

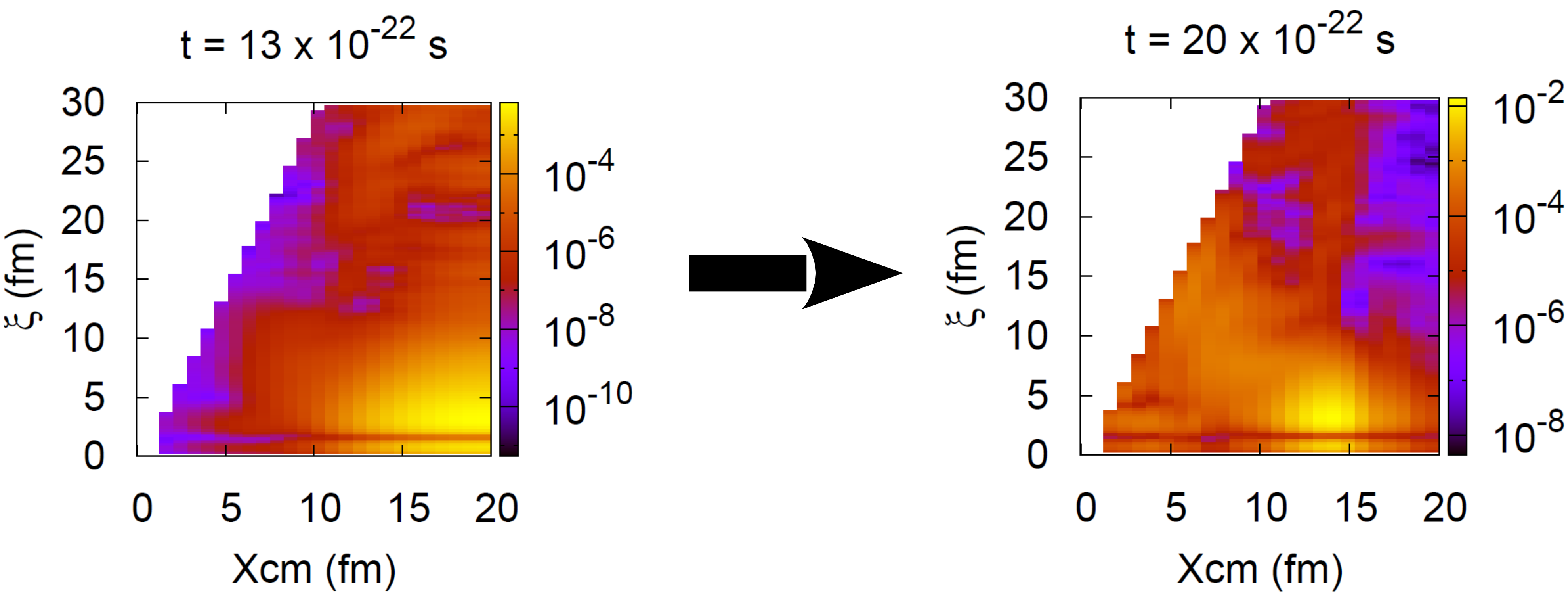
$$\Psi(t+\Delta t) = \exp\left(-\,i\frac{\hat{H}\,\Delta t}{\hbar}\right)\Psi(t)$$

$$\exp\left(-\,i\frac{\hat{H}\,\Delta t}{\hbar}\right) \approx \sum_n a_n\, Q_n(\hat{H}_{norm})$$

$$\hat{H}_{norm} = \frac{(\bar{H}\,\hat{1} - \hat{H})}{\Delta H}$$

The Chebyshev Propagator

$$a_n = i^n(2-\delta_{n0})\exp(-i\frac{\bar{H}\,\Delta t}{\hbar})\,J_n(\frac{\Delta H\,\Delta t}{\hbar})$$



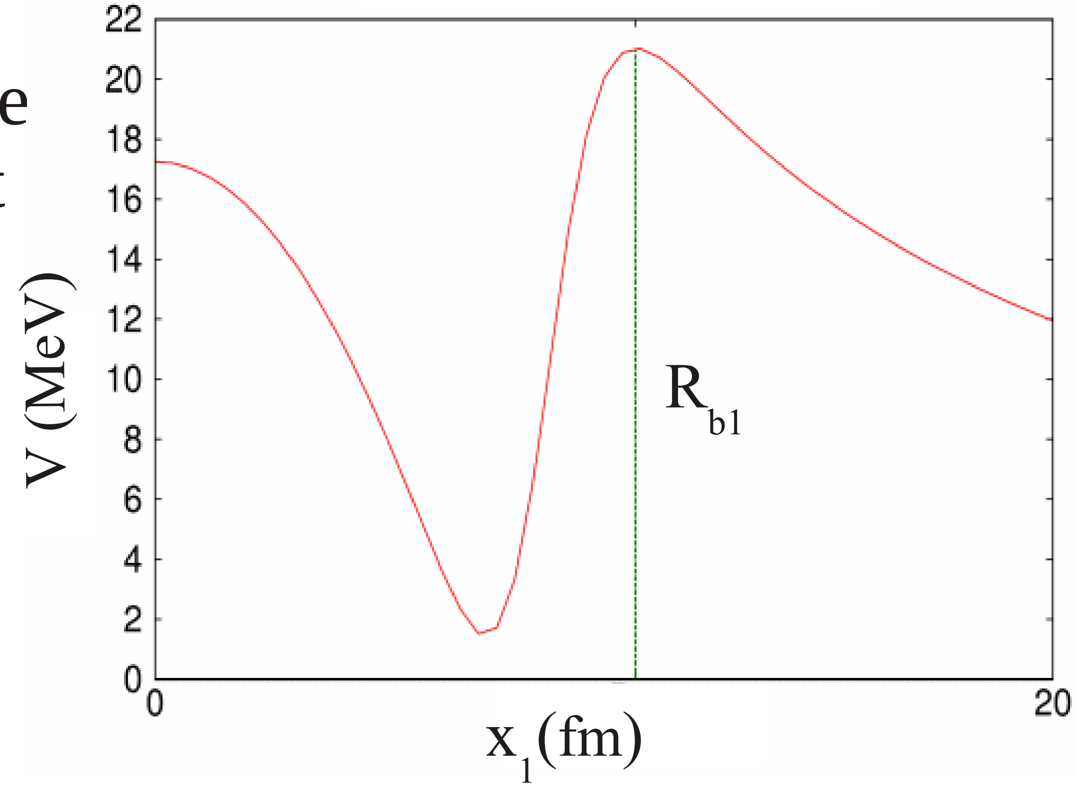
Slicing the Wave Function: A Novel Idea

- Projection operator acting on the position x_i of the fragment relative to the target

(Heaviside function)

$$P_i = \Theta(R_{bi} - x_i)$$
$$Q_i = 1 - P_i$$

Potential: ^{209}Bi - ^{4}He



	CAPTURED	NON CAPTURED
CF	🔴 🔵	
ICF	🔵	🔴

- Act with $(P_1+Q_1)(P_2+Q_2)=1$ on the wave function:

$$\tilde{\Psi}(x_1,x_2,t)=(P_1P_2+P_1Q_2+Q_1P_2+Q_1Q_2)\tilde{\Psi}(x_1,x_2,t)=\Psi_{CF}+\Psi_{ICF}+\Psi_{SCATT}$$

Analysis of the Wave Function

Power Spectrum of the Wave Function

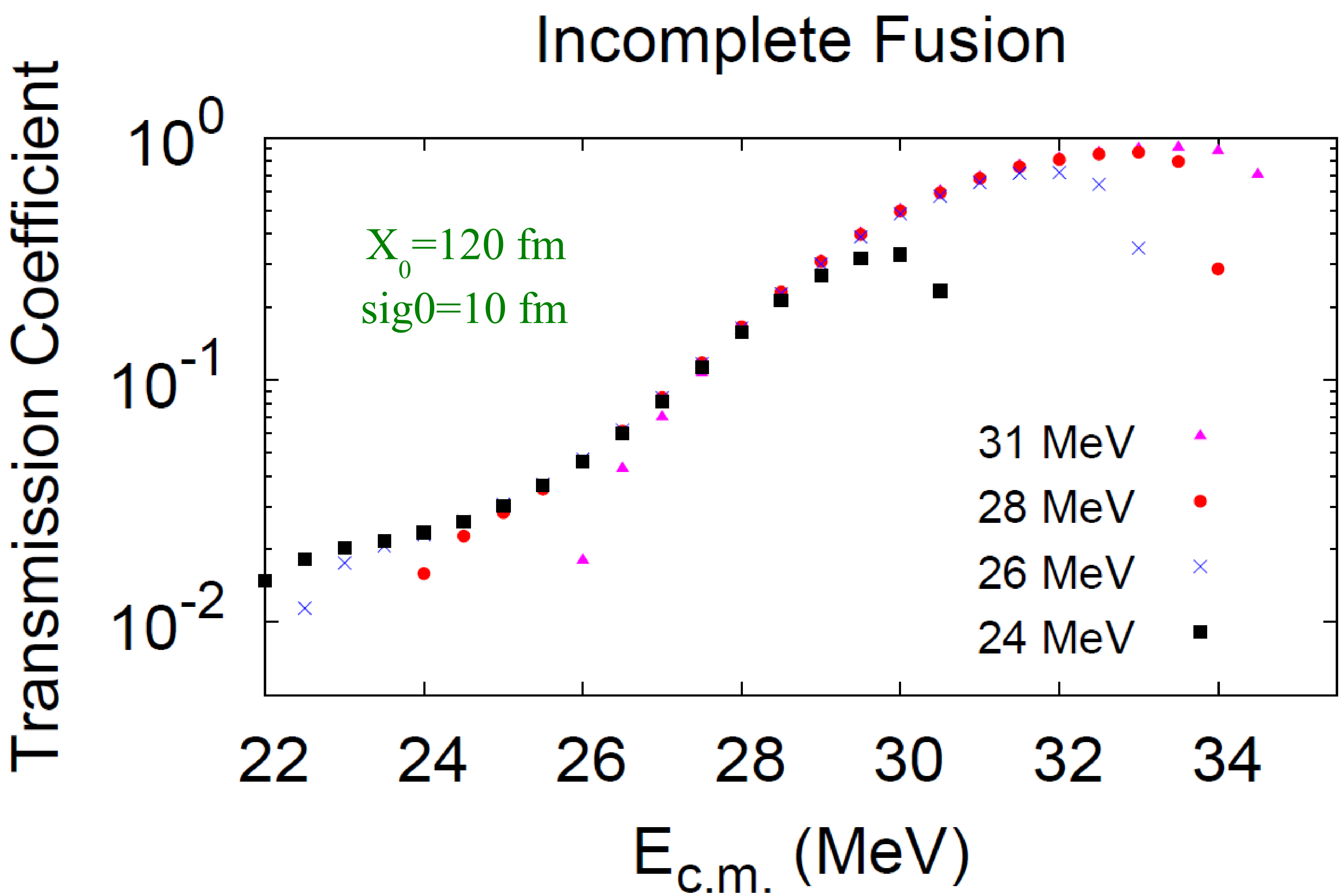
$$\mathcal{P}(E) = \langle \Psi(t) | \underbrace{\delta(E - \hat{H})}_{\text{Energy Projector}} | \Psi(t) \rangle$$

Reflection & Transmission Coefficients

$$\mathcal{R}(E) = \frac{\mathcal{P}^{final}(E)}{\mathcal{P}^{initial}(E)}$$

$$T(E) = 1 - \mathcal{R}(E)$$

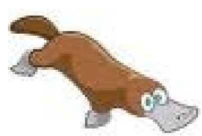
Example


Incomplete Fusion
Transmission Coefficient
10^0
10^-1
10^-2
22
24
26
28
30
32
34
E_c.m. (MeV)
X_0=120 fm
sig0=10 fm
31 MeV
28 MeV
26 MeV
24 MeV

Summary

- **The time-dependent perspective** is useful for understanding and quantifying low-energy reaction dynamics of exotic nuclei.

- **PLATYPUS** is a powerful tool for planning and interpreting (fusion & breakup) measurements, which allow its fine tuning.



AD-T, CPC **182** (2011) 1100

Outlook

- **A quantum dynamical 3D-model** is being developed.

Maddalena Boselli & AD-T, JPG **41** (2014) 094001

Understanding the breakup mechanisms and their impact on unambiguously separated **CF & ICF** processes could make for further progress in the field.