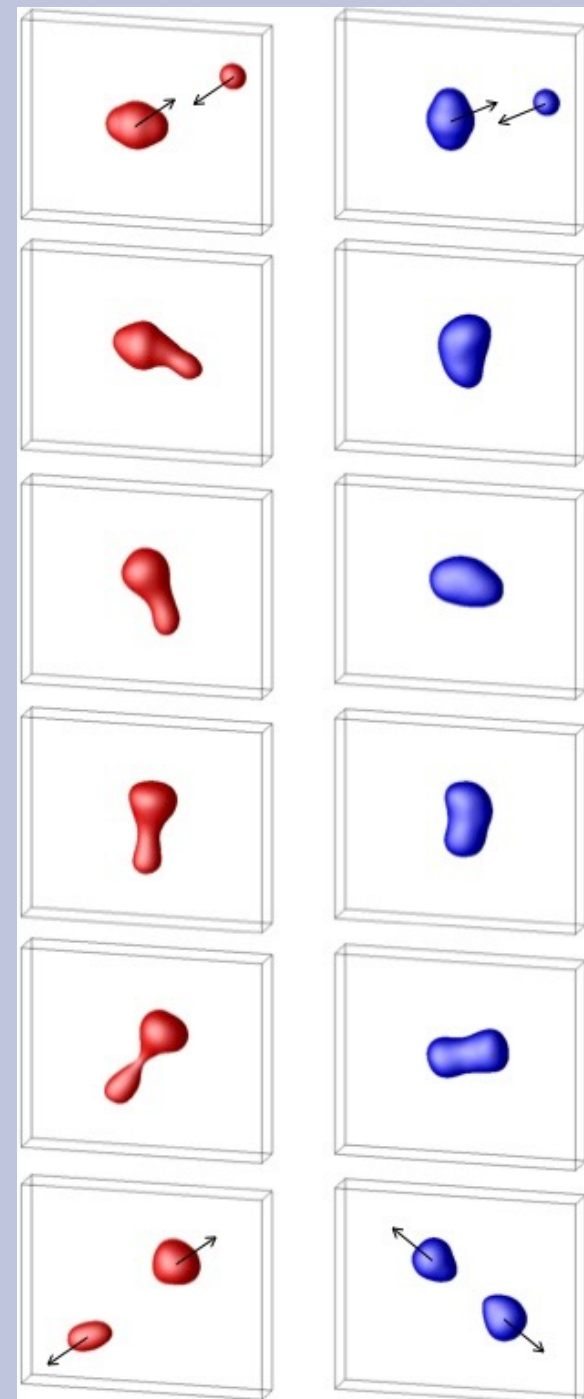


# Shell effects in quasi-fission: *a theoretical perspective (almost)*

Cedric Simenel

*Australian National University*



# Characteristics of quasi-fission

- **Full dissipation of kinetic energy**

$$\text{TKE} \approx \text{TKE}_{\text{Viola}} \text{ (fission fragments)}$$

- **Mass equilibration**

Mass transfer from heavy to light fragment

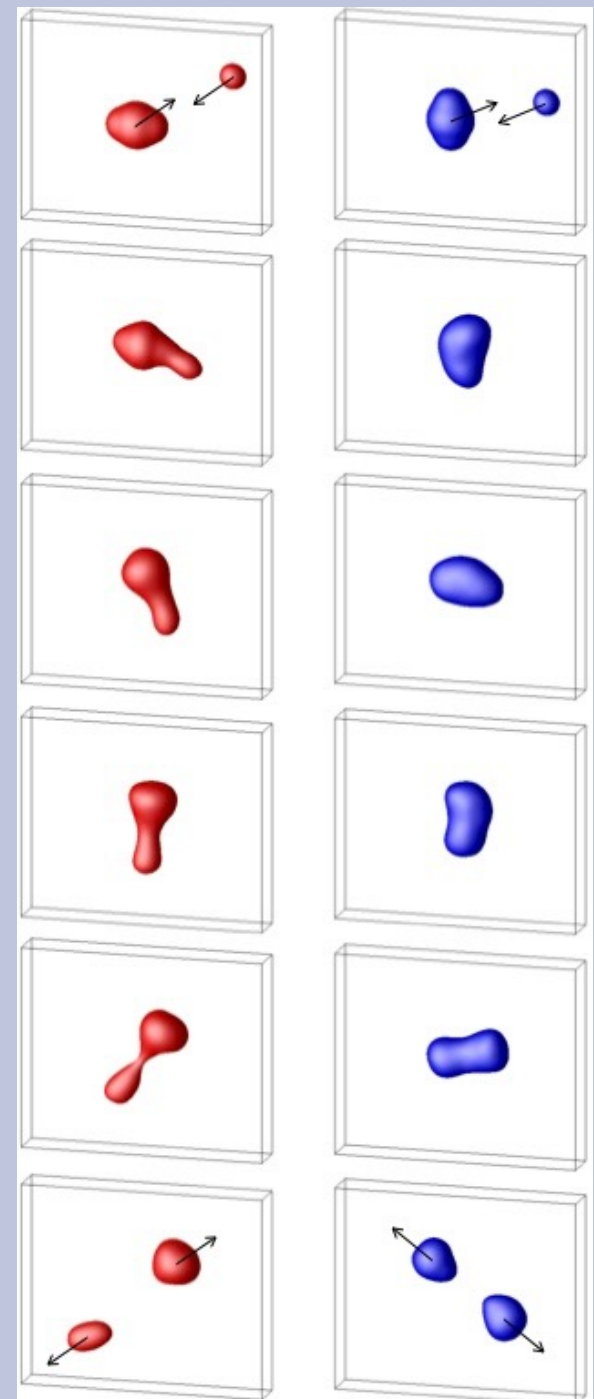
- **Angular correlations**

Non-isotropic distributions

- **Mass-angle correlations**

Contact times from few zs to few 10 zs

***No compound nucleus formation***



# Time-Dependent Hartree-Fock

Mean-field of independent particles

Only input is the interaction  
(Energy Density Functional)

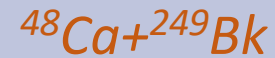
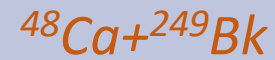
Skyrme-SLy4d



# Shell effects in quasi-fission fragments with TDHF

## Superheavy CN:

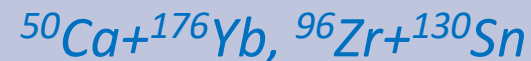
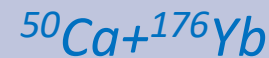
- Wakhle et al, PRL **113**, 182502 (2014)
- Oberacker et al, PRC **90**, 054605 (2014)
- Sekizawa & Yabana, PRC **93**, 054616 (2016)
- Umar et al, PRC **94**, 024605 (2016)
- Morjean et al, PRL **119**, 222502 (2017)
- L Guo et al, PRC **98**, 064609 (2018)
- Godbey et al, PRC **100**, 024610 (2019)
- L Li et al, PLB **833**, 137349 (2022)
- McGlynn & Simenel, PRC **107**, 054614 (2023)
- L Li et al, PRC **110**, 064607 (2024)



=> *Shell effects: Z=82 N=56,126 (= SHE superasymmetric fission)*

## Actinide CN:

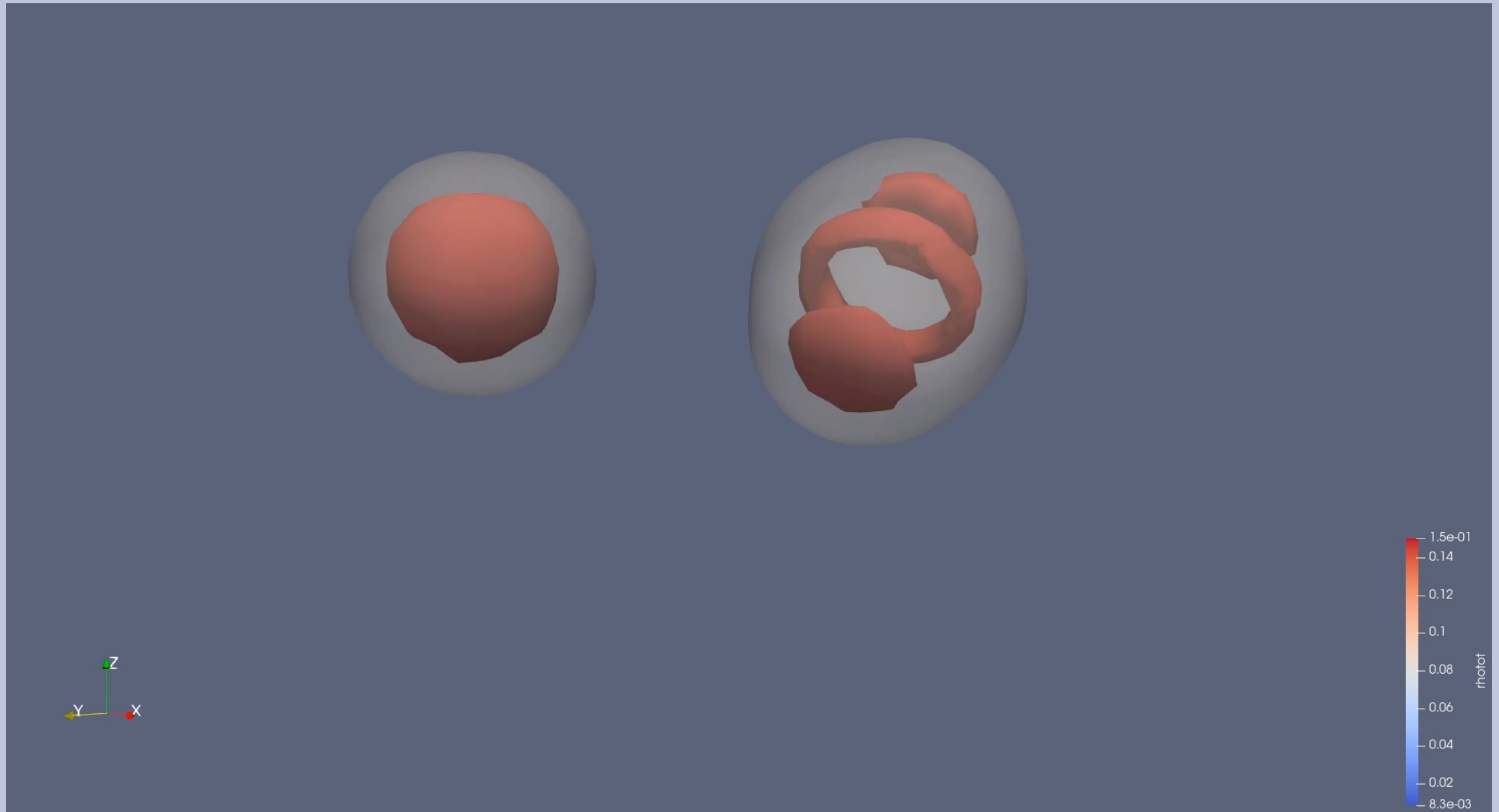
- Simenel et al, PLB **822**, 136648 (2021)
- H Lee et al, PRC **110**, 024606 (2024)
- Simenel et al, PLB **871**, 139955 (2025)



=> *Shell effects: Z=52,56 (= actinide asymmetric fission)*

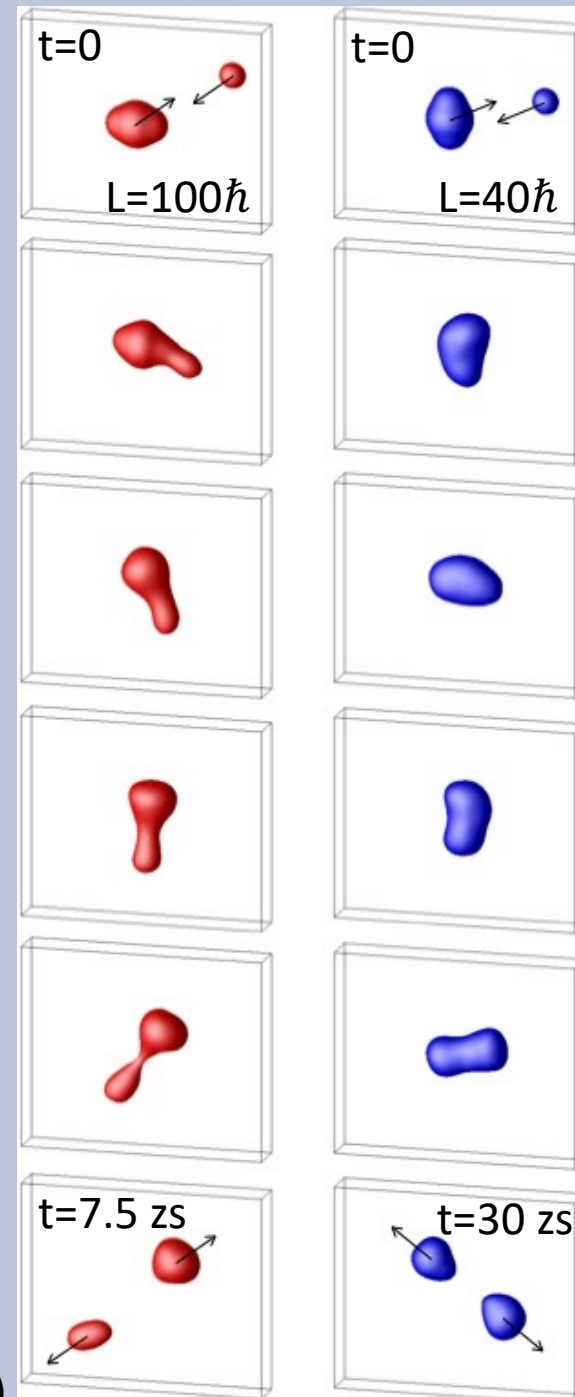
# TDHF studies of quasi-fission

Godbey et al, PRC **100**, 024610 (2019)



# TDHF studies of quasi-fission

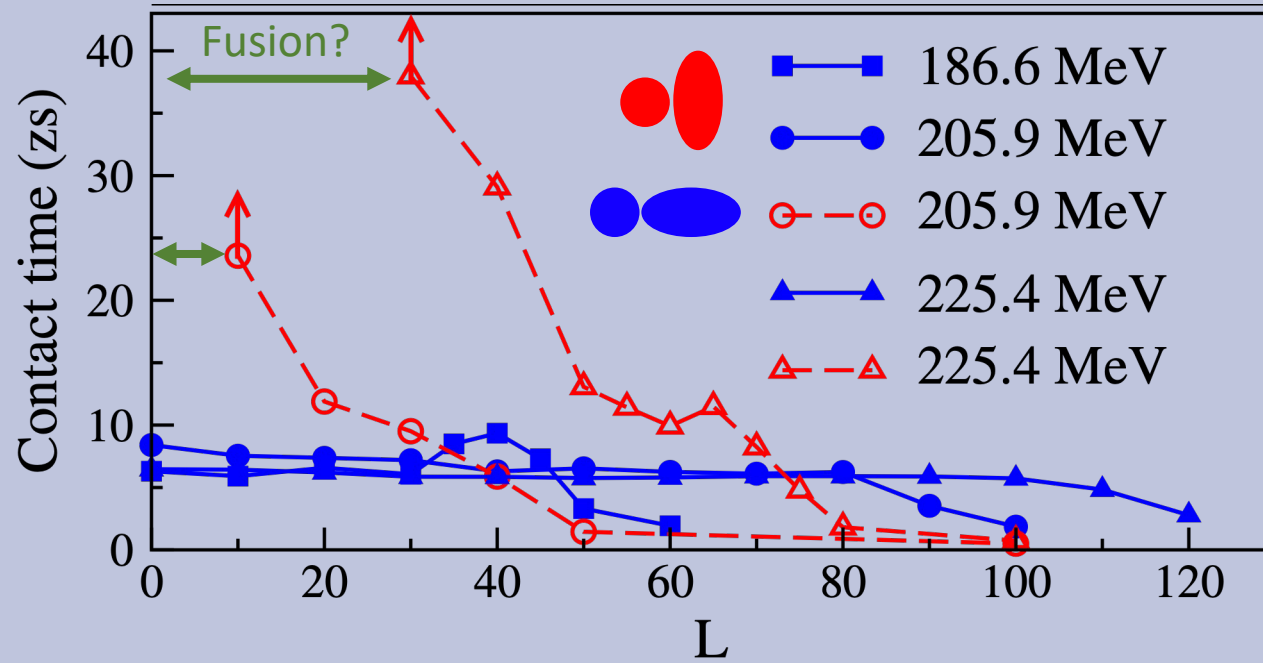
- Contact times from few zs to few 10 zs



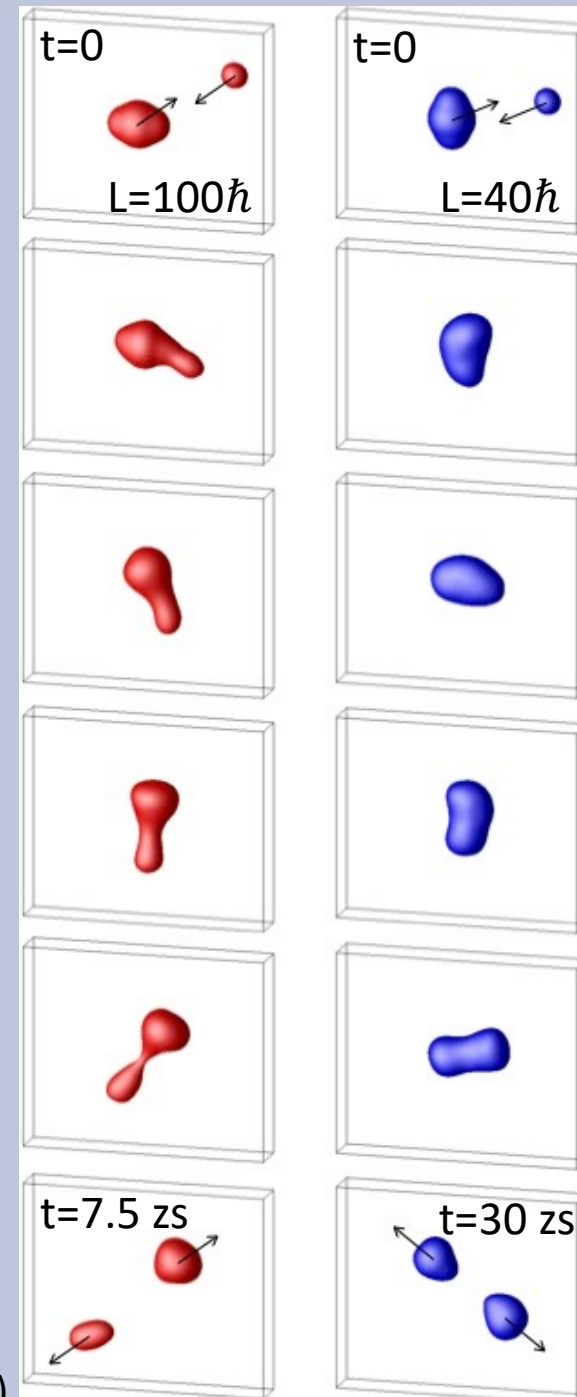
$^{40}\text{Ca} + ^{238}\text{U}$   
 $E_{\text{cm}} = 225.4\text{ MeV}$

# TDHF studies of quasi-fission

- Contact times from few zs to few 10 zs
- Orientation effect



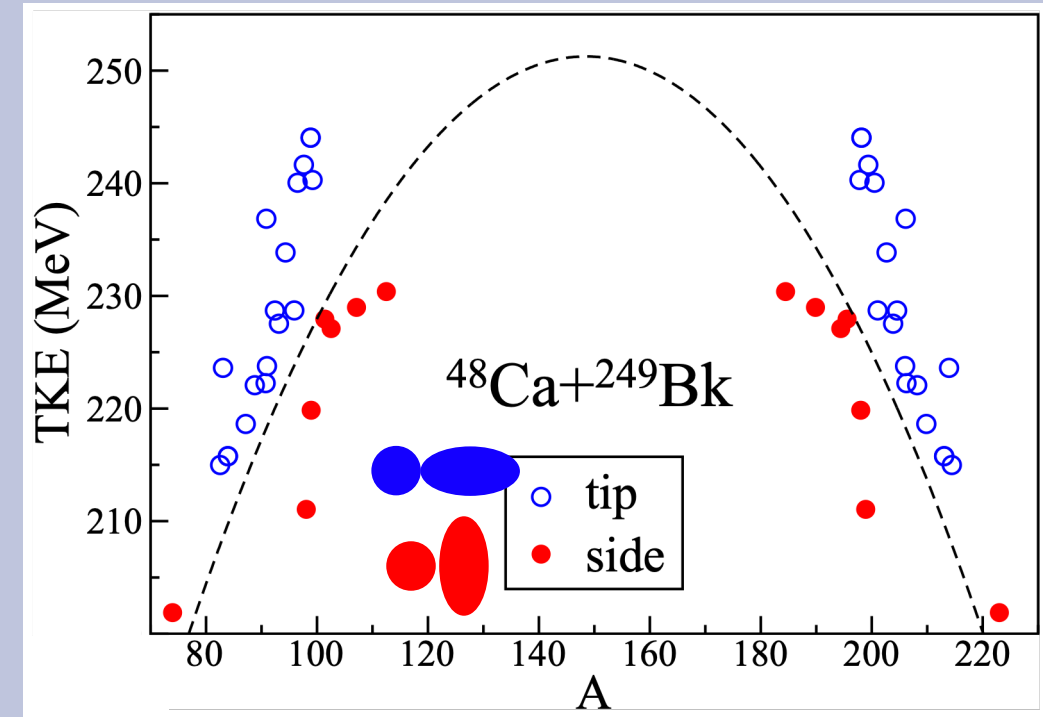
Wakhle et al, PRL **113**, 182502 (2014)



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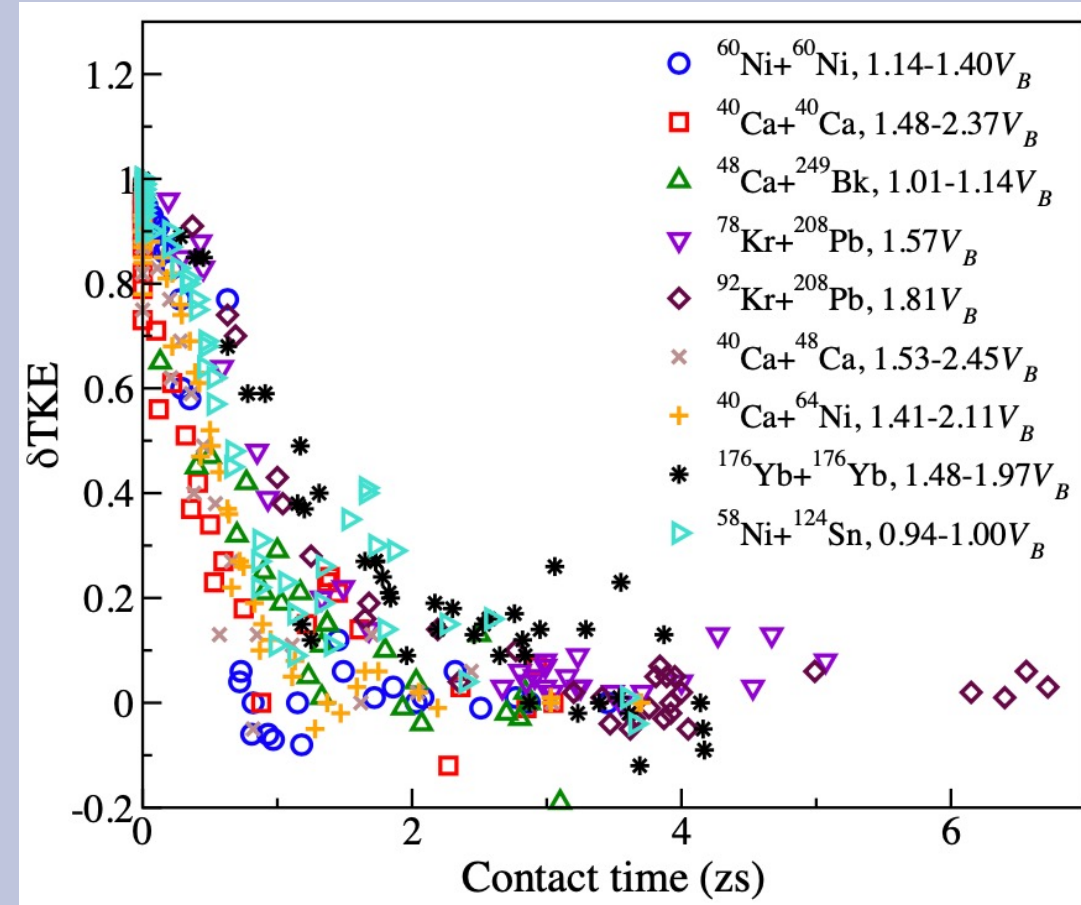
- Contact times from few zs to few 10 zs
- Orientation effect
- $TKE \approx TKE_{\text{Viola}}$  (fission fragments)



Umar et al, PRC **94**, 024605 (2016)

# TDHF studies of quasi-fission

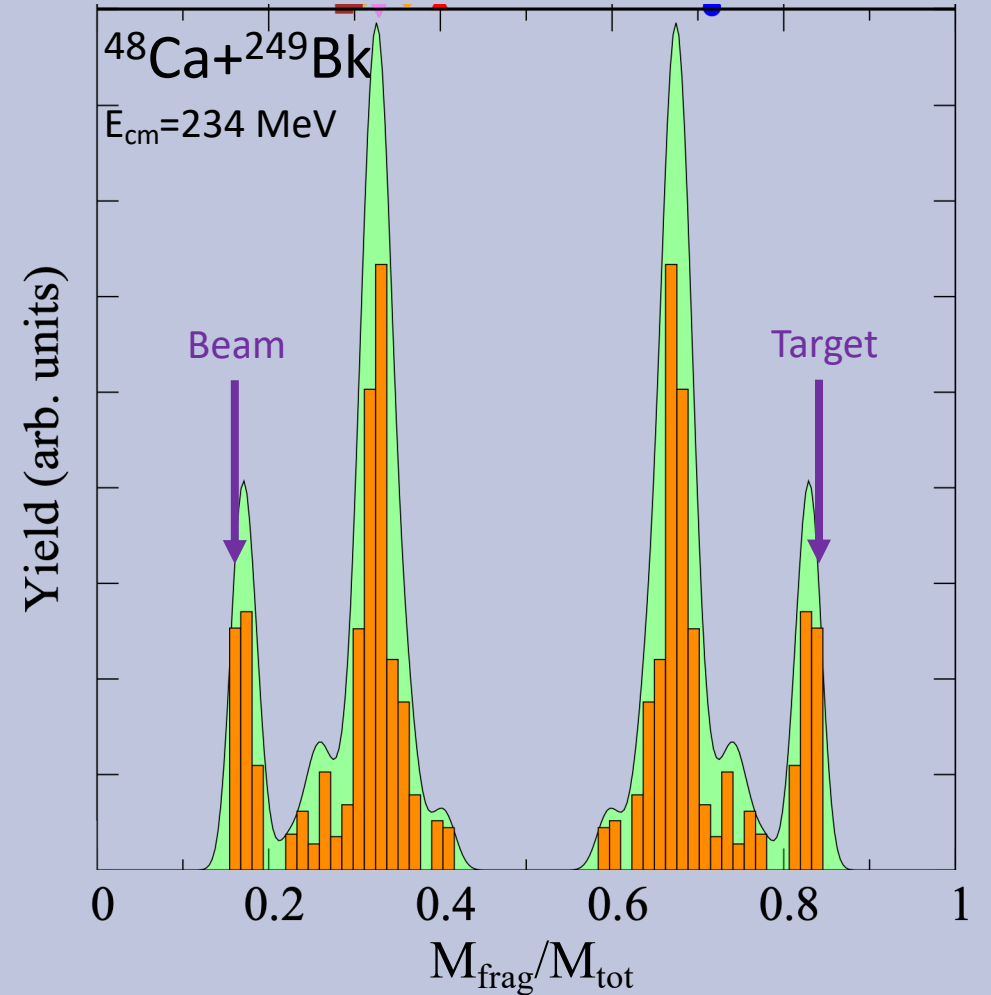
- Contact times from few zs to few 10 zs
- Orientation effect
- $TKE \approx TKE_{Viola}$  (fission fragments)
- Energy dissipation time 1-2 zs



CS et al, PRL **212**, 212504 (2020)

# TDHF studies of quasi-fission

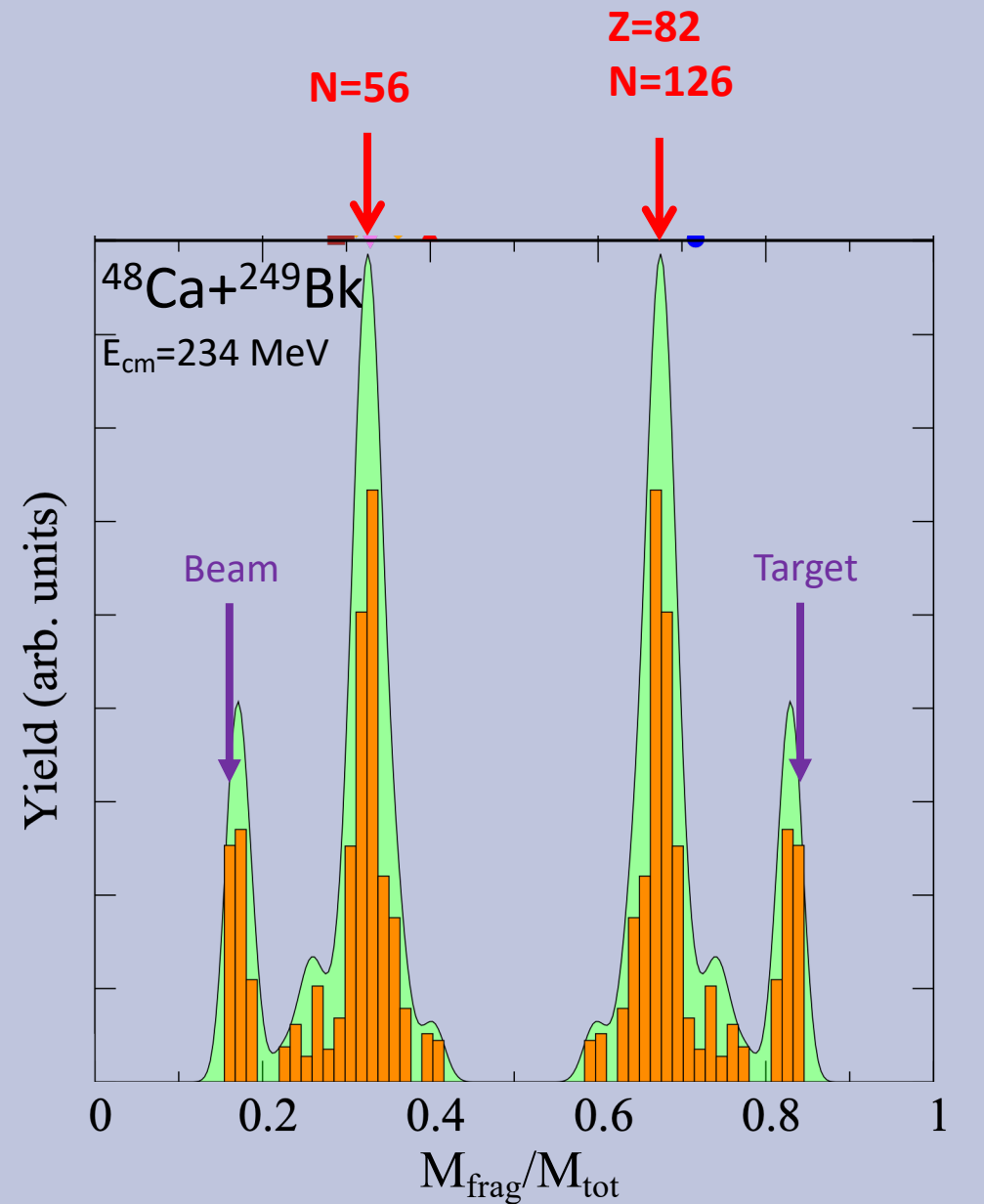
- Contact times from few zs to few 10 zs
- Orientation effect
- $TKE \approx TKE_{Viola}$  (fission fragments)
- Energy dissipation time 1-2 zs
- Partial mass equilibration



Godbey et al, PRC **100**, 024610 (2019)

# TDHF studies of quasi-fission

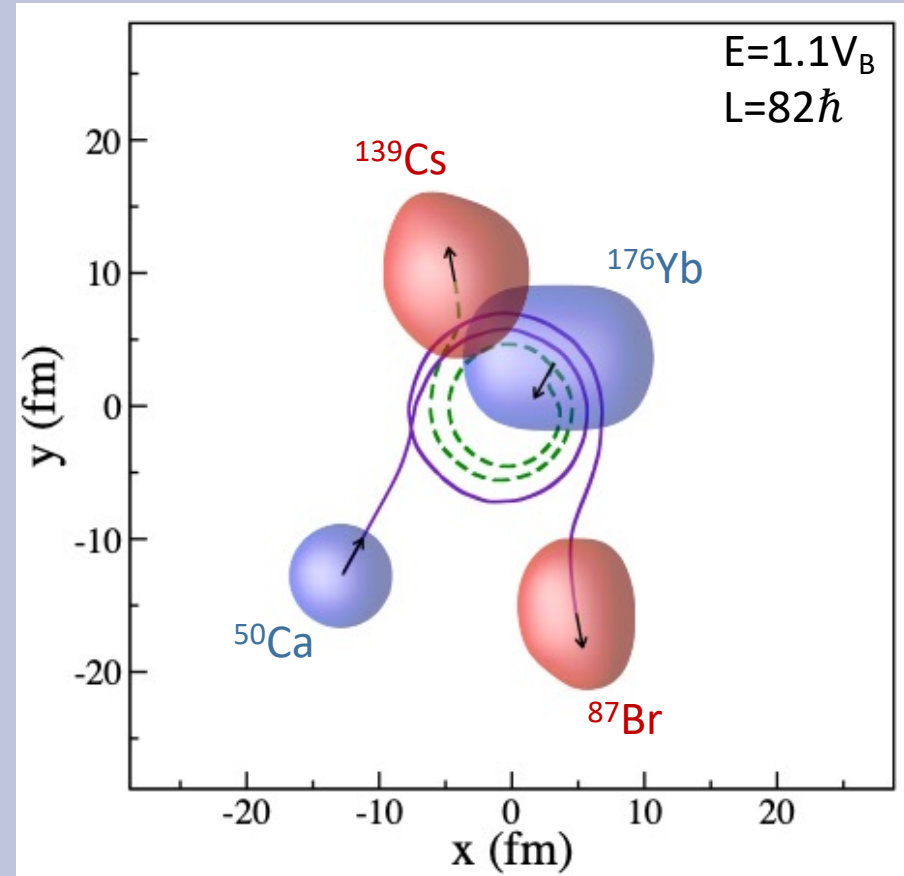
- Contact times from few zs to few 10 zs
- Orientation effect
- $TKE \approx TKE_{Viola}$  (fission fragments)
- Energy dissipation time 1-2 zs
- Partial mass equilibration
- Potential shell effects
  - super-asymmetric mode in SHE



Godbey et al, PRC **100**, 024610 (2019)

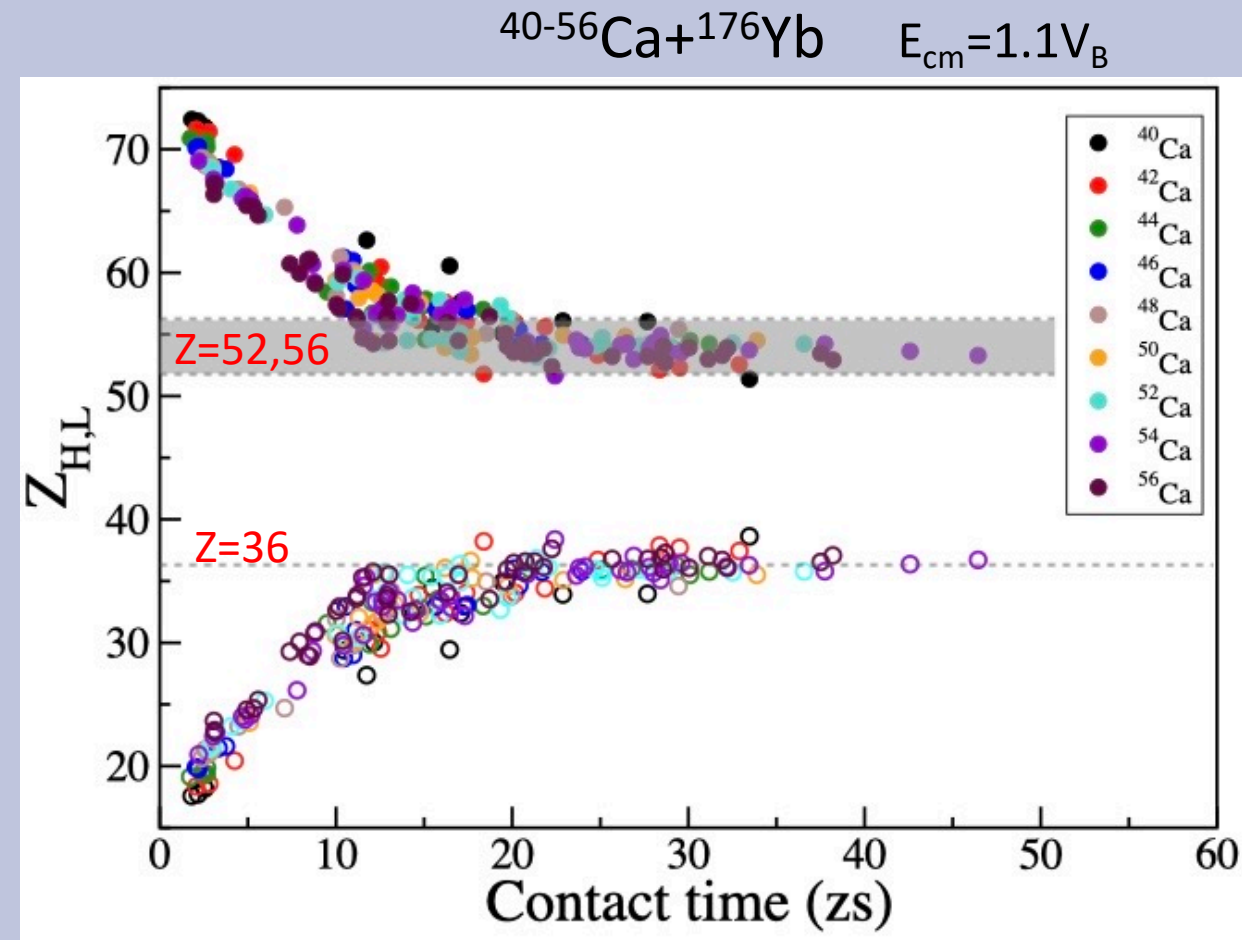
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  - super-asymmetric mode in SHE
  - asymmetric mode in actinides



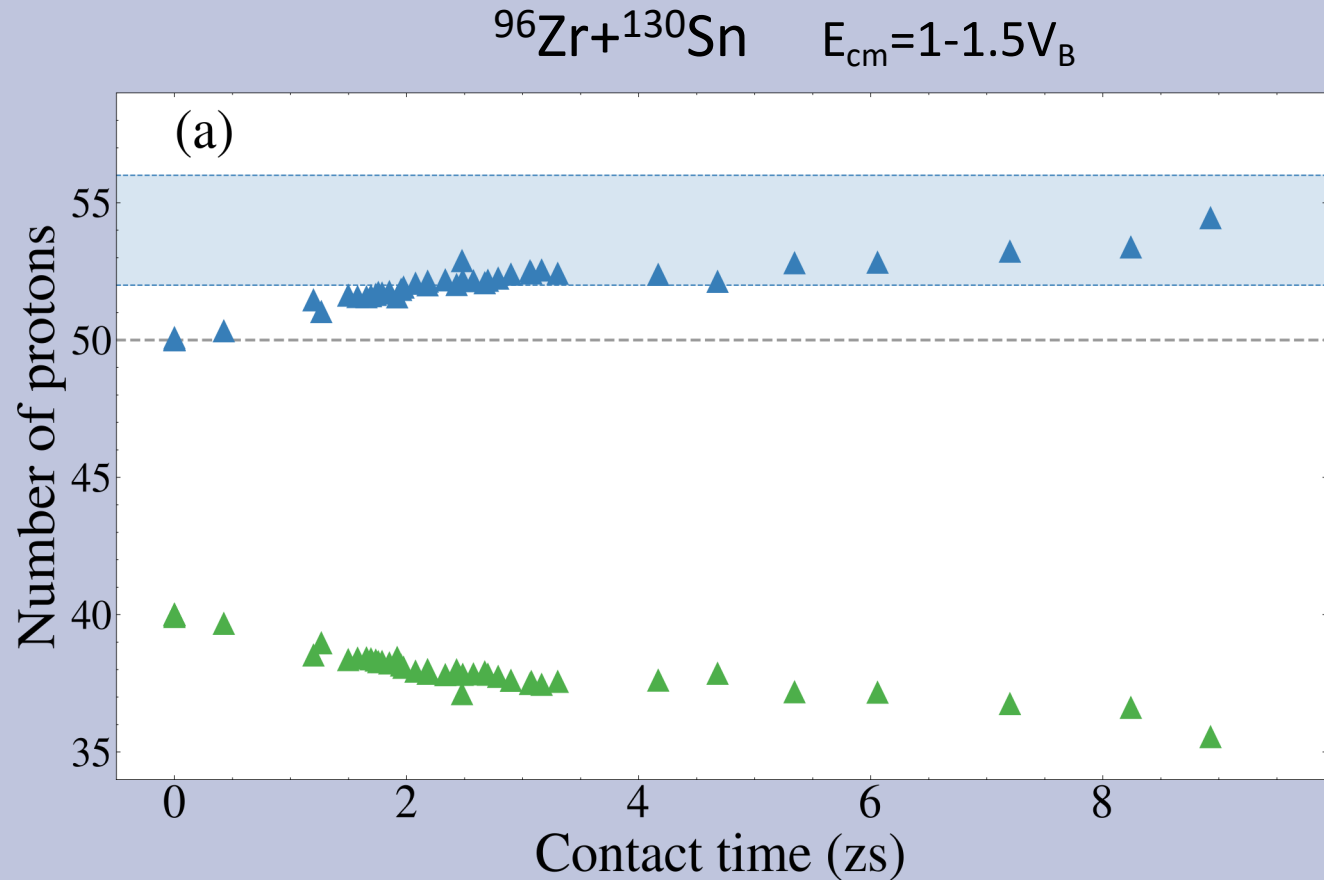
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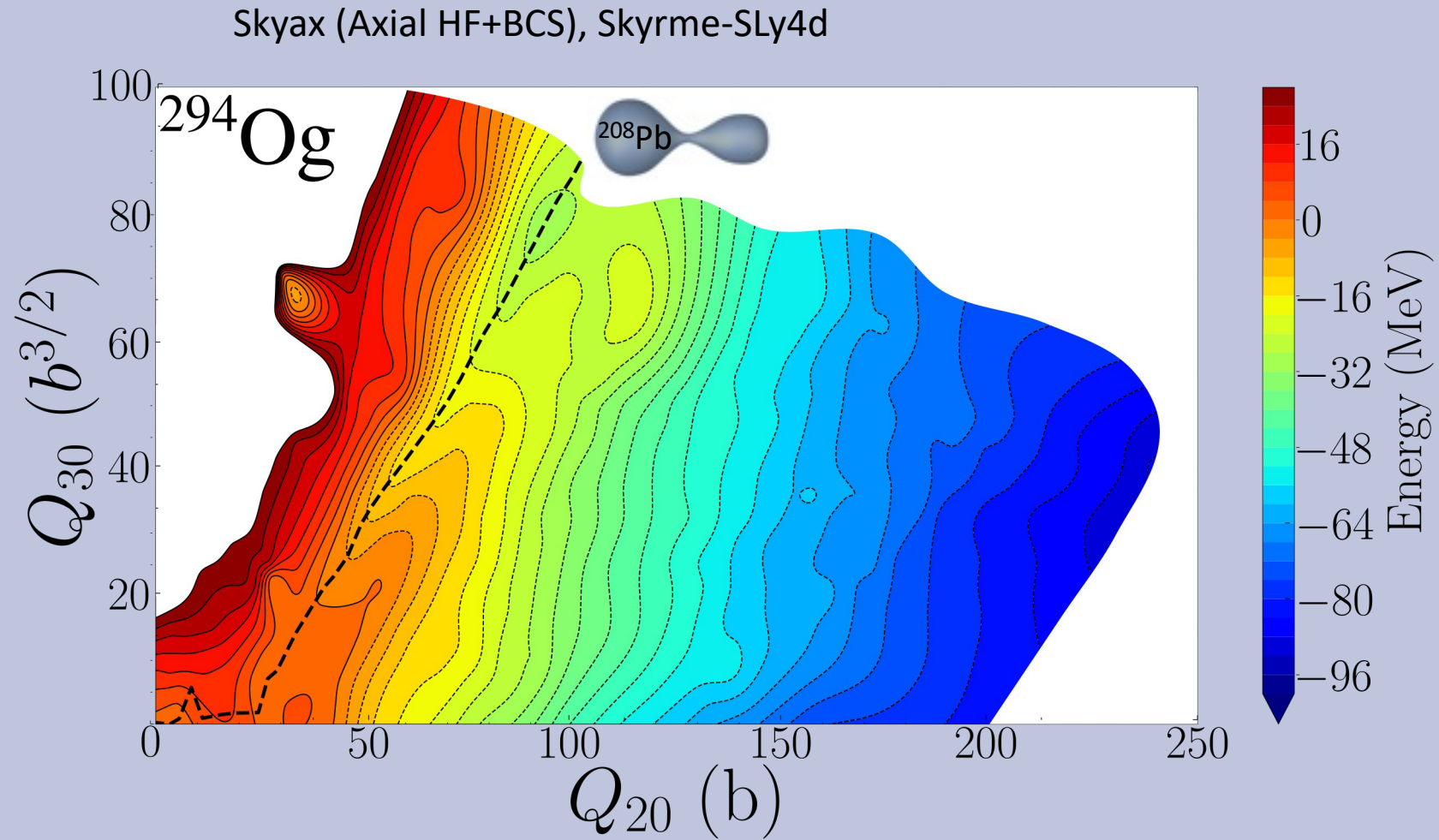
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- Partial mass equilibration
- Potential shell effects
  - super-asymmetric mode in SHE
  - asymmetric mode in actinides
  - inverse quasi-fission



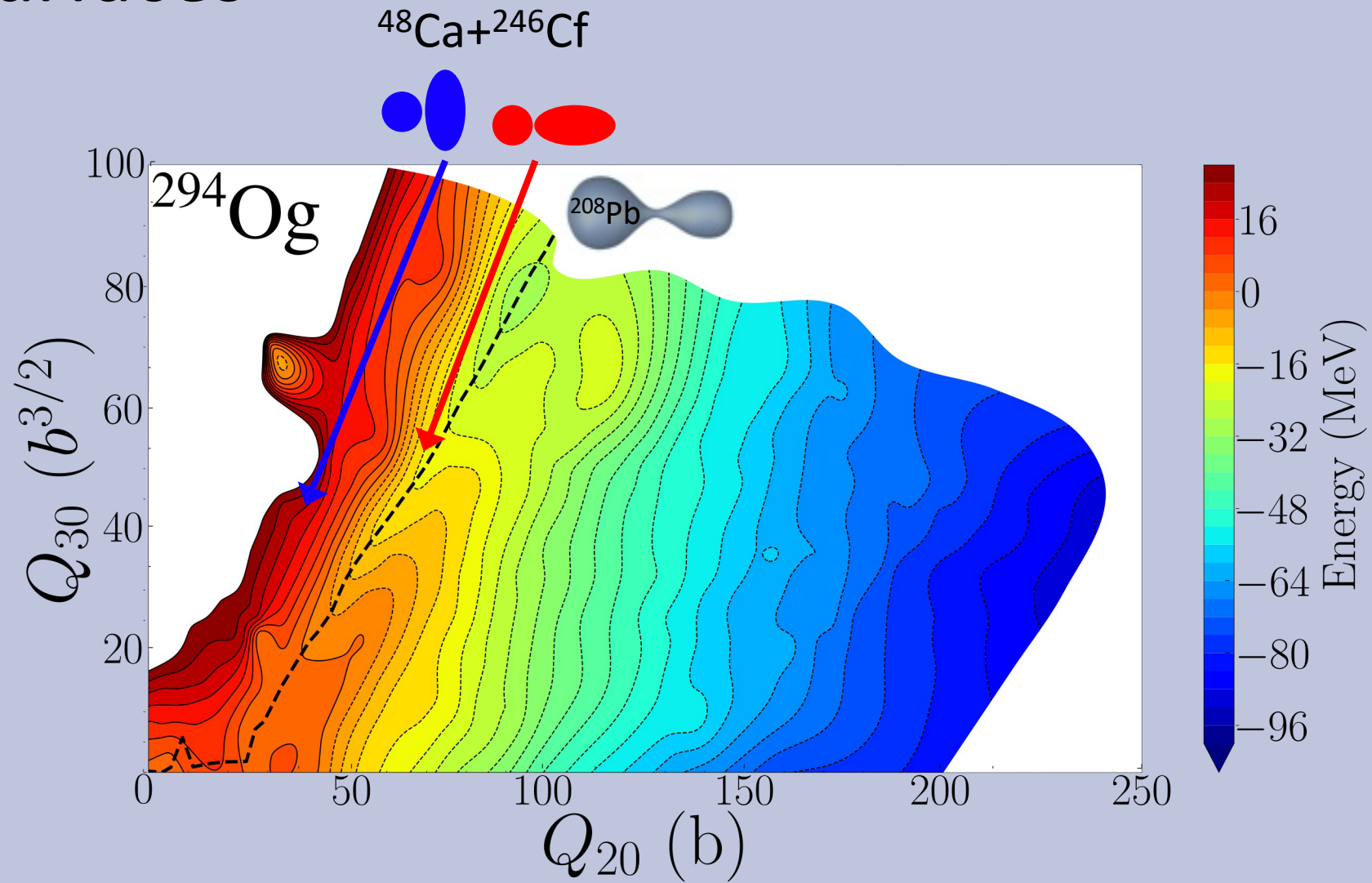
# Potential energy surfaces

- Axial sym.,  $E^*=0$ ,  $L=0$



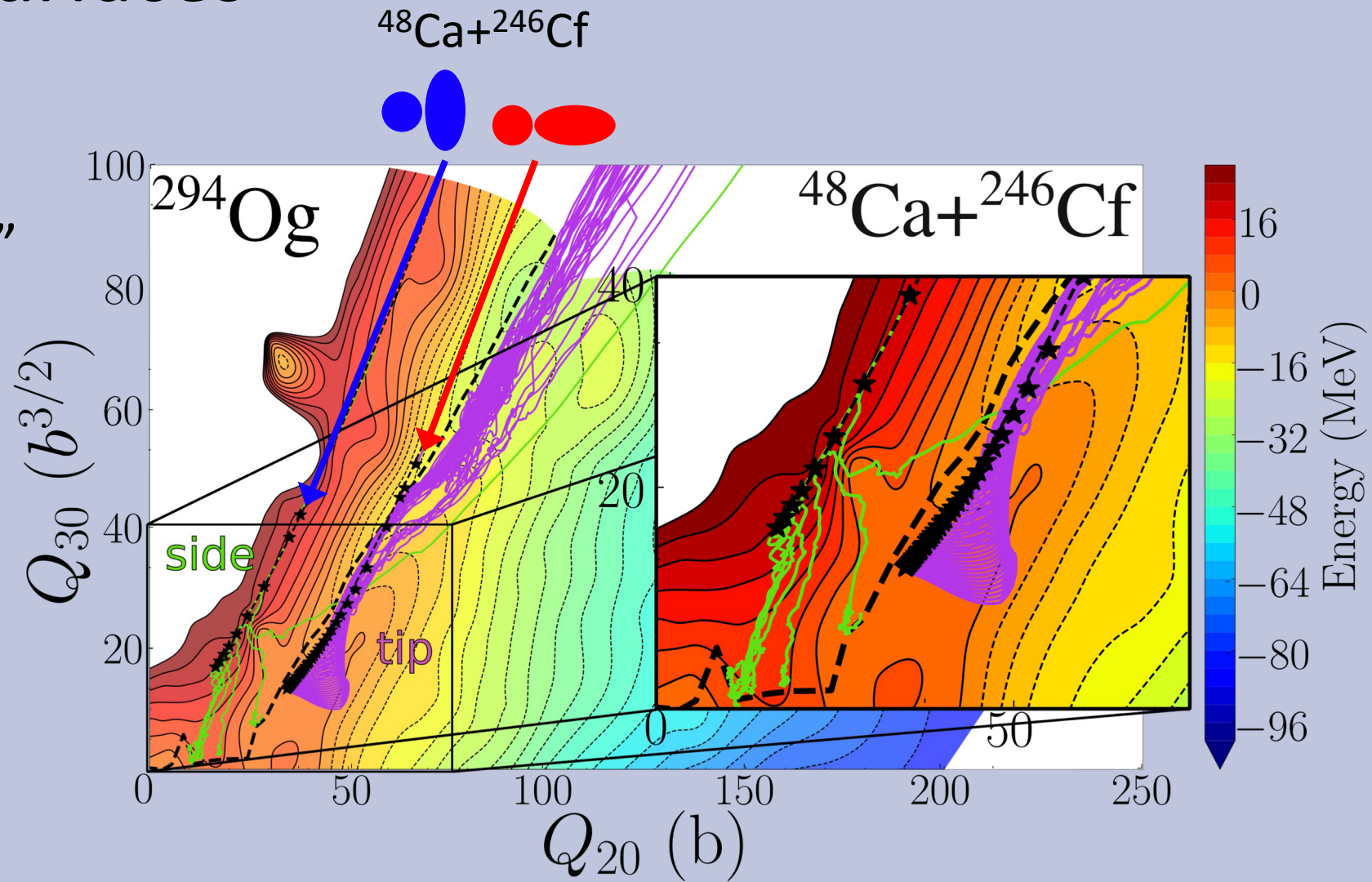
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- Axial sym.,  $E^*=0$ ,  $L=0$



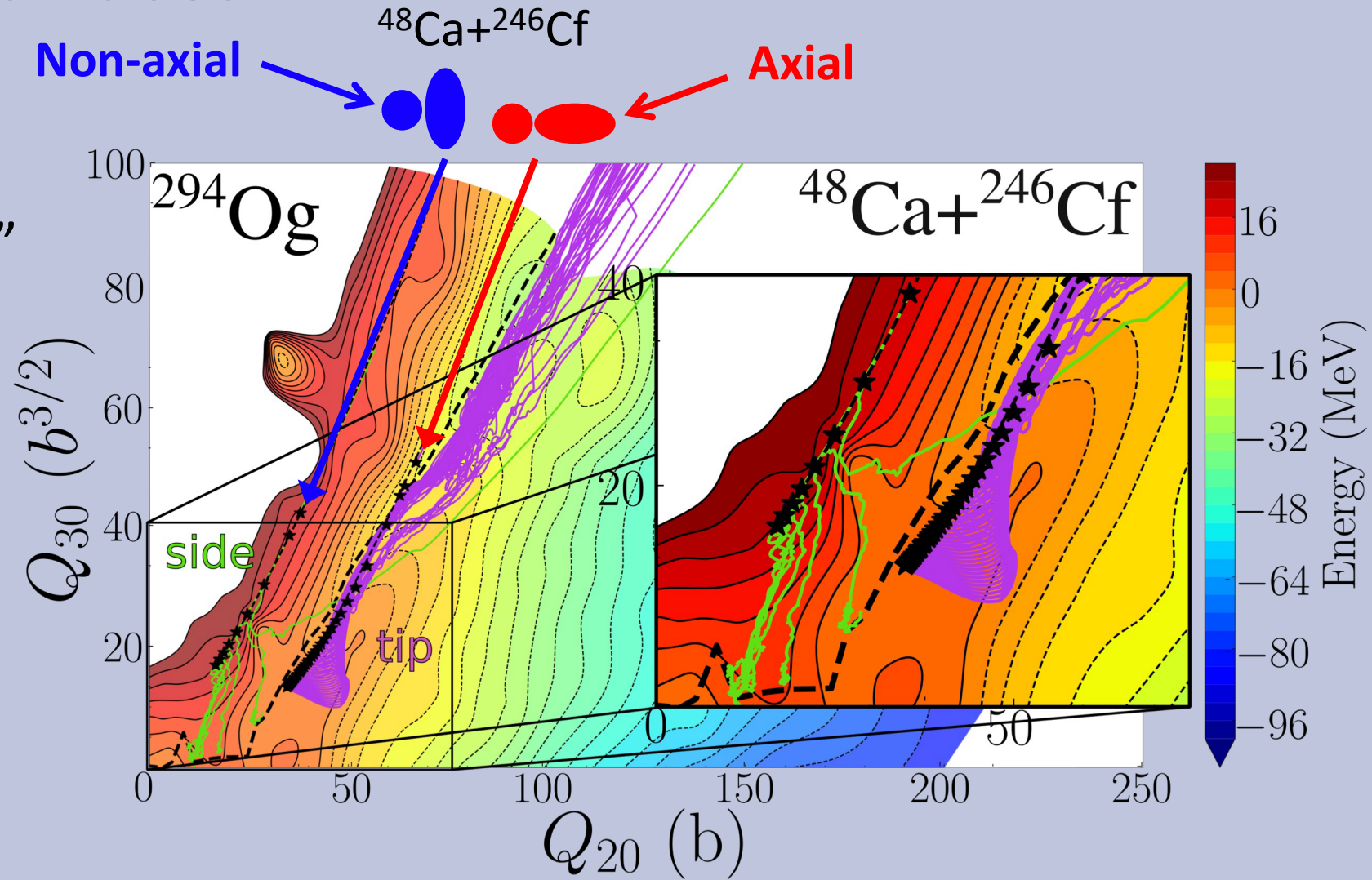
# Potential energy surfaces

- Axial sym.,  $E^*=0$ ,  $L=0$
- $L=0$  TDHF “trajectories”



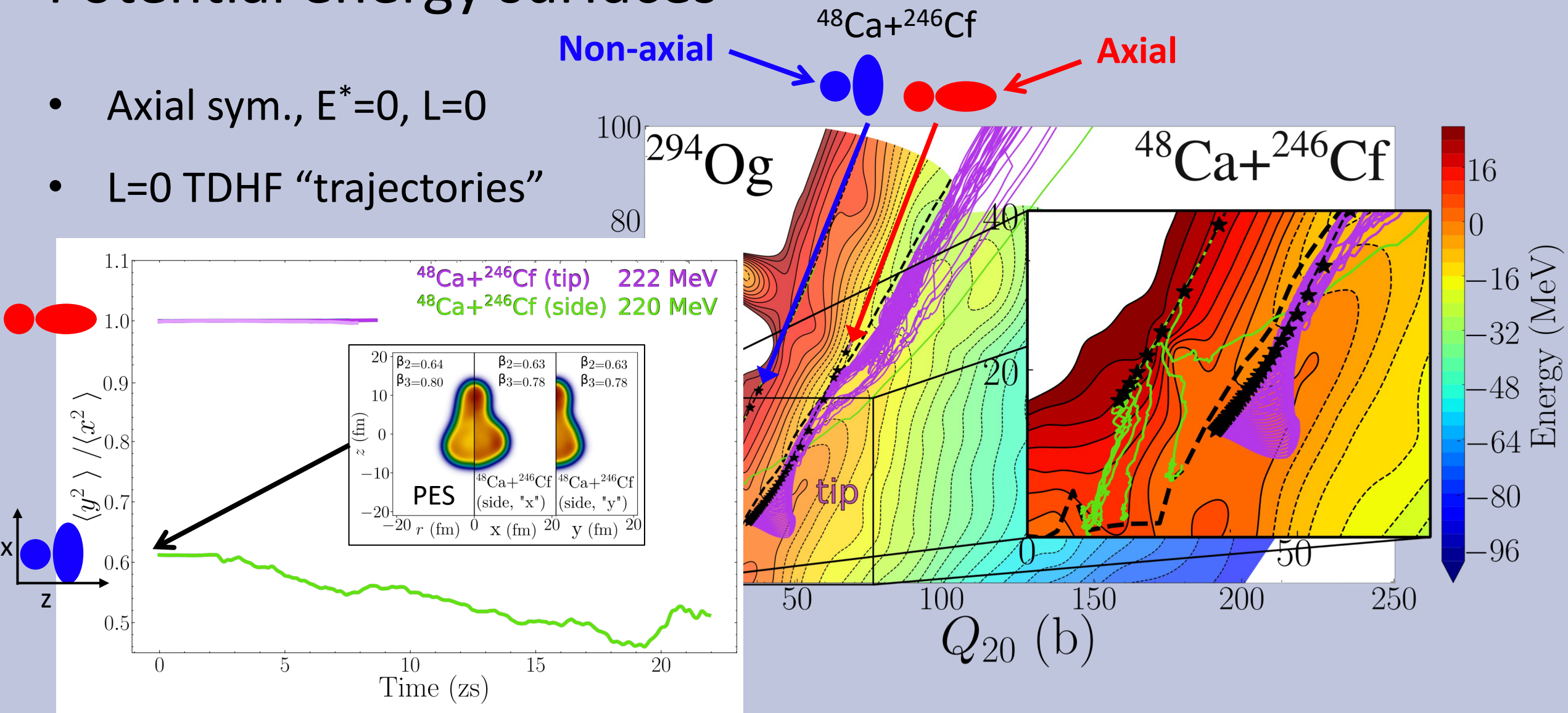
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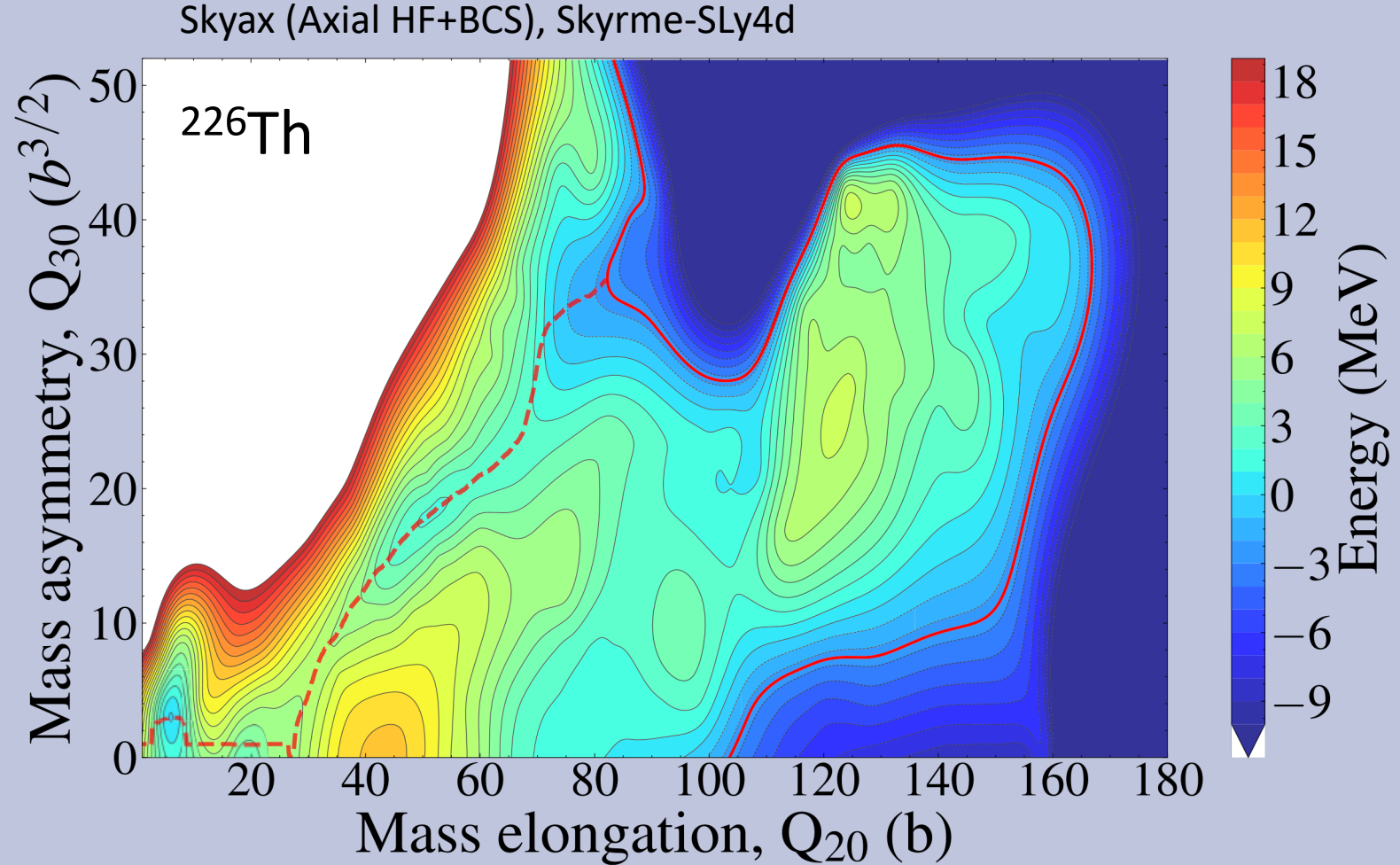
# Potential energy surfaces

- Axial sym.,  $E^*=0, L=0$
- $L=0$  TDHF “trajectories”



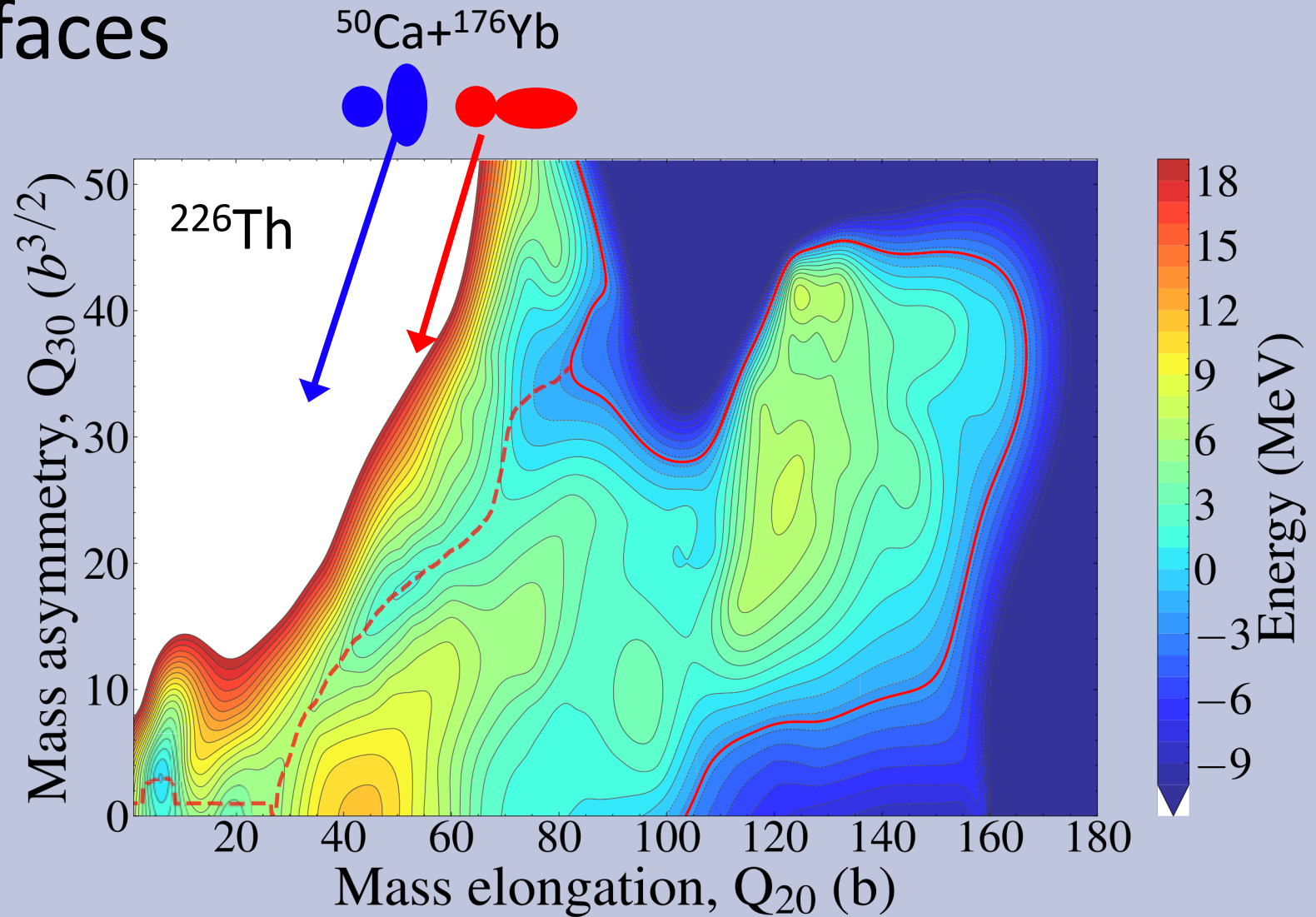
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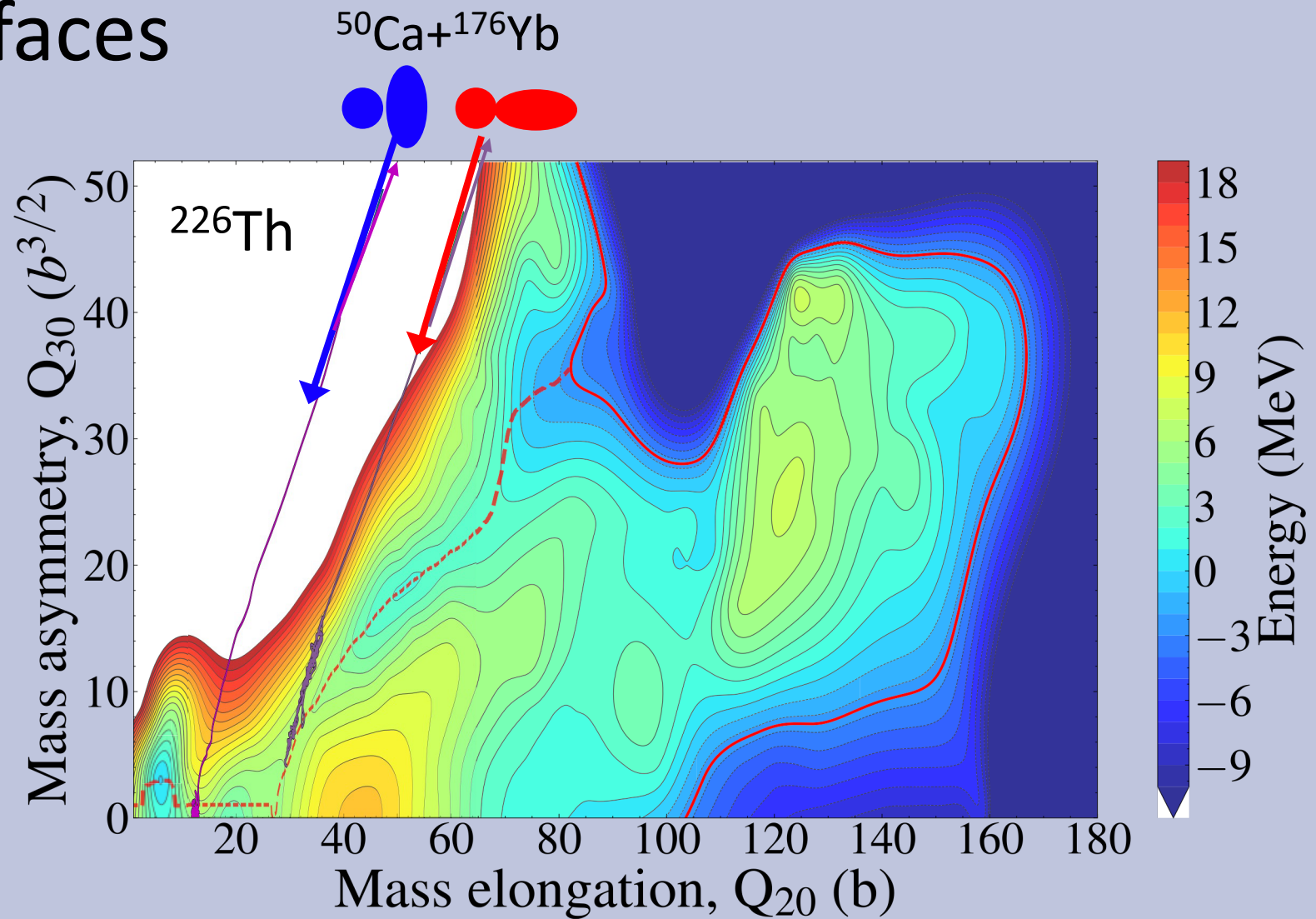
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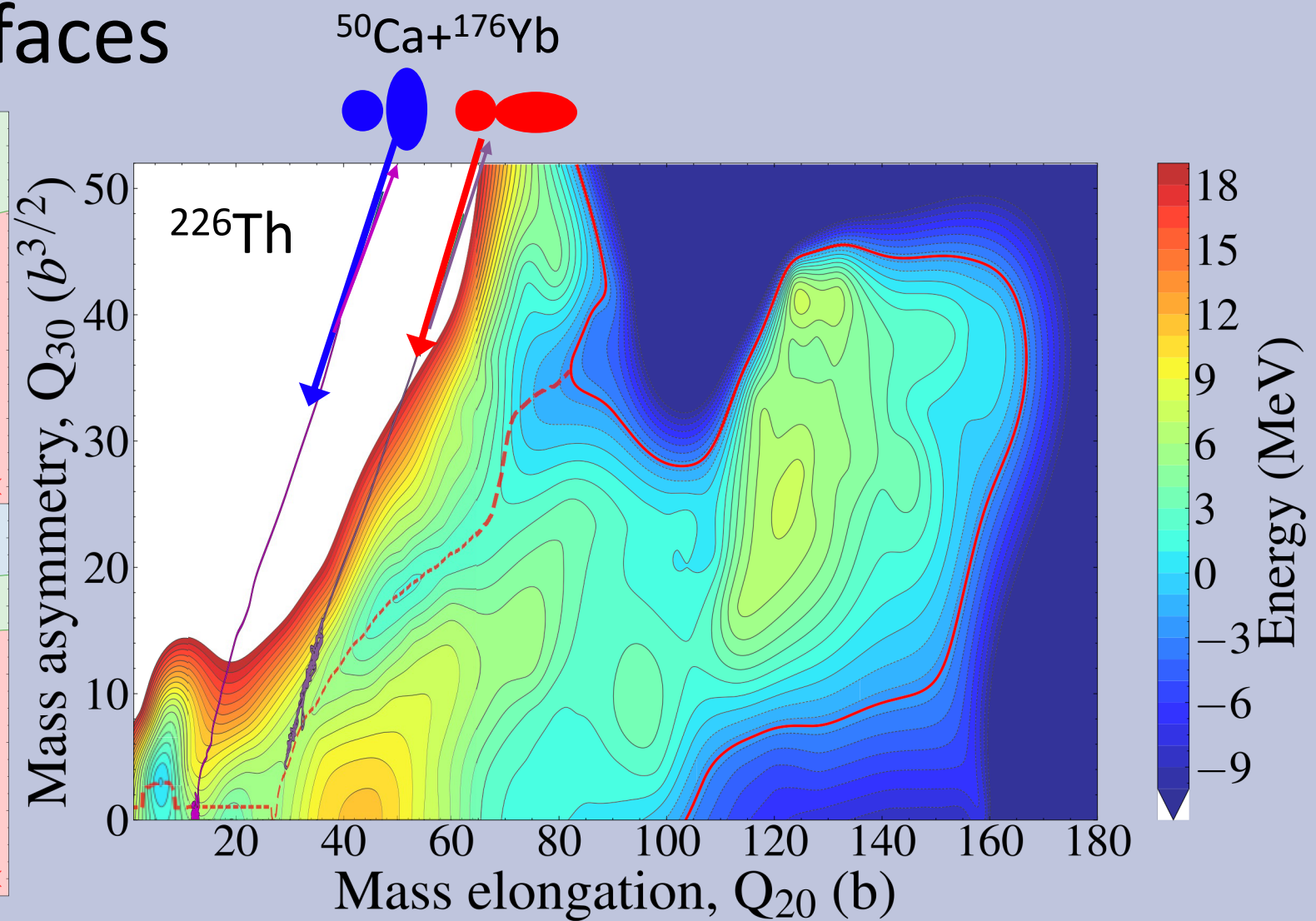
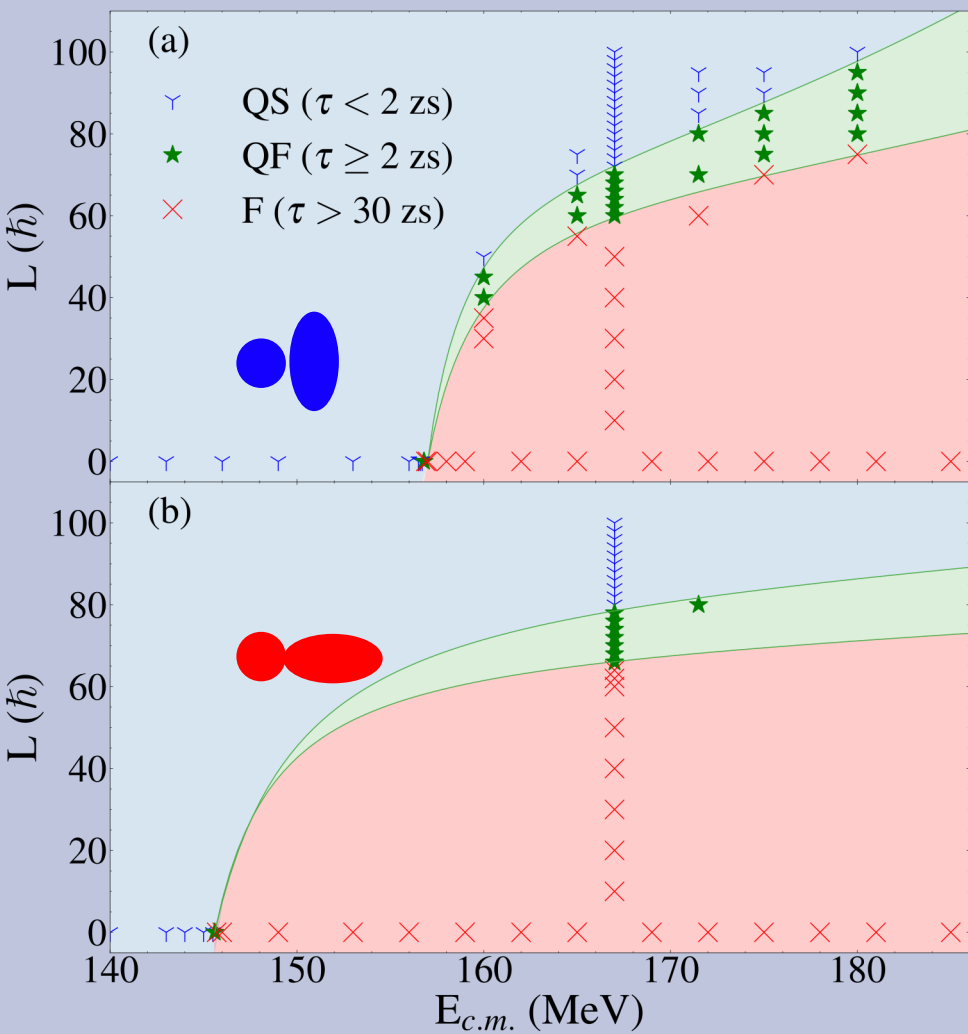


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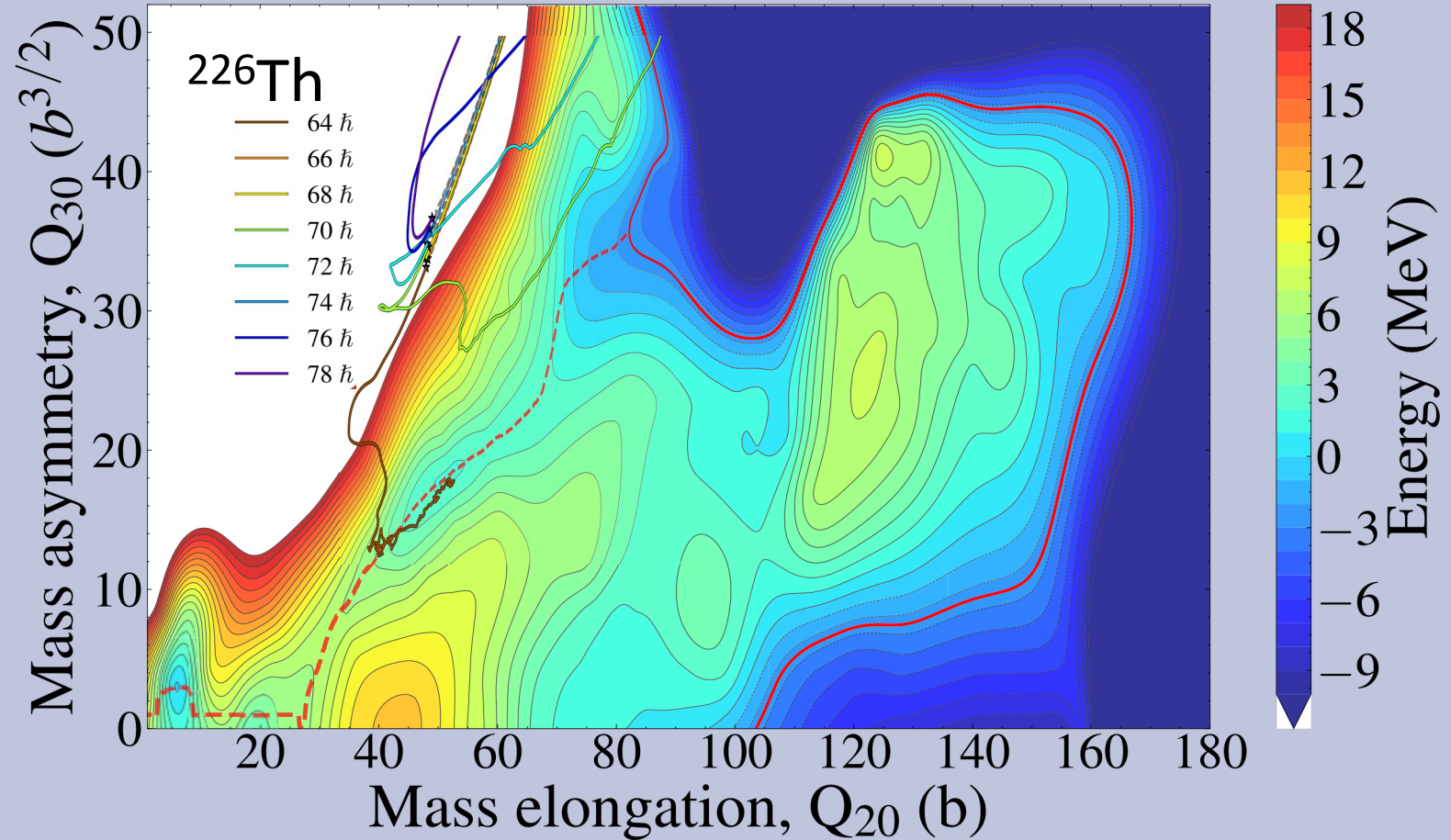


# Potential energy surfaces

$^{50}\text{Ca} + ^{176}\text{Yb}$   $E_{\text{cm}} = 167$  MeV

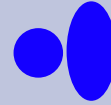


- Axial sym.,  $E^* = 0$ ,  $L = 0$
- $L \neq 0$  TDHF “trajectories”

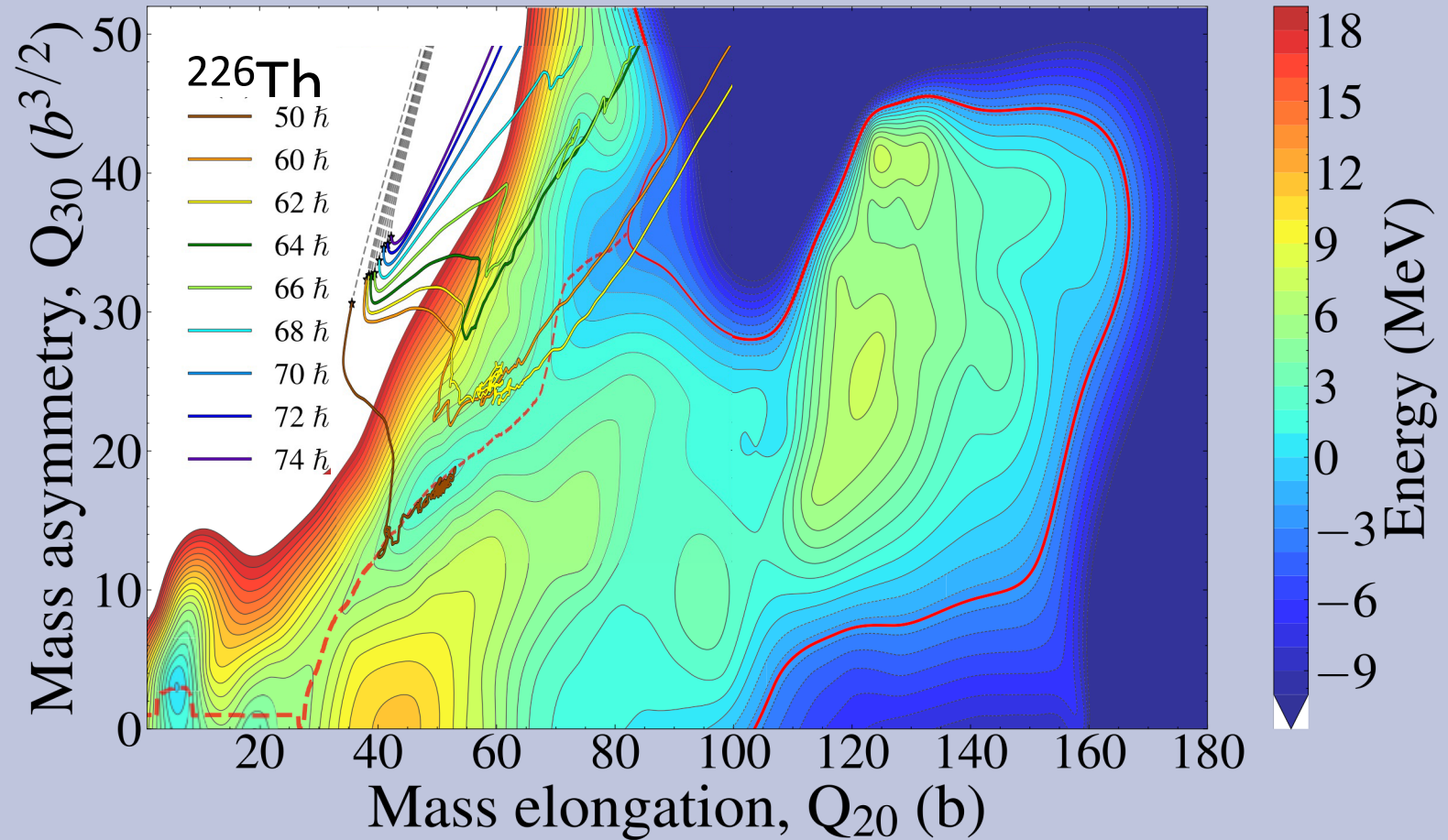


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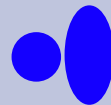
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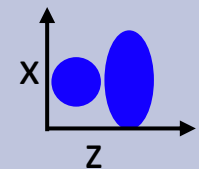
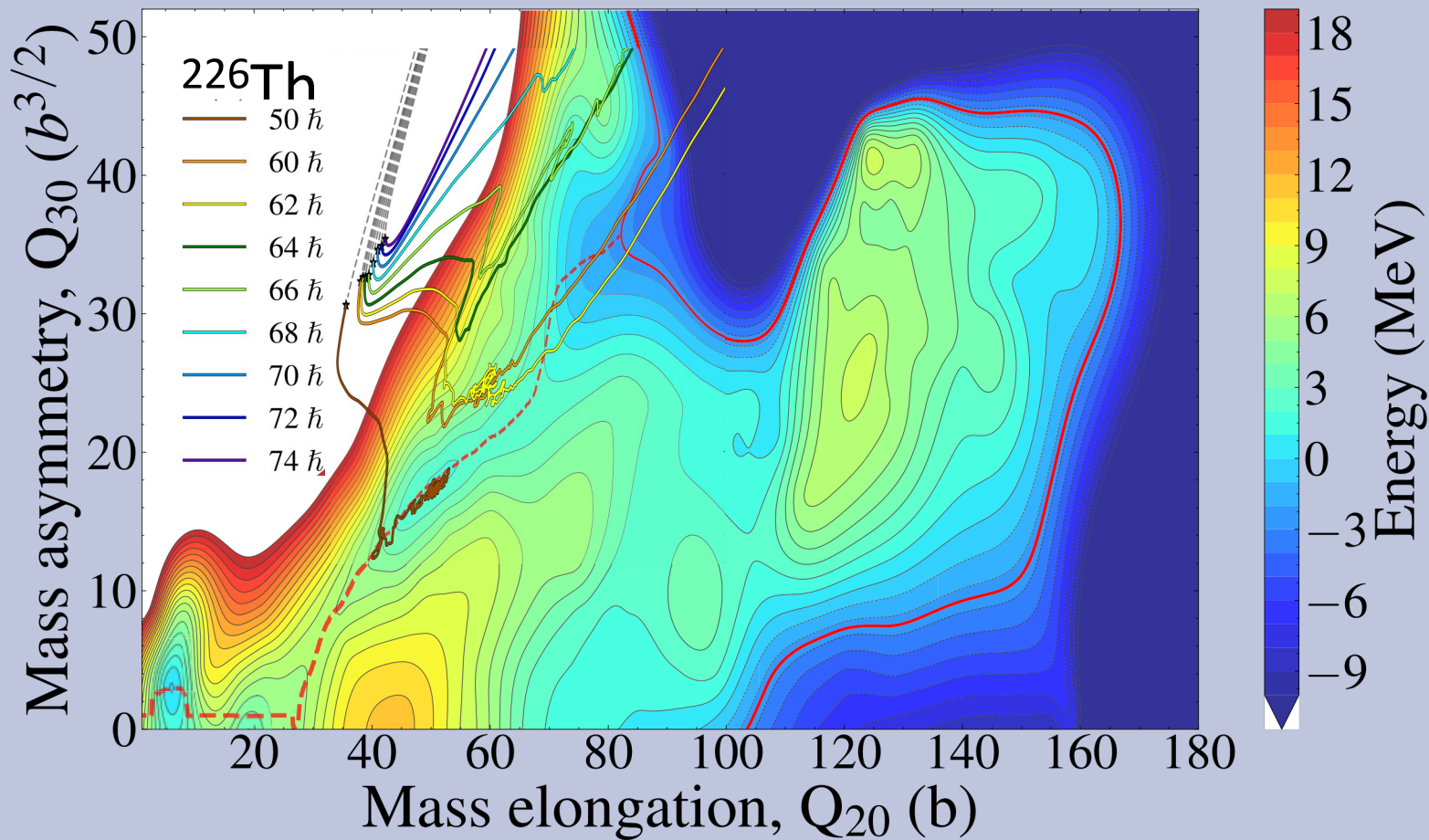
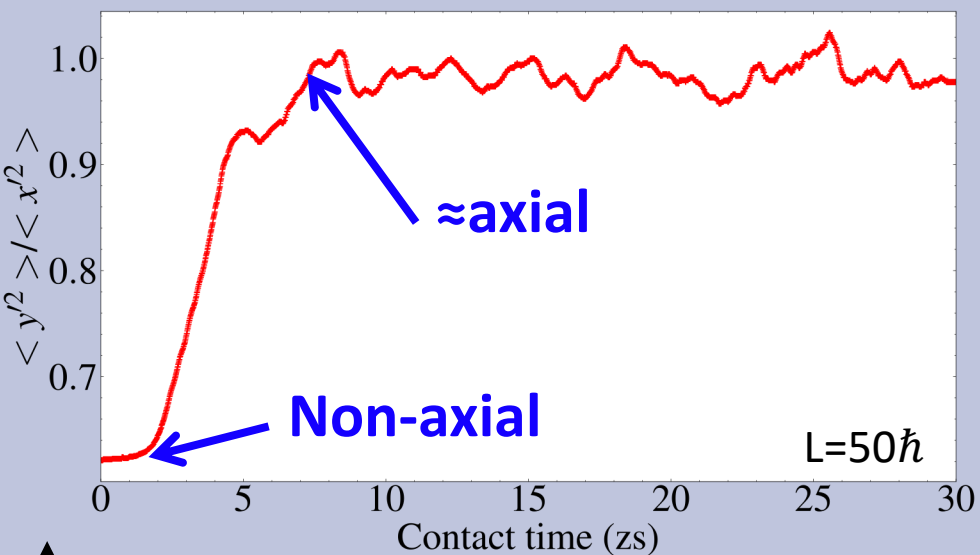
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Non-axial  $\rightarrow$

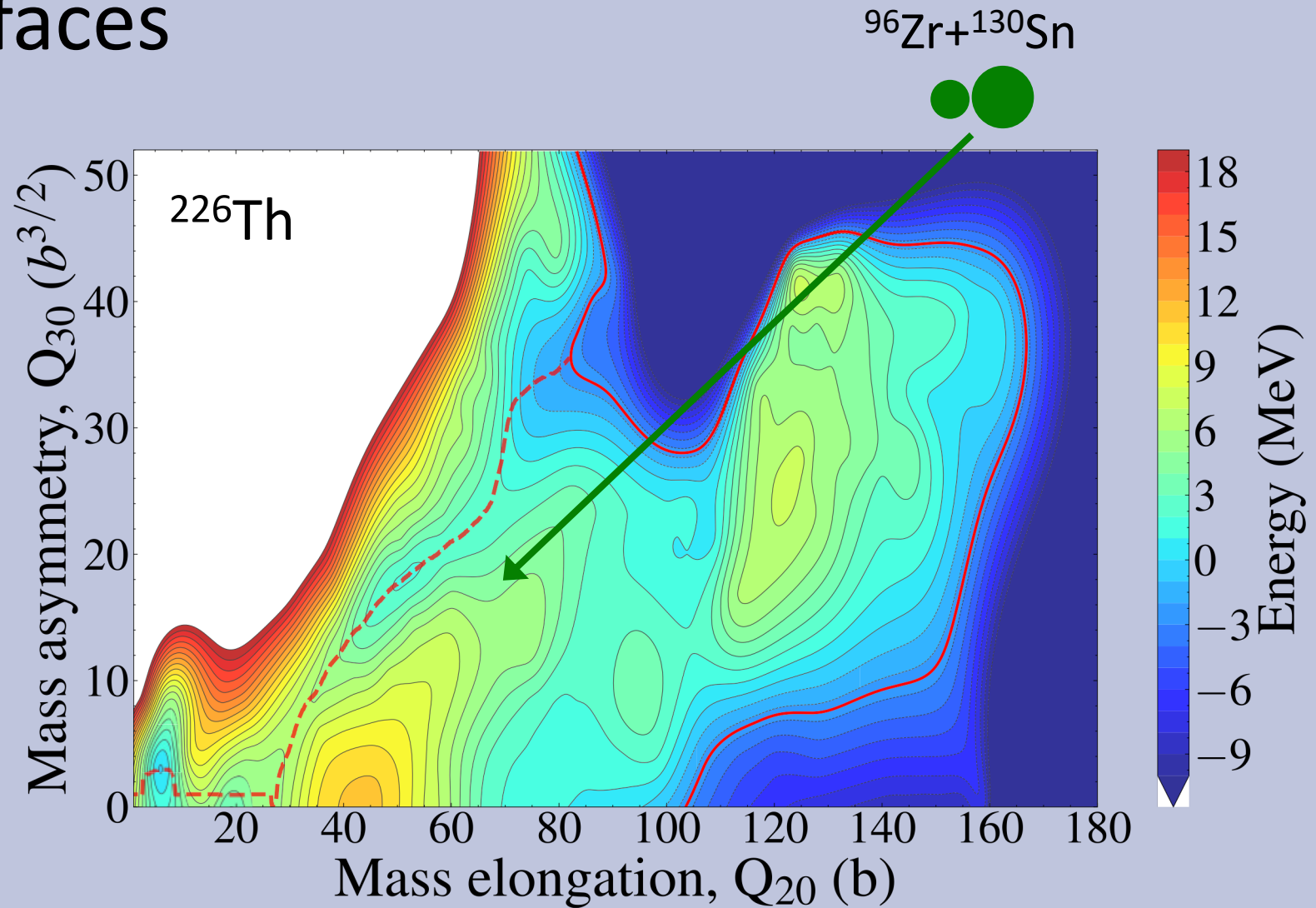


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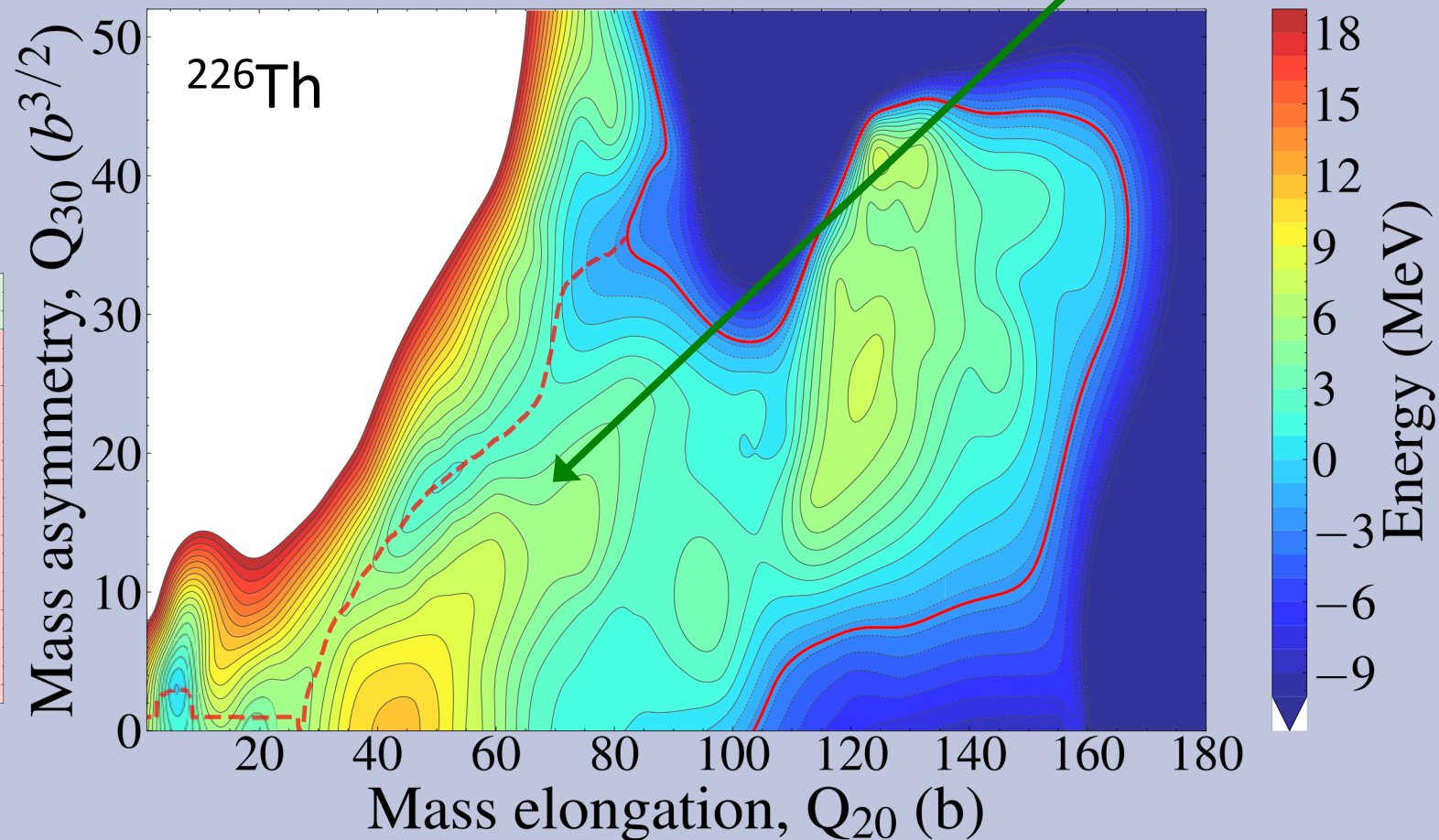
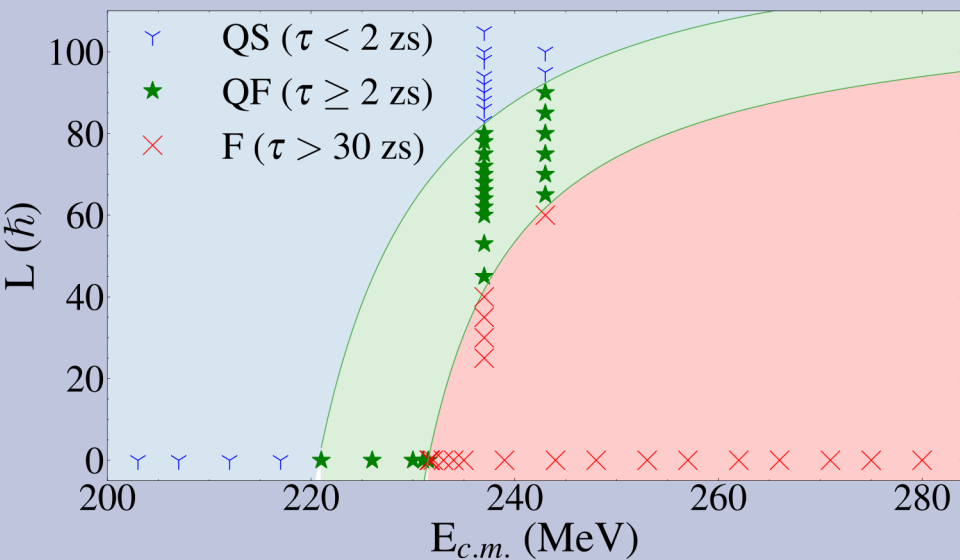
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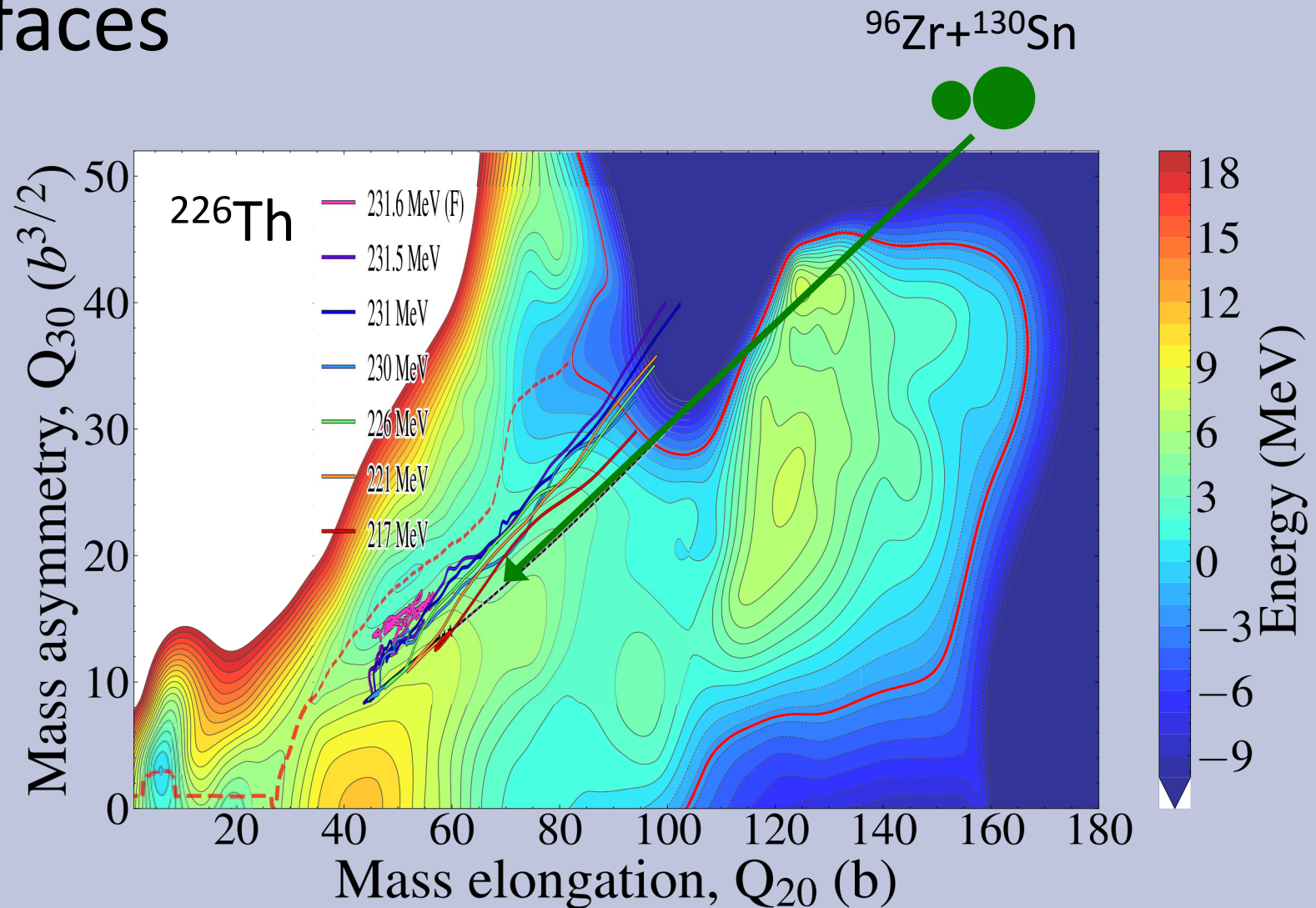
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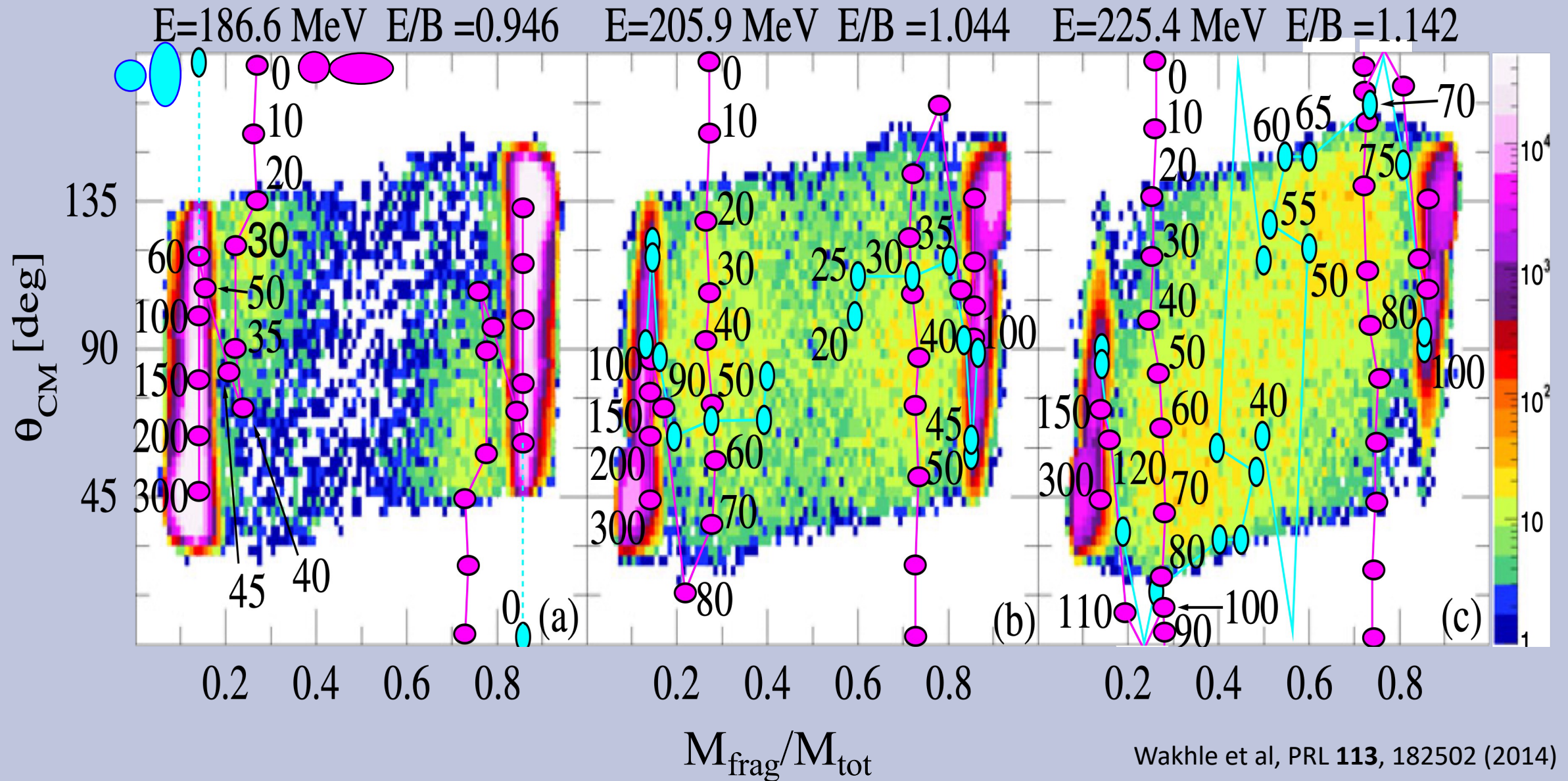
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- $L=0$  TDHF “trajectories”
- Inverse quasi-fission



# Mass-angle distributions

$^{40}\text{Ca}+^{238}\text{U}$

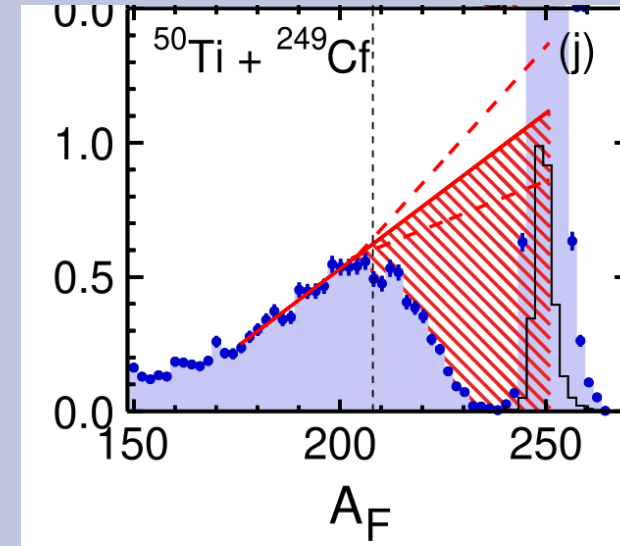


# Final remarks on experimental evidences of shell effects in quasi-fission

## - Role of sequential fission

The current experimental results and analysis lead directly to the conclusion that the Pb peak seen in binary quasifission mass-spectra cannot now be taken as reliable evidence for the influence of Pb closed shells on quasifission dynamics. Further experimental investigation is required.

Jeung et al, PLB **837**, 137641 (2023)



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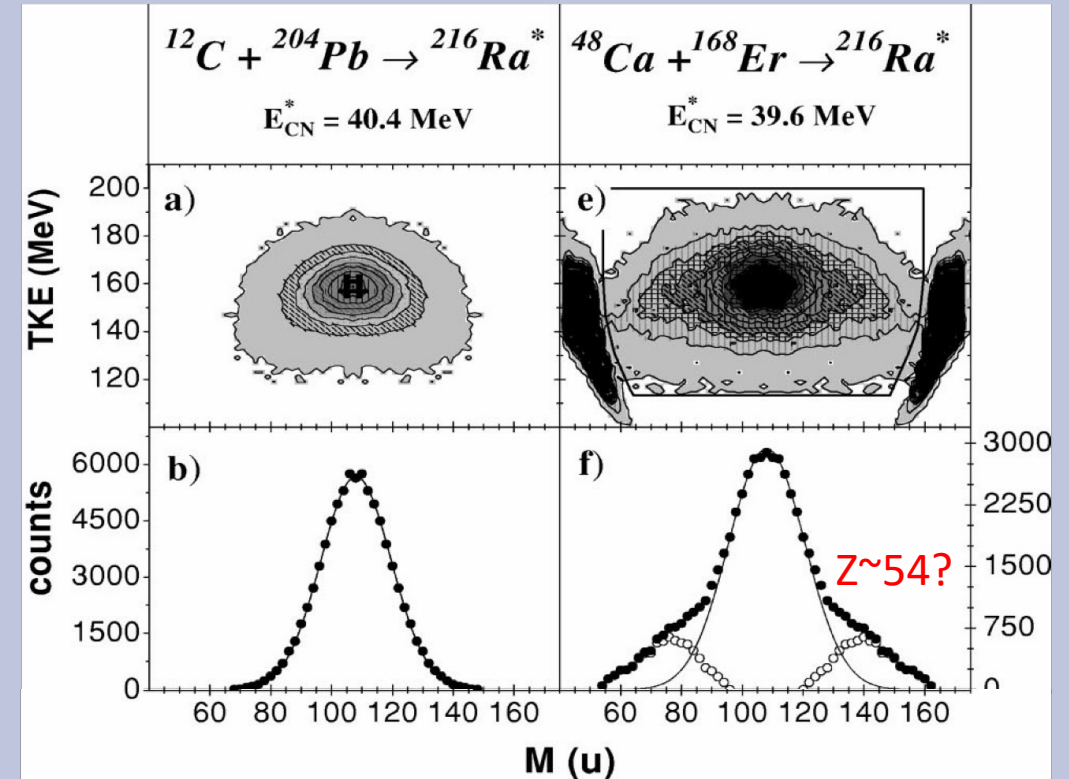
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asymmetric yield as a manifestation of the QF process. In the fission fragment MED for the reaction with  $^{48}\text{Ca}$ , shell effects are clearly seen. We interpret the MED for quasifission

Chizhov et al, PRC **67**, 011603(R) (2003)



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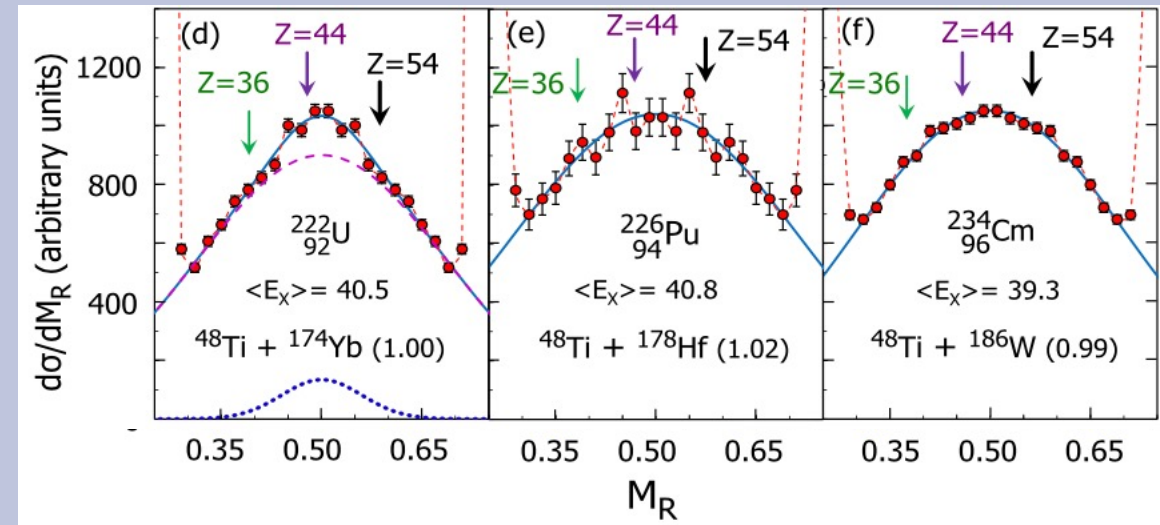
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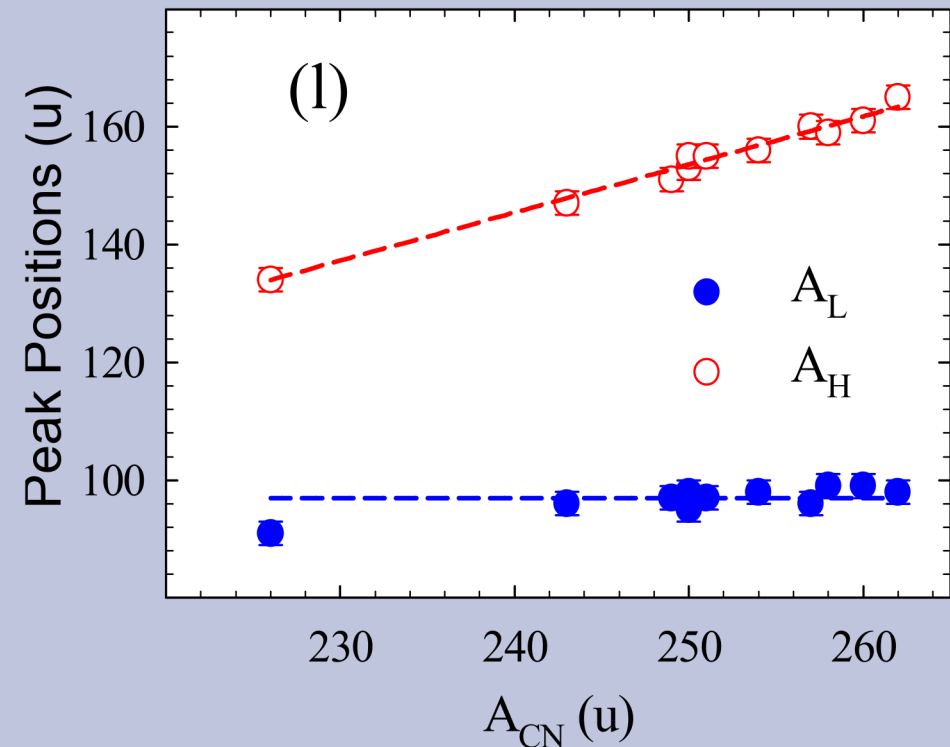
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All of the above observations can be treated as clear evidences of quantum shell effect in slow quasifission process. Therefore the present paper reveals the role of some shell closed nuclei in the mass region  $A \approx 96$ , governing the mechanism of the slow quasifission reaction. Our result is quite close to the theoretical observation by Godbey *et al.* [44],

Pal et al, PRC **110**, 034601 (2024)

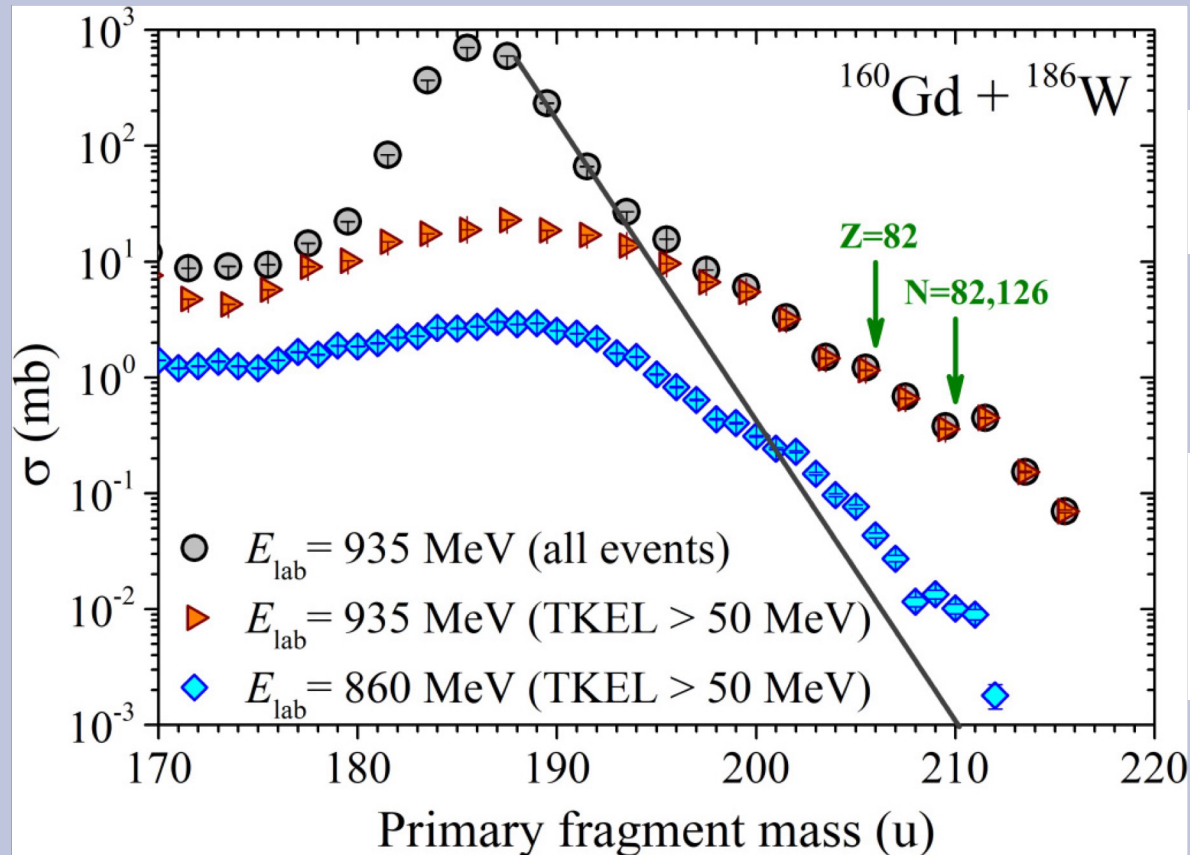


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Kozulin et al, PRC **96**, 064621 (2017)

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We have observed enhanced yields of trans-target nuclides in the region of Au that are similar in magnitude (although differing in  $N$  and  $Z$ ) to the shell-stabilized trans-target species predicted in [18].

Loveland et al, PRC **83**, 044610 (2011)

See also TDHF study by Wu et al, PRC **113**, 024618 (2026)

# Conclusions

- TDHF describes the main features of quasi-fission:
  - Energy fully dissipated
  - Mass equilibration
  - Contact times (from few zs to few 10zs)
- TDHF also predicts shell effects in quasi-fission:
  - Shell effects stop mass equilibration ( $Z=56,82$ ;  $N=56,126$ )
  - Same shell effects as in fission
  - Inverse quasi-fission
  - TDHF “trajectories” sensitive to PES
- Future
  - Experimental mass distributions including 3-body events
  - Quantitative comparison with experiment
  - Beyond TDHF approach if lack of shell effects experimentally confirmed (both in SHE and actinide regions)

# Collaborators



McGlynn



Lee



Godbey



Umar

