

Extraction of fission mode properties from fragment mass distributions

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Role of shell effects on fission modes

Bernard, et al. EPJA **59**, 51 (2023); **60**, 192 (2024)

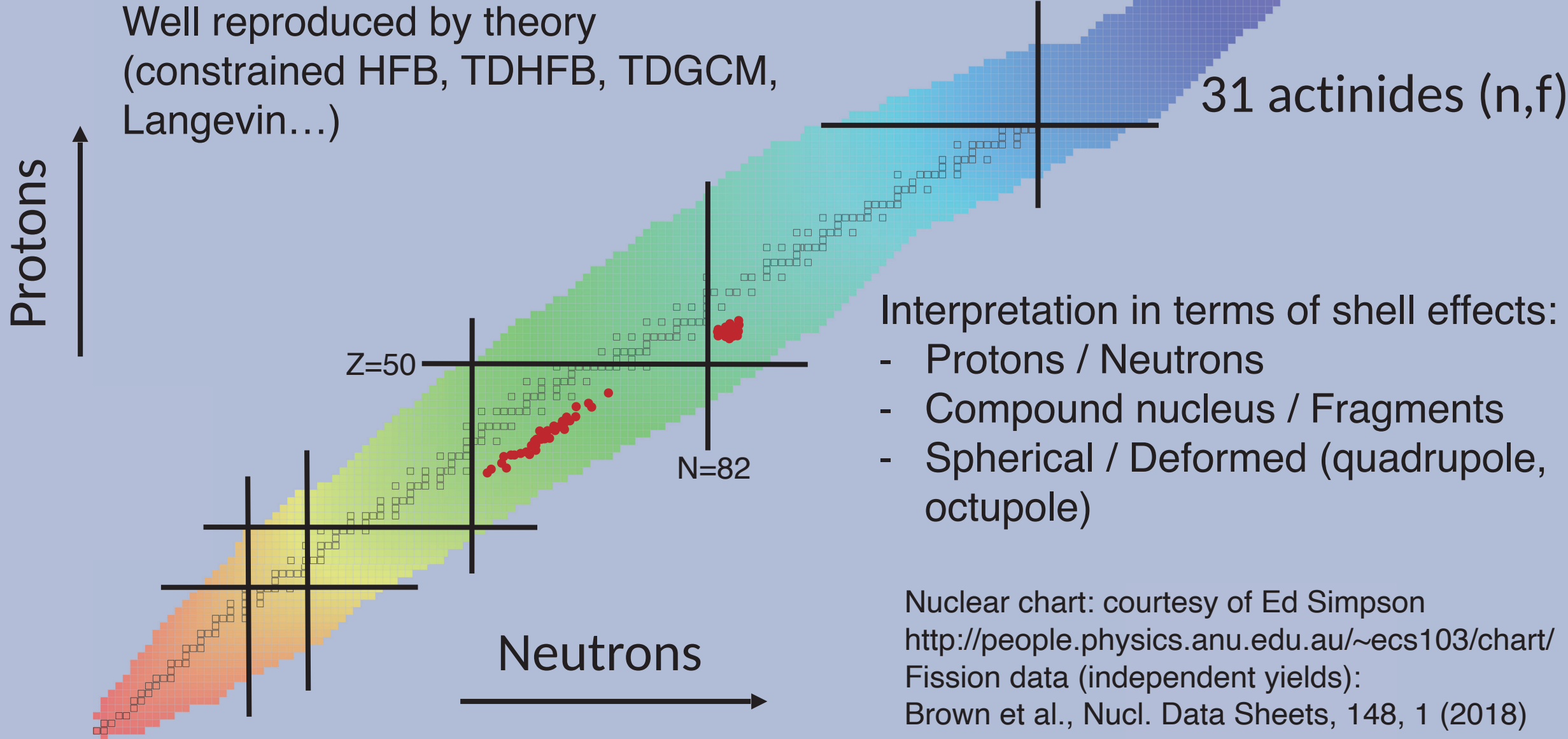
Connection with fragment mass distributions

McGlynn, CS, PRC **111**, 034619 (2025)



Credit: G. Scamps

Asymmetric fission (actinides)



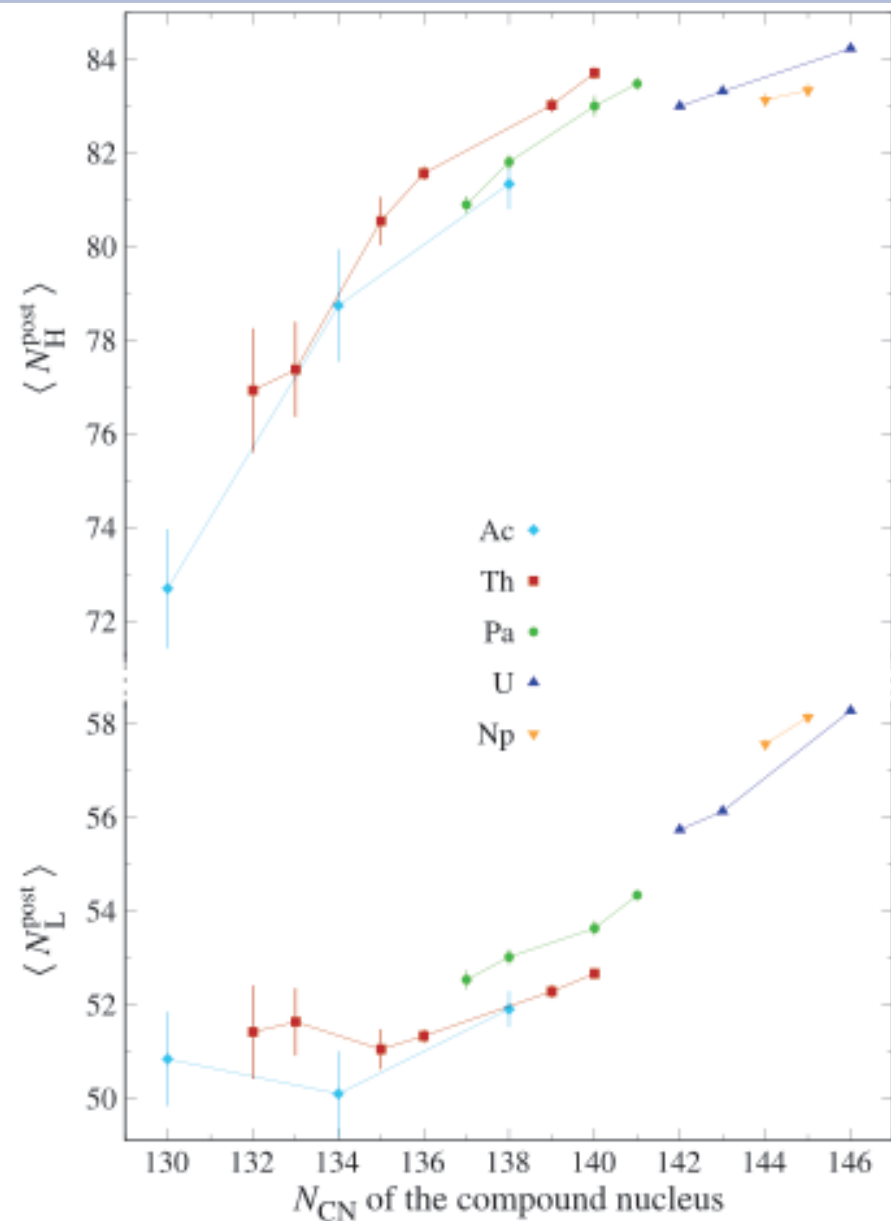
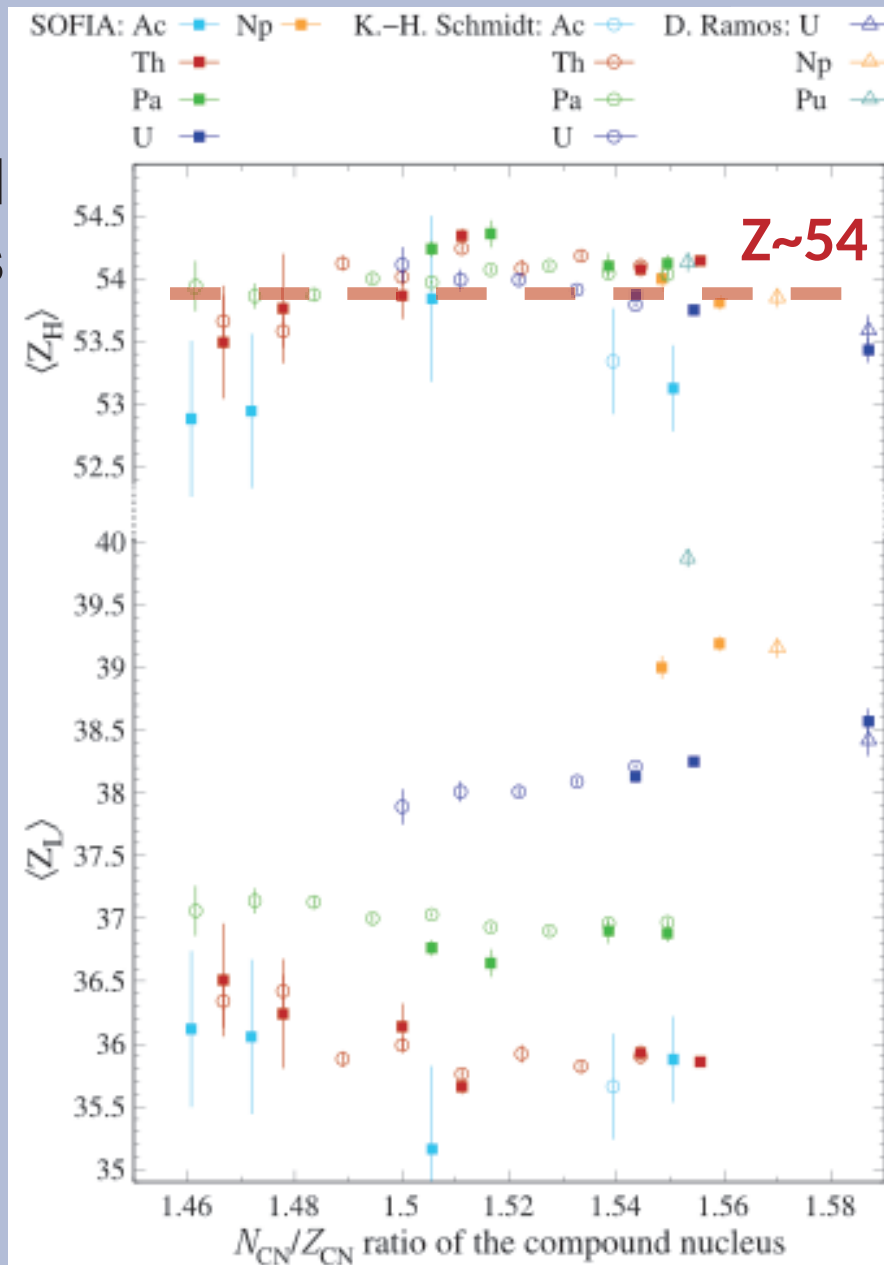
Asymmetric fission (actinides)

Final asymmetry fixed by proton shell effects in the heavy fragment

Chatillon et al, PRC **106**, 24618 (2022)

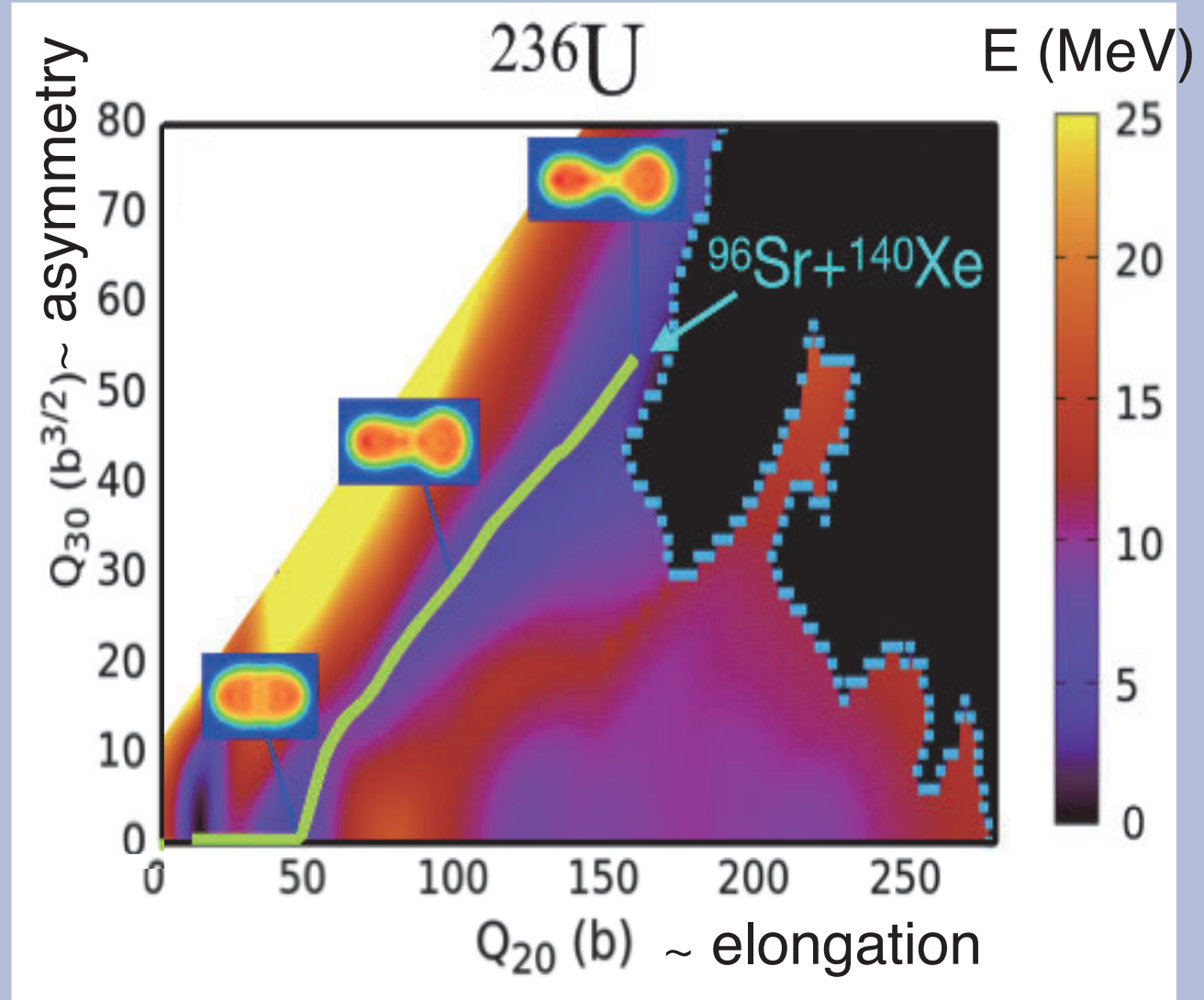
Schmidt et al, NPA **665**, 221 (2000)

Bockstiegel et al, NPA **802**, 12 (2008)



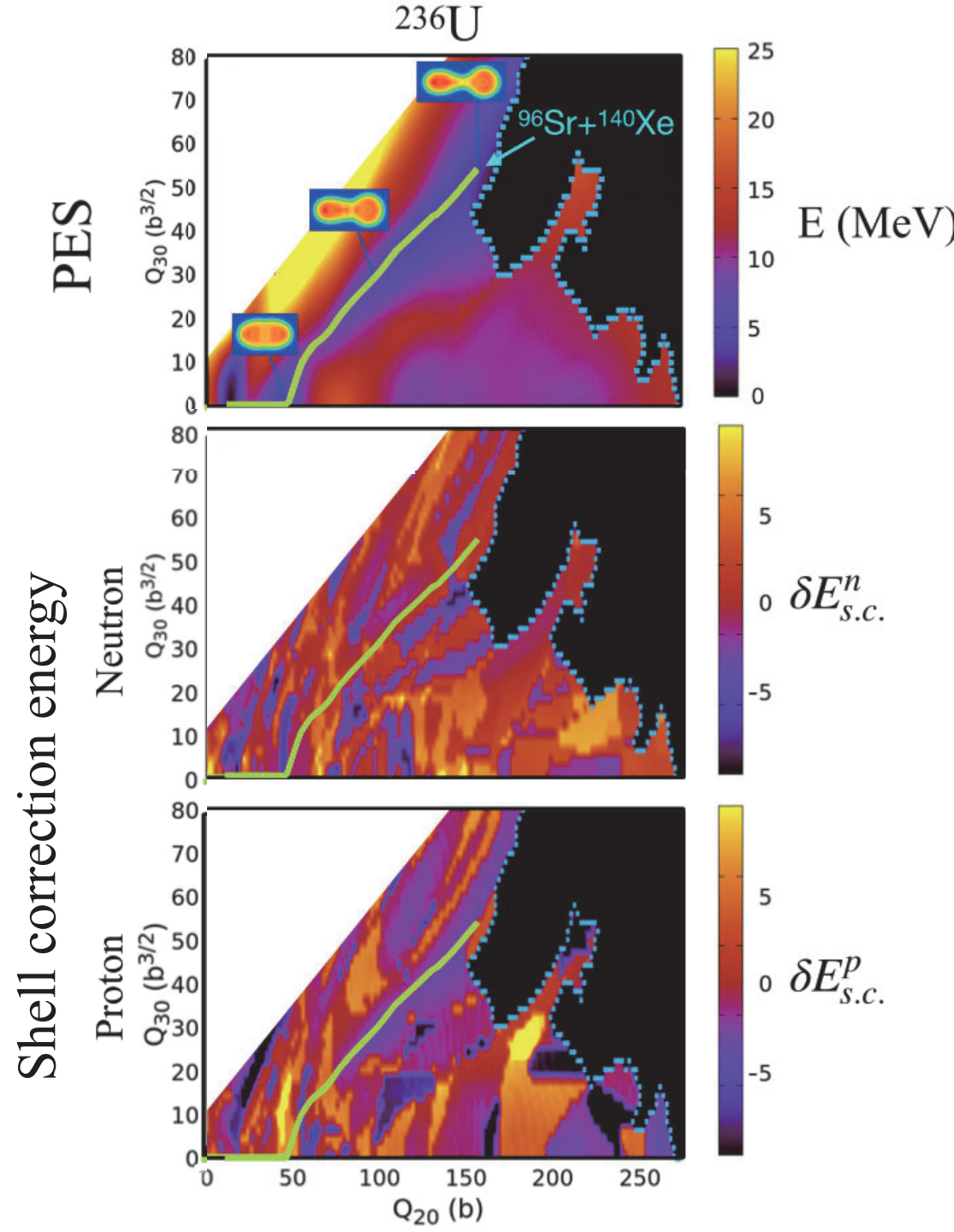
Shell effects along the fission path

Axial HFB, Gogny-D1S



Shell effects along the fission path

Shell correction energy (Strutinski)

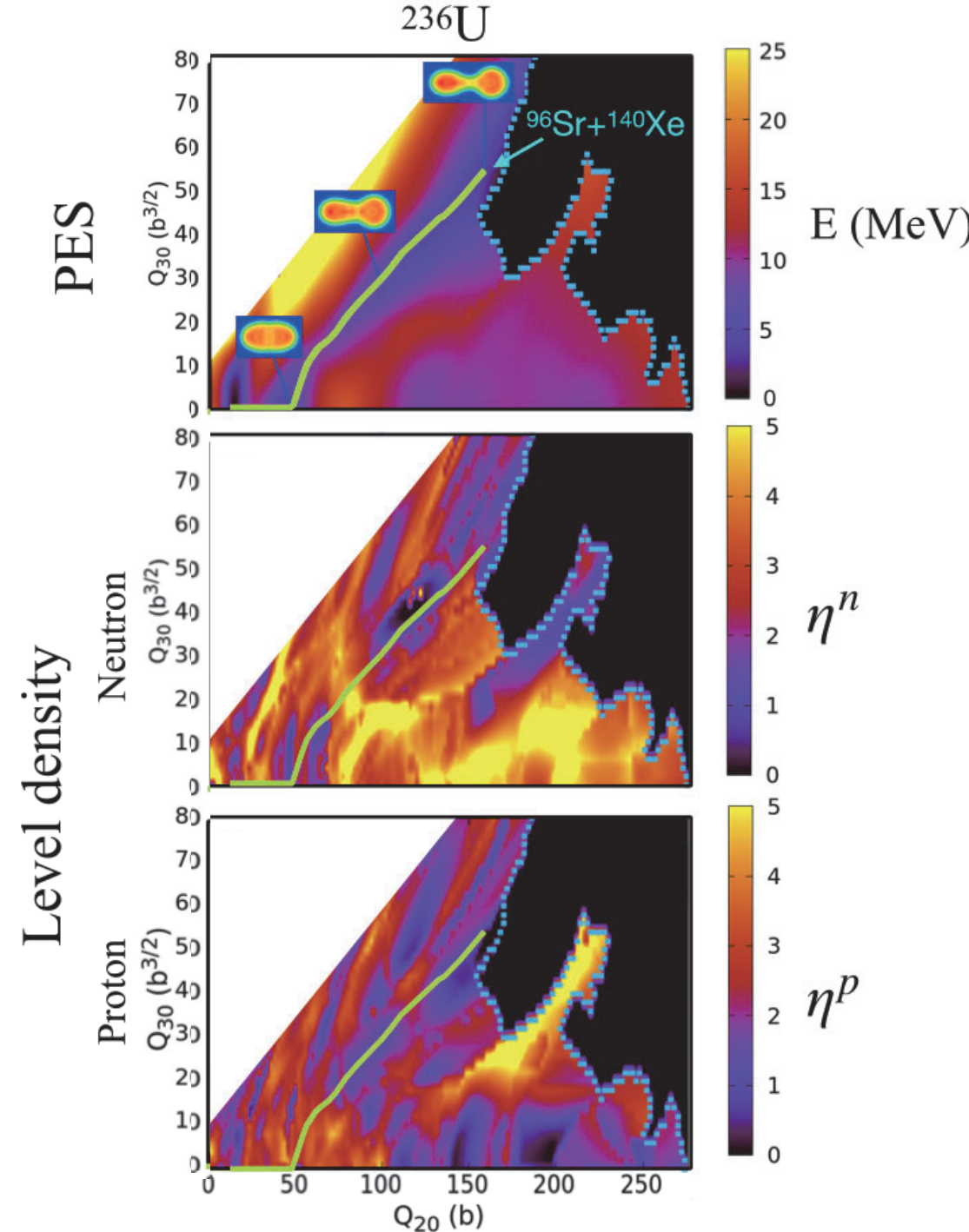
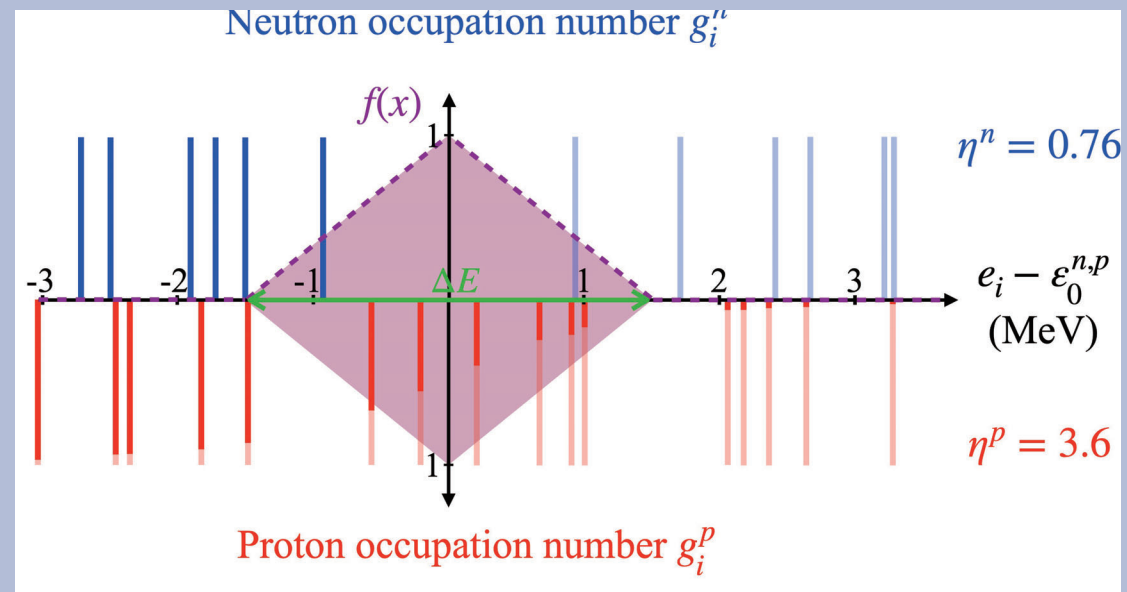


Shell effects along the fission path

Shell correction energy (Strutinski)

Level density near Fermi surface

$$\eta^{n,p} = \sum_i f(e_i - \epsilon_0^{n,p})$$



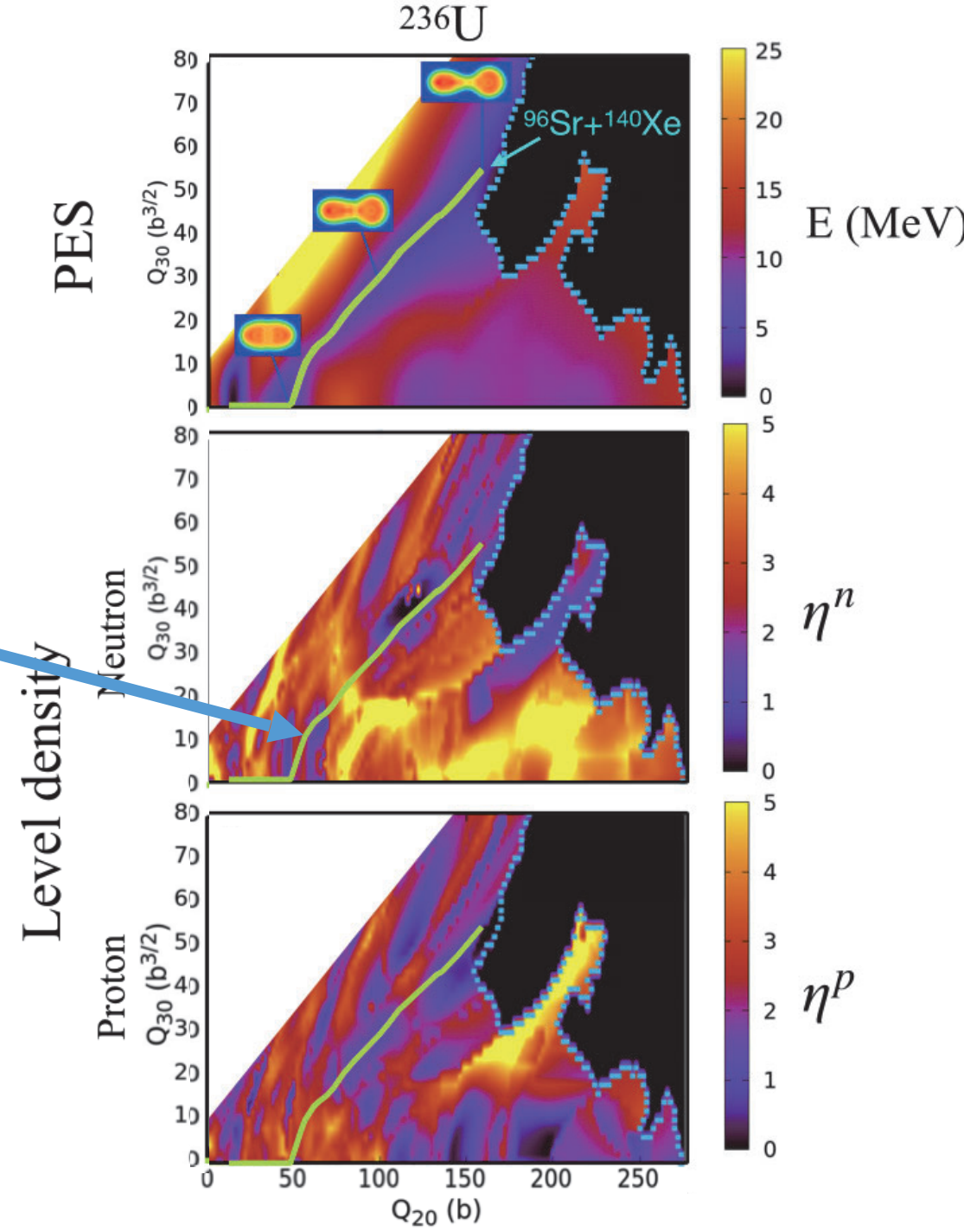
Shell effects along the fission path

Shell correction energy (Strutinski)

Level density near Fermi surface

Neutrons initiate asymmetry near 2nd barrier

Gustafsson et al, PLB 34, 349 (1971)



Shell effects along the fission path

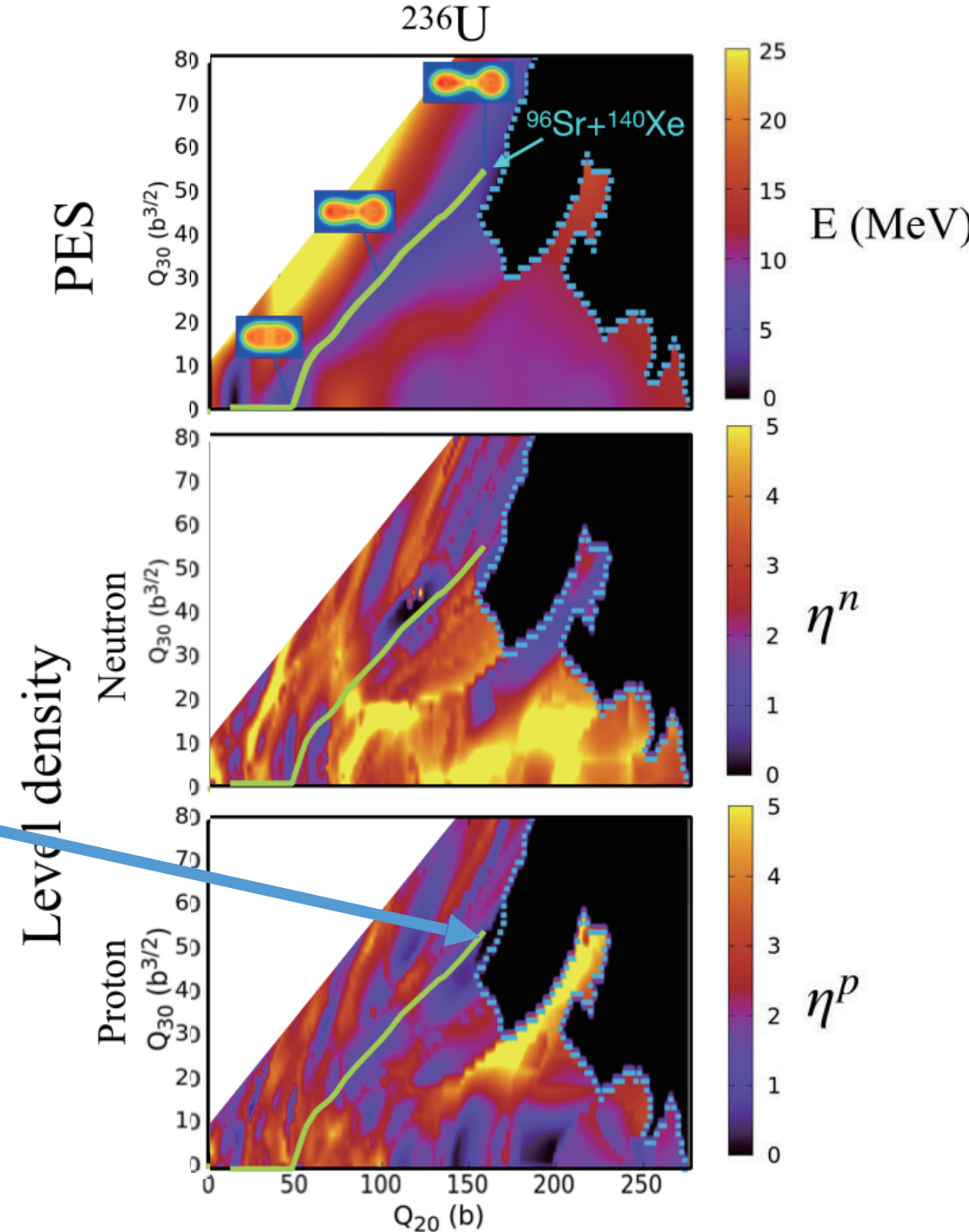
Shell correction energy (Strutinski)

Level density near Fermi surface

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Gustafsson et al, PLB 34, 349 (1971)

Proton shell effects fix final asymmetry in prefragment



Shell effects along the fission path

Shell correction energy (Strutinski)

Level density near Fermi surface

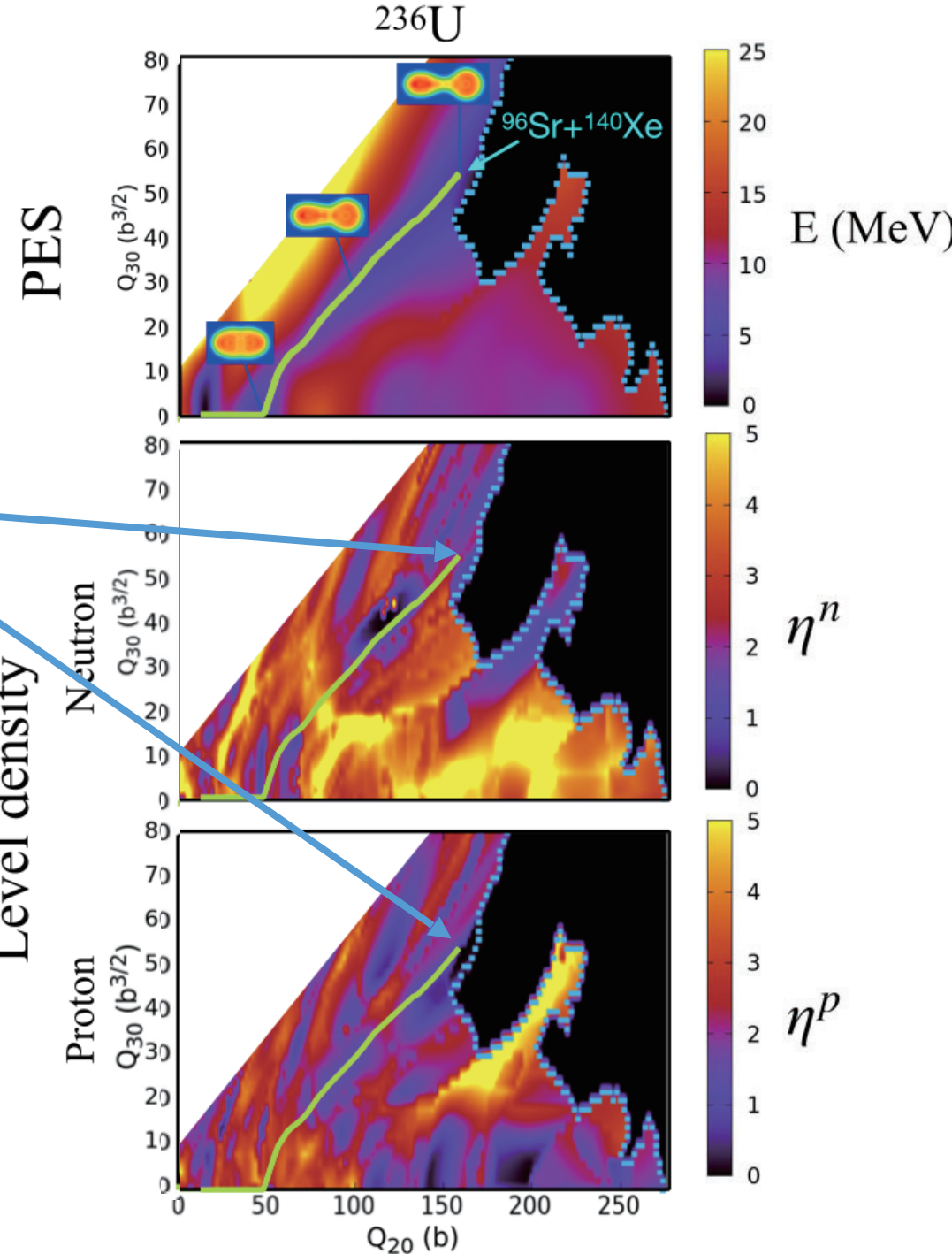
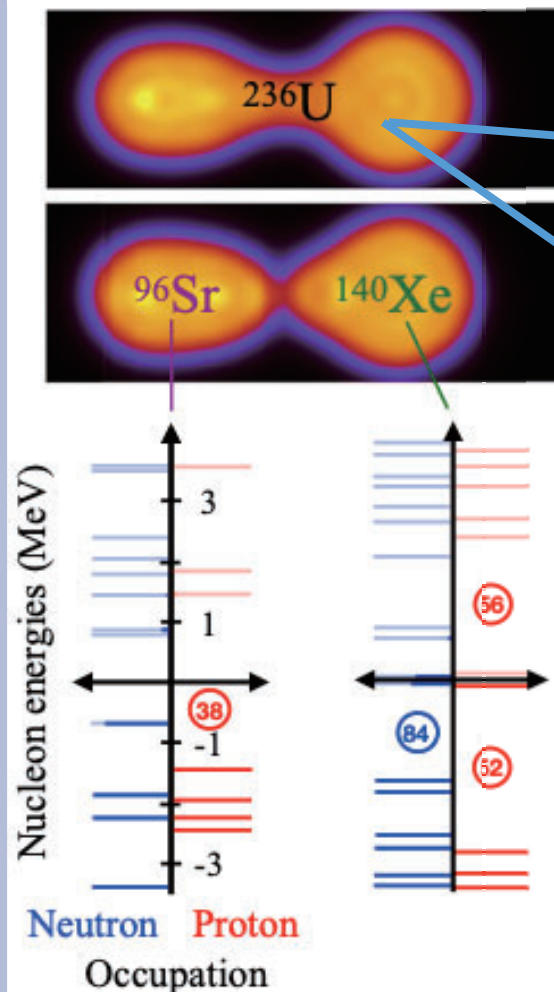
Neutrons initiate asymmetry near 2nd barrier

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Proton shell effects fix final asymmetry in prefragment

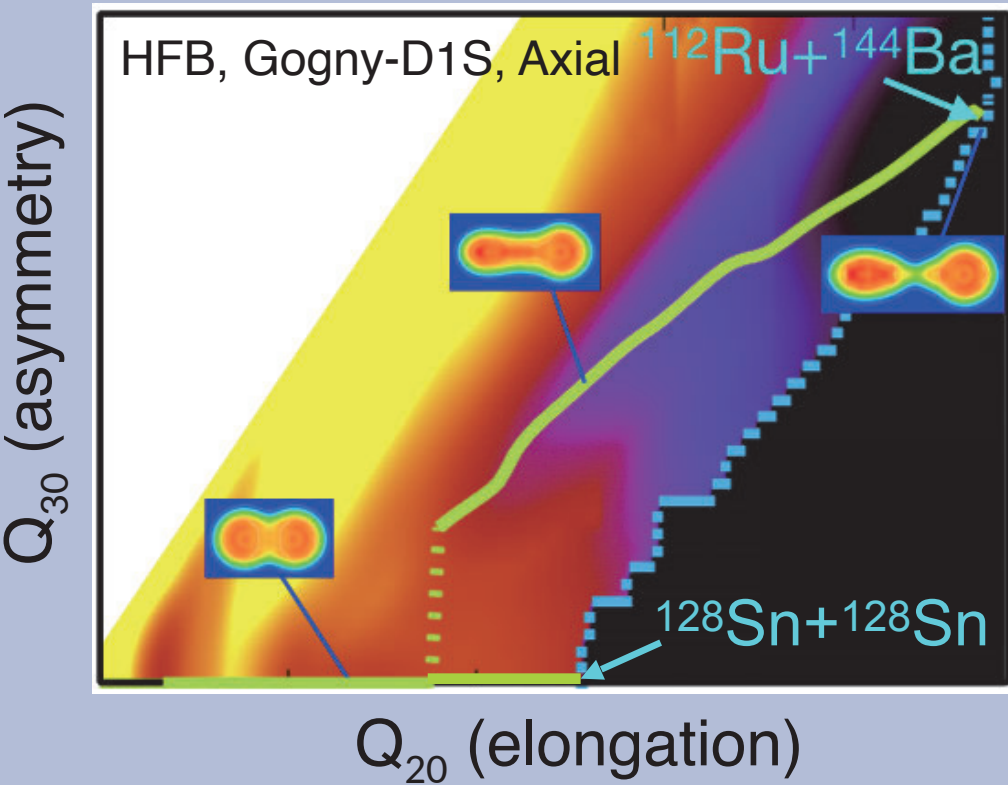
HFB of deformed fragments:
Z=52,56 octupole deformed shell gaps in heavy fragment

Butler, Nazarewicz, RMP 68, 349 (1996)



What about Z=50?

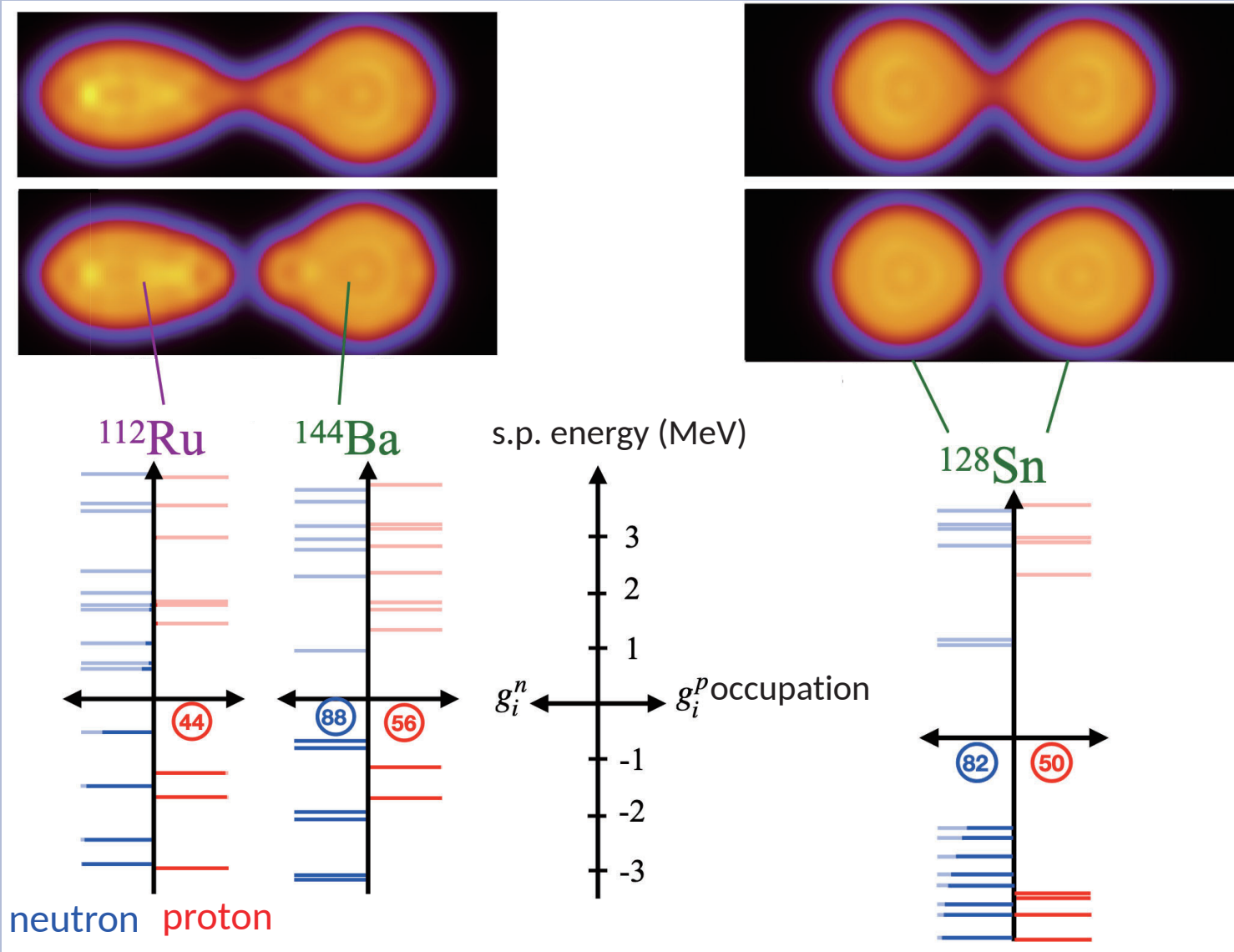
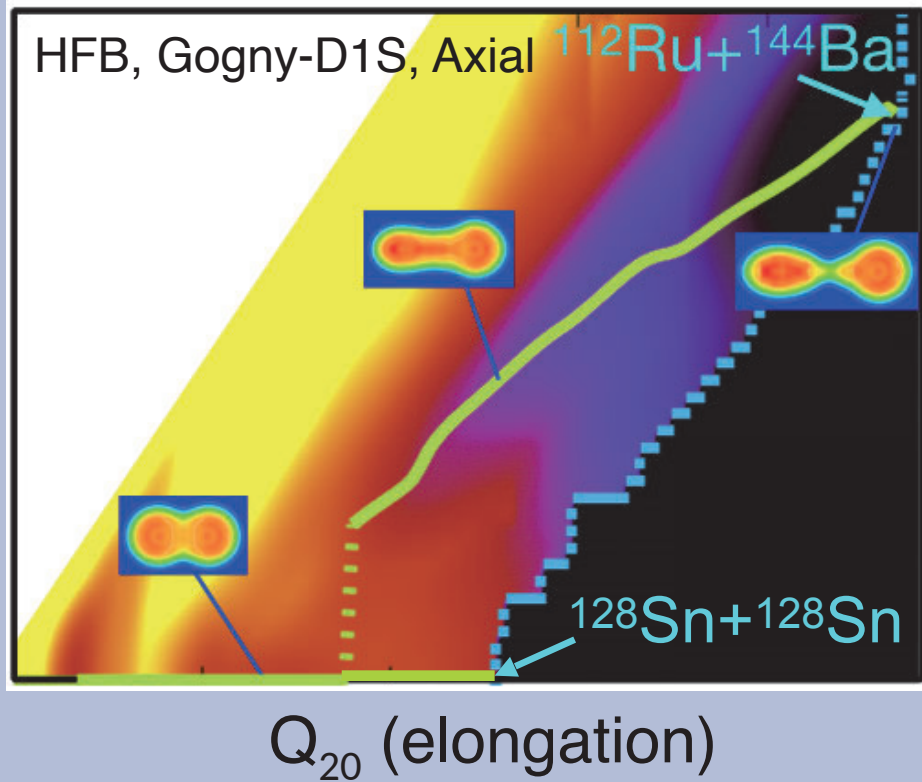
^{256}Fm



What about Z=50?

256Fm

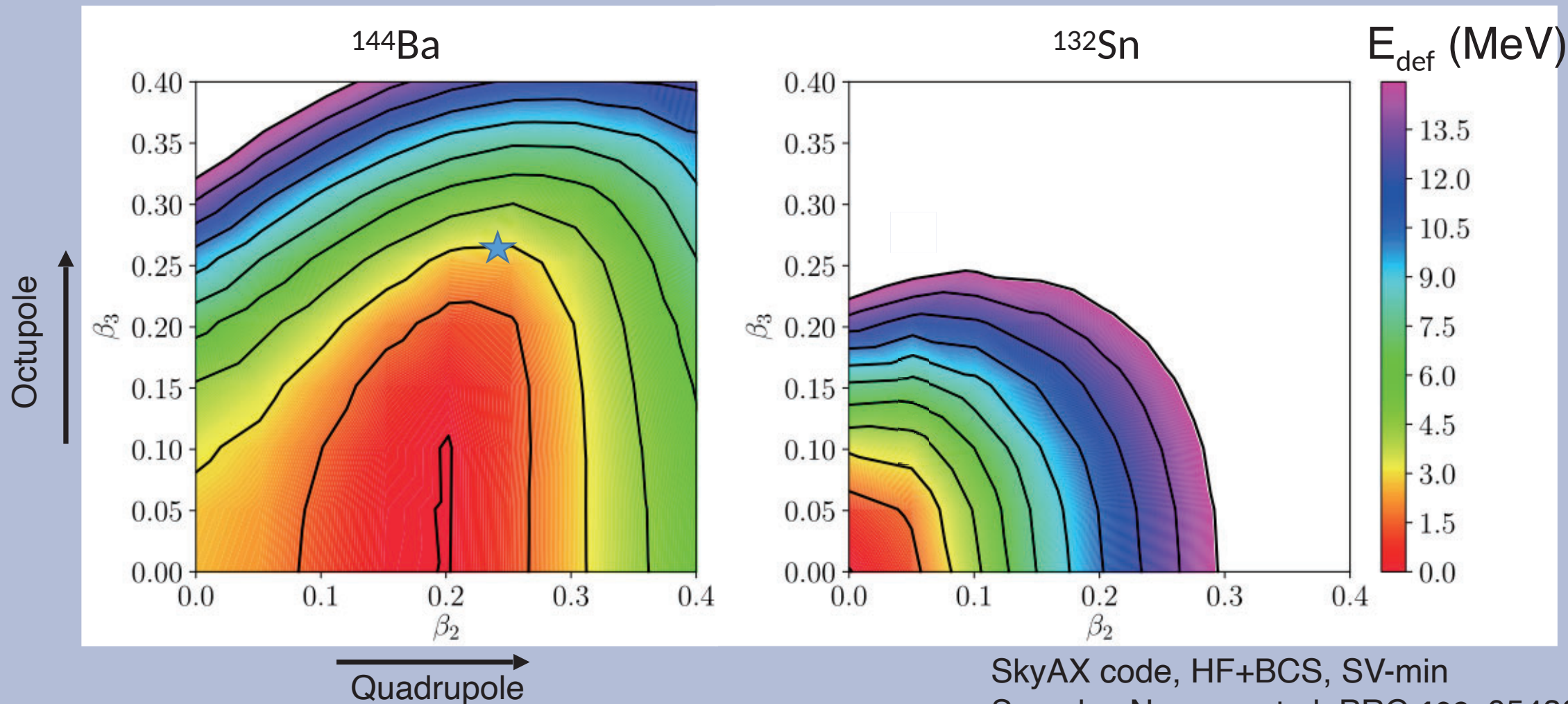
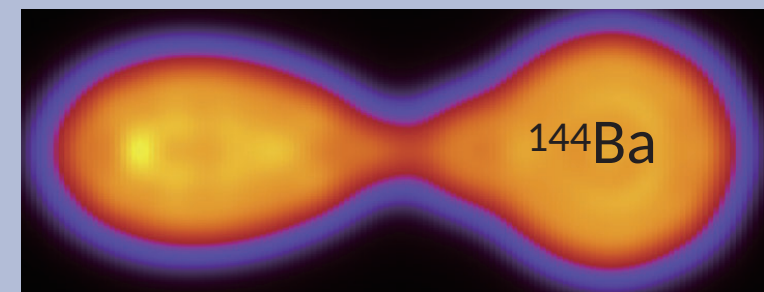
Q_{30} (asymmetry)



Why octupole shell effects matter?

Pear shapes at scission

=> Fragments that can be octupole deformed for no or little cost in energy are favoured [Scamps, CS, Nature **564**, 382 (2018)]



SkyAX code, HF+BCS, SV-min

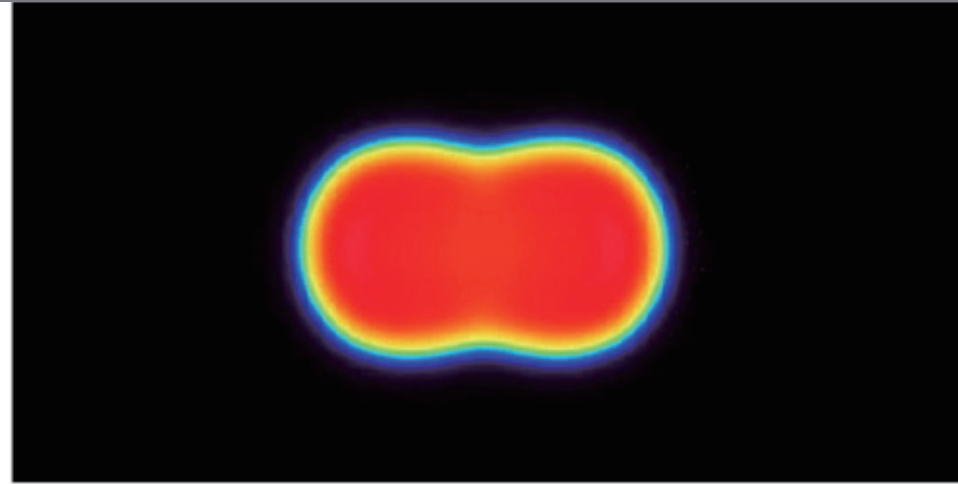
See also Nomura et al, PRC **103**, 054301 (2021)

What about TKE?

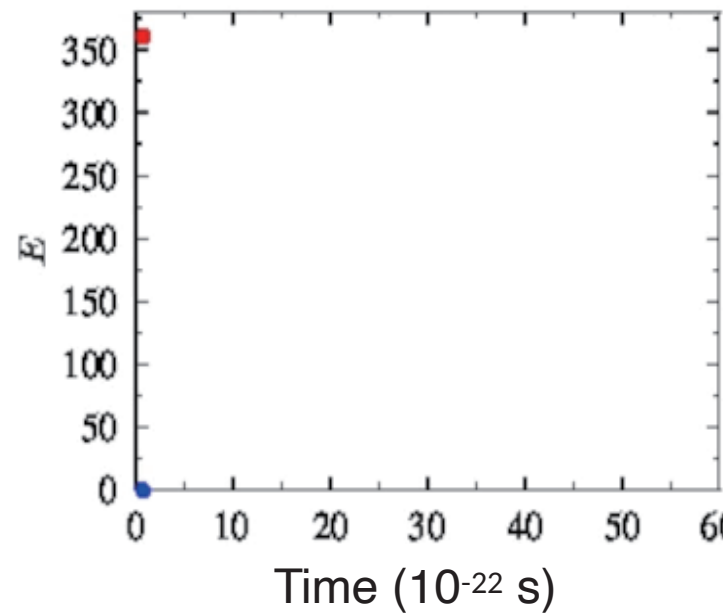
Scamps, CS, Lacroix, PRC 92, 011602(R), 2015

Time-dependent
Hartree-Fock-BCS

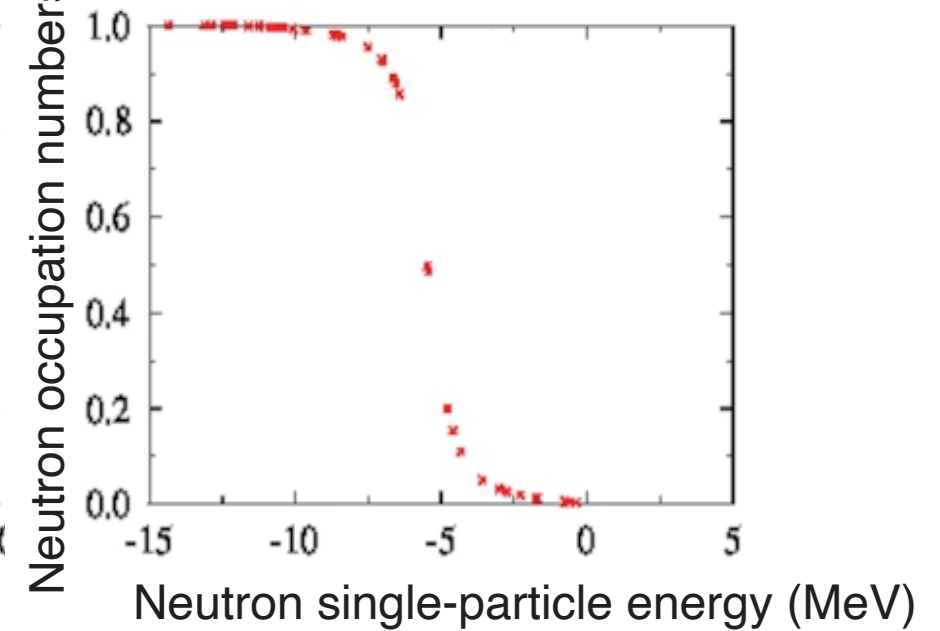
^{258}Fm
(sym.)



Coul., kin., tot. energies (MeV)



Neutron occupation numbers

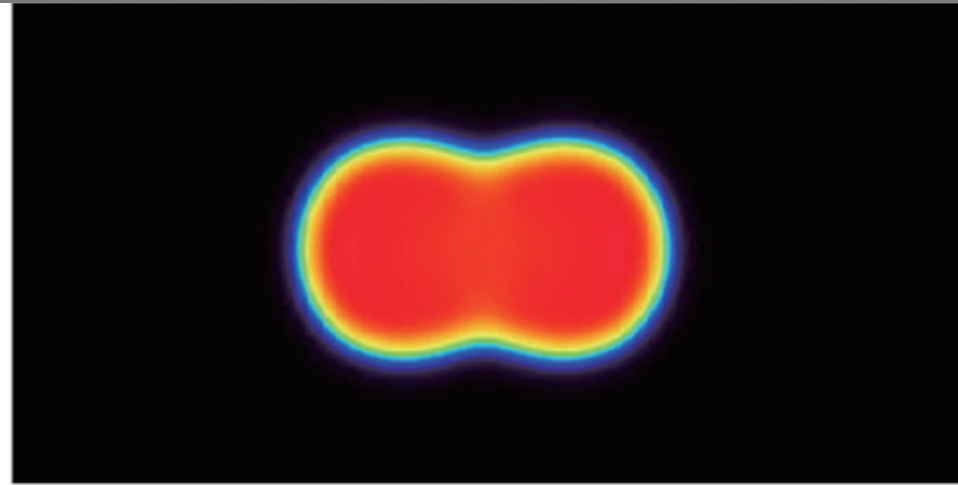


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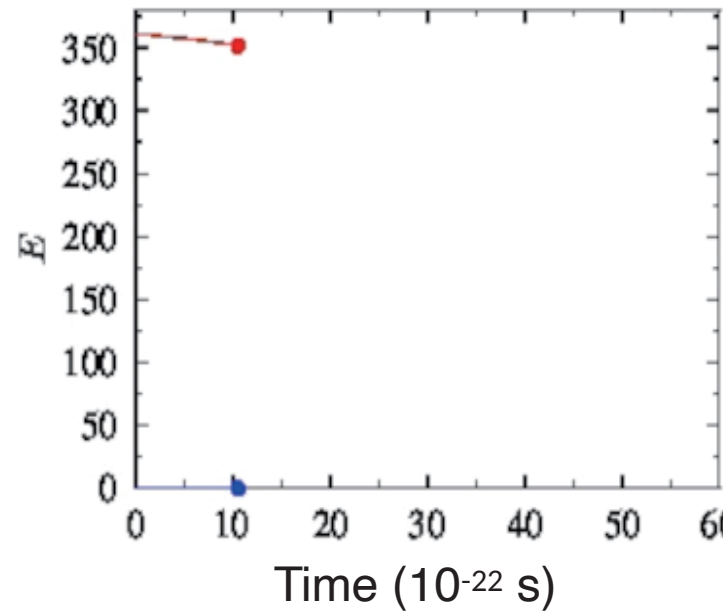
Scamps, CS, Lacroix, PRC 92, 011602(R), 2015

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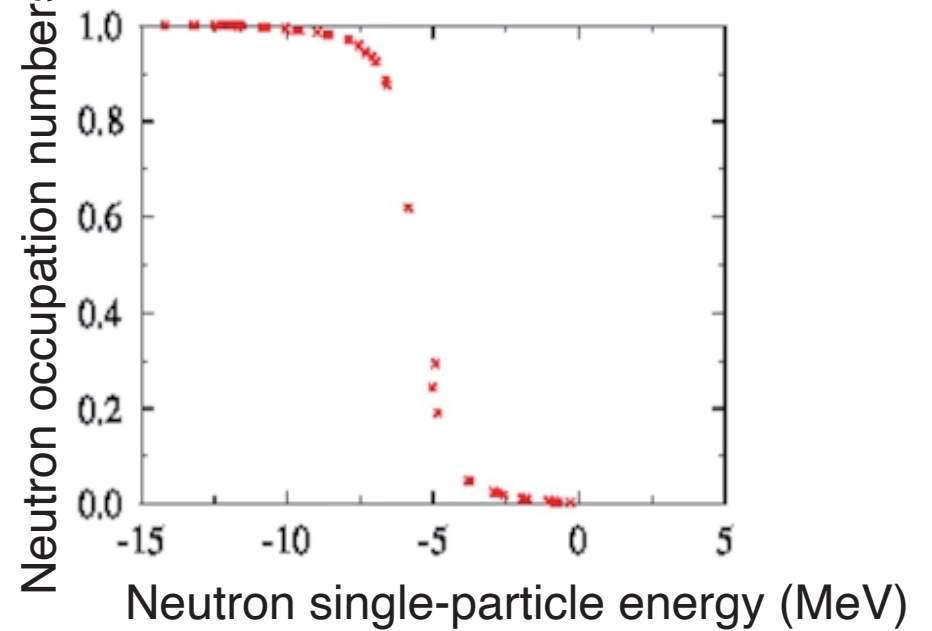
^{258}Fm
(sym.)



Coul., kin., tot. energies (MeV)



Neutron occupation numbers

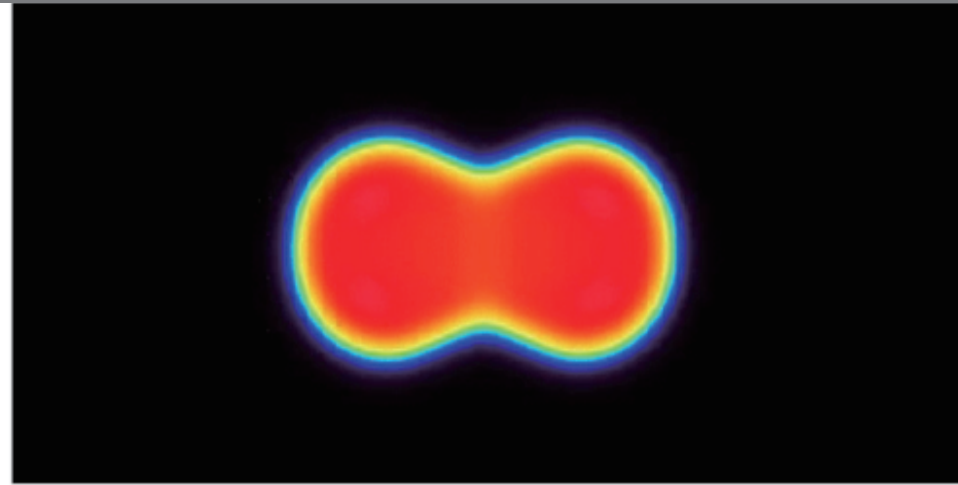


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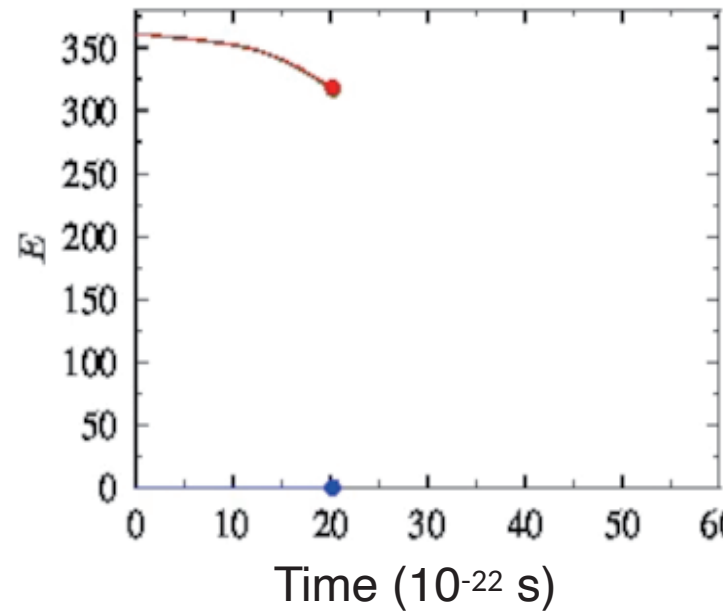
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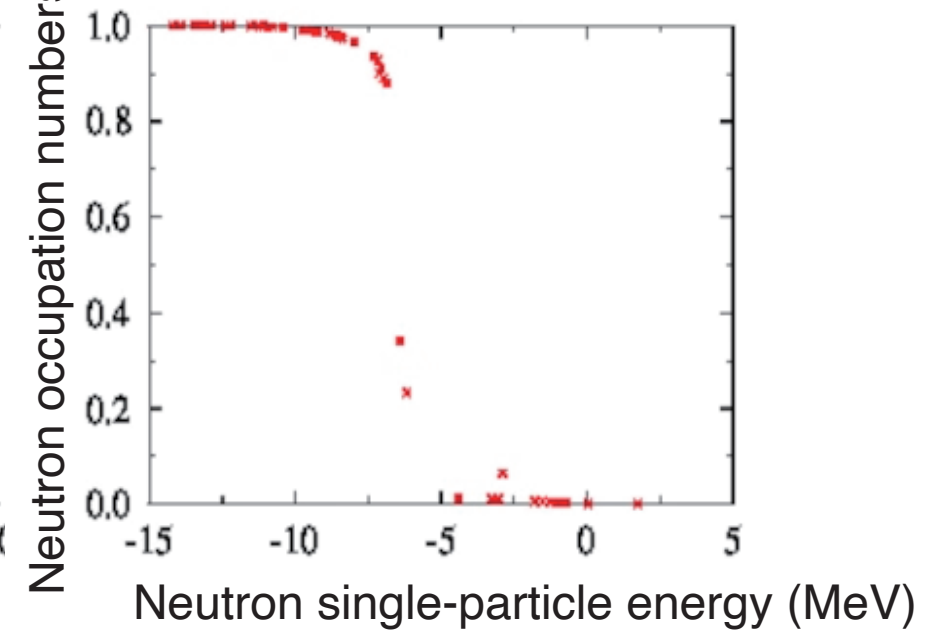
^{258}Fm
(sym.)



Coul., kin., tot. energies (MeV)



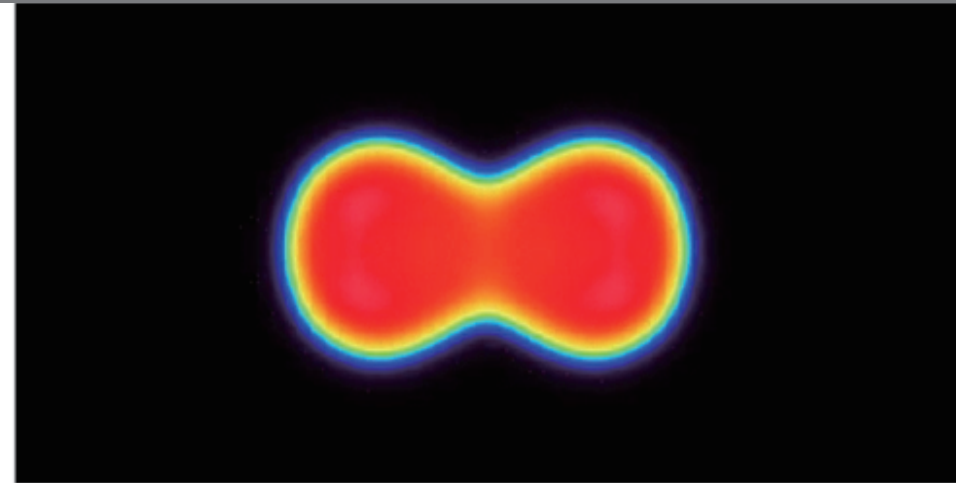
Neutron occupation numbers



What about TKE?

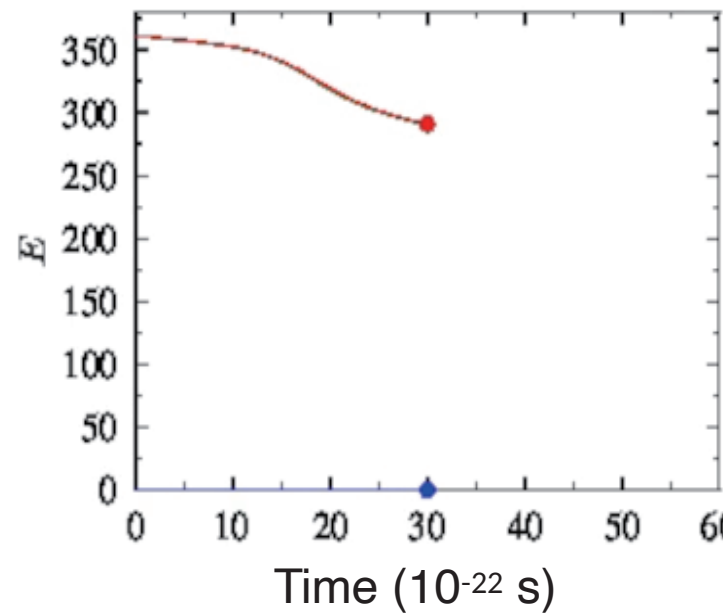
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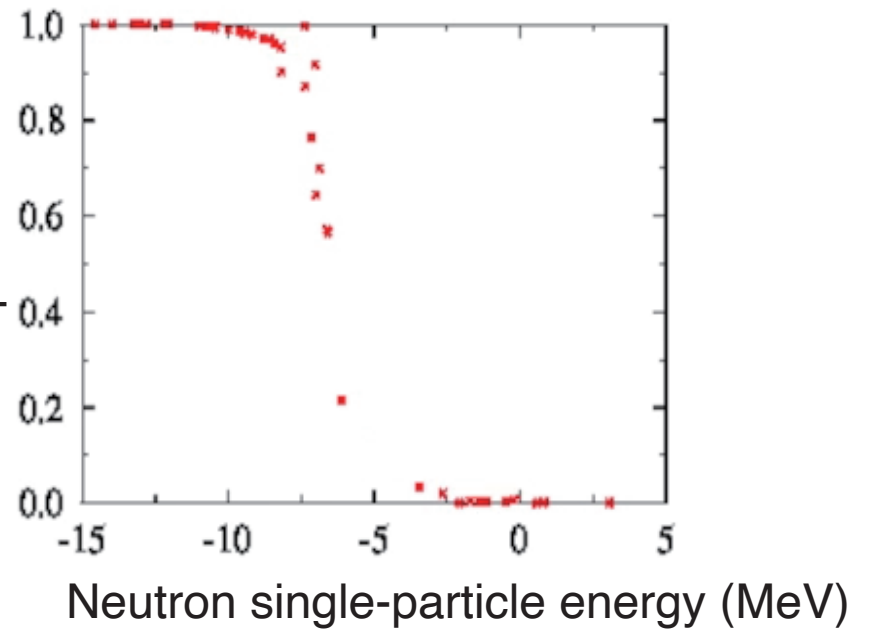


^{258}Fm
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Coul., kin., tot. energies (MeV)



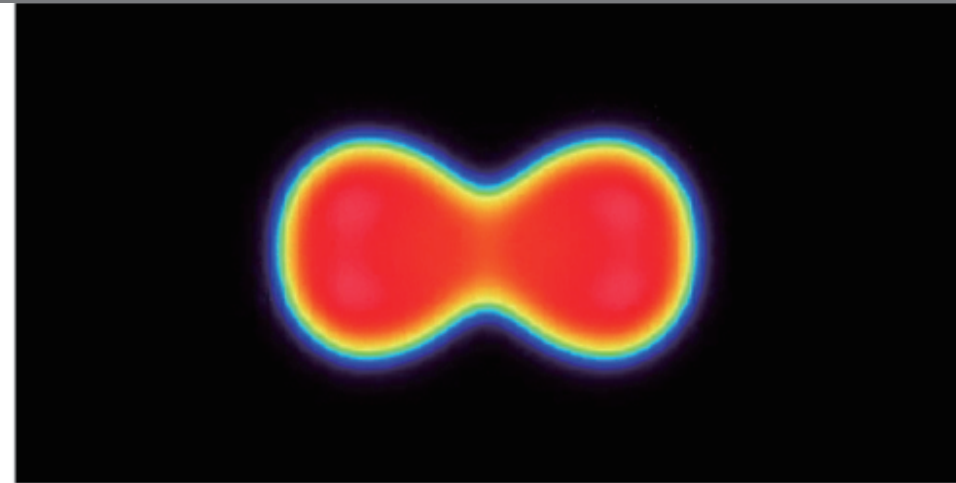
Neutron occupation numbers



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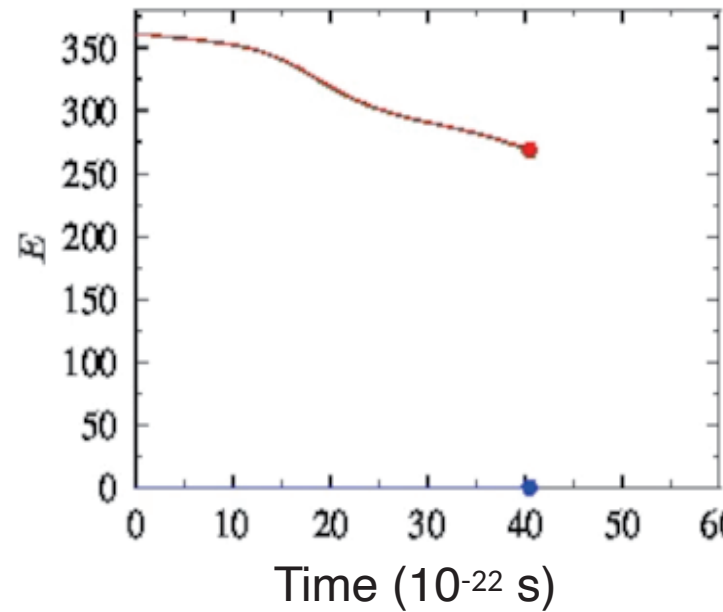
Scamps, CS, Lacroix, PRC 92, 011602(R), 2015

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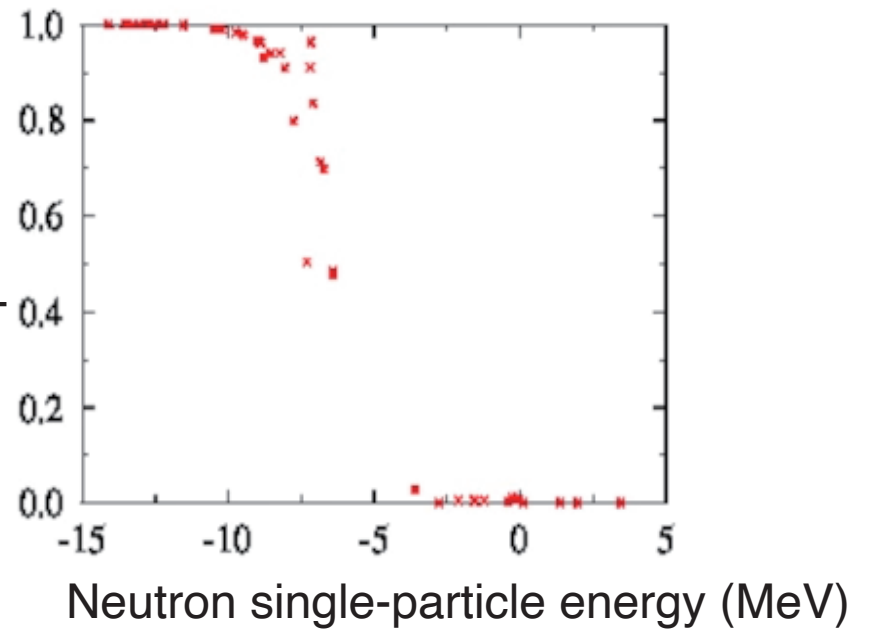


^{258}Fm
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Coul., kin., tot. energies (MeV)



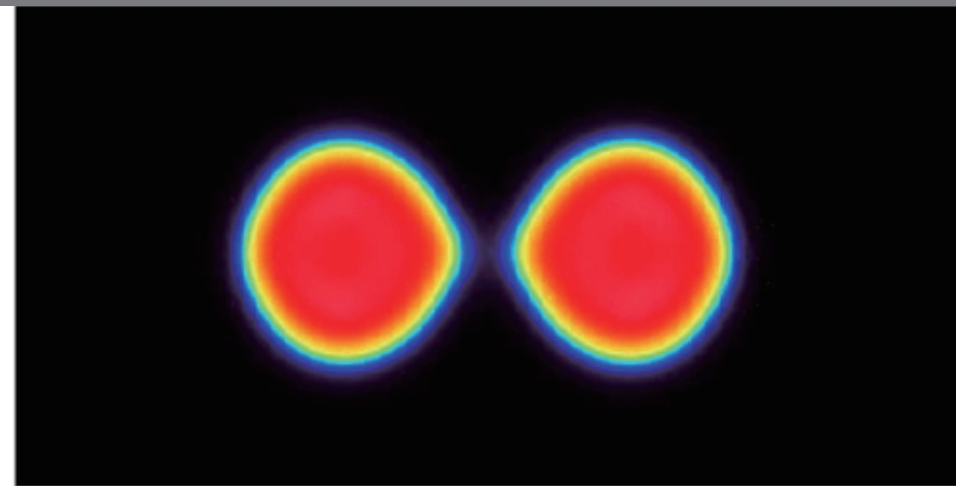
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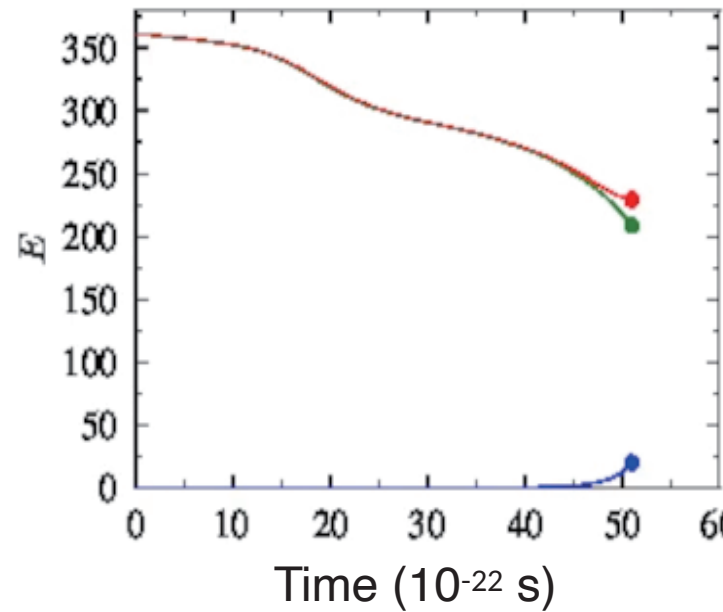
Scamps, CS, Lacroix, PRC 92, 011602(R), 2015

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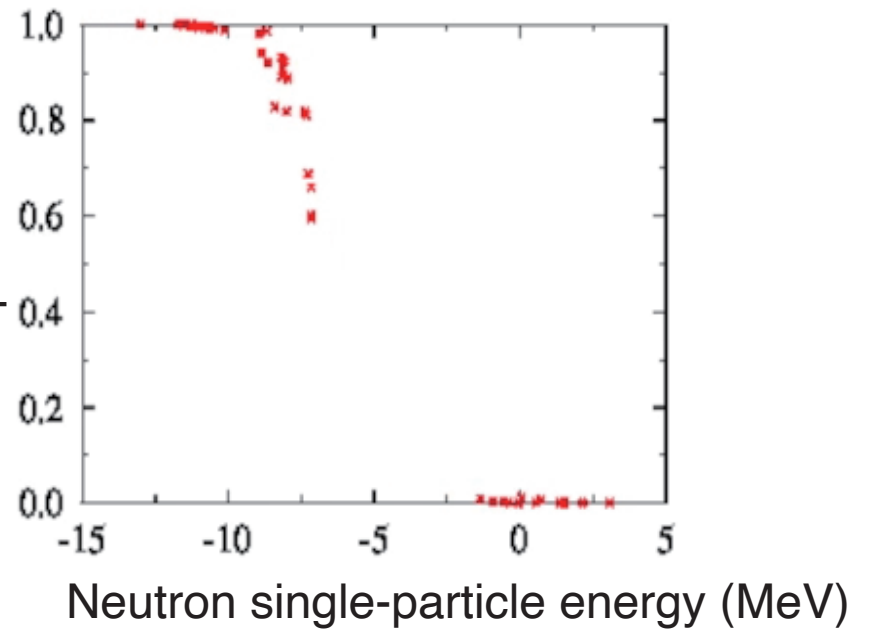


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Coul., kin., tot. energies (MeV)



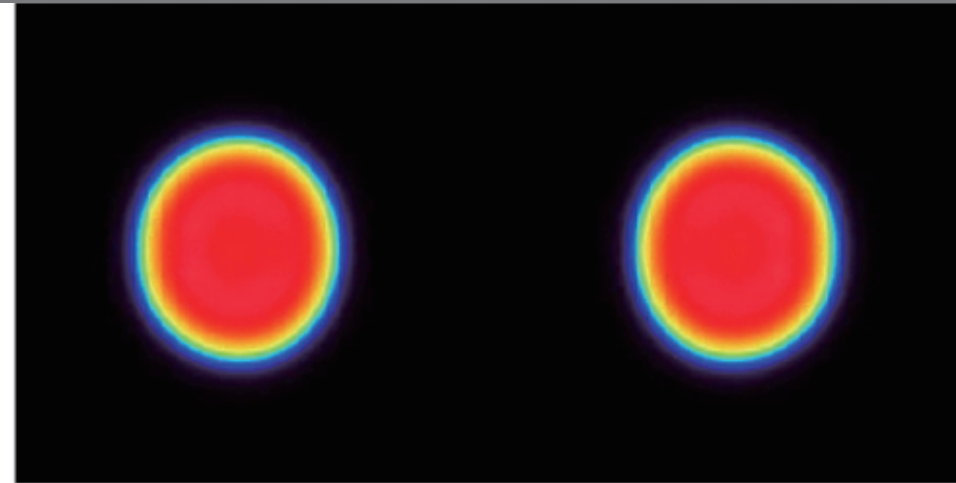
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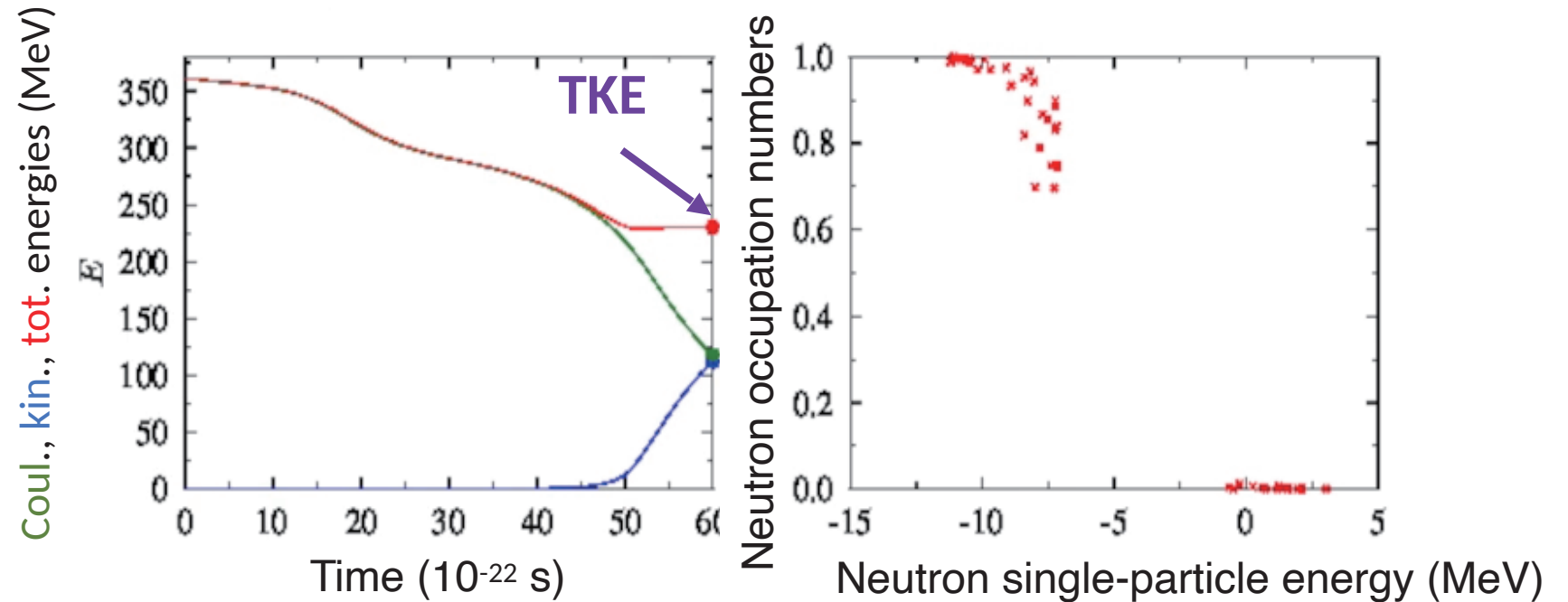
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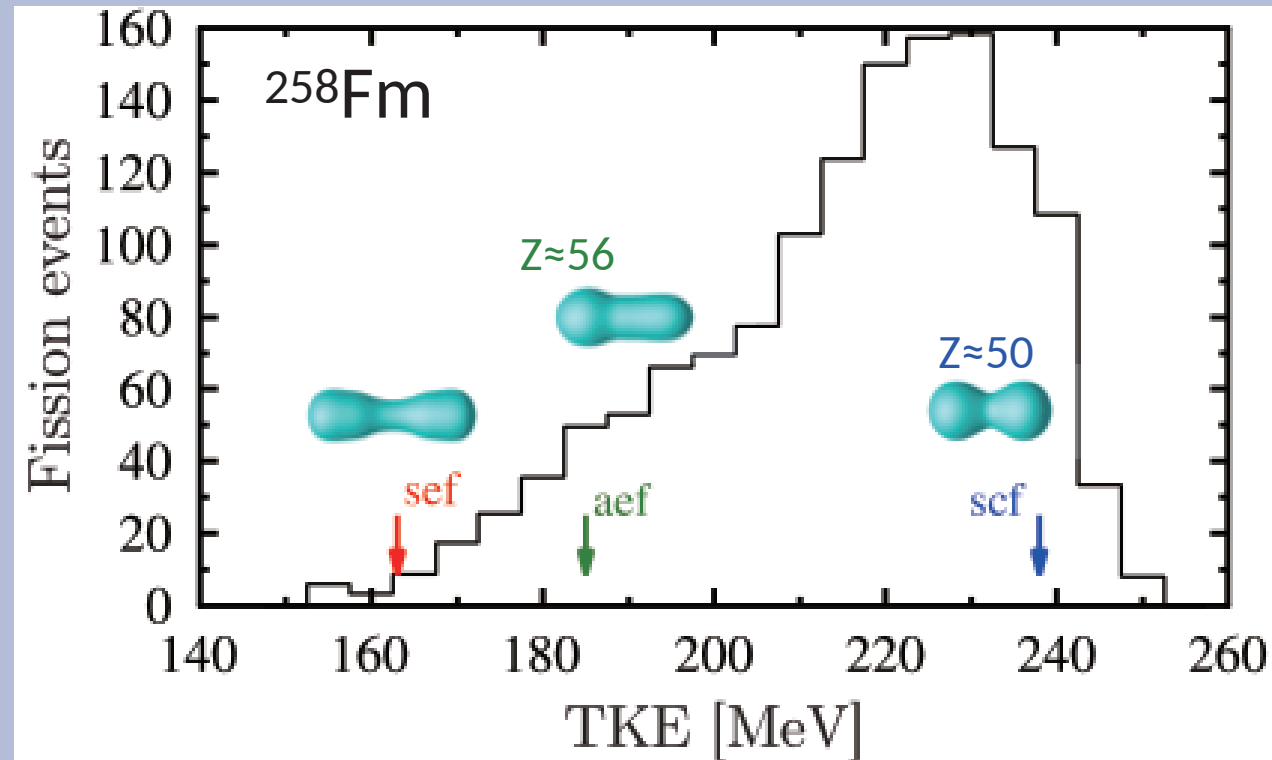


^{258}Fm
(sym.)

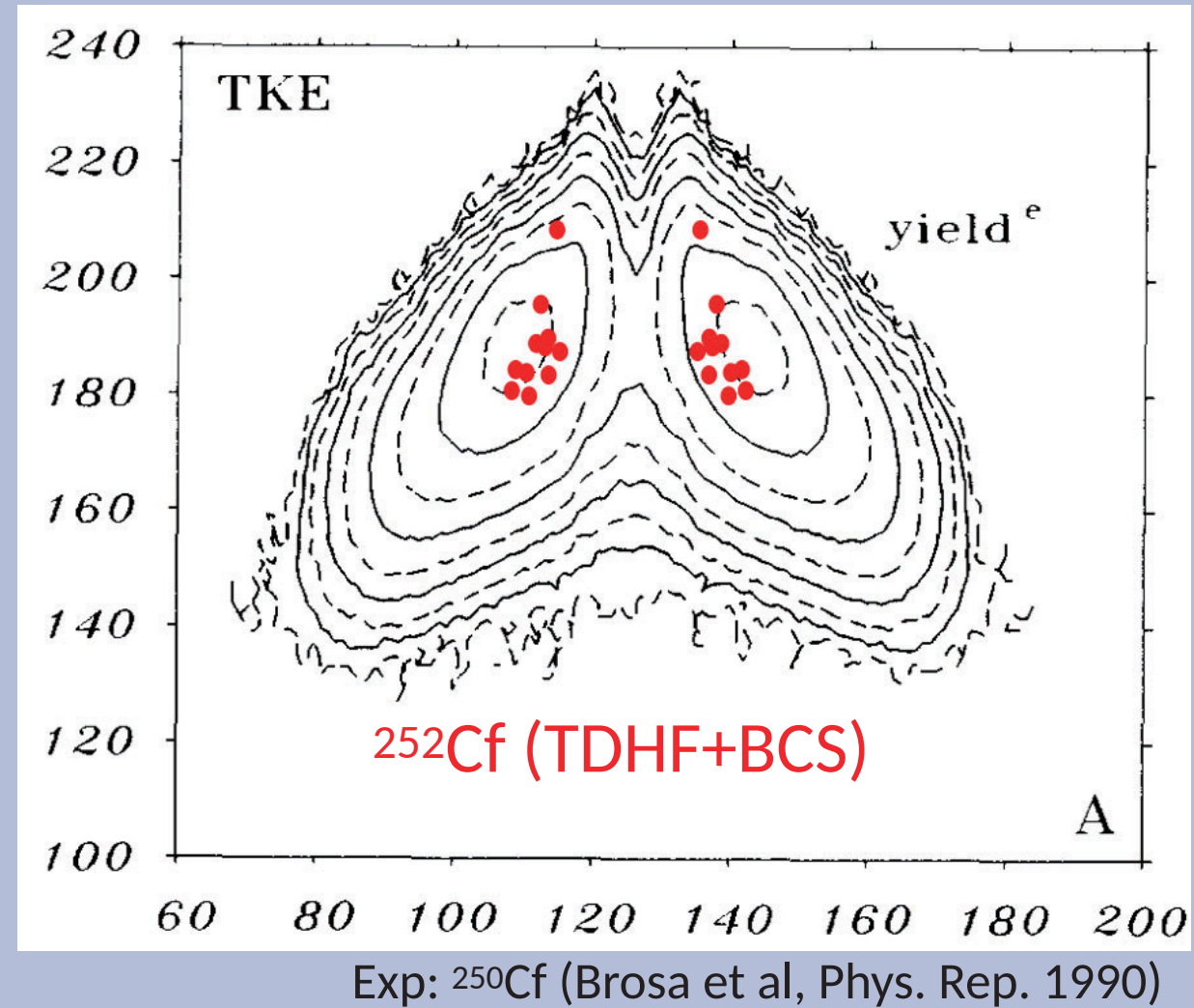


What about TKE?

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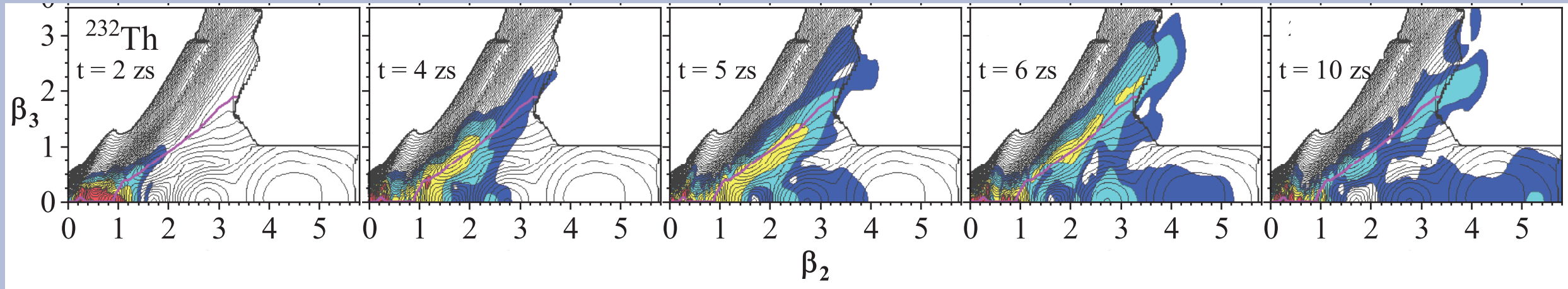


See also Stochastic Mean-Field:
Tanimura et al, PRL **118**, 152501 (2017)



From PES to fragment mass distribution

- Random walks (Brownian motion)
Randrup, Möller, PRL 106, 132503 (2011)
- Diffusion path (Langevin)
Aritomo, Chiba, PRC 88, 044614 (2013)
- Wave packet evolution (TDGCM)
Goutte et al, PRC 71, 024316 (2005)



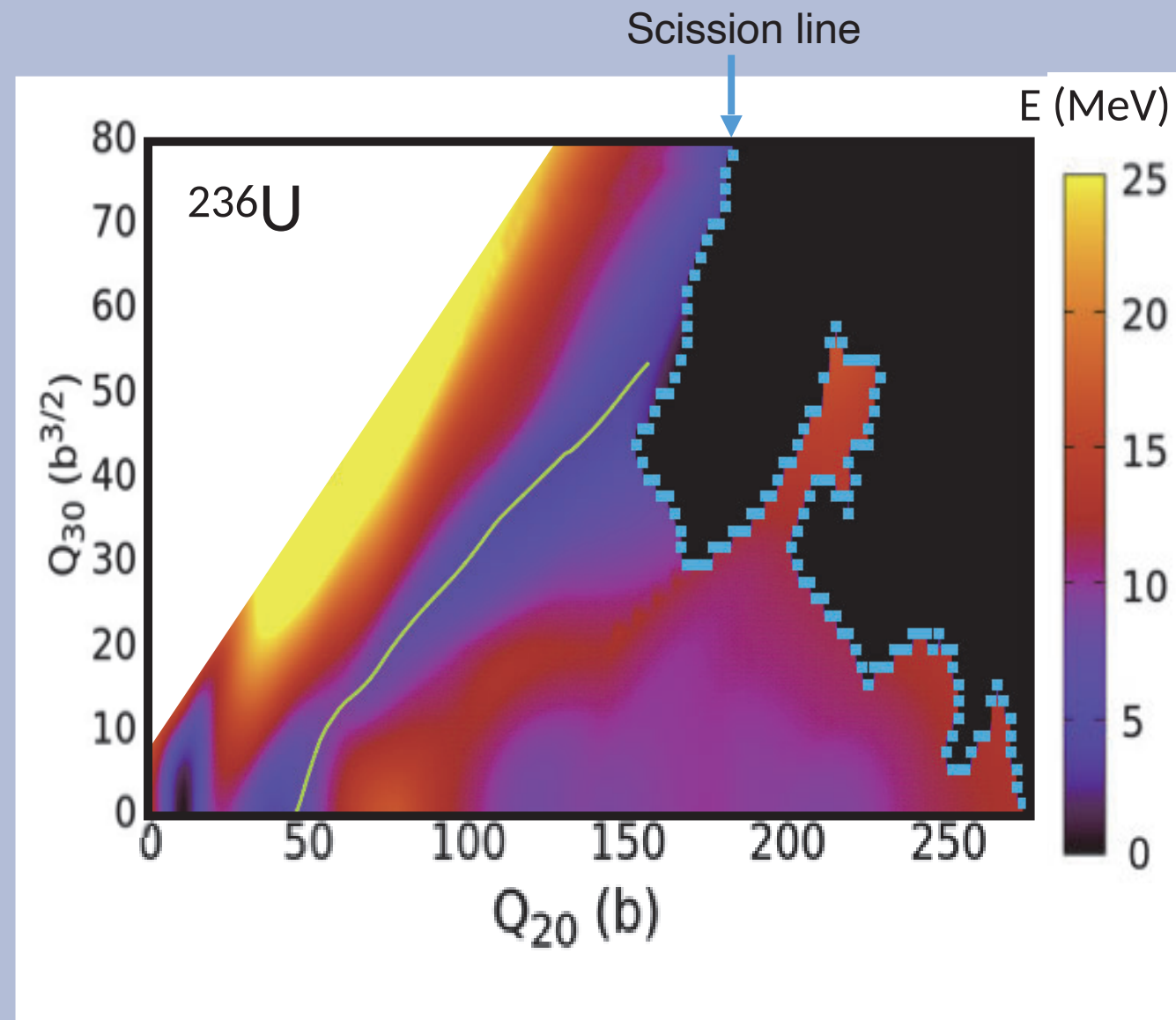
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- Wave packet evolution (TDGCM)
Goutte et al, PRC 71, 024316 (2005)
- Scission point model
Wilkins et al, PRC 14, 1832 (1976)

Quasi-equilibrium at scission

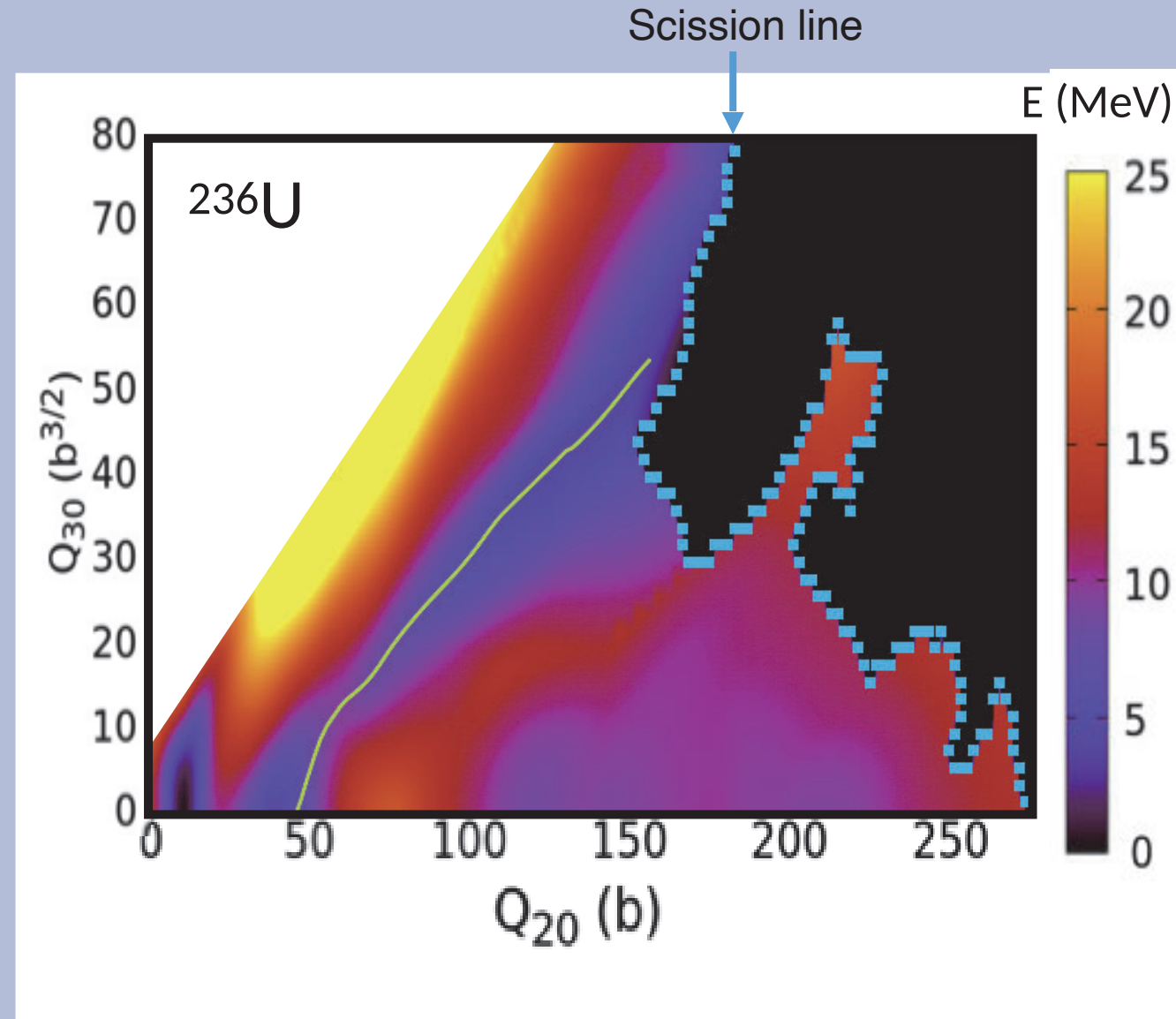
$$Y(x) = e^{-\frac{V(x)}{T}}$$

↑
e.g., mass ratio $x = A_{frag}/A_{tot}$



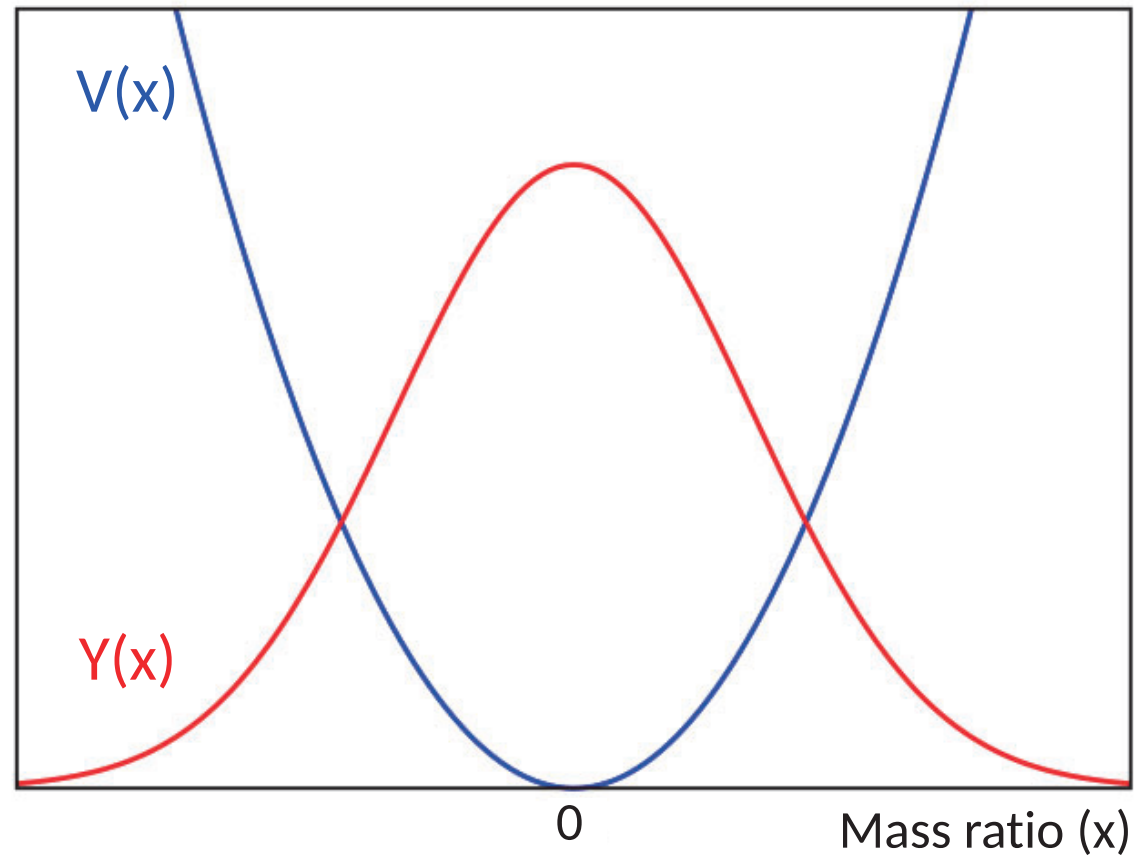
Definitions of fission modes

- **Theoretical mode**
Valleys in the PES
(or minima of $V(x)$ along scission line)
- **Gaussian mode**
From Gaussian fits of the yield
- **Effective mode**
Minima of $V(x)$ extracted from
experimental yields using $Y(x) = e^{-\frac{V(x)}{T}}$



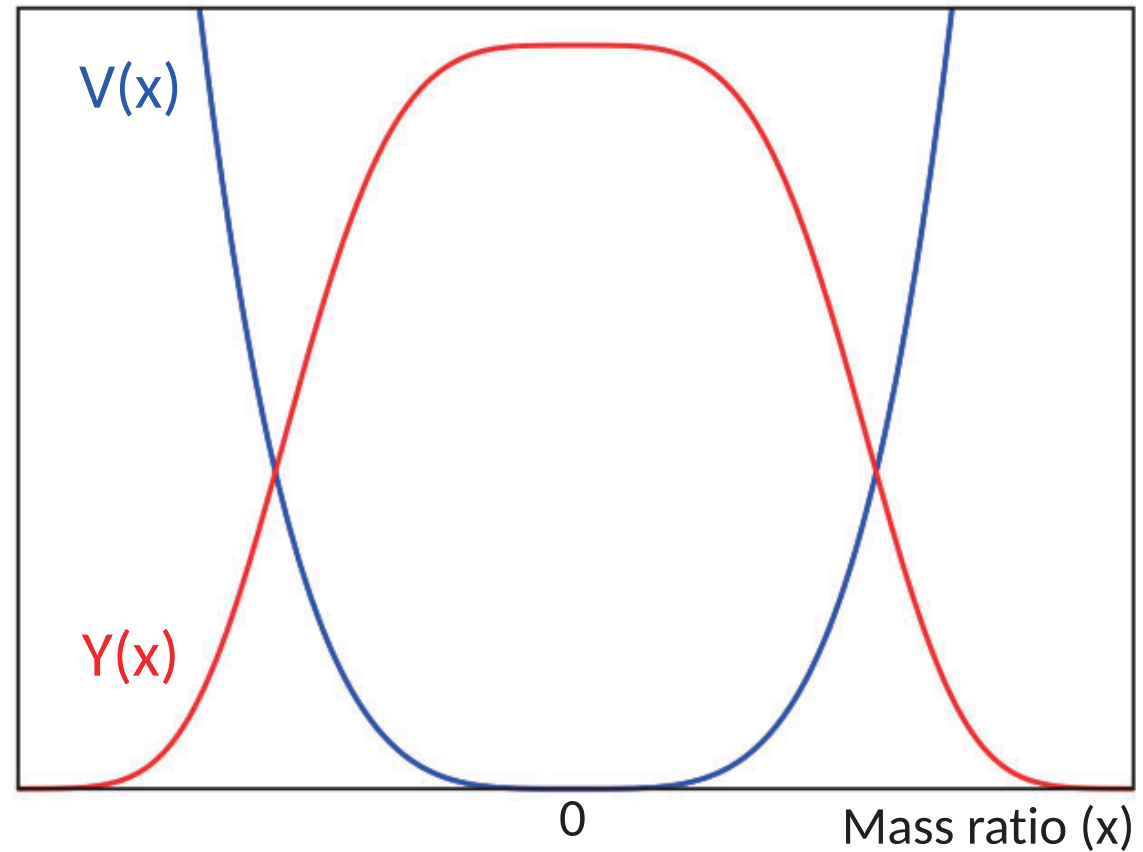
Symmetric theoretical mode

- Quadratic potential $V=x^2$
-> Gaussian yield $Y(x) = e^{-\frac{V(x)}{T}}$



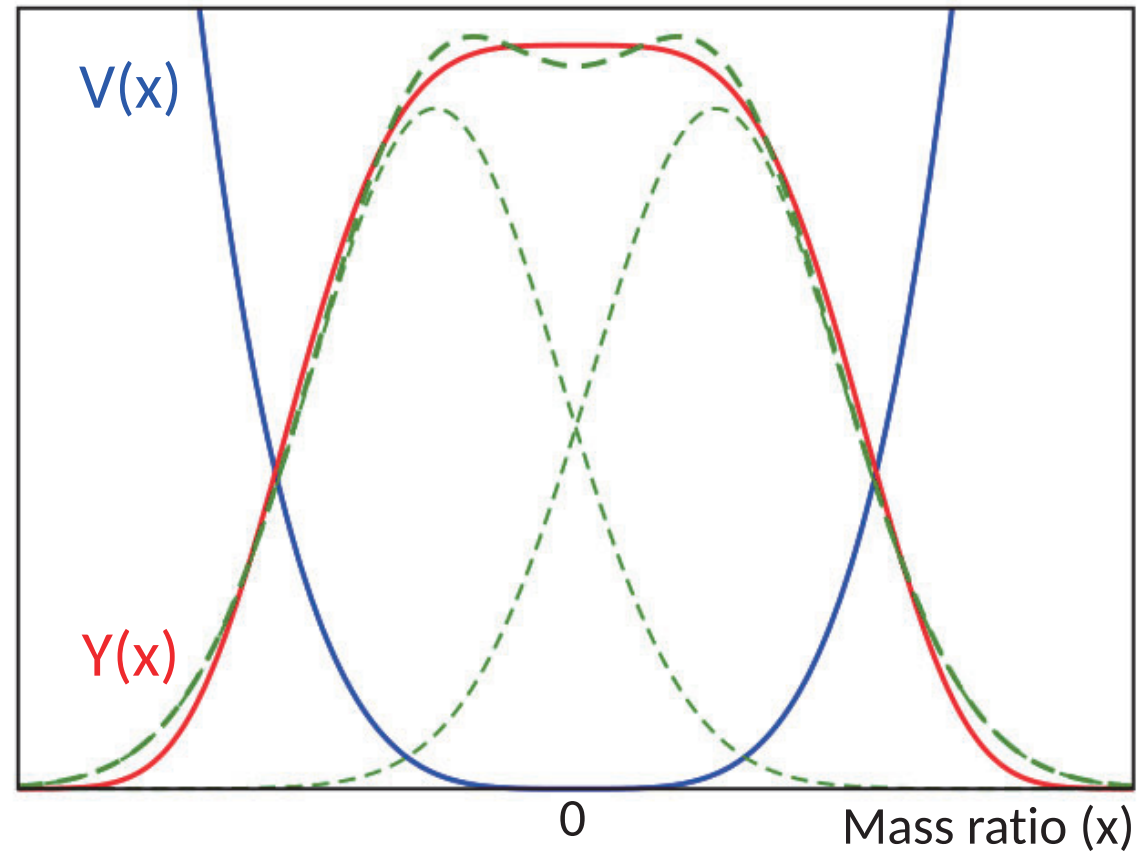
Symmetric theoretical mode

- Quadratic potential $V=x^2$
-> Gaussian yield $Y(x) = e^{-\frac{V(x)}{T}}$
- Quartic potential $V=x^4$
-> non-Gaussian yield



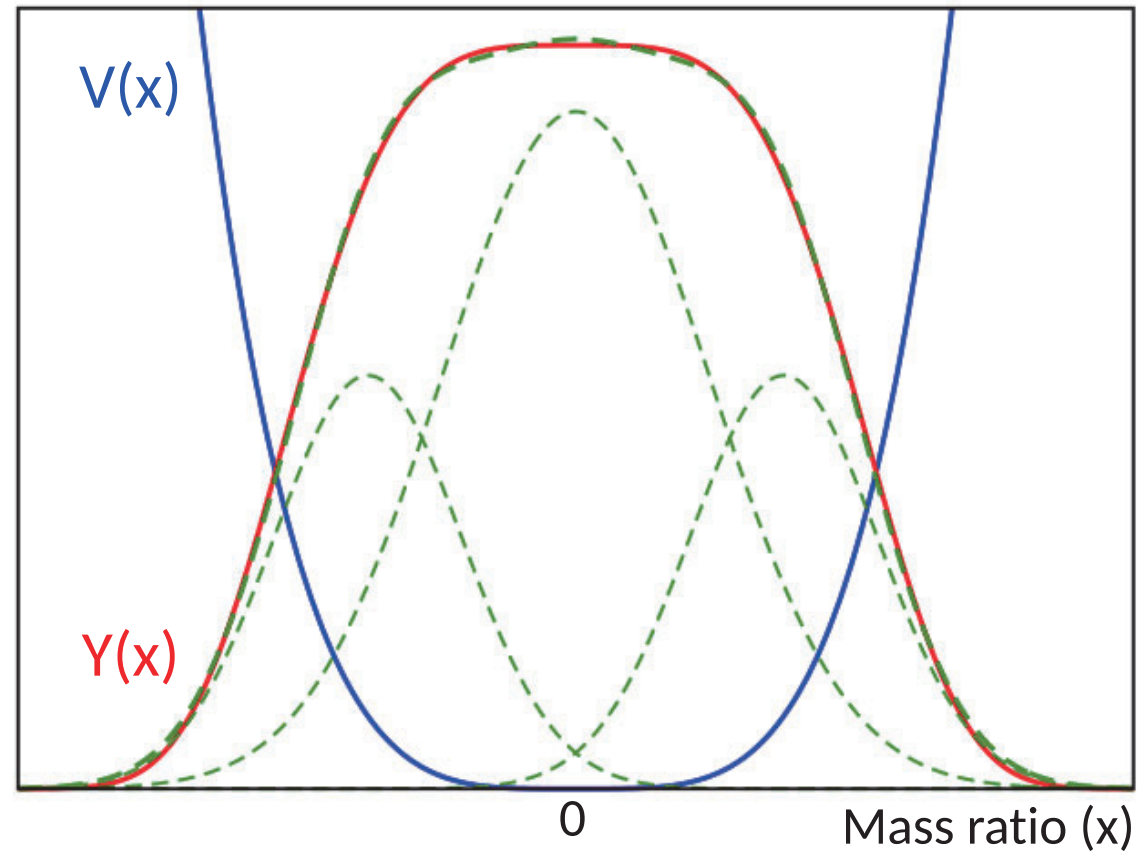
Symmetric theoretical mode

- Quadratic potential $V=x^2$
 -> Gaussian yield $Y(x) = e^{-\frac{V(x)}{T}}$
- Quartic potential $V=x^4$
 -> non-Gaussian yield
 -> 1 asym Gaussian mode



Symmetric theoretical mode

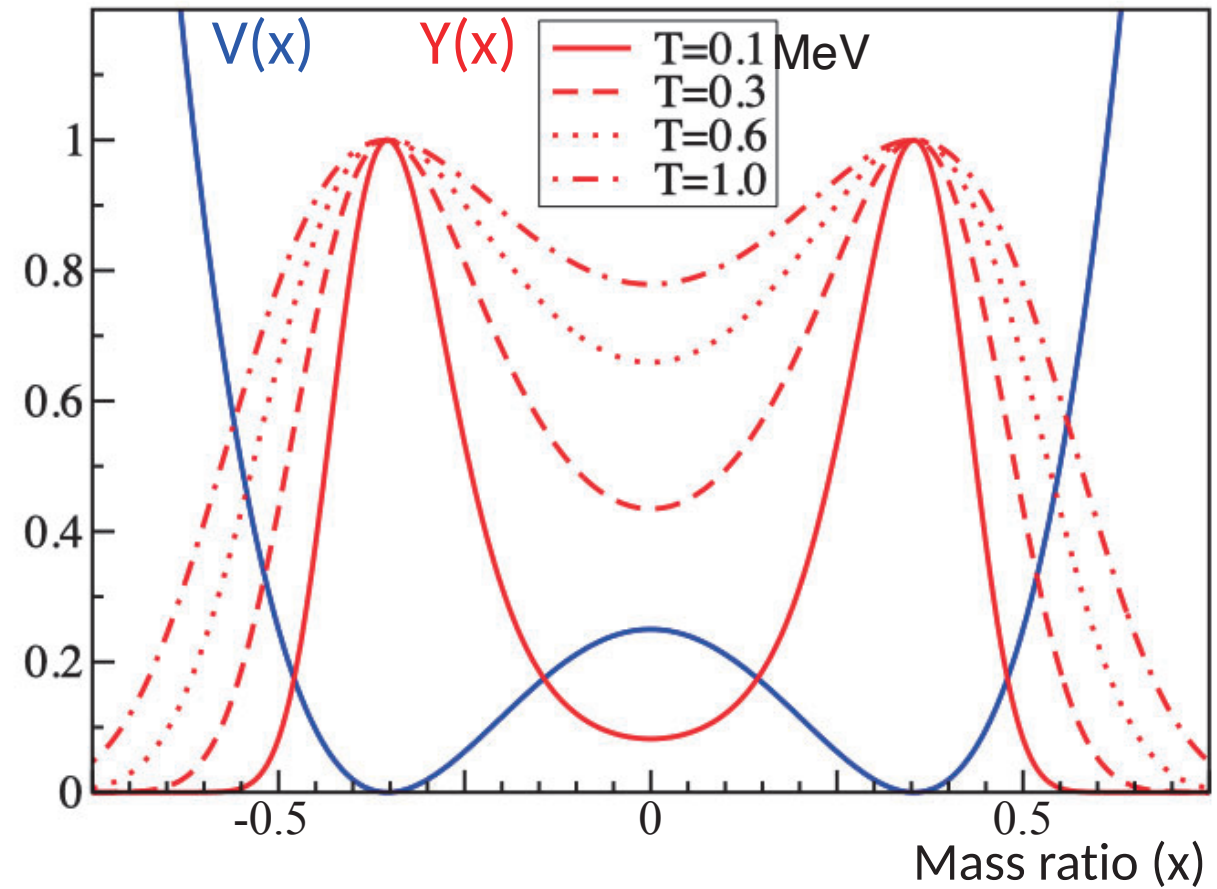
- Quadratic potential $V=x^2$
 -> Gaussian yield $Y(x) = e^{-\frac{V(x)}{T}}$
- Quartic potential $V=x^4$
 -> non-Gaussian yield
 -> 1 asym Gaussian mode
 -> or 1 sym and 1 asym Gaussian modes



Asymmetric theoretical mode

- Temperature dependence

$$Y(x) = e^{-\frac{V(x)}{T}}$$

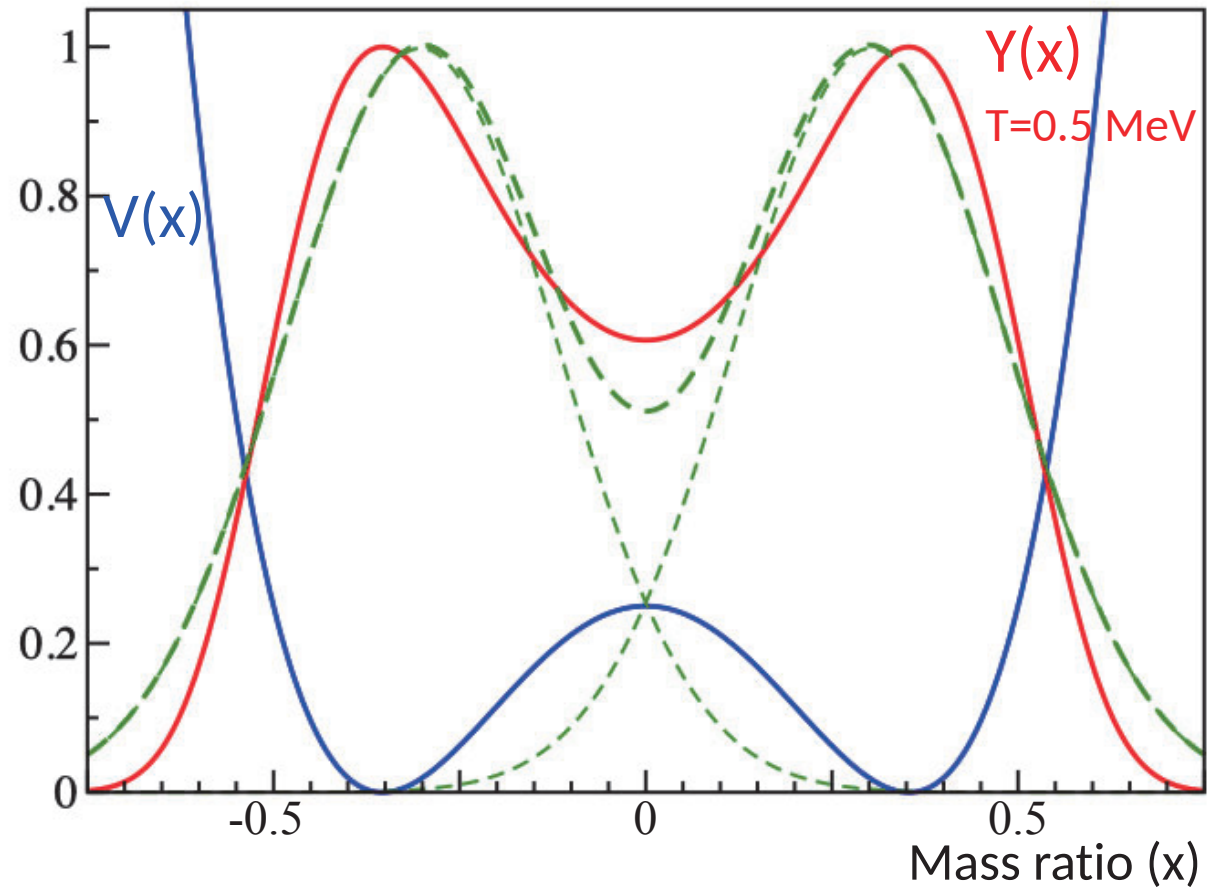


Asymmetric theoretical mode

- Temperature dependence

$$Y(x) = e^{-\frac{V(x)}{T}}$$

- 1 asym Gaussian mode
-> poor fit



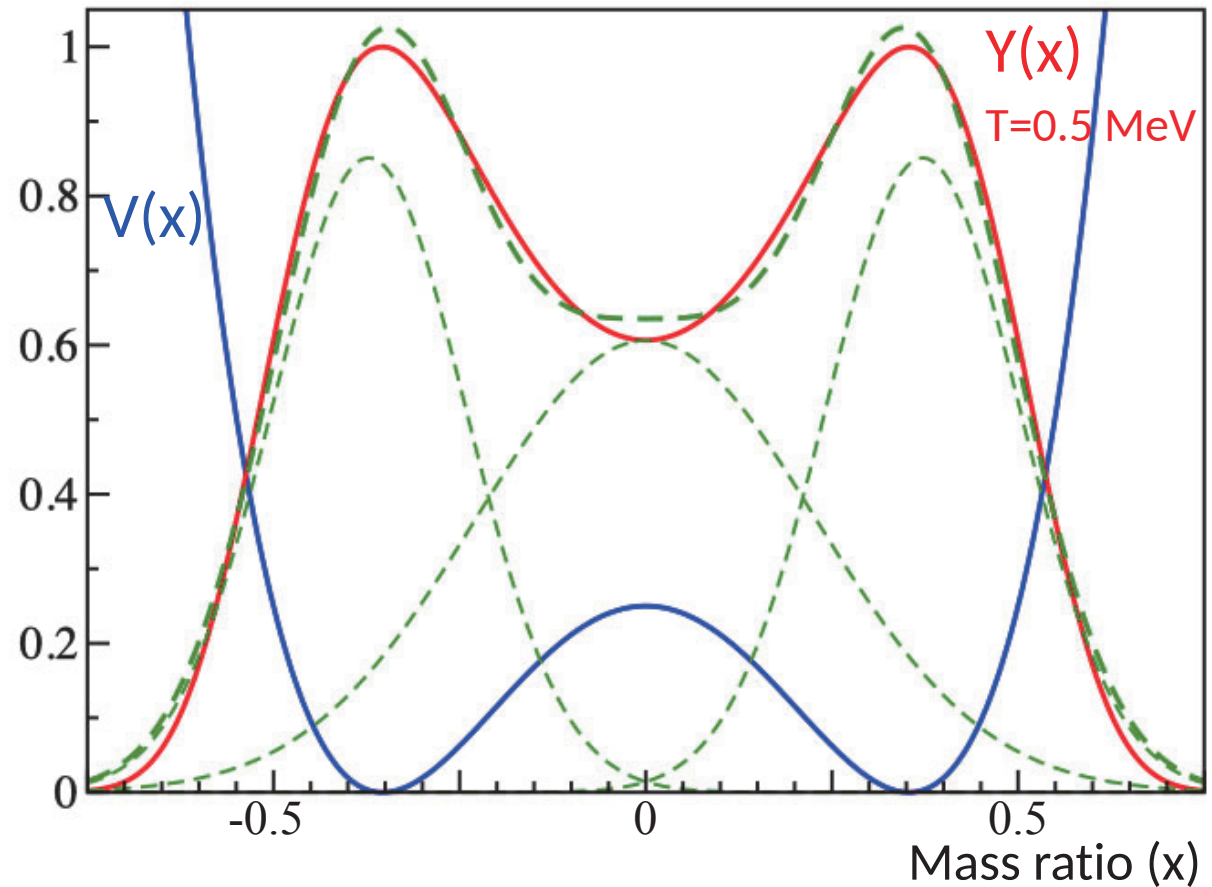
Asymmetric theoretical mode

- Temperature dependence

$$Y(x) = e^{-\frac{V(x)}{T}}$$

- 1 asym Gaussian mode
-> poor fit

- 1 asym + 1 sym Gaussian modes
-> better fit
-> wrong interpretation



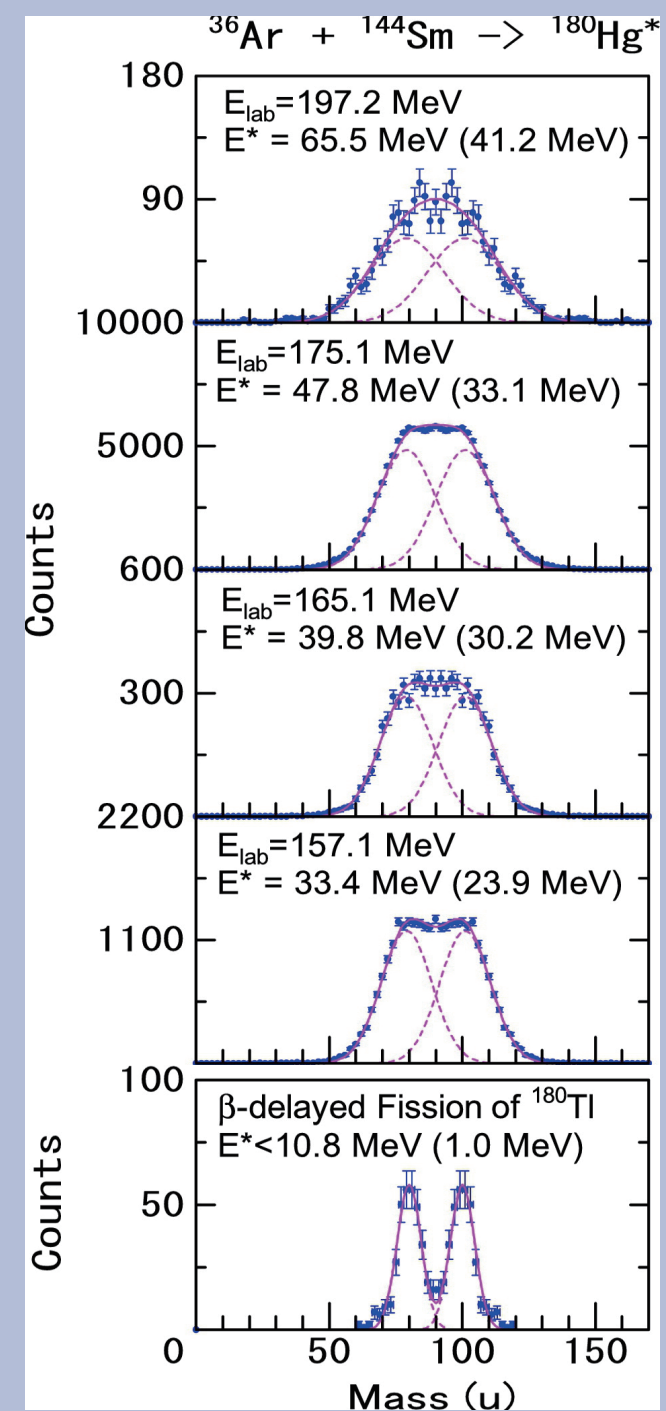
Effective mode

- Fission of ^{180}Hg

Andreyev et al PRL **105**, 252502 (2010)

Nishio et al PLB **748**, 89 (2015)

Prasad et al PRC **91**, 064605 (2015)



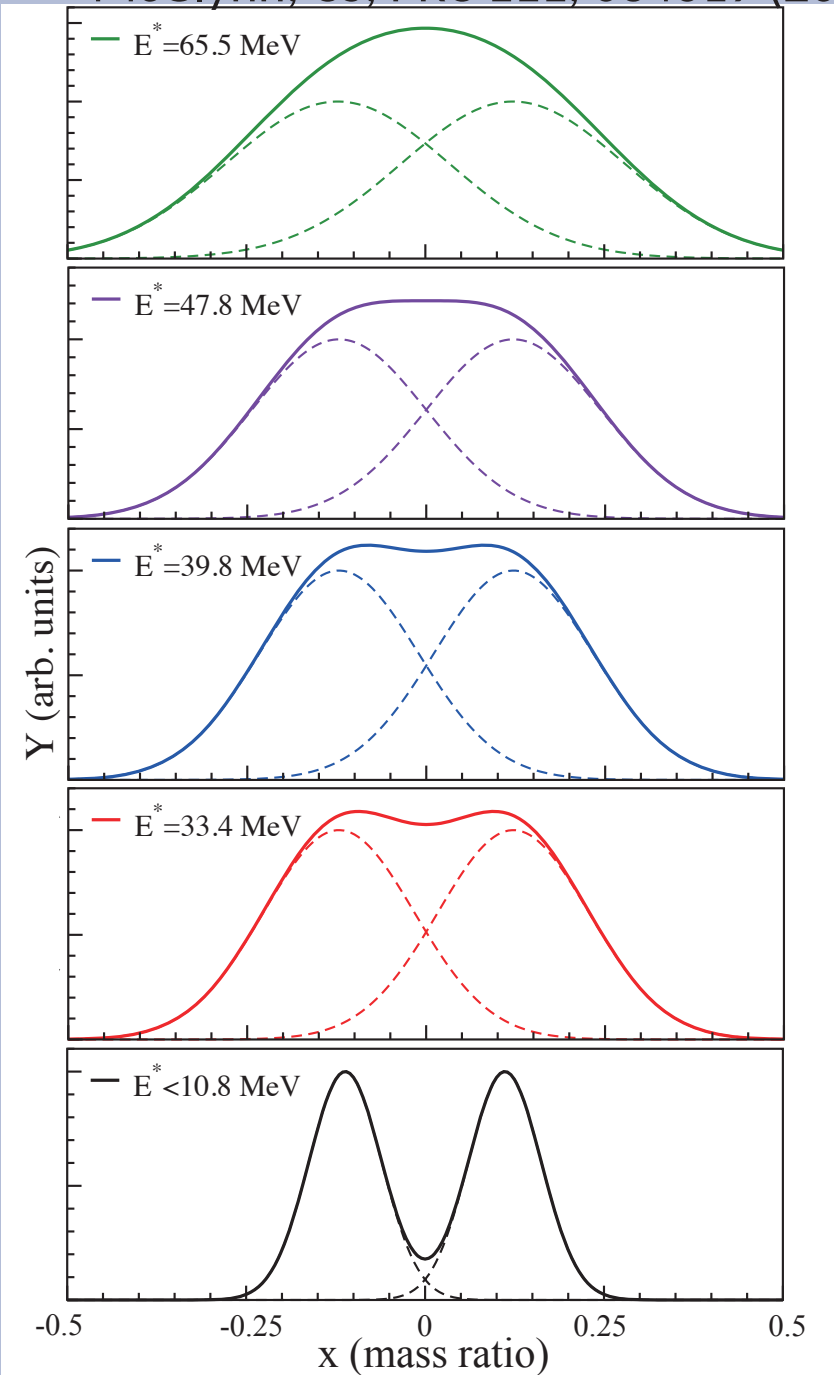
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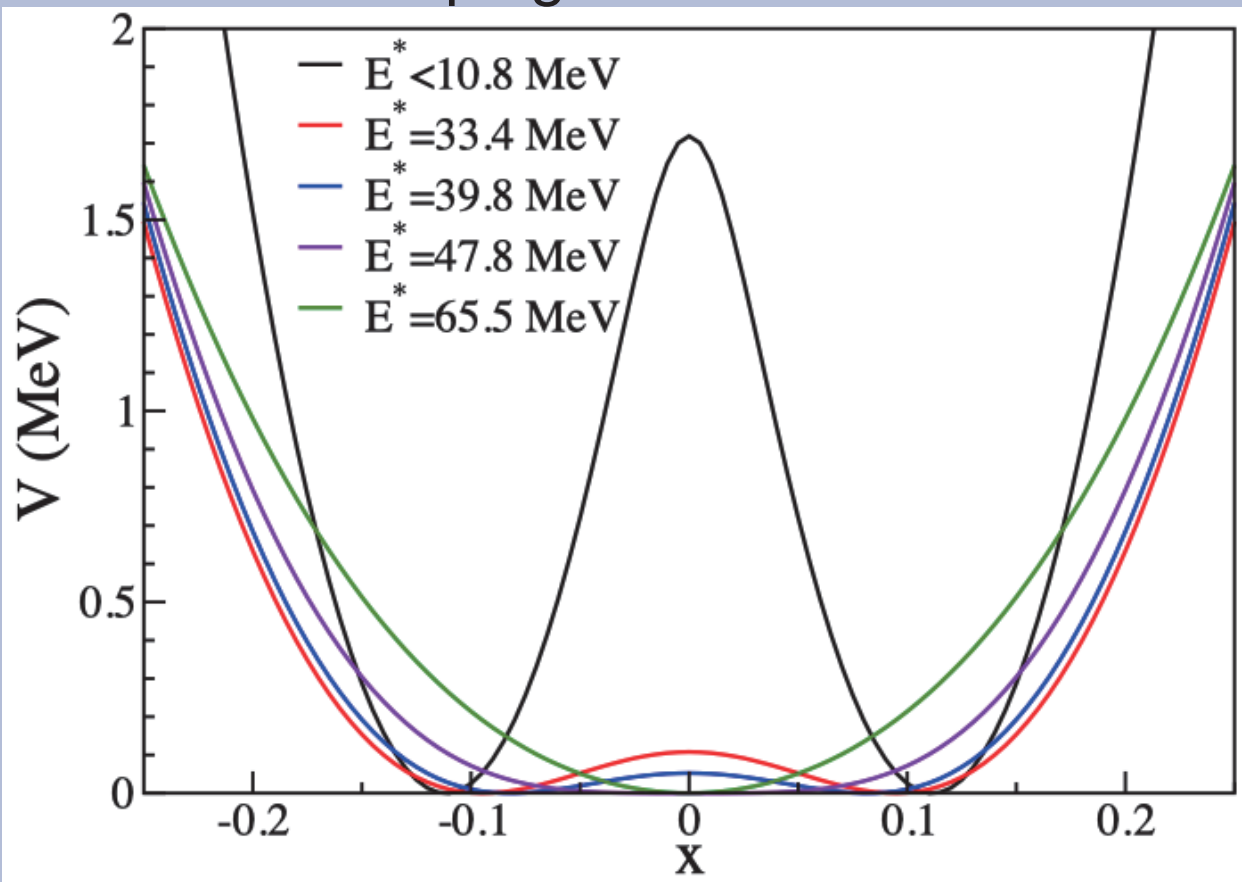
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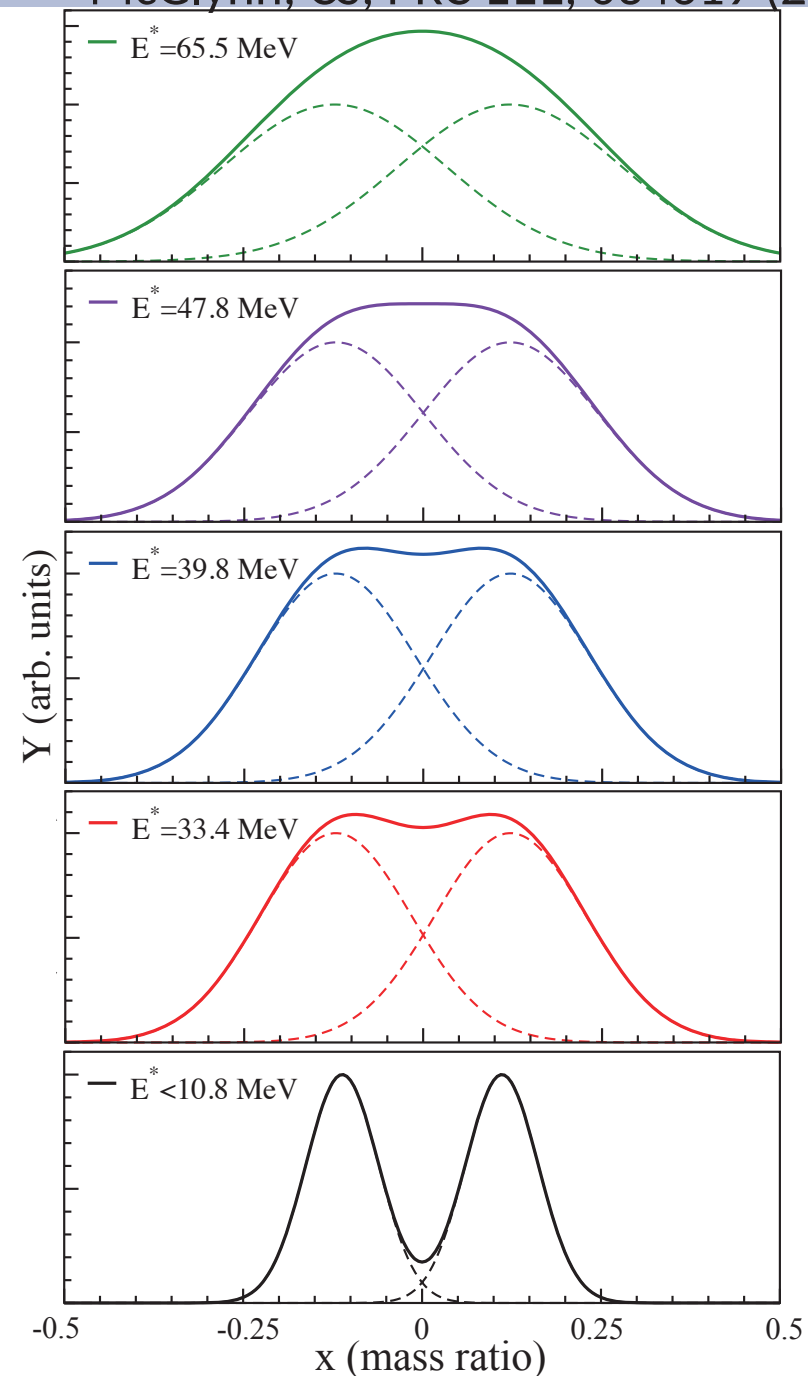


Effective mode

- Fission of ^{180}Hg
 - > asymmetric to symmetric transition
 - > damping of shell effects with E^*

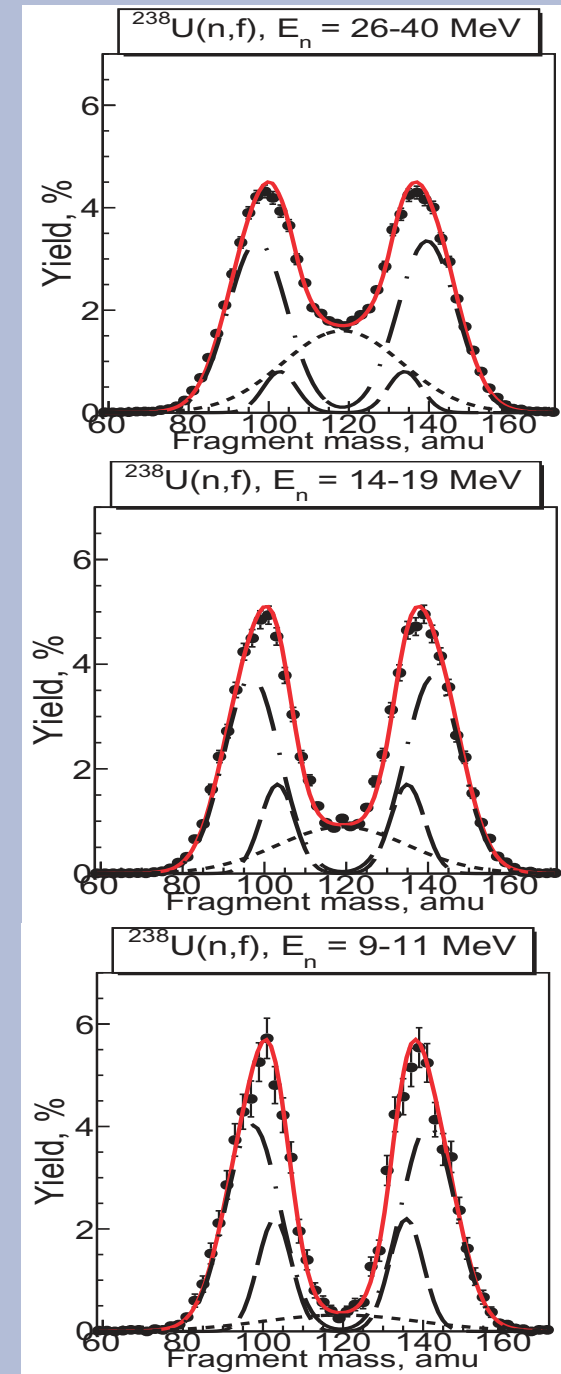


$$Y(x) = e^{-\frac{V(x)}{T}}$$



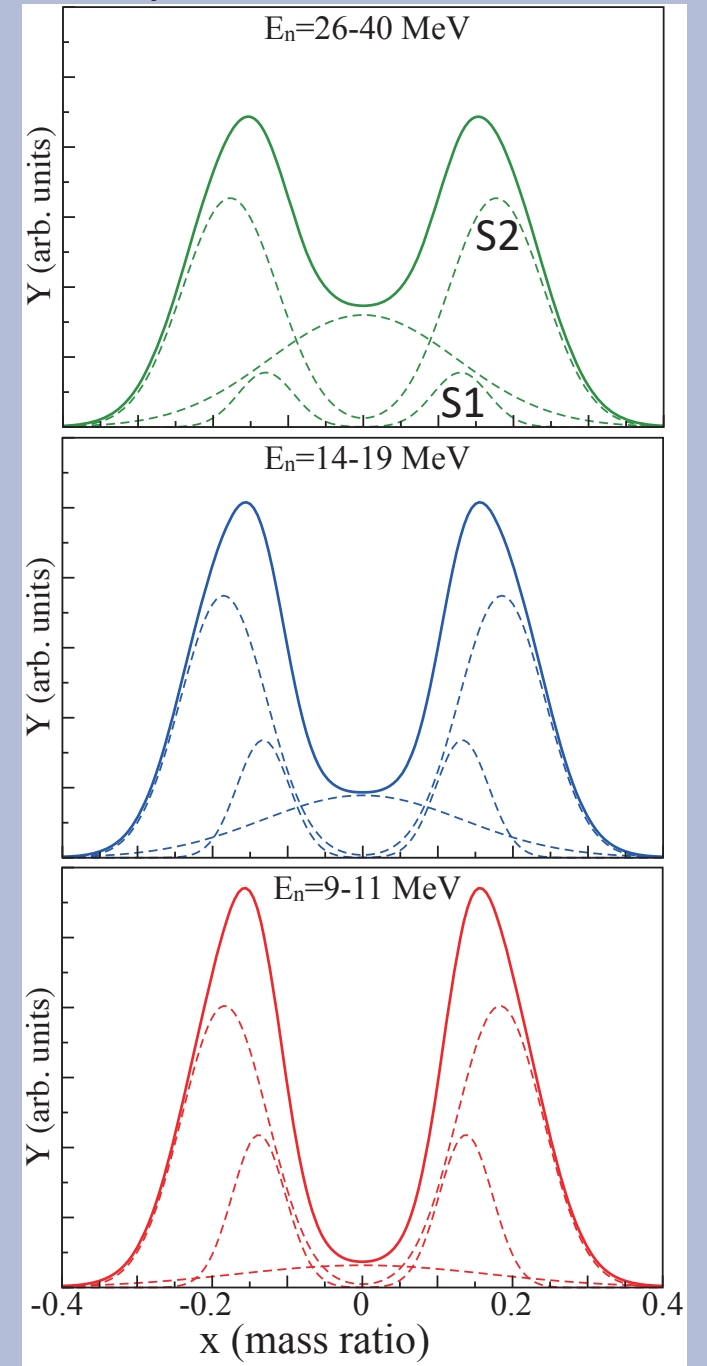
Effective mode

- Fission of ^{238}U



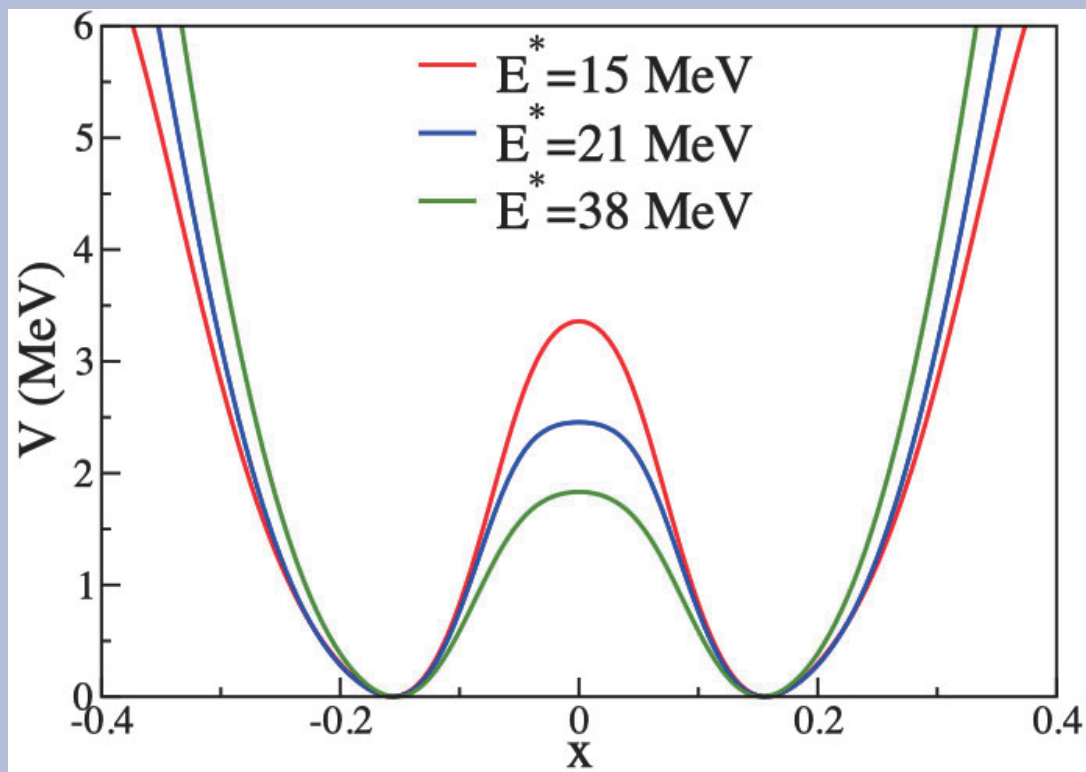
Effective mode

- Fission of ^{238}U
 - > Brosa Gaussian modes S1 ($Z\sim 52.5$) and S2 ($Z\sim 55$)
- Brosa et al, Phys. Rep. **197**, 167 (1990)

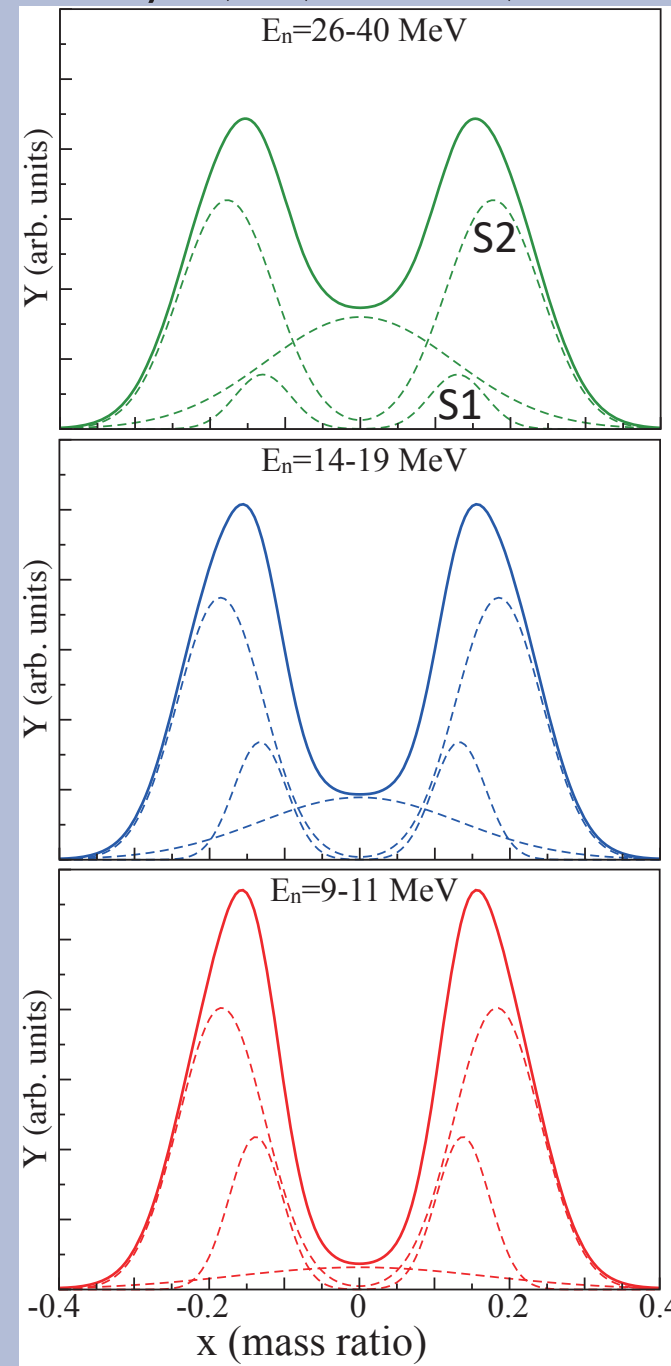


Effective mode

- Fission of ^{238}U
 - > Brose Gaussian modes S1 ($Z\sim 52.5$) and S2 ($Z\sim 55$)
Brose et al, Phys. Rep. **197**, 167 (1990)
 - > S1 and S2 contribute to the same effective mode
 - > No symmetric effective mode at these energies

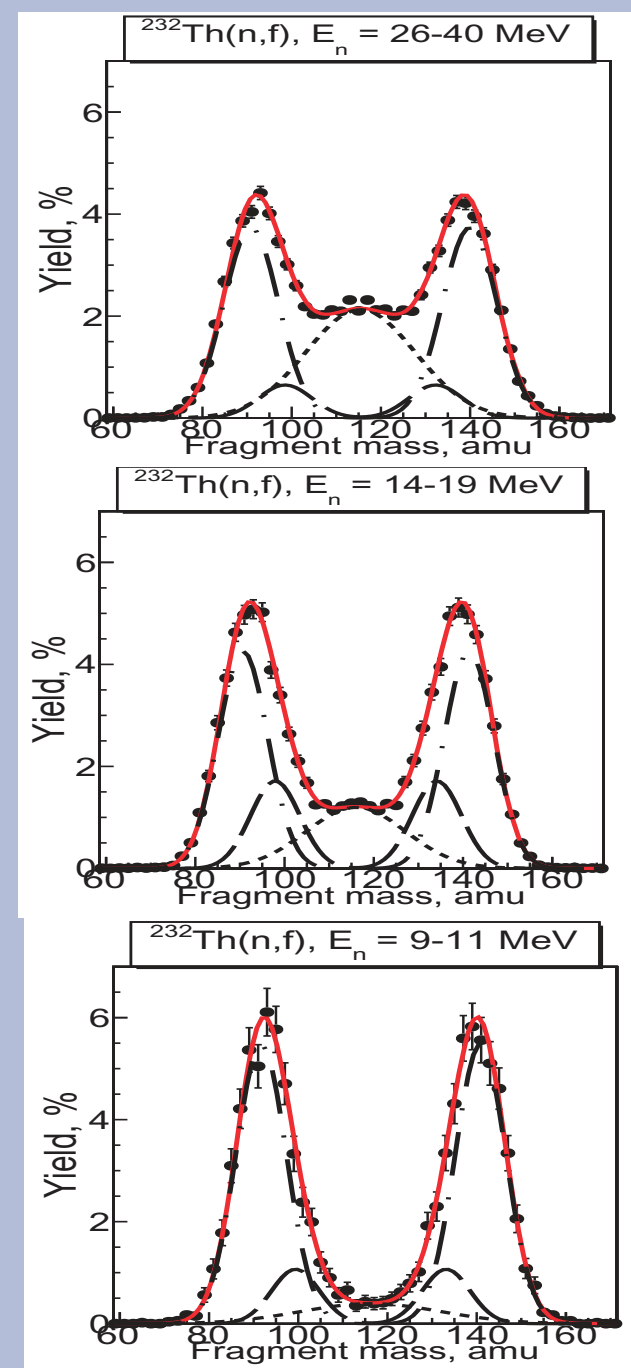


$$Y(x) = e^{-\frac{V(x)}{T}}$$



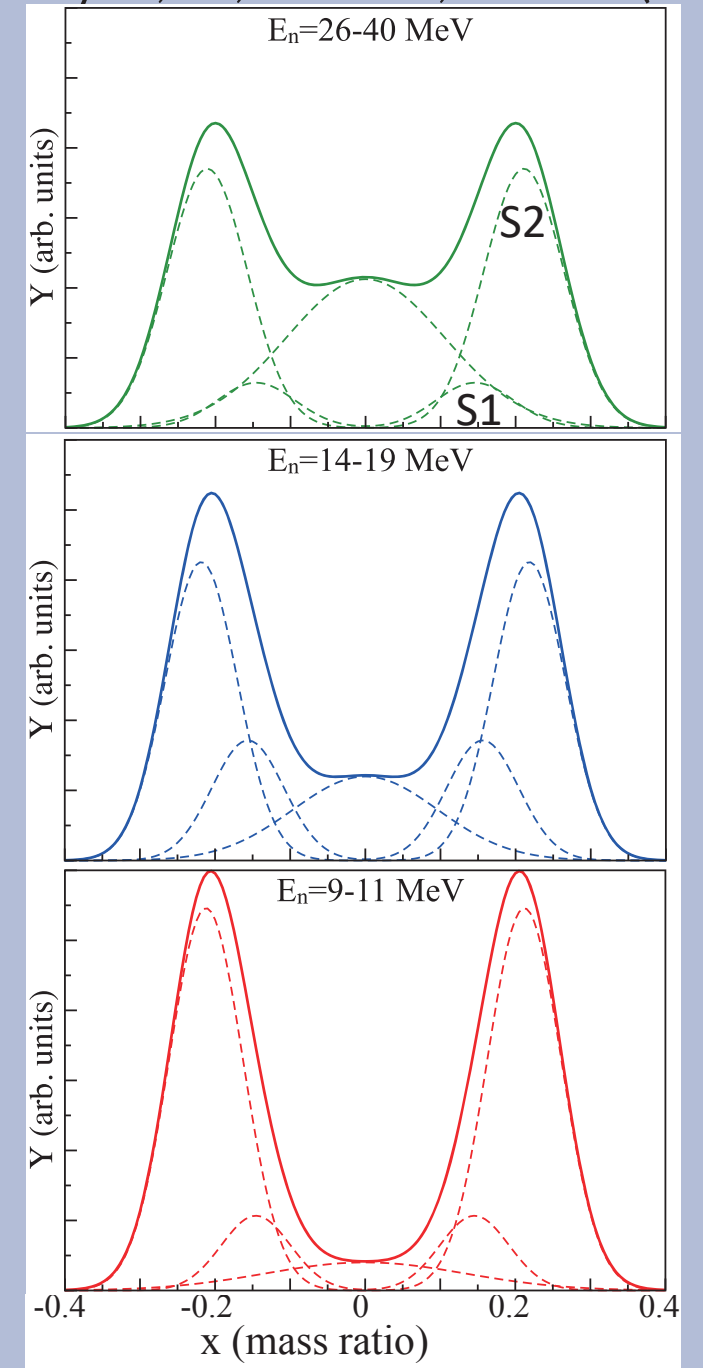
Effective mode

- Fission of ^{232}Th



Effective mode

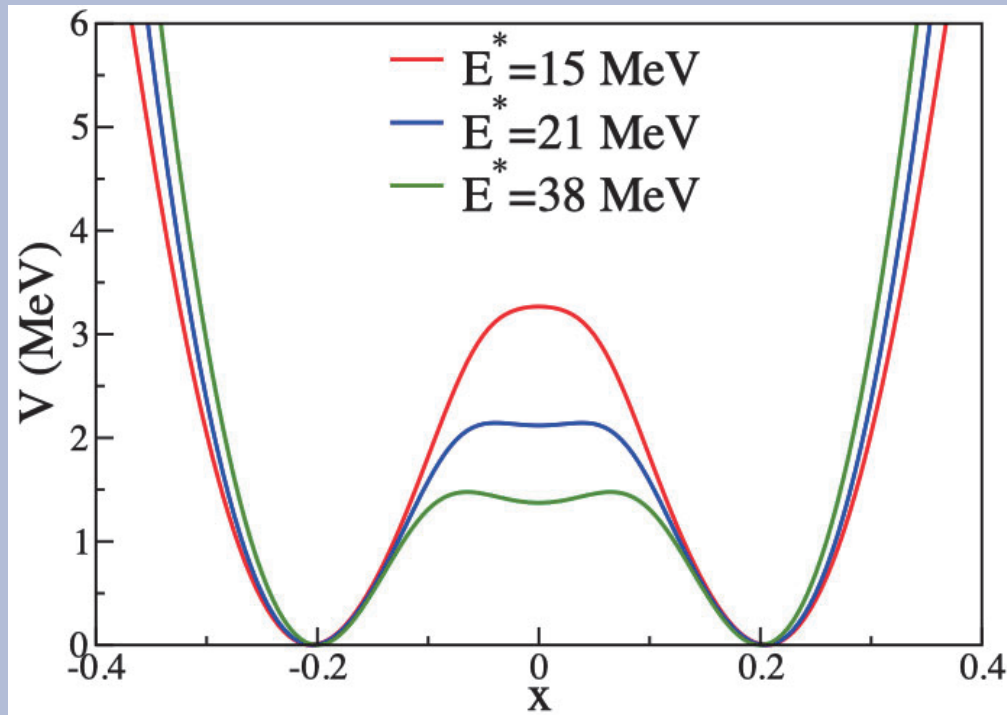
- Fission of ^{232}Th



Effective mode

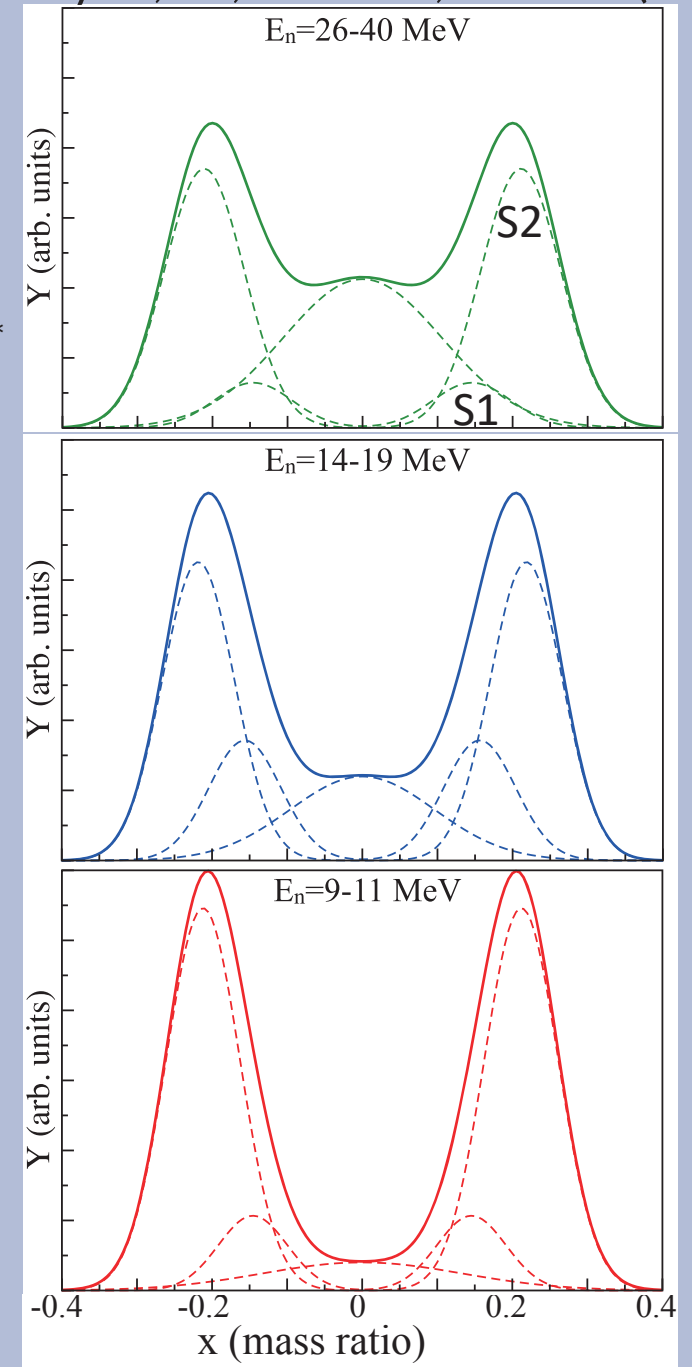
- Fission of ^{232}Th

-> appearance of symmetric effective mode at high E^*



$$Y(x) = e^{-\frac{V(x)}{T}}$$

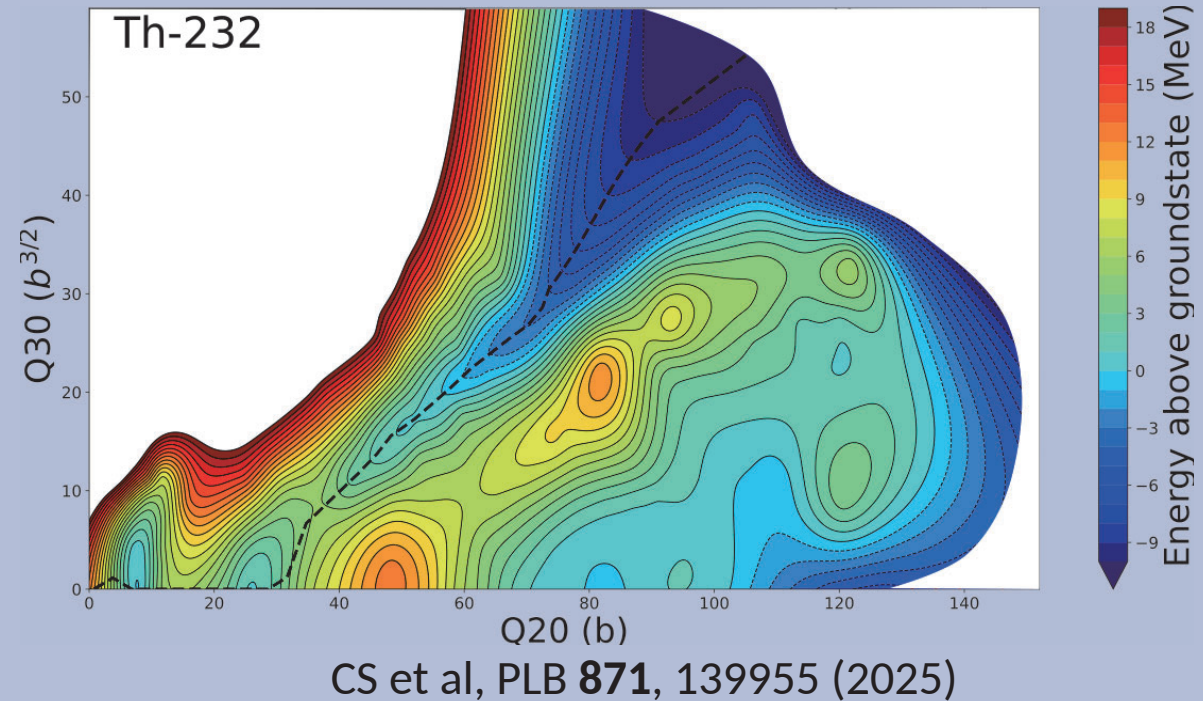
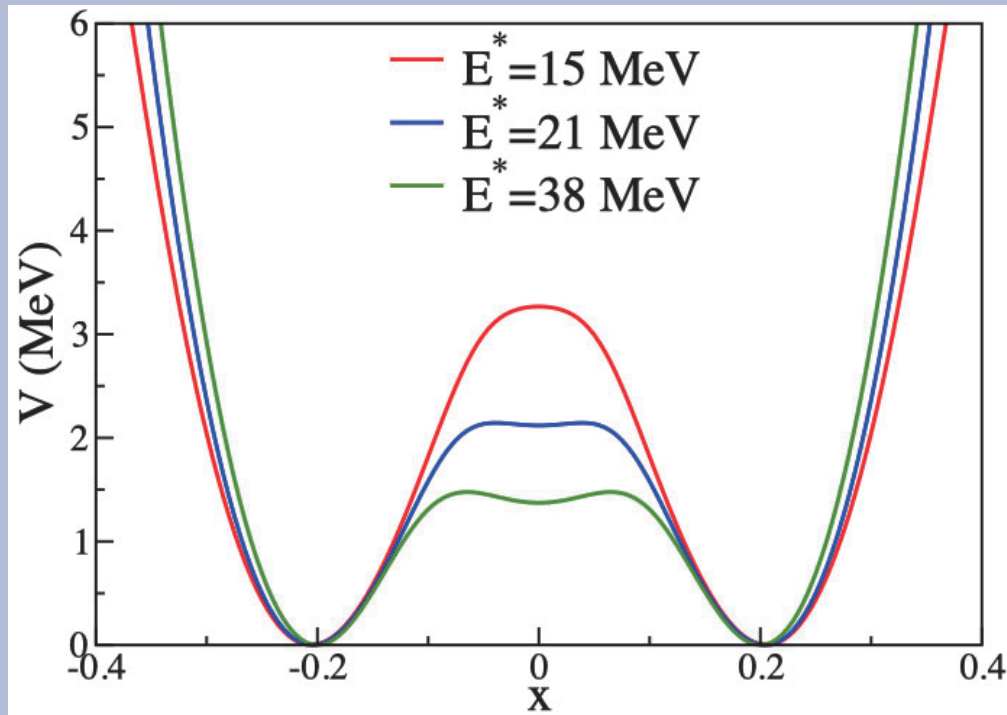
←



Effective mode

- Fission of ^{232}Th

- > appearance of symmetric effective mode at high E^*
- > Damping of shell effects or bifurcation on the PES?



Conclusions

- Level Density near Fermi surface to visualize shell effects in PES
- Octupole deformed proton shell effects (Z=52,56) -> S1,S2 Brossa modes
- Gaussian fits of yields usually not associated with potential valleys
- Fission modes from effective potential using $Y(x) = e^{-\frac{V(x)}{T}}$
- Systematics measurements at various E^* necessary to distinguish between damping of shell effects and bifurcation on PES
- Connect $V(x)$ and $Y(x)$ from TDGCM

