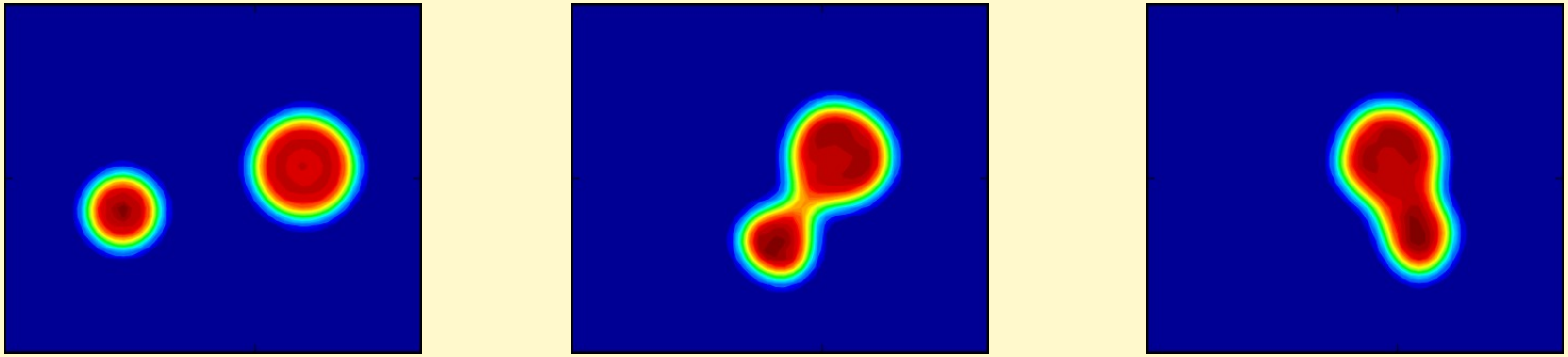
Time-dependent Hartree-Fock (TDHF) application: fusion, quasifission, and deep-inelastic reactions



- Fusion of exotic neutron-rich nuclei (Radioactive Ion Beam Facilities)

- Fusion leading to formation of superheavy elements Z=117,119
  (experiments and Dubna and GSI-TASCA)
  the main competing process is quasifission

TDHF Equations

- Equations of motion obtained from variation of the action

$$S = \int_{t_1}^{t_2} dt \, \langle \Phi(t) | H - i\hbar \partial_t | \Phi(t) \rangle$$

with

$$H = \sum_i^A t_i + \sum_{i<j}^A v_{ij}$$

Skyrme

- Many-body state is a single time-dependent Slater determinant

$$\Phi(r_1 ... r_A; t) = \frac{1}{\sqrt{A!}} \, det|\phi_\lambda(r_i, t)|$$

- TDHF equations for single-particle states

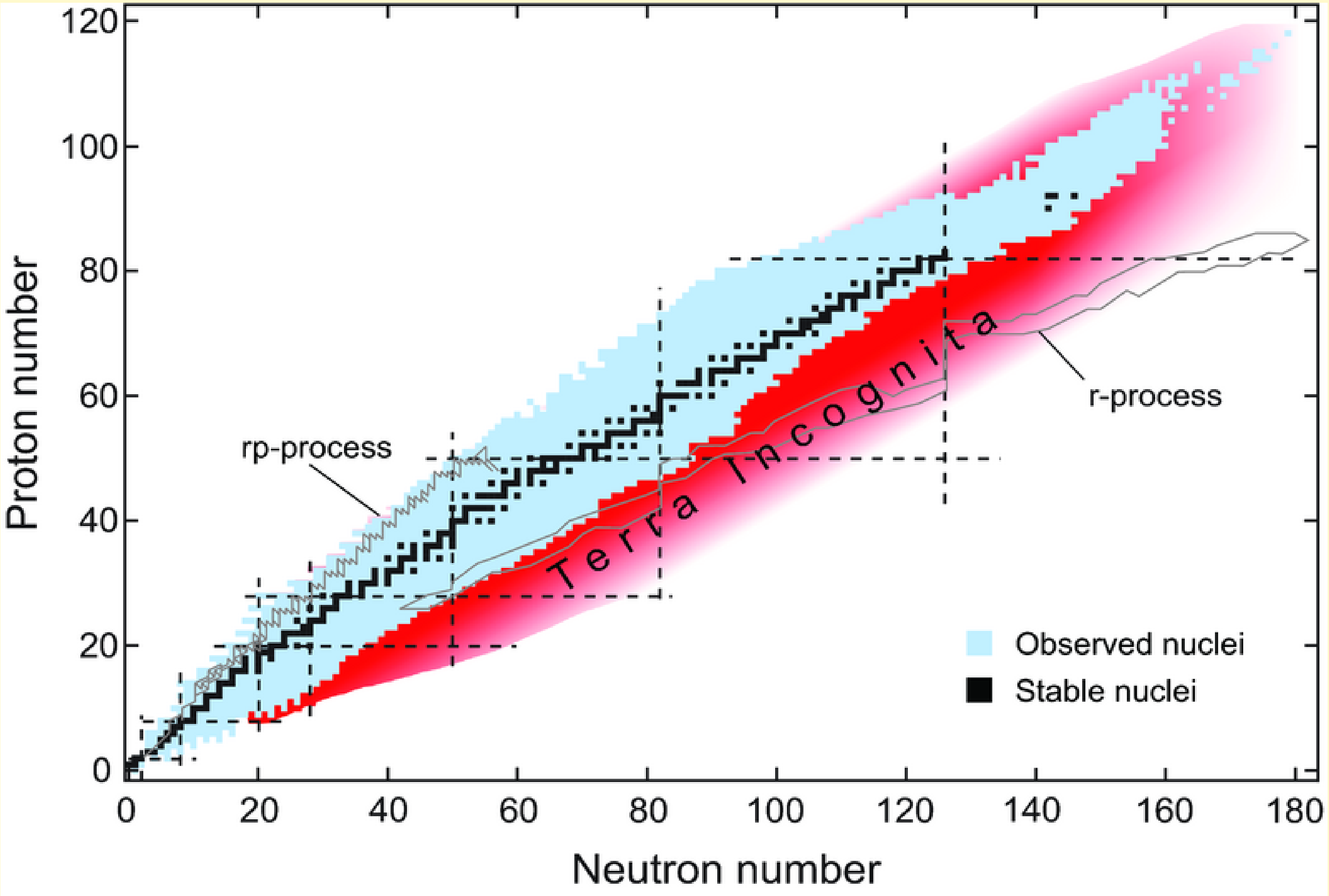
$$i\hbar \frac{\partial \phi_\lambda}{\partial t} = h(\phi_\mu)\phi_\lambda$$

- Skyrme energy functional is given by the 3D integral

$$E = \int d^3r \; H\left(\rho, \tau, \vec{j}, \vec{s}, \vec{T}, J_{\mu\nu}; \vec{r}\right)$$

Nuclear chart and the frontier of neutron-rich nuclei

Ref: Isotope Science Facility proposal, MSU (Nov. 2006)



Heavy-ion reactions as function of impact parameter b

impact
parameter b

Elastic collision, inelastic collision (Coulomb excitation)

large

Coulomb + nuclear inelastic excitation
few-nucleon transfer

medium

Multi-nucleon transfer

Deep-inelastic collisions ($E^* \approx 30$ MeV), 2 fragments emerge

Quasifission, large mass transfer, 2 fragments in exit channel

small

Fusion reactions, 1 fragment in exit channel

3D-TDHF: ^{48}Ca + ^{132}Sn at E_{cm} =130 MeV

The following two slides show TDHF calculations of a heavy-ion reaction between two nuclei; both of these are spherical in their ground state. ^{48}Ca is neutron-rich but stable, whereas ^{132}Sn is very neutron-rich and unstable against β- decay (half-life = 39.7 s). Reaction studied experimentally at ORNL.

The plots show contours of the mass density distribution of the system (in the collision plane) as a function of time, as predicted by TDHF.

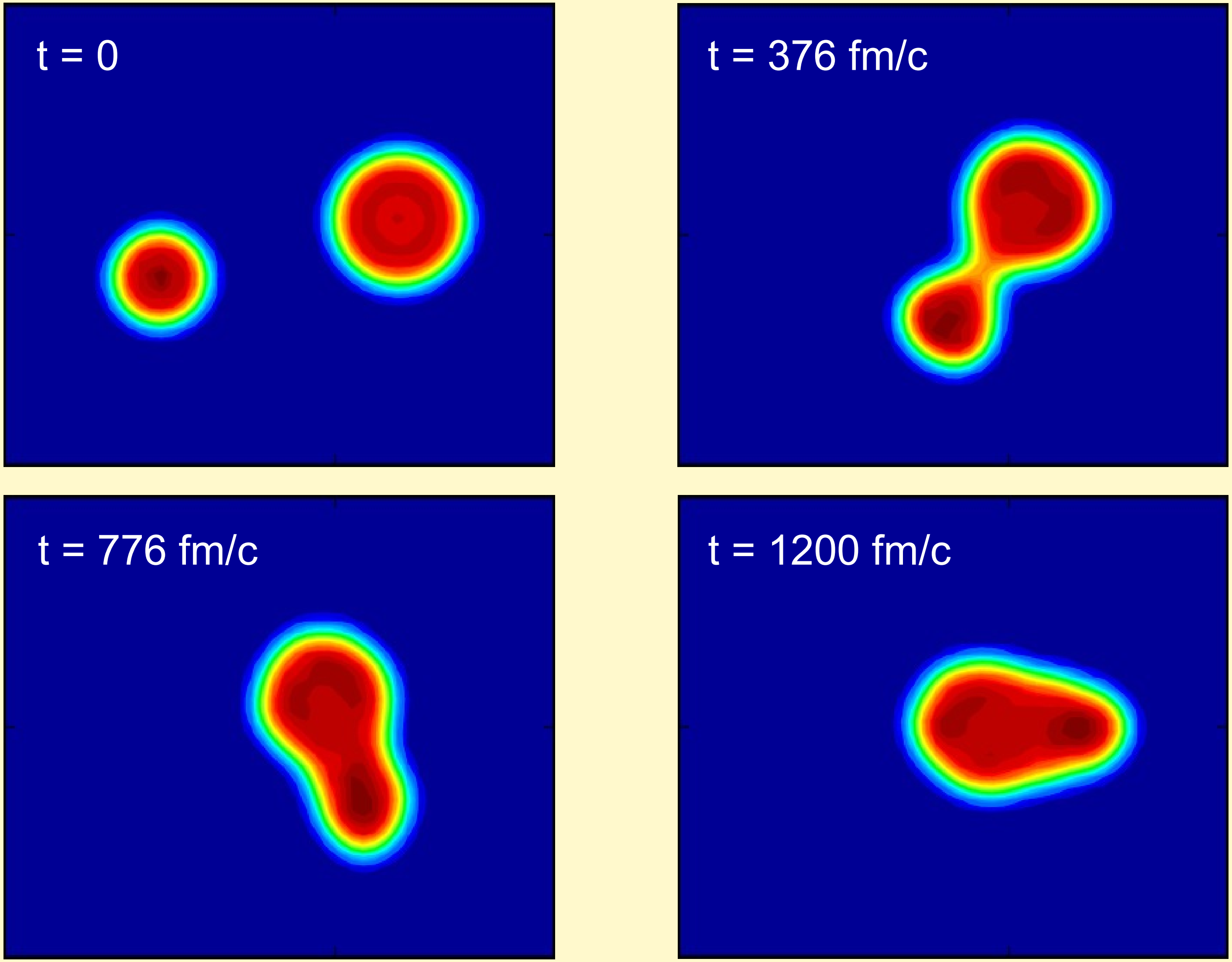
We observe that at small impact parameter (up to b=4.45 fm), the two nuclei fuse to form a strongly deformed shape isomer of ^{180}Yb.

At larger impact parameter (b>4.6 fm), the nuclei stick together only briefly and then disintegrate again. Some mass and charge transfer occurs and the fragments are highly excited. This is called a “deep-inelastic collision”.

The plots show collective rotation, surface vibrations and density oscillations (giant resonances) during the collision.

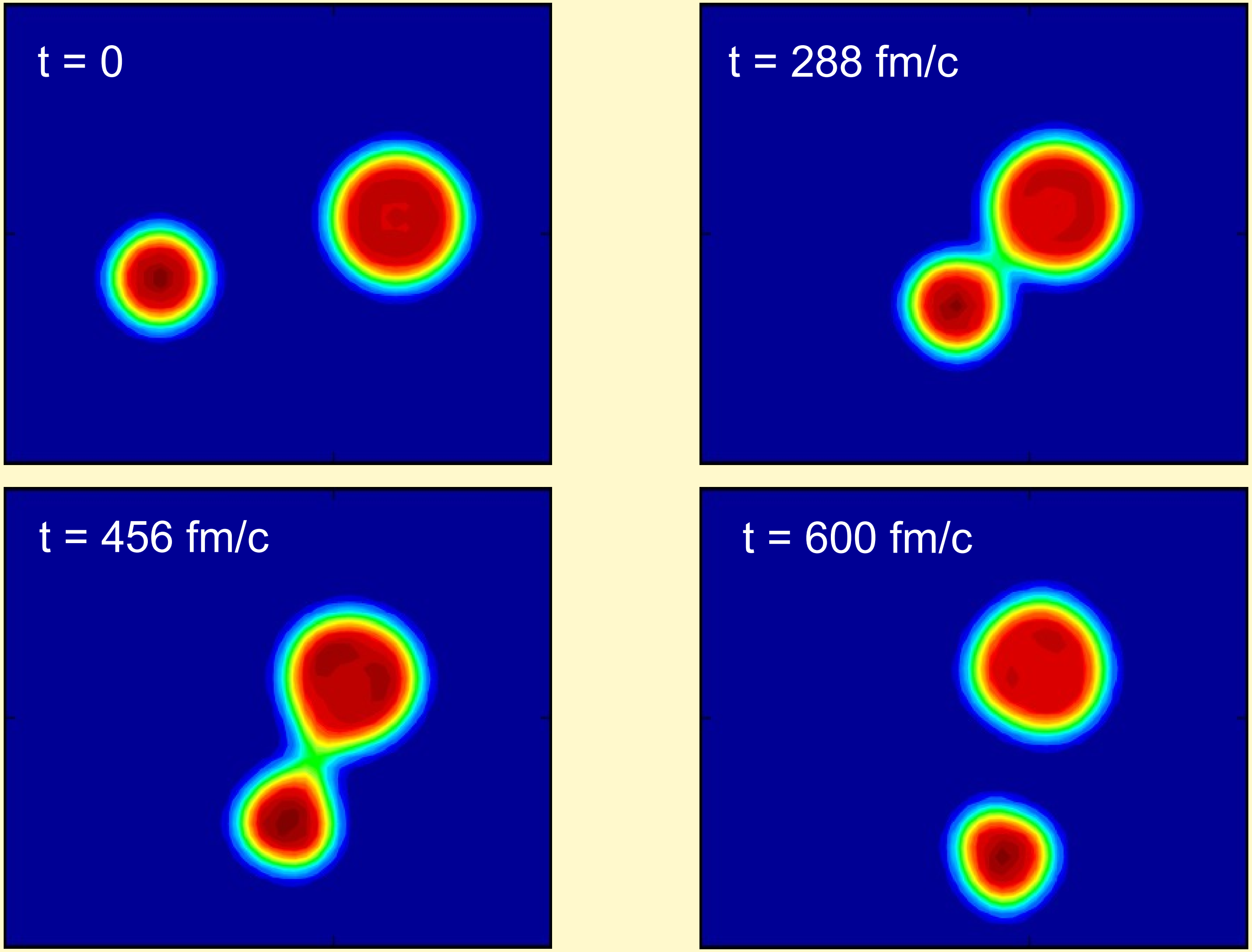
$^{48}Ca + {}^{132}Sn$, E_{cm} = 130 MeV, b = 4.45 fm (fusion)

TDHF, SLy4 interaction, 3-D lattice (50*40*30 points)

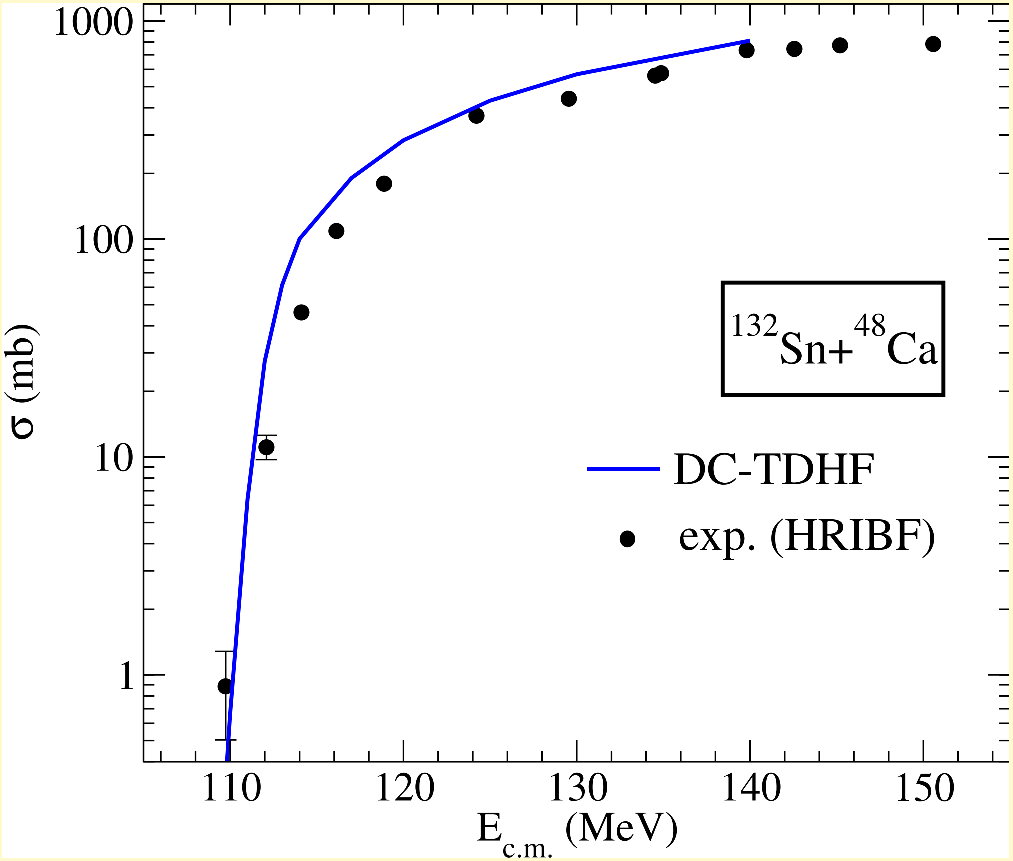


^{48}Ca + ^{132}Sn, E_{cm} = 130 MeV, b = 4.6 fm (deep-inelastic)

TDHF, SLy4 interaction, 3-D lattice (50*42*30 points)

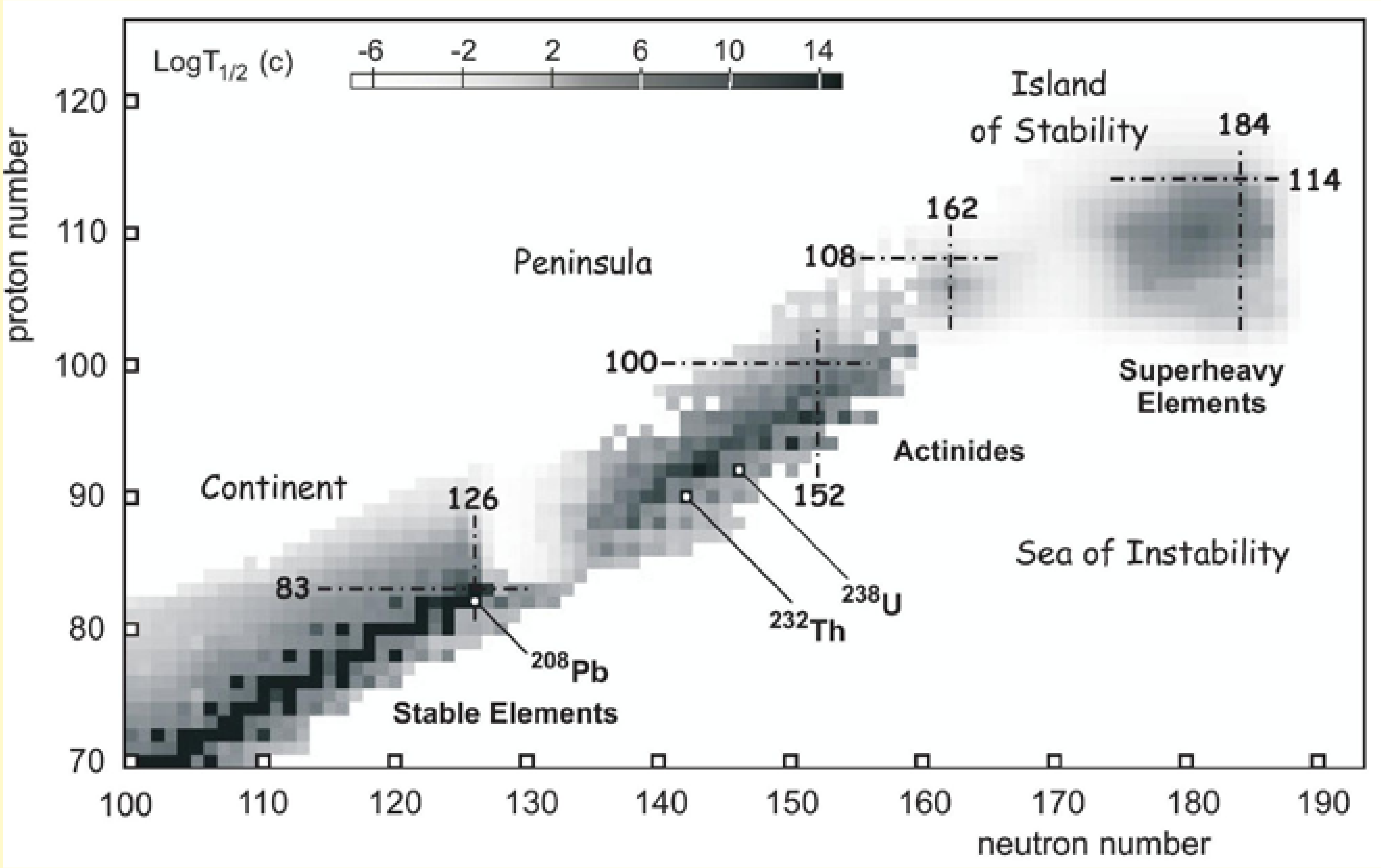


total fusion
cross section



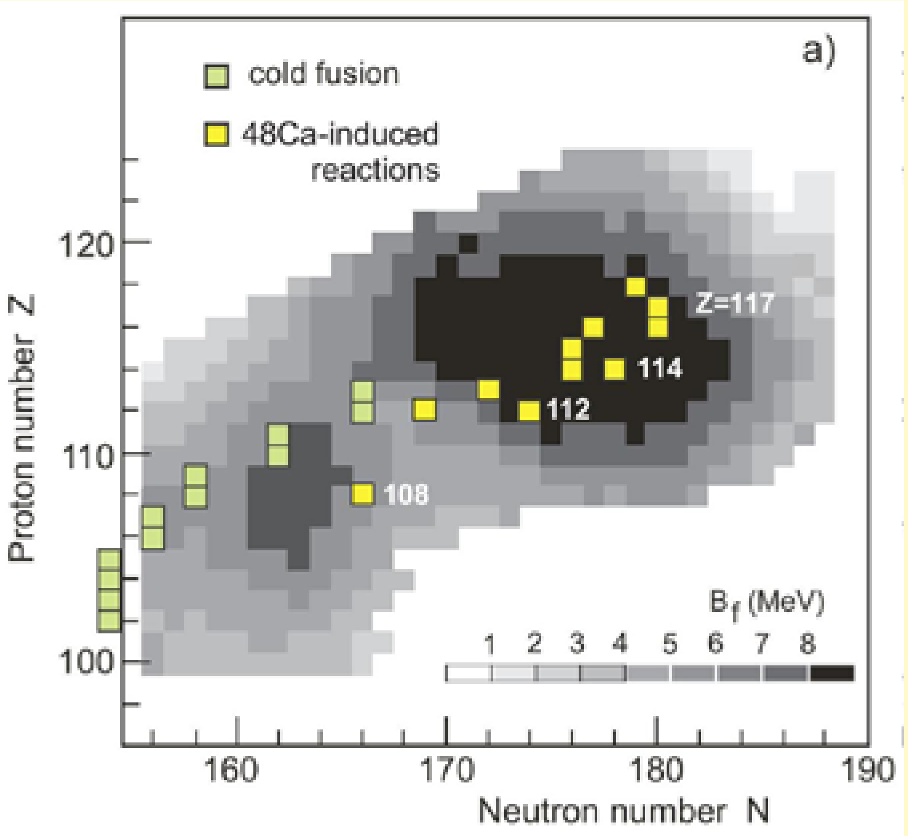
exp. data (HRIBF): J.J. Kolata, A. Roberts, A.M. Howard, D. Shapira, J.F. Liang, C.J. Gross, R.L. Varner, Z. Kohley, A.N. Villano, H. Amro, W. Loveland, and E. Chavez, Phys. Rev. C 85, 054603 (2012)

The frontier of superheavy nuclei



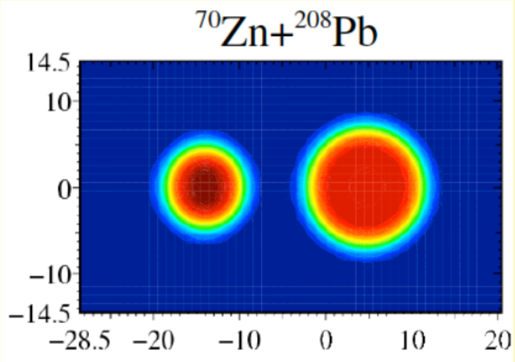
Synthesis of superheavy nuclei

Y. Oganessian, Nuclear Physics News Vol. 23, No. 1, 2013

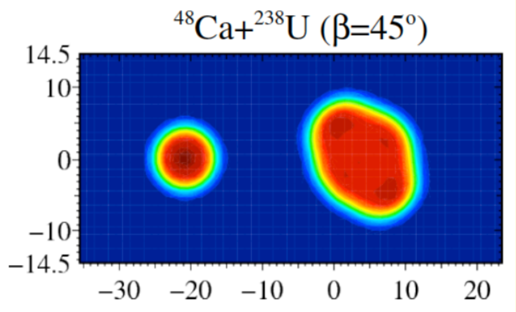


Fission barrier heights B_f calculated in the macroscopic-microscopic model (Möller & Sierk).

cold fusion

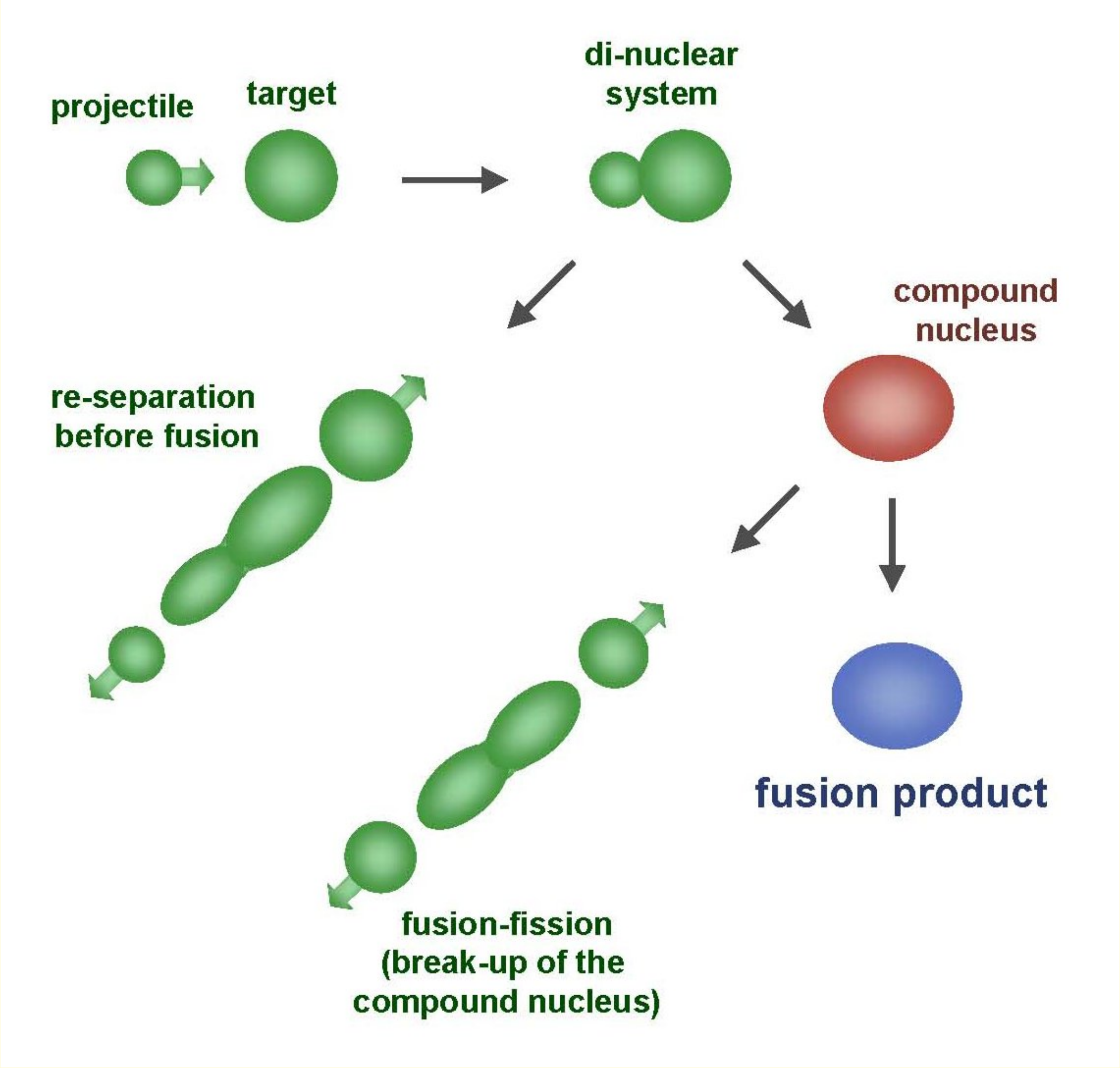


hot fusion



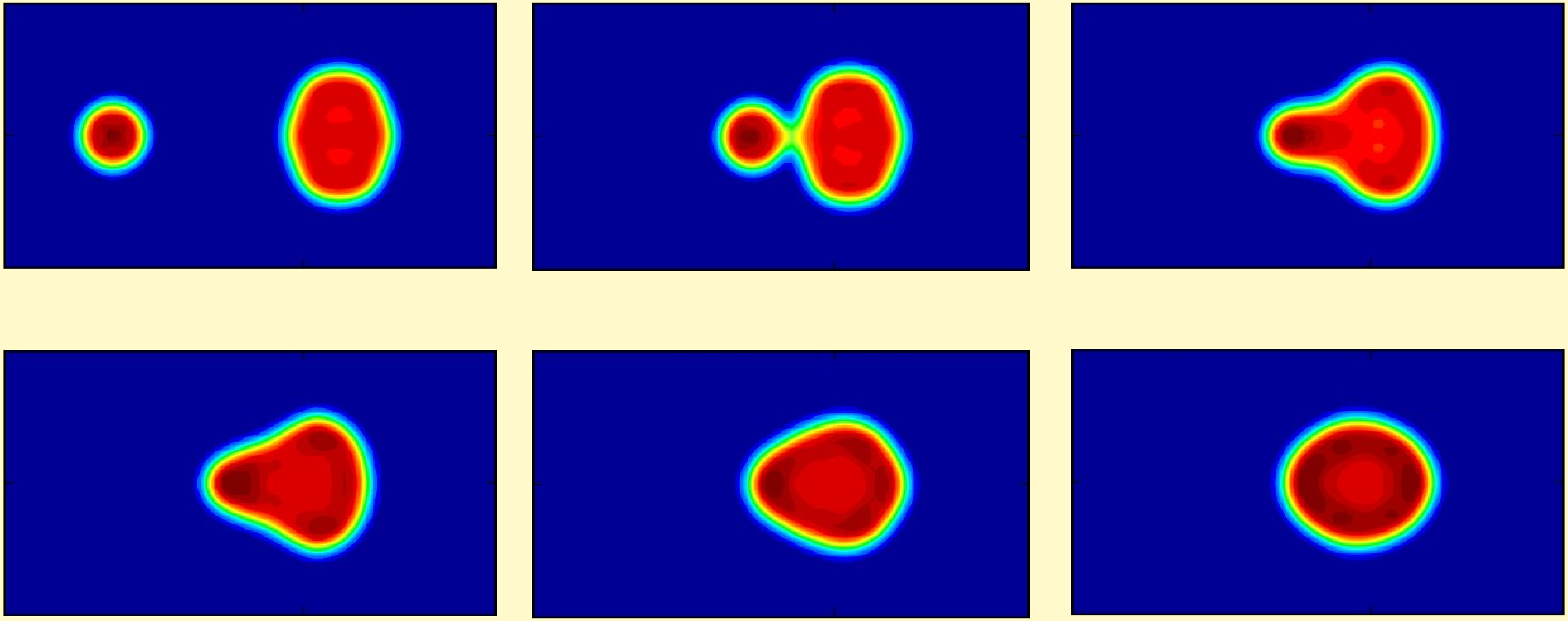
Umar, Oberacker, Maruhn, and Reinhard, PRC 81, 064607 (2010)

Quasifission and fusion-fission

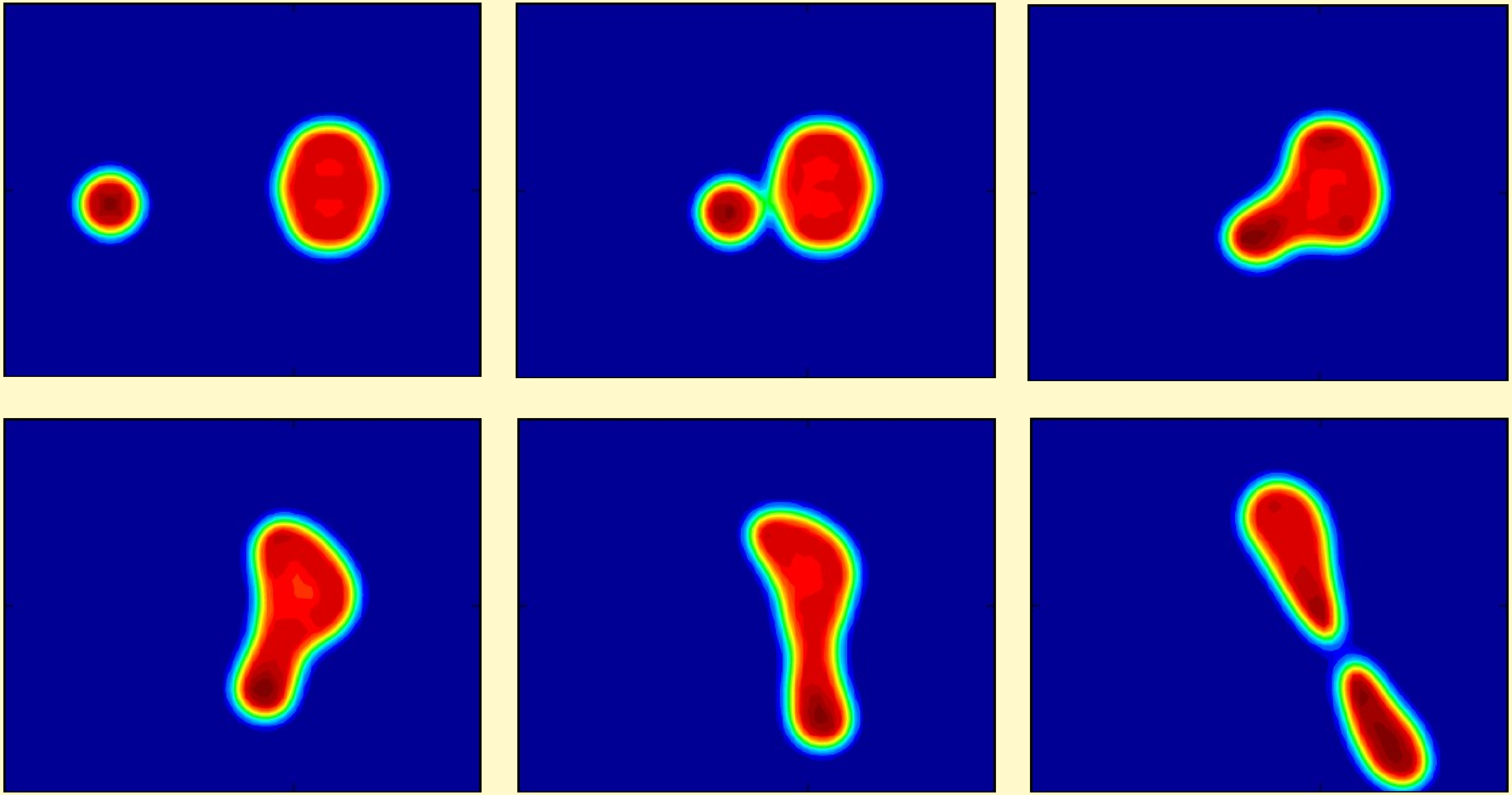


^{48}Ca+^{249}Bk, E_{cm}=218 MeV

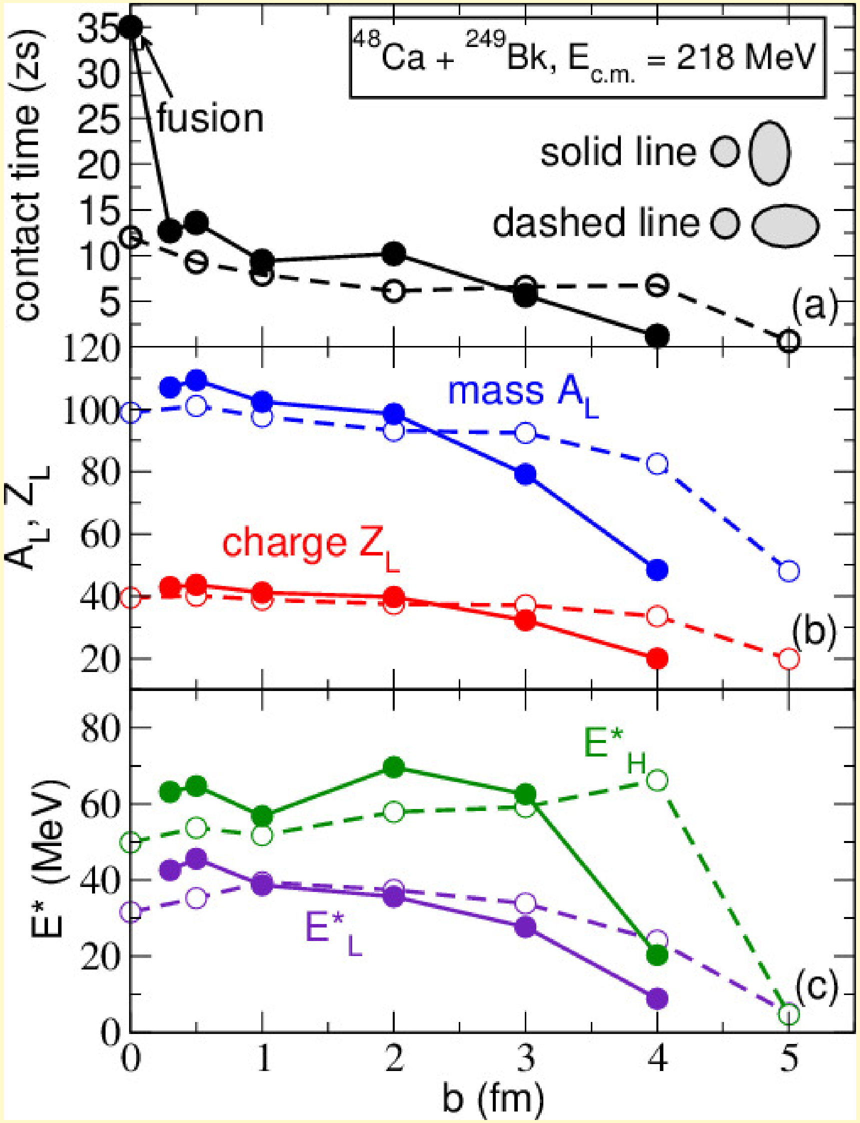
impact parameter b=0 fm, fusion (Z=117, A=297)

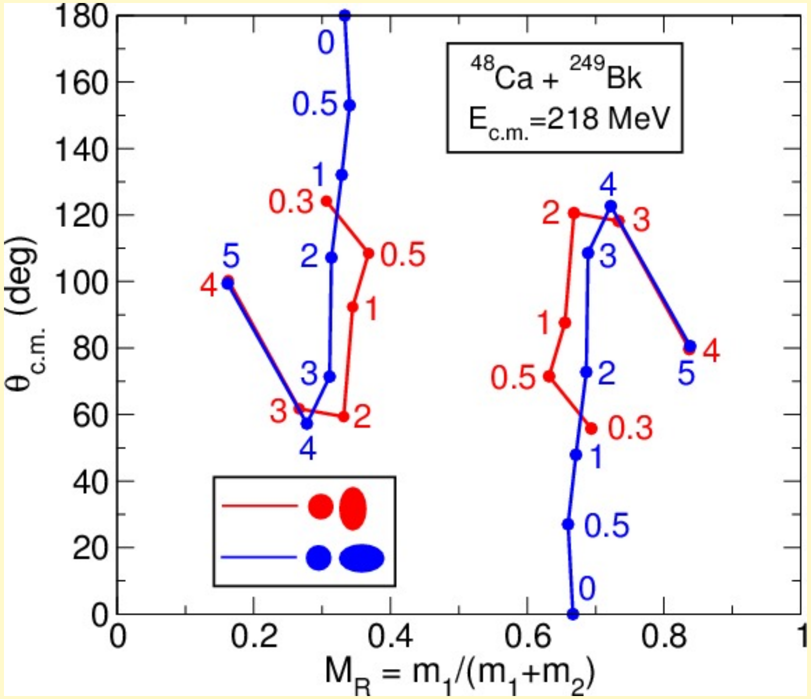


$^{48}Ca+^{249}Bk$, E_{cm}=218 MeV
impact parameter b=2 fm, quasifission



^{48}Ca+^{249}Bk, E_{cm}=218 MeV (preliminary, not yet published!)





Mass-angle distribution (MAD)