From Landscapes to Tides

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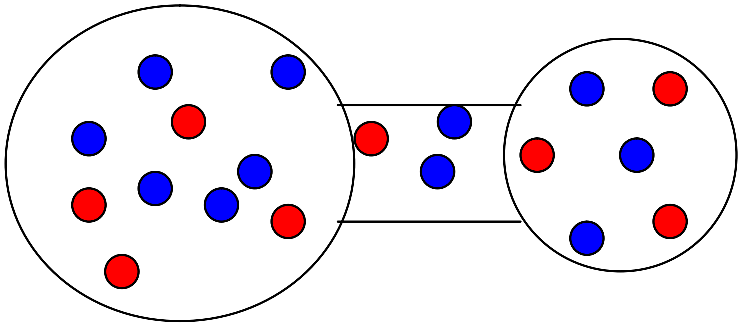
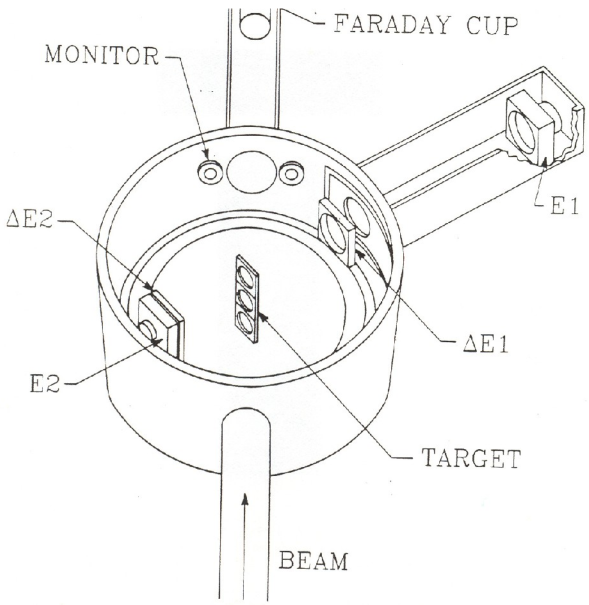
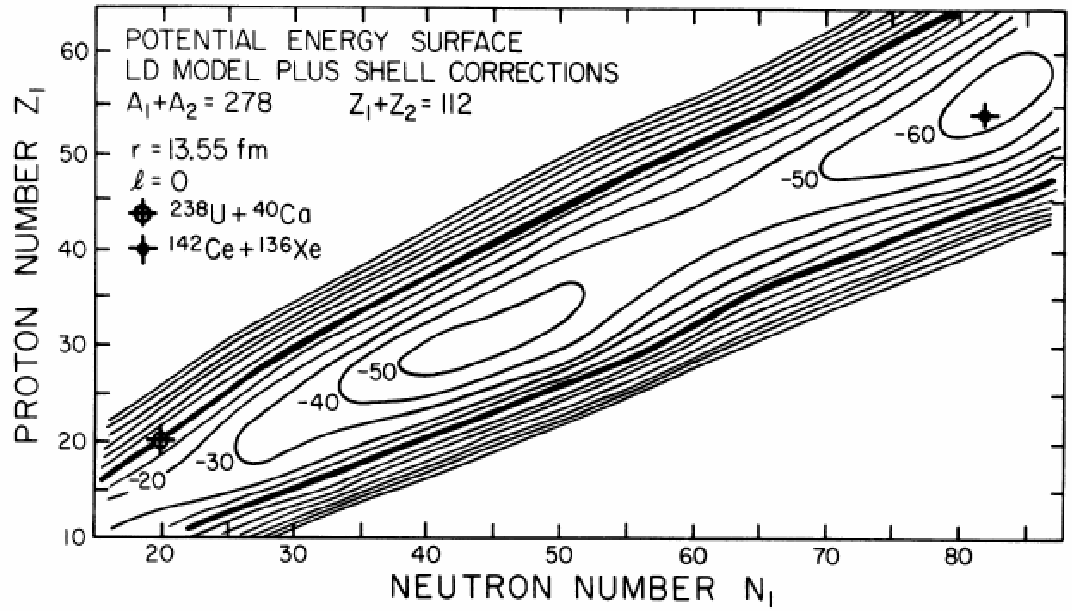
J.R. Huizenga Fest, April 21, 2006

N/Z equilibration in damped collisions between heavy nuclei near the Coulomb barrier

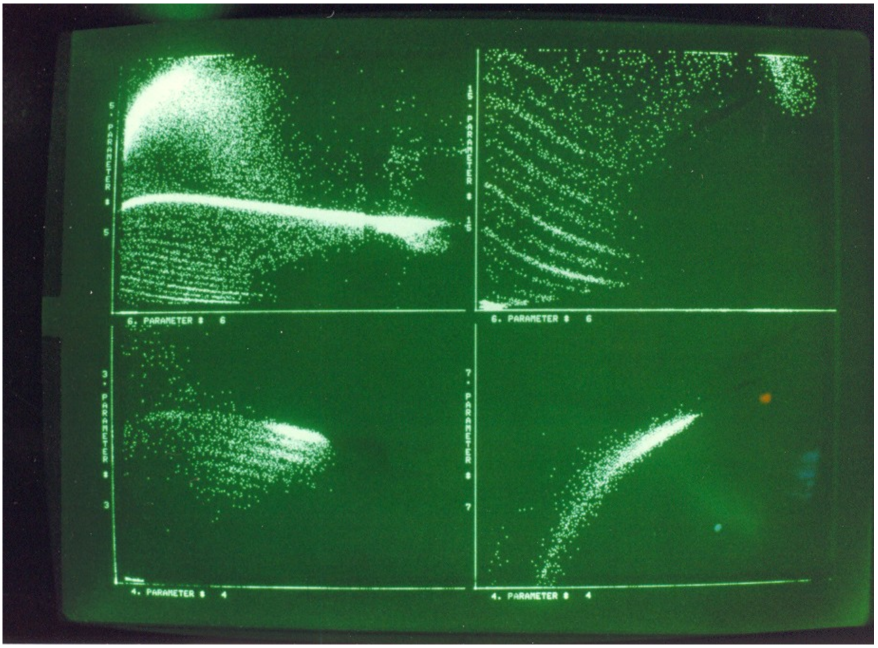


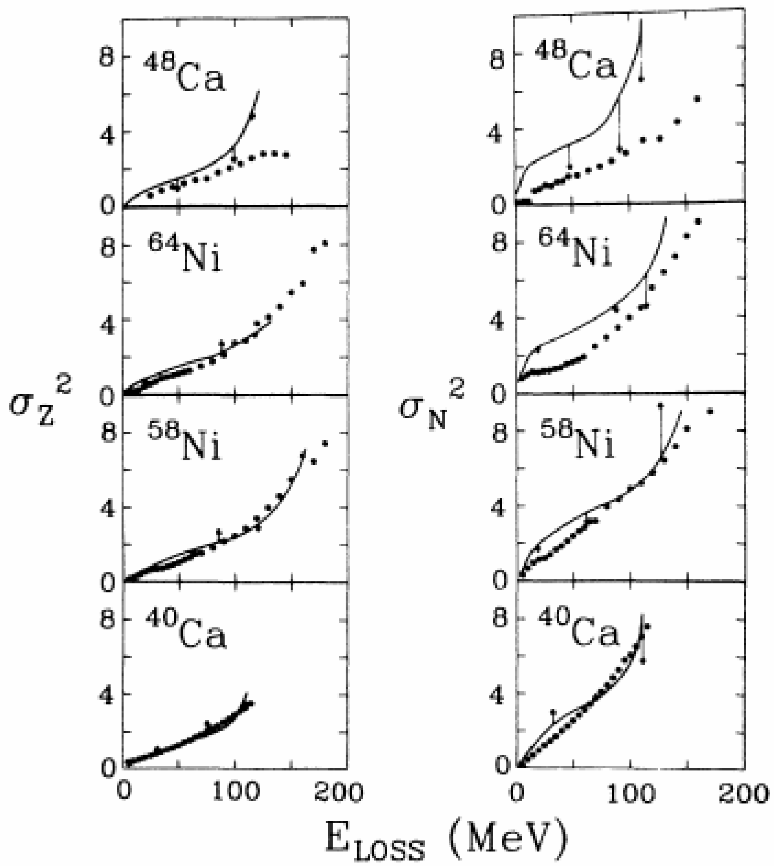


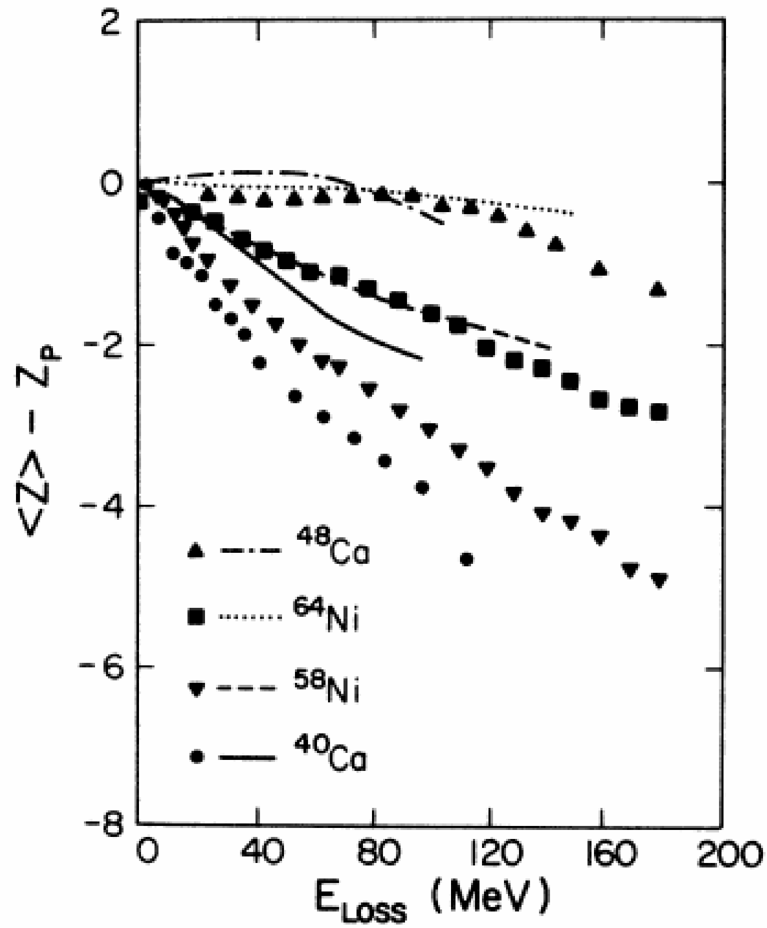


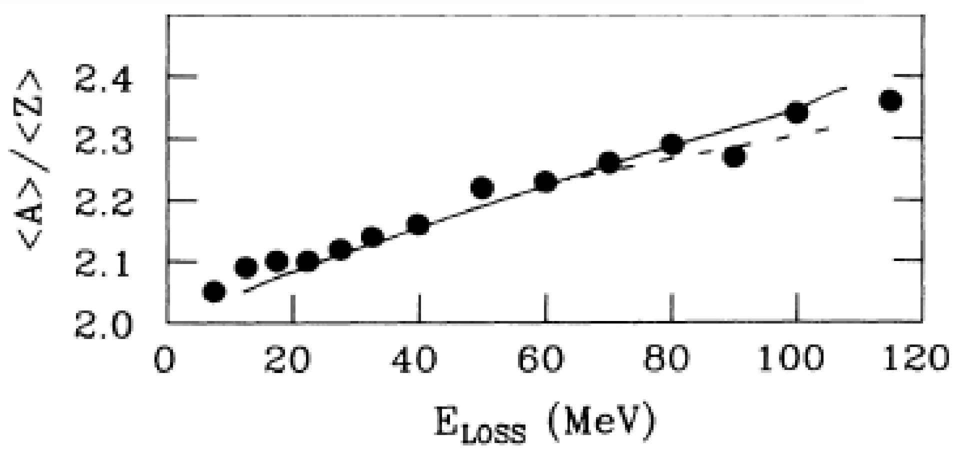
"Stochastic transport of individual nucleons governed by an underlying potential energy surface."– But what is the PES?

Ties with Indiana University









R.T. de Souza et al., PRC 37, 1901 (1988)

Fission

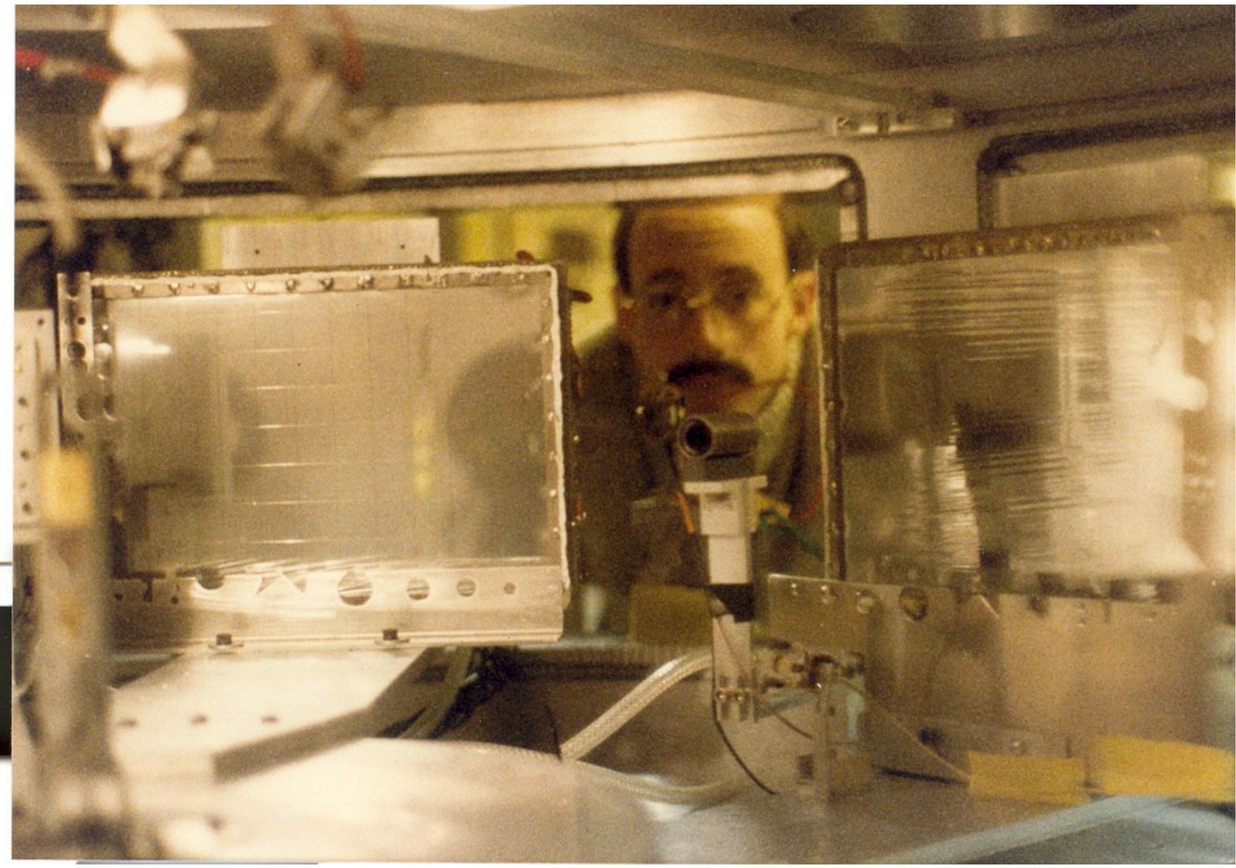
•Transition from a "spherical" nucleus to a very deformed, elongated configuration

↳ Change of the ratio $\frac{\text{Volume}}{\text{Surface}}$ with an increased role of **surface**

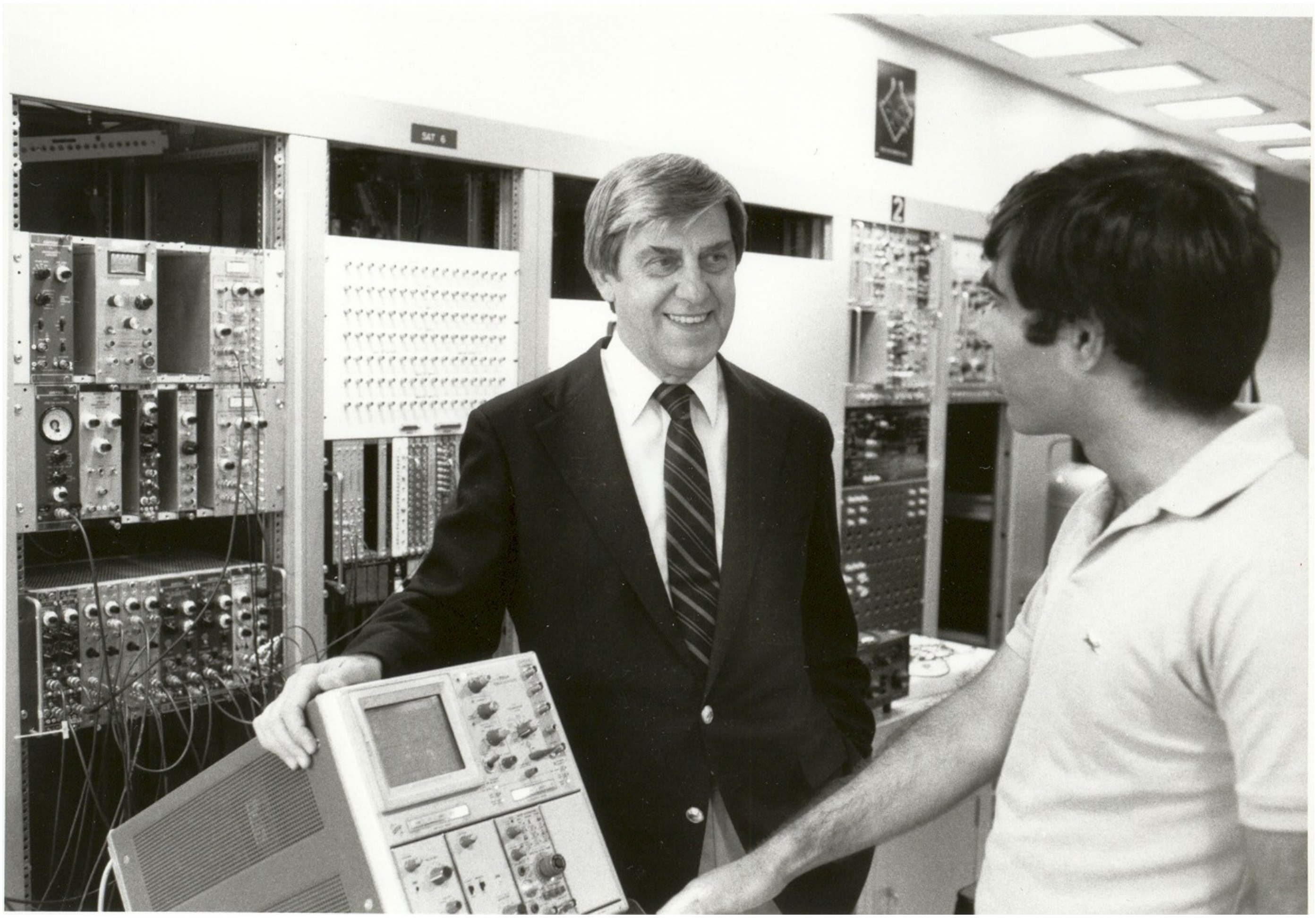
Relaxation of the mass-asymmetry degree of freedom

^{58}Ni + ^{165}Ho at E/A=5.9 and 6.5 MeV

M.A. Butler et al., Phys. Rev C34, 2016 (R) (1986)



Based on angular distributions, deduce relaxation of mass asymmetry degree-of-freedom at a few times 10^{-21} sec.

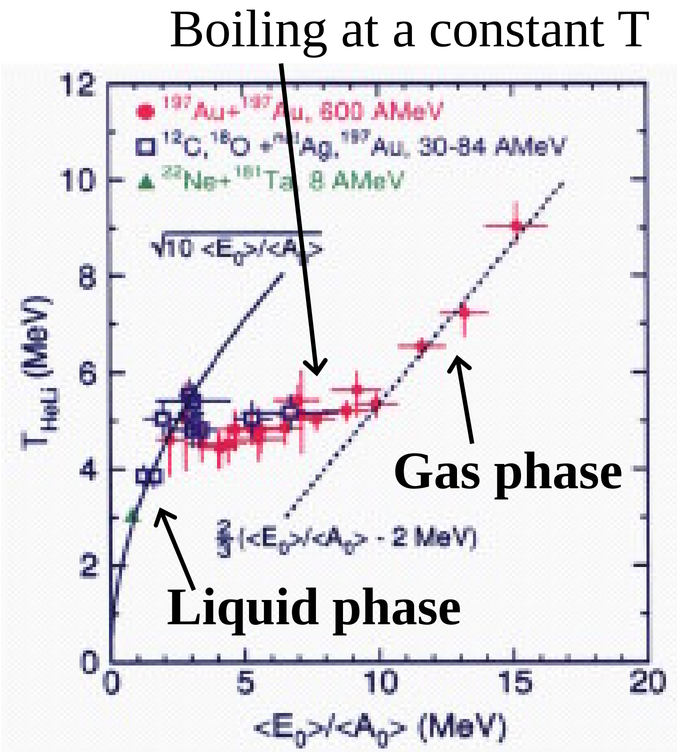

SAT 6
2

End of Practice Test !

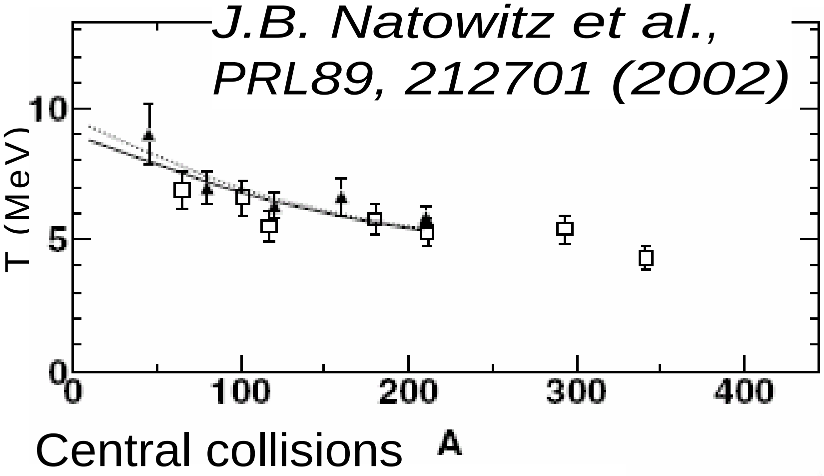
Now for the test --

John, How many of these “themes” do you recognize in the work that follows?

Liquid-gas phase transition

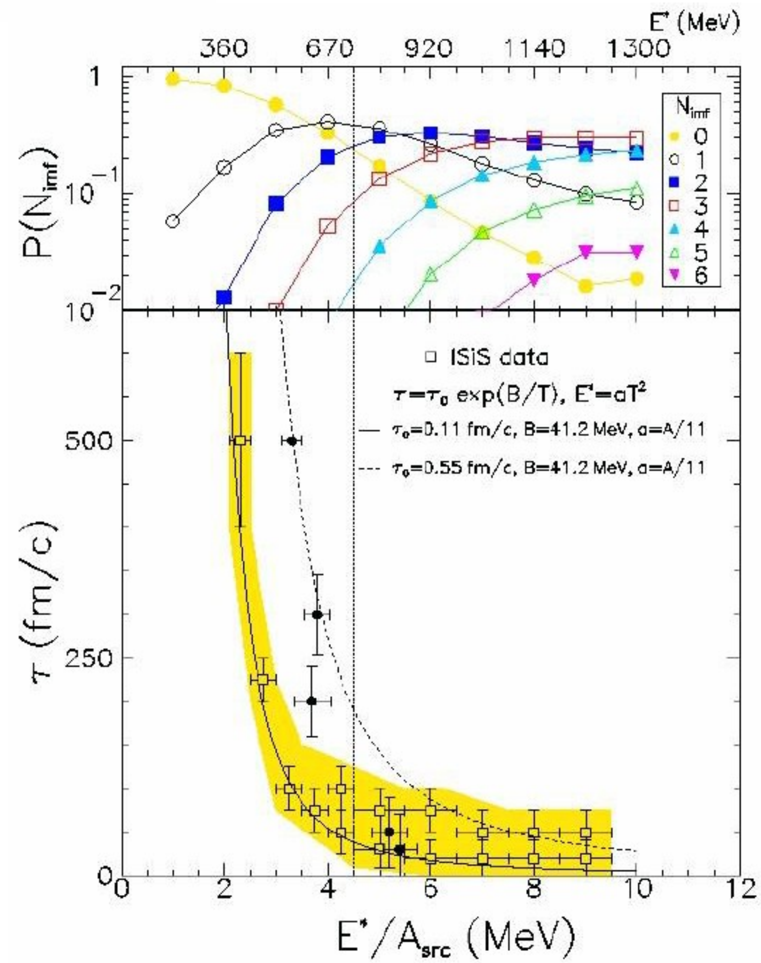


J. Pochodzalla et al., PRL75, 1040 (1995)



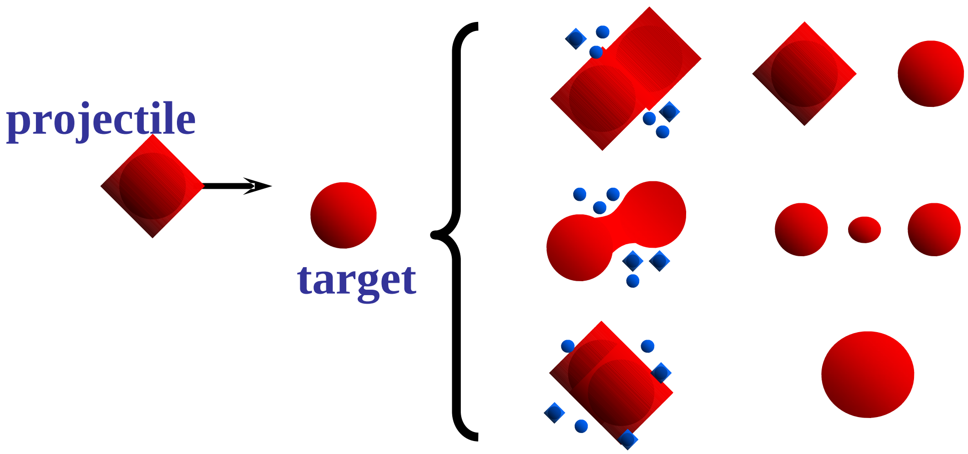
J.B. Natowitz et al., PRL89, 212701 (2002)

L. Beaulieu et al., PRL 84, 5971 (2000)

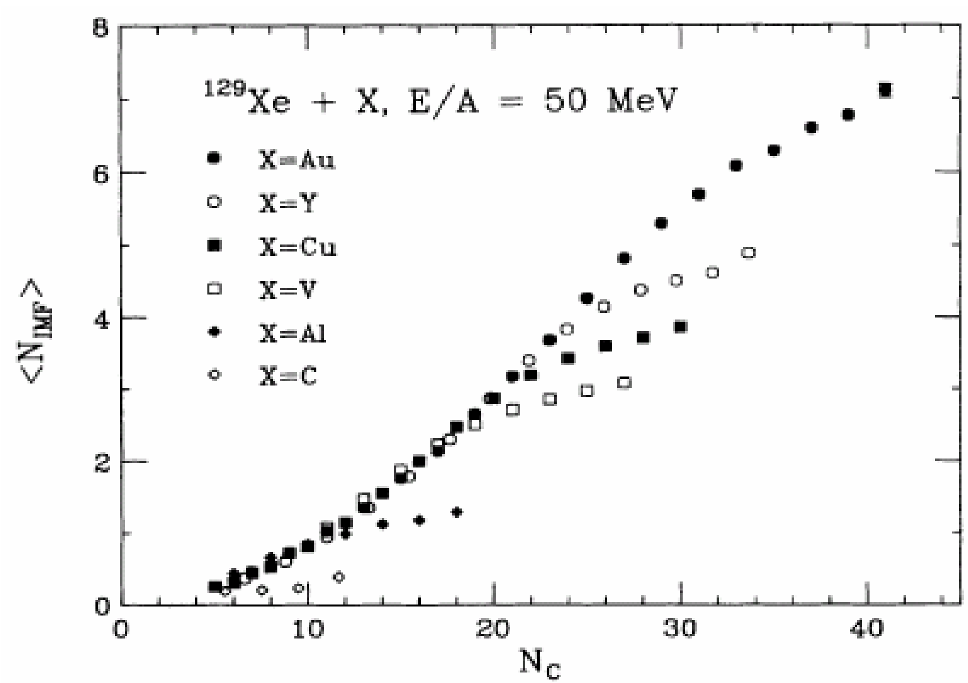


- Observed signals indicating a "phase transition"
- Statistical models assume a "box", e.g. volume, with uniform density in which particles and clusters are emitted
  - ↳ Definition of the box
  - ↳ Density fluctuations, gradient
  - ↳ Cluster formation

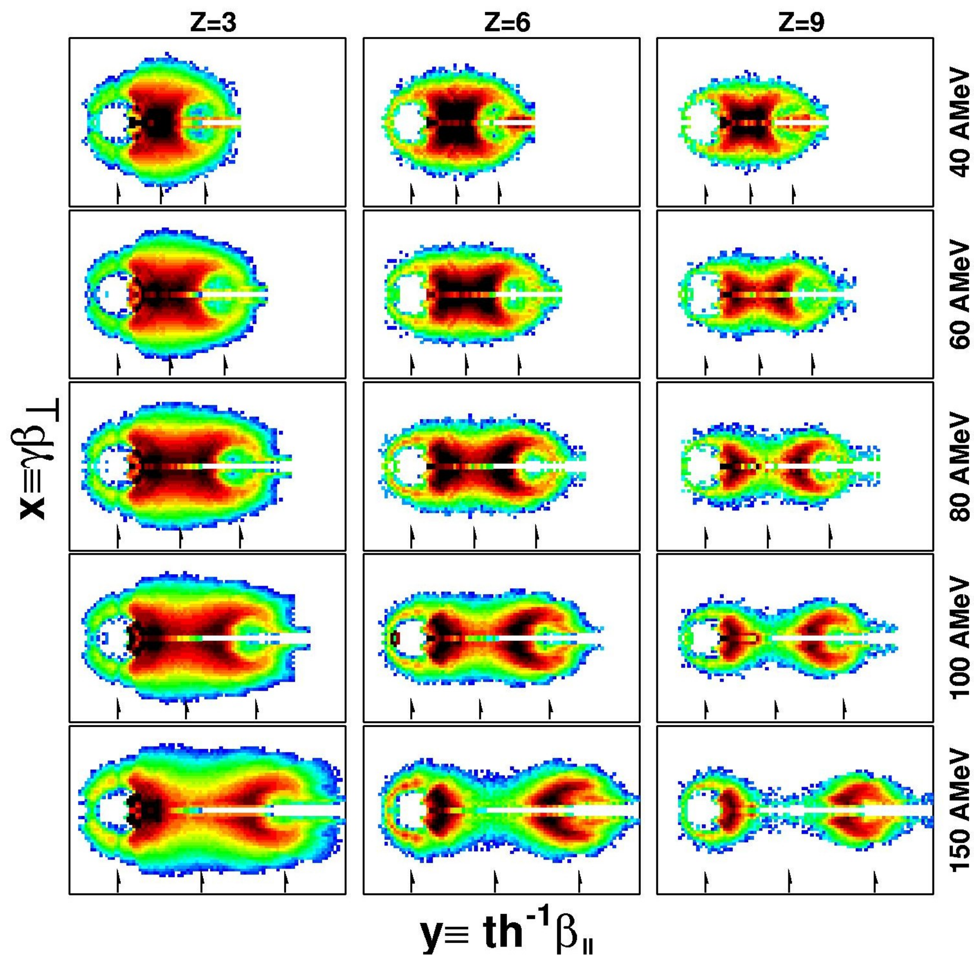
Tool: HI collisions at intermediate energy



D. R. Bowman et al., PRC 46, 1834 (1992)



Invariant cross sections for Au + Au at peripheral impact parameters

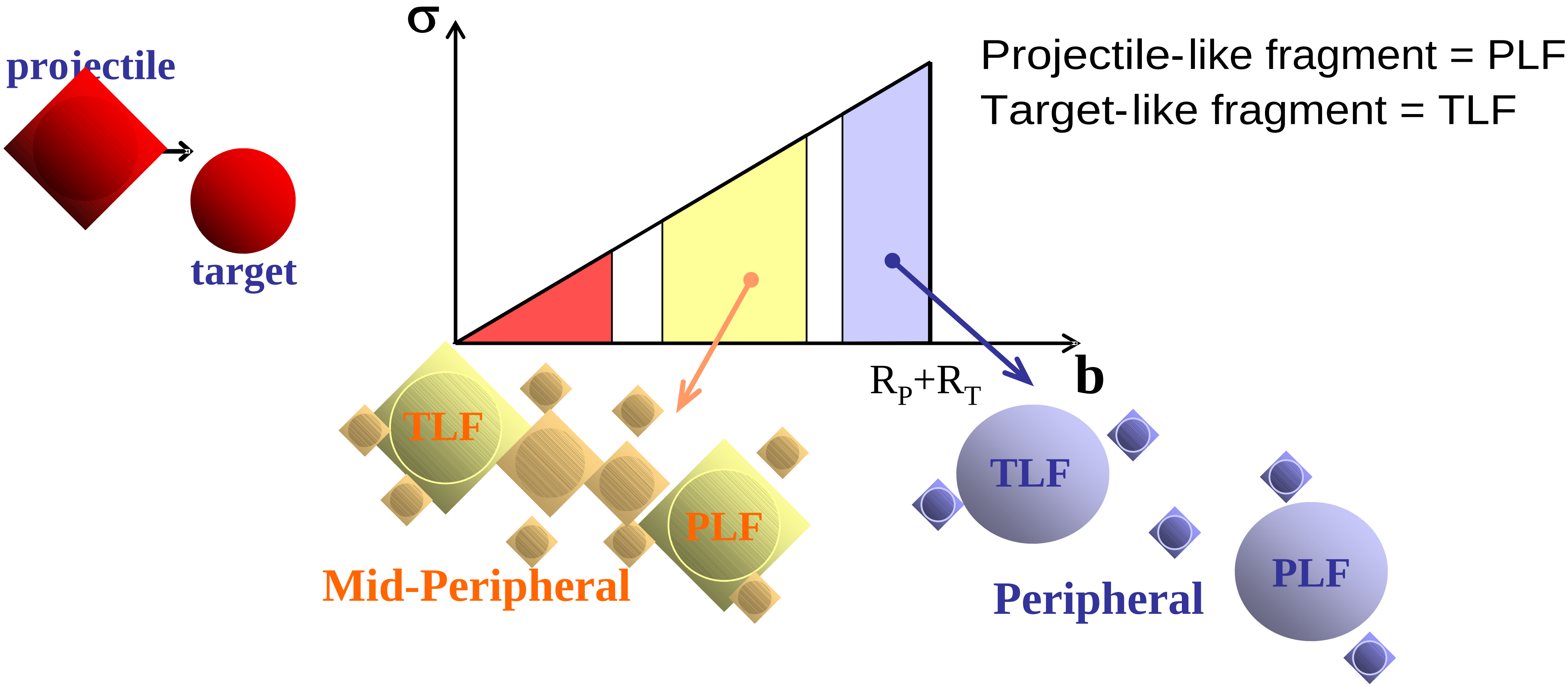


☞ Large production of fragments

J. Lukasik et al., PLB566, 76 (2003)

☞ Fragments mainly produced at intermediate velocities

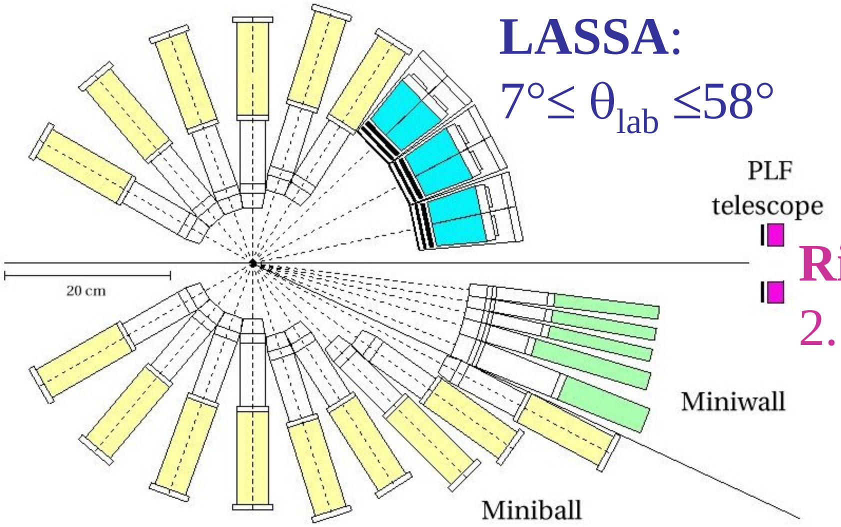
Peripheral and mid-peripheral collisions



- ☞ Large cross-section
- ☞ PLF/TLF:
  - ↳ Well-characterized (Size, E^*, J)
  - ↳ Normal density
  - ↳ Selectable

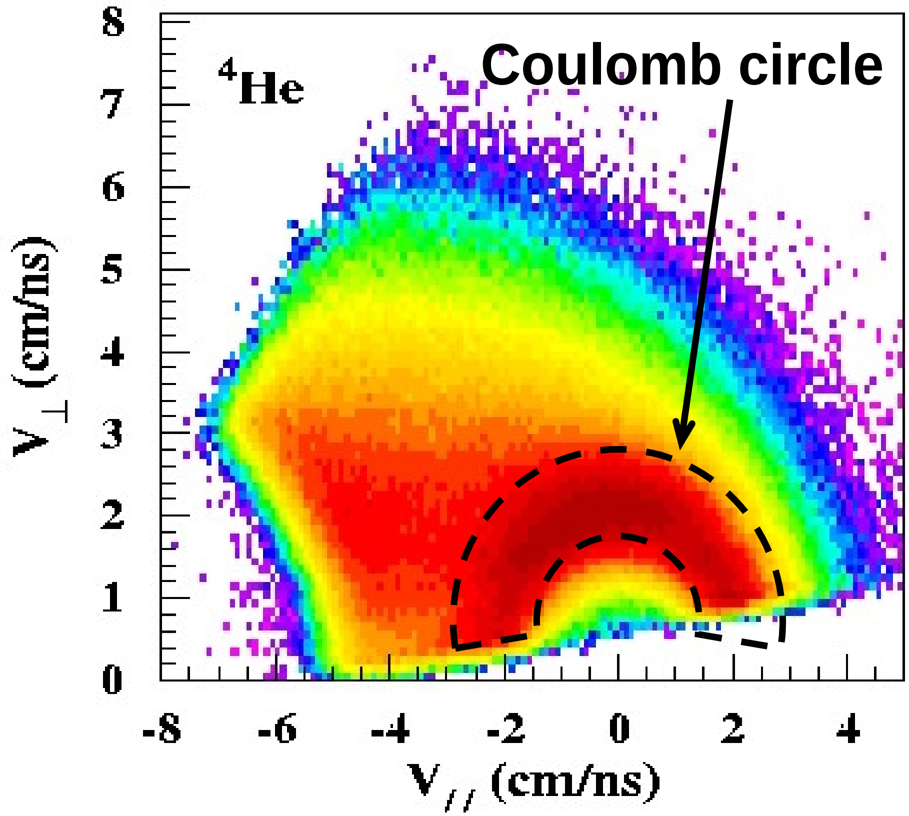
PLF*: Statistical decay

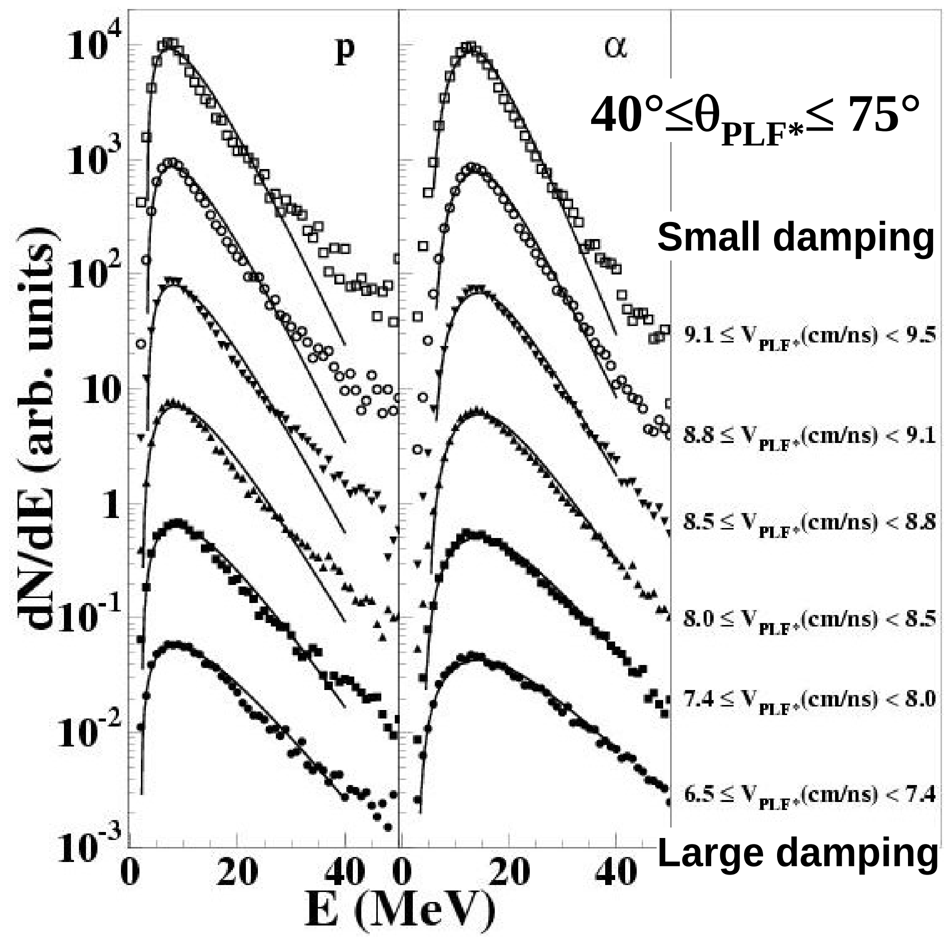
$^{114}Cd + ^{92}Mo$ at 50 MeV/ nucleon



- Measured PLF in the RC: $15 \le Z \le 46$
- Particles measured in LASSA

R. Yanez et al., PRC68, 011602 (R) (2003)

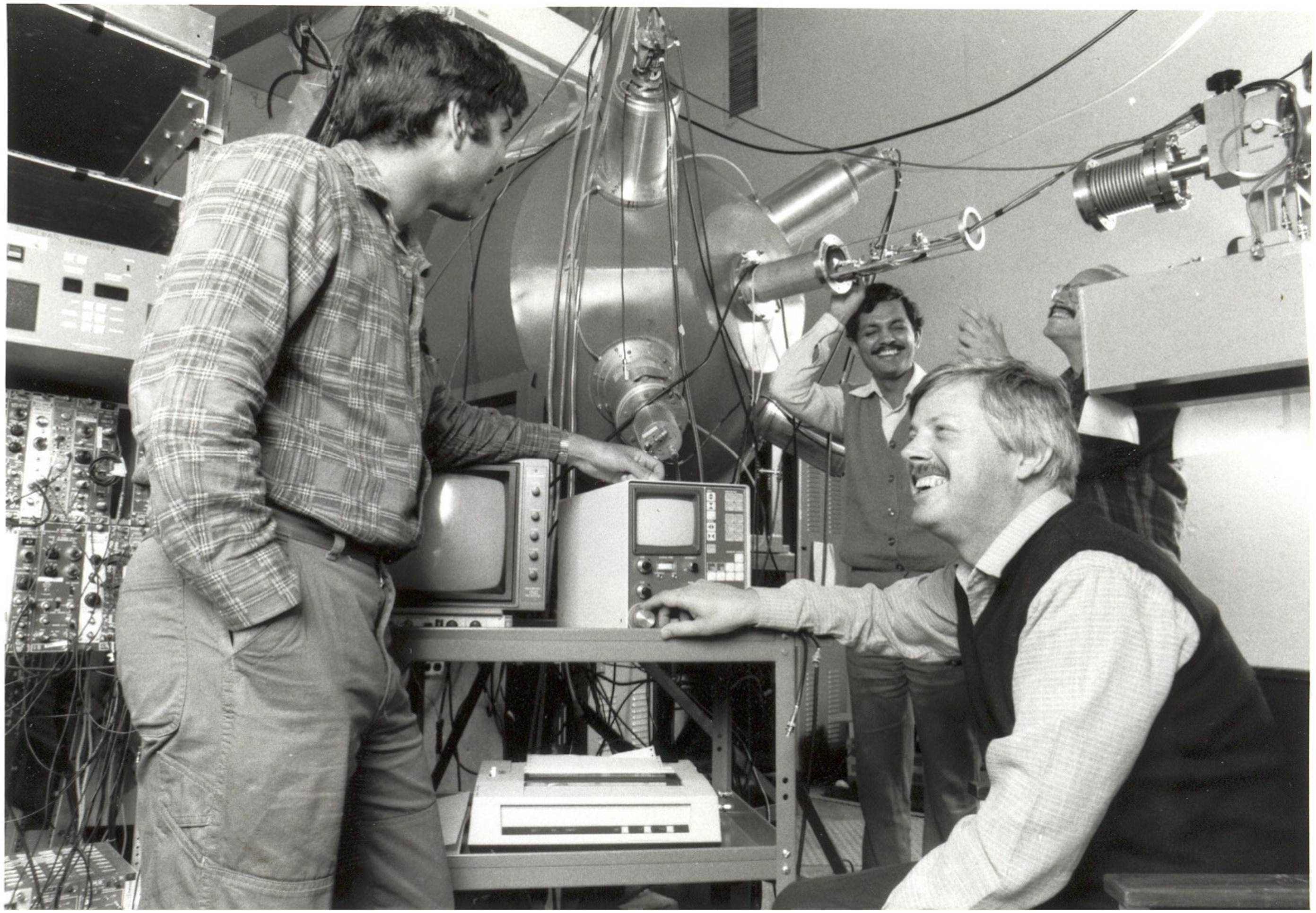




☞Isotropic emission forward of PLF*

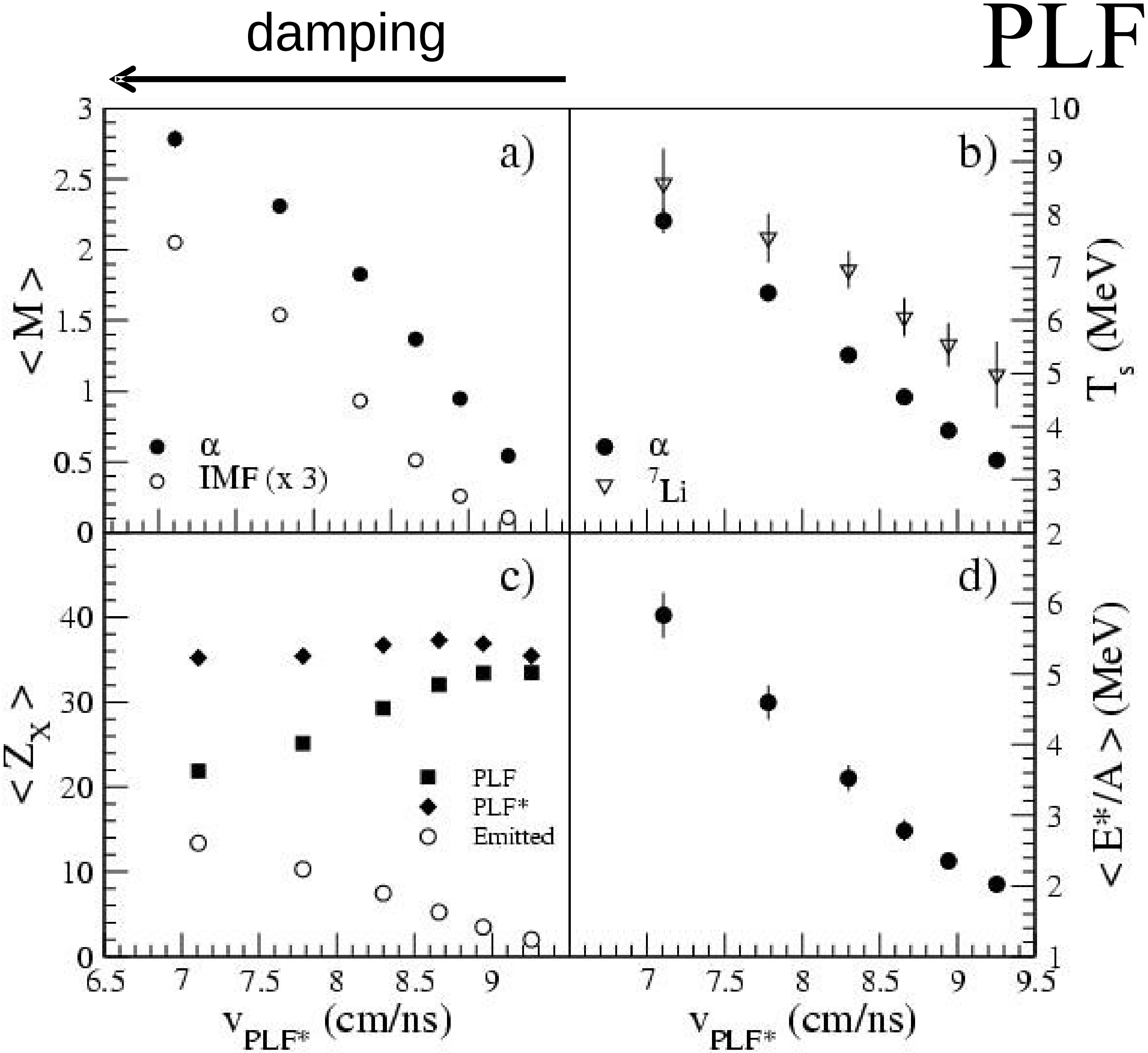
☞$T_{slope} = f(V_{PLF*})$

Calorimetry



“A good way to measure the excitation energy is to count.”

PLF^*: velocity damping



☞ More emitted particles for higher damping

☞ Higher slope parameter for higher damping

☞ Lower Z_{PLF} and higher $Z_{emitted}$ for higher damping

↳ Z_{PLF*} independent of damping

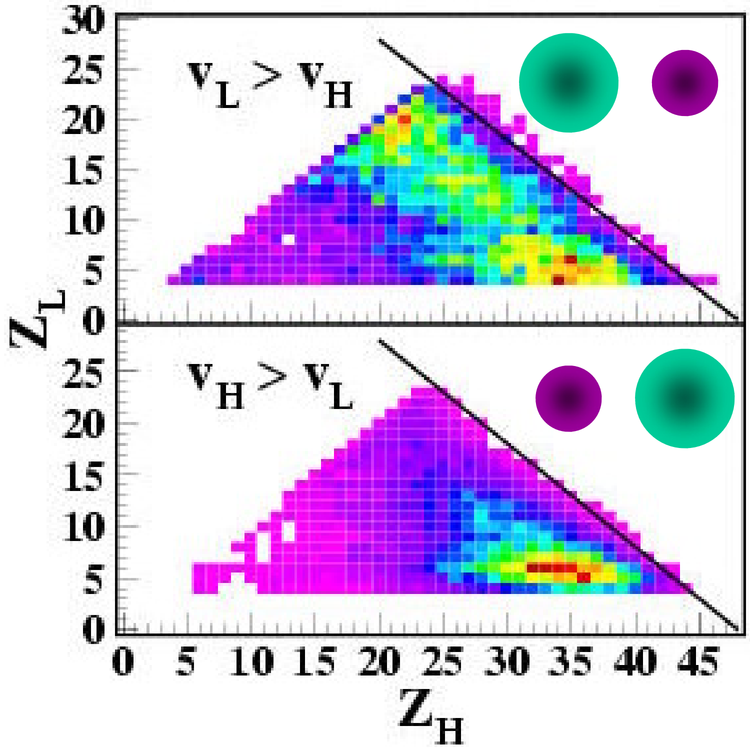
☞ Linear increase of E^*/A with damping

☞High E^*/A reached compatible with limiting T

$$E^* = \sum_{clusters} M_{cluster}.Ek_{cluster} + M_n.Ek_n + Q$$

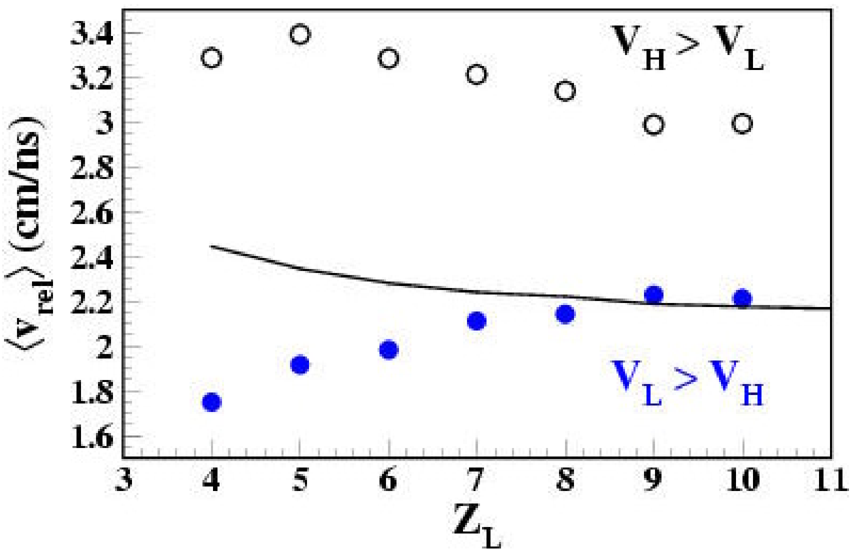
R. Yanez et al., PRC68, 011602 (R) (2003)

Dynamical fission

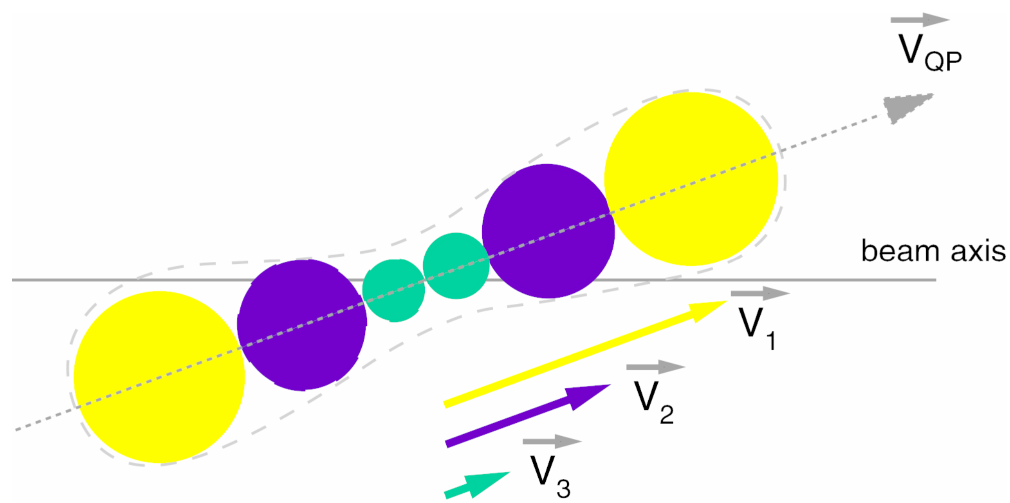


- ☞ Large asymmetry with preference for Z=6
- ☞ Large relative velocity
- ☞ Strong alignment along beam axis
- ☞ Large cross-section

Z, velocity, and angular correlations provide the following physical picture.



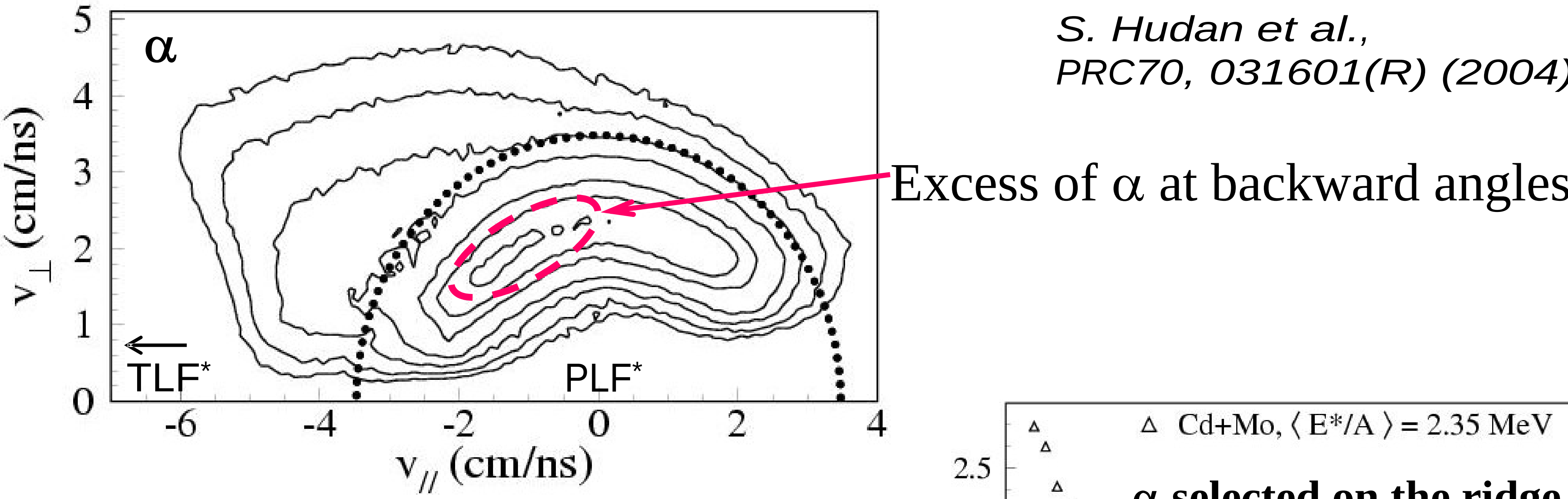
B. Davin et al., PRC65, 064614(2002)

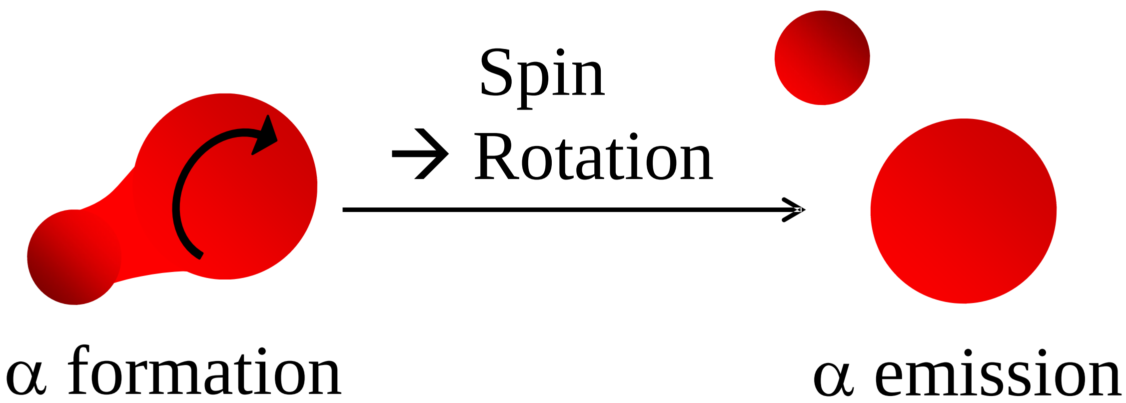


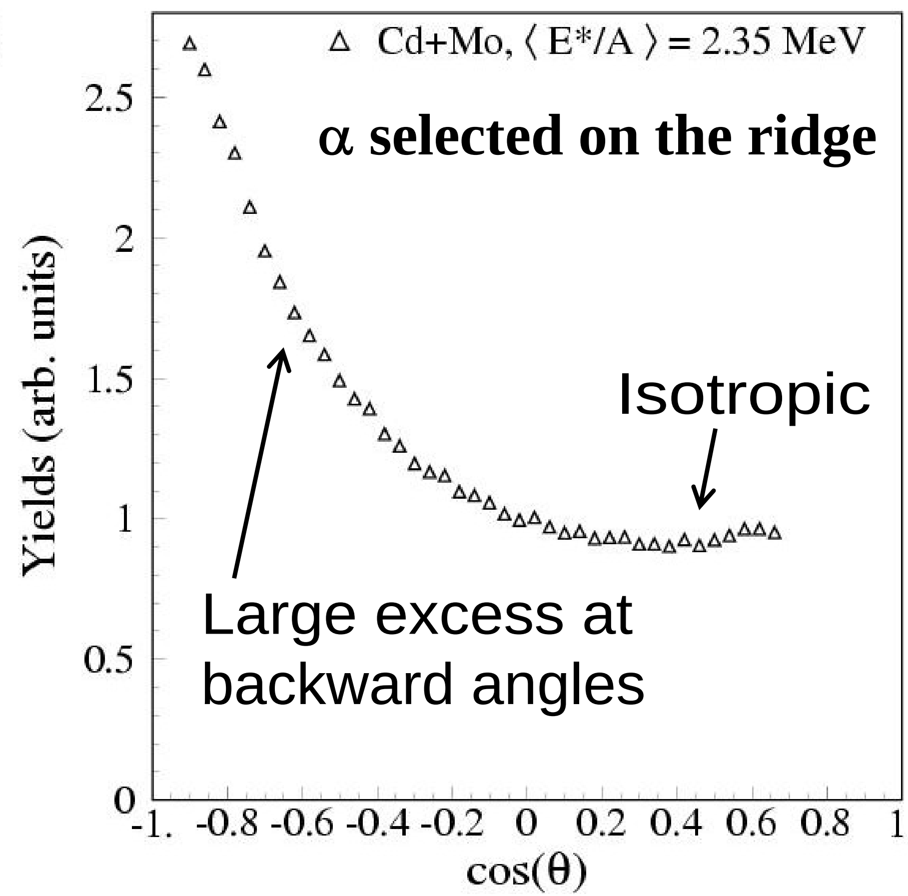
J. Colin et al., PRC67, 064603(2003)

Anisotropy in the alpha emission

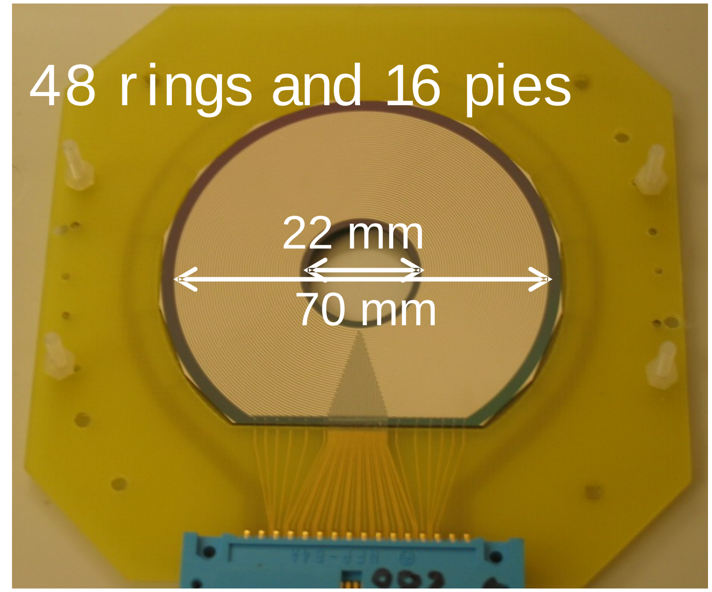
S. Hudan et al., PRC70, 031601(R) (2004)







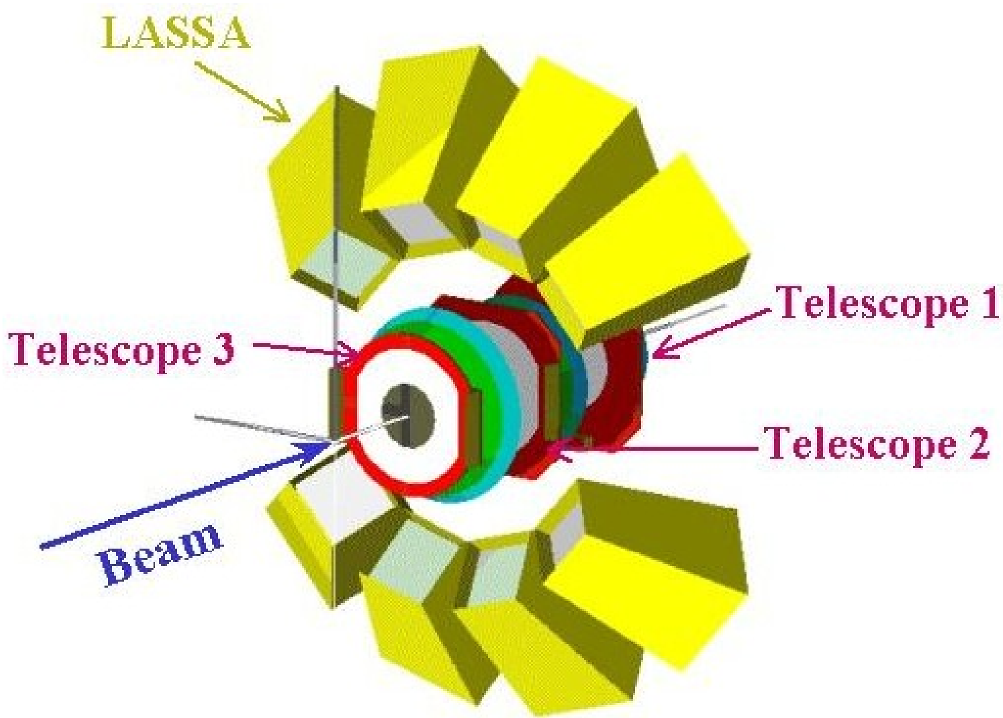
Detector: high segmentation



- Need to measure the PLF* decay products:

  PLF, particles and clusters

  → FIRST

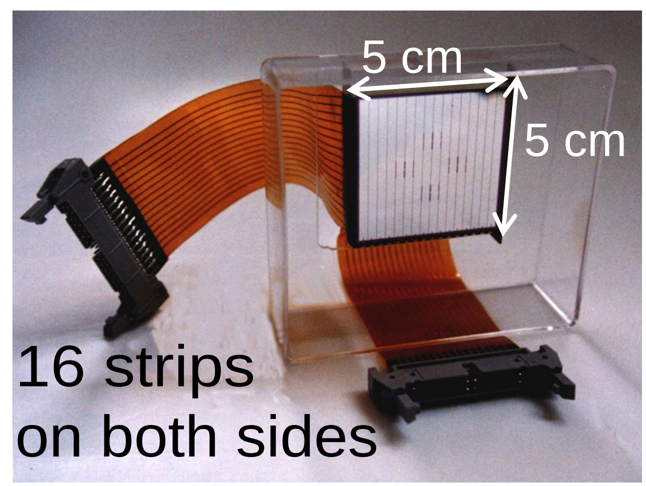


(Δθ<0.82°)

coverage in the angular range 2-28.5°

% occupancy

Small number of triggering channels

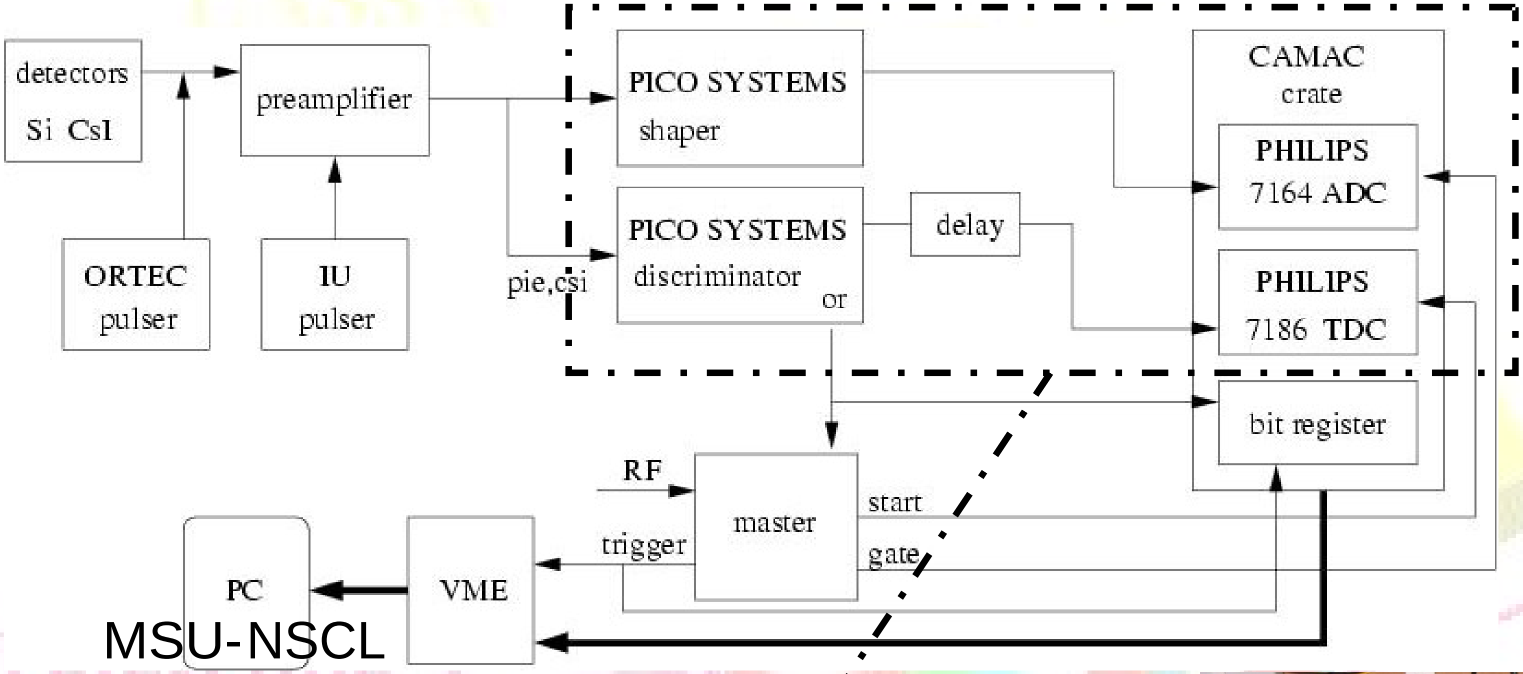


y clusters

→ LASSA, HiRA

❑ Large angular resolution (Δθ≈0.92°)

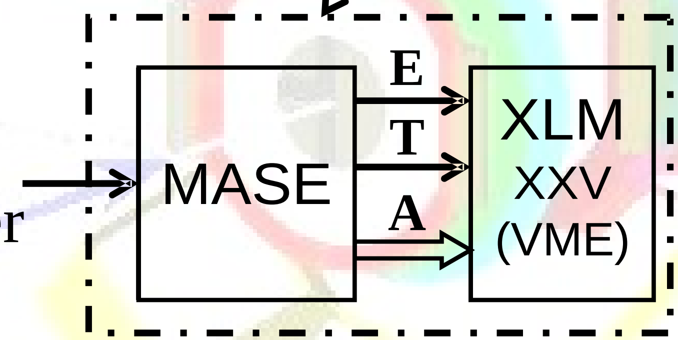
Signal processing



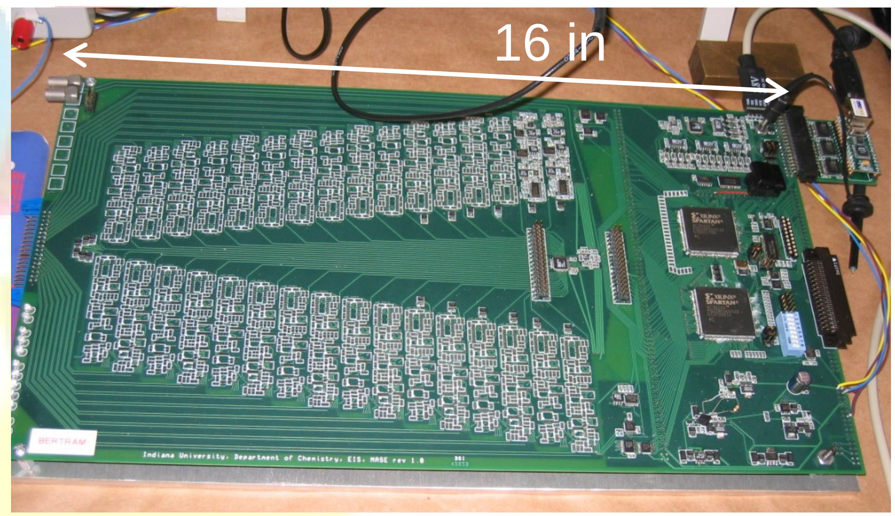
For each channel:

- ❑ shaper
- ❑ ADC
- ❑ discriminator
- ❑ TDC

- For each channel:
  - ❑ dual gain shaper
  - ❑ discriminator
  - ❑ TVC
- For all channels:
  - ❑ 1 ADC (XLM)



- 16 channels per board
- Zero skipping
- USB interface
- Logic through 2 FPGAs

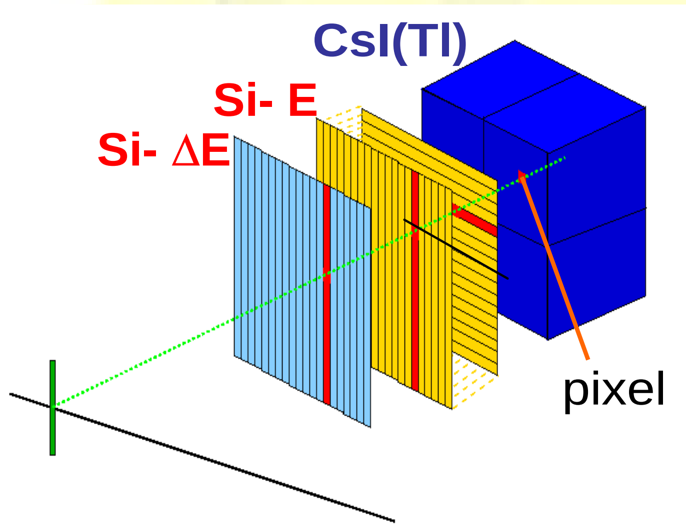


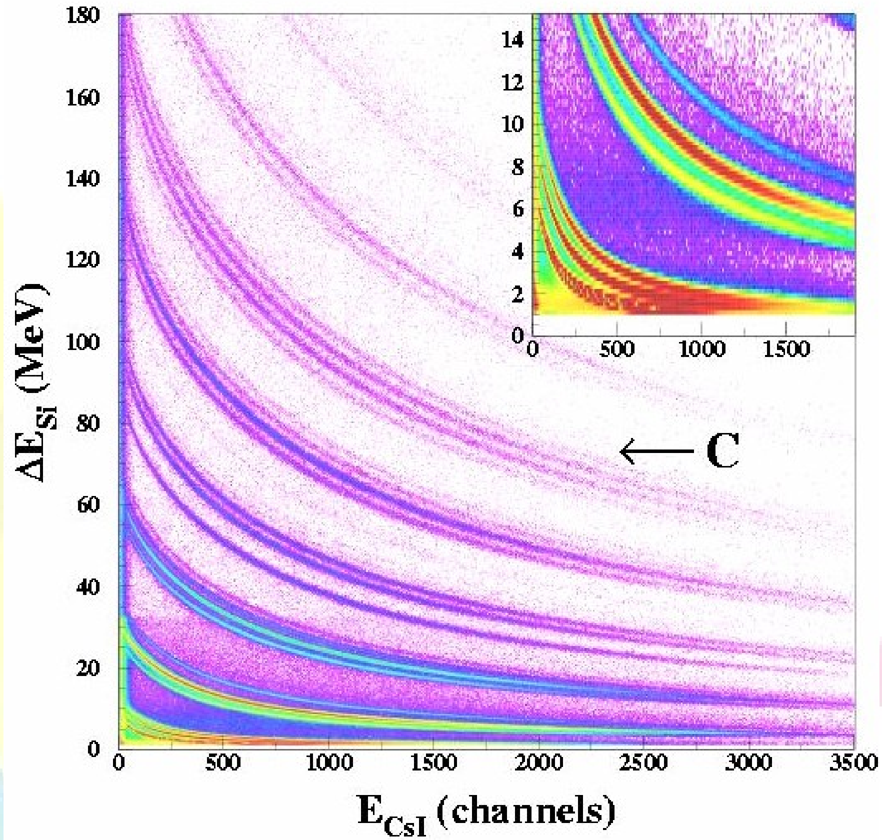
16 channel-boards (⇨256 channels) in 6U height rack

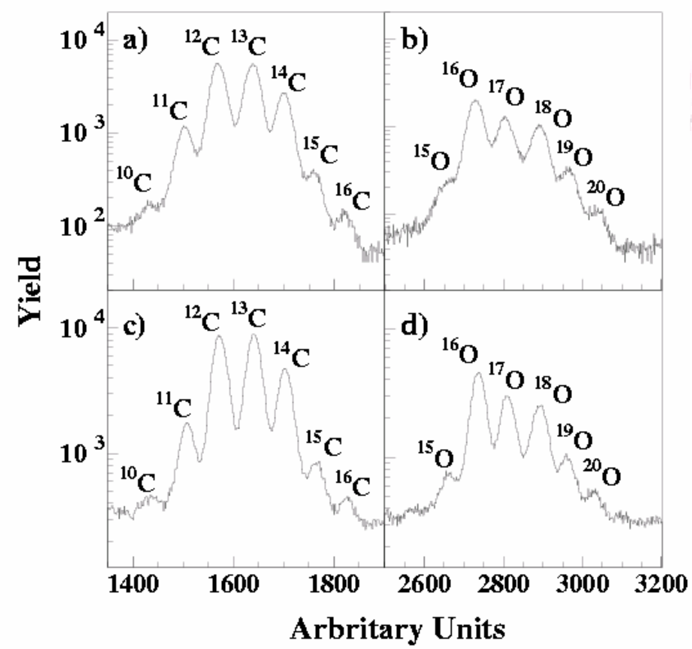
Particle identification

Energy loss given by: $\frac{dE}{dx} \propto \frac{Z^2 A}{E}$

↳ Higher discrimination in Z



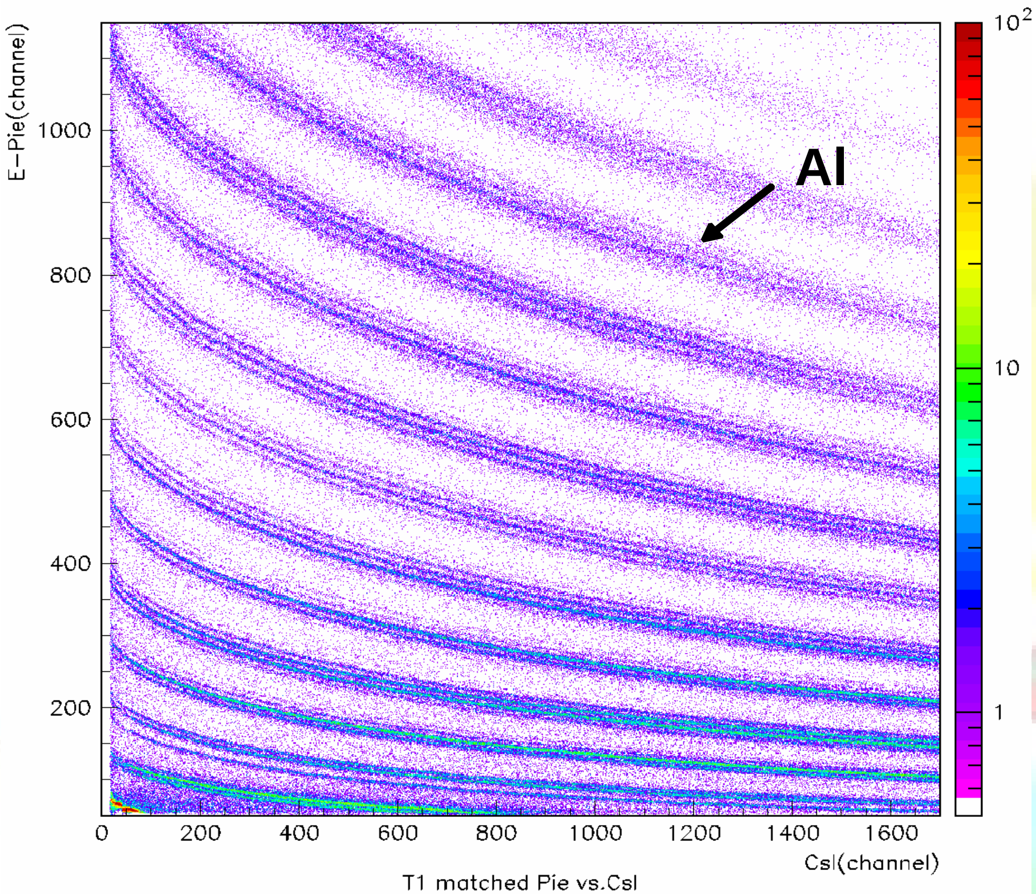




- Large number of strips
  - ↳ Matching of different strips
    - ❑ Thickness variation
    - ❑ Gain matching
- Experiments over days
  - ↳ Matching in time

B. Davin et al., NIMA473, 302 (2001)

FIRST performance

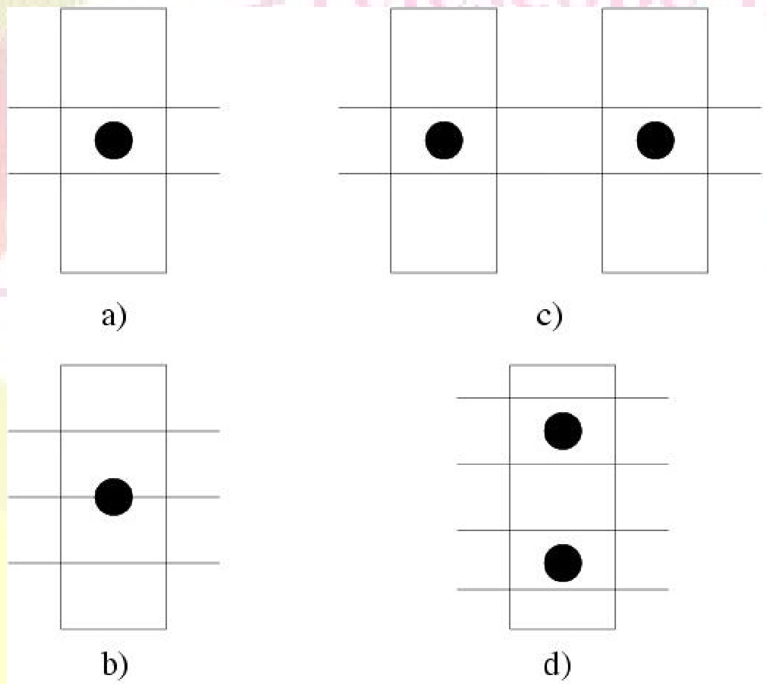


Resolution:

- T1:
  - ❑ A up to ≈ 30
  - ❑ Z up to projectile
- T2: A up to ≈ 18
- T3: A up to ≈ 15

Telescope	Case a	Case b	Case c	Case d	Reject
T1	16	**72**	0.04	1.2	10.8
T2	69	4.7			26.3
T3	49	24			27

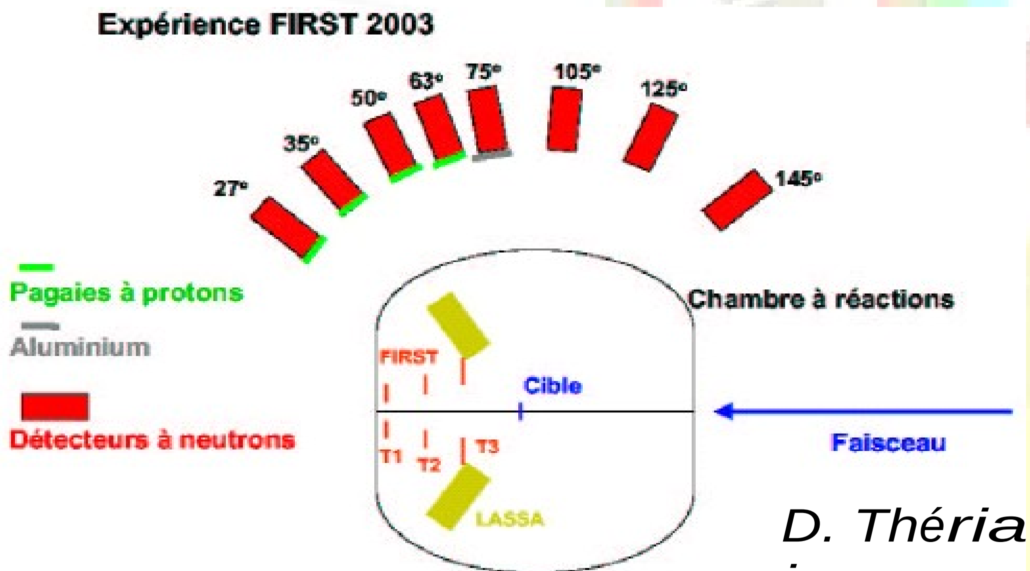
- Second Si of T1 = 1 mm
- Particle with large Z
  - ↳ Charge split on the rings



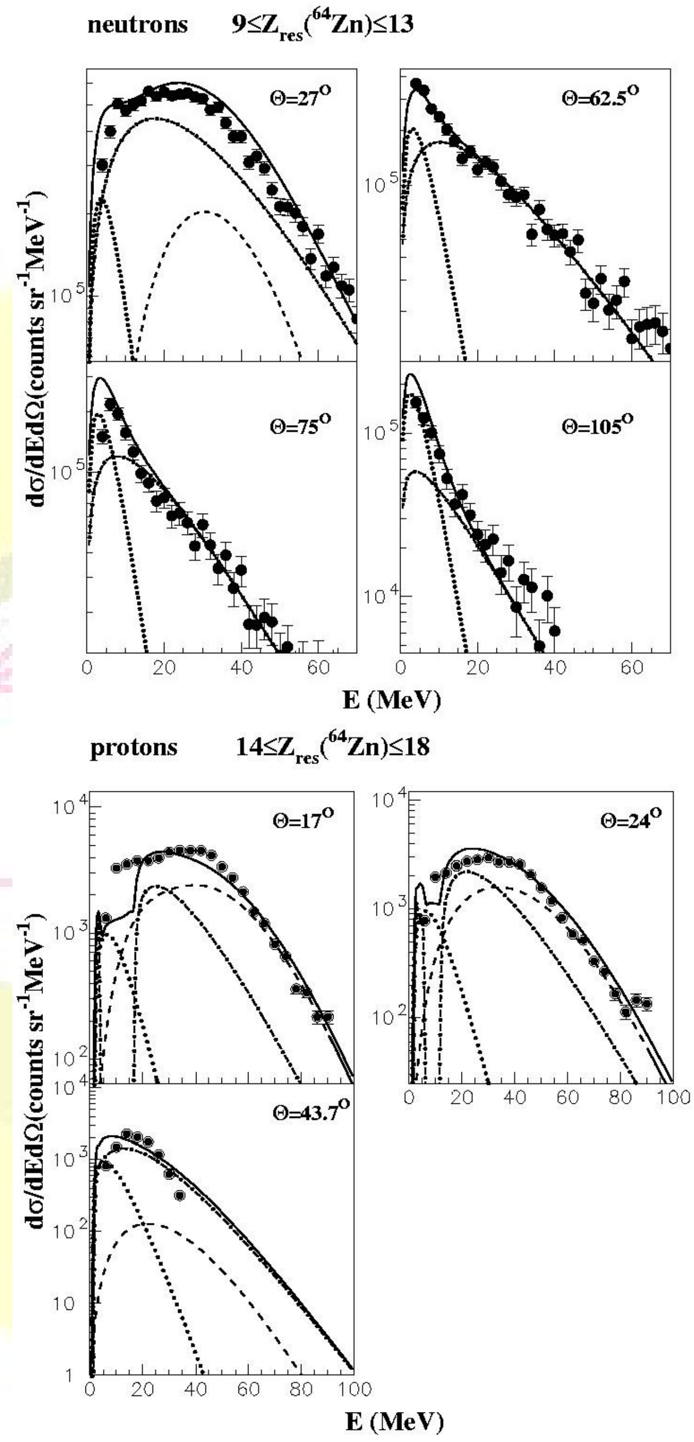
T. Paduszynski et al., NIMA547, 464 (2005)

FIRST@TAMU: Commissioning experiment

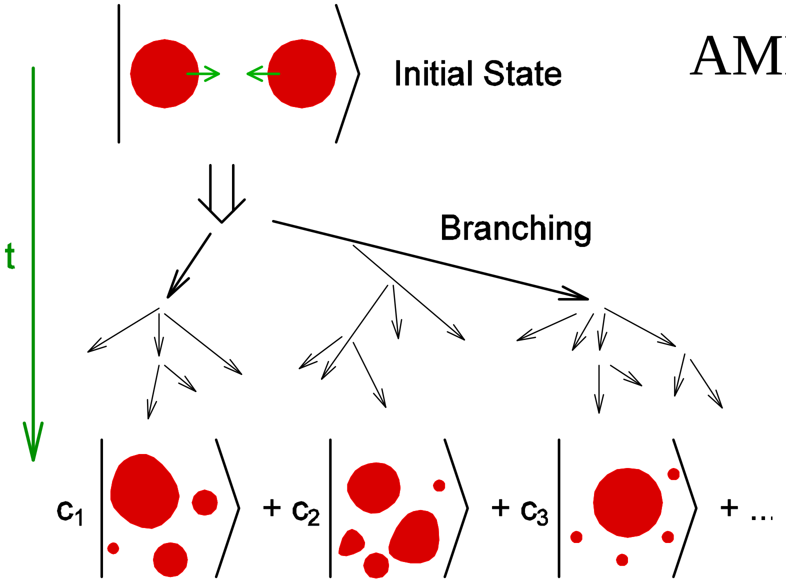
- $^{64}Zn+^{64}Zn$, ^{209}Bi and ^{27}Al at 45 MeV/nucleon
- Collaboration with Université Laval (Québec), TAMU
- Charged particles measurement with FIRST+LASSA
- Neutron measurement with n-TOF



D. Thériault at al., in preparation



AMD: Dynamics with quantum branching

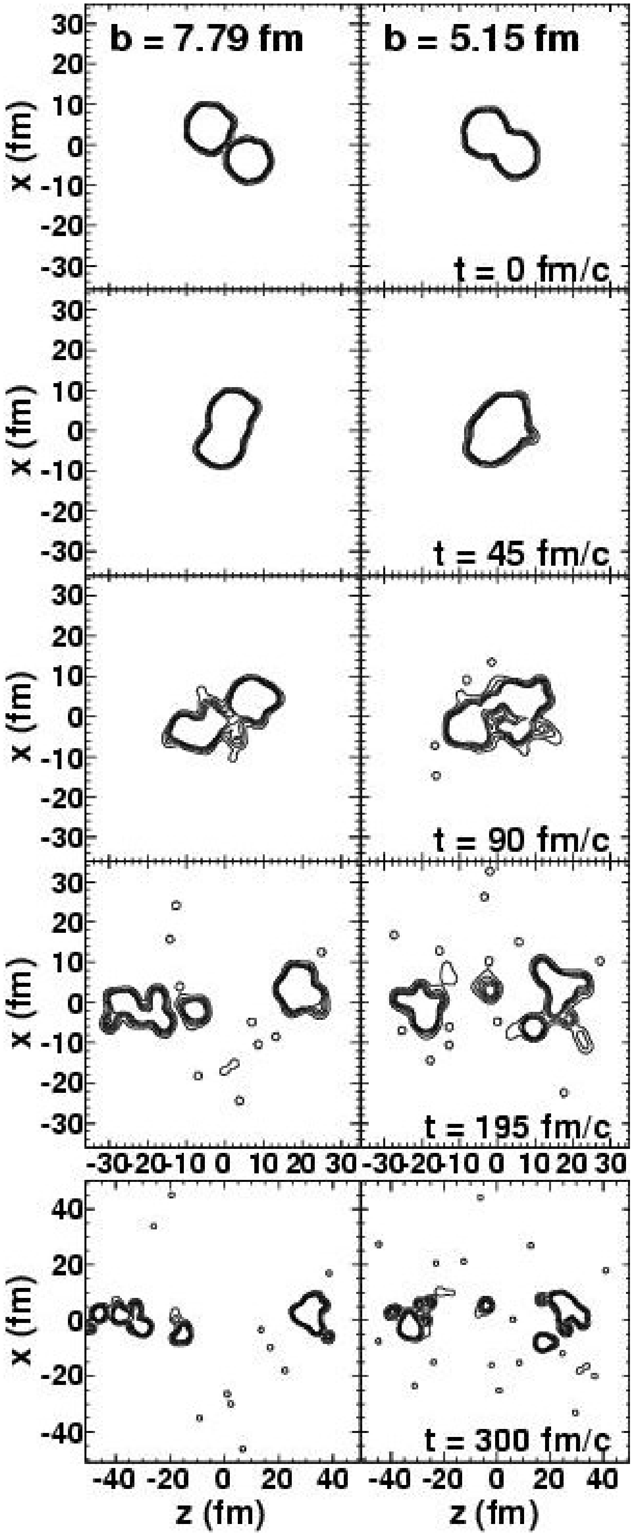


AMD: **A**ntisymmetrized **M**olecular **D**ynamics

- Slater determinant of Gaussian packets as each channel
- TDVP → Equation of motion for centroids
- Quantum branching processes
  - ↳ NN collisions
  - ↳ Wave packet diffusion and shrinking

1. t=0: touching spheres
2. $t \leq t_{clust}$: Dynamical calculation
3. At $t = t_{clust}$, cluster recognition (distance in phase space)
   - ↳ Hot clusters (Z, A, R, P, E*)
4. Statistical decay and Coulomb propagation
   - ↳ Cold clusters (Z, A, P)

A. Ono et al., Phys. Rev. Lett. 68, 2898 (1992)
Prog. Theor. Phys. 87, 1185 (1992)
Phys. Rev. C66, 014603 (2002)
Prog. Part. Nucl. Phys. 53, 501 (2004)



AMD: nucleon density

- System:
  ^{114}Cd + ^{92}Mo at 50 MeV/nucleon
- Sampling of all impact parameter range
  b = 0 – 13 fm
- Calculations performed on IU supercomputer
  12 – 24 CPU hours per event per node
- 25000 events accumulated (→34 - 68 years!)

☞ Mass, charge, energy exchange

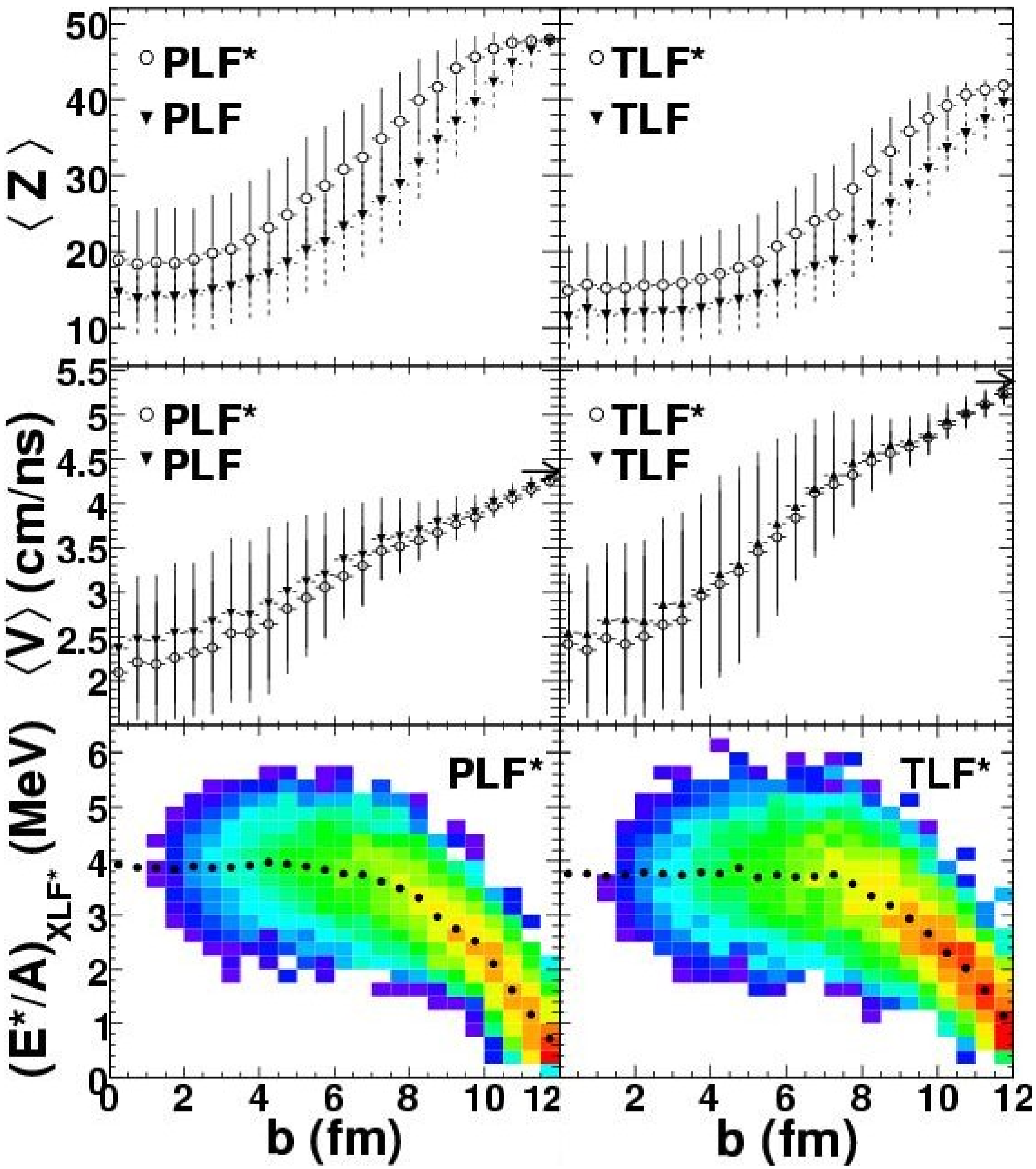
☞ Binary nature of the collision

☞ Transiently deformed nuclei

☞ Early cluster production, t ≈ 90 fm/c

S. Hudan, R.T. de Souza and A. Ono, PRC (in press)

AMD: PLF* and TLF* properties



t_{clust} = 300 fm/c

PLF* = biggest frag. forward of C.M.

TLF* = biggest frag. backward of C.M.

☞Smooth decrease of Z_{PLF*} with b and saturation at ≈19

☞Smooth decrease of v_{PLF*} with b

- ➢ Good b selector

☞Increase of the excitation energy (⇔T) with increasing centrality followed by saturation for b<6fm

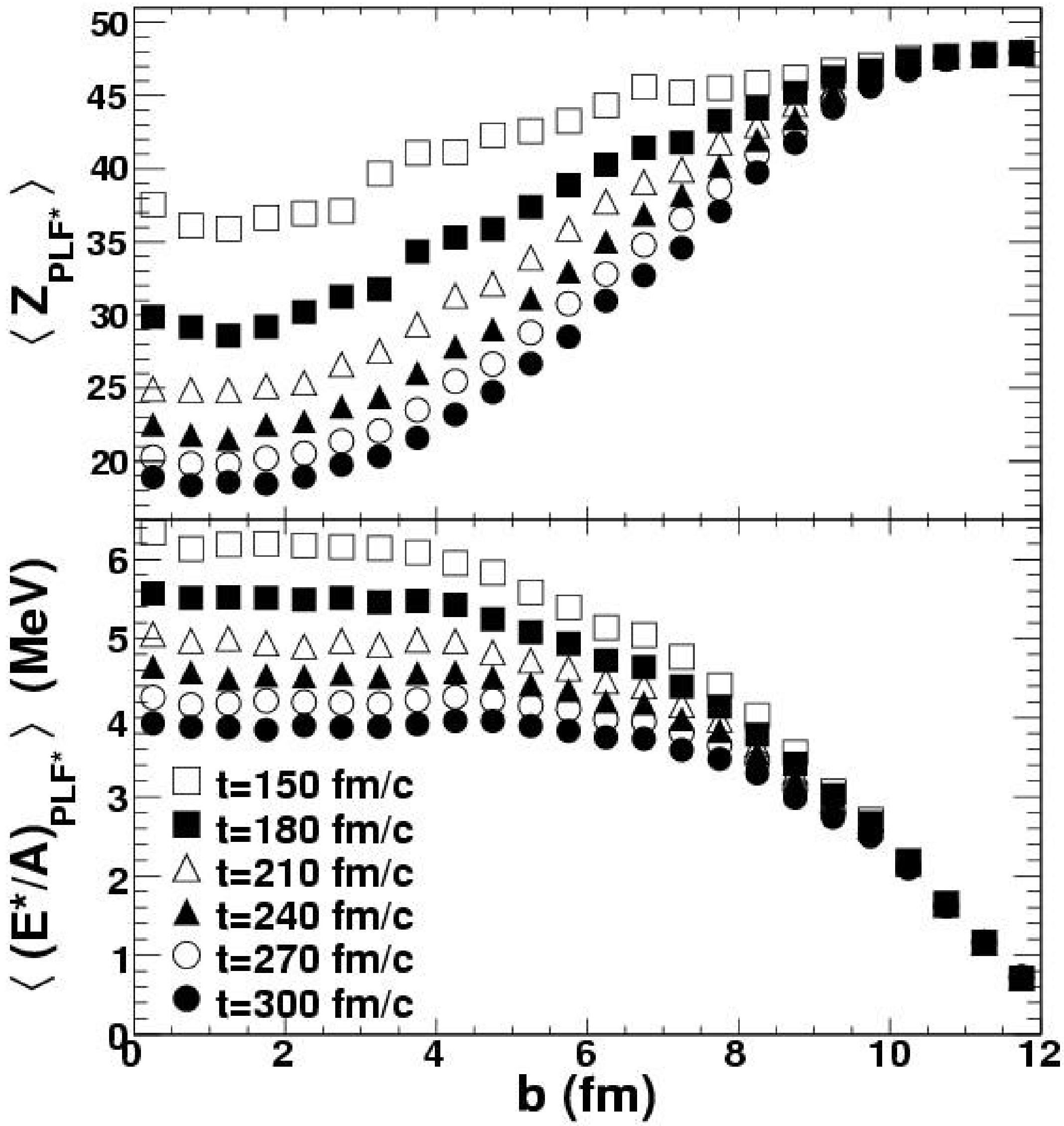
☞Similarity of PLF* and TLF*

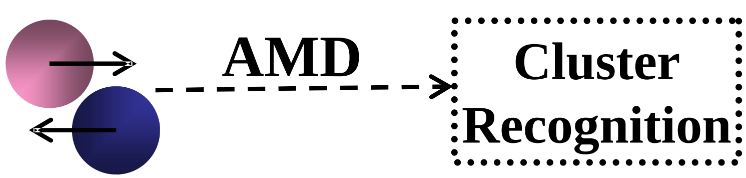
☞At b=0fm, same E*/A for PLF* and TLF*

? Thermalization

? Saturation of E*/A

AMD: Rapid cooling



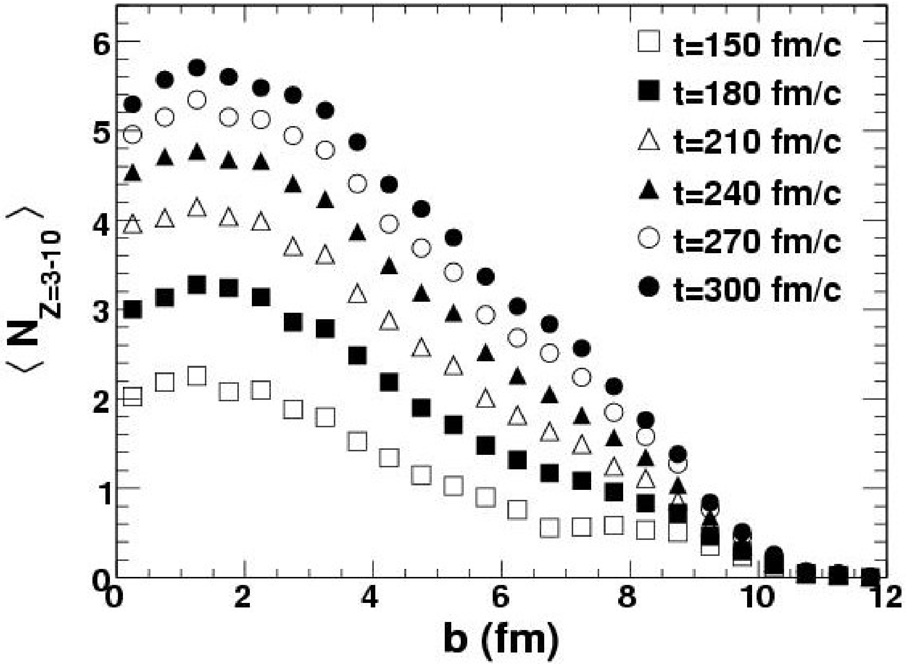


☞Peripheral collisions: $\langle E^*/A \rangle \neq f(t)$

☞Central collisions

- Higher E^* for earlier times
  - ❑ $\langle E^*/A \rangle \approx 6$ MeV for t=150 fm/c
  - ❑ $\langle E^*/A \rangle \approx$ 4 MeV for t=300 fm/c
  - → **Rapid cooling**
- Rapid decrease of Z_{PLF*}
  - ⇘Decrease of ≈**30%** between t=150 and 300 fm/c
- Different onset for different time
  - → **Large cross-section with maximum E^*/A**

AMD: particle production



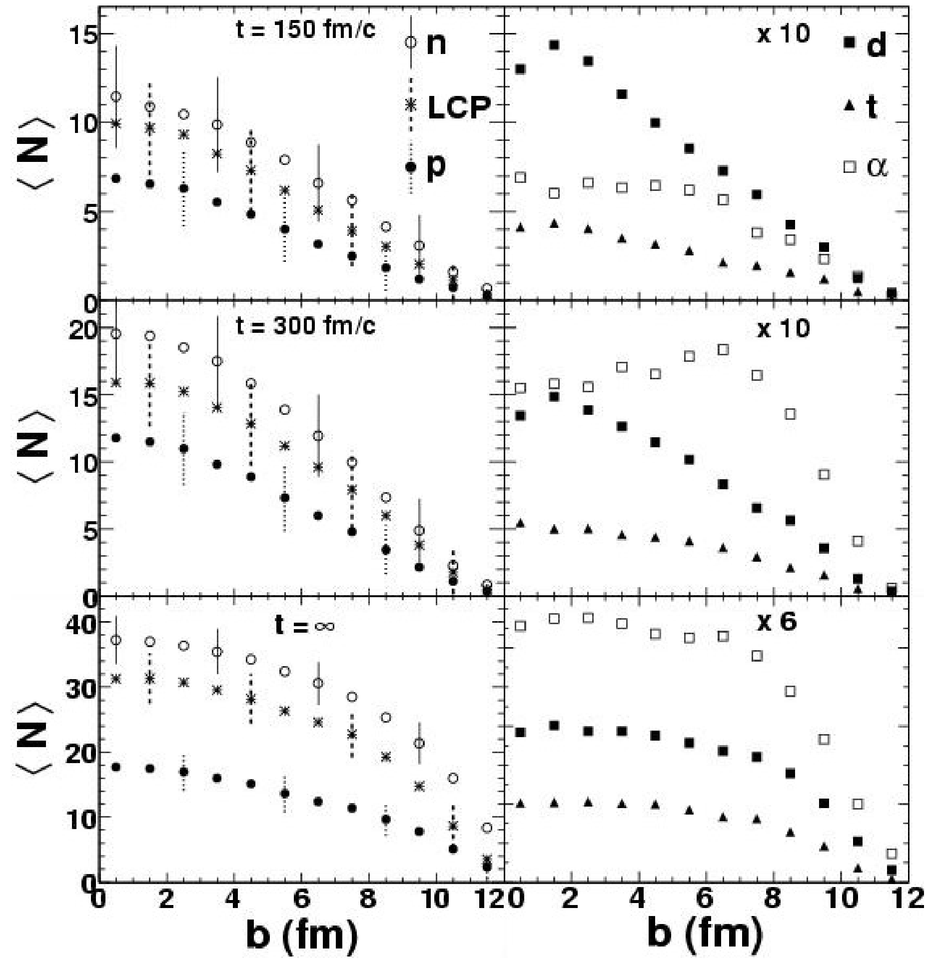
☞N_{IMF} increases with centrality with a saturation for b≈3 fm.

☞On average 1 IMF for b≈9 fm at 300 fm/c

☞Larger production rate for t=150-240 fm/c

IMF: Z = 3-10

LCP: Z=1,2



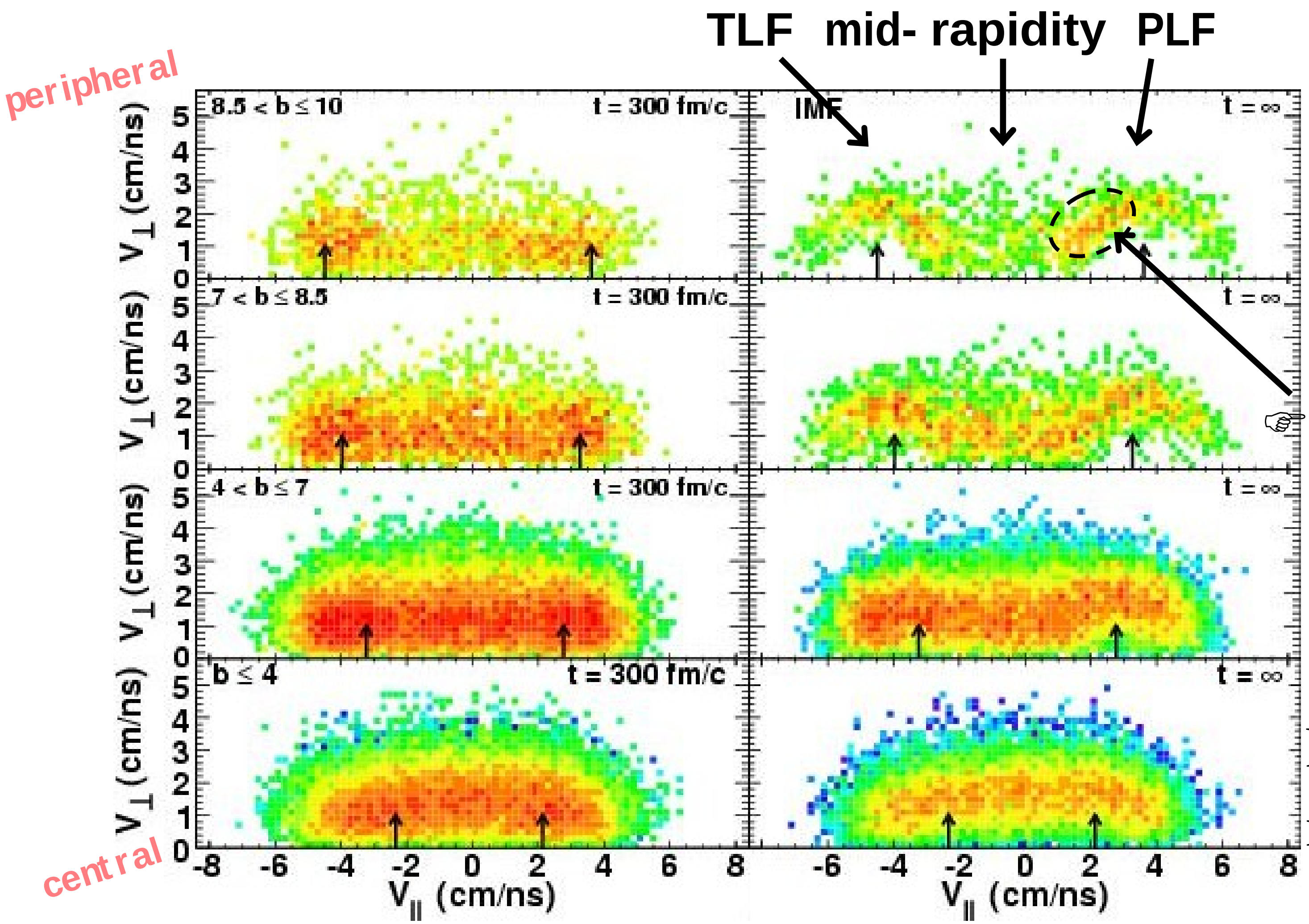
☞For t=150 and 300 fm/c, increase of n and LCP multiplicities with centrality

☞$N_{n, LCP}$ increase with t

☞Large α production between 150 and 300 fm/c

☞After decay, saturation of N for b<8fm

AMD: IMF velocities



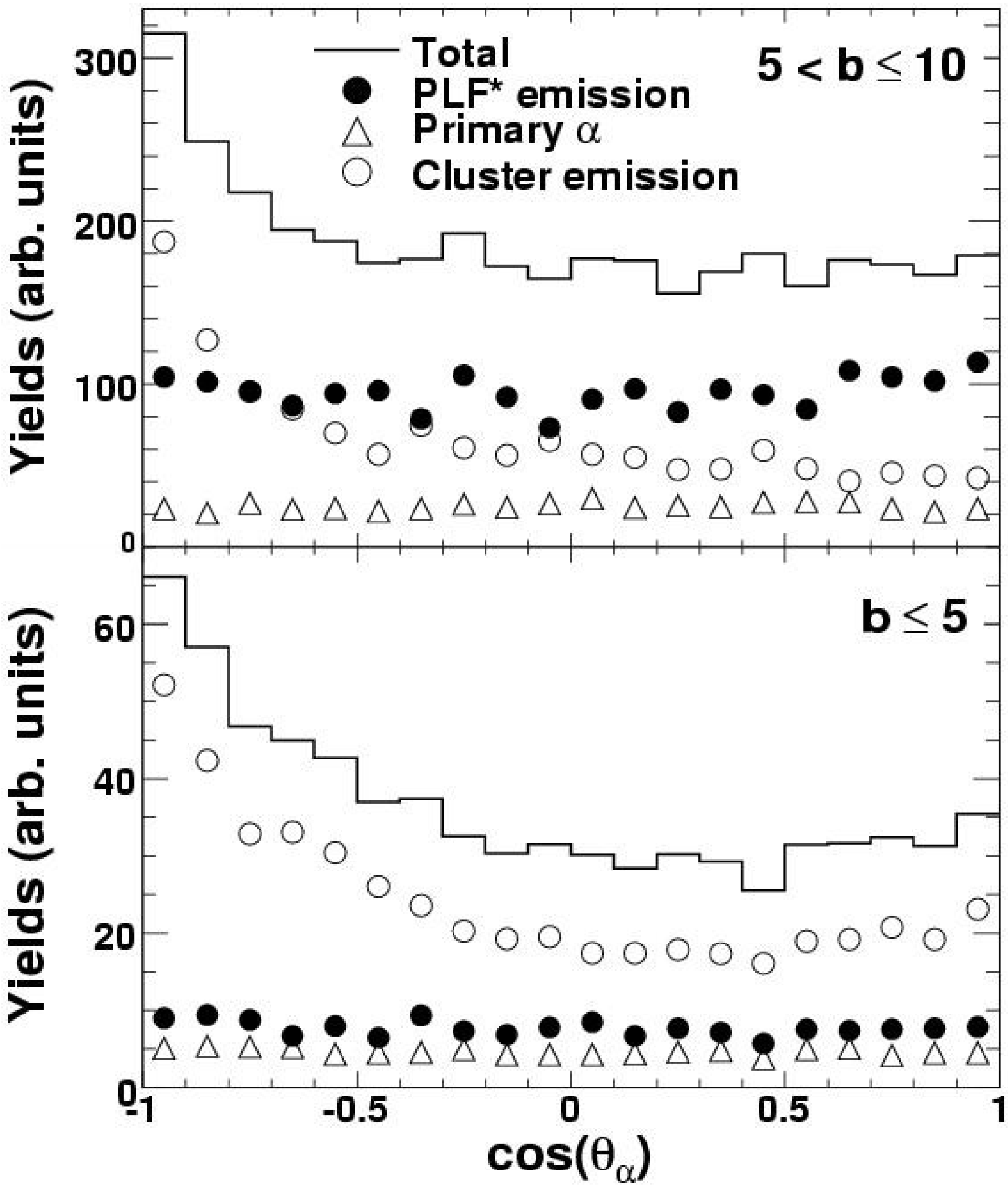
☞Anisotropy on the ridge

☞PLF*, TLF*, mid-rapidity components

☞More overlap and higher contribution from mid-rapidity for lower b

AMD: α on the ridge

$V_\alpha < 3.5$ cm/ns



☞ Enhanced backward emission

- Isotropic PLF* emission
- Isotropic "primary" emission (t≤300 fm/c)
- Anisotropic α emission from clusters

  ↳Anisotropy of excited clusters induces anisotropy of α particles

AMD: what did we learn?

- Peripheral and mid-central collisions: **binary** in nature
- Formation of transiently **deformed** nuclei
- PLF^* and TLF^* **excitation** associated with **velocity damping**
- **Saturation of $\langle E^*/A\rangle_{PLF*}$** for most central collisions with value depending on cluster recognition time

↳ **Rapid particle emission on the dynamical timescale**

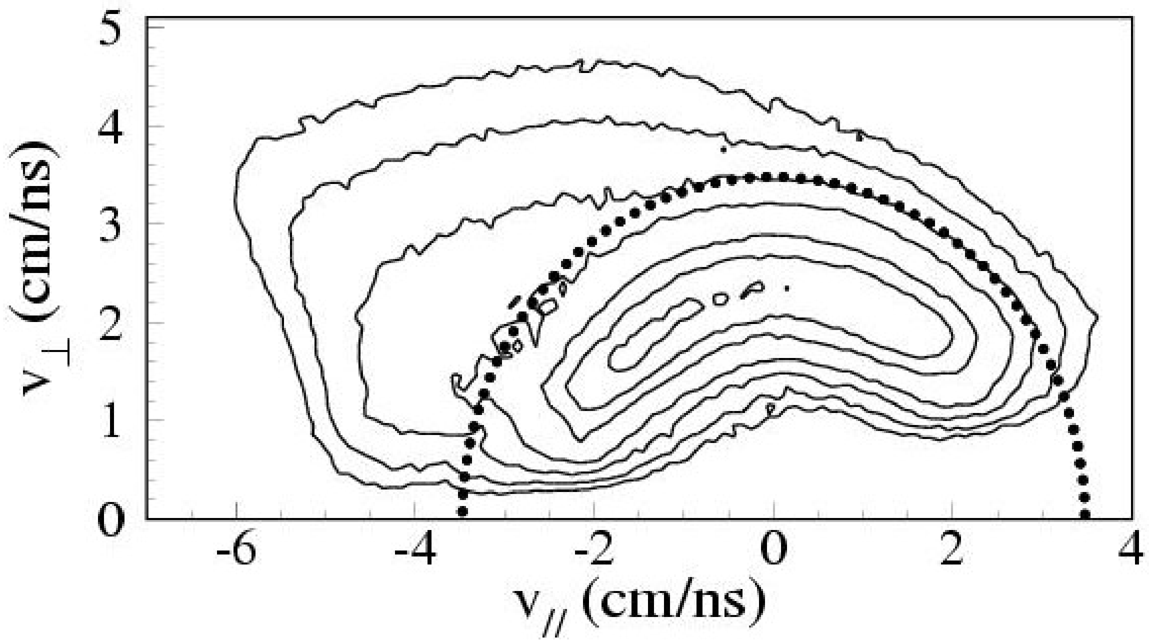
↳ **Dynamical phase and statistical decay coupling**

AMD: what do we need to change?

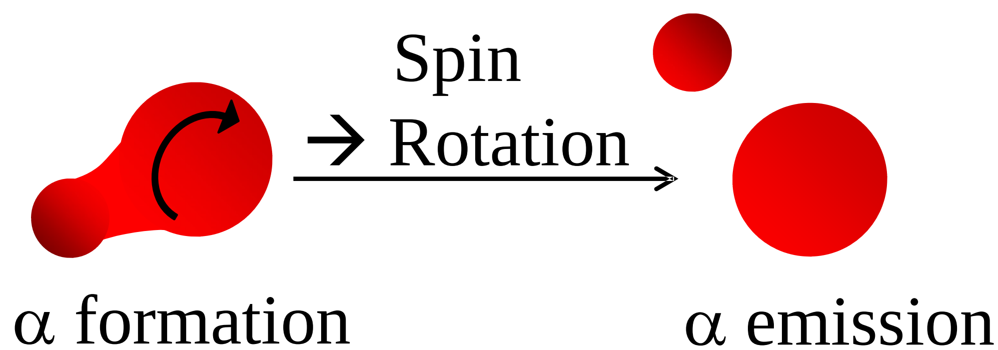
Account for:

- Deformation
- Coulomb proximity

Deformation:
Experimental observation?



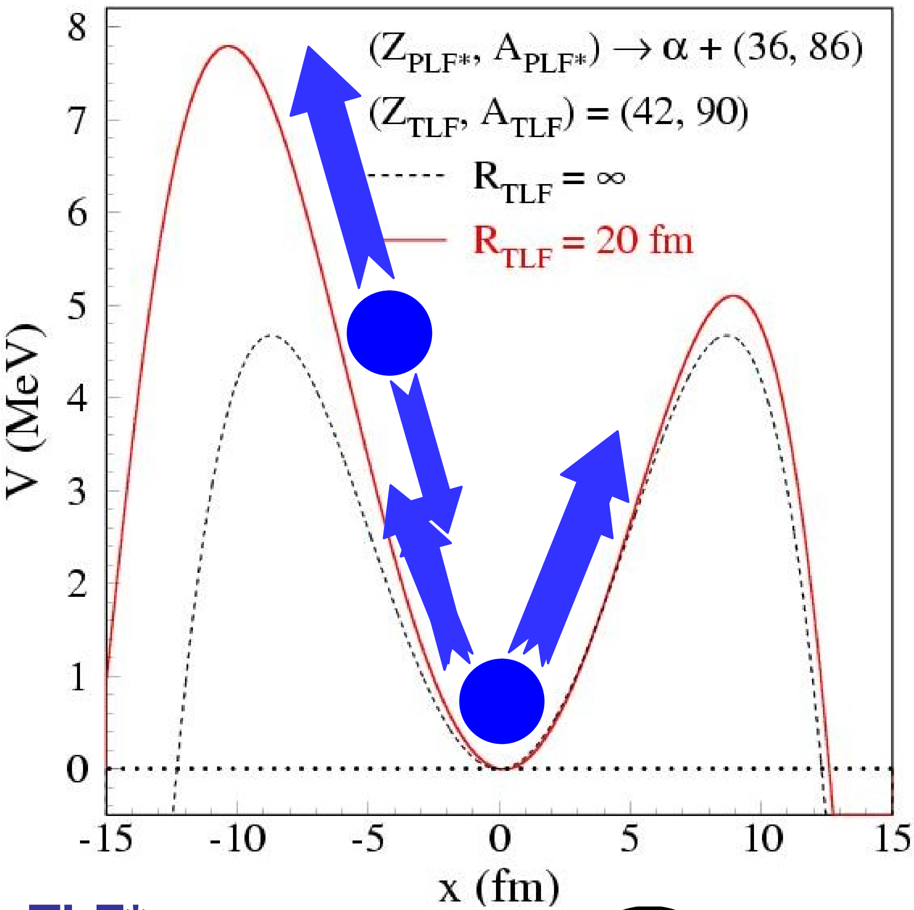
- ☞ Coulomb ridge
- ☞ Anisotropy along the ridge

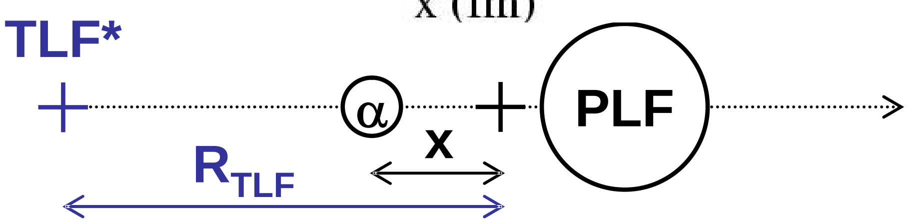


S. Hudan et al., PRC70, 031601(R) (2004)

Langevin calculation

Thanks to: R.J. Charity, L.G. Sobotka
Washington University





Calculation with:

$$V(x) = -(x-c)(x+c)\left(\frac{x}{d}\right)^2$$

1) α-PLF* interaction

2) TLF*- PLF* system Coulomb interaction

While the TLF* and PLF* separate, they evolve smoothly on a classical trajectory.

Observed angular asymmetry
↳initial deformation towards the TLF*

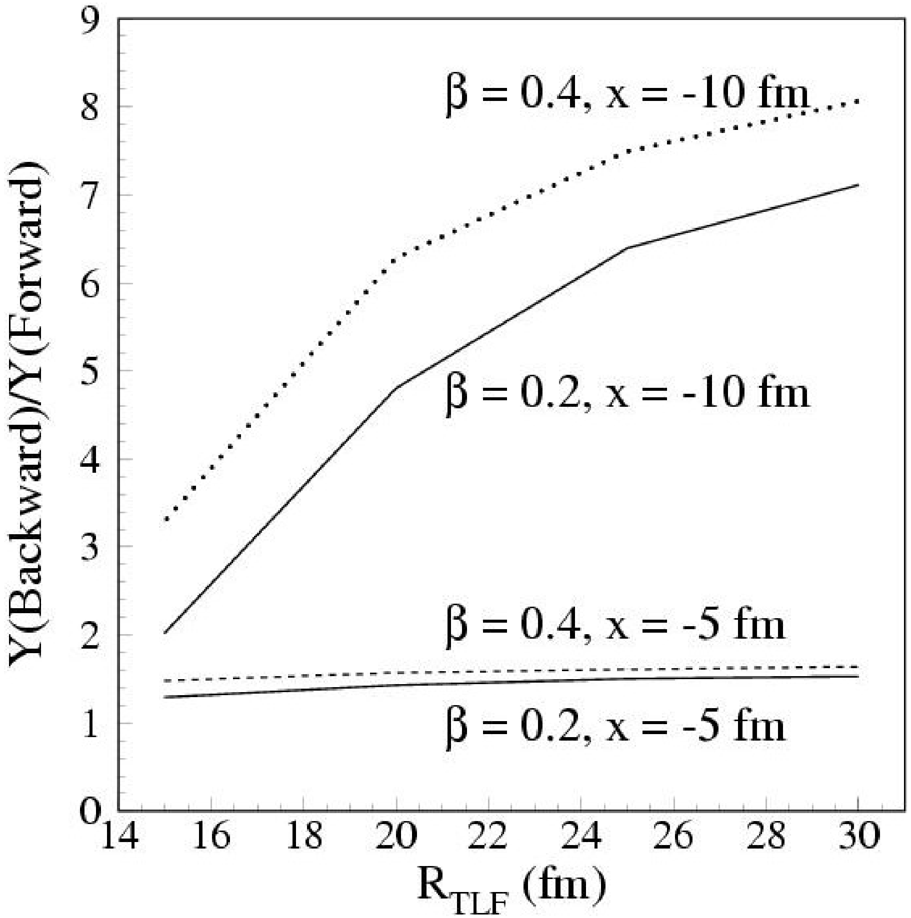
Persistence of the initial configuration
- ☞ High friction
- ☞ Initial configuration near barrier

Propagation in time of the system: $\Delta x = \frac{F\Delta t}{\beta} + k\sqrt{\frac{2T\Delta t}{\beta}}$, with β relative to the friction, F force due to the potential, temperature T, fluctuating term k (thermal).

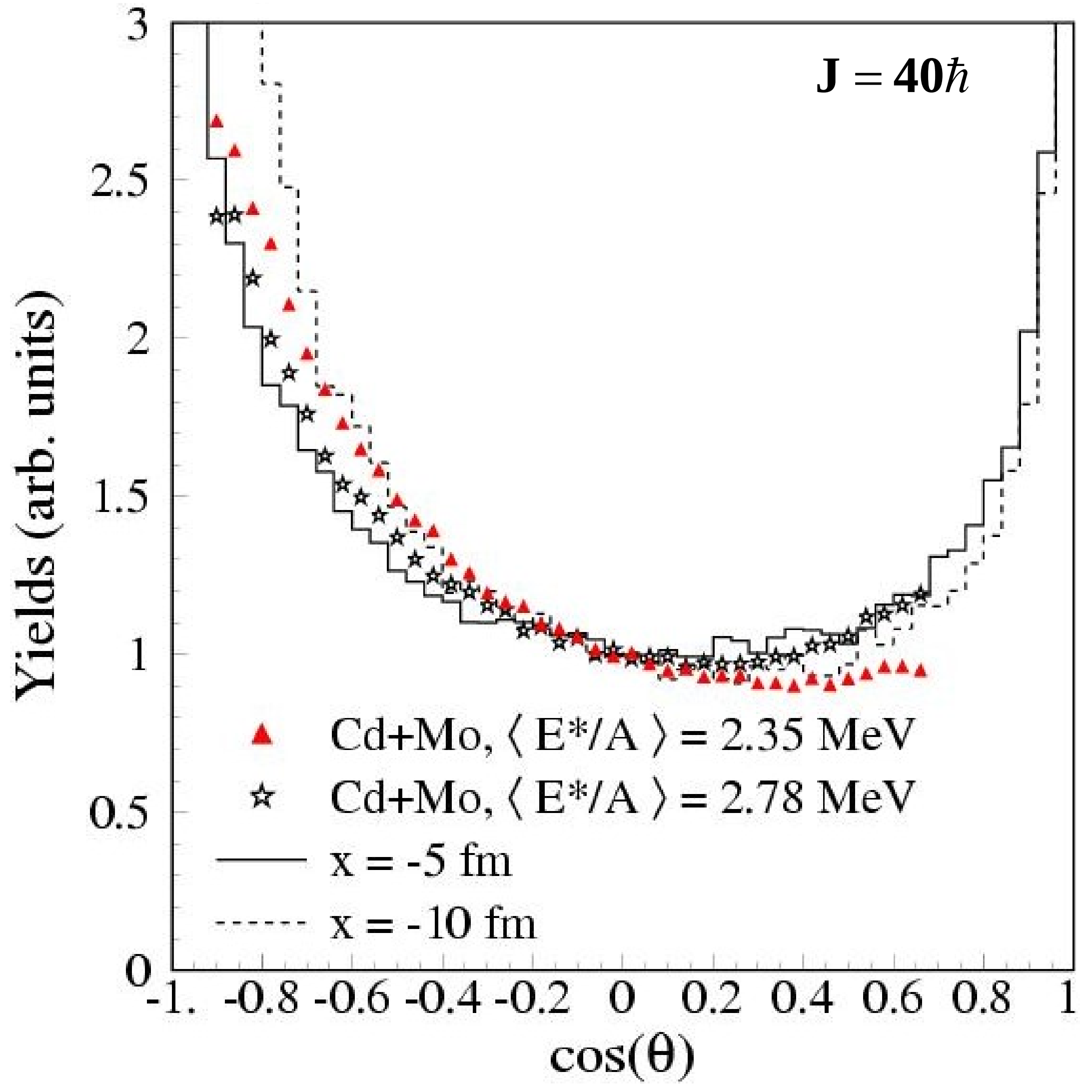
As the TLF* and PLF* separate the barrier changes.

Results of the calculation

This observed asymmetry is related to the observed angular asymmetry through the spin of the PLF*: **time – angle association**



- No initial deformation
-
-

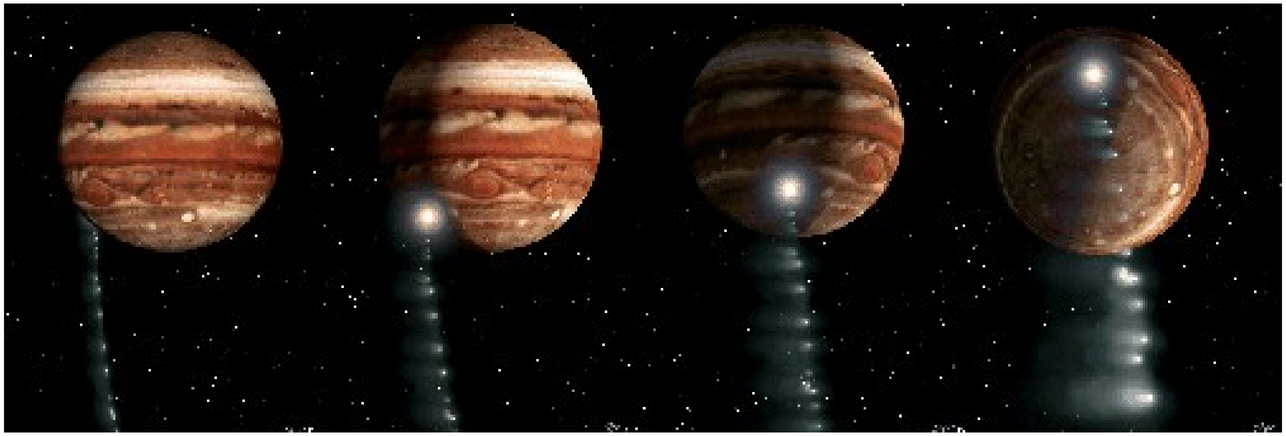


Strongly elongated initial configuration required to observe large asymmetry

↳ **Emission time < Rotational period**

↳ **Change in x (initial deformation) with E***

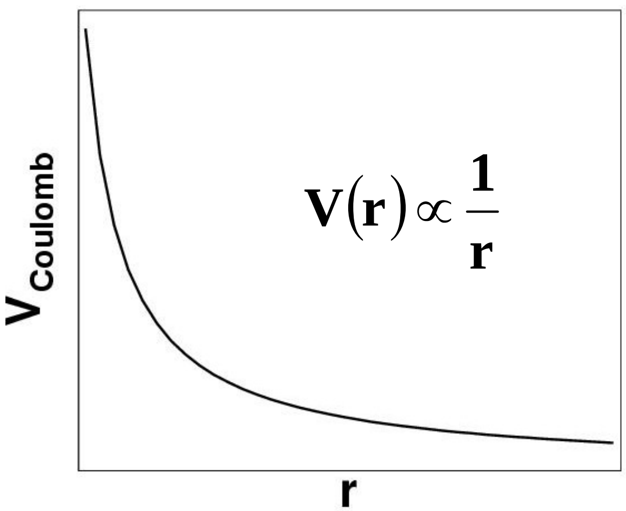
Tidal effects:
a manifestation of proximity decay

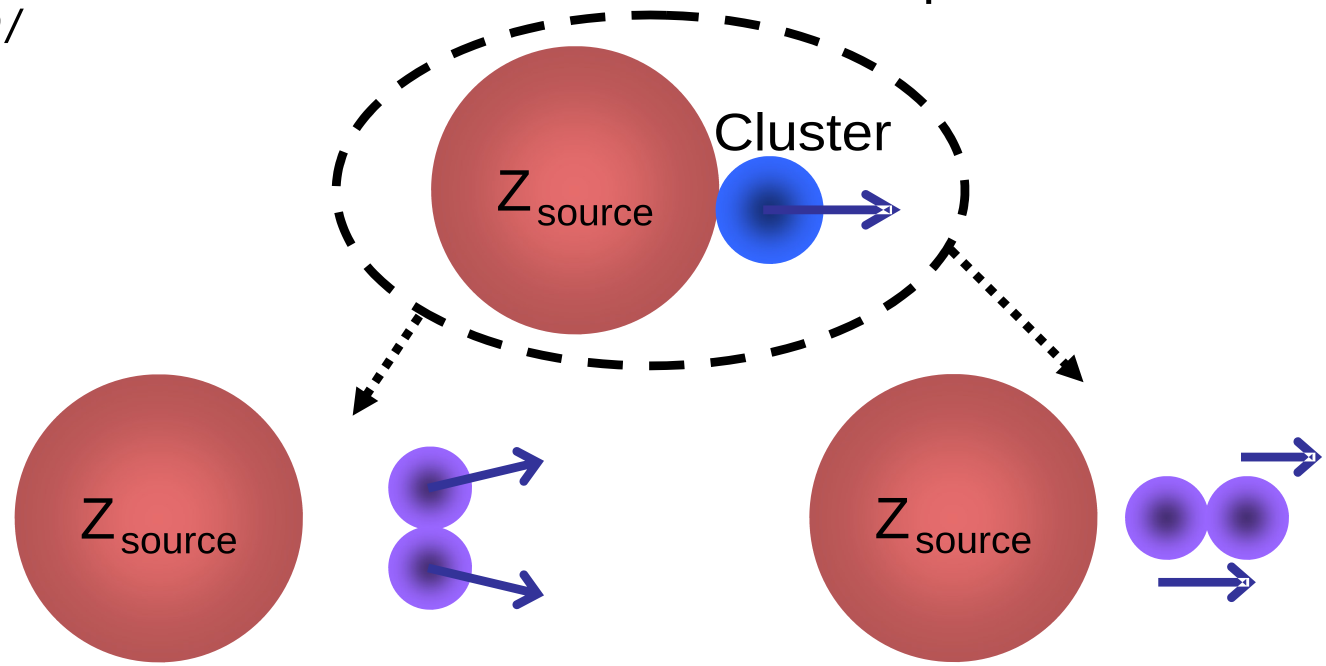


July 16 – 22 1994:
Comet P/Shoemaker-Levy 9 collided with Jupiter resulting in at least 21 discernable fragments with diameters estimated at up to 2 km.

http://www2.jpl.nasa.gov/sl9/

Nuclear case:
Coulomb interaction





Transverse
→ Higher E_{rel}

Longitudinal
→ Lower E_{rel}

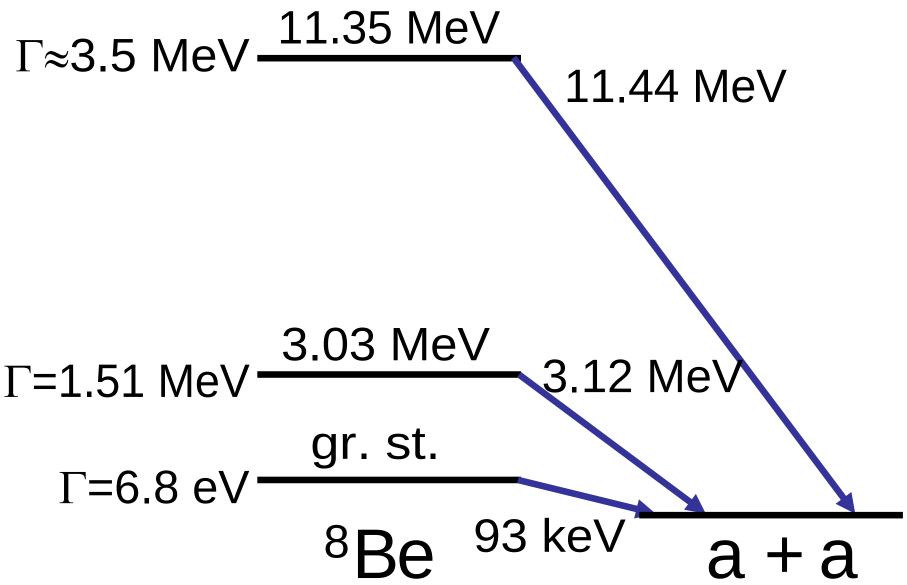
Tidal effects: gradient in the field

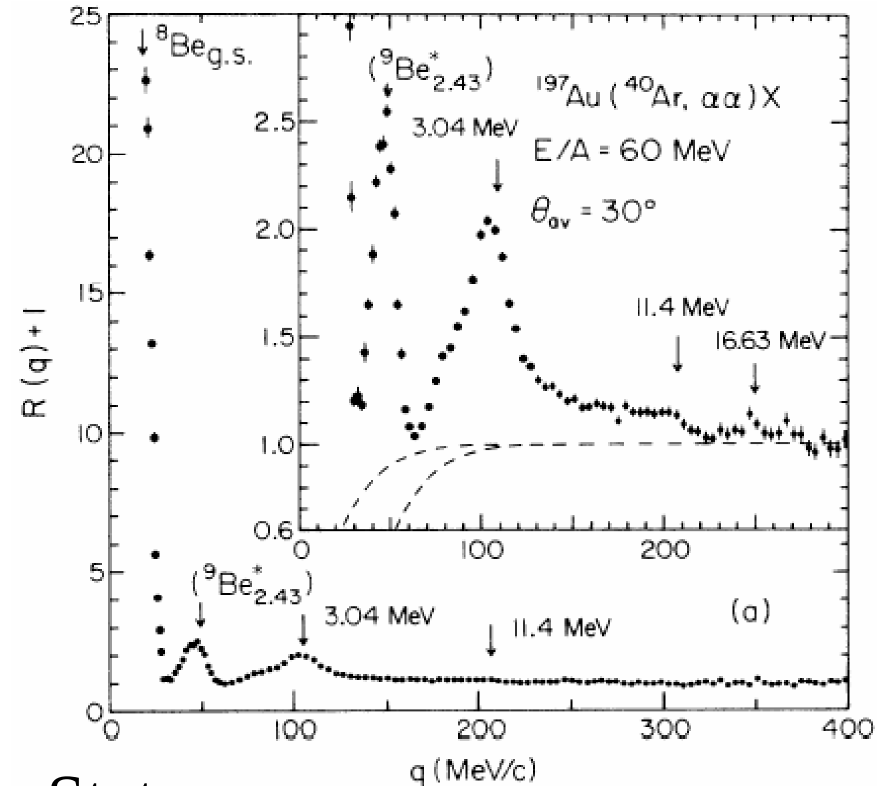
- Change of the relative velocity
  - ❑ Transverse decay with higher relative energy
  - ❑ Longitudinal decay with lower relative energy
- Decay angle dependence of the probability

$$\mathbf{P(E) \propto e^{-\frac{V}{T}} \text{ and } V = f(ß) \Rightarrow P(E, ß)}$$

  - ❑ Higher probability to decay transverse to the emission direction
  - ➢ New thermometer?
- Effect depends on:
  - ❑ Time spent in the field
    - ➯ Stronger effect when decaying close to the “source”
  - ❑ Field gradient
    - ➢ New method to probe anisotropies in the Coulomb force field?

Tidal effect: ^{8}Be





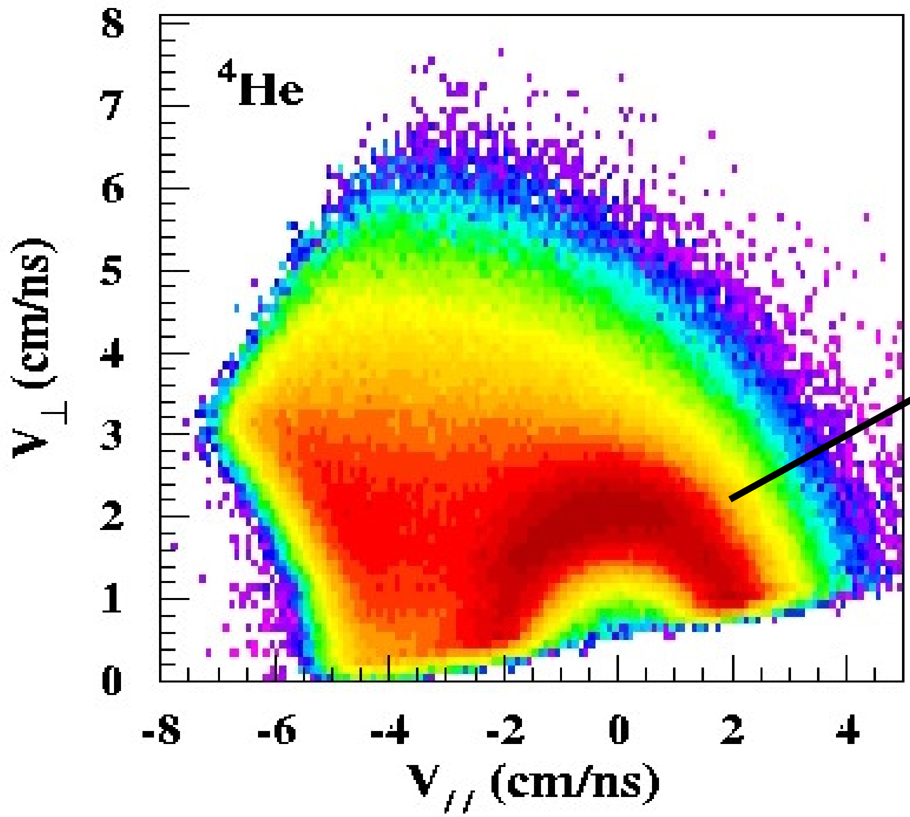
J. Pochodzalla et al., PRC 35, 1695 (1987)

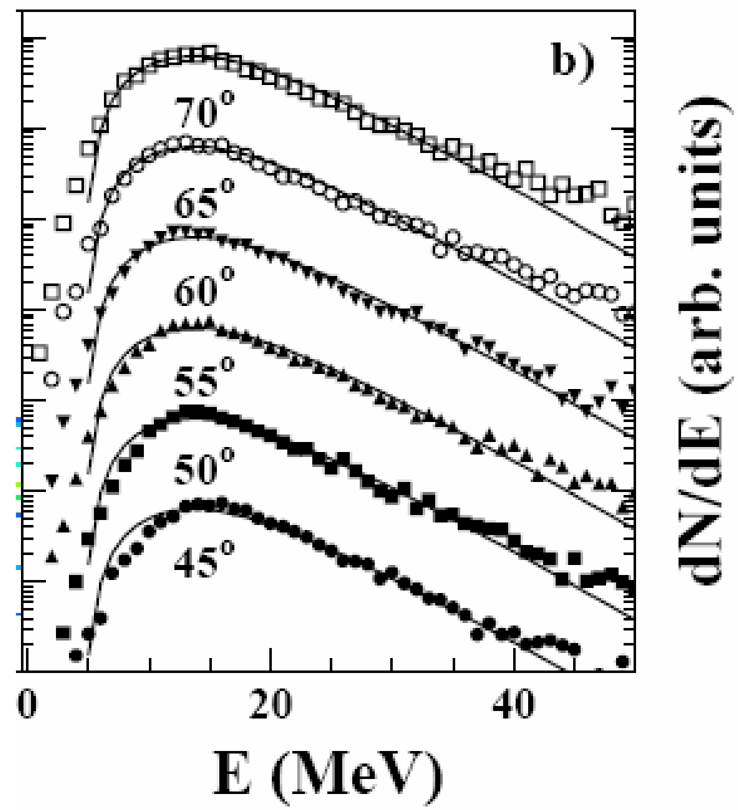
- Relative Energy Determined by Quantum State
- Tools to measure the existence and properties of short-lived intermediates
- Decay into two identical particles
  - ↳ Same acceleration after decay
- Probe of different lifetimes
  - ➢ 11 MeV sate decays practically on the nuclear surface
    - ↳ Study pre-formation factors?

Tidal effect: data selection

R. Yanez et al., PRC68, 011602 (R) (2003)

^{114}Cd + ^{92}Mo at 50 MeV/ nucleon



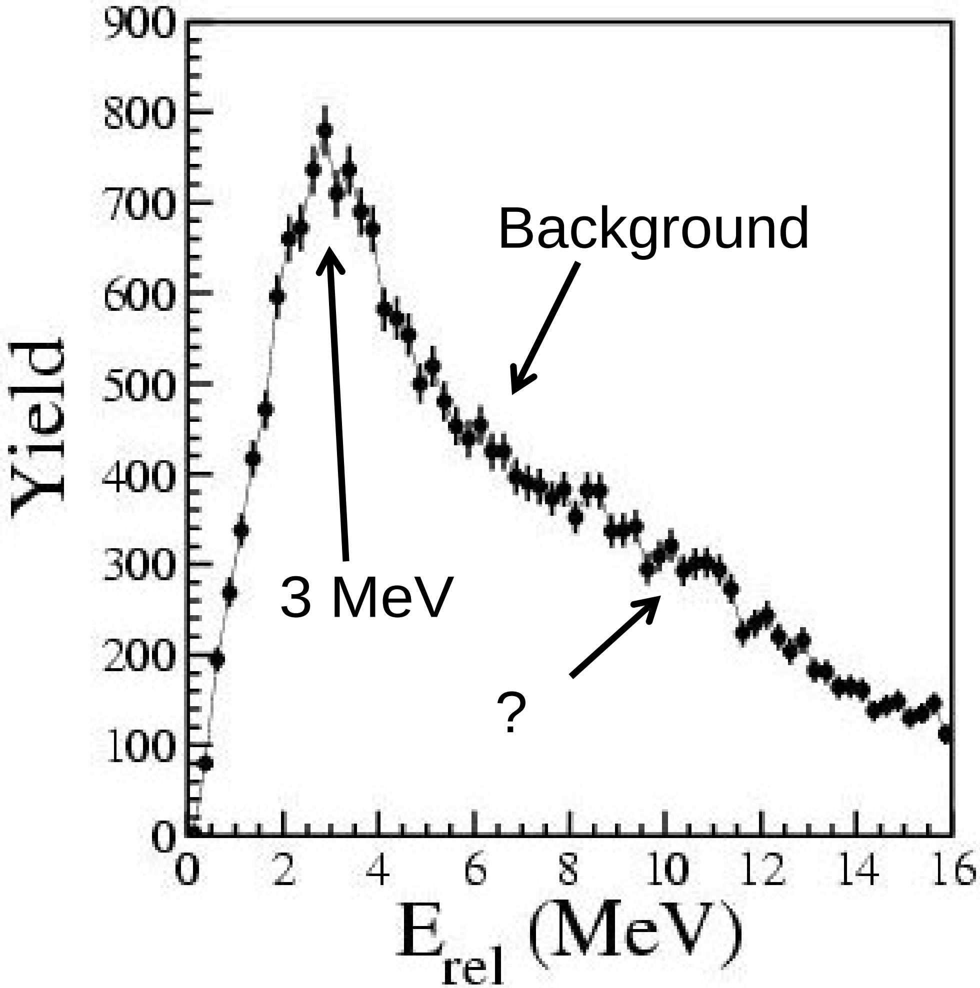


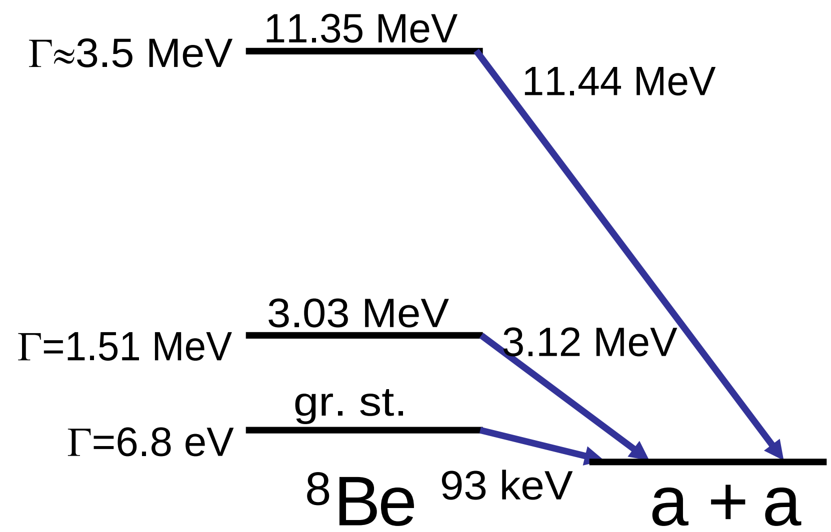
☞Isotropic emission forward of PLF*

Data selection:

- $15 \leq Z_{PLF} \leq 46$
- $8 \leq V_{PLF} \leq 9.5 \Leftrightarrow E^*/A = 2 - 4$ MeV
- 2 α particles forward of PLF ($\theta \leq 100°$)

Tidal effect: correlation function



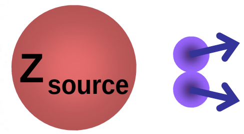


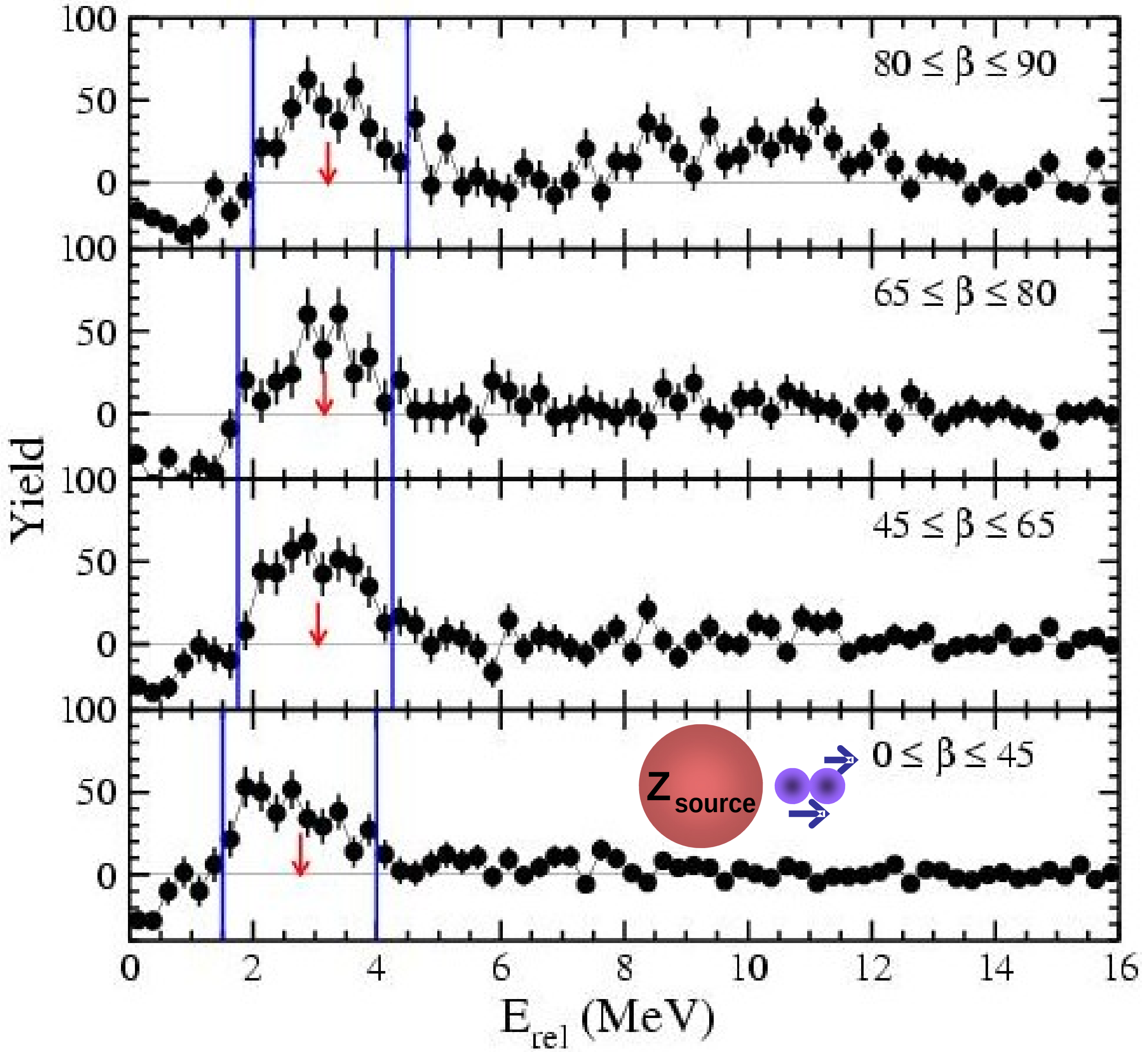
☞ Peak at 3 MeV

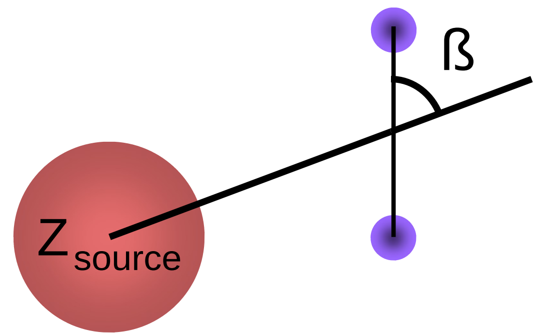
☞ No Ground State Peak

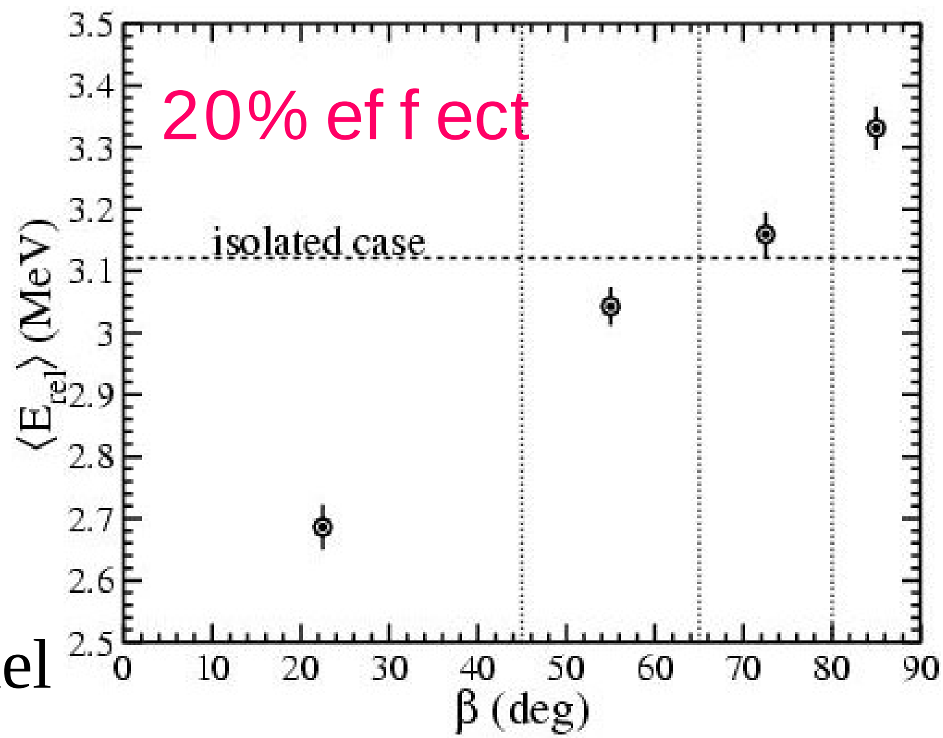
- Background primarily due to sequential emission of alphas
- Background constructed by the mixed event technique
  - ➢ Take two alphas from two different events

Tidal effect: angle dependence









- ☞ Lower E_{rel} for longitudinal decay
- ☞ Higher E_{rel} for transverse decay
  - ↳ Consistent with coulomb tides model
- ☞ 11 MeV state only for transverse decay

Tidal effect:
Simple idea with promising outcomes

- Ability to observe and characterize short-lived resonances
- Measured Tidal Effect on ^{8}Be

  ↳ **Experimental observation of the Coulomb proximity**

- Monte Carlo Simulation in progress

  ❑ Alternate background construction

  ❑ Quantify the observed tidal effect

Conclusions

- Peripheral and mid-peripheral collisions:
  a good opportunity to study warm nuclei/nuclear matter
- On a short timescale:
  - ⇨ production of fragments
    - ❑ Deformed
      - ⇨ Large role of the surface
    - ❑ Excited
      - ⇨ Coupling between dynamics and statistical decay
  - ⇨ Coulomb proximity

In the near future

- Experiment at GANIL (E432)
  - ➢ Investigate thermodynamics & dynamics in intermediate energy HI collisions
- Fission experiments: Study of very deformed nuclei
  - ❑ p, d + Pt, W, Os, ... at LBNL
  - ❑ $^{204, 208, 209}$Bi + p at MSU-NSCL (05105)