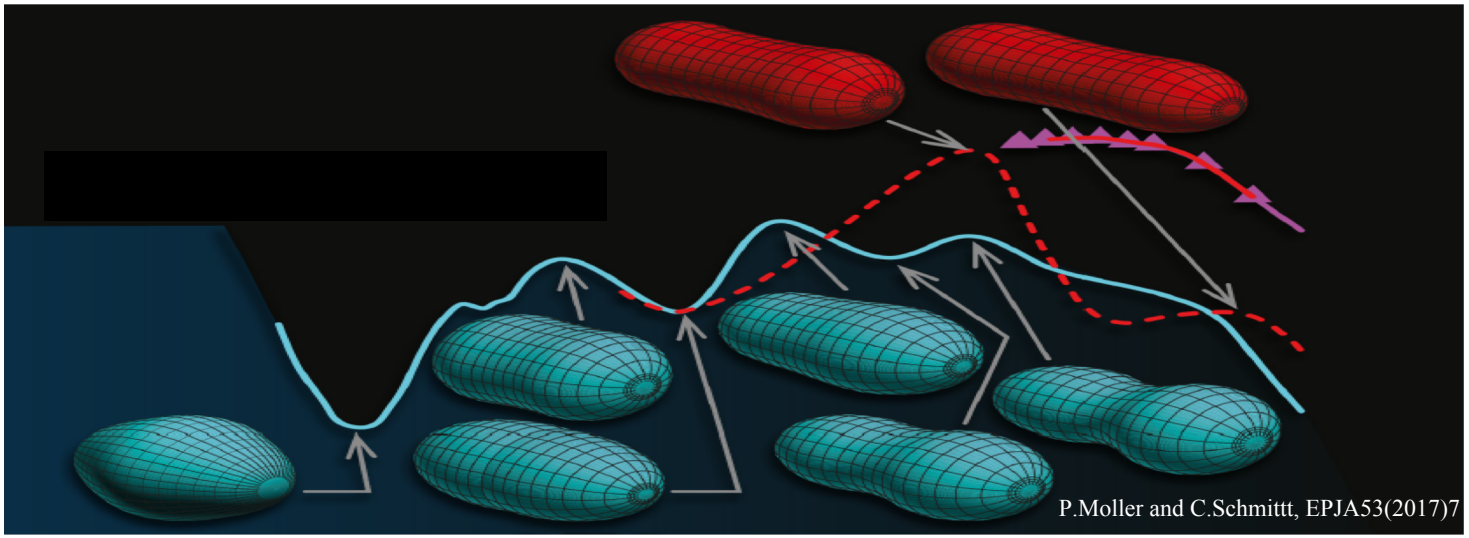


PARIS for study of fission at VAMOS

Marek Lewitowicz
GANIL

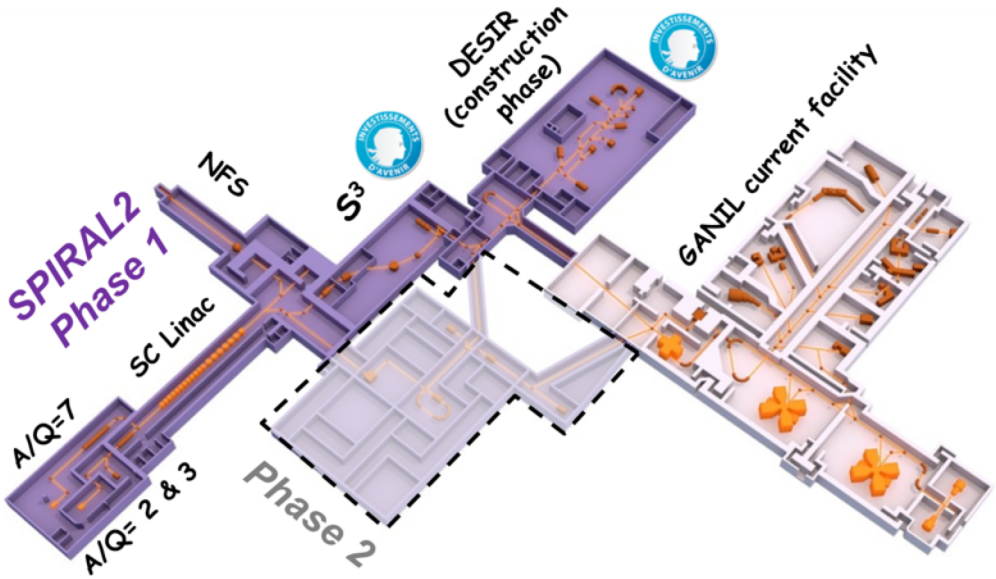
Based on material provided by:
Christel Schmitt, IPHC Strasbourg France
Diego Ramos, GANIL Caen France

Grand Accélérateur National d'Ions Lourds

TGIR Caen, Normandy

1976 Creation by CEA-CNRS
1983 First experiment
2001 SPIRAL1
2006 SPIRAL2 on the ESFRI roadmap (landmark today)
2019 First beam from SPIRAL2

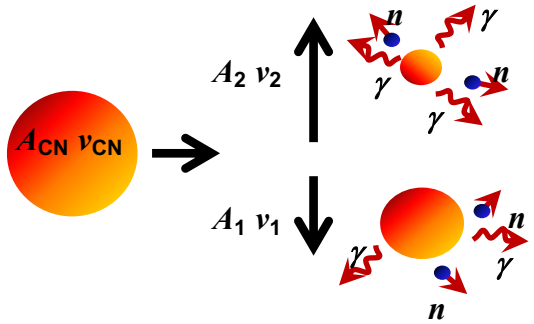
- Light and heavy-ion beams (p – U)
- Energy keV - 100 MeV/u
- Very high intensity beams with SPIRAL2
- Top level experimental equipment



Breaking news

On Nov. 27, 2019 the first proton beam was accelerated by the SPIRAL2 LINAC to the nominal energy of 33 MeV

FISSION…

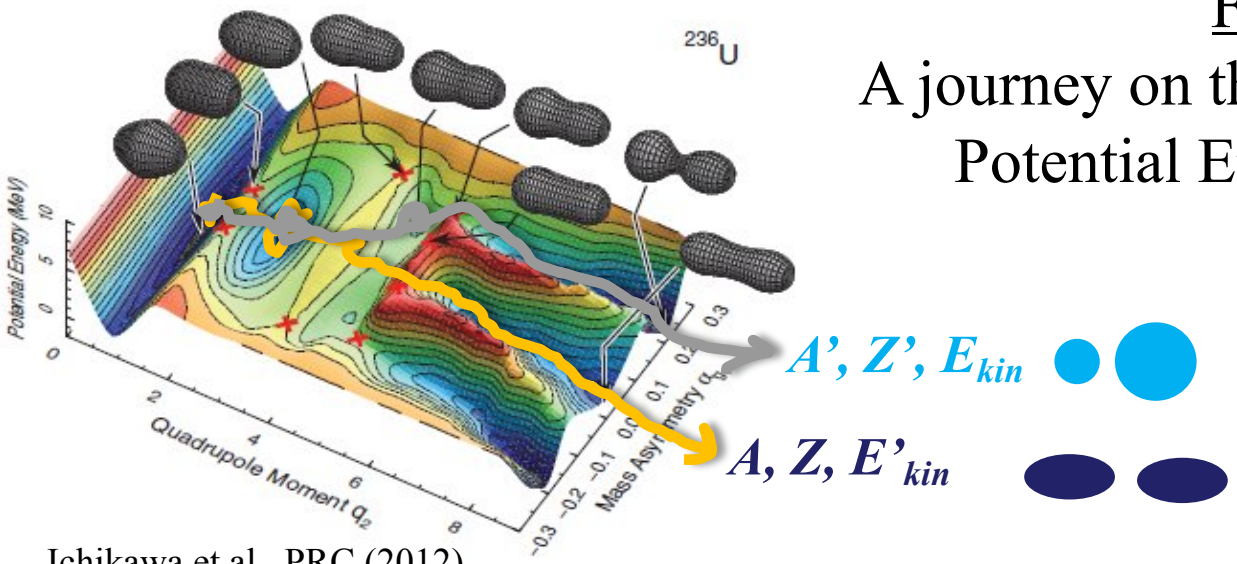


⇨ a dramatic rearrangement of nuclear structure

⇨ important for fundamental and applications (energy, isotopes for medicine,…)

⇨ low-energy fission ($E^* \lesssim 30$MeV)

Why investing effort in measuring accurately fragment (A, Z, E_{kin})



Ichikawa et al., PRC (2012)

Fission:

A journey on the fissioning nucleus Potential Energy Landscape

- ✓ Measure of (A, Z, A', Z') ☛ symmetric or asymmetric fission (~ *valleys*)
  ☛ evaporation (~ E^* *generation/release*)
- ✓ Measure of (E_{kin}, E'_{kin}) ☛ scission configuration

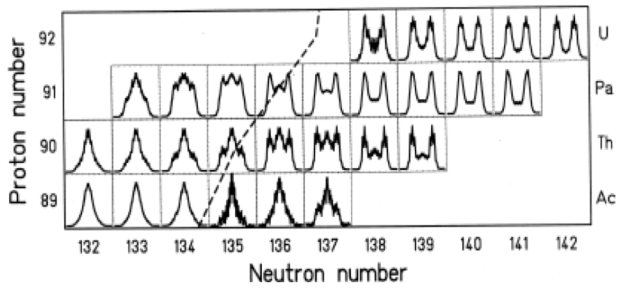
Potential Energy Landscape topography and of the dynamical evolution of the fission process

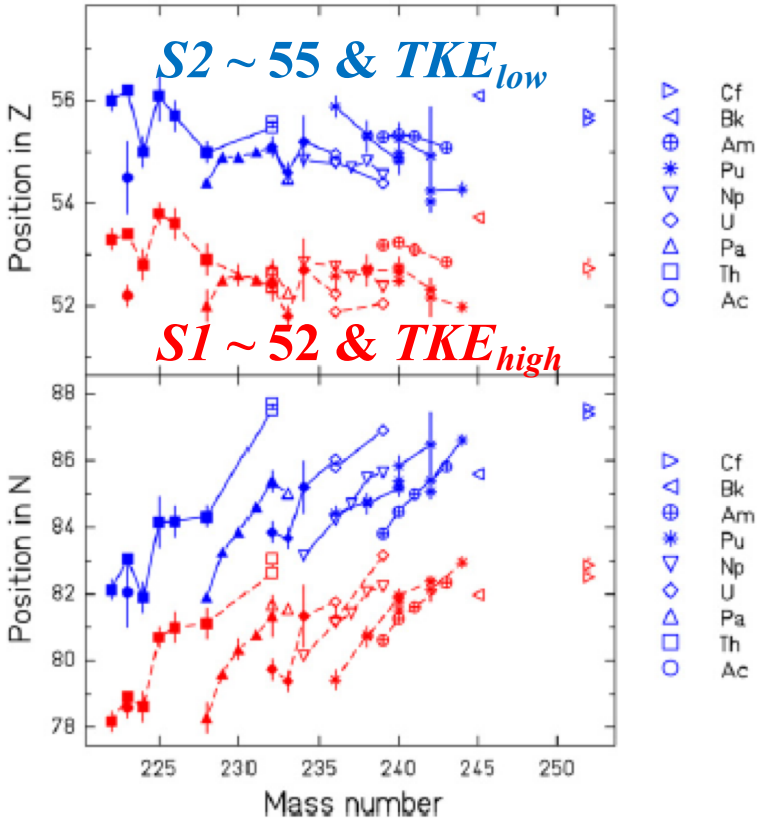
Complete and accurate *Z* distributions in 2000

K.-H.Schmidt et al., NPA (2000)

inverse kinematics + *FRS heavy-ion spectrometer*

SOFIA/ALADIN@GSI





Bockstiegel et al., NPA (2008)

⇨ **why are these *Z* favored?**
shell(s) behind?

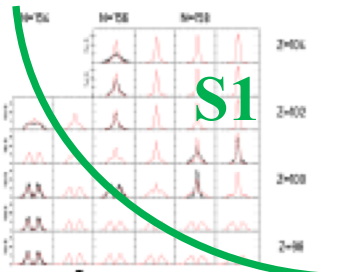
⇨ **neutron *vs.* proton role?**

Need *A* and *Z*
with unique precision

Summary of findings on A or Z distributions

- *Fragment A from different facilities/approaches*
  GEF model calculations ← ← ← ←
- ***Main trends from south-west to north-east***

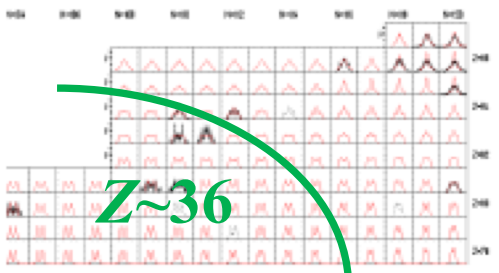
asym → sym



fermium corner

sym → asym

asym → sym

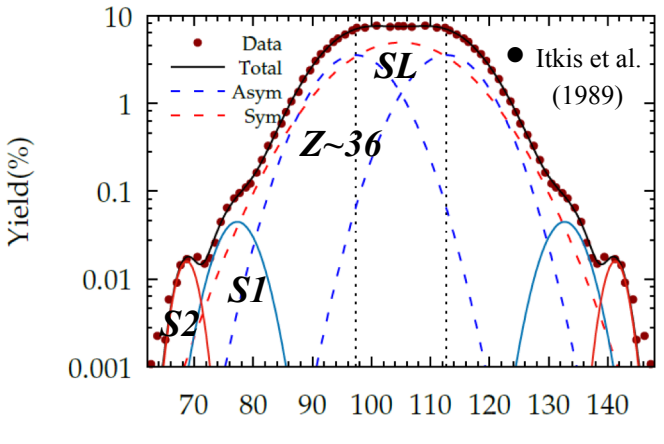


"new" preactinide area

"old" actinide region

210Po

Courtesy K. Mahata



Full control of fissioning system and its E* ?

Low-energy fission in n-deficient lead region with VAMOS@GANIL, Dec. 2017

Benefit from the assets of GANIL to go beyond current information → (A, Z)

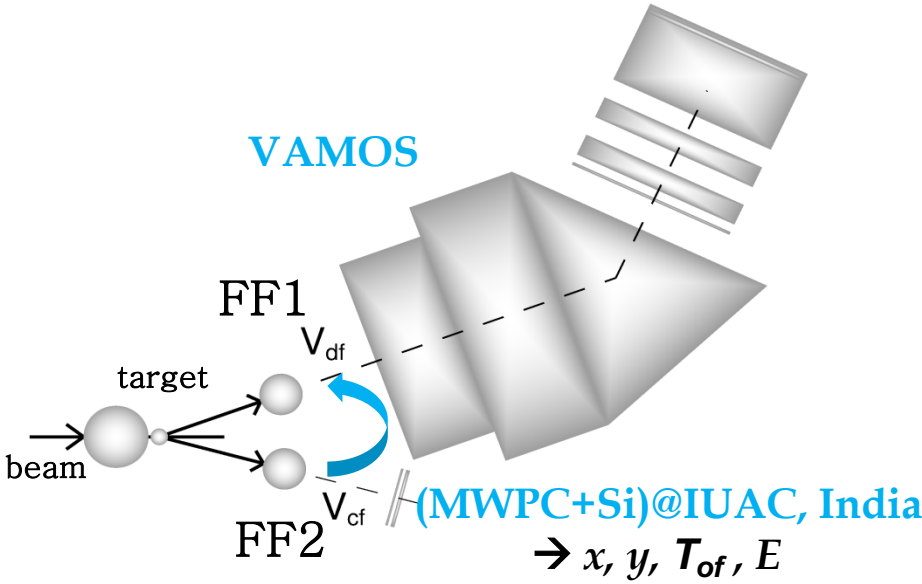
Method:

Inverse kinematics fusion-fission ^{124}Xe(4.3AMeV) + ^{54}Fe → ^{178}Hg (E^*~33MeV)

.....challenging ...“slow” (~1-3AMeV) fragments products....

Set-Up:

- **VAMOS @ 29°** for identifying one of the fragments $(A, Z, v, \vartheta, \varphi)$
- **2nd arm @ 35°** for identifying the partner $(A, v, \vartheta, \varphi)$



Innovative observables in this region:

{ unique A, Z of one fragment (→ Z of partner from $Z_{CN} - Z$)
{ v's and $TKE = E_{kin} + E'_{kin}$

First results on ^{178}Hg low-energy fission (1)

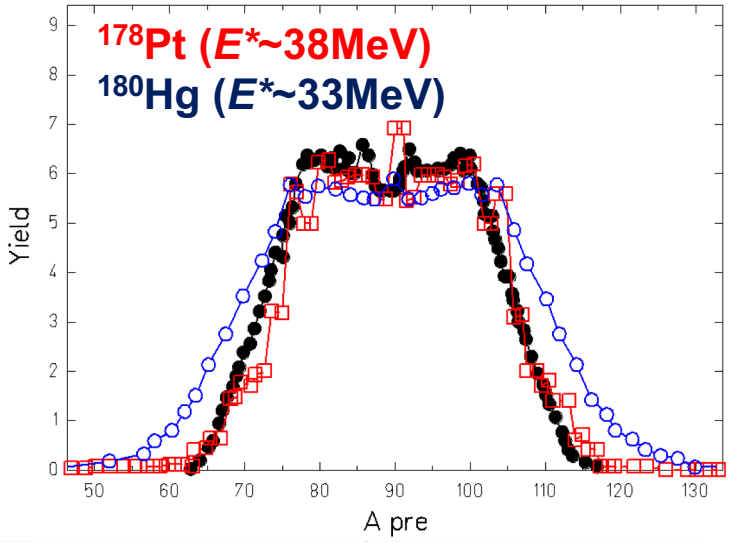
PRELIMINARY

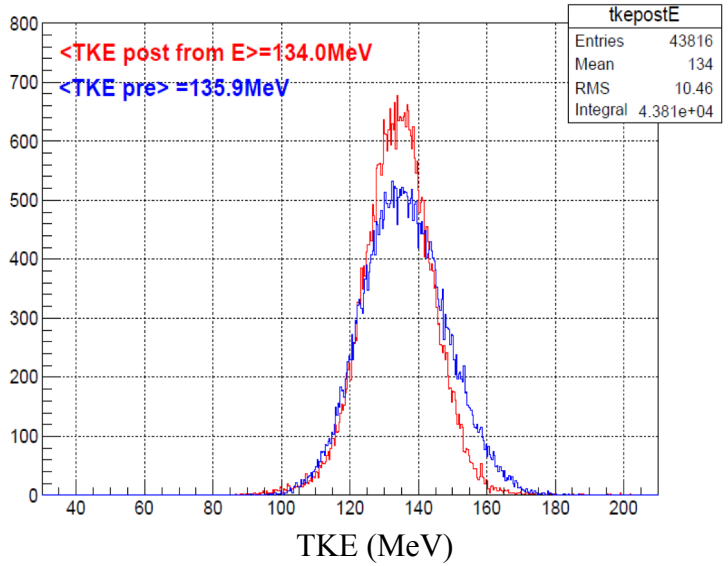
VAMOS T_{of} + Second Arm T'_{of}

→ A_{pre} **from 2*v* method**

VAMOS E_{kin} + Second Arm E'_{kin}

→ $TKE_{pre,\ post}$ **from 2*E* method**





✓ A_{pre} **indicates mixture of sym and asym fission**

✓ **Multi-fit for extracting the sym and asym properties**

✓ **Comparison with close-by systems**

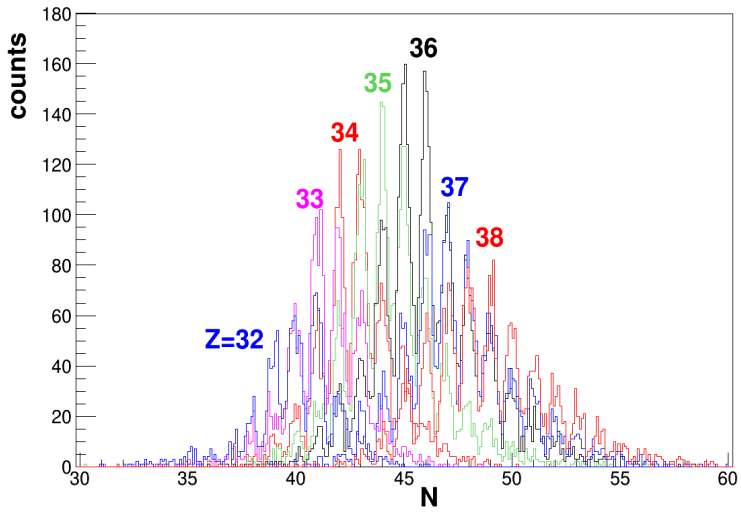
… what else ?

First results on ^{178}Hg low-energy fission (2)

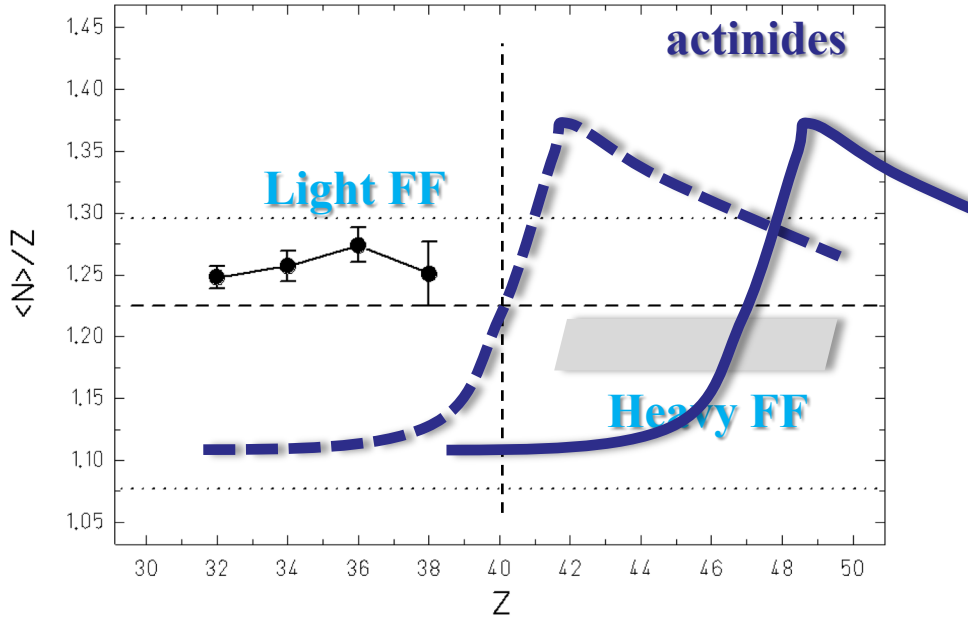
PRELIMINARY

✓ No integral high-resolution post-neutron *A* and *Z* distribution available yet

✓ Isotopic distributions for light elements



✓ <*N*>/*Z* new observable

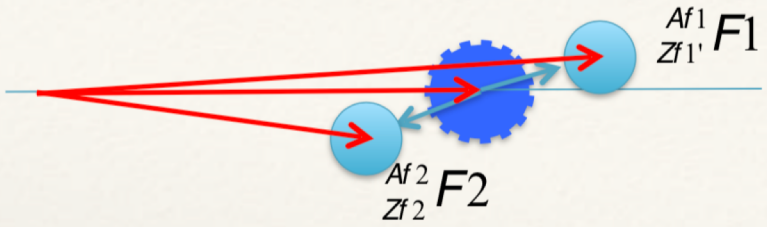


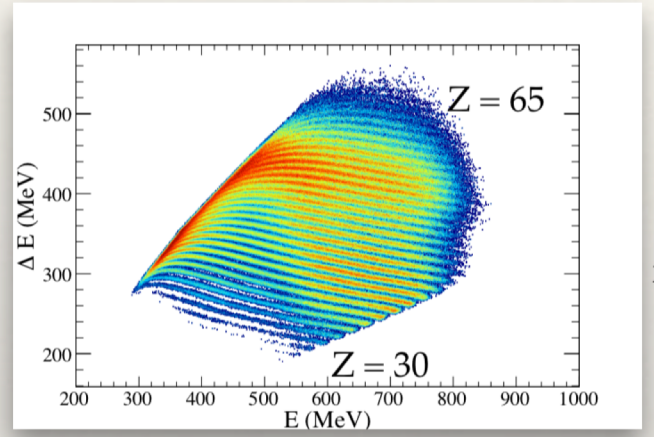
Full control of fissioning system and its E* ?

Analysis in progress

First direct measurement of isotopic fission yields of ^{239}U

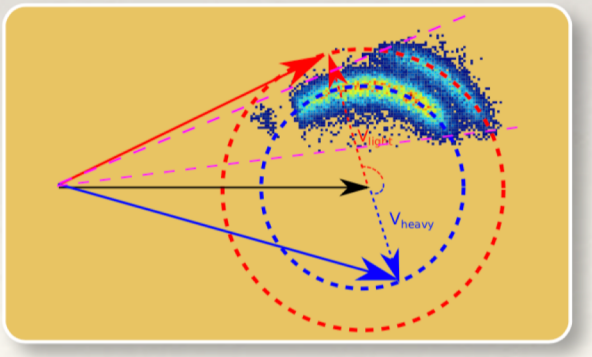
Inverse kinematics:



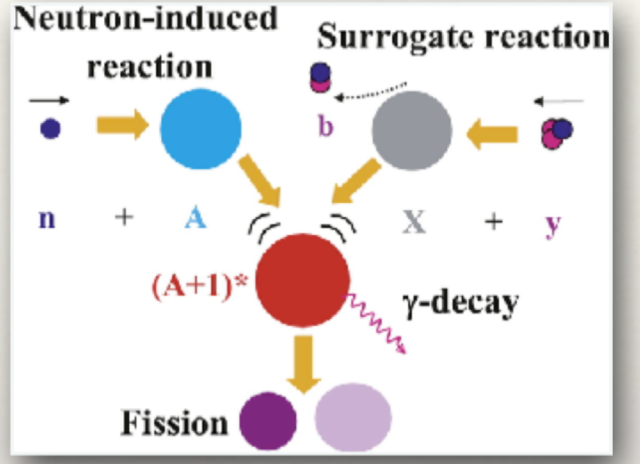


Inverse kinematics provide the capability of fission-fragments **nuclear-charge** identification

Coulomb energies provide low angular straggling and small Lorentz boost: **good velocity resolution in CM**



Surrogate reactions:



Surrogate reactions give access to **exotic fissioning systems**, impossible to produce through n-induced reactions

^{238}U (^{12}C, ^{11}B) ^{239}Np*

^{238}U (^{12}C, ^{6}He) ^{244}Cm*

Surrogate reactions permit to explore the **impact of the incoming channel** into the final fission-fragment distributions

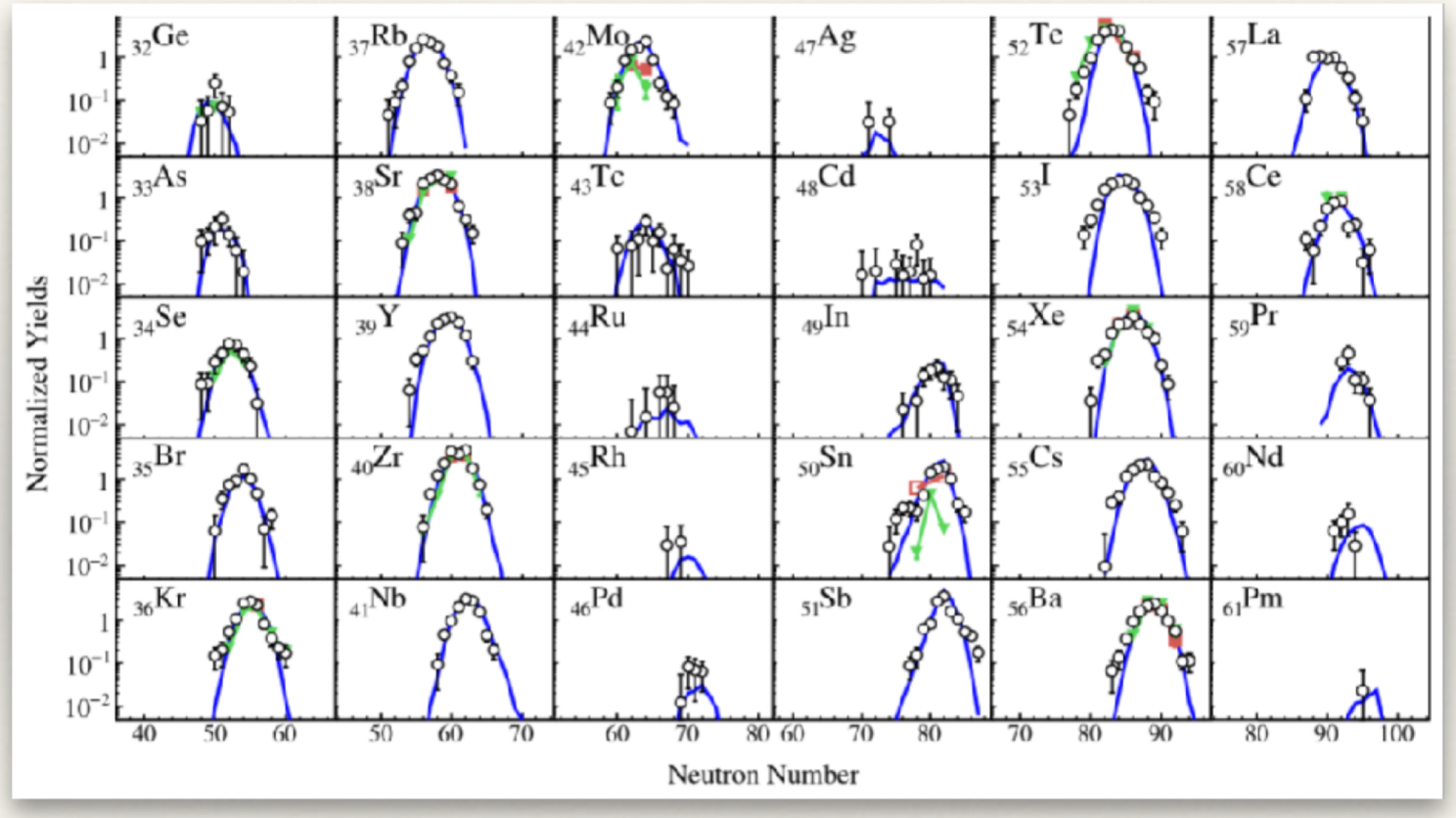
^{239}Pu(d,p) ^{240}Pu

First direct measurement of isotopic fission yields of ^{239}U

Isotopic fission yields

^{9}Be(^{238}U, ^{239}U) ^{8}Be (<Ex> = 8.3 MeV)

GEF (v. 2018/1.1)
J.N. Wilson *et al.*, Phys. Rev. Lett. 118, 222501 (2017)
N. Fotiades *et al.*, Phys. Rev. C 99, 024606 (2019)



More than 250 post-neutron-evaporation isotopes were identified

First direct measurement of the Isotopic Fragment Distribution of ^{239}U

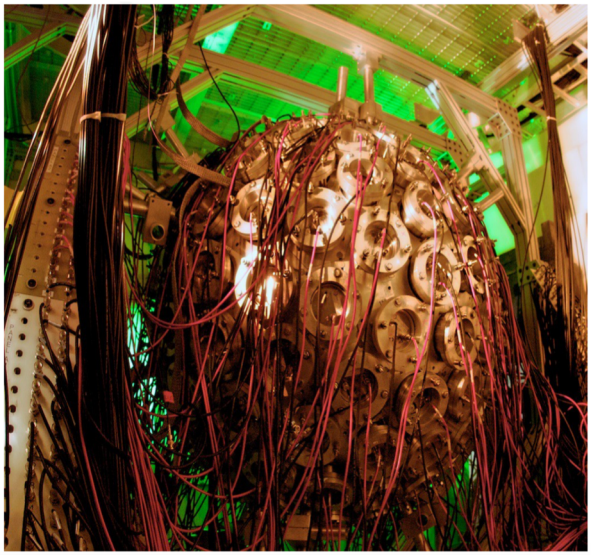
Full control of fissioning system and its E* - gamma-rays and neutrons ?

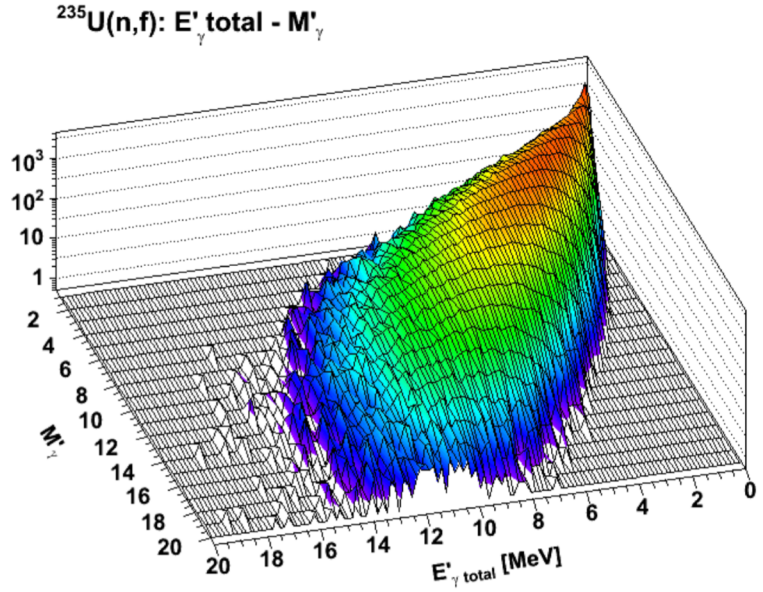
Prompt Gamma-Ray (PGR) from fission studies at Los Alamos

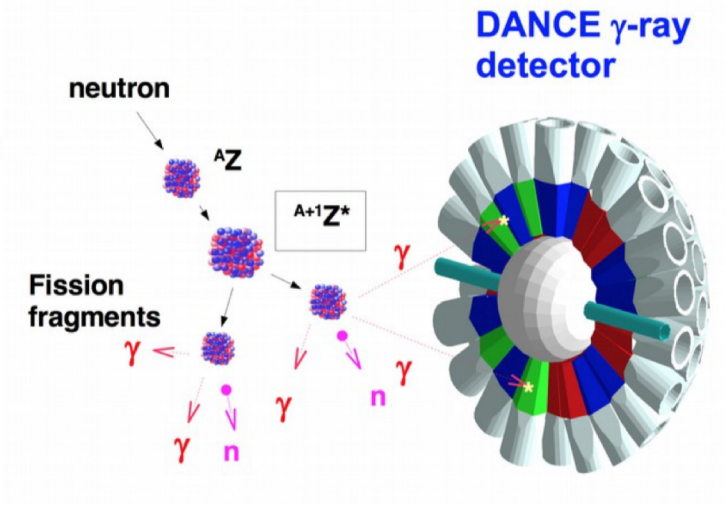
Marian Jandel et al. 2014

DANCE array + PPACs

- Large solid angle and granularity
  - 160 x BaF2 crystals in 4π geometry
  - Fast (6ns - dT), high efficiency calorimeter for γ-rays
- Digital DAQ – 324 channels
- Transition to 14bit 500 MS/s CAEN DAQ
- Neutrons, fission fragments, gamma-ray (spectroscopy)

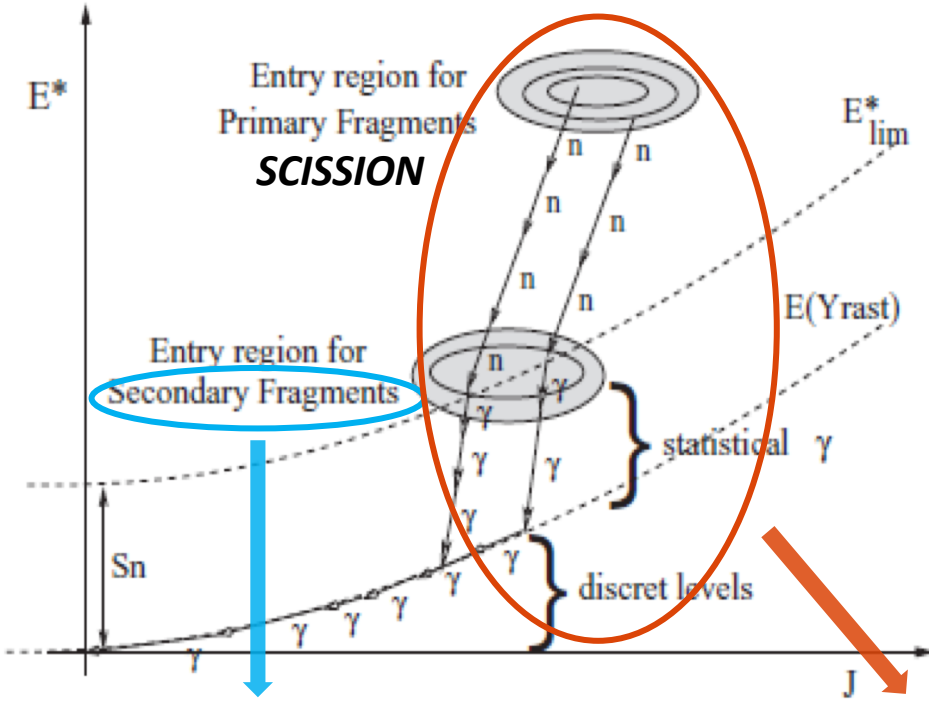






See also experiments at ALTO-LICORNE by J. N. Wilson et al.

PARIS @ VAMOS for fission (2021 onwards)



At scission : Excited rotating FF's

→ E^* released by n and statistical γ rays

→ L released by discrete γ's along yrast

Study n/γ competition to learn about:

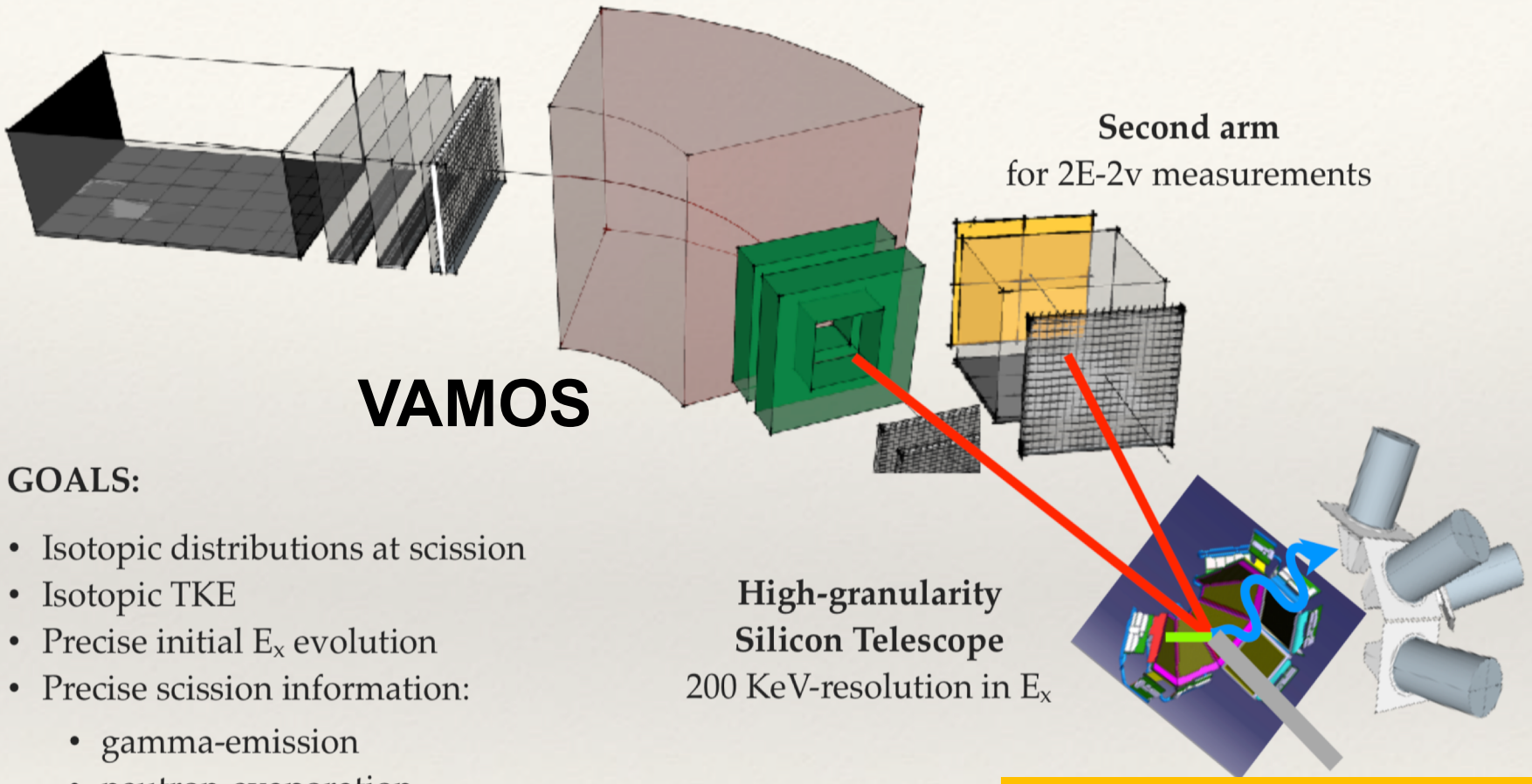
- **E* sharing at scission**
- **L generation at scission and sharing**
- **GDR vs. n decay-width**
- **γ-ray heating (applications)**

VAMOS: angle, velocity and $(A,Z)_{FF}$ identification + **PARIS: M_γ and E_γ spectrum up ~30MeV** + **GANIL Heavy beams** = **Unique Tool**

☞ **Challenge: measure M_γ and E_γ as a function of $(A,Z)_{FF}$**

☞ **Development of theoretical models**

Close to ideal setup



PARIS @ VAMOS for fission (2021 onwards)

VAMOS: angle, velocity and $(A,Z)_{FF}$ identification + **PARIS: M_γ and E_γ spectrum up ~30MeV** + **GANIL Heavy beams** = **Unique Tool**

- ☞ **Challenge: measure M_γ and E_γ as a function of $(A,Z)_{FF}$**
- ☞ **Controversial / no consistent models available**

Necessary Conditions:

- **≥ 8 PARIS clusters at < 35 cm from target (+ big $LaBr_3$?)**
- **Dedicated mechanics and full integration of electronics**
- **High statistics –> important beamtime request**

Interesting options:

- **Neutrons measured with PARIS ? – promising preliminary results**
- **Coupling with EXOGAM ?**

→ Simulations next year by M. Ciemala & Co.

Thank you for your attention