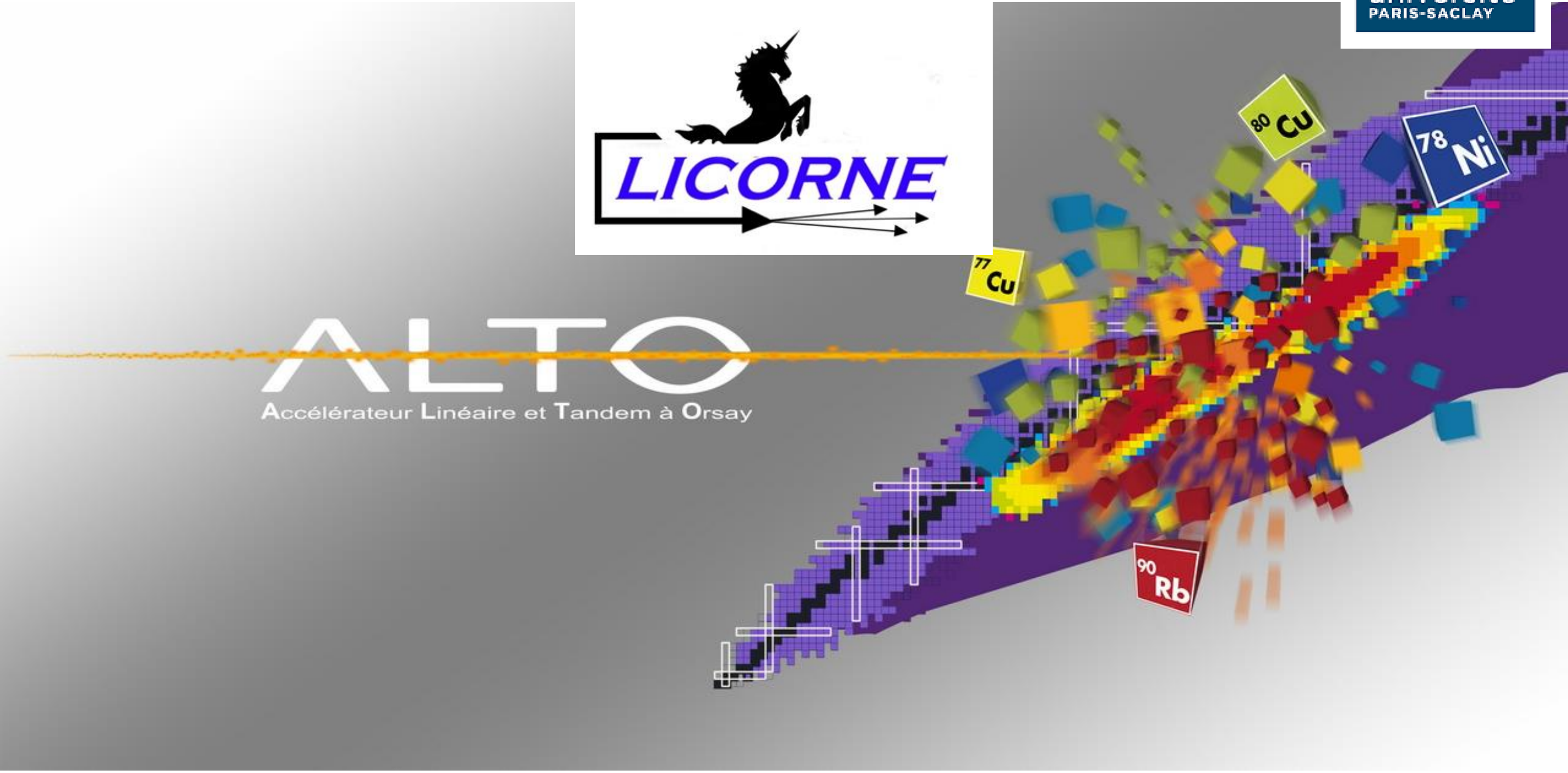
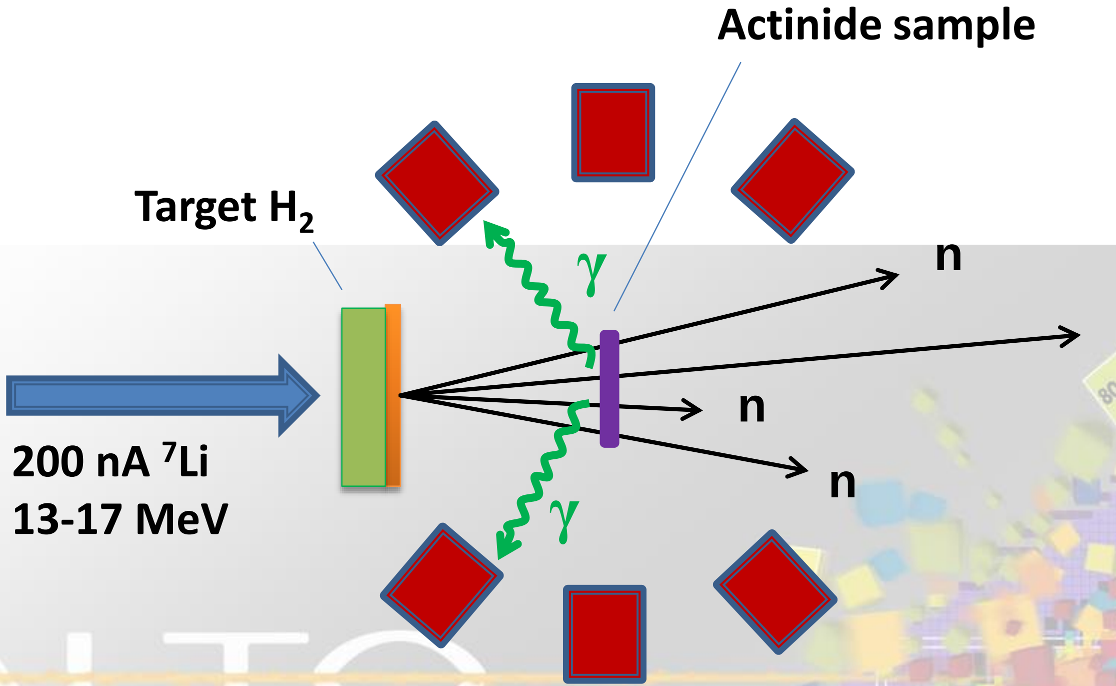
Highlights of the LICORNE physics program and prospects for future experiments at NFS

Jonathan Wilson, Matthieu Lebois, Liqiang Qi
IPN Orsay



LICORNE: Neutron production in inverse kinematics



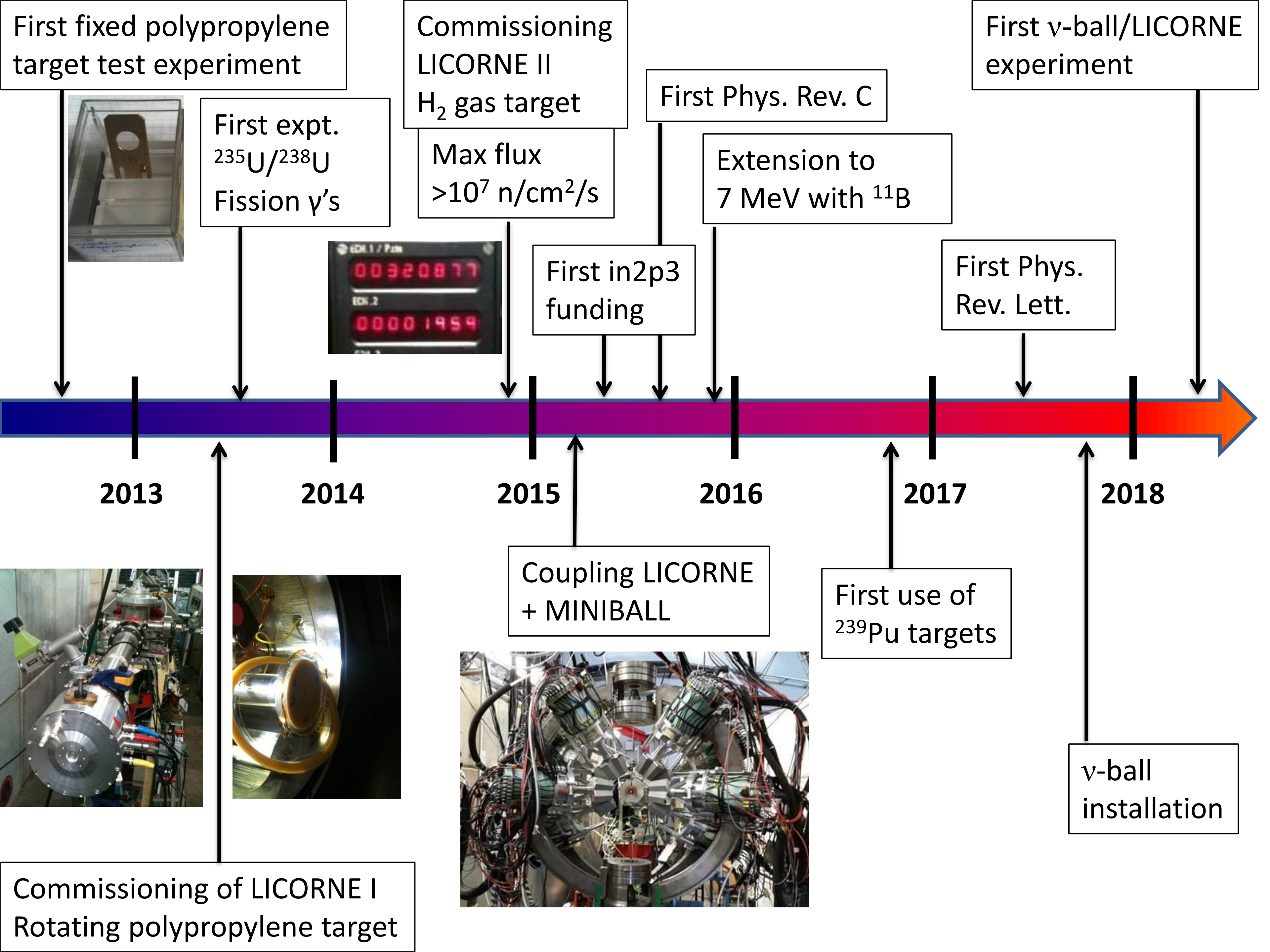
Lithium Inverse Cinematiques ORsay NEutron source

- reaction $p(^7Li,^7Be)n$ using inverse kinematics
- Source of fast focused neutrons (between 0.5 and 4 MeV)
- NATURAL DIRECTIONALITY AND HIGH FLUX: 10^7 $n/cm^2/s$ on target

LICORNE II

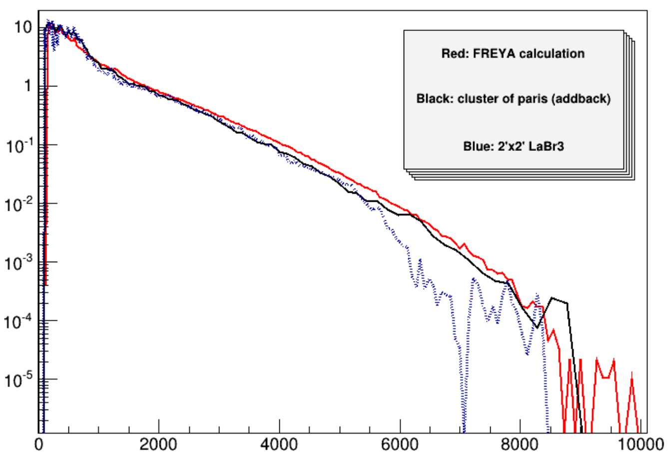
H_2 pressure and flow control system
+ automatic shutdown

Hydrogen gas cells

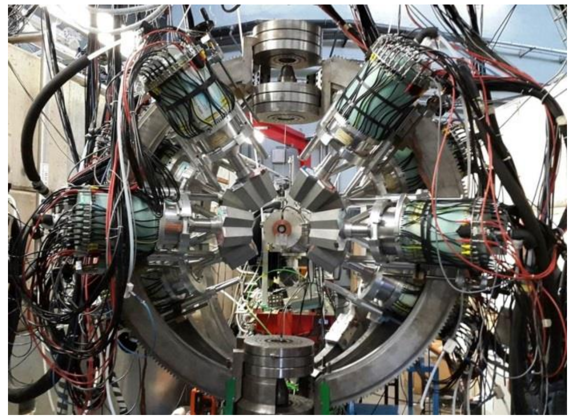

First fixed polypropylene target test experiment
First expt. $^{235}U/^{238}U$ Fission γ's
Commissioning LICORNE II H_2 gas target
Max flux $>10^7$ n/cm^2/s
First in2p3 funding
First Phys. Rev. C
Extension to 7 MeV with ^{11}B
First Phys. Rev. Lett.
First ν-ball/LICORNE experiment
2013
2014
2015
2016
2017
2018
Commissioning of LICORNE I Rotating polypropylene target
Coupling LICORNE + MINIBALL
First use of ^{239}Pu targets
ν-ball installation

The LICORNE Physics Program

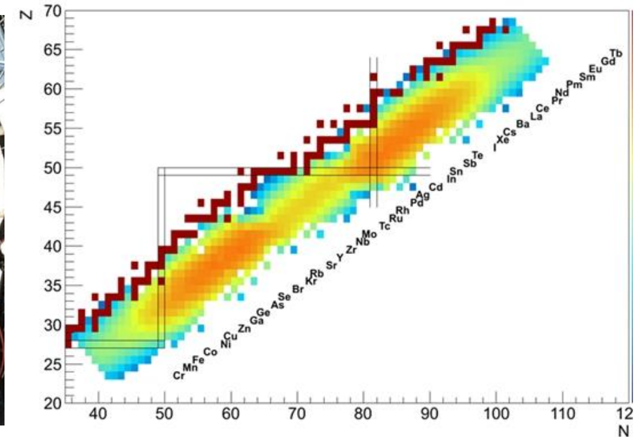
Prompt fission γ spectra characteristics



Procduction/Study of exotic nuclei

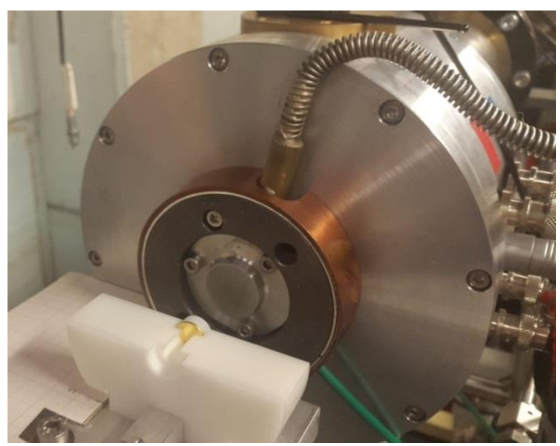


Fission yield measurements via γ-ray spectroscoopy

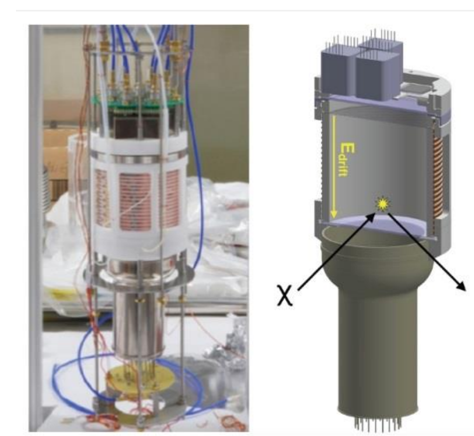


Fast Neutron Tomograpahy

Irradiations for Geochronology (x-section measurements)



Dark Matter TPC characterisation



LICORNE Publications (2013-2017)

14) Studies of fission fragment yields via high-resolution γ-ray spectroscopy
J.N. Wilson, M. Lebois, L. Qi, et al., Proceedings of the Theory-4 international workshop, Varna, Bulgaria (2017)
13) Neutron-rich isotopes from 238U(n,f) and 232Th(n,f) studied with the nu-ball spectrometer coupled to the LICORNE neutron source
J.N. Wilson, M. Lebois , and L. Qi, Proceedings of the FISSION-2017 international conference, Chamrousse (2017)
12) Anomalies in the charge yields of fission fragments from the 238U(n,f) reaction
J.N. Wilson, M. Lebois, L. Qi et al.,, Phys. Rev. Lett. 118, 222501 (2017)
11) Production and study of neutron-rich nuclei using the LICORNE directional neutron source
J.N. Wilson, M. Lebois, L. Qi et al., Proceedings of the Zakopane international conference, Acta Physica Polonica B Vol.48 395 (2017)
10) Studies of γ-ray emission in the fission process with LICORNE
M. Lebois, J.N. Wilson, et. al , Proceedings of the CNR*15 international conference , EPJ Web of Conferences 122, 01010 (2016)
9) Comparative measurement of prompt fission gamma-ray emission from fast neutron induced fission of 235U and 238U
M. Lebois, J.N. Wilson, et al, Phys. Rev. C 92 034 618 (2015)
8) Prompt Emission in Fission Induced with Fast Neutrons
J.N. Wilson, M. Lebois, P. Halipré, S. Oberstedt, A. Oberstedt, Physics Procedia, Volume 64, Pages 107–113 (2015)
7) Future research program on prompt gamma-ray emission in nuclear fission
S. Oberstedt, R. Billnert, F. -J. Hambsch, M. Lebois, A. Oberstedt and J. N. Wilson , Eur. Phys. J. A, 51 12 (2015) 178
6) Development of a kinematically focused neutron source with the p(7Li,n)7Be inverse reaction
M. Lebois, J.N. Wilson, P. Halipre, B. Leniau, I. Matea, A. Oberstedt, S. Oberstedt, D. Verney, Nucl. Instrum. Meth. A 735 46 (2014)
5) The LICORNE neutron source and measurements of prompt gamma rays emitted in fission
J.N. Wilson, M. Lebois, et al., Proceedings GAMMA-2 International Workshop, Sremski Karlovci, Serbia (2013)
4) Prompt fission gamma-rays from fast neutron-induced fission of 238U, 232Th and 235U with LICORNE
M. Lebois, J.N. Wilson et al., Proceedings GAMMA-2 International Workshop, Sremski Karlovci, Serbia (2013)
3) Measurements of prompt gamma-rays from fast-neutron induced fission with the LICORNE directional neutron source
J.N. Wilson, M. Lebois, P. Halipre, A. Oberstedt, S. Oberstedt, Proceedings of the final ERINDA meeting, CERN, Geneva (2013)
2) The LICORNE neutron source
J.N. Wilson, M. Lebois et al., Proceedings of the International Conference, FISSION2013, Caen, France (2013)
1) Nuclear Research with Quasi Mono-Energetic Neutrons at the IPNO LICORNE Facility
S. Oberstedt, J.N. Wilson, R. Billnert, G. Georgiev, P. Halipre, M. Lebois, B. Leniau, J. Ljungvall, I. Matea, A. Oberstedt, D. Verney, International Atomic Energy Agency (IAEA), Proceedings technical meeting IAEA-F1-TM-42752 (2013)

95 users from 34 different institutions in 13 different countries

LICORNE Highlights

γ-ray spectroscopy of the most neutron rich nuclei

Higher spin states of very neutron-rich nuclei?

In-flight

e.g. RIKEN - Big Rips separator + DALI2 spectrometer
Reaction: $^{9}Be(^{238}U,f)$ @ 345 MeV/a
Complete A,Z selectivity
Very high v/c: Extreme Doppler broadening of in-beam fragment γ-decay
➢ Decays from high spin states are thus very difficult to measure

ISOL

e.g. Isolde – Miniball spectrometer
Reaction: $^{238}U(p,f)$ @ 600 MeV
Complete A,Z selectivity
➢ γ-spectroscopy after beta-decay : High spin states not populated

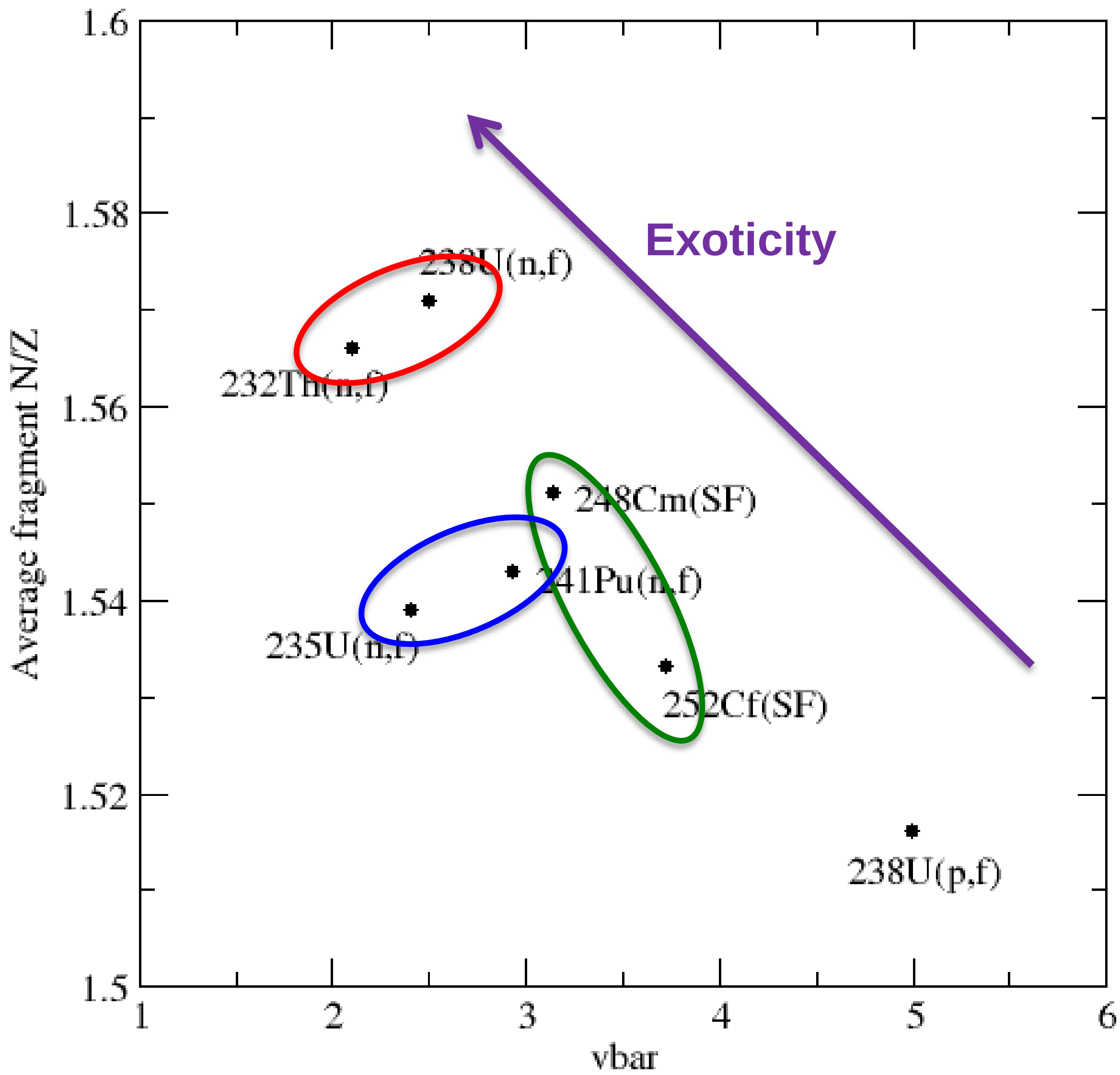
<u>Limited possibilities for access to information on higher spin states of very neutron-rich nuclei</u>

Exotic Nuclei Production/Study from Fission Reactions

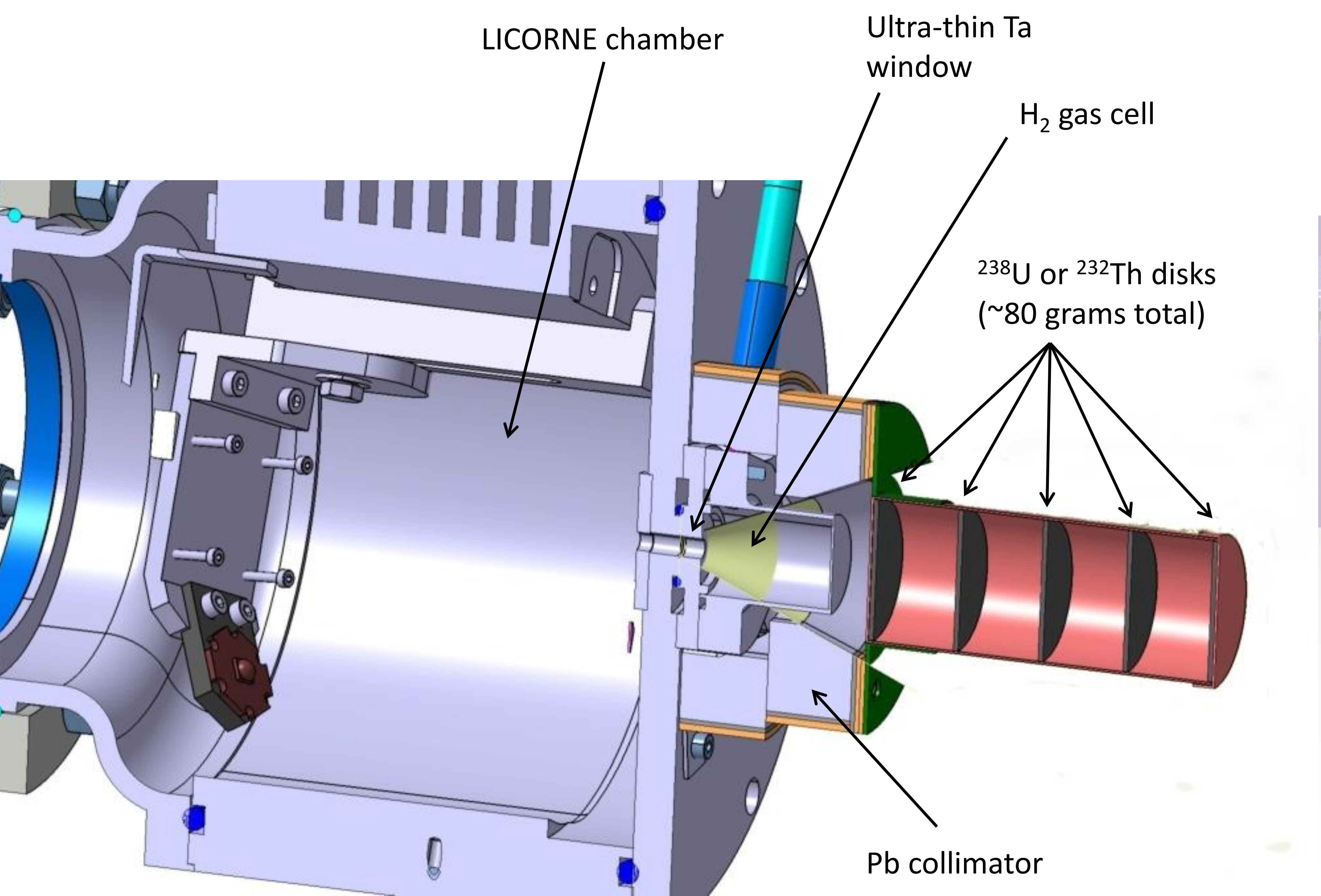
Spontaneous Fission
^{252}Cf(SF), ^{248}Cm(SF)
(Gammasphere, Euroball)

Fission induced by thermal neutrons
^{235}U(n_{th},f) ^{241}Pu(n_{th},f)
(EXILL Exogam@ILL)

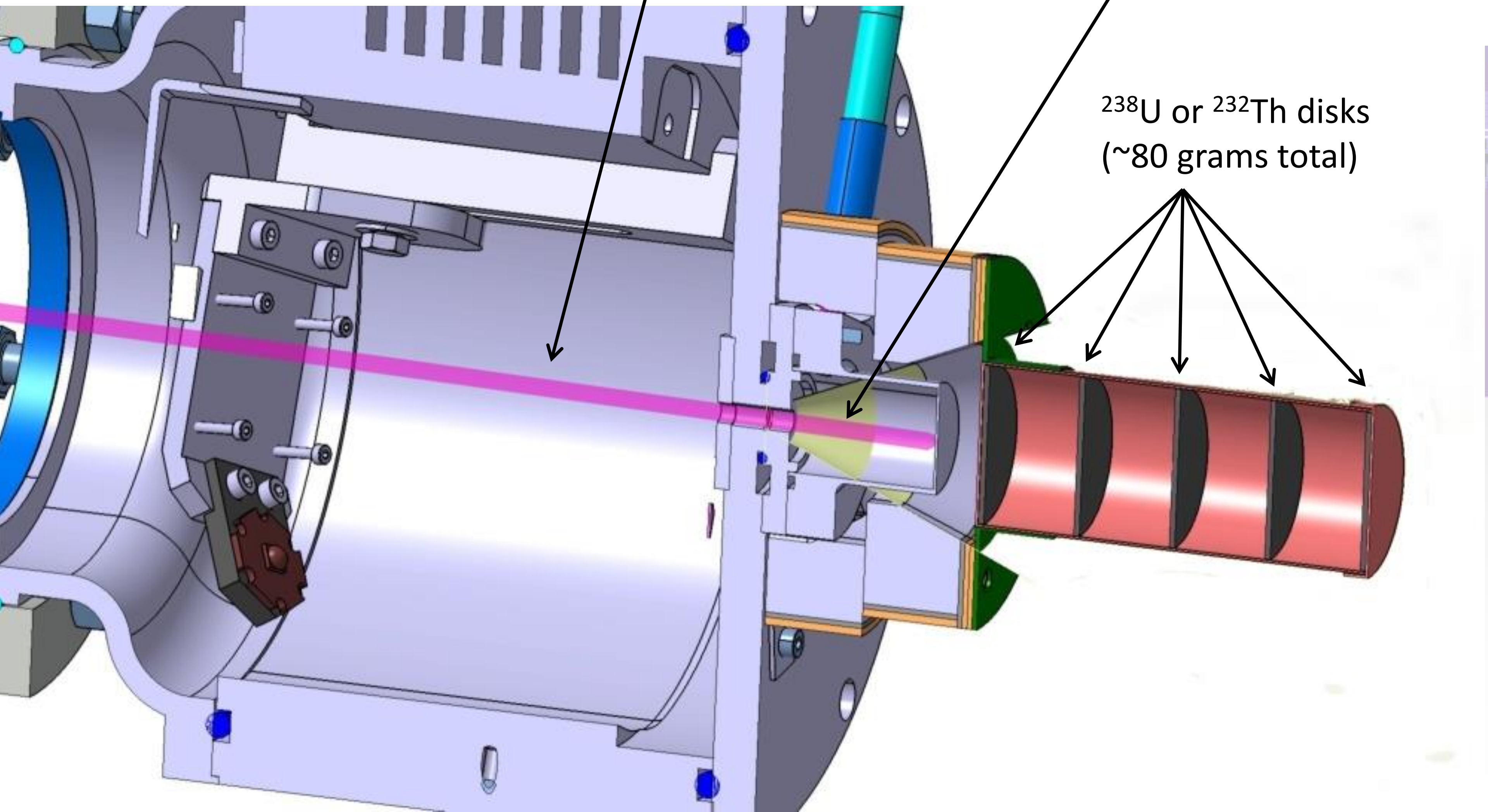
Fission induced by fast ~2 MeV neutrons
^{238}U(n,f), ^{232}Th(n,f)
(LICORNE @ IPN Orsay)



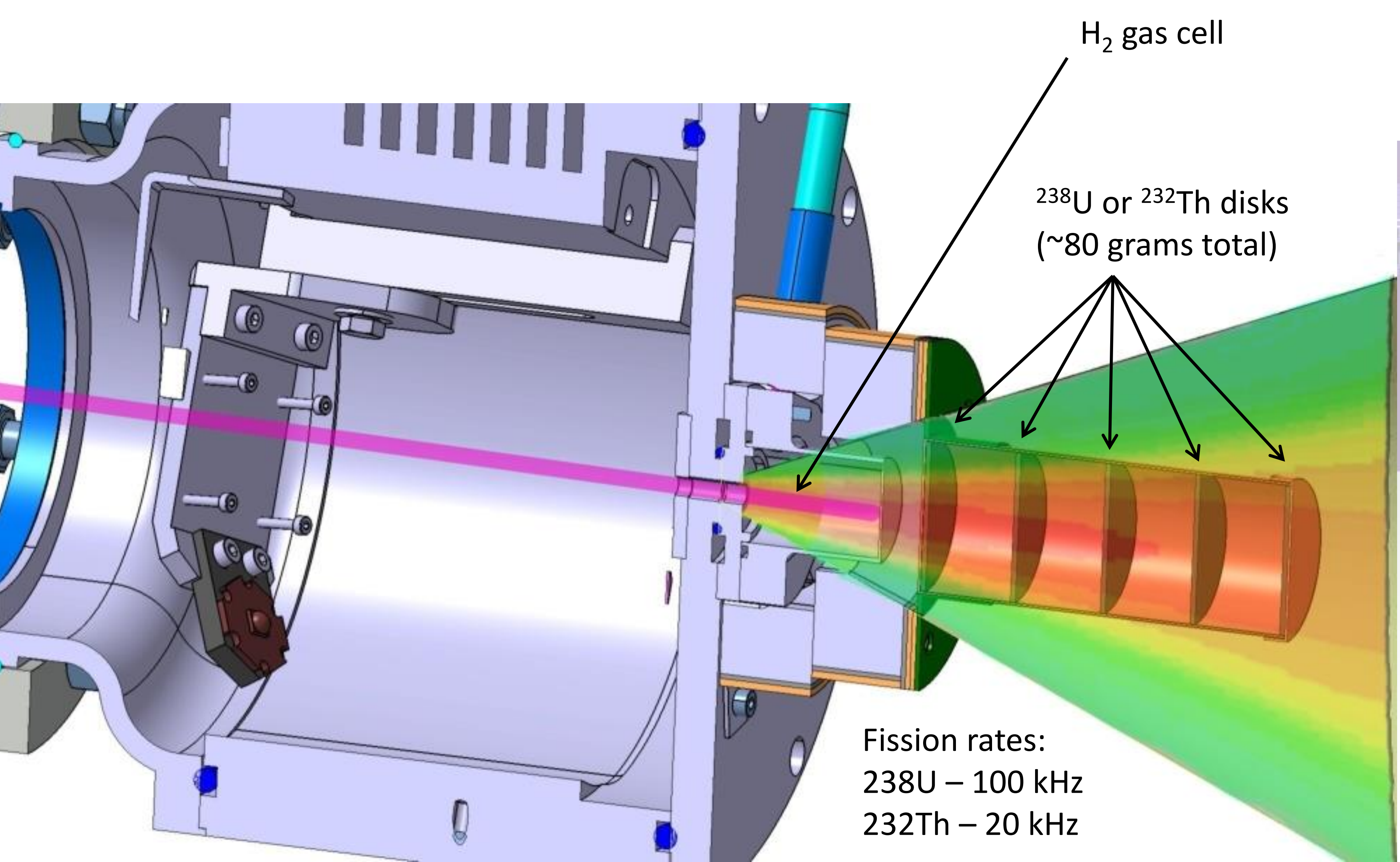
LICORNE/ν-ball concept



LICORNE/ν-ball concept

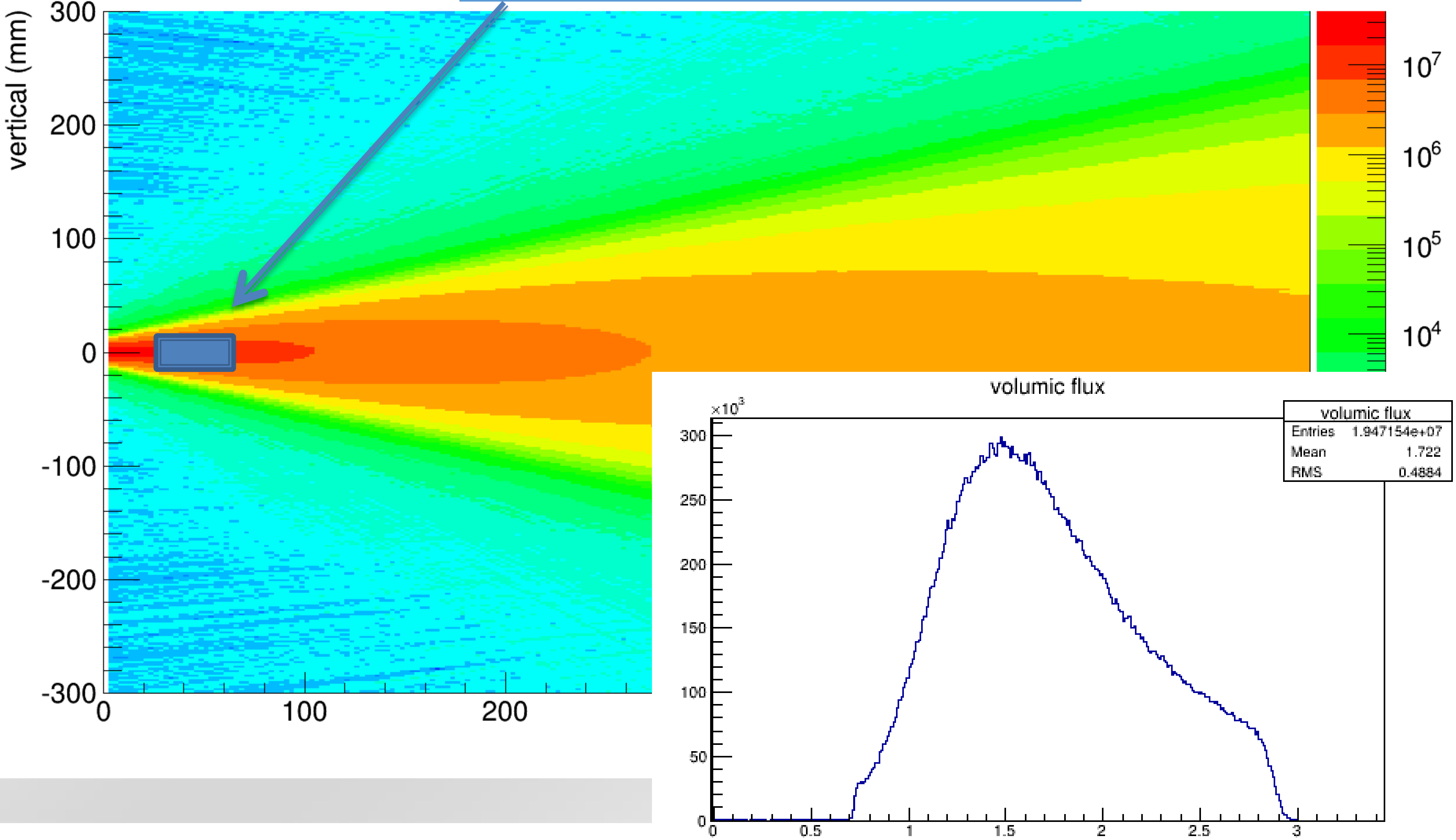


LICORNE/ν-ball concept

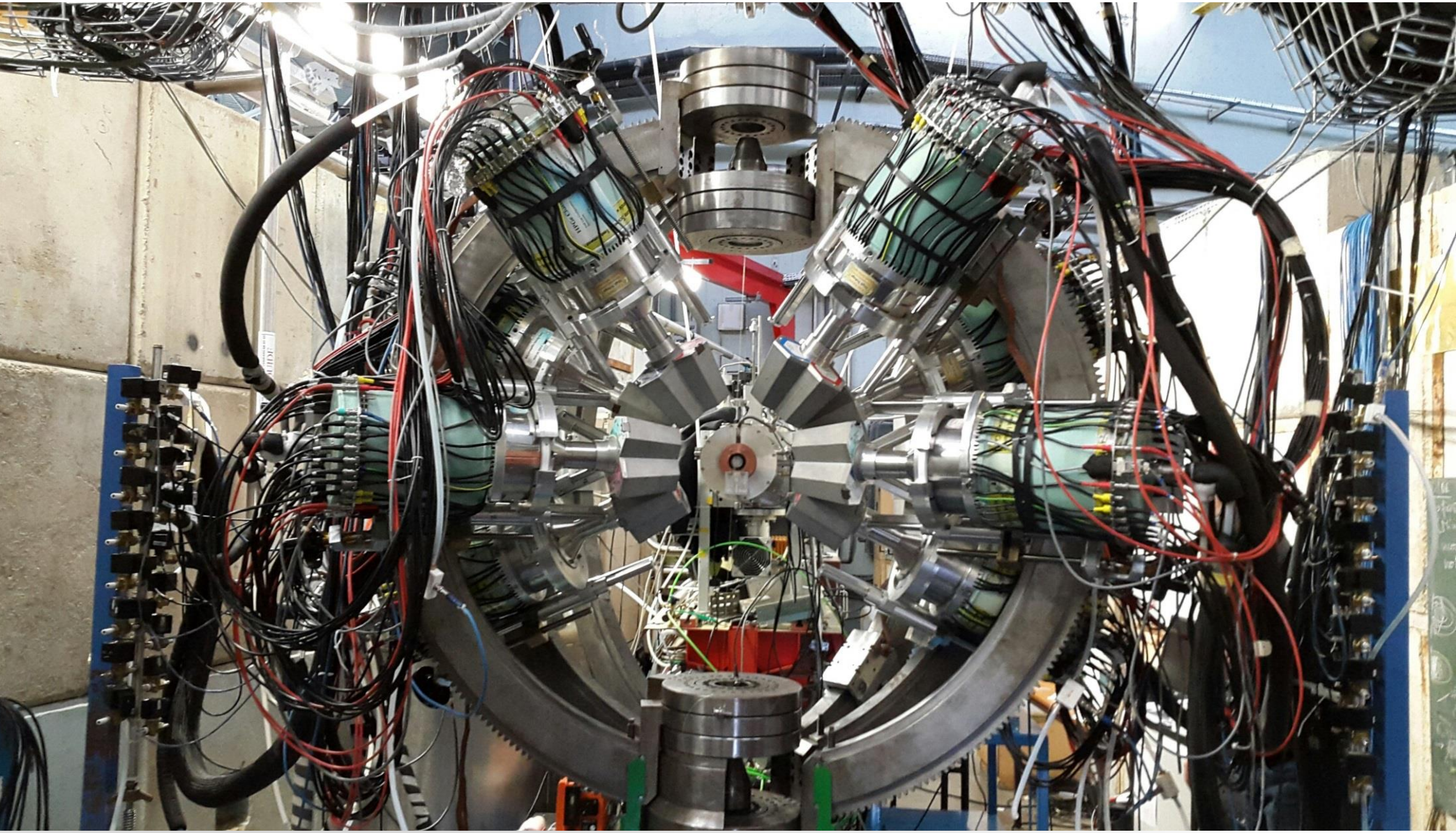


Achievable Fission Rates

~100 kHz fission rate for $^{238}U(n,f)$
~20 kHz fission rate for $^{232}Th(n,f)$



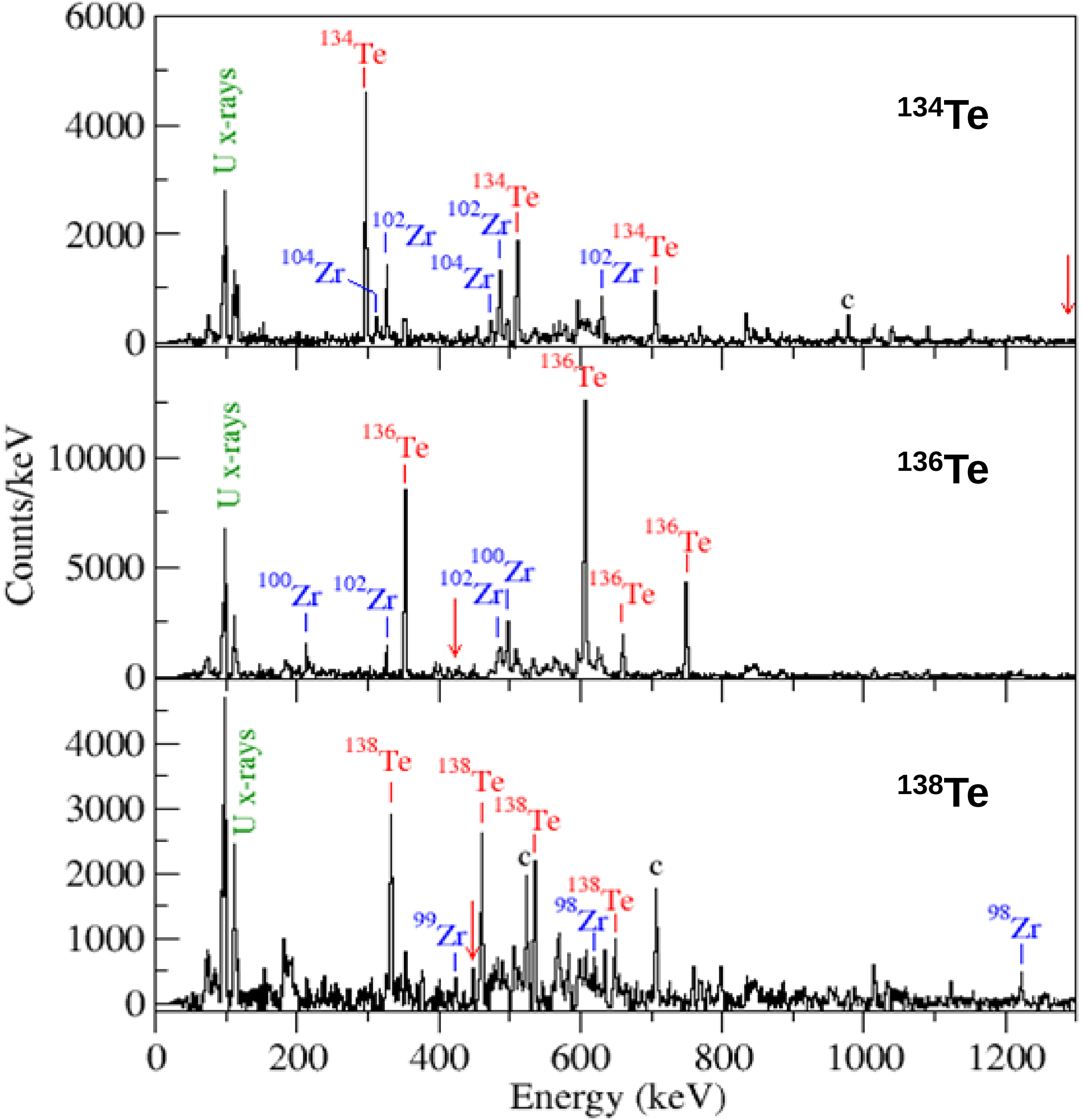
Coupling of LICORNE + MINIBALL (2015)



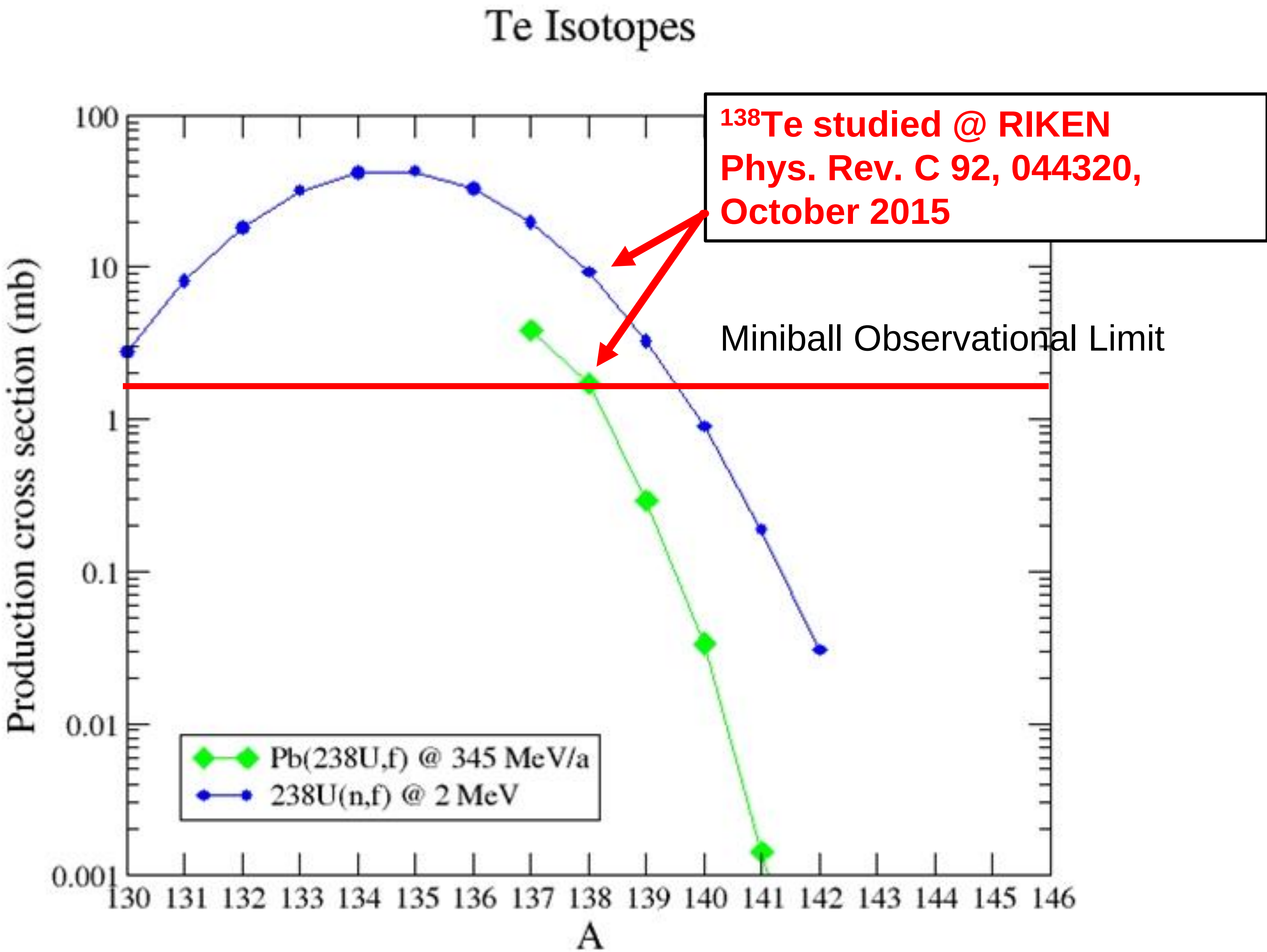
Coupling of LICORNE+MINIBALL (2015)

11 days of effective beam time: ~ 3 × 10^9 events with M_γ >= 3

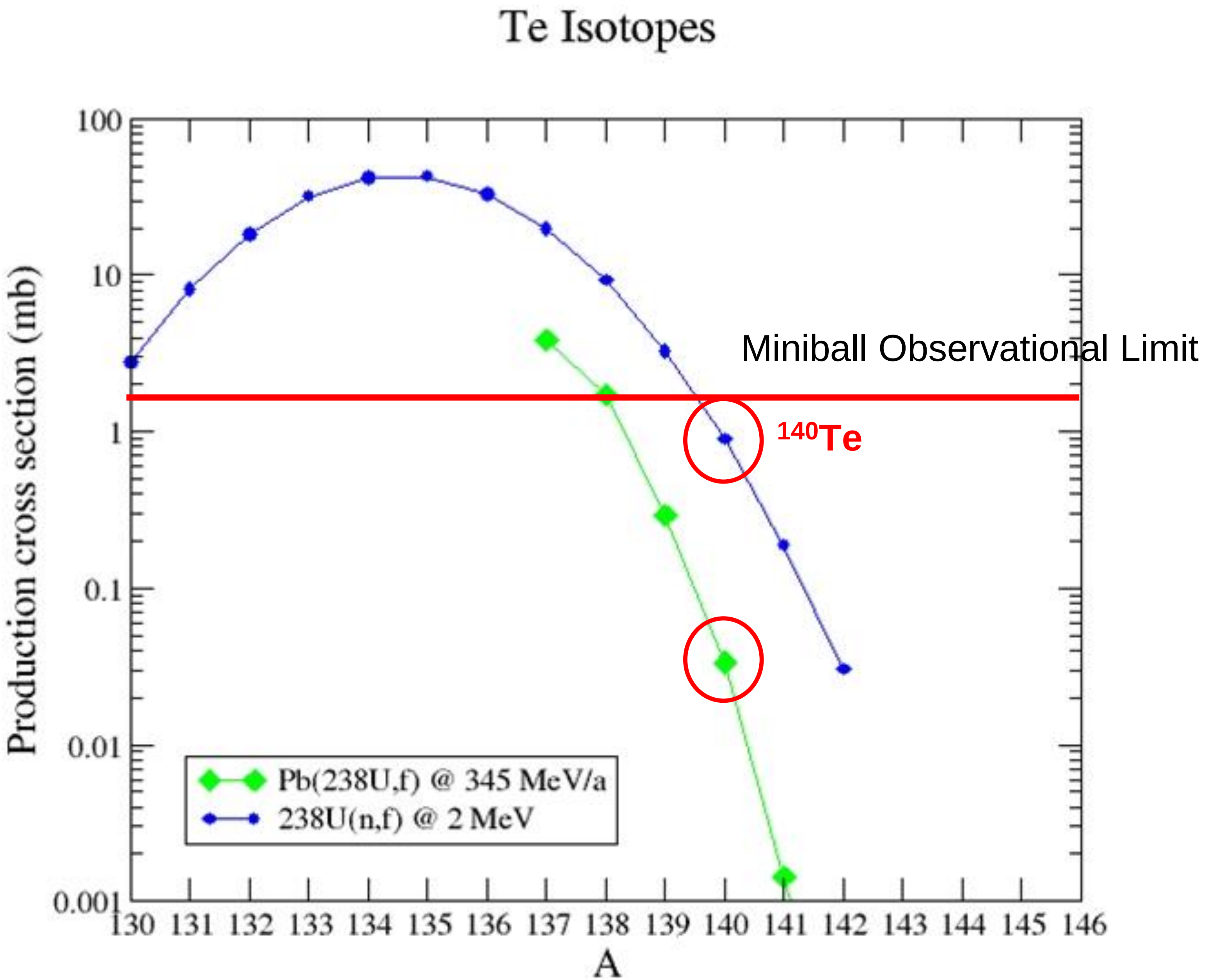
How far from stability can we get?



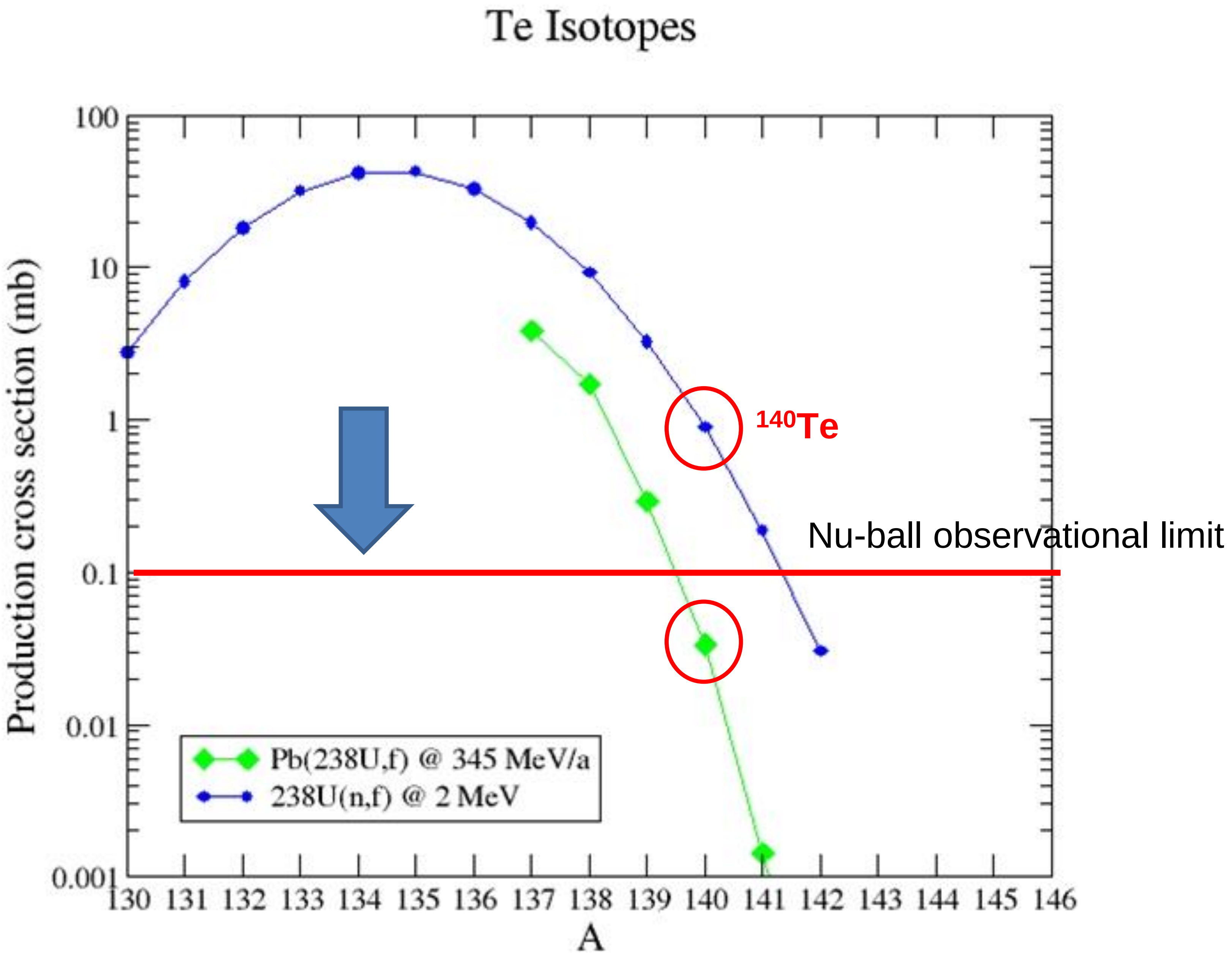
How far from stability can we get?



How far from stability can we get?

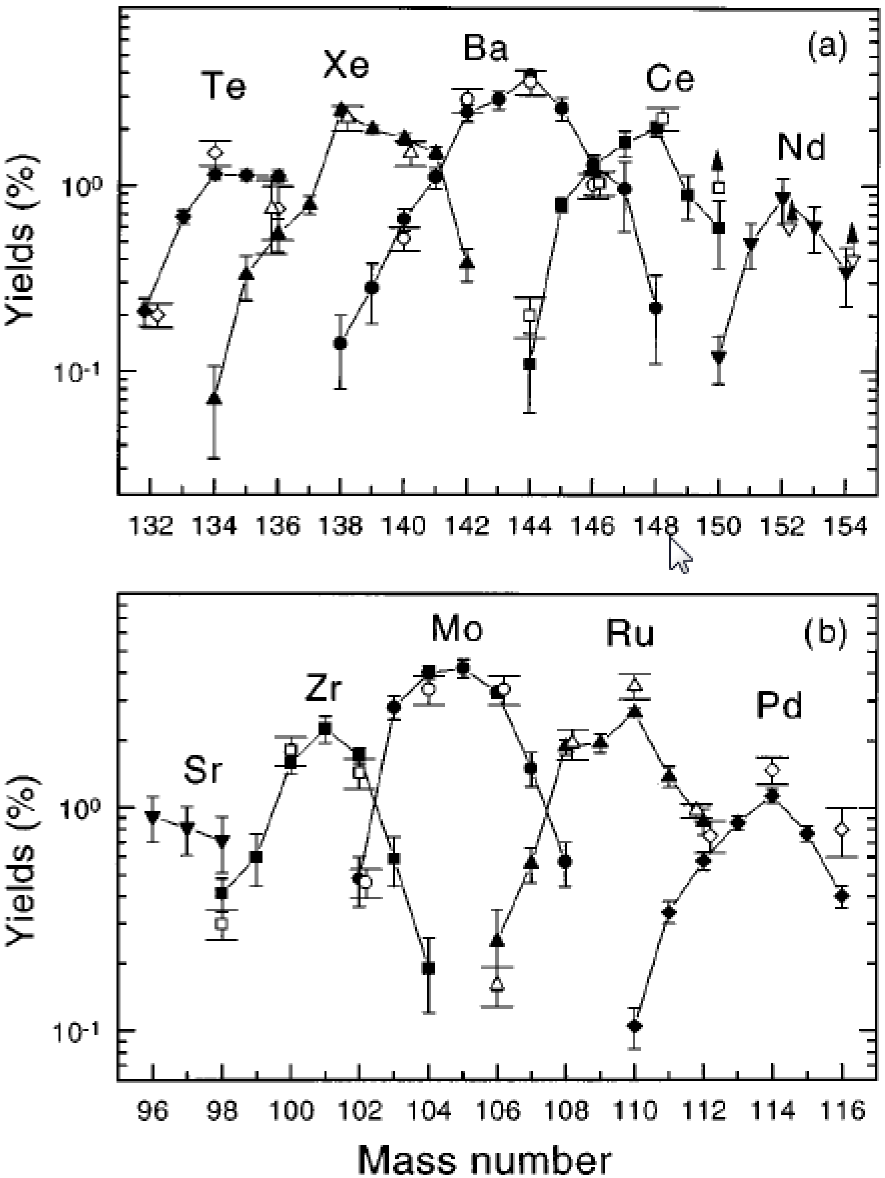


How far from stability can we get?

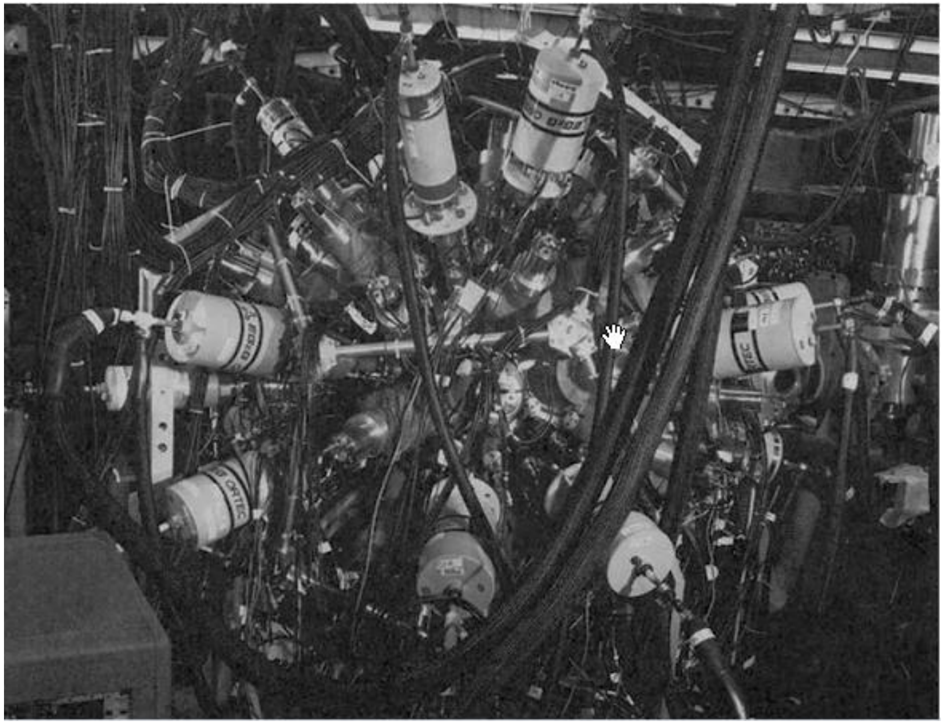


Fission Yield measurements via γ-ray spectroscopy

Fission Yield Measurements of ^{252}Cf(SF)

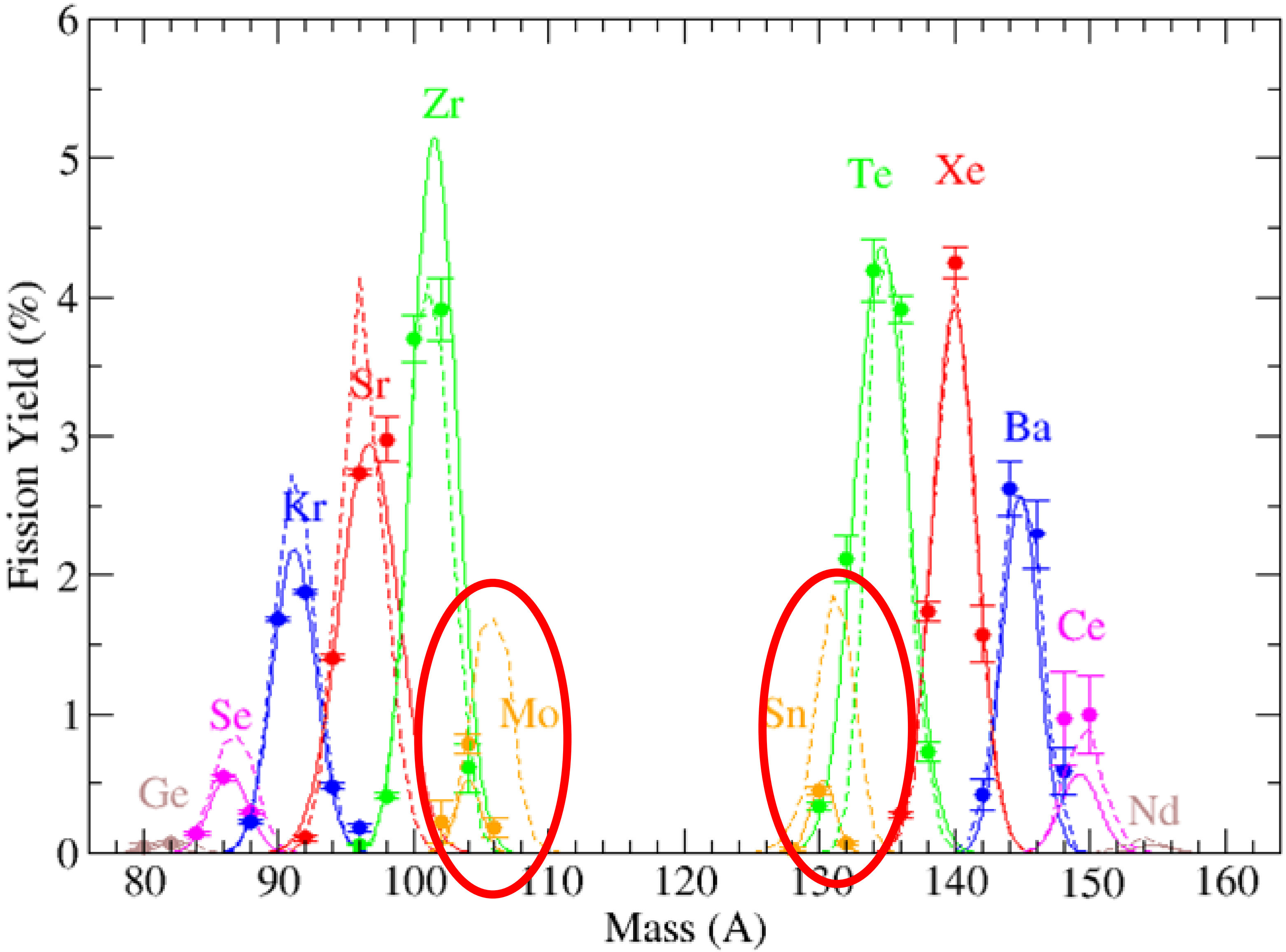


G.M. Ter-Akopian *et al.*
Phys. Rev. C55 3 (1997)



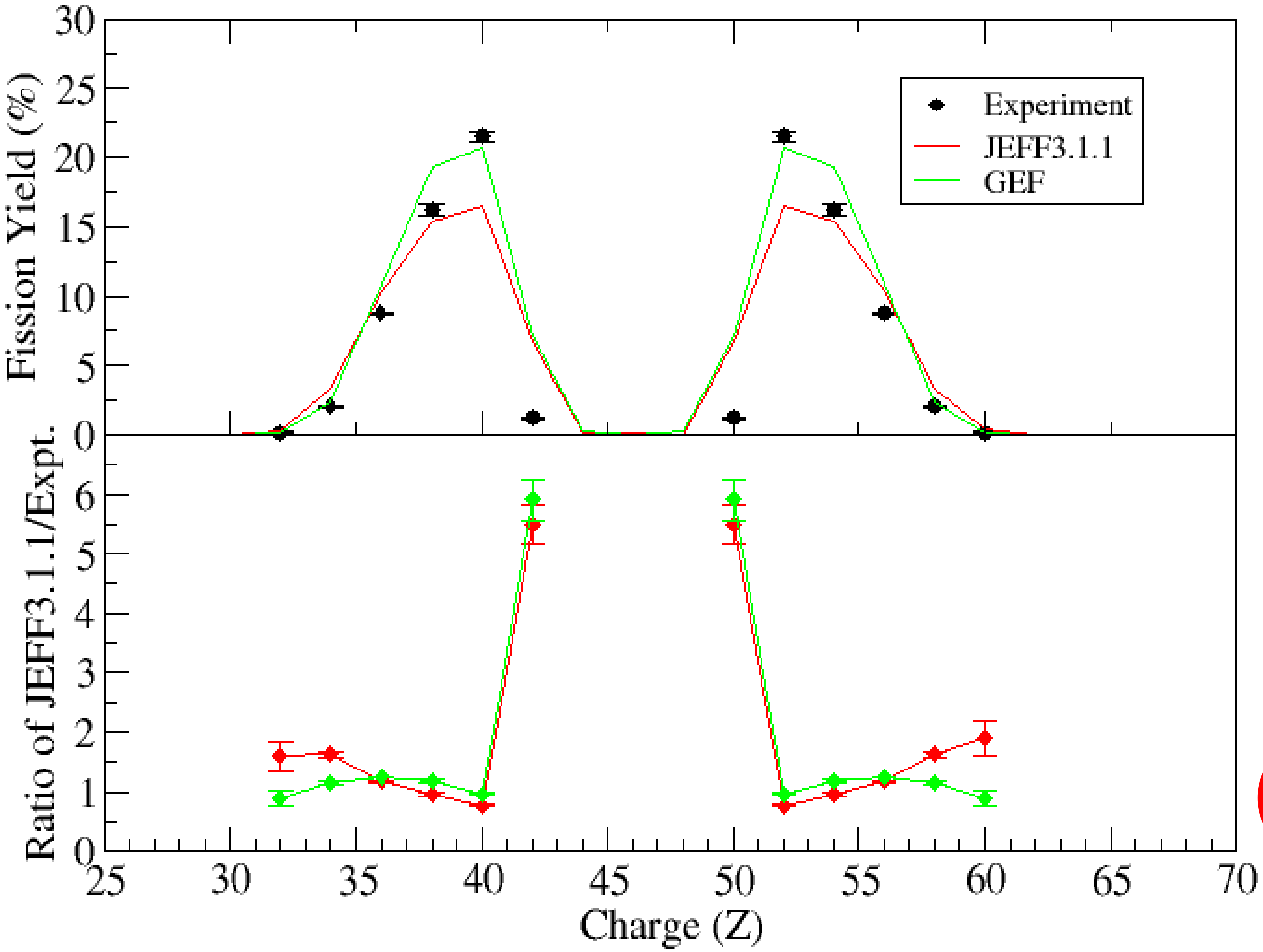
Oak Ridge Compton Suppressed Spectrometer System: 19 Ge detectors

$^{238}U(n,f)$ Fission Yield Measurements



Anomalies in the Charge Yields of Fission Fragments from 238U(n,f)

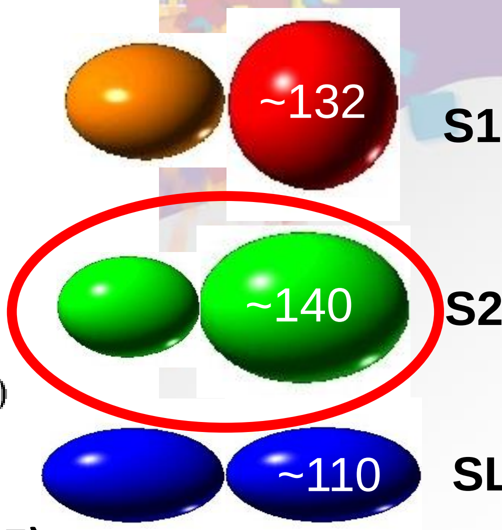
- **Measured charge yields for ^{238}U(n,f)show up to <u>600%</u> discrepencies between models and experiment!**



<u>Interpretation:</u>

Spherical shell effects in the nascent fragments (S1) become much less important

Fission modes



J.N. Wilson, M. Lebois, L. Qi et al., Phys. Rev. Lett. 118, 222501 (2017)

Fast Neutron Tomography with LICORNE and NEDA

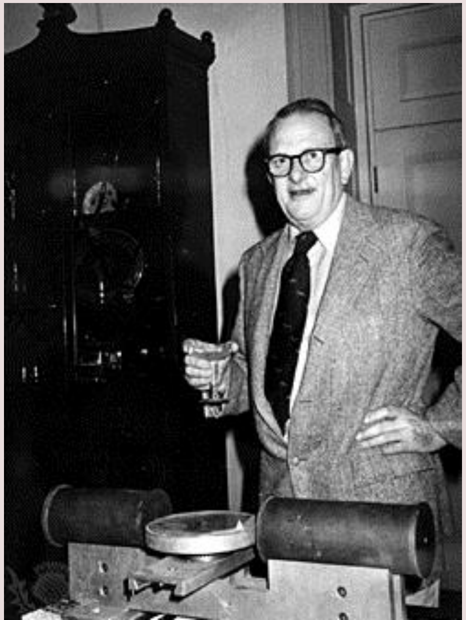
IPN
INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

First x-ray Images

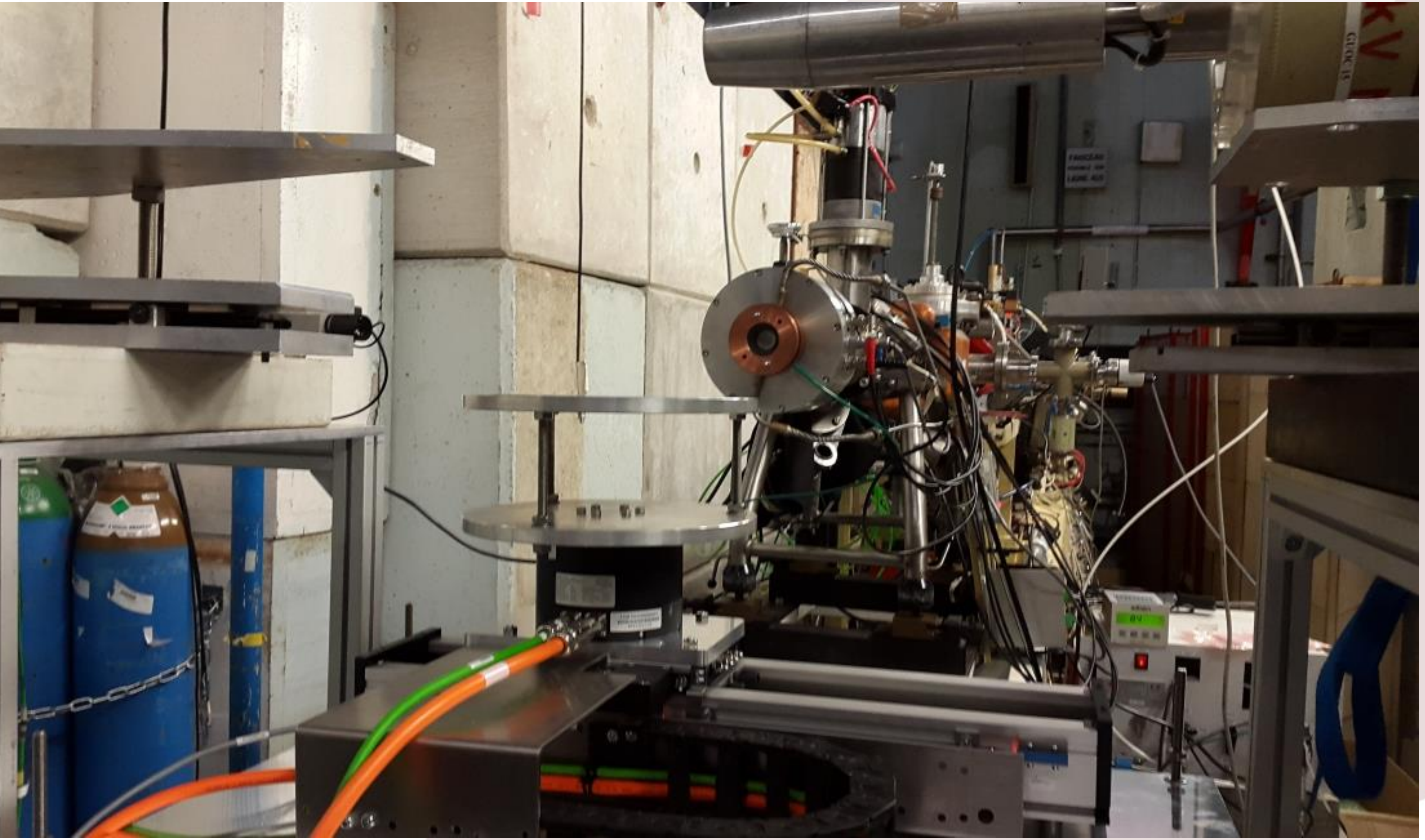
Willhelm Röntgen (1895)
1st ever Nobel Prize (1901)

First x-ray Computed Tomographic Images

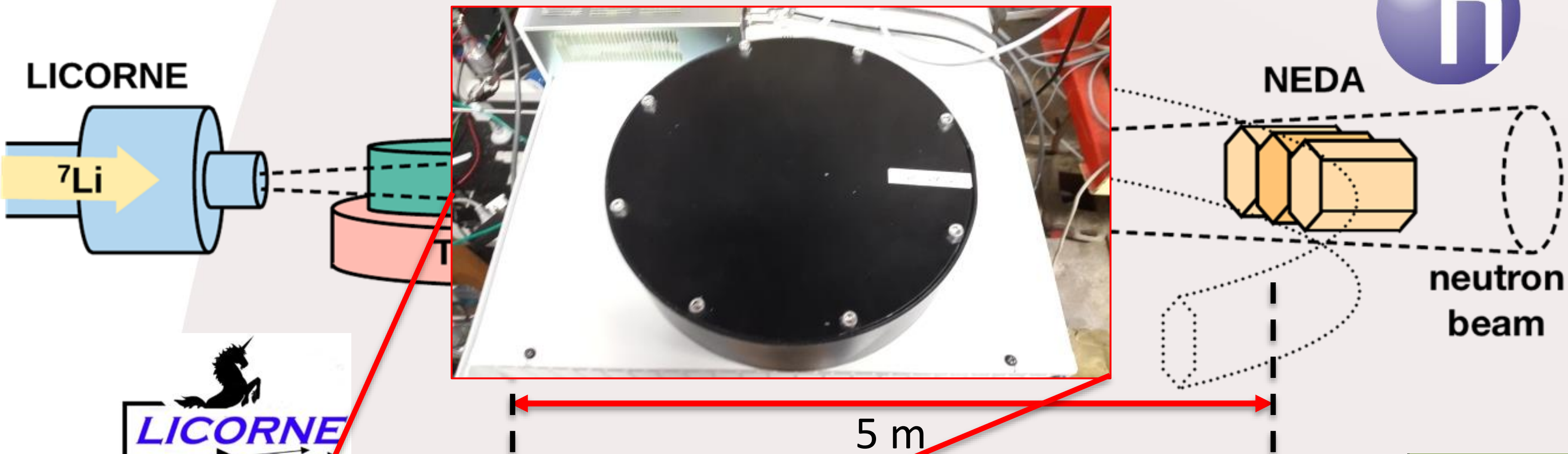
Allan M. Cormack &
Godfrey N. Hounsfield
Nobel Prize in Medicine (1979)

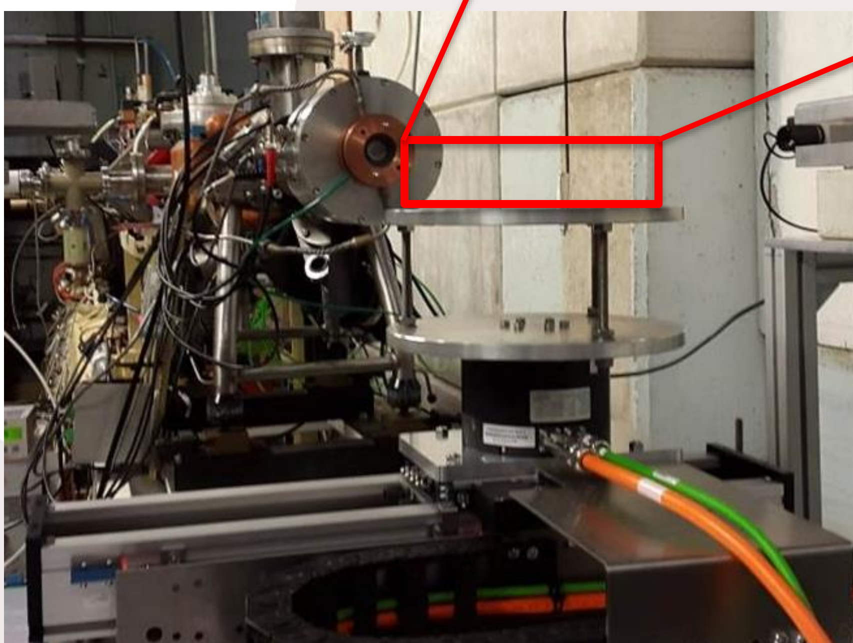


IPN Orsay scanning table + LICORNE

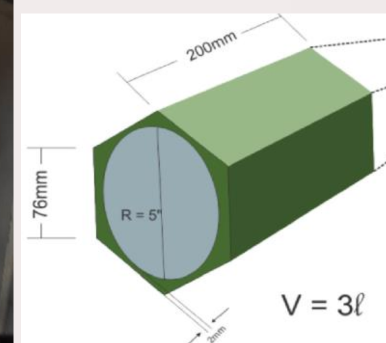


Fast Neutron Tomography with LICORNE and NEDA (december 2016)



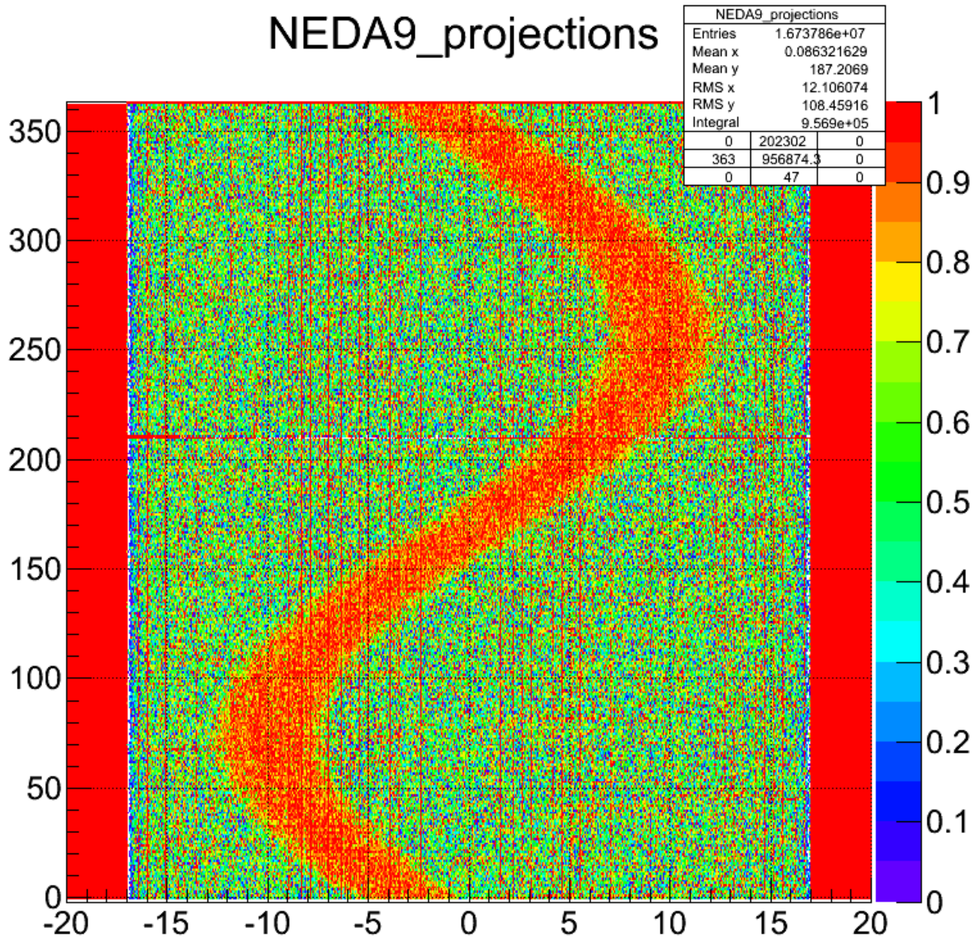


First Use of **NEDA** with FASTER

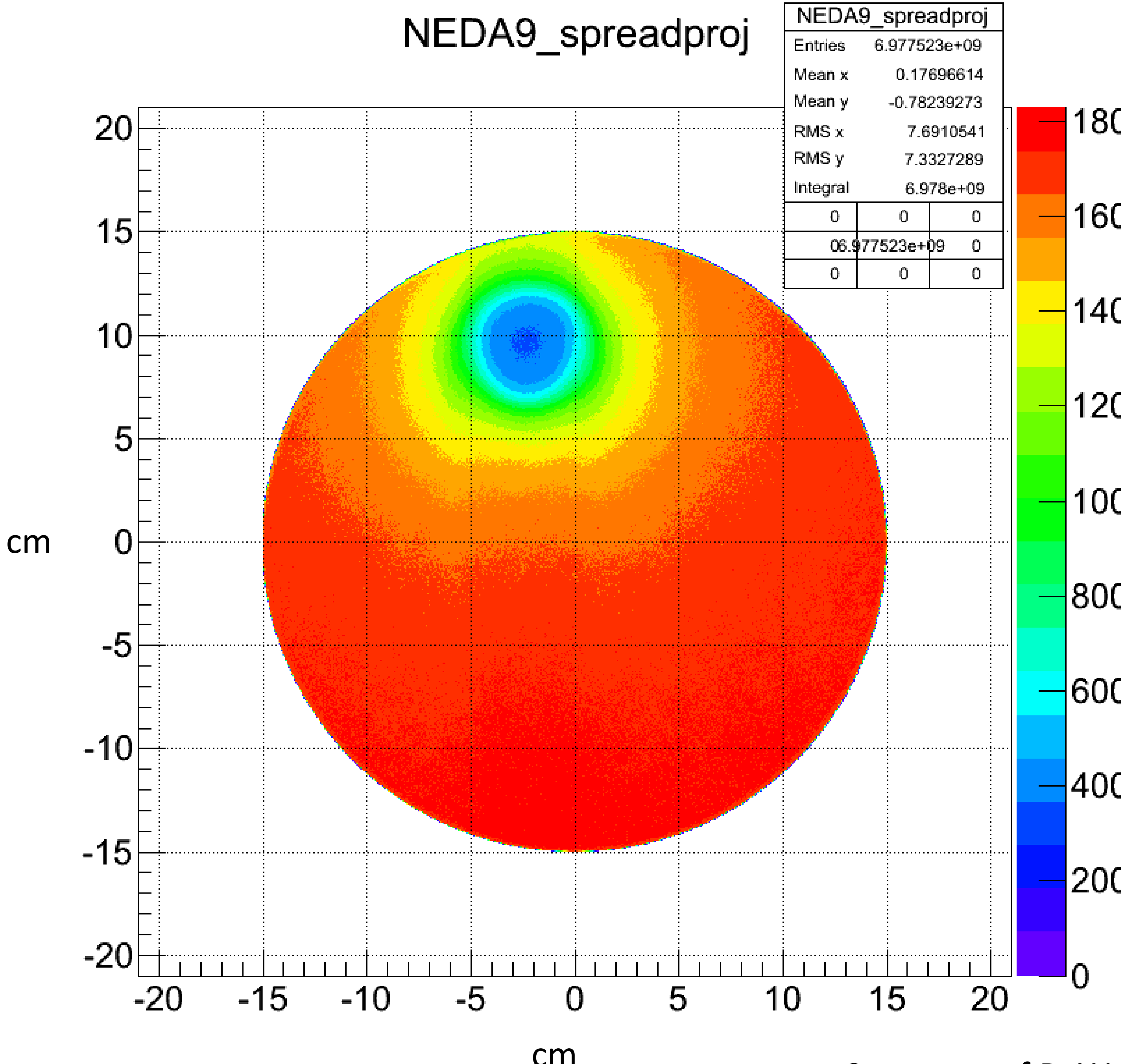


BC501A

First Results

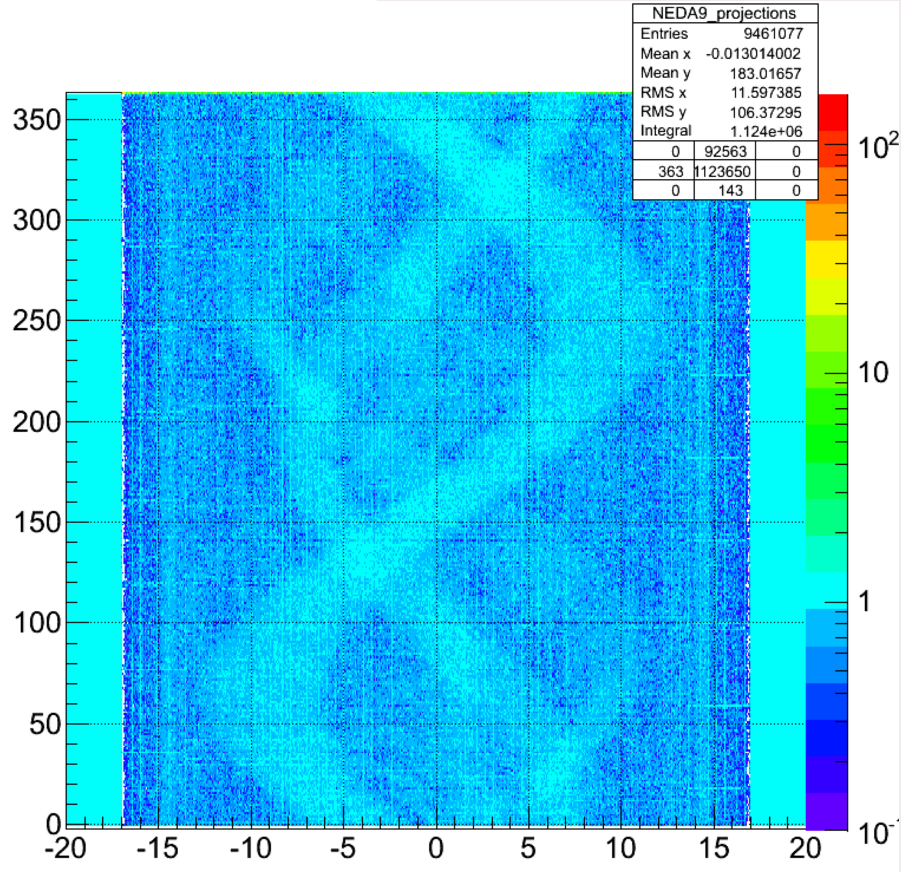


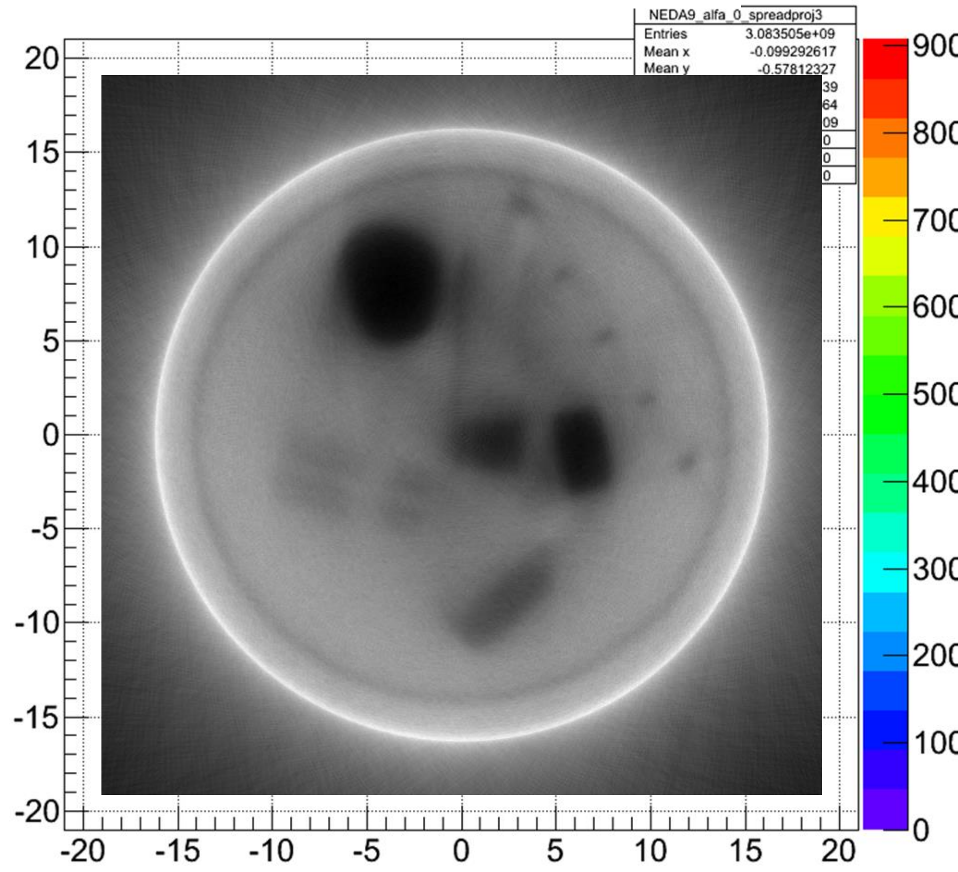
Courtesty of B. Wasilewska



Courtesty of B. Wasilewska

Fast Neutron Tomography with LICORNE and NEDA





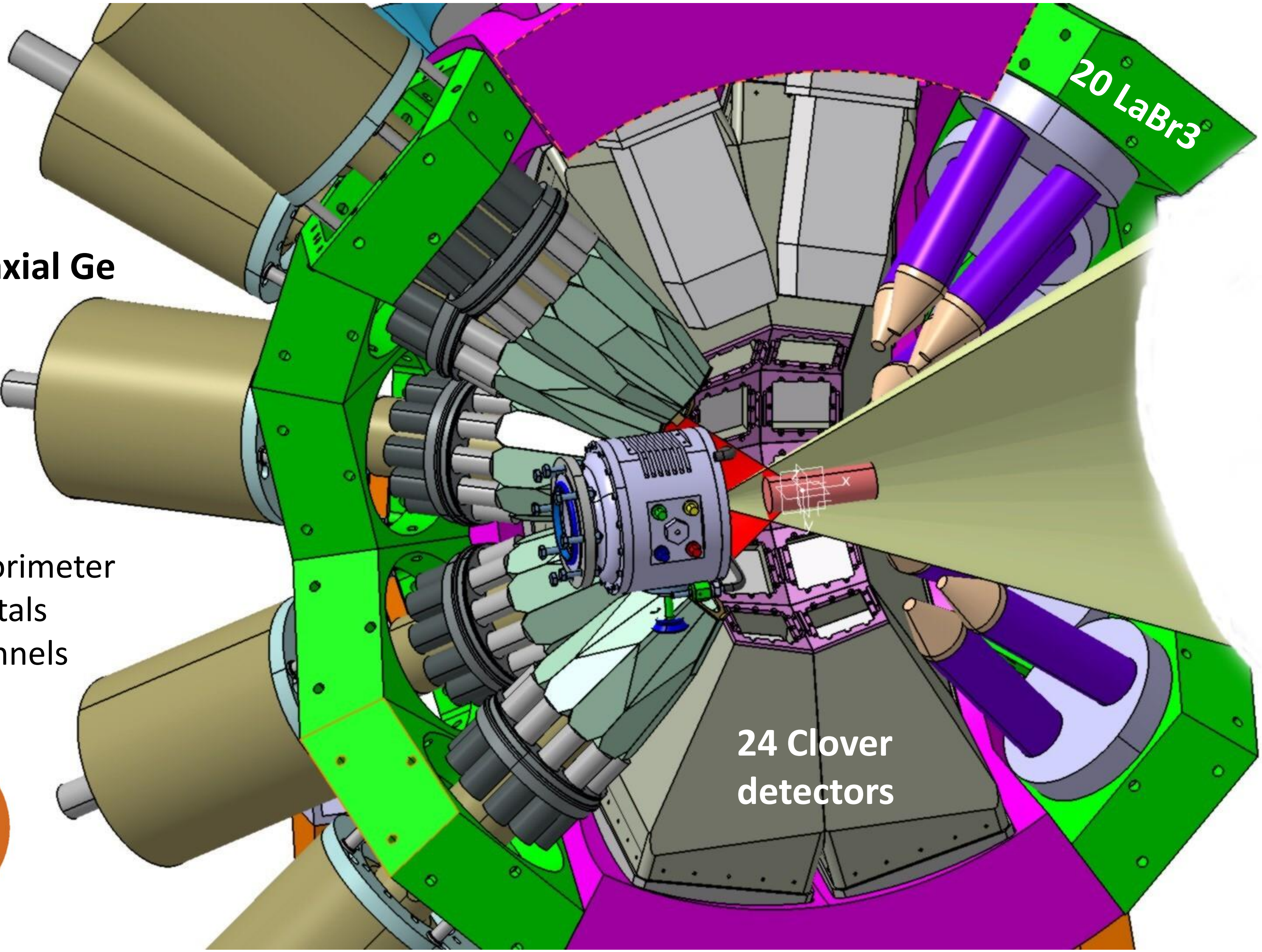
Courtesty of B. Wasilewska

The ν-ball project

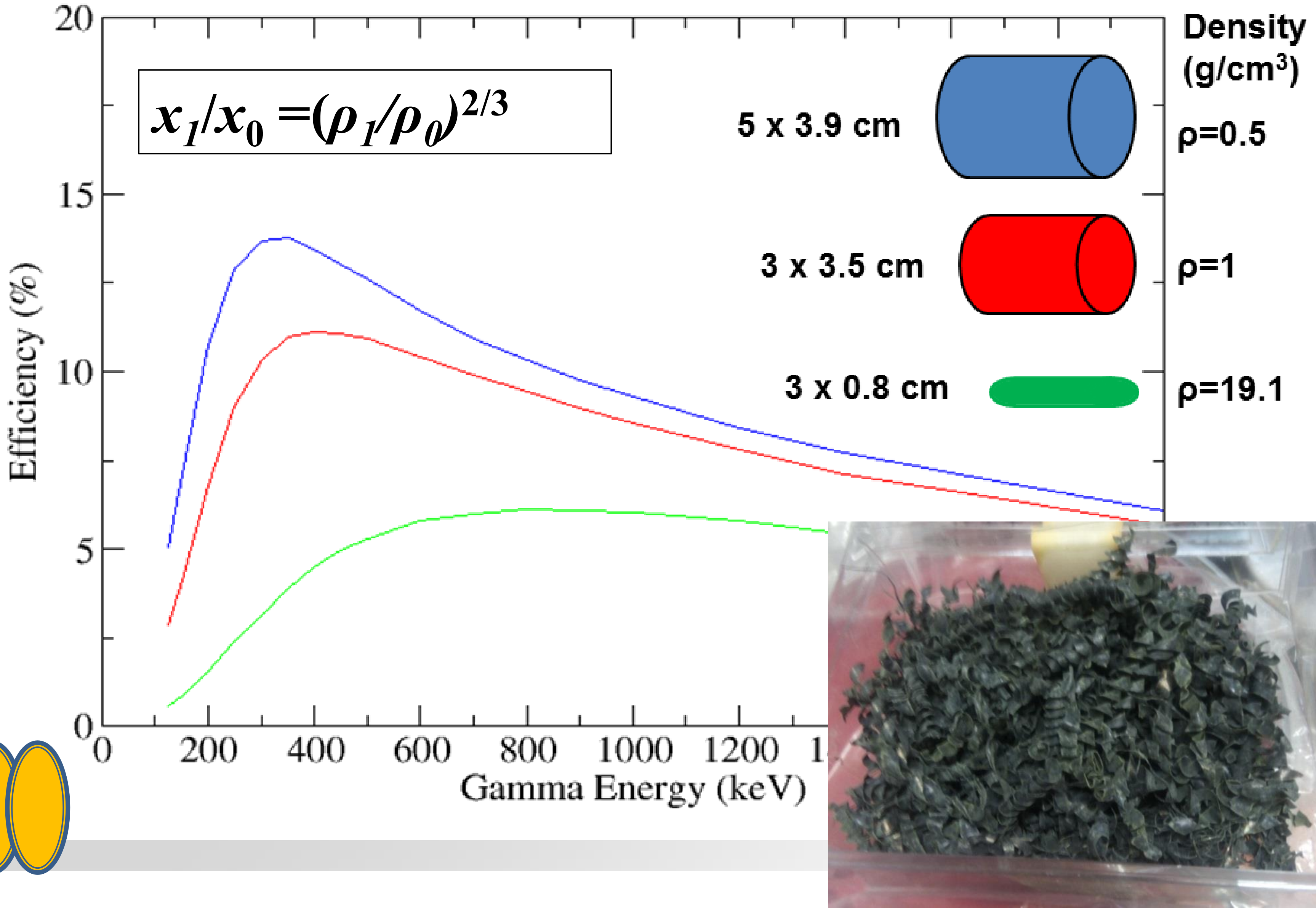
Nu-ball experimental campaign 2017/2018

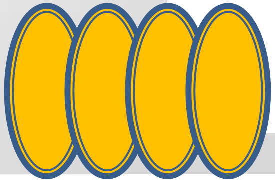
10 Co-axial Ge

ε=5.5%
70% calorimeter
610 crystals
184 channels

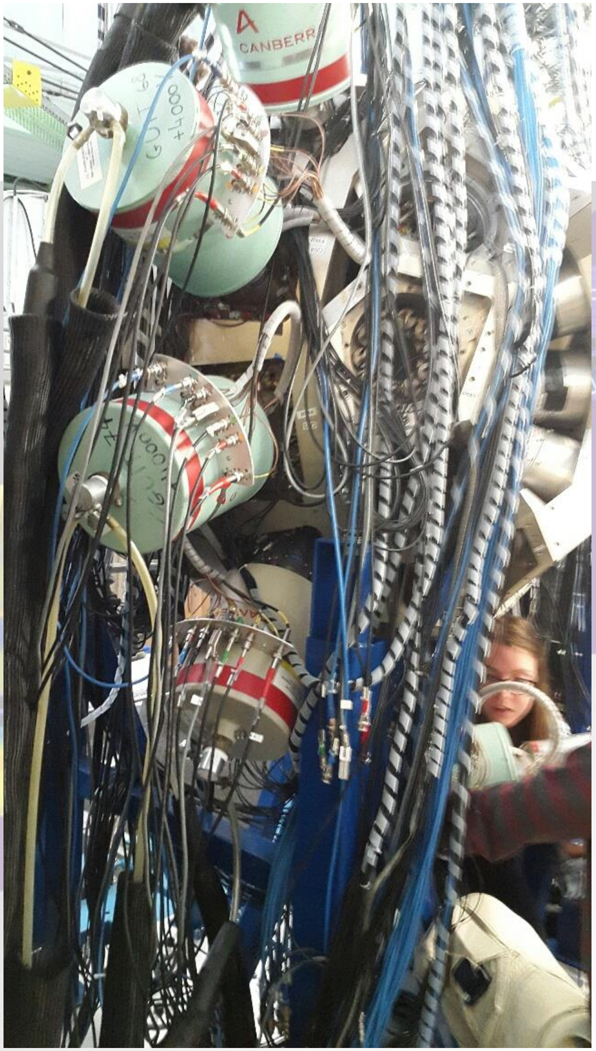


Solving the target self-shielding problem





Nu-ball setup september 2017

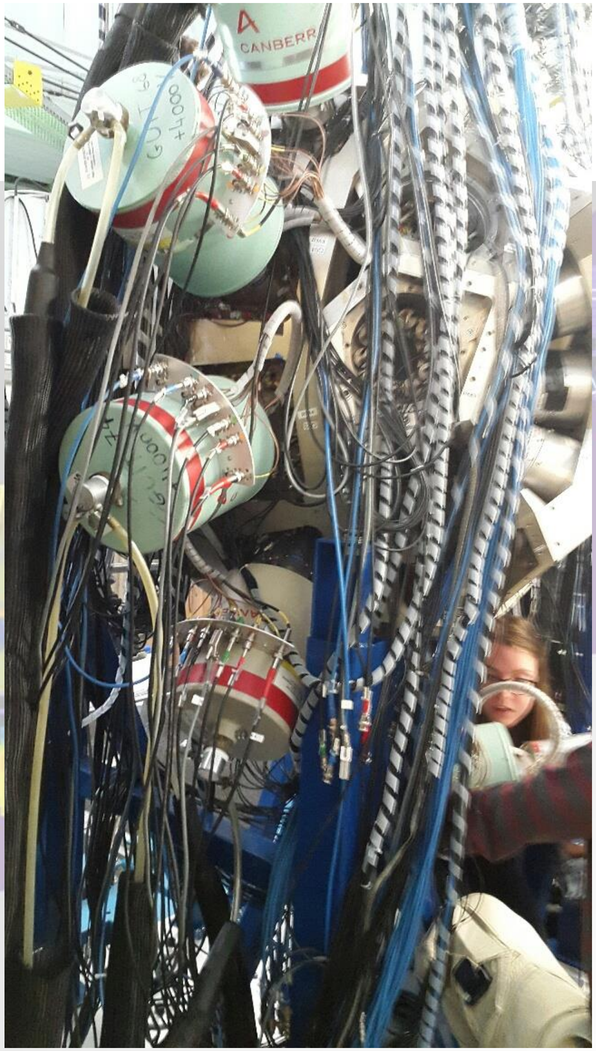


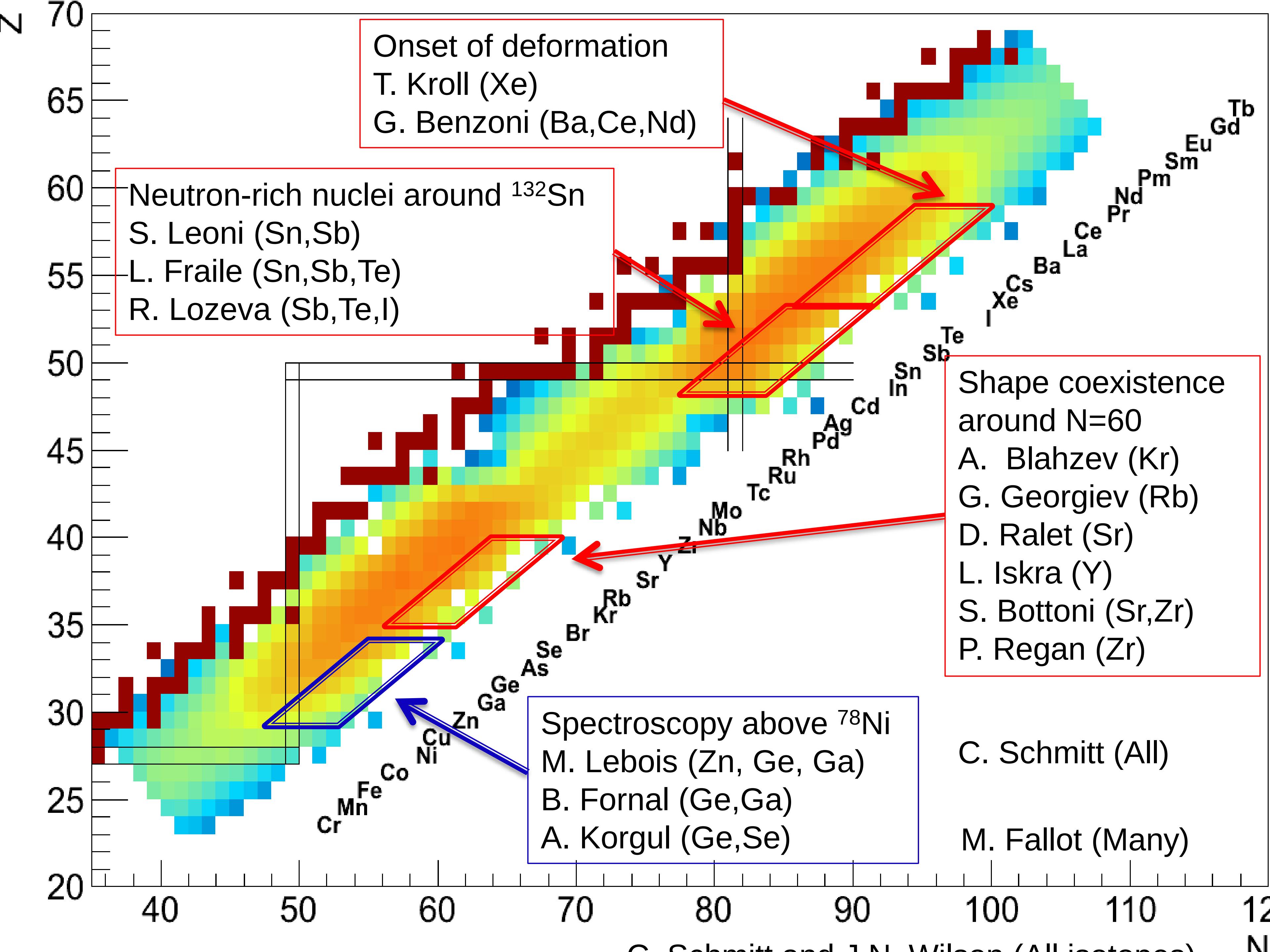
Nu-ball setup september 2017

nu – ball

Setup Improvements 2017

- Compton suppressed, high-efficiency spectrometer
- Higher detector granularity (106 Ge segments)
- Full digital triggerless DAQ
- Calorimetry for fission/beta-decay discrimination
- Addition of 20 LaBr3 for ps lifetime measurements
- New ion source (up to 5x more primary beam)
- Better beam bunching (< 1ns pulse width)
- Increased target mass (80g)
- Much lower target density (ρ=0.5 g/cm3)
- First use of 232Th targets
- Increased running time (> 1 month)

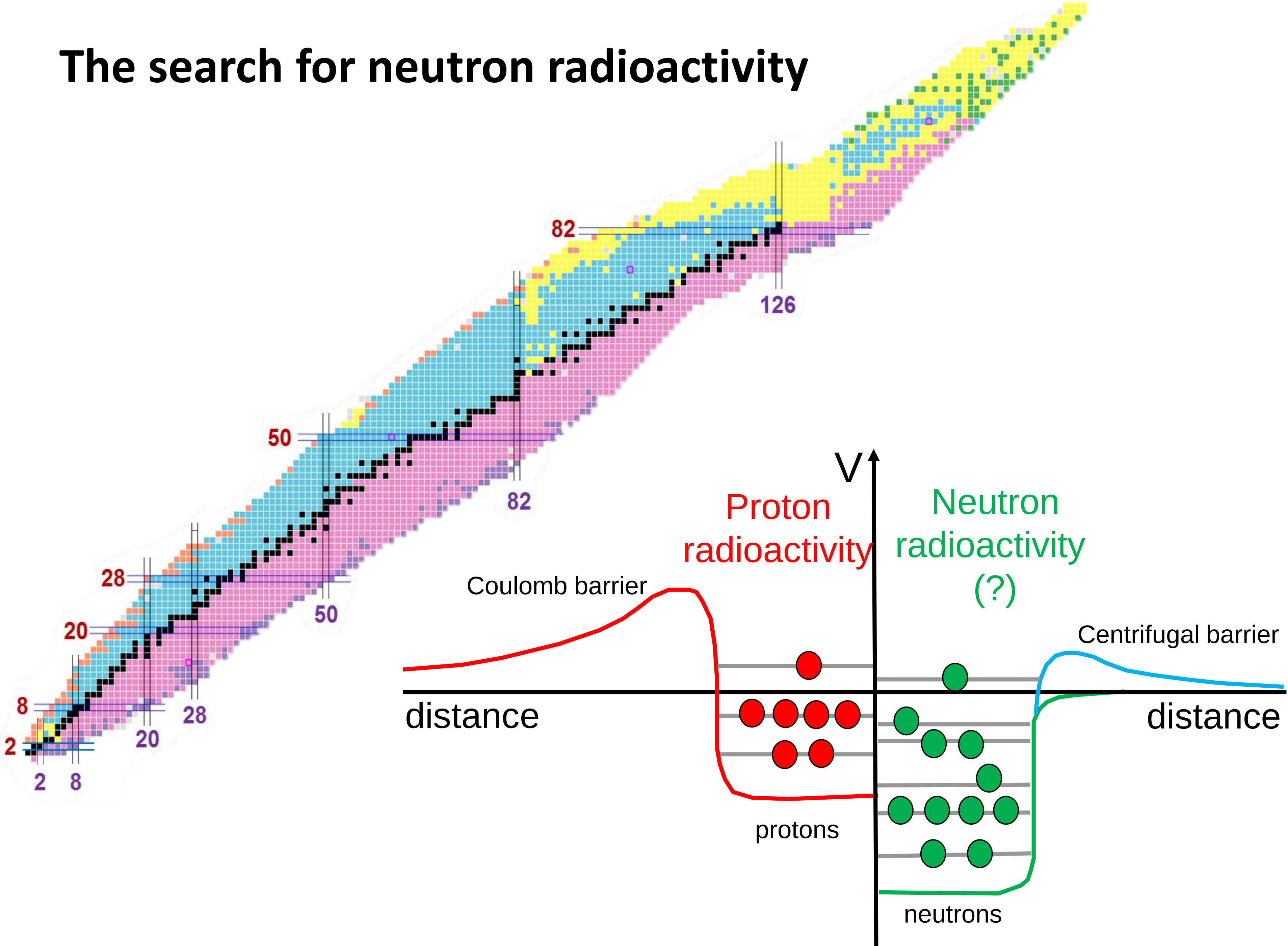




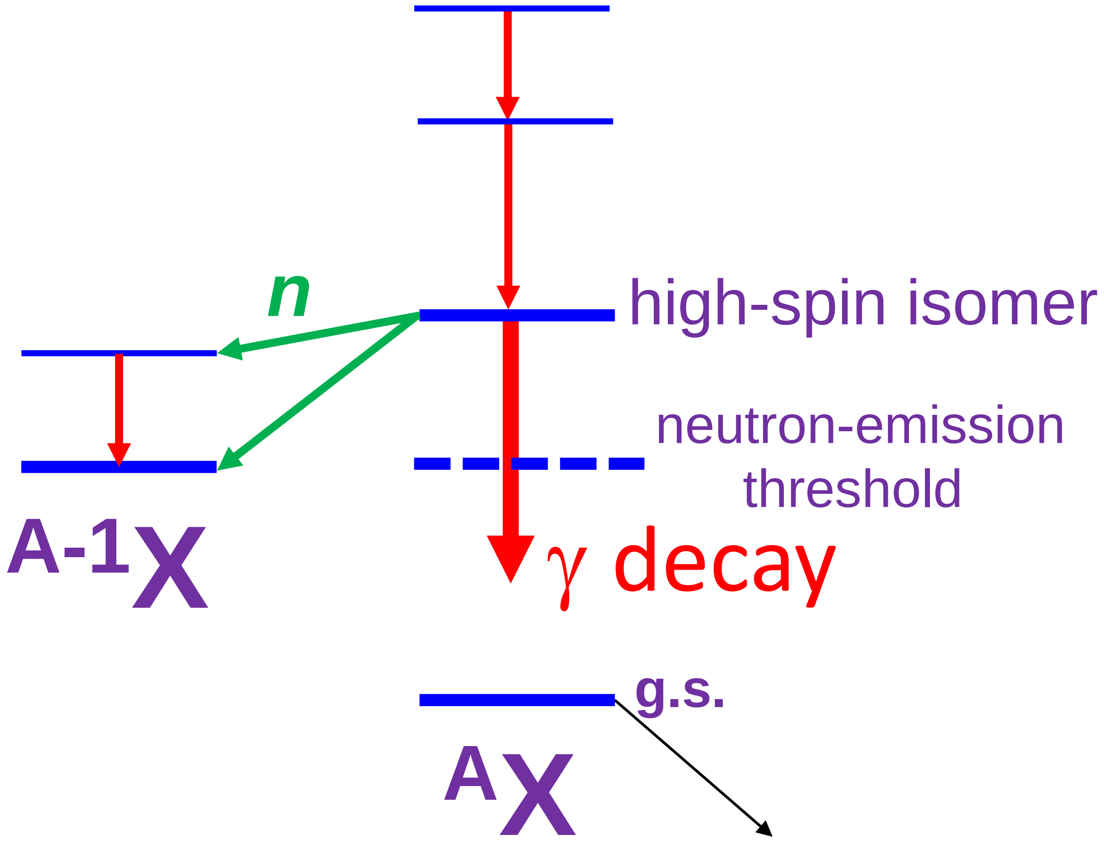
Onset of deformation
T. Kroll (Xe)
G. Benzoni (Ba,Ce,Nd)
Neutron-rich nuclei around ^{132}Sn
S. Leoni (Sn,Sb)
L. Fraile (Sn,Sb,Te)
R. Lozeva (Sb,Te,I)
Shape coexistence around N=60
A. Blahzev (Kr)
G. Georgiev (Rb)
D. Ralet (Sr)
L. Iskra (Y)
S. Bottoni (Sr,Zr)
P. Regan (Zr)
Spectroscopy above ^{78}Ni
M. Lebois (Zn, Ge, Ga)
B. Fornal (Ge,Ga)
A. Korgul (Ge,Se)
C. Schmitt (All)
M. Fallot (Many)
Z
N
Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe Cs Ba La Ce Pr Nd Pm Sm Eu Gd Tb
20 25 30 35 40 45 50 55 60 65 70
40 50 60 70 80 90 100 110

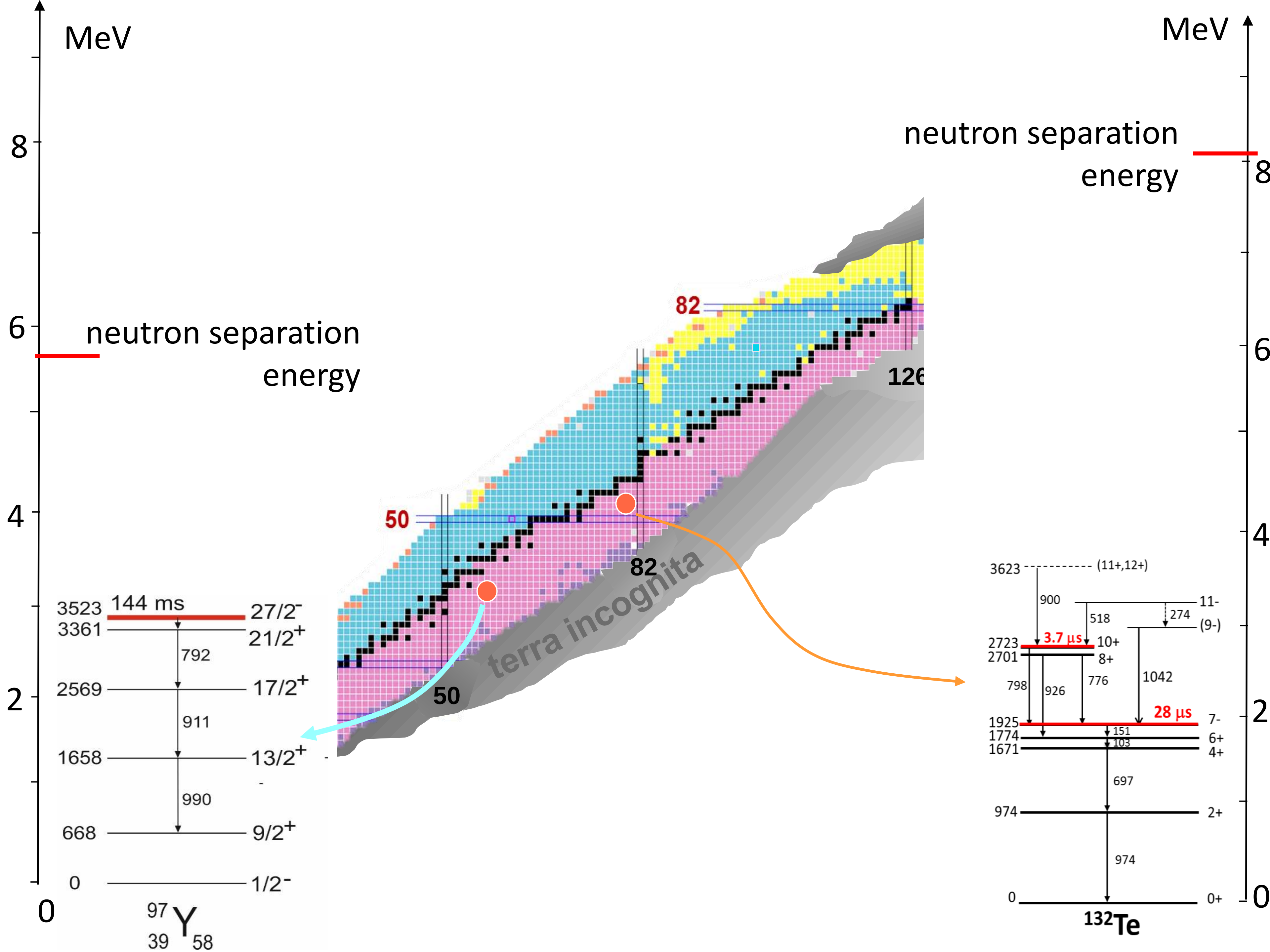
Prospects for future NFS experiments

The search for neutron radioactivity



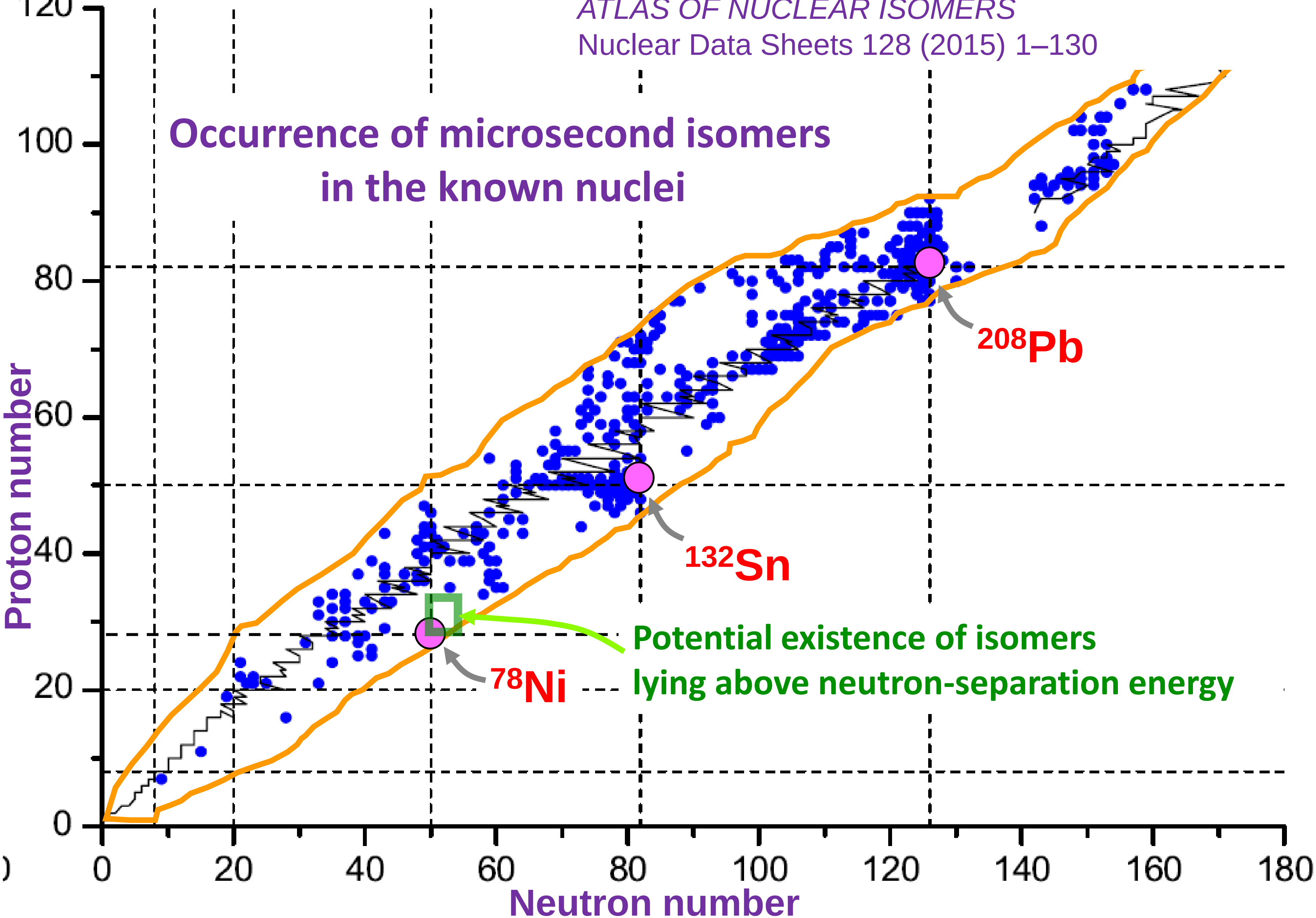
Neutron radioactivity

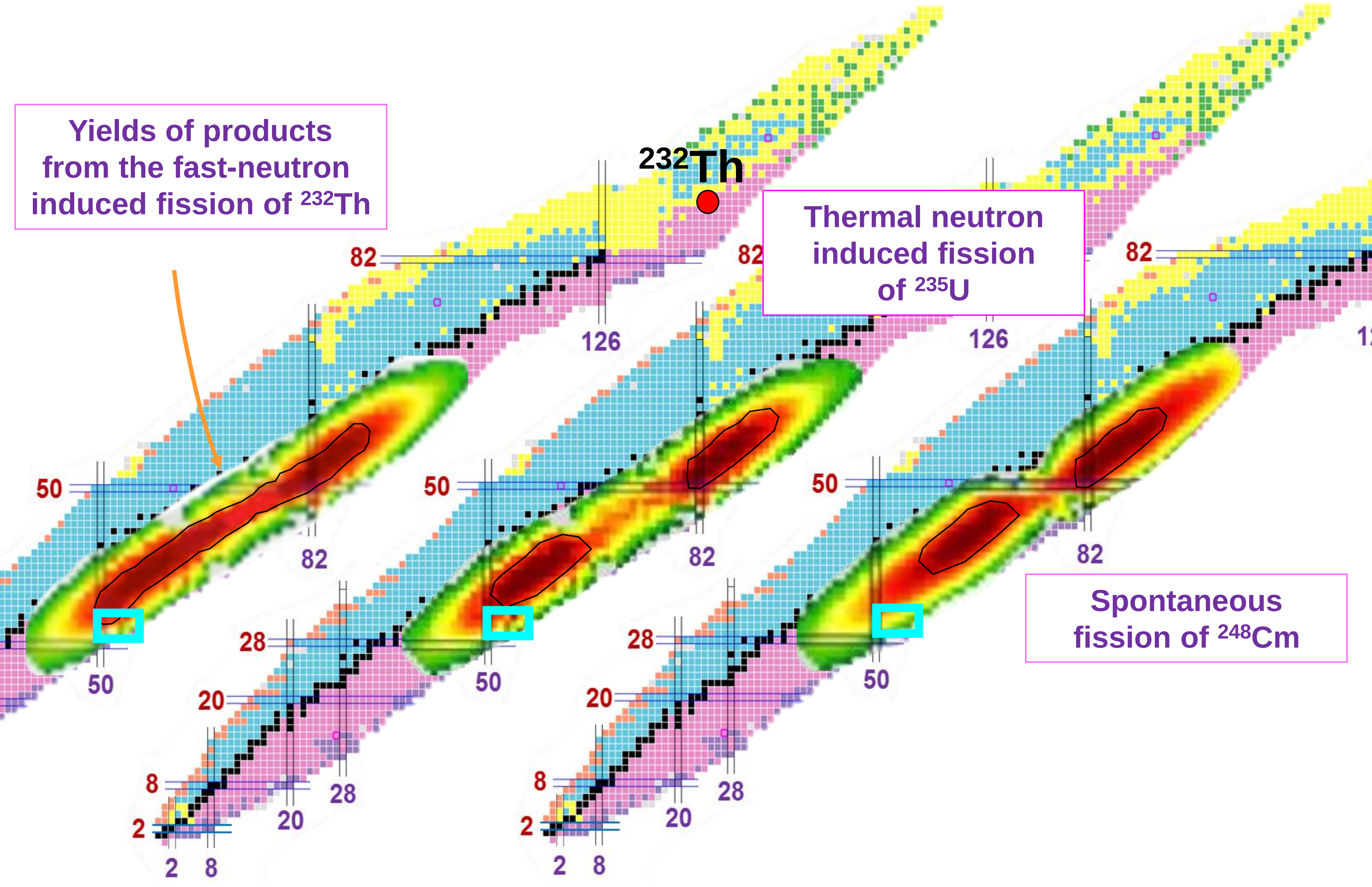




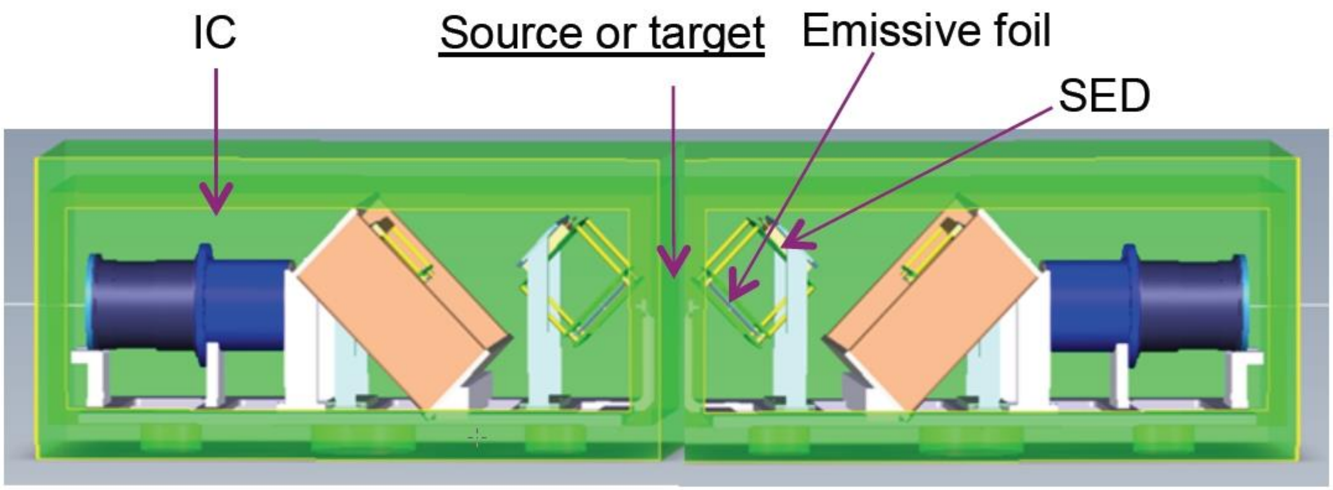
MeV
8
6
4
2
0
neutron separation energy
3523 144 ms 27/2-
3361 21/2+
792
2569 17/2+
911
1658 13/2+
990
668 9/2+
0 1/2-
97 39 Y 58
50
82
50
82
126
terra incognita
MeV
neutron separation energy
8
6
4
2
0
3623 (11+,12+)
900
11-
518
274
(9-)
2723 3.7 μs 10+
2701 8+
798
926
776
1042
1925 28 μs 7-
1774 151 6+
1671 103 4+
697
974 2+
974
0 0+
132Te

A.K. Jain, B. Maheshwari, S. Garg, M. Patial, and B. Singh
ATLAS OF NUCLEAR ISOMERS
Nuclear Data Sheets 128 (2015) 1–130



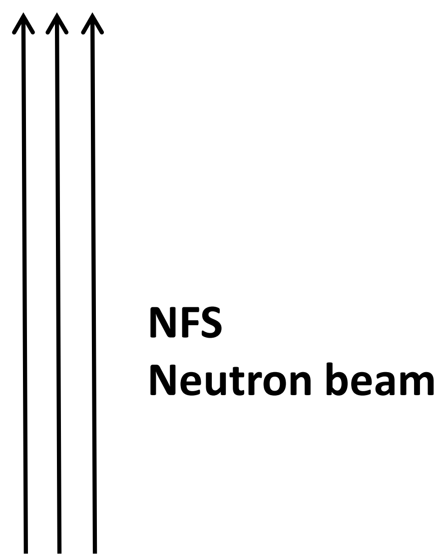

Yields of products from the fast-neutron induced fission of 232Th
232Th
Thermal neutron induced fission of 235U
Spontaneous fission of 248Cm
82
126
50
82
28
20
8
2
50
2
8
20
28
82
126
50
82
28
20
8
2
50
2
8
20
28
82
50
82
50

Fission Yields @NFS: An alternative approach?

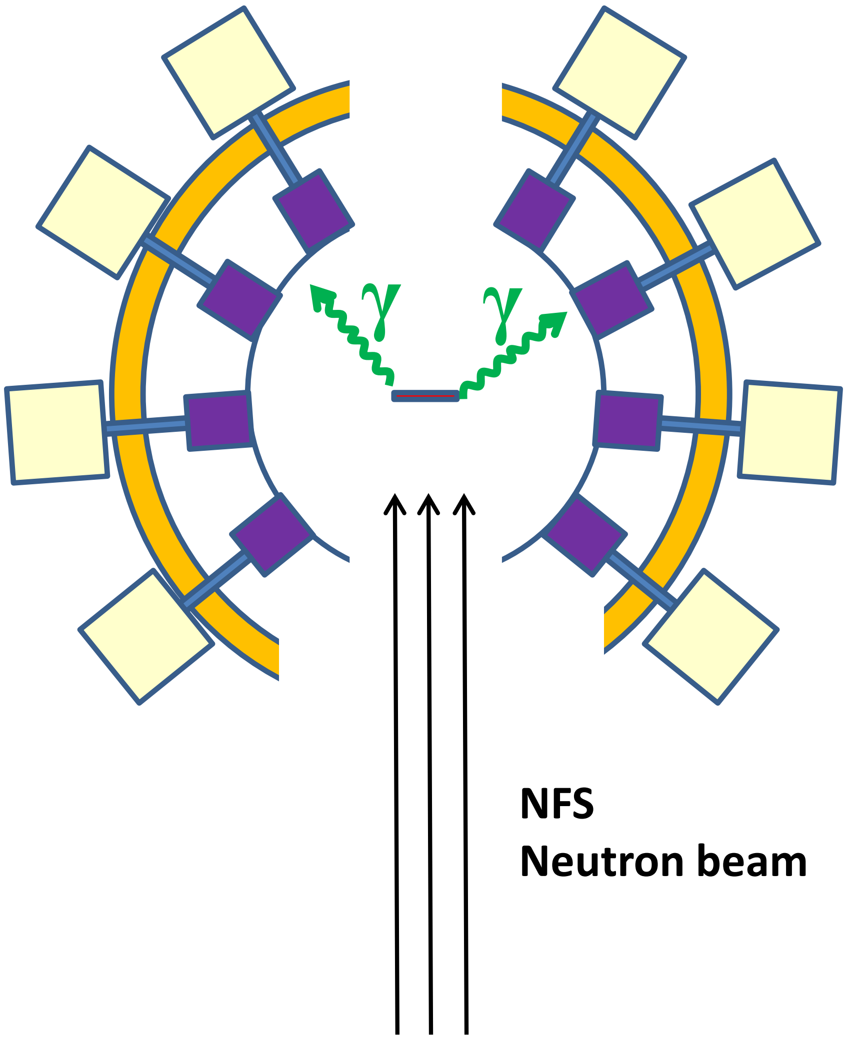


FALSTAFF
(D. Dore et al.)

Target mass ~1 mg
Fission rates (< 10 Hz)



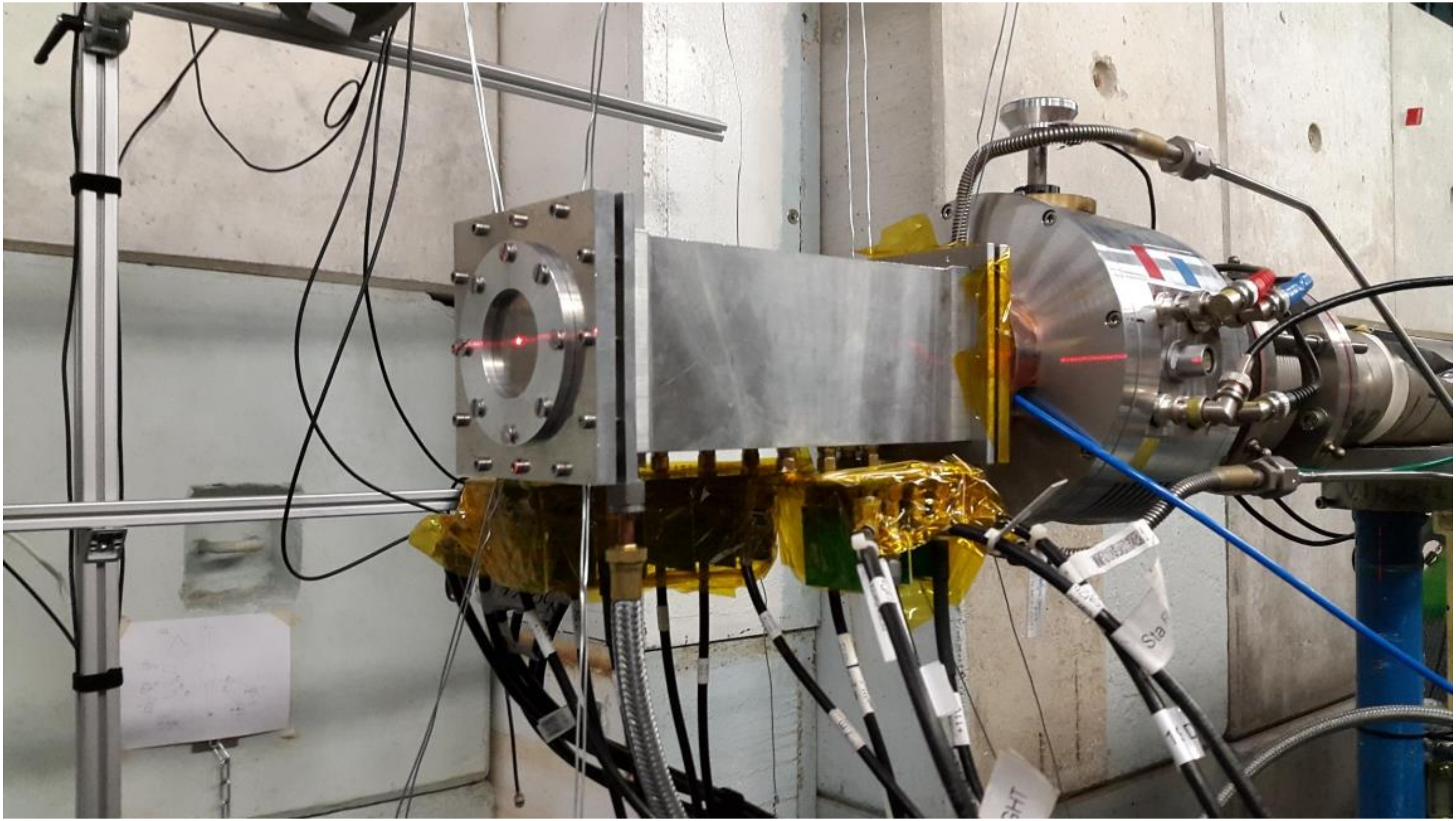
Fission Yields @NFS: An alternative approach?



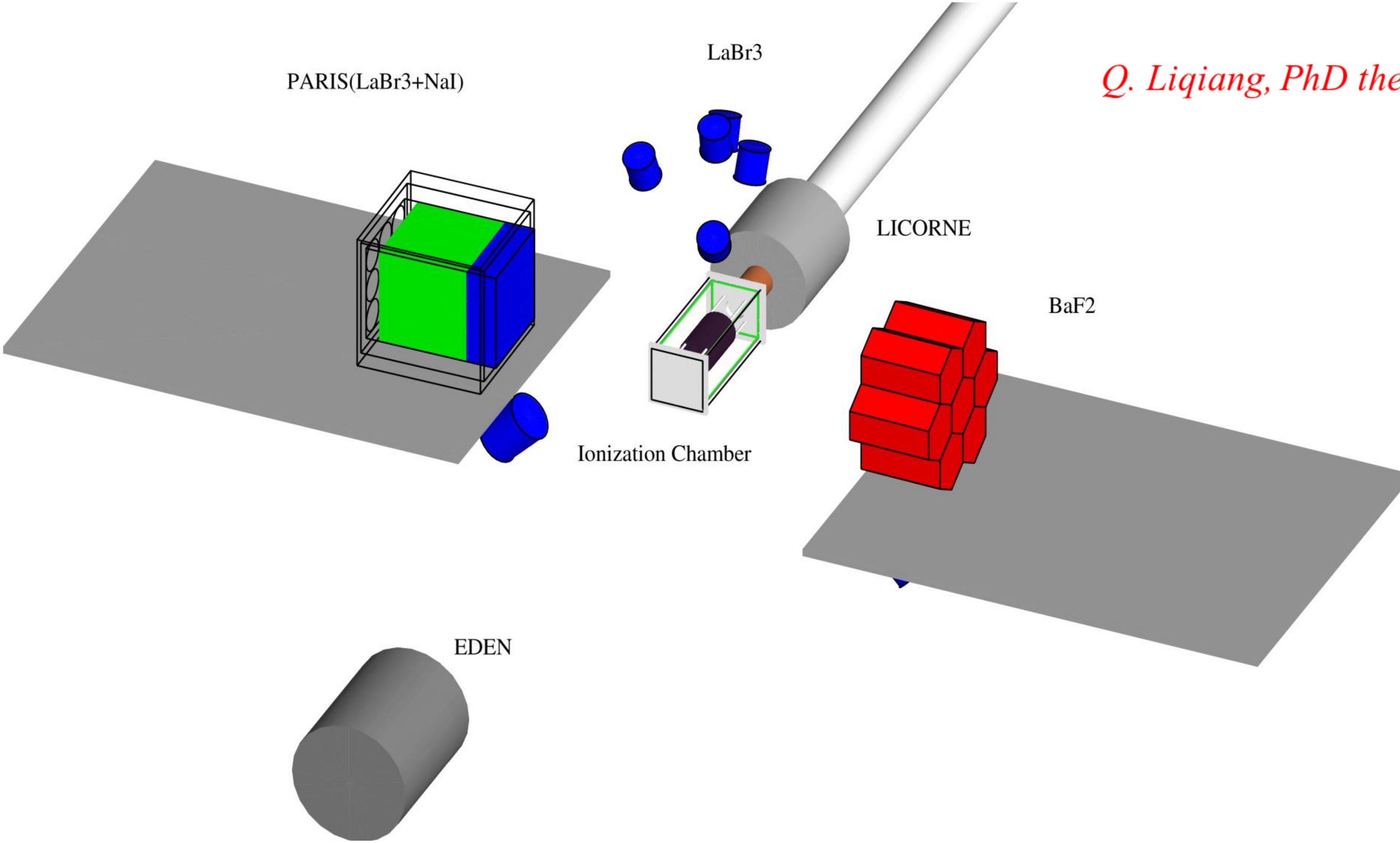
- ❑ Massive ^{238}U or ^{232}Th Targets to study energy dependence of the Fission Yields (~80g)
  Fission rates ~ 10^5 Hz

- ❑ Active actinide targets (~100 mg)
  Fission rates 10^2 Hz

Fission Yields @NFS: An alternative approach?



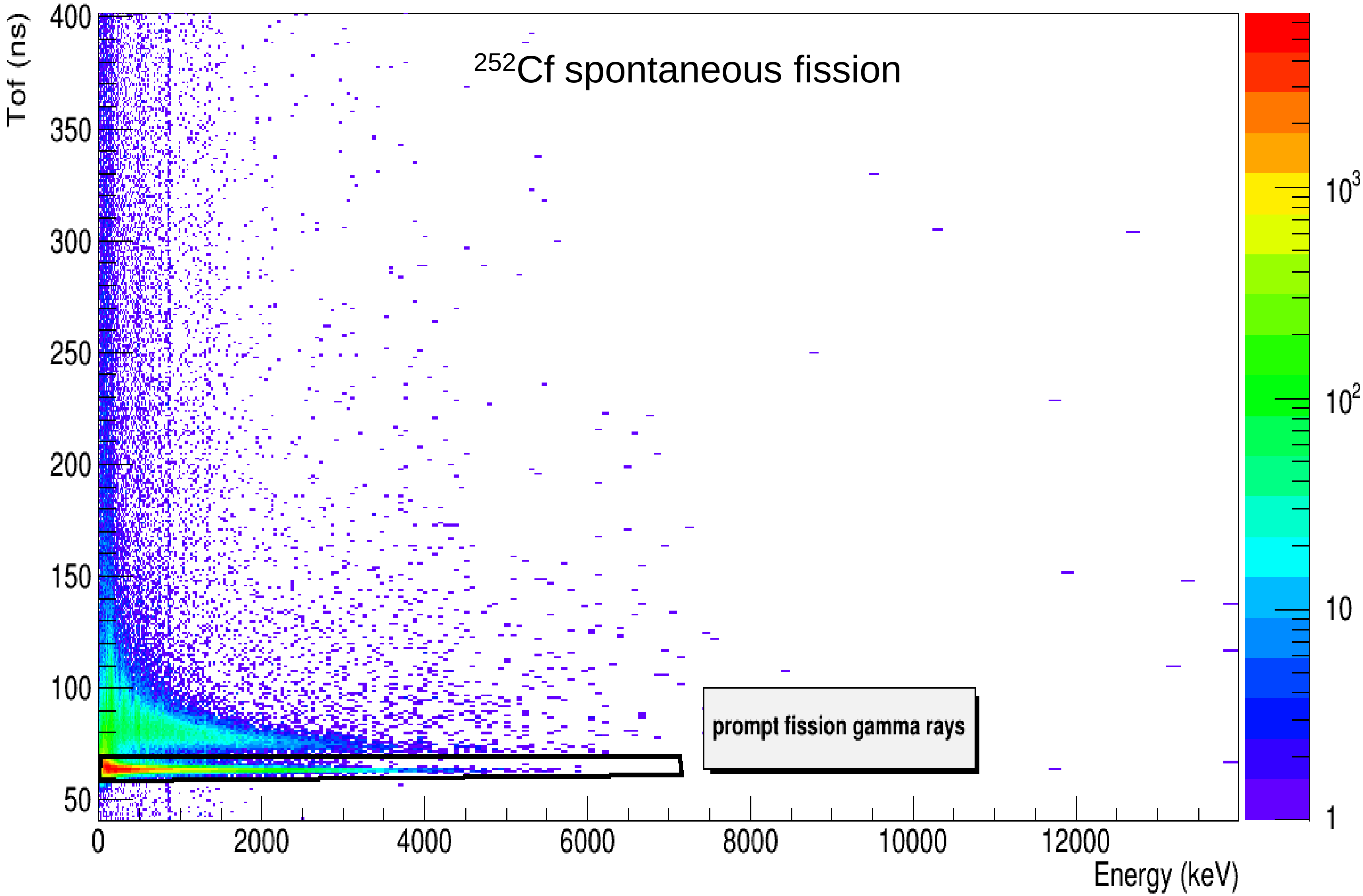
March 2016: Experimental Setup (Geant IV response model)



Q. Liqiang, PhD thesis

MARCH 2016 EXPERIMENT: DATA ANALYSIS (^{252}Cf STUDY)

Q. Liqiang, PhD thesis



UNKNOWN SHORT LIVED ISOMERS