Mass (and other) measurements along the r-process path at CARIBU

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&

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Nuclear Masses and Nucleosynthesis

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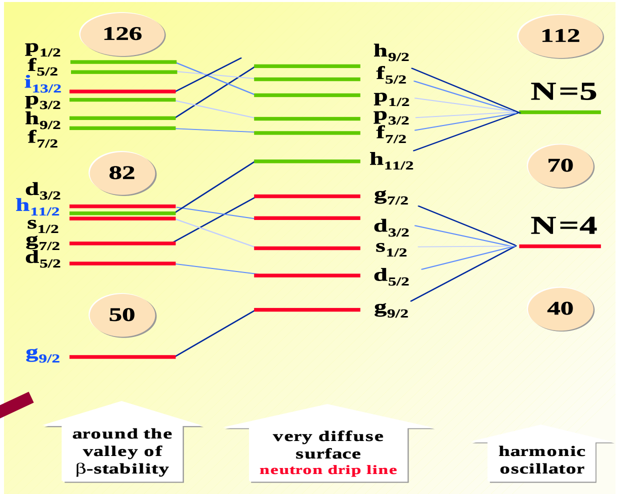
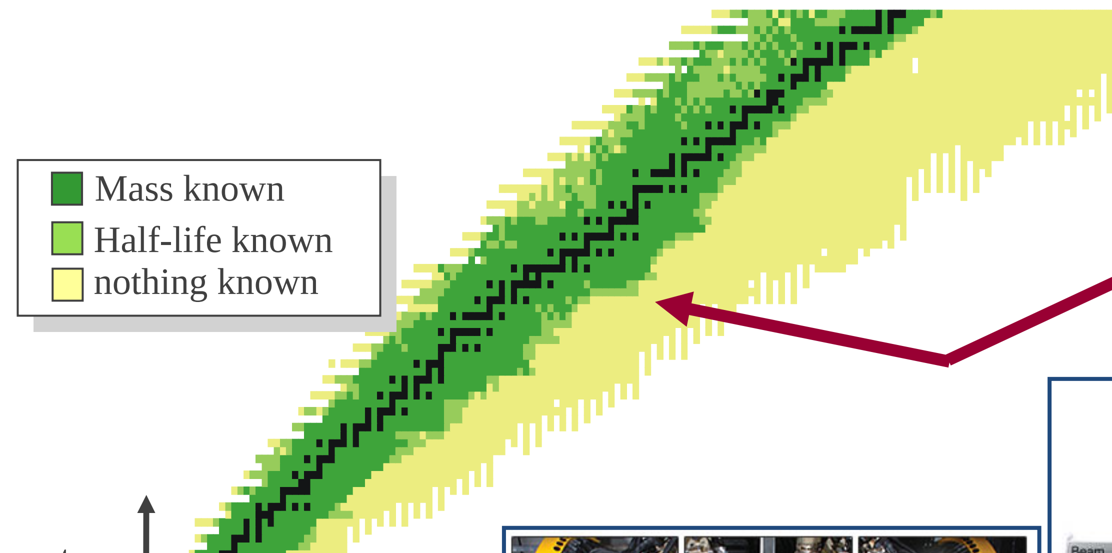
Outline

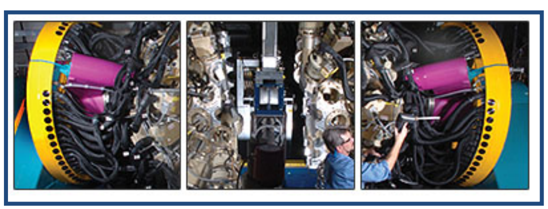
- Brief motivation for CARIBU
  - Nuclear structure
  - Nuclear astrophysics
  - Applications
- CARIBU description
- Early results … masses and other
- Ongoing upgrades
  - Gains
  - Available/new experimental equipment

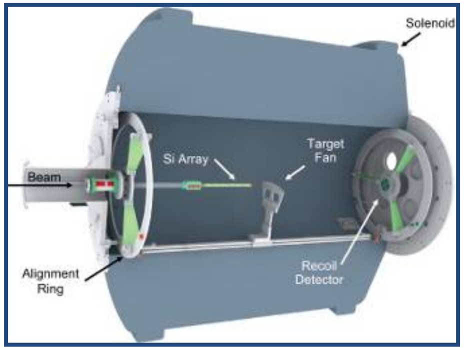
Nuclear structure of neutron-rich nuclei

- Heavy neutron-rich nuclei region:
  - region mostly unexplored even for the most basic properties
  - weakly bound with diffuse surface … reduced spin-orbit coupling, shell model possibly modified
  - signature can take many forms: single particle structure, ground state properties, etc …





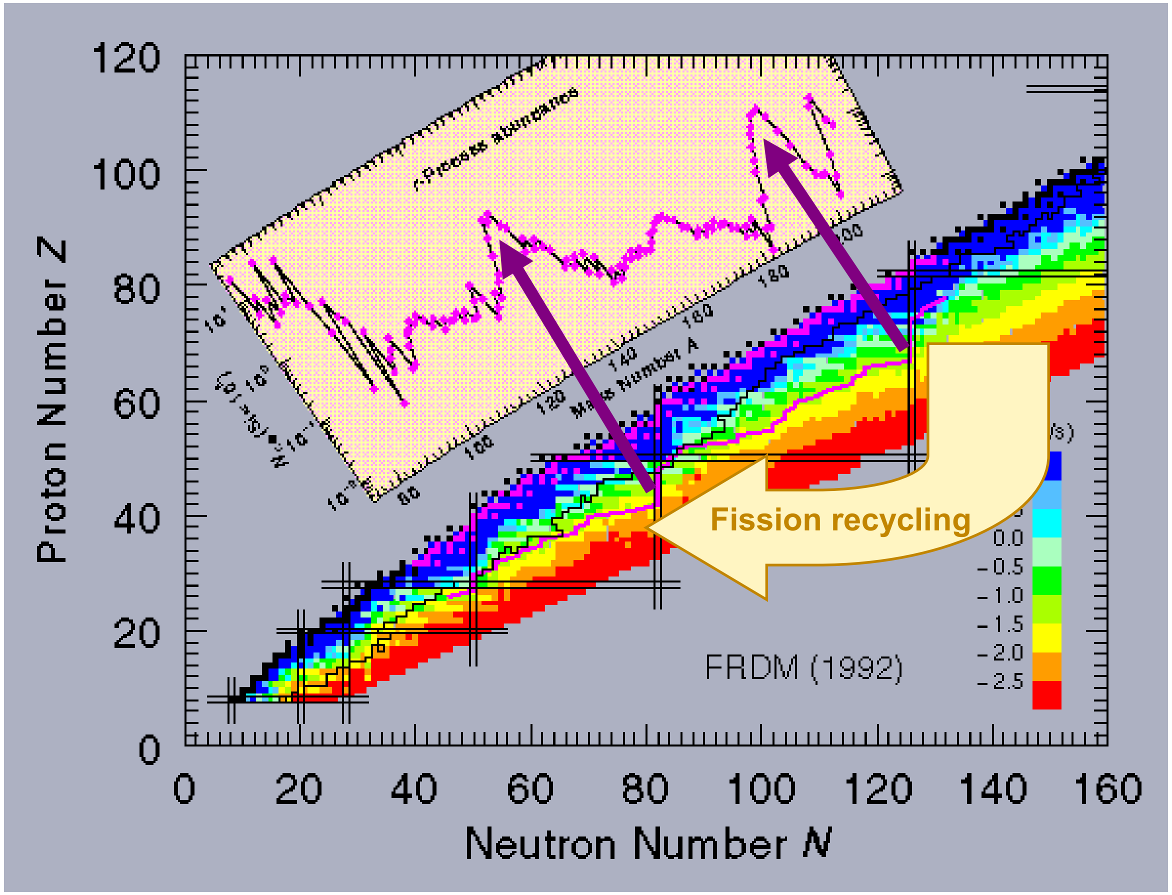




The r-process path

r-process:

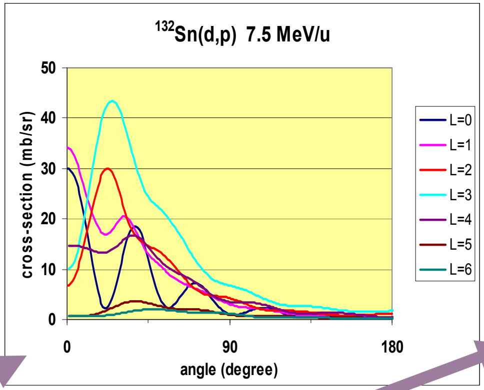
- Process known to exist
- Exact site unknown
- Path critically depends on nuclear properties of neutron-rich nuclei:
  - mass
  - lifetime
  - β-delayed neutrons
  - fissionability

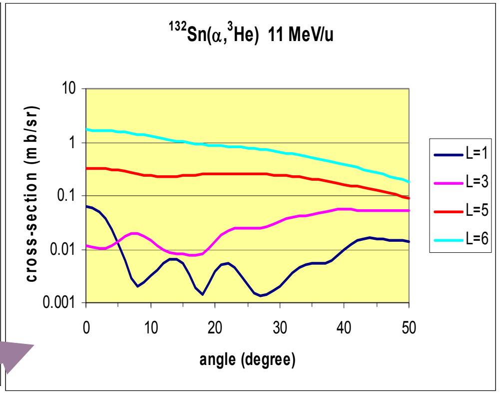


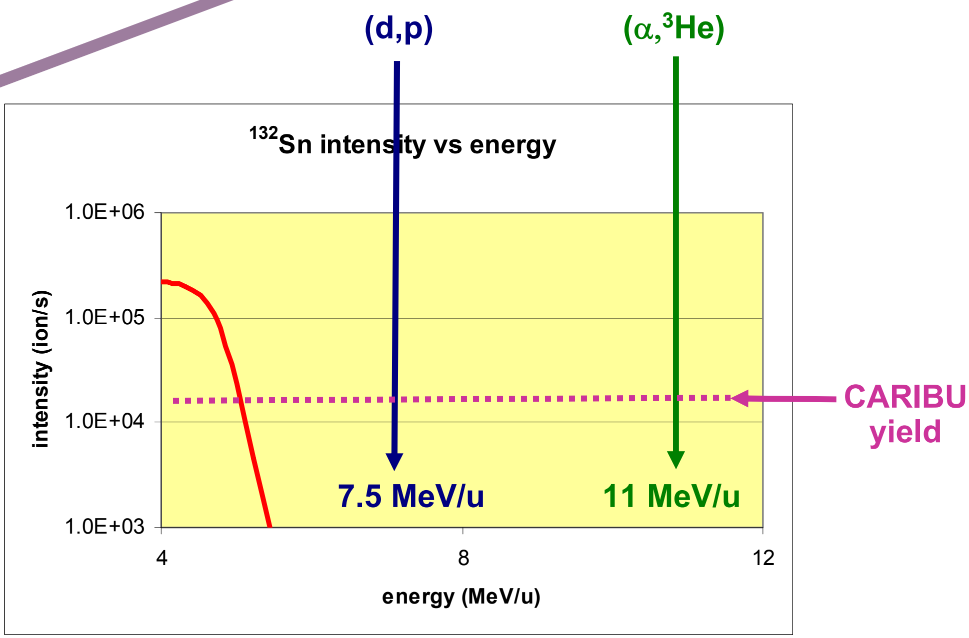
Efficient techniques exist to obtain this information but the required beams are missing in most of this region of the chart of nuclides.

Requirements of n-rich physics: Nucleon transfer reaction … single particle states (and reaction rates)

- Single particle/hole states around magic nuclei
  - *^{132}Sn, ^{104}Zr, ^{78}Ni*
- (d,p) reactions
  - best done well above Coulomb barrier in both entrance and exit channels … i.e. about 7.5 MeV/u around ^{132}Sn
  - requires 10^4 per second to get information on angular distribution
- (^{3}He, α), (α,t) reactions
  - Well matched to higher angular momentum transfer
  - Energy requirements again set by Coulomb barrier
  - Required beams are not available anywhere at present







(d,p) reactions can also be important to determine (n,γ) rates close to r-process path:

e.g. (d,p) on ^{84}Ge or ^{138}Te

CARIBU Decay Workshop

Workshop on "Decay Spectroscopy at CARIBU: Advanced Fuel Cycle Applications, Nuclear Structure and Astrophysics"

April 14-16, 2011 at

Argonne NATIONAL LABORATORY

A workshop on "Decay Spectroscopy at CARIBU: Advanced Fuel Cycle Applications, Nuclear Structure and Astrophysics" will be held at Argonne National Laboratory on April 14-16, 2011.

The aim of the workshop is to discuss opportunities for decay studies at the Californium Rare Isotope Breeder Upgrade (CARIBU) of the ATLAS facility with emphasis on advanced fuel cycle (AFC) applications, nuclear structure and astrophysics research. The workshop will consist of review and contributed talks. Presentations by members of the local groups, outlining the status of relevant in-house projects and available equipment, will also be organized. Time will also be set aside to discuss and develop working collaborations for future decay studies at CARIBU.

Topics of interest include:

- Decay data of relevance to AFC applications with emphasis on reactor decay heat
- Discrete high-resolution gamma-ray spectroscopy following radioactive decay and related topics
- Calorimetric studies of neutron-rich fission fragments using Total Absorption Gamma-ray Spectrometry (TAGS) technique
- Beta-delayed neutron emissions and related topics
- Decay data needs for nuclear astrophysics

Workshop Organizers

Dr. Michael Carpenter, Argonne National Laboratory
Prof. Partha Chowdhury, University of Massachusetts Lowell
Dr. Jason Clark, Argonne National Laboratory
Dr. Filip Kondev, Argonne National Laboratory
Dr. Kim Lister, Argonne National Laboratory
Dr. Dariusz Seweryniak, Argonne National Laboratory

Please visit the Workshop web site for additional information about registration, program, lodging and transportation to Argonne.

http://www.ne.anl.gov/capabilities/nd/AFC-Apr11/

14-16th April 2011

79 Participants from 13 countries and 28 institutions

Aimed at engaging the community in CARIBU decay (and accelerated beam) physics.

Decay Heat
Astrophysics
Nuclear Structure

CARIBU – Californium Rare Ion Breeder Upgrade

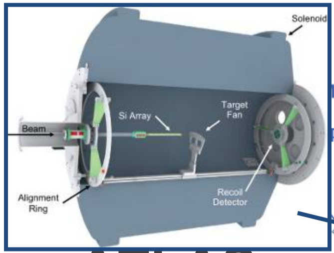
Access to n-rich region obtained at ATLAS via fission of the most neutron-rich “available” very heavy nuclei (e.g. ^{252}Cf)

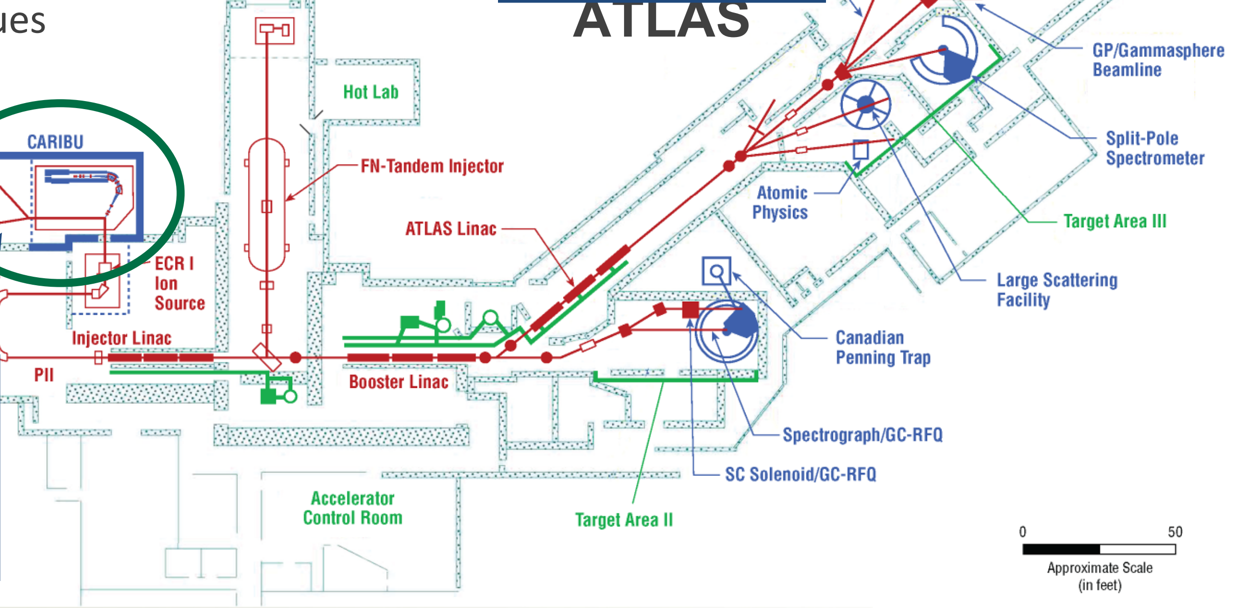
- Project goal: Provide neutron-rich radioactive beams to user community
  - Low-energy
    - Masses, decay spectroscopy, laser spectroscopy, …
  - Reaccelerated through ATLAS at up to 15 MeV/u
    - Single particle structure, gamma-ray spectroscopy, …

- Project Description
  - Gas catcher/RFQ cooler
  - Source and radiological issues
  - Isobar separator
  - ECR Charge-breeder
  - Diagnostics
  - Experimental equipment

Gammasphere

HELIOS spectrometer





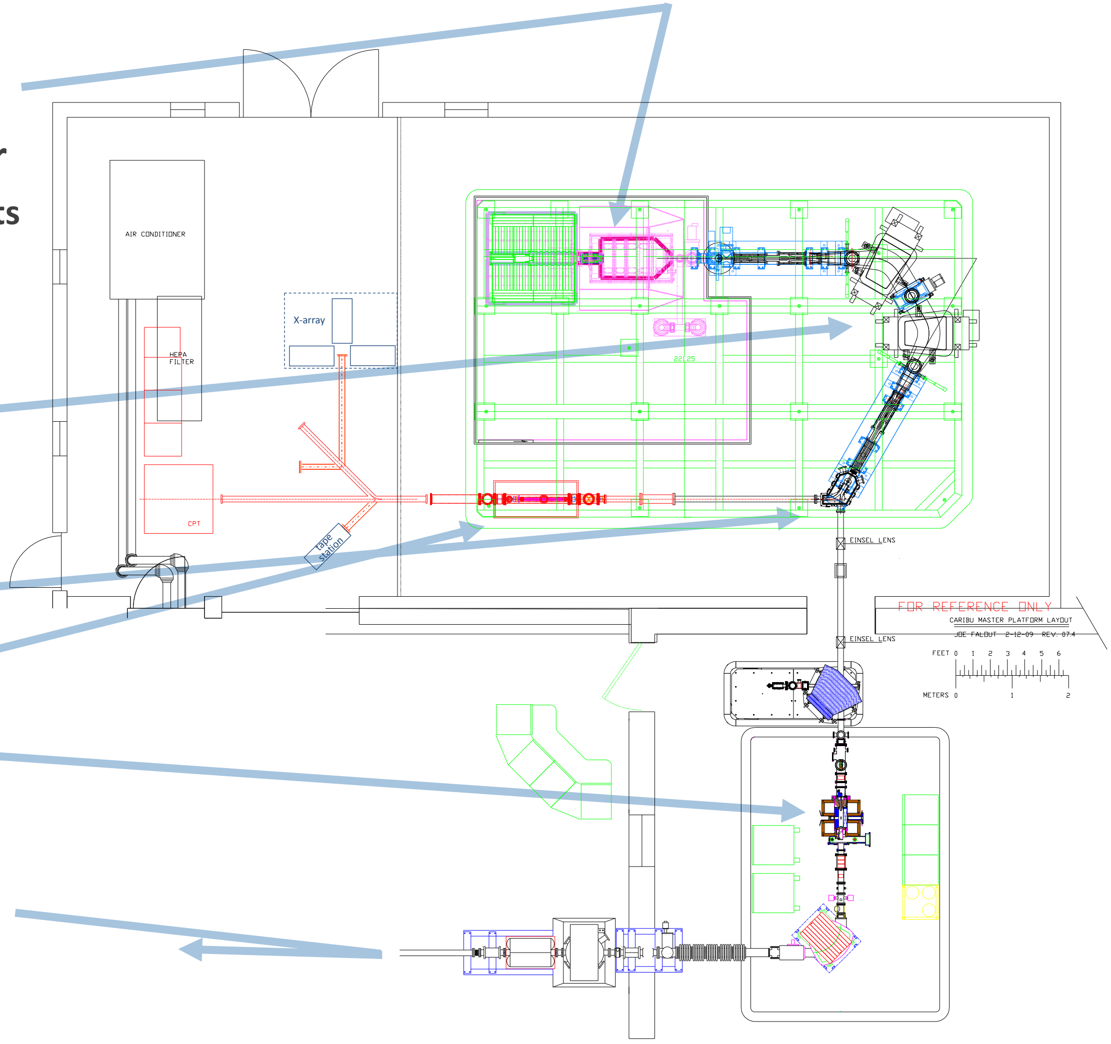
CPT mass spectrometer

X-array

Neutron-rich beam source: CARIBU "front end" layout

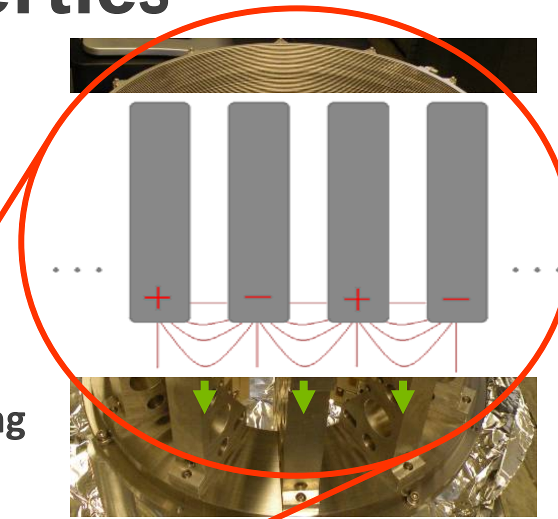
Main components of CARIBU

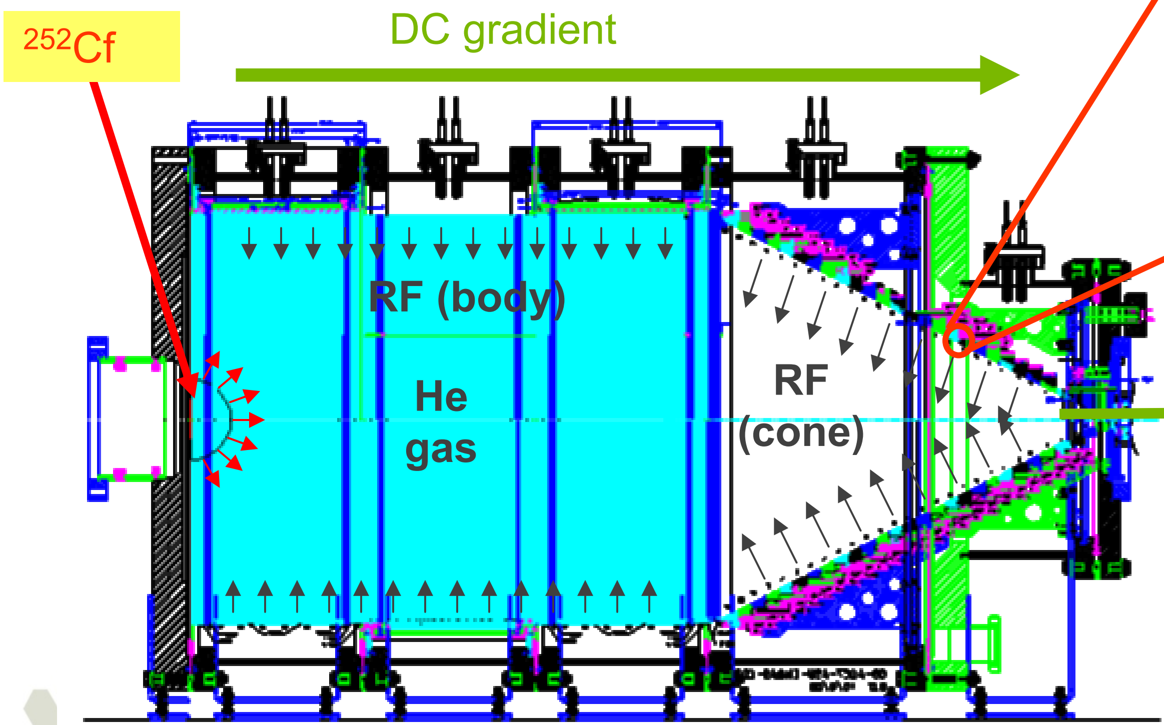
- **PRODUCTION**: "ion source" is ^{252}Cf source inside gas catcher
  - Thermalizes fission fragments
  - Extracts all species quickly
  - Forms low emittance beam
- **SELECTION**: Isobar separator
  - Purifies beam
- **DELIVERY**: beamlines and preparation
  - Switchyard
  - Low-energy buncher and beamlines
  - Charge breeder to Increase charge state for post-acceleration
  - Post-accelerator ATLAS and weak-beam diagnostics

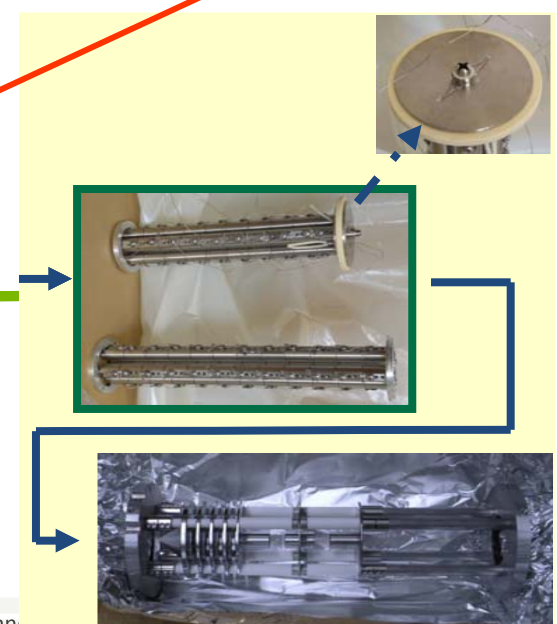


CARIBU gas catcher: transforms fission recoils into a beam with good optical properties

- Based on smaller devices developed at ANL
  - Radioactive recoils stop in sub-ppb level impurity Helium gas
  - Radioactive ion transport by RF field + DC field + gas flow
  - Stainless steel and ceramics construction (1.2 m length, 50 cm inner diameter)
  - Fast and essentially universally applicable
  - Extraction in 2 RFQ sections with µRFQs for differential pumping

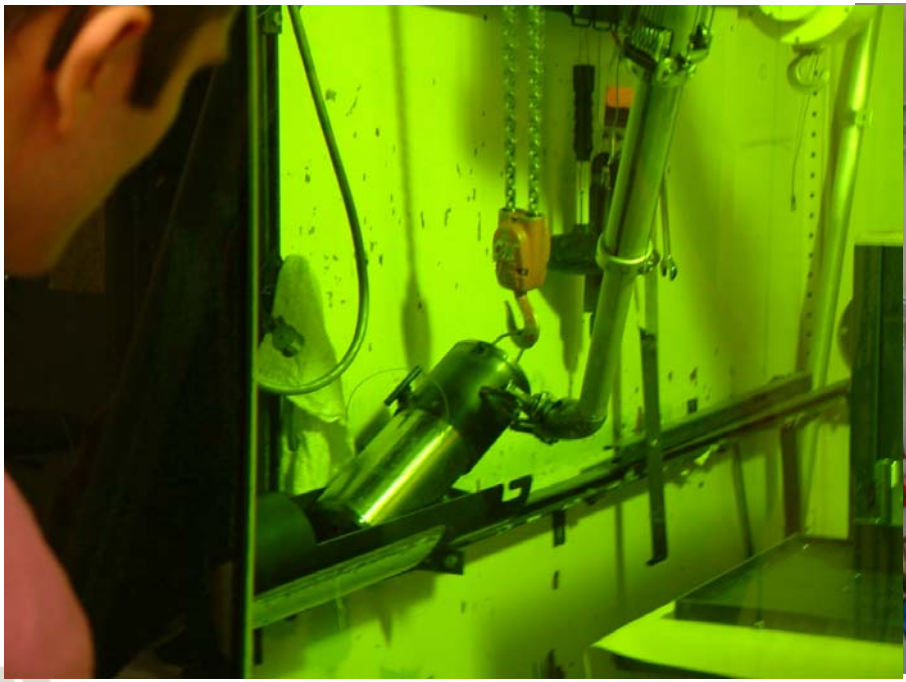






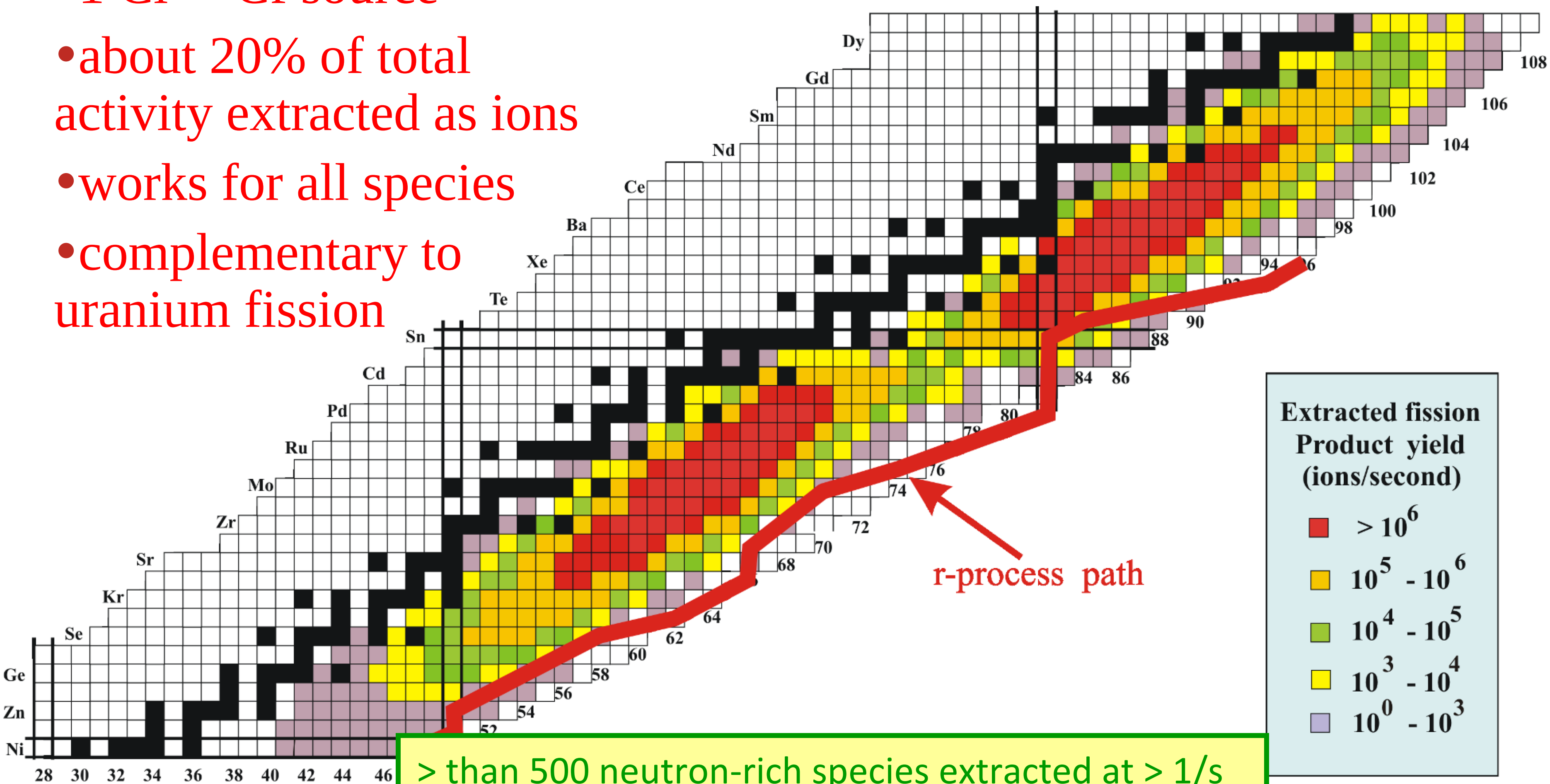
Californium source and transport cask

- Cf source is made at the HIFR high-flux reactor in Oak Ridge (~50 rem/hr unshielded)
  - Progression of 3 sources … 2 mCi, 80 mCi, "1 Ci"
- Transported in a steel/cement cask to Argonne
- Installed in the CARIBU transport cask using manipulators in hot cells at Argonne
- Move in the cask on site at Argonne
- For installation in the gas catcher, the source and shielding plug are pushed from the storage location into position at the end of the gas catcher.
- The assembly is sealed to the gas catcher, the source being inside the gas catcher.



Extracted isotope yield at low energy (50 keV)

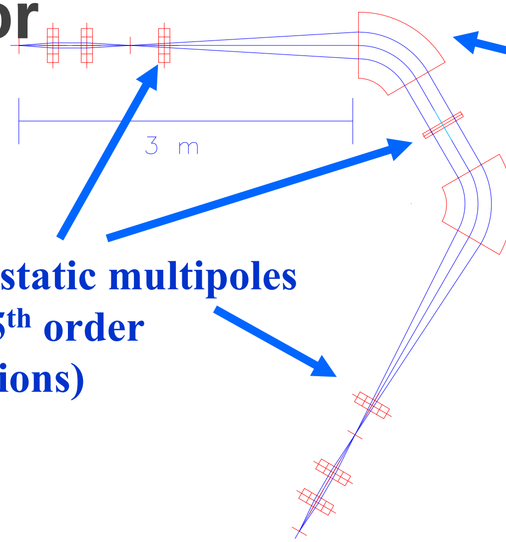
- 1 Ci ^{252}Cf source
- about 20% of total activity extracted as ions
- works for all species
- complementary to uranium fission



> than 500 neutron-rich species extracted at > 1/s

> 150 whose masses have never been measured

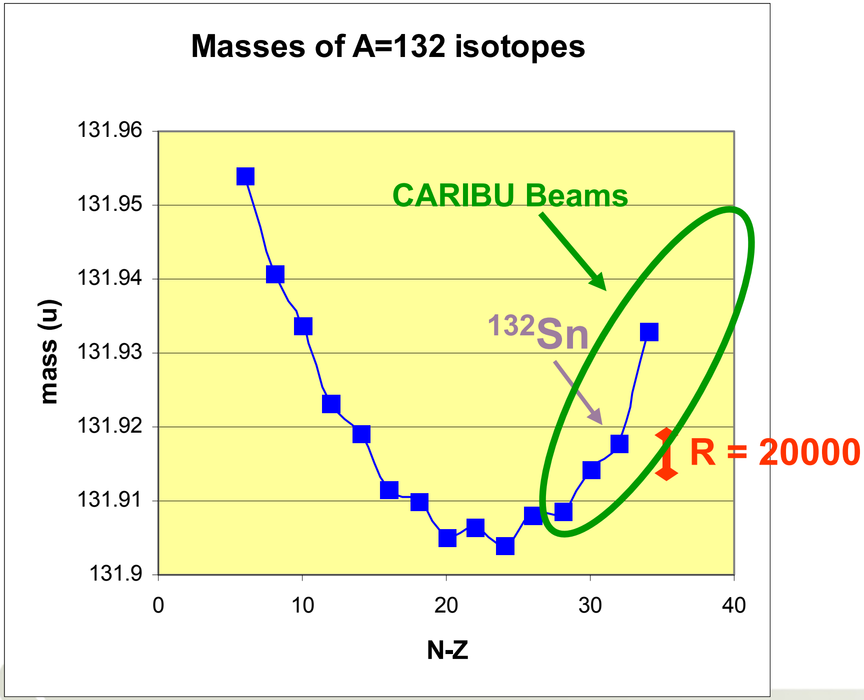
Fragment selection: Isobar separator

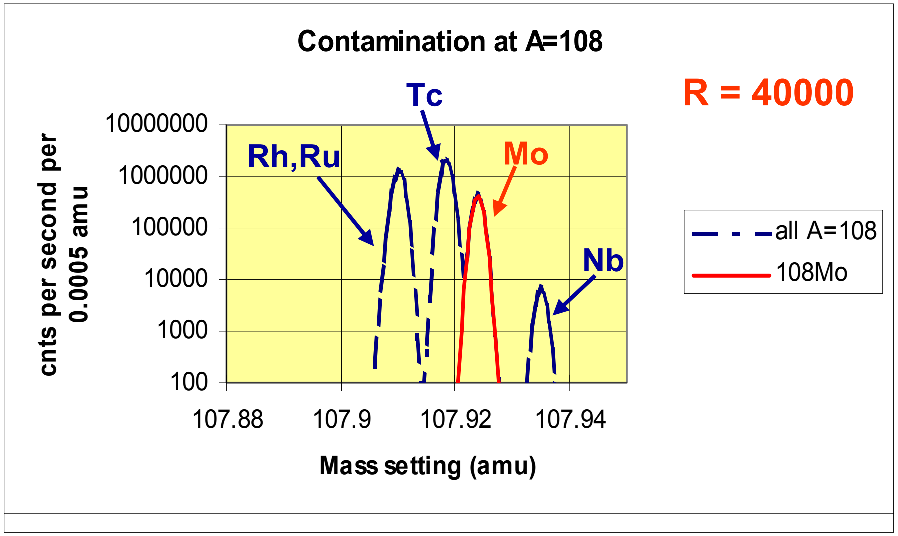


Compact design (fits on HV platform):

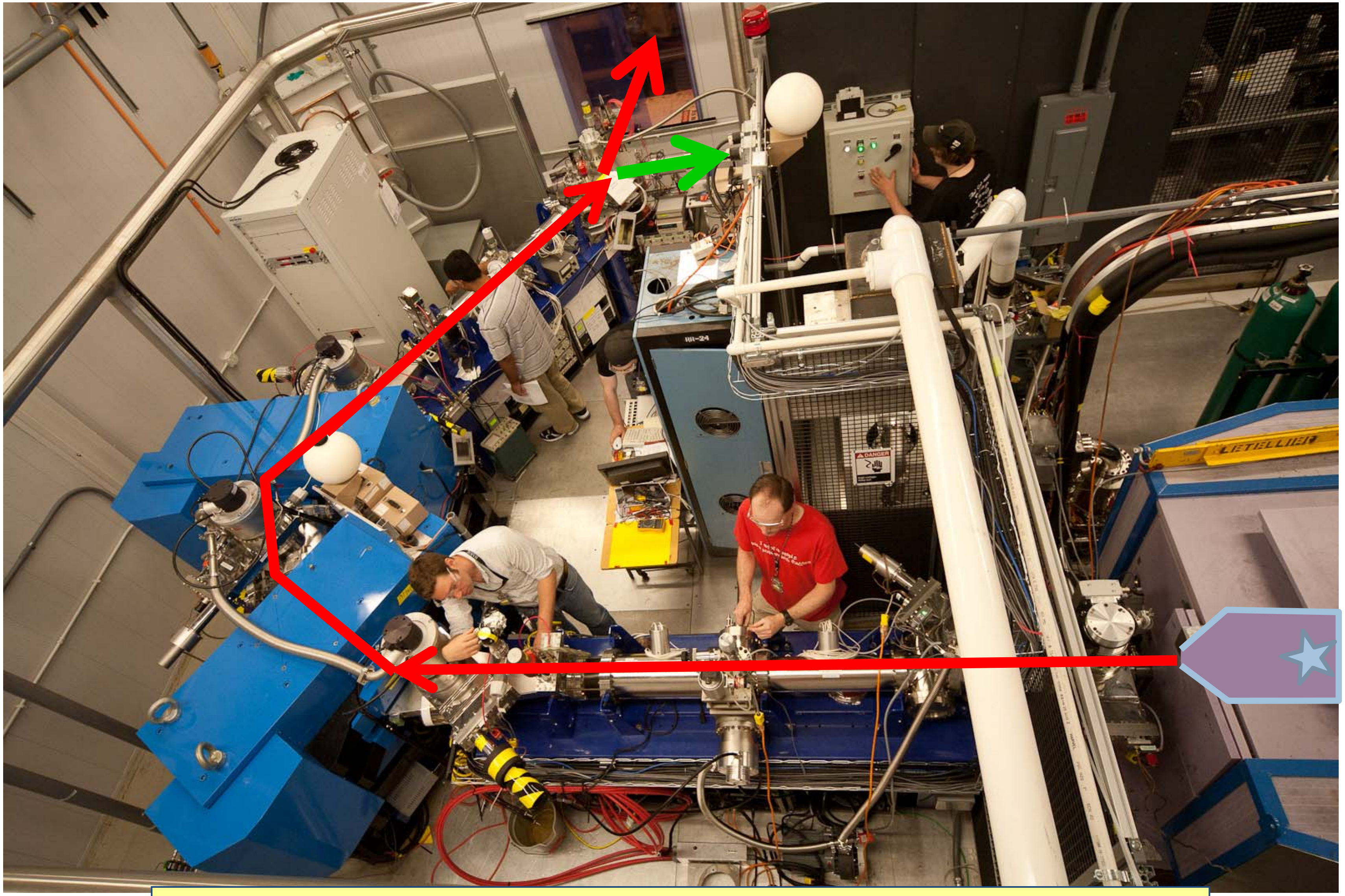
- two 60° bends
- 50 cm radius
- first-order mass resolving power: 20,000

Far from stability, mass separation is larger …





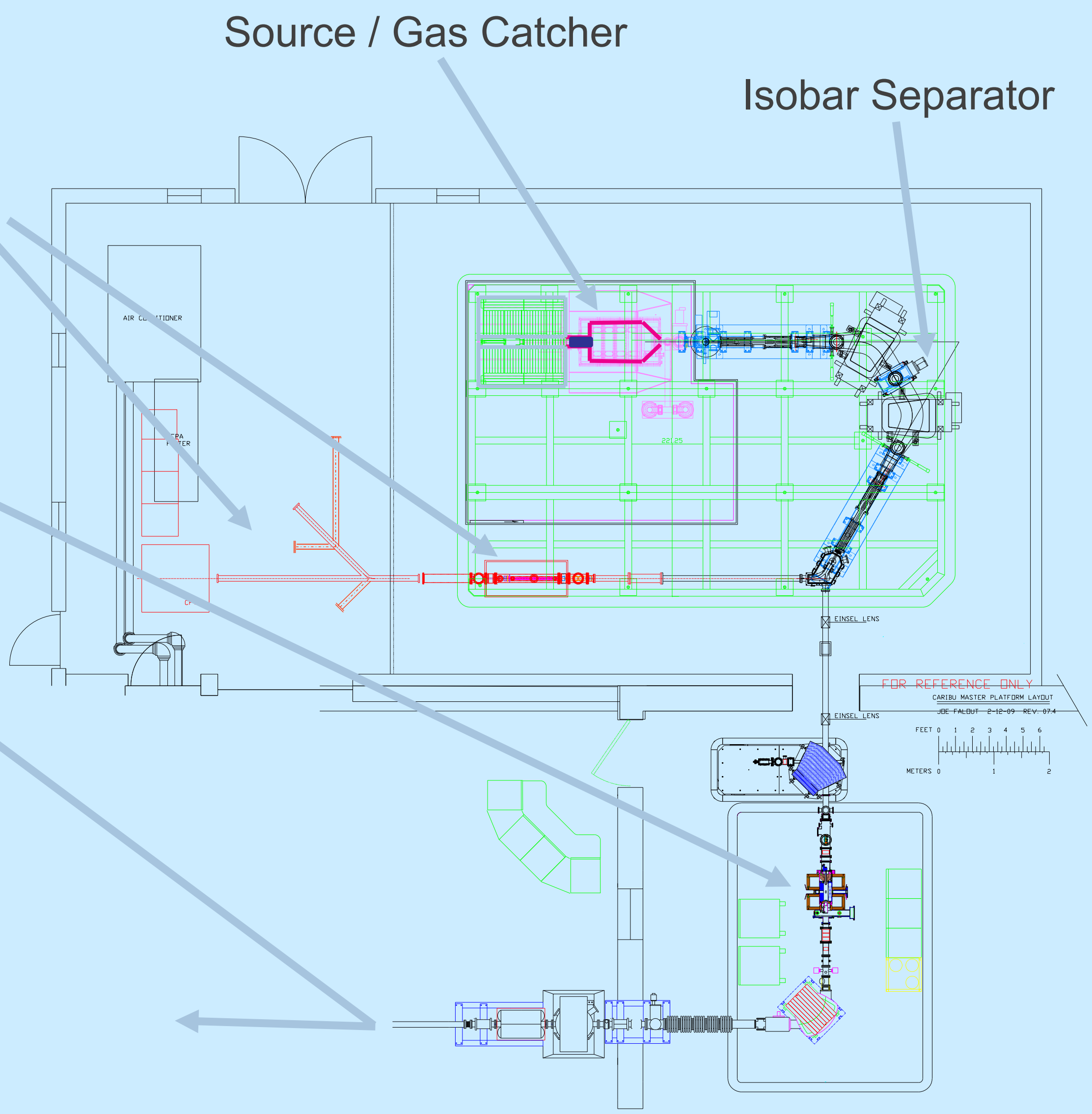
Selection by compact CARIBU isobar separator



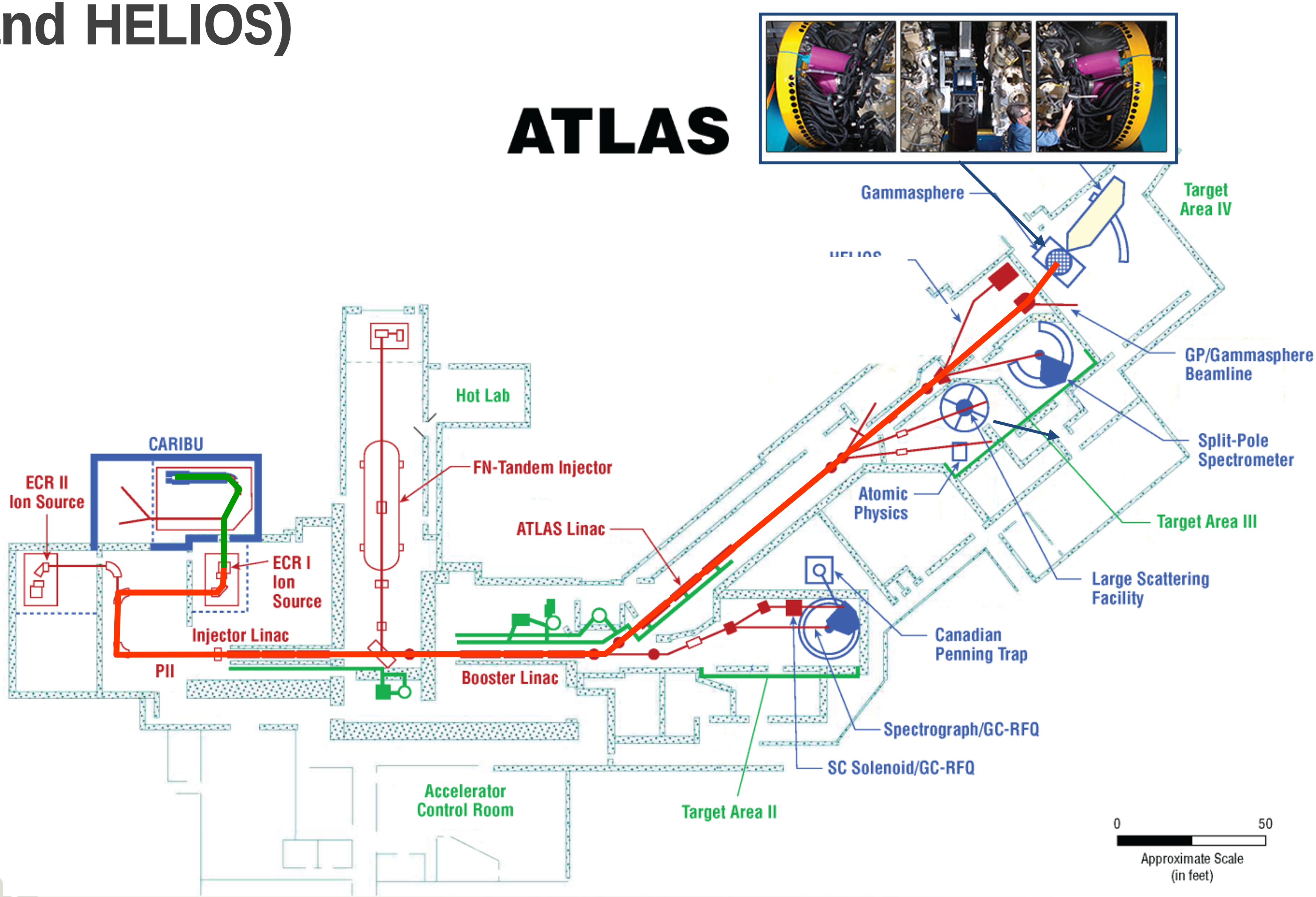
M/ΔM = 9000-14000 @ >80% transmission … still being improved

Beam Delivery

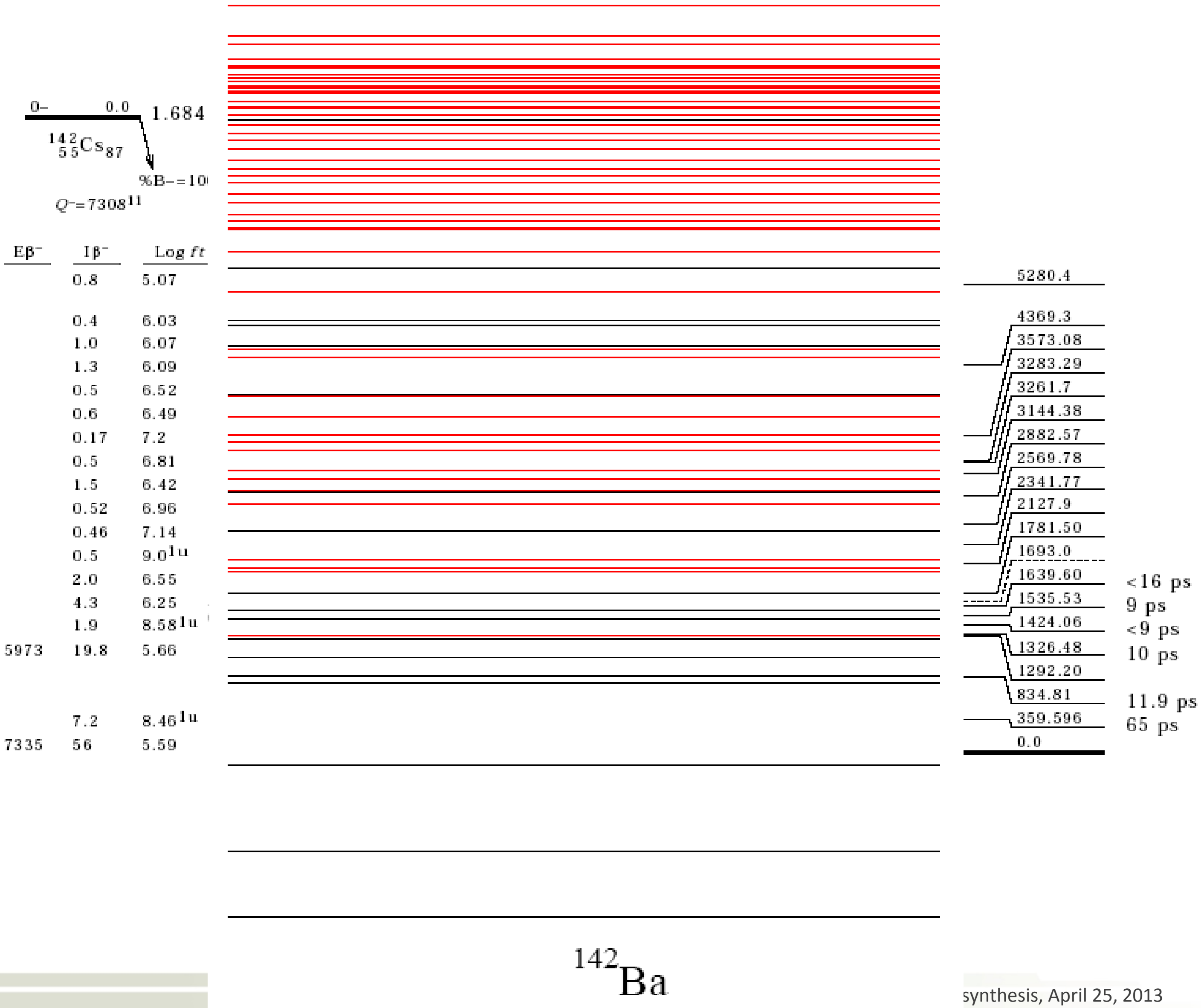
- **After isobar separation, two options for beam use**
- **Low energy experiments after beam bunching**
  - **Mass measurement**
  - **Laser Spectroscopy**
  - **Beta decay studies**
- **Reaccelerated Beams**
  - **Use ECR-1 as charge breeder**
  - **Inject ions into ATLAS in high charge state (q/m > 0.15) and energy (~100-200 keV)**



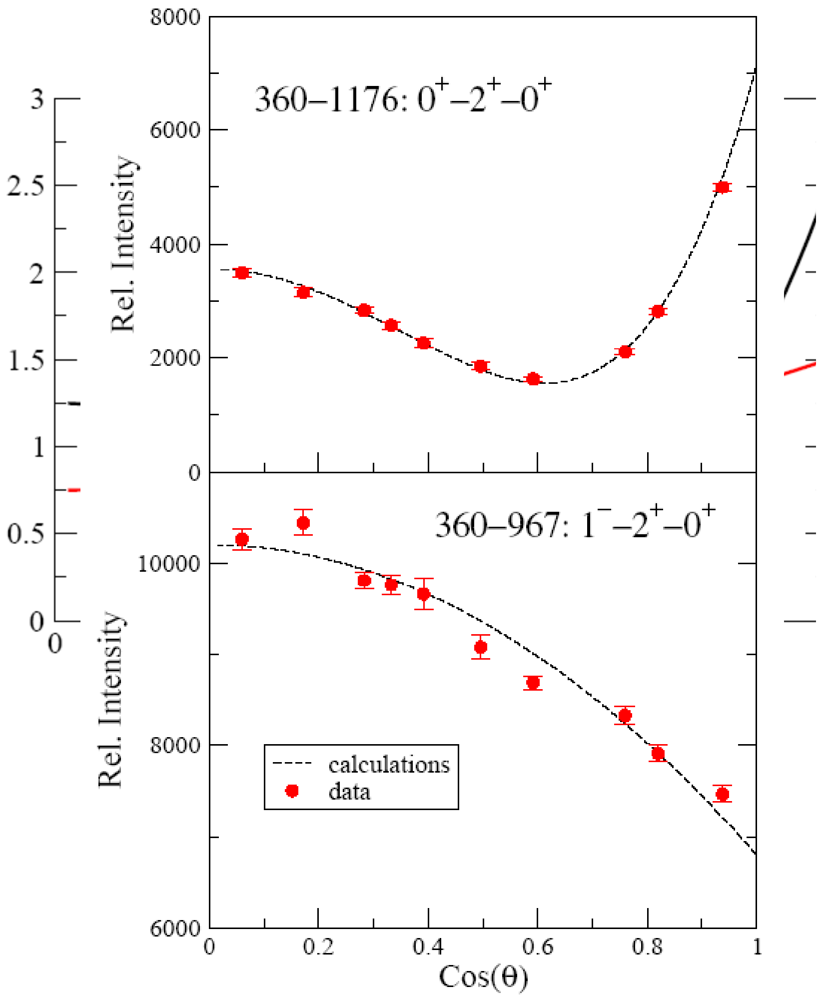
CARIBU beams reaccelerated to Gammasphere (… and HELIOS)

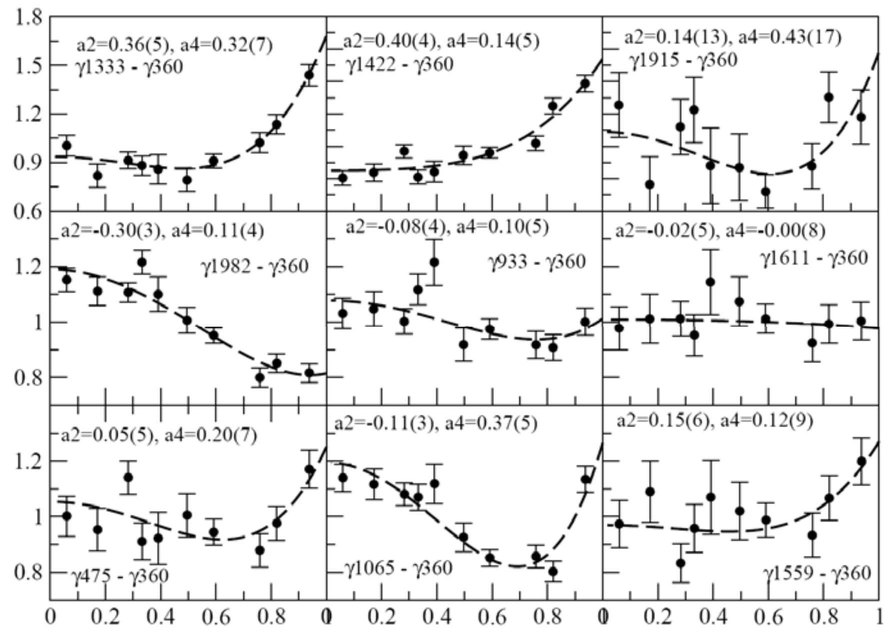


Decay of ^{142}Cs in Gammasphere: Expanded β-decay level scheme of ^{142}Ba



The power of Gammasphere: Spin-Parity Assignments via Angular Correlations





First Coulomb excitation measurement with a CARIBU beam

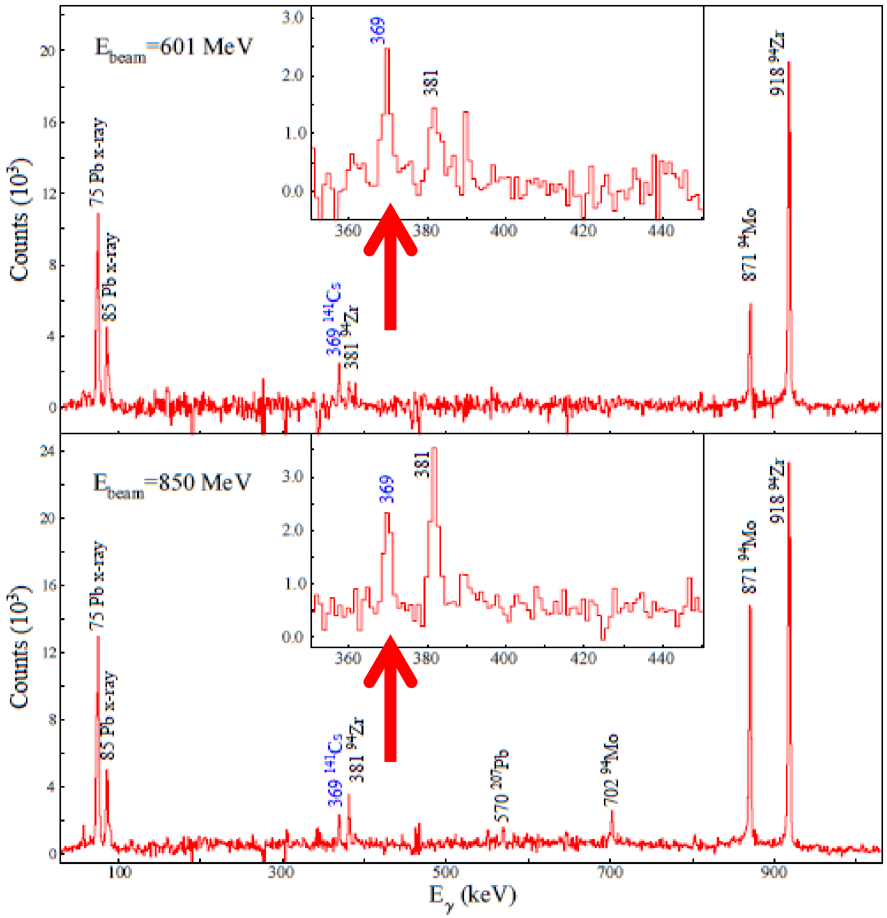


Figure: *Gamma-ray spectra from 601- & 850- MeV ^{141}Cs with the Coulomb excitation line at 369.2 keV.*

- First Coulex with ^{141}Cs – two goals:

1. Demonstrate feasibility & study backgrounds from stable beam contamination and β decay with 850 MeV beam on Pb; i.e., "unsafe" Coulomb excitation; 4300 part/sec for 14.5 hours run.

2. Measure B(E2) of the 11/2$^+$ state in ^{141}Cs, via "safe Coulex" at 601 MeV for ~62 hours with ~3360 part/sec.

- B(E2) = 20(5) W.u., smaller than the 2$^+$ level in ^{142}Ba (32(1) W.u.), but similar to the value for the 2$^+$ state in ^{140}Xe (25.6(8) W.u).

S. Zhu et al., to be published

Beam Delivery

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- Low energy experiments **after beam bunching**
  - Mass measurement
  - Laser Spectroscopy
  - Beta decay studies
- Reaccelerated Beams
  - Use ECR-1 as charge breeder
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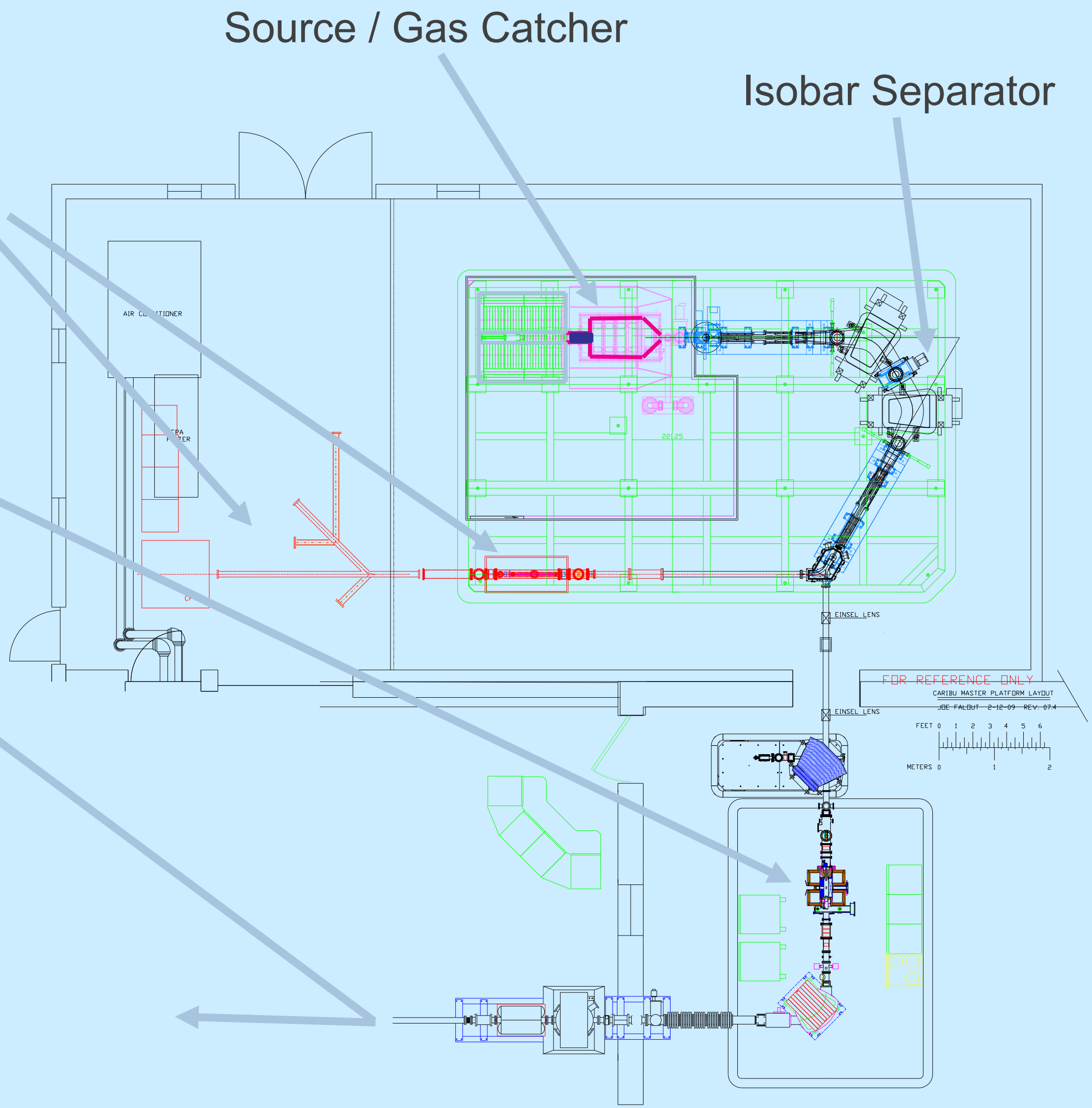
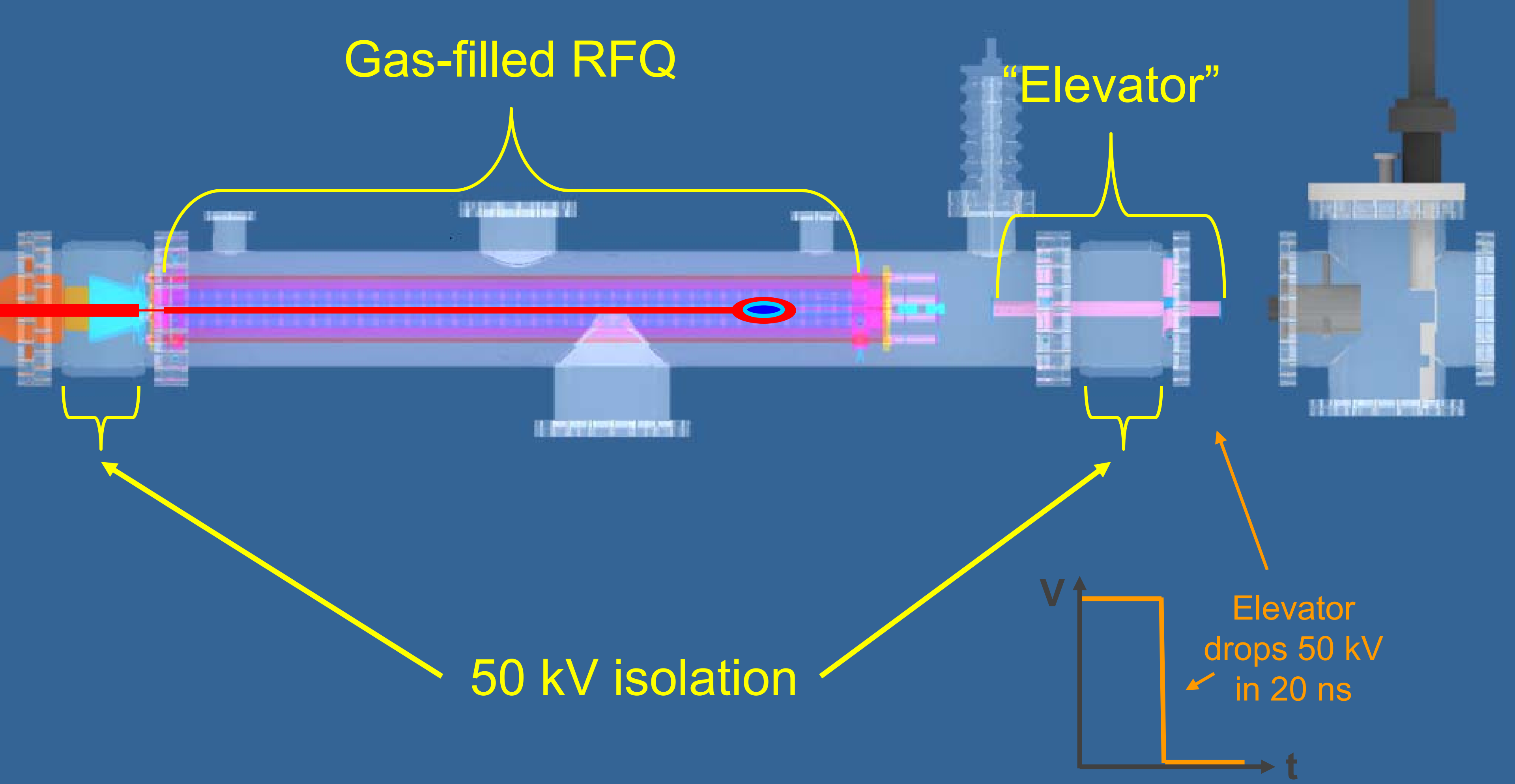


Low-energy buncher

- provides a pulse structure on low-energy beam and increases peak intensity by about 5 orders of magnitude
- Allows energy to be tuned from a few 100s of eV to 50 keV



The CARIBU low-energy experimental area

- Delivers 1.5 kV to 10 kV beam to experimental stations
- Pulsed beams with rates from ~ 50 ms to seconds
- Low emittance
- Experimental stations:

CPT

(installed)

TAPE STATION

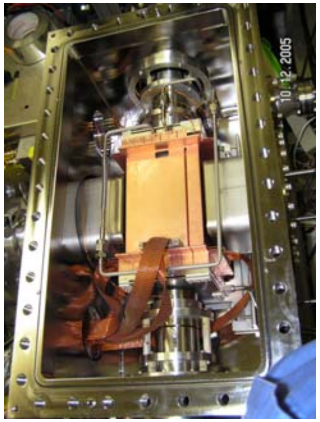
(installed)

X-ARRAY

(installed)

BPT

(late 2013)



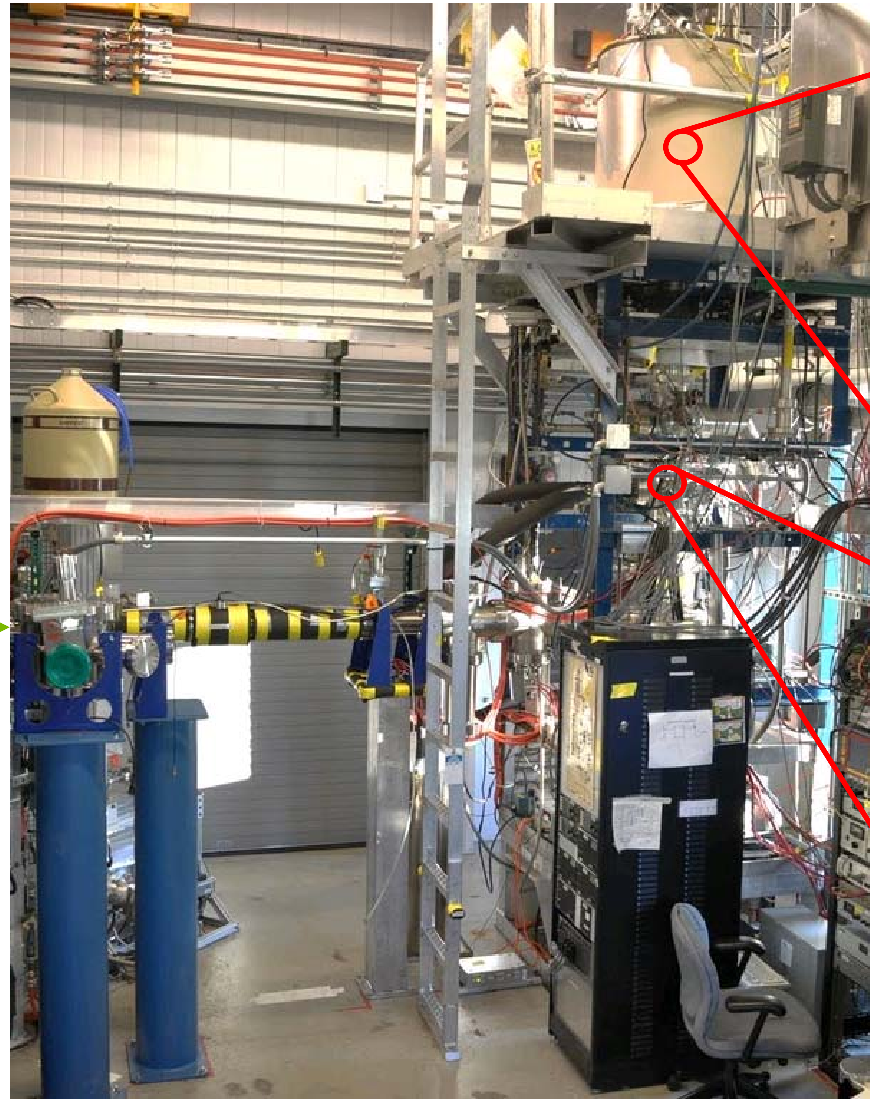
LASER SPECTROSCOPY: After CPT move (2013/2014)

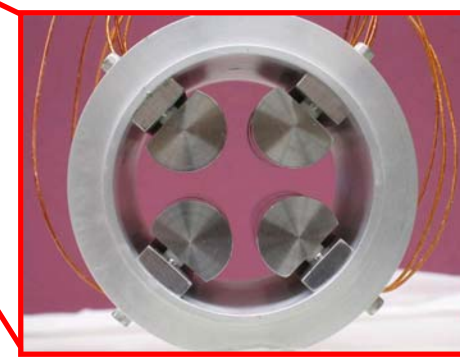
- **Limited amount of space … removal of Tandem will provide new experimental area**

The CPT apparatus at CARIBU

Penning Trap

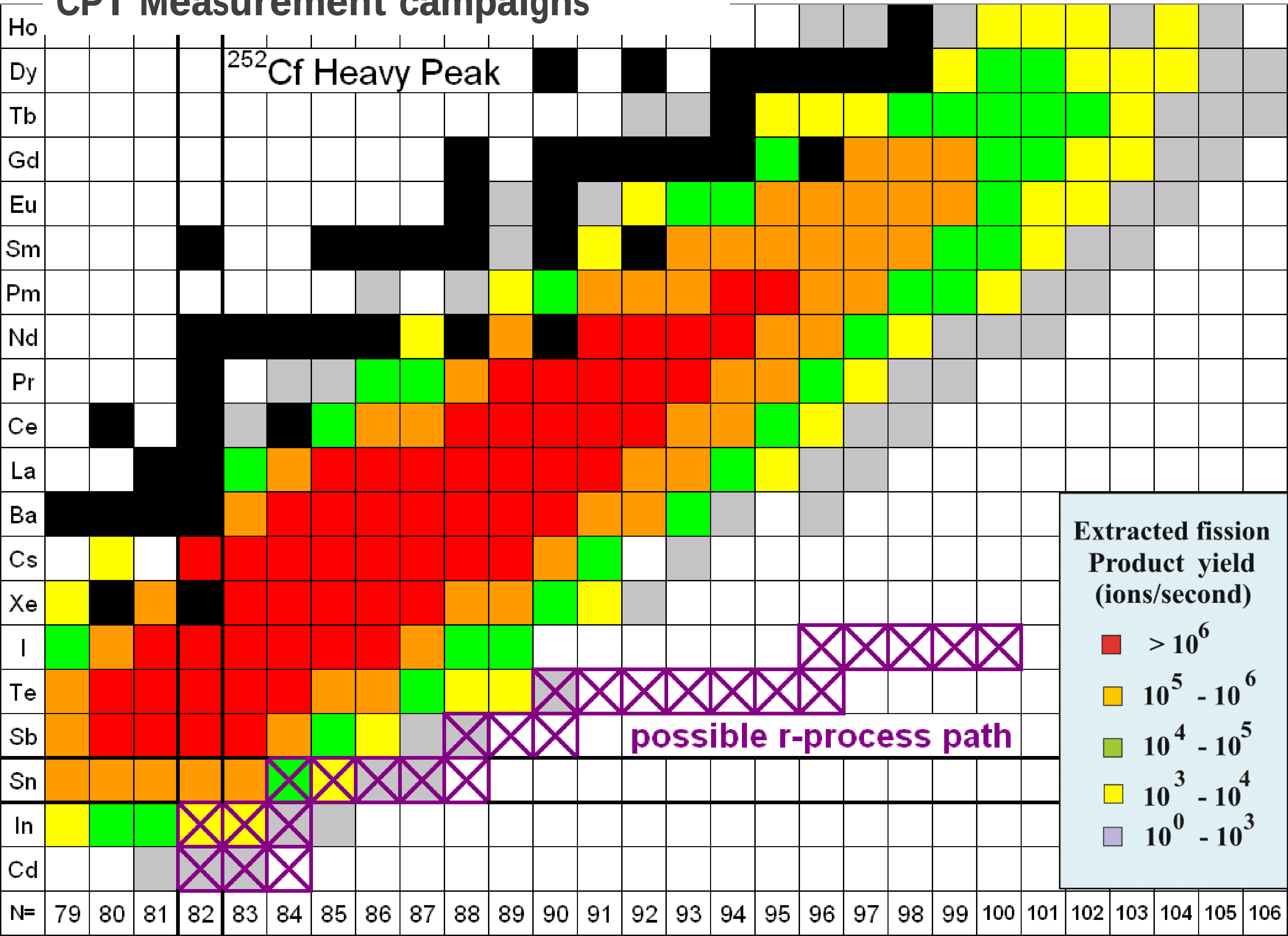
2 kV pulsed beam



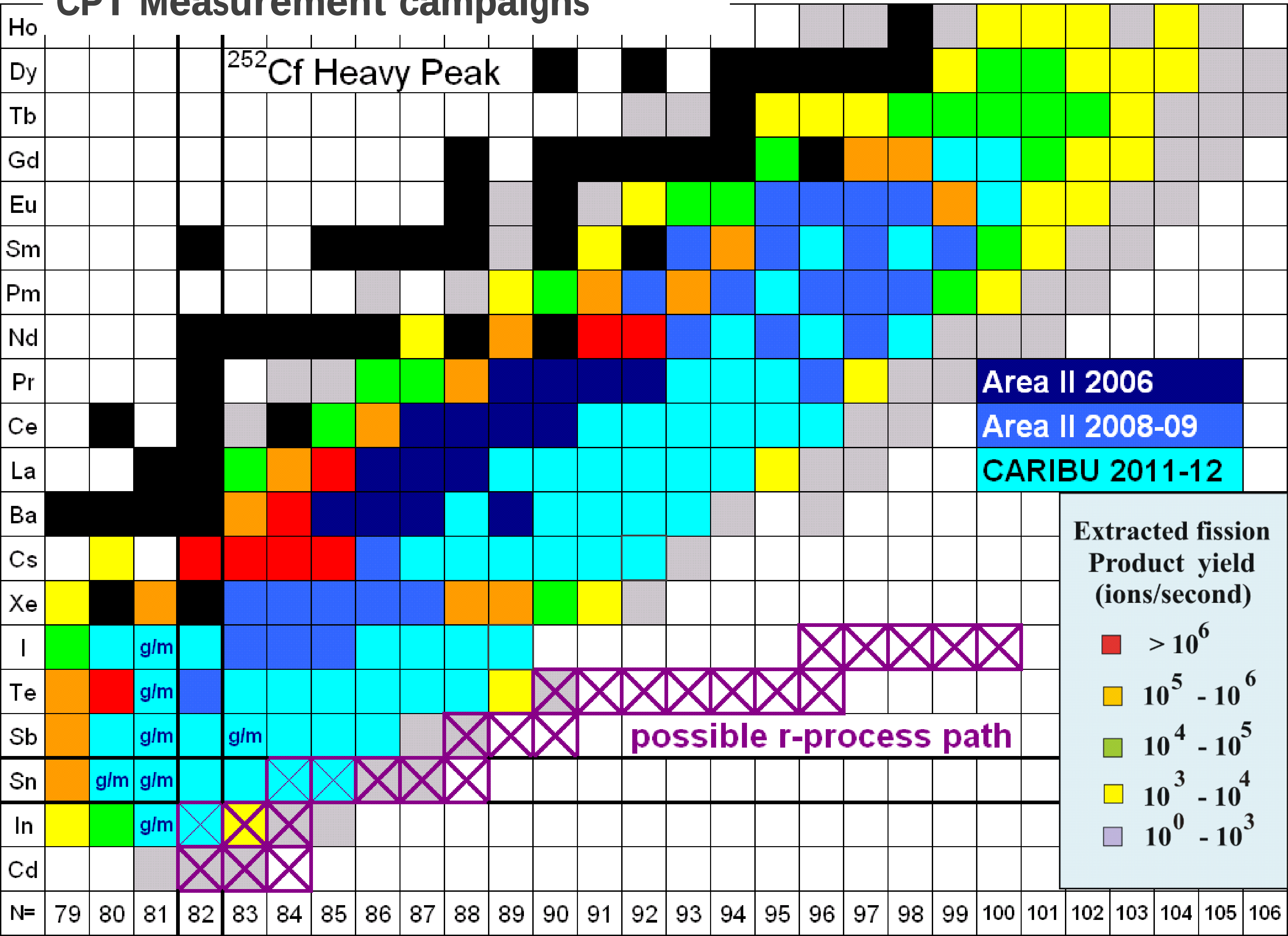


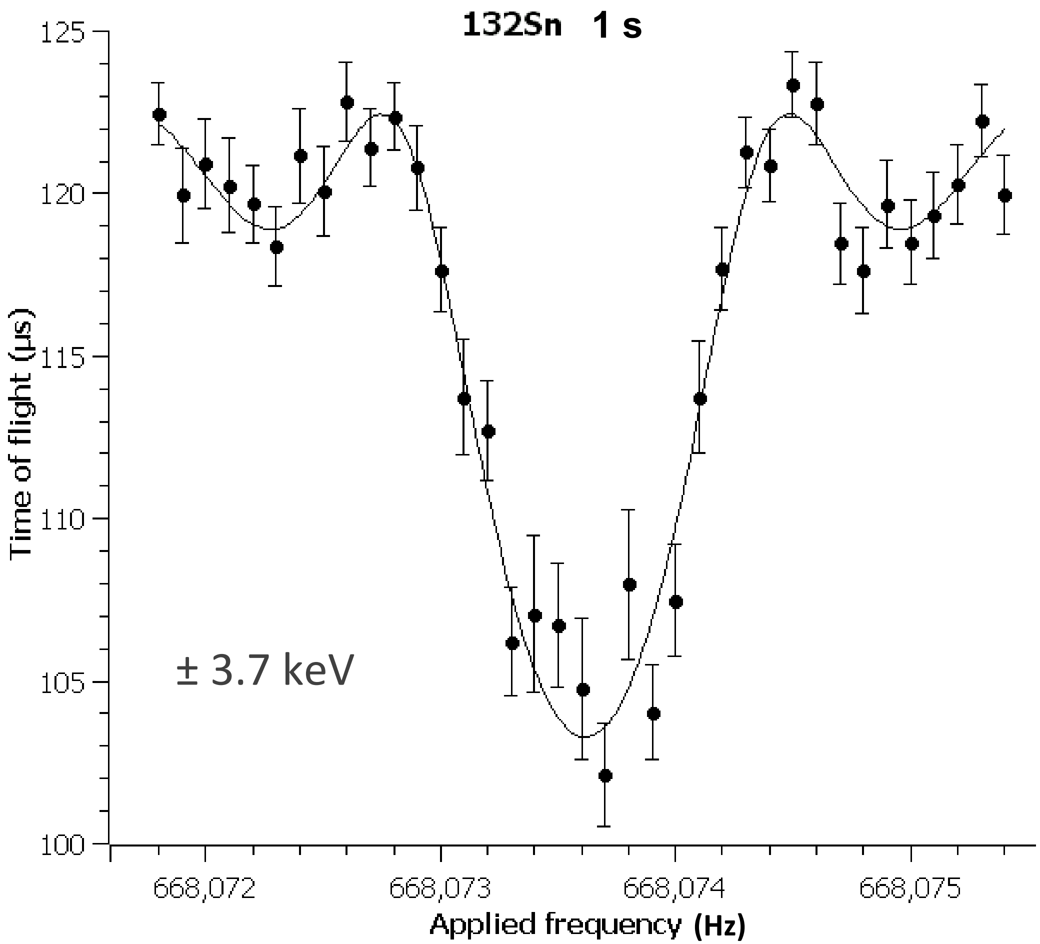
cryogenic linear ion trap

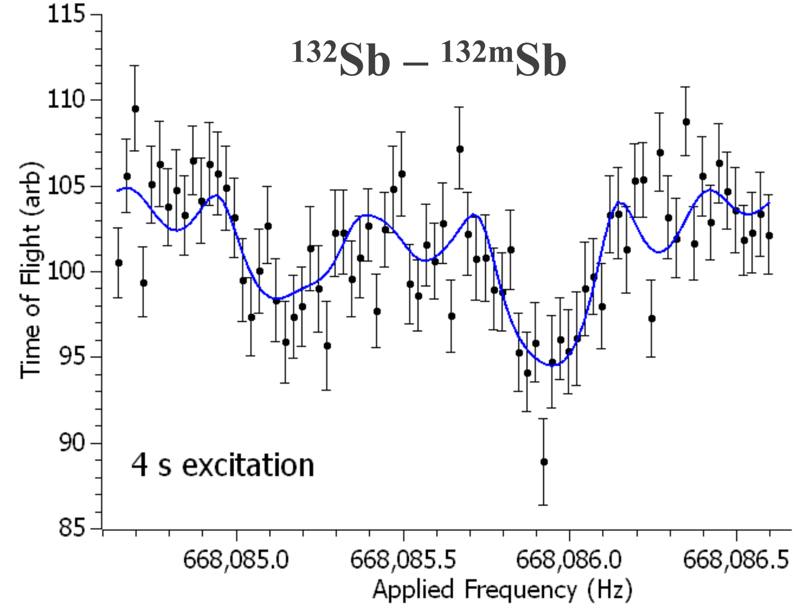
CPT Measurement campaigns

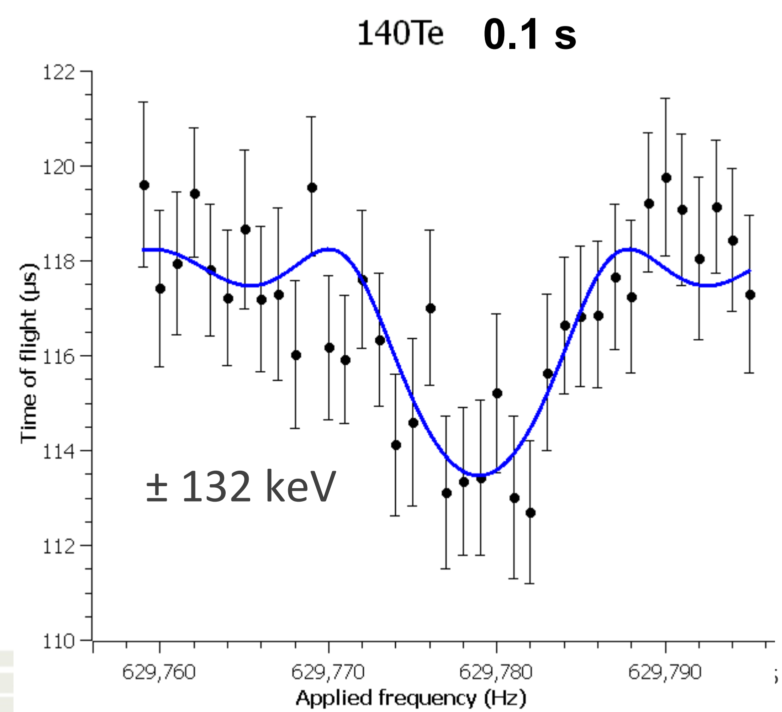


CPT Measurement campaigns





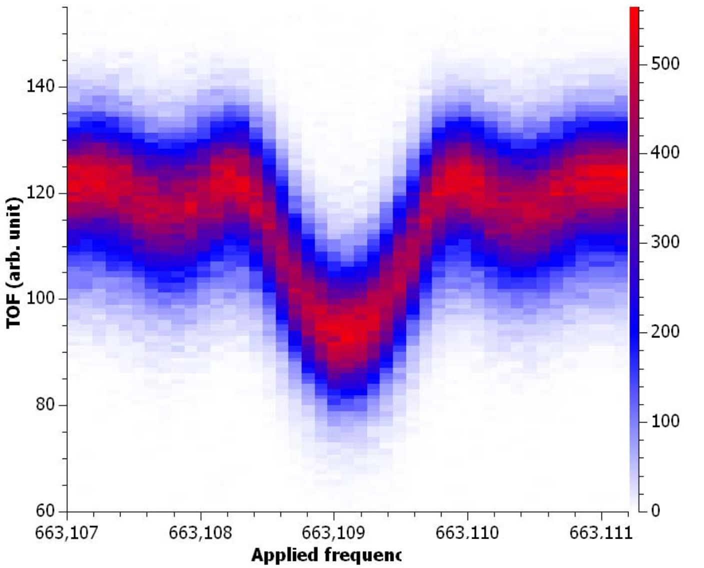




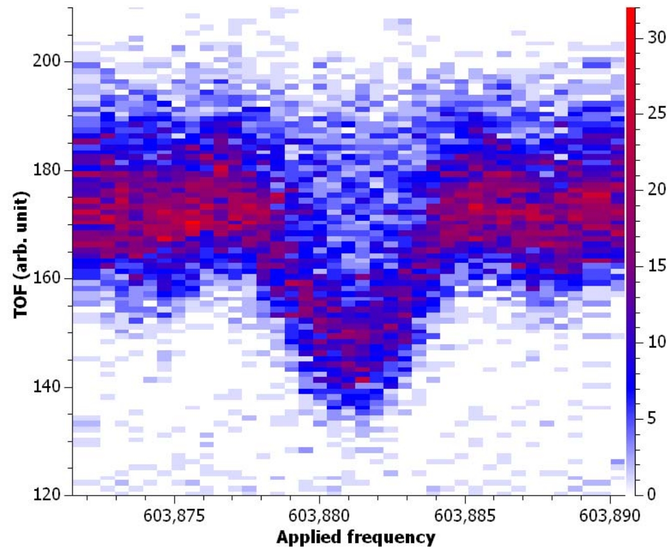
Typical precision 10-15 keV

Yield is still not the limitation … sample purity is

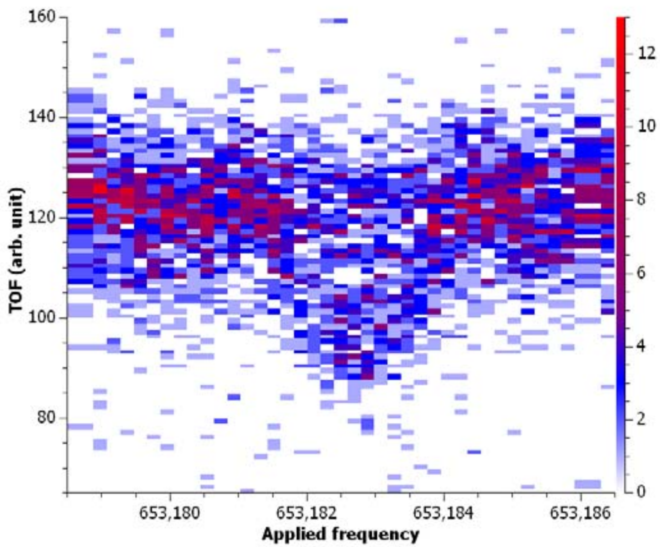
133Cs 1s excitation, 100% pure



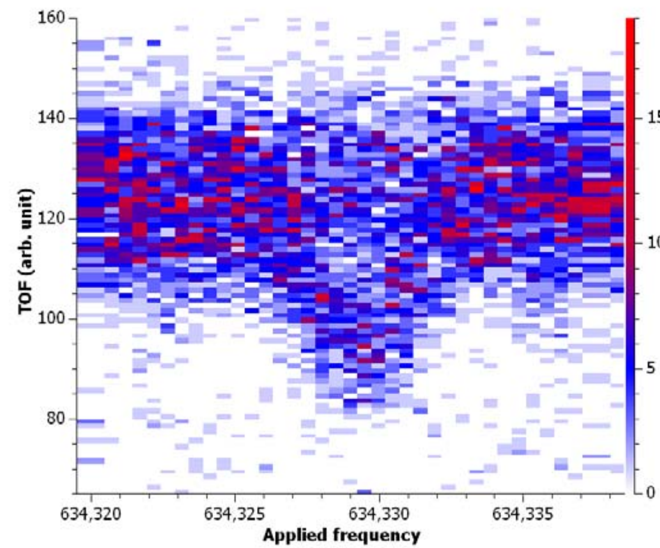
146Cs 0.2 s excitation, 64% pure



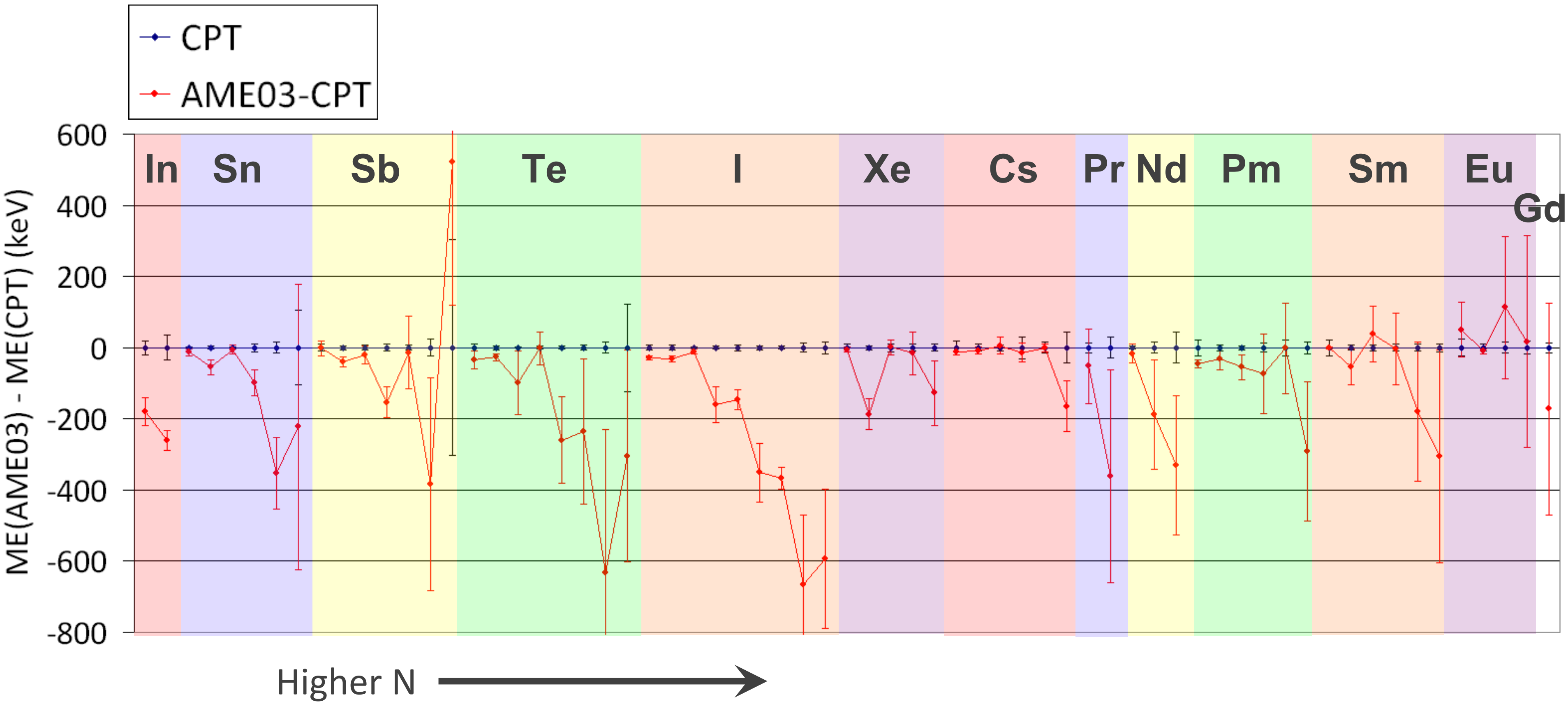
135Sb 0.5 s excitation, 49% pure



139Te 0.2 s excitation, 41% pure

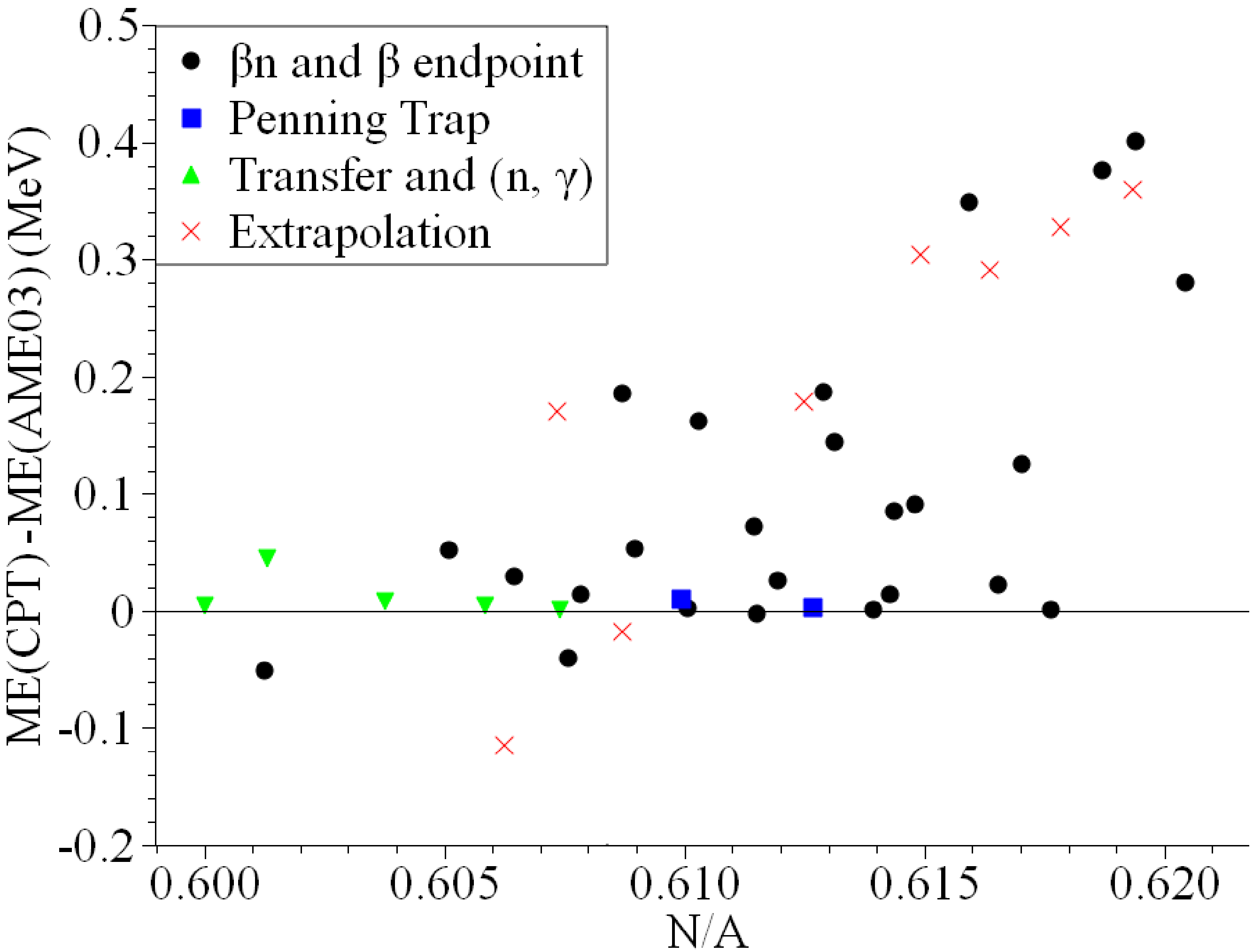


Atomic Mass Evaluation comparison



Trend: more neutron-rich nuclei are found to be less bound than expected away from stability

Why the difference with the atomic mass evaluation?



Adapted from J. Van Schelt et al, PRC85, 045805 (2012)

- **Deviations from 2003 atomic mass evaluation increase with neutron number**
- **Good agreement with other Penning trap results**
- **Good agreement with masses obtained through reaction Q values**
- **Large disagreement with results obtained with beta-decay measurements**

What is effect on *r* process? Simulate.

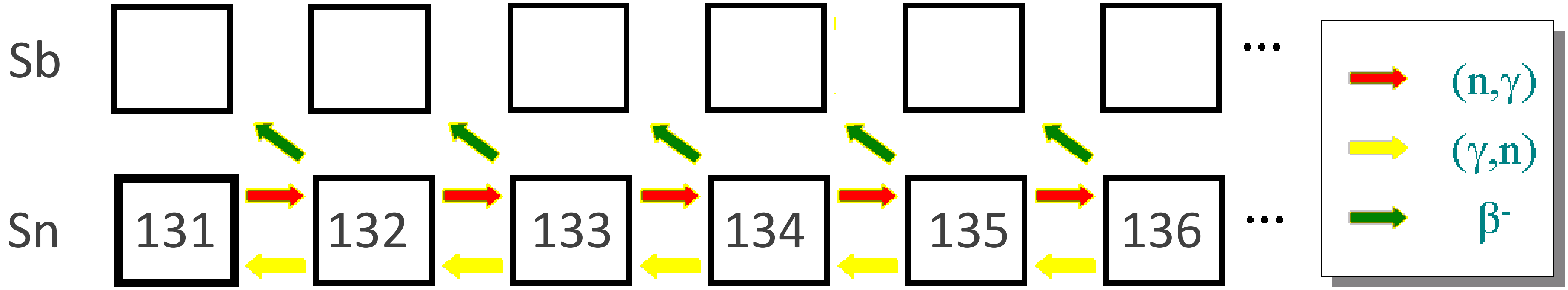
To see effect of new masses, ask a simple and answerable question:

What are the effective β-decay half-lives of the elements, and how do our new masses change them?

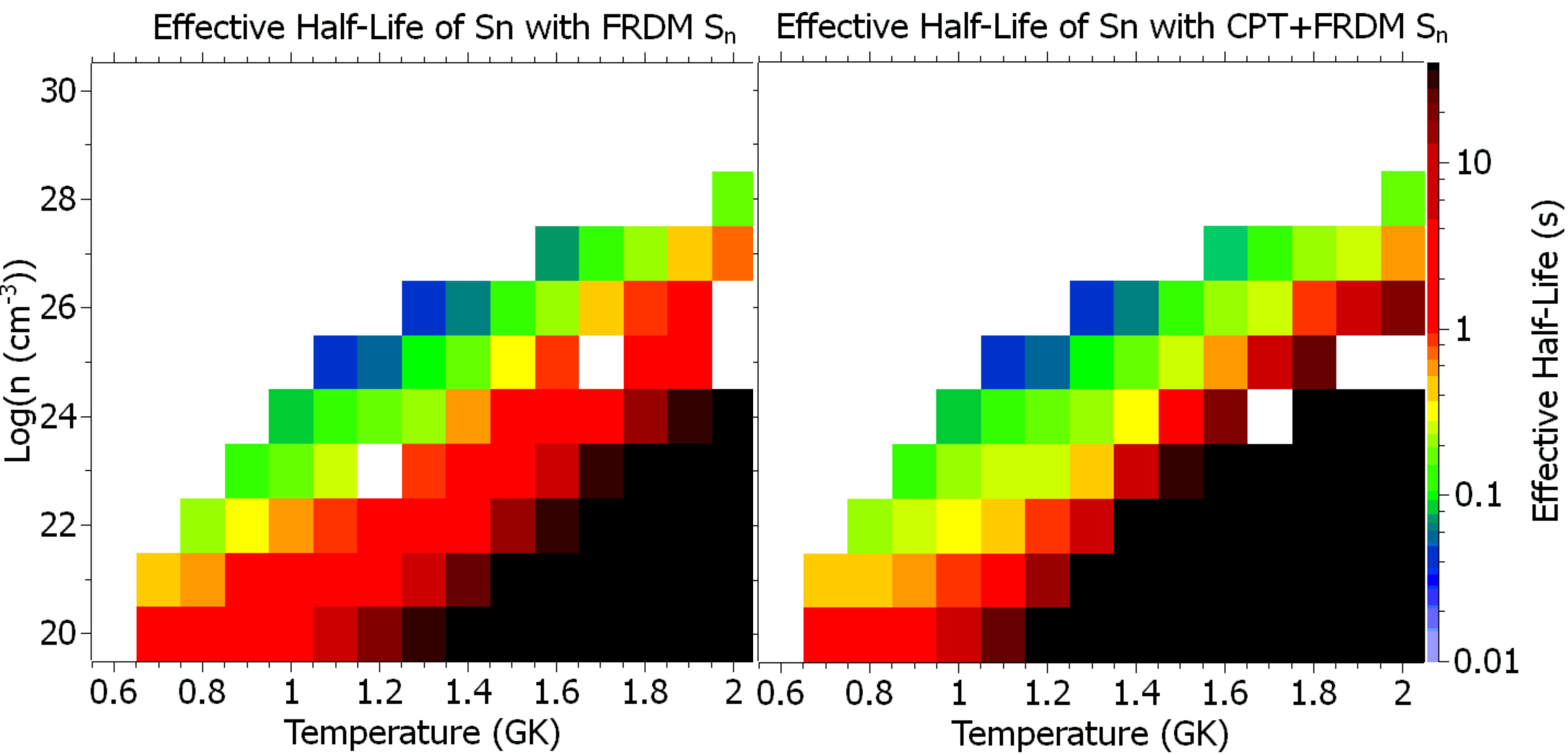
Sn will have biggest impact, but check at Sb and Te as well

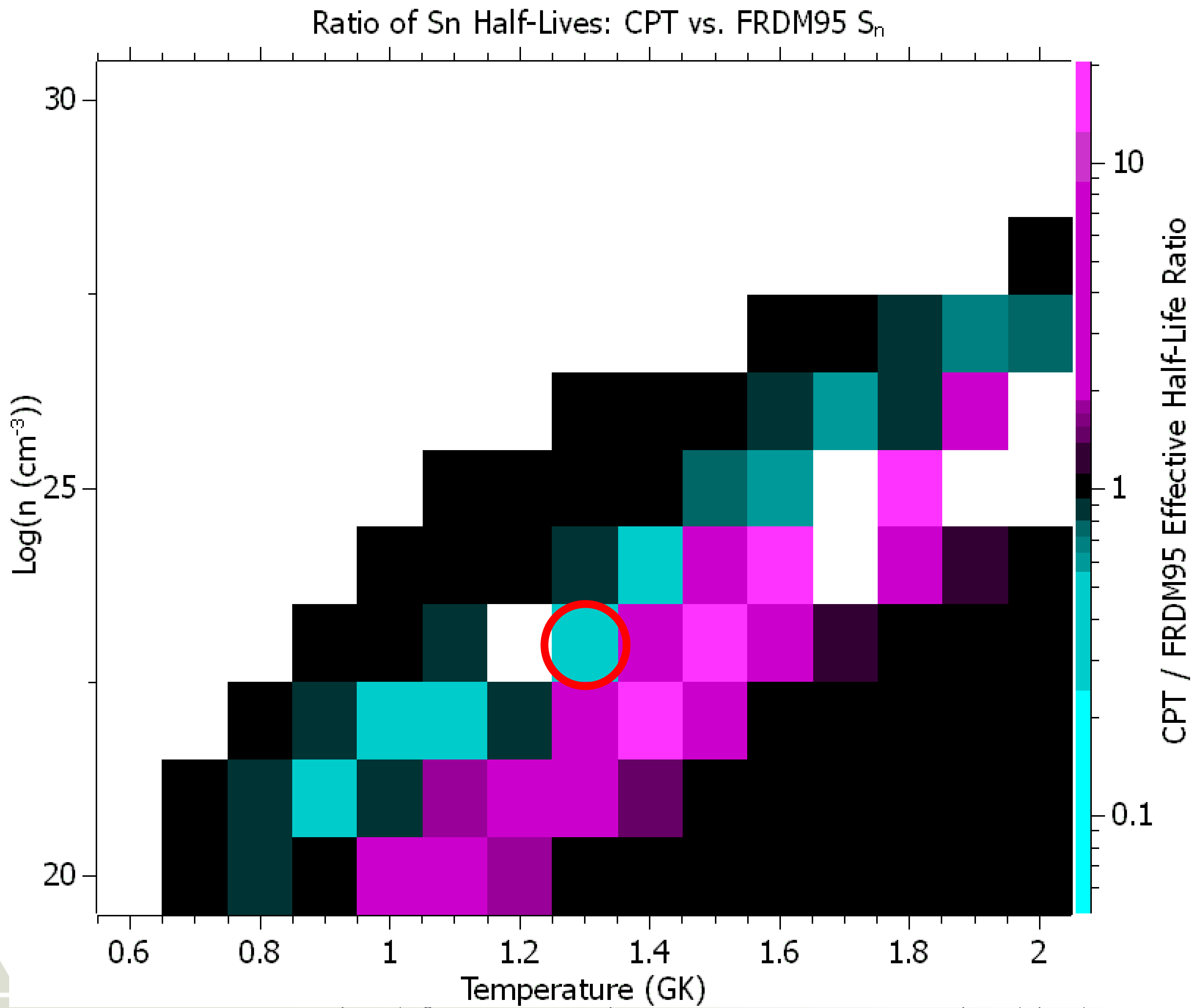
Simple numerical simulation:

- Select a temperature and density
- Seed on the side of stability, N=81
- Allow (n,γ), (γ,n), and β decay to occur
- See how long it takes for half of element to β-decay (or extrapolate if in equilibrium)
- Repeat over a range of temperatures and densities
- Repeat with real data and mass model to see impact of new masses

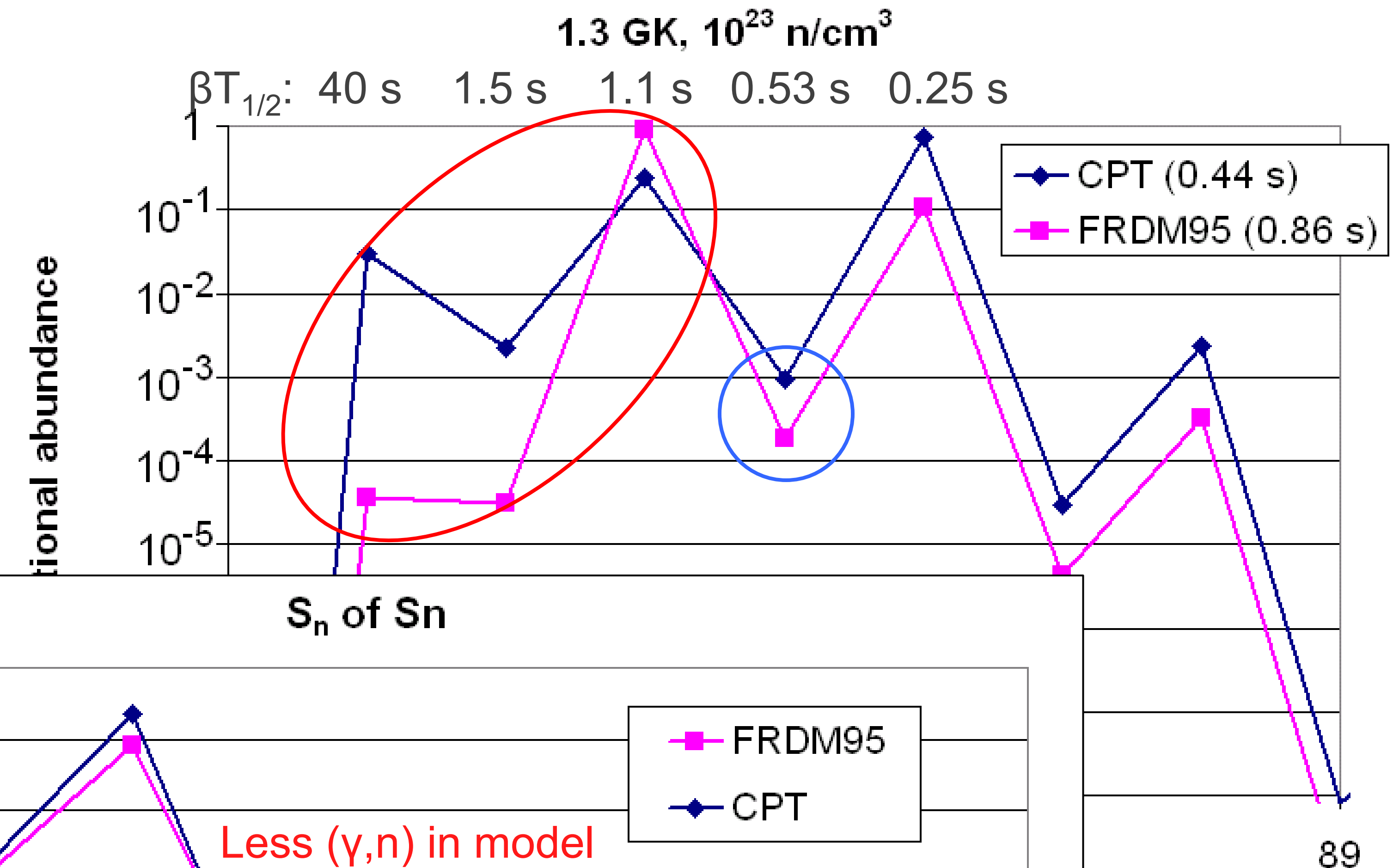


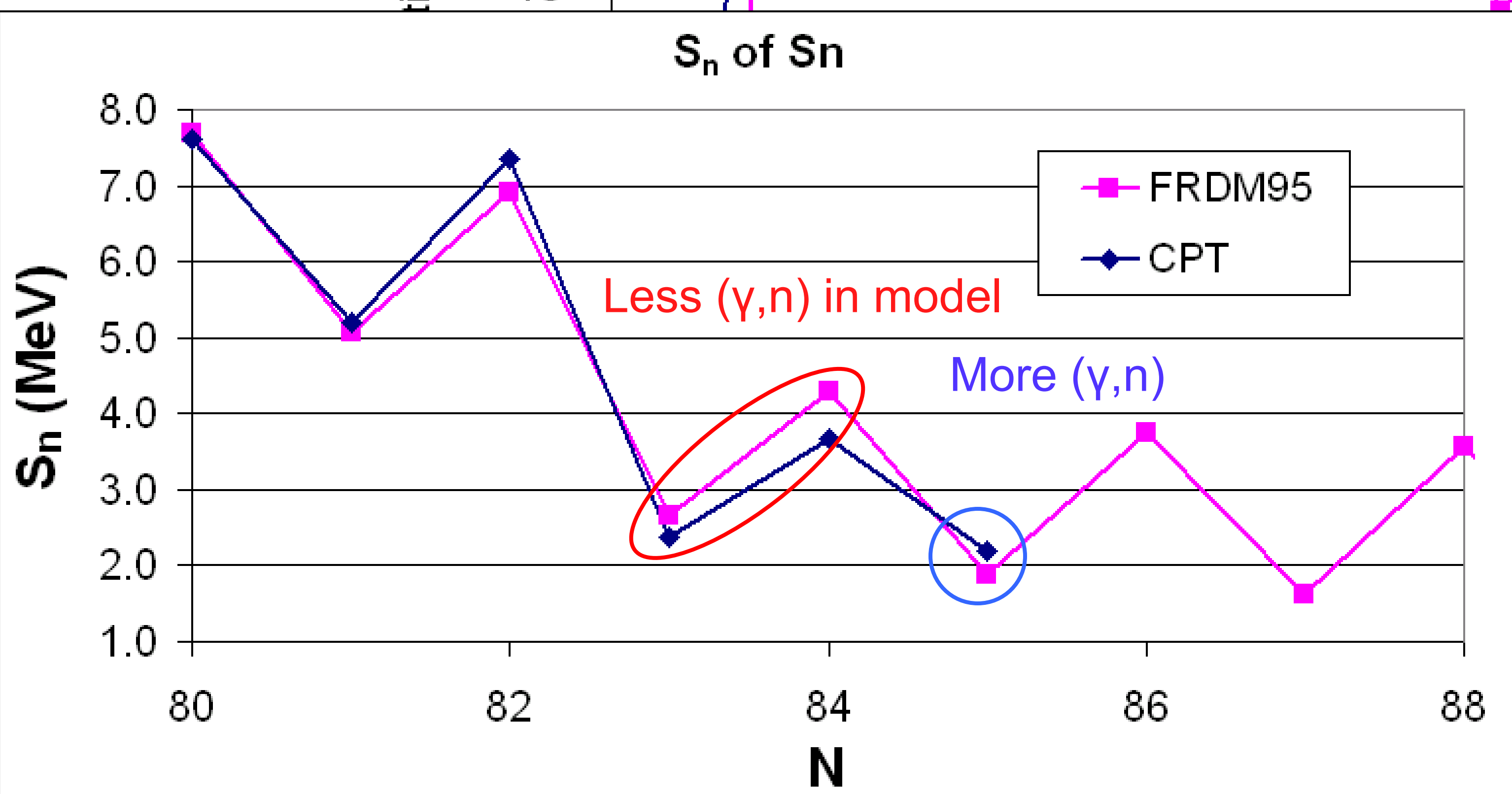
Effect of FRDM95 on Sn





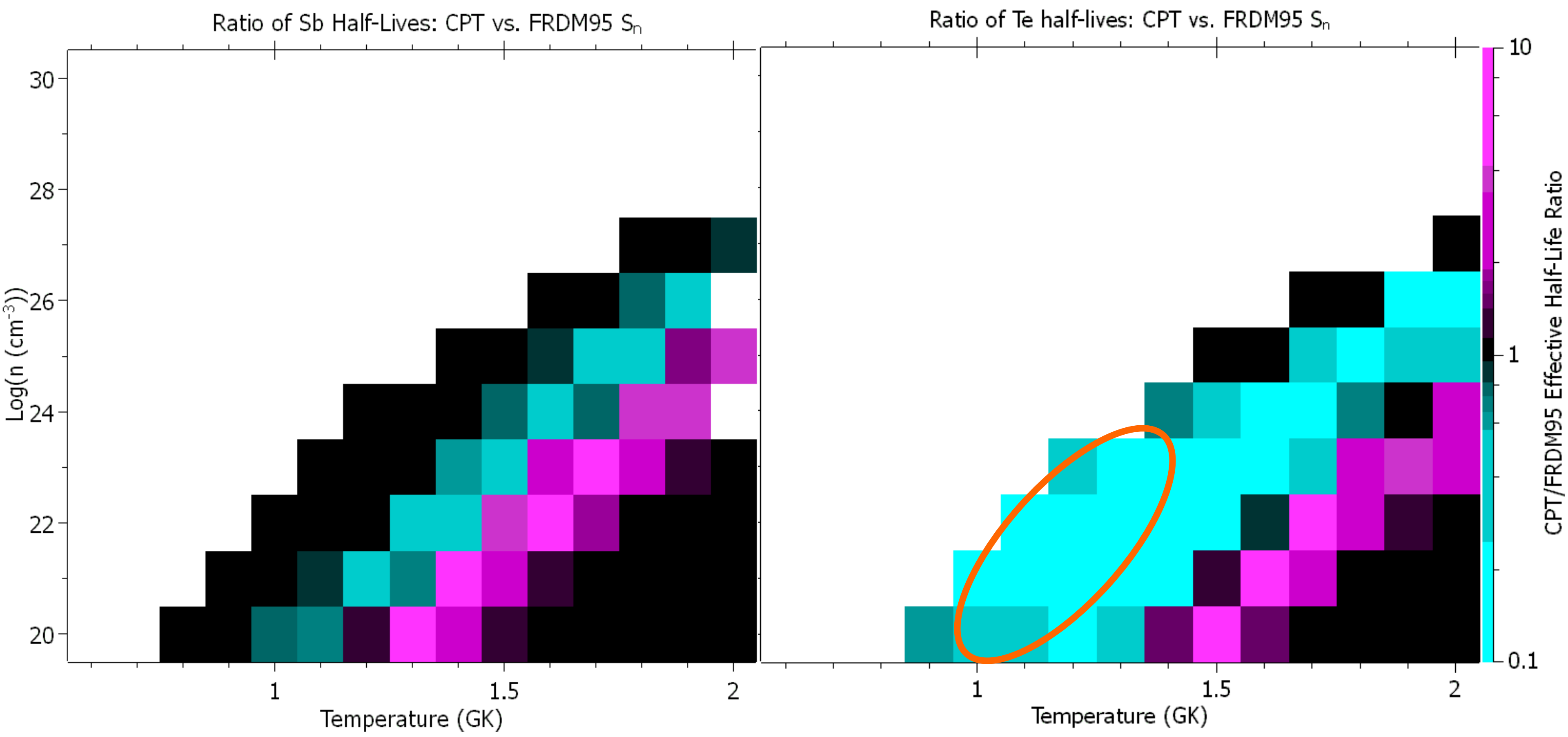
Ratio of Sn Half-Lives: CPT vs. FRDM95 S_n
Log(n (cm^{-3}))
30
25
20
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Temperature (GK)
10
1
0.1
CPT / FRDM95 Effective Half-Life Ratio


1.3 GK, 10^{23} n/cm^3
$\beta T_{1/2}$: 40 s 1.5 s 1.1 s 0.53 s 0.25 s
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
tional abundance
CPT (0.44 s)
FRDM95 (0.86 s)
89


S_n of Sn
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
S_n (MeV)
FRDM95
CPT
Less (γ,n) in model
More (γ,n)
80
82
84
86
88
N

Same effect vs FRDM95 in Sb and Te

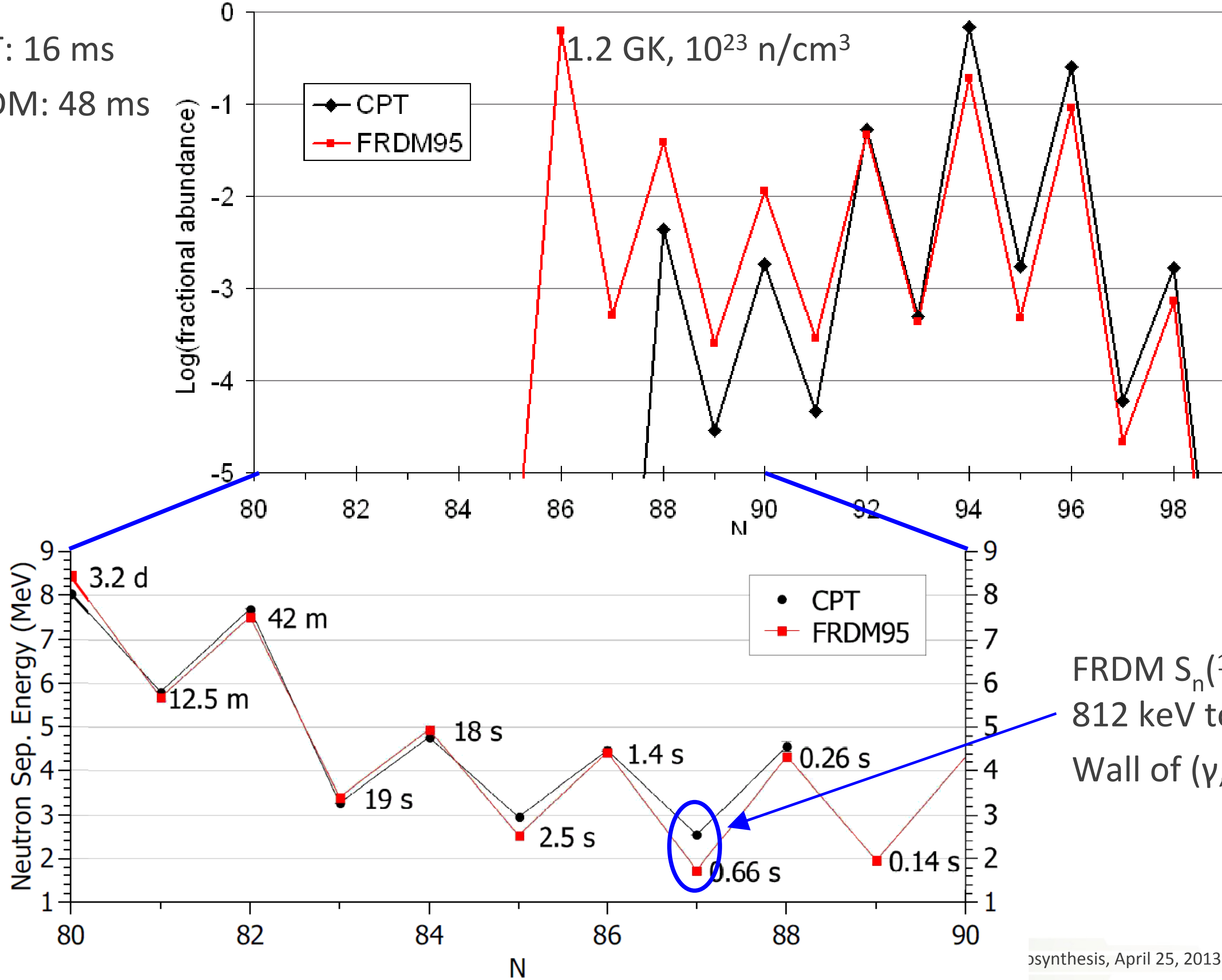
- Same trend in Sb and Te, plus a strong non-equilibrium effect in Te:



Non-equilibrium effects in Te

CPT: 16 ms

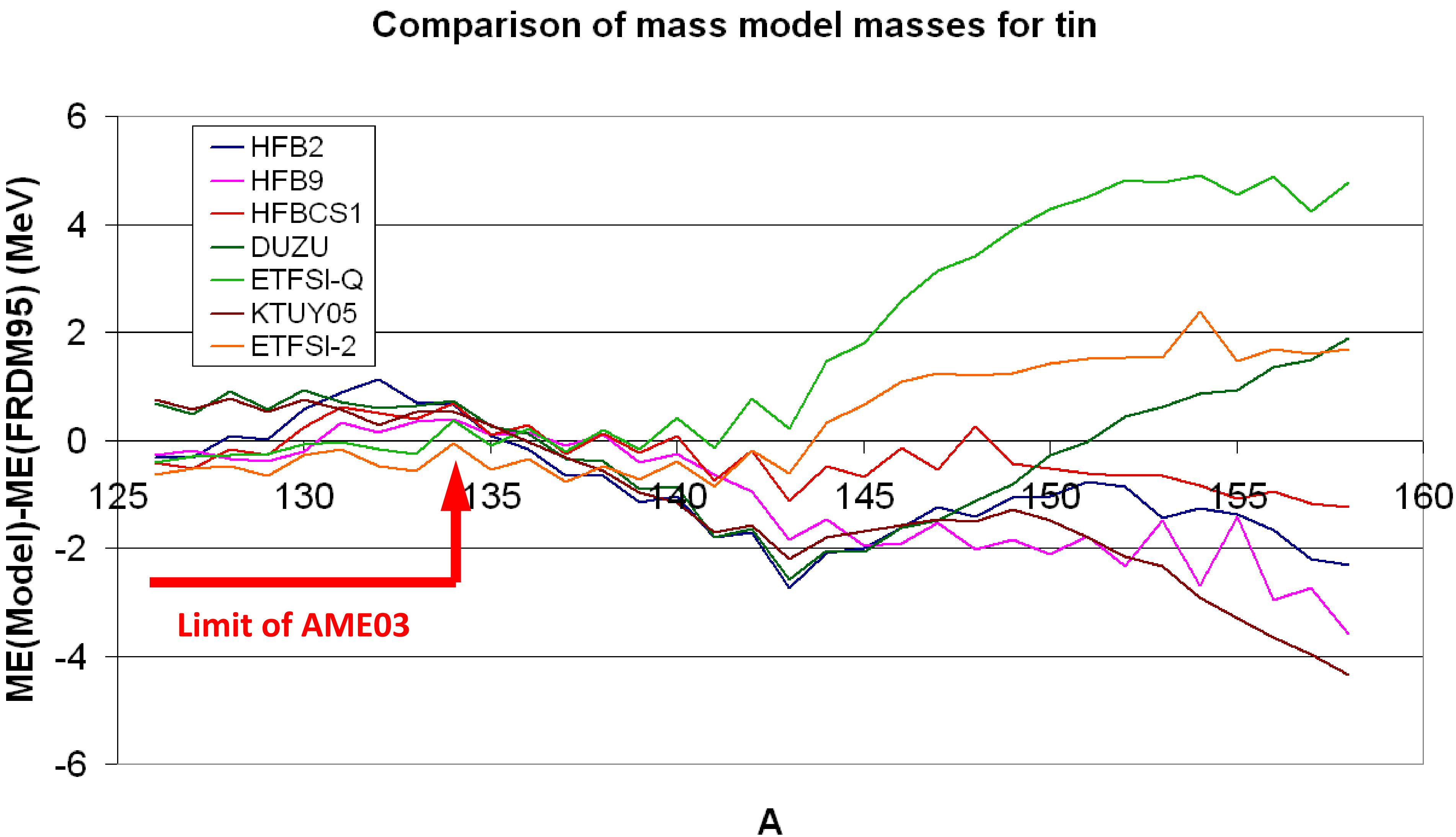
FRDM: 48 ms



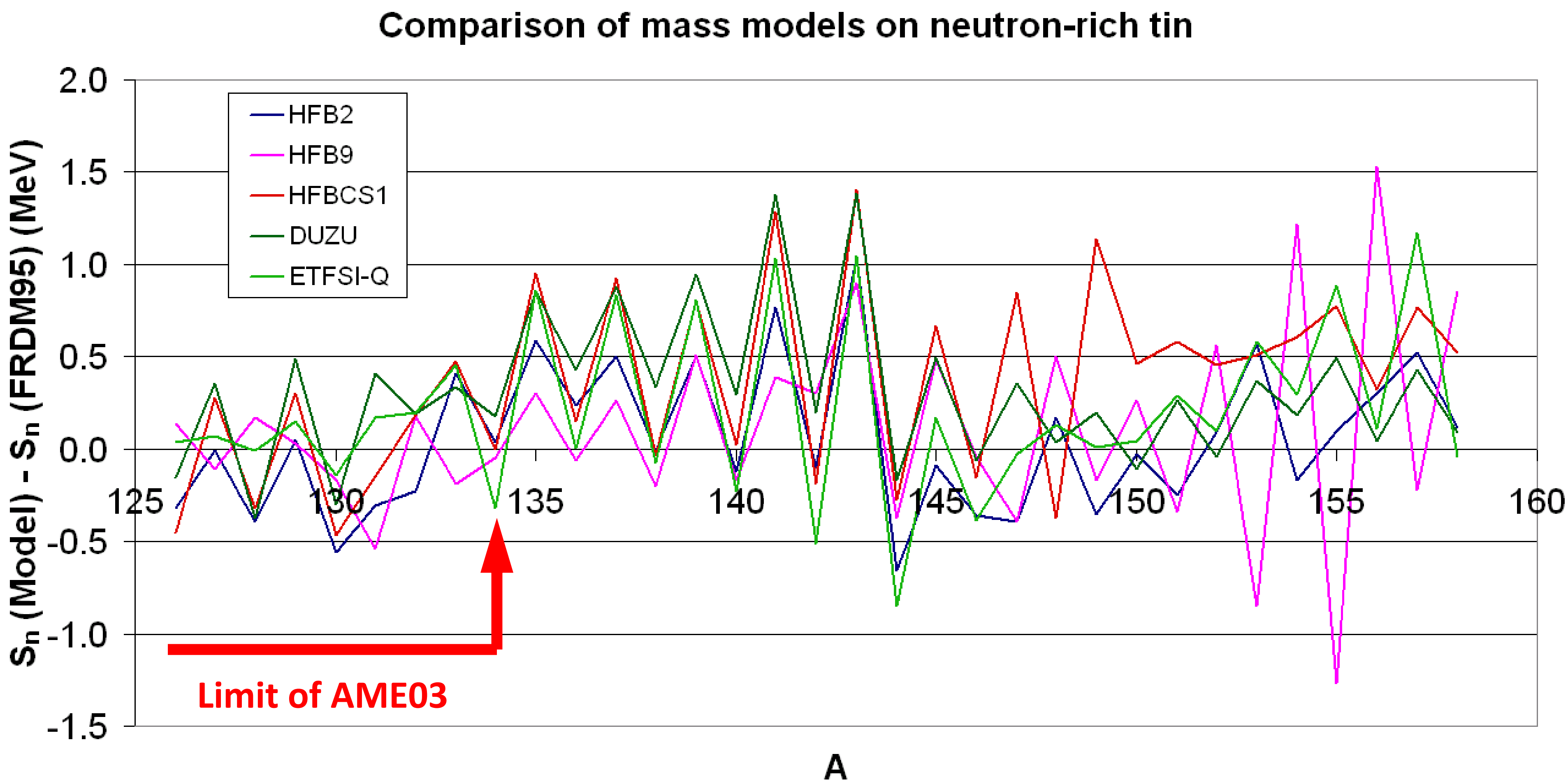
FRDM $S_n(^{139}Te)$ 812 keV too low:

Wall of (γ,n)

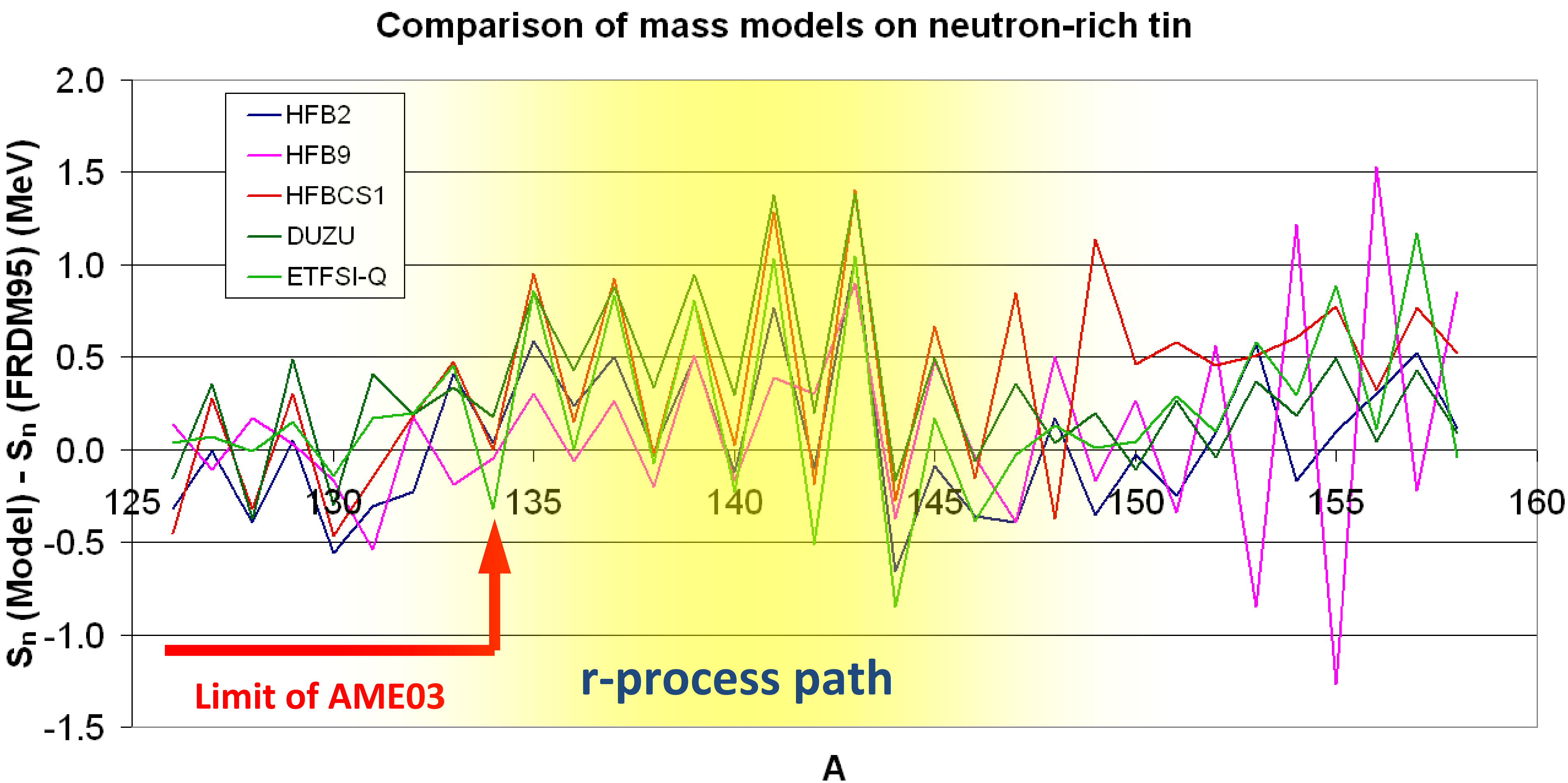
The trouble with mass models



The trouble with mass models

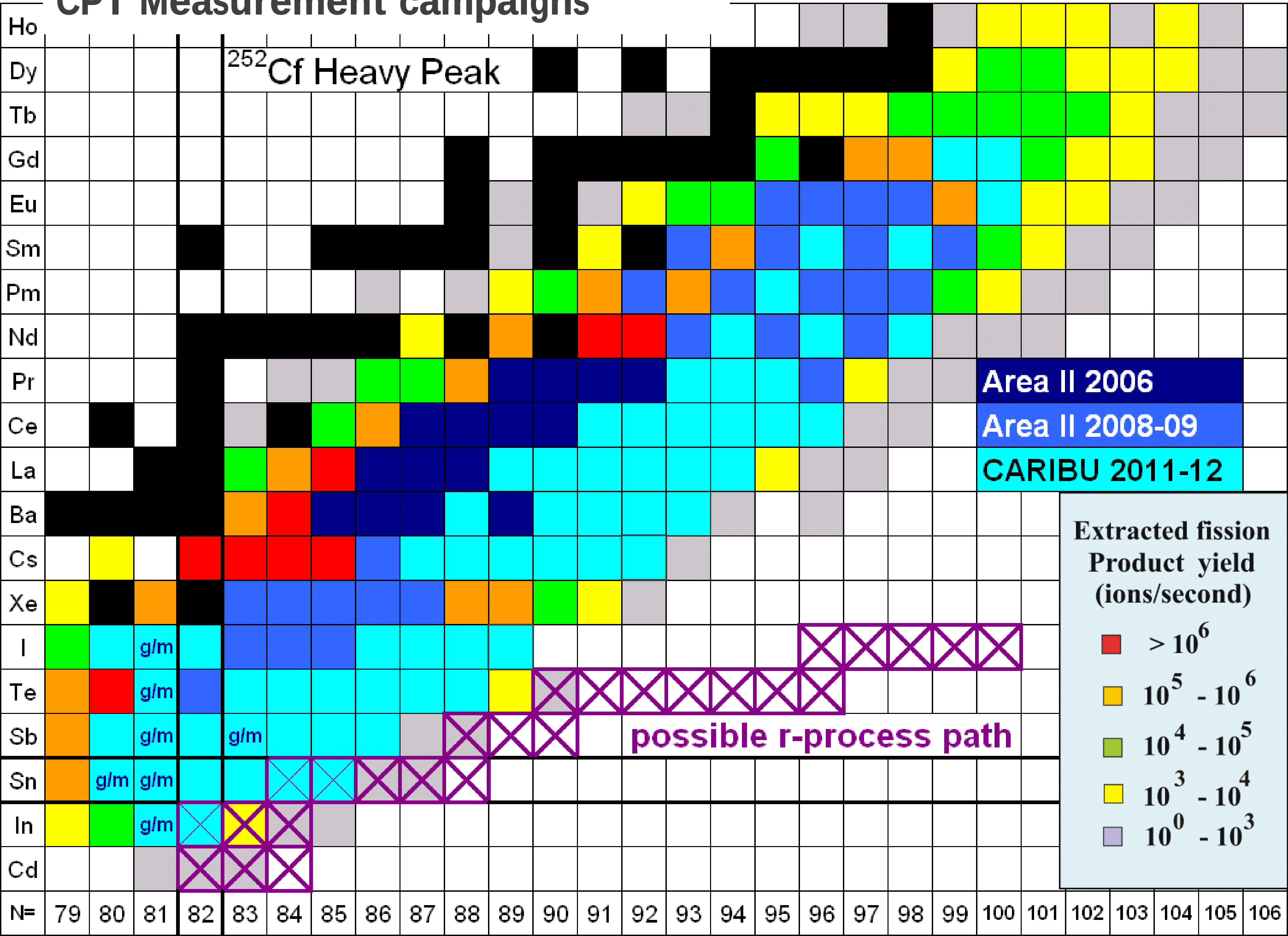


The trouble with mass models

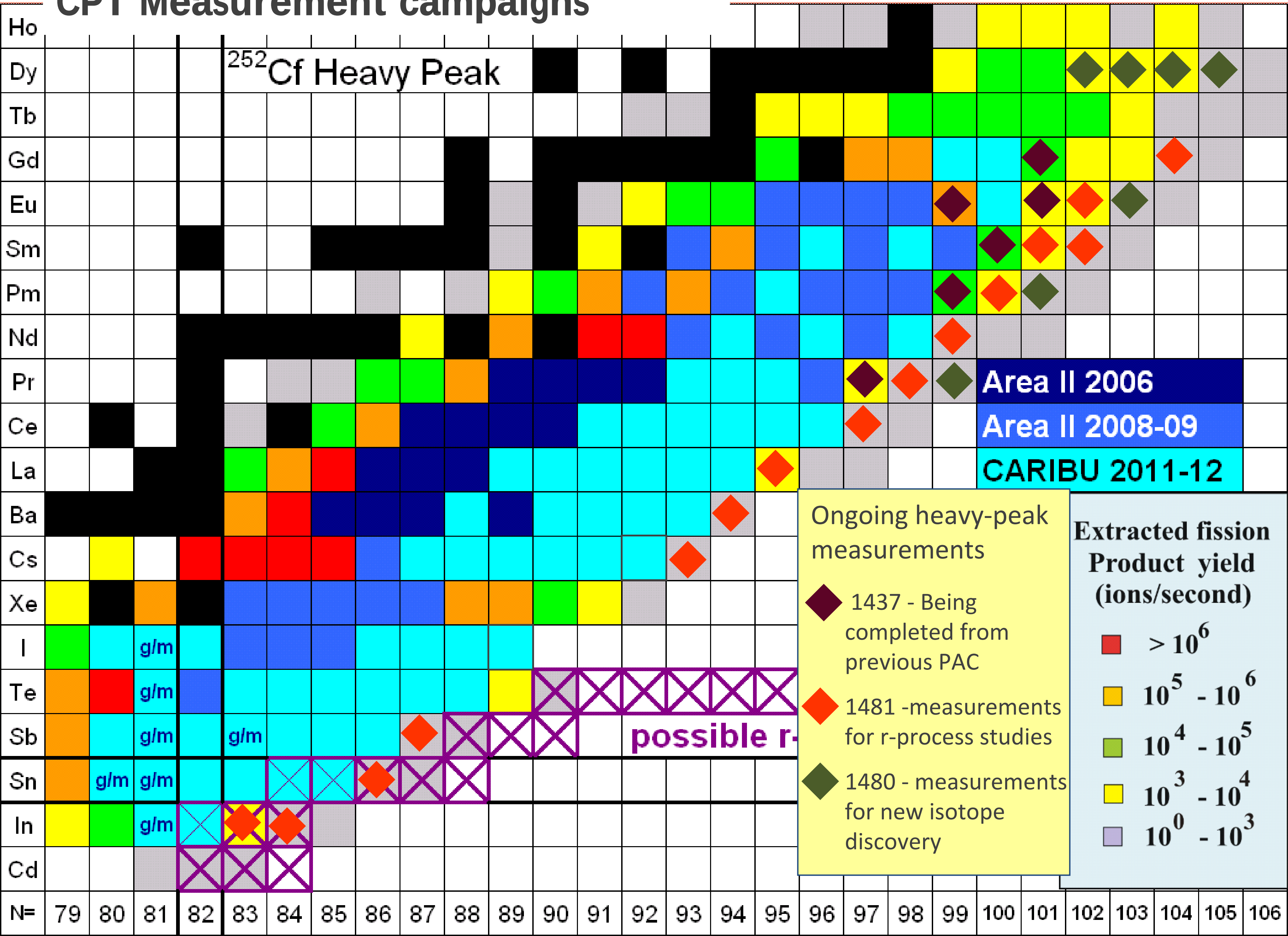


- Need to go out and measure these masses where we can … can't expect mass models to be better away from stability than they are at stability

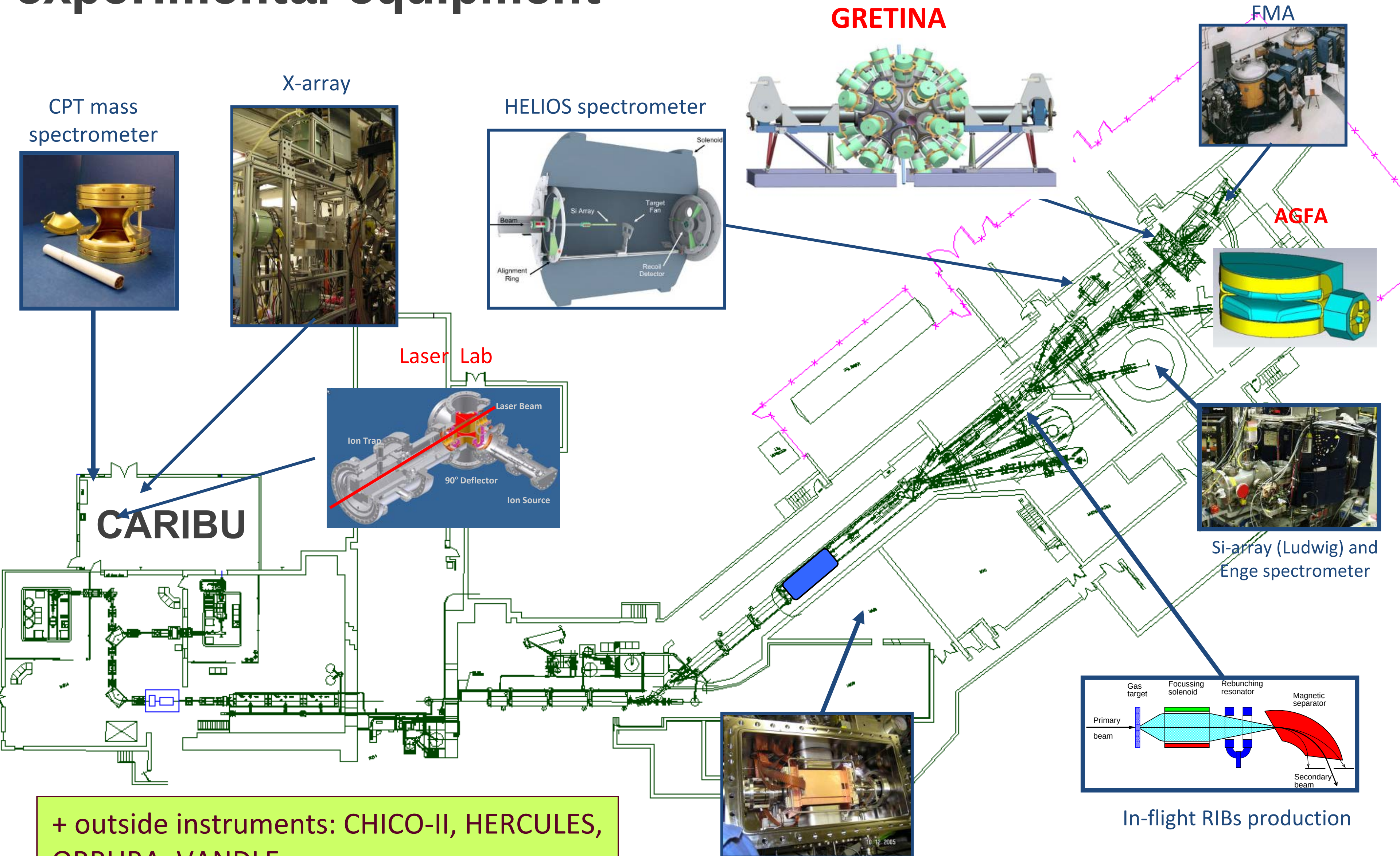
CPT Measurement campaigns



CPT Measurement campaigns

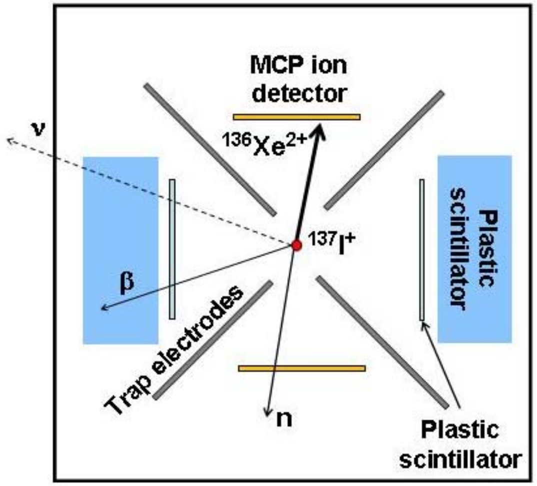


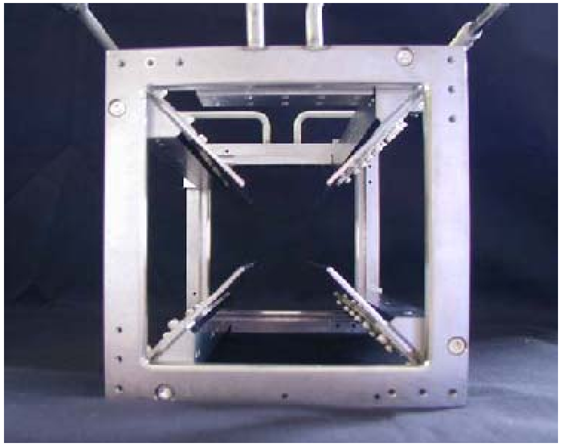
Main tools enabling the physics: ATLAS suite of experimental equipment



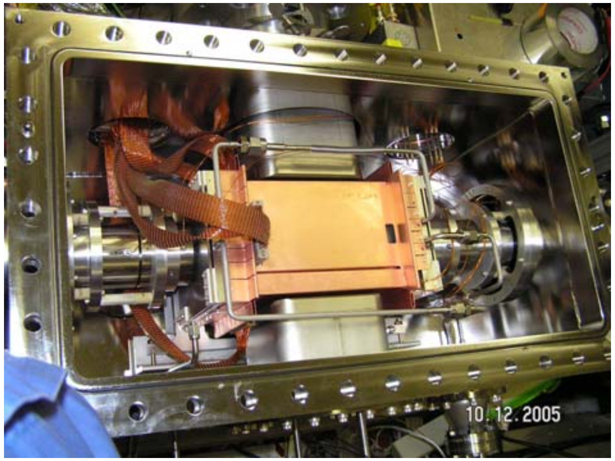
+ outside instruments: CHICO-II, HERCULES, ORRUBA, VANDLE, …

Future experiments at CARIBU – beta-delayed neutron measurements

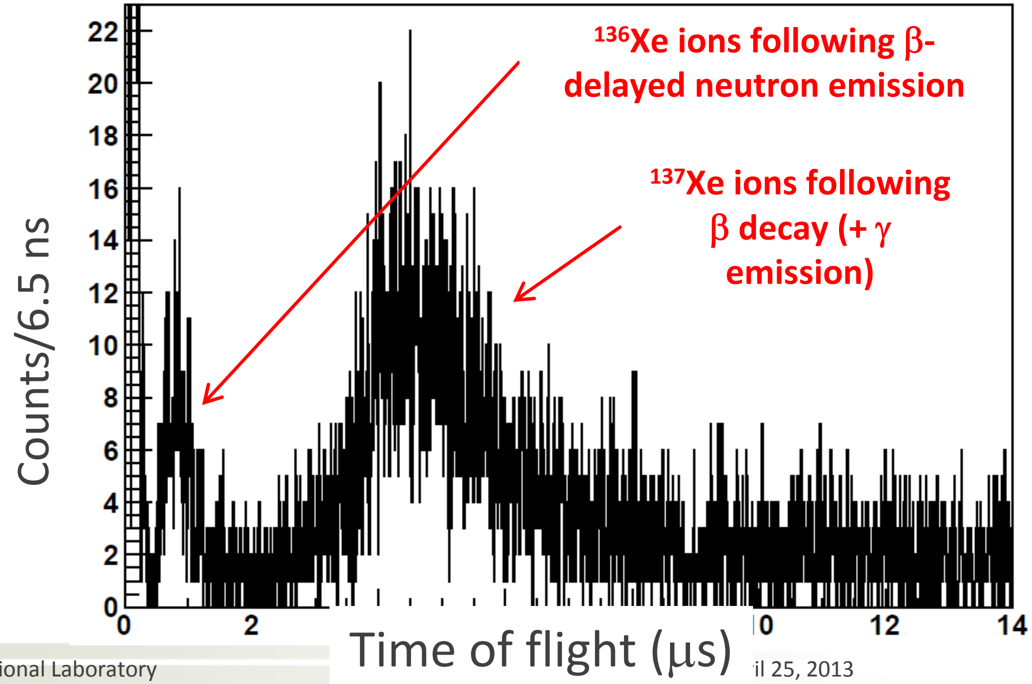




- Let ion decay from rest at center of ion trap (Paul trap)
- Surround ion trap (Paul trap) with plastic scintillators (to detect β's) and MCPs (to detect decay recoils)
- Beta-delayed neutron decay produces recoil detected by TOF with MCP

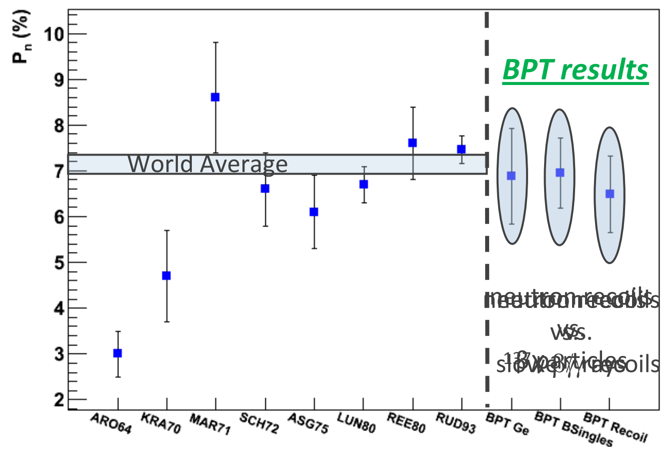


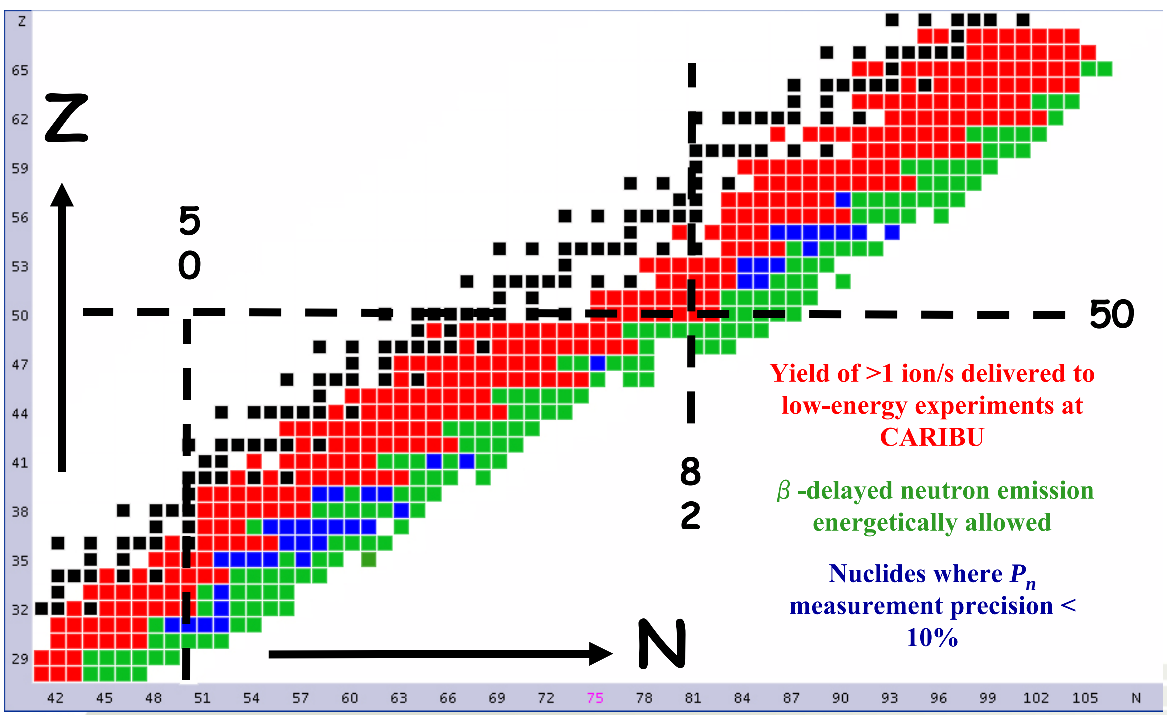
Trap chamber and instrumented trap



Future experiments at CARIBU – beta-delayed neutron measurements

- Data obtained using 1 mCi ^{252}Cf source:
  - branching ratios obtained with different methods give similar results





- Building new trap for dedicated program of beta-delayed neutron measurements at CARIBU (more detectors, stronger source)
  - $\Omega_\beta = 12\%$
  - $\Omega_r = 26\%$
  - $\Omega_\gamma = 28\%$
  - sensitive to 1 ions/s production rate (to obtain a 10% precision in branching ratio)
  - E_n resolution: 5%
  - E_n threshold: 50 keV
  - β threshold: 25 keV

Further development of CARIBU beams

Fall 2012:

- RFQ to replace PII ✓

Summer 2013:

- New cryomodule

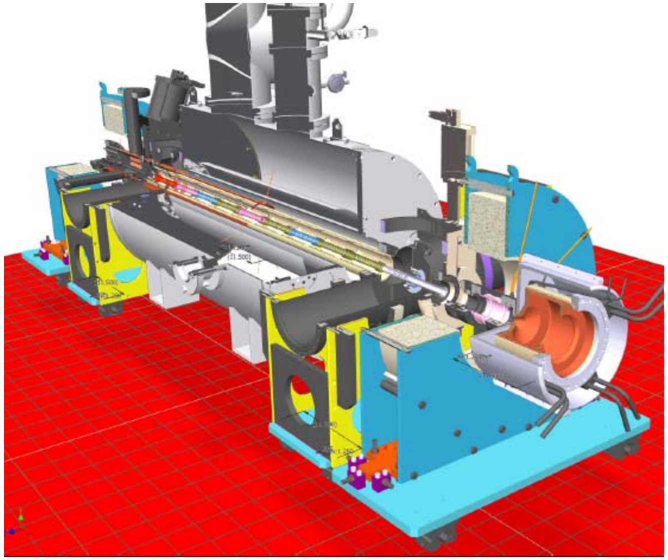
} Expect X2 gain ✓

Fall 2013:

- New stronger, thinner source: Expect X5-10 gain

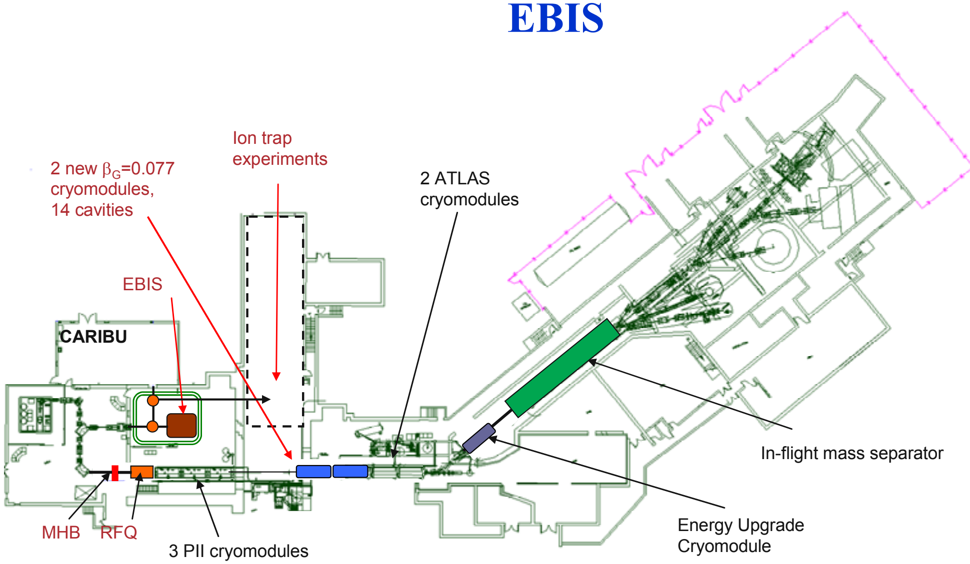
2014 – 2015:

- EBIS to replace ECR: Expect X2 gain
- New low-energy experimental area



EBIS

Isotope	Half-life (s)	Low-Energy Beam Yield (s^{-1})	Accelerated Beam Yield (s^{-1})
^{104}Zr	1.2	$6.0x10^5$	$2.1x10^4$
^{143}Ba	14.3	$1.2x10^7$	$4.3x10^5$
^{145}Ba	4.0	$5.5x10^6$	$2.0x10^5$
^{130}Sn	222.	$9.8x10^5$	$3.6x10^4$
^{132}Sn	40.	$3.7x10^5$	$1.4x10^4$
^{110}Mo	2.8	$6.2x10^4$	$2.3x10^3$
^{111}Mo	0.5	$3.3x10^3$	$1.2x10^2$



Status

- CARIBU facility is operational
  - First RIB facility based on a gas catcher … it works. Over 500 neutron-rich isotopes available at low energy
  - Over 70 different neutron-rich radioactive isotope species have been used for experiments in the last year
  - Low-energy program in full swing with experiments approved by last two PACs
  - Reaccelerated beam program initiated with decay experiments and first Coulomb excitation at Gammasphere, reaccelerated beam experiments approved in Dec 2012 PAC running now

- Current source (~ 150 mCi) will be replaced by a 1 Ci source in the fall. Combined with completion of ATLAS intensity upgrade, will yield gains of ~6-12 in intensity for low-energy and reaccelerated beams.

Next ATLAS/CARIBU PAC will be held in summer 2013 (call for proposals expected soon). Will accept proposals for all ATLAS/CARIBU beams and the first GRETINA campaign.

CPT Collaboration

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