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The determination of the masses of neutron-rich nuclides using the CPT mass spectrometer at CARIBU

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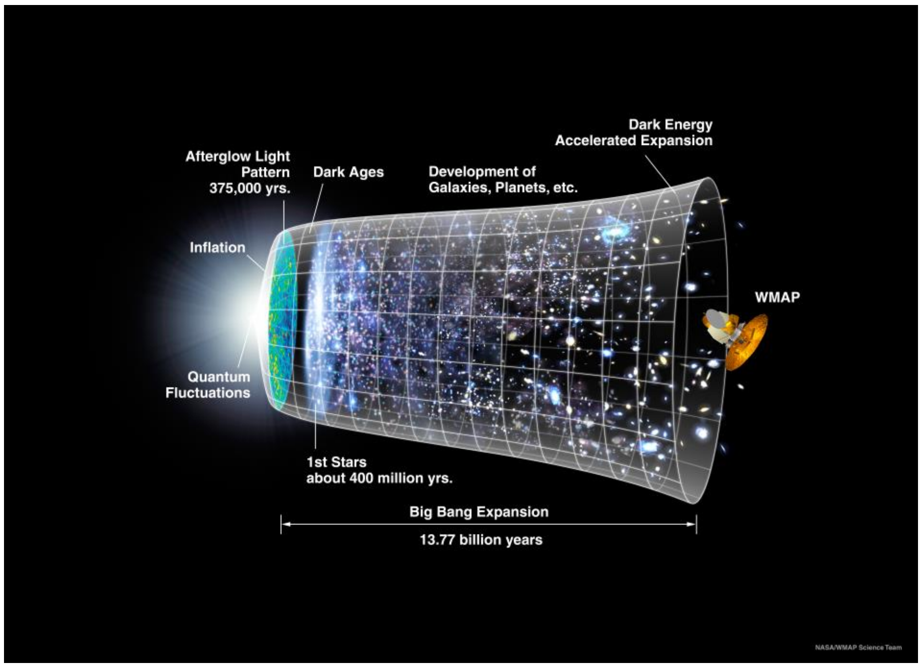
Outline:

- Quick introduction to the processes of nucleosynthesis
- Focus on the r-process and the data required to model the process.
- Talk about the general requirements for making measurements: production, half-life limitations, precision etc.
- Describe our set-up for making measurements at CARIBU
- Describe some of our results.
- Future plans

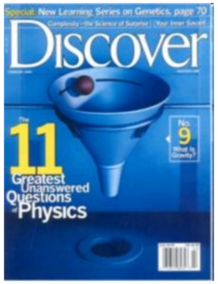
A brief history of the universe



- Big Bang – creation
- Cooling and some synthesis of light elements in the first 10 to 1000 seconds. Lots of H and He. Smaller quantities of D, T, ^{7}Li
- Formation of stars and the synthesis of heavier elements through fusion. Up to Fe.
- s-process nucleosynthesis
- Nucleosynthesis of the heavier elements during explosions: p-, rp-, r-, νp- processes

Observed elemental abundances

- Observed distribution (by mass number) of the elements in the solar neighborhood.
- One of the ‘Greatest Unanswered Questions of Physics’



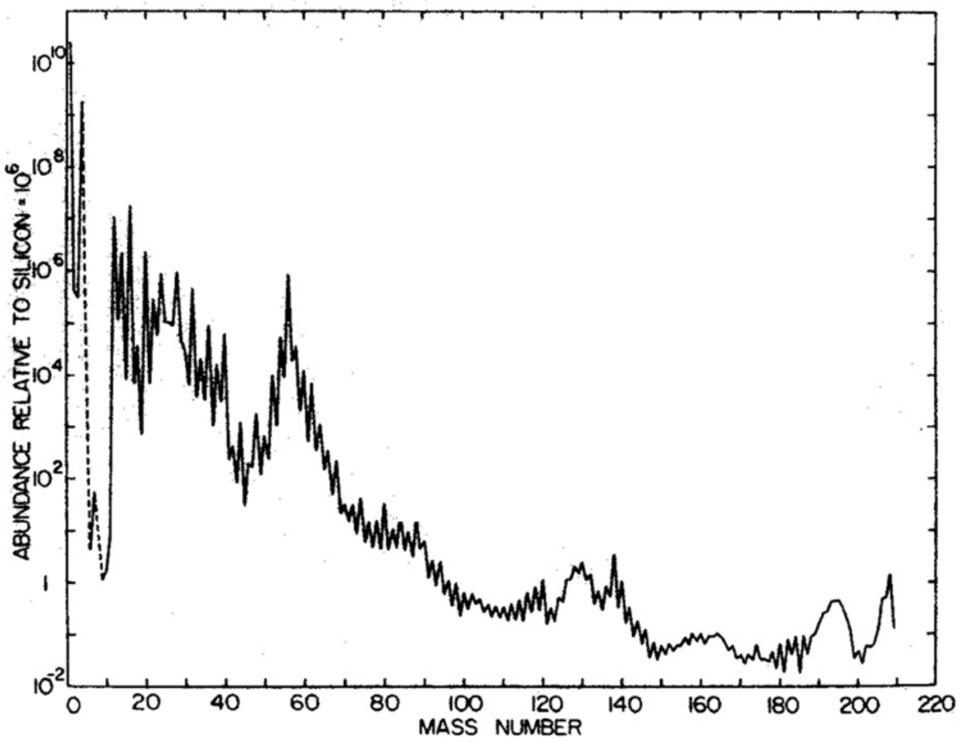


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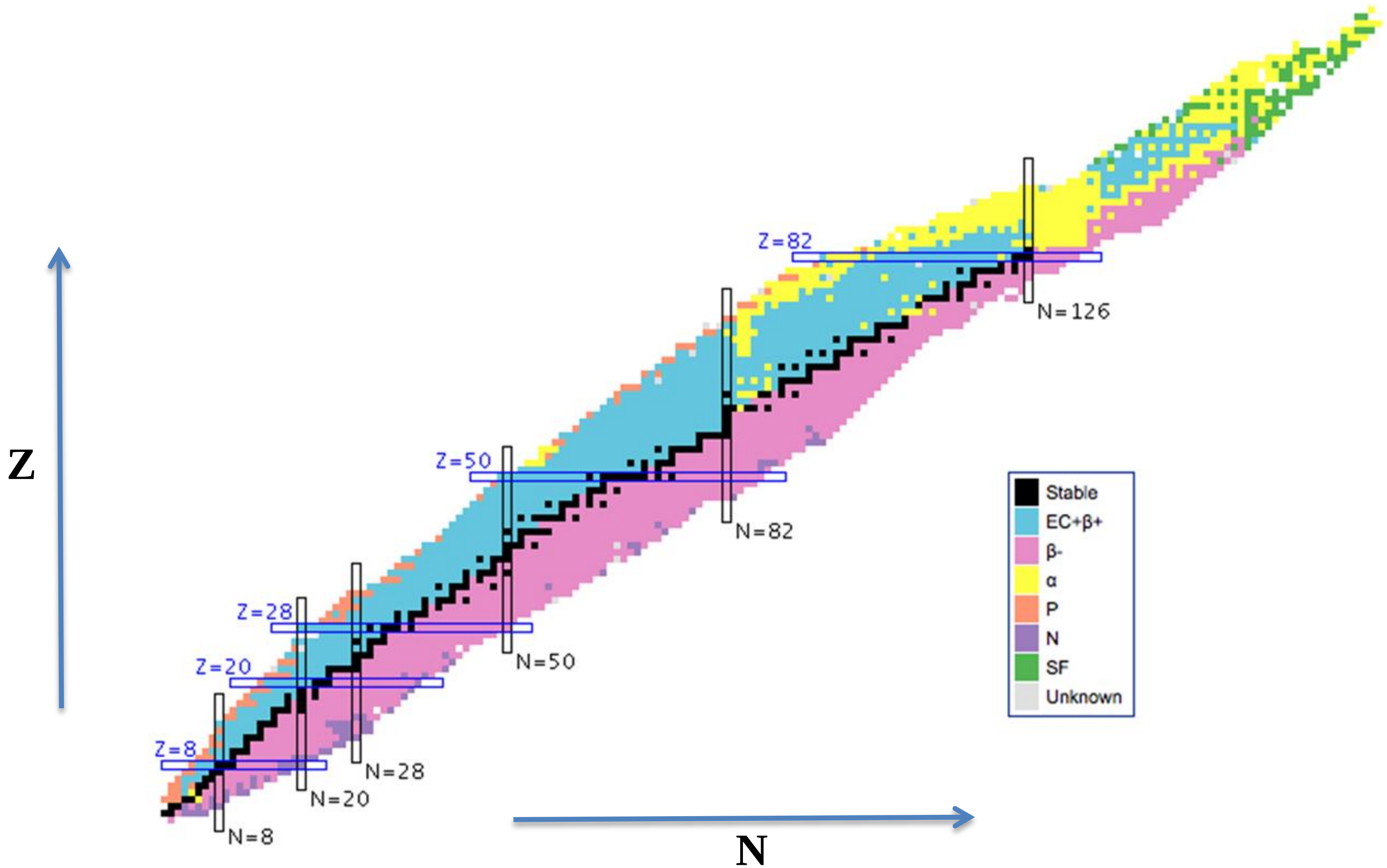
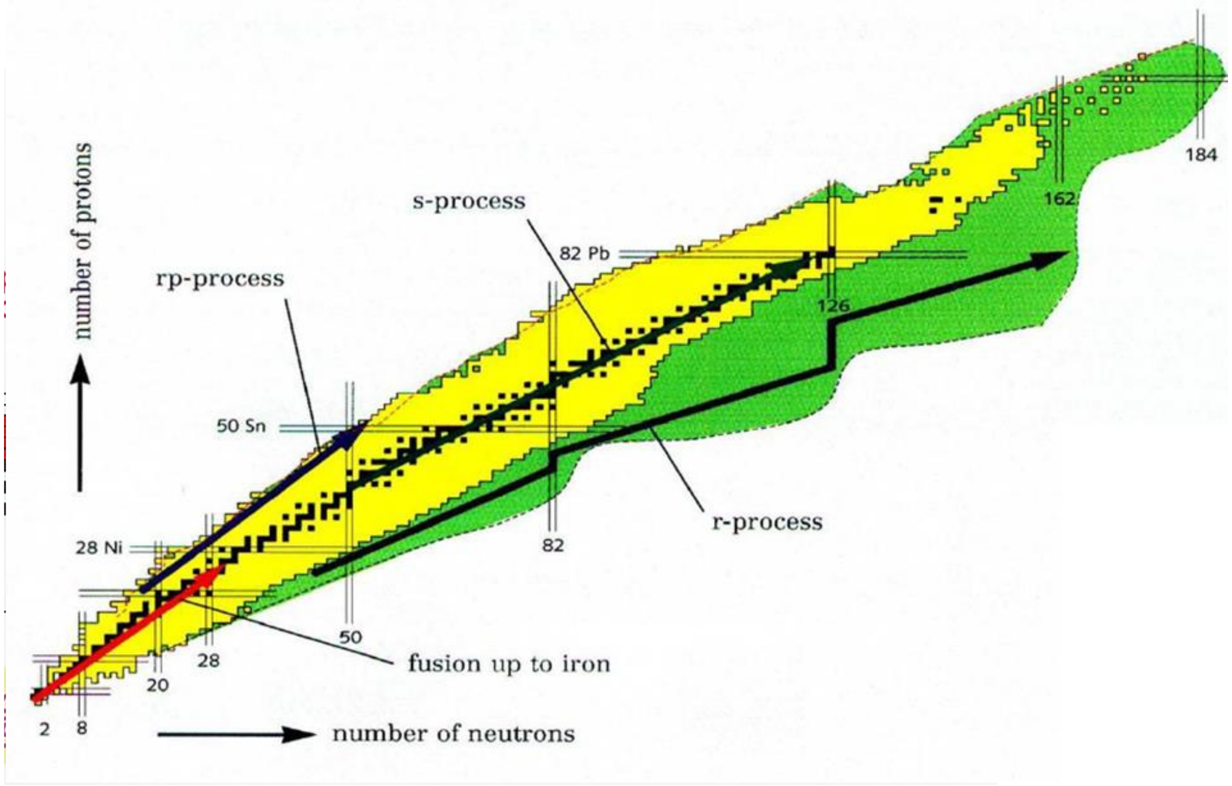
Chart of the nuclides



Reaction paths & processes

- ***rp/νp*-process (x-ray bursts) produce heavy elements, but are not released into the ISM**
- ***s*-process (AGB stars) produce heavy elements up to A=208 (half of all heavy nuclei)**
- ***r* process possibly produces the other half of heavy elements A>56**



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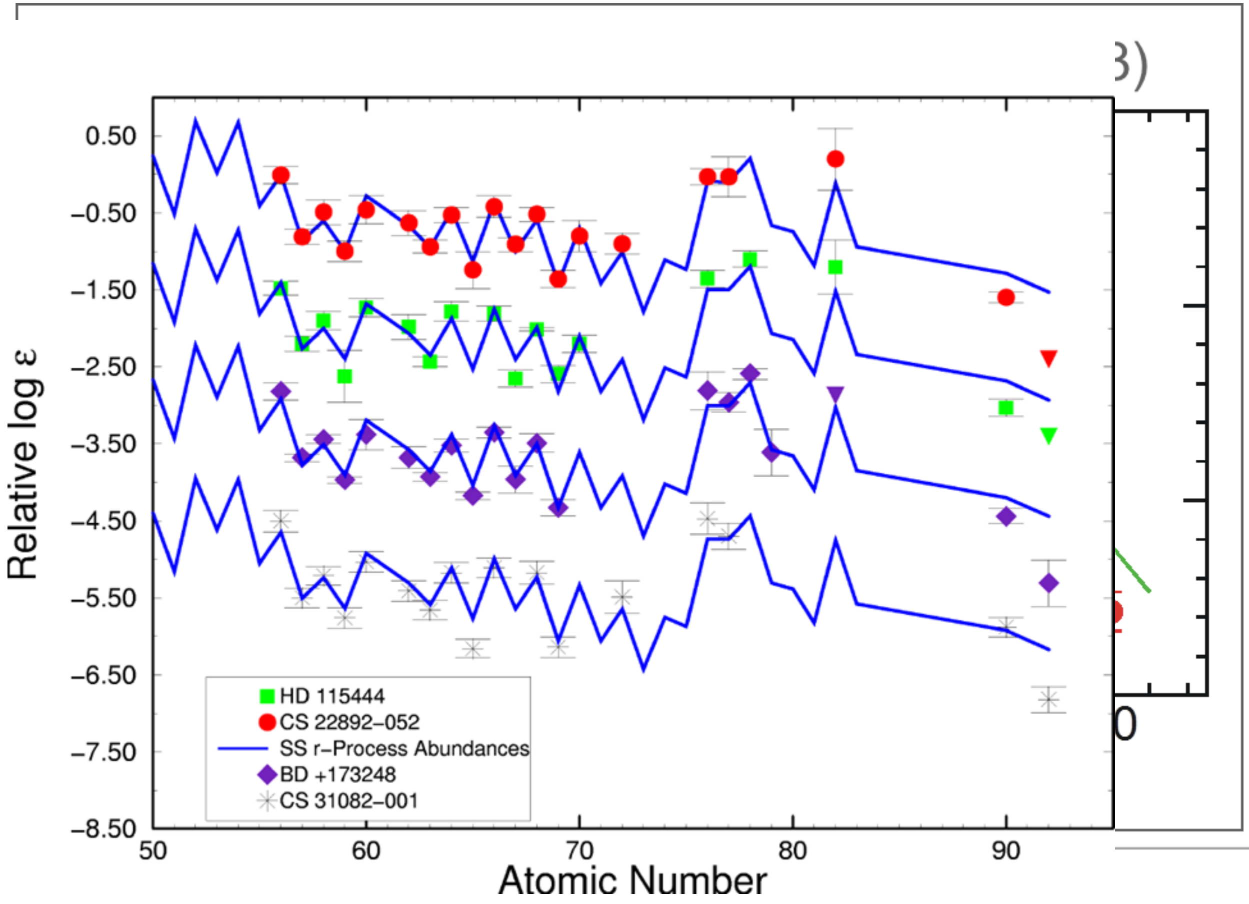
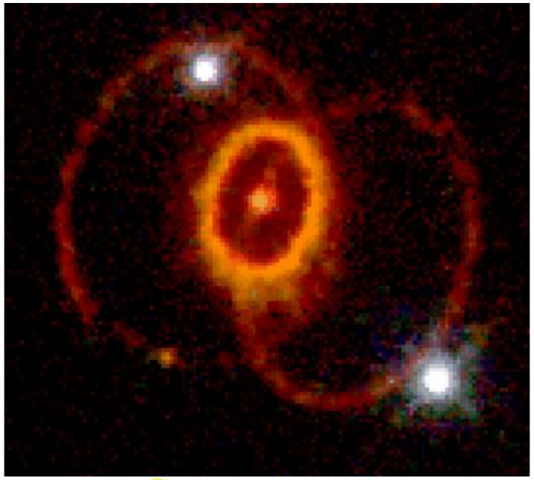
Is the r-process universal?

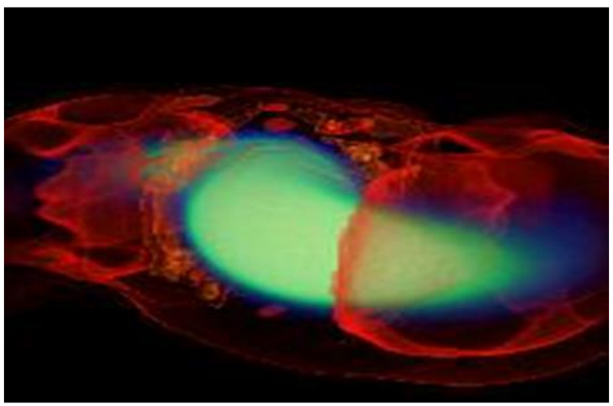


- r-process abundances: total abundances minus abundances from all other processes.
- Relative abundances from different stars are identical.
- **Indicates a common process which produced these elements!**

Possible sites for the r-process



Supernovae

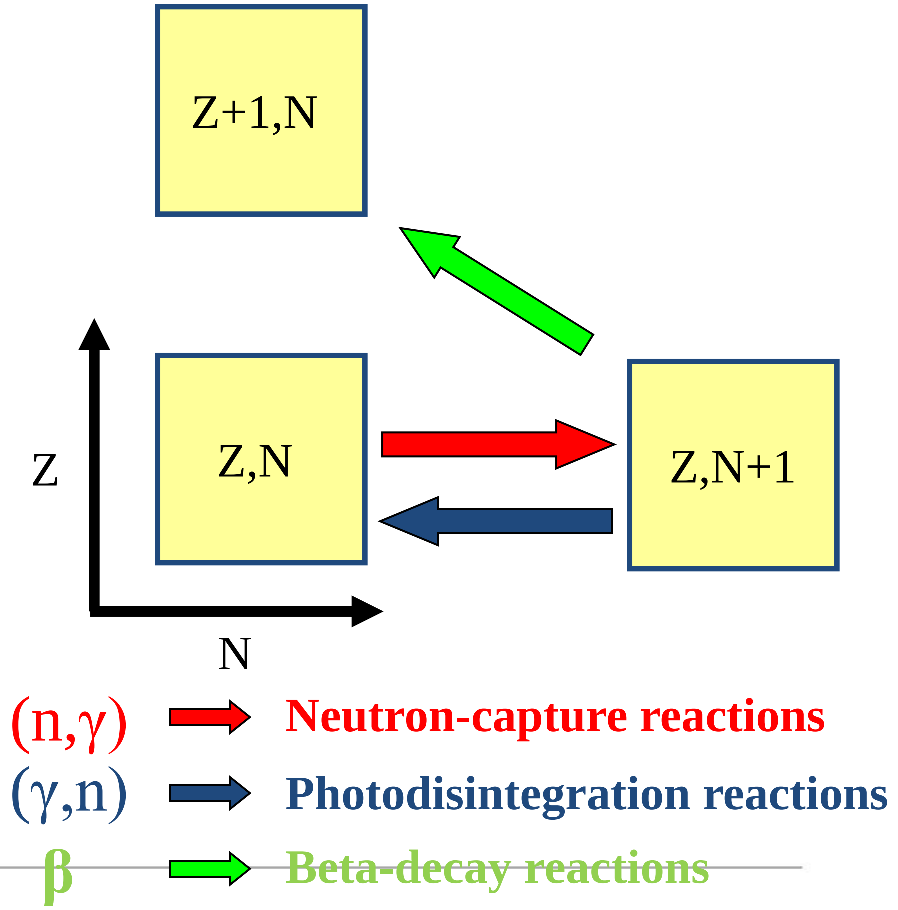


Merging neutron stars

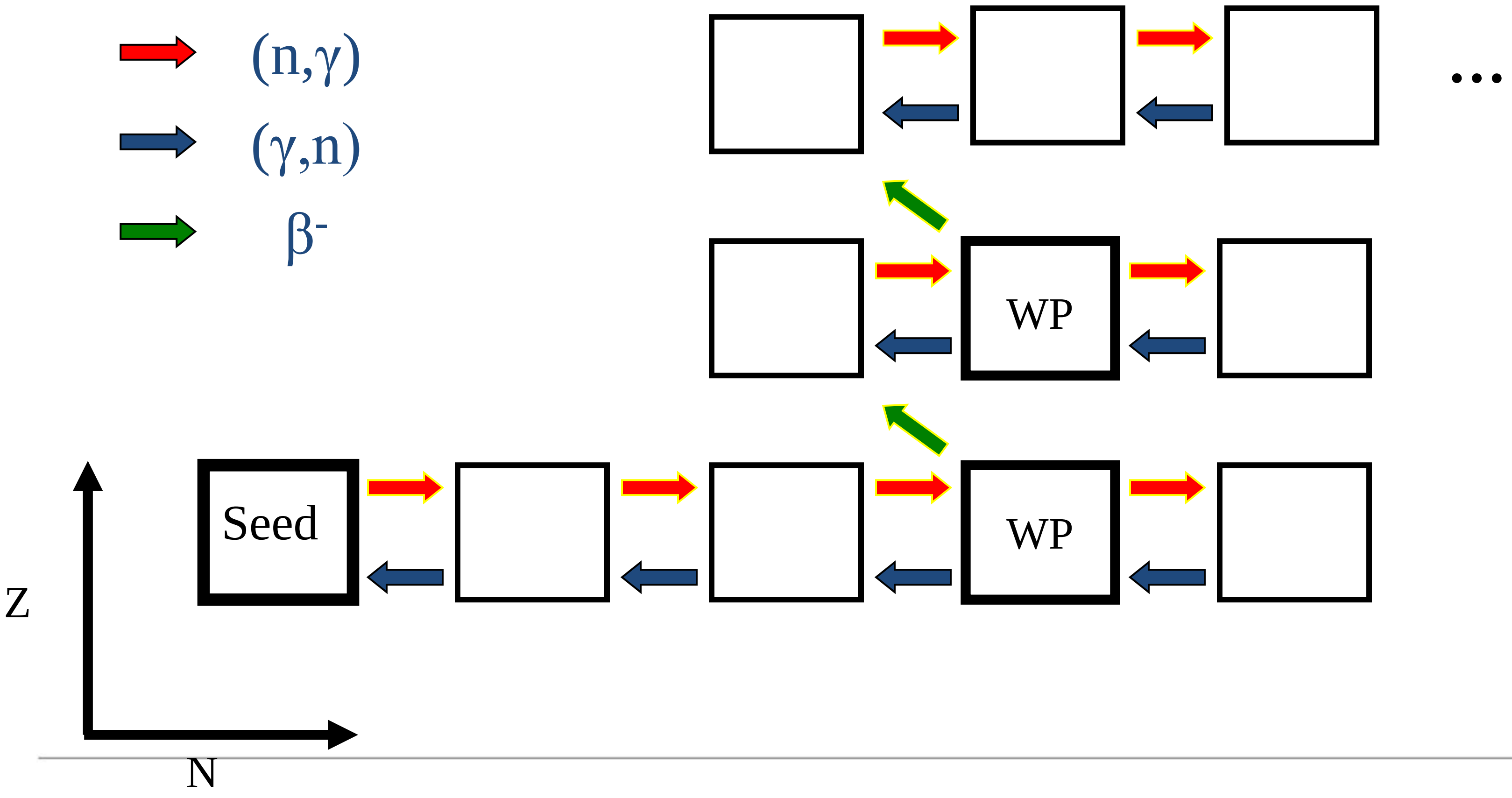
- Each site has different conditions, and it is still unclear which can produce the observed abundance distributions
- The models require a high density of neutrons, high temperature environment
- T ~ 1-2 GK
- Neutron number density ~ $10^{24}/cm^3$

Nuclear reactions involved in the astrophysical r-process

- Elements are created by a series of rapid neutron-capture events.
- Other reactions compete with this process.

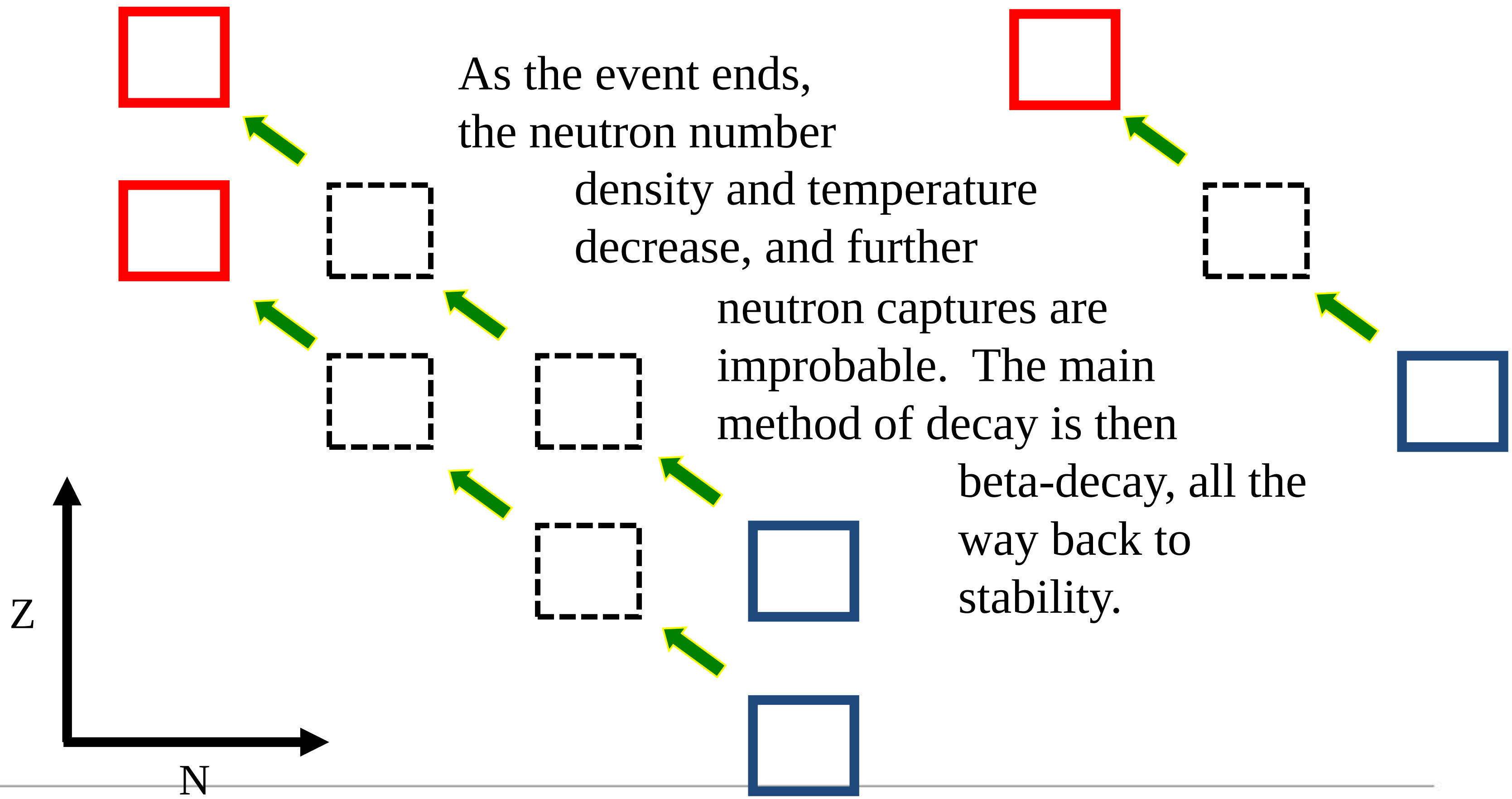


r-process element synthesis during event



At the end of the event

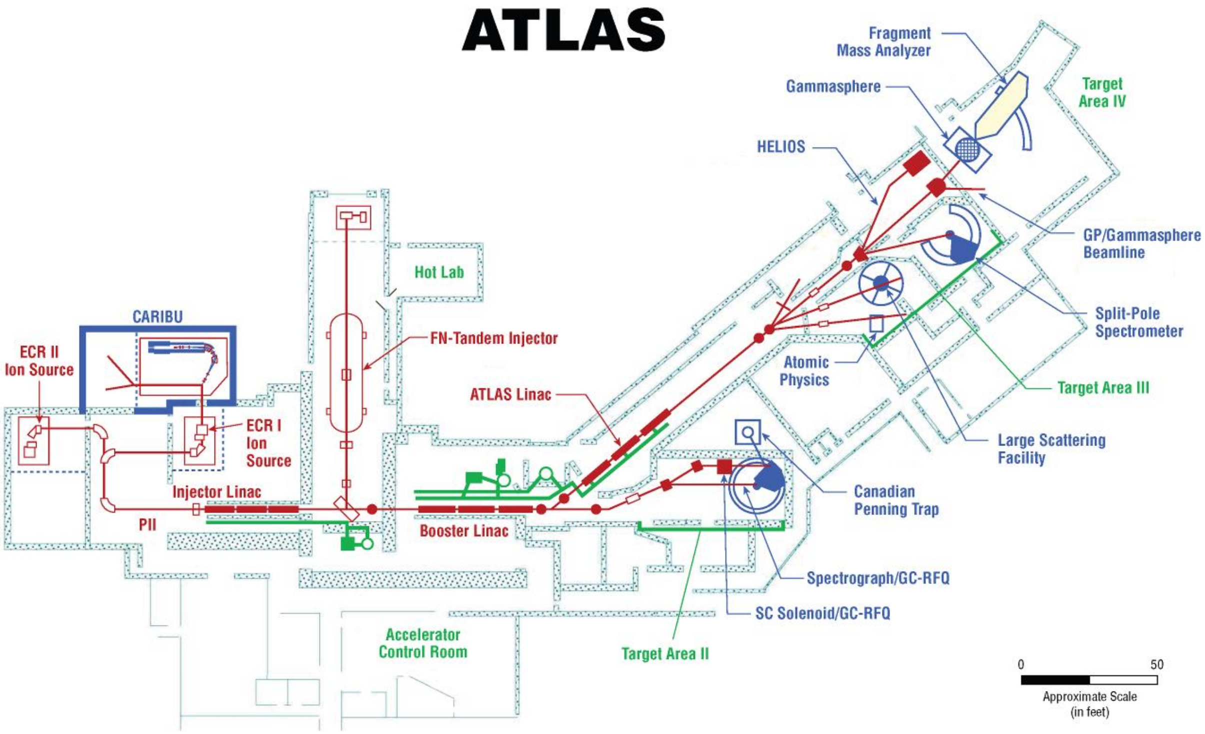
As the event ends, the neutron number density and temperature decrease, and further neutron captures are improbable. The main method of decay is then beta-decay, all the way back to stability.



What can nuclear physics provide?

- **masses**
- β-decay lifetimes
- β-delayed neutron emission
- (*n*, γ) rates
- fissionability

The ATLAS facility at the Argonne National Laboratory



- ANL: first national lab in U.S.
- roughly 3000 employees
- situated on 1500 acres

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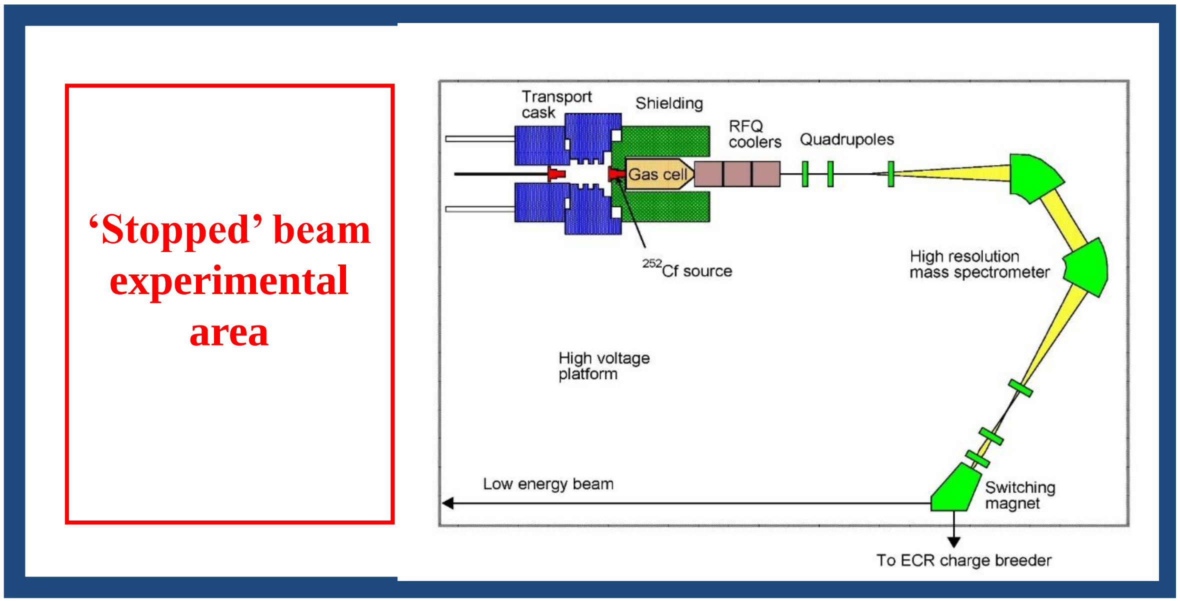
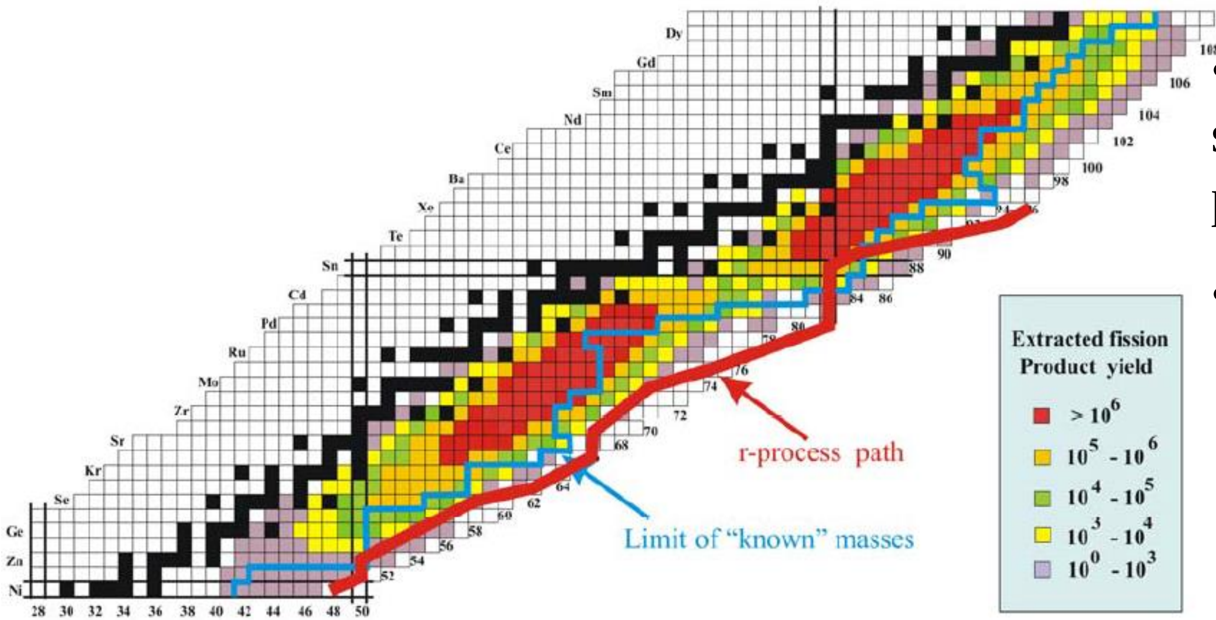
CARIBU (Californium Rare Isotope Breeder Upgrade)



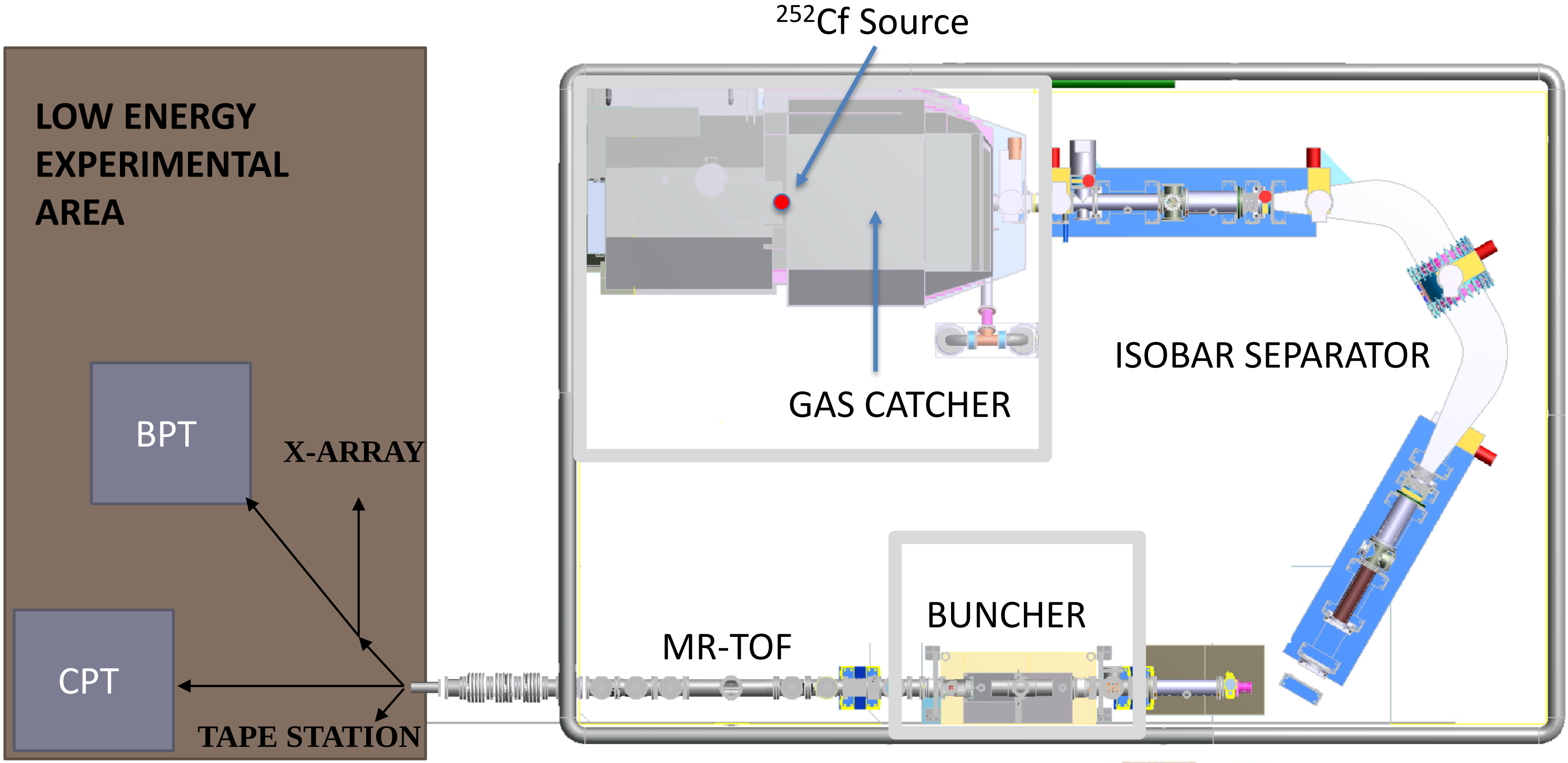
- CARIBU beams can be accelerated through ATLAS to ~ 15 MeV/A
- Basic properties of fission fragments can be measured with instruments in 'stopped' beam area

CARIBU production rates

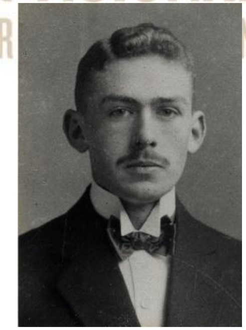


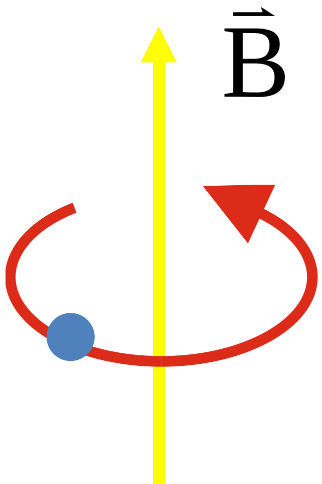
- CARIBU: uses ^{252}Cf spontaneous fission source to provide neutron-rich isotopes
- ^{252}Cf source properties:
  - 3% fission branch
  - 2.6 year half-life
  - ~ 1 Ci (40 billions decays / s)

CARIBU – Details



Intro to Penning traps





•Add a harmonic potential (along magnetic field axis) to confine particles.

Confining potential:

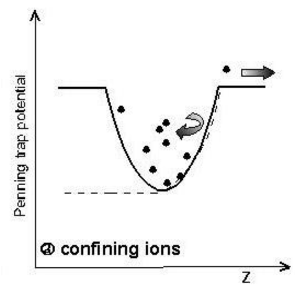
$$V = \frac{V_o}{2d^2}\left(z^2 - \frac{r^2}{2}\right)$$

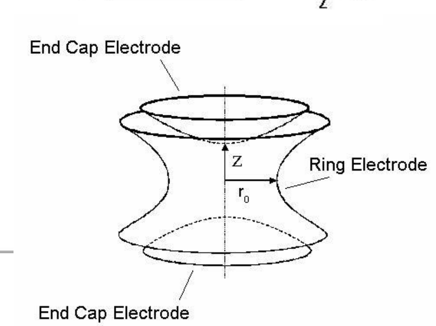
$$d = \sqrt{\frac{1}{2}\left(z_o^2 + \frac{r_o^2}{2}\right)}$$

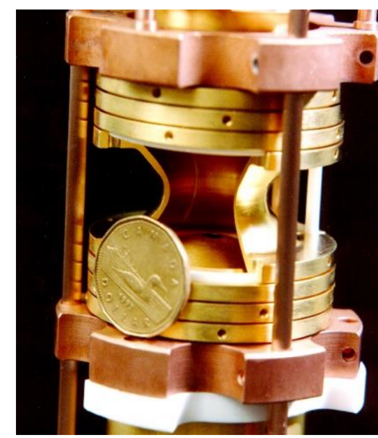
- constant axial magnetic field
- particle orbits in horizontal plane with cyclotron frequency:

$$\omega_c = \frac{qB}{m}$$

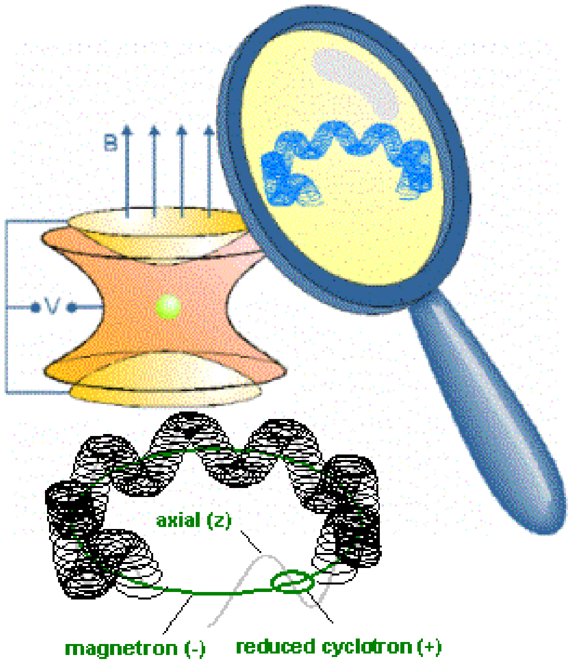
- free to escape axially







Motions in the Penning trap



picture from http://isoltrap.web.cern.ch/isoltrap/

The frequencies of motion are split:

$$\omega_{\pm} = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

ω_+: reduced cyclotron motion

ω_-: magnetron motion

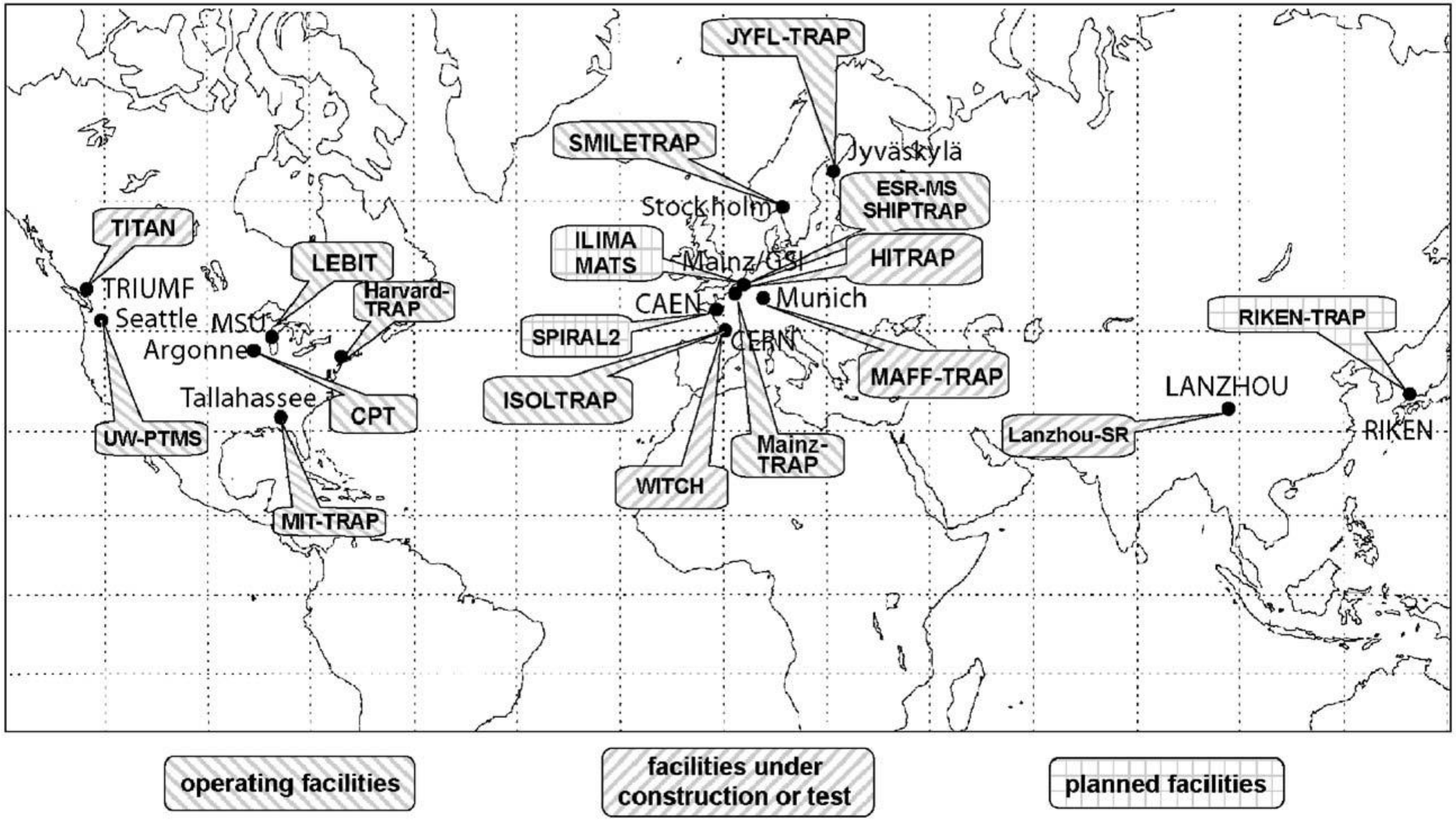
ω_z: axial motion

Frequencies are related by:

$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

$$\omega_c = \omega_+ + \omega_-$$

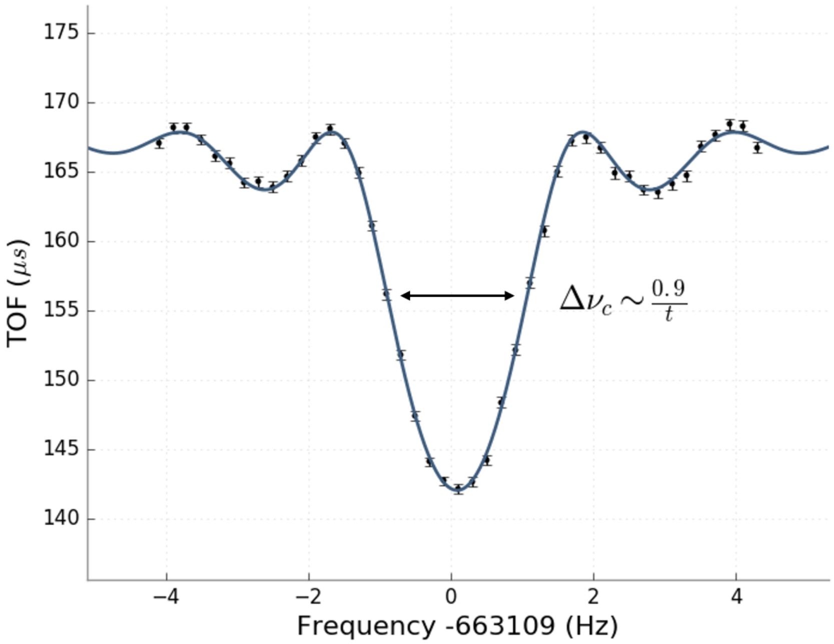
Penning trap projects - worldwide



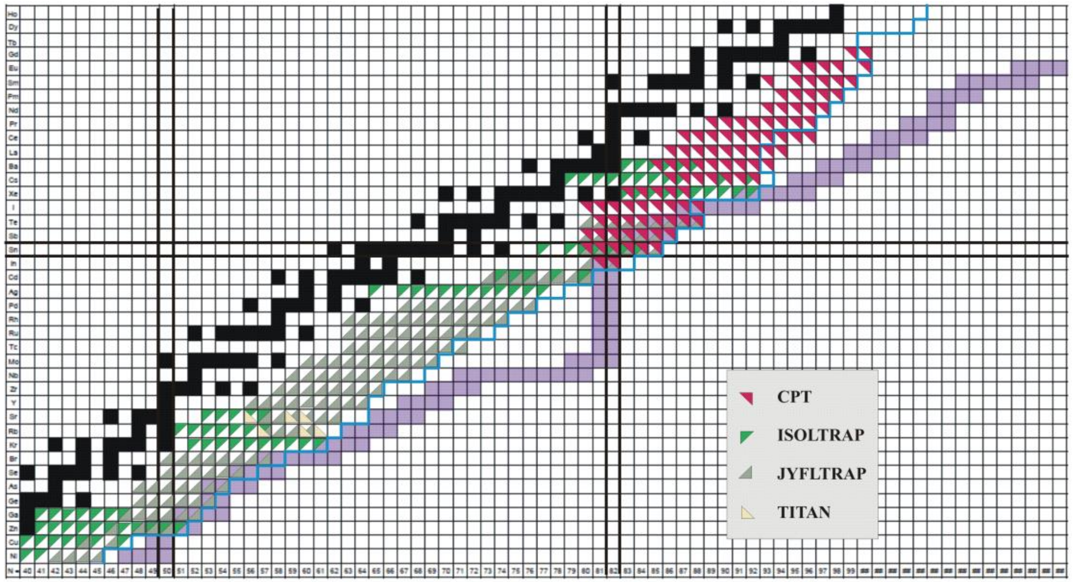
K. Blaum, Phys. Rep. **425** (2006) 1.

Time of Flight Ion Cyclotron Resonance

- TOF-ICR method
- 500 ms excitation
- ^{133}Cs
- Frequency measurement – Fourier limited
- Need to scan over extended frequency range.



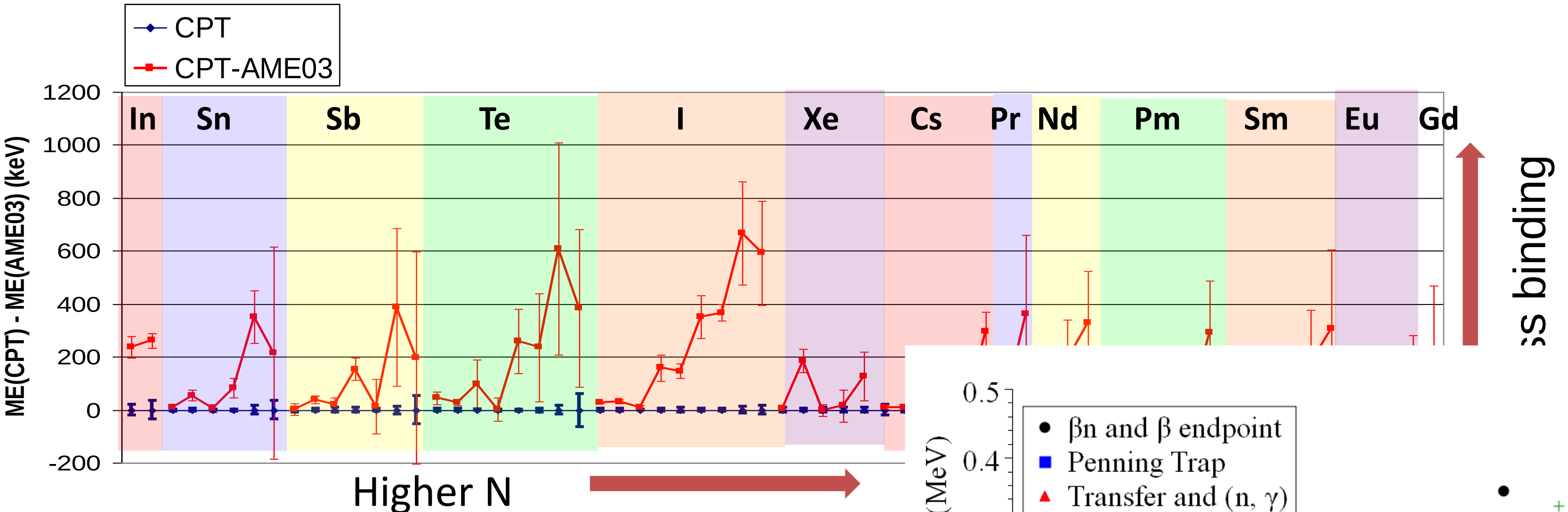
Mass measurements of neutron-rich nuclides

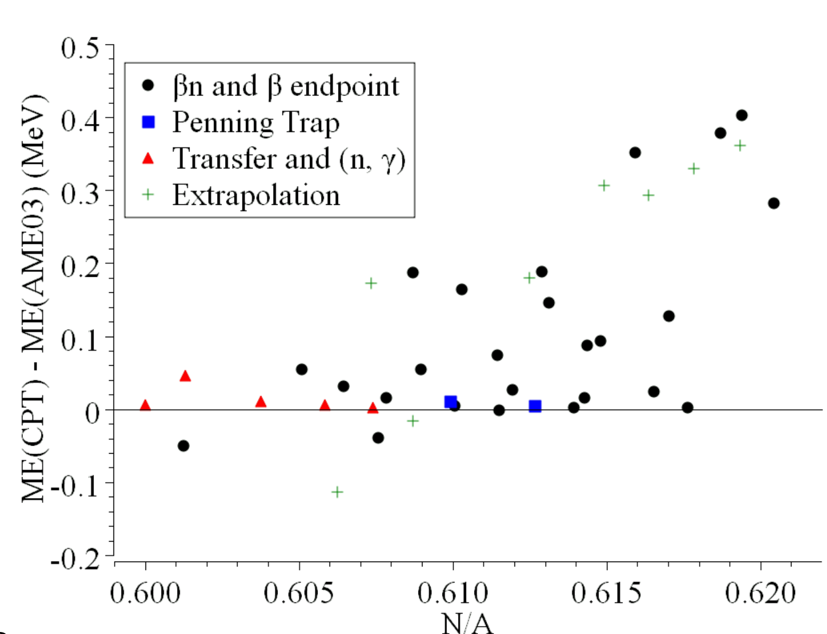


J. A. Clark and G. Savard, Int. J. Mass Spectrom. 349-350, 81 (2013).

- Much interest and increasing access to this region
- Canadian Penning Trap (CPT) has measured more than 150 neutron-rich nuclides.
- Mass precision ~ 10^{-7} to 10^{-8} (10 -100 keV/c^2) for masses approaching the r process
- Currently reaching isotopes produced at the 10^{-7} fission branch level

Comparison with evaluated data

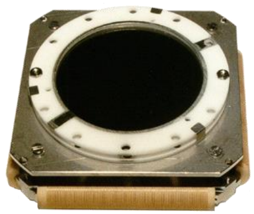




- Nuclei are less bound with neutron excess (affects the location of the r-process path)
- Good agreement with other Penning trap results and reaction Q value measurements
- Large disagreement with results obtained with β-decay measurements and extrapolations

New measurement technique – PI-ICR

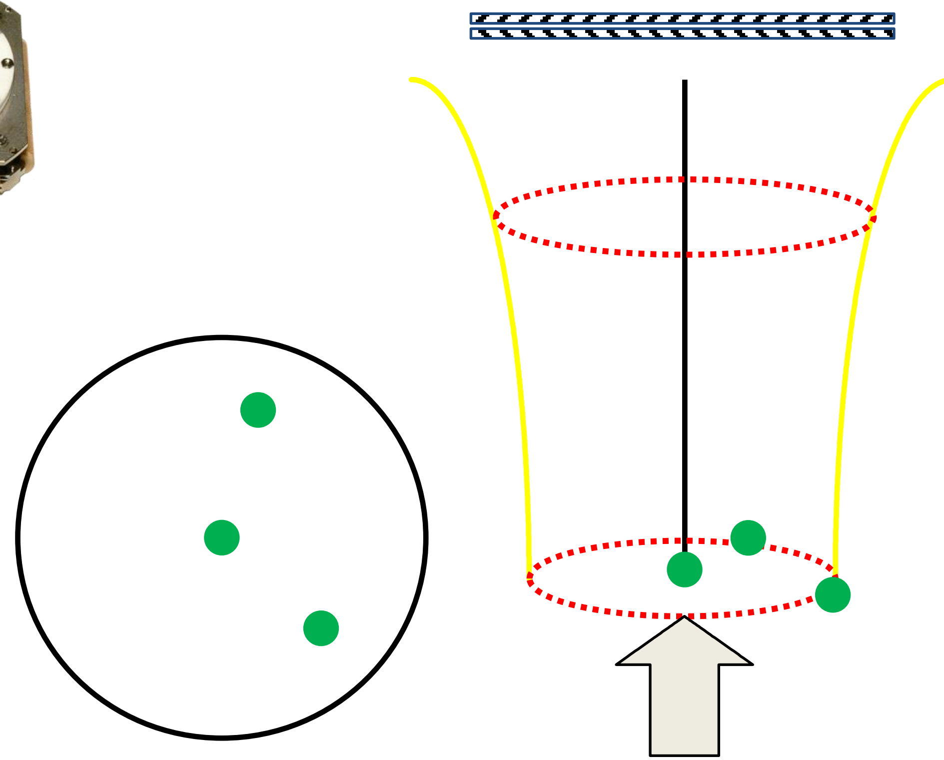
- Use a position-sensitive MCP detector and 'project' ion motion onto it



Phase **i**maging – **i**on **c**yclotron **r**esonance

- The orbital frequency of the ion's motion is calculated from the phase change over time.

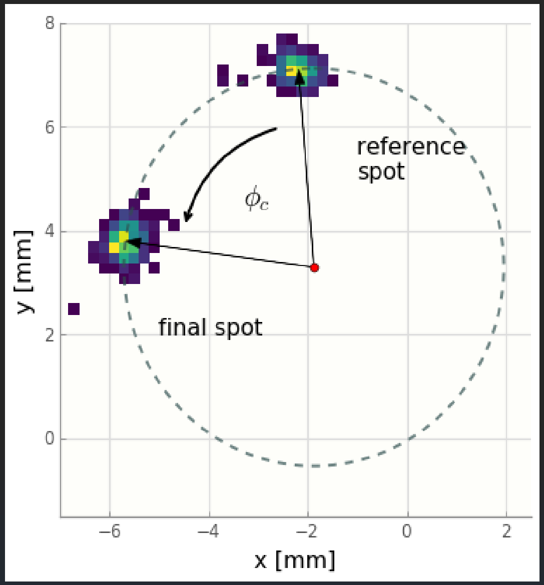
$$\omega = \frac{\phi + 2\pi n}{t} \qquad \Delta\omega = \frac{\Delta\phi}{t} \approx \frac{2\Delta r}{tr}$$



Phase-Imaging Ion-Cyclotron-Resonance

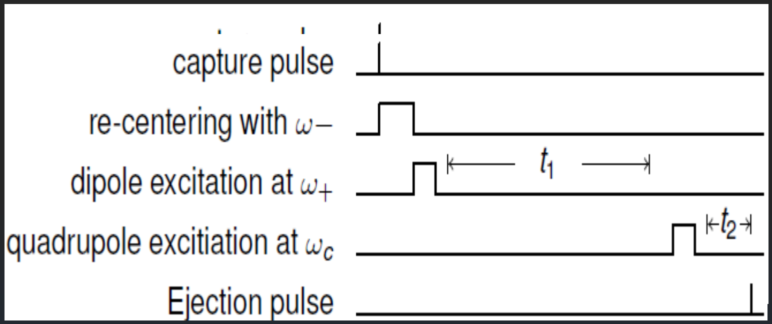
PI-ICR method at the CPT

- Position-sensitive MCP is used to measure the orbital phase of trapped ions



- Instead of measuring ω_c, we measure $\omega_+ + \omega_-$ in one measurement.

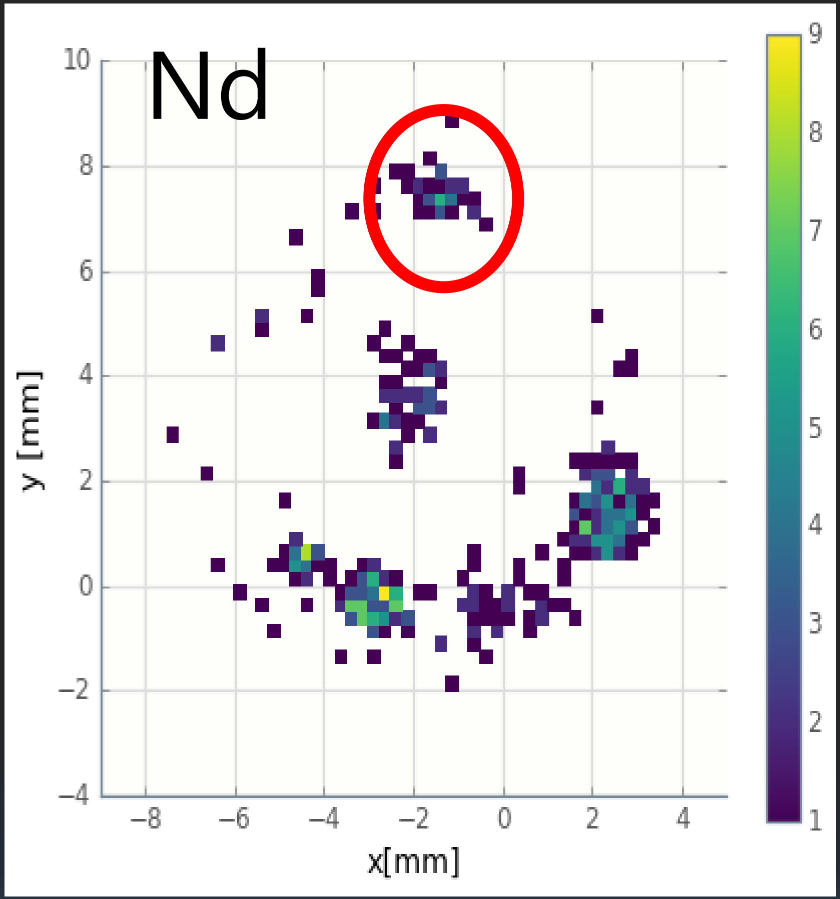
$$\nu_c = \frac{\phi_{tot}}{2\pi t_1} = \frac{\phi_c + 2\pi N}{2\pi t_1}$$



PI-ICR: Reaching weaker beams

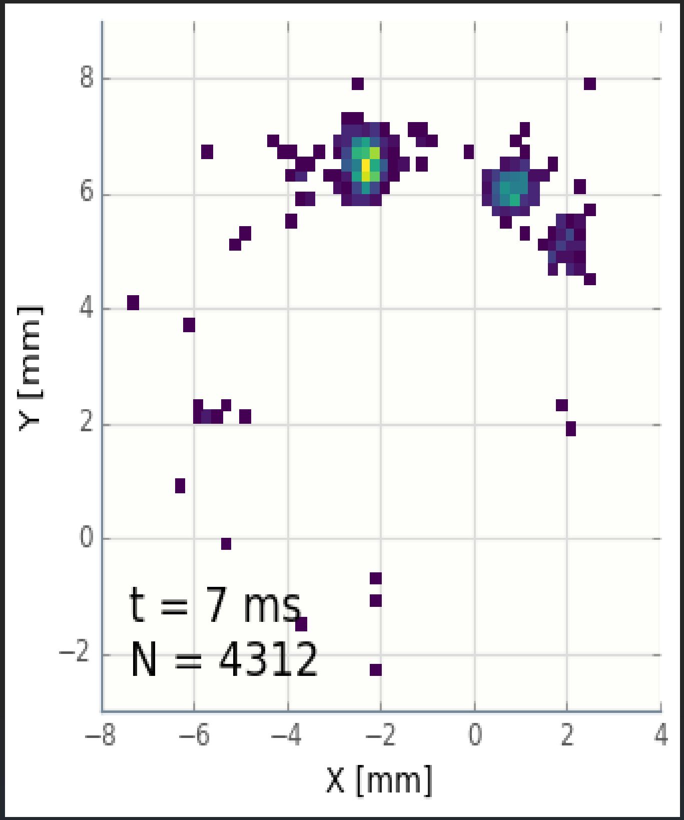
- ^{160}Nd is produced at ~$2x10^{-5}$ % from ^{252}Cf
- We saw ~5 ions/hr
- This plot shows ~25 Nd ions, and a mass uncertainty of <100 keV is found
- A resolution of R = 2,000,000 is achieved in less than 100ms, a feat which would take ~3 seconds in TOF-ICR

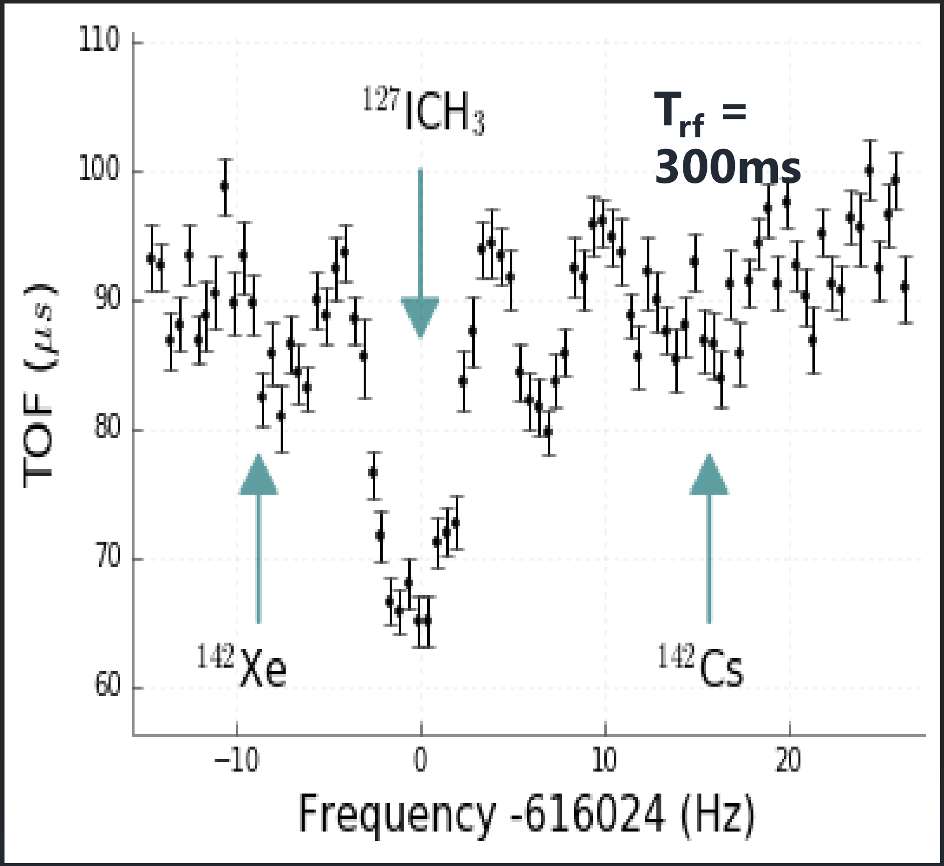
160 Nd



PI-ICR: Improved resolution

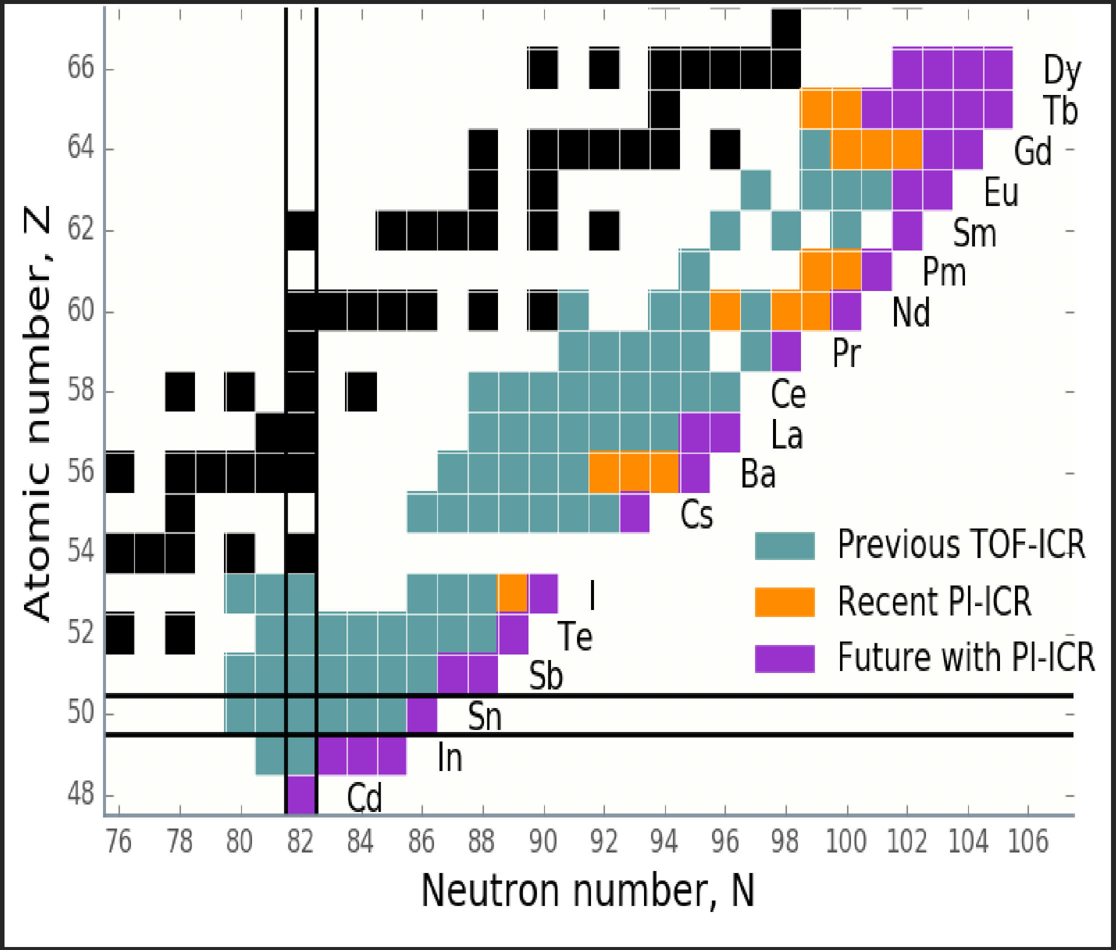
Beam of A = 142





Prospects:

- The MR-TOF has been installed at CARIBU, typically obtain resolving power of R = 50,000 in 10ms
- PI-ICR has been implemented at the CPT allowing us to probe 1-3 neutrons further from stability
- PI-ICR provides a factor of ~30 improvement in resolution, and is intrinsically more efficient than TOF-ICR



Conclusion:

- Elements in the universe were created by a variety of processes.
  - The *r* process is thought to create half the elements heavier than iron
  - Models of the *r* process rely on good data of nuclide properties
- Ion traps are revolutionizing the way nuclide properties are measured
  - Penning traps provide most reliable and precise mass measurements
- Access to previously elusive neutron-rich nuclides is becoming available with new facilities and new techniques
  - Studies of rare, short-lived nuclides require fast, efficient, and clean injection schemes
  - First measurements indicate interesting times lie ahead

Thank you for your attention

Collaboration

M. Burkey, J.A. Clark, J.P. Greene, A.F. Levand, G. Savard, B.J. Zabransky

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