# “TOF-Bρ Mass Measurements of Neutron-rich Nuclei at the NSCL”

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Frontiers Meeting

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# Outline

- Motivation
- Time-of-flight (TOF) Mass Spectrometry
- Pioneering Experiment of Neutron-rich Isotopes between N=32 to N=40
- Developments and Future Experiments

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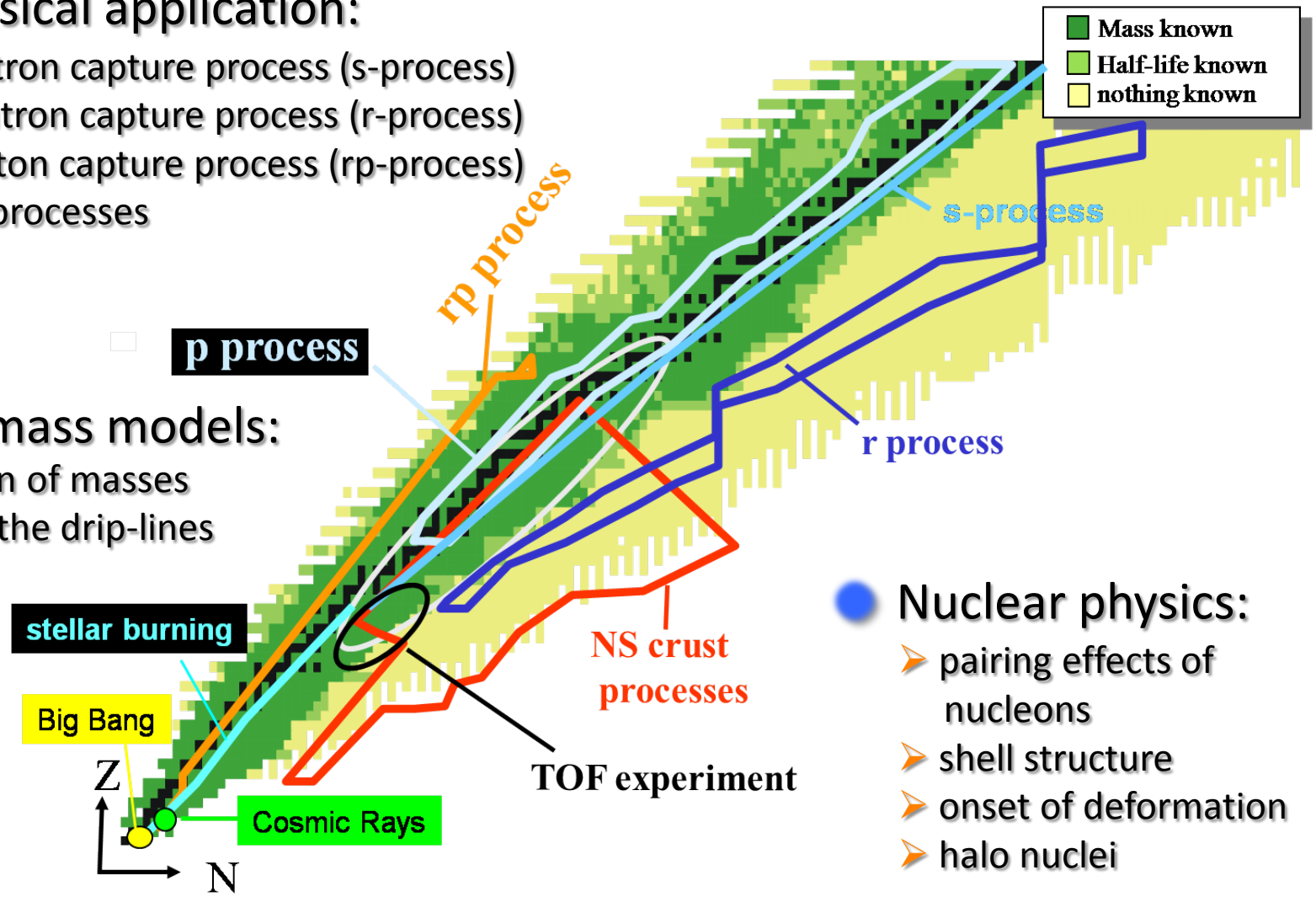
# Importance of Atomic Masses

- Astrophysical application:
  - slow neutron capture process (s-process)
  - rapid neutron capture process (r-process)
  - rapid proton capture process (rp-process)
  - NS crust processes

- Nuclear mass models:
  - prediction of masses towards the drip-lines




- Nuclear physics:
  - pairing effects of nucleons
  - shell structure
  - onset of deformation
  - halo nuclei

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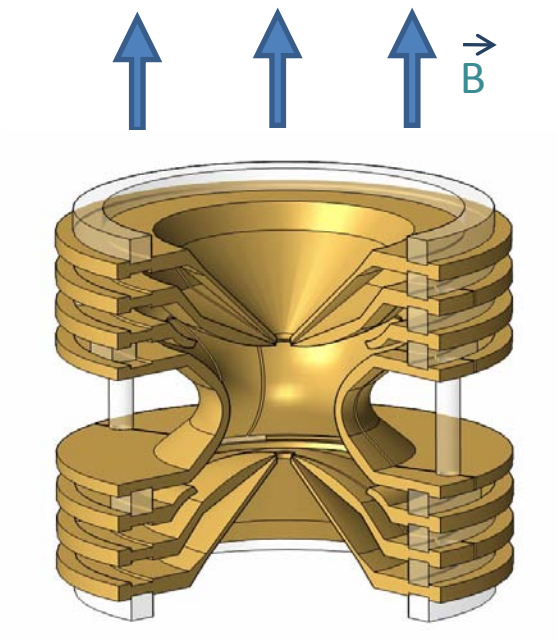
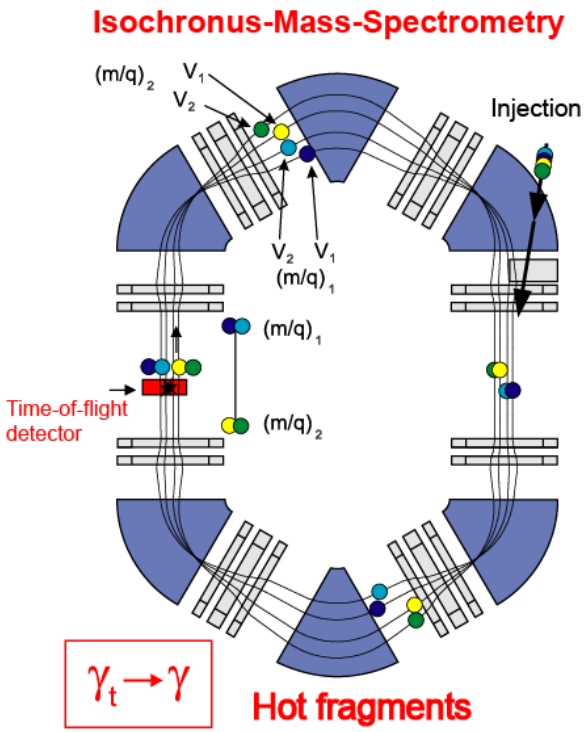
# Measurement Techniques

- Penning trap




- Storage ring




- highest precision ($10^{-9}$)
- required lifetime of a few ten milliseconds
- measurement time of a few hundred milliseconds

- **Time-of-flight measurement**

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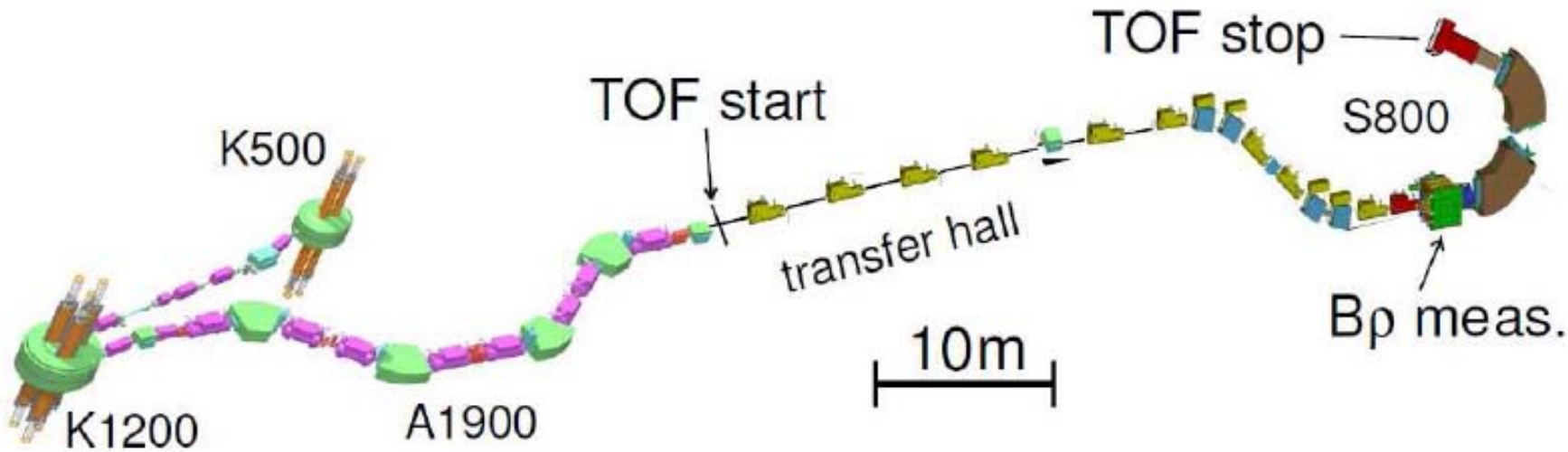
# Time-of-flight (TOF) Technique




- many different isotopes simultaneously
- measurement time in below 1 μs
- precision of $10^{-6}$ (sufficient for nuclear structure studies and astrophysics)

$$B\rho = \frac{p}{q} = \frac{\gamma m_0}{q}\left(\frac{L}{TOF}\right)$$

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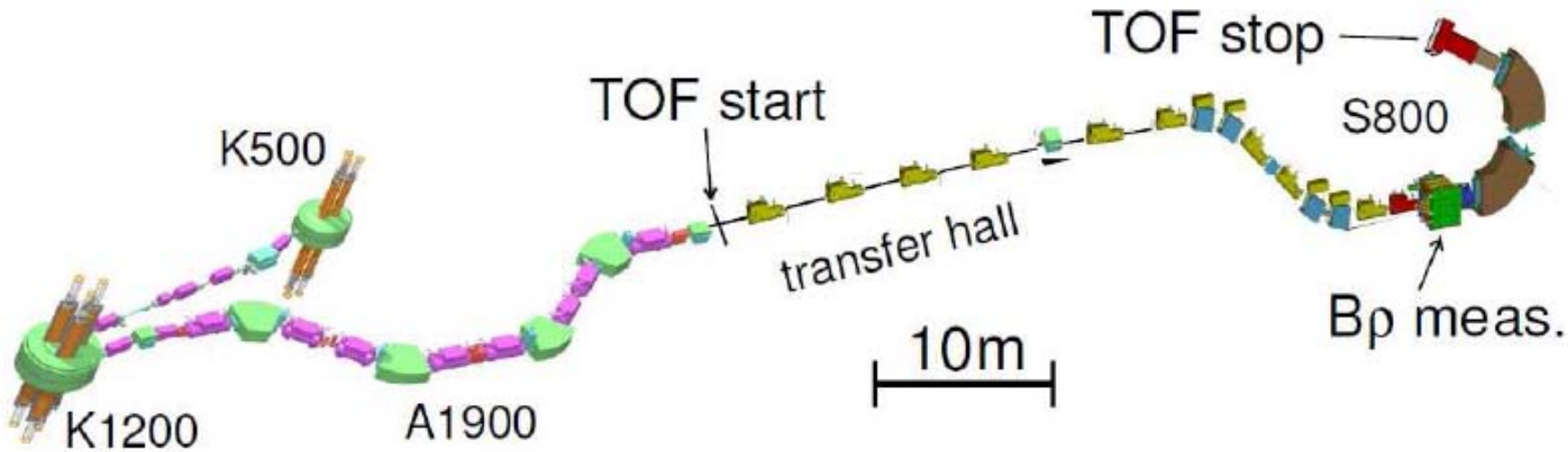
# Experimental Setup




NSCL:

- two coupled cyclotrons
- flight path of ≈ 58 m
- flight time of ≈ 460 ns
- momentum acceptance of 0.5%
- comparison with a known reference mass

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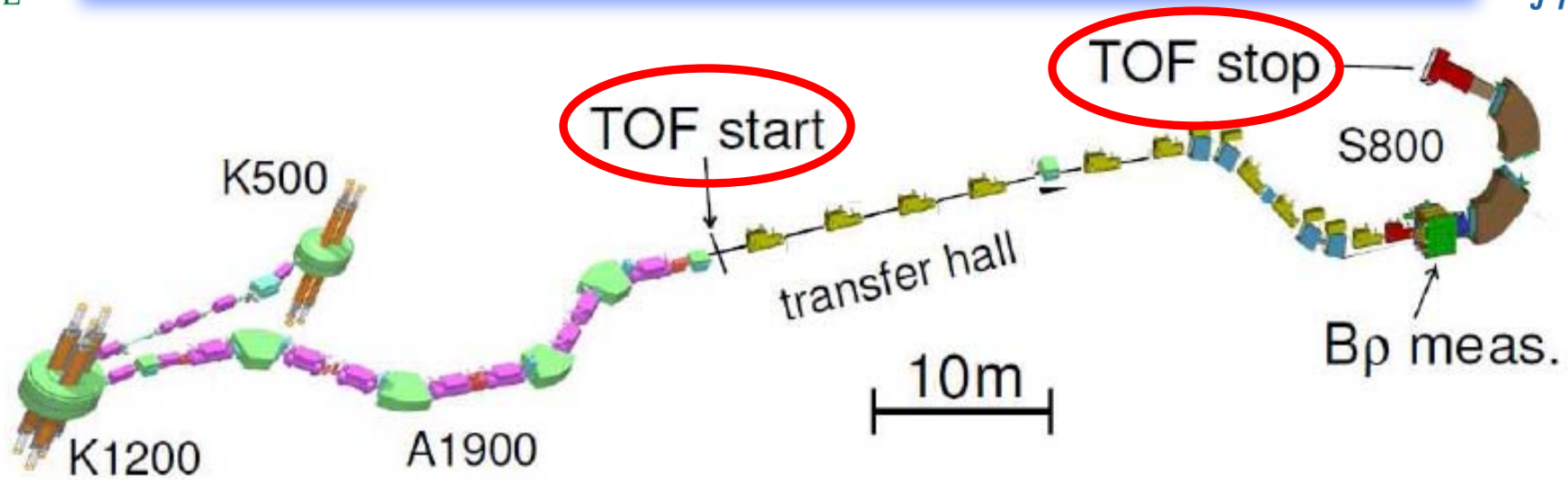
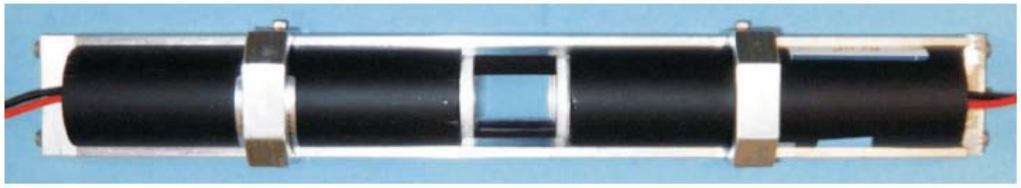
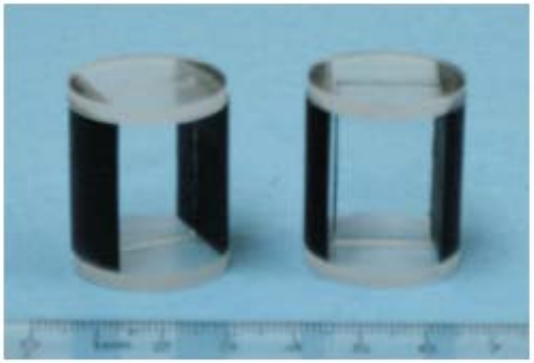
# TOF Measurement





- fast PMT (Hamamatsu R4998)
- small (1.5 x 2.54 cm) and fast scintillator (BC418)
- low attenuation cables (Belden 7810a)
- performance: $\sigma_{time}$=27 ps

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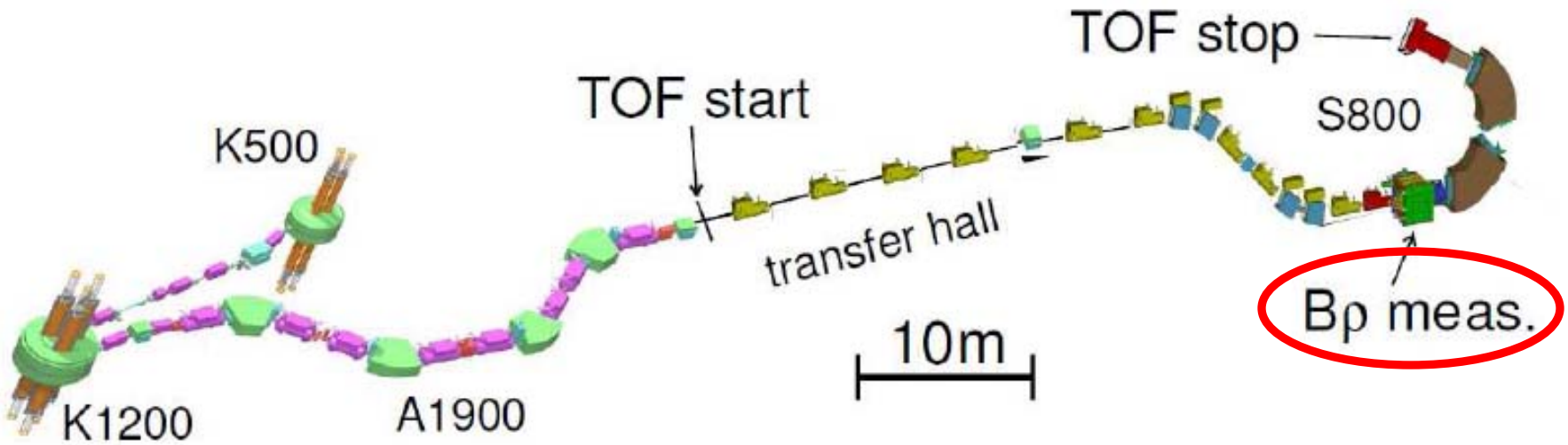
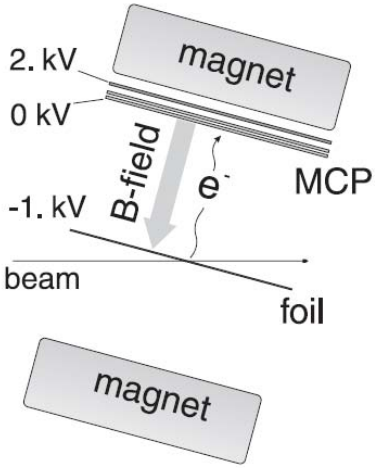
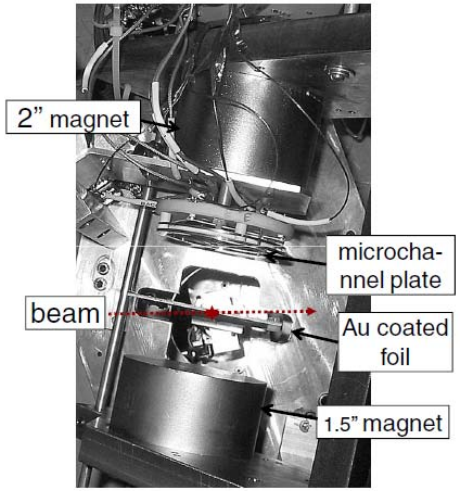
# Bρ Measurement




- different isotopes have different momentum distributions
- material in the beamline (scintillator for time-of-flight) changes energy (depending on the charge of the ions
  → measure the position of each particle

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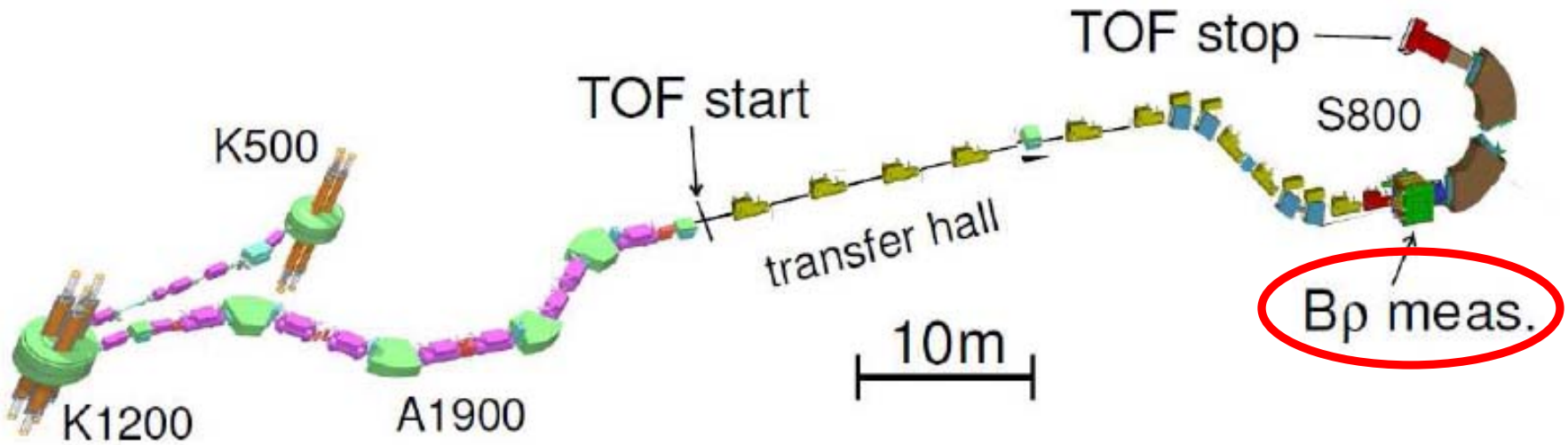
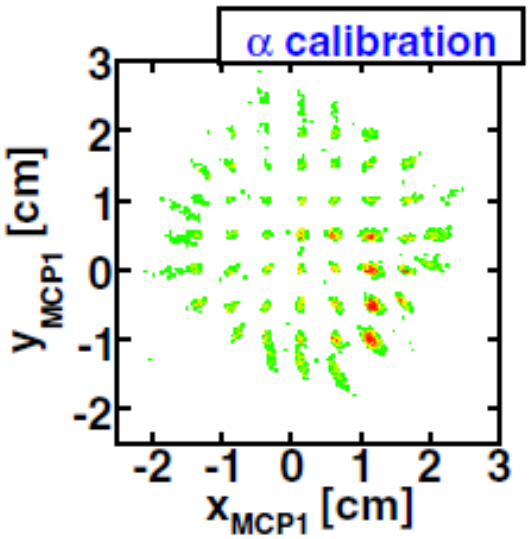
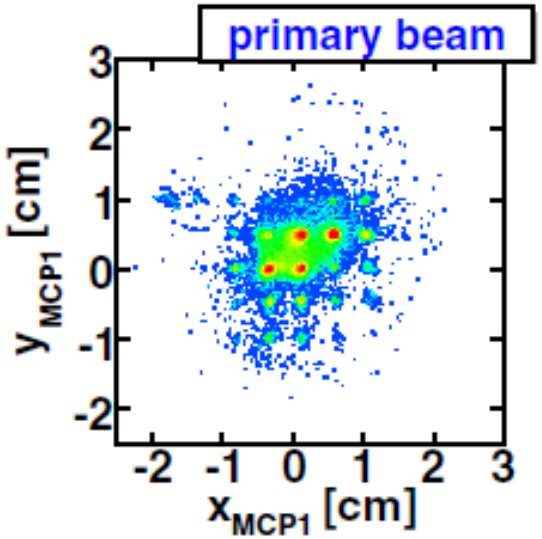
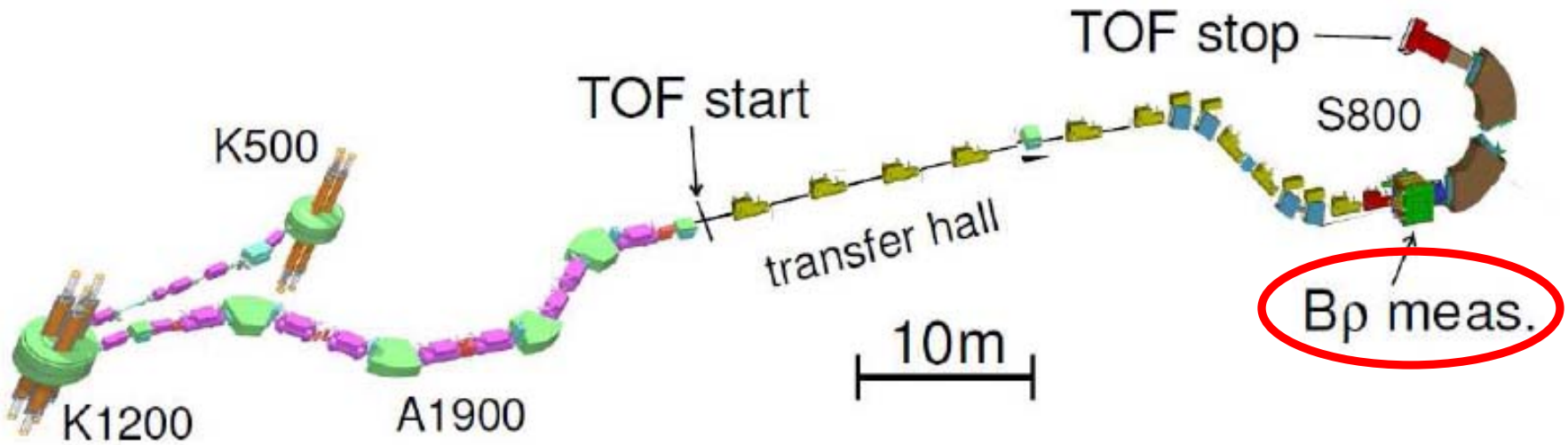
# Bρ Measurement

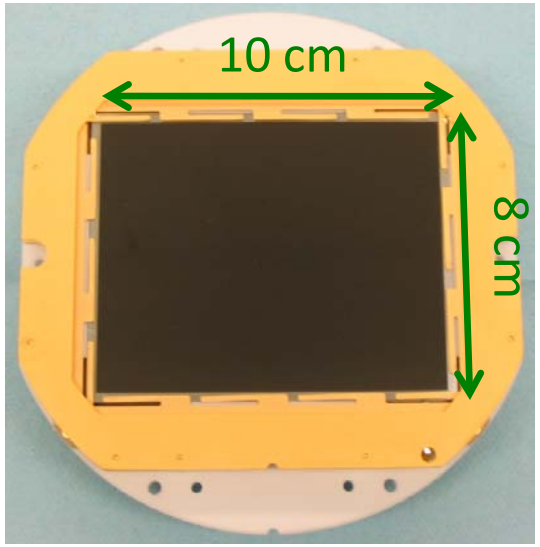


# Technical Development




- New MCP detector
  - 1st experiment: circular MCPs with a diameter of 5 cm
  - new experiment: 8 cm * 10 cm rectangular MCPs
    → larger acceptance
  - stronger permanent magnets

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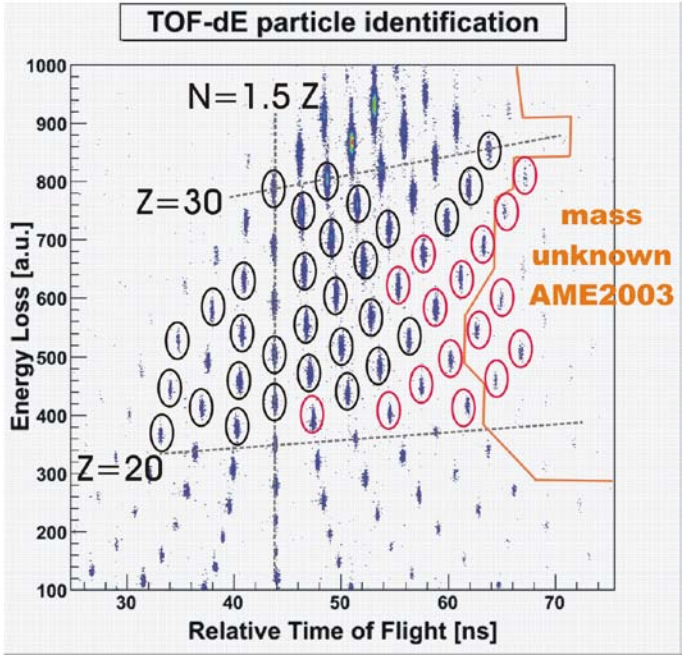
# First Results

- primary beam: $^{86}$Kr (100 MeV/u)
- 47 mg/cm$^2$ and 94 mg/cm$^2$ Be targets
- 6 nuclides measured for the first time
- 16 mass values ranging from $^{53}$Sc to $^{77}$Cu improved
- best mass uncertainty achieved: 240 keV




Mass excess / keV

| Isotope | This work | Literature | Mean |
|---|---|---|---|
| $^{53}$Sc | -38150 (240) | -37630 (250#) | -37930 (180) |
| $^{54}$Sc | -33590 (330) | -34190 (370) | -33860 (250) |
| $^{55}$Sc | -30320 (540) | -29620 (750) | -30080 (440) |
| $^{57}$Ti | -33820 (310) | -33530 (470) | -33730 (260) |
| $^{58}$Ti | -29740 (800) | | -29740 (800) |
| $^{60}$V | -33030 (350) | -32600 (470) | -32870 (280) |
| $^{61}$V | -30910 (940) | | -30910 (940) |
| $^{63}$Cr | -35270 (600) | | -35270 (600) |
| $^{65}$Mn | -40730 (280) | -40710 (560) | -40720 (250) |
| $^{66}$Mn | -36890 (770) | | -36880 (770) |
| $^{67}$Fe | -45880 (220) | -45740 (370) | -45840 (190) |
| $^{68}$Fe | -44010 (390) | -43130 (750) | -43830 (340) |
| $^{70}$Co | -46720 (250) | -45640 (840) | -46640 (240) |
| $^{71}$Co | -44530 (510) | -43870 (840) | -44360 (430) |
| $^{74}$Ni | -49390 (1040) | | -49390 (1040) |
| $^{77}$Cu | -46940 (1390) | | -46940 (1390) |

O calibration isotopes (known mass)

O mass measured in this experiment

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# Upcoming Experiment

- primary beam: $^{76}$Ge (130 MeV/u)
- 446 mg/cm$^2$ and 610 mg/cm$^2$ Be targets
- aiming for more than 30 nuclides ranging from $^{46}$S to $^{72}$Co
- 6 days of beamtime
- increased acceptance by use of larger MCP detector


| Isotope | N Events | Isotope | N Events |
|---|---|---|---|
| $^{45}$S | 1500 | $^{59}$Sc | 100 |
| $^{46}$S | 100 | $^{59}$Ti | 51300 |
| $^{47}$Cl | 7700 | $^{60}$Ti | 9400 |
| $^{48}$Cl | 300 | $^{61}$Ti | 400 |
| $^{48}$Ar | 138600 | $^{61}$V | 247300 |
| $^{49}$Ar | 9500 | $^{62}$V | 39300 |
| $^{50}$Ar | 900 | $^{63}$V | 4000 |
| $^{51}$K | 72300 | $^{64}$V | 200 |
| $^{52}$K | 1300 | $^{64}$Cr | 76200 |
| $^{53}$K | 200 | $^{65}$Cr | 6300 |
| $^{52}$Ca | 284200 | $^{66}$Cr | 800 |
| $^{53}$Ca | 31500 | $^{66}$Mn | 44800 |
| $^{54}$Ca | 7100 | $^{67}$Mn | 44100 |
| $^{55}$Ca | 200 | $^{68}$Mn | 1900 |
| $^{56}$Ca | 100 | $^{69}$Mn | 200 |
| $^{56}$Sc | 50400 | $^{69}$Fe | 16500 |
| $^{57}$Sc | 5800 | $^{70}$Fe | 13600 |
| $^{58}$Sc | 900 | $^{72}$Co | 880 |

- nuclear structure around 62Ti
- shell closure at N=34?

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# Thanks

…for your attention

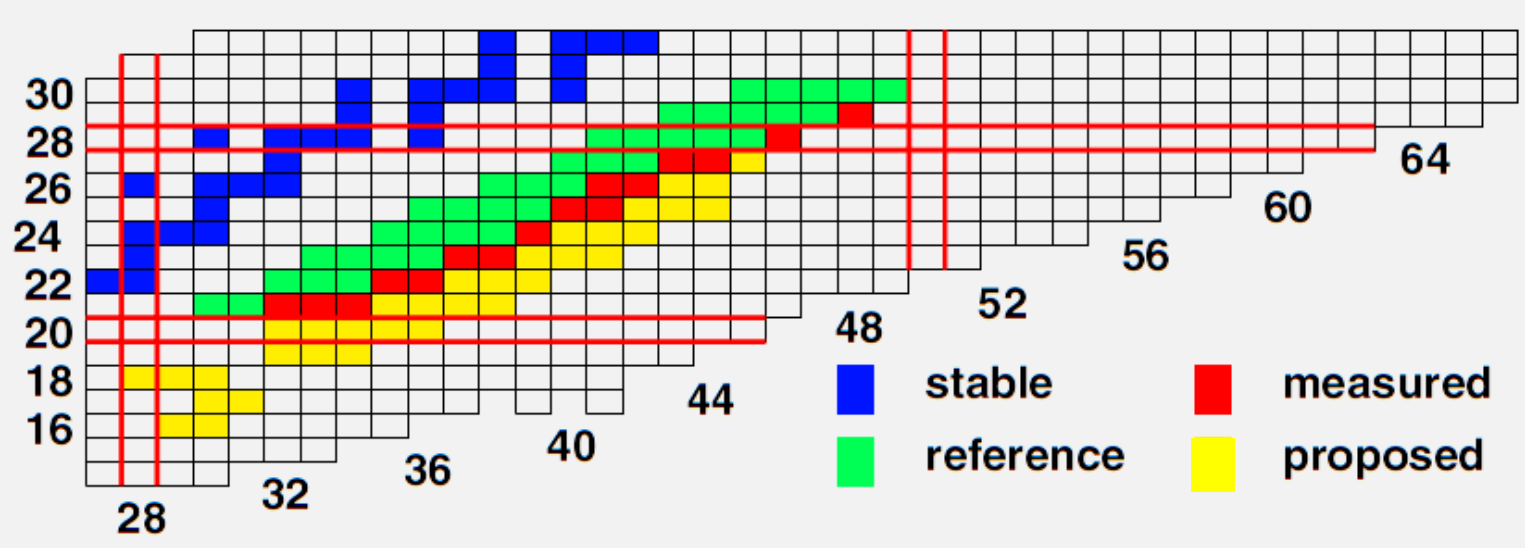
and

Thanks to

Milan Matos, Alfredo Estrade, Hendrik Schatz

Mathew A. Amthor, Daniel Bazin,
Ana D. Becerril, Marcelo Del Santo, Thom J. Elliot, Alexandra Gade,
Daniel Galaviz, Giuseppe Lorusso, Jorge Pereira, Mauricio Portillo,
Andrew Rogers, Dan Shapira, Edward Smith, Andreas Stolz, and Mark
S. Wallace

# Experimental Data

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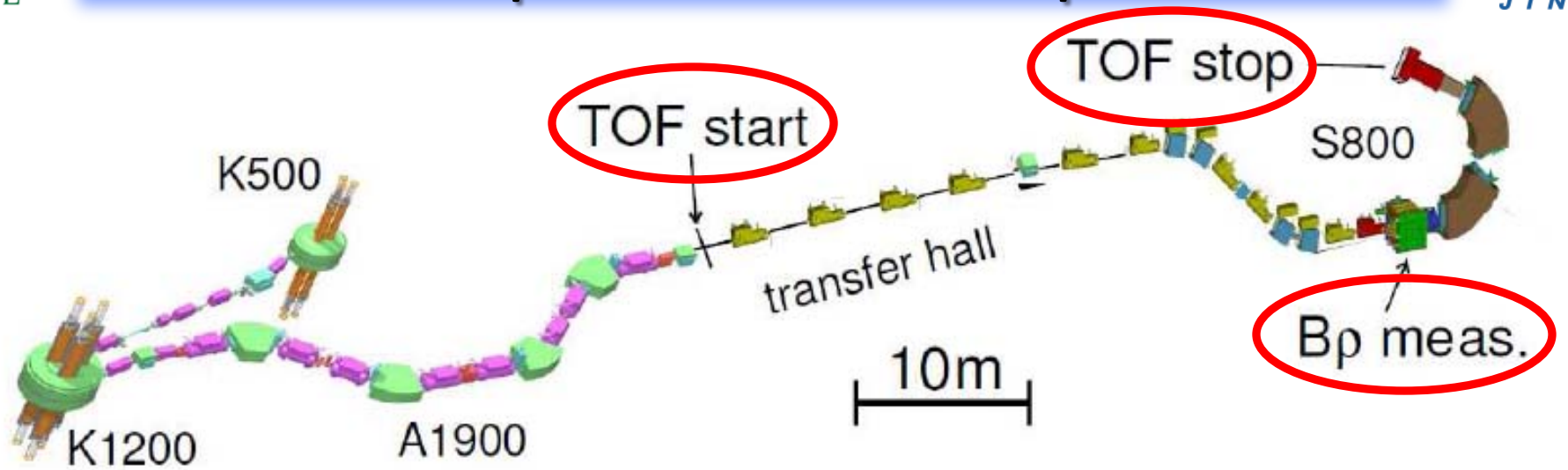
# Experimental Setup




**NSCL:**

- two coupled cyclotrons
- flight path of ≈ 58 m
- flight time of ≈ 460 ns
- < 1 μs flight time
- primary beam $^{86}$Kr 100 MeV/u
- 47mg/cm2 and 94 mg/cm2 Be targets
- momentum acceptance of 0.5%

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# Mass Determination

$$B\rho = \frac{\gamma p}{q} = \frac{\gamma m_0}{q}\left(\frac{L}{TOF}\right)$$

- desired precision: $10^{-6}$
- knowledge of the 58 m flight path with a precision of 58 µm

➔ comparison with a known reference mass

<u>but</u>

- momentum acceptance of 0.5%
- different isotopes have different momentum distributions
- material in the beamline (scintillator for time-of-flight) changes energy depending on the charge of the ions

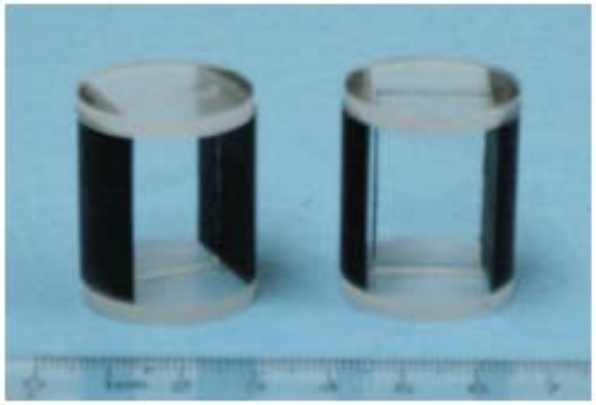
➔ measure the position of each particle

# TOF Measurement

primary beam: $^{86}$Kr 100 MeV/u targets: 47mg/cm$^2$ Be; 94 mg/cm$^2$ Be

## Timing scintillators

Ion beam
(fully stripped)



- fast PMT
- small (1.5 x 2.54 cm) and fast scintillator
- low attenuation cables
- timing with respect to distributed clock

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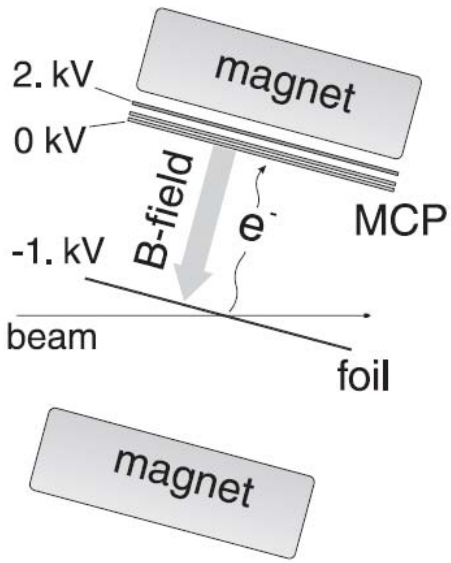
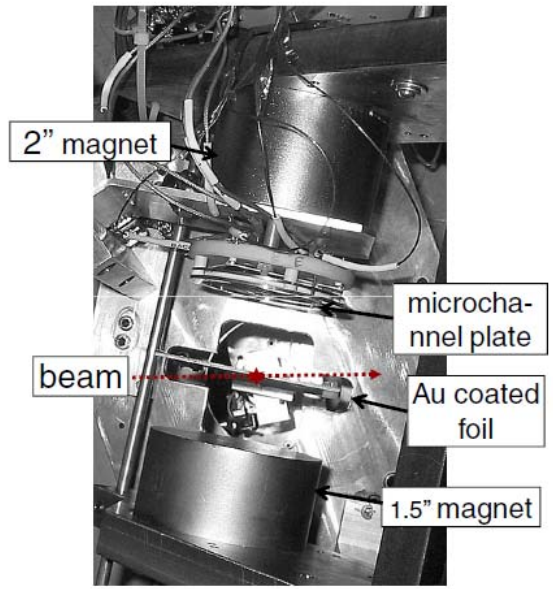
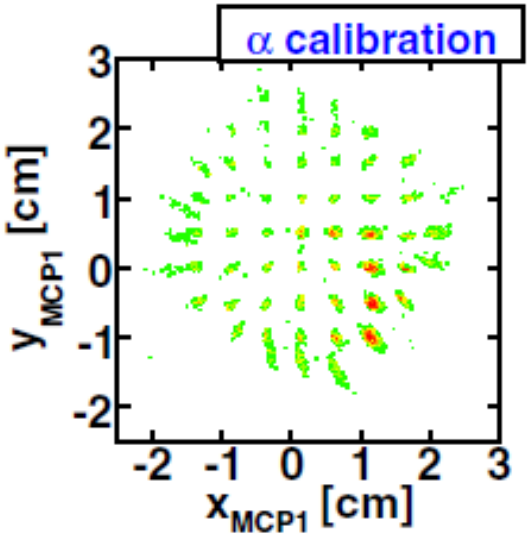
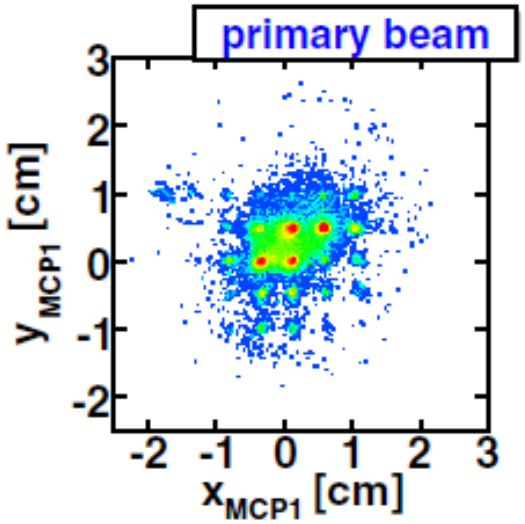
# Position Measurement

## Position-sensitive MCP detectors




- magnetic field of 0.2 T between MCP and foil
- position resolution ≈ 0.4 mm

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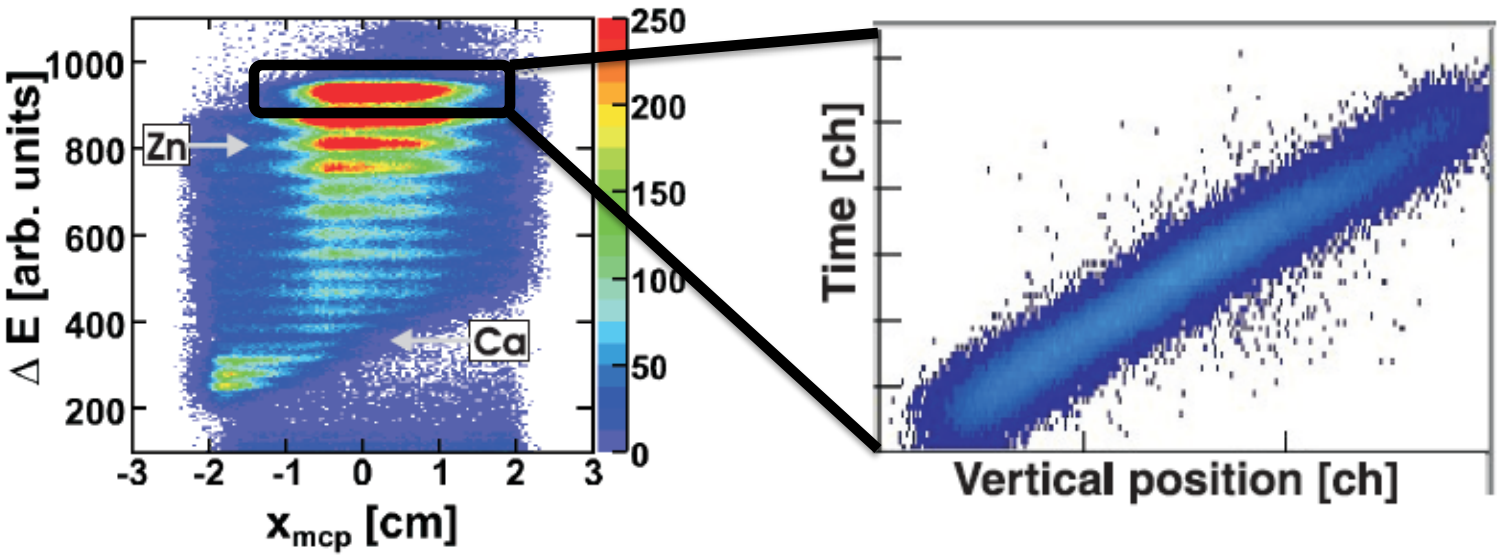
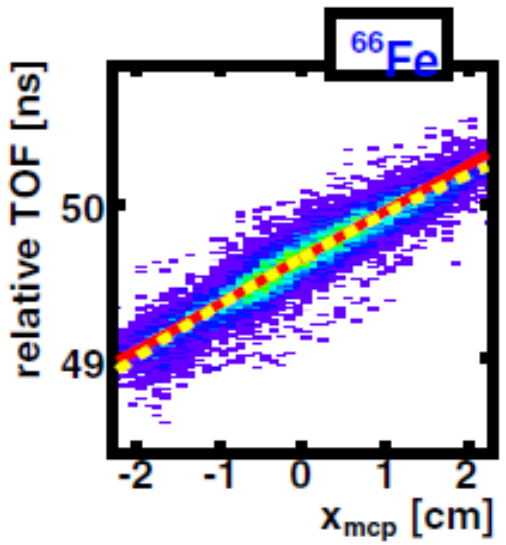
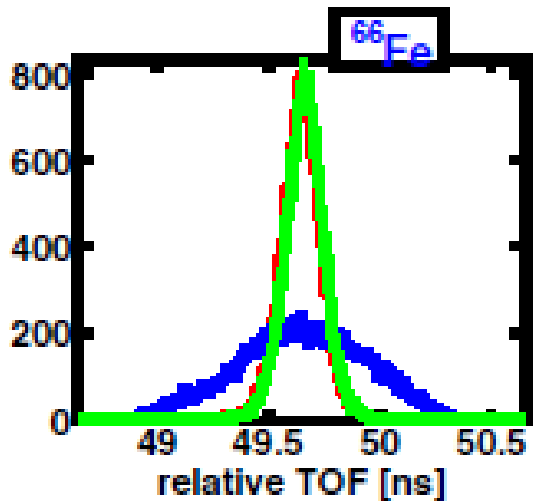
# Corrected TOF




$\sigma_{time}$=27 ps




- Mass resolution $R = 2 \cdot 10^{-4}$

$$\Delta m = 13\,MeV \Rightarrow \Delta TOF \approx 95\,ps$$

- For 5000 events

$$\delta m = \frac{\Delta m}{\sqrt{N}} \approx 180\,keV \Rightarrow \delta TOF \approx 1.3\,ps$$

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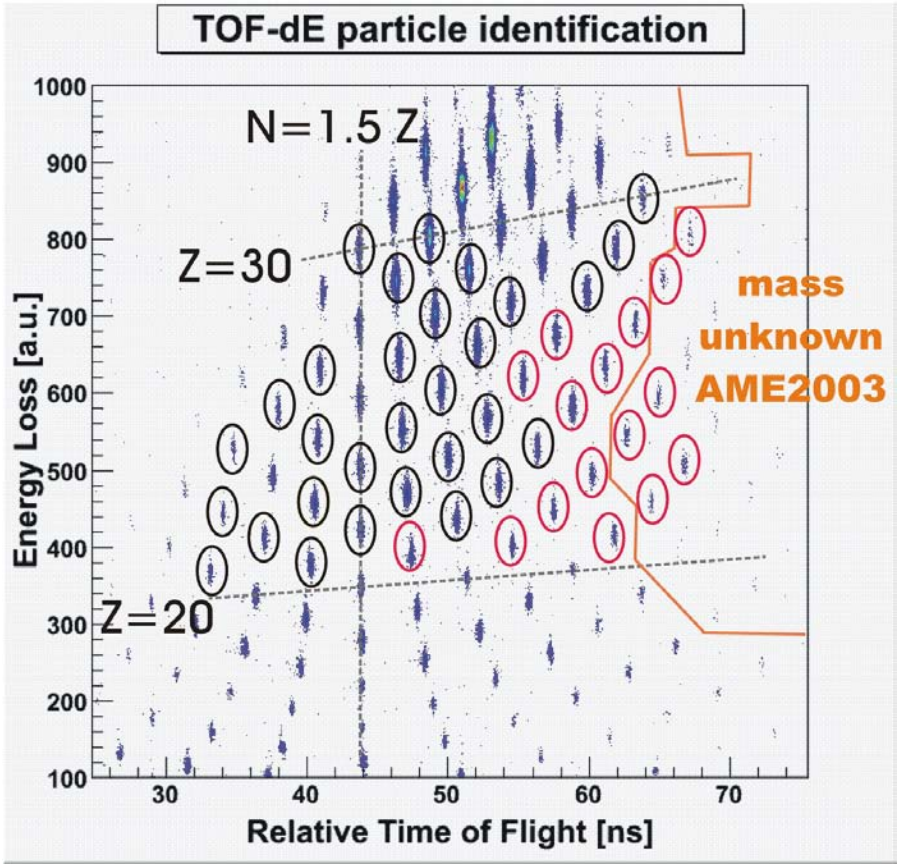
# Results




Mass excess in keV

| | This work | Literature | Mean |
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O calibration isotopes (known mass)

O mass measured in this experiment

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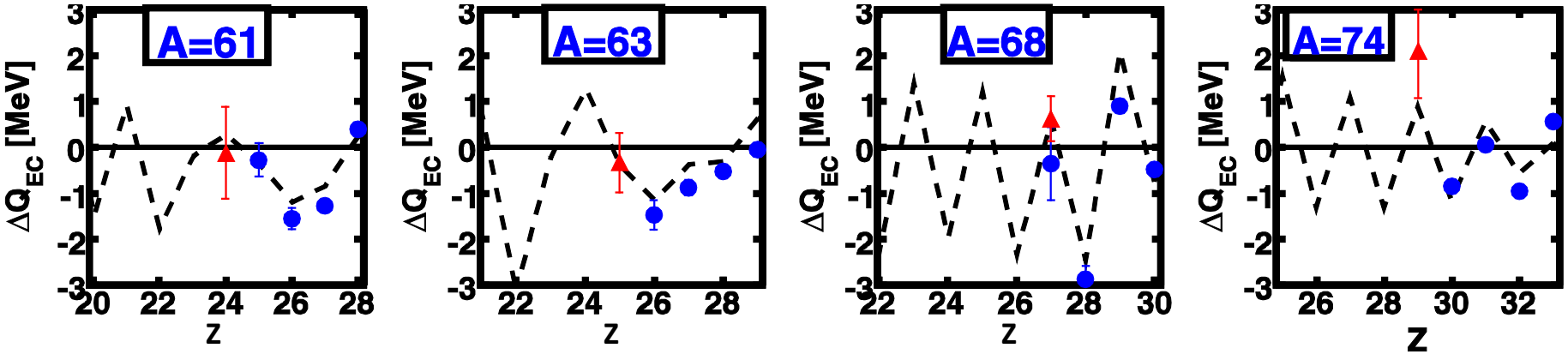
# Comparison with Mass Models

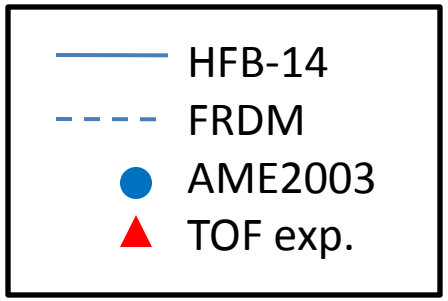
Better agreement with FRDM:

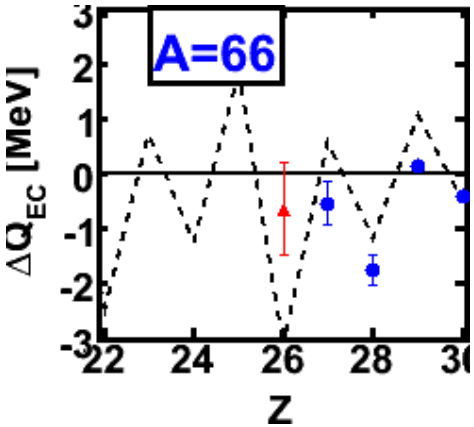


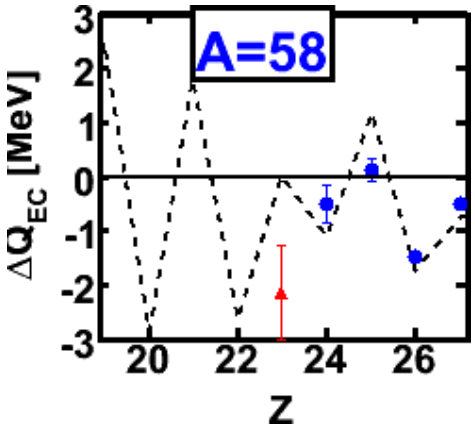

Better agreement with HFB-14:

Different to both:

$\Delta Q_{EC} = Q_{EC}(i) - Q_{EC}(\text{HFB-14})$

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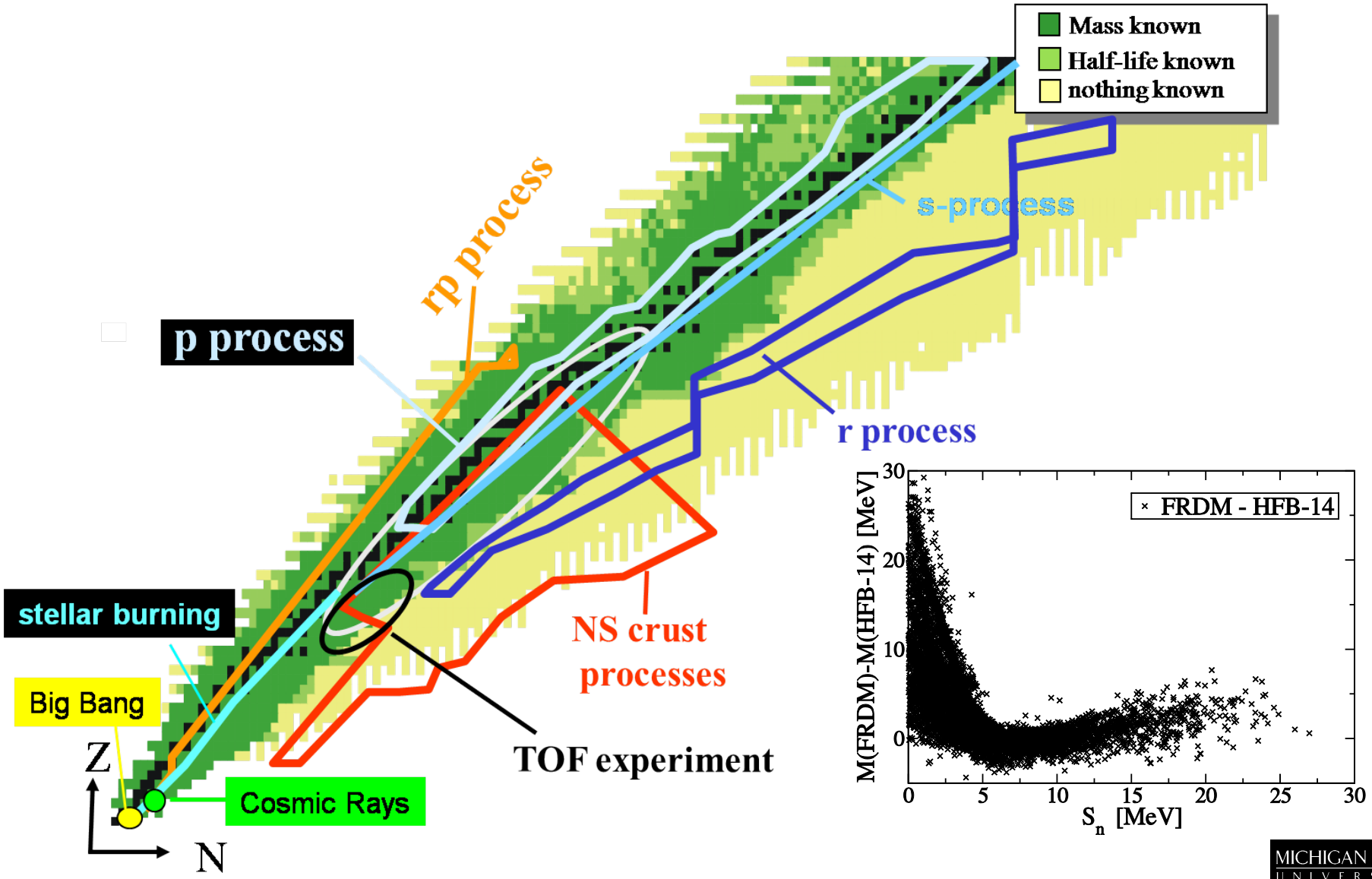
# Nuclear Masses in Astrophysics

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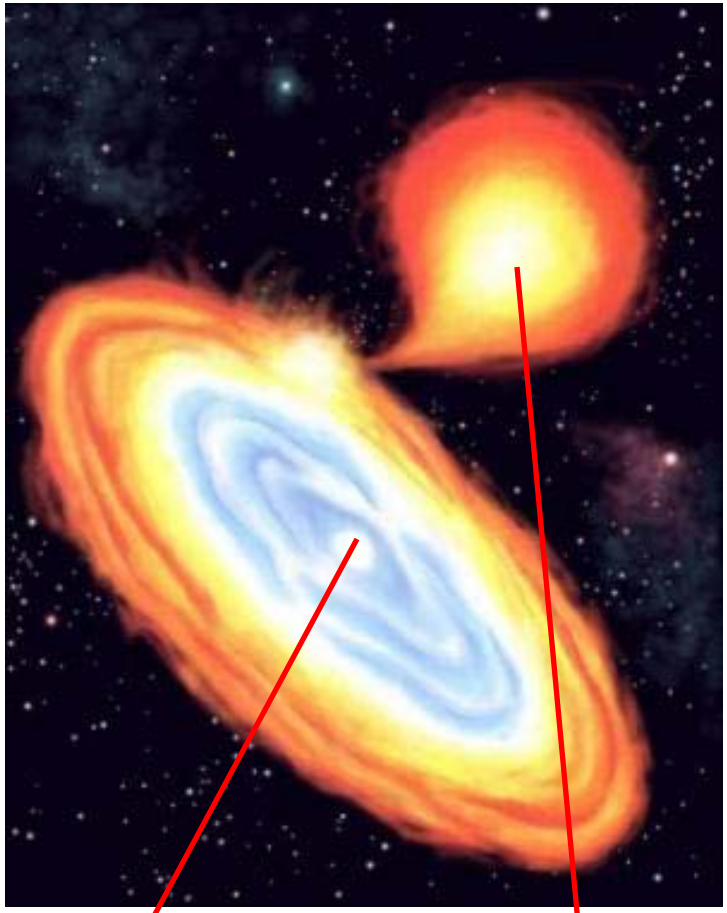
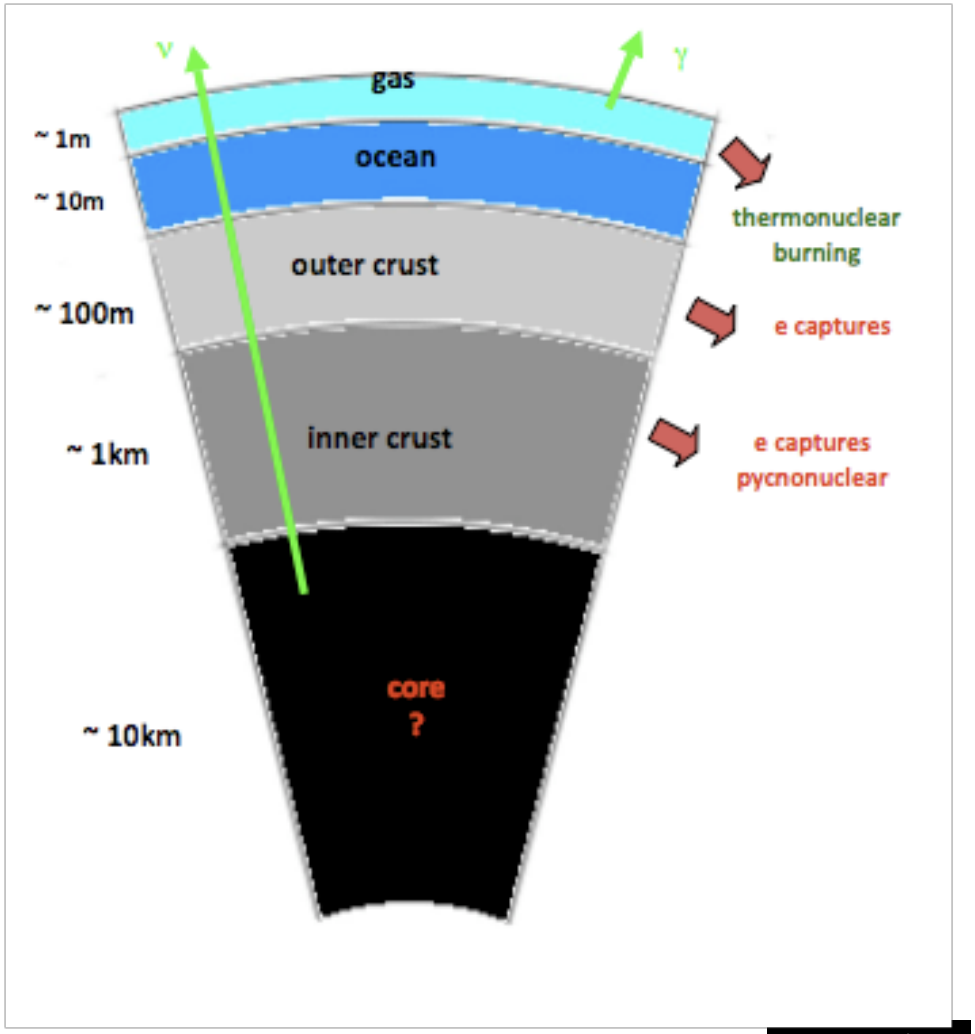
# Accreting Neutron Stars

- Artist rendition of an accreting neutron star.



neutron star

low mass companion star

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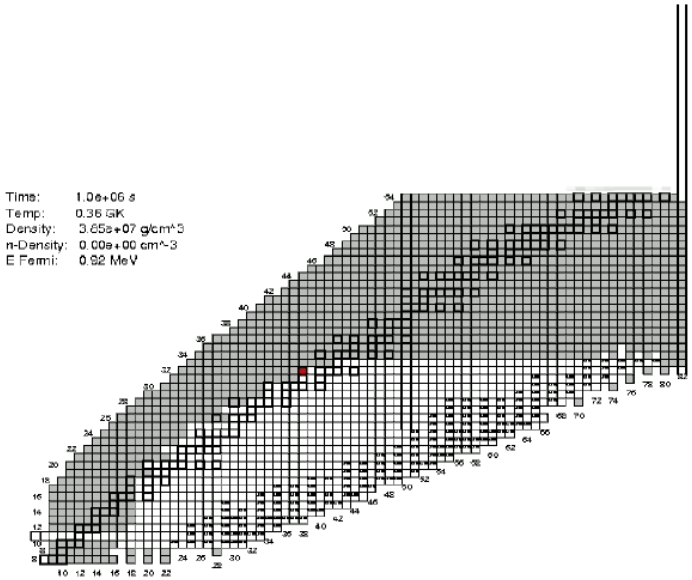


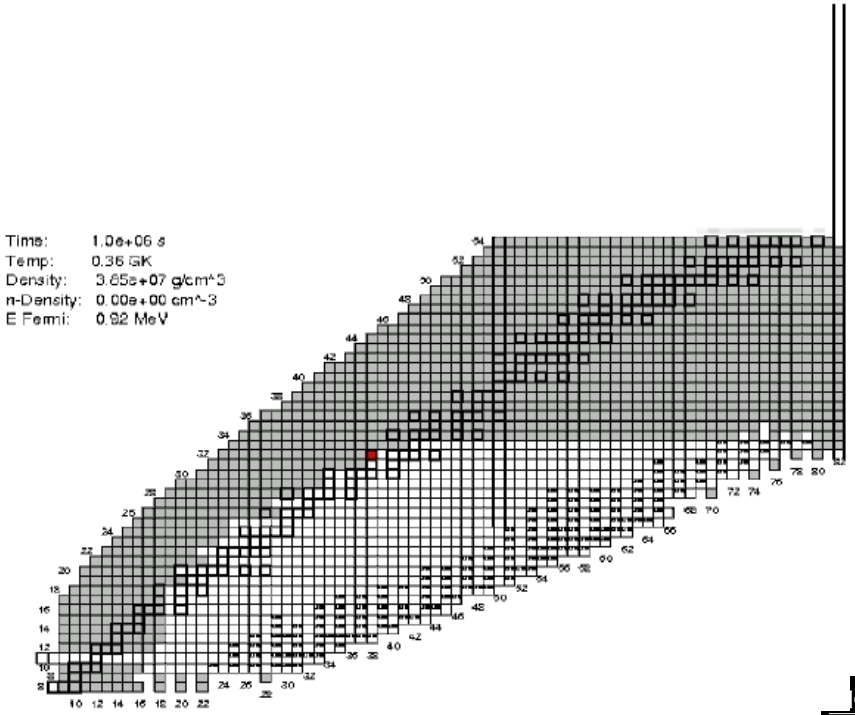


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# Conclusion

- Nuclear masses as key parameters in astrophysics
- Time-of-flight technique
- First results from the NSCL TOF project
- Impacts on accreting neutron stars

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# Thanks

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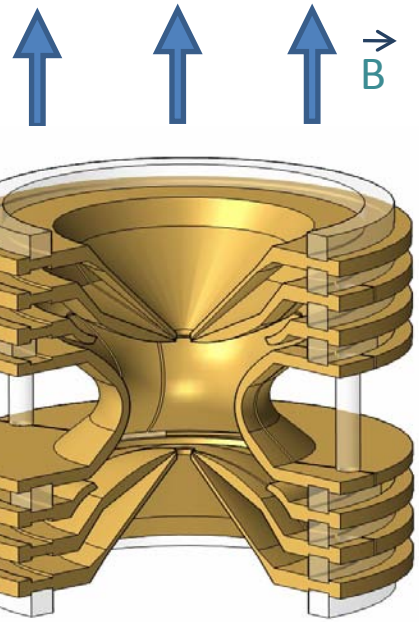
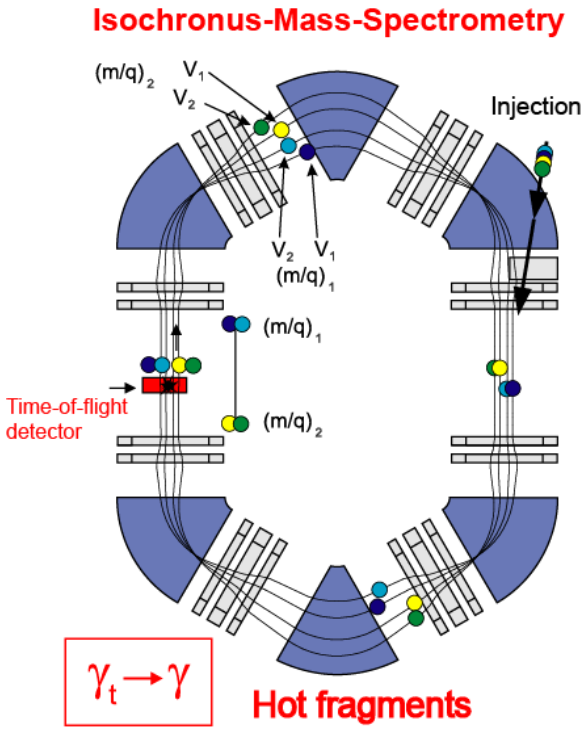
# Direct Measurements

## Penning trap




- highest precision ($10^{-9}$)
- required lifetime of a few milliseconds
- measurement time of a few hundred milliseconds

## Storage ring




- many different isotopes
- lower precision (a few $10^{-8}$) than Penning trap

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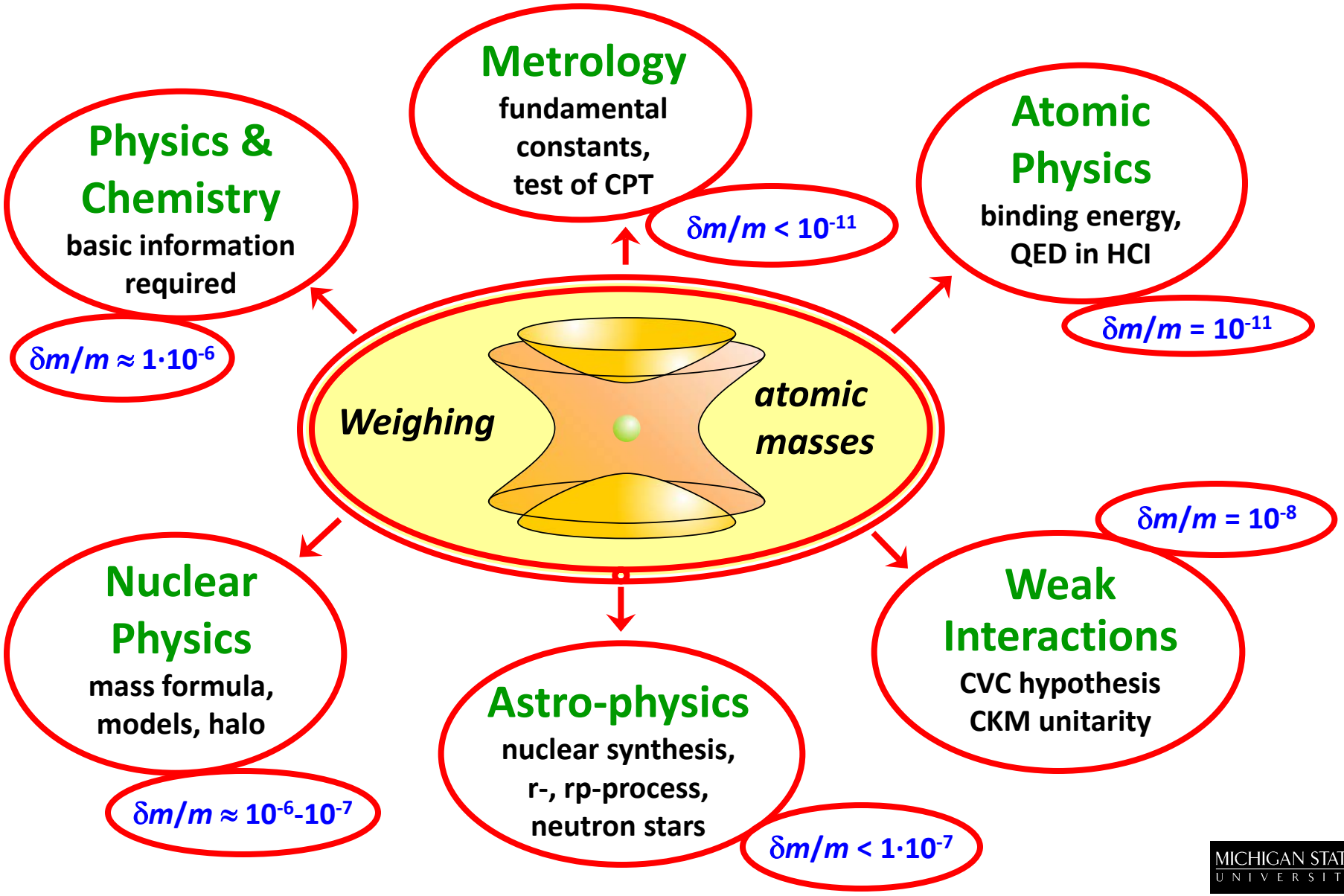
# Importance of Atomic Masses

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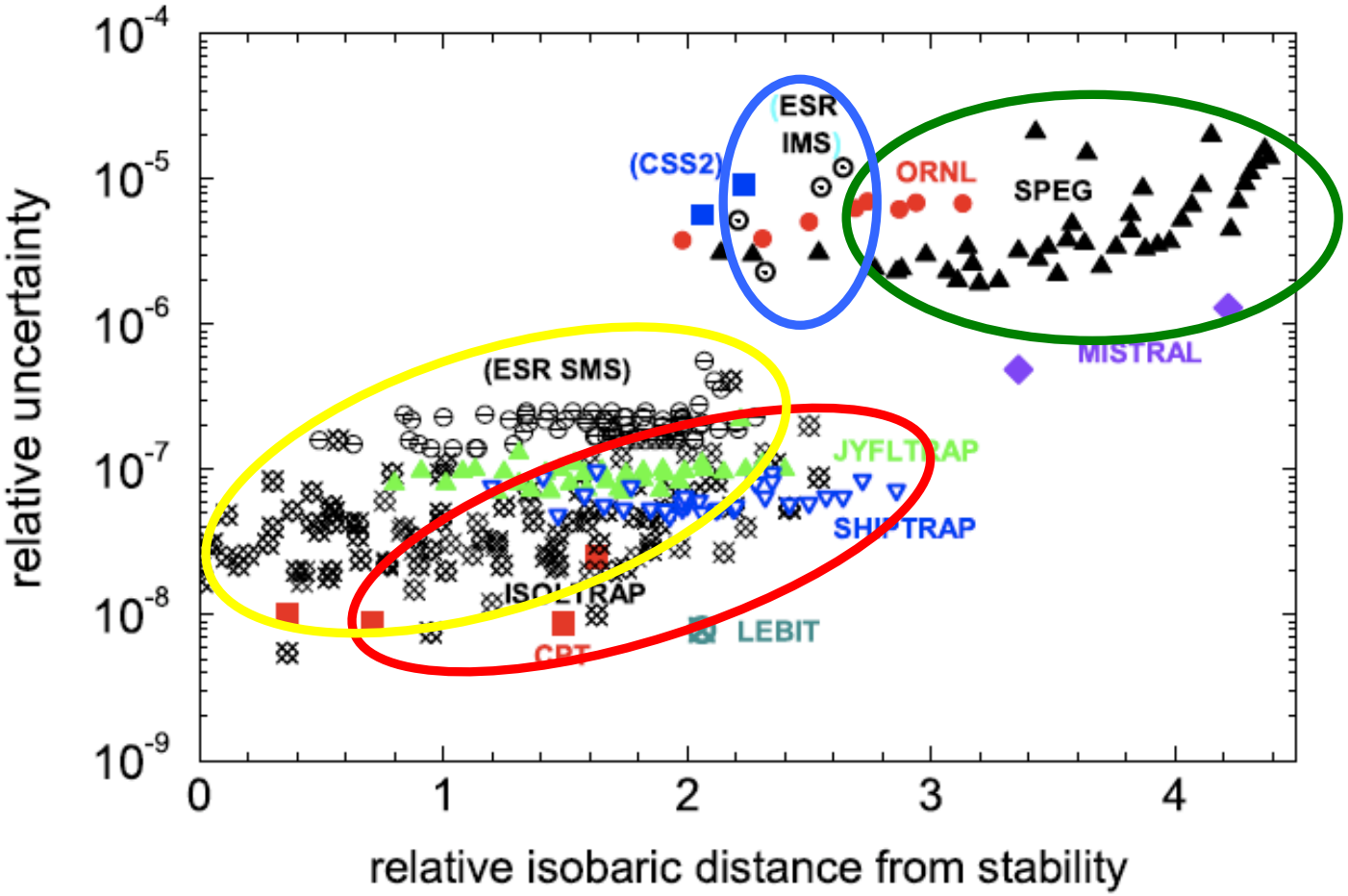
# Mass Measurements of Radioactive Isotopes




Penning trap

TOF (GANIL)

ESR-IMS

ESR-SMS

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