High-precision time-of-flight measurement: from neutron star mergers to medical imaging applications

Alfredo Estrade, Jacob Bromell, Shree Neupane, Sithira Samaranayake, Kailong Wang (Central Michigan University, USA), Leandro Bruno and Carolina Rabin (Universidad de la República, Uruguay)

FACULTAD DE CIENCIAS
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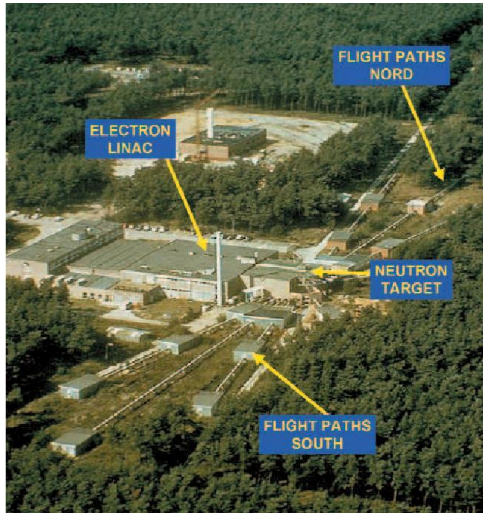
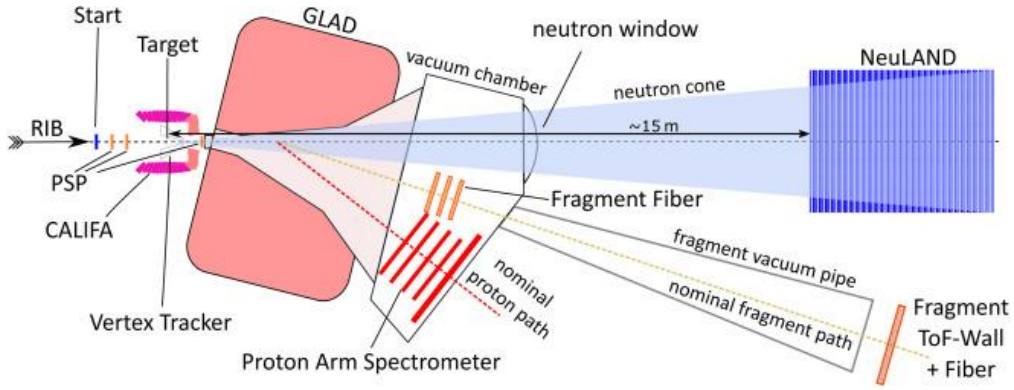
High-resolution time-of-flight measurements are a key tool in many areas of basic and applied nuclear physics

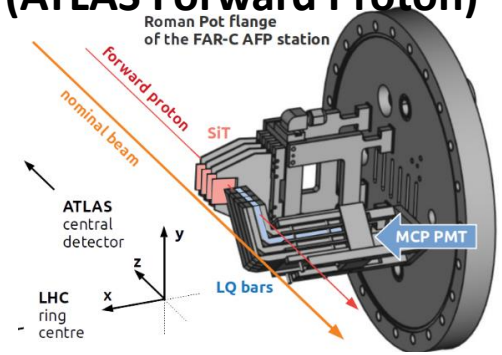
Neutron TOF (GELINA)



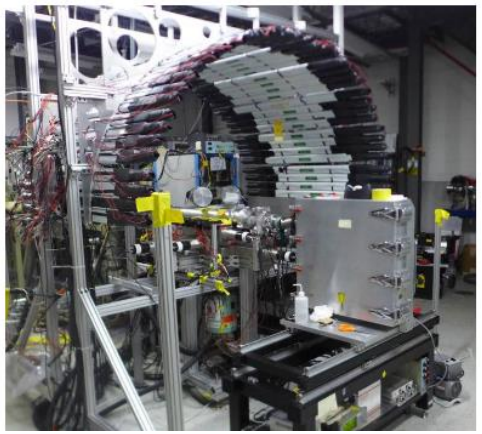
Nuclear reaction products (R3B)



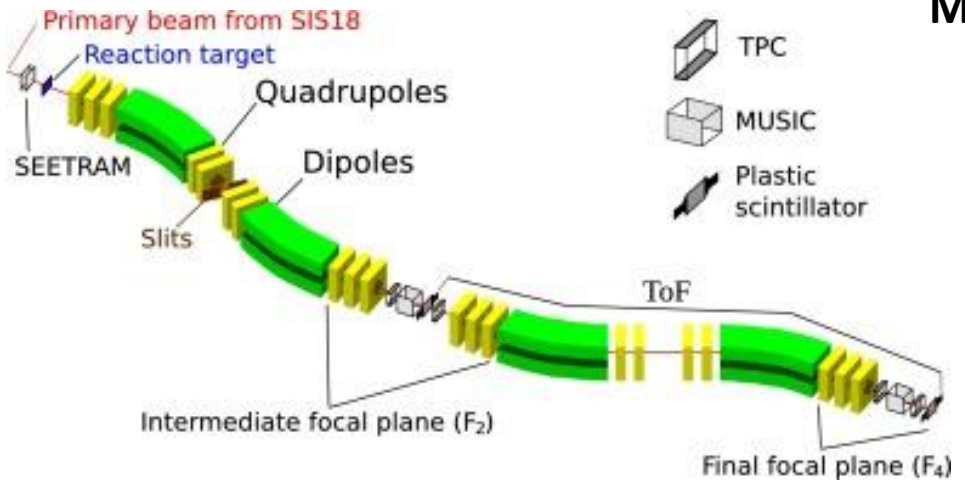
Collision protons (ATLAS Forward Proton)



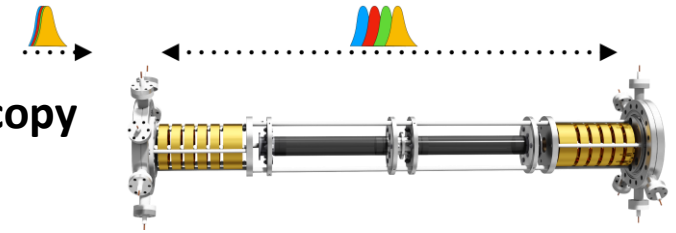
β-delayed neutrons (VANDLE)



Fragment separator (FRS)



Mass spectroscopy (MR-TOF)



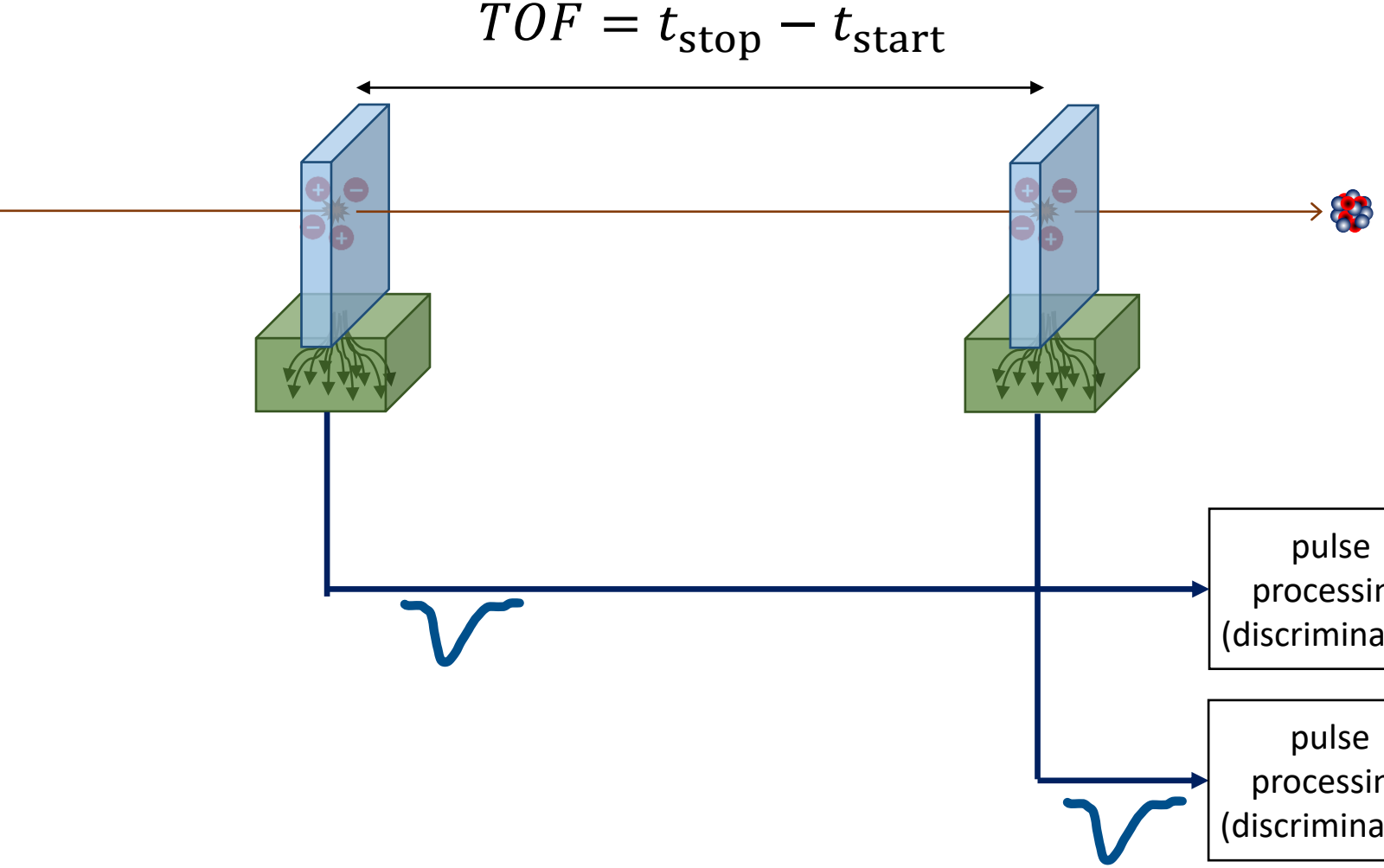
Resolution: $R = \frac{\delta TOF}{TOF}$

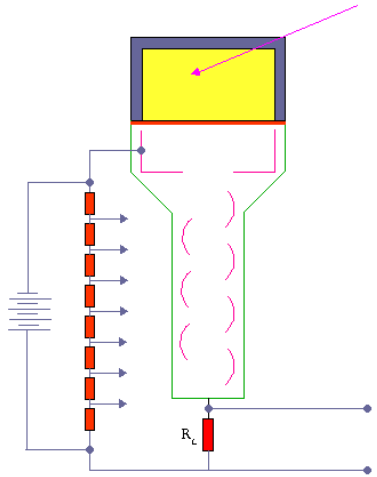
Challenges for 10 picosecond time-of-flight resolution

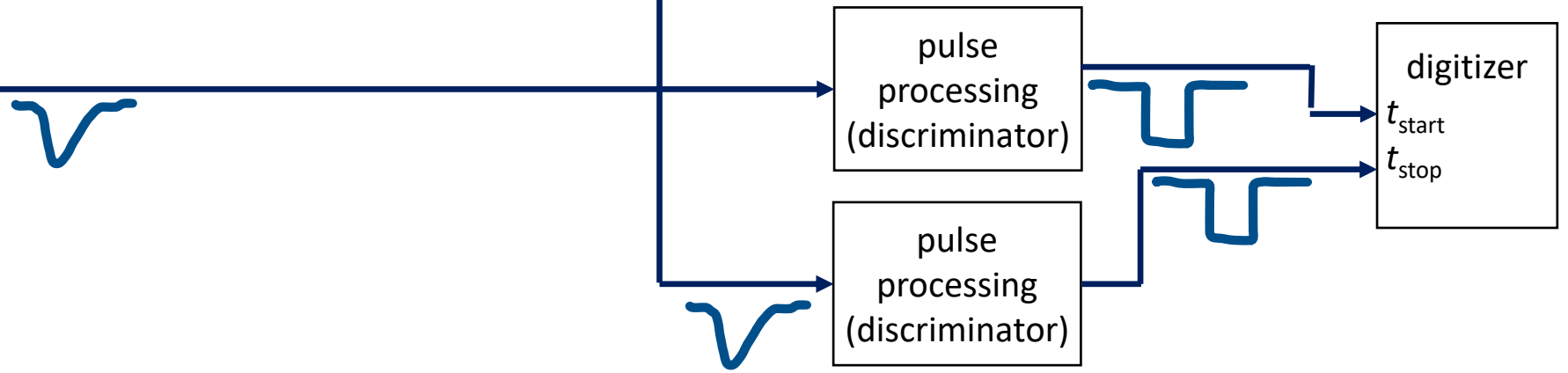
time-of-flight:

$$TOF = t_{\text{stop}} - t_{\text{start}}$$

10 ps @ speed of light → 3 mm!



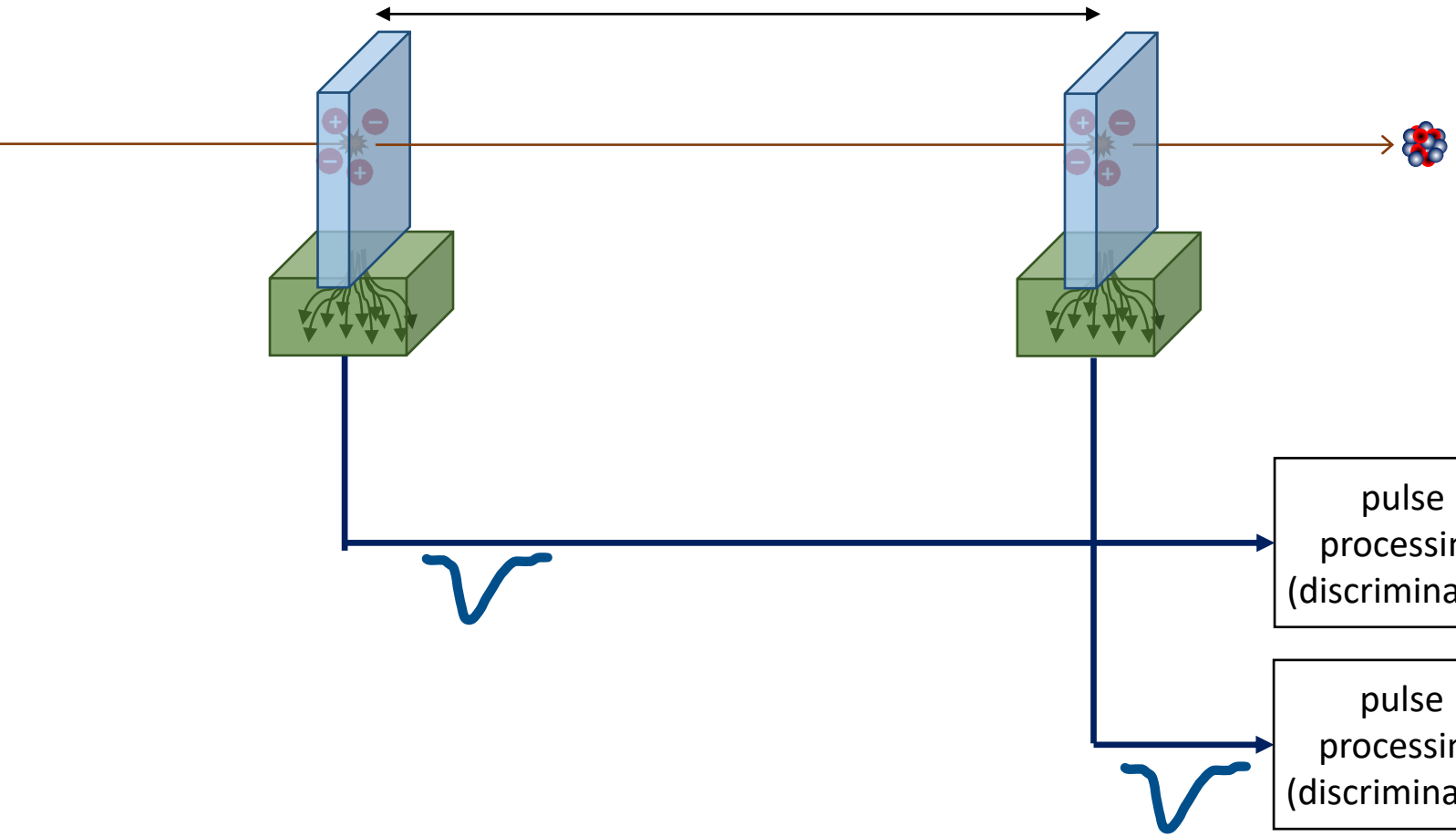




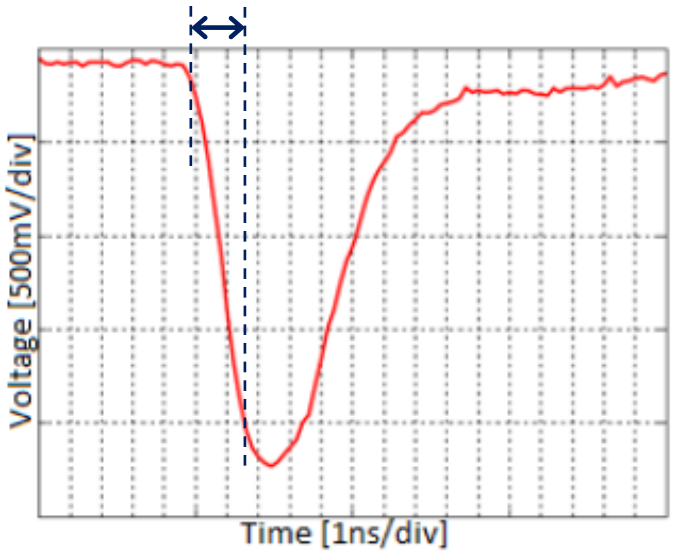
Challenges for 10 picosecond time-of-flight resolution

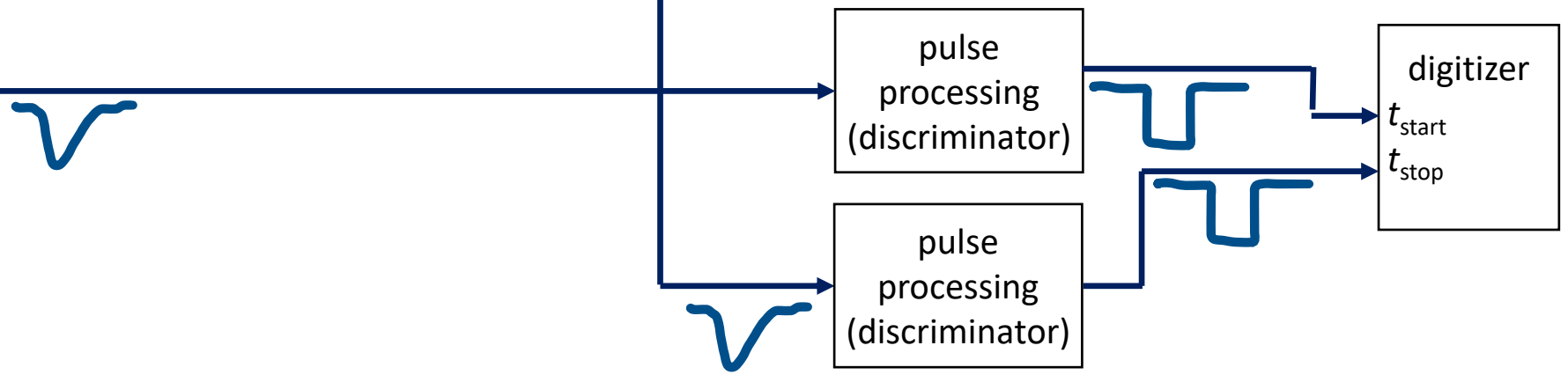
time-of-flight:

$$TOF = t_{\text{stop}} - t_{\text{start}}$$



rise time ≈ 1 ns

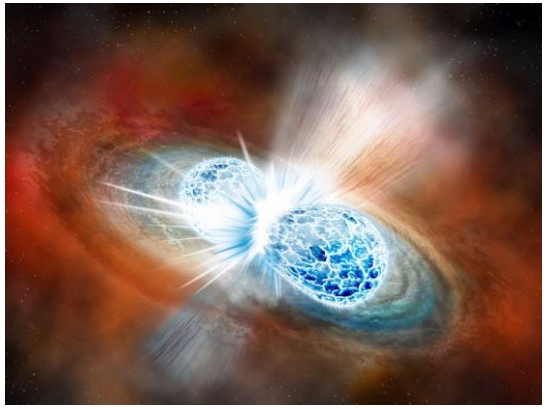




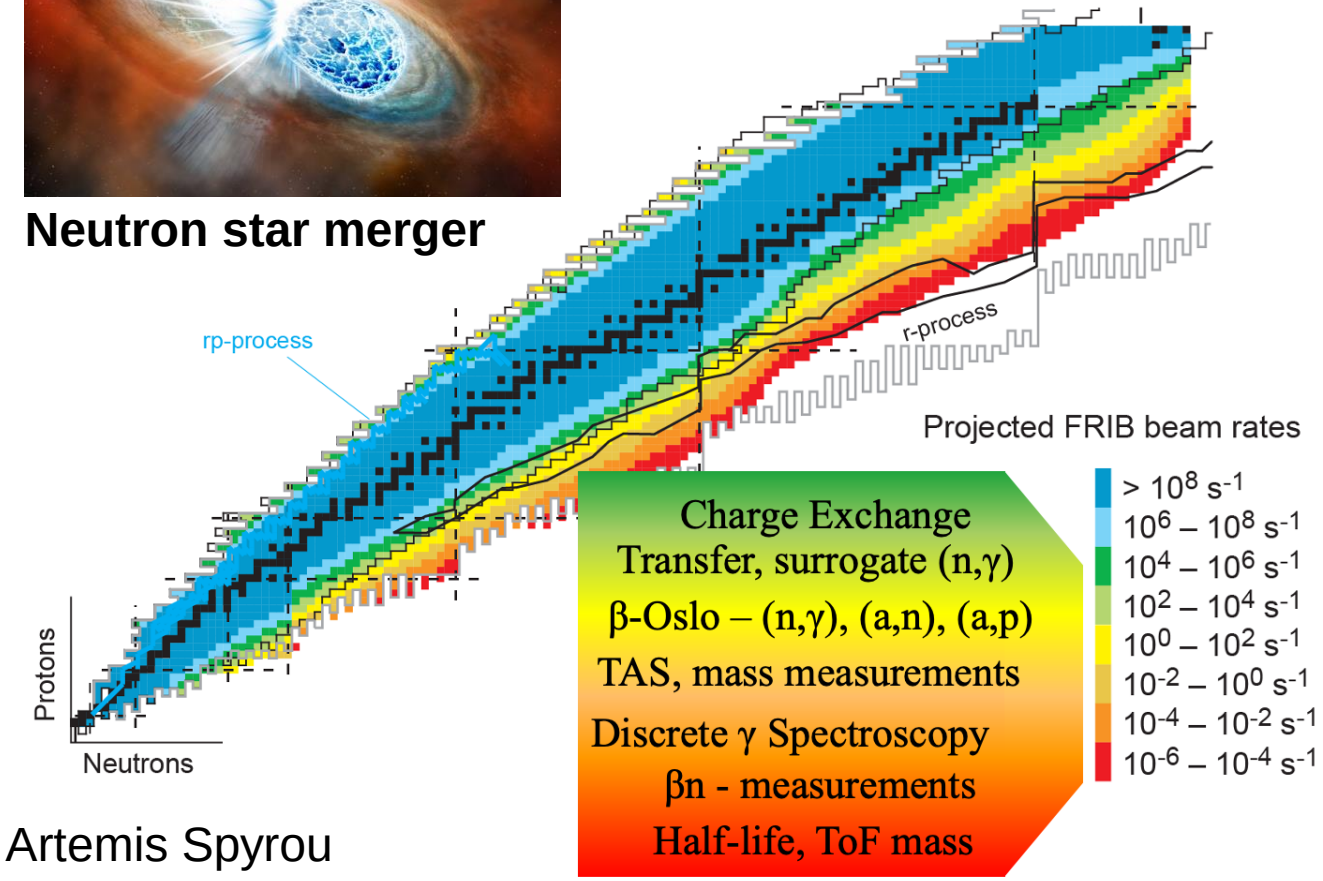
Outline | Summary

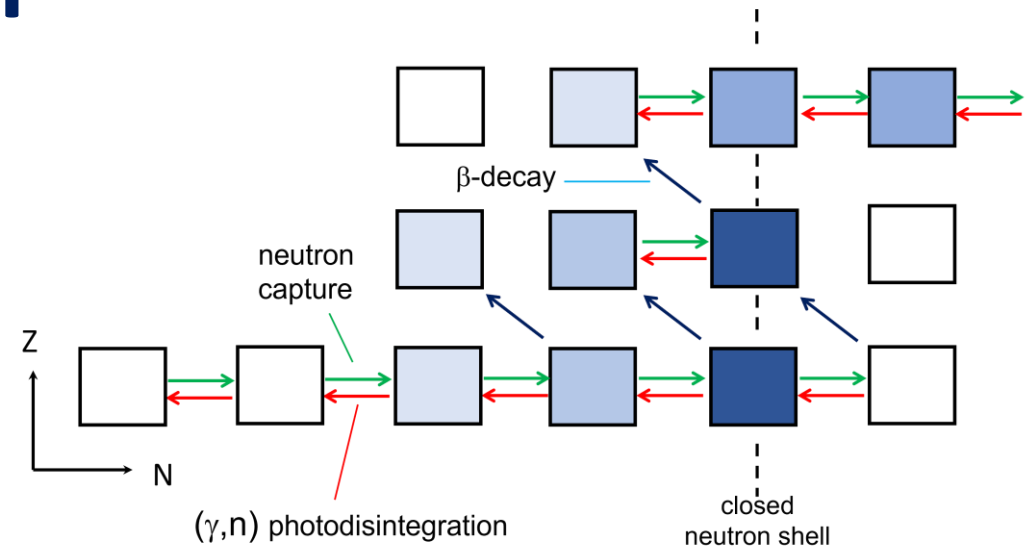
- A timing resolution of 10 picoseconds is a challenging goal for radiation detectors but a necessary characteristics for many applications in experimental and applied physics
- Nuclear Astrophysics: TOF-Bρ measurements can reach masses of very neutron-rich isotopes relevant to nucleosynthesis during the rapid neutron capture process and processes in the crust of accreting neutron stars
- At CMU we developed timing scintillator detectors with 8 ps resolution for TOF-Bρ mass measurements at NSCL and FRIB
- Medical Physics: TOF-PET detectors with a timing resolution of ≈10 ps would open new diagnostics opportunities for positron emission tomography
- We initiated a collaboration between U. de la R. (Uruguay) and CMU to evaluate multi-sensor TOF-PET detectors through simulations and characterization in the lab

Masses are a key nuclear data input to models of r-process nucleosynthesis

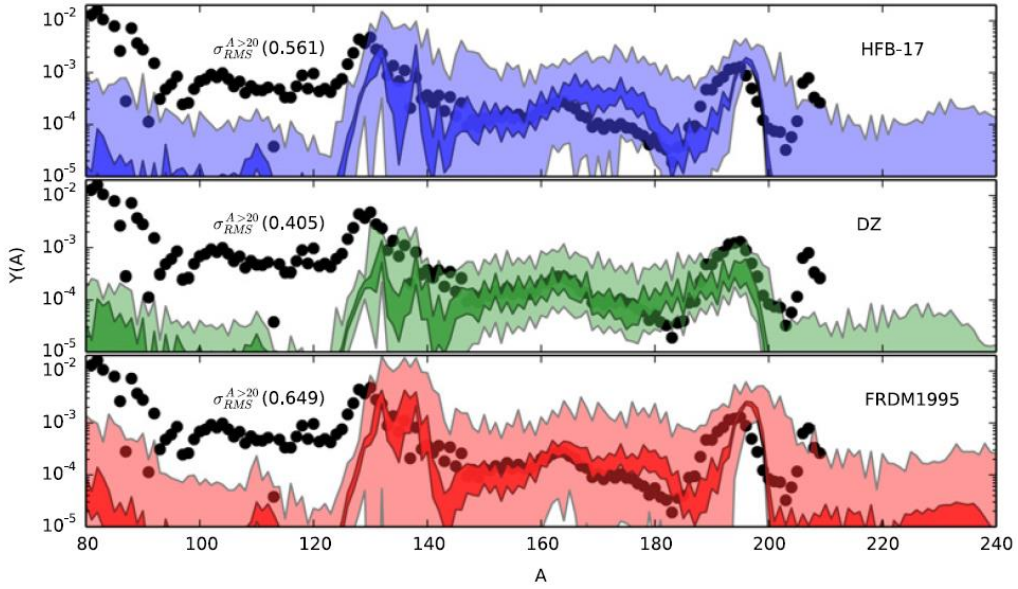


Neutron star merger





Sensitivity of models to nuclear masses

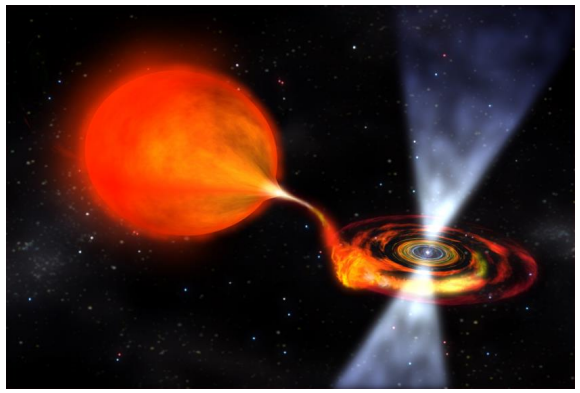


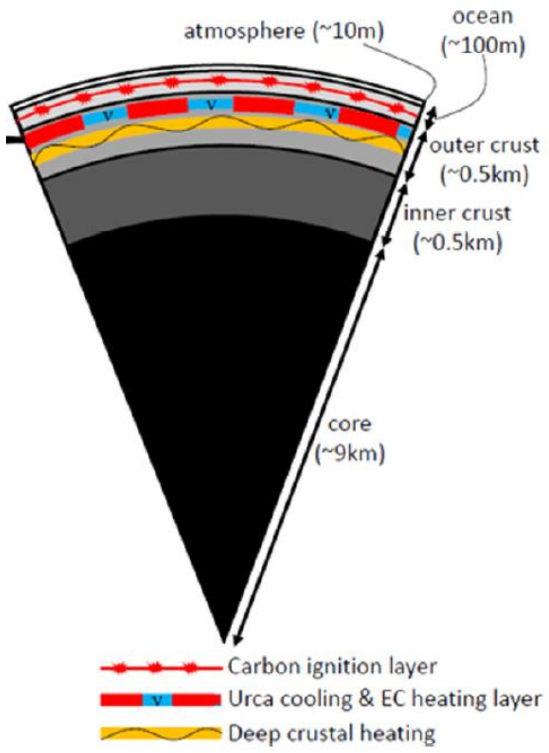
Artemis Spyrou

M. Mumpower et al (2015)

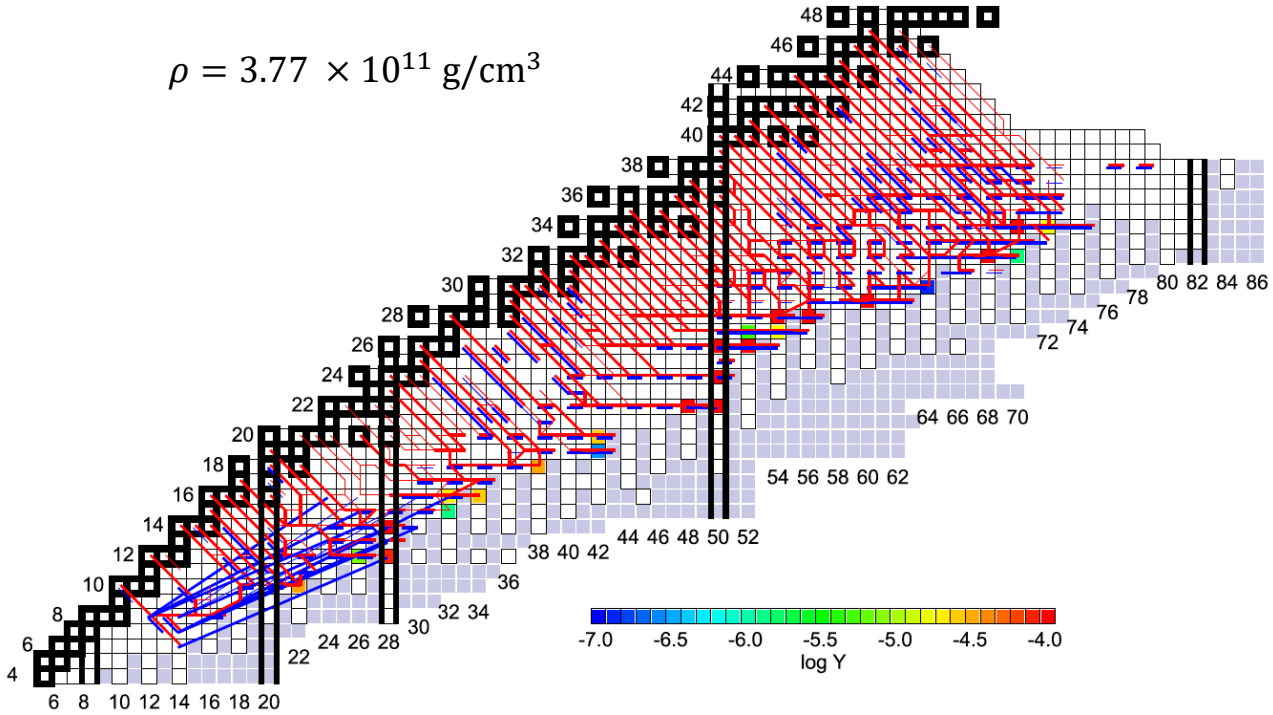
Nuclear masses of neutron-rich isotopes necessary to models the crust of accreting neutron stars

Accreting neutron star
NASA/Dana Berry





$\rho = 3.77 \times 10^{11}$ g/cm^3

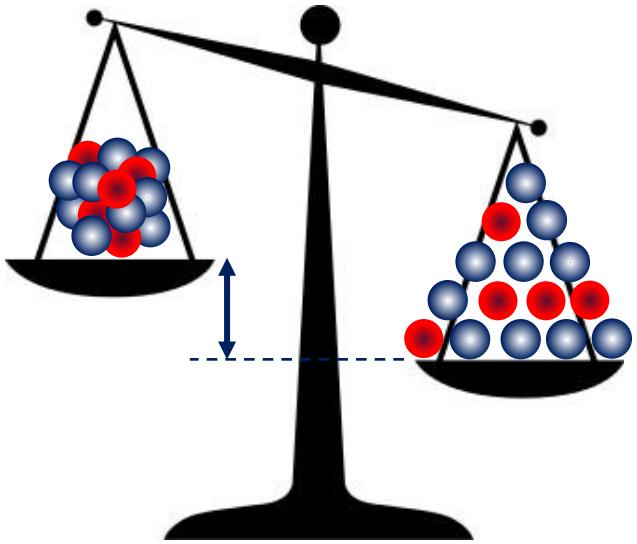


Masses affect thermal properties of the crust:

- location of heating and Urca-cooling sources
- composition and thermal conductivity

R. Lau et al, ApJ 859, 62 (2018)

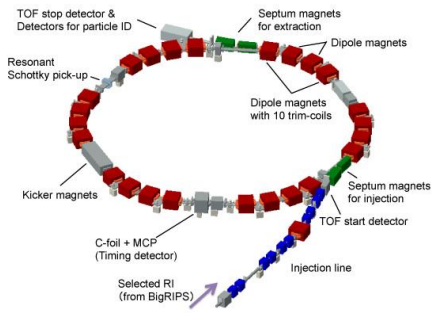
Masses provide a measurement of the nuclear binding energies of unstable short-lived isotopes

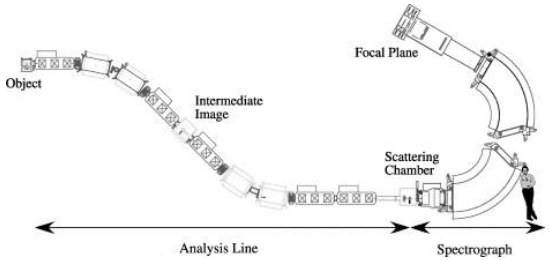


$$E = mc^2$$

nuclear binding energy!

PRODUCTION OF UNSTABLE ISOTOPES → BEAM PREPARATION → MASS MEASUREMENT



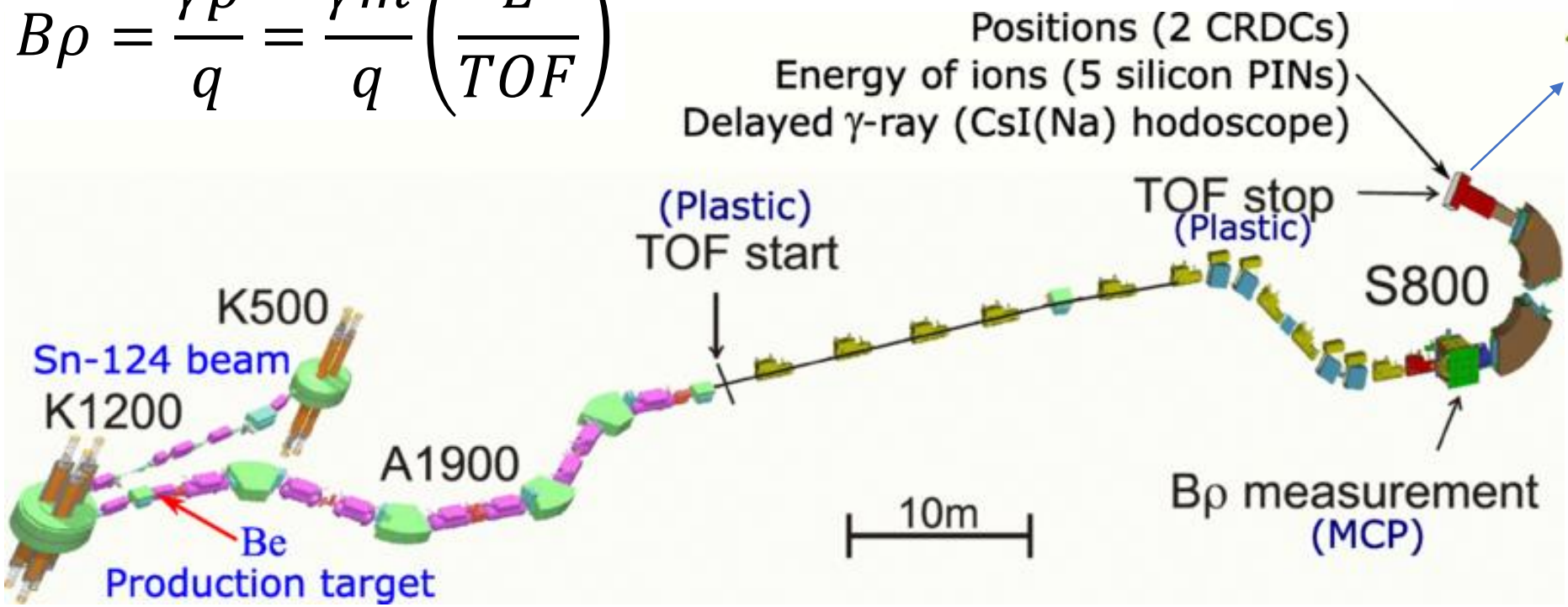


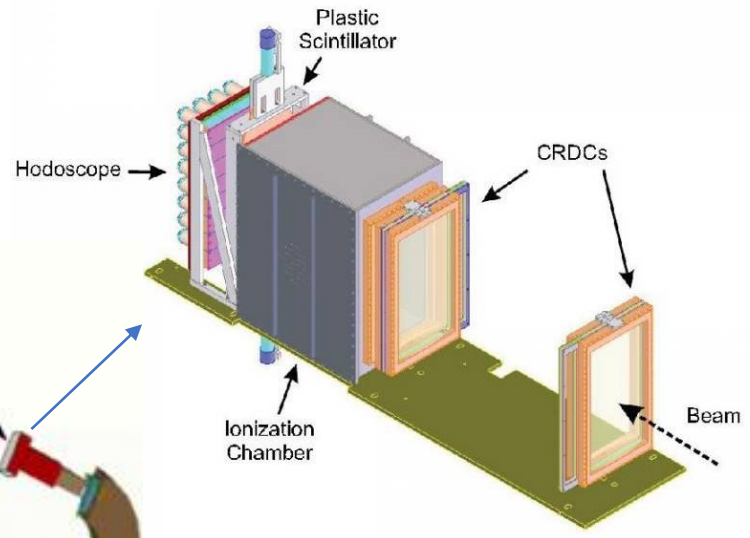
higher resolution

shorter lived isotopes

Time-of-flight Bρ mass measurement with the S800 Spectrometer at MSU

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





S800 focal plane detectors: ΔE, beam tracking

TOF-Bρ mass measurement programs:

S800 Spectrometer at NSCL (MSU)

Z. Meisel et al, Phys. Rev. Lett. 114, 022501 (2015)

M. Matos et al, NIM 696, 171 (2012).

A. Estrade et al, Phys. Rev. Lett. 107, 172503 (2011)

SHARAQ spectrometer at RIBF (RIKEN)

S. Michimasa et al, Phys. Rev. Lett. 125 12, 122501 (2020)

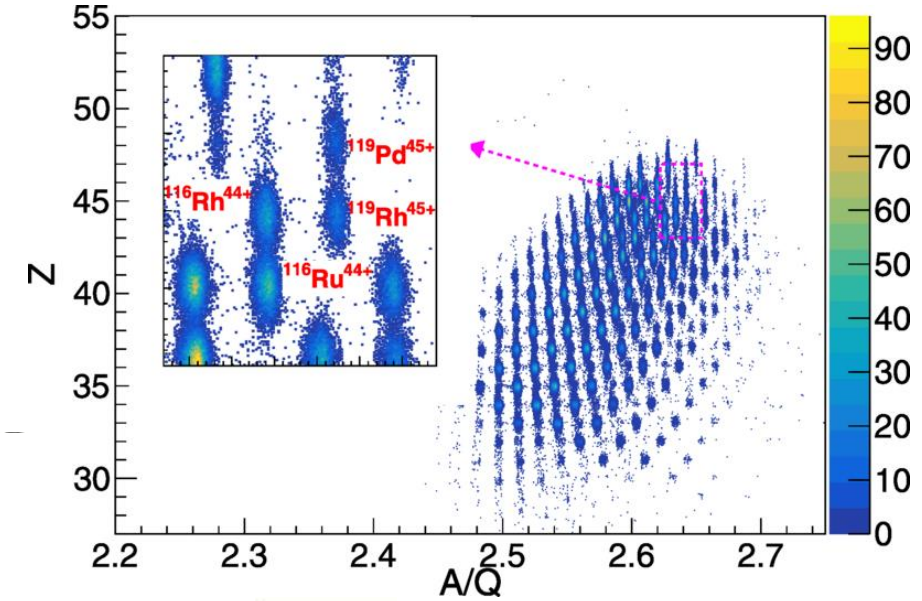
S. Michimasa et al, Phys. Rev. Lett. 121, 022506 (2018)

Particle identification of fast beams with TOF-Bρ-ΔE

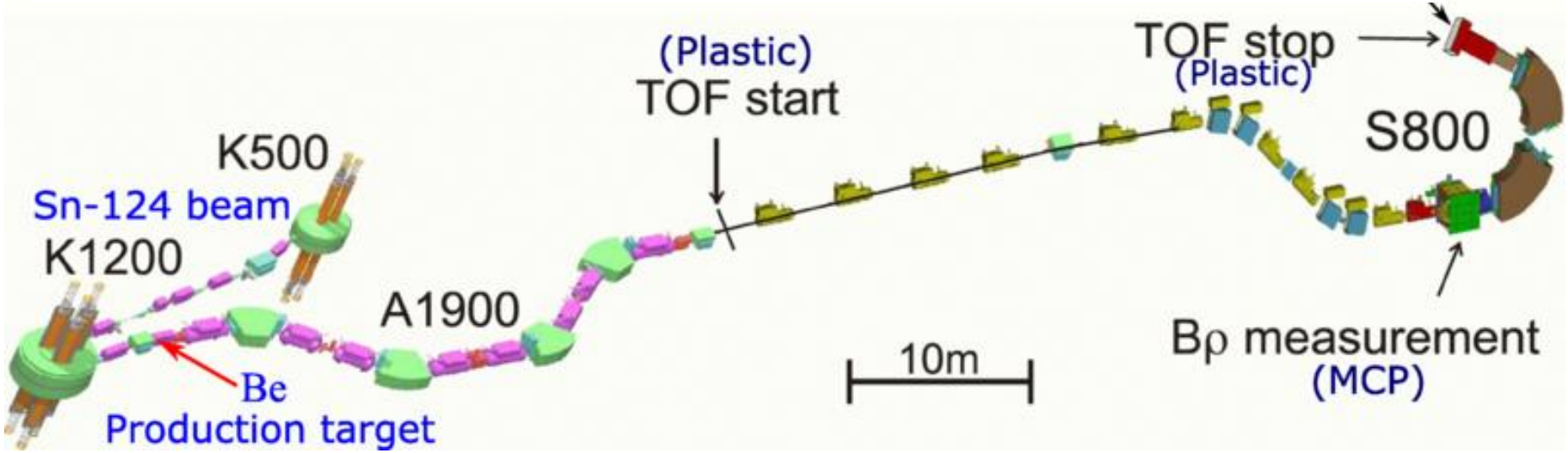
$Z^2 \sim \Delta E$

$A/Q \sim TOF$

High TOF resolution – $\sigma_{TOF} \sim 10$ ps



K. Wang et al, PRC (2024)

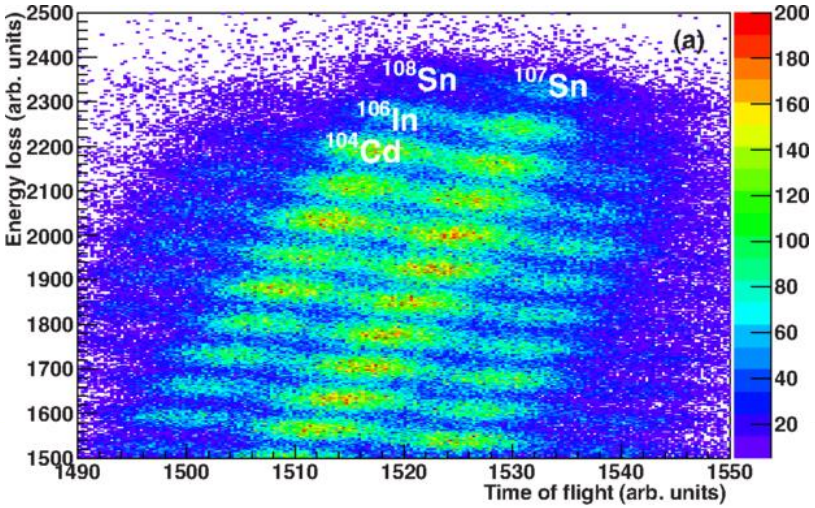


Particle identification of fast beams with TOF-Bρ-ΔE

$Z^2 \sim \Delta E$

$A/Q \sim TOF$

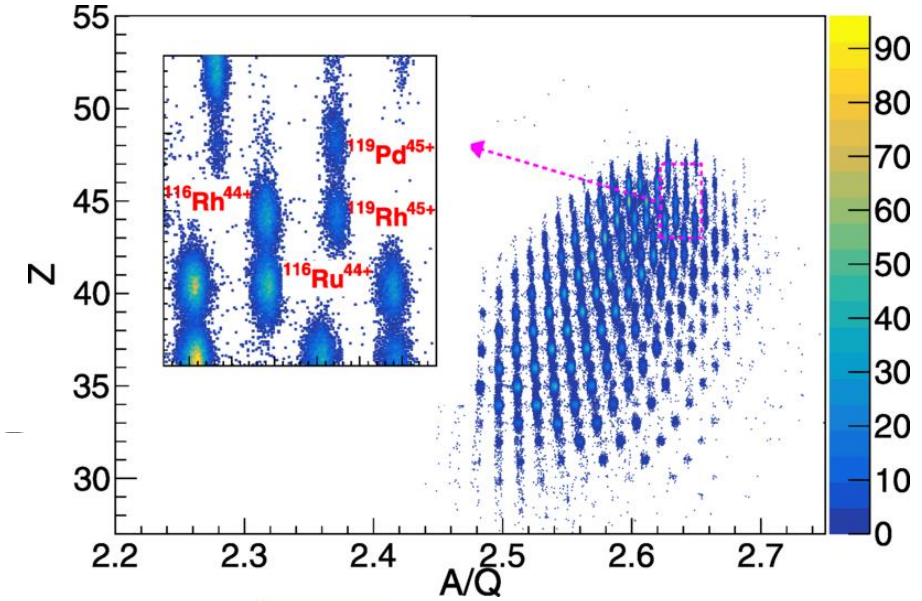
Moderate TOF resolution*



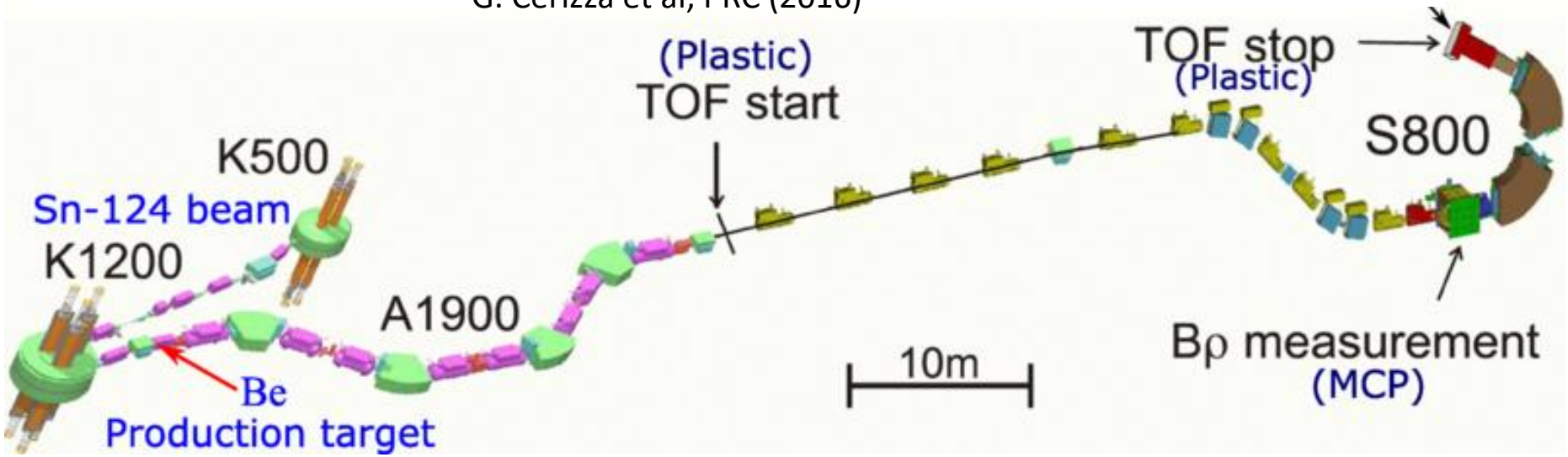
***S800 in focused optics mode**

G. Cerizza et al, PRC (2016)

High TOF resolution – $\sigma_{TOF} \sim 10$ ps



K. Wang et al, PRC (2024)

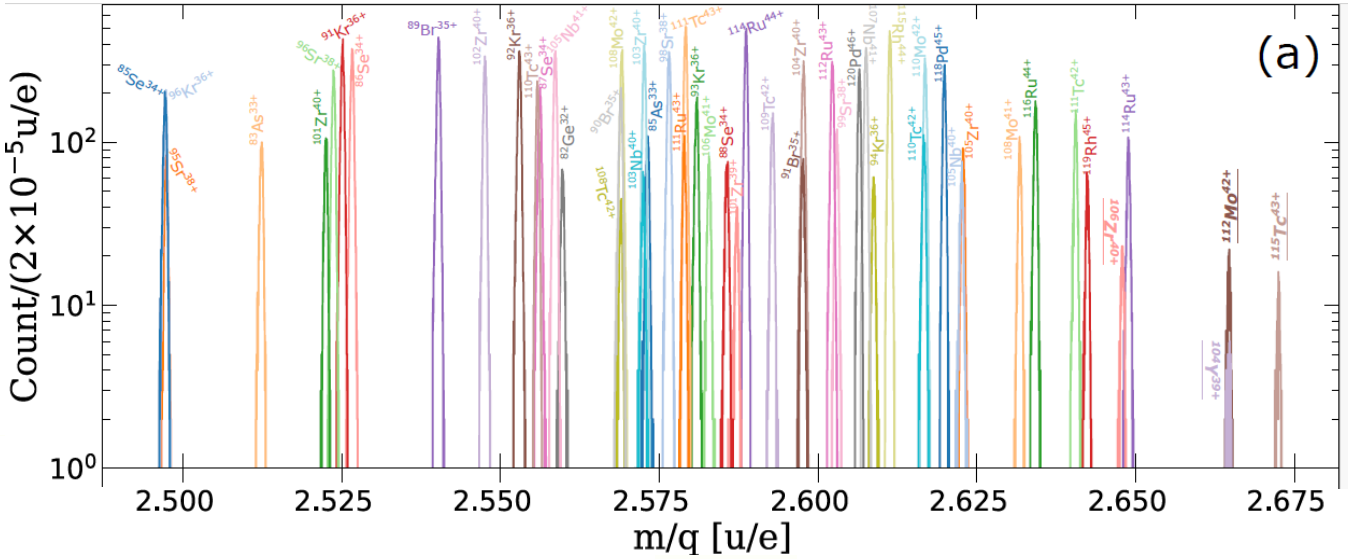


Time-of-flight-Bρ mass measurements require high-resolution timing

Mass resolution: $\frac{\delta m/q}{m/q} \approx \frac{\delta TOF_{\mathrm{corr}}}{TOF_{\mathrm{corr}}}$

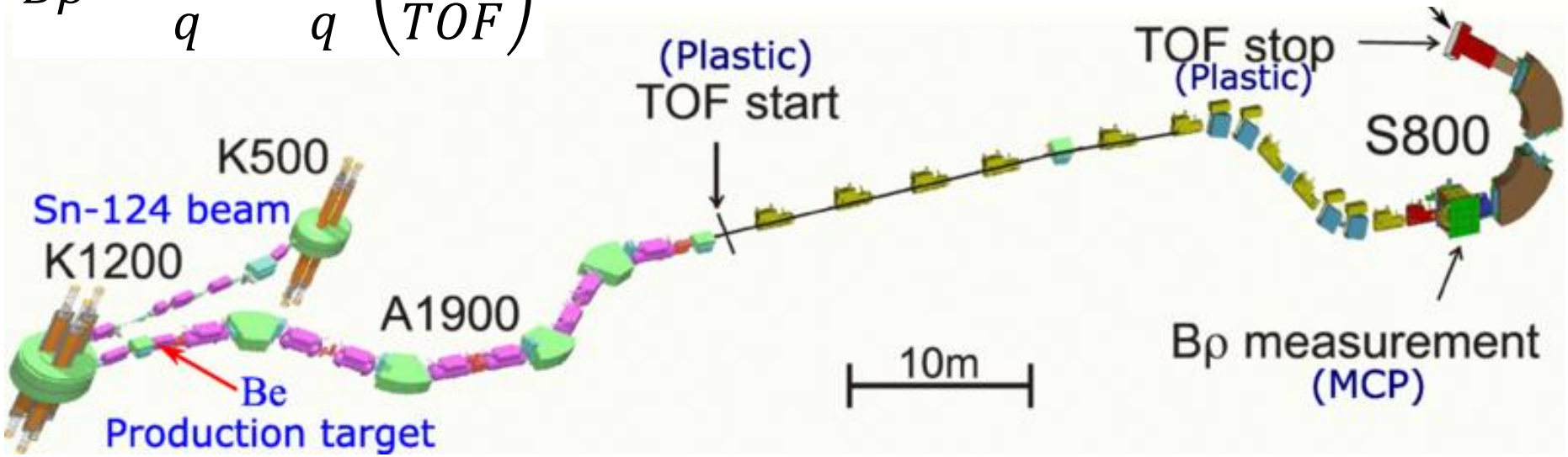
$R \sim 1 \times 10^{-4} \rightarrow \boldsymbol{\delta TOF_{\mathrm{corr}} < 50\ \mathrm{ps}}$

Mass-over-charge spectra for N=70 region

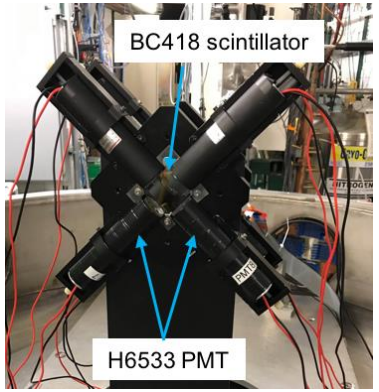


K. Wang et al, PRC (2024)

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



Resolution achieved with new CMU TOF detector!



Nuclear Physics at Central Michigan University

Mount Pleasant, Michigan

110 km

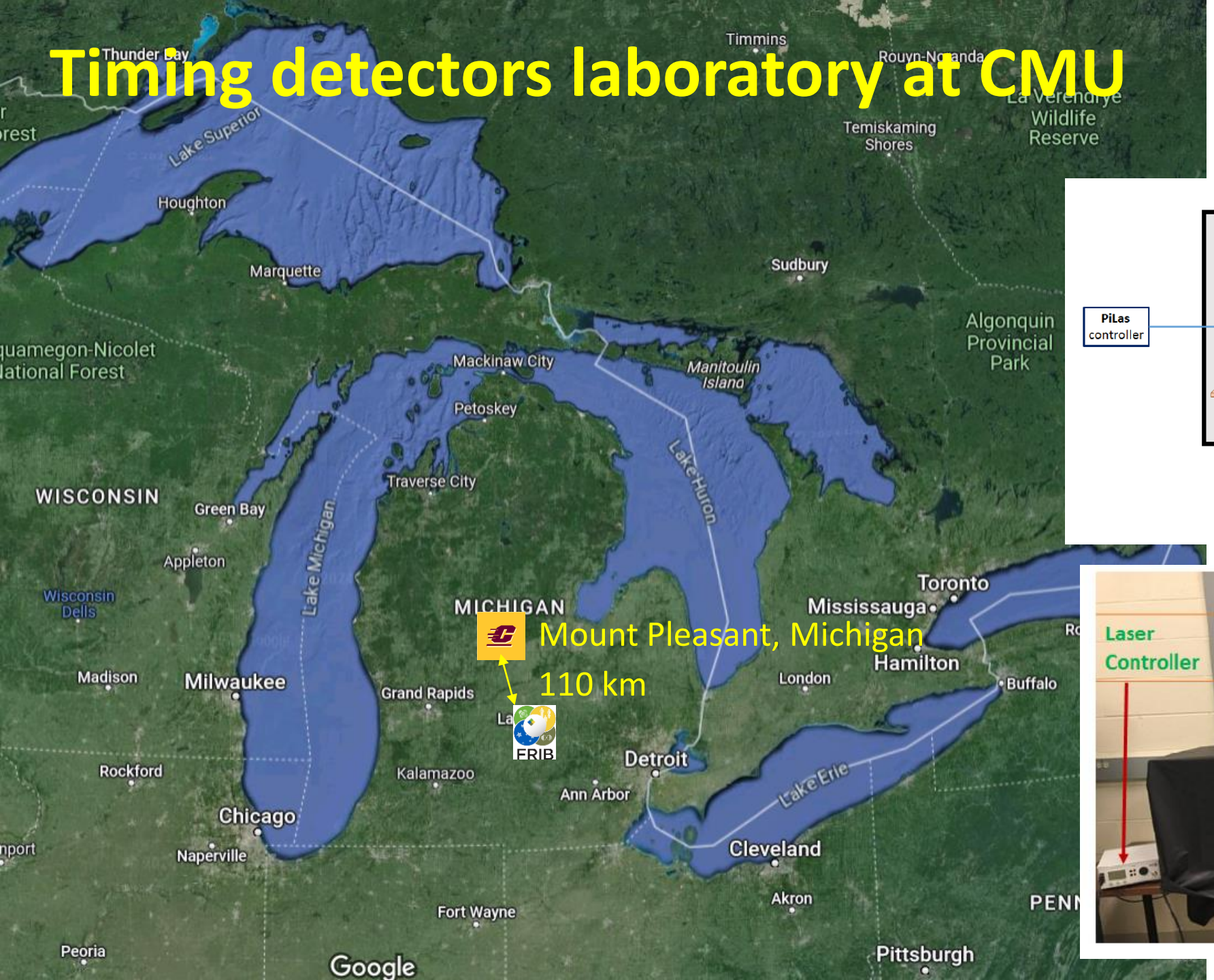
Mihai Horoi
Nuclear theory
Neutrinoless double-beta decay
Nuclear Level Densities

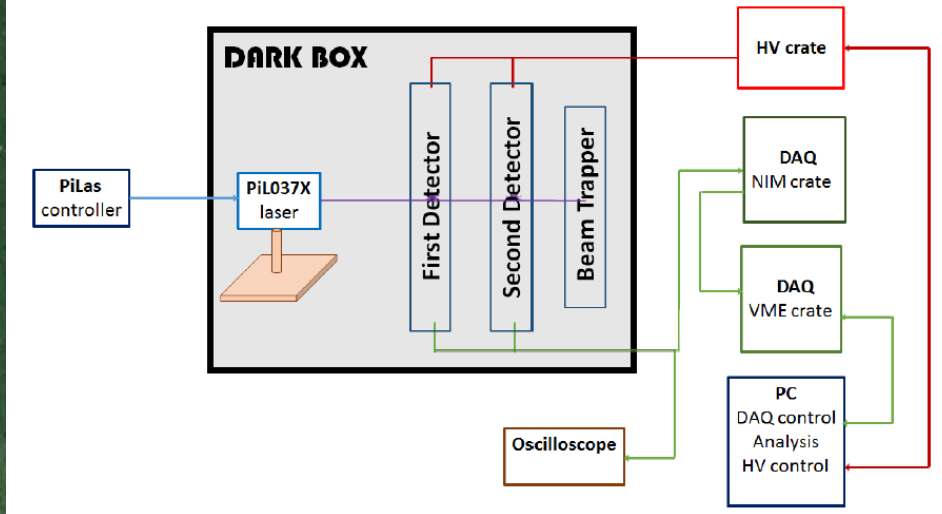
Georgios Perdikakis
Nuclear reaction experiments
Explosive nucleosynthesis
Radiogenic heating of exoplanets

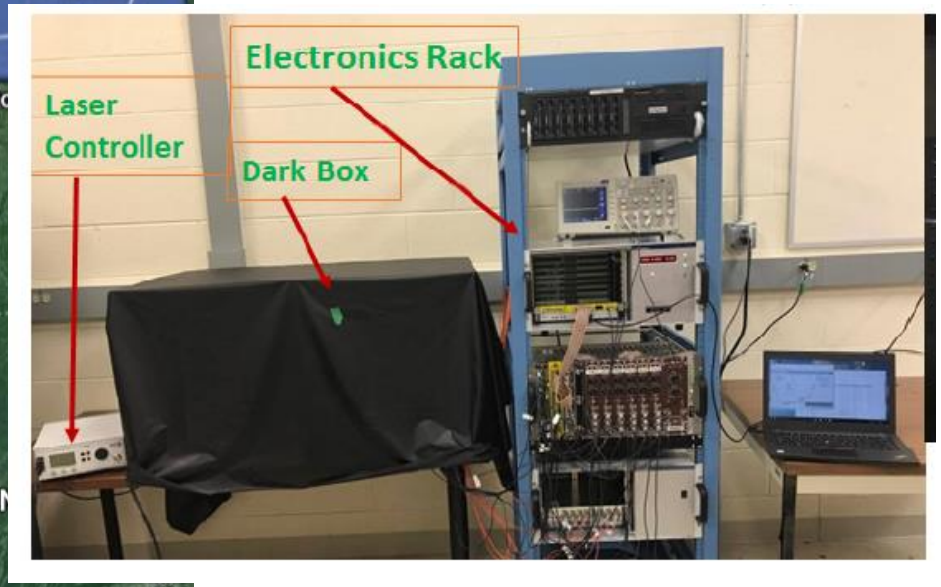
Matt Redshaw
High-precision mass measurements for neutrino physics and fundamental symmetries

Alfredo Estrade
Masses and decay of neutron-rich isotopes
Neutron stars and r-process

Timing detectors laboratory at CMU



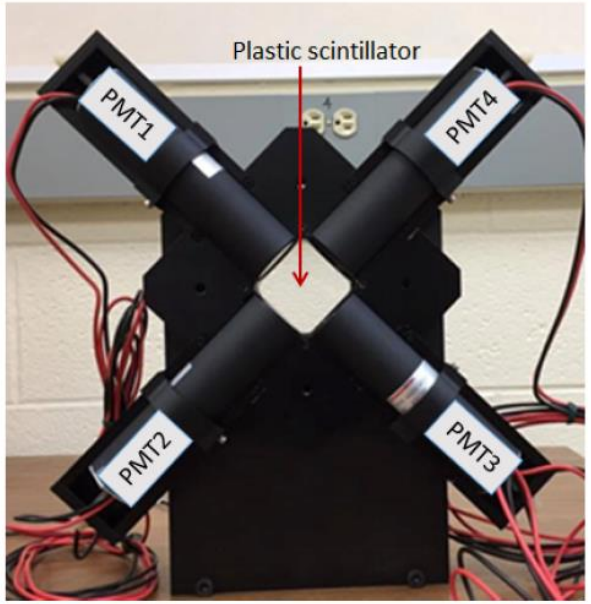




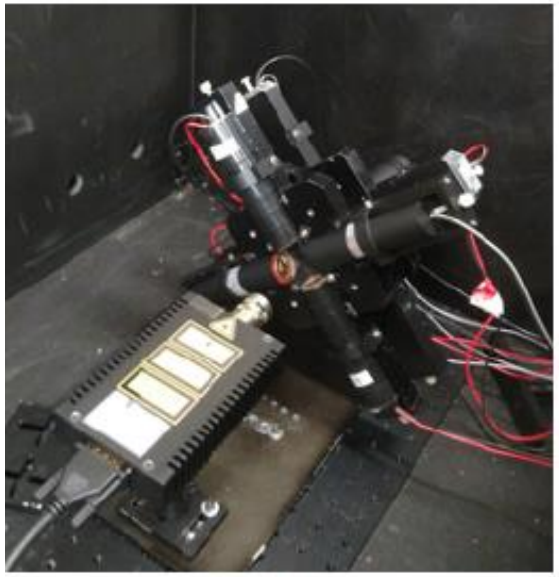
Development of a new designed for TOF scintillators of the TOF-Bρ collaboration

Timing detector based on 4 photomultiplier tubes:

- Scintillator: Eljen 228, 4x4 cm
- PMT: Hamamatsu H6533

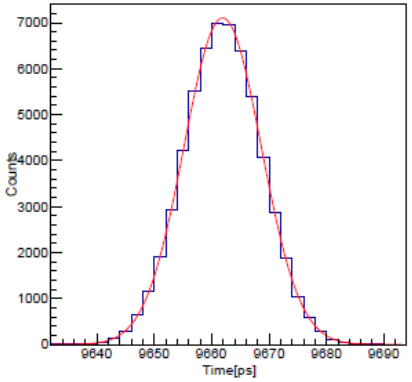


Test with pulsed picosecond laser (PiL037)



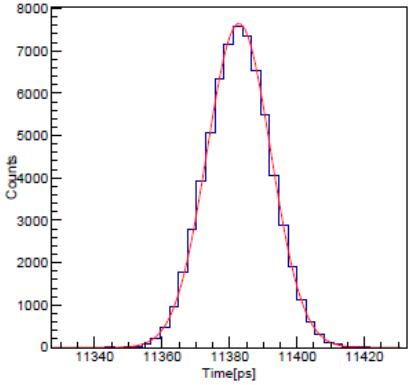
2-PMT:

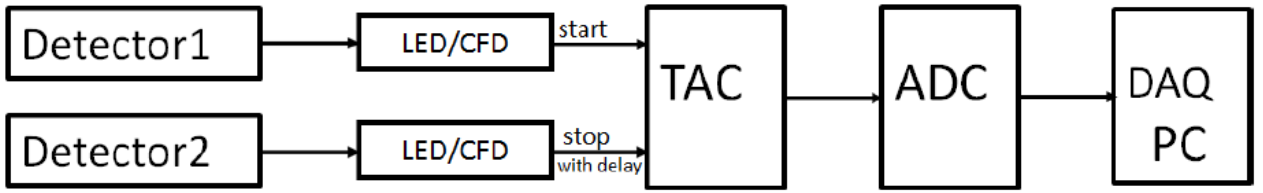
σ_{TOF}=9.4 ps



4-PMT:

σ_{TOF}=6.7 ps



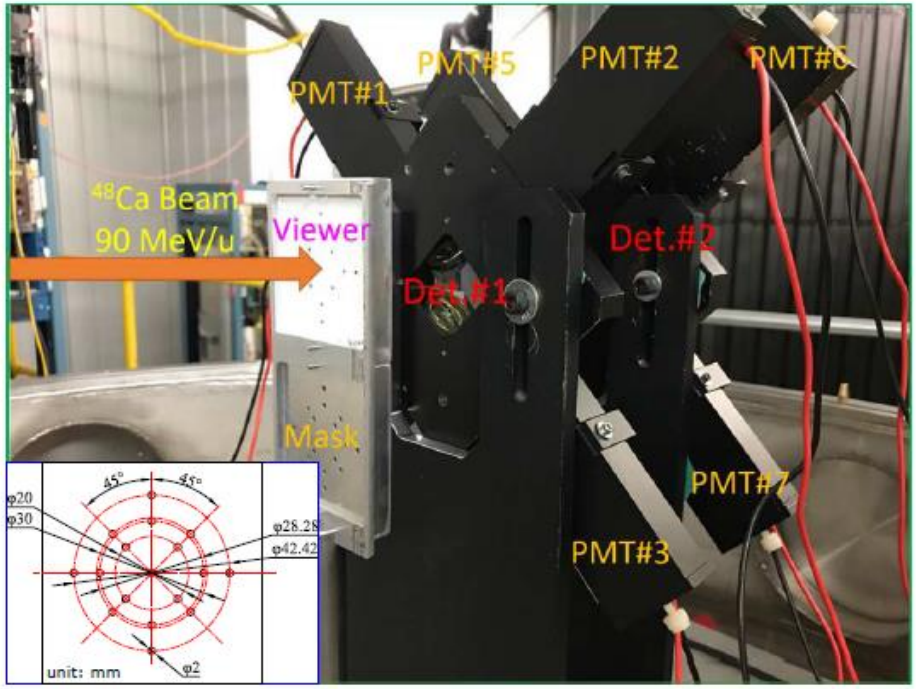


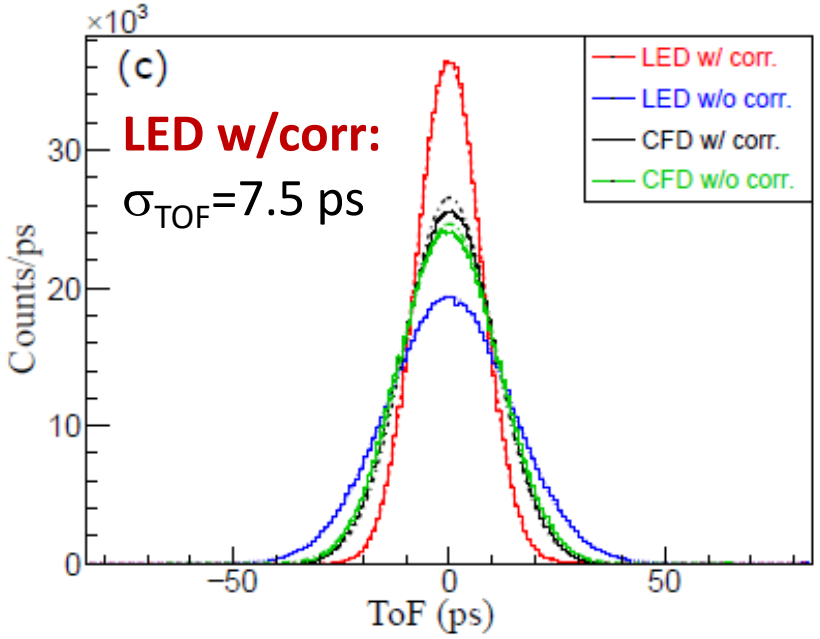
S. Neupane, MS thesis, 2018

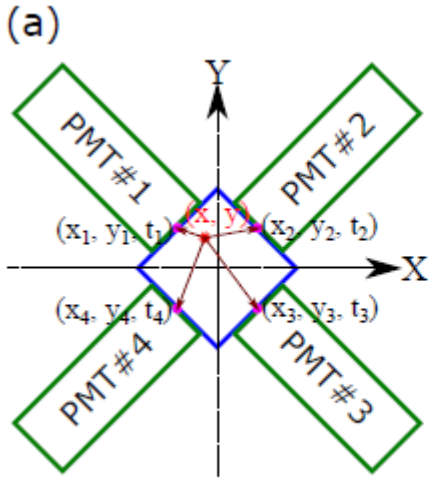
Wang, Estrade, Neupane et al, NIM A, 2020

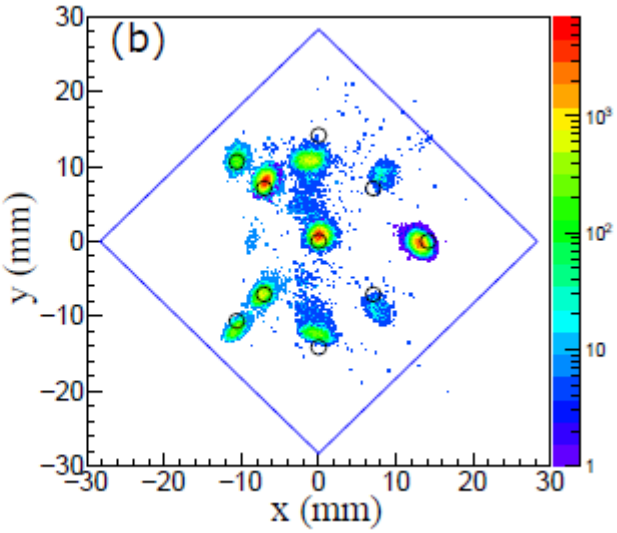
Beam test TOF-Bρ timing scintillators at the NSCL

- Test with ^{48}Ca primary beam at NSCL
- Obtained TOF resolution below 8 ps (σ) and observed sensitivity to beam position with resolution below 1 mm





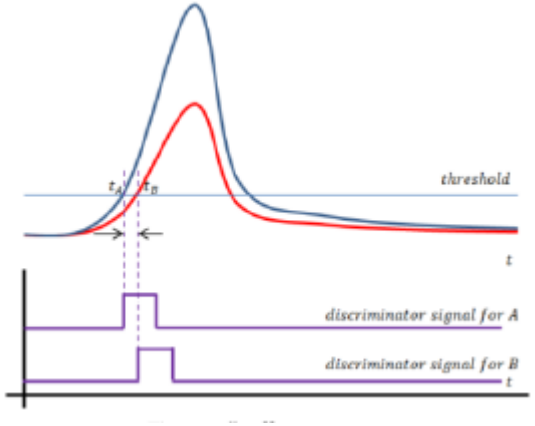




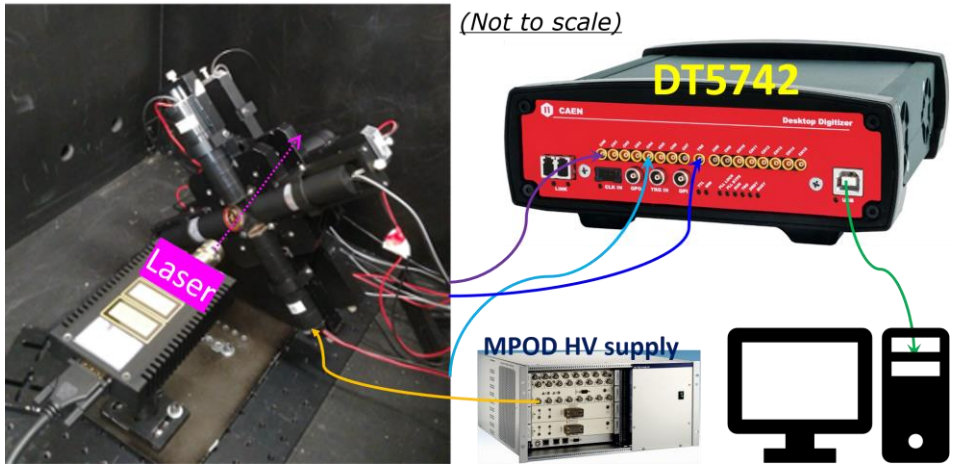
S. Neupane, MS thesis, 2018
Wang, Estrade, Neupane et al, NIM A, 2020

Systematic effects on TOF measurements

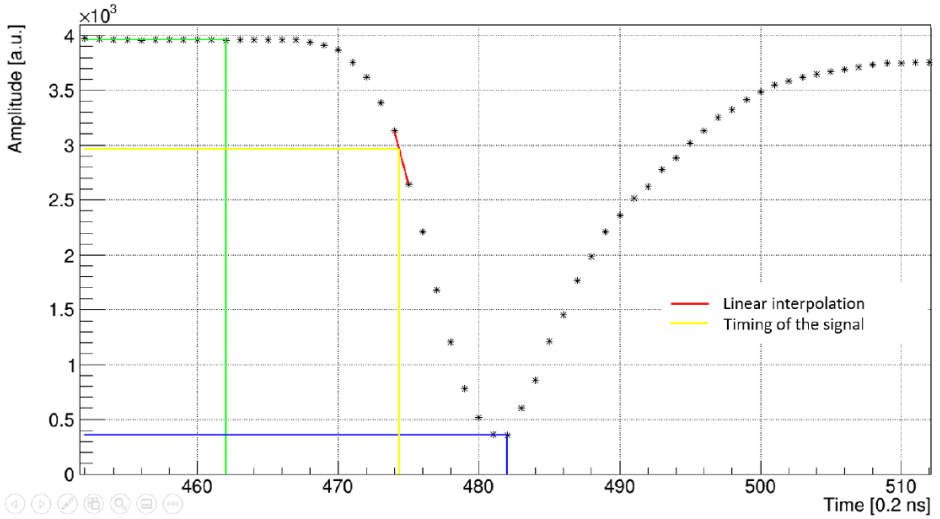
Constraining systematic effects: time-walk correction



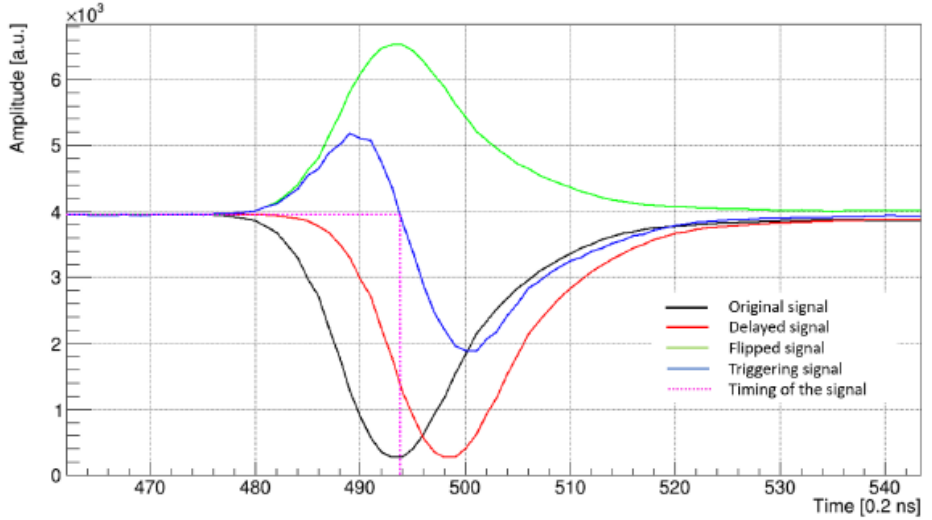
CAEN 742: a fast (5 GHz) switched-capacitor digitizer



LED: Leading-edge Discriminator



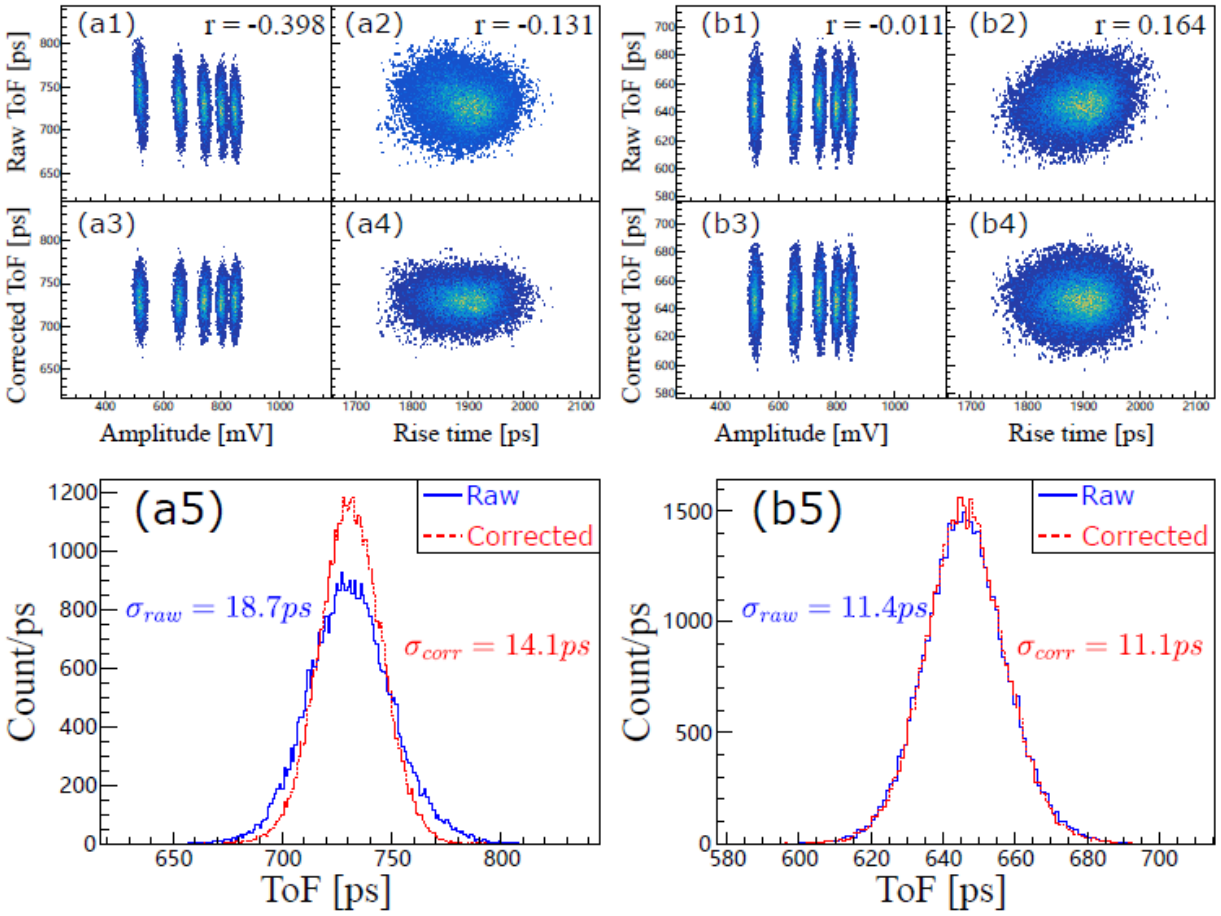
CFD: Constant-fraction Discriminator



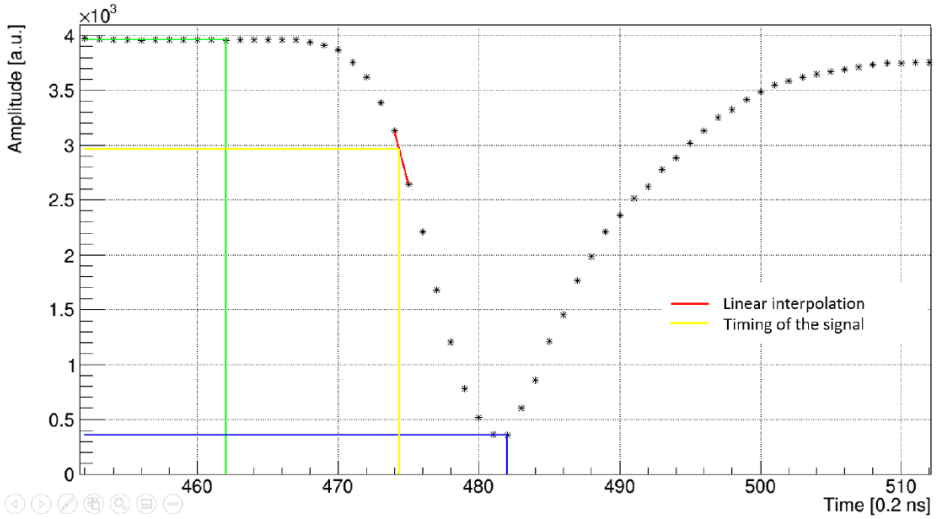
Systematic effects on TOF measurements

LED

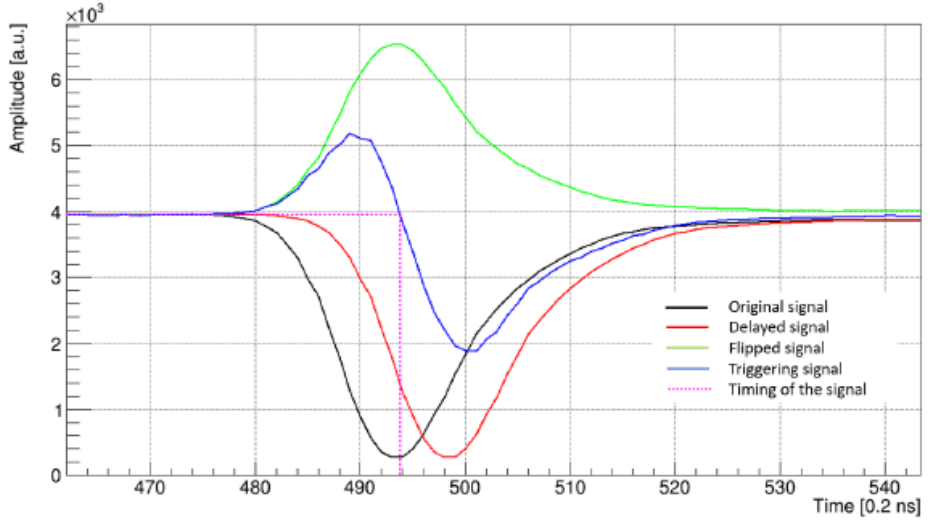
CFD



LED: Leading-edge Discriminator



CFD: Constant-fraction Discriminator

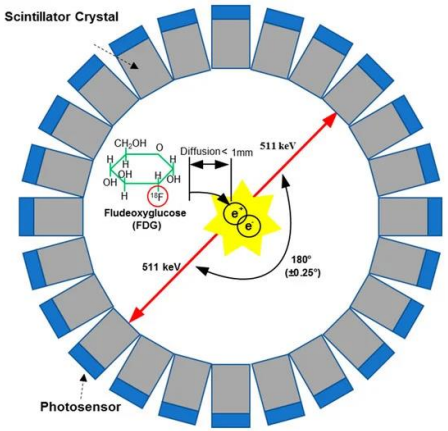


Wang, Estrade, Samaranayake, NIM A, 2022

ongoing: evaluation of non-linearities

TOF-PET: a high-resolution time-of-flight measurement can revolutionize positron emission tomography

PET



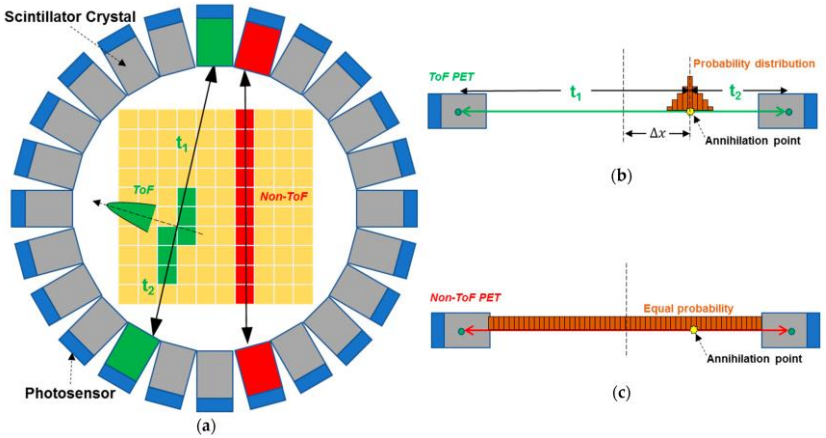
$$\frac{SNR_{\text{non TOF}}}{SNR_{\text{TOF}}} = \sqrt{\frac{2\,D}{c \times \boldsymbol{CTR}}}$$

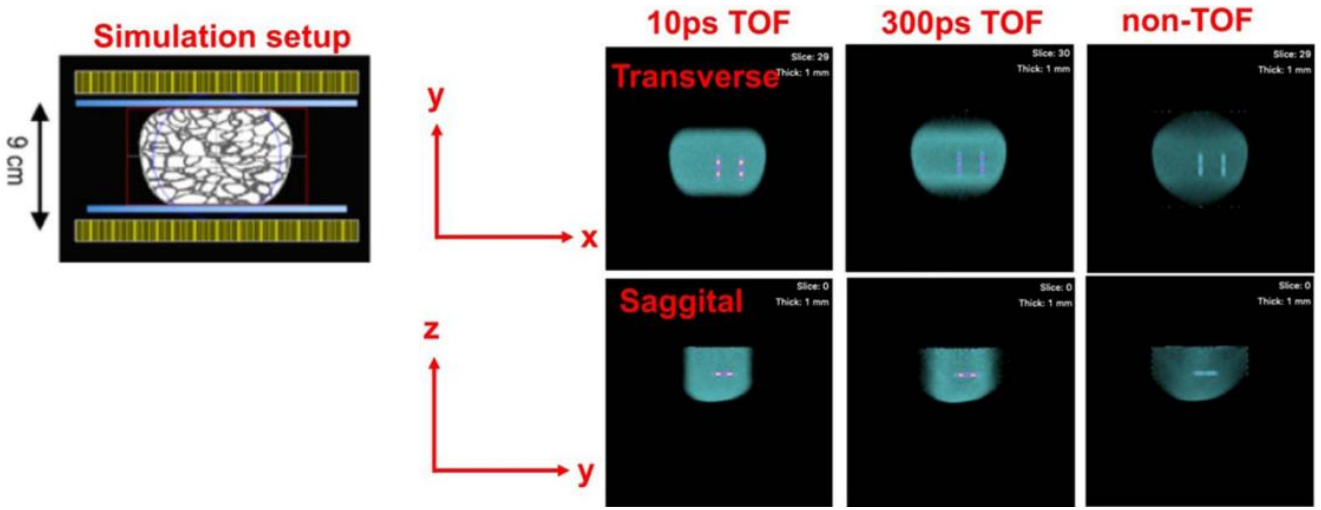
CTR: coincidence time resolution

10 ps *CTR* → δx≈1.5 mm

Simulated PET imaging of a compressed breast with four 5-mm diameter lesions

TOF-PET





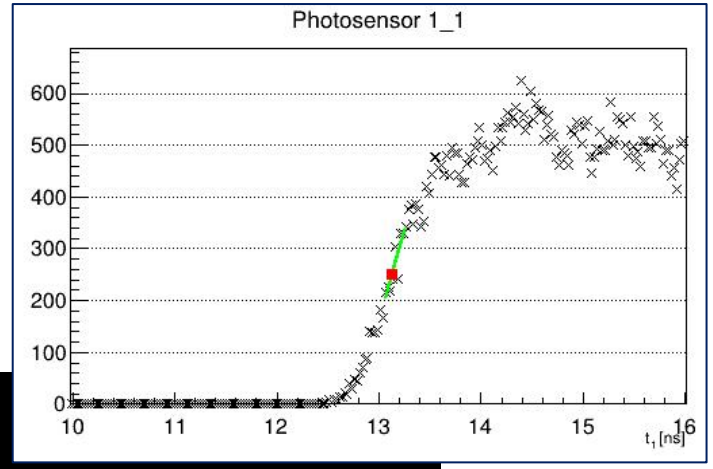
Lecoq et al, *Roadmap toward the 10 ps time-of-flight PET challenge,* Phys. Med. Biol. 65 (2022)

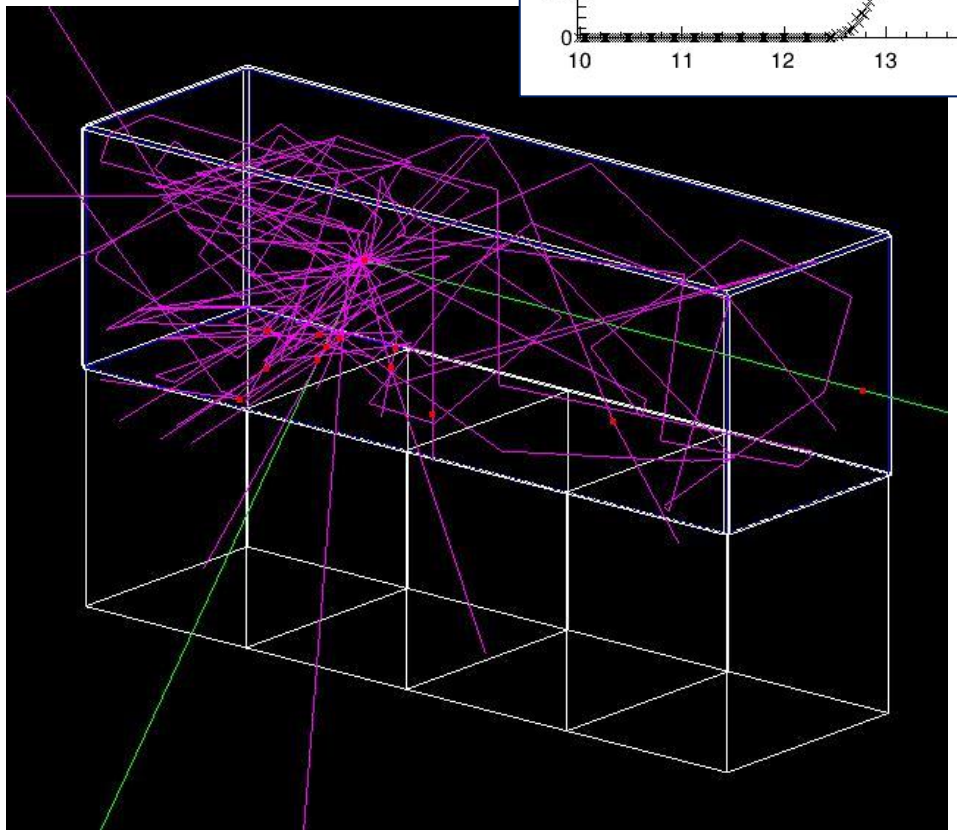
U. de la R.-CMU collaboration to investigate multi-sensor TOF-PET detectors

- Geant4 simulation of TOF-PET detectors: LYSO scintillator blocks, optical treatment and reflective Teflon in surface areas, photosensors modeled as *Sensitive Detectors*

- Post-processing of photon arrival time to simulate SiPM response in Root

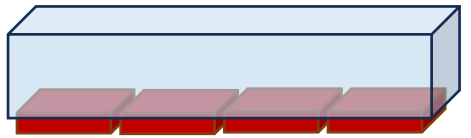
- Evaluate properties for multi-sensor detectors





Geant4 simulations

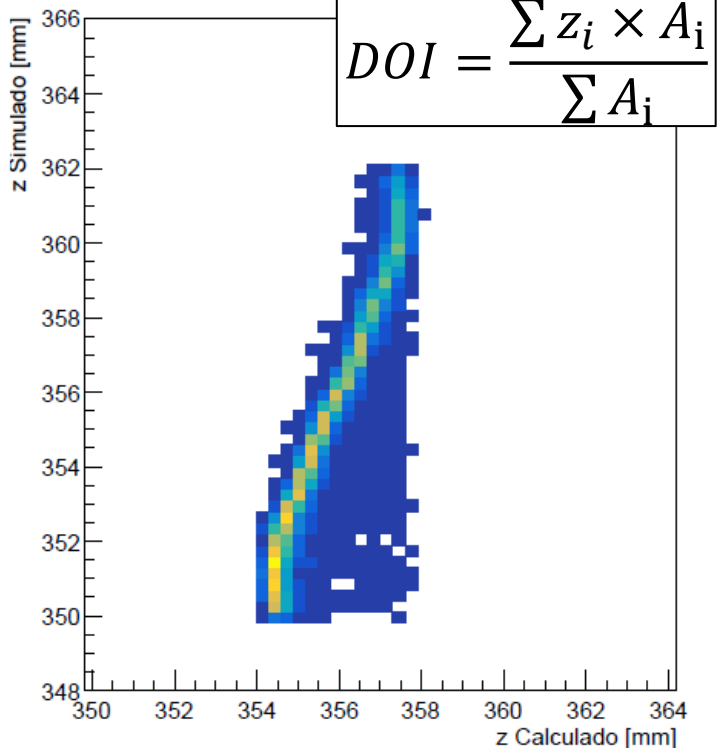
Preliminary results: TOF measurement corrected by dept-of-interaction result in resolution of 35 ps (sigma)

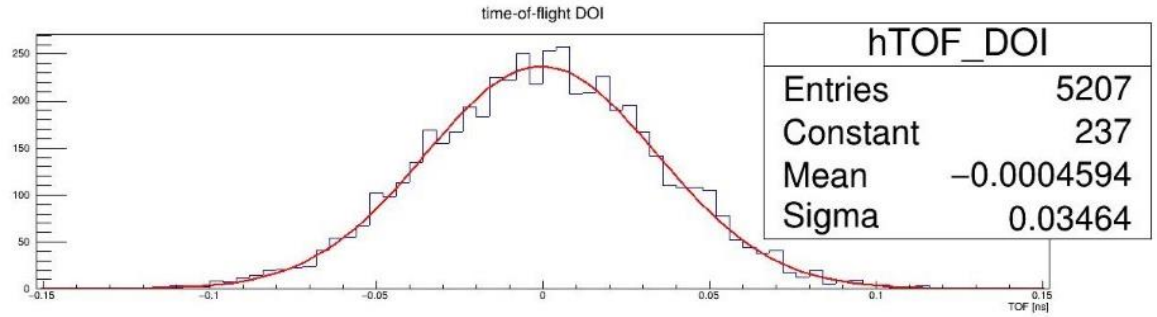


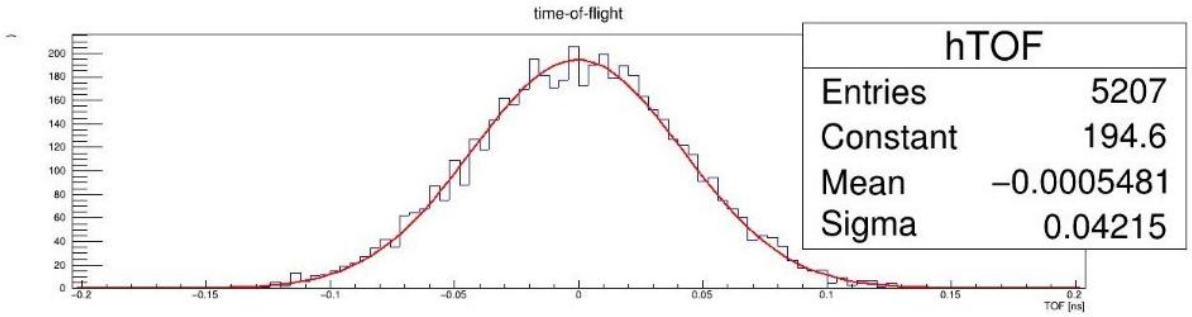
LYSO: 4x4x12 mm
4 SiPMs

Depth-of-interaction (DOI) obtained from weighting SiPM position (z) by their signal amplitude (A)

$$DOI = \frac{\sum z_i \times A_i}{\sum A_i}$$



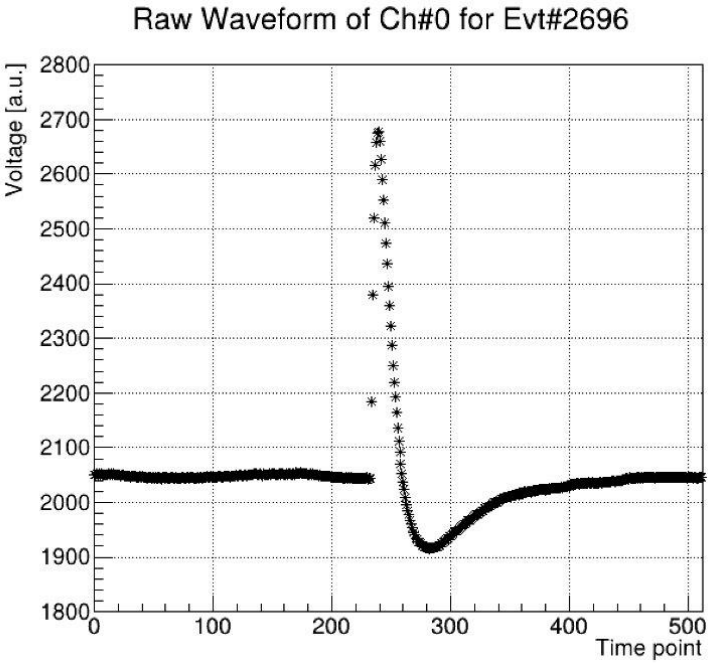


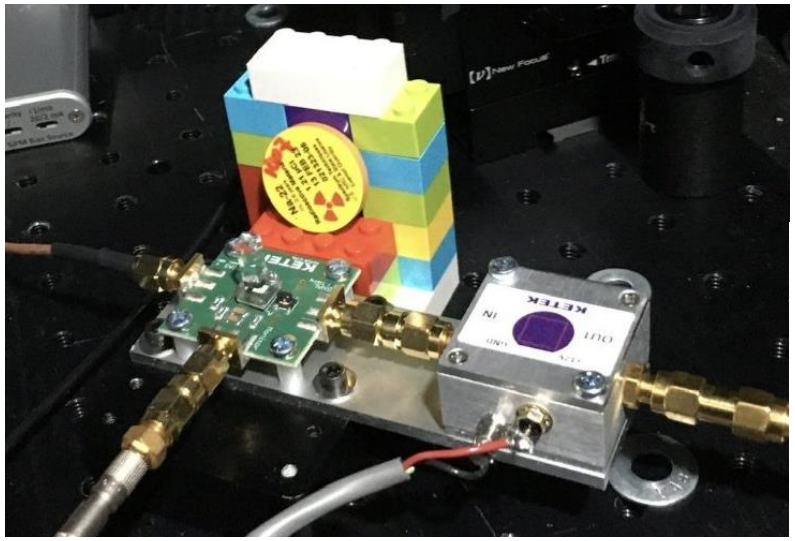


Test of TOF-PET detectors

First tests of TOF-PET prototypes at CMU detector lab:

- SiPM sensor
- LYSO:Ce scintillator (12x4x4 mm^3)
- BC630 silicone pads for optical coupling
- CAEN D720 digitizer for DAQ





Gracias!

TOF-Bρ detectors: **Kailong Wang** (Central Michigan University, USA and Institute for Modern Physics, Lanzhou, China), Shree Neupane, Sithira Samaranayake (Central Michigan University, USA), Michael Famiano (Western Michigan University, USA), Jorge Pereira, Hendrik Schatz (Michigan State University).

TOF-PET detectors: Nahuel Bruno, **Carolina Rabin** (Universidad de la República, Uruguay), Jacob Bromell (CMU)

work supported in part by DoE grants DE-SC0022538 and DE-SC0020406

Collaboration opportunities: **discussion of IReNA-IANNA connections on Thu. at 11:30 during coffee break**

IReNA: International Research Network for Nuclear Astrophysics
www.irenaweb.org

IANNA: Ibero American Network of Nuclear Astrophysics
www.inin.gob.mx/sitios/index.cfm?codigo_opc=240002000&cve_area=IANNA

Outline | Summary

- A timing resolution of 10 picoseconds is a challenging goal for radiation detectors but a necessary characteristics for many applications in experimental and applied physics
- Nuclear Astrophysics: TOF-Bρ measurements can reach masses of very neutron-rich isotopes relevant to nucleosynthesis during the rapid neutron capture process and processes in the crust of accreting neutron stars
- At CMU we developed timing scintillator detectors with 8 ps resolution for TOF-Bρ mass measurements at NSCL and FRIB
- Medical Physics: TOF-PET detectors with a timing resolution of ≈10 ps would open new diagnostics opportunities for positron emission tomography
- We initiated a collaboration between U. de la R. (Uruguay) and CMU to evaluate multi-sensor TOF-PET detectors through simulations and characterization in the lab

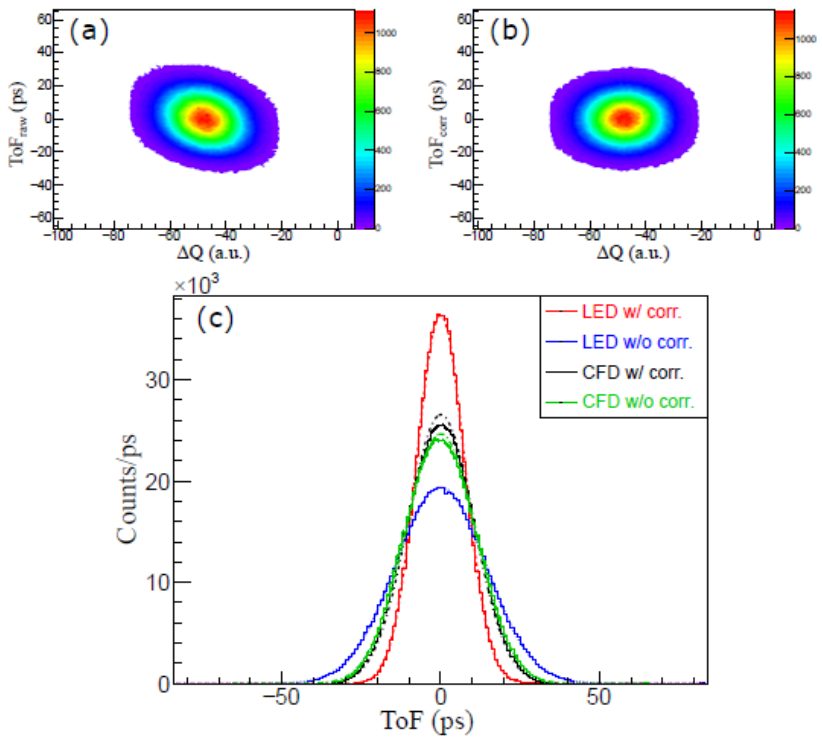
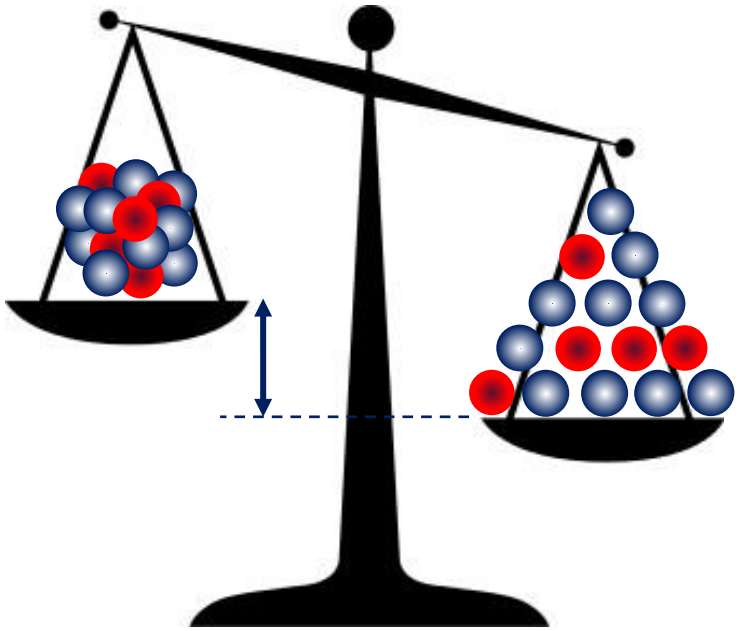


Figure 7: (color online). Correlation between ToF obtained by CFD+TAC+ADC electronics setup and the amplitude difference ΔQ (a) without and (b) with the time-walk correction. Panel (c) shows the comparison between the distributions of ToFs with LED (red and blue for corrected and raw distributions, respectively) and CFD (black and green for corrected and raw distributions, respectively) timing techniques. The Gaussian fitting functions are also plotted with the responding colors. For better comparing display, all the four ToF distributions are normalized to the same total counts and shifted to the position centered at 0. The data corresponds to settings 2 and 7 in Table 3.

Table 3: ToF properties at different conditions in the present experiment.[a]

Setting	PMT HV↓↑[b]	Electronics	Beam Position [mm, mm]	ToF Centroids [ps][c]		Time Resolution (σ) [ps]	
				Raw	Corrected	Raw	Corrected
(1)	0	LED+TDC	(0, 0)	0	0.0	16.6	11.7
(2)	0	LED+TAC+ADC	(0, 0)	0	0.0	14.2	7.5
(3)	0	LED+TAC+ADC	(-7, 7)	10.8	0.3	14.1	8.6
(4)	0	LED+TAC+ADC	(14, 0)	-25.4	2.6	14.3	8.0
(5)	0	LED+TAC+ADC	(21, 0)	21.9	2.4	20.8	9.5
(6)	0	LED+TAC+ADC	Defocused[d]	—	—	—	8.6
(7)	0	CFD+TAC+ADC	(0, 0)	0	0.1	11.2	10.3
(8)	0	CFD+TAC+ADC	(-7, 7)	-5.4	-0.6	12.2	11.3
(9)	0	CFD+TAC+ADC	(14, 0)	-0.4	-0.3	12.6	10.2
(10)	0	CFD+TAC+ADC	Defocused	—	—	—	12.2
(11)	↓50 V	CFD+TAC+ADC	(0, 0)	9.1	—	11.6	10.7
(12)	↑50 V	CFD+TAC+ADC	(0, 0)	23.0	—	11.0	10.2
(13)	↑50 V	CFD+TAC+ADC	(0, 0) with 10 kHz	21.5	—	11.6	10.6
(14)	↑50 V	CFD+TAC+ADC	(0, 0) with ¿100 kHz	—	—	299	299

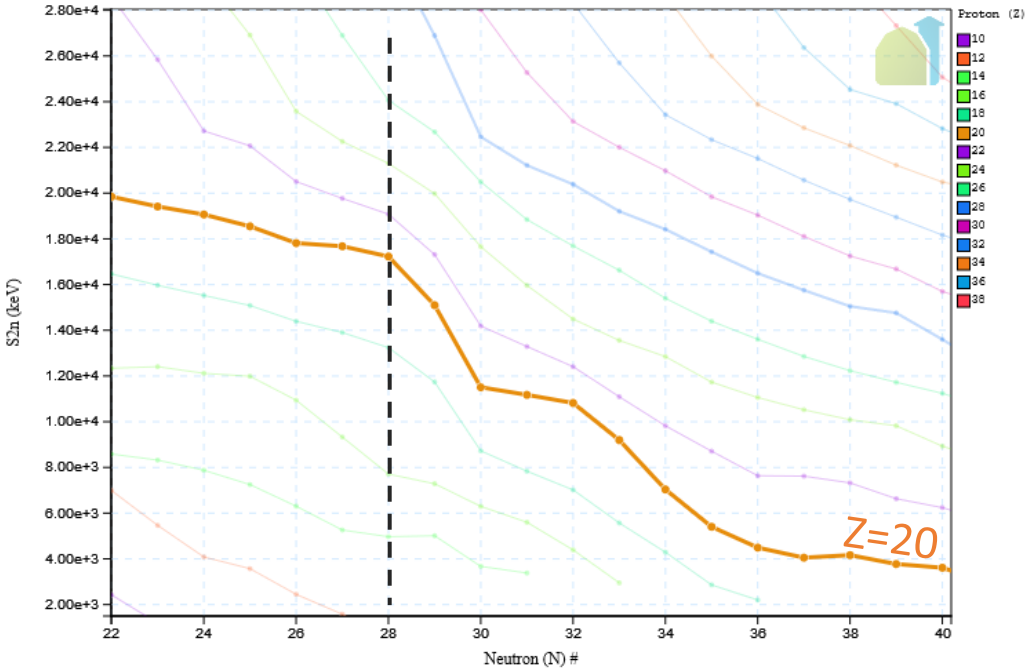
Masses provide a direct measurement of nuclear binding energies and the evolution of nuclear structure

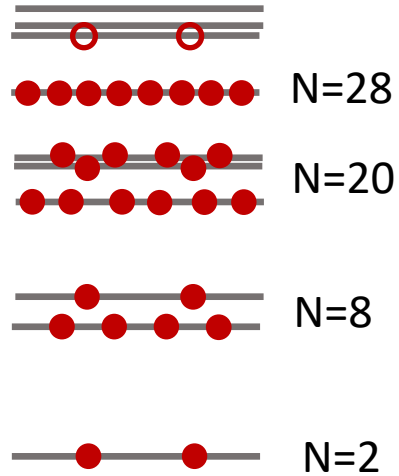


$$E = mc^2$$

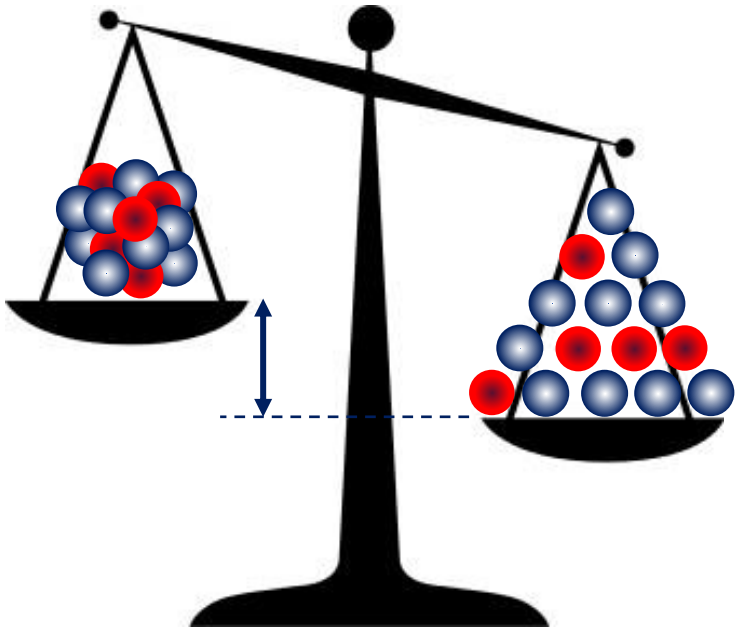
nuclear binding energy!

Two-neutron separation energies





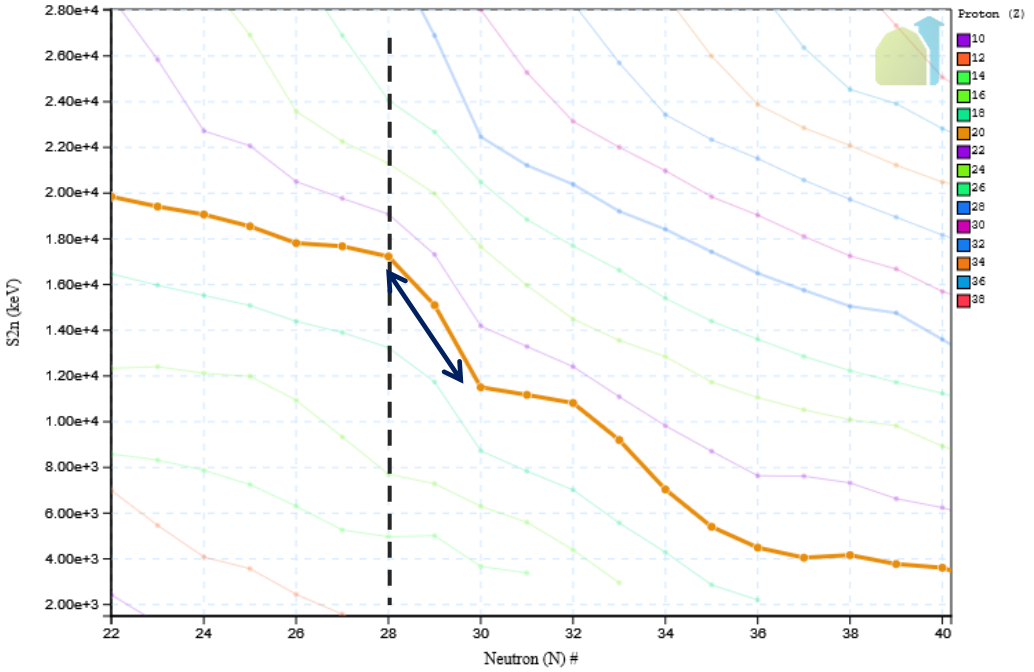
Masses provide a direct measurement of nuclear binding energies and the evolution of nuclear structure

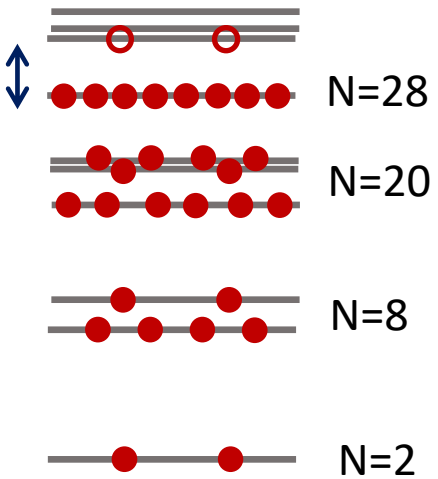


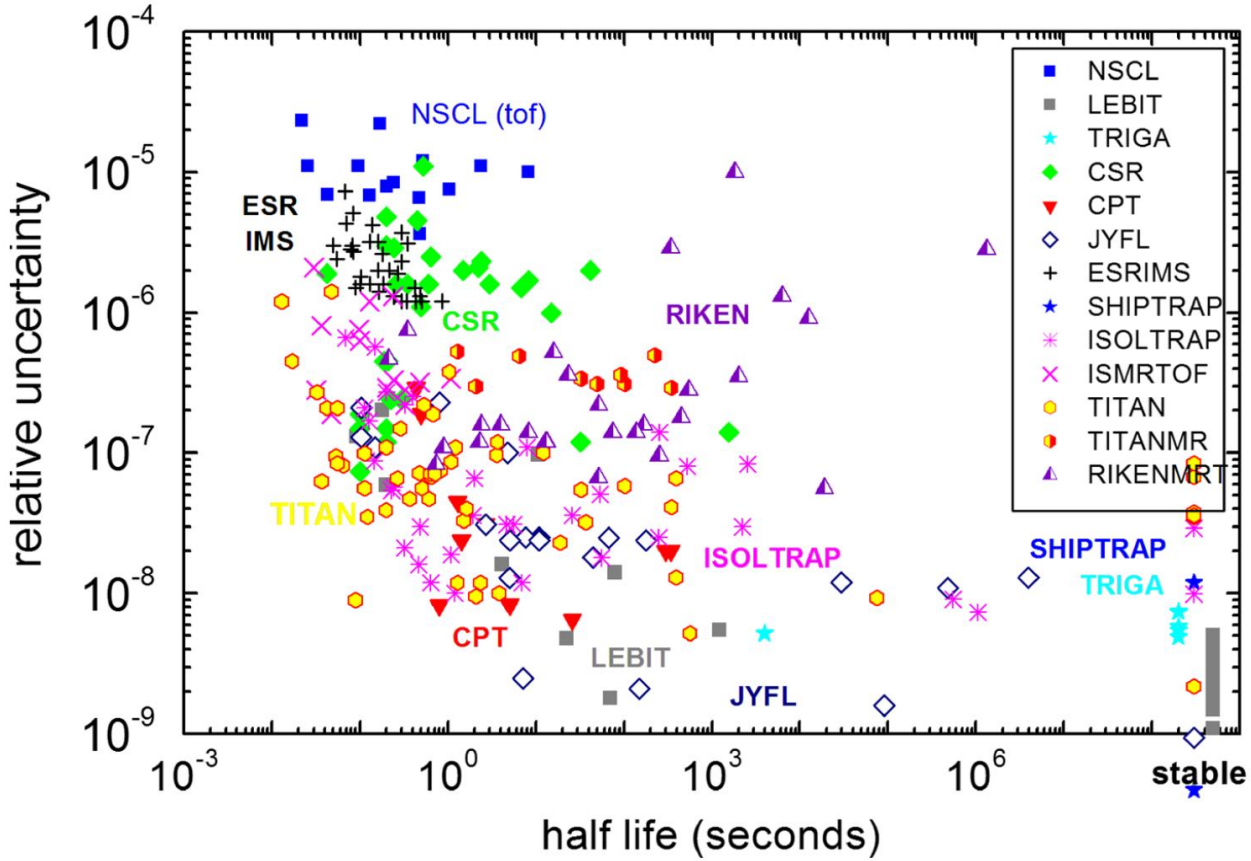
$$E = mc^2$$

nuclear binding energy!

Two-neutron separation energies



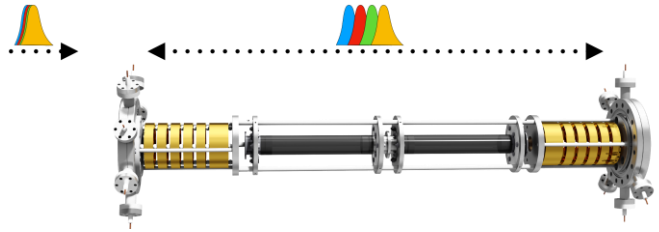


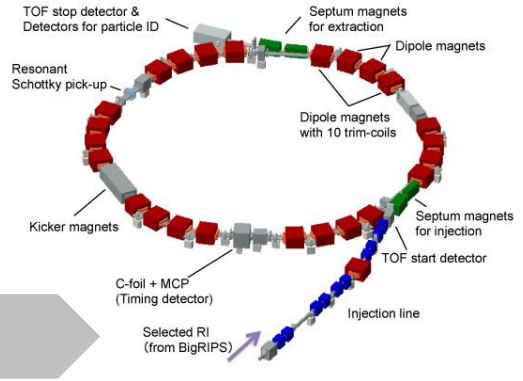


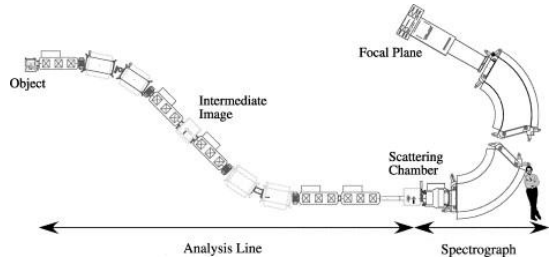
D. Lunney 2019

Experimental techniques differ on their precision and reach for unstable isotopes

PRODUCTION OF UNSTABLE ISOTOPES → BEAM PREPARATION → MASS MEASUREMENT







Storage rings

Penning traps | MR-TOF | TOF-Bρ

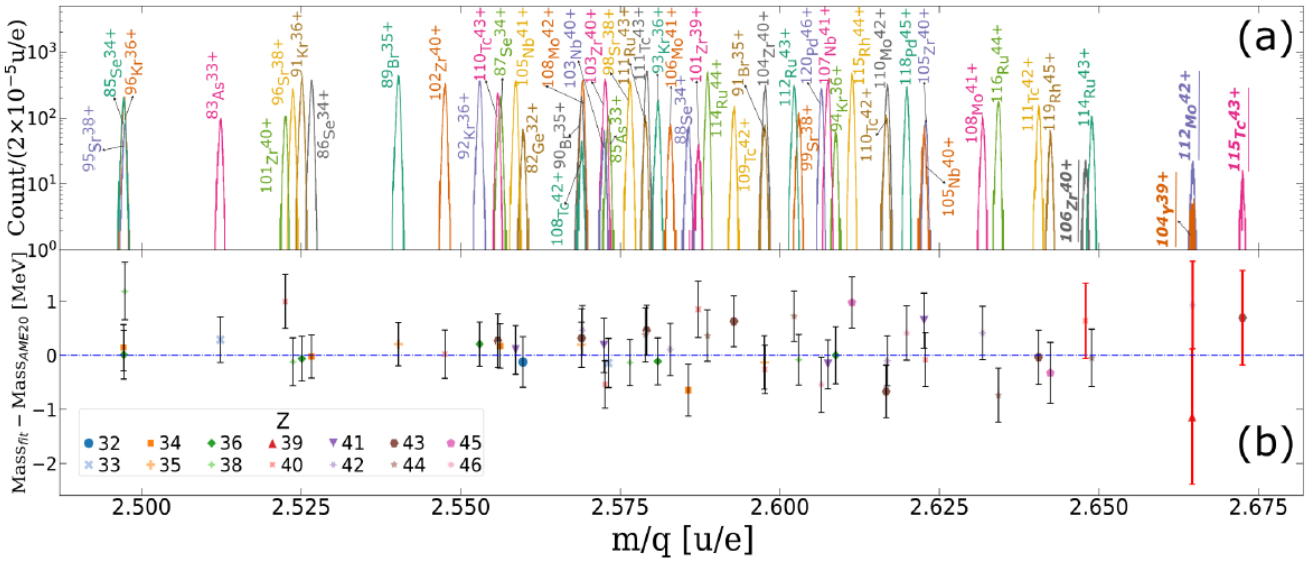
≈ 1 keV uncertainty for unstable isotopes ≈ 500 keV

New developments in the experimental setup now allow to measure heavy ions relevant to the r-process

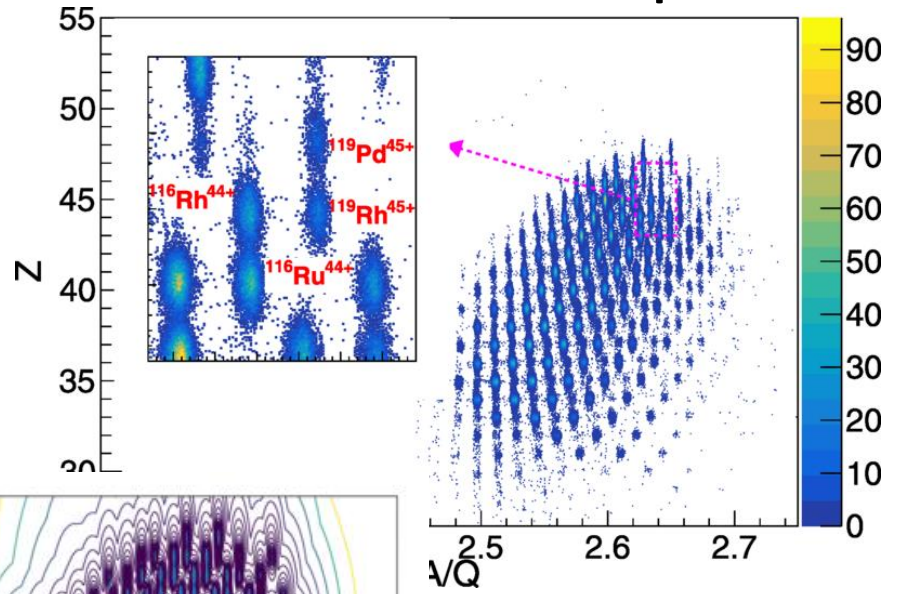
> Resolution improved to $\delta \frac{m}{q} = 9.5 \times 10^{-5}$

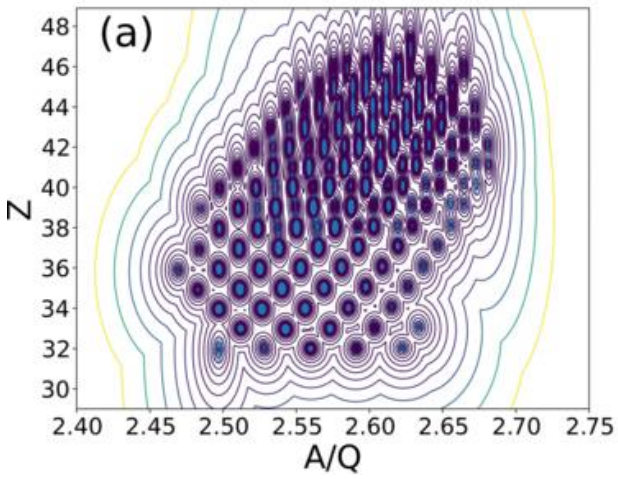
> Separation of Z ≈ 45 ions in the particle identification

Mass-over-charge spectra – N=70 region



Particle Identification Spectra

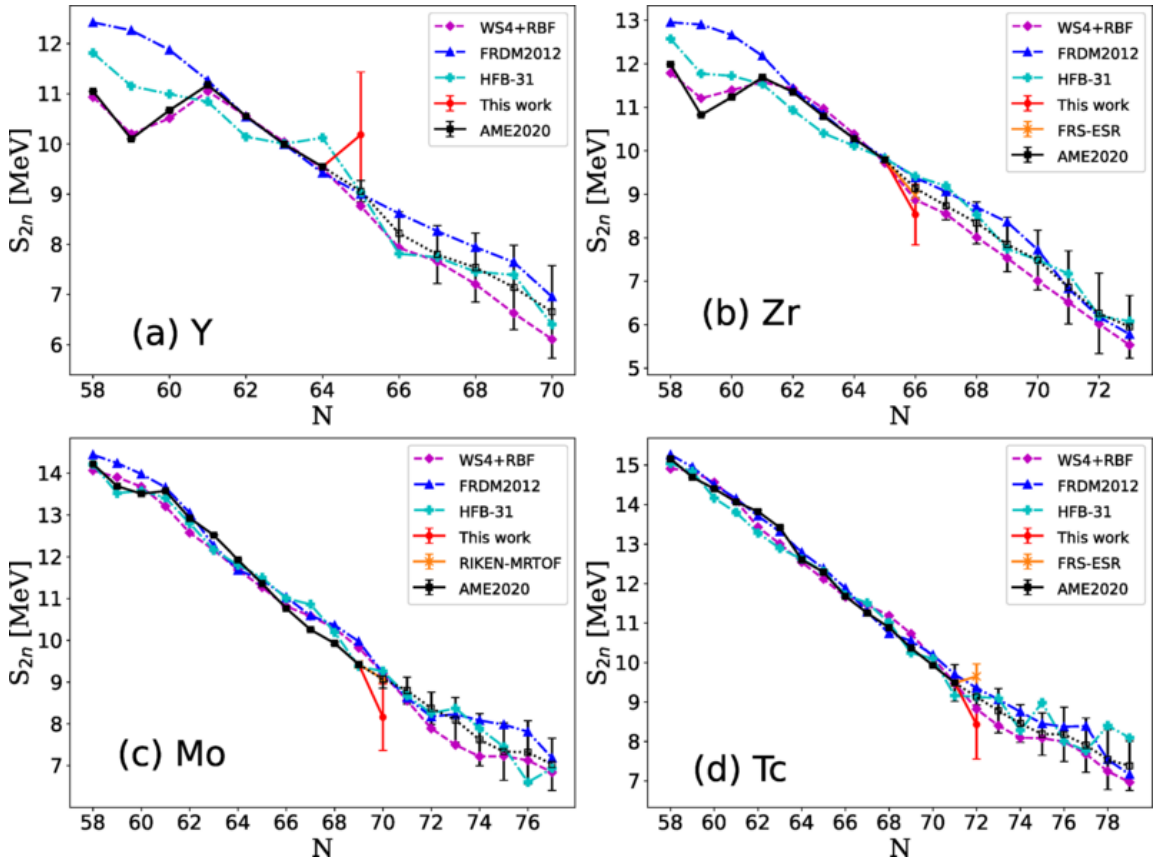




K. Wang et al, Phys. Rev. C 109, 035806 (2024)

Mass measurements of neutron-rich nuclei near N=70

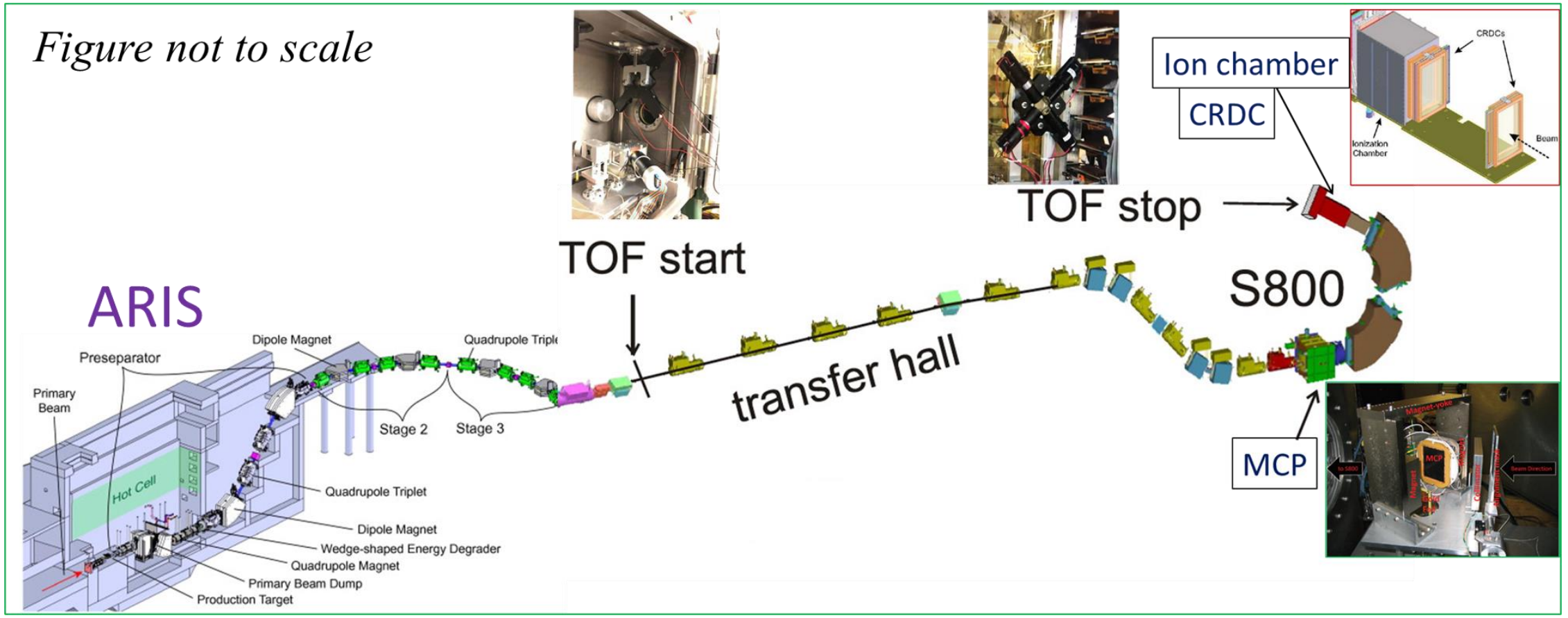
- First measurement of isotopes with Z>28, in regions relevant to the (weak) r-process with the TOF-Bρ technique.
- Measured nuclear mass of ^{104}Y, ^{106}Zr, ^{112}Mo and ^{115}Tc.
- Results agree with smooth trends of theoretical models and do not show onset of deformation at N=70



Nuclide	This work	Count	AME2020	Prev. Exp.	WS4+RBF	FRDM2012	HFB-31
^{104}Y	−55213(1251)	109	−54080(200)#		−53670	−54600	−53510
^{106}Zr	−58110(696)	605	−58750(200)#	−58550(173)	−58756	−59900	−58490
^{112}Mo	−56554(796)	462	−57480(200)#	−57470(8)	−57491	−58410	−57790
^{115}Tc	−55099(874)	299	−55800(200)#	−56320(316)	−55867	−56450	−55770

K. Wang et al, Phys. Rev. C 109, 035806 (2024)

TOF-Bρ experiments at FRIB will continue with the S800 and the future High Rigidity Spectrometer



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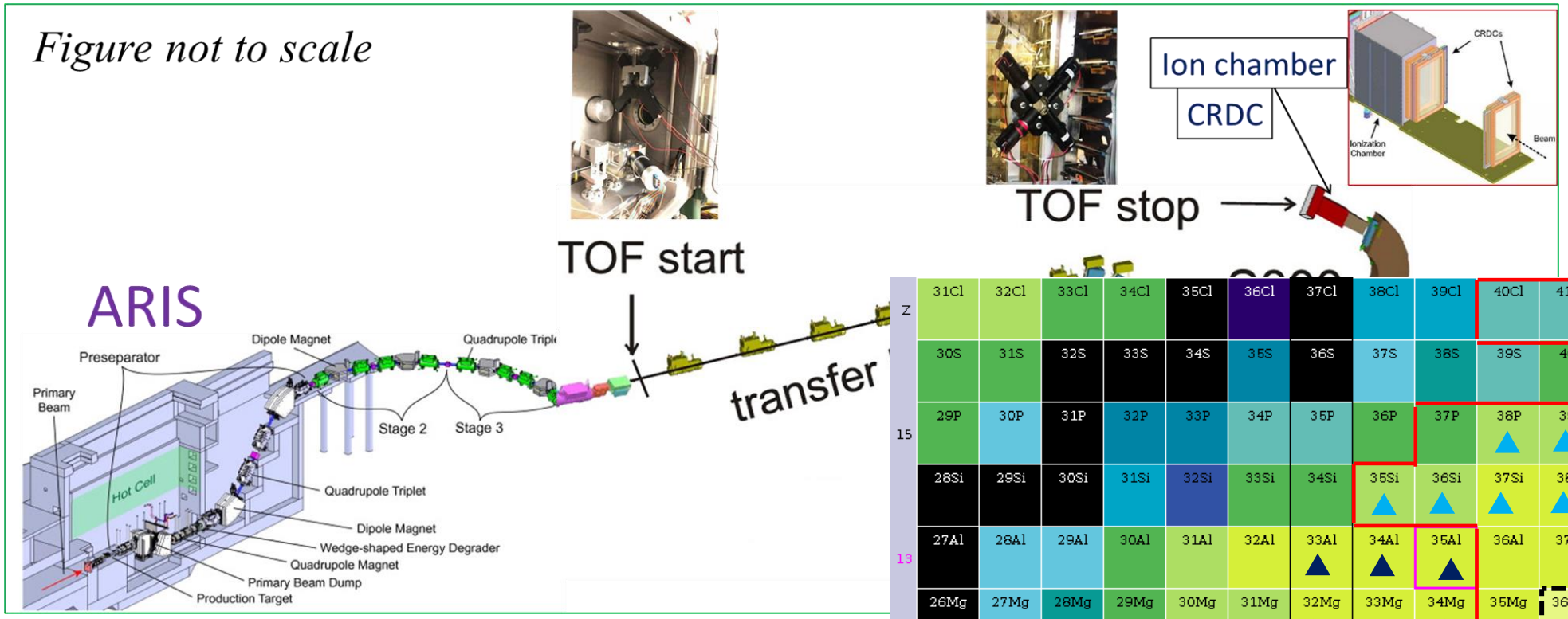
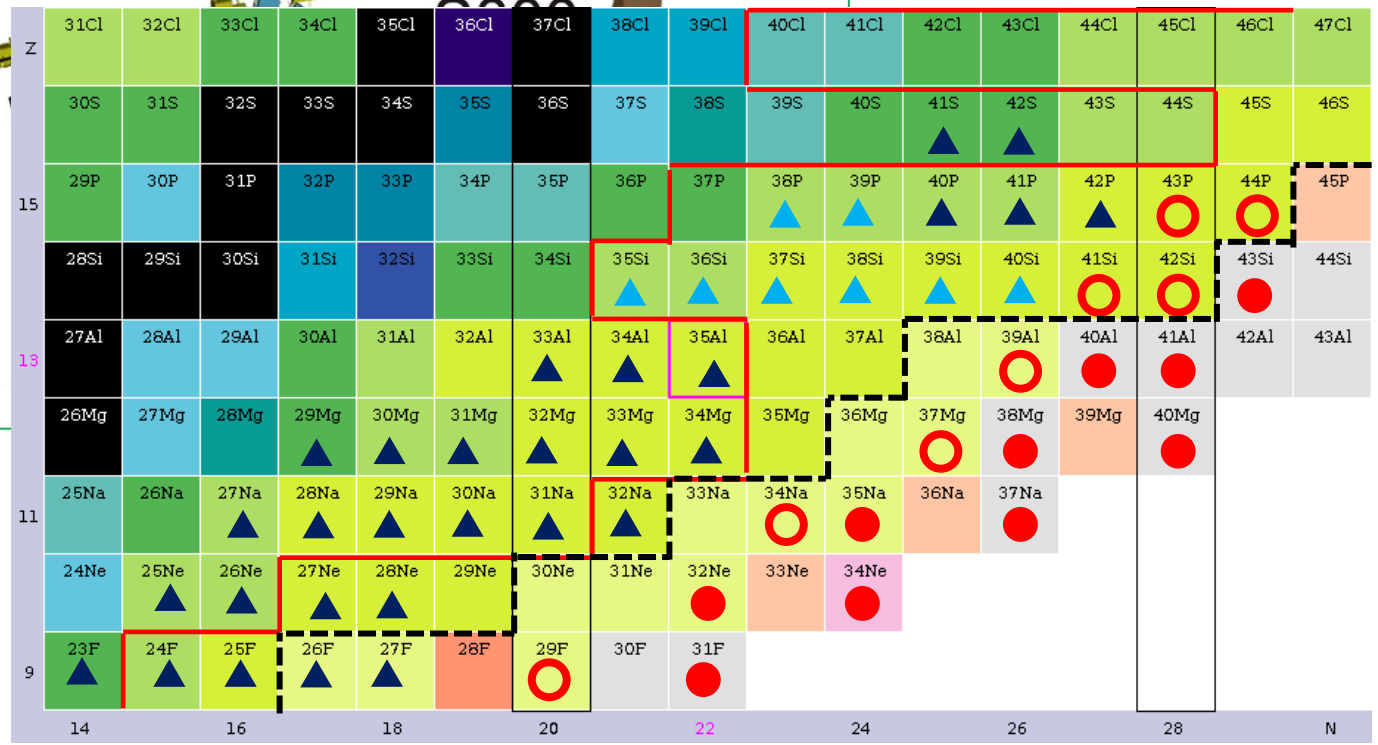
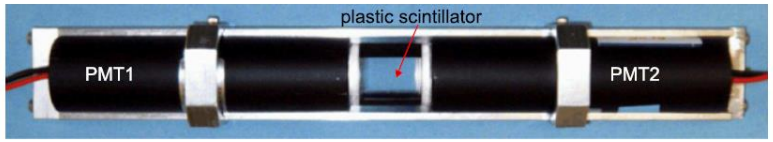
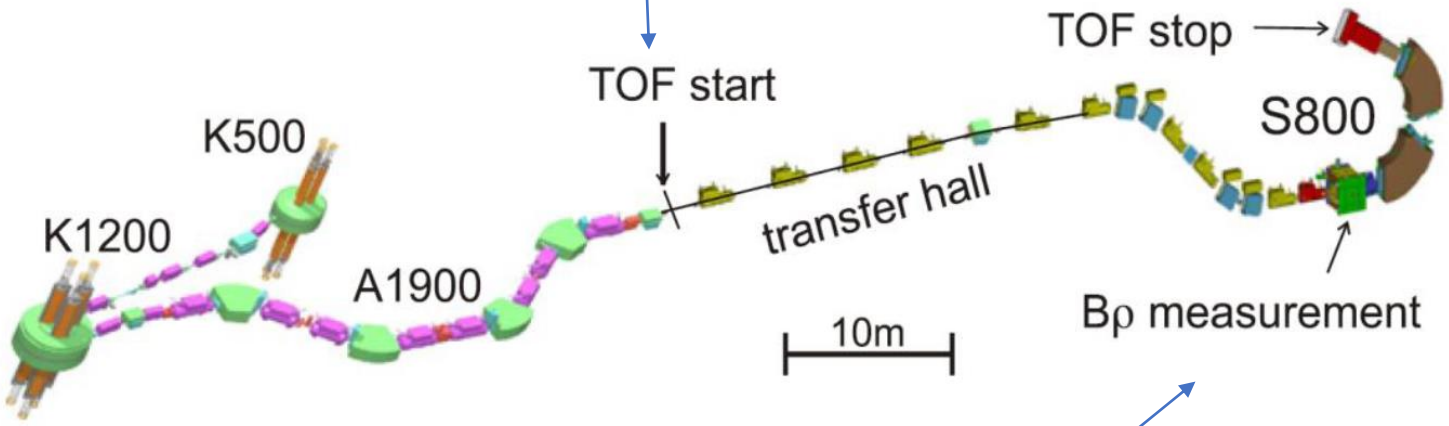


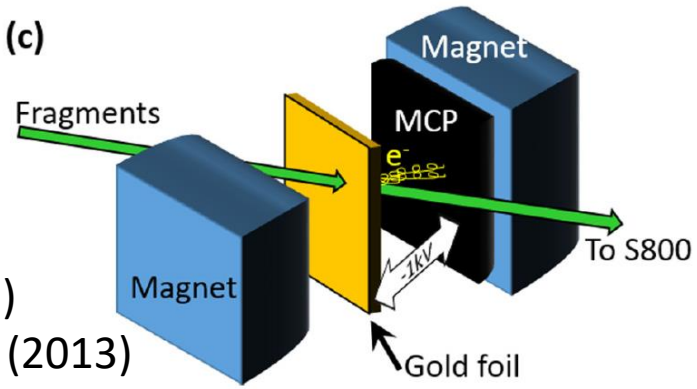


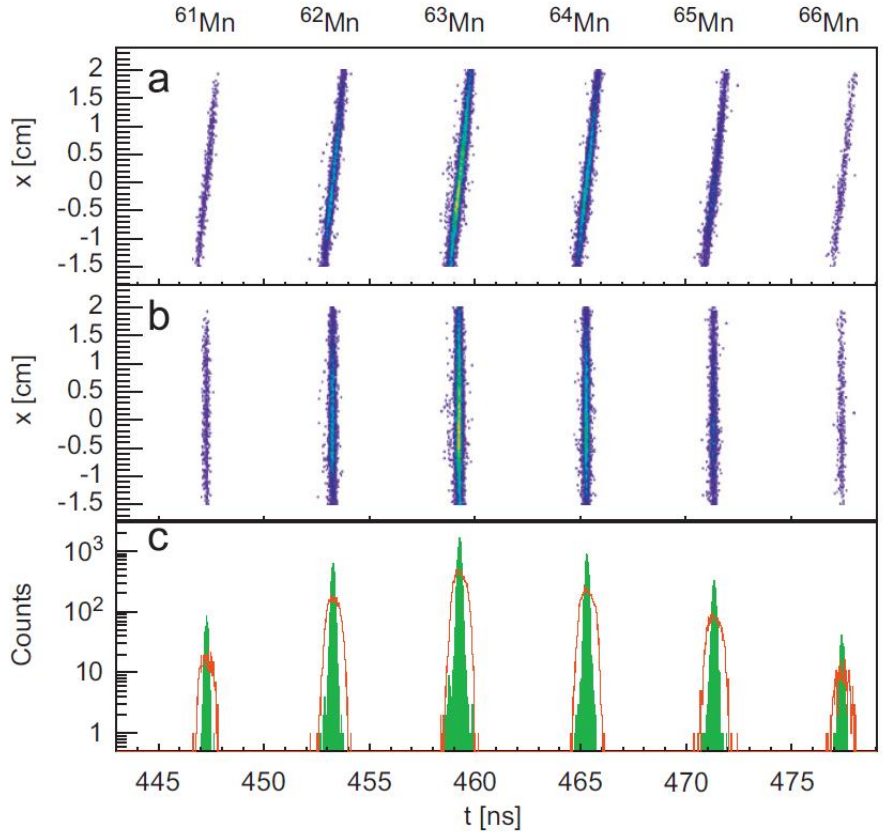
NEED CALIBRATION MASSES FARTHER FROM STABILITY

TOF-Bρ experiments at NSCL









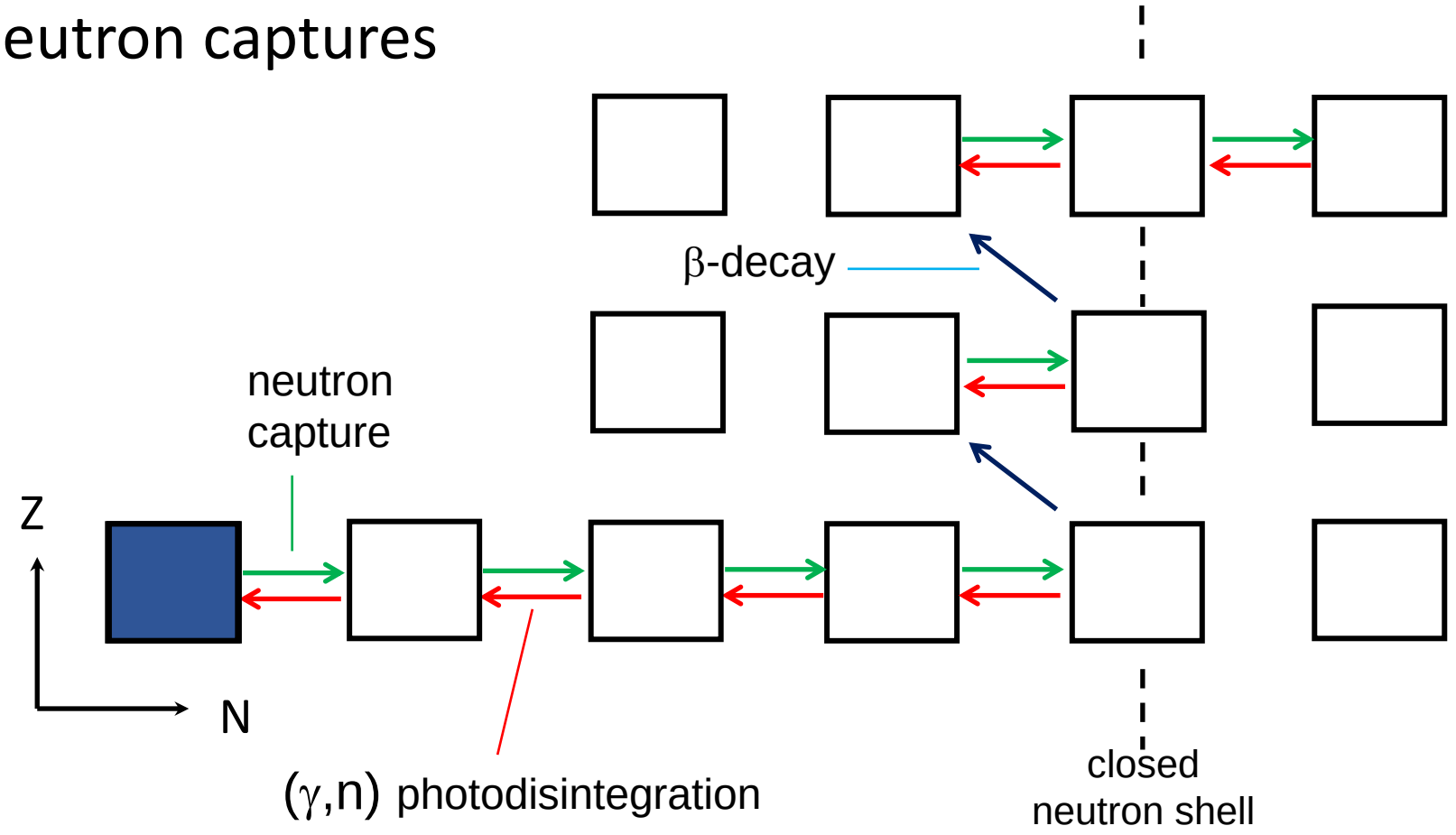
$$\frac{\delta m}{m} \approx 2 \times 10^{-4}$$

Matos et al , NIMA (2012)
Meisel and George, IJMS (2013)

Note: technique pioneered at GANIL (SPEG), currently also an active program at RIKEN (e.g. Michimasa et al, PRL 2018)

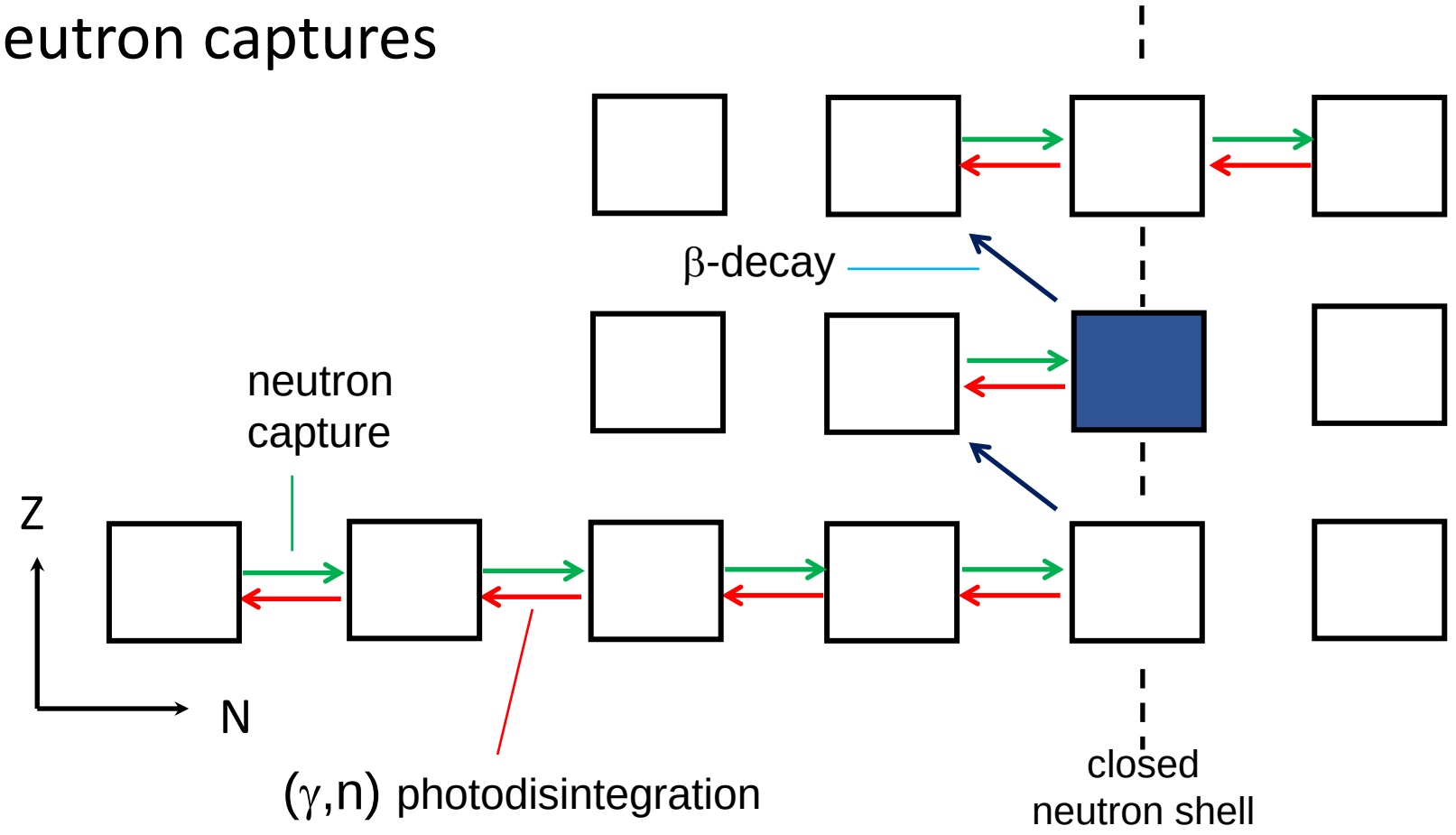
R-process nucleosynthesis

A sequence of neutron captures and β-decays



R-process nucleosynthesis

A sequence of neutron captures and β-decays

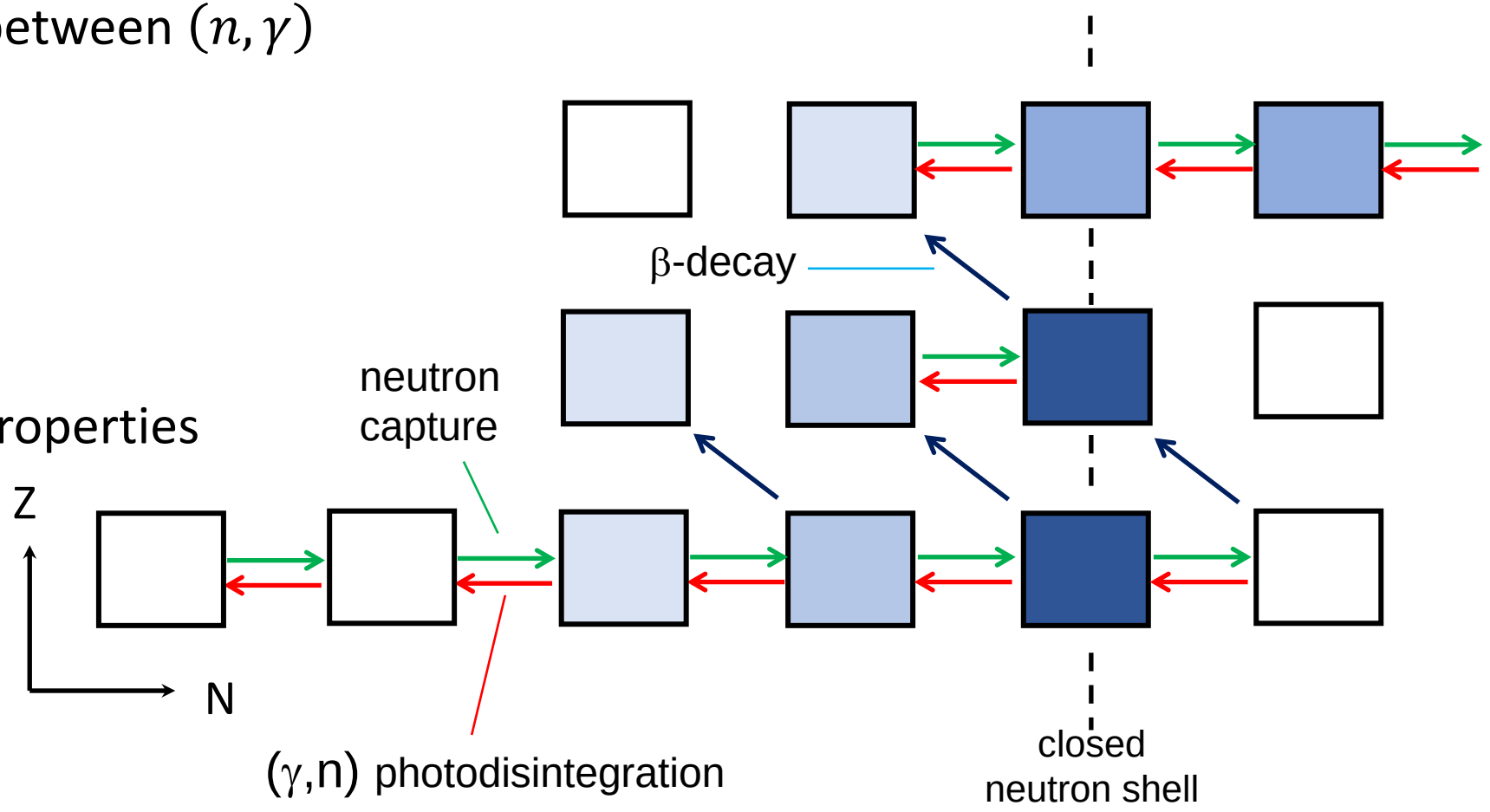


R-process nucleosynthesis

Statistical equilibrium between (n, γ) and (γ, n) reactions (*hot* r-process)

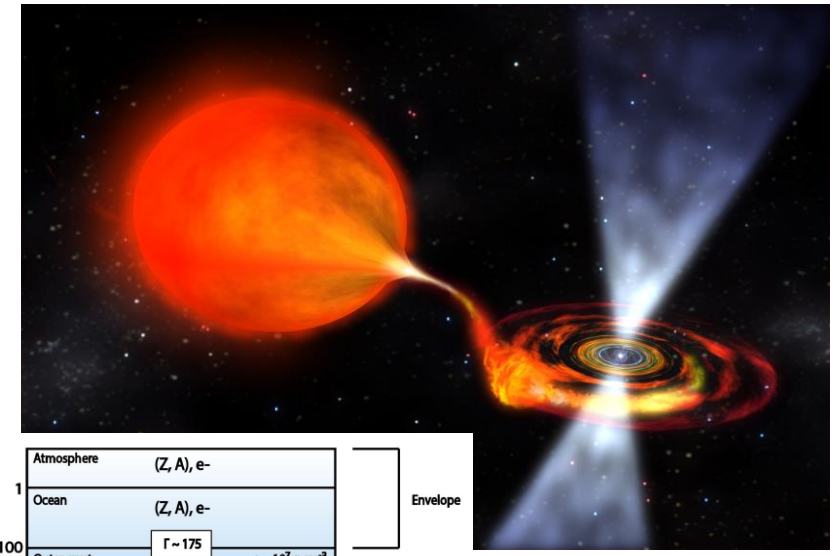
Data:

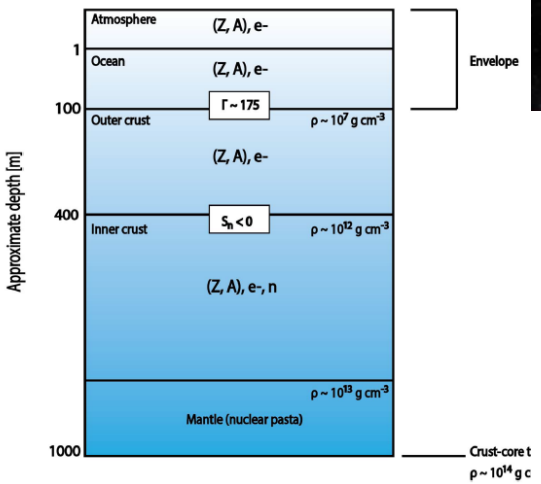
- Masses
- Half-lives and decay properties
- n-induced rates
- fission



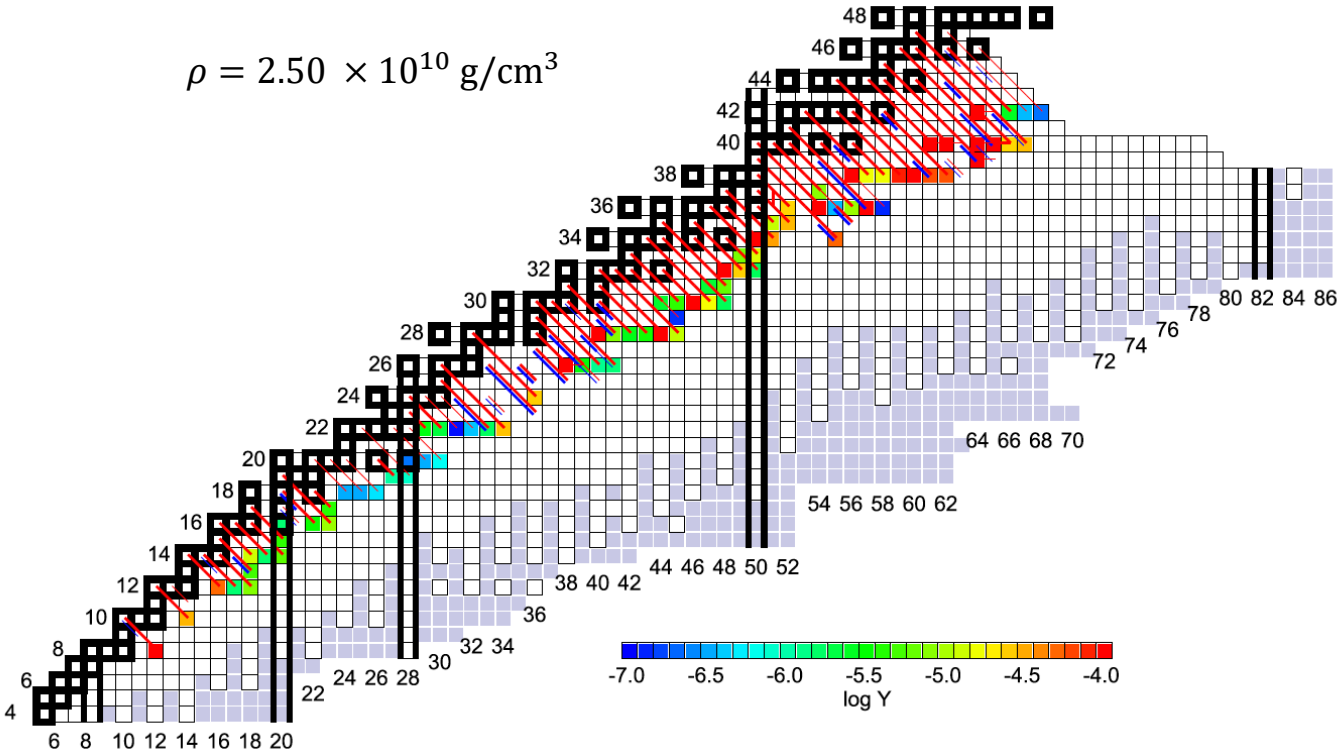
Nuclear masses of neutron-rich isotopes necessary to models the crust of accreting neutron stars

NASA/Dana Berry





Meisel++, Jour. Phys. G, 45 (2018)



R. Lau et al, ApJ 859, 62 (2018)

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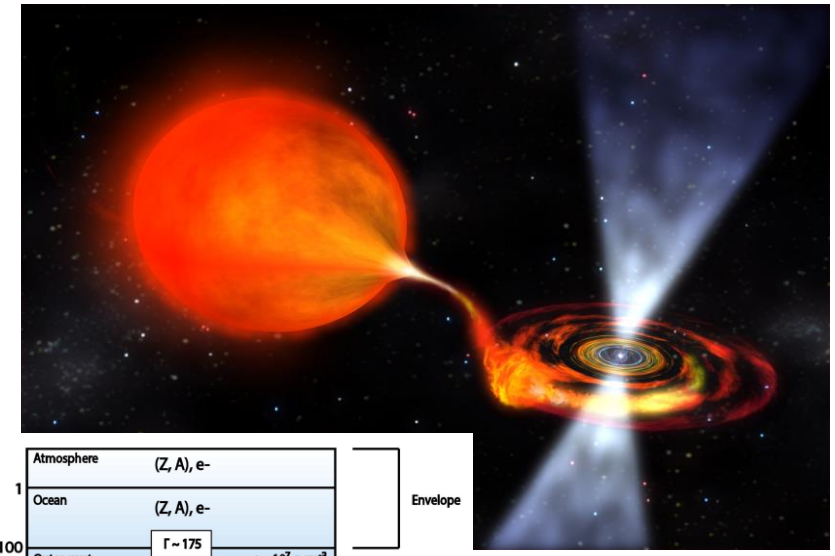
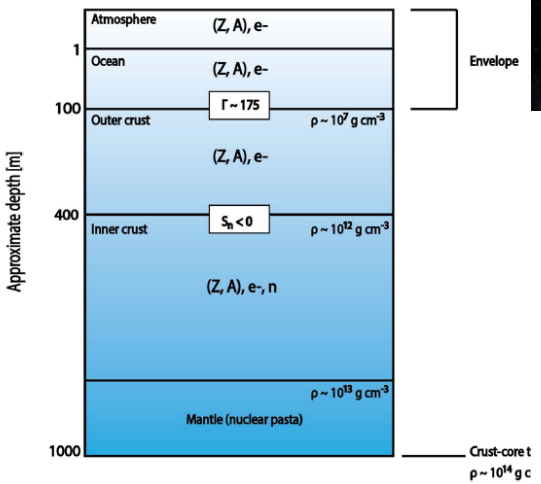
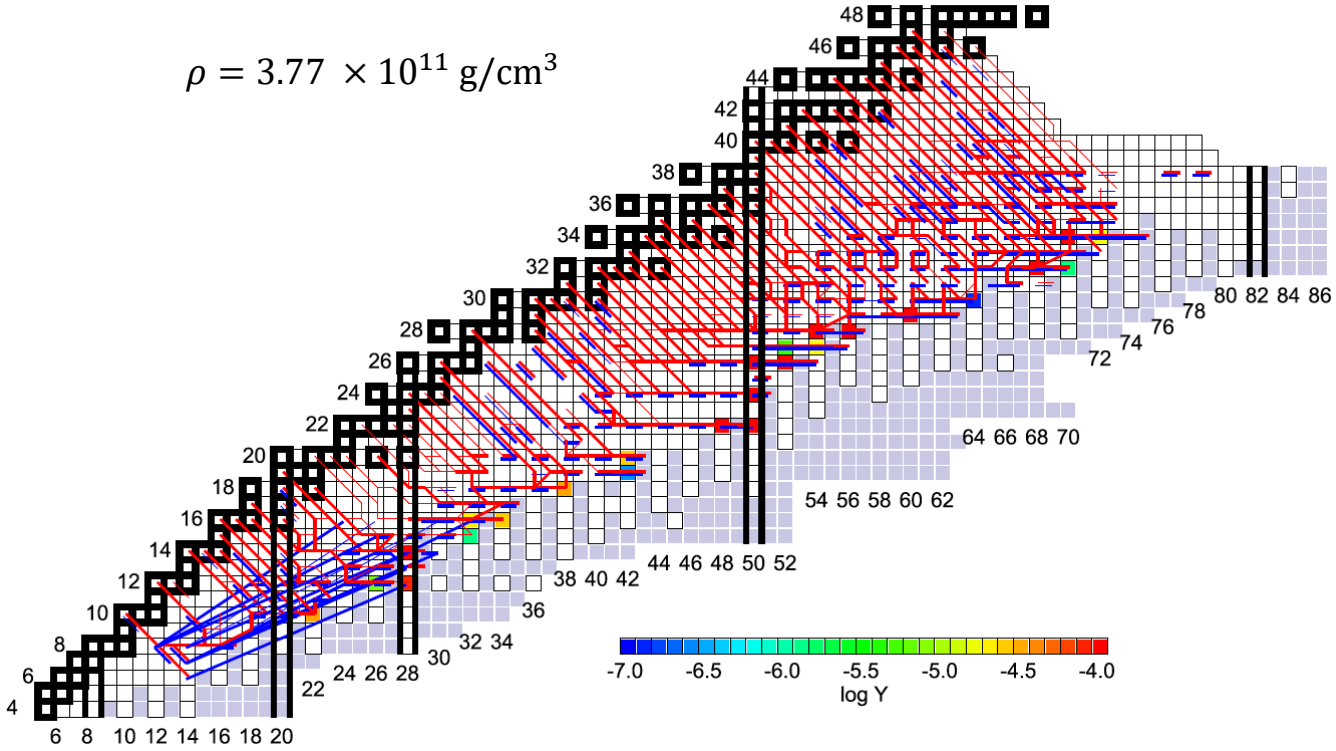




Meisel++, Jour. Phys. G, 45 (2018)

$\rho = 3.77 \times 10^{11}$ g/cm^3



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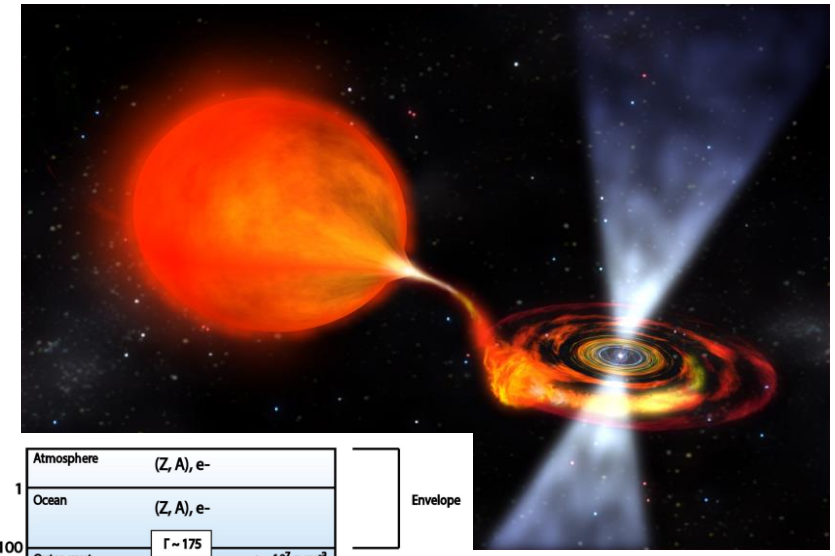
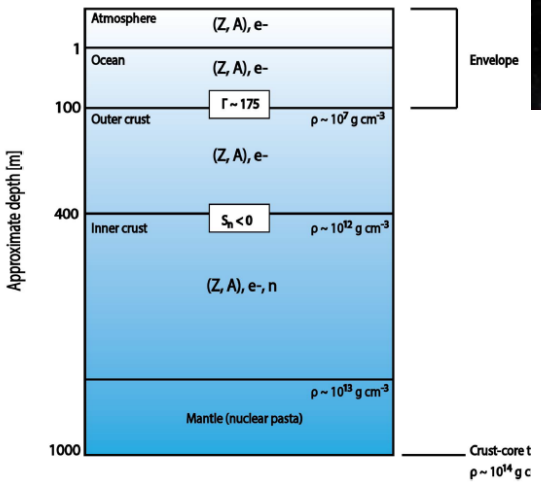
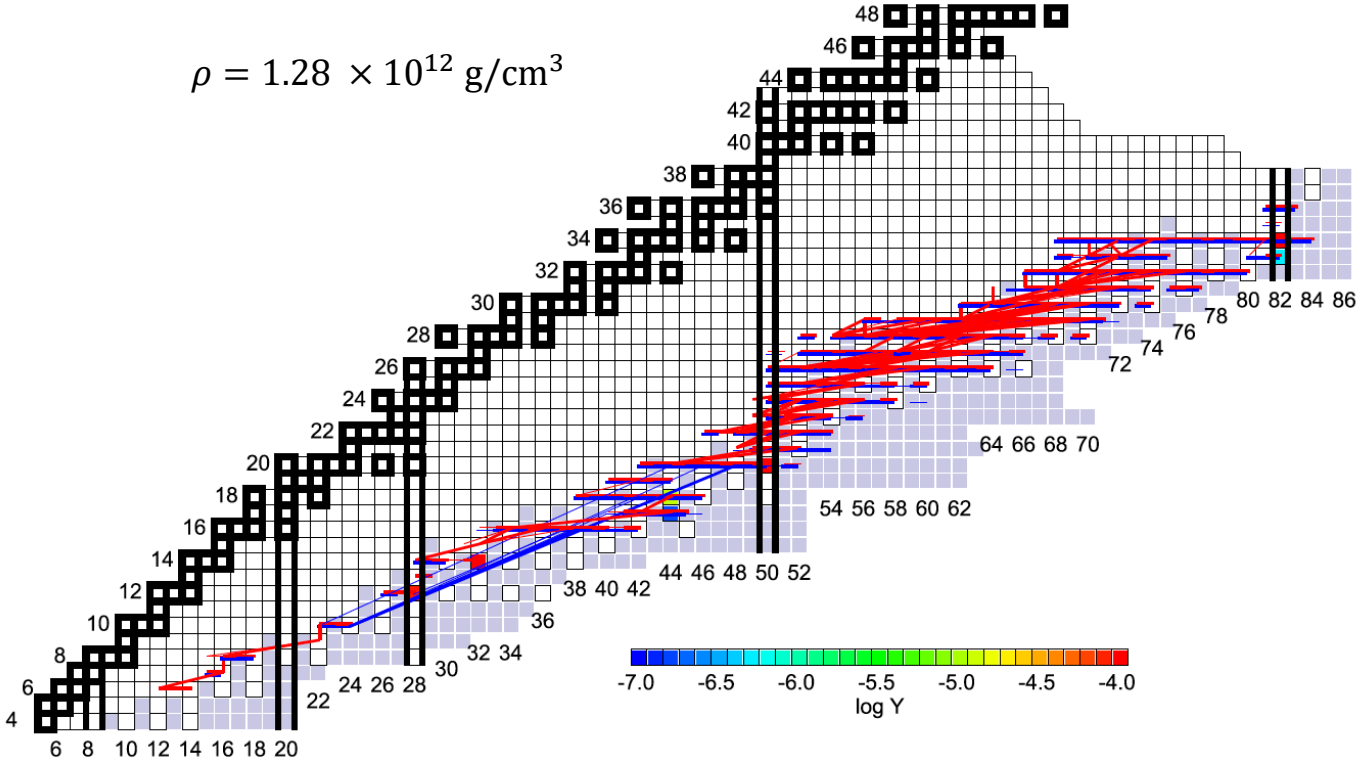




Meisel++, Jour. Phys. G, 45 (2018)

$\rho = 1.28 \times 10^{12}$ g/cm^3



R. Lau et al, ApJ 859, 62 (2018)

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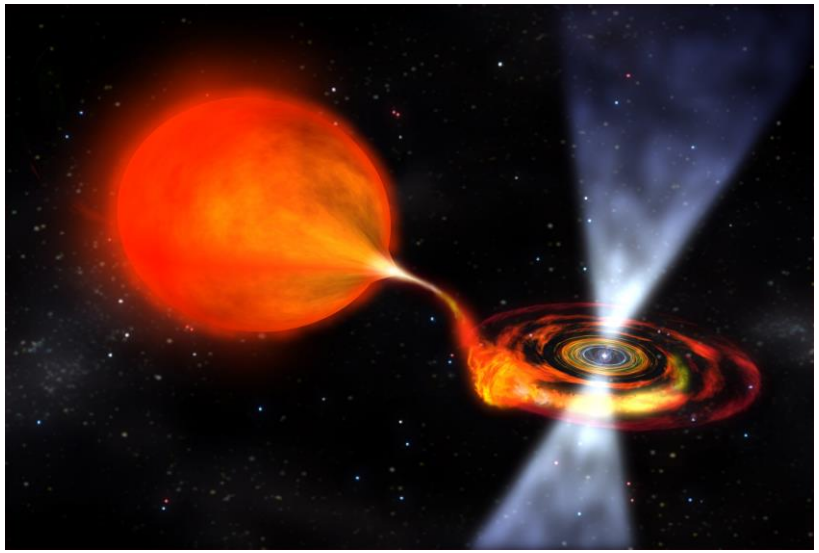
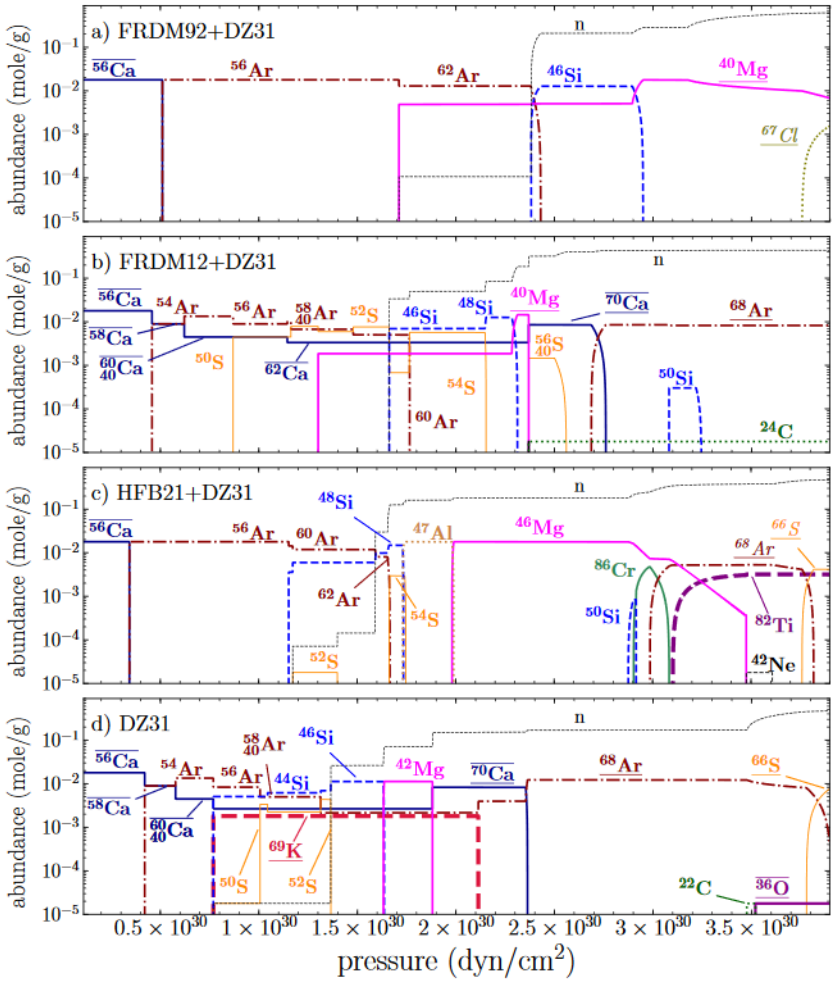


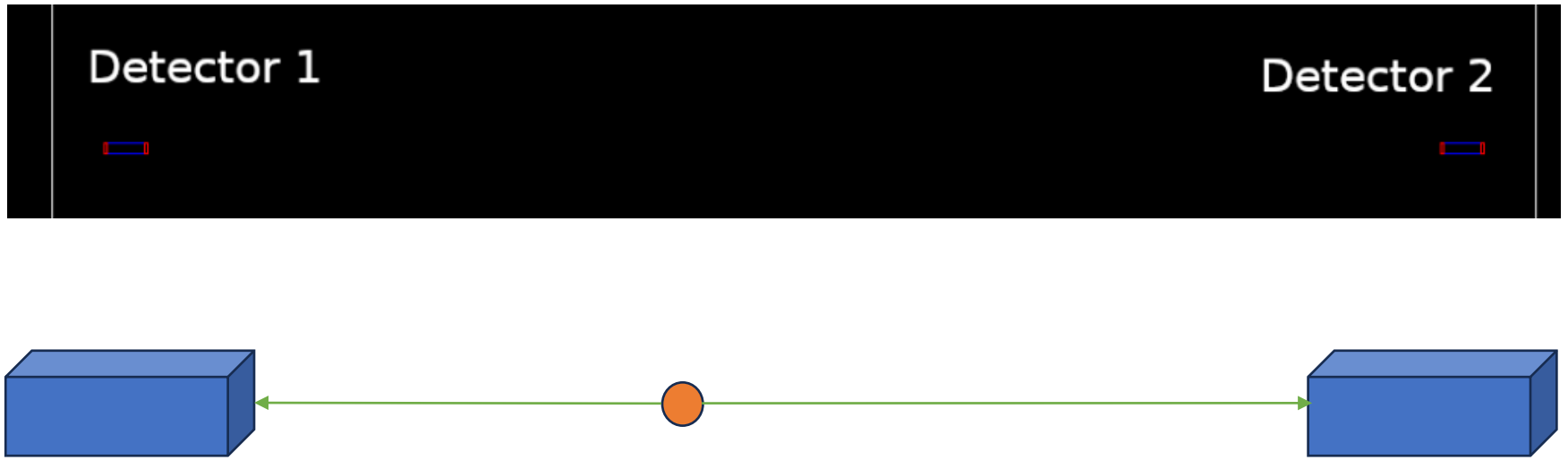
Masses affect thermal properties of the crust:

- location of heating and Urca-cooling sources
- composition and thermal conductivity



Shchechilin and Chugunov, NMRAS 490, 3454 (2019)

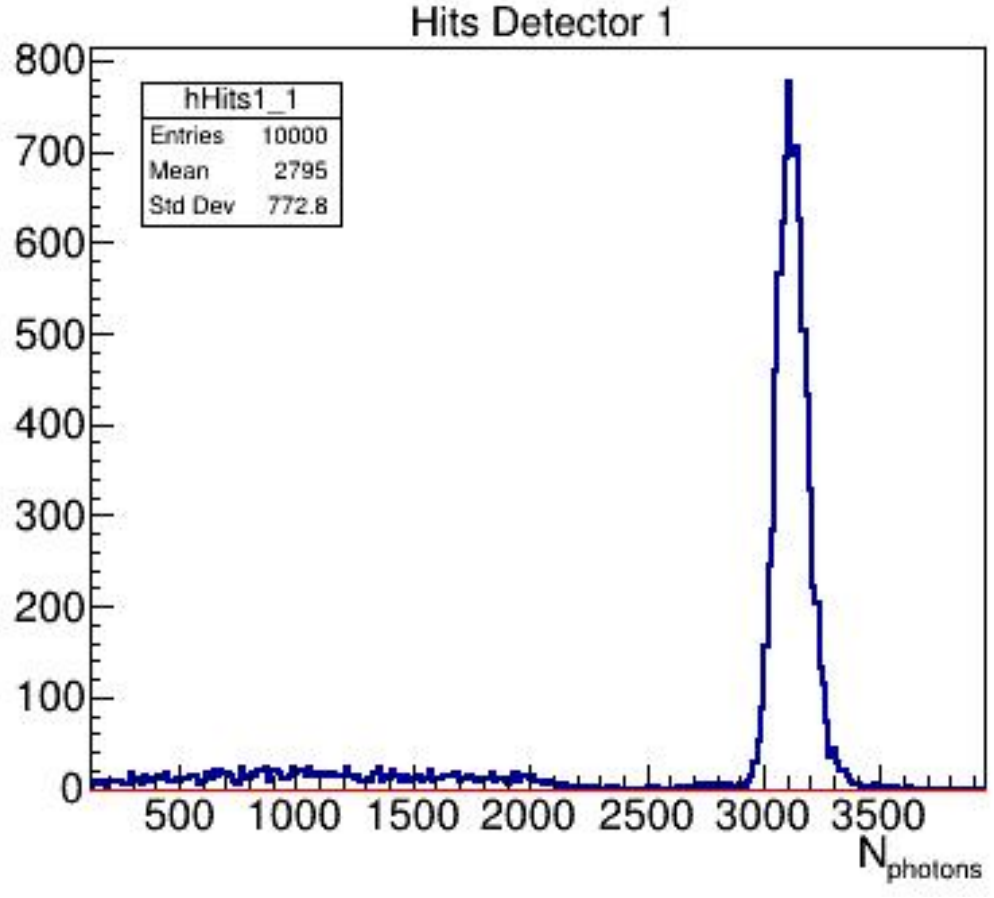
The follow-up is to make the TOF using two detectors at approximately 70 cm.



The scintillators have dimensions in millimeters or centimeters, and it is easy to see the difference in dimensions.

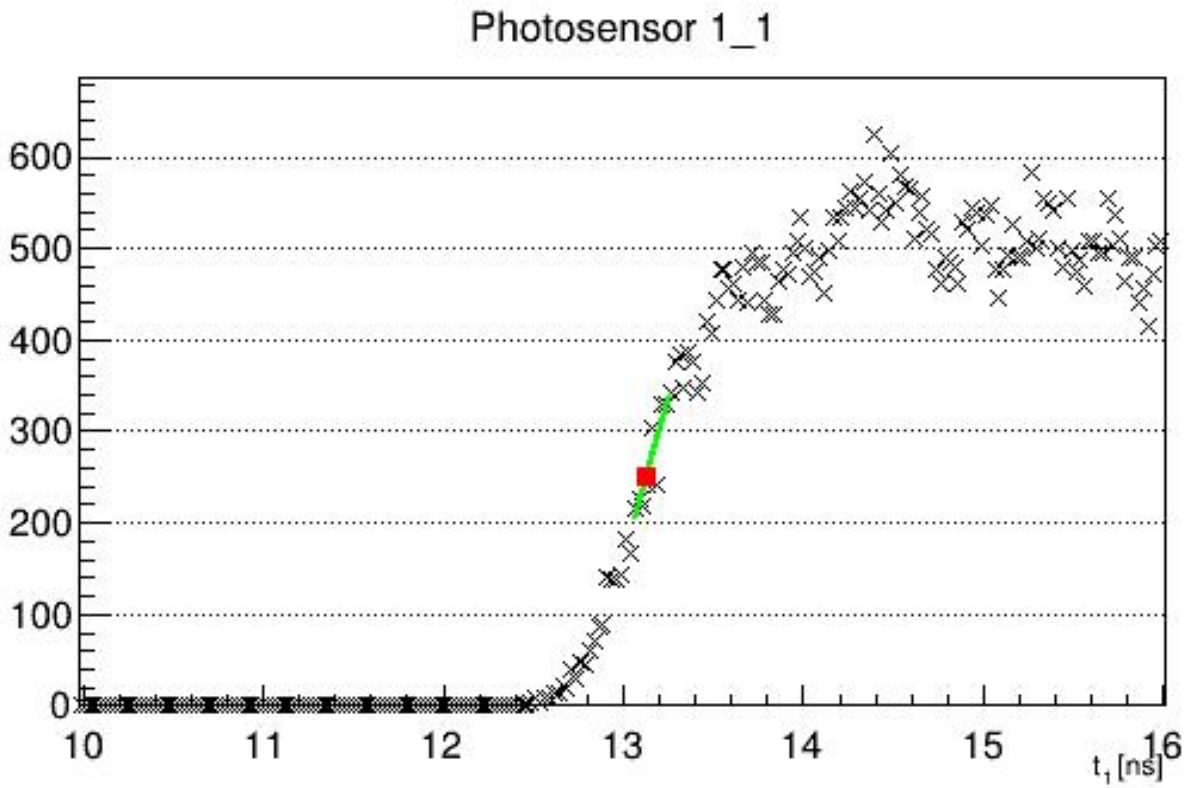
Analisis of this Simple Scintillators

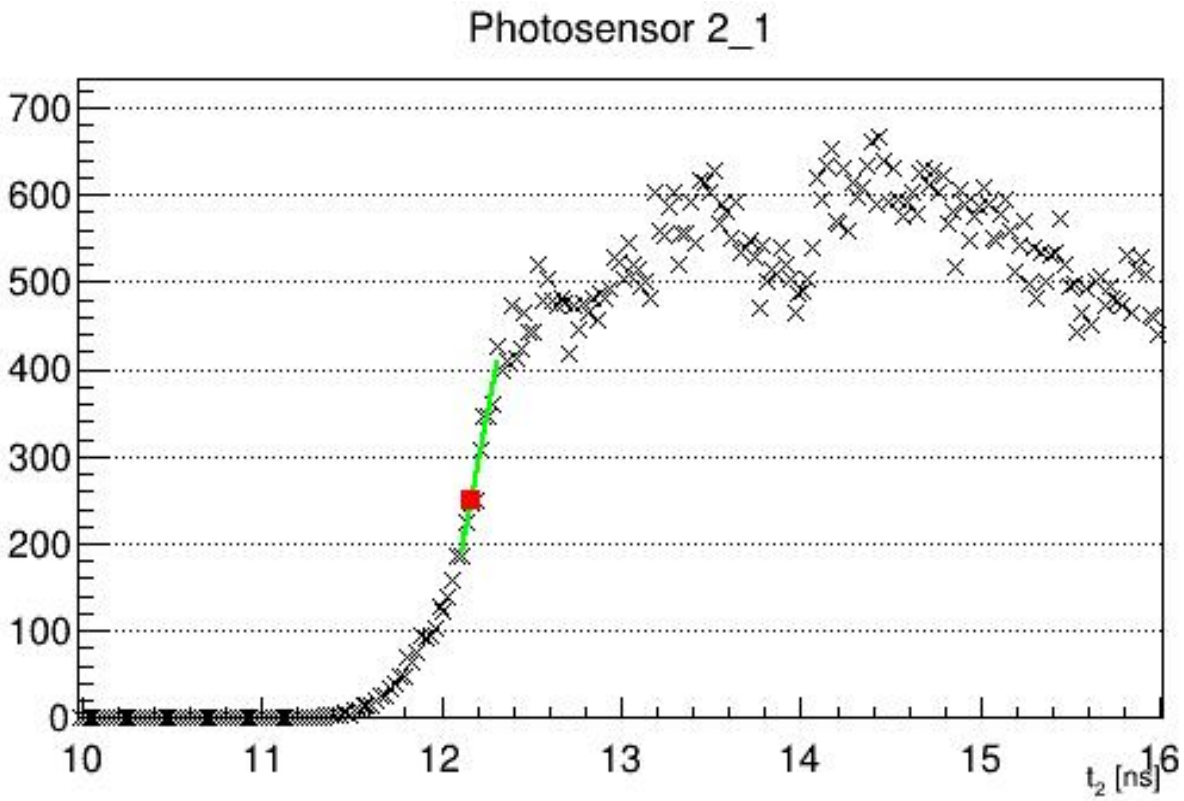
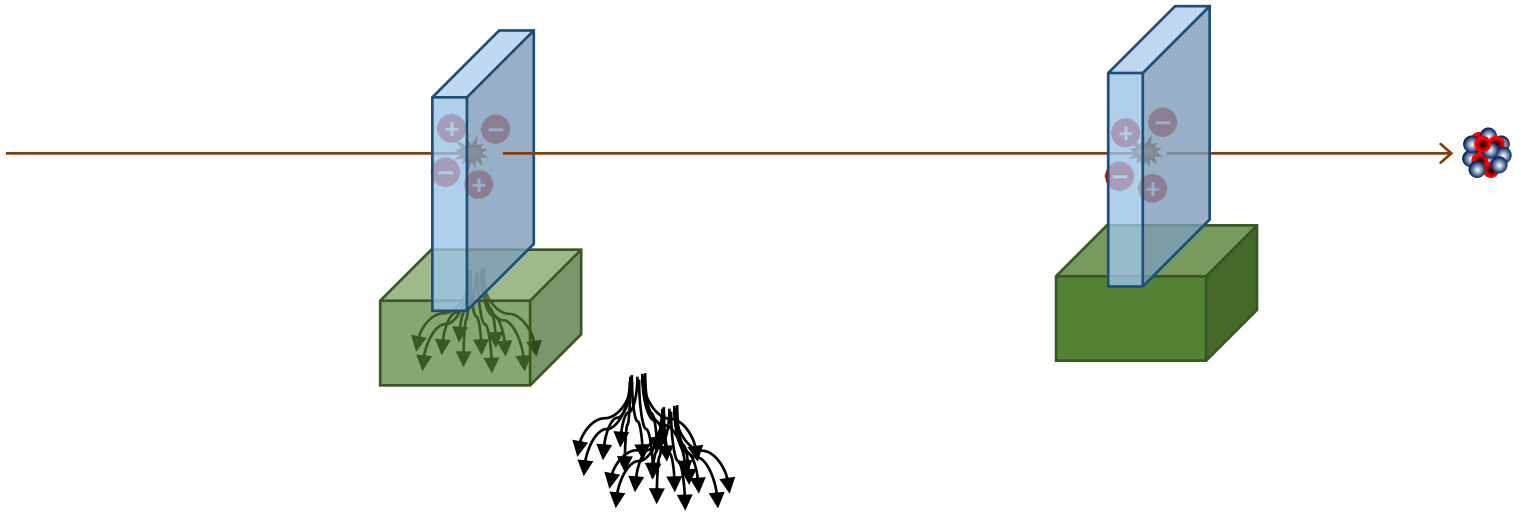
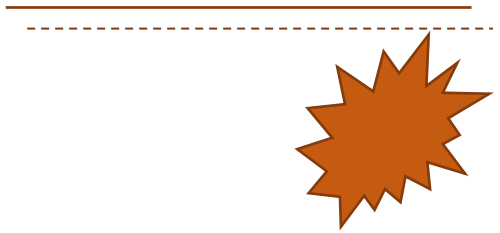
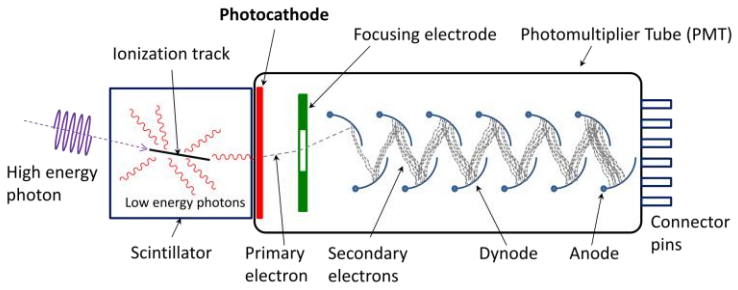
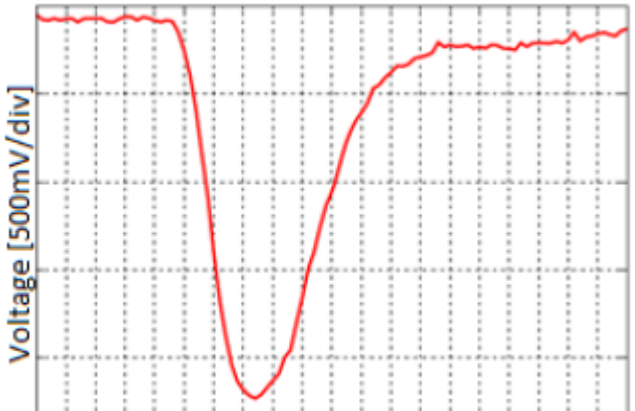
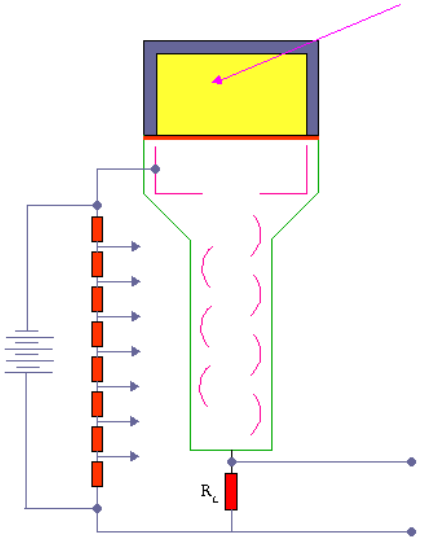
One of our first simulations have big scintillator (20x20x200 mm) and the source is displaced 15 cm to one side.



This is the spectrum of one of our detectors. The photopeak between 2800-3500 corresponds to the energy of 511 KeV made by the annihilation.

We measure the coincidence of the fast photons and obtain the time of the detectors for the TOF.





Challenges to achieve 10 ps resolution