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Mass measurements towards the r-process path at TITAN

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FRIB & the GW170817 Kilonova
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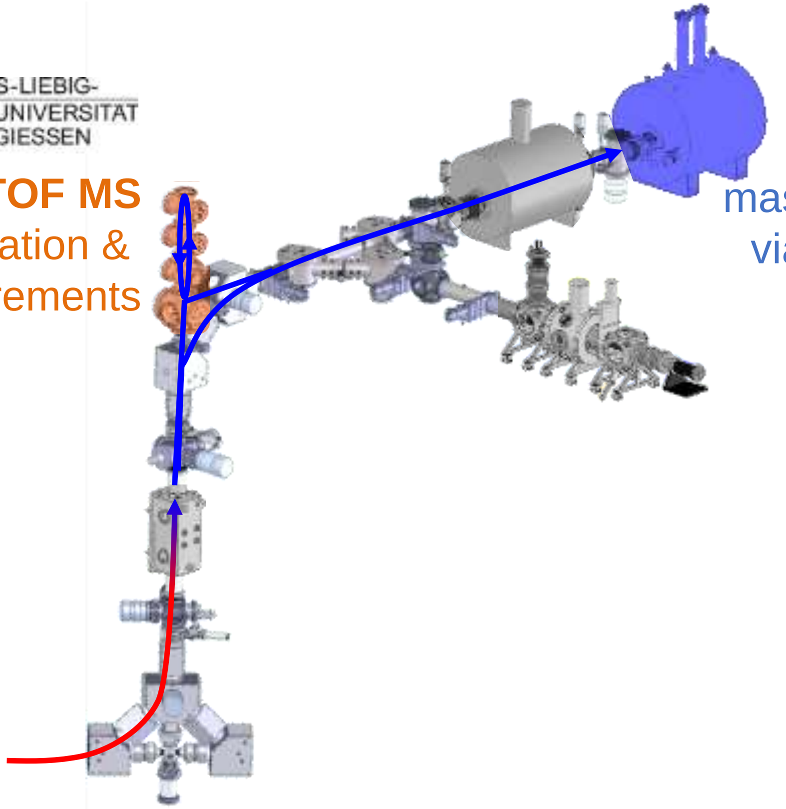
Two mass spectrometry techniques are used at TITAN.

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

MR-TOF MS
isobar purification &
ms mass measurements



MPET
mass measurement
via $2\pi \nu_c = q/m \cdot B$

J. Dilling *et al.*, NIMB **204** (2003) 492

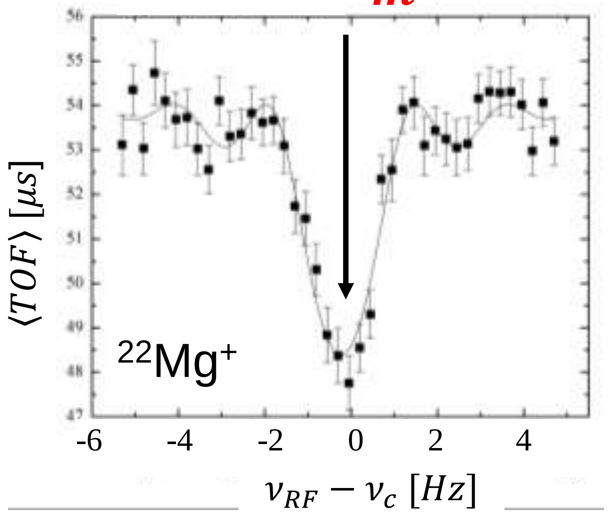
The Measurement PEnning Trap delivers the best resolving power.

$$2\pi\nu_c = \frac{qe}{\boldsymbol{m}} \cdot B$$

3.7 T

\+

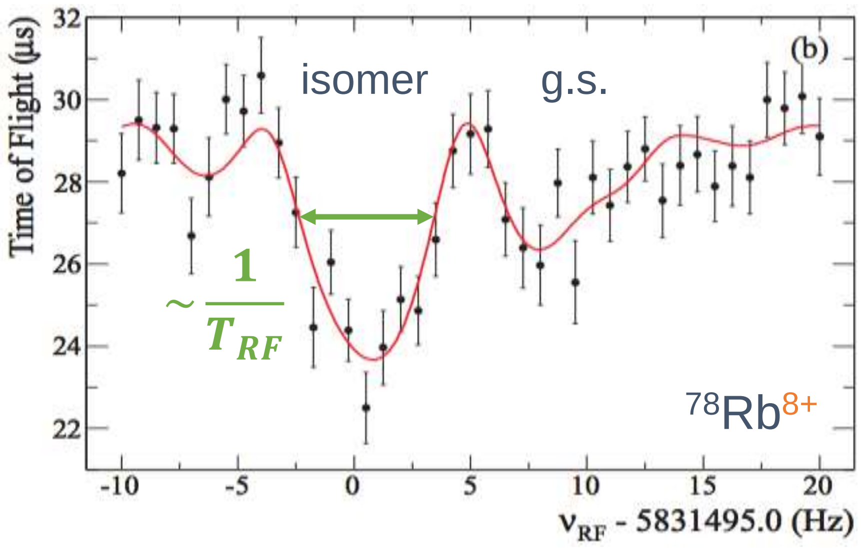
=



Fast beam preparation and the TOF-ICR technique has led to measurements for half-lives as low as 9 ms ($^{11}Li^{+}$).
(PI-ICR forthcoming)

M. Brodeur *et al.*, PRC **80** (2009) 024314; M. Brodeur *et al.*, IJMS **20** (2012) 310

Resolving power is boosted by higher charge states.



$$\frac{m}{\Delta m} \propto \frac{q e\, B\, T_{RF} \sqrt{N}}{m}$$

N = statistics → limited by production

T_{RF} = measurement time → limited by $T_{1/2}$

B = magnetic field → limited by technology

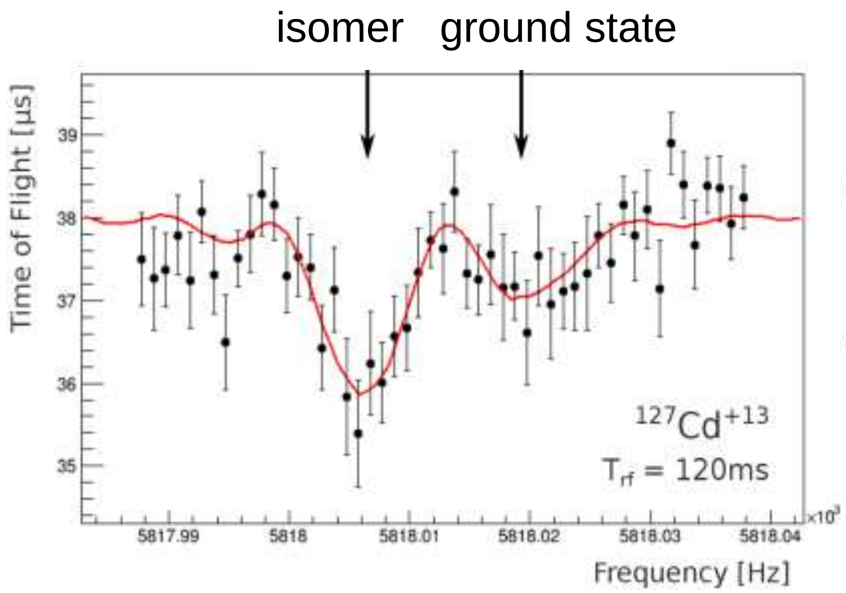
q = charge state → limited by Z

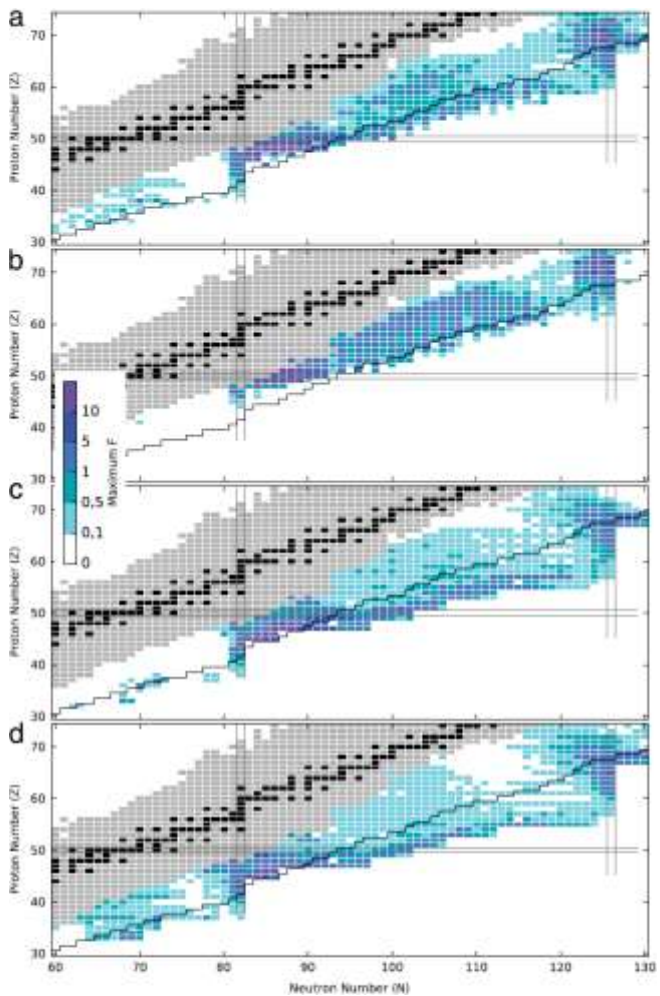
(gains also in PI-ICR)

M.C. Simon, *et al*, RSI 83 (2012) 02A912

TITAN alone uses highly charged ions for gains in *resolving power*, purification, & more.

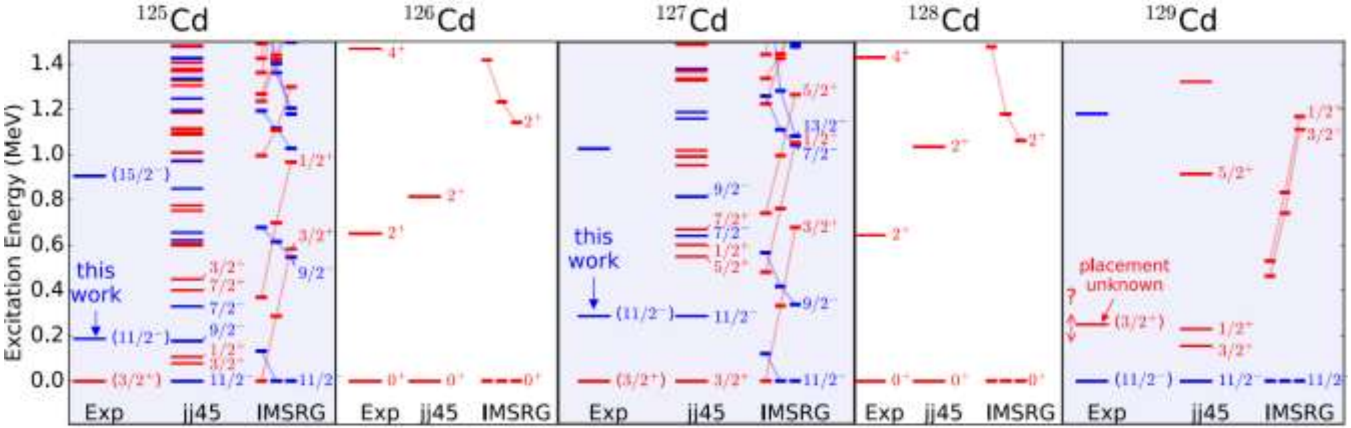
Higher charge states resolved isomers in $^{A\approx130}$In and odd-A $^{\leq129}$Cd isotopes.

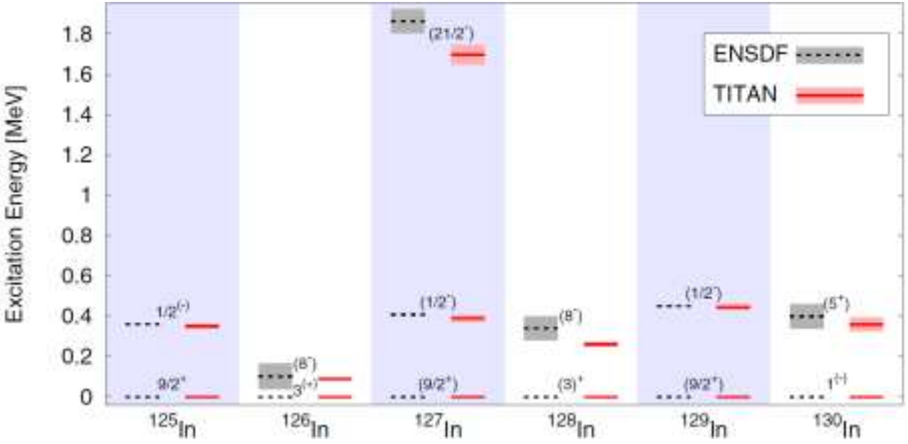




M. Mumpower, *et* al., PNPP 86 (2016) 86; D. Lascar, *et al.*, PRC, 96 (2017) 044323; C. Babcock, *et al.* PRC 97 (2018) 024312

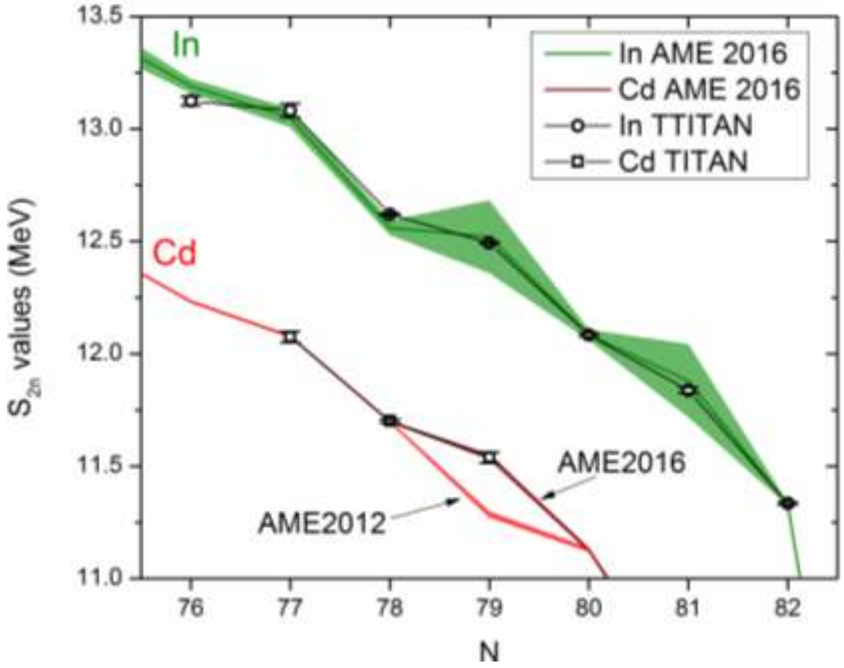
Isomers were used to improve the level schemes.





D. Lascar, *et al.*, PRC, 96 (2017) 044323; C. Babcock, *et al.* PRC 97 (2018) 024312

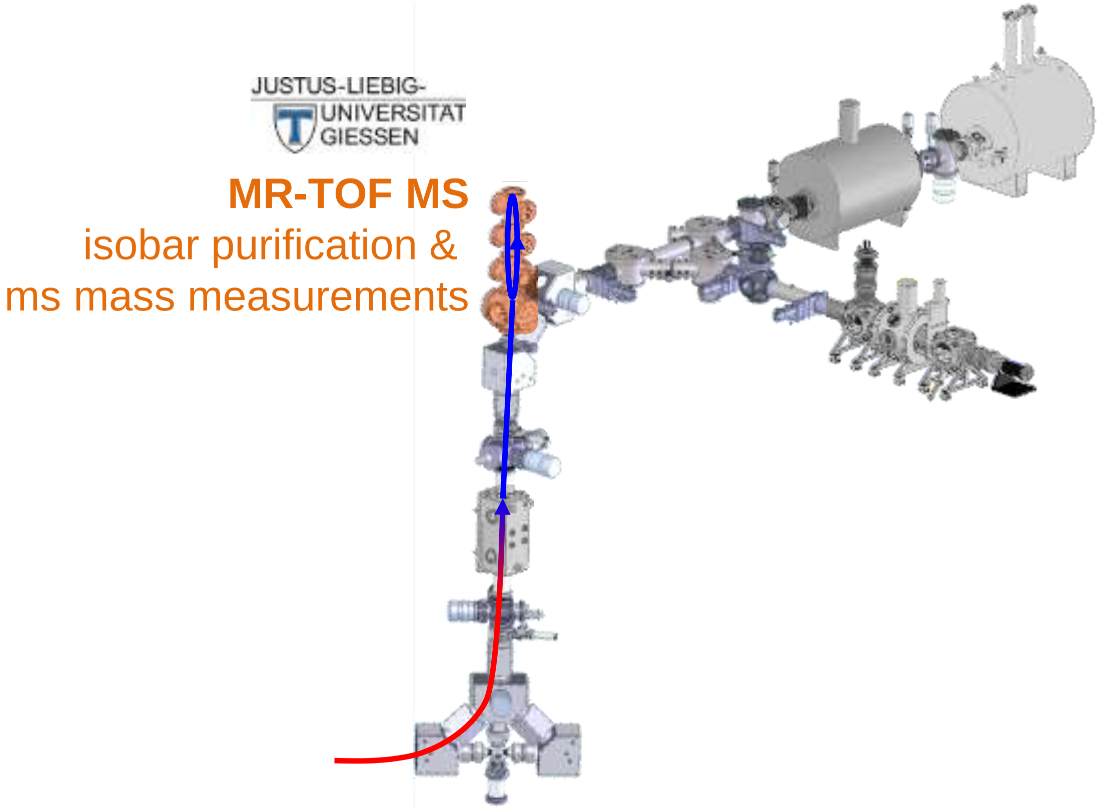
High resolving power is needed to discern the 100s of keV isomers with ground states.



D. Lascar, *et al.*, PRC, 96 (2017) 044323; C. Babcock, *et al.* PRC 97 (2018) 024312

Penning trap mass spectrometry offers (usually) higher precision than required.

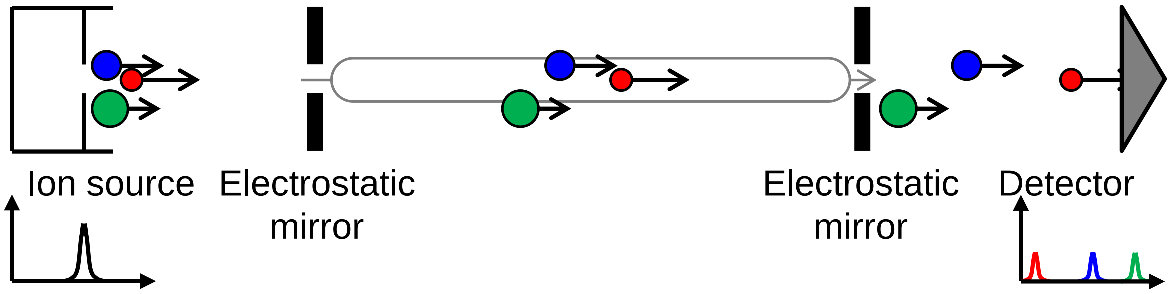
A less demanding technique is the MR-TOF MS.



J. Dilling *et al.*, NIMB **204** (2003) 492

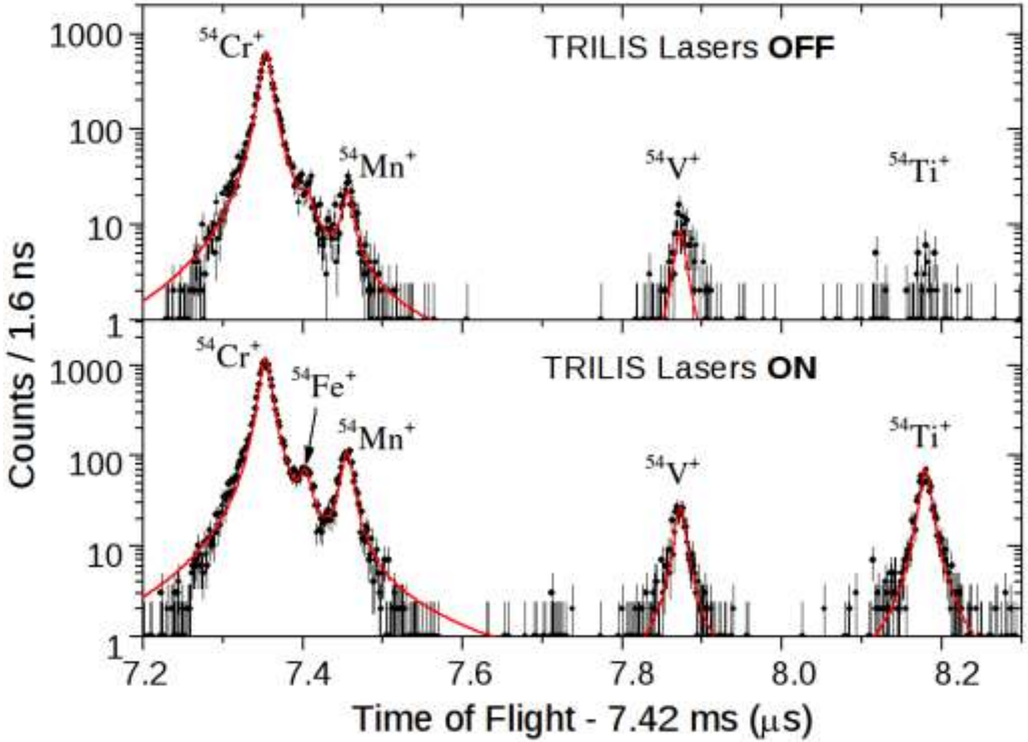
Multi-Reflection Time-Of-Flight Mass Spectrometers are based on simple kinematics.

$$TOF = \frac{L}{v} = \frac{L}{\sqrt{2E}} = \sqrt{\frac{m}{q}} \int \frac{dz}{\sqrt{2V(z)}}$$



Separation increases with flight path → longer path length OR multiple passes on same path

The TITAN MR-TOF was commissioned May 2017.

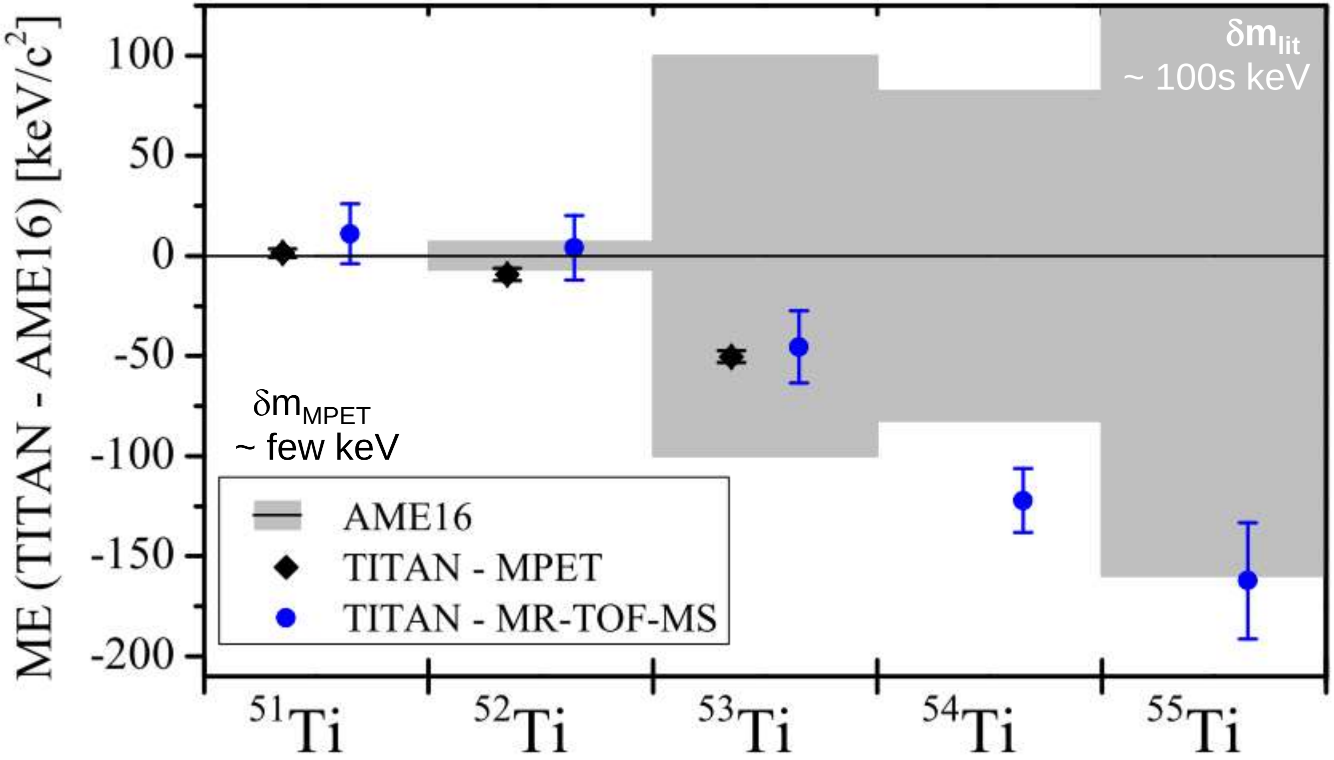


$$\frac{m}{q} = c(t - t_0)^2$$

c = device dependent
t_0 = constant offset
→ mass values can be recalibrated

E. Leistenschneider *et al.*, PRL 120 (2018) 062503; M.P. Reiter *et al.*, submitted to PRC

MR-TOF offers accuracy & requisite precision.

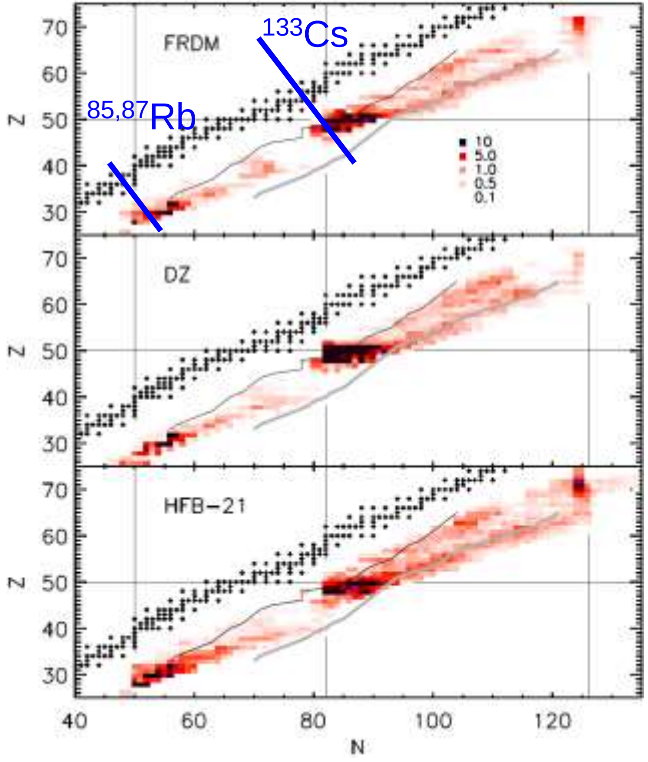


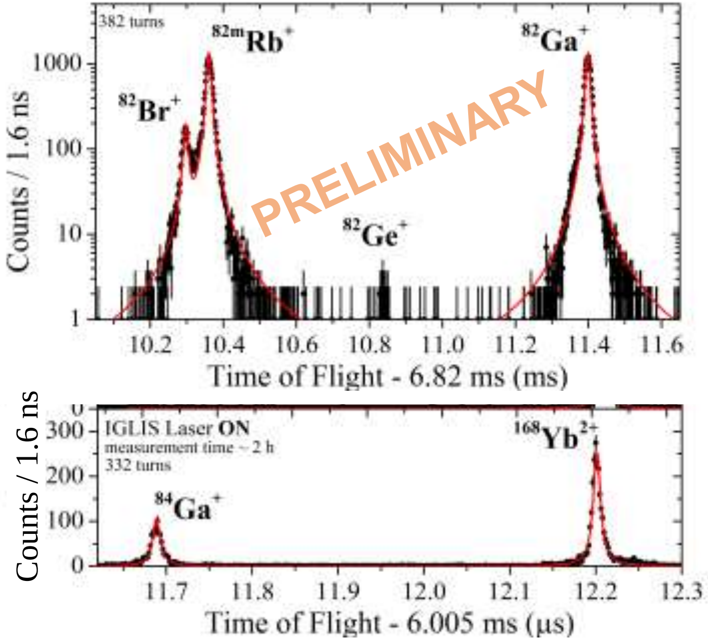
δ$m_{MR\text{-}TOF}$ <30 keV

E. Leistenschneider *et al.*, PRL 120 (2018) 062503; M.P. Reiter *et al.*, submitted to PRC

Back to the r-process …

Surface-ionized contaminants (Rb, Cs, lanthanides) pose a significant challenge.





R. Surman, *et* al. ICFN5 Proc. (2018), M.P. Reiter, H. Schatz, G. Martinez-Pinedo, *et al.*, in preparation

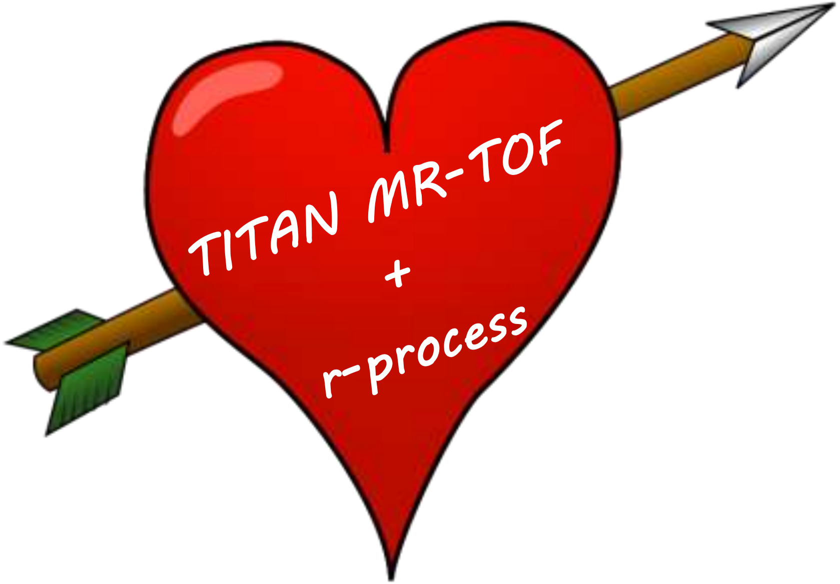
MR-TOF is well suited for nucleosynthesis studies.

Precisions of $\delta m/m \sim 10^{-7}$

Sensitivity ≥1 ion
→ low production yields

Fast (~3-10 ms)
→ short half-lives
→ short experiments

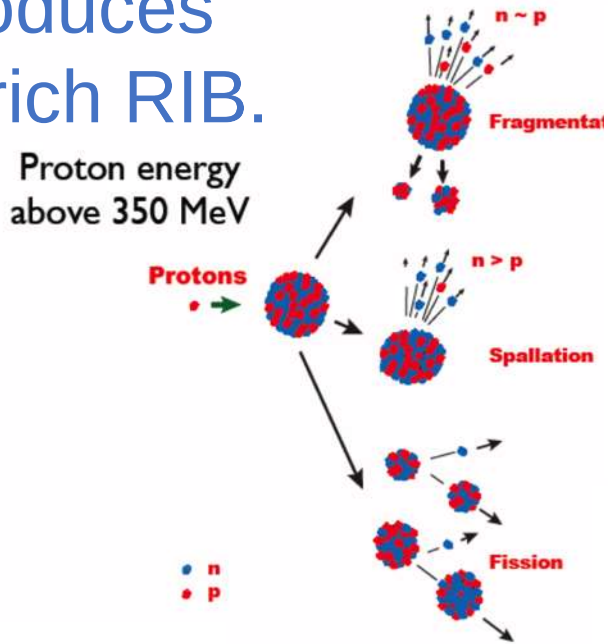
Broadband
→ simultaneous measurements
→ high contaminant rates



http://res.freestockphotos.biz/pictures/12/12889-illustration-of-a-red-heart-with-an-arrow-pv.png

Access to, quality of, & reach of beam are critical.

Fission produces cleaner n-rich RIB.



500MeV Protons on UCx

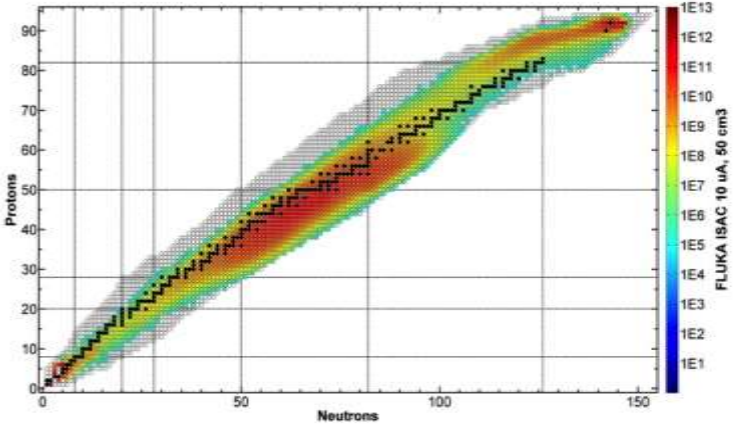
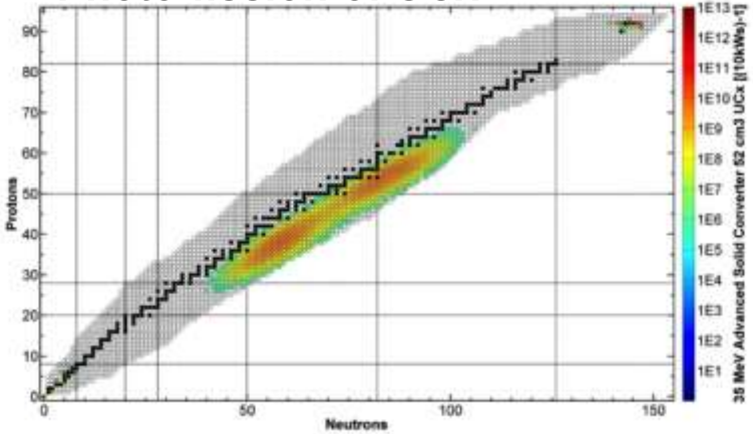


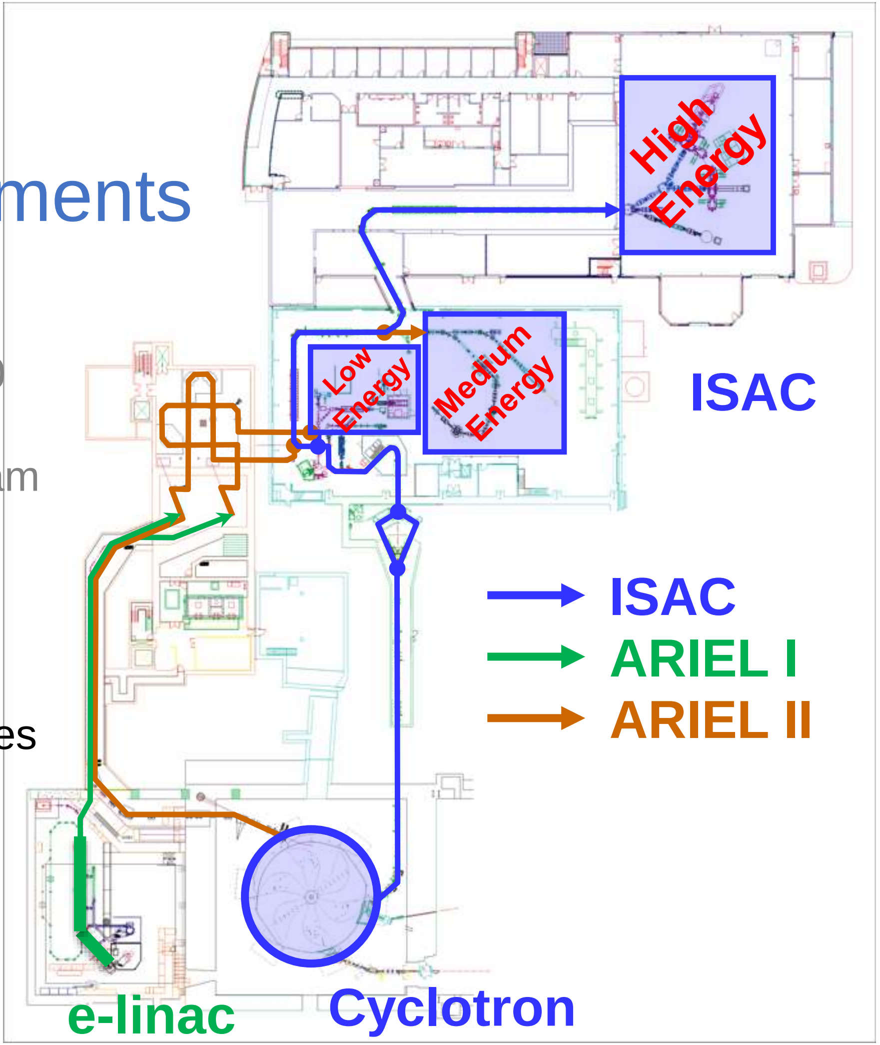
Photo-fission of UCx



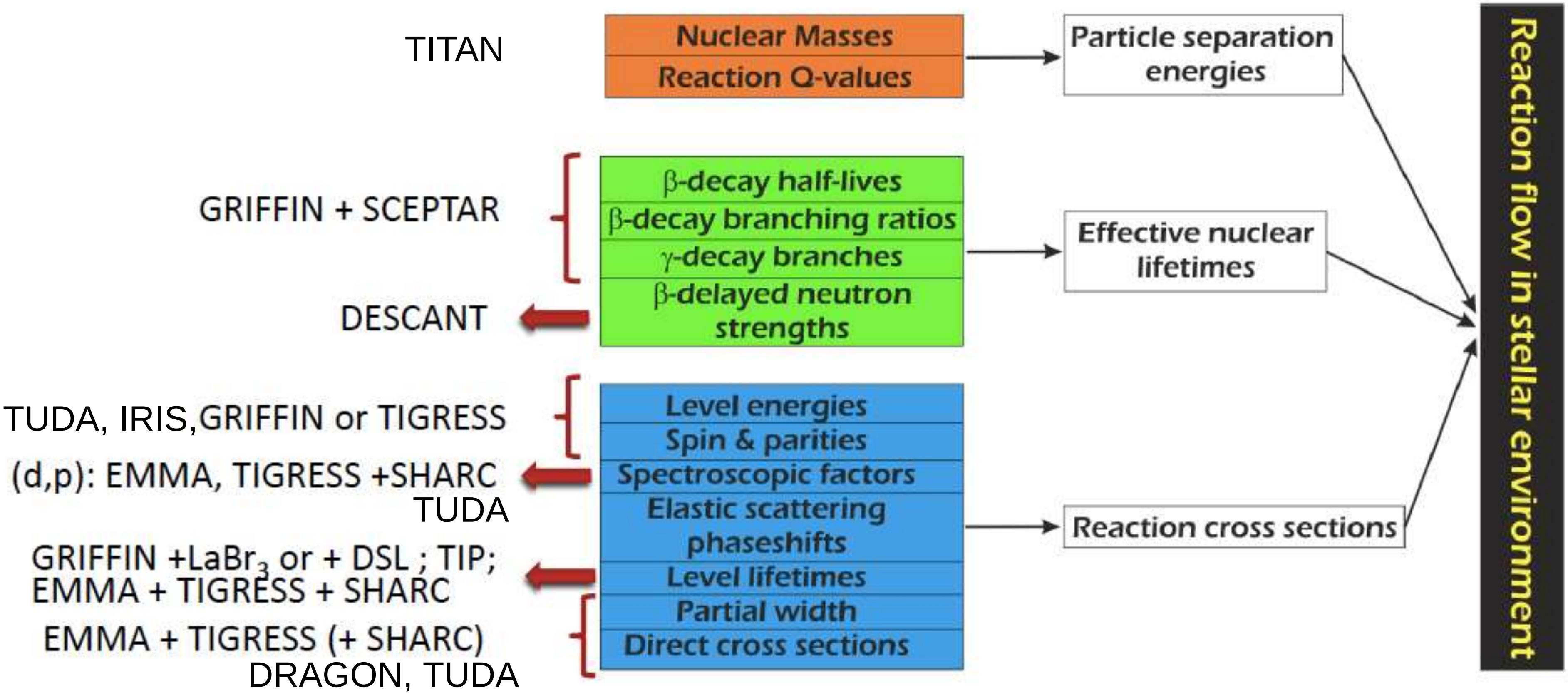
ISAC + ARIEL = 3 RIBs
= 3 experiments

- AETE: ≤100 kW, 35 MeV, electrons
- APTW / ITE / ITW: ≤50 kW, 500 MeV, ≤100 μA protons
- 2 low energy beams + 1 higher-energy beam
- > 9000 hours of RIB per year

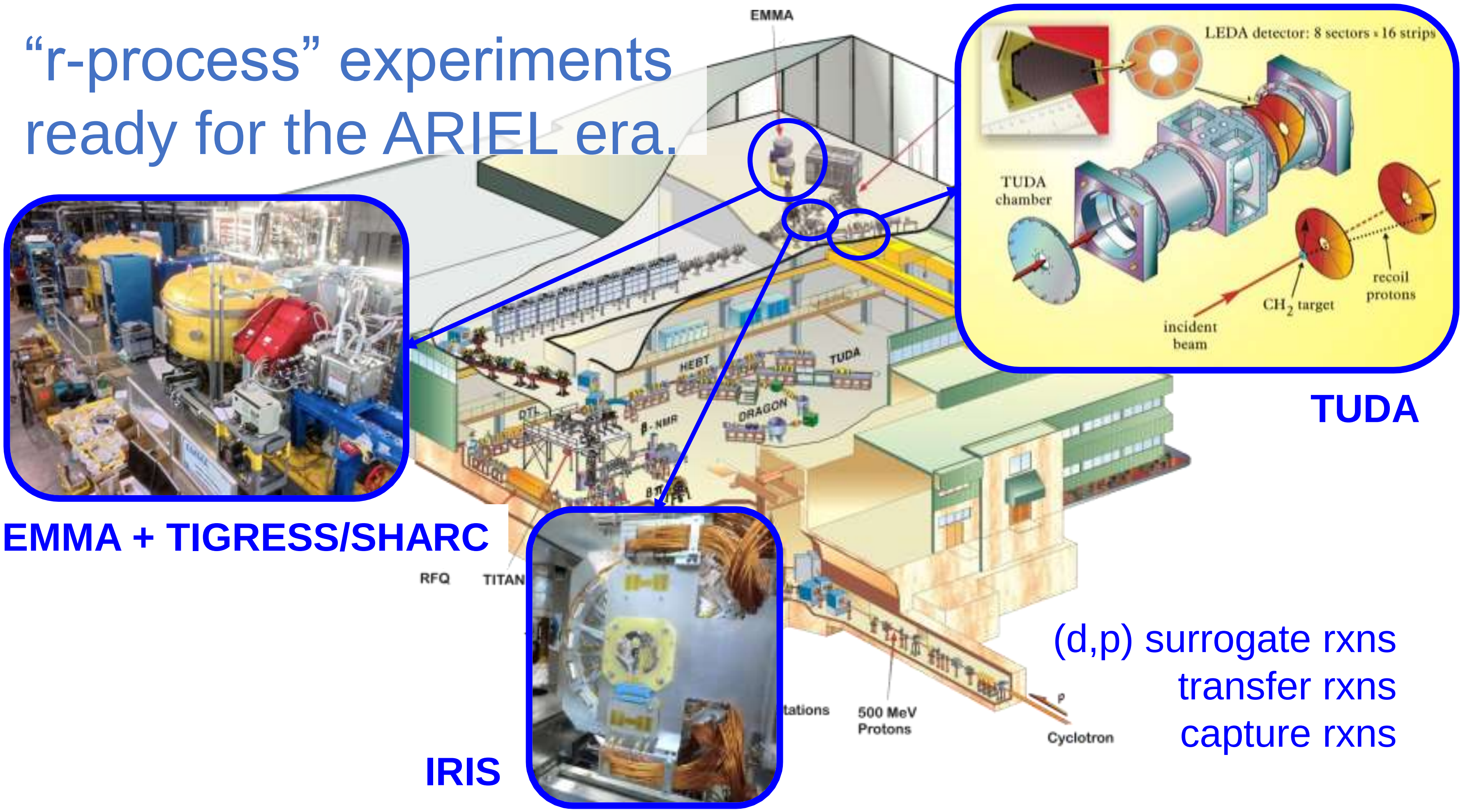
- science interwoven with technical milestones
- 2020 beam to βNMR
- 2021 photo-fission beam to experiments
- 2022 ISOL beam to experiments



ARIEL benefits a suite of “r-process” experiments.



"r-process" experiments ready for the ARIEL era.



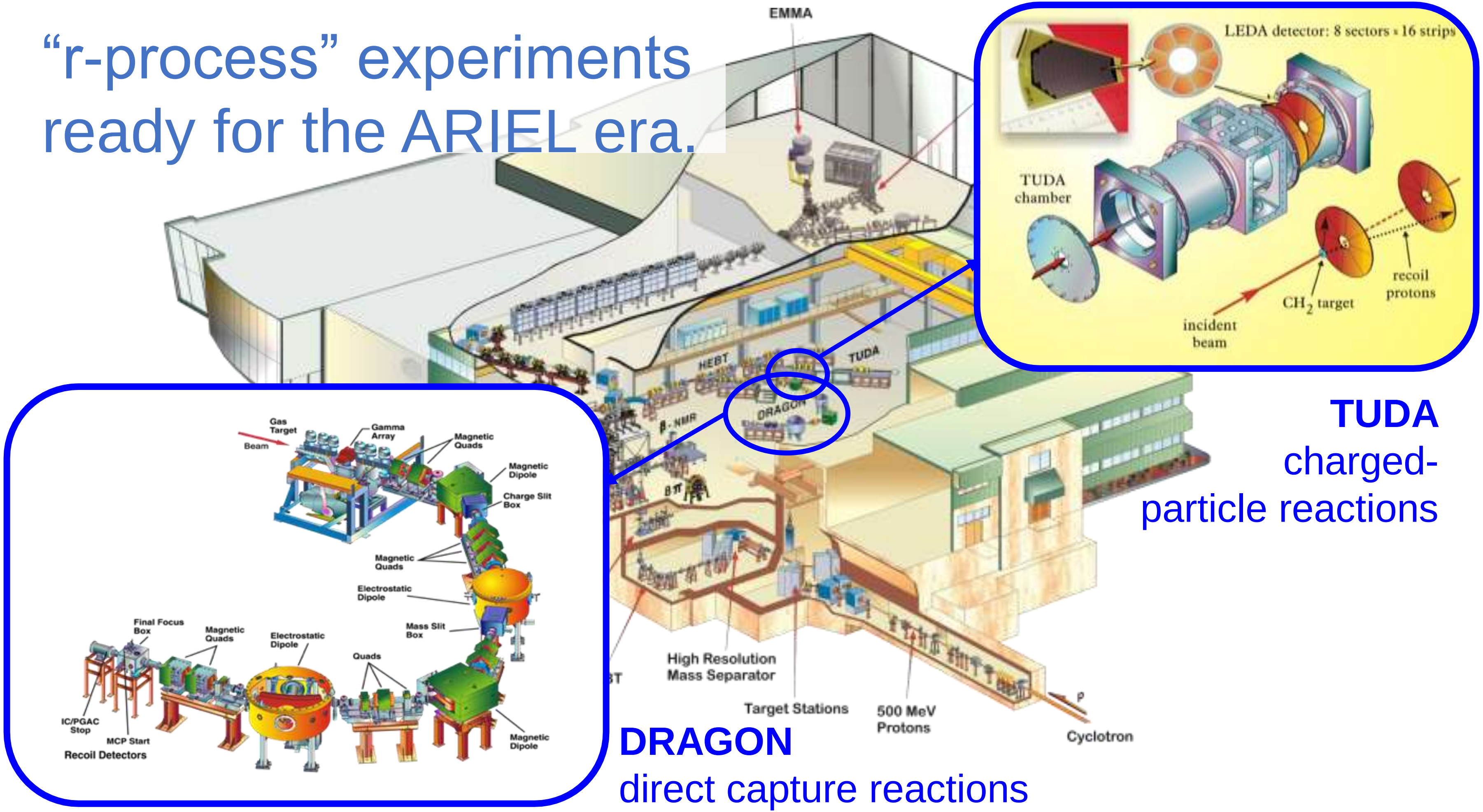
EMMA + TIGRESS/SHARC

TUDA

IRIS

(d,p) surrogate rxns
transfer rxns
capture rxns

“r-process” experiments ready for the ARIEL era.



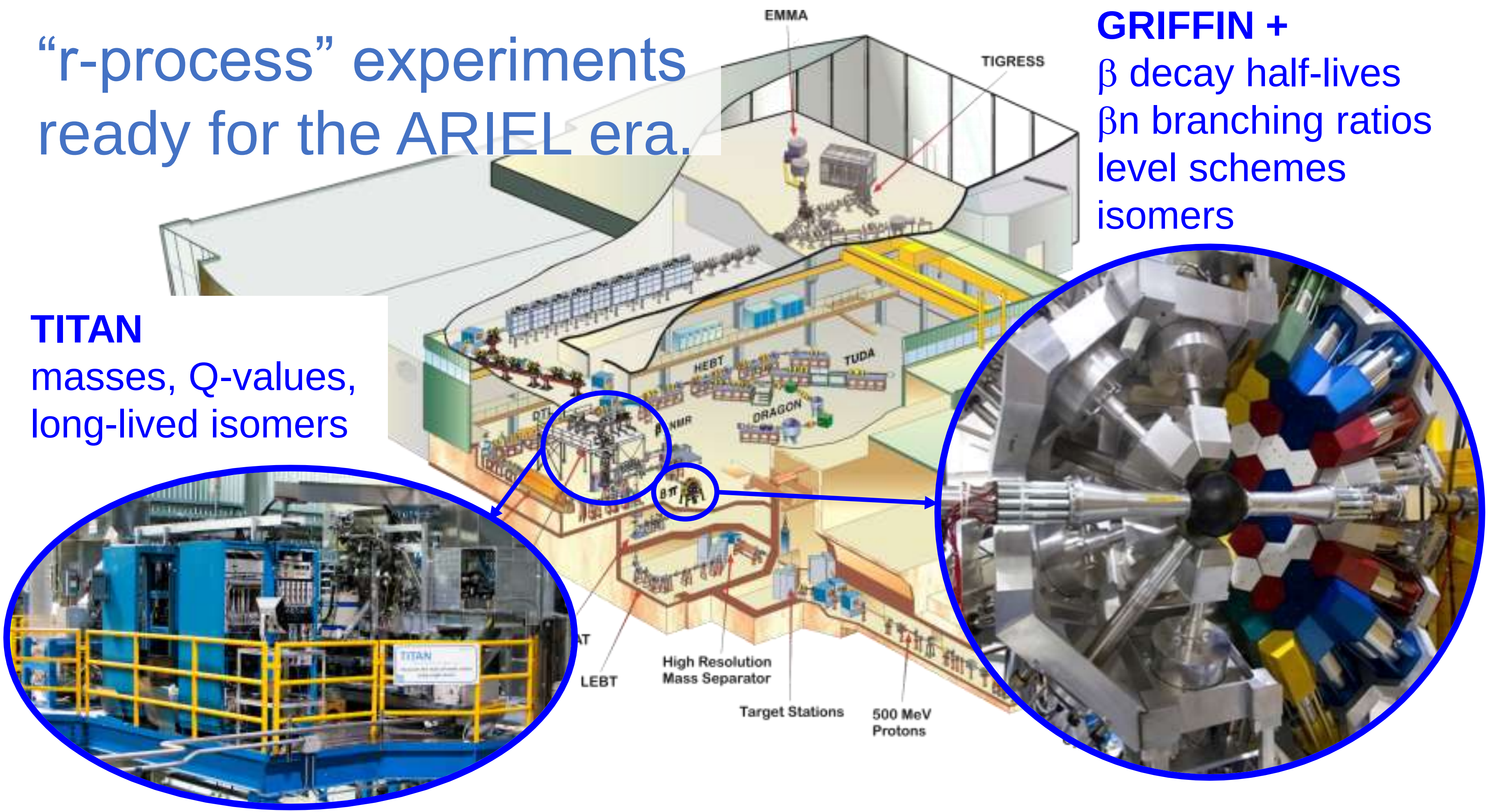
TUDA
charged-particle reactions

DRAGON
direct capture reactions

"r-process" experiments ready for the ARIEL era.

GRIFFIN +
β decay half-lives
βn branching ratios
level schemes
isomers

TITAN
masses, Q-values,
long-lived isomers



TITAN's mass measurements

- Precision (typical $\delta m \leq$ 10s keV)
- Single-ion sensitivity (MR-TOF)
- Broadband for contaminants (MR-TOF)
- High resolving powers (Penning trap + highly charged ions)

approach the r-process,

- $^{\sim 100}$Rb/Sr
- $^{<130}$Cd/In g.s. and isomers
- $^{\sim 85}$Ga

& will have better access with ARIEL.

- 2 spallation + 1 fission RIB
- >9000 RIB hours/y
- Increasing use of MR-TOF

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