TRIUMF

Nuclear Physics @ TRIUMF

Overview, recent science highlights and ARIEL

Jens Dilling

TRIUMF and University of British Columbia

2019-12-05

Discovery, accelerated

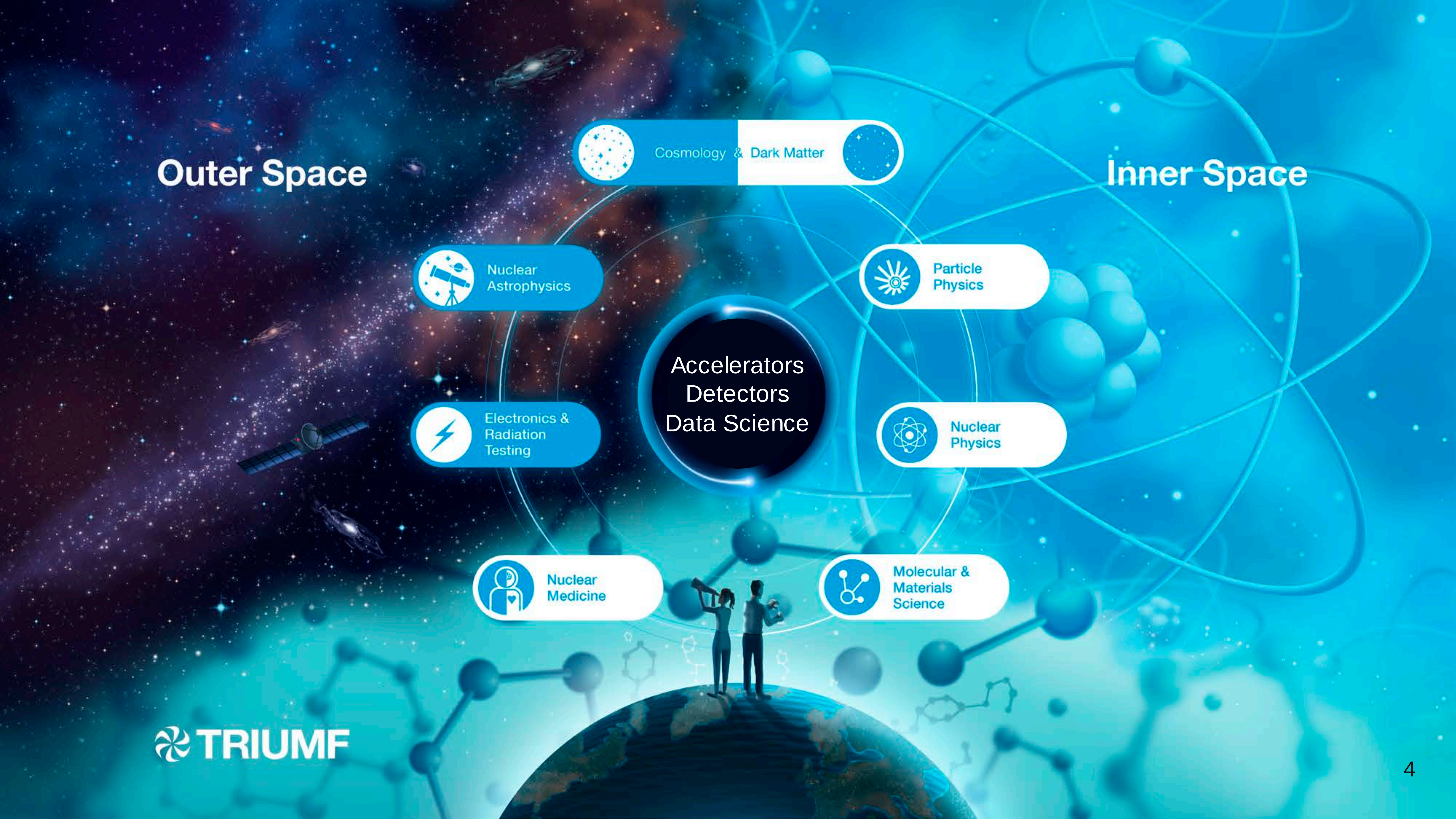
TRIUMF is one of Canada's major investments in large-scale research infrastructure

Founded in 1968, the laboratory is centered around the world’s largest cyclotron and its secondary beams.

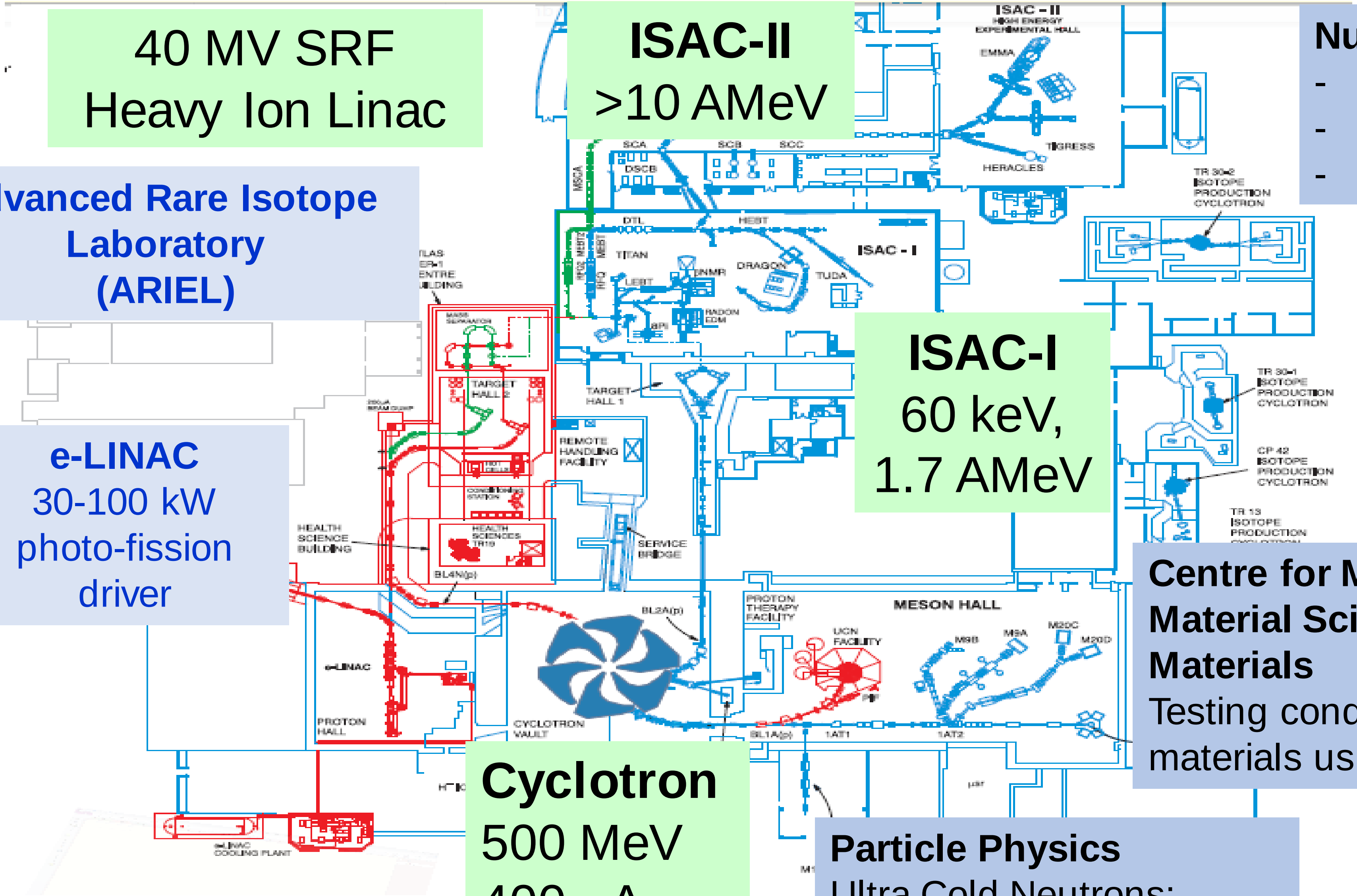
Our Mission is to serve as Canada’s particle accelerator centre:

To advance isotope science and technology, both fundamental and applied. We collaborate across communities and disciplines.

To operate major user infrastructure and participate in research and innovation together with our partners.


Outer Space
Inner Space
Cosmology & Dark Matter
Nuclear Astrophysics
Particle Physics
Electronics & Radiation Testing
Accelerators
Detectors
Data Science
Nuclear Physics
Nuclear Medicine
Molecular & Materials Science
TRIUMF

TRIUMF’s accelerator complex



40 MV SRF
Heavy Ion Linac

ISAC-II
>10 AMeV

Nuclear Physics
- Nuclear Structure
- Nuclear Astrophysics
- Fund. Symmetries

Advanced Rare Isotope Laboratory (ARIEL)

ISAC-I
60 keV,
1.7 AMeV

e-LINAC
30-100 kW
photo-fission driver

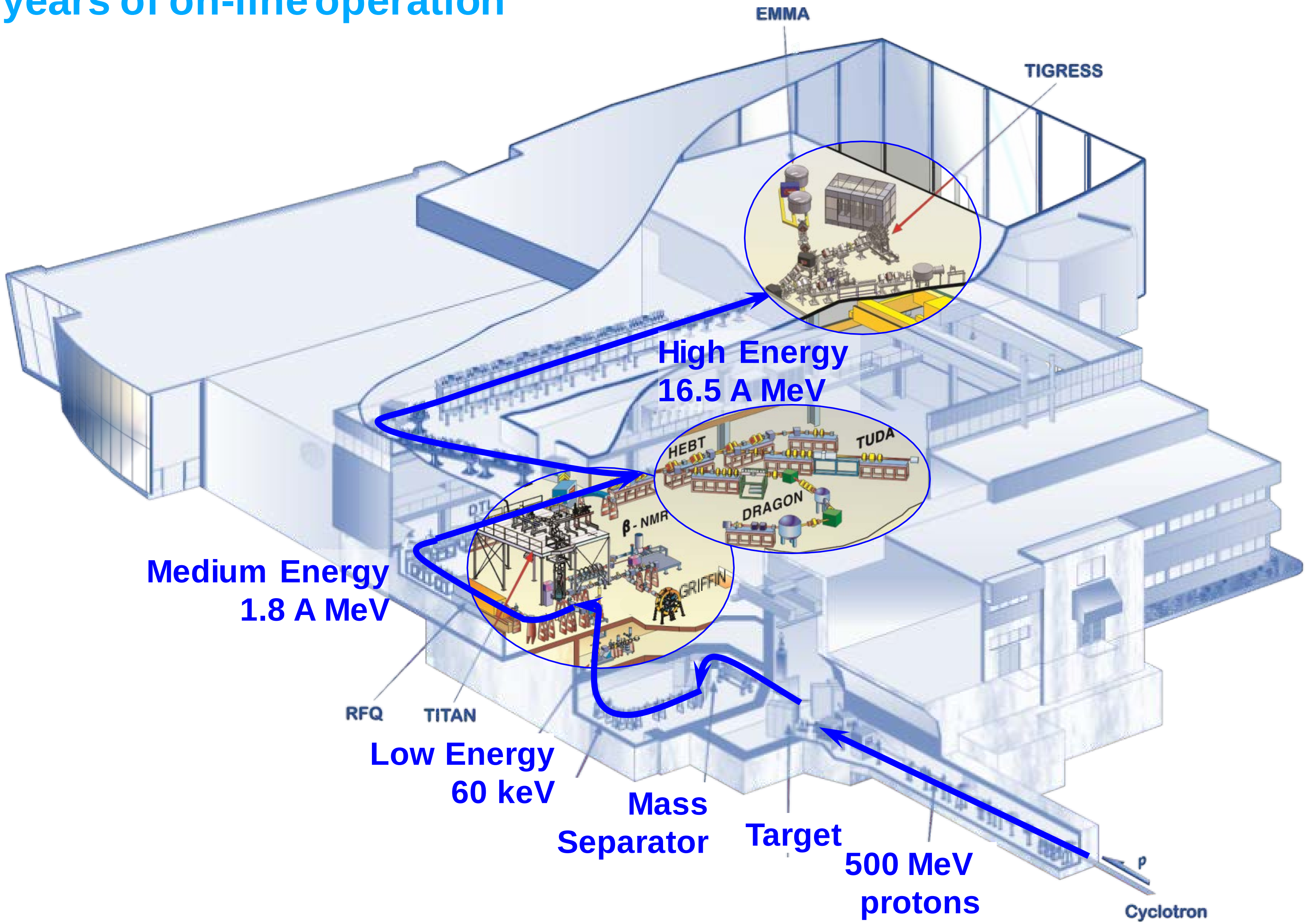
Centre for Molecular and Material Science & Quantum Materials
Testing condensed matter and materials using radioactive probes

Cyclotron
500 MeV
400 μA

Particle Physics
Ultra Cold Neutrons: towards a nEDM

ISAC-TRIUMF ISOL facility for rare isotope beams

ISAC20- 20 years of on-line operation



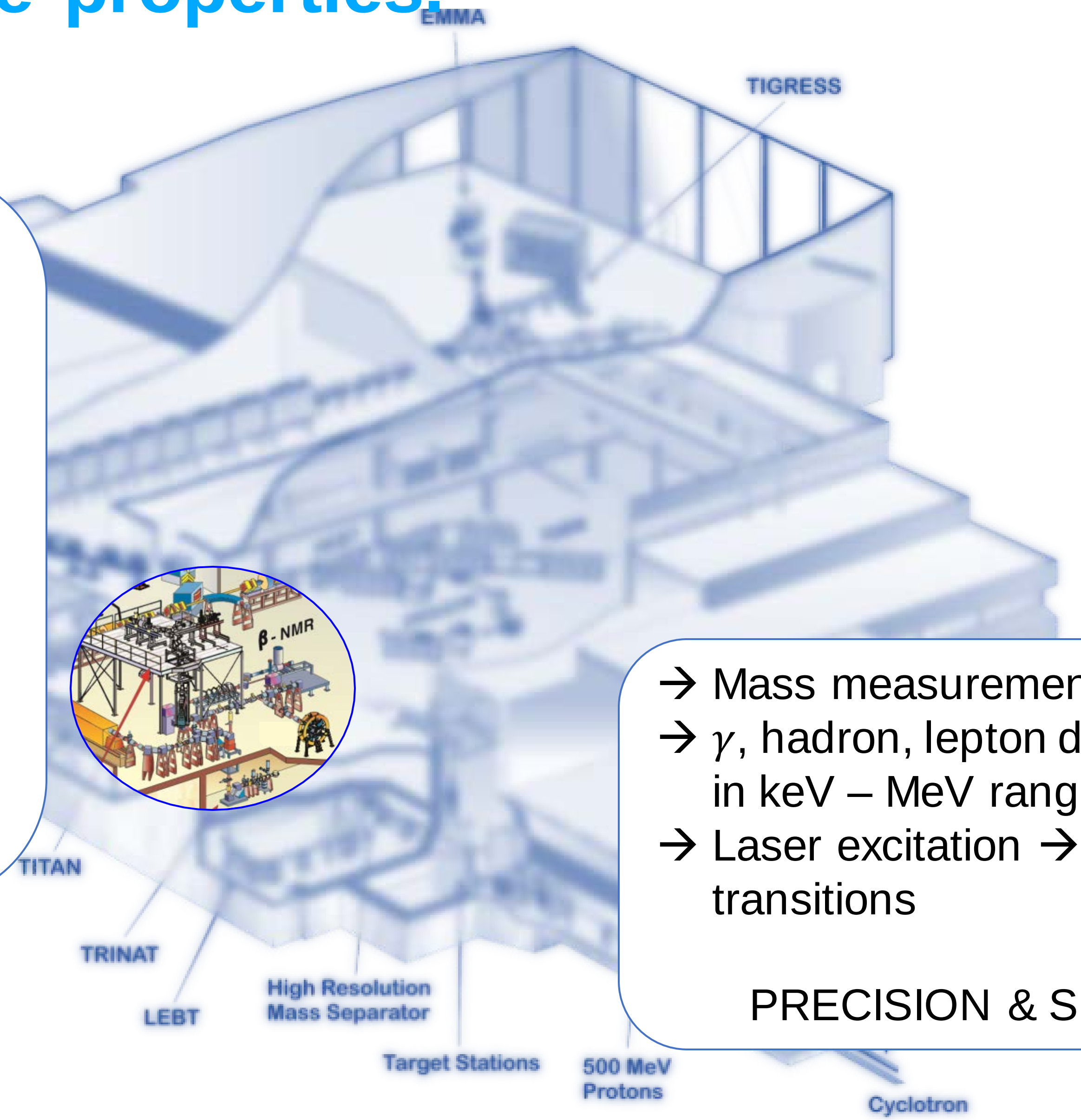
Low-energy RIB experiments (≤60 keV) access ground-state properties.

- Slow beams travelling for few μs per meter

→ Stop after nanometers in solids

→ Decelerate to a stop relatively easily with modest DC fields or using gas RFQ

- **Stopped Beams** that can be manipulated, rapped, re-ionized, neutralized, polarized, allowed to decay



→ Mass measurements

→ γ, hadron, lepton decay products in keV – MeV range

→ Laser excitation → atomic transitions

PRECISION & SENSITIVITY

Medium-energy RIB experiments:
tuned for astrophysics (0.15-1.8 A MeV)

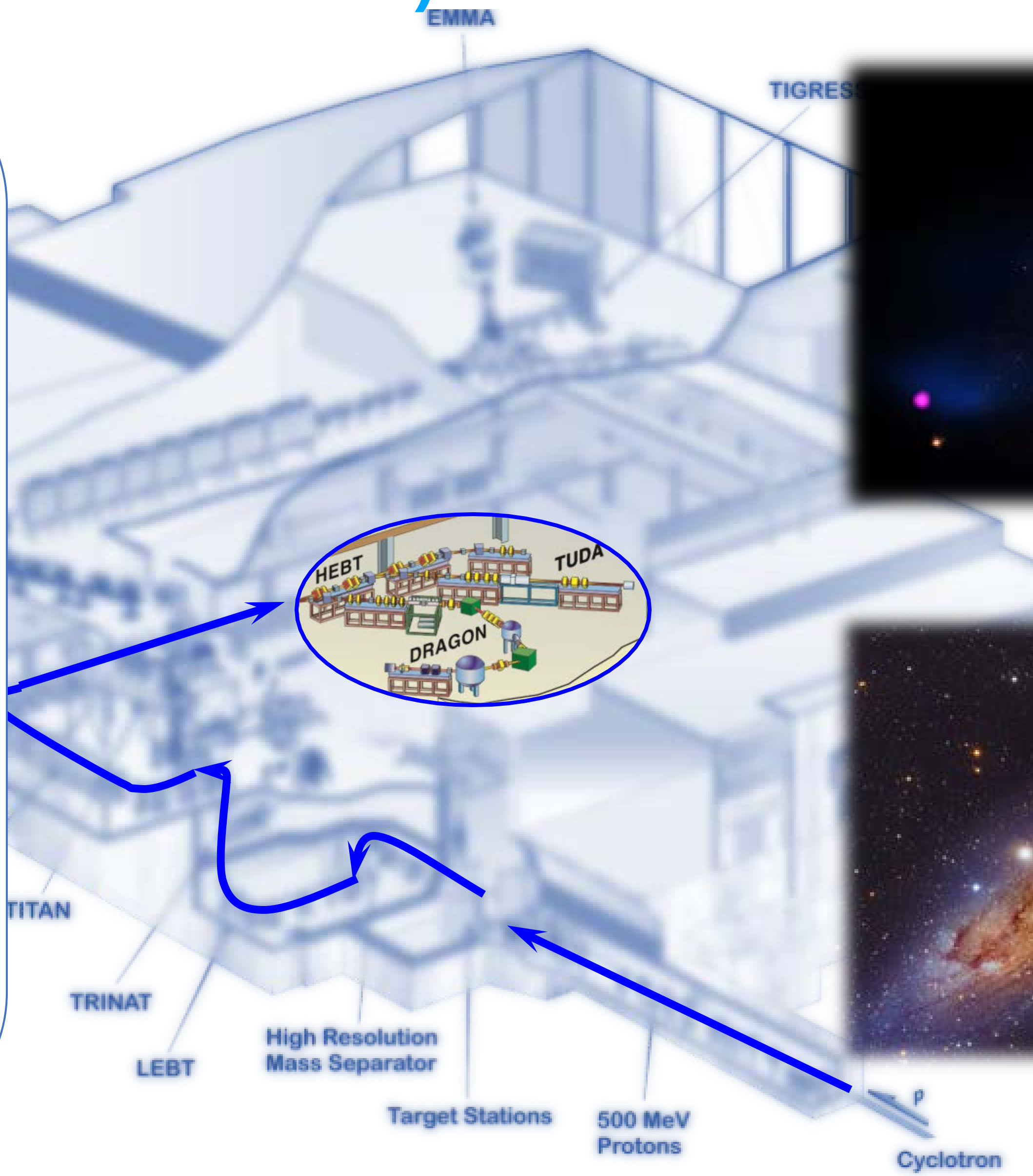
v=0.01*c* beams

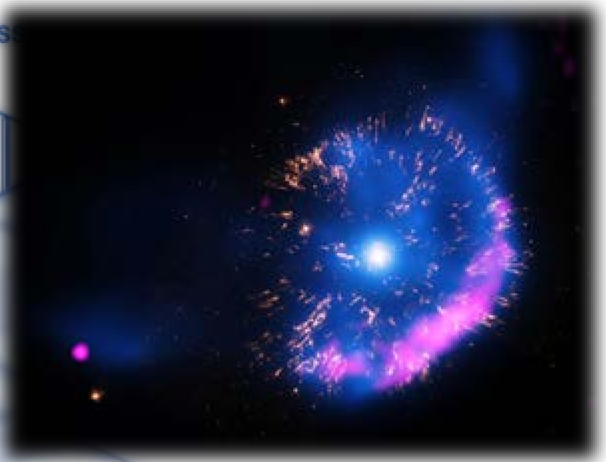
→ Sub Coulomb Barrier fusion reactions
Compound Nucleus and Direct mechanisms
Nuclear Resonances

Tuned to stellar energies for range of scenarios, from AGB stars to X-ray bursters to supernovae
+ tests of *ab initio* via scattering states

→ Largest beam intensities needed

PIONEERING DIRECT and INDIRECT MEASUREMENTS



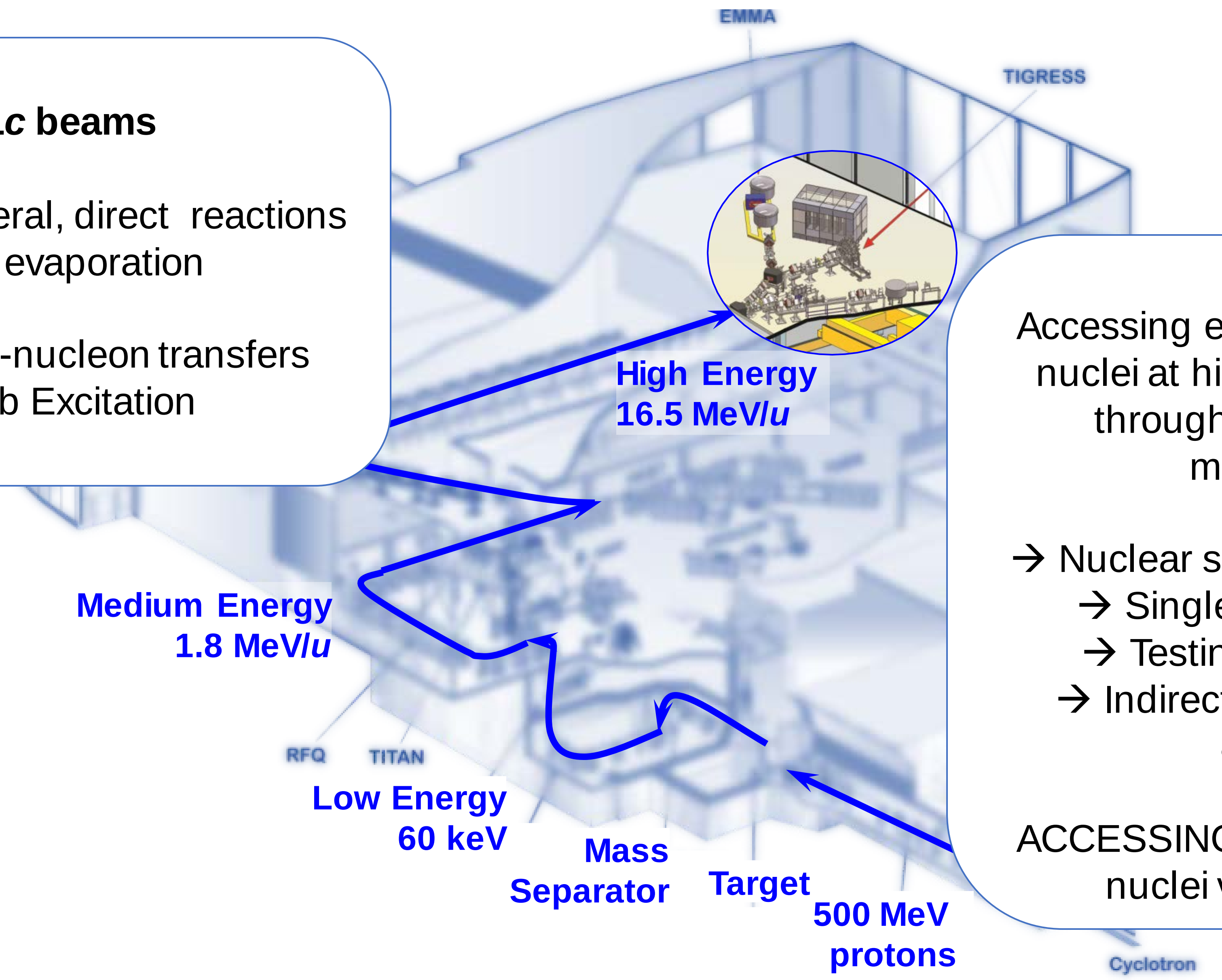


High-energy RIB Experiments (10-16.5 A MeV)

v=0.1*c* beams

→ Highly peripheral, direct reactions
+ fusion evaporation

Single or multi-nucleon transfers
Coulomb Excitation



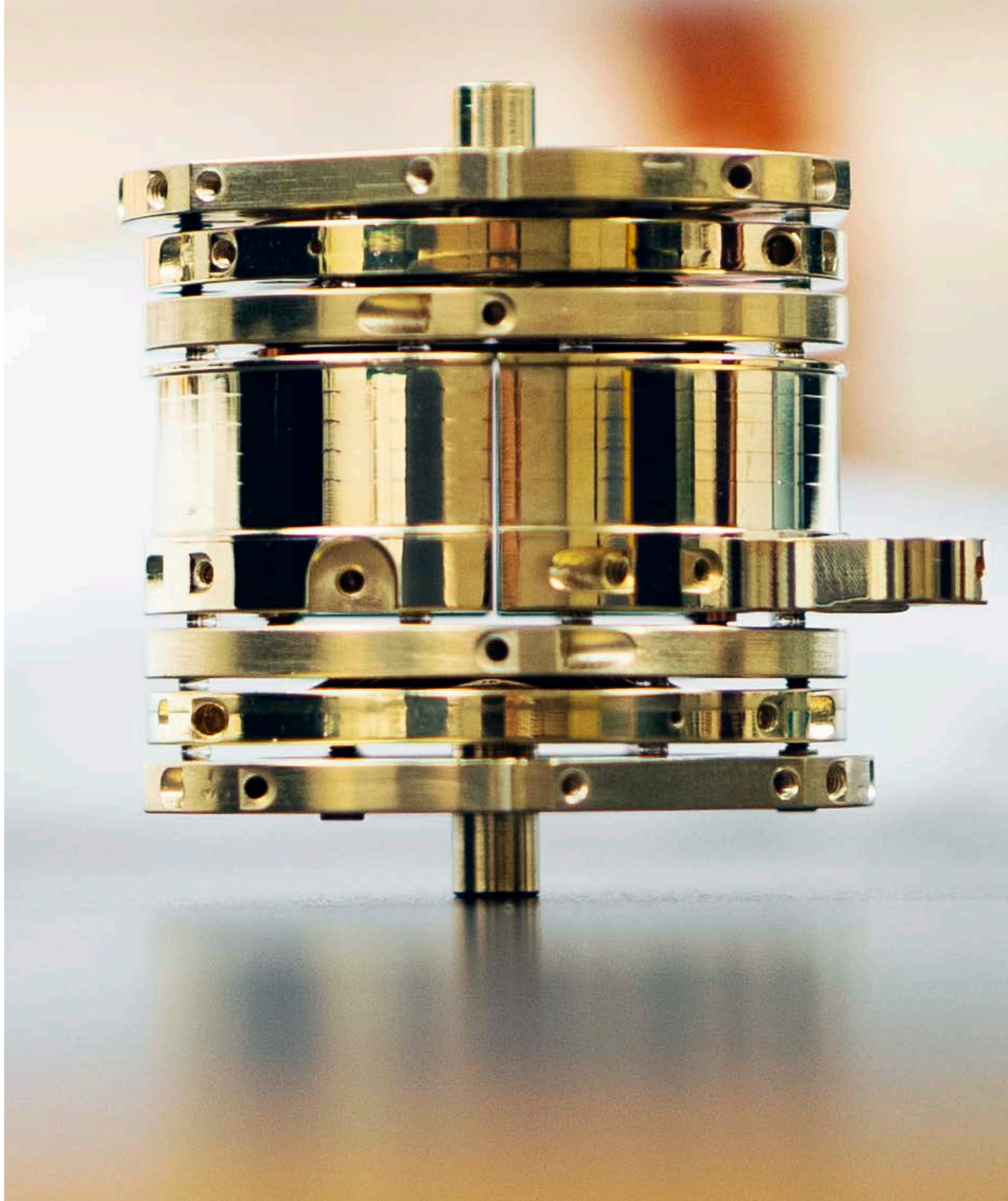
Accessing excited states of exotic nuclei at higher energies, spins through specific reaction mechanisms.

→ Nuclear shapes & deformations
→ Single particle structure
→ Testing nuclear models
→ Indirect measurements for astrophysics

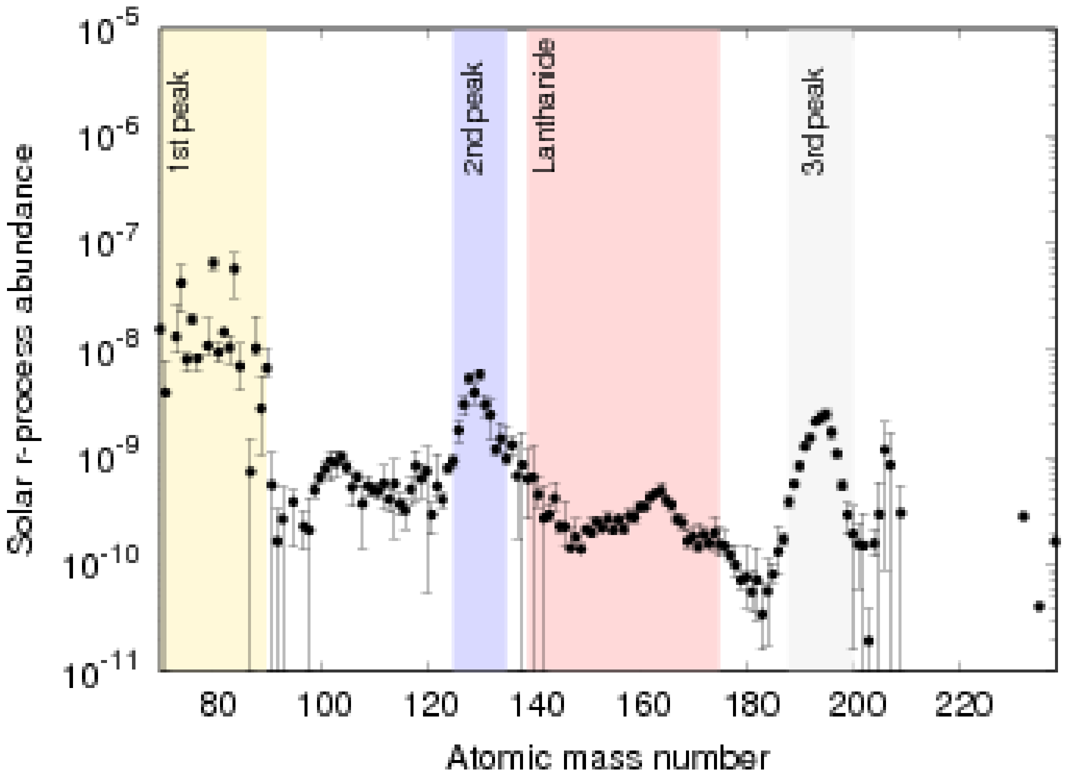
ACCESSING properties of exotic nuclei via *REACTIONS*

Recent Highlights

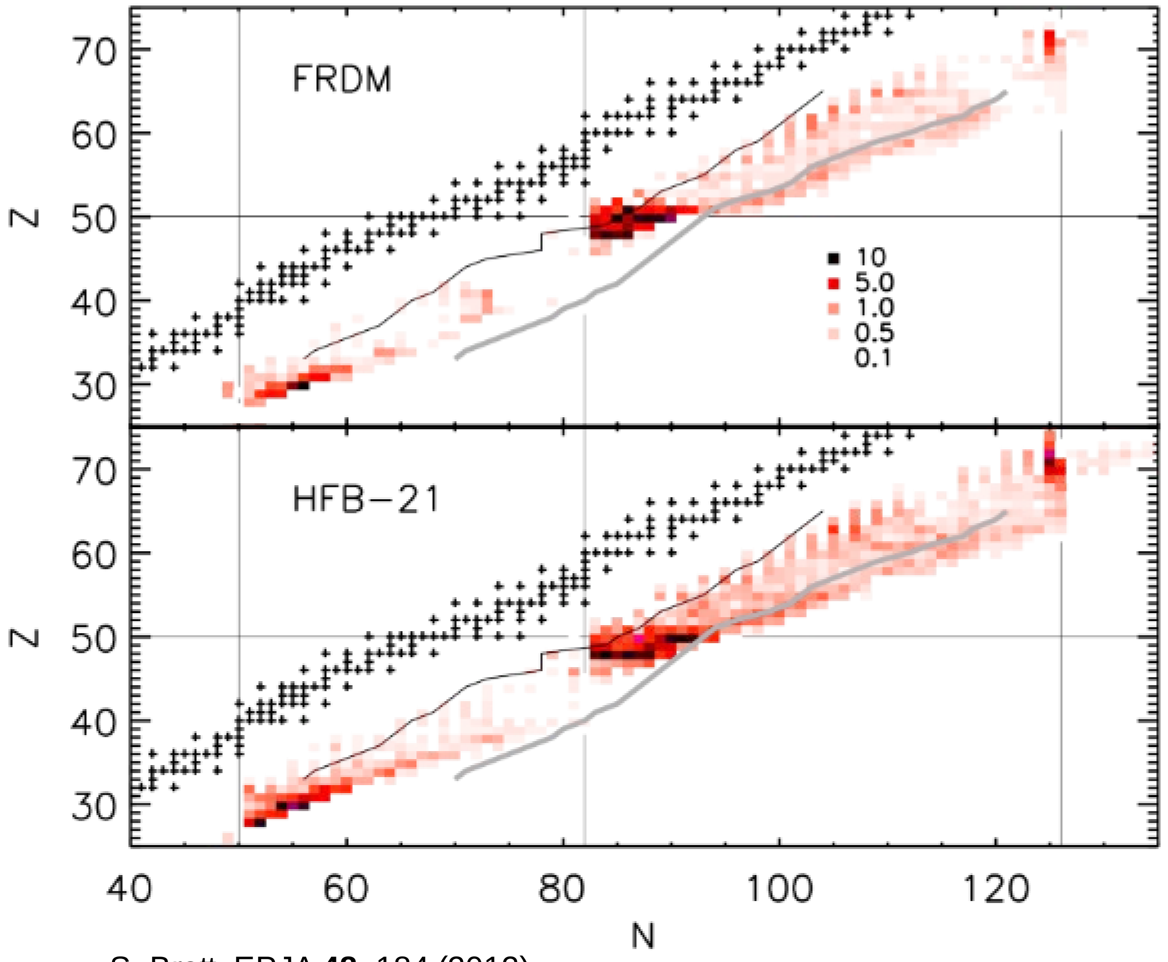
- TITAN mass measurements



Importance of Neutron-Rich Indium Masses for *r*-Process

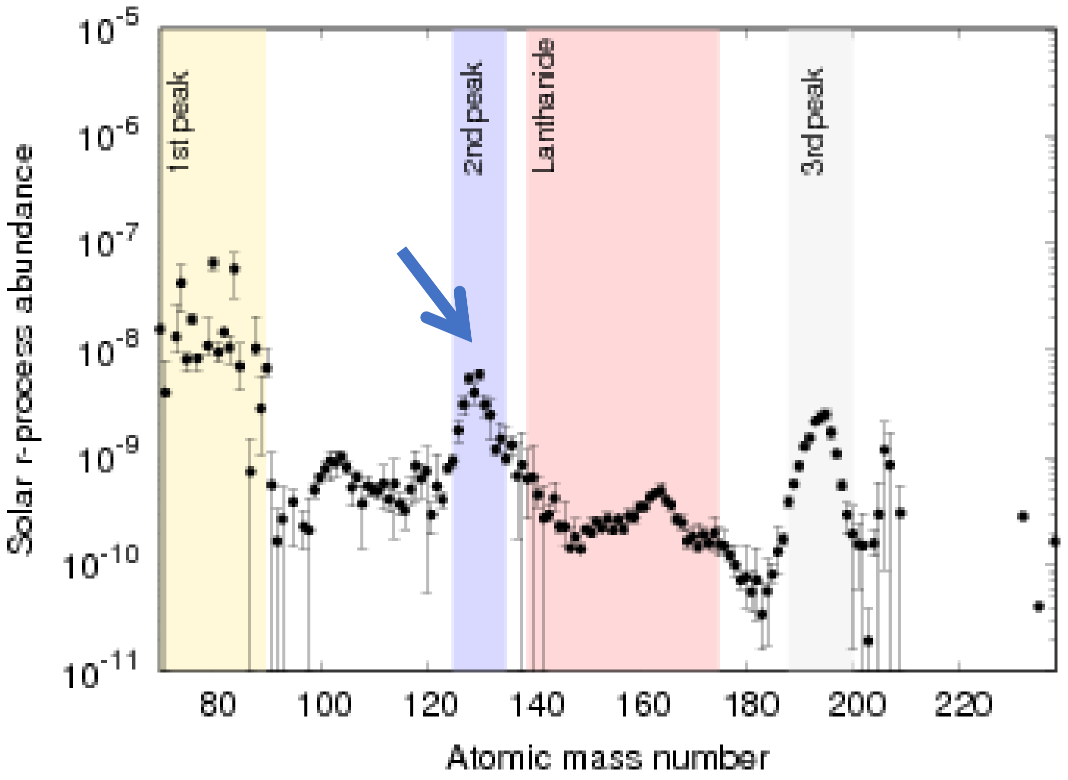


r-Process Mass Sensitivity



S. Brett, EPJA **48**, 184 (2012)

Importance of Neutron-Rich Indium Masses for *r*-Process



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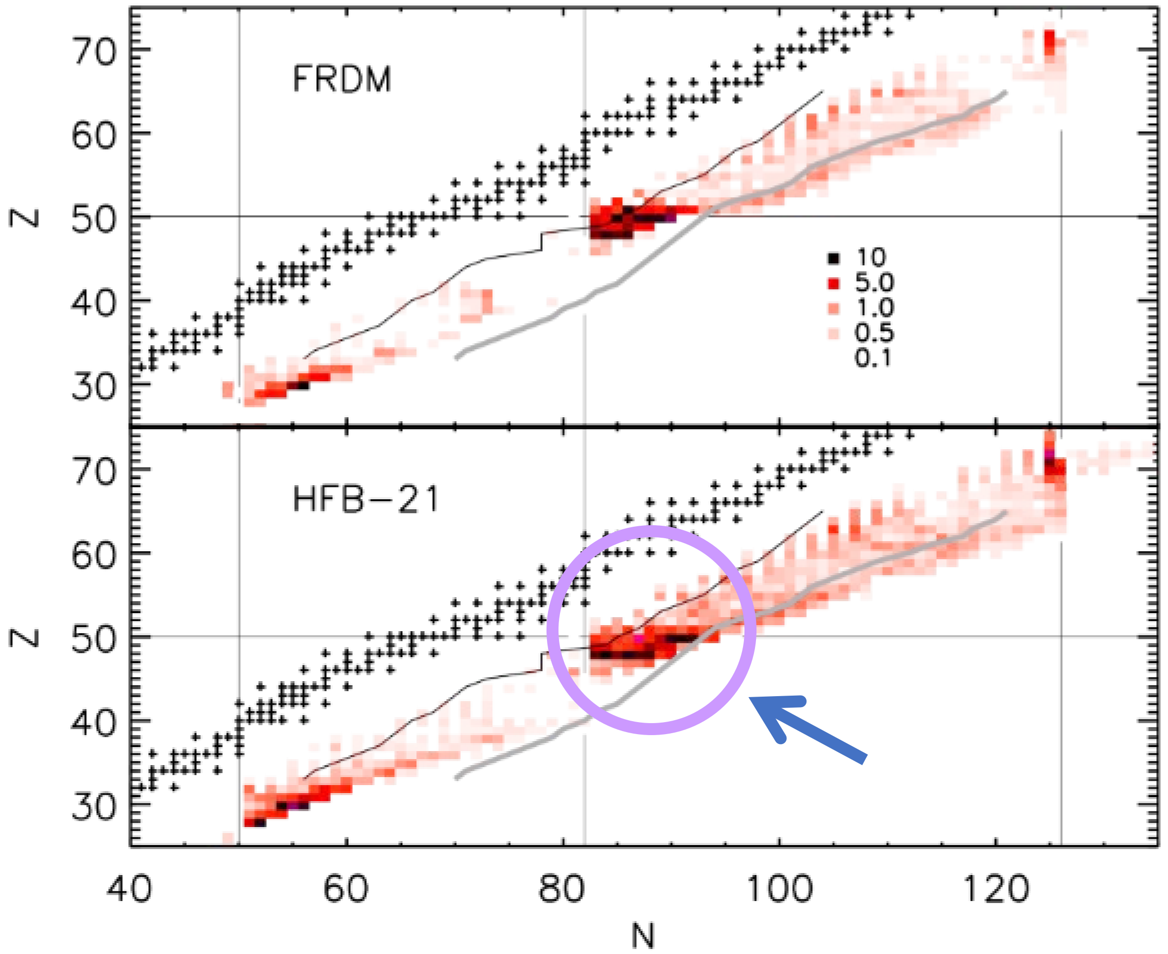

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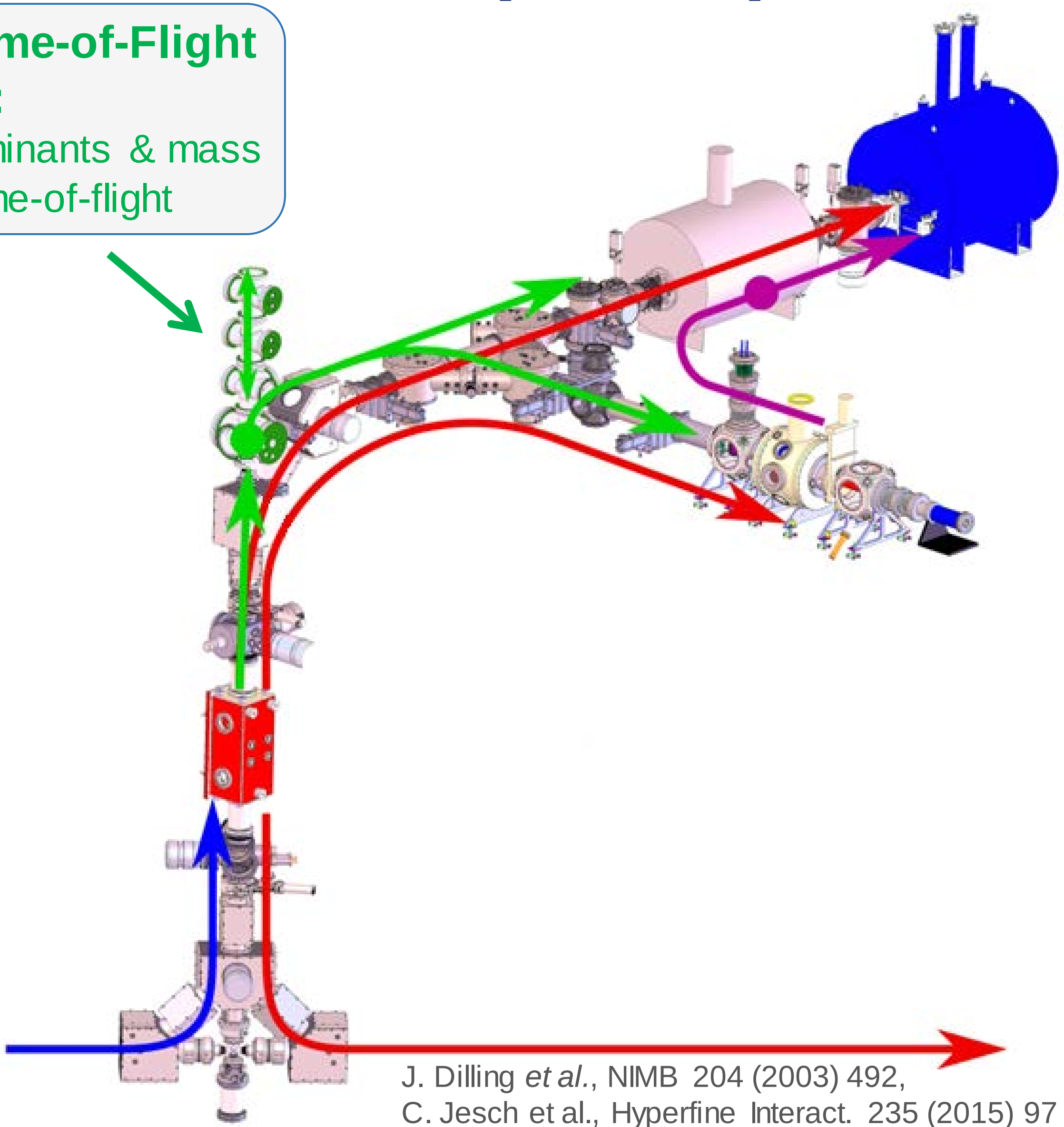
TRIUMF's Ion Trap for Atomic and Nuclear Science (TITAN)

Multiple-Reflection Time-of-Flight (MR-TOF):
removal of isobaric contaminants & mass measurements via time-of-flight

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN



Beam from ISAC

J. Dilling *et al.*, NIMB 204 (2003) 492,
C. Jesch et al., Hyperfine Interact. 235 (2015) 97

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SFU
UNIVERSITY OF CALGARY
McGill
COLORADO SCHOOL OF MINES
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UBC
Westfälische Wilhelms-Universität Münster
university of groningen
kvi - center for advanced radiation technology
cnrs
GANIL spiral2

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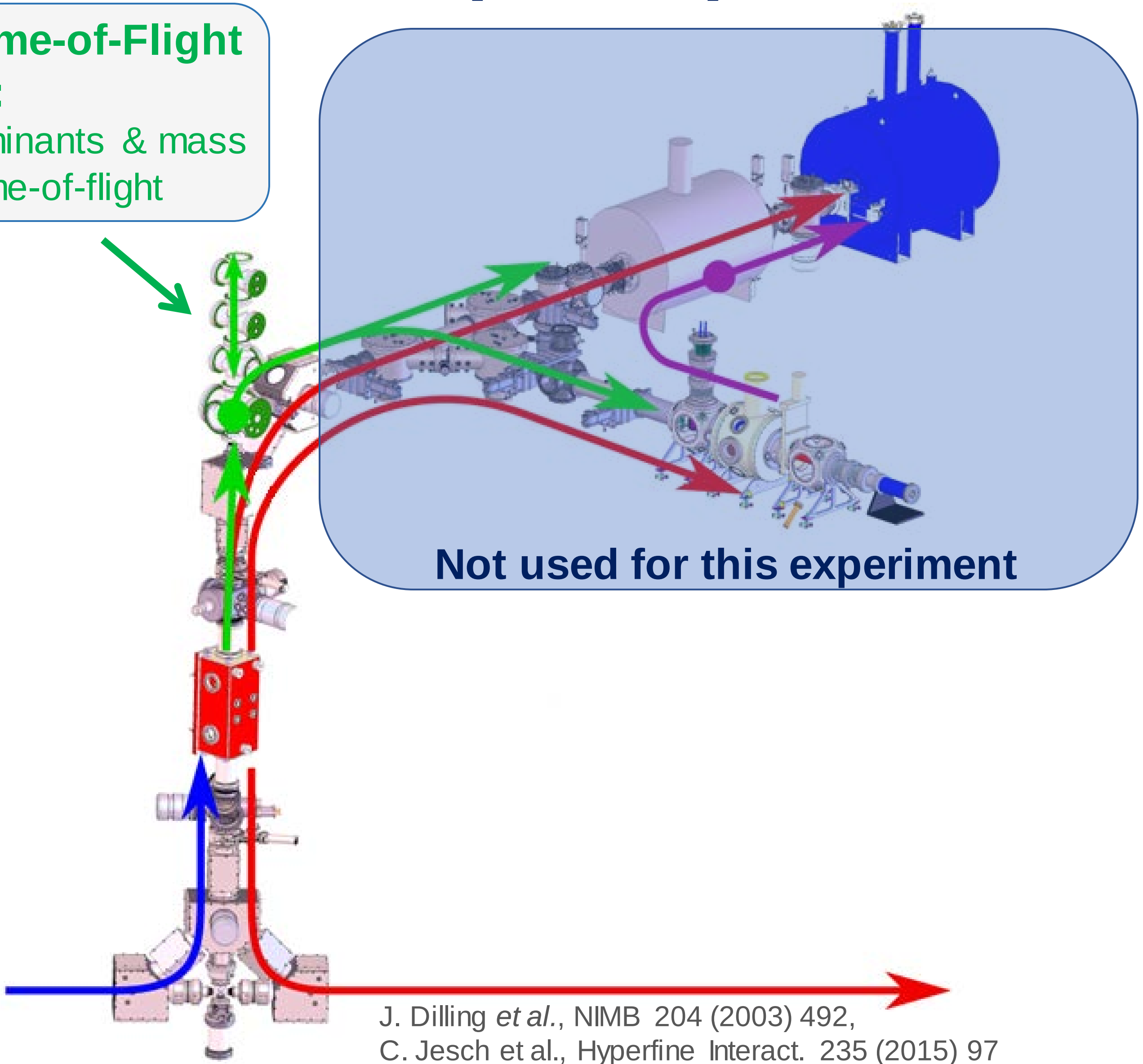

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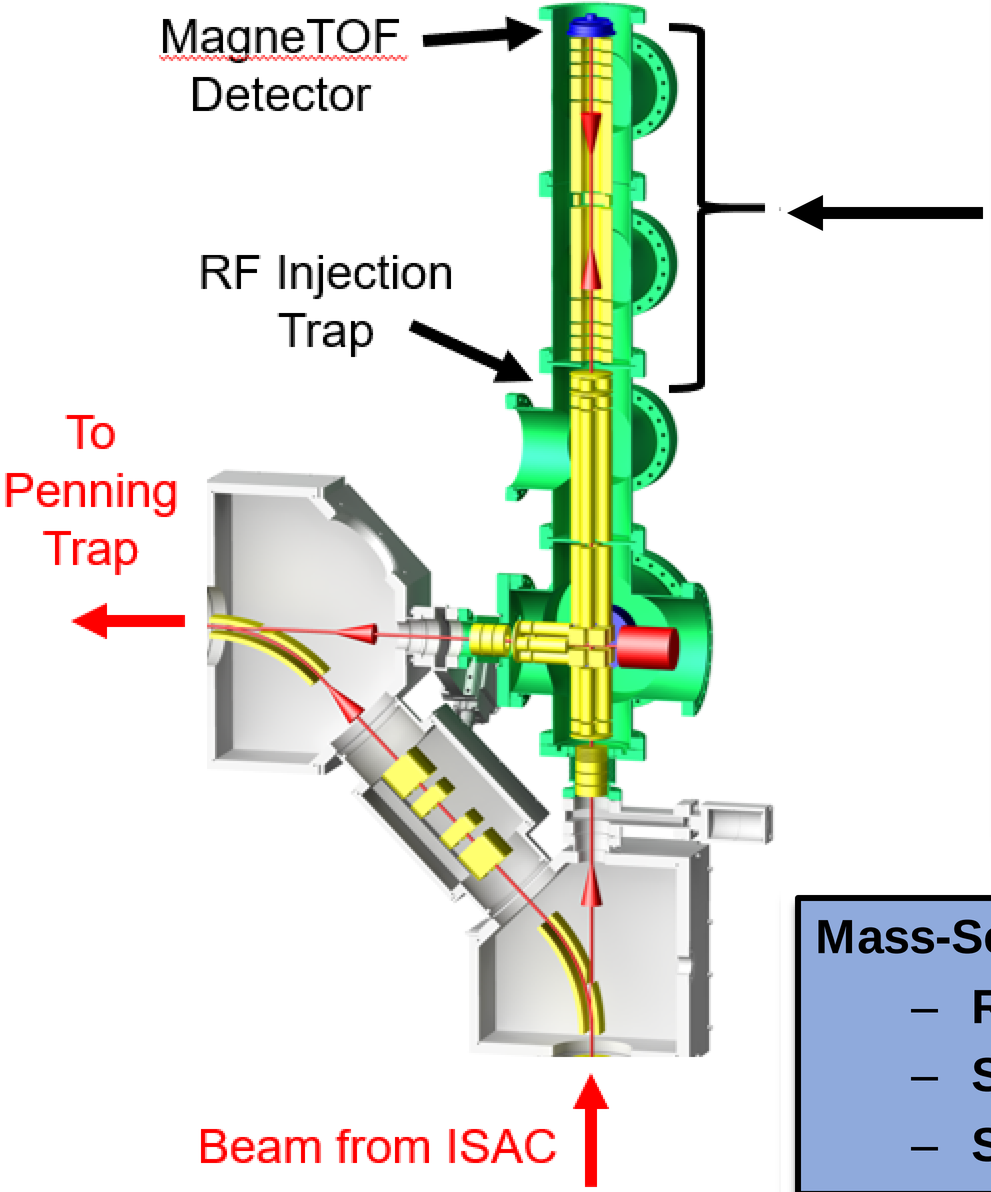
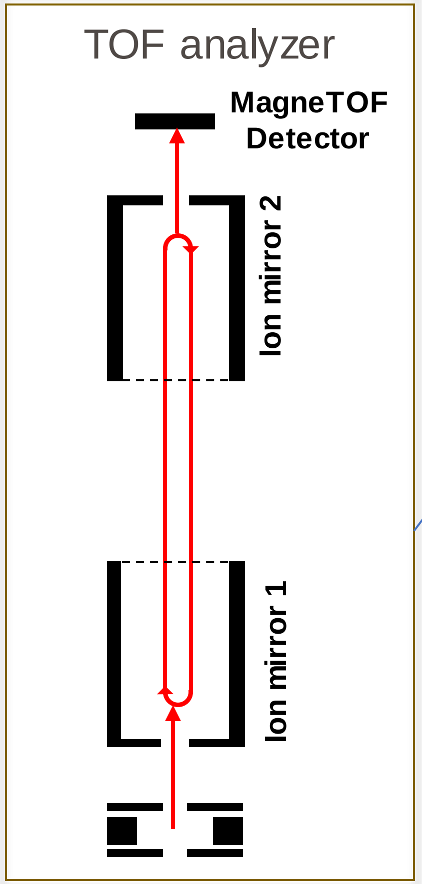
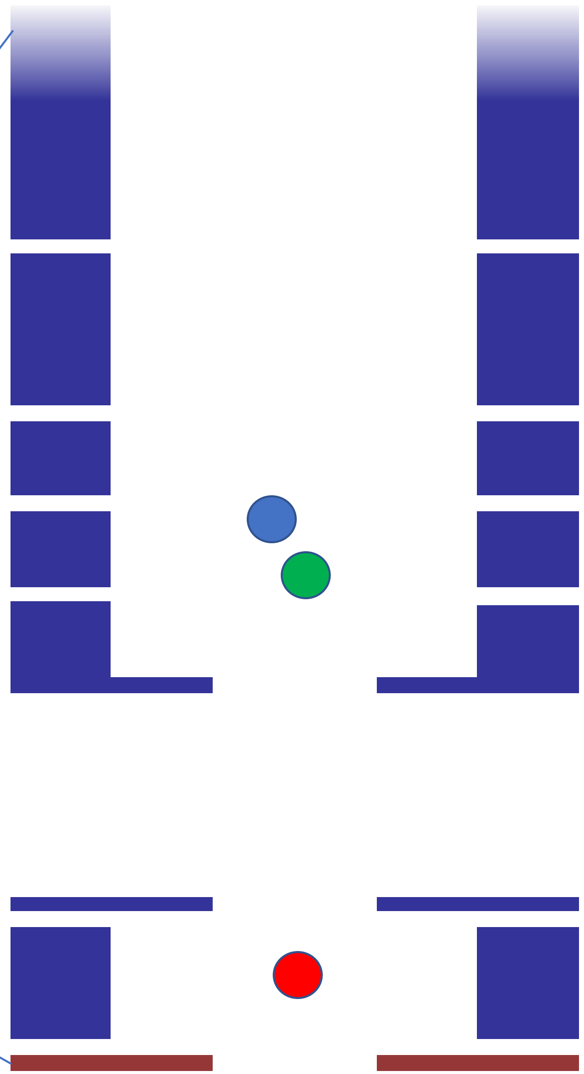
CNRS

TITAN's MR-TOF MS





Isobar separation with mass-selective re-trapping

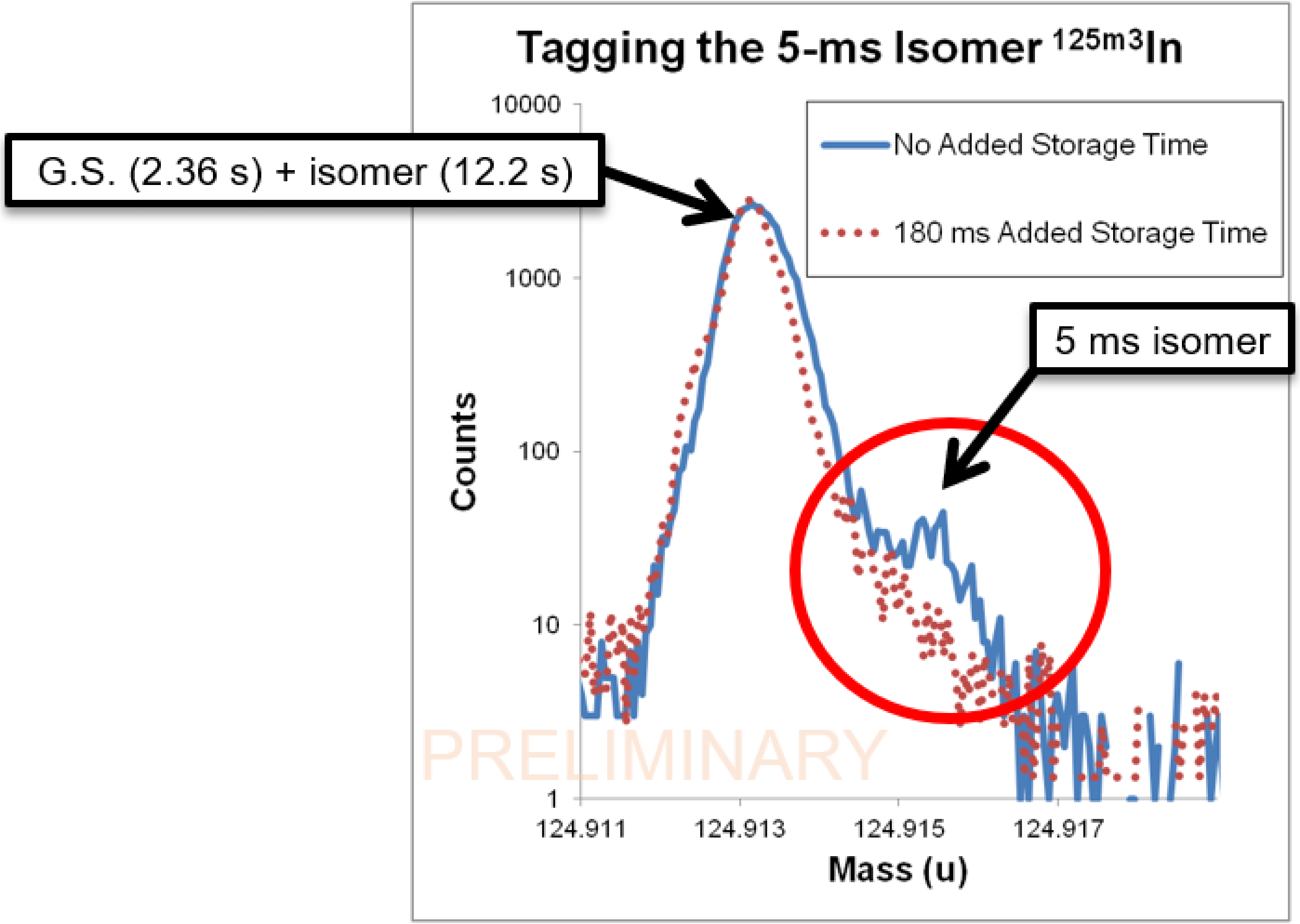


Mass-Selective Re-Trapping

- **Rate capability up to ~10^5 pps**
- **Suppression ~ 10^4**
- **Separation power 80k**

Pushing the limits with MR-TOF

1. New **shortest lived** ion measured at TITAN!



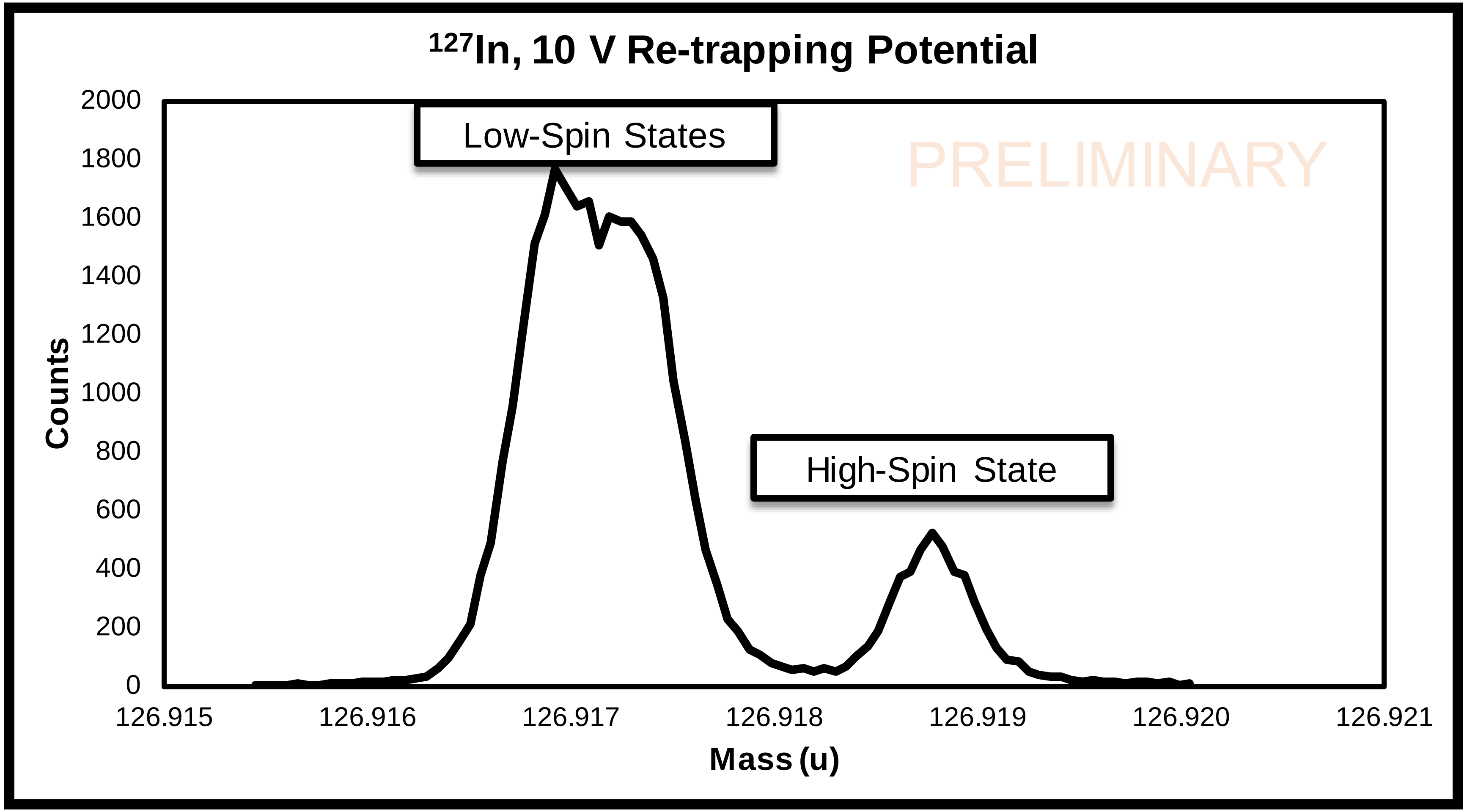
$^{125m3}In$

$T_{1/2} = 5.0$ ms

Good outlook for future measurements far from stability!

Pushing the limits with MR-TOF

2. Achieved **isomeric separation** with re-trapping



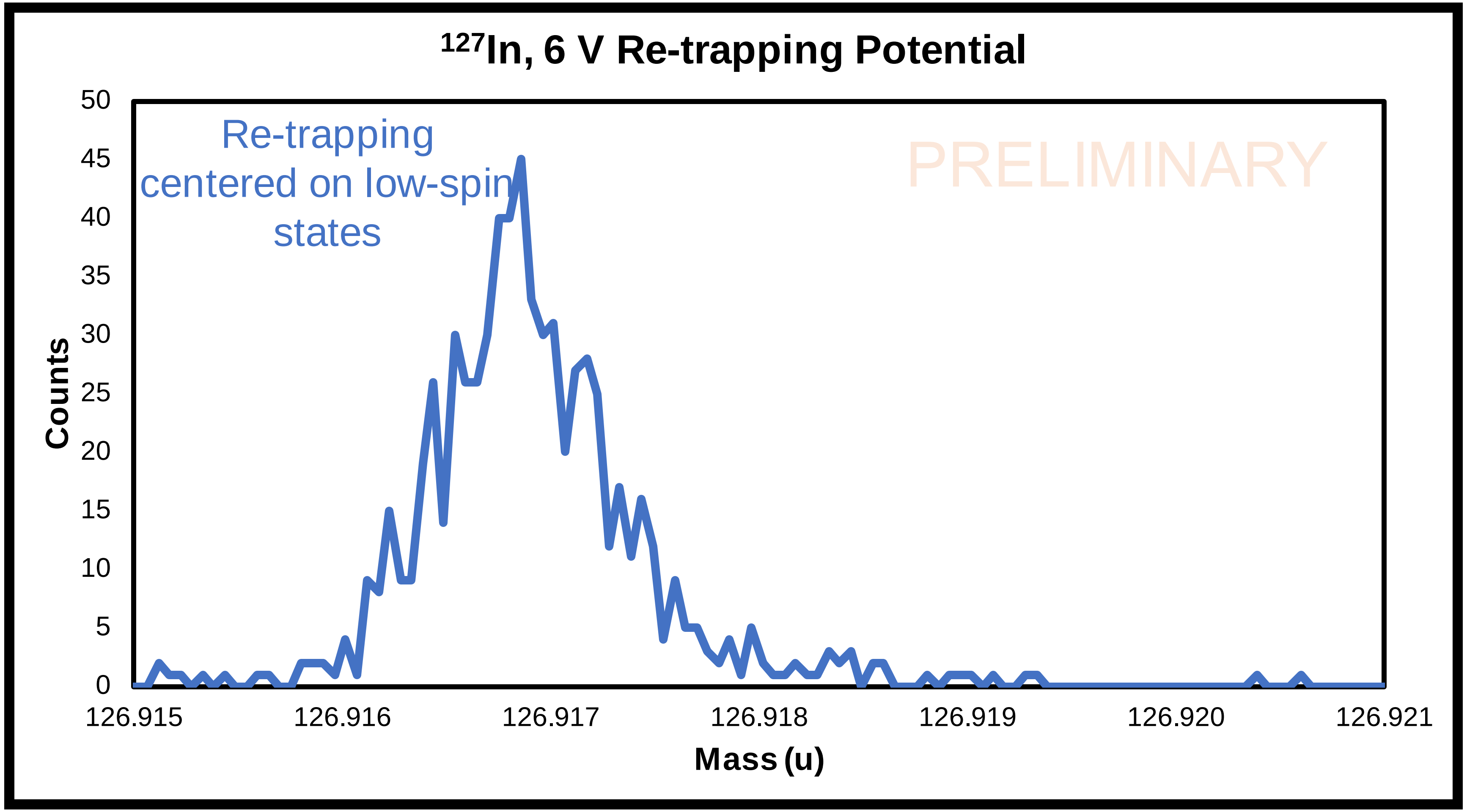
Shallower Trap Depth = Narrower Re-trapping Window

Strategy:

- **Narrow the re-trapping window**
- **Re-center to select only low-spin or high-spin states**

Pushing the limits with MR-TOF

2. Achieved isomeric separation with re-trapping



Shallower Trap Depth
=
Narrower Re-trapping Window

Strategy:

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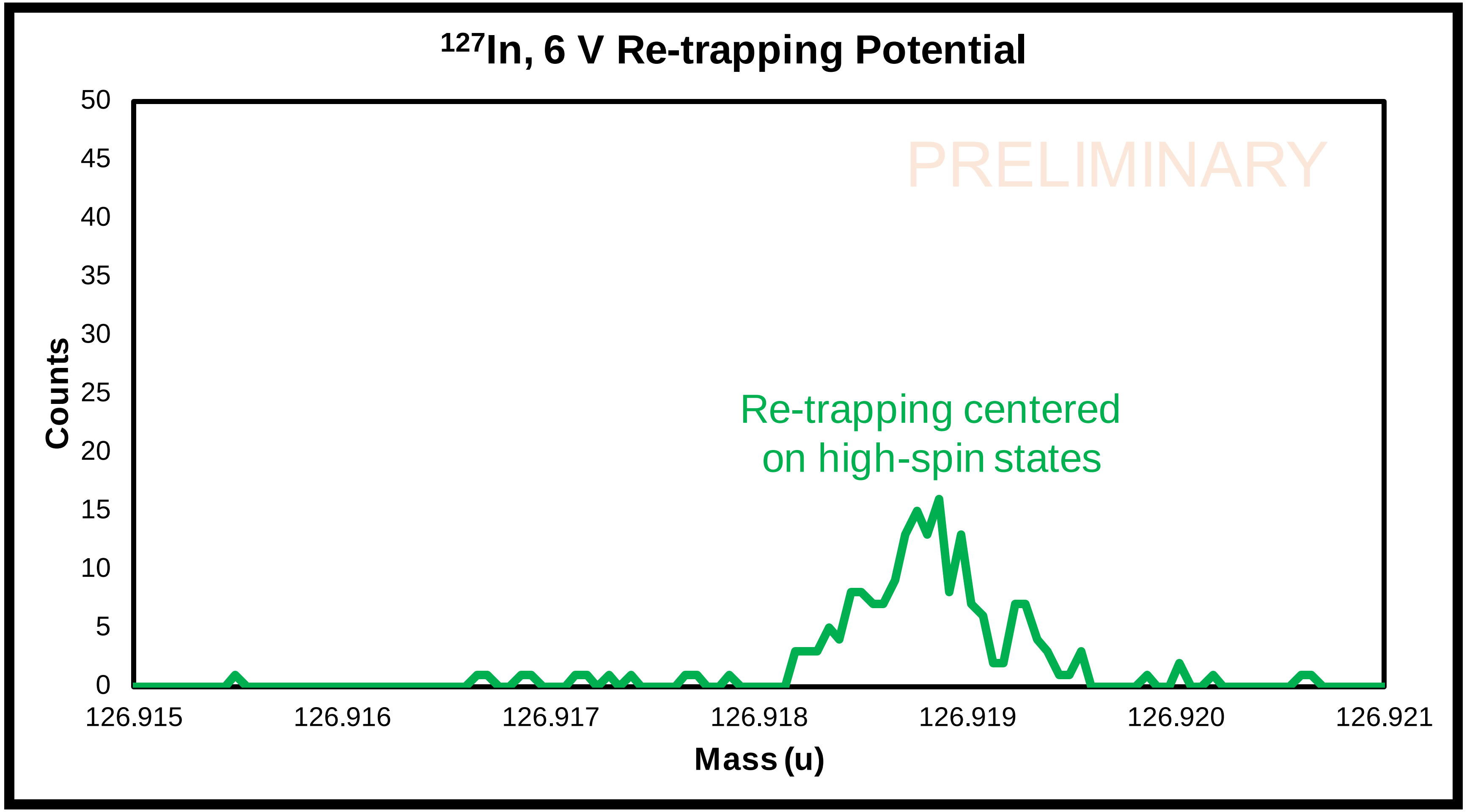
Pushing the limits with MR-TOF

2. Achieved **isomeric separation** with re-trapping



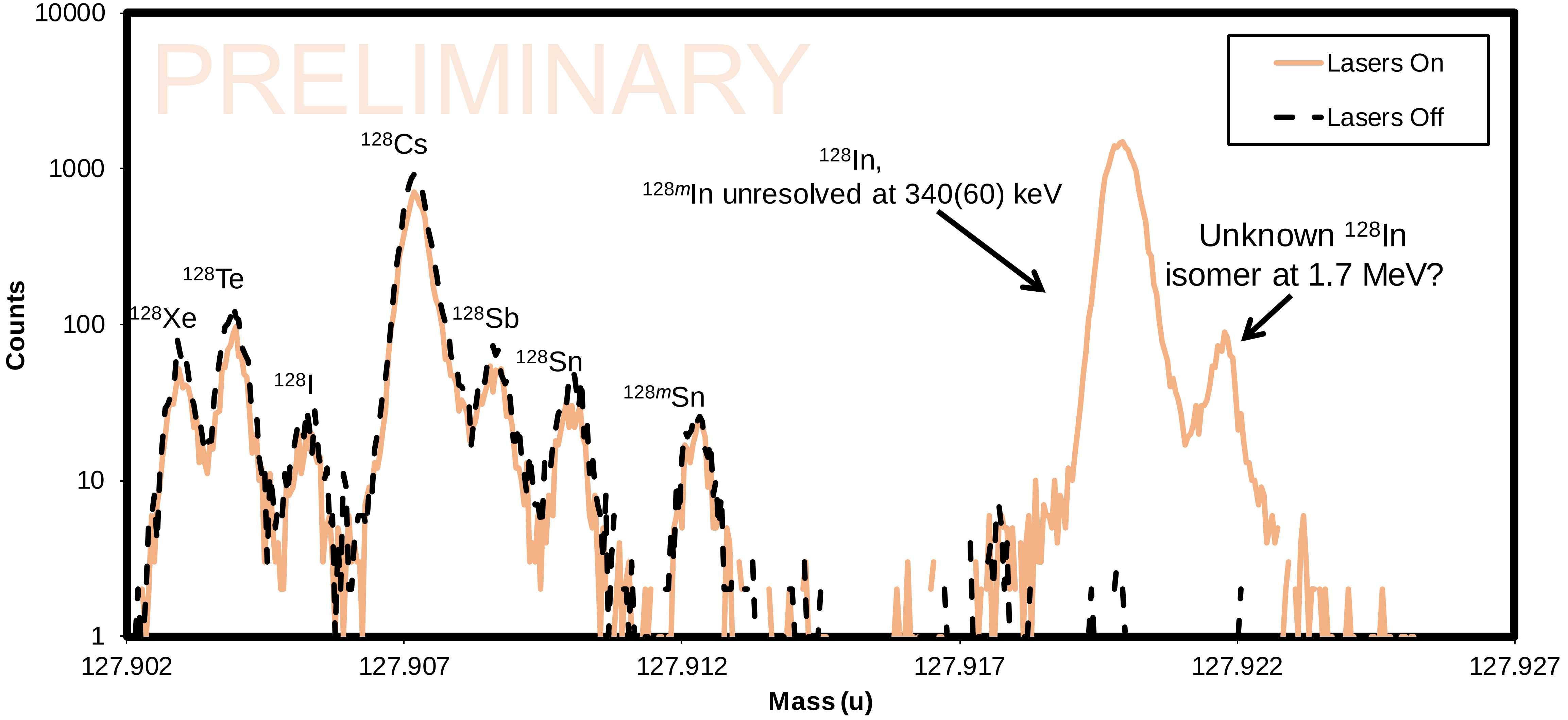
Shallower Trap Depth
=
Narrower Re-trapping Window

Strategy:

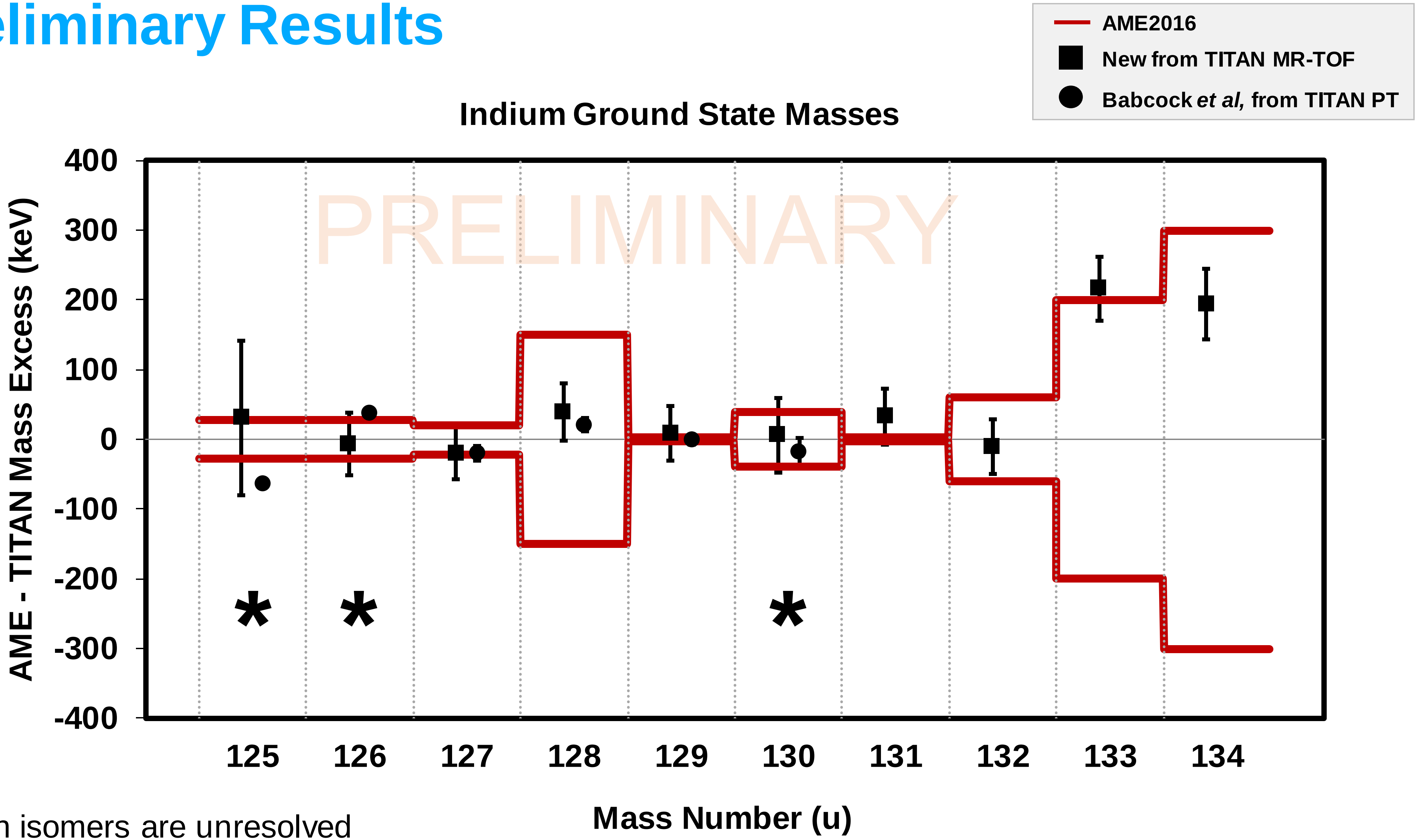
- **Narrow the re-trapping window**
- **Re-center to select only low-spin or high-spin states**

Pushing the limits with MR-TOF

3. Potential to identify **new isomers**

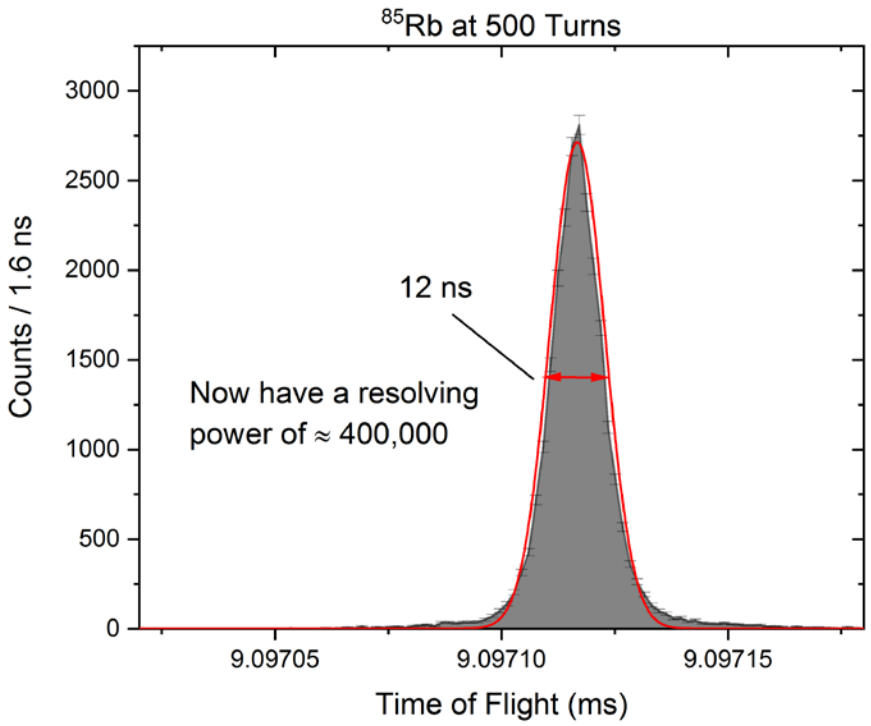


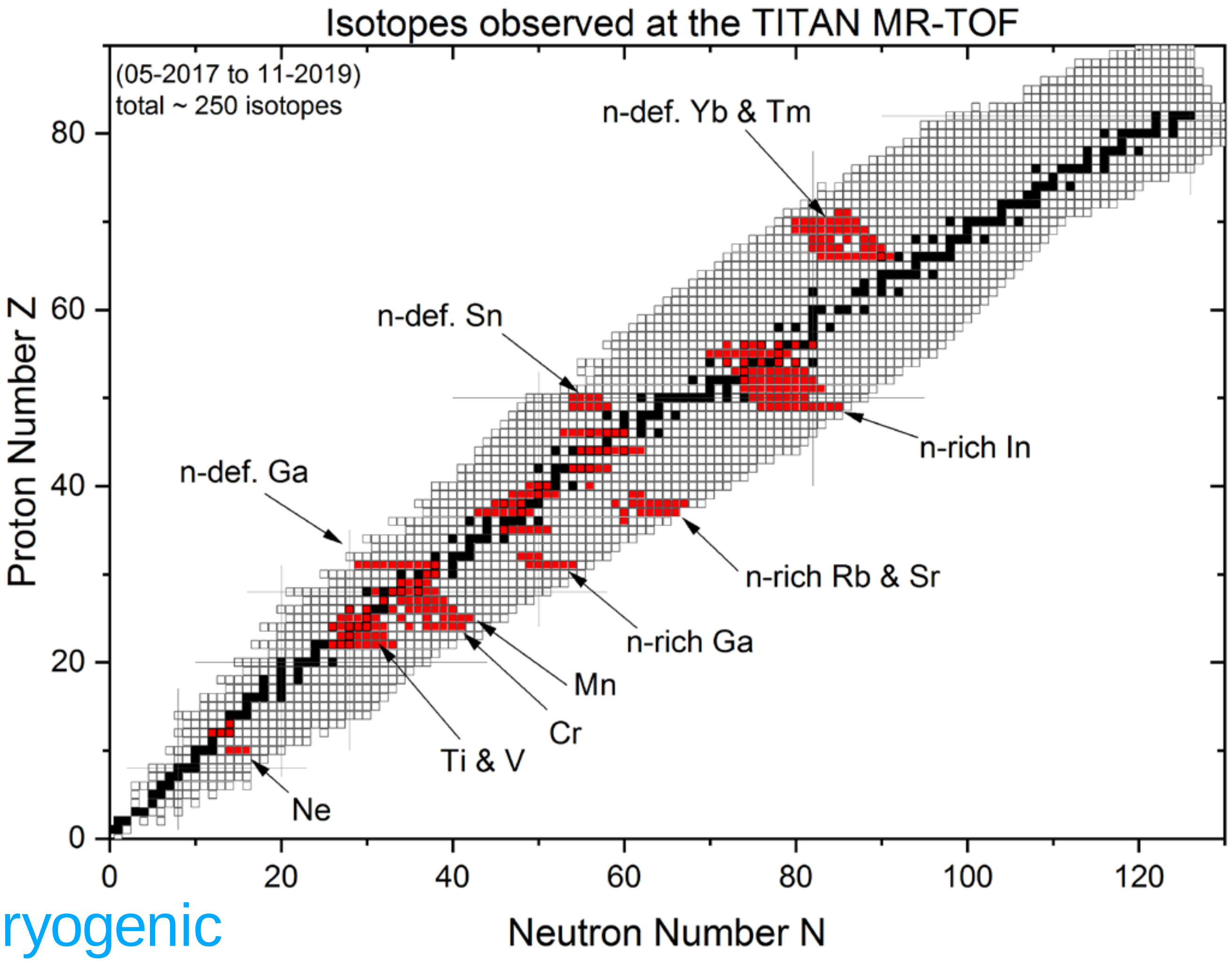
Preliminary Results



* Known isomers are unresolved

TITAN Status

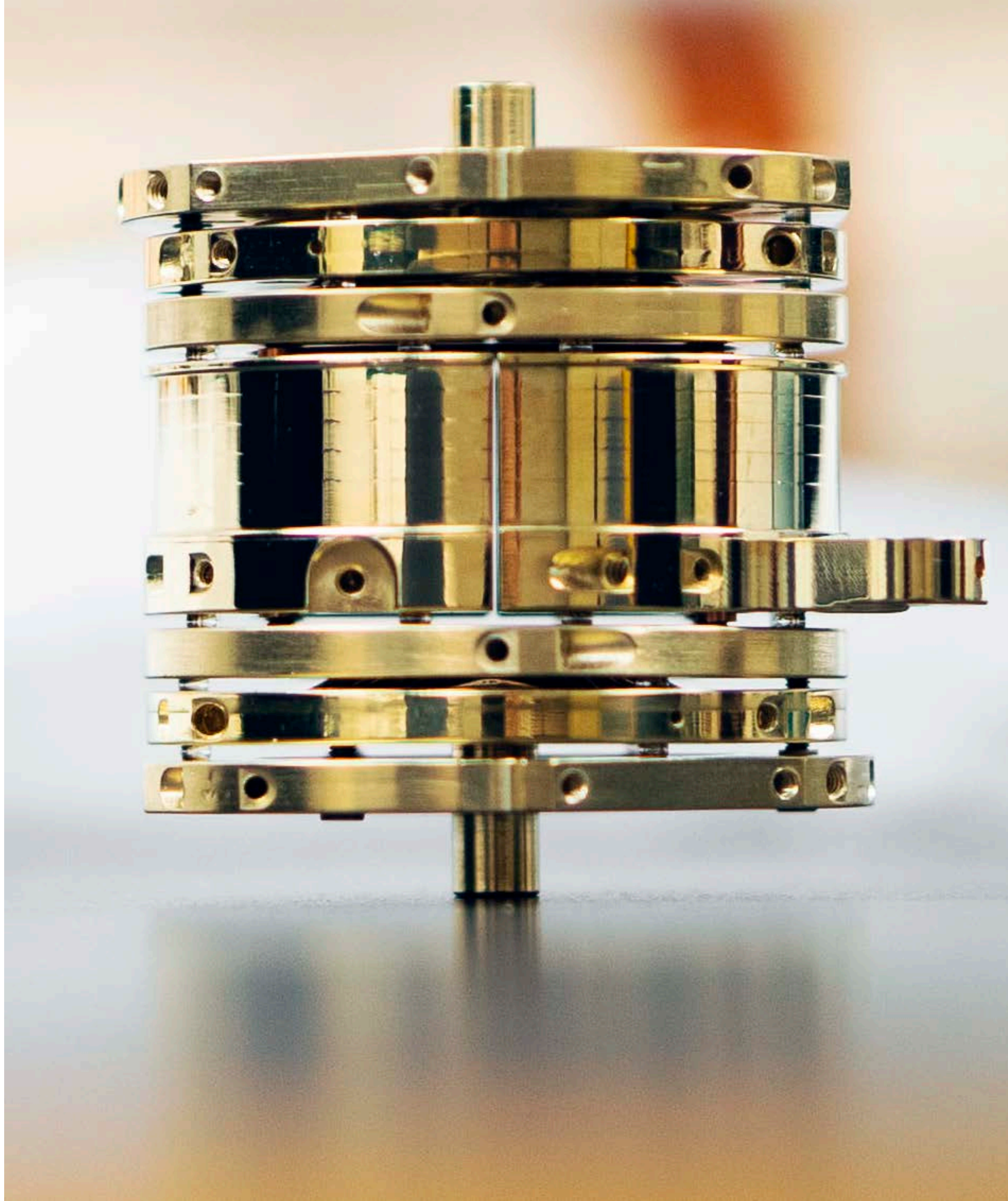




- MR-TOF: improved resolution
- Penning trap upgrade: going cryogenic
- EBIT upgrade: 60kV

Recent Highlights

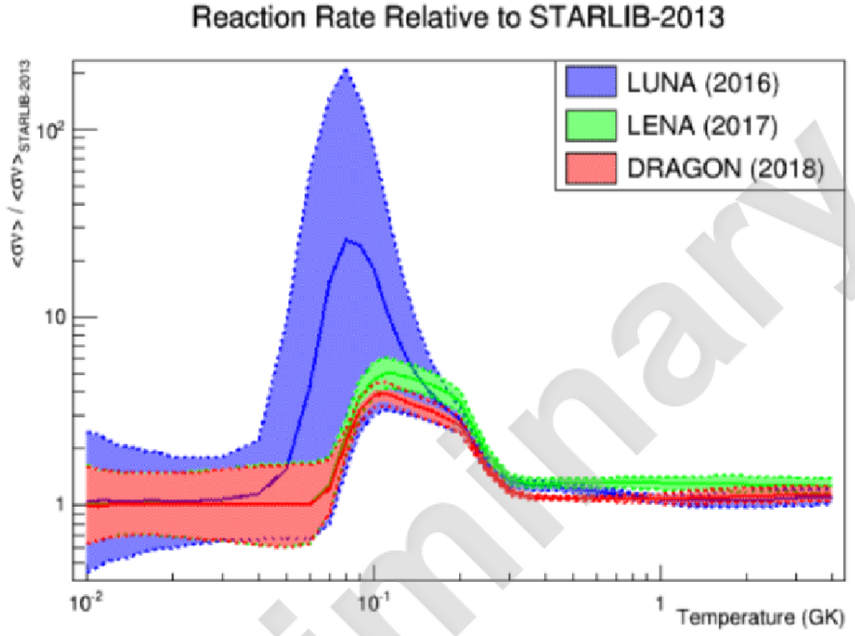
- TITAN mass measurements
  At low energies
- DRAGON astrophysics measurements
  At medium energies

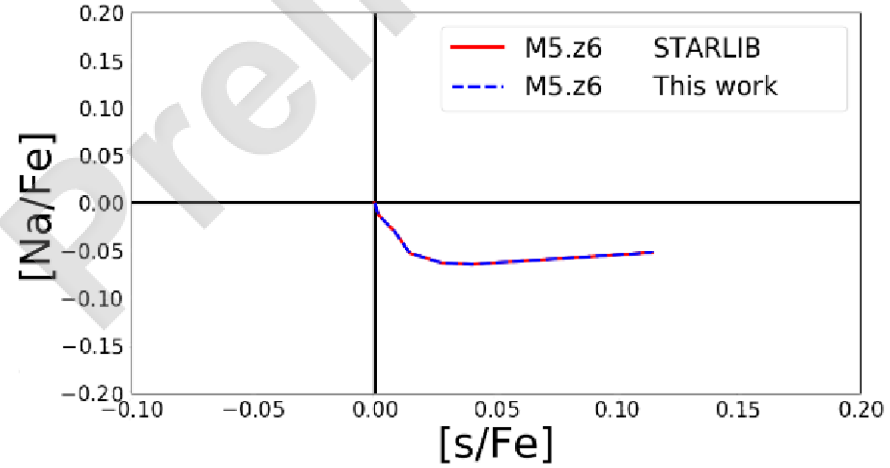


Nuclear Astrophysics: DRAGON

$^{22}Ne(p,\gamma)^{23}Na$
Affects Na-O formation in Globular Cluster

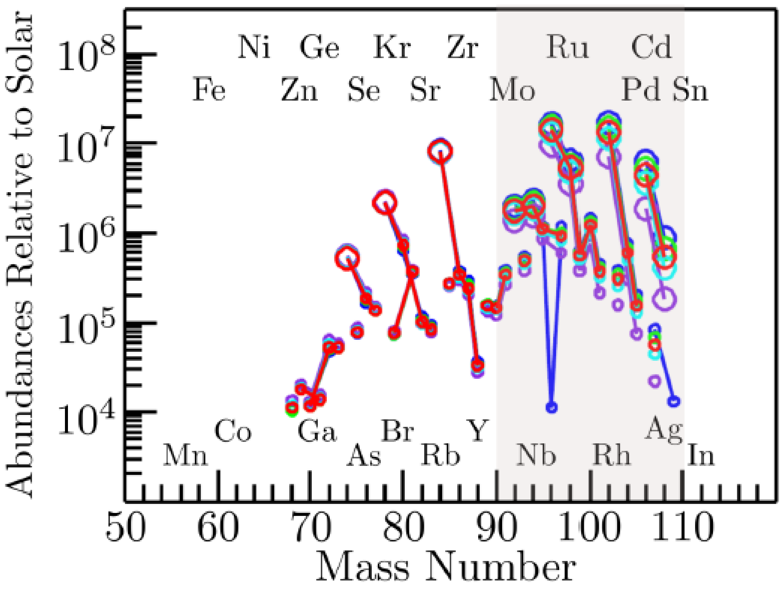
- Renormalization keeps other measurements in agreement with this work for low resonances
- Omitting LUNA 100, 68 keV resonances, new calculation has smaller uncertainties than LENA calculated rate





Calculation by U. Battino

DRAGON experiment: effect on A=90-110 in CCSN from $^{7}Be(\alpha,\gamma)^{11}C$

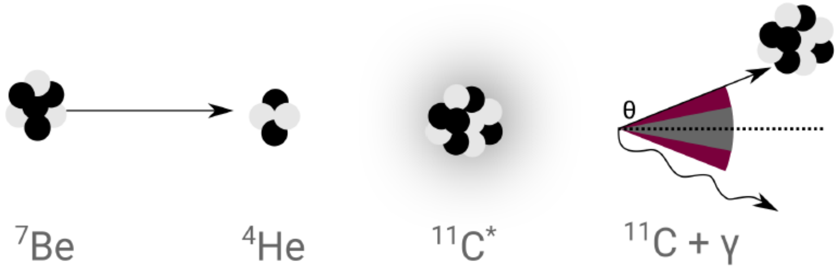


$^{7}Be(\alpha,\gamma)^{11}C$ reaction rate:

× 1 2 10

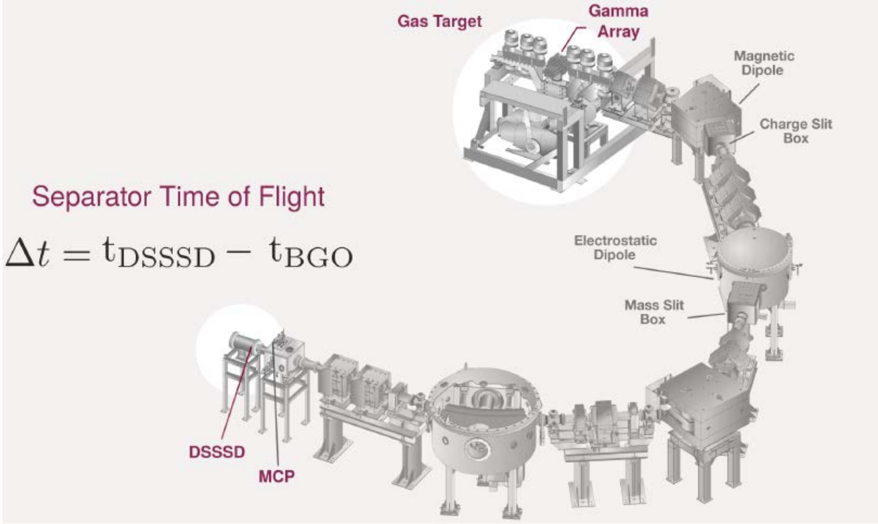
÷ 2 10

Inverse Kinematics Reactions - Momentum Cone



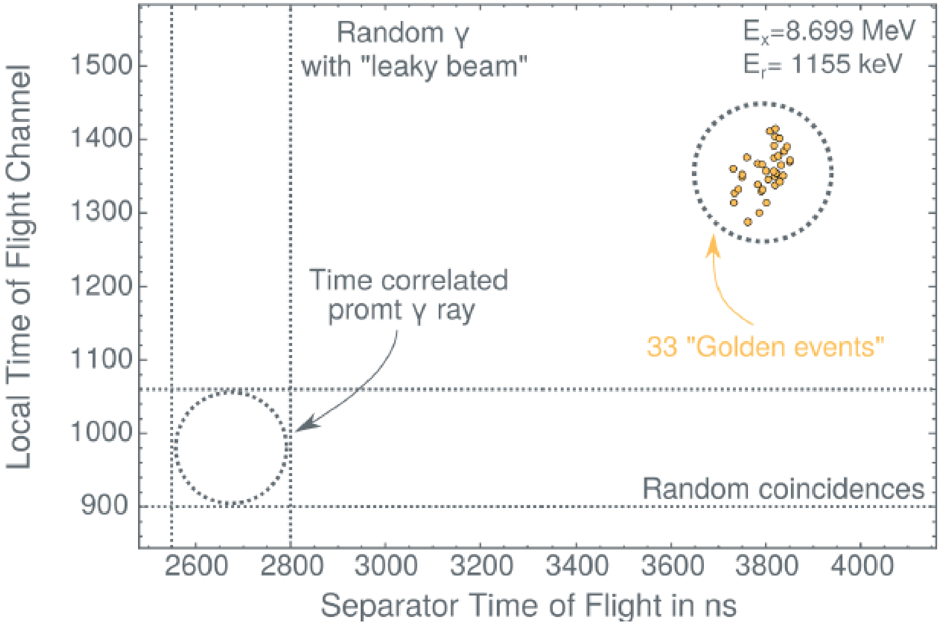
DRAGON's acceptance - θ_{DRAGON} ~ 21 mrad

$^{7}Be(\alpha,\gamma)^{11}C$ - θ_{max} ~ 43 mrad



$$\Delta t = t_{DSSSD} - t_{BGO}$$

$^{7}Be(\alpha,\gamma)^{11}C$ Particle Identification Plot



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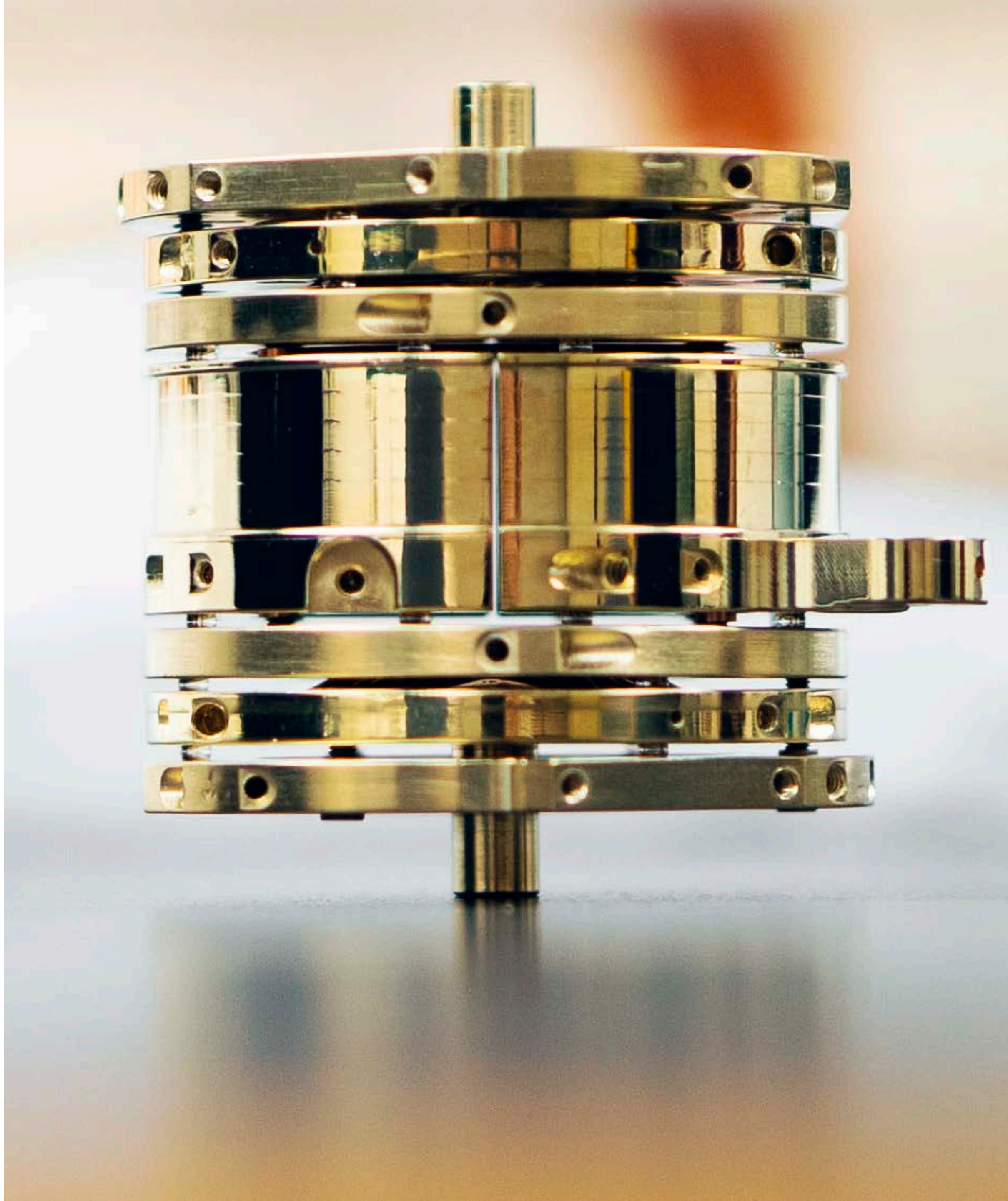
Recent Highlights

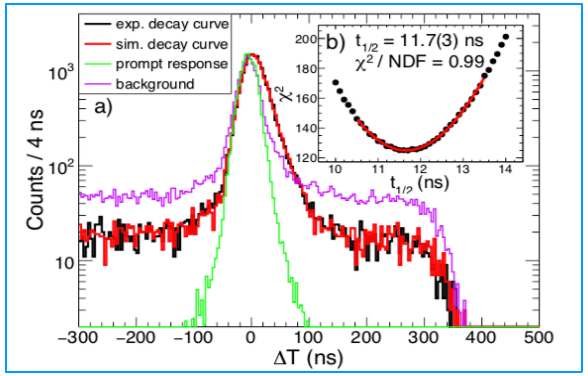
- TITAN mass measurements
  - At low energies
- DRAGON astrophysics measurements
  - At medium energies
- TIGRESS and EMMA experiments
  - At high energies



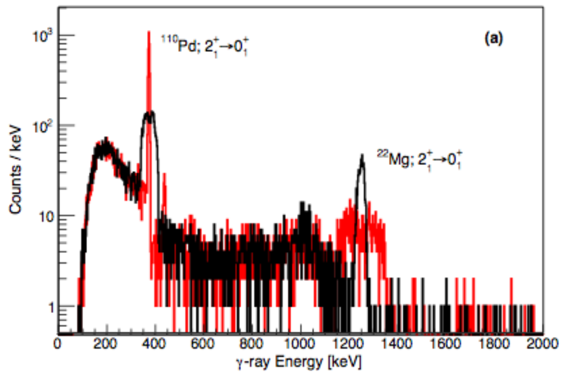
Nuclear Physics: Structure
TIGRESS: Electromagnetic transition rates in Mg isotopes

Motivation: accurate measurements of B(E2) transition matrix elements for comparison to effective-charge-free *ab initio* calculations, especially IM-SRG and SA-NCSM.

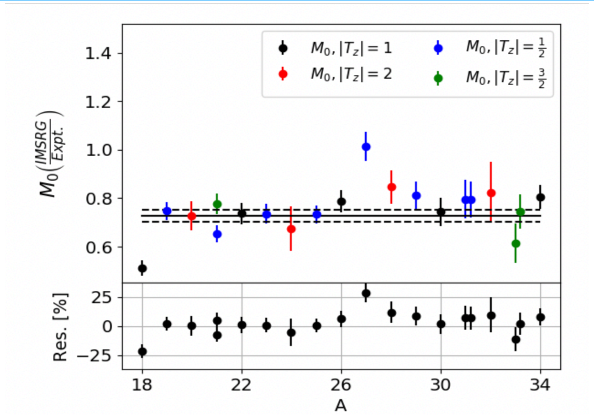
- ^{21}Mg electronic timing and Coulex: first gamma-ray detection from first excited state; first observation of $9/2^+$ excited state [1]
- ^{22}Mg Coulex: resolved long-standing disagreement between previous measurements [2]
- ^{23}Mg Coulex: Systematics of mirrors indicate SA-NCSM reproduces isoscalar B(E2) strength well, IM-SRG reproduces isovector part [3]
- ^{28}Mg DSAM [4] also measured & compared to theory



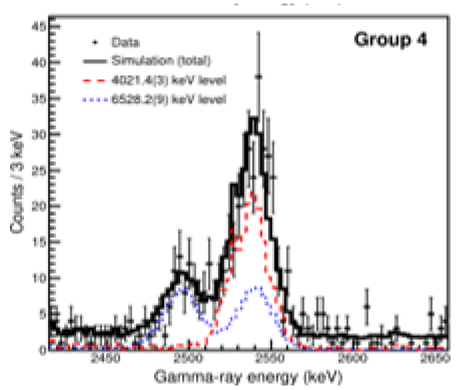
[1] Ruotsalainen et al., PRC **99**, 051301



[2] Henderson et al., PLB **782**, 468



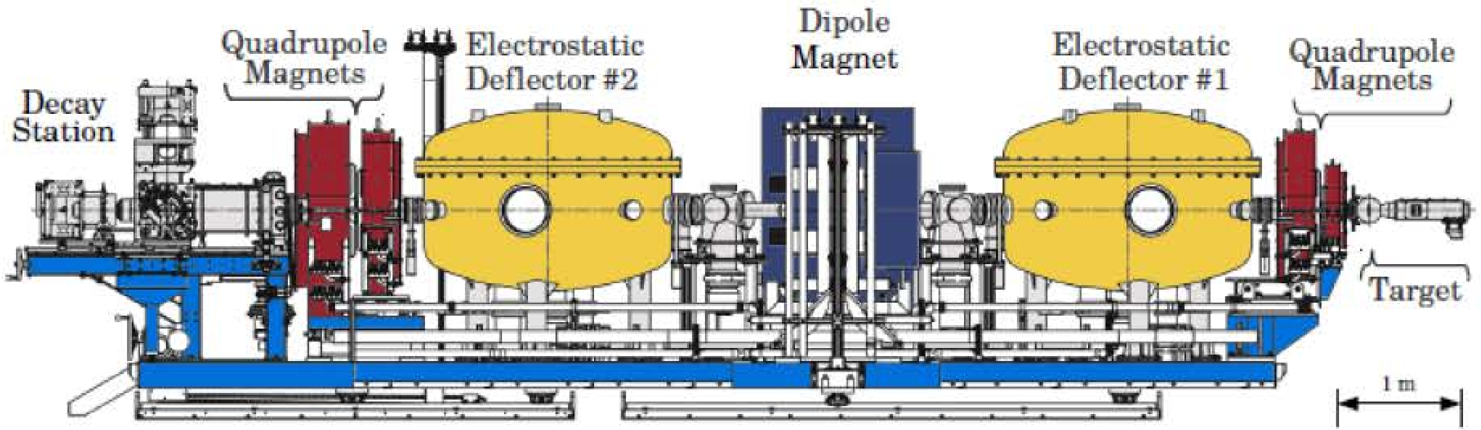
[3] Henderson et al, in progress

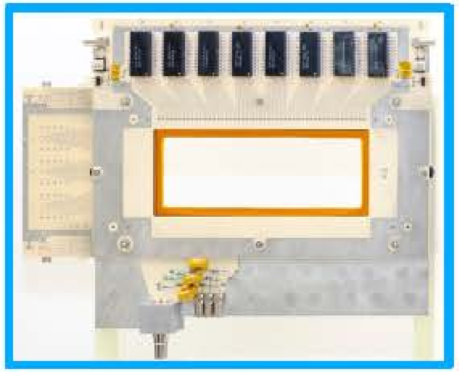


[4] Williams et al., PRC, accepted

EMMA & TIGRESS: first combined experiment with radioactive beam

- Use EMMA to select the recoils of interest by m/q.
- Correlate focal plane events with prompt γ-rays detected by TIGRESS.
- 12 TIGRESS HPGe clovers in the high-suppression mode for better background rejection.

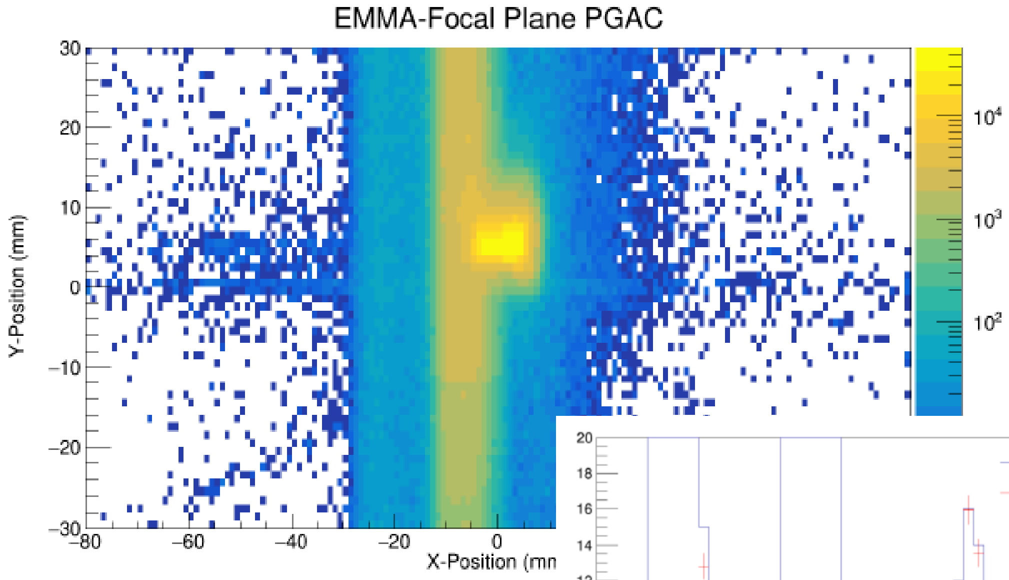




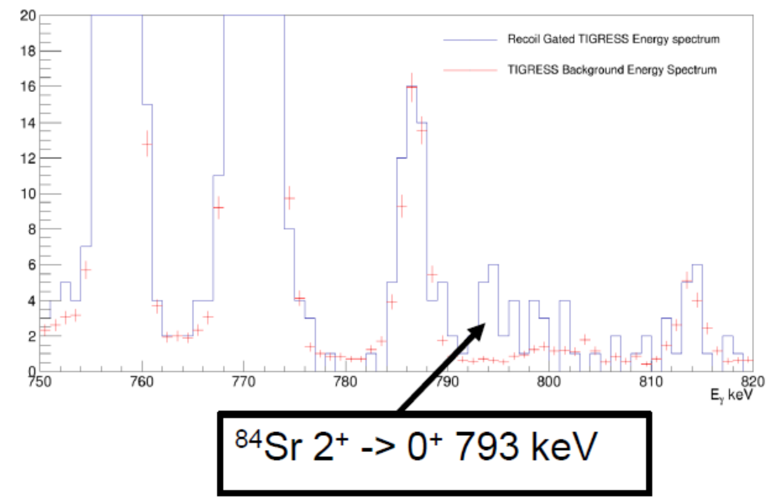
Focal plane detectors:

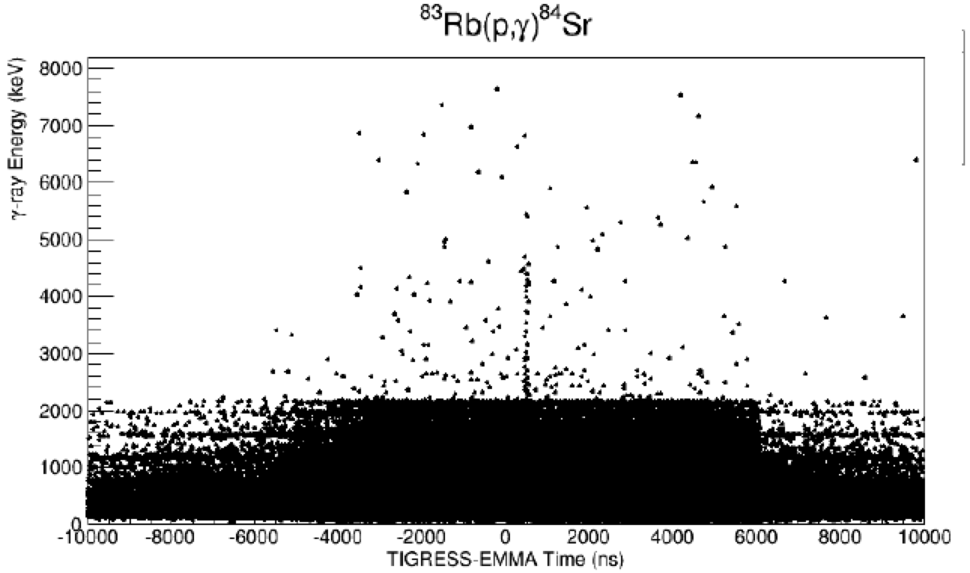
1) Position sensitive PGAC.
2) Ionization Chamber.
3) Ion-implanted silicon.

EMMA & TIGRESS: the power of two!
Excellent suppression and selection of beam



EMMA focal plane dominated by leaky beam. Need focal plane slits to reduce rate.





See clear peak in time difference between EMMA and TIGRESS events.

$^{83}Rb(p,\gamma)^{84}Sr$

First Radioactive Beam Experiment for a Supernova Reaction!

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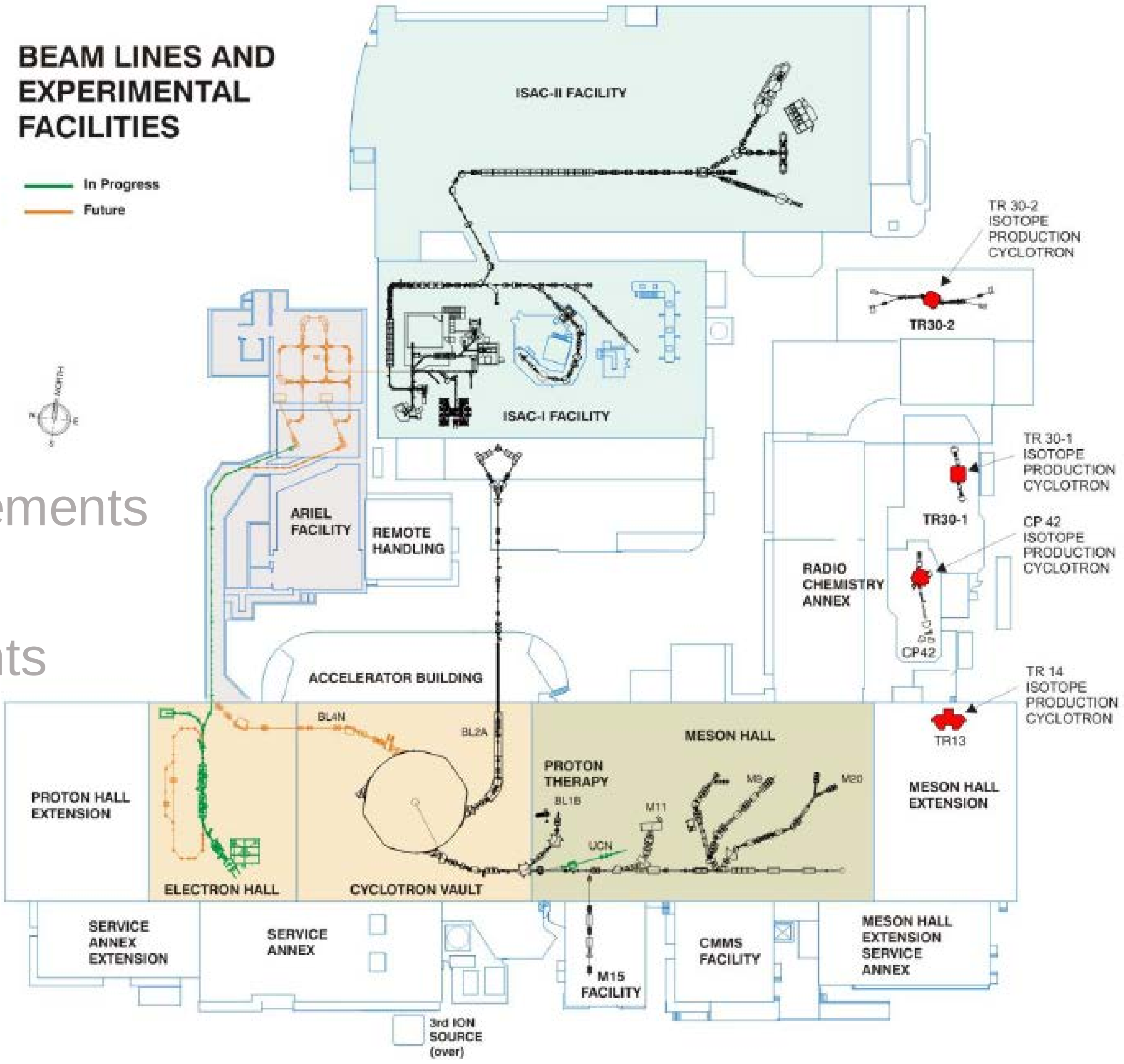
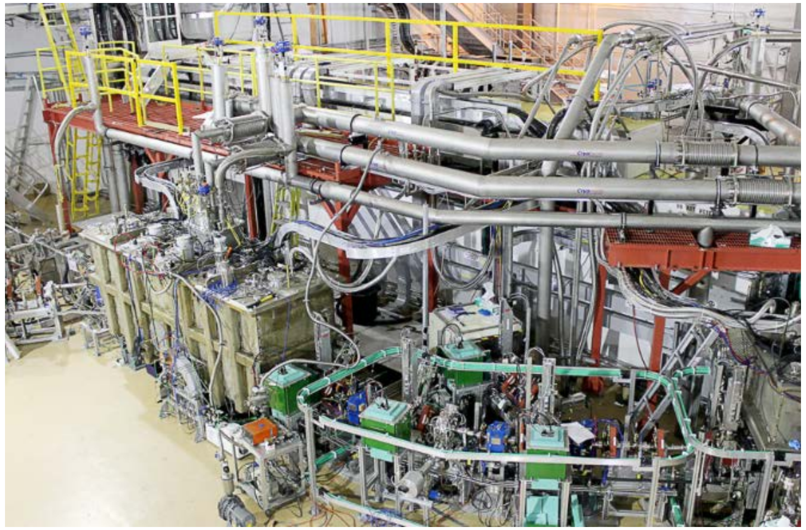
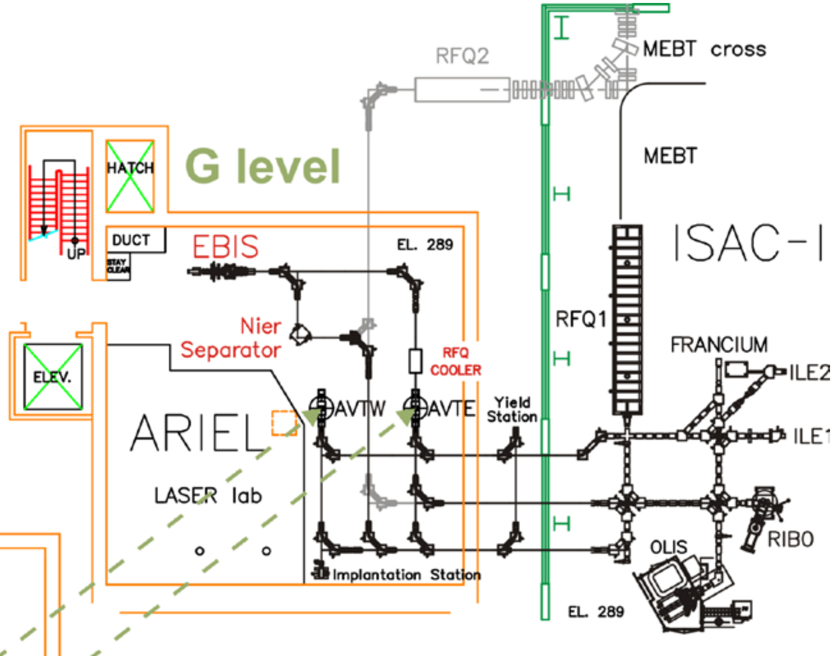
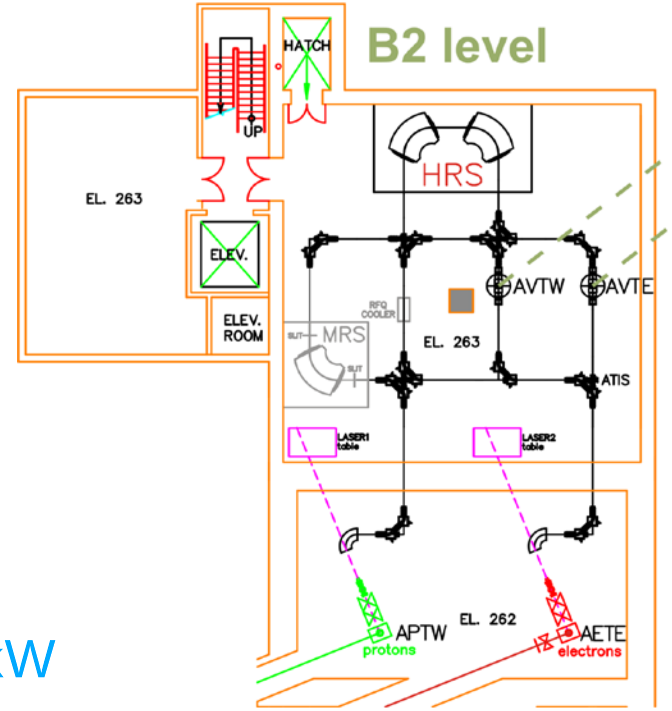
- ARIEL Update

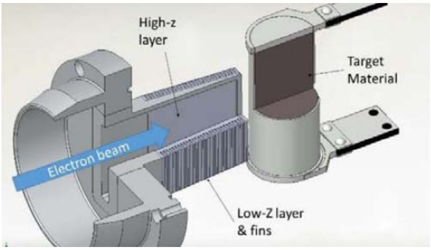


Overview

The **Advanced Rare Isotope Laboratory (ARIEL)** is the only purpose-built multi-user rare isotope facility as well as the world's most powerful Isotope Separation Online (ISOL) complex.





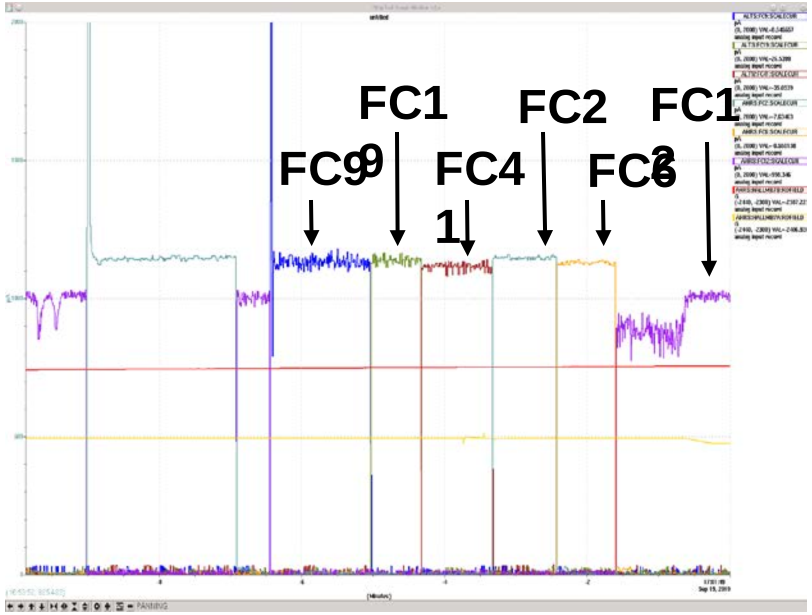
100 kW prototype converter
A. Gottberg et al.

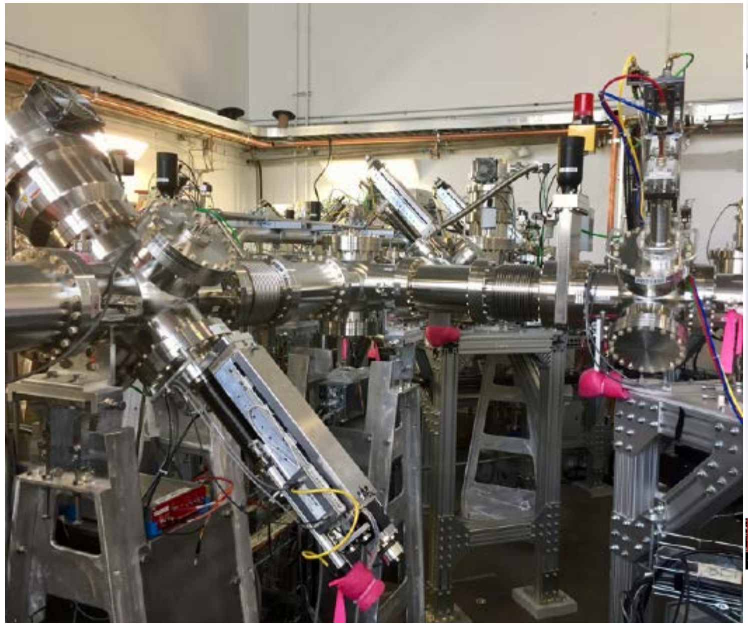
ARIEL:

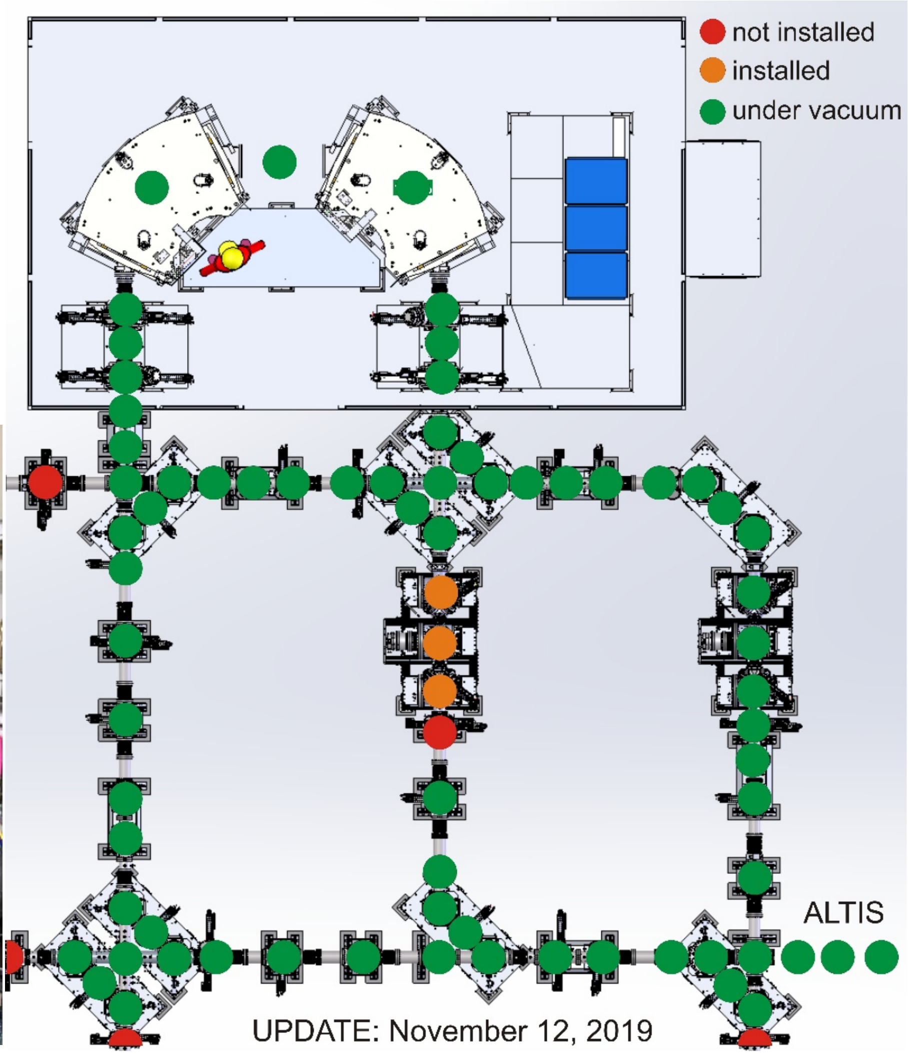
- superconducting e-linac 30MeV -100kW
- new proton beam line
- 2 target station with beam preparation
- triple the beam availability

Installation status at B2 and verticals

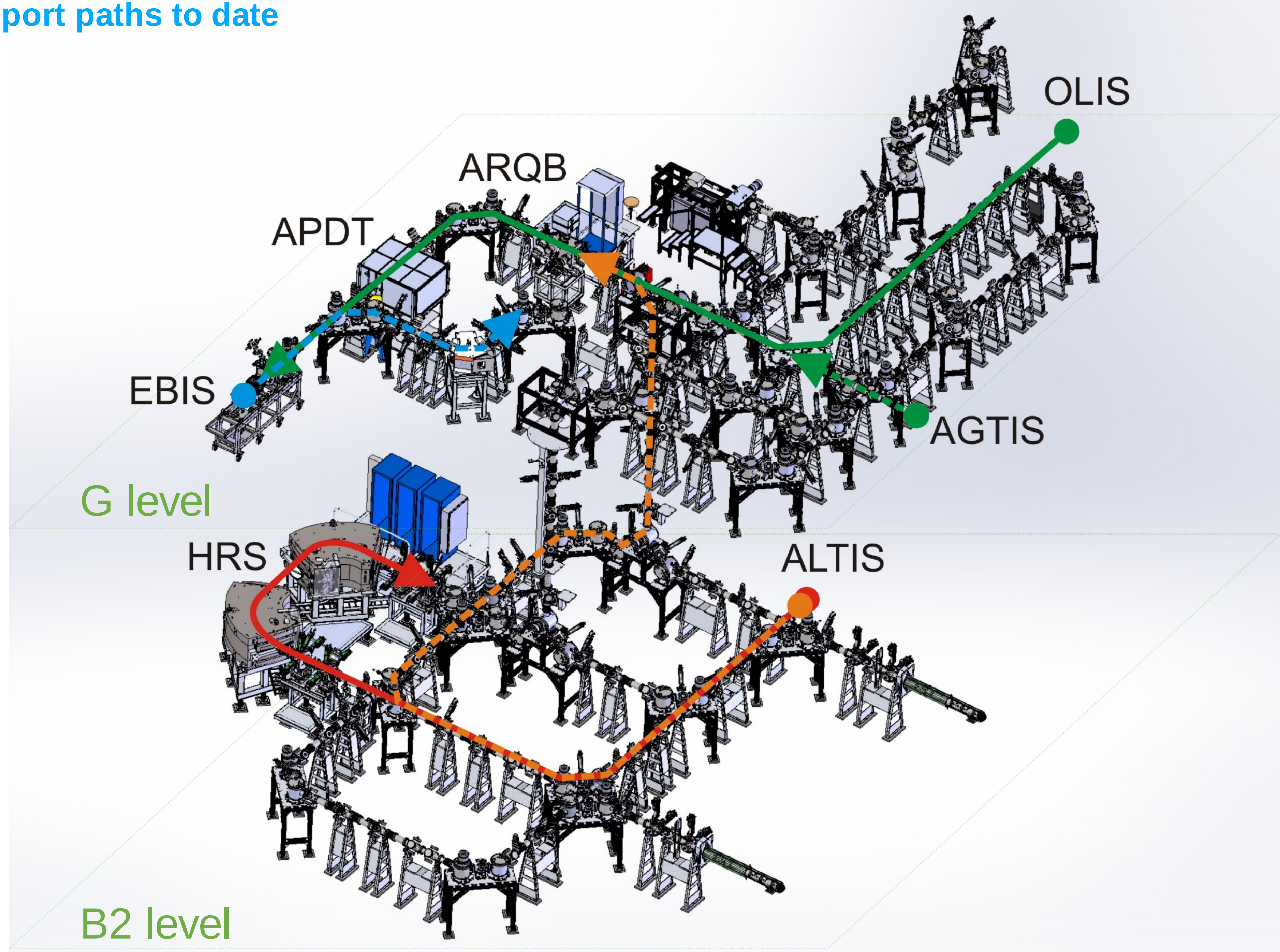
- LE beam lines installation completed
- Vertical section installation completed
- All section well below $3{\cdot}10^{-8}$ Torr
- Overall about 200 m of beam line
- Optics performs according to design
- 90% transmission reached within minutes with optics calculated values





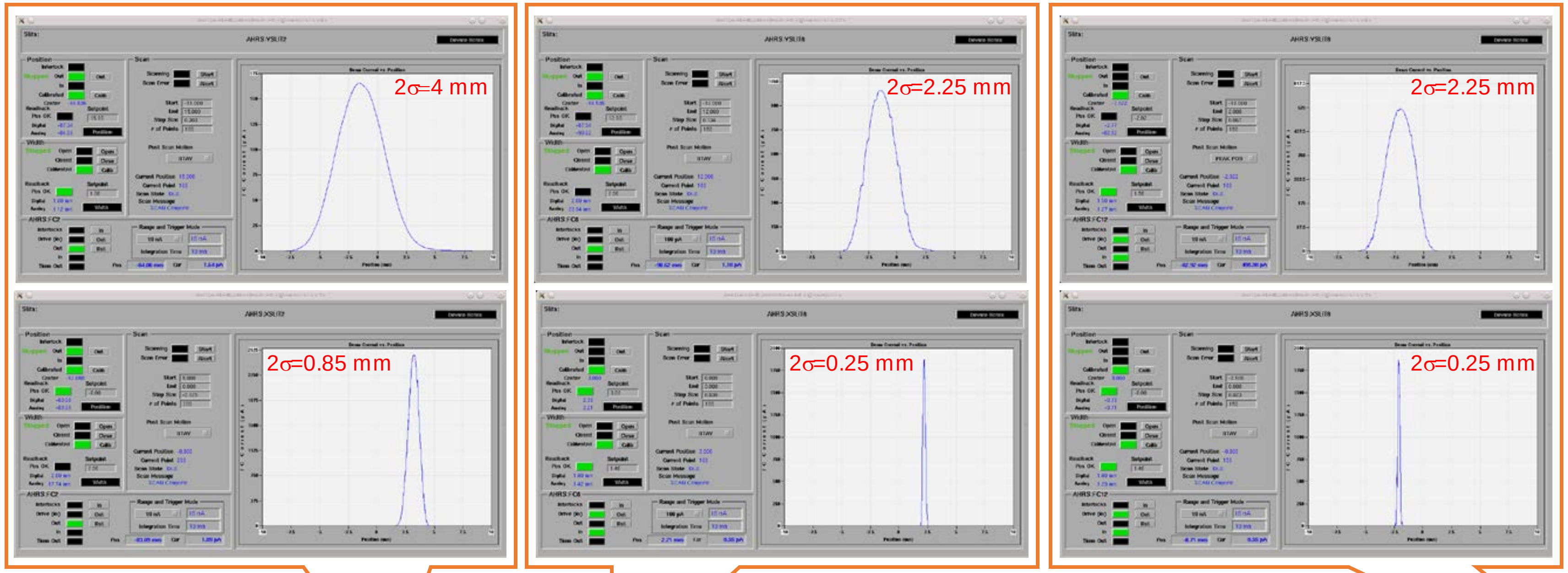


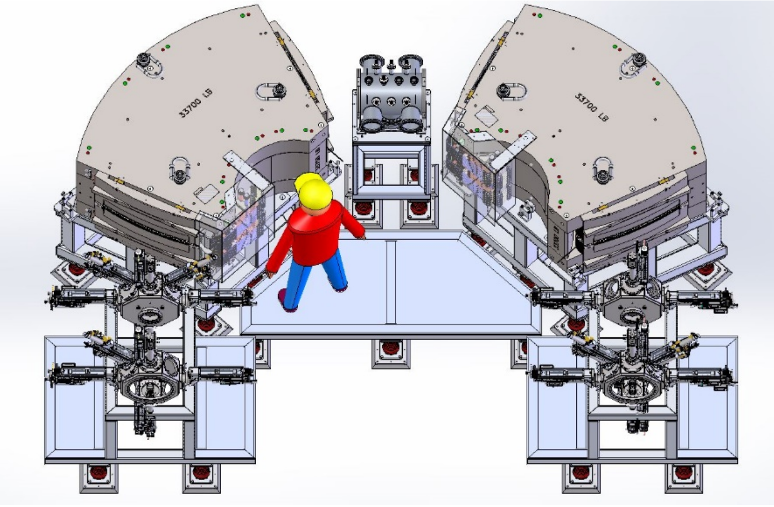
Beam transport paths to date

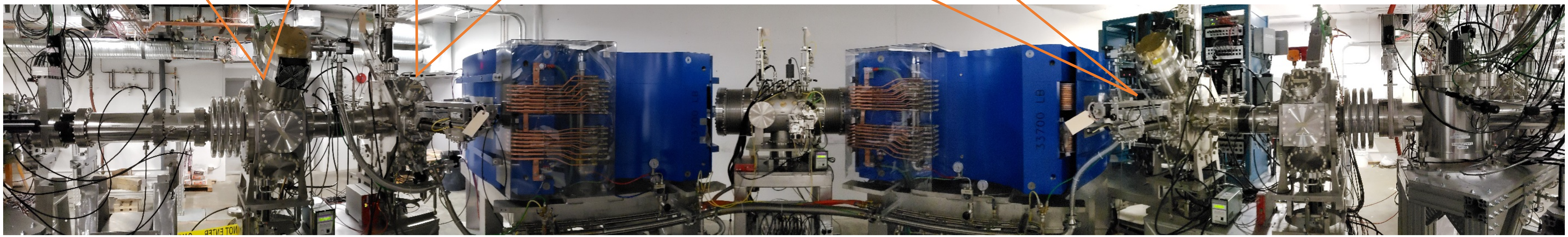


High Resolution Separator (HRS) commissioning

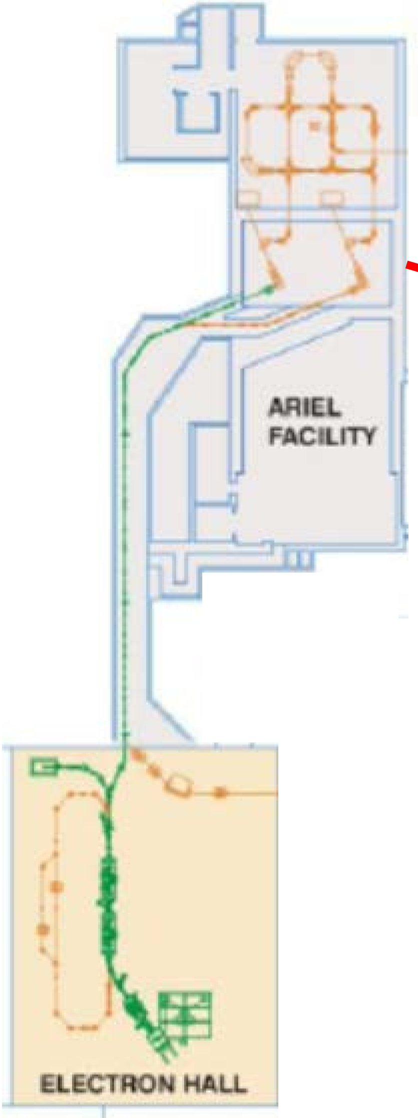
- HRS installation completed
- Beam profiles are consistent the calculated optics envelope
- Resolving power of 4000 with full transmission 3 μm emittance

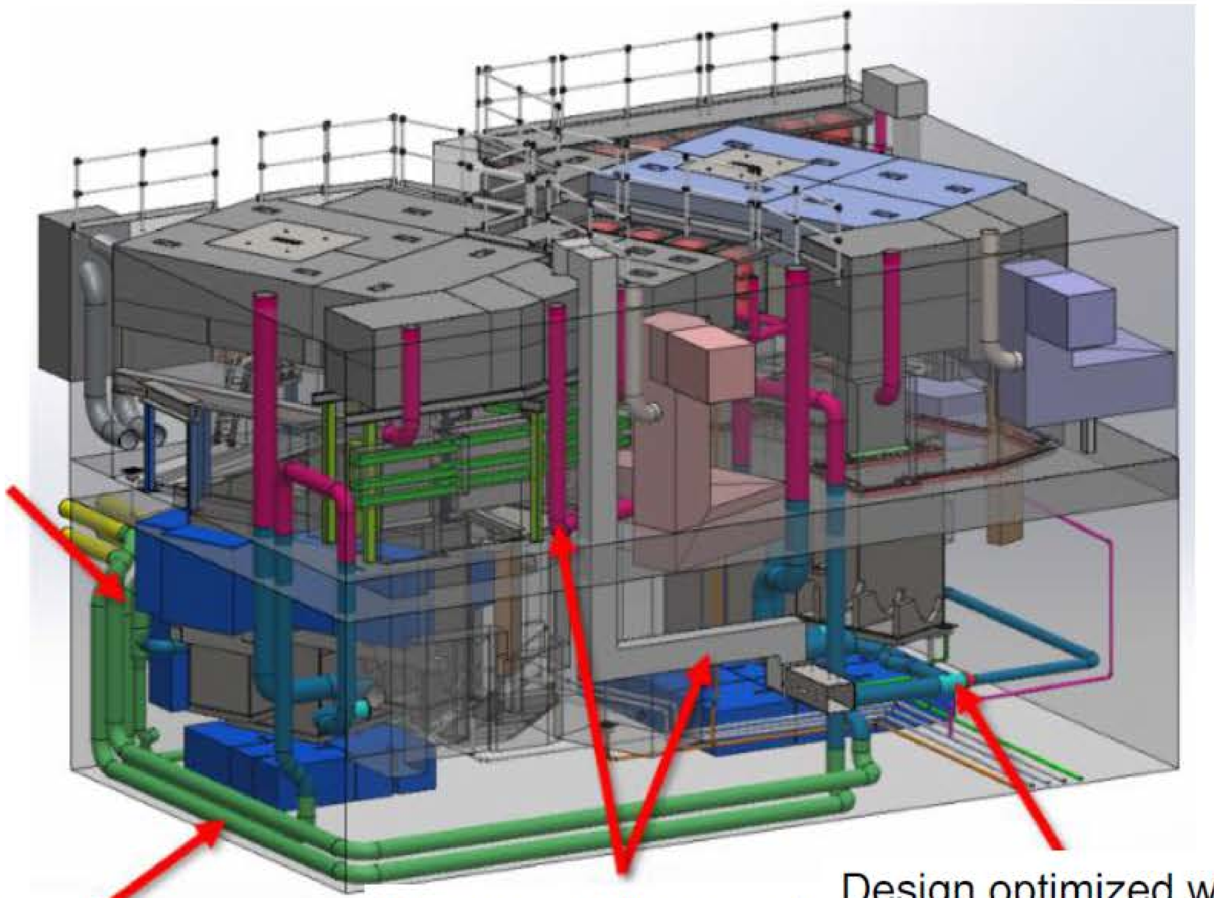






ARIEL next steps: Target Hall Design





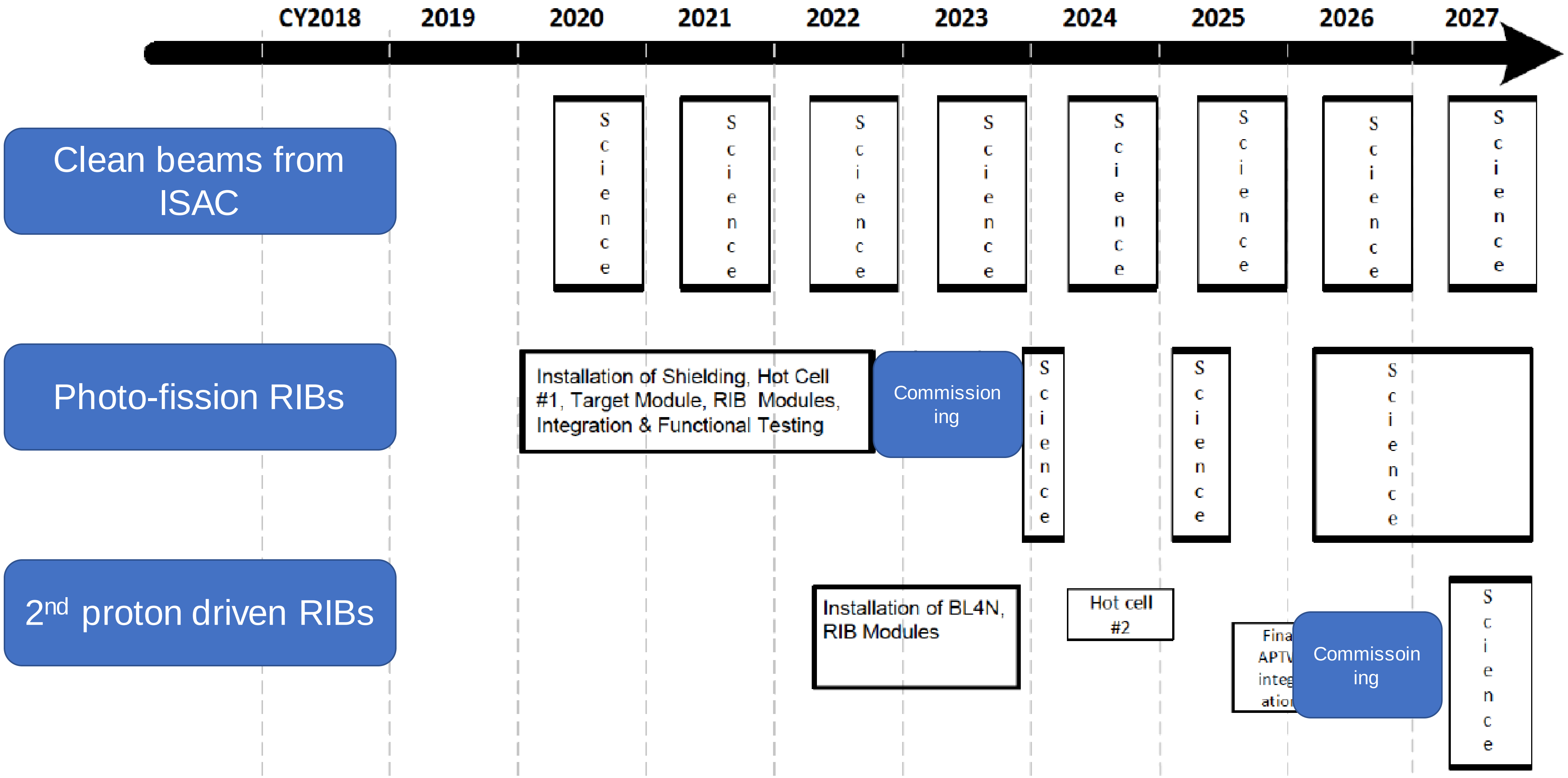
Improved routing for construction, shielding and better flow

Level 1 design being finalized

Vacuum package and ventilation added

Design optimized with shielding analysis

High-Level Strategy for ARIEL Science Delivery



ISAC will continue to operate at full capacity during construction and commissioning

Thank you
Merci

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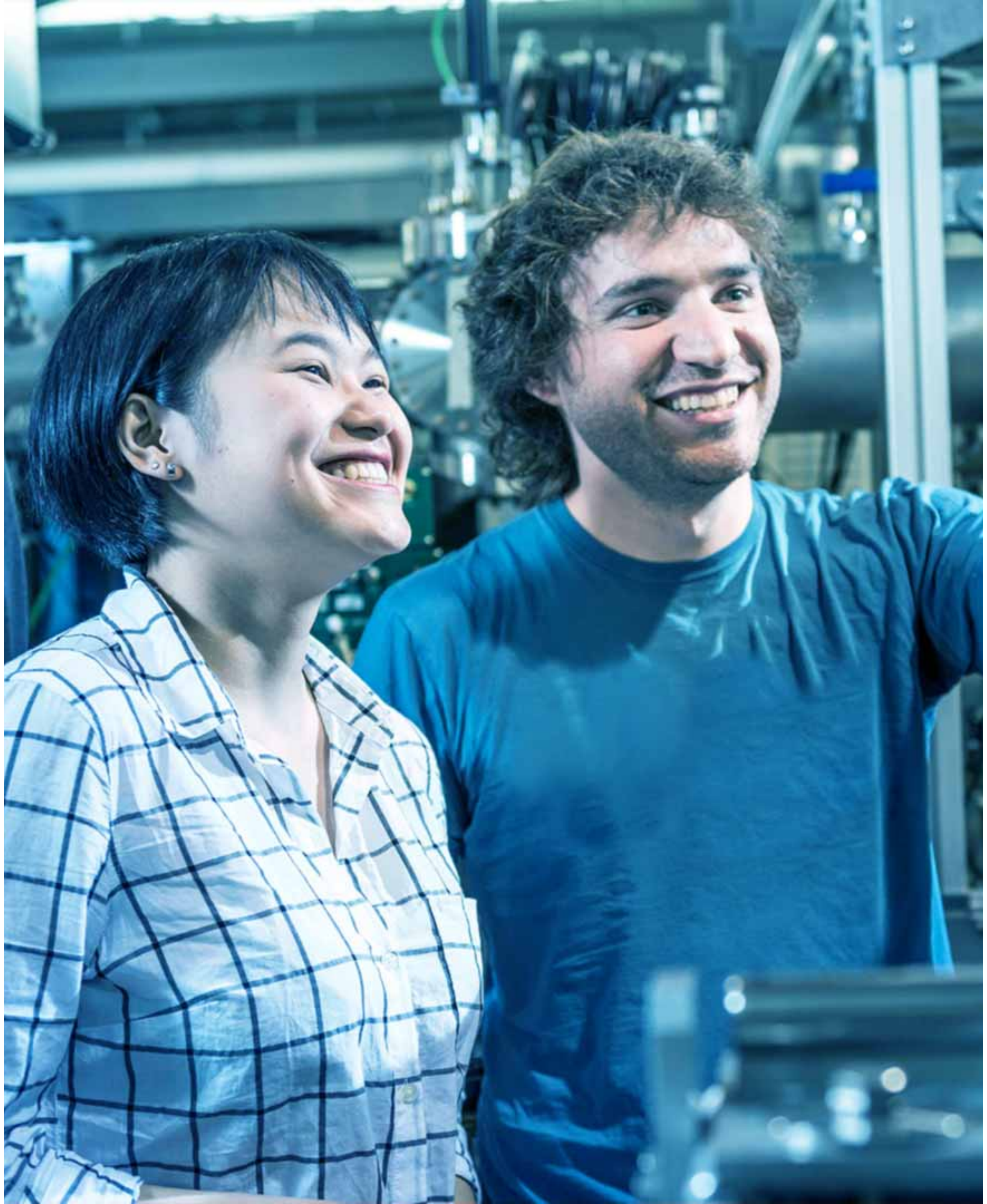

Discovery, accelerated