TRIUMF

Welcome to TRIUMF

Workshop on Progress in *Ab Initio* Nuclear Theory

TRIUMF, Vancouver, Canada

February 28 – March 3, 2023

Petr Navratil

TRIUMF Theory Department

Interim Director, Physical Sciences

2023-02-28

Discovery, accelerated

Our vision is for Canada to lead in science, discovery, and innovation, improving lives and building a better world.

TRIUMF is Canada’s particle accelerator centre.

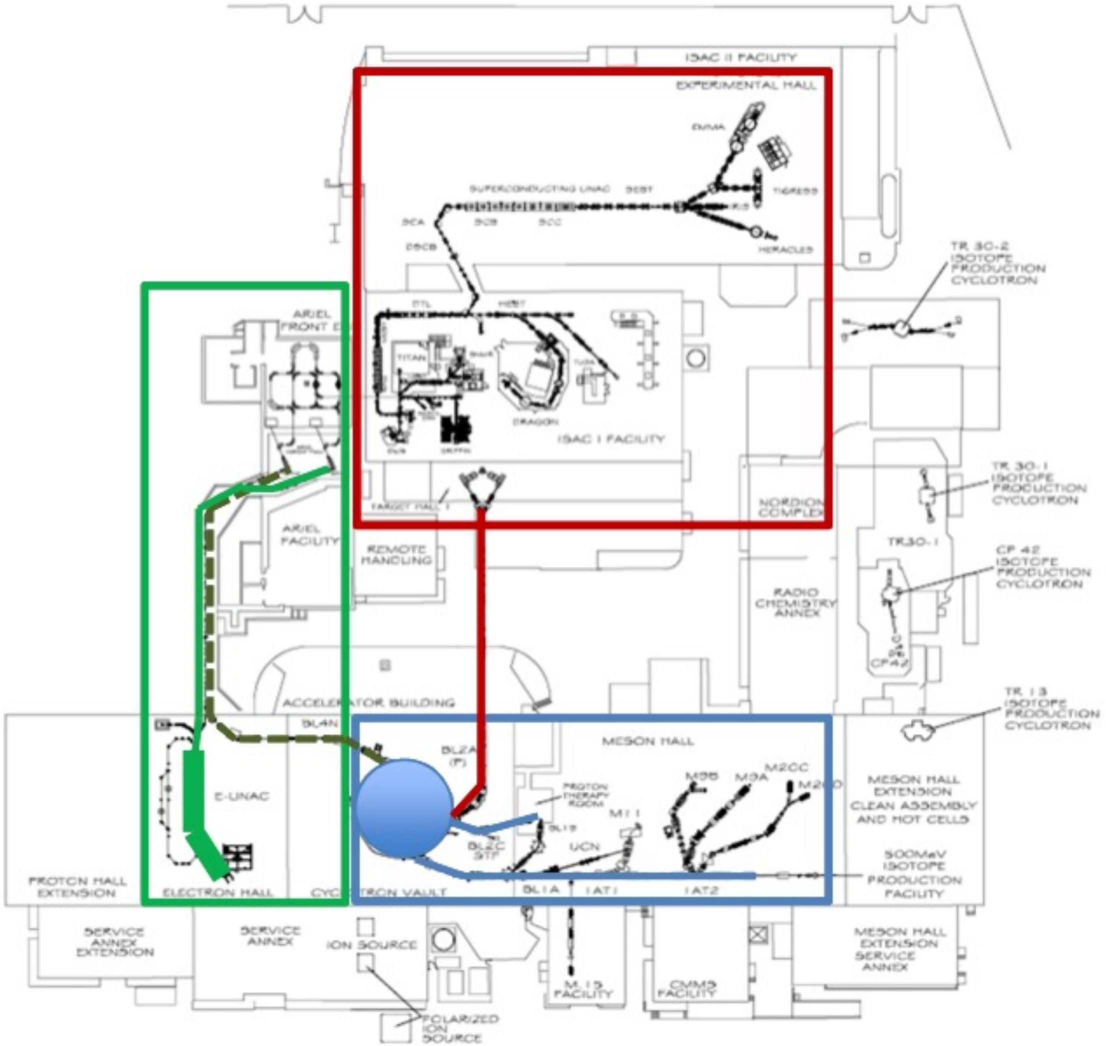
- We advance isotope science and technology, both fundamental and applied.
- We collaborate across communities and disciplines, from nuclear and particle physics to the life and material sciences.
- We discover and innovate, inspire and educate, creating knowledge and opportunity for all.

- Home to ~600 staff and students from 30 countries
- > 200 students & post-doctoral researchers

TRIUMF

TRIUMF history

- **500 MeV cyclotron** since 1974
  - One of the three Meson factories built at the same time – including LAMPF and PSI
- **Isotope Separator and ACcelerator (ISAC)** since 1995
  - Radioactive ion beam (RIB) facility
  - Driven by 500 MeV protons from cyclotron
- **Advanced Rare Isotope Facility (ARIEL)** in progress since 2010



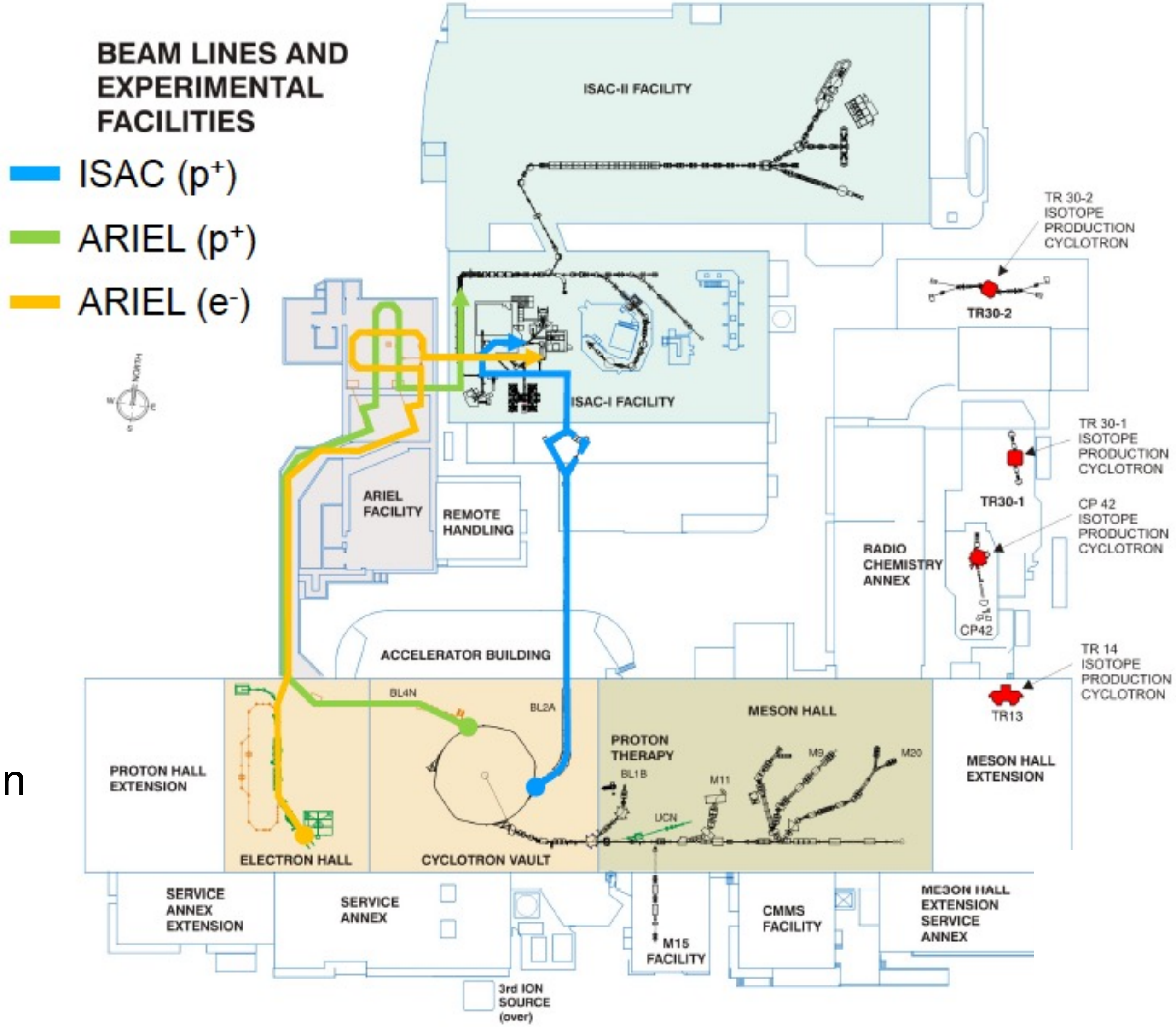
Advanced Rare Isotope Facility (ARIEL)

TRIUMF's flagship project

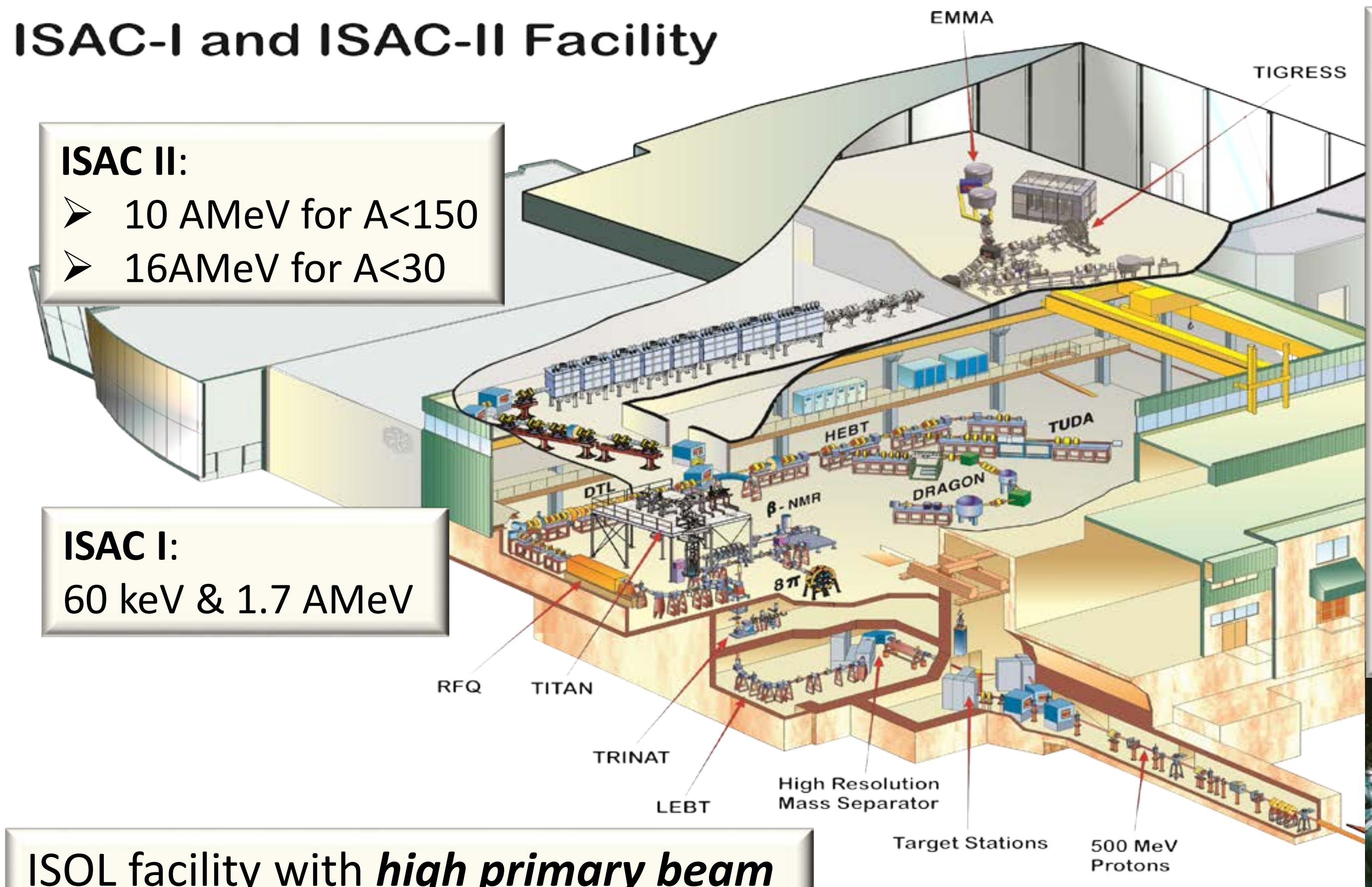
Substantially expands RIB capabilities:

- Simultaneous RIB production from 3 targets
  - 50 kW existing ISAC proton target
  - 50 kW new ARIEL proton target
  - 100 kW new ARIEL electron target
- More beam hours for science
- Multi-user capability with more and new isotopes for
  - Nuclear Physics (Structure, Nucl. Astro, Fund. Sym.)
  - Materials Science, Life Sciences
- Project completion in 2026 with phased implementation, interleaving science with construction

TRIUMF accelerator complex



TRIUMF ISAC/ARIEL Experiments

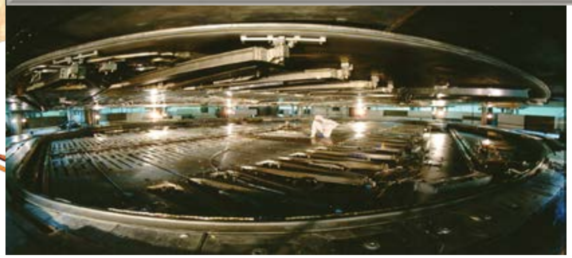


ISAC II:
- 10 AMeV for A<150
- 16AMeV for A<30

ISAC I:
60 keV & 1.7 AMeV

ISOL facility with ***high primary beam intensity*** (100 μA, 500 MeV, p)

Programs in
- Nuclear Structure & Dynamics
- Nuclear Astrophysics
- Electroweak Interaction Studies
- Material Science
- 16 permanent experiments



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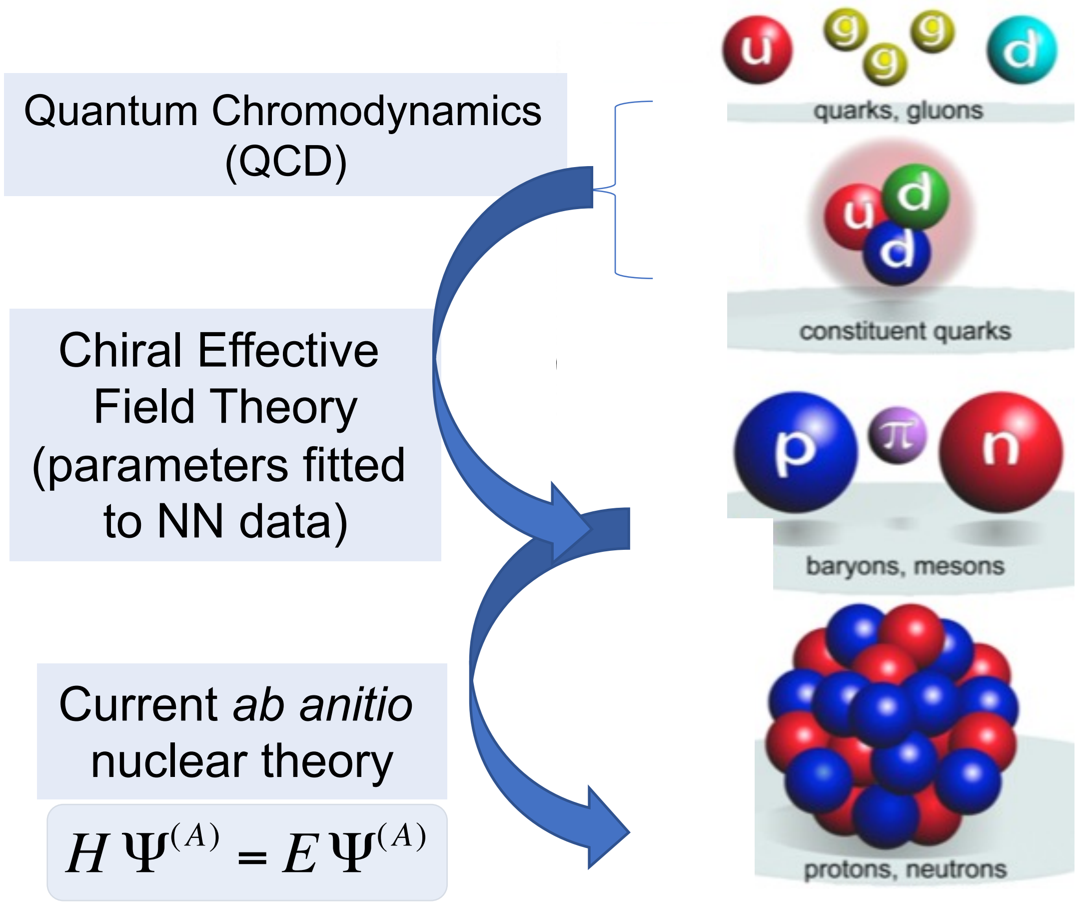
TRIUMF Theory

- First principles or *ab initio* nuclear theory
  - Input NN+3N interactions from chiral EFT
  - Solving many-nucleon Schrodinger equation
    - Quantum many-body problem
- Unique to TRIUMF nuclear theory:
  - Unified approach to nuclear structure and reactions for light nuclei: No-Core Shell Model with Continuum (NCSMC)
  - Powerful valence-space method for medium mass nuclei: Valence-Space In-Medium Similarity Renormalization Group (VS-IMSRG)
- Large-scale high-performance computation
  - Massively parallel codes
  - Summit@ORNL, Quartz@Livermore Computing, Cedar@Compute Canada

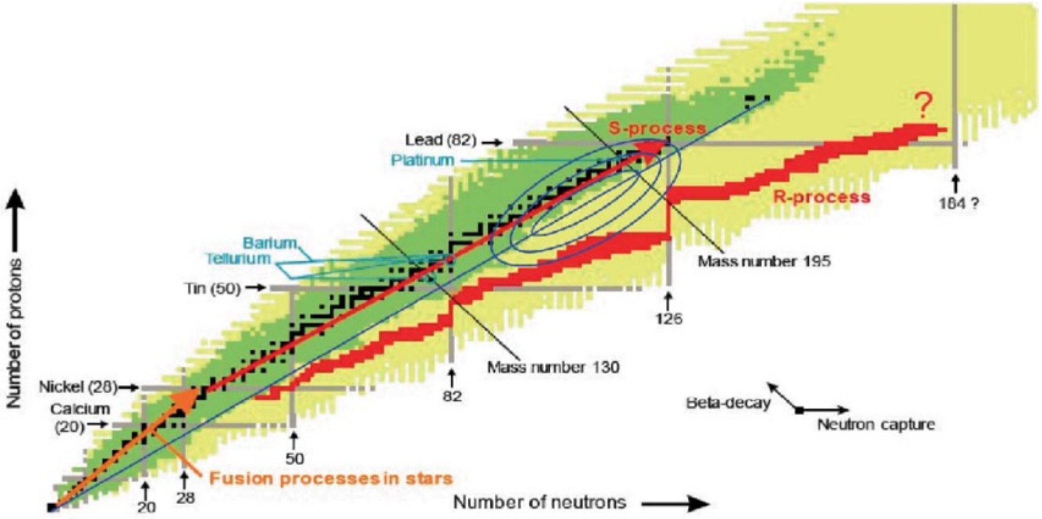


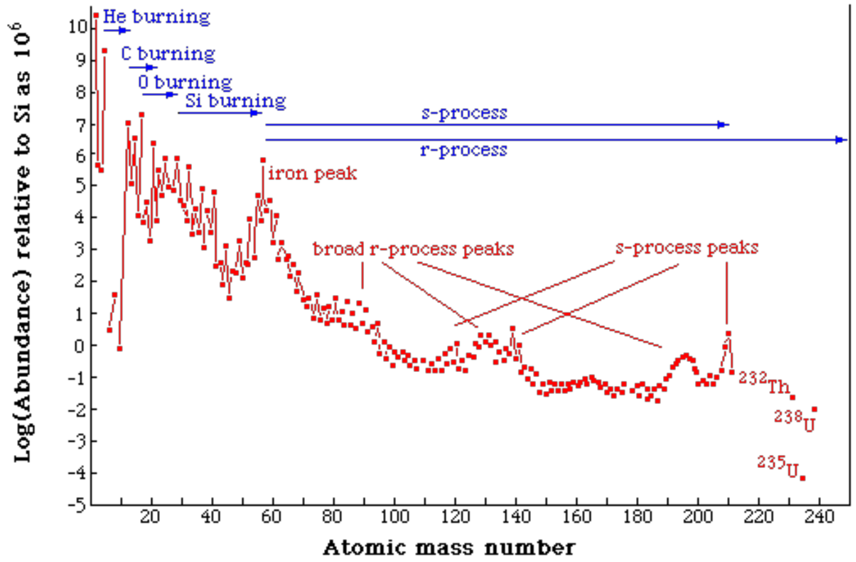
See presentations by Mack Atkinson, Peter Gysbers, Ragnar Stroberg, Michael Gennari (poster), Antoine Belley, Lotta Jokiniemi, Chloe Hebborn

TRIUMF Theory

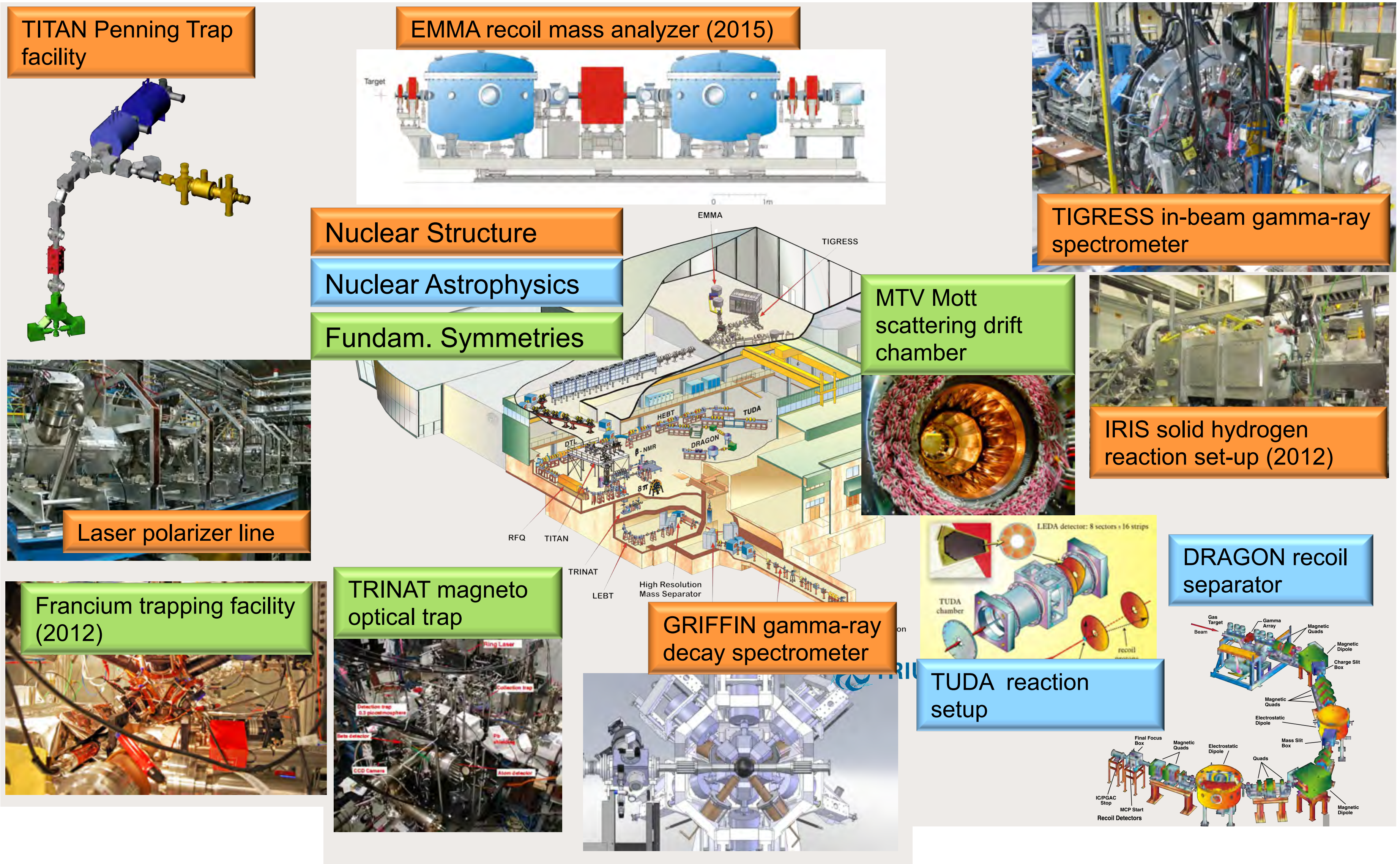
- Nuclear astrophysics
  - r-process nucleosynthesis
- Particle physics
  - Dark matter physics, collider phenomenology, neutrino physics, particle cosmology, hadronic physics

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + i\bar{\Psi}\not{D}\Psi + \bar{\Psi}_i y_{ij}\Psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

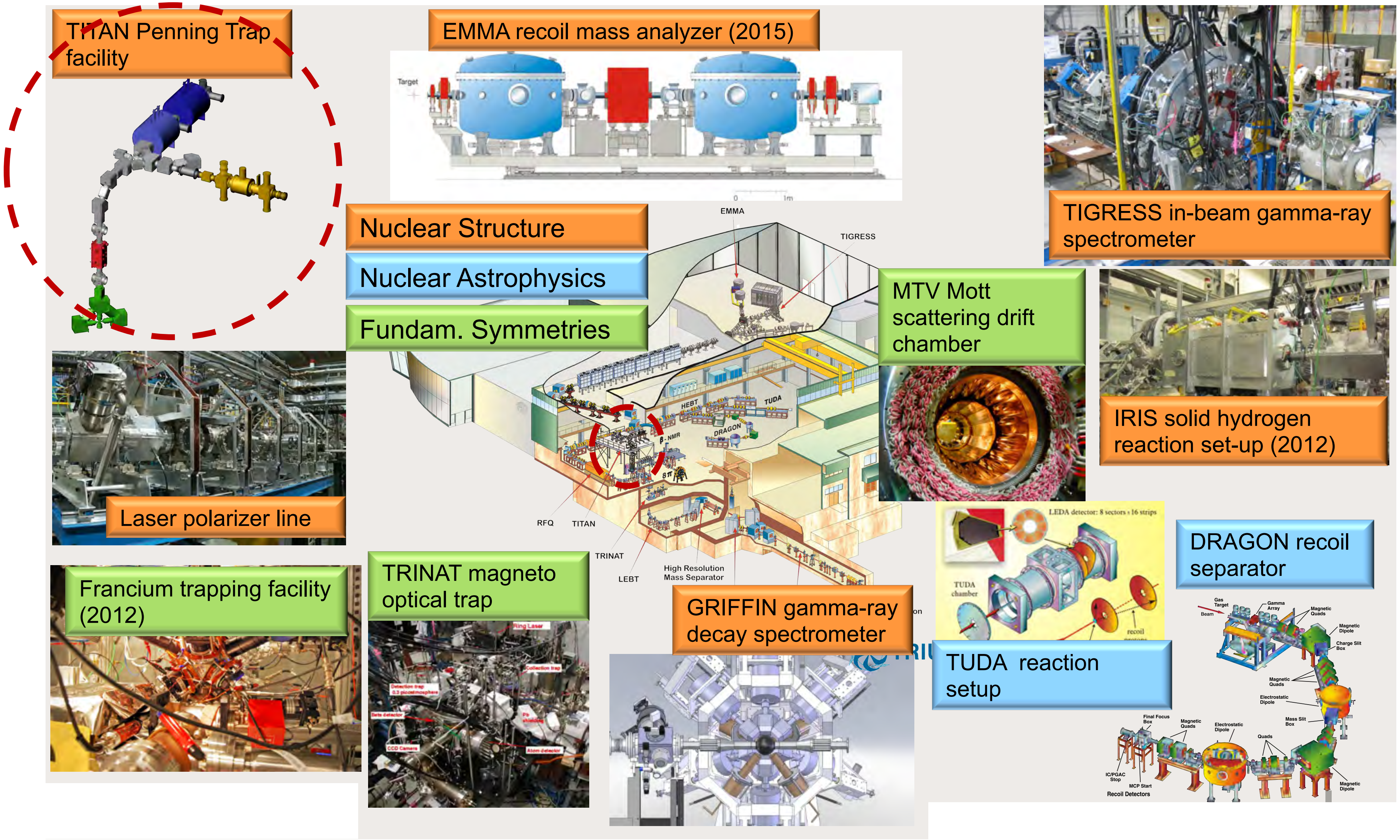




Leading edge ISAC experiments



Leading edge ISAC experiments



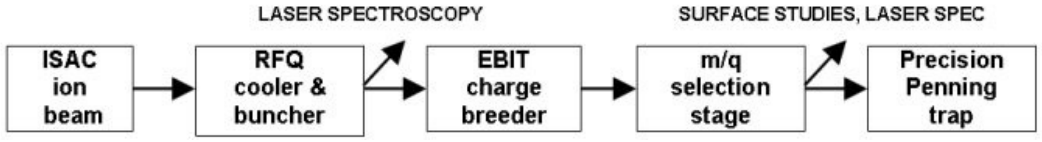
TRIUMF’s Ion Trap for Atomic & Nuclear science (TITAN)

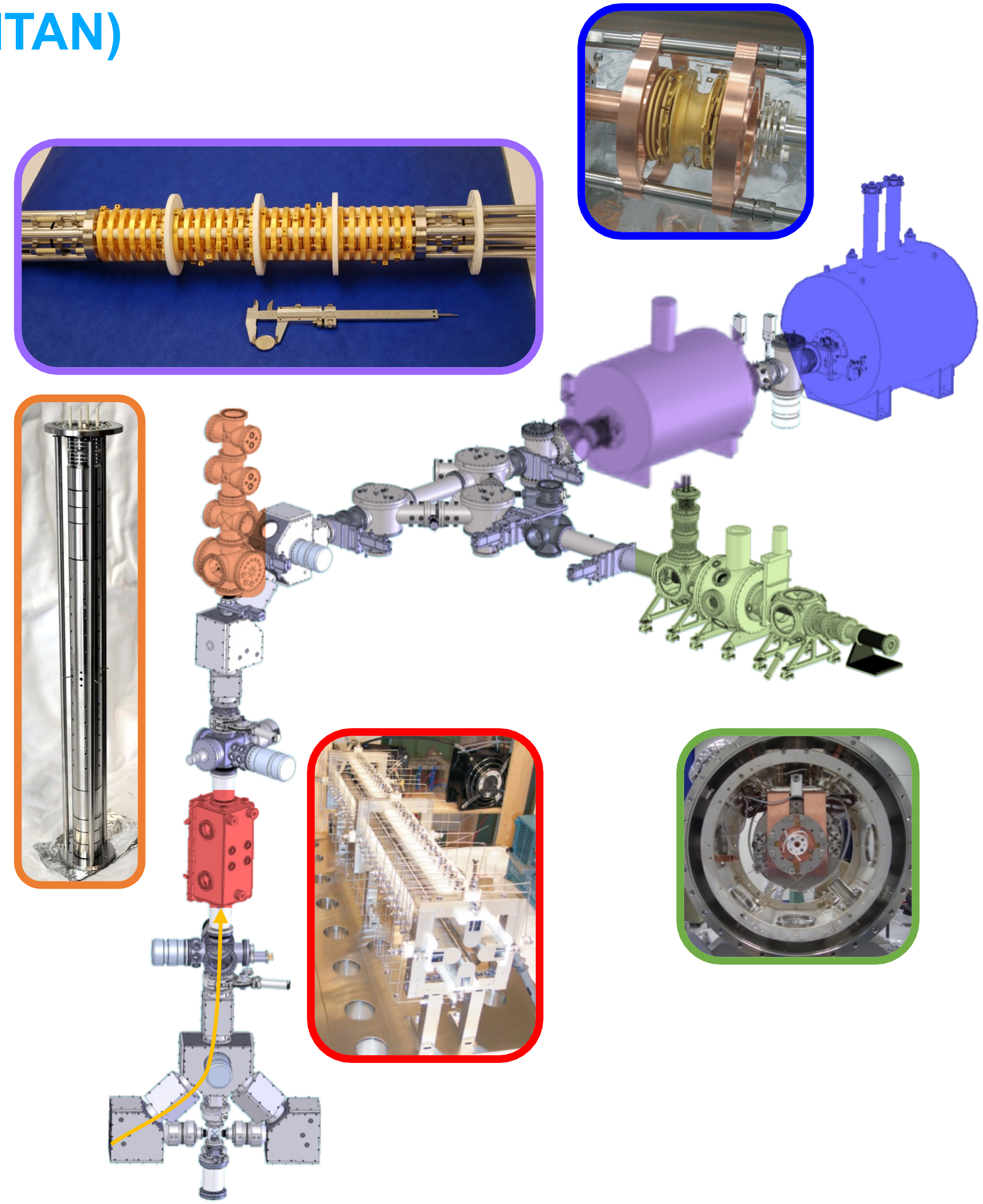
Scientific goals rely on access to radioactive beams.

- Evolution of nuclear shells away for rare isotopes
- Exotic nuclear structure like halo nuclei
- Nuclear astrophysics and nucleosynthesis
- High-precision tests of the Standard Model

Atomic-physics techniques executed in ≥5 ms

- High-precision Penning trap mass spectrometry
- Precision mass determinations through Multi-Reflection Time-of-Flight measurements
- In-ion-trap decay spectroscopy

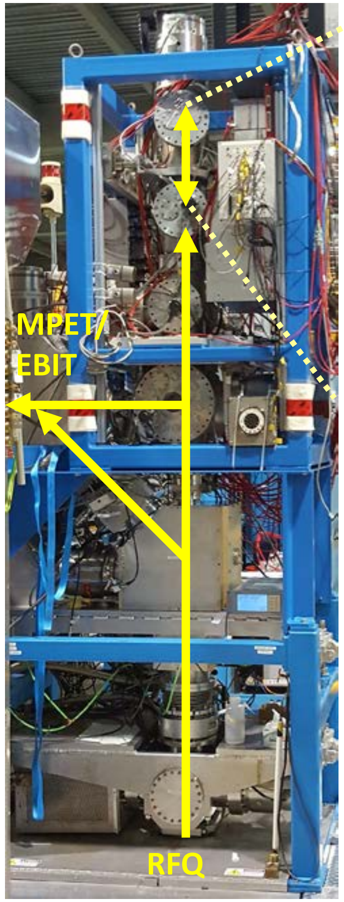




TRIUMF's Ion Trap for Atomic & Nuclear science (TITAN)

Recent research highlight

TITAN: precision mass measurement to test fundamental nuclear physics

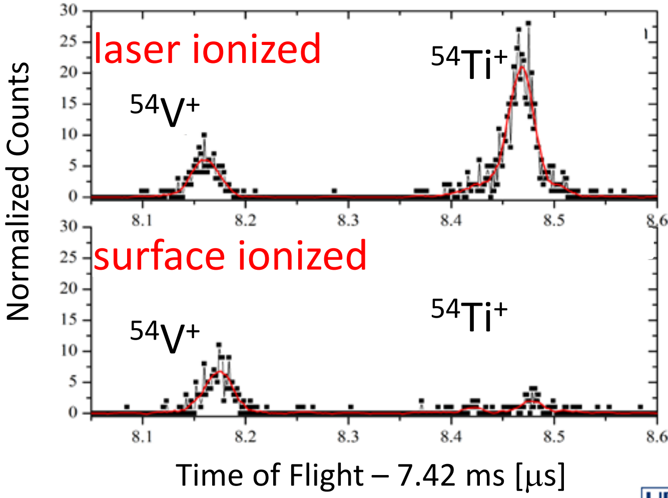


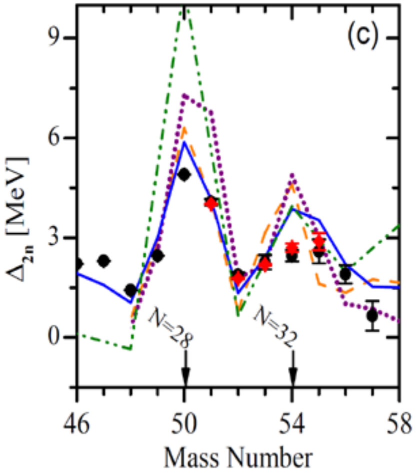
- MR-TOF successfully commissioned on-line
- 3 successful RIB experiments
- Verified accuracy w/ Penning trap mass spectrometry
- Investigation of N=32 shell closure in Ti isotopes

PHYSICAL REVIEW LETTERS **120**, 062503 (2018)

Dawning of the $N = 32$ Shell Closure Seen through Precision Mass Measurements of Neutron-Rich Titanium Isotopes

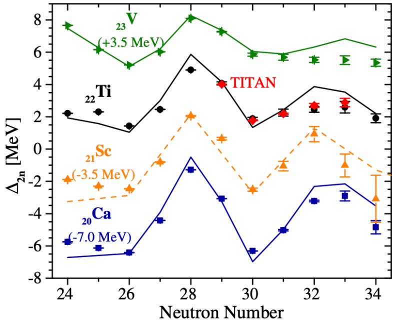
E. Leistenschneider,[1,2,*] M. P. Reiter,[1,3] S. Ayet San Andrés,[3,4] B. Kootte,[1,5] J. D. Holt,[1] P. Navrátil,[1] C. Babcock,[1] C. Barbieri,[6] B. R. Barquest,[1] J. Bergmann,[3] J. Bollig,[1,7] T. Brunner,[1,8] E. Dunling,[1,9] A. Finlay,[1,2] H. Geissel,[3,4] L. Graham,[1] F. Greiner,[3] H. Hergert,[10] C. Hornung,[3] C. Jesch,[3] R. Klawitter,[1,11] Y. Lan,[1,2] D. Lascar,[1,†] K. G. Leach,[12] W. Lippert,[3] J. E. McKay,[1,13] S. F. Paul,[1,7] A. Schwenk,[11,14,15] D. Short,[1,16] J. Simonis,[17] V. Somà,[18] R. Steinbrügge,[1] S. R. Stroberg,[1,19] R. Thompson,[20] M. E. Wieser,[20] C. Will,[3] M. Yavor,[21] C. Andreoiu,[16] T. Dickel,[3,4] I. Dillmann,[1,13] G. Gwinner,[5] W. R. Plaß,[3,4] C. Scheidenberger,[3,4] A. A. Kwiatkowski,[1,13] and J. Dilling[1,2]





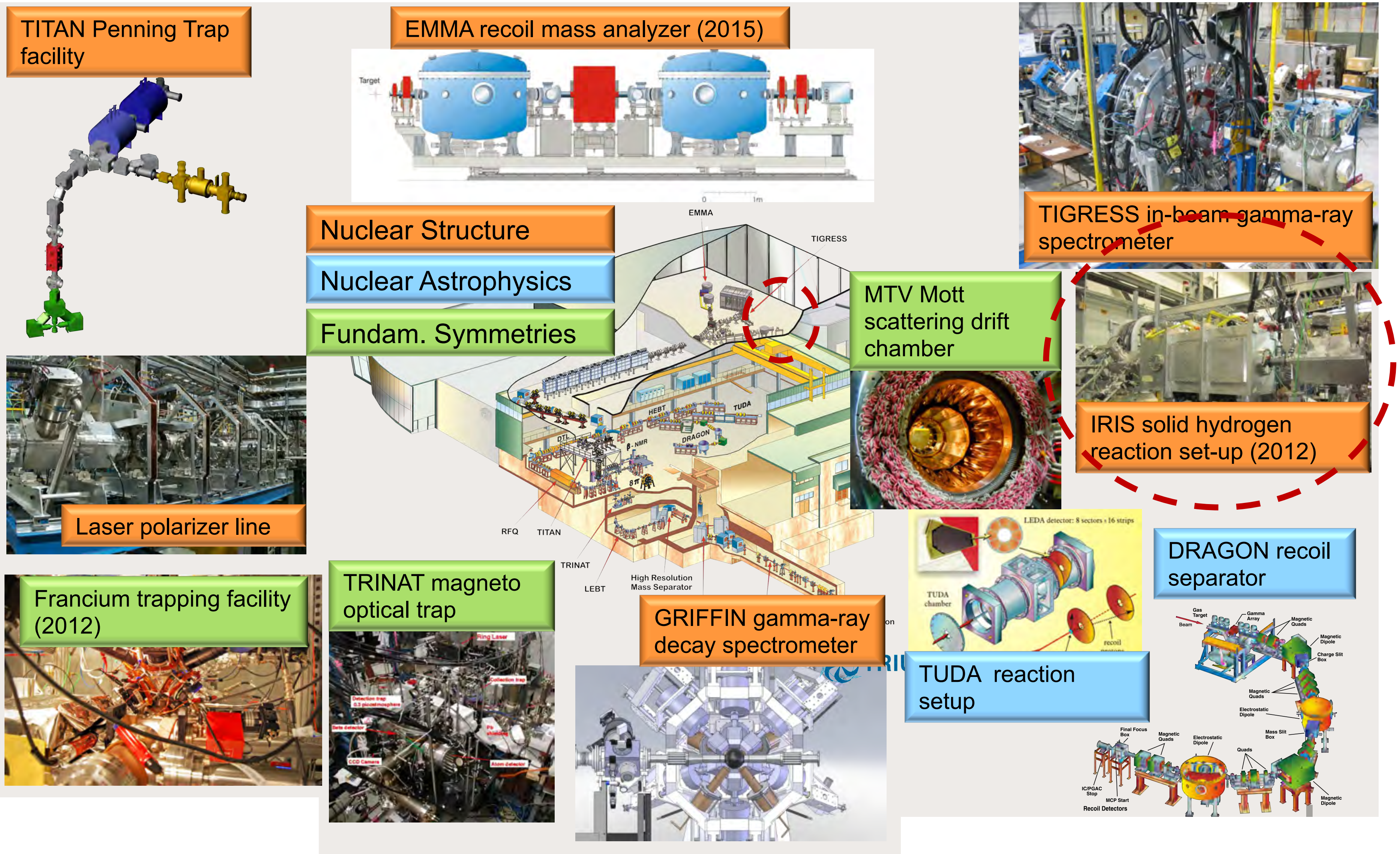
theory and experiment

- ● TITAN ◆ AME
- 1.8/2.0 (EM) VS-IMSRG
- NN+3N (lnl) GGF
- N^2LO_{sat} GGF
- N^2LO_{sat} MR-IMSRG



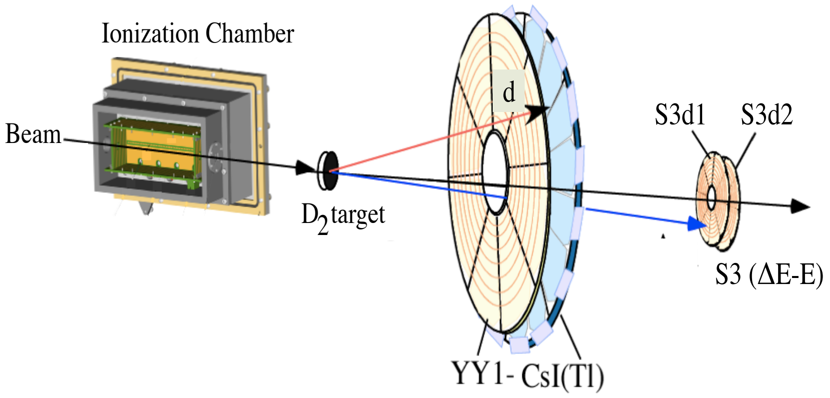
TRIUMF · UBC · University of Manitoba · Max-Planck-Institut für Kernphysik Heidelberg · University of Calgary · Justus-Liebig Universität Giessen · Colorado School of Mines · McGill University · Westfälische Wilhelms-Universität Münster · SFU · university of groningen · University of Notre Dame

Leading edge ISAC experiments



IRIS Innovative Rare Isotope reaction Spectroscopy facility

- Rare isotope reaction spectroscopy station
  - Lead by St. Mary's University
  - Commissioned in 2012
- Reactions with a frozen (solid) windowless hydrogen or deuterium target
- Charged particle spectrometer
  - Silicon strip detectors and CsI(TI) detectors



IRIS reaction spectroscopy facility – recent research highlight

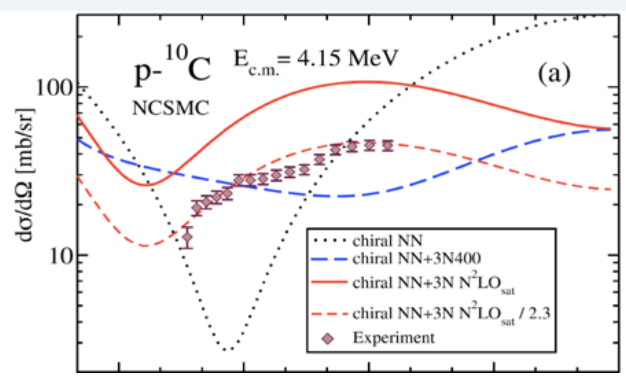
Selected for a Viewpoint in *Physics*
PRL **118,** 262502 (2017) PHYSICAL REVIEW LETTERS week ending 30 JUNE 2017

Nuclear Force Imprints Revealed on the Elastic Scattering of Protons with ^{10}C

A. Kumar,[1] R. Kanungo,[1*] A. Calci,[2] P. Navrátil,[2†] A. Sanetullaev,[1,2] M. Alcorta,[2] V. Bildstein,[3] G. Christian,[2] B. Davids,[2] J. Dohet-Eraly,[2,4] J. Fallis,[2] A. T. Gallant,[2] G. Hackman,[2] B. Hadinia,[3] G. Hupin,[5,6] S. Ishimoto,[7] R. Krücken,[2,8] A. T. Laffoley,[3] J. Lighthall,[2] D. Miller,[2] S. Quaglioni,[9] J. S. Randhawa,[1] E. T. Rand,[3] A. Rojas,[2] R. Roth,[10] A. Shotter,[11] J. Tanaka,[12] I. Tanihata,[12,13] and C. Unsworth[2]

Testing fundamental nuclear physics theory:
Led by R. Kanungo, St. Mary’s University

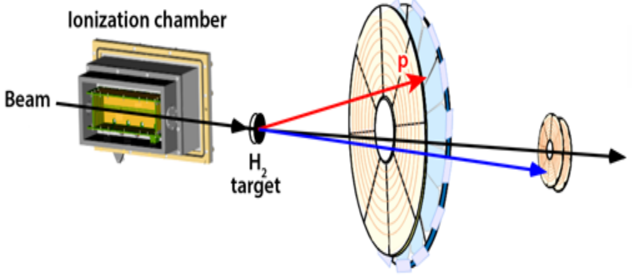
- **IRIS charged particle spectrometer**
- **Windowless solid hydrogen target**
- ^{10}C beam, 4.5 MeV/u from TRIUMF-ISAC-II

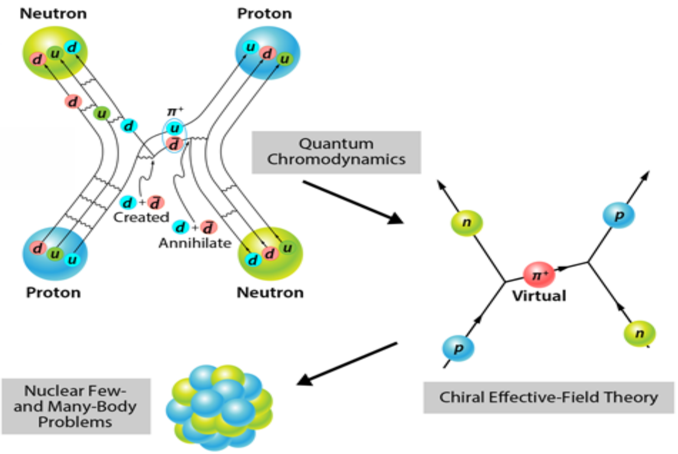


Theory from TRIUMF
- Ab initio with modern two- and three-nucleon forces

NN alone wrong – overpredicts fringe contrast

NN and 3N fit simultaneously : **shape correct** but fails to reproduce magnitude





SAINT MARY’S UNIVERSITY SINCE 1802 One University. One World. Yours.
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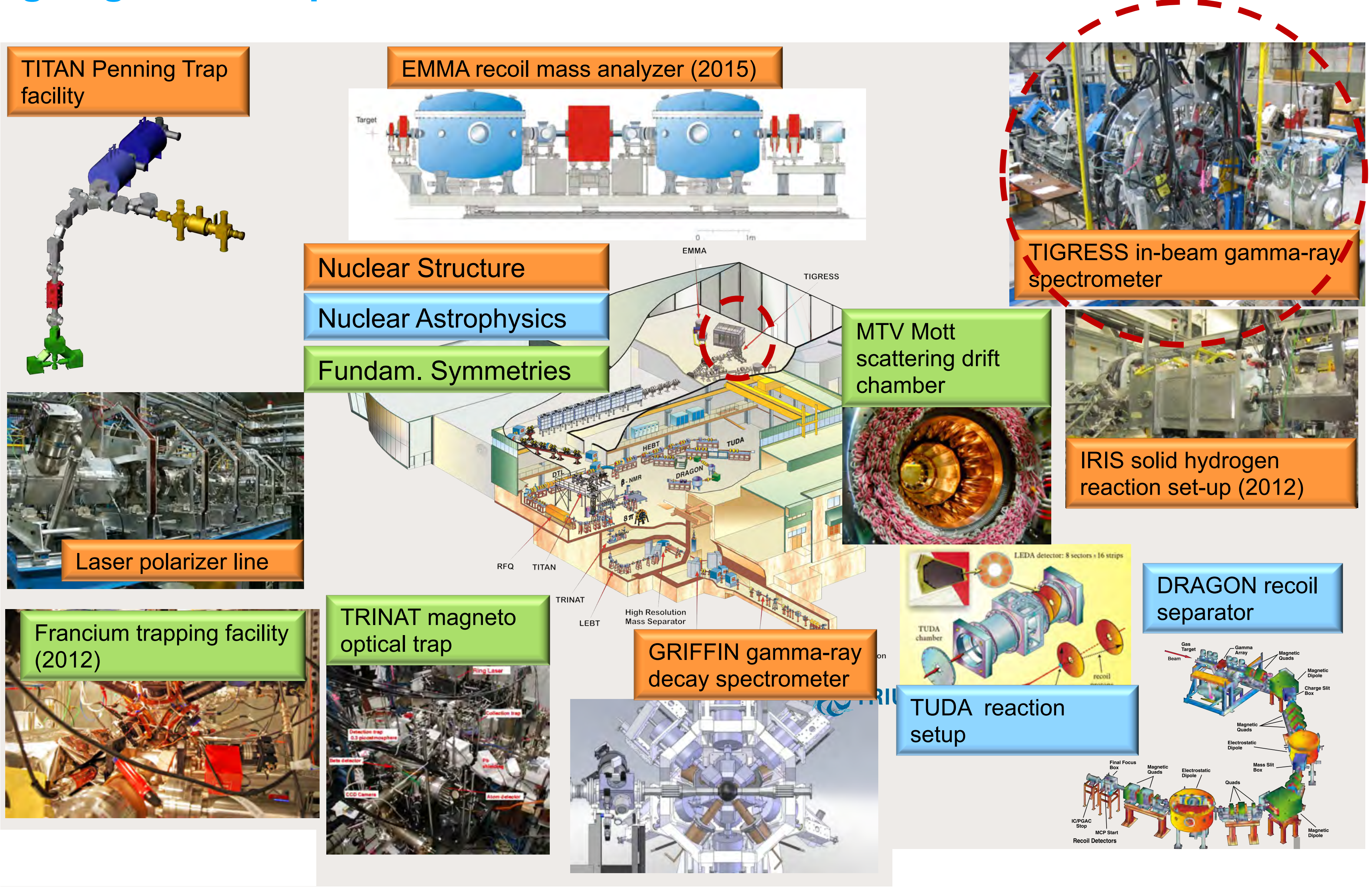
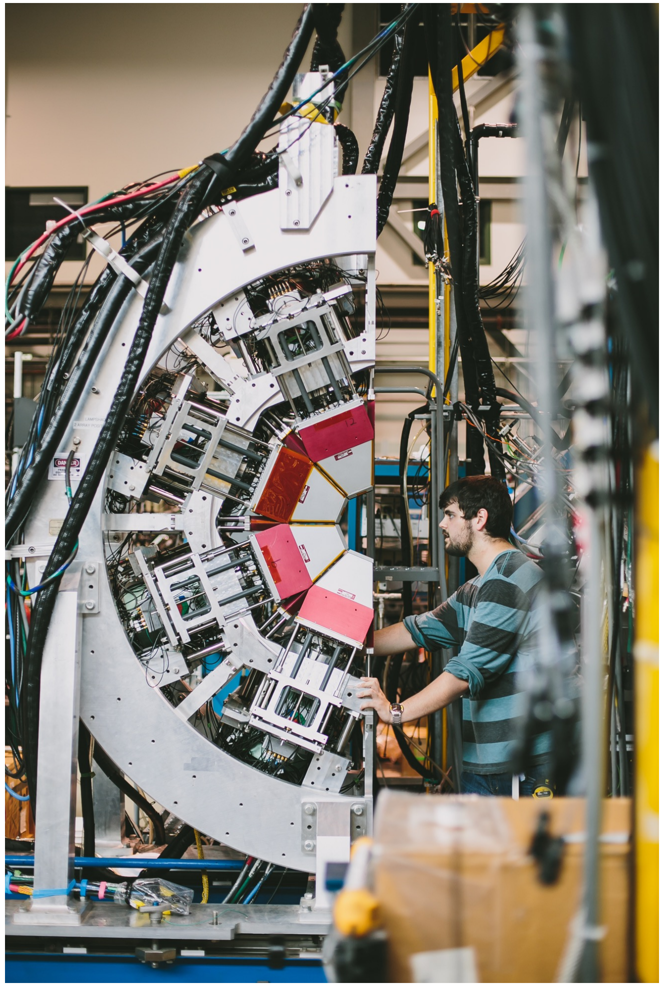
McMaster University
SFU SIMON FRASER UNIVERSITY
KEK-JAPAN
RCNP
THE UNIVERSITY OF EDINBURGH
TRIUMF
GANIL GRAND ACCELERATEUR NATIONAL D'IONS LOURDS

Leading edge ISAC experiments



TIGRESS: High efficiency and high energy-resolution gamma ray spectrometer

- TRIUMF-ISAC Gamma-Ray Escape Suppressed Spectrometer (TIGRESS)
- Array of 32-fold segmented high-purity germanium (HPGe) gamma-ray detectors
- The ability to determine gamma-ray interaction locations within the TIGRESS detectors enables accurate correction of the measured gamma-ray energies for the Doppler shifts
- Excellent gamma-ray energy resolution
- Very high gamma-ray detection efficiency
- Compton suppression shields from scintillator crystals bismuth germanate (BGO) and cesium iodide (CsI).



To work towards a complete theory of nuclear matter, we study shapes and modes of excitation of exotic nuclei

To understand heavy element nucleosynthesis, we study reaction and structure properties of exotic nuclei

We study these inner workings of exotic nuclei by measuring de-excitation gamma rays following high energy collisions

TIGRESS: High efficiency and high energy-resolution gamma ray spectrometer

Designed for experiments with exotic nuclei at ~10% speed of light

Research highlights – Nuclear Physics: TIGRESS Standalone Experiment – Coulex of ^{23}Mg & ^{23}Na

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covering nuclear physics
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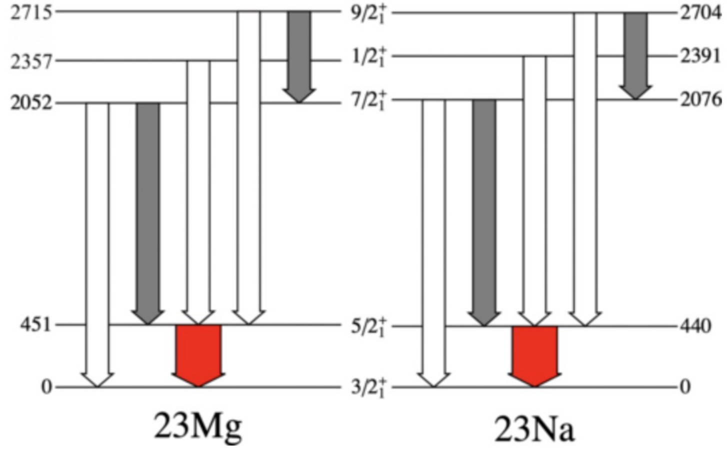
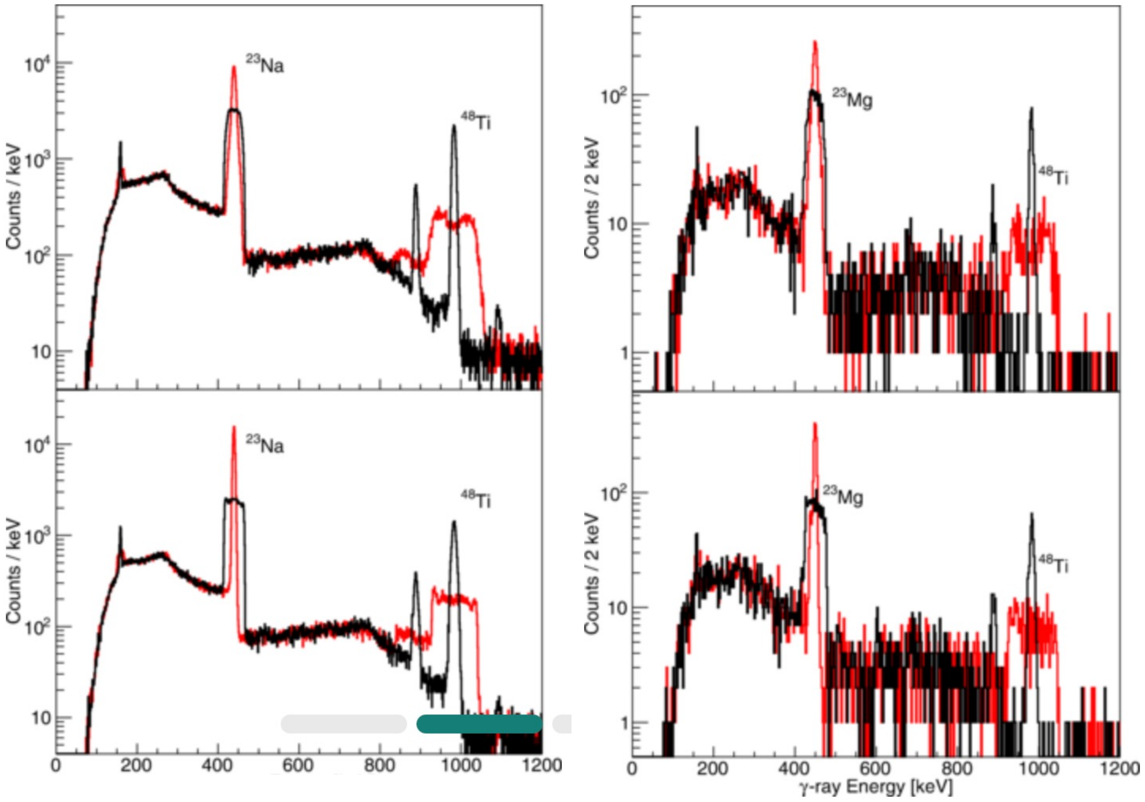
Coulomb excitation of the $|T_z| = \frac{1}{2},\ A = 23$ mirror pair

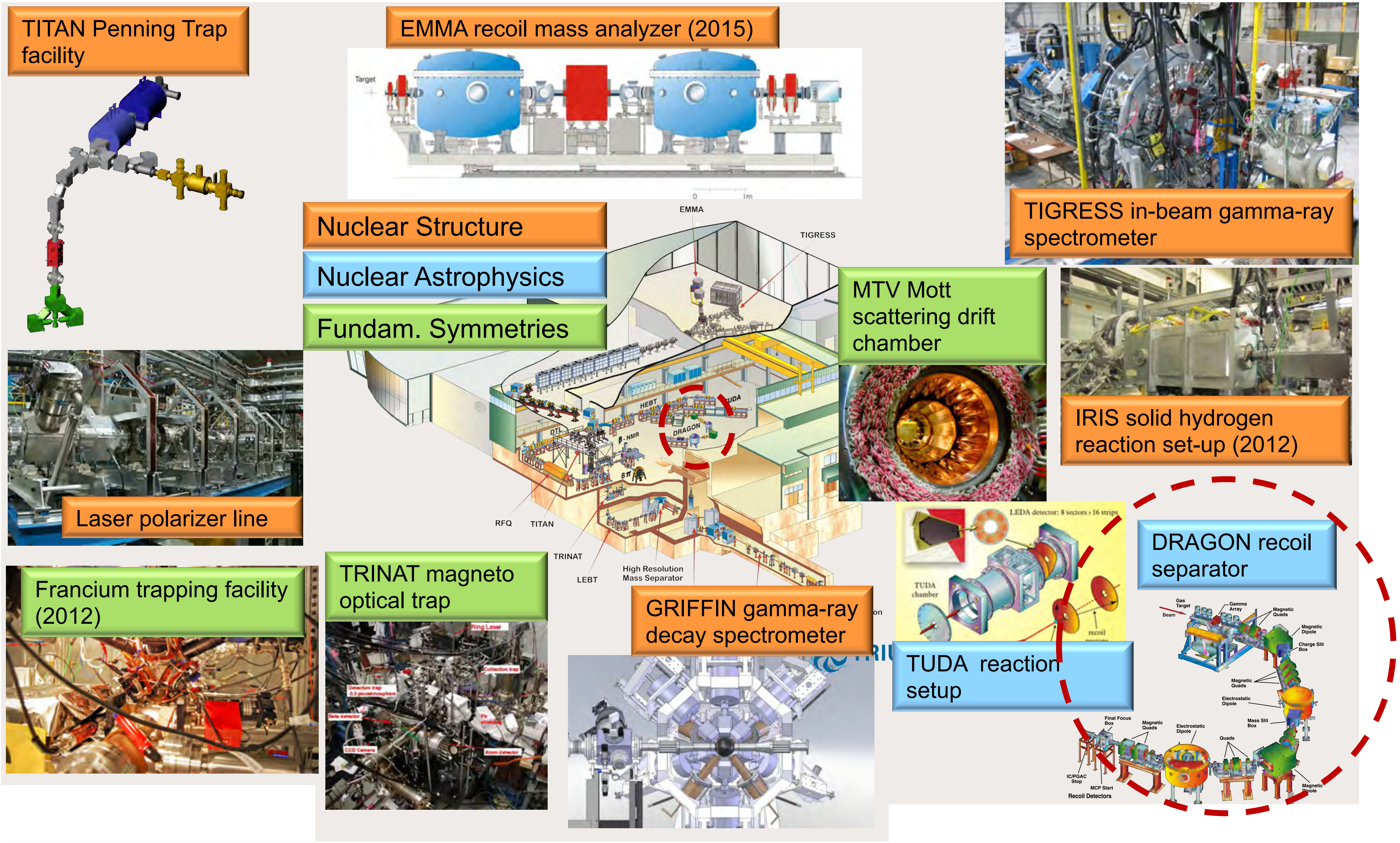
J. Henderson *et al.*
Phys. Rev. C **105**, 034332 – Published 28 March 2022





- Coulomb-excitation measurements of ^{23}Mg and ^{23}Na were performed at the TRIUMF-ISAC facility using the TIGRESS spectrometer. They were used to determine the E2 matrix elements of mixed E2/M1 transitions.
- Uncertainties from E2 strengths are some of largest in literature. Need to improve precision for better comparison with theory.
- Reduced E2 transition strengths, B(E2), were extracted for ^{23}Mg and ^{23}Na. Their precision was improved by factors of approximately 6 for both isotopes, while agreeing within uncertainties with previous measurements.
- **Conclusions:** A comparison was made with both shell-model and *ab initio* valence-space in-medium similarity renormalization group calculations. Valence-space in-medium similarity renormalization group calculations were found to underpredict the absolute E2 strength, in agreement with previous studies.

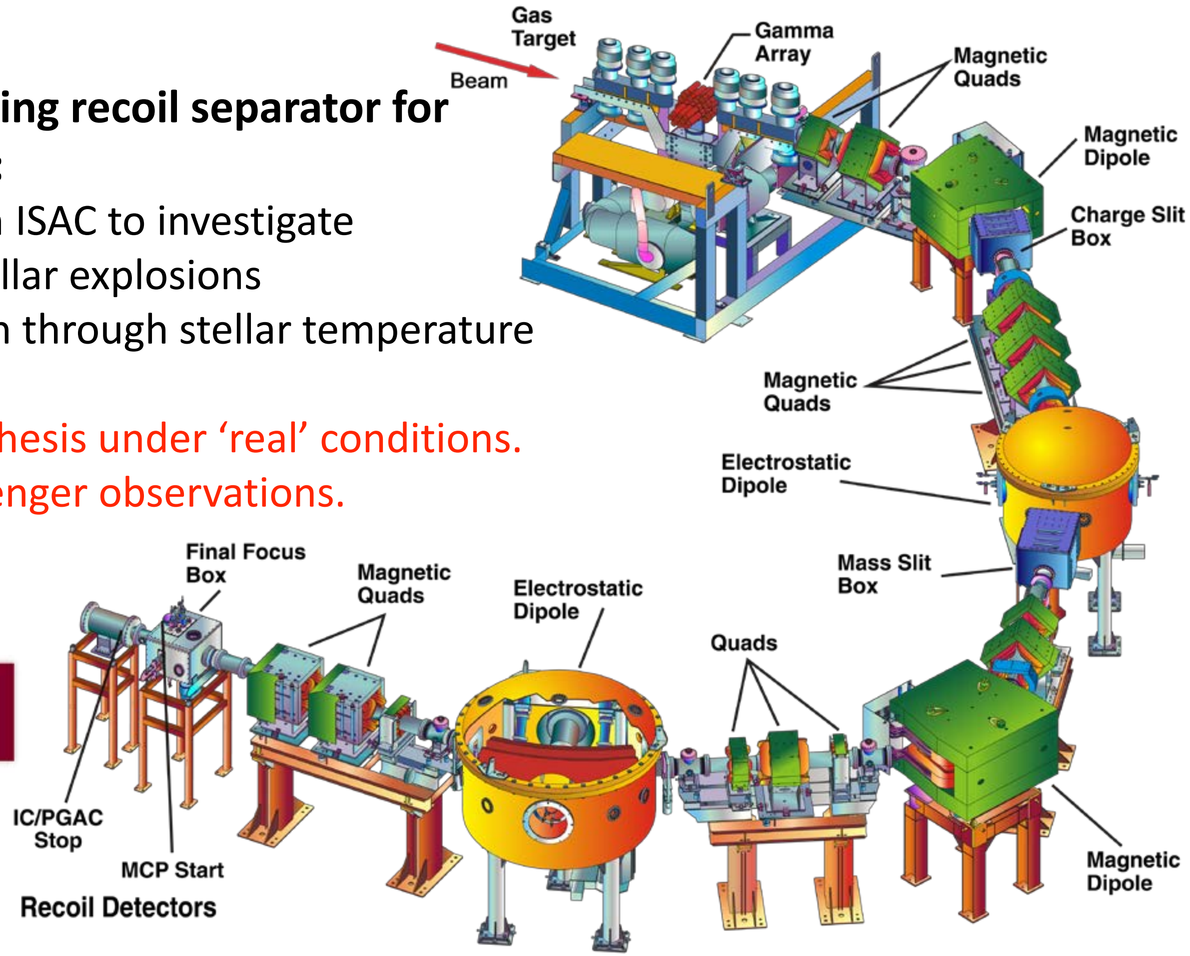
Leading edge ISAC experiments



DRAGON – Detector of Recoils And Gammas Of Nuclear reactions

DRAGON: world's highest performing recoil separator for measuring stellar fusion reactions:

- Uses exotic short-lived beams from ISAC to investigate nucleosynthesis & behaviour of stellar explosions
- Vary incoming beam energy to scan through stellar temperature and observe reactions.
- Stepwise re-creation of nucleosynthesis under 'real' conditions.
- Compare outcomes to multi-messenger observations.



University of Surrey · The University of Edinburgh · McMaster University · TRIUMF · Colorado School of Mines · University of York

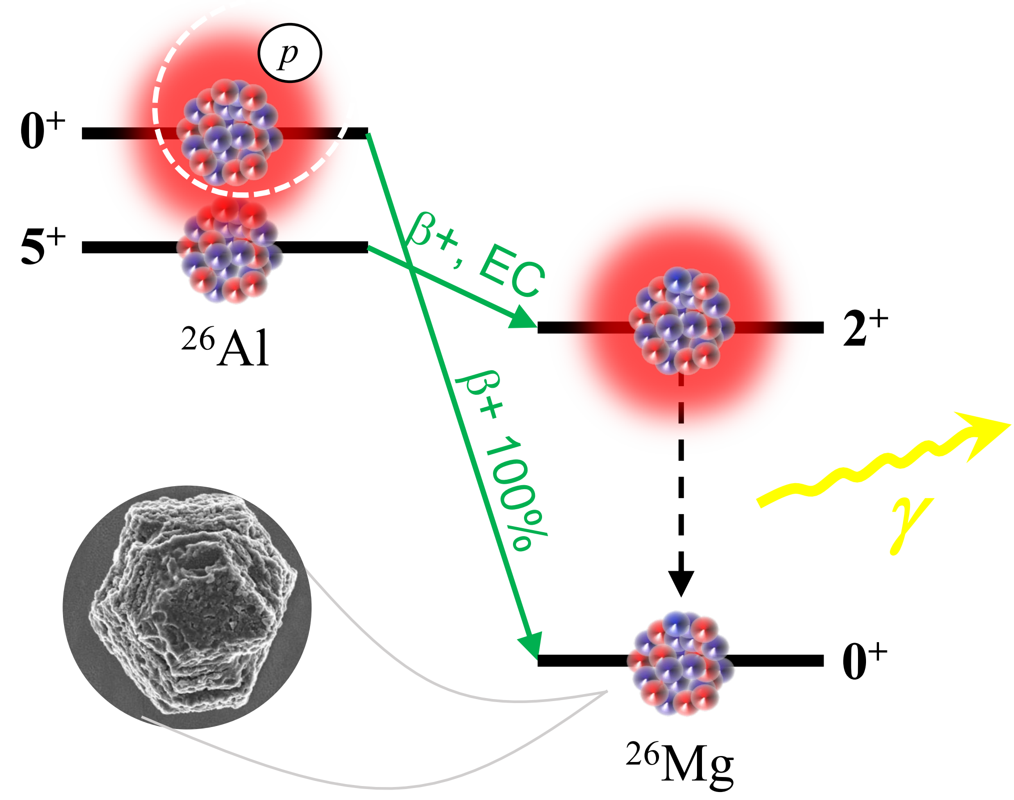
The astrophysical origin of ^{26}Al

Need to understand **production & destruction** of ^{26}Al in stellar scenarios!

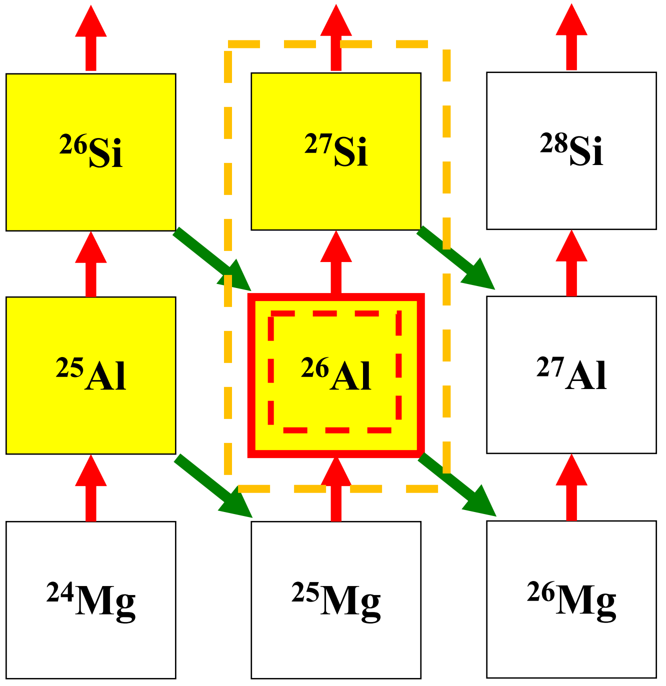
Nucleosynthesis of ^{26}Al is complicated by the presence of an isomer (E_x = 228.31(3) keV)

- Experimental physics has focused on nuclear ground states

^{26m}Al(p,γ)

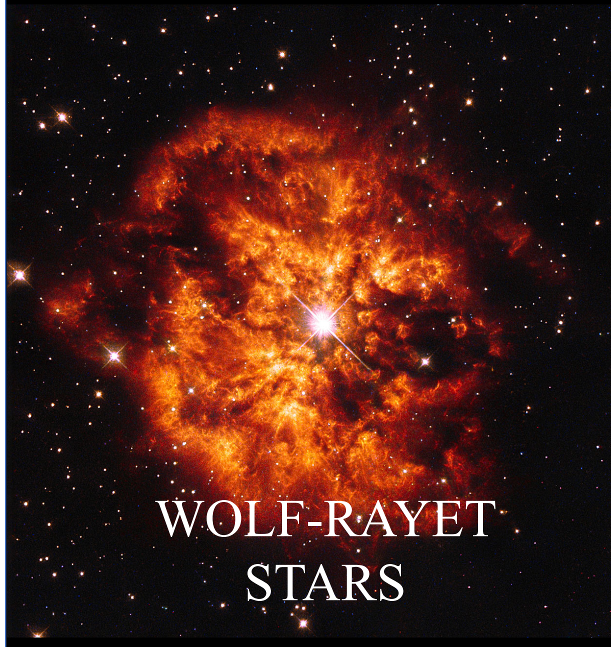


Courtesy of A. Lennartz



➔ Need to measure proton capture on excited quantum state of ^{26}Al

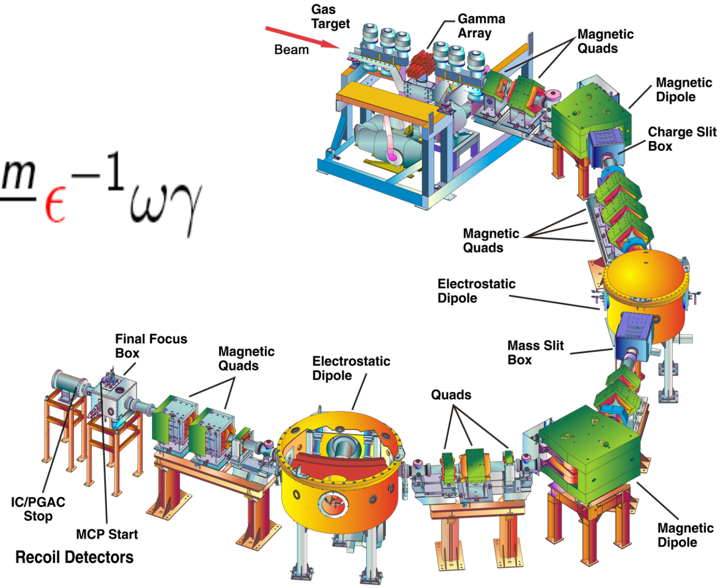
EXTREME EXPERIMENTAL CHALLENGE



DRAGON – Detector of Recoils and Gammas of Nuclear Reactions

$$Y(\infty) = \frac{\lambda^2}{2}\frac{M+m}{m}\epsilon^{-1}\omega\gamma$$

#reactions per incident ion



$$N_A\langle\sigma\upsilon\rangle = 1.54\times10^{11}\left(\mu T\right)^{-3/2}\omega\gamma\cdot\exp\left(-11.605\frac{E_R}{T_9}\right)$$

- Incoming beam composed of ^{26m}Al, ^{26g}Al, ^{26}Na
- **Isomeric component was identified** by its associated β+ decay to the ^{26}Mg g.s.

Total beam on target:

- 6.21(2)E+14 incident ^{26}Al g.s. beam ions
- 7.5(2)E+10 incident ^{26m}Al beam ions

Present result for ωγ: **$E_{c.m.}$ = 447 keV resonance** governs the entire ^{26m}Al(*p*,γ) stellar reaction rate over the peak temperature range of classical novae and supernovae

PHYSICAL REVIEW LETTERS

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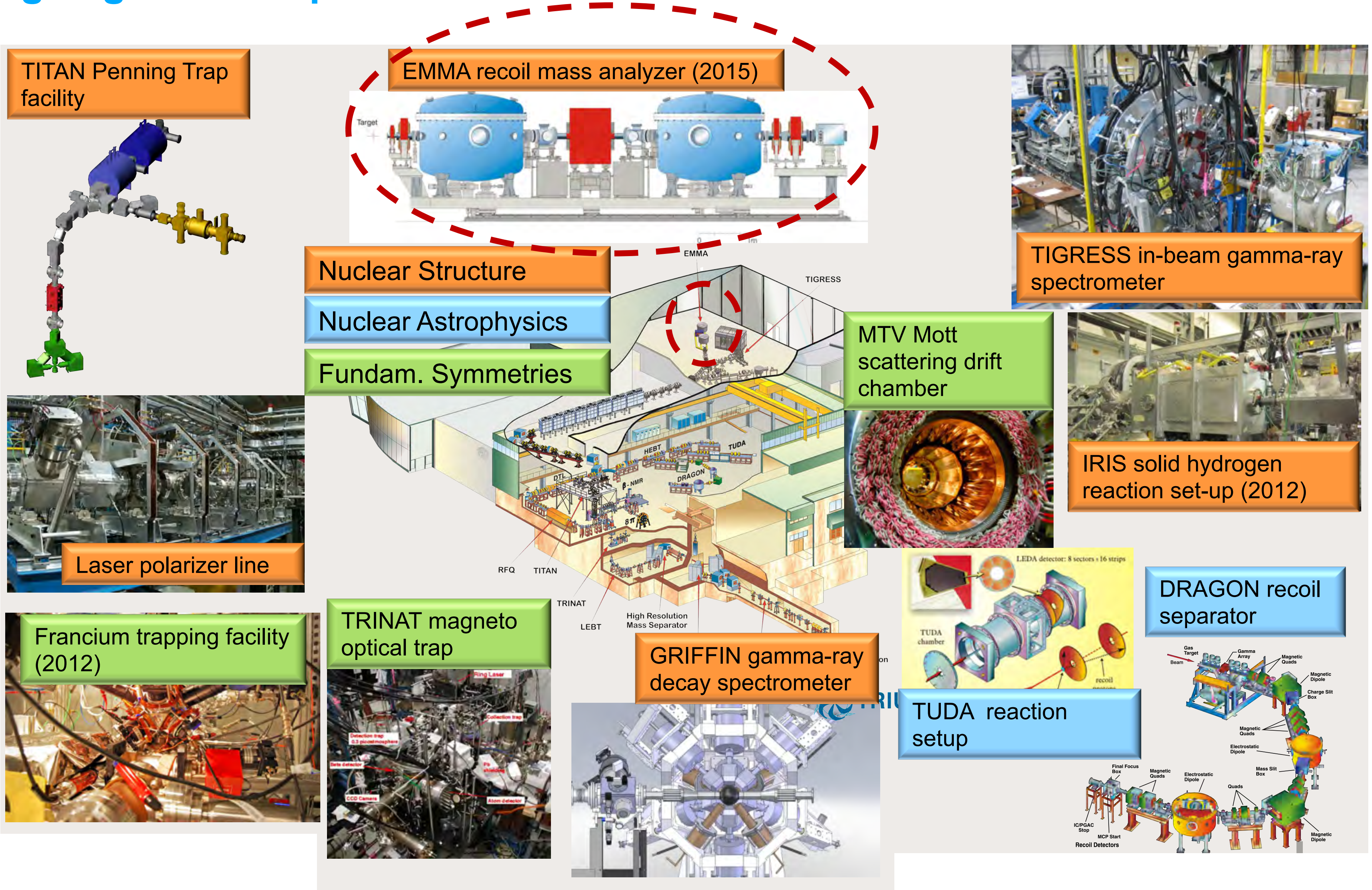
Radiative Capture on Nuclear Isomers: Direct Measurement of the $^{26m}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$ Reaction

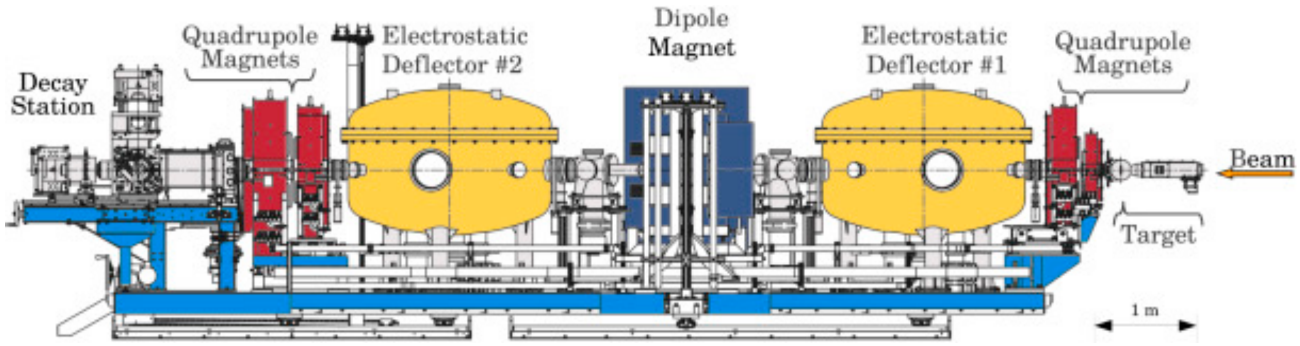
G. Lotay, A. Lennarz, C. Ruiz, C. Akers, A. A. Chen, G. Christian, D. Connolly, B. Davids, T. Davinson, J. Fallis, D. A. Hutcheon, P. Machule, L. Martin, D. J. Mountford, and A. St. J. Murphy

Phys. Rev. Lett. **128**, 042701 – Published 27 January 2022

Leading edge ISAC experiments

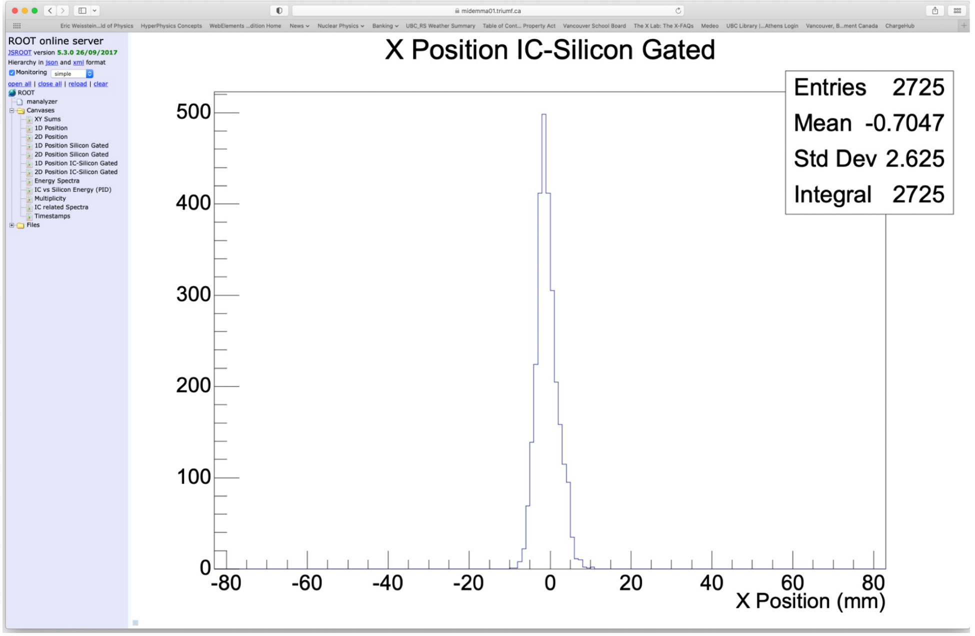


EMMA: Recoil Mass Spectrometer at ISACII



- EMMA (ElectroMagnetic Mass Analyser) in operation since 2017
- Study of transfer and fusion-evaporation reactions
  - Identify products of reactions by measuring their charge & mass
- 2^{nd} EMMA+TIGRESS RIB experiment
  - 84 MeV ^{21}Na RIB bombarded deuterated polyethylene target at 10^7 s^{-1}
  - EMMA transmitted ^{22}Na and ^{22}Mg recoils from (d,p) and (d,n) transfer reactions
  - > 10^5 recoils detected from a RIB induced reaction, a world record

^{22}Mg recoil position spectrum (1h of data)



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UNIVERSITY of GUELPH
McMaster University
TRIUMF

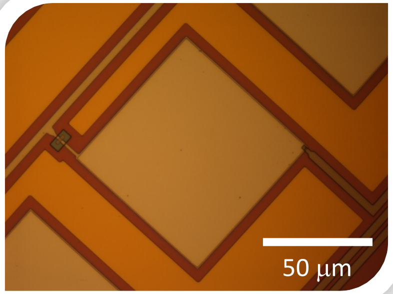
The BeEST Experiment

Rare-isotope implantation at TRIUMF-ISAC

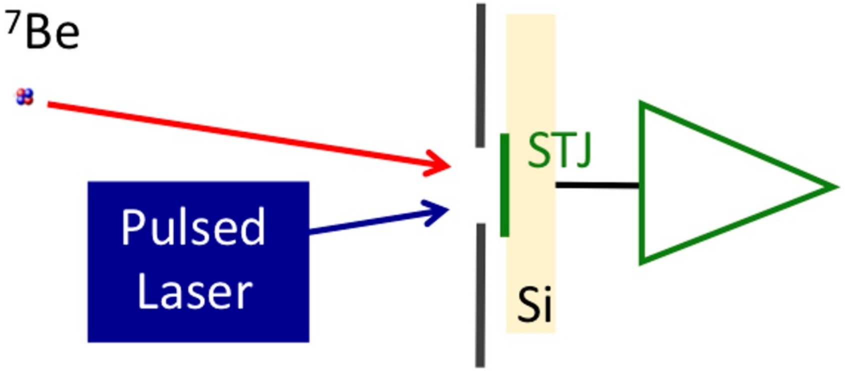
Beryllium Electron capture in Superconducting Tunnel junctions

K.G. Leach and S. Friedrich, arXiv:2112.02029 (2021)
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)
S. Fretwell *et al.*, Phys. Rev. Lett. **125**, 032701 (2020)

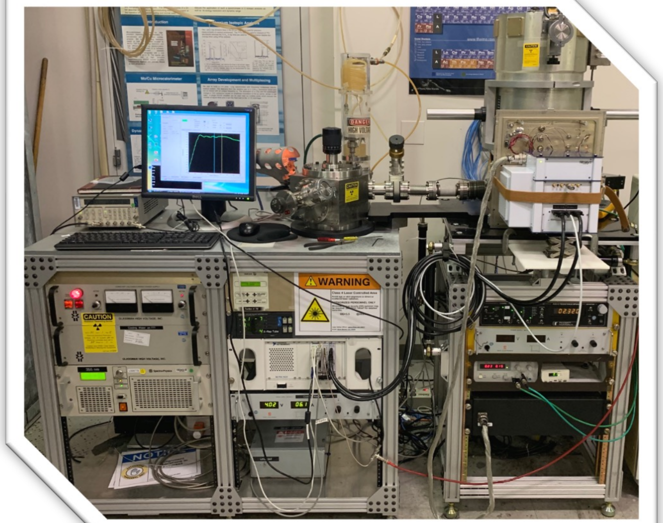
Ta, Al, and Nb-based STJ Sensors



STAR CRYOELECTRONICS



High-precision *In-situ* calibration and characterization

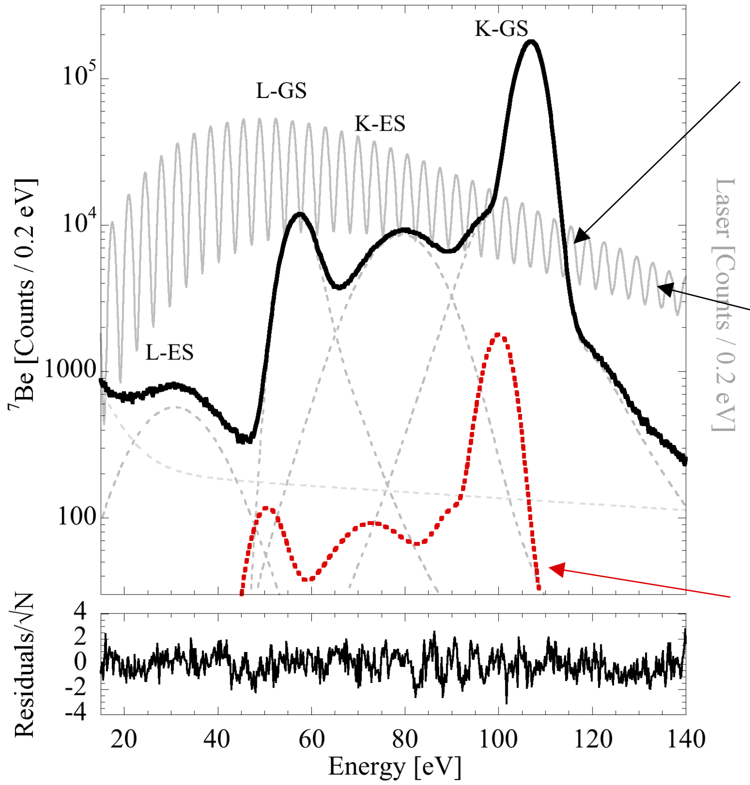


Cooling (<0.1 K) and measurement in ADR at LLNL

Courtesy of K. G. Leach

First Limits from BeEST Phase-II Data

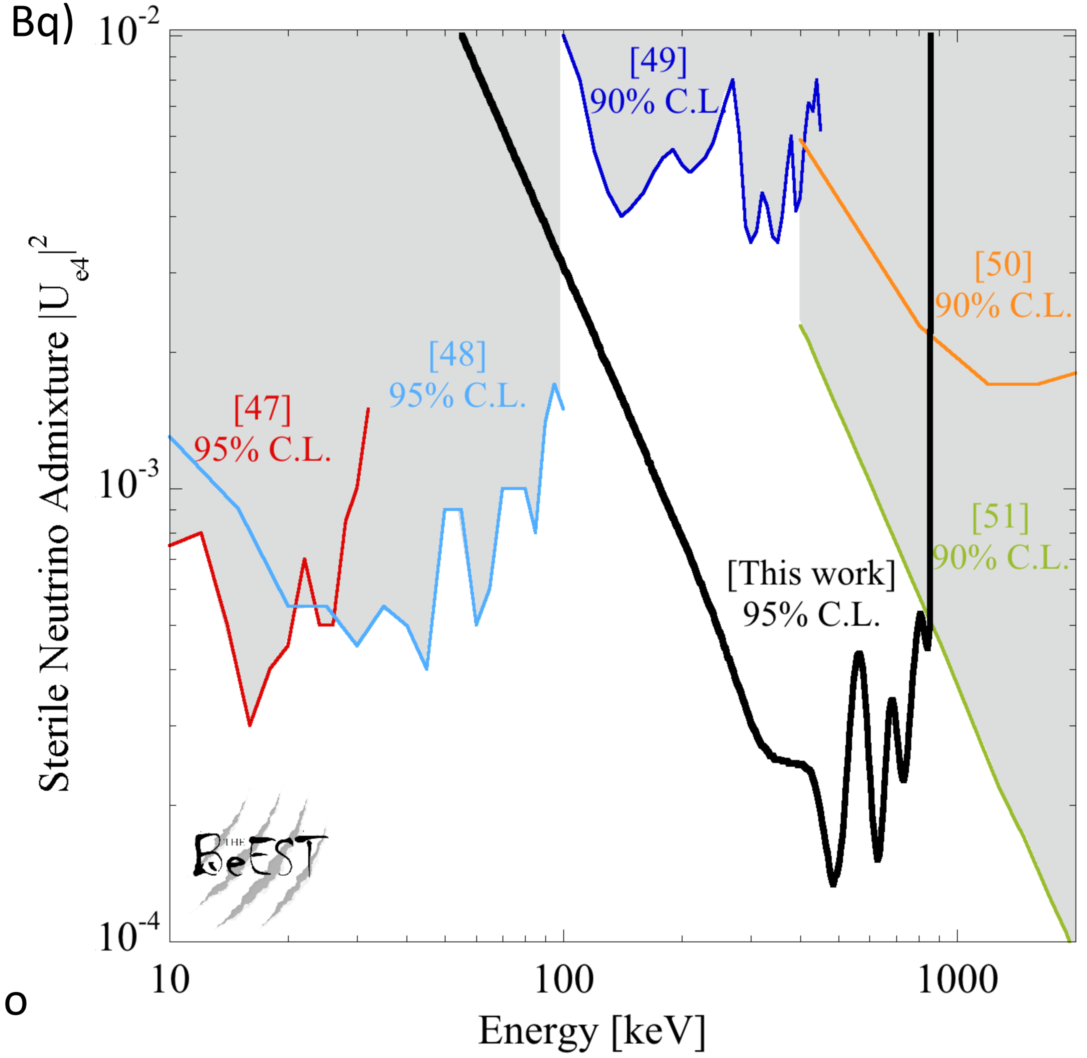
- Phase-II data from a single 138x138 μm^2 STJ counting at low rate (~10 Bq)



Recoil spectrum generated by pseudo-degenerate mass states from ~28 days of counting

Simultaneously acquired laser calibration spectrum

Example of signal that would be generated by 300 keV neutrino with 1% mixing



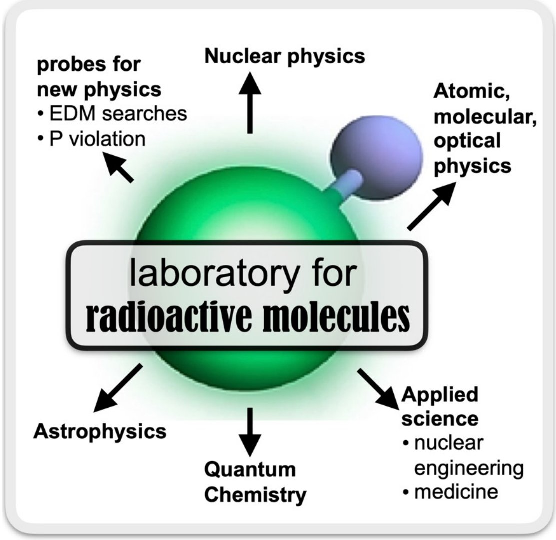
S. Friedrich *et al.*, Phys. Rev. Lett. **126**, 021803 (2021)

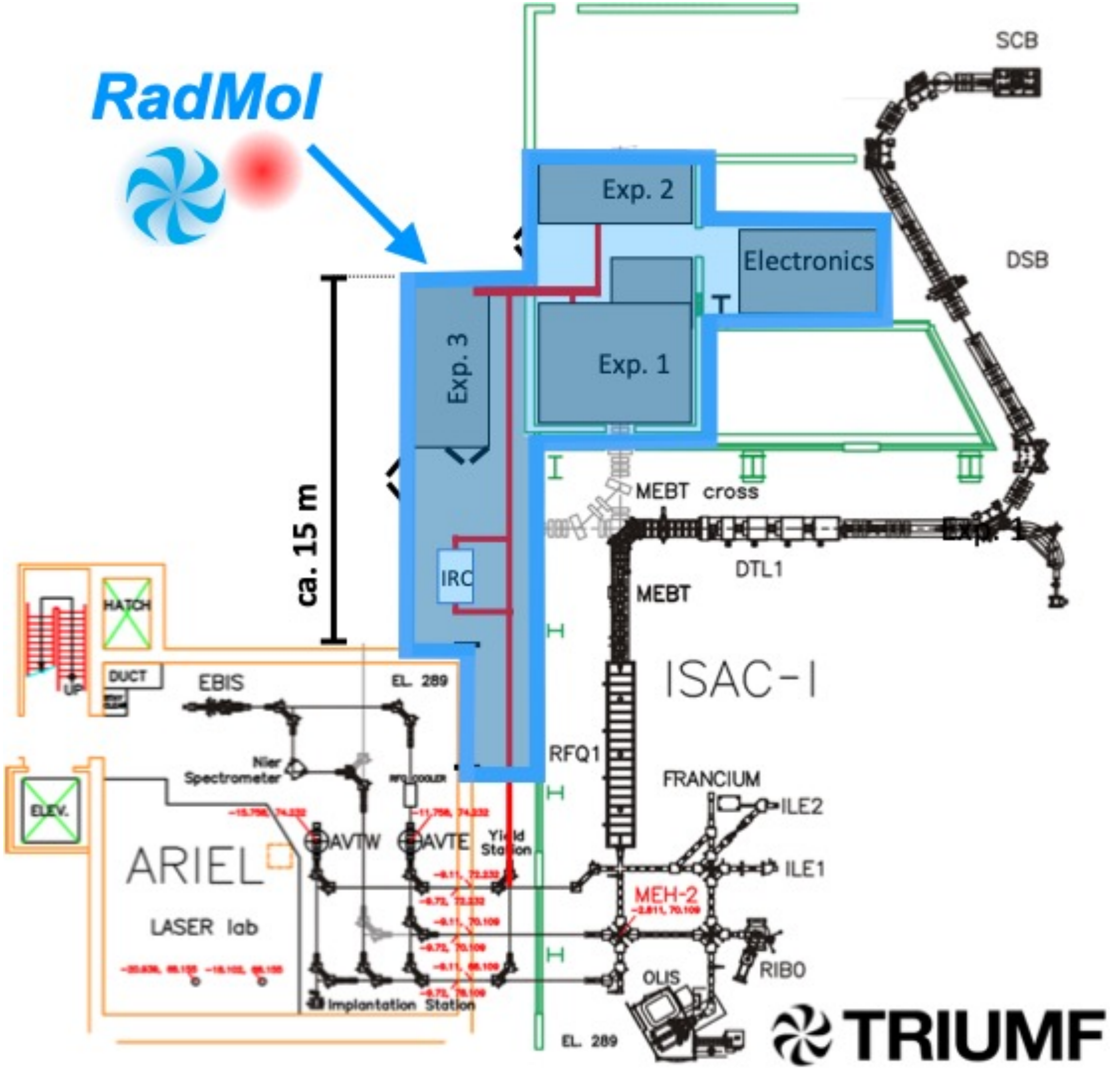
- Up to an order of magnitude improvement for limits on heavy neutrino admixtures to ν_e for masses of 100 – 850 keV

Courtesy of K. G. Leach

Future Radioactive Molecule (RadMol) Laboratory

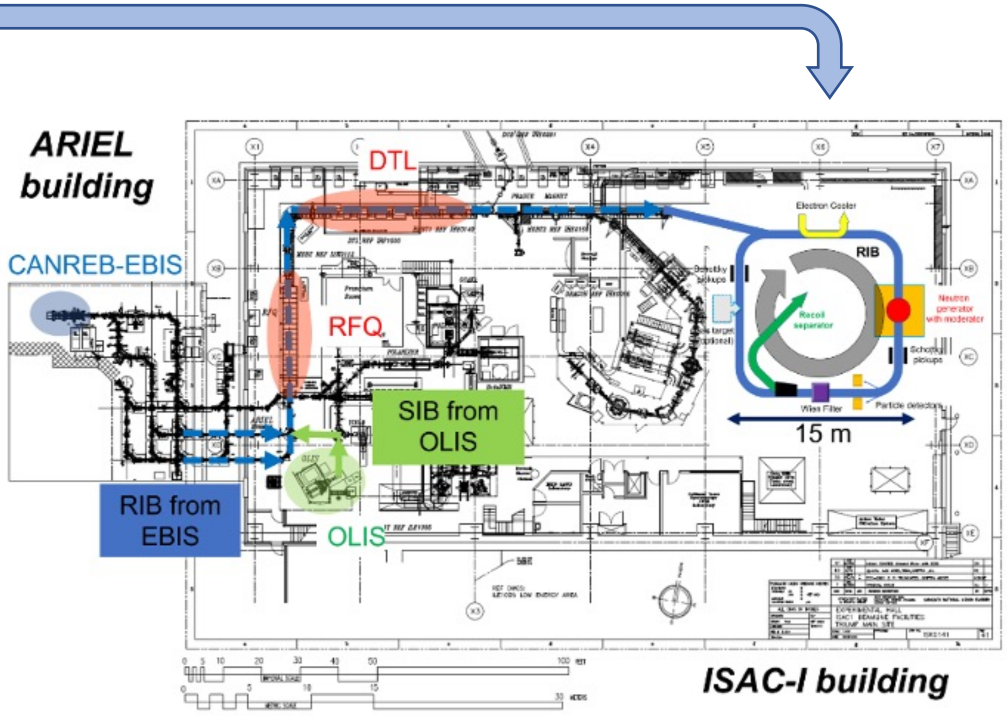
- Radioactive molecules as novel precision probes for fundamental physics
- Initial physics program:
  - Octuple-deformed nuclei incorporated into polar molecules ⇒ unmatched sensitivity for nuclear EDM
  - Access nuclear anapole moments via diatomic molecules
- Provision for expansions into other fields





Future TRIUMF Storage Ring (TRISR)

- TRISR – a storage ring for neutron capture on radioactive nuclei
  - Direct measurement in inverse kinematics
  - Coupled to ISAC radioactive beam facility
  - High-flux neutron generator – "neutron target" that intersects with orbiting ion beam
  - Nuclear astrophysics applications – r-process



TRIUMF

Thank you!
Merci!

Discovery, accelerated