Nuclear Physics

Overview

TRIUMF Science Week 2022

Chris Ruiz

Nuclear Physics Dept | Physical Sciences Division

2022-07-20

Discovery, accelerated

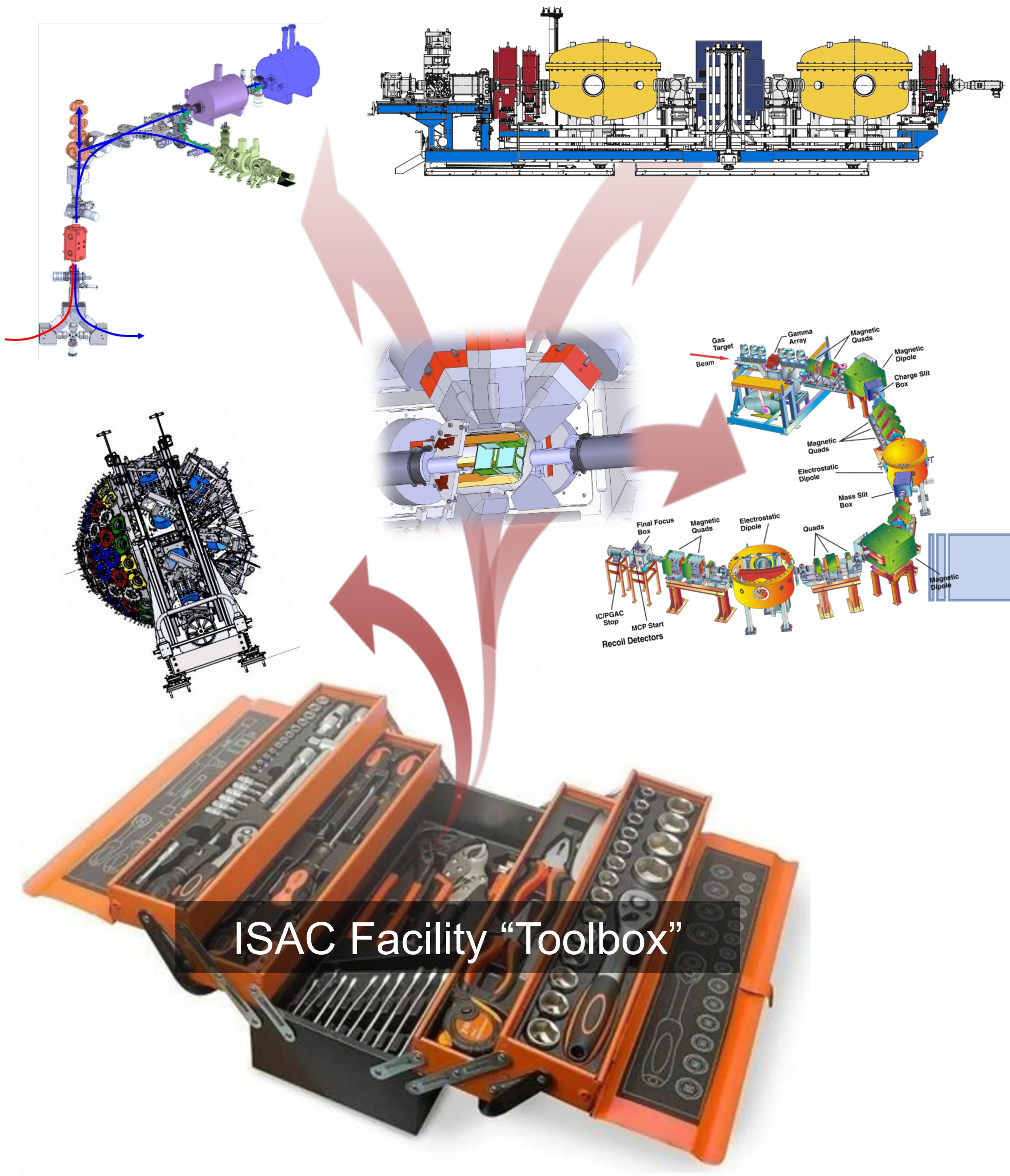
Session Intro

14:00			*TRIUMF / Zoom*	13:15 - 14:15
	Coffee Break		*TRIUMF / Zoom*	14:15 - 14:30
	Nuclear Physics overview	*Chris Ruiz*	*TRIUMF / Zoom*	14:30 - 14:45
	Nuclear Theory at TRIUMF	*Jason Holt*	*TRIUMF / Zoom*	14:45 - 15:00
15:00	**Sub-keV Decay Recoil Spectroscopy with Superconducting Quantum Sensors**	*Kyle Leach*	*TRIUMF / Zoom*	15:00 - 15:15
	The TRIUMF Storage Ring Project	*Iris Dillmann*	*TRIUMF / Zoom*	15:15 - 15:30
	Polarized Beams at TRIUMF	*Adam Garnsworthy*	*TRIUMF / Zoom*	15:30 - 15:45
	Break		*TRIUMF / Zoom*	15:45 - 16:00

Outline

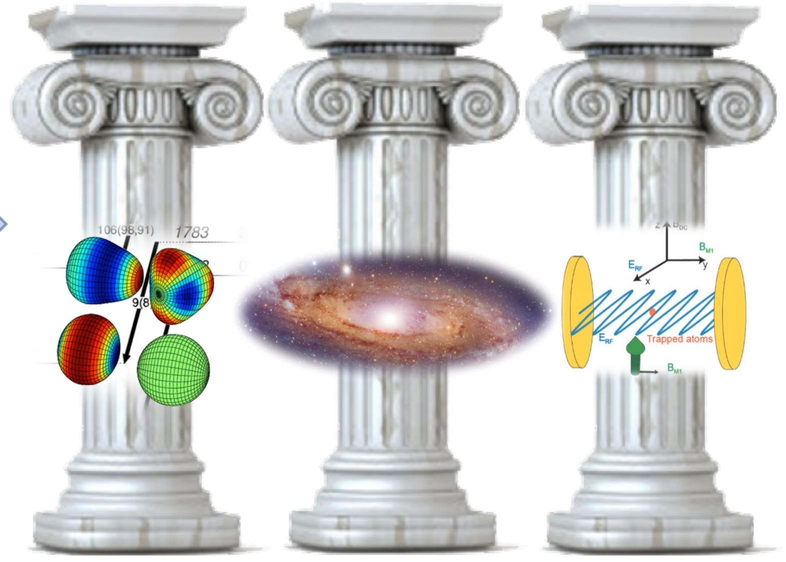
- Nuclear Physics using ISAC now
- Meeting the Challenge of ARIEL
  - How ARIEL will change landscape & what we'll need to get there
- Staying on the cutting edge, New Directions

Nuclear Physics @ ISAC: World Leading Capabilities



- Nuclear ground state & decay properties via decay spectroscopy
- Charged-particle-induced reaction cross section measurement
- Decay spectroscopy of reaction-induced excited states in exotic systems
- Ground state mass measurement
- Precise decay spectral shapes
- Preparation & measurement of quantum states via lasers / traps
- Neutron-induced reaction cross section measurement
- Radioactive molecule production

Nuclear Structure | Nuclear Astrophysics | Precise Tests of Fundamental Interactions



Orthogonality between most Facilities
→ Powerful Combinations Possible

- Add new tools
- Sharpen existing tools

Nuclear Physics @ ISAC: World Leading Capabilities

TRINAT	Precise, kinematically-complete measurements of beta-decay and associated parameters. Sensitive to time-reversal symmetry violation.
TITAN	Multi-instrument ion trap facility for masses & decay spectroscopy: MRTOF, MPET, EBIT: precision or coverage
FRANCIUM	Laser prepared Francium atoms probed towards Atomic Parity Violating signal
GRIFFIN / DESCANT	Decay spectrometer for gammas, betas, conversion electrons, neutrons
Polarizer / Laser-spec	Collinear probing of spin polarized isotopes for e.g. charge radii
DRAGON	Direct measurement of radiative proton & alpha capture reactions on exotic or stable isotopes
SONIK	Precision elastic scattering on radioactive nuclei → low energy scattering phase shifts
TUDA	Versatile direct & indirect charged particle reaction facility based around silicon arrays
DSL	Doppler-shift lifetime facility for determination of excited state lifetimes
IRIS	Solid hydrogen or deuterium target scattering facility using CsI & Silicon arrays → extracting structure information from reactions using weak exotic beams
TIGRESS	Gamma-ray spectroscopy of excited exotic reaction residues using escape-suppressed HPGe array
EMMA	Recoil Spectrometer for detection & analysis of exotic reaction residues

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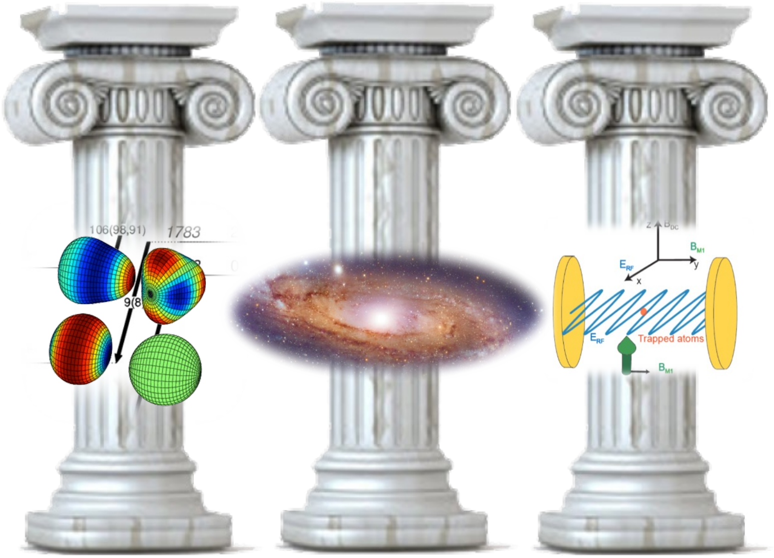

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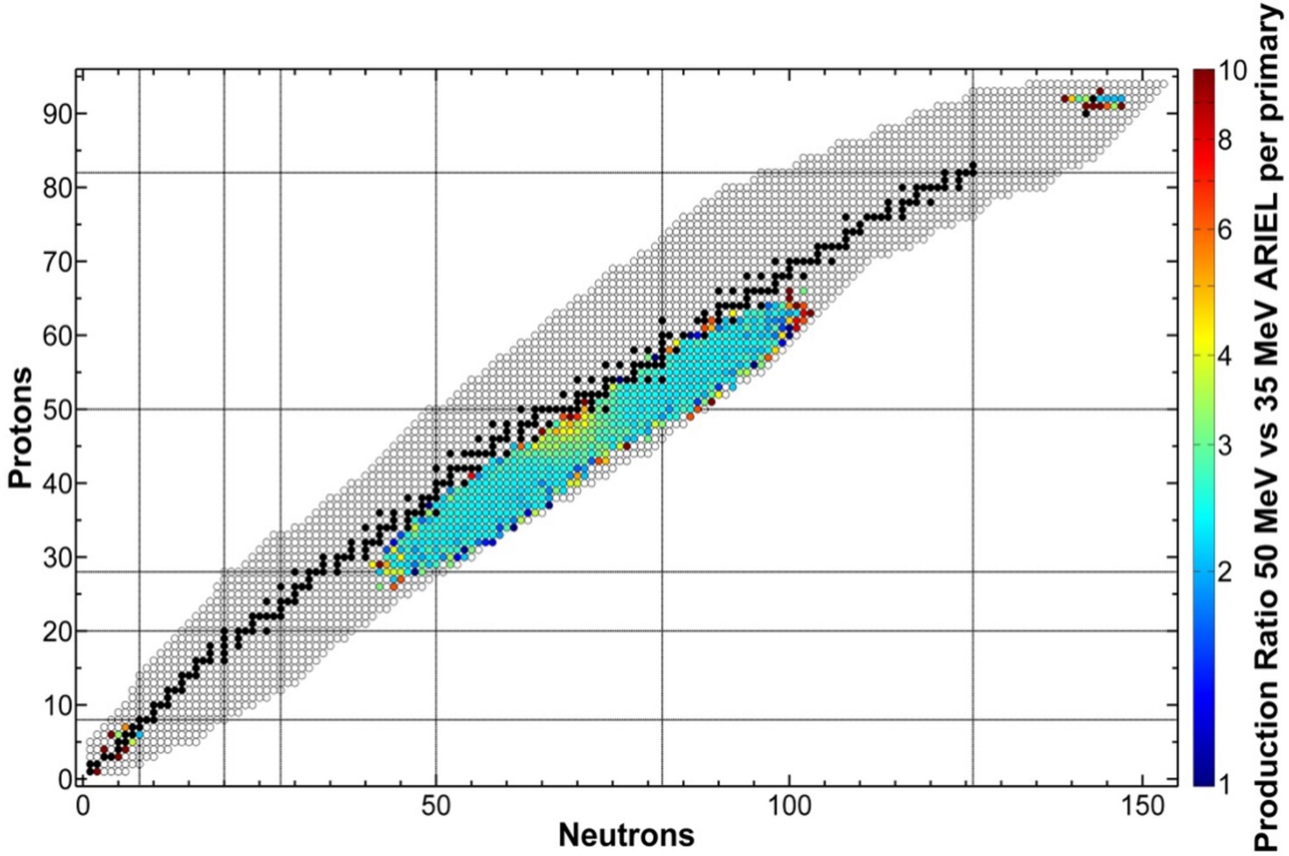
ARIEL: how it will affect the landscape

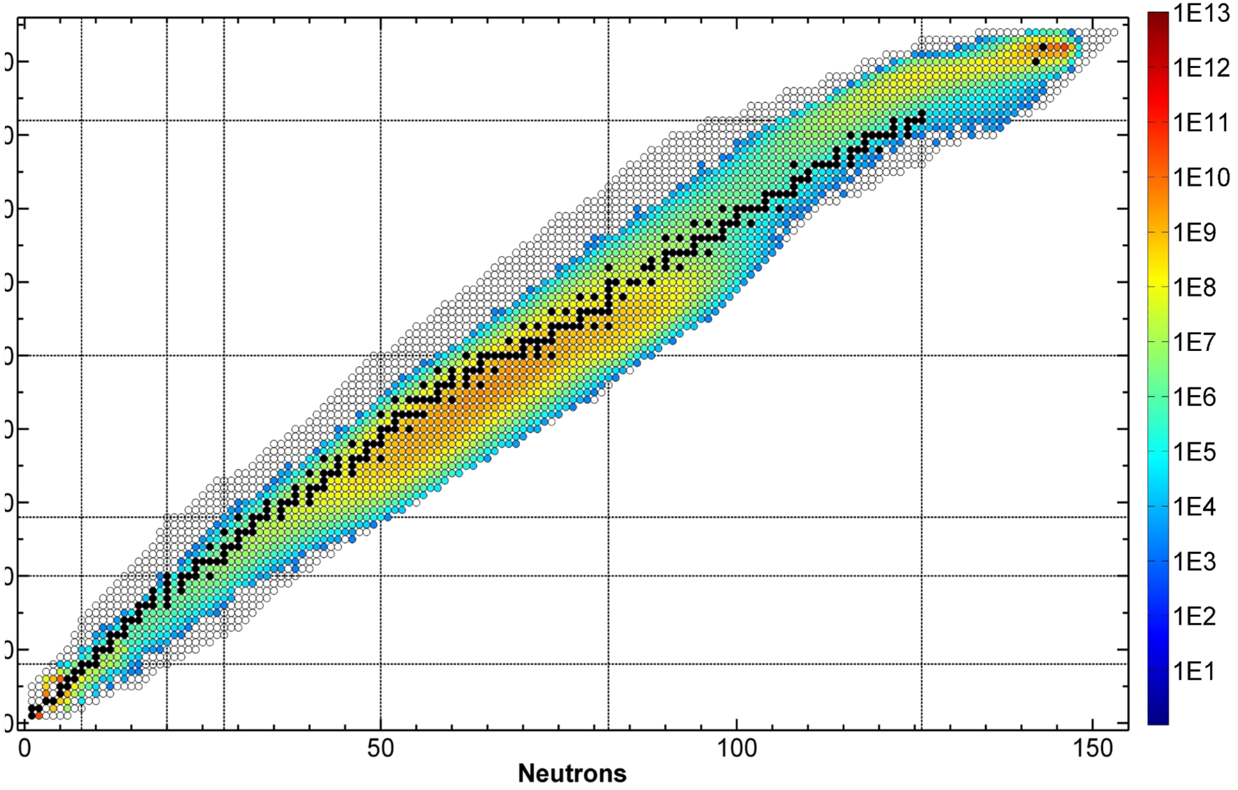
production intensity from $^{238}UC_x$

AETE



- Pure n-rich products from photofission
- Operational flexibility

ISAC / APTW
500 MeV x 10 µA protons [1/s]

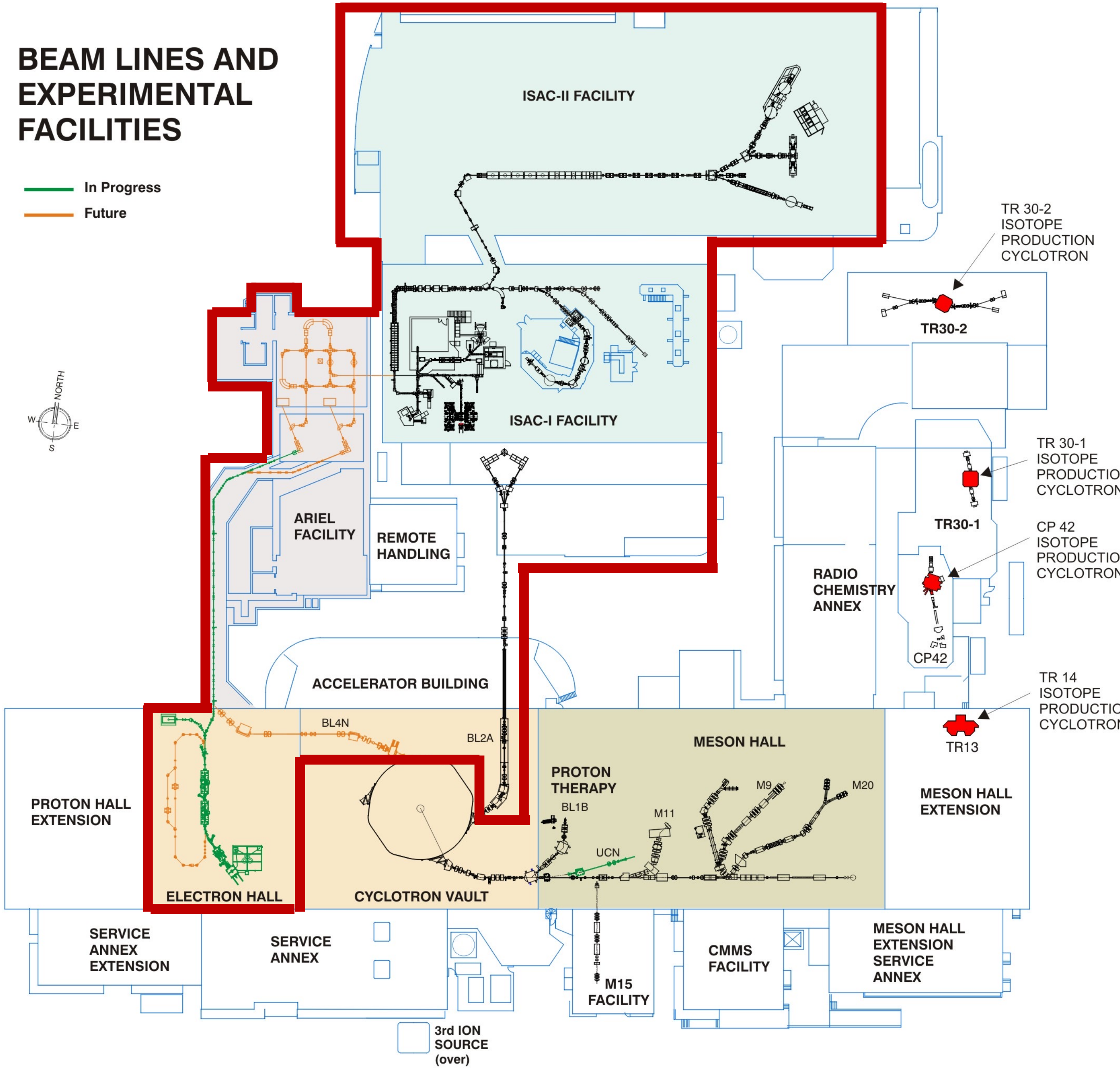


- High production intensities
- New development opportunities in APTW design

ARIEL Advantages (short term during ramp up starting 2026)

- Second proton target station and parallel beam delivery capabilities
- Significantly more targets, ion sources and beam development capabilities
- Independent driver beams
  → (potentially longer RIB schedules from the e-linac, less downtime, physics program when cyclotron is down for longer repairs or refurbishments)
- Possibilities of long beam times with “easy" n-rich isotopes while one or two exotic and demanding beams are delivered from the other two other stations.

ARIEL Beam Schedule will be : “Factory Mode”
(more predictability, flexibility, opportunity)



ARIEL Advantages (ultimately)

- More of intense, cleaner, neutron-rich beams
    - Though not with same reach as FRIB (further towards drip-line), higher intensity a few isotopes lighter enables different class of experiments – less “first glimpse”, more *precision and detail*
- 3 independent RIB delivery paths – one accelerated, two low-energy
    - In *principle,* 3x number of RIB shifts per year

      → With experimental community’s capacity, this will result in 1x<experiments<3x → publications
    - Ability to de-couple beam development from delivery → more new species delivered on a shorter timescale → More flexible & impactful experiments
    - *Longer beamtimes (both n-rich, n-deficient)* → greater sensitivity, e.g long precision measurements of small cross-section (e.g. astrophysics), more detailed surveys (multiple states probed in single run), long fundamental symmetries measurements
    - Greater standard of measurement in terms of coverage and/or precision

What we'll need to get there

- Facilities maintained at a competitive cutting edge, with full *coverage* vis-à-vis capabilities & techniques
- New directions to capture the ARIEL advantage
- Greater collaboration between groups/facilities
- More versatile, modular & portable ancillary equipment

Recall: by 2027, ramp up to 2-3x experiments running during year (+ New User Involvement!).

There will not necessarily be 2-3x postdocs & students

→ greater burden on local BAEs, techs & P&S physicists!

Need to keep our technical group adequately staffed & equipped

Sharpening the Tools: Decay Spectroscopy at GRIFFIN

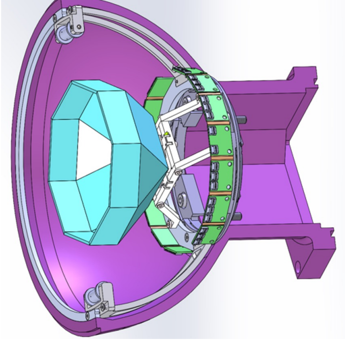
Wide-ranging and active science program in nuclear structure, nuclear astrophysics and fundamental symmetries → New n-rich isotopes, higher yields, cleaner beams from ARIEL

New upgrades will ensure a competitive edge over worldwide competition + enable new science opportunities:

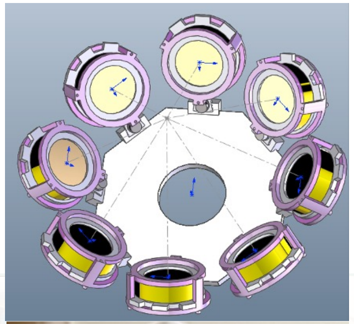
- Upgrade SCEPTAR beta-tagging array to ARIES.
- Upgrade PACES conversion electron spectrometer to CEDAR.
- New "RCMP" detector → charged-particle spectroscopy (eg. β-delayed proton and alpha)

"Everything except the neutrino!"

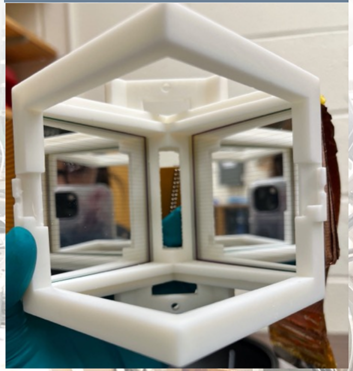
ARIES



CEDAR



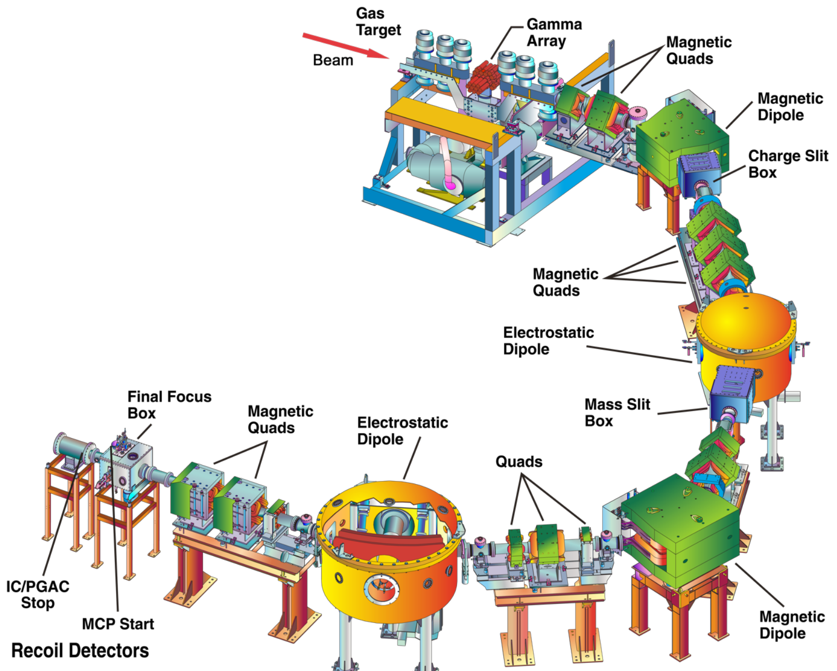
RCMP
(U. Regina)



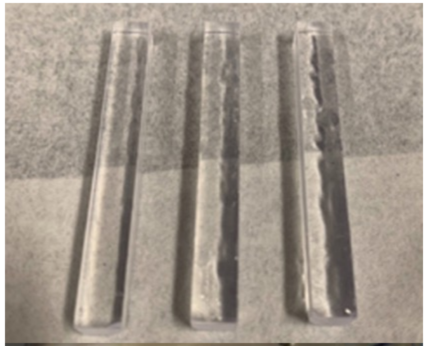
New Initiative: Couple GRIFFIN to the polarizer beamline
(see talk by Adam Garnsworthy)

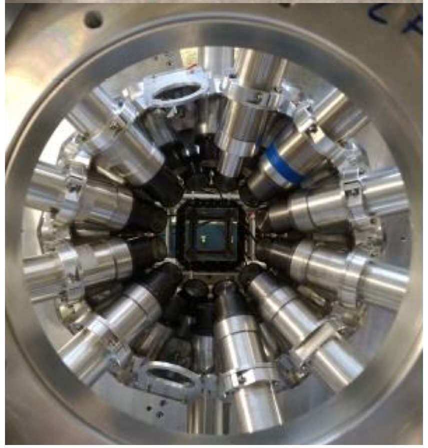
Sharpening the Tools:
Nuclear Astrophysics at medium energies (DRAGON, TUDA and ancillaries)

- Long RIB runs → statistics, systematics, coverage, completeness
  → Many excited states measured in single run “Doing it right”
- High intensity stable beam experiments with RF-booster cavity
  → Direct capture, low cross-section → weakly bound halo states, astrophysics
- New detectors: use of GRIFFIN HPGe, Surrey $LaBr_3$ array, neutron detection at target for (α,n) (Organic Glass scintillators)
  → Eventual development of replacement array for BGO (LYSO, Ce:GAGG) for high-efficiency + ultra-fast timing
- Competitive or unique world-standard direct measurements of radiative capture, (p,α), (α,p) + elastic scattering, c.f. FRIB



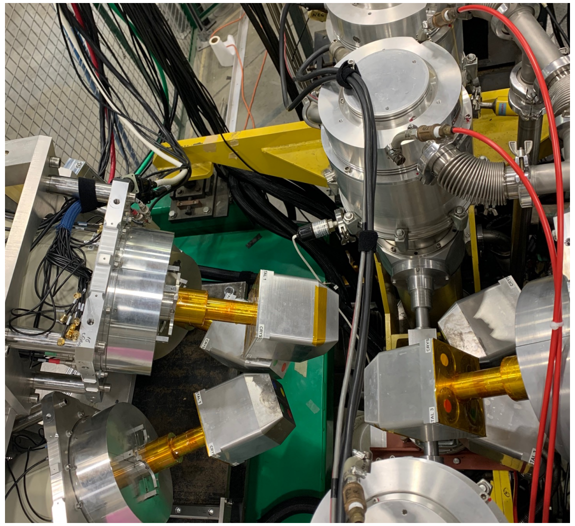
Melt-cast Organic Glass scintillators for neutron detection & (n/γ) pulse shape discrimination

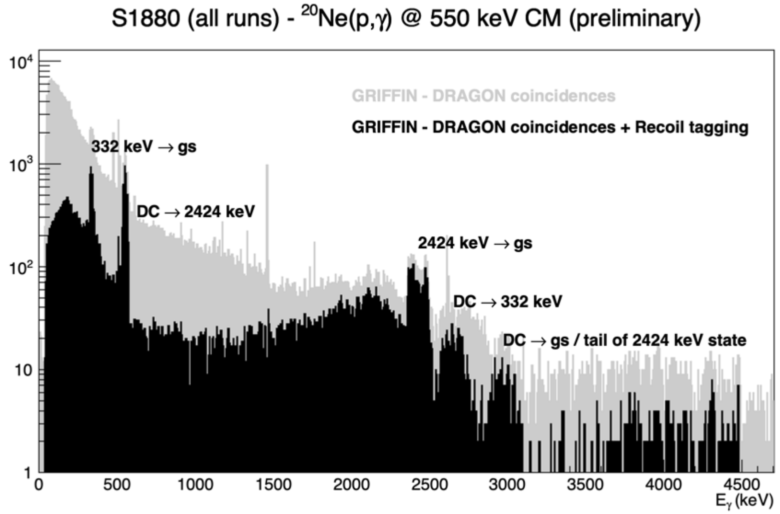




$LaBr_3$ (Ce) example: FATIMA array (U. Surrey)

GRIFFIN Clovers @ DRAGON



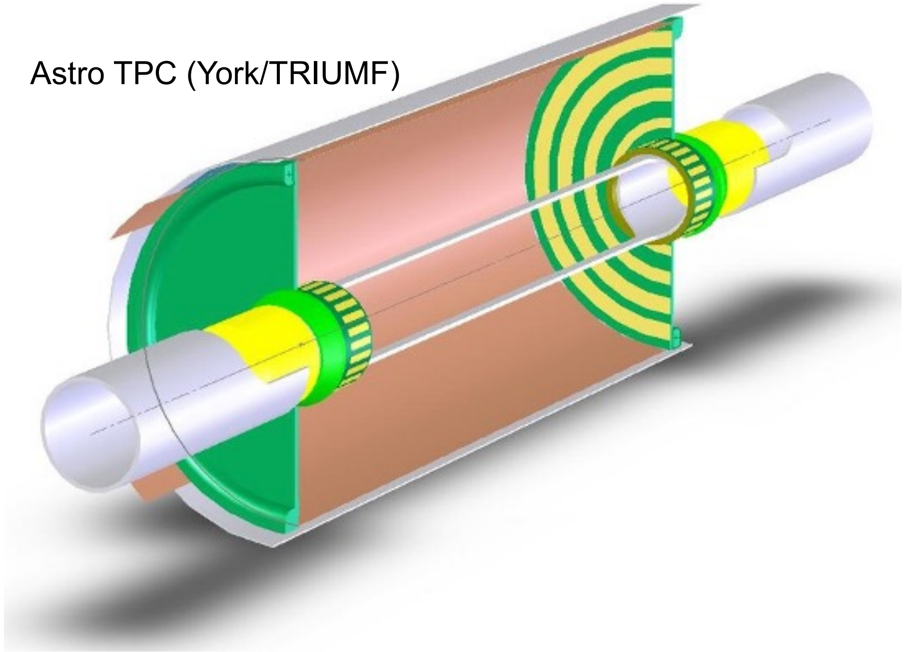


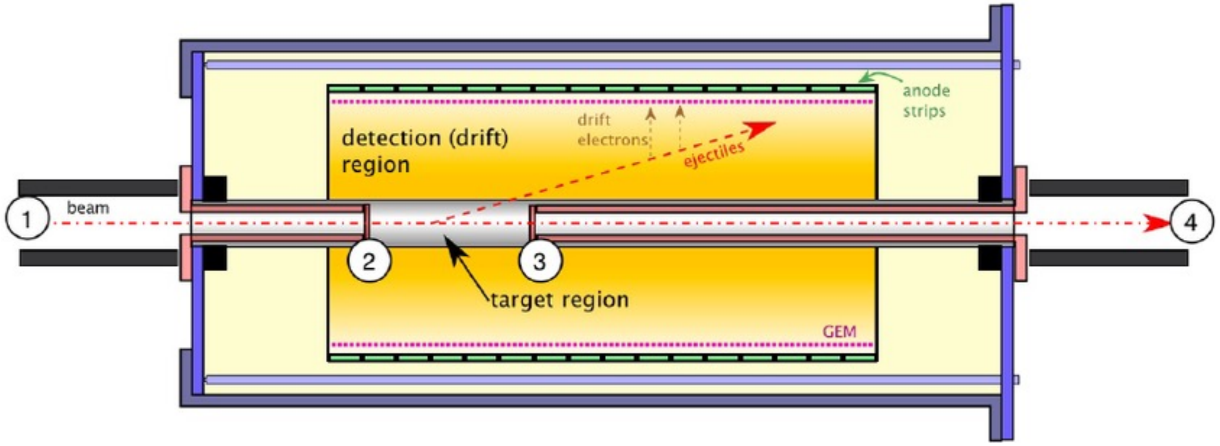
New Tools: Nuclear Astrophysics at medium energies

- TPC for v. low cross section / high beam intensity
  → V. low energy astrophysics measurements e.g. (p,α), (α,p), (α,n) for light nuclei e.g. Big Bang Nucleosynthesis, CNO etc
  Modified version for heavy mass
  → Co-axial separated design (beam doesn't overwhelm particles of interest)
  → New flexible UrWELL GEM technology
  → Future flexible silicon detectors
  → Suitability of UrWELL GEMs with ^{3}He gas, for neutron detection is also being explored

- Combination with external neutron array (OGS)

Astro TPC (York/TRIUMF)





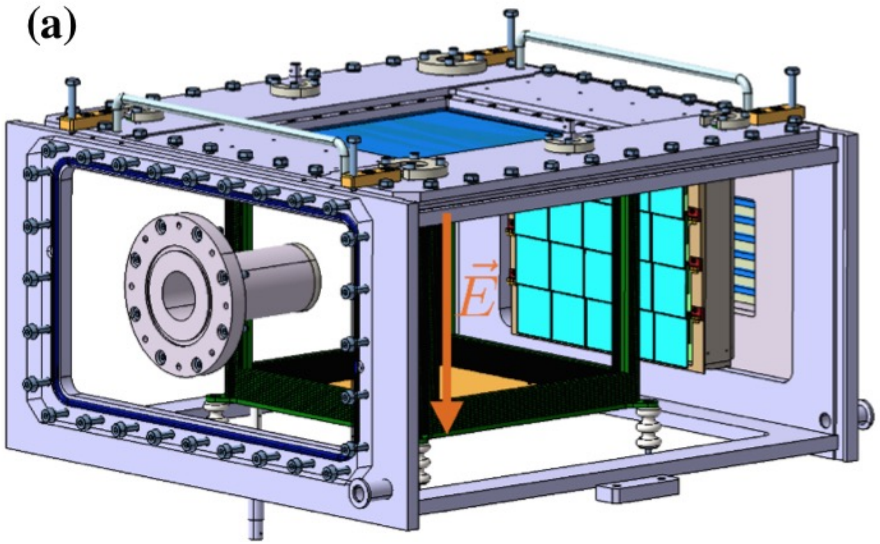
Added to existing facilities →
Complete "direct measurement toolkit section"

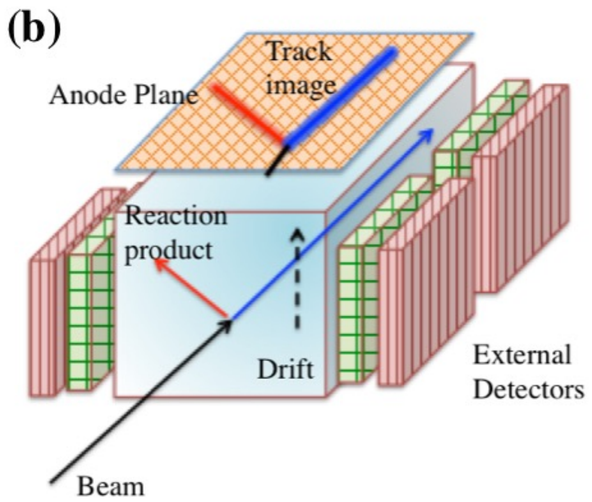
New Tools: Nuclear Reaction Spectroscopy with Active Target Time-Projection Chamber

Active target, allowing for ^{4}He or ^{3}He targets **"EXACT TPC"**

Designed to operate simultaneously with IRIS facility (in transmission mode)

Can be combined with ancillary detectors (e.g. neutron array)





→ With ARIEL, can measure $^{136,137}Sn(\alpha,\alpha')$ to search for resonances just above *n* threshold
→ Ideal tool to search for isoscalar giant monopole resonance as well

- Complementary to IRIS facility transfer reactions (*d,p*) (*p,d*) (*d,t*) to get knowledge of neutron orbitals, EXACT e.g. allows for (^{3}He,*d*) for proton orbitals to looks for changes in nuclear shells in heavy nuclei
- Two nucleon transfer for pairing correlations using (^{3}He,*p*) to study proton-neutron pairing in nuclei. e.g. $^{76}Sr(^{3}He,p)$ to investigate T=0 pair vibration mode
- Bonus astrophysics motivation: *rp*, *r*-process → Indirect measurements for proton capture in ^{23}Al;. ^{35}K, ^{59}Cu, ^{61}Ga
  → Thick target to measure excitation spectrum across various energies for resonant capture reactions

NUGRID

Generate stellar element yield sets covering entire mass and metallicity space

NuPyCEE
NuGrid Python Chemical Evolution Environment
A NEW GENERATION python galaxy framework

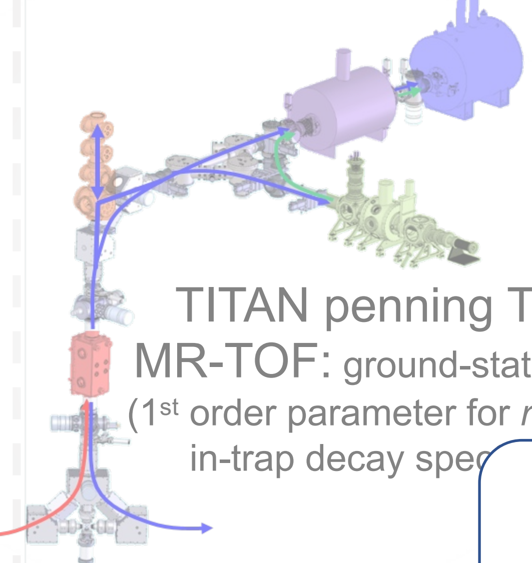
ChETEC

Chemical Elements as Tracers of the Evolution of the Cosmos

NASA JAMES WEBB SPACE TELESCOPE
GODDARD SPACE FLIGHT CENTER

“How do stars evolve and release the heavy elements they produce back into space for recycling into new generations of stars and planets?”

NUCLEAR ASTROPHYSICS Capabilities at ISAC (with exotic isotopes)

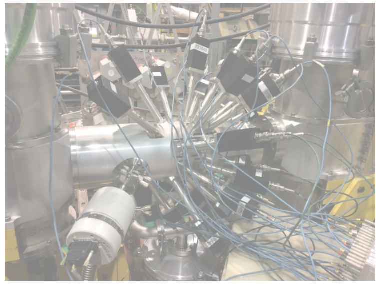


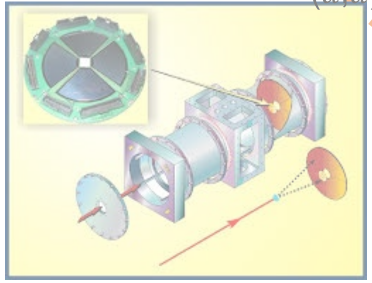
TITAN penning Trap & MR-TOF: ground-state masses (1st order parameter for r-process), in-trap decay spec

GRIFFIN Spectron
measurement of ground-s
properties: β+, β-, EC, e⁺e⁻, β-n, $t_{1/2}$ etc

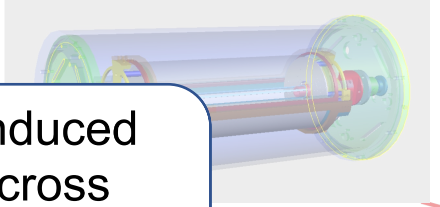
Low Energy (≤ 60 keV)

SONIK Array: elastic scattering phaseshifts (p,p), (α,α)





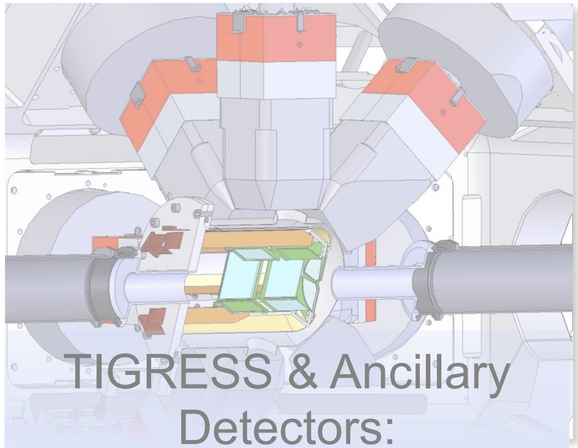
TUDA Array: direct measurement of (p,α), (α,p)



Active Target: direct measurement of (α,n), (α,p)

DRAGON

Medium Energy (0.15 – 1.8



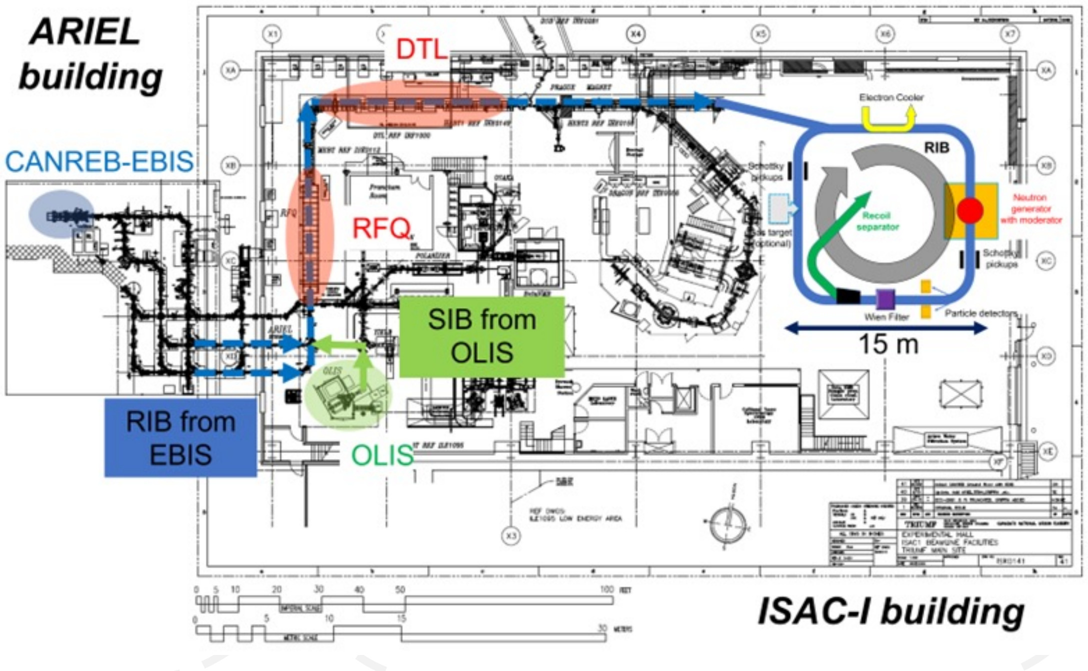
TIGRESS & Ancillary Detectors:
Fusion evaporation, transfer

target
Indirect measurements

Neutron-induced reaction cross section measurement

Radiative neutron-capture on n-rich species, within i-process & r-process, is one of the biggest open fields of study in astrophysics: Binary neutron star mergers, core-collapse supernovae, CEMP stars → nucleosynthesis of the heaviest elements!

→ Neutron capture Storage Ring "TRISR"
→ (See talk by Iris Dillmann)



TRIUMF

Thank you

Merci

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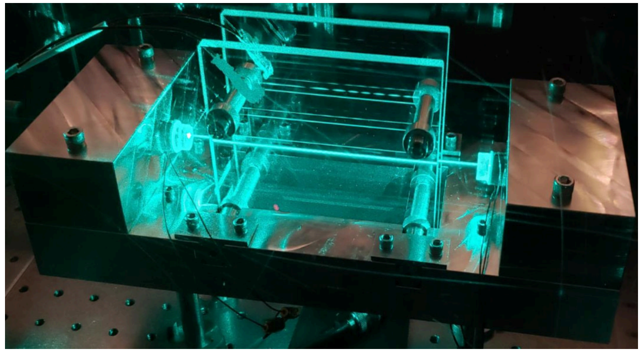
Discovery, accelerated

2023-2030 Strategy: Low Energy Experiments

→ Precision RIB Measurements / Fundamental Symmetries

Francium PNC Facility (Fr-PNC)

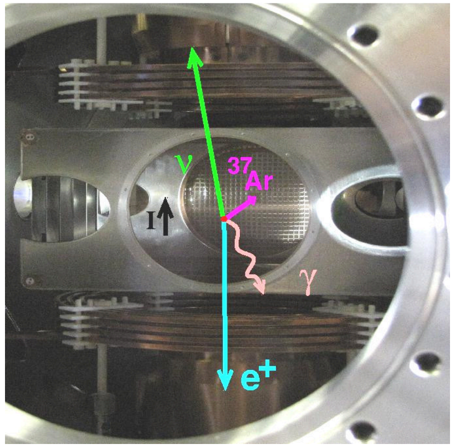
- Currently at level of E1/M1 Stark transition measurement → Sensitivity & methodology proven
- Atomic Parity-violating signal expected 2024
- APV measurement competitive with others, 2025+ (into 5YP)
  - Competitive electron-quark neutral weak coupling + nuclear anapole
- These measurements need maximum yields of $^{208-213}$Fr → n-dependent effects
- D. DeMille et al. have S2139LOI which would look for Francium dimers at Fr-PNC, towards full ^{223}FrAg EDM experiment (see AMO discussion)



FRANCIUM UHV Power Buildup Cavity
(T. Hucko, ACOT 2021)

TRINAT (neutral atom trap) → TRINAT-γ

- Extend β-ν-γ from T-reversal symmetry breaking in ^{37}K (expected finished in current 5YP)
- Consider isospin symmetry-breaking in isospin-suppressed Fermi-GT ^{36,45,47}K for V_{ud}
- Develop case for time-reversal enhancement by isospin-suppressed F-GT → competitive search for Time-breaking, Parity-even isospin-breaking nucleon-nucleon interactions



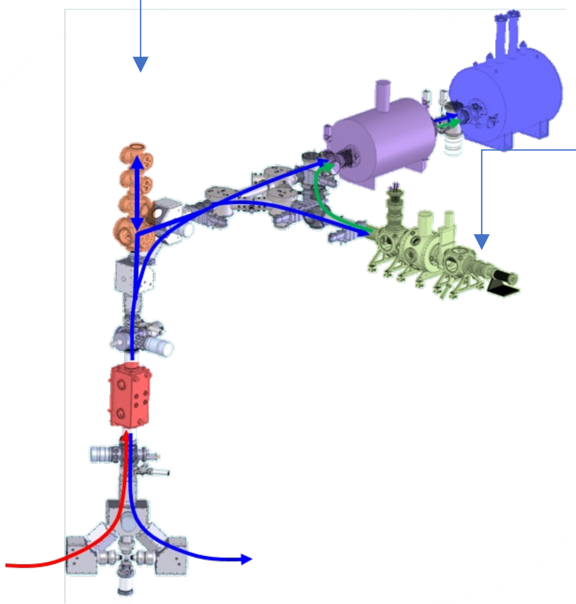
TRINAT Trap

TRINAT Needs:

- Digitization of waveforms for ion & beta counters
- Cryo vacuum upgrade
- Gradually longer beam times towards long blocks for precision measurements (stat √N + systematic tests) in 5YP

TITAN Ion Trap Facility

- MR-TOF: 10 year + program of measuring r-process nuclei for astrophysics (masses), plus instrument of standard for measuring low intensities from ARIEL
- MPET (Penning Trap): Precision mass measurements, v. high precision (1:1E+10) of heavy superallowed β-emitters → V_{ud}
    - Long runs ~1 week/isotope
    - More systematics controlled
- EBIT (highly-charged ions) [5-10 year program]
    - In-trap decay spectroscopy: nuclear structure & astro ~ 2-week runs
    - Extreme UV spectroscopy → absolute charge radii of heavies (e.g. Fr, Ra) for EDMs
    - Highly-charged radioactive molecules: establishing existence → RadMol facility



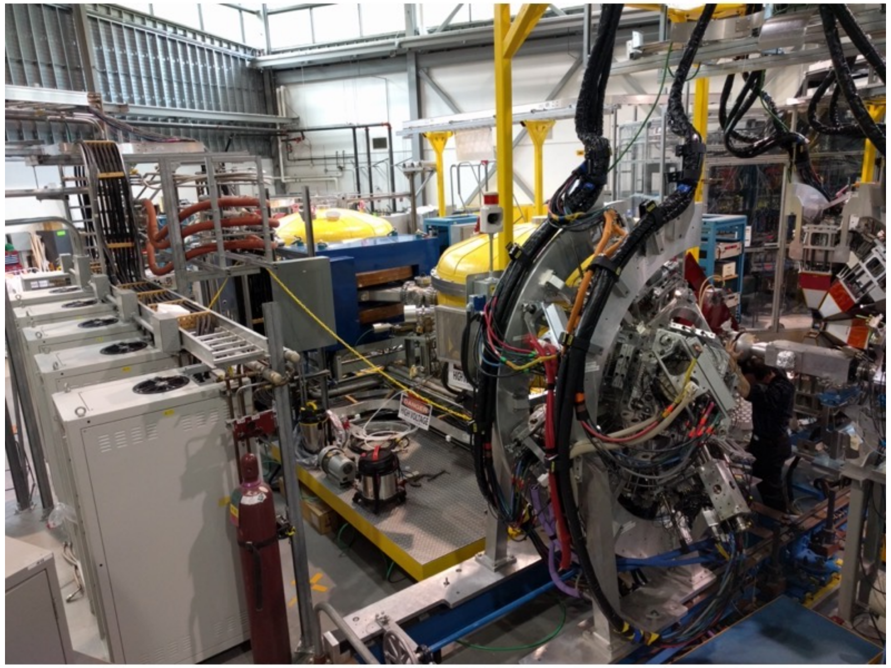
2023-2030 Strategy: High Energy Experiments

→ Pioneering & precision RIB Measurements / Nuclear Structure and Astrophysics

TIGRESS and EMMA

- Nuclear structure frontiers with RIBs:
  - Isospin: Exoticism, new magic numbers, indications of collectivity, ground states and small number of excited states
  - Precision & Sensitivity: nature of shapes and shape coexistence, microscopic origin of magic numbers, collectivity, rich excited structures and transitions
- Precision requires **high efficiency and high RIB flux** (intensity and time): highly efficient Ge detectors + recently upgraded GRIFFIN-style DAQ for ~30× the data throughput
- CANREB and ARIEL will push the frontiers of precision and sensitivity:
  - cleaner beams with lower isobaric contamination (esp. of fission products) & higher mass resolution lead to sensitivity; especially relevant for higher-mass fission peak largely unexplored by TIGRESS so far;
  - longer beam times and higher intensities will permit precise measurements

- Sensitivity requires a suite of auxiliary detectors and *clean* RIBs; coupling to EMMA greatly enhances sensitivity
- EMMA enhancements: direct measurements of reaction cross sections at supernova energies: solid He targets and neutron detectors will enable (α,n) in addition to (p,γ) and (α,p)
- Nuclear structure: 4 GRIFFIN HPGe detectors to be located near EMMA focal plane surrounding DSSD for decay spectroscopy of reaction products
- Addition of annular Si in SHARC-II target chamber for ΔE-E measurements of light ejectiles to reduce fusion-evaporation background in α transfer reactions, enhance sensitivity for (^{3}He,d) reactions



TIGRESS coupled to the EMMA recoil spectrometer target position