TRIUMF

The Physics Program at TRIUMF

On-site and off-site research in nuclear and particle physics.

Jens Dilling

Associate Laboratory Director
Physical Sciences TRIUMF

2020-11-03

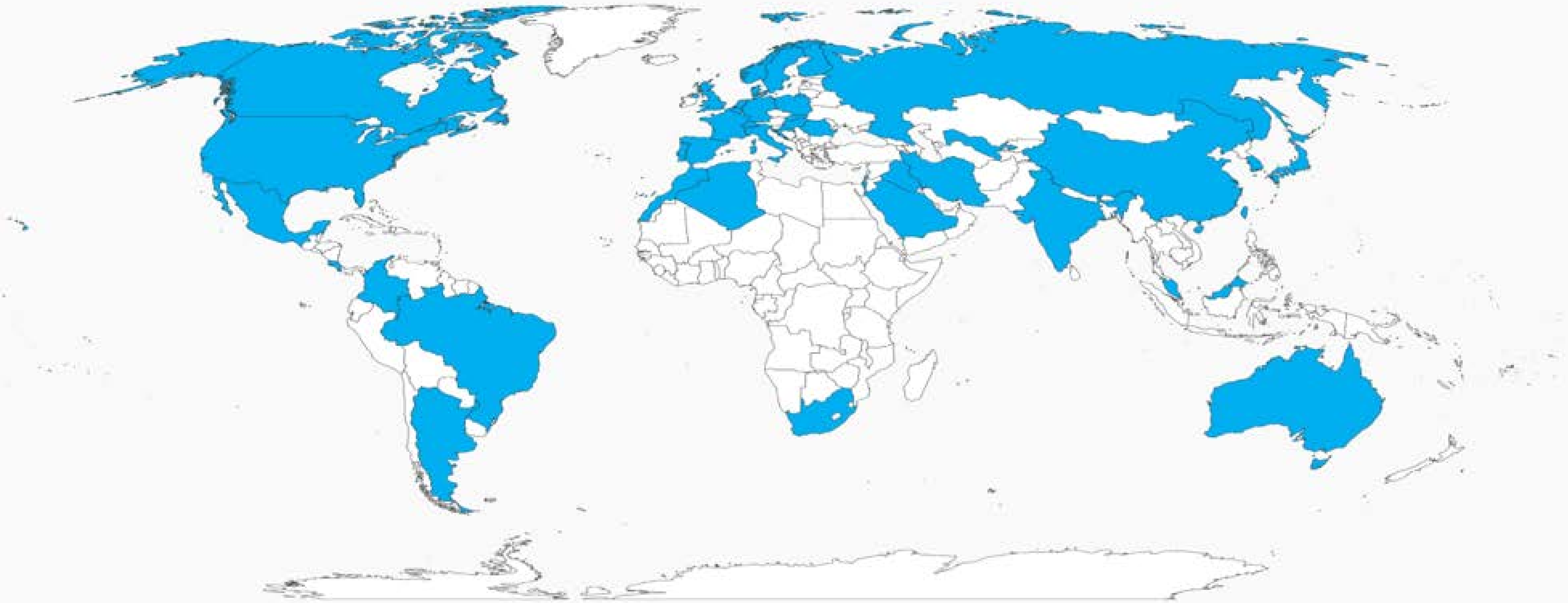
Discovery, accelerated

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.

Owned and operated by a consortium of 21 universities across Canada

University of Alberta
The University of British Columbia
University of Calgary
Carleton University — Canada's Capital University
University of Guelph
University of Manitoba
McGill
McMaster University
Université de Montréal
UNBC University of Northern British Columbia
Queen's University
University of Regina
Saint Mary's University — One University. One World. Yours.
Université de Sherbrooke
SFU Simon Fraser University
University of Toronto
University of Victoria
University of Waterloo
Western University · Canada
The University of Winnipeg
York Université University

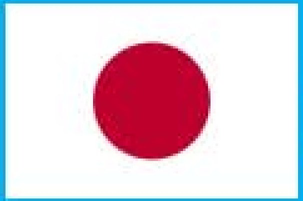


TRIUMF had in 2019 ~1200 users from over 40 countries

TRIUMF is a Canadian asset, a point of entry into the international ecosystem of sister laboratories around the world

CERN
Europe

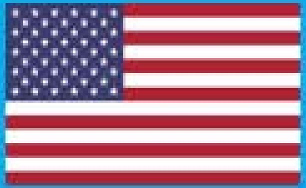
RAL / Daresbury
United Kingdom



KEK / J-PARC
Japan

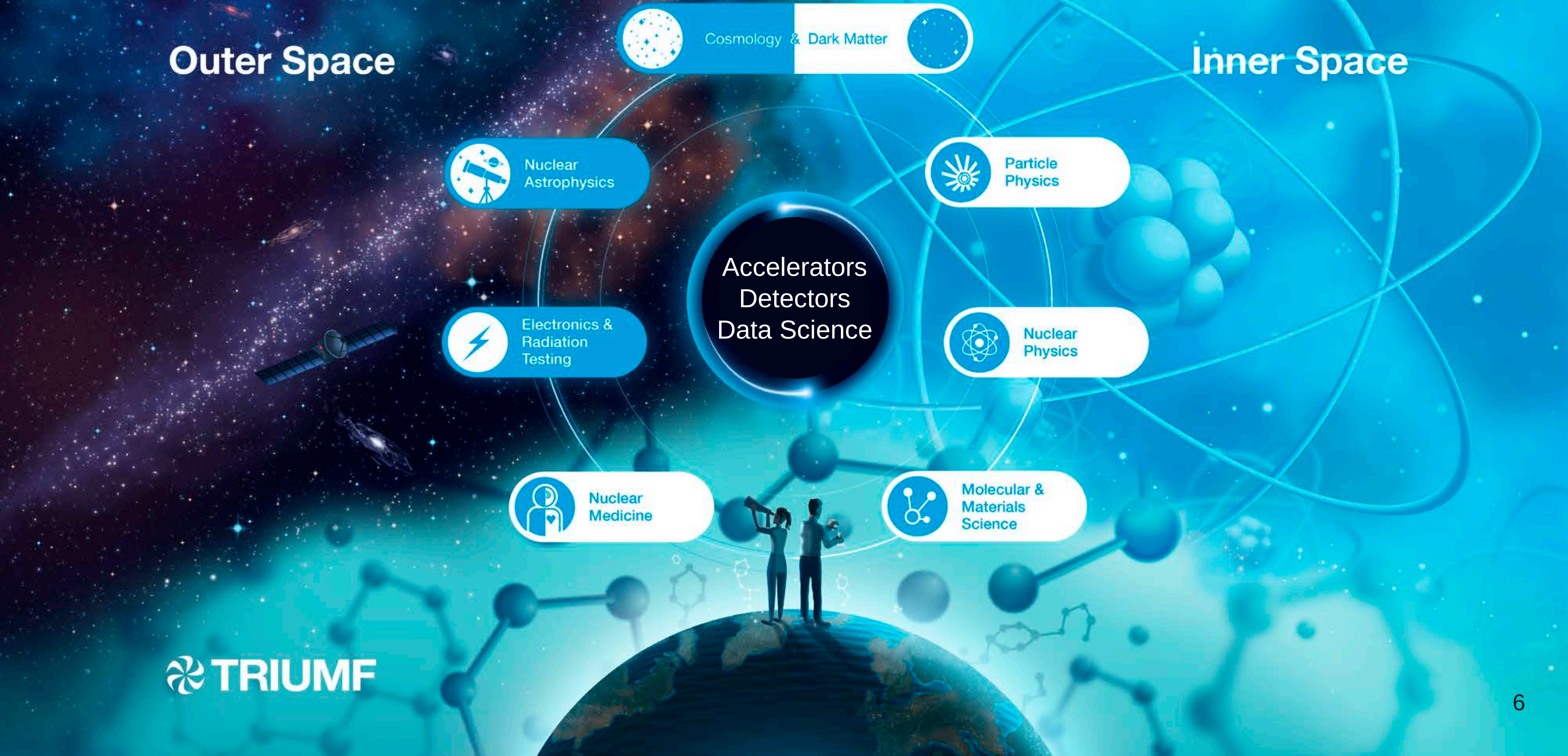
VECC
India

Helmholtz Association
Germany

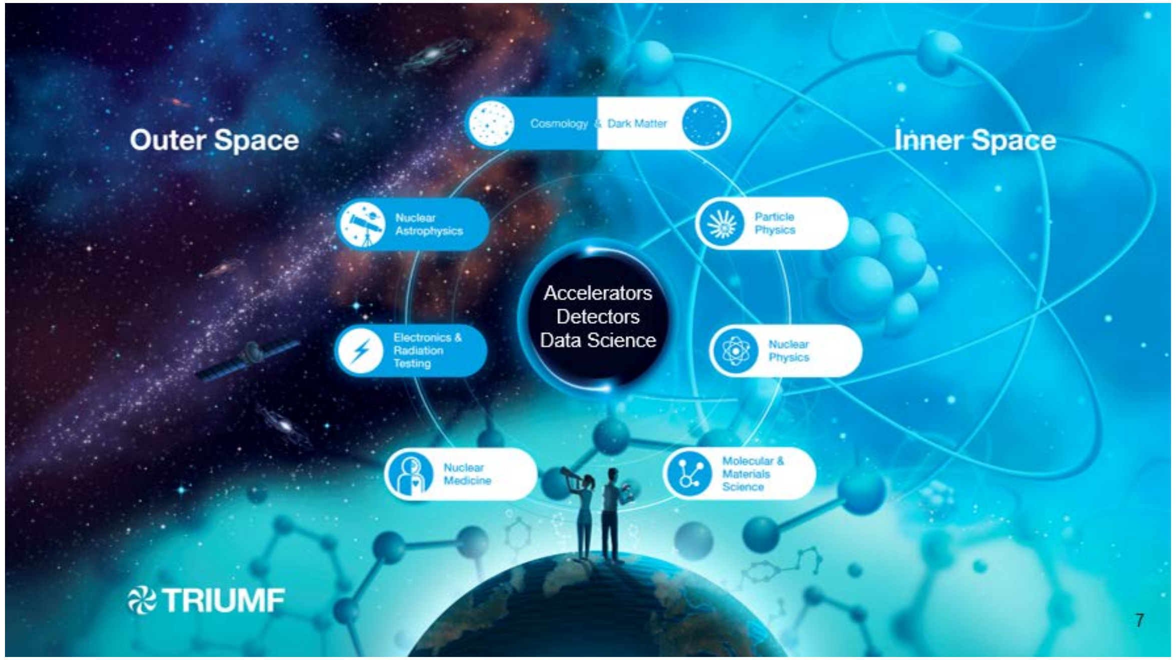


Department of Energy Laboratories
USA

TRIUMF's research portfolio on- and off-site

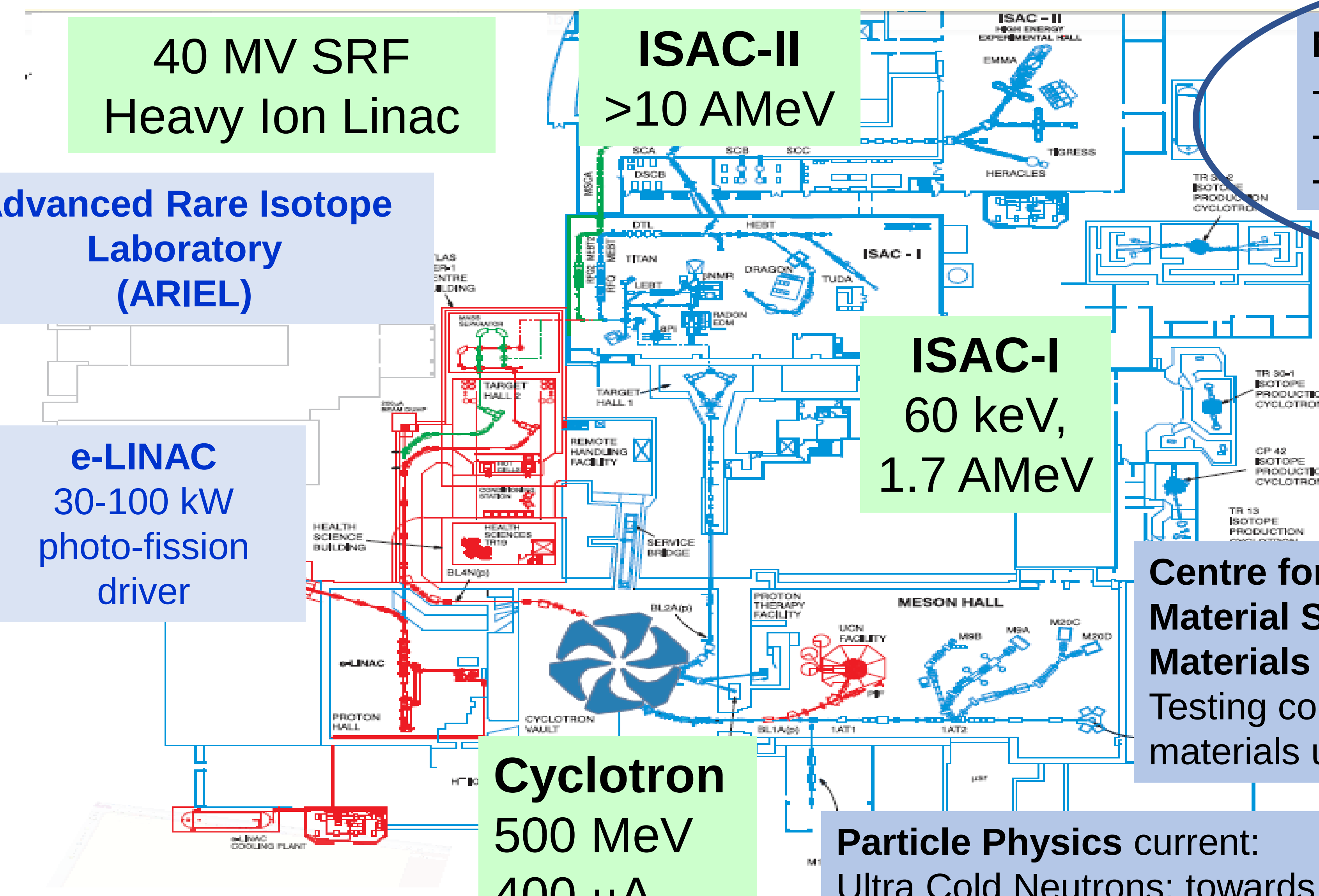


TRIUMF’s research portfolio



- Use of accelerators at TRIUMF:
  - Secondary beams available:
    - Radioactive isotopes
    - Muons & pions
    - Neutrons
  - We also have primary beams:
    - Protons and electrons
- Use of accelerators around the world (primary and 2^{nd} beams):
  - Hadron beams LHC at CERN
  - Anti-proton beams at CERN
  - Neutrino beams at J-PARC

TRIUMF's accelerator complex: on-site activities



40 MV SRF
Heavy Ion Linac

ISAC-II
>10 AMeV

Advanced Rare Isotope Laboratory (ARIEL)

e-LINAC
30-100 kW
photo-fission
driver

ISAC-I
60 keV,
1.7 AMeV

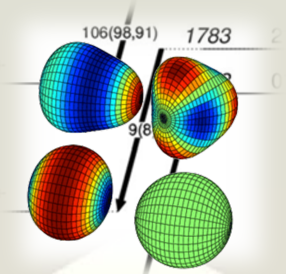
Cyclotron
500 MeV
400 μA

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

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

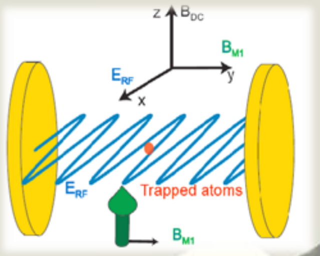
Particle Physics current:
Ultra Cold Neutrons: towards nEDM
Completed: PiENu & TWIST

Nuclear Physics at TRIUMF



Nuclear Structure & Dynamics

Exploration of evolution of nuclear shell structure, deformations, shapes, ground & excited state properties



Precision Tests of Fundamental Interactions

Precision tests of the Standard Model using atom trapping, laser manipulation, decay modes

Nuclear Astrophysics

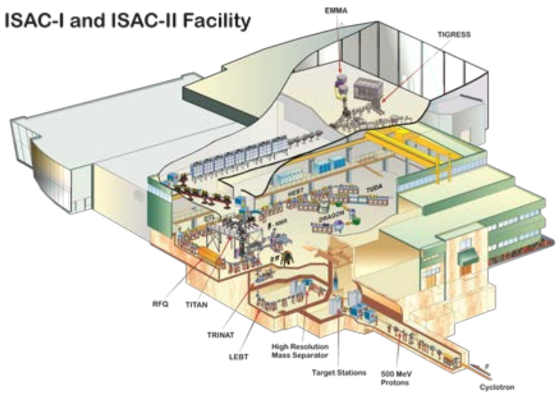
Direct and indirect measurements of important reactions and decays for nucleosynthesis and stellar evolution

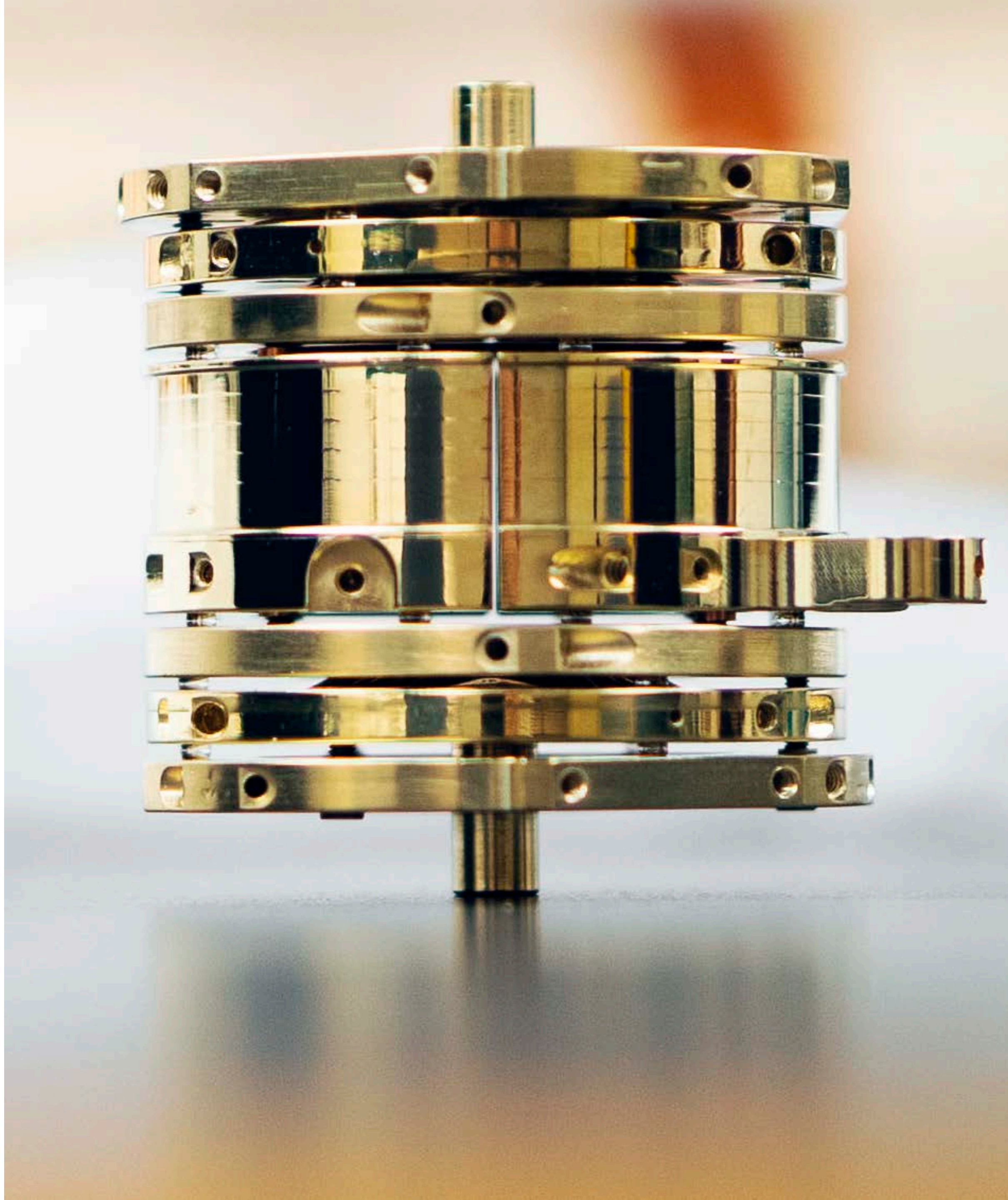
The “Three Pillars” of experimental nuclear physics research at TRIUMF-ISAC

DETAIL LOOK AT THE THREE PILLARS:

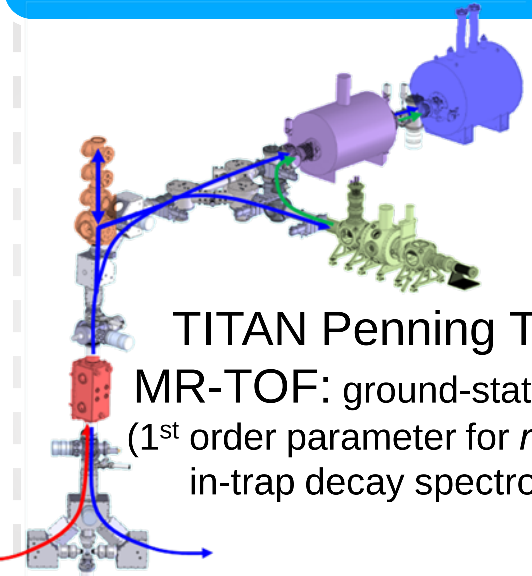
- NUCLEAR ASTROPHYSICS
- NUCLEAR STRUCTURE AND DYNAMICS
- PRECISION TEST OF FUNDAMENTAL INTERACTIONS

- **Very interdisciplinary approach of all three pillars**
- **18 experiment installations**



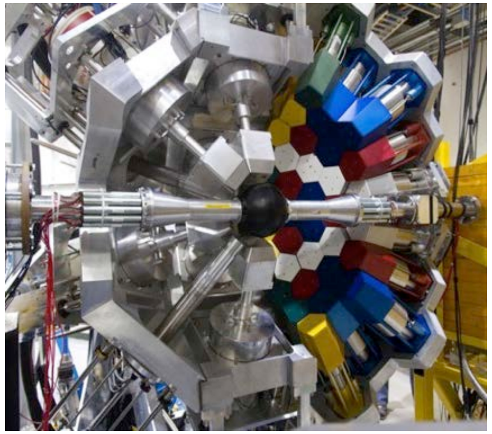


NUCLEAR ASTROPHYSICS Capabilities at ISAC



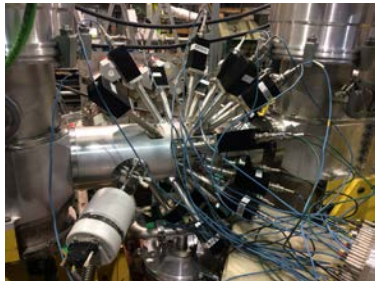
TITAN Penning Trap & MR-TOF: ground-state masses (1st order parameter for *r*-process), in-trap decay spectroscopy

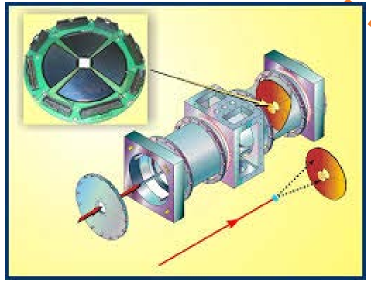
GRIFFIN Spectrometer: total measurement of ground-state & decay properties: β+, β-, EC, e^+e^-, β-*n*, $t_{1/2}$



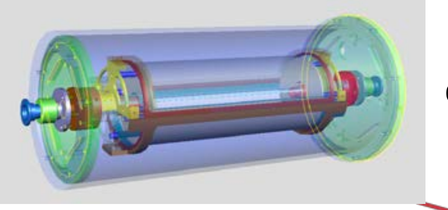
Low Energy (30 keV, stopped)

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



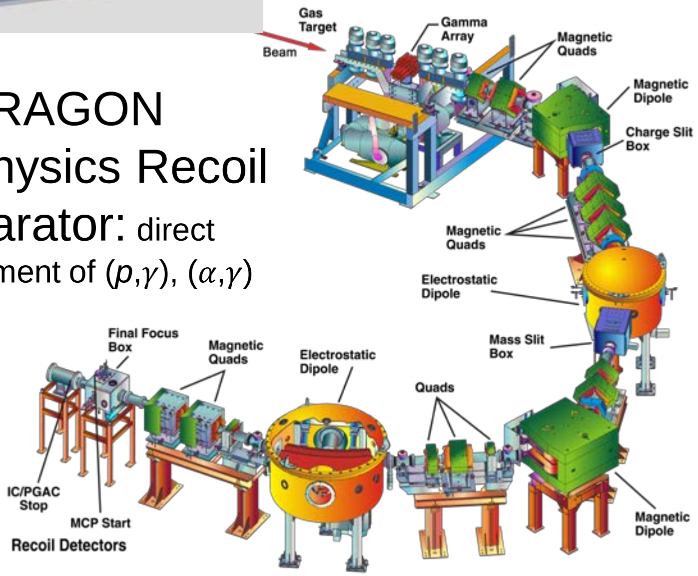


TUDA Array: direct measurement of (*p*,α), (α,*p*)



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

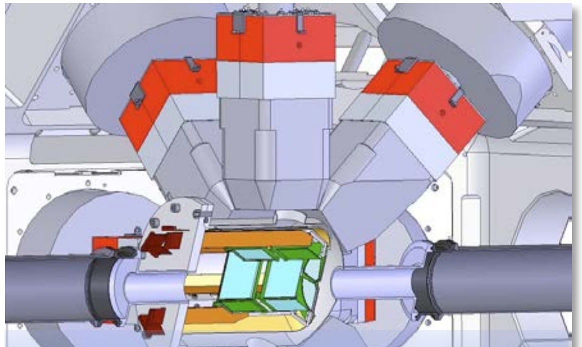
DRAGON Astrophysics Recoil Separator: direct measurement of (*p*,γ), (α,γ)



Medium Energy (0.15 – 1.8 MeV/a.m.u)

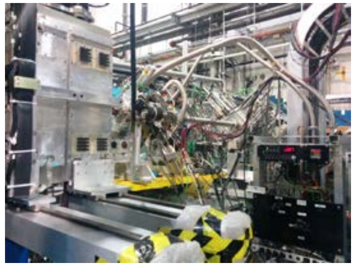
Indirect

Direct

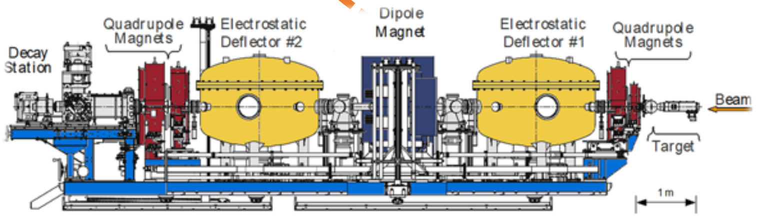


TIGRESS & Ancillary Detectors: Fusion-evaporation, transfer reaction studies e.g. (*d,p*) etc

IRIS Solid H, D target Indirect measurements (*d,p*), (p,n), (p,α) etc



EMMA Spectrometer: couple with TIGRESS for transfer, direct (*p*,γ) eytc

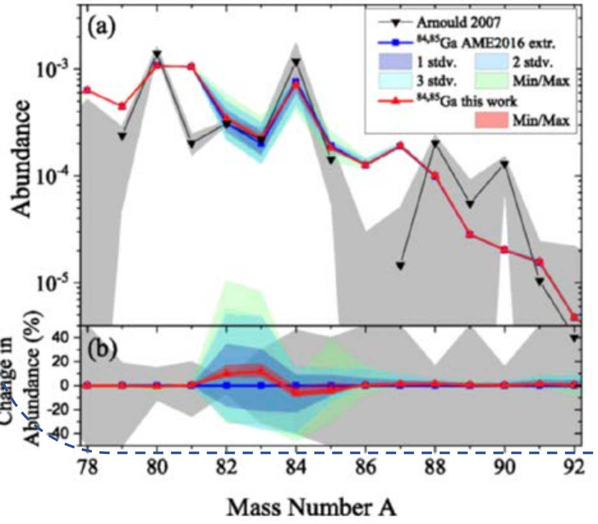


High Energy (1.8 – 16 MeV/a.m.u)

Mass measurements of neutron-rich gallium isotopes refine production of nuclei of the first r-process abundance peak in neutron-star merger calculations

M. P. Reiter *et al.*

Phys. Rev. C **101**, 025803 – Published 10 February 2020



TITAN measures exotic masses elucidating features in *r*-process peak in Neutron Star Merger!

The impact of (n,γ) reaction rate uncertainties of unstable isotopes on the i-process nucleosynthesis of the elements from Ba to W

Pavel A. Denissenkov,[1,2,3†*] Falk Herwig[1,2,†], Georgios Perdikakis[2,4,5] and Hendrik Schatz[2,5,6,†]

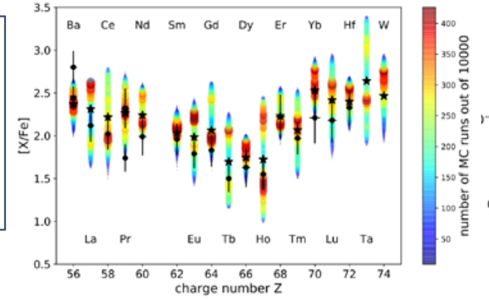
[1] Department of Physics & Astronomy, University of Victoria, Victoria, B.C., V8W 2Y2, Canada
[2] Joint Institute for Nuclear Astrophysics, Center for the Evolution of the Elements, Michigan State University, 640 South Shaw Lane, East Lansing, MI 48824, USA
[3] TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T 2A3, Canada
[4] Department of Physics, Central Michigan University, Mt. Pleasant, Michigan 48859, USA
[5] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA
[6] Department of Physics & Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
[†] NuGrid Collaboration, http://nugridstars.org

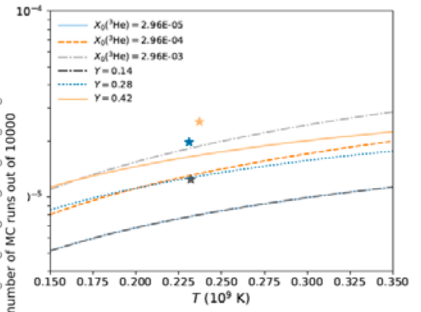
An evidence-based assumption that helps to reduce the discrepancy between the observed and predicted ^{7}Be abundances in novae

Pavel A. Denissenkov,[1,2,3,†*] Chris Ruiz[2,3], Sriteja Upadhyayula[3] and Falk Herwig[1,2,†]

[1] Department of Physics & Astronomy, University of Victoria, Victoria, B.C., V8W 2Y2, Canada
[2] Joint Institute for Nuclear Astrophysics, Center for the Evolution of the Elements, Michigan State University, 640 South Shaw Lane, East Lansing, MI 48824, USA
[3] TRIUMF, 4004 Wesbrook Mall, Vancouver, BC, V6T 2A3, Canada
[†] NuGrid Collaboration, http://nugridstars.org

Collaboration with UVic spawns computational estimates of important neutron captures for nucleosynthesis, and ^{7}Li production in novae





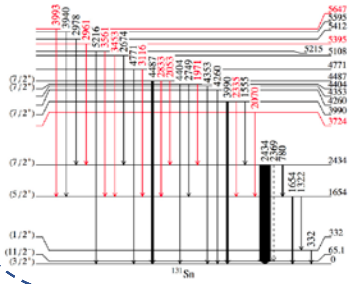
SCIENCE!

GRIFFIN measures exotic nucleus lifetime – constraining *ab initio* theory in mass region – implications for *r*-process via refinement of mass models

β decay and β-delayed neutron decay of the $N = 82$ nucleus $^{131}_{49}In_{82}$

R. Dunlop,[1,*] C. E. Svensson,[1] C. Andreoiu,[2] G. C. Ball,[3] N. Bernier,[3,4] H. Bidaman,[1] V. Bildstein,[1] M. Bowry,[3] D. S. Cross,[2] I. Dillmann,[3,5] M. R. Dunlop,[1] F. H. Garcia,[2] A. B. Garnsworthy,[3] P. E. Garrett,[1] G. Hackman,[3] J. Henderson,[3,†] J. Measures,[3,6] D. Mücher,[1] B. Olaizola,[1,3] K. Ortner,[2] J. Park,[3,4,‡] C. M. Petrache,[7] J. L. Pore,[2,§] J. K. Smith,[3,||] D. Southall,[3,¶] M. Ticu,[2] J. Turko,[1] K. Whitmore,[2] and T. Zidar[1]

[1] Department of Physics, University of Guelph, Guelph, Ontario, Canada N1G 2W1
[2] Department of Chemistry, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6
[3] TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3
[4] Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z4
[5] Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada V8P 5C2
[6] Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom
[7] Centre de Sciences Nucléaires et Sciences de la Matière, CNRS/IN2P3, Université Paris-Saclay, 91405 Orsay, France



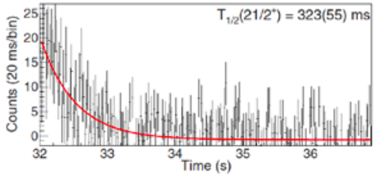


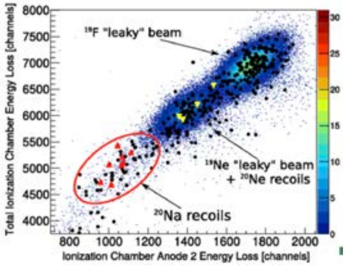
FIG. 10. Measurement of the half-life of the 21/2+ isomer in ^{131}In. The activity curve from the "beam-off" portion of the cycle was generated by placing a gate on the 171-, 173-, and 285-keV γ rays, which are emitted following the β decay of the 21/2+ state. The half-life from this fit was measured to be 323(55) ms.

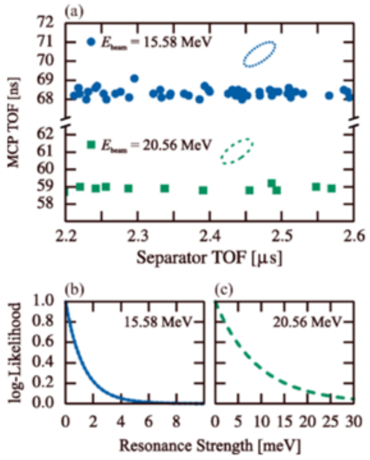
DRAGON measuring proton radiative capture on certain nuclei for first time – refining nova nucleosynthesis

Direct Measurement of the Key $E_{c.m.} = 456$ keV Resonance in the Astrophysical $^{19}Ne(p,\gamma)^{20}Na$ Reaction and Its Relevance for Explosive Binary Systems

R. Wilkinson, G. Lotay, A. Lennarz, C. Ruiz, G. Christian, C. Akers, W. N. Catford, A. A. Chen, D. Connolly, B. Davids, D. A. Hutcheon, D. Jedrejcic, A. M. Laird, L. Martin, E. McNeice, J. Riley, and M. Williams

Phys. Rev. Lett. **119**, 242701 – Published 11 December 2017





PHYSICAL REVIEW C
covering nuclear physics
Highlights Recent Accepted Authors Referees Search Press About Staff
Featured in Physics Editors' Suggestion

Direct measurement of astrophysically important resonances in $^{38}K(p,\gamma)^{39}Ca$

G. Christian, G. Lotay, C. Ruiz, C. Akers, D. S. Burke, W. N. Catford, A. A. Chen, D. Connolly, B. Davids, J. Fallis, U. Hager, D. Hutcheon, A. Mahl, A. Rojas, and X. Sun

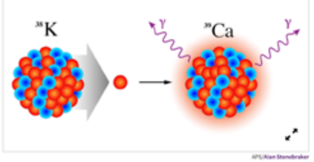
Phys. Rev. C **97**, 025802 – Published 21 February 2018
Physics See Synopsis: Intel on Stellar Element Production from Accelerator Data

Physics ABOUT BROWSE PRESS COLLECTIONS Search articles
SYNOPSIS

Intel on Stellar Element Production from Accelerator Data

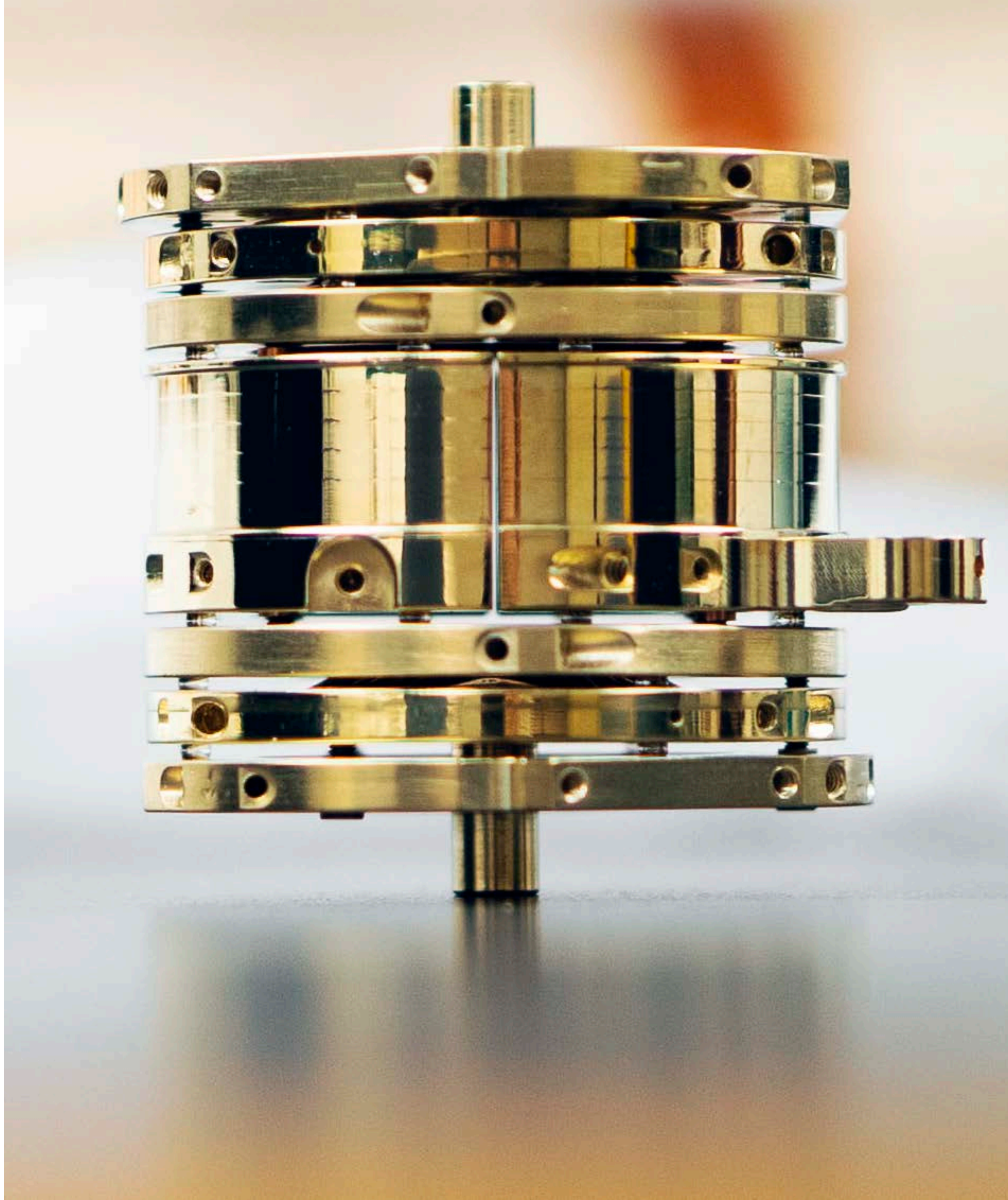
February 21, 2018 • Physics 11, s23

Measurements of a nuclear reaction relevant to the synthesis of calcium, potassium, and argon in stars boost the accuracy of models for predicting the elements' abundances.



DETAIL LOOK AT THE THREE PILLARS:

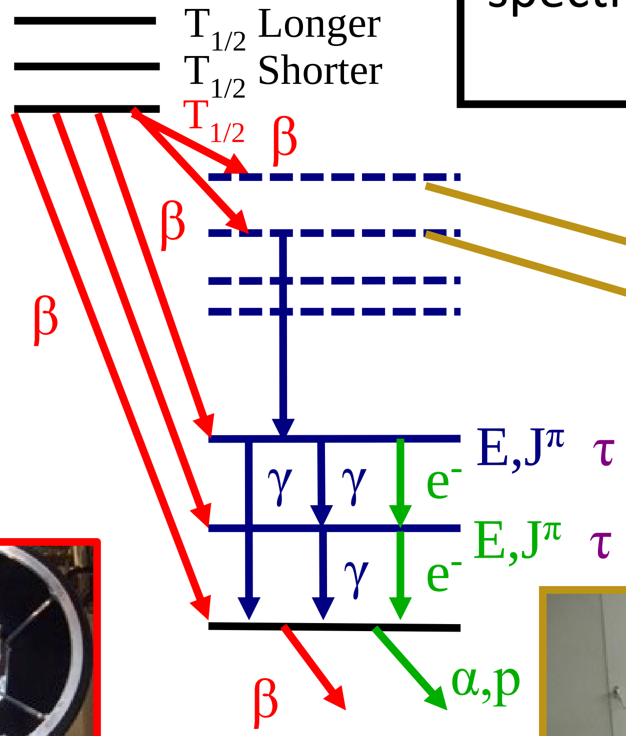
- NUCLEAR ASTROPHYSICS
- **NUCLEAR STRUCTURE AND DYNAMICS**
- PRECISION TEST OF FUNDAMENTAL INTERACTIONS



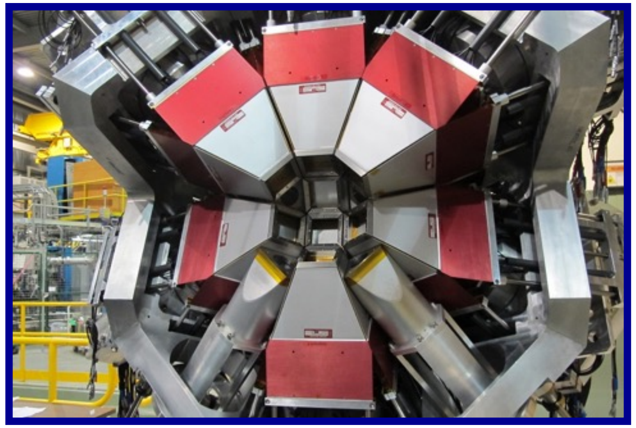
Nuclear Spectroscopy with GRIFFIN

Fast, in-vacuum tape system

Enhances decay of interest

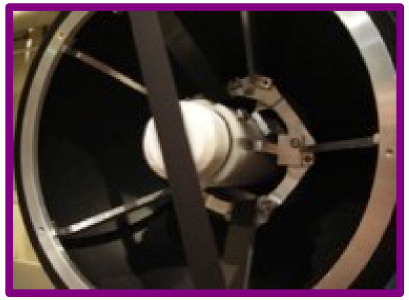


GRIFFIN is a powerful spectrometer for decay spectroscopy studies with rare-isotopes



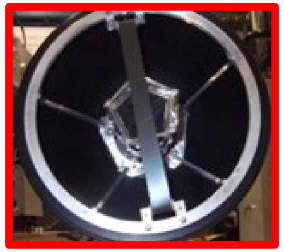
HPGe: *branching ratios, multipolarities and mixing ratios*

LaBr$_3$: *level lifetimes*



Zero-Degree Fast scintillator

Fast-timing signal for betas



SCEPTAR: 10+10 plastic scintillators

Detects beta decays and determines branching ratios

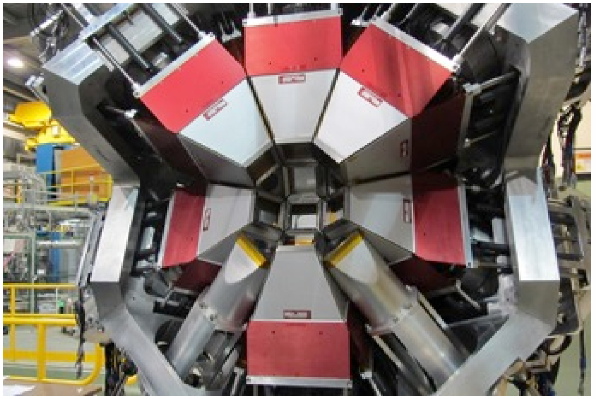
DESCANT Neutron array

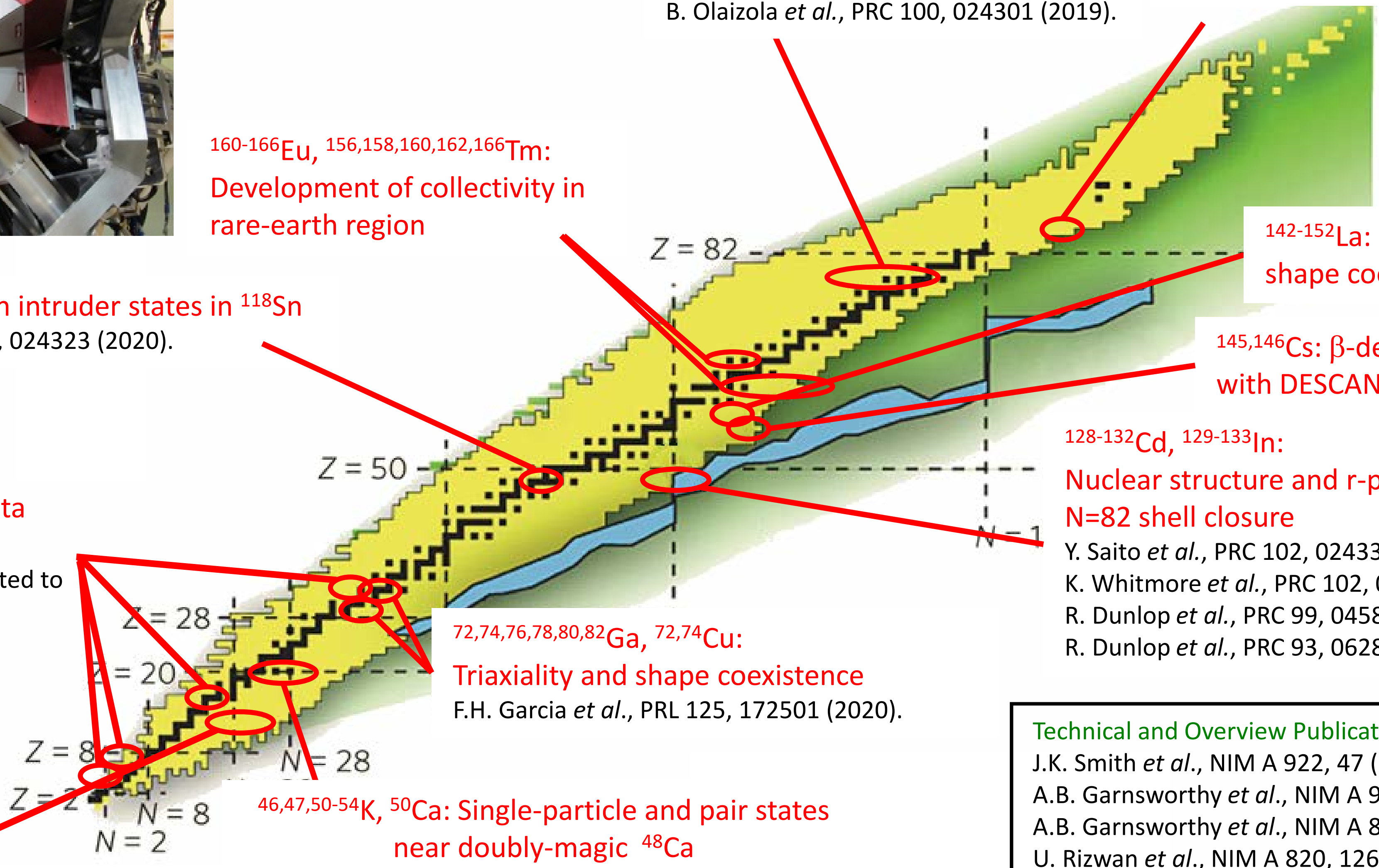
Detects neutrons to measure beta-delayed neutron branching ratios

PACES: 5 Cooled Si(Li)s

Detects Internal Conversion Electrons and alphas/protons

Recent Nuclear Structure and Dynamics studies at ISAC





$^{188\text{-}200}$Tl: Development of collectivity in Hg isotopes
B. Olaizola *et al.*, PRC 100, 024301 (2019).

^{228,230}Fr: Probing Octupole deformation and collectivity in Radium isotopes.

Calibrations and development with ^{9}Li, ^{26}Na, ^{66}Ga beams

$^{160\text{-}166}$Eu, ^{156,158,160,162,166}Tm: Development of collectivity in rare-earth region

$^{142\text{-}152}$La: Octupole collectivity and shape coexistence in Ce isotopes

^{118}In: Collective 2p-2h intruder states in ^{118}Sn
K. Ortner *et al.*, PRC 102, 024323 (2020).

^{145,146}Cs: β-delay neutron measurements with DESCANT, fast-timing with $LaBr_3$

$^{128\text{-}132}$Cd, $^{129\text{-}133}$In: Nuclear structure and r-process nucleosynthesis at the N=82 shell closure
Y. Saito *et al.*, PRC 102, 024337 (2020).
K. Whitmore *et al.*, PRC 102, 024327 (2020).
R. Dunlop *et al.*, PRC 99, 045805 (2019).
R. Dunlop *et al.*, PRC 93, 062801(R) (2016).

^{10}C, ^{14}O, ^{22}Mg, ^{62}Ga: Superallowed Fermi beta decays
A.D. MacLean *et al.*, Accepted to PRC (2020).
M.R. Dunlop *et al.*, PRC 96, 045502 (2017).

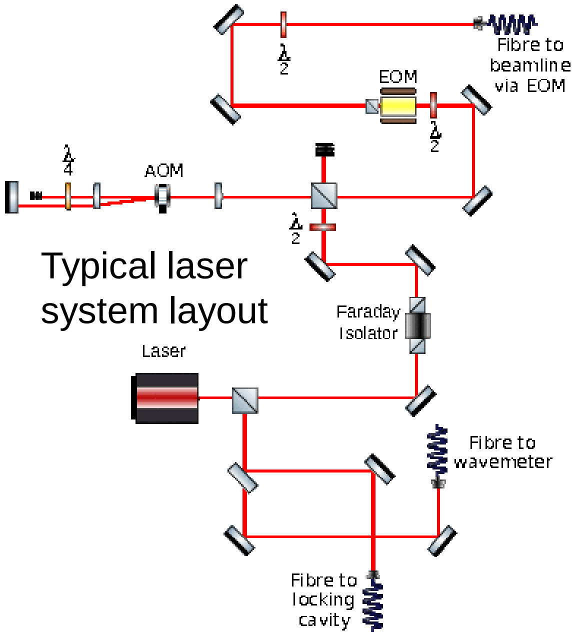
^{72,74,76,78,80,82}Ga, ^{72,74}Cu: Triaxiality and shape coexistence
F.H. Garcia *et al.*, PRL 125, 172501 (2020).

^{31,32}Na, $^{33\text{-}35}$Mg: Island of inversion

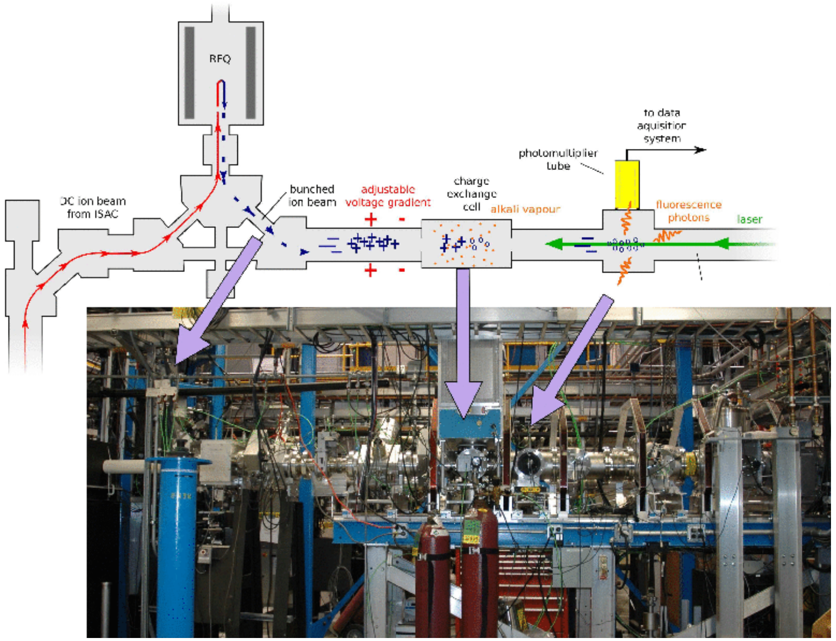
$^{46,47,50\text{-}54}$K, ^{50}Ca: Single-particle and pair states near doubly-magic ^{48}Ca
J.K. Smith *et al.*, Accepted to PRC (2020).
J. Pore *et al.*, PRC 100, 054327 (2019).
A.B. Garnsworthy *et al.*, PRC 96, 044329 (2017).

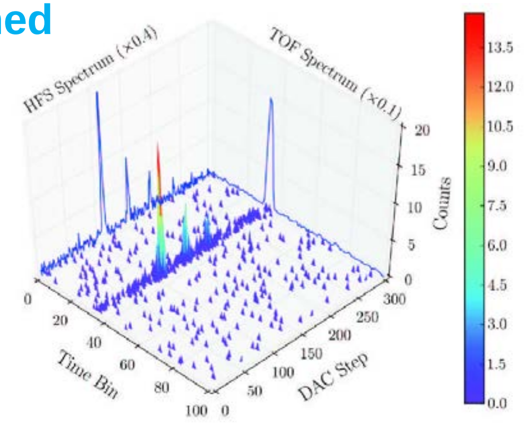
Technical and Overview Publications
J.K. Smith *et al.*, NIM A 922, 47 (2019).
A.B. Garnsworthy *et al.*, NIM A 918, 9 (2019).
A.B. Garnsworthy *et al.*, NIM A 853, 85 (2017).
U. Rizwan *et al.*, NIM A 820, 126 (2016).
A.B. Garnsworthy, Acta Phys.Pol. B, 47, 713 (2016).
C.E. Svensson and A.B. Garnsworthy, Hyp. Int. 225, 127 (2014).

Collinear Laser Spectroscopy at TRIUMF: Precision experiments for nuclear structure using DC and bunched radioactive beams



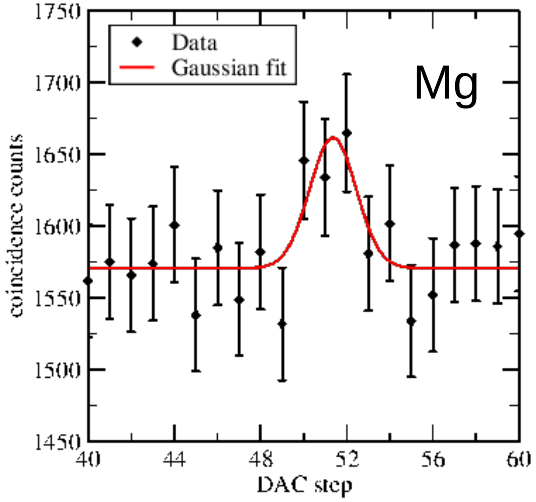
Typical laser system layout



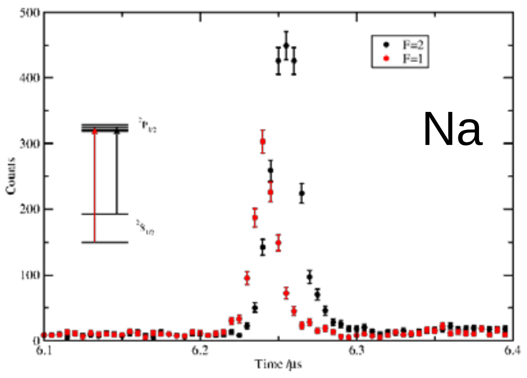


Utilise time resolved DAQ for laser spectroscopy

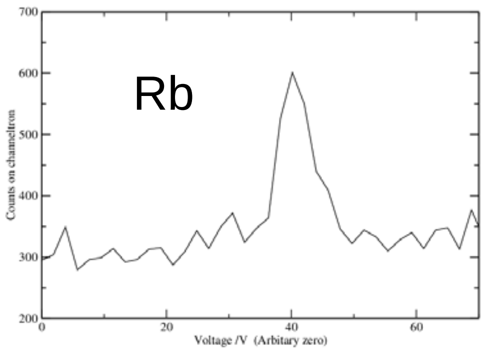
Current Development



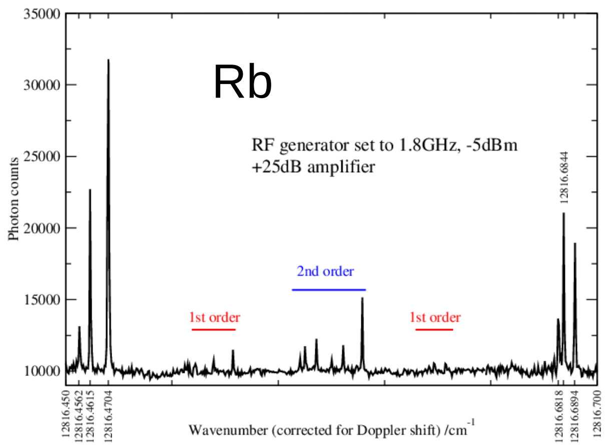
Trilis-photon-ion triple coincidence (unbunched beam)



Resonantly enhanced gas stripping



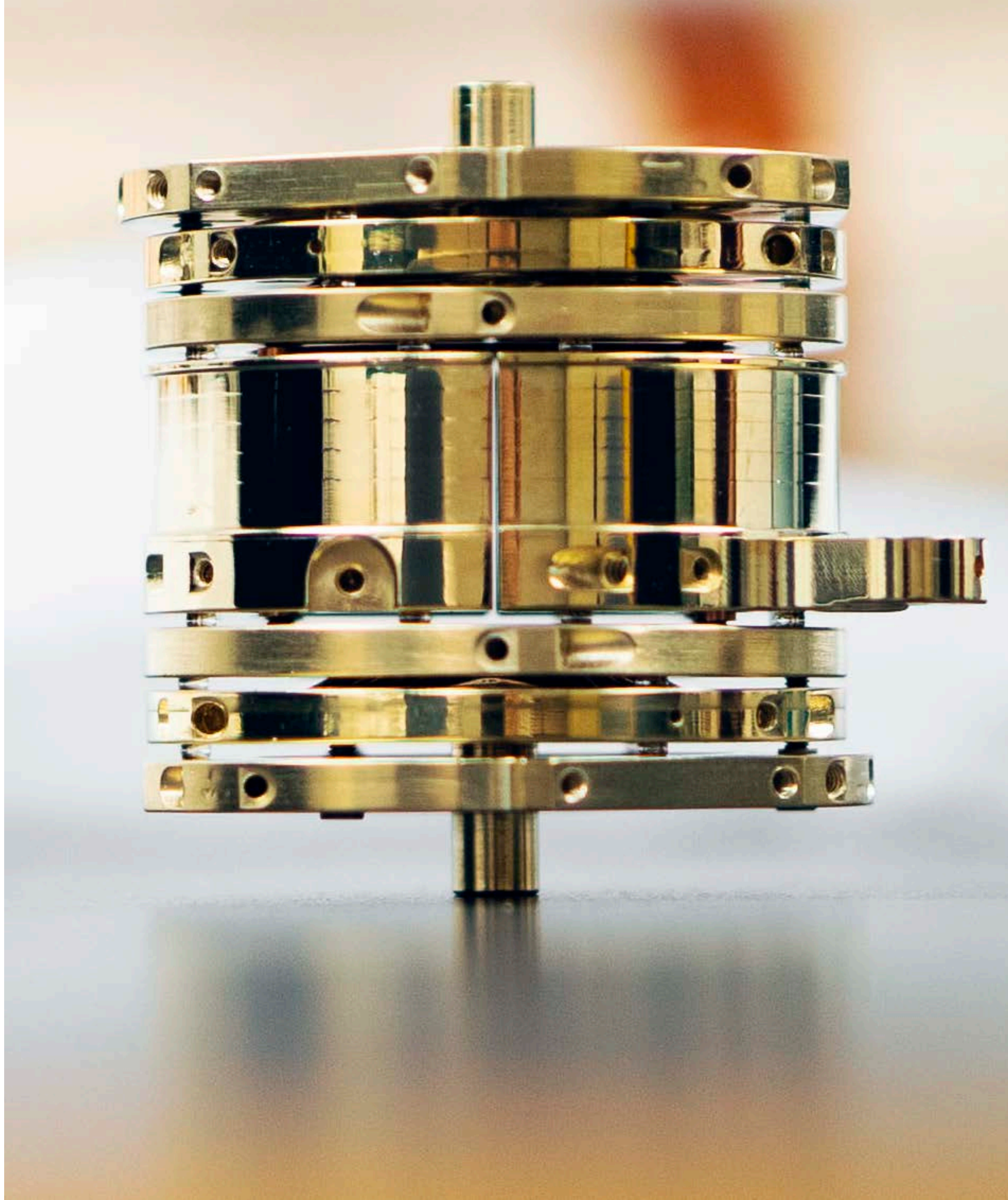
Resonance ionisation (isomeric separation)



Microwave techniques for high resolution, multi GHz scans

DETAIL LOOK AT THE THREE PILLARS:

- NUCLEAR ASTROPHYSICS
- NUCLEAR STRUCTURE AND DYNAMICS
- PRECISION TEST OF FUNDAMENTAL INTERACTIONS



Atomic parity violation test with laser trapped francium

FrPNC collab: Manitoba, TRIUMF, Maryland, W&M, San Luis Potosí

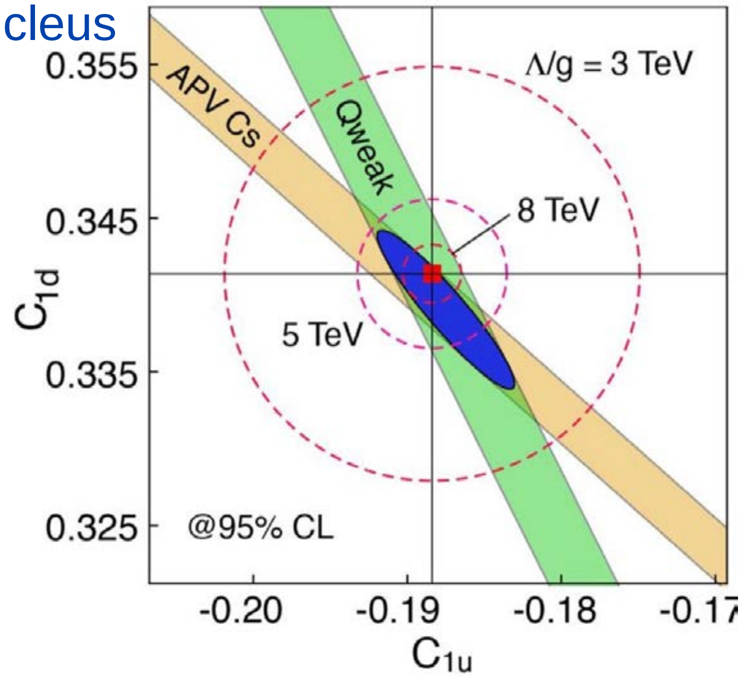
Z-boson exchange between atomic electrons and the quarks in the nucleus

PV interaction mixes electronic s & p states

drive strictly parity-forbidden s → s E1 transition

effect in Fr 18 x larger than in Cs

re-use atoms in laser trap → need ≈10^6 fewer atoms

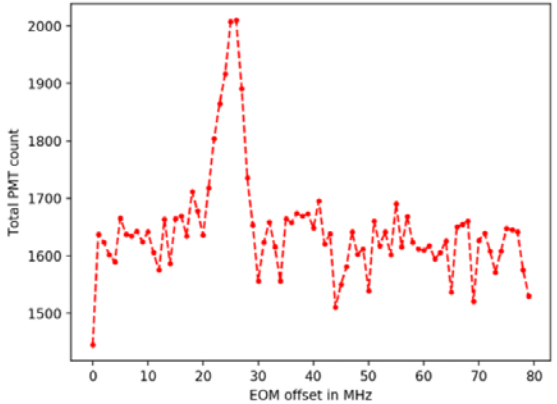


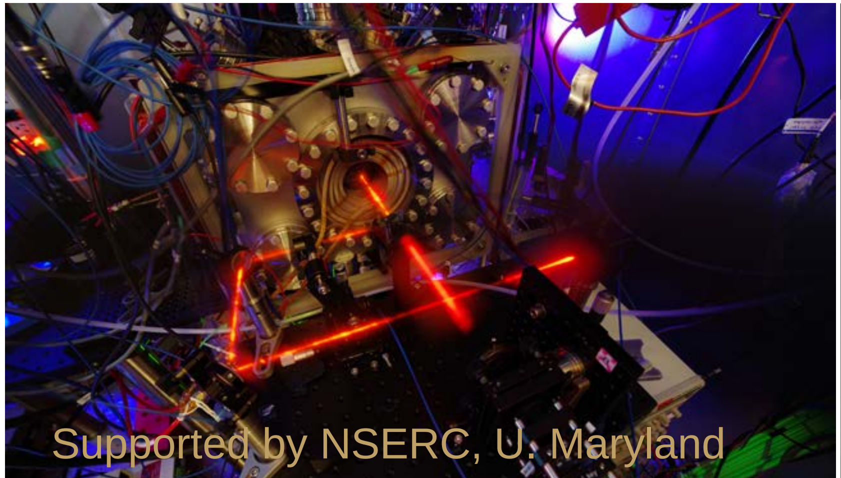
from: Carlini, PANIC 2017

APV **uniquely** provides the 'orthogonal' constraint on (C_{1u}, C_{1d}) [PV electron-quark couplings]

Recent results

- Observed "ß-type" Stark-induced 7s-8s transition
  - basis of APV test
  - 10^9-10^{10} × weaker than typical atomic transition





Supported by NSERC, U. Maryland

UHV power-buildup cavity, achieved 750 kW/cm^2 (!) of circulating 7s-8s (506 nm) light (not in online UHV chamber yet)

Francium Fountain Electric Dipole Moment (EDM) Experiment at TRIUMF

Collaborators:
B. Feinberg, H. Gould, Y. Li, C. Munger, Y. Murakami*, H. Nishimura, C. Timossi (**LBNL**);
R. Collister, C. Cummings*, P. Dicks*, J. MacFarlane* (**LBNL Alumni**) *Student
J. Behr, M. Pearson, A. Teigelhoefer (**TRIUMF**);
U. Jentschura (**Missouri S&T**)

Francium Fountain EDM Experiment

Francium is sensitive to an electron EDM and other T-violating moments.

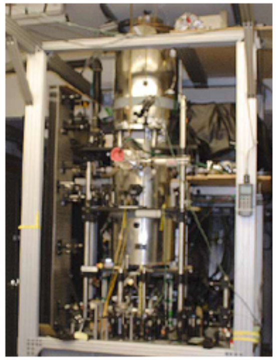
A fountain experiment has a low risk of false positive and false negative results

Trapping Fr Atoms at TRIUMF

- **More than 10^9 Fr^+ /s delivered**
- **TRIUMF expertise in trapping short-lived radioactive atoms.**
- **Maximize number of trapped Fr atoms**

- GOAL: Discover or rule out EDM beyond current limit.

Francium Fountain Electric Dipole Moment (EDM) Experiment at TRIUMF



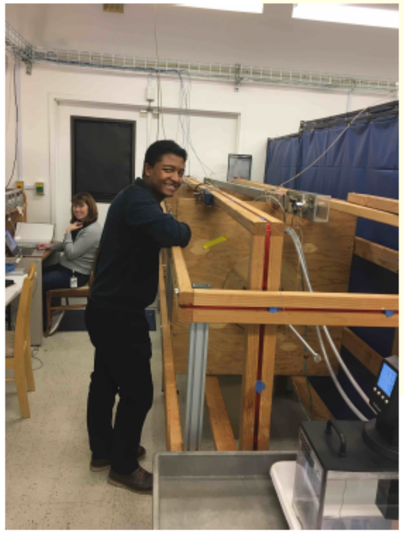
Early Cs Fountain EDM experiment

Experimental Development Using Cesium at LBNL

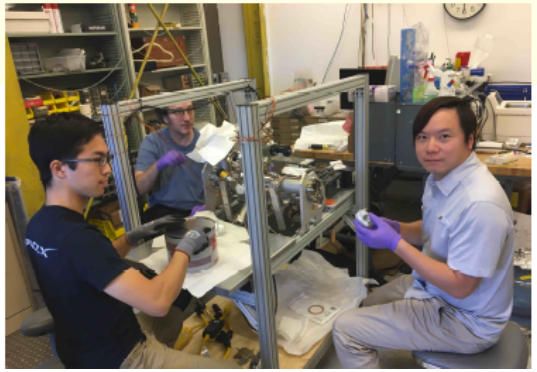
- Inexhaustible supply of stable Cs
- Inexpensive diode lasers

But compared to Fr, a Cs experiment is

- 9 times less sensitive to electron EDM
- 10 times more sensitive to systematics
- Delayed by wildfires and pandemics



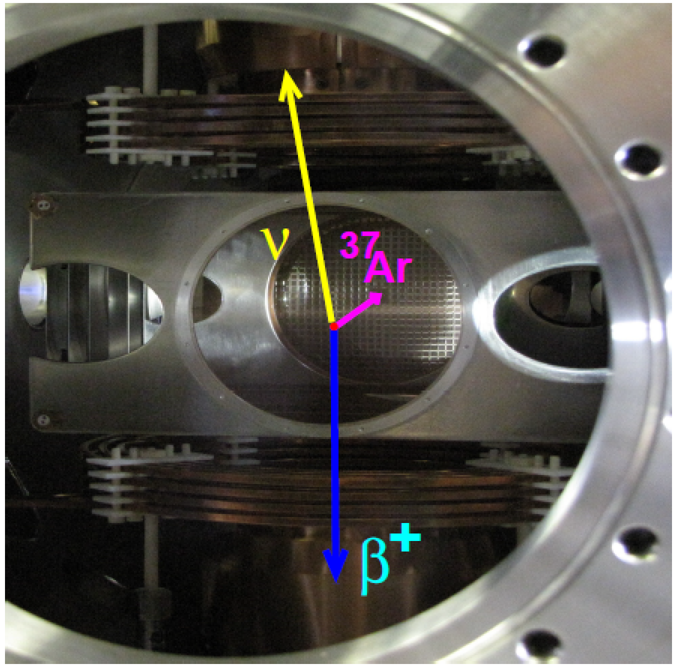
Jessica MacFarlane & Preston Dicks taking data with the magnetic shield test stand (2020)



Yukei Murakami, Rob Collister & Yan Li rebuiding a Cs magneto-optical trap (2019)

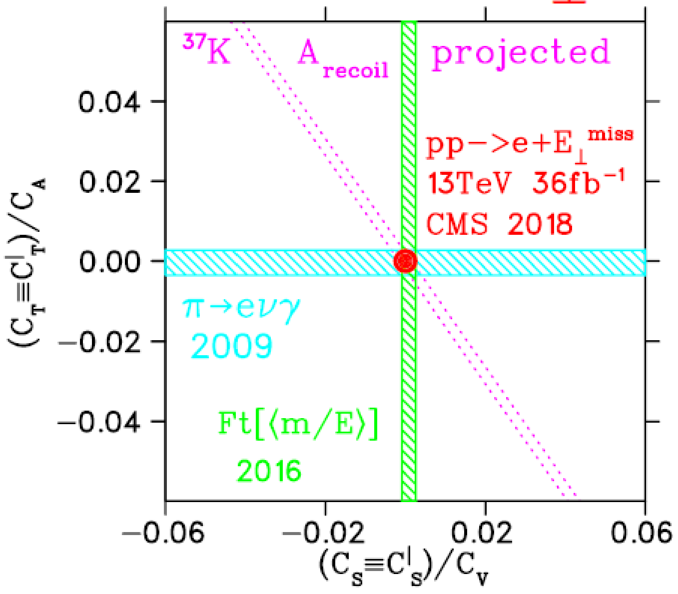
- GOAL: Plan to move set-up to TRIUMF in 2021/22.

TRINAT: TRIumf Neutral Atom Trap for β-decay



Most accurate nuclear β asymmetry using polarized ^{37}K
Fenker PRL 120 062502
$\rightarrow$ Complementary constraints on interactions making right-handed ν's

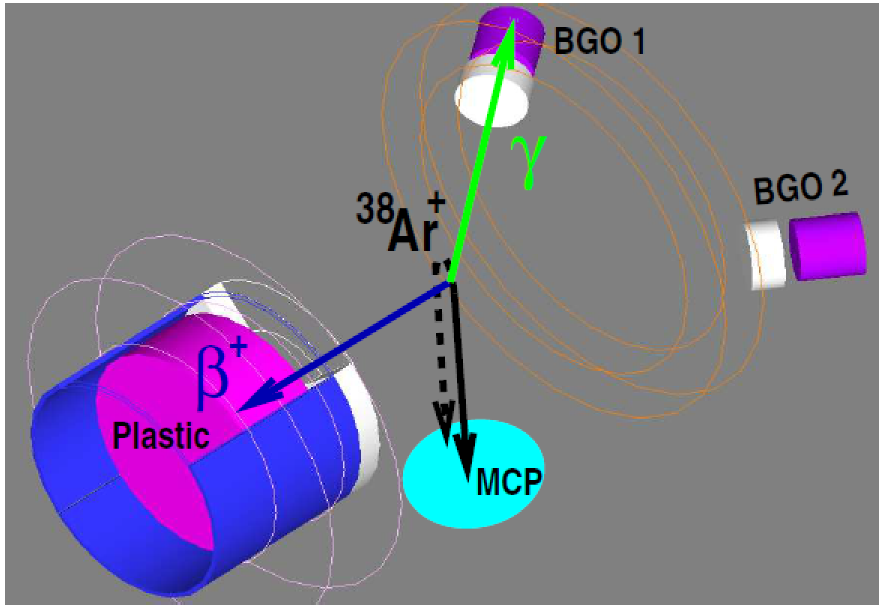
Next: asymmetry of nuclear recoils from ^{37}K
Similar sensitivity to 4-fermion contact interactions as
LHC p+p $\rightarrow e^- + E_\perp^{\rm miss}$



Test T-reversal $^{38{\rm m}}$K $\rightarrow$ ^{38}Ar+$\beta\nu\gamma$

$$\vec{p}_\nu \cdot \vec{p}_\beta \times \vec{p}_\gamma \xrightarrow{t \rightarrow -t} -\vec{p}_\nu \cdot \vec{p}_\beta \times \vec{p}_\gamma$$

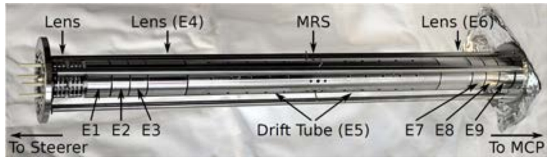
Unique for 1st generation



We consider $D\hat{J} \cdot \frac{\vec{p}_\beta}{E_\beta} \times \frac{\vec{p}_\nu}{E_\beta}$ in ^{45}K 'isospin-forbidden mirror' decay: T-reversal breaking enhanced by 4 to 100 X (must measure 1st) $\rightarrow$ complementary to neutron EDM

TITAN: Ion traps for high-precision mass spectrometry and in-trap decay spectroscopy.

Multi-Reflection Time-Of-Flight Mass Separator



- mass via TOF or
- beam purification
- precisions of $\frac{\delta m}{m} \geq 10^{-7}$
- demonstrated $T_{1/2}$ > 6 ms
- evolution of nuclear structure, nuclear astrophysics …

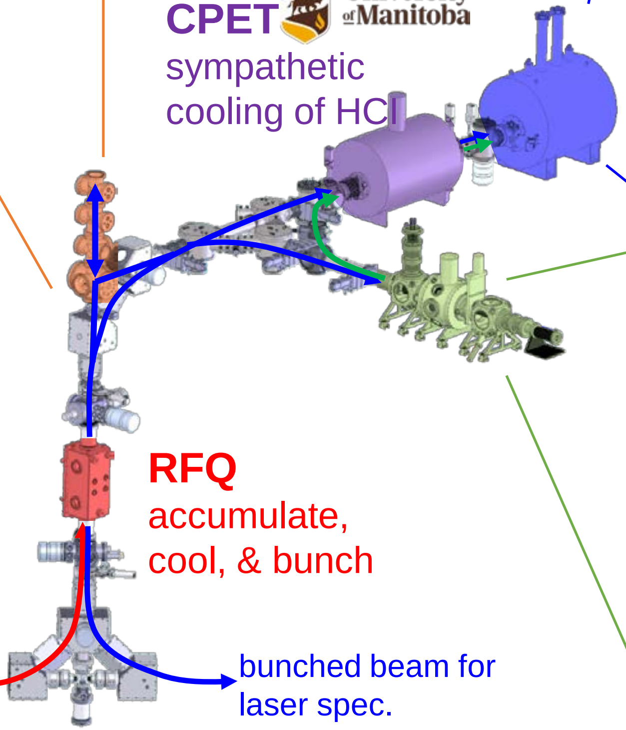
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Penning trap

- mass via $2\pi\ \nu_c$ = q/m · B
- Precisions of $\frac{\delta m}{m} \geq 10^{-9}$
- Demonstrated for $T_{1/2}$ > 9 ms
- Boosted by high charge states

- CVC hypothesis, unitarity of quark-mixing matrix, 2β0ν emitters, …

CPET University of Manitoba
sympathetic cooling of HCI



RFQ
accumulate, cool, & bunch

continuous ISAC beam

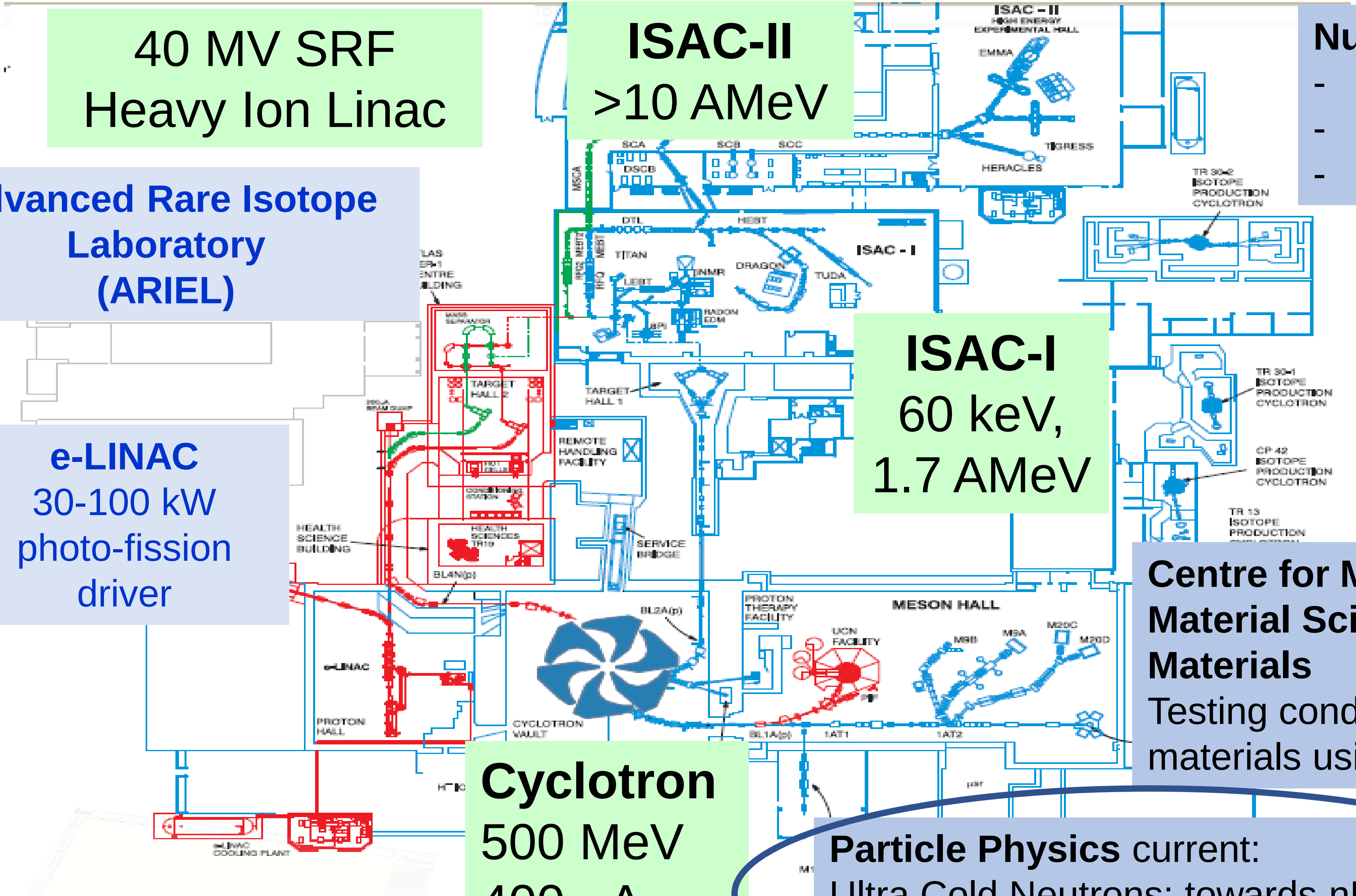
bunched beam for laser spec.

EBIT charge breeder

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

- ms charge breeding or
- in-trap decay spectroscopy
- 7 radially placed HPGe detectors
- stellar burning of highly charged ions, nuclear excitation by electron capture, certain forbidden decays

TRIUMF’s accelerator complex: on-site activities



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 current:
Ultra Cold Neutrons: towards nEDM
Completed: PiENu & TWIST

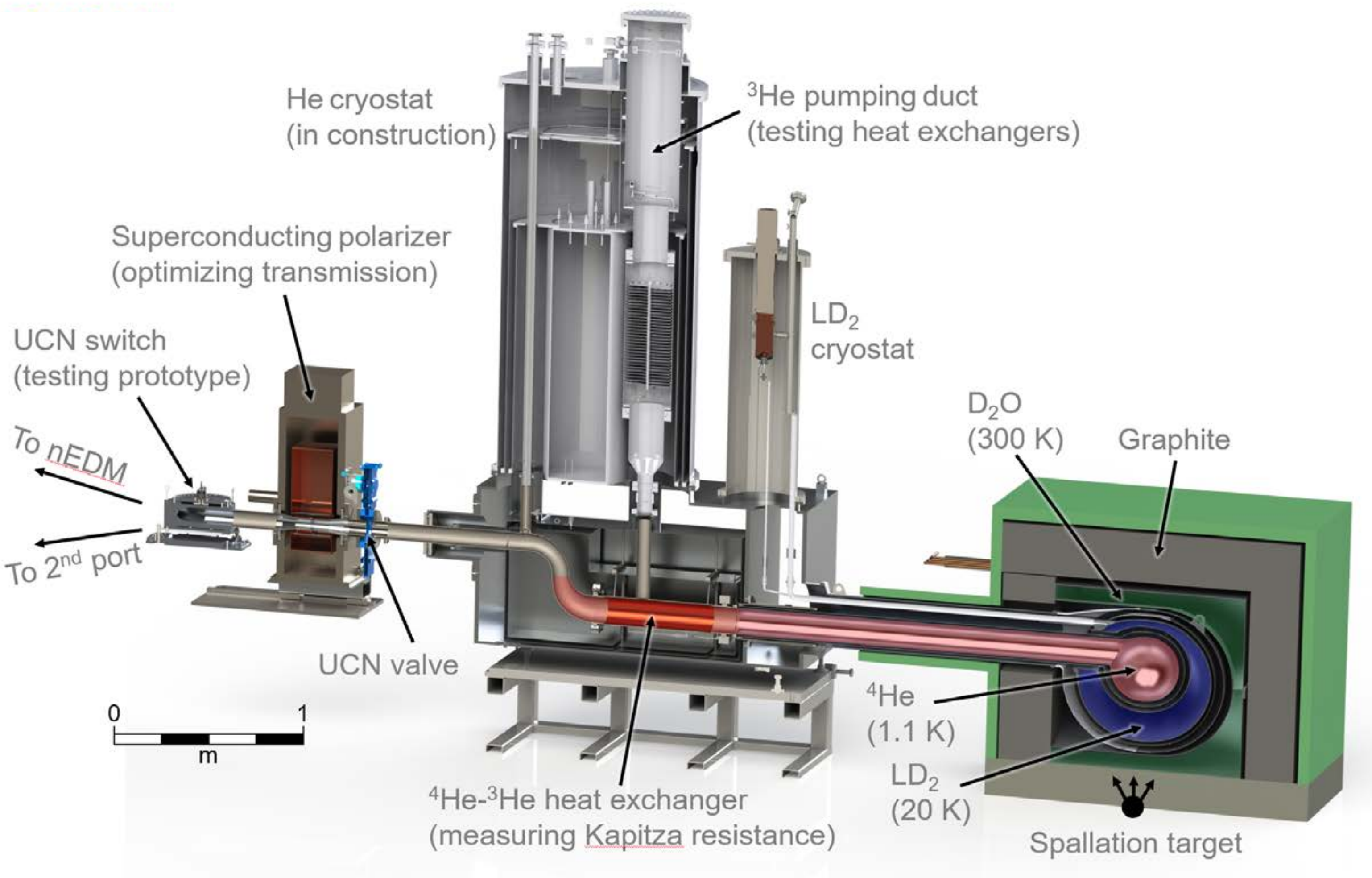
TUCAN project (TRIUMF UltraCold Advanced Neutron Source and EDM experiment)

Goals:
1) build the strongest UCN source in the world
2) search for neutron electric dipole moment (nEDM) with sensitivity of 10^{-27} ecm

UCN source
- Spallation neutron production
- Heavy water and deuterium moderator
- Superfluid helium-4 converter
- UCN are extracted to experiments
- Option: Two experiment ports: nEDM & additional experiment (option)

Status and timeline:
2017 - first UCN in Canada, 70 000 UCN per shot
2018 - UCN source conceptual design review completed
2018-2019 - experiments for next generation UCN source

2020 – He cryostat completed and successfully tested
2021 – Installation of source at TRIUMF and cryo testing
2022 – First UCN production with new source
2023 – Ready for EDM experiment

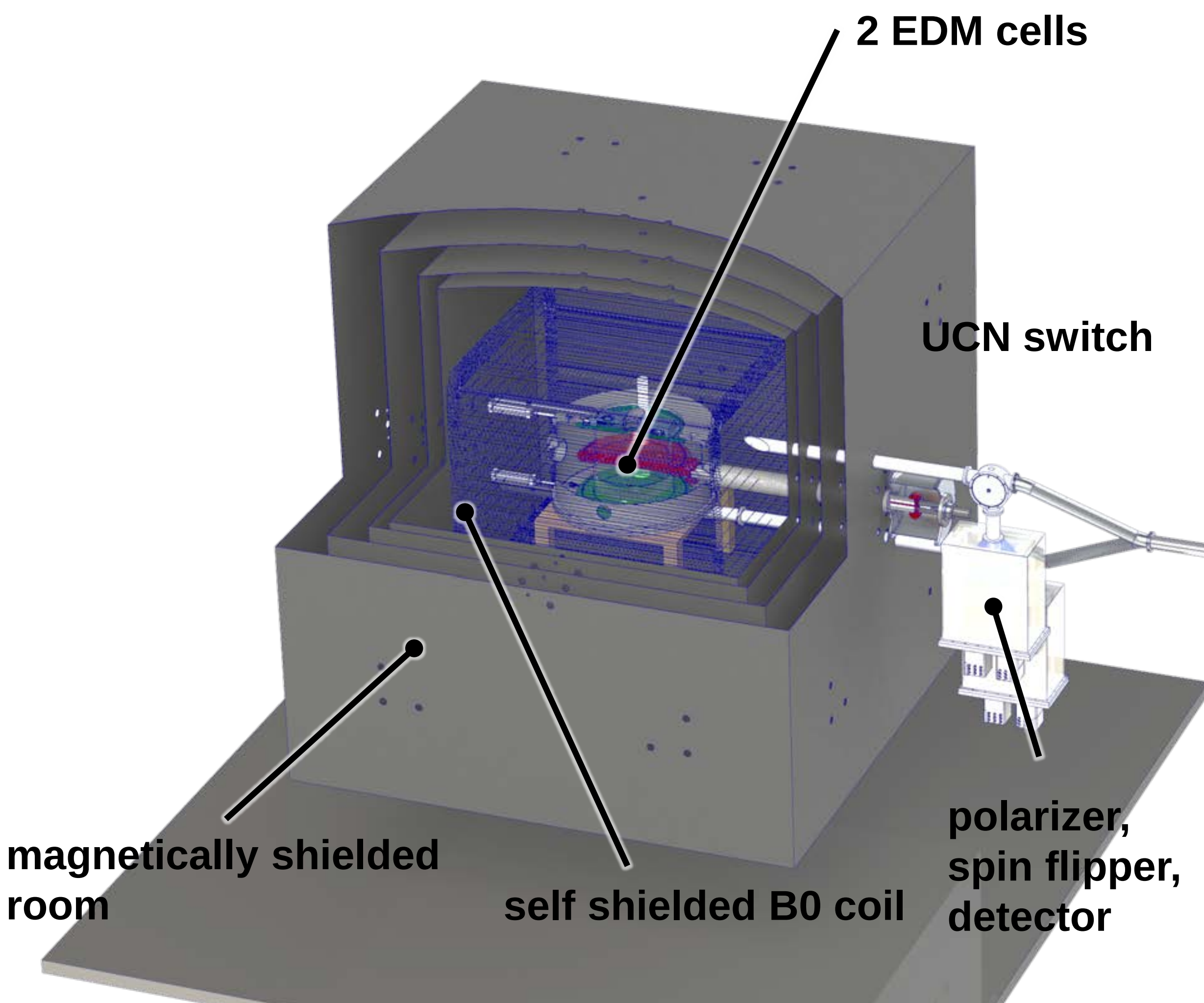


TUCAN project (TRIUMF UltraCold Advanced Neutron Source and EDM experiment)

Goals:
1) build the strongest UCN source in the world
2) search for neutron electric dipole moment (nEDM) with sensitivity of 10^{-27} ecm

nEDM
- Room-temperature spectrometer
- Ramsey-type experiment with polarized UCN
- Two measurement cells
- Superior B field control

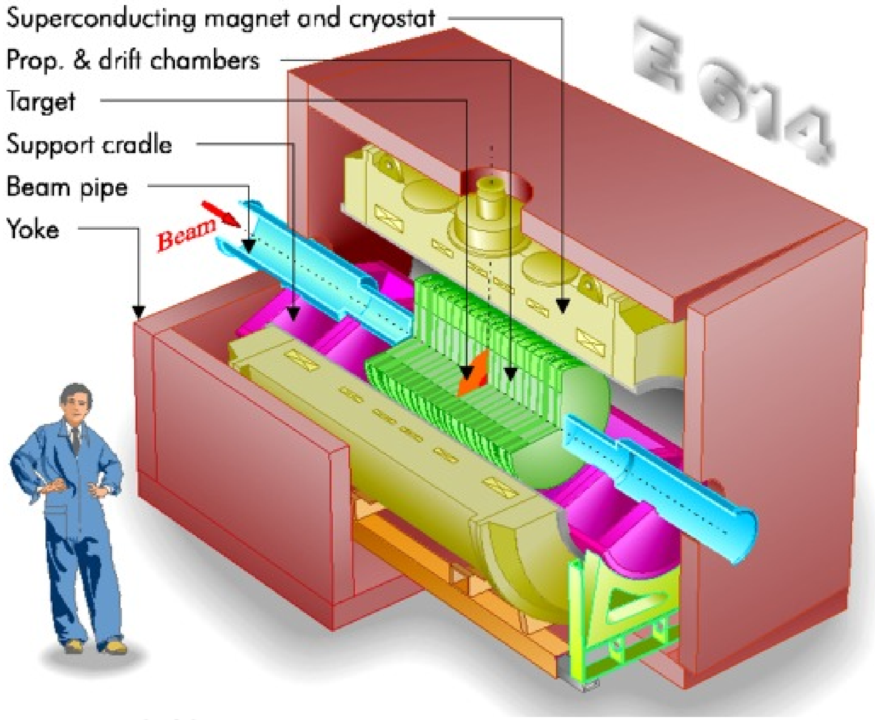
Status and timeline:
2020 – magnetically shielded room ordered
2021 – starting detailed design
2022 – assembly of MSR, first UCN storage in EDM cells
2023 – First Ramsey cycles

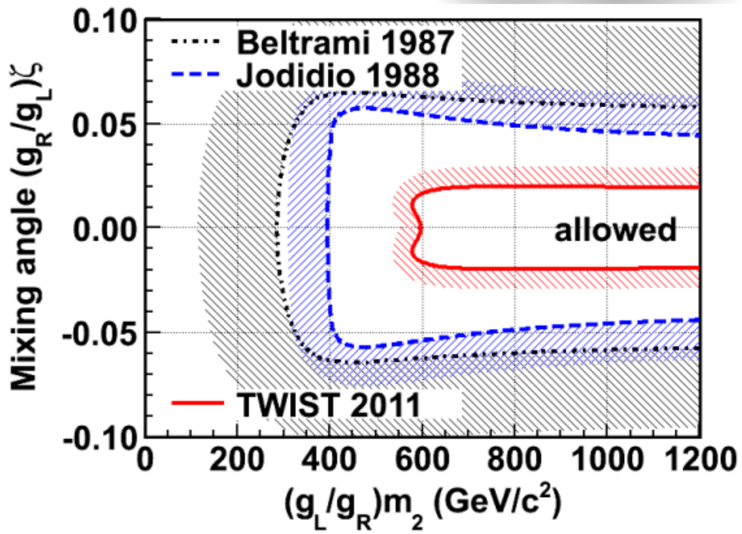


COMPLETED

TWIST: Precision Muon Decay

Alberta, UBC, Montreal, Regina, TRIUMF, Kurchatov, Texas A&M, Valparaiso





- **Test of Weak Interaction**
- ”Michel parameters” improved by a factor 10 compared to previous expt’s PRL 106, 041804 (2011)
  - Improved limits on right-handed current
  - Improved limits on new muon-electron coupling
- Inclusive limits on asymmetric two body muon decays PRD91, 052020(2015)
- Muon decay-in-orbit in μ^-Al PRD 80, 052012 (2009)
- Charged-particle spectra from μ^- capture on Al PRC101, 035502(2020)

PIENU

COMPLETED

Measurement of the $\frac{\pi^+ \to e^+\nu(\gamma)}{\pi^+ \to \mu^+\nu(\gamma)}$ Branching Ratio

Most Accurate Test of Charged Current Lepton Flavor Universality (comparable to τ decays)

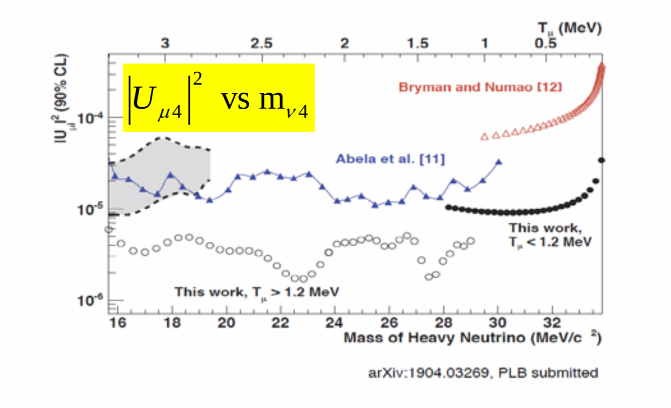
$$Theory: \quad R_{e/\mu}^{th} = (1.2352 \pm 0.0002)\, x10^{-4}$$

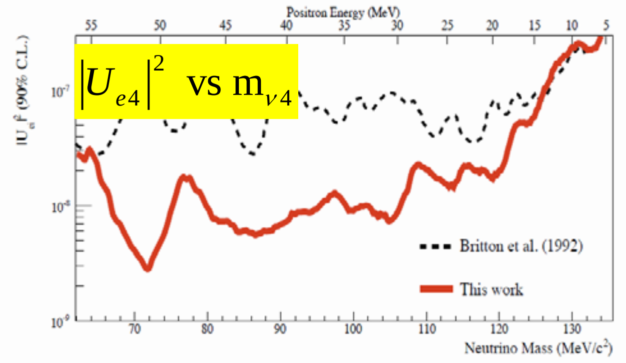
$$\text{PIENU Result}: \quad R_{e/\mu}^{\exp\pi} = 1.2344 \pm 0.0030 x10^{-4}$$

Order of magnitude improvements on sterile ν mixing coefficients and rare decays:

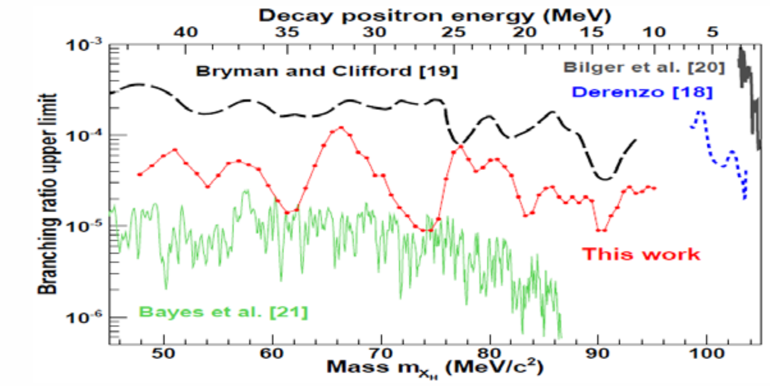
New rare decays (2020): $BR(\pi^+ \to \mu^+ \nu\nu\bar{\nu}) < 8.6x10^{-6}; \; BR(\pi^+ \to e^+ \nu\nu\bar{\nu}) < 1.7x10^{-7}$

LFU Violation: Massive Sterile Neutrinos in $\pi^+ \to \mu/e^+ \nu_h$





LF Violation: Exotic muon decay: μ→eX

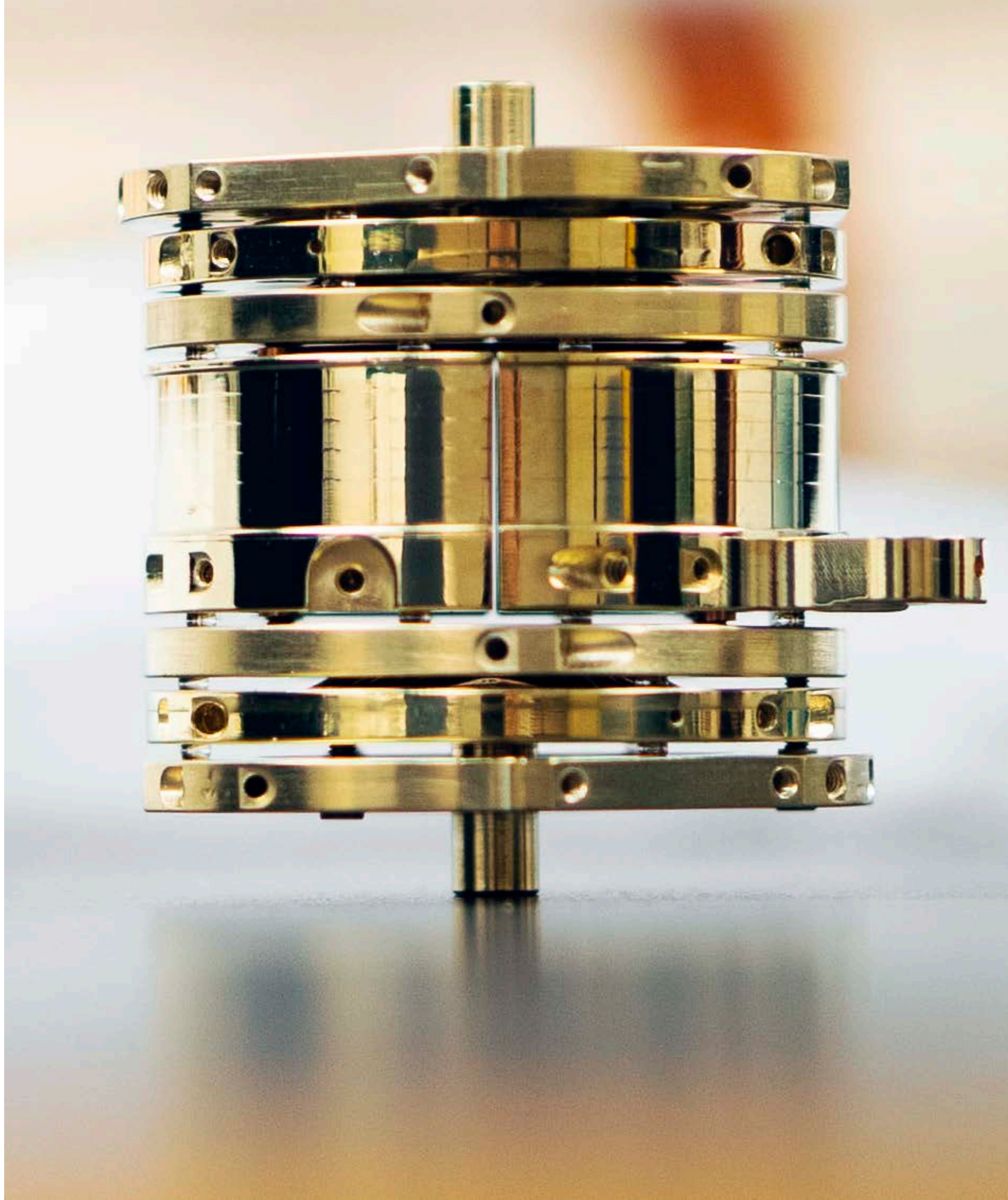


TRIUMF

Off site research program

- CERN:
  - ATLAS
  - ALPHA

- J-PARC:
  - T2K
  - Hyper-K

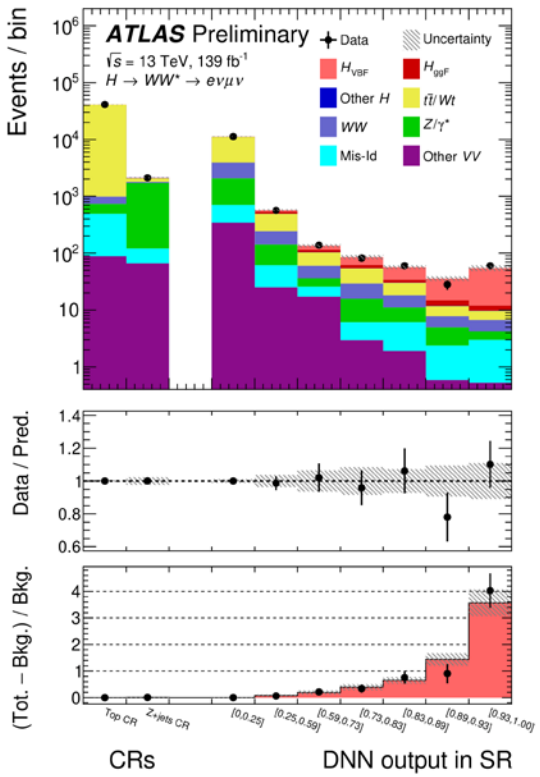


ATLAS @LHC (CERN) – Operation & Analysis

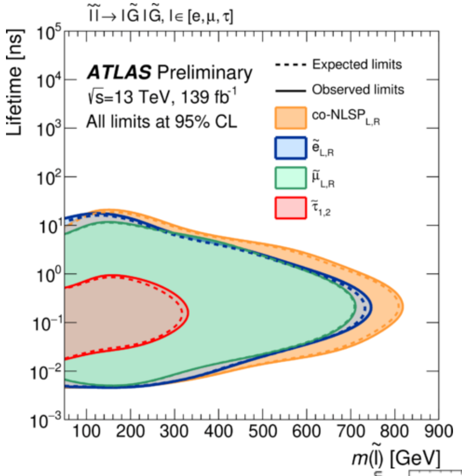
- TRIUMF ATLAS group:
  - 5 BAEs (1 currently based at CERN)
  - detector physicist
  - 2 affiliated scientists
  - 3 university-based joint faculty
  - 3 post-docs at CERN
  - ~ 4 grad students + ~2-5 undergrad/year
  - + 8 Tier 1 comp. experts, sTGC techs, ITk engineer & techs, LAr engineer,…

ATLAS @LHC (CERN) – involvement in upgrades

- Analysis: Recent Run-2 results with TRIUMF contributions

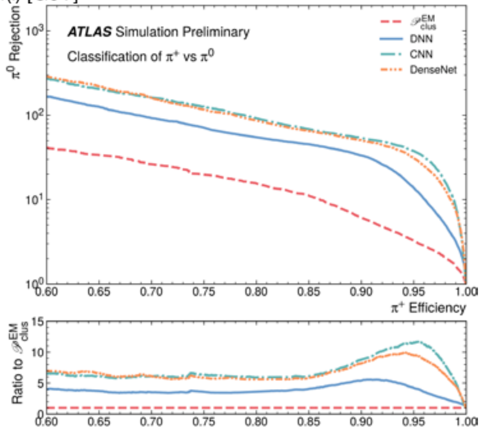


ATLAS-CONF-2020-045: Higgs (decaying to WW)



ATLAS-CONF-2020-051: Search long-lived particles

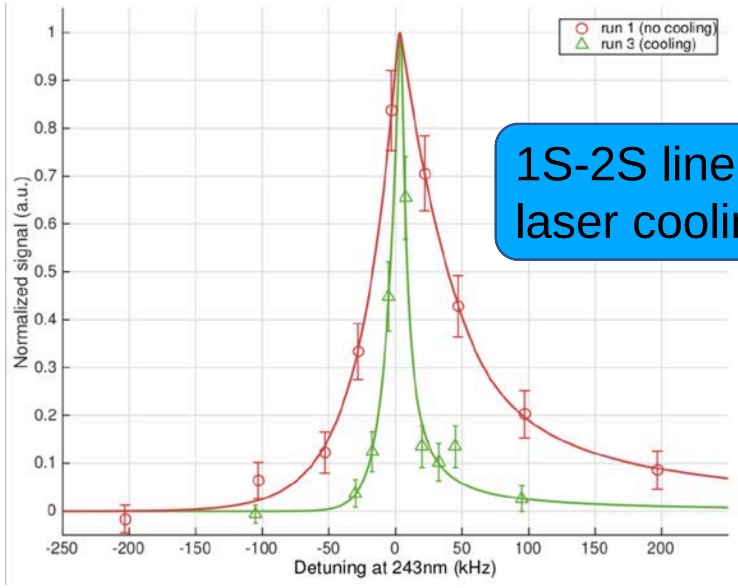
ATL-PHYS-PUB-2020-018: Machine Learning for event classification



ALPHA Antihydrogen Experiment at CERN

ALPHA-2: spectroscopy

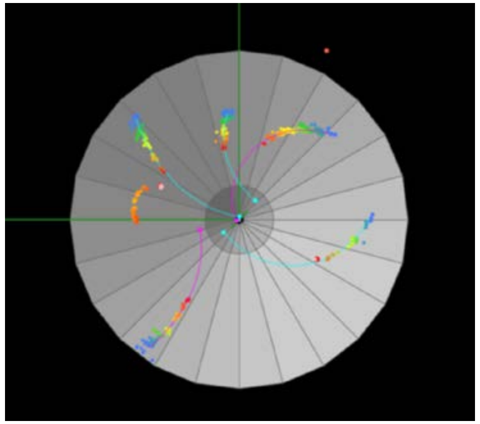
- **Test of CPT invariance via precision spectroscopy**
- Some recent highlights
  - Hyperfine spectroscopy [Nature 2017]
  - 1S-2S spectroscopy at 10^{-12} level [Nature 2018]
  - 1S-2P Lyman-alpha transition [Nature 2018]
  - Fine structure and Lamb shift [Nature 2020]
  - Demonstration of Laser cooling [Submitted]



1S-2S line narrowing due to laser cooling (preliminary)

ALPHA-g: gravity

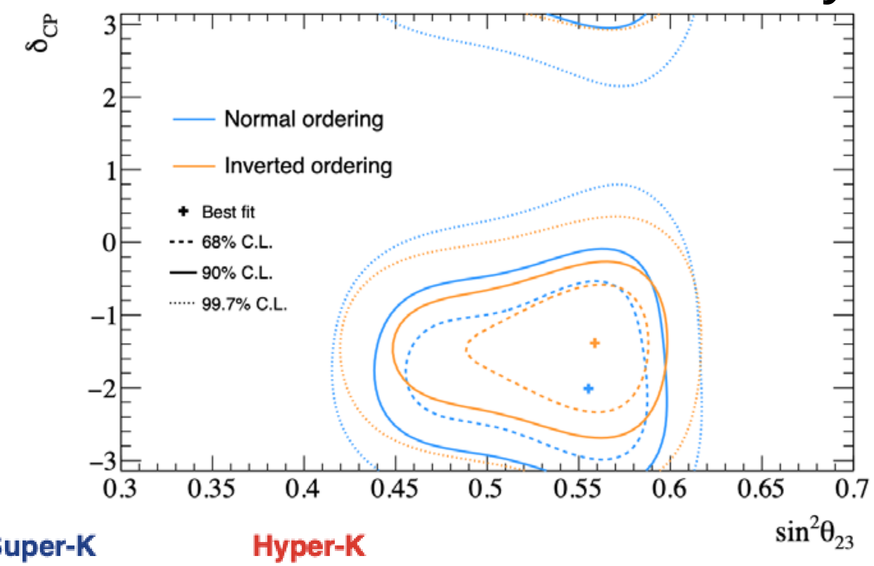
- **Test of Weak Equiv. Principle by “dropping” anti-H**
- Radial TPC designed and built at TRIUMF
- Getting ready for first measurement in 2021

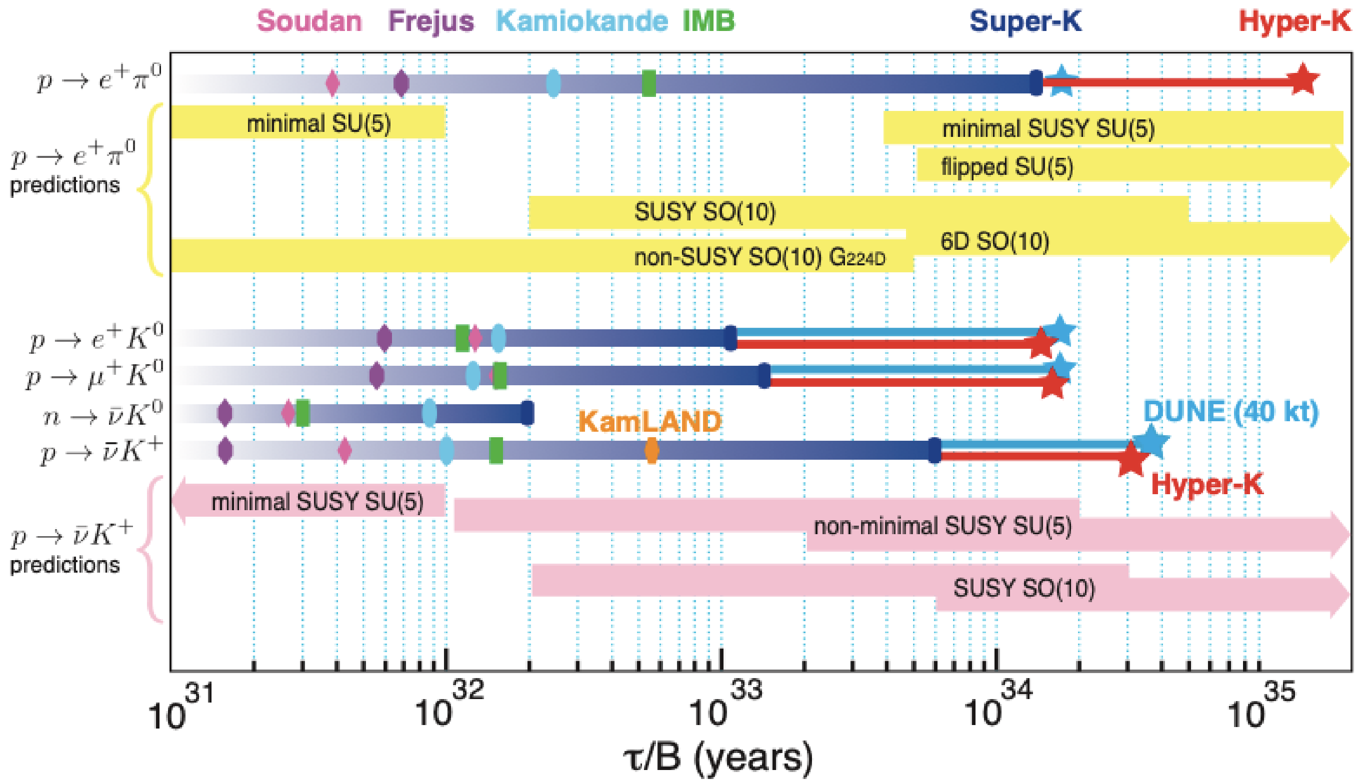


Physics at T2K and Hyper-K

- **Neutrino oscillations and CP violation**
  - T2K analysis shows weak indication of CP violation in neutrino oscillations
  - Hyper-K will have CP violation discovery potential at 5σ for 57% of parameter space
  - TRIUMF leadership in analysis for both experiments
- and atmospheric neutrino measurements

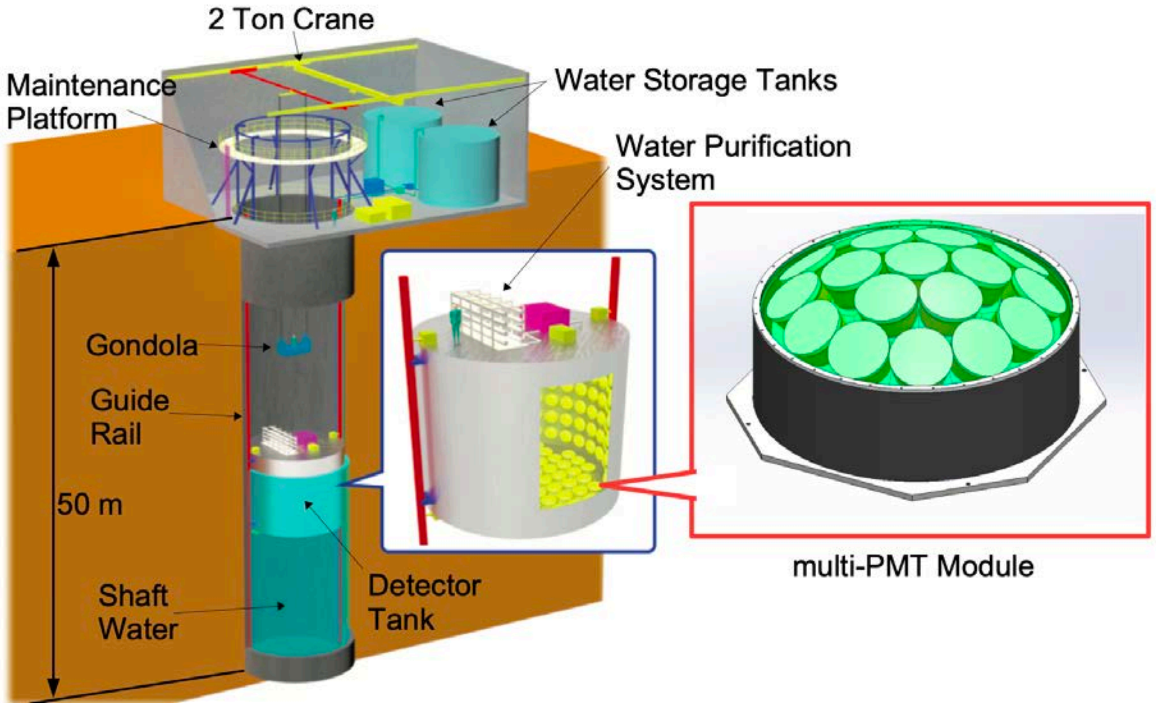
T2K Preliminary

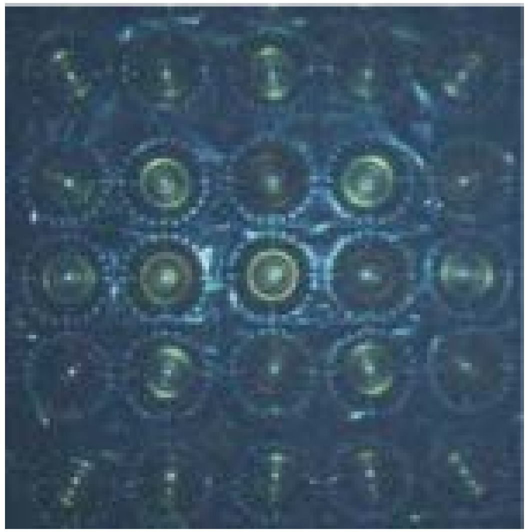


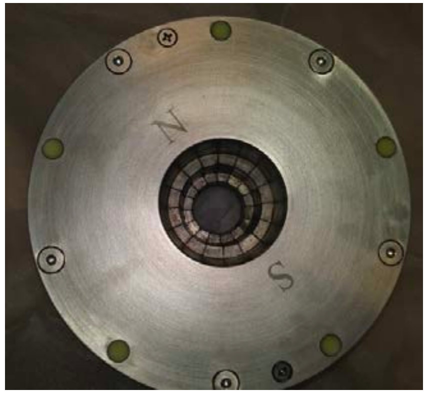


TRIUMF/Canadian contributions to HyperK

- Intermediate Water Cherenkov
  - NuPRISM concept
    - moving near detector to cancel systematics
  - mPMT
    - photosensor with fine granularity
  - Calibration
    - photogrammetry
    - photosensor test facility (PTF)
- Beam
  - hadron production study (EMPHATIC)
    - compact spectrometer with Nd permanent magnet
- Data analysis
  - Event reconstruction using machine learning







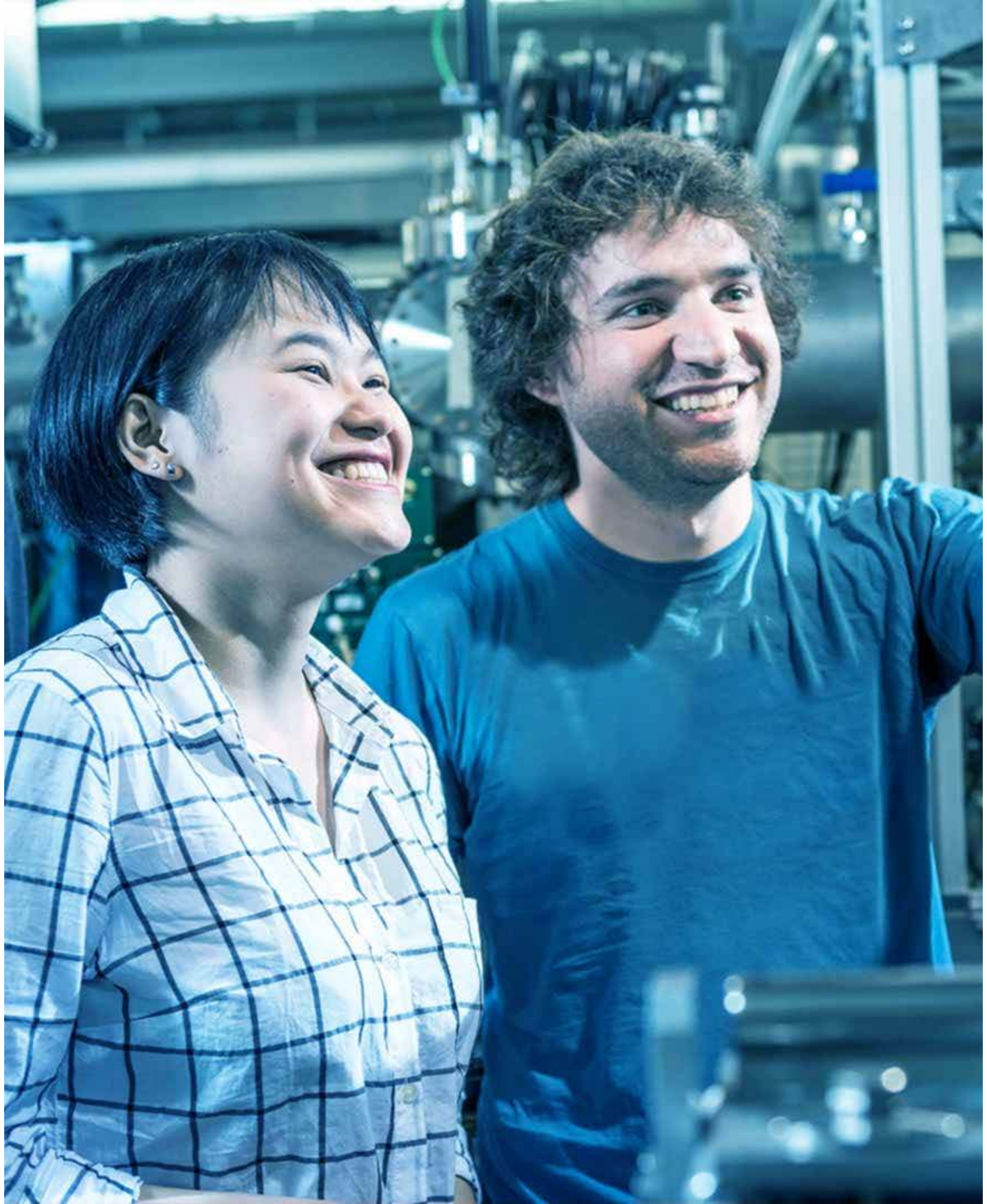
Summary

- TRIUMF has a comprehensive and complementary physics program in NP and PP, experiment and theory.
- Precision experiments with 2nd beams
- Energy frontier
- Strength in AMO techniques and BSM tests
- Expertise in detectors, DAQ and analysis

- Broad user base and well-connected to universities as well as international partners

TRIUMF

Thank you
Merci



www.triumf.ca

Follow us **@TRIUMFLab**

Discovery,
accelerated