Recent Results from Neutrino Experiments at ORNL
PROSPECT, COHERENT AND NEW INITIATIVES

Atomic nuclei as
laboratories for BSM physics

ECT* Trento - Italy

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ORNL is managed by UT-Battelle, LLC for the US Department of Energy

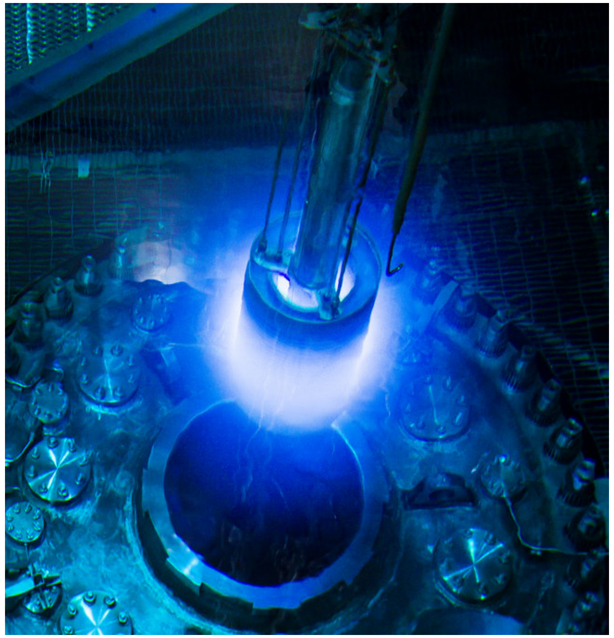
Outline

- Motivation and New opportunities at ORNL
- Projects Highlights
  - PROSPECT
  - COHERENT
    - A new experiment – a relative measurement
  - New Initiatives
    - Tritium Beams
    - Ultra low trace detection
    - Resonant Ionization Mass Spectrometry
    - Rydberg States
    - Clusters
- Results
- Conclusions

ORNL's Opportunities: World Class *Neutrino* Sources

Spallation Neutron Source: SNS

- Pulsed neutron source
- 1 GeV protons on Hg target
- 1.4 MW beam power
- 2nd target station

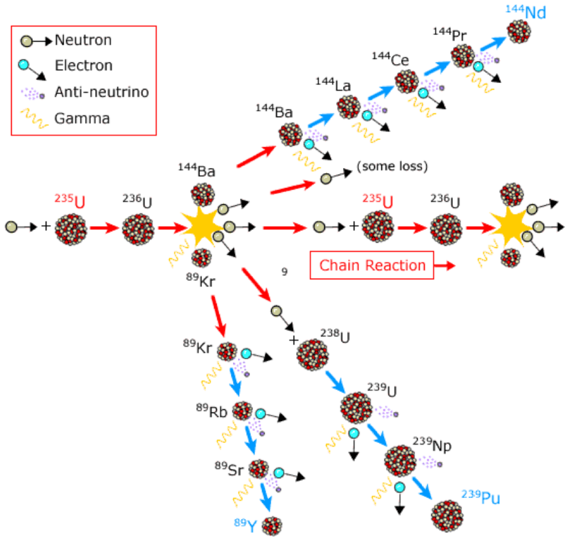


High Flux Isotope Reactor: HFIR

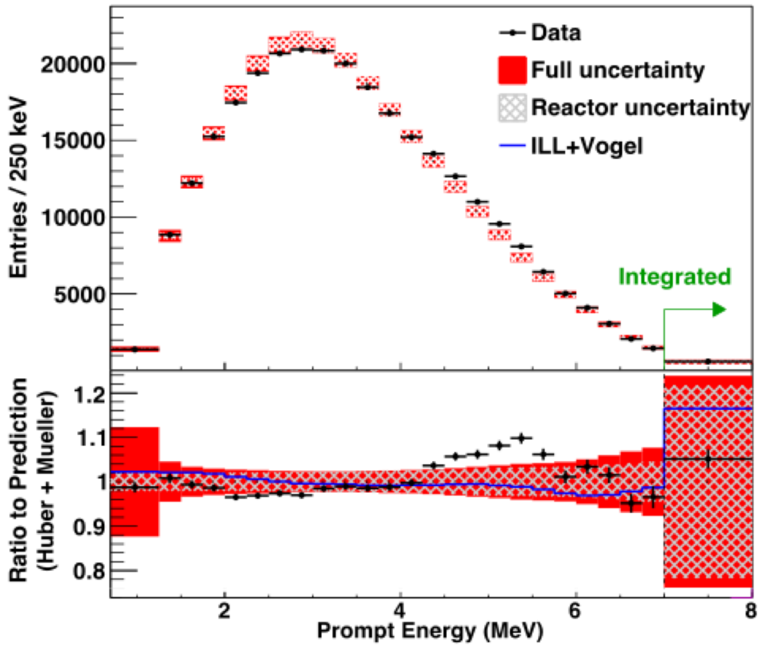
- 85 MW research reactor
- Compact core
- Highly-enriched uranium fuel

Neutrino flux origin and spectra

HFIR Fission

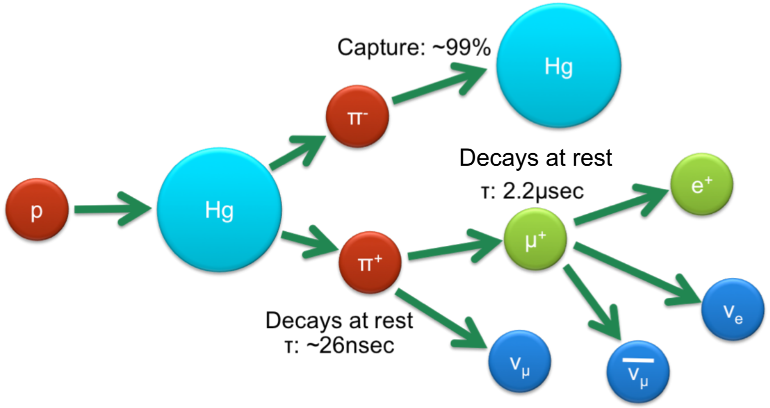


Beta decay fission fragments ($\bar{\nu}_e$)

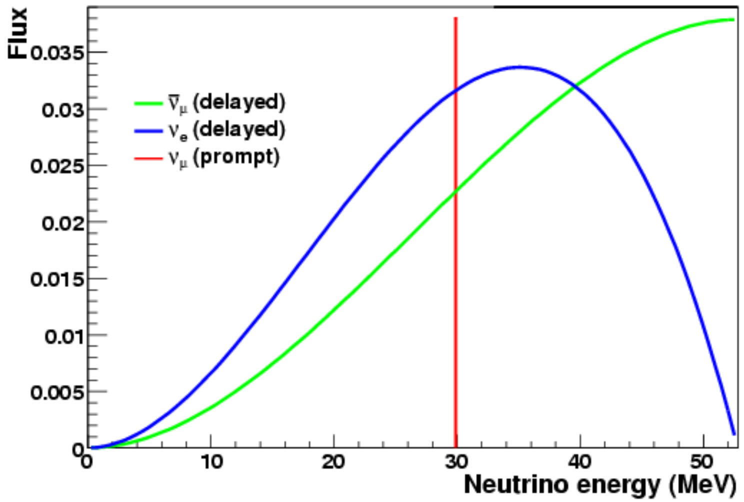


Huge flux
Few MeV
No timing structure

SNS Spallation



Pion-decay-at-rest neutrino source



Large Flux
Few tens-of-MeV,
Sharply-pulsed timing
Background rejection

Other ORNL Resources:

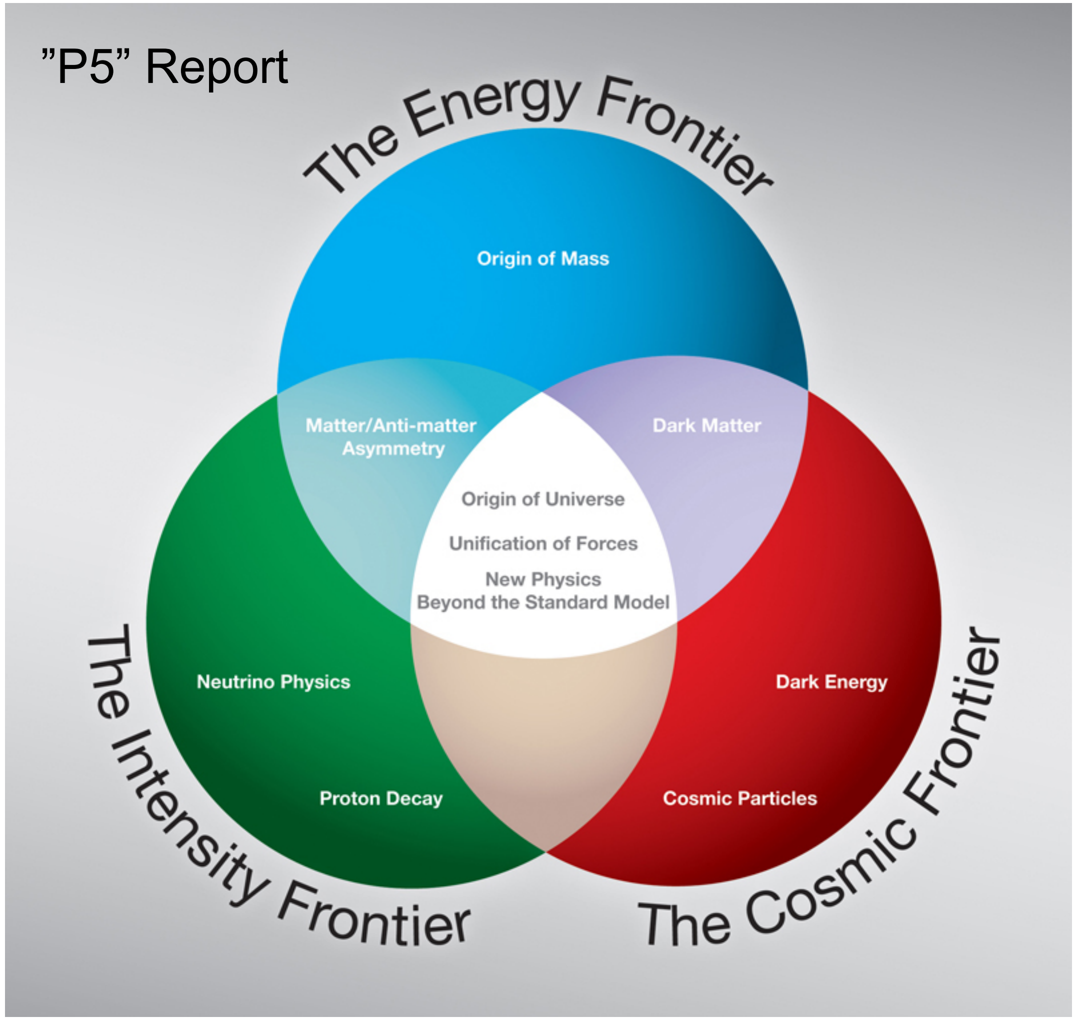
The Oak Ridge Leadership Computing Facility

- World class expertise in scientific computing
- Computing and data analysis resources
- Summit Supercomputer - World's Fastest

Physics Division

- Computer Cluster
- Laboratory Space
- High-bay area
- Office and Meeting space for Visitors
- No-cost dormitories (JINPA)

Research Program - Physics Division



Particle Physics Project Prioritization Panel

Pursuing a broad research program in nuclear, particle, and astrophysics with emphasis on weak interactions and fundamental interactions.

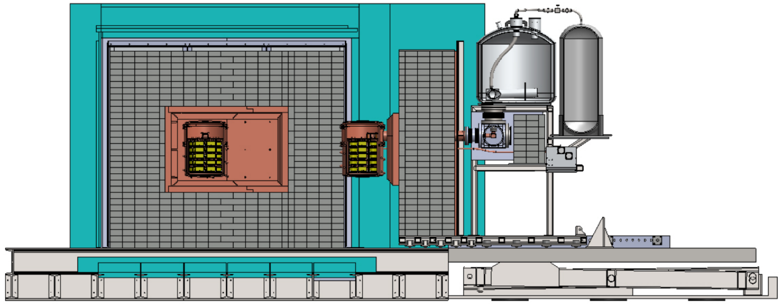
The research program of the Physics Division includes:

- studies of neutrino oscillation
- neutrino properties
- neutrinoless double beta decay.

The initial success of this program is enabling the discussion of new ideas for future collaborations.

Current ORNL interests in neutrino physics

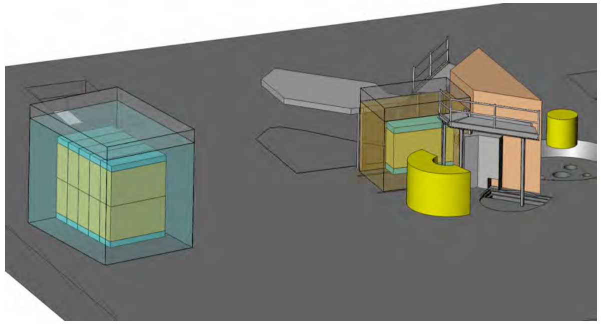
The Majorana Demonstrator (MJD)- A ^{76}Ge 0νββ experiment at SURF



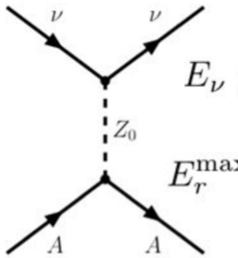
LEGEND 200/ LEGEND 1000- towards 1 tonne ^{76}Ge experiment

LEGEND

PROSPECT- A Precision Reactor Neutrino Oscillation and Spectrum Experiment at the 85MW HFIR



COHERENT- Coherent elastic neutrino-nucleus scattering using the neutrino emissions from the SNS spallation source at ORNL

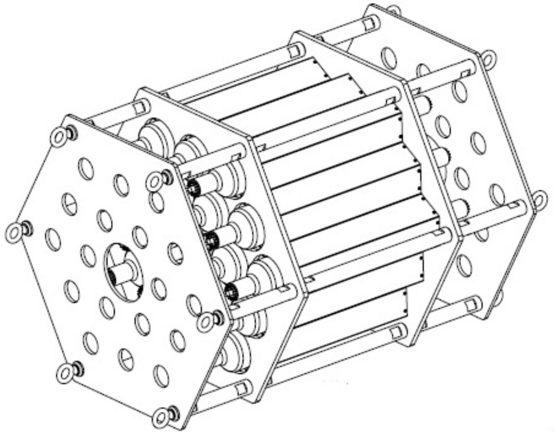


$$E_\nu \lesssim \frac{hc}{R_N} \cong 50\ \mathrm{MeV}$$

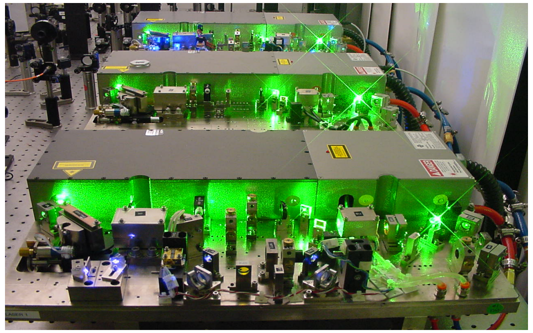
$$E_r^{\max} \simeq \frac{2E_\nu^2}{M} \simeq 50\ \mathrm{keV}$$

Current ORNL interests related to neutrino physics

Modular Total Absorption Spectrometer (MTAS)-
β-decays of n-rich nuclei, in particular fission products efficiently and with segmentation



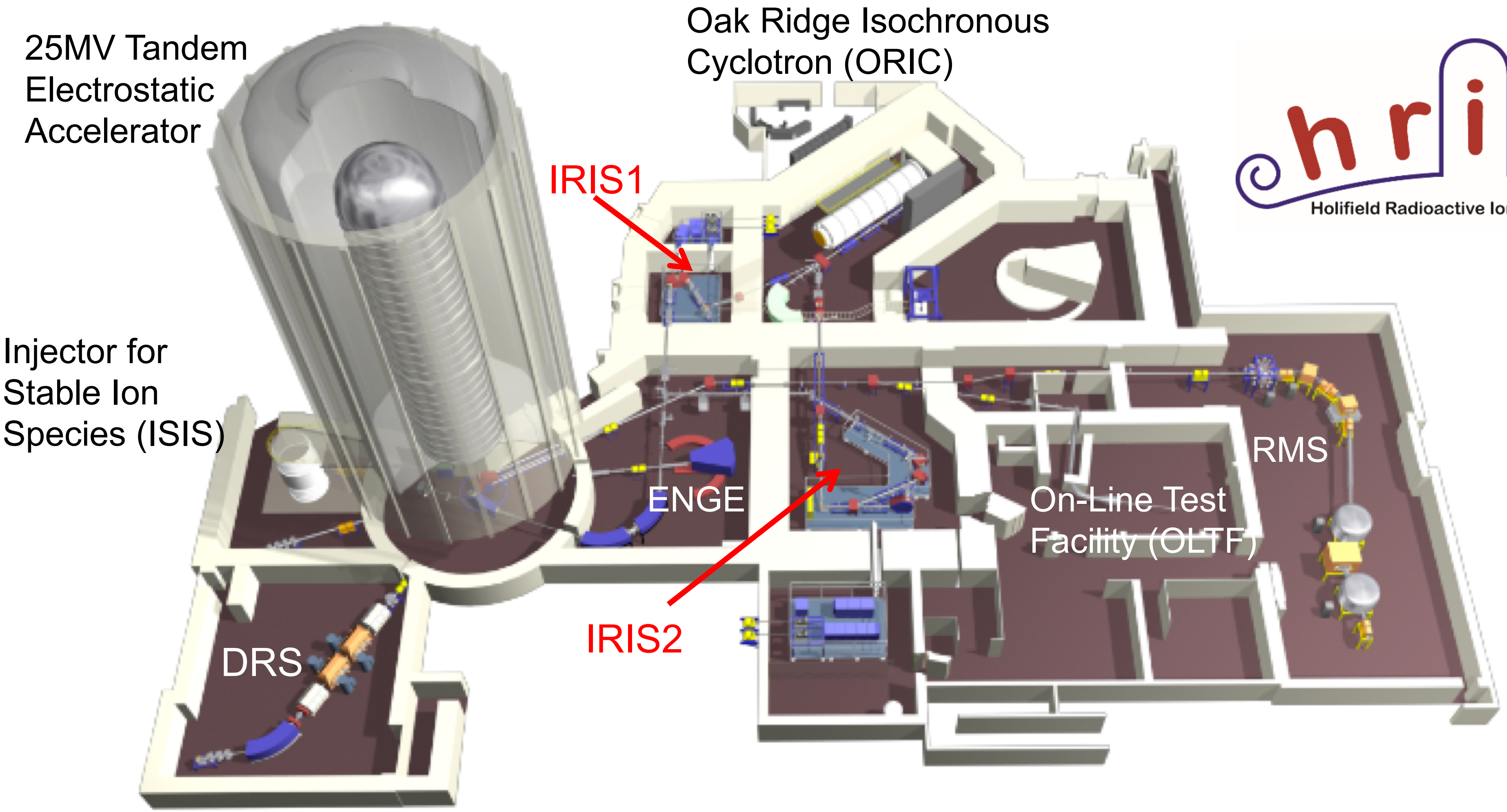
Ultra sensitive analytical techniques-
Accelerator Mass Spectrometry
RILIS in Actinides
Nuclear Activation Analysis



Isotope Program:
Stable and Radioactive-
New capabilities

TRITON BEAMS

HRIBF and the 25MV Tandem Accelerator (1996-2012)



hribf
Holifield Radioactive Ion Beam Facility

Pioneer experiments using accelerated beams of radioactive nuclei to probe nuclear structure and investigate nuclear reactions that govern astrophysical processes.

First acceleration of neutron-rich fission fragments, and confirming the doubly-magic nature of 132Sn.

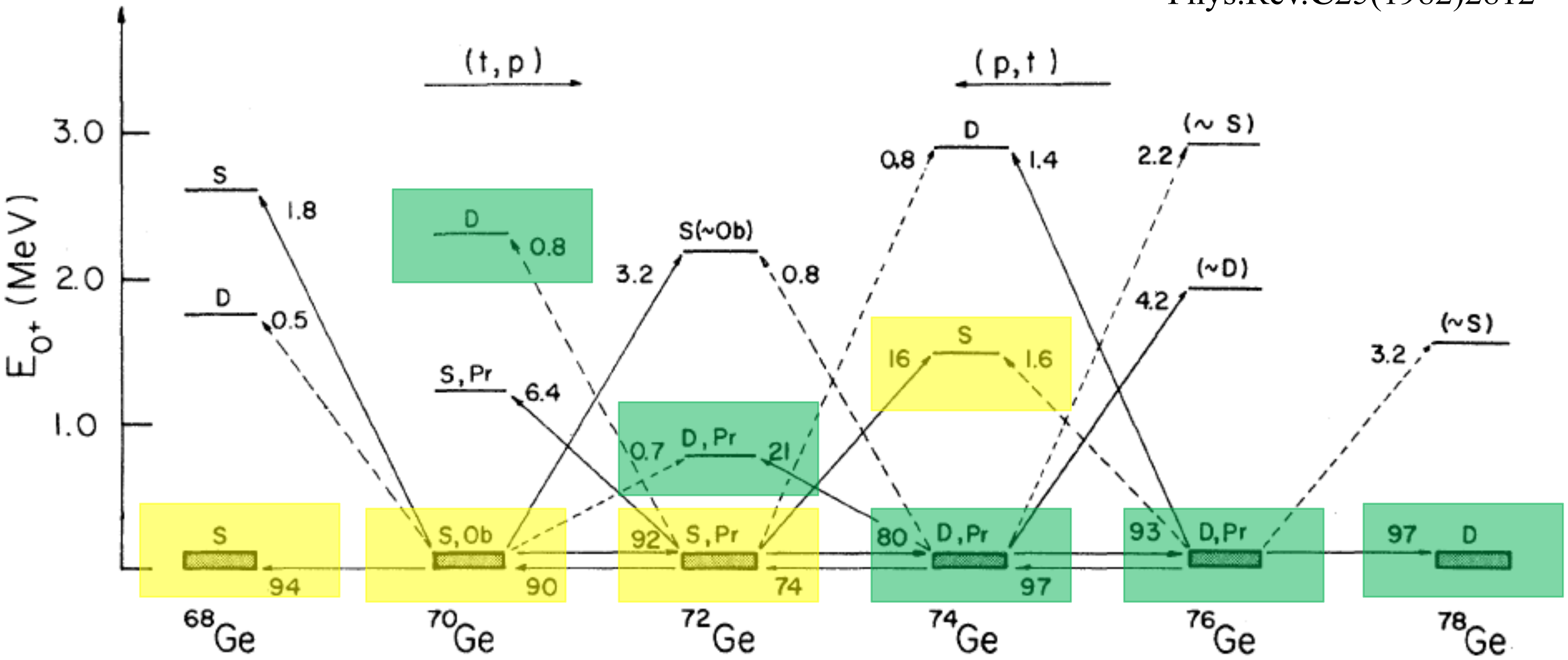
Tritium beams and targets

- There are a significant number of nuclear reactions involving tritium that are crucial for Stockpile Stewardship, Nuclear Fusion, Nuclear Structure and Nuclear Astrophysics. For many of these, the cross sections and the distribution of reaction products are either unknown or uncertain.
- For several years we have studied the possibility of using the 25MV Tandem and associated beamlines and spectrometers to produce tritium beams.
- No facility exists to produce low energy pure tritium beams.
- Tritium beam could be useful for various measurements, including the t+t reaction and indirect cross section measurements using surrogate (t,p)
- National Ignition Facility (NIF) at LLNL:
  - Need to understand various light-ion reactions: t+ ^{9}Be, ^{12}C, ^{13}C, ^{18}O
  - Discrepancy needs to be resolved t(t,n)nα experiments
- General interest in the reactions and structure community in tritium beams, as well as tritium targets (pairing studies, surrogate, astro, …)
- Plans with Florida State University to develop tritium beams

two neutron transfer reactions

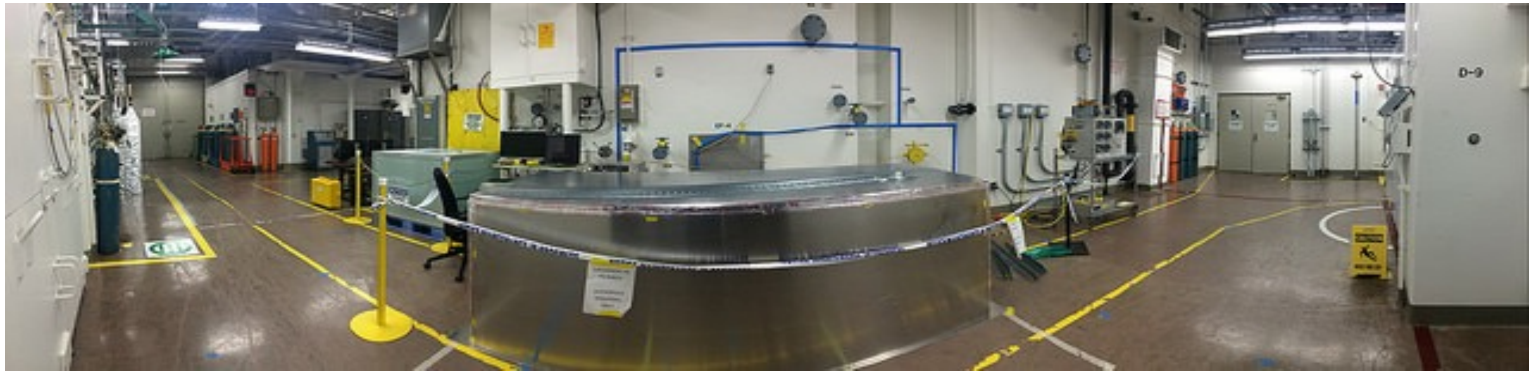
Transition strength between states with ***similar*** (***different***) nature is ***favored*** (***unfavored***)

Phys.Rev.**C**25(1982)2812



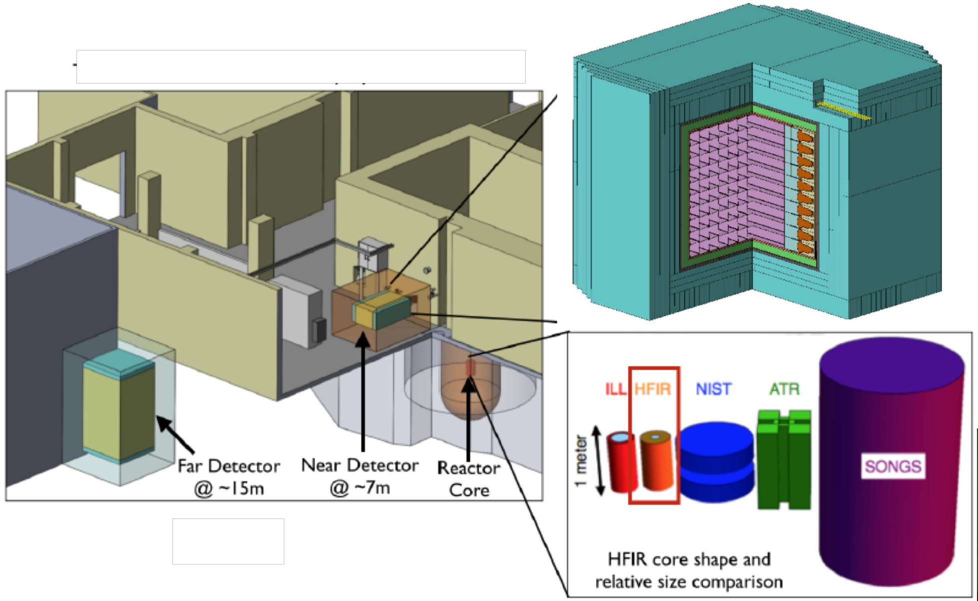
(t, p) and (p, t) reactions indicates a ***shape transition*** around $N = 41$

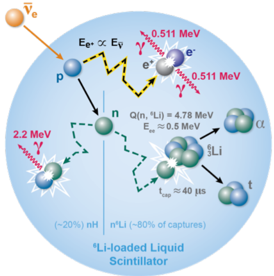
PROSPECT

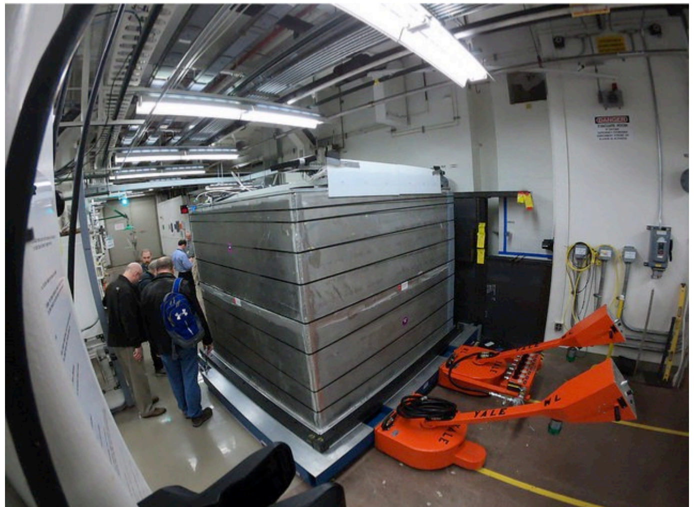


PROSPECT

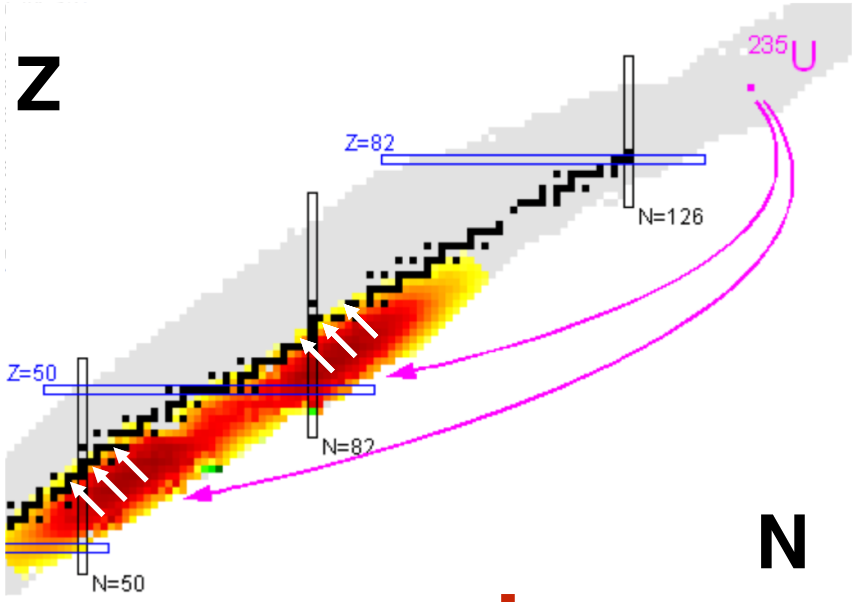
A Precision Oscillation and Spectrum Experiment



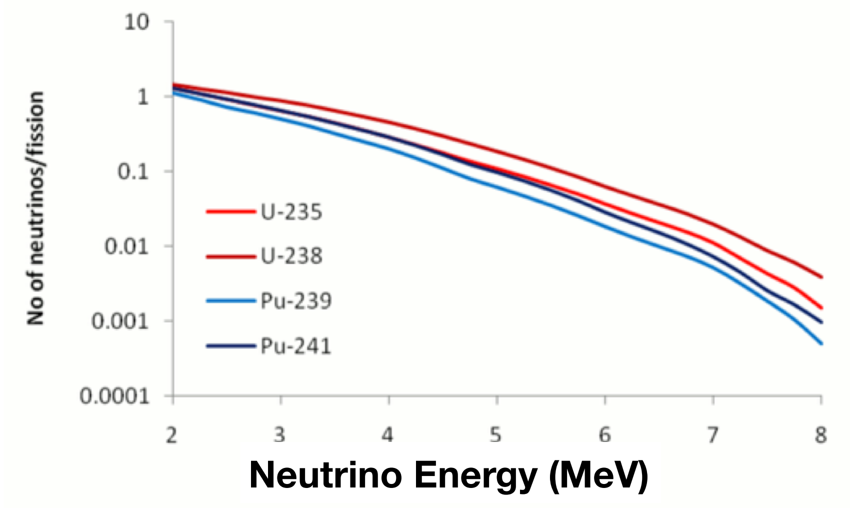




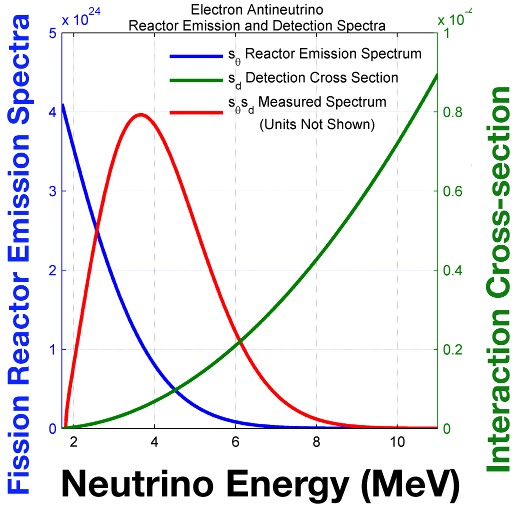
Neutrinos from Reactor



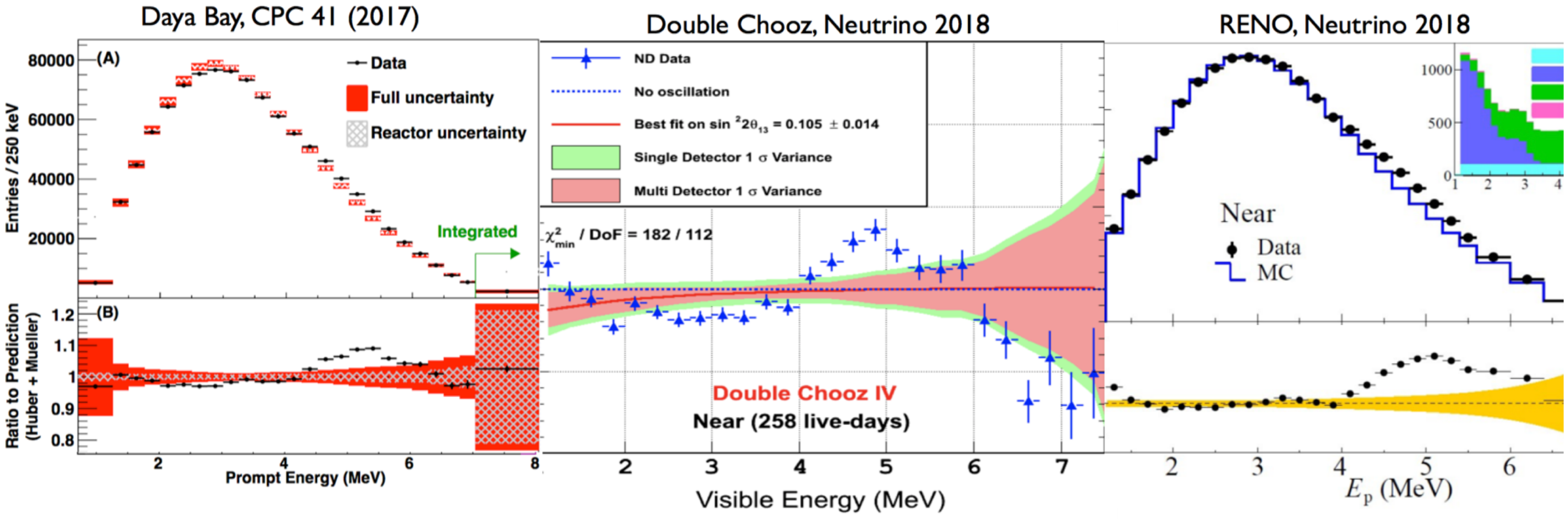
- Fission produces neutron rich daughters
- They beta decay and produce antineutrinos
- Fissioning isotopes: ^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu
- Spectra different for different isotopes
- Detect via Inverse Beta Decay (IBD)



$$\bar{\nu}_e + p \rightarrow e^+ + n$$



Neutrino Spectrum Measurements from Power Reactors



Spectrum models don't match experimental data in low enriched uranium (LEU) power reactors

Neutrino events come from a mixture of fissile isotopes: 235U, 238U, 239Pu, 241Pu

'Bump' in 4-6 MeV (prompt energy) range

Poor fit overall.

Need new reactor data to clarify source of deviations

HFIR

85 MW Highly Enriched Uranium (HEU) fuel (235U) reactor

46% duty-cycle, 7 cycles/yr, 24 day reactor-on periods

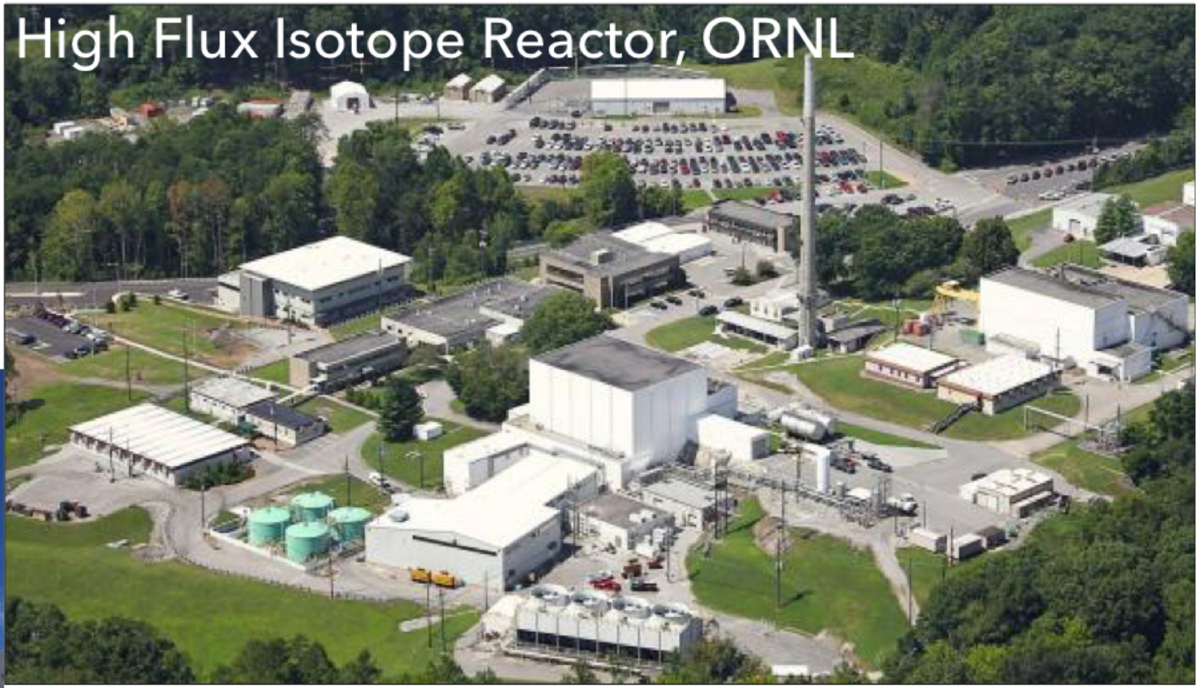
>99% of ve flux from 235U fission

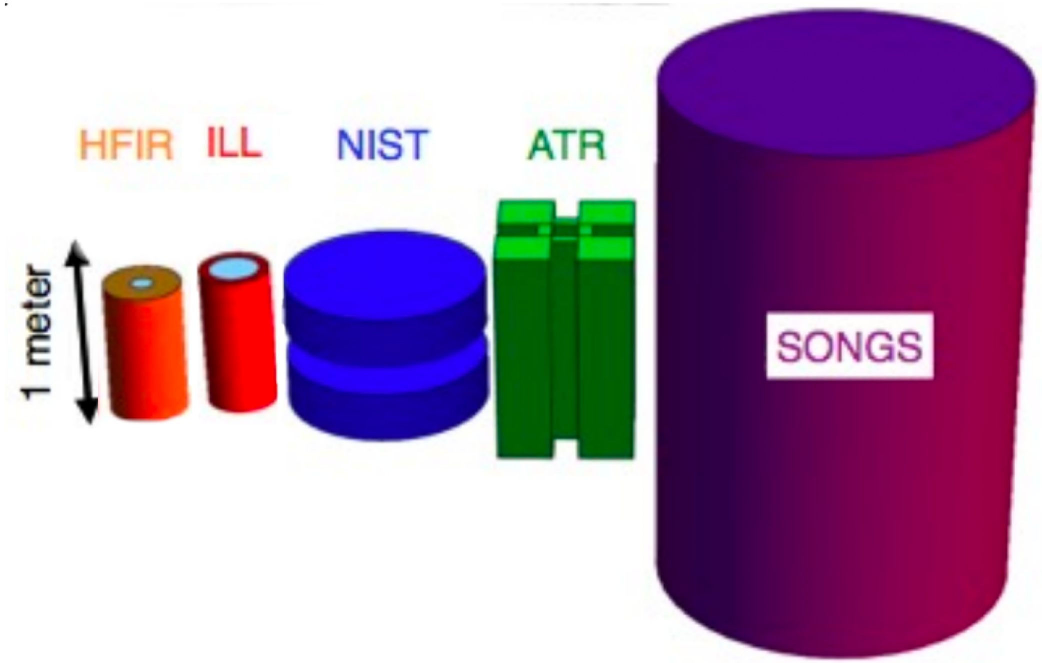
Challenges:

Minimal overburden (<1 mwe)

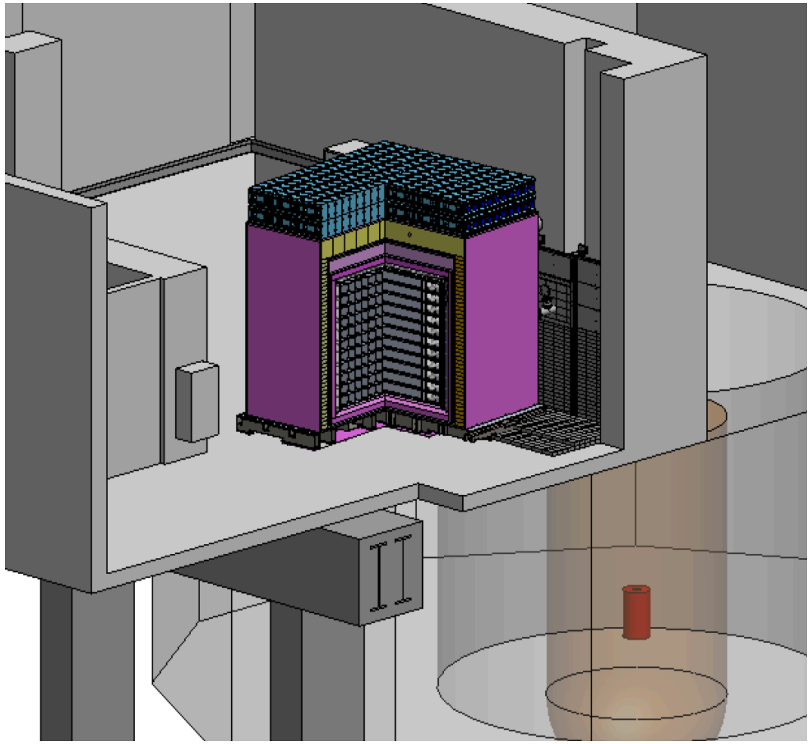
High gamma background

Limited space for shielding

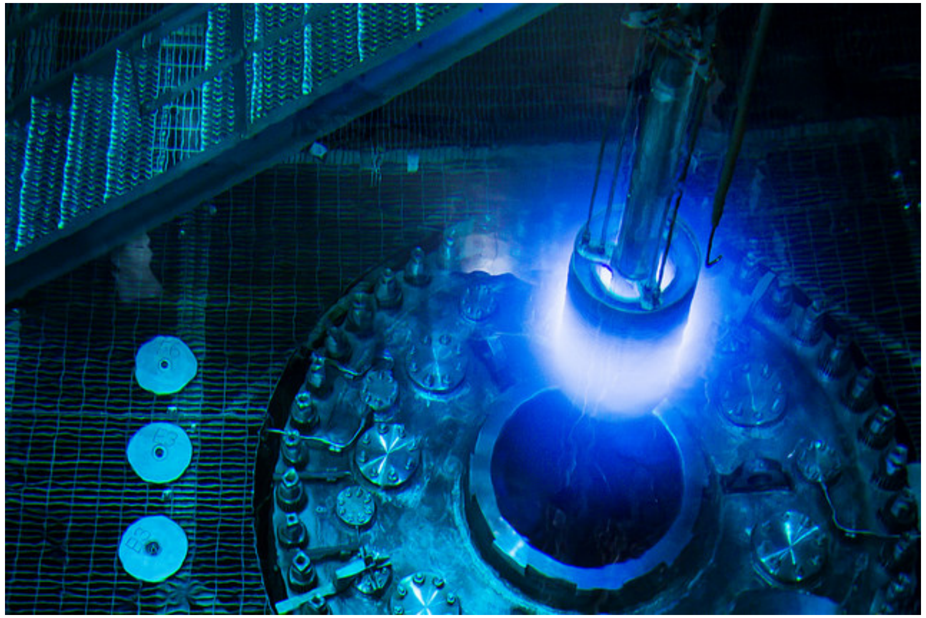


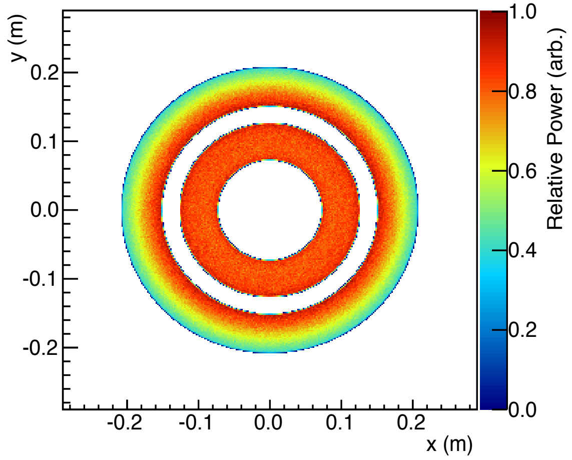


HFIR – High Flux Isotope Reactor



- Favorable positioning, 7-12 m from the core
- Fresh core each cycle
- Fuel evolution is negligible
- Detailed core model available for simulation





Oak Ridge National Laboratory
PROSPECT

PROSPECT - Motivation

Spectral Shape as a Function of Energy and Baseline

- Possibility of sterile neutrino oscillation as an explanation of observed electron antineutrino deficits
- Reactor-model independent search for sterile neutrinos at the eV-scale

Precision Measurement of Reactor Spectrum

- Anomalies in spectral shape at ~ 5-6 MeV
- Provide complementary measurement of 235U (fuel evolution)

Safeguards - a Passive Standoff Capability

PROSPECT - Motivation

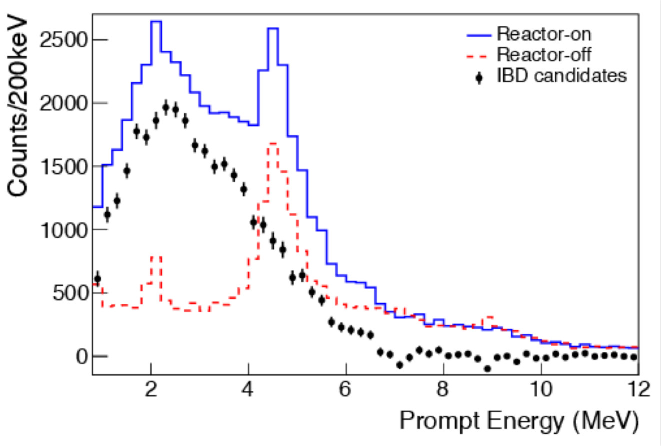
- Started taking data in March 2018

✓ Detection of neutrinos at surface (HFIR)

✓ First oscillation analysis (PRL) – published

✓ First spectrum analysis (submitted to PRL)

- Updated oscillation + spectrum results
- Joint analysis with other experiments



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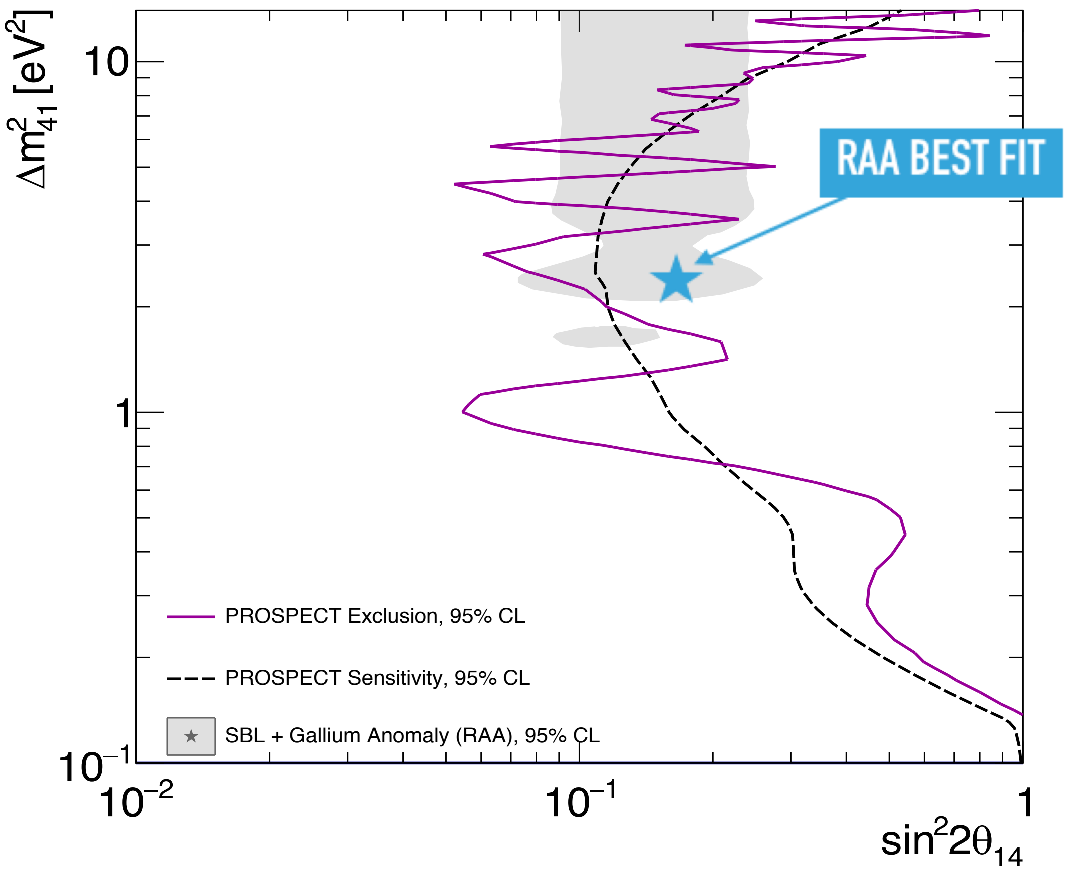
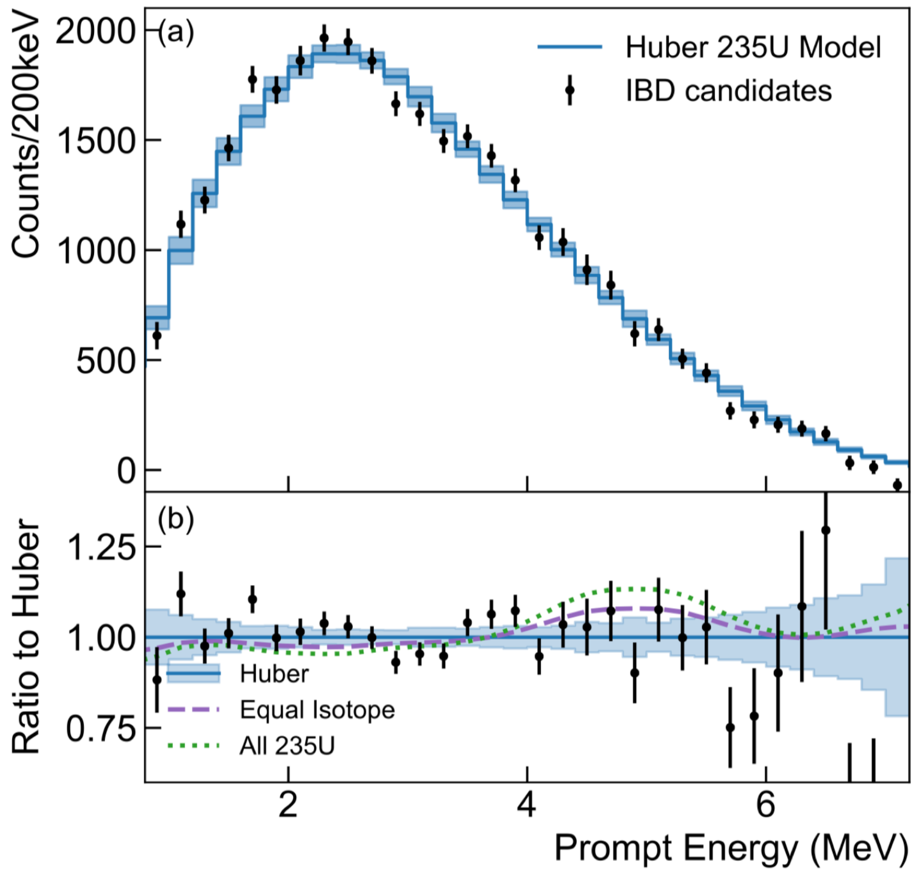
PROSPECT – First Results





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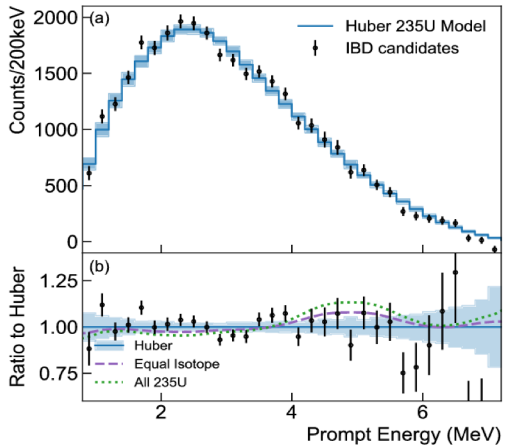
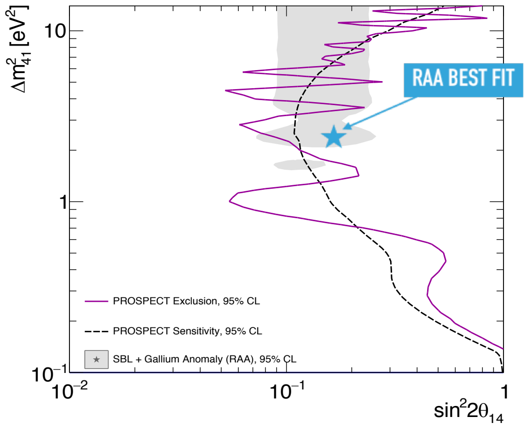
Recent Publications PROSPECT - Physics

- **Measurement of the Antineutrino Spectrum from 235U Fission at HFIR with PROSPECT**
  Submitted to Phys. Rev. Lett. - 28 December 2018; arXiv:1812.10877
- **First search for short-baseline neutrino oscillations at HFIR with PROSPECT**
  Phys. Rev. Lett. 121, 251802 – Published 19 December 2018
- **The PROSPECT Physics program**
  Journal of Physics G 43 (2016) 11
- **The PROSPECT reactor antineutrino experiment -** NIM A: 922, 1 April 2019, Pages 287-309
- **Lithium-loaded Liquid Scintillator Production for the PROSPECT experiment -** Submitted to the JINST (17 Jan 2019); arXiv:1901.05569
- **Performance of a segmented 6Li-loaded liquid scintillator detector for the PROSPECT experiment -** JINST 13 (2018) P06023
- **Background Radiation Measurements at High Power Research Reactors -** NIM A: 806, 11 January 2016, Pages 401-419
- **A Low-Mass Optical Grid for the PROSPECT Reactor Antineutrino Detector –** Submitted to the JINST; arXiv:1902.06430v3





SUMMARY

- PROSPECT started taking data on March 6, 2018
- Background rejection and energy resolution meet expectation and match Monte Carlo
- World-leading signal-to-background for a surface-based detector (<1 mwe overburden)
- First oscillation analysis on 33 days of reactor-on data disfavors the RAA best-fit at 2.2σ
- Made first modern measurement of an antineutrino spectrum from a HEU reactor with a surface-based experiment
- Based on results of PROSPECT and other experiments sterile neutrinos are increasingly disfavored

PROSPECT

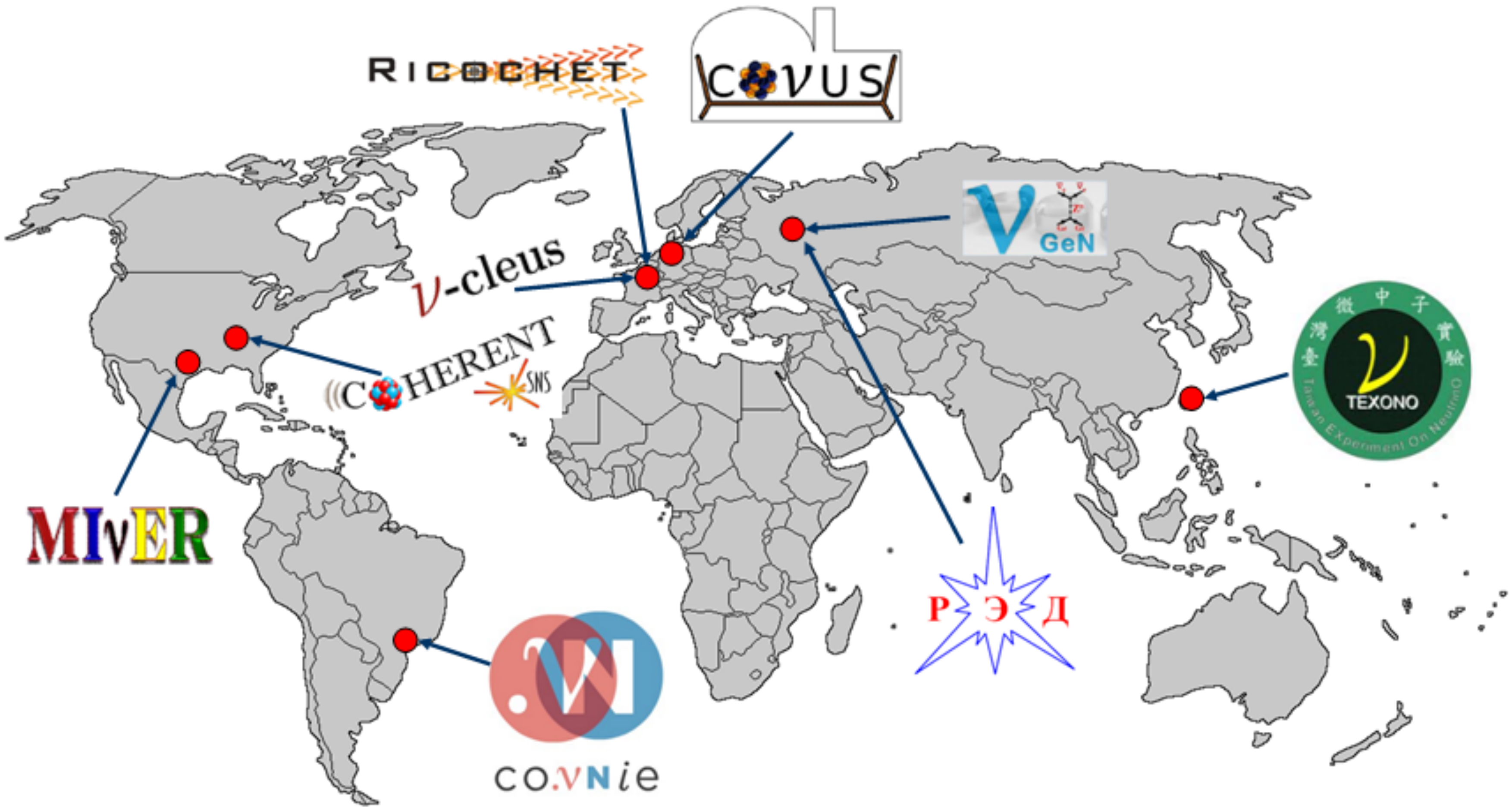

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA
BROOKHAVEN
NATIONAL LABORATORY
OAK RIDGE
National Laboratory
W&M
Yale
Drexel
UNIVERSITY
NIST
HEISING-SIMONS
FOUNDATION

ORNL provides strong support for Neutrino Program

PROSPECT Collaboration with ORNL personnel at HFIR

COHERENT

World Wide Efforts to Detect CEvNS



SNS as a neutrino source

- The SNS provides a source of decay-at-rest neutrinos that is unique in the world, in its intensity and time structure

- Neutrino energies at SNS are ideal to study CEvNS and Supernovae related neutrino cross sections.
  For most of neutrinos $E_\nu < 53$ MeV

- Fine duty factor let suppression of steady background by a factor of 2000.
  ~ 1000 m.w.e underground

- There is a nice place at the SNS basement with protection from SNS produced neutrons and hadronic component of cosmic rays.

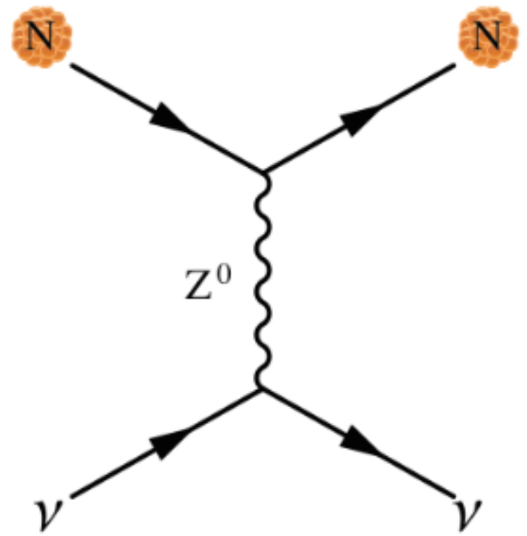
- Neutrinos, space, and utilities are provided

- The discovery of Coherent scattering could lead further new physics in a cost effective way."

Coherent Elastic neutrino-Nucleus Scattering (CEvNS)

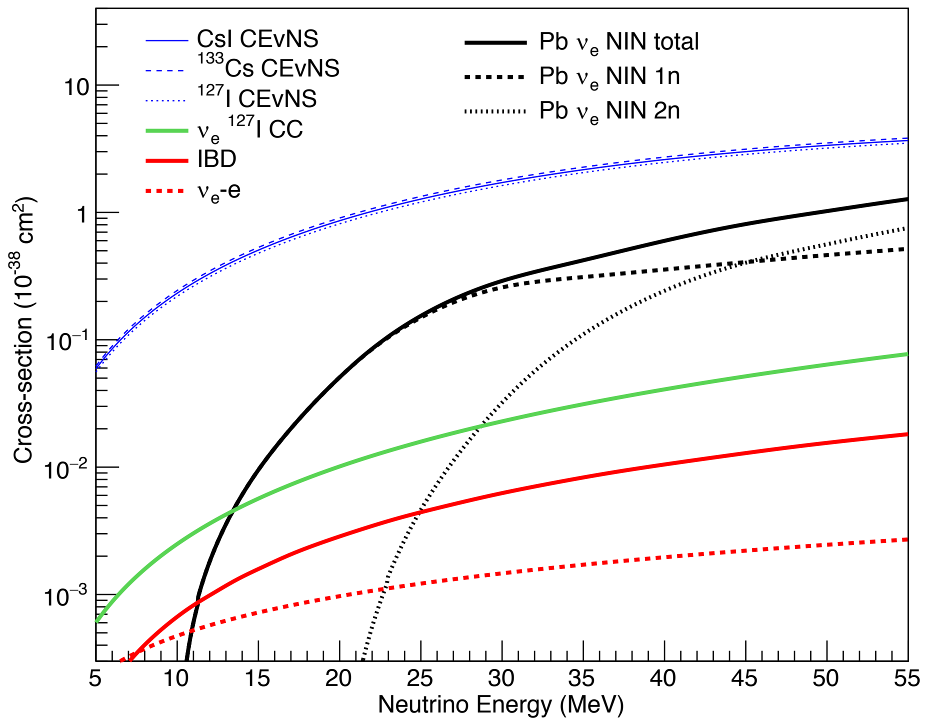
A neutrino scatters on a nucleus via exchange of a Z, and the nucleus recoils as a whole;

coherent up to $E_\nu \sim 50$ MeV



D.Z. Freedman PRD 9 (1974)
Submitted Oct 15, 1973

V.B.Kopeliovich & L.L.Frankfurt
JETP Lett. 19 (1974)
Submitted Jan 7, 1974



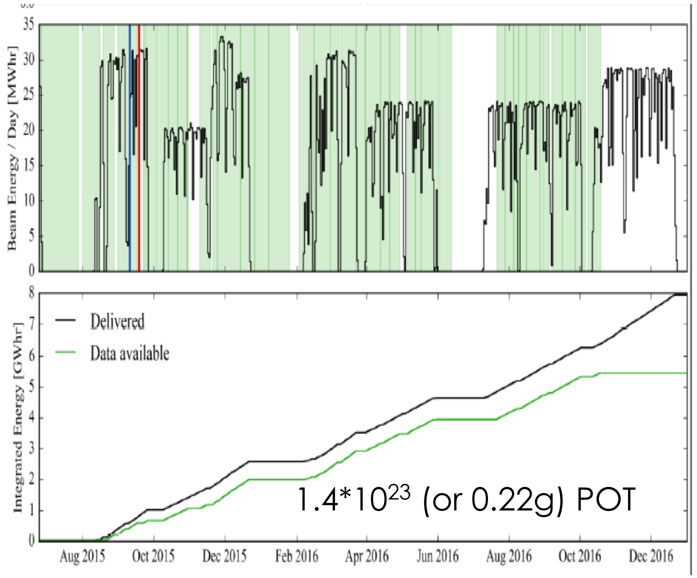
CEvNS cross-section is large!

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2}k^2(1+\cos\theta)\frac{(N-(1-4\sin^2\theta_W)Z)^2}{4}F^2(Q^2) \quad \boxed{\propto N^2}$$

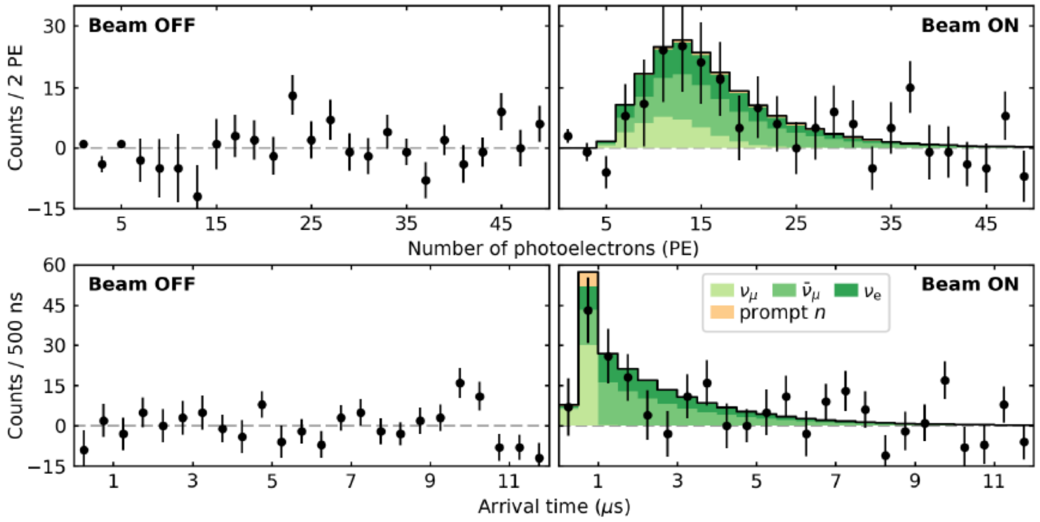
CEvNS cross section is well calculated in the Standard Model

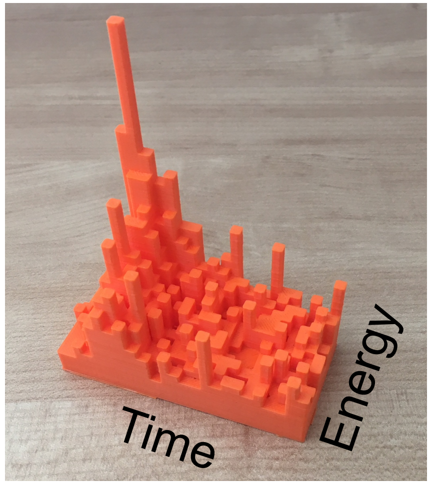
First Detection of CEvNS

Hand held neutrino detector

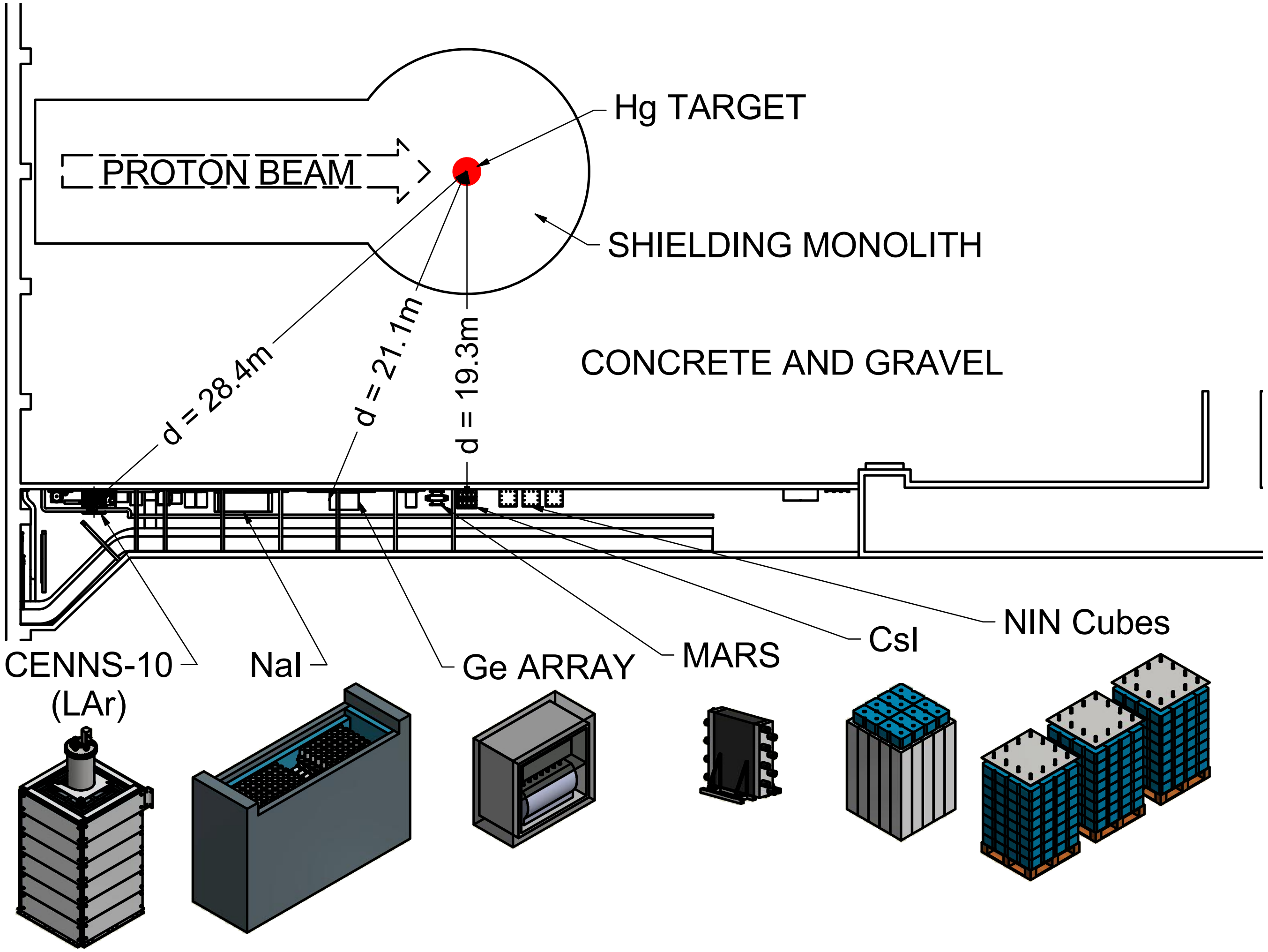


16 Month of data





Ongoing Neutrino Alley Activities



Taking data with 22 kg LAr detector. Advanced analysis stage.

Taking data with 185 kg NaI detectors.

Study of neutron backgrounds. MARS commissioning and calibration.

Taking data with CsI(Na).

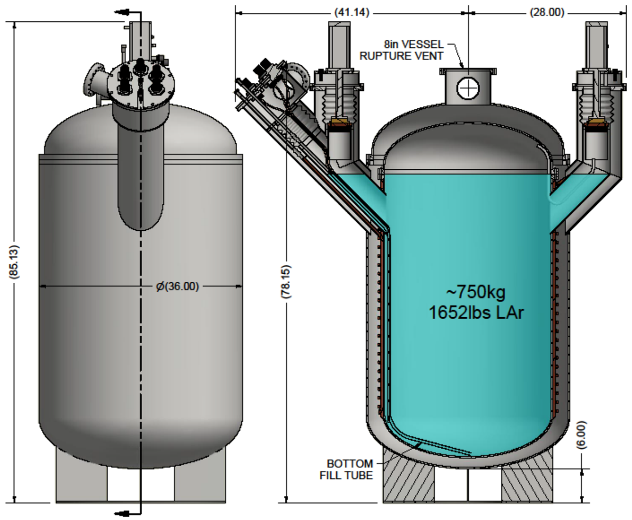
Study of ν Induced Neutrons on Pb and Fe. upgrade using PROSPECT LiLS

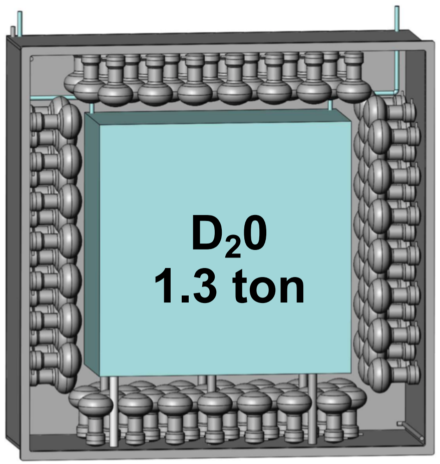
Immediate Goal for COHERENT

- Test of the Standard Model prediction of proportionality of the CEvNS cross section to neutron number squared.
  - 10 kg germanium (Ge) detector
  - 2.0 tonne sodium iodide (NaI) detector
  - 1.0 tonne liquid argon (LAr) detector
  - 1.3 tonne heavy water (D2O) detector

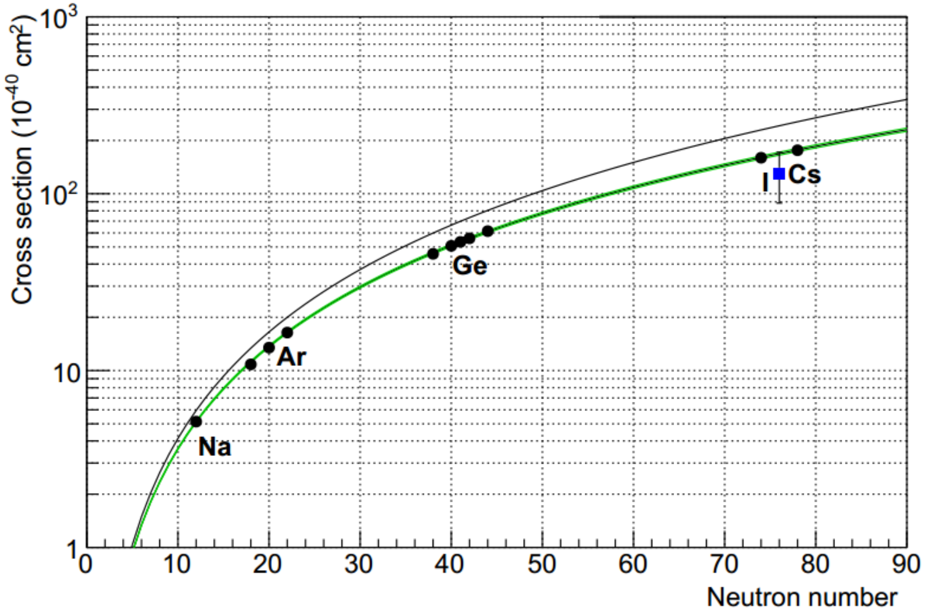
Measure CEvNS (Ge, NaI, LAr)

Calibrate neutrino flux (D2O)





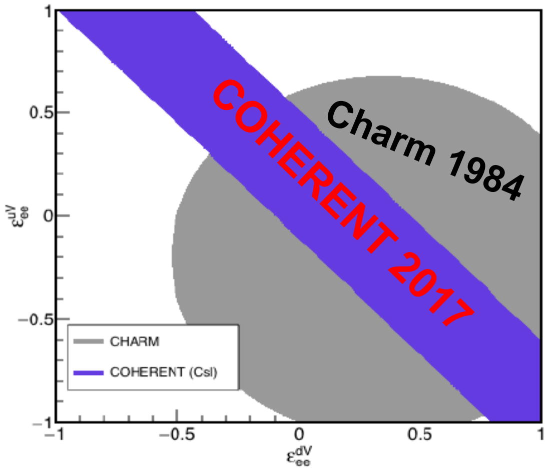
Future Physics for COHERENT



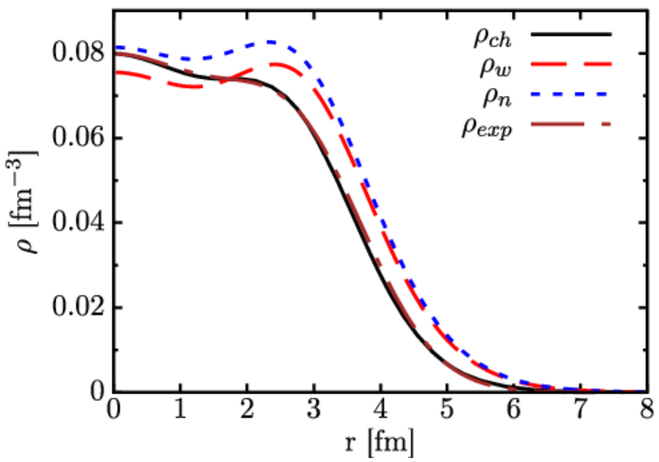
We need large detectors with various targets to untangle effects of nuclear form factors

Large statistics with accurate measurements of recoil spectra:

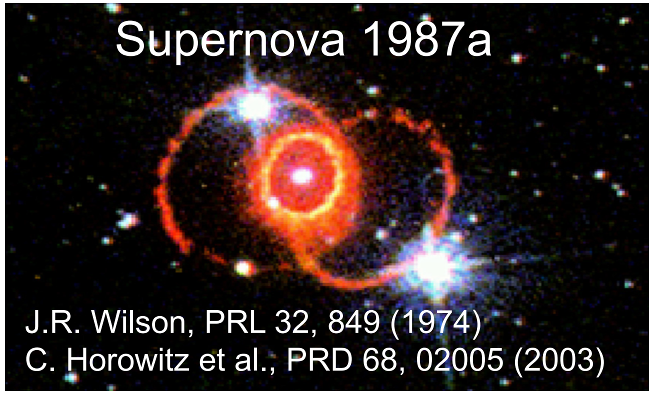
Non-Standard ν Interactions: Test of the SM, DM



Nuclear Physics Form Factors, Axial Currents



Supernovae Cross Sections and E_W Measurements



Coherent scattering and NSI

$$\frac{\mathrm{d}\sigma}{\mathrm{d}T}(E_\nu, T) \simeq \frac{G_F^2 M}{\pi}\left(1-\frac{MT}{2E_\nu^2}\right)\left\{\left[Z\left(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}\right)F_Z^V(Q^2) + N\left(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}\right)F_N^V(Q^2)\right]^2 \right.$$

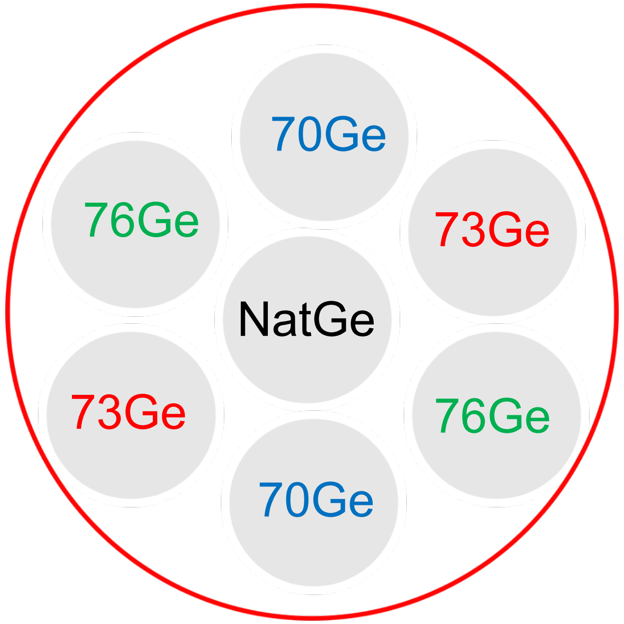
$$\left. + \sum_\alpha \left[Z\left(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}\right)F_Z^V(Q^2) + N\left(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV}\right)F_Z^V(Q^2)\right]^2\right\}.$$

$$\varepsilon_{\alpha\beta}^{qL}$$

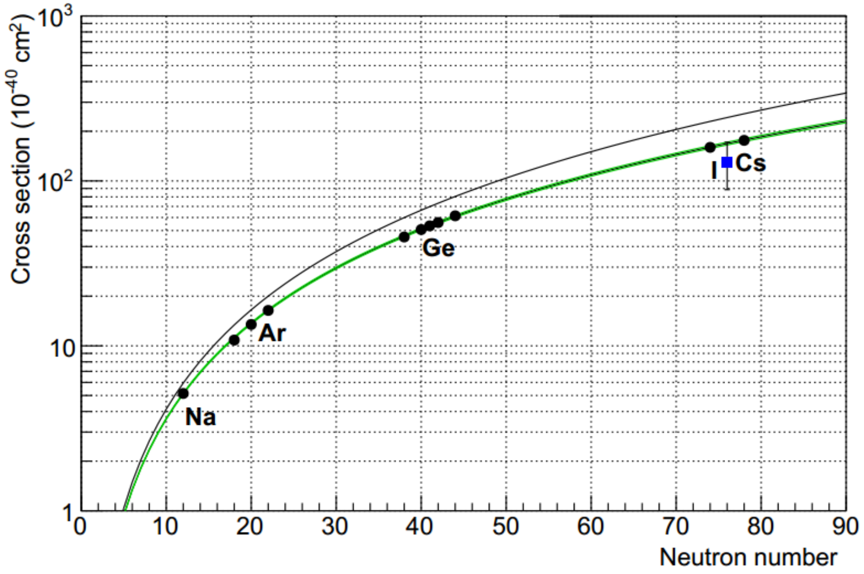
$$\frac{\mathrm{d}\sigma}{\mathrm{d}T}(E_\nu, T) \simeq \frac{G_F^2 M}{\pi}\left(1-\frac{MT}{2E_\nu^2}\right)\left[Z g_V^p F_Z^V(Q^2) + N g_V^n F_N^V(Q^2)\right]^2.$$

COHERENT scattering – Relative measurements

- Experiment with **identical** detectors
- **Different** isotopic composition
- Use **enriched** isotopes
- Perform **simultaneous** measurements
- **Cancelation os some systematic** errors
- Use **odd A** nuclei (Axial)



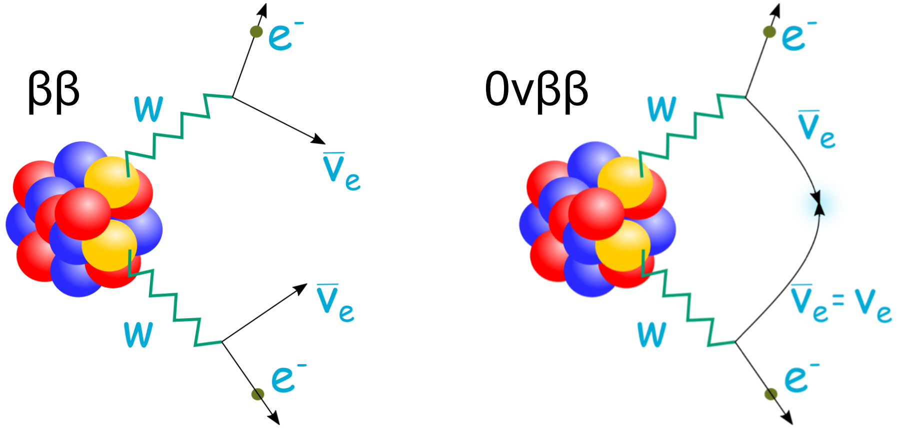
Mass	Natural Abundance	Decay Mode	Nuclear Spin
70	20.57%	STABLE	0+
72	27.45%	STABLE	0+
73	7.75%	STABLE	9/2+
74	36.50%	STABLE	0+
76	7.73%	STABLE	0+



0vbb

Search for Neutrinoless Double Beta Decay (0νββ)

This research has been identified by recent national and international review panels as being one of the highest priorities in all of physics.



NSAC is an advisory committee that provides official advice to the Department of Energy (DOE) and the National Science Foundation (NSF) on the national program for basic nuclear science research.

- If 0νββ is observed, then
  - Lepton number is not conserved
  - The neutrino is a Majorana particle (its own anti-particle)
  - It will provide information in the absolute neutrino mass scale

$$Sensitivity \propto \frac{1}{Background}$$

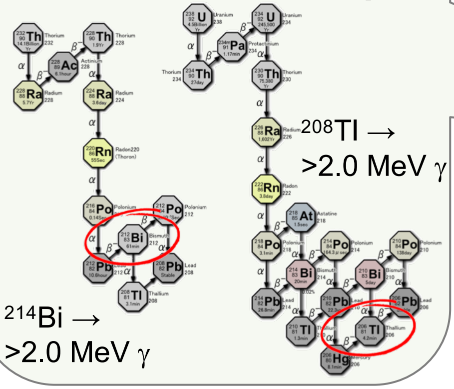
Advantages of ^{76}Ge

^{76}Ge offers a number of important advantages over other candidate isotopes

- Intrinsic high-purity Ge diodes
- Excellent energy resolution; 0.14% at 2.039 MeV
- Powerful background rejection
  - Pulse shape discrimination
- Well-understood technologies
  - Commercial Ge diodes
  - Large Ge arrays (GRETINA, Gammasphere)
  - Point contact detectors
- Ge as both source and detector
- Demonstrated ability to enrich from natural 7.8% to 87%

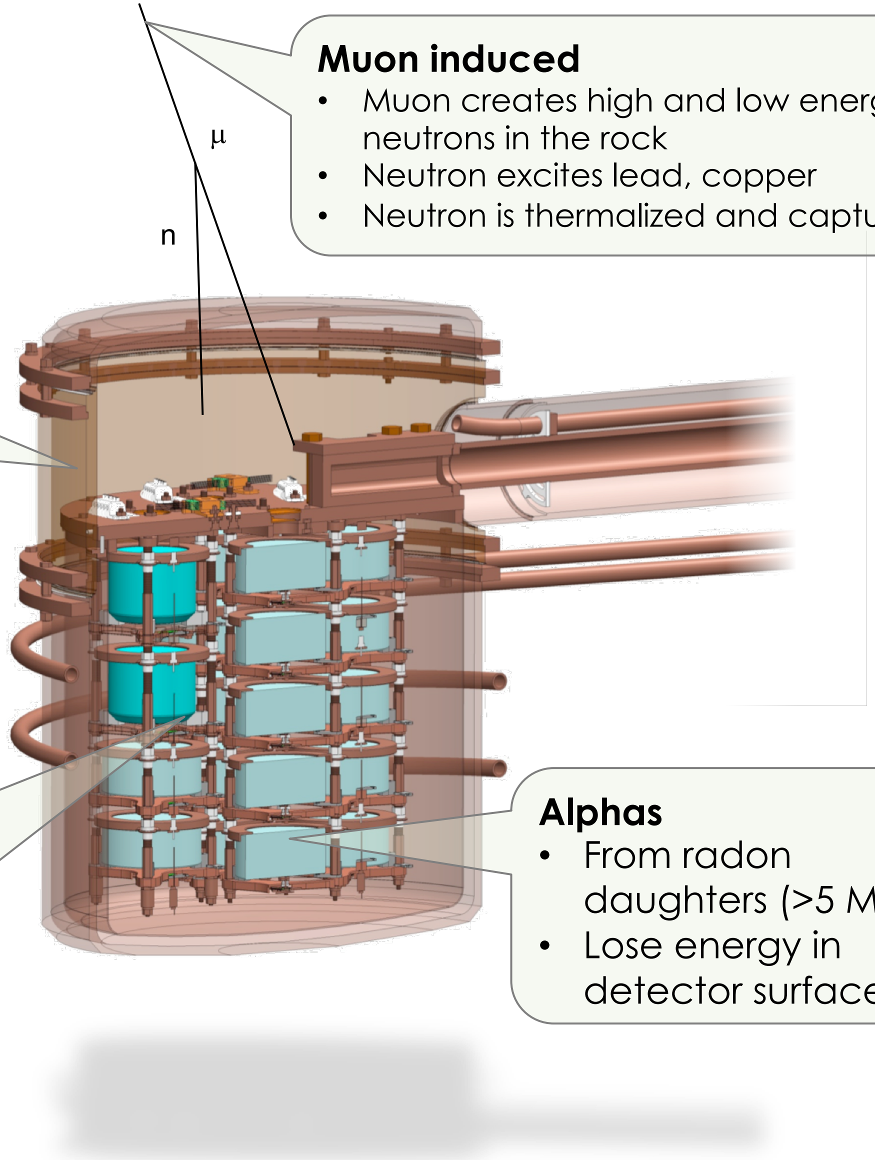
It's all about the Backgrounds

Natural radioactivity



Cosmogentic activation

- High energy neutrons and muons break up copper, lead, etc. and make radioactive isotopes (e.g. Ge-68, Co-60)
- They decay and produce betas and gammas in the ROI



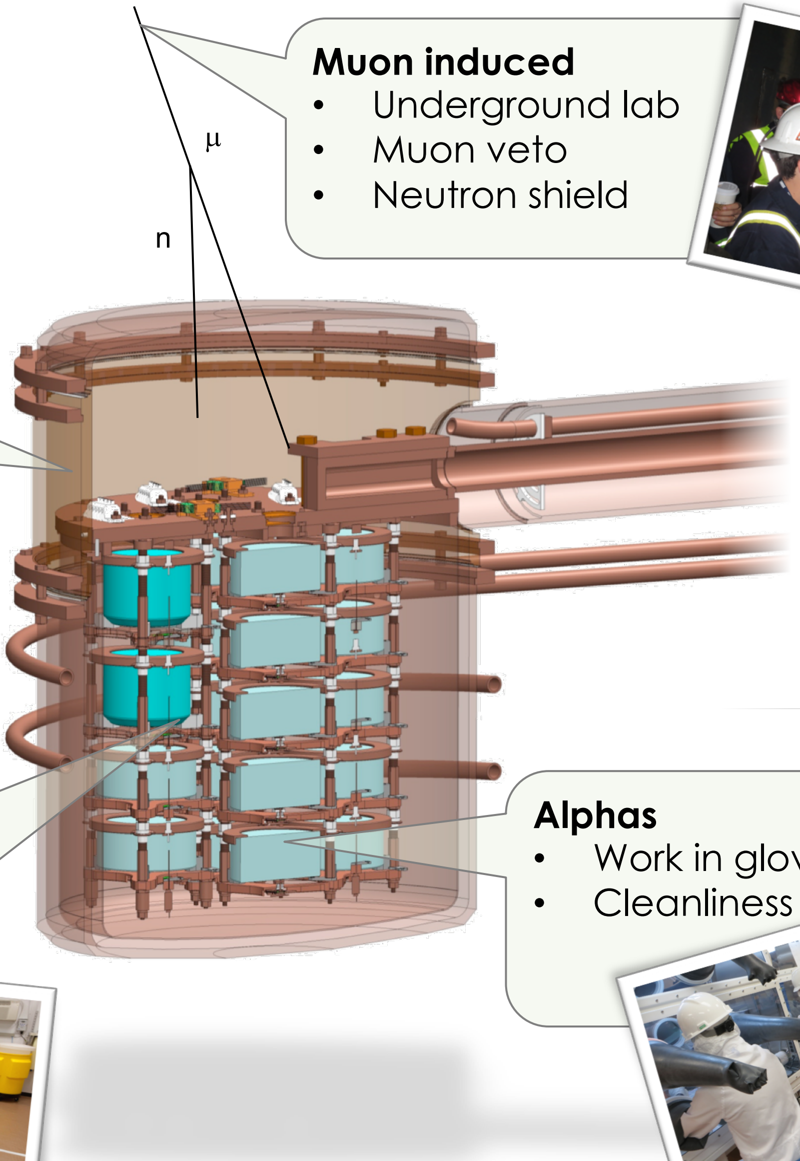
Muon induced

- Muon creates high and low energy neutrons in the rock
- Neutron excites lead, copper
- Neutron is thermalized and captured

Alphas

- From radon daughters (>5 MeV)
- Lose energy in detector surface

How to Reduce the Backgrounds



Muon induced
- Underground lab
- Muon veto
- Neutron shield

Natural radioactivity
- High radiopurity
- Cleanliness
- Shielding

Cosmogentic activation
- Minimize above-ground time
- Copper electro-forming underground
- Analysis cuts

Alphas
- Work in glovebox
- Cleanliness

LEGEND

47 Institutions, 219 Scientists

Univ. New Mexico
L'Aquila Univ. and INFN
Gran Sasso Science Inst.
Lab. Naz. Gran Sasso
Univ. Texas
Tsinghua Univ.
Lawrence Berkeley Natl. Lab.
Leibniz Inst. Crystal Growth
Comenius Univ.
Lab. Naz. Sud
Univ. of North Carolina
Sichuan Univ.
Univ. of South Carolina
Jagiellonian Univ.
Banaras Hindu Univ.
Univ. of Dortmund
Tech. Univ. – Dresden
Joint Inst. Nucl. Res. Inst.
Nucl. Res. Russian Acad. Sci.

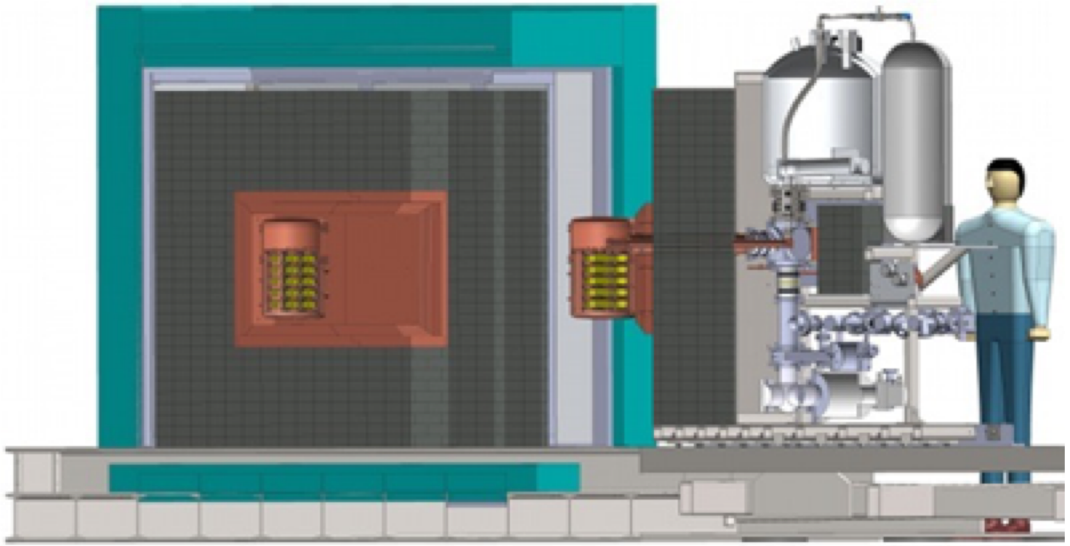
Joint Res. Centre, Geel
Chalmers Univ. Tech.
Max Planck Inst., Heidelberg
Dokuz Eylul Univ.
Queens Univ.

Univ. Tennessee
Argonne Natl. lab.
Univ. Liverpool
Univ. College London
Los Alamos Natl. Lab.

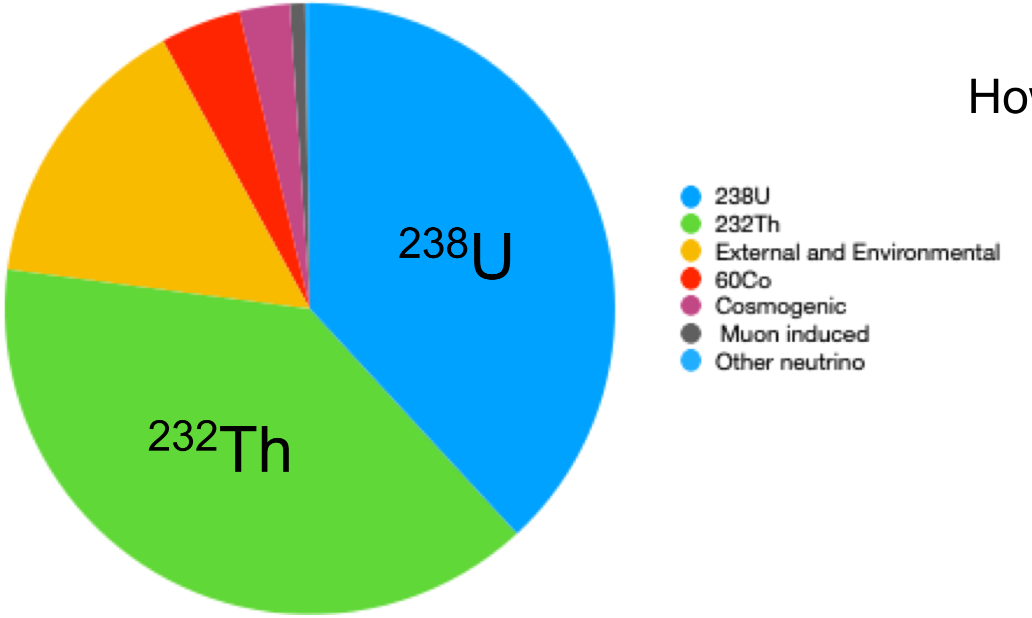
Lund Univ.
INFN Milano Bicocca
Milano Univ. and Milano INFN
Natl. Res. Center Kurchatov Inst.
Lab. for Exper. Nucl. Phy. MEPhI
Max Planck Inst., Munich
Tech. Univ. Munich
Oak Ridge Natl. Lab.
Padova Univ. and Padova INFN
Czech Tech. Univ. Prague
Princeton Univ.
North Carolina State Univ.
South Dakota School Mines Tech.
Univ. Washington
Academia Sinica
Univ. Tuebingen
Univ. South Dakota
Univ. Zurich

Majorana Demonstrator

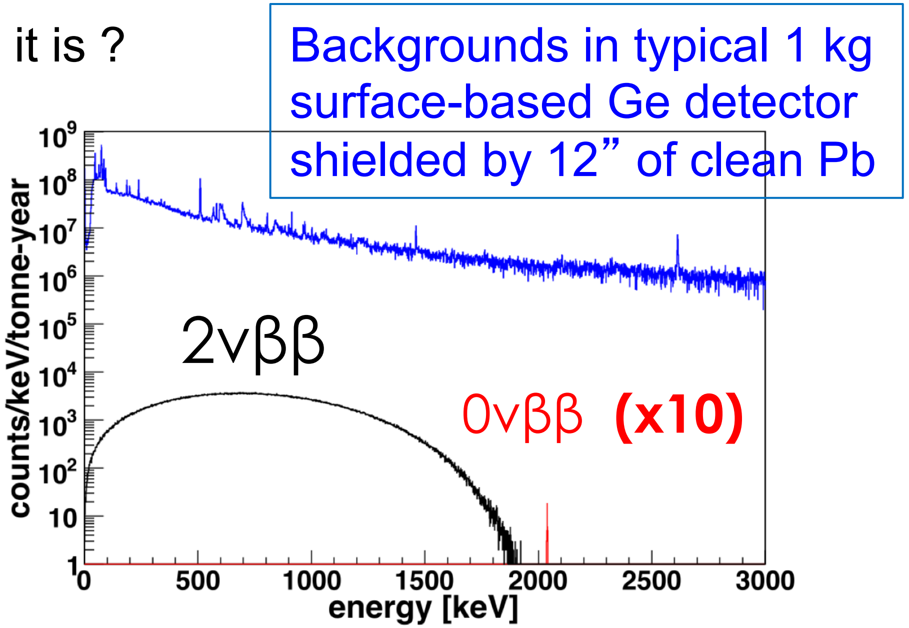
Demonstrate backgrounds low enough to justify building a tonne scale experiment.



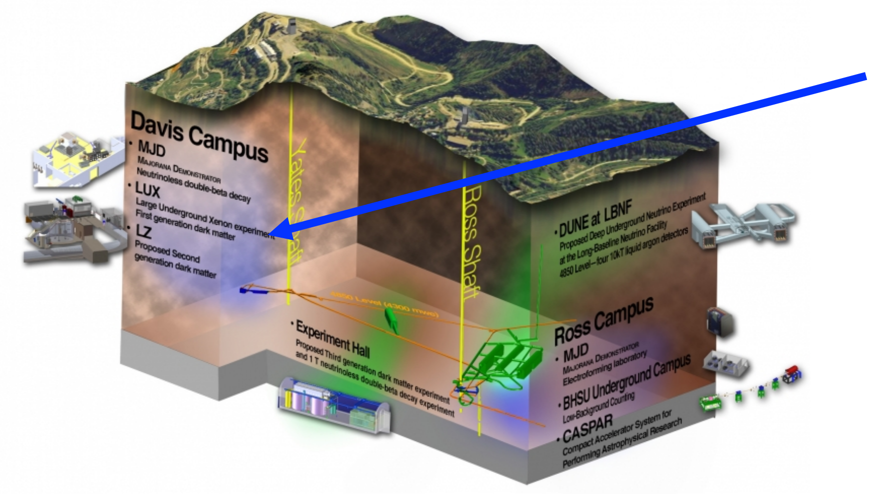
Background contributions



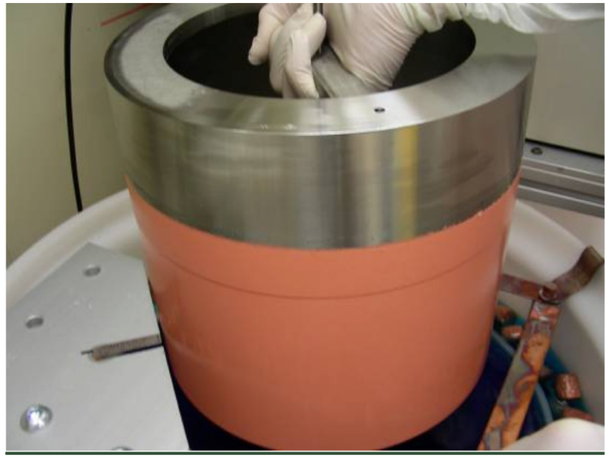
How hard it is ?



Reducing Background



Located at ~1 mile underground Sanford Underground Research Facility



The most stringent radiopurity goal is that for copper used in the inner shield and detector components

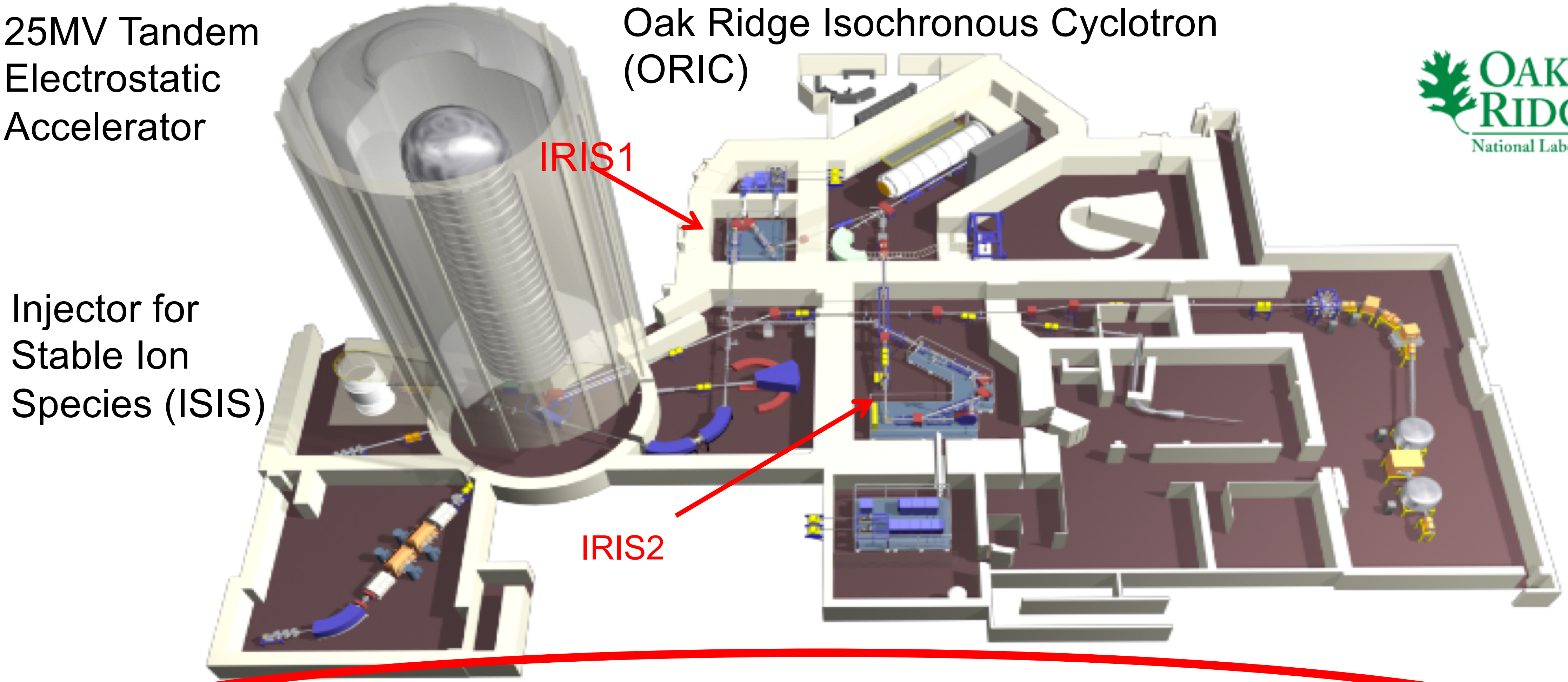
Producing ultrapure Cu made by electroforming Cu underground

Reaching ultra-low levels:

0.024×10^{-12} g ^{238}U/g Cu

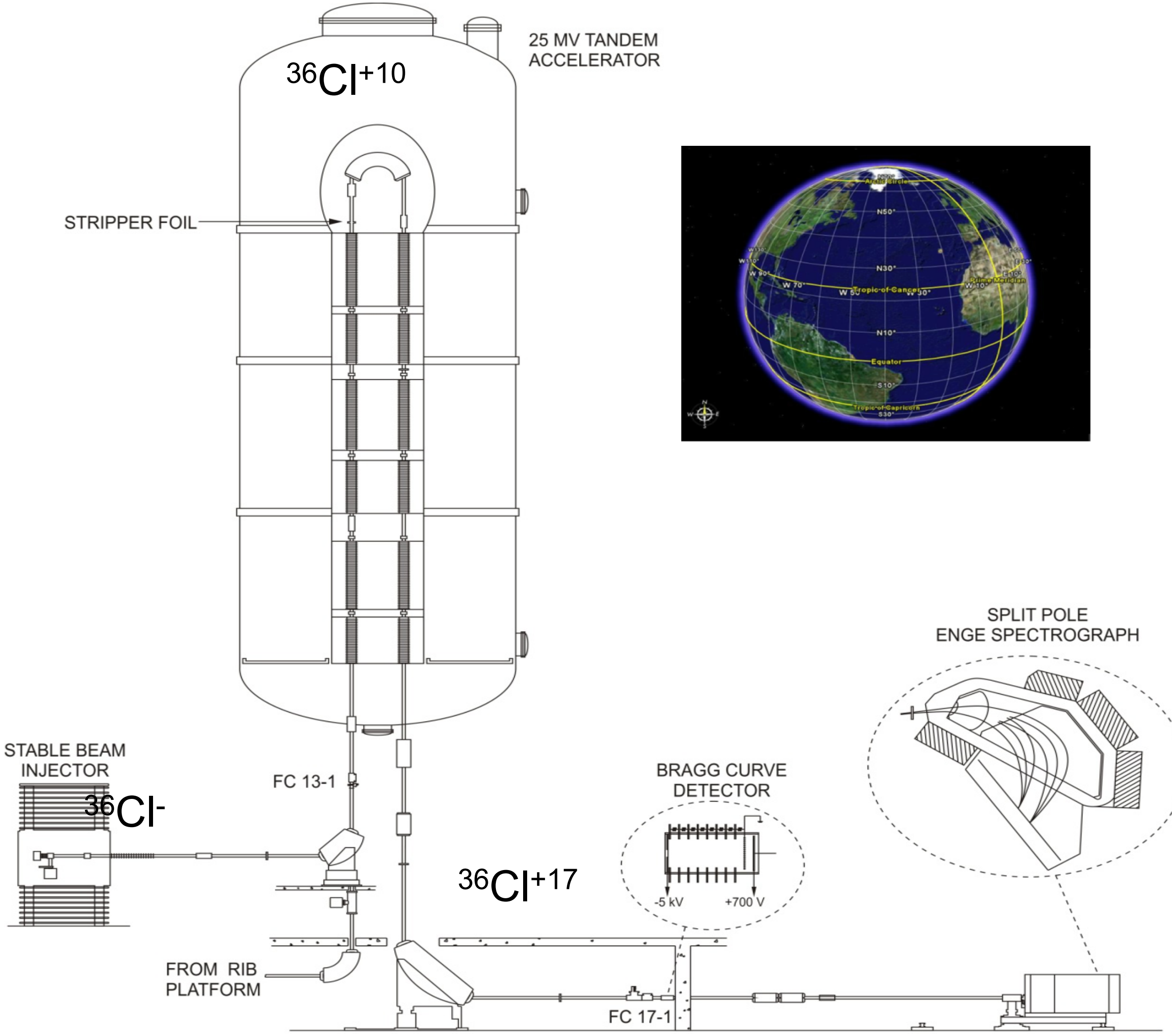
0.075×10^{-12} g ^{232}Th/g Cu

HRIBF and the 25MV Tandem Accelerator

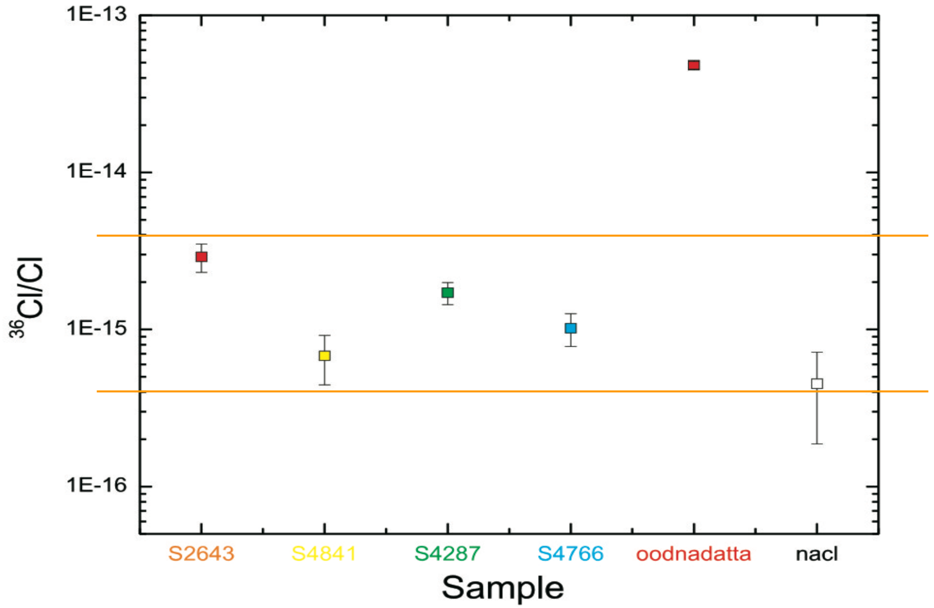


As part of its infrastructure HRIBF has a variety of equipment for beam transport and analysis ideal to do AMS

AMS setup at ORNL



^{36}Cl in seawater samples from around the world: Comparison



Pushing the limits of accelerator mass spectrometry by an order of magnitude

Measurement of ^{36}Cl in seawater samples
A. G-U, et al. NIM B 259 (2007)123

OAK RIDGE
National Laboratory

Analytical Techniques

Need of a diagnostic technique with **high efficiency** and with the **required sensitivity** to characterize the ultra-trace contaminants levels

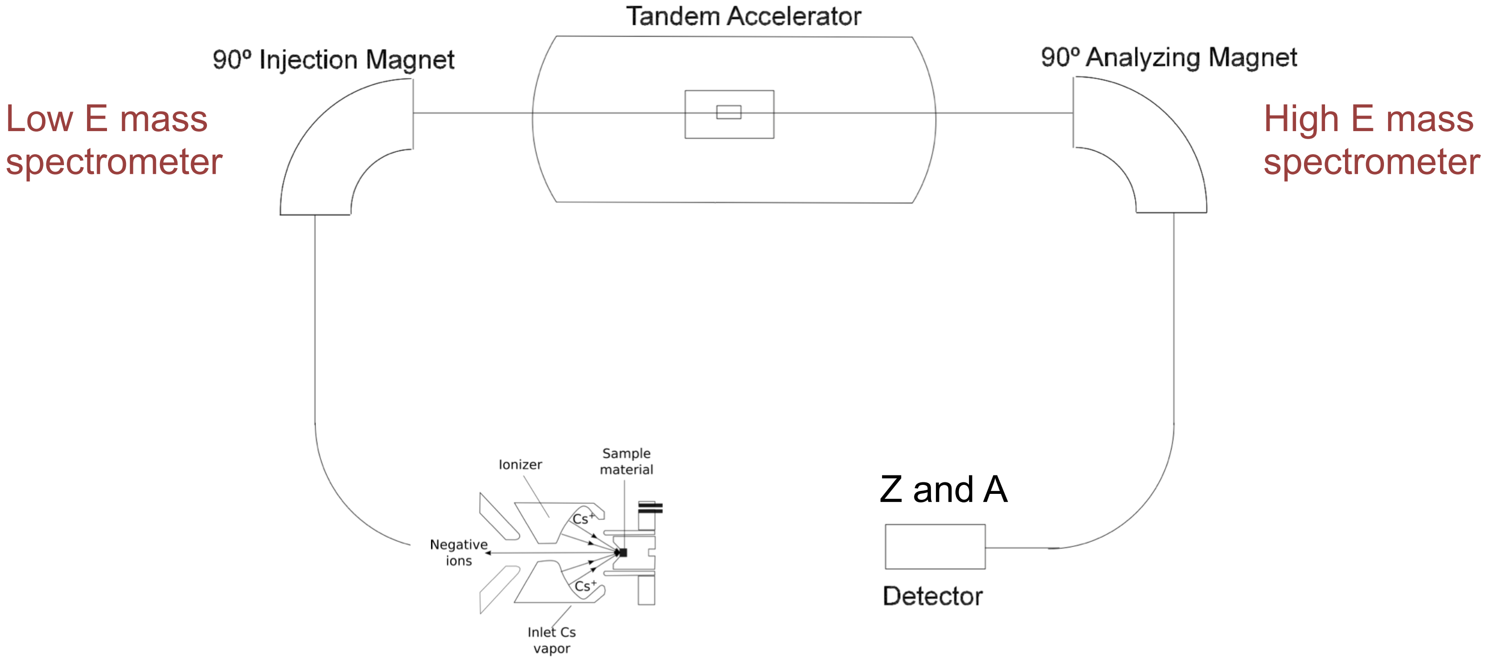
- ICP-MS-Inductively Coupled Plasma Mass Spectrometry
- Gamma ray spectroscopy
- NAA-Neutron Activation Analysis
- **AMS-Accelerator Mass Spectroscopy**

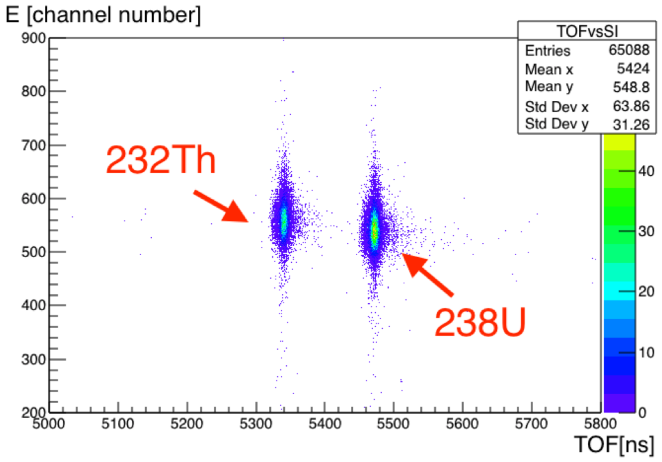
- Efficiency
- Sensitivity

Novel Technique:

RIMS - Resonant Ionization Mass Spectroscopy

Accelerator Mass Spectrometry

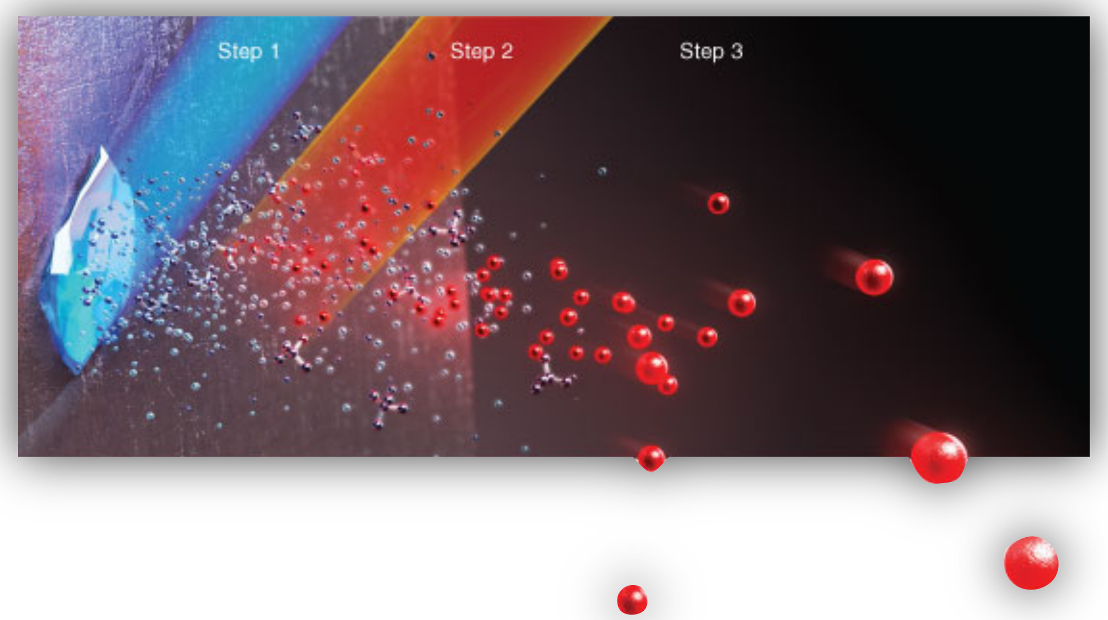


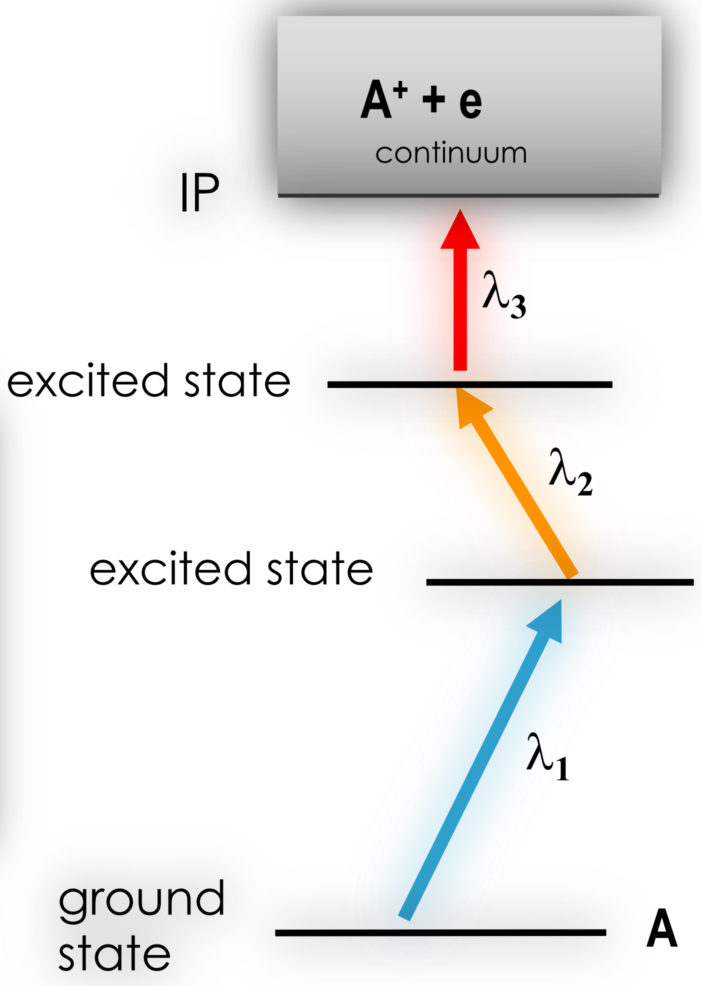


- Measured U and Th in ultra-pure Cu
- Cs Sputter source efficiency for actinides 0.01-0.1%

Resonant Ionization Mass Spectrometry

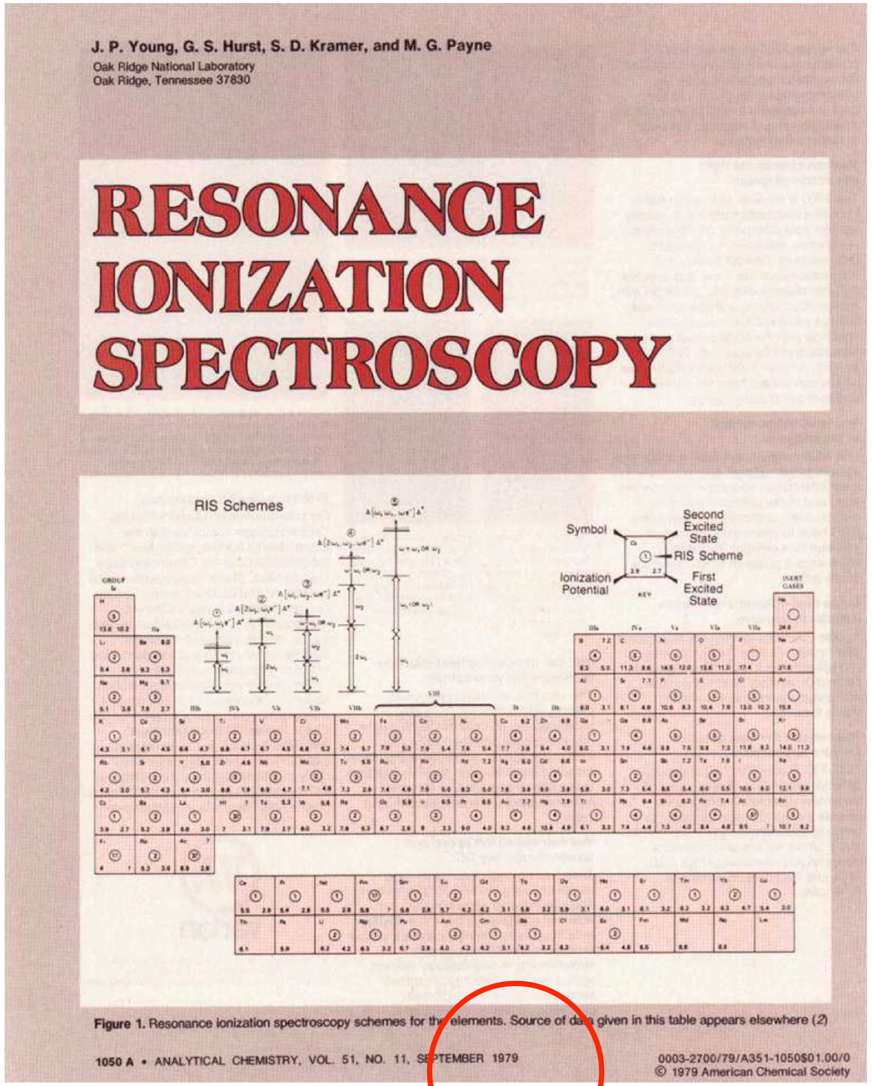
Analytical technique that uses photons from lasers to resonantly excite an electron in an atom through various excited states to the continuum





ORNL one of the pioneers of RIMS

From left are J. P. Young, G. S. Hurst, M. G. Payne, and S. D. Kramer, standing in front of the Van de Graaff generator that was used in the first RIS experiment with He



J. P. Young, G. S. Hurst, S. D. Kramer, and M. G. Payne
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

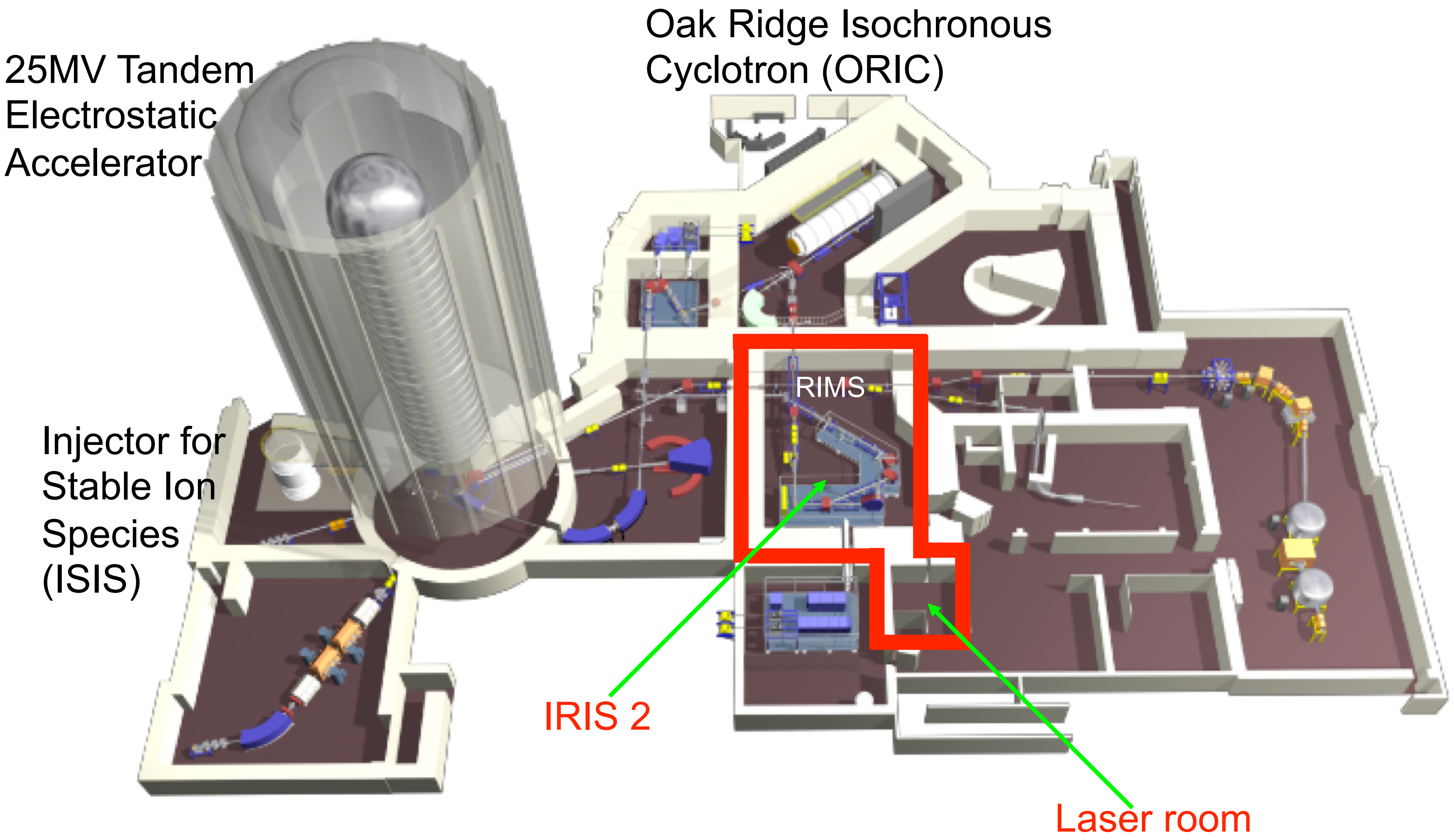
RESONANCE IONIZATION SPECTROSCOPY

Figure 1. Resonance ionization spectroscopy schemes for the elements. Source of data given in this table appears elsewhere (2)

1050 A • ANALYTICAL CHEMISTRY, VOL. 51, NO. 11, SEPTEMBER 1979
0003-2700/79/A351-1050$01.00/0

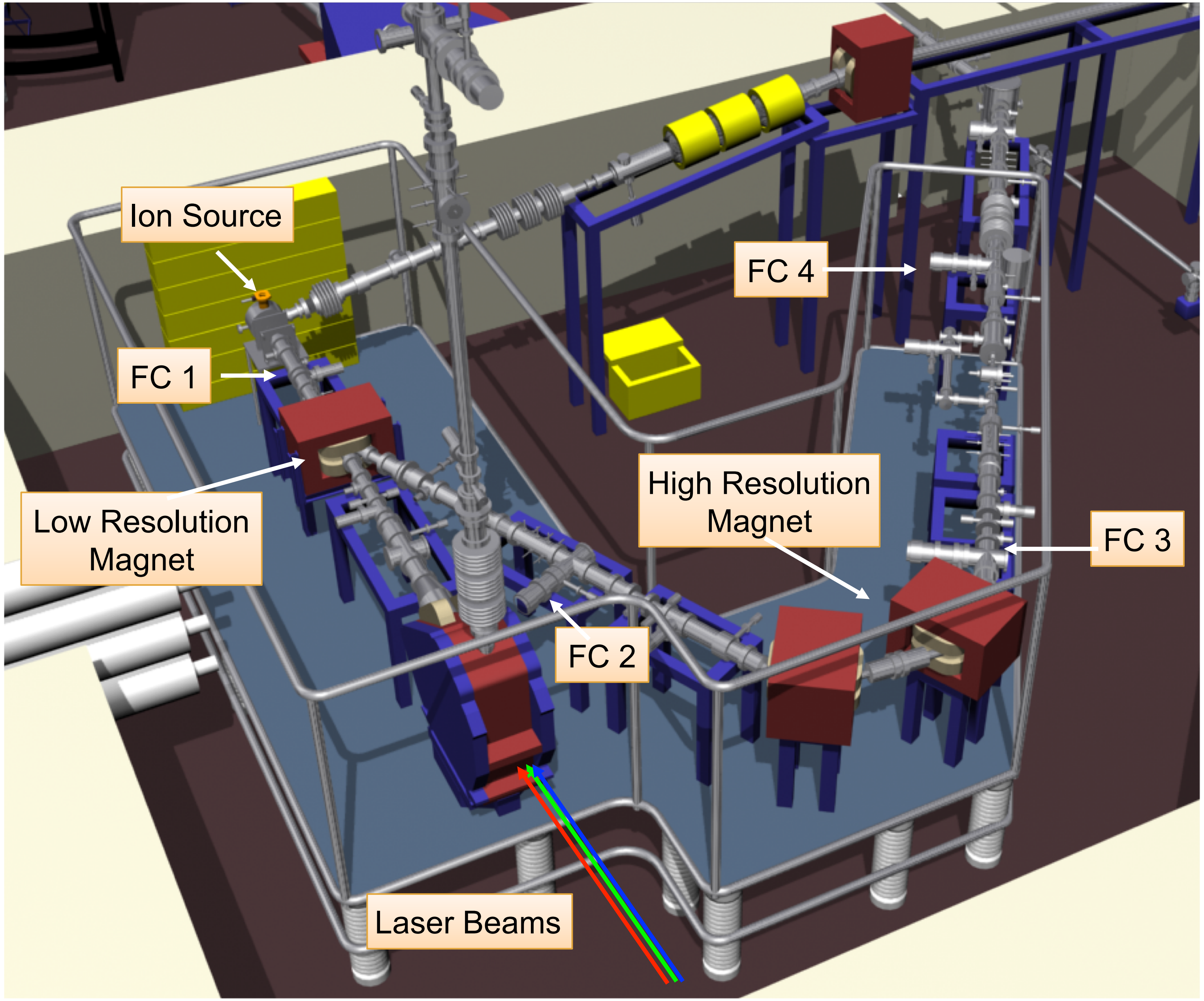
Analytical chemical division

Injector for Radioactive Ion Species 2 (IRIS 2)

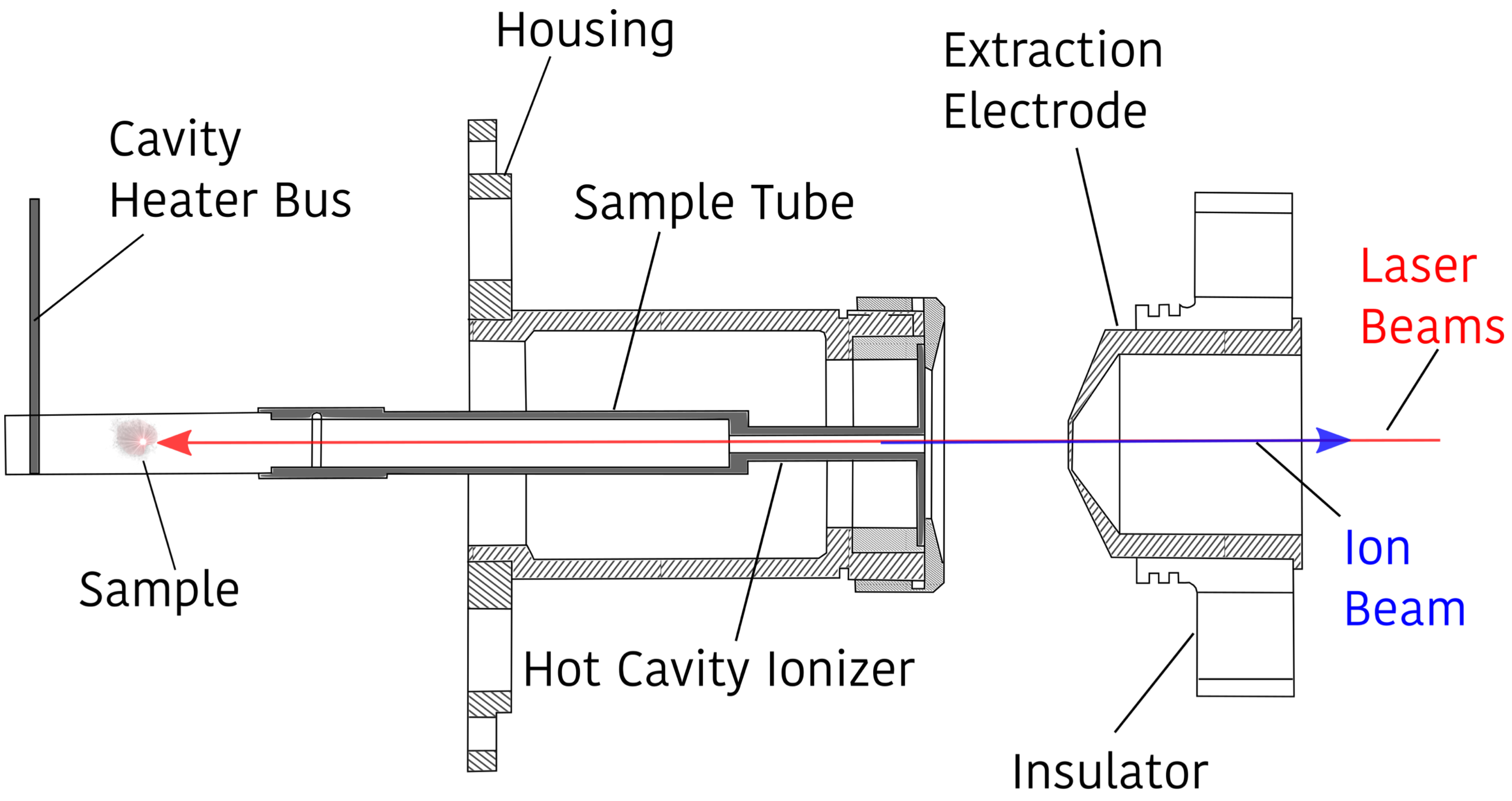


HRIBF shut down since 2012

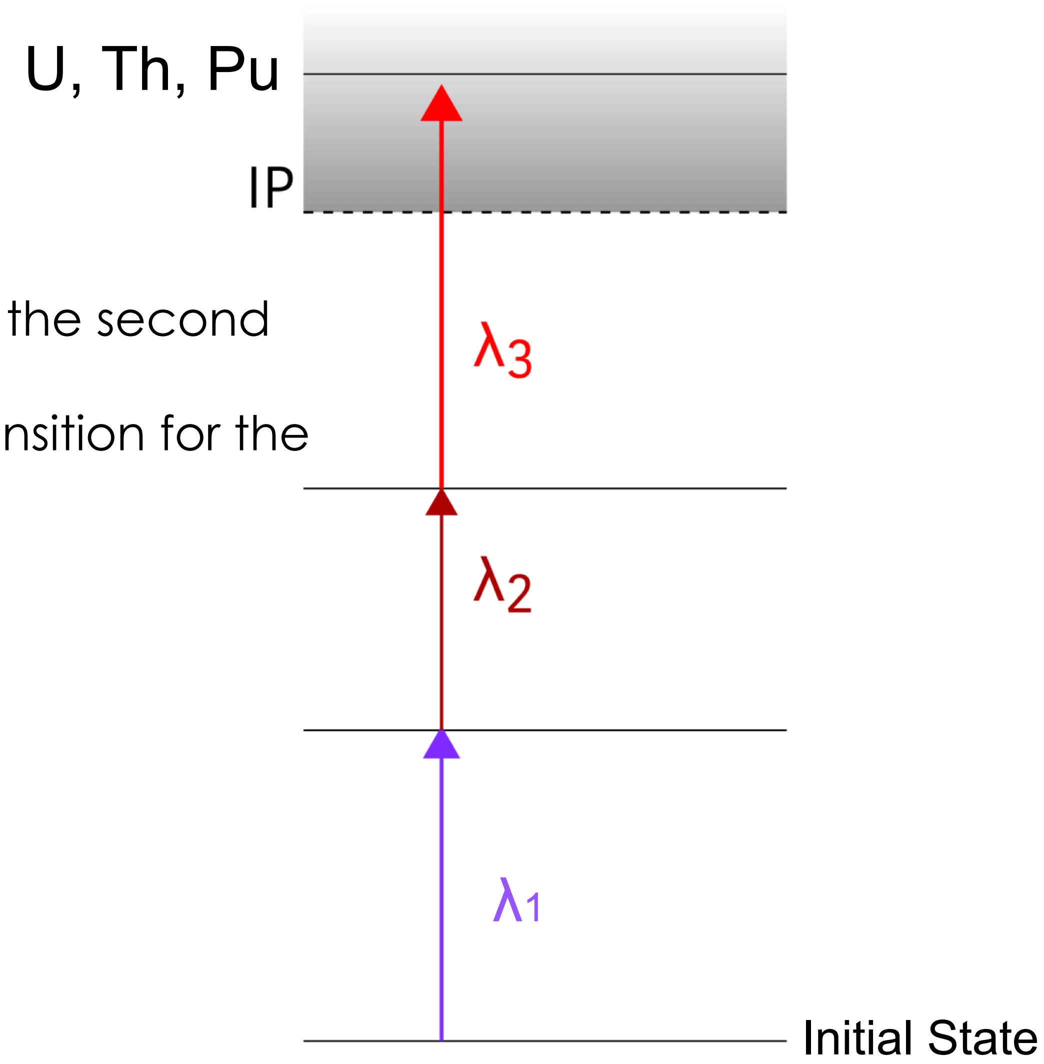
RIMS at ORNL: Experimental Setup



Resonant Ionization Laser Ion Source



Searching for Three Step Resonant Ionization schemes



1. Scan the wavelength of the second step excitation laser
2. We select a resonant transition for the second step
3. Perform third step scan

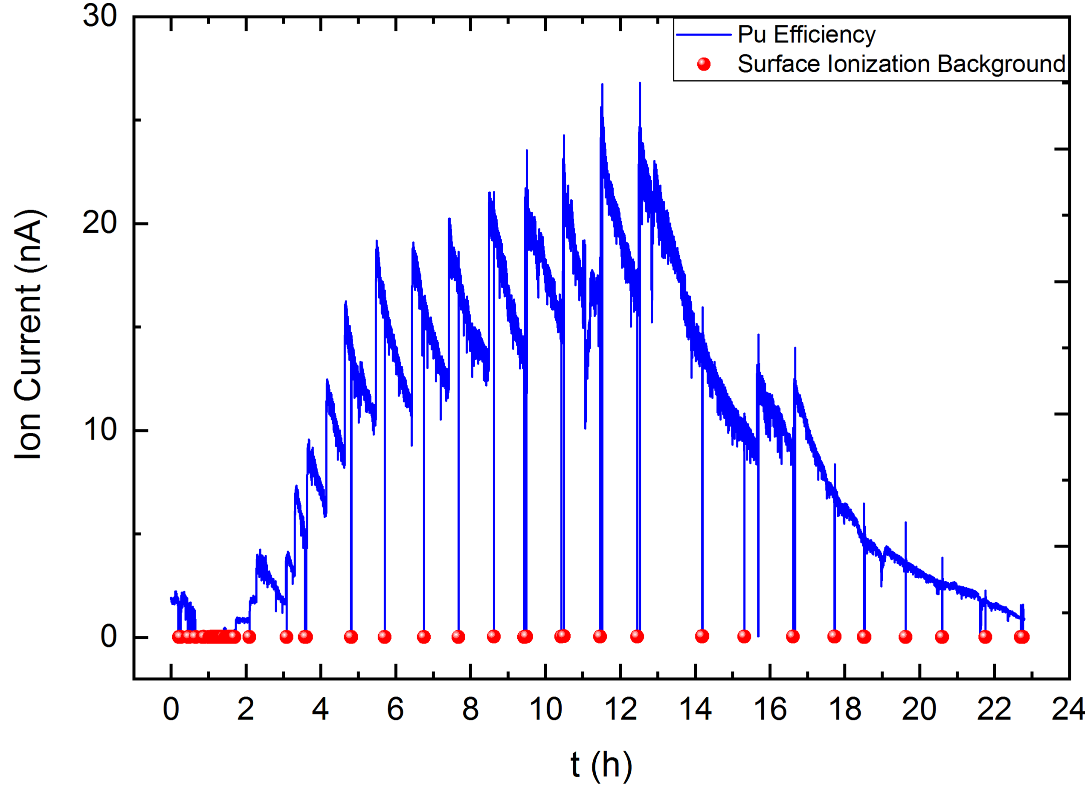
Sample size : 40 μg

Efficiency Measurement of Pu

Sample: 4 μg Pu wrapped in Zr foil

$$Ionization\ efficiency = \frac{\#\ of\ ions\ detected}{\#\ of\ neutral\ atoms\ in\ the\ sample}$$

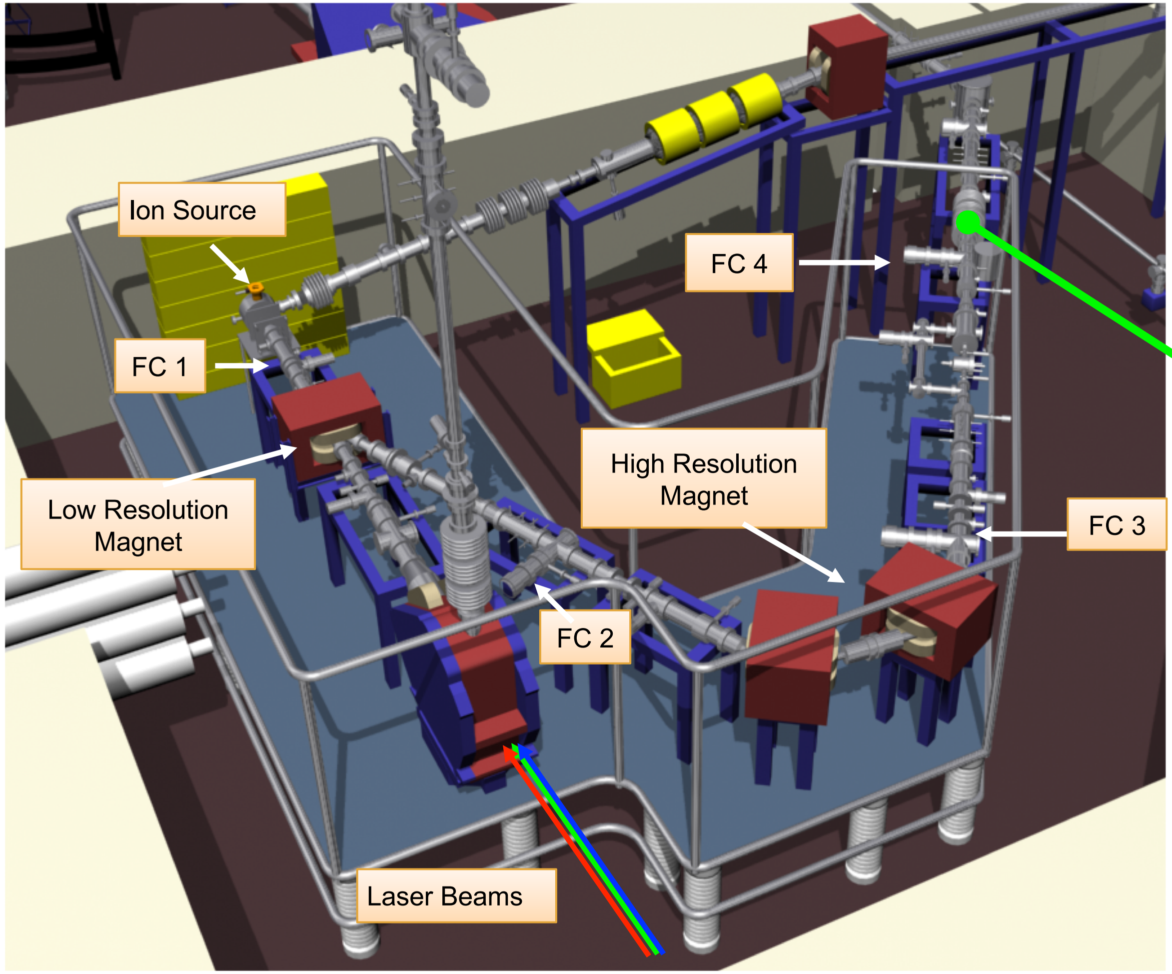
Measured Efficiency:
51% ± 4%



E. Romero-Romero
UTK Ph.D. Thesis 2019

Sensitivity studies

- Efficient positive ion source demonstrated for U, Th and Pu



Modification to current setup by adding a single atom counter detector

RIMS at ORNL

Injector for Radioactive Ion Species (IRIS 2)

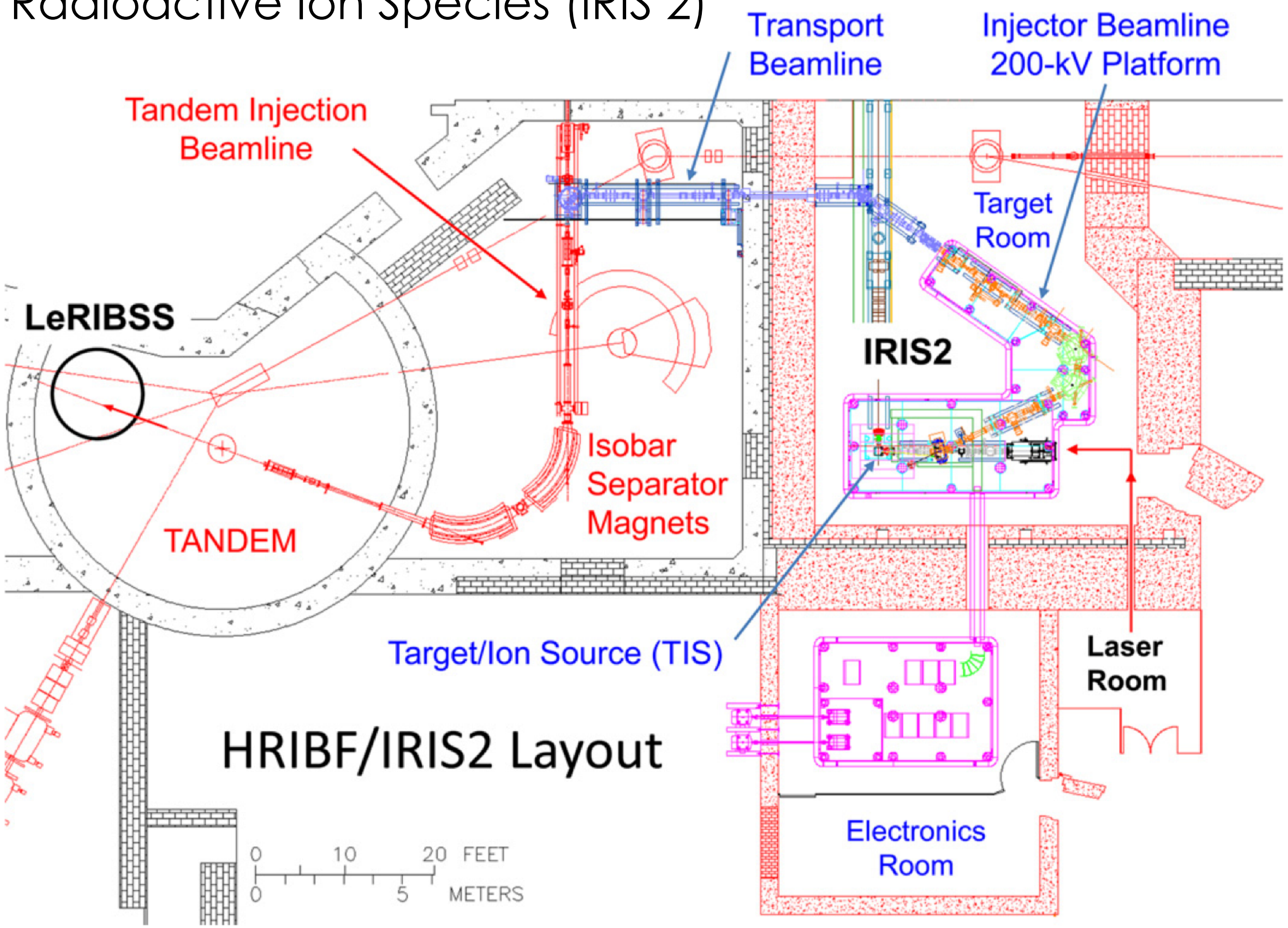
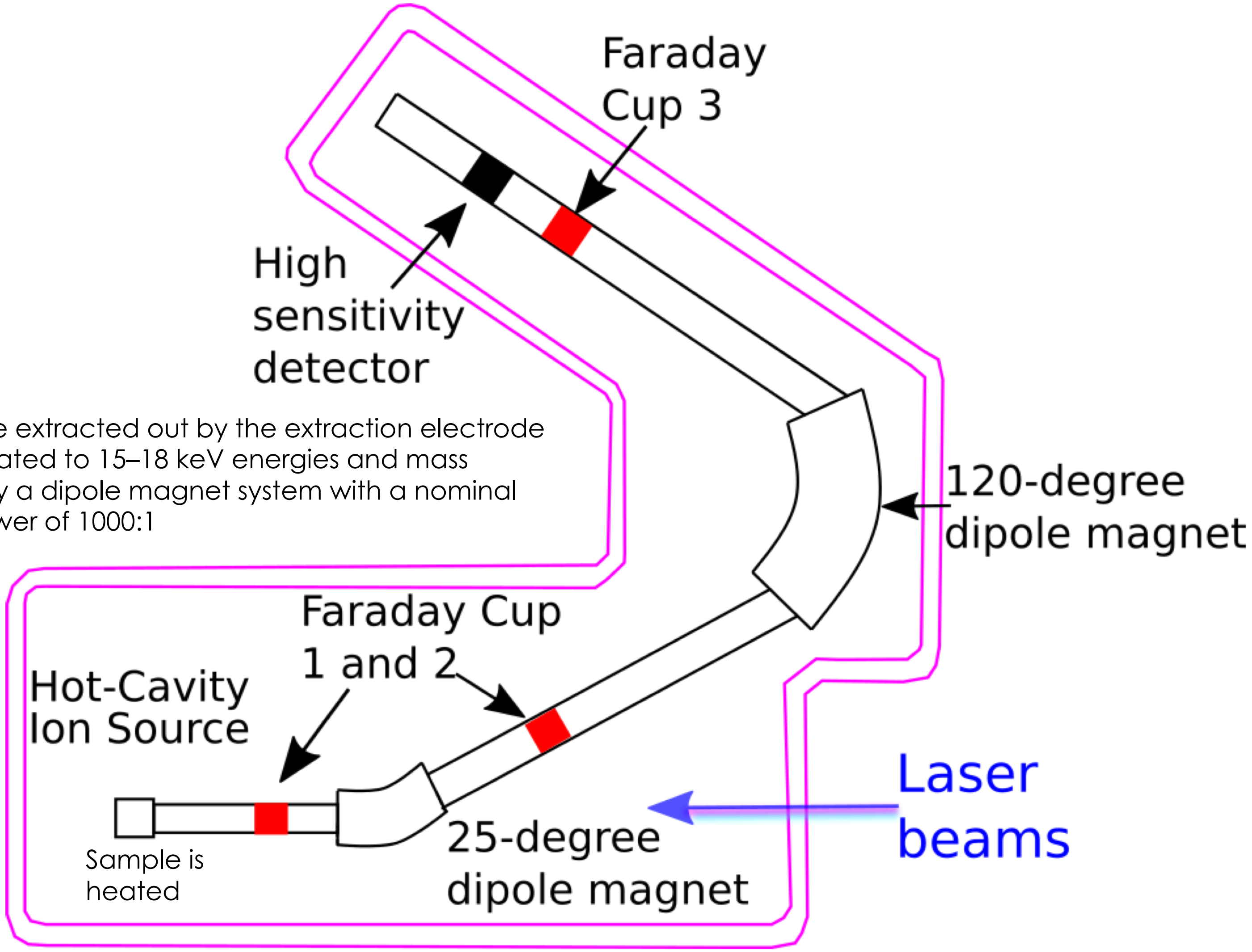


Fig. 3. Partial layout of the HRIBF showing the IRIS2, laser room, tandem accelerator, and LeRIBSS areas.

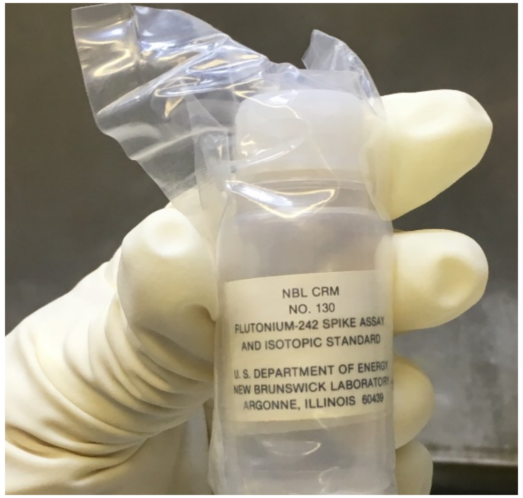
HRIBF shut down since 2012

Experimental Setup

The ions were extracted out by the extraction electrode and accelerated to 15–18 keV energies and mass separated by a dipole magnet system with a nominal resolving power of 1000:1



^{242}Pu Sample Preparation



- 1 mg evaporated plutonium nitrate standard in a 30 mL Teflon bottle
- 30 μCi !

NEW BRUNSWICK LABORATORY

- Hood and PPE in the hot sample laboratory at Physics Division

- Dilution with 1 ml 8M HNO_3 at 100 °C
- Dilution to a final solution of 100 ppm ^{242}Pu
- ^{242}Pu is one of the easiest Pu isotopes to work with

Sensitivity Measurements for ^{242}Pu

- ^{242}Pu diluted sample to 10 fg (10^{-14} g)

^{242}Pu sample composition

	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	^{244}Pu
Atom %:	4.19E-03	4.78E-03	**1.97E-02**	2.47E-02	**99.95**	4.00E-04
Uncertainty:	0.00026	0.00012	0.00038	0.00034	0.00065	0.00010

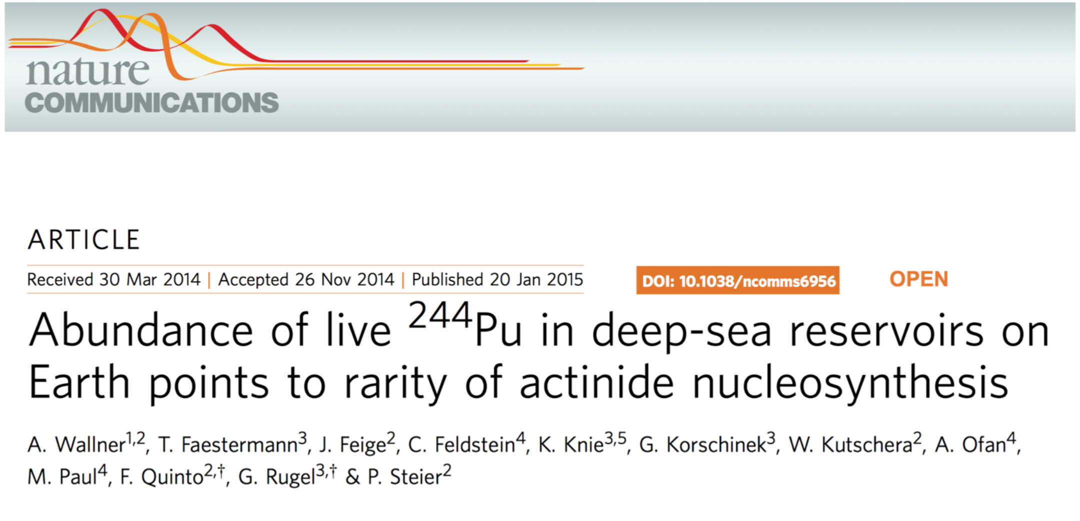
$$\frac{^{240}Pu_{counts}}{^{242}Pu_{counts}} = \frac{^{240}Pu_{atom\%}}{^{242}Pu_{atom\%}} = 2 \times 10^{-4}$$

Our sensitivity is 0.002 fg!

E. Romero-Romero
UTK Ph.D. Thesis 2019

^{244}Pu in deep sediments and Accelerator Mass Spectrometry

AMS is the most sensitive technique for isotopic analysis in which atoms extracted from a sample are ionized; accelerated to high energies; separated according to their momentum, charge and energy; and then individually counted.


nature COMMUNICATIONS

ARTICLE

Received 30 Mar 2014 | Accepted 26 Nov 2014 | Published 20 Jan 2015 DOI: 10.1038/ncomms6956 OPEN

Abundance of live ^{244}Pu in deep-sea reservoirs on Earth points to rarity of actinide nucleosynthesis

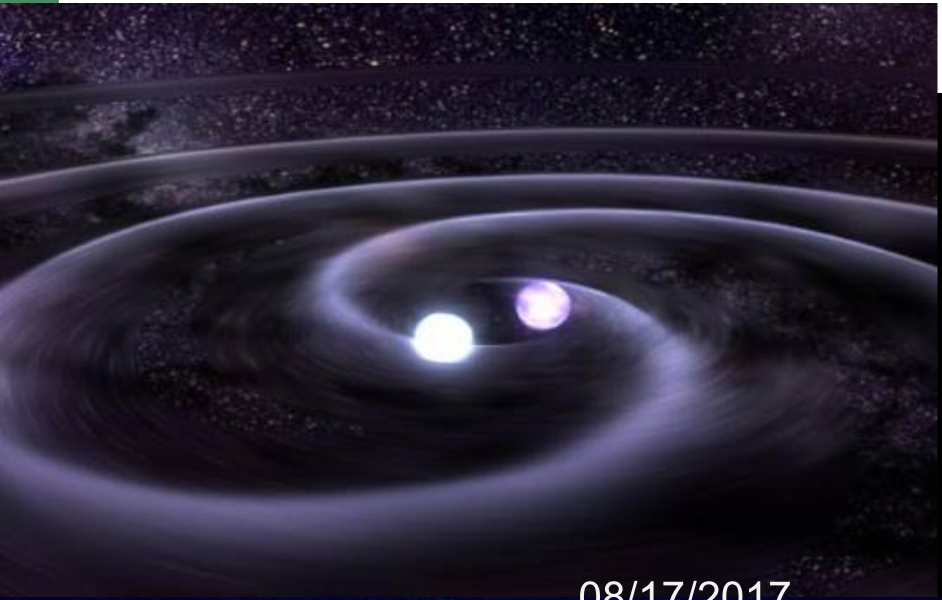
A. Wallner[1,2], T. Faestermann[3], J. Feige[2], C. Feldstein[4], K. Knie[3,5], G. Korschinek[3], W. Kutschera[2], A. Ofan[4], M. Paul[4], F. Quinto[2,†], G. Rugel[3,†] & P. Steier[2]

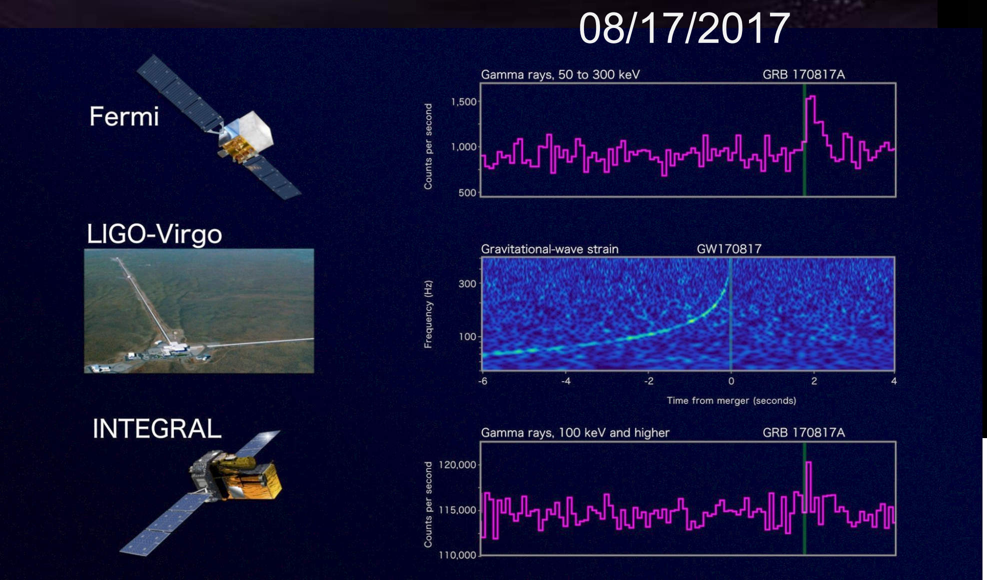
Signal consists of two counts!

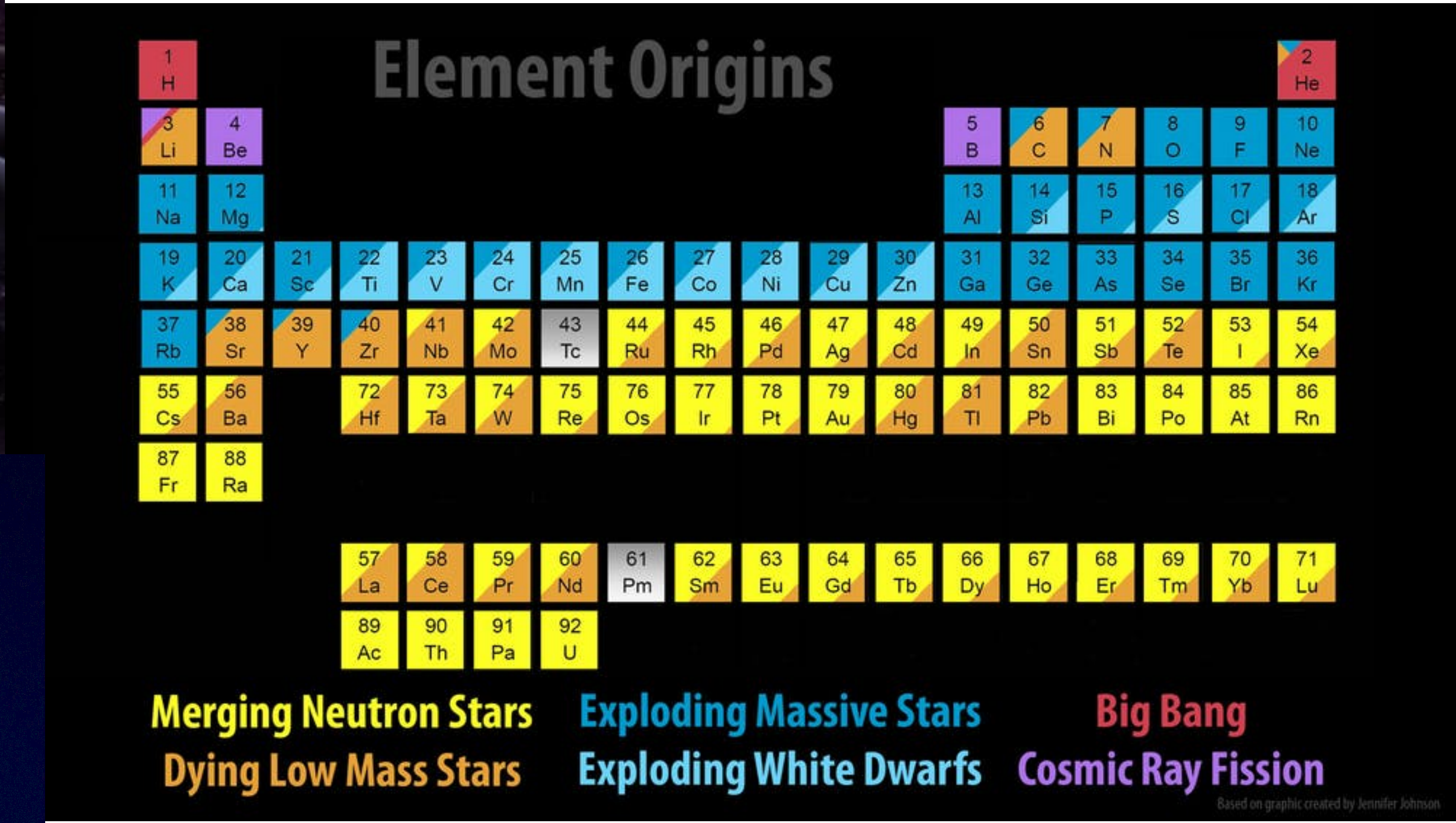
Cs-Sputtering source for actinides of the order of 0.1-1% efficiency

Neutron Star Mergers create heavy elements

'Multi-messenger astronomy', observation of gravitational waves and electromagnetic radiation,



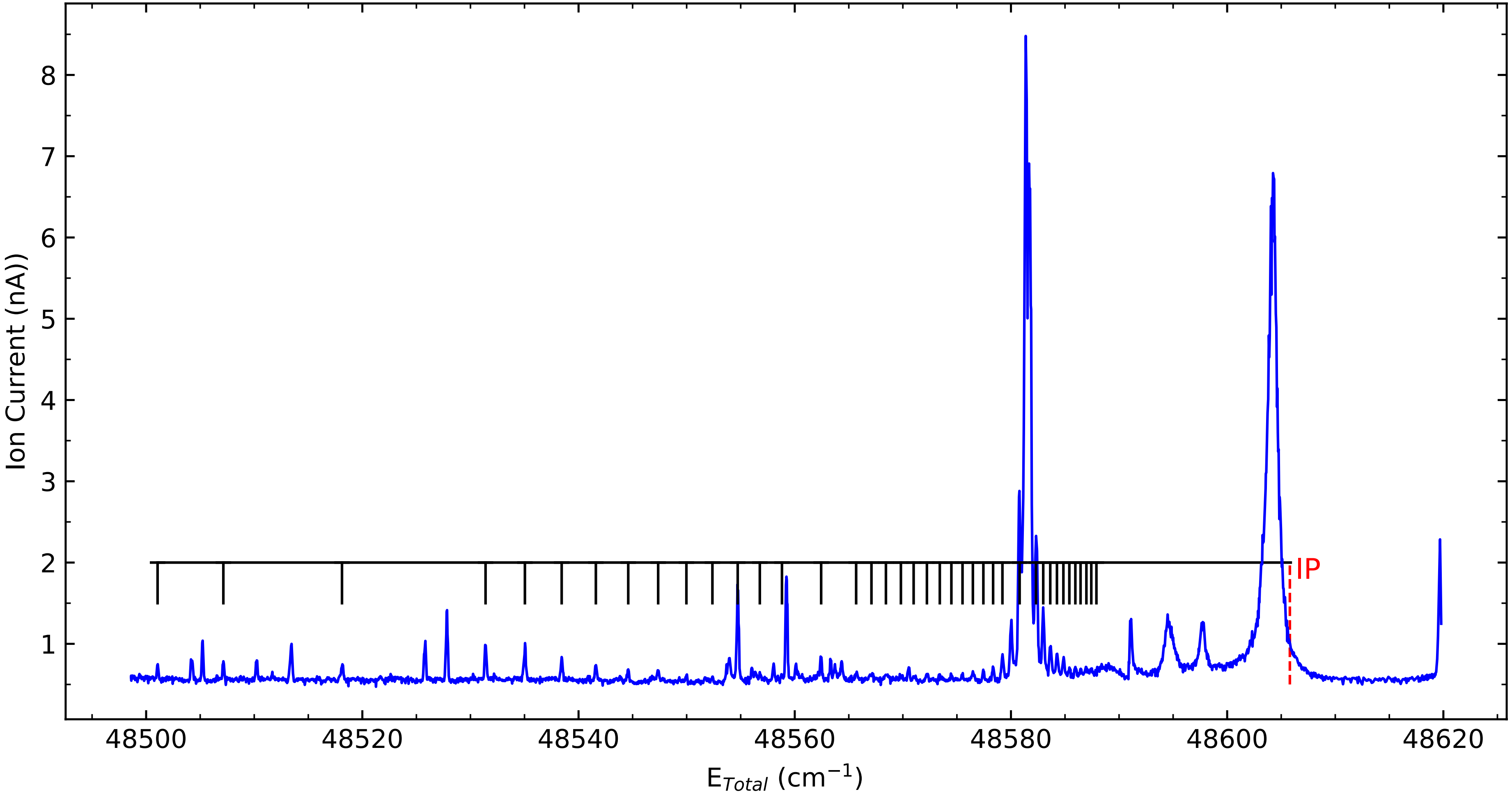




RYDBERG and IP Pu

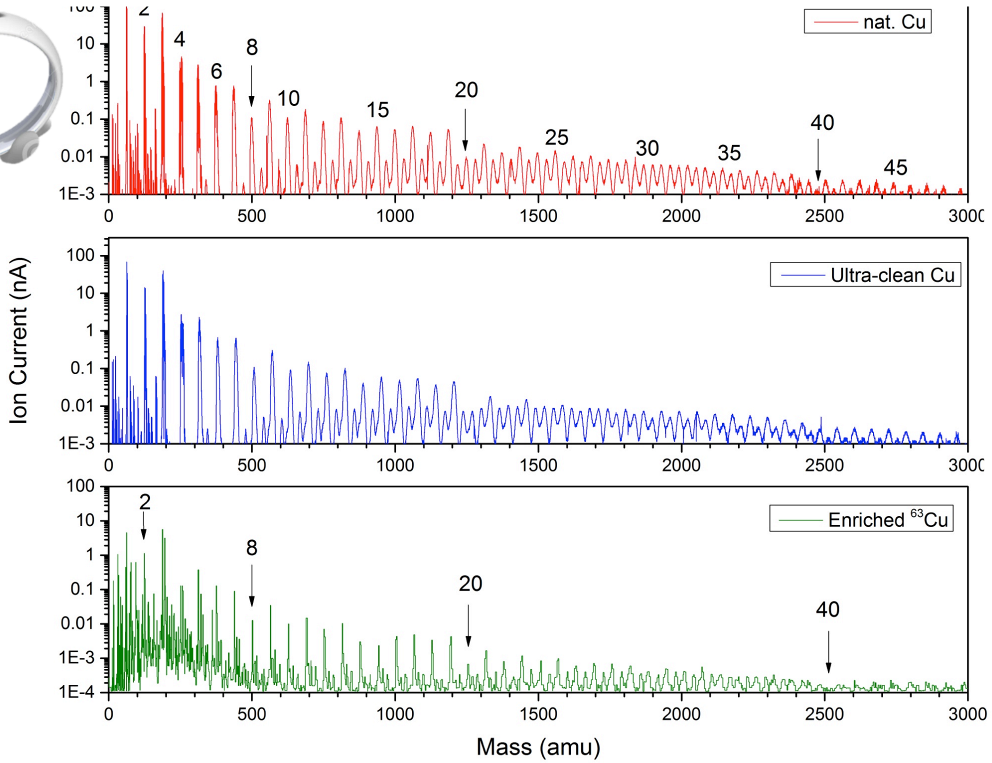
PRELIMINARY

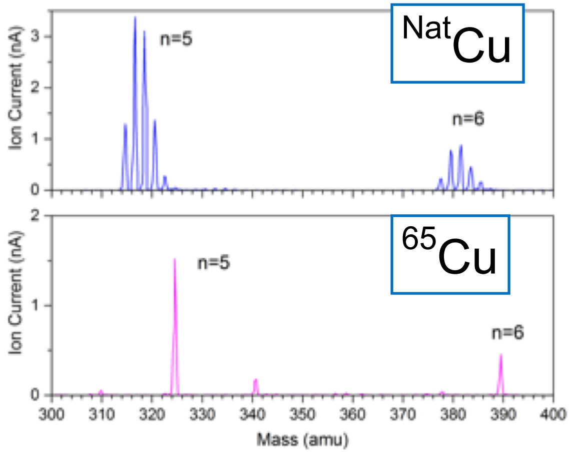
Spectroscopy of Pu and observation of 2 Rydberg series



CLUSTERS

Mass spectra of negative clusters





Chu, Ran. UTK Master Thesis. October 2016

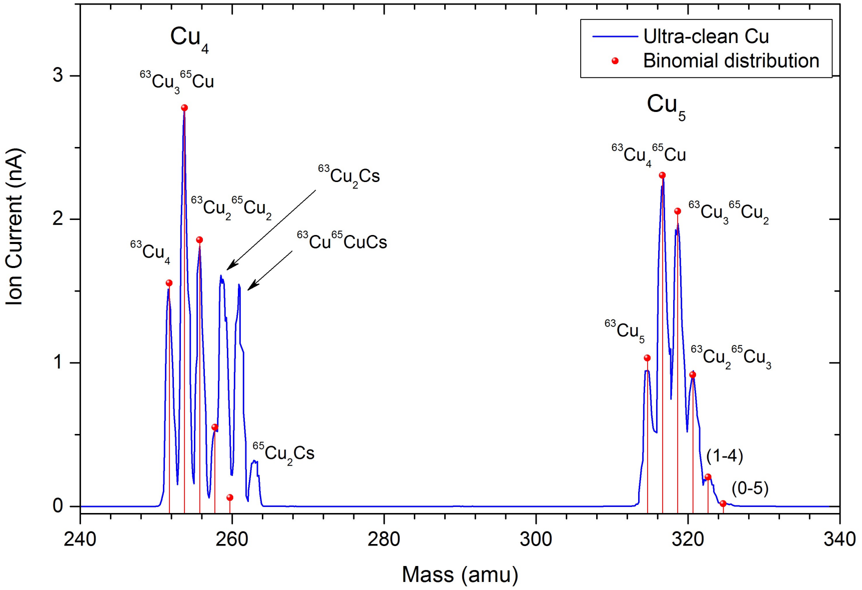
Magic Numbers at n= 2, 8, 20, 40

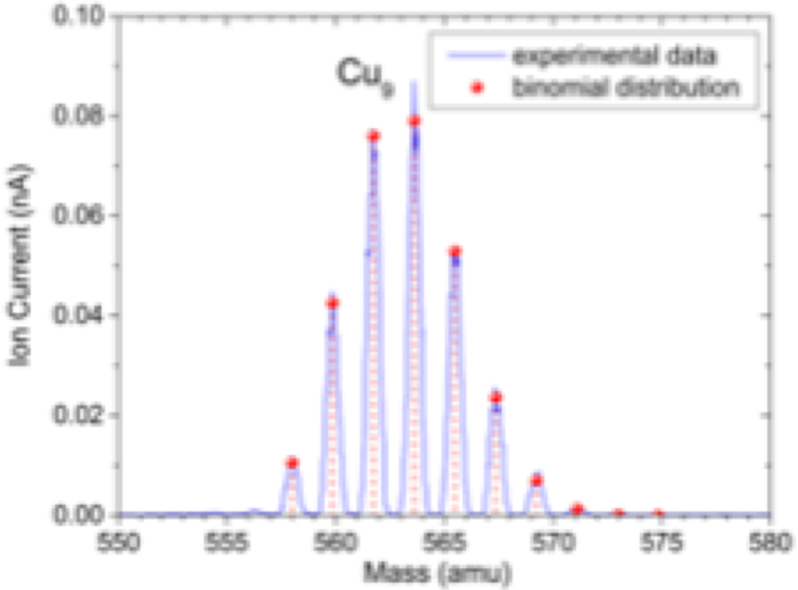
The conduction electrons in clusters of simple metal atoms are approximately independent and free. Nucleons in nuclei also behave as delocalized and independent fermions. This generic behavior generates analogies between metal clusters and nuclei, such as the shell structure, shapes and dipole vibration mode, fission.

Binomial Distribution

The relative intensities of the $^{63}Cu_x{}^{65}Cu_{n-x}$ compositions follows a binomial distribution (p=0.6917, the natural abundance of Cu-63): No isotope preference.

$$F(n,x) = p^x(1-p)^{n-x}\frac{n!}{x!(n-x)!}$$

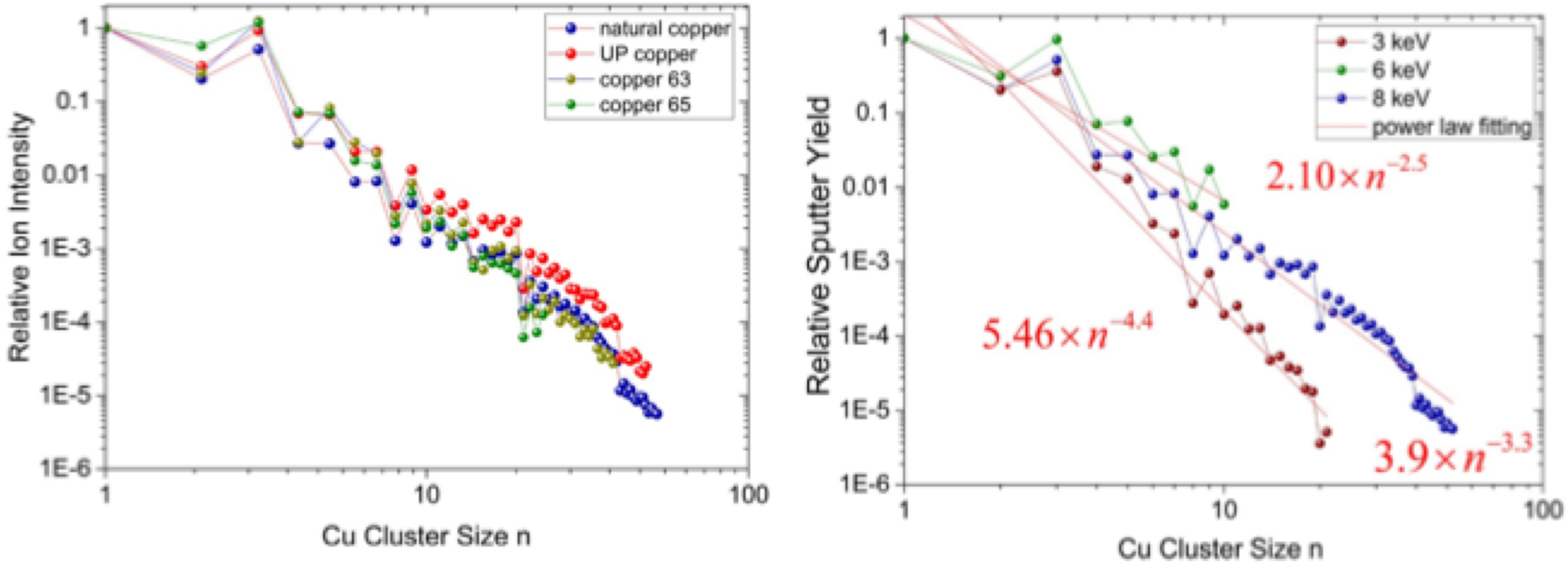




Power Law Dependence

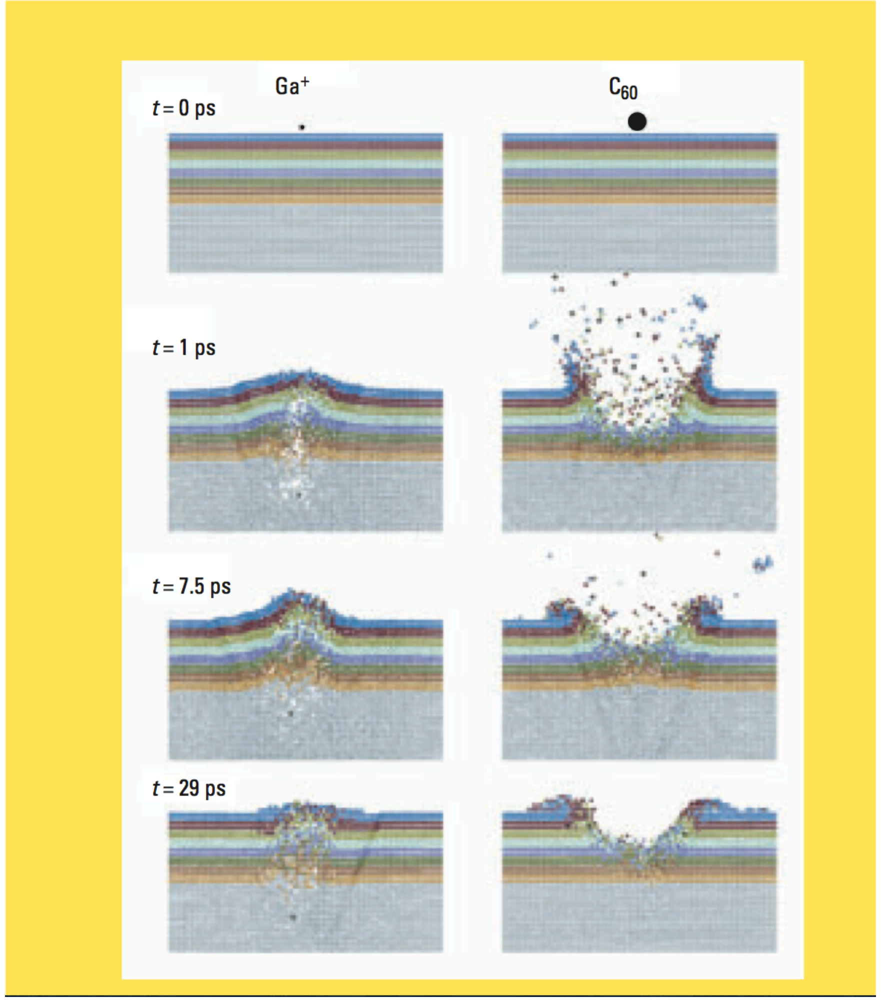
The intensity of sputtered Cu clusters decreases with size n and follows a power law dependence

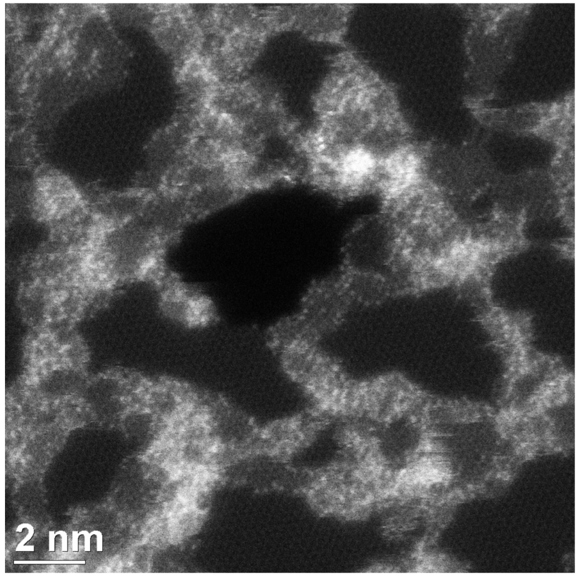
$$Y(n) \propto n^{-\alpha}$$



Applications

e.g. Biological samples, semiconductors, creating pores in one-atom thick graphene sheets.





Summary

- World class resources at ORNL: HFIR, SNS and Leadership Computing Facility
- Unique cost-effective scientific program with 2 shallow-depth experiments (PROSPECT and COHERENT) and 1 deep experiment (LEGEND)
  - Sterile oscillations
  - Standard Model tests
  - Background floor for dark matter direct detection
  - Nuclear safeguard applications
- Proposed experiment for coherent neutrino scattering from various Ge isotopes
- Efficient and ultra-sensitive analysis of actinides ifor underground physics
- Spectroscopy studies to search for efficient ionization schemes for U, Th and Pu using RILIS
- Overall efficiency of 51% for Pu, 40% for Th and 9% for U was obtained by RILIS
- We obtained a sensitivity of 0.002 fg using RIMS
- We demonstrated that RIMS is a highly selective powerful method that meet the requirements for ultra-trace detection having a high efficiency and the required sensitivity
- Studied formation of molecules and large clusters of atoms

Thank you