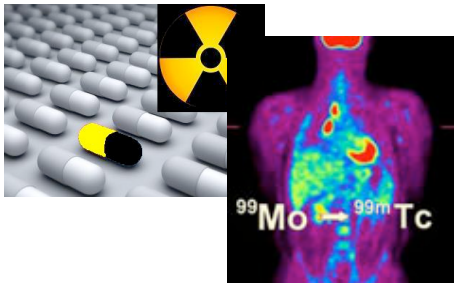
Unique Properties of Nuclei Allow the Broad NP Field to Address Many "Societal Needs"

- **Energy**
  - Fusion Research (NIF,ITER, …)
  - Fission (Reactors)

- **Medicine**
  - Medical radio-pharmaceuticals
  - Medical Imaging
  - Radiation therapy



- **Nuclear Security**
  - Nuclear Forensics
  - Non-proliferation & Border defense

- **Supercomputing**
  - Data manipulation and visualization
  - Physics of complex phenomena, …

NP Decadal Study:
Exploring the Heart of Matter (2013)

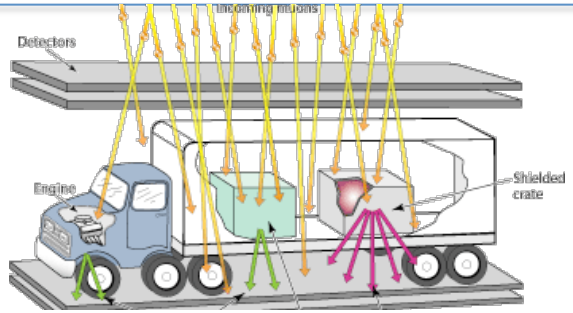
Growing number of applications from Fundamental Symmetries, Neutrinos, and Nuclear Astrophysics

Some examples…

Muon Imaging, extended to 3-D Tomography, is addressing several of Today's societal problems

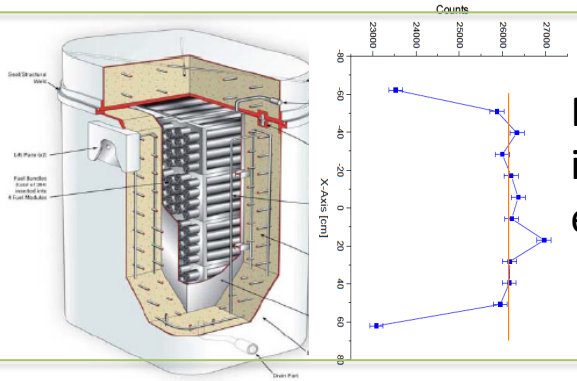
Coulomb scattering of muons from a target is approx

$$\sigma_0 = \frac{13.6MeV}{\beta cp}\sqrt{\frac{x}{X_0}}\left[1-0.038\ln\left(\frac{x}{X_0}\right)\right] \qquad X_o \sim 1/Z$$



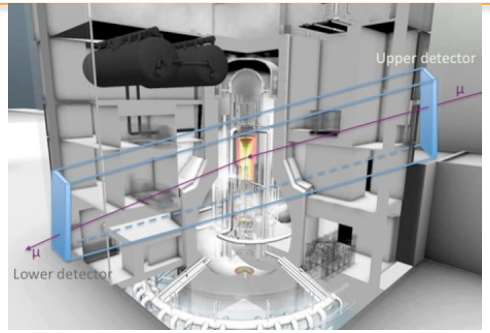
⇒ Spread of scattering angles discriminates between low and high Z material– very short time scale required

Sensitivity for material accountancy for spent fuel in Dry Storage Containers exceeds the IAEA requirements – time scales ~10 days (AECL, Canada)



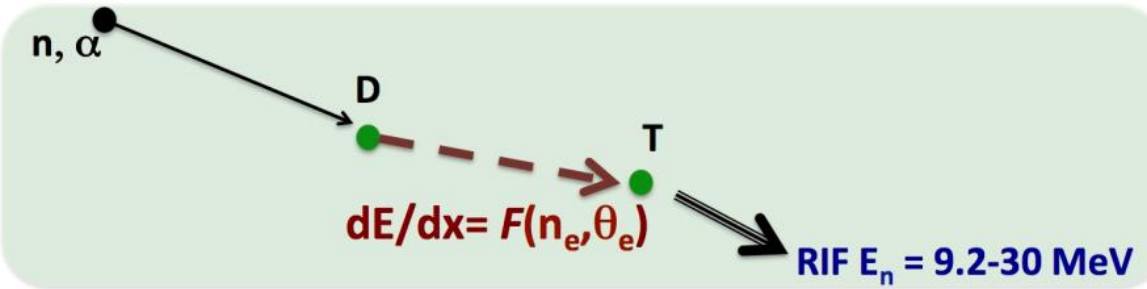
Missing fuel in one column easily detectable

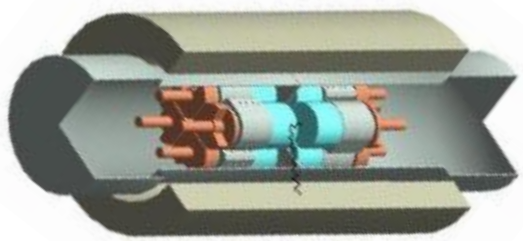
A system using muon detectors should be able to determine the locations of the molten cores of the damaged Fukushima Daiichi reactors.



Clover Detector, Originally a Prototype for Majorana, allowed 1st Measurement of Reaction-in-Flight neutrons at NIF

RIF neutrons are fusion products from in-flight fuel ions
They provide a key diagnostic of the plasma ρ, θ, dE/dx
RIFs= 10^{-4}-10^{-5} of the n-spectrum

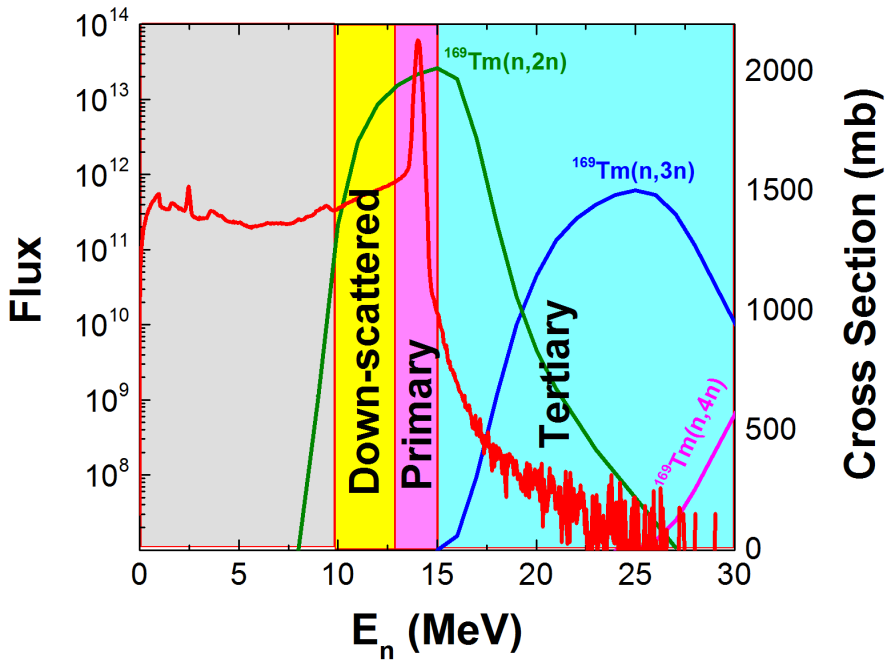




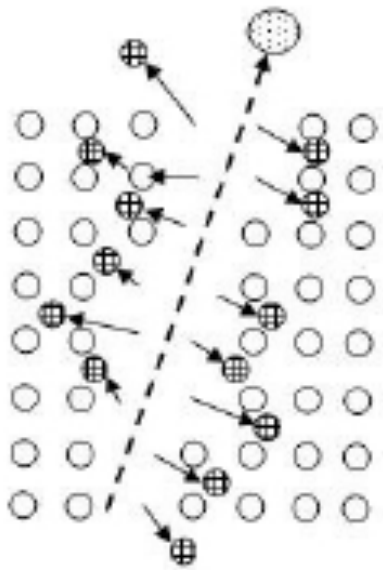
4π clover detector provides sensitivity and background suppression to measure the ^{169}Tm(n,3n)^{167}Tm reaction.

Showed that the cold fuel is a strongly coupled quantum degenerate plasma

A second clover detector is being installed at NIF to search for other low-yield reactions



Ultra Cold Neutrons
Fission Studies of Surface Sputtering and Damage in Actinides

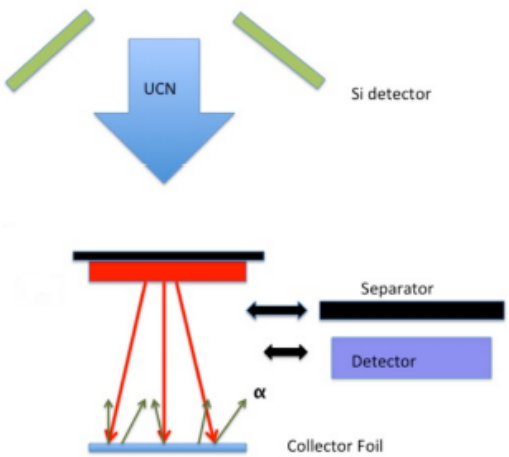


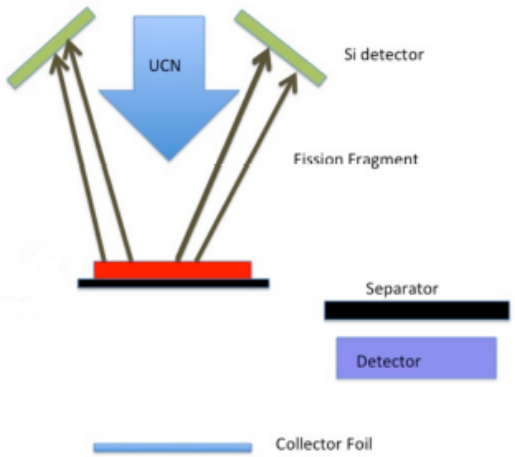
Fission fragment deposit ~200 MeV within ~ 2x10 μm on a psec timescale

⇒ Extremely dense energy deposition, coupling to the bulk material

⇒ Surface material ejection and extreme damage

The range of ultra cold neutrons make them ideal probes of surface fission damage and sputtering processes





Can control the penetration depth

Physics is strongly tied to the multi-institutional **Cimarron Project**, focused on the properties of dense, highly collisional, and strongly-coupled plasmas

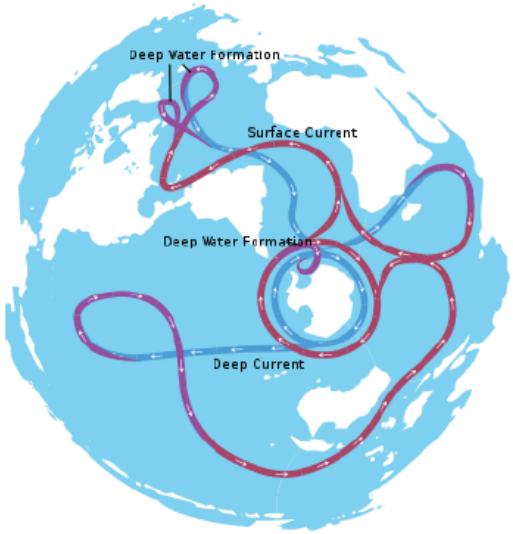
Atom Trap Trace Analysis, used similar techniques as in Nuclear EDMs searches, are addressing problems in earth and climate science

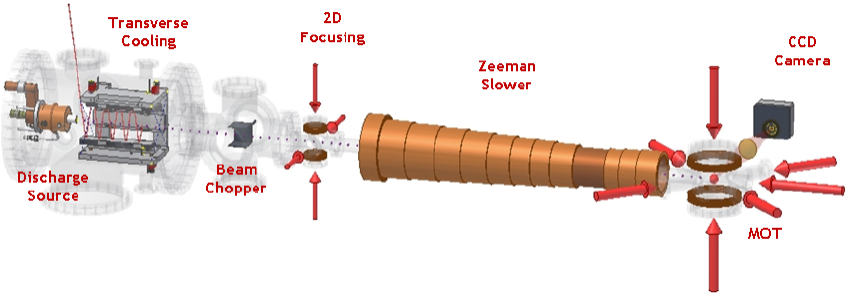
The half-life, inertness, and low water solubility of ^{39}Ar and ^{81}Kr makes them very good probes of many Earth Science problems

But 1 liter water => 4×10^{-7} decays of ^{81}Kr per hour

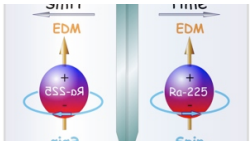
Measuring trace noble gases for:

- **Assessing groundwater availability**
- **Groundwater recharge rates**
- **Atmospheric history from ice cores**
- **Oceanic circulation**
- **Geothermal processes**





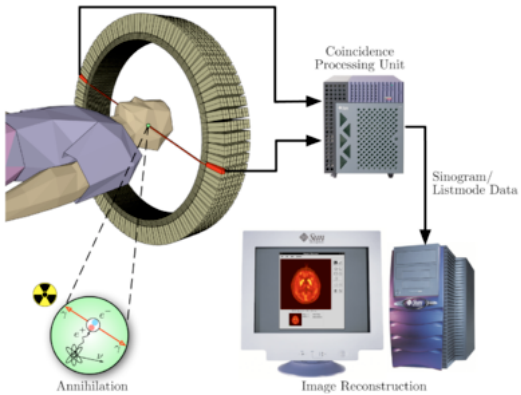
Many of these application are made possible by ATTA, which requires extremely small samples, and measure Ar and Kr isotopes to $1:10^{16}$

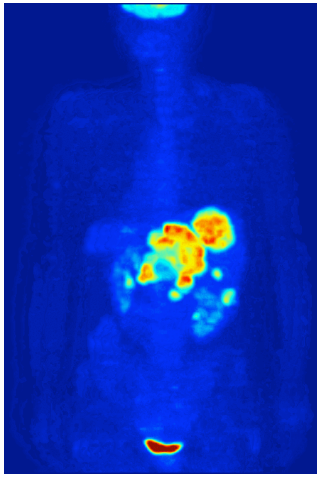


Z-T Lu, Physics Today March 2013

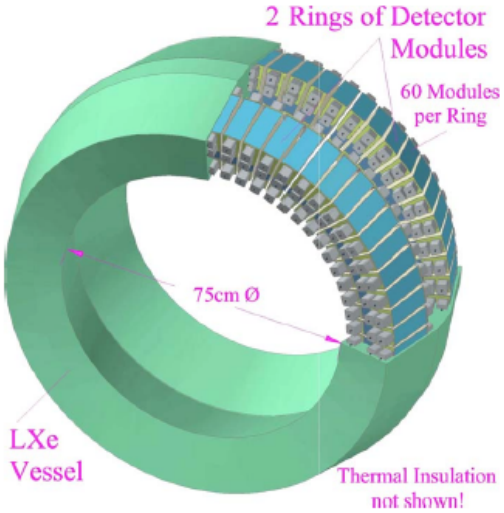
Development of LXe PET Detectors for Medical Imaging

Positron Emission Tomography provides 3D imaging of tumors by injecting ^{18}F into the patient and measuring the the back-to-back 511 keV annihilation photons



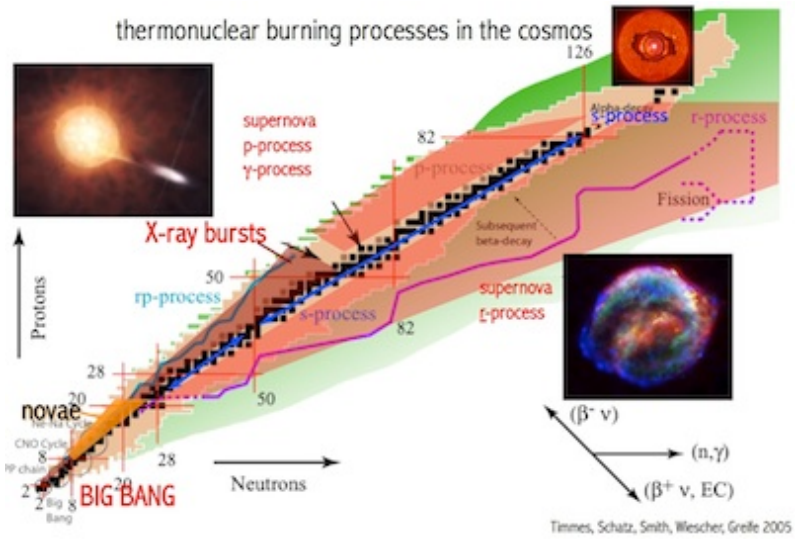


LXe based PET detectors are being explored by several groups around the world to improved on both energy and position resolution



Researchers are aiming to achieve an energy resolution of ~4% and a spatial resolution of ~ few mm = about 3 times better than commercial detectors

Nuclear Astrophysics



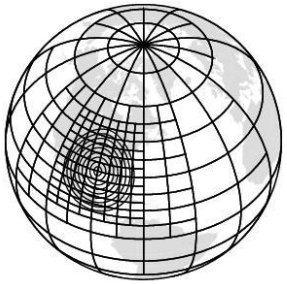
From the ORNL Nuclear Astrophysics Data Project

Data on a wide variety of nuclear processes are needed for astrophysical simulations

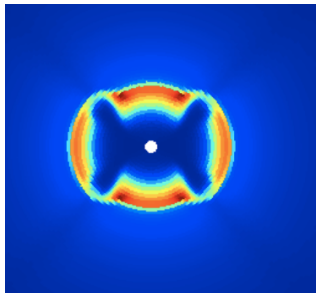
Much of this same data is crucial for applied nuclear physics

Nuclear masses, thermonuclear and neutron-induced reaction cross sections, weak decay rates, level densities, beta decays, fission yields, …

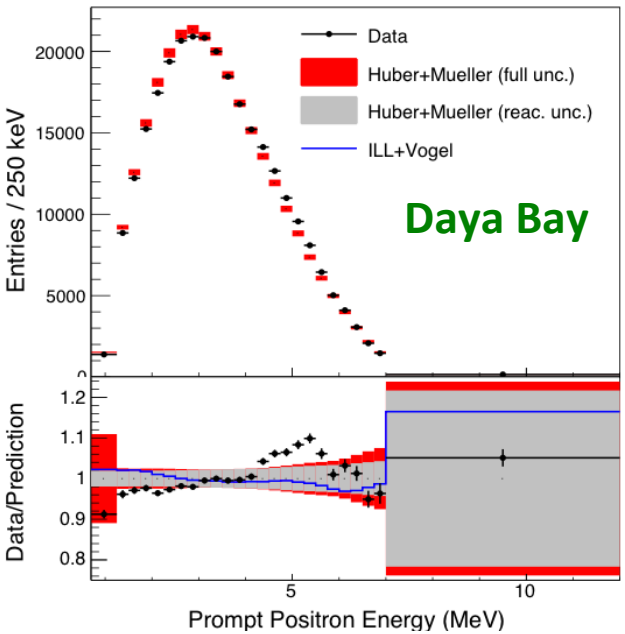
Computational Techniques from stellar formation and stellar explosion codes have lead the way in a number of areas of applied nuclear burn codes.

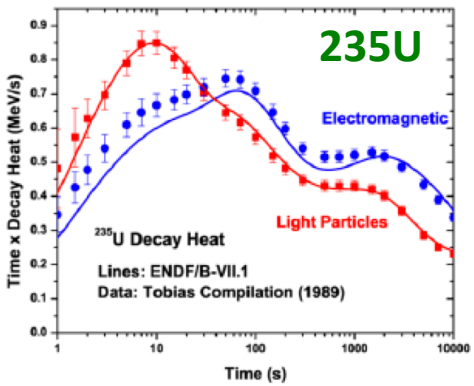


Example: LA-Compass Code (designed for galaxy and stellar formation) shows that small (~10^{-4}) perturbations in the drive conditions of NIF capsules result in huge distortions at large radii of convergence ($R:R_0$=1:30)

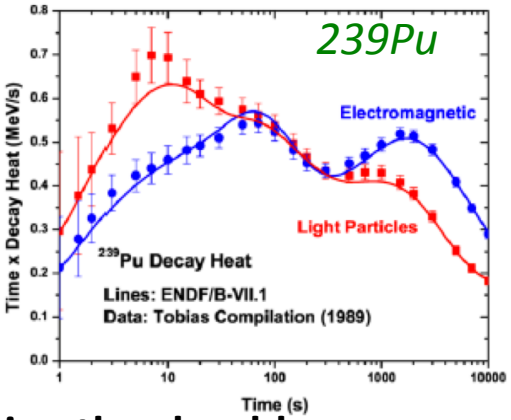


Reactor Neutrino Experiments
-Near Detector Spectra Testing/Constraining Nuclear Database

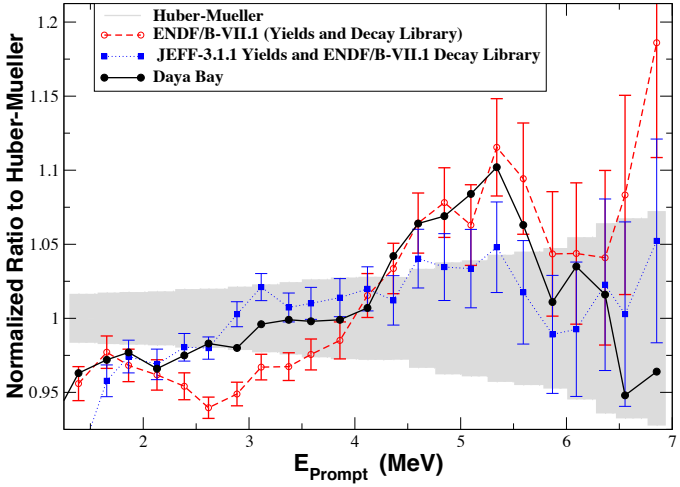




Decay Heat



Many of the nuclei dominating the shoulder contribute significantly to reactor decay heat

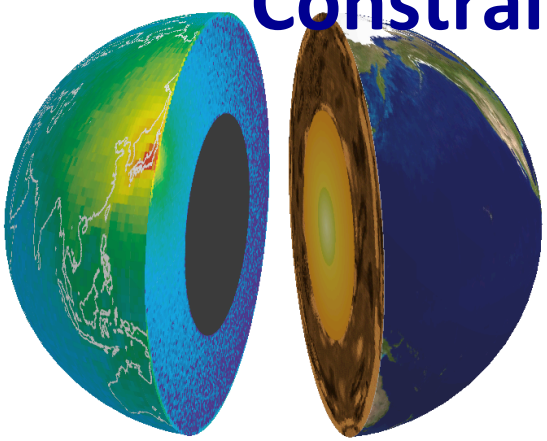


Databases vs Daya Bay

Different databases (ENDF vs JEFF) recommend different fission yields for some dominant nuclei in the bump, e.g. ^{96}Y

The neutrino measurements are placing unique constraints on the evaluated fission yields

Geo-neutrinos
Constraining the Earth's Heat Source

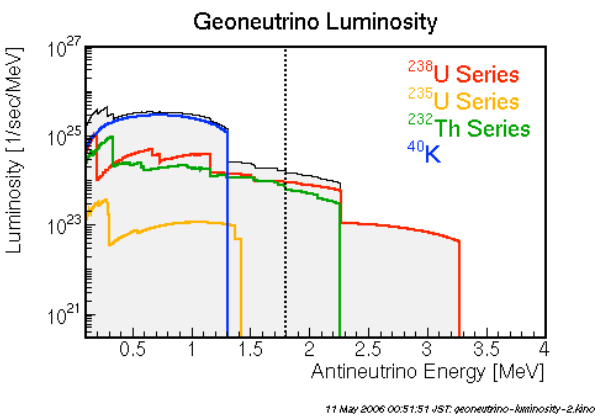


The Earth's internal heat drives several important dynamic processes, such as plate-tectonic motion, earthquakes, and volcanic eruptions.

Total energy loss =46+/-3 TW

The rate of heat loss from the Earth is a balance between cooling of the mantle, energy loss from the core, and radiogenic production.

The budget between the core, mantle, and crust is unknown



Radiogenic sources: K, U , Th

^{238}U and ^{232}Th have maximum E_ν> 1.8 MeV - detectable

Borexino and KamLAND data:

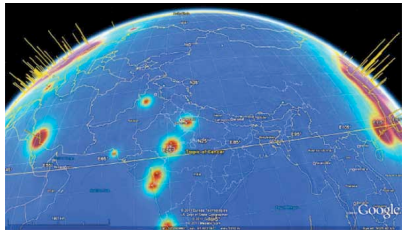
- U/TH source 29+/-9 TW
- Core radiogenic source < 3 TW
- Mantle radiogenic source estimated to be small
- Future experiments with directional information would be ideal

Many other Applications

- **Neutron-Diagnosed Subcritical Experiments (NDSEs) will reach unprecedented precision in Nuclear Criticality Experiments**
  - **made possible by the gamma-ray detection developments from the n+p→d+γ PNC experiments**

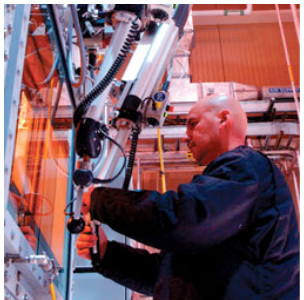
- **Watchman**

  Water Cherenkov neutrino detector to monitor reactors



- **Enhanced detectors for nuclear non-proliferation**
  - **Many neutrino detector designs ideal, e.g., MiniBoone and LSND**
  - **Liquid Argon and Xenon Detection for WIMP searches optimized to quantify neutron backgrounds**

- **Strong collaborations with the Isotope Program**
  - **E.g., 169Ho**



From the Education and Innovations Town Meeting, 6-8 Aug, East Lansing, MI

Recommendation

The interface between basic research in nuclear physics and exciting innovations in applied nuclear science is a particularly vital component that has driven economic development, increased national competitiveness, and attracts students into the field. It is critical that federal funding agencies provide and coordinate funding opportunities for innovative ideas for potential future applications.