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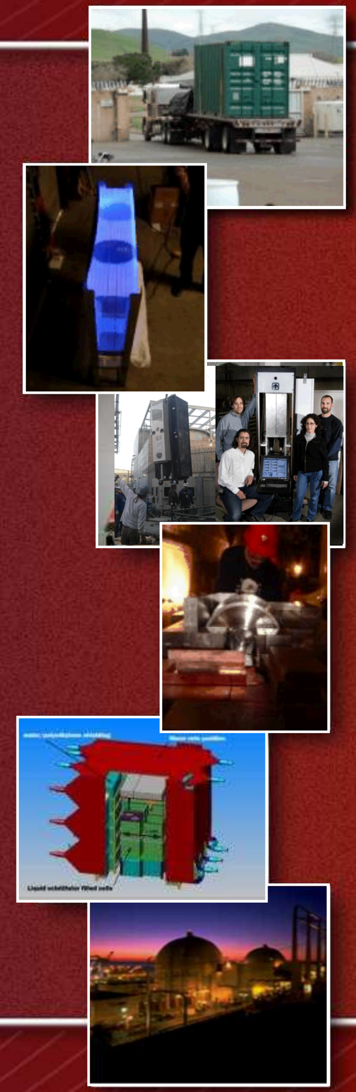

# Application of Antineutrino Detectors for Reactor Safeguards and Security

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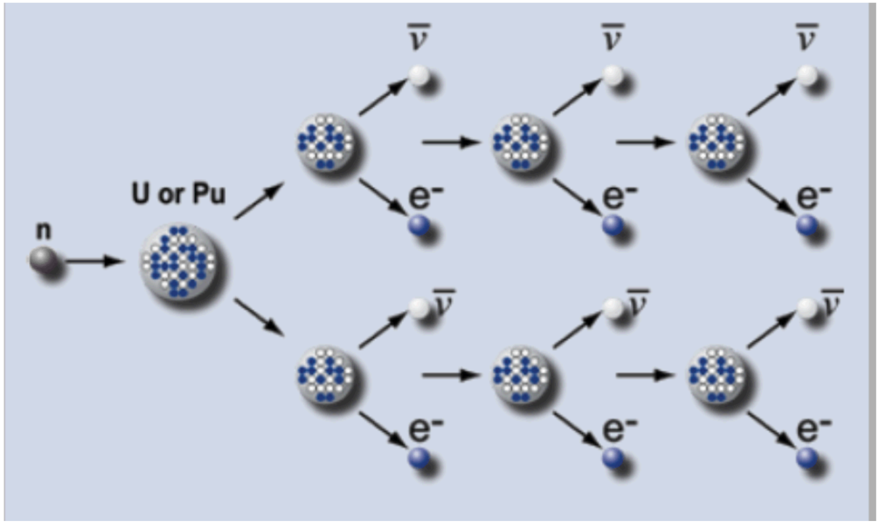
# Why Antineutrinos?




- Antineutrinos are produced after any fission event
  - Approximately 6 antineutrino for each fissioning U or Pu atom
  - Energy of antineutrinos are dependent on source atom (i.e. information on fissile content can be extracted)
- Antineutrinos are highly penetrating and detectable at very long ranges
  - Antineutrinos are detected from astrophysical sources
- The antineutrino signal is effectively impossible to shield, disguise, or falsify
- Provides a unique capability for detection or monitoring that is non-intrusive, remote and unambiguous

# Antineutrino Sources

- Reactors
  - Reactor power directly relates to size/cost of detectors (smaller reactor = larger detector)
    - Range of power covers 2-3 orders of magnitude
  - Operational history can verify declarations and/or look for anomalous intervals where fuel could be exchanged
  - Fuel composition can be determined to verify fuel loading, fuel cycle, plutonium content, etc.
- Explosions
  - Short/intense burst of antineutrinos can be easier to see vs. continuous backgrounds
  - Signal is very weak compared to continuous reactors (1kt ≈ 50 MW-days)
  - Antineutrino existence is unambiguous signature of criticality
- Sub-critical items
  - Low activity implies only gross information and requires large detectors
  - Ex: monitoring a spent fuel pond, one could see an entire core being discharged, but not individual fuel elements (245 tons $^{238}Pu \approx 1\ W_{th}$)

# Handheld Neutrino Detectors?

**For a perfect 100 $cm^3$ detector at 1 meter from a 3 GW reactor:**

**~ 2 x $10^{-2}$ interactions/second**

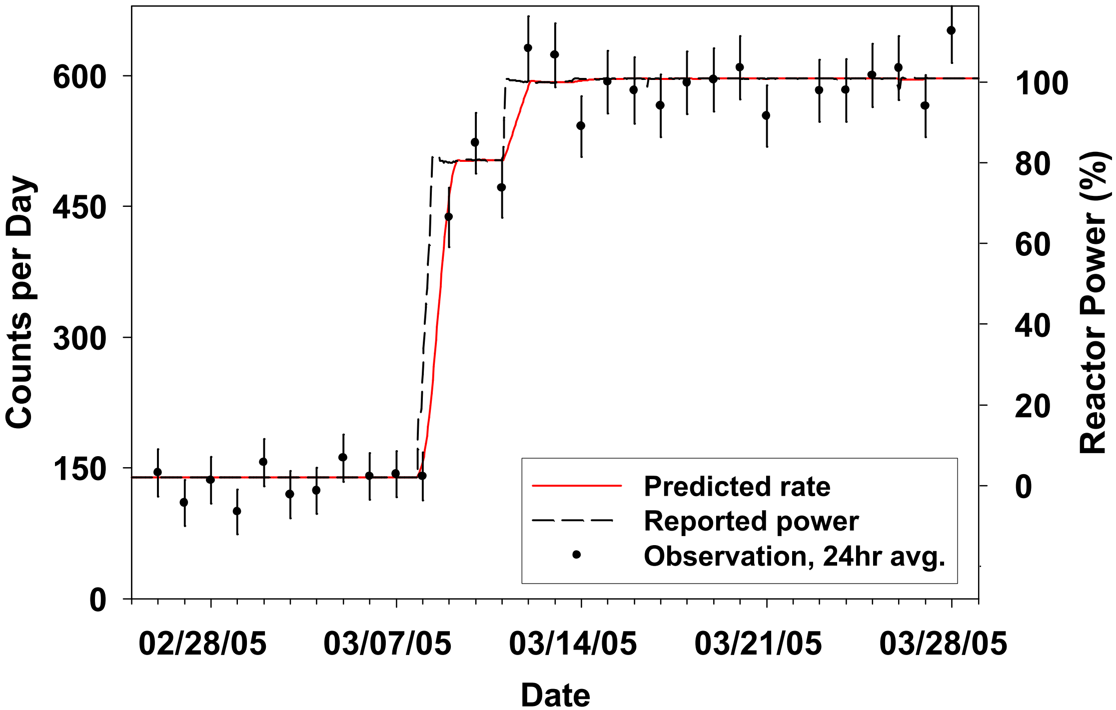
**At a more realistic 20 meters:**

**~ 5 x $10^{-5}$ interactions/second**

**Theoretical cross-sections such as coherent elastic scattering could only add ~3 orders of magnitude. Much higher is ruled out by supernova dynamics.**

## Highly Unlikely!

# Reactor Power Monitoring using <u>only</u> $\bar{\nu}$




**Timescale**

**1 – 3 Hours:**

**Sudden changes in operational status (on/off)**

**1 Day:**

**Large power changes**

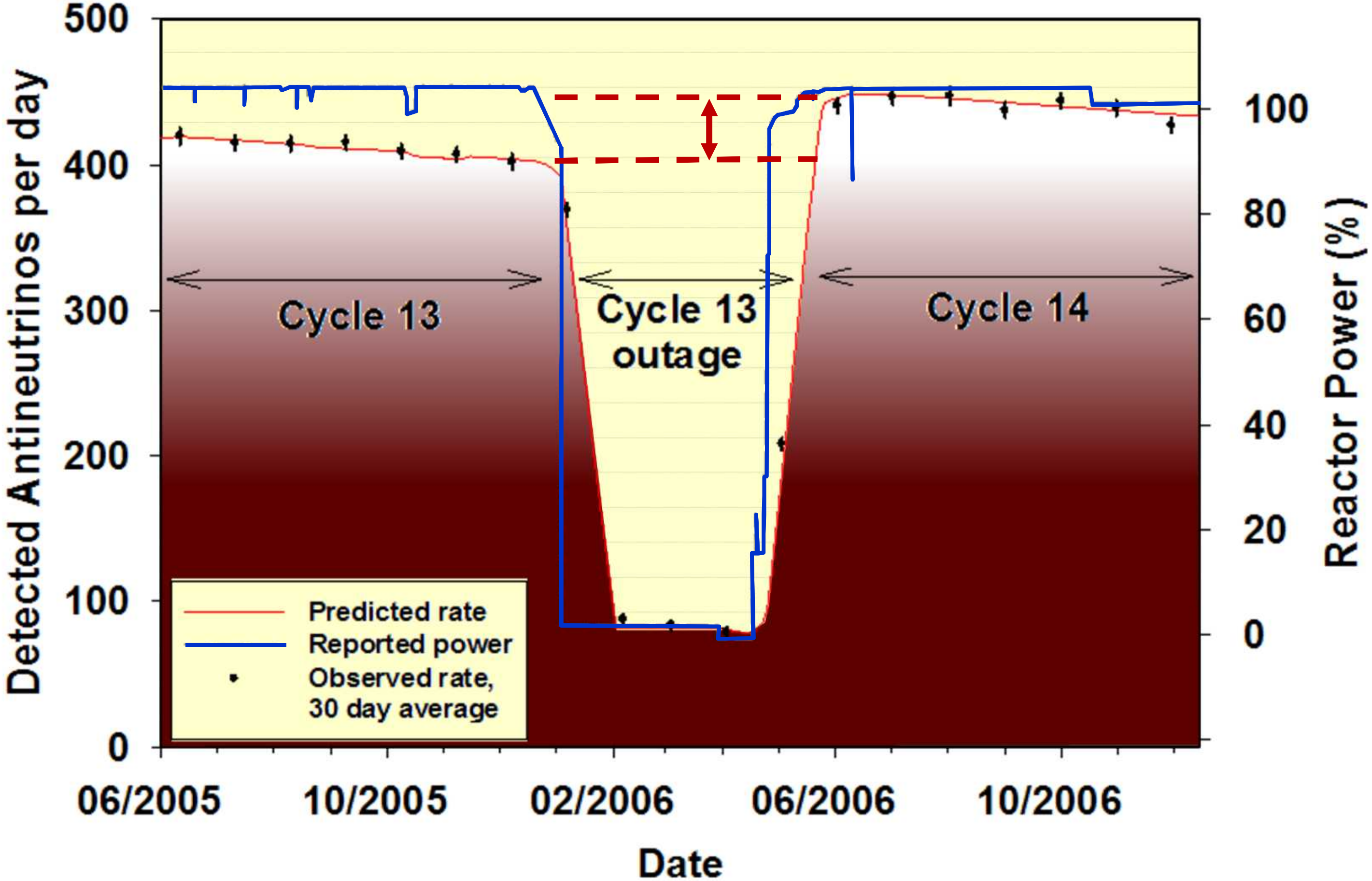
**7 Days:**

**Relative thermal power measurement (2 – 3%)**

**Large power changes are readily observed with no physical connection to the plant**

# $\overline{\nu}$ Provides Information on Fuel Composition

## Standard Refueling is Clearly Visible

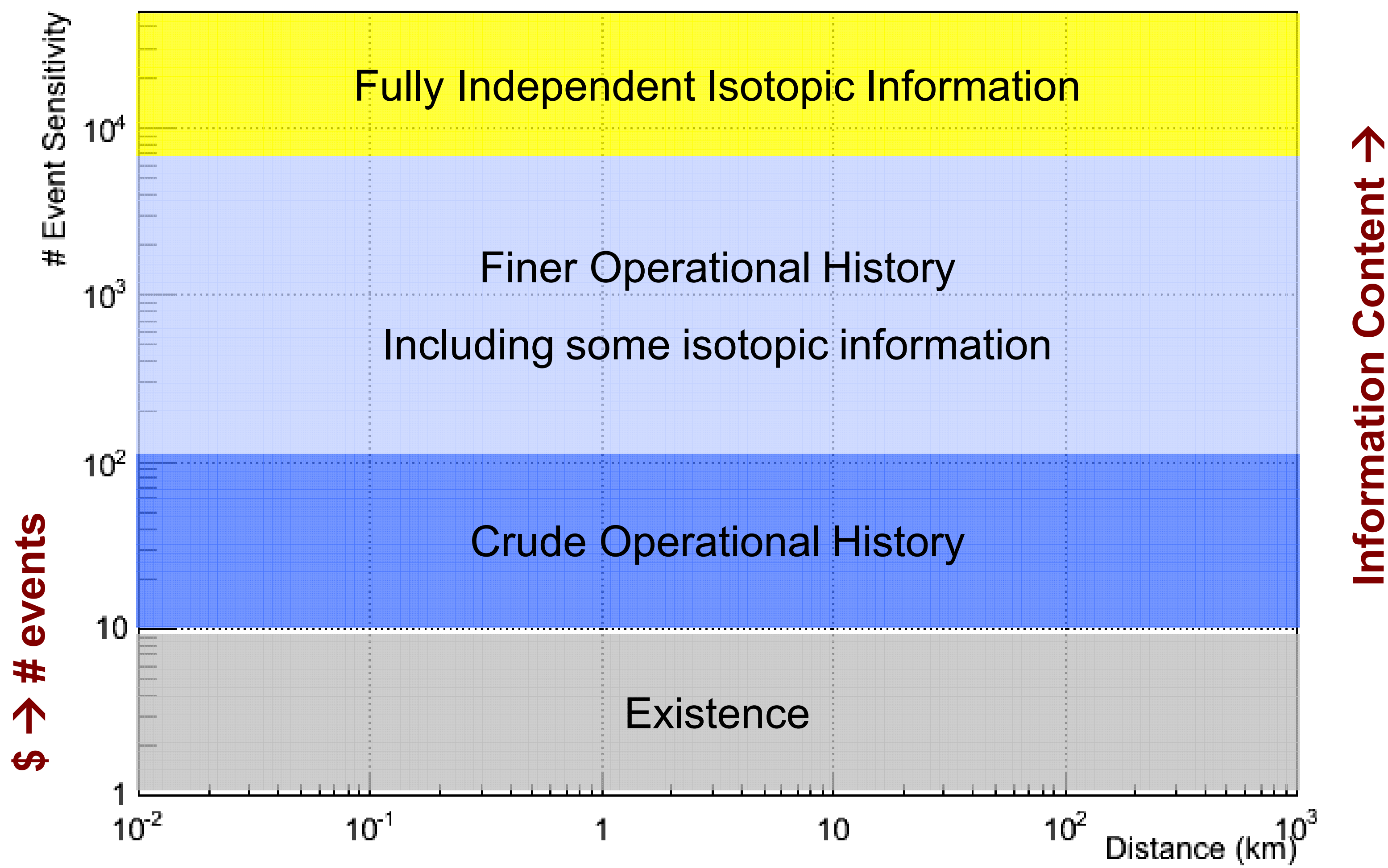



**Sensitive to undeclared removal of 70 kg $^{239}$Pu**

# Information Content

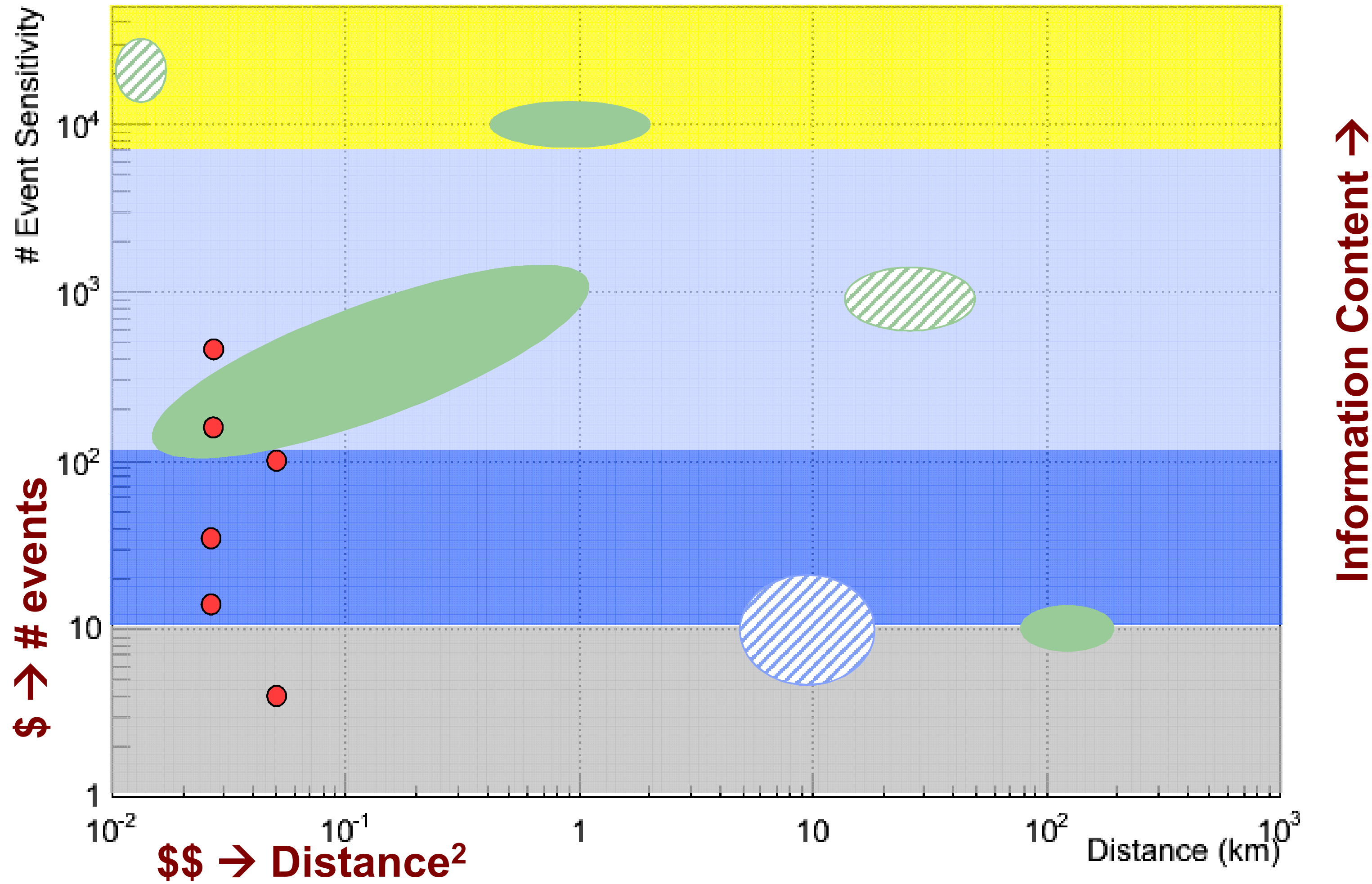
- **Exclusion Zone (i.e. Existence):**
  - **Sensitivity to small signals over long times**
  - **Of order 1-10 events per day change?**
  - **Trigger condition could be on order of 30-90 days, allowing S:B of 1:3 or 1:4**
- **Verify Declarations (i.e. operational history):**
  - **Sensitivity to daily changes in operations (on/off)**
  - **Of order 10-100 events/day change**
  - **Trigger condition needs to be on order of 1 day, allowing S:B of up to 1:4 but probably closer to 1:2 or 1:1**
- **Fissile Characterization (i.e. reactor fuel composition)**
  - **Sensitive to neutrino spectrum within "reasonable" time**
  - **Requires an integral of ~10k events within 1-30 days**
  - **Requires good characterization of backgrounds and probably S:B of better than 10:1**

# Antineutrino Applications Space




$$ → Distance²

# The Known World



# Applications Space

- Cooperative
  - Part of treaty negotiations – could be seen as direct monitoring and verification or just as a confidence building measure
  - Access to the facility is available -> short baseline is an option
  - Additional information can be obtained by using complementary technologies
- Unilateral
  - Need for clandestine monitoring/detection implies long standoff (> 50km)
  - Minimal information available due to low detectable rates

# Central Conclusions of the Study

- Non-cooperative applications require long-standoff that presents a significant challenge
- Cooperative reactor applications have credibility but it is a disruptive technology that requires a new paradigm for safeguards
  - No likely end-user requests until current system fails
  - Needs multilateral demonstration of new safeguards paradigm to be fully understood and accepted
- Cooperative applications to weapons tests (SCE or Low-Yield) is worth further investigation

# Cooperative Reactor

- Cooperative = close
- Potentially part of a re-vamped NPT
  - provides independent operational history and could eliminate need for inspectors
- Potential application to new treaty negotiations
  - Information on fuel composition could be relevant to identification of types of core composition (LEU/HEU)
- Implementation requires a change in paradigm
  - Not currently part of the established toolbox means that there is not much willingness to re-design how safeguards are applied
  - Not considered an option for new scenarios either
  - Will likely only come up if there is an un-solvable problem
    - unlikely given current experience

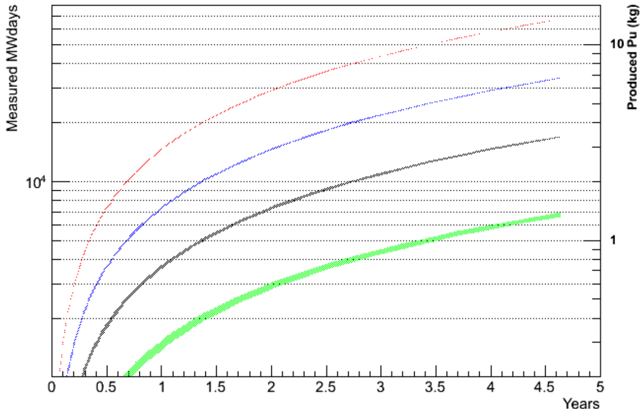
# Specific Near-Field (Cooperative) Applications

- **Monitoring of reactors under future safeguards**
  - Inventory tracking for future reactor cycles (Th, MOX,others.)
  - Confidence Building Measures or Continuity of Knowledge for reactors under future safeguards implementations
- **Applications to special-case bi/tri-lateral agreements**
  - US/Russia Plutonium Management and Disposition
  - Potential Fissile Material Cutoff Treaty
- **US National Capability**
  - Transportable post reactor meltdown criticality monitor
  - Challenge to CTBT based On-Site Inspections at the NTS

# Antineutrino detector at Arak

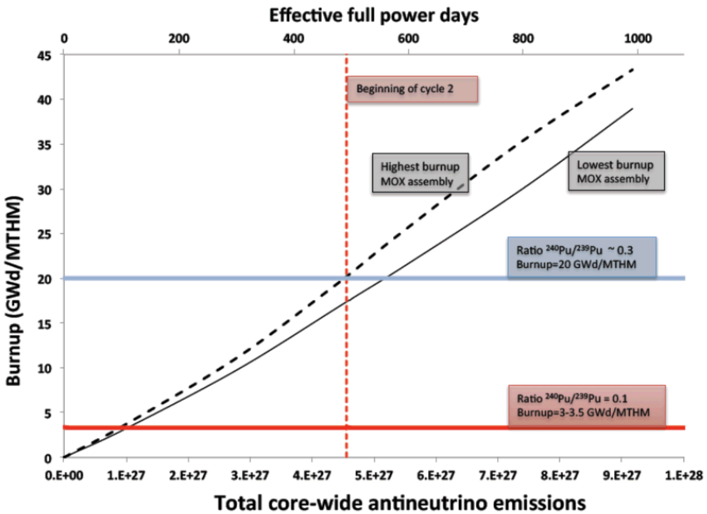
- Major concern is the ability to produce plutonium
  - Reconfiguration to LEU would reduce quality of Pu
- Science engagement could be seen as a key advantage
- Direct inventory measurement and continuity of knowledge are unique features

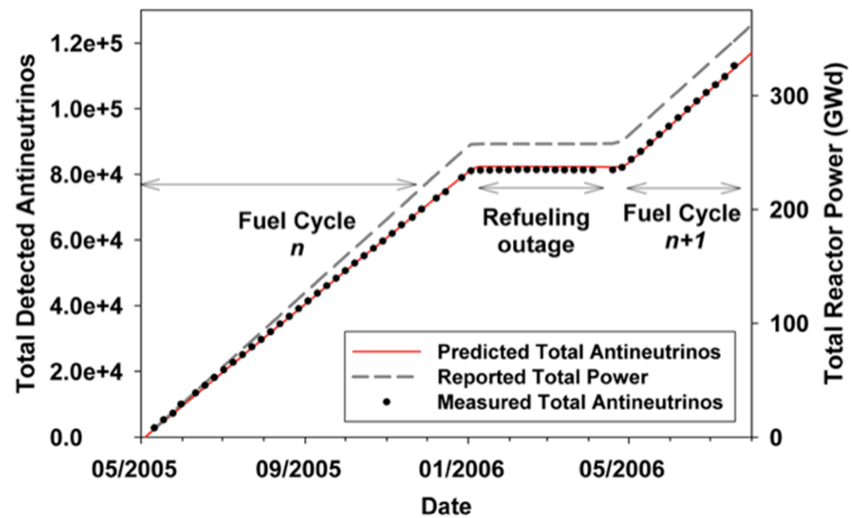
Could provide direct information on total Pu produced over lifetime of reactor




- However, Iranians don't want anything "different" from existing implementations of IAEA-SG
  - Demonstrates need for fully developed capability and policy engagement for future situations

# Plutonium Management and Disposition Agreement (PMDA)




- PMDA requires verification that the burnup of the irradiated WGPu MOX assemblies meet specific standards
- Verification of integrated fuel burnup can be achieved with high-confidence by antineutrino monitoring
  - Antineutrinos provide direct evidence of core fissions
  - Spectra could provide even more information
- IAEA insisted on implementation with existing technologies
  - led to an absence of independent verification

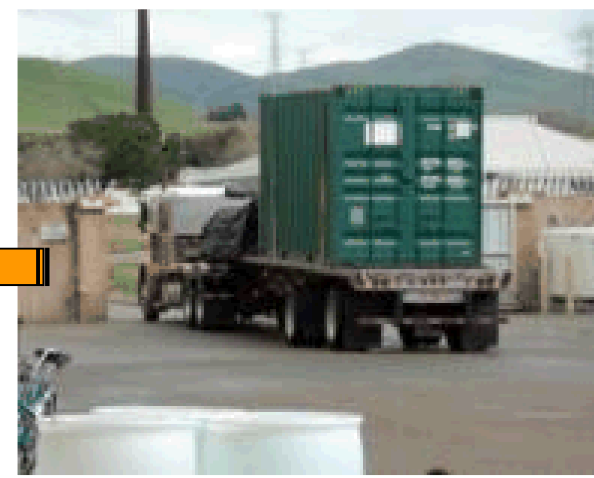
# Fissile Material Cutoff Treaty (FMCT)

- Use of HEU for naval reactor cores is presumed to be un-verifiable
  - Can monitor the removal of HEU from a safeguarded stockpile, but military sensitivity precludes further inspection once the core is assembled and installed
- Antineutrino spectral measurements could provide clear evidence of HEU vs. LEU cores in-situ from outside of the vessel
  - 50-100 ton detector could provide sufficient information within 12-24 hours of operation
  - Only need one or two in the world for verification
- FMCT is always 20 years away because of “unsolvable” issues
  - Could we provide a visionary of a path forward?

# Reactor Meltdown

- Loss of reactor instrumentation creates uncertainty in post accident response
  - Chernobyl was known to remain critical while Fukushima was unknown for several weeks
- Current disaster response relies on detecting secondary emissions, such as iodine, which can be difficult to detect in a high-radiation environment and are highly scenario dependent.
- A single transportable detector system could be brought in within 24 hours and provide sensitivity down to ~1MWth (possibly lower)

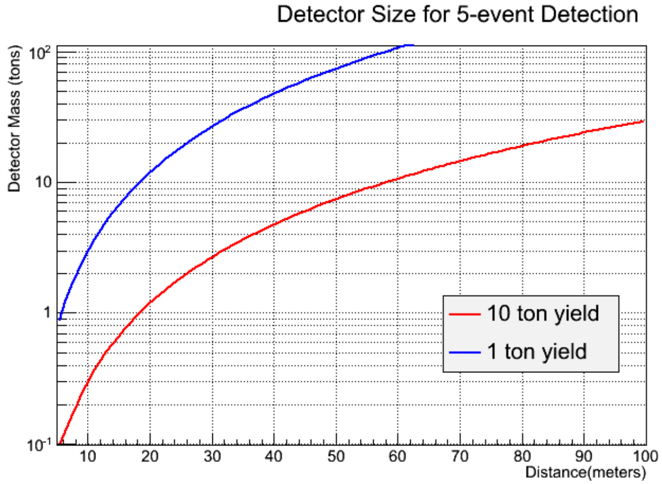
*Fukushima post Tsunami*



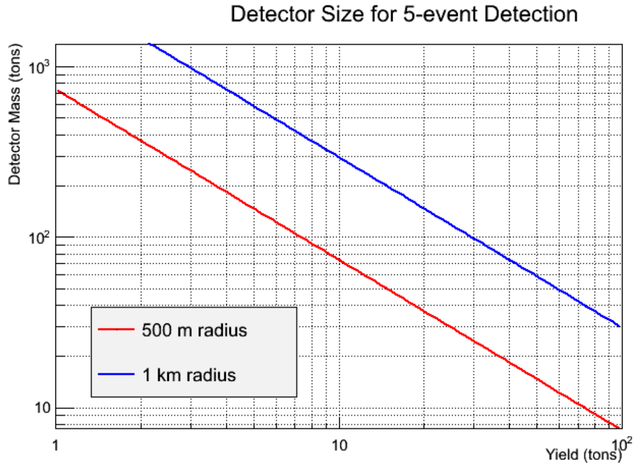
# Cooperative Nuclear Test Monitoring

- Can be used as a threshold to verify that no yield above some value has been achieved
  - Antineutrinos are the unambiguous signature of a nuclear device
  - Monitoring could be performed in close proximity to tests, providing as low as kg scale thresholds
- Other technologies do apply but have issues
  - Existing capabilities have more ambiguity:
    - Seismic gives "explosive" yield, not nuclear
    - Radio-isotopes are also the result of medical isotope production
  - Neutrons would provide "too much" information

## Single Cavern Monitoring



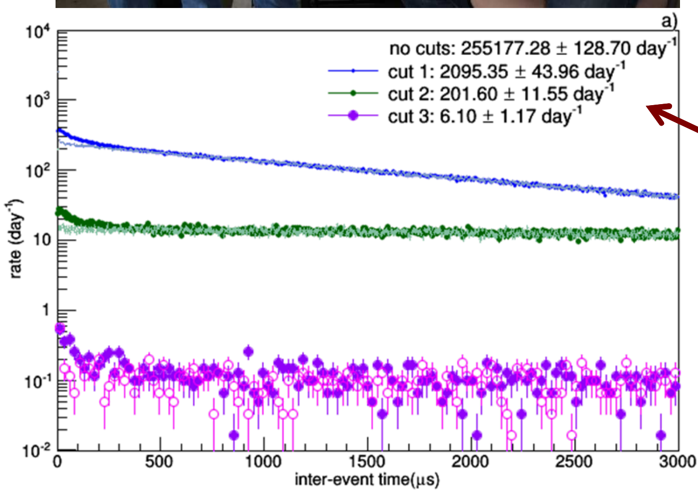

## Tunnel Complex Monitoring



# What Would It Take?

- Implementation requires a change in paradigm
  - Not currently part of the established toolbox means that there is not much willingness to re-design how safeguards are applied
- Requires fully proven technology
  - More than just proof-of-principle, requires a fully packaged detector and a demonstration that doesn't require a visionary leap

# SNL Near-Field Monitoring




- **Demonstrated capability for short and long term relative monitoring of power, operational status, and fissile content in reactors**
- **Exploring potentially broader applications space**
  - **Antineutrinos provide a capability to detect and monitor any man-made nuclear fission process**
    - **Post disaster (reactor meltdown) characterization**
    - **Unilateral Monitoring**
    - **Treaty verification (CTBT, FMCT, PMDA)**
- **Very encouraged by performance of Segmented Scintillator prototype**
  - **This technology is focused on reducing the overall footprint and enabling a transportable detector that can be deployed in high-background or unshielded locations**
  - **Demonstrated rejection of backgrounds of 5 orders of magnitude even without an external shield**
    - **Data from unshielded deployment at SONGS showing rejection of backgrounds as successive selections are applied**
    - **Patent application filed based on recent improvements**

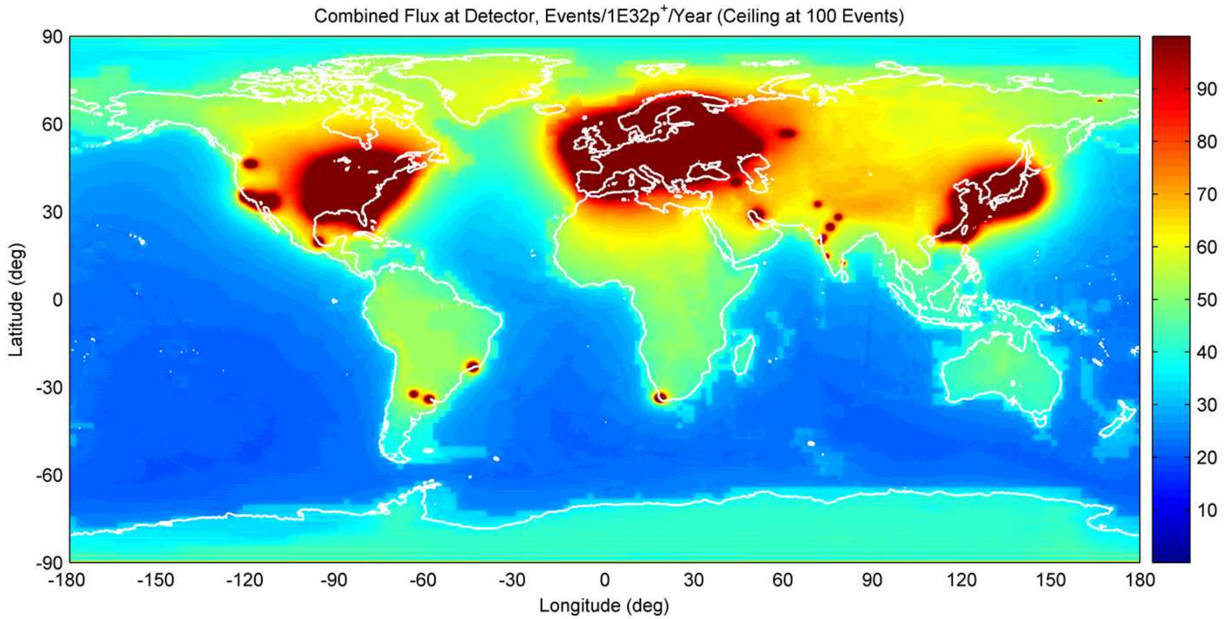
# Future Directions

- Relevant R&D
  - Segmented detectors for improved background rejection and robust aboveground operation
    - Small scale Lab studies to confirm background modeling
    - Reactor deployment to confirm performance
    - ACRR deployment to confirm NuDet performance or reactor meltdown monitoring
- Relevant Policy Engagement Needed
  - Work with academics to further develop policy and applications studies
  - Expand contacts with OGAs such as Center for Nonproliferation Studies
  - Work with international community to create collaborative deployment example of “over-the-horizon” safeguards paradigm
    - Requires fully proven technology: more than just proof-of-principle, requires a fully packaged detector and a demonstration that doesn’t require a visionary leap

## BACKUP SLIDES

# Unilateral Reactor

- Unilateral = long standoff (> 50km)
  - Existing reactor backgrounds complicated matters




- What's the goal?
  - Detection of unknown reactor = major failure of IC
  - Monitoring of reactor operation has major competition
    - Also limitations due to existing reactor backgrounds
    - Antineutrino monitoring does offer some unique benefits, but since a detector is not mobile, it has to be applied to a single source.

# Unilateral Nuclear Test Detection

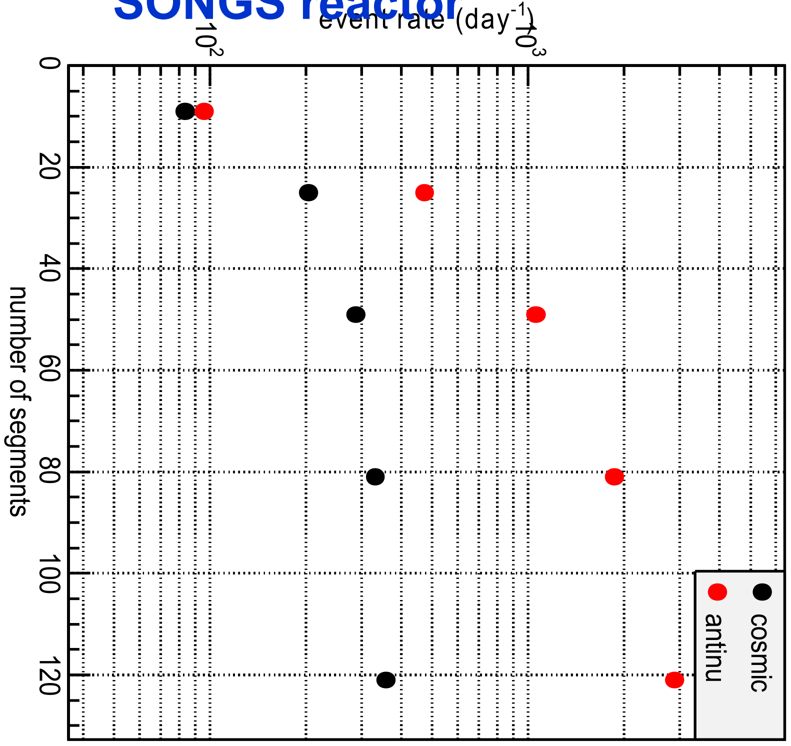
- High instantaneous rate does not equal high counts
  - 1 kton = 50 MWdays at a reactor
  - At ~100km it would require a 100kton detector to have a 99% probability of detecting at least 1 event from a 1 kton test
- Most applications need greater standoff and sensitivity to lower yields
  - At these sizes (> 10 ktons) detectors are not mobile

**Practical limits make this unreasonable**

# Simulations Show Possibilities for Aboveground Deployments

- Simulations suggest major improvements are possible
  - Expect efficiency for antineutrino detection to improve as more segments are used
  - Expect background rejection to improve as more segments are used
- Next step would be to validate these results with laboratory tests

**Simulation of aboveground performance 25m from SONGS reactor**




**Simulated backgrounds for 4-segment detector were roughly consistent with 2010 SONGS measurements**

# Science vs. Safeguards

- Need to develop an understanding for what circumstances warrant bringing in Basic Science collaborations for SG applications
  - Potentially engages local scientific community
  - Provides access for technical assets
  - Can provide long-term continuous operation
- However, scientific community wants "cutting edge" research
  - Desires for multiple PhD topics may lead to a lack of consistency for a single monitoring goal
  - Tend to exhaust a field/facility within 5-10 years leading to a severe reduction in support
- Existence proofs of long-term stability suggest limited support
  - In waning years, participation reduces to only a few active professors
  - Funding from Office of Science tends to be reduced to levels that don't encourage new students/faculty to engage