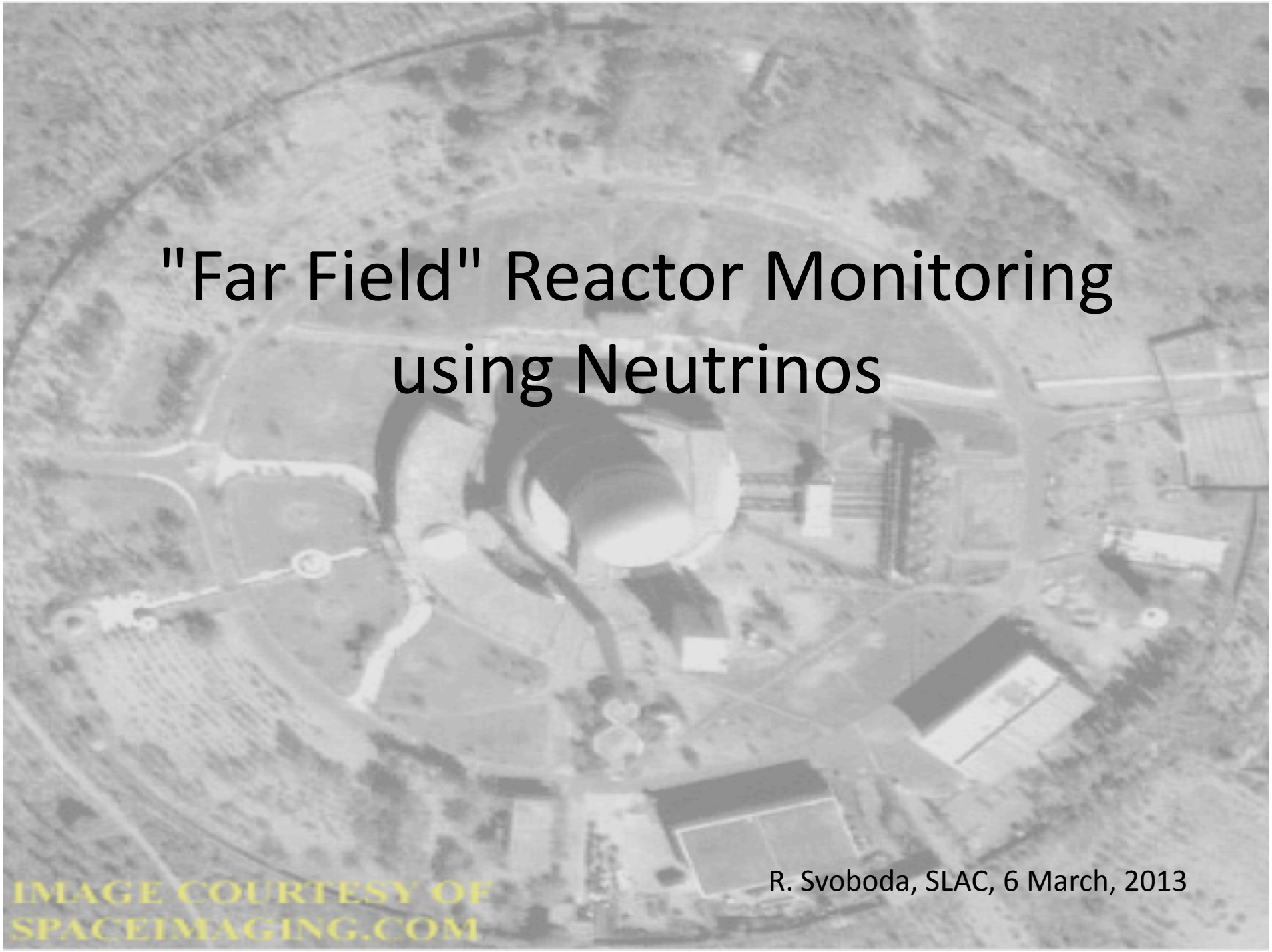
"Far Field" Reactor Monitoring using Neutrinos



R. Svoboda, SLAC, 6 March, 2013

The monitoring of weapons production reactors at long distance is a national security initiative. Also important for future arms control treaties.

National Nuclear Security Administration

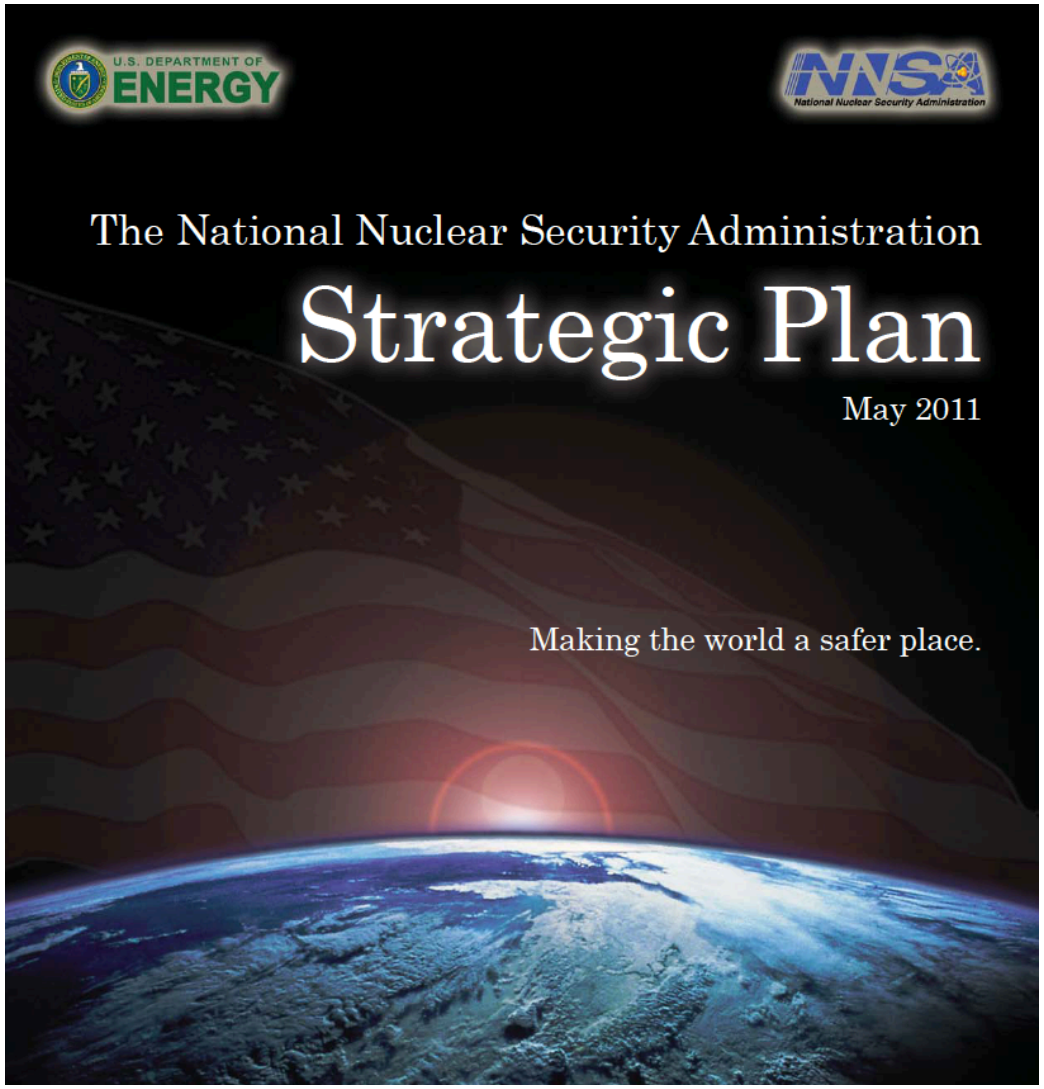
Select Initiatives

Strengthen Nuclear Safeguards:

- By 2013, deploy new non-destructive assay technologies to directly quantify plutonium in spent fuel.
- By 2016, demonstrate remote monitoring capabilities for reactor operations.

Counterterrorism and Nuclear Threat Response:

- By 2012, hold joint nuclear facility or transportation security exercises with two established foreign partners.
- By 2012, establish new partnerships with two additional foreign partners.
- By 2012, complete nuclear materials and energetic materials characterization and prioritization, initiate development of new nuclear counterterrorism render safe tools, and conduct the 100th counterterrorism tabletop exercise.



This is a different challenge from "Near Field" technology

Plutonium Production

$^{238}U + n \rightarrow {}^{239}U + \gamma$

$\hookrightarrow {}^{239}Np + e + \nu$ (23.45 m)

$\hookrightarrow {}^{239}Pu + e + \nu$ (2.36 d)

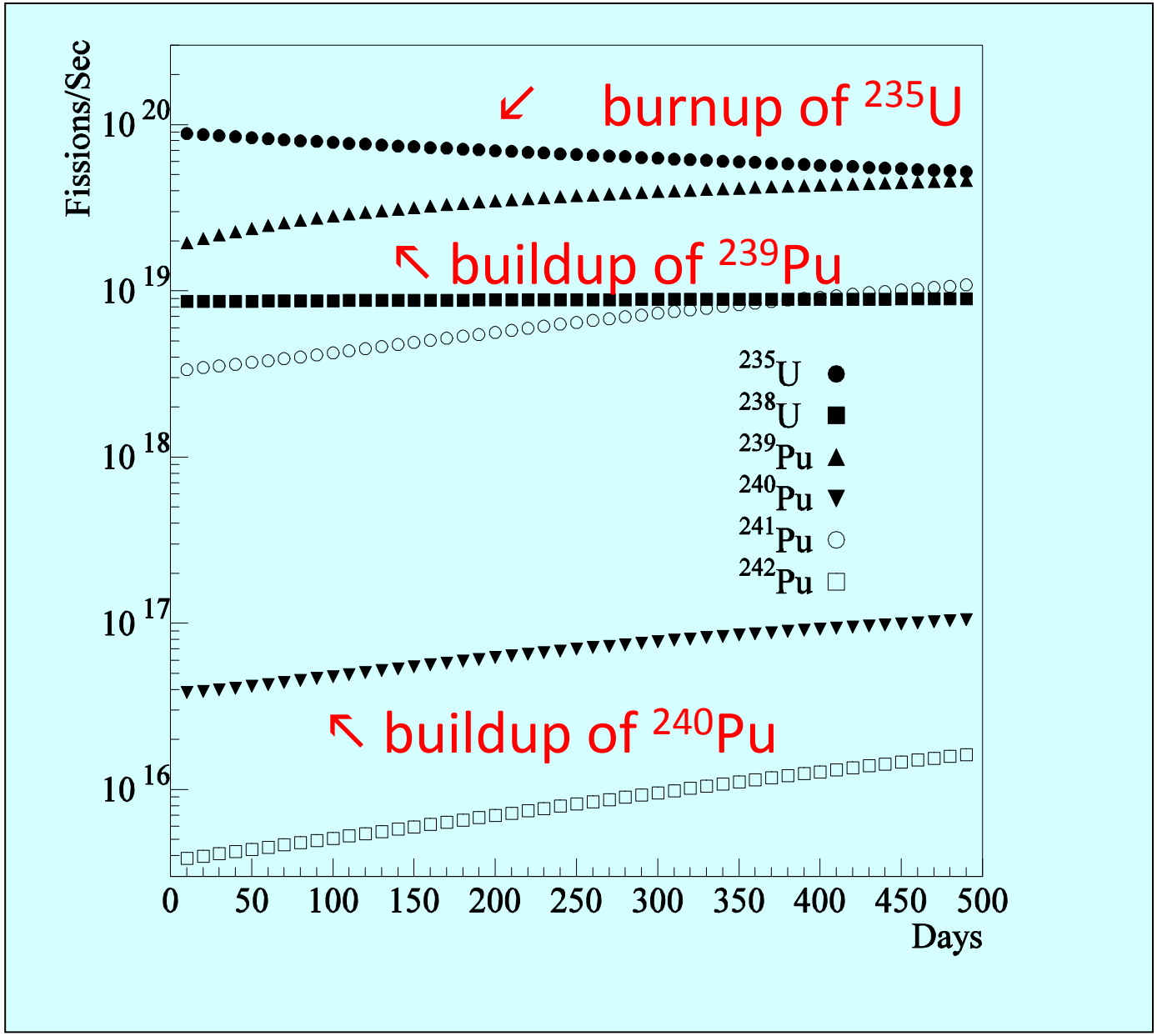
$^{239}Pu + n \rightarrow {}^{240}Pu + \gamma$ (~ 30%)

$\rightarrow$ fission (~ 70%)

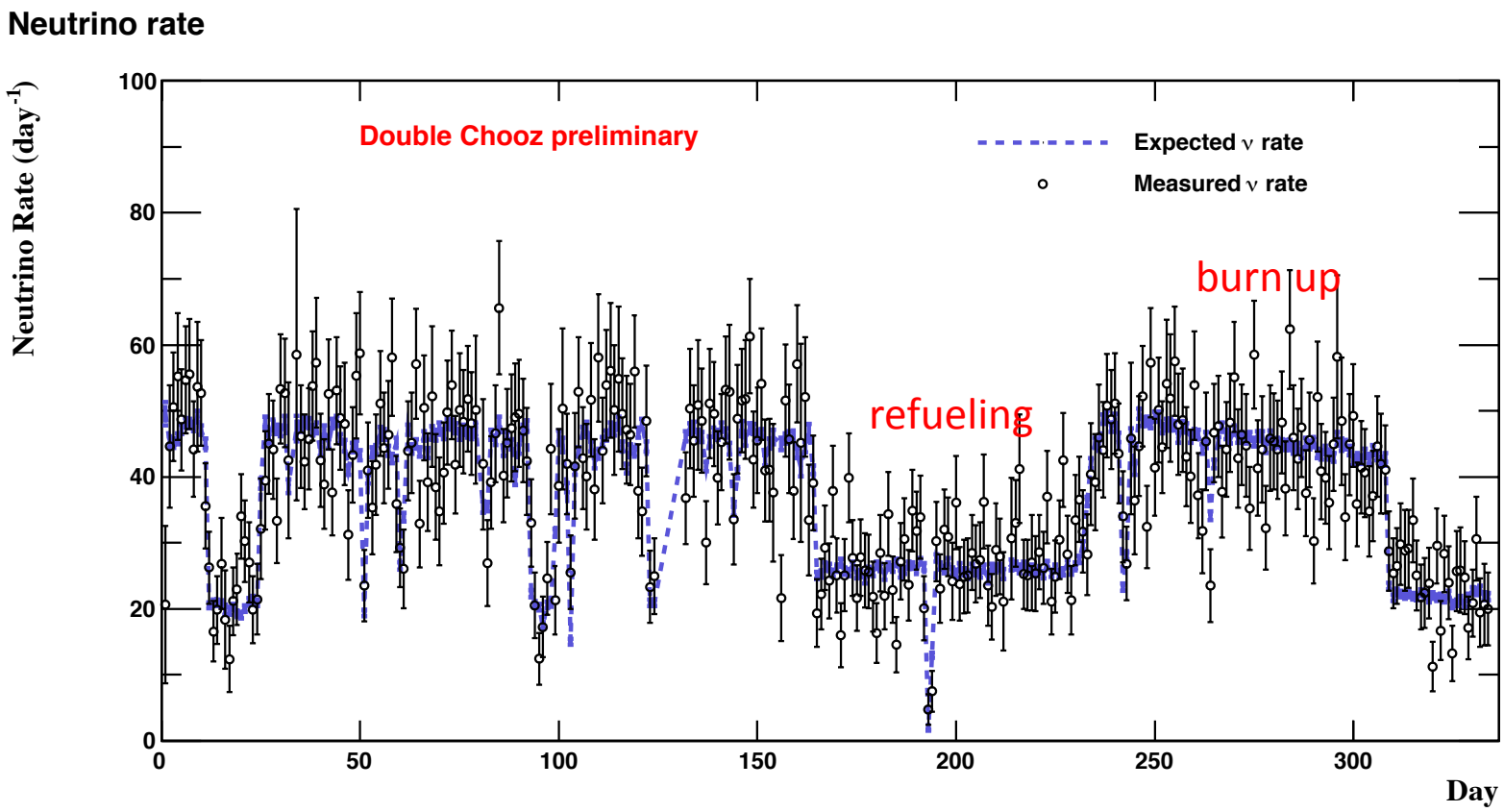
$^{240}Pu + n \rightarrow {}^{241}Pu + \gamma$

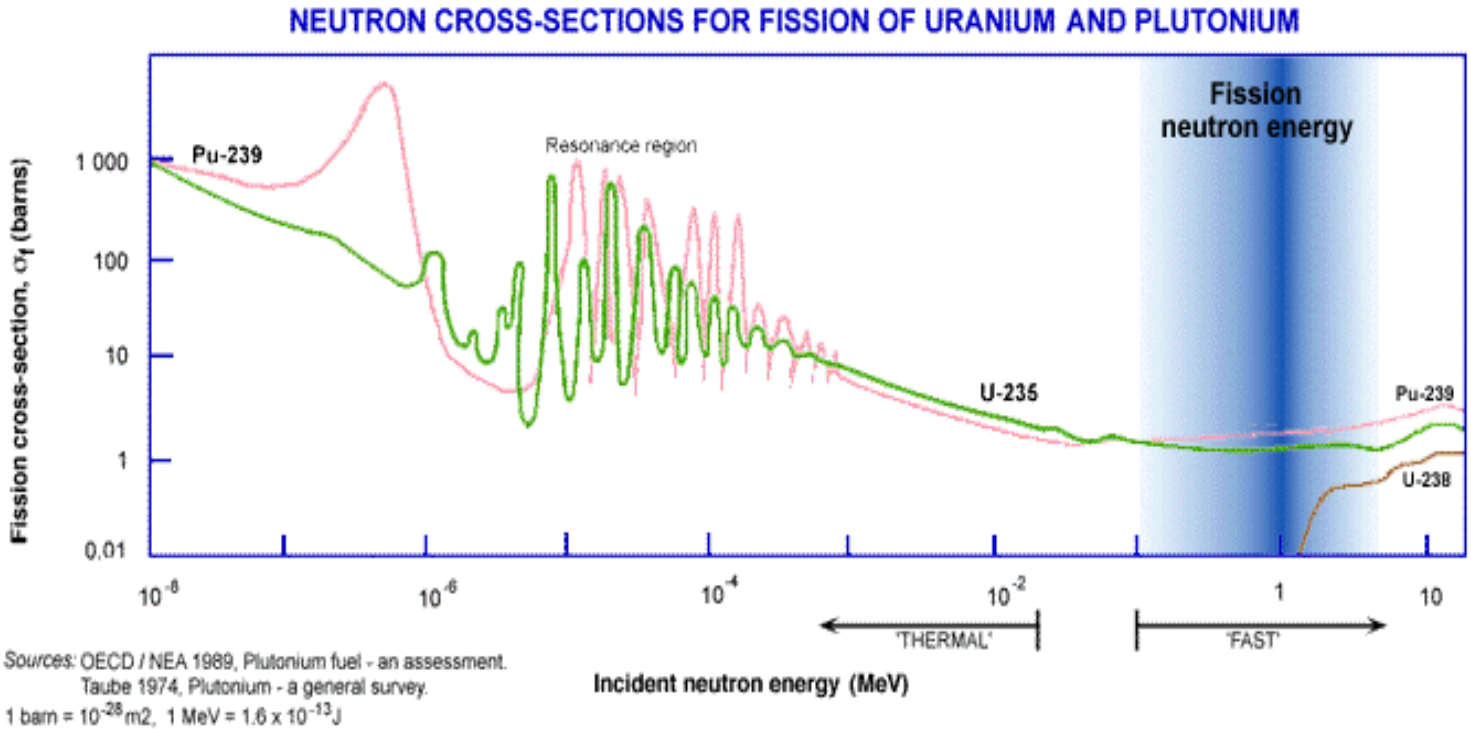
Note: ^{238}U and ^{240}Pu have small cross sections for *fast* fission.

The content of nuclear fuel changes with time as the reactor core "evolves". The $^{240}Pu/^{239}Pu$ ratio increases as the core evolves.


Fissions/Sec
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
0
50
100
150
200
250
300
350
400
450
500
Days
burnup of ^{235}U
buildup of ^{239}Pu
buildup of ^{240}Pu
^{235}U
^{238}U
^{239}Pu
^{240}Pu
^{241}Pu
^{242}Pu

Operation Pattern of Typical Power Reactor





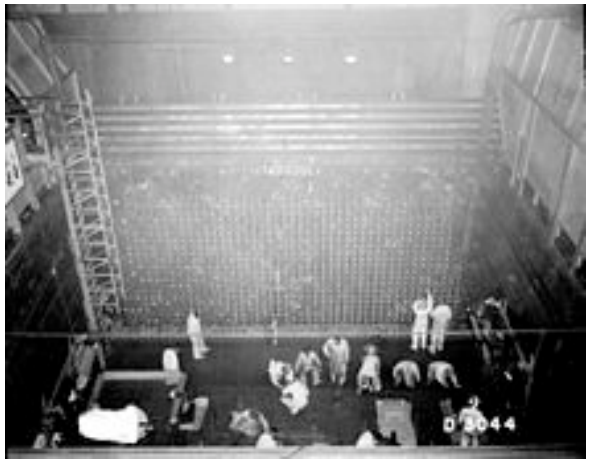
Pu-239 can be used to make nuclear weapons. Easier to extract chemically than to try and isotopically separate uranium.

Pu-240 is undesirable due to smaller fission cross section and relatively large branching ratio to spontaneous fission which can cause "pre-detonation" or result in a "fizzle".

Pu-240 content < 7% “weapons grade”
> 20% “reactor grade”

The Challenges

- 239-Pu can be produced in relatively small (100 MWth or less) reactors operating with a short duty cycle of few weeks. E.g. the reactors the U.S. used at Hanford were originally 250 MWth.
- Limited thermal signature, remote location.
- Large detectors needed (megaton scale)

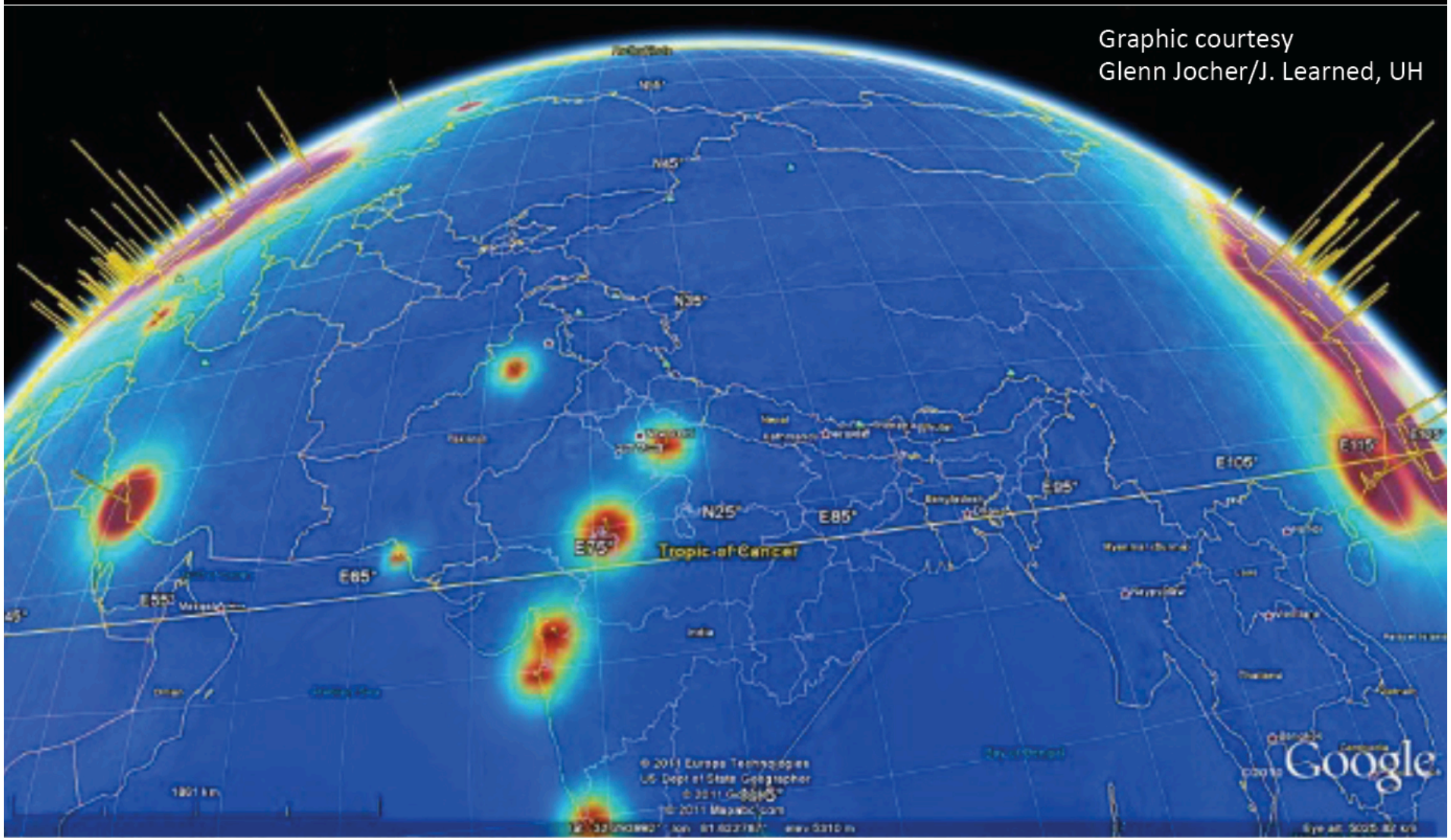


Reactor name	Start-up date	Shutdown date	Initial power (MWt)	Final power (MWt)
B Reactor	Sep 1944	Feb 1968	250	2210
D Reactor	Dec 1944	Jun 1967	250	2165
F Reactor	Feb 1945	Jun 1965	250	2040
H Reactor	Oct 1949	Apr 1965	400	2140
DR ("D Replacement") Reactor	Oct 1950	Dec 1964	250	2015
C Reactor	Nov 1952	Apr 1969	650	2500
KW ("K West") Reactor	Jan 1955	Feb 1970	1800	4400
KE ("K East") Reactor	Apr 1955	Jan 1971	1800	4400
N Reactor	Dec 1963	Jan 1987	4000	4000

These reactors produced 239-Pu for 60,000 Nuclear weapons

WATCHMAN

WATer CHernkov Monitoring
of Anti-Neutrinos



WATCHMAN Collaboration

A. Bernstein, N. Bowden, S. Dazeley, D. Dobie, M. Sweany	Lawrence Livermore National Laboratory
P. Marleau, W. Hsu, , J. Goldsmith, S. Kiff, D. Reyna, C. Tewell	Sandia National Laboratories*
K. Van Bibber, R. Norman, K. Vetter, C. Roecker, J. Vujic, T. Shokair	UC Berkeley
R. Svoboda, M. Bergevin, M. Askins	UC Davis
J. Learned, S. Dye , J. Maricic	University of Hawaii
M. Vagins	UC Irvine

WATCHMAN: Development of Critical Technologies

- Megaton scale detectors with neutron detection capability to tag IBD events (e.g. Gd doping)
- Sophisticated background rejection capability
- Low theshold (1 MeV is ideal) to achieve high efficiency
- Low cost light sensors, e.g. large area MCP's
- Enhanced light yield (water based liquid scintillator, WbLS)

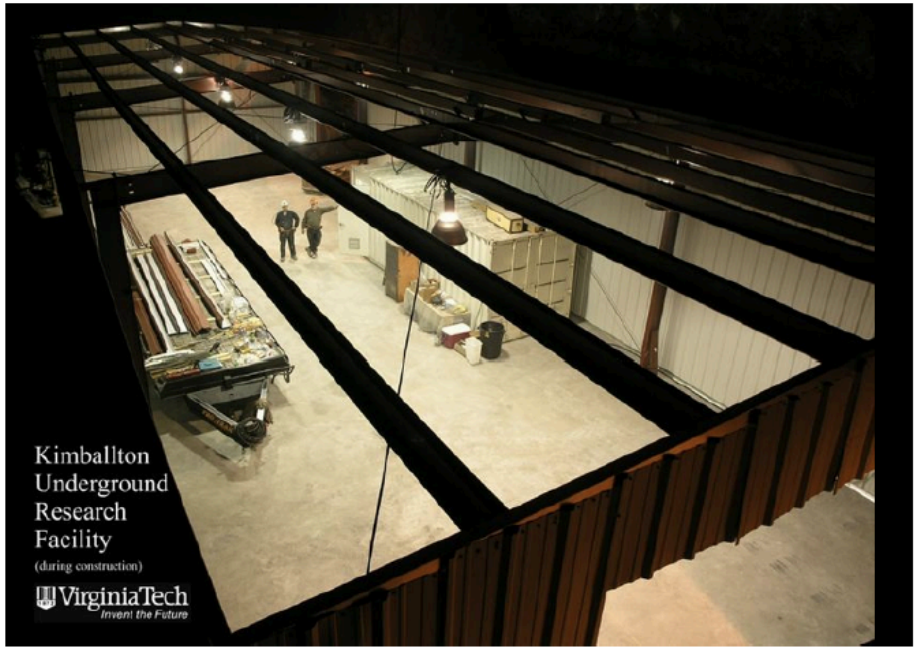
Inverse beta event rates in a 1 Megaton detector	Reactor Thermal power (MWt)	Standoff distance (km)	Signal rate (per month)	background (non-reactor, per month)	Detection efficiency	Over-burden (mwe)	3 sigma significance
	10	400	1	0.5	50%	2000	1 year

Two-Phase Project Timeline

- Two intermediate phases to evaluate background and feasibility of technology
  - Phase I (funded, content of this talk):
    - Fast neutron assay at varying depth
    - Radionuclide production studies in water target
    - Deployment planned for June 2013 -2014 at KURF.
  - Phase II (proposed):
    - 1 kiloton water-based Cherenkov detector at 1 to 10 km standoff from a 0.1 to 10 GWt reactor.
    - Decision late 2014 to early 2015

See M.Bergevin's talk at AARM meeting

Phase I : Measurement at KURF (Kimballton Underground Research Facility)

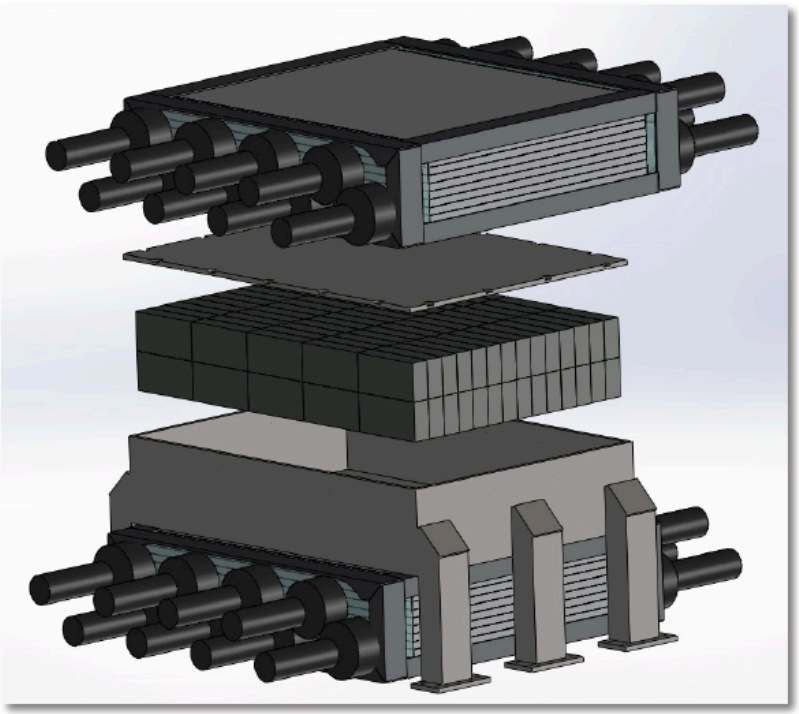


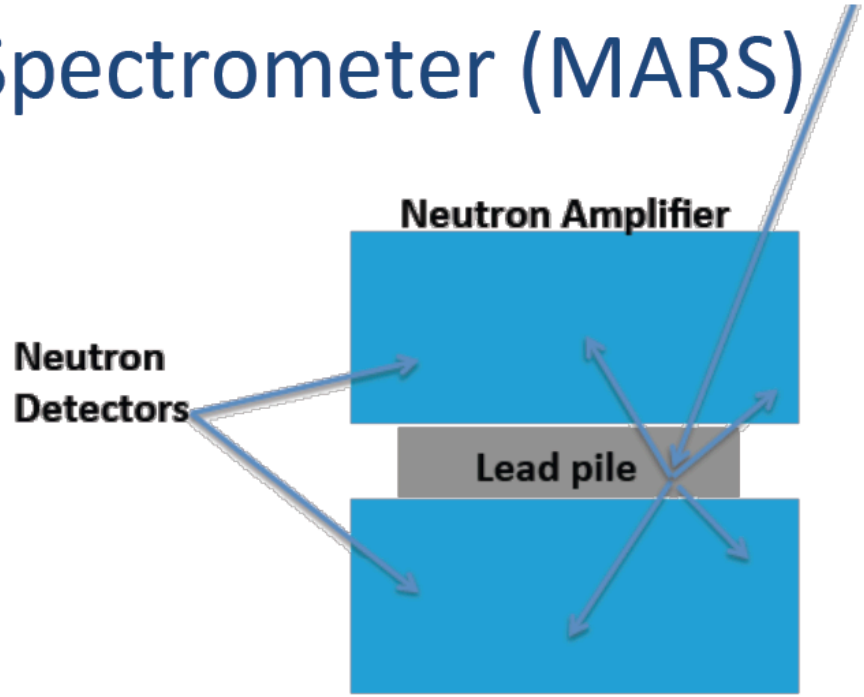
Background data will be acquired at a range of depths at KURF in 2013-2014.

KURF is an operating underground science facility operated by the Virginia Tech Neutrino Science Center.

Access to multiple depths 100 - 600 m.w.e.

Phase I: Fast Neutron detector Multiplier and Recoil Spectrometer (MARS)

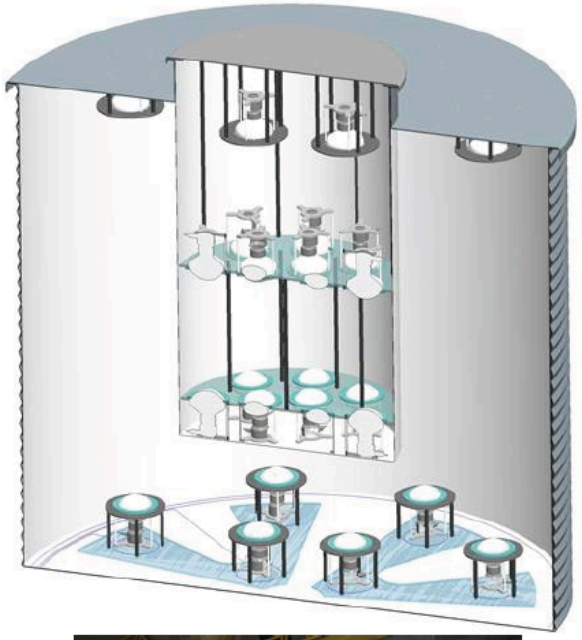




Set a flux at different depth and do relative measurements

- Plastic scintillator/Gd doped paint detectors sandwich ~4 tons of lead.
- Direct interaction with scintillator for E < ~100 MeV.
- Neutron multiplication off of the lead for E > ~50 MeV.
- Expect 3000-5000 events per month at 100 m.w.e.

Radio-isotope production Detector



Properties

- 3.5x3.5 meter detector
- 1.5x1.5 meter active inner volume.
- 0.1% Gd doping.
- Depth chosen as to produce a muon rate of 1 Hz within the inner volume of the detector

Timeline

Starting in June:

– One year at 300 m.w.e..

WbLS Development at BNL

What is water-based LS?

WbLS is not a mix of water and fluor or shifter.

A net light gain of 4.4 ±0.5

X. Dai et al., NIM-A 589 (2008) 290.

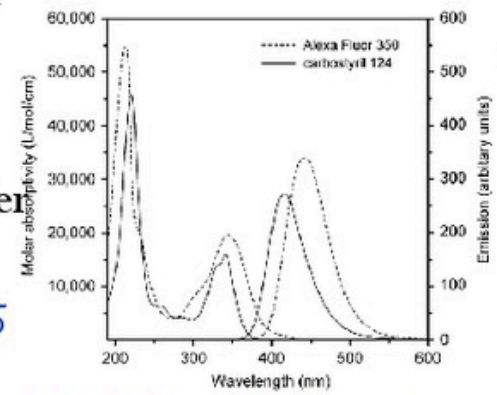
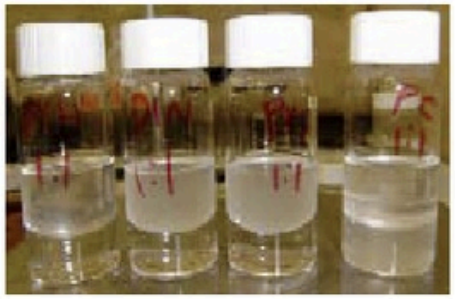
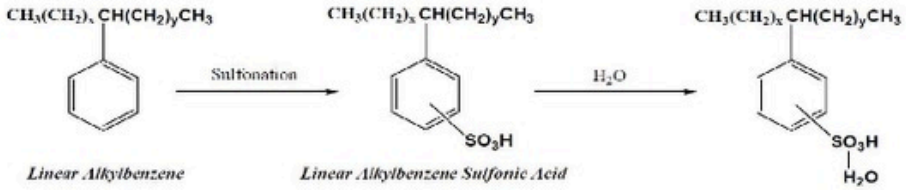
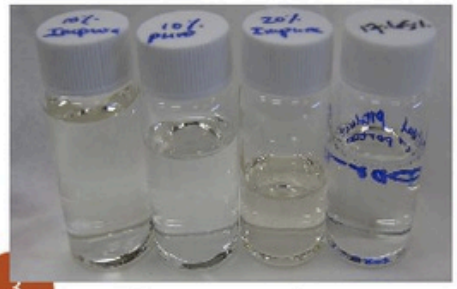


Fig. 2. The UV/VIS absorption (left) and fluorescence emission spectra (right) for carbostyril 124 and Alexa Fluor 350.



Previous WbLS trials are either gel-like or not stable over time.

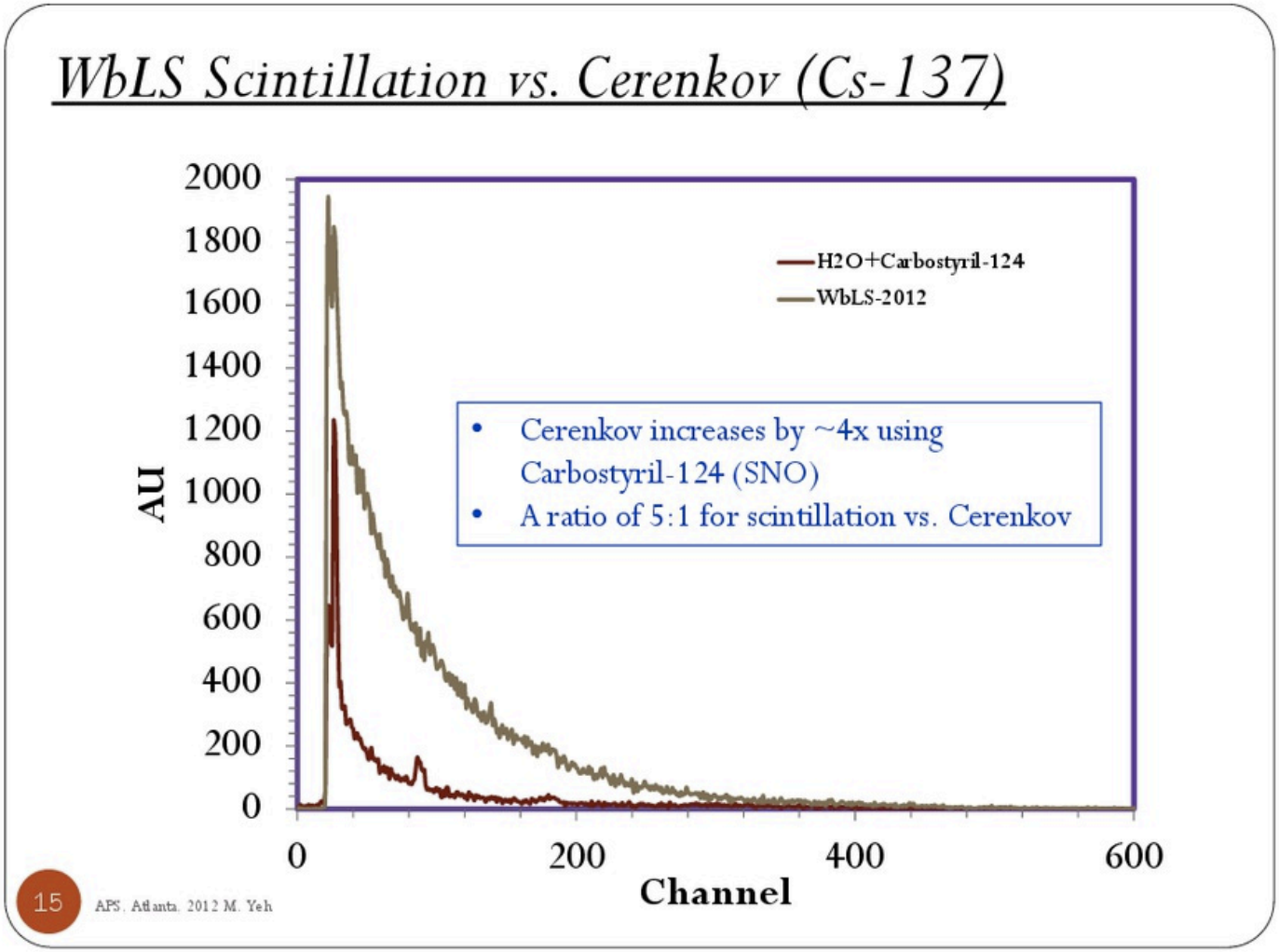




A scintillation water serves as energy spectrometer that probes physics below Cerenkov threshold.

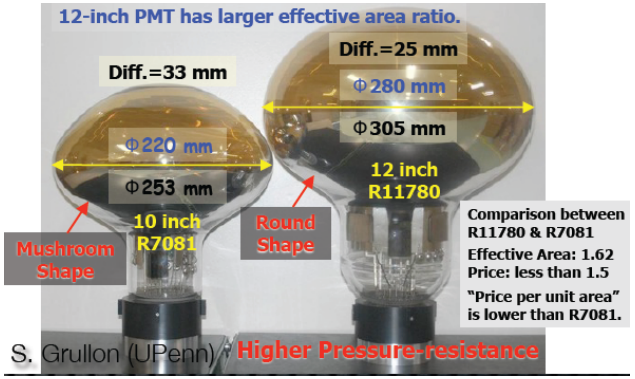
bridged by non-ionic syurfactant, i.e. LAB derivatives, sulfonate, sulfonic amine, etc.

Factor of 20 in light yield from 137-Cs source

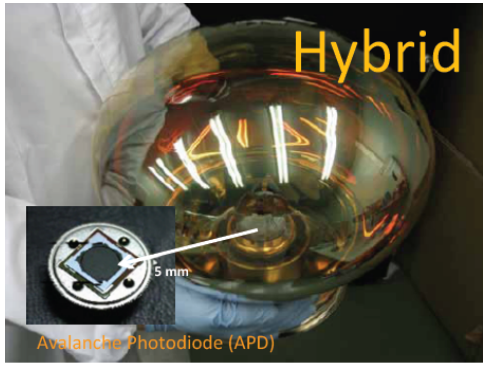


M.Yeh, BNL APS 2012 March meeting

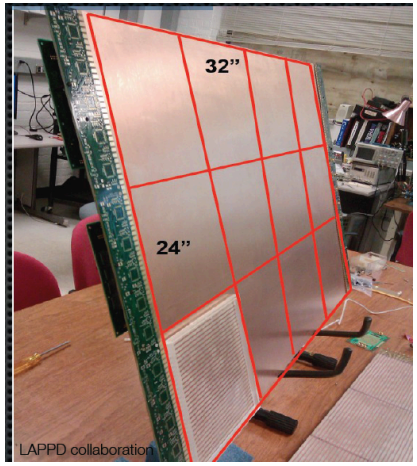
New Photosensors



New 12" HQE PMT's from Hamamatsu developed for LBNE:
- 60% improvement over Super-K PMT's per sq.cm



New Hybrid PMT's developed for Hyper-Kamiokande:
- goal is low cost
- high p.e. resolution



Large Area Picosecond Photon Detectors:
- cover large areas
- goal is low cost, high resolution
- possibility of PPD mode operation

Conclusions

- Far field monitoring of small nuclear reactors is on the edge of being technically feasible
- There are a few critical technologies that are being developed (rather independently) for neutrino physics that could significantly enhance the feasibility
- There is a dedicated group (WATCHMAN) that is pursuing a demonstration prototype at the 1-kton scale within the immediate future