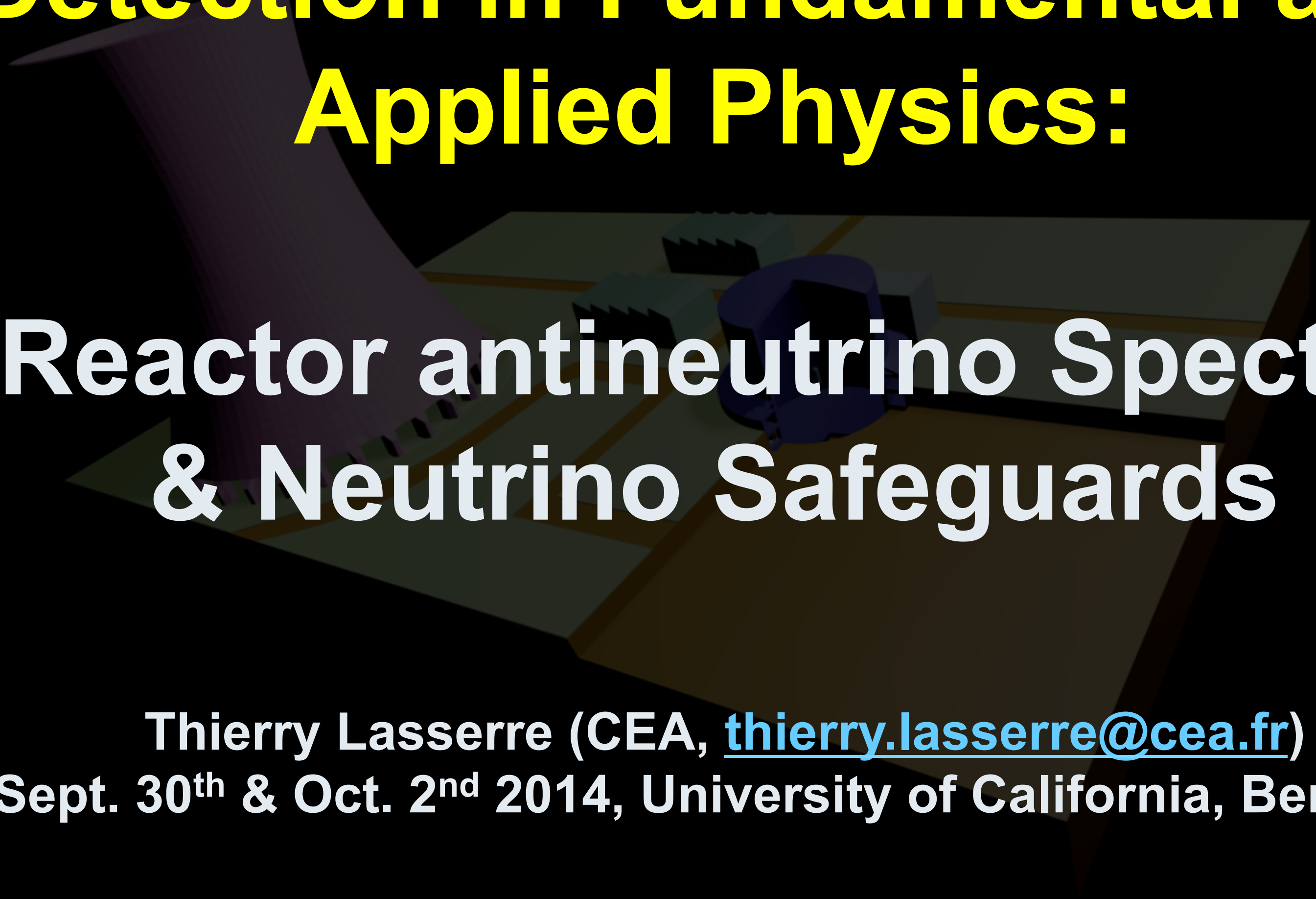
NE290D: Rare Neutral Particle Detection in Fundamental and Applied Physics:



Reactor antineutrino Spectra & Neutrino Safeguards

Thierry Lasserre (CEA, thierry.lasserre@cea.fr)
Sept. 30th & Oct. 2nd 2014, University of California, Berkeley

NE290D Lecture #11

- Reactor Neutrinos & non proliferation
    - U/Pu Neutrino Flux/Spectra & differences
    - Near –Field Monitoring: Experimental Issues
    - Monitoring Nuclear Reactor with Neutrinos

- Neutrino Safeguards
    - Rate Only Analysis
        - Test of a diversion scenario
    - Rate + Shape Analysis – The DPRK case
        - Retrieving fissile content

- Detection Considerations

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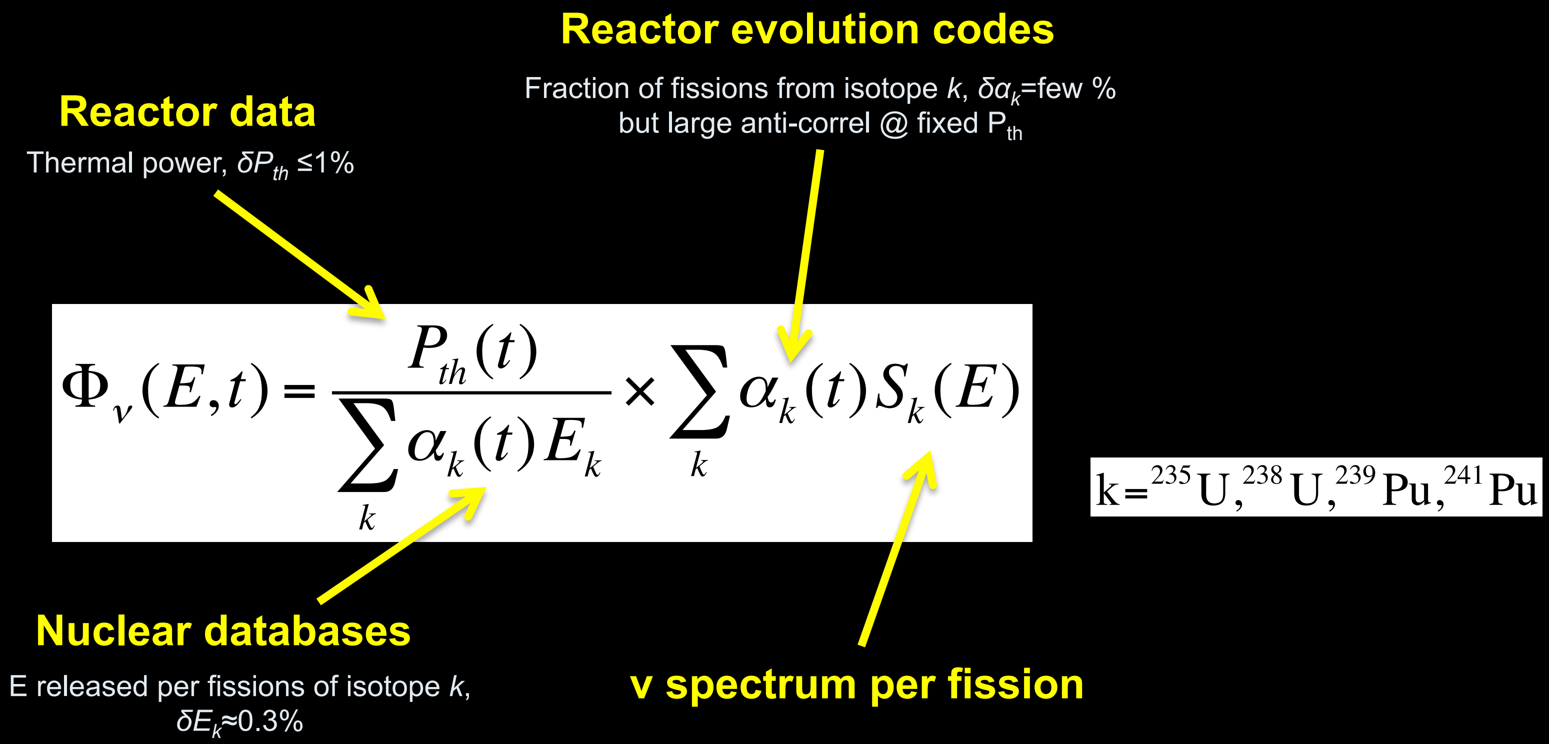
Summary: reactor ν spectrum

The prediction of reactor ν spectrum is the dominant source of systematic error for single detector reactor neutrino experiments



Reactor evolution codes

Fraction of fissions from isotope *k*, $\delta\alpha_k$=few %
but large anti-correl @ fixed P_{th}

Reactor data

Thermal power, $\delta P_{th} \leq 1\%$

$$\Phi_\nu(E,t) = \frac{P_{th}(t)}{\sum_k \alpha_k(t) E_k} \times \sum_k \alpha_k(t) S_k(E)$$

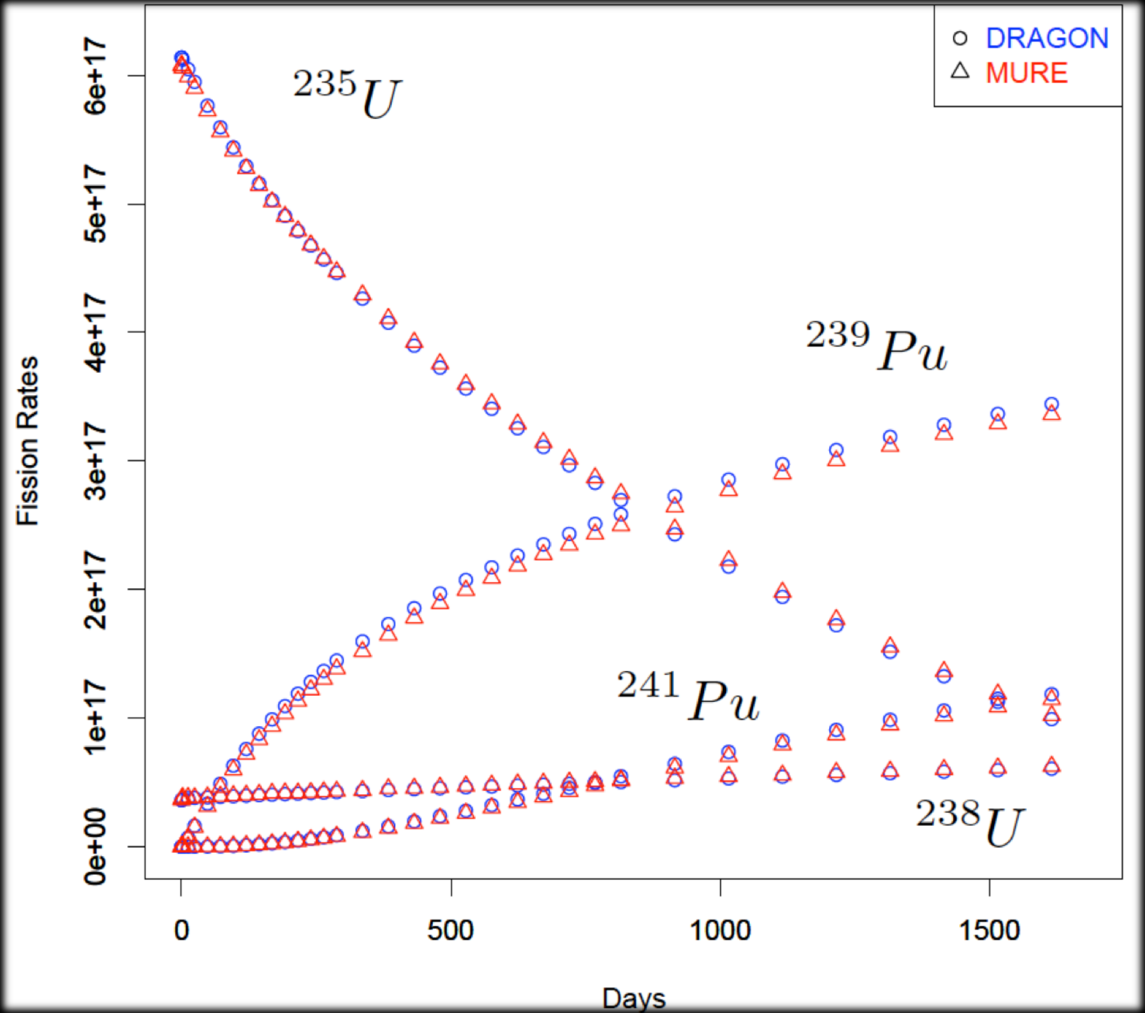
$$k = {}^{235}\mathrm{U}, {}^{238}\mathrm{U}, {}^{239}\mathrm{Pu}, {}^{241}\mathrm{Pu}$$

Nuclear databases

E released per fissions of isotope *k*,
$\delta E_k \approx 0.3\%$

ν spectrum per fission

Reactors: Plutonium Factories



^{238}U + n → ^{239}U

^{239}U →

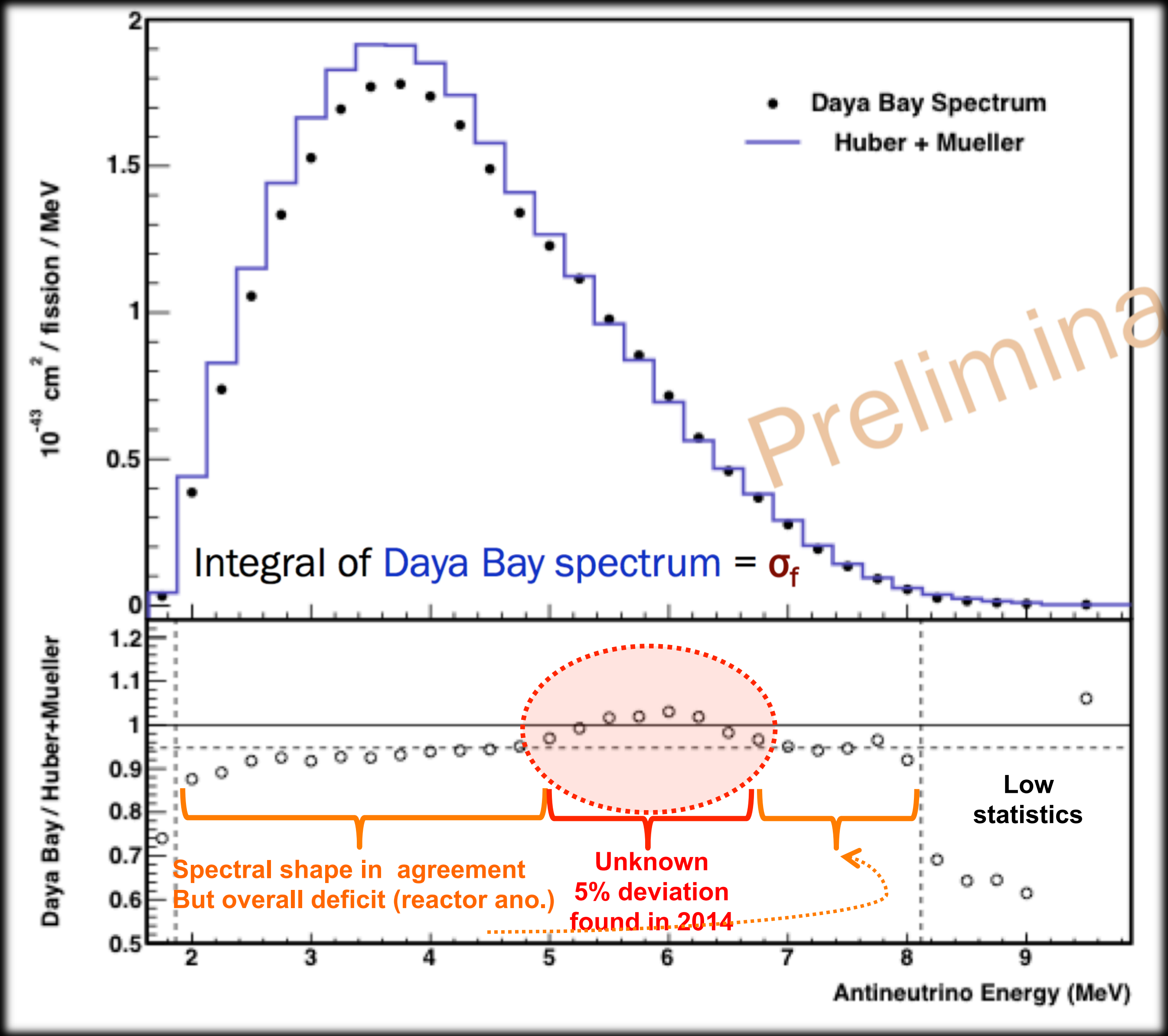
→ ^{239}Np + β^-

→ ^{239}Pu +β^-

(≈8 kg for a SQ,

IAEA Significant Quantity)

Absolute Neutrino Spectrum measurement



Integral of Daya Bay spectrum = σ_f

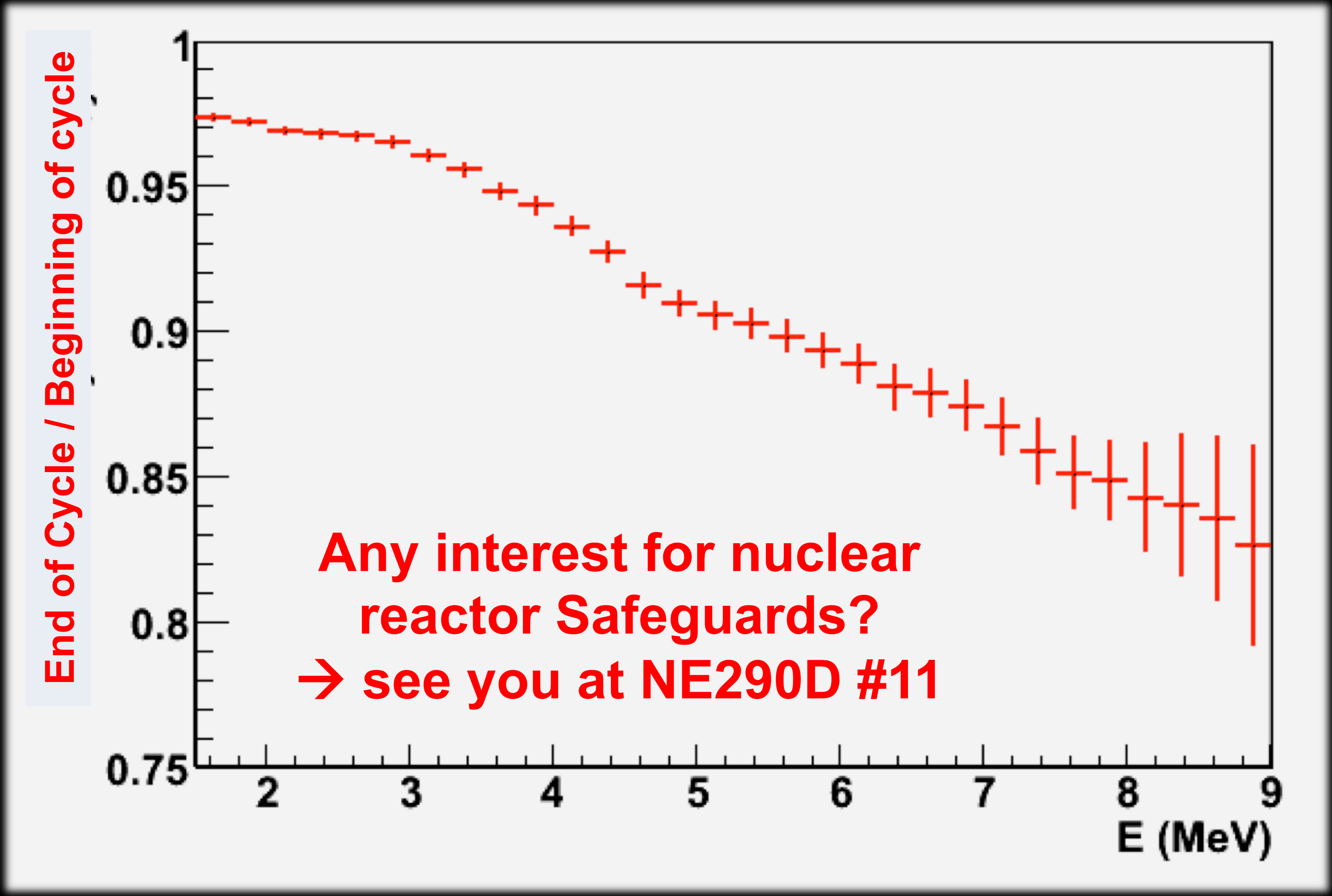
Spectral shape in agreement
But overall deficit (reactor ano.)

Unknown
5% deviation
found in 2014

Low
statistics

Neutrino Spectrum shape & burnup

The energy dependent neutrino yields vary with the burn-up

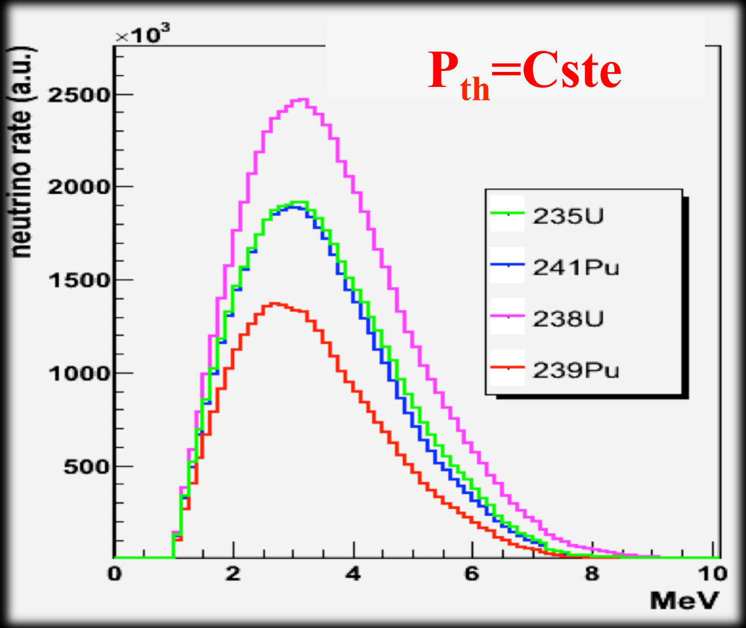


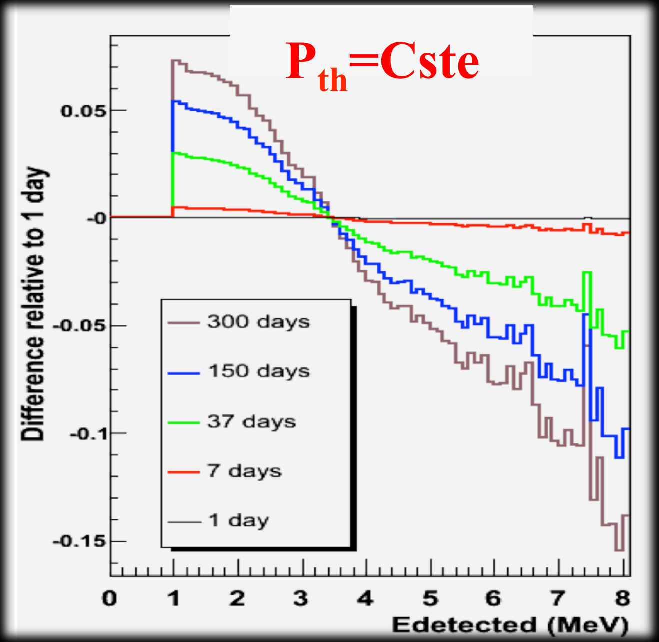
Any interest for nuclear reactor Safeguards?

→ see you at NE290D #11

^{235}U & ^{239}Pu reactor neutrinos

- Imagining a virtual reactor operating only with
    - ^{239}Pu → N_{239} antineutrinos emitted
    - ^{235}U → $N_{235} = 1.6\ N_{239}$ antineutrinos emitted





- A change in fissile mass content in a reactor core – when uranium is consumed and plutonium produced – creates a measurable systematic shift in the antineutrino count rate & spectral shape

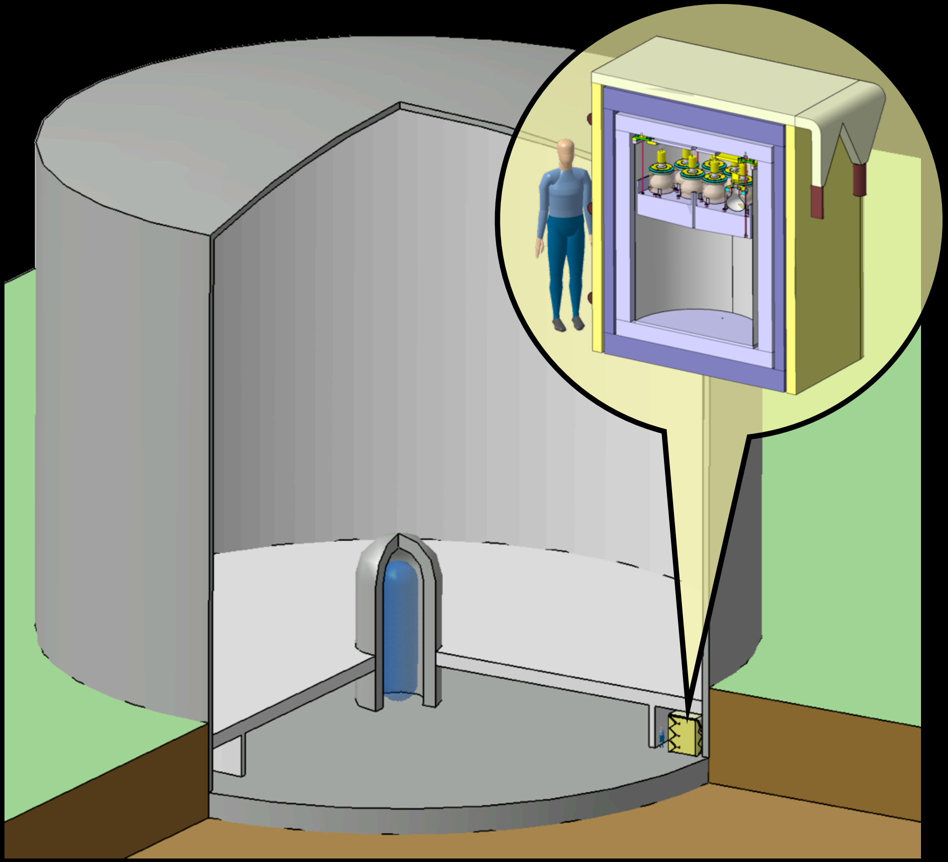
Simulation of the neutrino signal

- Reactor Core Simulation for baseline or diversion scenarios
  - Prediction from a reactor simulation code system for calculating the buildup, decay, and processing of radioactive materials
    - Inputs:
      - Operator-declared thermal power
      - Initial fissile isotopic masses
      - Other reactor parameters
    - Outputs:
      - Fission rates for each isotope

- Neutrino Flux
  - Fission rates are converted into a predicted emitted antineutrino flux

- Neutrino Count Rate
  - Emitted antineutrino flux is converted to a measured antineutrino count rate
    - Modelization of a detector setup (mass, distance)
    - Include a detector response function (efficiency)
    - Include systematics and backgrounds

Experimental Setup



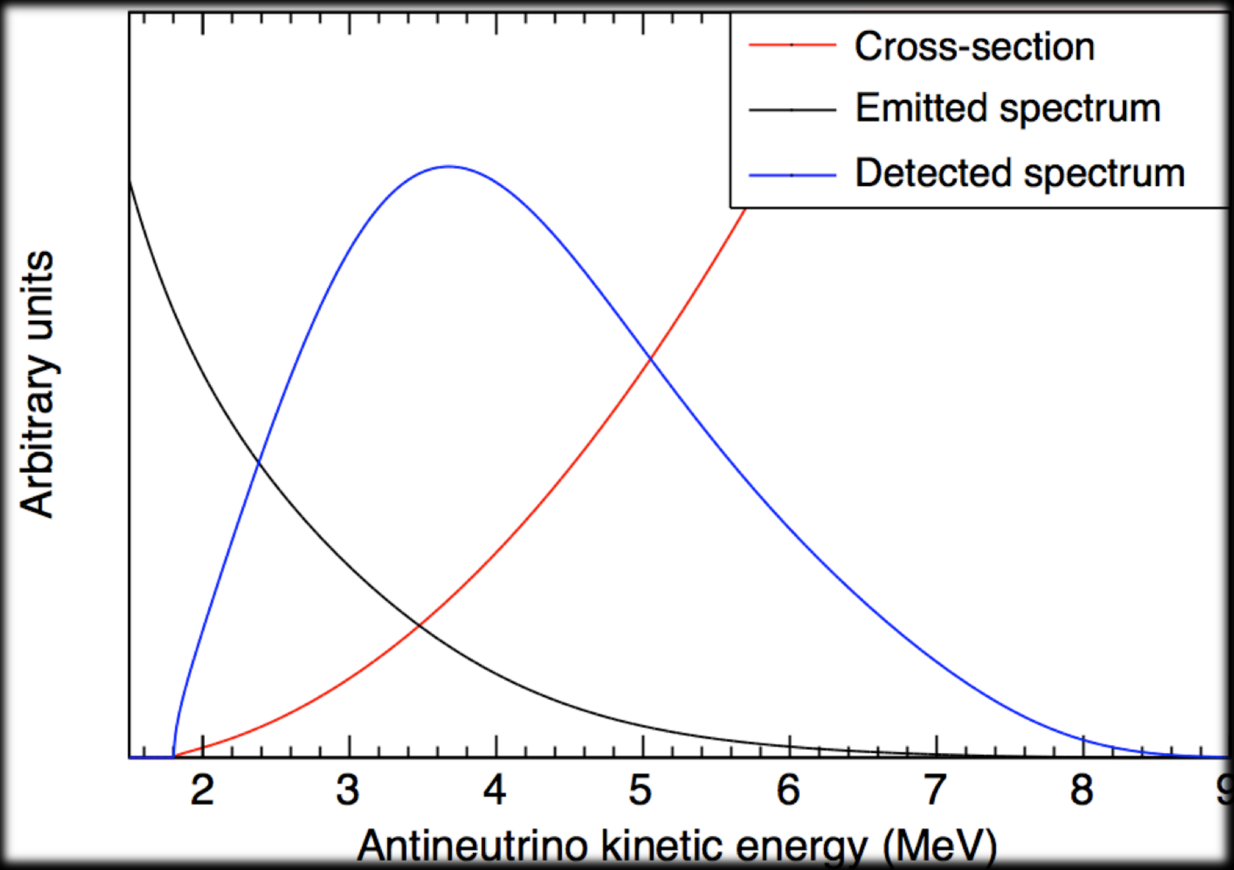
P_{th} (MW)	4000
Fresh fuel	U0x pellets
Enrichment	~3% of 235U
Fuel replacement	1/3rd every ~1.5 y
Core dimensions (cm)	200 x 200 x 480
Distance from core	20 m
v_e flux at det. center	Few 10^{12} cm^{-2}.s^{-1}
v_e int/day (1 m^3)	~12 000
m flux attenuation	x3 needed…

Next experimental challenge: above ground detection (not yet realized)

IBD Cross Section Per Fission

$$\sigma_f^{\text{pred}} = \int_0^{+\infty} S_{\text{tot}}(E_\nu)\sigma_{\text{V-A}}(E_\nu)dE_\nu = \sum_k f_k \sigma_{f,k}^{\text{pred}}$$

Ex: ^{235}U → 6.6(1)10^{-43} cm^2



Detected Spectrum

- Threshold : 1.8 MeV (neutrino energy)
- Mean neutrino energy : 3.6 MeV

Reactor Anti-neutrino Detection

$$\sigma_f^{pred} = \int_0^{\infty} S_{tot}(E_\nu)\sigma_{\mathrm{V-A}}(E_\nu)dE_\nu = \sum_k f_k \sigma_{f,k}^{pred}$$

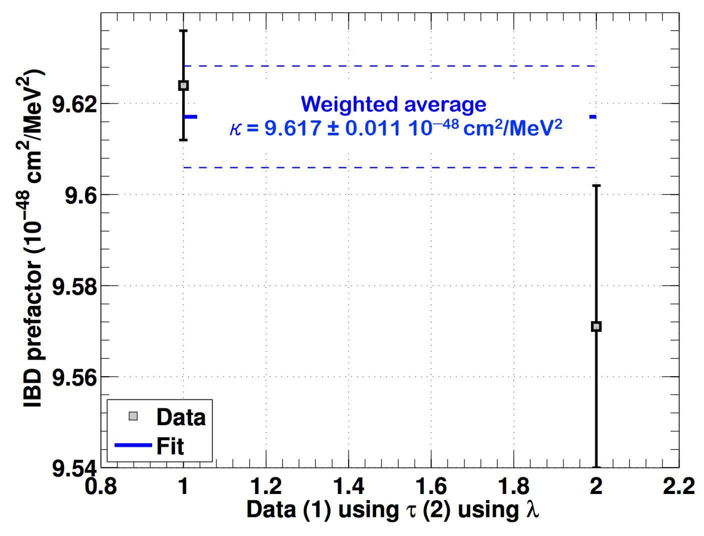
- **Inverse Beta Decay:** $\bar{\nu}_e + p \rightarrow e^+ + n$
- **V-A cross section**

$$\sigma_{\mathrm{V-A}}(E_e) = \kappa p_e E_e$$
$$(1 + \delta_{rec} + \delta_{wm} + \delta_{rad})$$

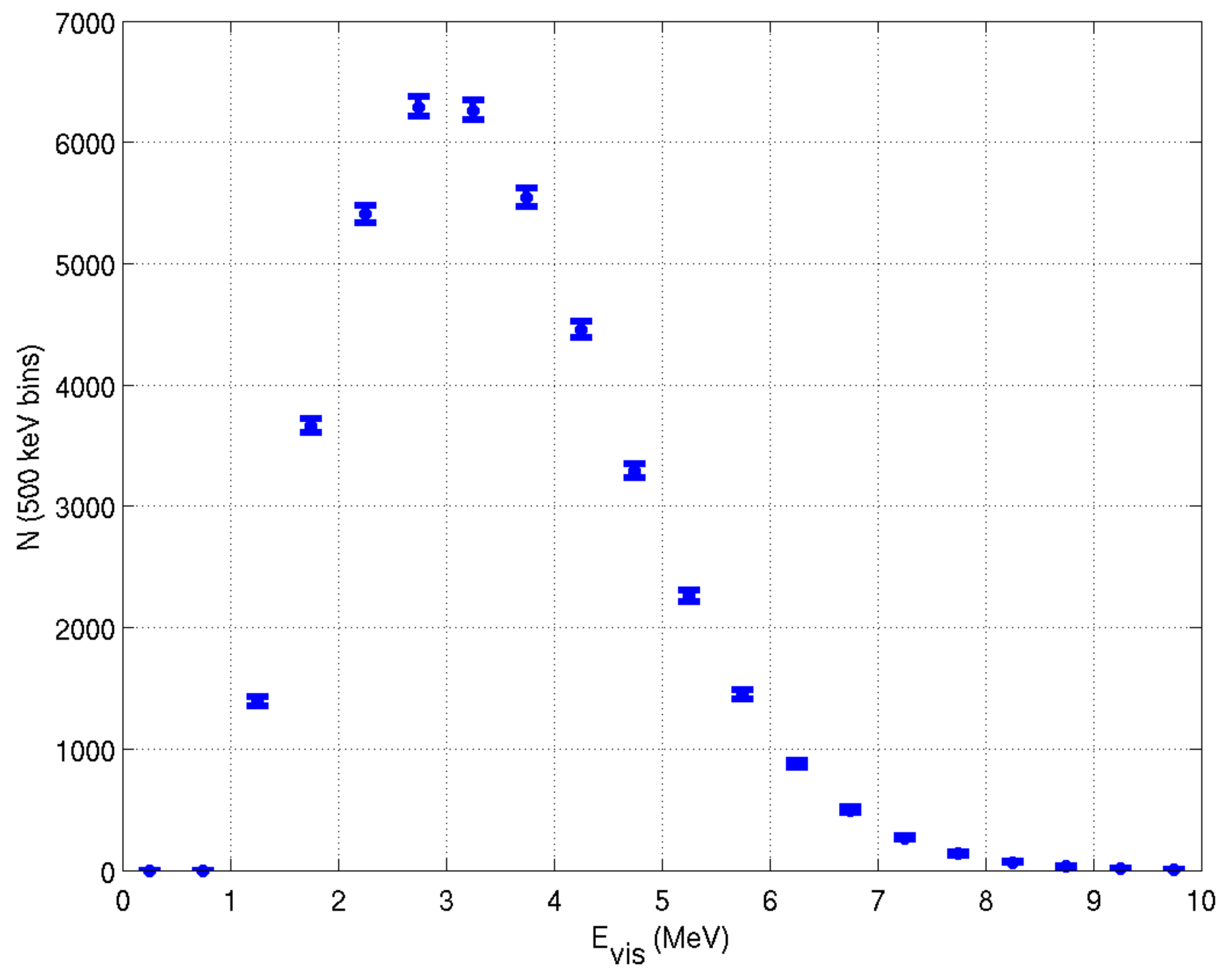
- **Outgoing e⁺ and incoming ν energies are related by**

$$E_\nu = E_e + \Delta + \frac{E_e(E_e+\Delta)}{M} + \frac{1}{2}\frac{(\Delta^2 - m_e^2)}{M}$$

- **Pre-factor κ (cm^2 MeV^{-2})**
  - 1) neutron mean life (τ_n)
  - 2) Axial/Vector coupling constant ratio (g_A/g_V)



Visible Energy Spectrum



Expected Event Rate: 1 m^3 20m 4GW

- **Inverse Beta Decay – No oscillation**

- **Anti-ν_e interaction rate:**

$$n_\nu = \frac{1}{4\pi R^2}\frac{P_{\text{th}}}{\langle E_f\rangle}N_p\varepsilon\sigma_f$$

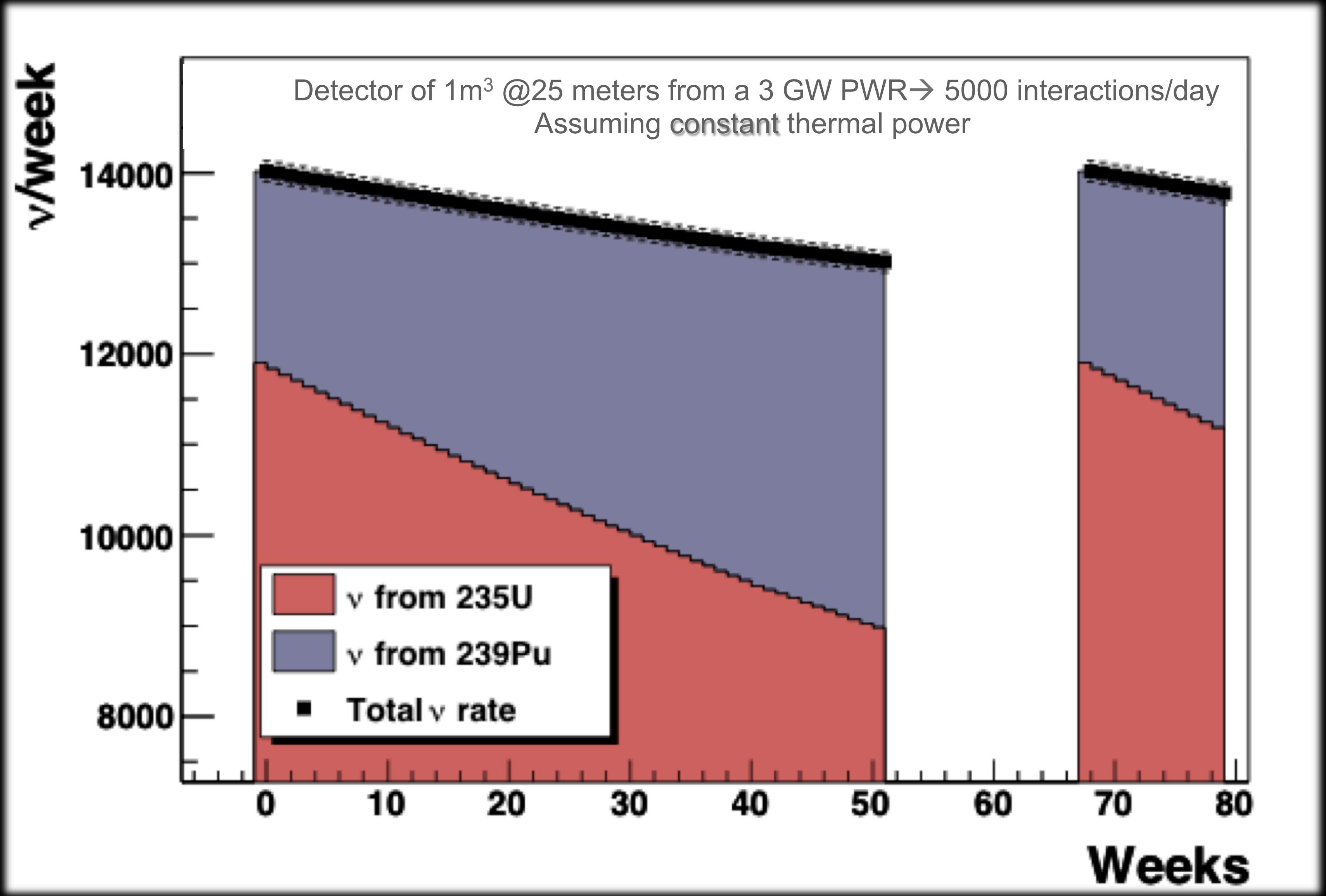
  - $P = 1 \times 4.$ GW$_{th}$
  - $R = 2000$ cm
  - $E_f = 204$ MeV
  - 1.5 neutrinos per fission above IBD threshold – $\varepsilon = 1$
  - $N_p = 1$ m^3 x 6.6 10^{28} H/m^3 = 6.6 10^{28} H
  - $\sigma_f = 6\ 10^{-43}$ cm^2 fission^{-1}
  - 1 day = 86400 s

  → **4e9 / (204*1e6*1.6e-19)*1.5*6.6e28*6e-43/4/pi/(2e3)^2*86400**

  → **≈12500 interactions per day**

- **Anti-ν_e flux (above 1.8 MeV):**
  - Fission number x 1.5 neutrinos/sec
  - 2 10^{20} neutrinos/sec emitted by a core & 3.6 10^{12} neutrinos/cm^2/sec at 20 m

Thermal Power & Neutrino Rate



Detector of 1m^3 @25 meters from a 3 GW PWR→ 5000 interactions/day
Assuming constant thermal power

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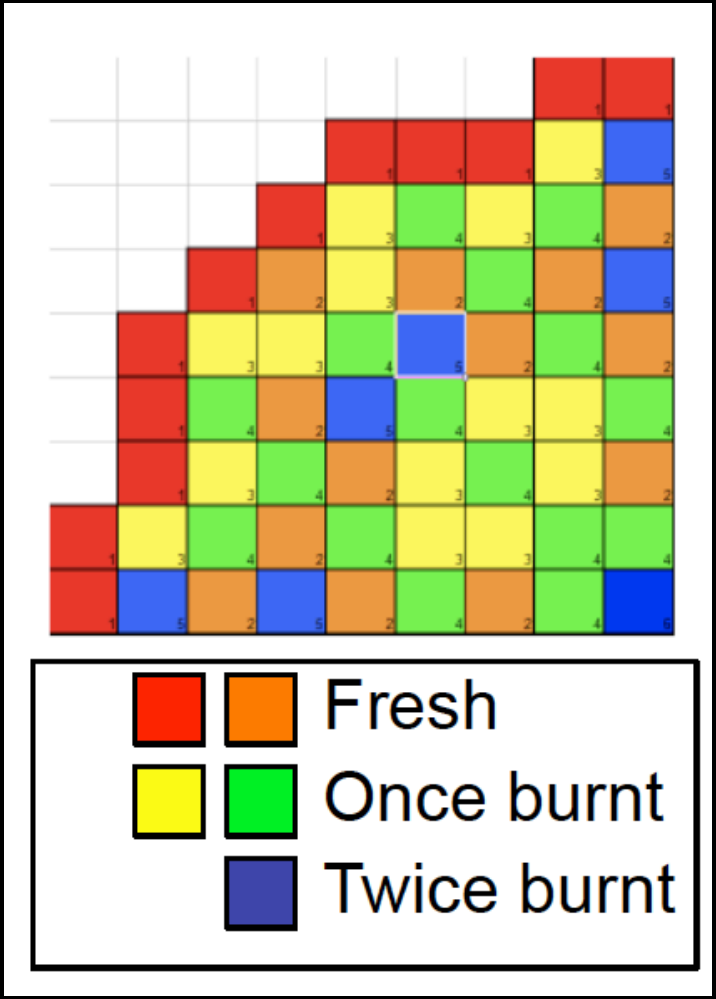
Effect of changes in plutonium content on the reactor antineutrino rate

- Neutrino rate-only analysis
  - No spectral information used
  - J. Appl. Phys. 109, 114909 (2011)

- Compare two different fuel cycles
  - Baseline Cycle
    - Standard fuelling
  - Diversion Cycle
    - Replace 10 once burnt assemblies (70 kg of ^{239}Pu) with 10 fresh assemblies (^{239}Pu free)
  - <u>Thermal power stays constant</u>



Rate Method to tag Pu Diversion

- Parameterization of the count rates as a function of time, t
  - t* is the mean of t values
  - Baseline counts: $N^B(t) = \gamma_0^B + \gamma_1^B \cdot (t - t^*) + \gamma_2^B \cdot (t - t^*)^2$
    - $\gamma^B_{0,1,2}$ obtained from the standard simulation (ORIGEN)
    - Include 1% Gaussian systematic fluctuation on the normalization at t*
  - Model counts: $N^M(t) = \gamma_0^M + \gamma_1^M \cdot (t - t^*) + \gamma_2^M \cdot (t - t^*)^2$
    - $\gamma^M_{0,1,2}$ obtained from the standard simulation (ORIGEN) for Baseline or Diversion
    - Include Poisson statistics

- Statistical test (Student's)
  - Generate the data according to both baseline & diversion scenarios
  - Obtain the coefficient $\gamma_i^{B,M}$ (and uncertainties) from a least square regression
  - Apply the test statistics

$$s_i = \frac{\gamma_i^M - \gamma_i^B}{\sqrt{\left(\sigma_i^M\right)^2 + \left(\sigma_i^B\right)^2}}$$

- Test one hypothesis (baseline) versus the other (diversion)
  - Check the compatibility of <u>each</u> $\gamma_i^{B,M}$ with respect to the γ_i^B
  - Need to define Fake Positive and True Positive cases

Hypothesis Testing

- Simulate N_{sim}=100 000 fake experiments for both baseline & diversion

- Determine the coefficients $\gamma^{B}_{0,1,2}$ & $\gamma^{M=B,D}_{0,1,2}$ for each cases

- Compute the the value of the statistical estimator, s_i for each cases
- Define a threshold

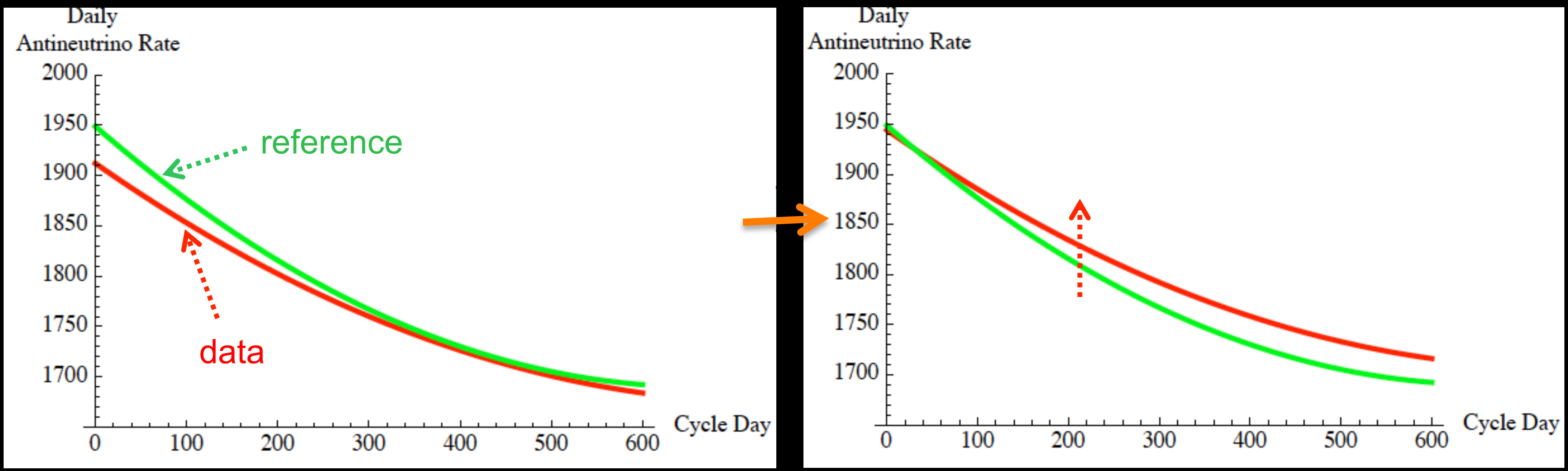
- False Positive
  - Probability of a false positive at a given threshold = the proportion of N_{sim} baseline scenario evolutions found to be different from the baseline

- True Positive
  - Probability of a true positive <u>at the same threshold</u> = the proportion of N_{sim} diversion scenario evolutions found to be different from the baseline

- ROC Curve
  - Repeat the above for a series of thresholds to obtain a receiver-operator characteristic
  - Get the probability of true positive versus of the probability of false positive

Systematics in detector response

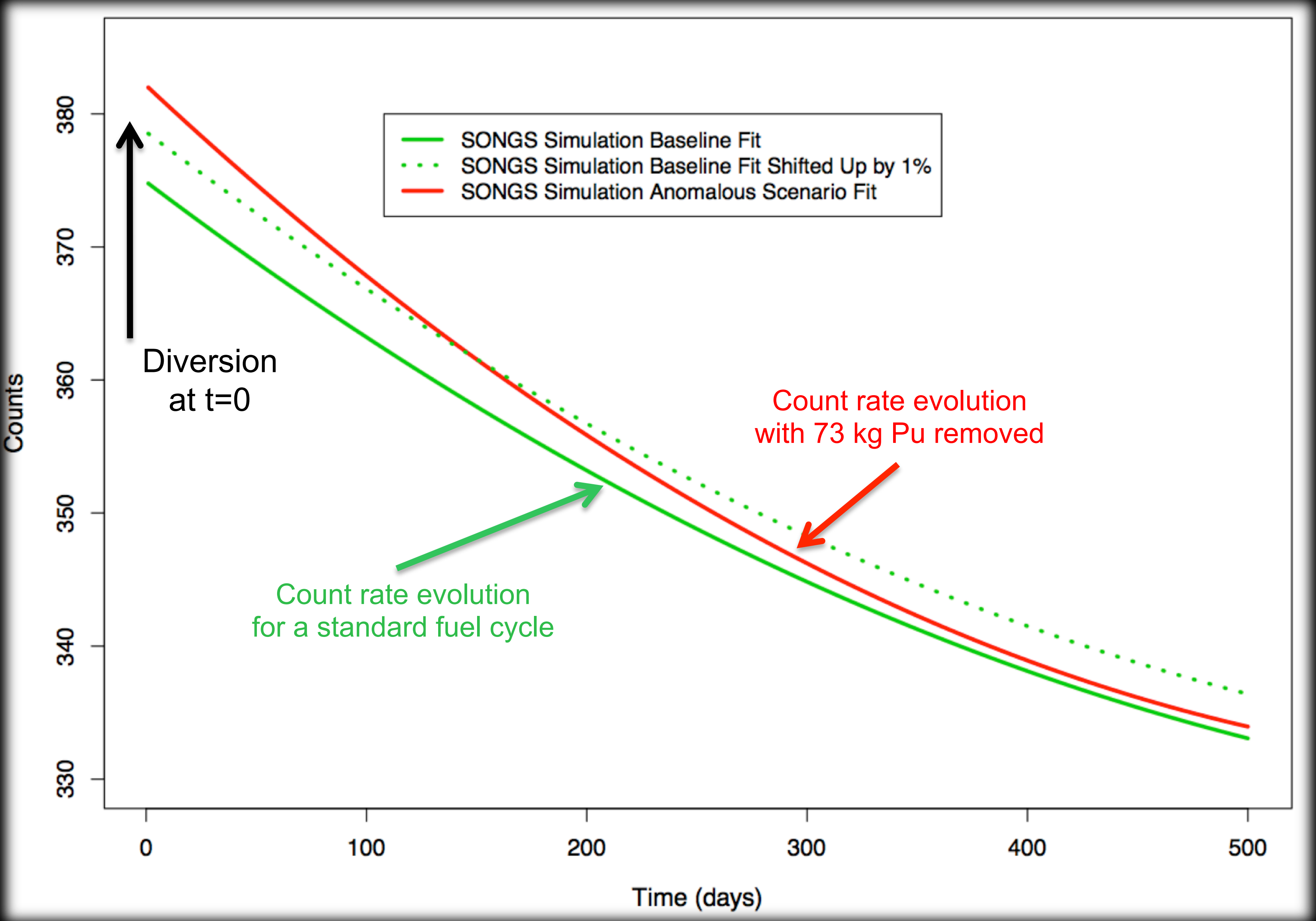
- 2% shift between prediction and measurement at beginning of cycle
  - overall systematic shift in detector response



  - Not a diversion
  - High false positive rate → results in poor test performance…

- Solution: create a single measured template antineutrino rate evolution based on a known baseline cycle. Use this template in future cycles
  - The test performs well. Need to trust the reference cycle and stability.
  - Data driven: becomes independent of reactor core simulations
  - Require very good detector stability

Baseline/Diversion Count Rates

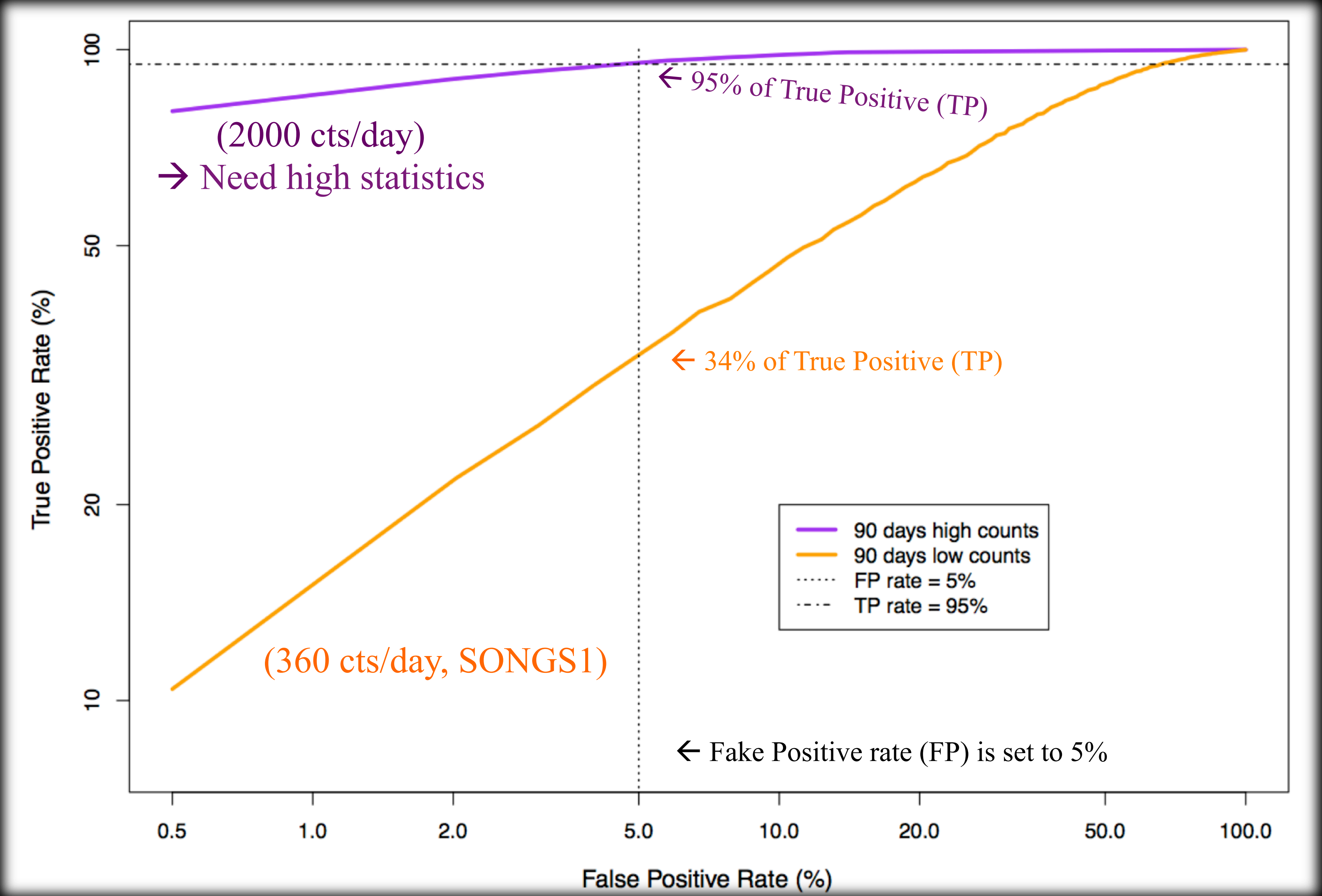


Diversion at t=0

Count rate evolution with 73 kg Pu removed

Count rate evolution for a standard fuel cycle

Results for 90 days (rate only)



(2000 cts/day)
→ Need high statistics

← 95% of True Positive (TP)

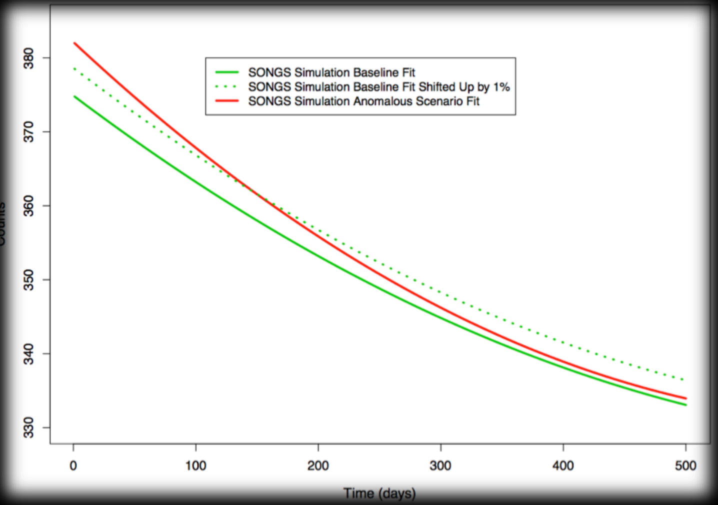
← 34% of True Positive (TP)

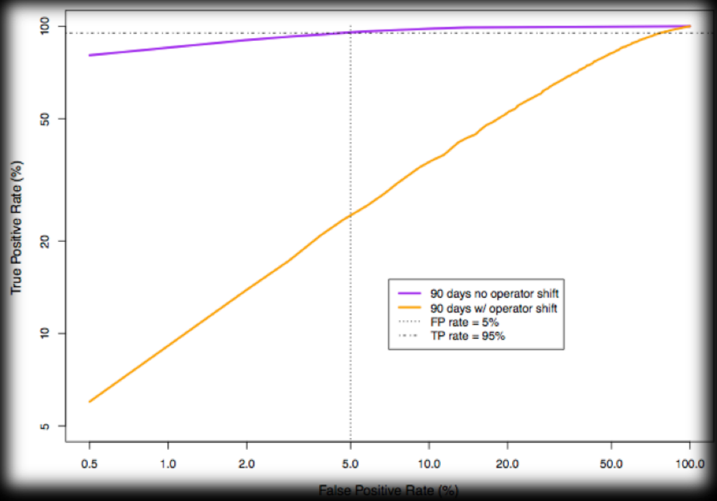
(360 cts/day, SONGS1)

← Fake Positive rate (FP) is set to 5%

Misreported Thermal Power

- For the rate computation we use $N(t) = \alpha \,.\, P_{th}(t) \,.\, (1 + k(t))$
    - P_{th}: thermal power
    - α: normalization coefficient (experimental setup)
    - k: changing fissile isotopic content of the core (burnup)
    - Both P_{th} and k rely on the declarations of the operator
- But the reactor operator could report a higher thermal power value than the true operating power.
    - simulation incorrectly predicts a systematic upward shift in the baseline evolution
- Evaluation of the impact of misreported power
    - 1% upward systematic shift of the baseline evolution → TP → 23% only …





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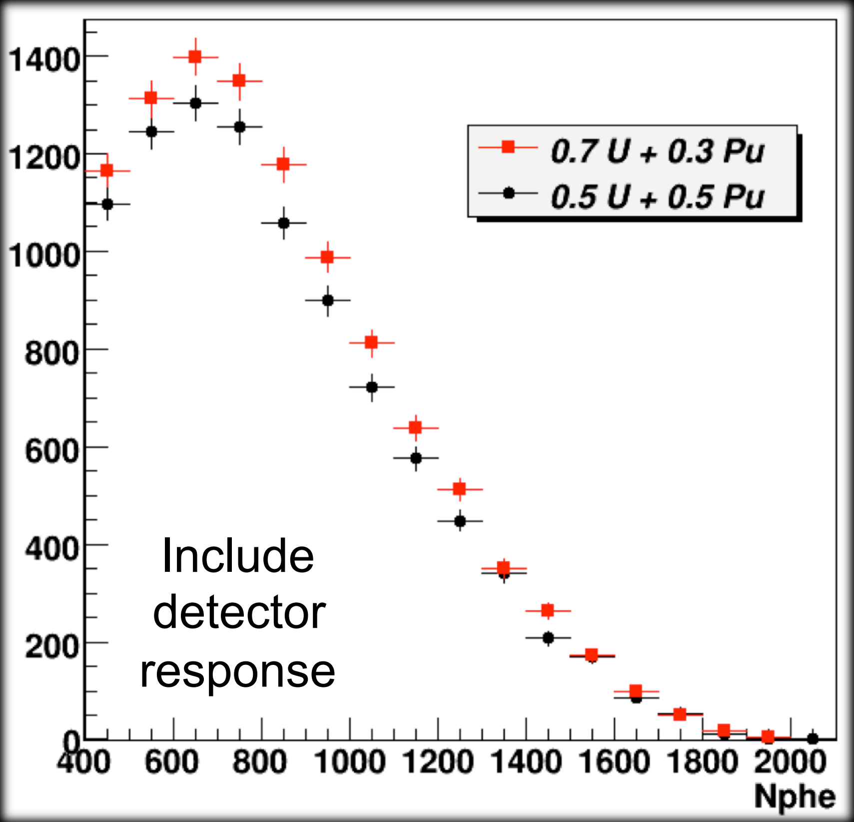
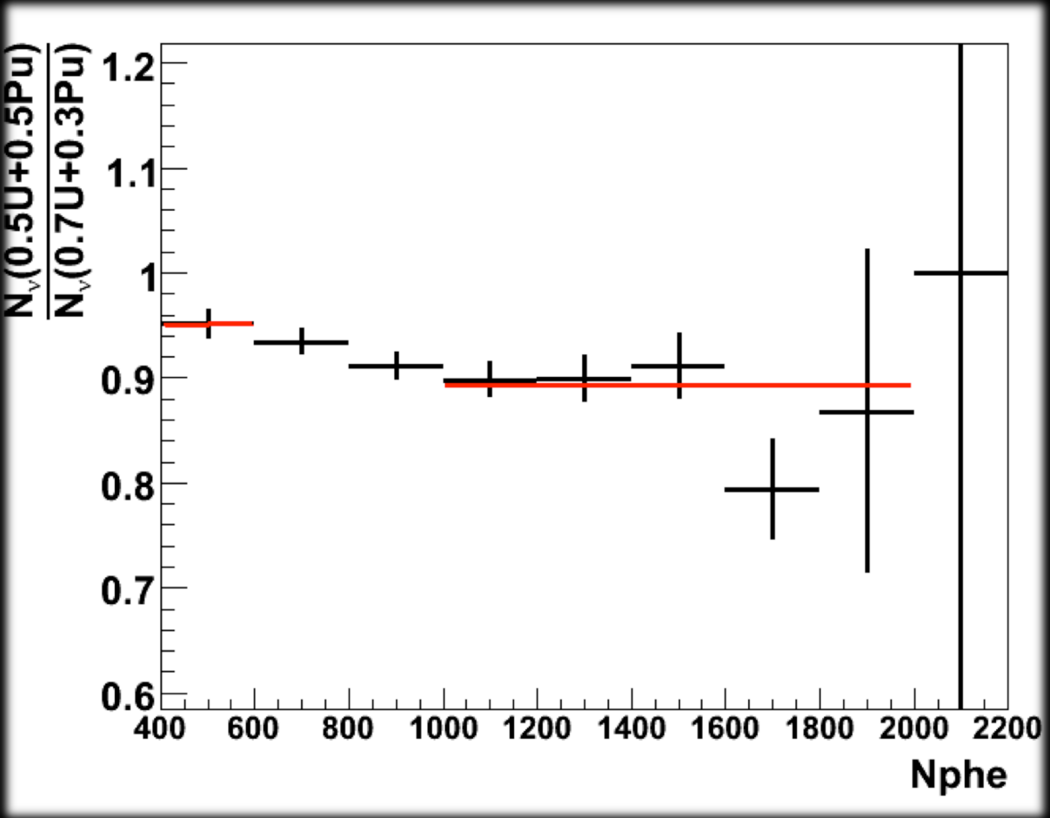
Interest of ν-spectra for Safeguards

- Left: Simulation of ν spectra at various time of a reactor cycle
  - 0.70 235U + 0.30 239Pu (black) & 0.50 235U + 0.50 239Pu (red)

- Right: Ratio of 2x16 day data, before and after refueling 1/3 of the reactor core
  - Pu retrieval can distorts the ν energy spectrum!

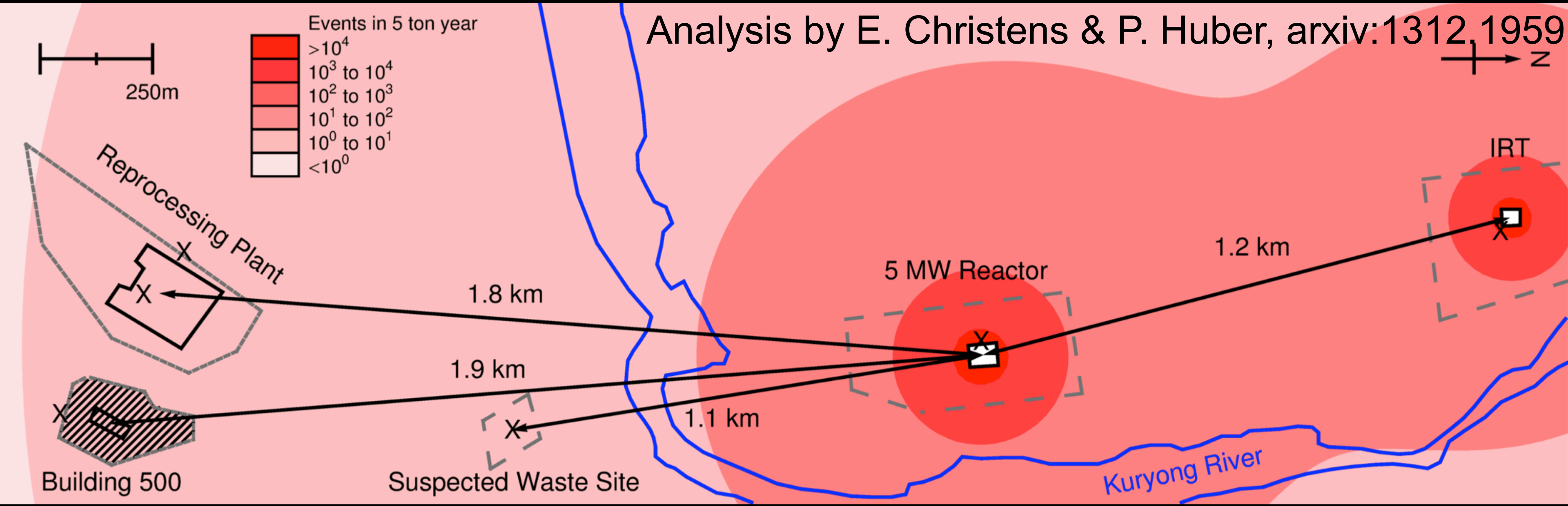


Include detector response



DPRK: Nuclear Program

- IRT reactor starts in 1977
  - 6 MW_{th} light water moderated. HEU fueled reactor, supplied by the Soviet Union
  - Under IAEA safeguards since 1977
- 5MWe reactor starts in 1986 – 70 days shutdown in 1989
  - 20 MW_{th} graphite moderated. Natural uranium fueled reactor
  - Designed and built by the DPRK. Uses magnox fuel cladding →impossible to keep SNF in wet storage for long periods of time
- Radiochemical Laboratory starts operating in 1989
  - A reprocessing facility for the SNF from the 5MWe
  - Capacity of 100-200 ton per year



Analysis by E. Christens & P. Huber, arxiv:1312.1959

DPRK: Suspicion for Pu Diversion

- In its initial declaration to IAEA, the DPRK declared

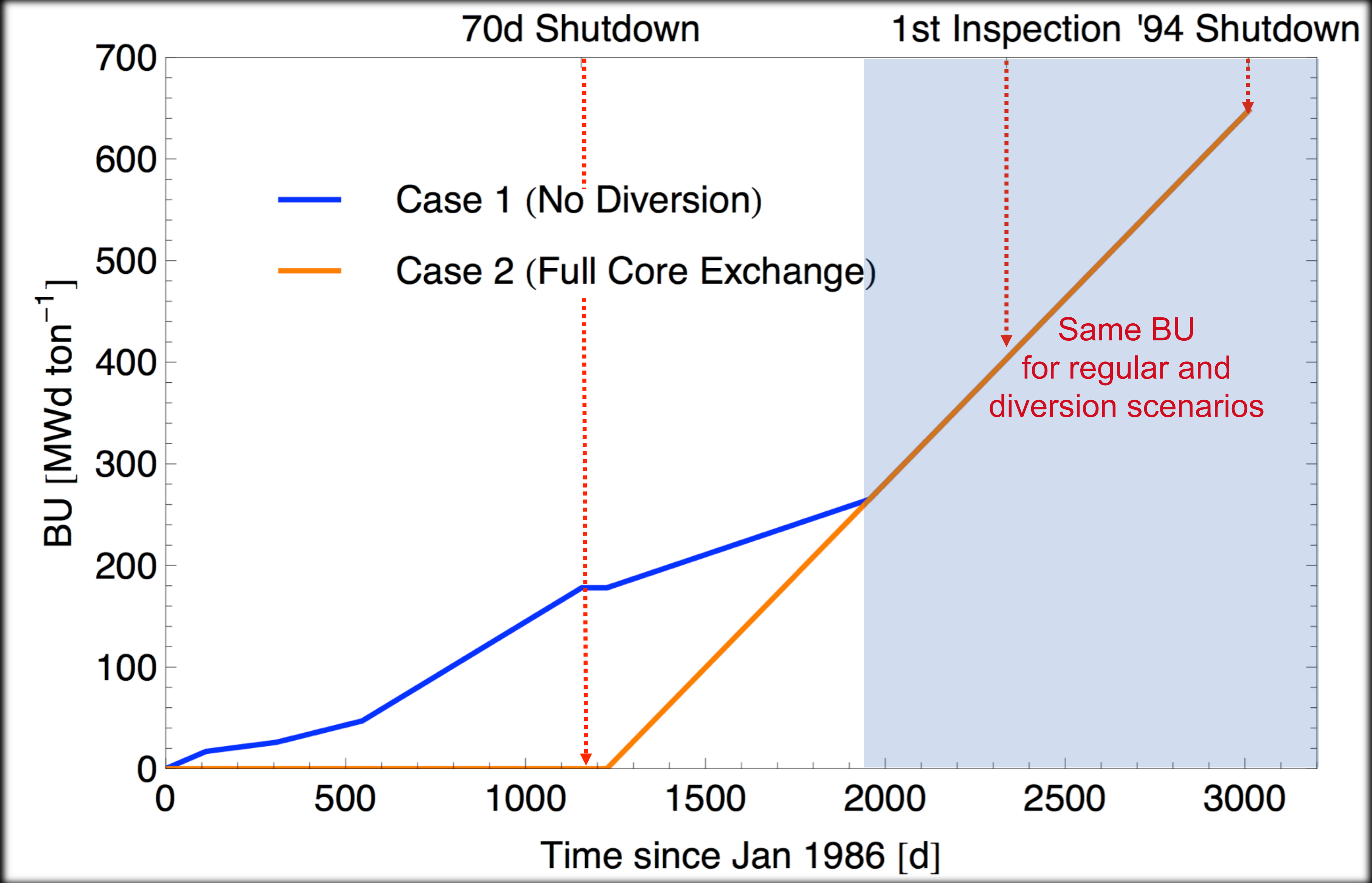
  - In 1989 during the shutdown of their 5MWe reactor a few hundred (out of 8 000 total) fuel elements were discharged

  - A part of the discharged fuel was reprocessed in a hot cell of their reprocessing facility resulting in about 90 g of separated Pu

- IAEA investigations
  - Isotope analysis of samples taking during its first inspections in 1992 Indicated that there must have been at least 3 reprocessing campaigns
  - This raises the possibility that in 1989 the DPRK may have discharged the full core, containing ≈8 kg of Plutonium

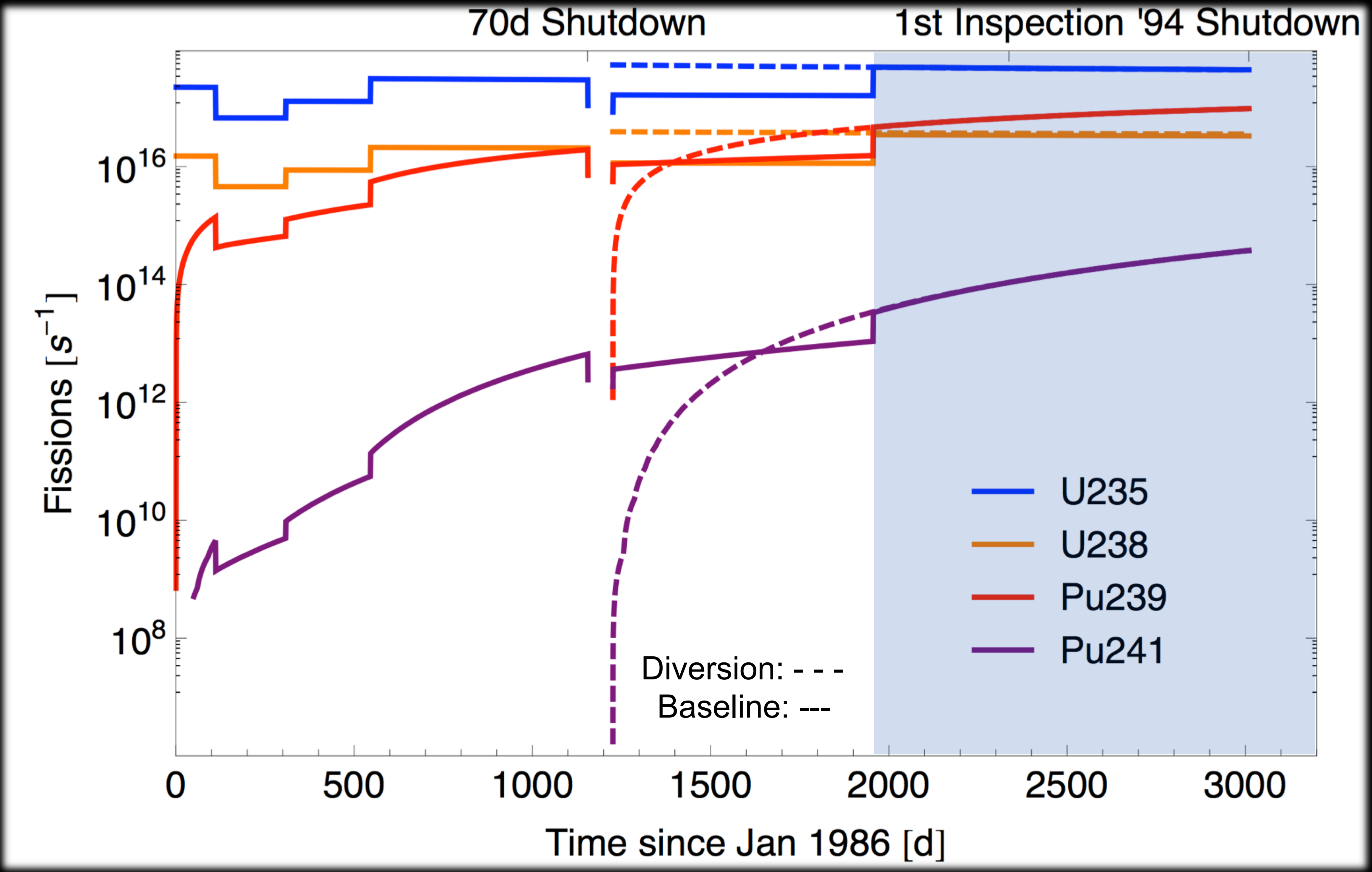
- Question: how much plutonium the DPRK had separated
  - Min: 90 g (DPRK's initial declaration)
  - Max: 8.8 kg (assuming full core -200 MWd/t- unloading in 1989)

DPRK: Burnup for Baseline/Diversion



DPRK: Simulation of Baseline/Diversion

Fission yield full core simulation (SCALE code) using a detailed power history



^{235,238}U/$^{239+241}$Pu contributions to v flux

- Goal:
  - Use the ^{235,238}**U/**$^{239+241}$**Pu** different spectral neutrino yields to disentangle their contribution to the neutrino flux
  - No assumption on the thermal power nor burn-up history

- Expected neutrino event rate in an energy bin i (for binned X^2 analysis)

$$n_i(f) = \zeta \sum_k f_k \int_{E_i-\delta E/2}^{E_i+\delta E/2} \sigma(E) S_k(E)\, dE$$

  - E_i : central energy of bin i
  - δE : bin width
  - σ(E) : IBD cross section
  - f_k : fission rate of isotope k = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu
  - $S_k(E)$: neutrino yield of isotope k at the energy E
  - ζ : detector normalization constant (#H, distance, efficiency, data taking time)

- Notations
  - n_0^i : true number of neutrino events in bin i for $f^0=f^0_{235U}, f^0_{238U}, f^0_{239Pu}, f^0_{241Pu}$
  - n^i : number of neutrino event in bin i for $f=f_{235U}, f_{238U}, f_{239Pu}, f_{241Pu}$

^{235,238}U/$^{239+241}$Pu contributions to ν flux

- Define the X^2 function to estimate the fission rates (assuming no information but n_0^i)

$$\chi^2(f) = \frac{\sum_i \left[n^i(f) - n_0^i\right]^2}{\left(\sigma_{stat}^i\right)^2}$$

  - where $\sigma_{stat} = (n_0^i)^{0.5}$ is the statistical uncertainty
  - $X^2 = 0$ for $f=f^0$
  - Allowed region for f obtained by defining the f such as $X^2(f)<X_c^2$
    - X_c^2 : critical value determined from a X^2 probability distribution with ω dof

- Measurement of the total number of fissions in plutonium, $f_{Pu}= f_{239Pu} + f_{241Pu}$

$$\chi^2_{Pu}(f_{Pu}) = \min_{f_{235U}, f_{238U}, \kappa} \chi^2(f_{U235}, f_{U238}, f_{Pu}, (1-\kappa) f_{Pu})$$

Measuring Thermal Power, BU, Pu inventory

- Define the X^2 estimator to compare data with the declared power history

$$\chi^2 = \frac{\sum_i \left[\zeta P_{th} \left(\sum_k F_k S_k^i \right) - n_i^0 \right]^2}{\sigma_{stat}^2}$$

  - ζ : detector normalization constant
  - P_{th} : thermal power
  - F_k : relative fission yields, k = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu, with $\Sigma F_k = 1$
  - S_k^i : neutrino yield in energy bin i for isotope k
  - n_0^i : measured number of neutrino events in bin i

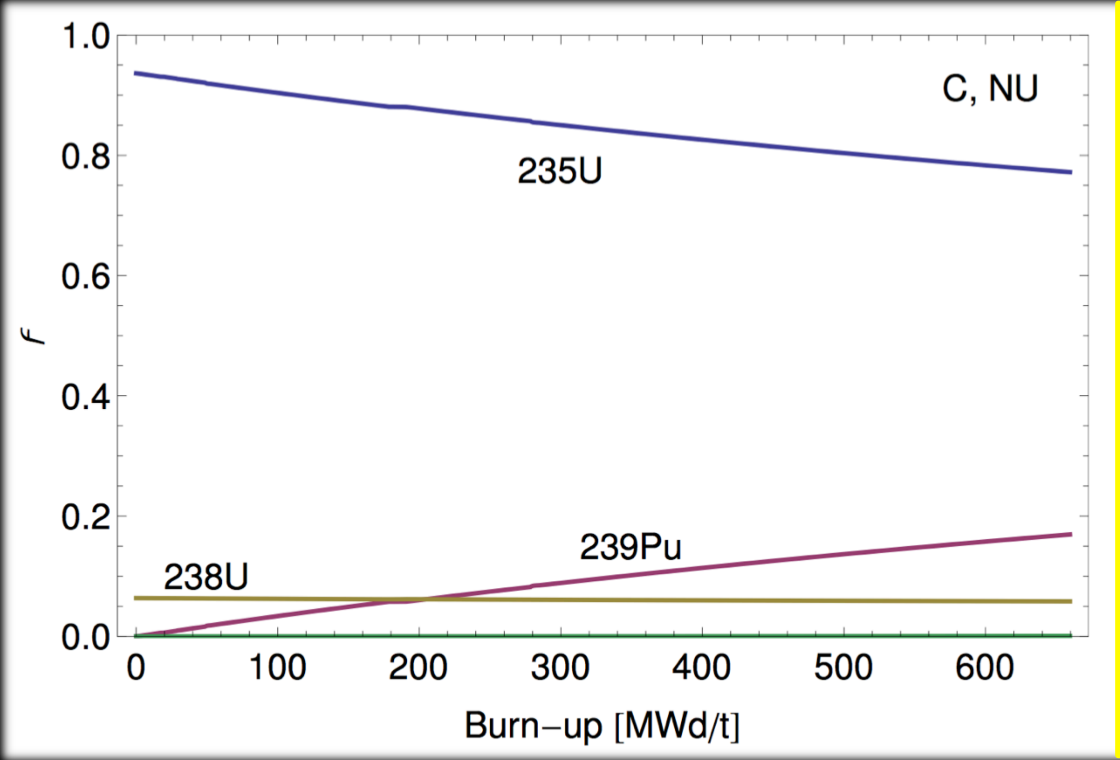
- Fit of the thermal power
  - Minimized X^2 as a function of P_{th} with F_k are free parameters in the fit

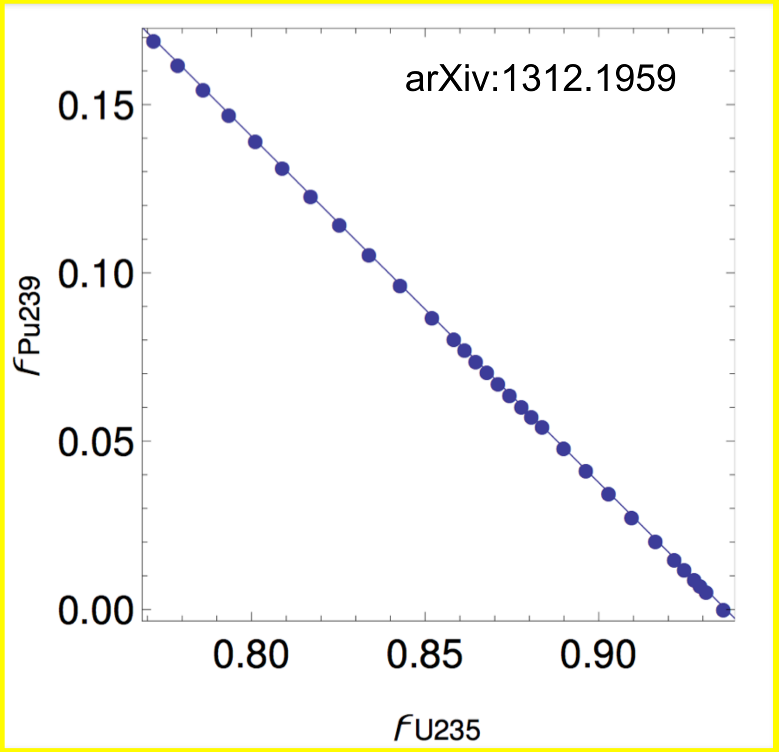
- Fit of the burn-up (BU)
  - P_{th} is free, $F_k = \Psi(\mathrm{BU})$, Ψ provided by a reactor core evolution simulation

- Fit of the plutonium content
  - Option 1 : P_{th}, F_{U235}, F_{238U}, κ are free
  - Option 2 : P_{th} is free, F_{U235}, F_{238U}, κ are constrained by a reactor model

Burn-up: ^{235}U-^{239}Pu anticorrelation

- Reactor evolution code: provide the evolution of the fission fractions in a graphite moderated natural uranium fueled reactor as a function of burn-up
- Anticorrelation of the fission fractions in uranium-235 and plutonium-239
- Tiny amount of plutonium-241 produced for this Magnox reactor type

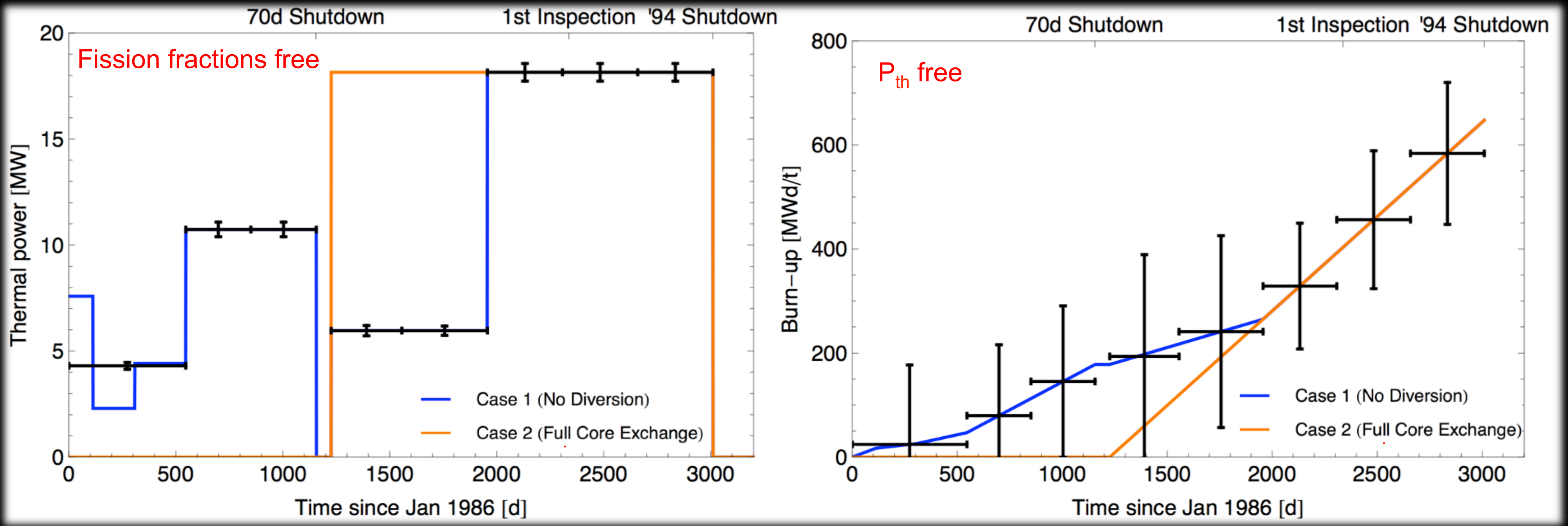



arXiv:1312.1959

DPRK: Thermal Power & Burn-up

- Neutrino detector setup (point like) starting in 1986
  - Target mass: 5 tons – baseline: 20 m – 95 000 neutrinos events
  - 2% normalization uncertainty – Low backgrounds, well known and subtracted

- Observables
  - Left: Continuous measurement of the thermal power (P_{th})
  - Right: Continuous measurement of the burn-up (BU)

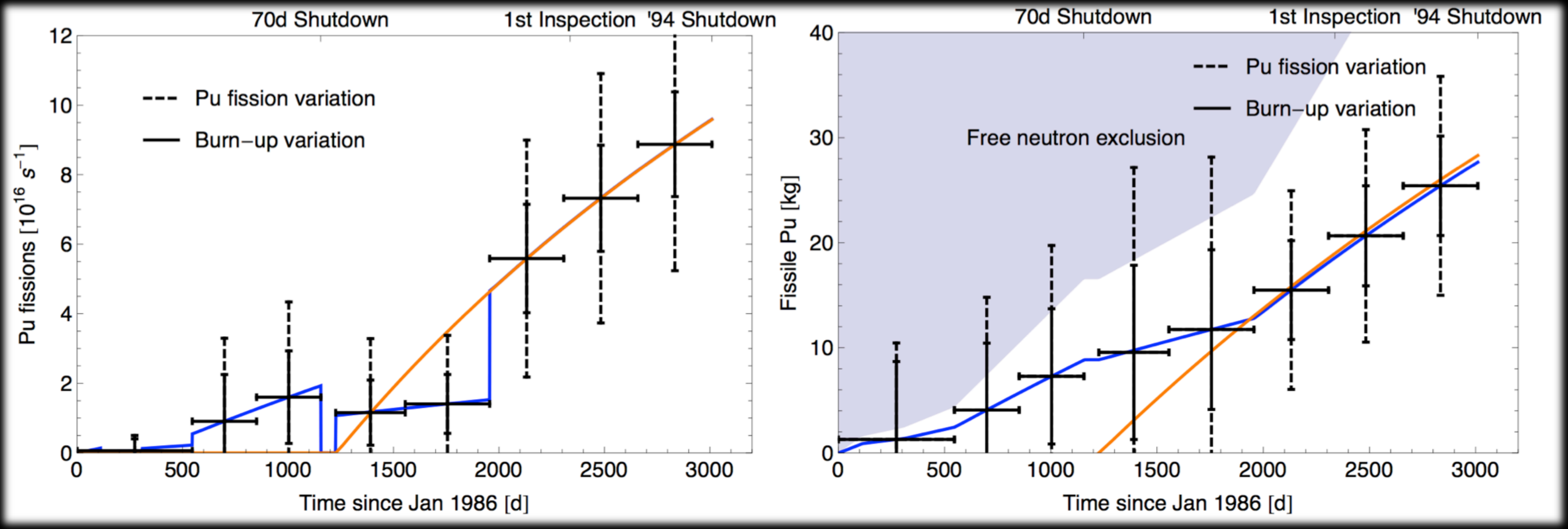


- Neutrinos would have tagged a hypothetical false declaration of $P_{th}(t)$ and BU(t)

DPRK: Plutonium Content

- Neutrino detector setup (point like) starting in 1986
  - Target mass: 5 tons – baseline: 20 m – 95 000 neutrinos events
  - 2% normalization uncertainty – Low backgrounds, well known and subtracted

- Observables
  - Left: Continuous measurement of the plutonium fission rate
  - Right: Continuous measurement of plutonium mass



- 2 σ detection of full core replacement without assuming a full power history

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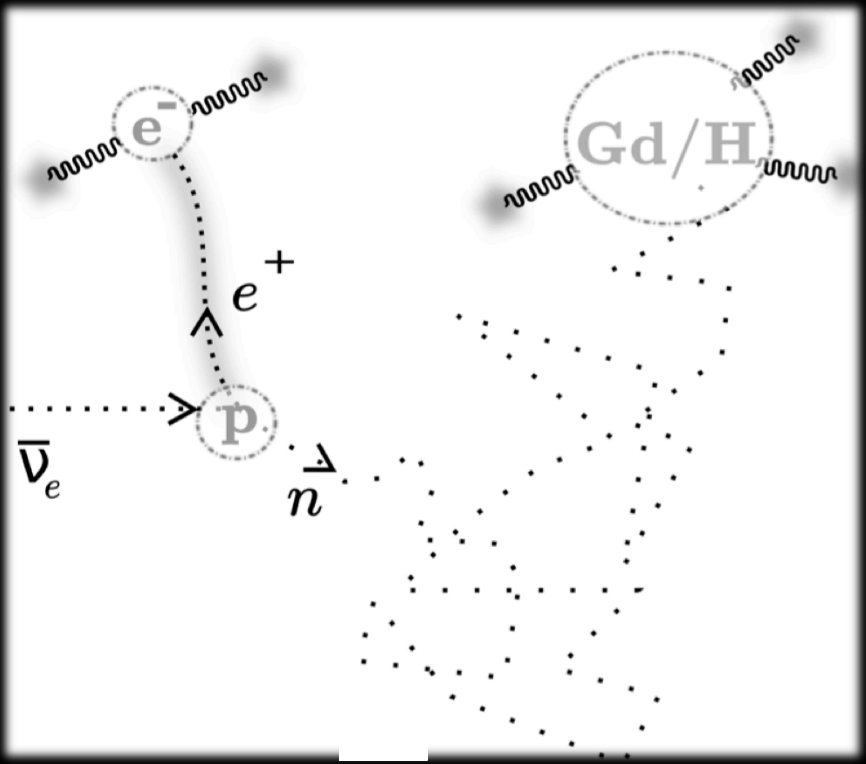
IBD Signal & Backgrounds

Inverse Beta Decay



Selective coincidence
e^+ prompt signal & n-capture H,Gd, Li)

Background rejection

- Accidental γ-neutron coincidence
  - Shielding
  - Segmentation
  - Neutron discrimination
- Fast-n correlated background
  - Rejection of recoil protons with PSD
  - Cosmic rays induced:
    Reactor OFF
    Overburden
  - Reactor induced:
    - must be negligible

IDB: Basics Kinematics

- Inverse beta-decay: $\overline{\nu}_e + p \rightarrow e^+ + n$
- Momentum conservation:

$$\overrightarrow{p_{\nu_e}} + \overrightarrow{p_p} = \overrightarrow{p_{e^+}} + \overrightarrow{p_n}$$

$$\text{Most of the time } \overrightarrow{p_p} = \vec{0} \text{ (lab frame)}$$

- Energy conservation:

$$E_{\nu_e} + E_p = E_{e^+} + E_n$$

neglecting neutron recoil

$$E_{\nu_e} + m_p c^2 = E_{e^+} + m_n c^2$$

$$E_{\nu_e} = E_{e^+} + (m_n - m_p)c^2 = E_{e^+} + \Delta$$

$$E_{e^+} = T_{e^+} + m_e c^2$$

$$E_{\nu_e} = T_{e^+} + m_e c^2 + \Delta$$

- Energy threshold:

$$\Delta \approx 1.293 \text{ MeV}$$

$$m_e c^2 \approx 0.5 \text{ MeV}$$

$$T_{e^+} = \Delta + m_e c^2 - E_{\nu_e}$$

$$T_{e^+} = 0 \rightarrow E_{\nu_e} = 1.804 \text{ MeV} = \mathrm{E}_{\text{th,approx}}$$

But exact threshold given by :

$$\mathrm{E}_{\text{th,true}} = \frac{(m_n + m_e)^2 - m_p^2}{2m_p} = 1.806 \text{ MeV}$$

IDB: positron angular distribution

- Inverse beta-decay: $\overline{\nu_e} + p \rightarrow e^+ + n$
- Positron angular resolution given by (Vogel-Beacom 1999)

$$\frac{d\sigma}{d\cos\theta} \approx 1 + velocity_{e^+} a(E_\nu)\cos\theta$$

- θ positron-neutrino angle
- Valid for reactor neutrino energies
- Average <cos θ > :

$$\langle \cos\theta \rangle \approx \frac{velocity_{e^+} a(E_\nu)}{3} \approx -0.03$$

  - velocity = 1 (but near to the threshold)
  - Infinite nucleon mass approximation a(E)=a
  - Fermi/Gamow-Teller transitions competition → a=-0.1
- Angular distribution of the positron is slightly backward
- Rarely accessible…

IDB: neutron kinetic energy

- Finite Neutron Mass → 1/M terms dev.

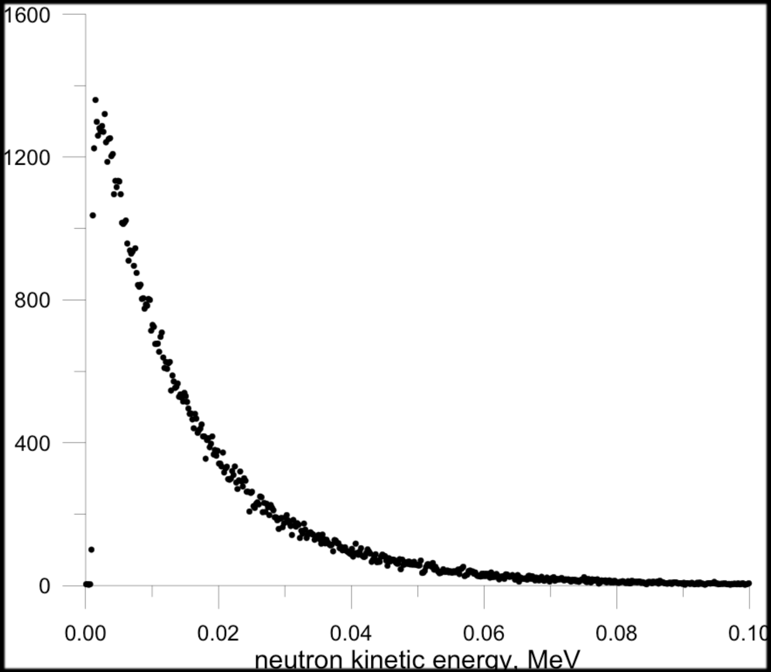
$$E_e^{(1)} = (E_\nu - \Delta)\left(1 - \frac{E_\nu}{M}(1-\cos\theta)\right) - \frac{\Delta^2 - m_e^2}{2M}$$

$$T_n = \frac{E_\nu(E_\nu - \Delta)}{M}(1-\cos\theta) + \frac{\Delta^2 - m_e^2}{2M}$$

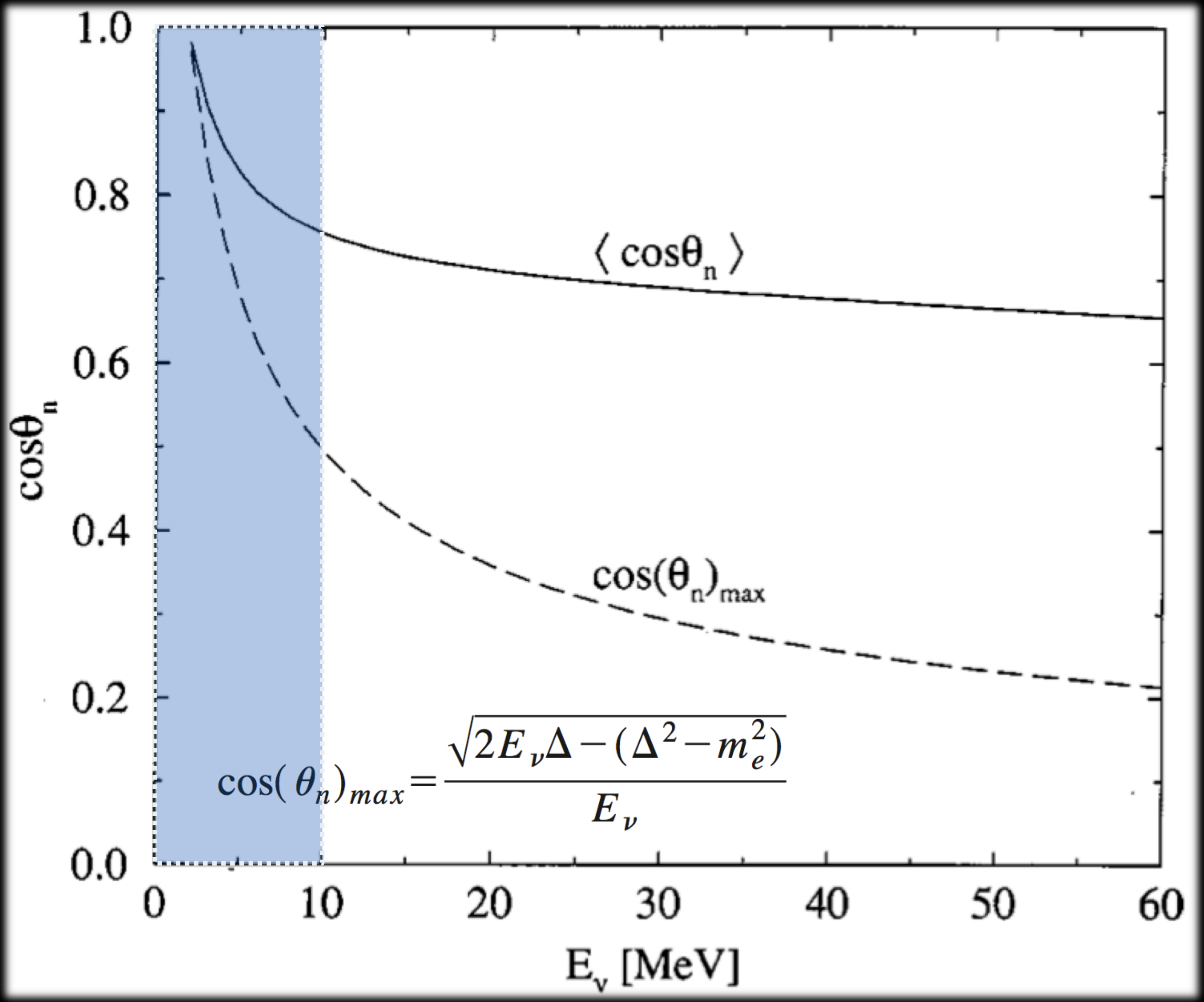
- E_ν = 3.5 MeV
- $E_e = E_\nu - \Delta$ = 3.5-1.3=2.2 MeV
- velocity=1
- assuming cos θ = 0
- M=938 MeV

→ T_n=1/938 (3.5 x 2.2 + 0.7) = 10 keV

IBD generated events



IDB: neutron angular distribution



$$\cos(\theta_n)_{max} = \frac{\sqrt{2E_\nu\Delta - (\Delta^2 - m_e^2)}}{E_\nu}$$

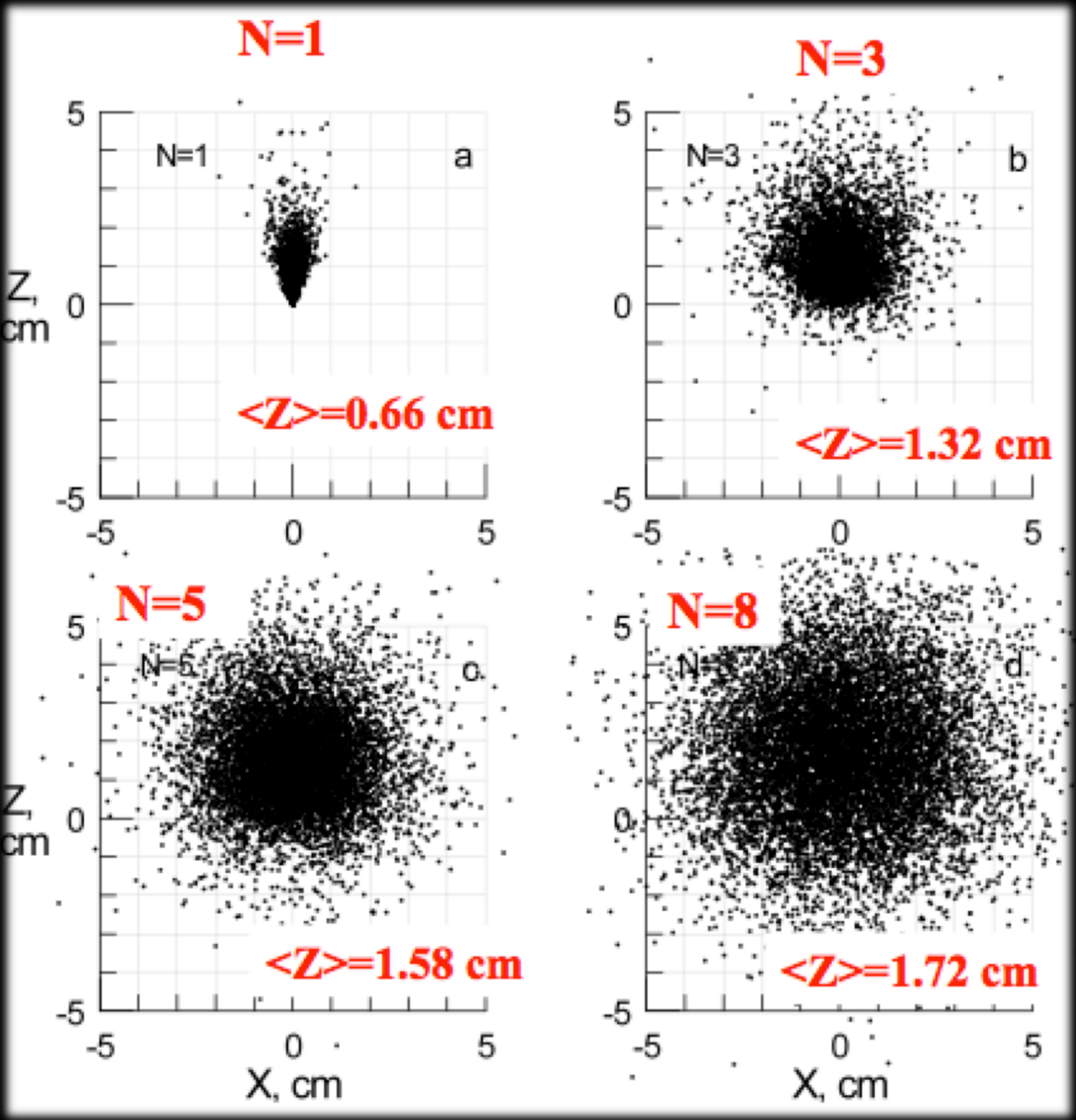
IDB: Directionality

- First neutron step before collision: very clear forward emission

- First few collisions with scintillator atoms the memory is partially conserved and neutron is displaced from the reaction point in +Z direction

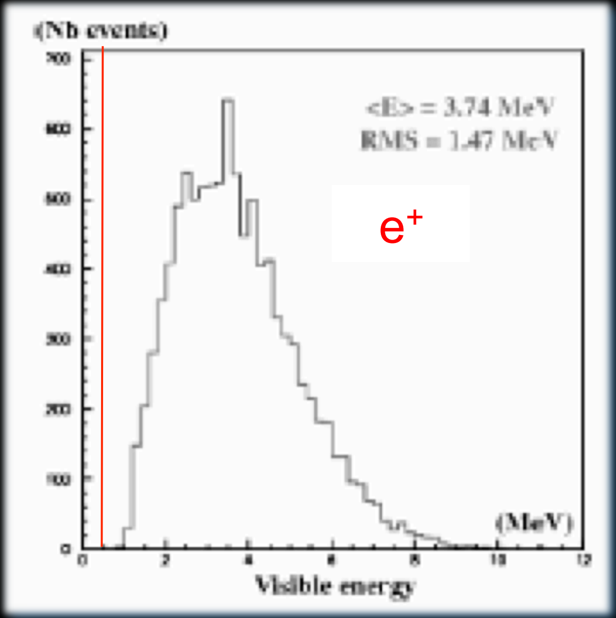
- After 8 collisions the memory is lost and neutrons slow down and diffuse symmetrically around the displaced center.

- After 20 collisions the neutron is thermalized (0.025 eV) and captured

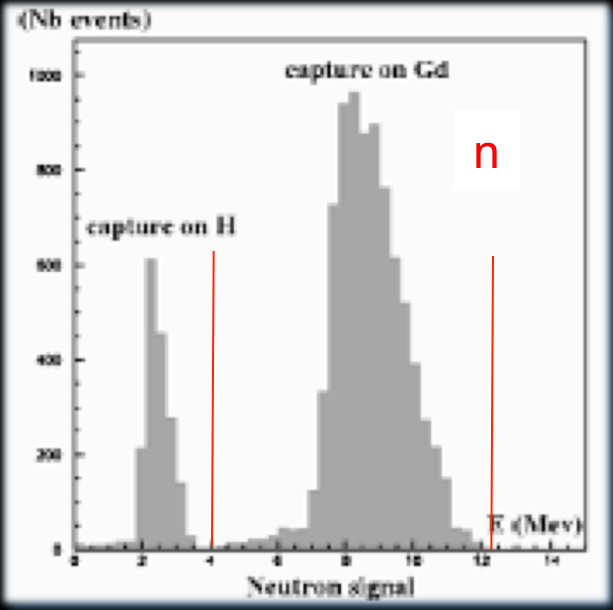


Neutrino Selection Criteria

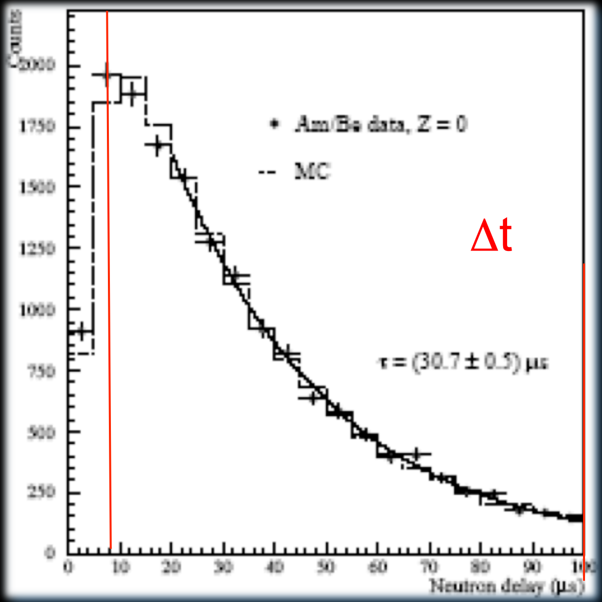
Positron Cut



Neutron Cut



Time Coincidence Cut



IDB: neutron angular distribution

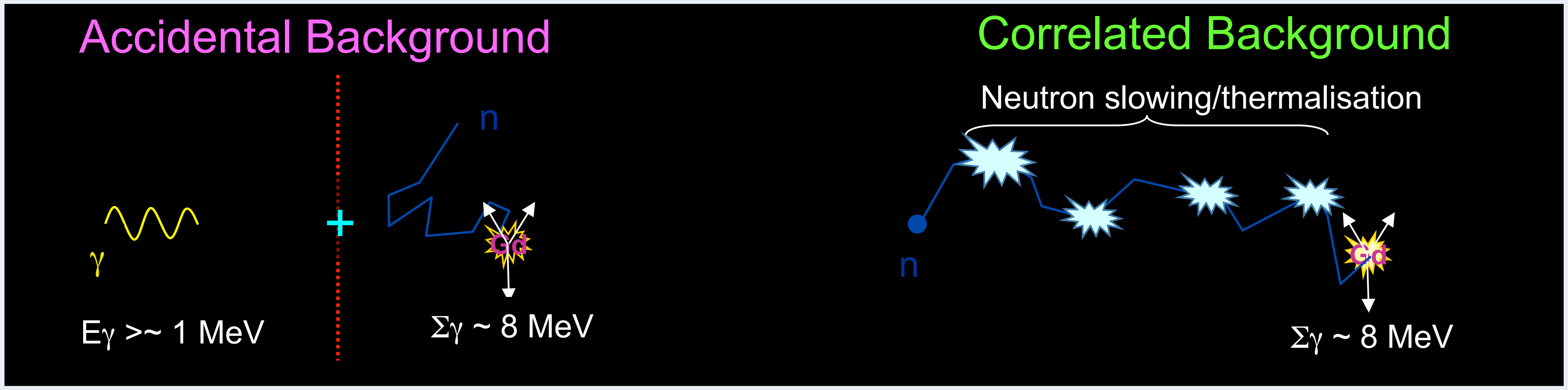
- **IDB reaction**
  - Positron emission (no position information): vertex reconstruction
  - First neutron step in the forward direction → directionality information
  - Then neutron thermalization → random walk → loose directionality
  - Finally neutron capture → vertex localization possible

- After vertex reconstruction: (e^+,n) vertex vector reconstructed for all events and statistically studied → 1.5-2 cm displacement in the antineutrino direction

- **Experimentally**
  - Observed in the Goesgen experiment (10 sigmas)
    - Segmented detector
  - Observed in the Bugey-3 experiment
    - Segmented detector
  - Observed in the CHOOZ experiment
    - Unsegmented detector

- **Future Goal: Could directionaly being used for background rejection?**

Backgrounds



CAUTION: backgrounds at very short baseline cannot be scaled from middle (km) and long (100 km) baseline reactor neutrino experiment

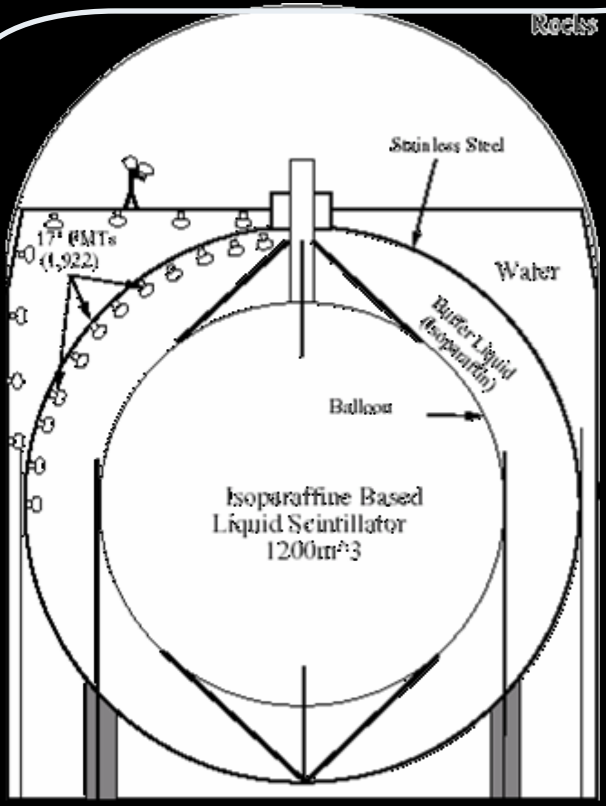
- **Shallower overburden**
- **Accidental backgrounds from the reactor core**
- **Correlated backgrounds from the reactor core**

→ Backgrounds are significantly site dependent !!!

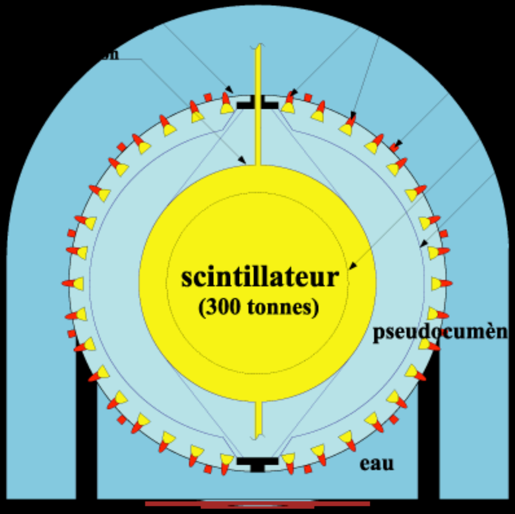
Neutrino Detector Scales

Neutrinos for fundamental Physics (and potentially far field monitoring)

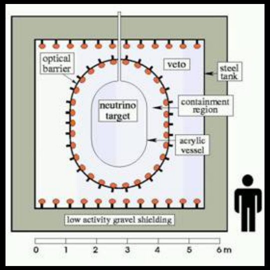
Neutrinos for reactor monitoring



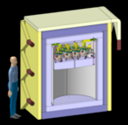
KamLAND
1000 t



Borexino
300 t



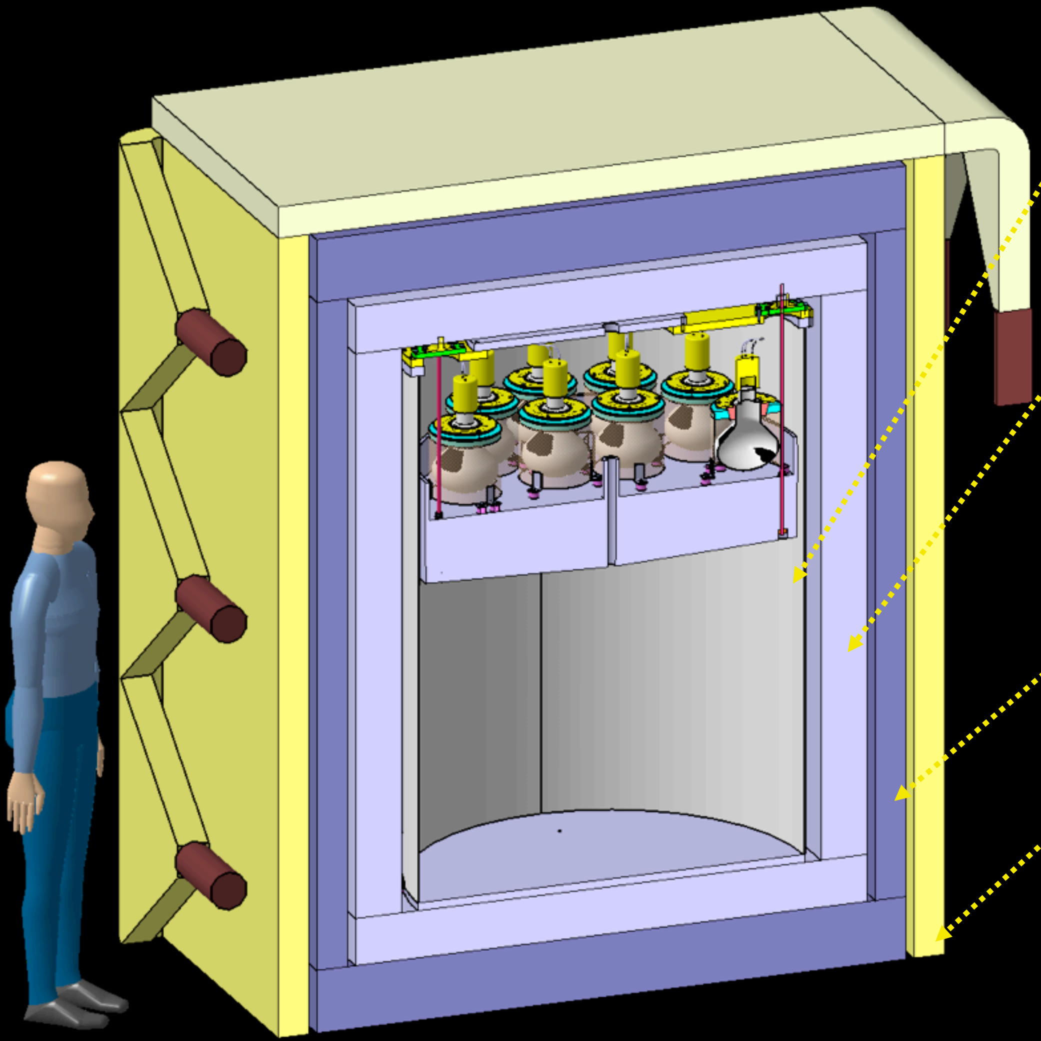
Double Chooz
& CHOOZ
~10 t



Nucifer
1 t

Rate-only: detector considerations

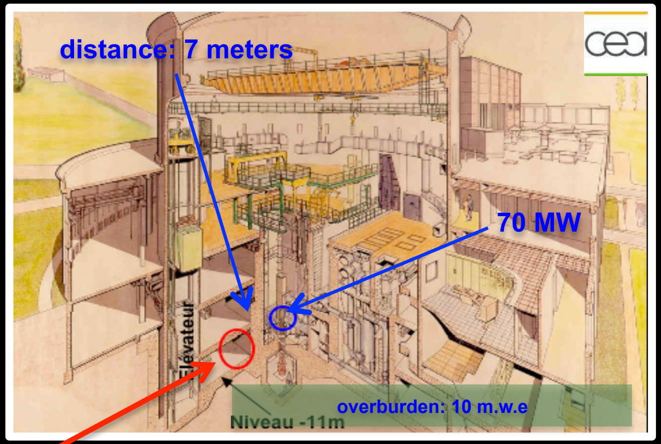
- Small target size – uncontained events - simple readout from the top → rate-only



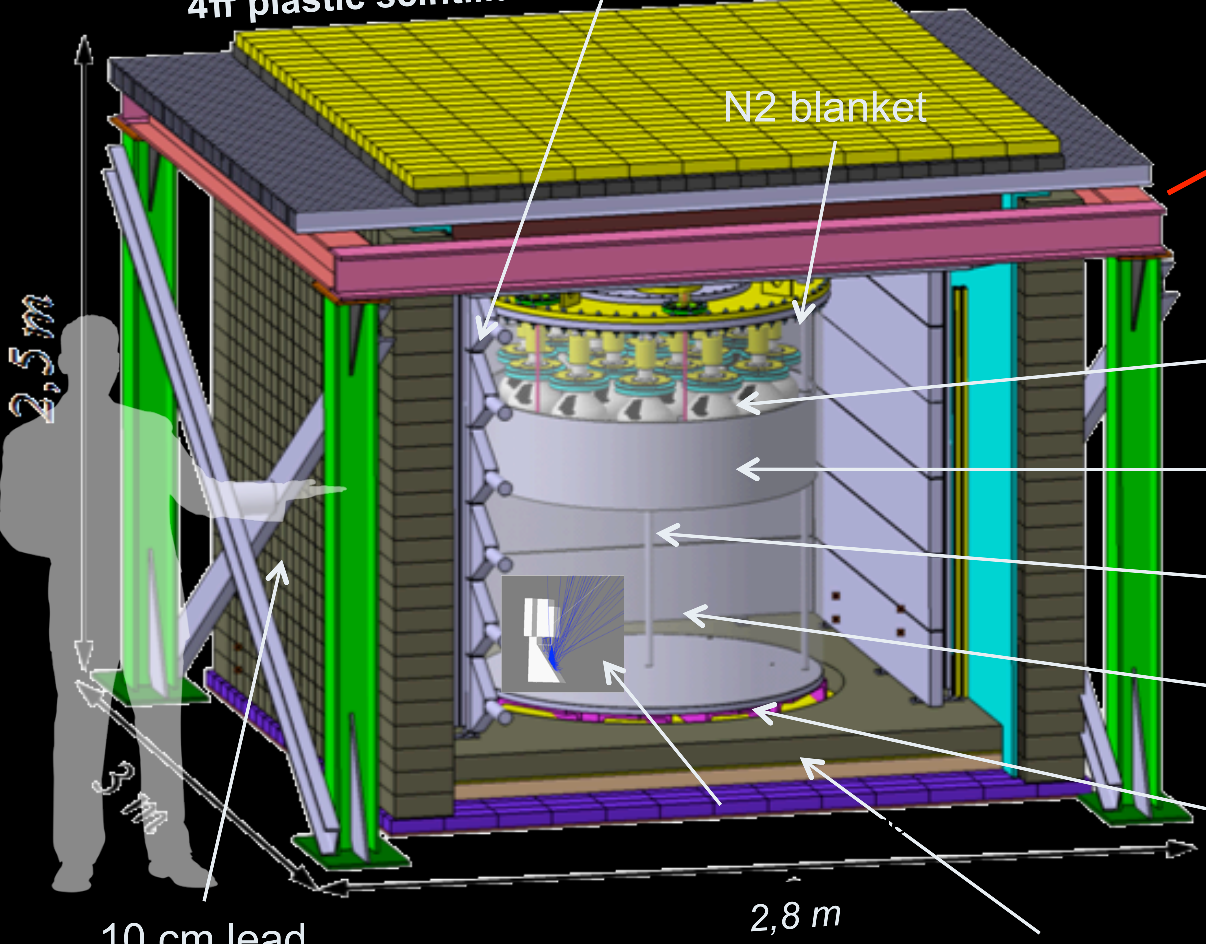
- Target: ~1 m^3 Gadolinium loaded liquid scintillator
- Steel vessel + reflective Coating Inside to wash non uniformities – box geometry for final detector to maximize the volume
- 10 cm H-Z Shielding for Gammas
- 15 cm L-Z Shielding for neutrons
- Muon Veto (plastic scintillator)

No directionality

Nucifer @Osiris (Saclay, France)



Osiris research reactor
CEA-Saclay (600 ν/d) - CEA – IN2P3 coll.



4π plastic scintillator Muon Veto (30 PMTs)

N2 blanket

16 x 8' PMTs low background

25 cm acrylics buffer

Calibration pipe

Target: 0.85 m^3 Gd-LS (0.5%)

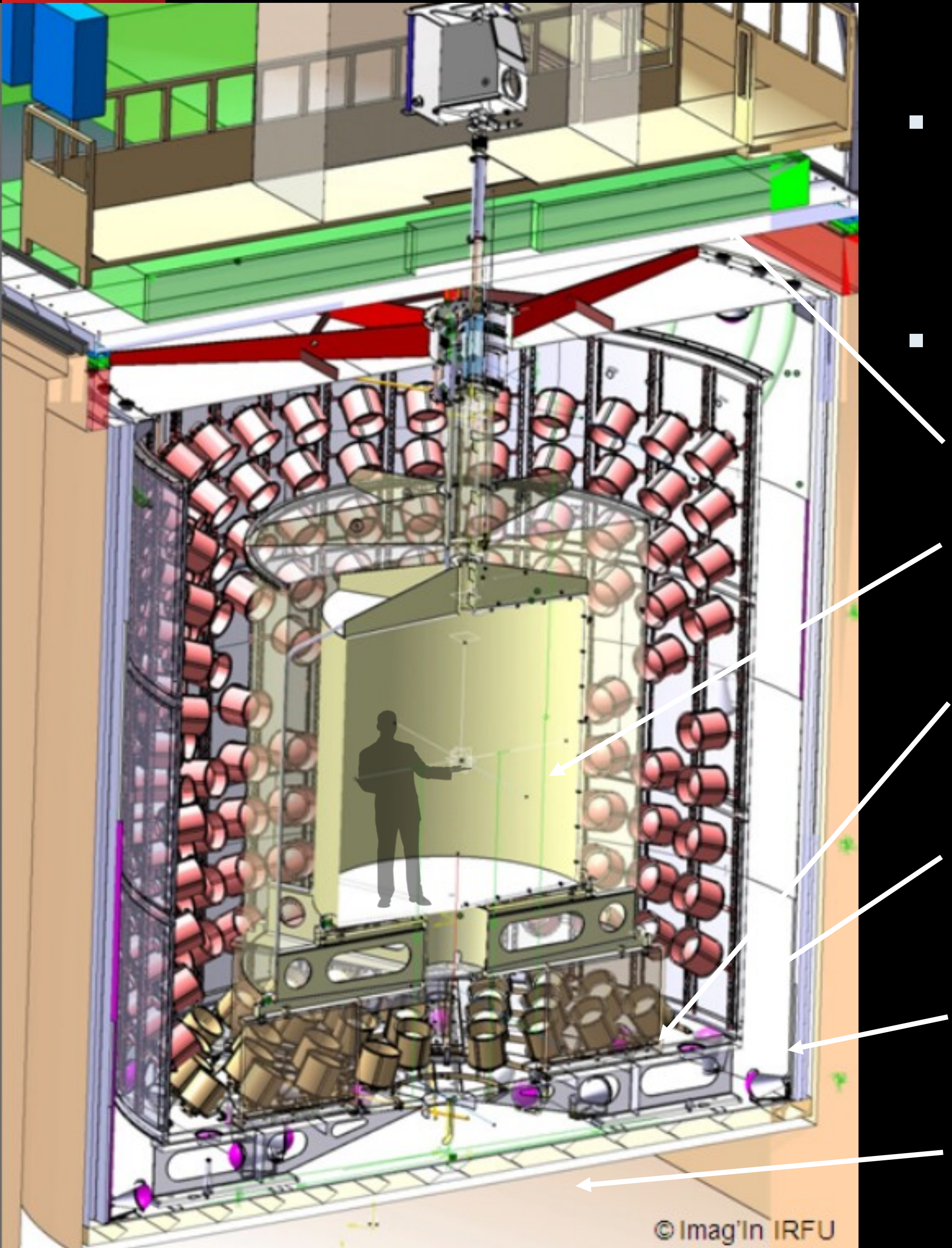
Stainless steel double containment vessel coated with white Teflon coating inside

10 cm lead

T. Lasserre 29/02/2012

Rate+Shape: detector considerations

- Large target size – contained events – 4π light collection system – low systematics – low background → rate +shape
- Directionality : 6° precision



Outer Veto: plastic scintillator strips (400 mm)

ν-Target: 10,3 m^3 scintillator doped with 1g/l of Gd compound in an acrylic vessel (8 mm)

γ-Catcher: 22,3 m^3 scintillator in an acrylic vessel (12 mm)

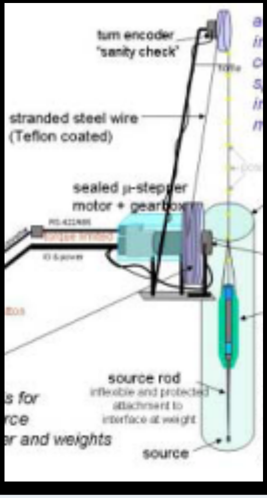
Buffer: 110 m^3 of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs

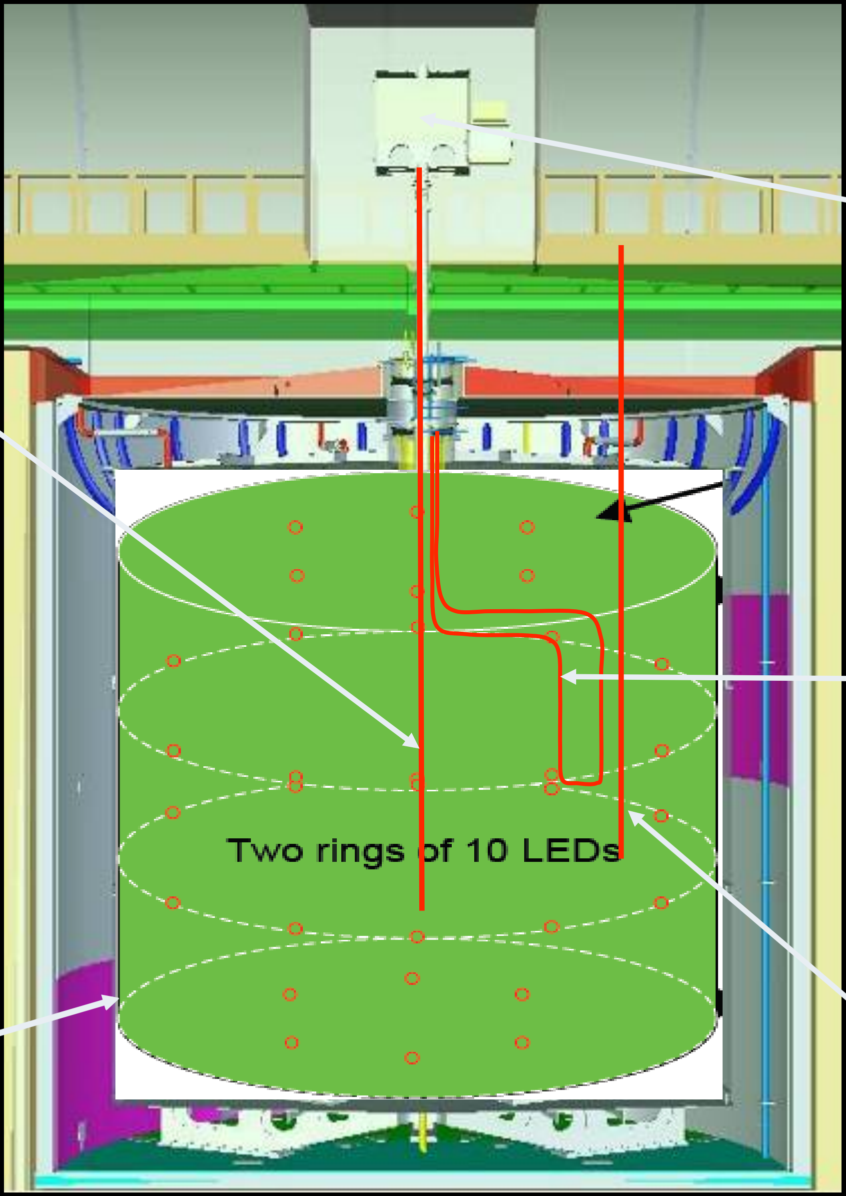
Inner Veto: 90m^3 of scintillator in a steel vessel equipped with 78 PMTs

Veto Vessel (10mm) & Steel Shielding (150 mm)

Detector Calibration Systems

Fish-line



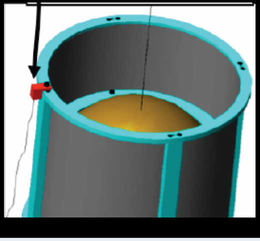


Glove Box

guide Tube

guide Tube

Embedded LED calibration system 385, 420, 470 nm



Homework

Homework

- Using Phys. Rev. C84, 024617 (2011) plot the emitted neutrino spectra of ^{239}Pu and ^{235}U as a function of the neutrino energy. Plot the weighed sum for the following composition: 70% of fission from ^{235}U and 30% from ^{239}Pu.

- Estimate the expected IBD neutrino rate per day in a 5 m^3 detector composed of a pseudocumene-based (C_9H_{12},d=0.88) liquid scintillator detector located at 25 m from a 4 GW PWR core (80% efficiency).

- Plot the IBD interaction rate as a function of the IBD positron energy, including statistical uncertainties, for 30 days of data taking.

- Compare the IBD positron spectra for two core compositions:
  a) 70% of ^{235}U and 30% of ^{239}Pu
  b) 60% of ^{235}U and 40% of ^{239}Pu

In each case the thermal power is supposed to be constant at 4 GW and the data taking time is taken to be 30 days.

ν-Monitoring for Heavy Water Reactors

- Article: PRL 113, 042503 (2014)

- Abstract
  - In this Letter we discuss the potential application of antineutrino monitoring to the Iranian heavy water reactor at Arak, the IR-40, as a nonproliferation measure. An above ground detector positioned right outside the IR-40 reactor building could meet IAEA verification goals for reactor plutonium inventories. While detectors with the needed spectral sensitivity have been demonstrated below ground, additional research and development is needed to demonstrate an above-ground detector with this same level of sensitivity. In addition to monitoring the reactor during operation, observing antineutrino emissions from long-lived fission products could also allow monitoring the reactor when it is shut down, provided very low detector backgrounds can be achieved. Antineutrino monitoring could also be used to distinguish different levels of fuel enrichment. Most importantly, these capabilities would not require a complete reactor operational history and could provide a means to reestablish continuity of knowledge in safeguards conclusions should this become necessary.