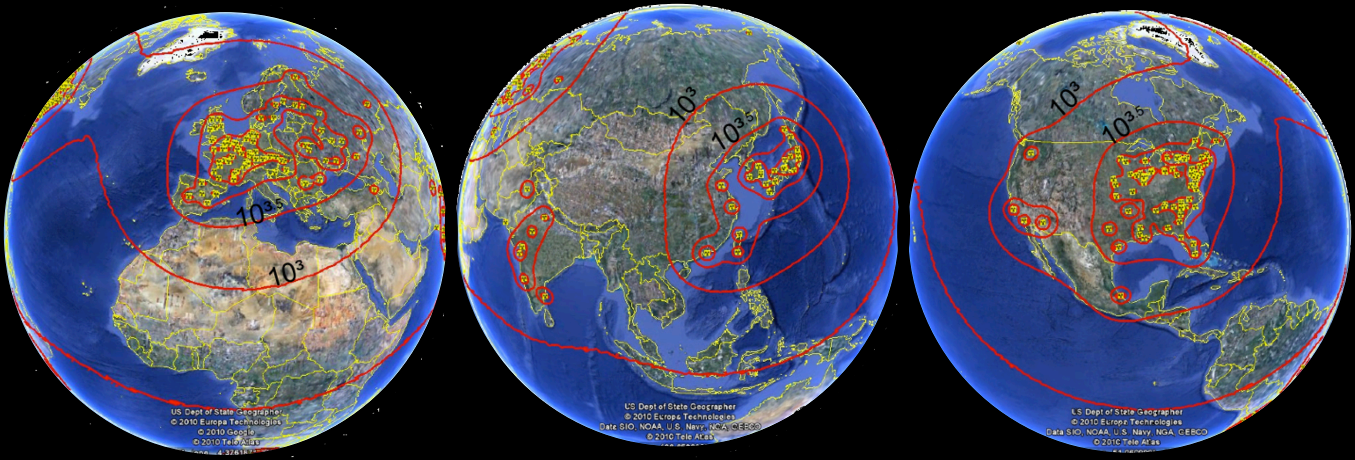
Reactor antineutrino



Thierry Lasserre
Saclay

ECT Lectures

-I: Nuclear Reactors & Reactor Neutrinos
-II: Reactor Neutrino Detection
-III: Reactor Neutrino Oscillation Physics
-IV: The Reactor Antineutrino Anomaly
-V: Non-oscillation physics
  - Geo-neutrinos
  - Non-proliferation
  - Neutrino Coherent Scattering

Nuclear Reactor Antineutrinos

- 1946 : Pontecorvo suggested to use nuclear reactors in order to perform neutrino experiments.

- 1953-1959 : Reines and Cowan showed that neutrinos are real particles using nuclear reactors as a source.

- Since then : reactors, powerful sources with 6×10^{20} / sec electron antineutrinos emitted by a modern 4 $GW_{thermal}$ reactor, have been used often in neutrino studies.

(Petr Vogel, 2005)

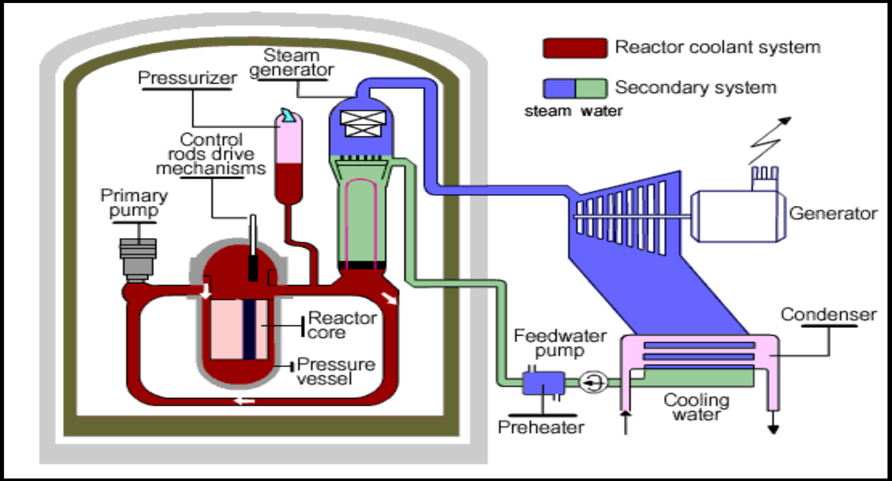
ECT Lecture 1

- Nuclear Reactors
- Reactor Antineutrino Flux & Spectrum

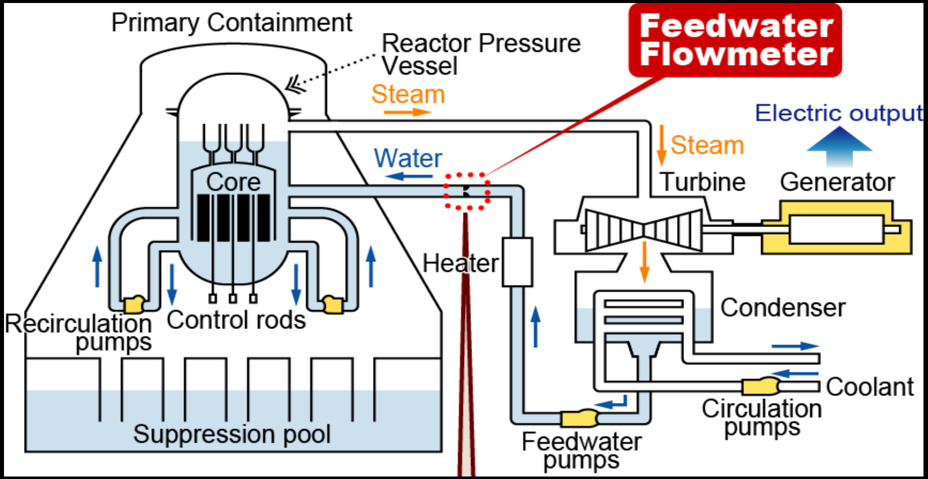
Thierry Lasserre (Saclay)

Pressurized Light Water Reactor

- **Reactor Vessel:**
  - ^{235}U Fuel in assemblies
  - LW is used as neutron moderator
  - Control rods
- **Primary Circuit Loop:**
  - Fission heats LW (300°C, 155 bars)
  - Water is use as heat carrier
- **Secondary Circuit Loop:**
  - Heat exchange with primary Water Circuit
  - Water is converted in Vapor
- **Generator**
  - Production of electricity
- **Third Cooling Loop**
  - Condensation of the Vapor into water
  - Cooling source: river, sea, or ‘evaporation’ tower if needed



PWR

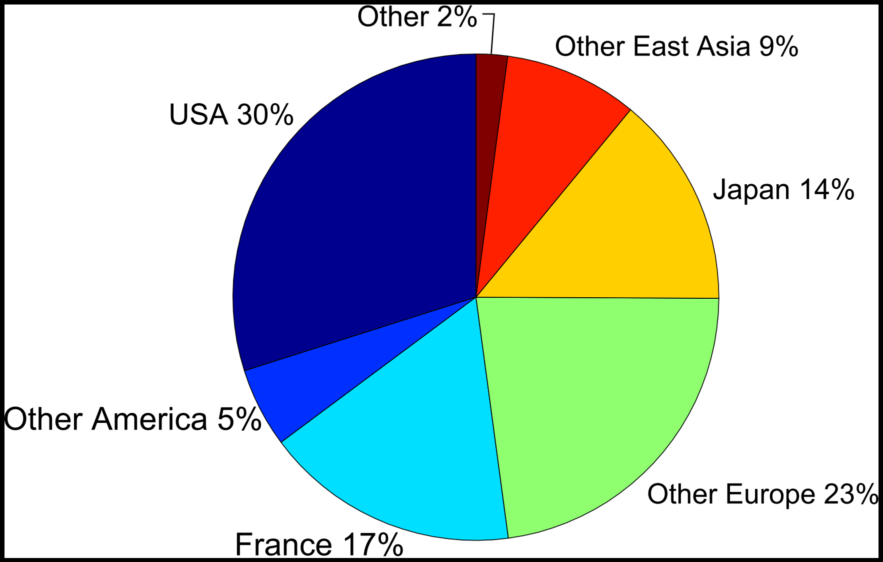


BWR

Nuclear Reactors

- **Power Nuclear Stations:**
  - 201 in the world (most of them having multiple units)
  - Total thermal power = 1134 GWth total thermal power
  - Mixed fuel (^{235,238}U & ^{239,241}Pu)
  - Thermal neutron flux (0.025 eV)
  - Extended neutrino source:
    - 3-4m diameter, 4m high
- **Non-Power Nuclear Reactors:**
  - Research reactors used as neutron source
  - Reactors used for propulsion
  - Highly enriched in ^{235}U
  - Thermal neutron flux
  - Extended/Compact neutrino source (0.6mx0.6m possible)

- **Pressurized Light Water Reactor (PWR)**
- **Boiling Water Reactor (BWR)**
- **CANDU (heavy water)**
- **Naval**
- **Research**
- **Weapons Production**
- **New Technology**



Nuclear Fuel

- **Uranium based fuel**
  - Mainly ^{238}U (99.2745%, $T_{1/2}$=4.47 10^9 y)
  - 0.7% of ^{235}U (fissile, $T_{1/2}$=703.8 10^6 y)

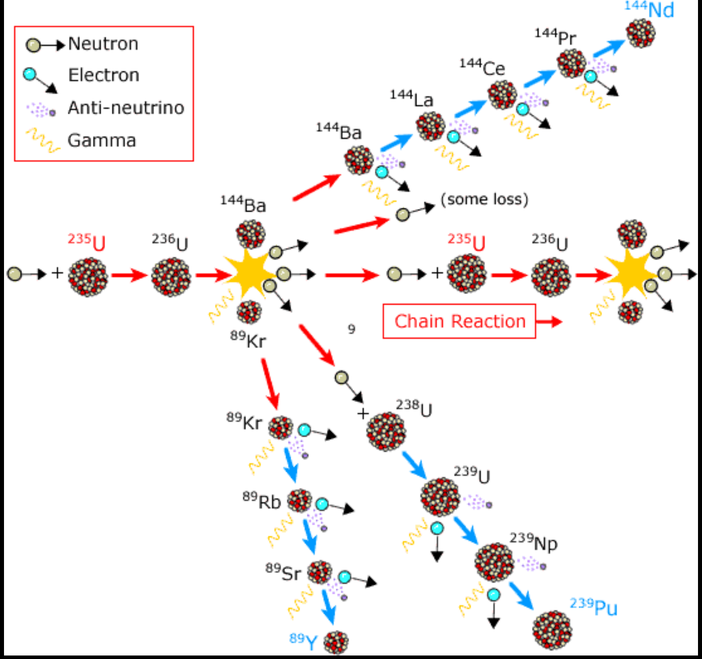
  → in form of UO_2

- **^{238}U**
  - High neutron capture threshold (0.8 MeV)
  - No fission with thermal neutrons
  - Some fissions induced by fast neutrons

- **Enrichment in ^{235}U (3.5% in PWR)**
  - Fission chain reactions induced by thermal neutrons on ^{235}U

- **But other reactions:**
  - ^{238}U capture neutrons

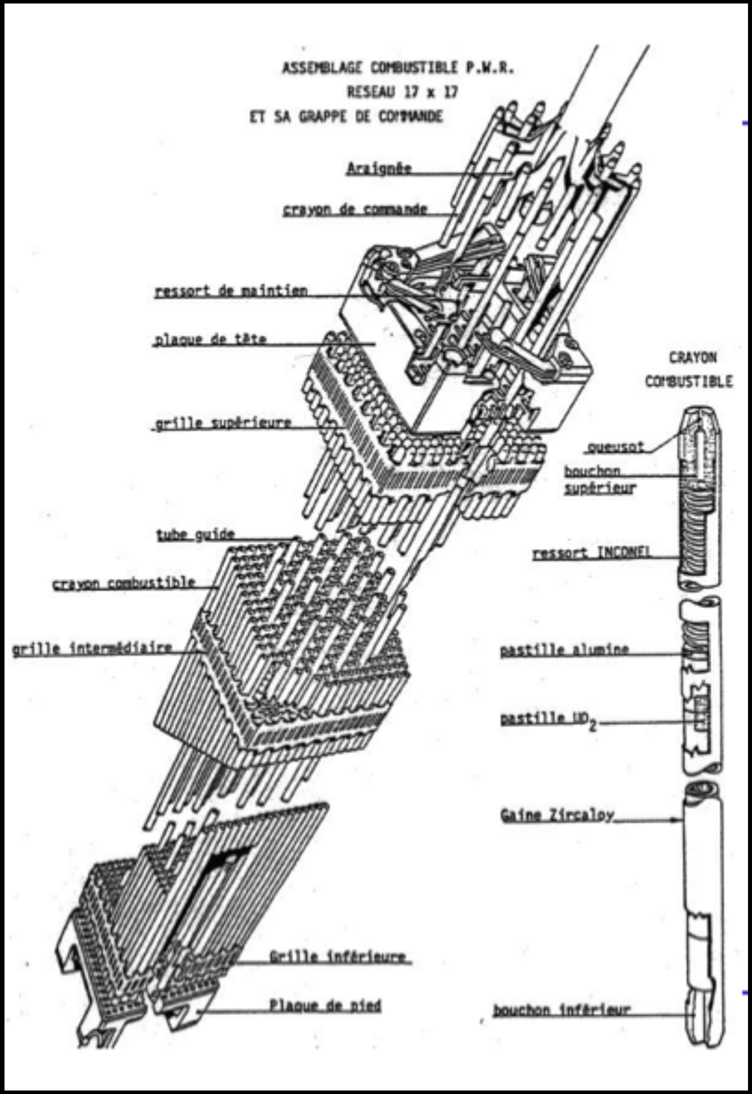
  → in-situ production of ^{239}Pu, ^{241}Pu



Nuclear Fuel

- Fuel in N4-reactors (Chooz)
  - 120 tons of UO_2
  - $^{235}U \approx 3.45\%$: 3.60 tons
- 205 fuel assembly
  - 264 rods per assembly
  - 272 "pellets" per rods
  - 8 g per "*pastilles »*

- Loading/unloading
  - by third
  - every 1.5 years
- Energy extracted
  - 45 GWd/ton = 3.89 10^{15} J/t

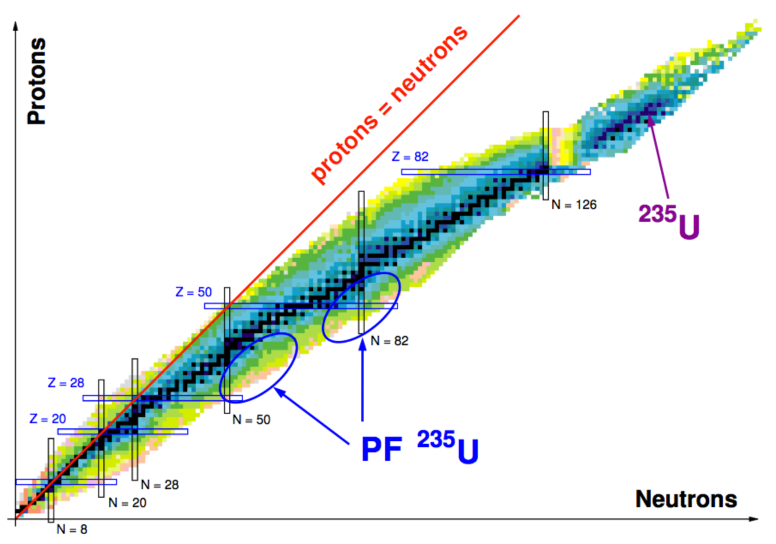


Fission Products (FP) & Yield (FY)

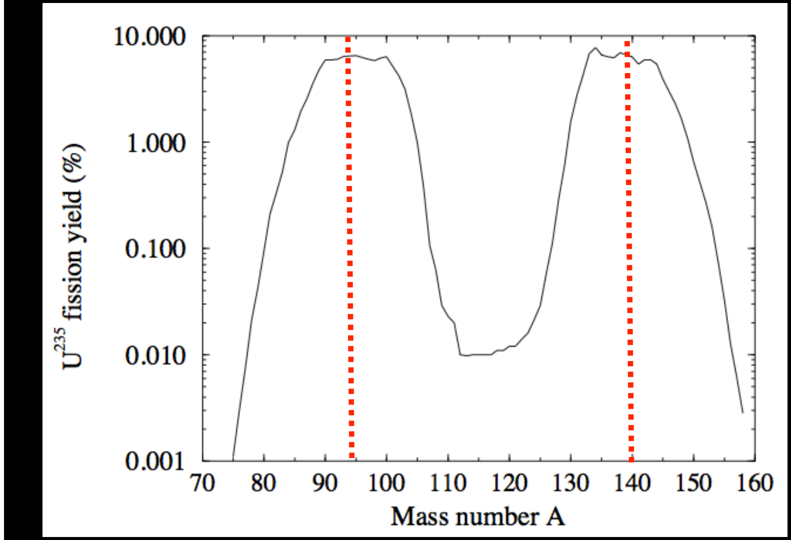
- Fission of ^{235}U

$U(235,92) + n_{th} \rightarrow X(A1,Z1) + Y(A2,Z2) + 2\ n_{fast}$

- The many X and Y are called ‘Fission Fragments’ or ‘Fission Products’
- Highest fission yields for the couple: Zr(94,40) and Ce(140,58)
  - Together: 40+58=98 protons & 94+140=234 neutrons
  - On average 6 neutrons have to β-decay to 6 protons to reach stability → 6 ν
  - On average 1.5 ν (25%) are emitted with energy > 1.8 MeV



Two ‘’Mass’ Bumps: Z=86-104, Z=130-148



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Plutonium Production

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

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

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

- $^{239}\mathrm{Pu} + \mathrm{n} \rightarrow {}^{240}\mathrm{Pu} + \gamma$

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

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

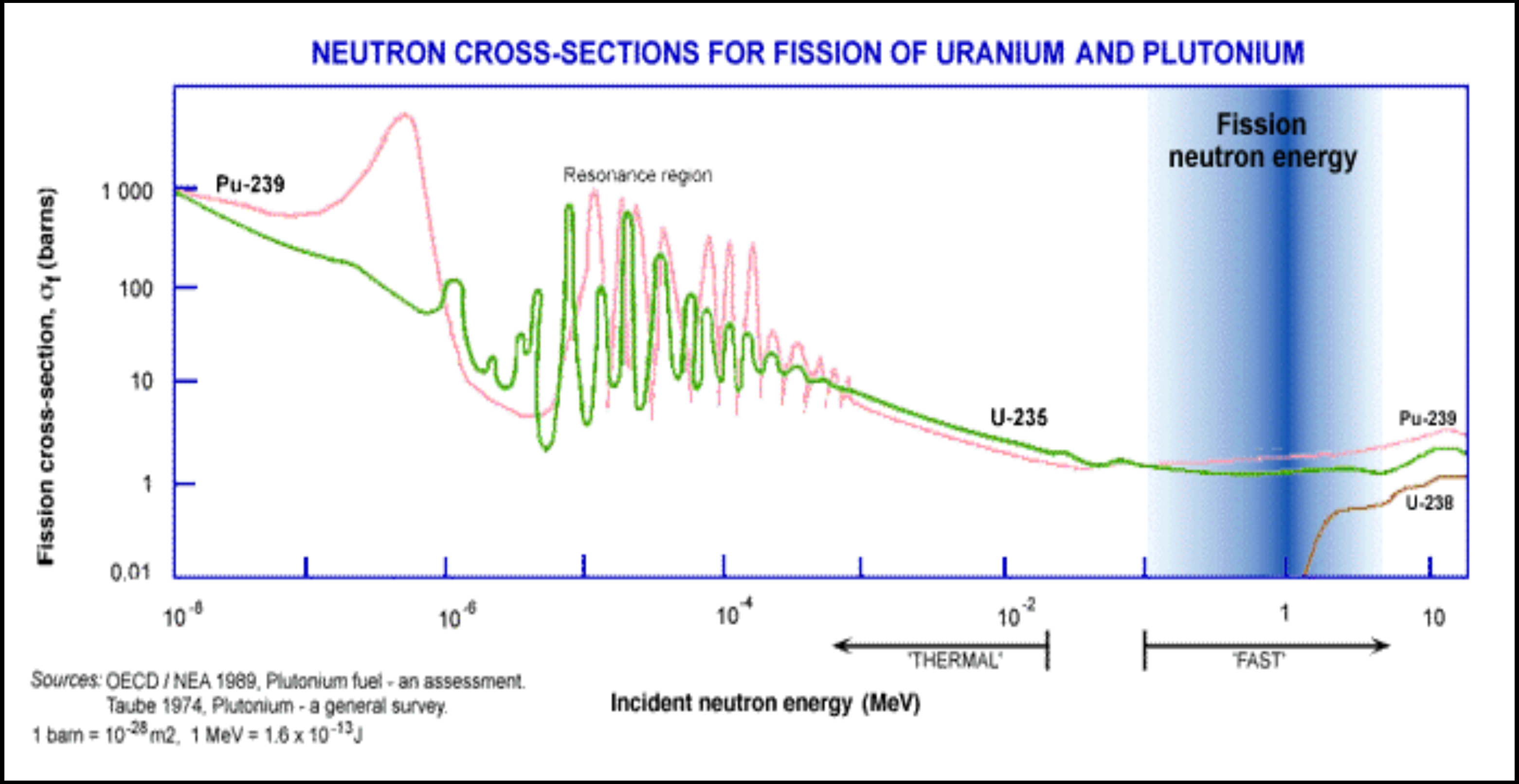
- ^{239}Pu, ^{241}Pu are fissile isotopes (thermal neutrons)

→ Content of nuclear fuel changes with time as the reactor core “evolves”.

Fission Cross Section

$^{235}U + n_{th} \rightarrow X + Y + 2\ n_{fast}$

$^{239}Pu + n_{th} \rightarrow X + Y + 2\ n_{fast}$



NEUTRON CROSS-SECTIONS FOR FISSION OF URANIUM AND PLUTONIUM

Sources: OECD / NEA 1989, Plutonium fuel - an assessment.
Taube 1974, Plutonium - a general survey.
1 barn = 10^{-28} m2, 1 MeV = 1.6×10^{-13} J

Nuclear Chain Reaction

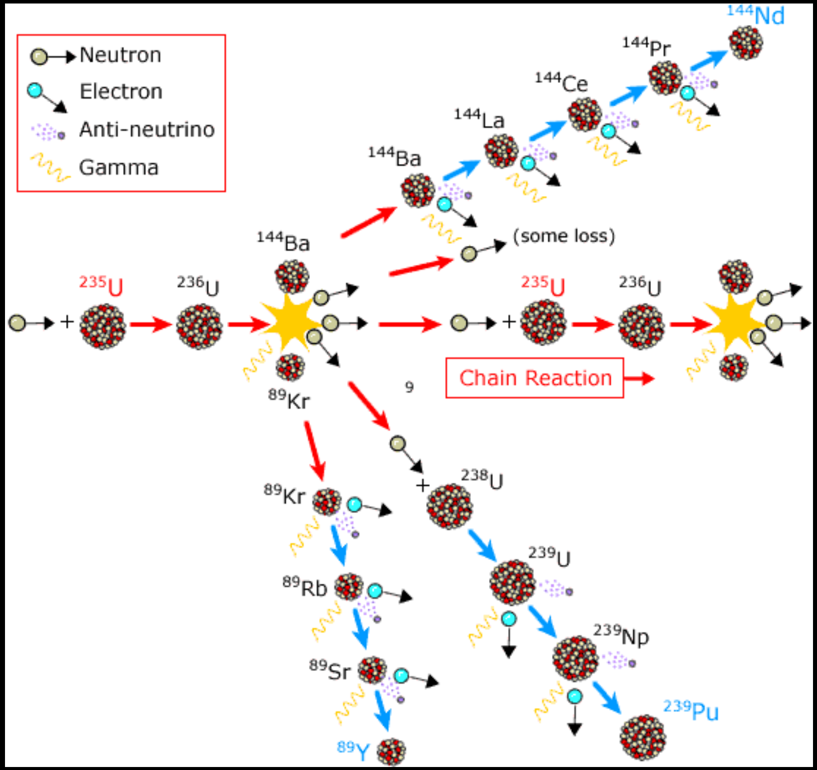
- Nuclear reactors are copious, isotropic sources of electron antineutrinos

- Neutrinos come from β-fission fragments, not directly from the fission

- Fission of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu

- β-decay of neutron rich fission fragments
    - $X(A,Z) \rightarrow Y(A,Z+1) + e^{-} + \text{anti-}\nu_e$
    - 200 MeV / fission is released
    - Fission rate is 4 GW / 200 MeV ~ 2.10^{20} fissions / sec
    - 6 anti-ν_e emitted per fission
    - 7.5 10^{20} anti-ν_e/s for a typical 4 GW core

- Antineutrino spectrum is time dependent as the beta daughters come into equilibrium



Reactor Antineutrino Flux Estimate

Fissions in nuclear cores (average)

200 MeV et 6 neutrinos per fission of $U^{235,238}$, $Pu^{239,241}$

- 200 MeV released per fission:

  → 200 MeV = 200 * 10^6 * 1,6 10^{-19} J = **3,2 10^{-11} Joules**

- Thermal Power:

  → 1 GW = 1 **10^9 W (J / s)**

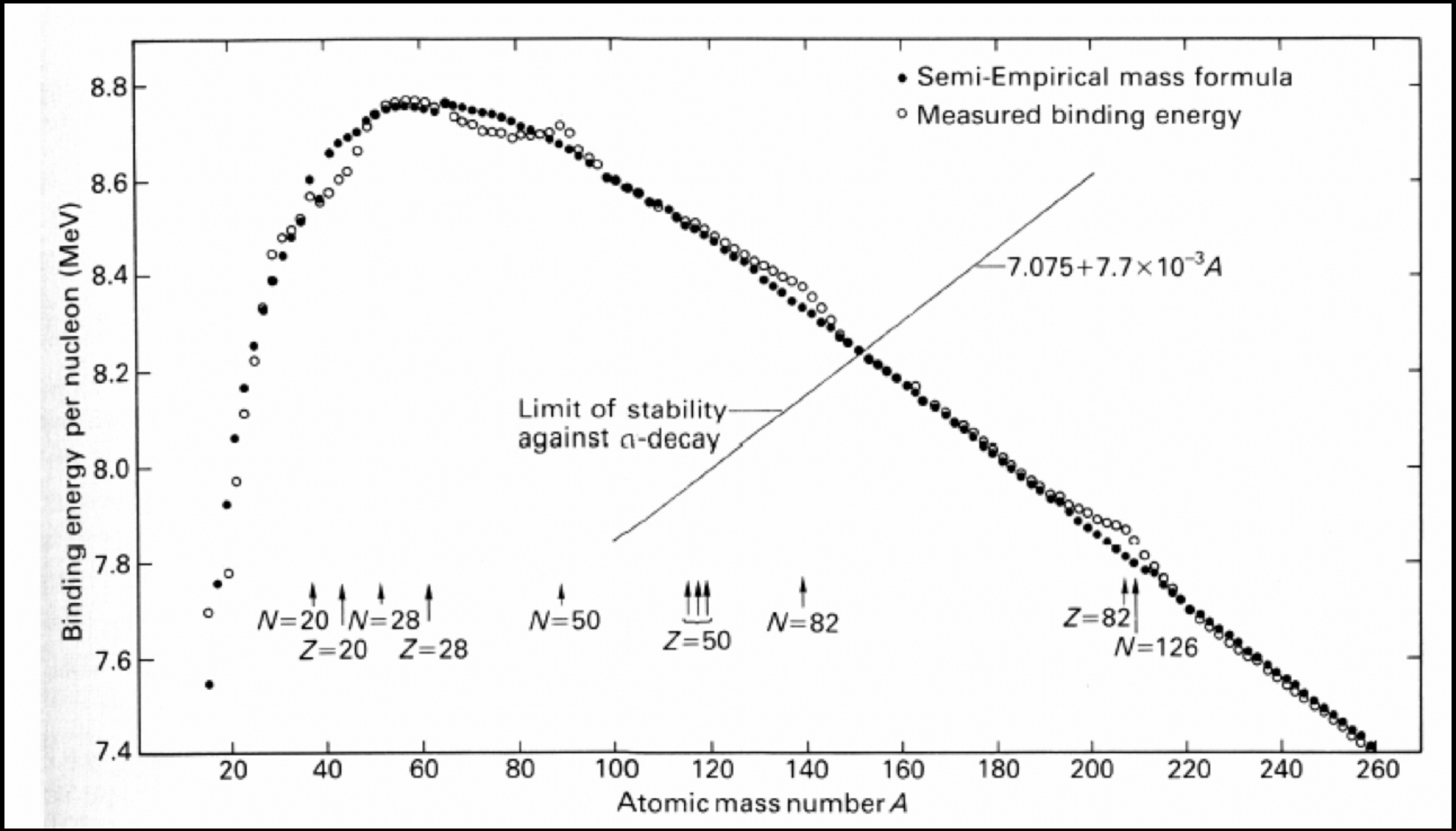
- Electron anti-neutrinos

  → 10^9 W / **3,2 10^{-11} Joules * 6**

  → **2 10^{20} neutrinos / s**

Energy Released per fission

- Considering: $^{238}_{92}\mathrm{U} \rightarrow {}^{119}_{46}\mathrm{Cs} + {}^{119}_{46}\mathrm{Cs}$
    - U(92,238) : B(Z,A)/A=7.6 MeV/nucleon
    - Cs(46,119): B(Z,A)/A=8.5 MeV/nucleon
    - Energy released = 238x8.5 MeV – 2x119x7.6 = 215 MeV



Time Evolution of the antineutrino spectrum

- **Inverse beta decay threshold: Q=1.8 MeV**
  - Ensures that only large Q-value decays are observed
  - Ensures that only short half-life decays are observed
  - Typical time to equilibrium is a few hours

- **Spent-fuel**
  - Fuel stored > a few years on power plant site for cooling
  - Potential emitted of antineutrinos
  - Main isotopes with Q>1.8 MeV: ^{140}Ba, ^{144}Ce, ^{106}Ru, ^{90}Sr
  - Typically add <0.1% due to long half life and low Q → negligible

- But there are other time-dependent effects…

Long Lived Fission Products & Yield

Isotope	$T_{1/2}$	Fission Yield		Mass (kg)	ß EndPoint	$\frac{M \times \langle\sigma\rangle}{T_{1/2}}$
		^{235}U	^{239}Pu			
^{131}I	8.02 d	$2.88\ 10^{-2}$	$3.84\ 10^{-2}$		0.971	-------
^{140}Ba/^{140}La	12.752 d	$6.12\ 10^{-2}$	$5.59\ 10^{-2}$	6.15	3.762	
^{141}Ce	32.501 d				0.581	-------
^{89}Sr	50.53 d				1.495	-------
^{95}Zr/^{95}Nb	64.02 d				1.16	-------
^{144}Ce/^{144}Pr	284.893 d	$5.26\ 10^{-2}$	$3.73\ 10^{-2}$	5.44	2.997	
^{106}Ru/^{106}Rh	373.59 d	$4.02\ 10^{-3}$	$4.28\ 10^{-2}$	3.06	3.678	
^{147}Pm/^{147}Sm	2.6234 y	$2.09\ 10^{-2}$	$2.04\ 10^{-2}$		0.224	-------
^{90}Sr/^{90}Y	28.79 y	$5.90\ 10^{-2}$	$2.10\ 10^{-2}$	3.81	2.280	
^{137}Cs	30.07 y	$6.27\ 10^{-2}$	$6.55\ 10^{-3}$		1.176	-------
^{99}Tc	$0.21\ 10^{6}$ y					
^{93}Zr	$1.5\ 10^{6}$ y					
135Cs	2.0 106 y					
^{129}I	$16.\ 10^{6}$ y					

Masses are given for the full load of Uranium
after a combustion at 45 GW days per ton of fuel (GW . d / t)

Fuel Evolution: Burnup

- Fuel evolve with time

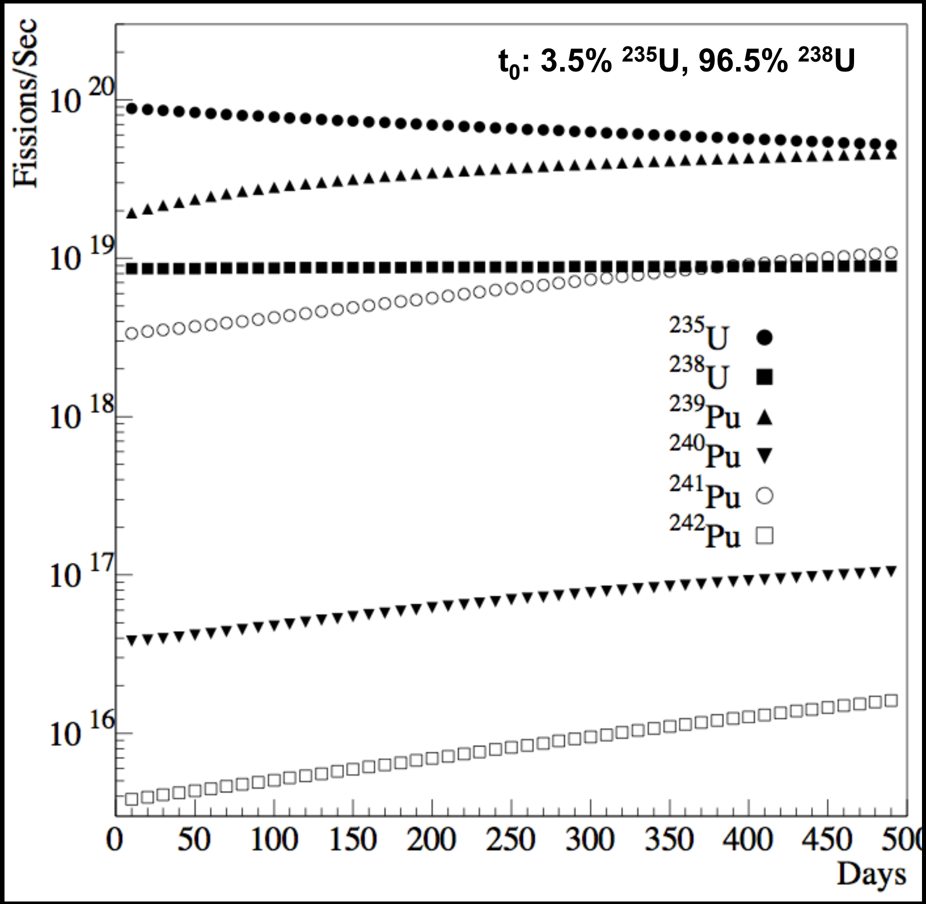
- A typical cycle last 500 days

- Then 1/3 of the fuel is being replaced

- Four main fissioning isotopes
  - ^{238}U: 53.8%
  - ^{239}Pu : 32.8%
  - ^{238}U : 7.8%
  - ^{241}Pu : 5.6%
  - Others <0.1%

- Plutonium breeding during fuel cycle (250 kg) changes the antineutrino flux
  - N (s^{-1})= a . (1+k) P (GW)
  - k : burnup factor (Pu/U fraction)
  - A <10% correction

Need information from the power company



Reactor Time Variation

- Example: CHOOZ experiment Eur.Phys.J.C27:331-374,2003

- 3-6 week shutdown every 12-18 months

- 1/4-1/3 of fuel assemblies are replaced, remaining fuel repositioned

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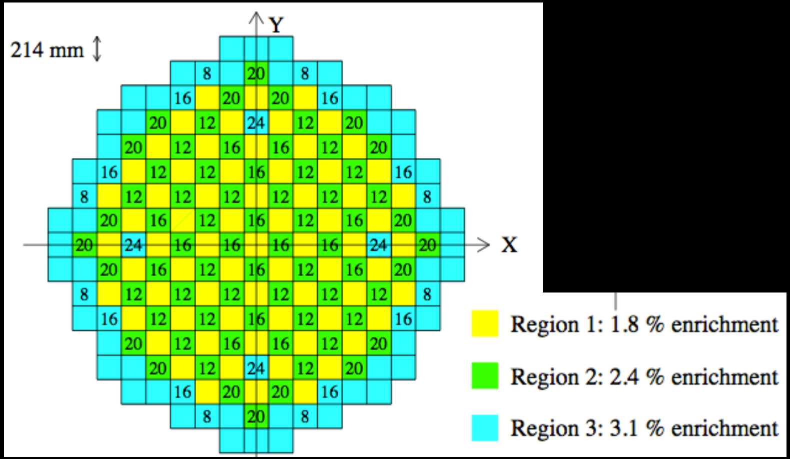
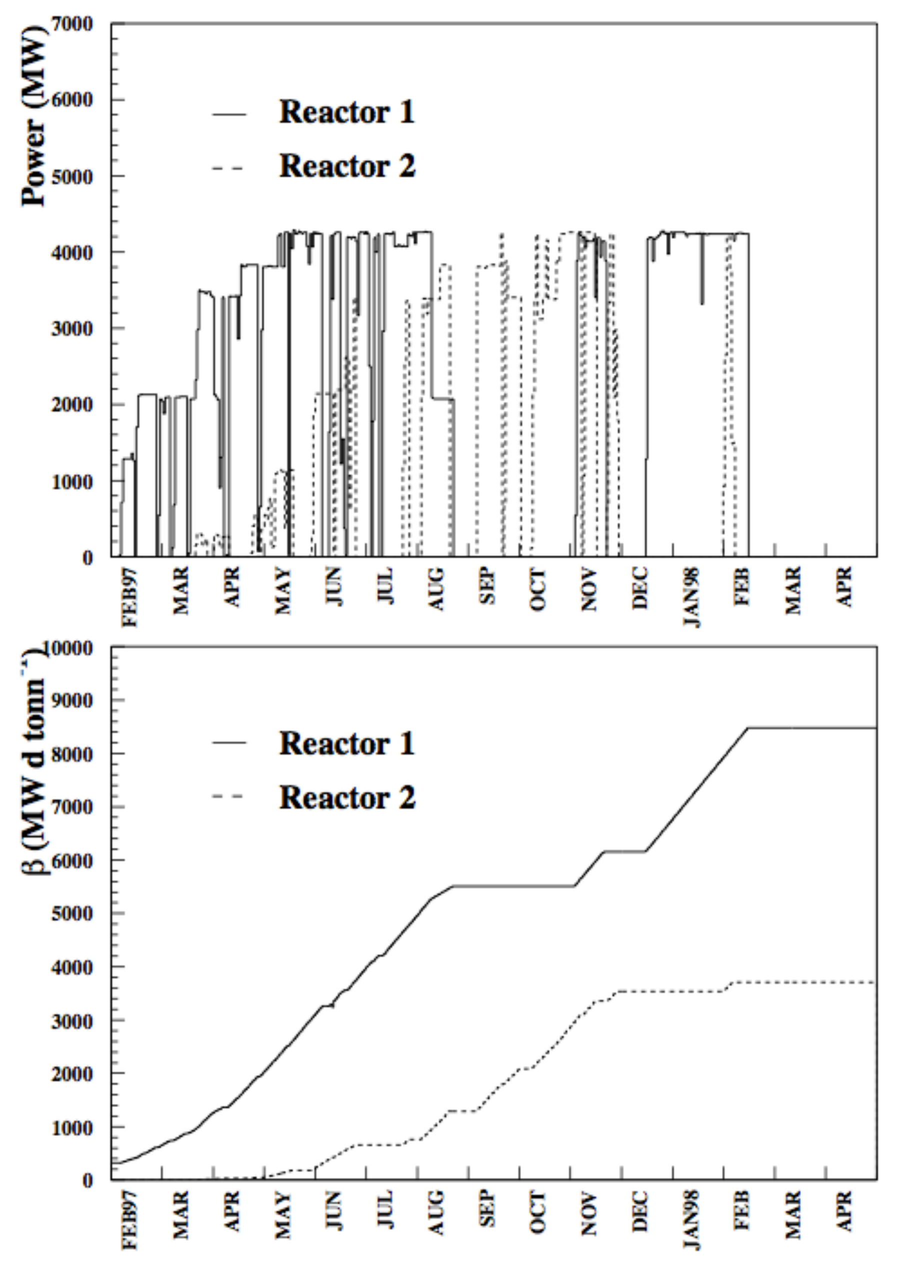


- Long shutdown of 6 months every 10 years



ECT Lecture 1

- Nuclear Reactors
- Reactor Antineutrino Flux & Spectrum

Thierry Lasserre (Saclay)

Flux & Spectrum Prediction

- **Antineutrino flux**
  - >99.9% antineutrinos produced by ^{235}U, ^{239}Pu, ^{238}U, ^{241}Pu
  - >90% antineutrinos produced by ^{235}U, ^{239}Pu

- **^{235}U, ^{239}Pu, ^{241}Pu**
  - electron spectrum measurement (ILL reactor, 1980's)
  - electron → neutrino spectrum conversion
    - Old conversion (Schreckenbach et al., 1980's)
    - New conversion method (Mueller et al., 2011, +3%, w.r. old)

- **^{238}U**
  - Computation based on nuclear databases
    - Old computation (Vogel et al., 1980's)
    - New computation (Mueller et al., 2011, +9.6% w.r. old)

Reactor beta-spectrum

- **$S_{tot}(E)$: integrated neutrino spectrum**

$$S_{\rm tot}(E) = \sum_{k={}^{235}\rm U,{}^{238}U,{}^{239}Pu,{}^{241}Pu} \alpha_k \times S_k(E)$$

- **$S_k(E)$: spectrum normalized to 1 fission**
  - E: electron kinetic energy
  - α_k: number of fission of the isotope k, at a given time

- **Each isotope 'k' undergo fission producing fission products 'fp'**
  - $A_{fp}(t)$: activity of the fpth fission product, normalized to 1 fission of isotope 'k'

- **Each fission products decay, through N_b branches connecting the ground state of the parent nucleus to the exited states of the daughter nucleus**
  - $BR_{fb}{}^{p}$: branching ratio of the bth branch of the fpth fission product
  - $E0_{fp}{}^{p}$: the end-point energy of the bth branch of the fpth fission product.
  - Z_f : charge of the parent nucleus.
  - A_f : atomic number of the parent nucleus.

$S_k(E)$: spectra per fission per isotopes

Sum of all fission products' activities

$$S_k(E) = \sum_{fp=1}^{N_{fp}} \mathcal{A}_{fp}(T) \times S_{fp}(E)$$

Sum of all β-branch of each fission product

$$S_{fp}(E) = \sum_{b=1}^{N_b} BR^b_{fp} \times S^b_{fp}(Z_{fp}, A_{fp}, E^b_{0fp}, E)$$

Theory of β-decay

$$\underbrace{K^b_{fp}}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_{fp}, A_{fp}, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E^b_{0fp})^2}_{\text{Phase space}}$$

$$\underbrace{C^b_{fp}(E)}_{\text{Shape factor}} \times \underbrace{\left(1 + \delta^b_{fp}(Z_{fp}, A_{fp}, E)\right)}_{\text{Correction}}$$

$$\delta^b_{fp}(Z_{fp}, A_{fp}, E) = \delta_{QED}(E) + A_C(Z_{fp}, A_{fp}) \times E + A_W \times E$$

A_c & A_w corrections

- **Weak-magnetism correction (finite size of the nucleons)**
  - Approx: difference of proton and neutron magnetic mome
  - $A_w>0$

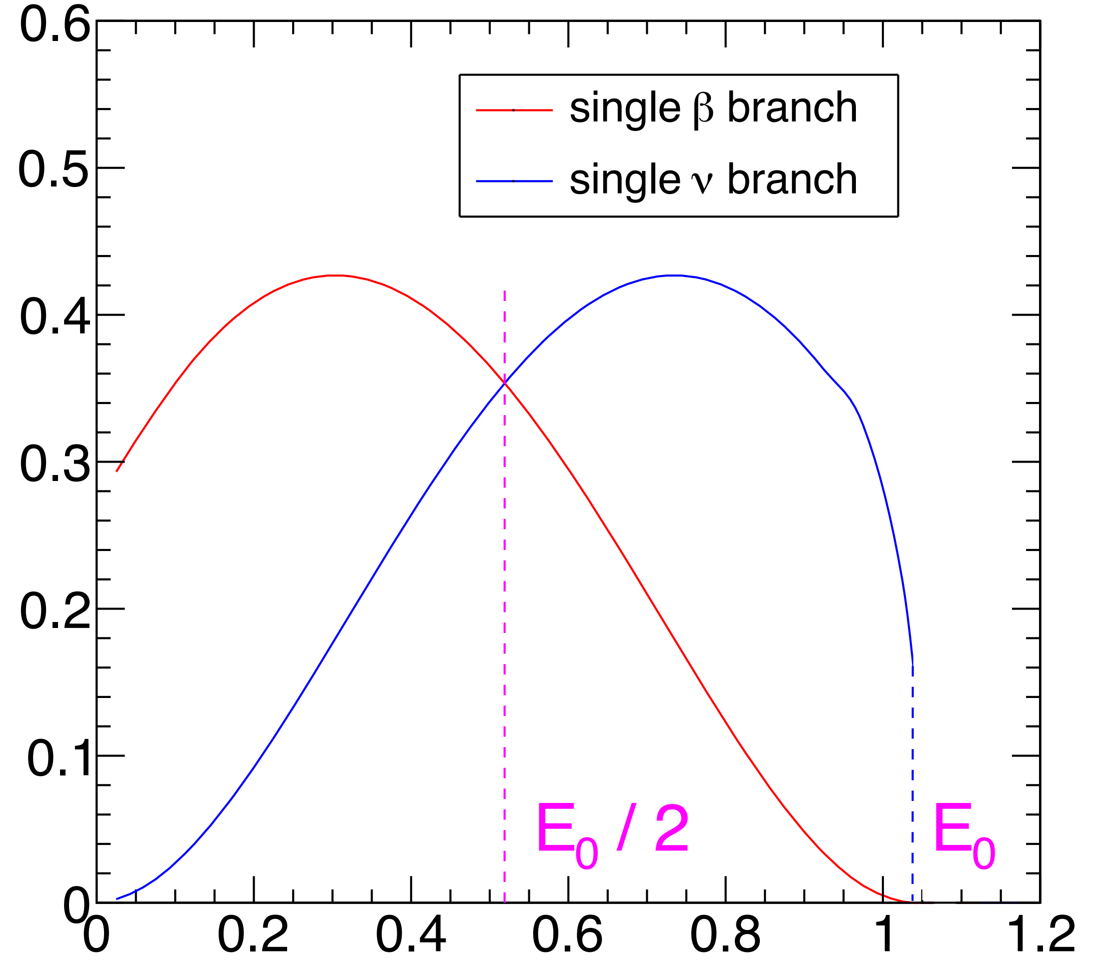
$$A_W = \frac{4}{3}\frac{\langle l + (\mu_p - \mu_n)\sigma\rangle}{m_N\langle\sigma\rangle\lambda} \approx \frac{\mu_p - \mu_n - \frac{1}{2}}{m_N\lambda} \approx 0.47\%/MeV$$

- **Coulomb correction (finite size of the decaying nucleus)**
  - electron spectrum measurement (ILL reactor, 1980’s)
  - electron → neutrino spectrum conversion
    - Old conversion (Schreckenbach et al., 1980’s)
    - New conversion method (Mueller et al., 2011, +3%, w.r. old)

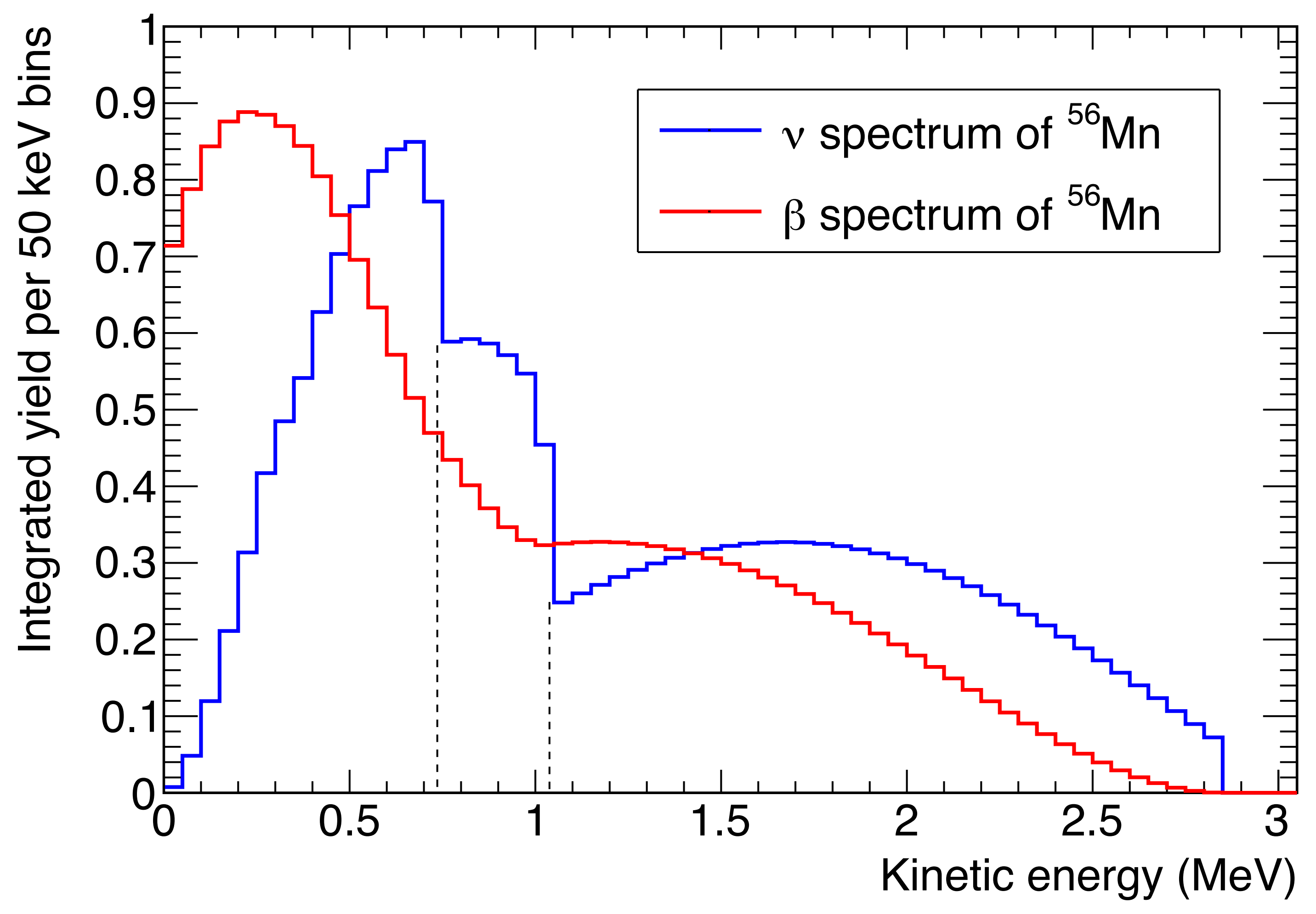
$$A_C = -\frac{10Z\alpha R}{9\hbar c}$$

From e⁻ to neutrino spectrum

$$E_\nu = E^b_{0fp} - E$$



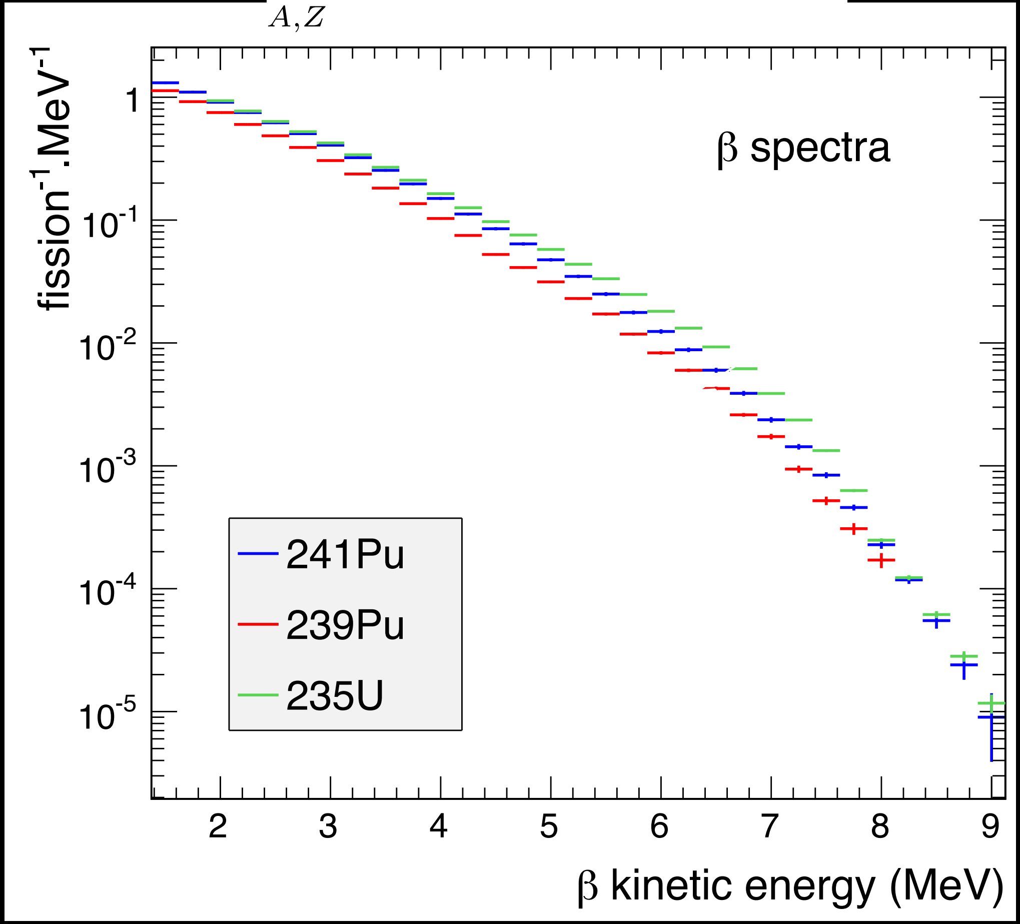
From e⁻ to neutrino spectrum



The ILL electron Data Anchorage

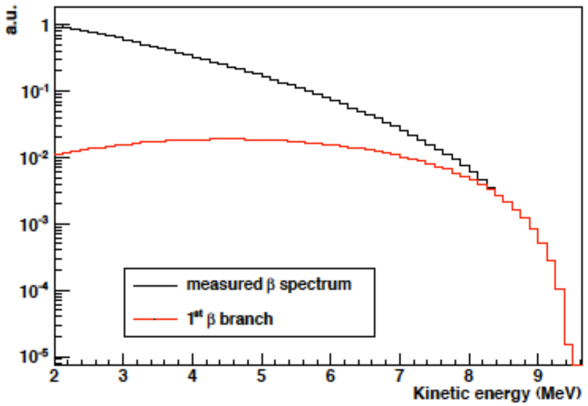
- Accurate e^- measurements @ ILL' (1980-89):
  - High resolution magn. spectrometer
  - Intense and pure thermal n spectrum from the core
  - Extensive use of reference internal conversion electron lines → Normalization (1.8%)

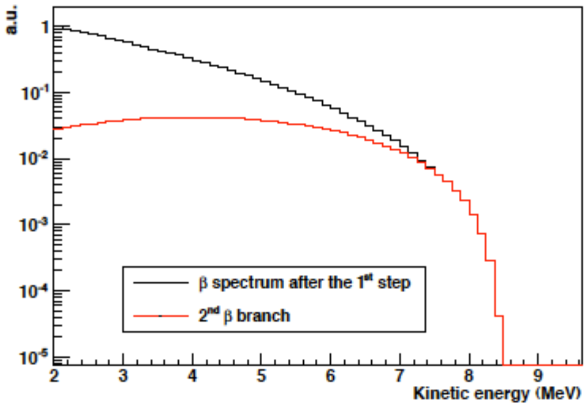
$$\sum_{A,Z} \left\{ {}^{A}_{Z}X \longrightarrow {}_{Z+1}^{\;A}Y + e^{-} + \bar{\nu}_e \right\}$$

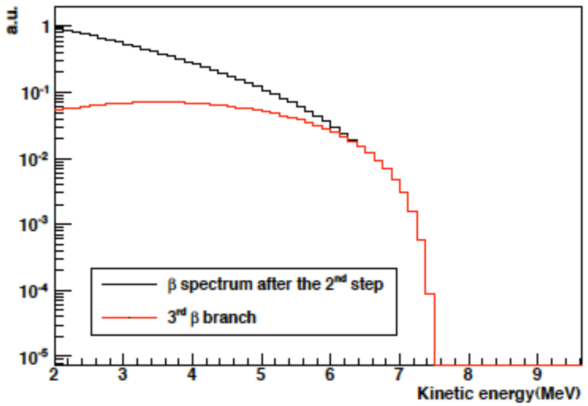


ILL data: conversion to ν spectra

- Fit e^- spectrum with a sum of 30 effective branches
- Conversion of the effective branches to ν spectra







- All theory included in these effective branches but:

  - What Z? : Mean fit on nuclear data *Z=f(E0)*

$$Z(E_0) \approx 49.5 - 0.7E_0 - 0.09E_0^2, \quad Z \geq 34$$

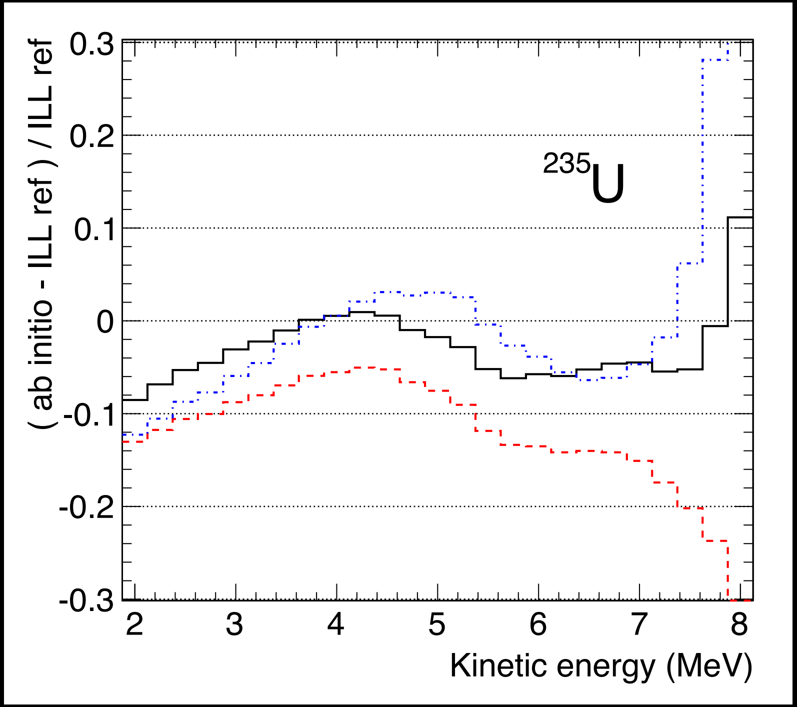
  - What A_{CW}? : effective correction on the ν-spectra

$$\mathrm{DN}_n^{C,W}(E_n) \approx 0.65 \times (E_n - 4\mathrm{MeV}) \quad \%$$

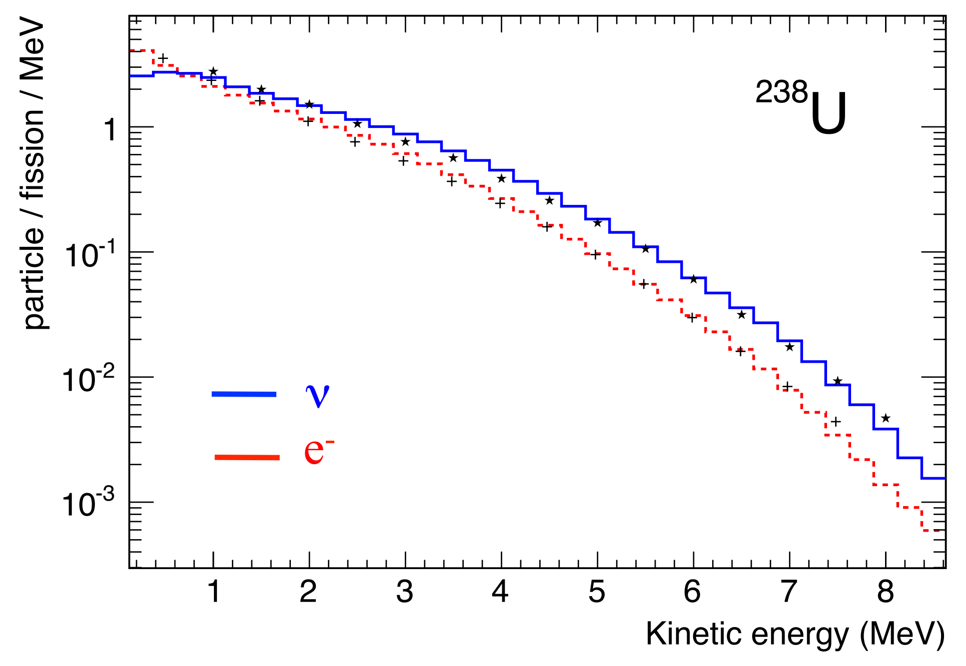
The Full ***Ab Initio*** **Attempt (electron data)**

- MURE evolution code: core composition and off equilibrium effects
- BESTIOLE code: build up database of ~800 nuclei and 10000 β-branches

Residues w.r.t. reference ILL e- data



New ^{238}U spectrum prediction

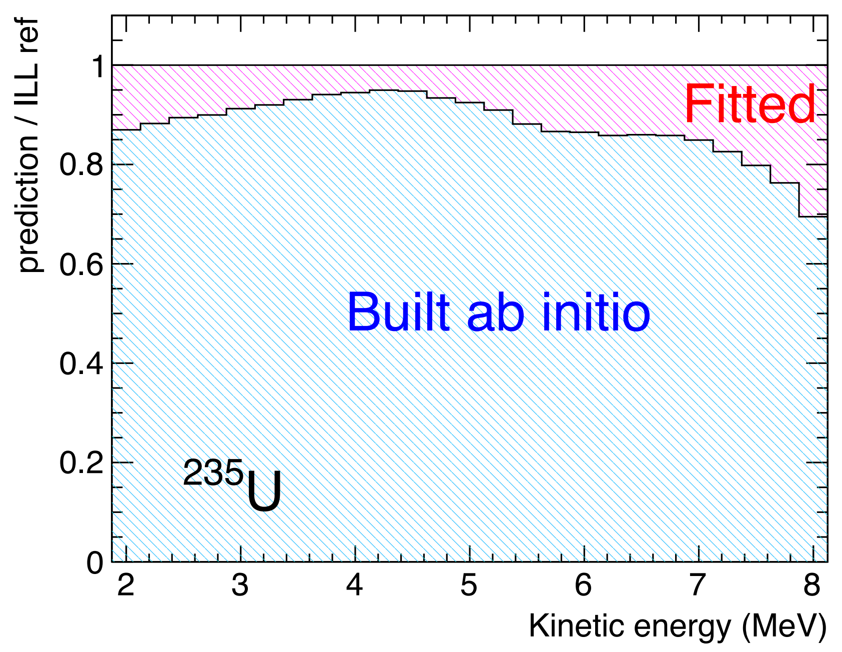


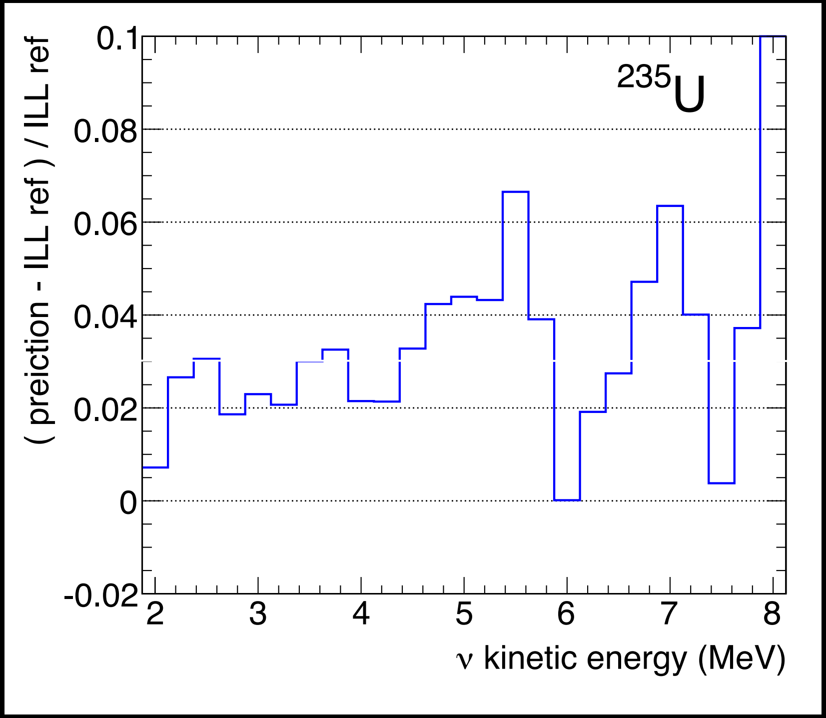
→ 95+/-5% of the spectrum reproduced but still not meeting required precision
→ Useful estimate of ^{238}U spectrum which couldn't be measured @ ILL
→ Measurement at FRMII ongoing (N. Haag & K Schreckenbach)

T. Lasserre

The New Mixed Conversion Approach

1. **SAME** ILL e- data Anchorage
2. Ab-Initio: “true” distribution of β-branches reproduces >90% of ILL e⁻ data.
3. Old-procedure: five effective anchorage-branches to the remaining 10%.

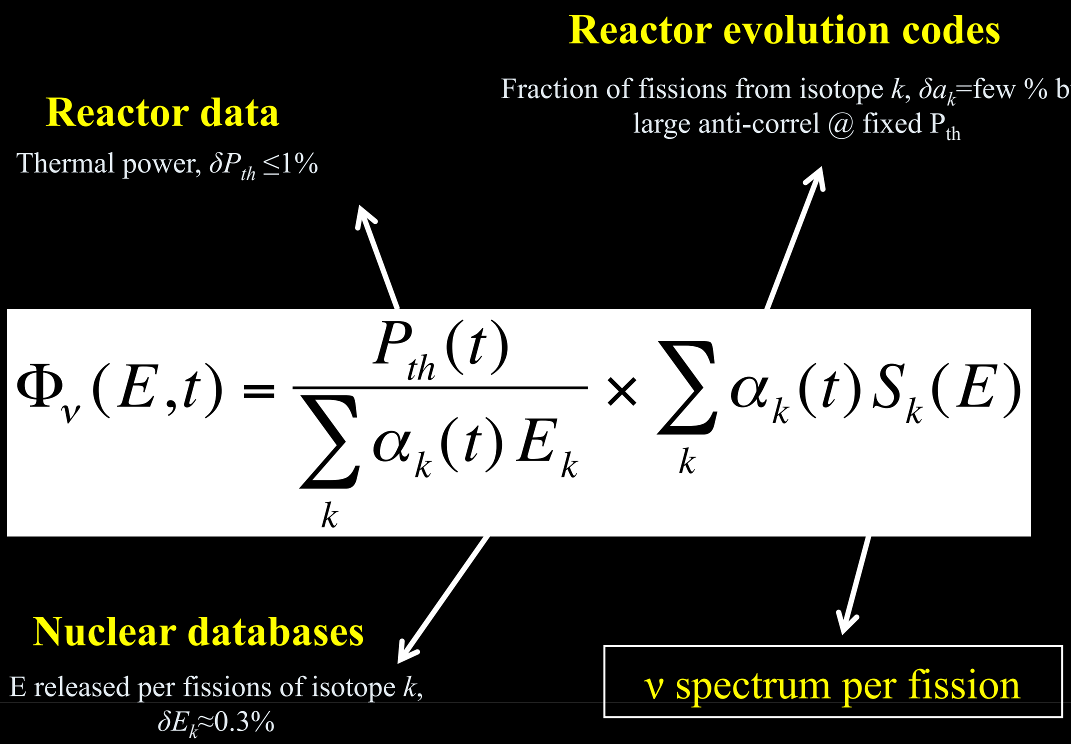




- **+3% normalization shift with respect to old ν spectrum**
- **Similar result for all isotopes (^{235}U, ^{239}Pu, ^{241}Pu)**
- **Stringent Test Performed – Origin of the bias identified**

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*, δa_k=few % but large anti-correl @ fixed P_{th}

Reactor data

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

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

Nuclear databases

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

ν spectrum per fission

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

Flux & Spectrum