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

Reactor antineutrino Spectra & Neutrino Safeguards

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- **NE290D Lecture #10 :**
  - Reactor antineutrinos spectra
- **NE290D Lecture #11:**
  - Neutrino Safeguards

NE290D Lecture #10

- Nuclear Reactors
- Reactor Antineutrino Flux
- Fuel Burn-up & Neutrino Flux
- Reactor Antineutrino Energy Spectra
    - Ab-Initio Computation using Nuclear Databases
    - Computation using Experimental Integral β-Data

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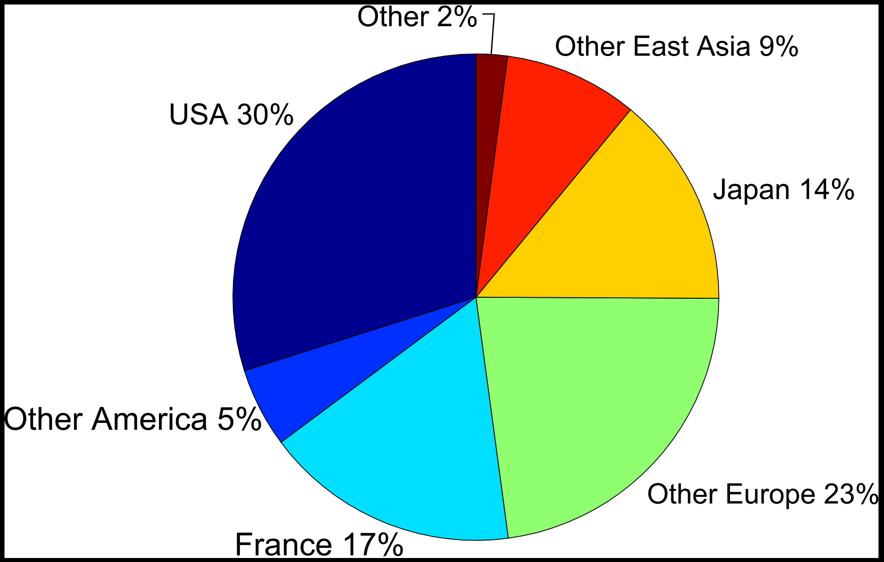
Nuclear Reactors

- **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)

- **Reactor Types**
- 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)
  - Naturally: 0.7% of ^{235}U (fissile, $T_{1/2}$=703.8 10^6 y)

  → fuel in form of UO_2

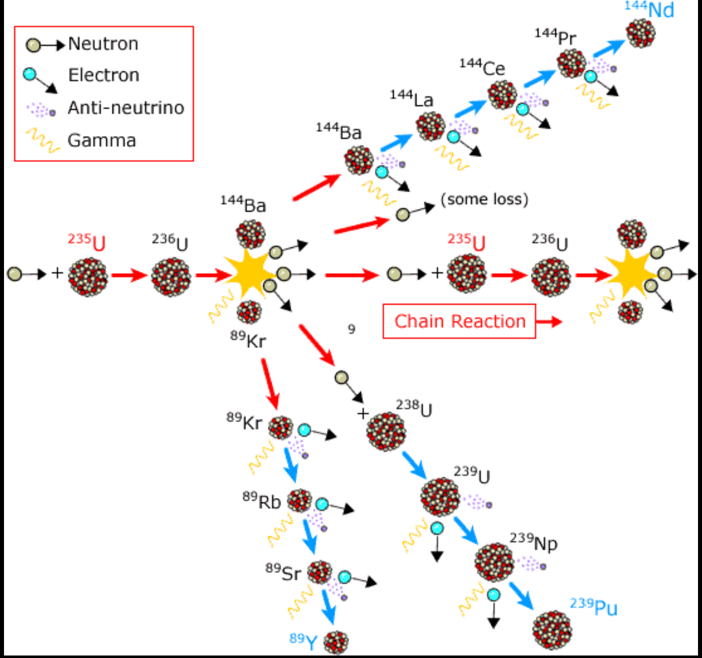
- **^{238}U**
  - High neutron capture threshold (0.8 MeV)
  - No fission with thermal neutrons
  - Fissions induced by fast neutrons

- **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

  → Proliferate

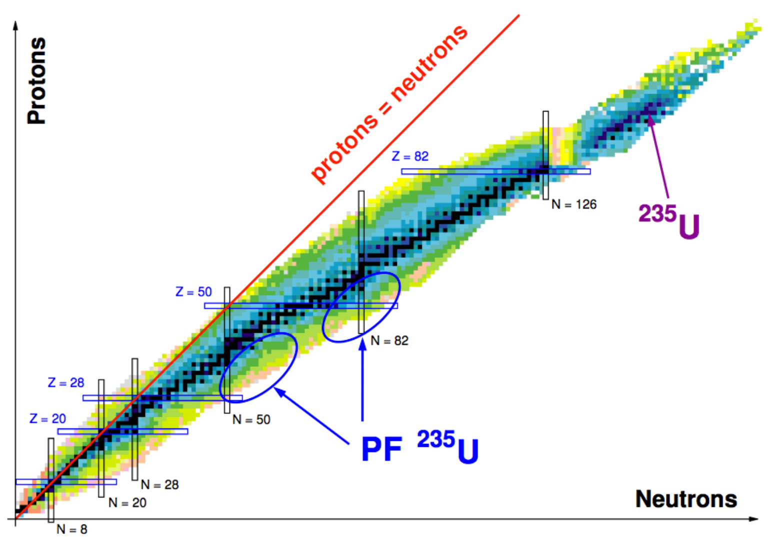


Fission Products & Fission Yields

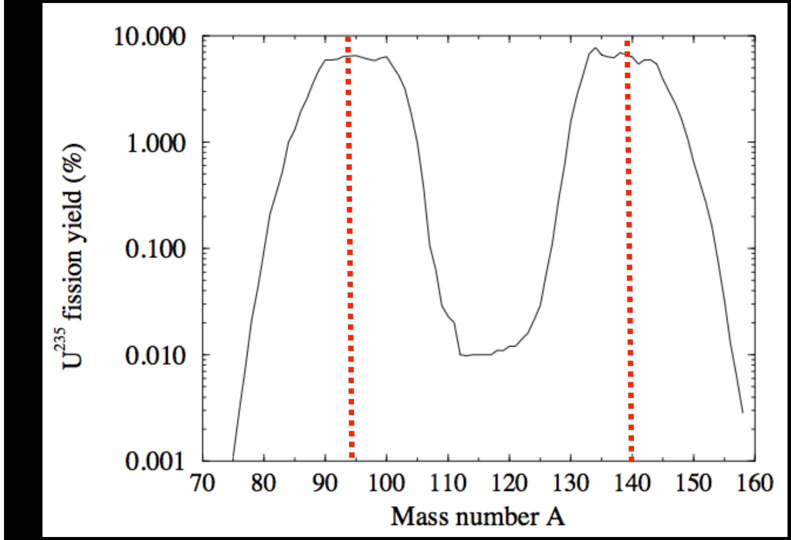
- Fission of ^{235}U

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

- X, Y are called ‘Fission Fragments’ or ‘Fission Products’
- Highest fission yields for the couple: Zr(94,40) and Ce(140,58)
  - X+Y: 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 Eν > 1.8 MeV

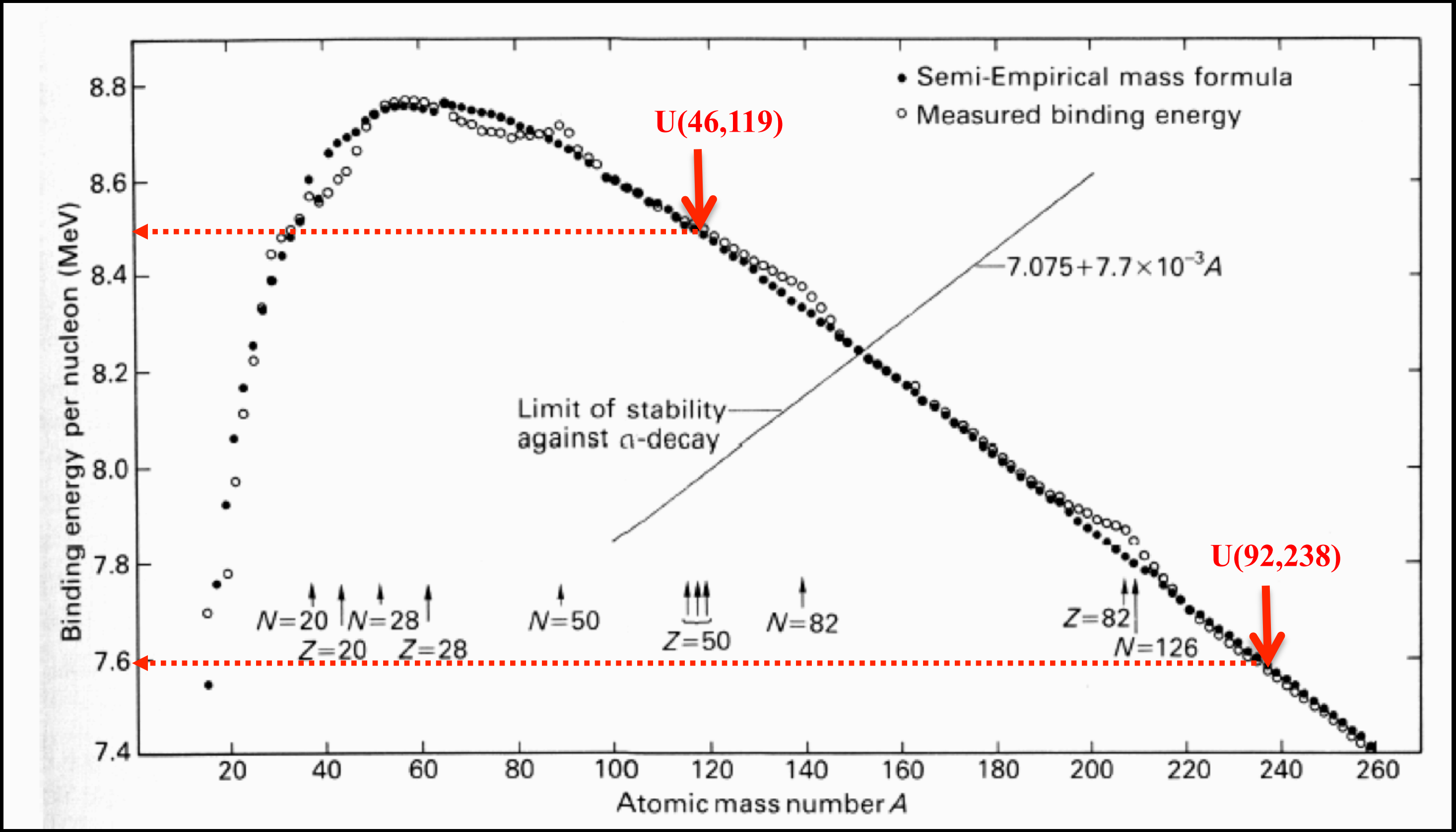


Two ‘’Mass’ Bumps: Z=86-104, Z=130-148



Energy Released per Fission

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

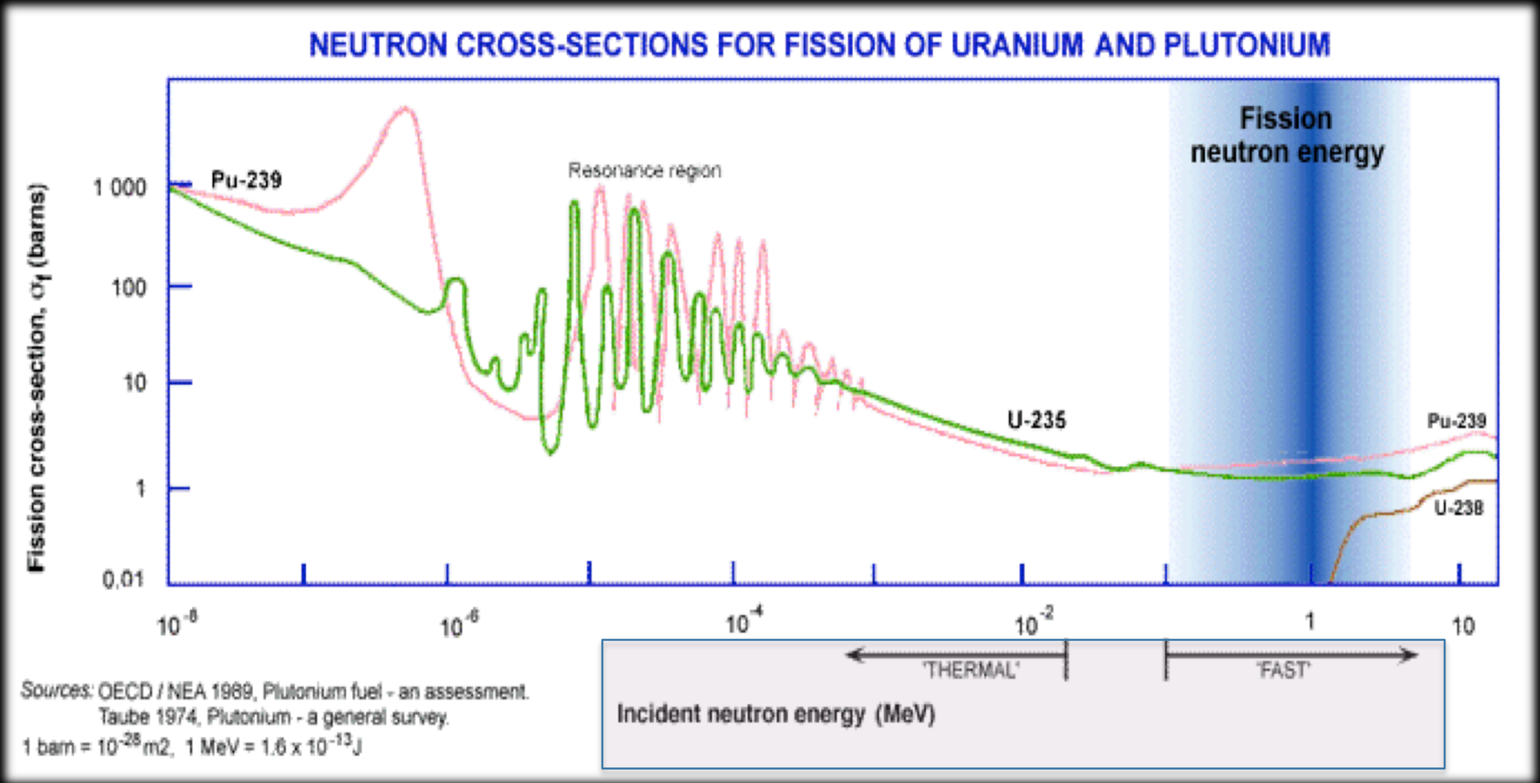


U/Pu Fission Cross Sections

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

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

$$^{238}\mathrm{U} + n_{fast} \rightarrow X + Y + 2\, n_{fast}$$



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 & Neutrinos

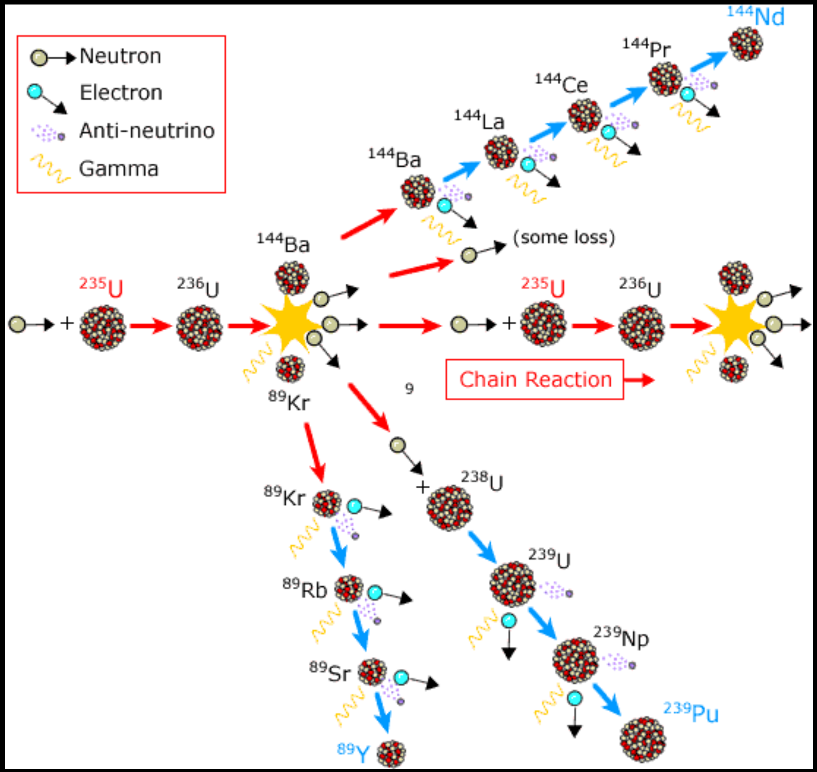
- Nuclear reactors are copious, isotropic sources of electron antineutrinos

- 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
  - $X(A,Z) \rightarrow Y(A,Z+1)+e^{-}+\text{anti-}\nu_e +Q$
  - Q ≈ 200 MeV / fission released
  - Fission rate ≈ 4 GW/200 MeV ~ 2.10^{20} /s
  - 6 anti-ν_e emitted per fission
  - $7.5\ 10^{20}$ anti-ν_e/s for a 4 GW nuclear core

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



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Reactor neutrino Flux: Guesstimate

10^{20} fissions in a 4 GW nuclear core (estimate)

200 MeV/fission et 6 v/fission of U^{235}, $Pu^{239,241}$

- 200 MeV released per fission:

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

- Thermal Power:

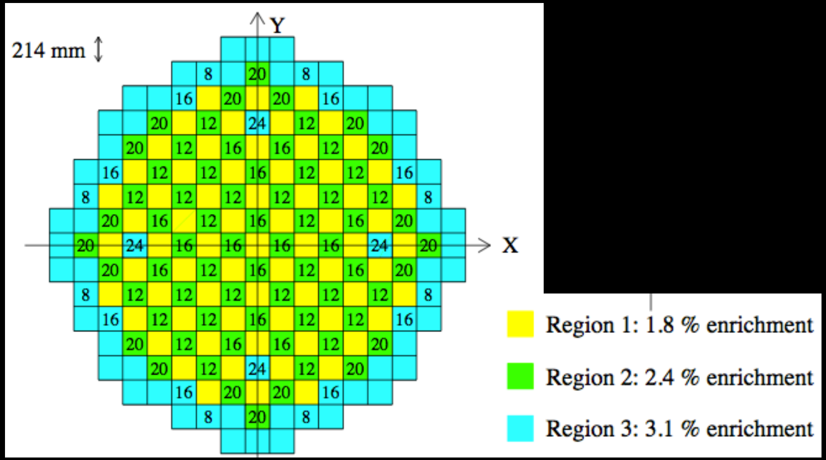
  → 4 GW = 4 **10^9 W (J / s)**

- Electron anti-neutrinos

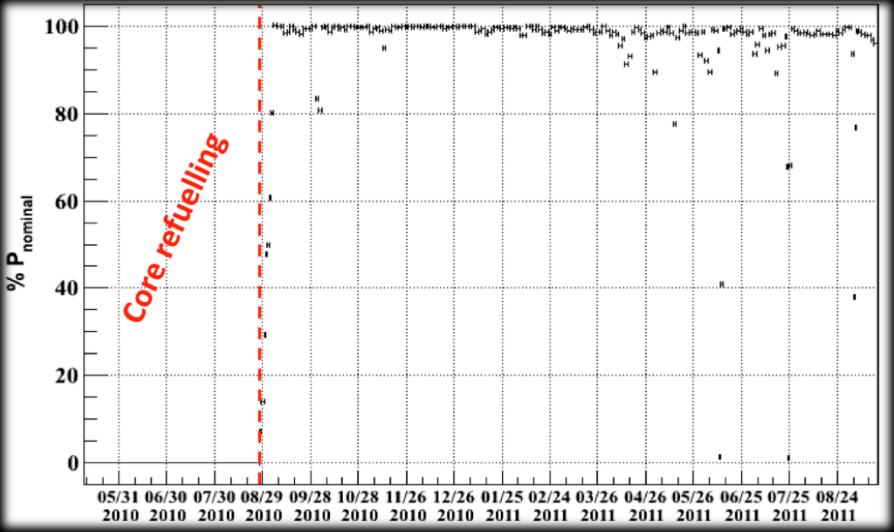
  → 4.10^9 W / **3,2 10^{-11} fissions/sec * 6 neutrinos/fission**

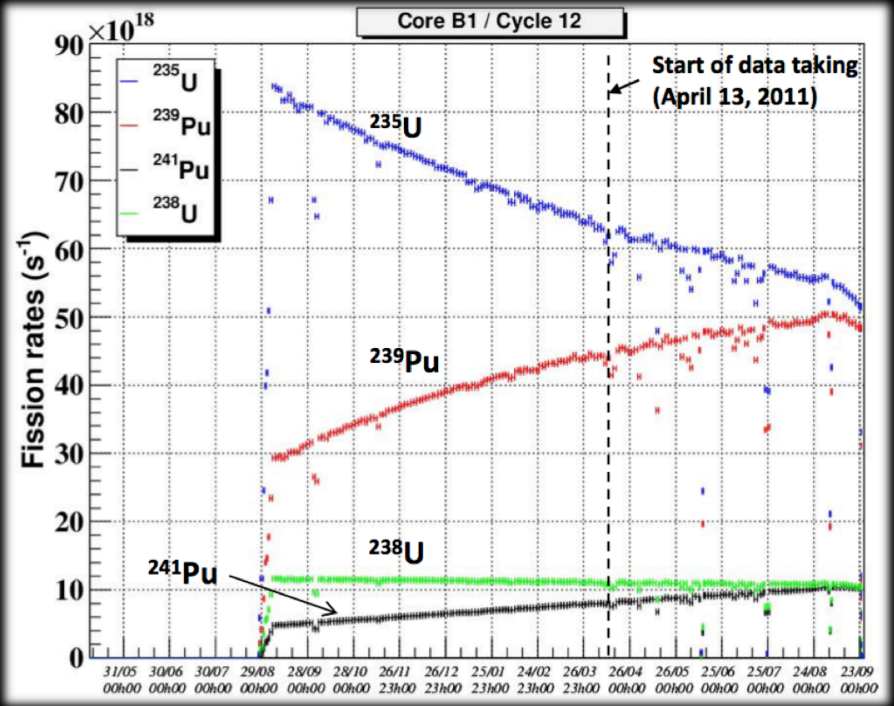
  → $(\phi_v)^R$ = **7.5 10^{20} neutrinos / s**

Typical Reactor Running Cycle

- Example: Double Chooz experiment
- 3-6 week shutdown every 12-18 months
- 1/4-1/3 of fuel assemblies are replaced, remaining fuel repositioned
- 

- 6 months shutdown every 10 years





Production of Plutonium in reactors

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

  $\hookrightarrow {}^{239}\mathrm{Np} + e^- + \overline{\nu}_e \quad (23.45\ \mathrm{m})$

  $\hookrightarrow {}^{239}\mathrm{Pu} + e^- + \overline{\nu}_e \quad (2.36\ \mathrm{d})$

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

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

- Plutonium 239, 240, and 241 are being produced as U is burnt

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

- ^{239}Pu, ^{241}Pu are fissile isotopes (thermal neutrons)
  - Beta decays → electron antineutrino emission

Nuclear Reactor Physics: Basics

- Fission rate of isotope k: $f_k(t) = \Phi_n(t)\, \sigma_k(t)\, N_k(t)$ in fissions/s
  - k : ^{235}Pu, ^{238}U, ^{239}Pu, ^{241}Pu
  - $\Phi_n(t)$: neutron flux (cm^2/s)
  - $\sigma_k(t)$: energy averaged fission cross section (cm^2)
  - $N_k(t)$: Number of isotope k (from the mass of isotope k)
  - t is the time running during the fuel cycle

- The evolution of the core isotopic content is ruled by the Bateman equations

- Fission fraction:

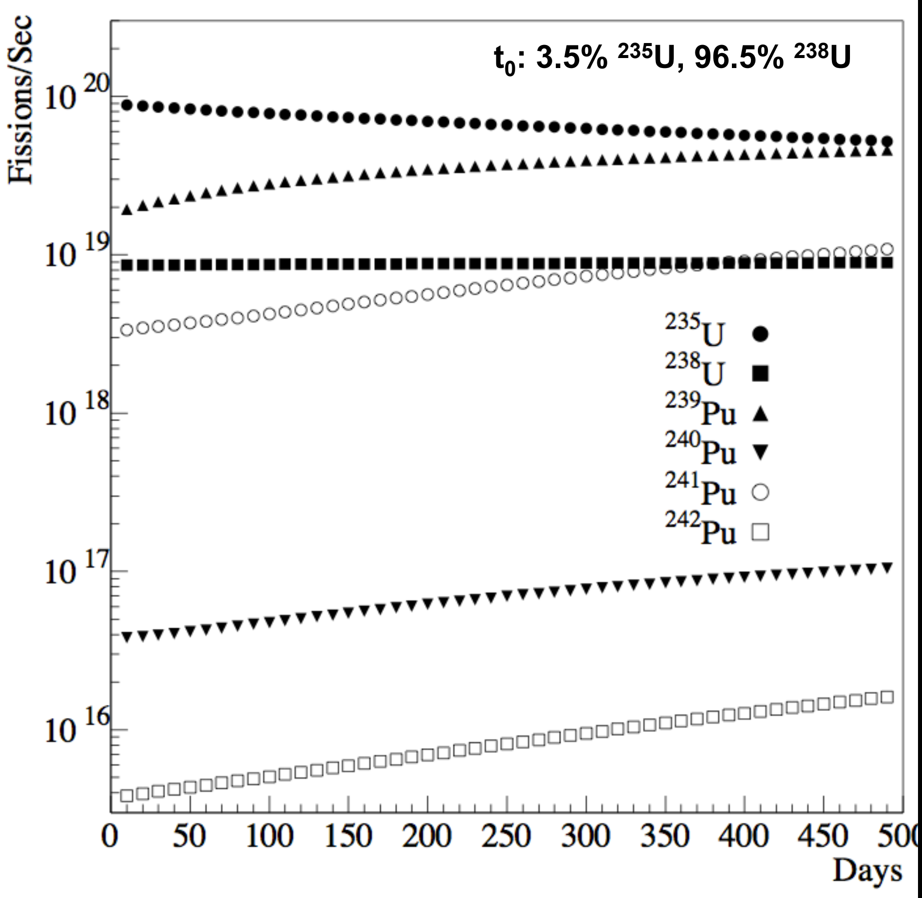
$$F_k = \frac{f_k}{\sum_k f_k}, \quad \text{with } \sum_k F_k = 1$$

- Burn-up:
  - Measure the number of fissions that occur per unit of mass
  - Equivalent to the amount of energy extracted from a nuclear core
  - Unit: Joules/ton or more commonly MWd/t

Fuel Evolution in a PWR (burn-up)

- Fuel evolve with time
- A typical cycle last 500 days
  then 1/3 of the fuel is being replaced

Information from the operator
or
You reactor core simulation



- Average fission fractions
  - <F(^{238}U)>: 53.8%
  - <F(^{239}Pu)> : 32.8%
  - <F(^{238}U)>: 7.8%
  - <F(^{241}Pu)> : 5.6%
  - Others <0.1%

- 250 kg of plutonium produced during a fuel cycle, mainly ^{239}Pu

- Evolution of the antineutrino flux
  - N (s^{-1})= a . (1+k) P (GW)
  - k: burn-up factor (Pu/U fraction)
  - k: <10% correction

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Reactor Neutrino Yields

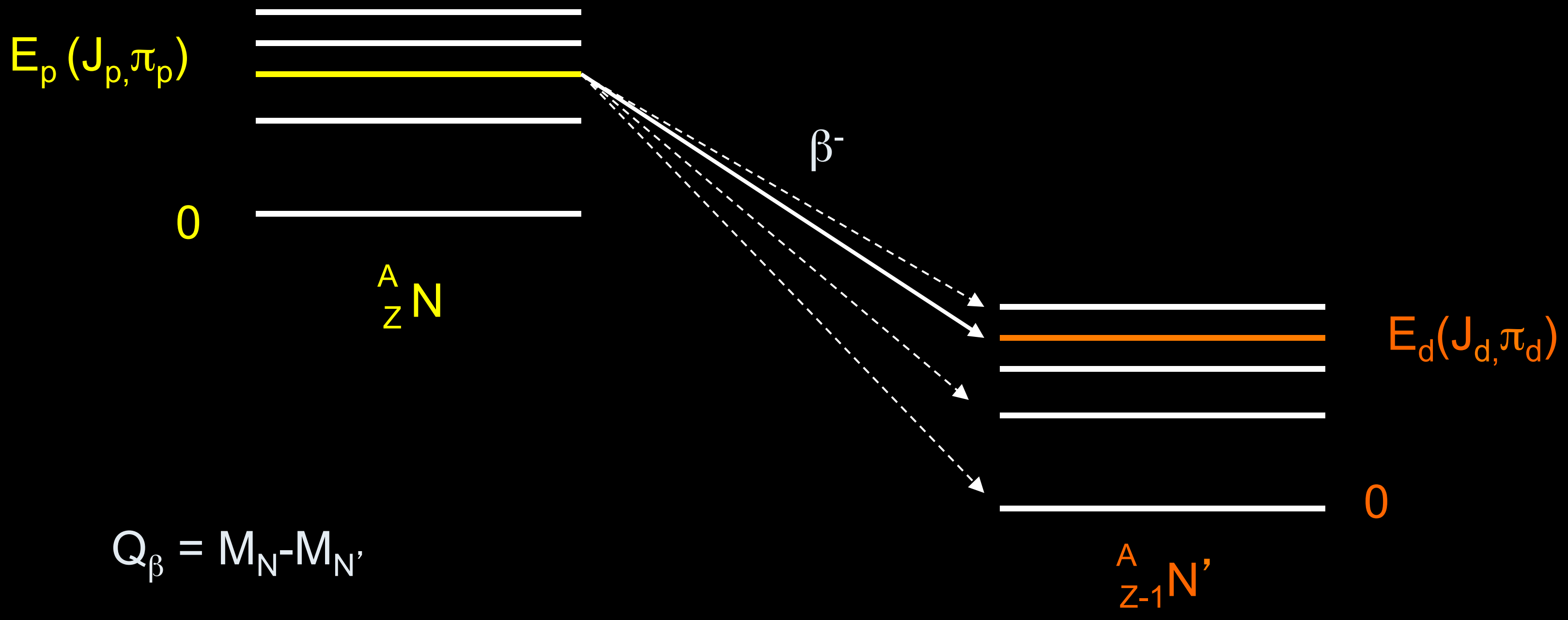
- Thermal power, P_{th} in Watt
  - $P_{th}(t) = \Sigma\, f_k\, p_k$
    - f_k : fission rate for the fission isotope k (mainly ^{235,238}U, ^{239,241}Pu)
    - p_k: thermal energy released in one fission of the isotope k

- Total neutrino flux from a reactor
  - $\Phi(E,t) = \Sigma\, f_k\,(t)\, S_k(E)$
    - $S_k(E,t)$: neutrino yield for the fission isotope k

- Energy dependent neutrino yield $S_k(E)$
  - $S_k(E,t) = \Sigma\, Y_I^k\,(t)\, v_i(E)$
  - $Y_i^k\,(t)$: cumulative yield for each fission fragment i of fission isotope k
  - $v_i(E)$: neutrino spectra for a given fission fragment i
  - i runs over ≈800 isotopes

- Neutrino spectrum $v_i(E)$
  - Never directly measured, even for a given fission fragment i
  - Has to be inferred from the corresponding β-spectrum (e^-)
  - Challenging since β-decay is a complicated process…

β^- decay



$Q_\beta = M_N - M_{N'}$

$E_0 = Q_\beta + E_p - E_d$ (end point)

β-decay: Classification

Classification	L	S	$\Delta J = \lvert \mathbf{L}+\mathbf{S} \rvert$	$\Delta\pi$	Log ft
Allowed	0	0,1	0, 1 ($0^+ \rightarrow 0^+$)	No	4-6
1st forbid. non-unique	1	0,1	0, 1	Yes	6-10
1st forbid. unique	1	1	2	Yes	7-10
2nd forbid. non-unique	2	0,1	2	No	11-14
2nd forbid. unique	2	1	3	No	14
3rd forbid. non-unique	3	0,1	3	Yes	17-19
3rd forbid. unique	3	1	4	Yes	18

- All non-unique transitions involve several nuclear matrix elements with complex E dependence → spectrum shape is unknown
- Forbidden decays are less probable because they contain an orbital angular momentum change (higher log ft)

β-decay: Fermi theory & Corrections

Fermi theory:

$$N_\beta^F(W) = K\ \underbrace{p^2(W-W_0)^2}_{\text{Phase space}}\ \underbrace{F(Z,W)}_{\text{Fermi function}}\ \underbrace{C_{Shape}(W)}_{\text{Shape factor of forbidden transitions}}$$

- Unit of m_e, $W=E/m_e$
- W = e^- total energy
- W_0 = end-point
- p = e^- momentum
- Z = Nuclear charge

Corrections:

$$N_\beta(W) = N_\beta^F(W)\, L_0(Z,W)\, S(Z,W)\, C(Z,W)\, G_\beta(Z,W)\, (1+\delta_{WM} W)$$

Finite size of nuclear electric charge

Screening of atomic e-

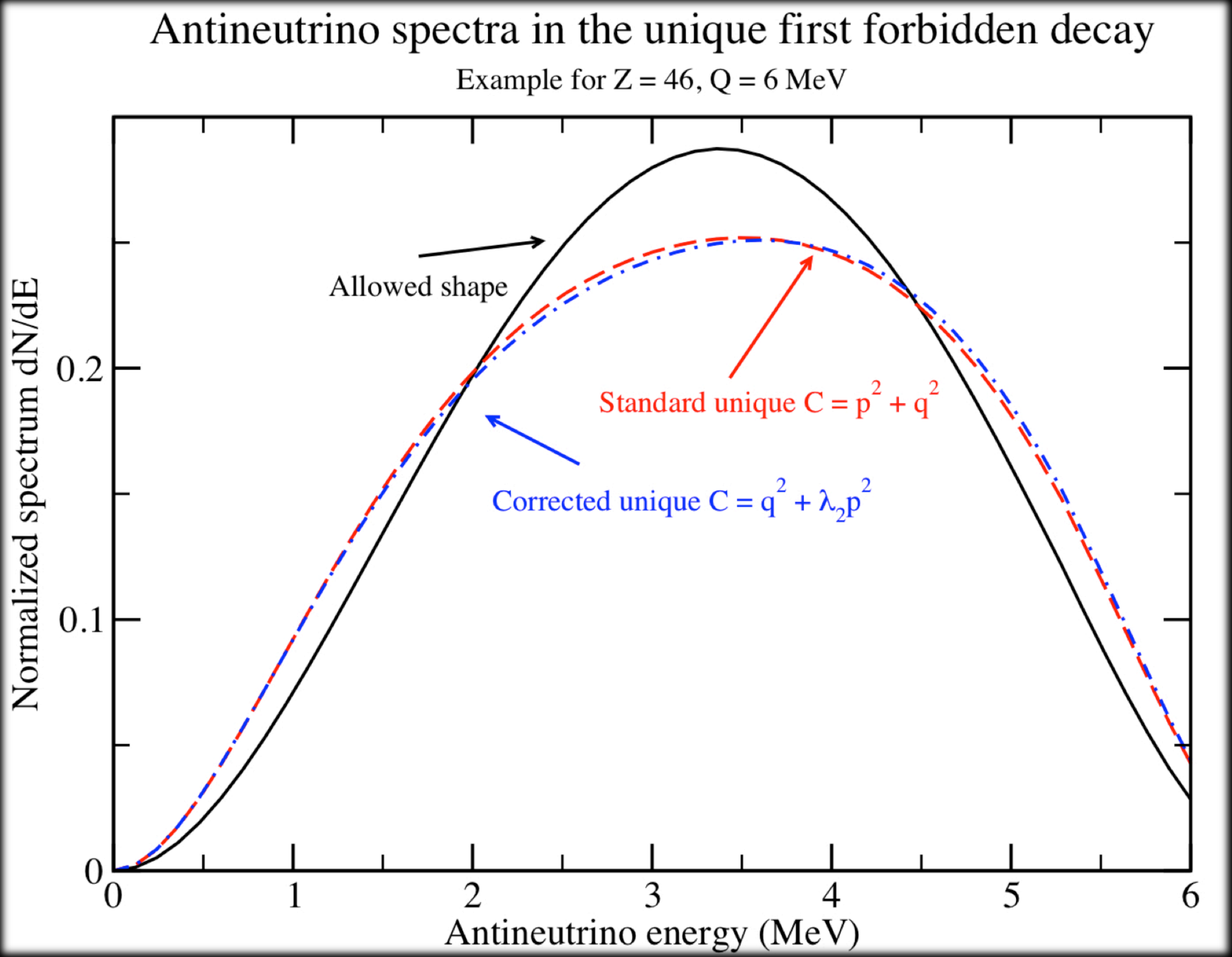
Finite size distrib. of decaying neutron

QED radiative correction

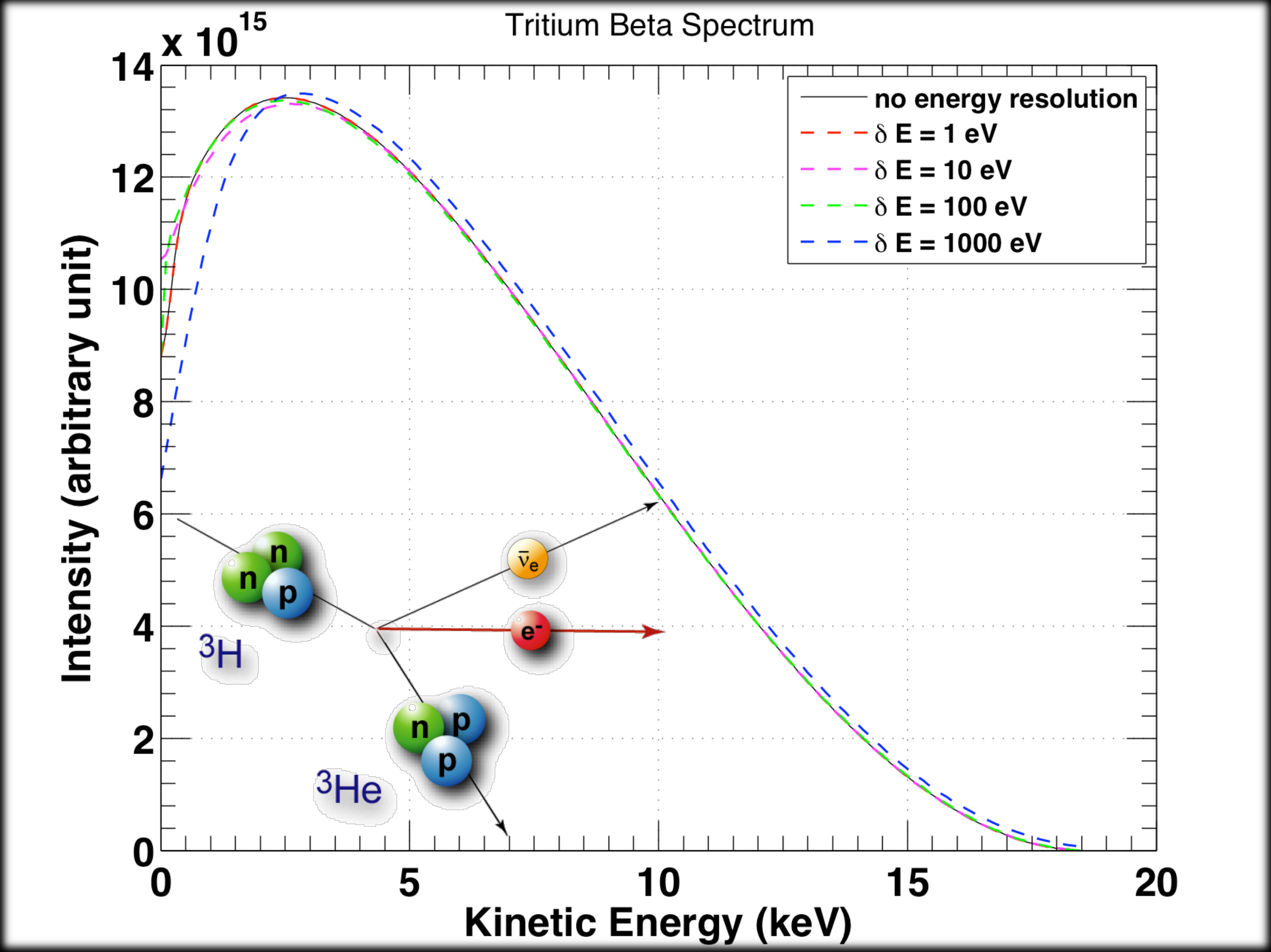
Weak magnetism

Neutrino branch obtained by replacing:
$W_\nu \rightarrow W_0 - W_\beta$, $G_\beta \rightarrow G_\nu$

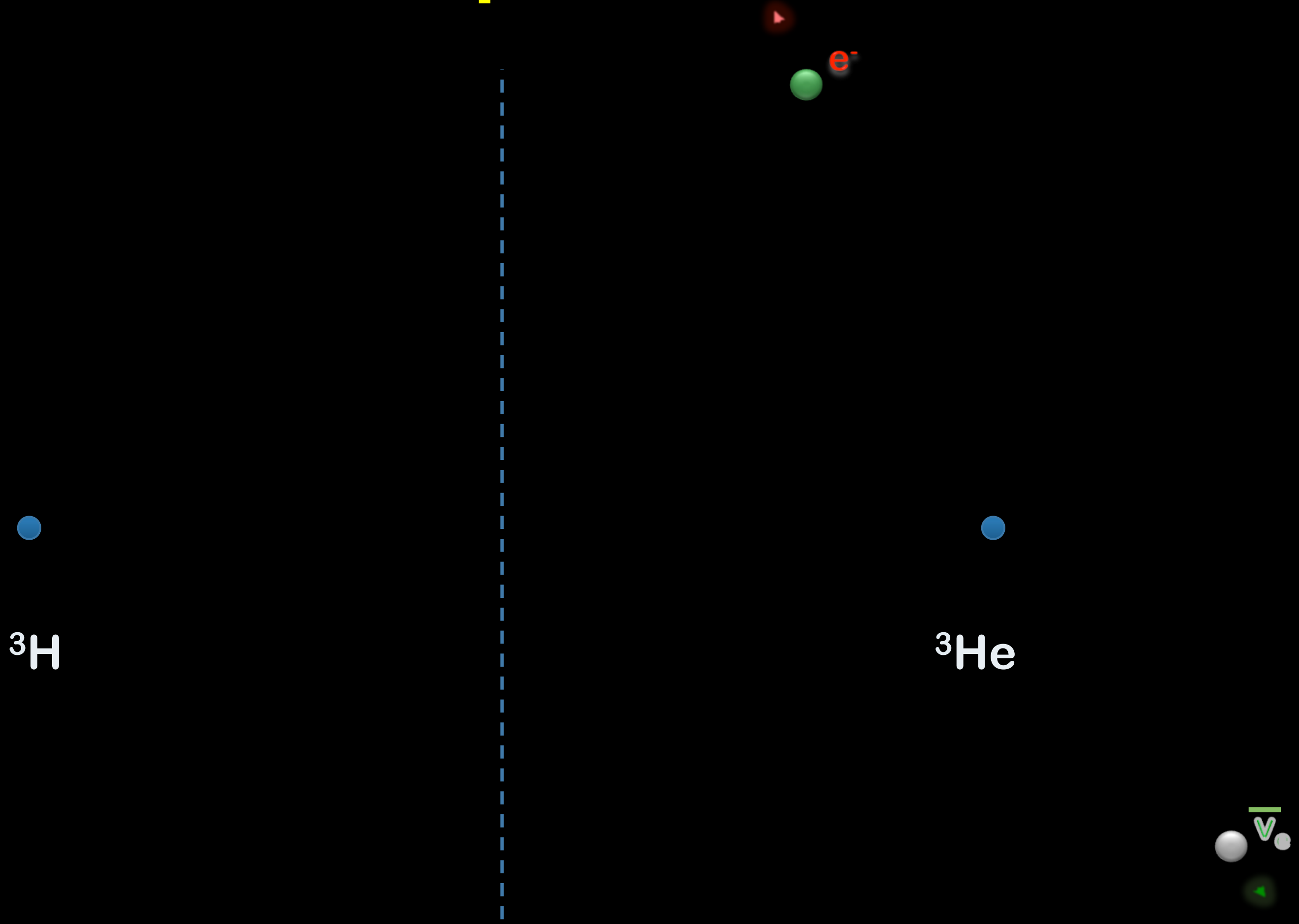
β-decay: shape factor (C_{shape})



β-decay: Tritium academic example

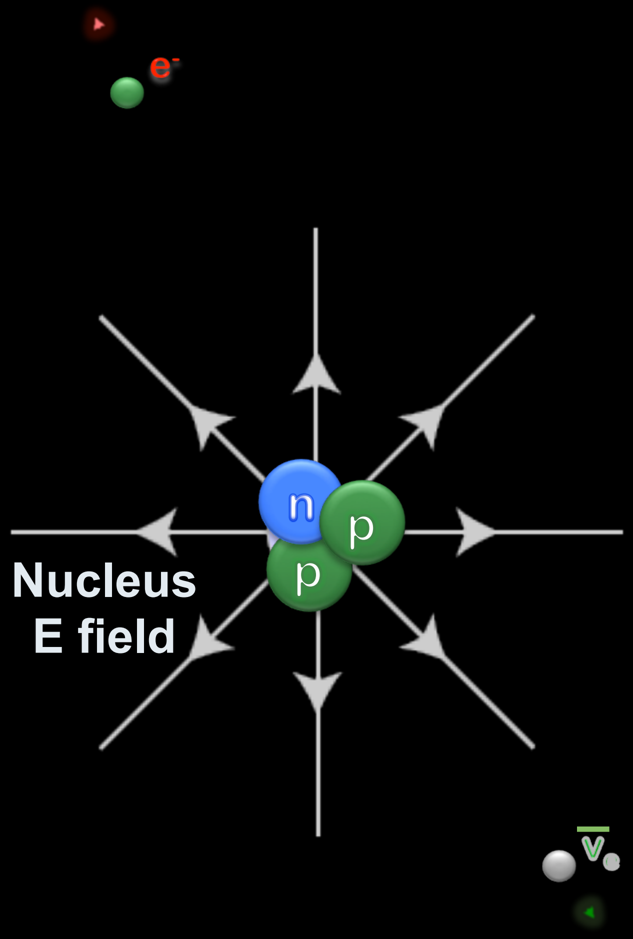


Phase space factor

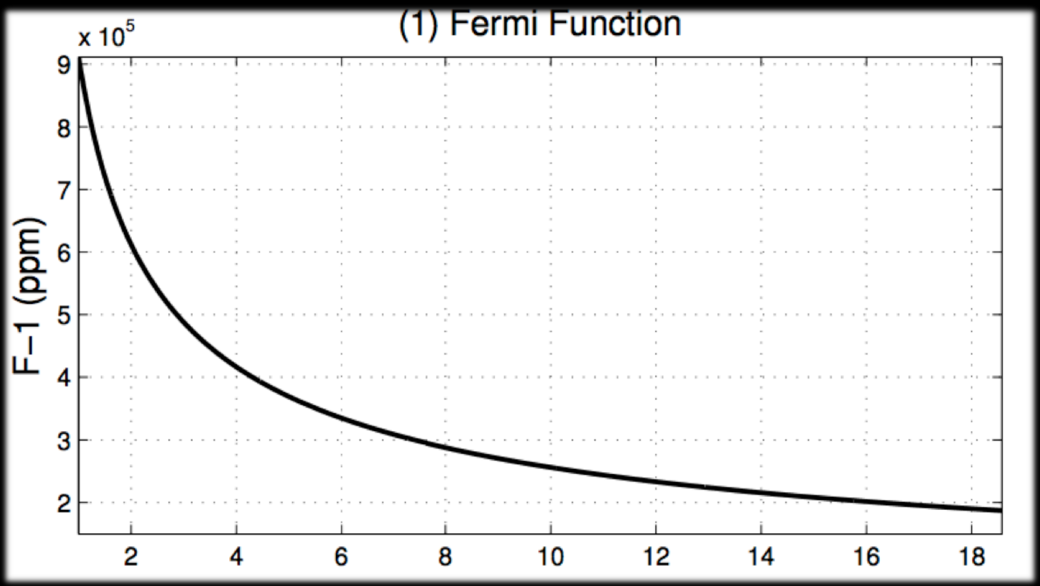


$$\frac{d\Gamma}{dE_e}(m_{\nu_i}) = C \cdot p_e E_e \cdot \sqrt{(E_e - E_0)^2 - \cancel{m^2_{\nu_i}}} \cdot (E_e - E_0)$$

Coulomb field of the daughter He nucleus



$$\frac{d\Gamma}{dE_e}(m_{\nu_i}) = C \cdot p_e E_e \cdot \sqrt{\left(E_e - E_0\right)^2 - m_{\nu_i}^2} \cdot \left(E_e - E_0\right) \cdot F(E_e, Z)$$

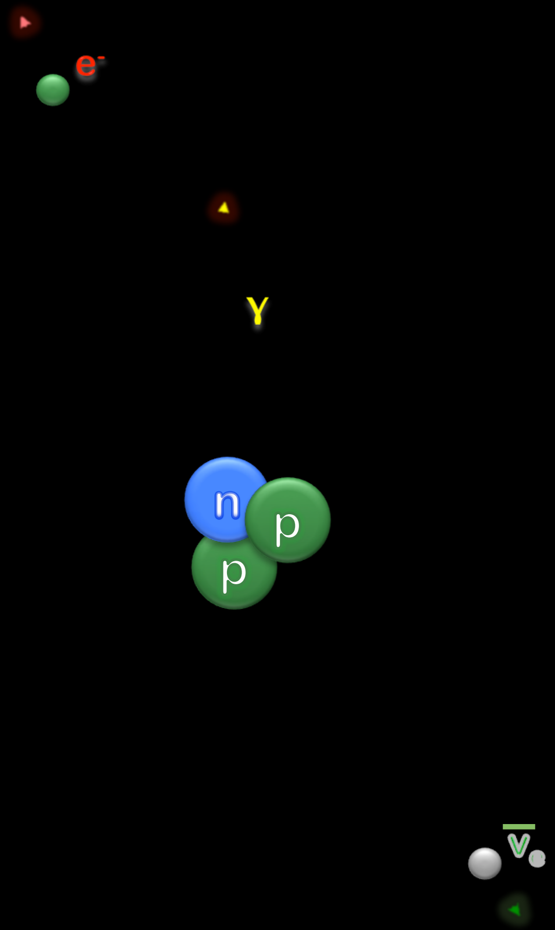


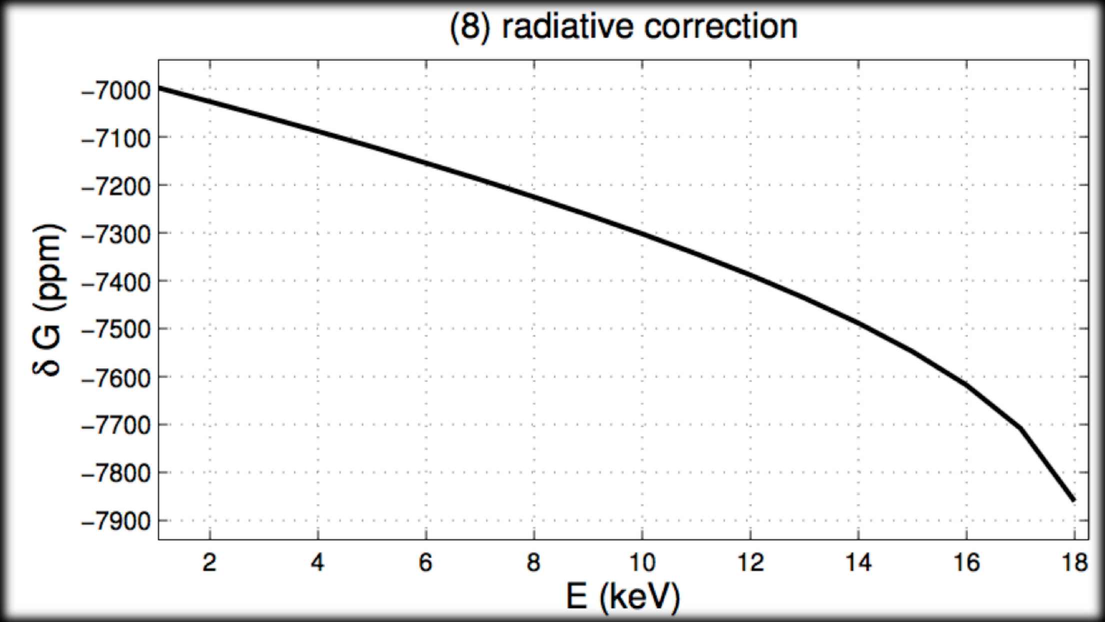
2nd order corrections to Fermi theory

$$\left(\frac{d\Gamma}{dE_e}\right)^{corr} = \frac{d\Gamma}{dE_e} \cdot \left[\prod_{\Psi = L_0, S, E, Q, R, G} \Psi(E_e, Z) \right]$$

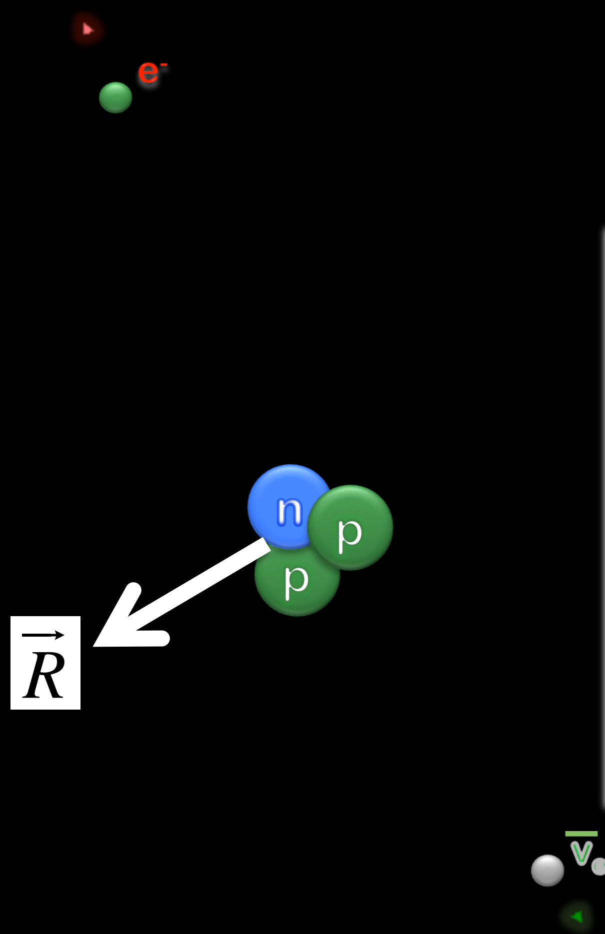
- Screening Correction (S)
- He recoil corrections (R)
- Recoiling Coulomb field (Q)
- Finite extension of the nucleus
- Radiative corrections (G)

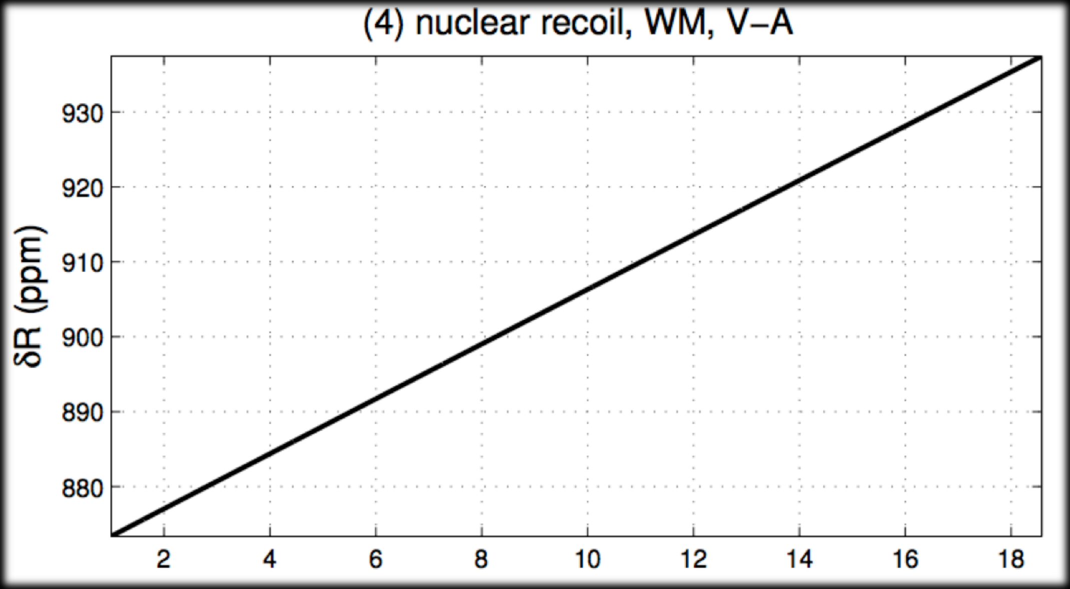
Radiative Correction



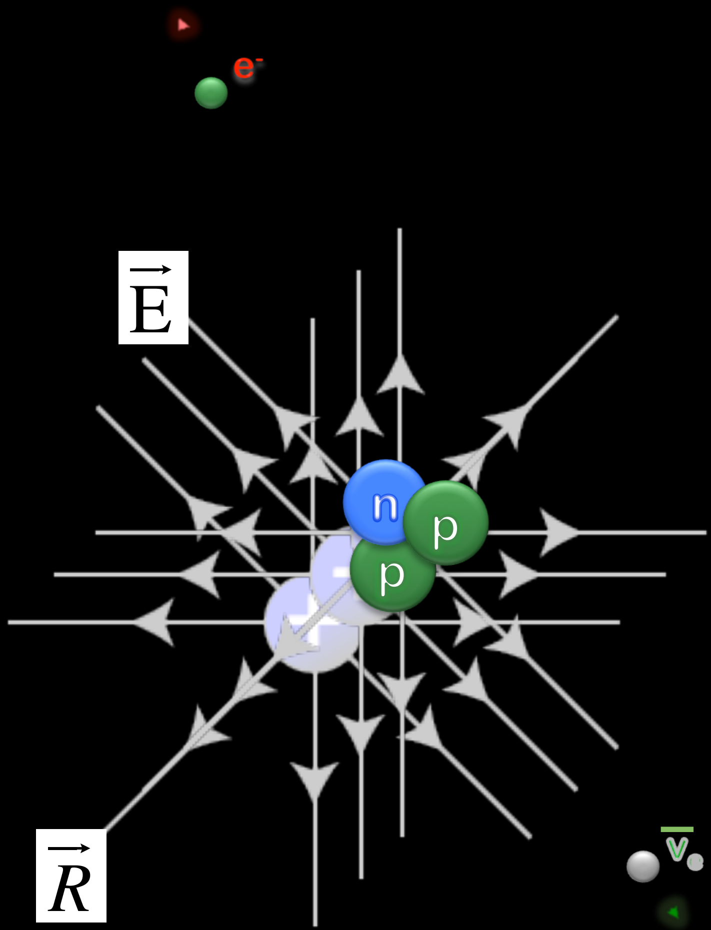

(8) radiative correction

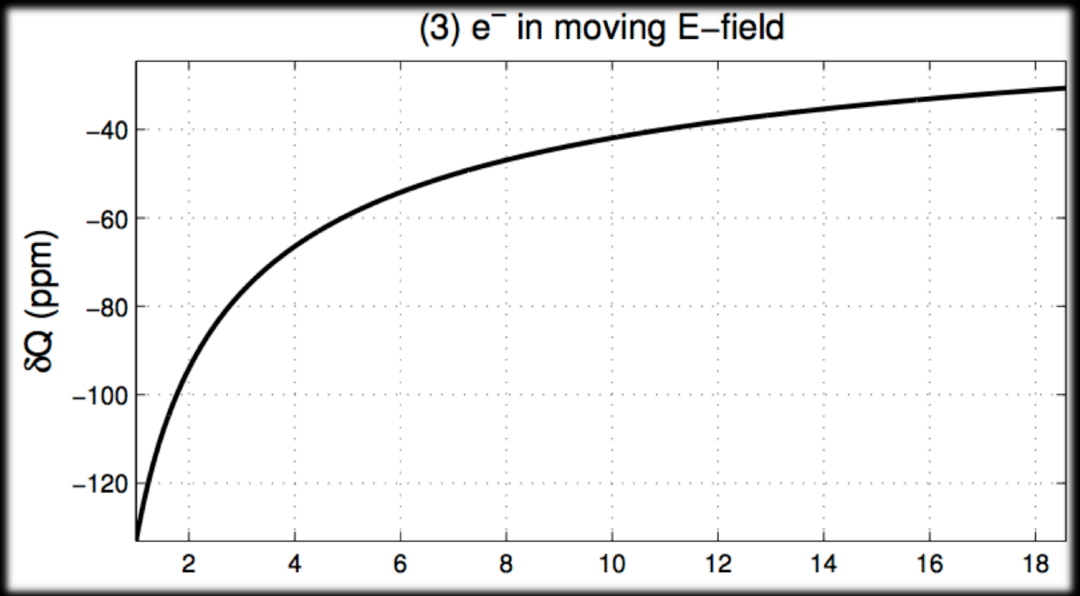
Recoil of the daugther nucleus (+ Weak Magnetism)



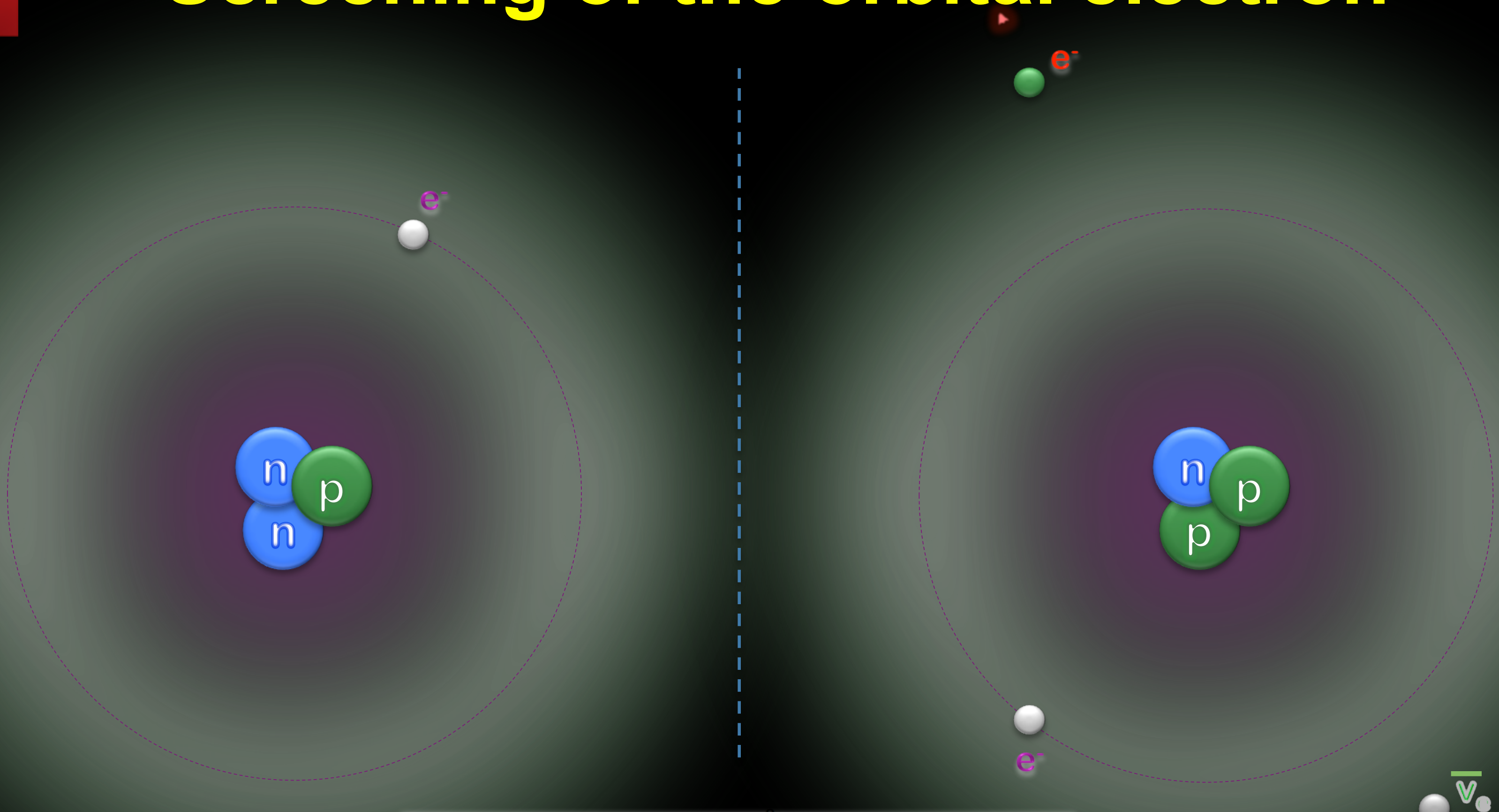


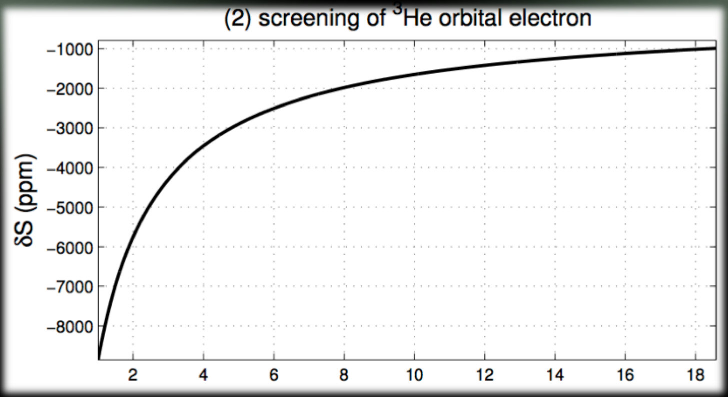
Recoiling Coulomb field of ^{3}He



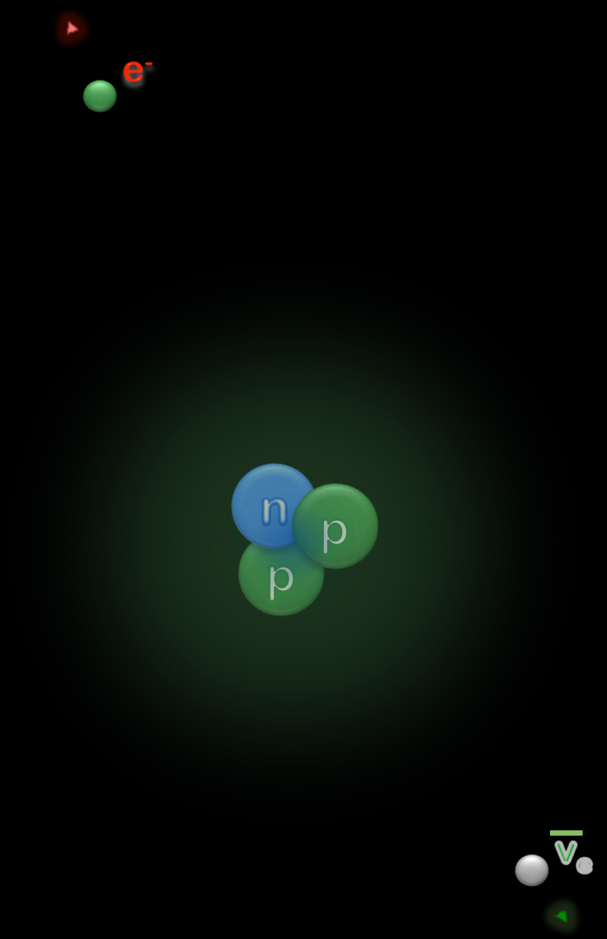


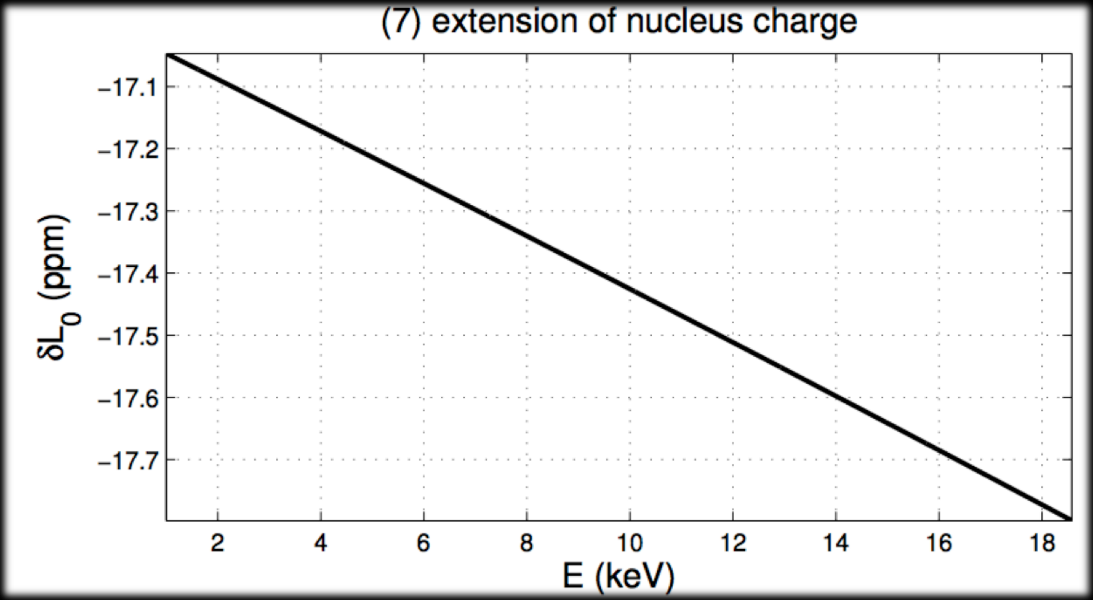
Screening of the orbital electron

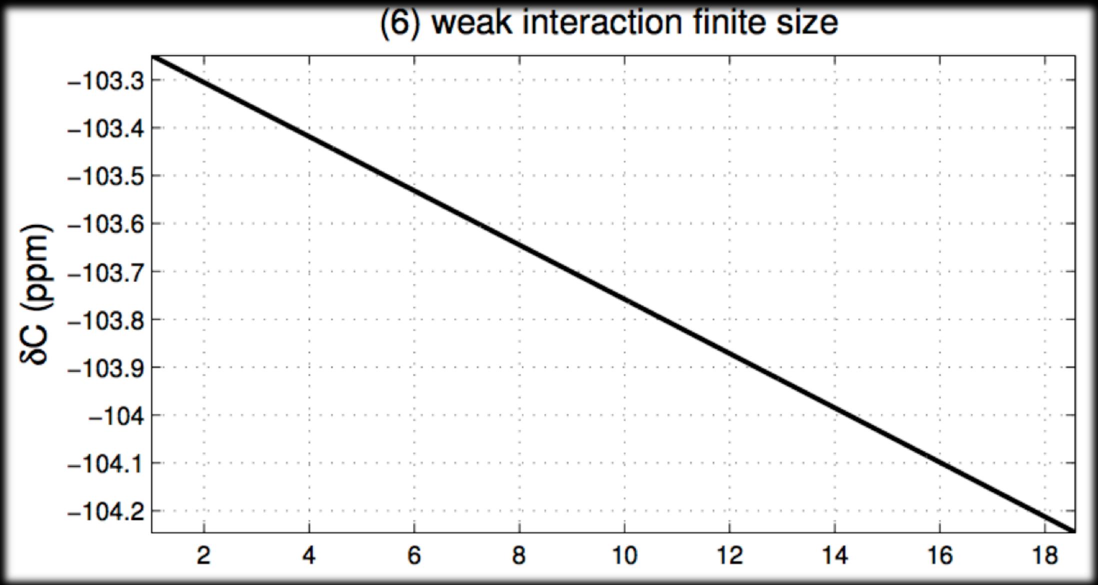



(2) screening of ^{3}He orbital electron

Finite Extension of the nucleus




(7) extension of nucleus charge


(6) weak interaction finite size

Reactor Neutrino Flux/Spectra

- **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, and ^{238}U**
  - Case A: ab-inito method – 15% uncertainties
    - computation based on nuclear databases
      - old computation (Vogel et al., 1980's)
      - new computation (Mueller/Huber, 2011, +10% w.r. old)
  - Case B: Conversion method – 3% uncertainties
    - electron spectrum measurement
    - electron → neutrino spectrum conversion
      - old conversion (Schreckenbach et al., 1980's)
      - new conversion (Mueller/Huber et al., 2011, +3.5%, w/r old)

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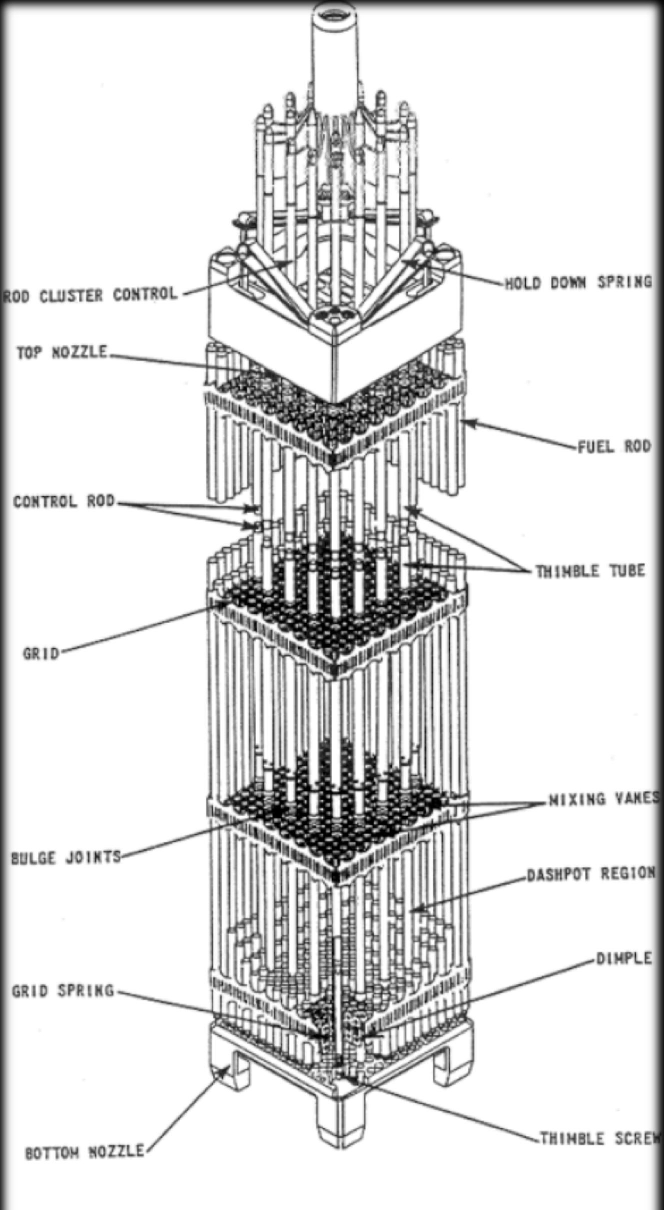
- **Reactor Antineutrino Energy Spectra**
  - **Ab-Initio Computation using Nuclear Databases**
  - Computation using Experimental Integral β-Data

Nuclear Fuel Assemblies

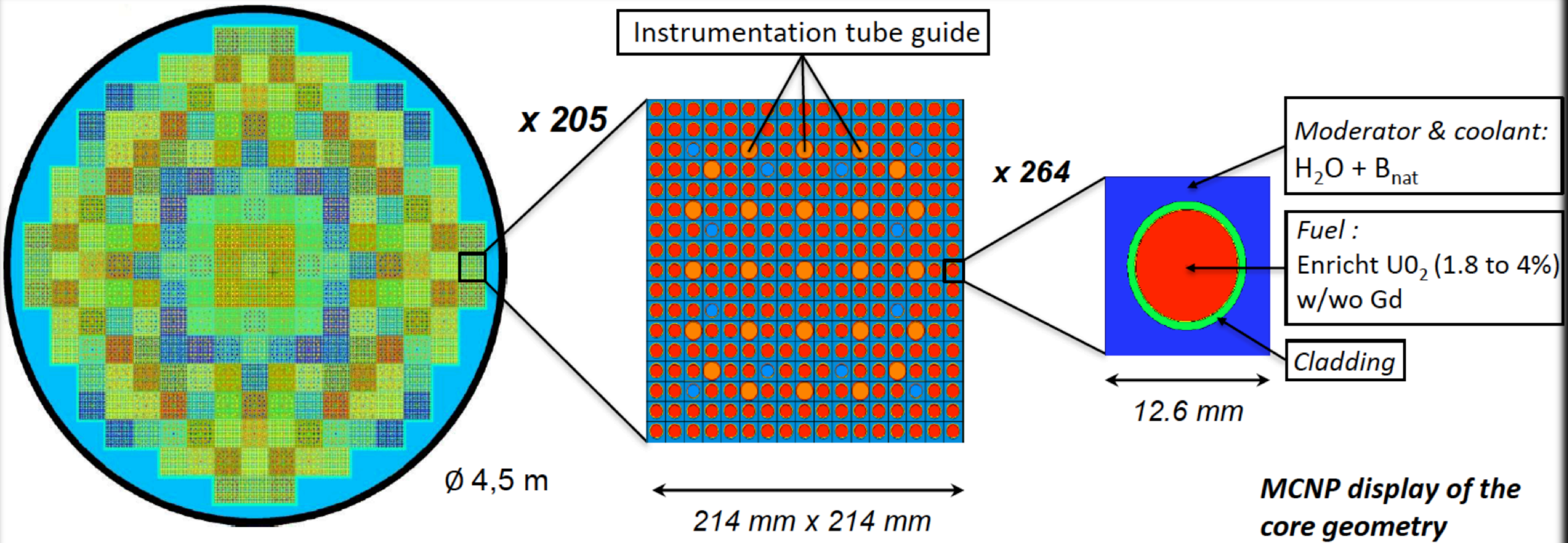
- Fuel in N4-type reactors (Chooz, France)
    - 120 tons of UO_2
    - $^{235}U \approx 3.45\%$: 3.60 tons
- 205 fuel assemblies
    - 264 rods per assembly
    - 272 pellets per rods
    - 8 g per pellets

- Loading/unloading
    - by one/third
    - every 1.5 years
- Typical energy extracted
    - 45 GW.d/ton = 3.89 10^{15} J/ton
    - Called ‘burn-up’

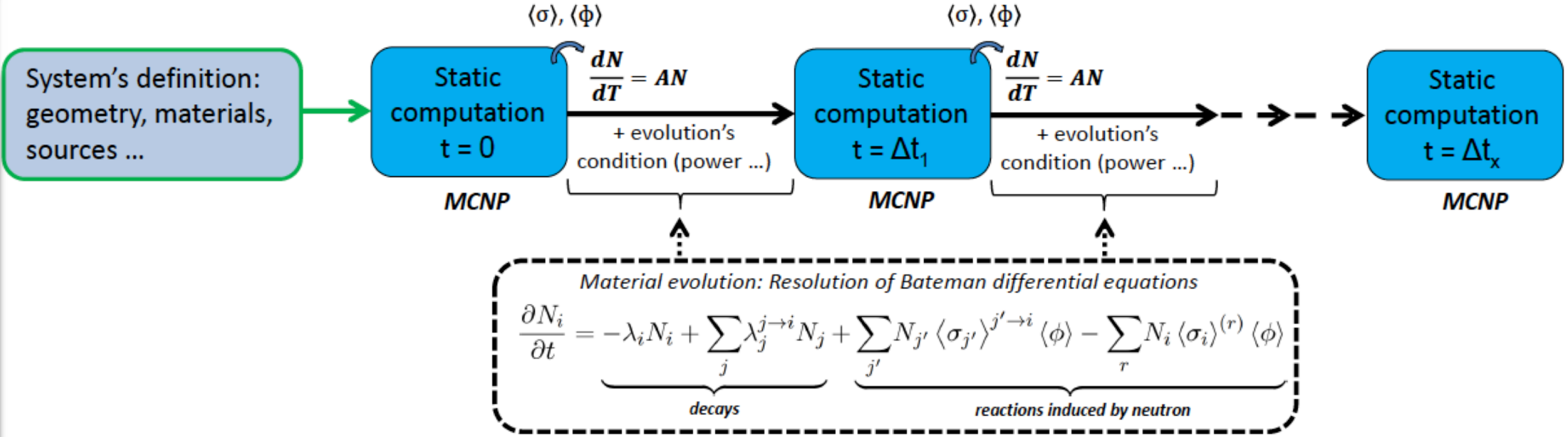


Reactor Fuel Assembly

A) Reactor Core Evolution Simulation



MCNP display of the core geometry



System's definition: geometry, materials, sources ...

Static computation t = 0

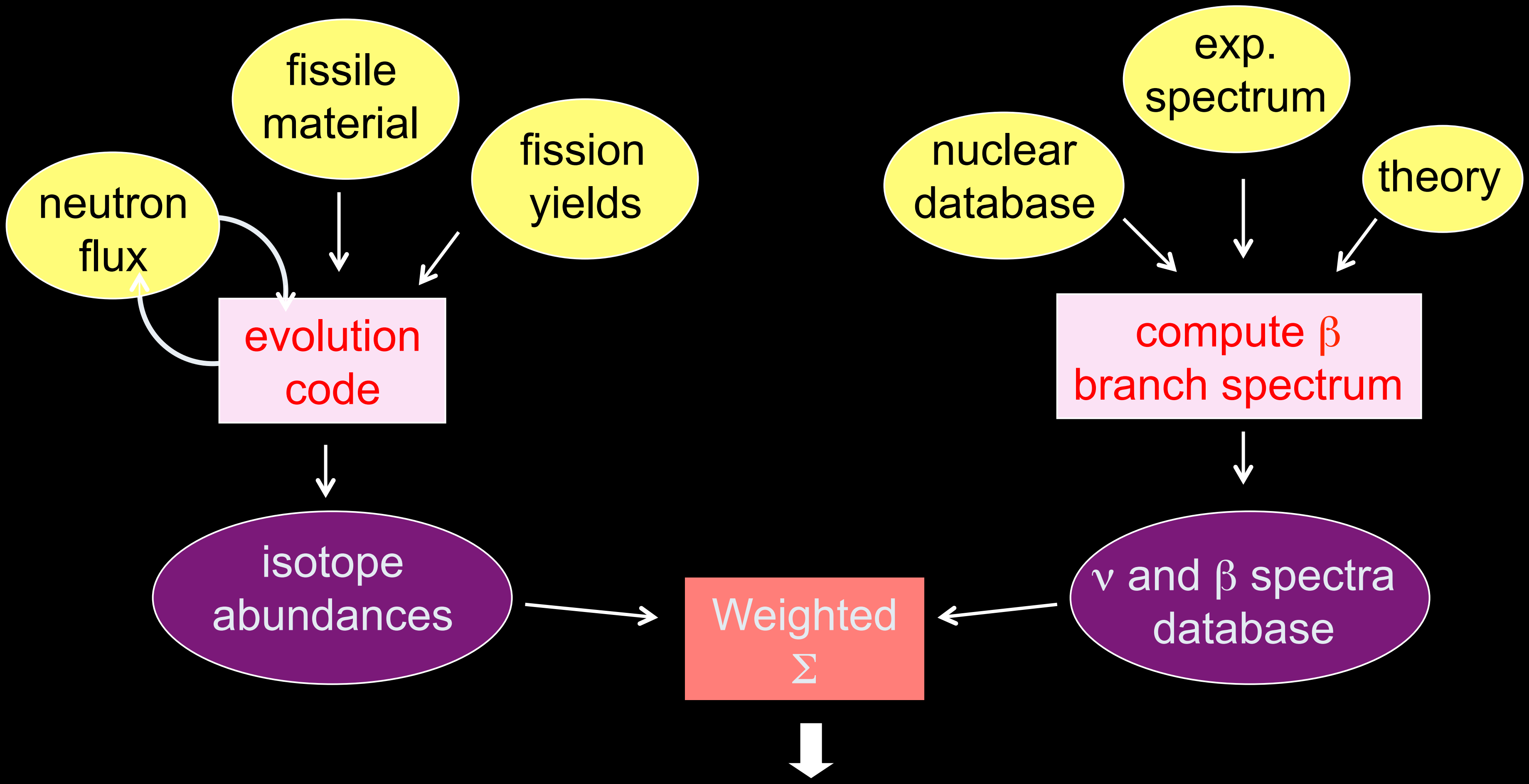
Static computation t = Δt_1

Static computation t = Δt_x

Material evolution: Resolution of Bateman differential equations

$$\frac{\partial N_i}{\partial t} = \underbrace{-\lambda_i N_i + \sum_j \lambda_j^{j\to i} N_j}_{\text{decays}} + \underbrace{\sum_{j'} N_{j'} \langle\sigma_{j'}\rangle^{j'\to i} \langle\phi\rangle - \sum_r N_i \langle\sigma_i\rangle^{(r)} \langle\phi\rangle}_{\text{reactions induced by neutron}}$$

A) Reactor Neutrino Flux/Spectra



neutron flux

fissile material

fission yields

evolution code

isotope abundances

nuclear database

exp. spectrum

theory

compute β branch spectrum

ν and β spectra database

Weighted Σ

Total ν and β energy spectra

Reactor neutrino spectrum: notations

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

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

- **$S_k(E)$: neutrino yield normalized to 1 fission of the isotope k**
  - E: electron 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 product decays, via 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 b^{th} branch of the fp^{th} fission product
  - E_{0fp}^{p} : end-point energy of the b^{th} branch of the fp^{th} fission product.
  - Z_f : charge of the parent nucleus.
  - A_f : atomic number of the parent nucleus.

$S_k(E)$: neutrino yield for isotope k

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

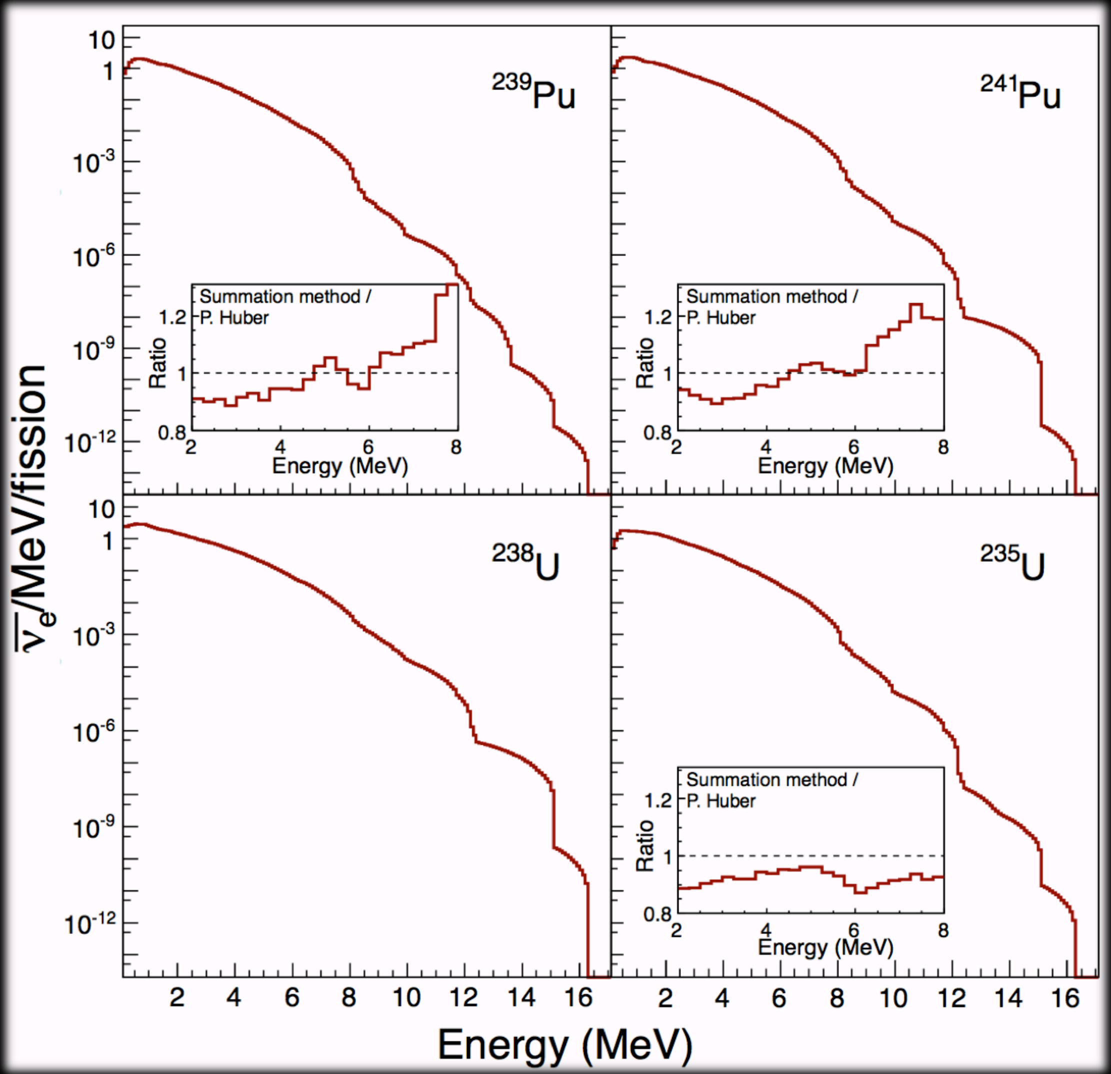
$$\underbrace{K^b_{fp}}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_{fp}, A_{fp}, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E^b_{0fp})^2}_{\text{Phase space}}$$

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

Correction factors

$$\delta^b_{fp} = G_{\nu\,(QED)} + L_{0(coulomb\ size)} + C_{(weak\ size)} + S_{(screening)} + \delta_{WM\ (weak\ magnetism)}$$

A) ab-inito reactor neutrino spectra

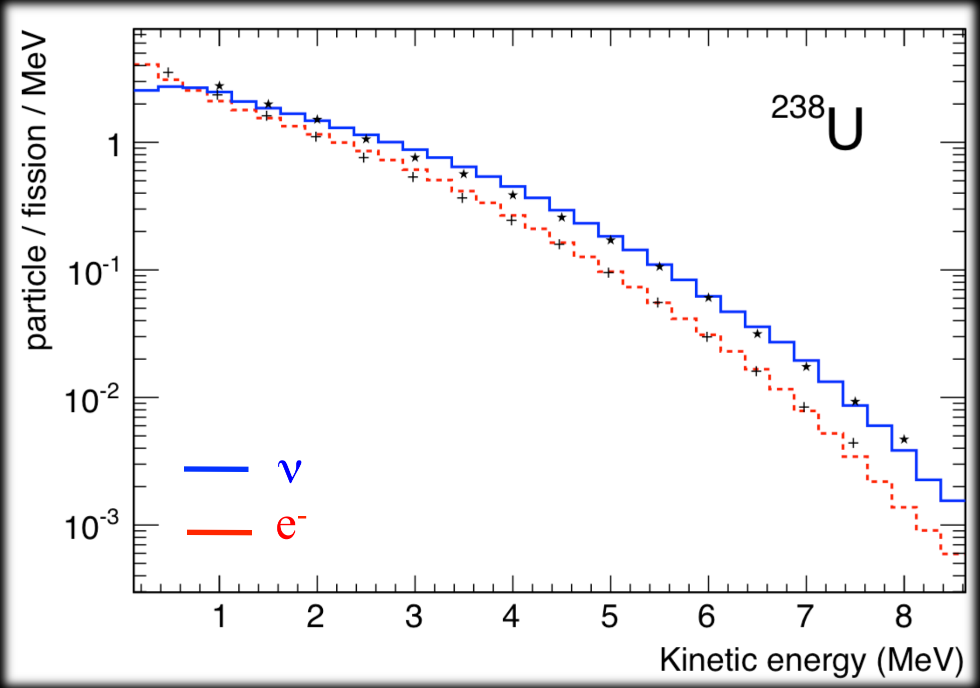


- Ab-initio computation
  - based on nuclear databases
  - reactor core evolution simulation
  - 800 nuclei
    10 000 decay branches
- γ-spectroscopy yields energy levels and branching fractions, but with experimental limitations
- 10-20% discrepancy with the ILL β-spectrum data
- SAME uncertainty for neutrino spectra

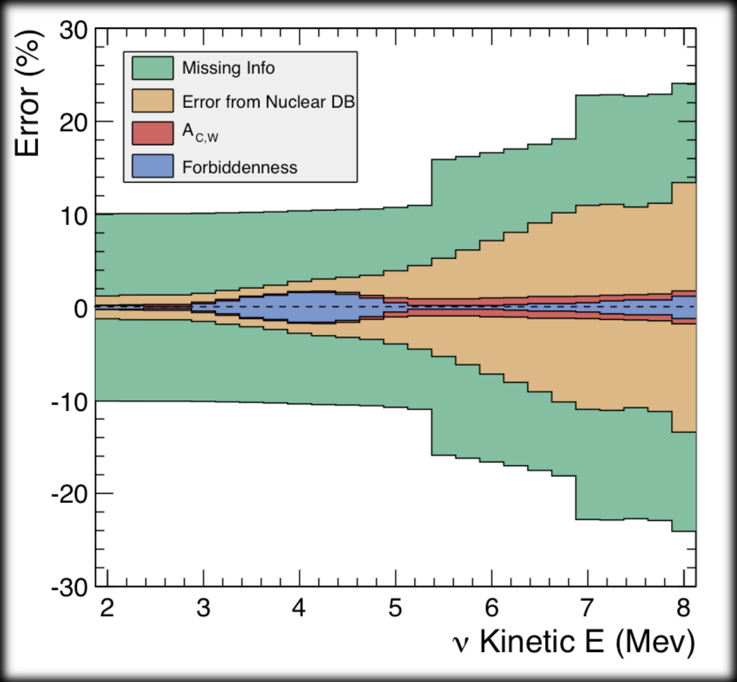
A) Ab-Initio Approach: Results

- MURE: Reactor core evolution
- BESTIOLE: β-ν conversion code: database of ~800 nuclei and 10000 β-branches

^{238}U spectrum prediction (not a fit to data)



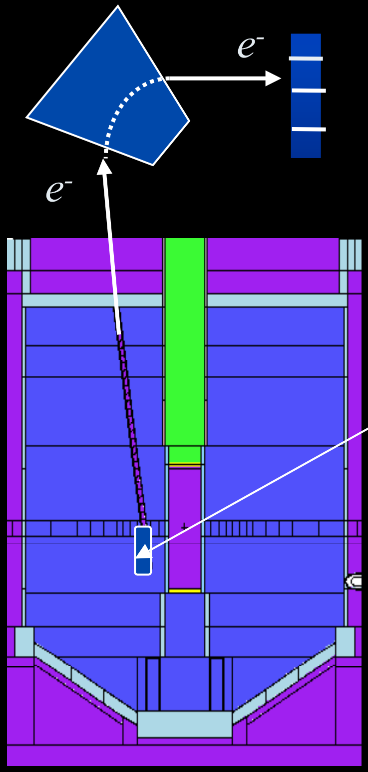
Stack of the uncertainties



- Total error in the 10-20% range.
- Dominated by systematics of nuclear databases & missing informations

ILL β-spectrum data (e^-)

A measurement of the cumulated beta spectrum from ^{235}U ^{239,241}Pu fission products was performed with a magnetic spectrometer at the ILL reactor (France) in the 1980's

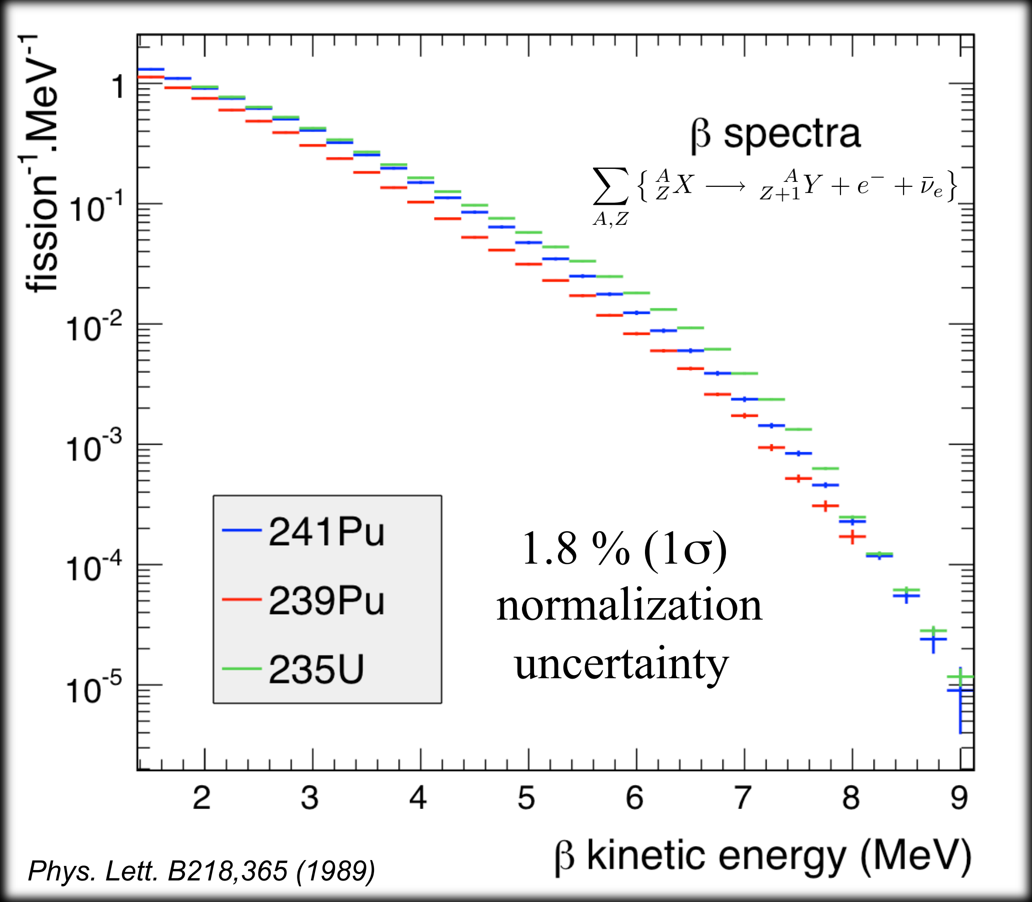


High resolution spectrometer

Target foil (^{235}U, ^{239}Pu, ^{241}Pu) in thermal n flux

ILL research reactor (Grenoble, France)

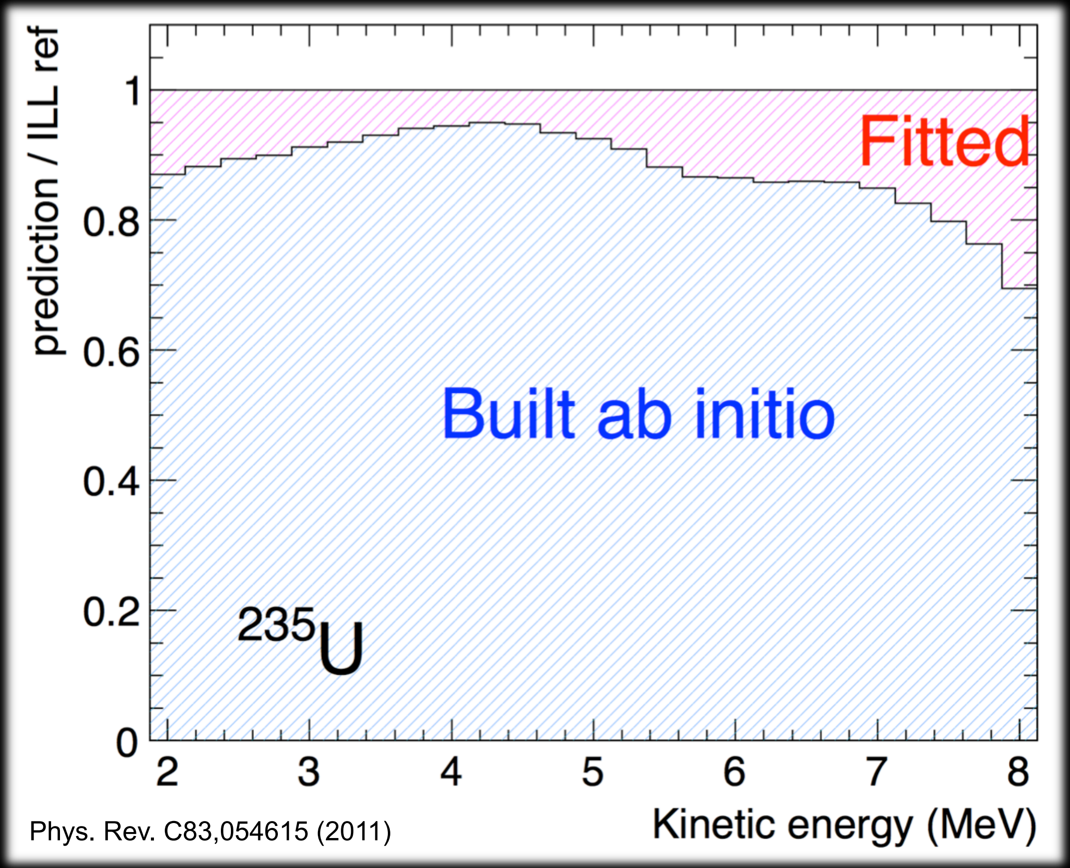
Emitted β spectra per fission of each isotope k



Phys. Lett. B218,365 (1989)

A) Ab-Initio Approach: Uncertainty

Comparison of the ILL β spectra (electron data) with the ab-initio computation



Phys. Rev. C83,054615 (2011)

- Built ab initio
  - 90% of the total β spectra of ^{235}U and ^{239,241}Pu are described by the sum of measured β-decays x fission yields.
- Fitted:
  - 10% missing information has to be inferred (fit by 5 virtual β-branches)
  Main uncertainty

NE290D Lecture #10

- Nuclear Reactors
- Reactor Antineutrino Flux
- Fuel Burn-up & Neutrino Flux
- Reactor Antineutrino Energy Spectra
  - Ab-Initio Computation using Nuclear Databases
  - Computation using Experimental Integral β-Data

B) Conversion method (1)

- **The total β-spectrum, N_β, is a sum of all decay branches**

$$N_\beta(W) = \int N_\beta(W, W_0; Z_{eff})\eta(W_0)dW_0$$

  - W : electron energy, in unit of m_e
  - W_0 : end-point energy
  - Z_{eff} : effective nuclear charge
  - $\eta_0(W)$: underlying (weighter) distribution of all end-points

- **The ILL spectrum can be fitted with N_{vb} effective virtual branches**

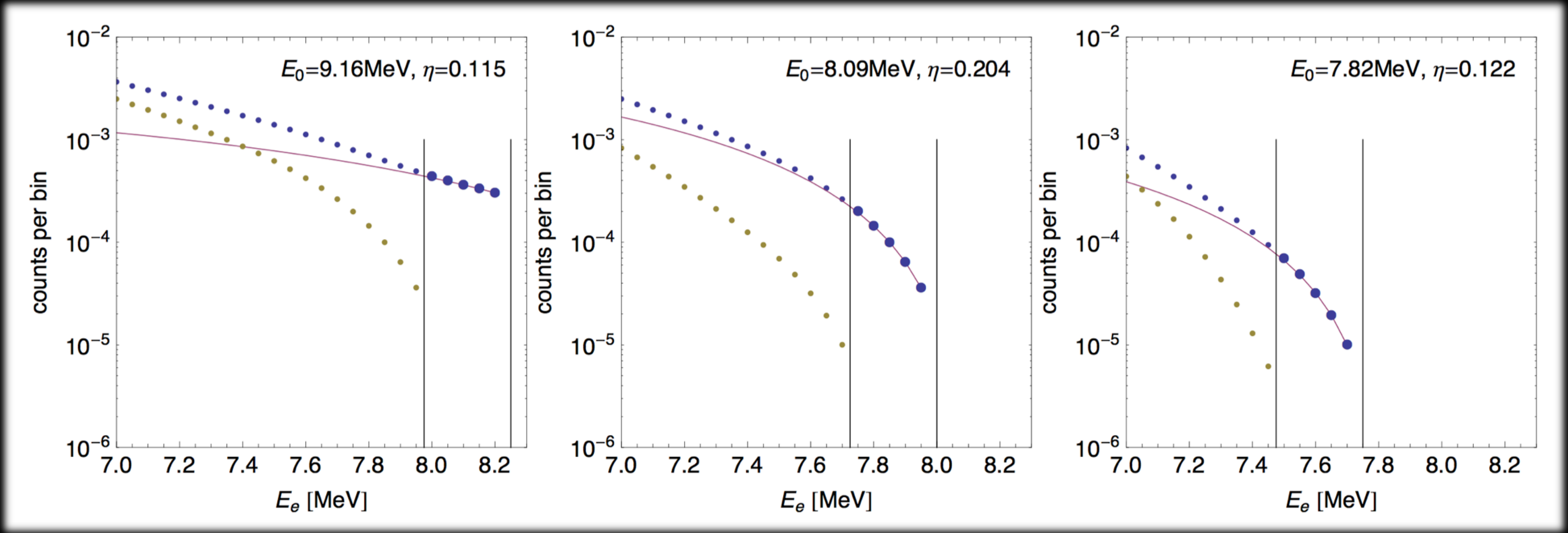
- **Use ILL electron data - Fitting Procedure**

1 – fit an allowed β-spectrum the last s data points
with free normalization η and endpoint energy W_0
2 – delete the last s data points
3 – subtract the fitted spectrum from the data
4 – goto 1

- **Invert each virtual branch using energy conservation into a neutrino spectrum and add them all**

B) Conversion method (2)

- Fit ILL electron spectrum with a sum of N_{vb}=30 effective branches

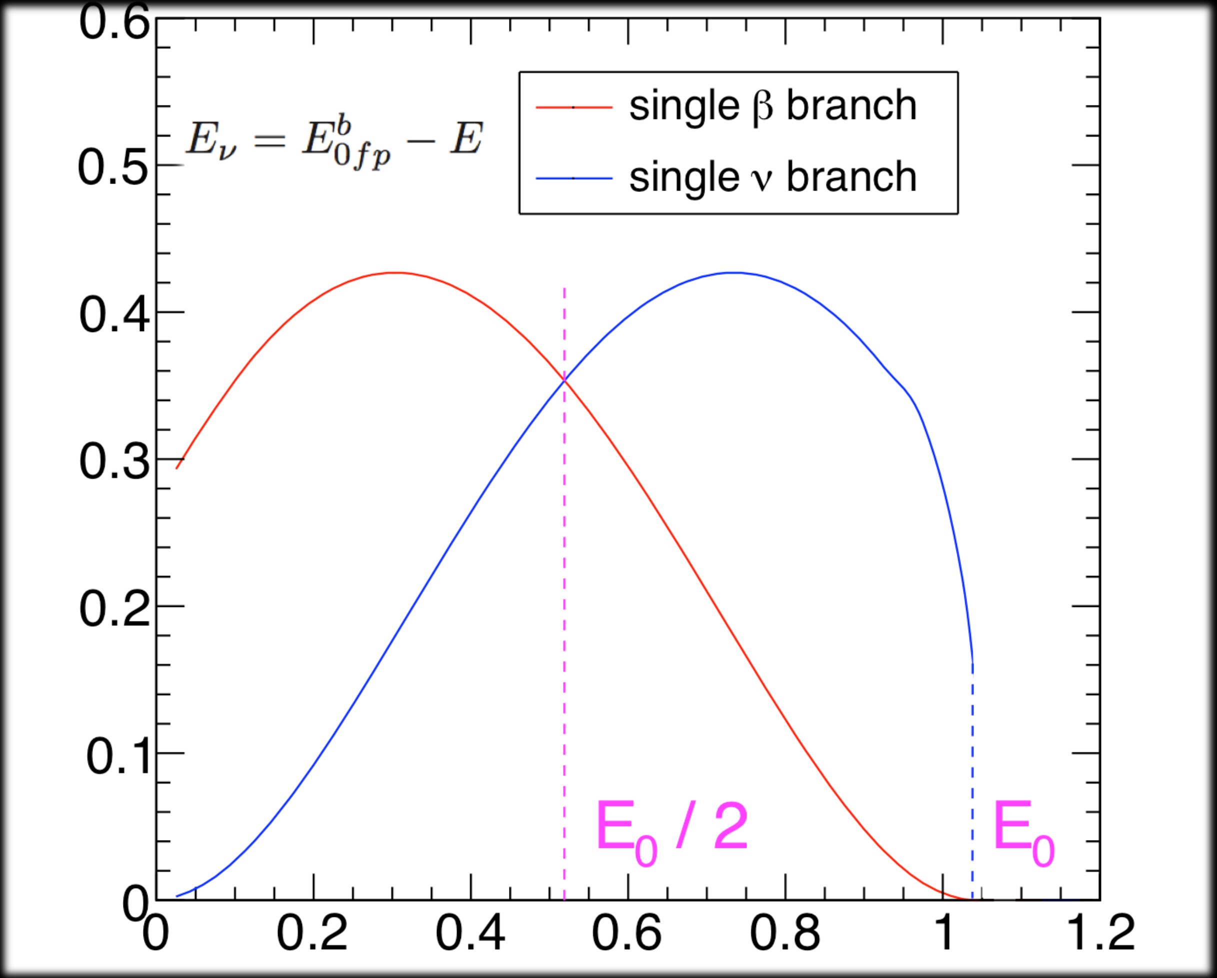


- Conversion of the effective branches to ν spectra (next slide)
- a Z_{eff} associated to each virtual branch: mean fit on nuclear data $Z=f(W_0)$

$$Z(W_0) \approx 49.5 - 0.7E_0 - 0.09E_0^2, \quad Z \geq 34$$

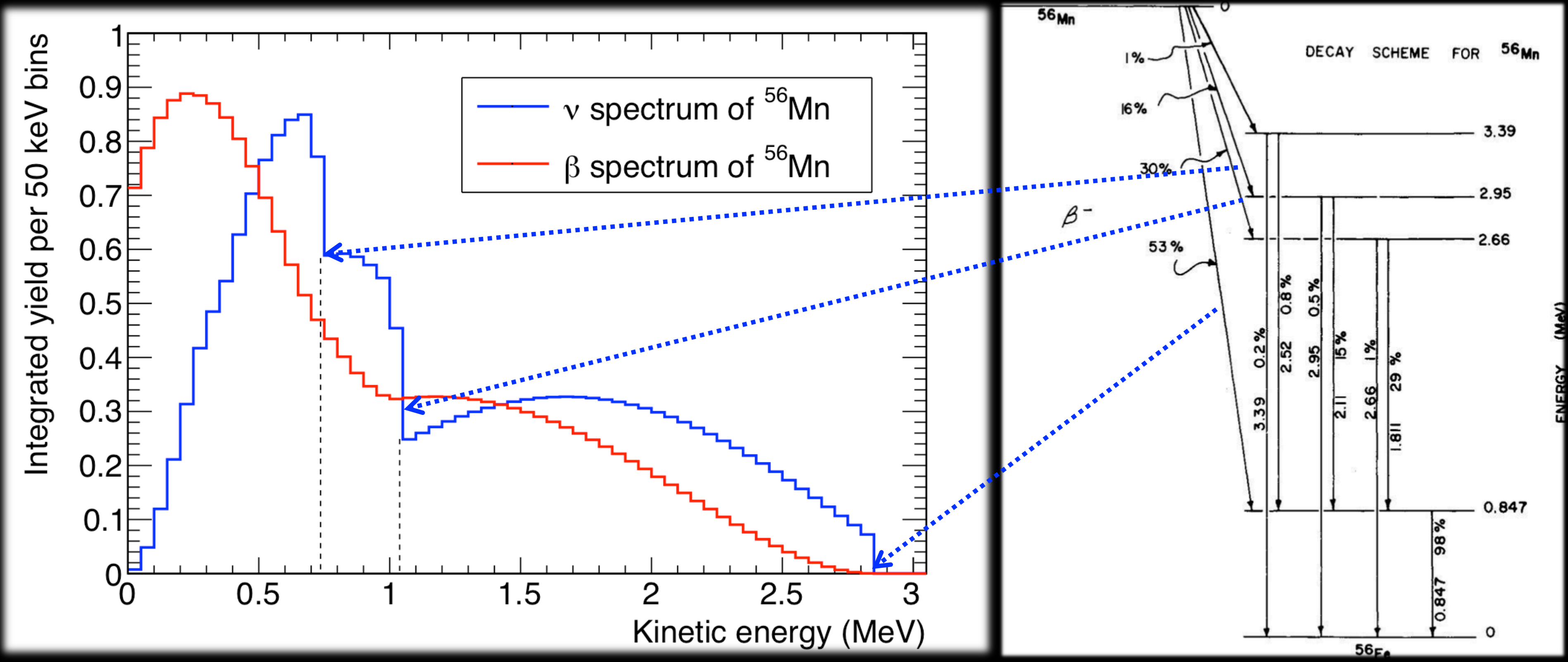
From e^- to ν: a single branch

For a single branch energy conservation implies a <u>one-to-one</u> correspondence between β and ν spectrum



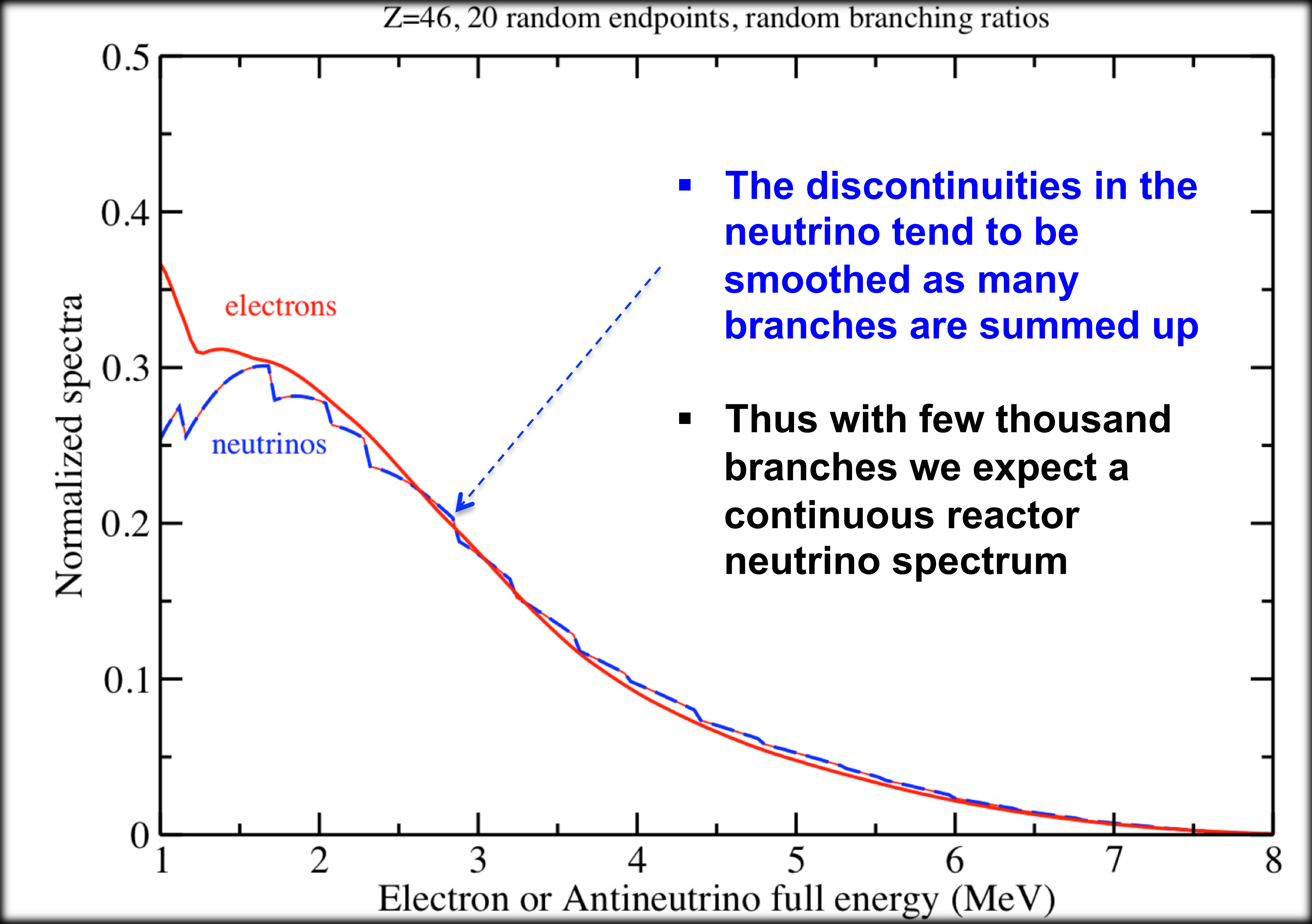
From e$^-$ to ν: multiple branches

For multiple branches the conversion has to be applied separately for each branch



But not all the branches properties are well known…

From e^- to ν: 20 branches



- The discontinuities in the neutrino tend to be smoothed as many branches are summed up
- Thus with few thousand branches we expect a continuous reactor neutrino spectrum

Apply corrections to Fermi theory

Applied to each virtual branch

Example for a single branch with Z=46, A=117, E_0=10 MeV

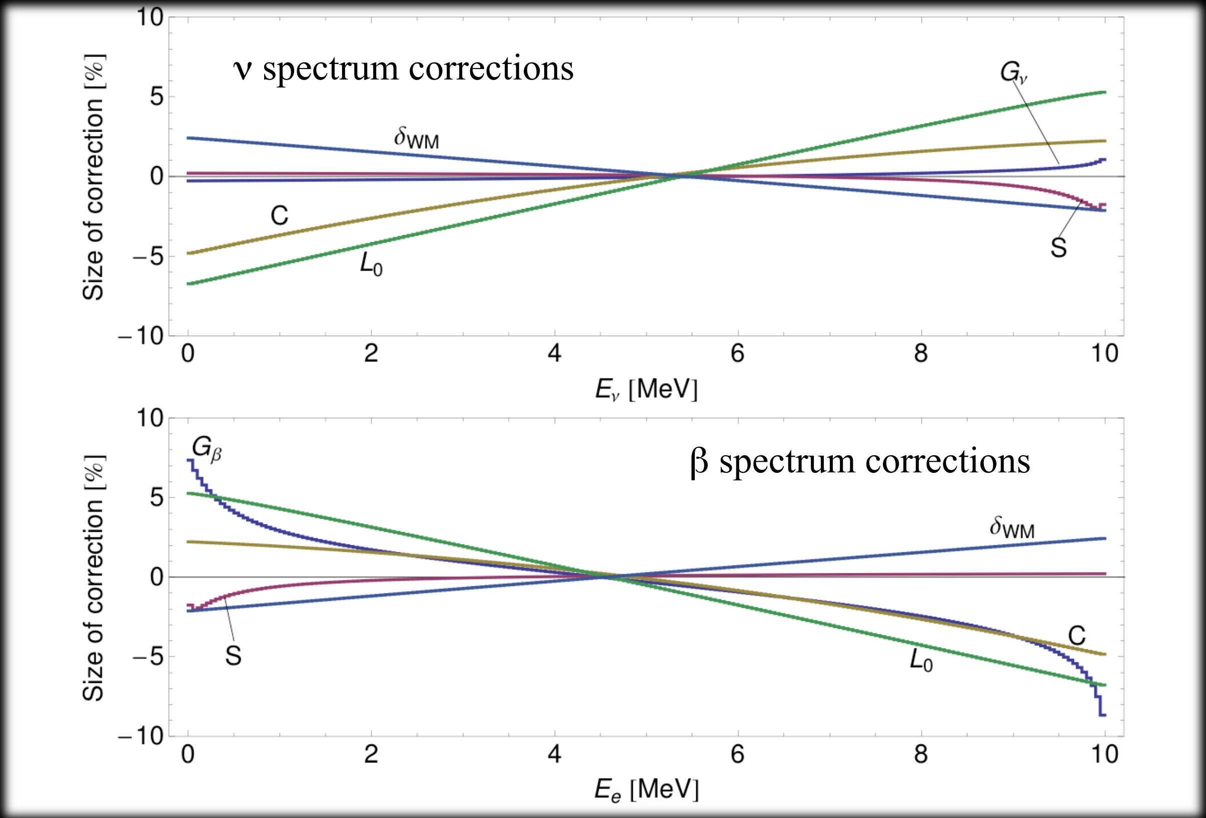
L_0: finite size of nuclear charge

G: QED radiative correction

S: screening of atomic e-

C: finite size distrib. of decaying neutron

d_{WM}: weak magnetism



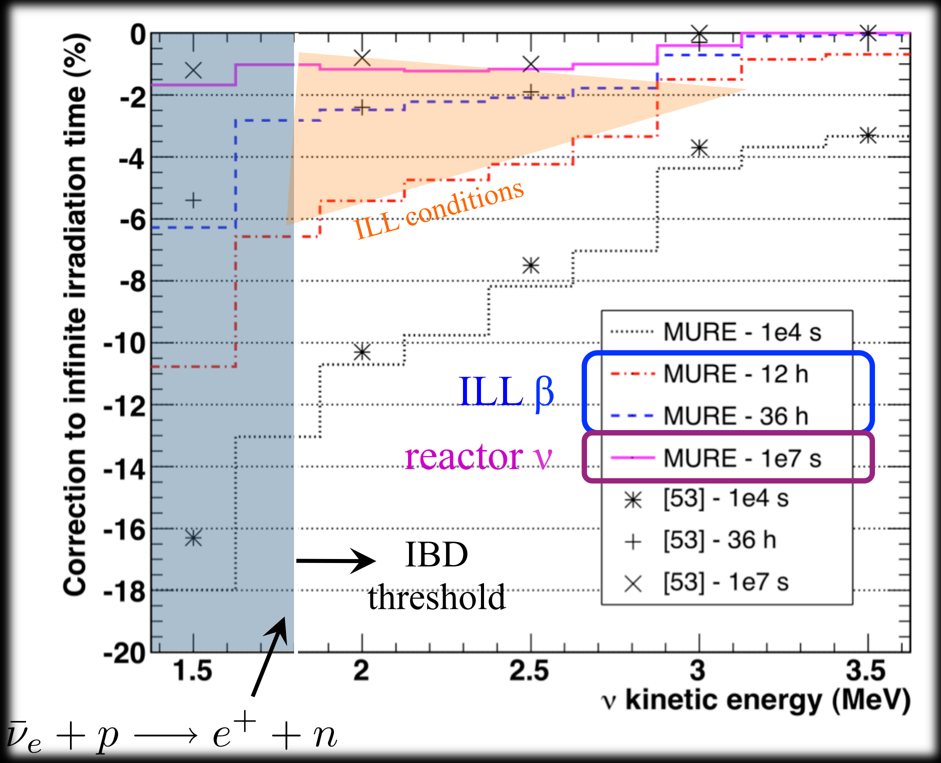
→ **Corrections up to 10% - apply to both neutrino/beta spectra**

Off-equilibrium effects

- ILL electron reference spectra : 12 to 40 hours irradiation time
- Neutrino reactor experiments irradiation time >> months
- **BUT 10% of fission products have a β-decay life-time long enough to keep accumulating after several days**

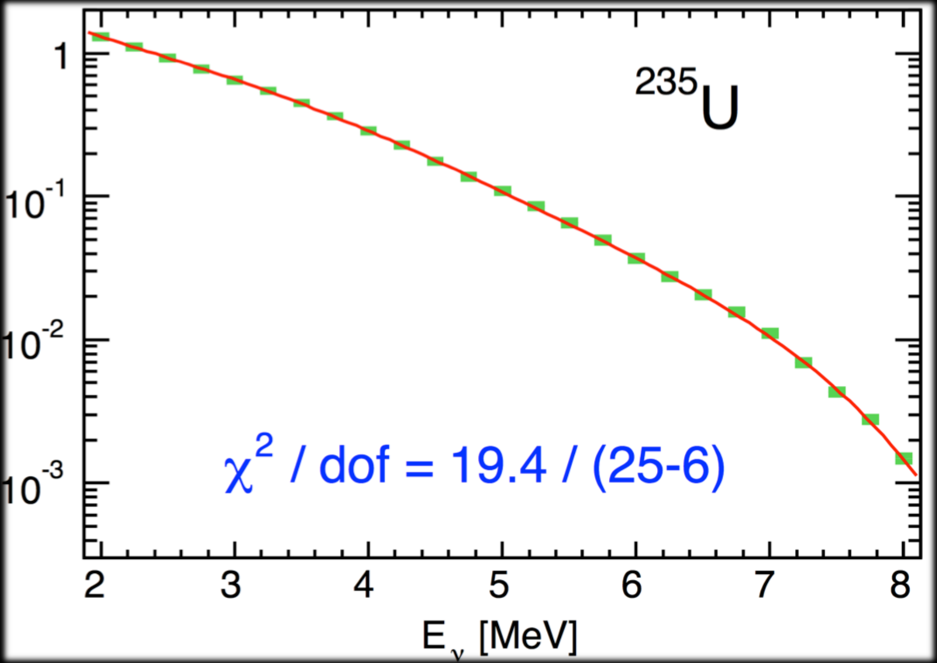
→ need a correction through reactor core evolution simulation

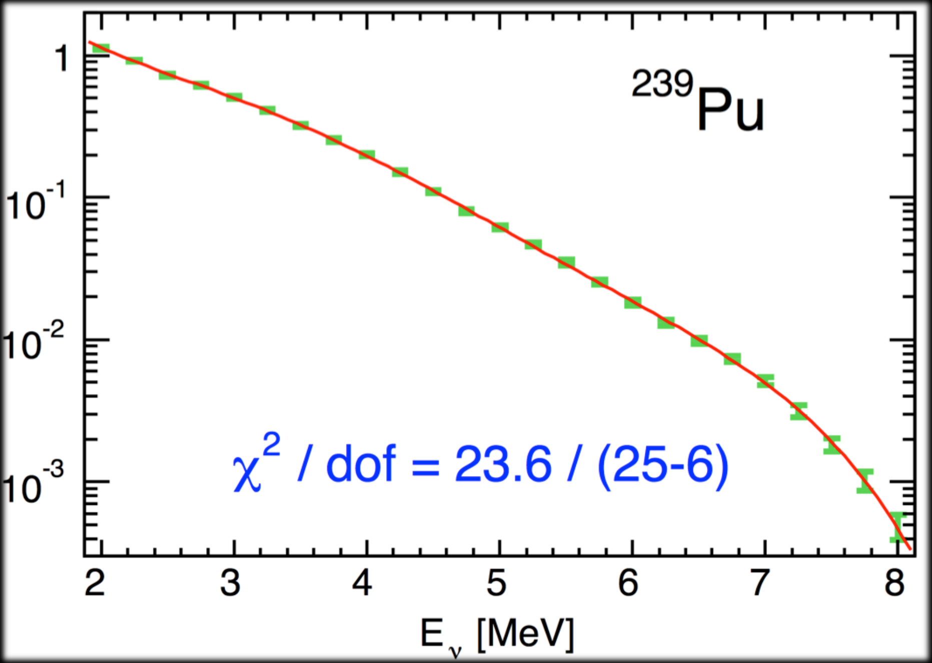
- Relative change of ν spectrum w.r.t. infinite irradiation time
- 1% correction at E<3 MeV
- Can be computed accurately



$\bar{\nu}_e + p \longrightarrow e^+ + n$

B) Reactor Neutrino Spectra



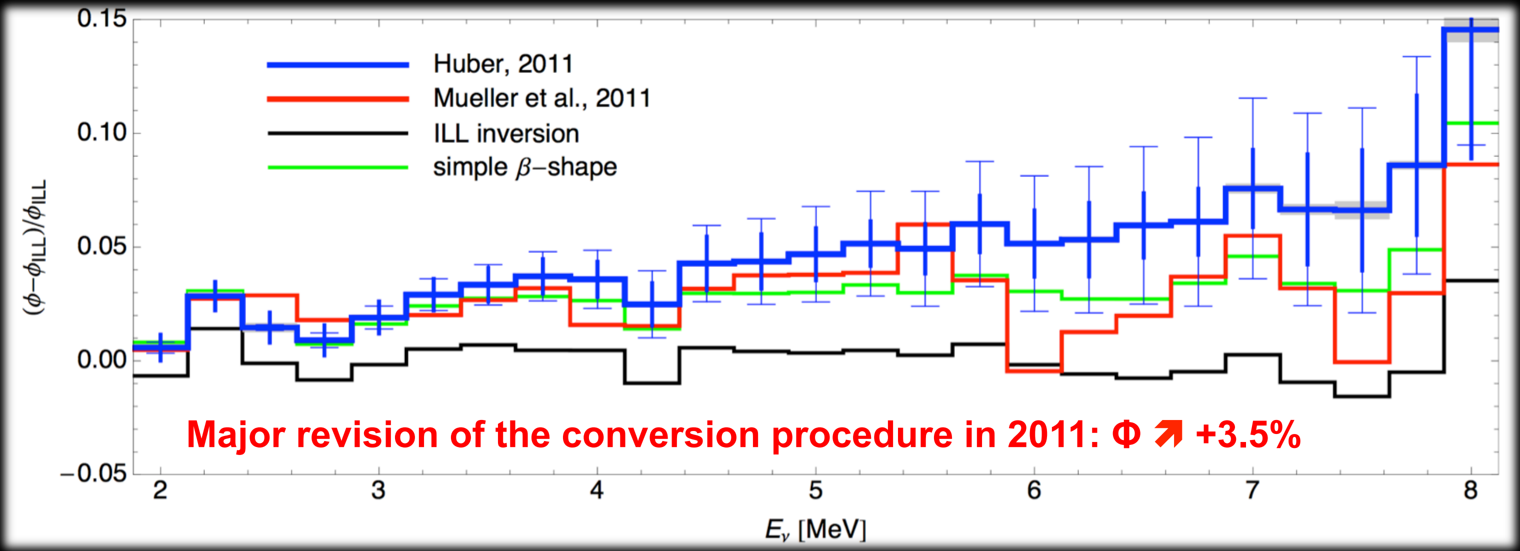


- **Useful parameterization:**

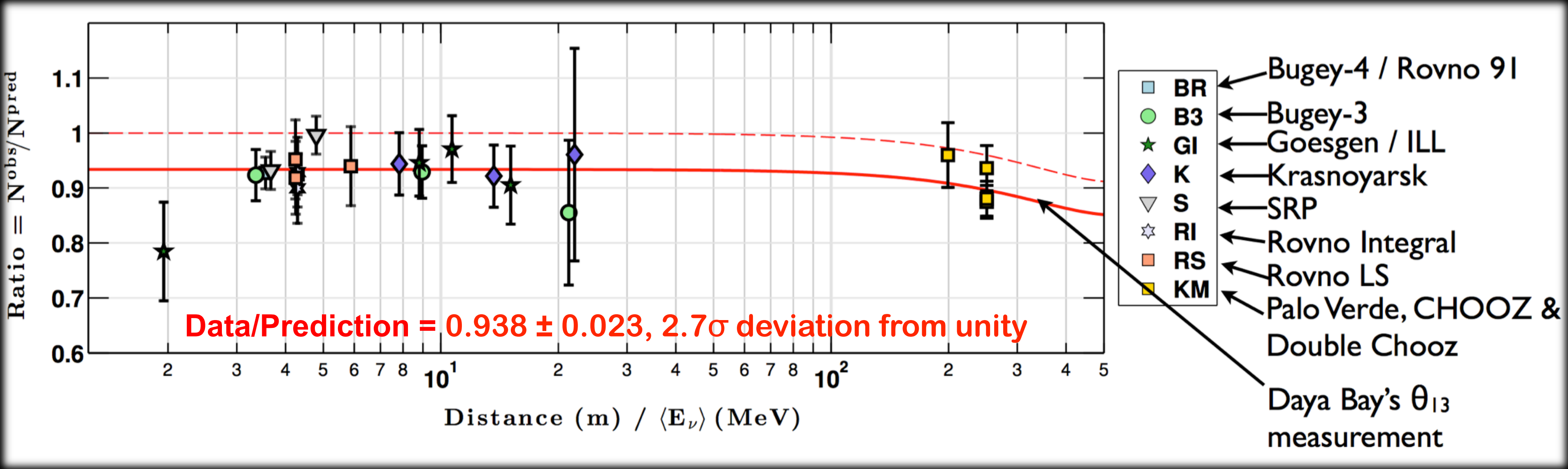
$$S_{k,\mathrm{fit}}(E_\nu) = \exp\left(\sum_{p=1}^{6} \alpha_{pk} E_\nu^{p-1}\right)$$

- **α parameters can be found in**
  - T. Mueller et al., Phys. Rev. C83,054615 (2011)
  - P. Huber, Phys. Rev. C84, 024617(2011)

The Reactor Anomaly: still a mystery



Major revision of the conversion procedure in 2011: Φ ↗ +3.5%



Data/Prediction = 0.938 ± 0.023, 2.7σ deviation from unity

Comparison of A & B

A) Ab initio calculation

Complete simulation of nuclear reactor core evolution

- Fuel loading, geometry, n-capture and fission physics
→ Fission product inventory

Description of all β-decays
- Nuclear databases
- Fermi theory + corrections
- Nuclear models

→ β and ν total spectra from some 10^4 β-branches

→ 10-20% uncertainty

B) Conversion of total β spectra

Total β spectra of fissile isotopes measured at ILL in the 80's

→ Accurate reference electron spectra

Conversion to antineutrinos
- Use of "virtual" β-branches
- Fermi theory + corrections
- Control of approximations

→ Reference ν spectra per isotope to be combined with prediction of fissions rates

→ ≈3% uncertainty

Summary: reactor ν spectrum

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

Reactor data

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

Reactor evolution codes

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

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

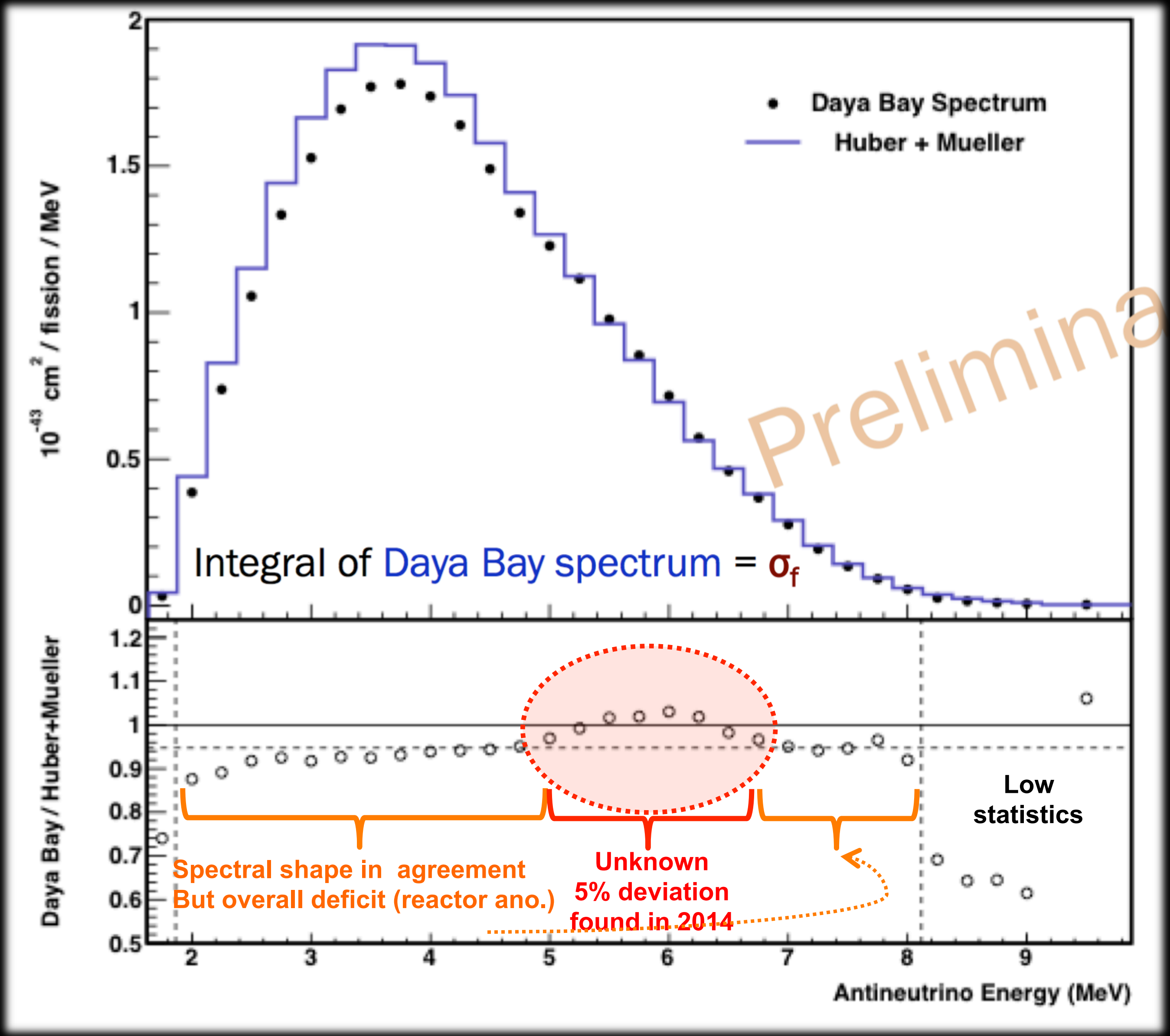
$$k = {}^{235}\mathrm{U}, {}^{238}\mathrm{U}, {}^{239}\mathrm{Pu}, {}^{241}\mathrm{Pu}$$

Nuclear databases

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

ν spectrum per fission

Absolute Neutrino Spectrum measurement



Integral of Daya Bay spectrum = σ_f

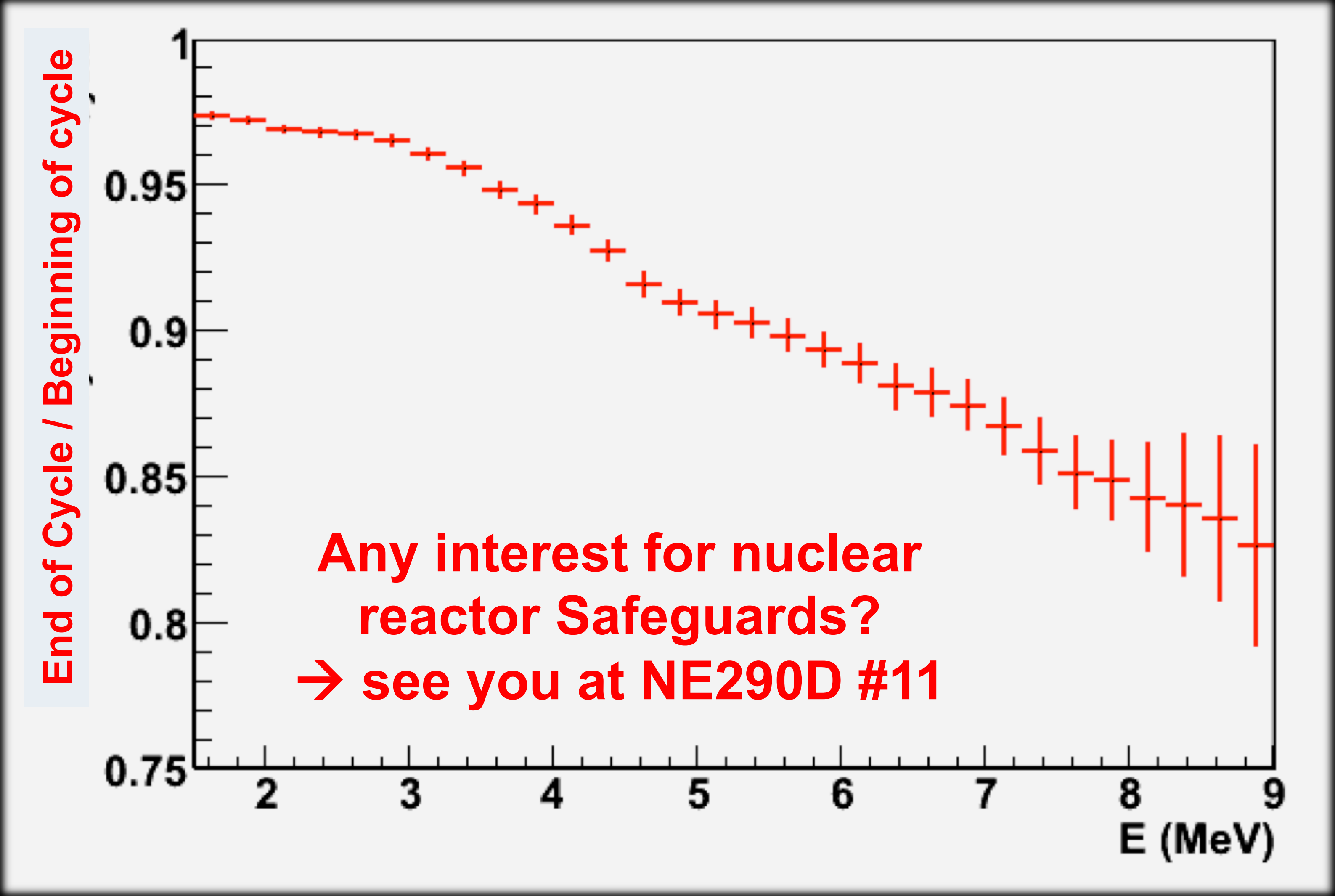
Spectral shape in agreement
But overall deficit (reactor ano.)

Unknown
5% deviation
found in 2014

Low
statistics

Neutrino Spectrum shape & burnup

The energy dependent neutrino yields vary with the burn-up



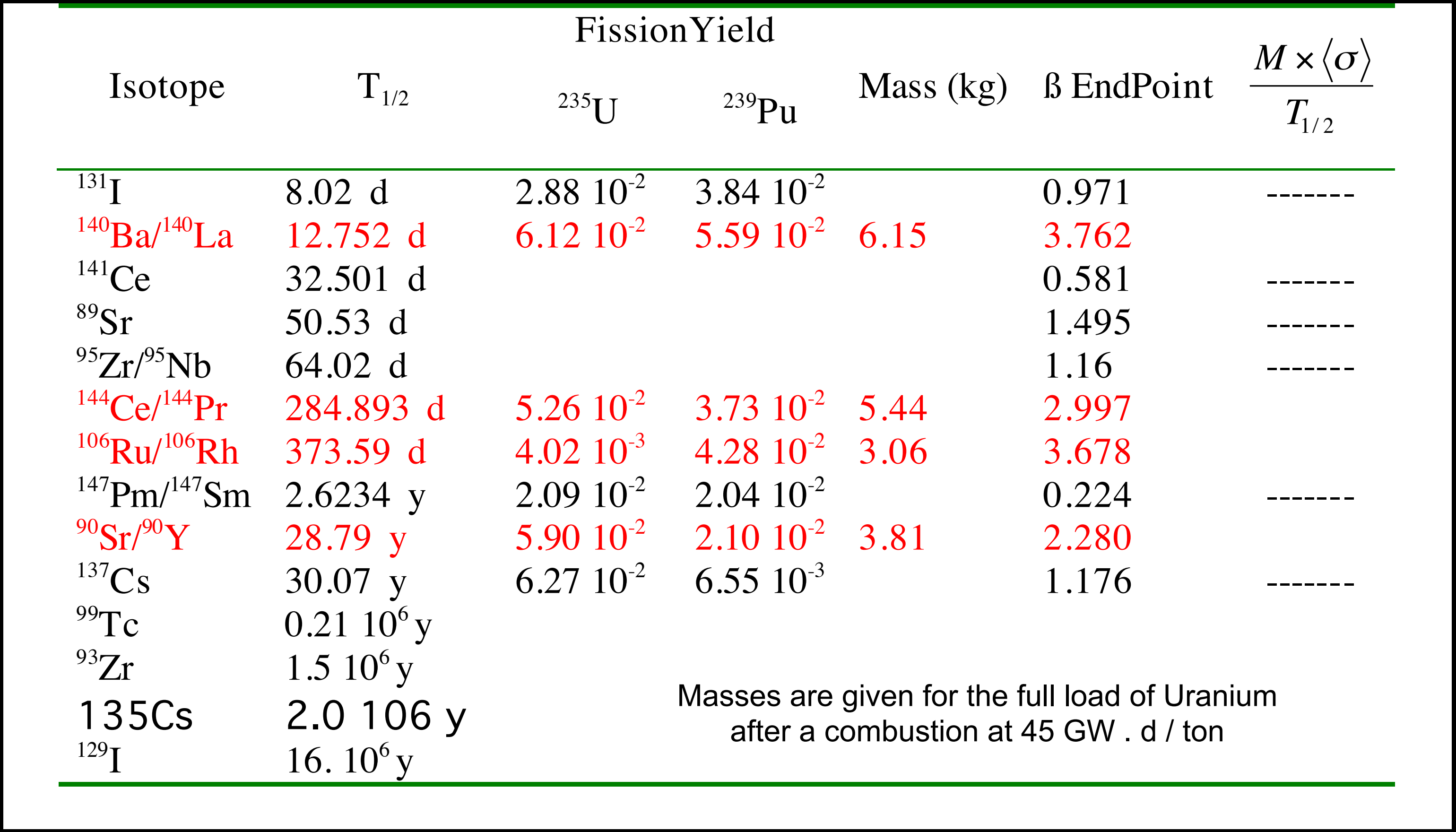
Any interest for nuclear reactor Safeguards?

→ see you at NE290D #11

BACKUP SLIDES

Spent-fuel repository

- Fuel stored for a few years on power plant site in cooling pools
- Potential emitter of antineutrinos
- Main isotopes with Q>1.8 MeV: ^{140}Ba, ^{144}Ce, ^{106}Ru, ^{90}Sr
- Typically add $(\phi_\nu)^{sf} < 0.5\% \, (\phi_\nu)^{R}$ due to long half life and low Q



Isotope	$T_{1/2}$	FissionYield ^{235}U	^{239}Pu	Mass (kg)	ß EndPoint	$\frac{M \times \langle\sigma\rangle}{T_{1/2}}$
^{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 . d / ton