# New TAS Results for Antineutrino Spectra

A.-A. Zakari, M. Fallot, A. Porta

**On-behalf of the TAS Collaboration**

J. Agramunt[1], A. Algora[1], J. Äystö[4], V.M. Bui[2], D. Cano-Ott[5], C. Domingo-Pardo[1], V. Eloma[4], E. Estévez[1], T. Eronen[4], M. Fallot[2], W. Gelletly[3], G. Giubrone[1], J. Hakala[4], A. Jokinen[4], M.D. Jordan[1], A. Kankainen[4], E. Mendoza[5], F. Molina[1], ,I. Moore[4], S.E.A. Orrigo[1], A. Pérez[1], Zs. Podolyák[3], H. Penttilä[4], A.Porta[2], P. H. Regan[3], S. Rice[3], J. Rissanen[4], B. Rubio[1],J.L. Taín[1], E. Valencia[1], C. Weber[4], A. Zakari[2] + IGISOL people

1 IFIC, CSIC-Univ. Valencia, Valencia, Spain

2 **Subatech, CNRS/IN2P3, Univ. Nantes, EMN, Nantes, France**

3 Univ. Surrey, Guilford, UK

4 IGISOL, Univ. Jyväskylä, Finland

5 Ciemat- Madrid, Spain

Many thanks to A. Algora and J.L. Tain for the inputs provided

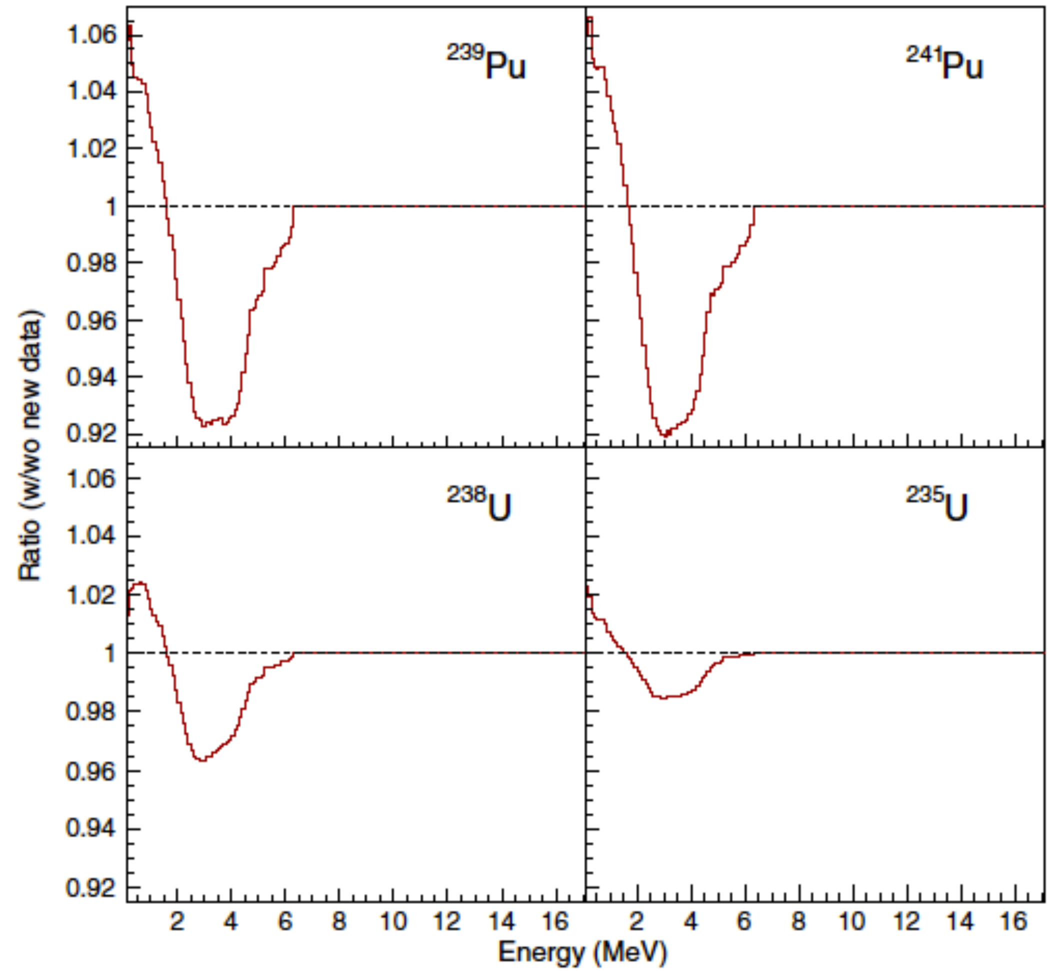
# Outline

- Total Absorbtion Spetroscopy (TAS) measurements and antineutrino spectra calculation
- Results from 2009 experiment @ Jyväskylä
- Present and future activities

# Impact of TAS data on Antineutrino Spectra

Phys. Rev. Lett. 109, 202504 (2012)

Ratios of summation antineutrino spectra including the new TAS data for $^{102;104-107}Tc$, $^{105}Mo$, and $^{101}Nb$ over the same spectra but with the JEFF3.1 data




- $^{239;241}Pu$ energy spectra: noticeable deviation from unity observed in the 0–6 MeV energy range reaching an 8% decrease.
- $^{238}U$ energy spectrum: effect reaches a value of 3.5% at 2.5–3 MeV.
- $^{235}U$: 1.5% at 2.5–3.5 MeV, expected since these nuclei are a small contribution to the $^{235}U$ spectrum.

⇒ Shows the important role of the Pandemonium nuclei in the $\bar{\nu}$ summation spectra
⇒ New measurements required, list of nuclei identified from our simulation results

→ See M.Fallot talk

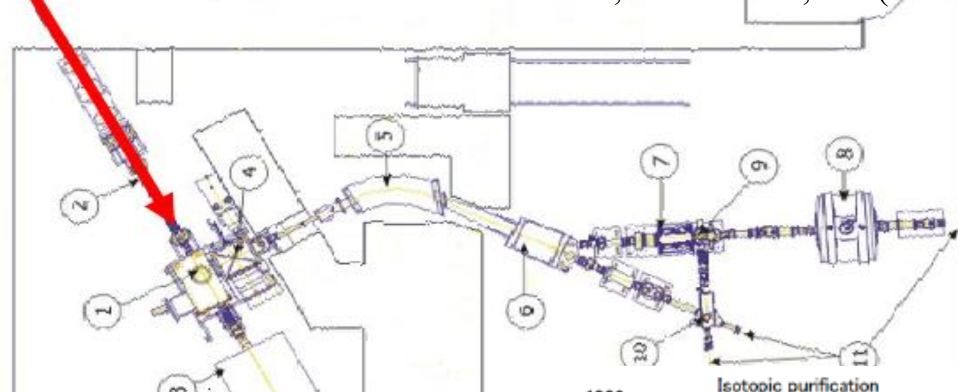
# 2009 Jyväskylä measurements

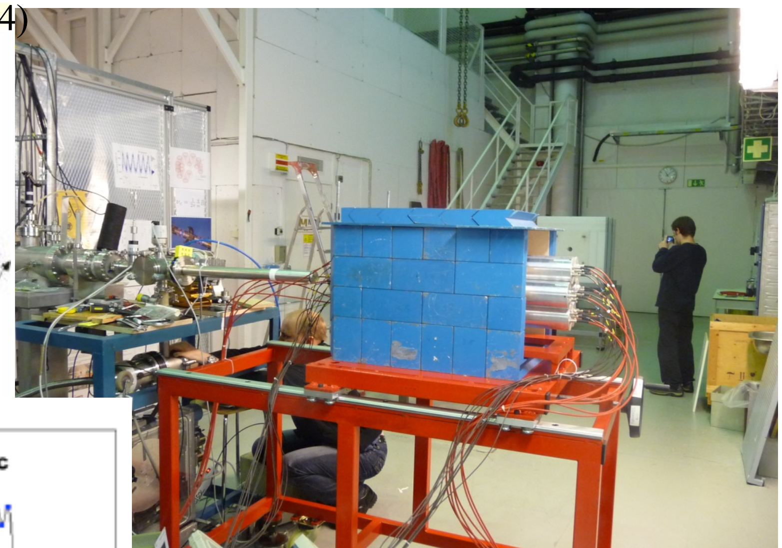
7 isotopes of Br and Rb have been measured at JYFL of Jyväskylä (Finland) :

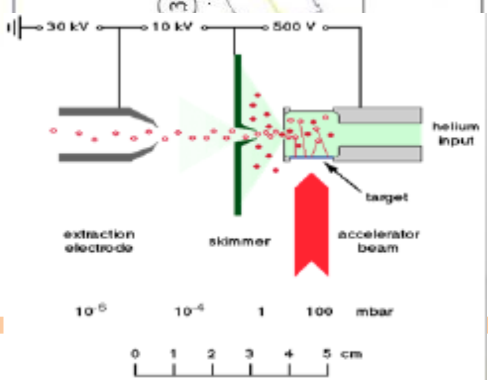
- Delayed neutron emitters (for delayed neutron measurements with BELEN see: J.L. Tain 2012 JEFF meeting)
- Priority 1 for Decay Heat calculations (U/Pu and Th/U cycles)
- Determination of gamma-neutron competition $\Gamma\gamma/\Gamma n$ → see talk by A. Algora last year
- 2 of them ($^{92,93}$Rb) extracted from the neutrino proposal : Reactor antineutrino Priority 1

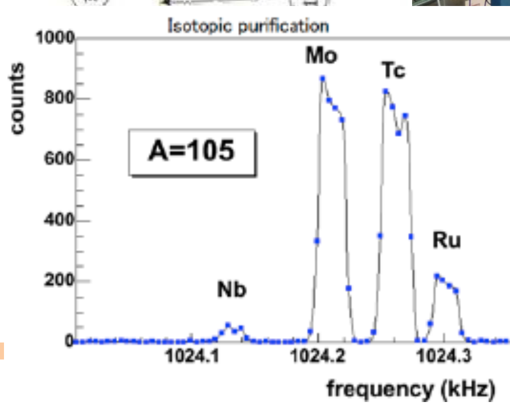
Why JYFL: good selection of the measured nucleus needed → IGISOL* + penning trap JYFLTRAP**

*J.Ärje et al., NIM A 247,431 (1986)
**V.S.Kolhinen et al., NIM A 528,776 (2004)







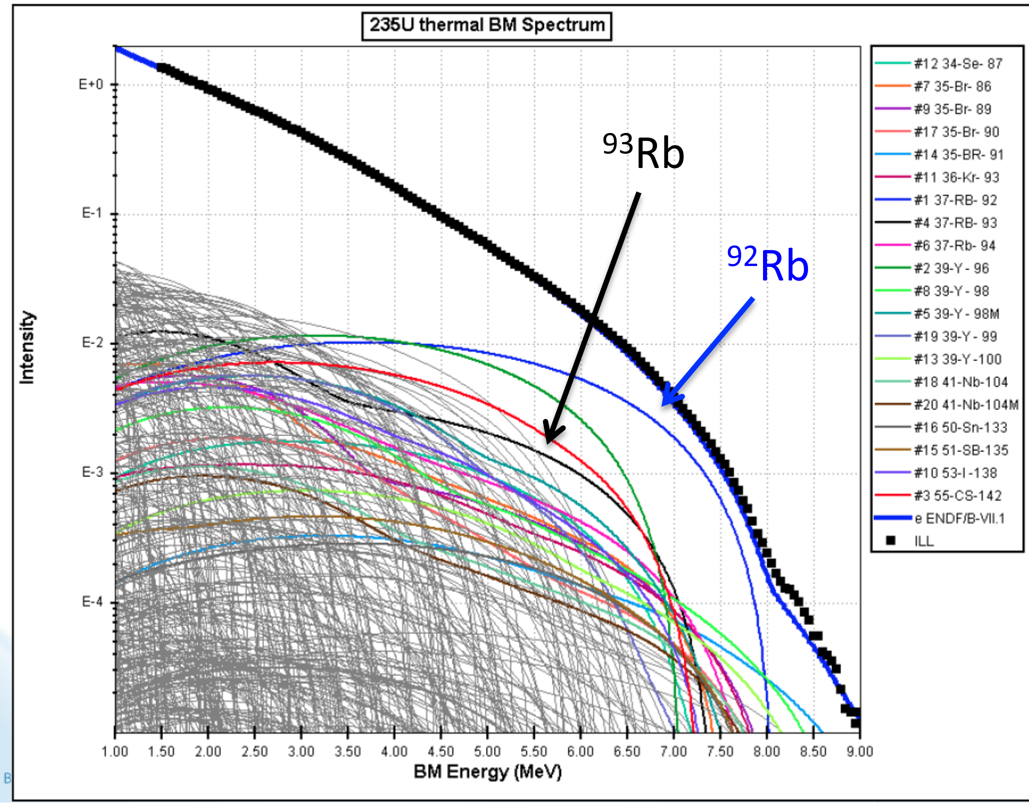




PhD Thesis work:

- E. Valencia (IFIC-Valencia)
- S. Rice (University of Surrey)
- Z. Issoufou (SUBATECH-Nantes)

# The cases of $^{92,93}$Rb: motivations

- They were candidate **pandemonium nuclei**, GS-GS 1st forbidden transition with high $I_\beta$
- **Big contribution in 235U and 339Pu ν spectra:** respectively expected to be around 32% and 25.7% in [6-7] MeV, 34% and 33% in [7-8] MeV




A.Sonzoni presentation @ INT neutrino Workshop, Seattle, November 2013.

**Our summation calculations give the following priority list:**

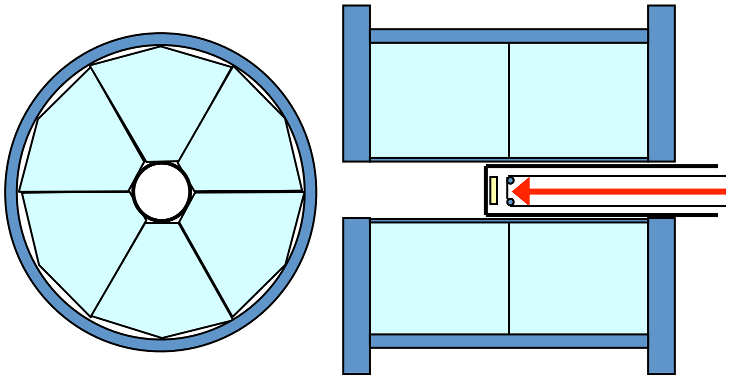
TABLE I. Main Contributors to a standard PWR antineutrino energy spectrum computed using the summation method described in [12].

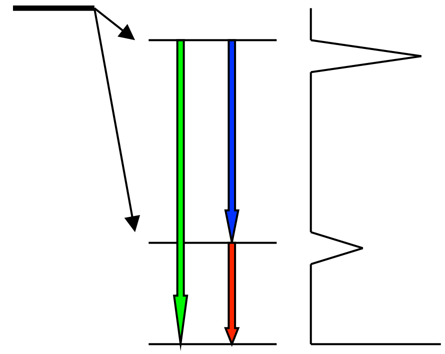
| | 4 - 5 MeV | 5 - 6 MeV | 6 - 7 MeV | 7 - 8 MeV |
|---|---|---|---|---|
| $^{92}$Rb | 4.74% | 11.49% | 24.27% | 37.98% |
| $^{96}$Y | 5.56% | 10.75% | 14.10% | - |
| $^{142}$Cs | 3.35% | 6.02% | 7.93% | 3.52% |
| $^{100}$Nb | 5.52% | 6.03% | - | - |
| $^{93}$Rb | 2.34% | 4.17% | 6.78% | 4.21% |

**$^{92}$Rb =~16% of the antineutrino energy spectrum emitted by PWRs in the region of energy 5 to 8 MeV !!!**

- $^{92}$Rb also priority 2 for **Decay Heat** in U/Pu cycle and Priority 1 in Th/U cycle

# Analysis to obtain β-feeding → β-strength





An ideal TAS would give directly the β-intensity $I_\beta$ which is linked with the β-strength $S_\beta$:

$$S_i = \frac{I_i}{f(Q_\beta - E_i)T_{1/2}} \quad \left[s^{-1}\right]$$

$$I_i = \frac{f_i}{\sum_k f_k}$$

**Statement of the problem:**

Relation between TAS data and the β-intensity distribution:

$$d_i = \sum_j R_{ij} f_j$$

$$\mathbf{R_j} = \sum_{k=0}^{j-1} b_{jk}\mathbf{g_{jk}} \otimes \mathbf{R_k}$$

Deconvolution (Inverse problem) algorithm→ expectation minimization method

Monte Carlo simulations
+
Nuclear statistical model

- Spectrum must be clean from background and contaminants
- Response must be accurately known
- Solution of inverse problem must be stable

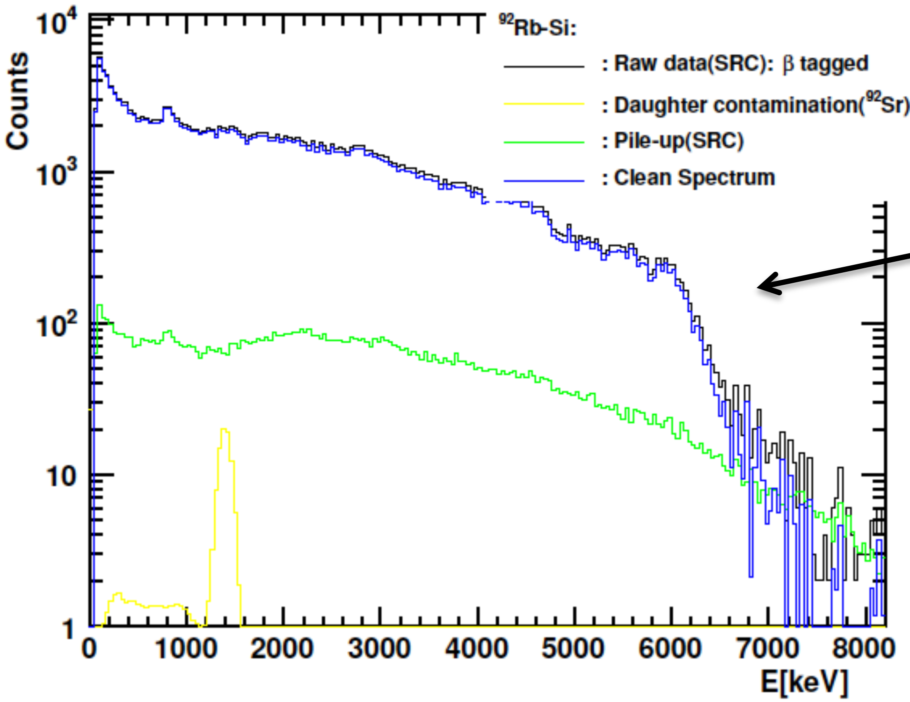
NIM A430 (1999) 333
NIM A430 (1999) 488

Tain et al. NIM A571 (2007) 719,728

→ See J. Tain talk

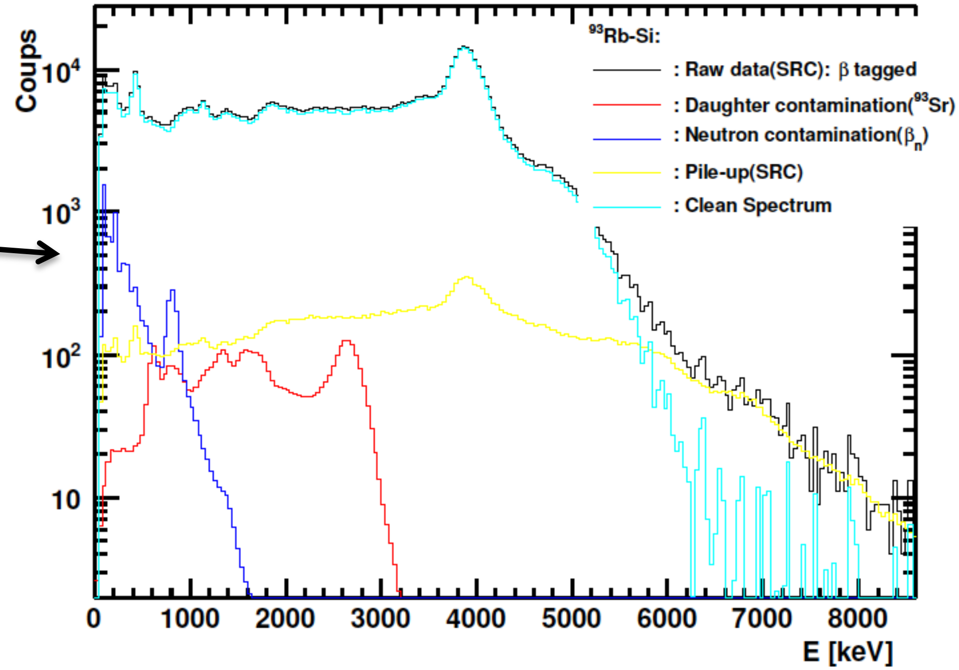
# Data Cleaning

**PhD Thesis work:**
**Zakari Issoufou (Subatech, Nantes)**




$^{92}$Rb contamination:
- Daughter $^{92}$Sr
- Pile-up

$^{93}$Rb contamination:
- Daughter $^{93}$Sr
- Pile-up
- Neutrons from b-n branch (Pn=1.39%)



# The result for $^{92}$Rb

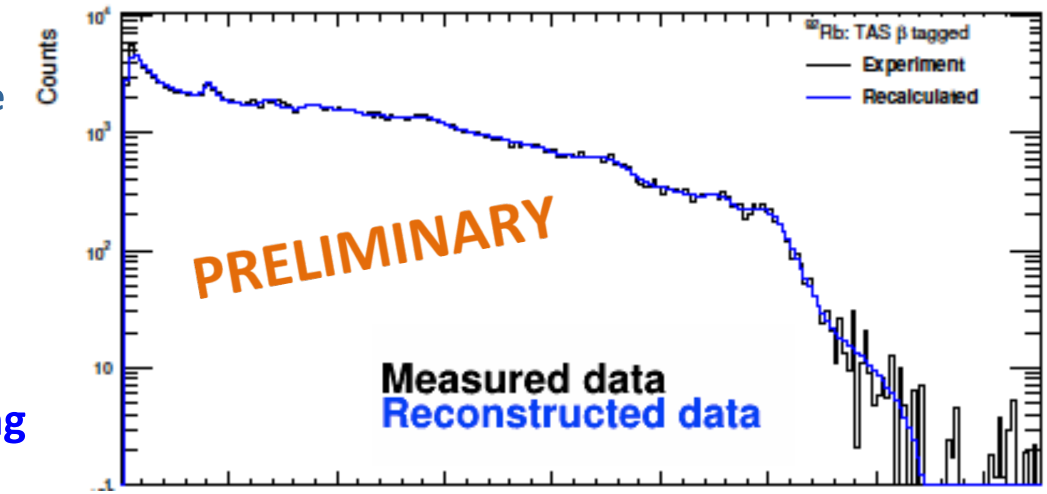
**PhD Thesis work:**

**Zakari Issoufou (Subatech, Nantes)**

**Calculation of level energy feeding through the resolution of the inverse problem**

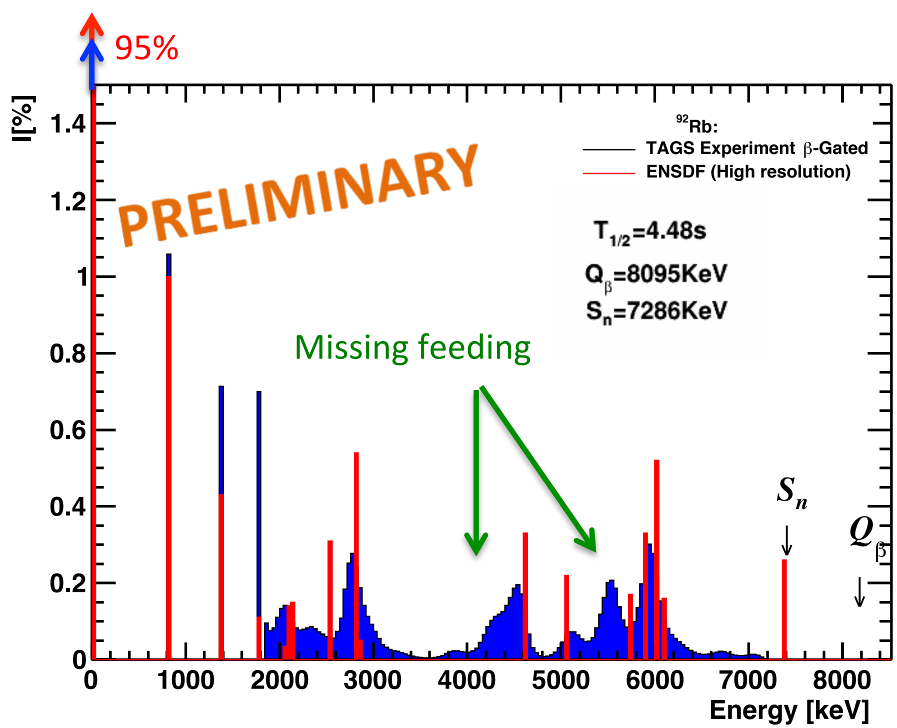
$d_i = \Sigma R_{ij} * f_j$

**Clean data** — **Response matrix** — **Level feeding**




**Ingredient of the inverse problem:**

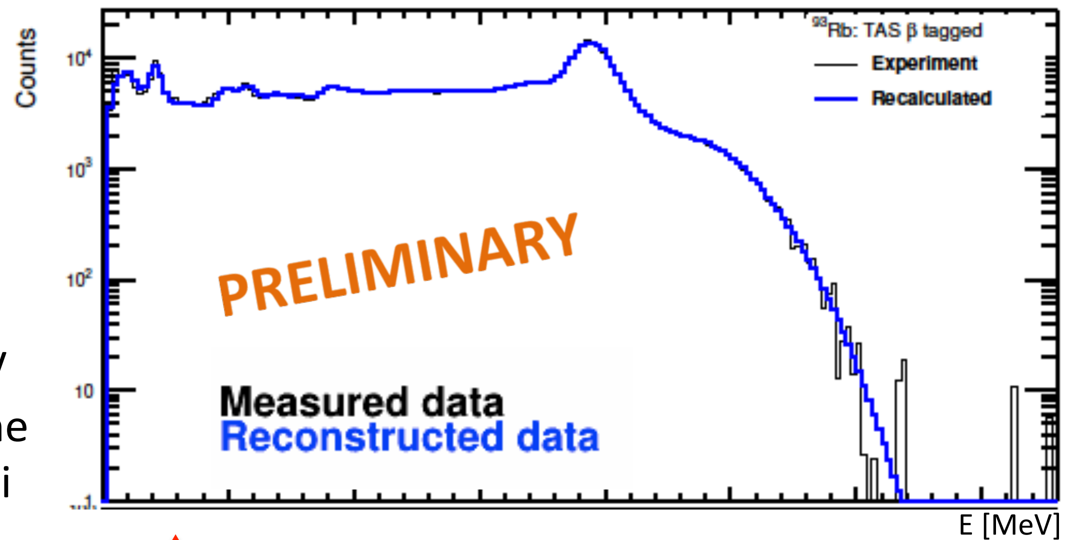
- Known level scheme till 1778 keV
- Branching ratio in continuum zone obtained with Gilbert Cameron formulation* for level density and Lorentz function for gamma strength
- Feeding to level 1673.3 keV was forbidden (4+)
- Impact of these choices on the results has been estimated




*A. GILBERT et A. G. W. CAMERON. « A COMPOSITE NUCLEAR-LEVEL DENSITY FORMULA WITH SHELL CORRECTIONS ». In : Canadian Journal of Physics 43.8 (1965), p. 1446–1496.

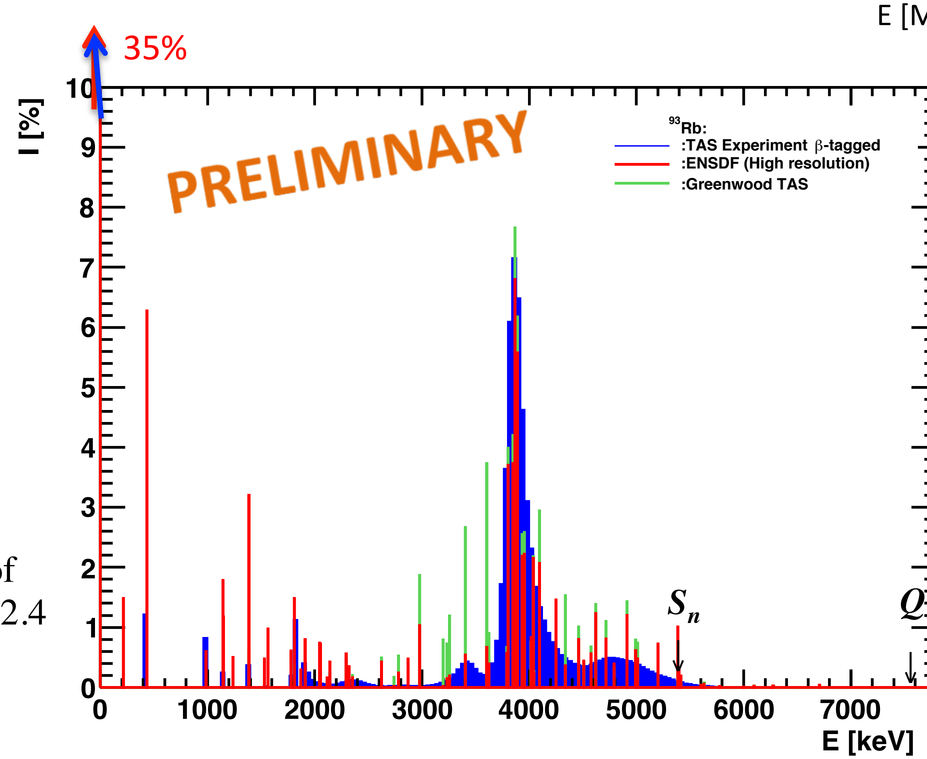
# The result for $^{93}$Rb

**PhD Thesis work:**
**Zakari Issoufou (Subatech, Nantes)**



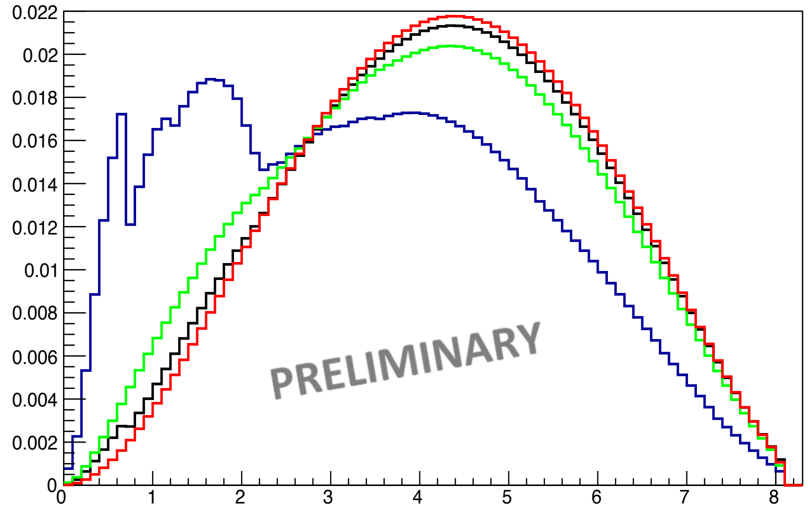

### Ingredient of the inverse problem:

- Known level scheme till 1808 keV
- Branching ratio in continuum zone obtained with Back Shifted Fermi Gas formula (Edigy formulation*) for level density and Lorentz function for gamma strength
- 7 known levels has spin which is not well known, we used 7/2 for these levels.
- Impact of these choices on the results has been estimated.



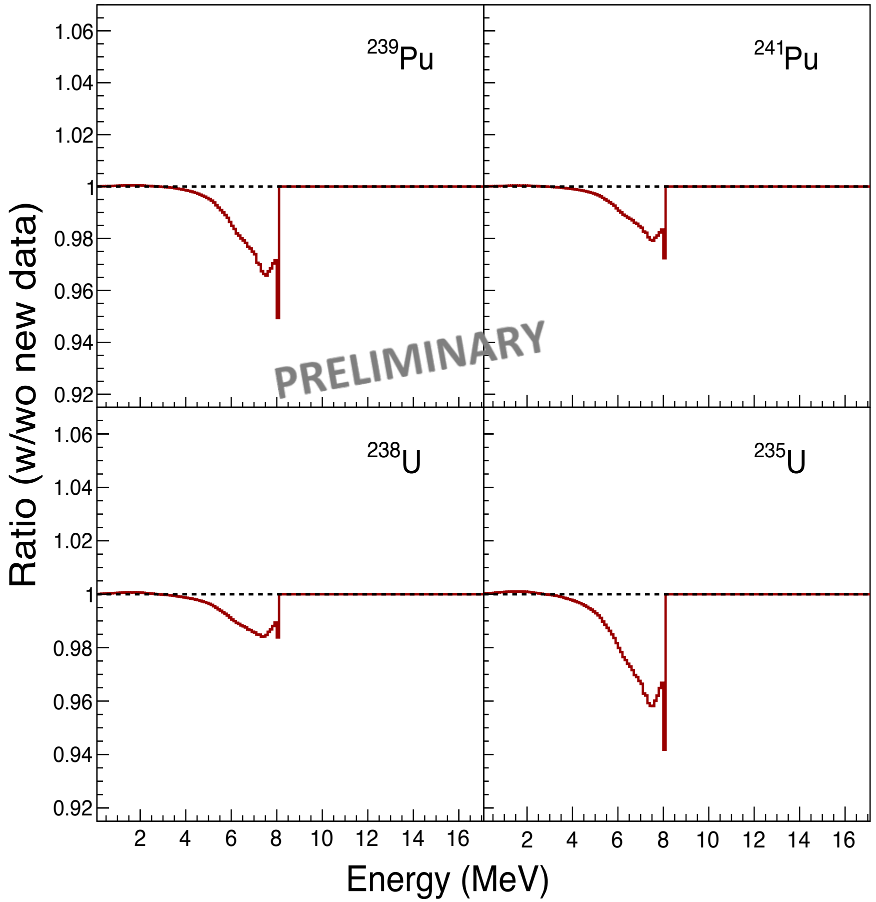

*Till EGIDY et Dorel BUCURESCU. « Systematics of nuclear level density parameters ». In : Phys. Rev. C 72.4 (oct. 2005).

# Antineutrino spectra calculation: the case of $^{92}$Rb




**Antineutrino energy spectra:**

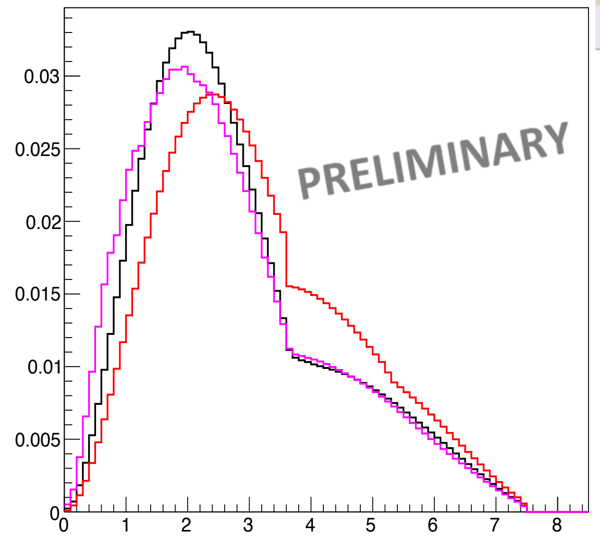
- Rudstam's data
- ENSDF before 2012
- ENSDF since 2012
- New TAS data




**Ratios of summation anti-neutrino spectra including the new TAS data for $^{92}$Rb over the same spectra but with the Rudstam data:**

- **$^{241}$Pu energy spectra: reaching a 2% decrease at 7 MeV;**
- **$^{238}$U energy spectrum:reaching a 1.5% decrease at 7 MeV;**
- **$^{239}$Pu energy spectra: reaching a 3.5% decrease at 7 MeV;**
- **$^{235}$Uenergy spectrum: reaching a 4.5% decrease at 7 MeV;**

# Antineutrino spectra calculation: the case of $^{93}Rb$

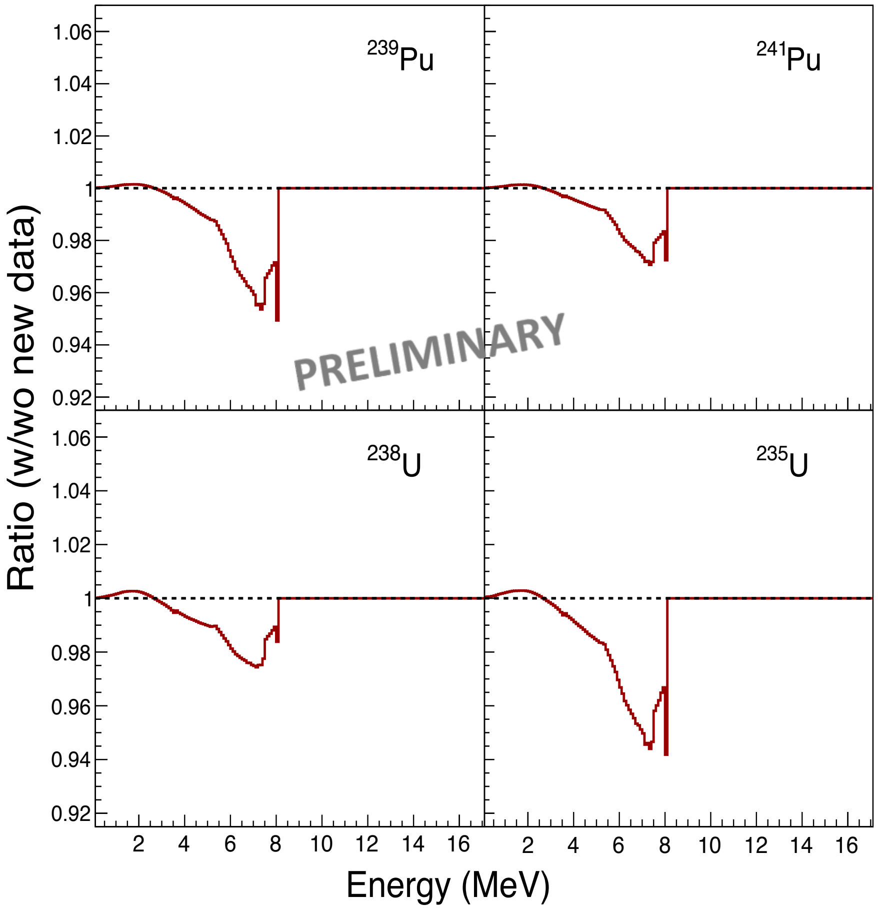



**Antineutrino energy spectra:**

- Rudstam's data
- JEFF3.1
- New TAS data

**Ratios of summation anti-neutrino spectra including the new TAS data for $^{92}Rb$ and $^{93}Rb$ over the same spectra but with the Rudstam data:**

- **$^{241}Pu$ energy spectra: reaching a 3% decrease at 7 MeV;**
- **$^{238}U$ energy spectrum:reaching a 3% decrease at 7 MeV;**
- **$^{239}Pu$ energy spectra: reaching a 5% decrease at 7 MeV;**
- **$^{235}U$energy spectrum: reaching a 6% decrease at 7 MeV;**



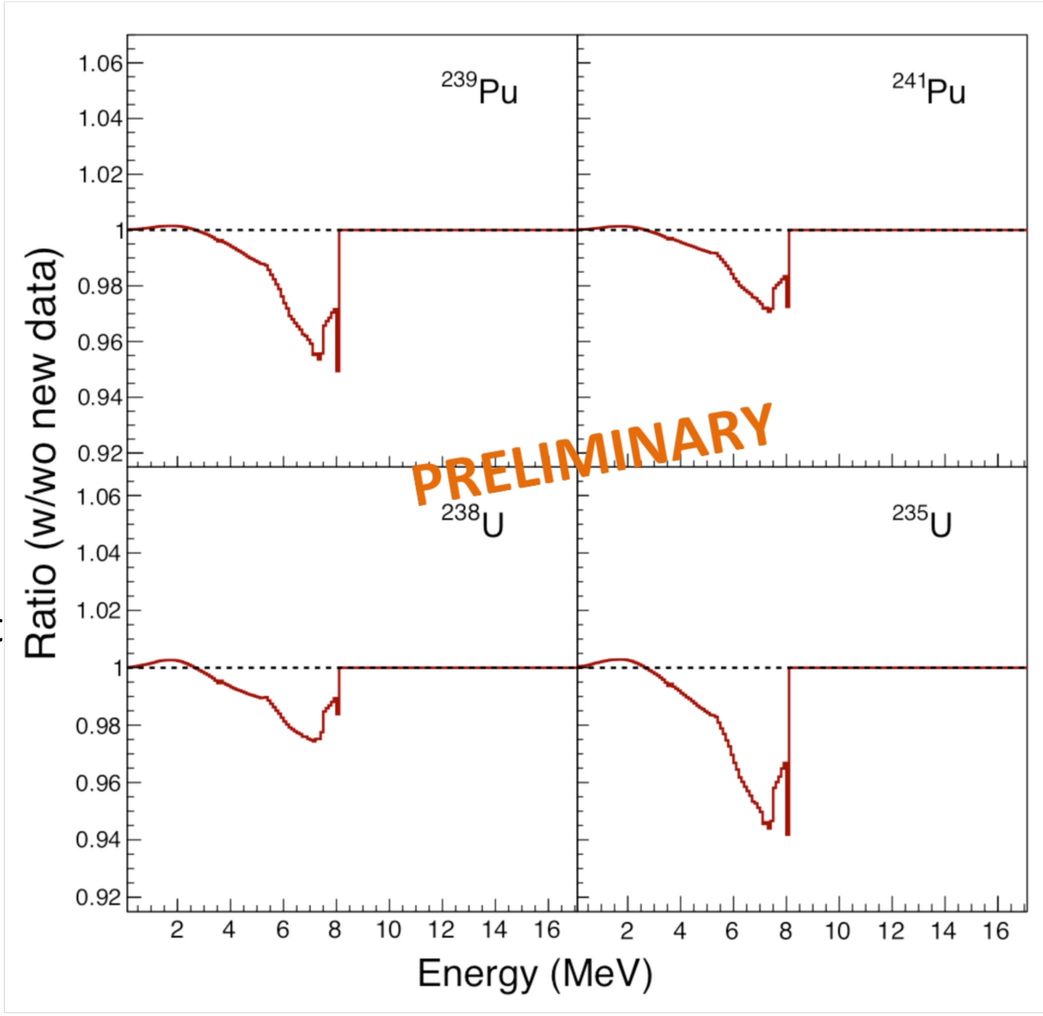
# Impact of these measurements on antineutrino spectra calculation

- Main effect in 4 to 8MeV energy range and it is about 6% for 235U, 5% for 239Pu, 3% for 241Pu and 2.5% for 238U.

- Sharp drop of the ratio at high energy is because of a different Q value between Rudstam et al. and ENSDF.

- We have compared these new energy spectra with converted spectra from P.Huber*. The overall agreement is improved in the 4 to 8 MeV range except in the case of 235U for which the summation method spectrum is always below the converted spectrum.

$^{92}$Rb + $^{93}$Rb




*P. Huber, Phys. Rev. C 84, 024617 (2011).

# Conclusion

- Analysis of 7 nuclei measured at JYFL of Jyväskylä (Finland) in 2009 is terminated.
- Nuclei analyzed by Subatech: $^{92}$Rb (neutrino and decay heat) and $^{93}$Rb (neutrino) (A.A. Zakari PhD thesis).
- Impact of these nuclei in antineutrino spectra has been calculated. Paper will be published very soon.
- Performed TAS experiment at Jyväskylä in February 2014 from the SUBATECH 2009 proposal: 23 Nuclei measured, mainly interesting for antineutrino spectra and decay heat ! Analysis of the nuclei is shared among SUBATECH and IFIC.

# 2014 experiment @ Jyvaskyla

**Proposal to the PAC of Jyvaskyla**

**Study of nuclei relevant for precise predictions of reactor neutrino spectra**


V.M. Bui, M. Fallot, L. Giot, J. Martino, A. Porta, F. Yermia
*Subatech*, CNRS/IN2P3, University of Nantes, EMN, Nantes, France

J. Agramunt, A. Algora, E. Estevez, D. Jordán, F. Molina,
B. Rubio, J. L. Taín, E. Valencia
*IFIC,CSIC-Univ. Valencia, Valencia, Spain*

C. Weber, J. Rissanen, A. Jokinen, H. Penttilä, T. Eronen, J. Äystö, A. Kankainen, V. Elomaa, J. Hakala, I. Moore + IGISOL people
*University of Jyvaskyla, Jyvaskyla, Finland*

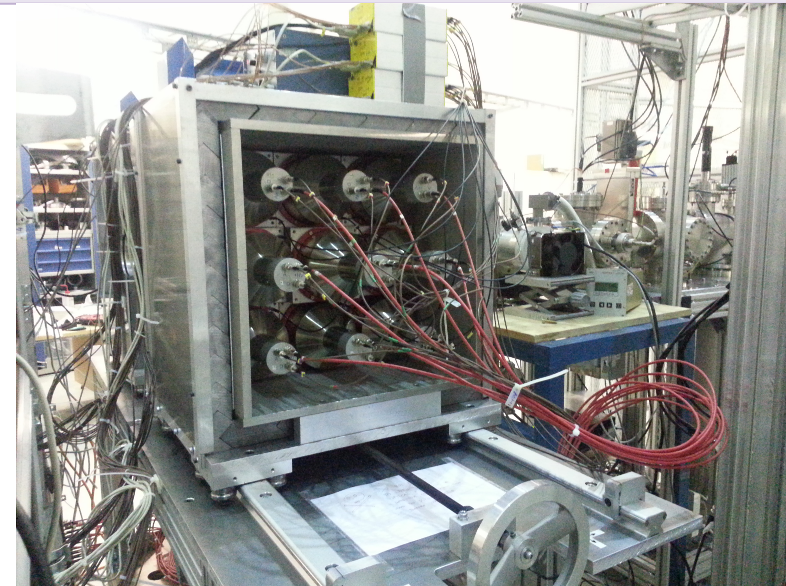
M. Csatlós, A. Krasznahorkay
*Inst. of Nuclear Research of the Hungarian Academy of Sciences, Debrecen, Hungary*

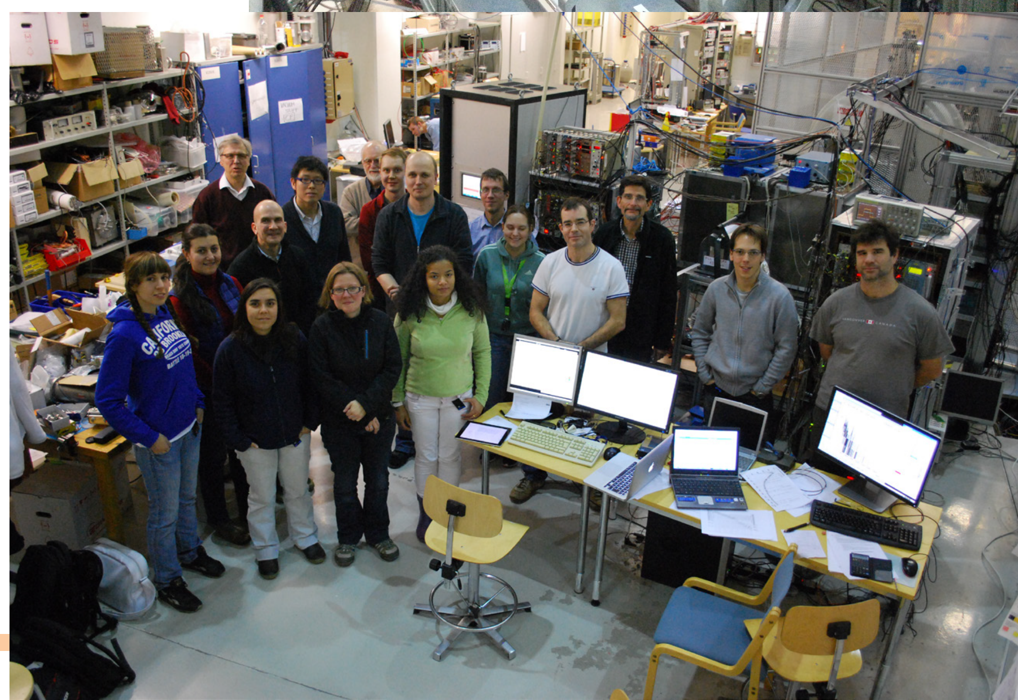
L. Batist
*PNPI, Gatchina, Russia*

D. Cano-Ott, T. Martinez
*CIEMAT-Madrid, Spain*

W. Gelletly
*Univ. Surrey, Guilford, UK*

**Spokespersons : M. Fallot, J.L. Tain and A. Algora**



- 12 nuclei for antineutrino measured (11 for decay heat)
- First use of new DTAS (17+1 NaI) developed by IFIC (Valencia)
- Successful use of the new IGISOL-4 facility
- First use of precision trap with IGISOL-4

→ See A. Algora talk

THANK YOU

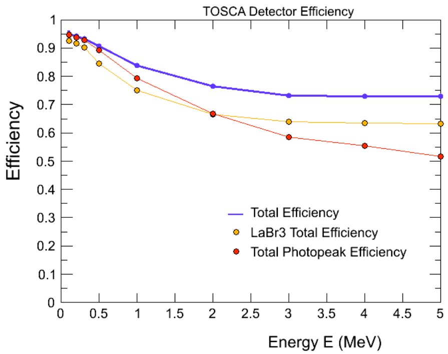
Back up

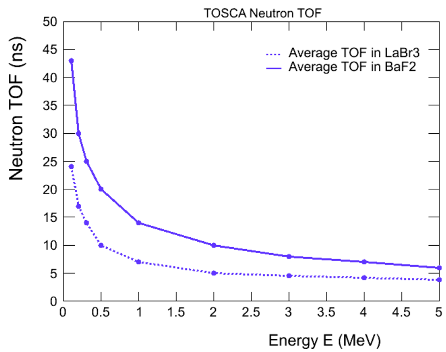
# TOSCA : The Orsay Subatech Calorimeter Array

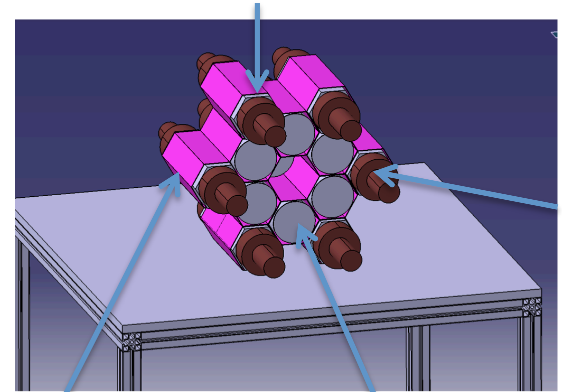
A multipurpose detector for reactor safety, composed by 7 big $LaBr_3$ (9 cm diameter, 25 cm length) and 12 hexagonal $BaF_2$.

Two goals:

- Total Absorption Spectroscopy of fission products with a compact configuration
  - ✓ Total efficiency bigger than 70 % at 5 MeV
  - ✓ Possible neutron discrimination through ToF

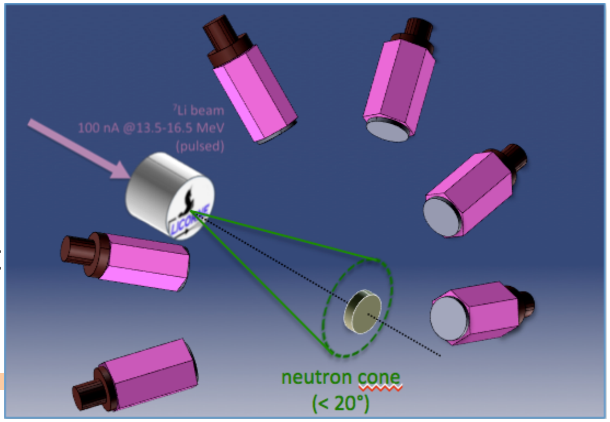



  - ✓ Good resolution of $LaBr_3$
  - ✓ Allowing for stand-alone measurement of β and β-n decay of exotic fission product (decay heat calculation and reactor control)

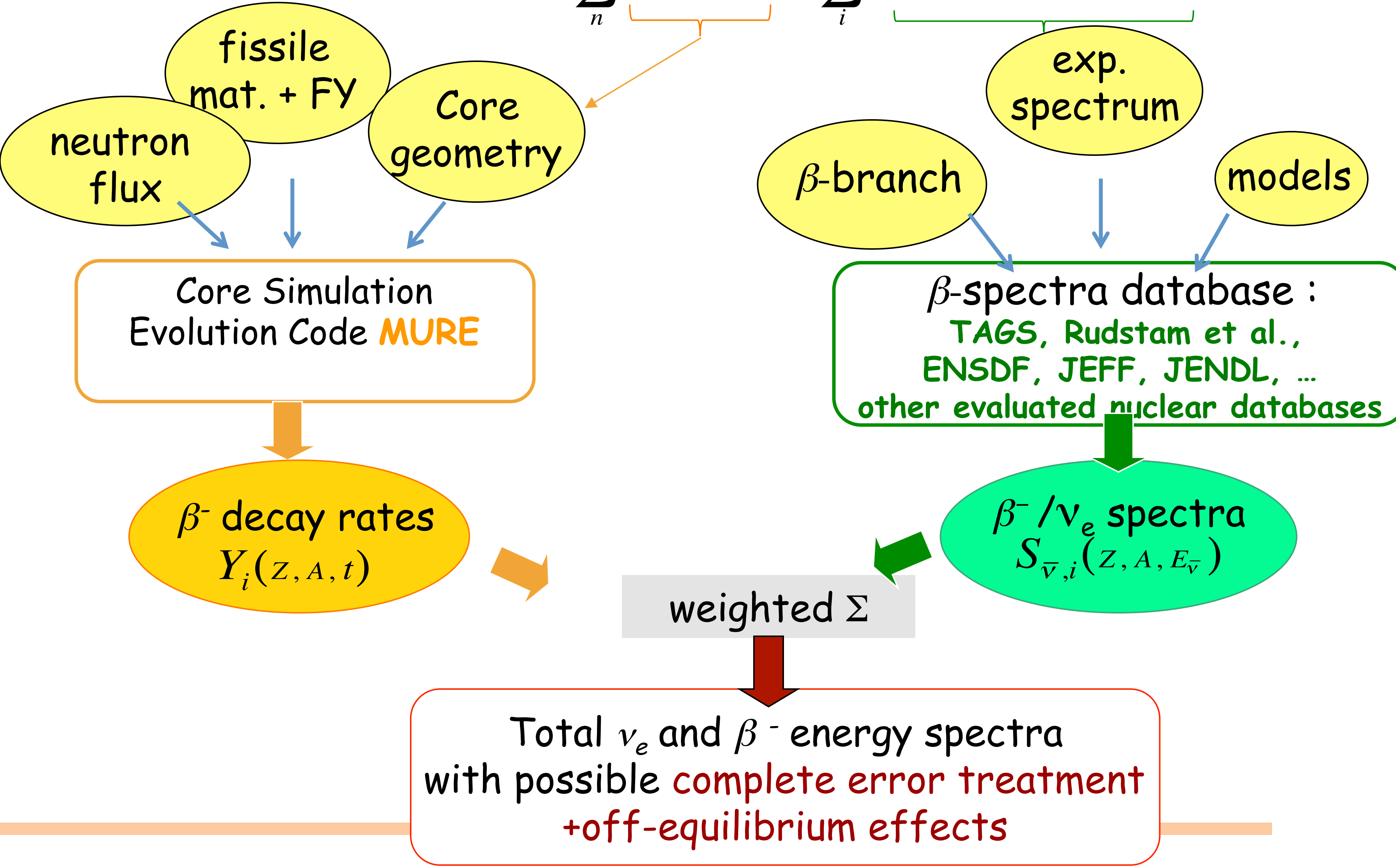
- Prompt fission gamma ray detection with a ring configuration
  - ✓ Neutron- gamma discrimination through ToF
  - ✓ No data exist for prompt gamma (and neutron) emission for fast neutron induced fission (fission process knowledge and reactor safety)




Collaboration IPNO-SUBATECH → submission of an ANR 2015

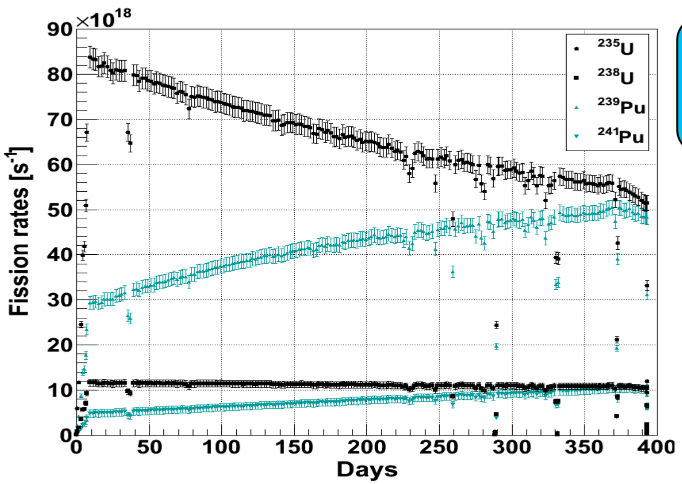
# Summation Method: Method based on individual fission product beta decay summation

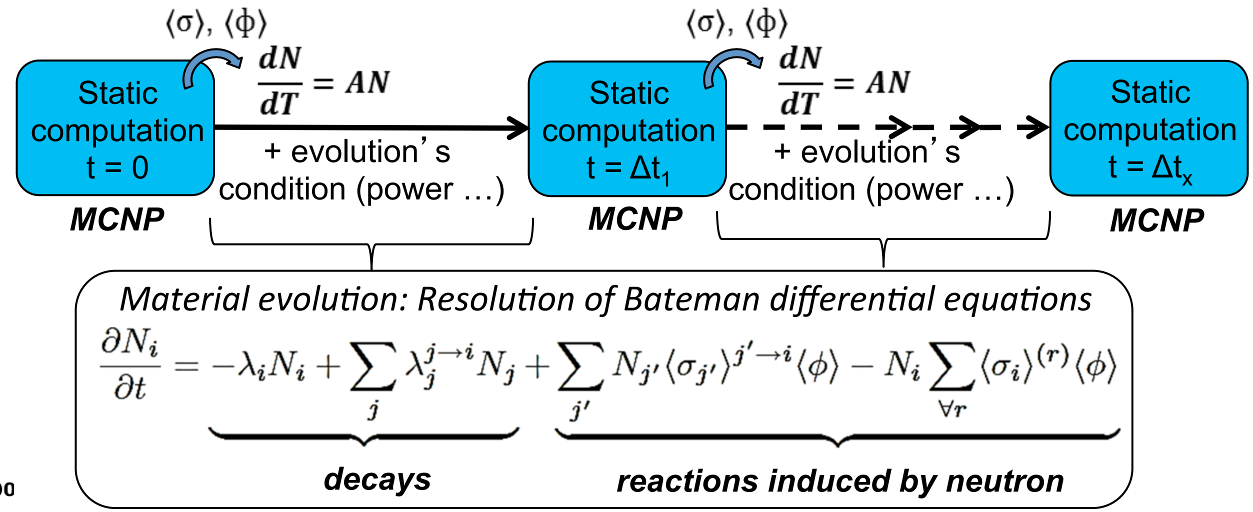
$$N(E_\nu) = \sum_n Y_n(Z,A,t) \cdot \sum_i b_{n,i}(E_0^i) P_\nu(E_\nu, E_0^i, Z)$$



# The MURE* Code

- The MURE Code (MCNP Utility for Reactor Evolution) :
- C++ interface to the Monte Carlo code MCNP (static particle transport code)
- Open source code available @ NEA: http://www.oecd-nea.org/tools/abstract/detail/nea-1845




$$\frac{\partial N_i}{\partial t} = -\lambda_i N_i + \sum_j \lambda_j^{j\to i} N_j + \sum_{j'} N_{j'} \langle\sigma_{j'}\rangle^{j'\to i}\langle\phi\rangle - N_i \sum_{\forall r}\langle\sigma_i\rangle^{(r)}\langle\phi\rangle$$

➡ Outputs provided: keff, neutron flux, inventory, reaction rates + adapted to compute antineutrino spectra

➡ Development of a complete core simulation with a follow up of core operating parameters

➡ Can be used also for simple geometries: ILL spectra computation

From A. Onillon

# Outline of the latest ESARDA sub-WG

## ESARDA

**NOVEL APPROACHES / NOVEL TECHNOLOGIES WORKING GROUP (NA/NT WG)**

**Location:** Zaal Bach, Congrescentrum Oud St. Jan, Bruges Belgium

**ESARDA**
European SAfeguards Research and Development Association

Agenda

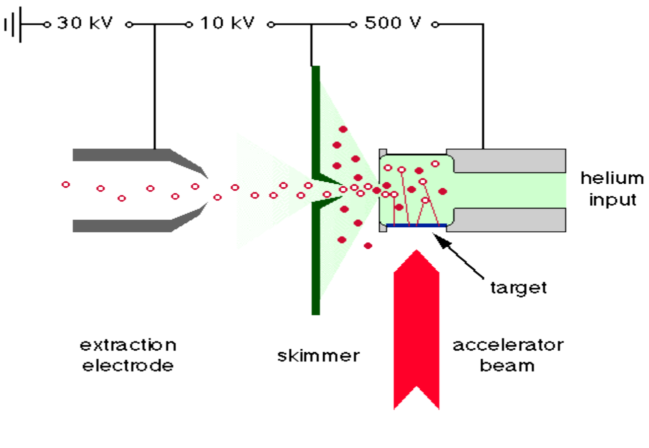
**@ESARDA 2013**
**Brugge, Belgium, May 30. 2013**

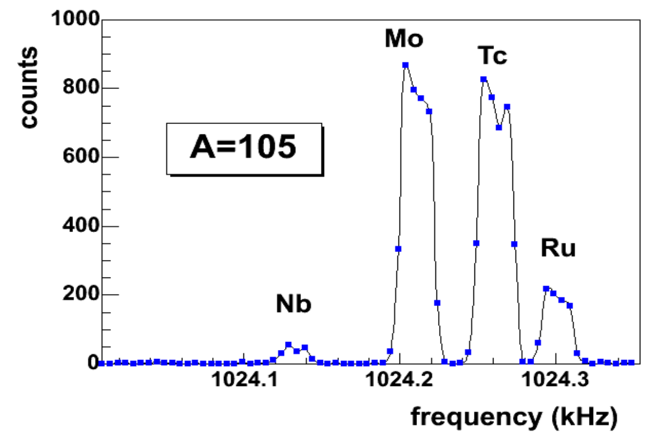
| Time | Activity | Session Chair / Presenter |
|---|---|---|
| 11:00 | **Opening Session:**<br>Welcome of participants and general business (10 mins.) | Harri Toivonen (NA/NT WG Chairperson) |
| | ***Antineutrino detection in support of safeguards applications*** | **Muriel Fallot** |
| 11:10 | Presentation of the ***Report of the First Meeting of the Ad Hoc Working Group on Safeguards Applications of Antineutrino Detection and Monitoring*** (50 mins.) | T. Shea<br>A. Bernstein |
| 12:00 | Review talk on detectors based on liquid scintillator doped with Gd (20 mins.) | D. Lhuillier<br>H. Furuta |
| 12:20 | Review talk on detectors based on solid segmented plastics with Gd and 6Li (20 mins.) | V. Egorov<br>A. Vacheret |
| 12:40 | Review talk on detectors based on water + Gd (20 mins.) | J. Anjos<br>A. Bernstein |
| **13:00** | **Lunch (1 hour)** | |
| 14:00 | Review talk on reactor simulations for antineutrino detection (20 mins.) | A. Erickson<br>M. Fallot |
| 14:20 | Capture-gated fast neutron measurement – possible application to antineutrino detection (20 mins.) | H. Toivonen |
| 14:40 | Synergies with sterile neutrinos experiments @ reactors? (20 mins.) | P. Huber<br>A. Cucoanes |
| 15:00 | Link with nuclear data (20 mins.) | A. Algora<br>M. Fallot |

# JYFLTRAP @ Jyväskylä University

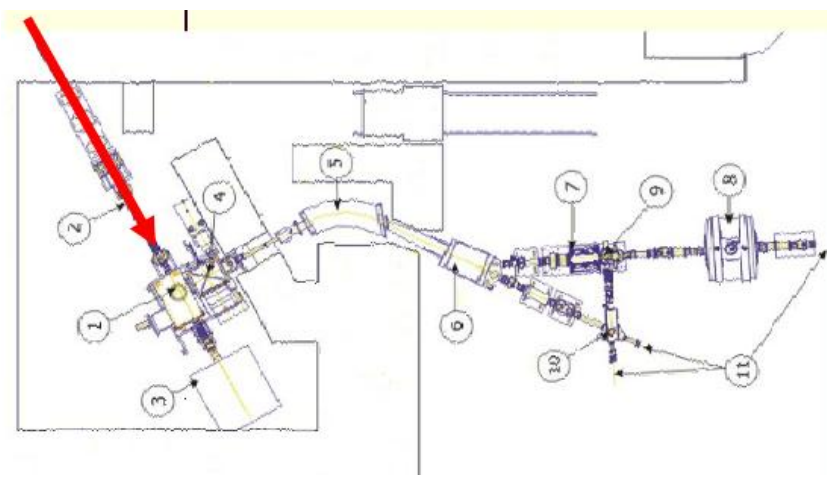
- Penning trap to separate the beam created by IGISOL

IGISOL




Isotopic purification



1) Ion guide
2) K130 cyclotron beamline
3) Beam dump
4) Acceleration chamber
5) Dipole magnet
6) Switchyard
7) RFQ cooler
8) Tandem penning trap
9) Miniquadrupole deflector
10) Electrostatic deflector and beamline to upstairs
11) Experimental setups

# Reactor antineutrinos detection

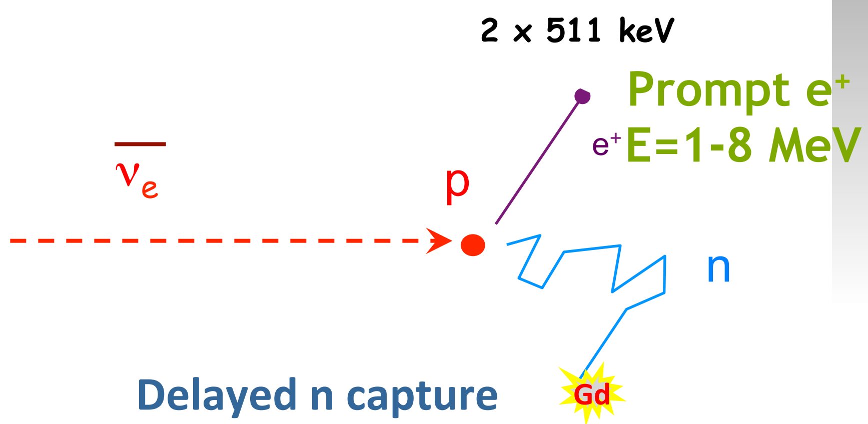
- **Standard nuclear power plant 900 MWe :**

$$\frac{2800\ \mathrm{MW_{th}}}{200\ \mathrm{MeV}} \times 6\ \overline{\nu}_e \qquad \sim\ 5\cdot 10^{20}\ \overline{\nu}_e / s$$

- **Usually detection through inverse-β process on quasi-free protons :**

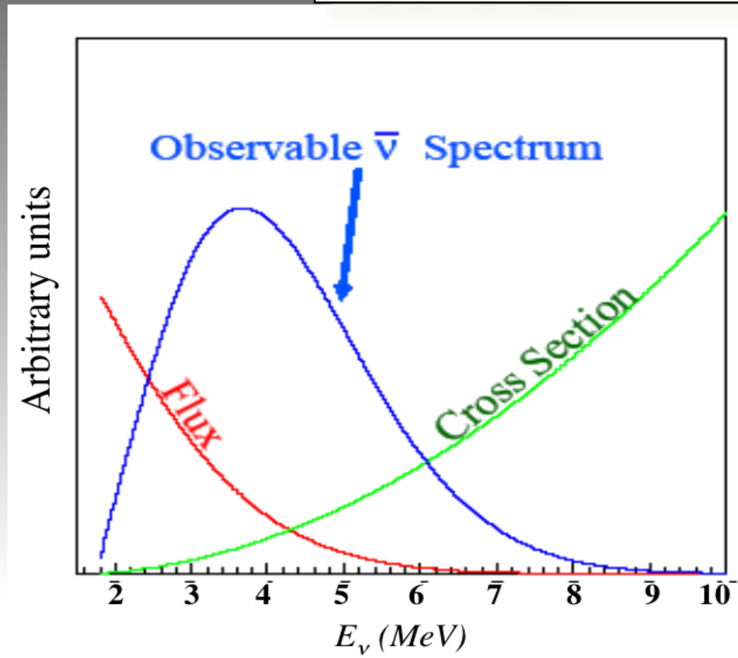
$$\overline{\nu}_e + p \rightarrow e^+ + n$$

- ❑ Reaction threshold : **1.8 MeV**
- ❑ Cross section $(\alpha\, E_n^{\ 2})$ : $<\sigma> \sim 10^{-43} cm^2$




**Delayed n capture**
**Gd nuclei**
**$\Sigma\gamma \sim 8$ MeV**

[C. Bemporad et al,. Rev. of Mod. Phys., **74** (2002)}

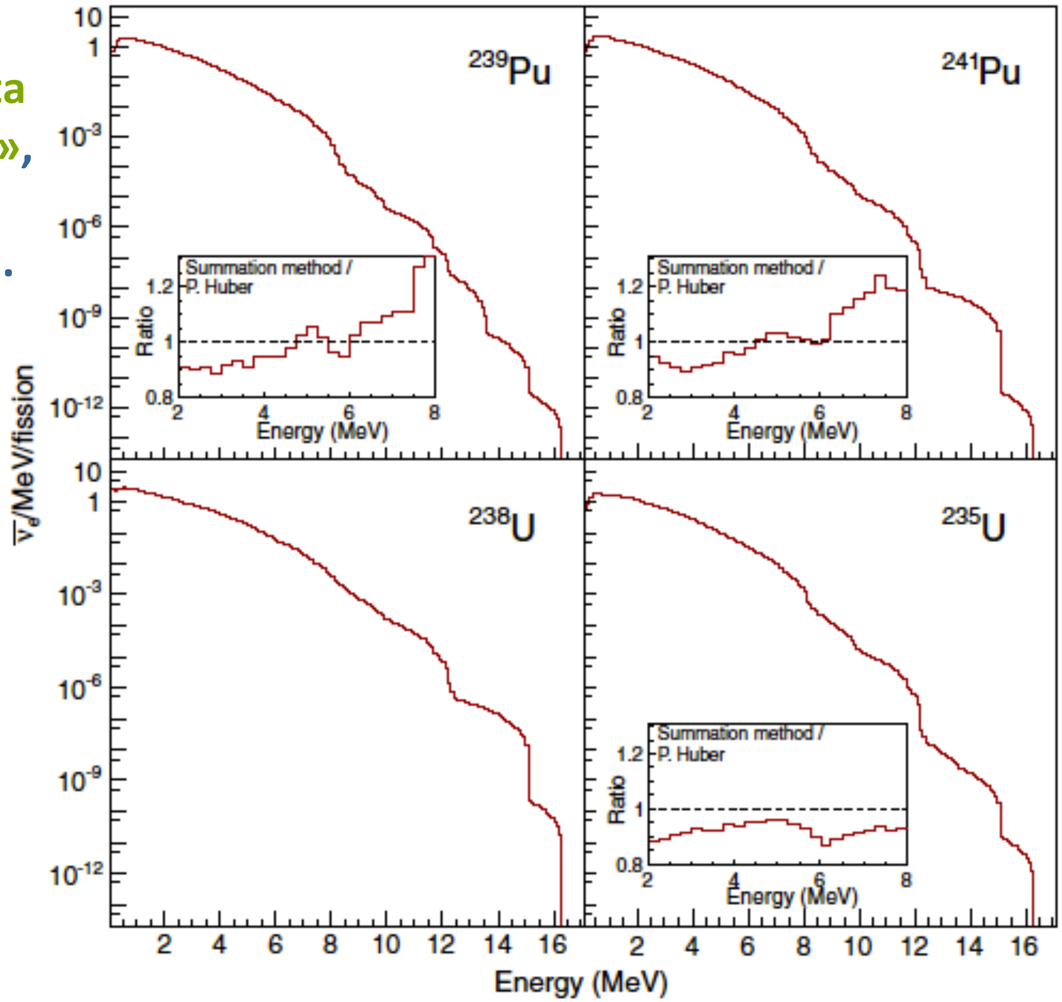



- ➢ **Time correlation : $\tau \sim 30\mu s$**
- ➢ **Space correlation : < 1m**

# Inclusion of the latest TAS data in the Antineutrino Summation Spectra:

« New antineutrino energy spectra predictions from the summation of beta decay branches of the fission products »,
Phys. Rev. Lett. 109, 202504 (2012),
M. Fallot, S. Cormon, M. Estienne et al.

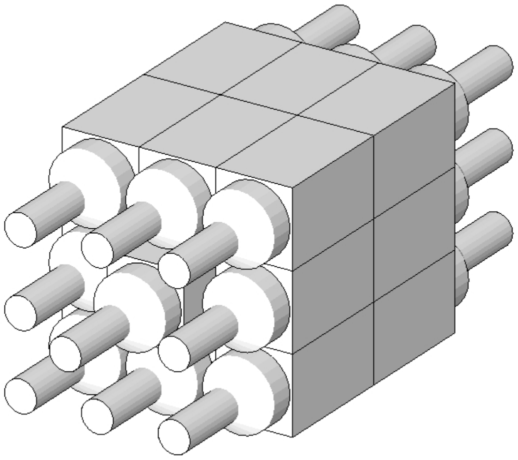
Reconstructed antineutrino energy spectra, including the latest TAS data from Algora et al.



For the presented spectra, the used databases are the following (ordered by priority): the Greenwood TAS dataset (29 nuclei), the recently measured TAS dataset by A. Algora et al., the experimental data measured by Tengblad et al. (85 nuclei), experimental data from the evaluated nuclear databases JEFF31 (305, 345, 347 and 318 nuclei resp. for 235 U, 239 Pu, 241 Pu and 238 U) and JENDL2000 (61, 62, 61, 58 nuclei resp.), ENSDF nuclei (87, 98, 101, 90 nuclei resp.), Gross Theory spectra from JENDL (214, 215, 227, 221 nuclei resp.) and the Qbeta approximation for the remaining unknown nuclei (22, 32, 38, 33 nuclei resp.). Indeed, for a non negligible amount of very neutron-rich ssion products no data can be found in the databases quoted above. In this case, as a rst milestone, the associated beta spectra could be built with 3 equiprobable allowed decay branches feeding the ground state, and excited states located at Q /3MeV and 2Q /3MeV above the ground state respectively. We call this approximation the Qbeta approximation.

# TAS detectors

- New TAS for FAIR-DESPEC: DTAS
  - 16 + 1 modules:
  - 15×15×25 $cm^3$ NaI(Tl)
  - 5" PMT (50% light col.)
  - V= 95 L, M= 351 kg
  - $\Delta E/E \sim 5\%$ (@1.3MeV), $\Delta t \sim 2$ ns

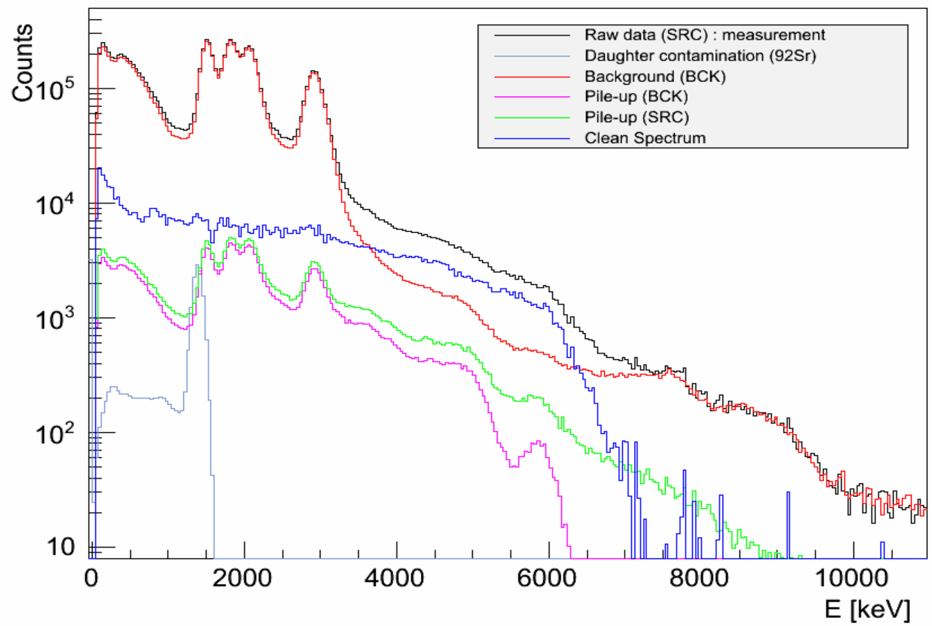


⇒ **TDR approved for FAIR, DTAS for NUSTAR**
⇒ **Full assembly for Sept. 2013**
⇒ **Outlooks contemplated for FAIR-DESPEC**

**from A. Algora, B. Rubio and J.-L. Taín– IFIC-Valencia**

## Data analysis:

**Cleaning of the raw data from contaminants (background and pile-up) to obtain the clean spectra (blue)**




**Calculation of level energy feeding through the resolution of the inverse problem**

$$d_i = \Sigma R_{ij} * f_j$$

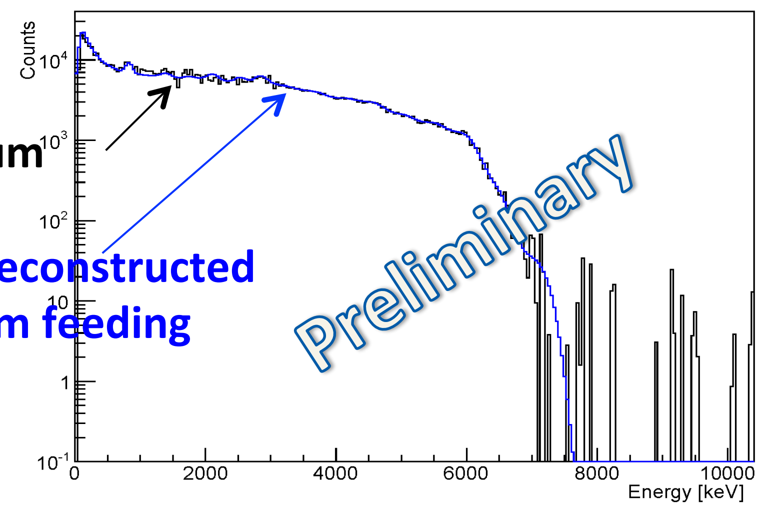
**Clean data**

**Response matrix From GEANT4 Detector simulation**

**Level feeding**

**Clean spectrum**

**Example of Reconstructed spectrum from feeding estimation**




**On-going…**

**PhD Thesis work:**

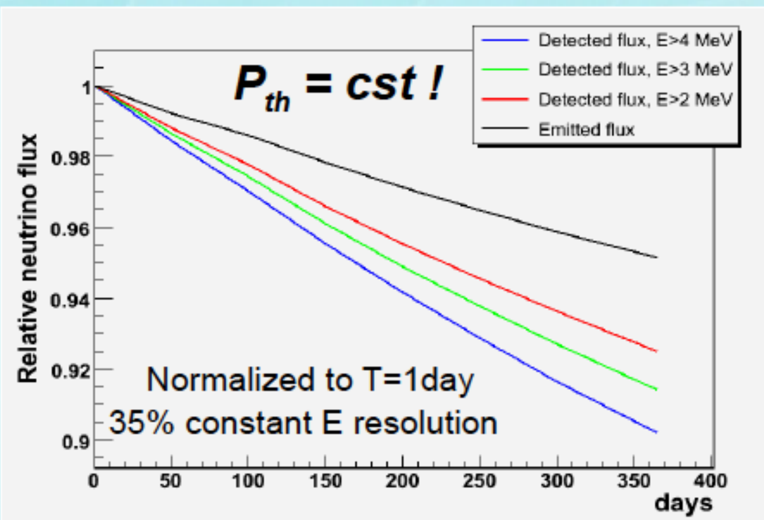
- **Z. Issoufou (Subatech – Nantes)**

Neutrino rate: $N_{\bar{\nu}} = \gamma\left[1 + k(t)\right] P_{th}$

Detector (constant)

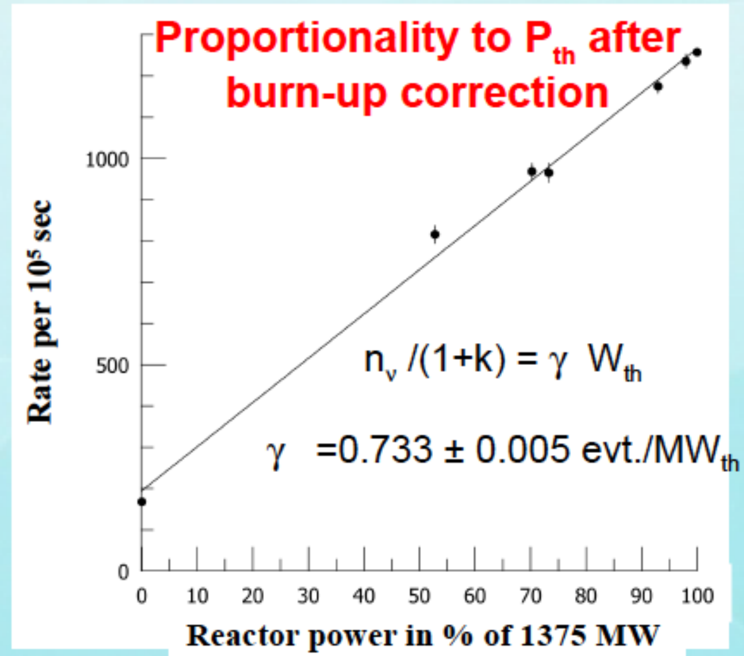
Fuel composition (time dependent)

1+k(t) parameter: simulation of 1 year cycle of a PWR reactor @ $P_e$ = 0.9 GW: 10% decrease




Rovno experiment results:

Yu.V.Klimov et. al.,
Atomic Energy, vol. 76, n. 2 (1994)



ENDF before 2012

ENDF after 2012

Rudstam

TAS