Measurement of Neutron Capture and Fission Cross Sections at n_TOF

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LIP

Lisbon, April 11th 2013

Outline

- Motivations
- The n_TOF facility
- Results
- Perspectives

Motivations

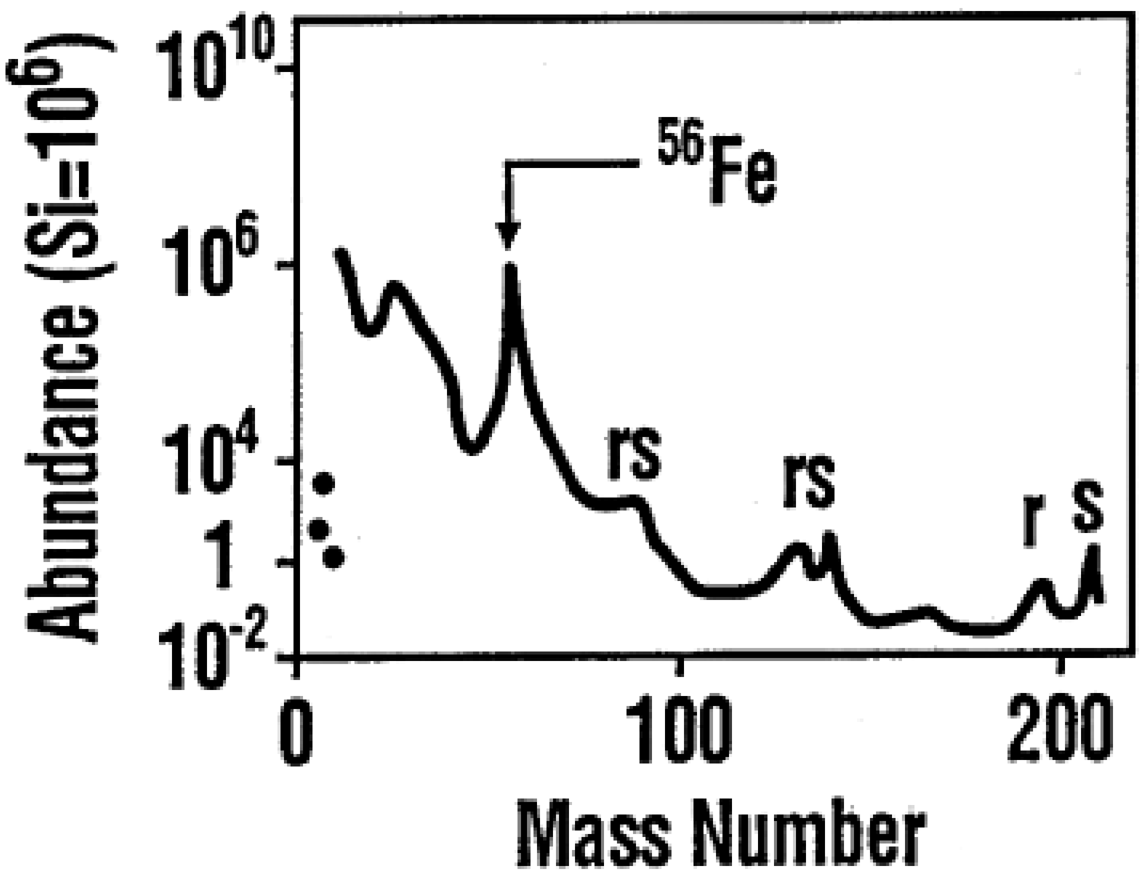
neutron Time-Of-Flight

- Measurements of neutron cross sections
- TOF technique/spectrometer at CERN
  - In a wide energy range
  - At high energy resolution
  - With high accuracy (~ 3 to 5 % rel. unc.)
- Fission and neutron capture
- For nuclear astrophysics and nuclear technology

Stellar Nucleosynthesis

Abundances

- ɣ-ray spectroscopy data (e.g. Hubble)
- Synthesis of elements heavier than Fe: mostly by neutron-capture reactions
- Main features are well known

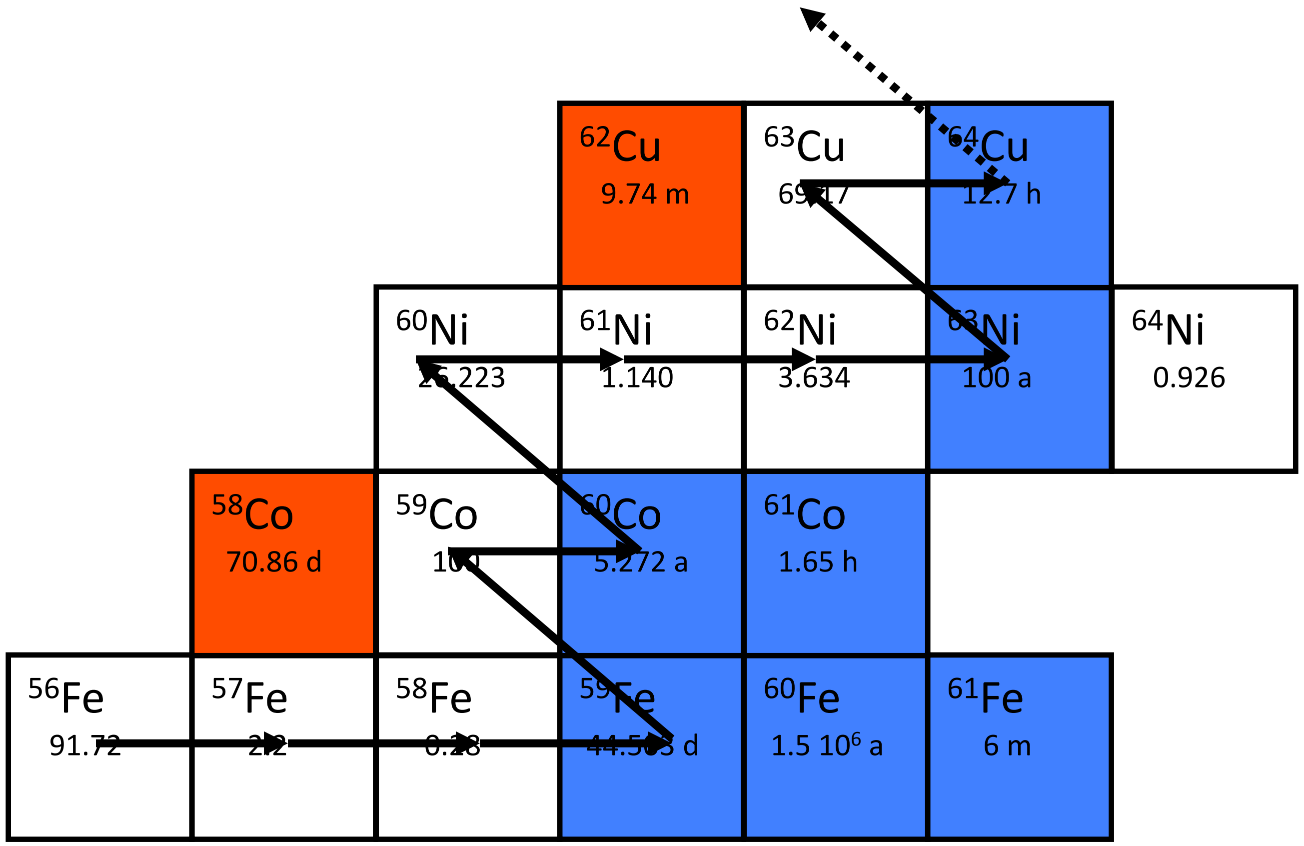


Double peaks at neutron magic numbers
Two separate processes: **s** (slow) and **r** (rapid)

Slow and Rapid Processes

S-process

- Red giants
- Neutron density ~ 10^8 n/cm^3
- Capture times small compared with β-decay lifetimes
- Valley of β-stability: stable nuclei



R-process

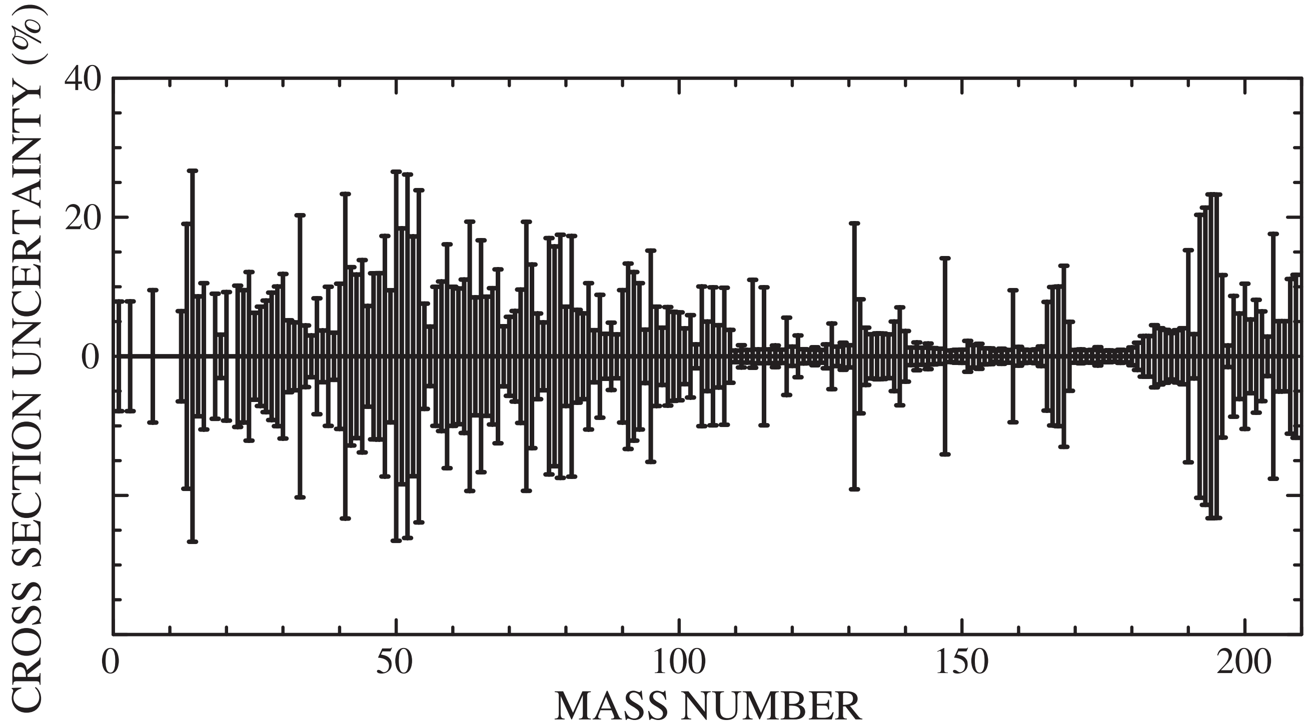
- Supernovae
- Neutron density: 10^{20} to 10^{30} n/cm^3
- Rapid process: neutron-rich nuclei

Data for nuclear astrophysics

capture rate: $\lambda_n = N_n \langle \sigma(n,\gamma) \cdot v \rangle_{kT}$

- Capture cross sections

- Astrophysics models: thermodynamic conditions (temperature, neutron density, pressure)



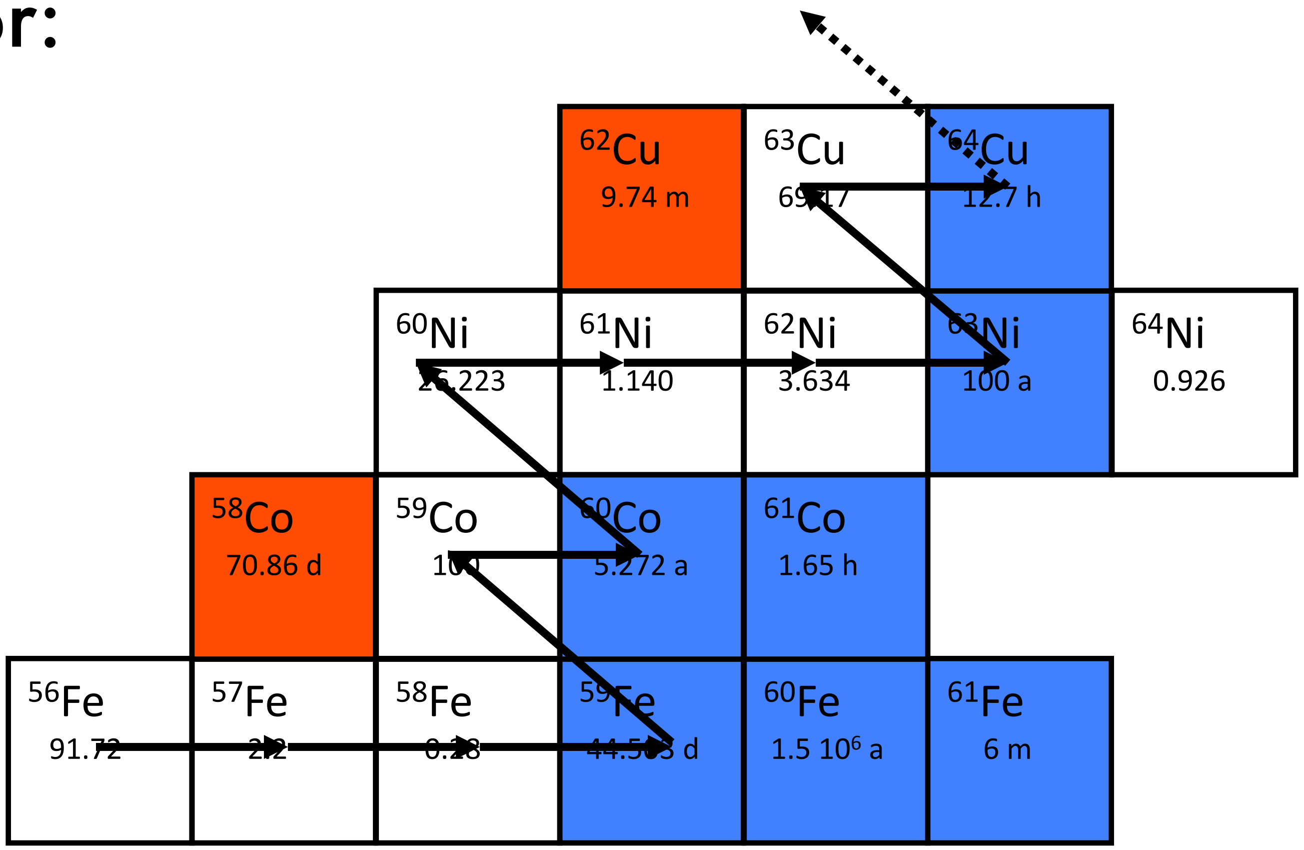
- Details of s-process: discrepancies for A<90 ("*weak*" s-process)

- Neutron data targetted accuracy (up to hundreds keV): 3 to 5 %

Data for nuclear astrophysics

Capture cross sections required for:

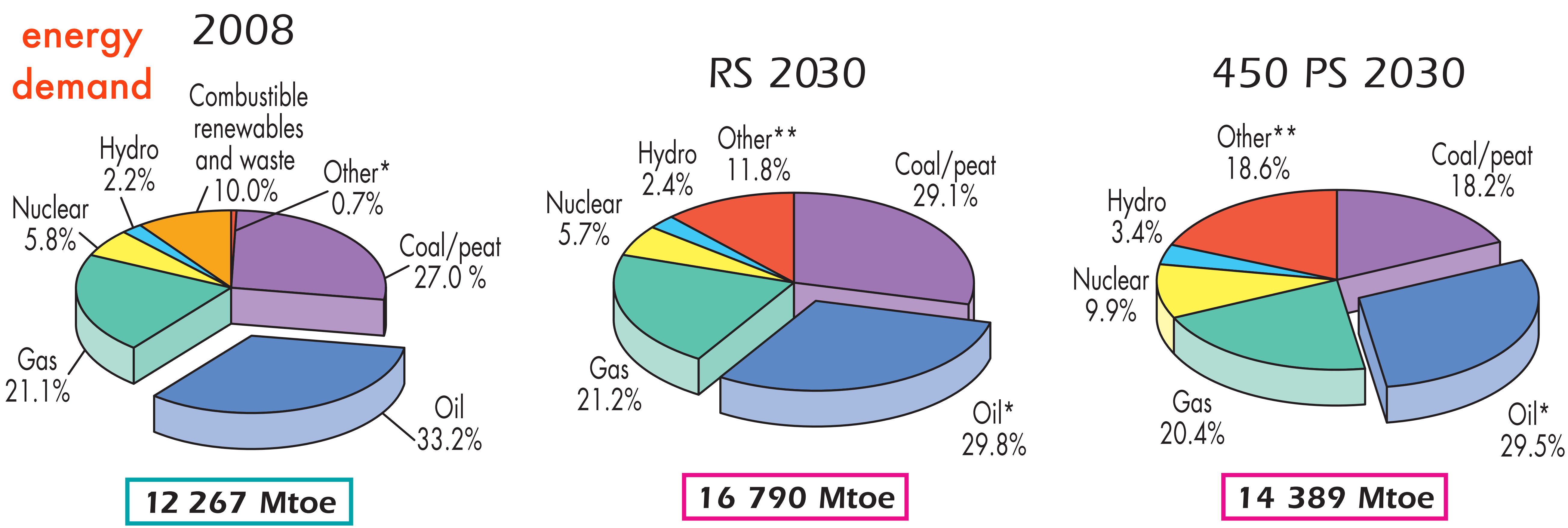
- S-process seeds (Fe, Ni)
- Bottleneck isotopes (low cross sections, ^{90}Zr)
- Branching-point isotopes (radioactive)



Nuclear energy

- ➡ Recent R&D motivated by world energy outlook (IEA)
- ➡ Climate changes, fossil fuels long-term availability

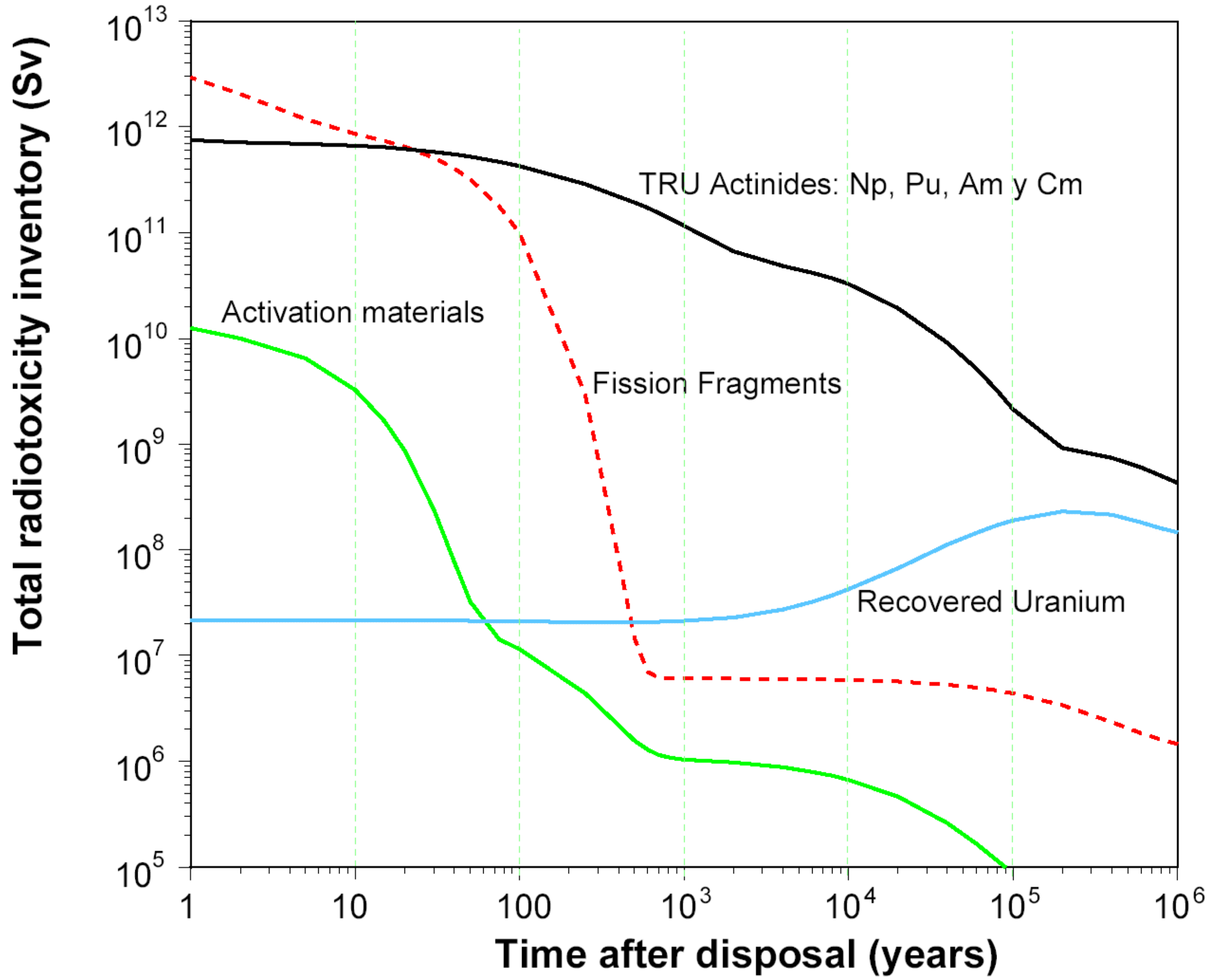
World energy demand



Nuclear energy considered: low carbon emissions, peak-load power, market availability

Radioactive waste

ISSUE OF RADIOACTIVE WASTE



Others:

- Safety aspects
- Proliferation resistance

➡ Geological disposals - the present solution

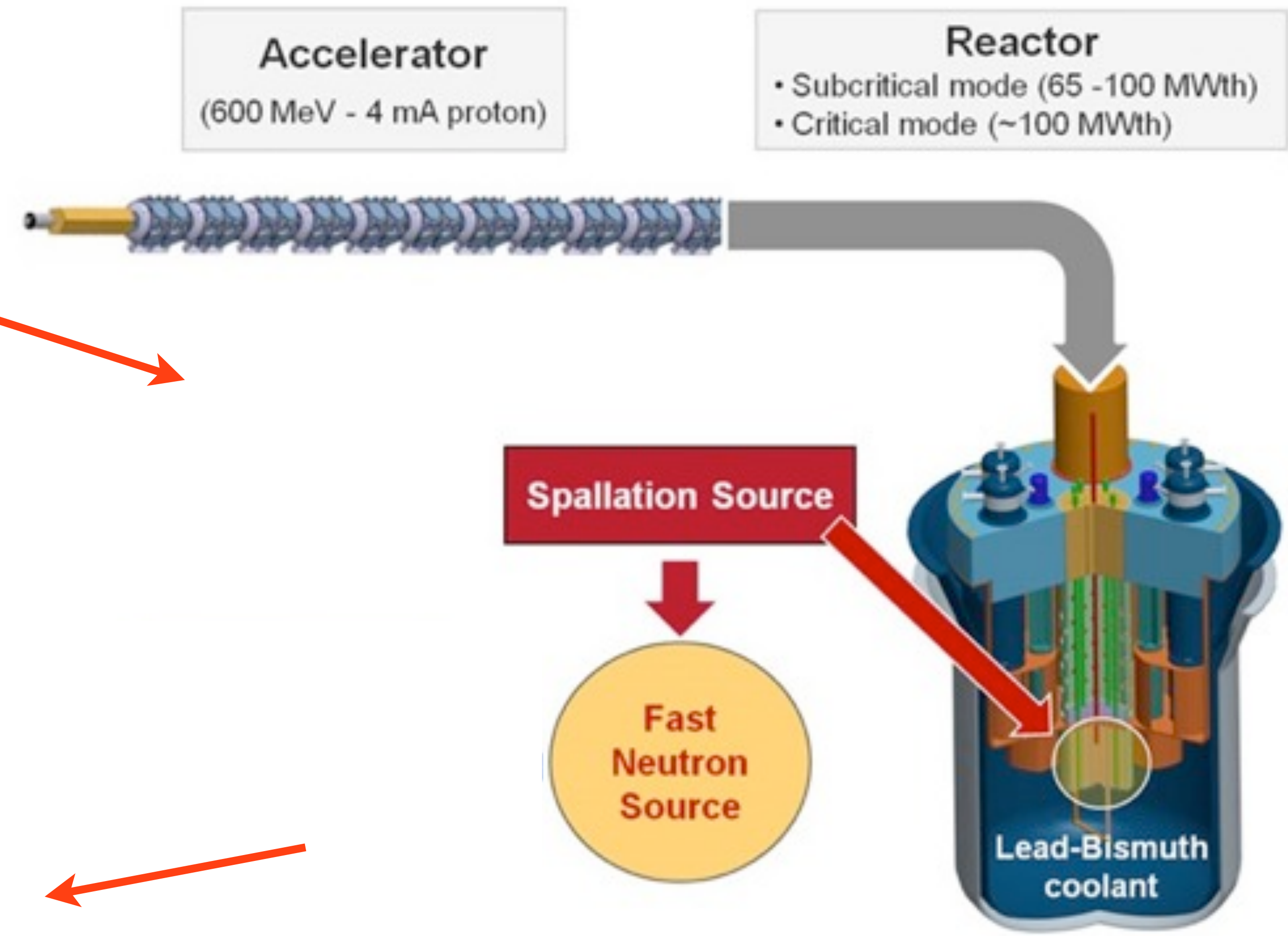
TRANSMUTATION of radiotoxic materials

- Fast neutrons (MeV): fission of actinides
- Moderated spectra (meV to keV): capture on structural materials and LLFP

ADS and Gen-IV reactors

NEW CONCEPTS

- Generation-IV reactors (fuel recycling)
- Accelerator-Driven Systems (ADS)



- External source: surplus of neutrons
- Switch-off by accelerator
- Fast/moderated spectrum

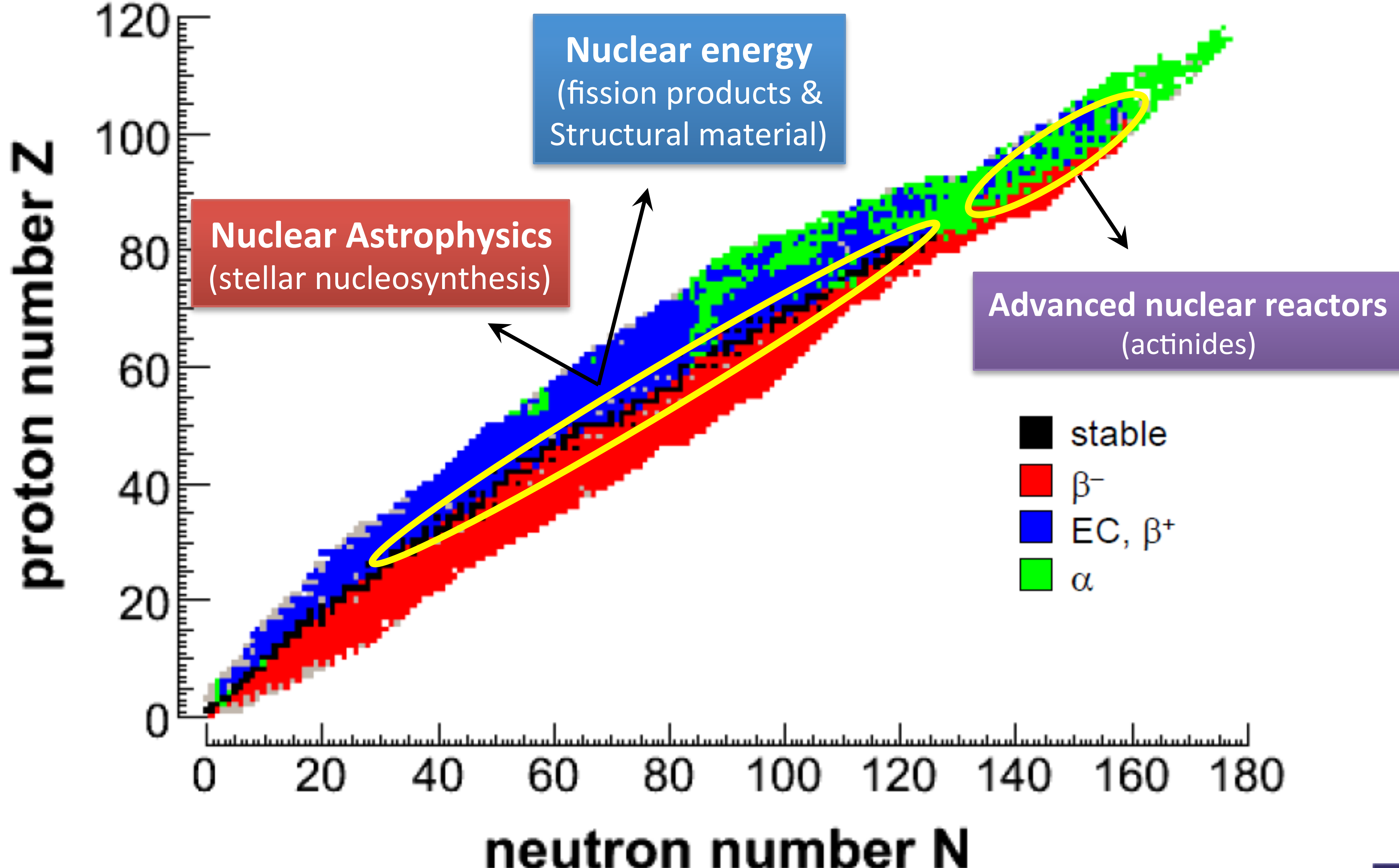
- MYRRHA facility (Belgium)
- Construction/commissioning: 2015-2023

Data for nuclear technology

Fission and capture cross sections for:

- Fuel elements (U/Pu, Th/U cycles)
- TRU actinides (Np, Pu, Am, Cm)
- Long-lived fission products (Tc, Cs, Sm)
- Structural materials (Zr, Fe, Ni)

Chart of nuclides



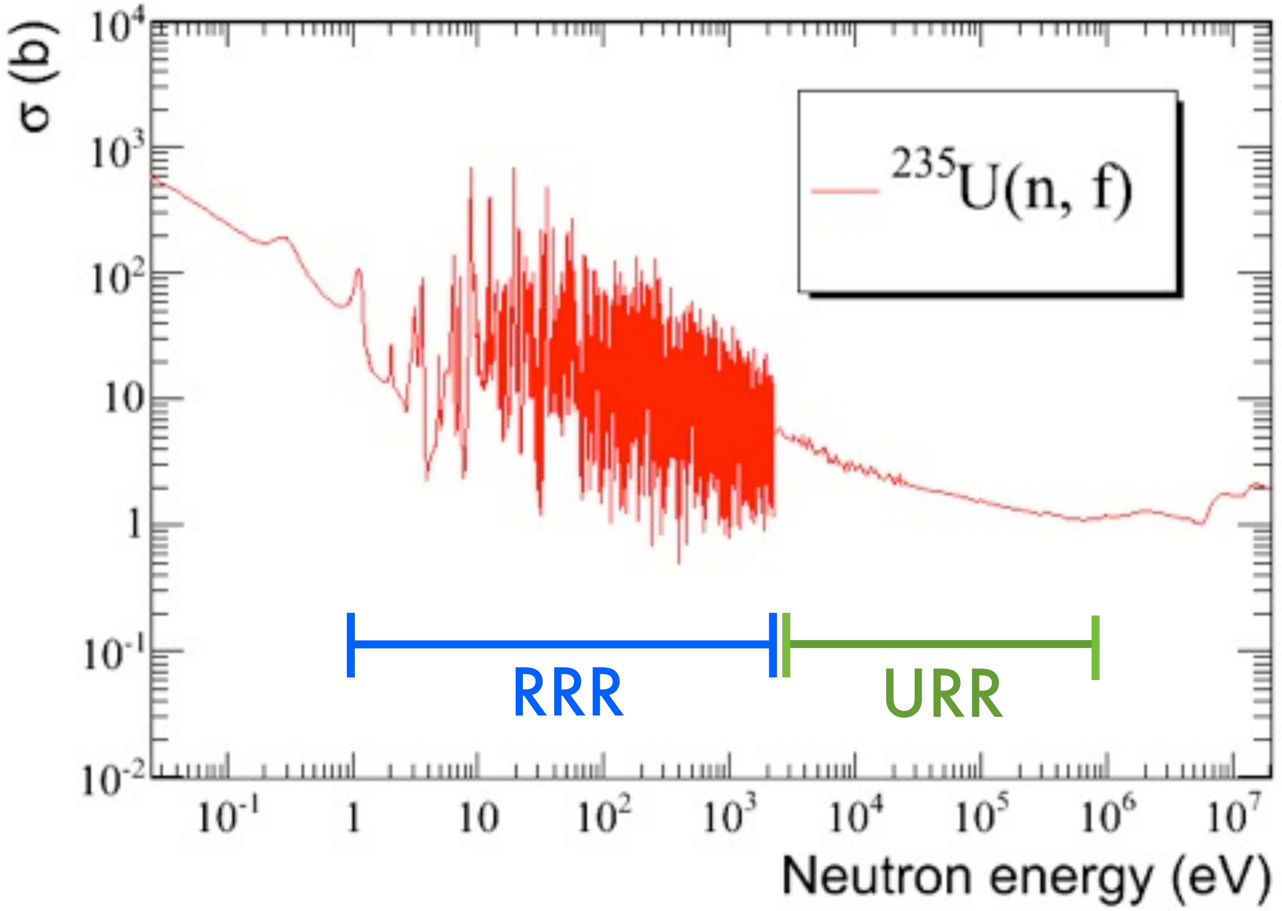
Neutron Cross Sections

- Wide range of neutron kinetic energies

- Resonant structure:

- Resolved Resonance Region (RRR)
- Unresolved Resonance Region (URR)

- General cross-section expressions given by R-matrix theory

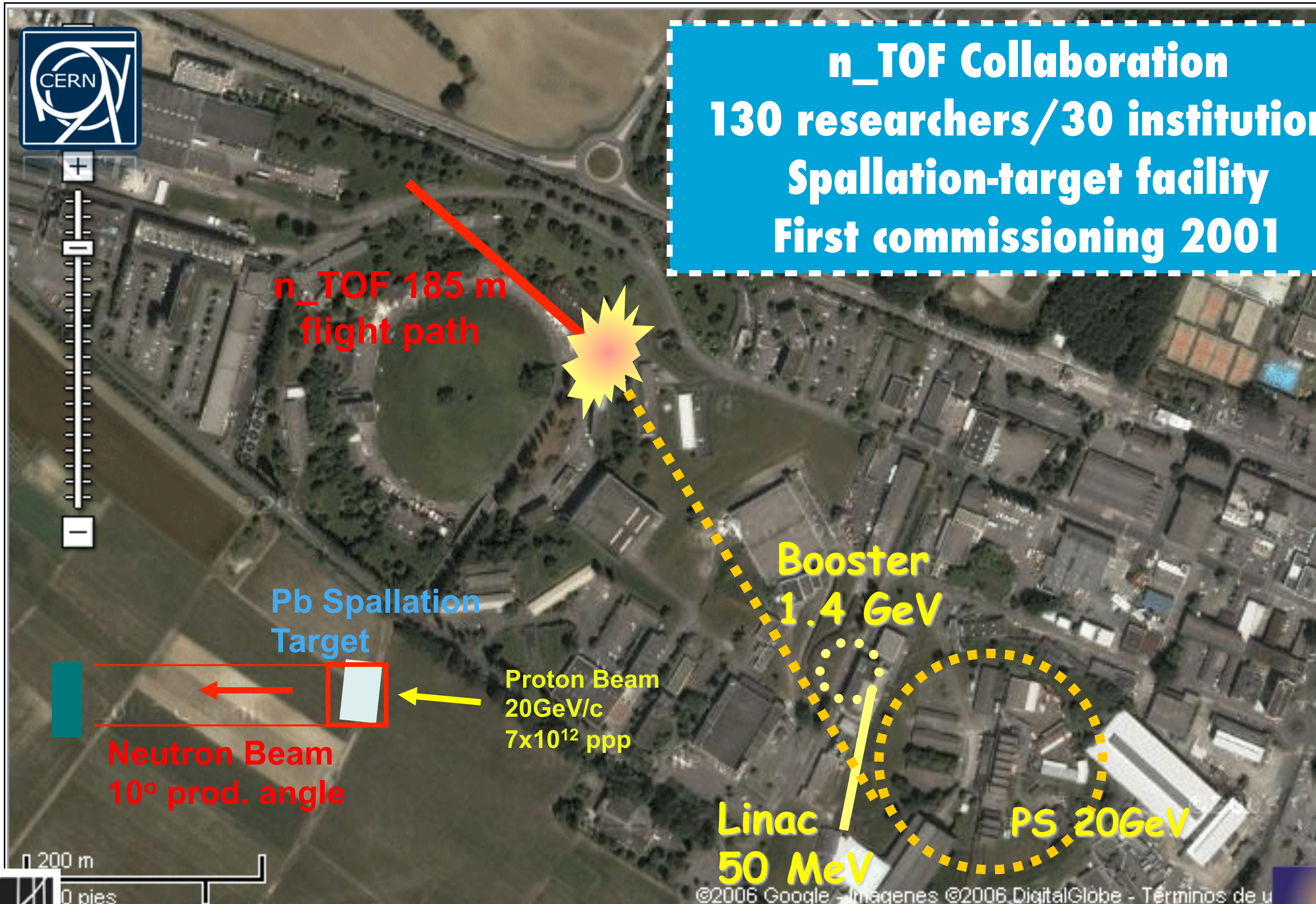


Only statistical estimates of the number/widths of resonances

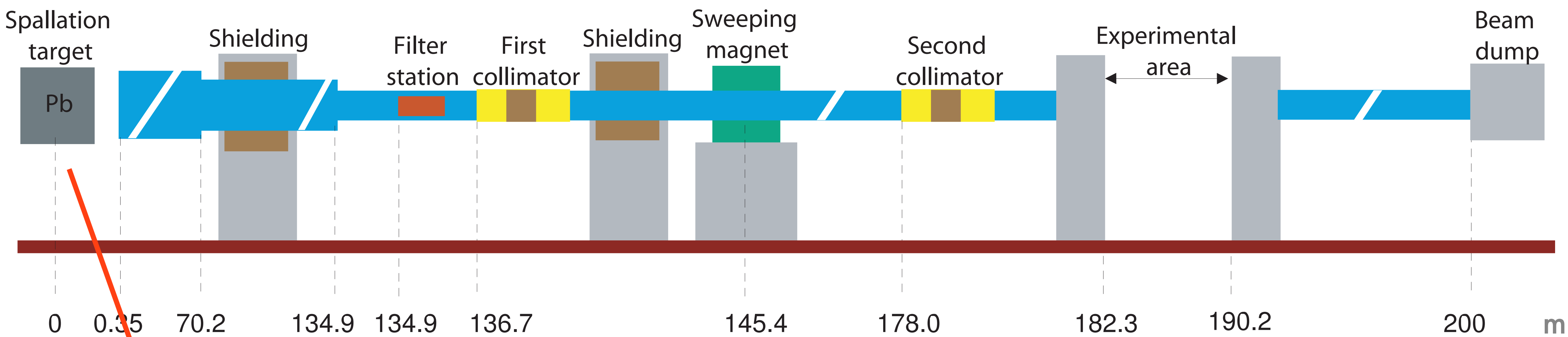
Strong need for measurements!

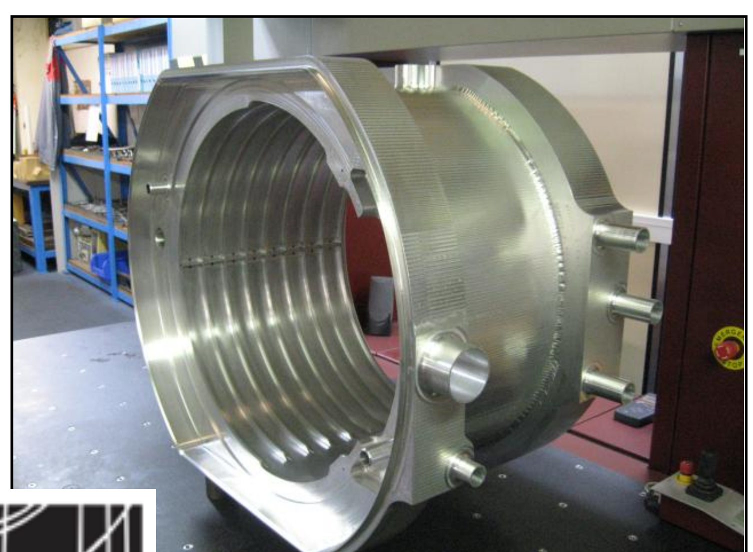
The n_TOF facility

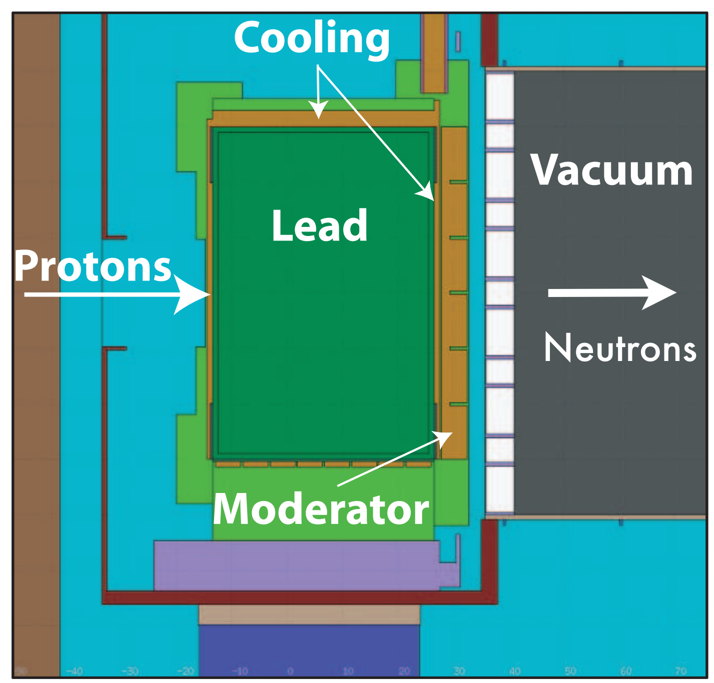
n_TOF Collaboration
130 researchers/30 institutions
Spallation-target facility
First commissioning 2001



Spallation target



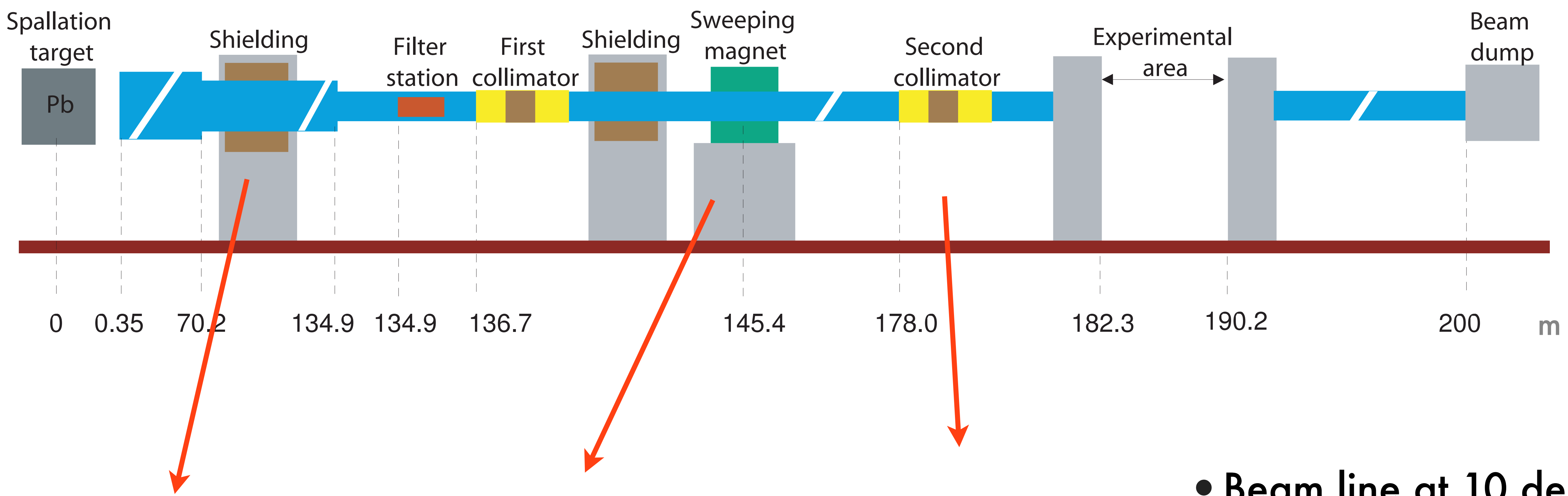


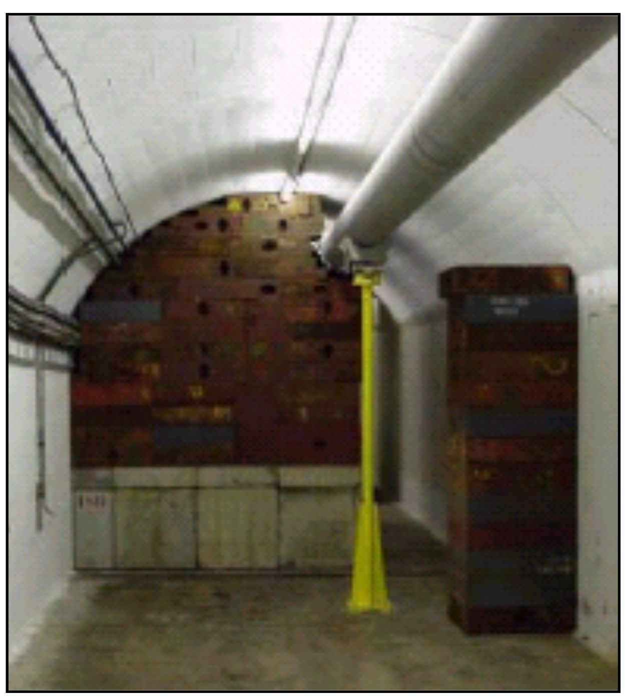


- 40 cm long, 60 cm diameter
- Pb target

- Neutron yield ~ 300 n/p
- Water cooling and moderation (isolethargic flux)
- Concrete shields

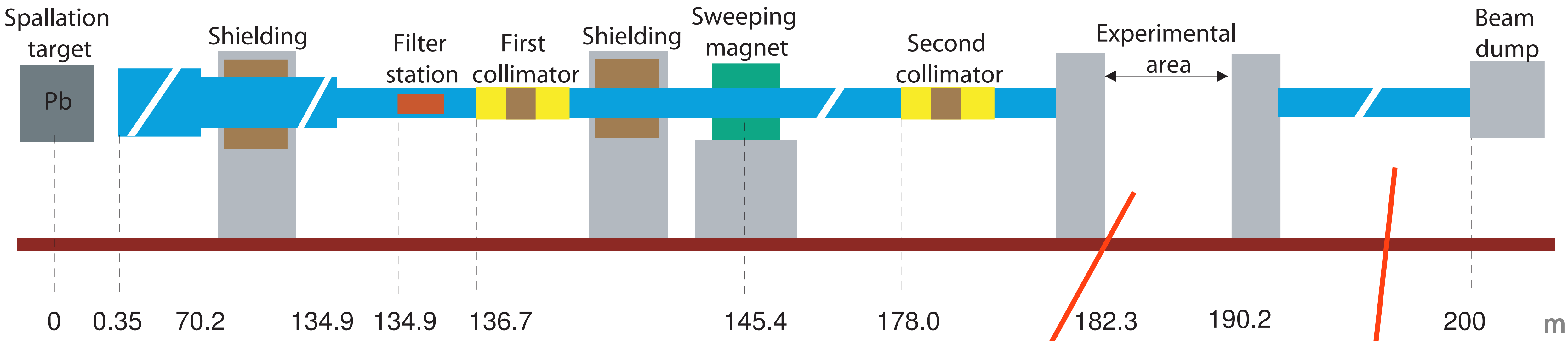
TOF tunnel





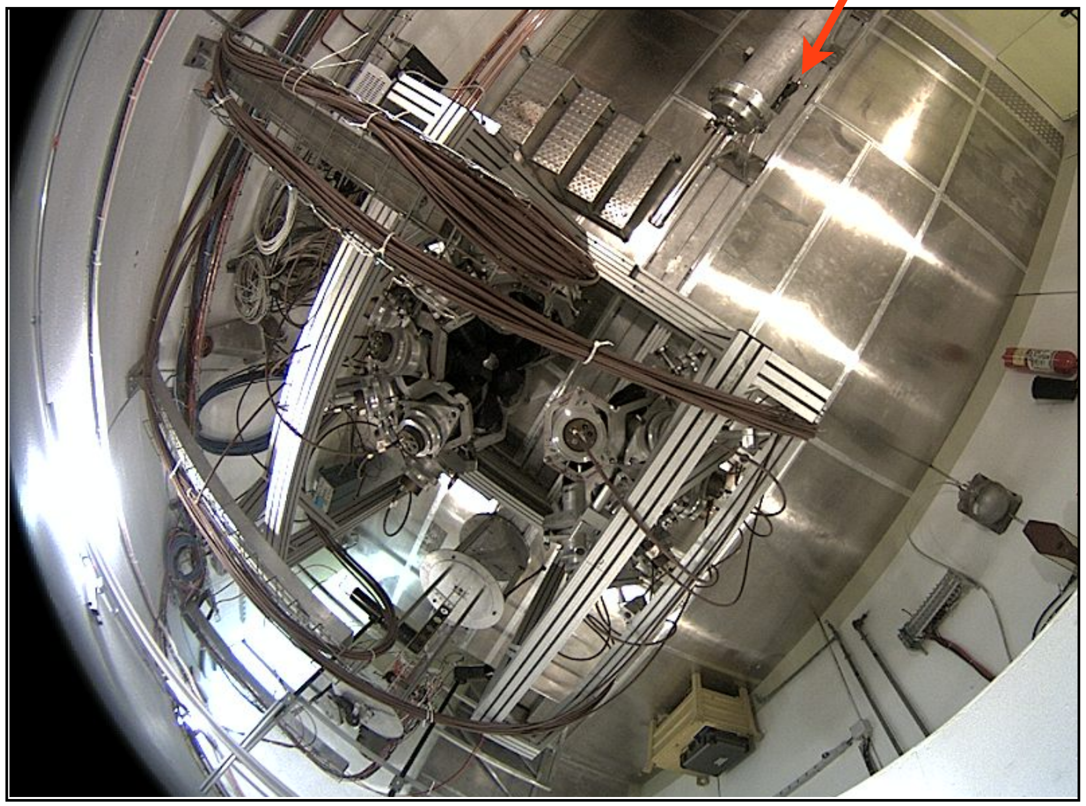
- Beam line at 10 deg. horiz.
- Iron/concrete shields (scattered n, γ,μ)
- Sweeping magnet
- Collimators

EAR-1

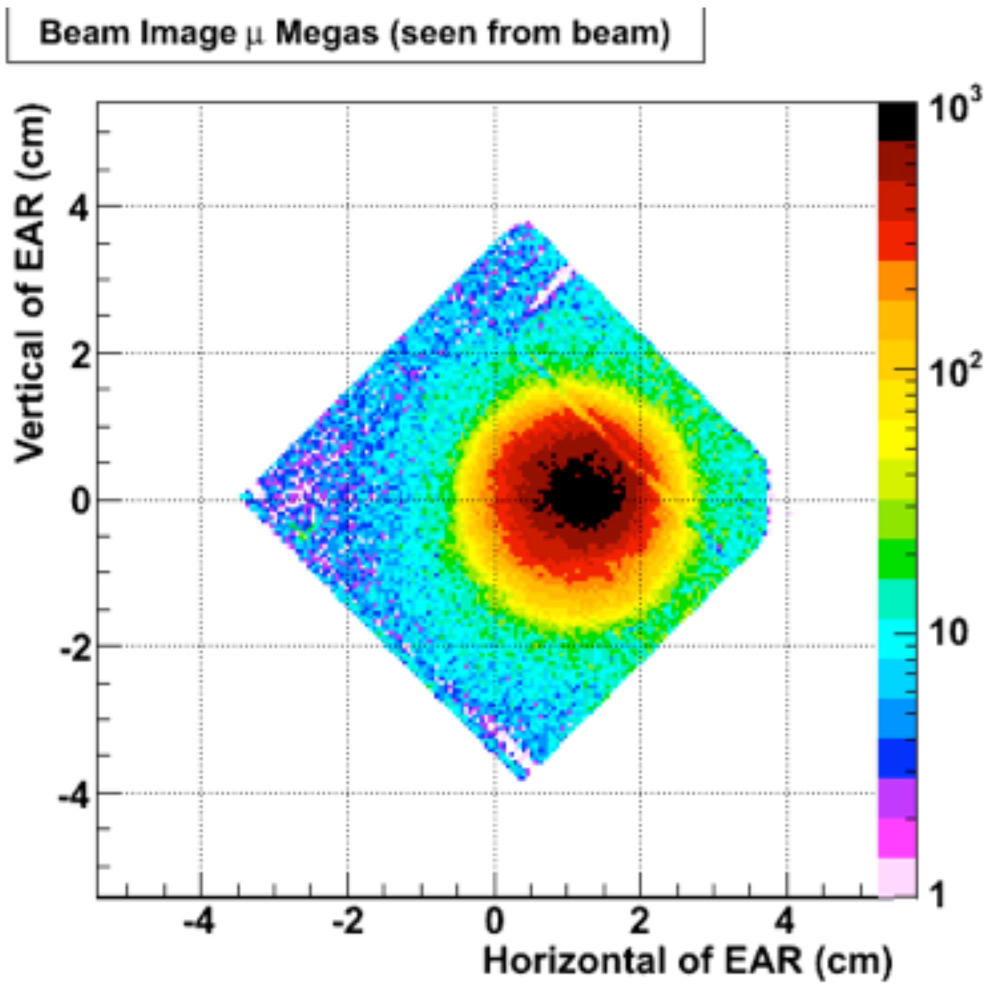


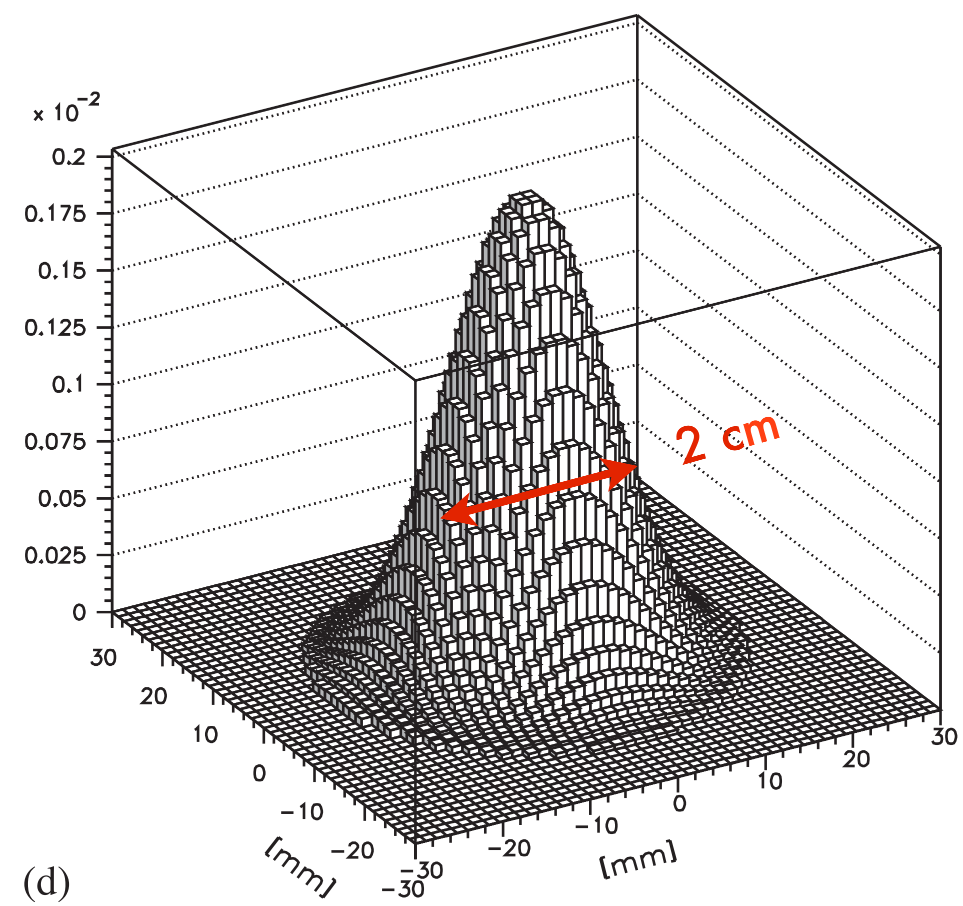
- Beam profile in EAR-1: shapped by second collimator

- Class-A lab. (2010): EAR-1 + escape line



Beam profile



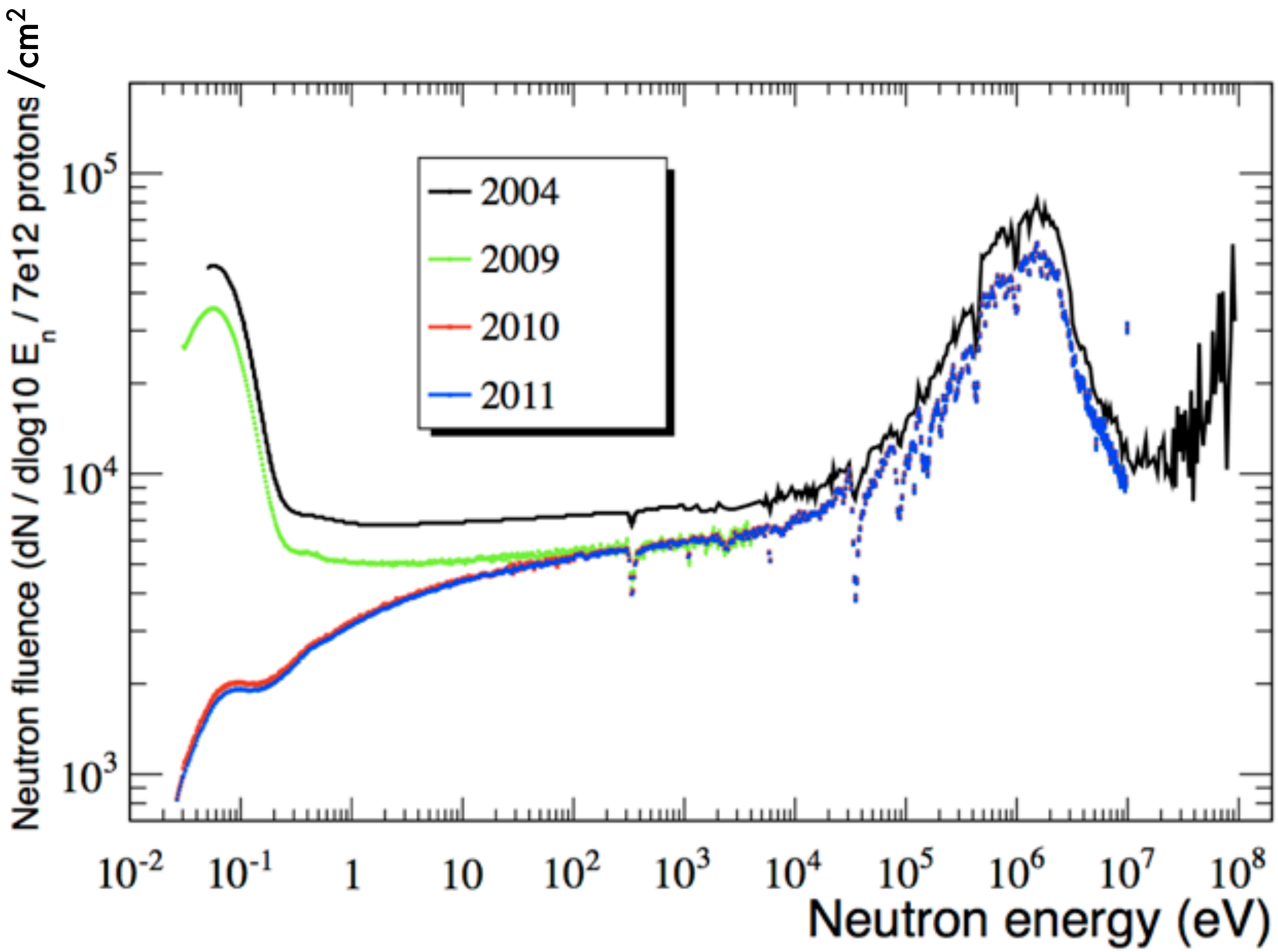


Radioactive samples: small mass (few mg to 2 g)

- Radiation safety
- Maximize signal-to-noise ratio

- Fission collimation: 8 cm

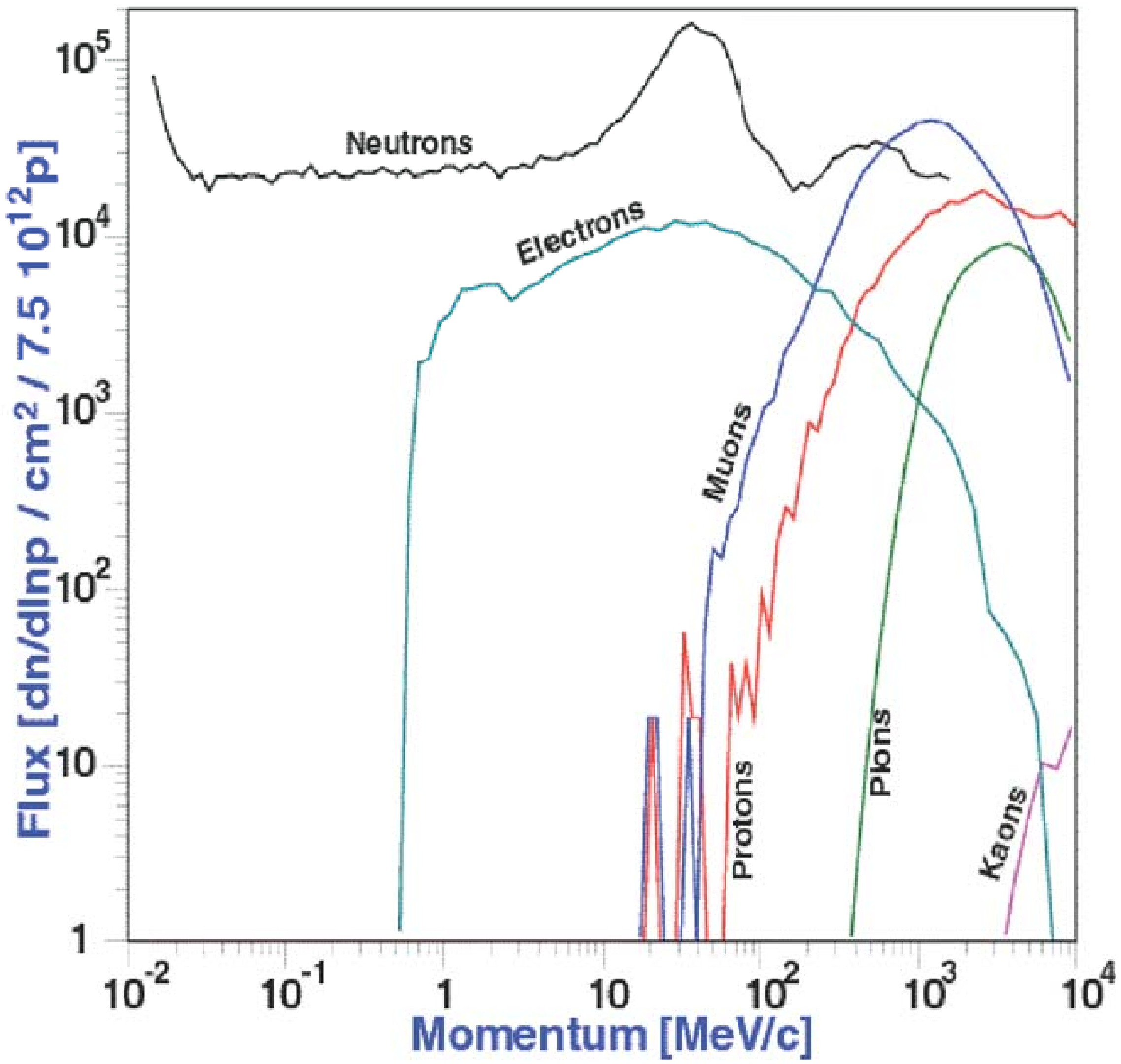
Neutron fluence



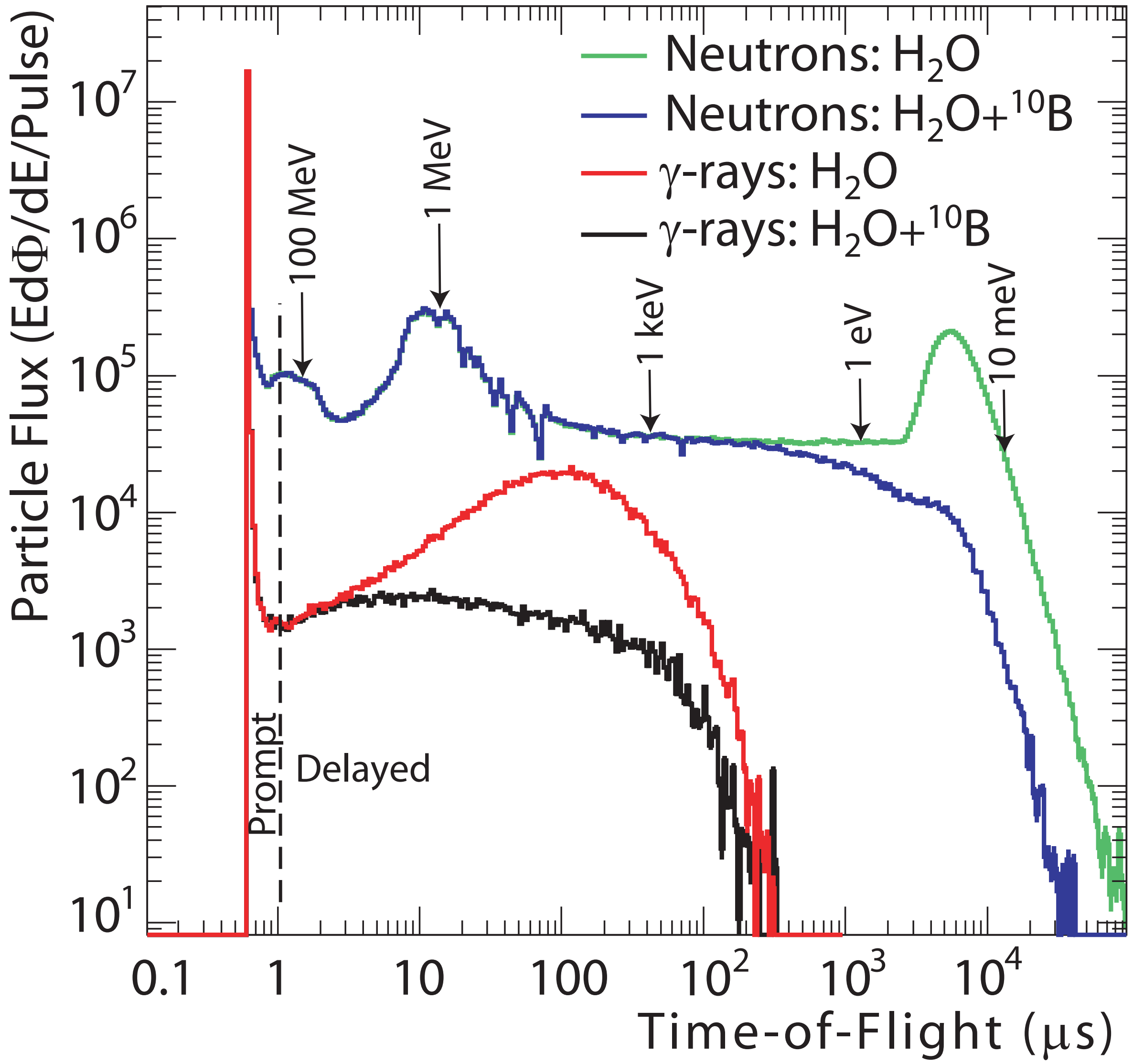
Evaluated neutron fluence

- Wide energy range
- Thermal peak (25 meV)
- Isolethargic flux (eV, keV)
- Absorption dips
- Evaporation peak (1 MeV)
- Knockout neutrons (100 MeV)

In-beam background



Charged particles - deflected



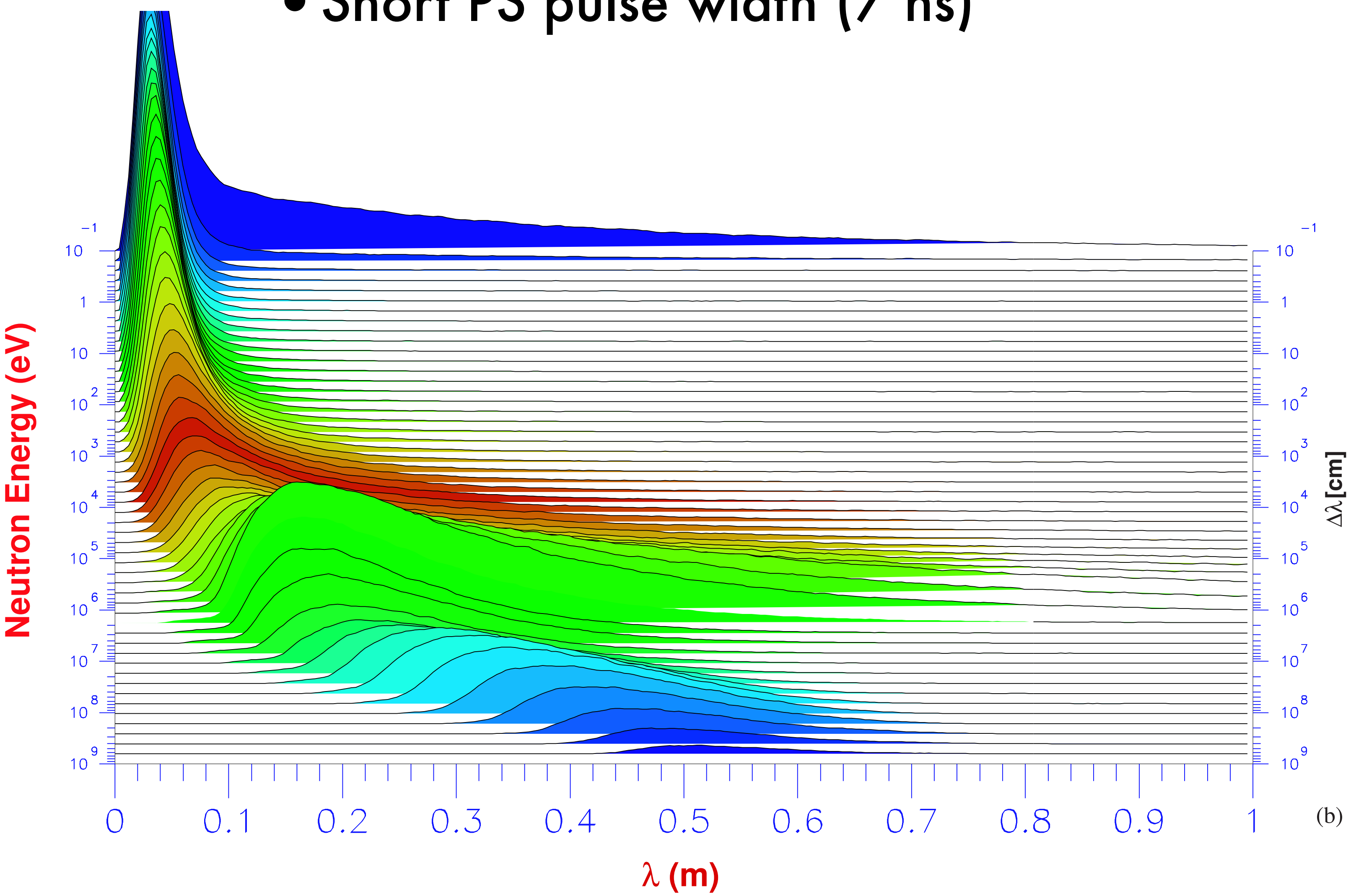
Neutrals in experimental area

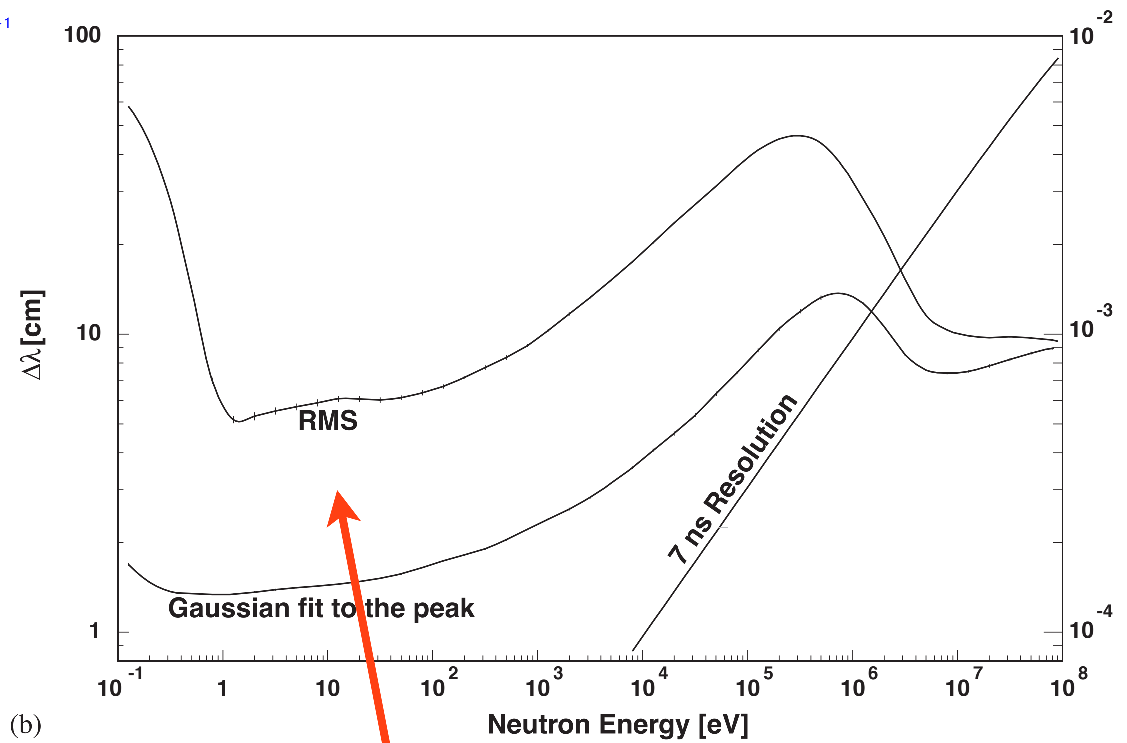
No wrap-around

Neutron energy resolution

High resolution (~0.1% at 10 keV): cross-section resonances

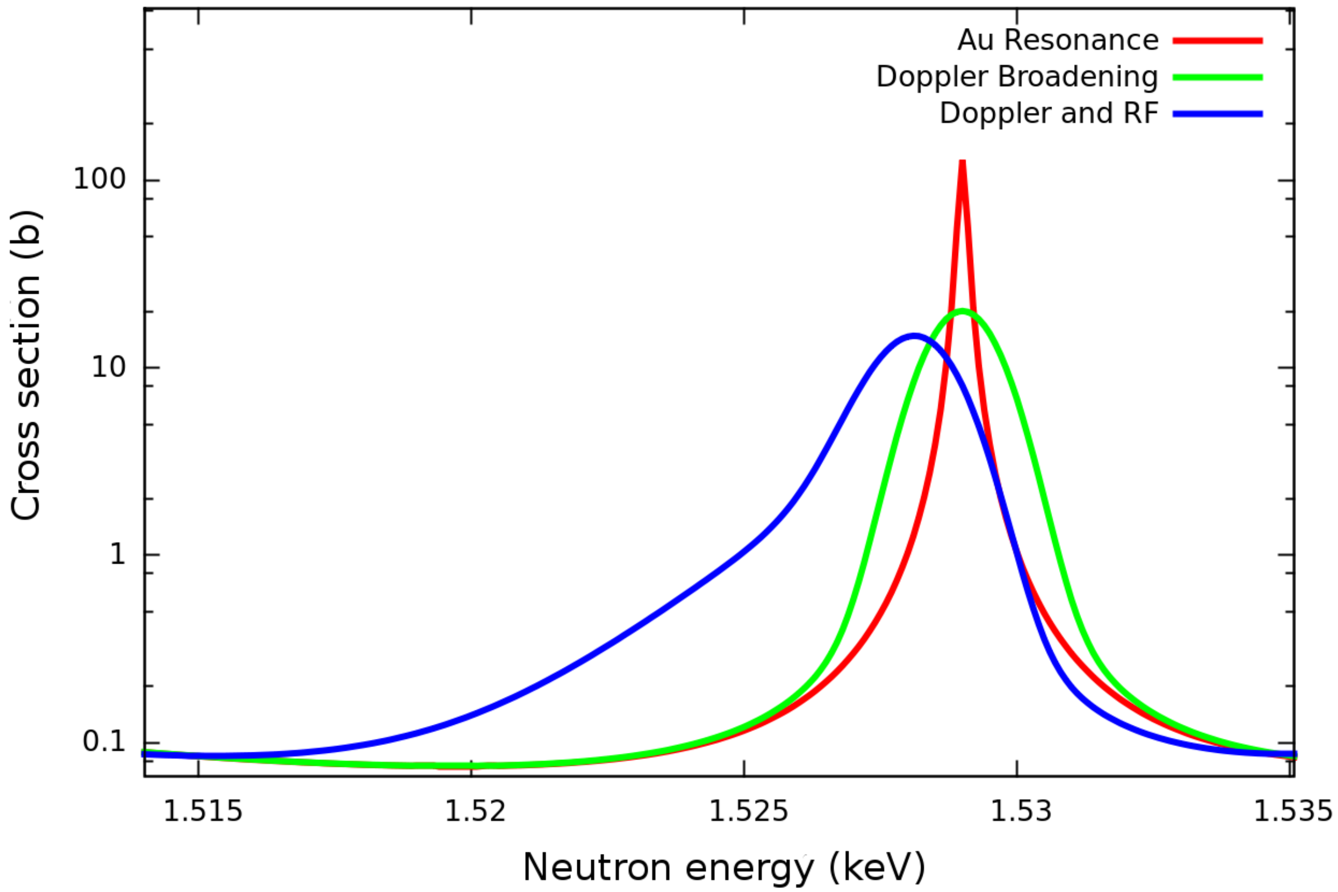
- Long flight distance (200 m)
- Short PS pulse width (7 ns)

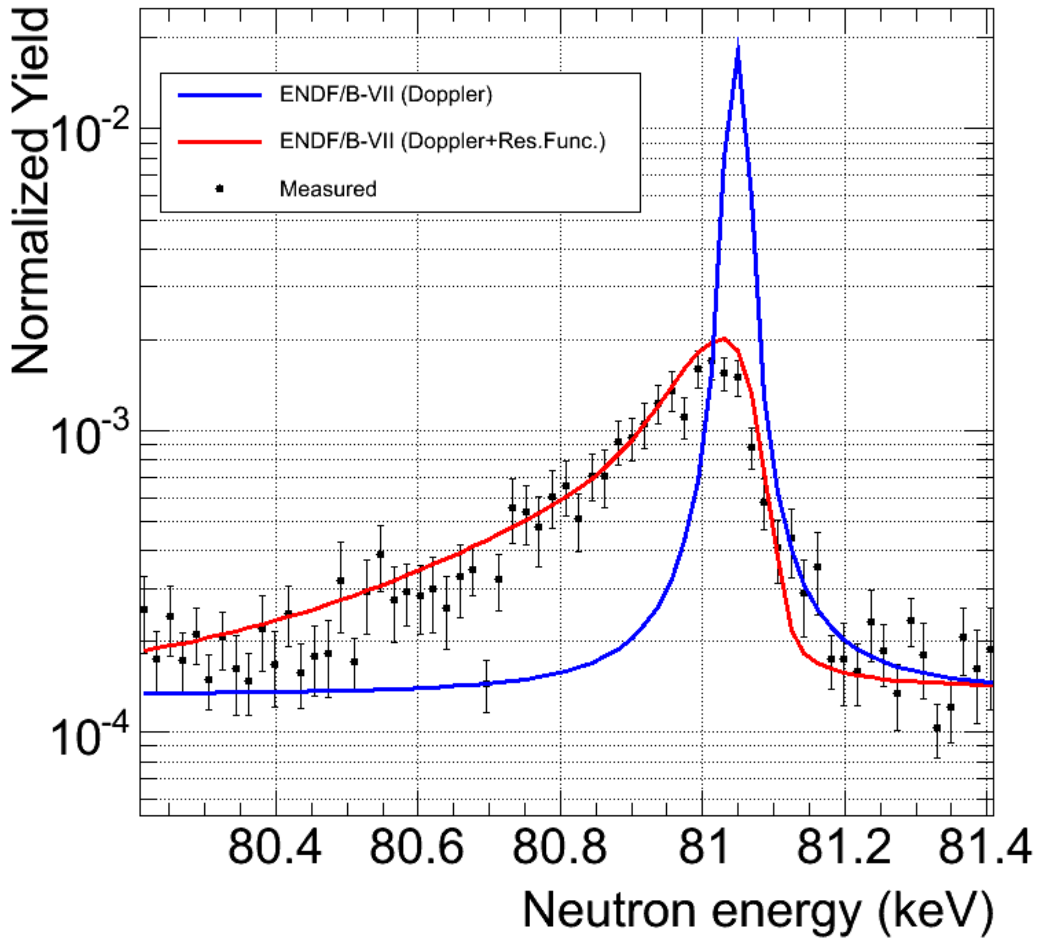




- Moderation lenght in the (old) target/moderator: resolution function

Neutron energy resolution

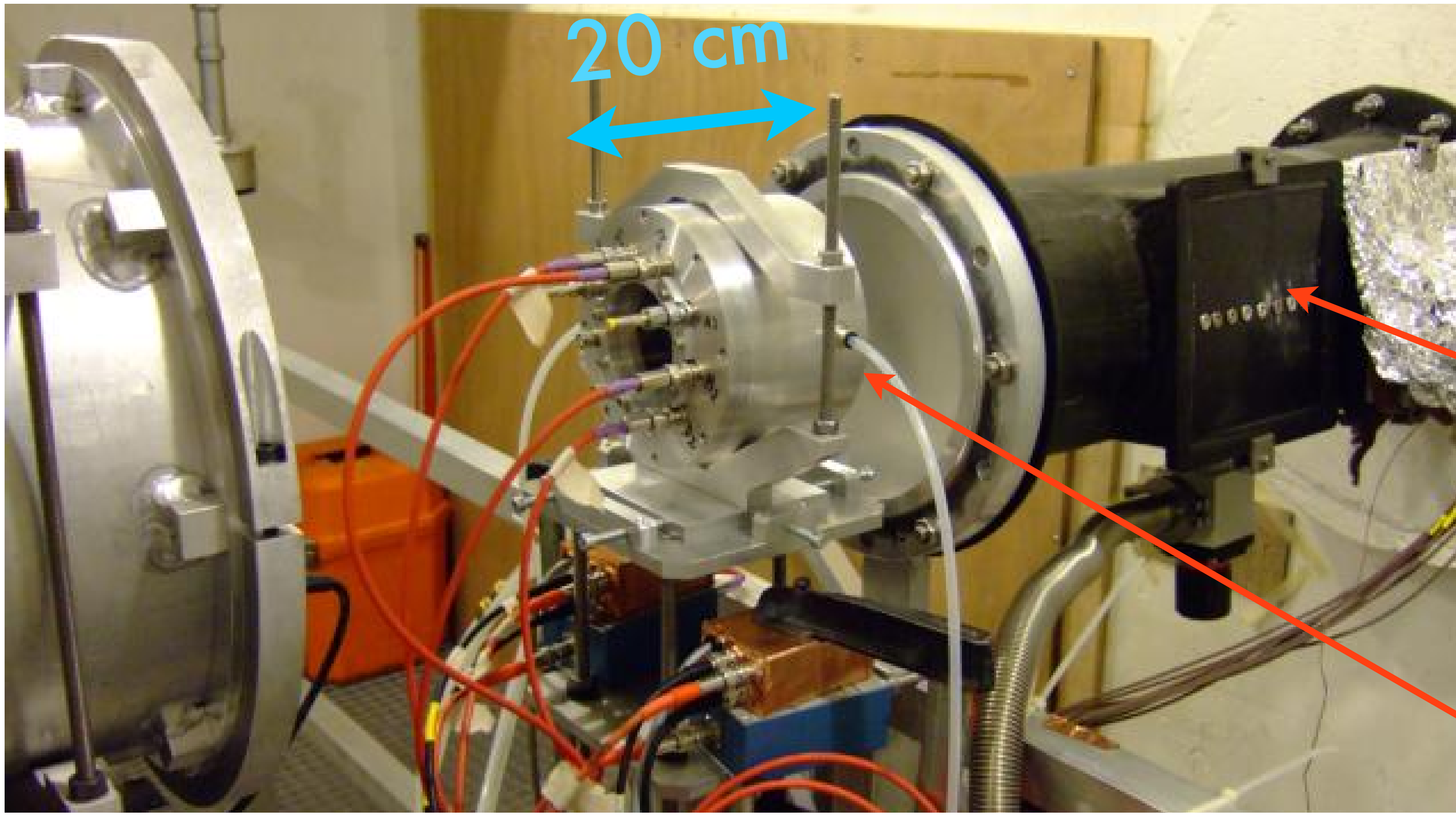




- Doppler broadening dominant up to 1 keV

- RF measured with well-known capture resonances (e.g. ^{56}Fe near 81 keV)

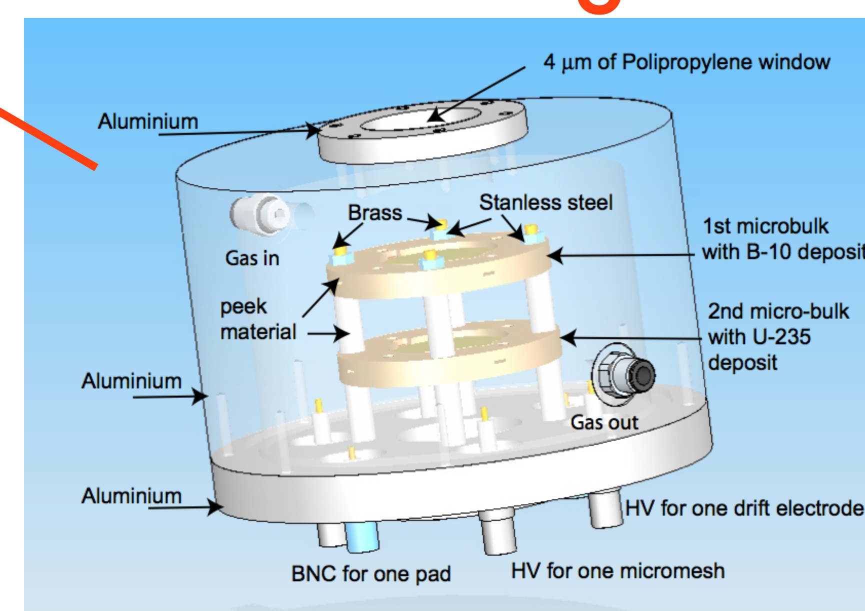
Detectors: flux monitors



neutron beam

Silicon plates

Micromegas



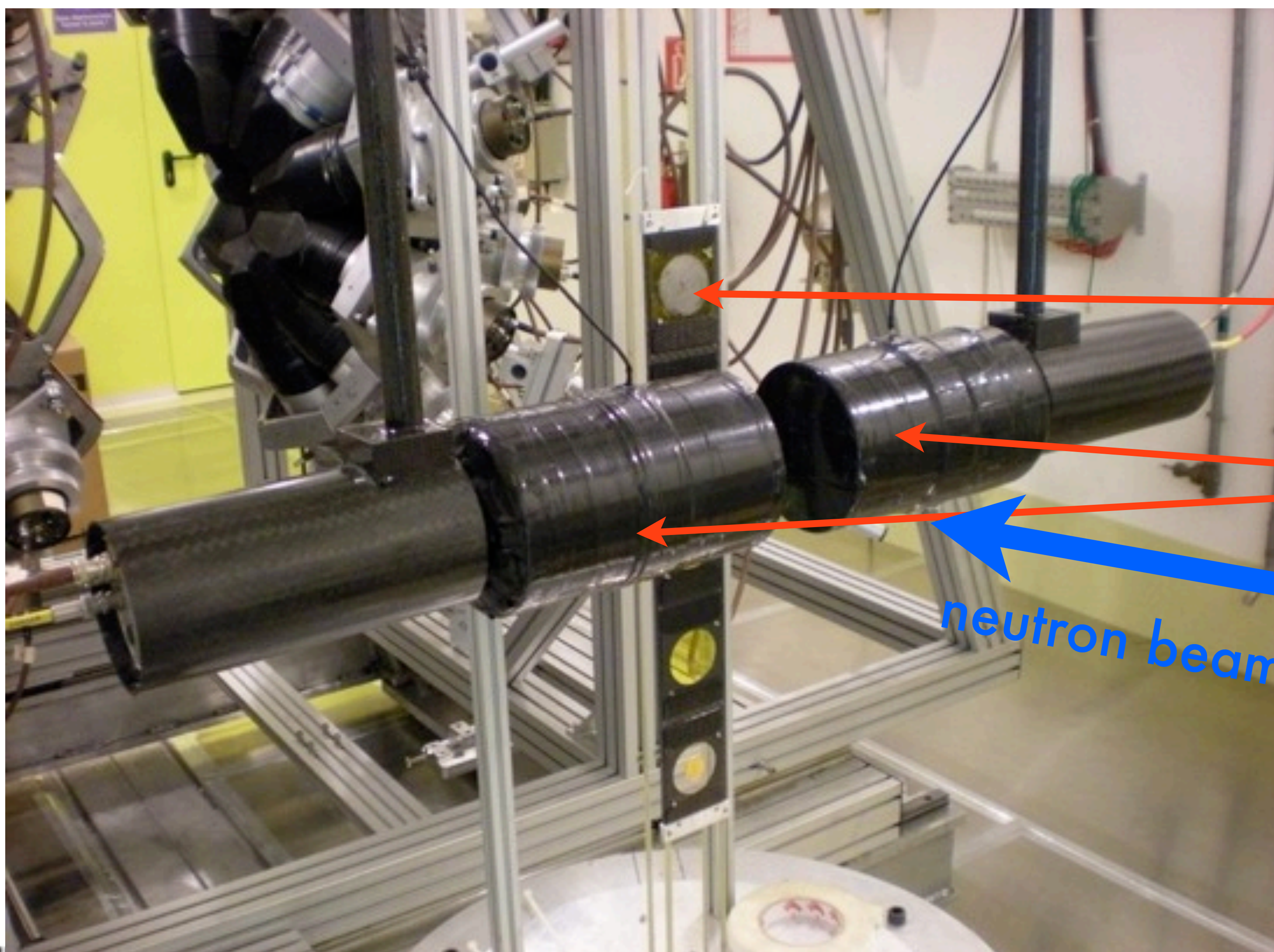
- *"Transparent"*: thin layers (~µm)
- Standard cross-sections: ^{6}Li(n, α), ^{10}B(n, α) and ^{235}U(n, f)
- Beam monitoring / Fluence evaluation

Detectors for neutron capture

- Capture measurements: based on detection of γ's from nuclear de-excitation cascade

Main Backgrounds

- γ's from scattered neutrons captured in the setup (neutron sensitivity)
- Sample activity, competing reactions, environmental

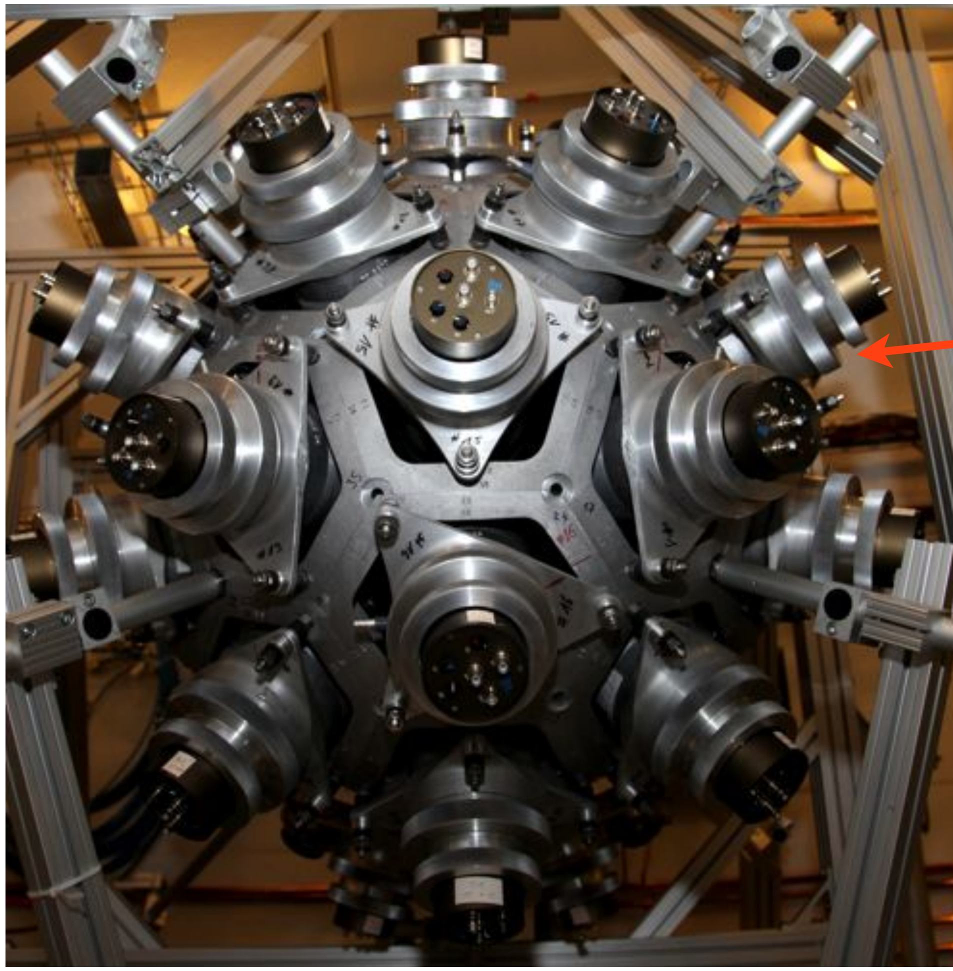


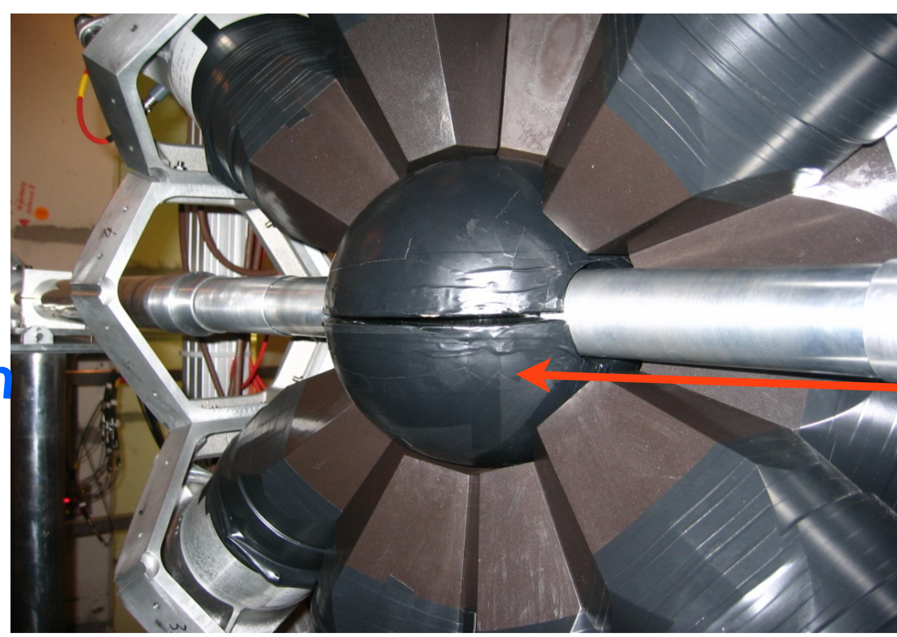
Sample holder and exchanger

C_6D_6 detectors

- Low efficiency
- Low neutron sensitivity (carbon fiber, few material)

Detectors for neutron capture



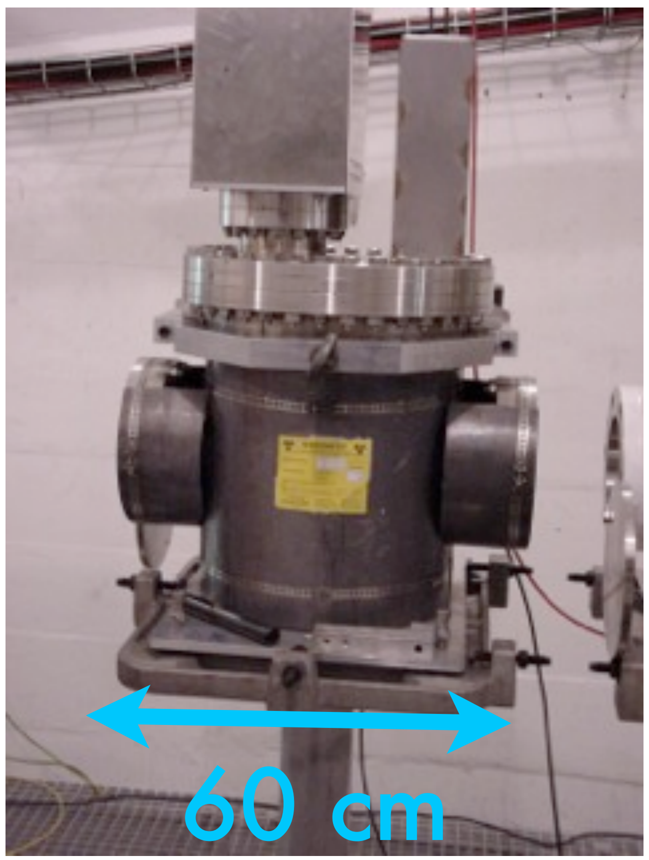


Total Absorption Calorimeter (TAC)

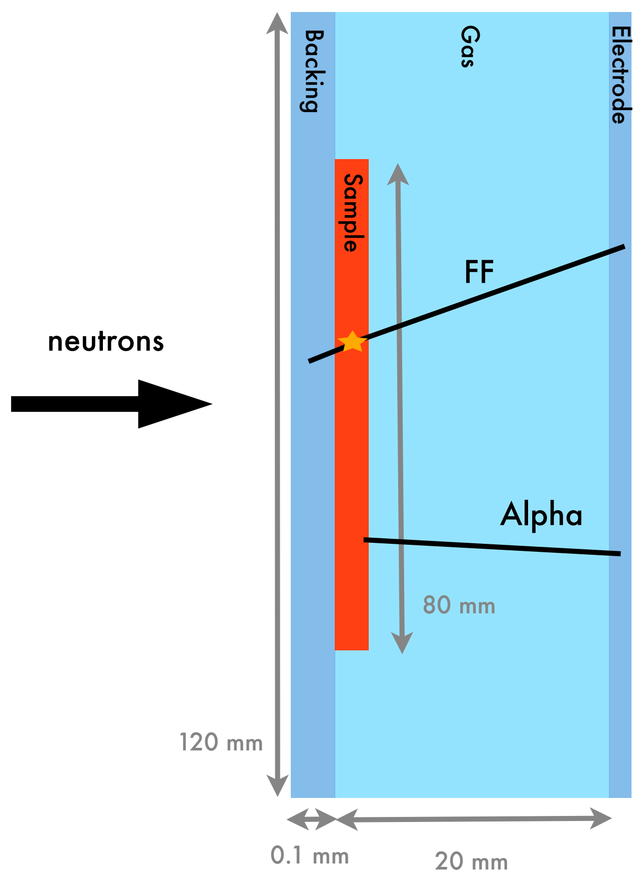
- 40 BaF_2 crystals
- High efficiency: total cascade energy
- Background discrimination: fission γ's, samples activity (Actinides)
- Neutron sensitivity: neutron absorber around sample position

Detectors for fission

- Fission measurements: energy deposition of Fission Fragments in detector gas



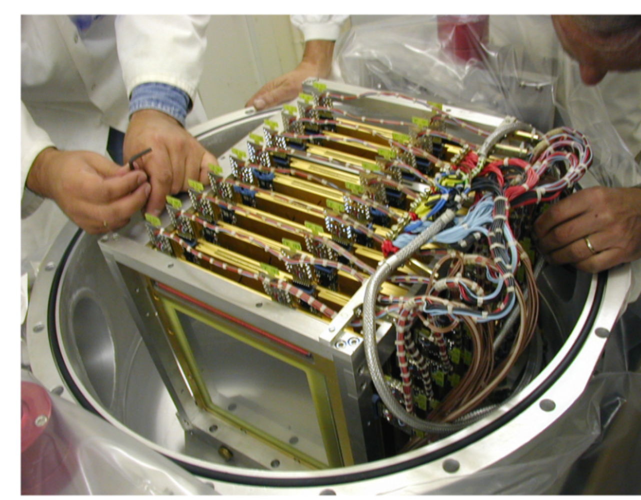
Fast Ionization Chamber



- Discrimination against α-background from signal amplitude

- Multi-stack: simultaneous measurements

Parallel Plates Ionization Chamber



n_TOF features

- Wide range of neutron energies (10 decades!)
- High neutron fluence (> 10^5 n/pulse/cm^2)
- Excellent neutron-energy resolution (< 0.1% at 10 keV)
- Low background
- Low duty cycle (0.8 Hz, no neutron overlap)
- State-of-the-art detection and DAQ systems

Results

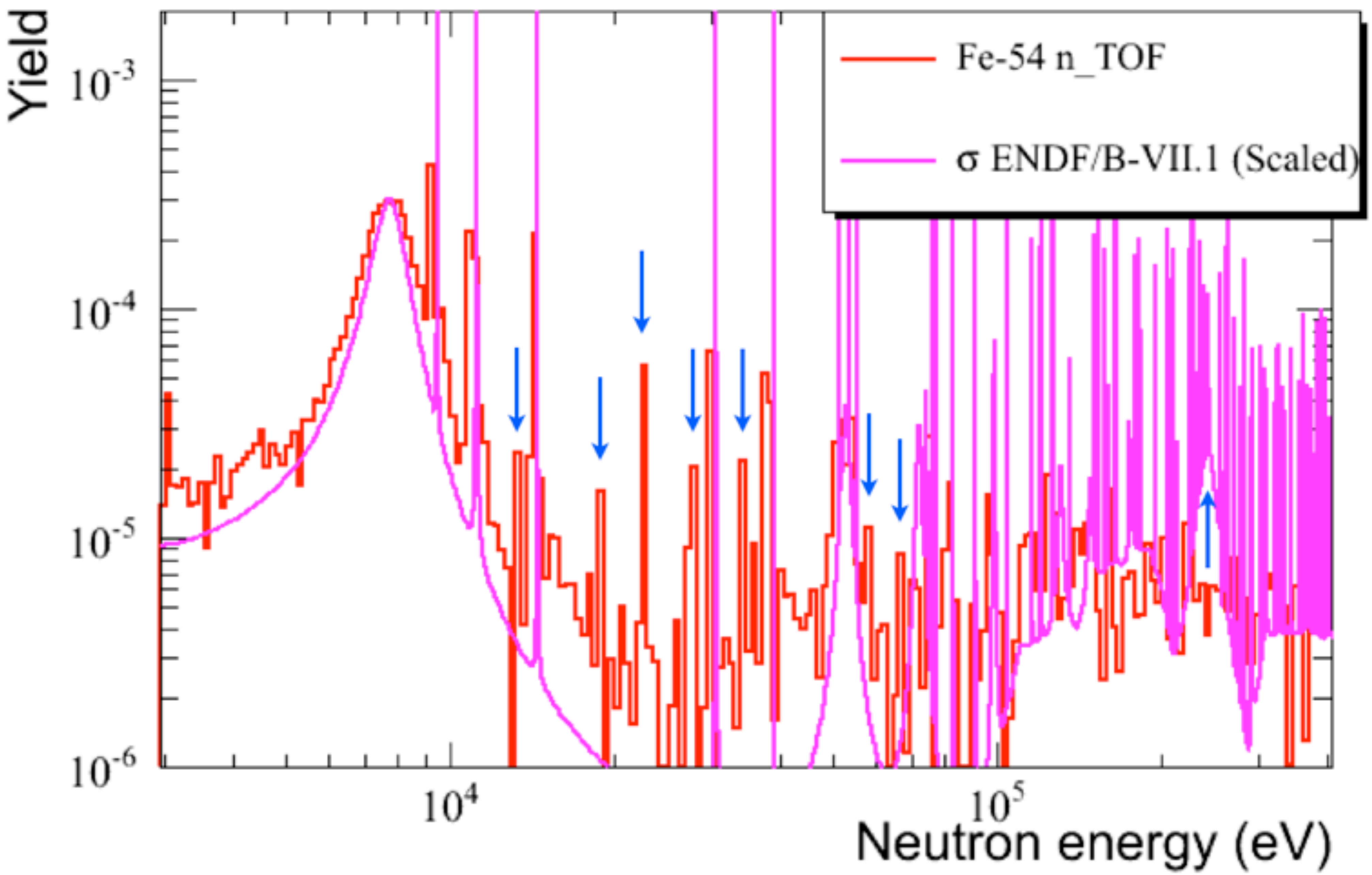
n_TOF campaigns

- Phase-1 (2001-2004)
- Stoppage (2005-2007)
- Phase-2 (2008-2012)

	CERN-PS Experiment	Measurements
nTOF12	n_TOF New target commissioning and beam characterization [80]	Neutron fluence Beam profile Energy resolution
nTOF13	The role of Fe and Ni for s-process nucleosynthesis in the early Universe and for innovative nuclear technologies [9]	^{54,56,57,58*}Fe(n, γ) ^{58,60*,61*,62,64*}Ni(n, γ)
nTOF14	Angular distributions in the neutron-induced fission of actinides [81, 82]	^{232}Th(n, f) ^{237}Np(n, f) ^{235,238}U(n, f)
nTOF15	Neutron capture cross section measurements of ^{238}U, ^{241}Am and ^{243}Am at n_TOF [83]	^{238}U(n, γ) ^{241}Am(n, γ)
nTOF16	Measurement of the fission cross-section of ^{240}Pu and ^{242}Pu at CERN's n_TOF Facility [84]	^{240,242}Pu(n, f)
nTOF17	The neutron capture cross section of the s-process branch point isotope ^{63}Ni [85]	^{63}Ni(n, γ)

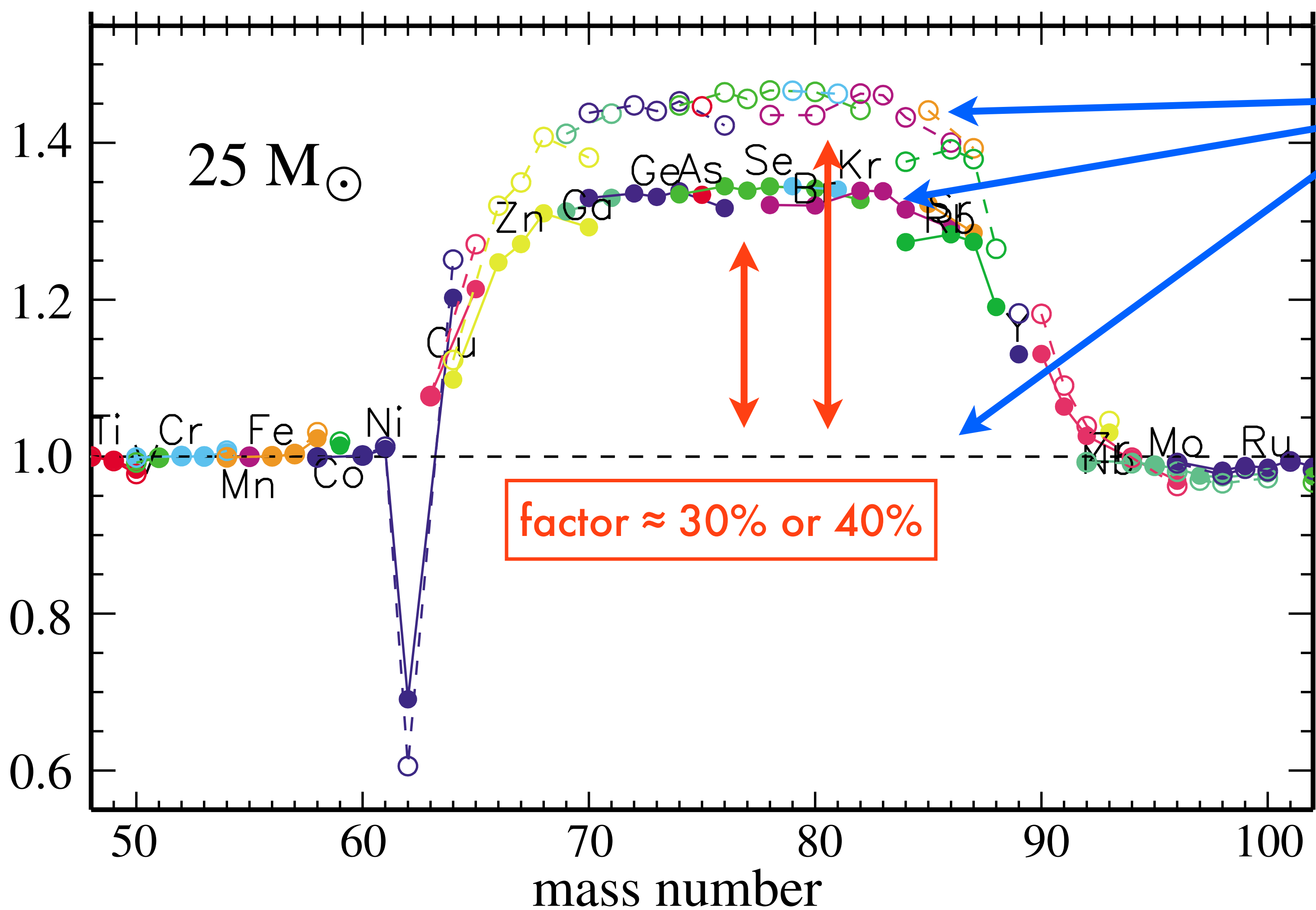
$^{54}Fe(n,\gamma)$

^{54}Fe neutron-capture yield: new resonances



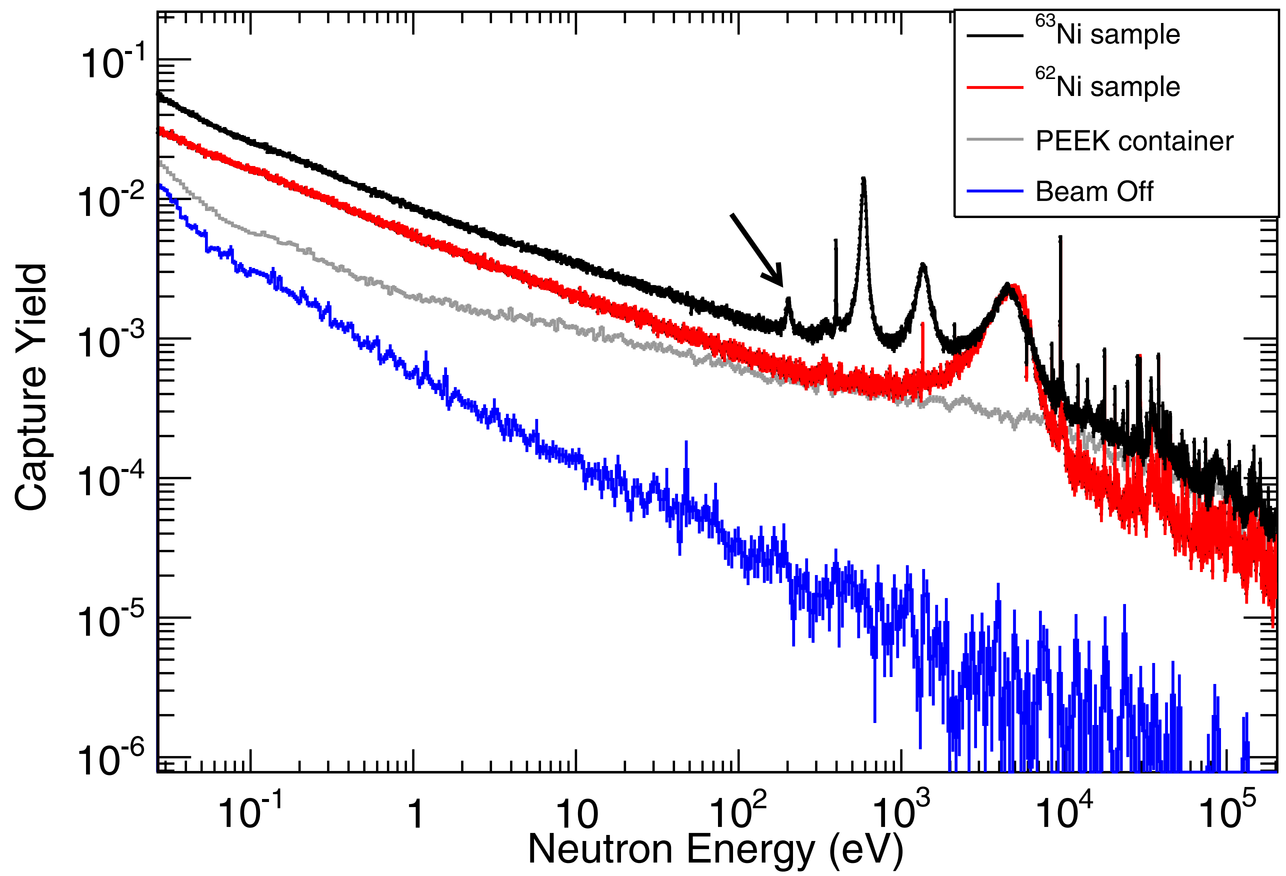
$^{62,63}Ni(n,\gamma)$

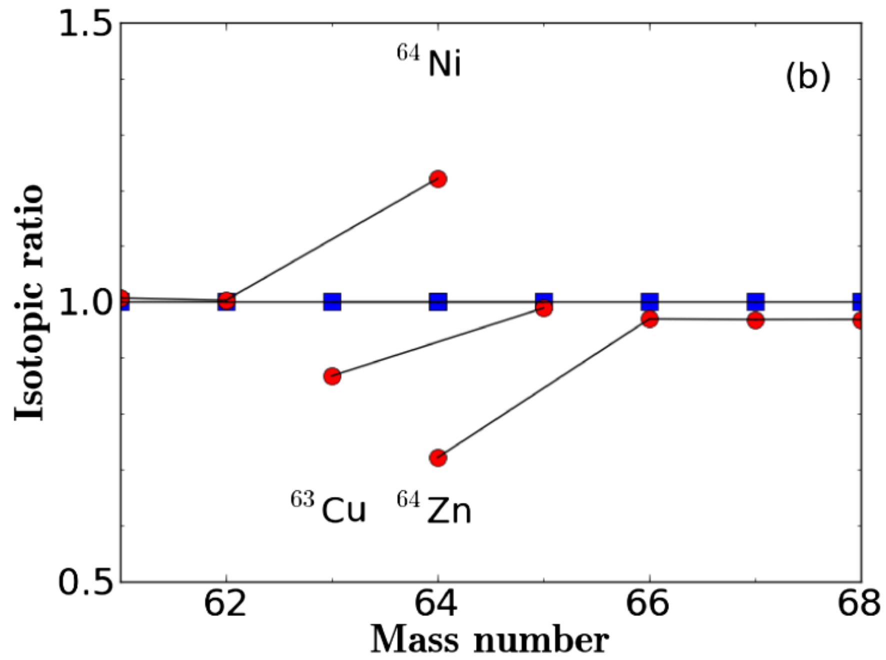
- S-process seeds



- Measurements of $^{62}Ni(n,\gamma)$ cross section: abundance yields with big discrepancies

$^{62,63}Ni(n,\gamma)$





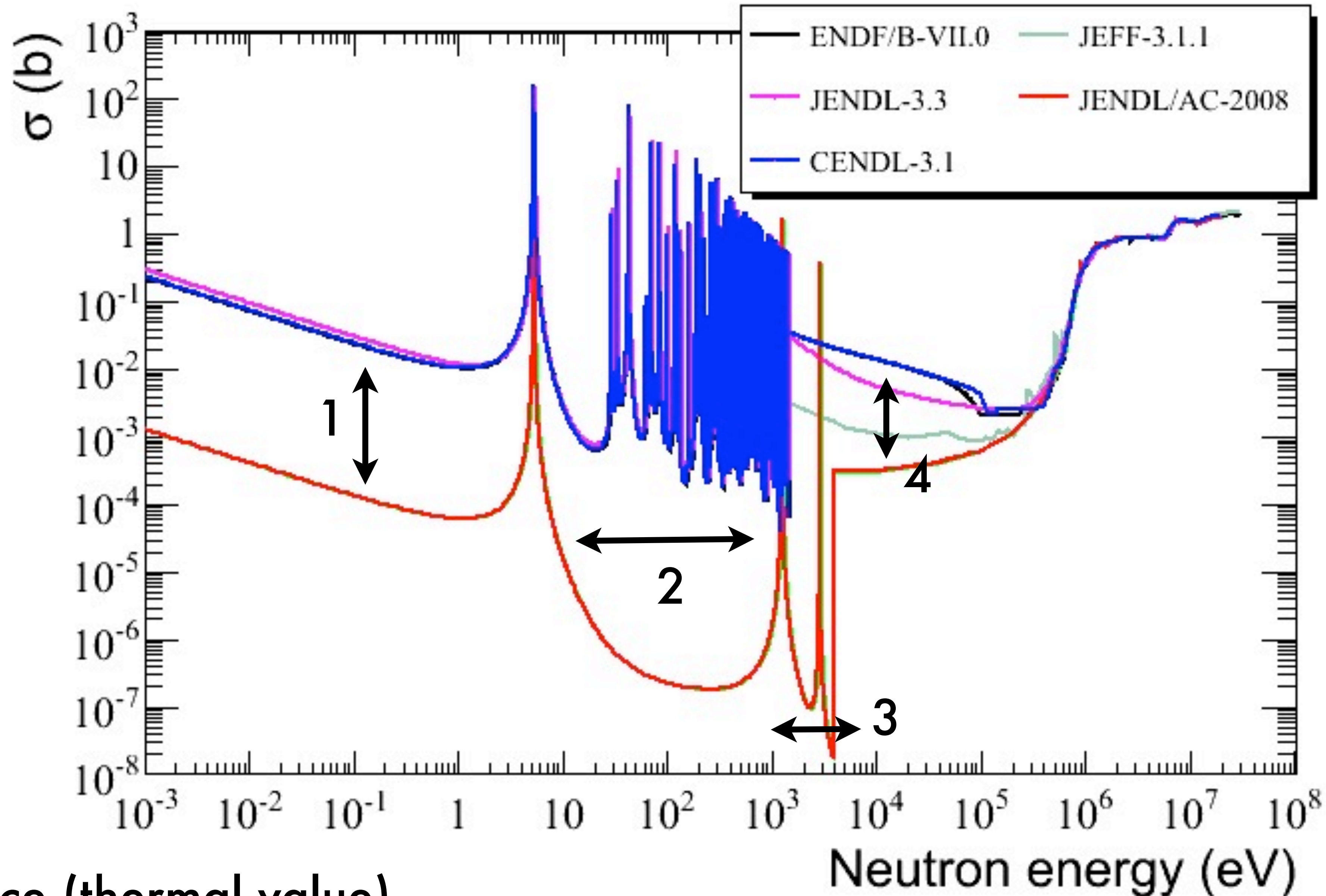
Phys. Rev. Lett. 110, 022501 (2013)

- Branching-point isotope
- First measurement
- New isotopic s-process distributions

$^{236}U(n,f)$

Logarithmic scale!

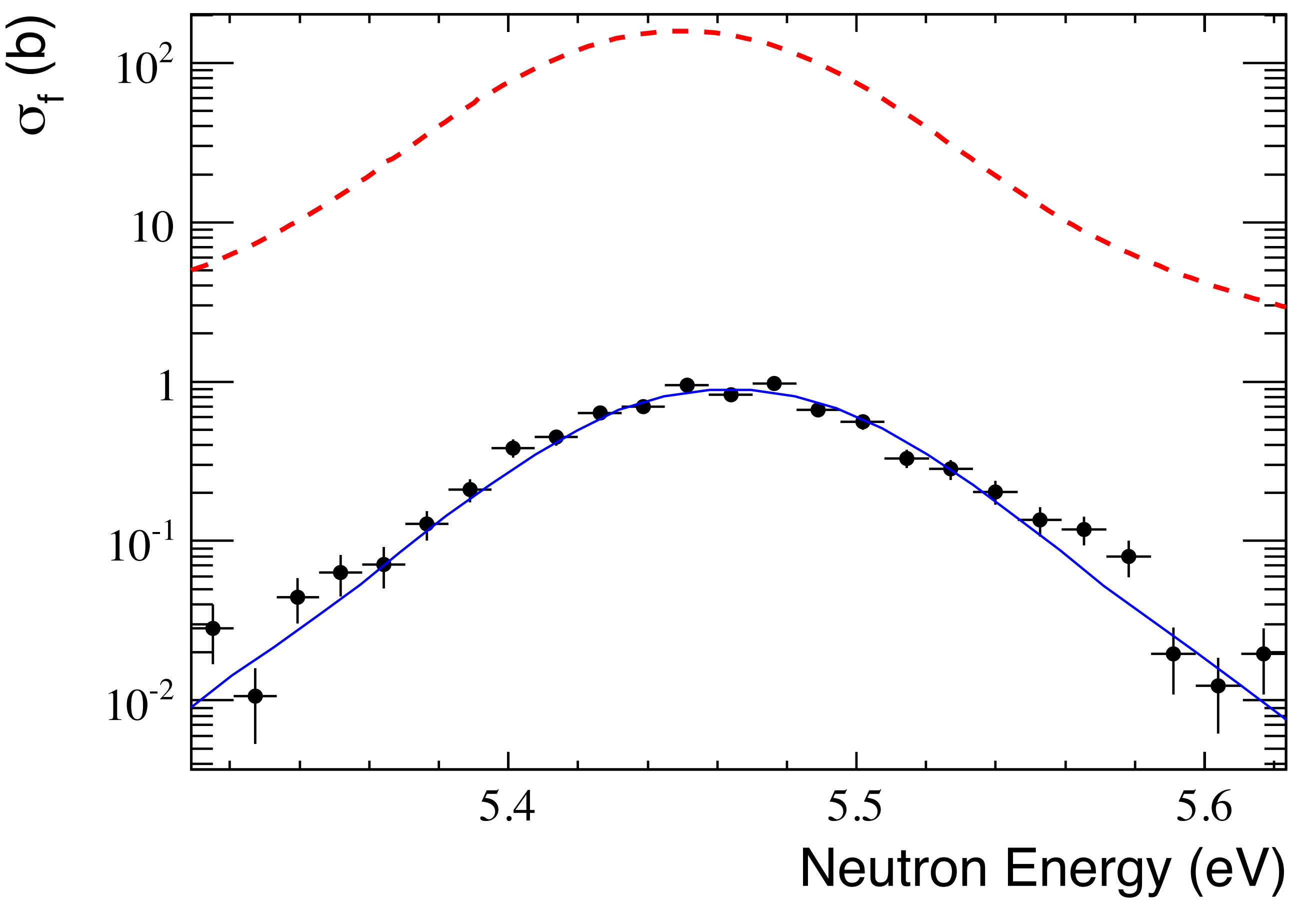
- Neutron poison / radioactive waste

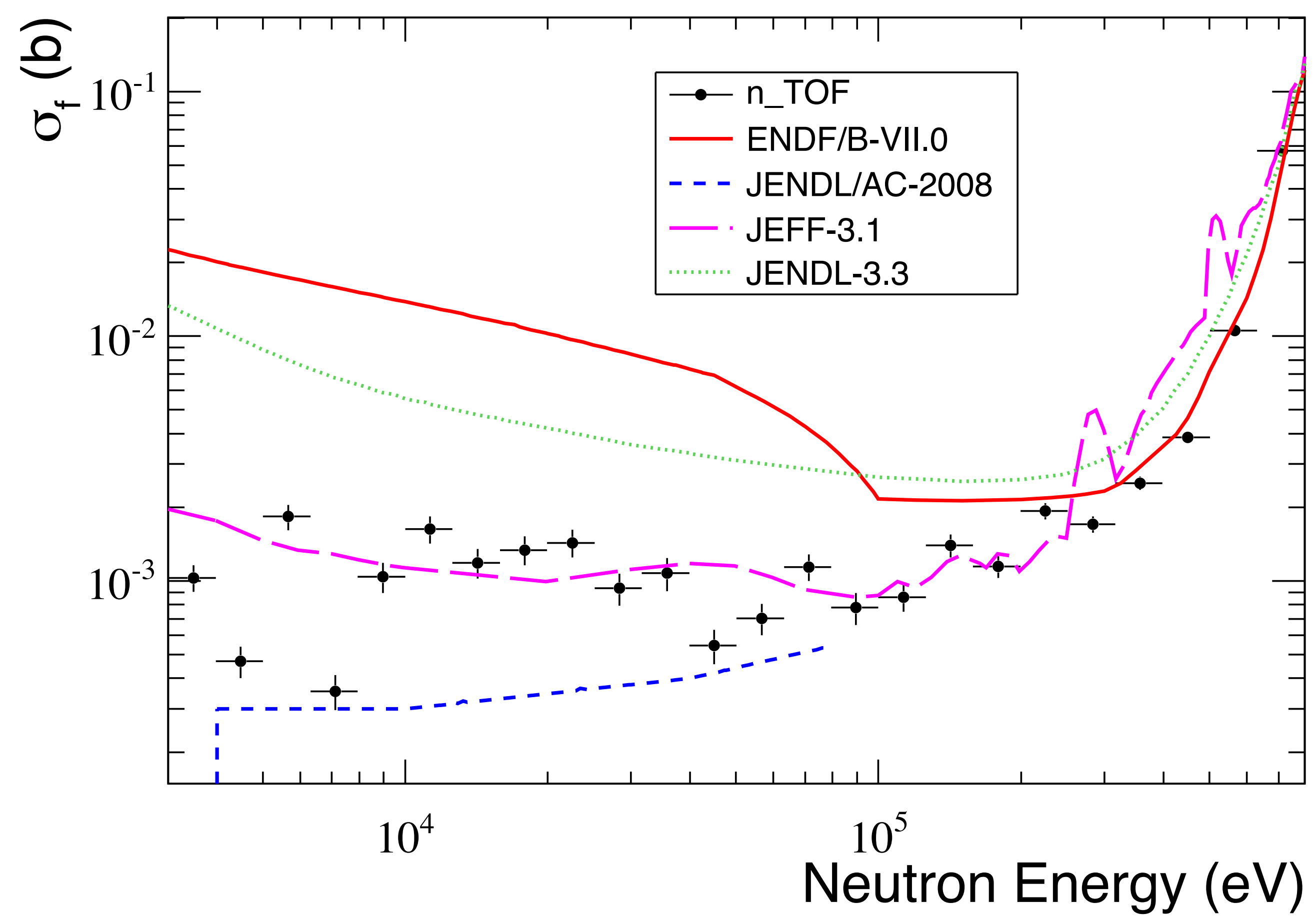


Discrepancies in data libraries:

1. Width of the first resonance (thermal value)
2. Resonances number/widths: 10 eV up to 1 keV
3. Intermediate-energy resonances number/width: above 1 keV
4. Cross-section values below the fission threshold

$^{236}U(n,f)$

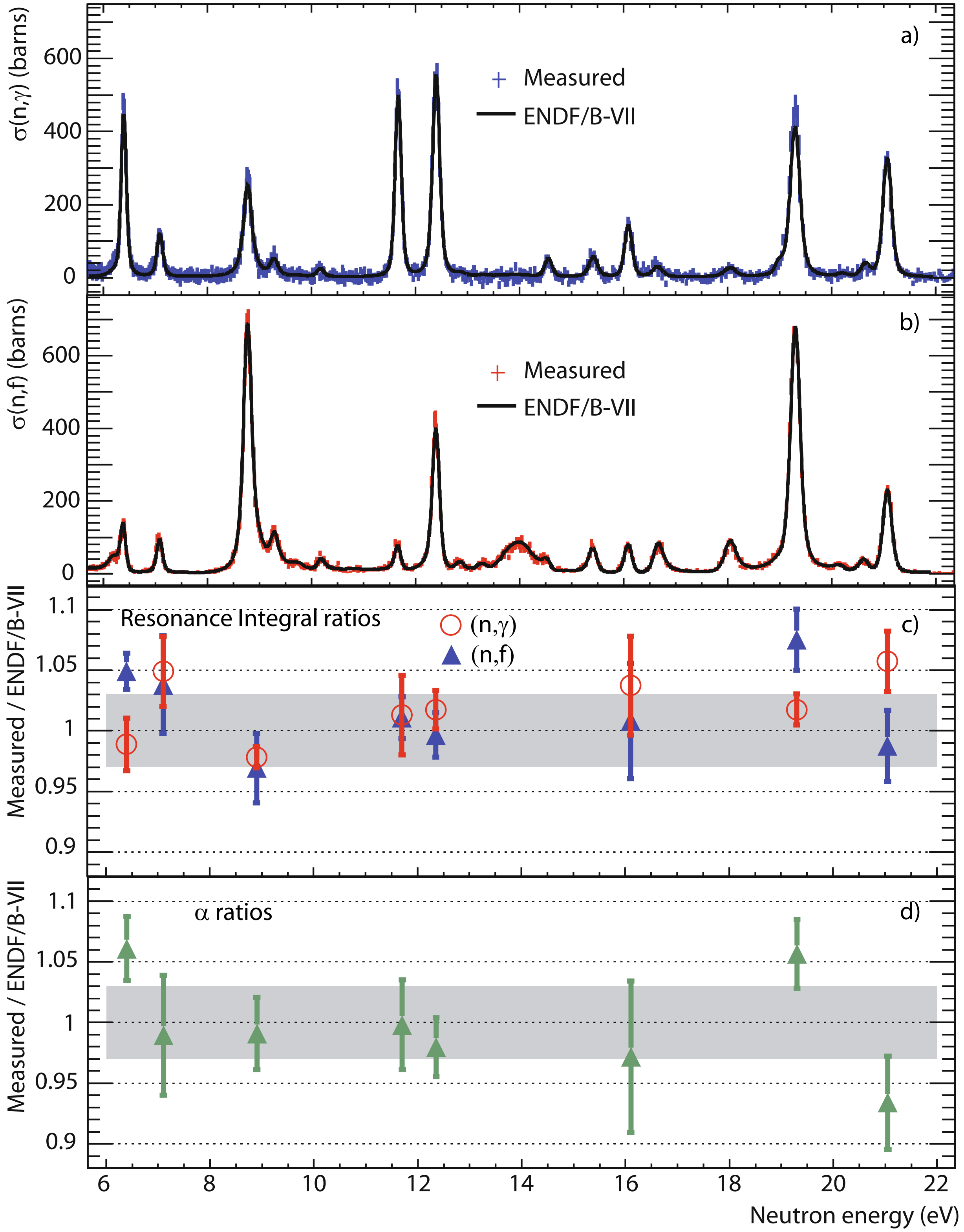




Phys. Rev. C 84, 044618 (2011)

- New resonance parameters and tabulated cross-sections

$^{235}U(n,f)$ & $^{235}U(n,\gamma)$



Eur. Phys. J. A 48, 1 (2012)

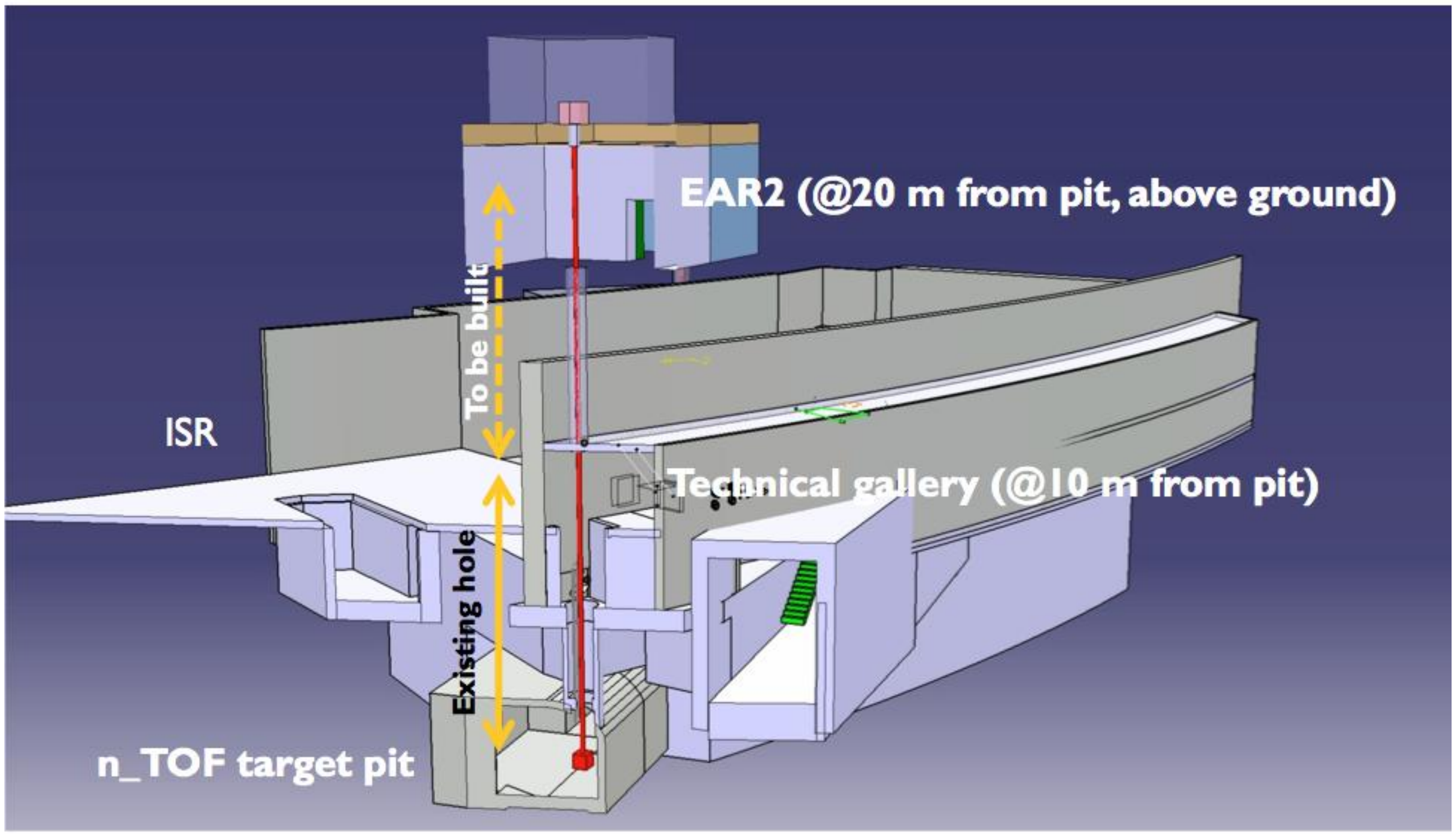
- New technique to measure fission and capture cross-sections simultaneously
- Tagging fission γ's in TAC crystals from fission fragments signals in Micromegas
- Discriminate background for capture γ's

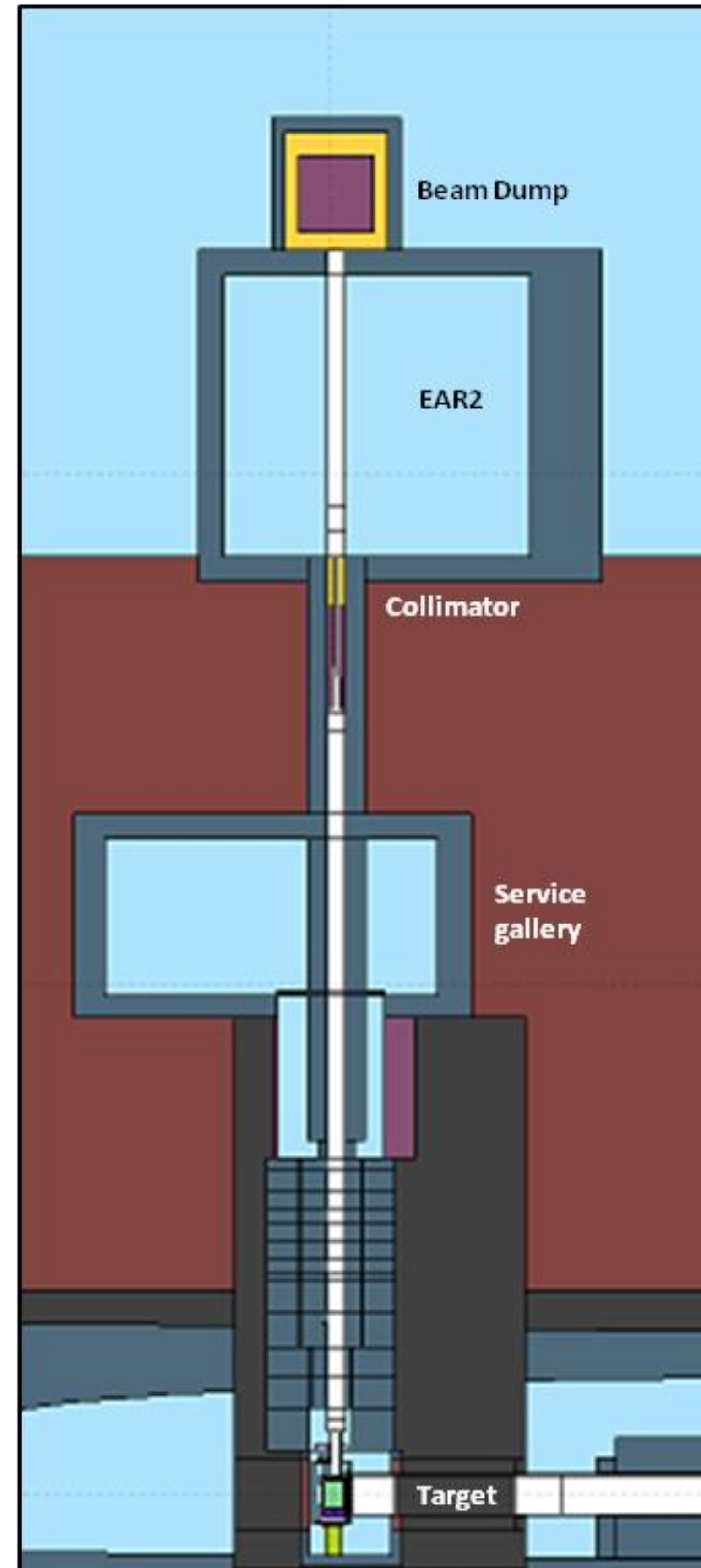
Perspectives

- Phase-2 analysis ongoing: more results soon
- Phase-3 of measurements after CERN accelerators stoppage

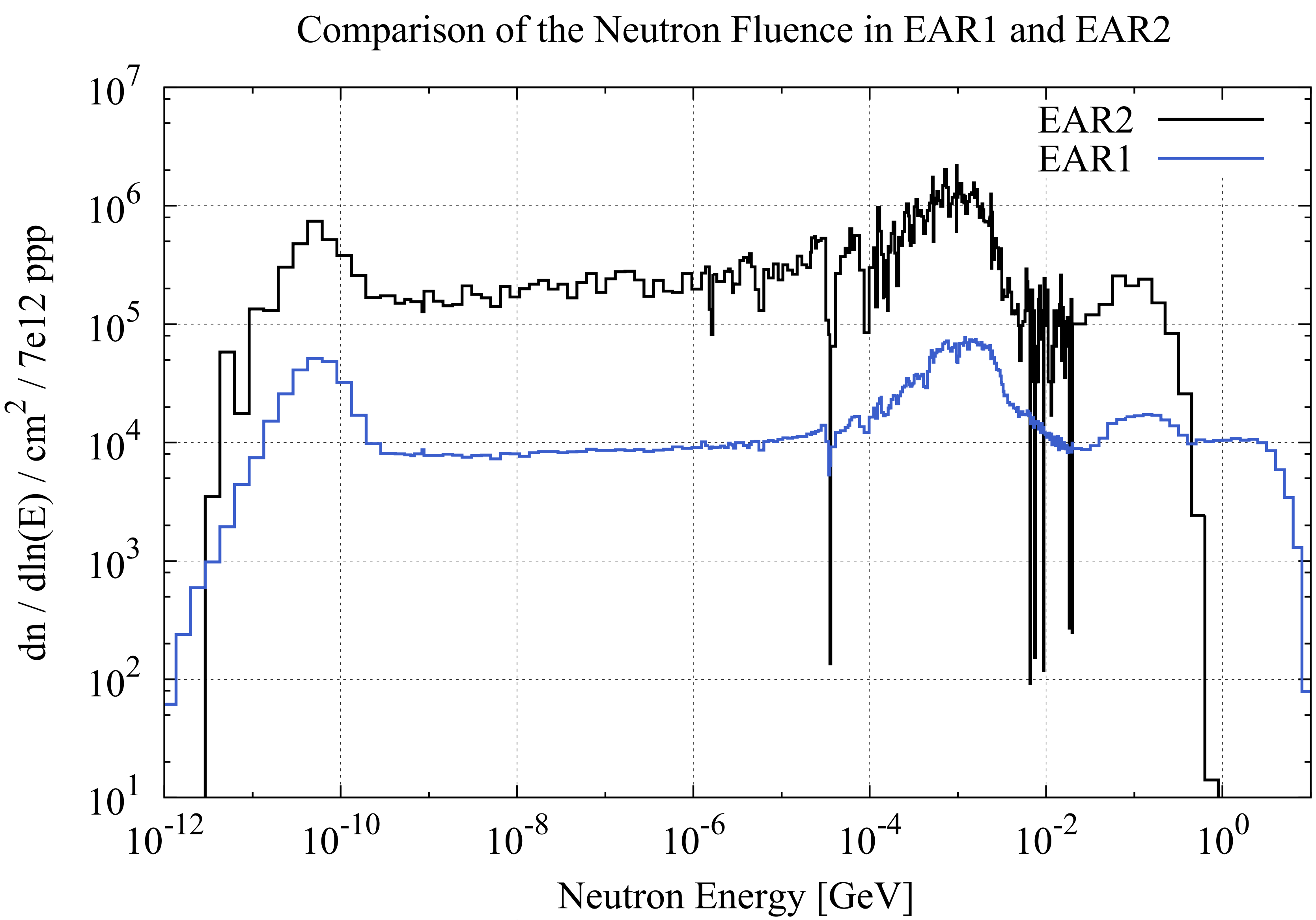
- Construction of a second experimental area: EAR-2
- Second, 20-m long vertical flight-path

EAR-2


EAR2 (@20 m from pit, above ground)
To be built
ISR
Technical gallery (@10 m from pit)
Existing hole
n_TOF target pit

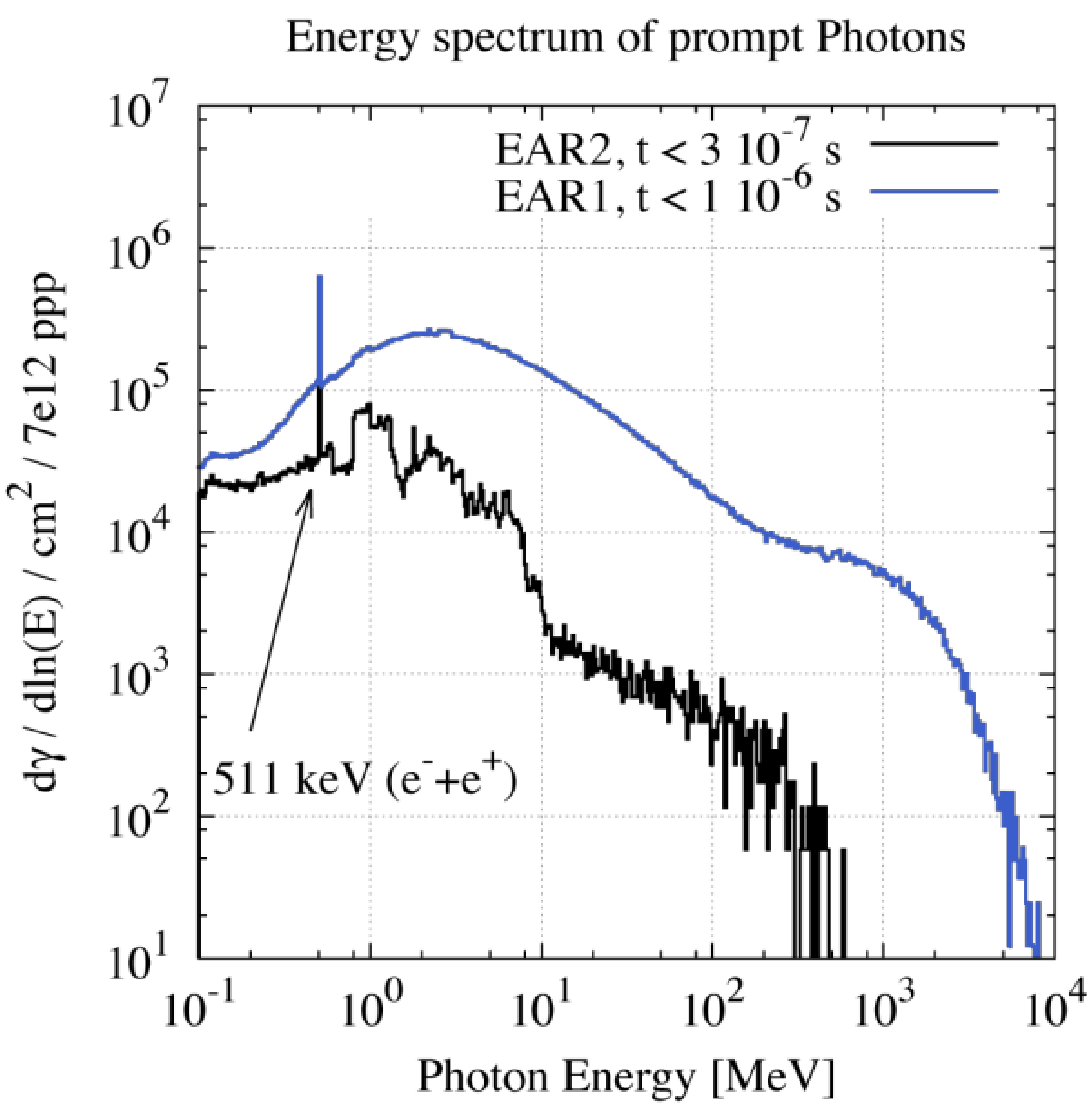

Beam Dump
EAR2
Collimator
Service gallery
Target

Performance



Instantaneous flux 25x higher
Up to 300 MeV

Performance



Reduction of prompt γ-flash

Improve measurements at higher energies

Outlook

Advantageous for samples of:

- Very low mass (< 1mg)
- Thin (n, charged particle) reactions
- Very high activity

New window to dedicated proposals:

- Increased number of measurements/year
- Basic nuclear physics, e.g. γ-ray transition prob. (PSF)

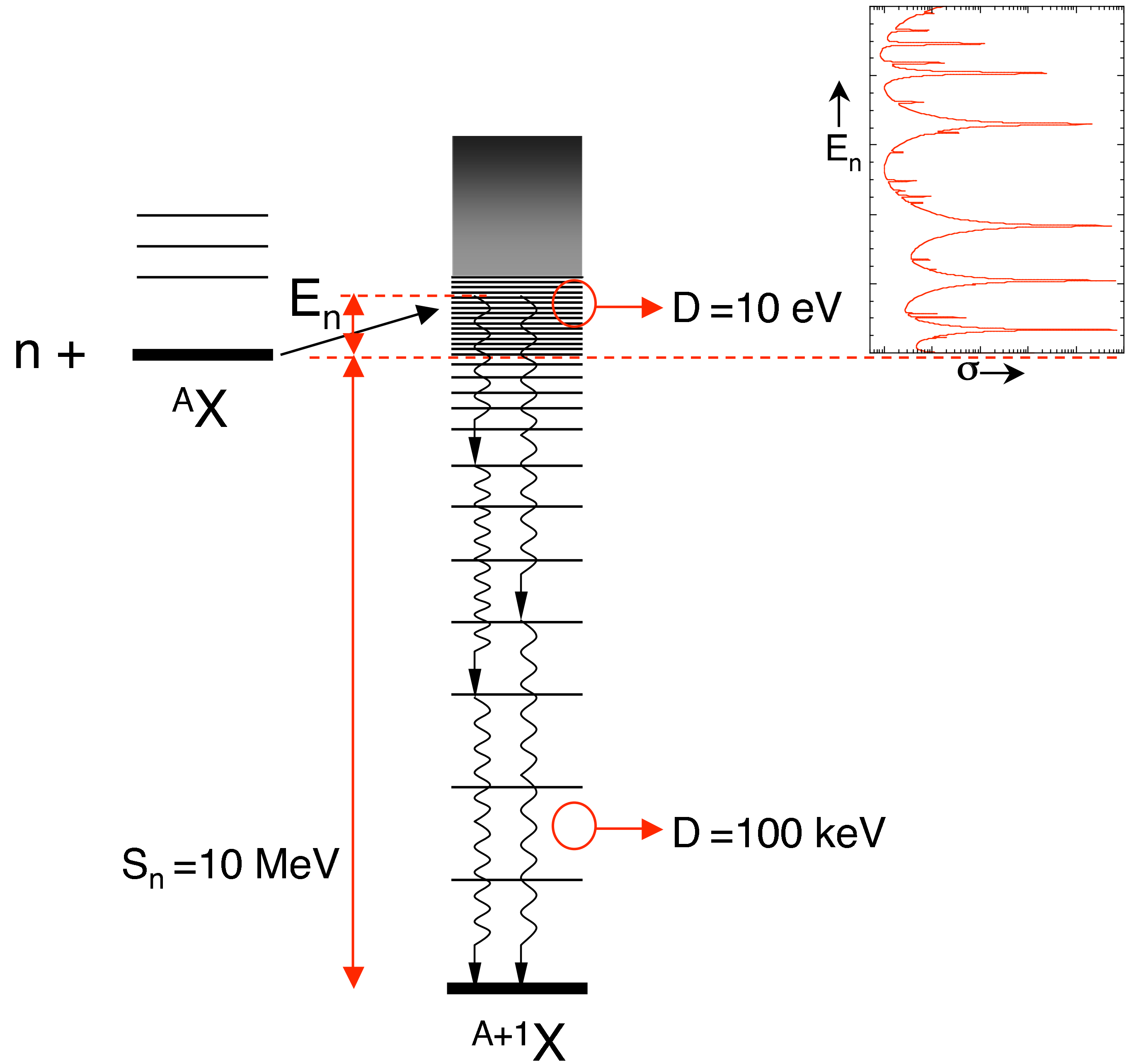
Also:

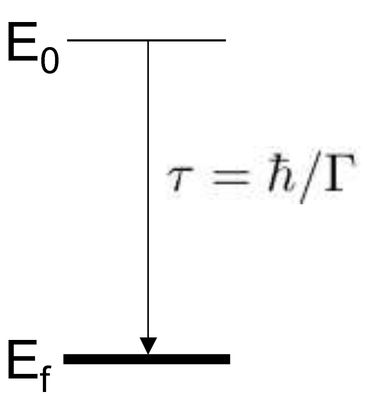
- Irradiation purposes
- Dosimetric/radiation-damage studies

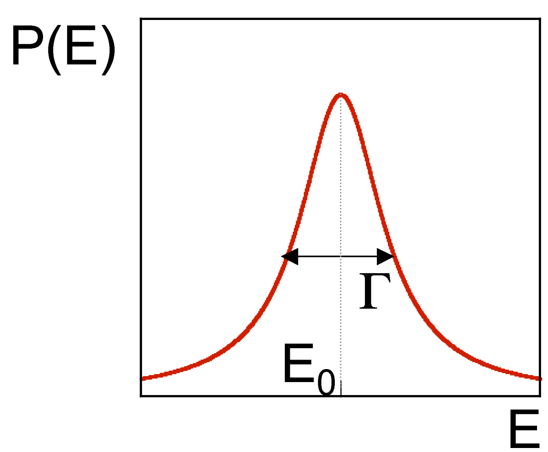
Thank you

Neutron Cross Sections

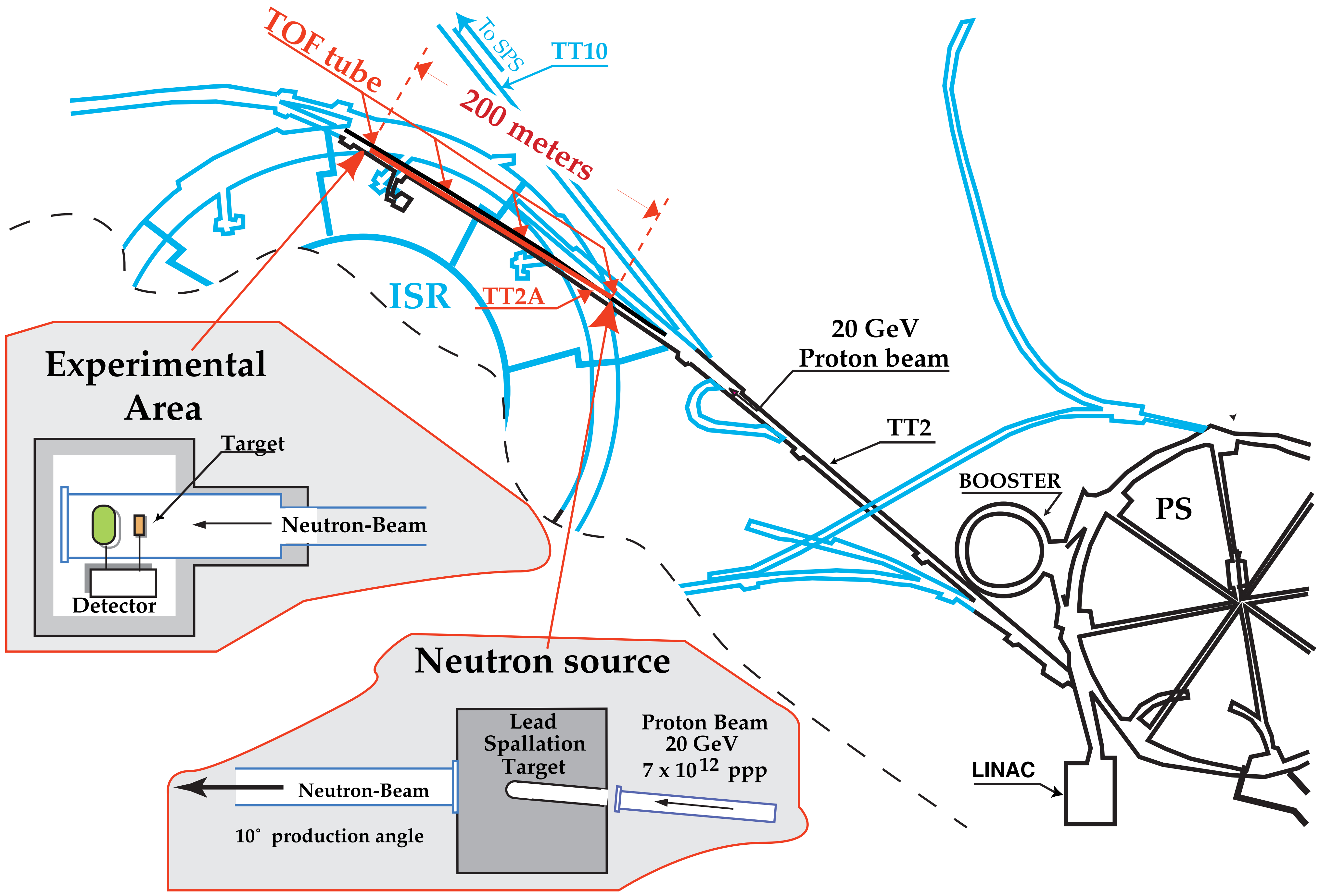
- Compound nucleus (CN) mechanism
- CN decay $h/\Gamma = 10^{-15}$ s
- Cross-section resonance described by a Breit-Wigner with Γ = 1 eV







Backup



TOF tube
To SPS
TT10
200 meters
ISR
TT2A
20 GeV
Proton beam
TT2
BOOSTER
PS
LINAC
Experimental
Area
Target
Neutron-Beam
Detector
Neutron source
Lead
Spallation
Target
Proton Beam
20 GeV
7 x 10^12 ppp
Neutron-Beam
10° production angle