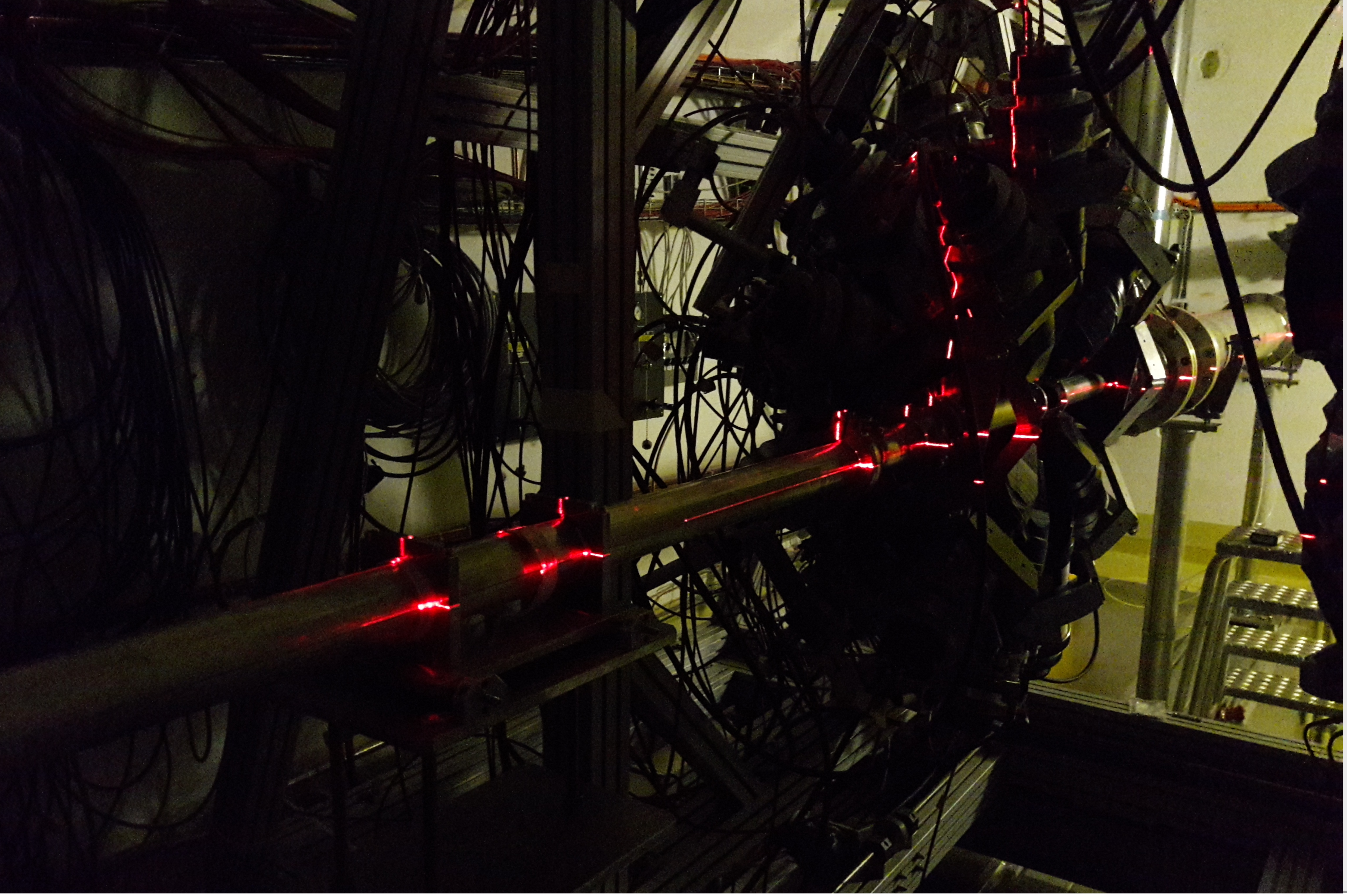
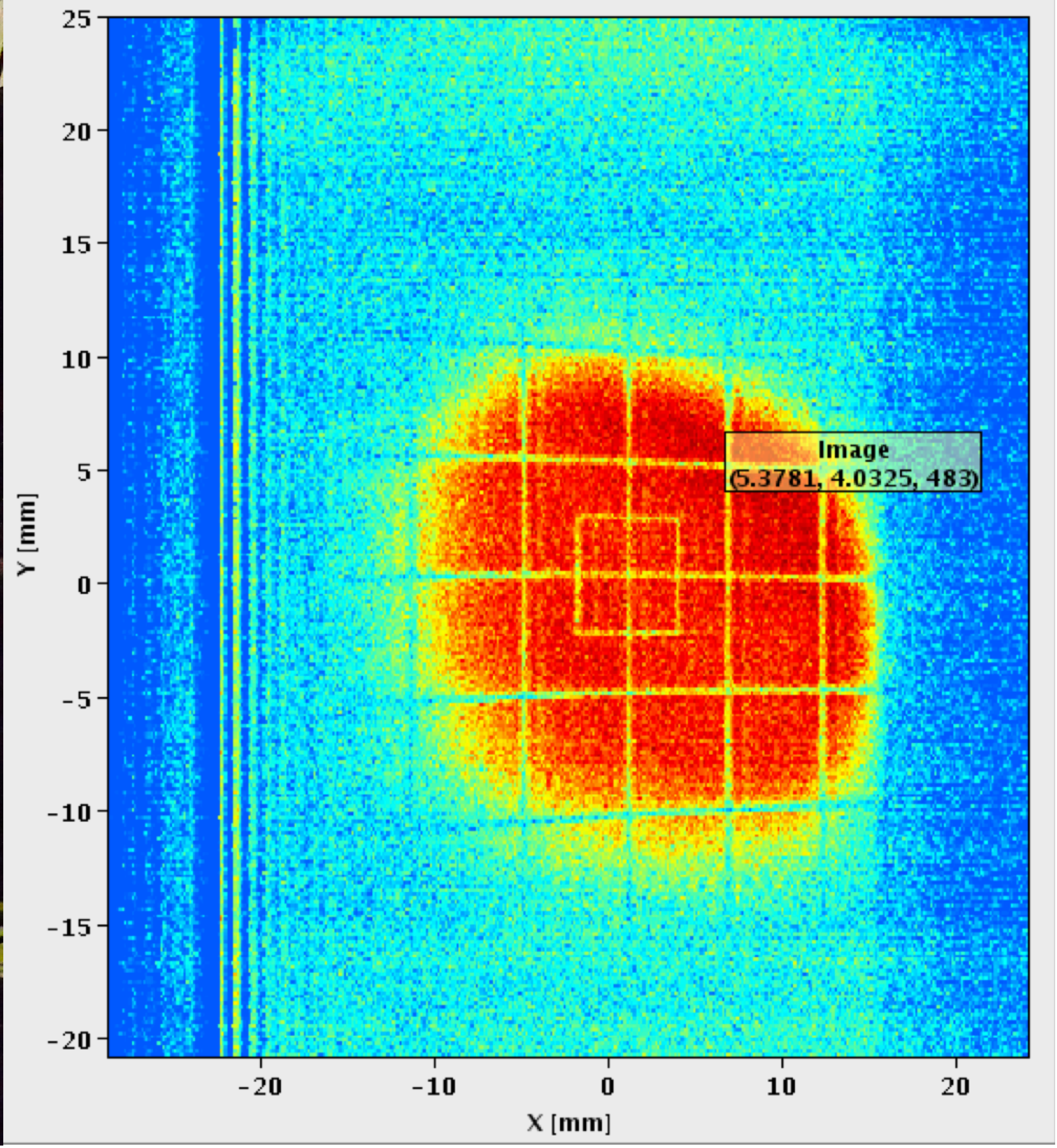




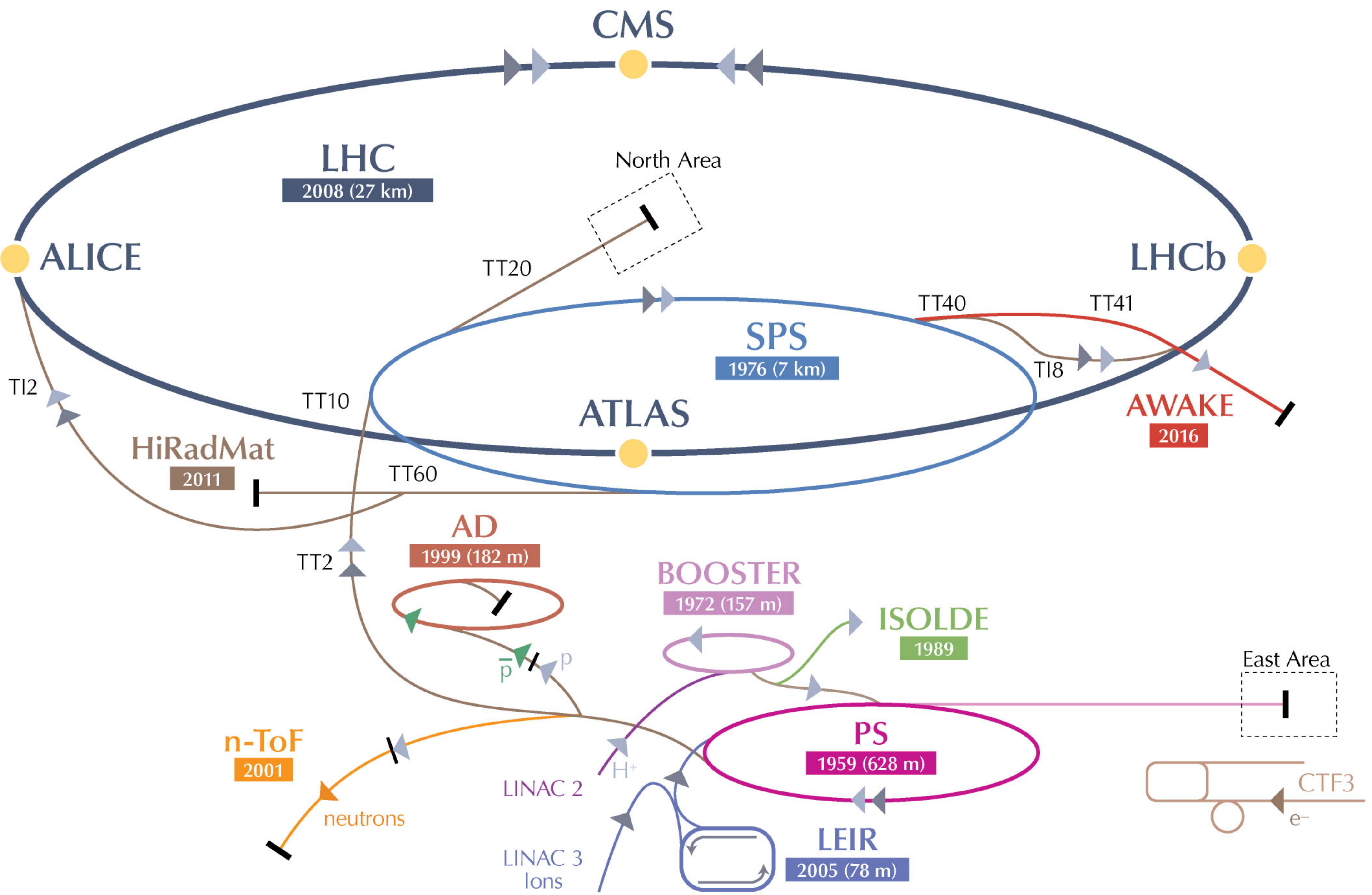
Status and perspectives of the neutron time-of-flight facility n_TOF at CERN

F. Mingrone, C. Massimi on behalf of the n_TOF Collaboration

The n_TOF facility @ CERN

CERN: European Organization for Nuclear Research (Geneva, Switzerland)

- Since 1954
- Various accelerator complex
- More than LHC: injectors “feeding” minor experiments



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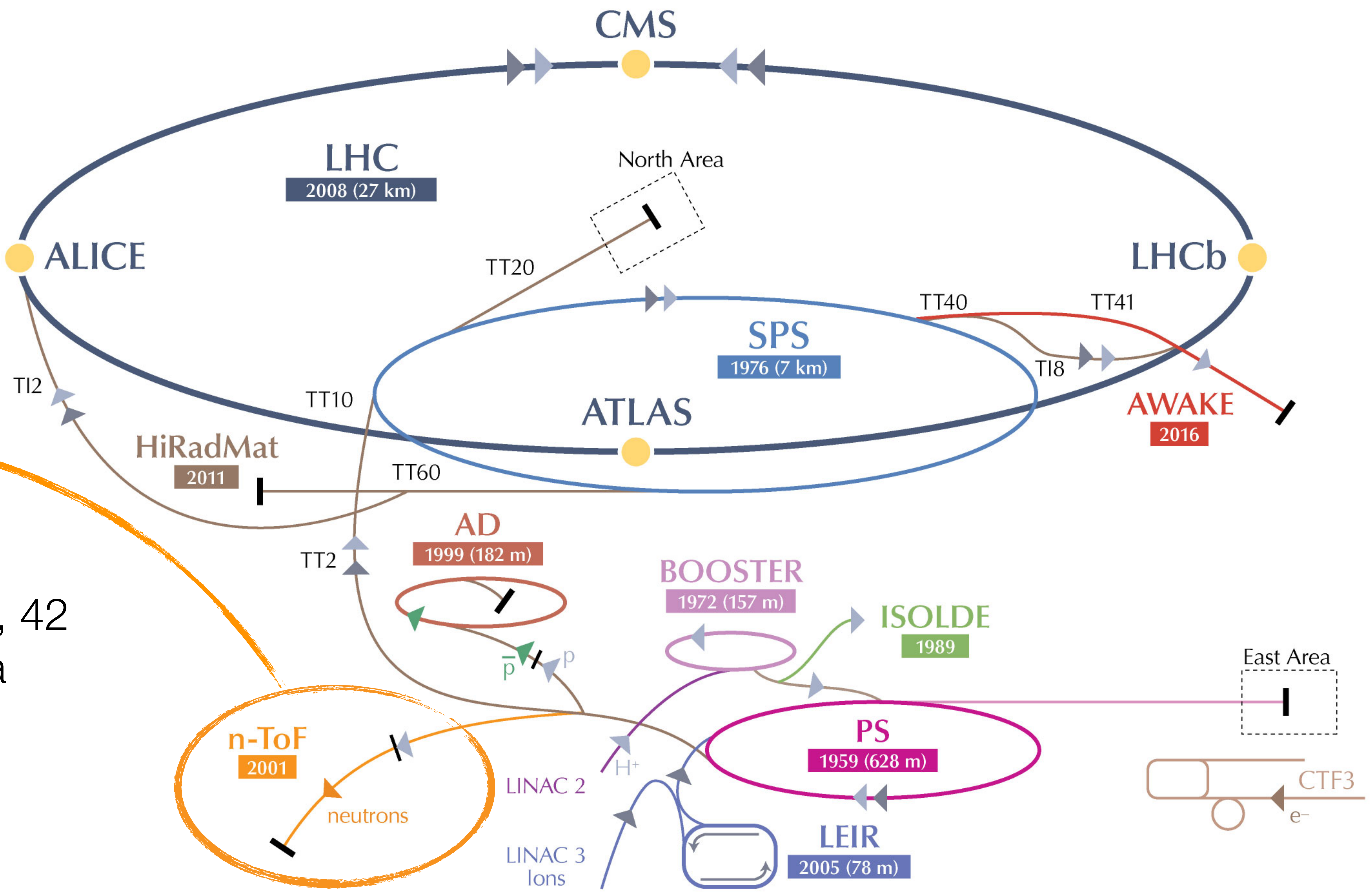
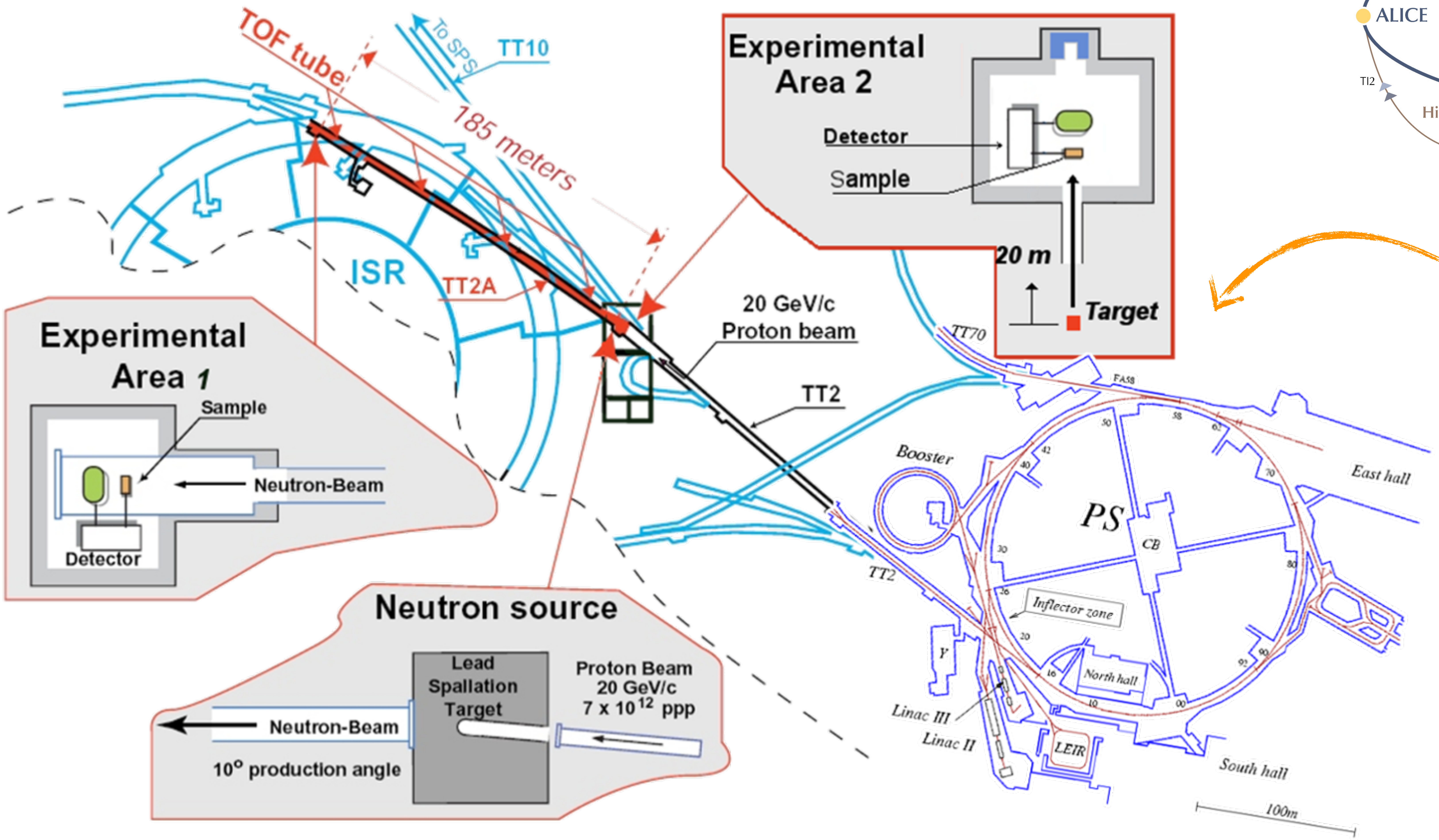
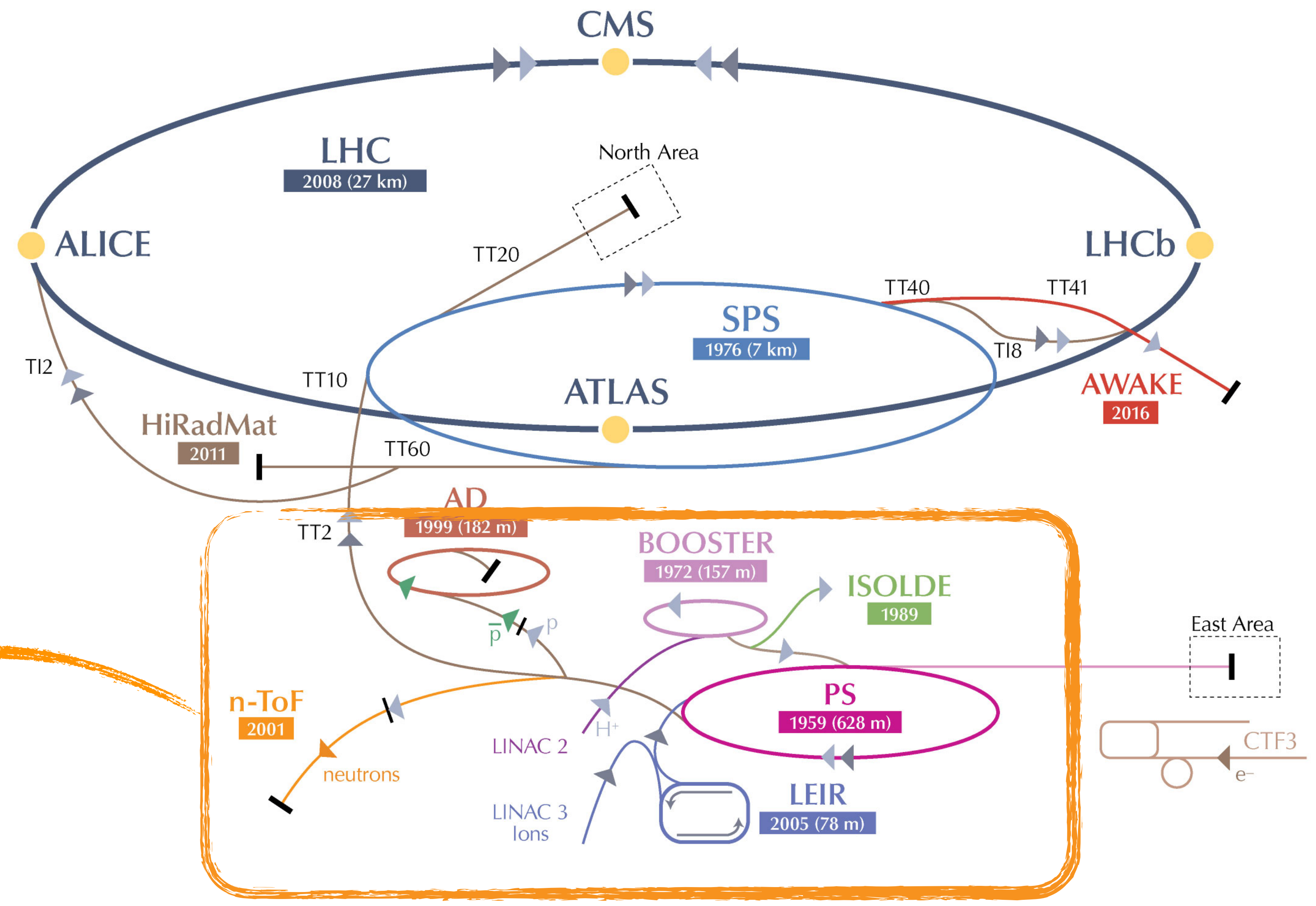


n_TOF: neutron Time-Of-Flight facility

- International Collaboration – 117 researchers, 42 institutes from EU, Russia, India and Australia
- Neutron source
- Neutron energy spectrometer with the tof technique

The n_TOF beam: PS proton bunch





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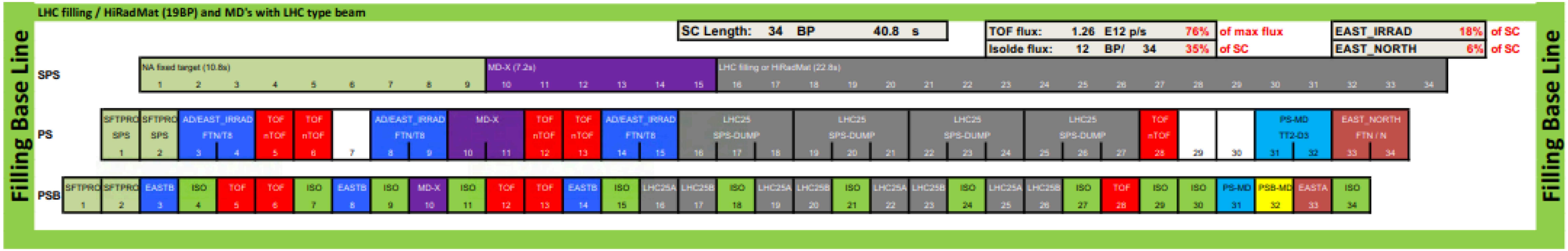
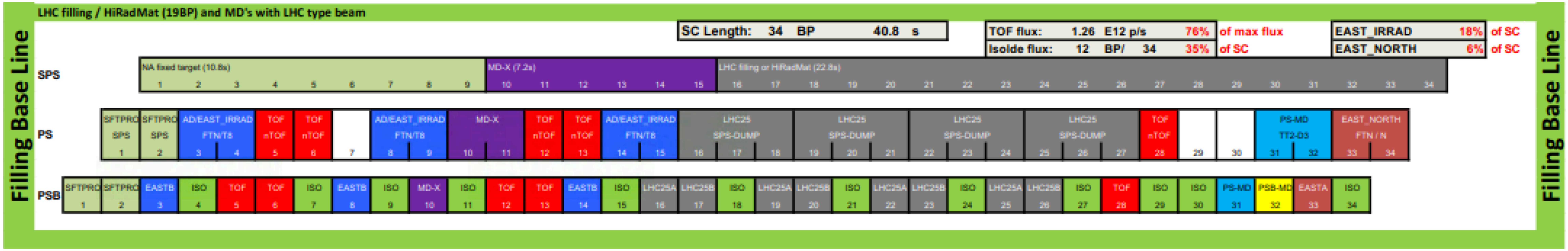


2 type of n_TOF beam:

- dedicated (TOF cycle)
- parasitic (EAST cycle)

The n_TOF beam: PS proton bunch

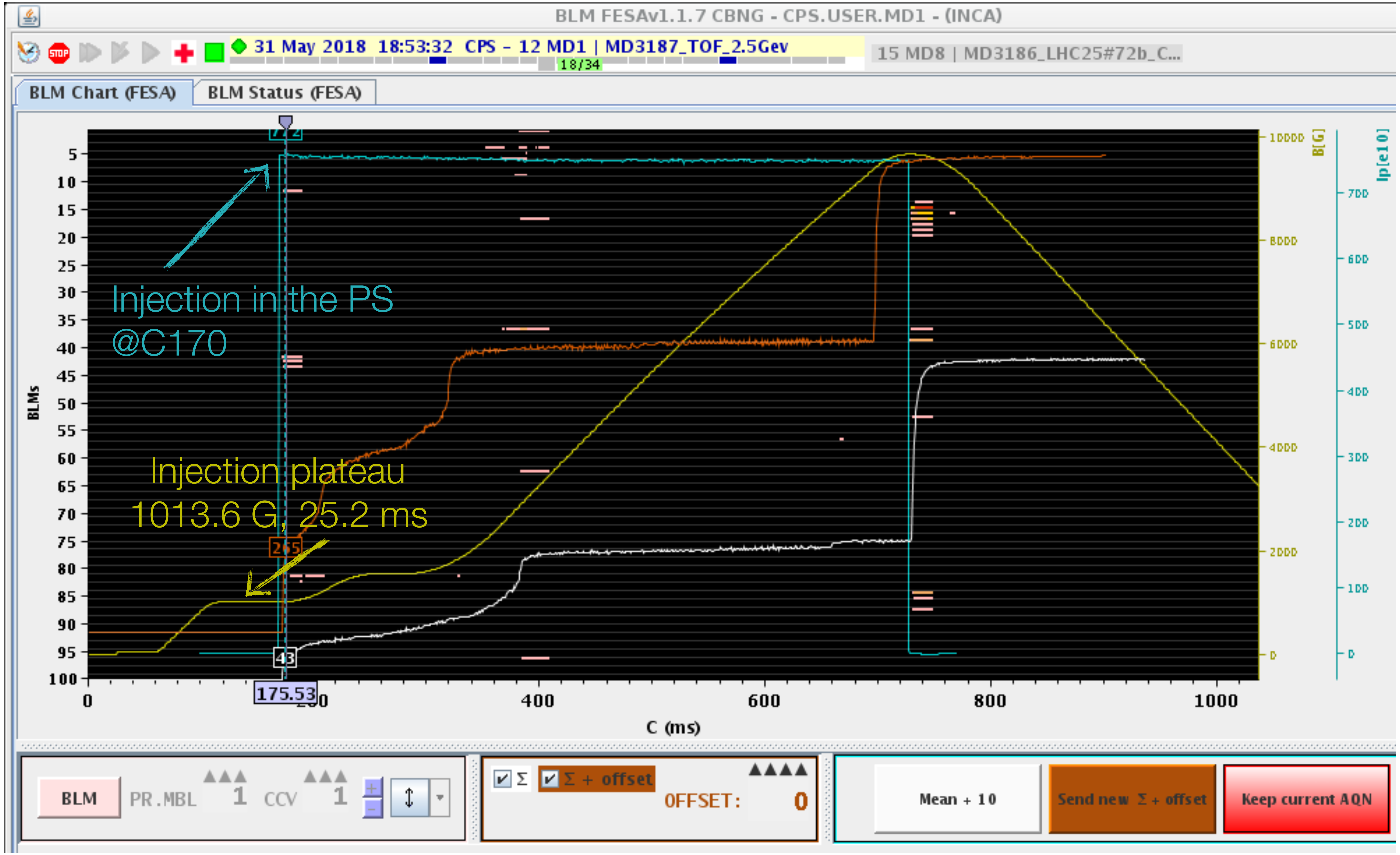


2 type of n_TOF beam:

- dedicated (TOF cycle)
- parasitic (EAST cycle)

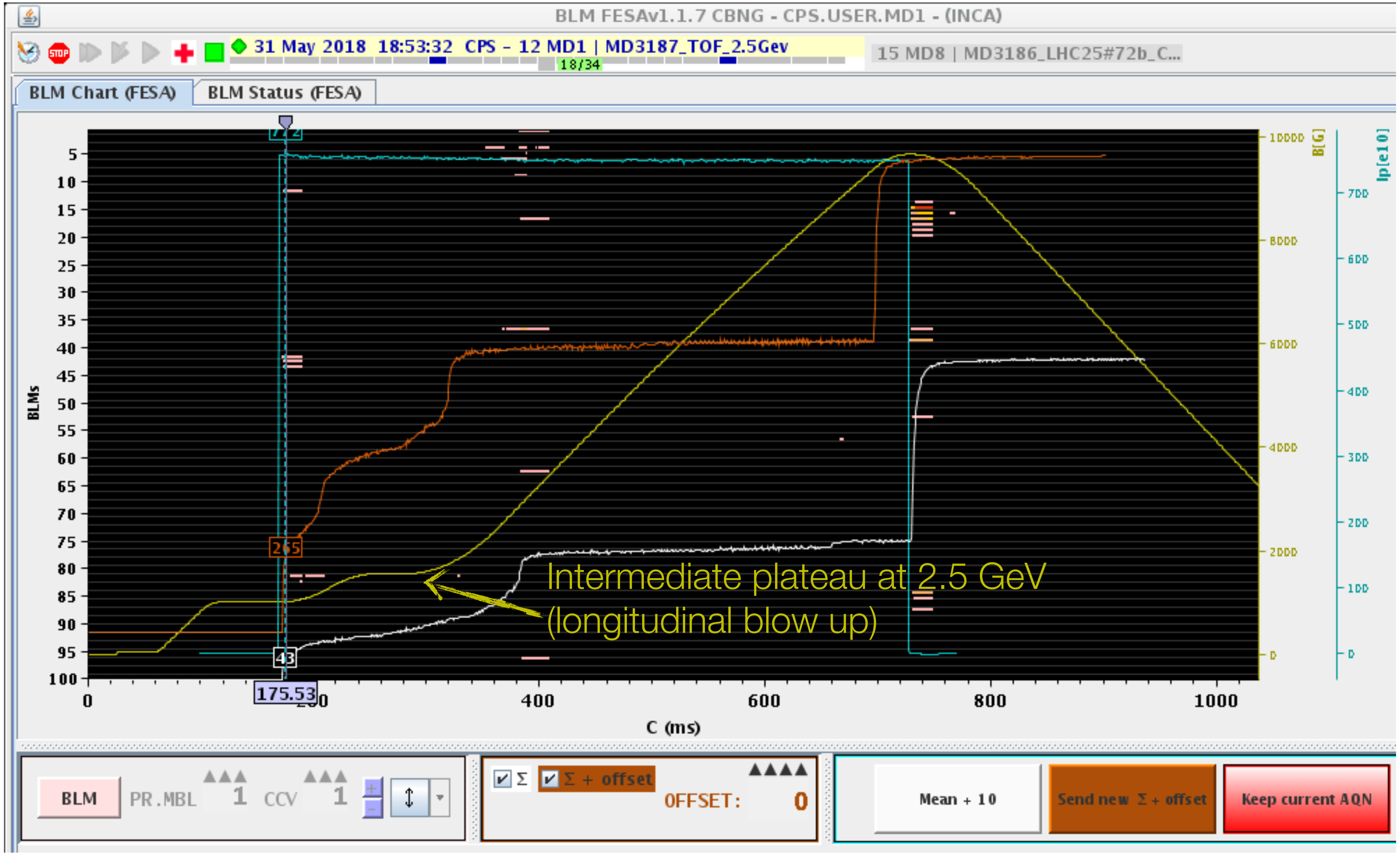
	IN - Booster Ring 2	EXT - Dedicated	EXT - Parasitic
Kinetic Energy (GeV)	1.387	19.403	
Momentum (GeV/c)	**2.128**	**20.32**	
RF Harmonic	8	8	
Number of Bunches	1	1	
Intensity per bunch (E10 p)	**up to 850**	**up to 850**	**up to 300**
Bunch Length [4σ] (ns)	**210**	**25**	**25**
Momentum spread Δp/p [1σ]	1.7E-03	7.85 E-4 @C690	3 E-01 @C690
εL (matched area) (eV s)	1.75	3.22 @C690	0.55 @C690
εH [1σ, normalized] (π mm mrad)	11	21.6 @C690	7.0 @C690
εV [1σ, normalized] (π mm mrad)	9	7.7 @C690	7.0 @C690

The n_TOF beam: PS proton bunch



Event	Timing (ms)
Injection	170

The n_TOF beam: PS proton bunch

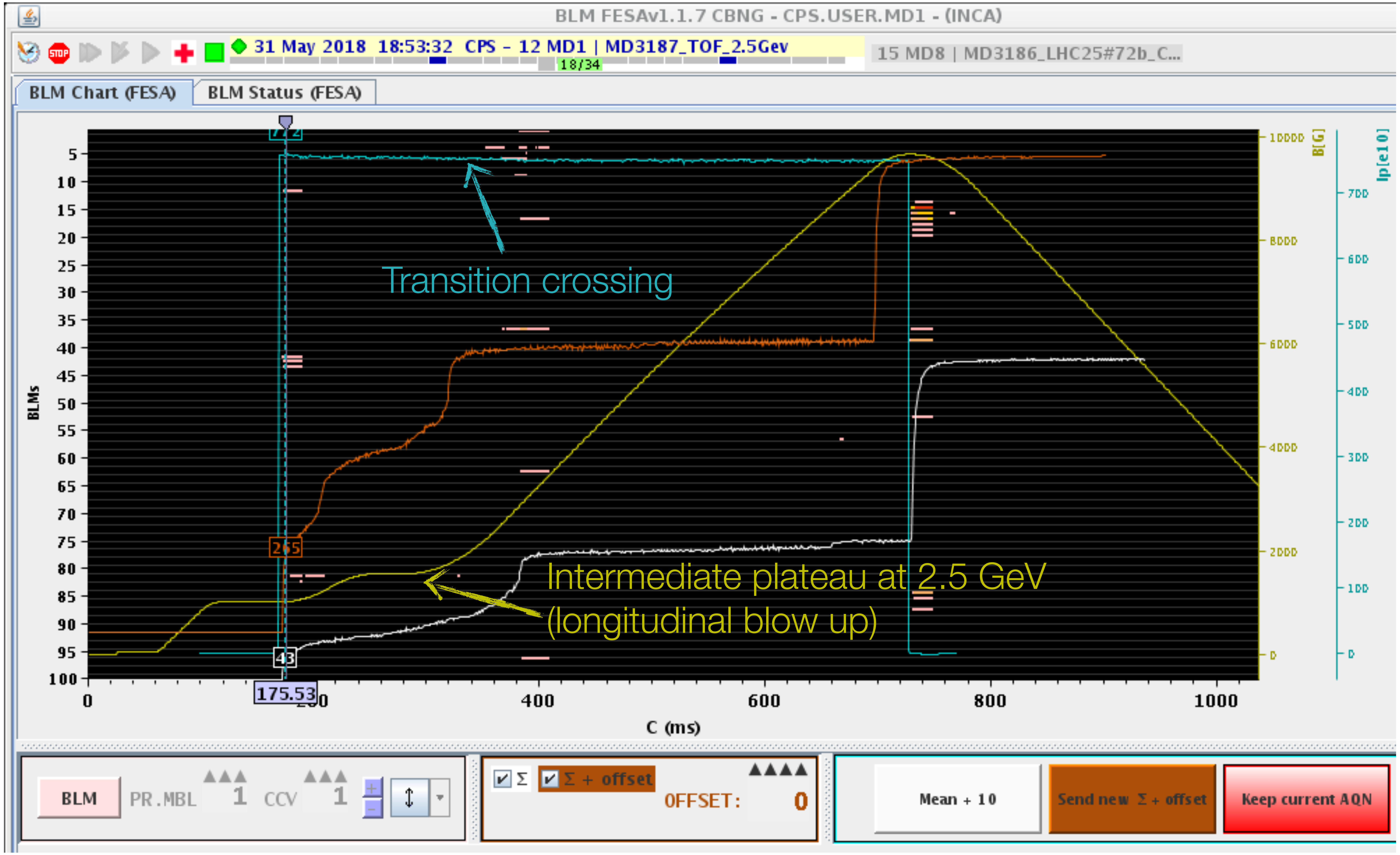


Event	Timing (ms)
Injection	170

Longitudinal blow-up

- immediately after the injection
- increases the momentum spread of the particle within the bunch through (200 MHz) RF modulation
- eases transition crossing
- improves bunch rotation

The n_TOF beam: PS proton bunch

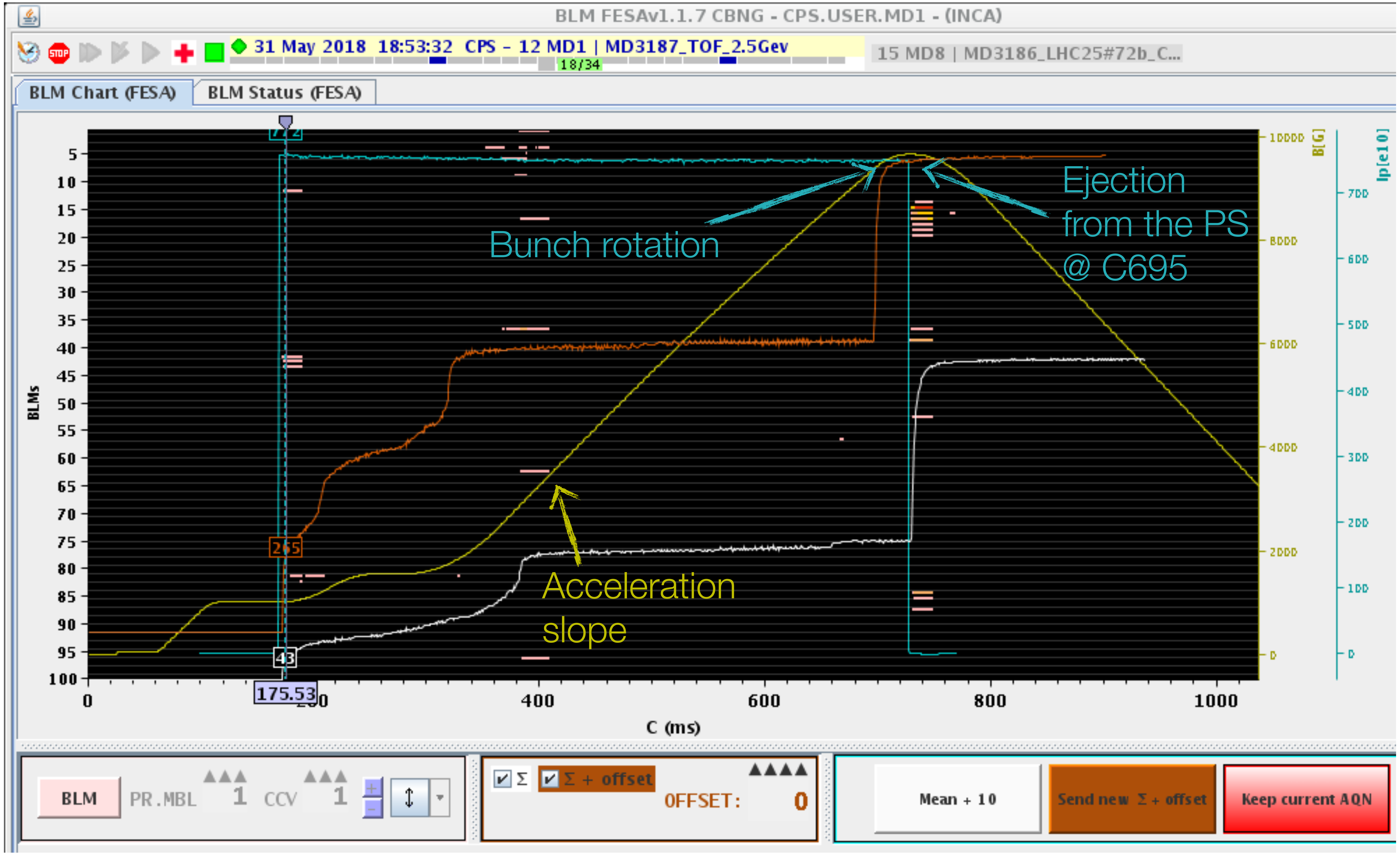


Event	Timing (ms)
Injection	170
Transition	316

Longitudinal blow-up

- immediately after the injection
- increases the momentum spread of the particle within the bunch through (200 MHz) RF modulation
- eases transition crossing
- improves bunch rotation

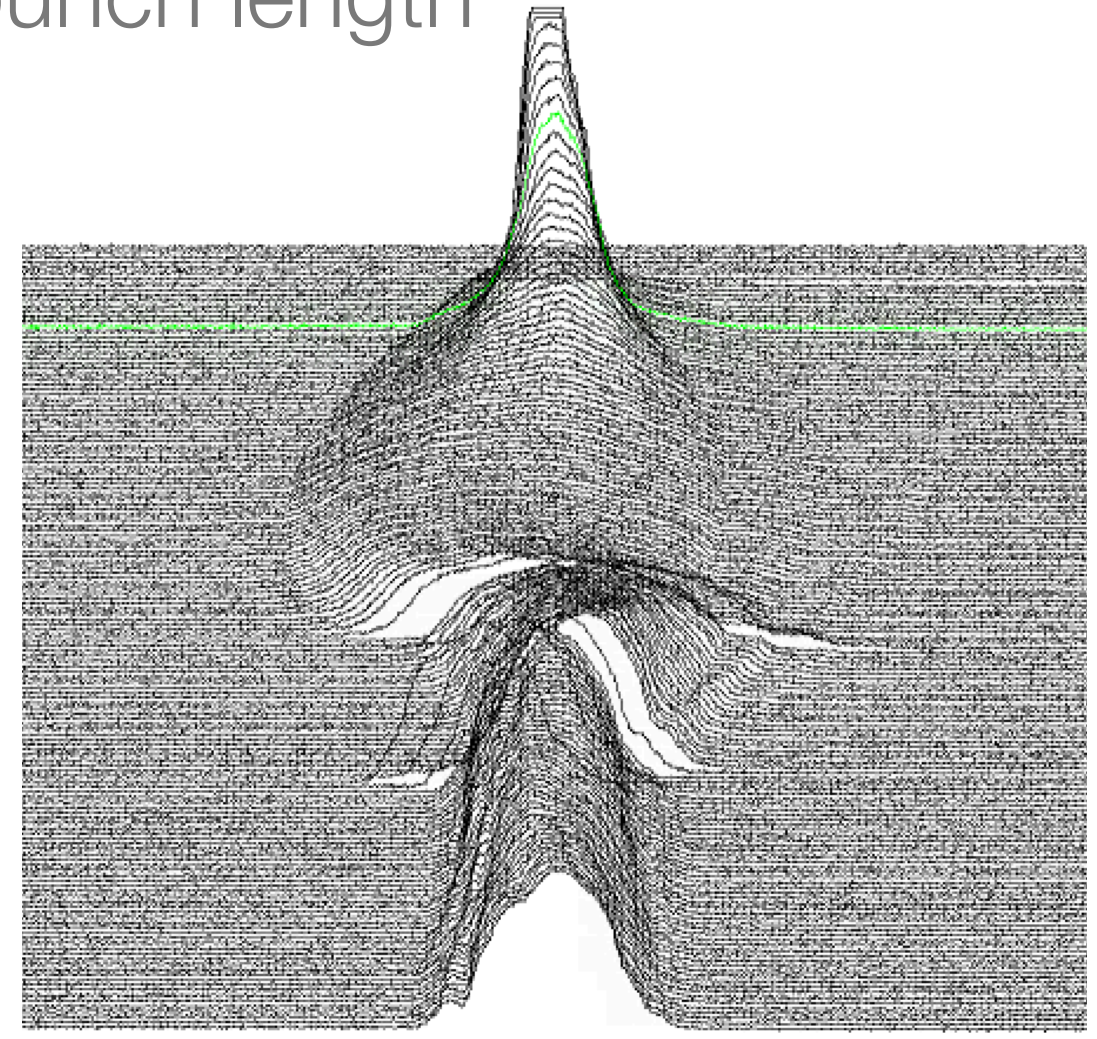
The n_TOF beam: PS proton bunch



Event	Timing (ms)
Injection	170
Transition	316
Bunch Rotation	692.96
Ejection	695

Bunch rotation

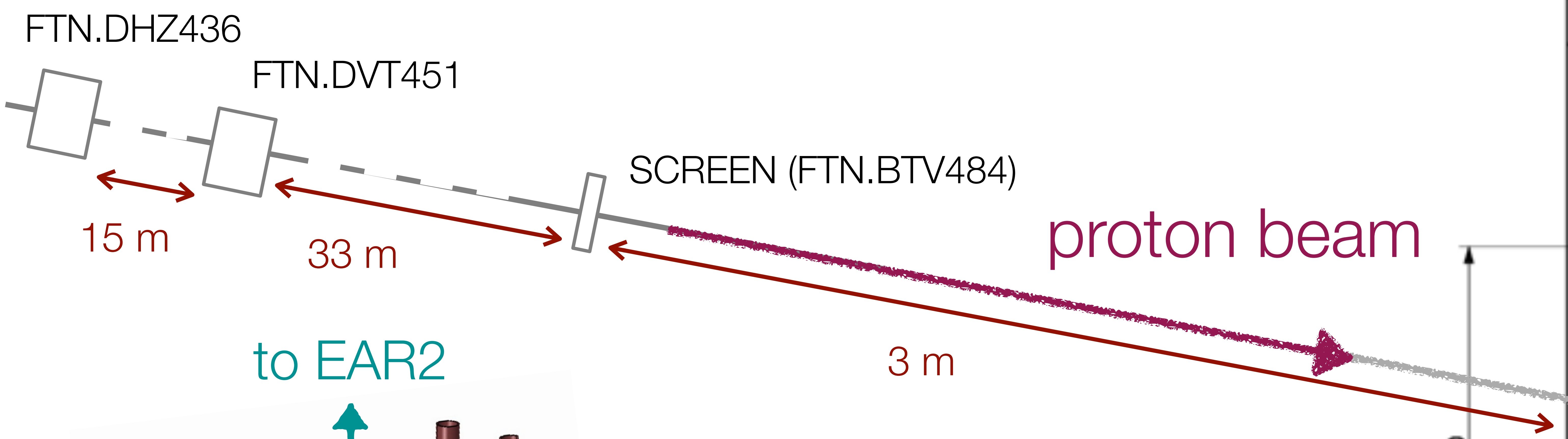
- immediately before the extraction
- allows to shorten the bunch length

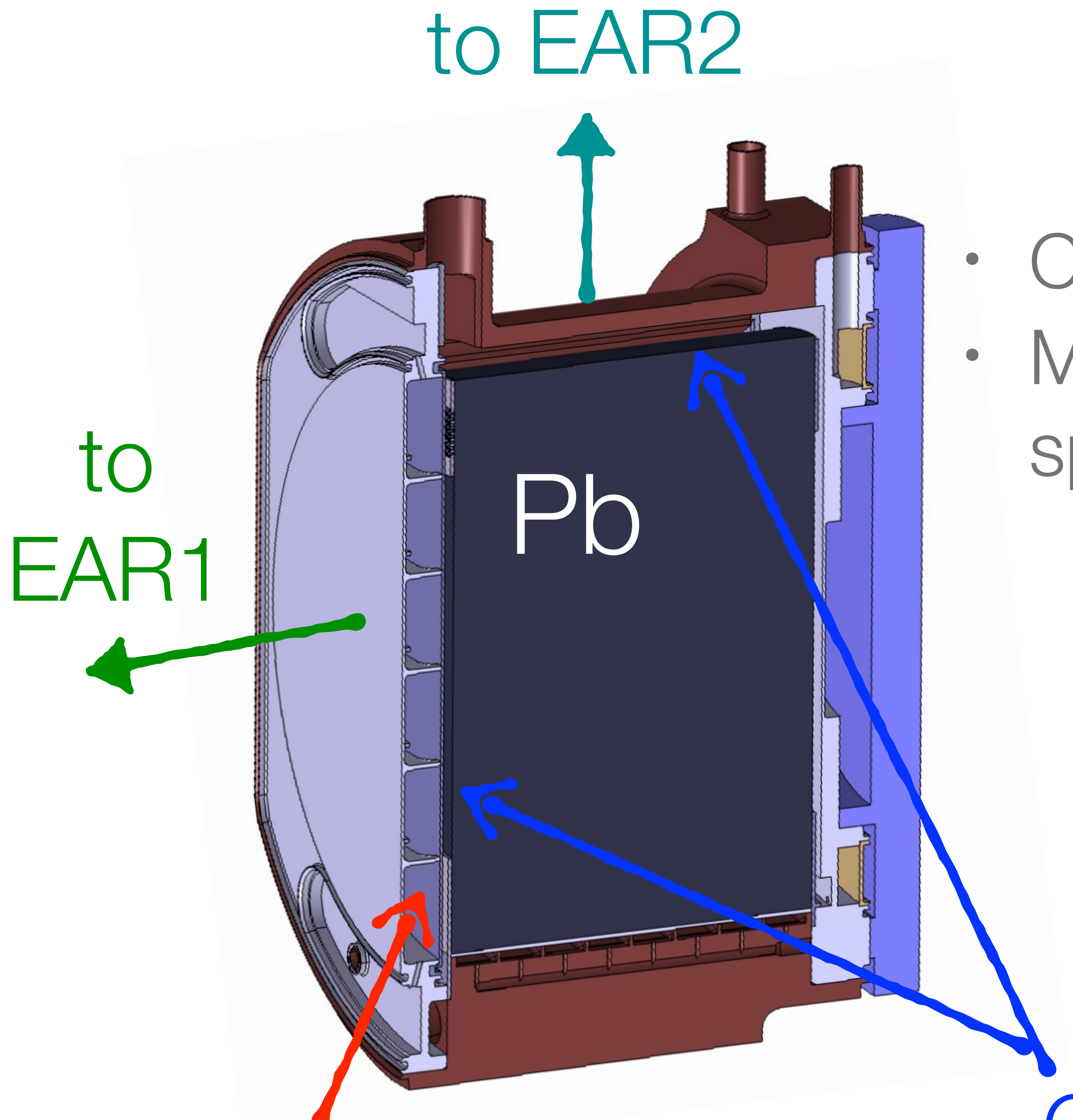


The n_TOF beam: spallation target

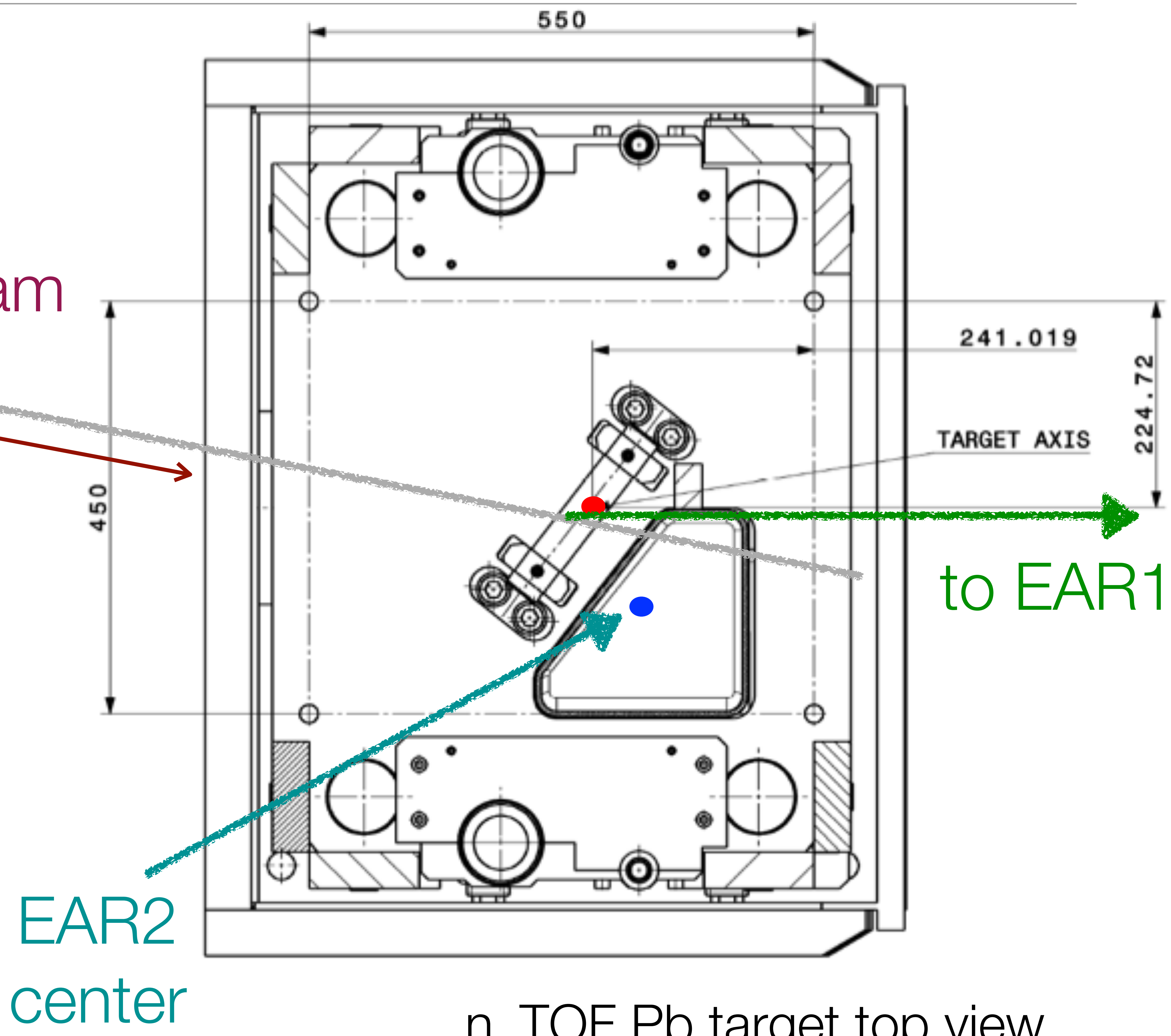
n_TOF Pb target top view

The n_TOF beam: spallation target





- Current of ~ μA
- Moderator layer of 5 cm (energy spectrum from meV to GeV):
  - **EAR1**: 1 cm of normal water + 4 cm ^{10}B-water (H_2O + 1.28% H_3BO_3)
  - **EAR2**: 5 cm of normal water from the cooling circuit

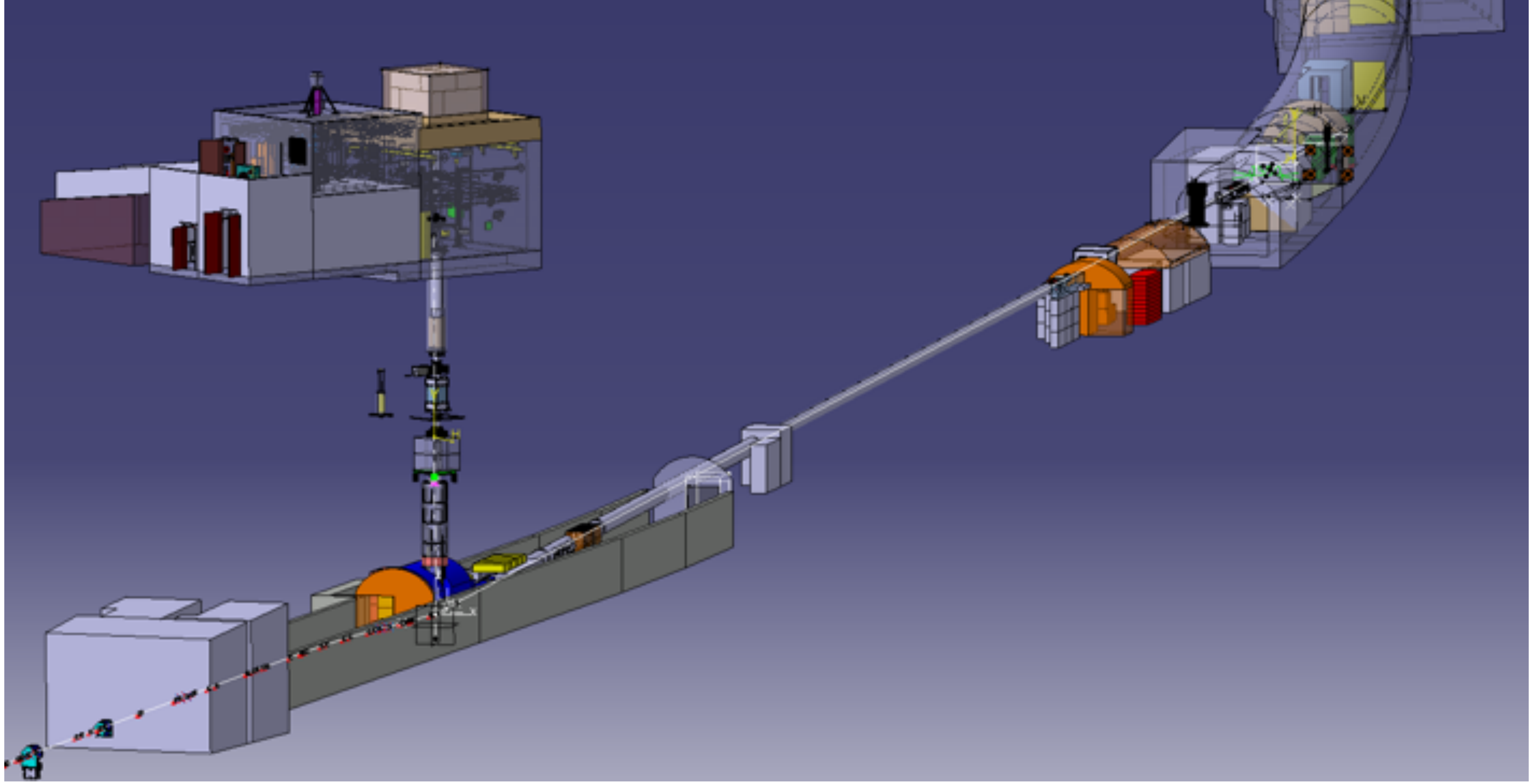


n_TOF Pb target top view

The n_TOF beam: neutron beam lines

2 beam lines (185 and 20 m)

2 experimental areas (EAR1 and EAR2), both Class-A lab



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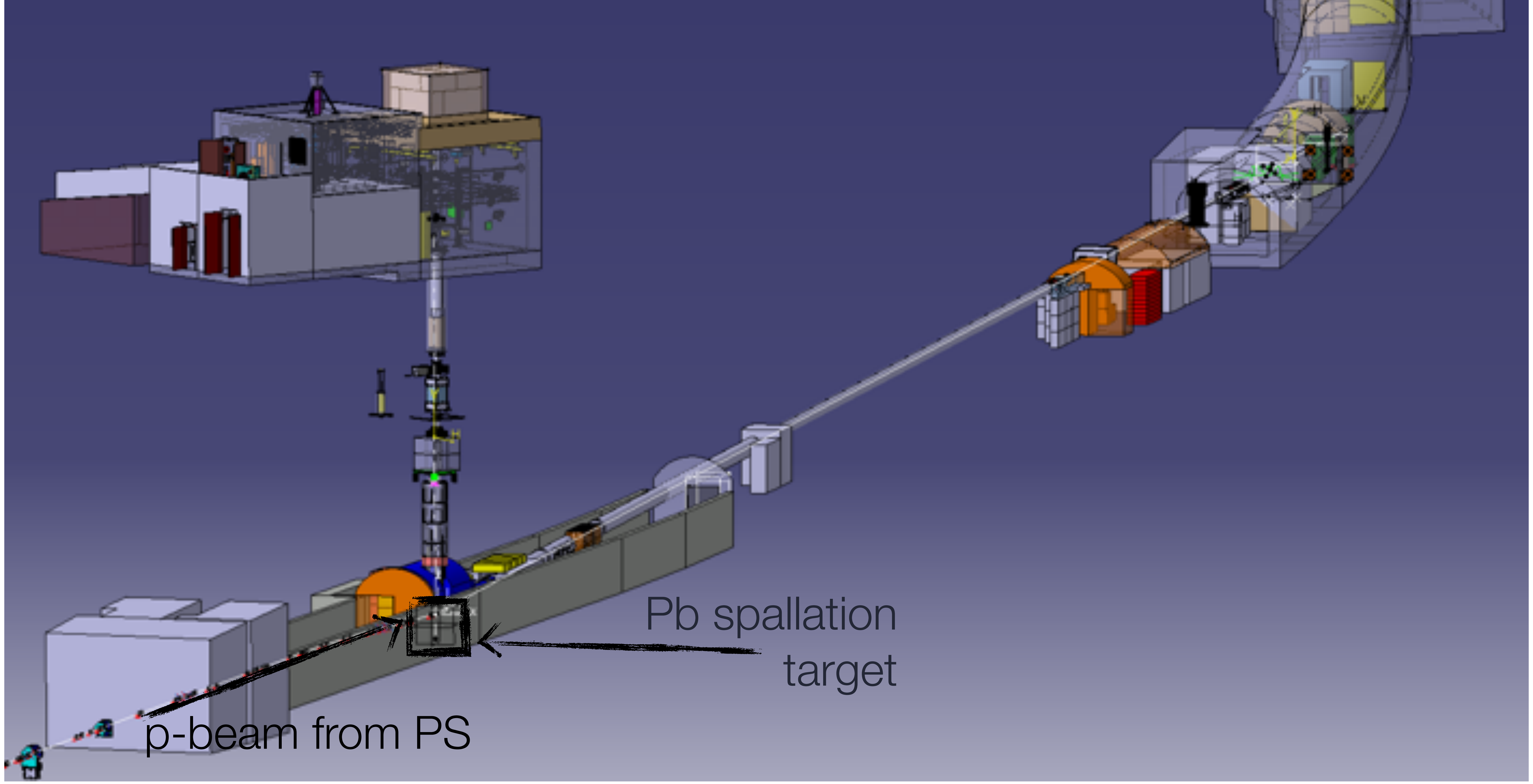

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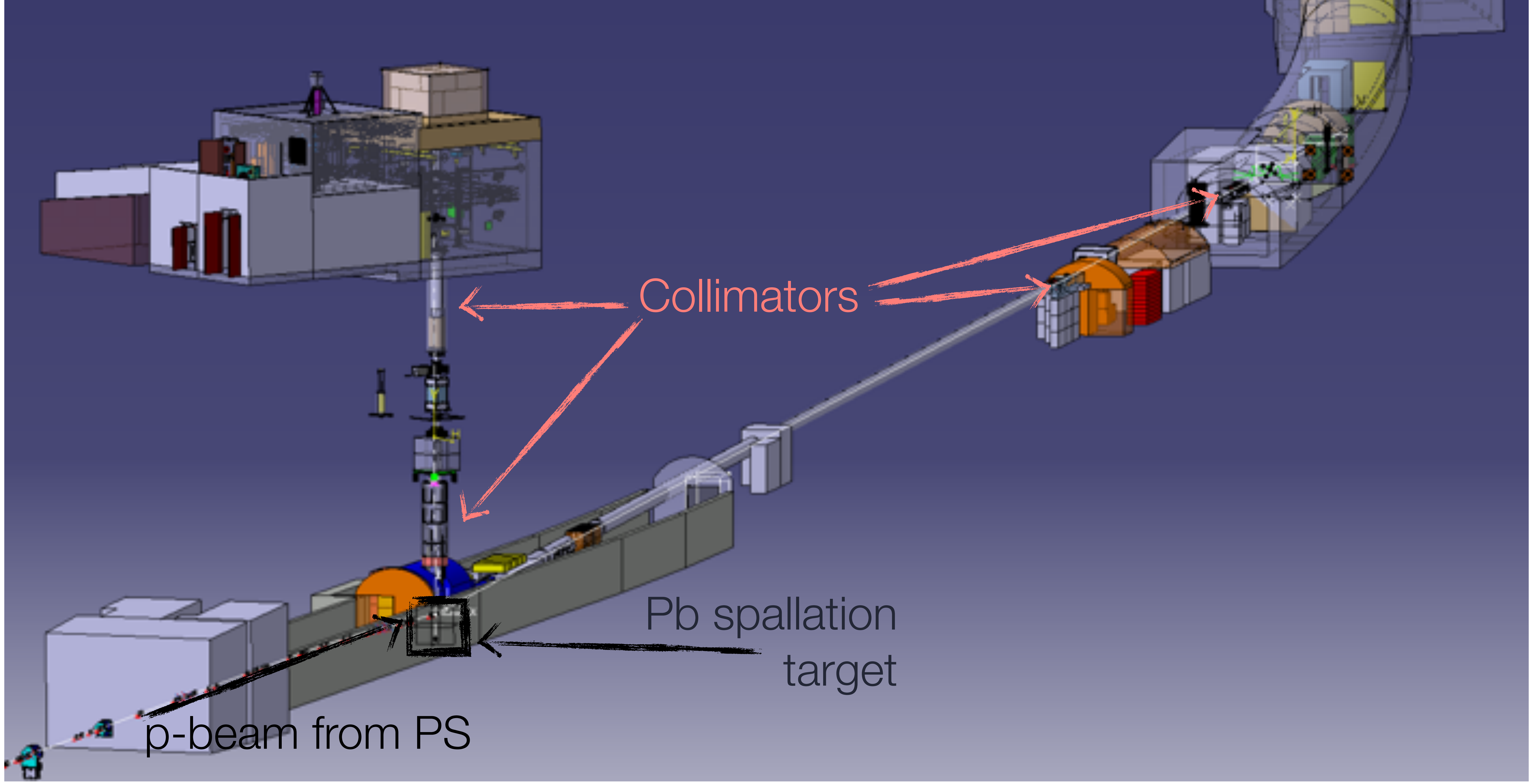

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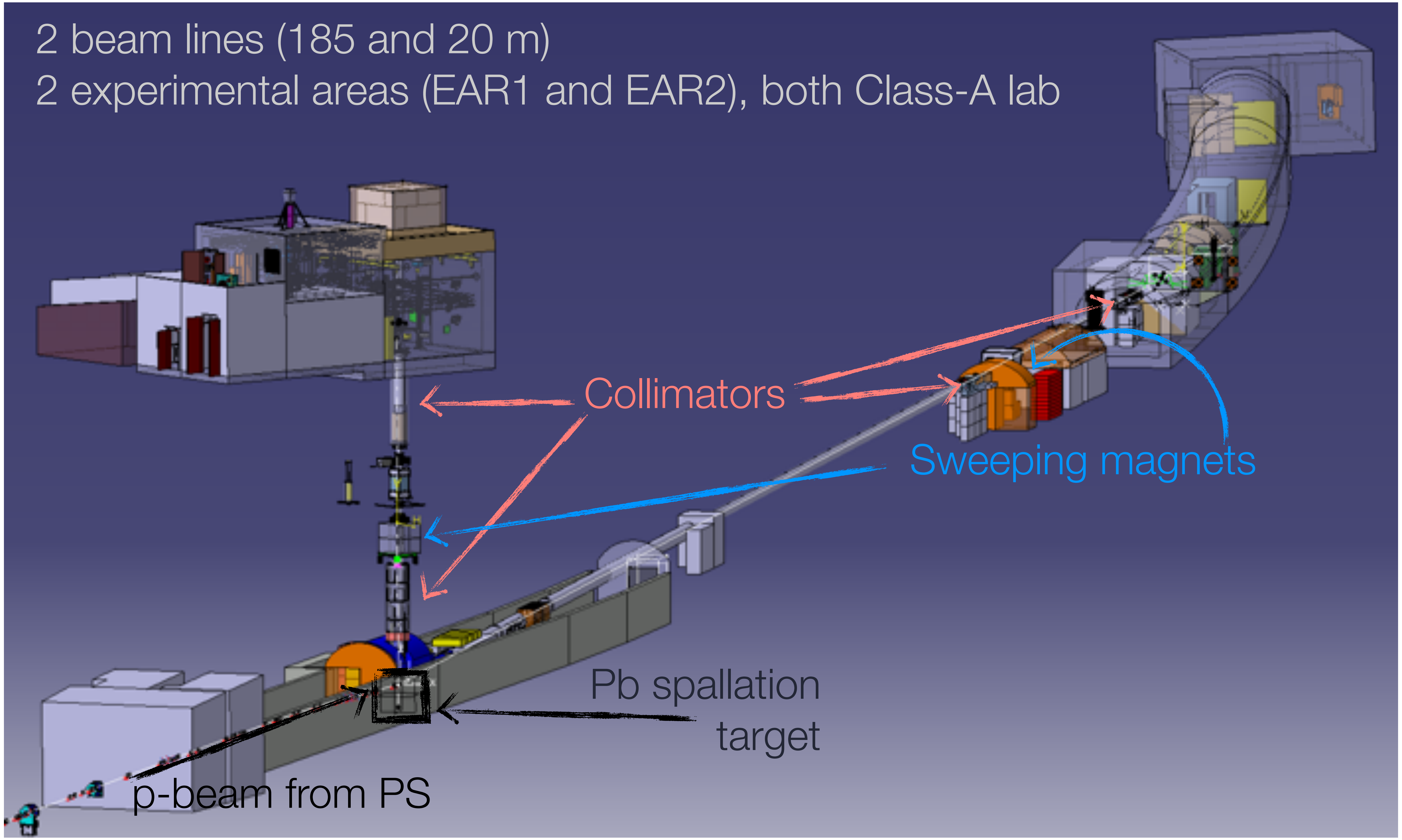

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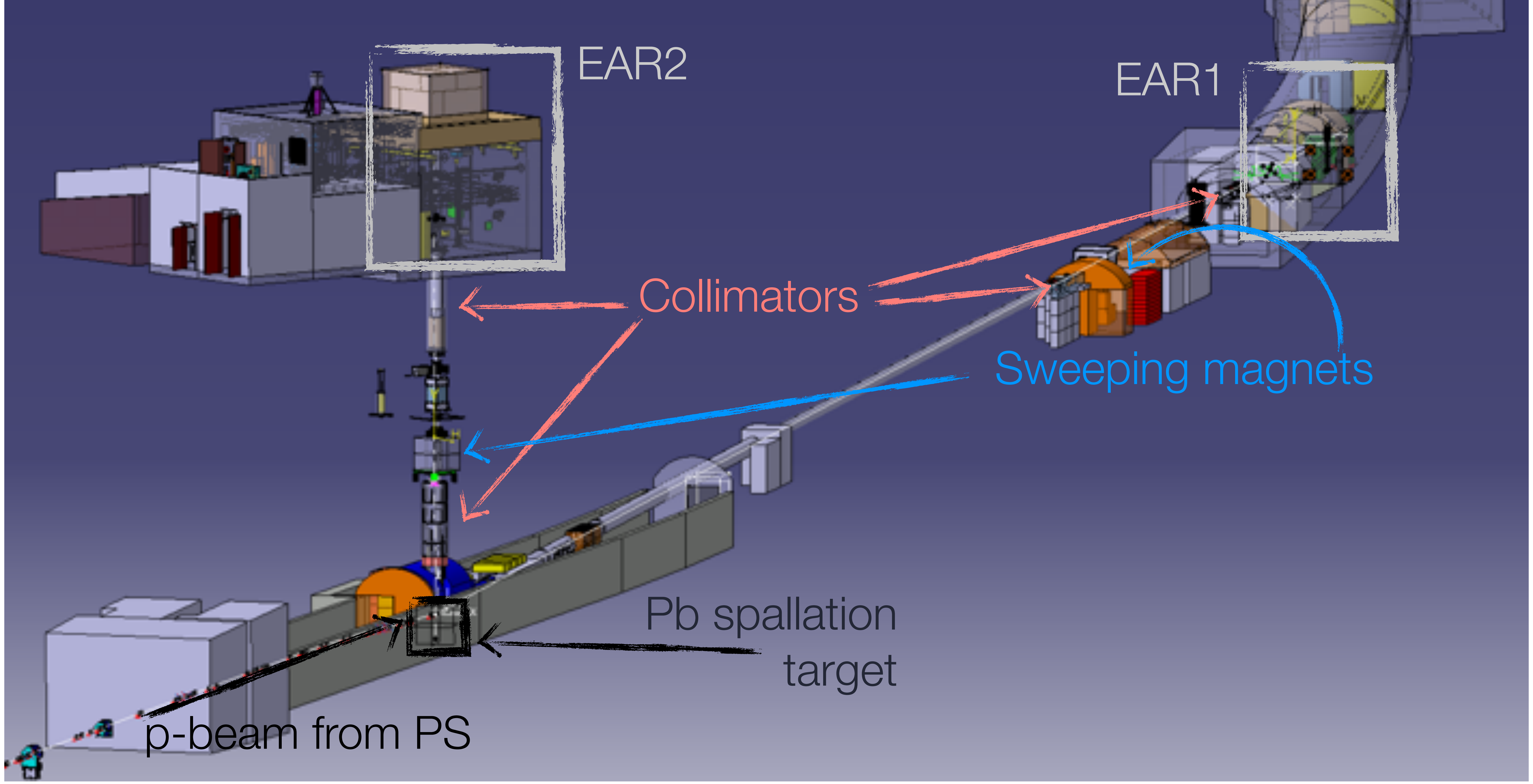

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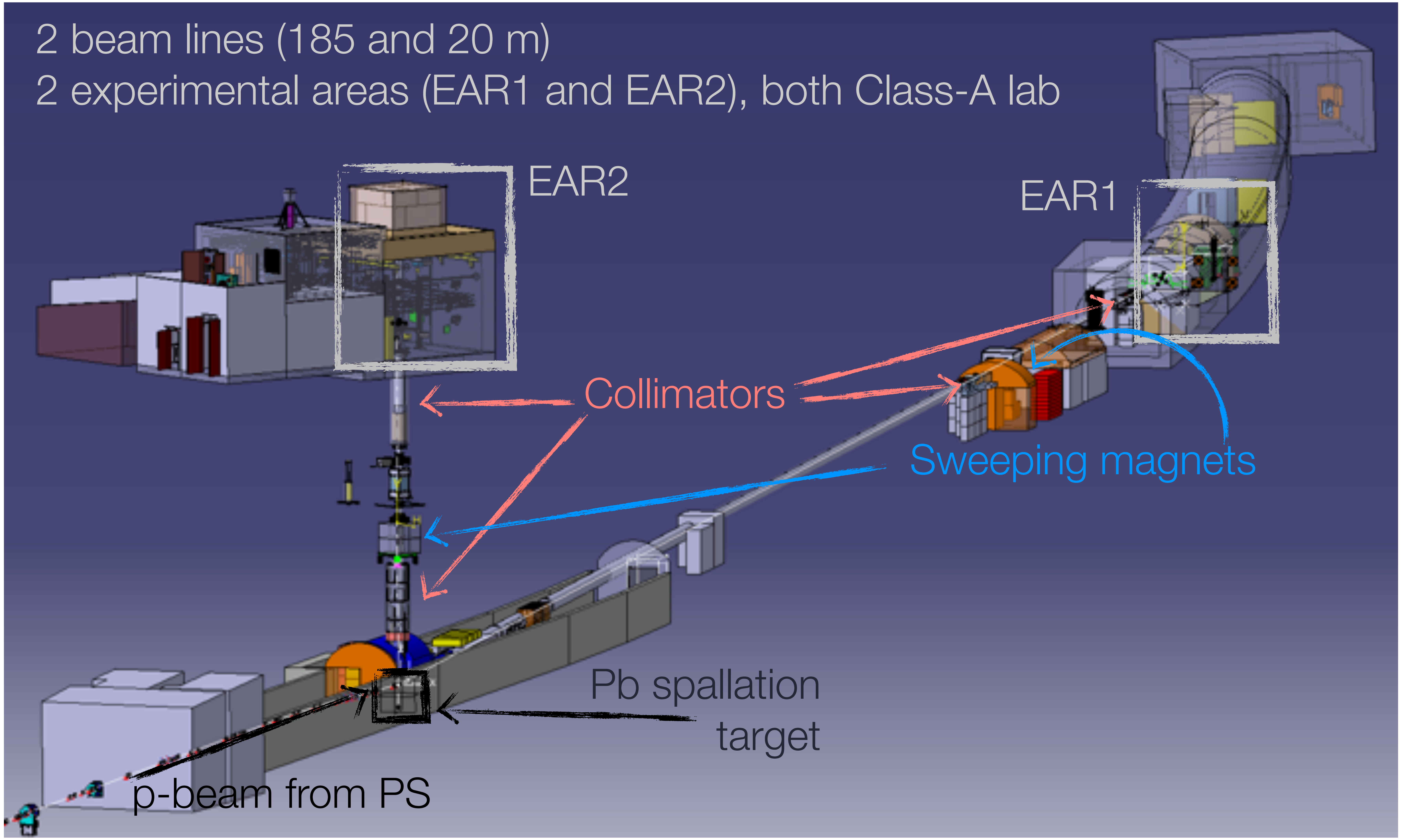

Some figures

	EAR1	EAR2
Wide energy range	thermal to 1 GeV	thermal to 300 MeV
High instantaneous neutron flux	2 x 10^5 n/cm^2/pulse	3 x 10^6 n/cm^2/pulse
Low repetition rate	< 0.8 Hz (1 pulse/2.4 s max)	
High energy resolution	$\Delta E/E=10^{-4}$ (@10 keV)	$\Delta E/E=10^{-3}$ (@10 keV)

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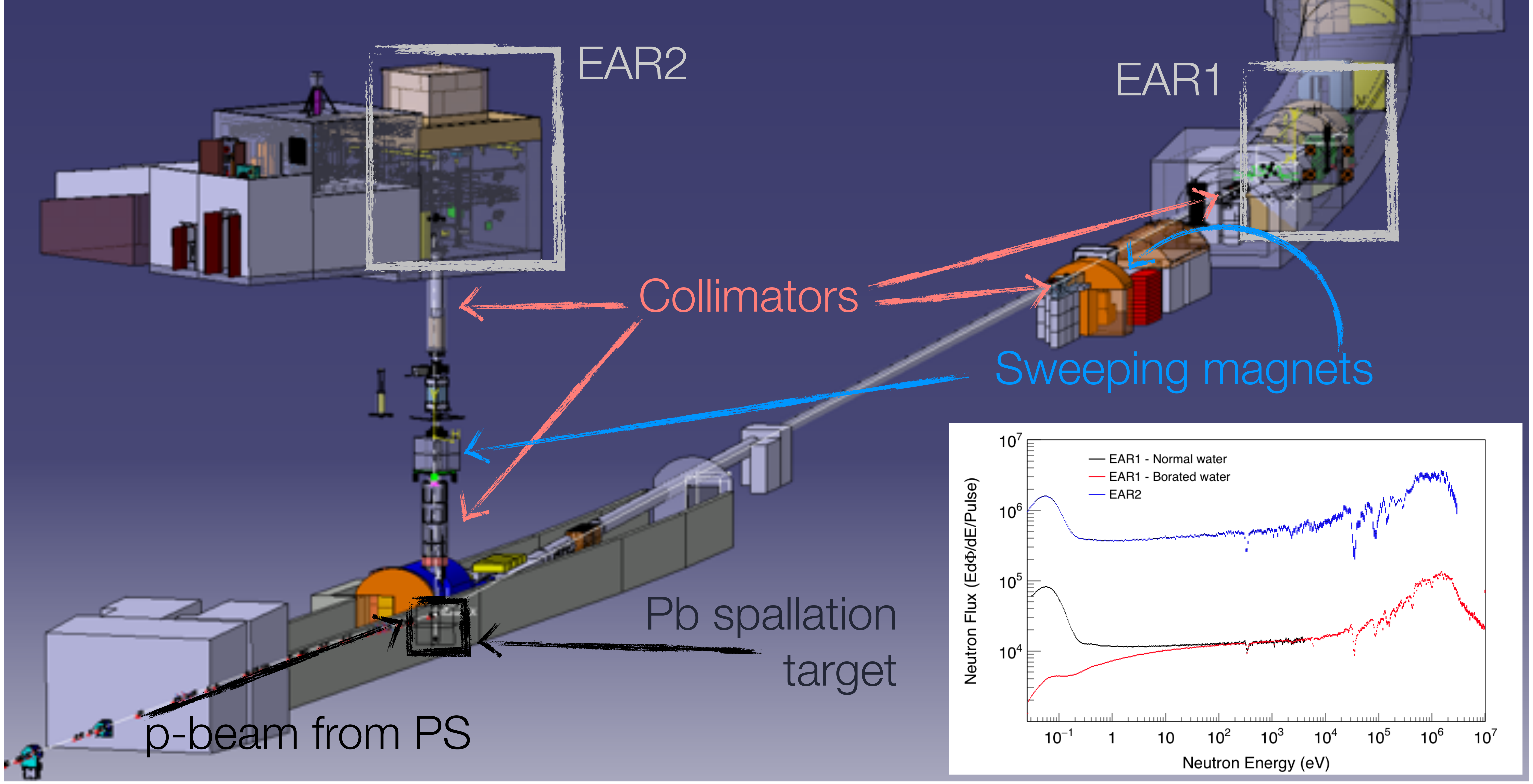

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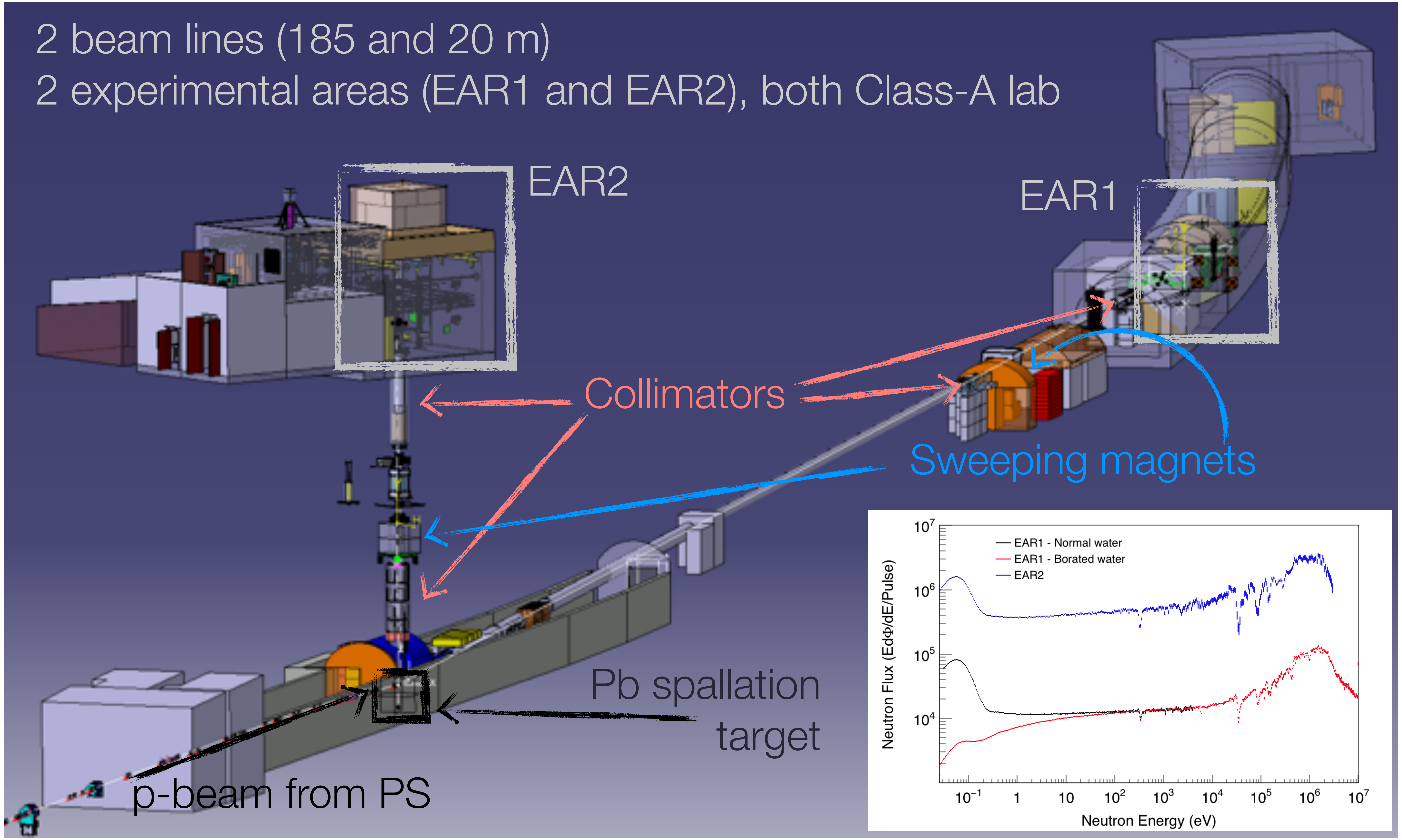

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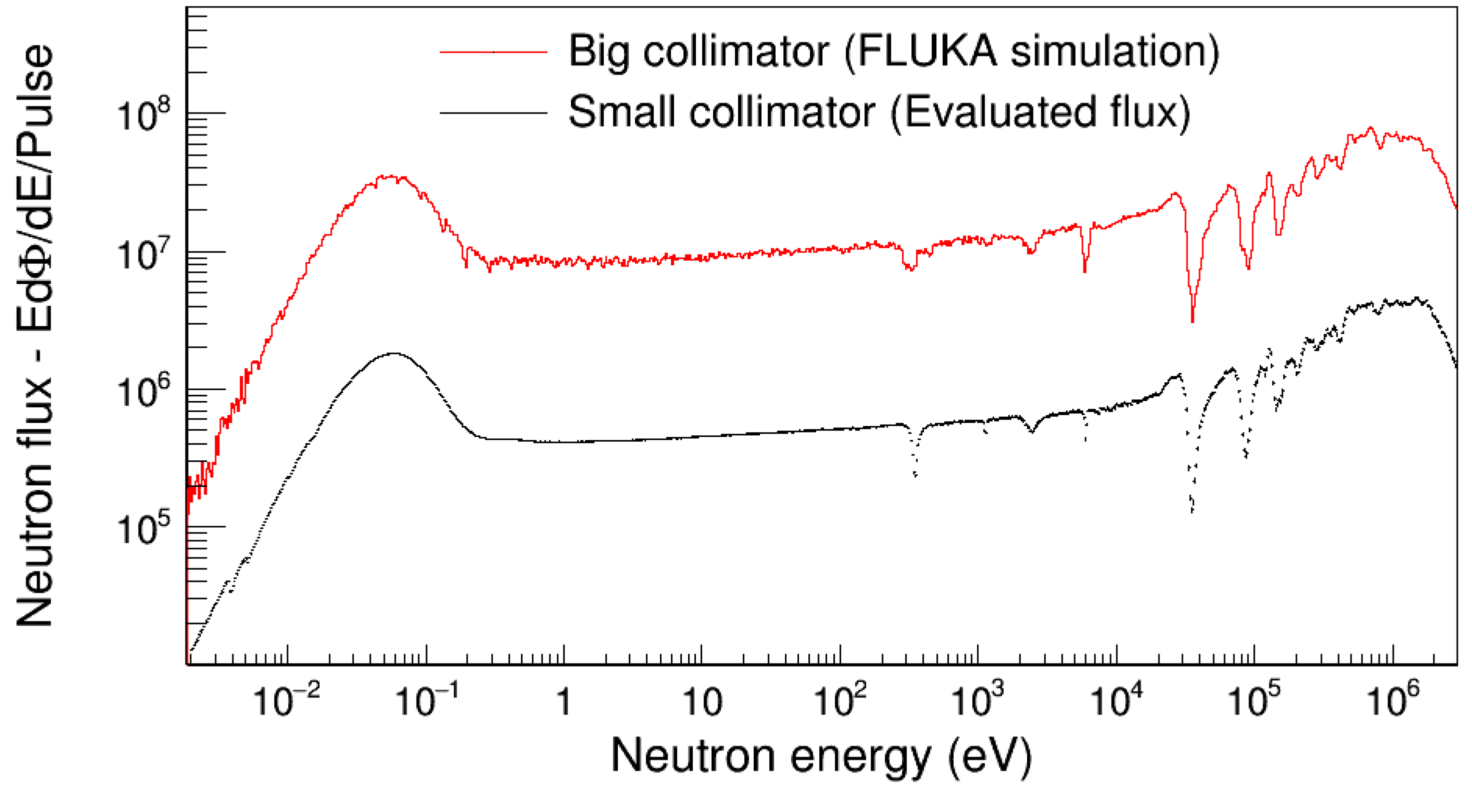
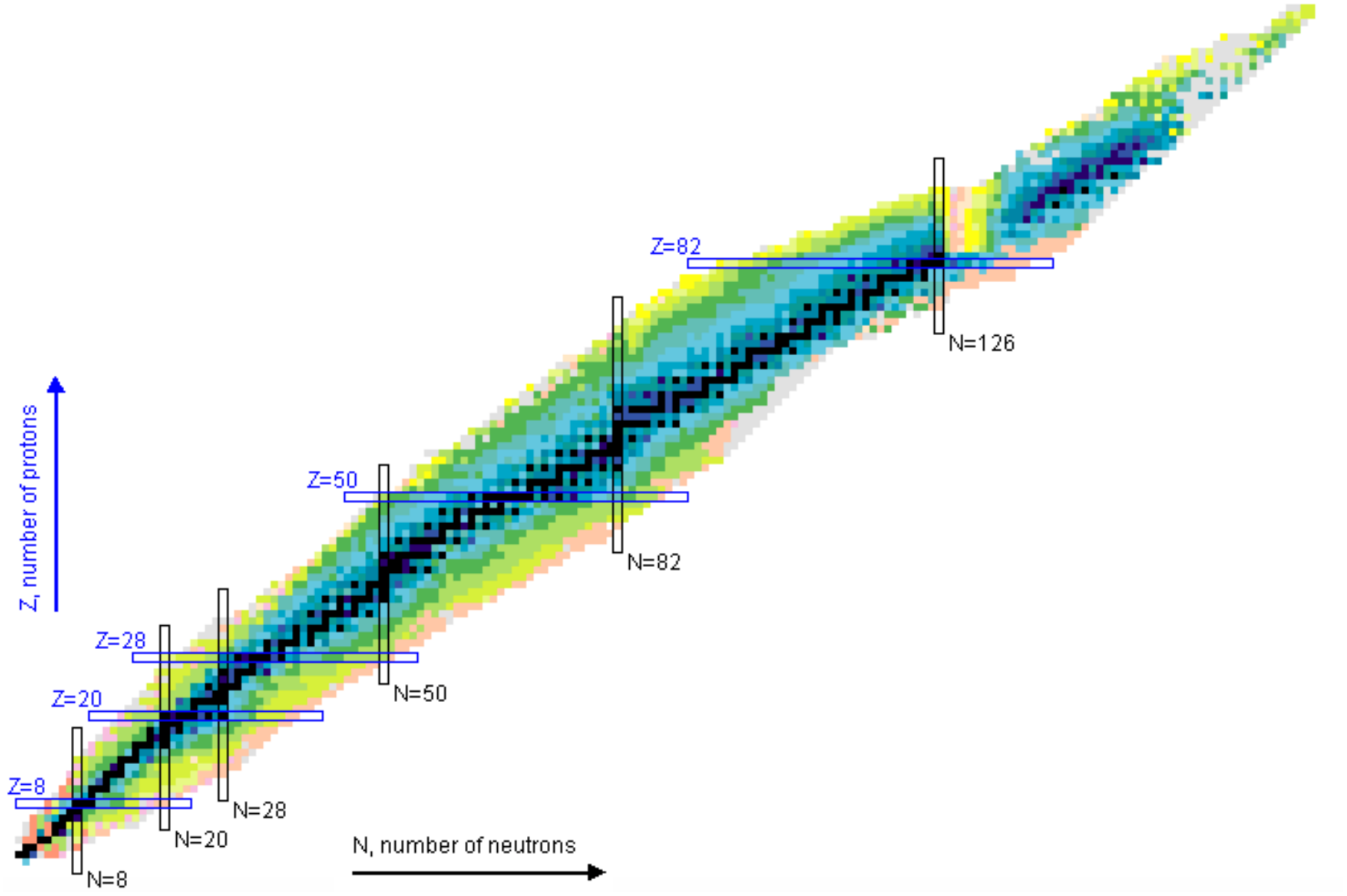


The n_TOF physics program: neutron-induced reaction measurements



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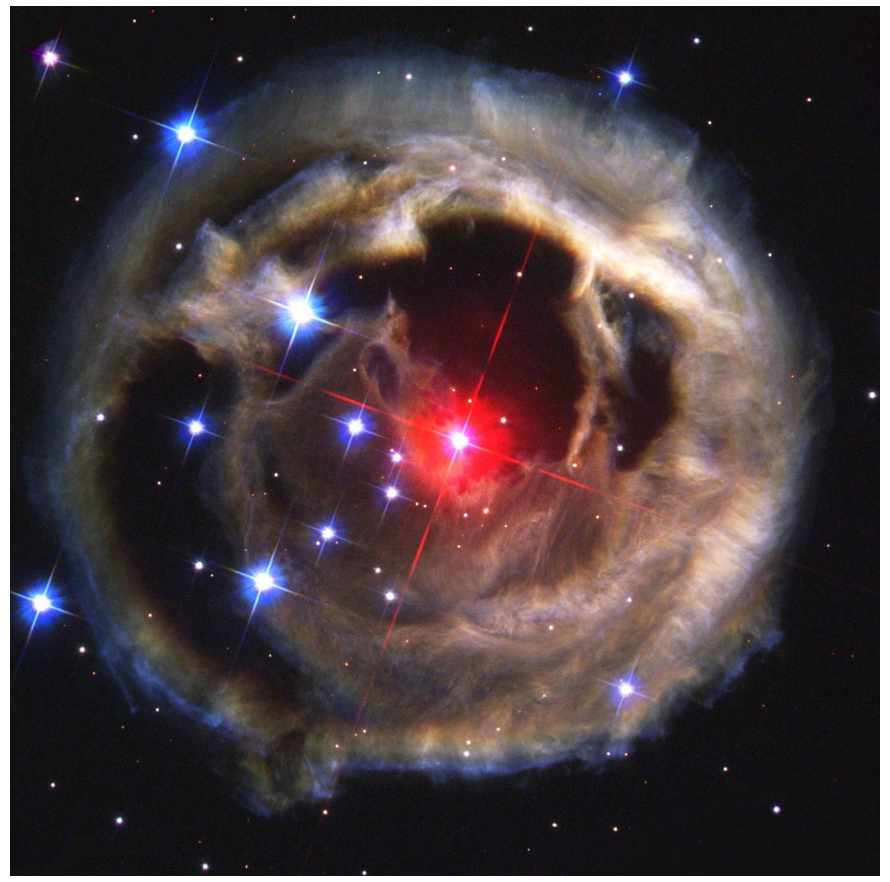
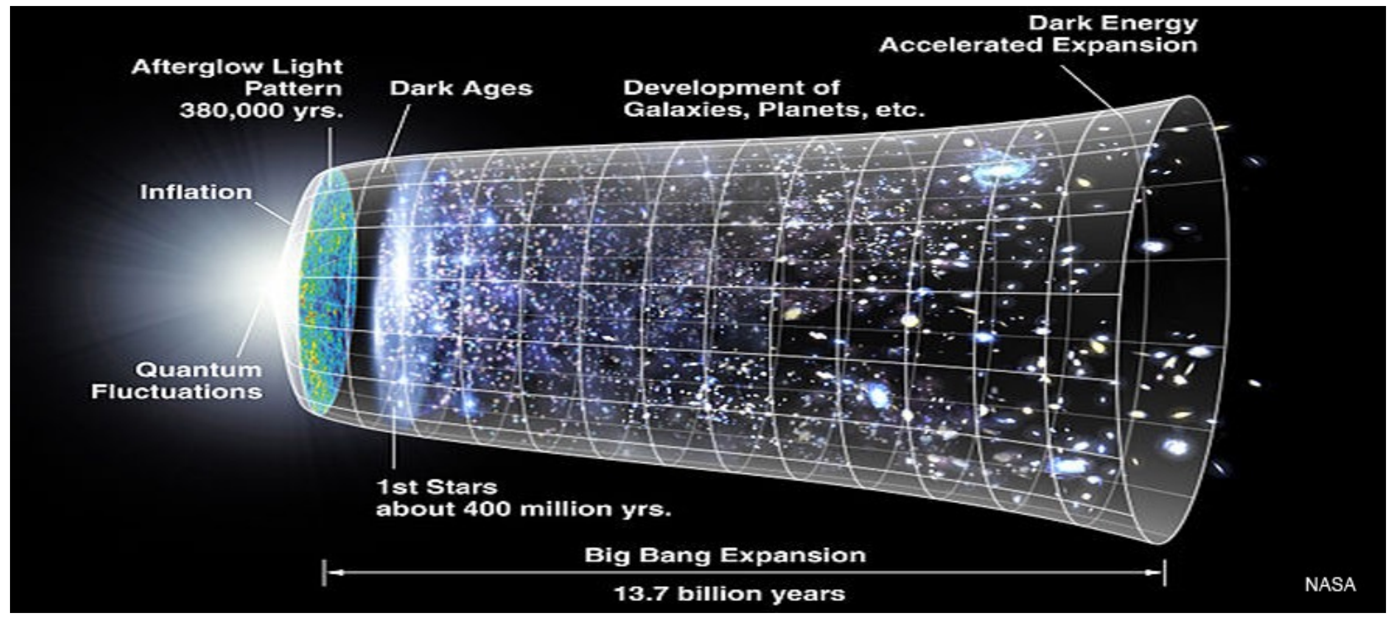
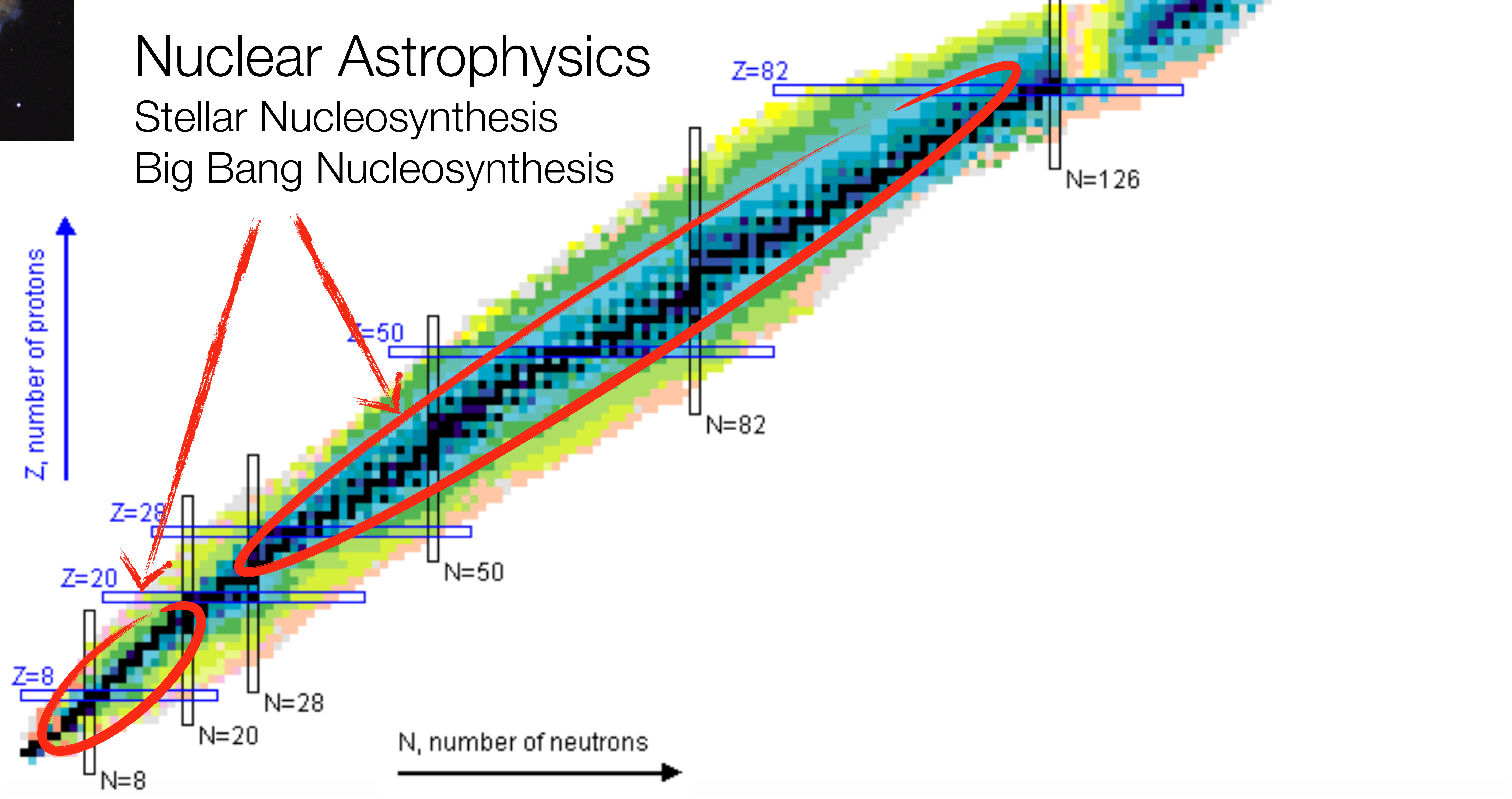




Nuclear Astrophysics

Stellar Nucleosynthesis

Big Bang Nucleosynthesis



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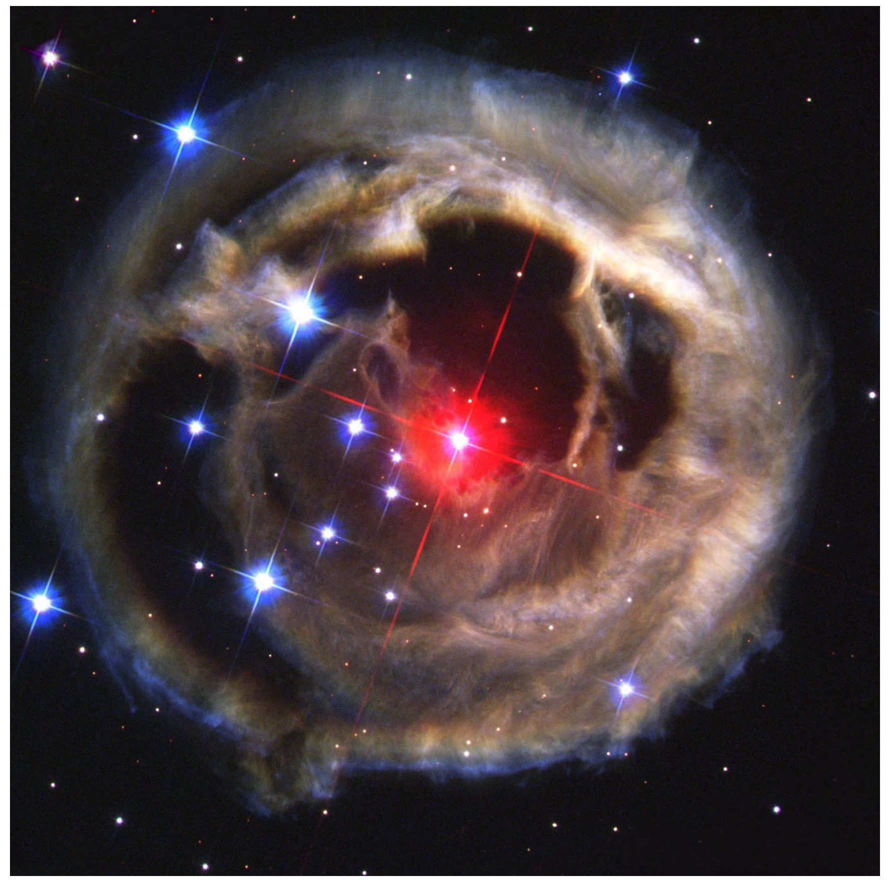
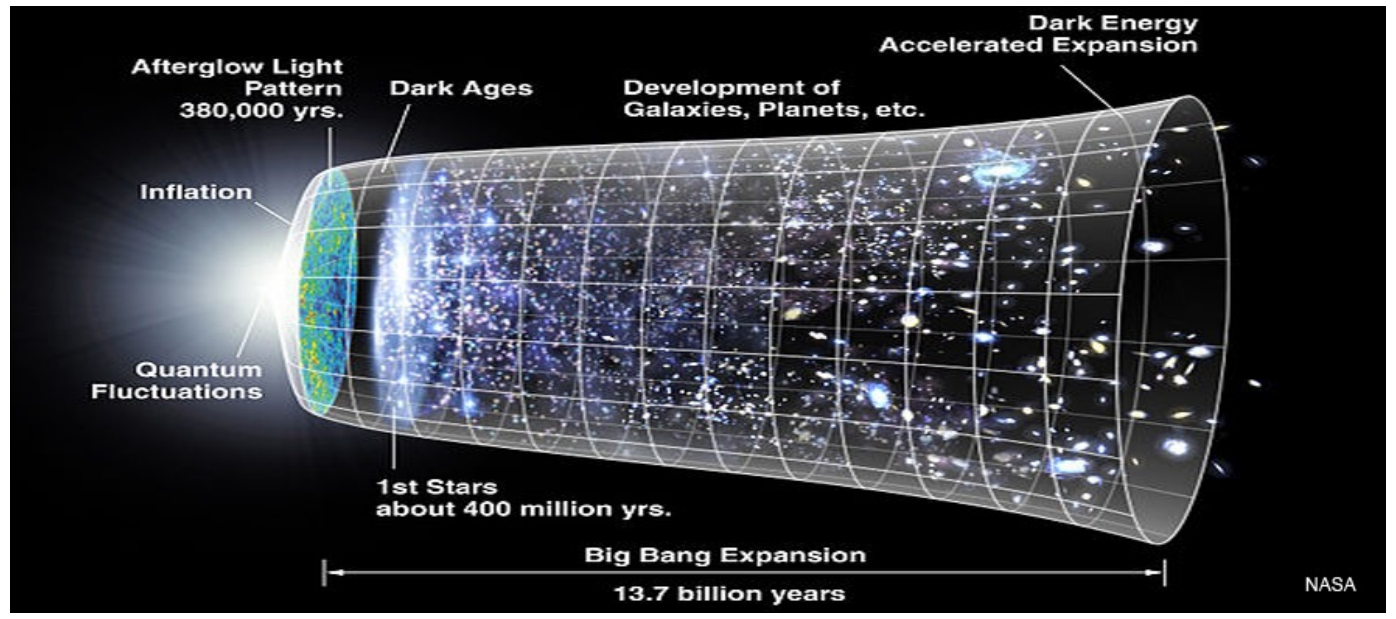
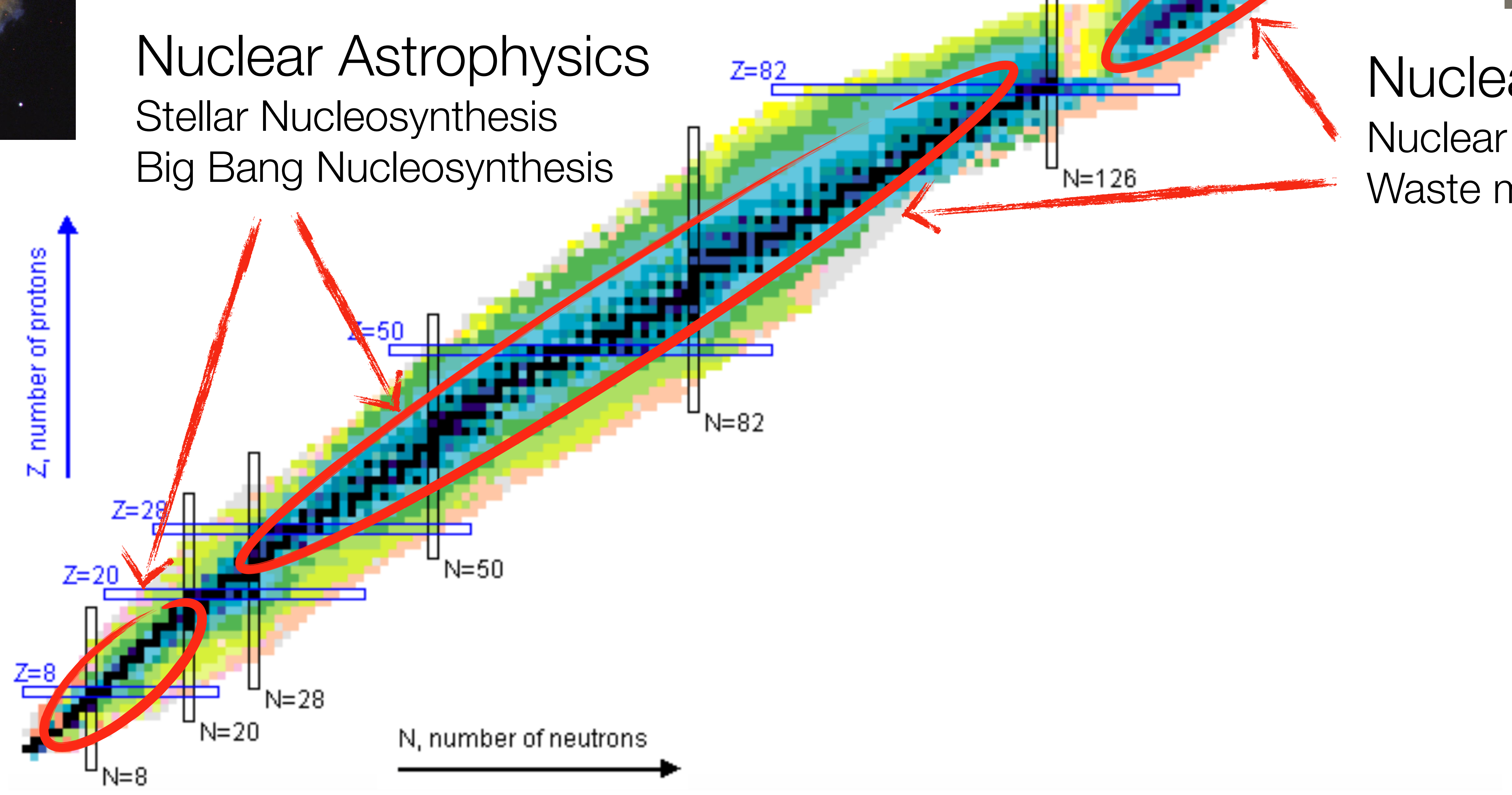
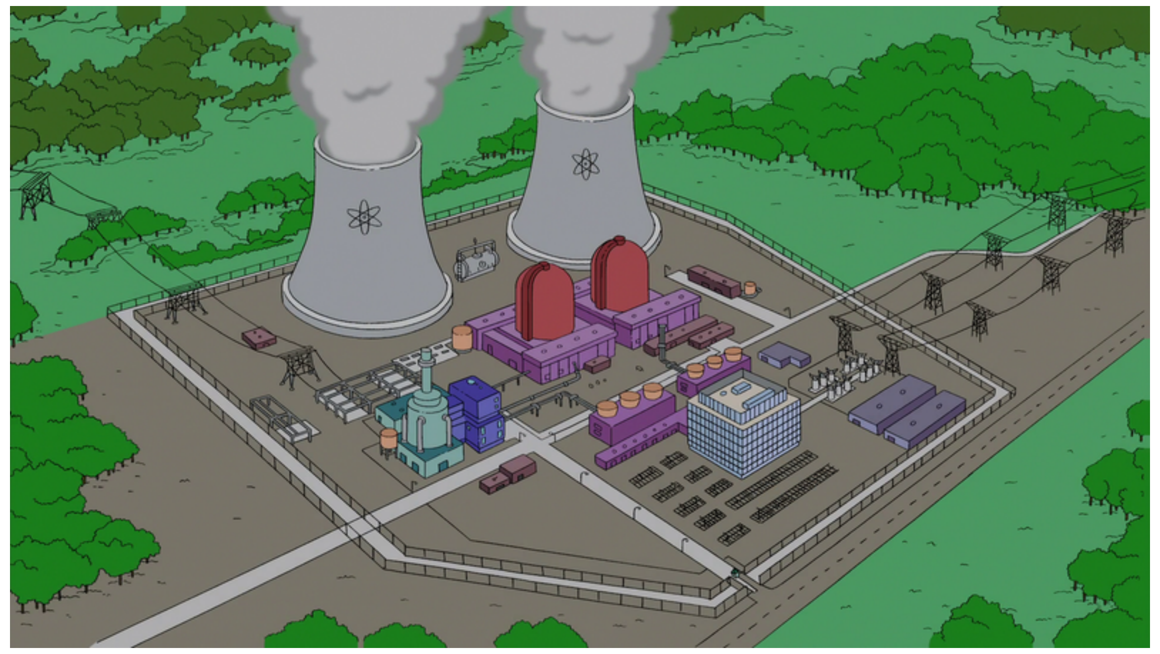




Nuclear Astrophysics

Stellar Nucleosynthesis
Big Bang Nucleosynthesis

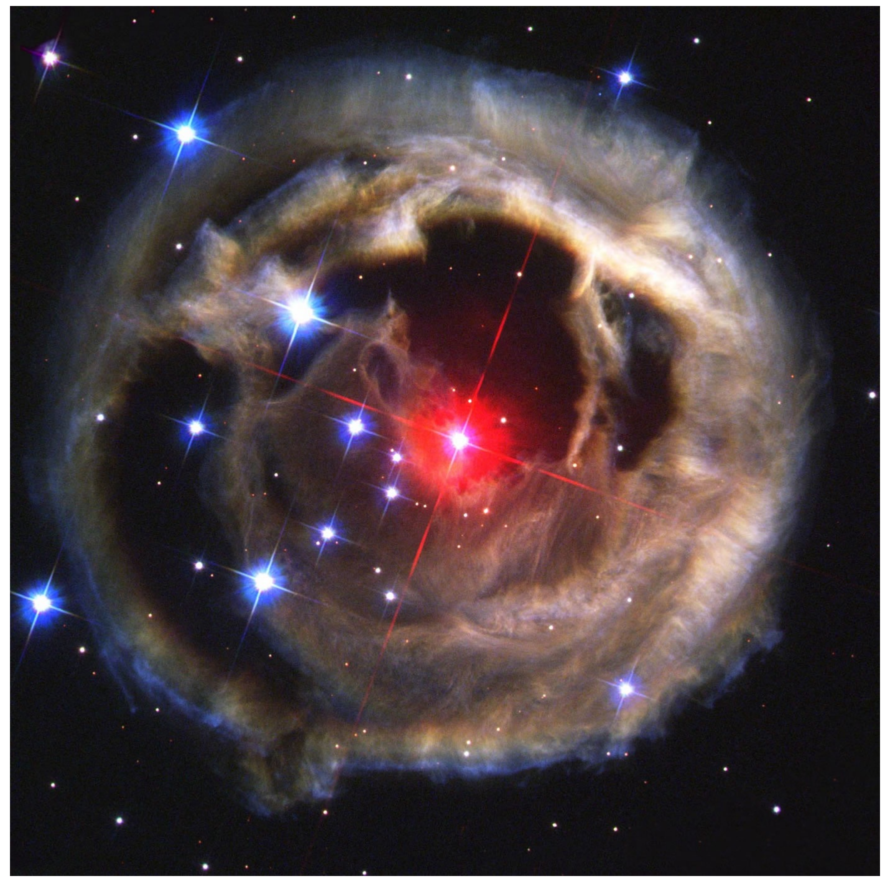


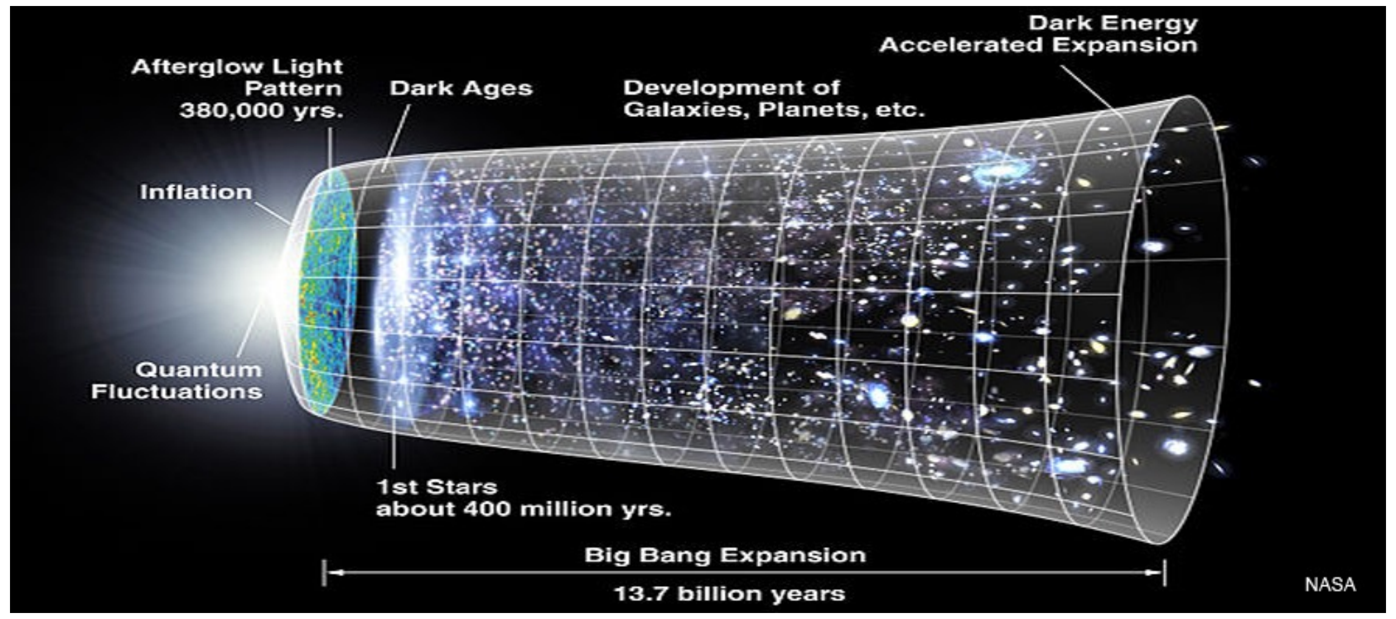


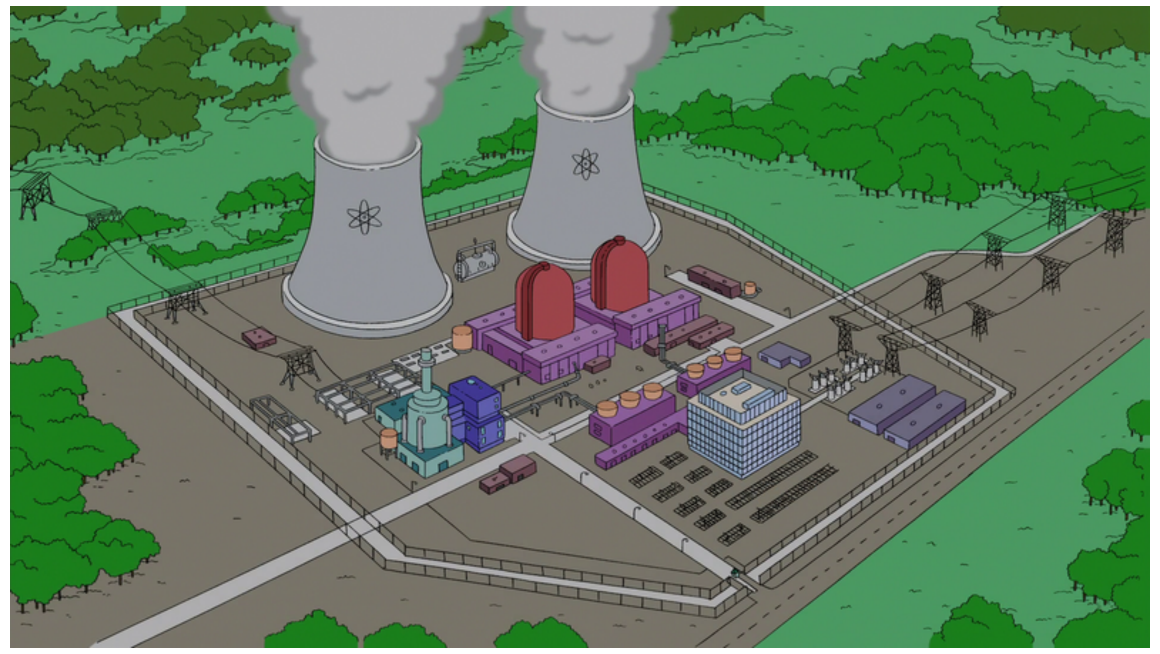
Nuclear Technologies

Nuclear reactors (energy production)
Waste management

The n_TOF physics program: neutron-induced reaction measurements







Nuclear Astrophysics
Stellar Nucleosynthesis
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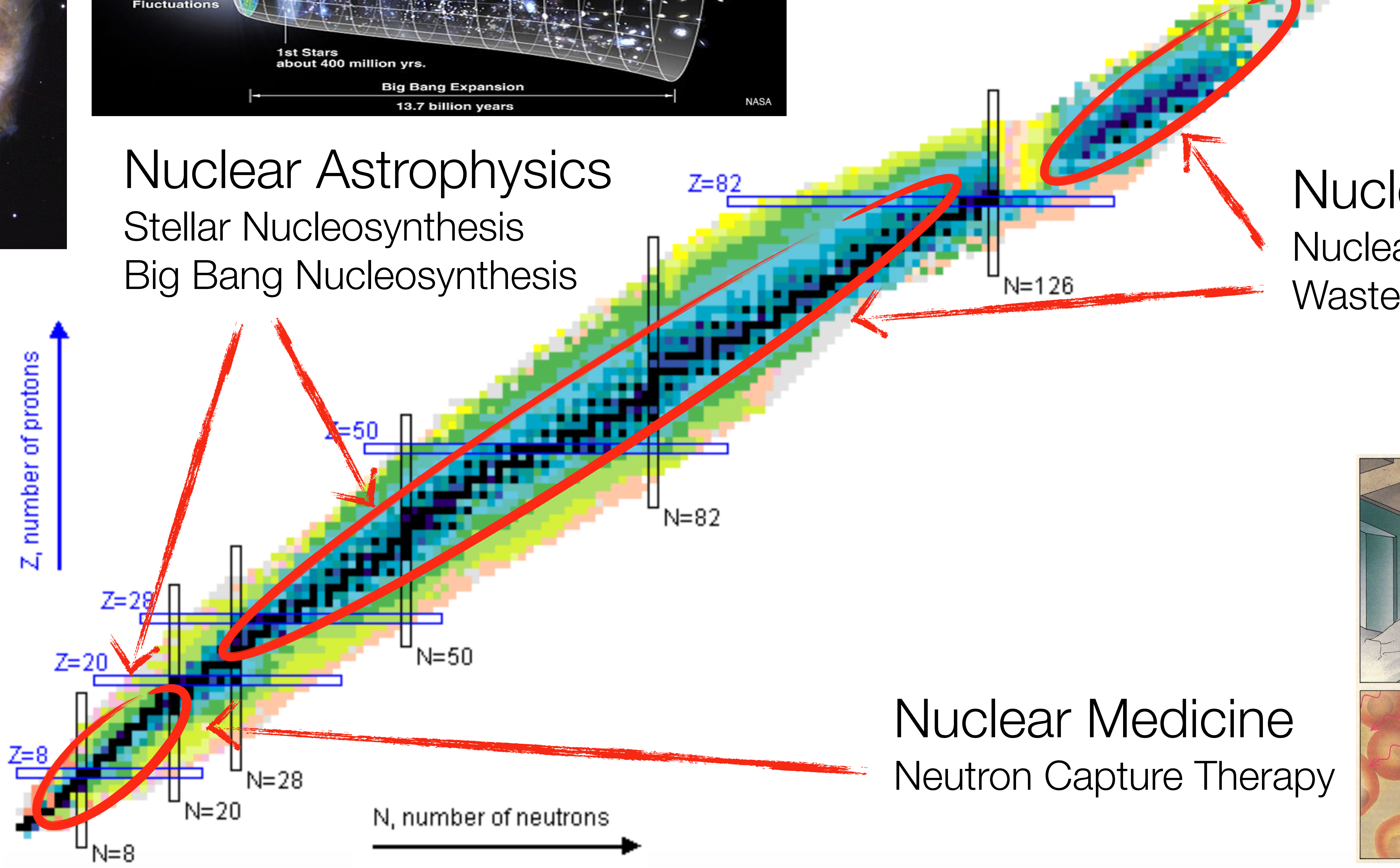
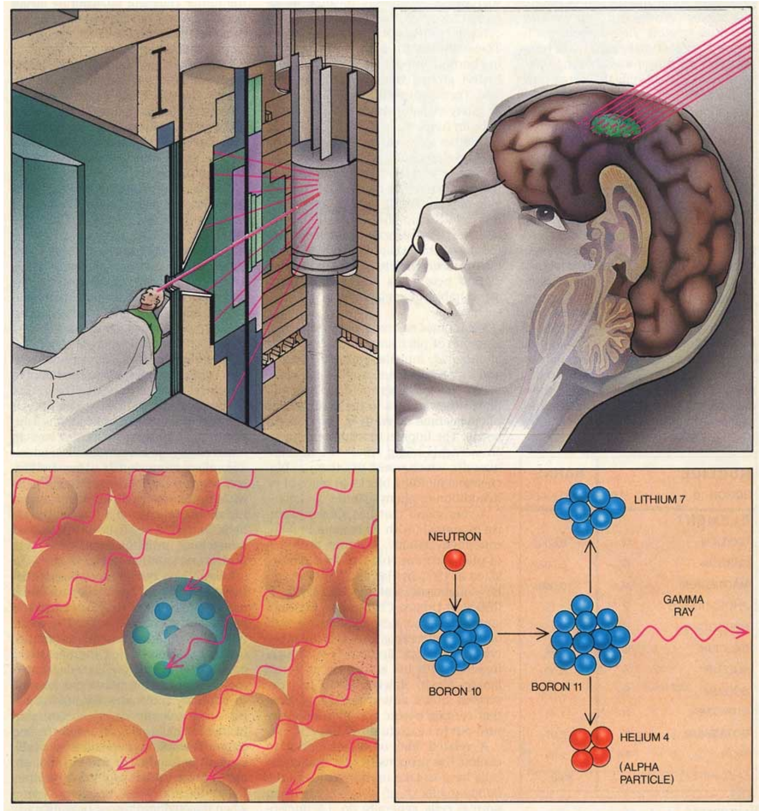
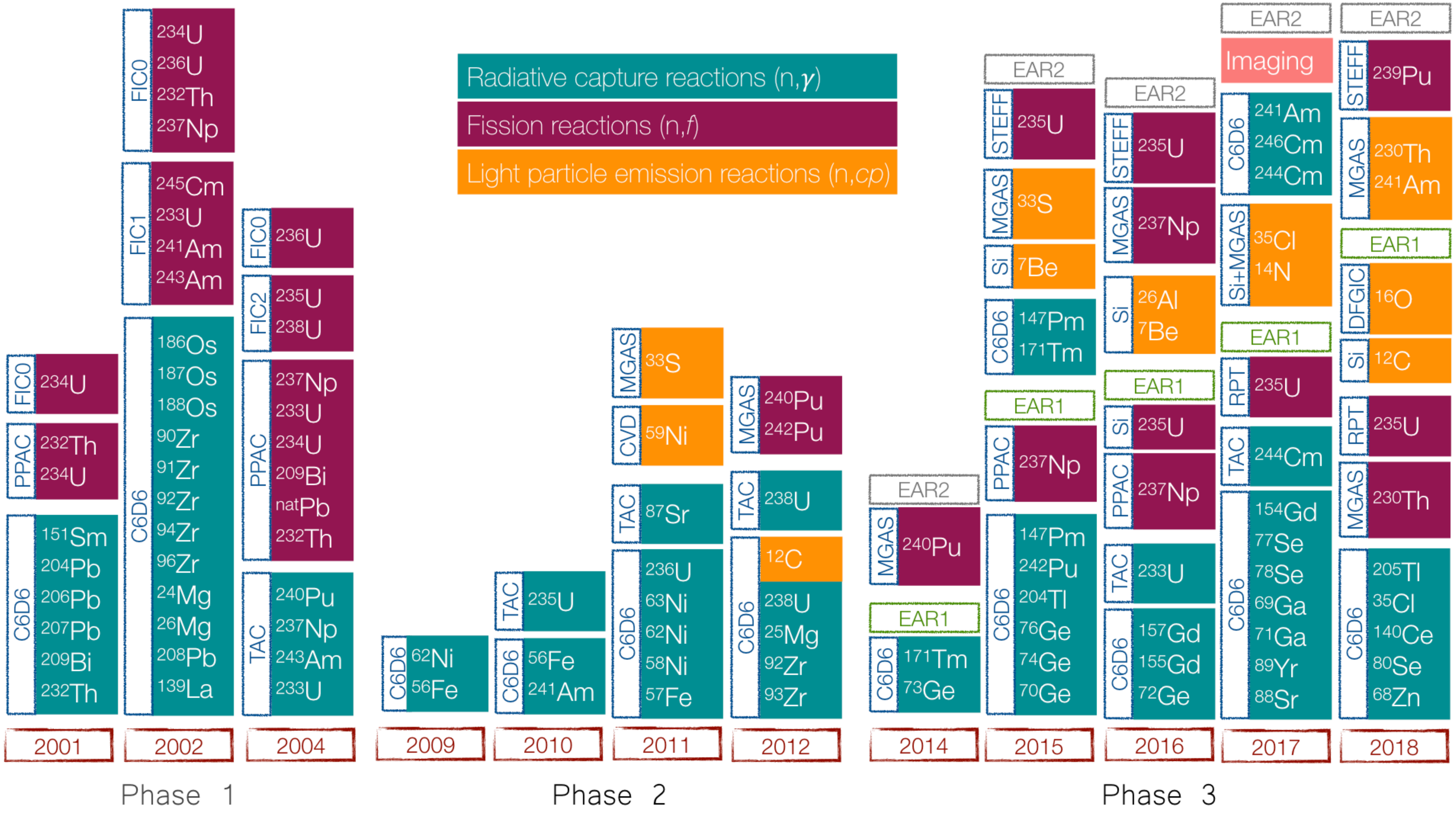


Nuclear Technologies
Nuclear reactors (energy production)
Waste management

Nuclear Medicine
Neutron Capture Therapy



The n_TOF physics program: neutron-induced reaction measurements



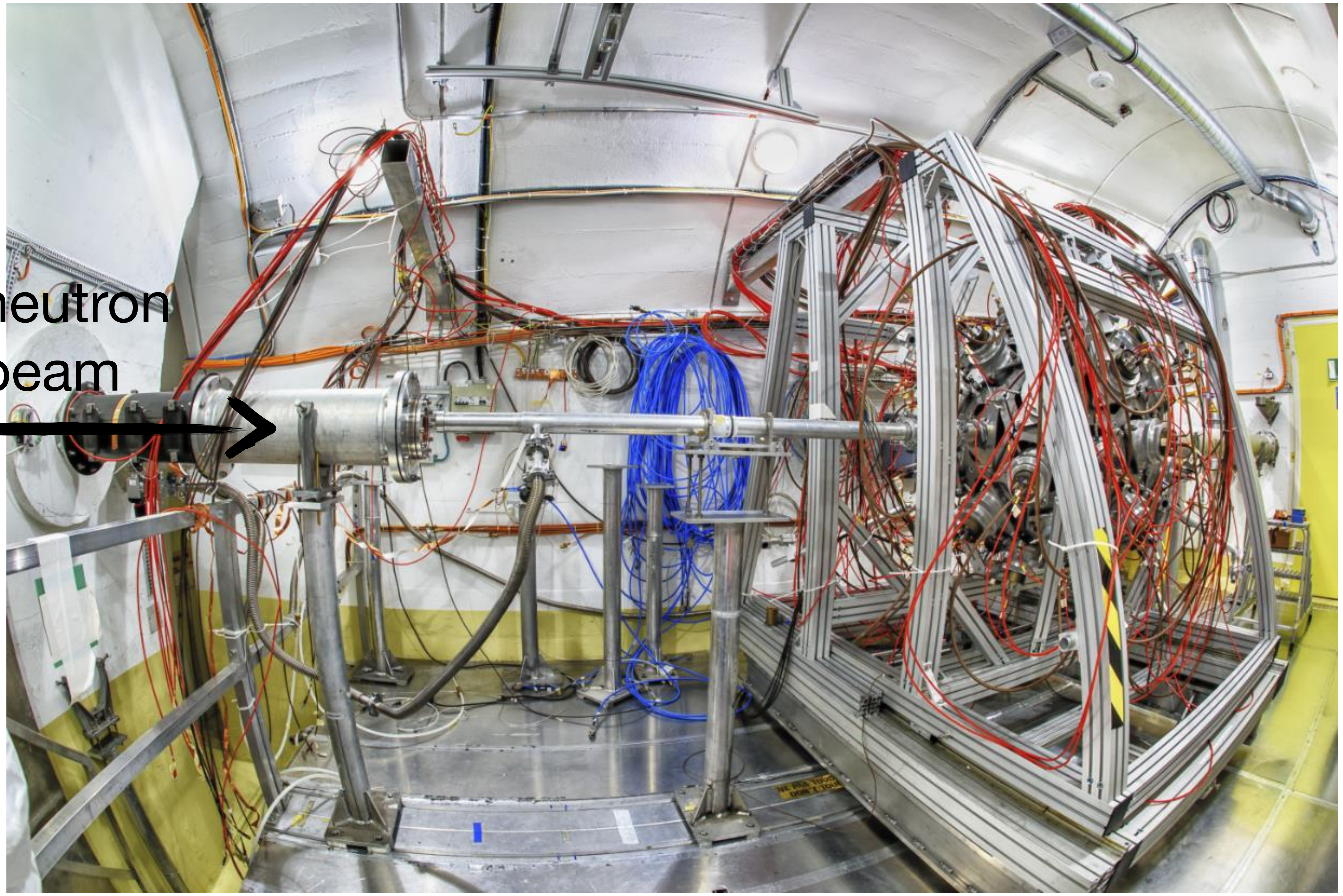
Different detection setups:

- Fission, (n,cp): gaseous and solid state detectors
- Radiative capture: liquid scintillators
- (Highly) enriched samples, thin material and backing

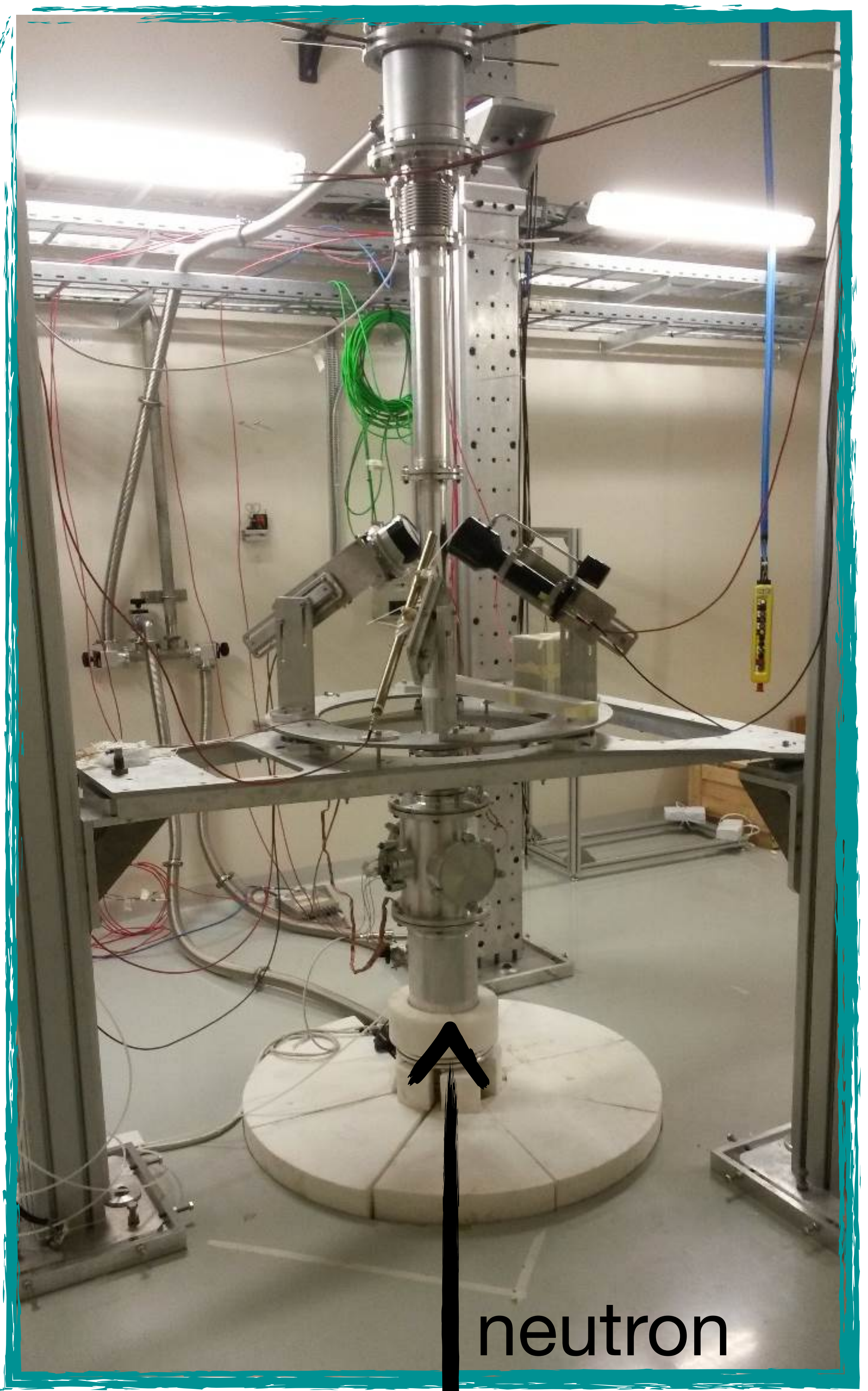
To minimise the systematic uncertainties:

- Characterisation of sample homogeneity and areal density
- Monitoring and characterisation of the neutron beam

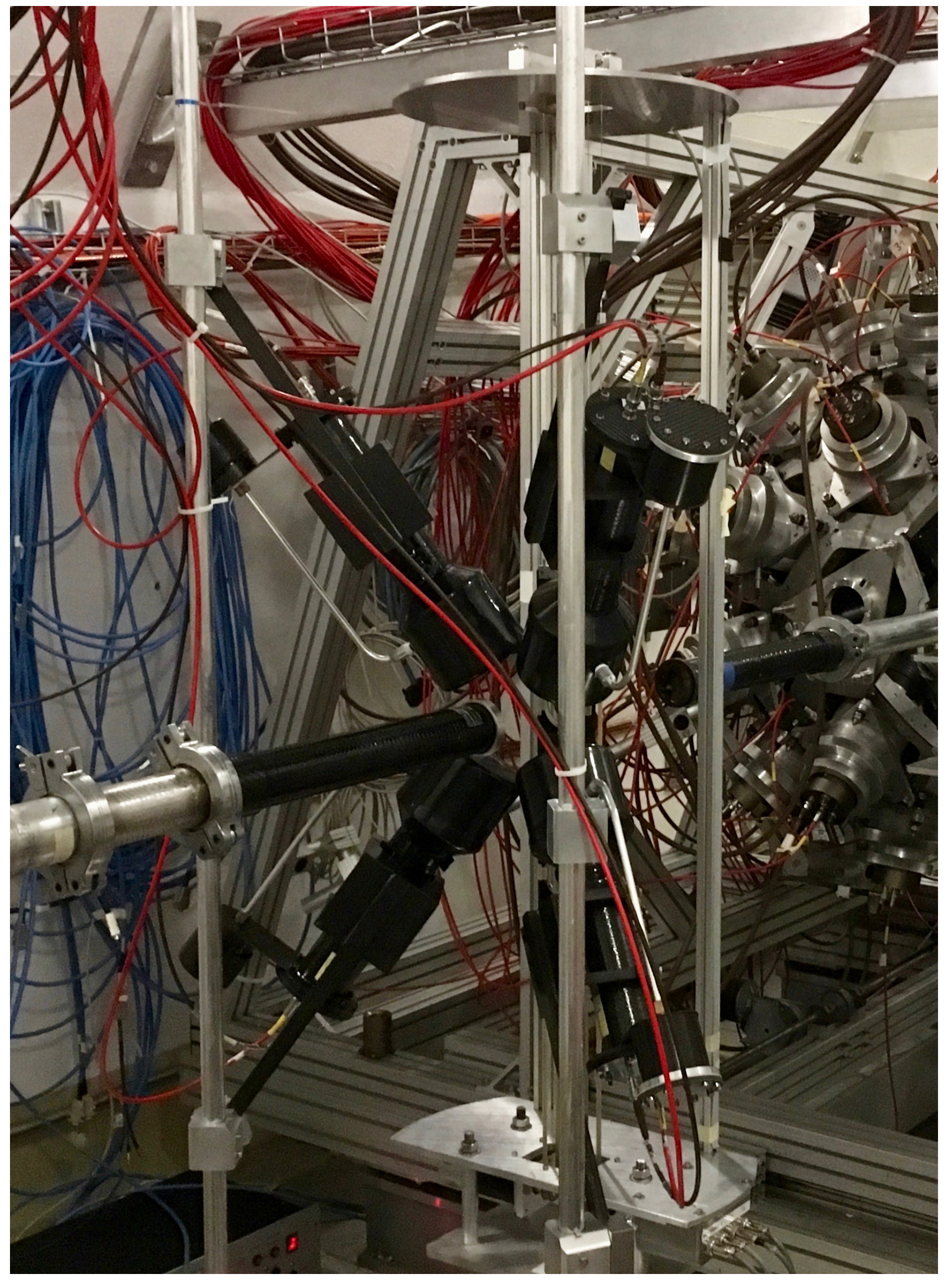
The n_TOF facility: class A laboratories

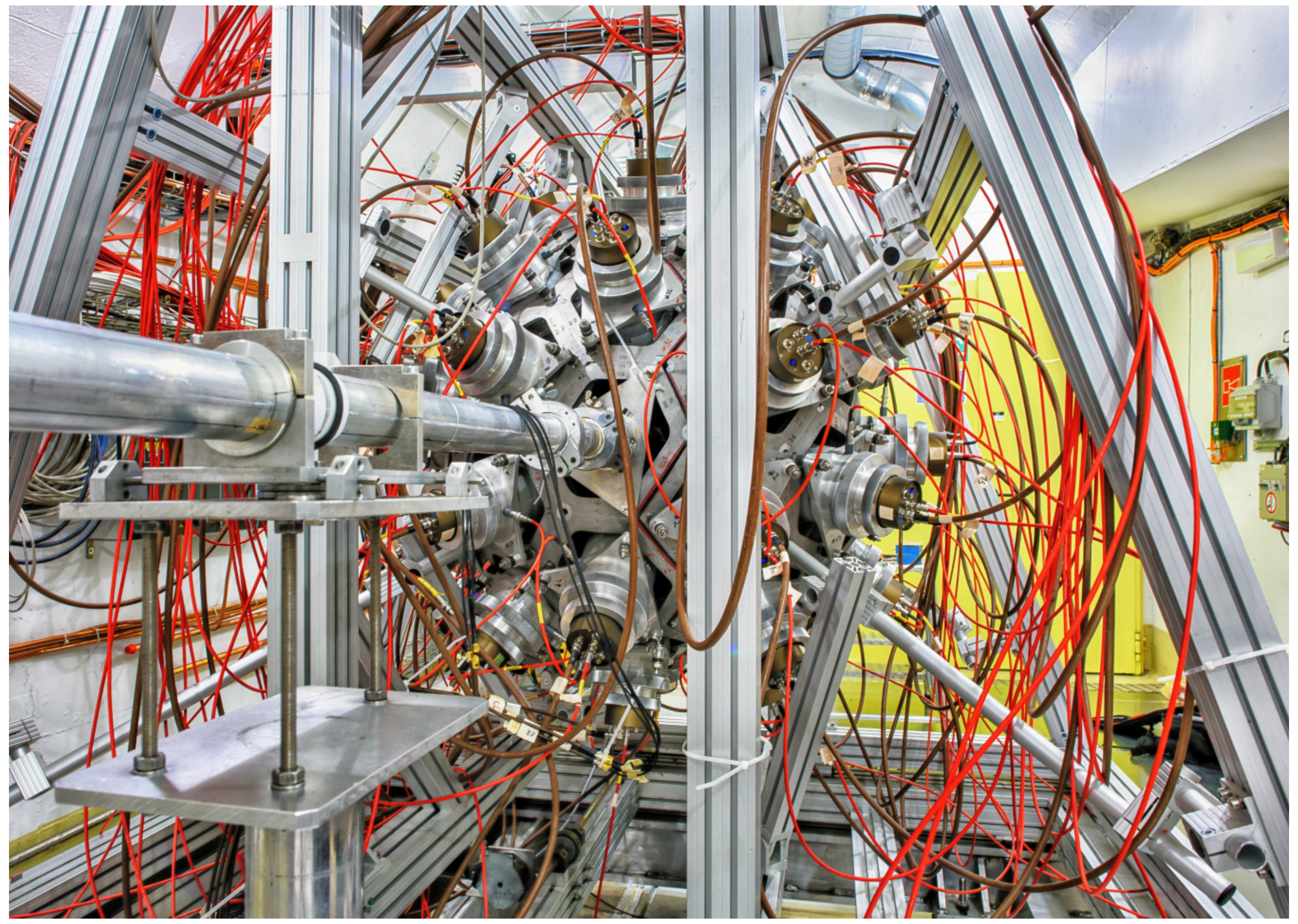


Work Sector Type A: use of unsealed radioactive samples allowed
(since 2010 in EAR-1, since 2014 in EAR-2)

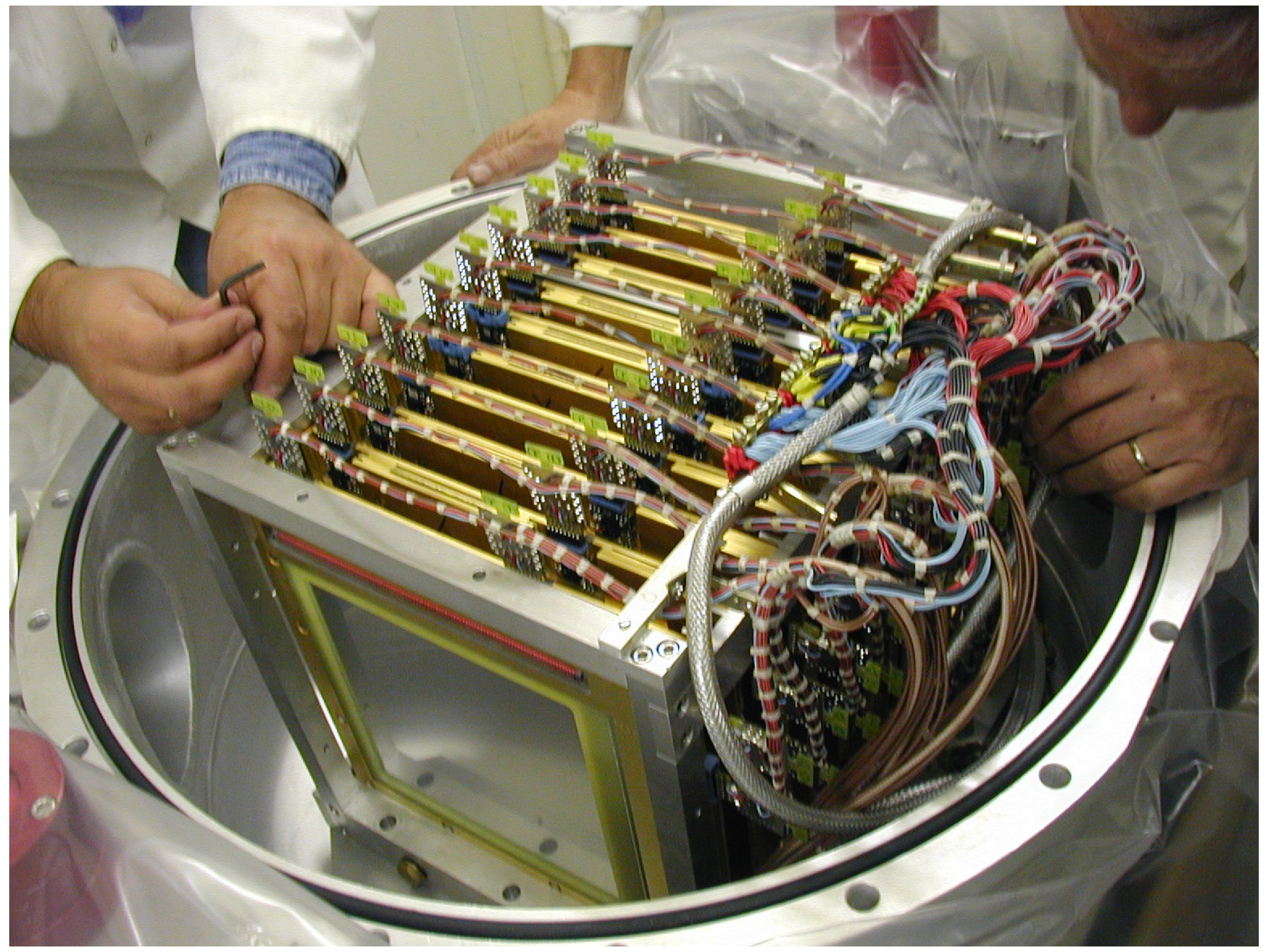


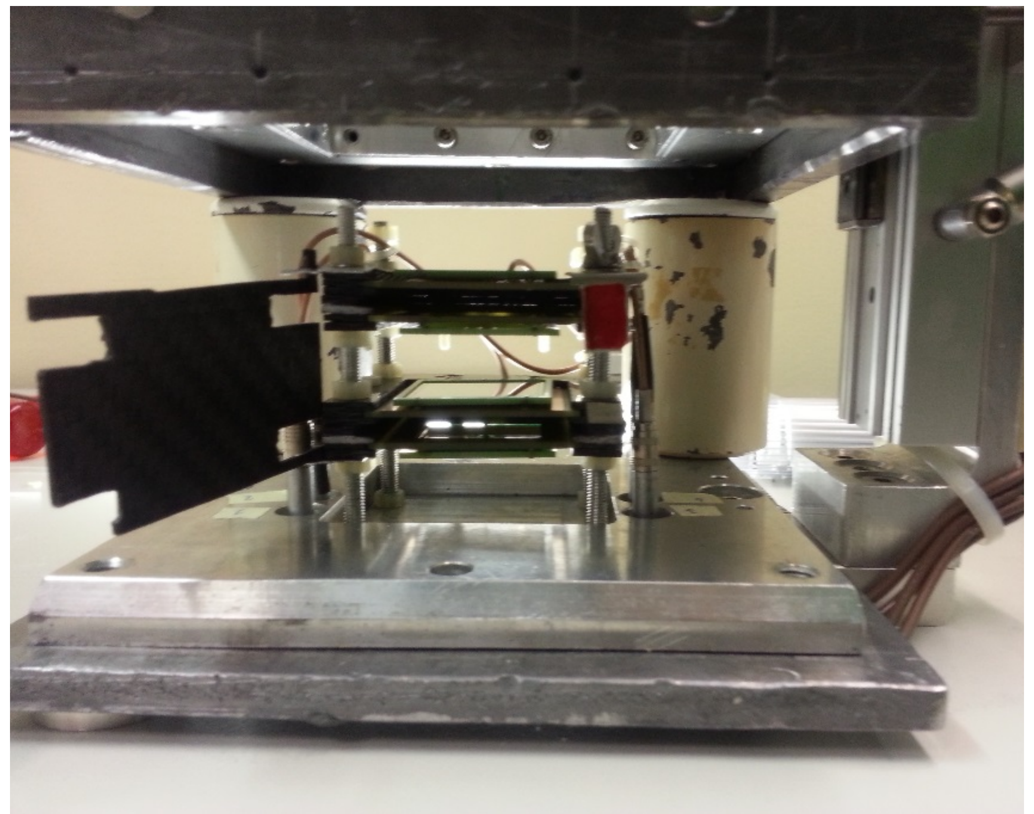
The n_TOF facility: detection systems

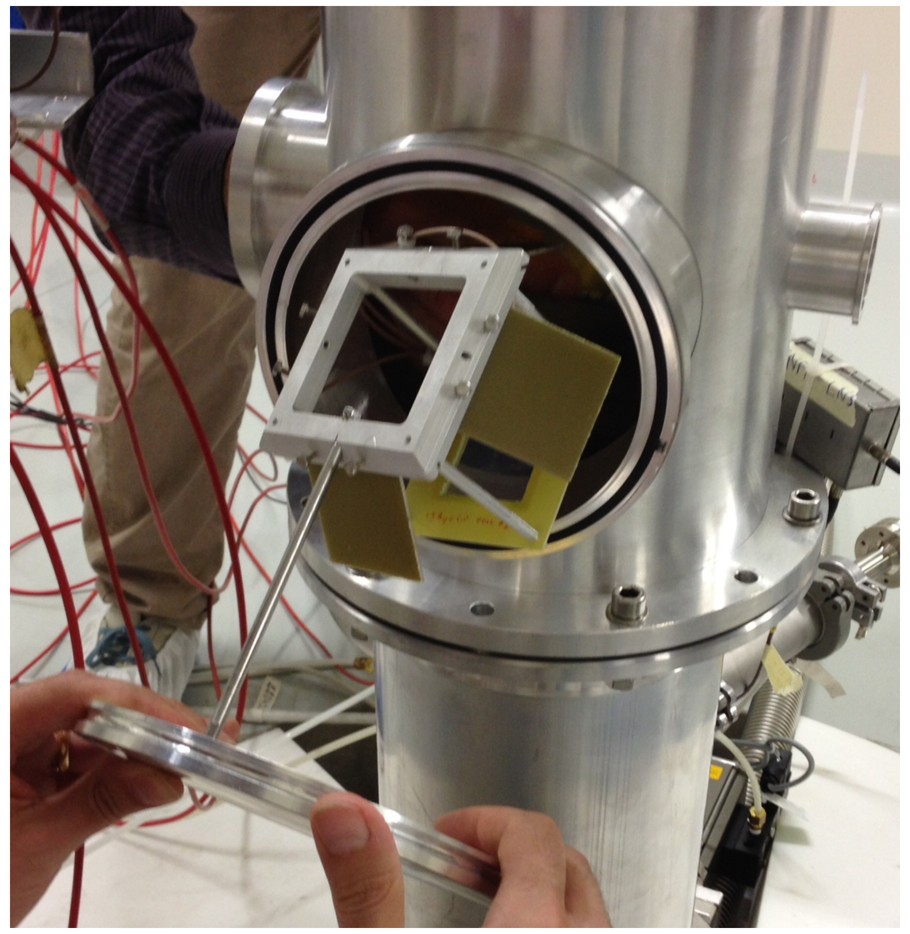




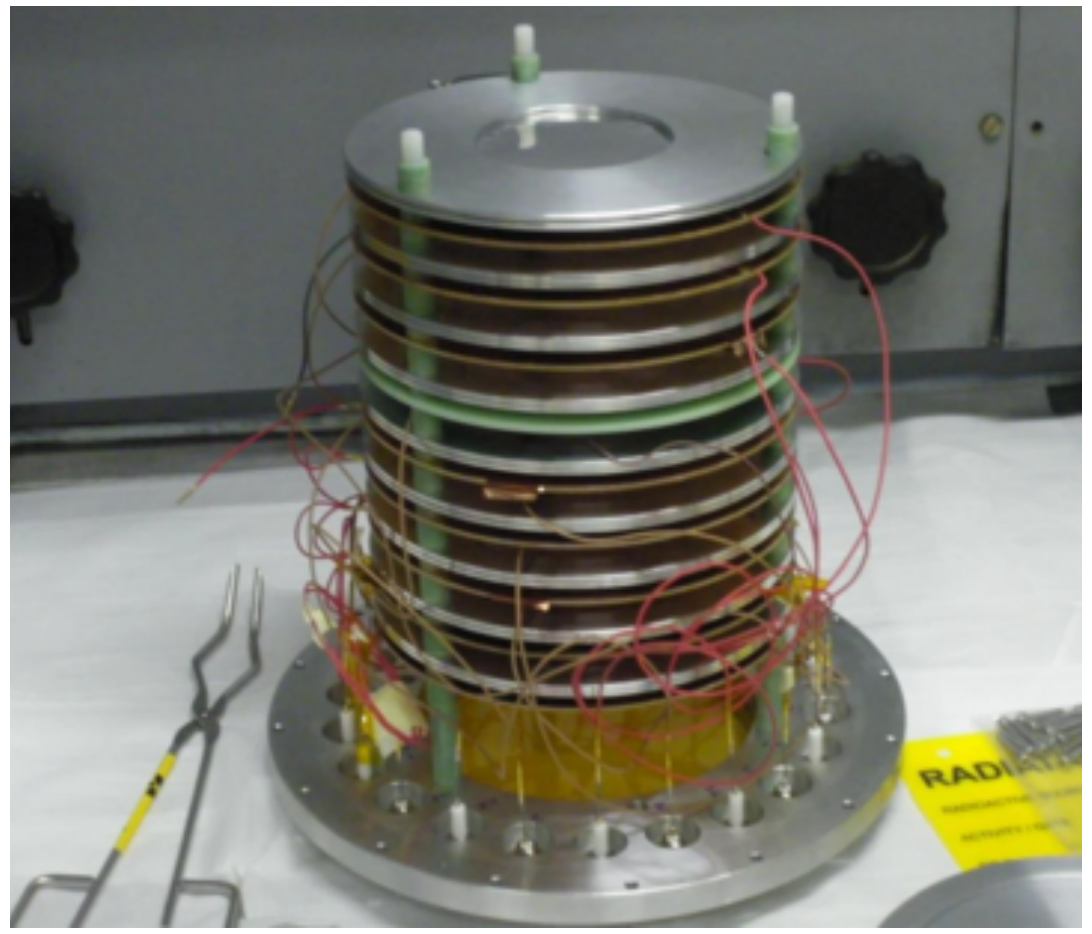
(n,γ): TAC, C6D6







(n,cp):Silicon, sCVD, MicroMegas

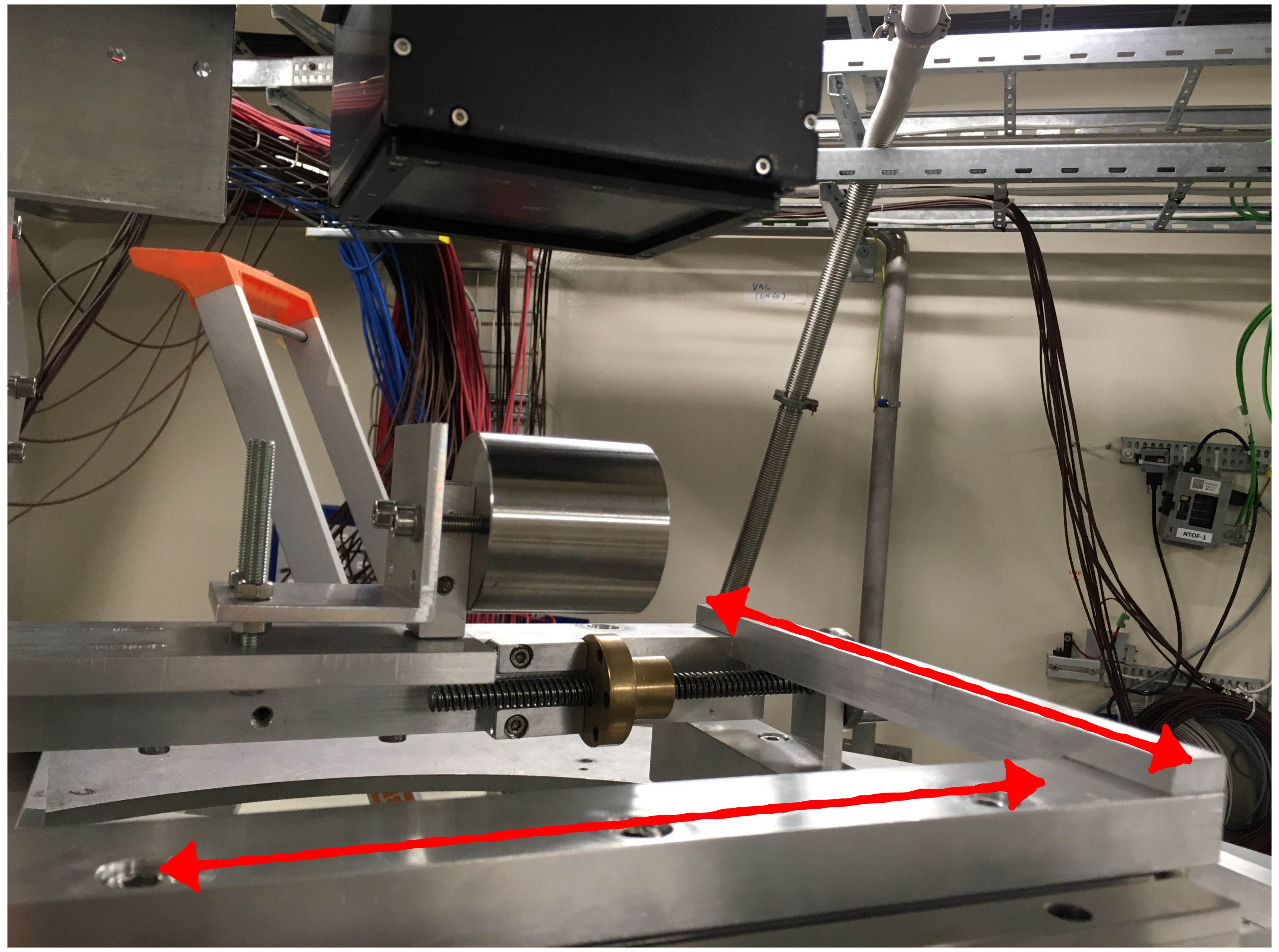


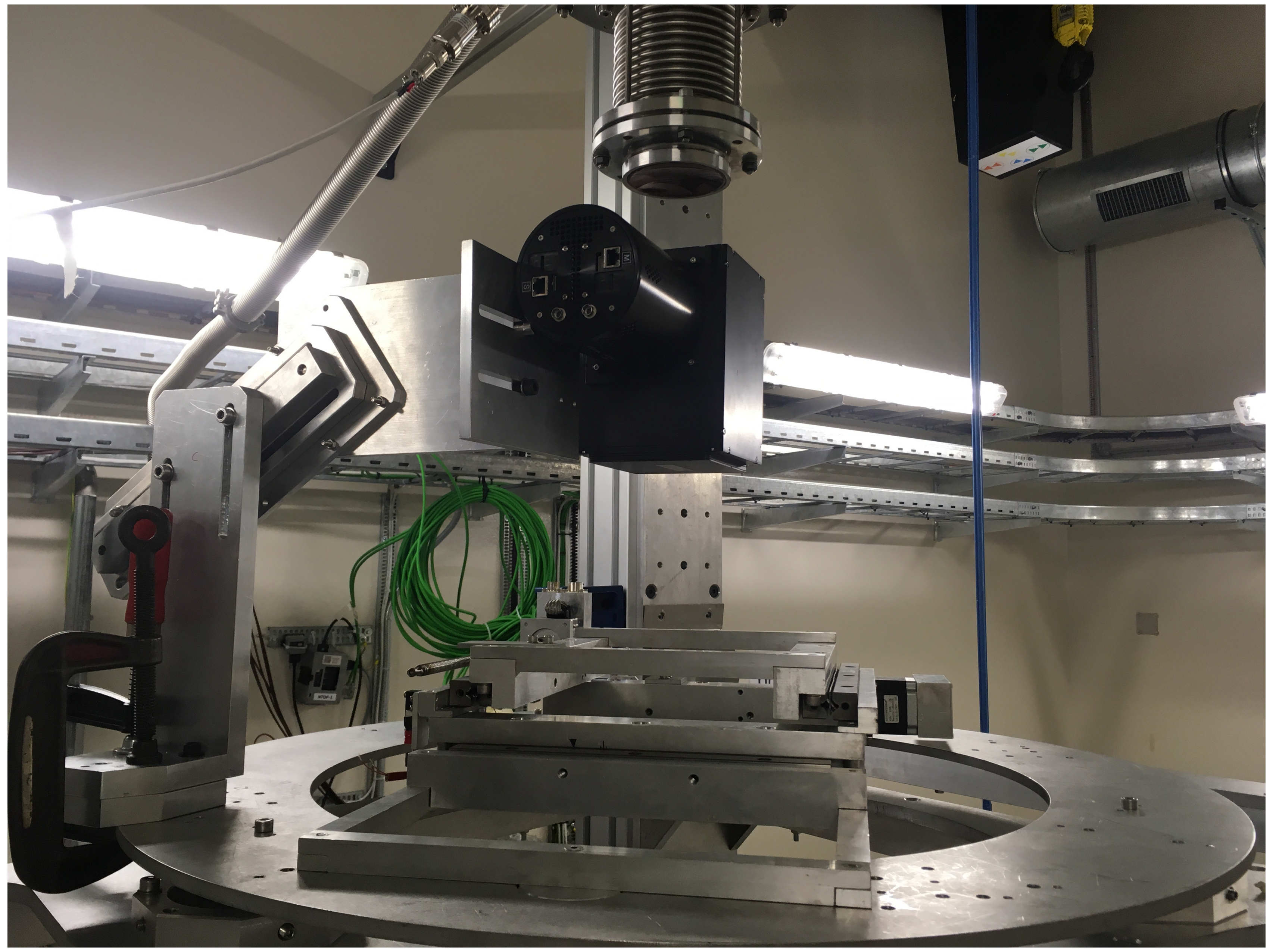
(n,f): PPAC, MicroMegas

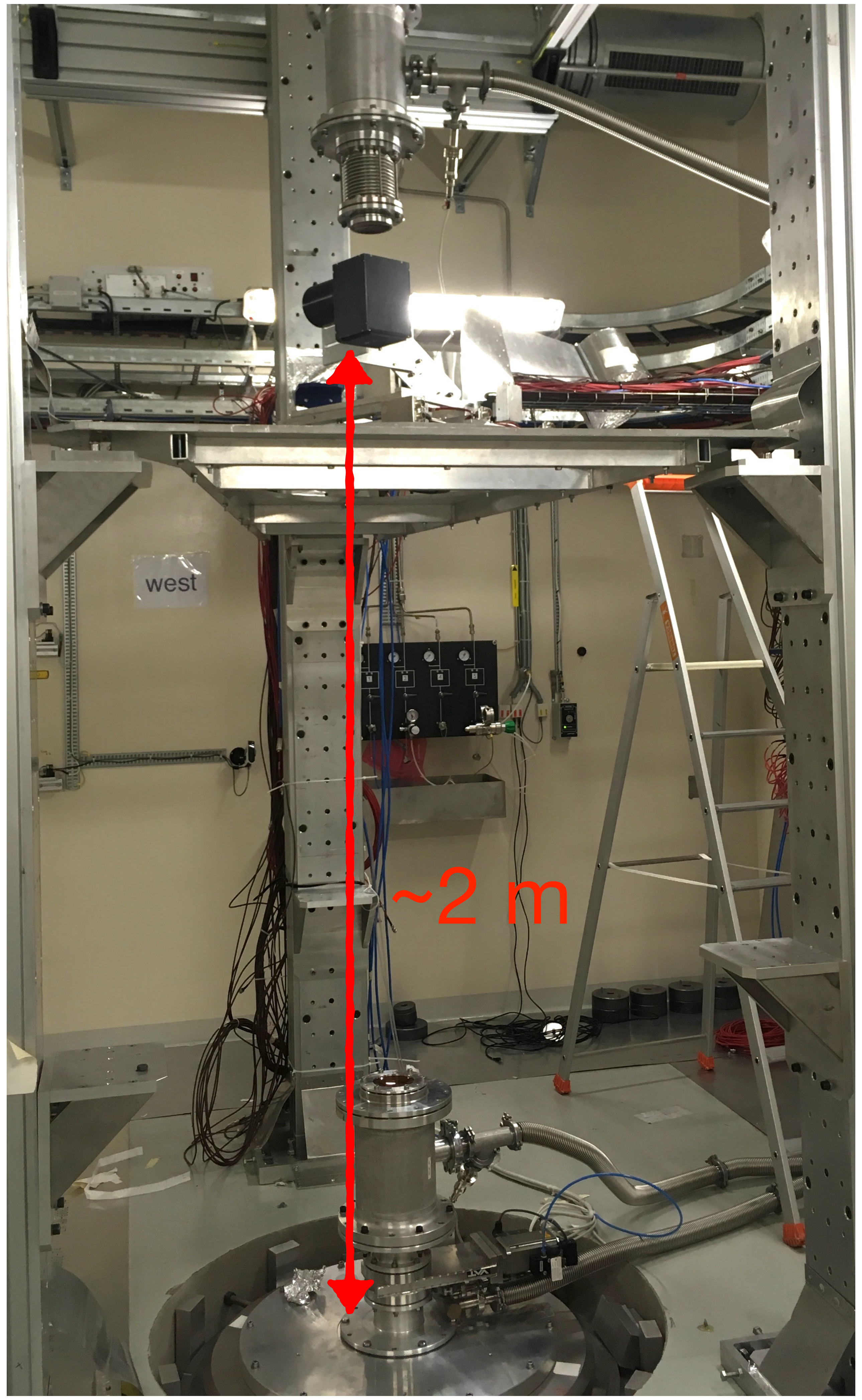
Behind neutron-induced reactions: neutron Imaging @ EAR2

Measuring station

- Height ≈ 220 cm from the floor
- Sample-camera distance ≈ 5 cm
- Able to host different sample, possibility to fine tune the sample position



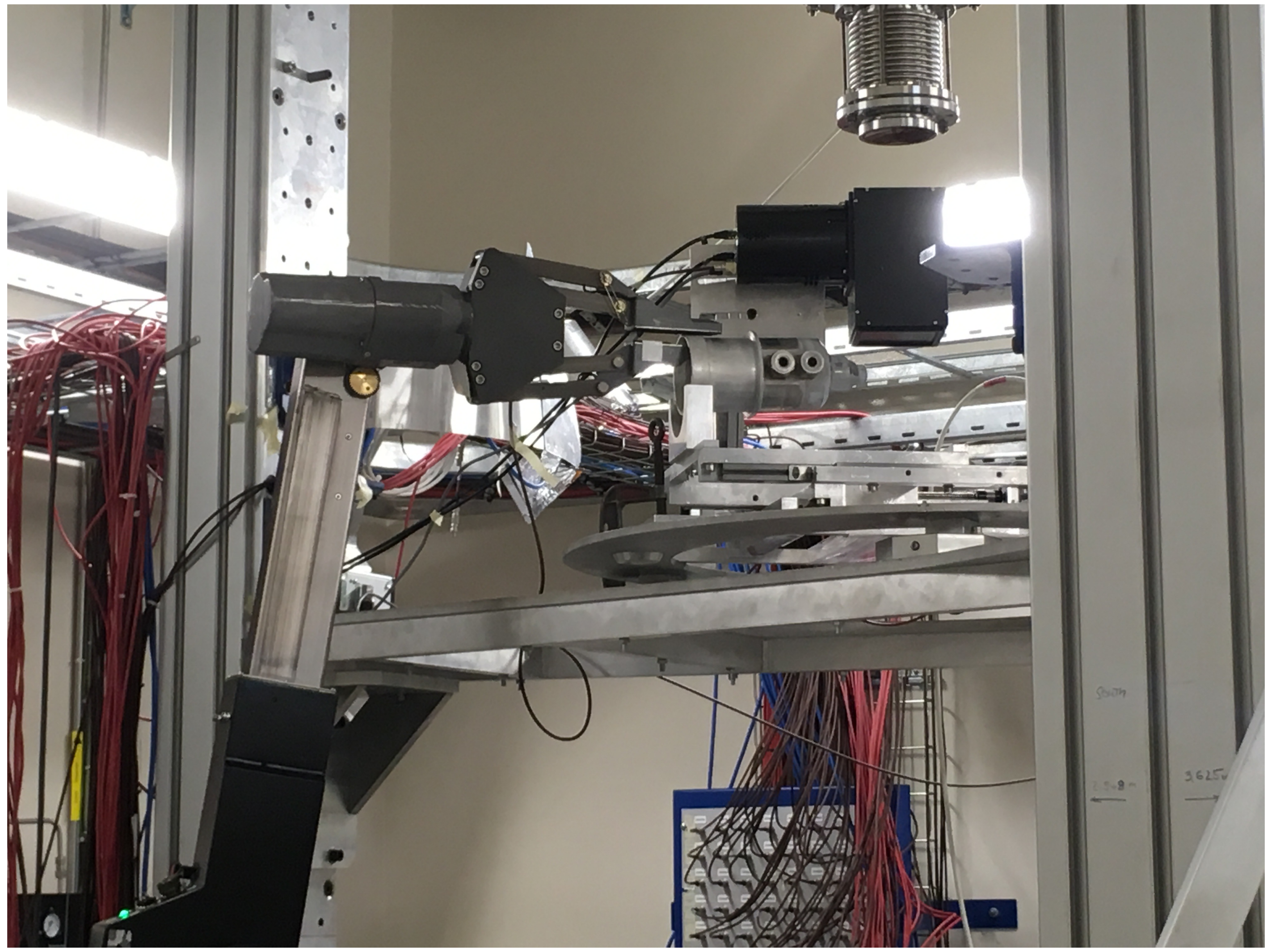




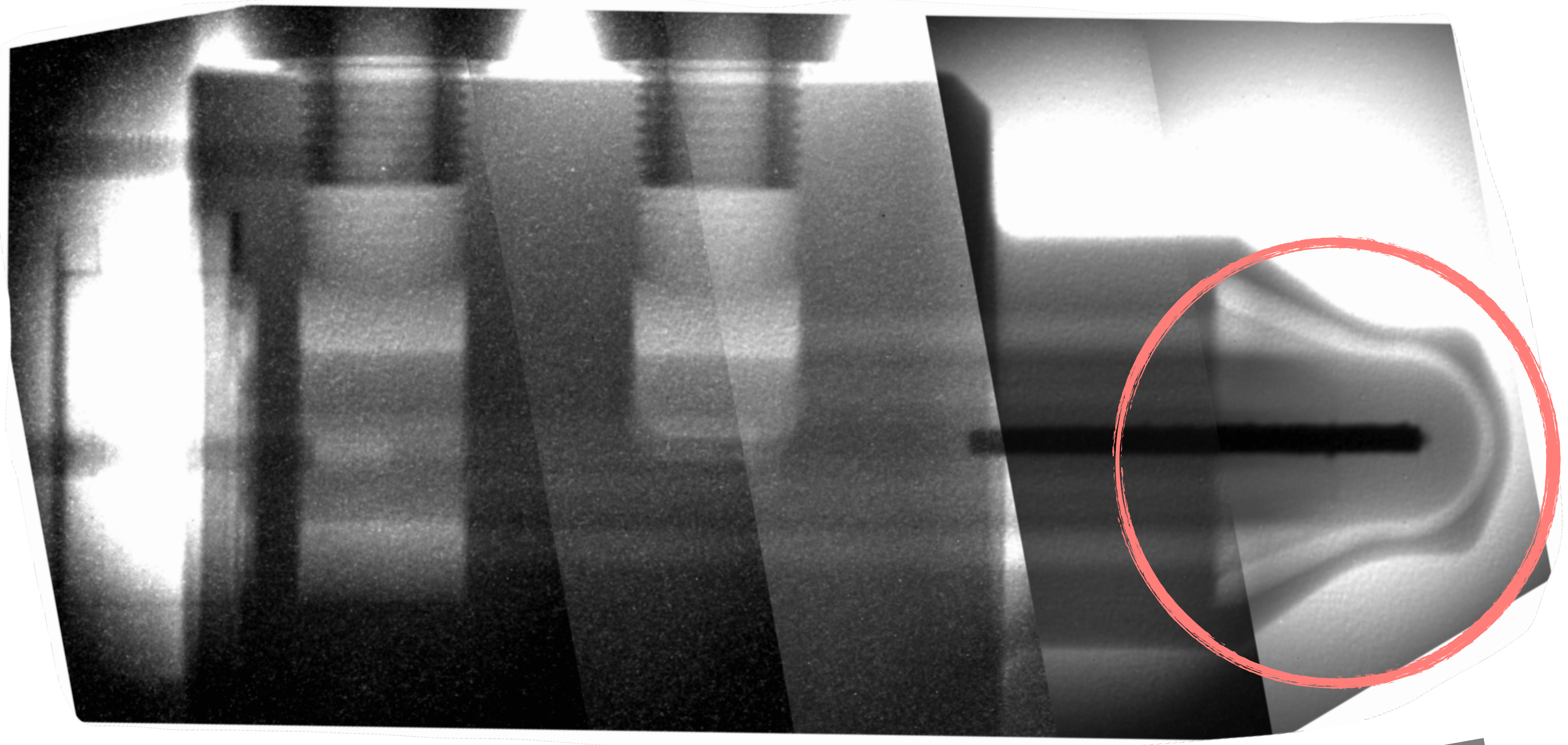
Behind neutron-induced reactions: neutron Imaging @ EAR2

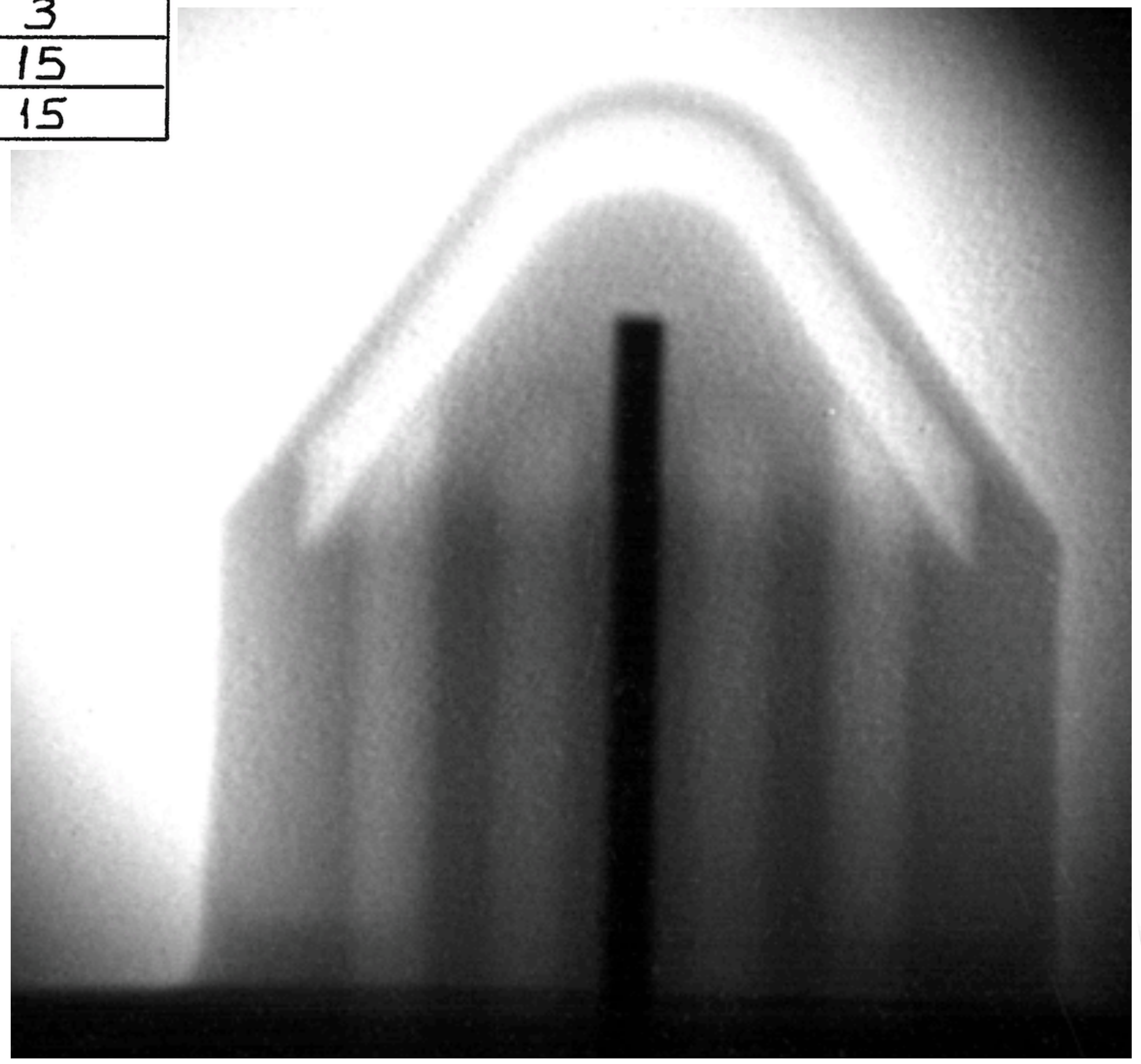
Inspection of a spent Antiproton Decelerator target

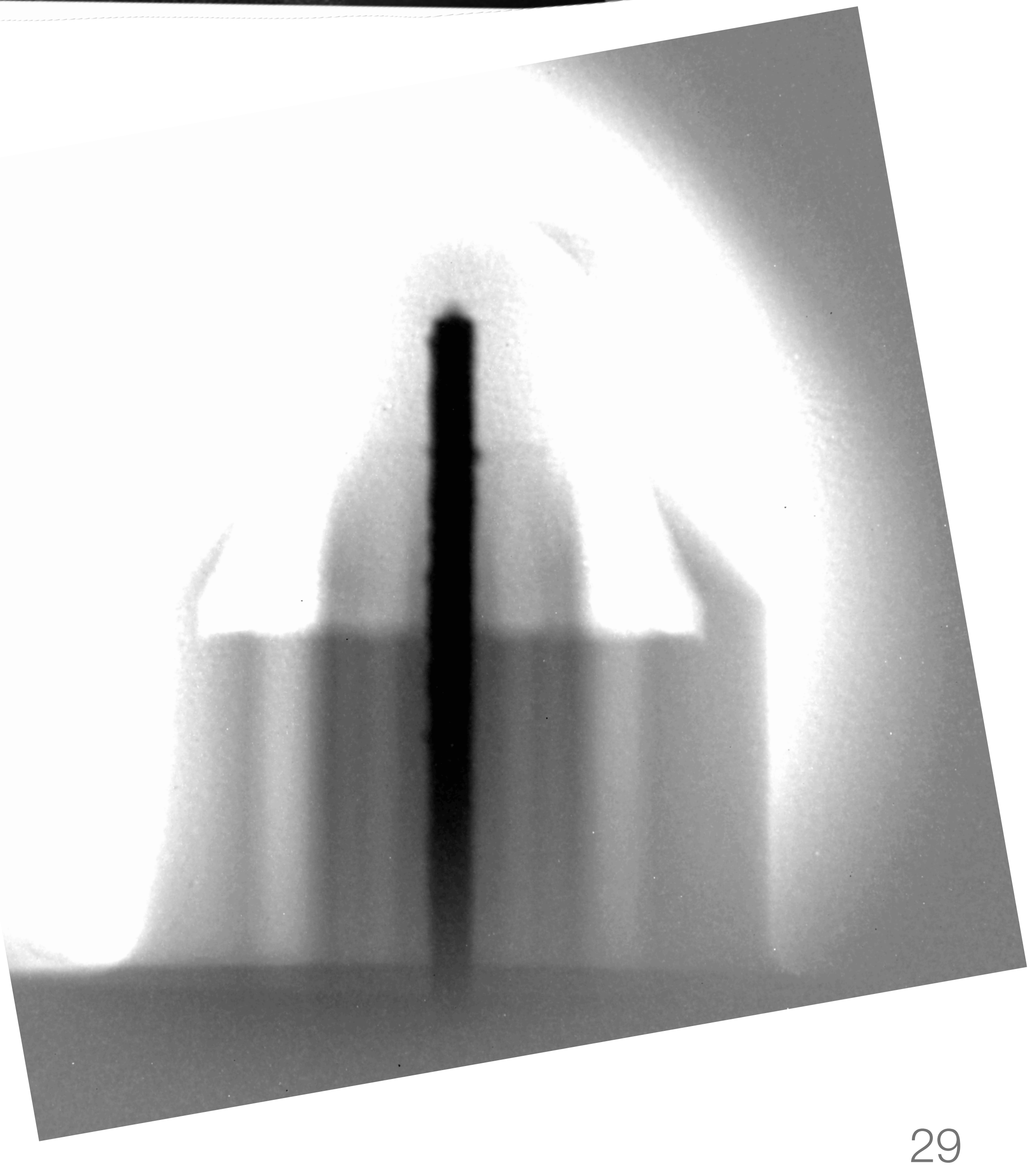
- Highly radioactive (≈ 5 mSv/h @ 10 cm)
- Automated measuring station
- Handling of the target with CERNbot and Teodor robots



SPECIFICATION REMPLISSAGE		
MATIERE	LONGUEUR	DIAMETRE
Graphite	4.5	–
Alumine	1	6
Iridium	55	3
Graphite	23	15
Titane	3.5	15







Conclusions and perspectives

- The n_TOF facility exploits as a powerful **neutron source** a pulsed proton beam (20 GeV/c) from the CERN Proton Synchrotron coupled to a lead spallation target
- Unique characteristics: very **high resolution** neutron spectrometer exploiting a **white energy spectrum** and a very **high instantaneous flux**
- The Class-A experimental areas combined with flexible detection systems allows to perform a variety of **neutron-induced cross section measurements** and to be exploited for technical application as **neutron imaging**
- n_TOF after LS2

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  - **Neutron beam-line:** neutron imaging material-selective, irradiation station with Target #3

Conclusions and perspectives

- The n_TOF facility exploits as a powerful **neutron source** a pulsed proton beam (20 GeV/c) from the CERN Proton Synchrotron coupled to a lead spallation target
- Unique characteristics: very **high resolution** neutron spectrometer exploiting a **white energy spectrum** and a very **high instantaneous flux**
- The Class-A experimental areas combined with flexible detection systems allows to perform a variety of **neutron-induced cross section measurements** and to be exploited for technical application as **neutron imaging**
- n_TOF after LS2
  - **Proton beam - target assembly:** higher proton intensity (up to 10^{13} ppp), double bunch spill from PS Booster
  - **Neutron beam-line:** neutron imaging material-selective, irradiation station with Target #3
  - **Detection techniques:** gaseous targets, γ spectrometry with Ge detectors, position sensitive scintillators for (n,γ) measurements (i-TED)

THANK YOU FOR YOUR ATTENTION!

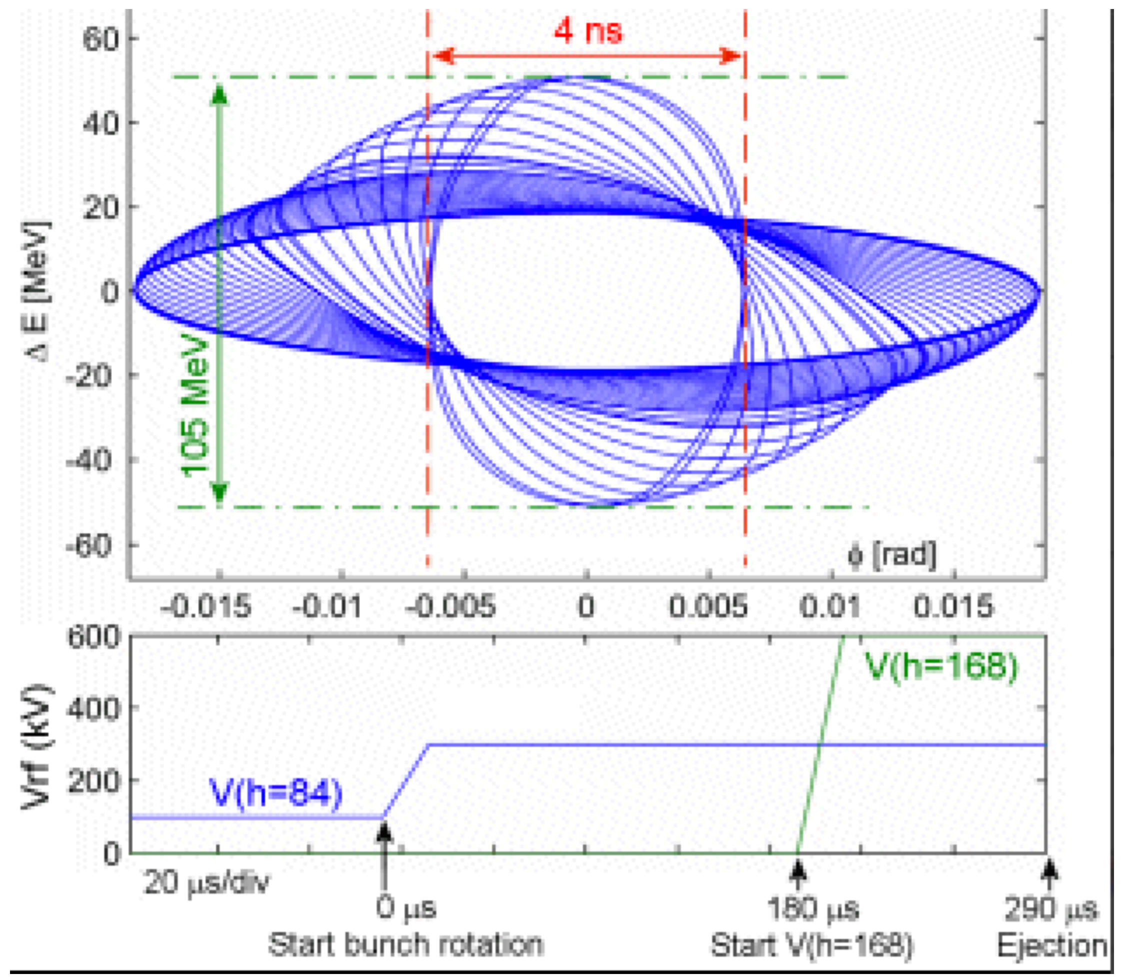
Federica Mingrone

federica.mingrone@cern.ch

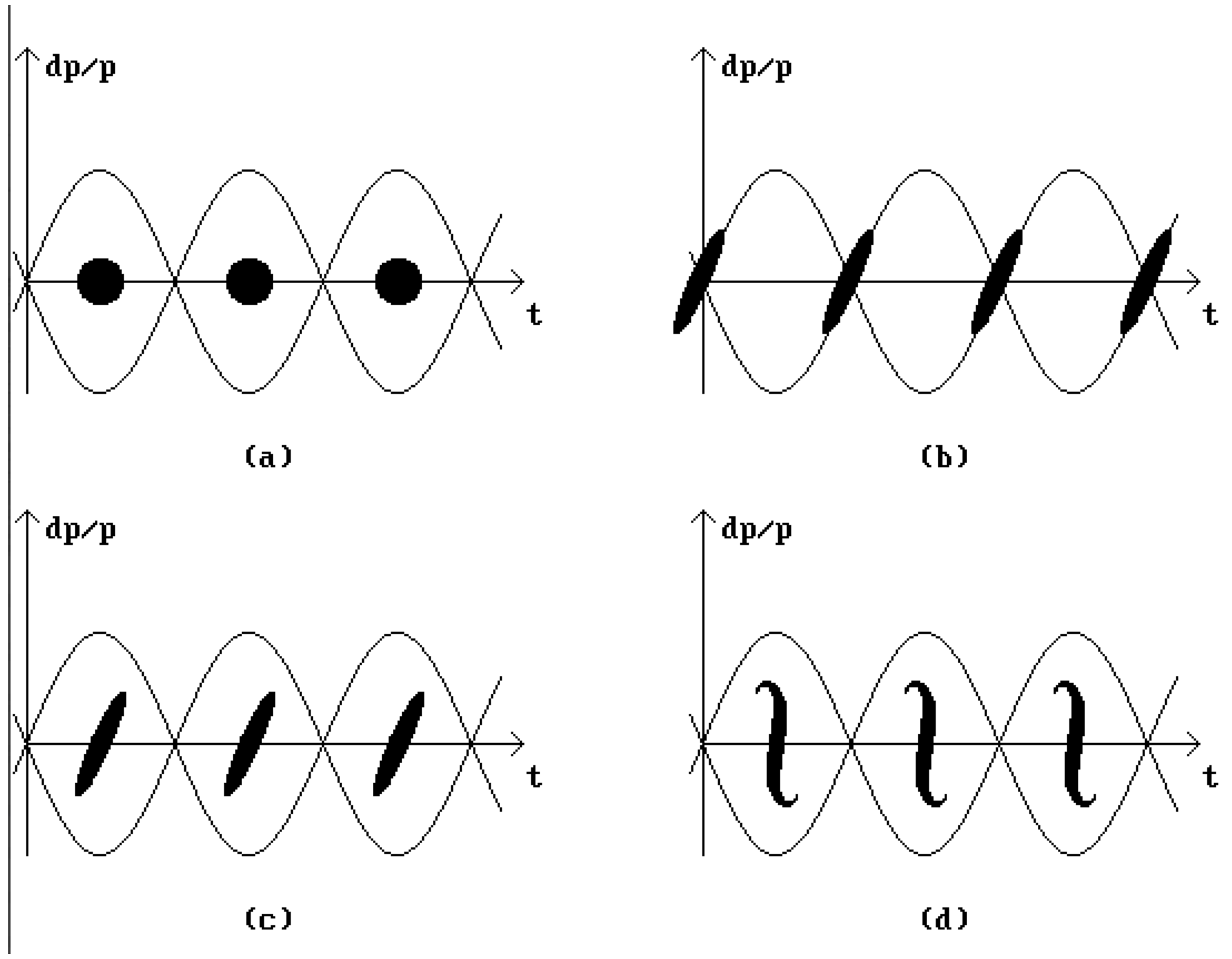
Bunch rotation

- Used to shorten the bunch length just before extraction
- The bunch is rotating in longitudinal phase space with its synchrotron frequency inside its RF-bucket
- It oscillates between a big amplitude with a short bunch length and vice versa
- Two ways to start a bunch rotation:
  1. Drastic and sudden increase of the cavity voltage → used with 80 MHz cavities
  2. Sudden change of phase by 180° between bucket and bunch. The bunch starts to stretch along the separatrix. Not to lose the beam outside of the bucket it is necessary to jump back after short time to the original phase → used with 10 MHz cavities (limitation of the RF-voltage). Used for n_TOF as the H8 does not allow to use the 80 MHz cavities.
- Duration of the bunch rotation: depends on the speed of bunch lengthening. If applied too long, the bunch cannot be recaptured completely (normally below one quarter of a synchrotron period).
- End of the bunch rotation: difficult to come back to the exact initial conditions as before starting the bunch rotation, but one can still achieve it partly. To stop the bunch rotation the same methods as for starting it are used for a quarter of synchrotron period at the proper instant. If the bunch rotation is not stopped a filamentation will start, resulting in a blow up of the beam.

1)



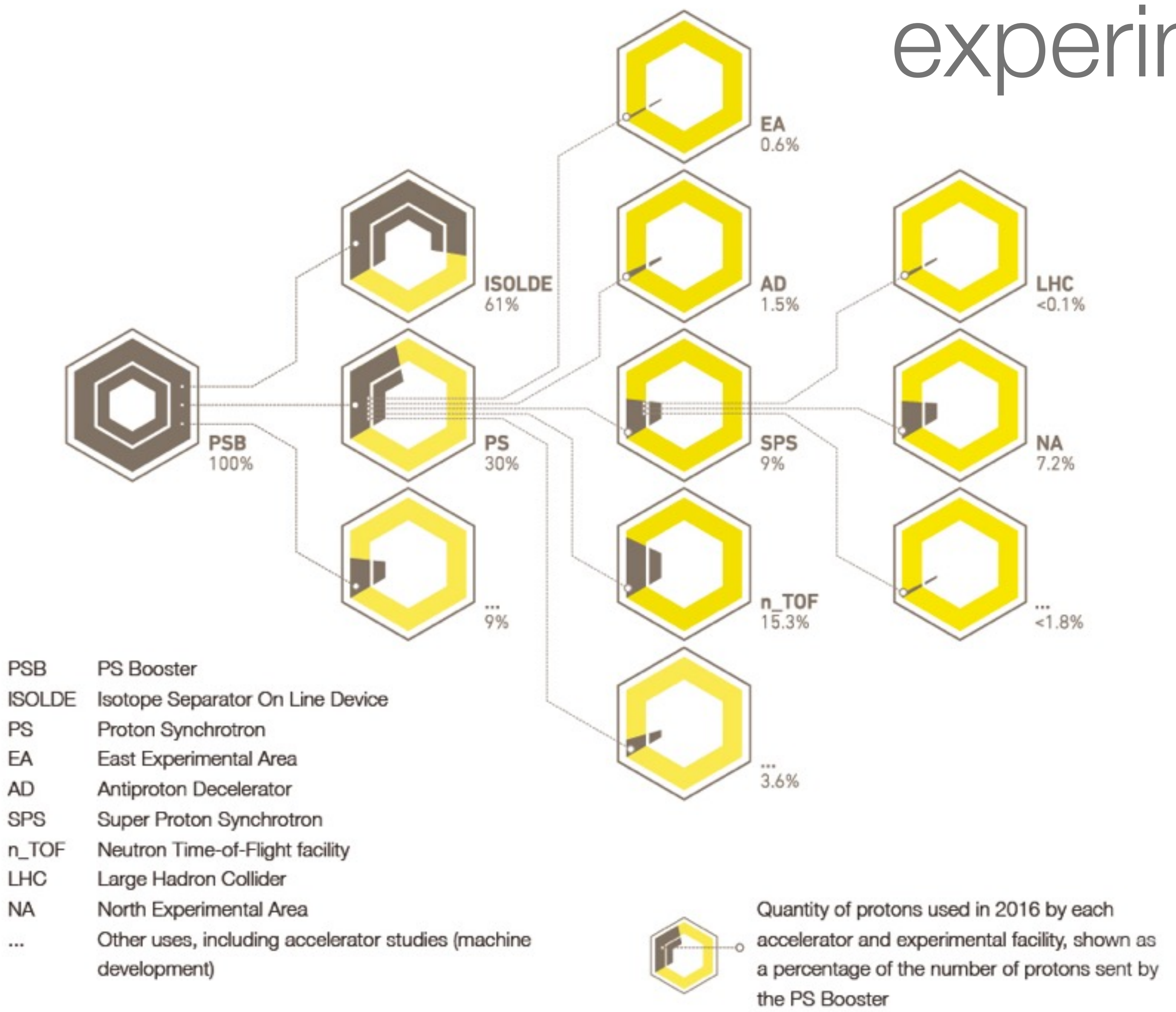
2)

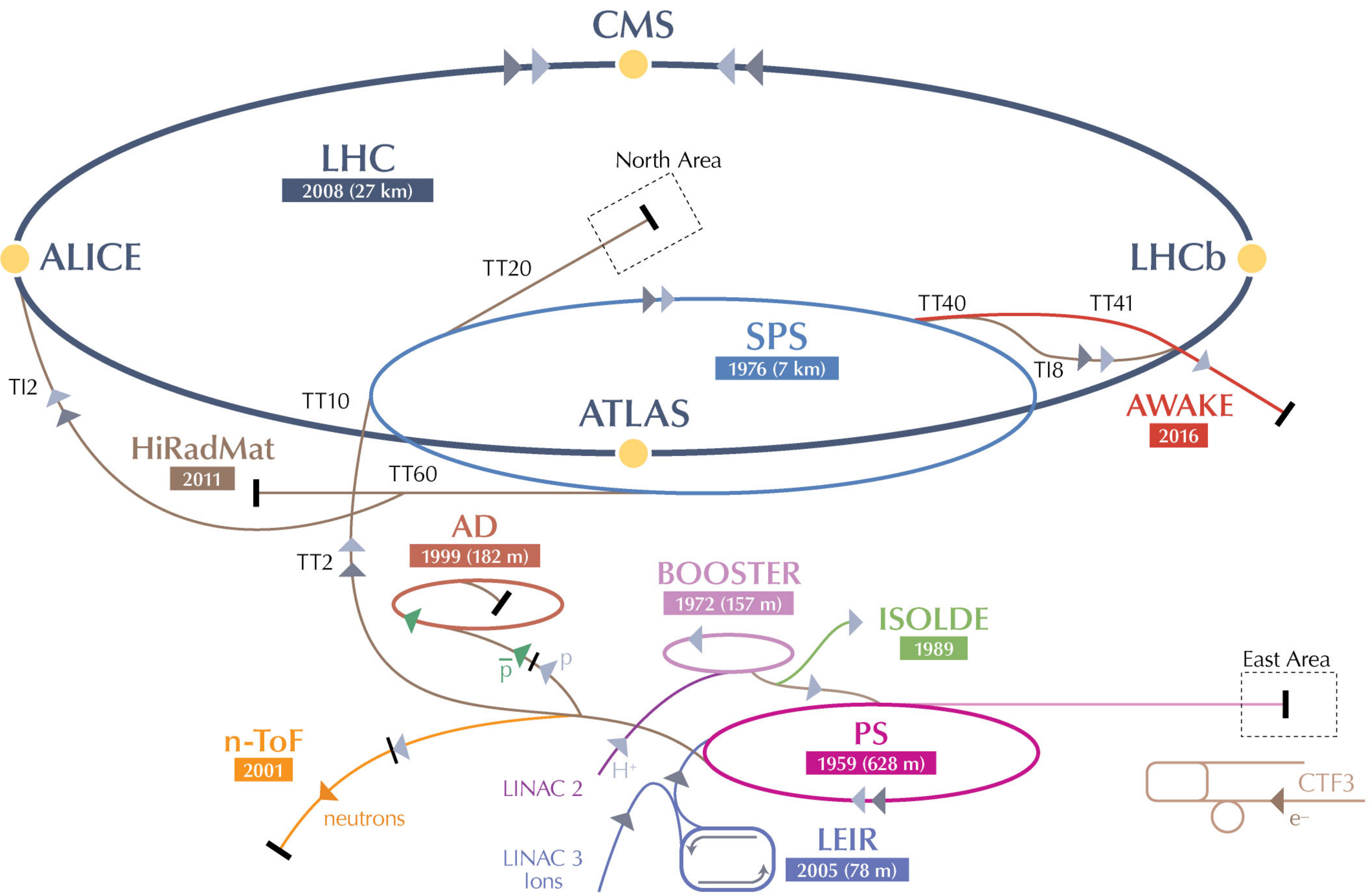


The n_TOF facility @ CERN

CERN: European Organization for Nuclear Research (Geneva, Switzerland)

- Since 1954
- Various accelerator complex
- More than LHC: injectors "feeding" minor experiments

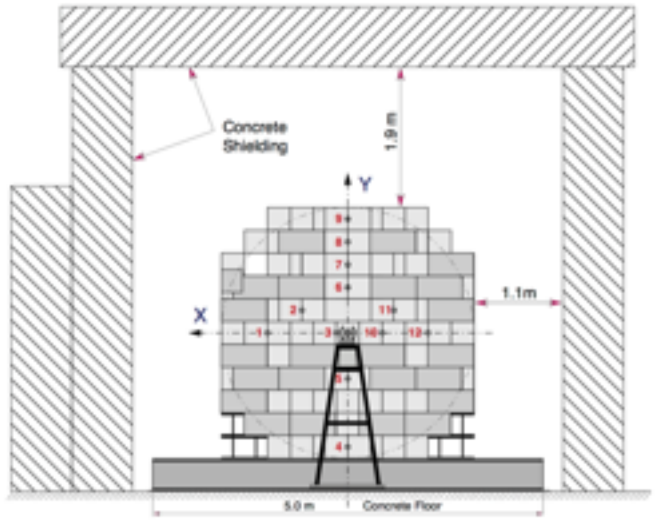




The n_TOF facility: timeline

1996 — **2018**

1995 – 1997



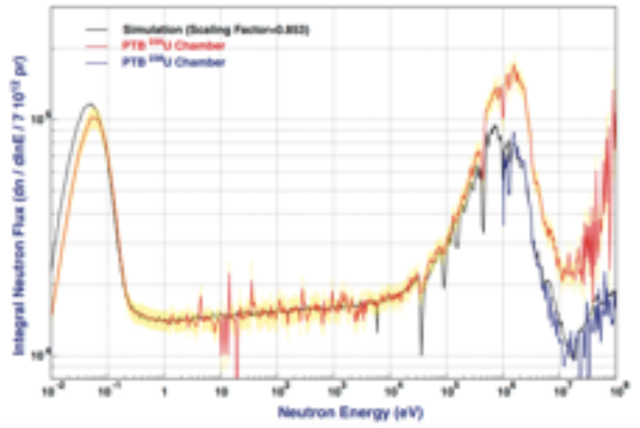
TARC Experiment

May 1998

Feasibility
CERN/LHC/
98-02+Add

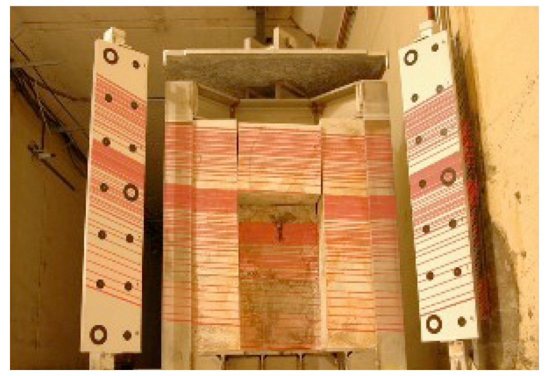
2000

Commissioning



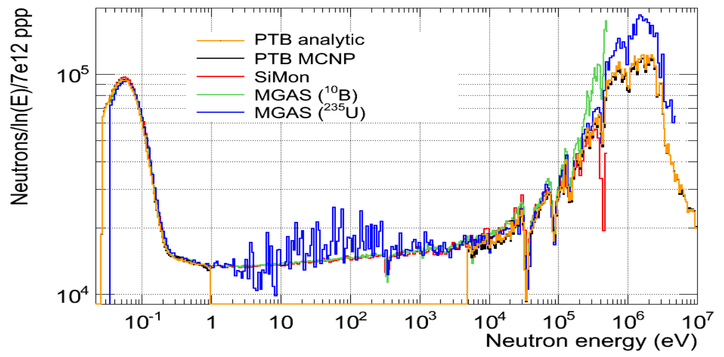
2004-2007

Target activation
R&D of new
solutions



May 2009

Commissioning

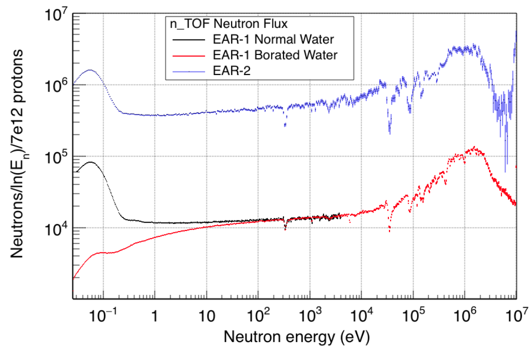


2009

Upgrades
Borated-H_2O
Class-A
Second Line

2014

Commissioning



2019 – …

Future
Target #3
Irradiation
station
…

1997

Concept
by C. Rubbia
CERN/ET/Int.
Note 97-19

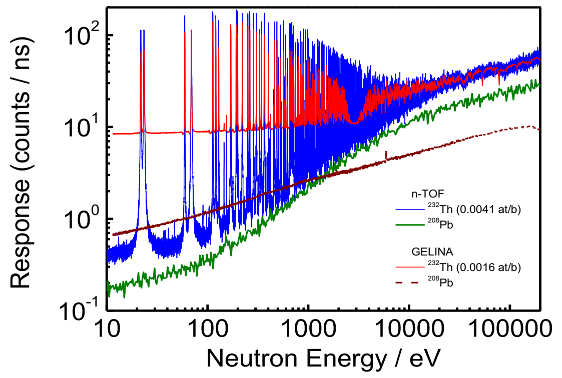
Aug 1998

Proposal
submitted

1999

Construction
started

2001 – 2004

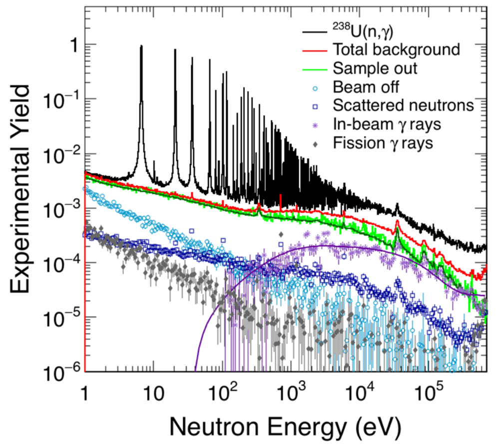


Phase I
Isotopes
Capture: 25
Fission: 11

2008

Target #2
construction

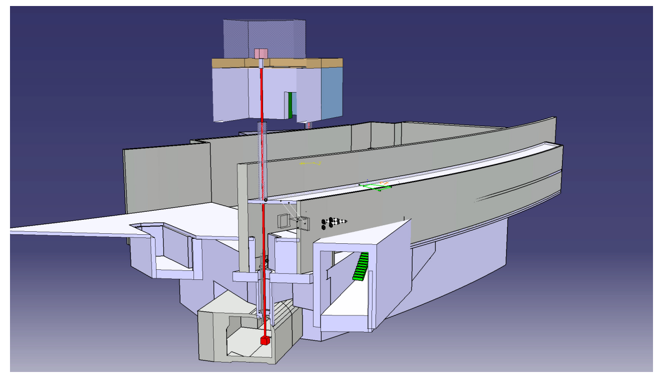
2009 – 2012



Phase II
Isotopes
Capture: 14
Fission: 3
(n,cp): 2

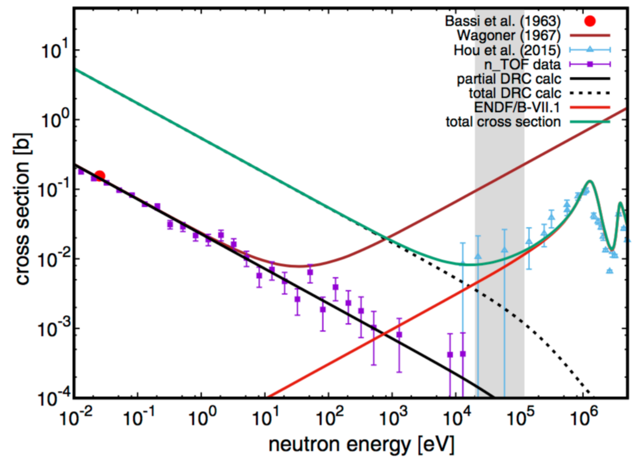
2011 – 2013

EAR2
Design and
Construction



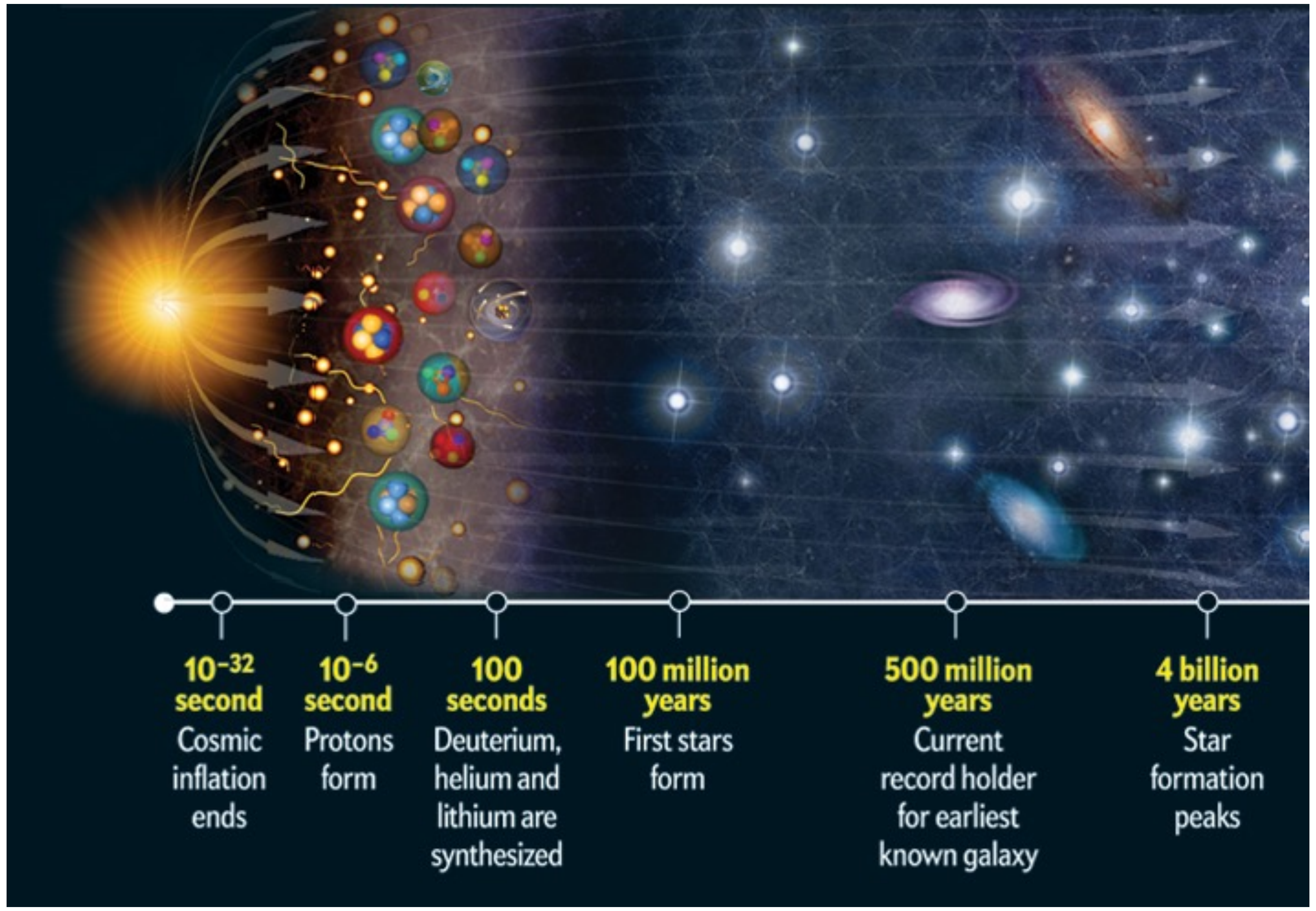
2014 – 2018

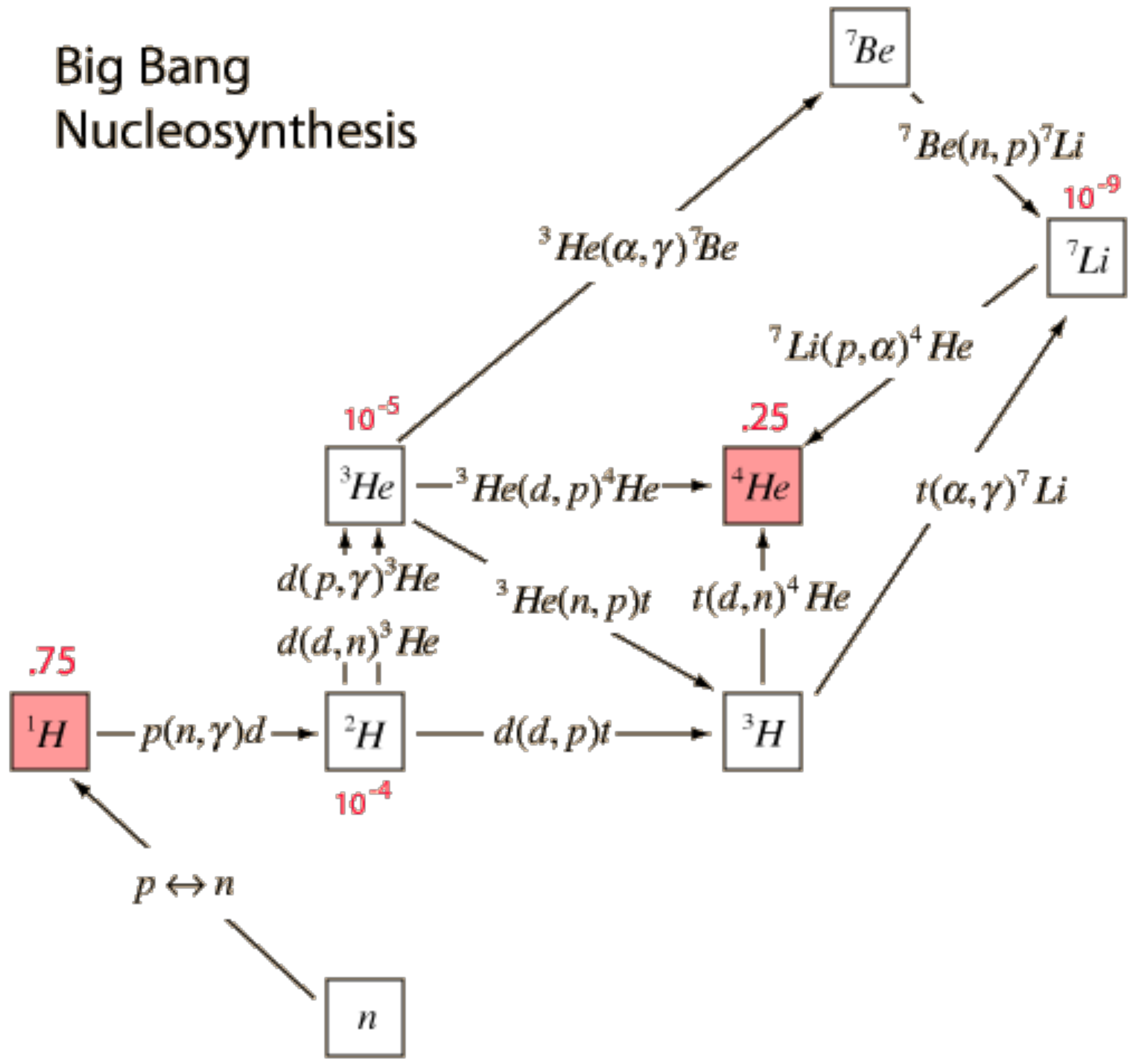
Phase III
Isotopes
Capture: 18
Fission: 5
(n,cp): 9
Neutron Imaging

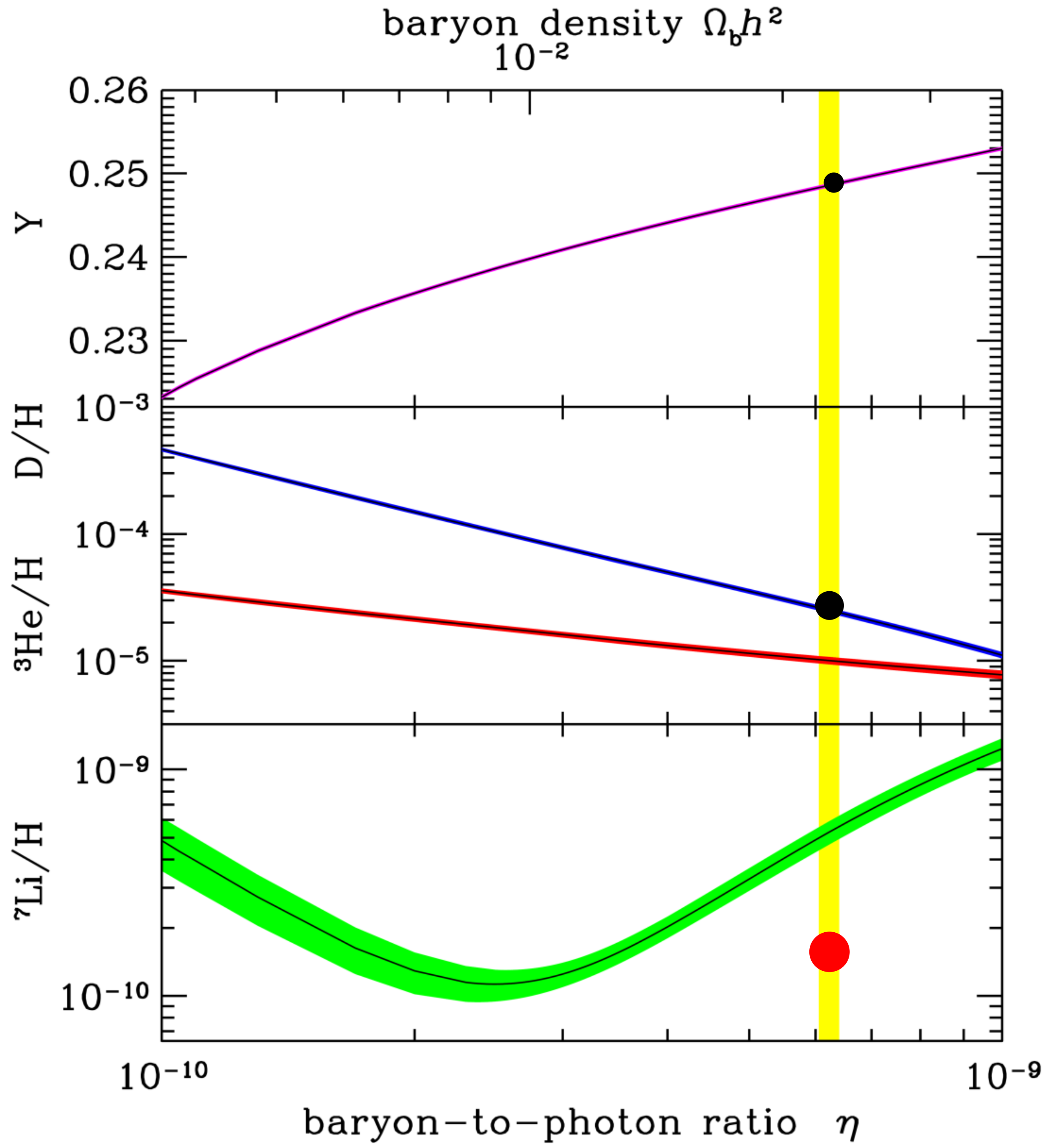


Big Bang Nucleosynthesis

- The BBN Theory defines the nuclear-reaction chain which leads to the formation (synthesis) of the lightest elements in the initial phase of the Universe (0.001 to 200 s)
- Conditions are similar to those that exist in stars today or in thermonuclear bombs. Heavier nuclei such as deuterium, helium and lithium soak up the neutrons that are present
- The remaining neutrons either decay (τ~1000 s) or **induce further reactions**







Cross-section measurement on ^{7}Be(n,α) and ^{7}Be(n,p) @ EAR2: See talk by M. Mastromarco

Stellar Nucleosynthesis: s-process

- One out of 8 physical processes responsible for the synthesis of elements in stars – M. Burbridge, G.R. Burbidge, W.A. Fowler and F. Hoyle, Reviews of Modern Physics 29 (1957)
- Based on a balance between radiative neutron-capture and subsequent beta-decays
- Production of the majority of the isotopes in the range $23 \leq A \leq 46$ (weak component) and for a considerable proportion of the isotopes in the range $63 \leq A \leq 209$ (main component)
- Time scale: from about 100 to 10^5 years for each neutron capture
- The abundance of elements in the Universe depends on the **thermodynamical conditions** of the stellar medium (temperature and neutron density) and on the **neutron capture cross-section**

REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

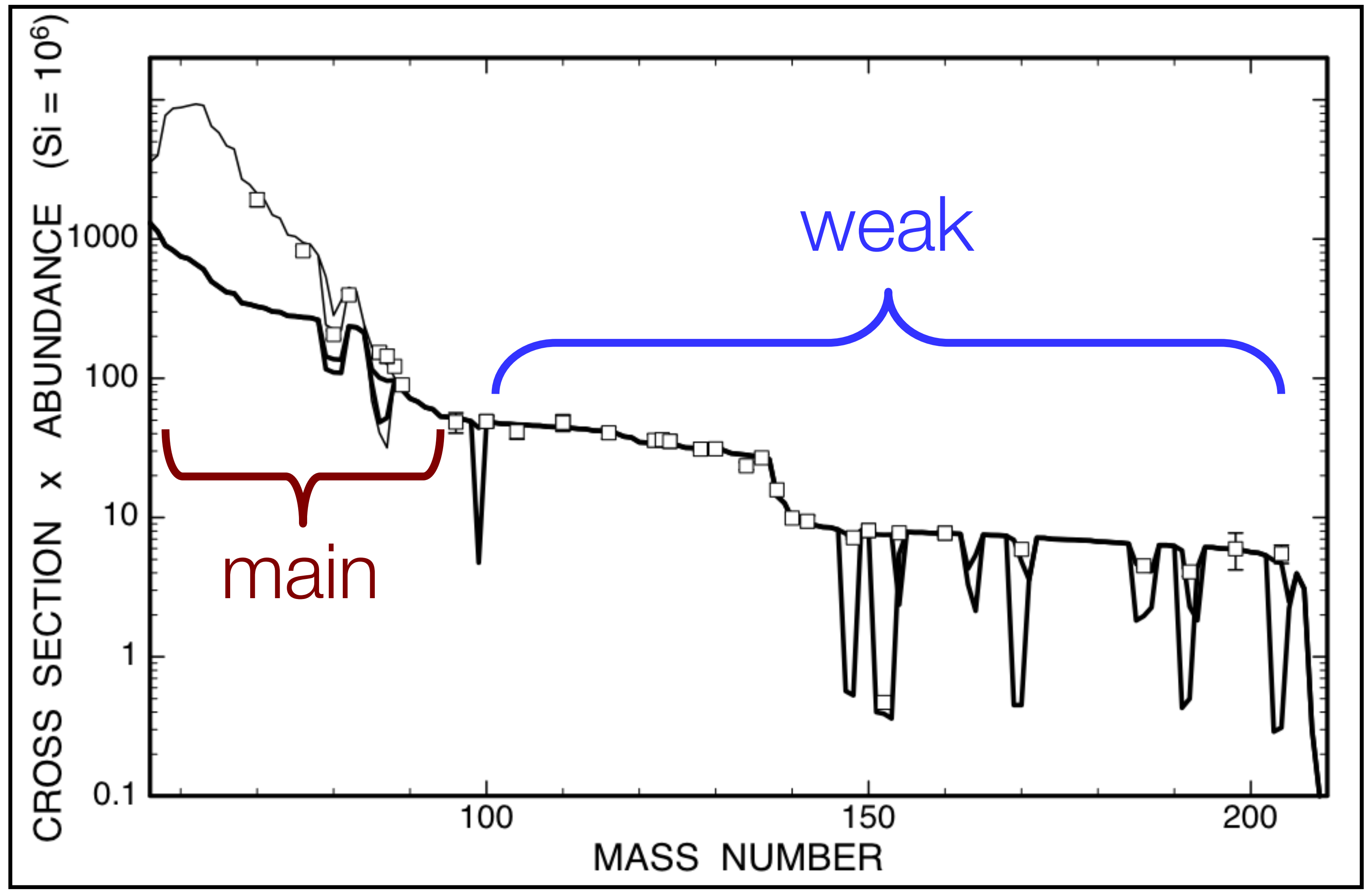
E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)



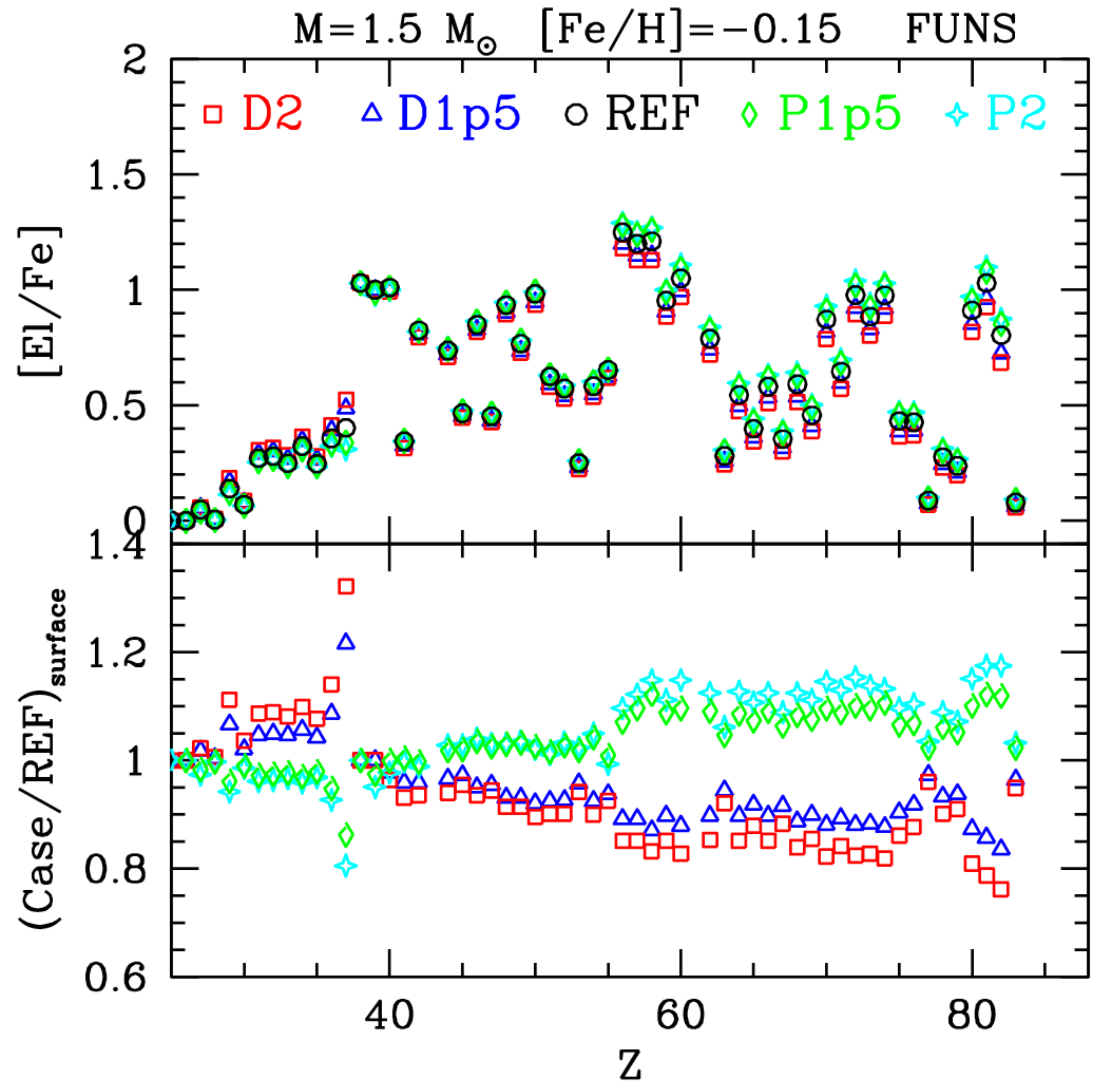
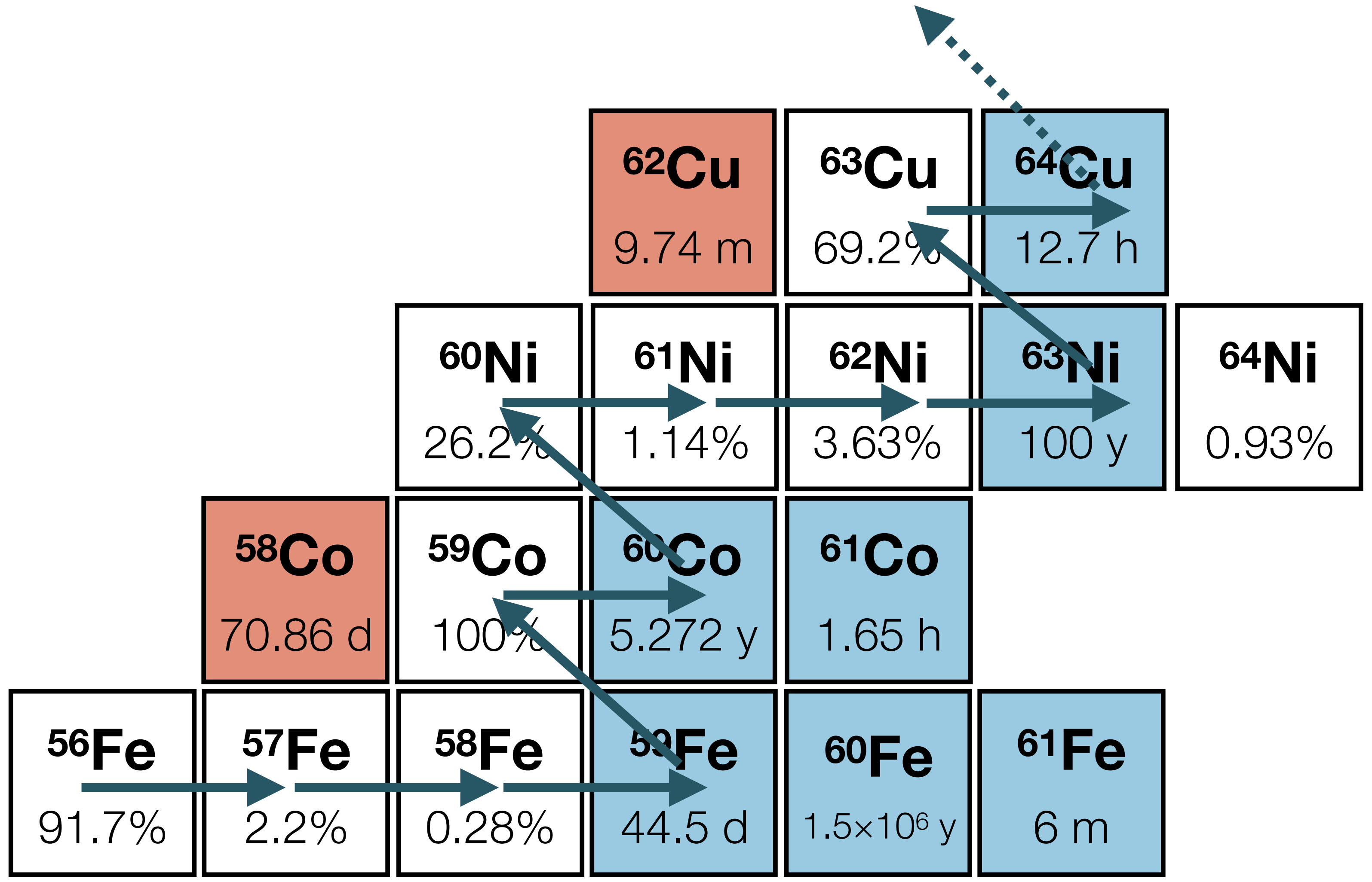


Figure 2. FUNS heavy-element surface distribution for an AGB star with initial mass $M = 1.5\ M_\odot$ and [Fe/H] = −0.15. Various symbols relate to different choices for the $^{13}C(\alpha,n)^{16}O$ rate (see text for details).

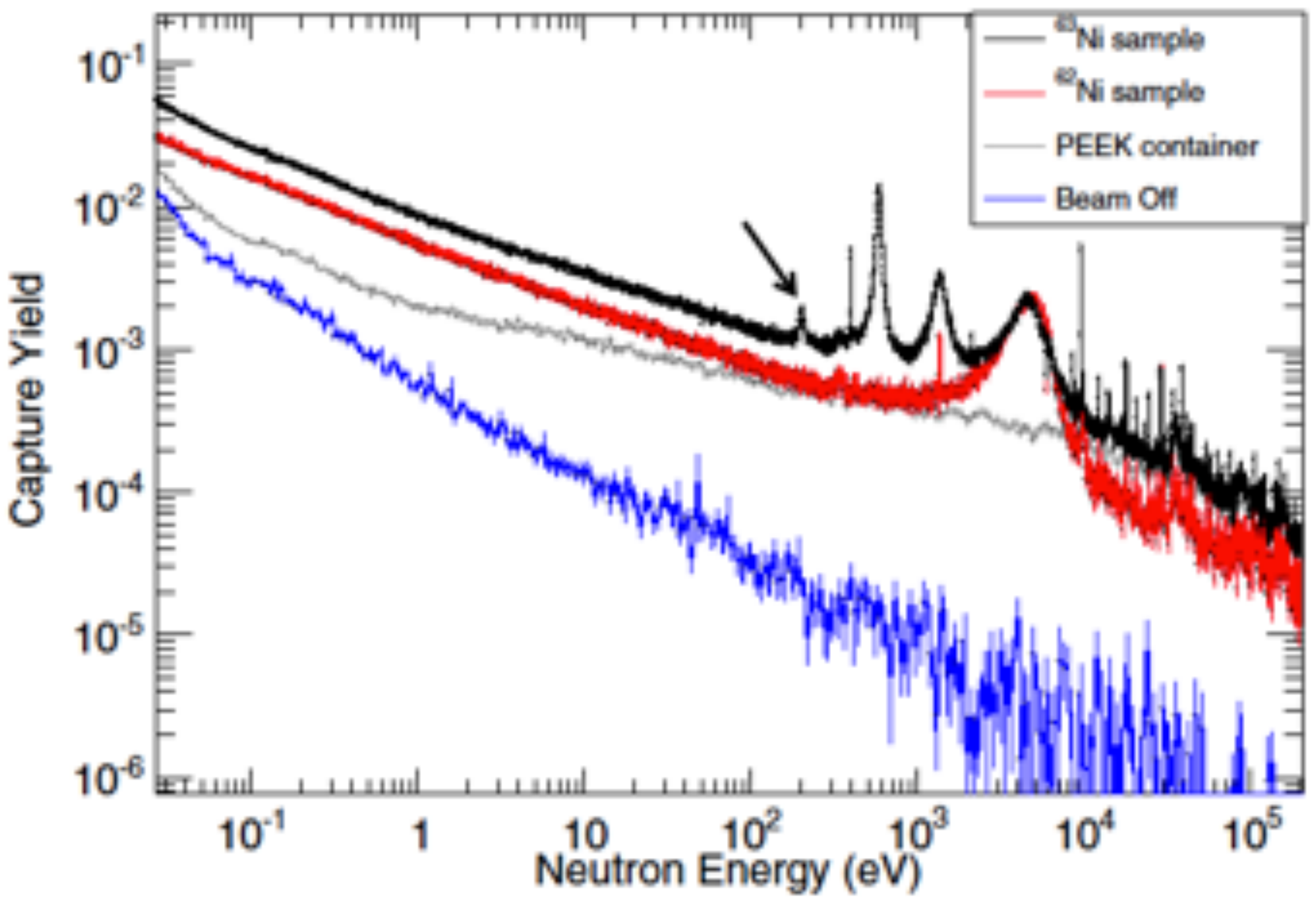
S. Cristallo et al.,
The Astrophysical Journal, 859:105 (2018)

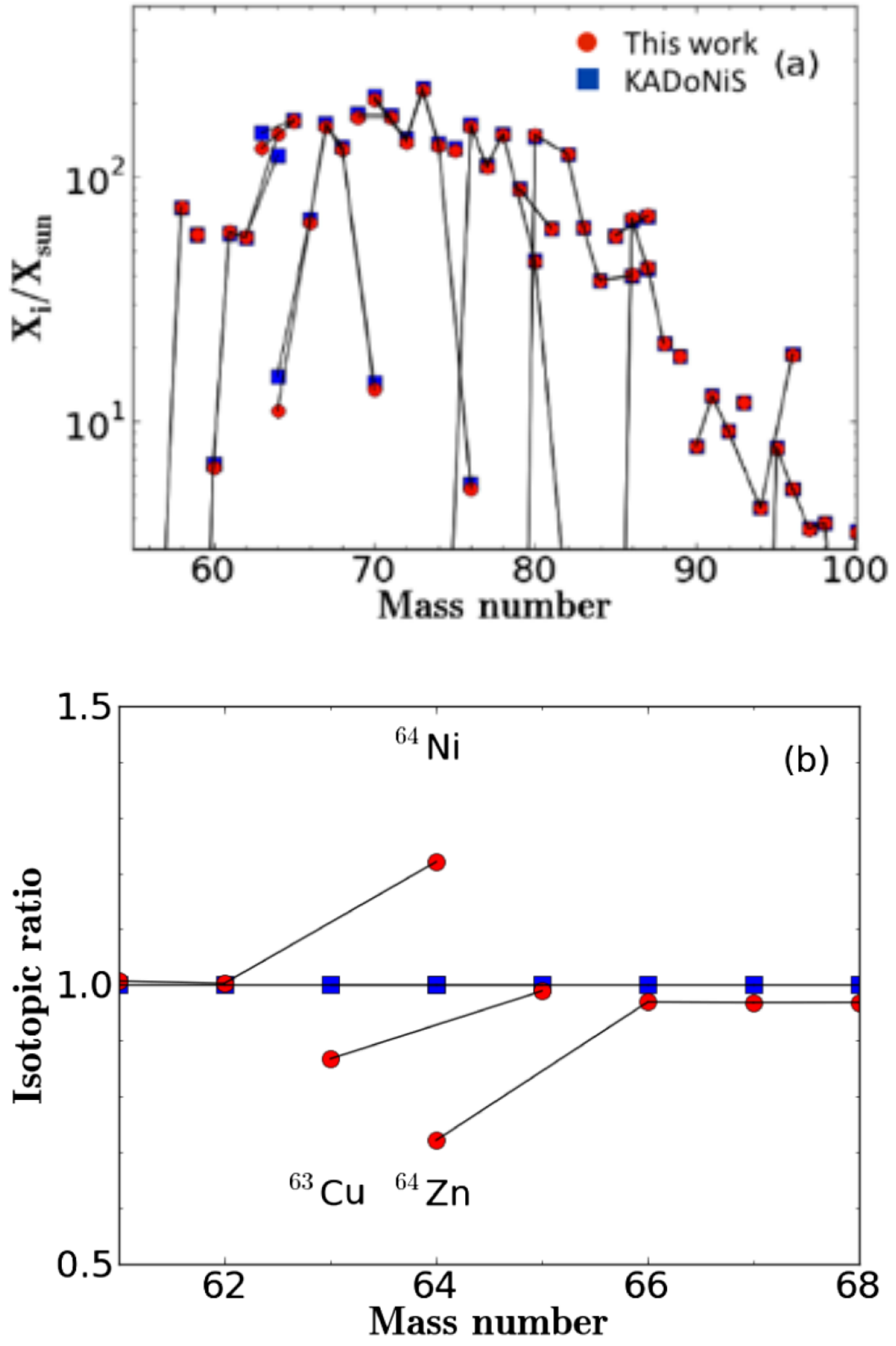
Stellar Nucleosynthesis: s-process

^{63}Ni(n,γ) – radiative capture cross section on a branching isotope



- EAR1
- Radioactive isotope ($t_{1/2}$ = 101.2 ± 1.5 yr)
  ⇒ branching point
- Sample preparation: separation of ^{63}Cu impurities
- Detection setup: C6D6 liquid scintillators





C. Lederer et al.,
Phys. Rev. Lett. 110 (2013) 022501

Nuclear technology

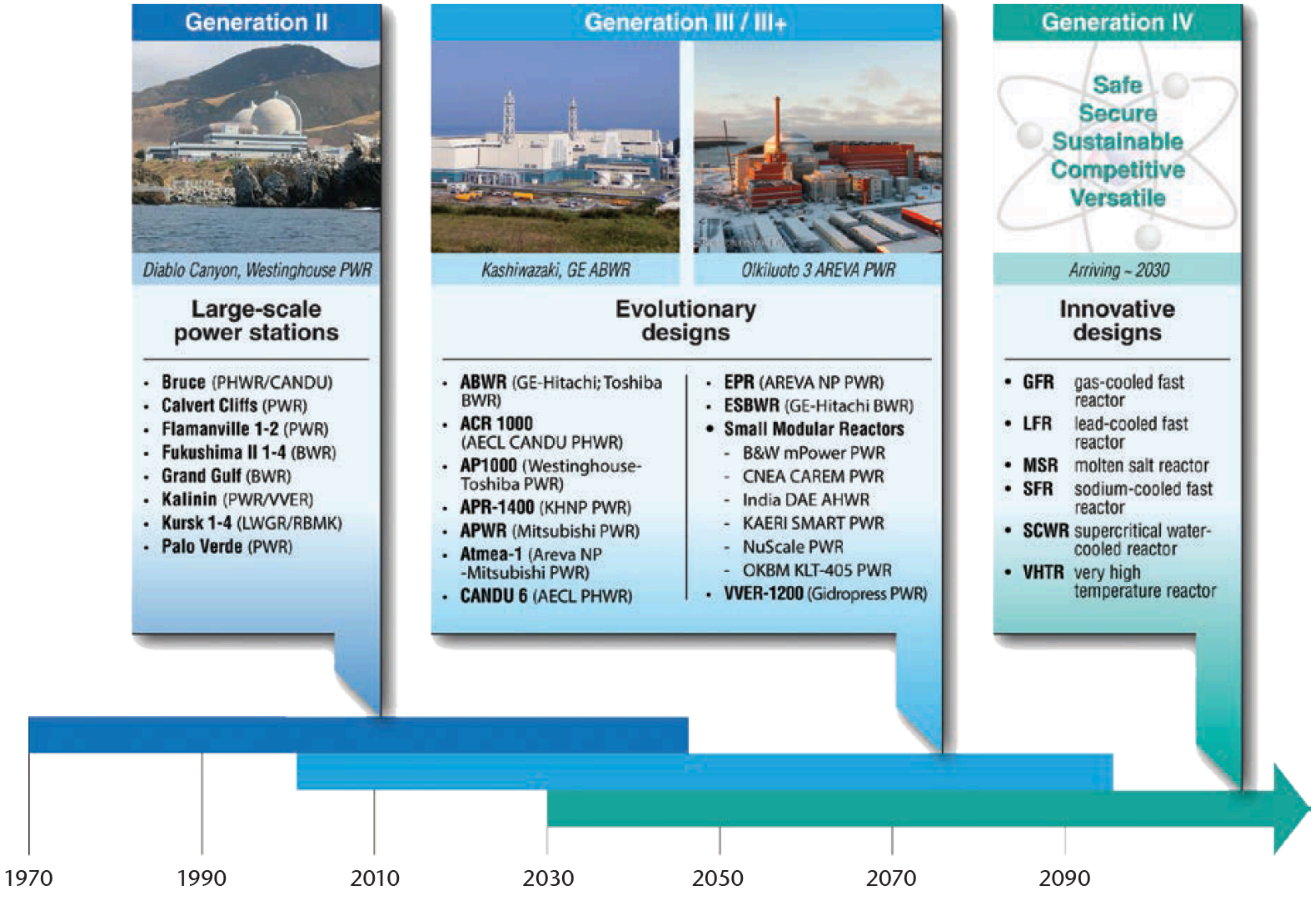
R&D to solve the longstanding problems of nuclear technologies

- Safety
- Non-proliferation
- Efficiency
- Cost effectiveness
- Waste management

New reactor concepts

- Fast reactors and ADS (new fuel cycles, e.g. Th-U)
  Multi-recycling of the fuel
  Improving waste management (reduction of the long-term radio-toxicity of the ultimate waste)
- SCWR
  higher efficiency and plant simplification
- VHTRs
  passive safety features and the ability to provide very-high-temperature process heat (used ad example in the massive production of hydrogen)

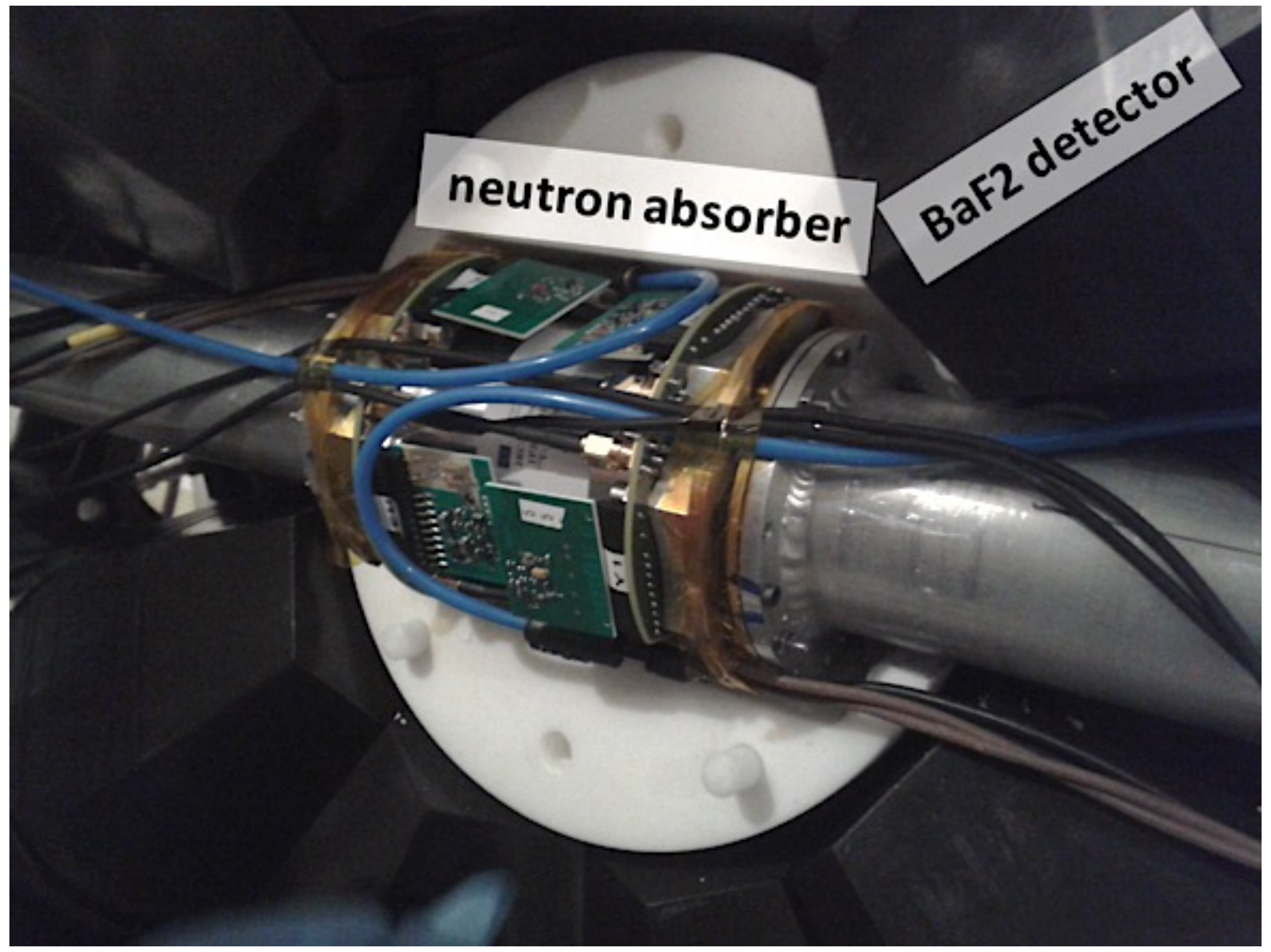
ADS
Accelerator Driven System



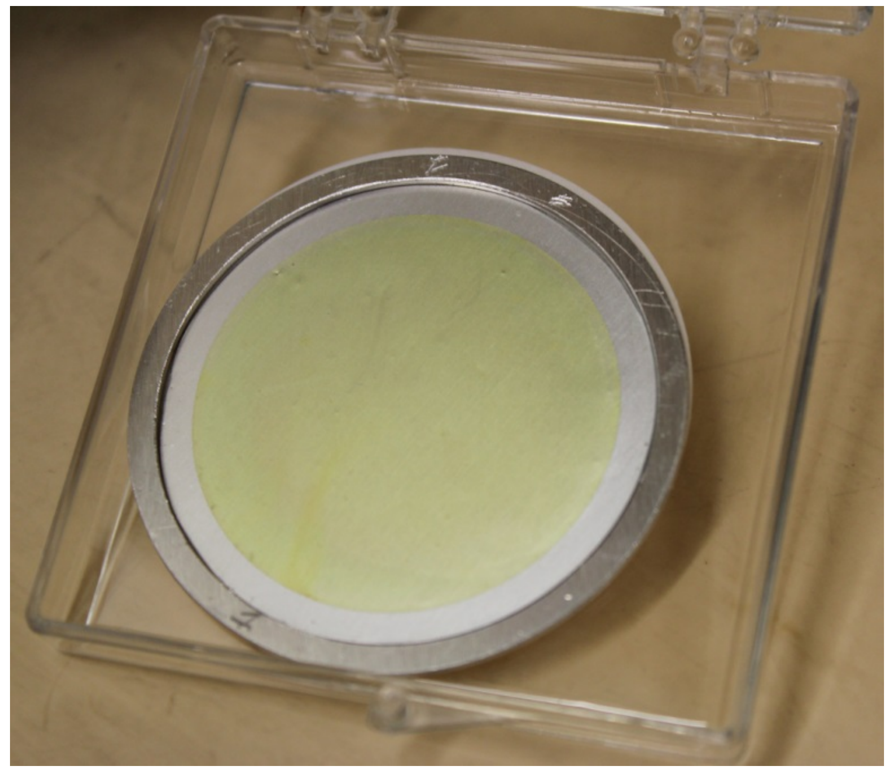
Source: Generation IV International Forum, www.gen-4.org.

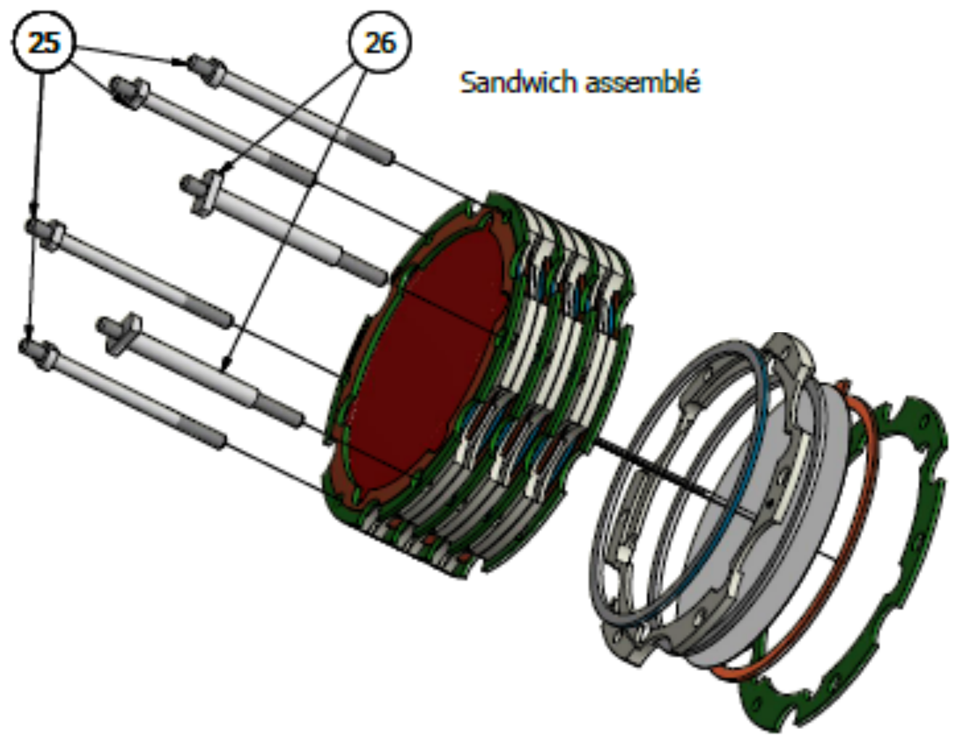
Nuclear technology

^{233}U(n,γ/f) – radiative capture cross section on a fissile isotope

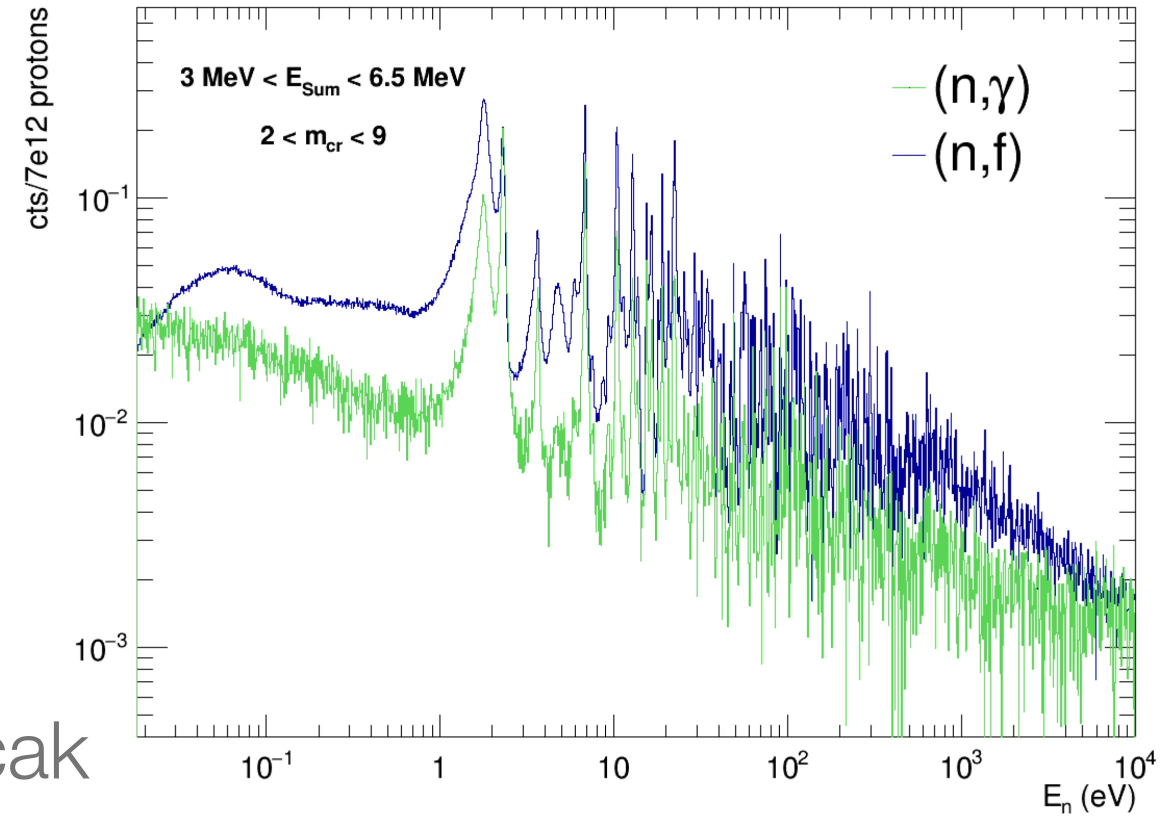


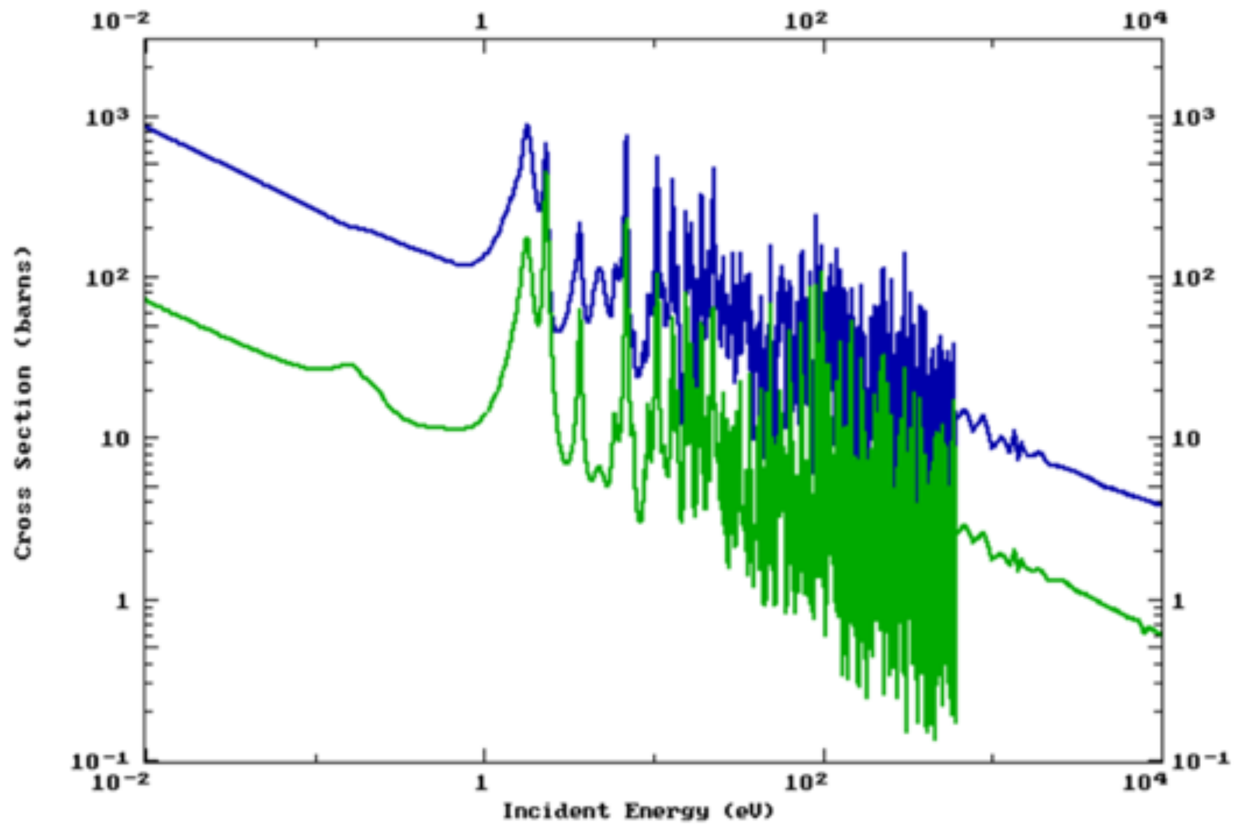
- EAR1
- Fissile isotope ($\sigma_\gamma/\sigma_f \sim 10^{-1}$), highly radioactive
- Sample preparation:
  - 14 sealed spots, high purity material
  - about 1.5 MBq/sample + very compact design $\Longrightarrow$ assembly of the samples in the fission chamber particularly challenging
- Detection setup: combined detection technique
  - Total Absorption Calorimeter (TAC): 4π array of 40 BaF crystals
  - Compact multi-plate fission chamber to be put in the TAC centre and housing 14 different samples



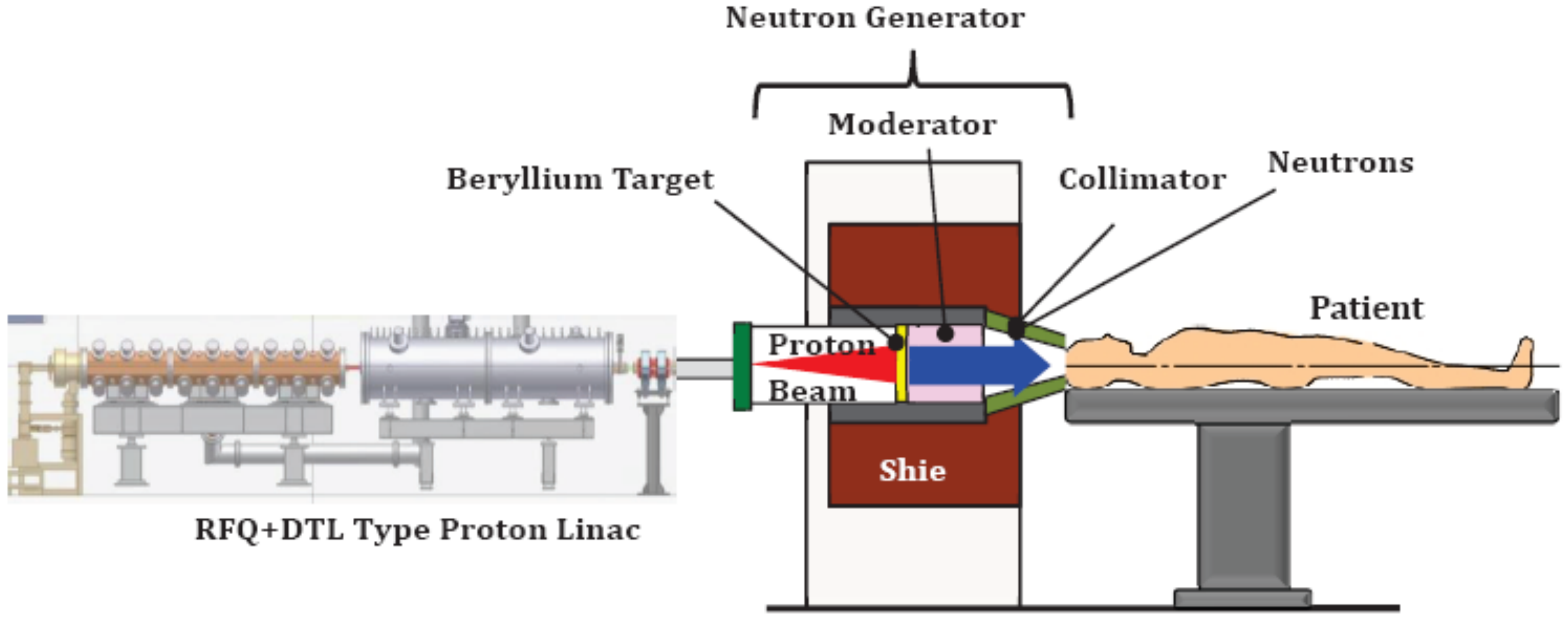


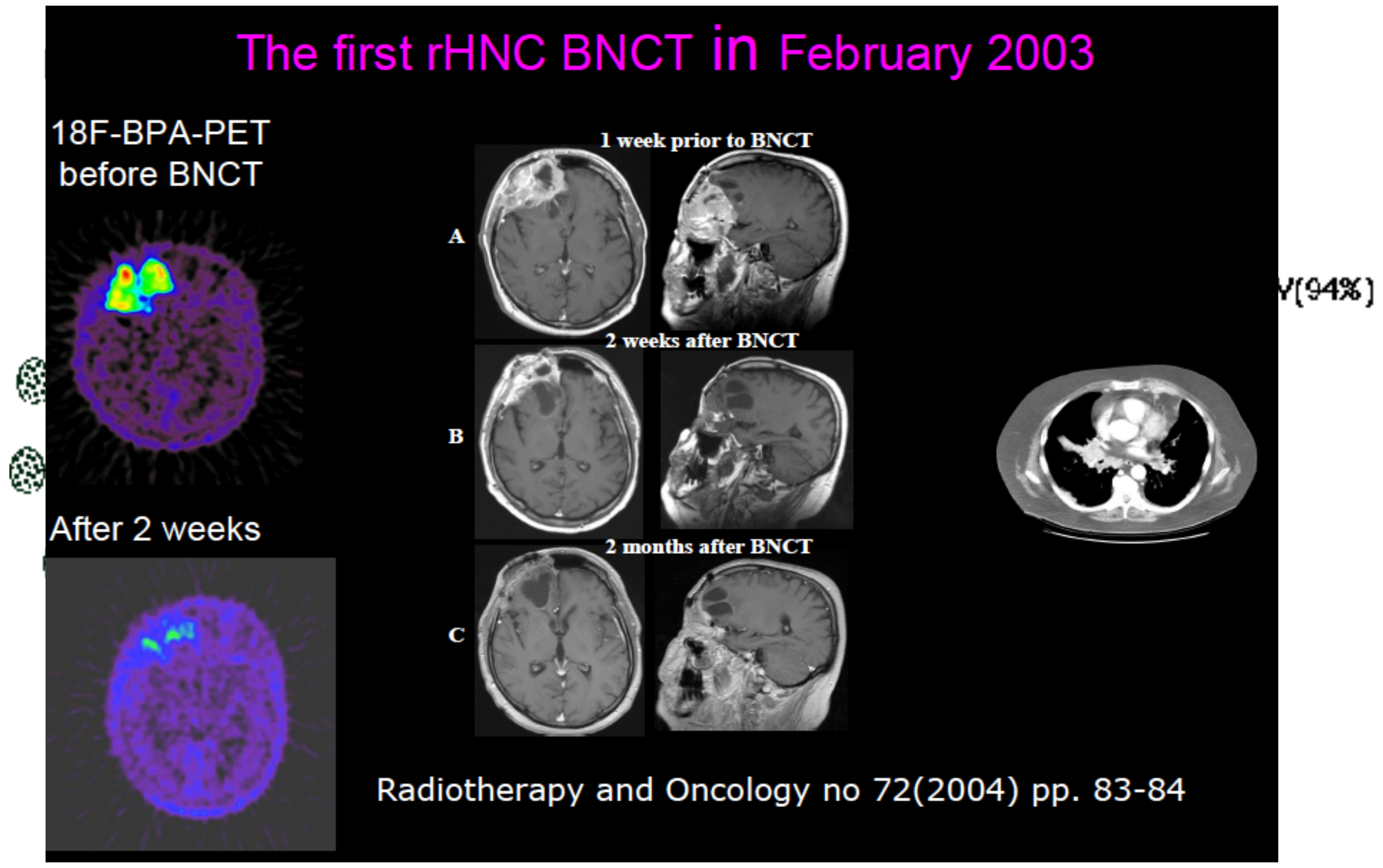
Courtesy of M. Bacak



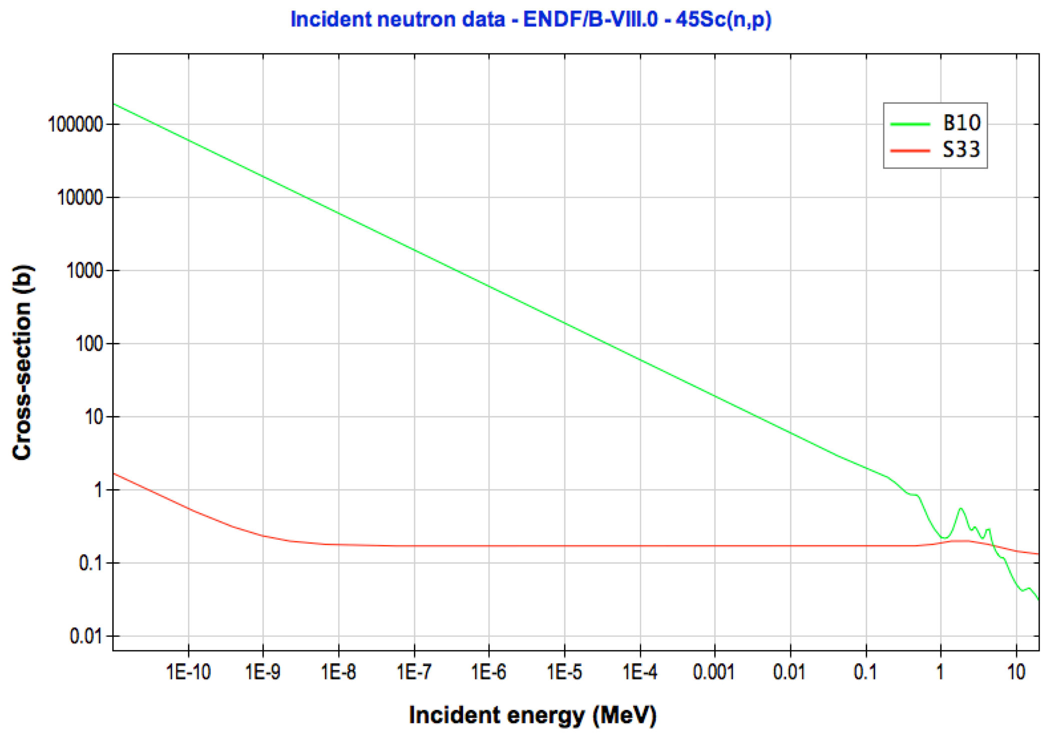


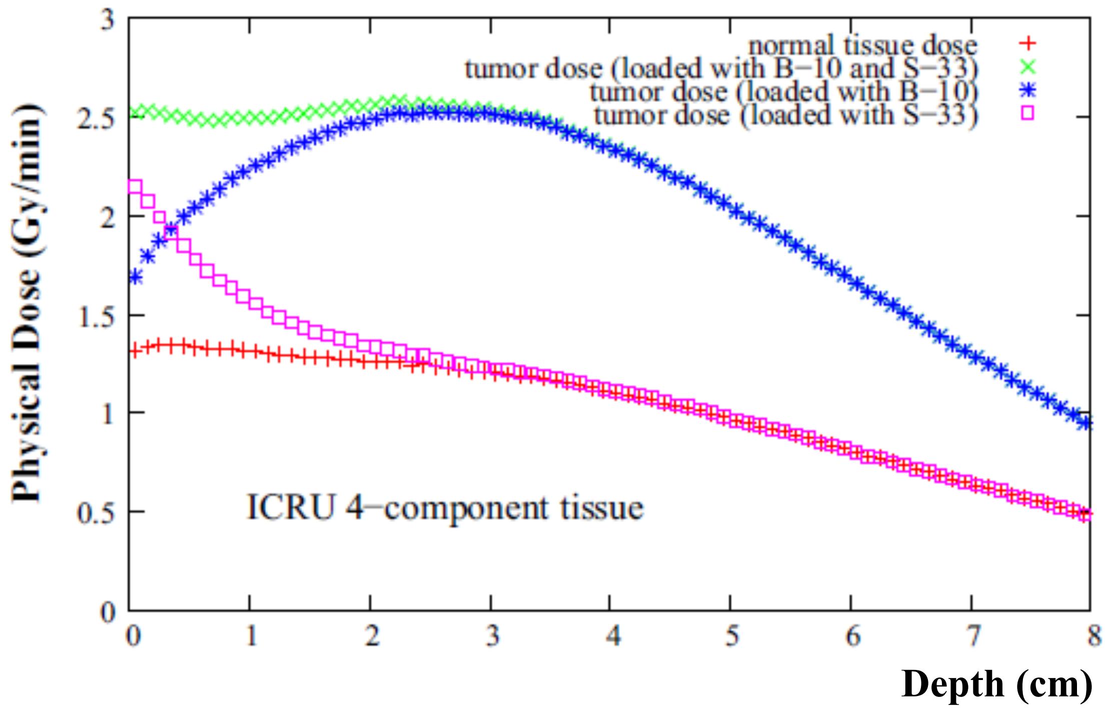
NCT – Neutron Capture Therapy





- The technique is based on the "ability" of isotopes (e.g. ^{10}B) to capture low energy neutrons.
- Chemical compounds containing the particular isotope are accumulated in the cancer cells, and the patient is afterwards irradiated with a neutron beam.
- The neutron-induced reaction generates secondary particles (e.g. alpha particles and ^{7}Li nuclei in the $^{10}B(n,\alpha)^{7}Li$) that are able to destroy the cancer cell
- **KEY QUANTITY**: neutron-induced reaction cross section σ

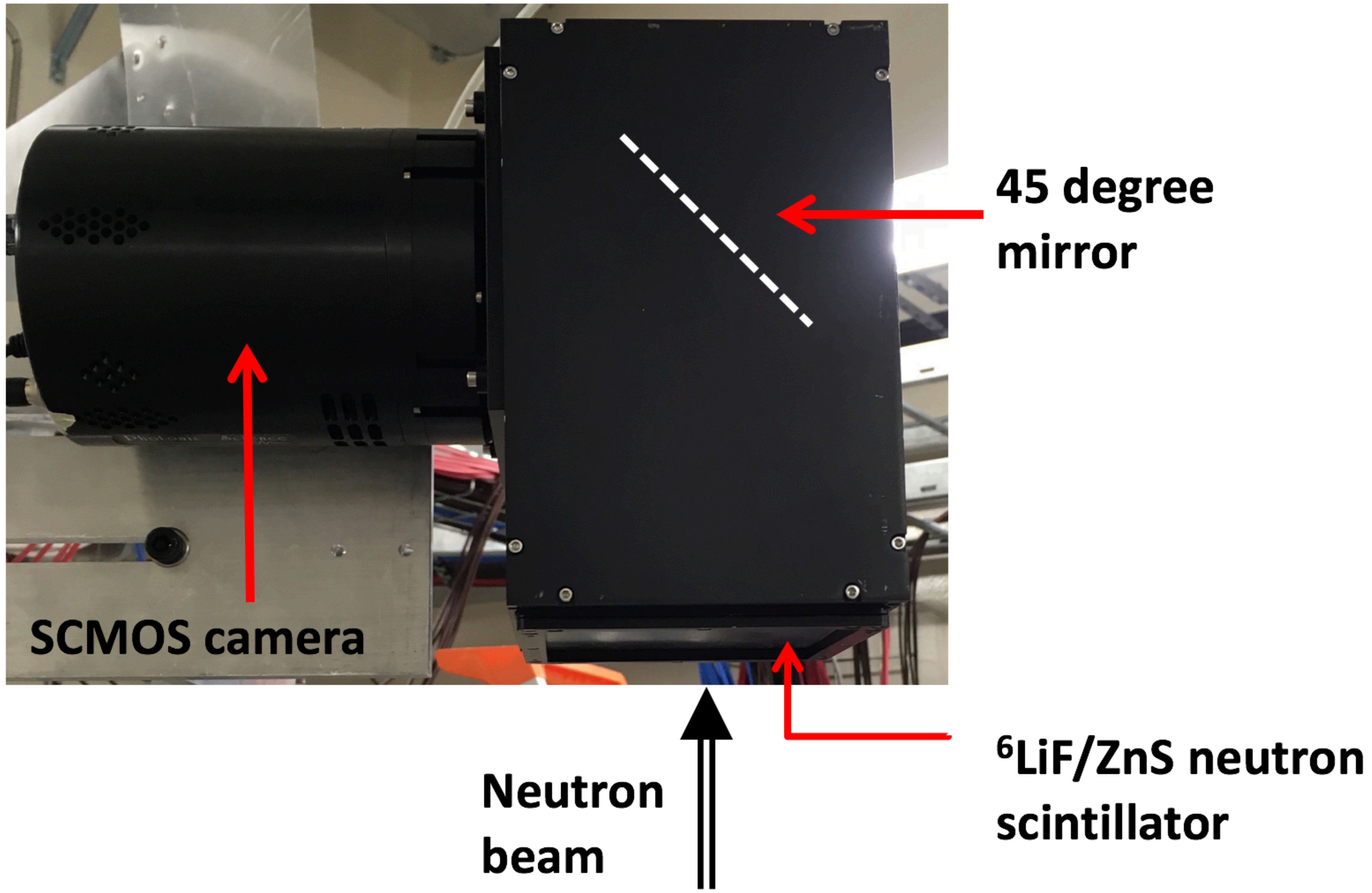




Coderre et al., J. Nucl. Med. 27, 1157 (1986)

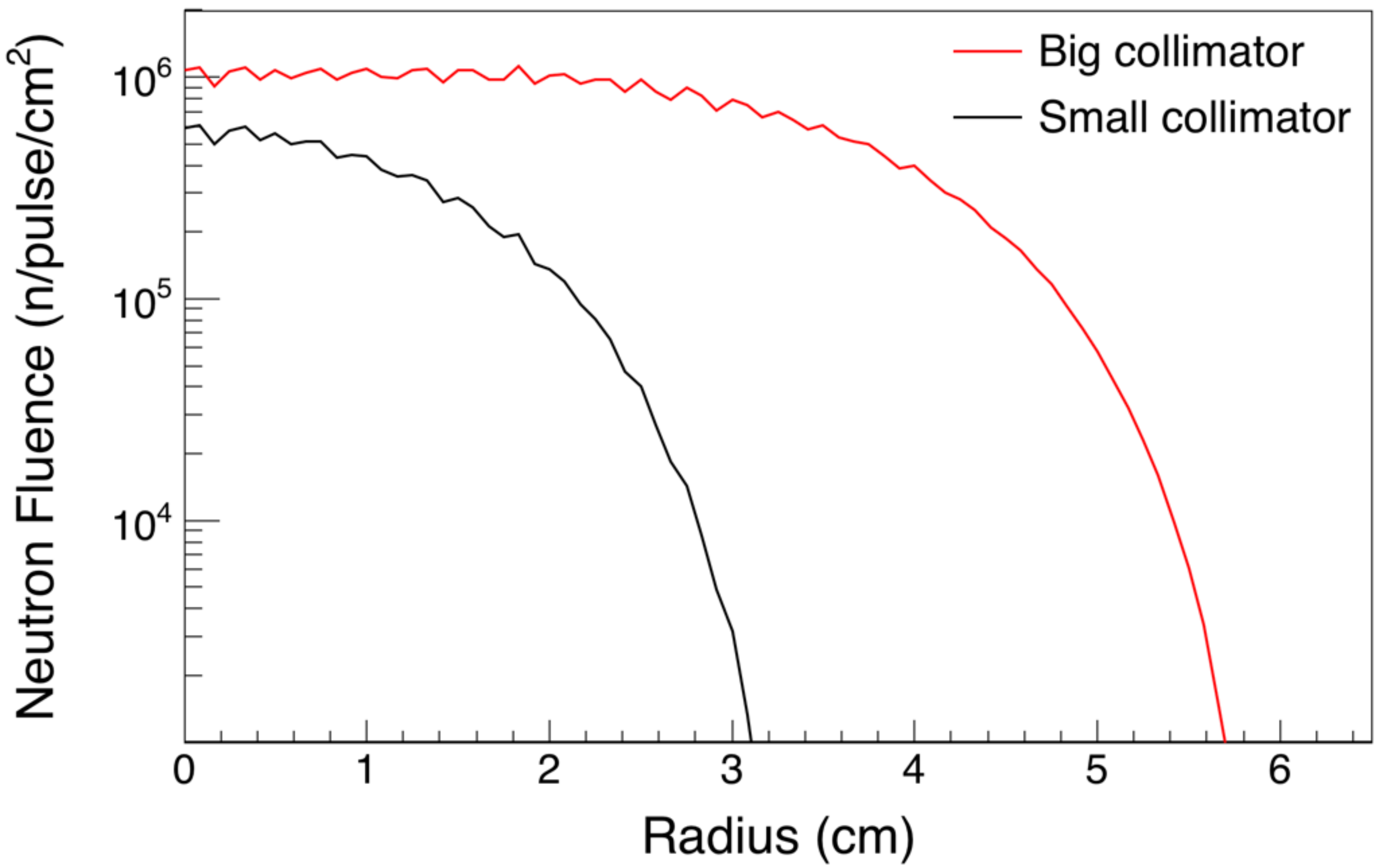
Neutron Imaging @ EAR2: detection system

- Detection system from Photonic Science:
  - $ZnS/^6LiF$ based neutron scintillator, active area of 100x100 mm^2, thickness ≈ 100 μm
  - 45 degree mirror to allow the positioning of the camera off-beam
  - Air-cooled SCMOS camera, 2048×2048 pixel for a 13.3×13.3 mm^2 active input area
  - Optical pixel resolution: 6.5 μm
- Remote control of the apparatus
- Possibility to externally trigger the camera with the PS trigger



Beam profile

- n_TOF big collimator
  - 66.7 mm inner diameter
  - About 1×10^6 neutrons/cm^2/pulse (8×10^5 n/cm^2/s if 1 pulse every 1.2 seconds) @ thermal
  - Beam profile: 9 to 11 cm diameter
- n_TOF small collimator
  - 21.8 mm inner diameter
  - About 6×10^5 neutrons/cm^2/pulse (5×10^5 n/cm^2/s if 1 pulse every 1.2 seconds) @ thermal
  - Beam profile: 4 to 6 cm diameter



Neutron beam profile obtained with FLUKA simulation @ 220cm height