CSN3 experiments @ "ROMA1"

LUNA

ERNA
European Recoil separator for Nuclear Astrophysics

nTOF

NUCLEAR ASTROPHYSICS

salvatore.fiore@roma1.infn.it
alba.formicola@roma1.infn.it
carlo.gustavino@roma1.infn.it

FOOT

HADRONTHERAPY

Michela.Marafini@cref.it

e- JLab12

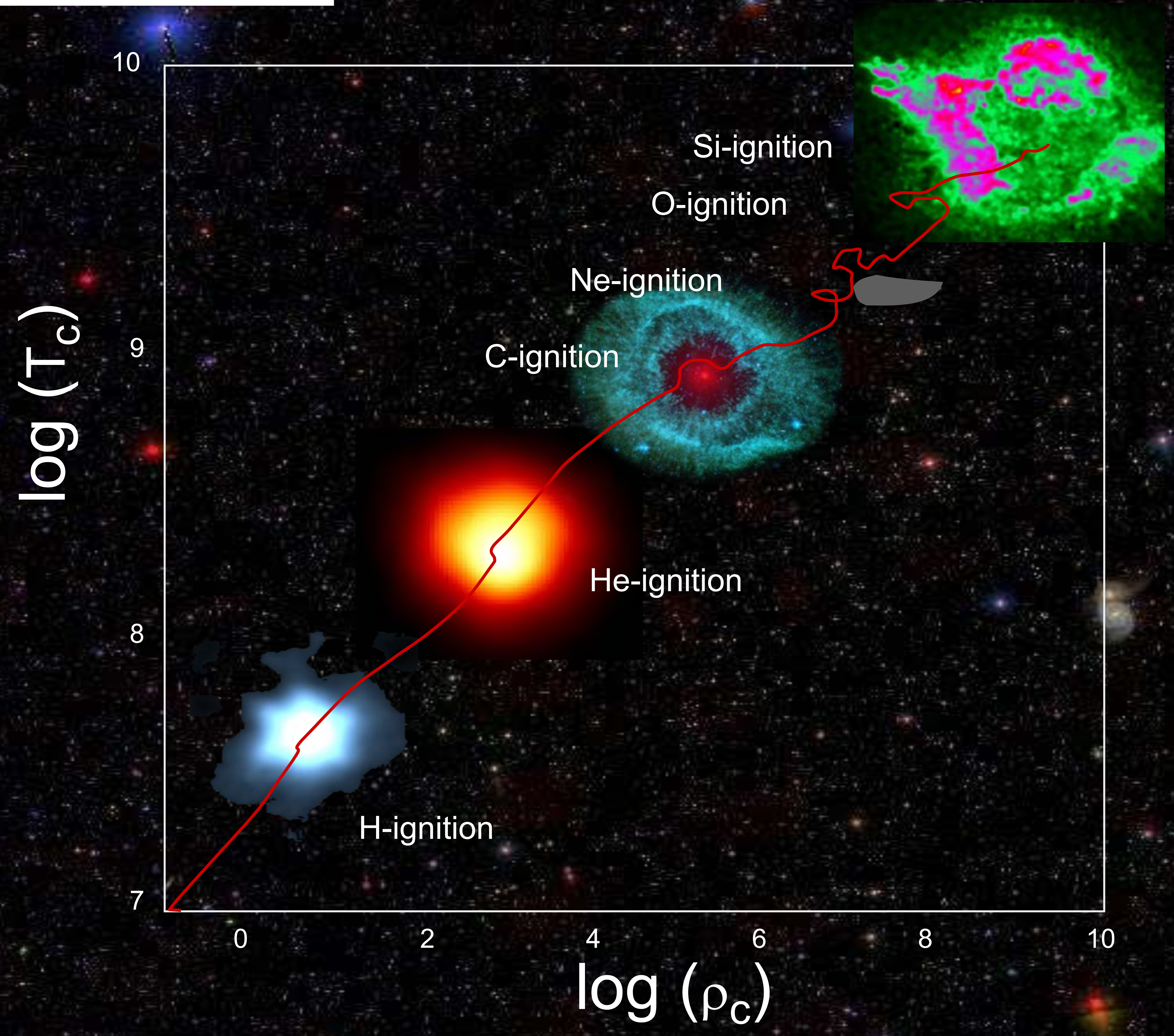
Electron Ion Collider

QUARK AND HADRON DYNAMICS

Evaristo.Cisbani@roma1.infn.it
guido.maria.urciuoli@roma1.infn.it

carlo.gustavino@roma1.infn.it

Why Nuclear astrophysics?



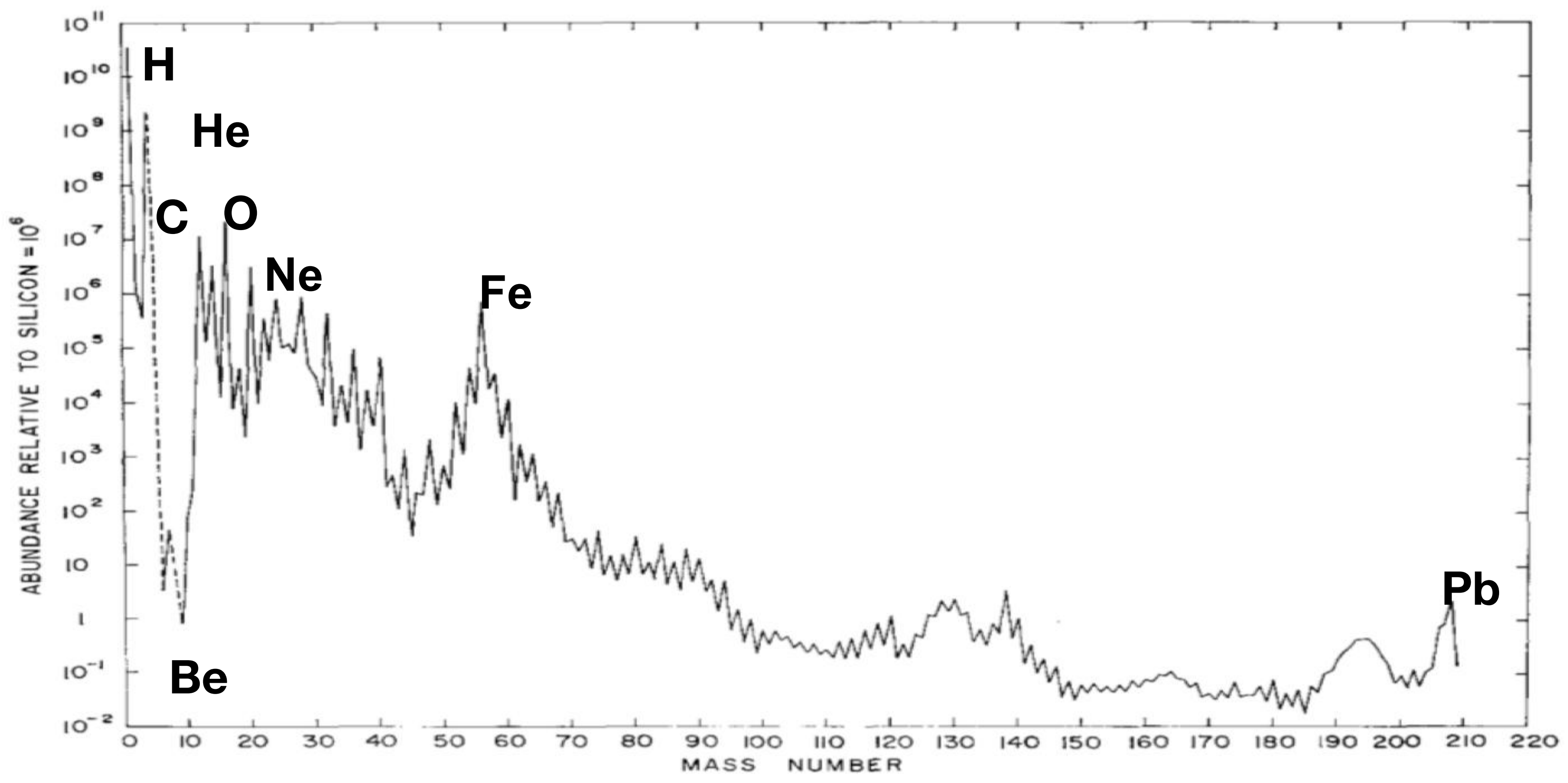
For a 15 M_{sun} star:

Reaction	Timescale
Hydrogen burning	10 million years
Helium burning	1 million years
Carbon burning	300 years
Oxygen burning	200 days
Silicon burning	2 days

Nuclear reactions are responsible for the synthesis of elements in the celestial bodies and BBN:
Low energy measurements are required

- Understanding the Sun
- Stellar population
- Evolution and fate of stars
- Isotopic abundances in the cosmos
- Big Bang Nucleosynthesis

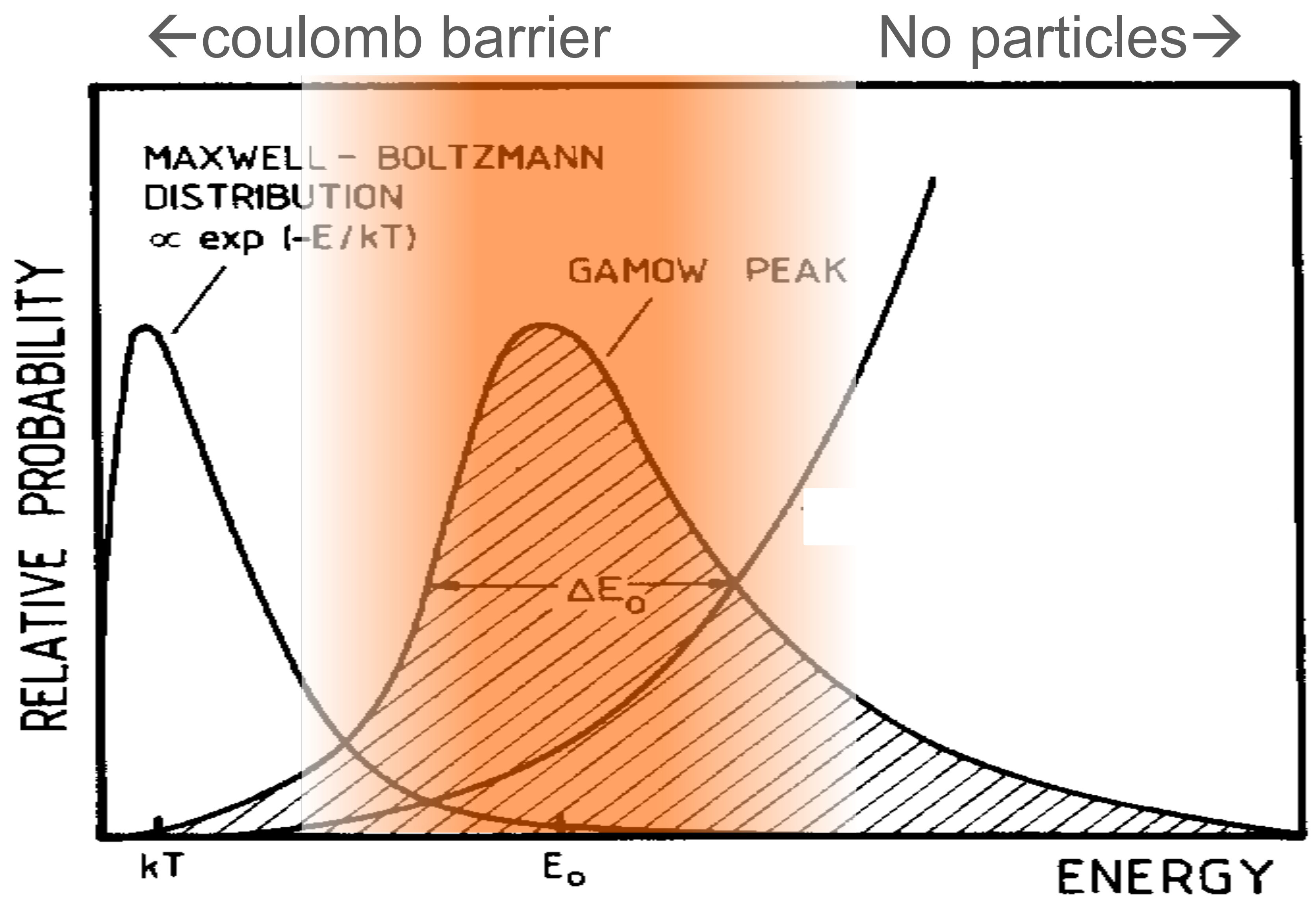
- Astrophysics
- Cosmology
- Particle Physics
- Theoretical nuclear physics

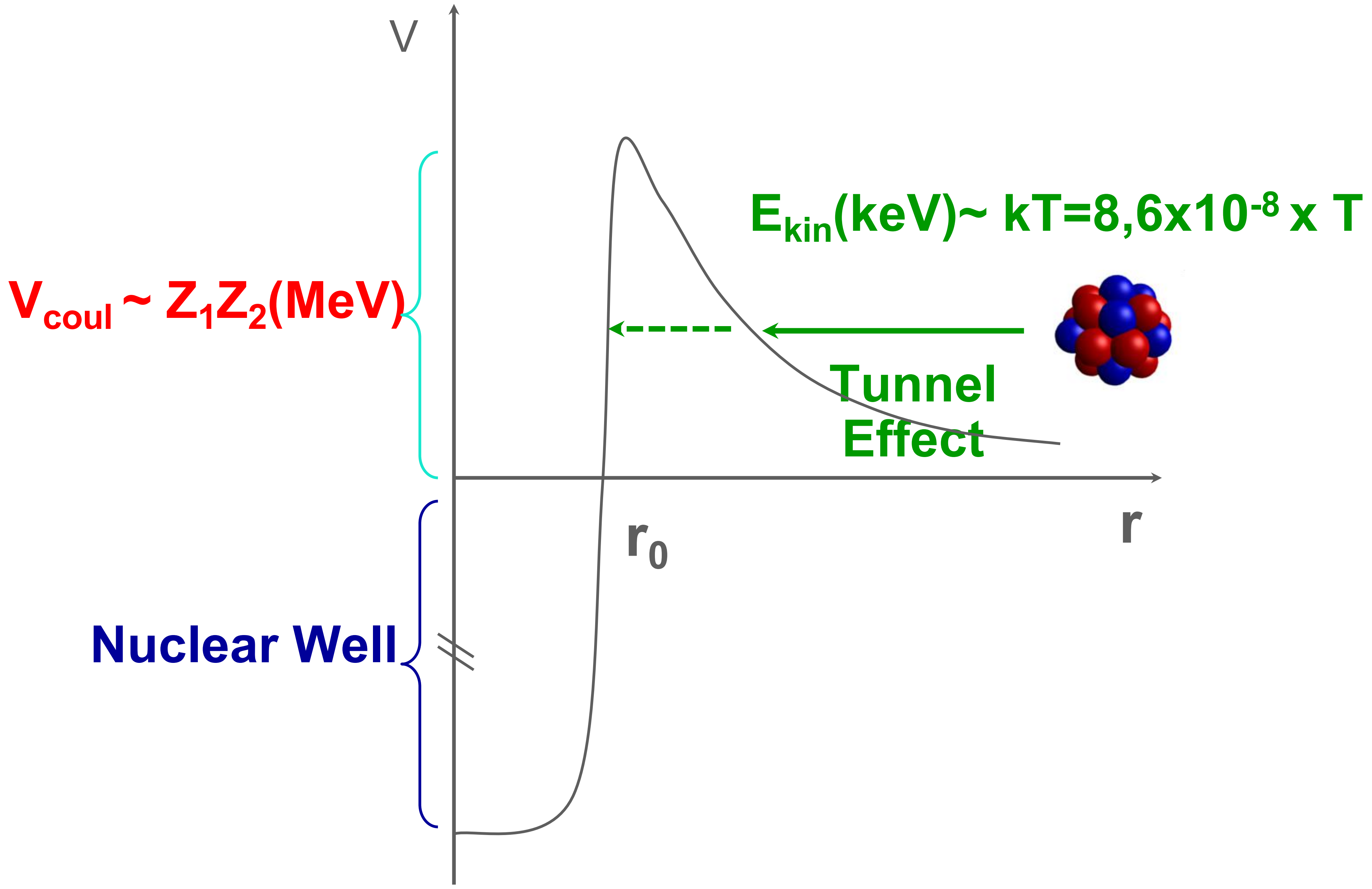


Astrophysical Factor

Coulomb Barrier

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi \mu}} (k_B T)^{-3/2} \int_0^{\infty} E \; \exp[-E/k_B T] \; \sigma(E) dE \qquad \sigma(E) = \frac{S(E)}{E} e^{-2\pi Z_1 Z_2 \alpha \sqrt{\frac{\mu}{2E}}}$$





Measurements at very low energies→

Very low cross sections because of the Coulomb barrier

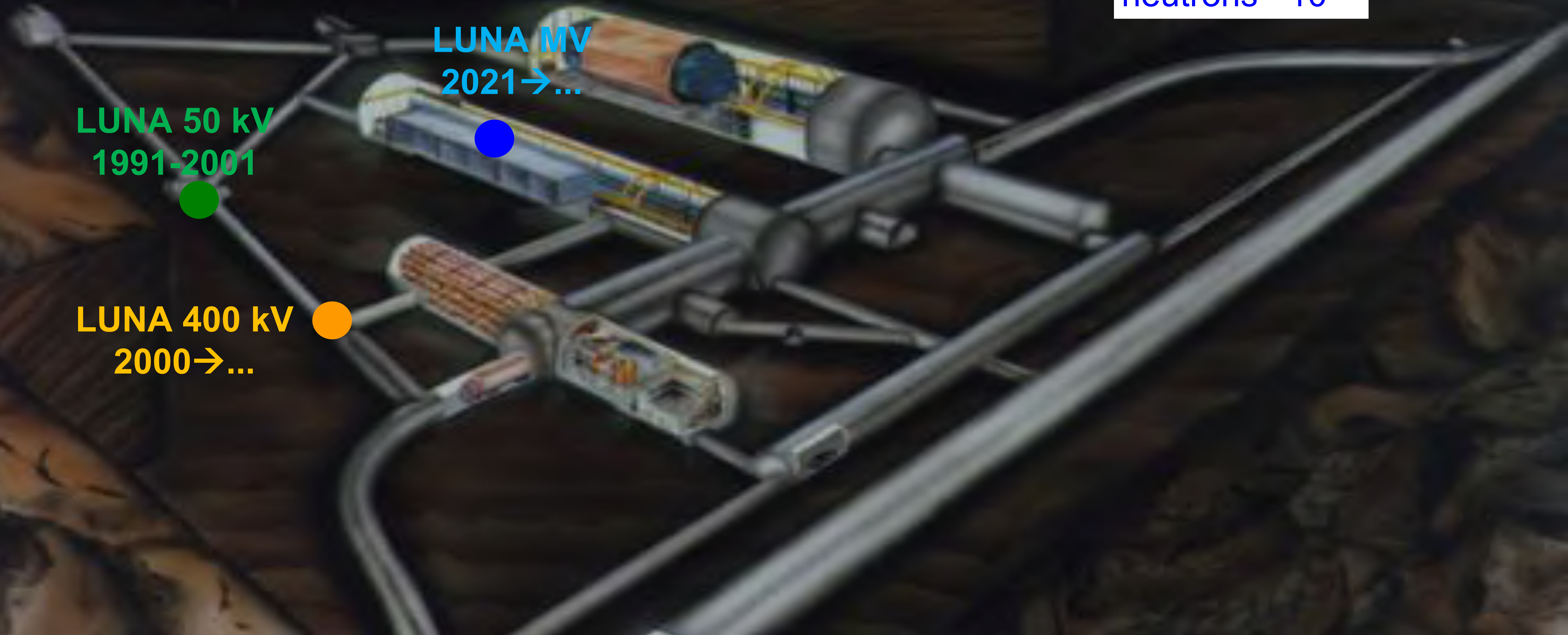
Gran Sasso National Laboratories

Background reduction with respect to Earth's surface:

$\mu \sim 10^{-6}$

$\gamma \sim 10^{-2}$-10^{-5}

neutrons $\sim 10^{-3}$



LUNA MV

Starting program:

$^{14}N(p,\gamma)^{15}O$ (CNO I Cycle)

$^{12}C+^{12}C$ (Carbon burning)

$^{13}C(\alpha,n)^{16}O$ (s-process)

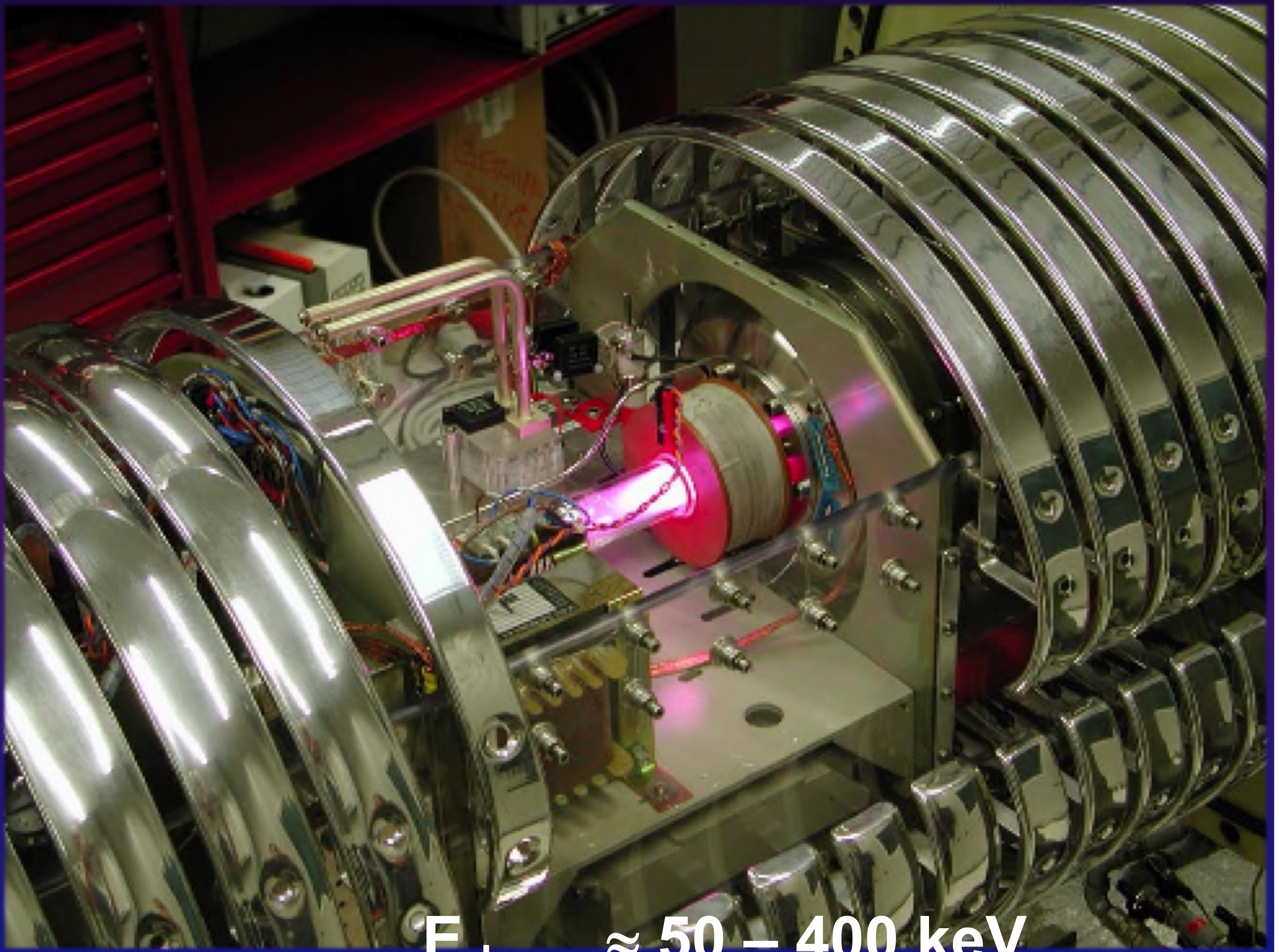
$^{22}Ne(\alpha,n)^{25}Mg$ (s-process)

$^{12}C(\alpha,\gamma)^{16}O$ (Helium burning)

Terminal Voltage ≈ 0.2 – 3.5 MV

I_{max} ≈ 100-1000 μA protons, ^{4}He, $^{12}C^{+}$, $^{12}C^{++}$

LUNA 400 kV



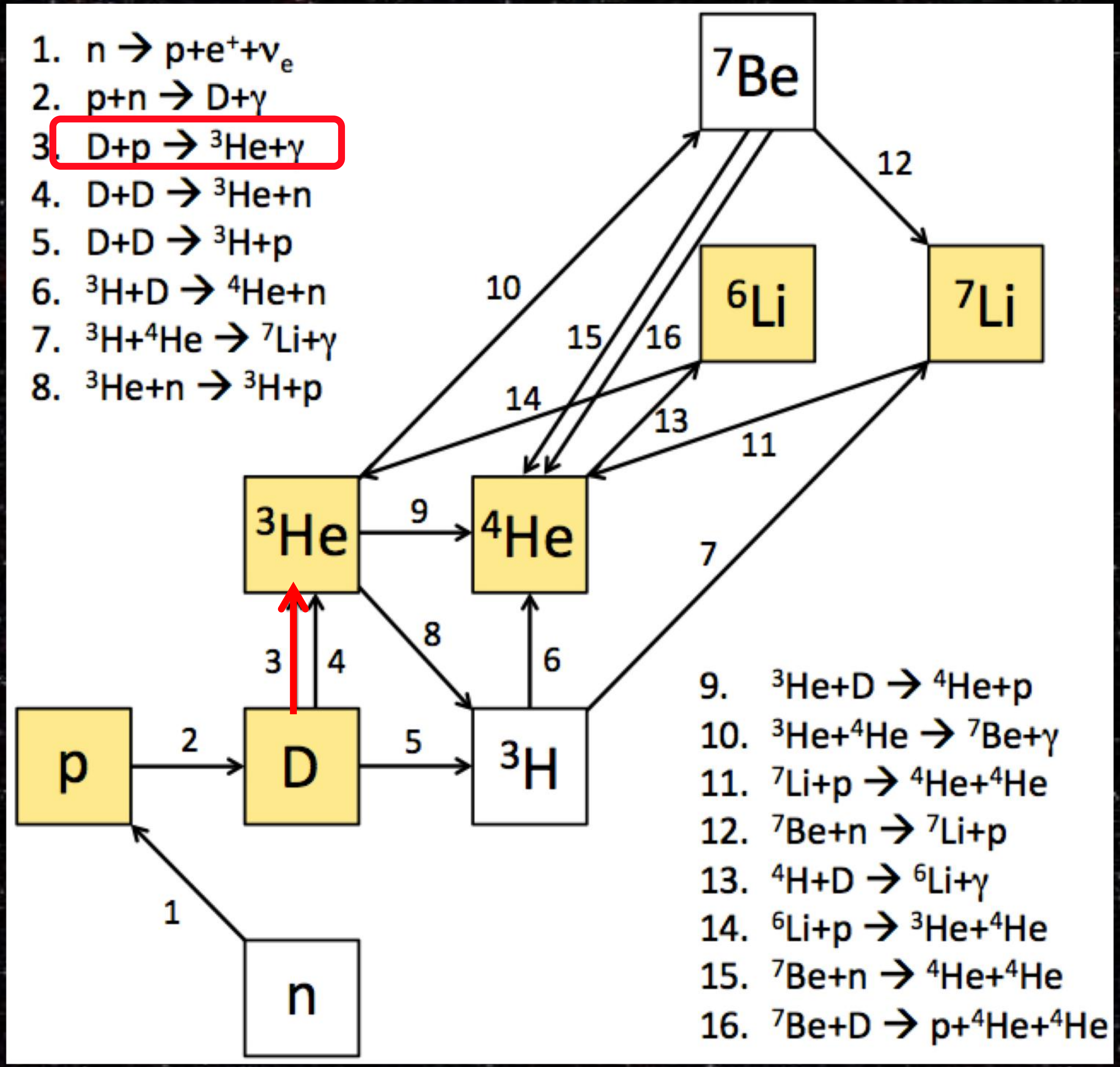
$E_{beam} \approx 50 – 400$ keV

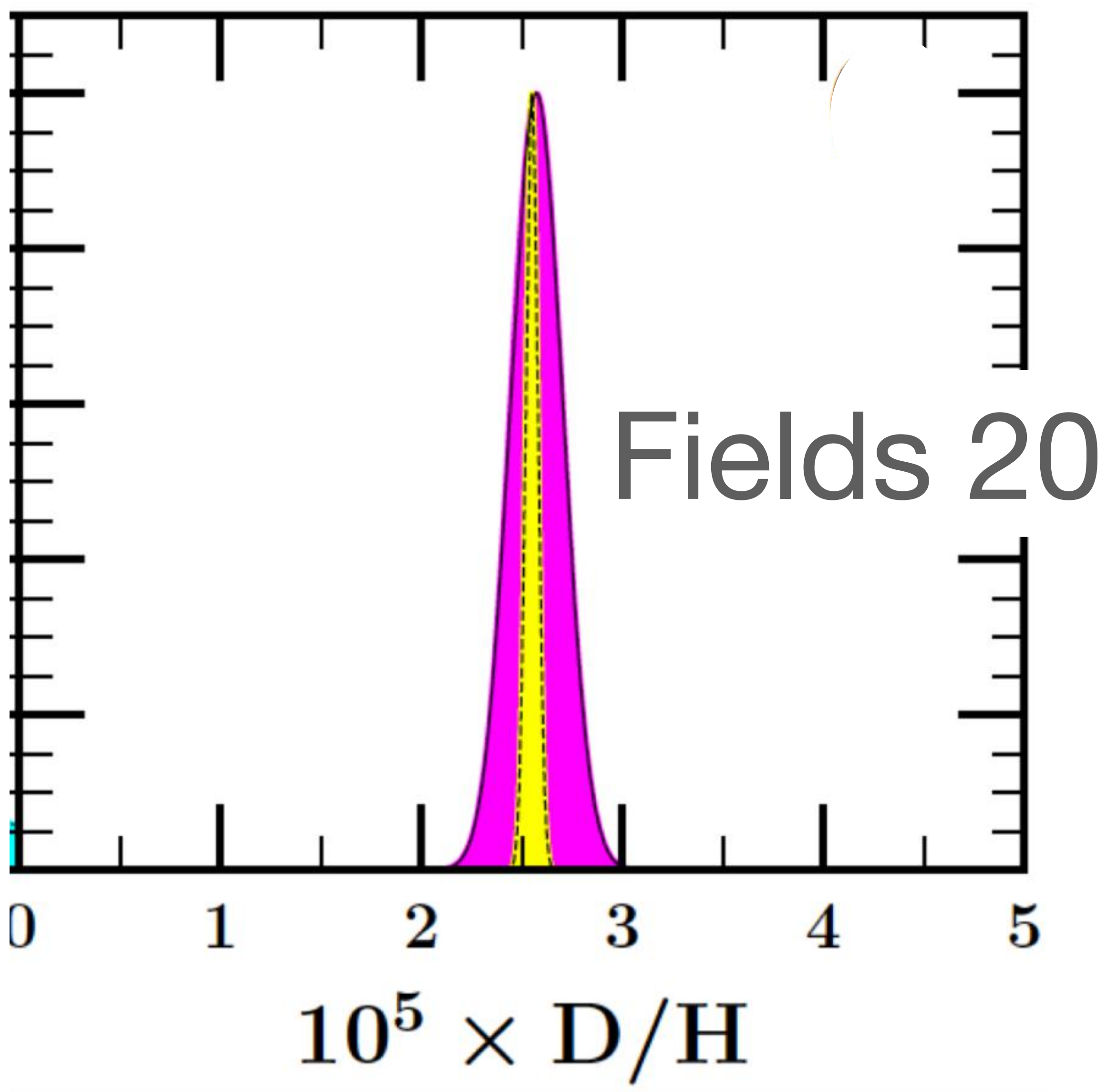
$I_{max} \approx 300\ \mu A$ protons, ^{4}He

Energy spread ≈ 70 eV

- $^{14}N(p,\gamma)^{15}O$ (Sun,CNO-I cycle)
- $^{3}He(^{4}He,\gamma)^{7}Be$ (Sun, BBN)
- $^{25}Mg(p,\gamma)^{26}Al$ (Mg-Al Cycle)
- $^{15}N(p,\gamma)^{16}O$ (CNO-II Cycle)
- $^{17}O(p,\gamma)^{18}F$ (CNO-III Cycle)
- $^{2}H(^{4}He,\gamma)^{6}Li$ (BBN)
- $^{22}Ne(p,\gamma)^{23}Na$ (Ne-Na Cycle)
- $^{2}H(p,\gamma)^{3}He$ (BBN)
- $^{13}C(\alpha,n)^{16}O$ (s-process)
- $^{12,13}C(p,\gamma)^{13,14}N$ ($^{12}C/^{13}C$ ratio)
- $^{22}Ne(\alpha,\gamma)^{23}Na$ (s-process)

$D(p,\gamma)^3He$ reaction Vs BBN





Fields 2019

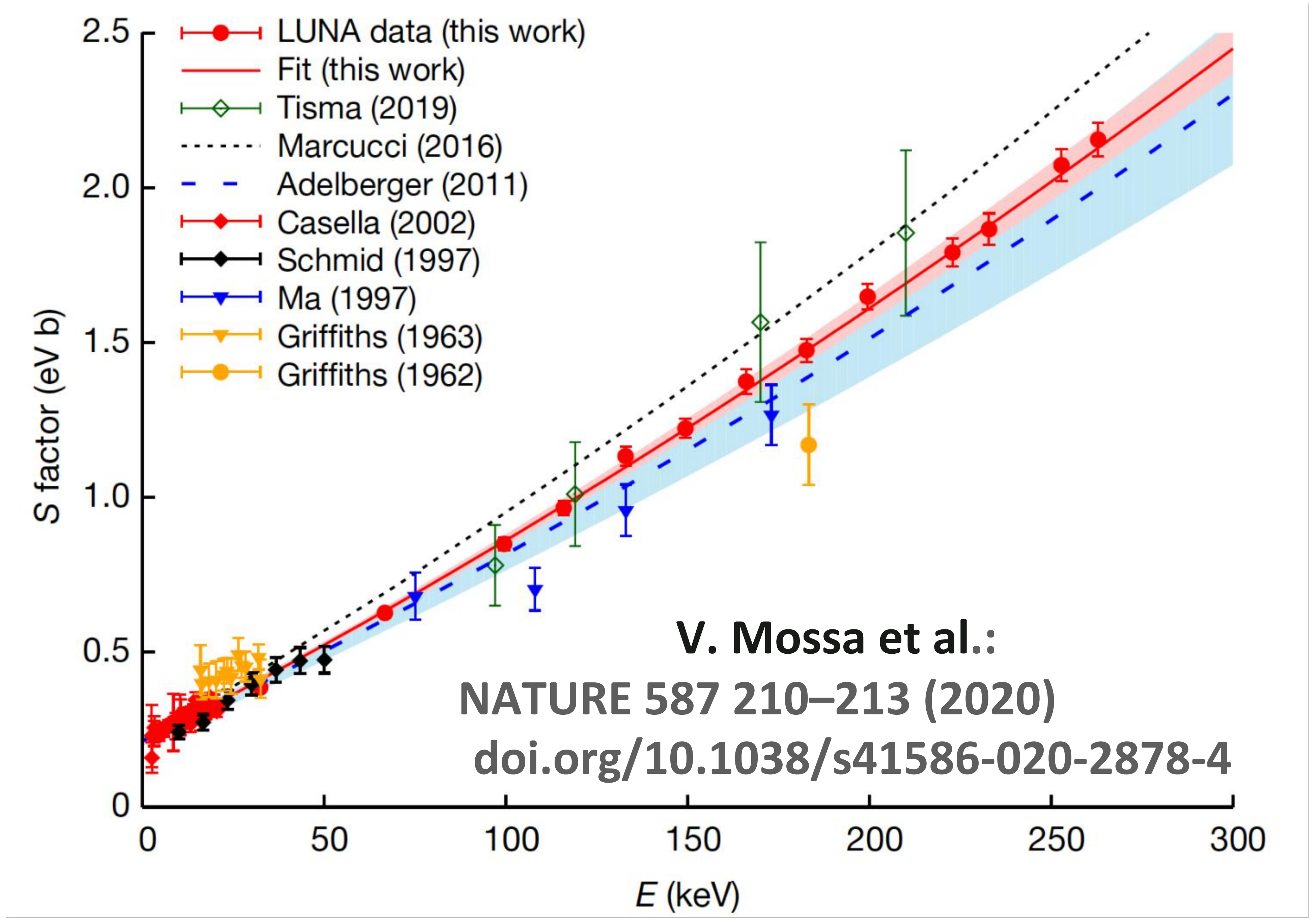
Reaction	$\Delta(D/H)_{BBN}/(D/H)_{BBN}$
$p(n,\gamma)D$	0.08%
$D(p,\gamma)^3He$	2.34%
$D(d,n)^3He$	0.75%
$D(d,p)^3H$	0.49%

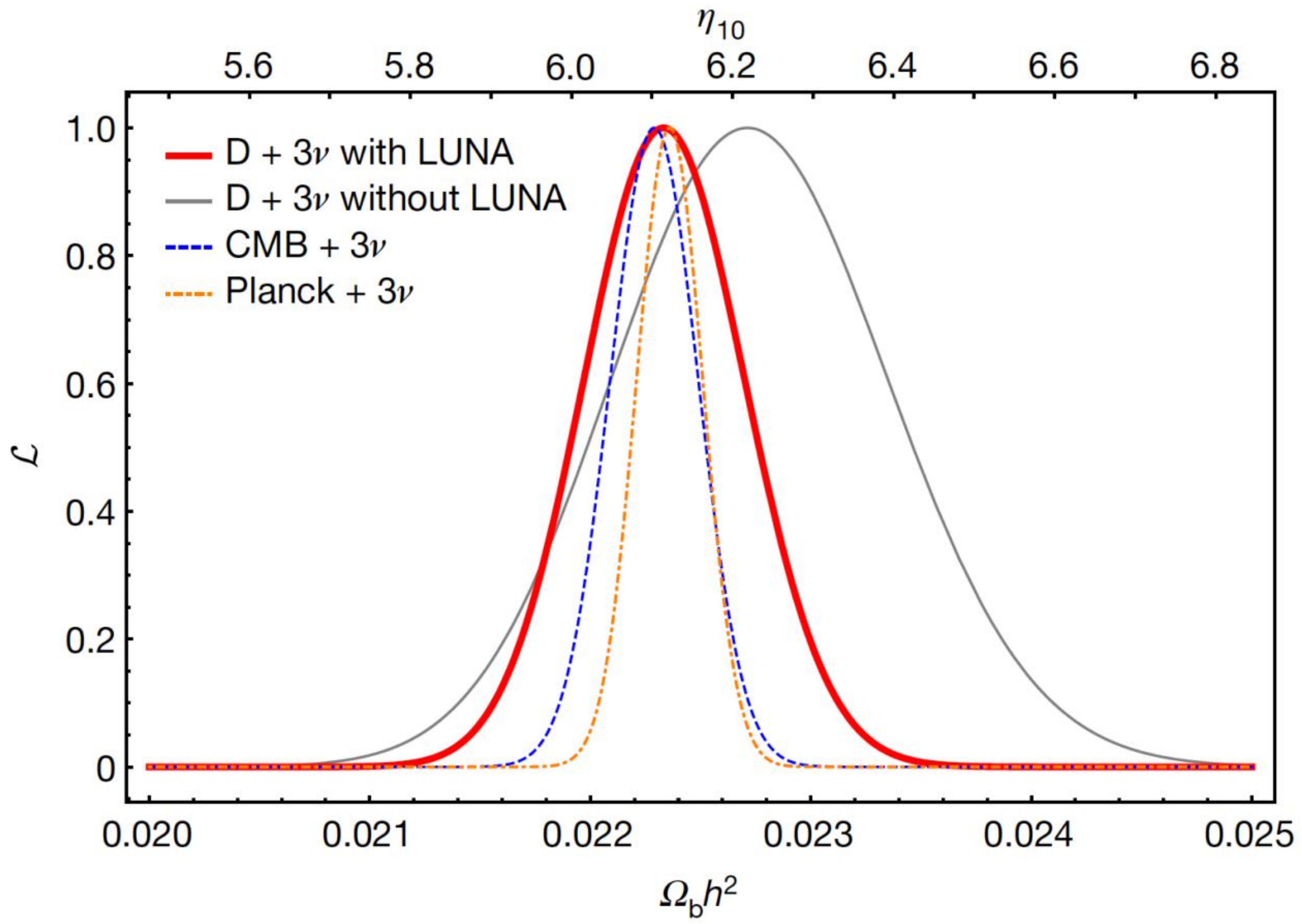
(Di Valentino, C.G. et al. 2014)

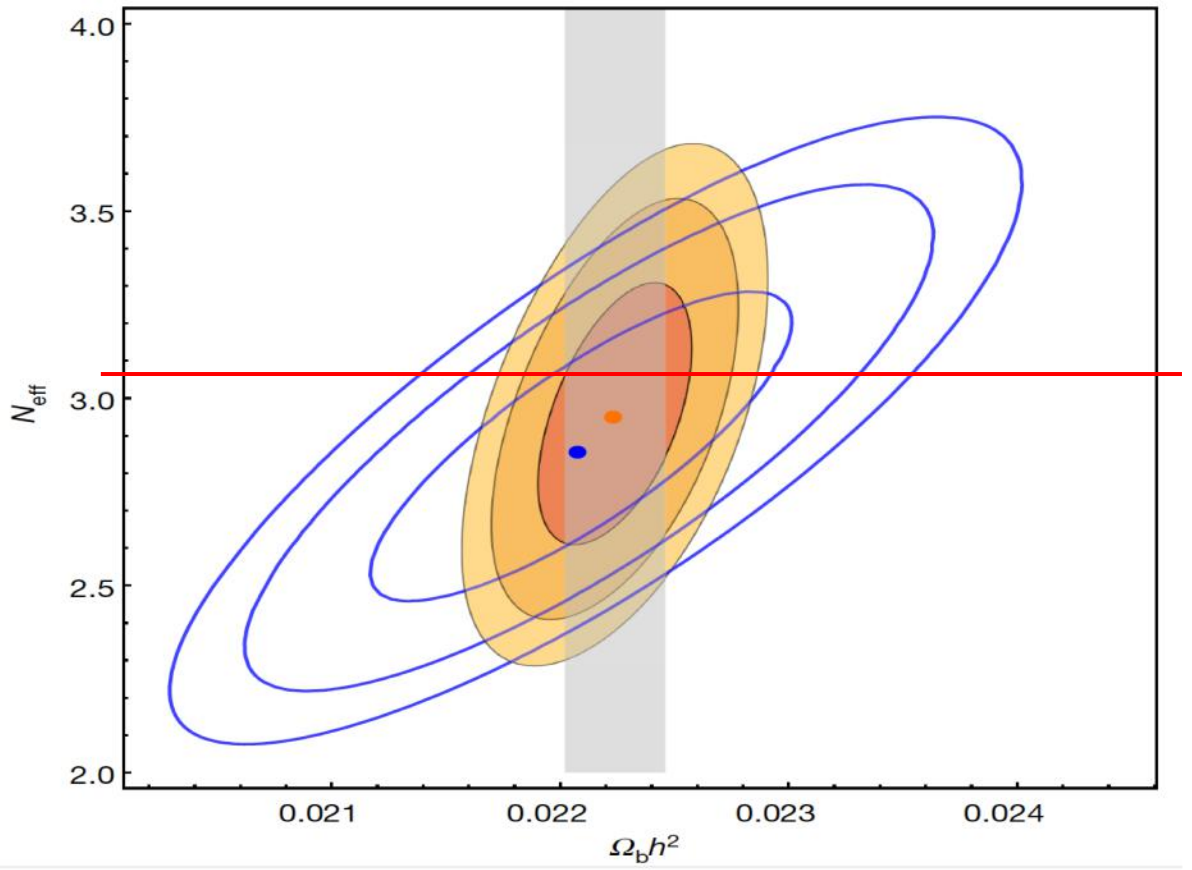
- The error budget of computed abundance of deuterium was much worst than direct observations, mainly because of the paucity of $D(p,\gamma)^3He$ reaction data

D(p,γ)^{3}He measurement results

	$\Omega_b h^2$	δ (%)	N_{eff}
D + 3ν (without LUNA data)	0.02271 ± 0.00062	2.73	3.045
D + 3ν (with new LUNA data)	0.02233 ± 0.00036	1.61	3.045
CMB + 3ν	0.02230 ± 0.00021[a]	0.94	3.045
Planck + 3ν	0.02236 ± 0.00015	0.67	3.045
(D + CMB)	0.02224 ± 0.00022	0.99	2.95 ± 0.22
(D + Y_p)	0.0221 ± 0.0006	2.71	$2.86^{+0.28}_{-0.27}$

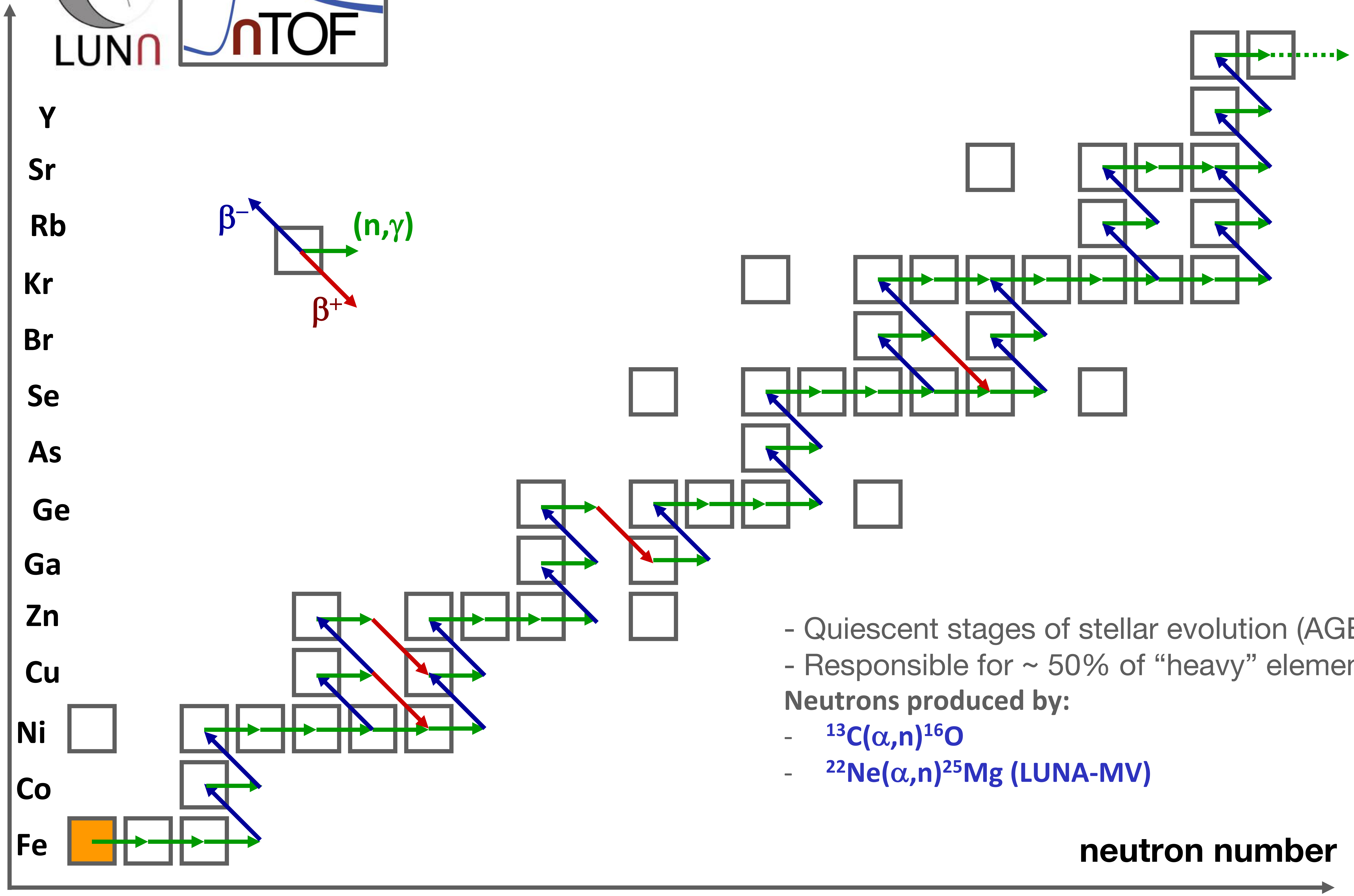






- Improved Ω_b(BBN) of a factor 2
- 1% agreement between Ω_b(BBN) and Ω_b(CMB)
- Comparable accuracy (1% level)
- LUNA data are consistent with the existence of only 3 neutrino families. No evidence of a sizeable amount of hypothetical "dark radiation" (e.g. sterile neutrinos, hot axions).

Beyond Iron: s-process

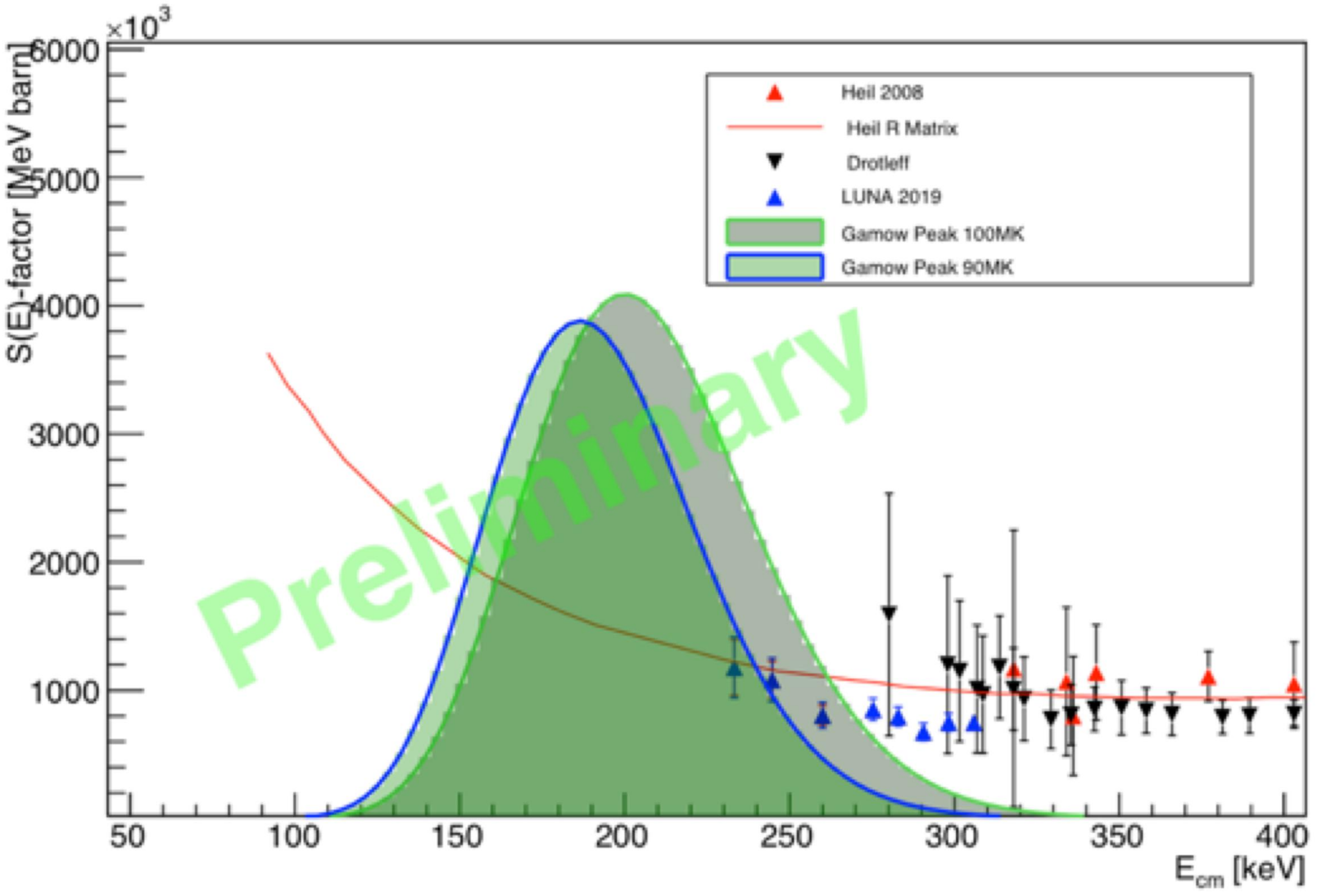


- Quiescent stages of stellar evolution (AGB and massive stars)
- Responsible for ~ 50% of "heavy" elements

Neutrons produced by:

- **$^{13}C(\alpha,n)^{16}O$**
- **$^{22}Ne(\alpha,n)^{25}Mg$ (LUNA-MV)**

$^{13}C(\alpha,n)^{16}O$ @ LUNA400



Hydrogen burning cycles

Sun: ~15 MK
Massive Stars: ~ 100 MK
AGB:~30-100 MK
Novae~100-400 MK

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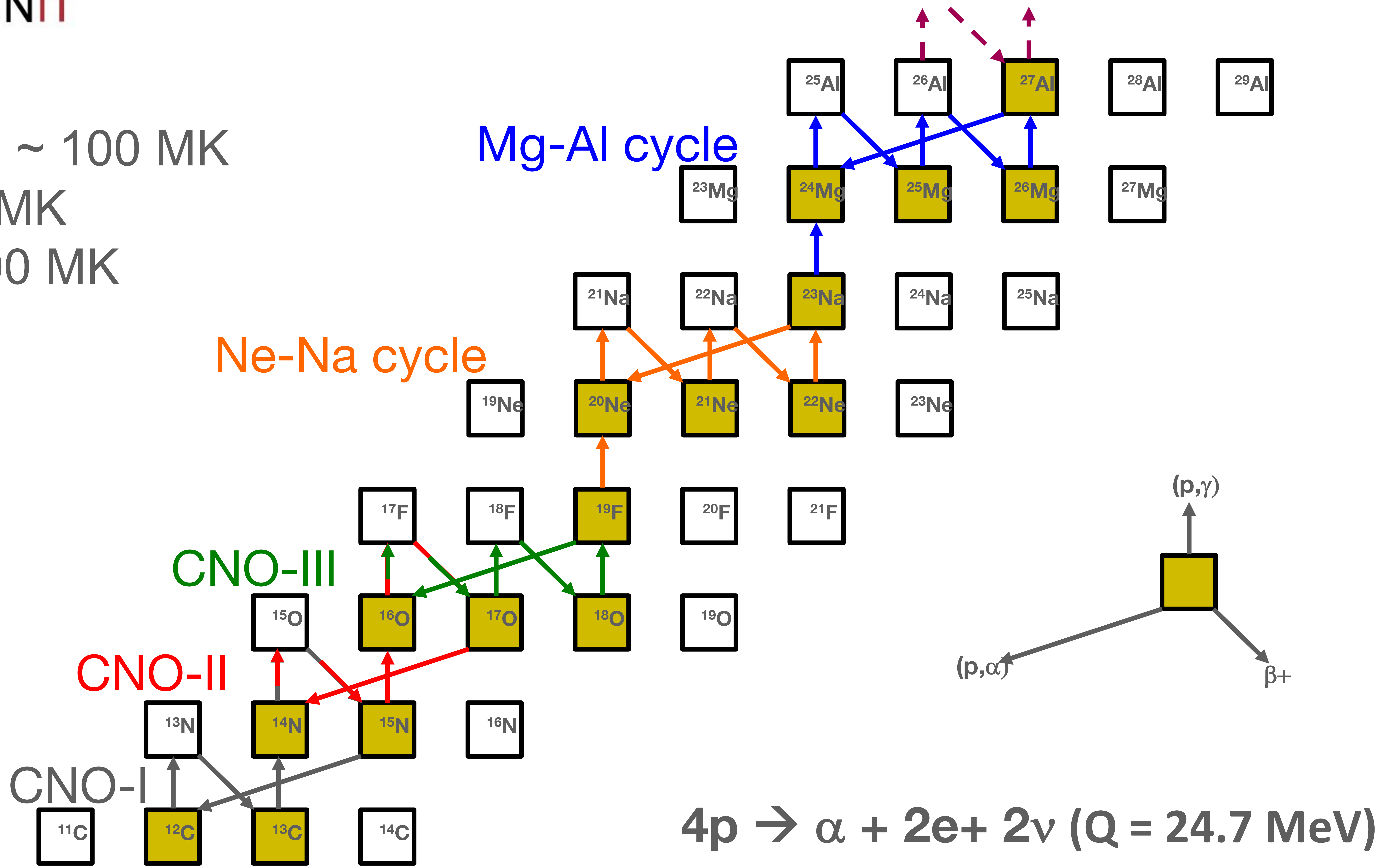
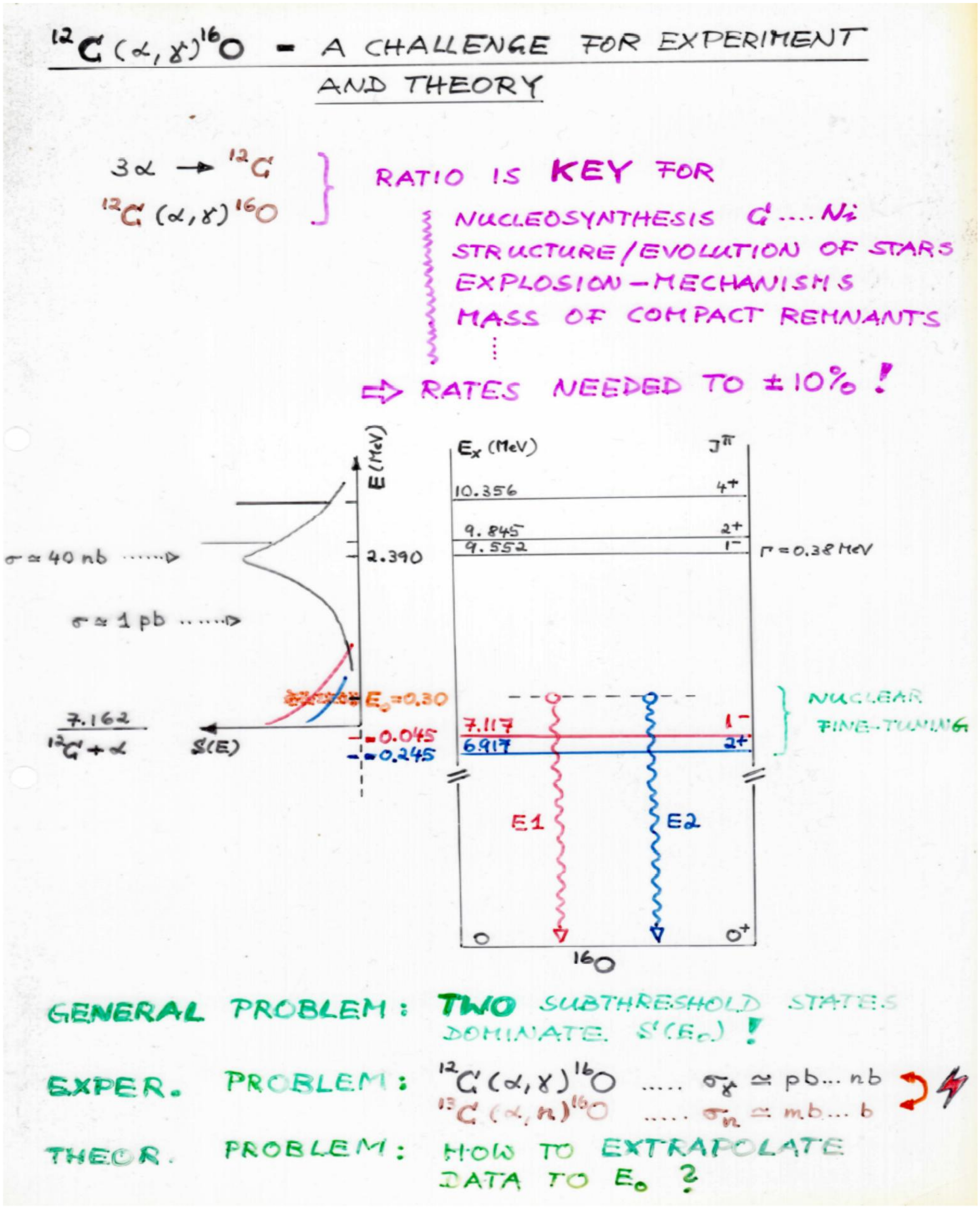


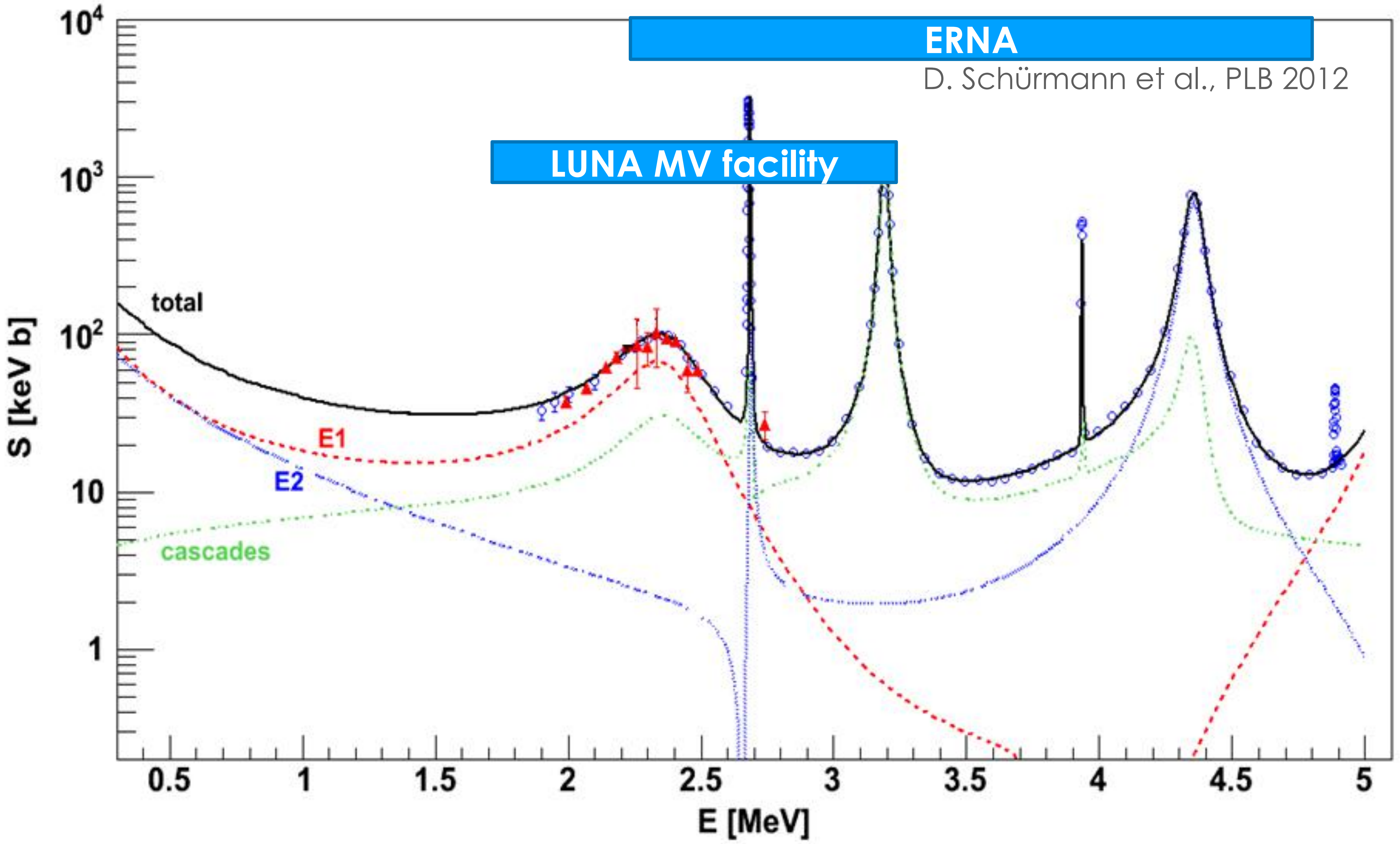
$$4p \rightarrow \alpha + 2e^{+} + 2\nu \ (Q = 24.7 \text{ MeV})$$

$^{12}C(\alpha,\gamma)^{16}O$

"The Holy Grail of Nuclear Astrophysics"(Nobel Lecture, December 8, 1983, William A.Fowler)



Experimental situation:



Experimental Problem!!

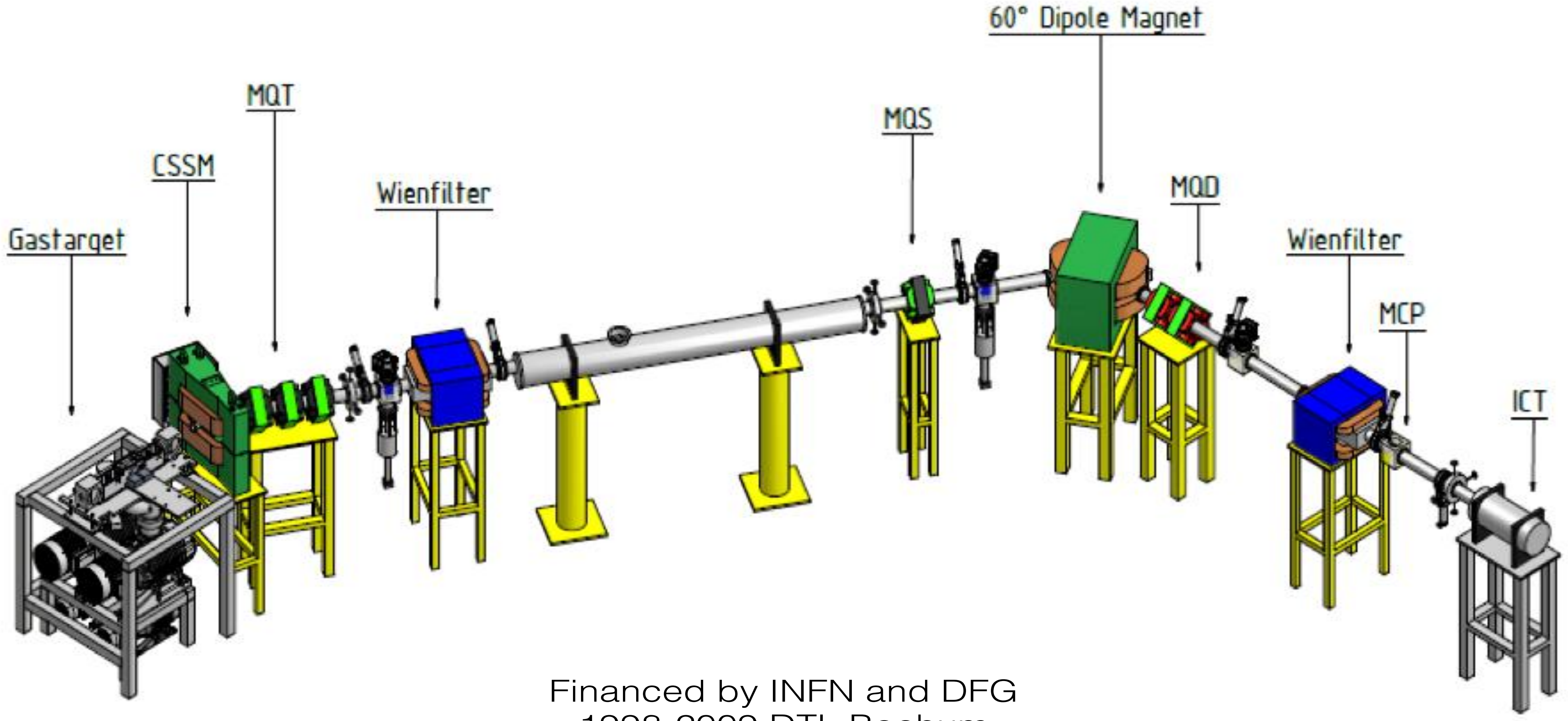
$^{12}C(\alpha,\gamma)^{16}O$ σ_{γ}= pb→nb

$^{13}C(\alpha,n)^{16}O$ σ_{n}=mb→b

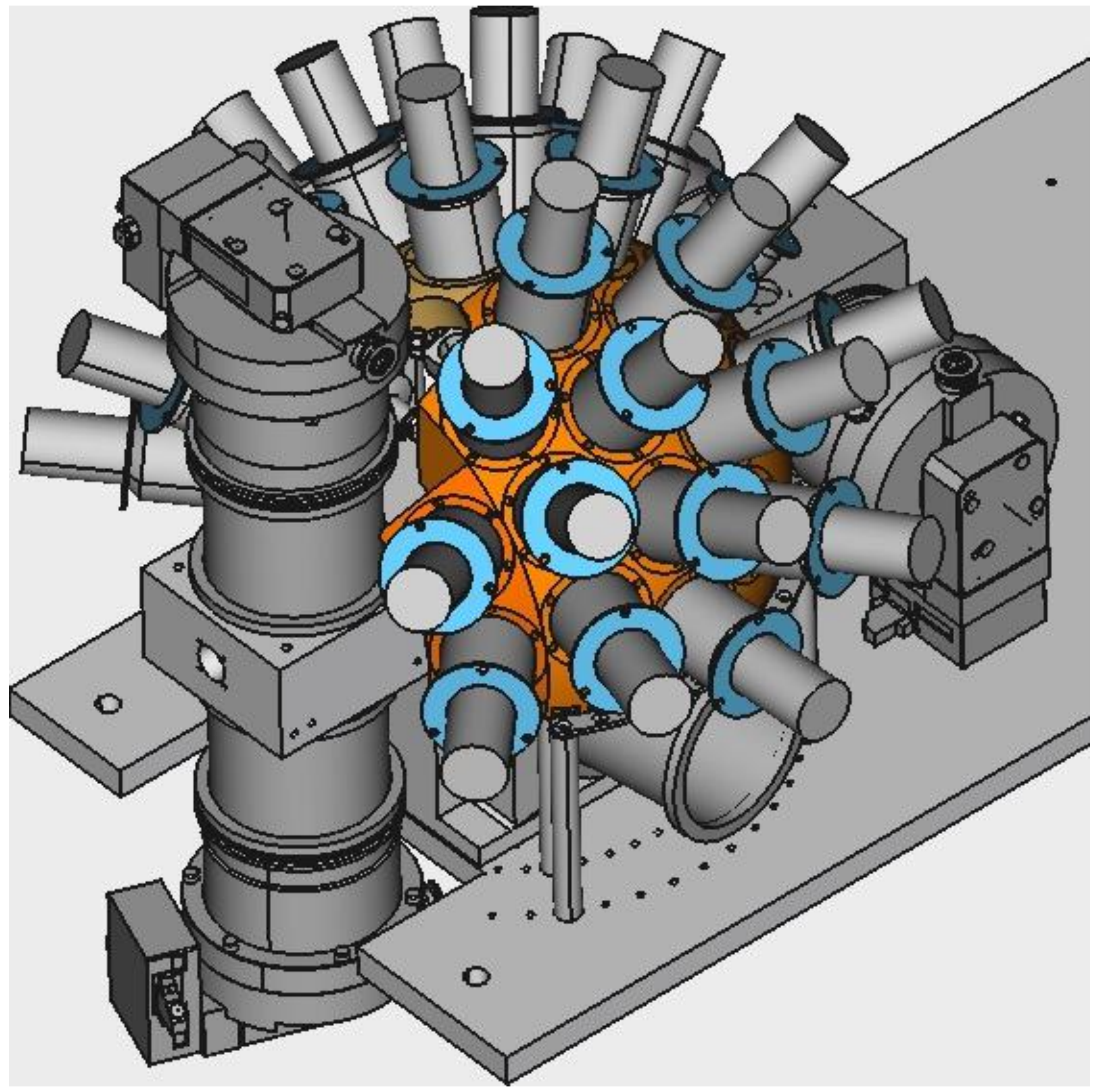
→inverse kinematics

ERNA
European Recoil separator for Nuclear Astrophysics

European Recoil Separator for Nuclear Astrophysics

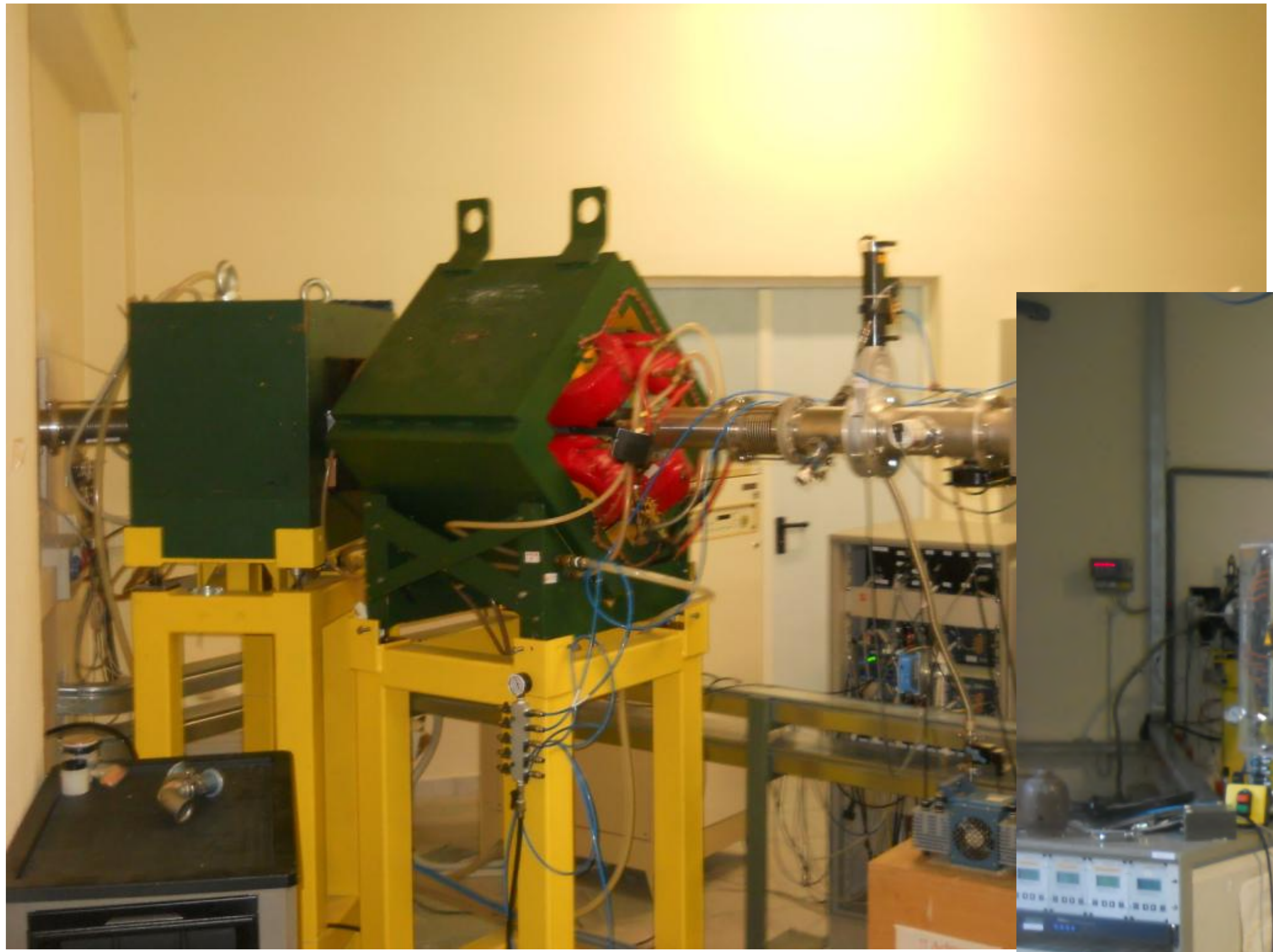


Financed by INFN and DFG
1998-2009 DTL Bochum
2009 moved to CIRCE Caserta

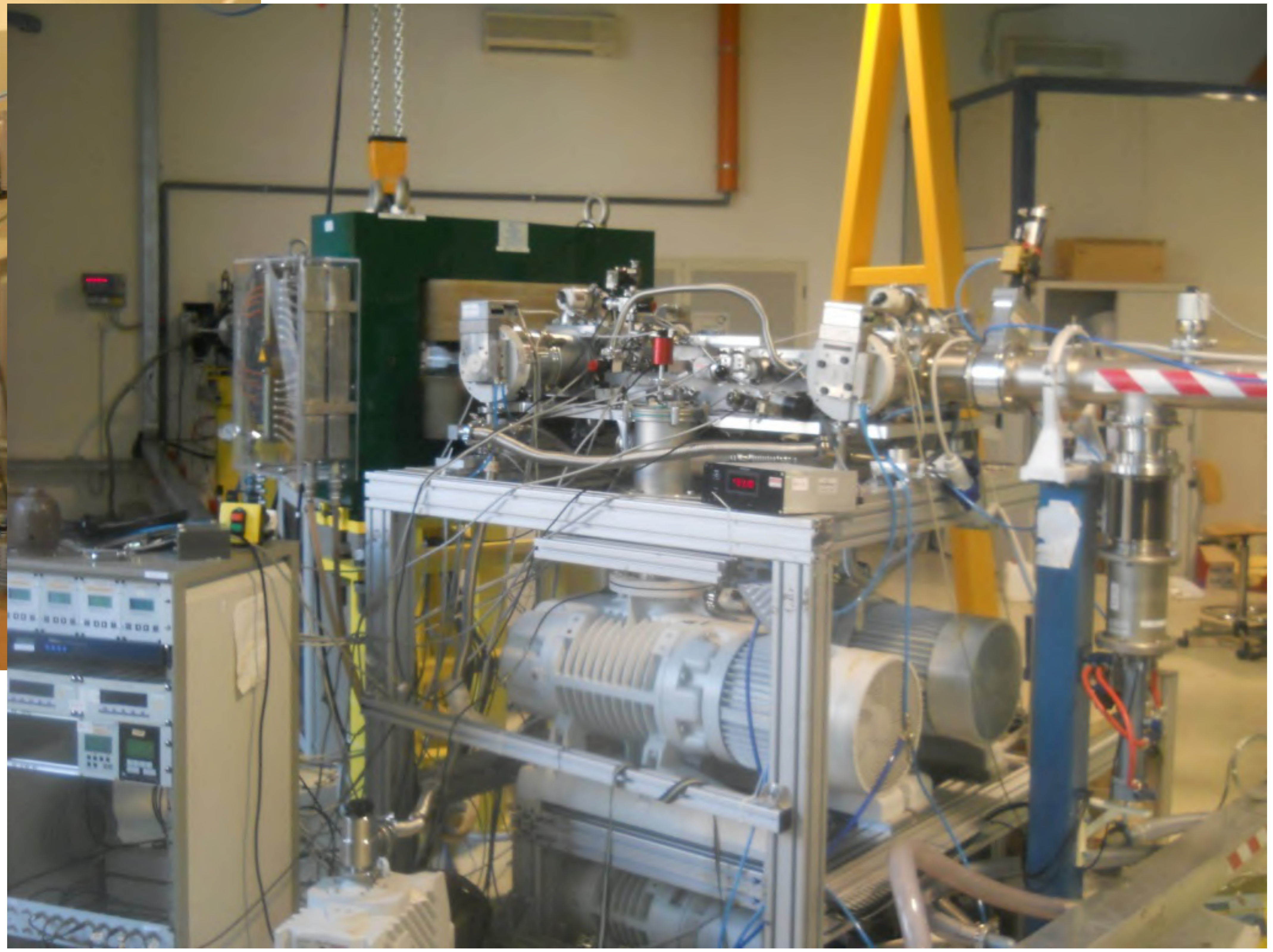


ERNA
European Recoil separator for Nuclear Astrophysics

Direct measurement of nuclear astrophysics cross section with inverse kinematics

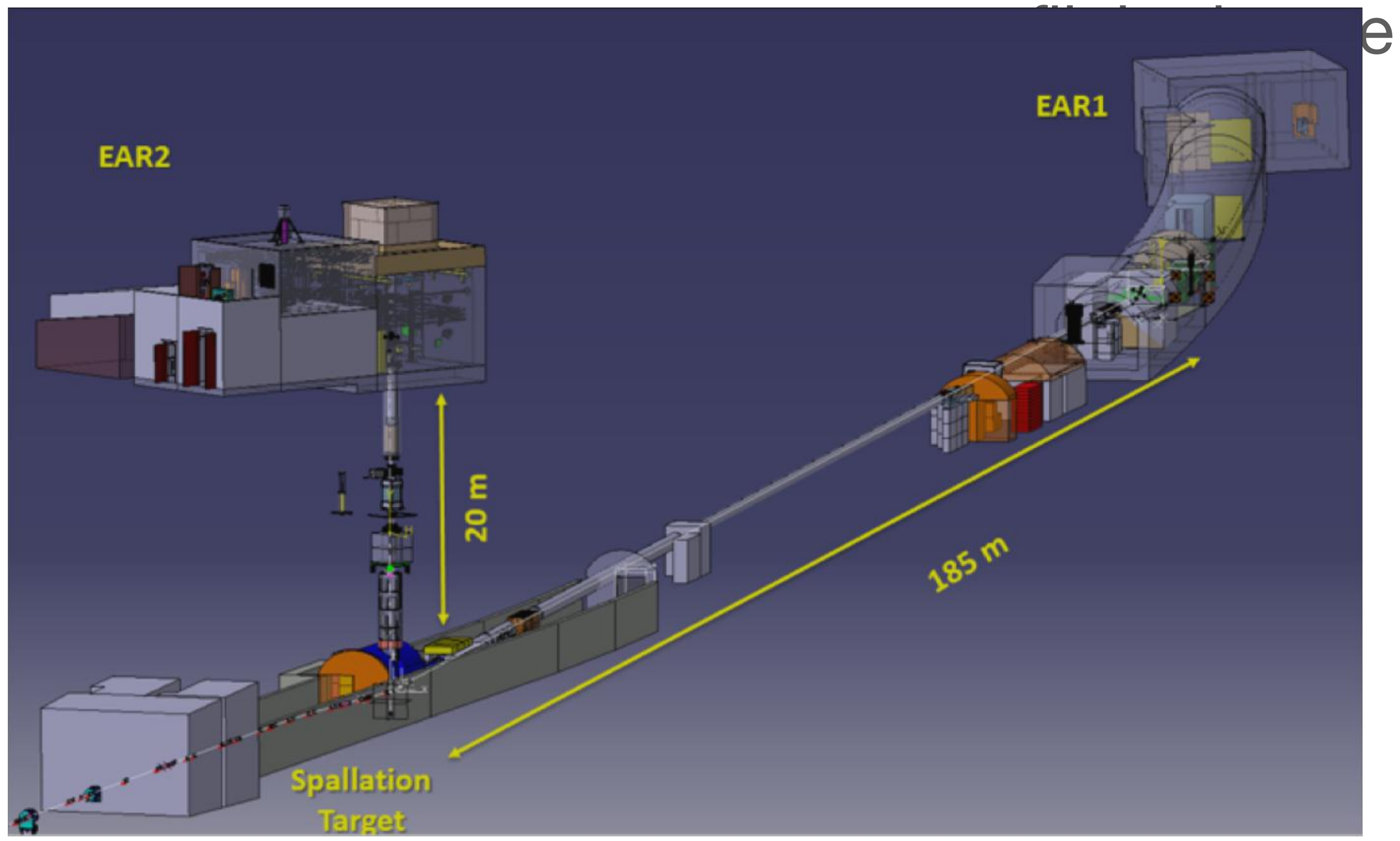


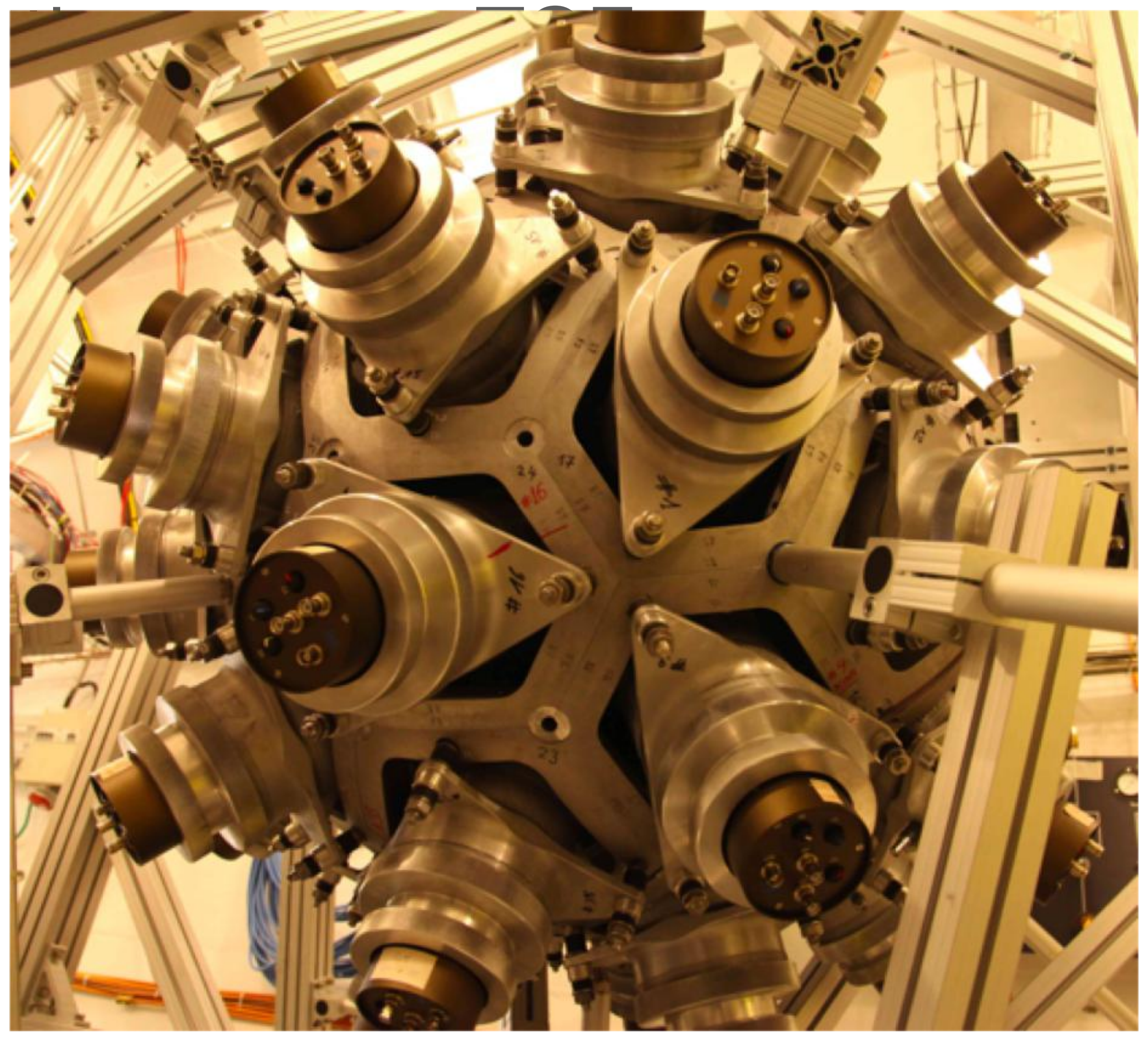
3MV Pelletron
stable and high intensity
radioactive (^{7,10}Be) beam

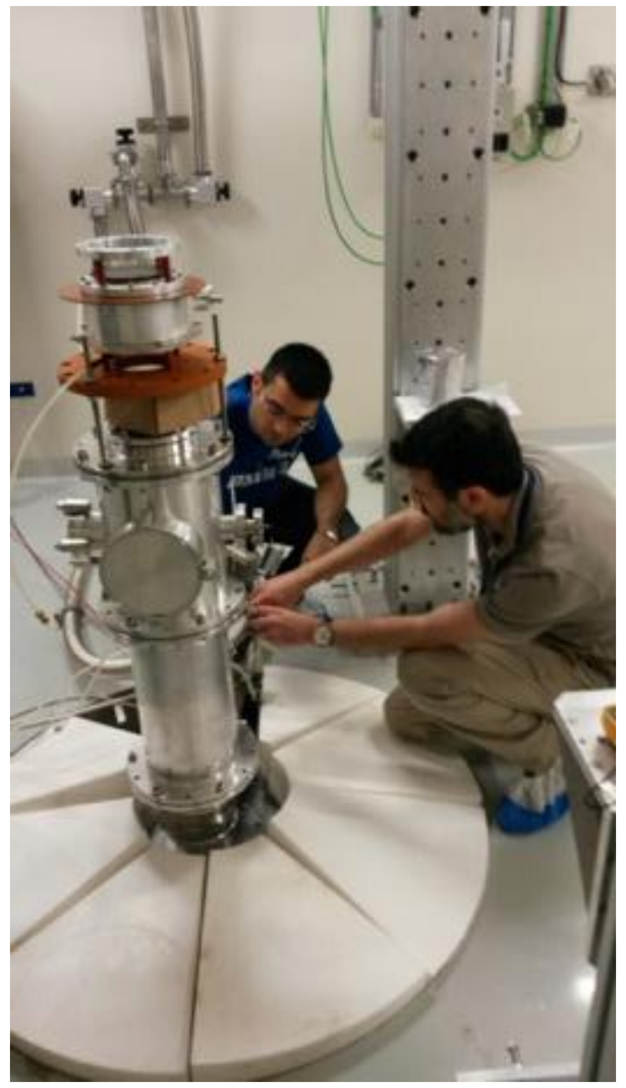


n_ToF (CERN)

n_TOF experiment at CERN is a pulsed neutron source coupled to long flight path designed to study neutron-nucleus interactions for neutron kinetic energies ranging from a few meV to several GeV. The neutron kinetic energy is determined by time-of-

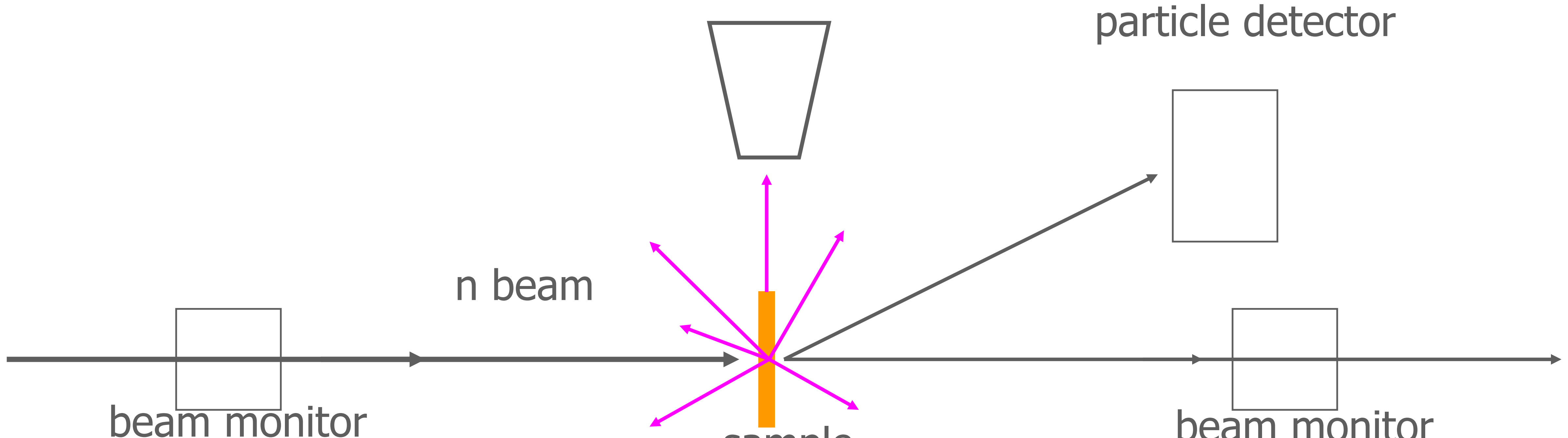






Neutrons are generated using a pulsed beam of 20 GeV protons from CERN PS hitting a lead target

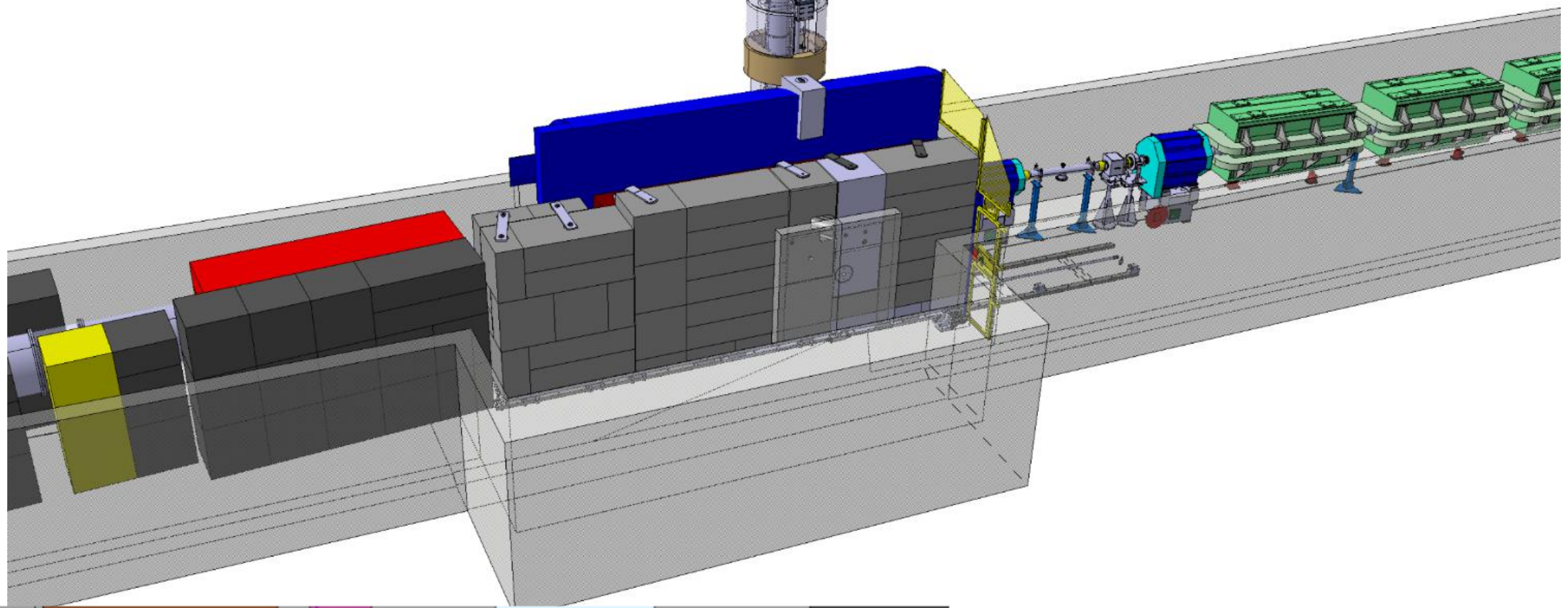
- **Pulse width: 6 ns , ΔT: 1.2 s**
- **10^{15} neutrons per pulse**
- **neutron energy: meV-GeV**

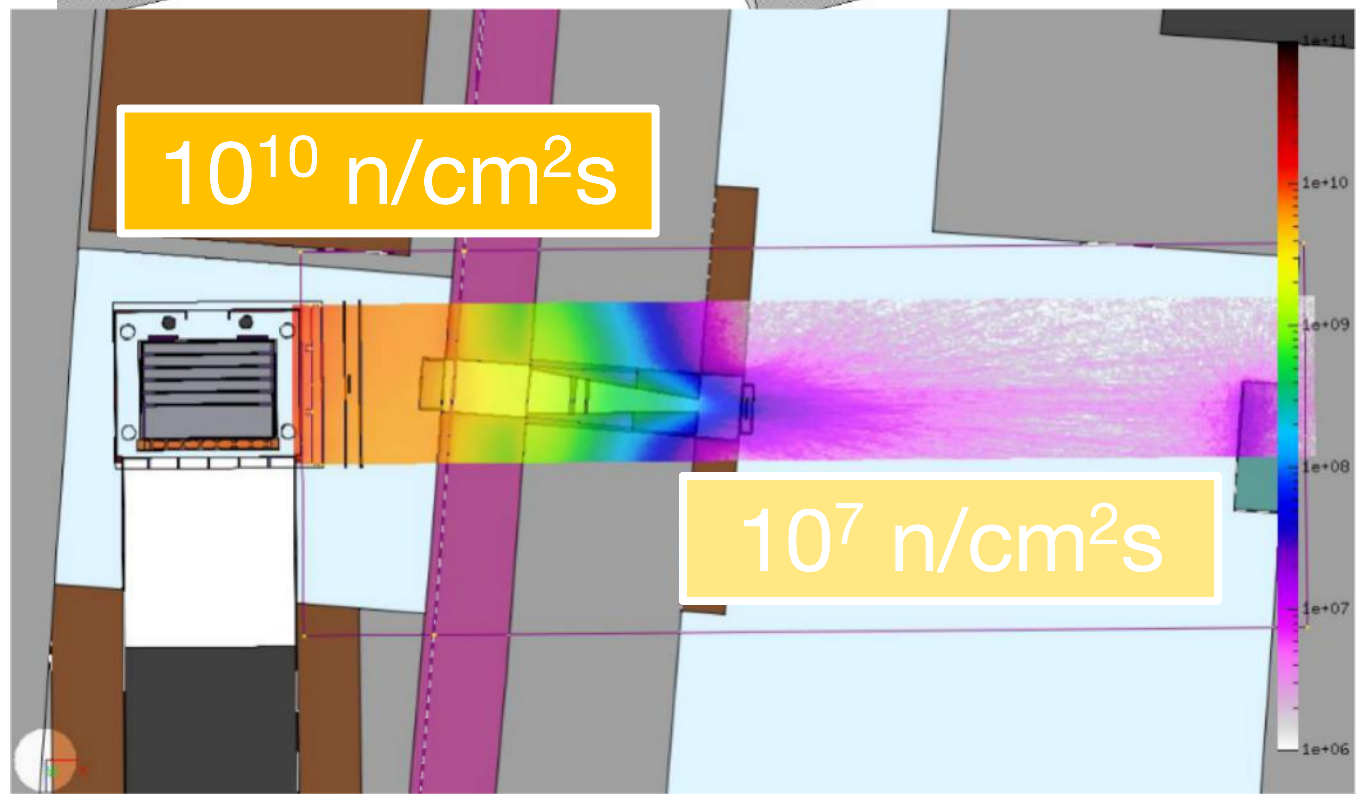


n_ToF near station and target

n_TOF has a broad physics program ranging from stellar nucleosynthesis, symmetry breaking effects in compound nuclei, and the investigation of nuclear level densities, to applications of nuclear technology, including nuclear fusion, transmutation of nuclear waste and nuclear fuel cycle investigations, **fundamental physics**.

A new experimental area is under construction: located close to the spallation target, the NEAR station will be commissioned during the next data taking period starting in 2021.



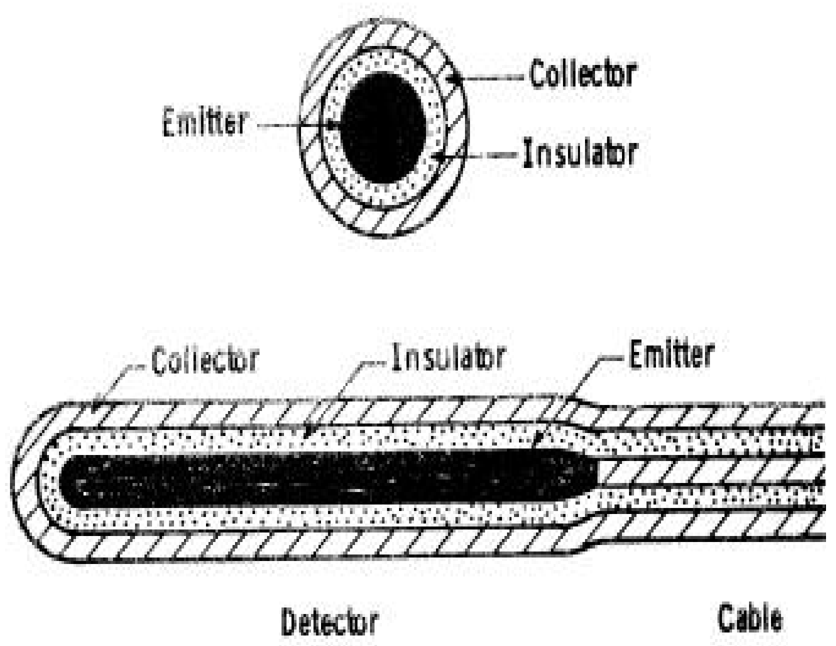


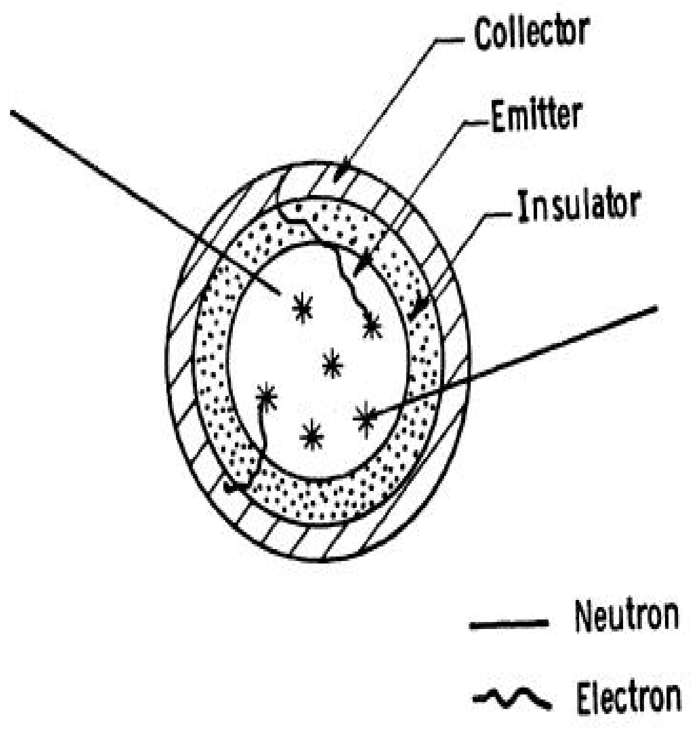
n_ToF: SPND development

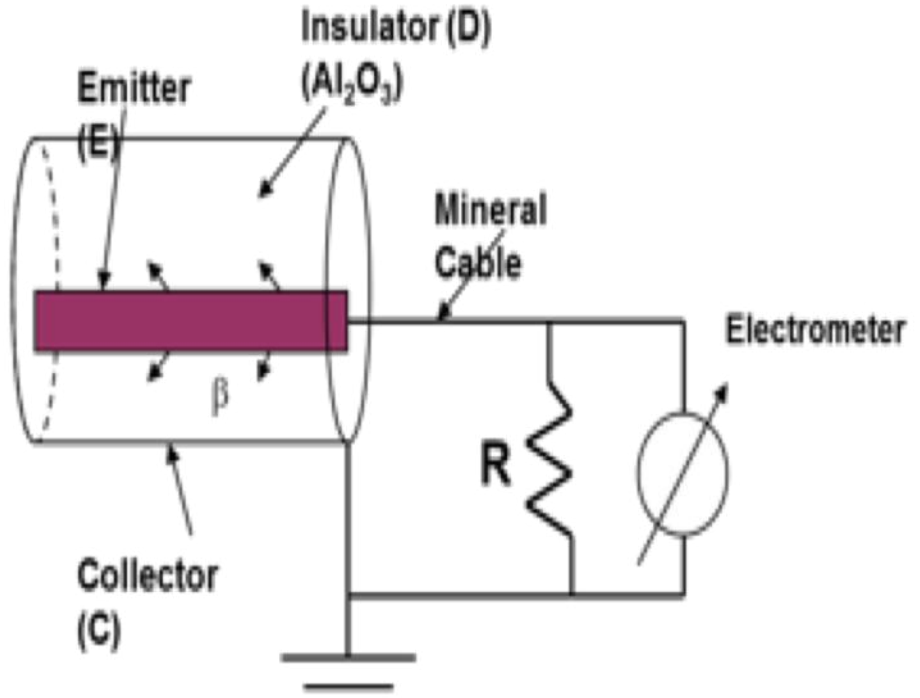
Development of Self Powered Neutron Detectors for high fluxes and mixed fields

SPNDs signal generated by:

- ❖ β decay electrons from emitter following
- ❖ γ from neutron radiative capture
- ❖ γ background







New emitters will be tested in dedicated setup in the new NEAR station area

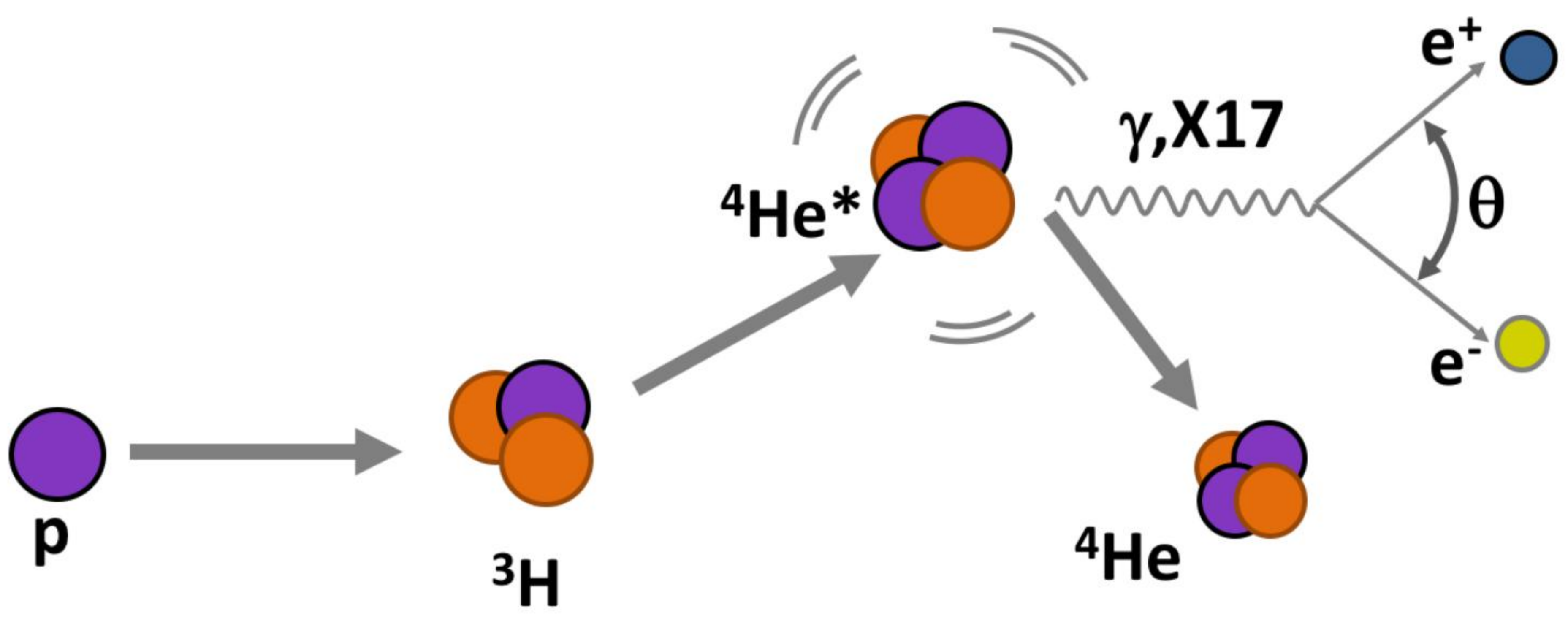
- ❖ At n_TOF distinct proton pulses allow to study prompt and delayed signal
- ❖ 10 SPND on new spallation target to study fast neutron response in mixed field
- ❖ Rh, Co, V, Pt sensitive material

Master theses:

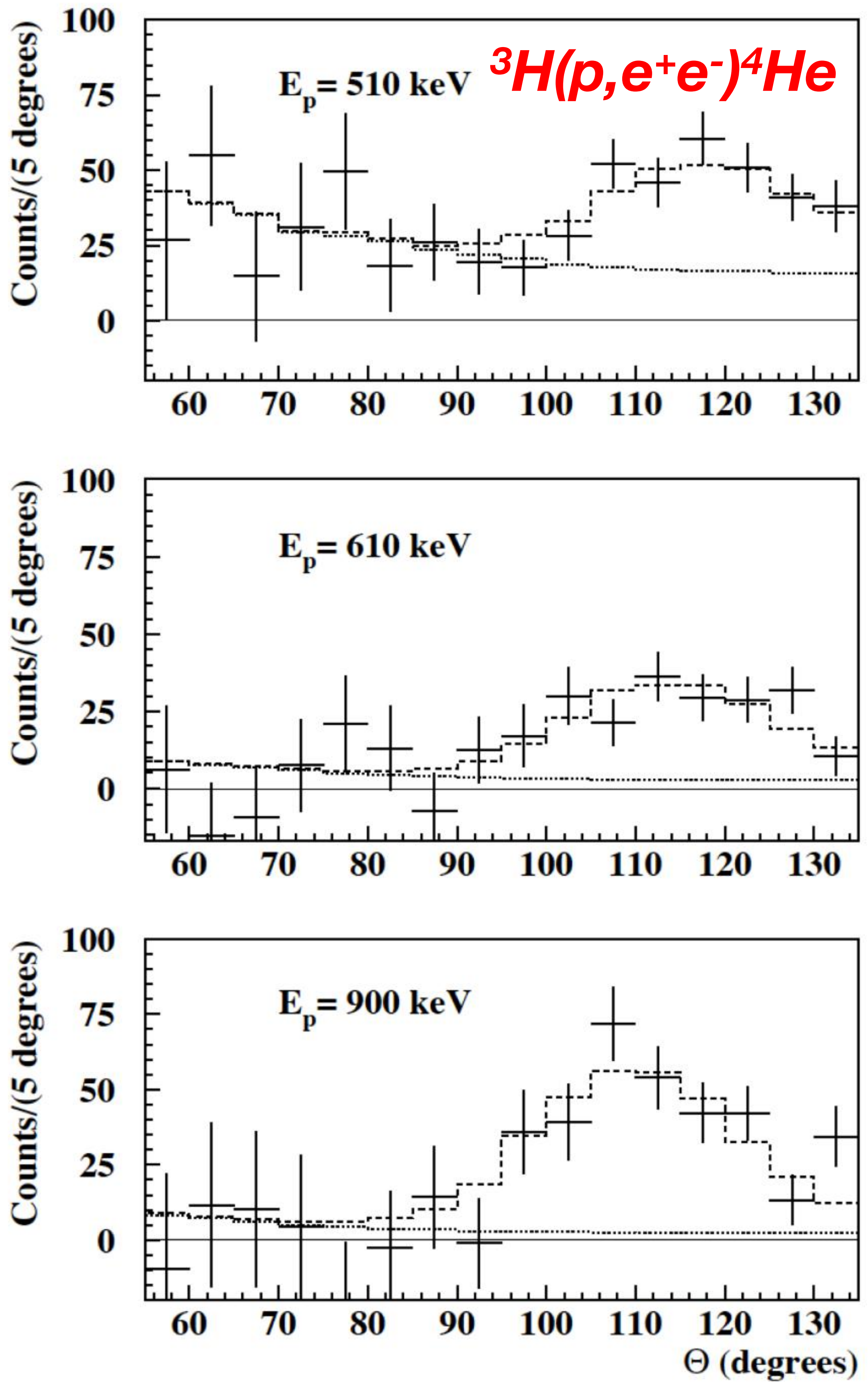
- **Development of new Self Powered Particle Detectors for mixed fields and high fluxes**
- **NEAR station neutron flux characterisation**

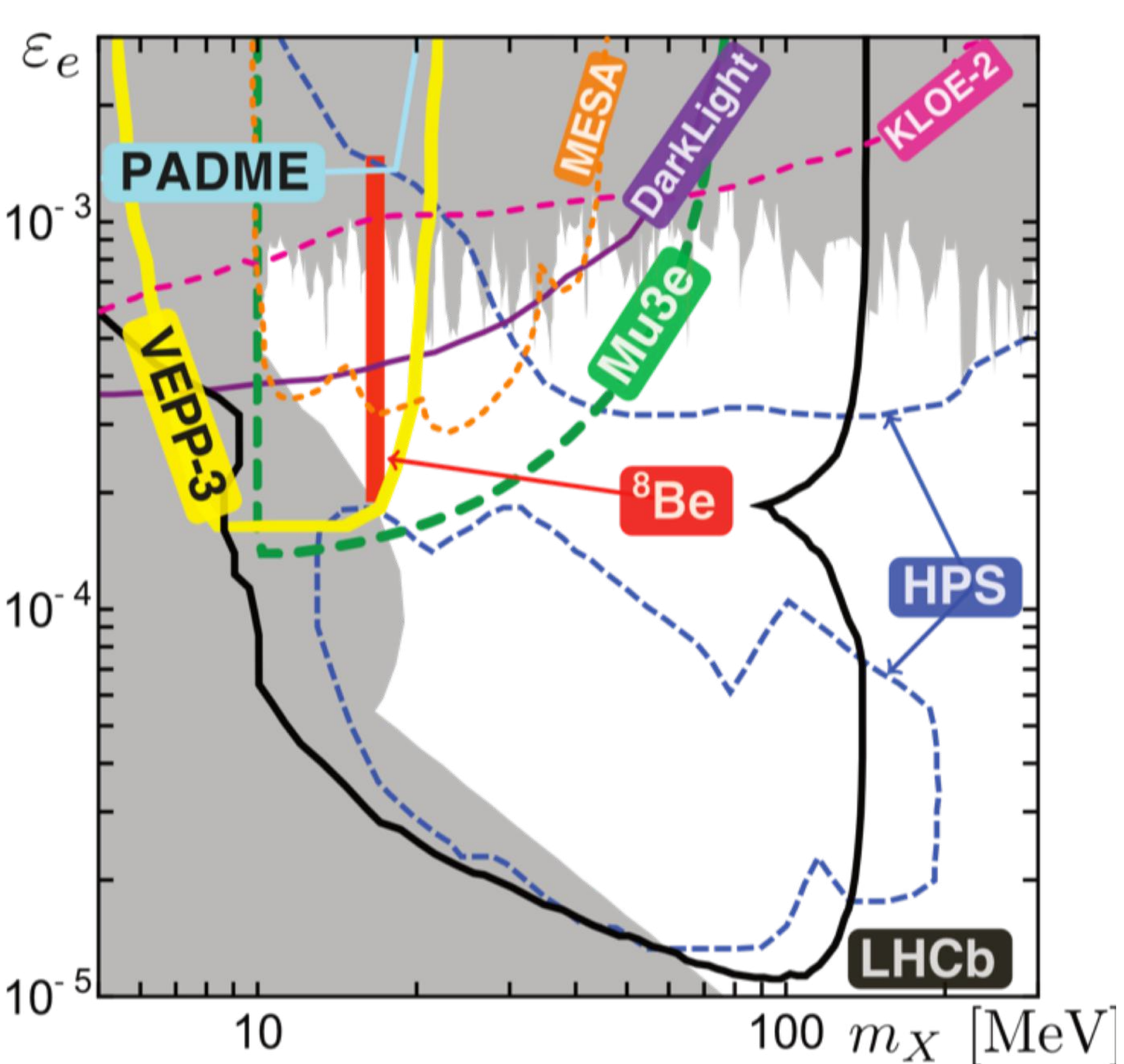
X17 @ n_TOF

-A significant excess of electron-positron pairs at large relative angle has been recently observed in the ***$^{7}Li(p,e^{+}e^{-})^{8}Be$*** *and* ***$^{3}H(p,e^{+}e^{-})^{4}He$*** *reactions.*
-This anomaly has been interpreted as the signature of a 17 MeV BOSON, not foreseen in the standard model of particle physics.
-The so called X17 boson could be a mediator of a fifth force, characterized by a strong coupling suppression of protons compared to neutrons.
-This evidence/scenario is presently not confirmed or excluded by other experiments or groups.



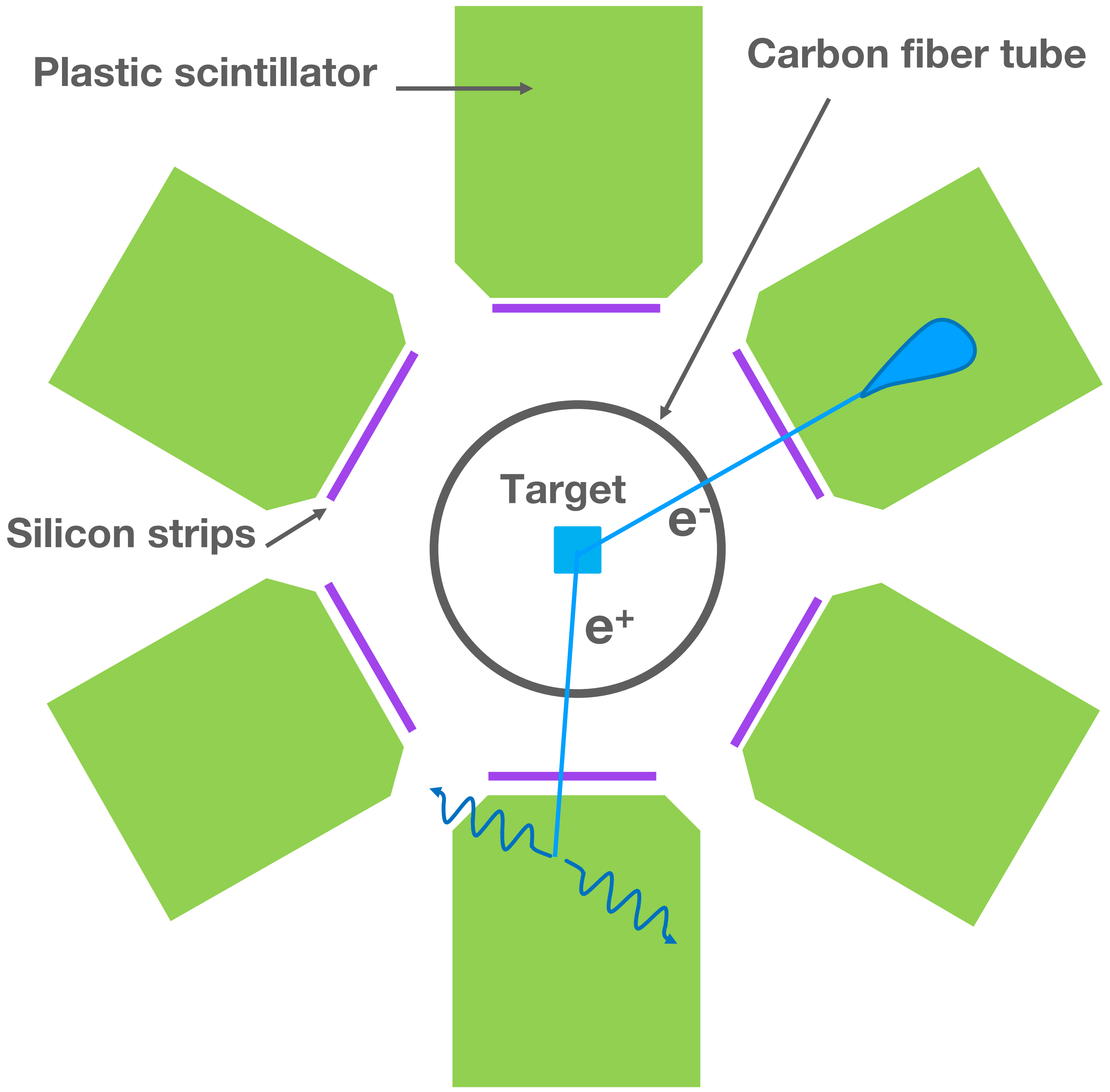
Reaction	$M_{X17}\pm\Delta M_{stat}\pm\Delta M_{syst}$ (MeV)	Statistical evidence
$^{7}Li(p,e^{+}e^{-})^{8}Be$	16.70±0.35±0,50	>5 sigma
$^{3}H(p,e^{+}e^{-})^{4}He$	16.94±0.12±0.21	>9 sigma

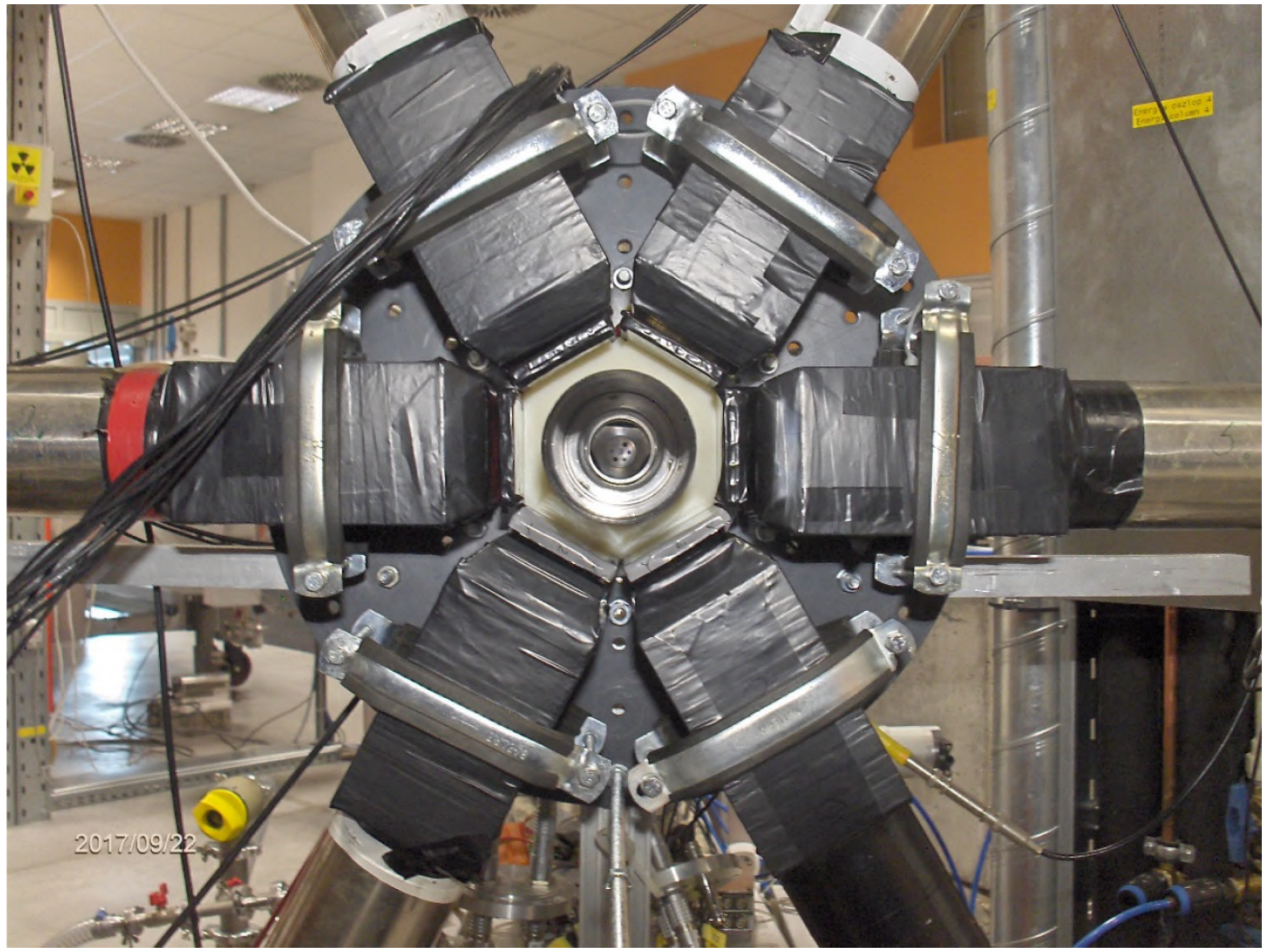




$^{3}H(p,e^{+}e^{-})^{4}He$ setup @ ATOMKI

- ❖^{3}H adsorbed on Ti layer
- ❖6 plastic scintillator 82x86x80 mm^3
- ❖6 double-sided silicon strip detector (3 mm wide strips, 0.5 mm thick)
- ❖1 mm thick carbon fiber tube
- ❖Detector acceptance only around 90° with respect to the beam axis
- ❖no tracking

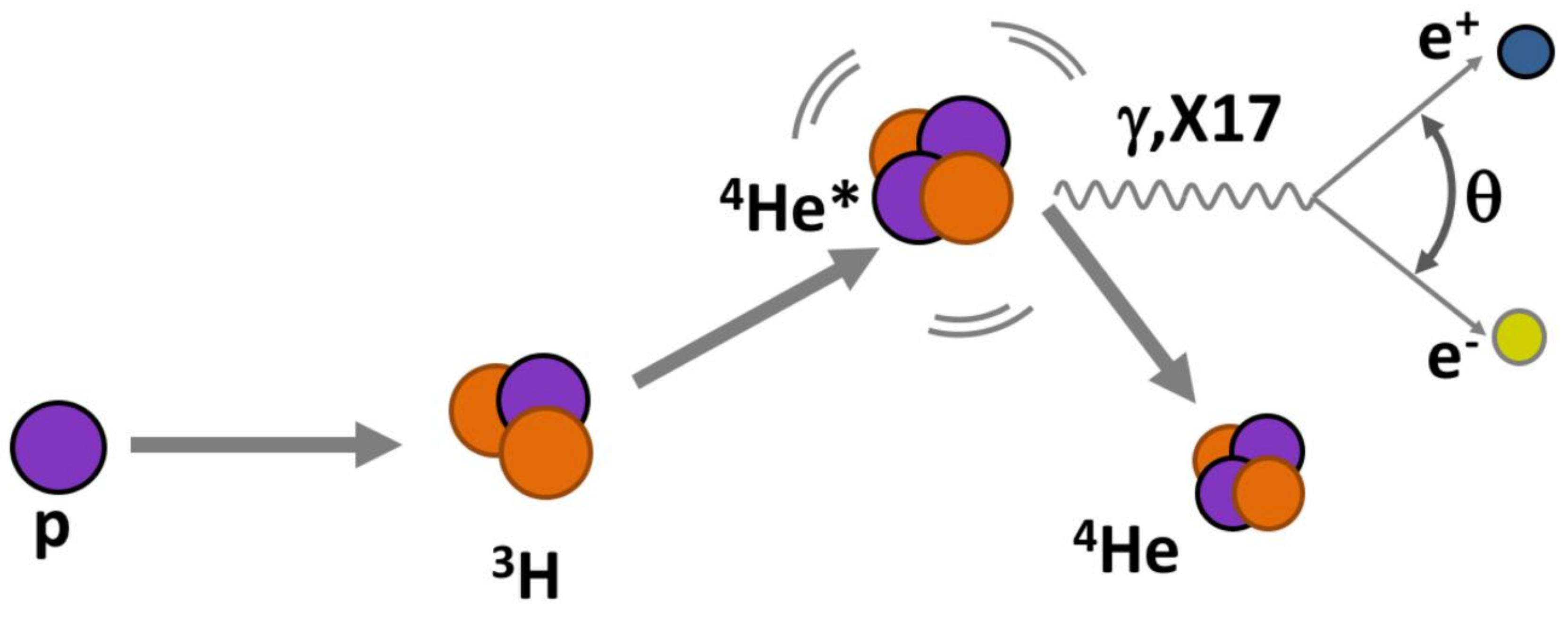




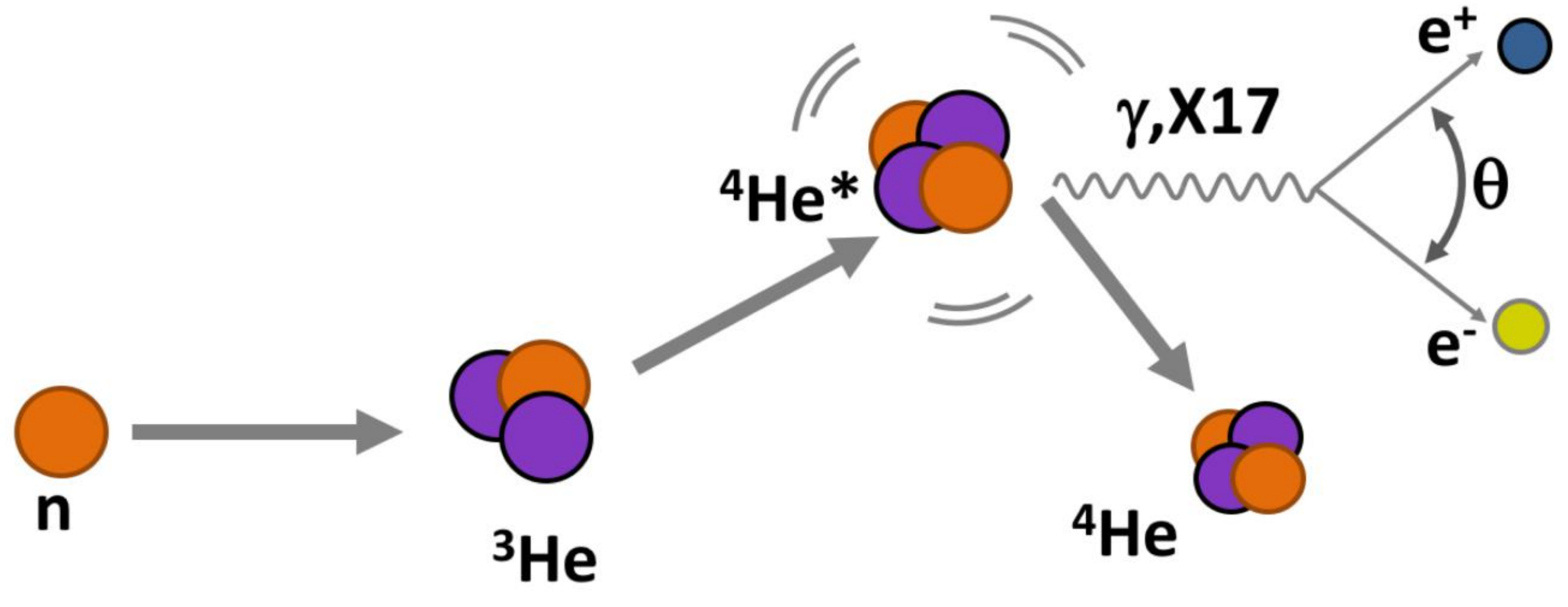
X17 @ nToF

Basic idea: new study of excited ^{4}He exploiting both the conjugated reactions:

$^{3}H(p,e^{+}e^{-})^{4}He$ → $^{3}He(n,e^{+}e^{-})^{4}He$



ATOMKI REACTION

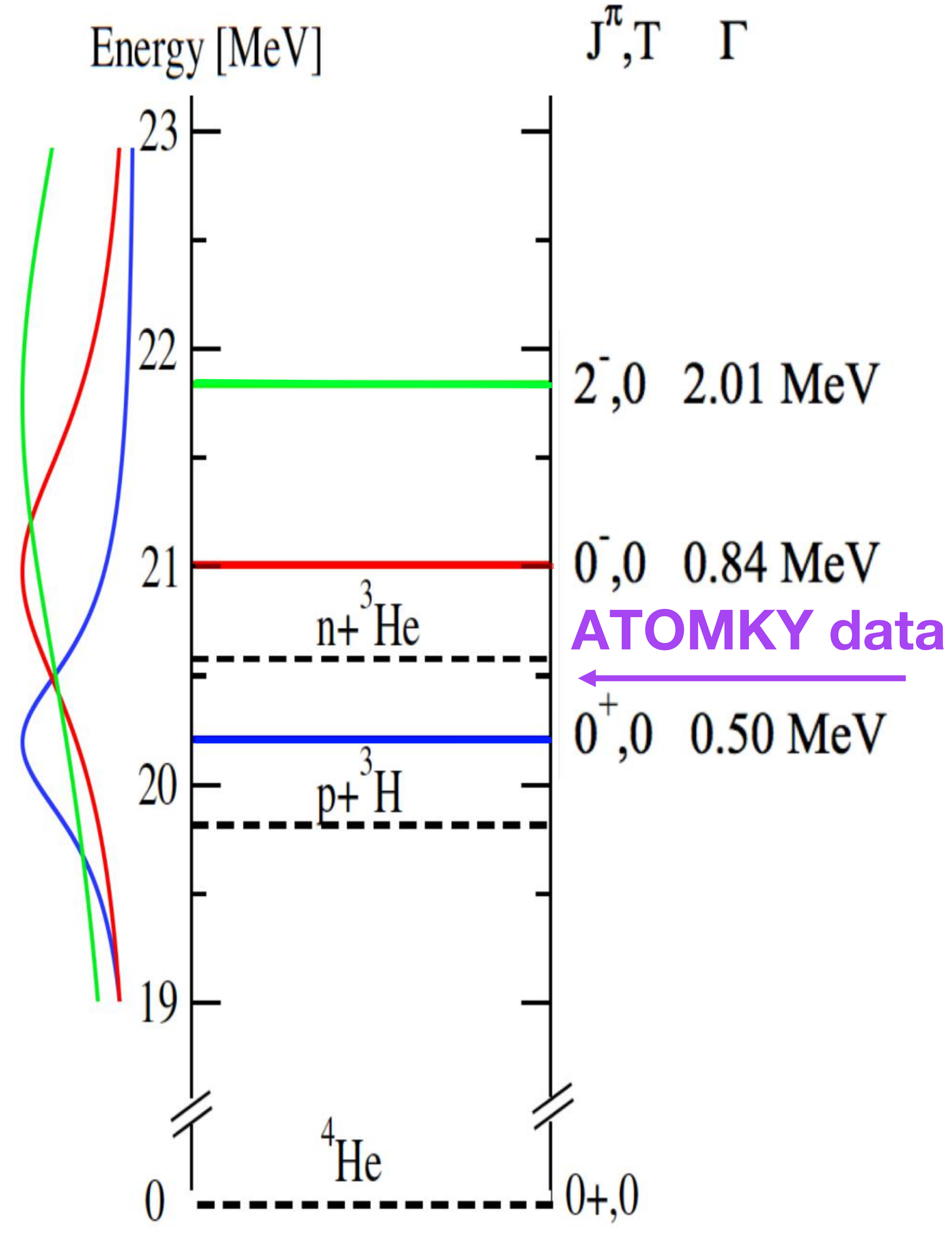


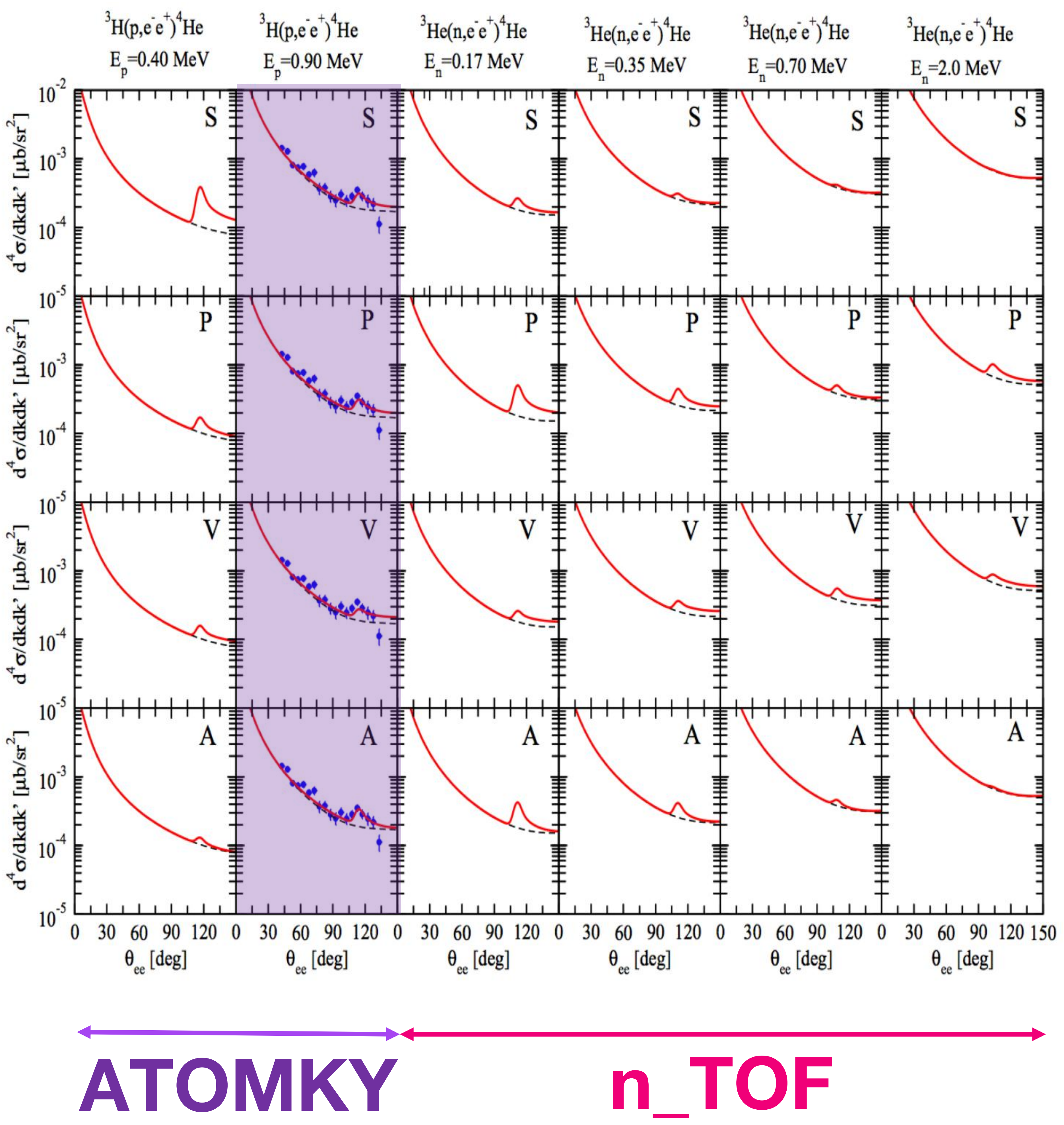
n_TOF REACTION

Physics:

- Probing X17 existence
- X17 Mass, quantic numbers, coupling, life time,..
- proto-phobic nature of the fifth force.
- First measurement of $\sigma(E)$ $^{3}He(n,e^{+}e^{-})^{4}He$
- Data Vs Theoretical nuclear physics

X17 @ nToF

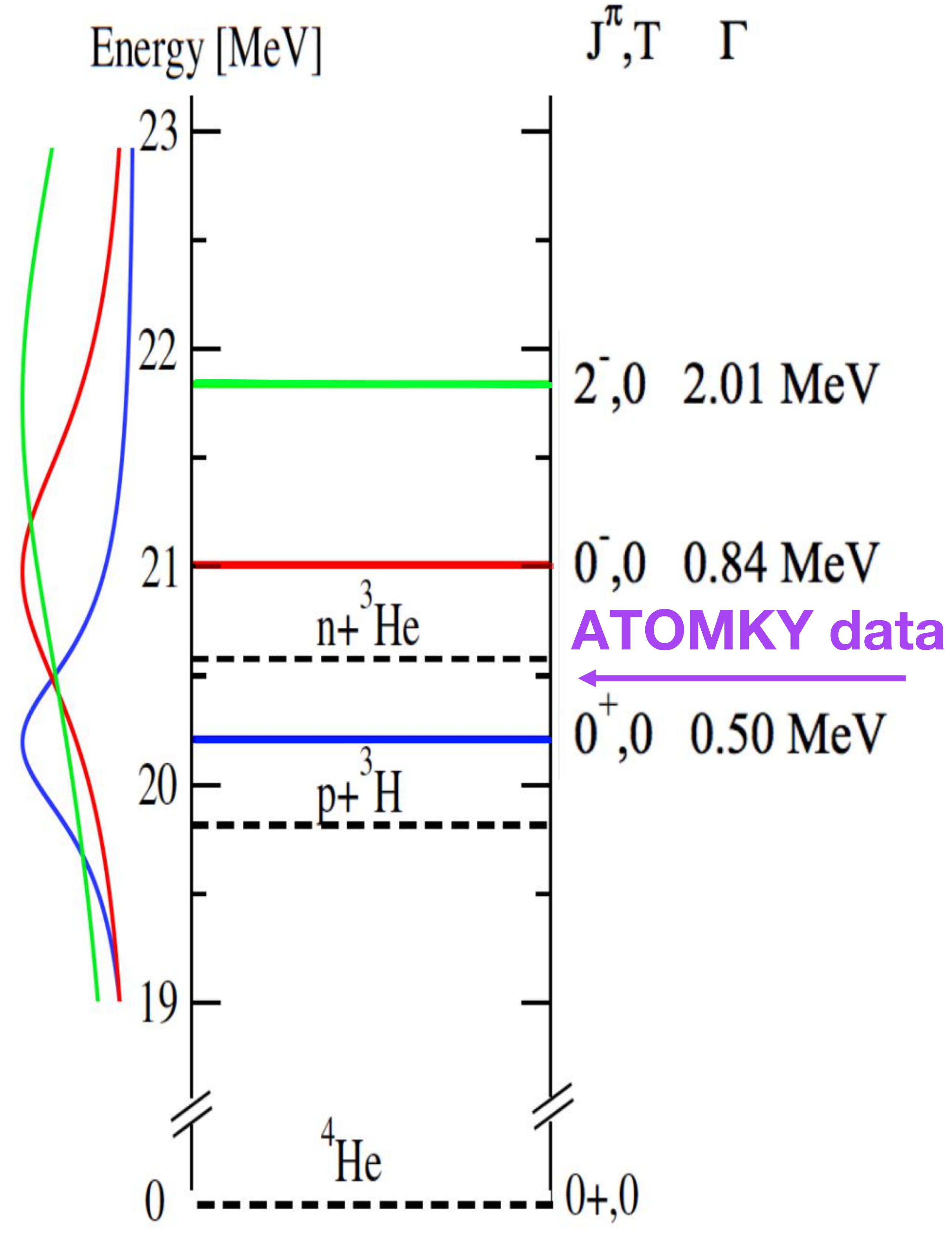


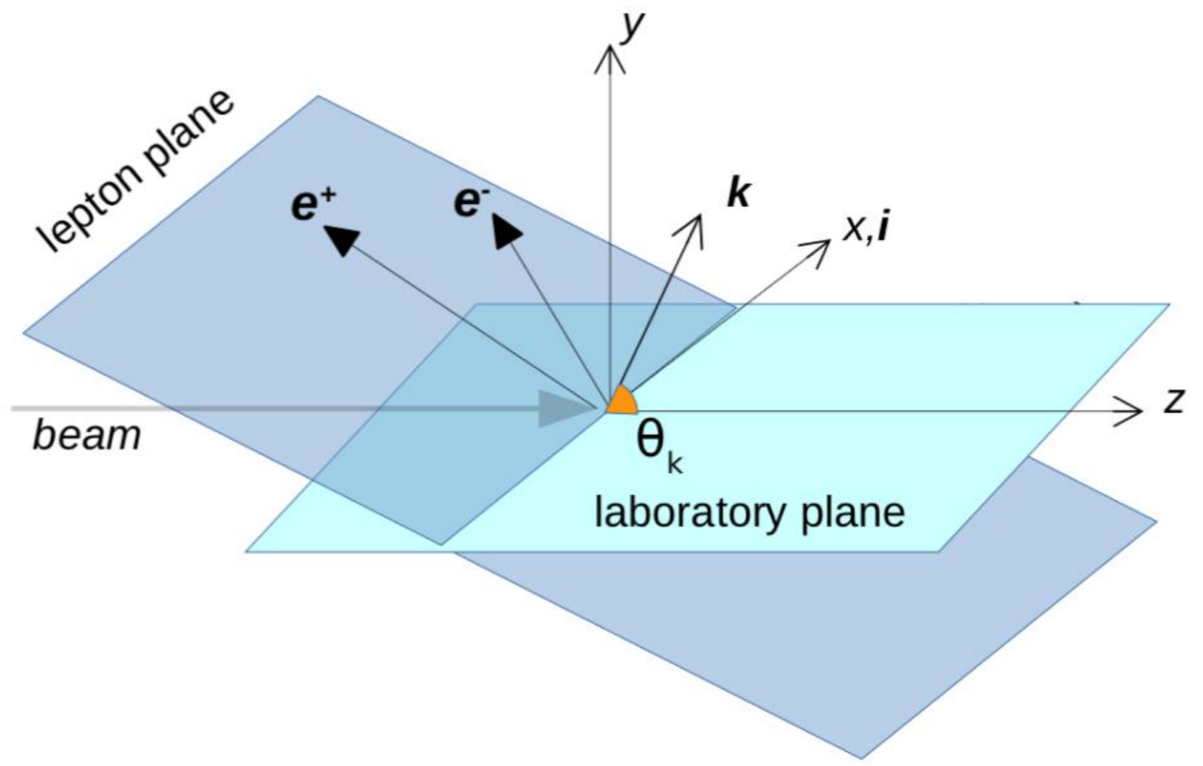


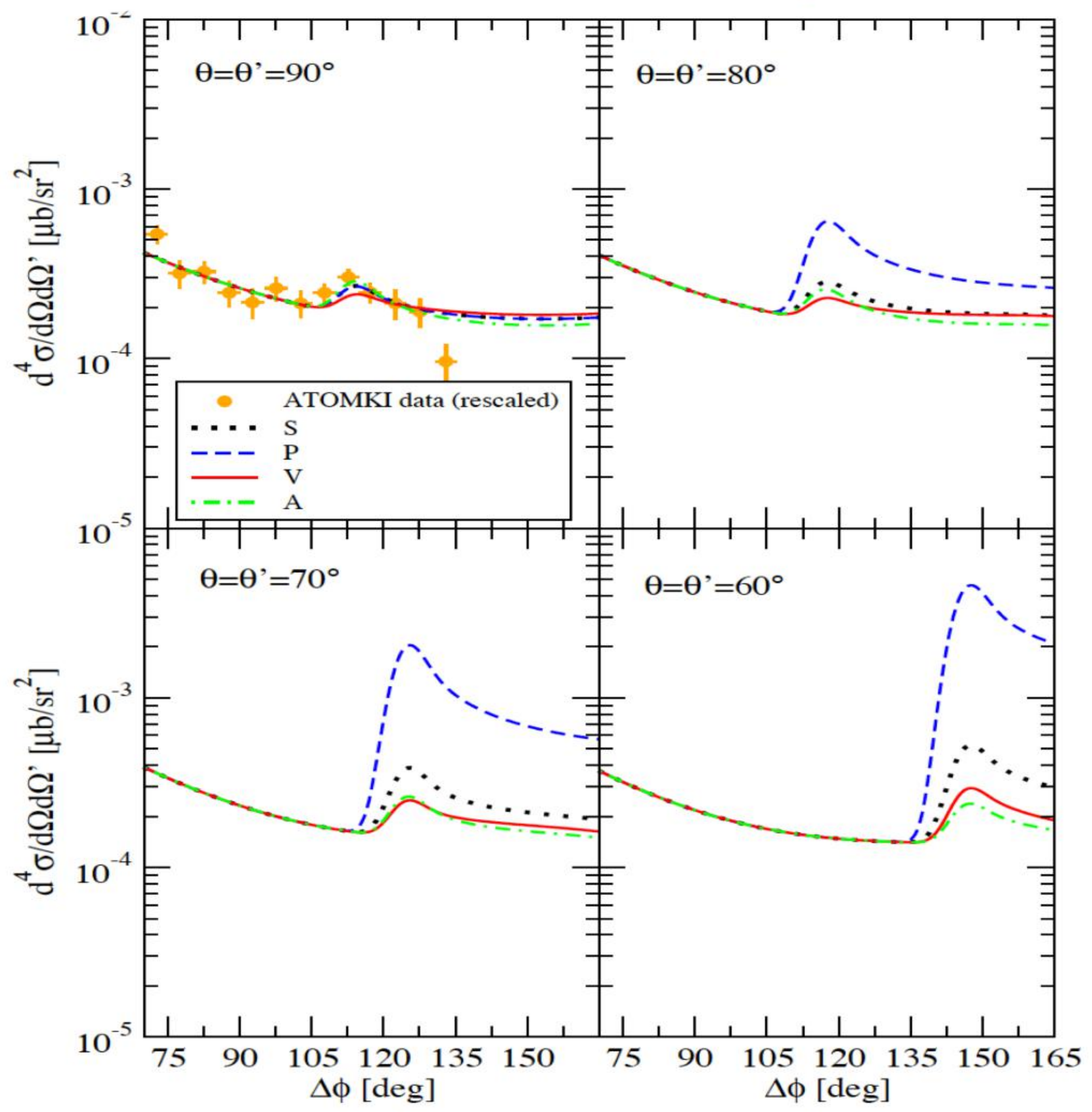
❖ **Wide energy range (proton and neutron beams) to explore all resonances with different J^π**

courtesy M. Viviani

X17 @ nToF







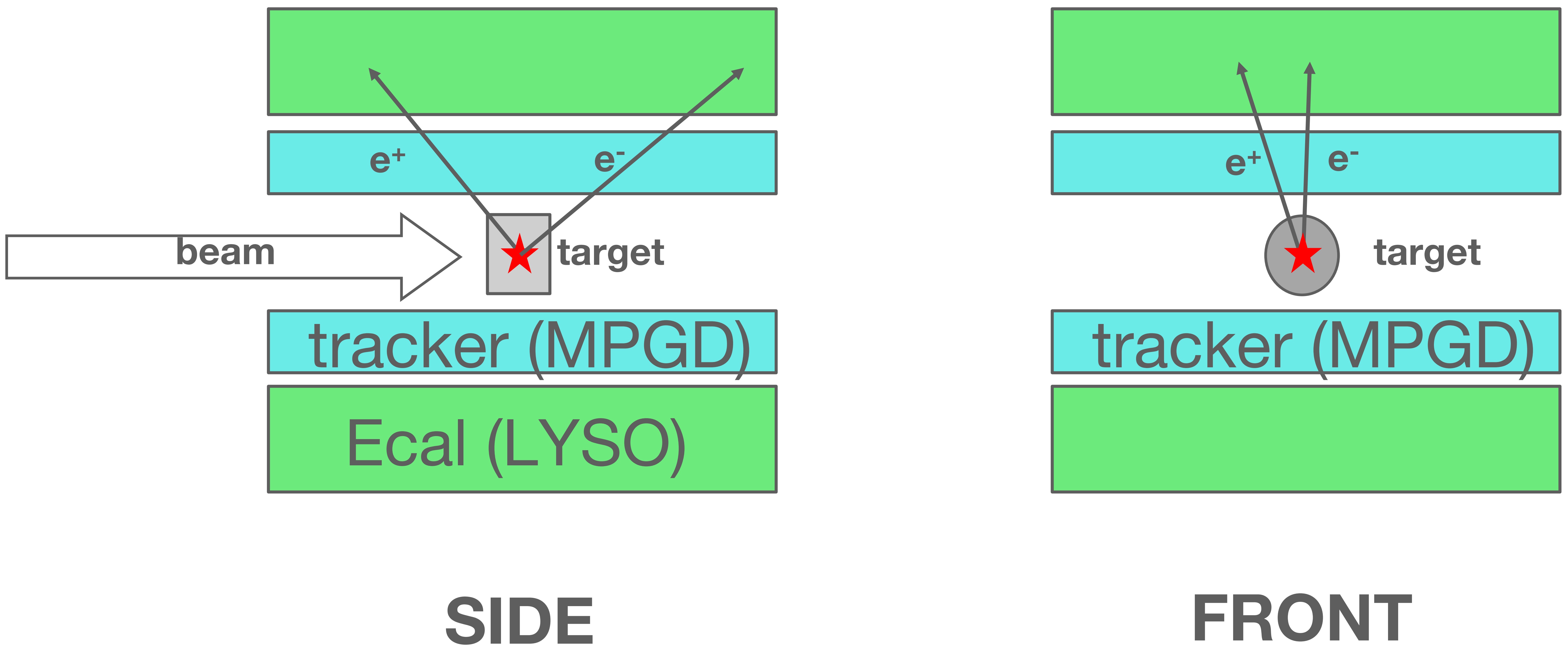
❖ **Wide energy range (proton and neutron beams) to explore all resonances with different J^{π}**

❖ **Large detector acceptance (statistics and kinematics)**

M. Viviani et al.: arXiv:2104.07808 [nucl-th] , submitted to PRC

courtesy M. Viviani

DETECTOR Conceptual design



High intensity neutron beam $0<E_n[\mathrm{MeV}]<3$

High density target $\rho=10^{21}$ atoms/cm^3

Tracking (vertex and Pairs aperture angle energy)

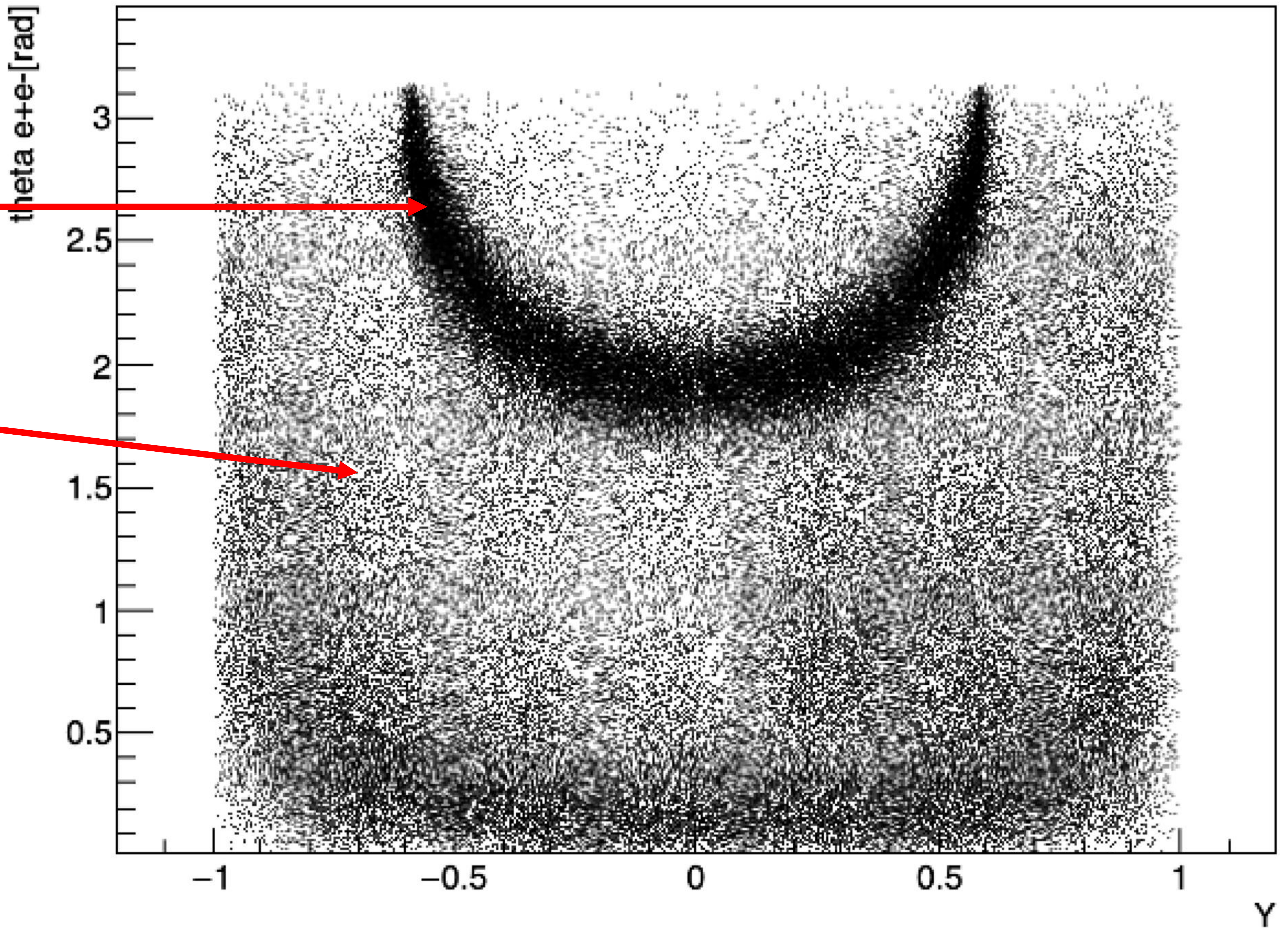
4-momenta

X17 SIGNAL AND (irreducible) BACKGROUND

target: ^3He at P=30 bar, T= 300 k
thickness of Carbon fibre= 1 mm
Multiple scattering included
IPC background included
DATA From M. Viviani ab-initio calculations, normailzed to the ATOMKY results

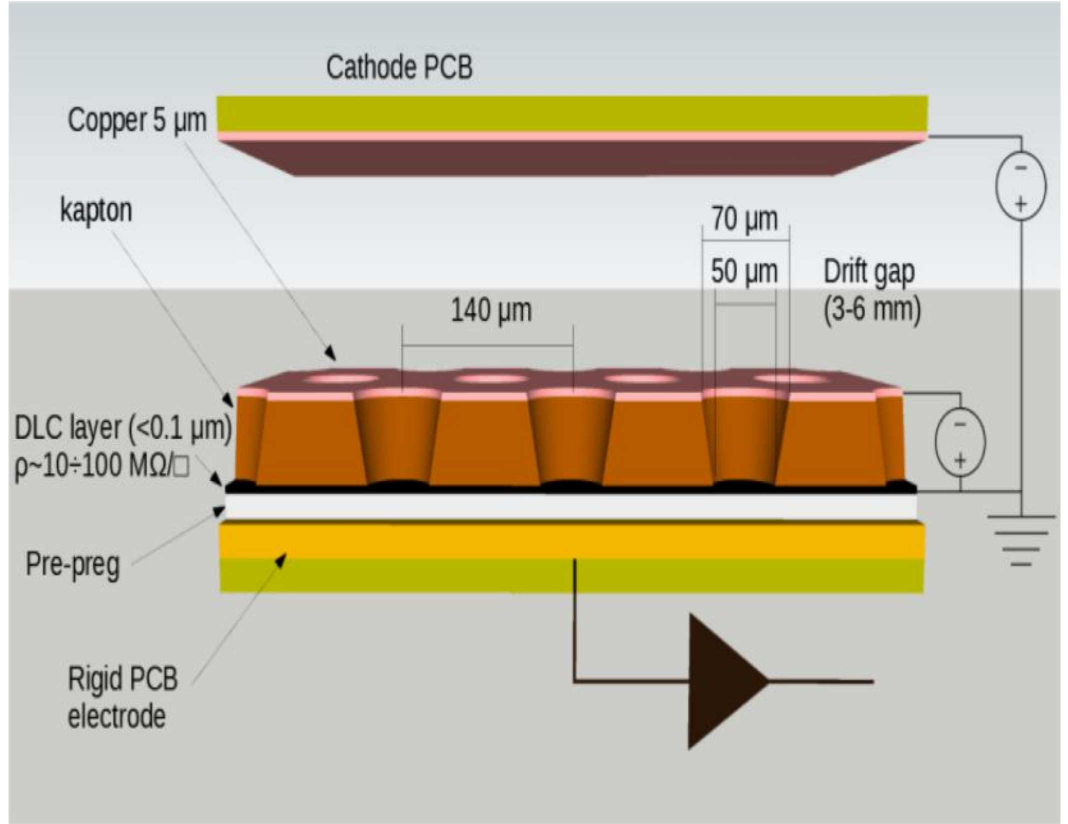
X17 Signal

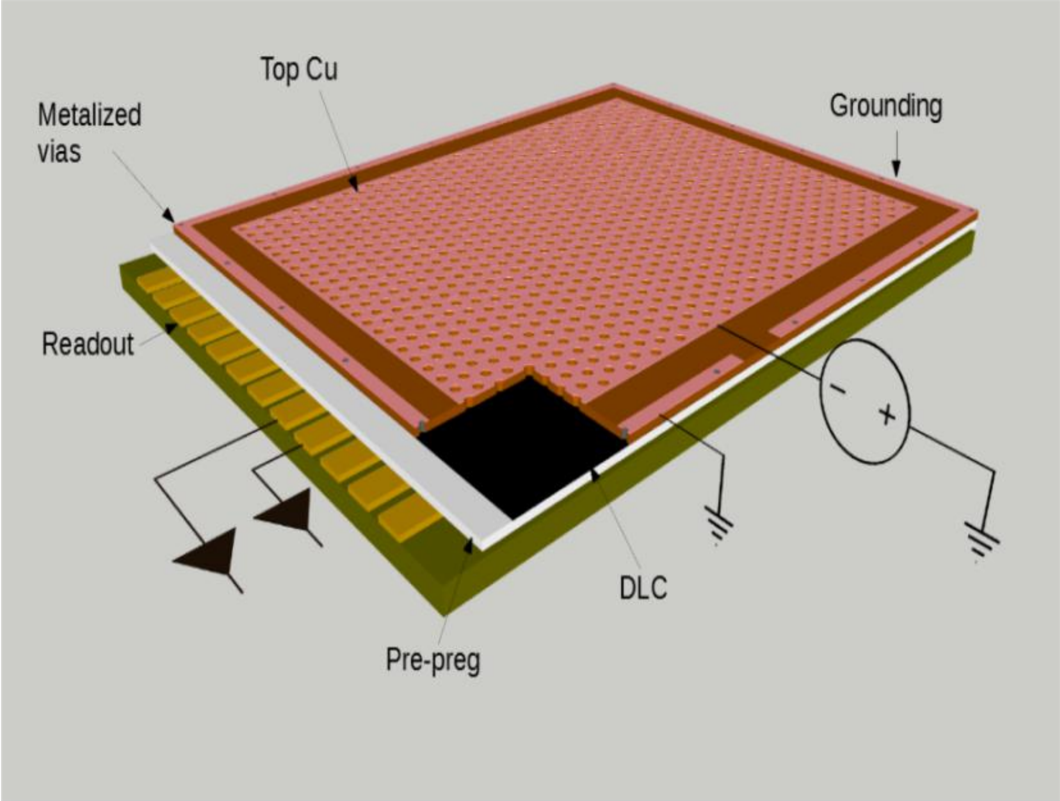
IPC background

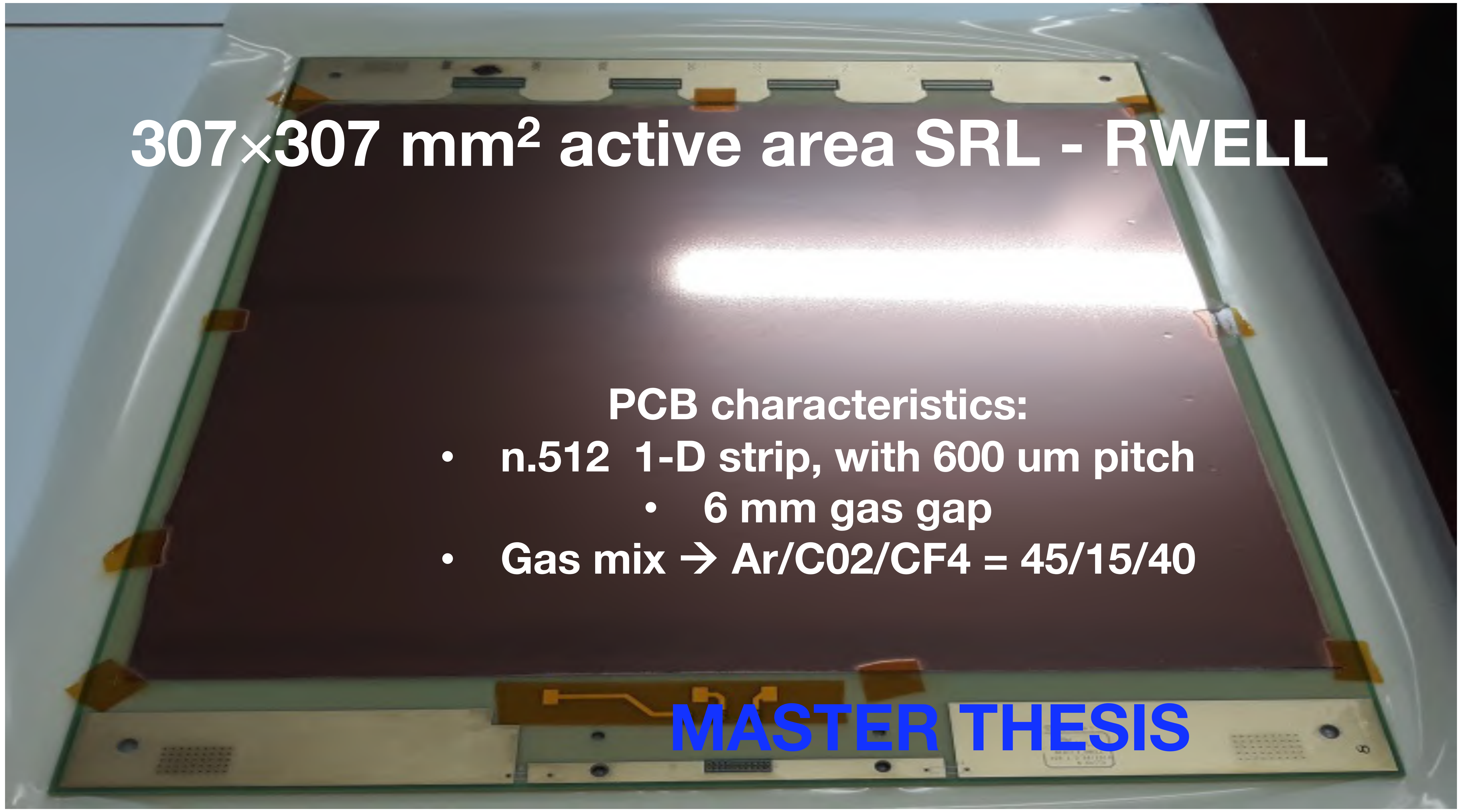


$Y=(E_{e-} - E_{e+})/(E_{e-} + E_{e+})$
θ_{ee}= aperture angle of e+e- pairs

μ–Rwell prototype ready for the test beam at CERN







307×307 mm^2 active area SRL - RWELL

PCB characteristics:

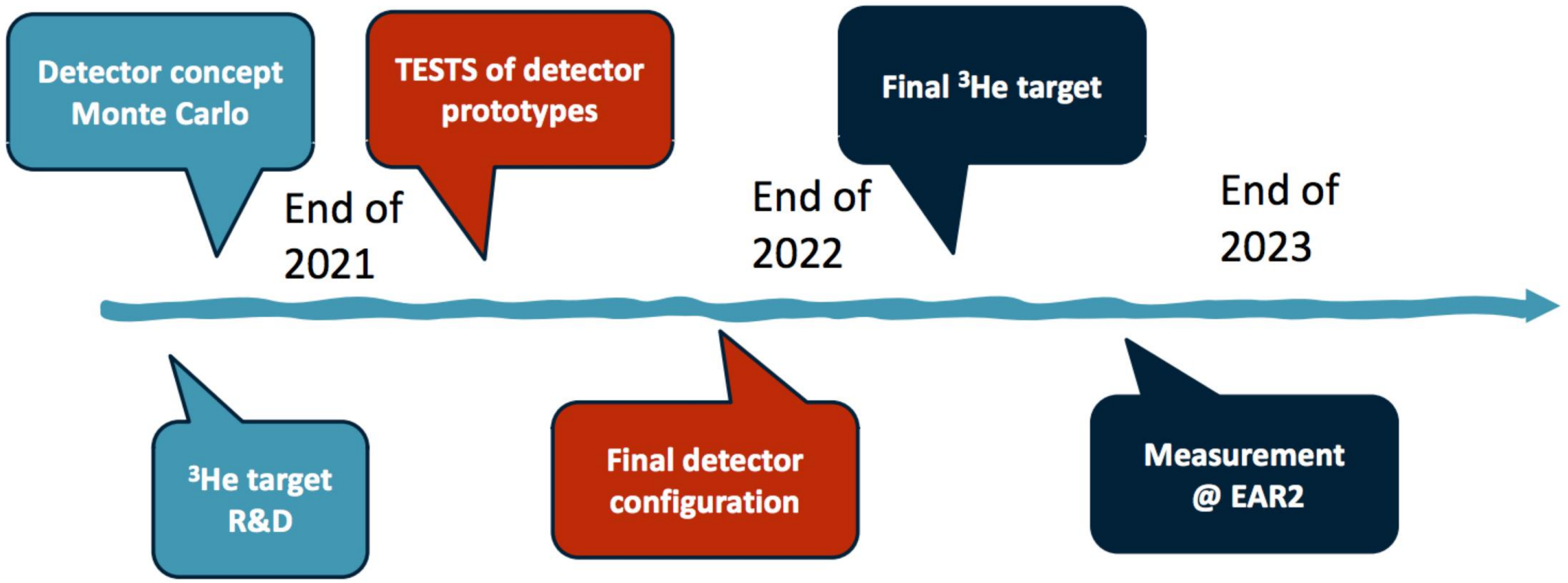
- **n.512 1-D strip, with 600 um pitch**
- **6 mm gas gap**
- **Gas mix → Ar/C02/CF4 = 45/15/40**

MASTER THESIS

Probing X17 boson with n_ToF:
Detector design:
Simulation (GEANT4)
Validation (beam tests at CERN/LNL,

Timeline of X17 @n_TOF

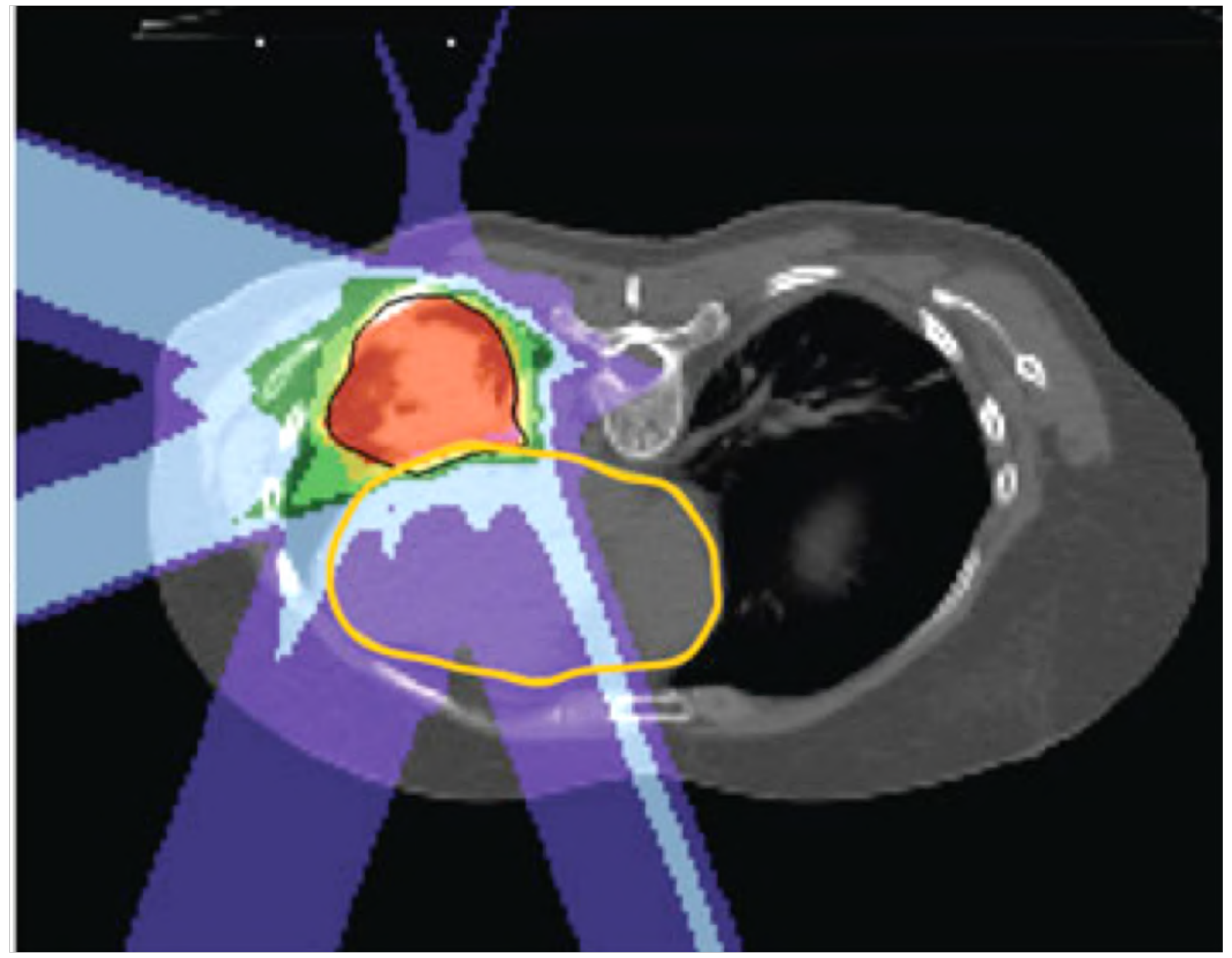
- The ATOMKY anomaly has been interpreted as the signature of a particle (X17 boson) not foreseen in the standard model of particle physics.
- A new measurement to confirm (or reject) the existence of X17 particle is mandatory.
- With n_ToF it is possible to exploits the new reaction $^{3}He(n,e+e-)^{4}He$ in a wide energy range and using a dedicated setup, to probe the purpoted protophobic nature of fifth force and to measure X17 properties.
- Standard $^{3}He(n,e+e-)^{4}He$ and $^{3}H(p,\gamma)^{4}He$ reactions are also of great interest in nuclear physics, providing an important experimental footing for "ab initio" calculations.
- R&D, simulations and theoretical calculations are in progress. Feasibility tests are approved and funded by INFN.

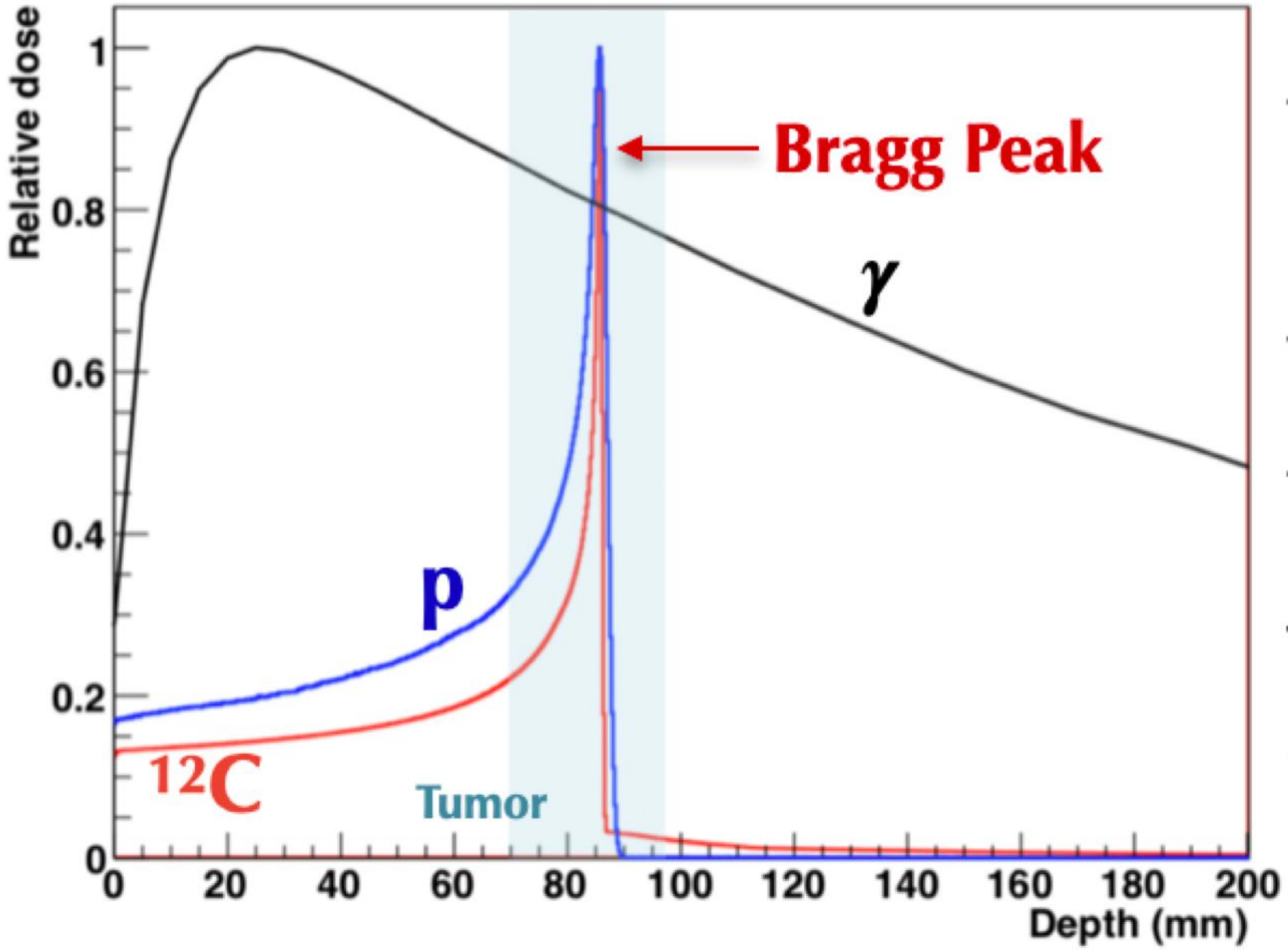


Timeline of X17 @n_TOF

FragmentatiOn Of Target (FOOT) experiment

Measurements of target and projectile fragmentation cross section relevant for **PT** and for **Radio Protection in Space** applications.

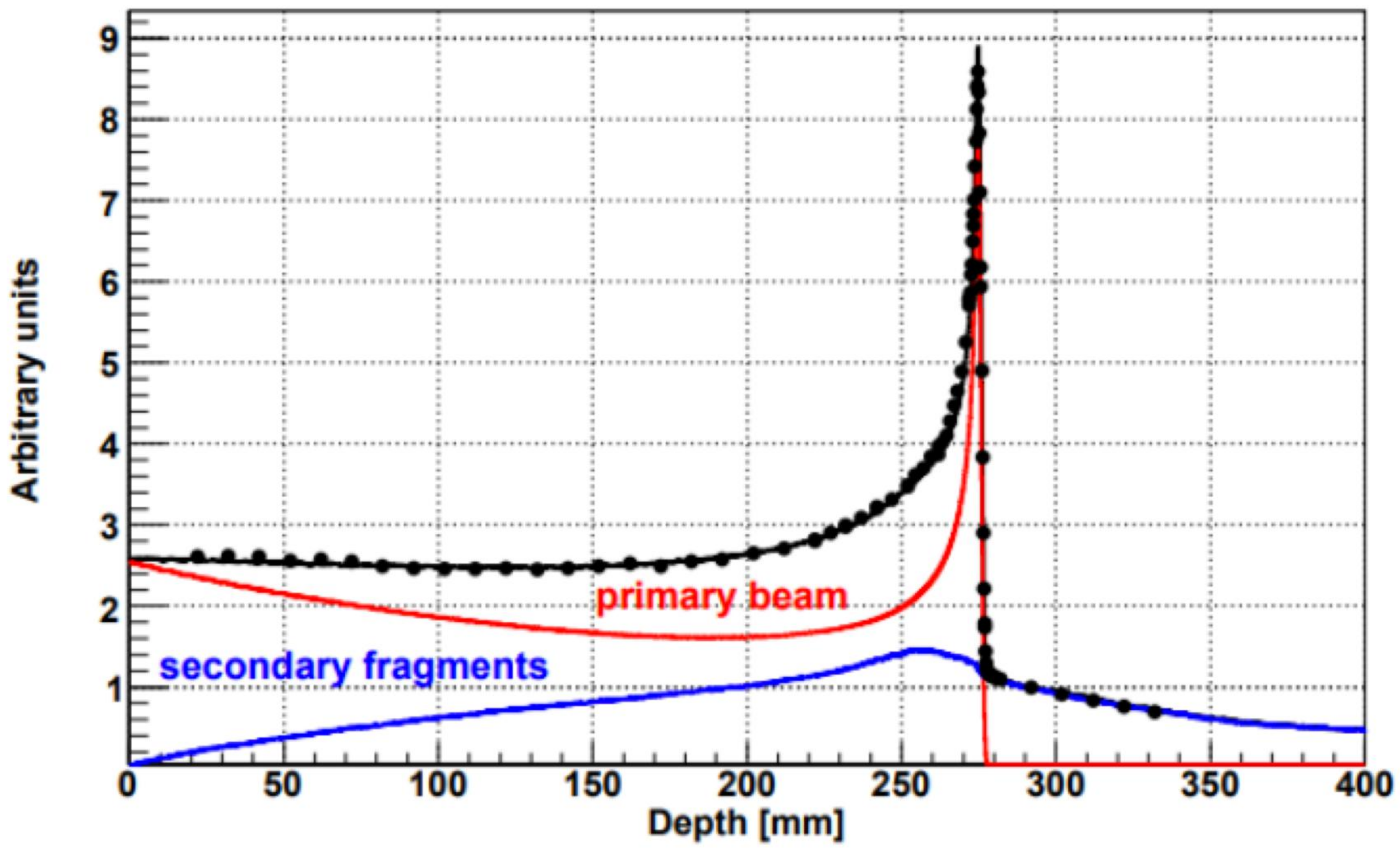




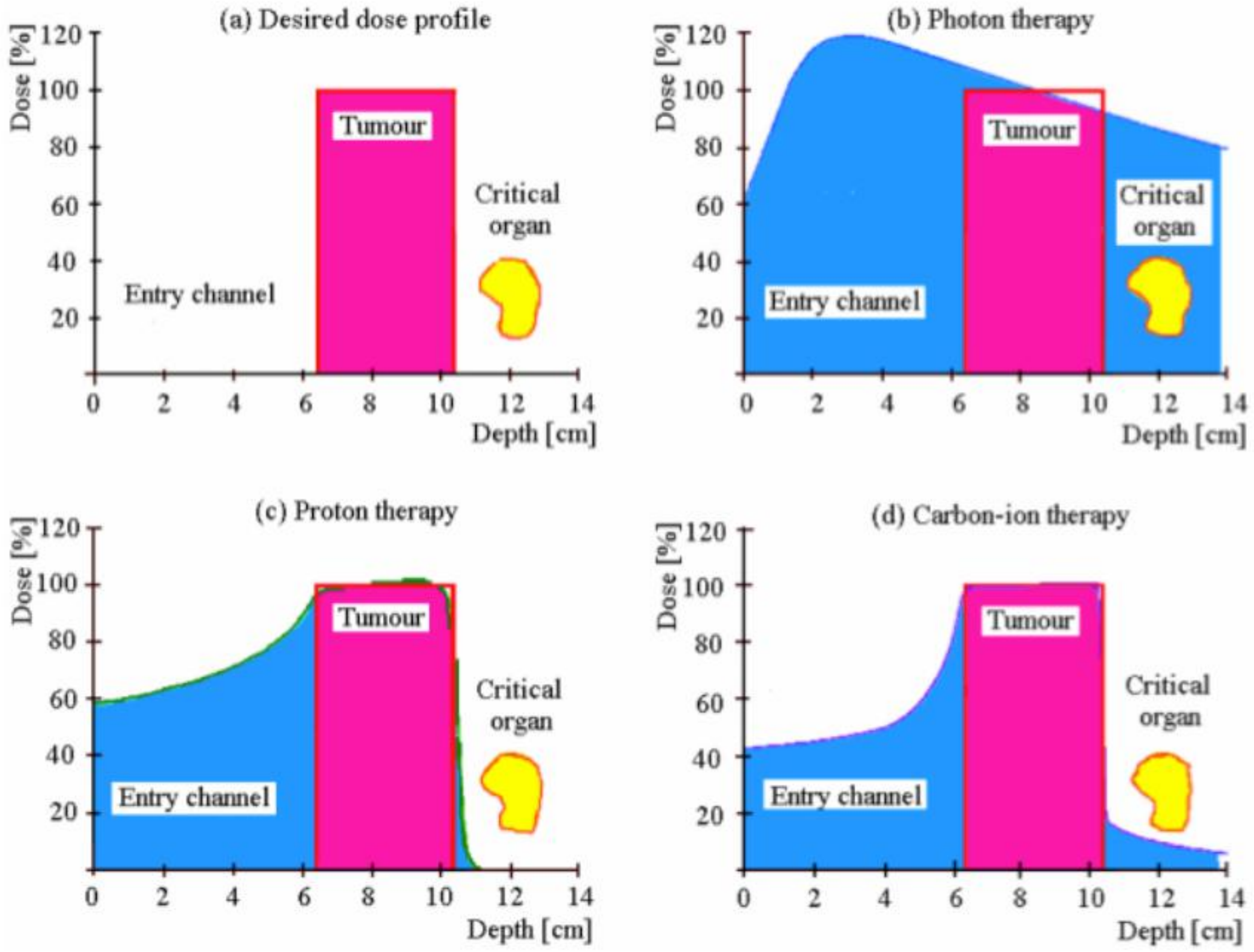
D. Cussol, *Nuclear Physics and Hadrontherapy* (2000)

Experiment with translational approach: focus on nuclear physics, physics applied to medicine and radioprotection in space (doi.org/10.3389/fphy.2020.568242)

Fragmentation consequences



A. Mairani, PhD Thesis 2008



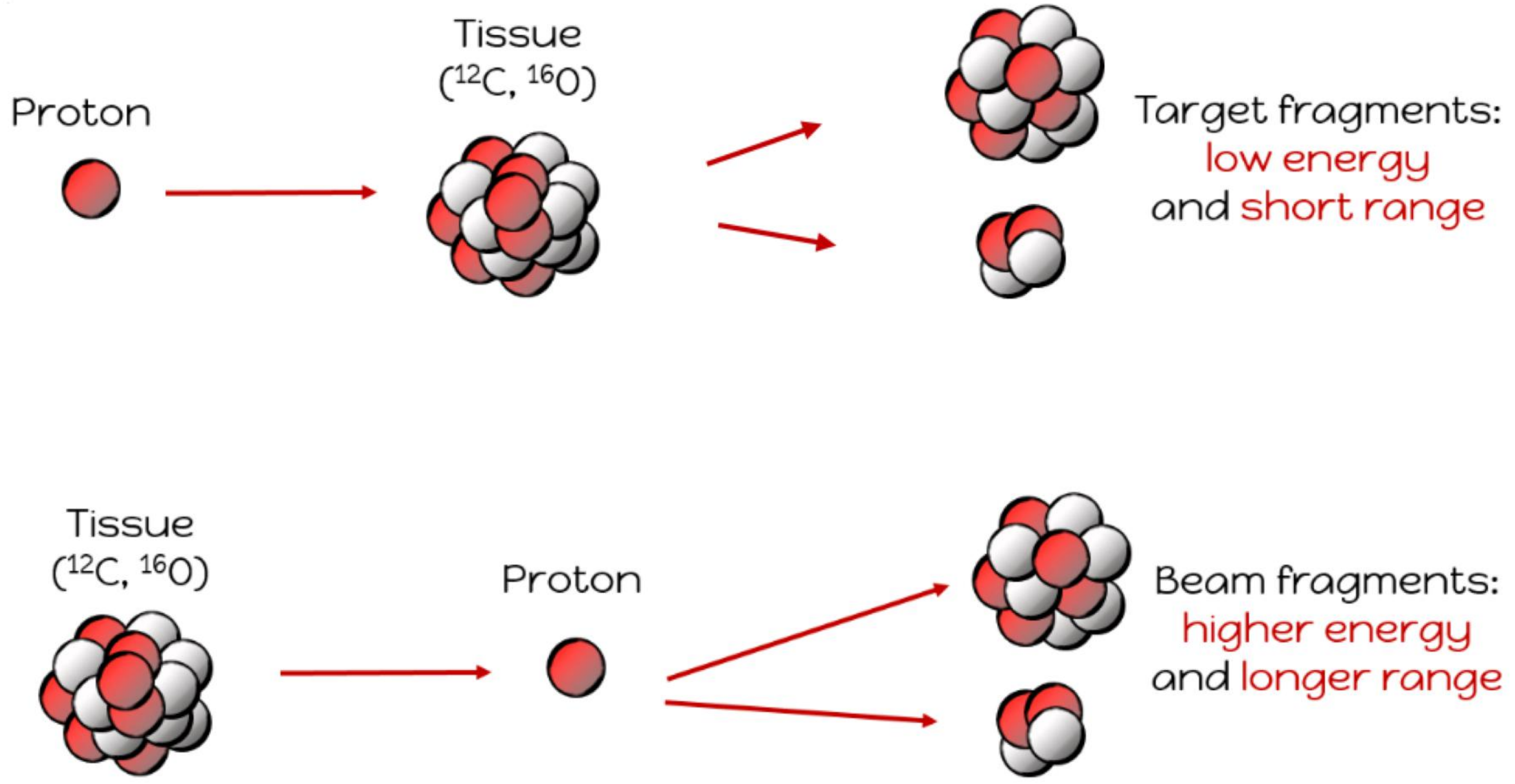
- **Treatment plans for Proton Therapy (PT) are not yet able to include the fragmentation contribution with the accuracy (3%) required for radiotherapy**
- **This is due to the lack of experimental data, and in particular of fragmentation cross section**

Fragmentation measurement approach

Target fragments have a very **low energy** and so a very **low range** that make the detection really difficult.

Direct kinematic

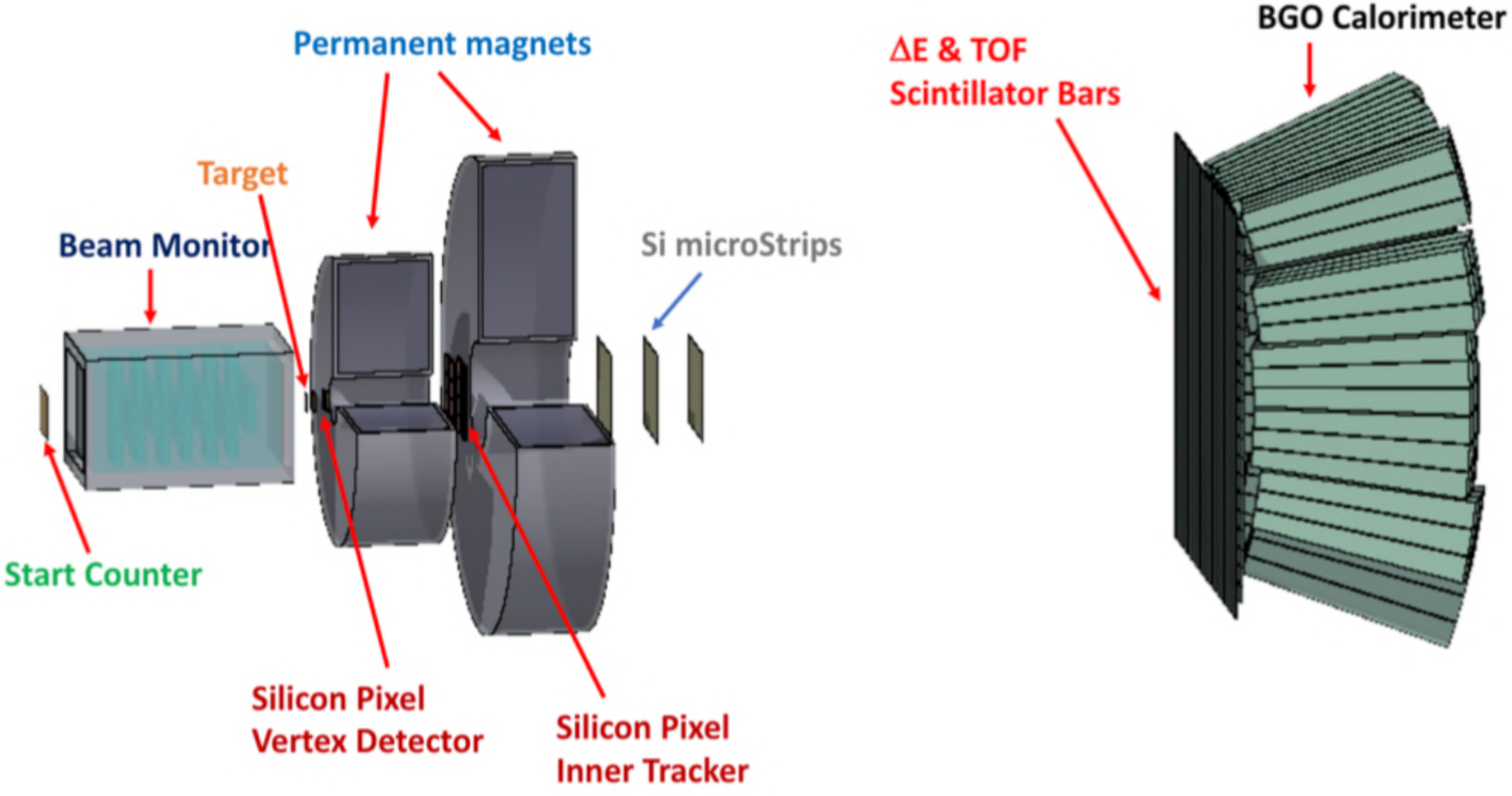
Inverse kinematic



By applying a Lorentz boost it is possible to switch from the laboratory frame to the "patient frame"

With this strategy the fragmentation of **tissue-like ion beams** (mainly C and O) impinging on a **hydrogen enriched target** are studied moving from the challenging measurement of target fragmentation to the easier case of projectile fragmentation

FOOT detector



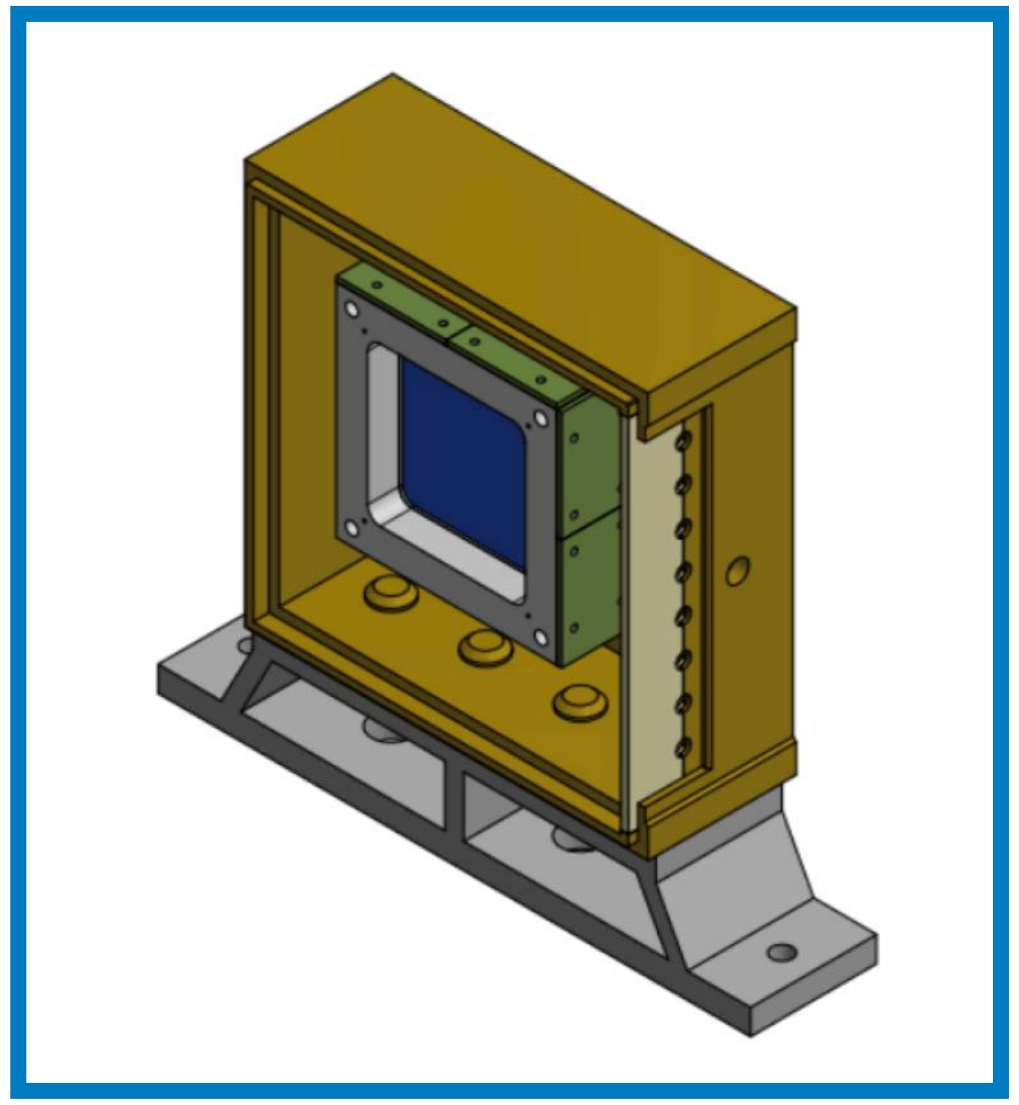
- **Fixed target** experiment with magnetic spectrometer for the identification of fragments, optimitezed fot Z>2 fragments

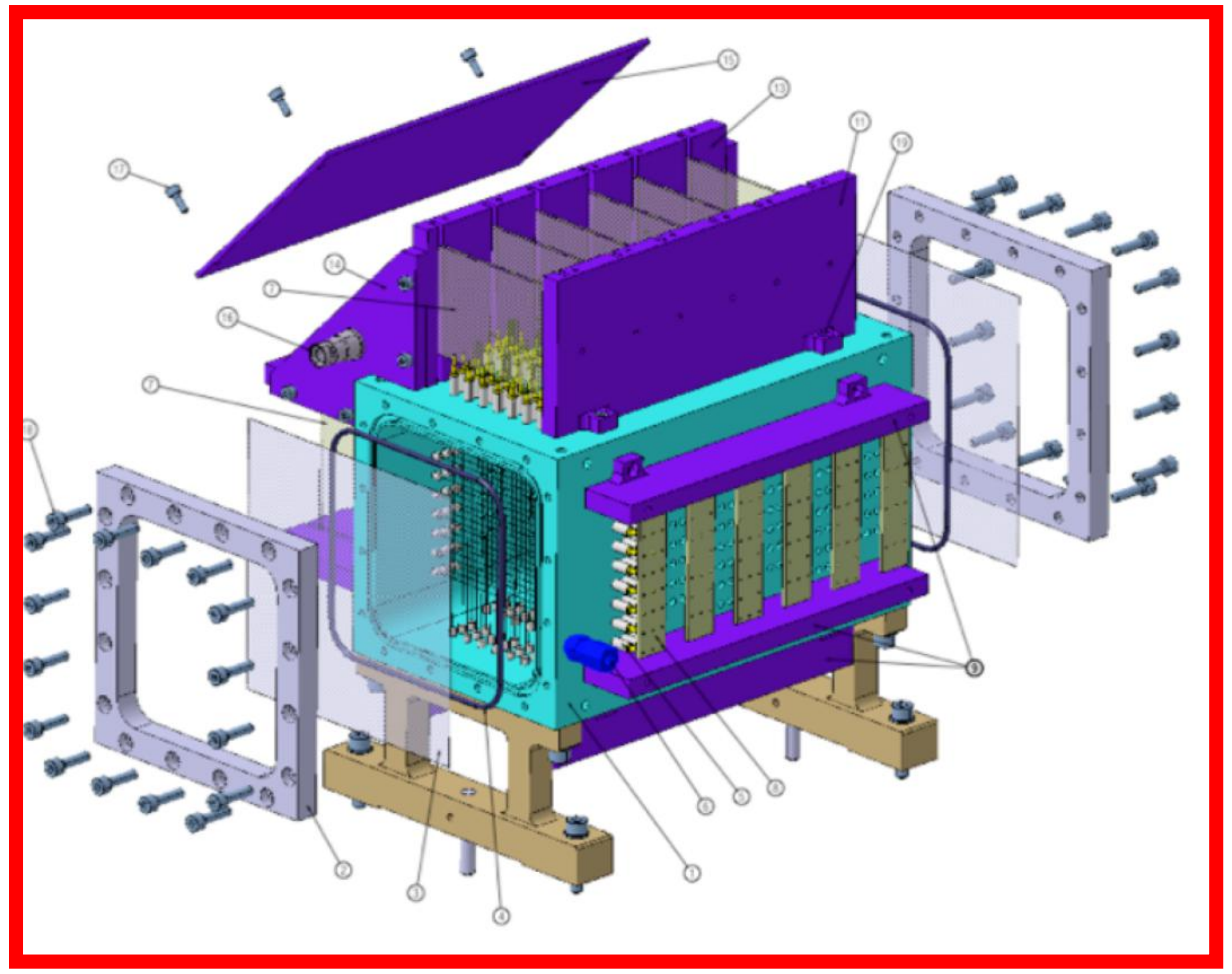
Required performances for cross section precision < 10%

- $\sigma(p)/p \sim 5\%$
- $\sigma(E_k)/E_k \sim 2\%$
- $\sigma(\Delta E)/\Delta E \sim 3-10\%$
- $\sigma(TOF)/TOF \sim 100ps$

The FOOT detector is a movable set-up to fit the experimental rooms dimensions of different PT treatment centers / experimental facility (CNAO, HIT, GSI) with ions beams.

Start Counter and Beam monitor





- The Beam Monitor (BM) is a drift chamber consisting of twelve wire layers, with three drift cells per layer
- Planes with wires oriented along the x and y axes are alternated allowing the beam profile reconstruction in both views
- The cell shape is rectangular (16 mm × 10 mm)
- The BM operates at ≃ 0.9 bar with a 80/20% gas mixture of Ar/CO2

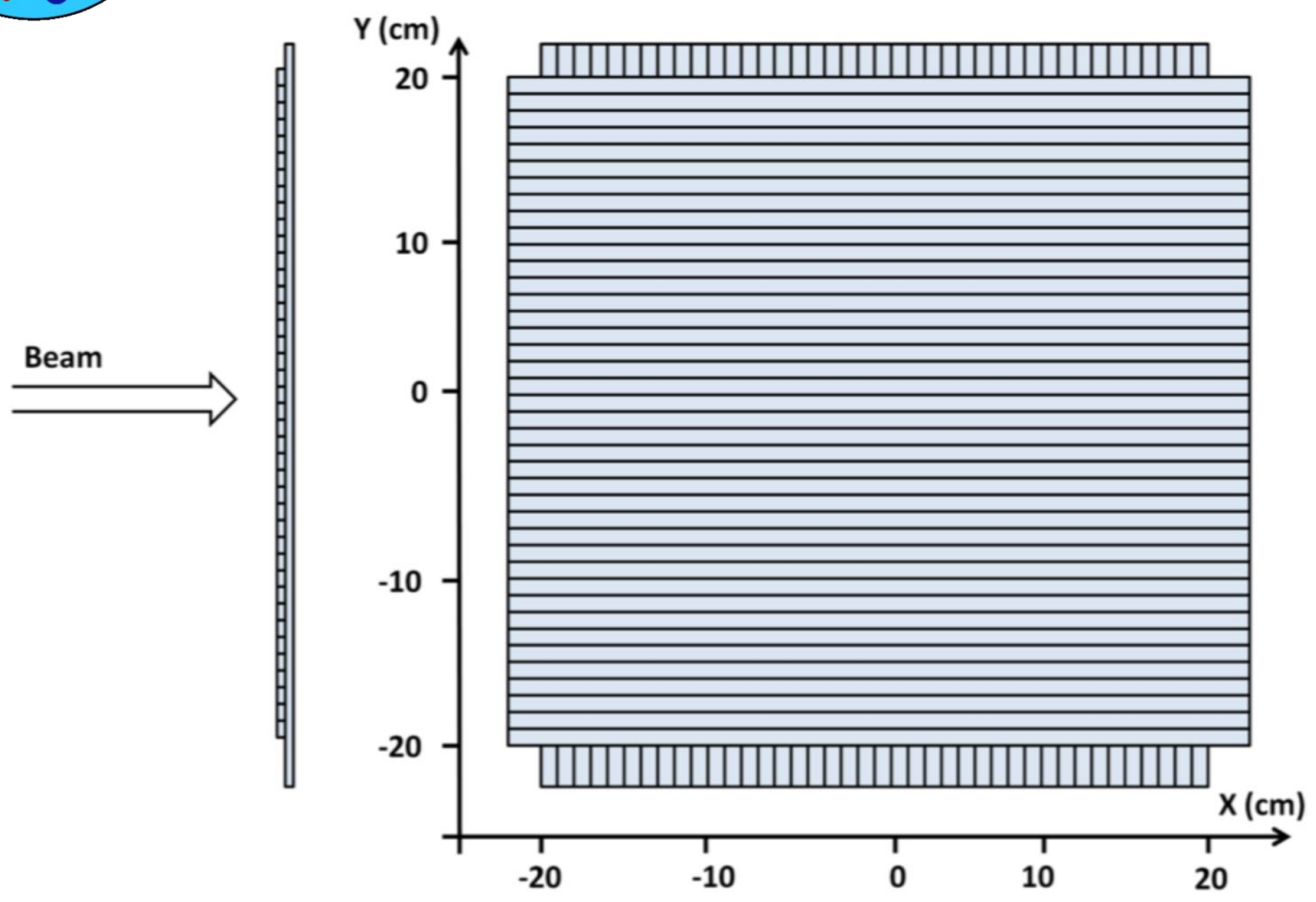
- The Start Counter (SC) is a **thin plastic scintillator layer** (EJ-204 – [250 μm, 1mm] thick) placed about 30 cm before the target with an active surface of $5\ x\ 5\ cm^2$
- Coupled to **48 SiPM** (8 channel readout)
- Layout optimized to **maximize the light collection**, minimizing the out of target fragmentation probability

It provides:

1. The **start of the TOF** masurements
2. The **trigger signal**
3. The measurement of the incoming **ion flux**

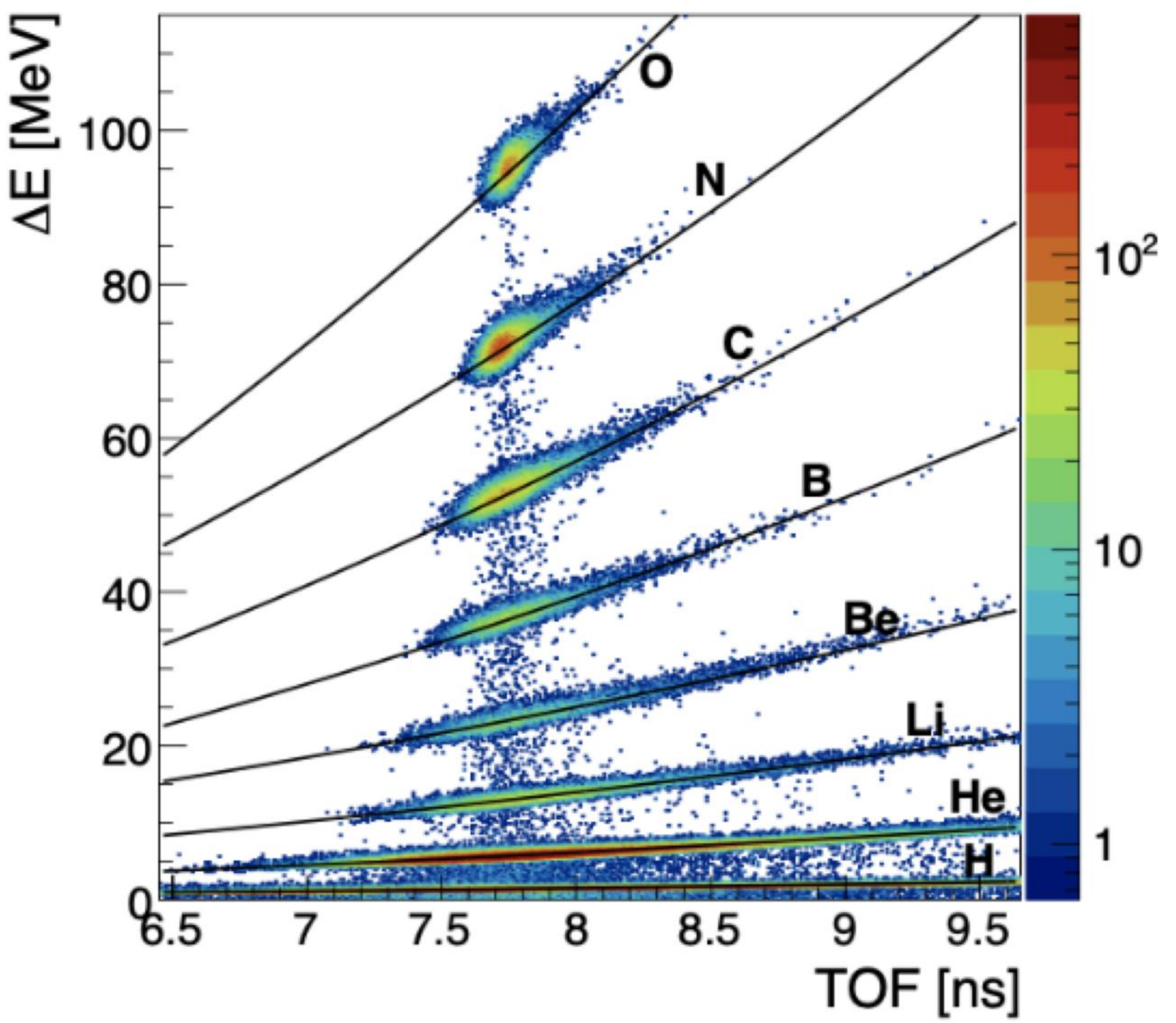
- The BM detector will be placed between the SC and the target and will be used to measure the direction and impinging point of the beam ions on the target

Charge ID of the fragments



TW provides:

1. Deposited energy ***ΔE***
2. Time of flight **TOF** (using the t_0 provides by ST)
3. Hit **positions**



Fragment charge Z identification performed using a Bethe-Bloch parametrization as a function of TOF for each Z

- The **Tof-Wall** detector (TW) is composed of **two layers of 20 scintillator bars** (0.3 cm thick, 2 cm wide, 44 cm long) arranged orthogonally with a $40\ x\ 40\ cm^2$ active area
- Each of two edges of the TW bars is coupled to **4 SiPM** with a $3\ x\ 3\ cm^2$ active area and 25 μm microcell pitch.

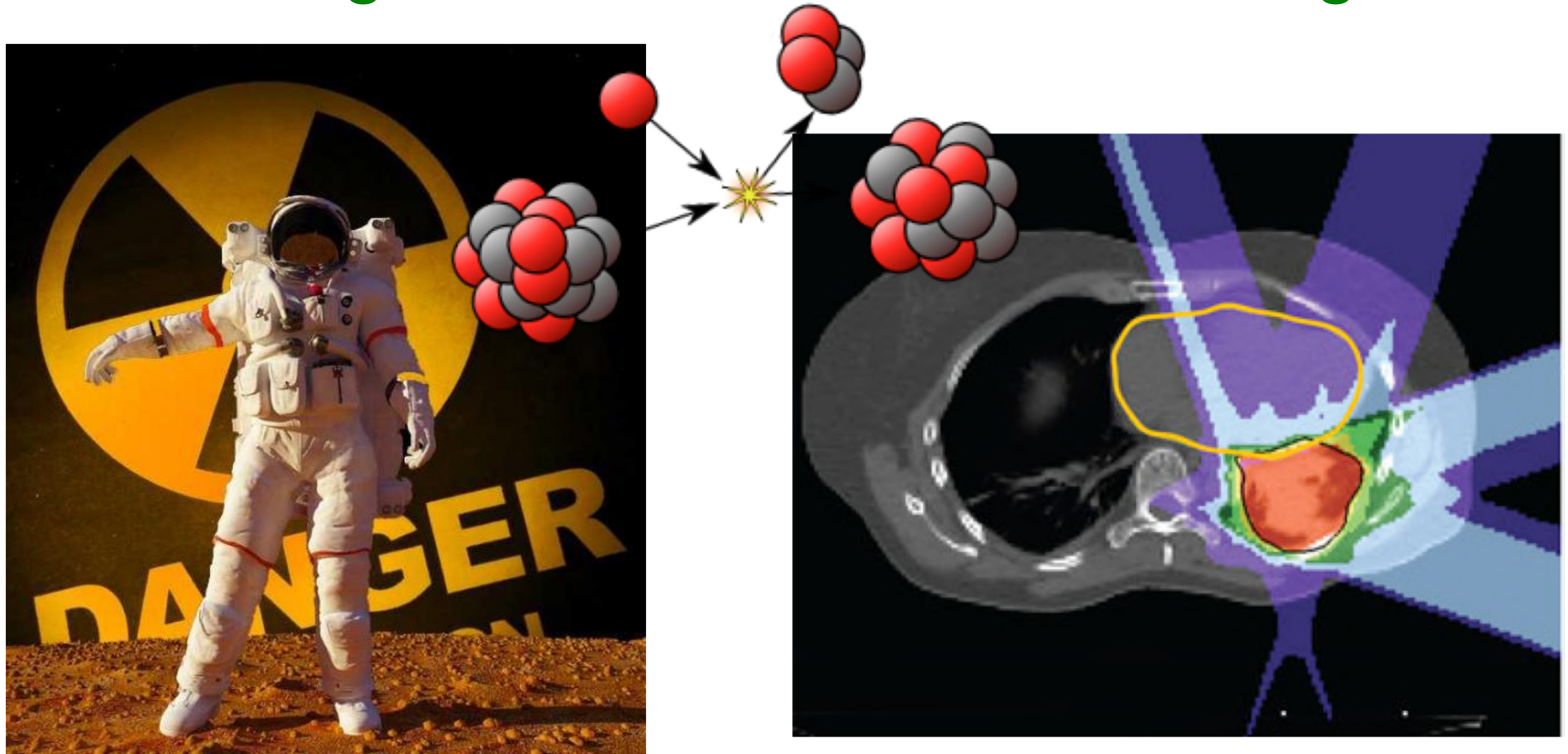
FOOT in Pills

Bologna, Frascati, Milano, Napoli, Perugia, (Pavia), Pisa, Roma1, Roma2, Torino, Trento

Strasbourg, GSI, Aachen, Nagoya

People: ~70 researcher, ~27 FTE

Data taking 2018-2022@ GSI, Heidelberg, CNAO



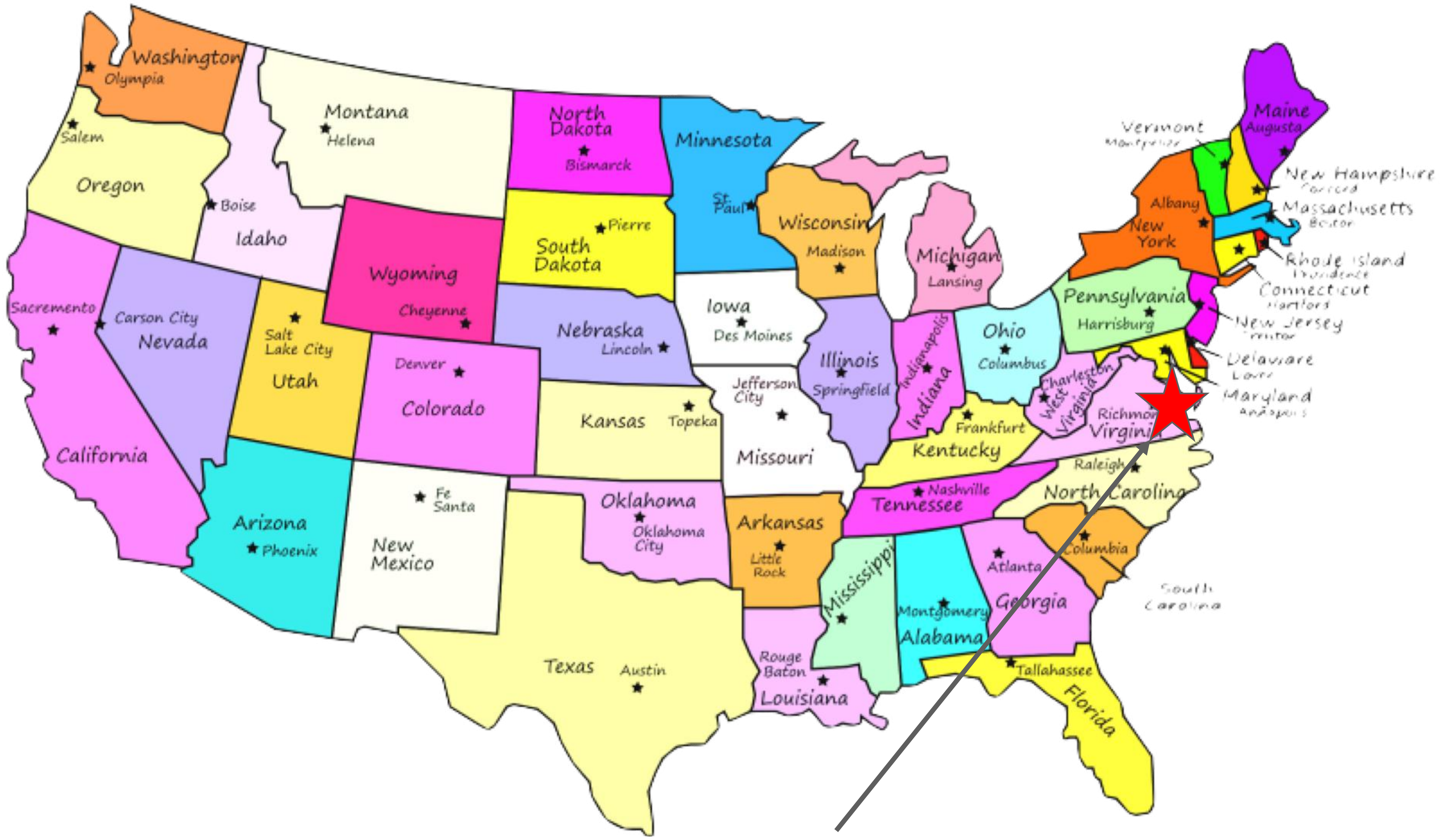
Experiment with translational approach: focus on nuclear physics, physics applied to medicine and radioprotection in space

The Jefferson Laboratory

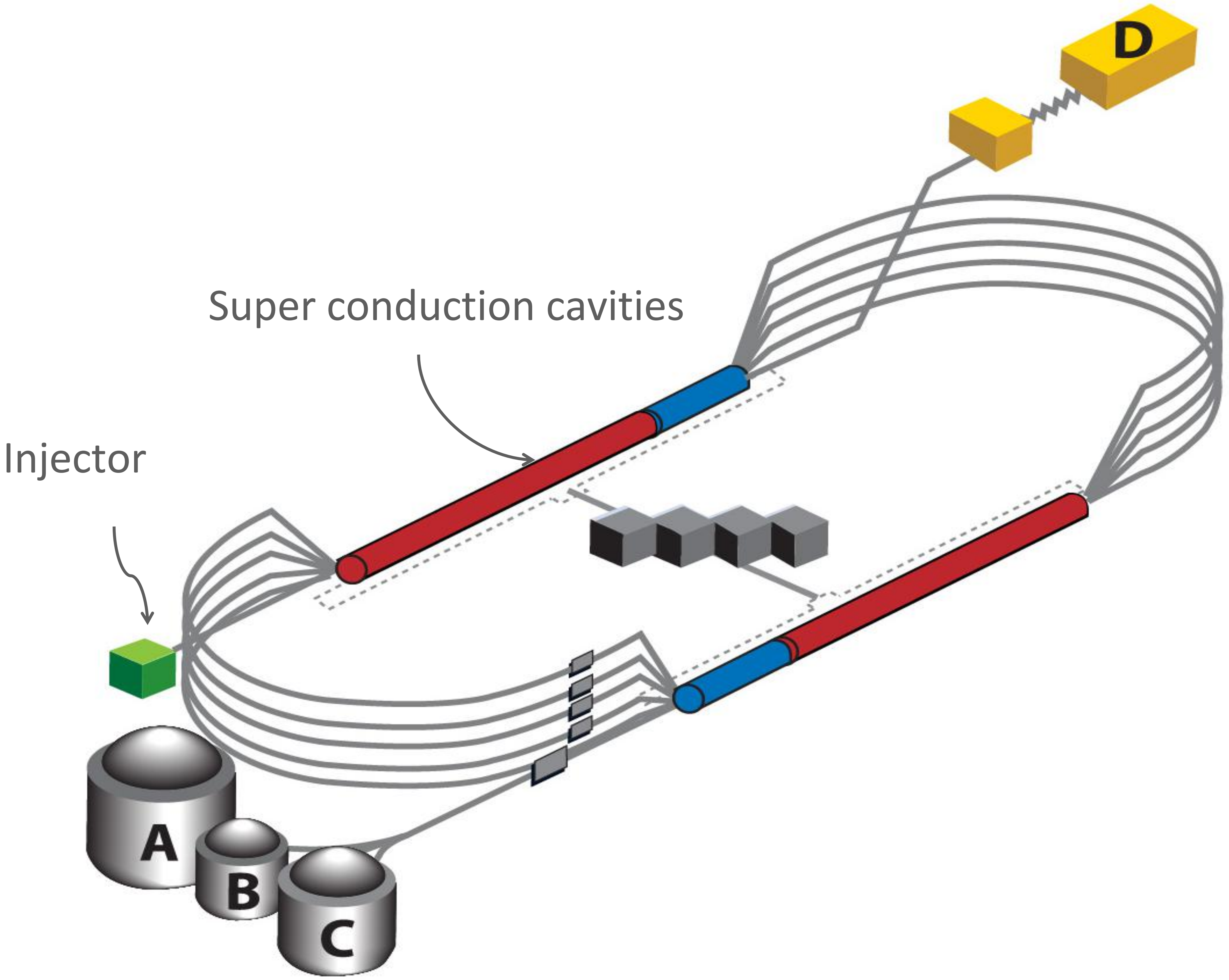
Accelerator:

- Polarized electron beam
- Polarized targets (H→Pb)
- $E_{beam} \leq 12$ GeV ($\delta E/E \sim 10^{-4}$)
- $I_{beam} \leq 100\ \mu A$
- Emittance: ~ few nm-rad

- High statistics
- rare processes investigation/discovery



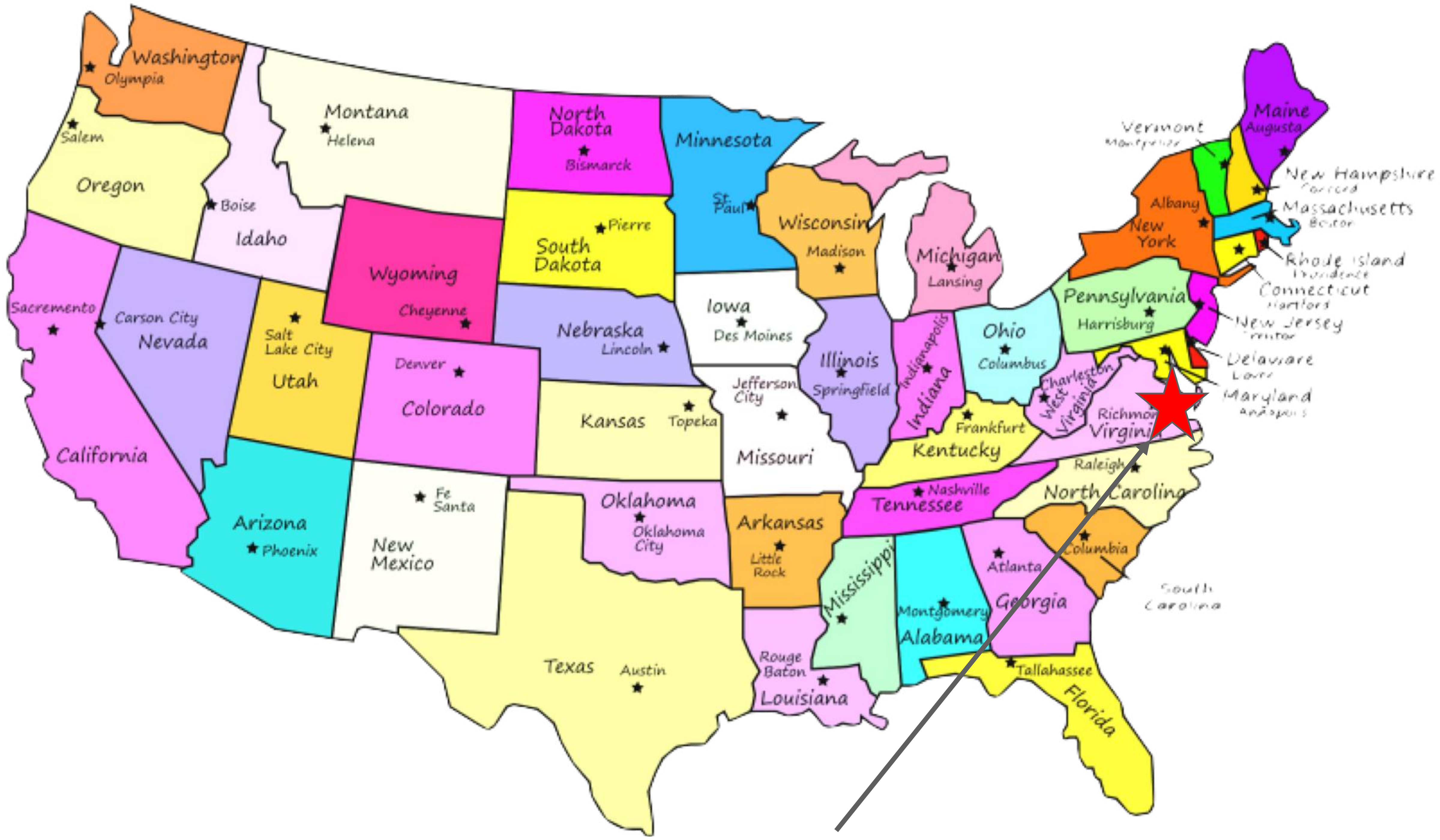
Jefferson Laboratory (Virginia, USA)



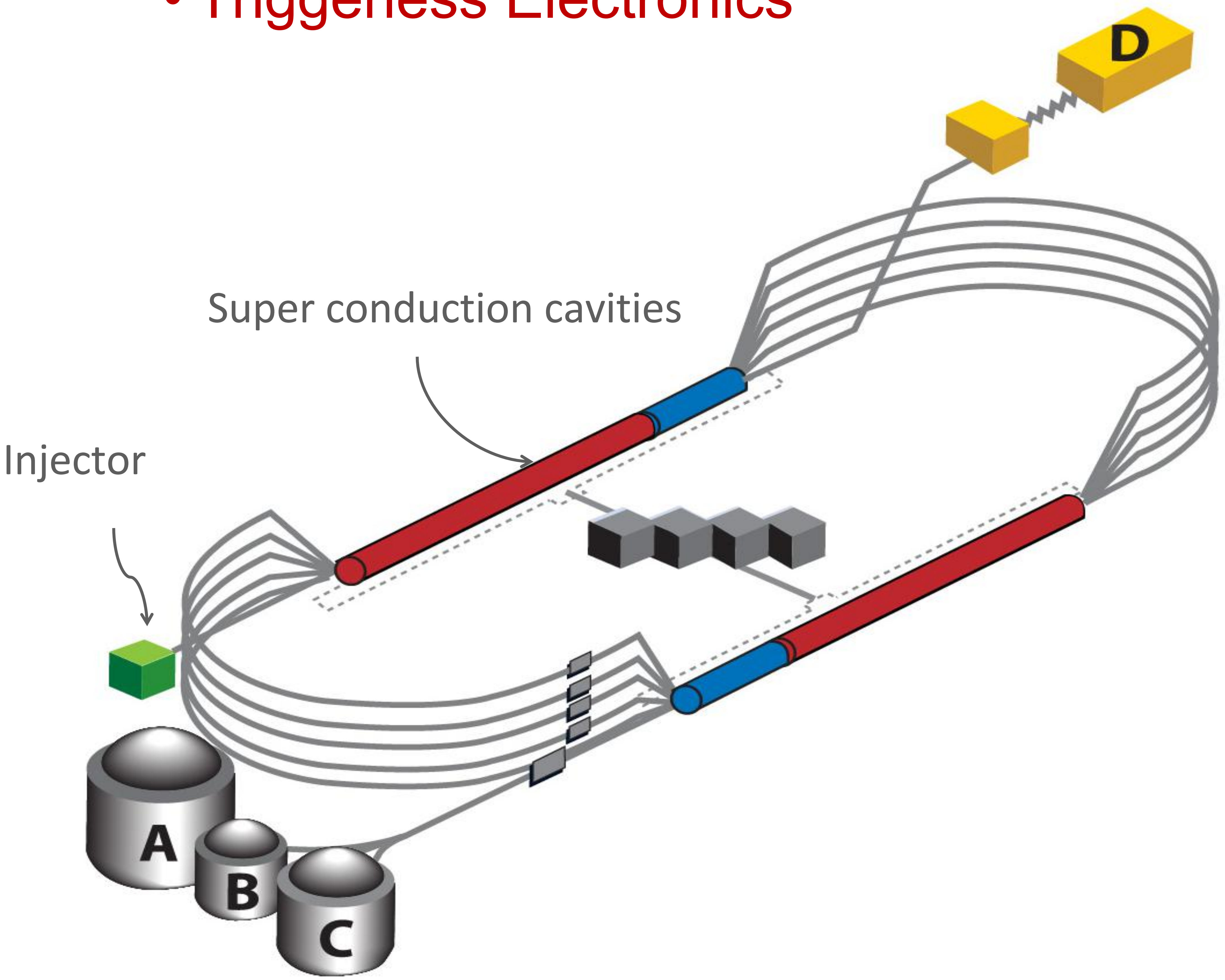
Rome group activity

Physics:
- Proton/neutron structure/dynamics
- Hypernuclei → Neutron Stars
- Parity violation (Physics beyond Standard Model)

Instrumentation:
- Gas Electron Multipliers (GEM)
- Silicon Microstrip trackers
- Ring Imaging detector (RiCH)
- Triggerless Electronics



Jefferson Laboratory (Virginia, USA)



Proton and neutron mysteries

- **Mass origin**:

sum of constituent quark "rest" masses account for 2% of proton (neutron) mass only!

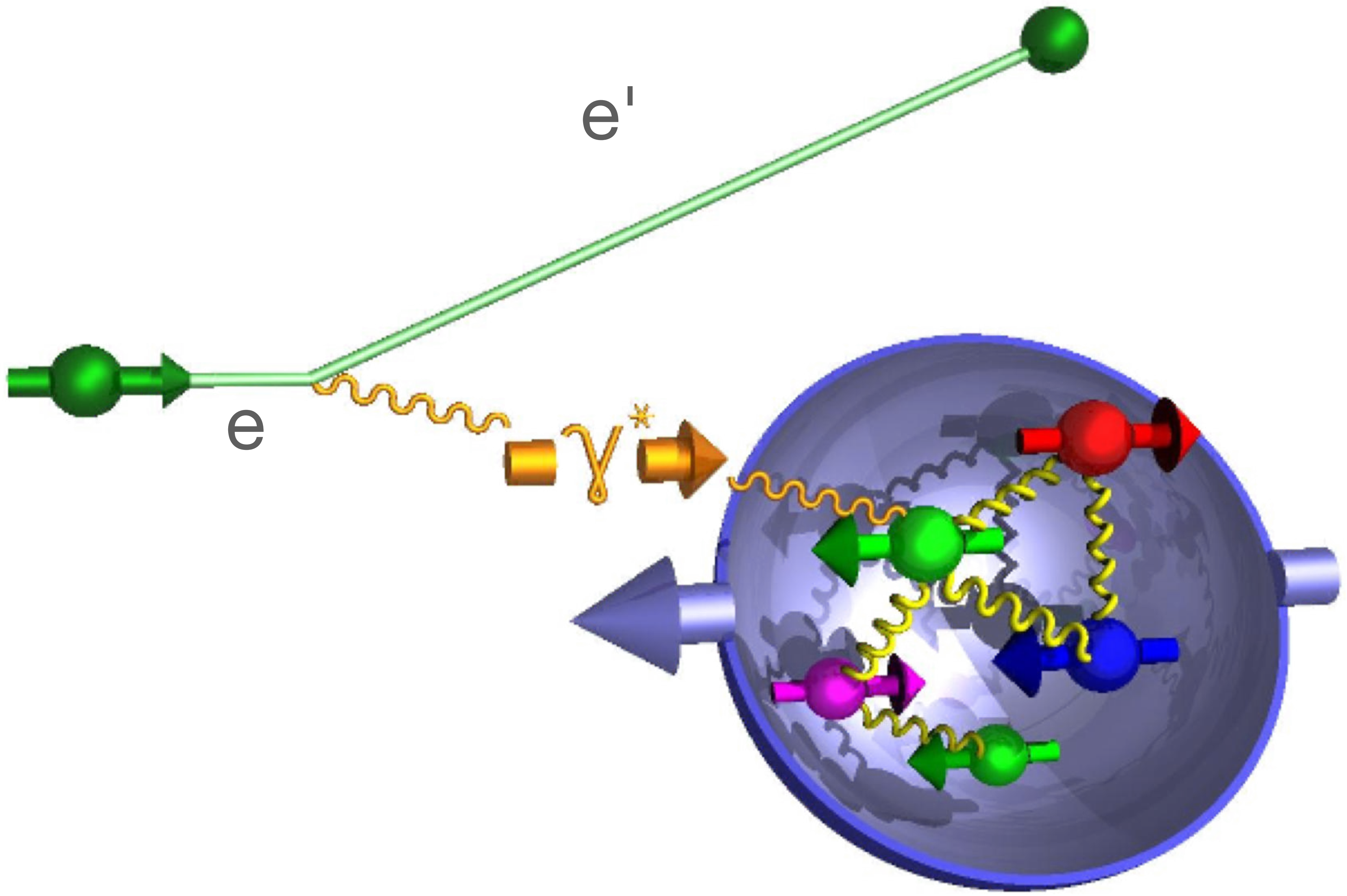
- **Spin origin**:

only 20% of proton spin is originated from quark spins

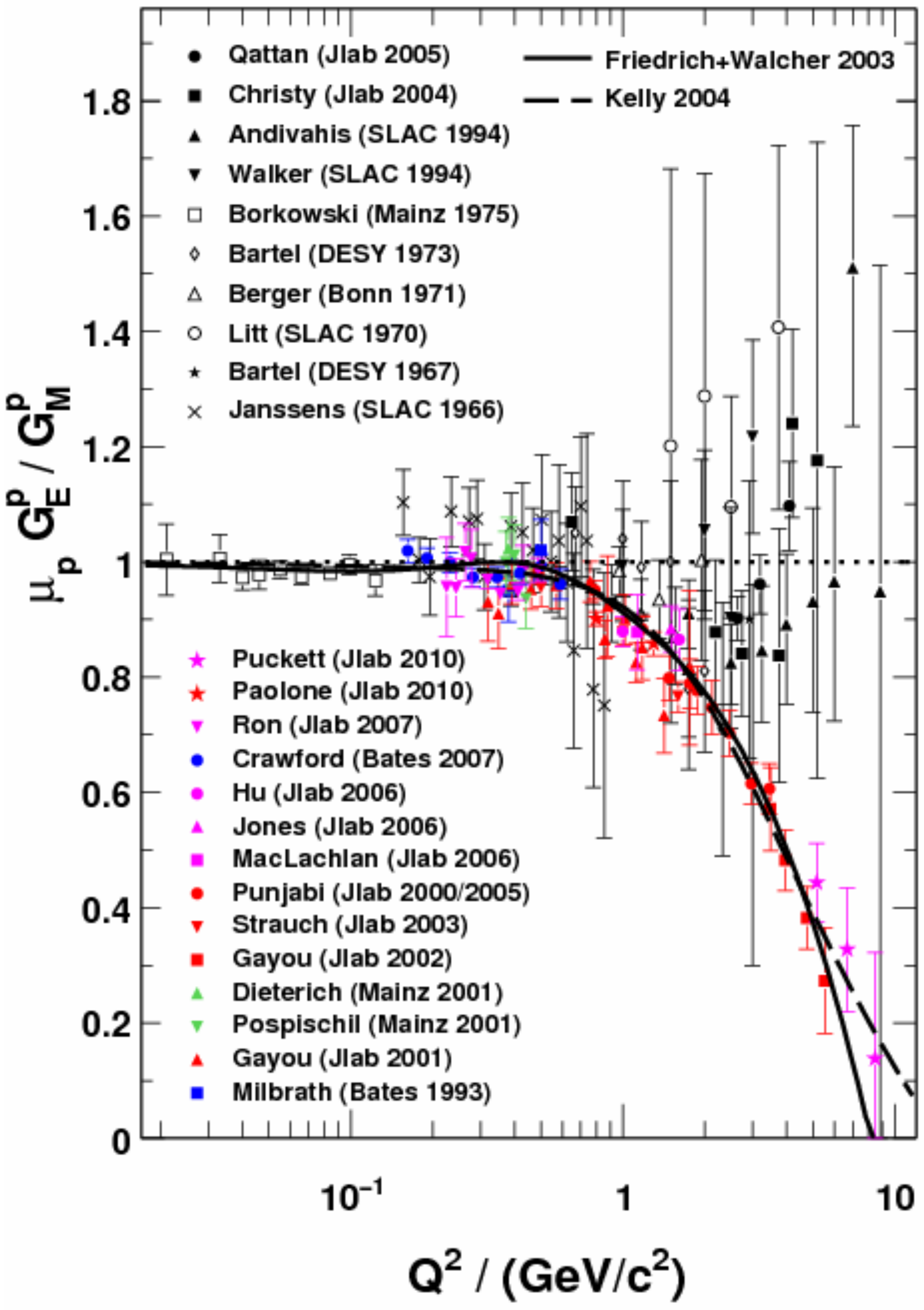
- **Radius measurements**:

strong disagreement between different experimental approaches

Electron-nucleus scattering experiments offer real chance to shed light on these puzzles



Nucleon (proton/neutron) form factors



Electric and Magnetic **Form Factors** of the nucleon describe the internal **spatial distribution** of their electric and magnetic "charges".

They can be measured by **elastics electron+nucleon scattering** – the "simplest" scattering processes governed by the well known electromagnetic interaction!

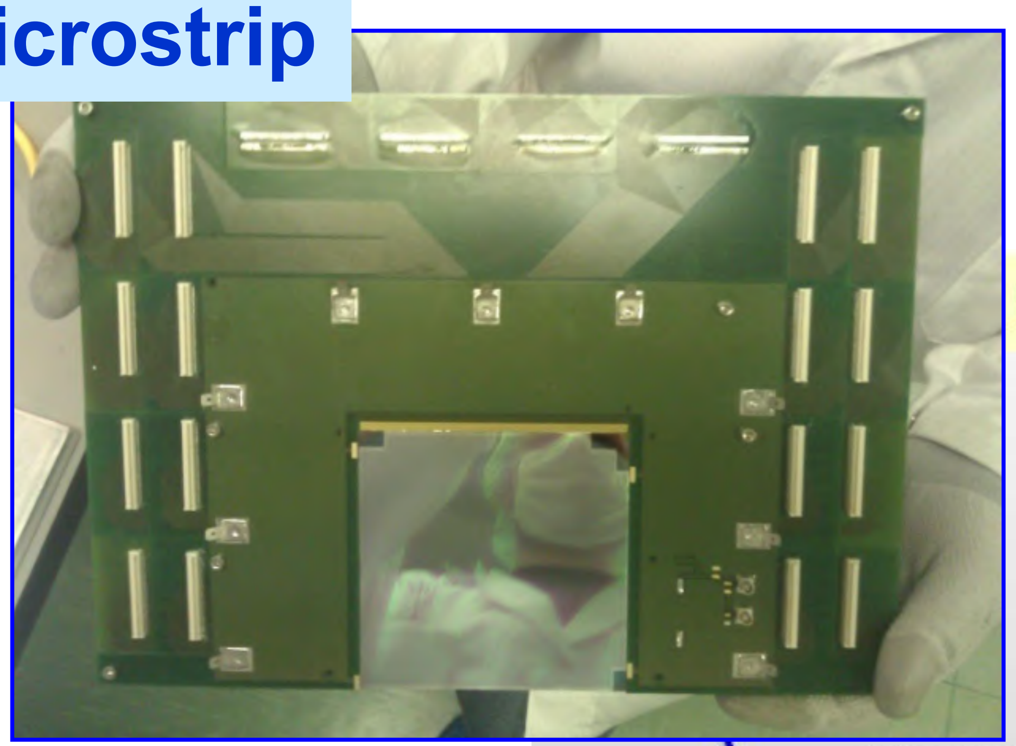
Current theoretical picture of nucleon Form Factors is under strong revision due to last 2 decades experiments with **polarized electron beams** that largely disagree with previous measurements from unpolarized processes

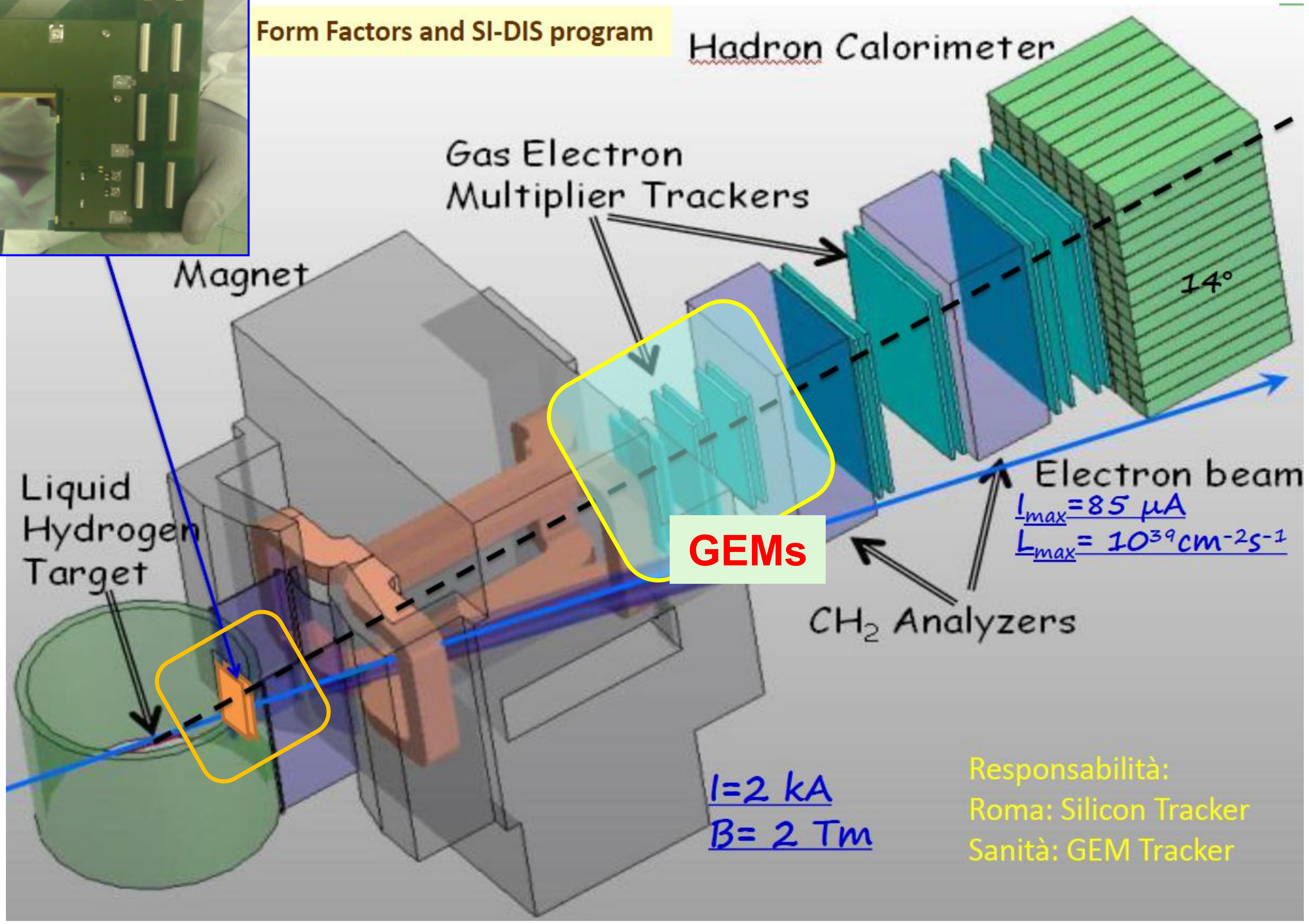
SuperBigbite Spectrometer in Hall A/JLab

Nucleon Form Factors, Neutron spin, Pion structure functions

… **an experimental tool for hadron structure investigation**

Silicon microstrip





State of the art detector technologies in conventional spectrometer configuration

===

Largely dedicated to explore the nucleon inner structure

JLab12-Thesis

(Form Factors and Tracking)

Data taking and instrumental optimization ongoing:

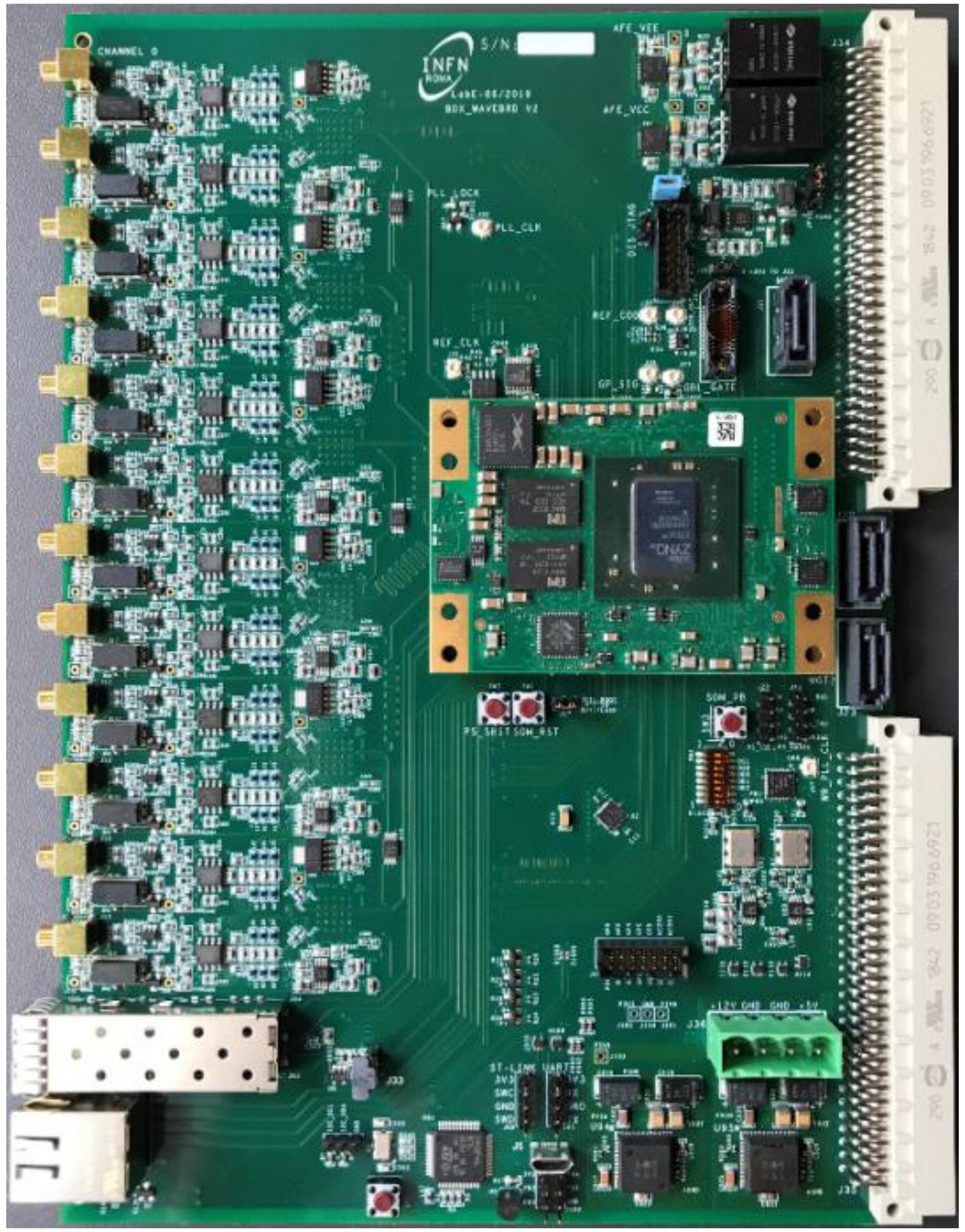
- GEM tracker operation, commissioning, characterization and tuning
- Physics analysis of the acquired data
- Preparation of Silicon Detector

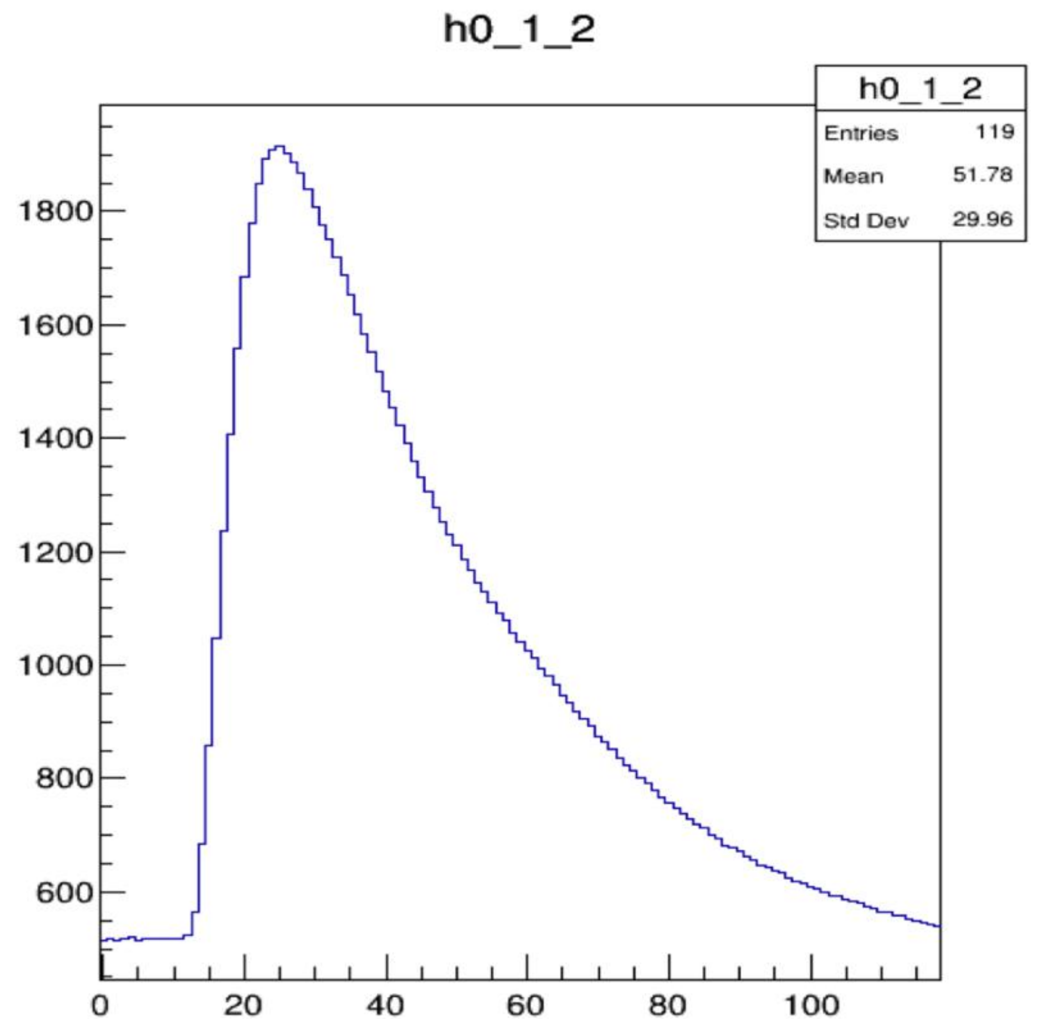
Possibility to spend ~1 month at JLab (Virginia/USA)

Two GEM chambers ready for installation

The Roma1 WaveBoard digitizer for BDX

BDX experiment proposal is dedicated to the Dark Matter Serach (see *arxiv.org/abs/1607.01390). DAQ is based on the board developed in Rome.*





continuous streaming readout (triggerless system)

The new frontier of DAQ in high energy / nuclear physics experiments

First results on prototype detector @ JLab

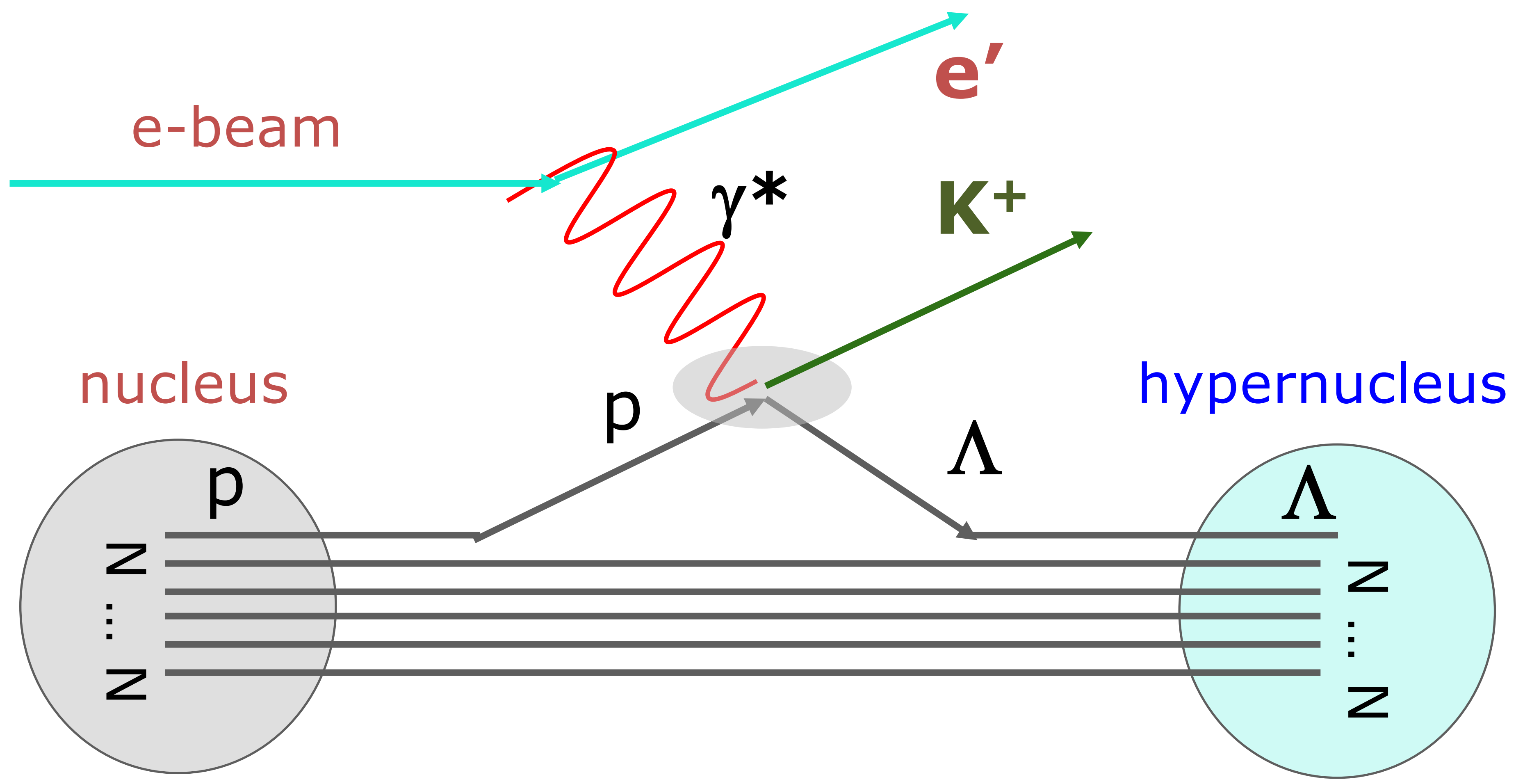
- Commercial-Off-The-Shelf (COTS) System On Module (SOM)
- Mezzanine card hosting a **Zynq-7030** FPGA
- There are 12 analog front end channels
  - 6 dual-channel ultra low-power ADCs (**12/14** bit up to **250MHz**)
  - Pre-amplifier on board: **selectable gain** (either 2 or 50)
  - **HV** provided and monitored on-board
  - pedestal set by DAC
- Timing interfaces:
  - PLL to clean, generate, and distribute clocks
  - External clock and reference signals
  - White Rabbit enabled board
- ARM-M4 controls on-board peripherals (ADCs, DACs, PLL, …)
- On board peripherals:
  - High speed: GbE, SFP, USB OTG
  - Low Speed: serial, I2C, temperature monitor

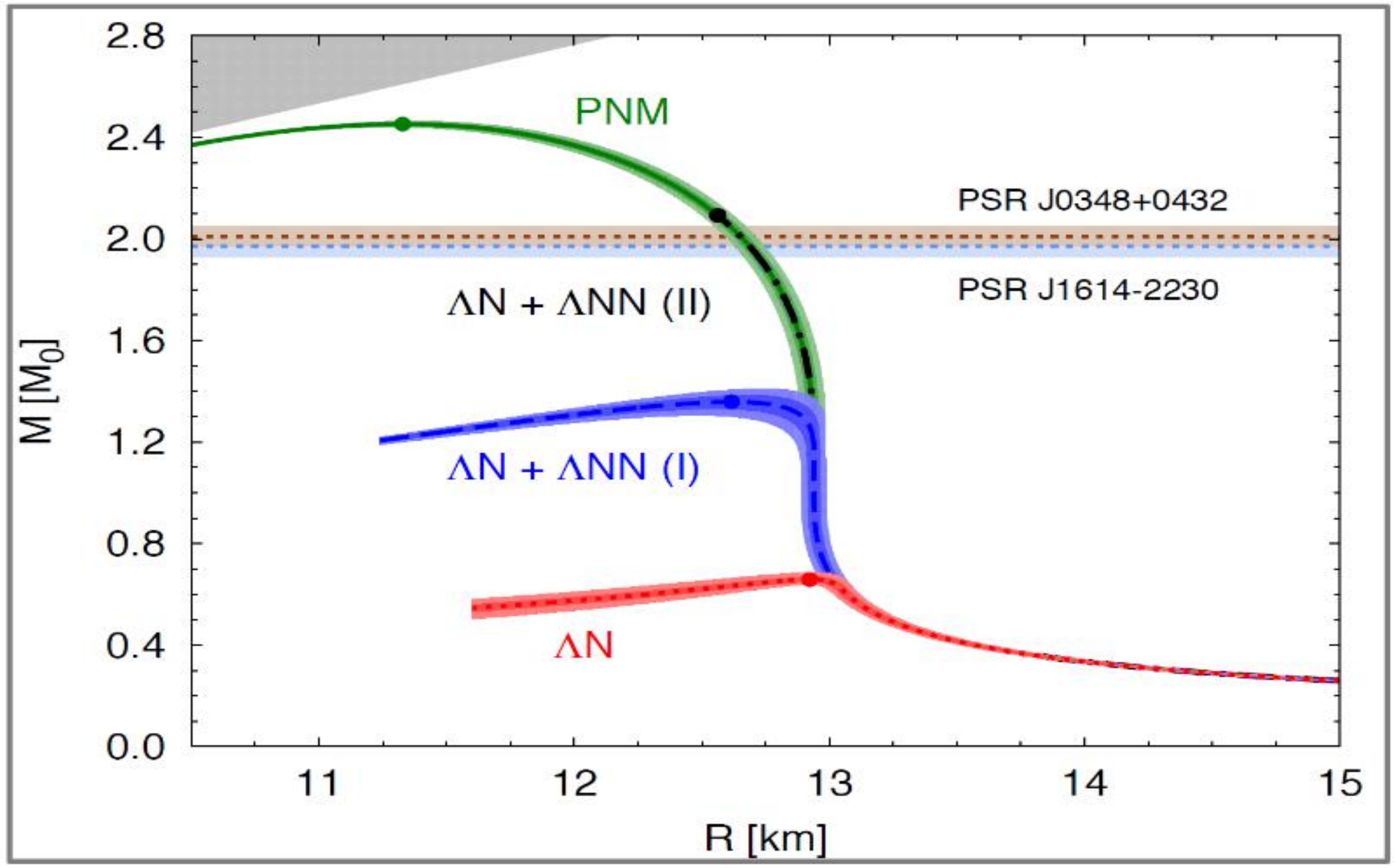
Neutron stars, Hyperons and Nucl. Phys

The Neutron Stars (NS) are nuclear objects with ρ~10^{17} kg/m^3. Their core is supposed to be a sort of neutral fluid of neutrons, protons, muons and electrons in equilibrium.

This fluid is described by the Equation of State (**EoS**) of strong interacting matter: relate Pressure, Energy density and Temperature.

Modeling is of primary importance in Astrophysics, Gravitational waves, Nuclear physics, Particle physics...





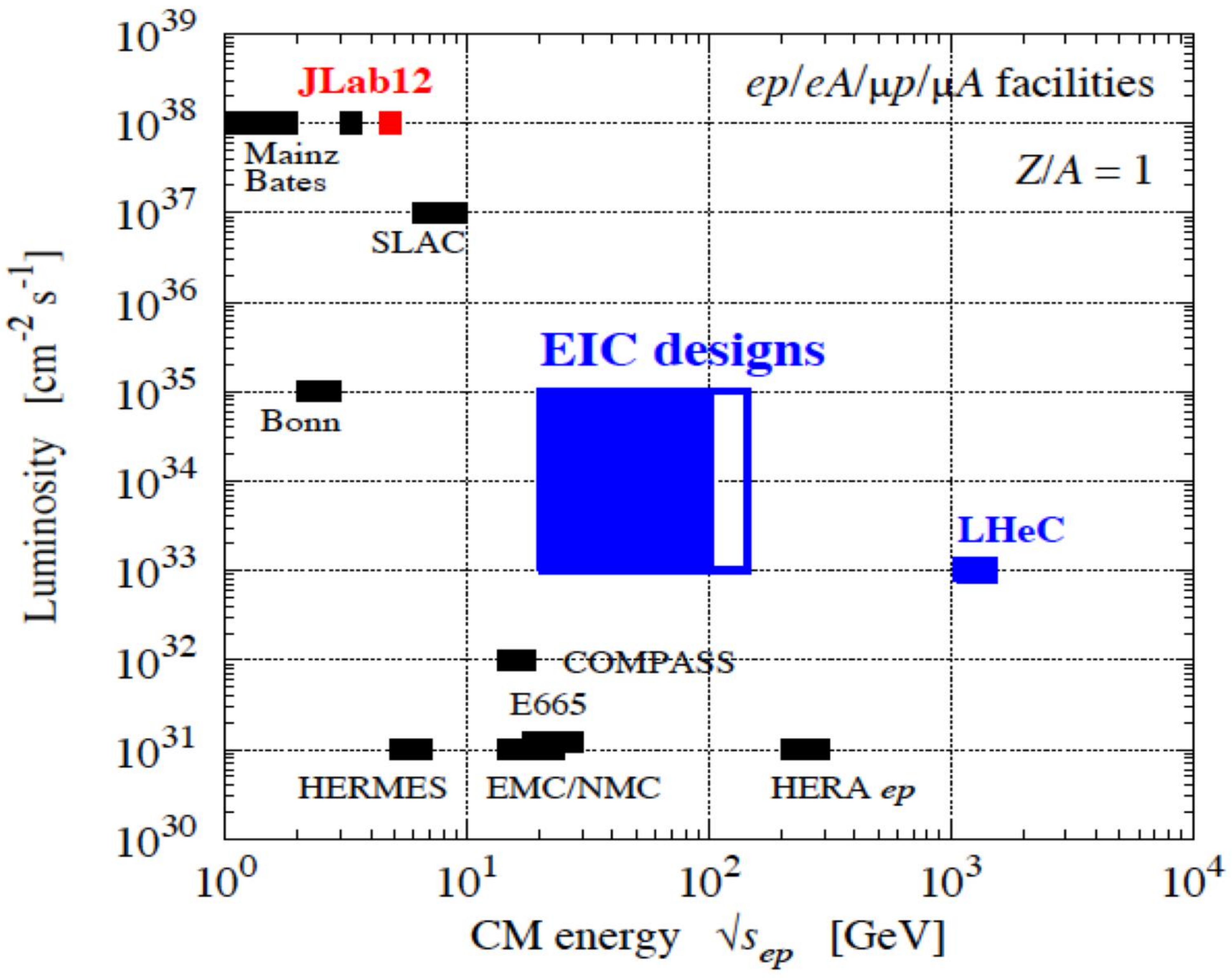
D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva Phys. Rev. Lett. 114, 092301 (2015)

EIC @BNL Electron Ion Collider

Main characteristics:

- Electron (and positron) and ion beams from proton to Pb/U
- Polarization (e, p, d, ^{3}He) >70%
- Luminosity up to ≈10^{34}/(cm s) (1000 x Desy/HERA)
- CM energy large and variable (20-100 GeV)

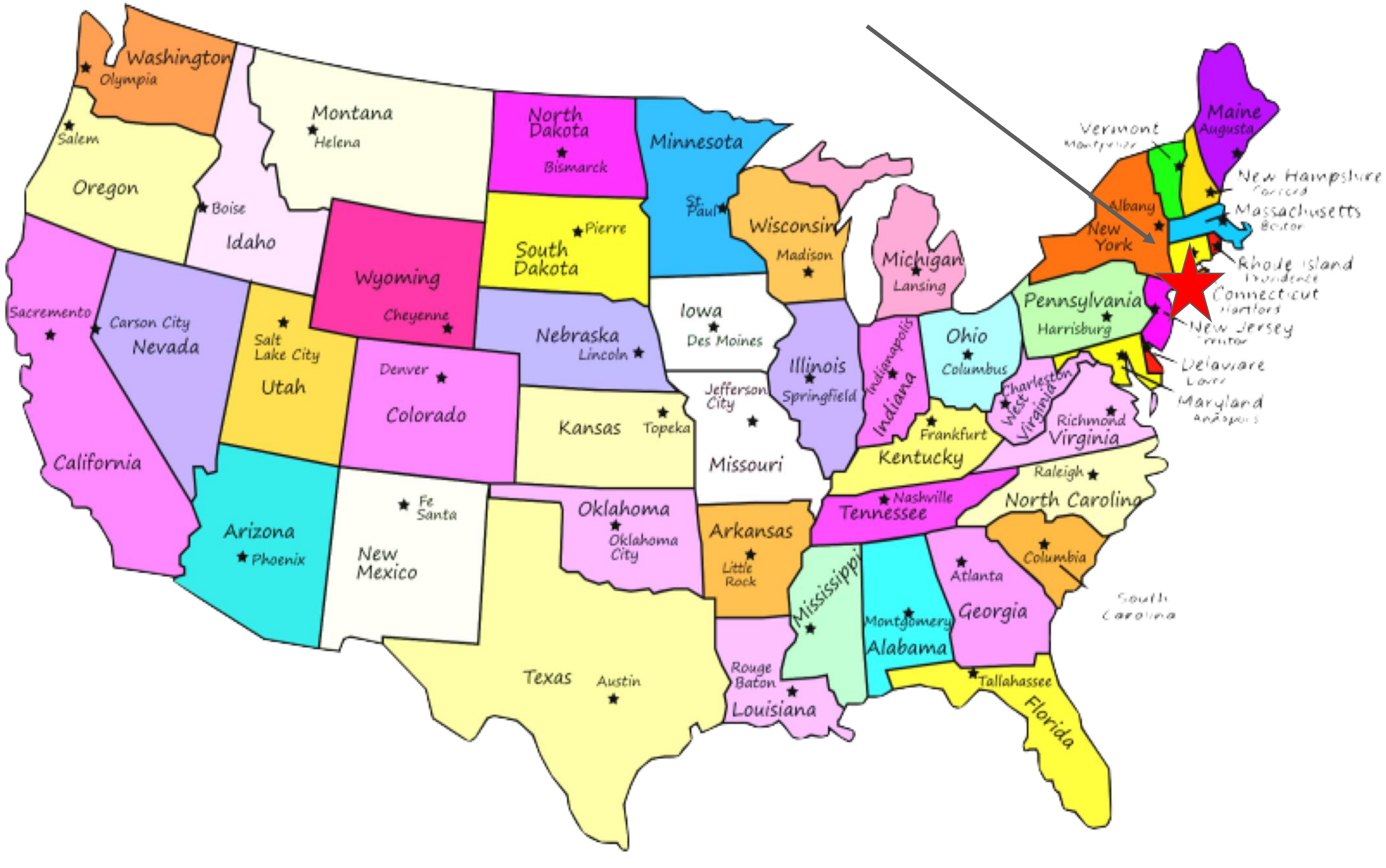
Completion of EIC facility construction ~ 2026



Main requirements for detector:

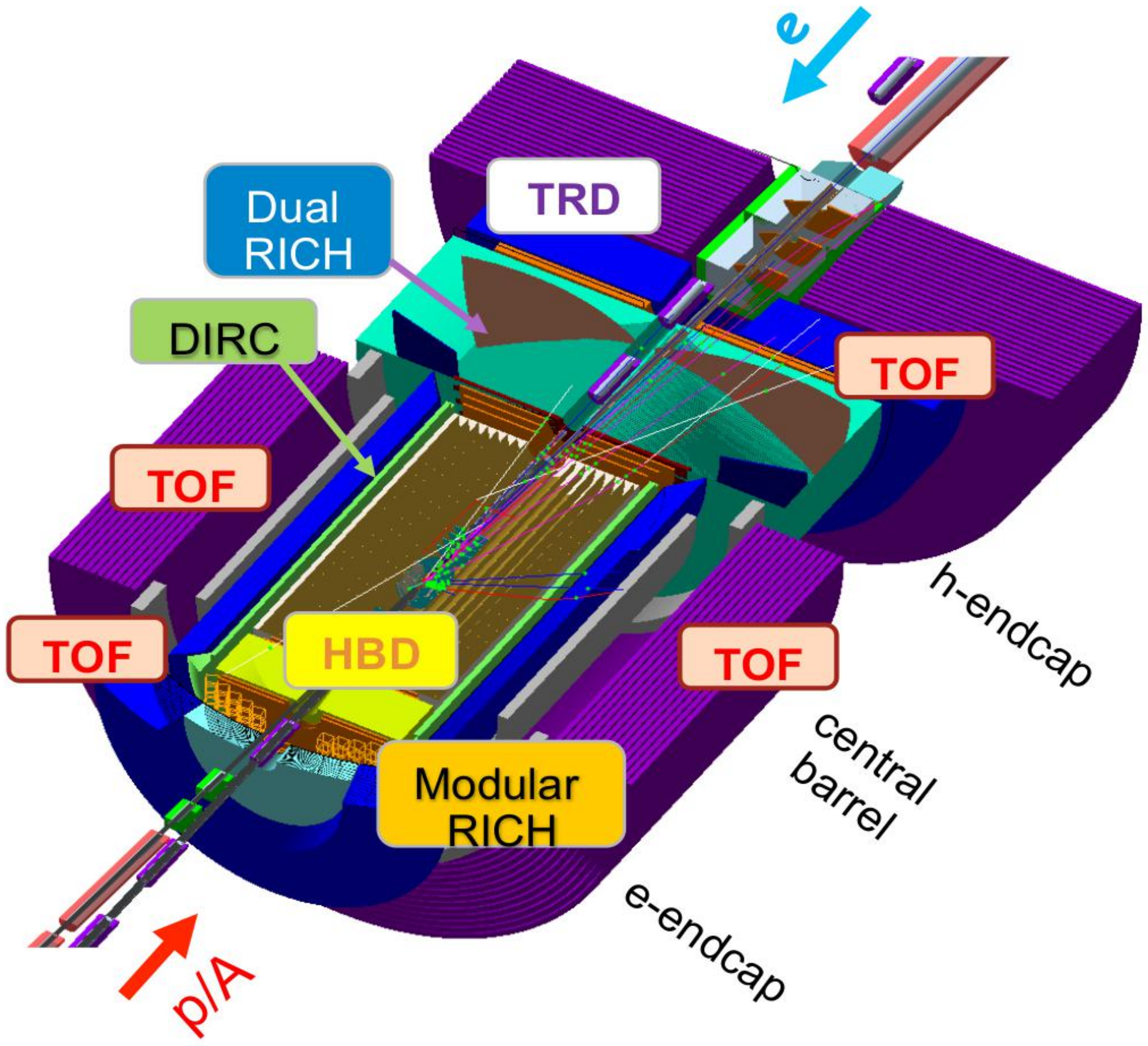
- Good Particle ID for hadrons and leptons
- Vertex Resolution down to 0.1 mm
- Momentum Resolution (down to ≈100 MeV ≈1%)

(Electron ion collider (NY, USA))

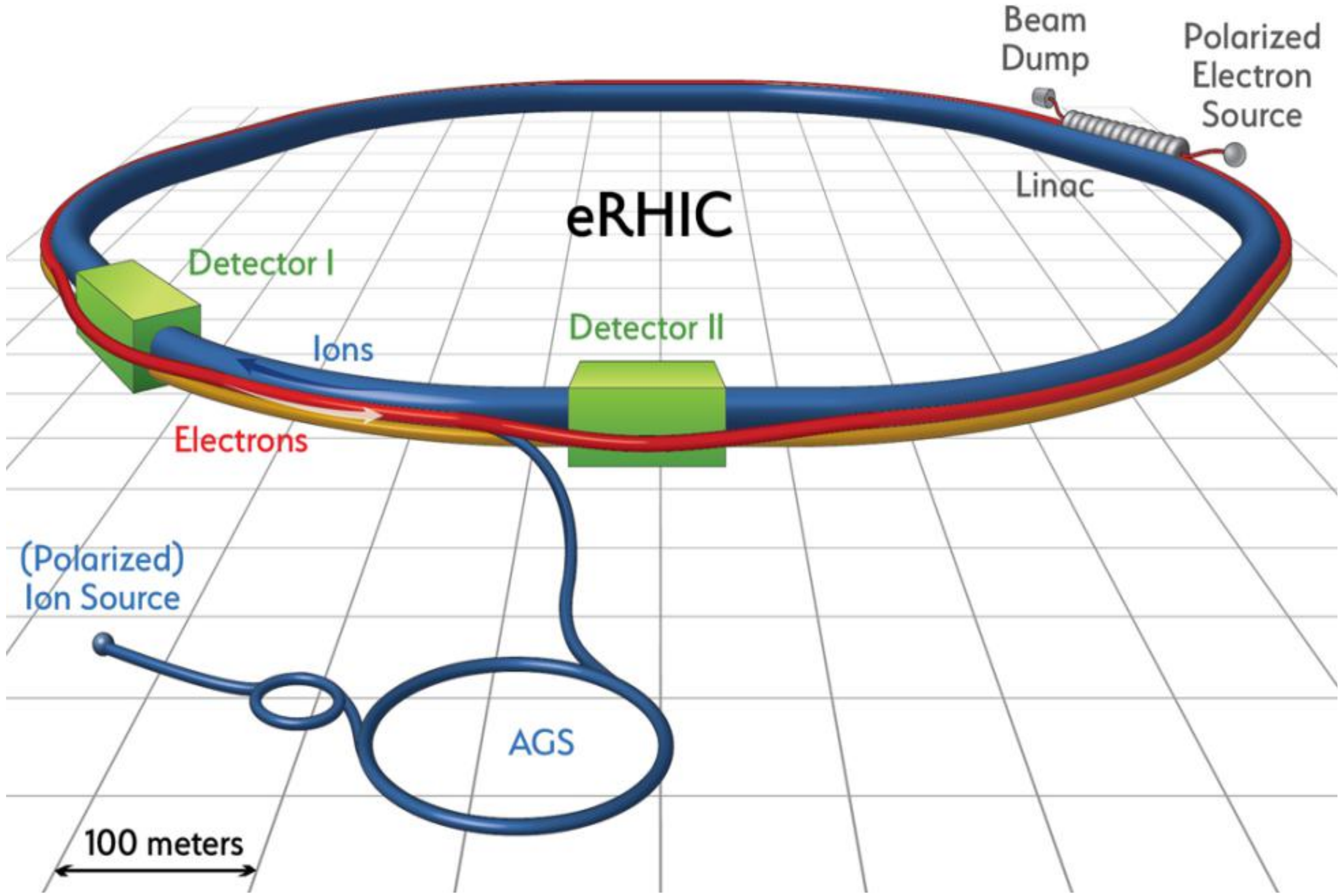


EIC Rome group activity

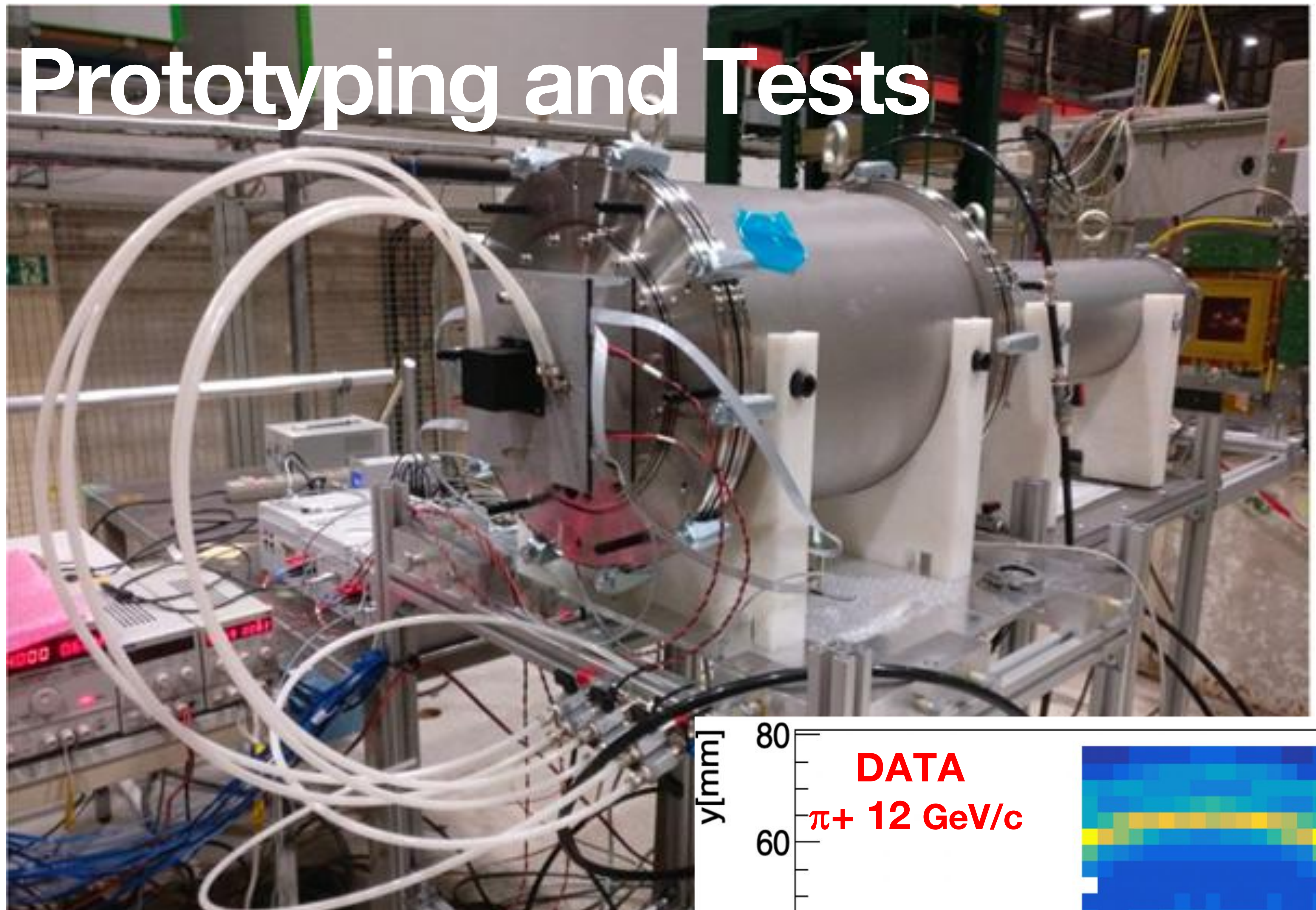
Physics:
Semi Inclusive and Exclusive Deep Inelastic Scattering at low x-Bjorken

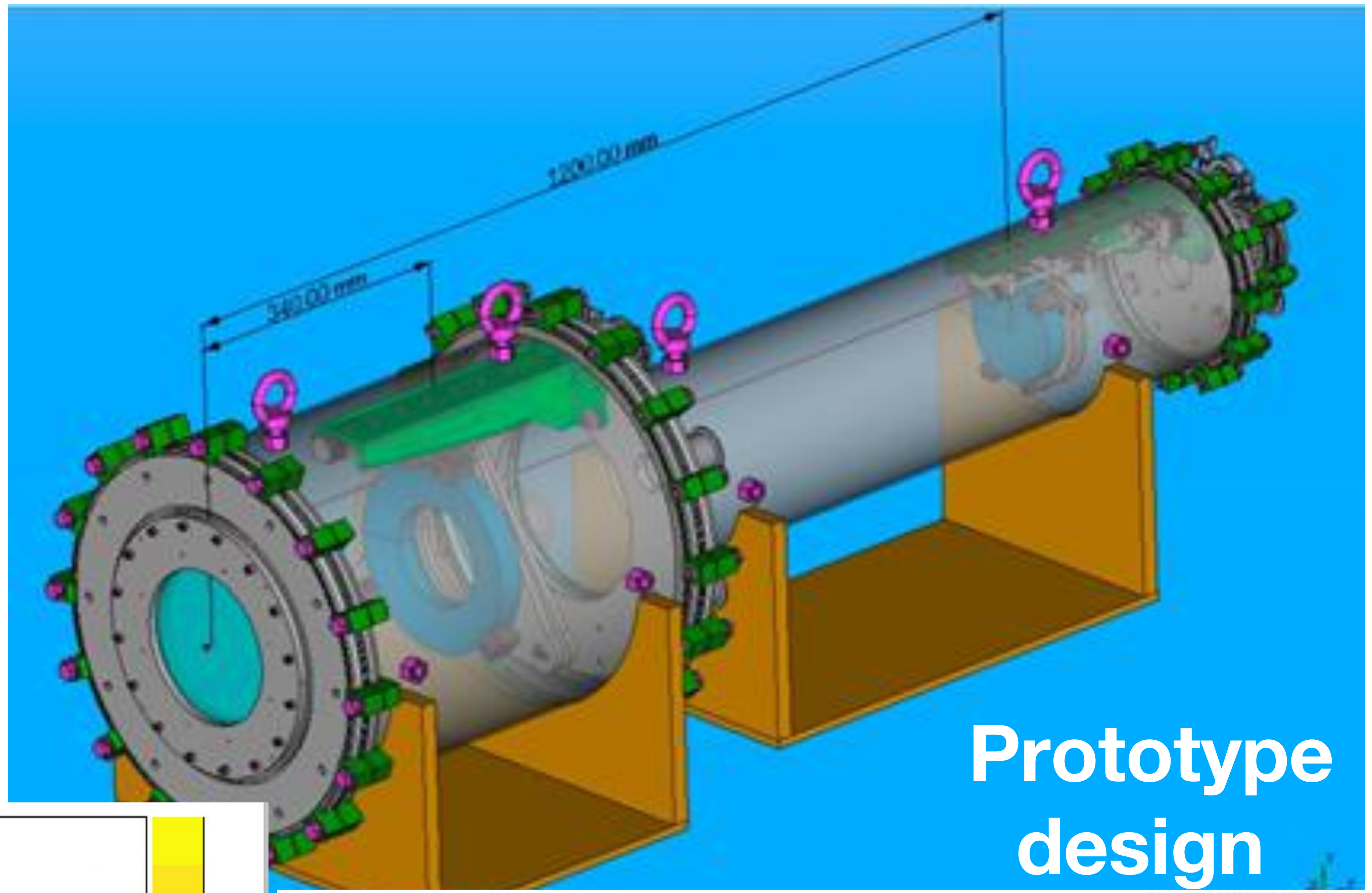


Instrumentation:
Dual radiator RICH detector for hadron identification

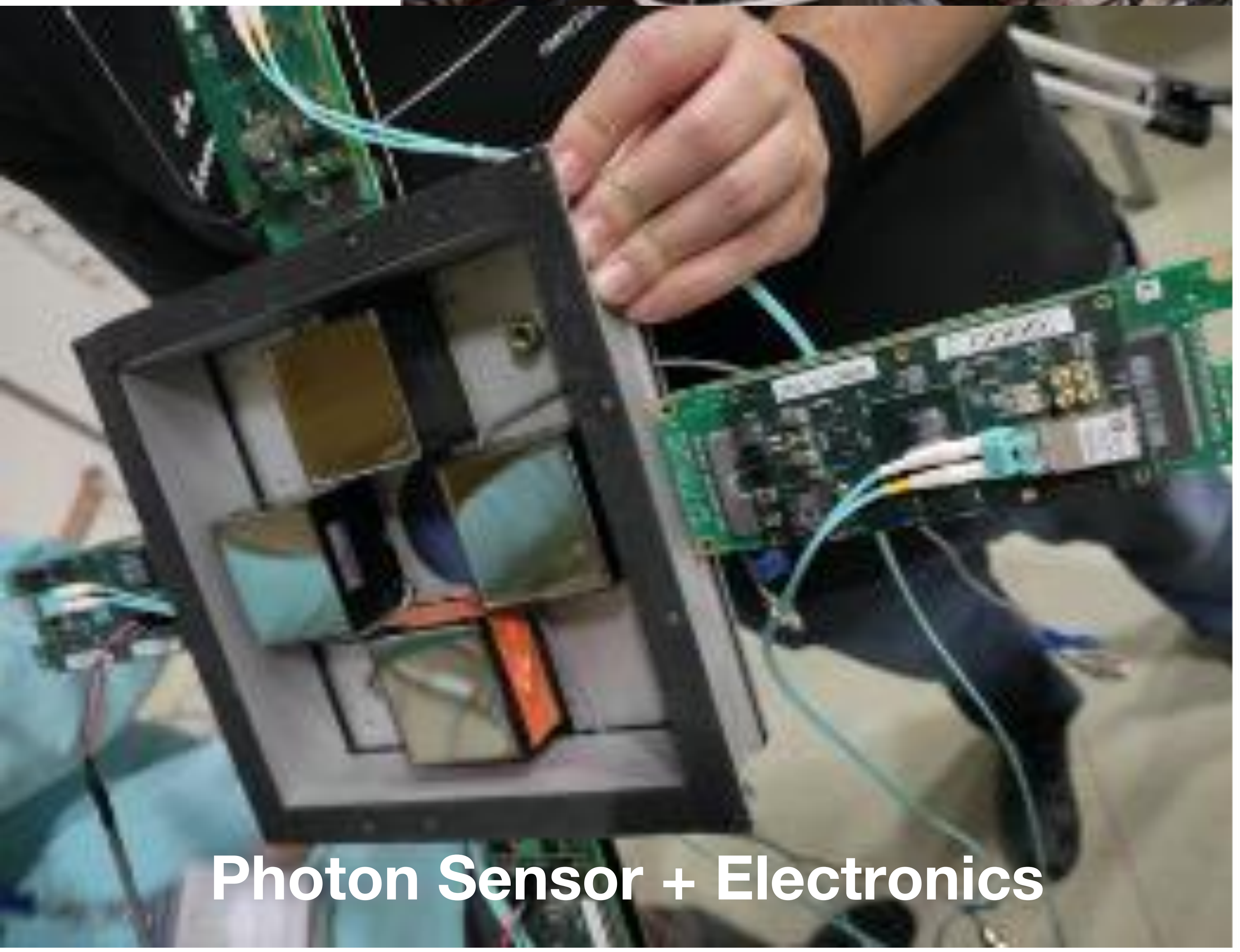


dRICH Prototyping and Tests

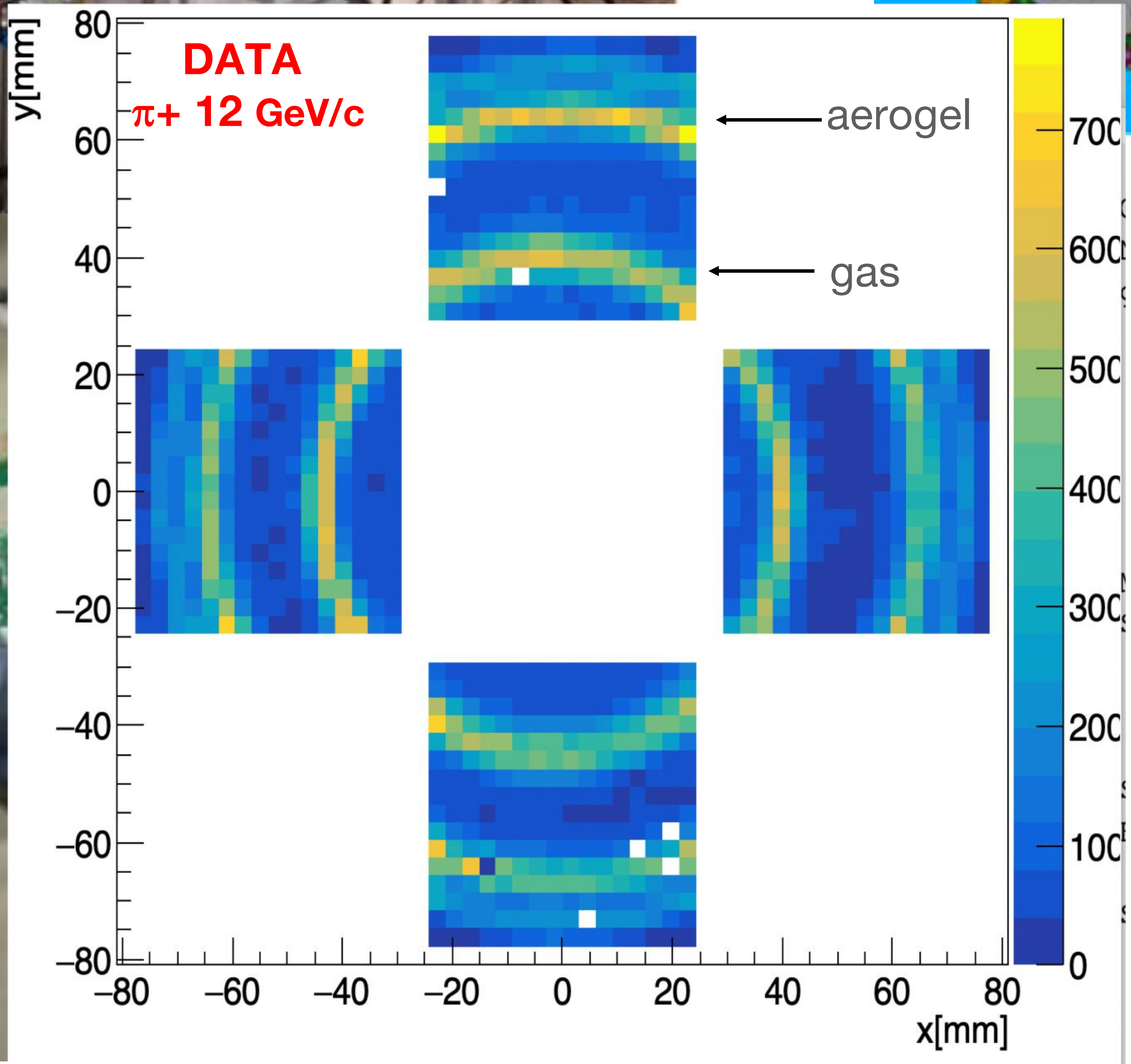


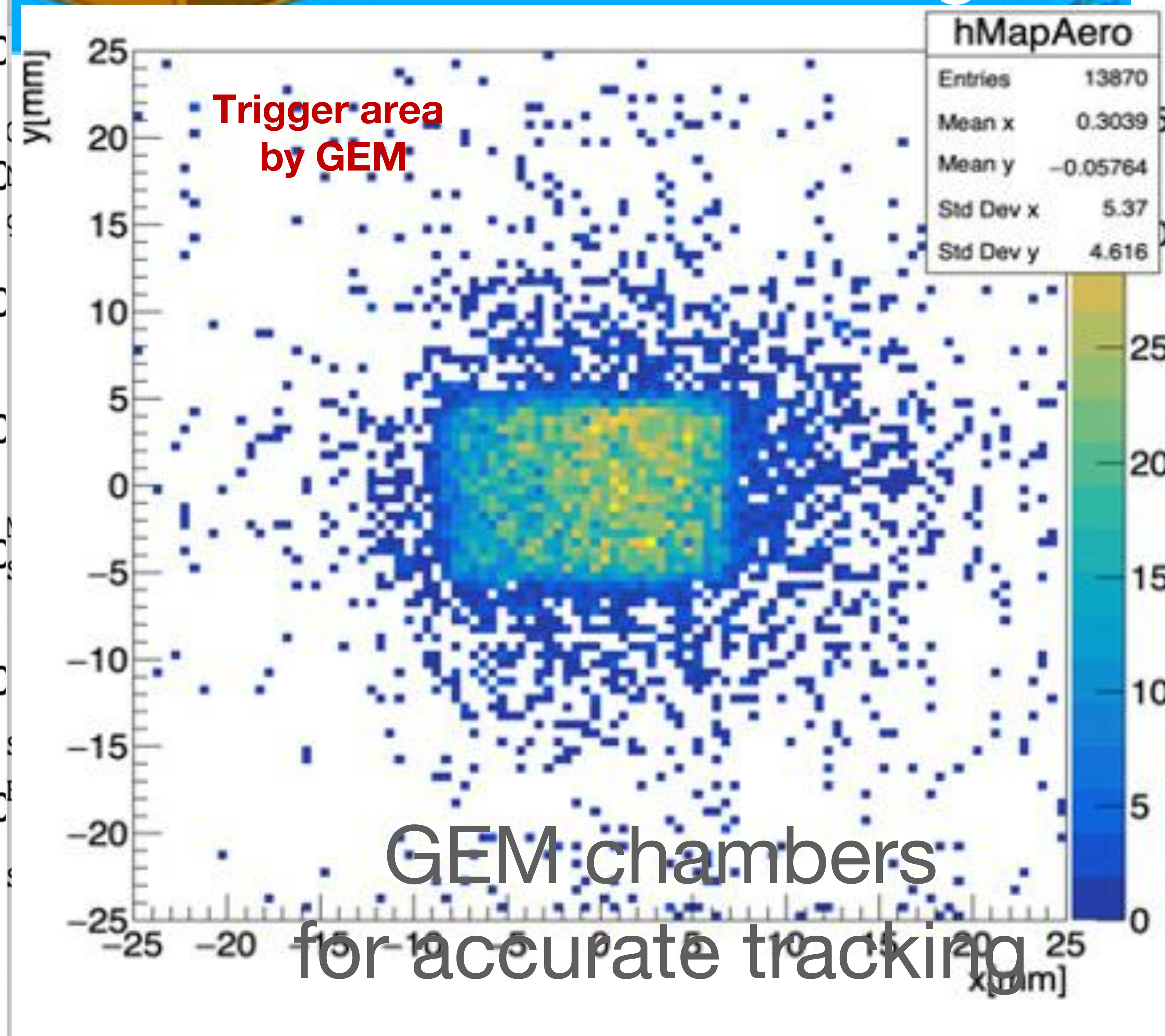


Prototype design



Photon Sensor + Electronics



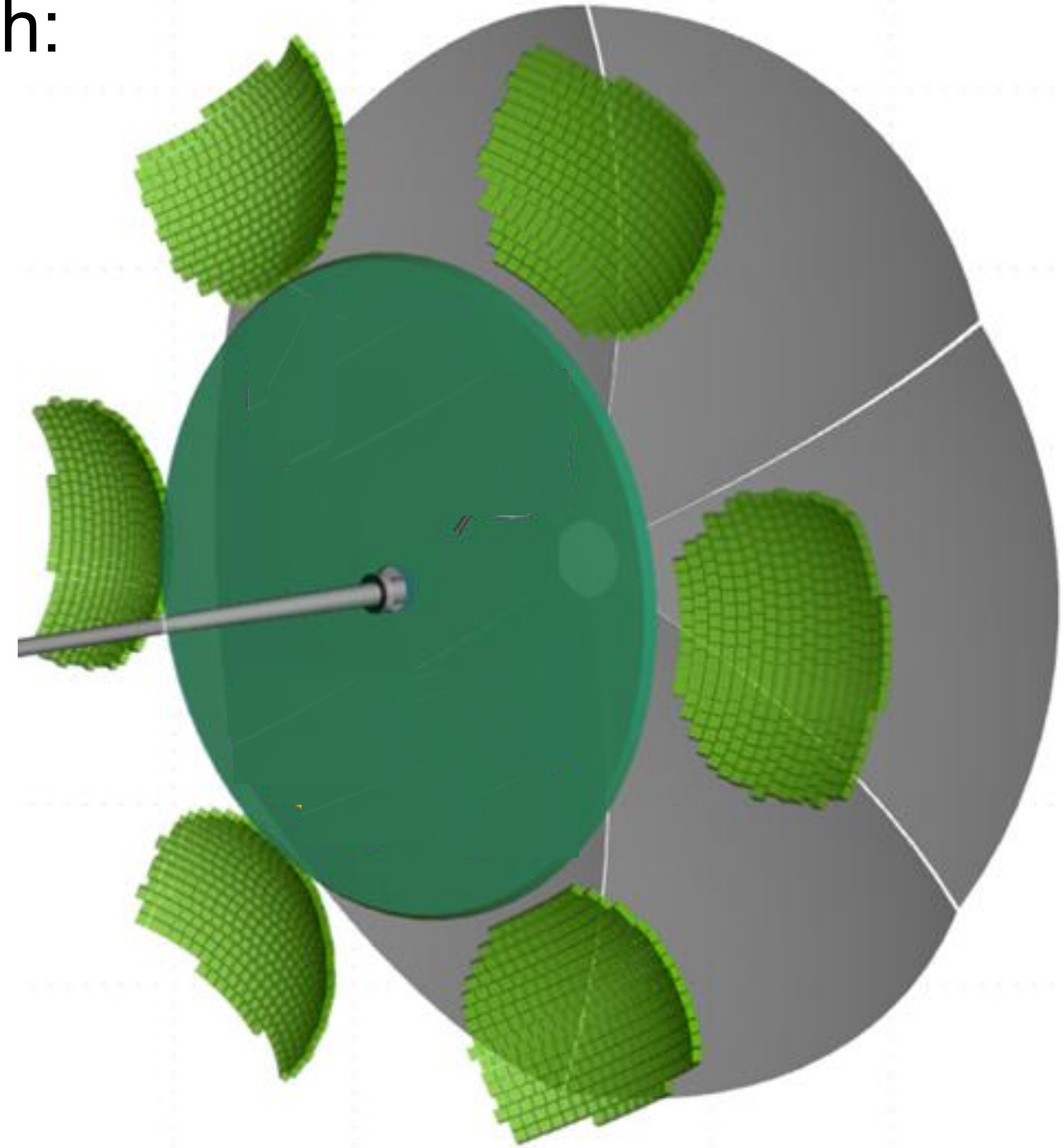


GEM chambers
for accurate tracking

EIC thesis activities

Research and Development on the dRICh:

- Prototype beam tests at CERN (and US)
- Analysis of the test data
- Study and optimize detector performances (combining simulation, prototype beam test results and Bayesian statistics)
- Development of the full reconstruction algorithms



Activities carried on together with groups from: INFN-Ferrara, Bologna, Catania, Torino and Trieste, Duke-University, JLab, BNL, …