Extreme Light Infrastructure-Nuclear Physics (ELI-NP) - Phase II

Project co-financed by the European Regional Development Fund through the Competitiveness Operational Programme
"Investing in Sustainable Development"

New Opportunities in Nuclear Physics and its applications with 2X10 PW Lasers and 20 MeV brilliant gamma beams

Sydney Galés IFIN-HH/ELI-NP and IPN Orsay –IN2P3/CNRS(Fr)

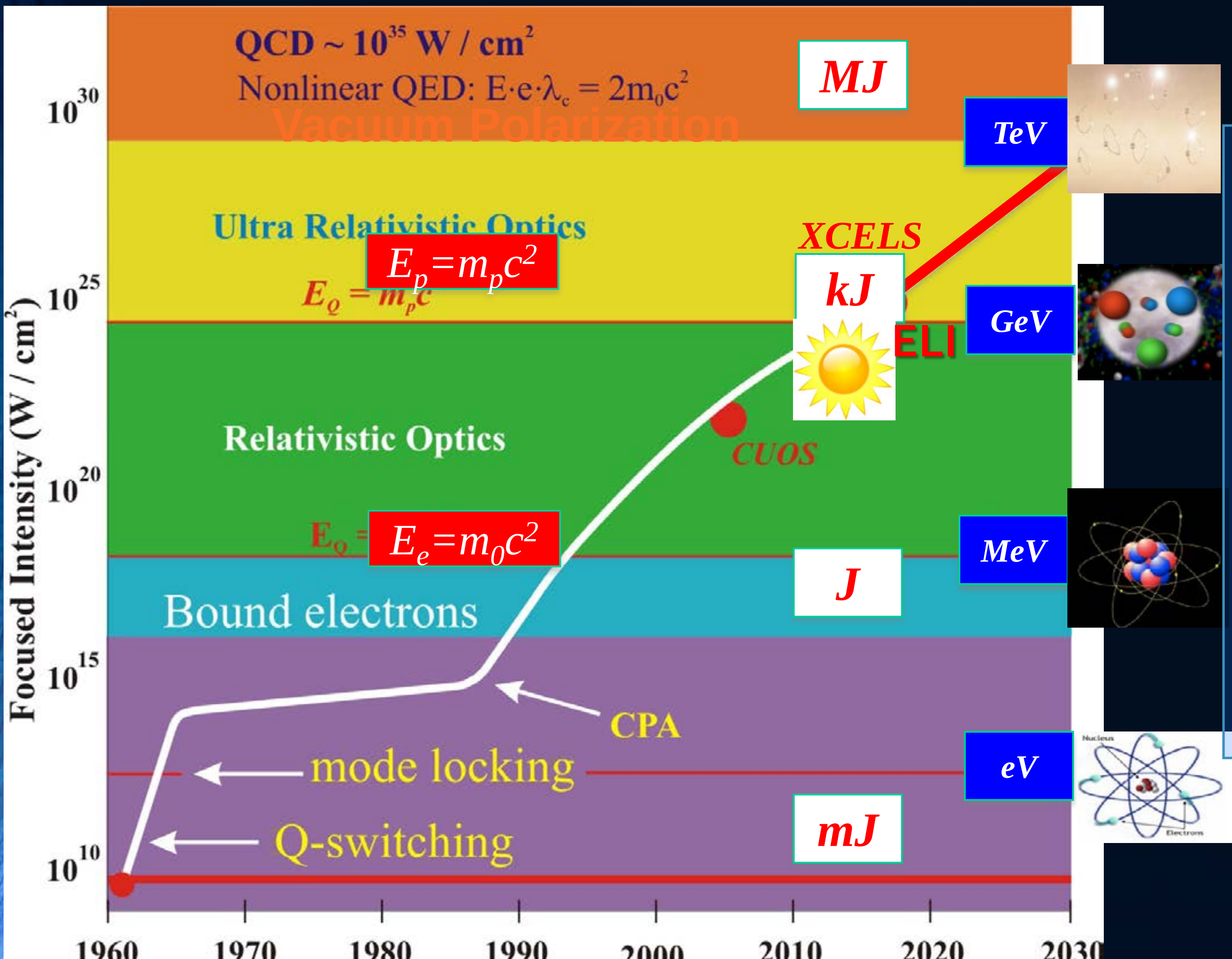
What is ELI?
Extreme Light Infrastructure

ELI will be

- The world's first international laser research infrastructure, providing unique science and research opportunities for international users
- A distributed research infrastructure based initially on 3 facilities in CZ, HU and RO
- The first ESFRI project to be implemented in the new EU Member States EU13
- Pioneering a novel funding model: combining structural funds (ERDF)**1B€ 3 sites** for the implementation and member contributions to an ERIC for the operation

Extreme Light Road Map and Ultra high Intensity "A revolution"

Nuclear Physics



At focal point of the laser(microns)
E= 9x10^{6} MV/cm for an intensity of 10^{23}W/cm2

30 GeV e- acceleration within few mm

LRP 2018

Up-coming Facilities

In Bucharest : one pillar of the distributed facility

Emerging New field « Nuclear Photonics»

Nuclear astrophysics-Nuclear structure& reactions-Fusion- Fission -applications

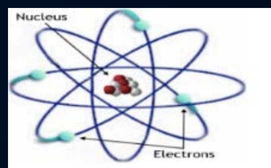
1) Ultra-short High power laser pulse (25fs) 2 X1O PW, 1/mn

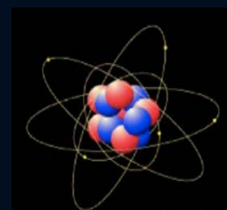
2) GAMMA beams high flux , monochromatic, E= 0-19 MeV

Experimental set ups under construction- scientific program with electromagnetic probes unique

ELI-NP (Ro)

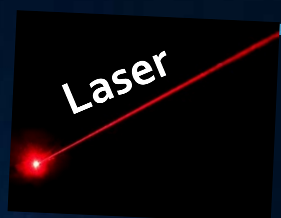
Explore matter and its constituents : from atom to vacuum
with new powerful e-m probes at the frontiers of existing technologies
High Power lasers and High energy, brilliant gamma beams

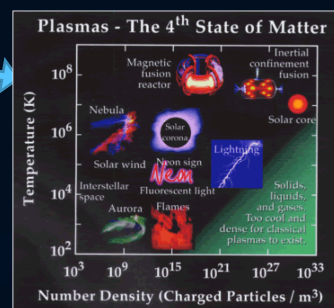


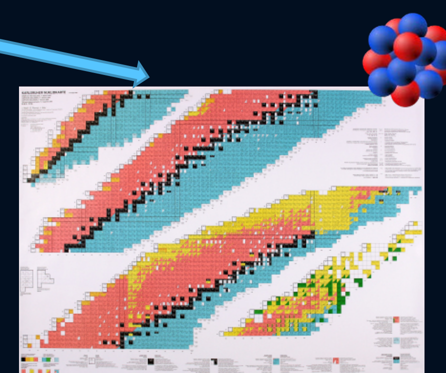


1) Ultra-short High power laser pulse (25fs) 2 X1O PW, 1shot/mn

Femto-scale (10^{-15}m)

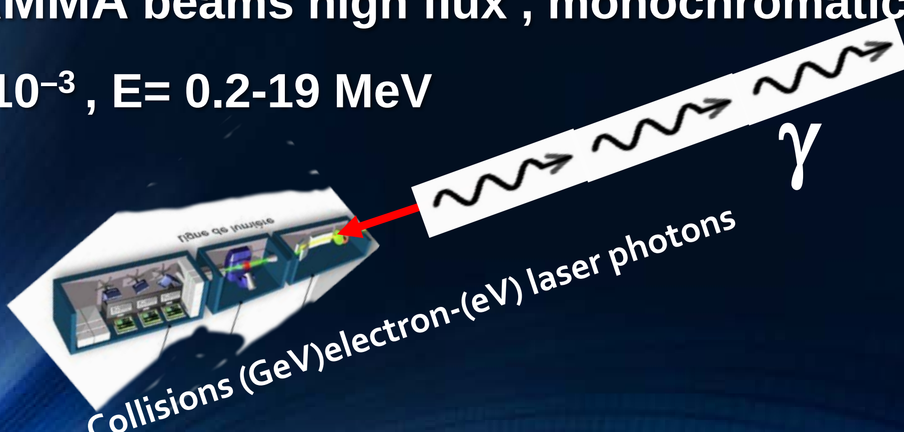




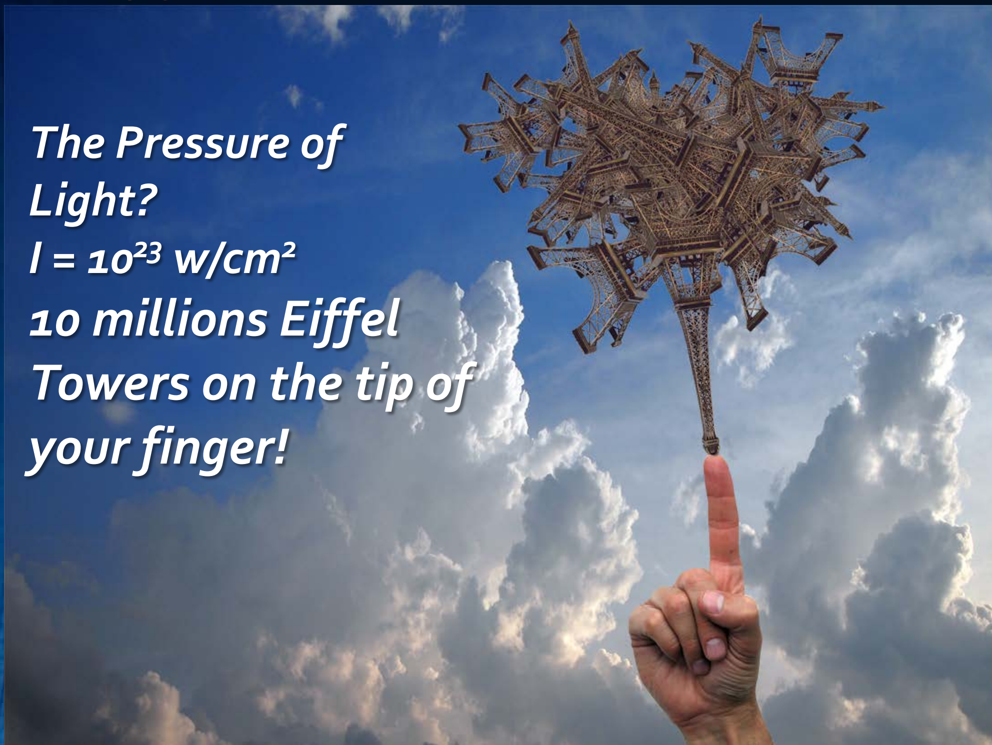


2) GAMMA beams high flux , monochromatic

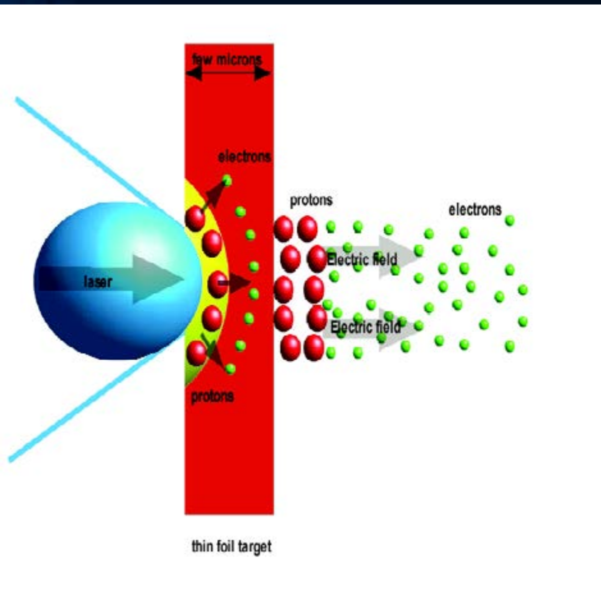
~qqs10^{-3}, E= 0.2-19 MeV



Laser Driven Nuclear Physics



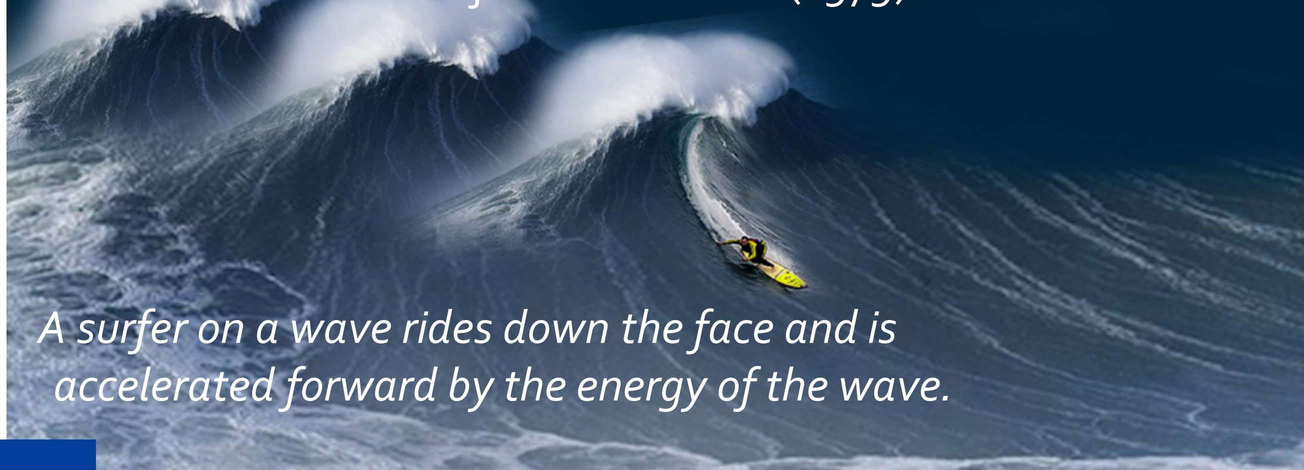
Laser Driven Nuclear Physics



Ultra-intense laser can generate a formidable Tsunami in a plasma where the particles could surf along.

Laser Driven Wake Field (LDWF)

Tajima et Dawson (1979)



A surfer on a wave rides down the face and is accelerated forward by the energy of the wave.

Electrons, ions, bunches acceleration, gamma conversion energy , dispersion, emmittance, rep rates

- **E -Field ~ TV/m**
- **E_e ~ Ten's of GeV in mm**
- **$E_{ion} \leq 150$ MeV/u**
- **charge ~ 10's of pC**
- **DE/E ~ 1-2% (e^-)**

e~10^{-5} mm mrad

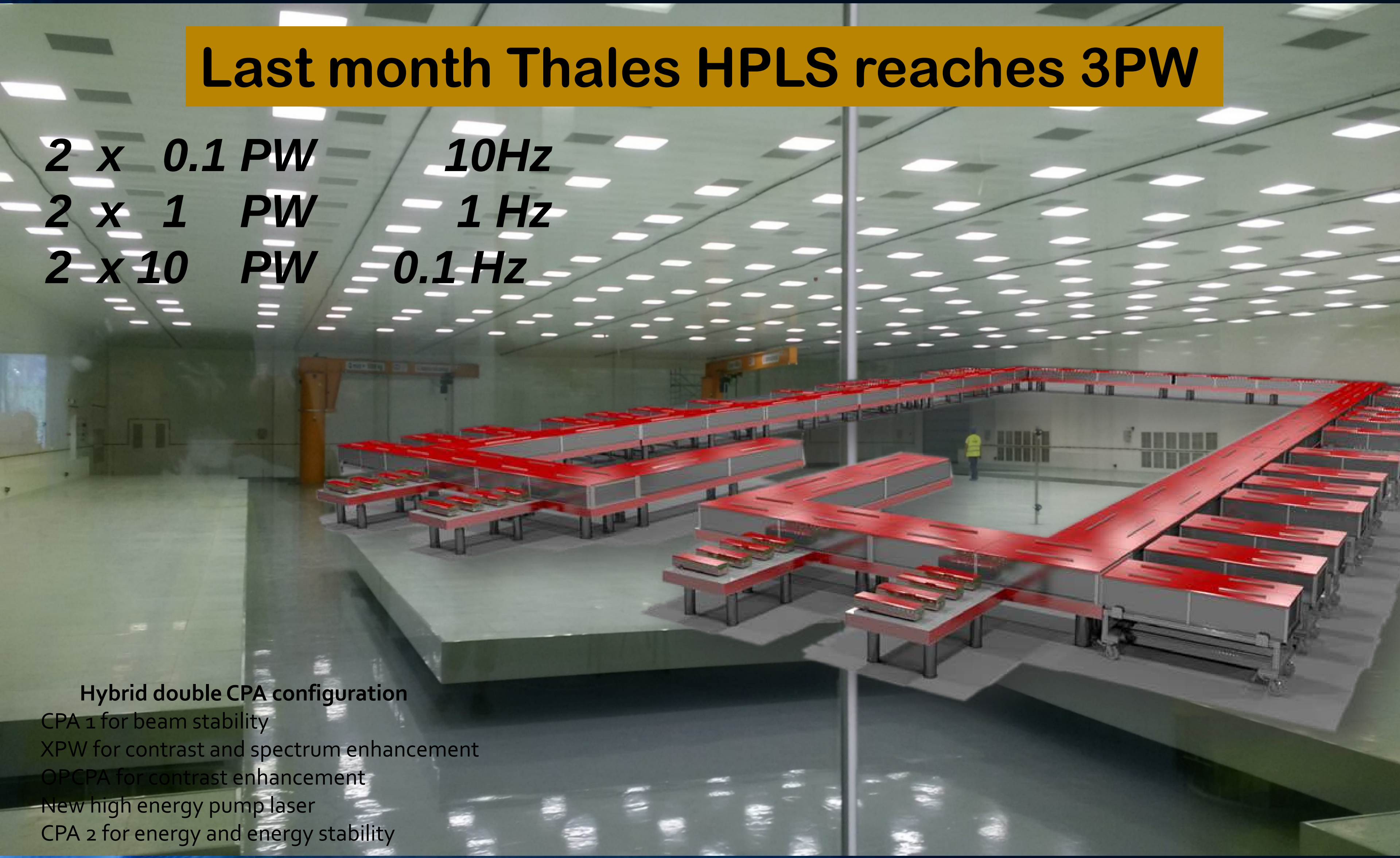
Highest Intensity Laser System
Large Clean Room Ready 70X20m

Last month Thales HPLS reaches 3PW

2 x 0.1 PW 10Hz

2 x 1 PW 1 Hz

2 x 10 PW 0.1 Hz



Hybrid double CPA configuration

CPA 1 for beam stability

XPW for contrast and spectrum enhancement

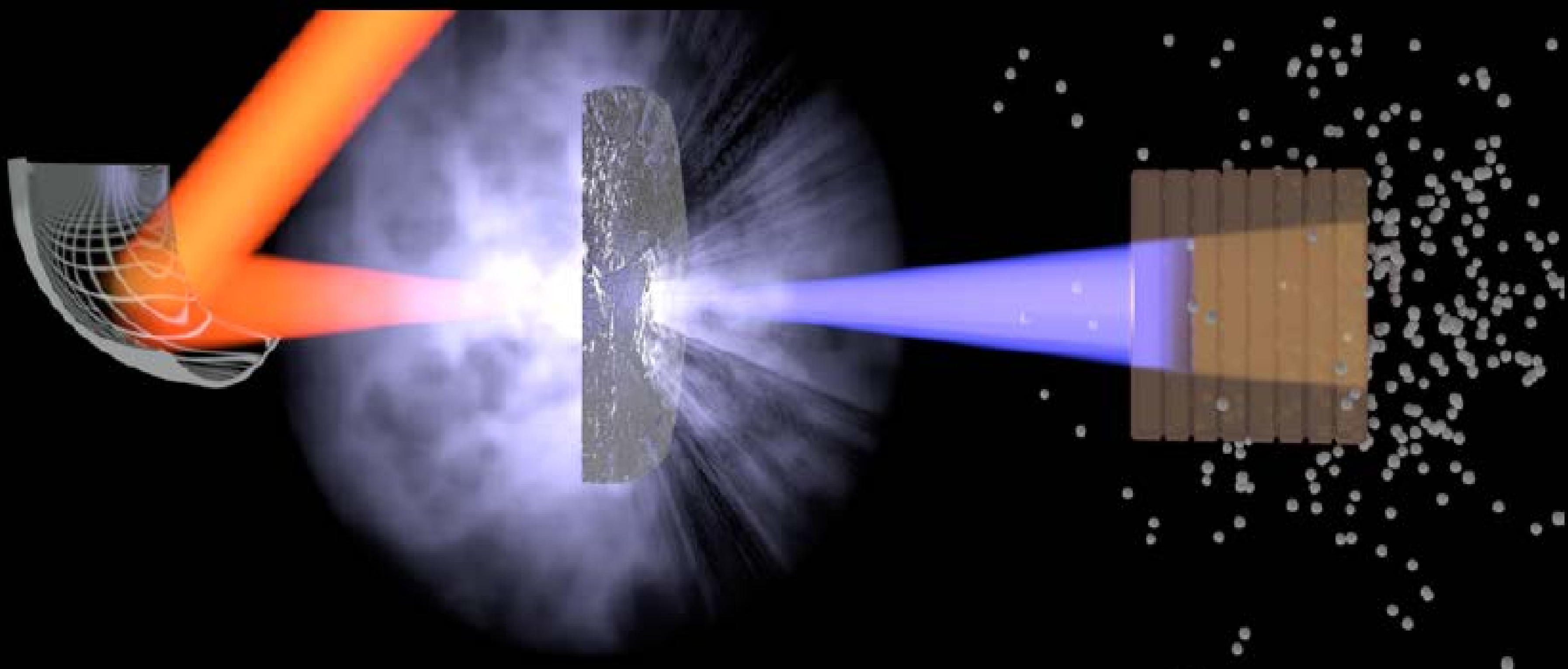
OPCPA for contrast enhancement

New high energy pump laser

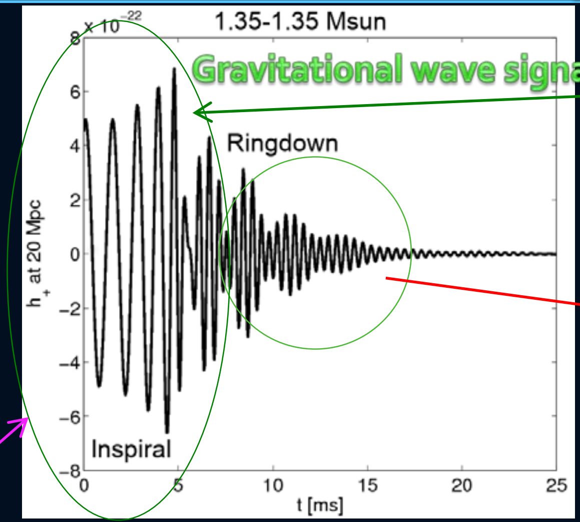
CPA 2 for energy and energy stability

LASER DRIVEN Nuclear PHYSICS

- interesting for astrophysics of light element nucleosynthesis (bare nuclei, nuclear reactions in plasma as in stars)
- nucleosynthesis of heavy element
- Production and photoexcitation of isomers (laser+gamma)
- Neutron production



Neutron star mergers: gravitational waves and production of heavy elements



Neutron star mass

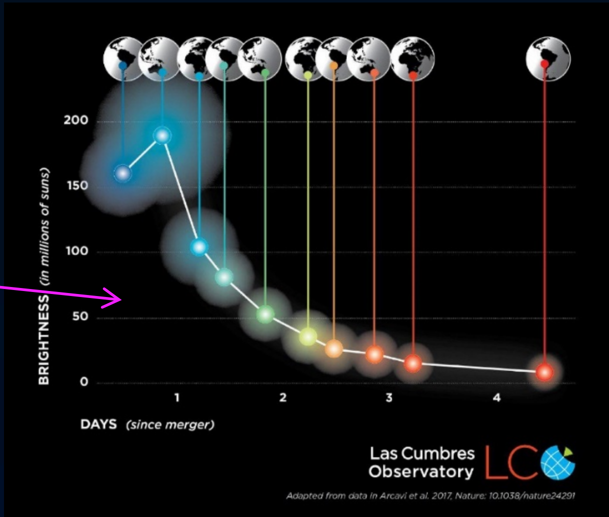
This depends on the Nuclear equation of state

The messengers from neutron star mergers :

- Gravitational waves
- Electromagnetic signals characterizing the nuclei in the ejecta
- neutrinos

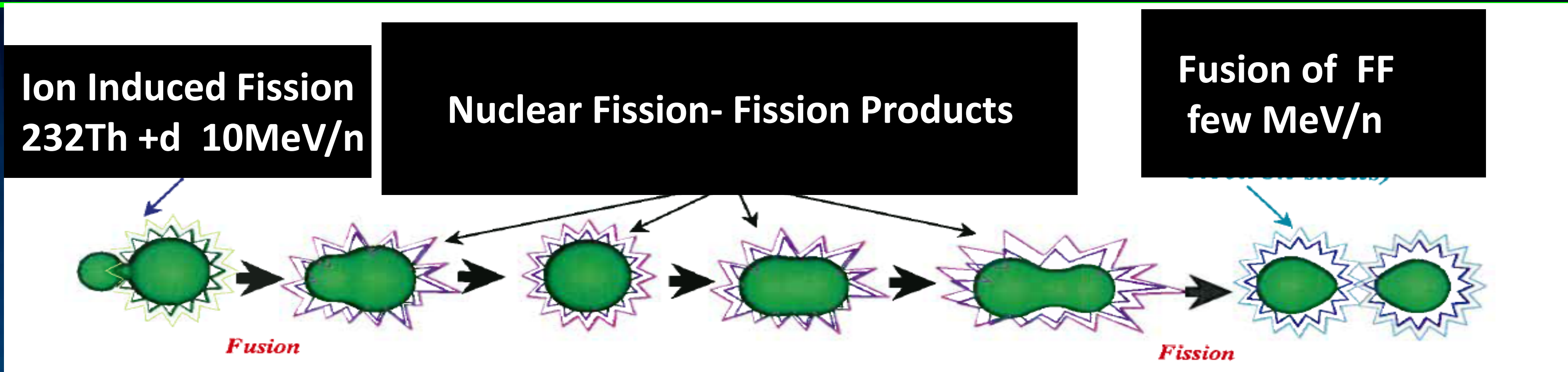
Gravitational wave emission seen together with electromagnetic signals

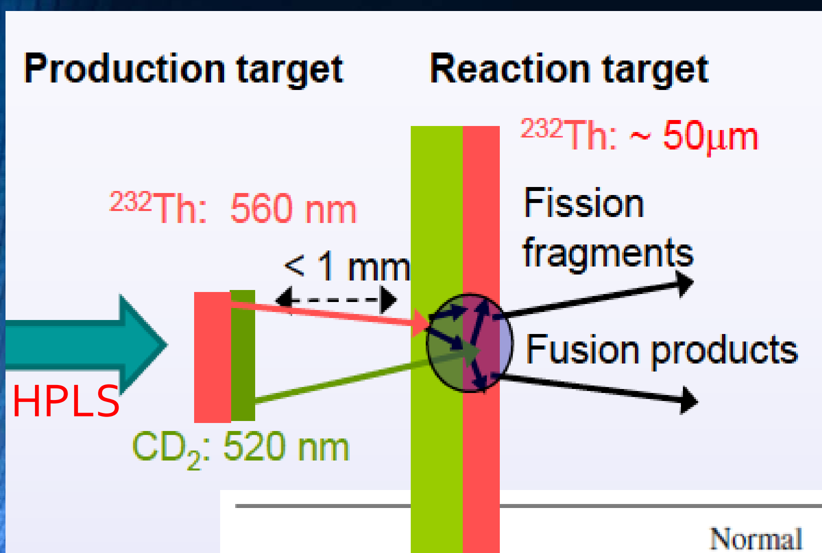
Time evolution determined by the radioactive decay of r-process nuclei
(science drive of facilities with RIB)



Laser driven Fission-Fusion (Flagship expt @ELI-NP)

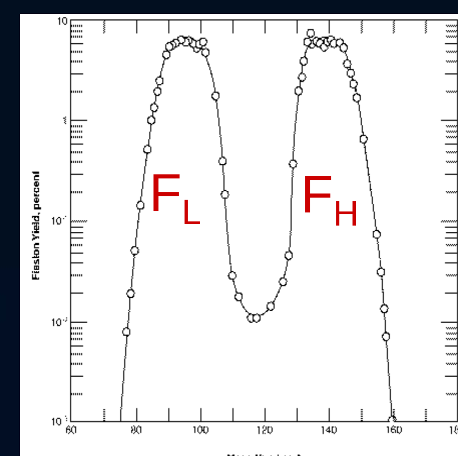
P.Thirof ,F.Negoita et al





*Dense bunches of heavy ions (Au) can be efficiently accelerated to the 10 MeV/u range by shooting on ultrathin (20 nm) metal foils a linearly polarized laser, with intensity in the 10 *22W/cm2 range*

Fusion of (light) fission products : $F_L + F_L$ => (A~200, Z~70, N ~ 126) Access to nuclei very far from stability



Laser driven Fission-Fusion (Flagship expt)

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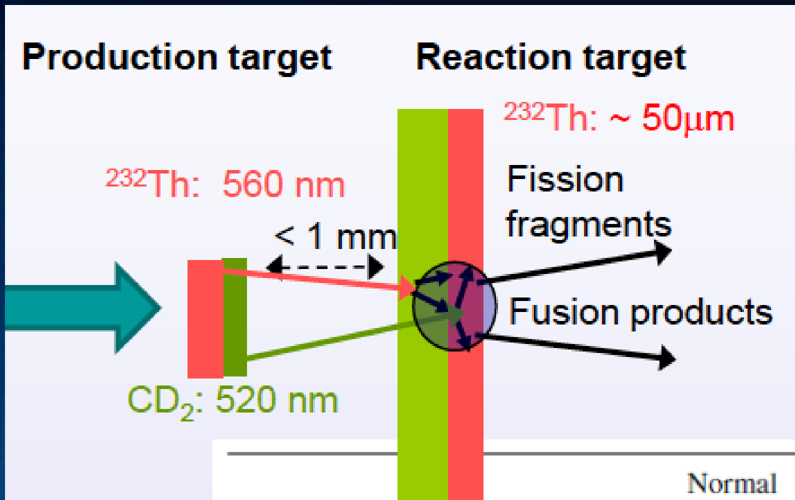
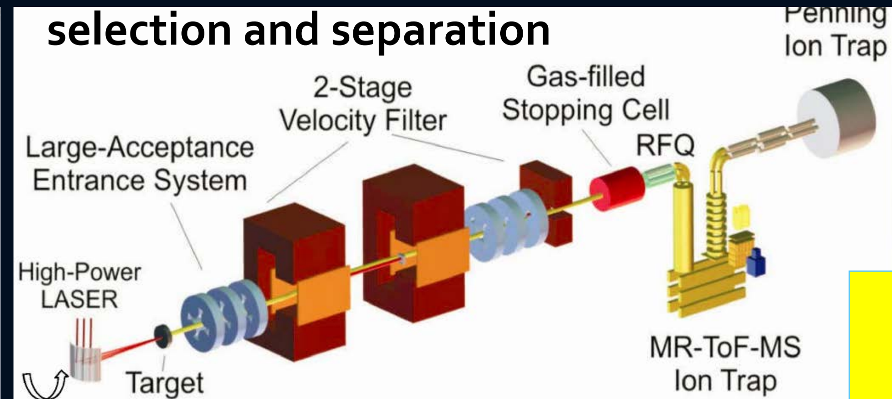
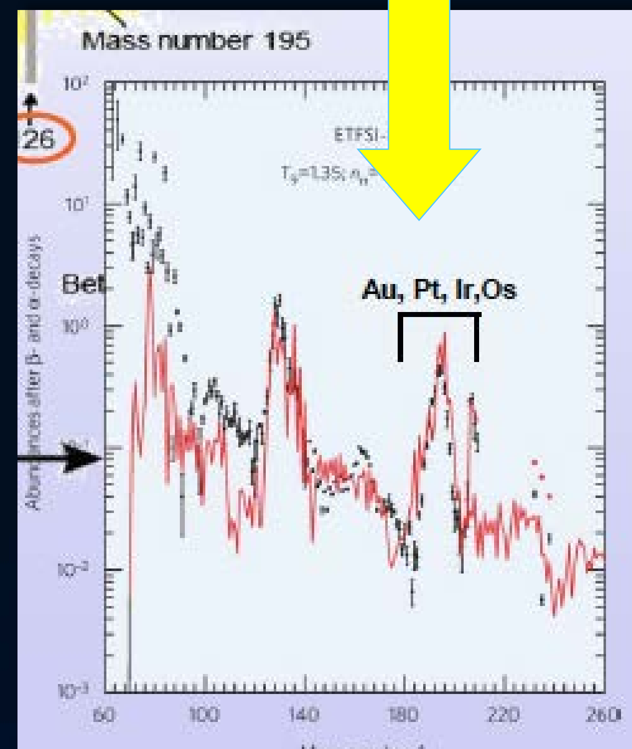
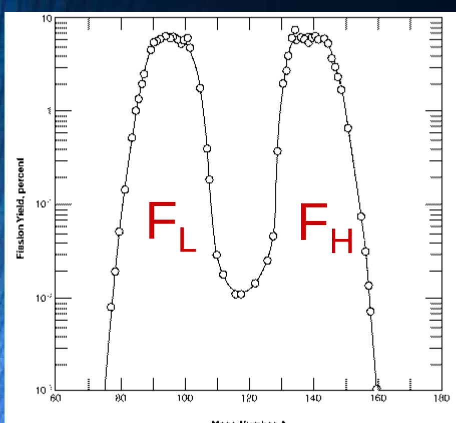




N= 126 waiting point bottleneck for nucleosynthesis of actinides



Mass distribution of fission of ^{232}Th



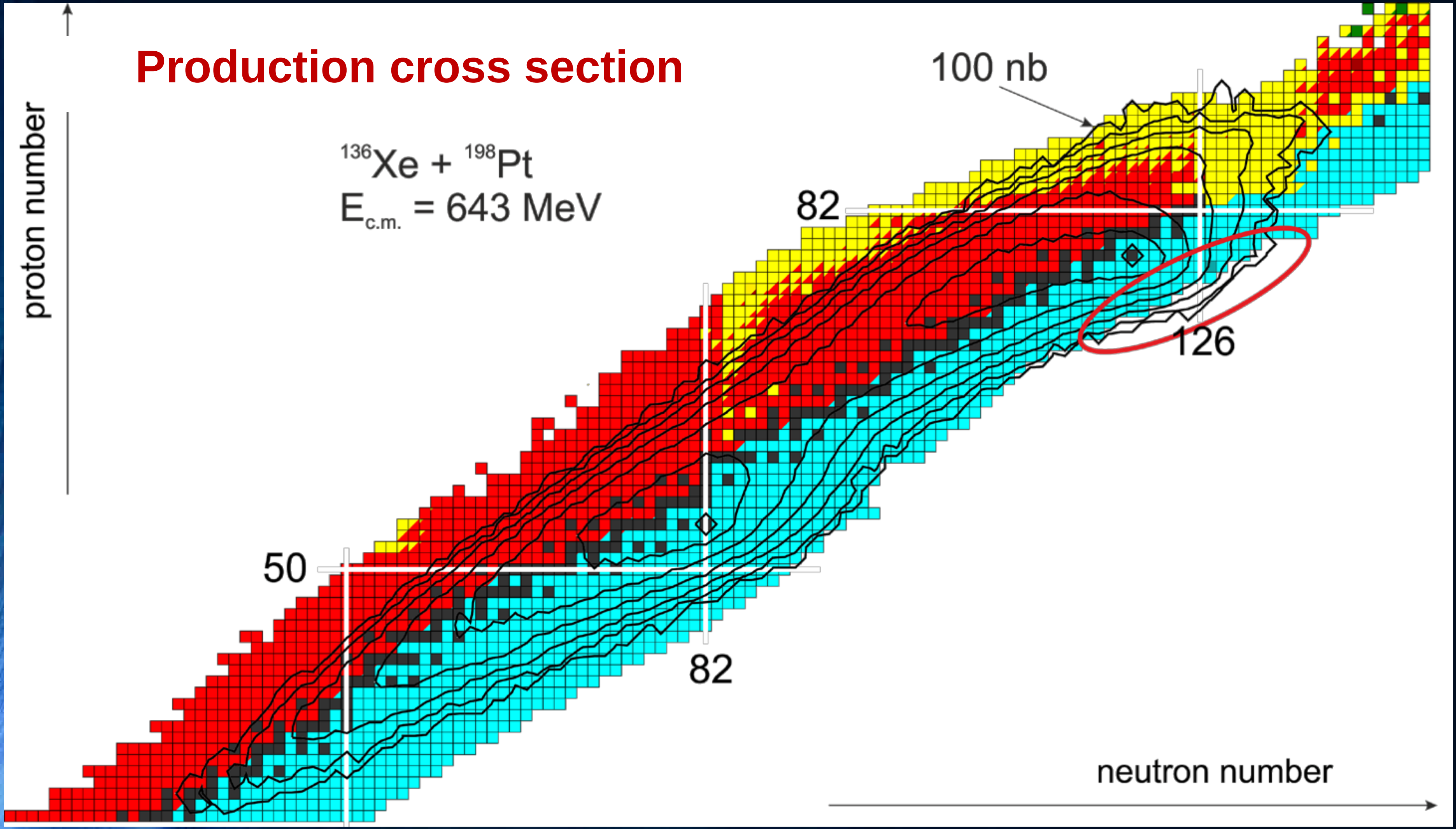
Fusion of (light) fission products :

$F_L + F_L$ => (A~200, Z~70, N ~ 126)

Motivations and MUCH MORE………

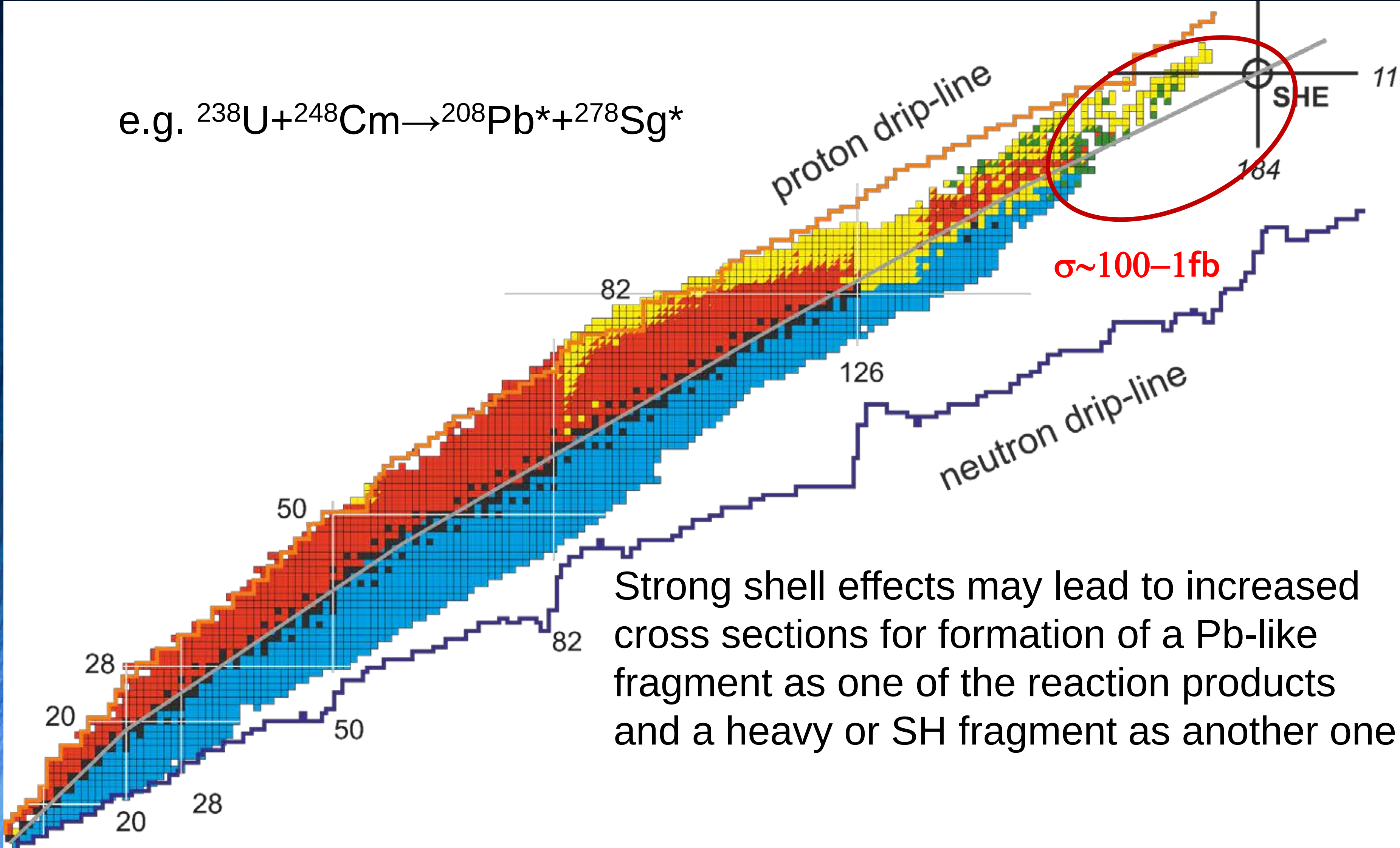
***Multi-nucleon* transfer reactions** are thought to be an efficient method of synthesis of new neutron-rich heavy and superheavy nuclei

A. Karpov(Flerov Lab; JINR Dubna)



Production of neutron-rich heavy and SH nuclei in actinide-actinide collisions (U+smth.)

A. Karpov(Flerov Lab; JINR Dubna)

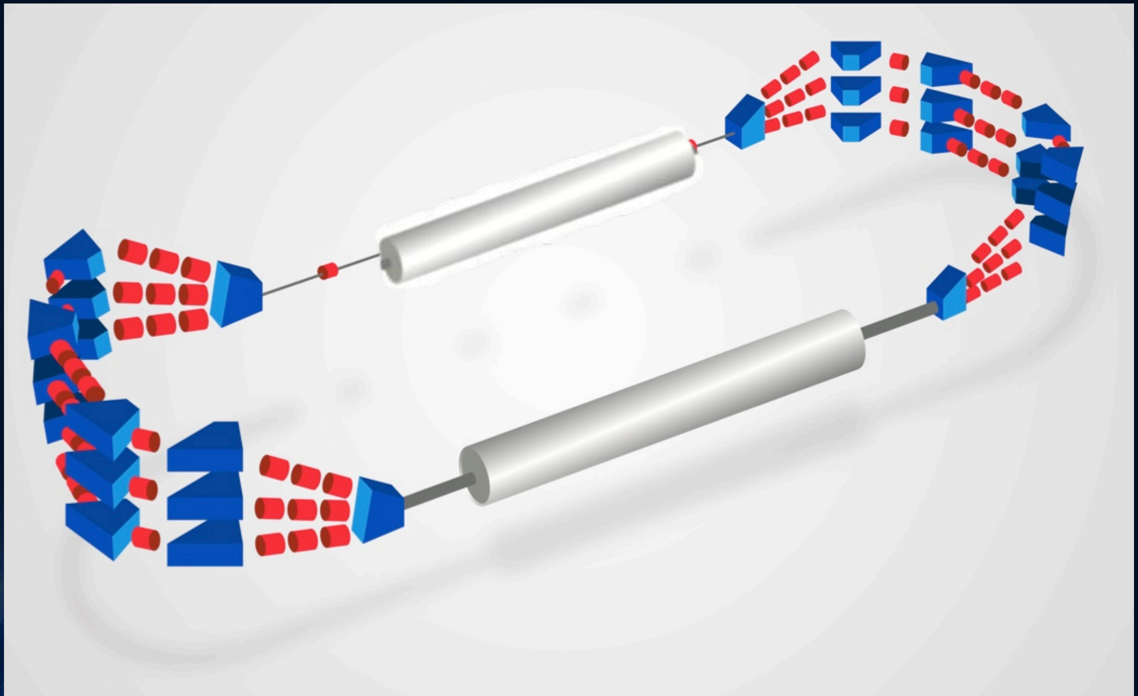


e.g. $^{238}U+^{248}Cm \rightarrow ^{208}Pb^{*}+^{278}Sg^{*}$

Strong shell effects may lead to increased cross sections for formation of a Pb-like fragment as one of the reaction products and a heavy or SH fragment as another one

on possible nuclear-physics avenues offered by
a Orsay-hosted 450-MeV PERLE version
From David Verney

"Nuclear Photonics" with Intense GeV class electron acc ERL accelerator
Few ev mJ green laser collides with GeV electron bunch gives many MeV monochromatic brilliant real photon beams



Gamma Beam System – Basic Concepts

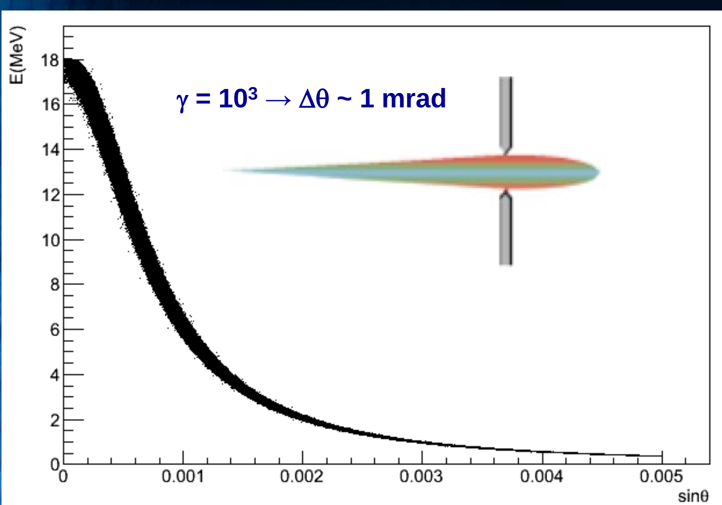
Gamma–rays from Inverse **Compton Scattering**

Low energy photon (eV) scattering on ultra relativistic electrons ($\gamma \gg 1$)

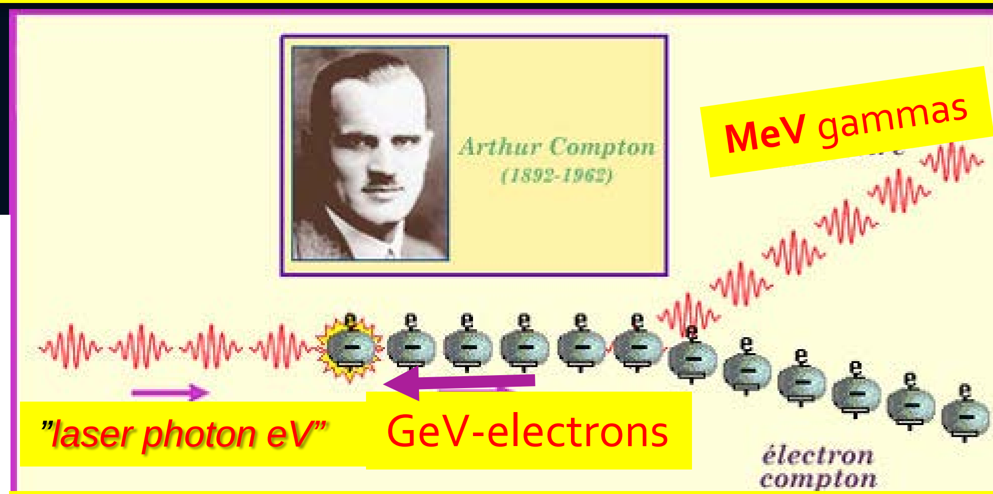
"Photon accelerator"

Discovery 1923!

Strong forward focusing



… but low cross section ~ 10^{-25} cm²



Scattered radiation is Doppler upshifted by more than 1,000,000x and is forwardly-directed in a narrow, polarized, tunable, laser-like beam

$$E_\gamma = 4\gamma_e^2 E_L$$

$E_\gamma \approx 2\gamma_e^2 E_L$ $\quad E_\gamma \approx 4\gamma_e^2 E_L$

E_e=720 MeV => γ_e~ 700 => E_γ ~20 MeV

ELI–NP Gamma Beam System

A collider based on the *most advanced* components: electron accelerator and lasers ,unique in the world

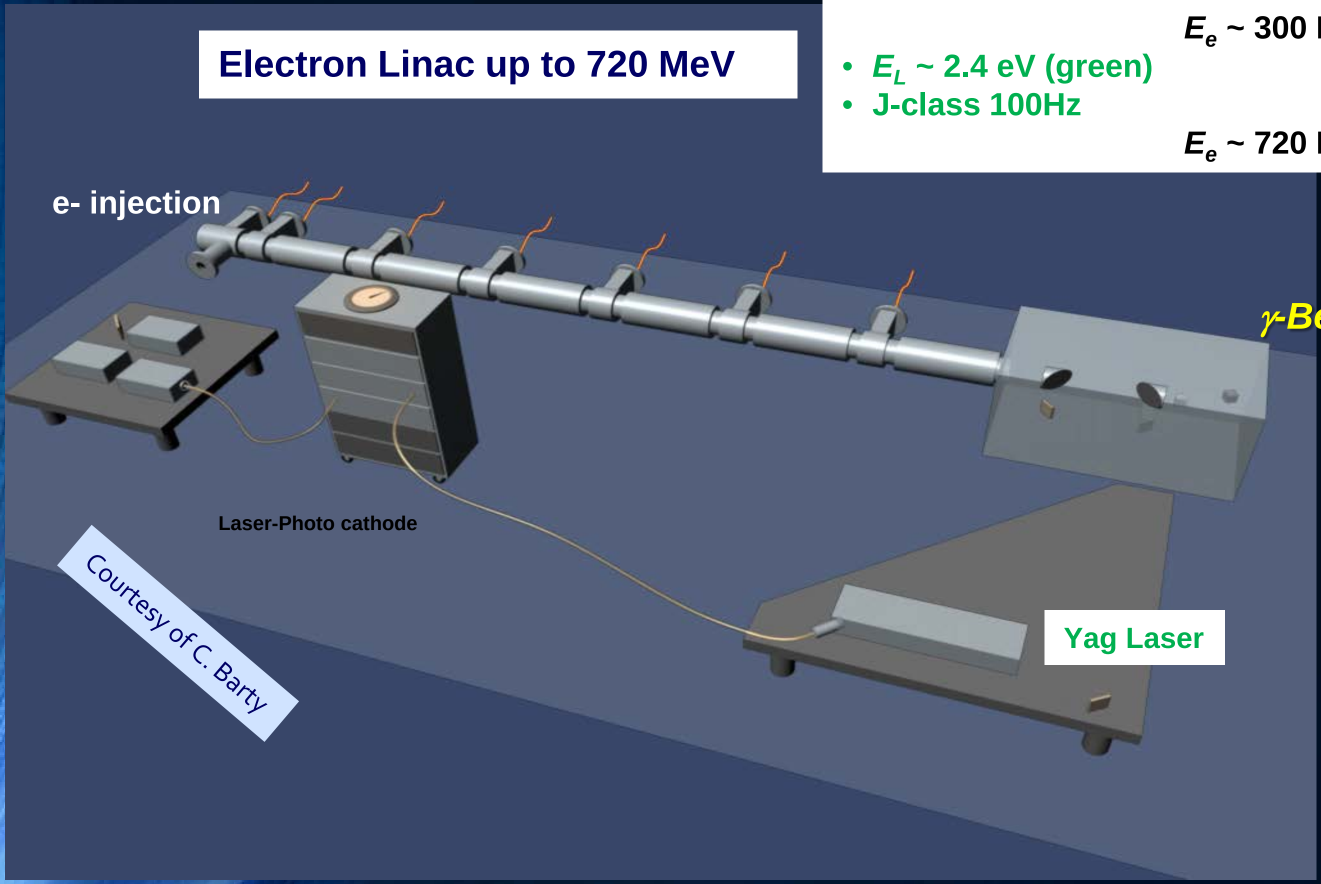
EuroGammas Consortium

Istituto Nazionale di Fisica Nucleare, INFN Italy, CNRS France,Research Institutes and HighTech Companies from 8 EU Countries

E_e ~ 300 MeV — E_g < 3.5 MeV

- E_L ~ 2.4 eV (green)
- J-class 100Hz

E_e ~ 720 MeV — E_g < 20 MeV



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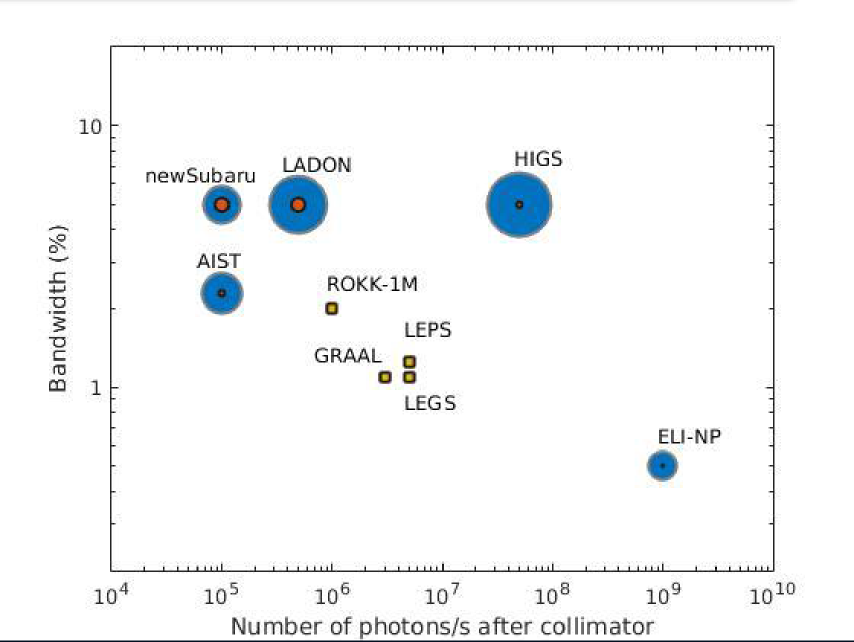


<u>High peak brilliance</u>

$>10^{21}$ ph/s · mm^2 · mrad^2 · 0.1%bw

high spectral density

> 0.5 · 10^4 ph/s · eV

<u>tunable energy</u>

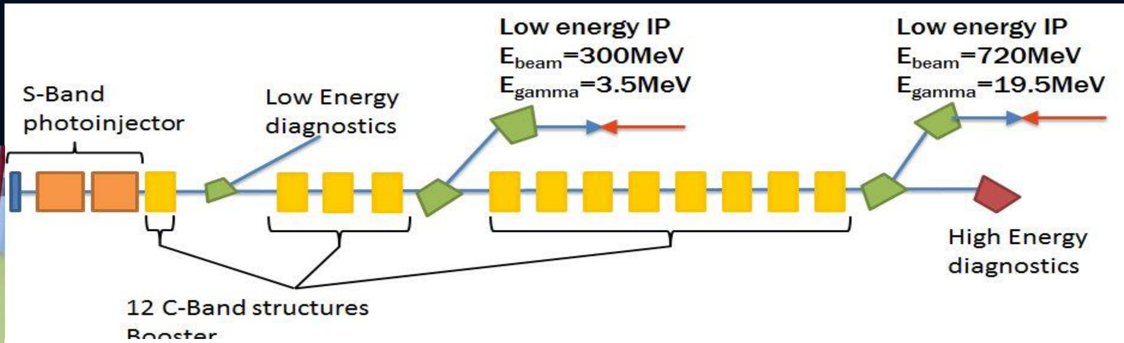
0.2 – 19.5 MeV

<u>quasi–monochromatic</u>

relative bandwidth < 0.5%

<u>High degree of linear polarization > *95%*</u>

EuroGammaS Association



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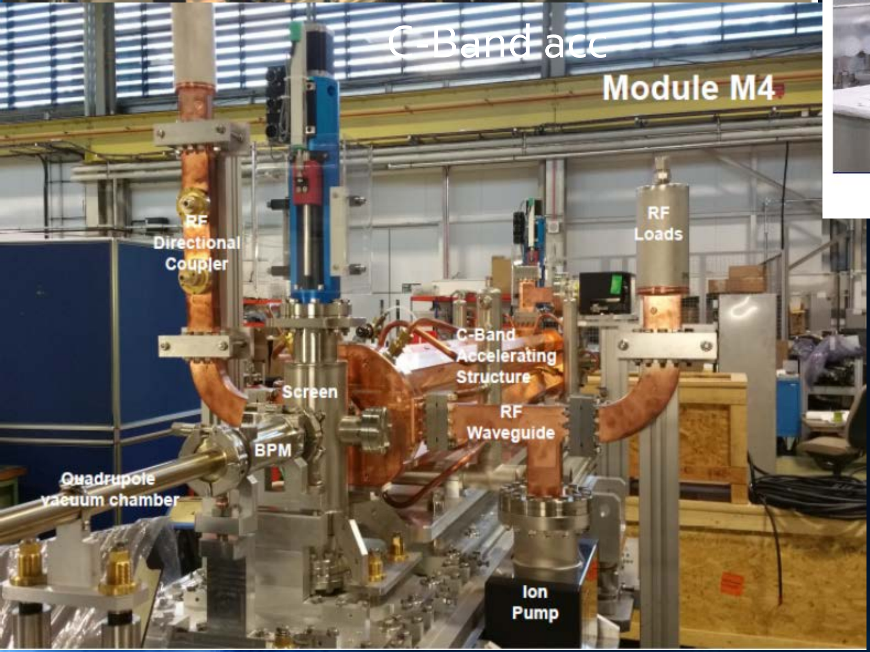
Gamma Beam System



Accelerator Modules

Under assembly at STFC

ELI-NP Scientific Program and Instruments
TDR's for Experiments completed and published

Experiments with High Power Laser System

- *Laser-driven nuclear physics*
- *High-field QED experiments*
- *Materials in extreme environments for energy, accelerators and space applications*
- *Monitoring and control systems for experiments*

Experiments with Gamma Beam System

- *Nuclear resonance fluorescence experiments*
- *Gamma above neutron threshold*
- *Photo-fission experiments*
- *Charged-particle detection*
- *Positron production by gamma beam*
- *Gamma-beam industrial applications*
- *Radioisotopes production for medical applications*
- *Gamma-beam delivery and diagnostics*

Combined laser-gamma experiments

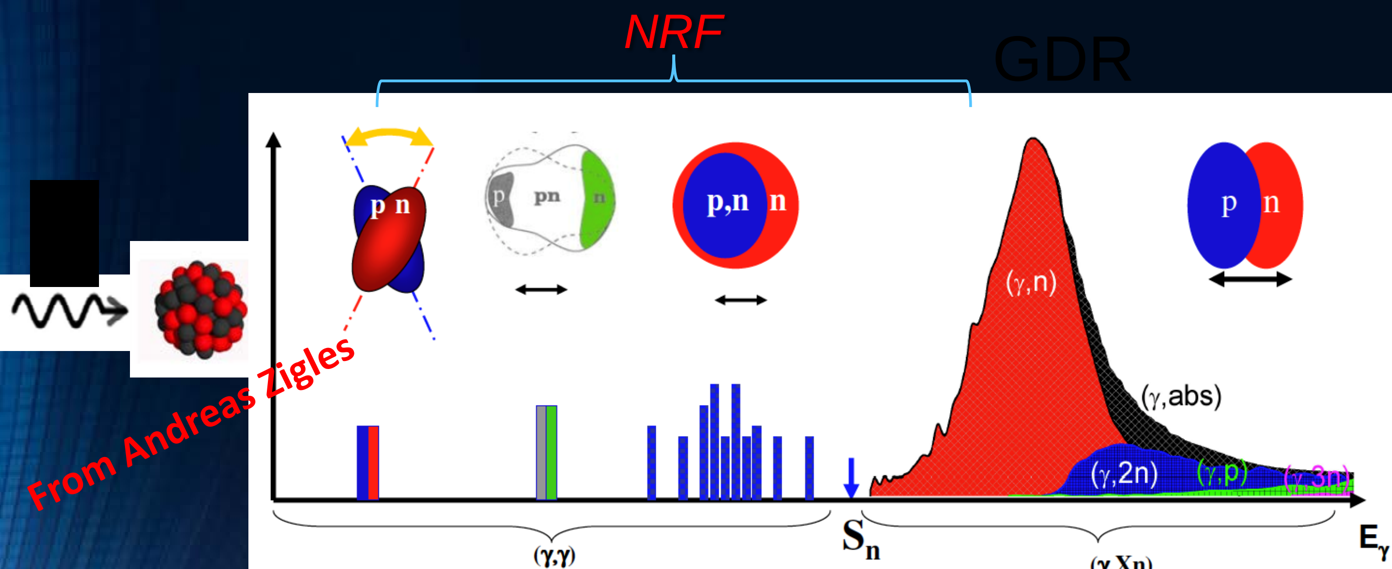
International Working groups
3 international workshops in 2013-2014 and 2015
(more than 150 part)

>30 MoU's and about 20 research contracts with major Laser and NP labs and Institutions (EU and Worldwide)

http://www.rrp.infim.ro/

Experiments with high-brilliance gamma beams at ELI-NP

Electromagnetic dipole response of nuclei

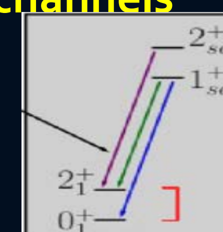


Availability frontier

***p*-nuclei and actinides**

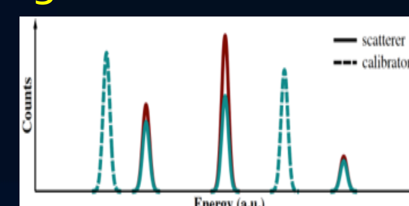
Sensitivity frontier

weak channels



Precision frontier

high statistics



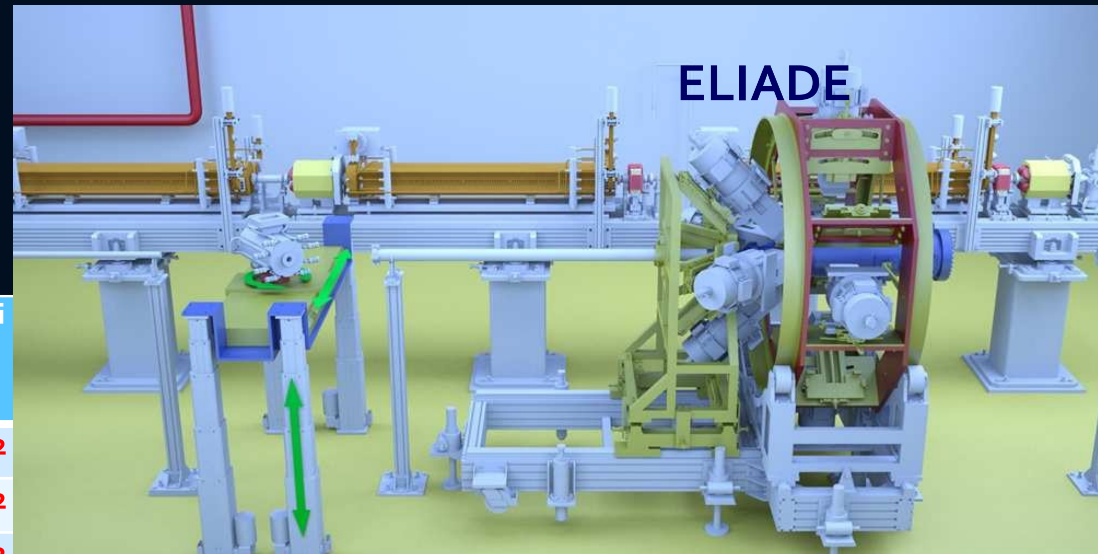
Nuclear Resonance Fluorescence (NRF)
Giant/Pigmy Resonances (GANT) ; Decay channels
Photonuclear reactions (γ,n), (γ,p), (γ,α) and Nuclear Astrophysics

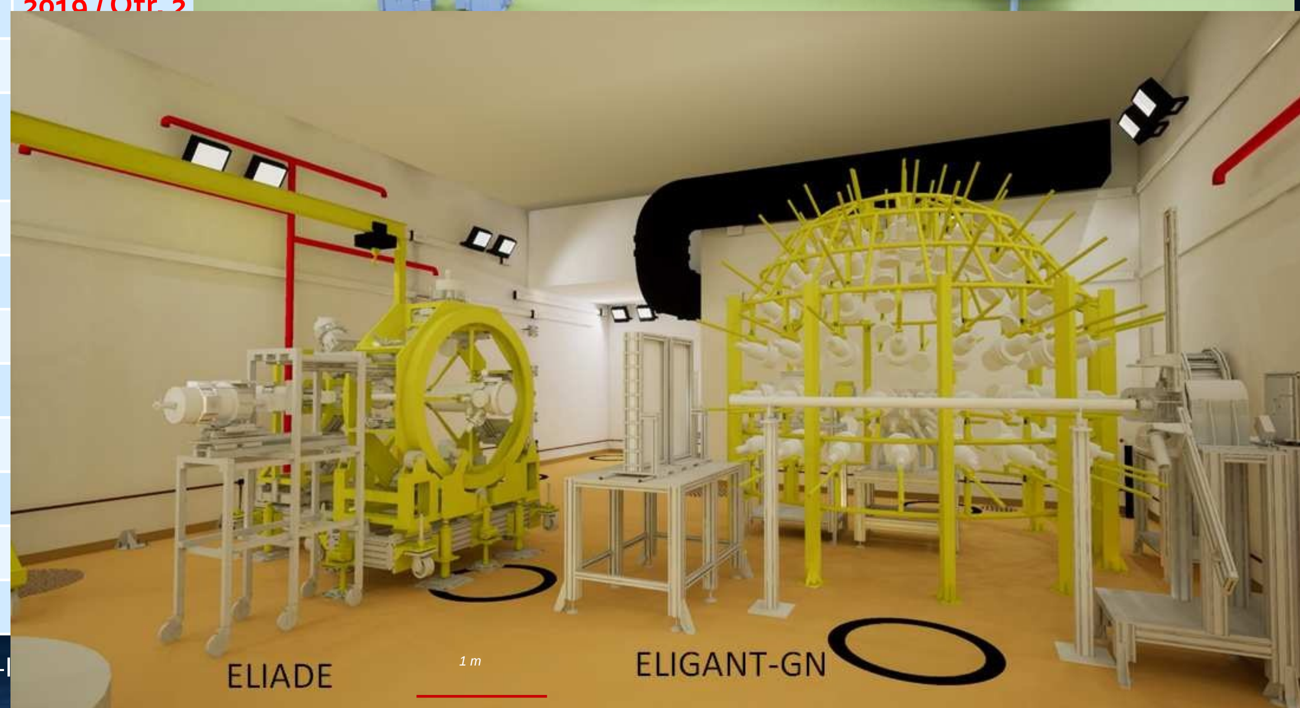
Photofission (γ,ff) , Exotic Nuclei via IGISOL gas cell

Gamma –tomography , radio isotopes and nuclear medecine

Experimental set-ups

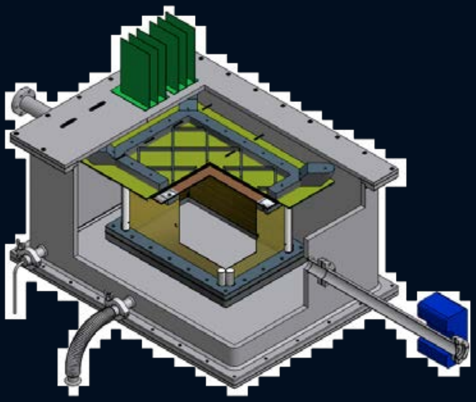
Experimental area	Experimental set-up	Commissioning Started
E1	Laser-gamma conversion	2019 / Qtr. 2
	200 MeV p	2019 / Qtr. 2
	Dense heavy ions	2019 / Qtr. 2
E6	10 PW wakefield acceleration	
E7	Isomer production and photoexcitation	
	ELITHGEM	
	ELI-BIC	
	ELI-TPC	
	ELISSA	
	Irradiation Station	
E8	ELIGANT - GN	
	ELIGANT-TN	
	ELIADE	





Astrophysics on Earth@ELI-NP with Gamma Beams

- **How the elements are made in the Cosmos**
- **–a central question for Astrophysics**



C,N,O elements essential for the emergence of life
Carbon Nuclear process 3 x 4He ------12C
Oxygen Nuclear reaction 12 C+4He---16O

Determination of the reaction rates by an absolute cross section measurement is possible in the lab with the **mono-energetic photon beams produced at ELI-NP**

$\gamma + {}^{12}C \longrightarrow 3\,\alpha$

${}^{16}O + \gamma \longrightarrow 12C + \alpha$

The ELITPC (ELI-NP Time Projection Chamber) detector is an active target detector, which is designed in collaboration with the University of Warsaw. It is most suitable to investigate the multi alpha-particle decay of light nuclei such as 12C and 16O and the cross section of astrophysically relevant (γ,p) or (γ,α) photo- dissociation reactions

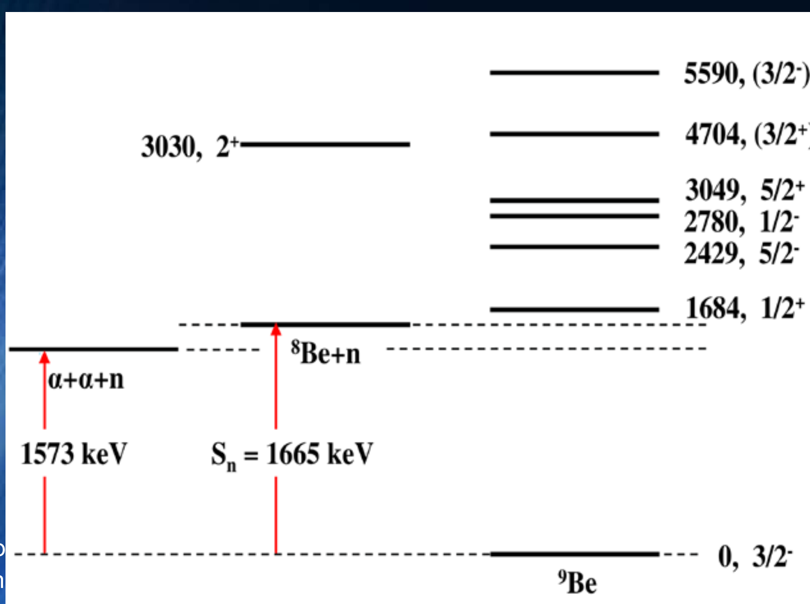
Tremendous advance to measure these rates directly- very high intense γ beam needed @ELI-NP

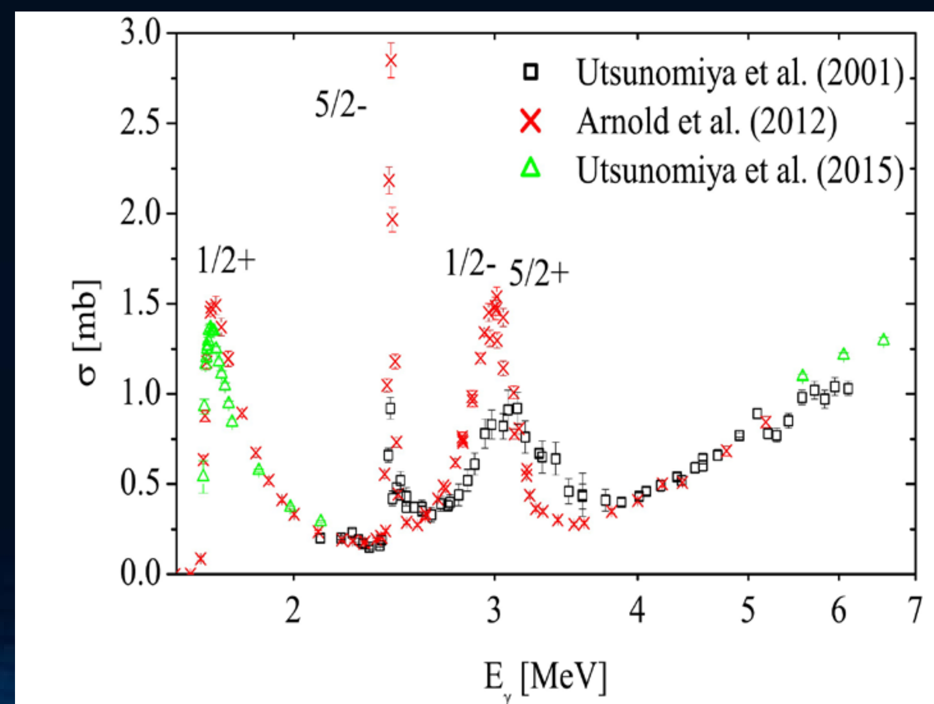
Astrophysics on Earth@ELI-NP with Gamma Beams

photo-dissociation reactions relevant to Big Bang Nucleosynthesis (BBN), supernova explosions, and p-process studies (Tesileanu et al. 2016, Matei et al. 2017).

Photoneutron reactions ***(γ,n)***

a day-one study at ELI-NP: photodisintegration of $_9$Be, whose inverse neutron capture reaction on the unstable $_8$Be is directly related to the production rate of heavy nuclei in astrophysical sites like Type-II supernovae (Woosley et al. 1994) or neutron star mergers (Freiburghaus et al. 1999),





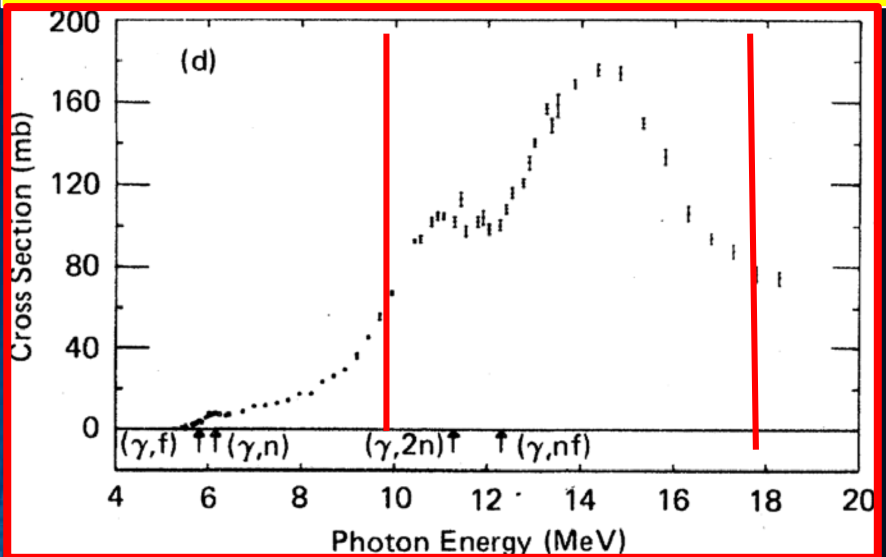
Exotic Neutron-Rich Isotopes : A new window

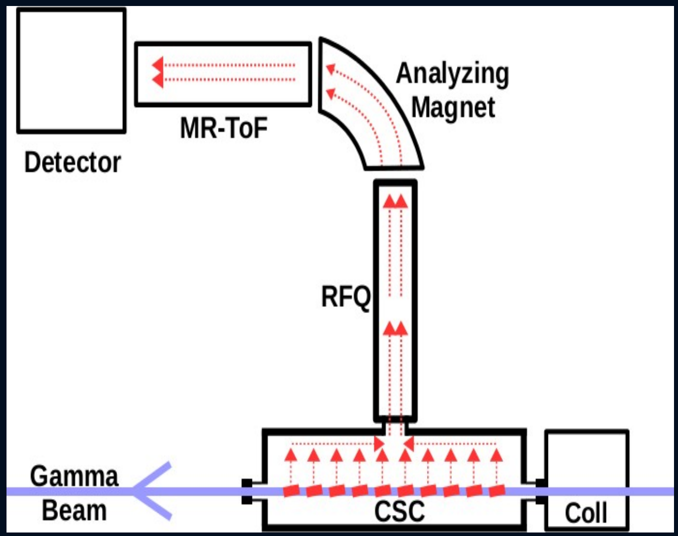
IGISOL beamline at ELI-NP

Rom. Rep. Phys. 68, S621 (2016)

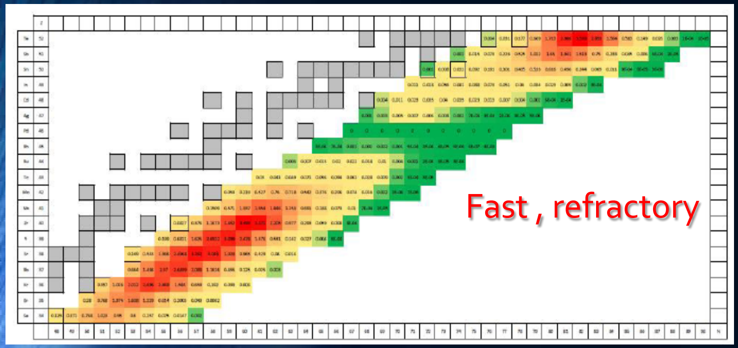
Production of fission fragments by Photofission by ELI-NP GBS

D.Balabansky et al , P. Constantin et al, NIM B 378, 78 (2016)+.........





Dickel et al., NIM B 376 (2016) 216



Production of exotic neutron-rich fission fragments Refractory elements: light region Zr-Mo-Rh and heavy rare-earths region around Ce

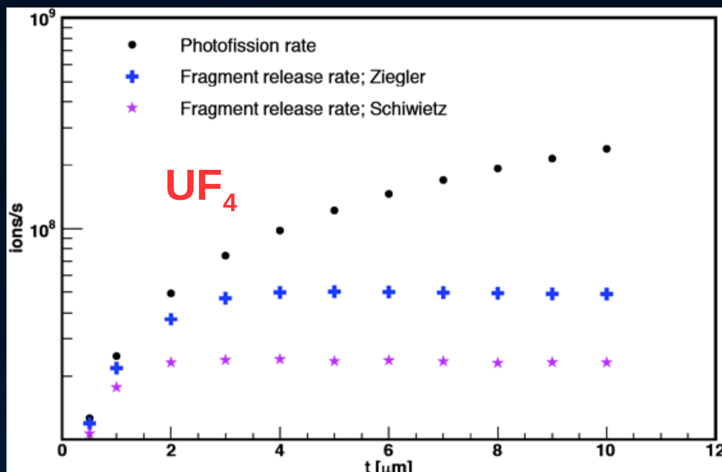
^{238}U target:

- thick because σ(γ,f)~1b
- sliced in many thin foils: refractory, fast extraction

An unique niche!
Refractory element Short lifetime

Production rates and target system design with GEANT

Geant4 photofission implementation. Target foils: 4µm UF with 0.5µm graphite backing



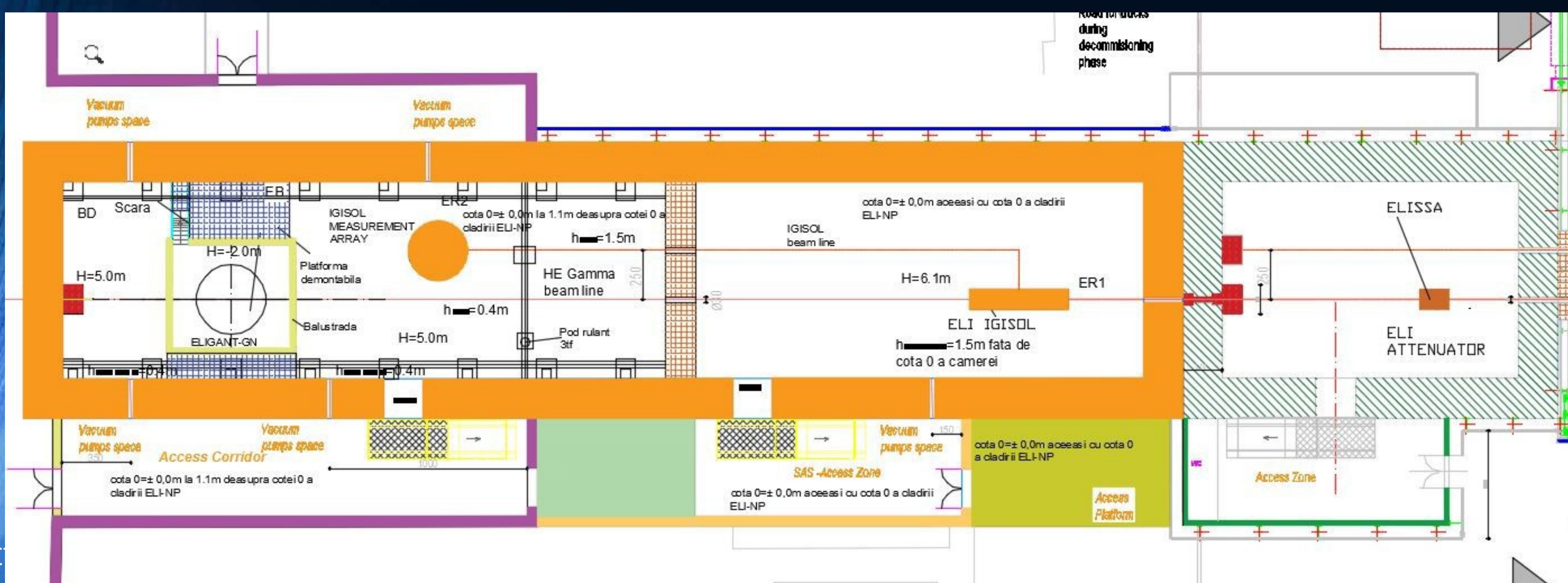
Production (target release) rates

$10^{12}\gamma$/s → **10^7 frag/s**

An unique niche!

Refractory element Short lifetime

B. Mei et al., Phys. Rev C 96 (2017) 064610



Multi-PW Lasers &Multi-MeV GBS like ELI-NP are Research Infrastructure Facilities where basic research as well as applied research are interacting to generate innovations for our daily life

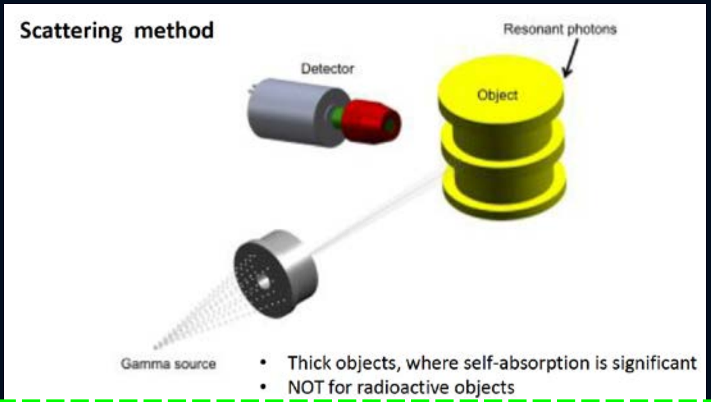
Applications of Gamma Beams

nuclear physics

Industrial tomography

material inspection: nuclearwaste
food contaminations

Rom. Rep. Phys. 68, S799 (2016)

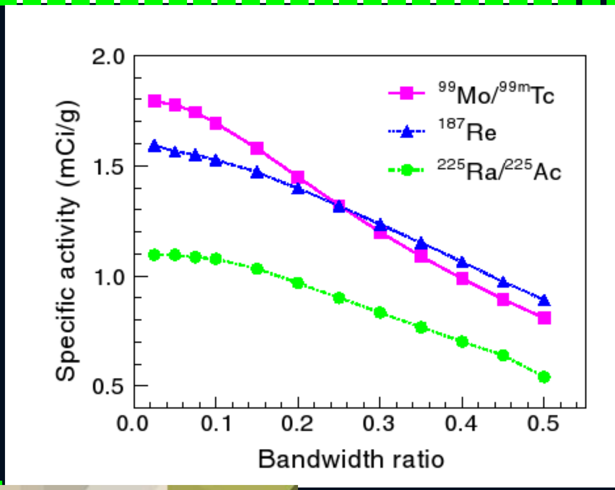


Medical radioisotopes at ELI-NP

•^{195m}Pt: In chemotherapy of tumors

•it can be used to exclude ”non responding” patients from unnecessary chemotherapy and optimizing the dose of all chemotherapy

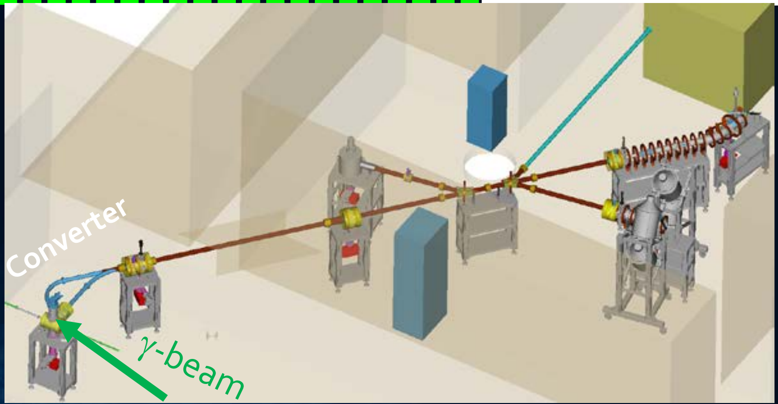
feasibility study: Wen Luo et al., Appl. Phys. B 122, 8 (2016)



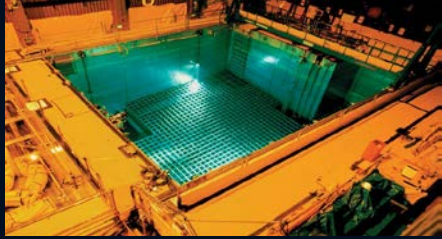
Positron beams for material science at ELI-NP

Rom. Rep. Phys. 68, S735 (2016)

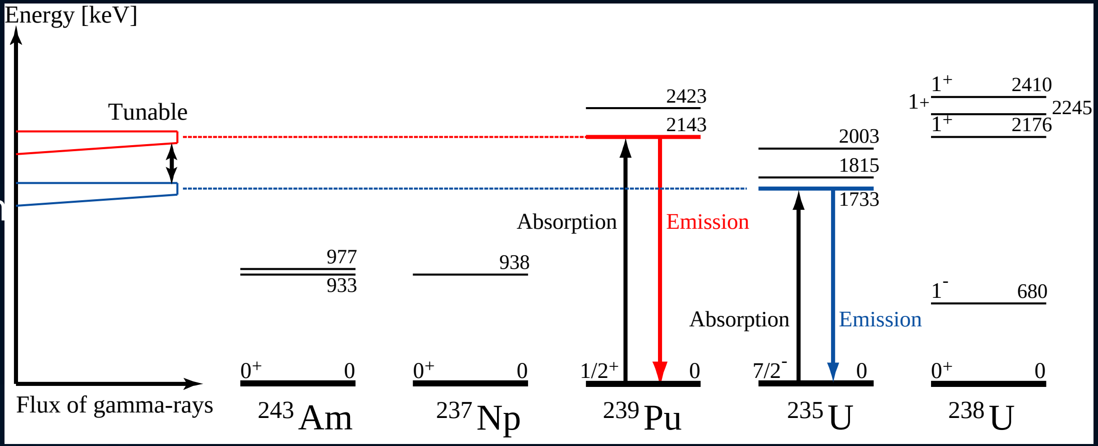
ELI-NP Positron Laboratory



Gamma Beam Applications To Nuclear Materials

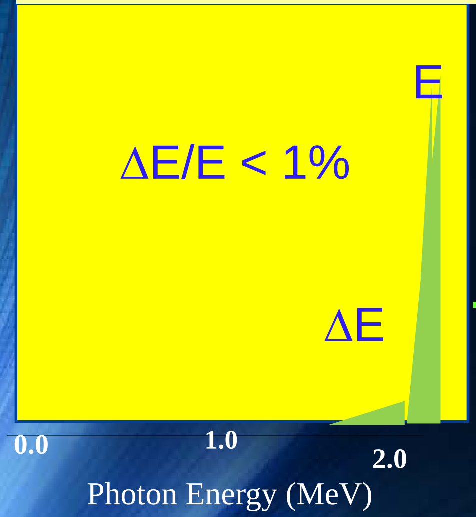


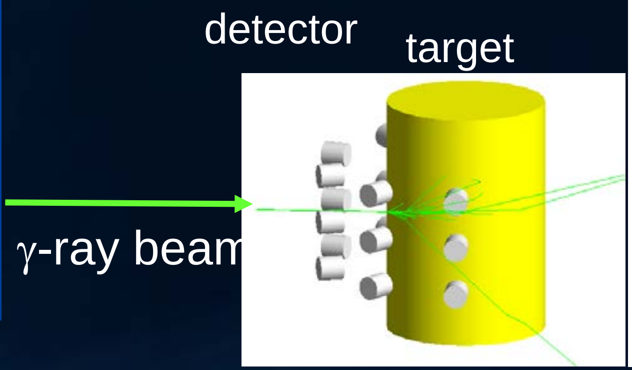
Mono-Chromatic Tunable GBS from ELI-NP

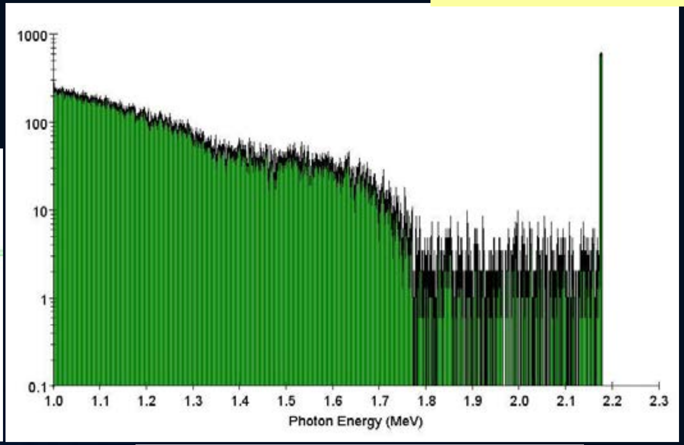


NRF signal U-238 2.176 MeV

2.176 MeV for U-238



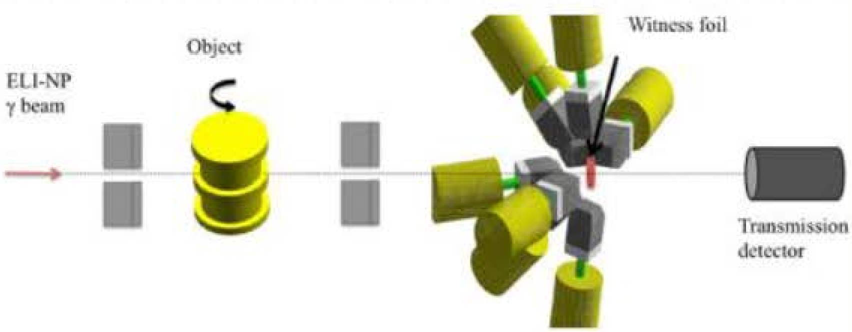




Photon energy (MeV)

Security applications

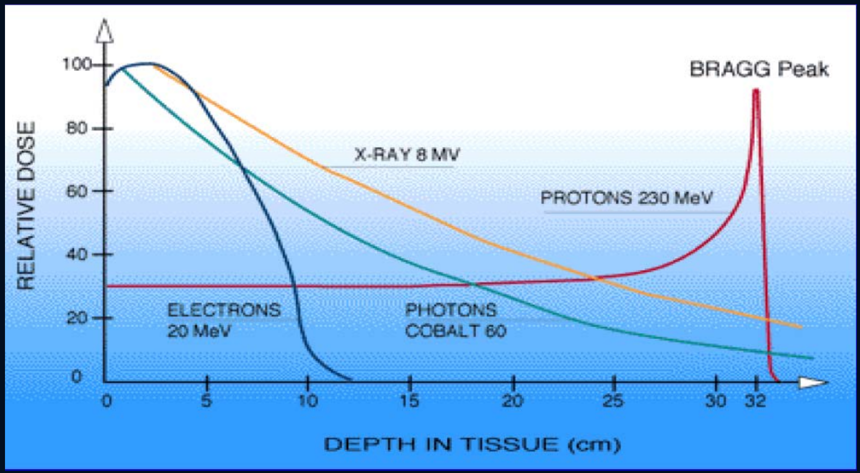
Need to enhance capabilities against CBRNE (chemical, biological, radiological, nuclear, explosives) threats



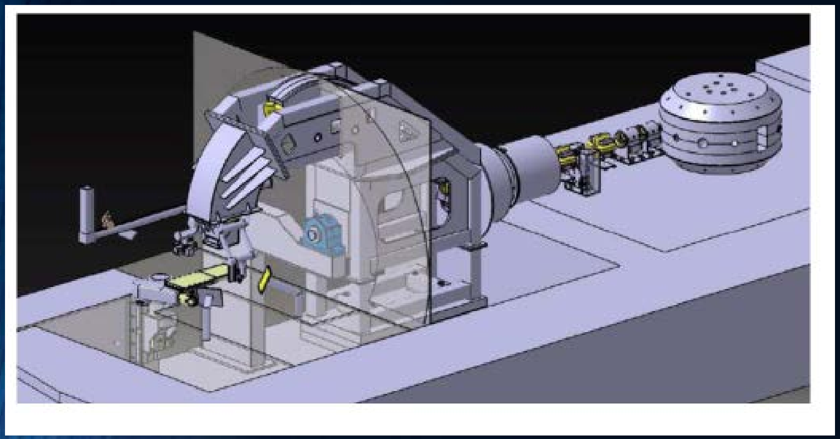
Detection of special nuclear materials hidden in high-density matrices could be achieved at ELI-NP in less than two minutes

- Interrogation methods
  - n or γ sources, muons
- Improved radiation detection systems
  - Detection of γ, prompt or delayed n
  - New high-light yield scintillators (ex $LaBr_3$, SrI_2...)
  - Lightweight detectors
- Nuclear data
  - Photonuclear reactions
- AMS

Laser Driven Proton therapy

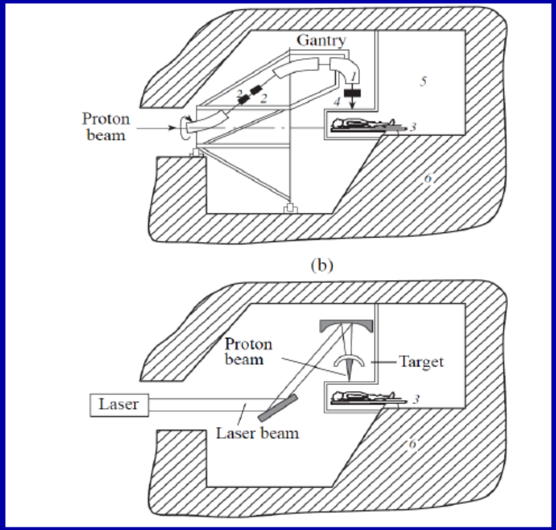


Sate of the art Proton cyclotron 250 Mev



Protheus one IBA 13X14X27 m3

- If 200 MeV proton accelerators would be as cheap and small as the 10 MeV electron linacs used in conventional radiotherapy, at least 90% of the patients would be treated with proton beams.



Gantries for conventional accelerator 100 tons and an optical gantry which is very compact, light using mirrors

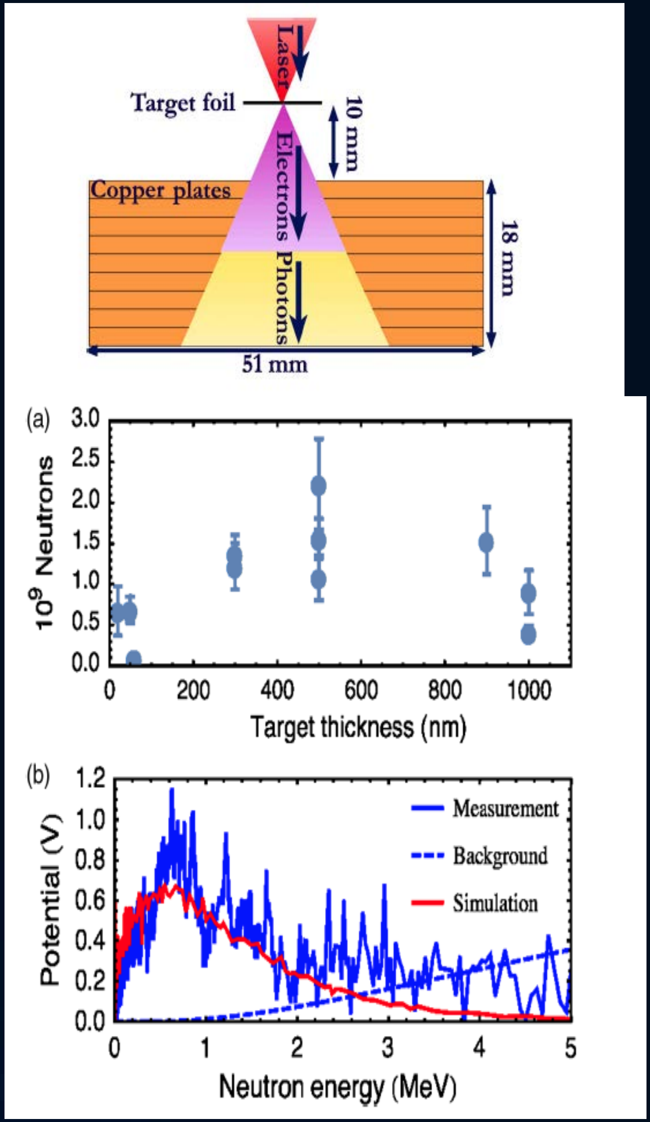
Laser electron driven Neutron source

I. Pomerantz, et al. Phys. Rev. Lett. 113, 184801 (2014)

PW laser facility at the University of Texas at Austin [17]. The setup is depicted in Fig. 1. **Ultrashort laser pulses of 150 fs (FWHM), with 90 J of energy on target** and a wavelength of 1057 nm were focused to a ~10 μm diameter spot on thin (0.02–3 μm) plastic targets

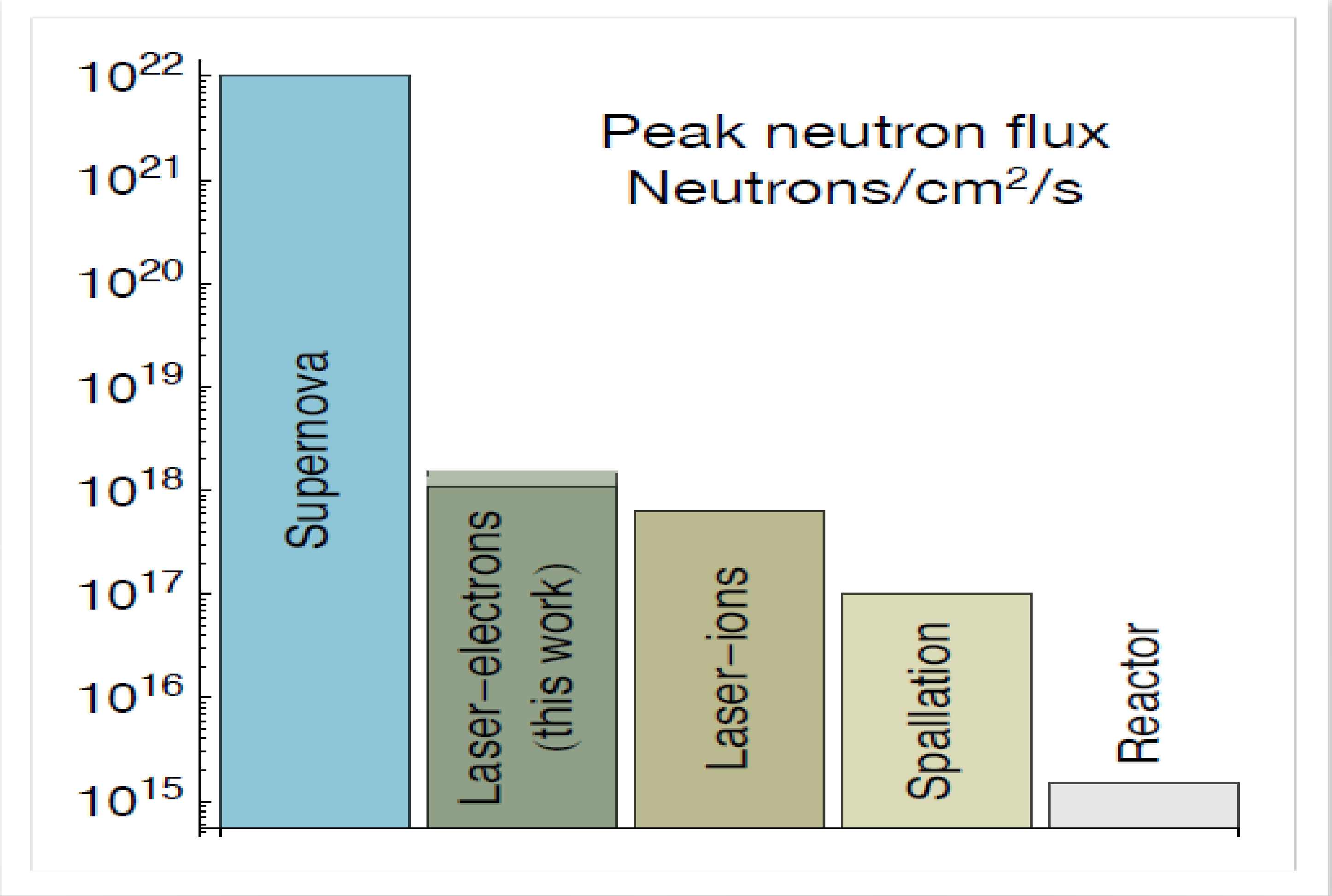
This pulse duration corresponds to a peak neutron flux of **1.1×10^{18} n/cm^2/s**, which is emitted isotopically into 4π sr (50 ps /pulse)

This peak neutron flux may be compared with **the laser-ion driven method (6×10^{17} n=cm^2=s)** [4] as well as with **accelerator driven generators like spallation sources (10^{17} n=cm^2=s) [36] and fission reactors (10^{15} n=cm^2=s) [37**neutrons [38].



Laser driven neutron sources
High peak neutron flux Neutrons/cm^2/s

I. Pomerantz, et al. Phys. Rev. Lett. 113, 184801 (2014)



New horizons with ELI-NP

Fission-fusion
Inverse capture reactions
s and p and r-processes
NRF, Dipole Response, GR&PDR
Level density ….

→ Astrophysics, Nuclear Physics

Gamma Imaging — Nuclear Security
Material Science — Fusion Reactor Eng.
Medical Isotopes — Cancer Therapy

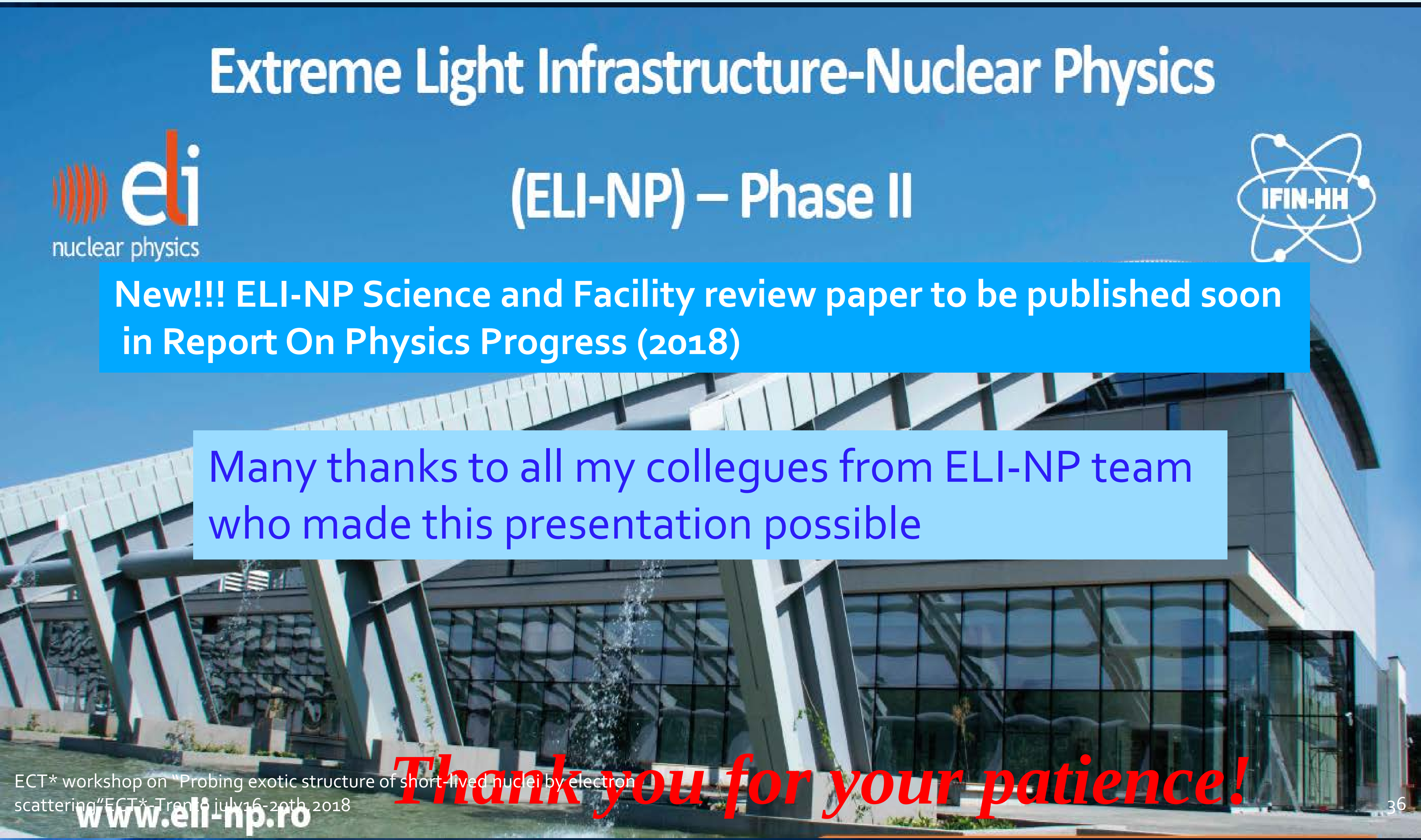
"Go East"

Very attractive science and large discovery potential at reach at the interface of High power laser , plasma , accelerator and nuclear physics

Project co-financed by the European Regional Development Fund through the Competitiveness Operational Programme
"Investing in Sustainable Development"

Extreme Light Infrastructure-Nuclear Physics

(ELI-NP) – Phase II



New!!! ELI-NP Science and Facility review paper to be published soon in Report On Physics Progress (2018)

Many thanks to all my collegues from ELI-NP team who made this presentation possible

Thank you for your patience!