Nuclear astrophysics at ELI-NP

or «conditions created by one
Extreme**L**y hot **I**nfrastructure for **N**uclear astro**P**hysics»

Livius Trache

with material from N.V. Zamfir, I.I. Ursu, P. Thirolfs,
ELI-NP workshops participants et al.

IFIN-HH Bucharest-Magurele

11th Russbach School on Nuclear Astrophysics
9-15 March 2014 Russbach (Austria)

Summary

1. Nuclear physics for astrophysics (NPA)
   - Direct measurements
   - Indirect methods – radioactive nuclear beam
2. ELI-NP in Bucharest – presentation
3. ELI-NP: RIB production
4. ELI-NP: stellar plasmas

1 Nuclear Physics for Astrophysics

NPA: study in the lab nuclear reactions that happen(ed) in the stars – which are cold

- Low energies => low cross sectios: nb, pb, … fb!
- exotic partners (unstable)

a) Direct measurements: very low rates (=> w stable beams so far)
   - high intensities
   - high detection efficiency
   - selectivity
   - reduced background

b) Indirect methods – with stable beams and radioactive beams

   A. Coulomb dissociation

   B. Transfer reactions (ANC method)

   C. Breakup of loosely bound nuclei

   D. Spectroscopy of resonances: β-decay, β-delayed proton decay, transfer reactions, resonant elastic scatt., etc

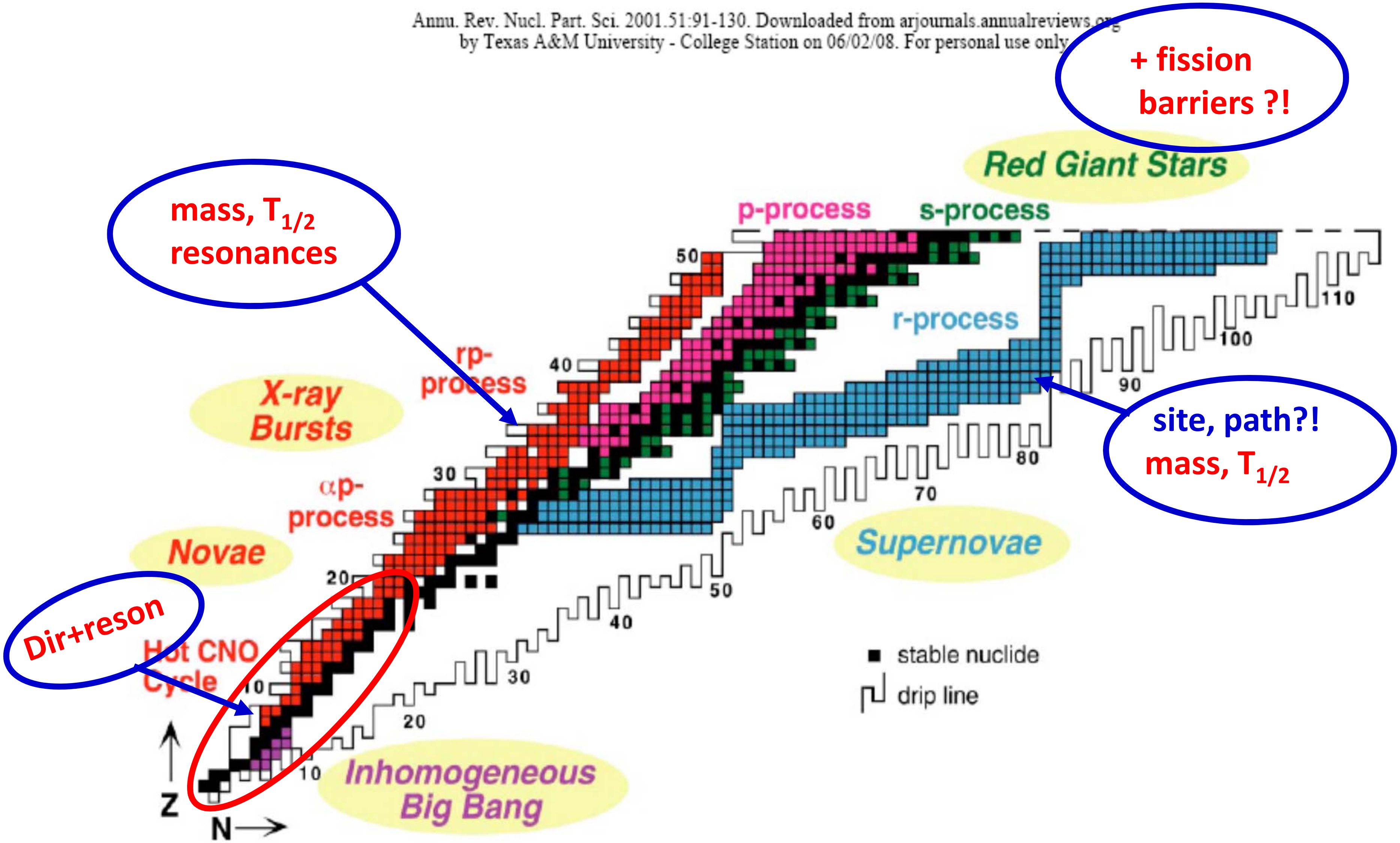
      Decay spectroscopy

      Any spectroscopy …

   E. Trojan Horse Method

   - …

M. Smith & E. Rehm

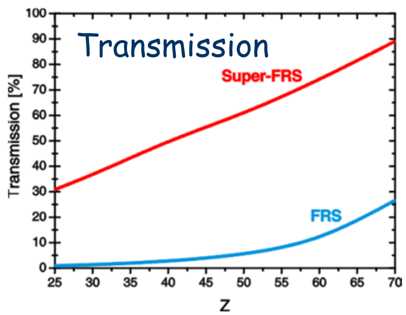


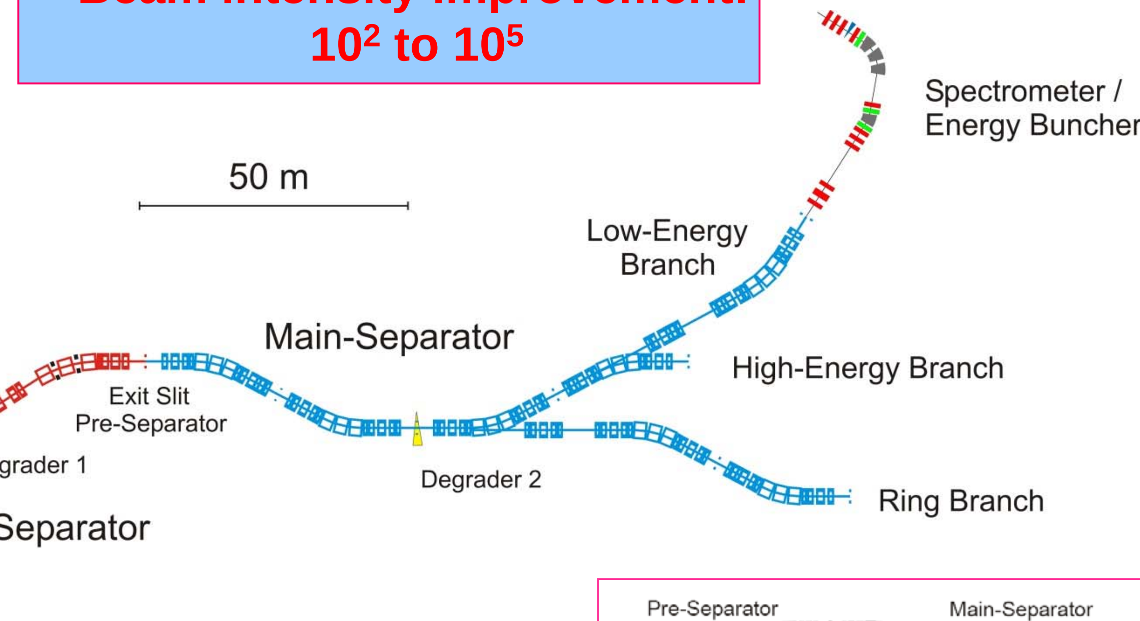
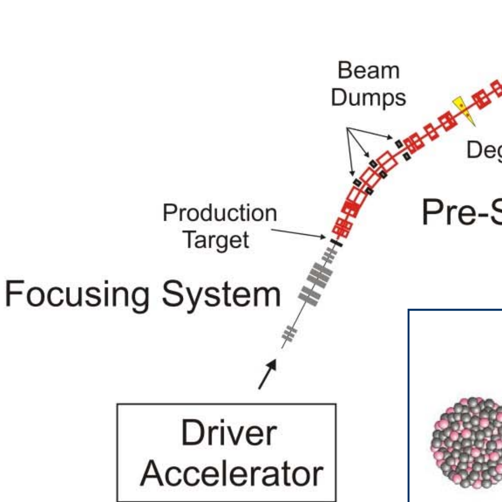
Two big problems:

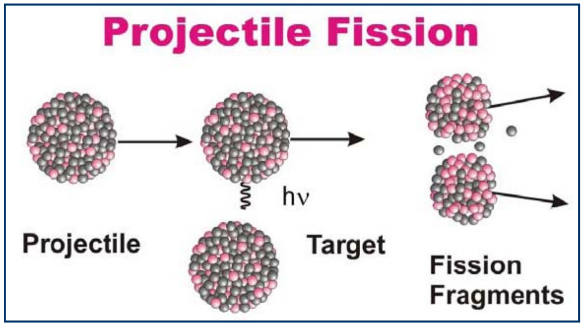
1. **- reactions in stars involve(d) radioactive nuclei ⇒ use RNB**
2. **- very small energies and very small cross sections ⇒indirect methods**

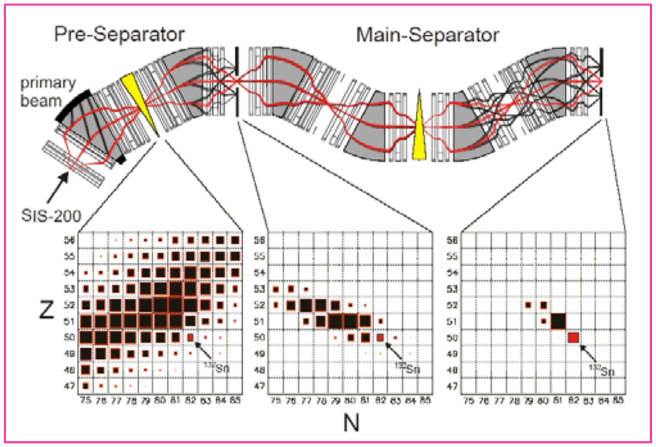
Superconducting **FR**agment **S**eparator at FAIR

Beam intensity improvement:
10^2 to 10^5



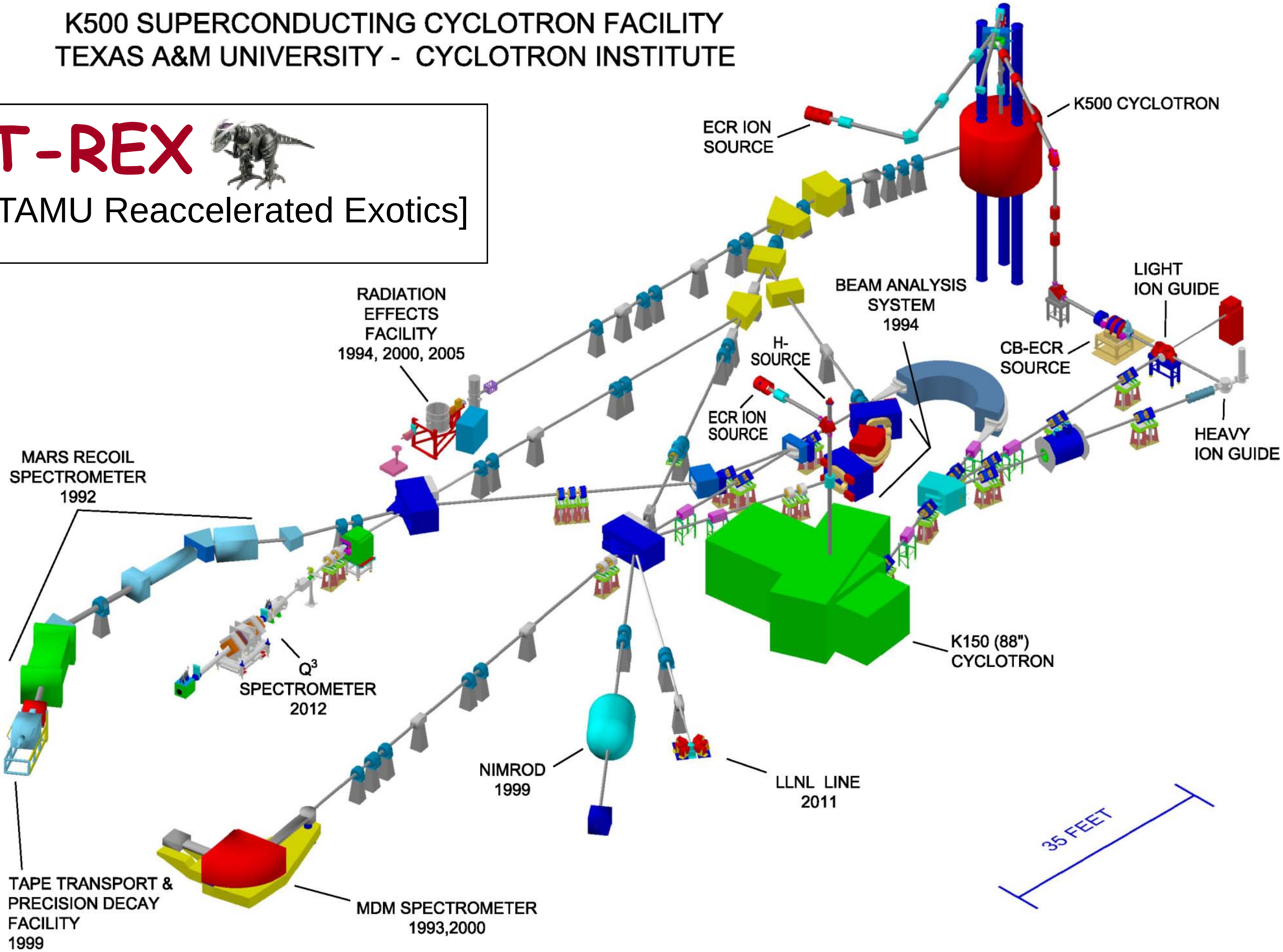




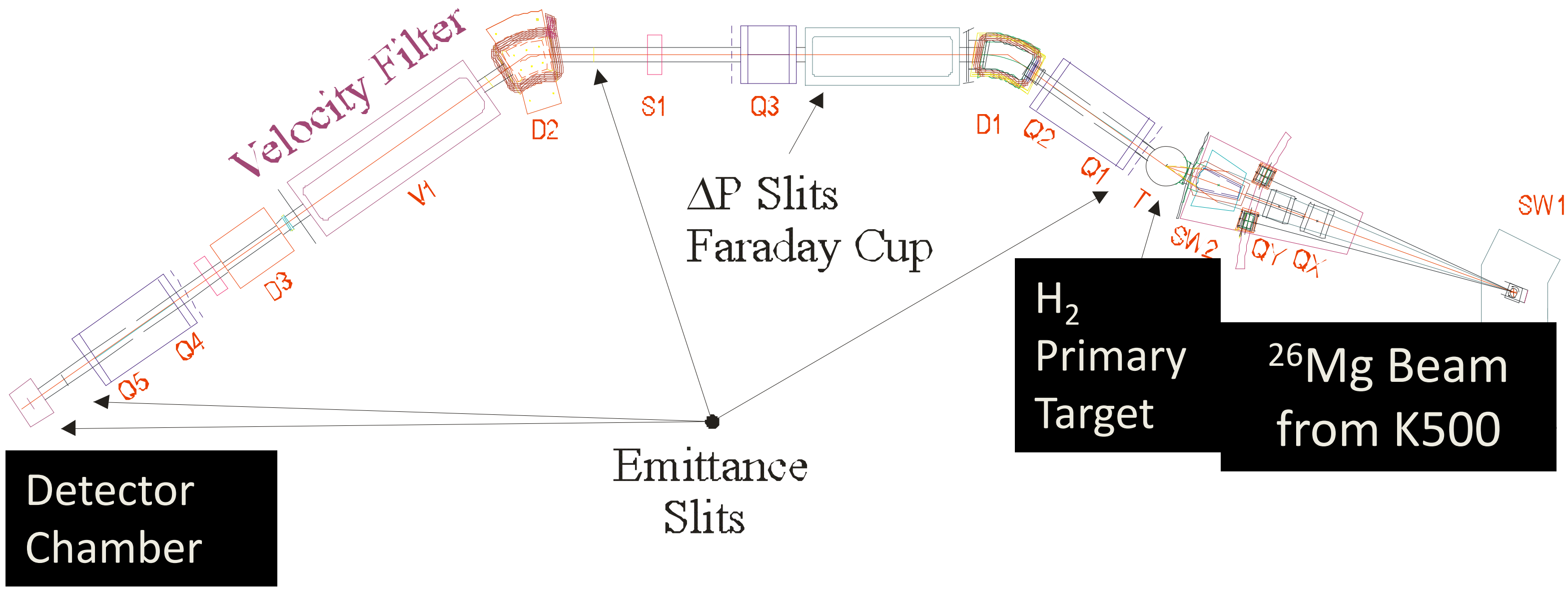
K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE

T-REX

[TAMU Reaccelerated Exotics]

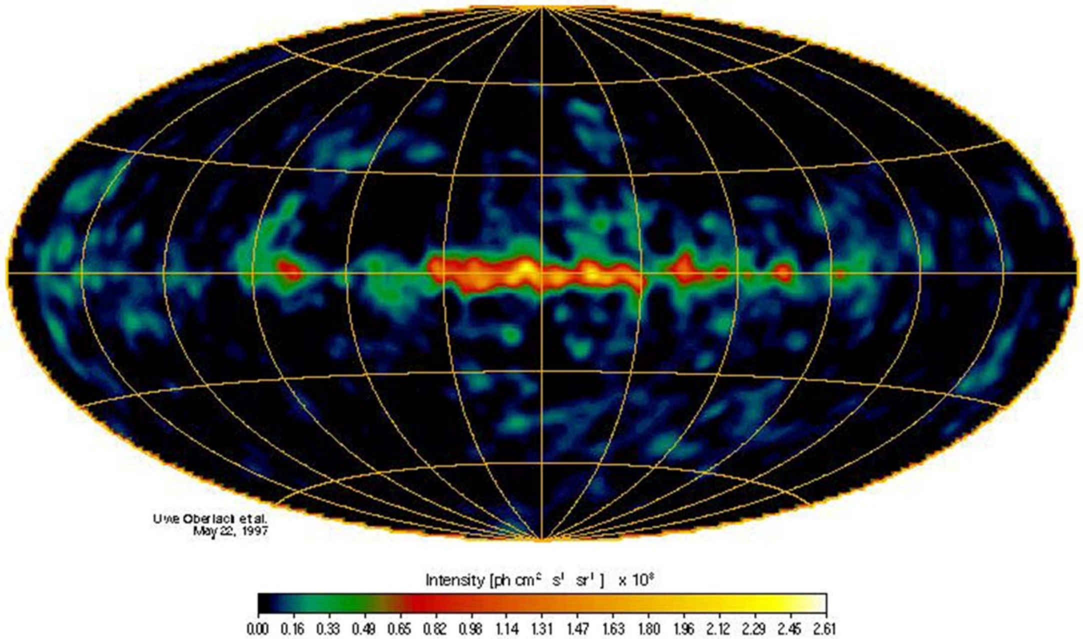


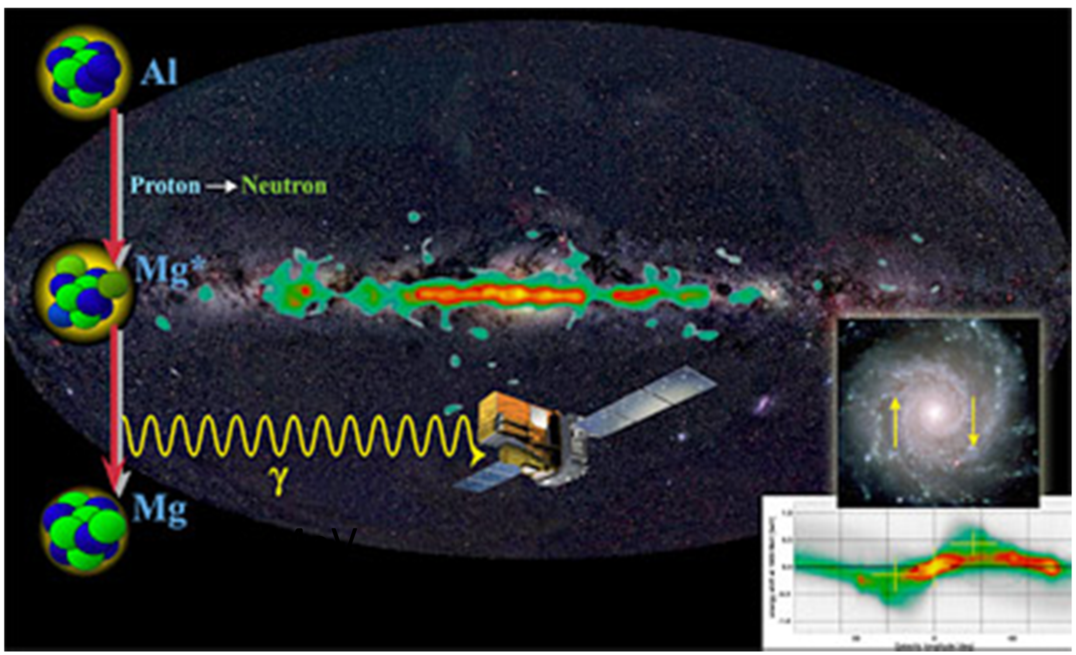
MARS spectrograph



- ^{26}Mg primary beam from K500 at 16 MeV/u.
- Produce ^{26}Al beam with ^{26}Mg(p,n) reaction.
- Refocus Beam in detector chamber on CD_2 target.
- Separation by production mechanism:
  - Fusion-evaporation: 3×10^6 pps 67% ^{26}Al gs
  - Transfer (charge exchange (p,n)): 3×10^5 pps, 67% ^{26m}Al

Motivation: cosmic production of ^{26}Al, ^{26m}Al





Galactic images with Comptel and Integral

- Satellites detect 1.8 MeV gamma ray from ^{26g}Al β-decay.
- Lifetime of ^{26g}Al is $7.2*10^5$ yrs. For ^{26m}Al is 6.2 sec.
- Gives evidence of ongoing Nucleosynthesis in stars in the galaxy.
- Want to understand production and destruction of nuclei like ^{26}Al in stars – maybe ^{26m}Al (0^+) is important?

Destruction of ^{26}Al

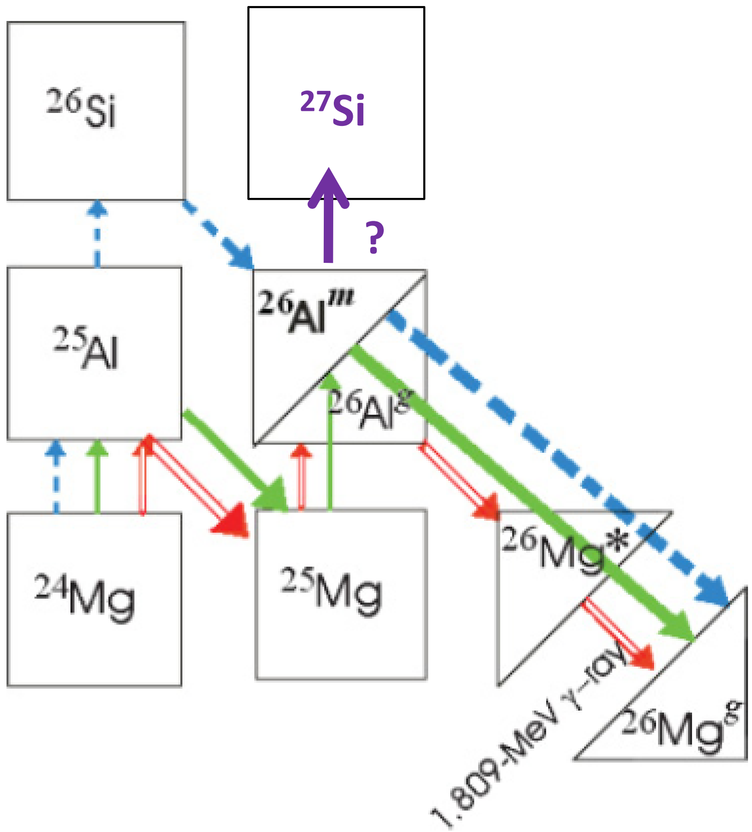
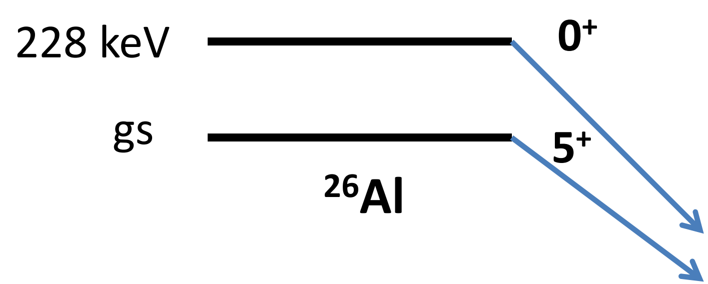


Figure: C.M. Deibel et al. PRC 80

- Satellites detect less 1.8 MeV γ-rays than expected.
- In astrophysical environment (0.1 GK < T < 0.4 GK → 100 keV < E_{CM} < 600 keV) ^{26}Al can also be destroyed by ^{26}Al(p,γ).
- Try to investigate levels of interest for ^{26m}Al(p,γ) and ^{26g}Al(p,γ) by studying IAS states in ^{27}Al with ^{26}Al(d,p) reaction.



2

Extreme Light Infrastructure - Nuclear Physics ELI – NP

Bucharest-Magurele, Romania

Project leader: Nicolae-Victor Zamfir

Bucharest-Magurele, Romania

Extreme Light Infrastructure

2006 – ELI on ESFRI Roadmap

ELI-PP 2007-2010 (FP7)

- ELI-Beamlines (Czech Republic)
- ELI-Attoseconds (Hungary)
- ELI-Nuclear Physics (Romania)

Project Approved by the European Competitiveness Council (December 2009)

ELI-DC (Delivery Consortium): April 2010

Bucharest: June 2013 – civil constr start

Nuclear Physics

ROMANIA FOR ELI
www.eli-np.ro

ANCS

IFIN-HH

Extreme Light Infrastructure – Nuclear Physics (ELI-NP)

•A chance for Romania to havethe most powerful laser system and the most brilliant gamma beams in the world at the level of 2015 for 280 MEuro from EU Structural Funds.

ELI will be an European Research Infrastructure for high-level research on ultra-high intensity lasers and laser-matter interaction.

ELI will have 4 pillars:

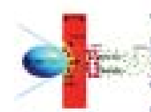
- ELI – Attoseconds in Szeged (Hungary)
- ELI – Beamlines in Prague (Czech Republic)
- ELI – Nuclear Physics in Magurele (Romania)
- ELI – High Fields (to be decided in 2012)

ELI-NP 20 PW Laser

Two synchronized arms of 10 PW (200 J / 20 fs) with:
- 0.02 Hz repetition rate
- OPCPA Front-End
- Ti:Sapphire amplification

Astra-Gemini system in operation at CLF (Central Laser Facility) in Oxfordshire, UK

ELI-NP Research



Fundamental

- Understanding laser-driven acceleration mechanism
- Exotic nuclei and astrophysics studies
- Vacuum properties and particle creation in laser-gamma beams interactions
- Materials under ex-treme irradiation

Applicative

- Management of Nuclear Materials
- Industrial tomography
- Brilliant positron and neutron sources for materials/processes characterization

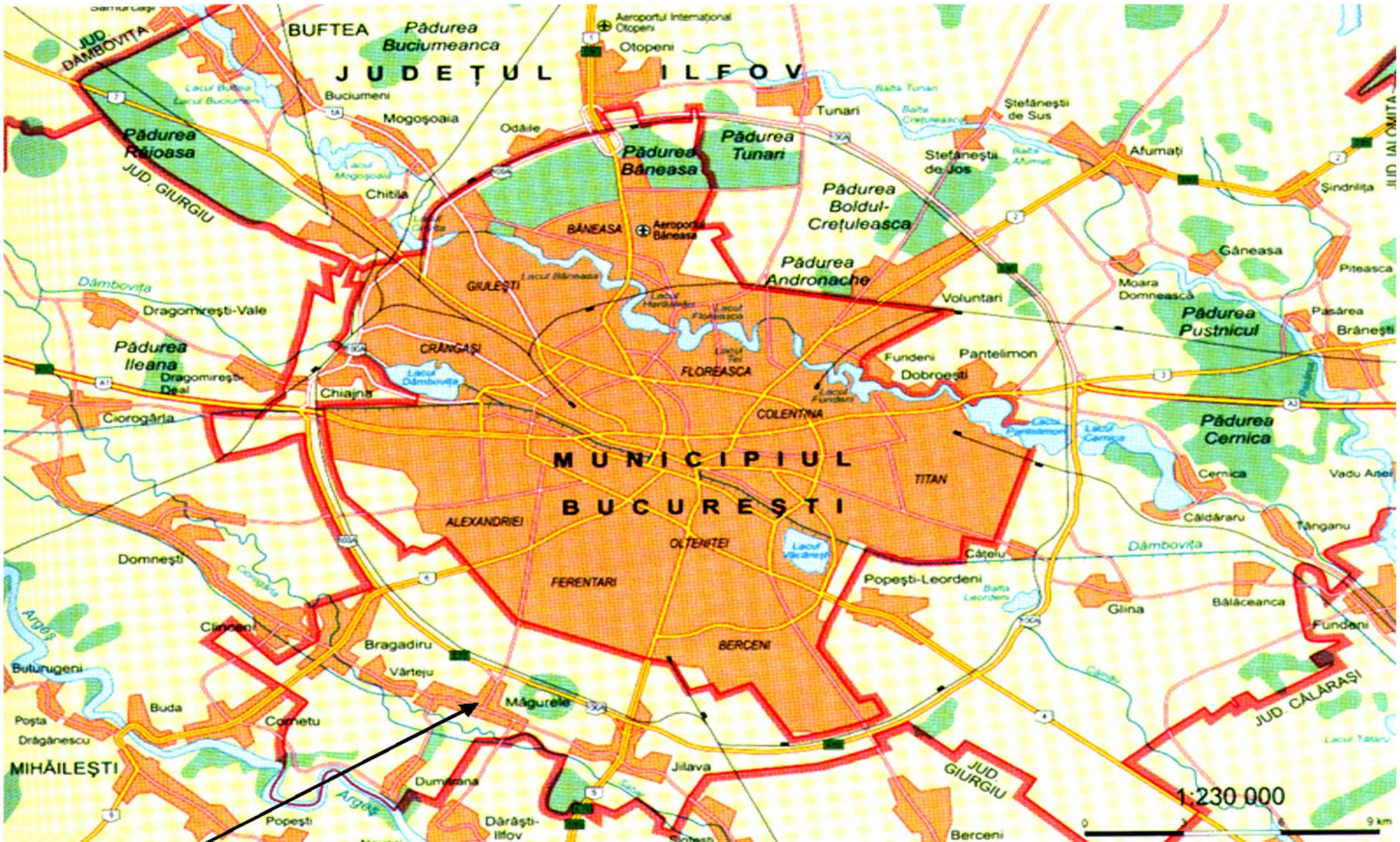
ELI-NP γ-beams

Max. γ energy: 19 MeV
Total flux: 10^{13} photons/sec
Bandwidth: 0.1%

Production method:
light photons (10 J laser) scattered on high energy electrons (600 MeV linear accelerator)

T-REX facility at Lawrence Livermore National Laboratory (SUA)

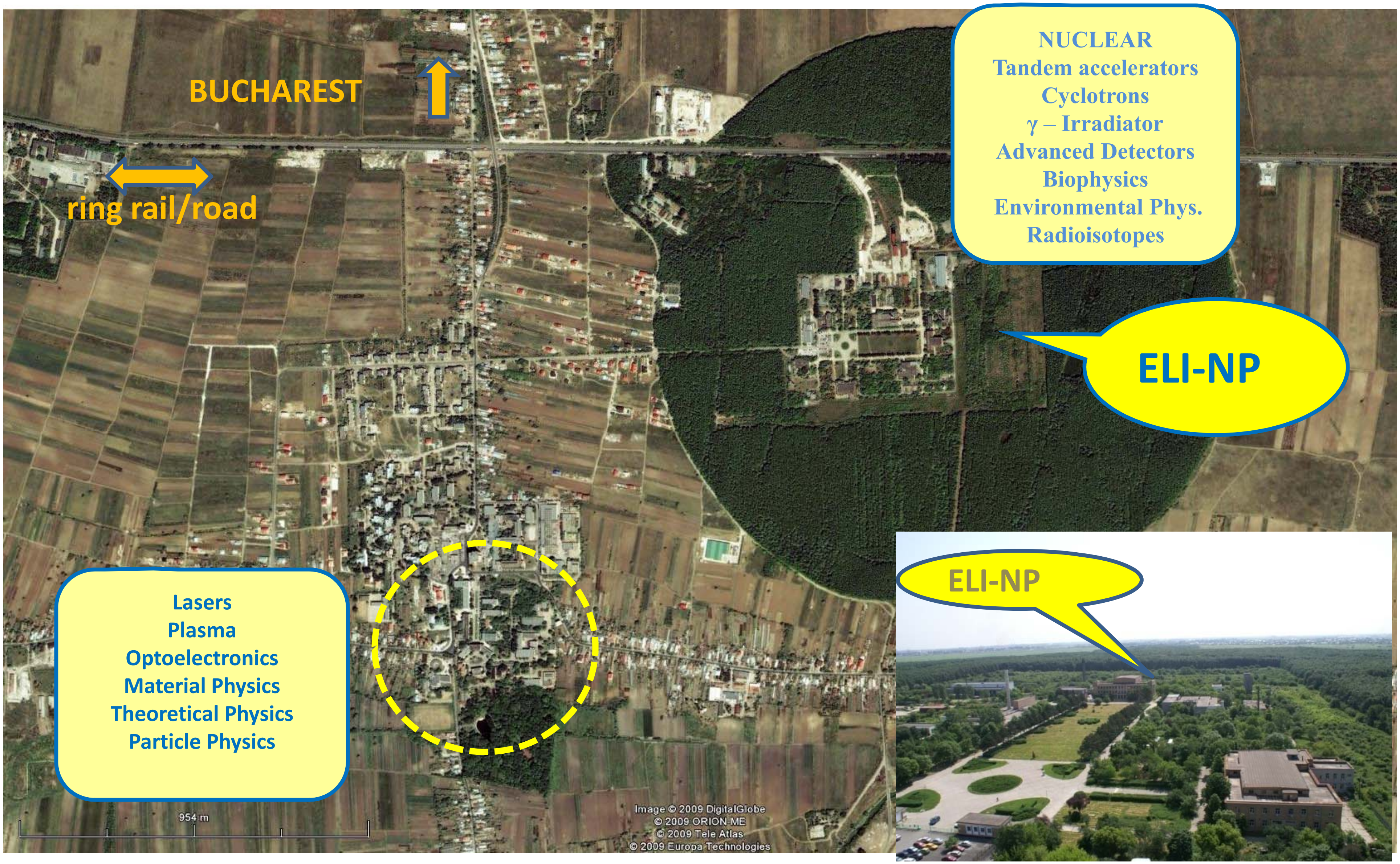
Bucharest – Magurele Physics Institutes



Magurele

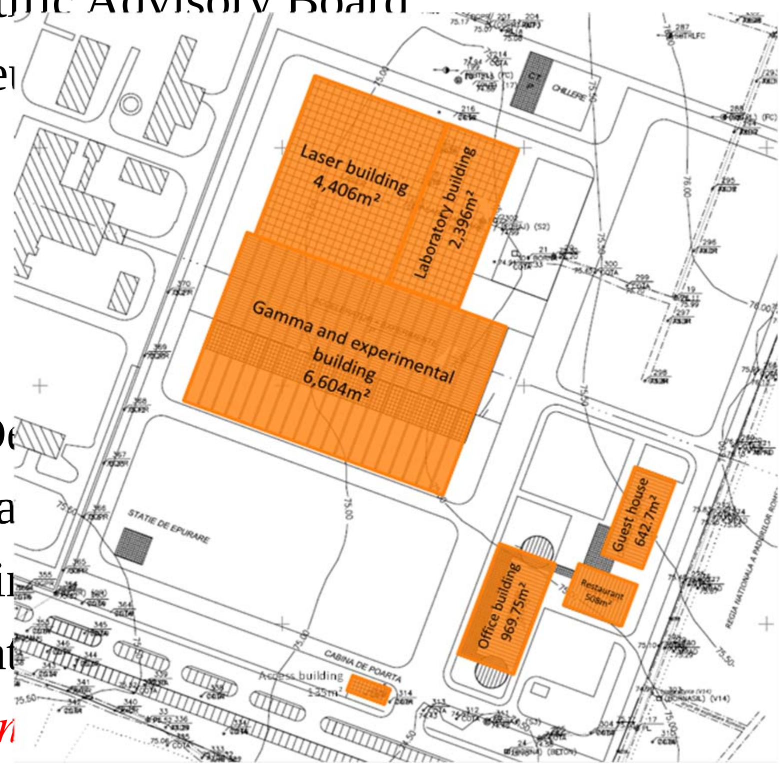
Nuclear Physics

Bucharest-Magurele National Physics Institutes



ELI-NP "Start-up" Activities

- **February-April 2010**
  Scientific case **"White Book"** (100 scientists, 30 institutions) (www.eli-np.ro)
  approved by ELI-NP International Scientific Advisory Board
- **August 2010:** Feasibility Study: 293 Me
  - Buildings: 60 M€
  - Lasers: 60 M€
  - Gamma Beam: 60 M€
  - Beam Transport 20 M€
  - Exp. equipments: 30 M€
- **August 2011 – March 2012:** Technical De
- **January 2012:** Submission of the applica
- **July 2012:** Government Decision approvi
- **September 2012**: Approval of the applicat
- ***June 14, 2013:** Foundation stone ceremon*
- ***March 2014:** all components contracted, work started*



ELI-Nuclear Physics

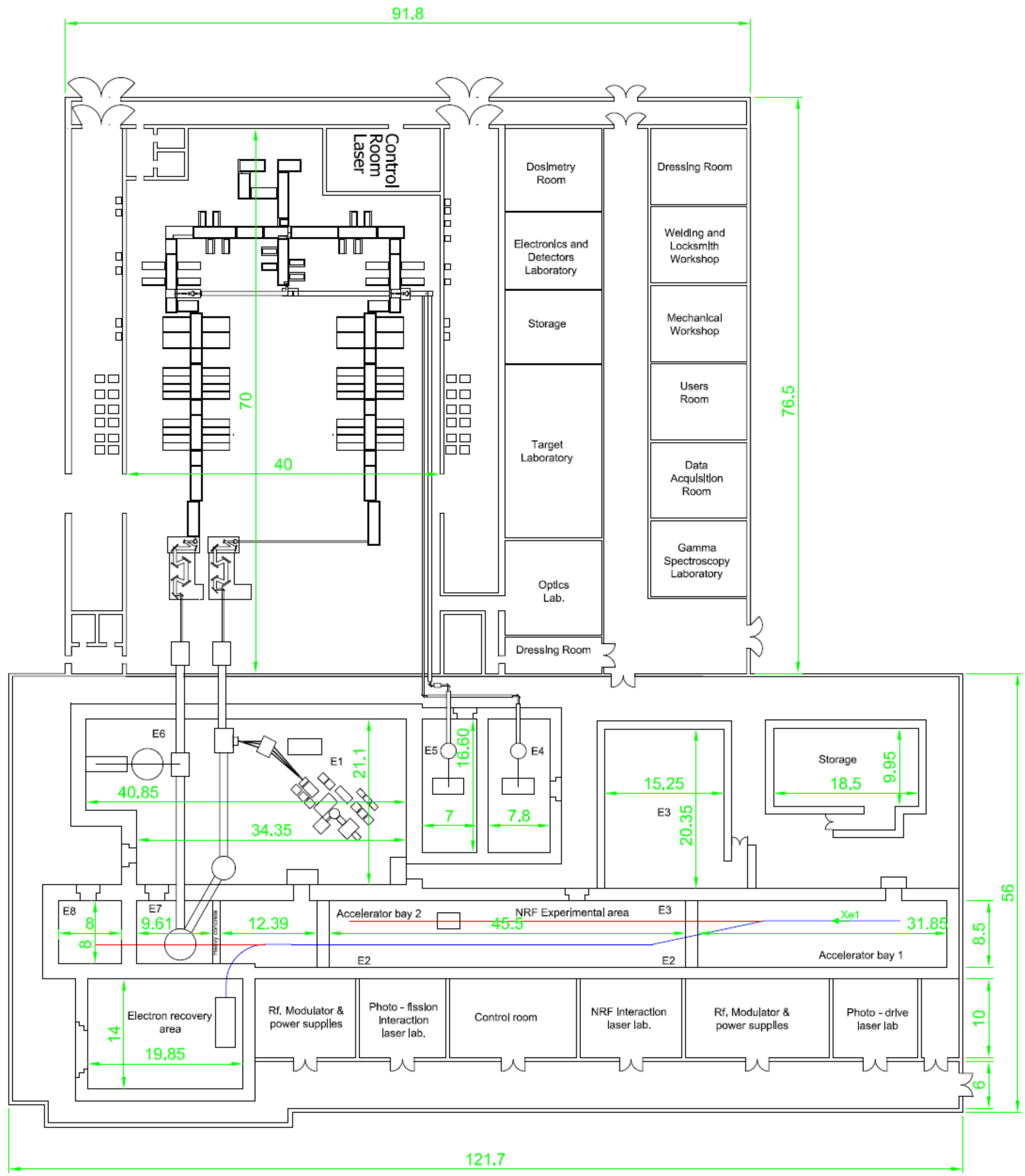
"Extreme Light" :

- *two 10 PW APOLLON-type lasers*

- *brilliant γ beam, up to 20 MeV, BW:0.1% produced by Compton scattering of a laser beam on a 700 MeV electron beam*

ELI-NP
Main buildings

- Lasers
- Gamma
- experiments
- Laboratories

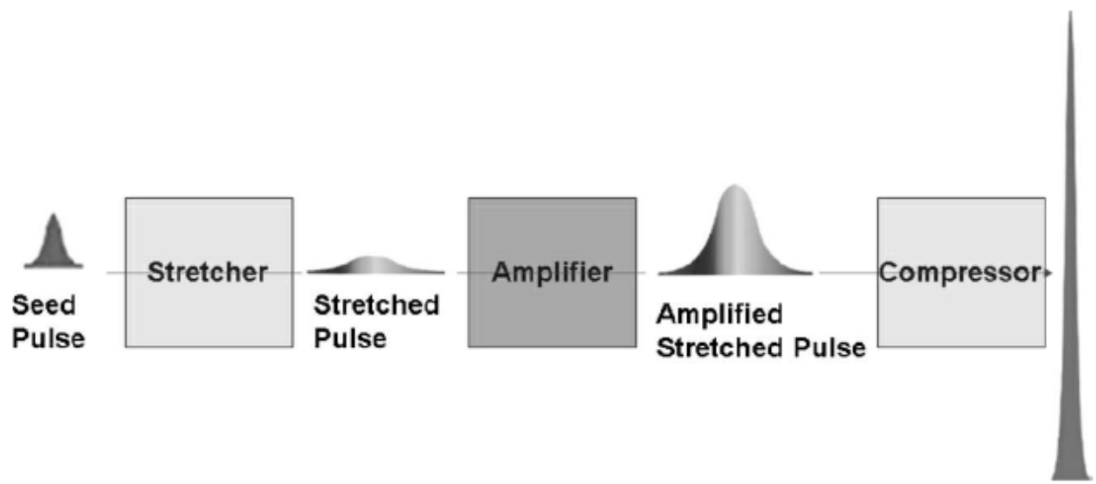


Chirped Pulse Amplification (CPA)

Idea: to stretch (and chirp) a fs pulse from an oscillator (up to 10,000 times), increase the energy by linear amplification, and thereafter recompress the pulse to the original pulse duration and shape

During amplification, the laser intensity is significantly decreased in order

- to avoid the damage of the optical components of the amplifiers;
- to reduce the temporal and spatial profile distortion by non-linear optical effects during the pulse propagation



ELI-NP Next Steps

- *January 2012: Submission of the Application to DG-Regio*
- *July 2012: Romanian Government Approval*
- *August 2012: Tender Procedures start*

- *November 2012- end 2014: Civil Construction*
- *July 2015 : Lasers and Gamma Beam – Phase 1*
- *December 2016 : Lasers and Gamma beam Phase 2*
- *2013-2015: TDR for experiments*
- *2016-2018: experimental set-ups*
- *2018: beginning of operation*

ELI – Nuclear Physics Research

- *Nuclear Physics experiments to characterize laser – target interact.*
- *Photonuclear reactions – most brilliant γ-beam, good resol.*
- *Exotic Nuclear Physics and Astrophysics -* ***complementary to other NP large facilities*** ***(FAIR, SPIRAL2, EURISOL)****.*
- *Applications based on high intensity laser and very brilliant γ beams.*

Complementary to the other pillars

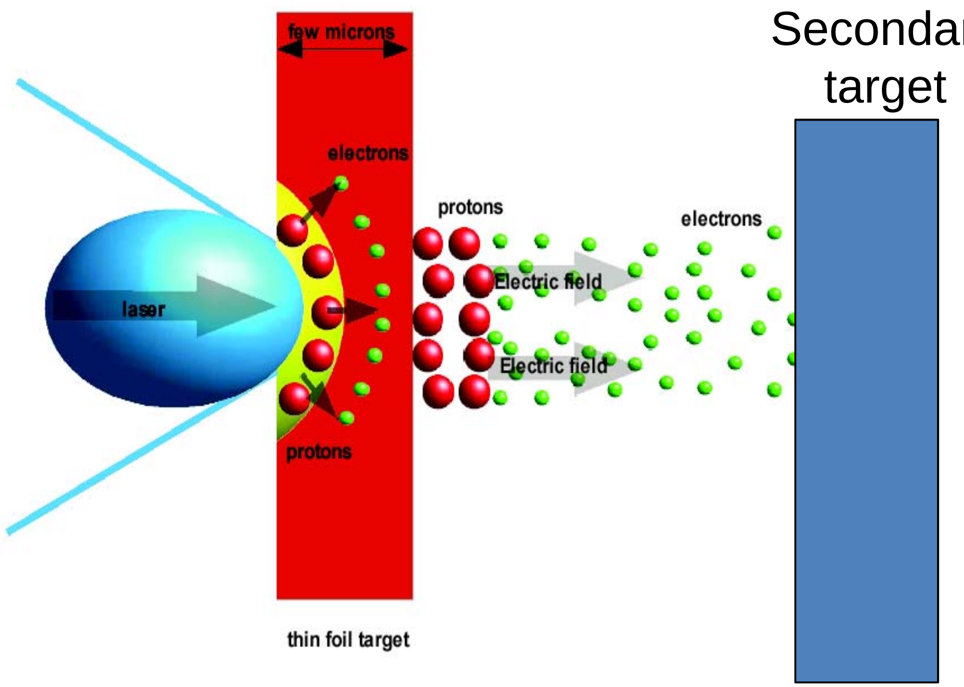
ELI - Nuclear Physics

*in '**Nuclear Physics Long Range Plan in Europe**' as a major facility*

3

Nuclear Astrophysics:
RIB production & ELI-NP

Target Normal Sheath Acceleration (TNSA)



Secondary radiations
- electrons bremssstrahlung
- gamma rays, neutrons

Primary radiations

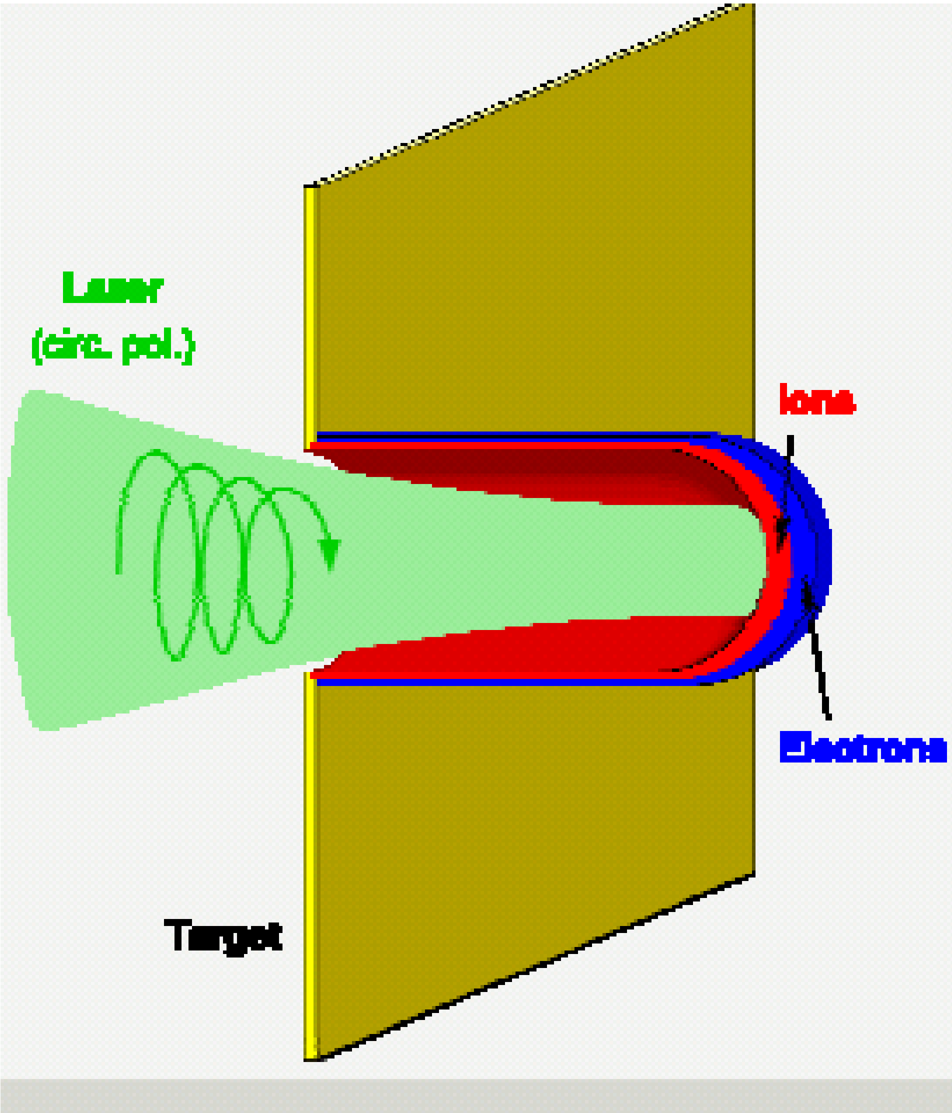
Electrons are expelled from the target due to the ponderomotive force

Heavy ions are accelerated in the field created by the electrons

$E \sim I_{laser}^{1/2}$

S.C. Wilks et al., Phys. Plasmas **8**, 542 (2001).

Radiation Pressure Acceleration RPA



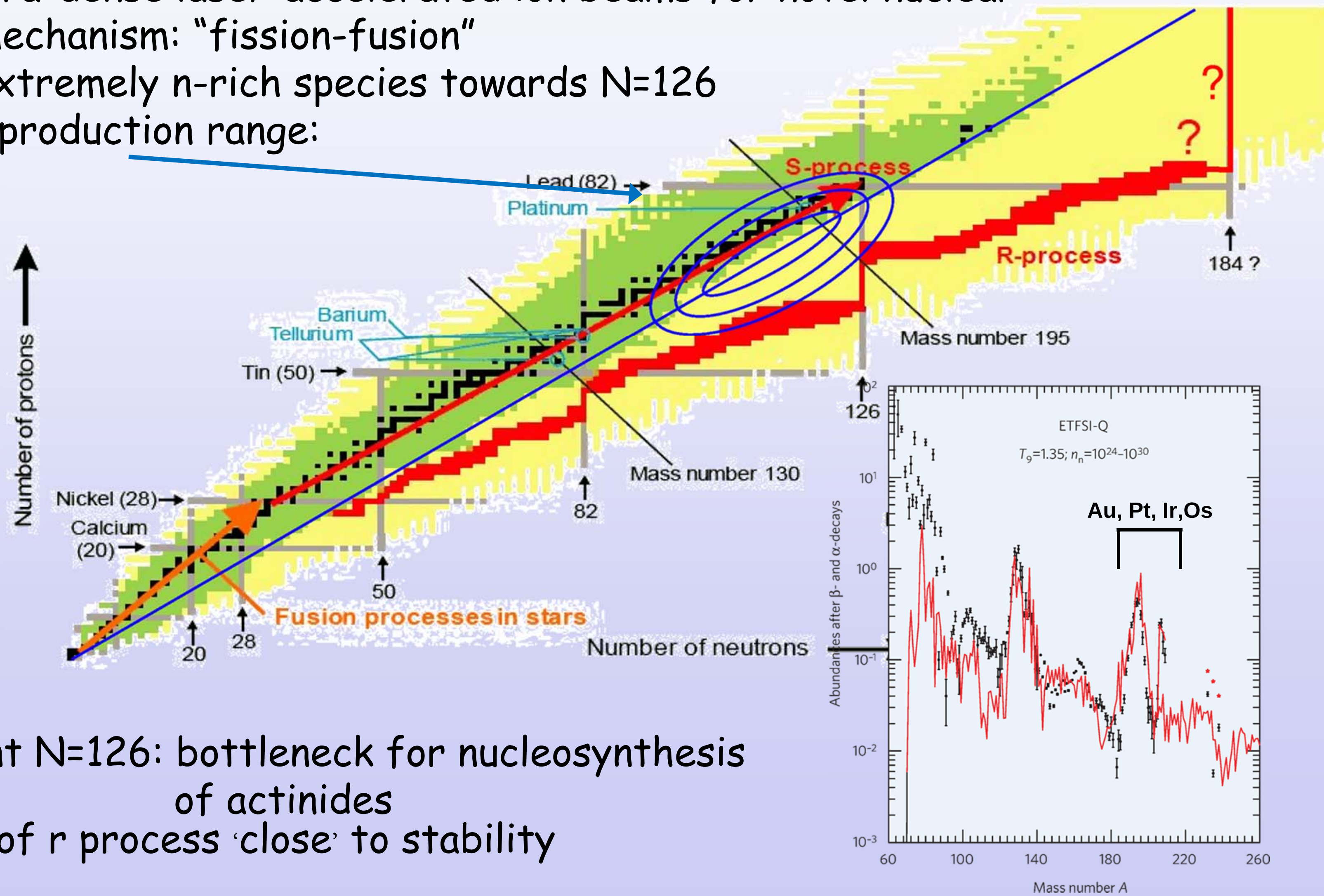
Electrons and ions accelerated
at solid state densities 10^{24}e cm^{-3}
(Classical beam densities 10^{8}e cm^{-3})

$E \sim I_{laser}$

Production of Extremely Neutron-Rich Isotopes

LoI: P. Thirolf et al. (LMU Munich)

- motivation:
  - exploit ultra-dense laser-accelerated ion beams for novel nuclear reaction mechanism: “fission-fusion”
  - produce extremely n-rich species towards N=126
  - expected production range:

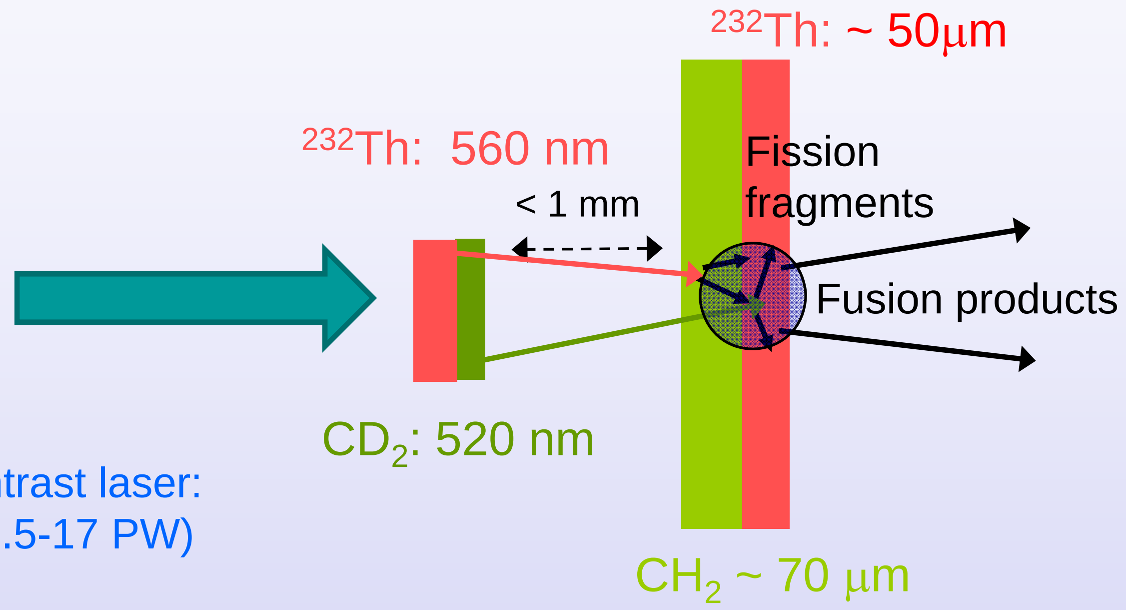


- waiting point N=126: bottleneck for nucleosynthesis of actinides
- last region of r process ‘close’ to stability

Exp. Scheme for "Fission-Fusion"

Production target **Reaction target**

conventional stopping:

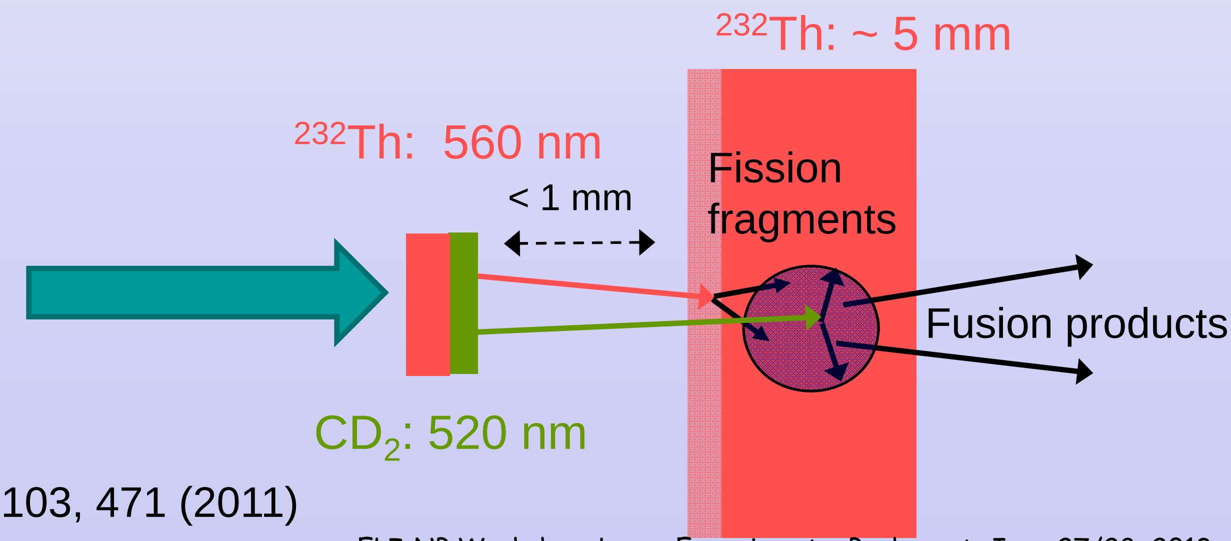


high-power, high-contrast laser:
150-300 J, ~32 fs (8.5-17 PW)

$1.2 \cdot 10^{23}$ W/cm^2

focal diam. ~ 3 µm

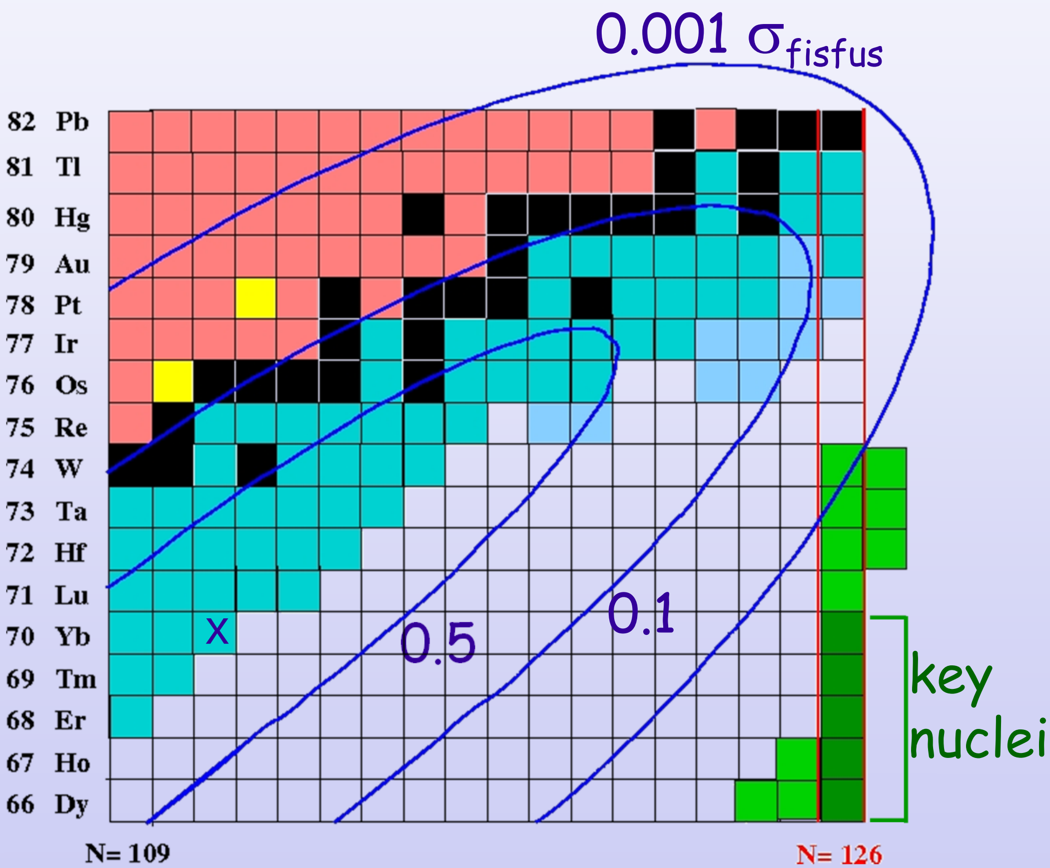
collective stopping:



D. Habs, PT et al., Appl. Phys. B 103, 471 (2011)

Towards N=126 Waiting Point

- r process path:
  - known isotopes ~15 neutrons away from r-process path (Z≈ 70)



- measure:
  - masses, lifetimes, structure
  - lifetime measurements: already with ~ 10 pps

- visions:
  - test predictions: r process branch to long-lived (~ 10^9 a) superheavies (Z≥110) → search in nature ?
  - improve formation predictions for U, Th
  - recycling of fission fragments in r-process loops ?

Nuclear Astrophysics - Indirect methods
1. with RIBs: Steps at ELI-NP

- RNB production: mechanism $\rightarrow$ study production w. spectrometer(s), w. gas-filled separator ?!
- RNB separation – momentum achromat + velocity filter ?!
- Secondary beam preparation – Filters?! Reacceleration?!
- Secondary reaction – target station
- Detection – complex array(s): gas, Si, γ, PID, position sensitive, …
- Extract NS information - difficult theory calc: structure and reactions
- (Normalization) - may need absolute values from elsewhere
- NA interpretation - theory support again!
- Comparison with direct measurements/ normalization – develop strong program of direct measurements at the 3 MV tandetron

ISOL (currently)

ISOL (future)

In-Flight (currently)

In-Flight (future)

4

2. Laser-induced "stellar plasma"?!

- Short-lived plasmas w conditions similar to stellar plasmas?!
  - Characterization
  - Nuclear astrophysics: capture reactions on excited states – very imp for quantitative descr of stellar nucleosynthesis, but out of the range of our current experimental possibilities. Can we…?!!
  - How?! What setups?!

CETAL – 1 PW laser to work in 2014, in Bucharest!!!

Topics so far …

- NA proposals
  - NA in the neutron channel (Utsunomyia)
  - NA with gamma-ray beams (Ugalde et al.)
  - NA with γ-ray beams and OTPC (M. Gai et al)
  - Study on n-rich in the r-proc path (P. Thirolfs, Habs, …)
  - (γ, γ'n) reactions (K. Sonnabend et al)
  - Active target TPC (C. Mazzocchi, M. Pfuetzner e.a.)
  - Laser induced rections (A Bonasera, Anzalone, L. T., …)
  - Indirect reactions with RIBs (Catania group, LT, etc)
  - …

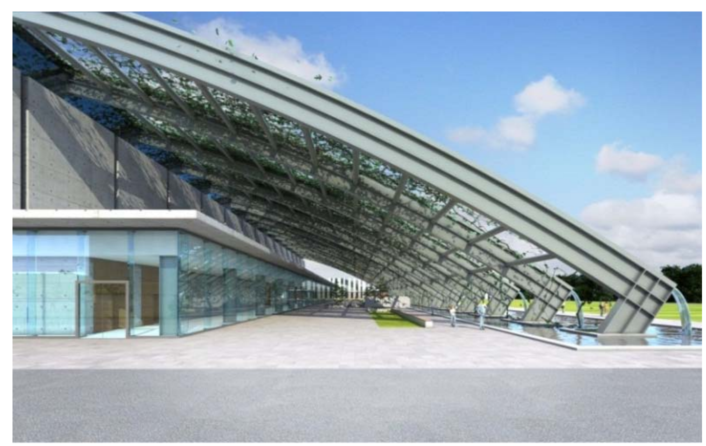
Conclusions: Expected Impact of ELI-NP

European laboratory to consistently investigate a very broad range of science domains, from new fields [obscured] f fundamental physics, new nuclear physics and astrophysics topics, to applications in material science, life sciences and [obscured] materials management.

- World-class research infrastructure
 (+200 positions of researchers)
- Education – high-level training
in science and engineering
- Increasing employment opportunities
in research, decreasing brain drain
- Knowledge and technology transf[...]
as a primary objective, collabo[...]
the local for-profit sector [...]earch);
significant expectati[...]ional Patents
- Positive d[...] effects on
the loca[...]conomic environment
– [...] frontier research for companies,
 s[...] effects on high-tech industries

Message from Bucharest: we are hiring!

Time past and time future
What might have been and what has been
Point to one end, which is always present
T.S. Eliot: Burnt Norton (I), Four Quartets (1943)



Status right now (March 2014):

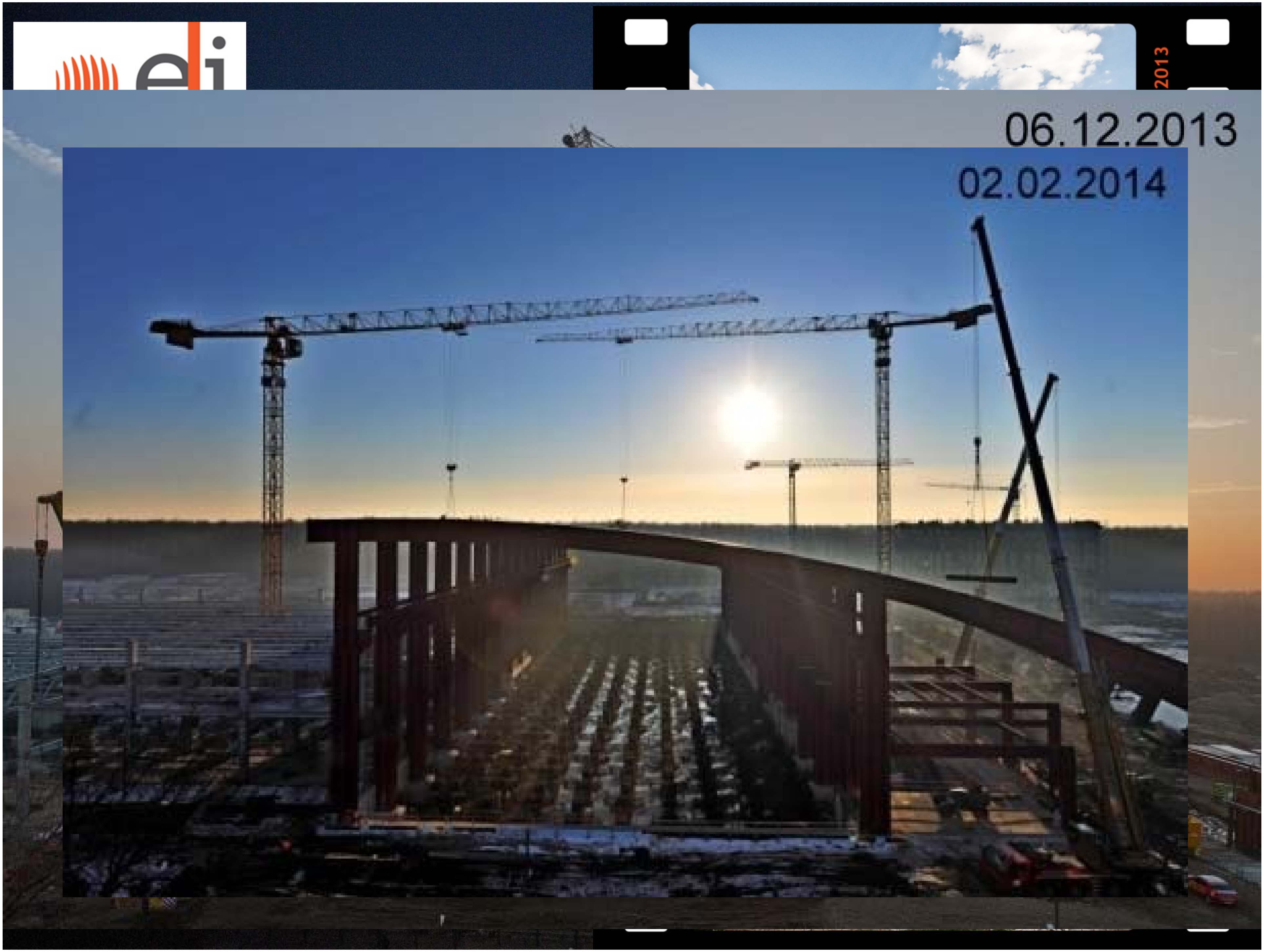
- ELI-NP activities going on:

  Civil construction

  Lasers

  Gamma-ray source – to be signed next week!

  TDR (Techn Design Report) under preparation for experiments and equipment
- ELI-NP workshops:
  - April 2-4 experiments with lasers
  - April 16-17 experiments with gamma-ray beam


2013
06.12.2013
02.02.2014

Status right now (March 2014):

- ELI-NP activities going on:

  Civil construction

  Lasers

  Gamma-ray source – to be signed next week!

  TDR (Techn Design Report) under preparation for experiments and equipment

- ELI-NP workshops:
  - April 2-4 experiments with lasers
  - April 16-17 experiments with gamma-ray beam

Carpathian Summer School of Physics
Sinaia, Romania, July 13-26, 2014

livius.trache@nipne.ro
cssp14@nipne.ro

Website **http://cssp14.nipne.ro**


Thank you!