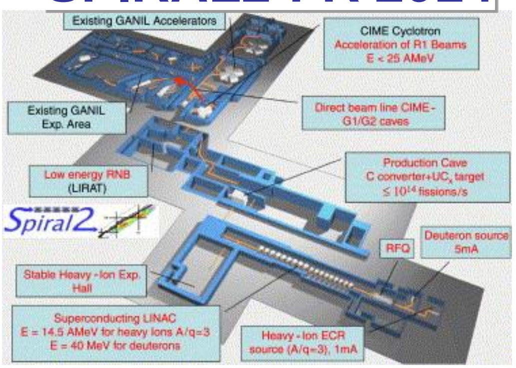
Les nouvelles frontières de la physique nucléaire

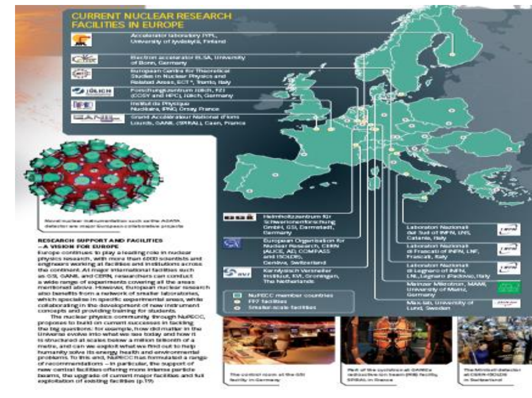
FAIR –DE 2018

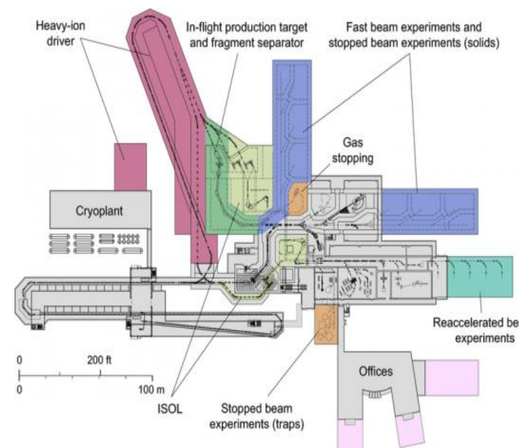
SPIRAL2-FR 2014



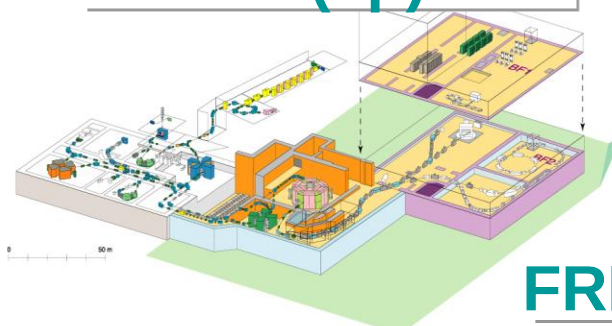
ELI-NP-Ro 2017

NuPECC LRP2010 Recommendations- June 2010





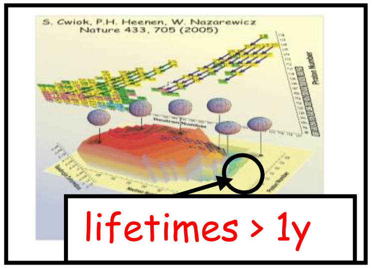
RIKEN (Jp)2007



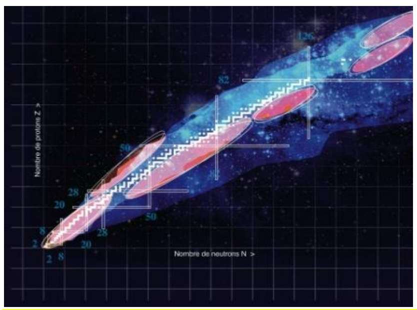
FRIB NSCL-USA 2019

Nuclear Structure, Nuclear Astrophysics and Reactions

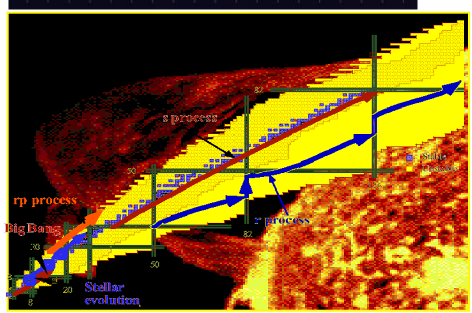
Key Questions



What are the limits of the heaviest elements?



What are the limits of stability ?
Exploration of terra incognita, neutron rich region, haloes and skin, elusive magic numbers, new decays, new shapes, EOS and symmetry



How the elements are made in the Universe

Nuclear Astrophysics

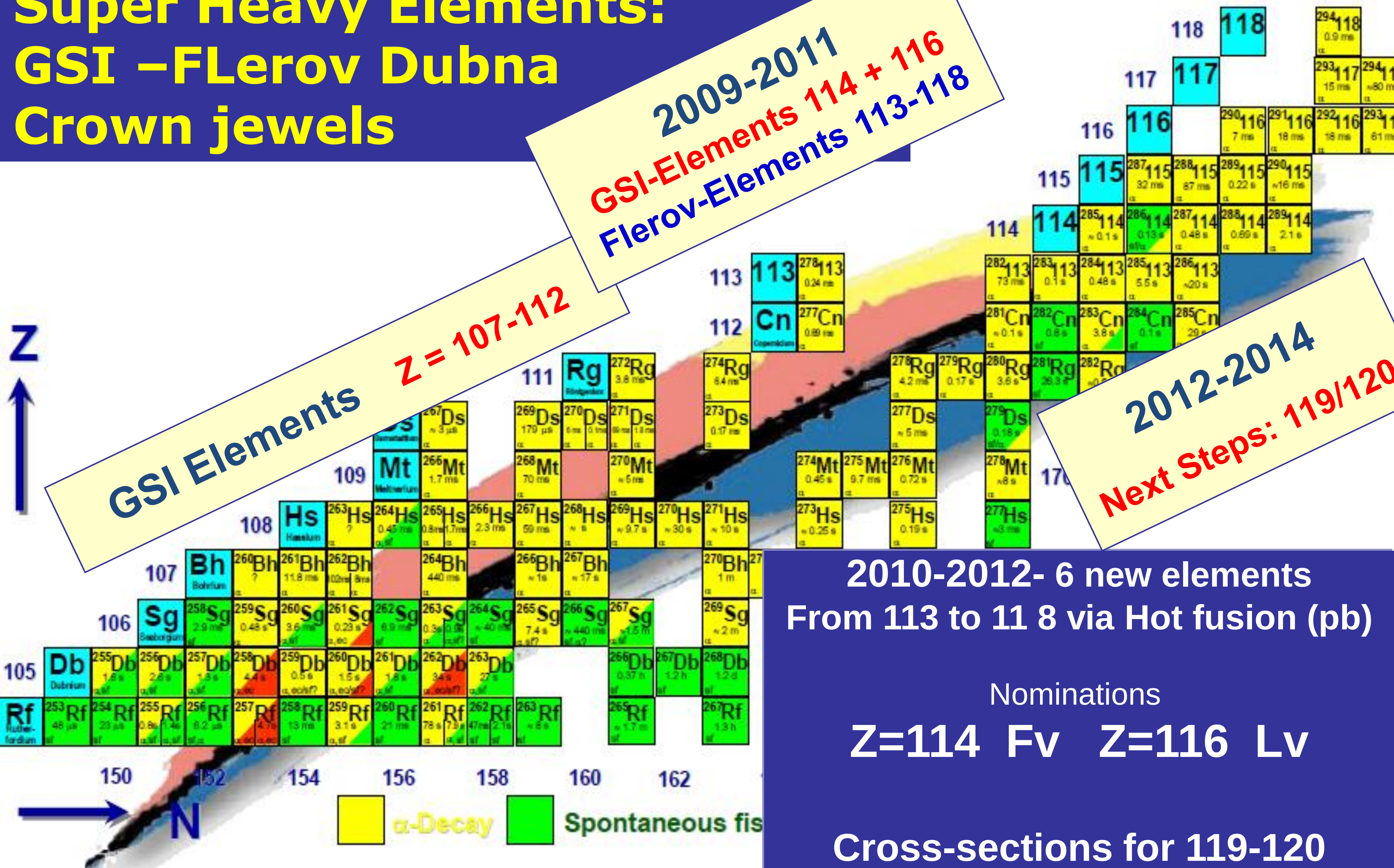
The nucleus ,a laboratory to study Fundamental interactions- High precision experiments

Super Heavy Elements: GSI –FLerov Dubna Crown jewels

2009-2011
GSI-Elements 114 + 116
Flerov-Elements 113-118

GSI Elements Z = 107-112

2012-2014
Next Steps: 119/120



2010-2012- 6 new elements
From 113 to 11 8 via Hot fusion (pb)

Nominations

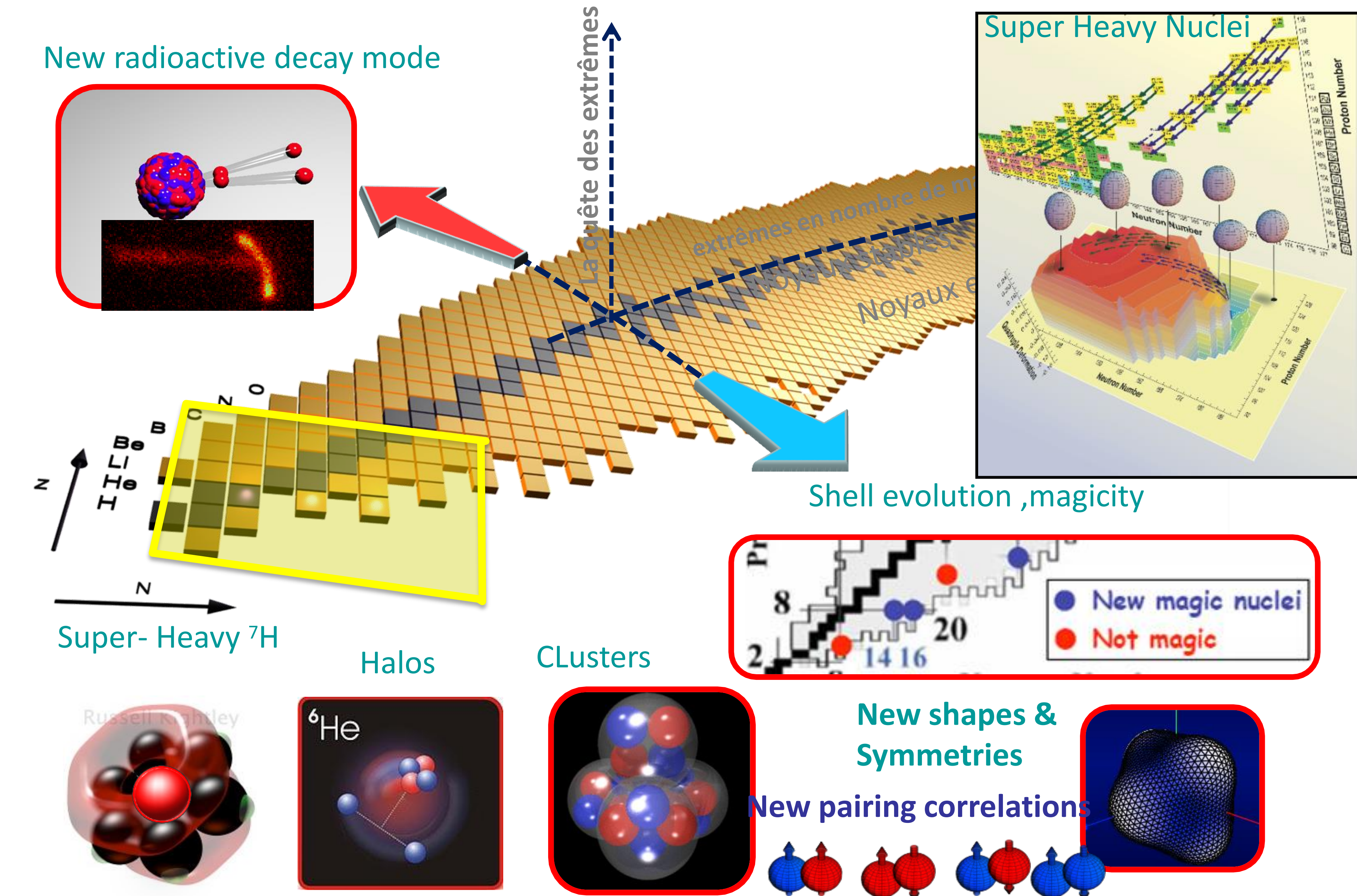
Z=114 Fv Z=116 Lv

Cross-sections for 119-120
Below 60fb

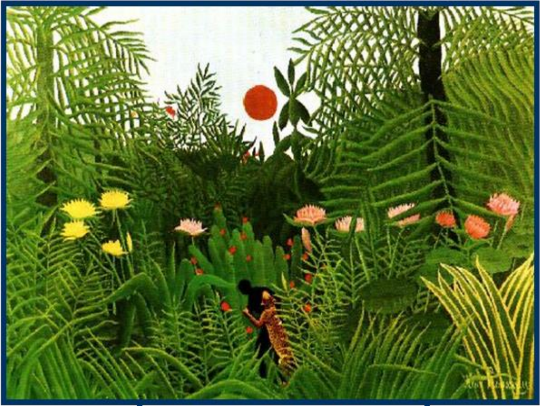
IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

Physics of « exotic » nuclei

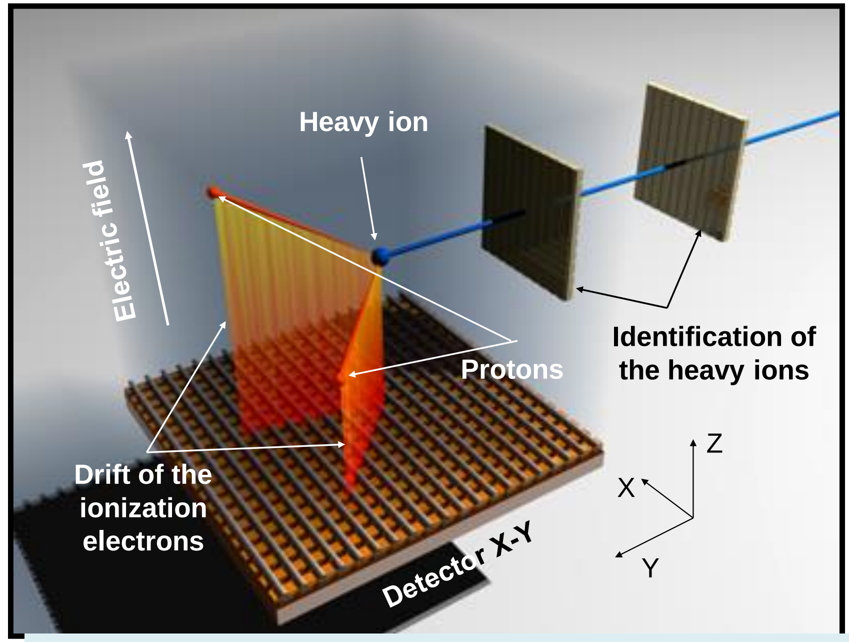
Emerging phenomena and theoritical challenges



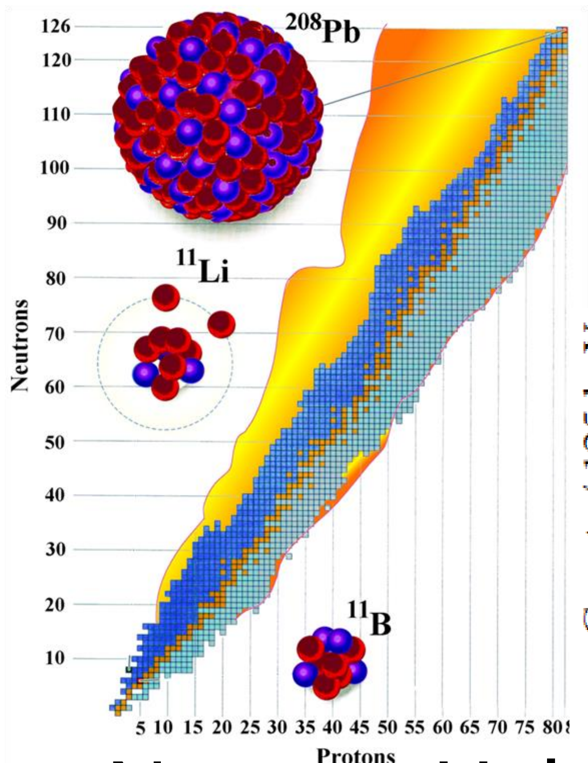
Exotic Nuclei :Discoveries



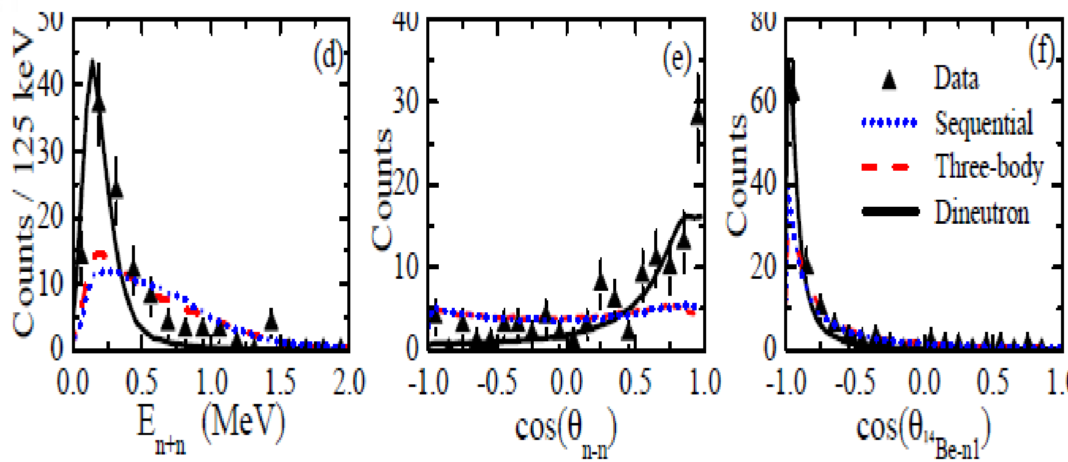
H. Rousseau, *Forêt Vierge ...*



Two-proton radioactivity ^{54}Zn

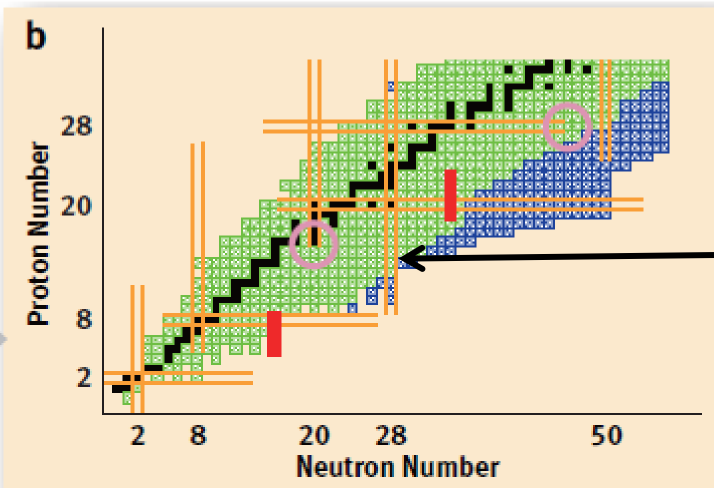


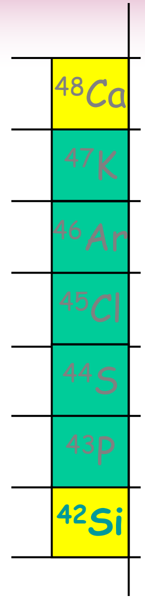
Neutron Halo

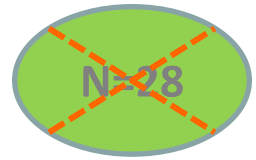


^{16}Be decays by correlated 2n

Shell Structure : N=28 « Magicity lost ?

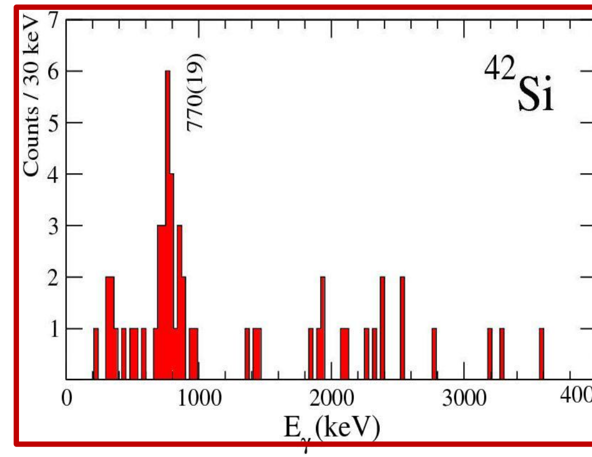


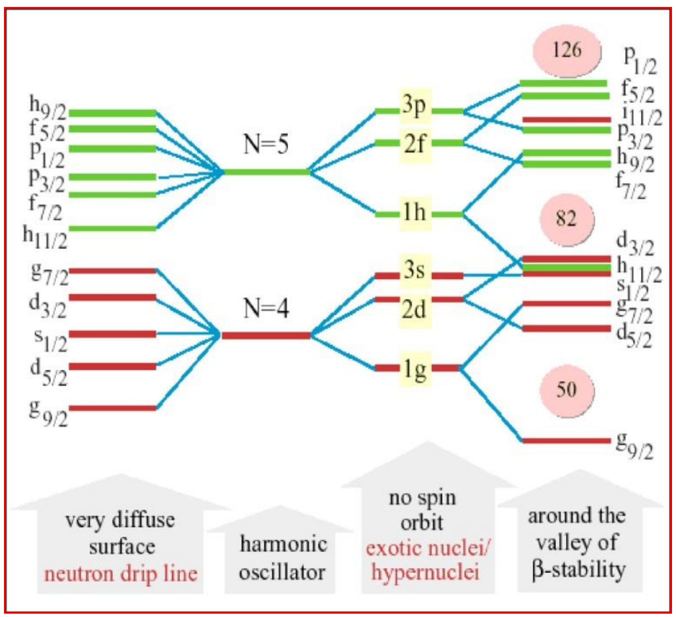




First exemple associated to
change of spin-orbit gap

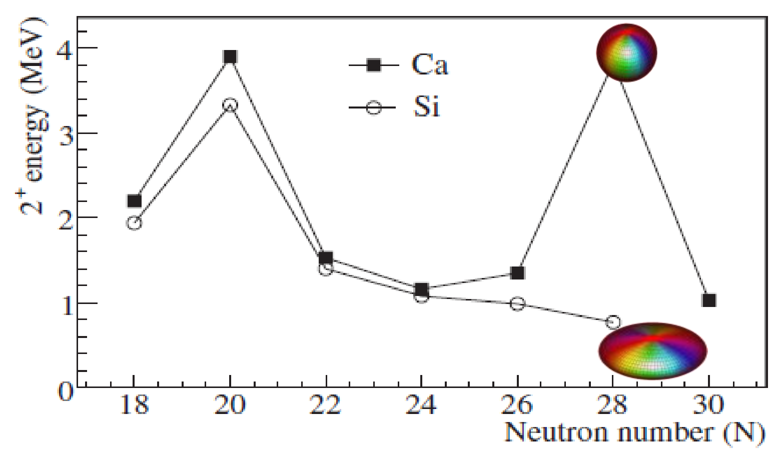
Expts at GANIL





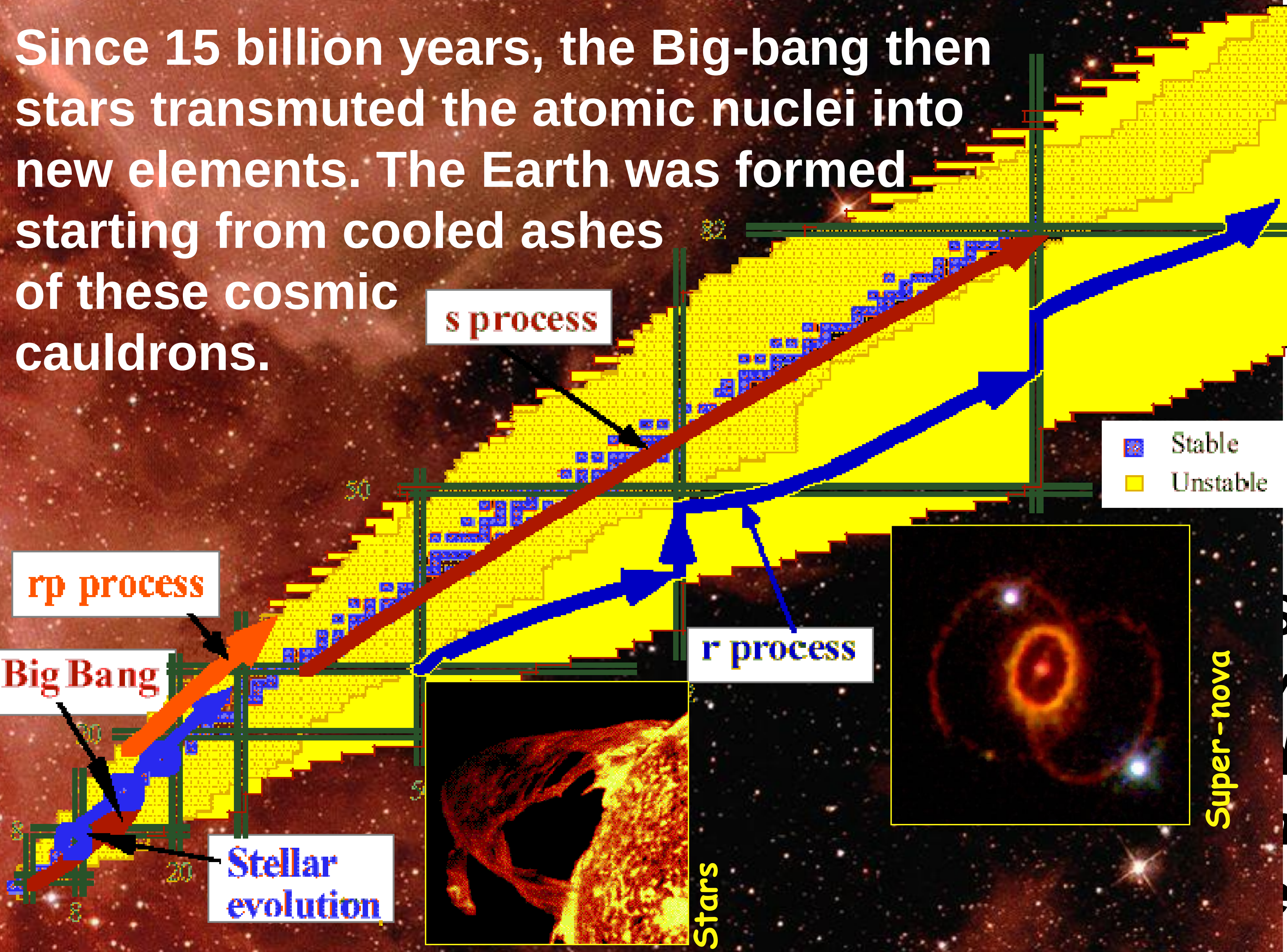
Role of the tensor force

Strong Gs deformation in 42Si
« in –fligth gamma spectroscopy »



Isospin Dependence of Mean Field

Since 15 billion years, the Big-bang then stars transmuted the atomic nuclei into new elements. The Earth was formed starting from cooled ashes of these cosmic cauldrons.

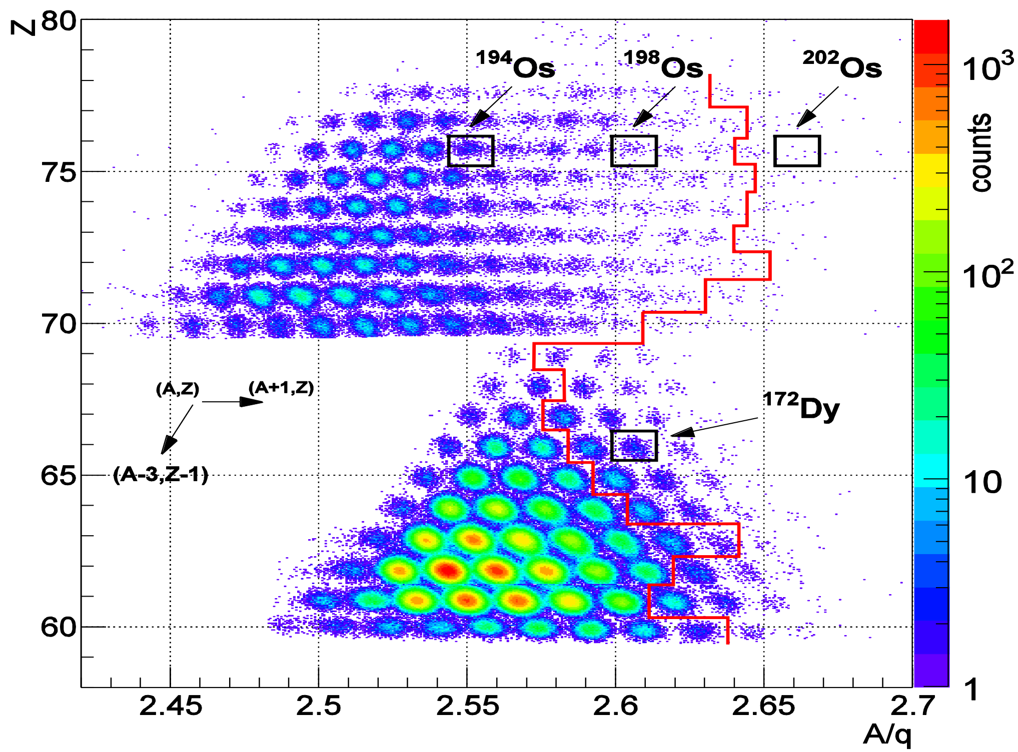


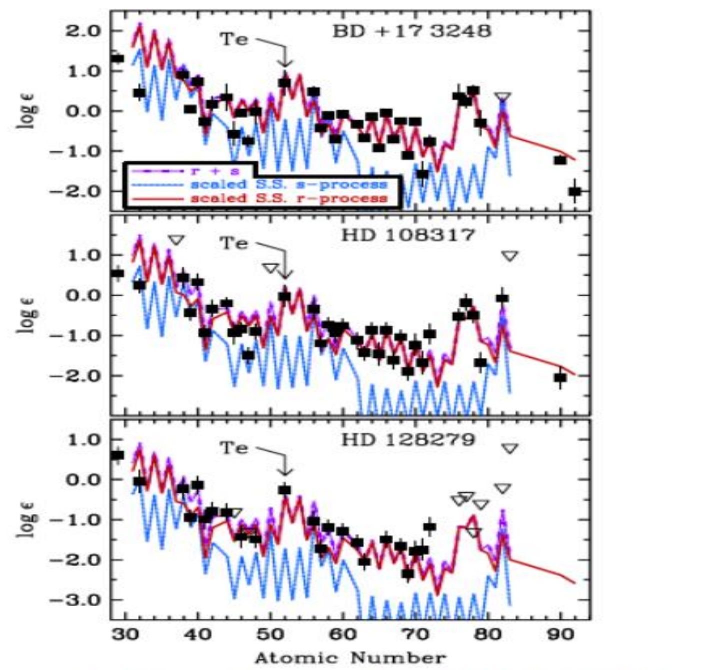
GSI- Discovery of 57 New Isotopes South –east of 208Pb

Jan Kurcewicz, Fabio Farinon et al.

Neutron Rich Nuclei and R –process nucleosynthesis

A>100 Abundance pattern Fit the solar abundance well





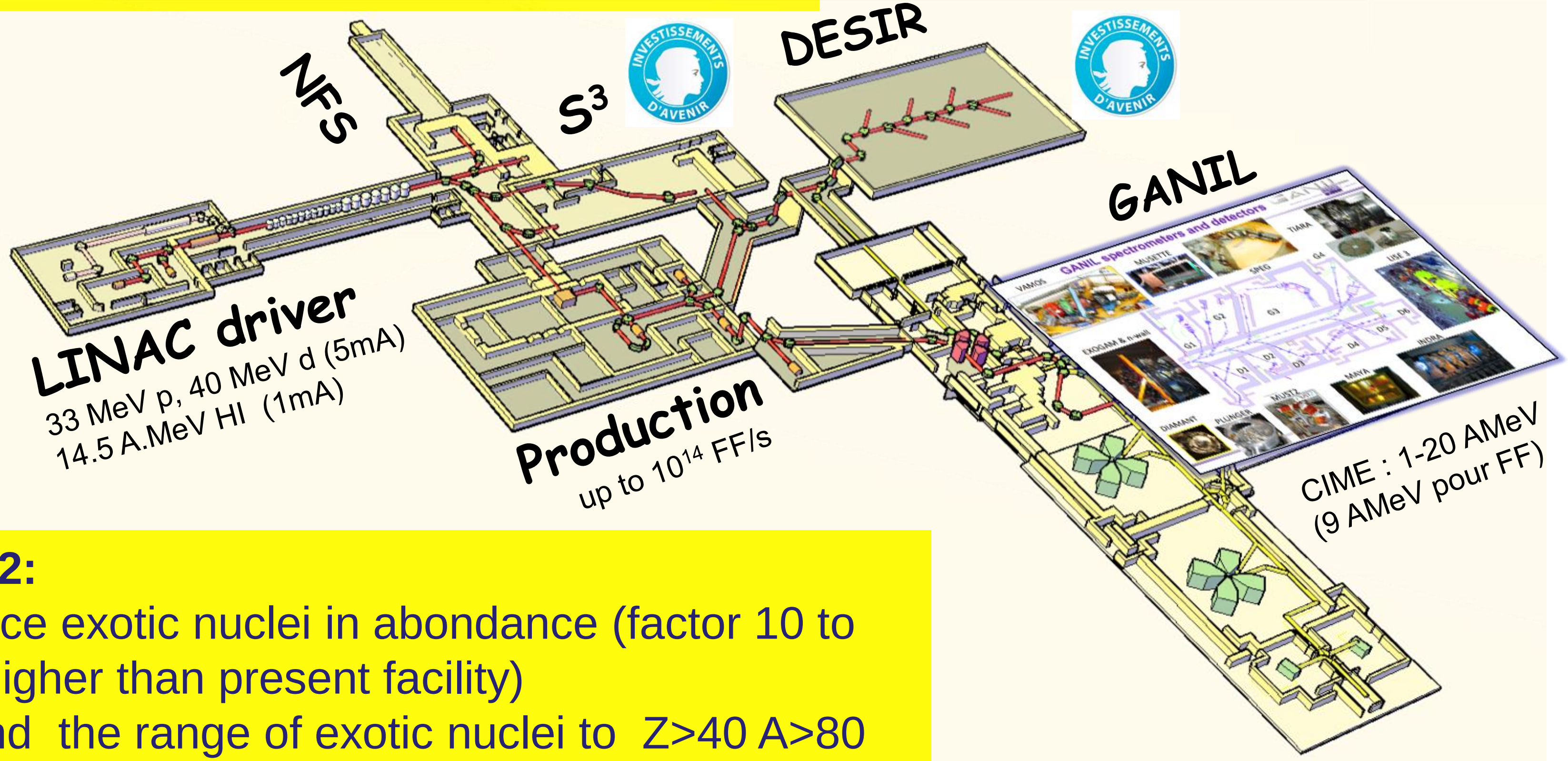
Roederer *et al.*, Ap. J. Lett. **747**, L8 (2012)

Impressive interplay between Observations, Astrophysics models and Nuclear properties (Mass,lifetime,cross-sections,decay modes)

SPIRAL2 a national priority

Phase1: Increase the intensity of stable beams by a factor 10 to 100 – High intense neutron source *10pμA (6.10^{13}pps) A<50*

DESIR (low energy facility)

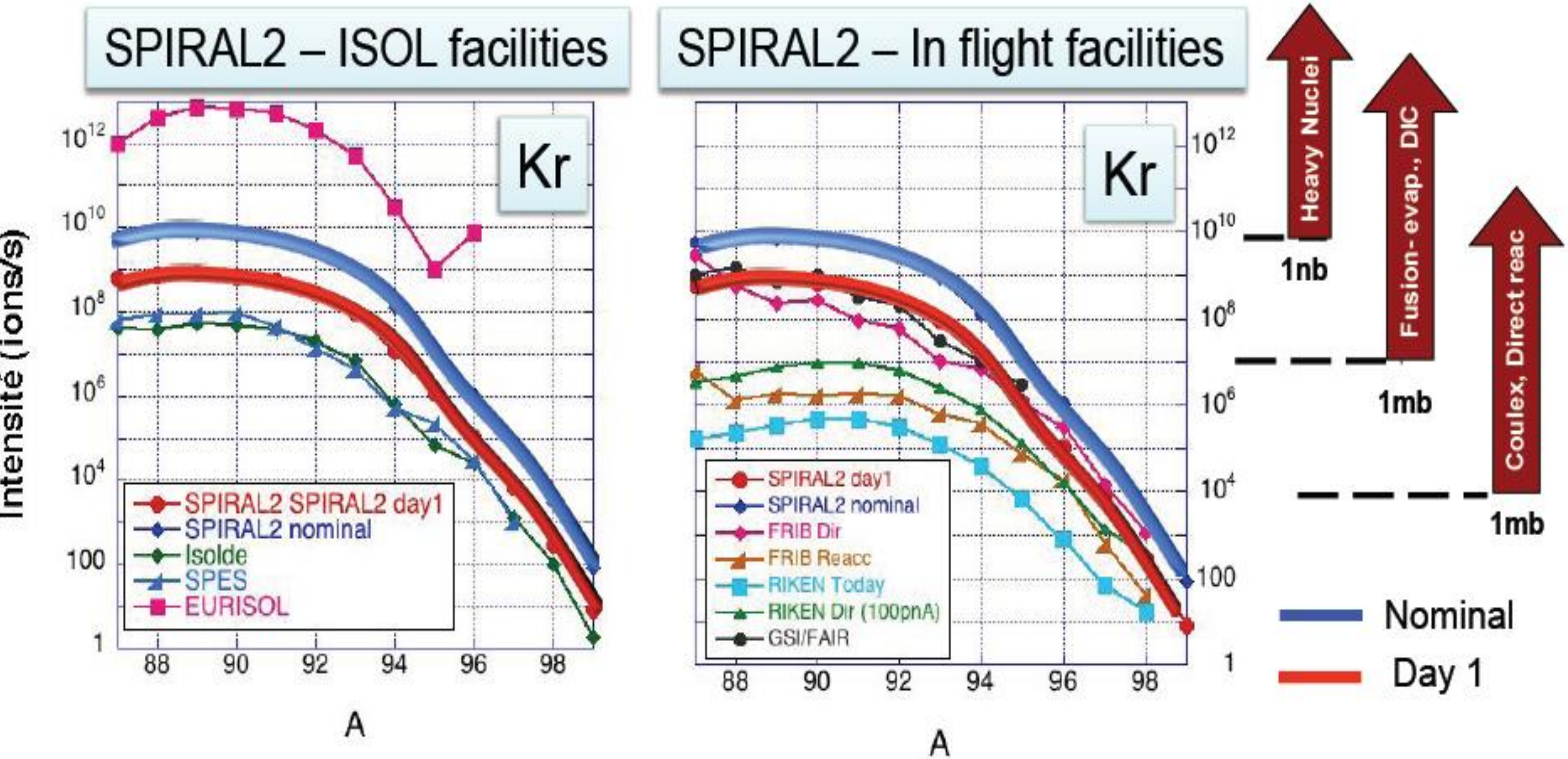


Phase2:
- Produce exotic nuclei in abondance (factor 10 to 1000 higher than present facility)
- Expand the range of exotic nuclei to Z>40 A>80

Investment :
Cost: 151,7 M€ & >23 M€ detectors

Post-acceleration of high intensity RIB through the CIME cyclotron to the curent GANIL facility

SPIRAL 2: Experiments with RIB at low cross sections and very exotic nuclei at few MeV/nucleon



ISOL RIB beams:

- **high intensity, optical quality & purity**

Versatility:

- **light & HI, high-intensity stable-ion & RIB**
- **Multi-beam capabilities,**
- **Months of beam-time**
- **World-class arrays & detectors**

Phase 1

Civil Construction

98 % of the concrete done (14000m^3)

Feb 2011

May 2011

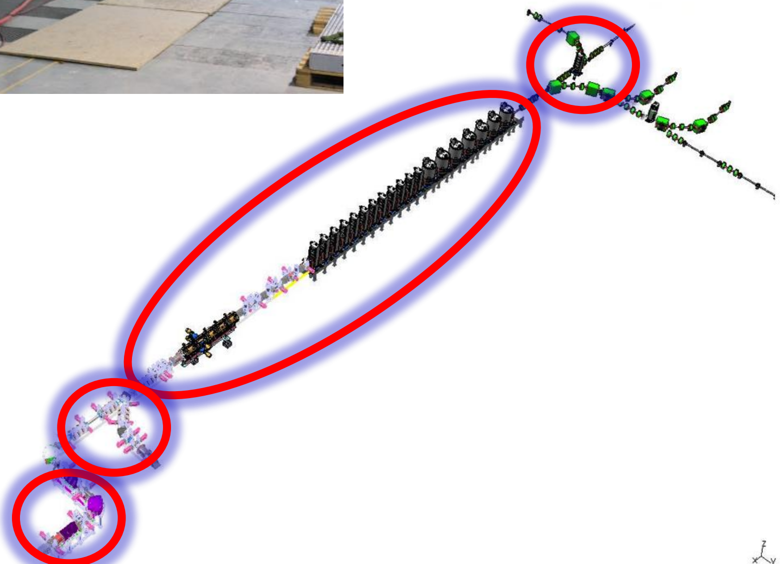
Oct 2011

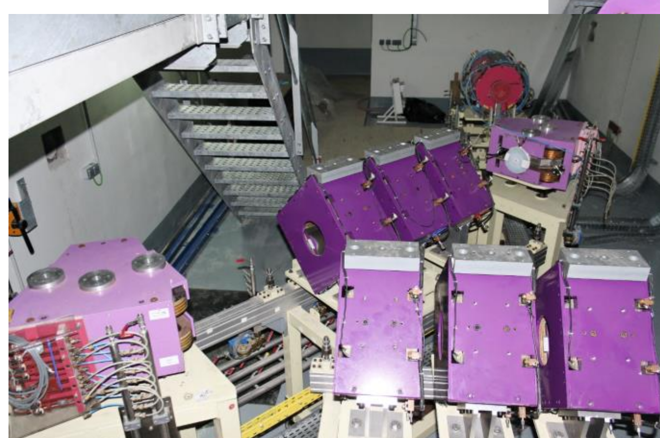
May 2012

Oct 2012

March 2013

Installation is ongoing

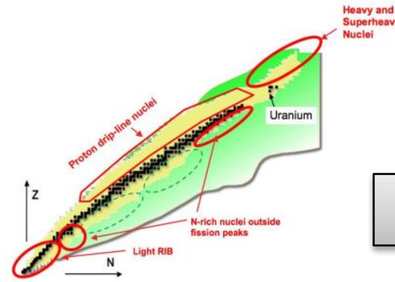




March 2013

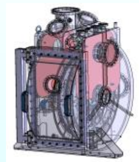
S3 Physics case (16 LoIs)

- VHE – SHE elements
- Proton drip-line and N=Z
- Nuclear astrophysics
- Atomic physics

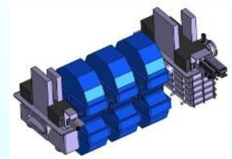


First experiment in 2015

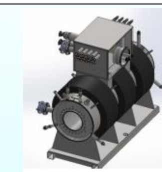
High power Rotating targets including actinides



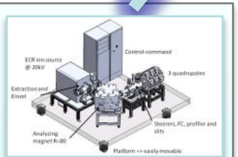
Beam dump & Movable fingers



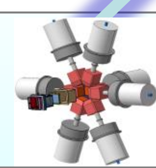
Large acceptance SC Multipoles



FISIC setup Fast Ion Slow Ion Collisions

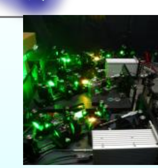


Implantation-decay station at the mass dispersive plan



DESIR

Low Energy Branch



IPN
INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

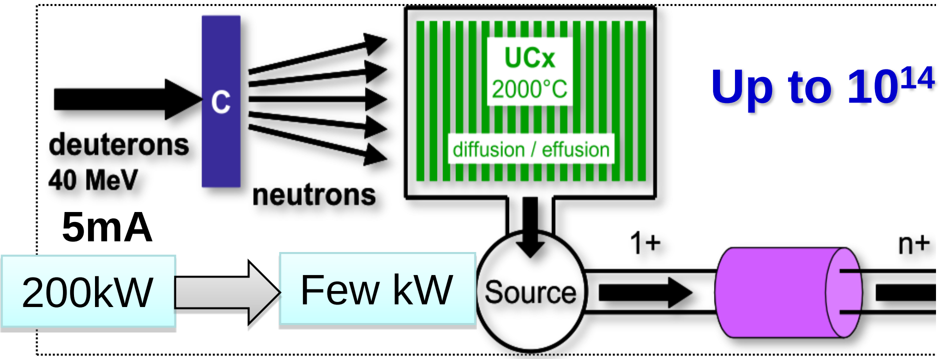
Phase 2

ISOL Rare Isotope Beams at SPIRAL 2

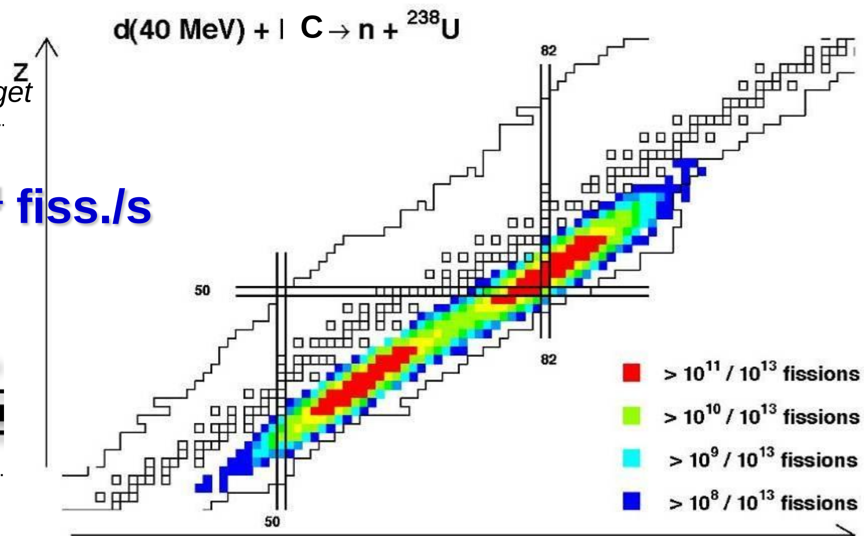
IPN
INSTITUT DE PHYSIQUE NUCLÉAIRE
ORSAY

Up to 2.3 kg HD UC_2

Decoupling the power of the driver beam from the RIB production target



Up to 10^{14} fiss./s



J. Benlliure

^2H, → Converter → n → UCx | IS → 1+ → Fission fragments

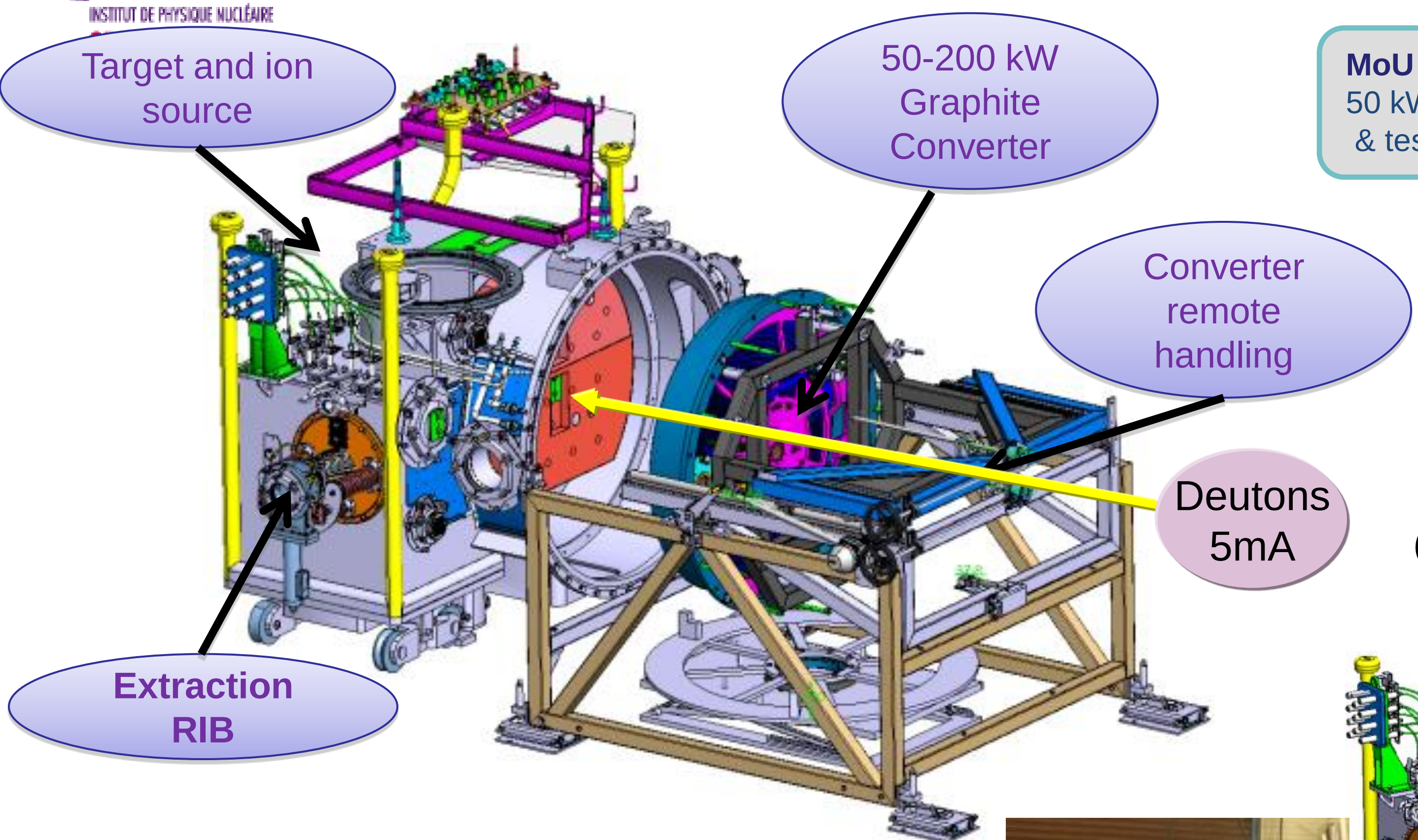
^2H → Converter → n → Target | IS → 1+ → e.g. $^9Be(n,\alpha)\,^6He$ 10^{12}pps

Direct Target

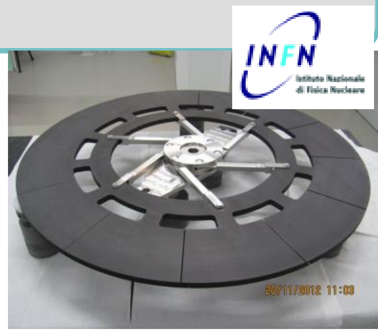
p, d → UCx | IS → 1+ → Fission fragments

HI → Target | IS → 1+ → e.g. $^{14,15}O$, ^{11}C, $^{102-106}Sn$

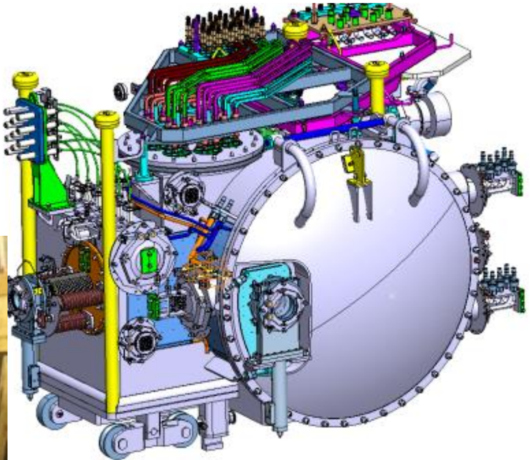
RIB Production module



MoU with LNL Legnaro
50 kW Converter Production
& testing



GANIL & ESS Bilbao



This equipment is very ambitious :

- Dimensions : 3,1x2,2x2 m and 9 T,
- Mounting and dismounting by robot every 3 month,
- HV : 60 KV,
- High neutron and gamma integrate dose,
- Positioning in all directions at +/-0,5 mm,
- Vacuum at 10^{-6} mbar,
- Many servitudes

MoU signed with ESS Bilbao
- manufacturing design study
- chamber construction
- Source inspection
- Testing and validation

FAIR Full Version

D.G. : Boris Sharkov

Austria China Finnland France Germany Greece India Italy Poland Slovakia Slovenia Spain Sweden Romania Russia UK

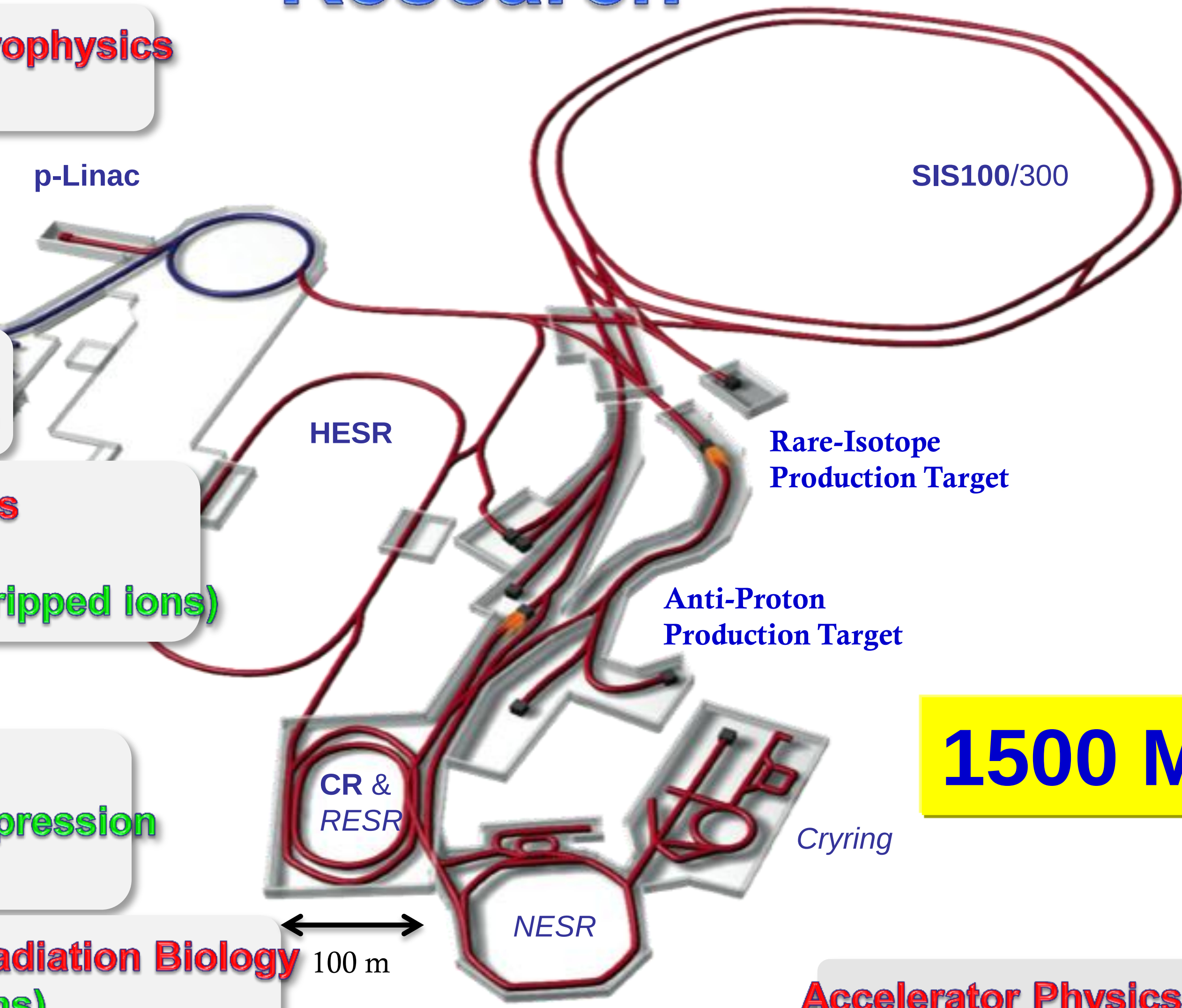
Facility for Antiproton & Ion Research

Nuclear Structure & Astrophysics
(Rare-isotope beams)

Hadron Physics
(Stored and cooled
14 GeV/c anti-protons)

QCD-Phase Diagram
(HI beams 2 to 45 GeV/u)

Fundamental Symmetries
& Ultra-High EM Fields
(Antiprotons & highly stripped ions)



1500 M€

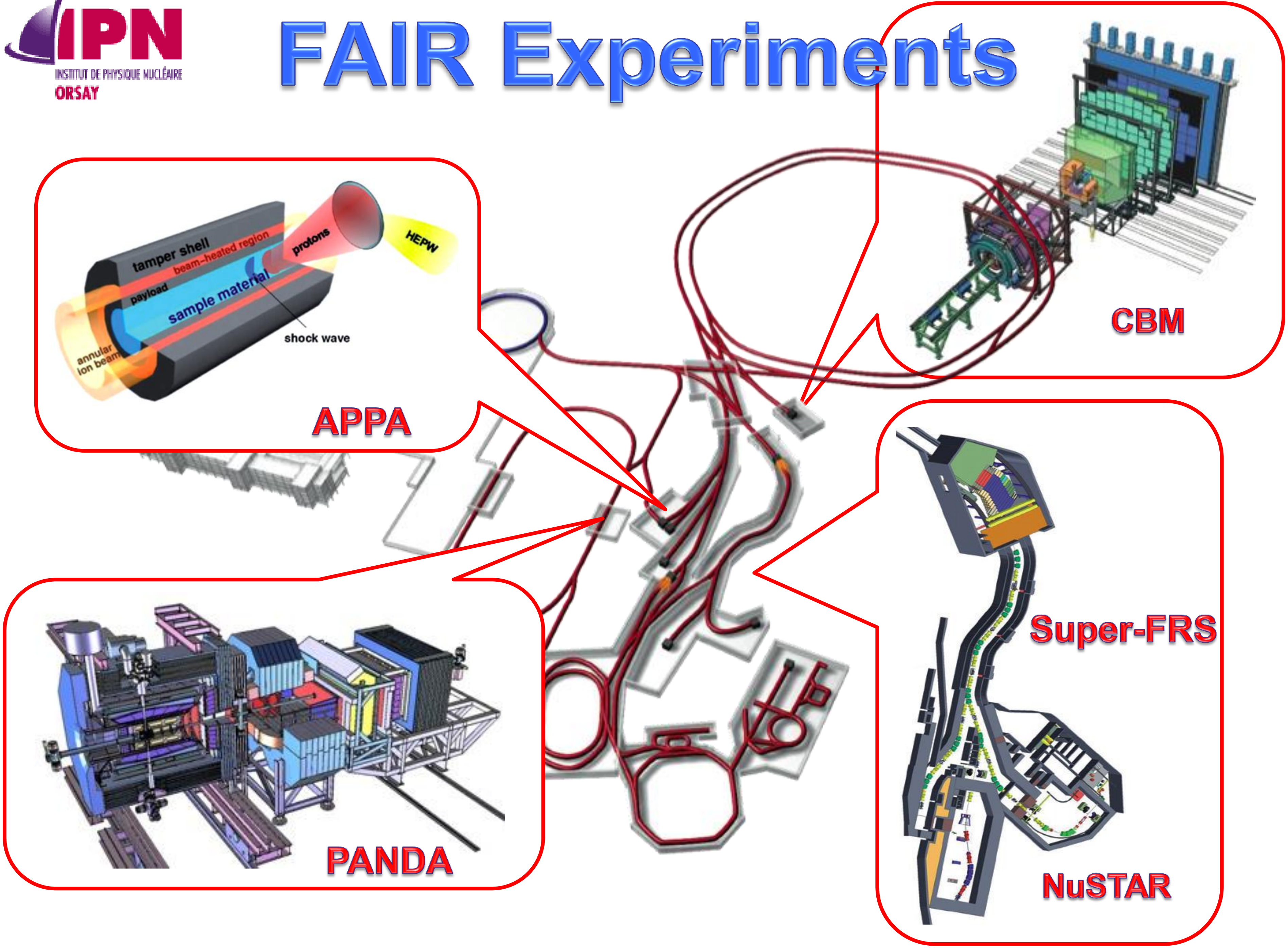
Dense Bulk Plasmas
(Ion-beam bunch compression
& petawatt-laser)

Materials Science & Radiation Biology
(Ion & antiproton beams)

Accelerator Physics

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

FAIR Experiments

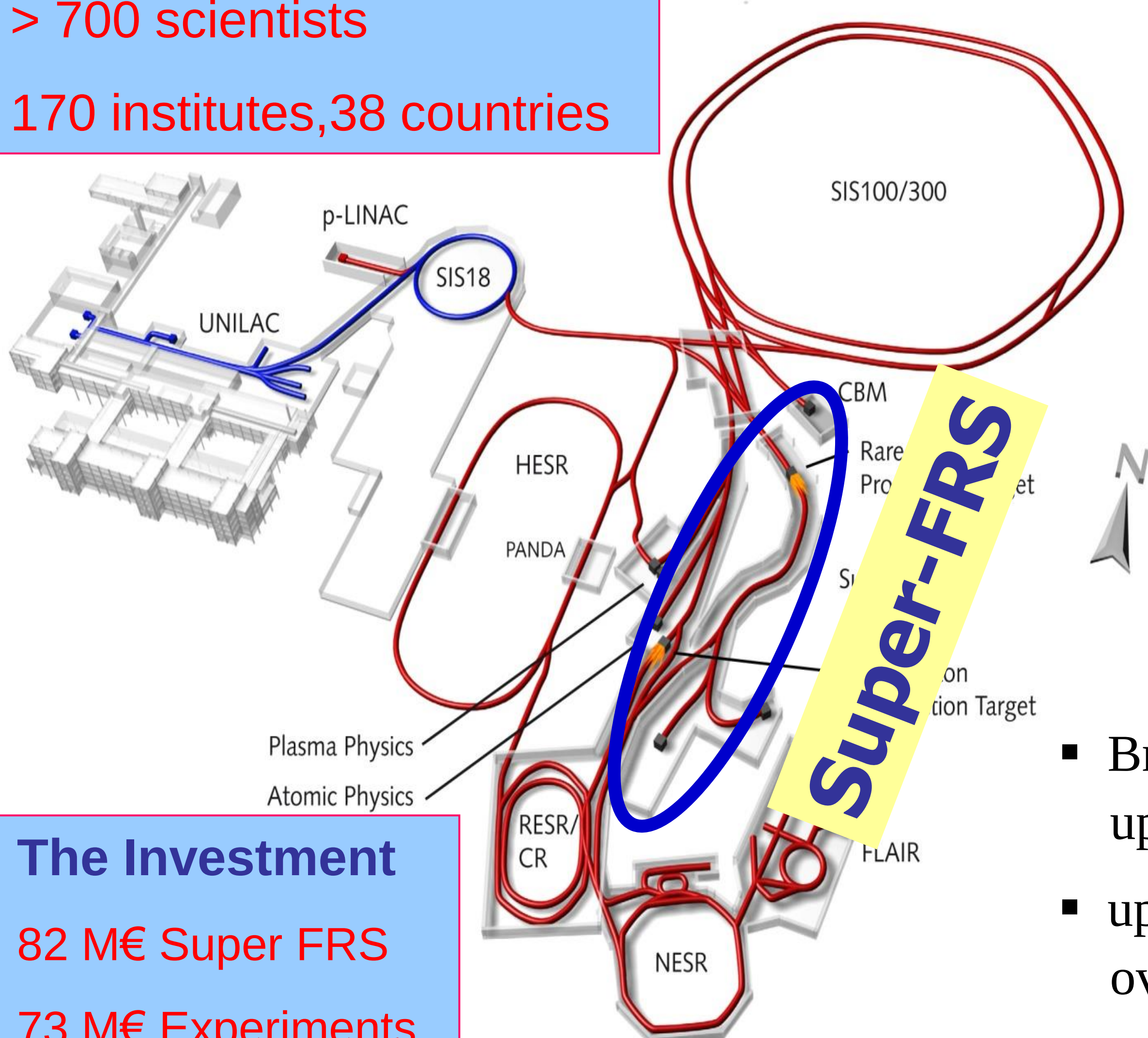


NUSTAR@FAIR

The Collaboration

> 700 scientists

170 institutes,38 countries



Primary Beams

- **3.5·10^{11} $^{238}U^{28+}$/s (DC)** @ 1.5 GeV/u
- **5·10^{11} $^{238}U^{28+}$ (pulsed)** @ 1 GeV/u
- factor **100** in intensity over present

Secondary Beams

- Broad range of radioactive beams up to **1.5 GeV/u**
- up to **factor 10 000 in intensity** over present

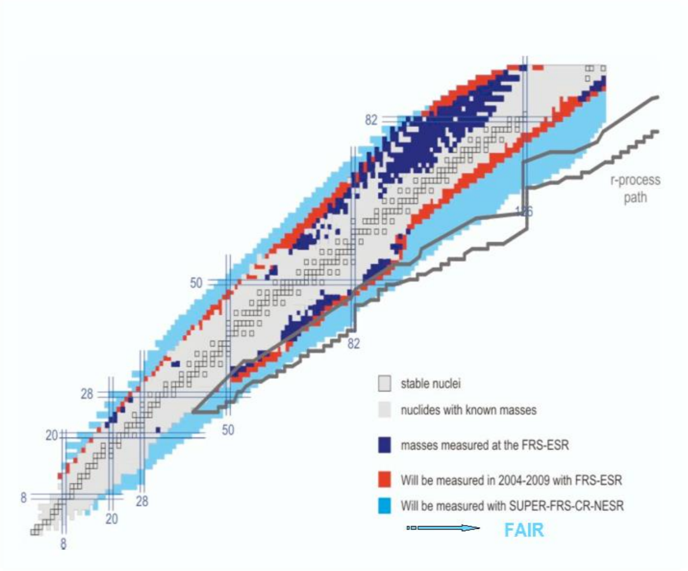
The Investment

82 M€ Super FRS

73 M€ Experiments

FAIR Chance: NUSTAR, CBM, SPARC

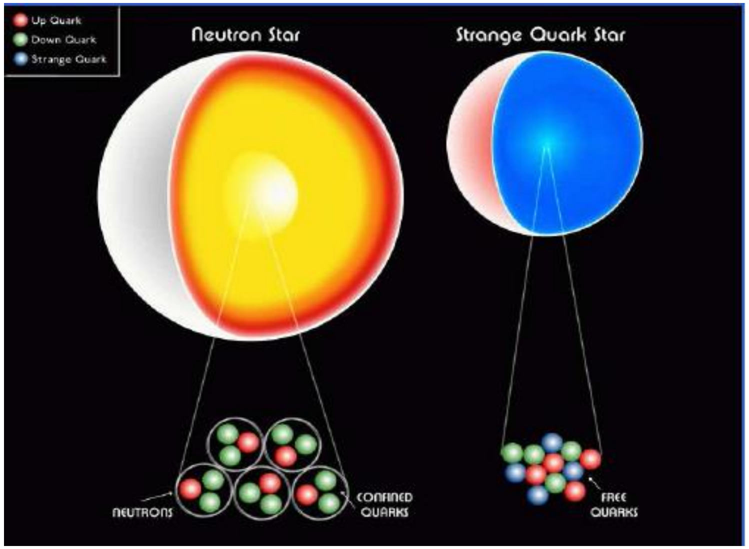
The r-process



Hundreds of nuclei will be observed at FAIR for first time!

- nuclear masses
- half lives
- neutron capture rates,fission

Neutron stars



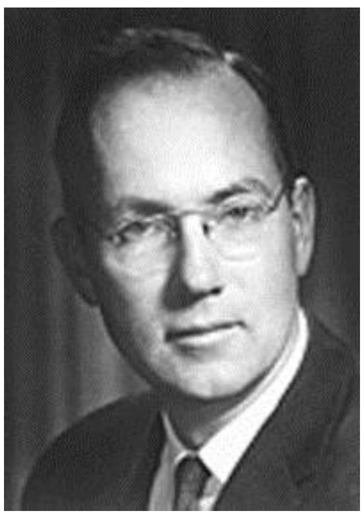
Are neutron stars in the interior made of quark matter? (quark stars)

Laboratory for matter
under extreme density
neutron-rich nuclei
nuclear matter
exotic phases?

Construction site today

21st Century; the Photon Century
Could basic research be driven
by the massless and chargeless Photons??

Large Scale Lasers: Could they become the Next Large Scale Fondamental Research Infrastructures?



The First exemple is the Extreme Light Infrastructure ELI.

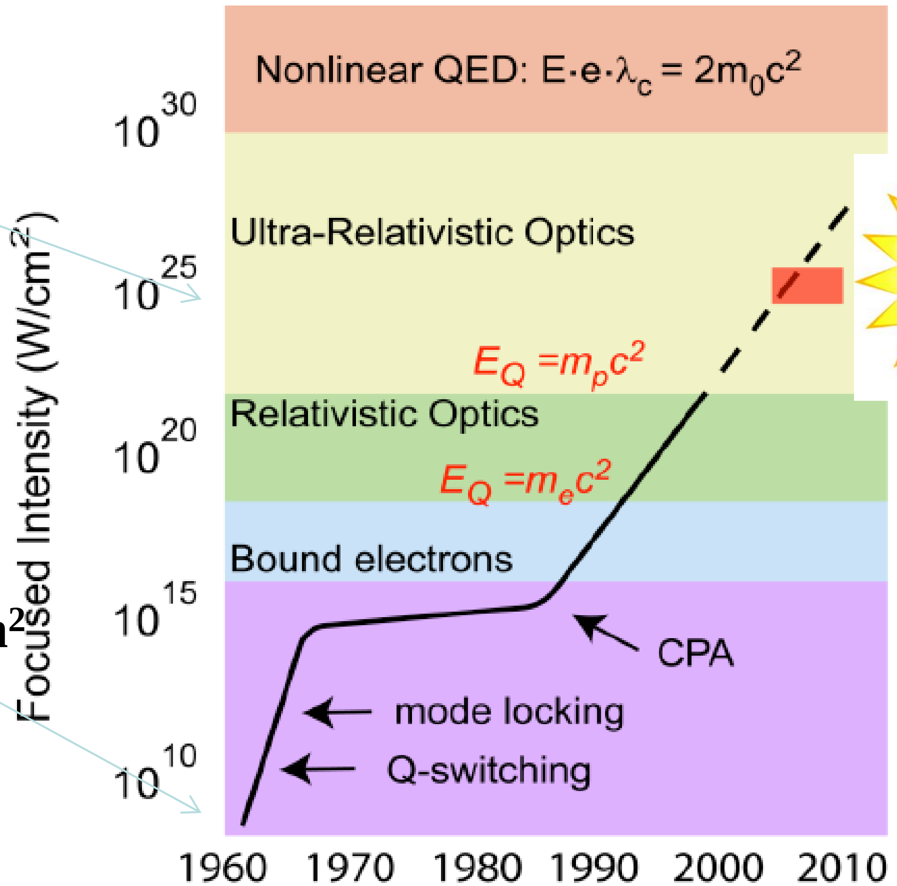
Extreme Light Infrastructure

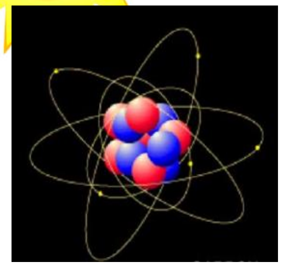
A world laser roadmap

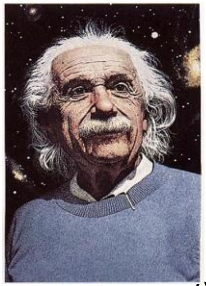
Gerard Mourou 1985: Chirped Pulse Amplification (CPA)

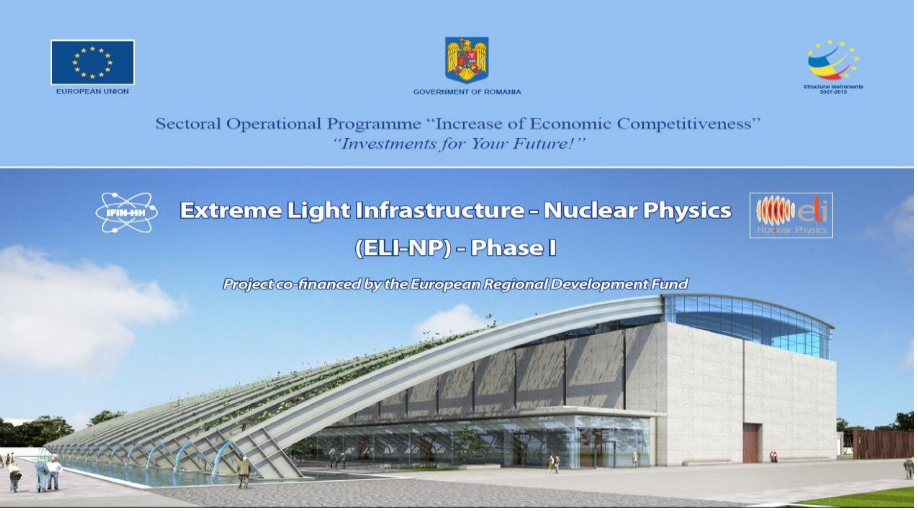
10^{25}W~ 10% of Sun's total power on 1 cm^2

10^9W ~ Power of a nuclear reactor on 1 cm^2









Europe has decided to build the highest intensity laser ELI

For

Extreme Light Infrastructure

1PW, 1 µm

~highest power laser today

2006 – ELI on ESFRI Roadmap

ELI-PP 2007-2010 (FP7)

Three Pillars

ELI-Beamlines (Czech Republic)

ELI-Attoseconds (Hungary)

ELI-Nuclear Physics (Romania)

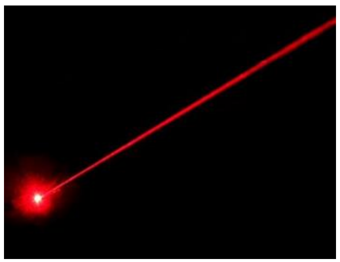
Project Approved by the European Competitiveness Council (December 2009)

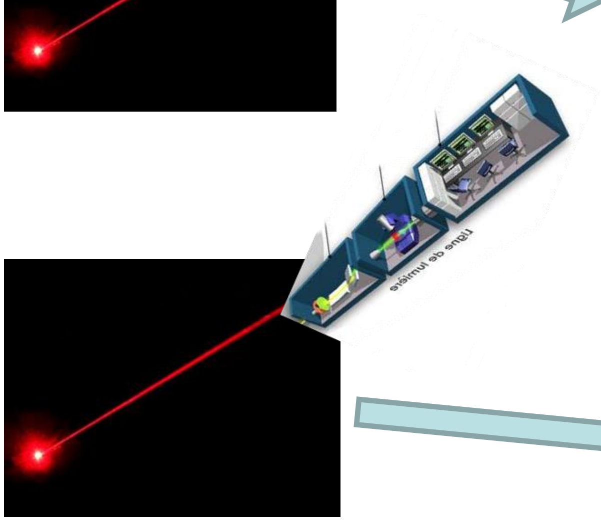
ELI-DC (Delivery Consortium): April 2010

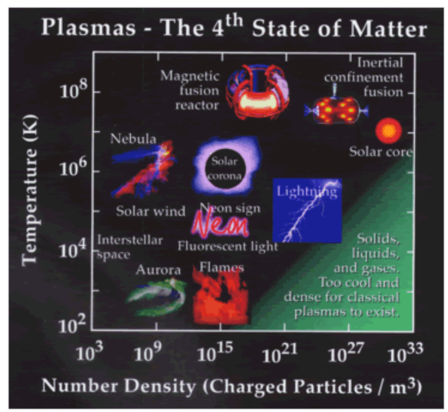
ELI-NP

Observation of matter with new powerful probes
Large discovery potential

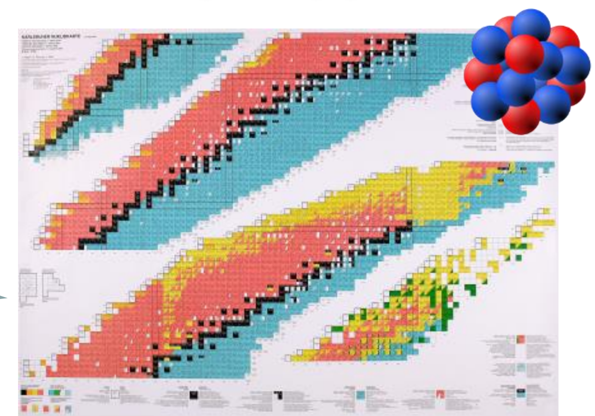
Light







Femto-



Gamma beams

Power

Nuclear Physics

ELI-NP - the probes

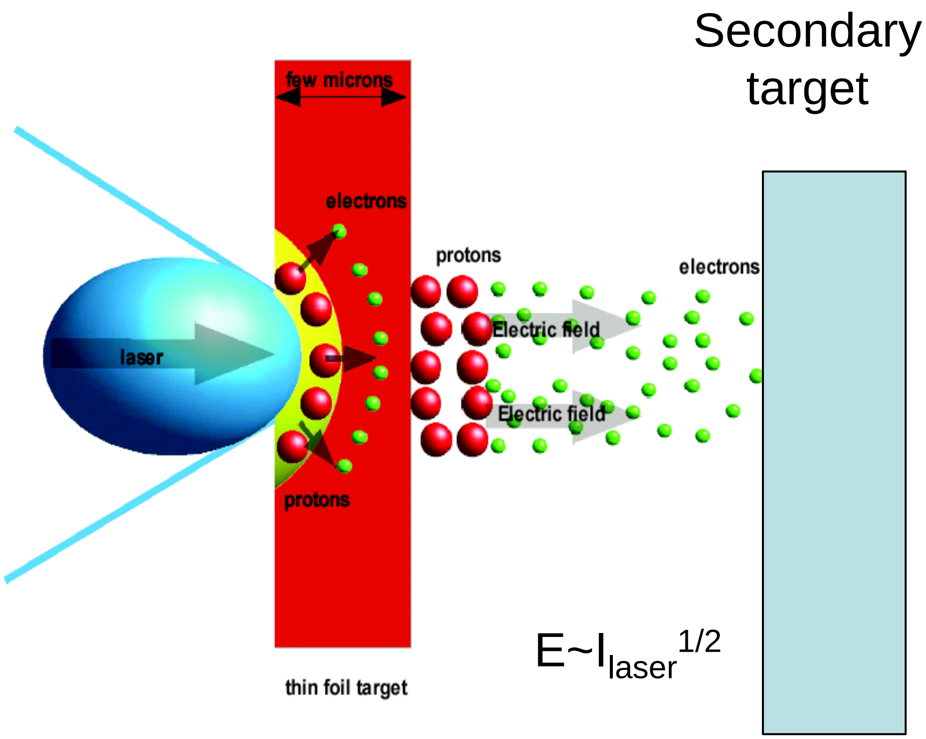
Large equipment at the frontier of technology:

- Ultra-short pulse high power laser system, 2 x 10PW maximum power (new acceleration schemes)
- **+**Gamma radiation beam, high intensity, tunable energy up to 20MeV, relative bandwidth 10^{-3} **(unique new probe worldwide, going to explore unknown territory)**

Experiments – the tools:

- 8 experimental areas, for gamma, laser, and gamma+laser

Target Normal Sheath Acceleration (TNSA)



Primary radiations

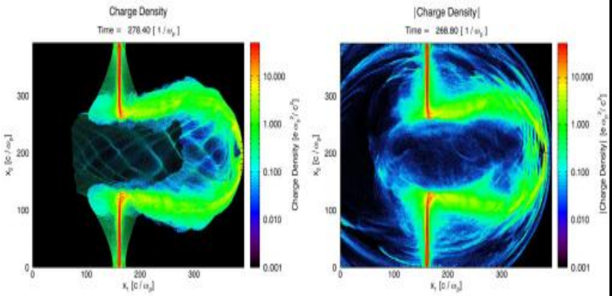
Electrons are expelled from the target due to the chock wave induced by the powerful laser
Heavy ions are accelerated in the field created by the electrons

Electrons and ions accelerated at solid state densities 10^{24}e cm^{-3}
never reached before
(Classical beam densities 10^{8}e cm^{-3})
on very short distance (µm-mm)
Nuclear reactions in target in dense plasma

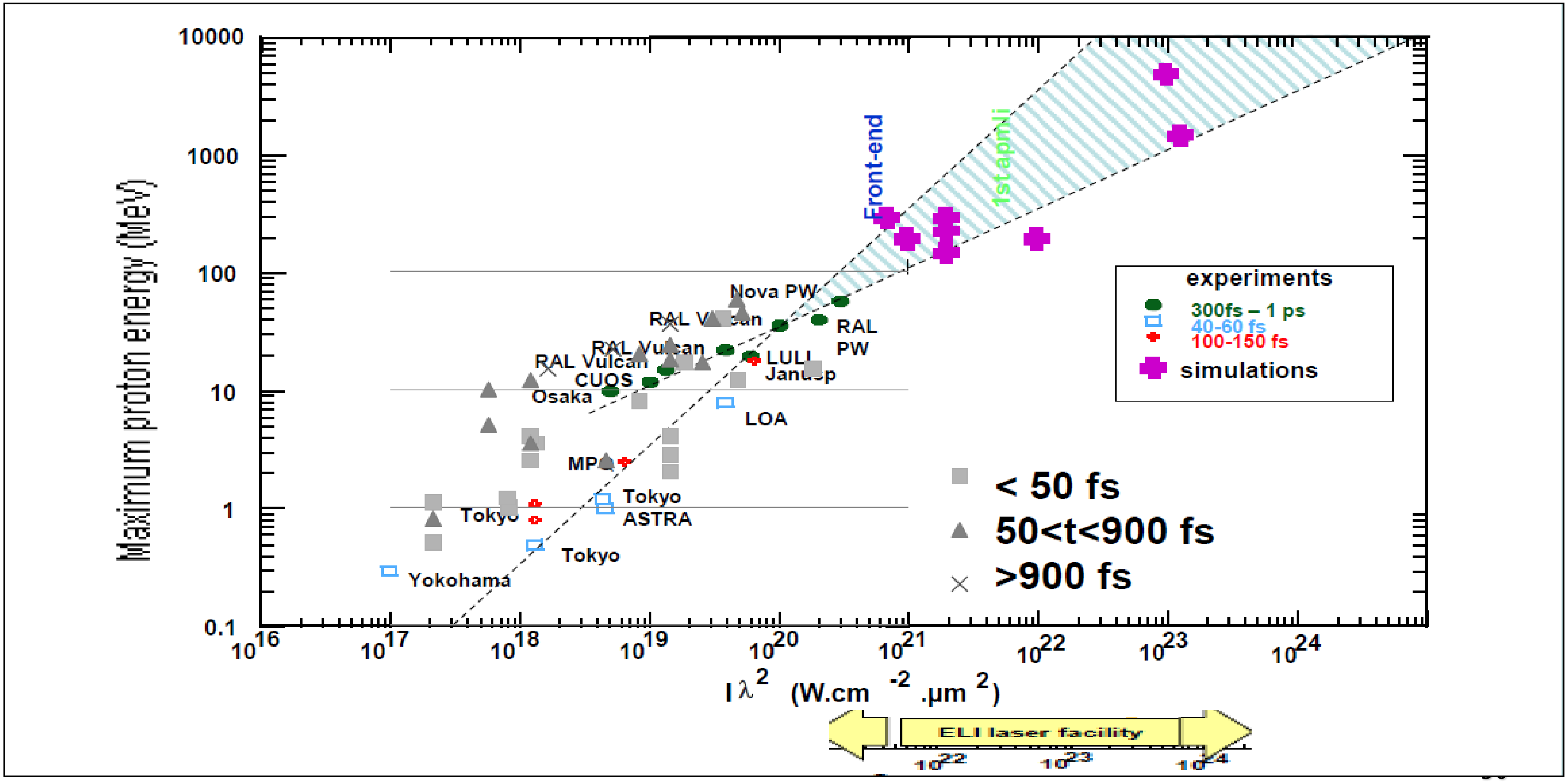
Energy reached equal to a 400m up-to-date accelerator (reduction of scale of 10^{9})

Proton acceleration

- Maximum energy scales with laser beam intensity approximately as $I^{0.5}$



RPA simulations 10 [23] W/cm2 ,15 fs



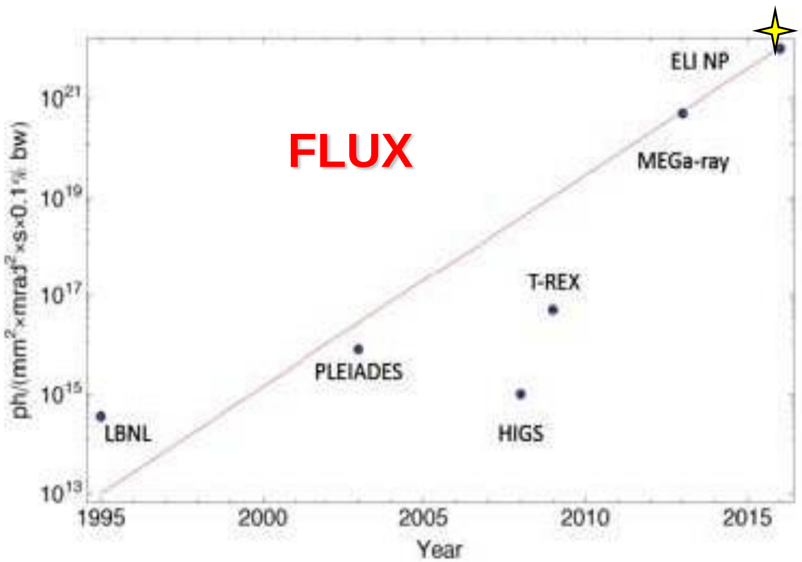
S.Gales ELI-NP-Ro

ELI – NP Experiments (1)

Stand-alone High Power Laser Experiments

- **Nuclear Techniques for Characterization of Laser-Induced Radiations**
- Modelling of High-Intensity Laser Interaction with Matter
- Stopping Power of Charge Particles Bunches with Ultra-High Density
- **Laser Acceleration of very dense Electrons, Protons and Heavy Ions Beams**
- **Laser-Accelerated Th Beam to produce Neutron-Rich Nuclei around the N = 126 Waiting Point of the r-Process via the Fission-Fusion Reaction**
- **Studies of enhanced decay of ^{26}Al in hot plasma environments**

ELI-NP γ beam



Laser Back-Compton Scattering

Most efficient frequency amplifier

Ee-=300 MeV , Eg= 3 MeV

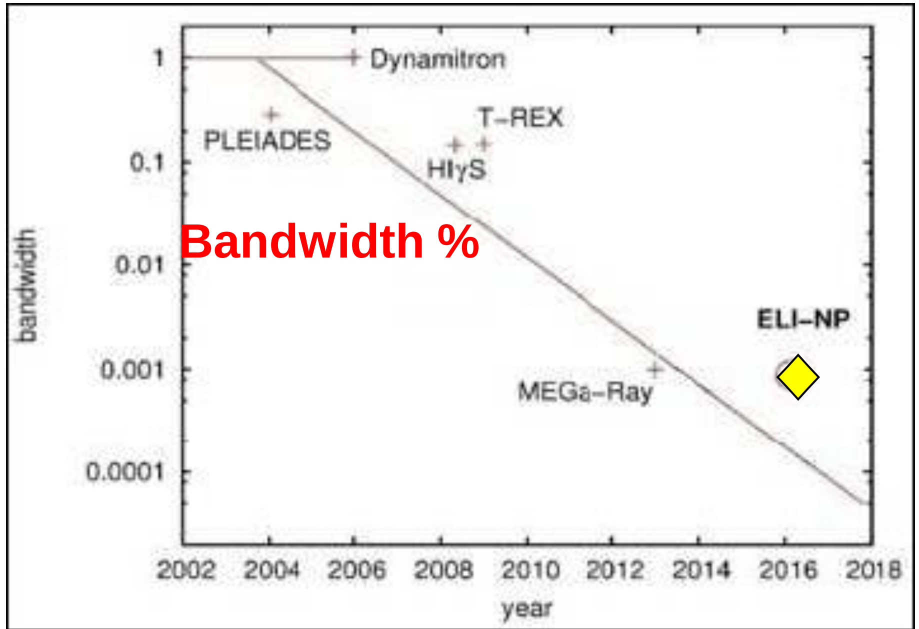
but very weak cross-section ~ 6,65 10^{-25} cm^2

Needs

High intensity e- beam

Very brillant high rep/rate Laser

Small collision volume



ELI-NP Timeline

- June 2012: Funding Phase 1 approved (180M€)
- Launch of large tender procedures- Civil engineering, Lasers ,Gamma beams
- May 2013 **Building –Contract signed –Construction Started**
- June 2013 **2X10 PW Lasers –Choice of procurement compagny**
- **June 2013- End 2014: TDRs for experiments ready**
- June 14th, 2013 : Foundation Stone Ceremony
- End 2015: Lasers and Gamma Beam – end of Phase 1
- 2017: Lasers and Gamma beam Phase 2 -Beginning of operation

Science drivers at ELI-NP

1-High-resolution nuclear spectroscopy:

- ***.NUCLEAR PHOTONICS***
- *Study of pygmy and giant dipole resonances*
- *Gamma scattering on nuclei*
- *Fine-structure of Photo-response above the Particle Threshold: the (γ ,α), (γ,p) and (γ ,n)*
- *Nuclear Resonance Fluorescence on Rare Isotopes and Isomers*
- *Multiple Nuclear Excitons*
- *Nuclear level density , Transition order-chaos*
- *High Resolution Inelastic Electron Scattering (e,e')*

2-Few body systems via photodesintegration, (d, t,He,Li)

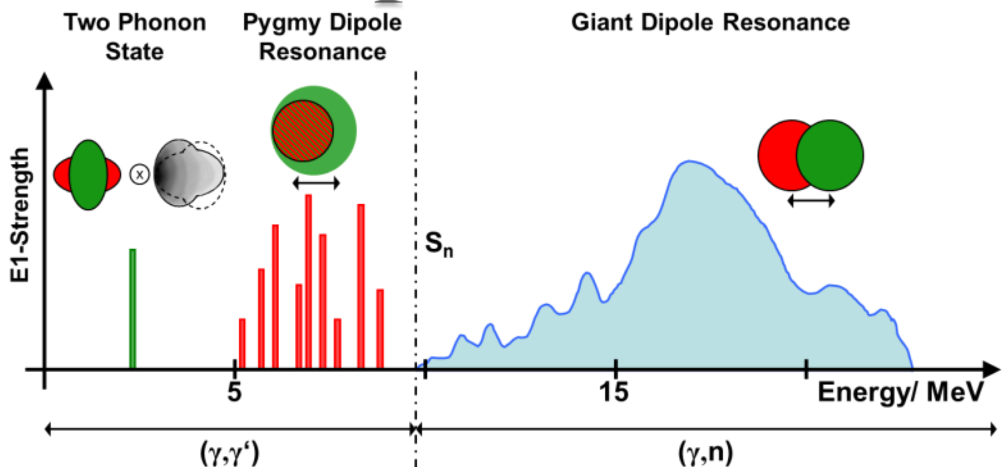
3- Photo-fission (resonances ,isomers, production)

4-Astrophysics of the r-, s-, p-processes in nucleosynthesis: *masses of waiting point nuclei, pygmy resonance.*

- *Neutron Capture Cross Section of s-Process Branching Nuclei with Inverse Reactions*
- *Measurements of (γ, p) and (γ, α) Reaction Cross Sections for p-Process Nucleosynthesis*

5-Fundamental Physics of Perturbative and Non-perturbative High-Field QED: Pair creation, high energy γ rays, birefringence of the quantum vacuum.

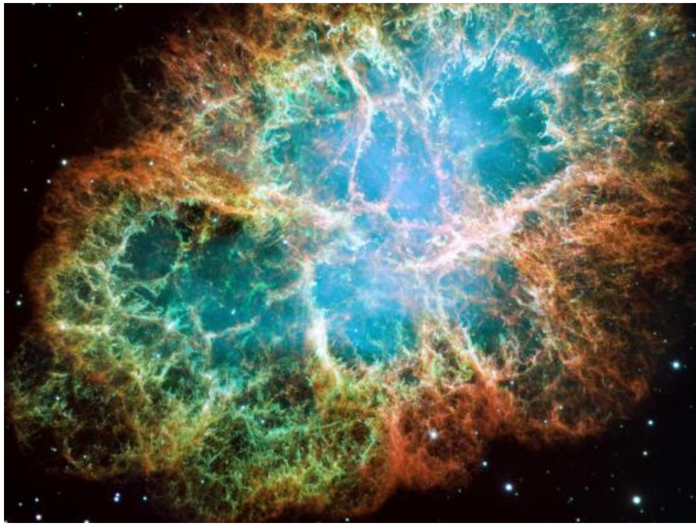
Nuclear photonics



$$B(\lambda L)\uparrow = \Gamma_0 \cdot \left(8\pi \sum_L \left(\frac{E_j}{\hbar c}\right)^{2L+1} \cdot \frac{(L+1)}{L[(2L+1)!!]^2} \cdot g\right)^{-1}$$

- aim: determination of transition strengths: need absolute values for ground state transition width
- NRF-experiments give product with branching ratio: $A_{j\rightarrow 0} \propto I_{j\rightarrow 0} \propto \frac{\Gamma_0^2}{\Gamma}$
- assumption:
  - no transition in low-lying states observed
  - but: many small branchings in other states?
- self-absorption: measurement of absolute ground state transition widths

Astrophysics – related studies



- **Production of heavy elements in the Universe –a central question for Astrophysics**
- **Neutron Capture Cross Section of s-Process Branch - Nuclei with Inverse Reactions (γ, n)**
  - the single studies on long-lived branching points (e.g. ^{147}Pm, ^{151}Sm, ^{155}Eu) showed that the recommended values of neutron capture cross sections in the models differ by up to 50% from the experimentally determined values

Measurements of (γ, p) and (γ, α) Reaction Cross Sections for p –Process-Nucleosynthesis

Determination of the reaction rates by an absolute cross section measurement is possible using **monoenergetic photon beams produced at ELI-NP**

tremendous advance to measure these rates directly

broad database of reactions – high intense γ beam needed

Potential Nuclear Photonics Applications from C.P.J. Barty (LLNL)

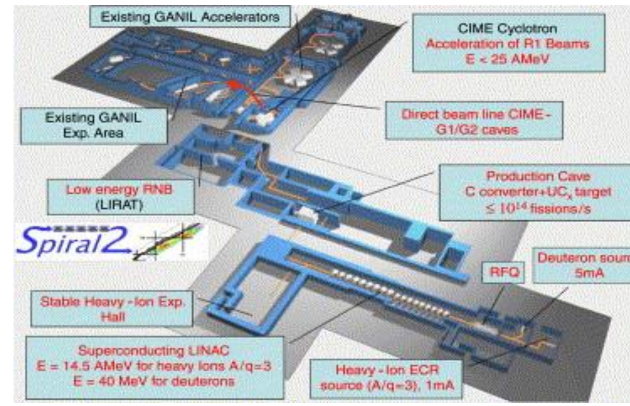
S.Gales ELI-NP-Ro

Les nouvelles frontières de la physique nucléaire

FAIR –DE 2018

ELI-NP-Ro 2017

SPIRAL2-FR 2014

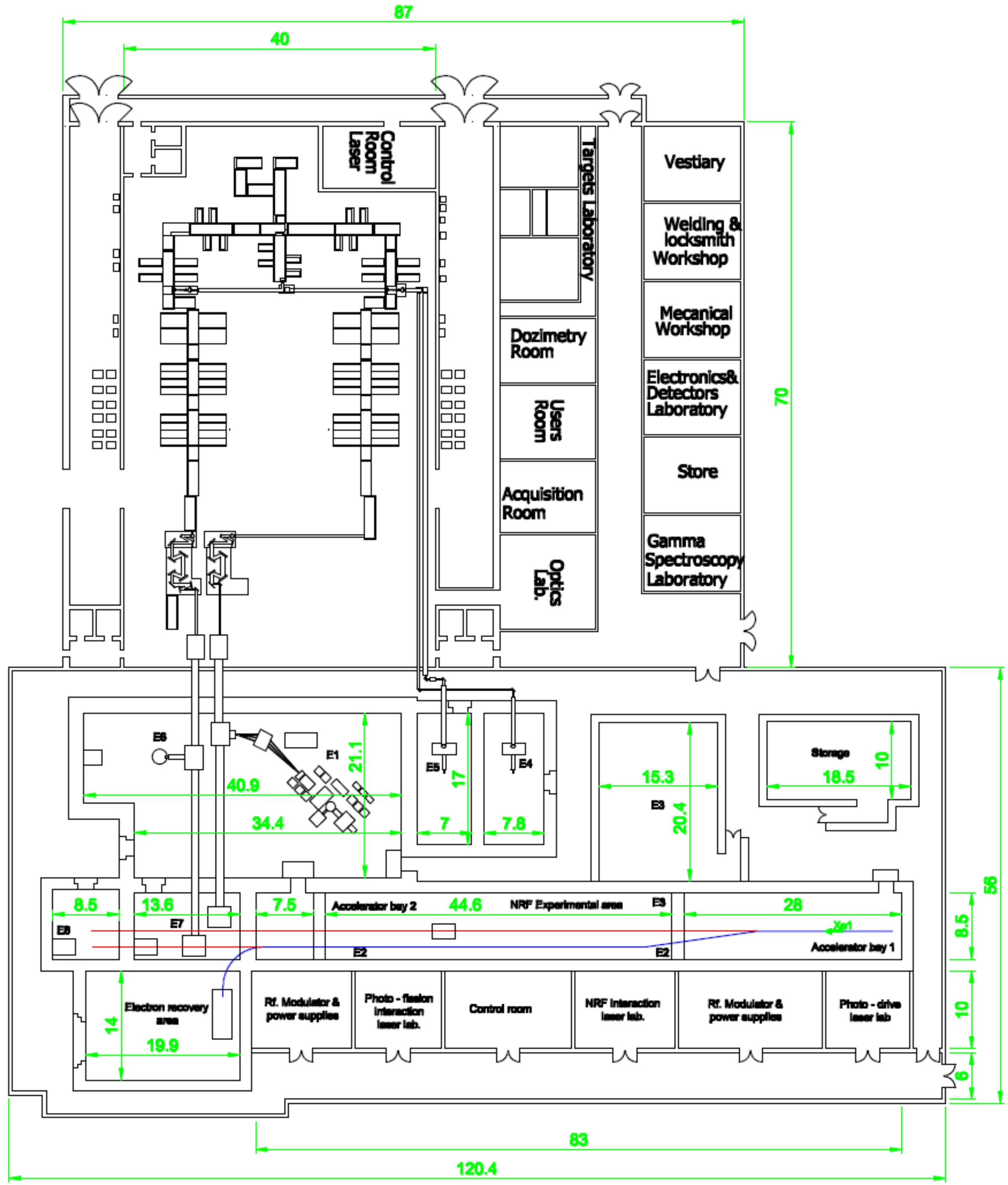


Merci pour votre patience

Nuclear Physics

ELI-NP
Main buildings

- Lasers
- Gamma and experiments
- Laboratories
- Unique architecture



EUROPEAN UNION

GOVERNMENT OF ROMANIA

Structural Instruments 2007-2013

ELI-NP will put Romania on the world map of frontier research facilities

Thank you for your patience!

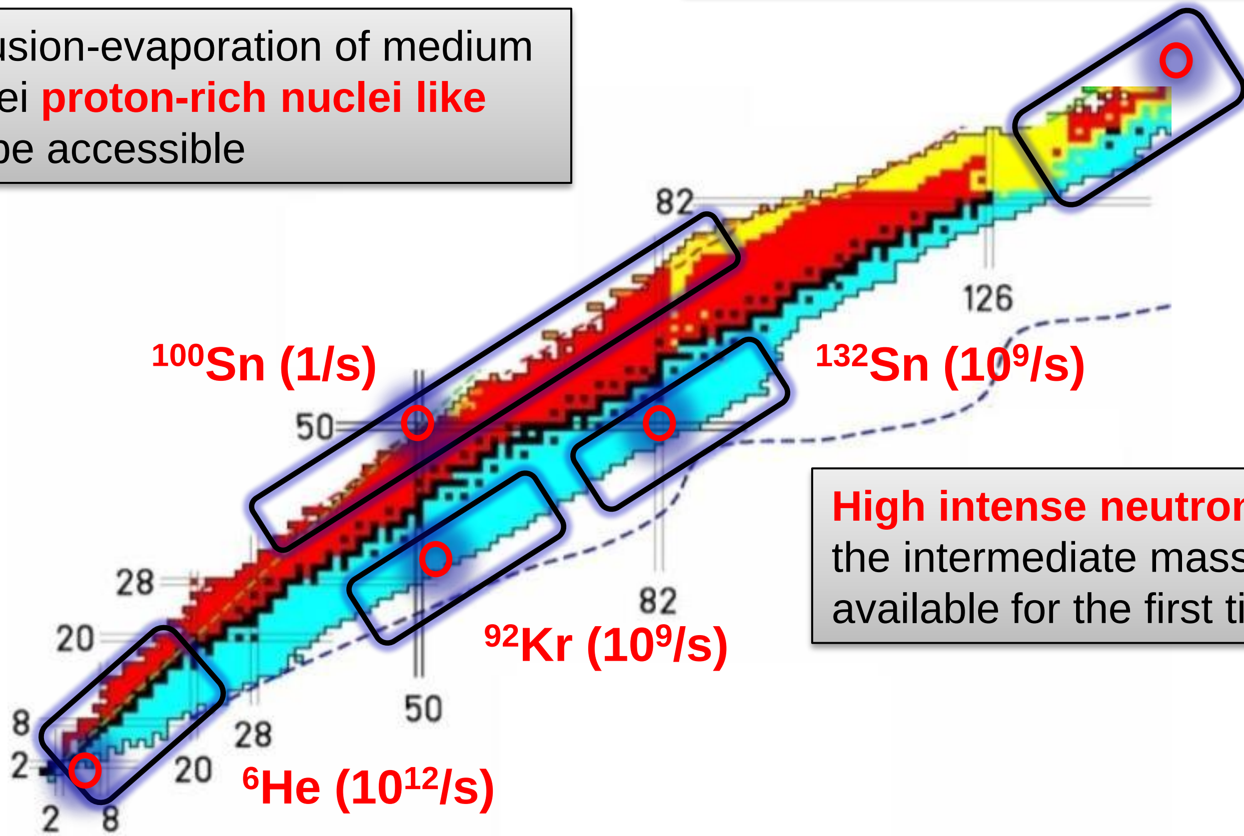
Extreme Light Infrastructure - Nuclear Physics (ELI-NP) - Phase I

Project Co-financed by the European Regional Development Fund

SPIRAL2 area of excellence

The primary beam intensities of the LINAC open new opportunity in the race for **super-heavy nuclei**

With the fusion-evaporation of medium mass nuclei **proton-rich nuclei like ^{100}Sn** will be accessible



High intense neutron rich beams, in the intermediate masses, will be available for the first time

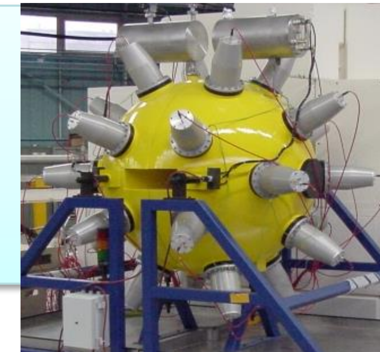
With the stable light ions induced reactions :
light exotic nuclei will be produced with intensities comparable to current stable beam

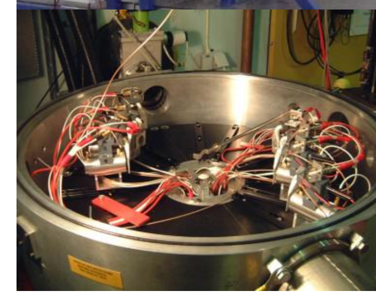
High intense white neutron source covering the 1–40 MeV energy range will be available

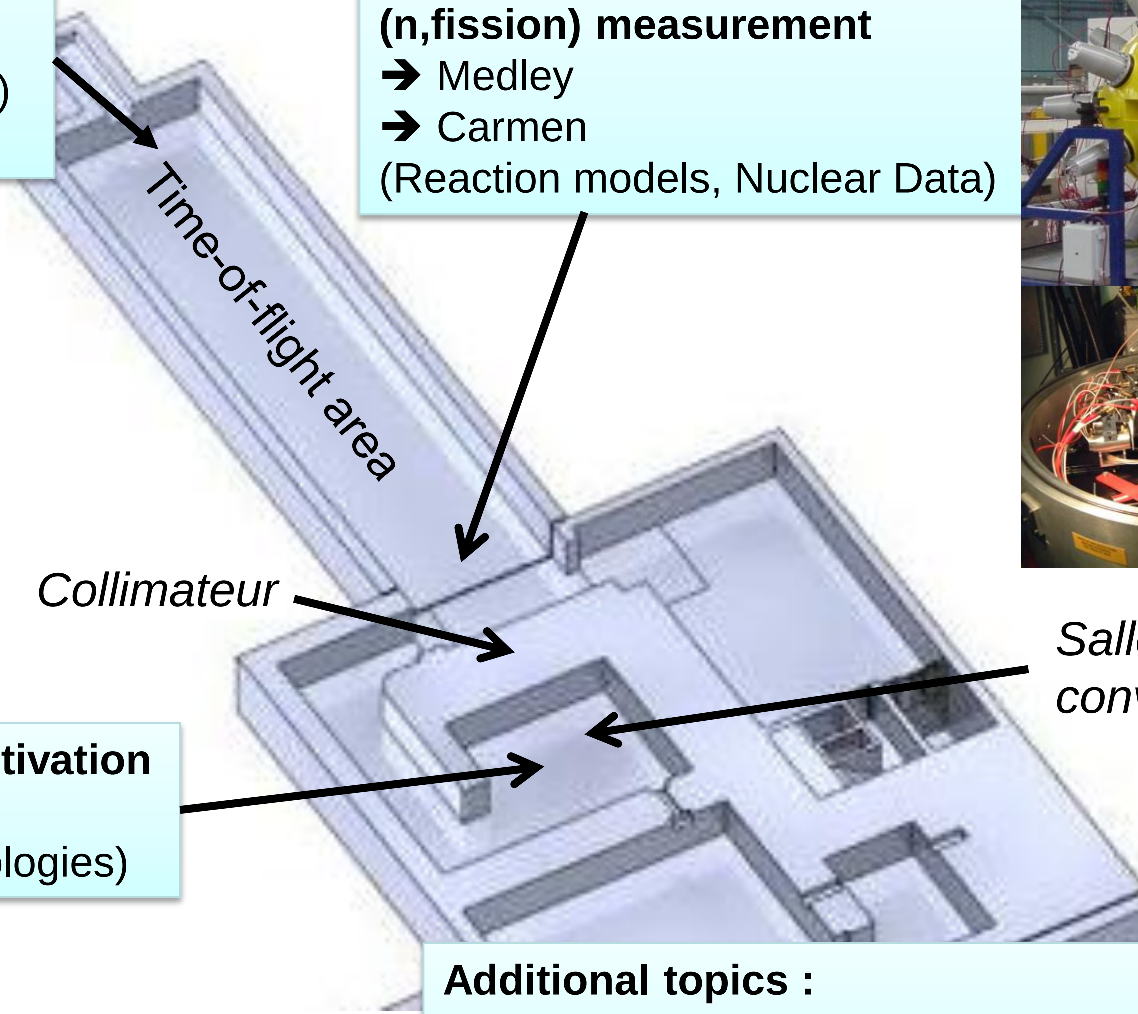
NFS Experimental Techniques

Differential XS (n,n'γ)
High Energy resolution measurement
➔ GAIN setup (Ge array)
(Nuclear Data)

Differential XS: (n,Xn), (n,LCP) (n,fission) measurement
➔ Medley
➔ Carmen
(Reaction models, Nuclear Data)

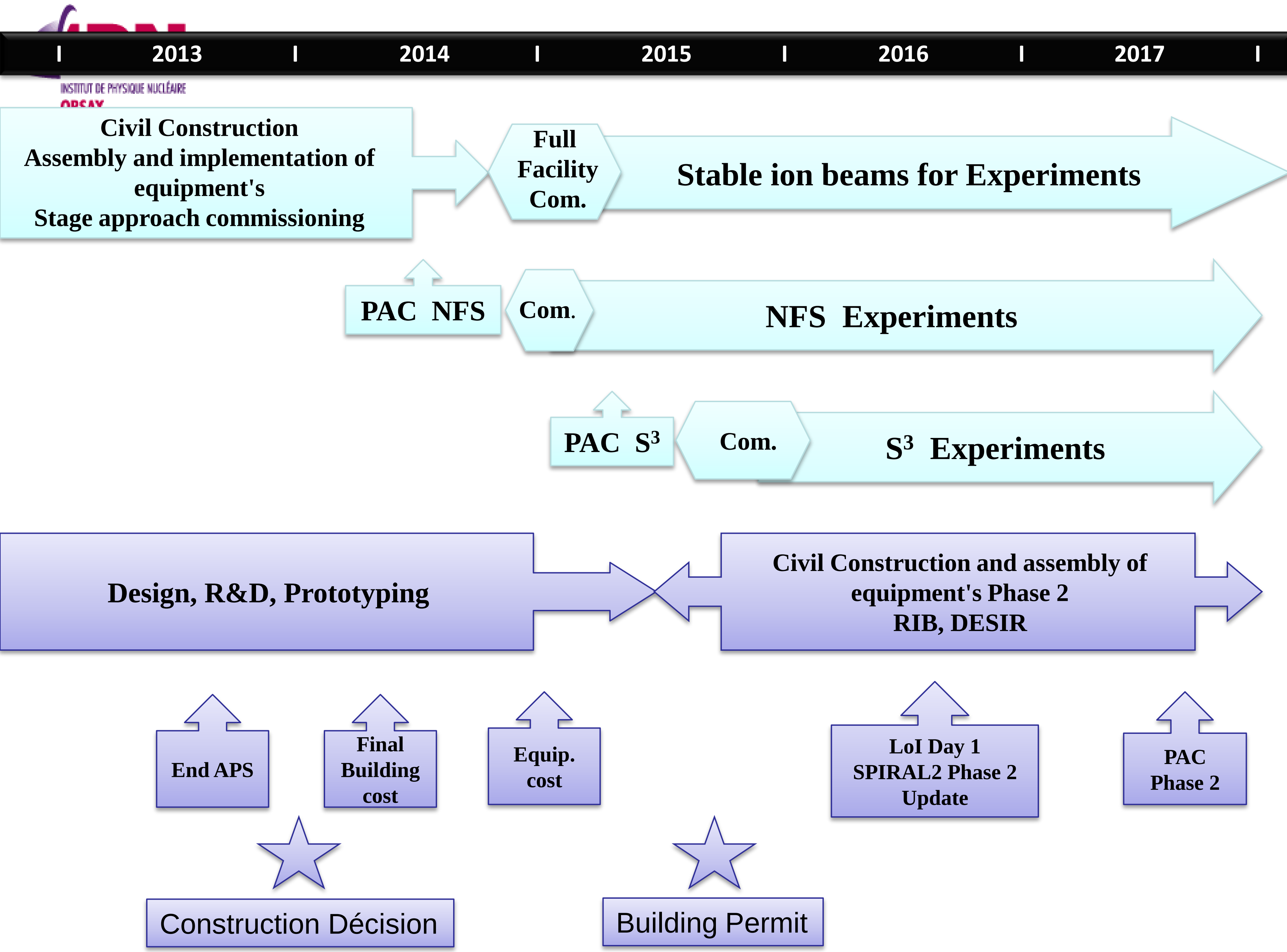






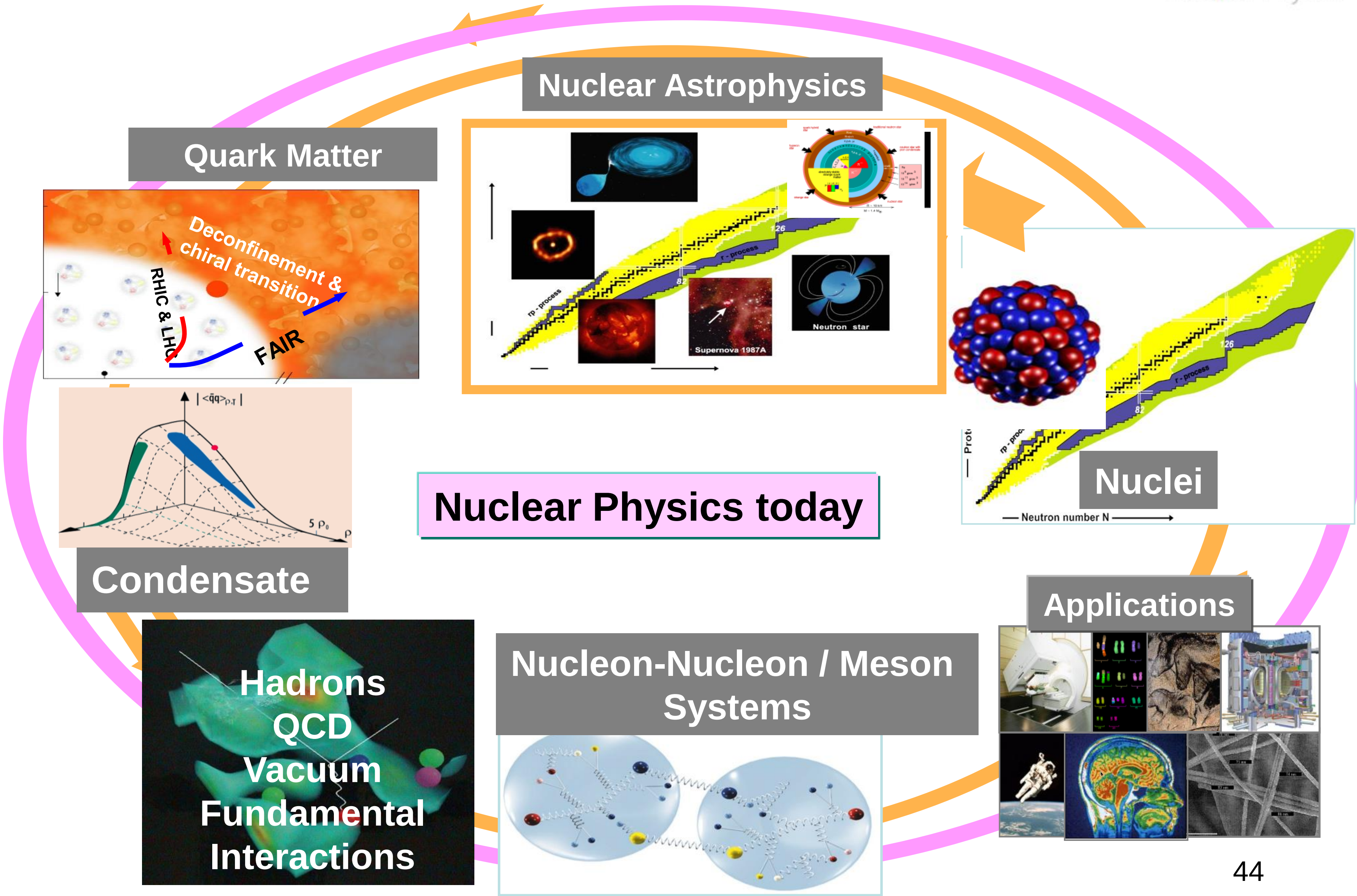
XS measurement by activation
➔ p,d,n,HI
(Fusion & Fission technologies)

Additional topics :
- Irradiation of electronic components, cells, …
- Detector characterization


2013
2014
2015
2016
2017
Civil Construction
Assembly and implementation of equipment's
Stage approach commissioning
Full Facility Com.
Stable ion beams for Experiments
PAC NFS
Com.
NFS Experiments
PAC S³
Com.
S³ Experiments
Design, R&D, Prototyping
Civil Construction and assembly of equipment's Phase 2
RIB, DESIR
End APS
Final Building cost
Equip. cost
LoI Day 1
SPIRAL2 Phase 2 Update
PAC Phase 2
Construction Décision
Building Permit

IPN INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

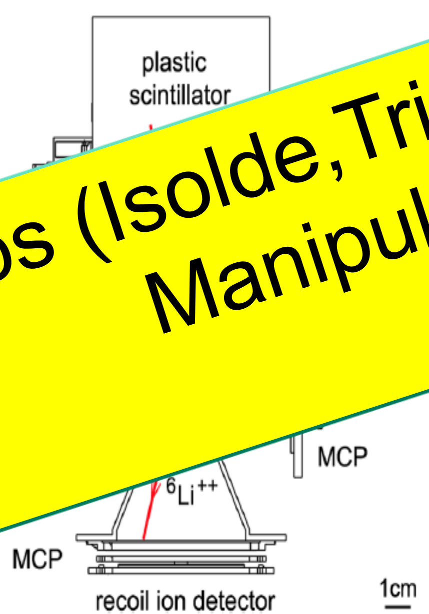
eli Nuclear Physics



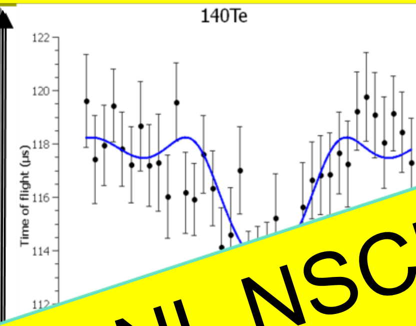
The nucleus ,a laboratory to study Fundamental interactions- High precision experiments

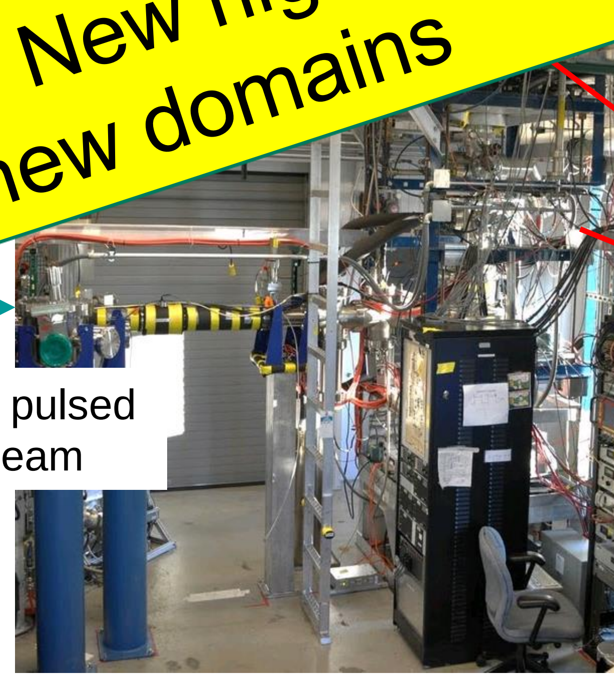
The LPC Penning Trap

CKM matrix – super-allowed transitions $0+ \rightarrow 0+$ Vud, Unitarity?
Scalar interaction? Rigth-handed currents?
– Study of β-neutrino coorelations



The CPT apparatus at CARIBU



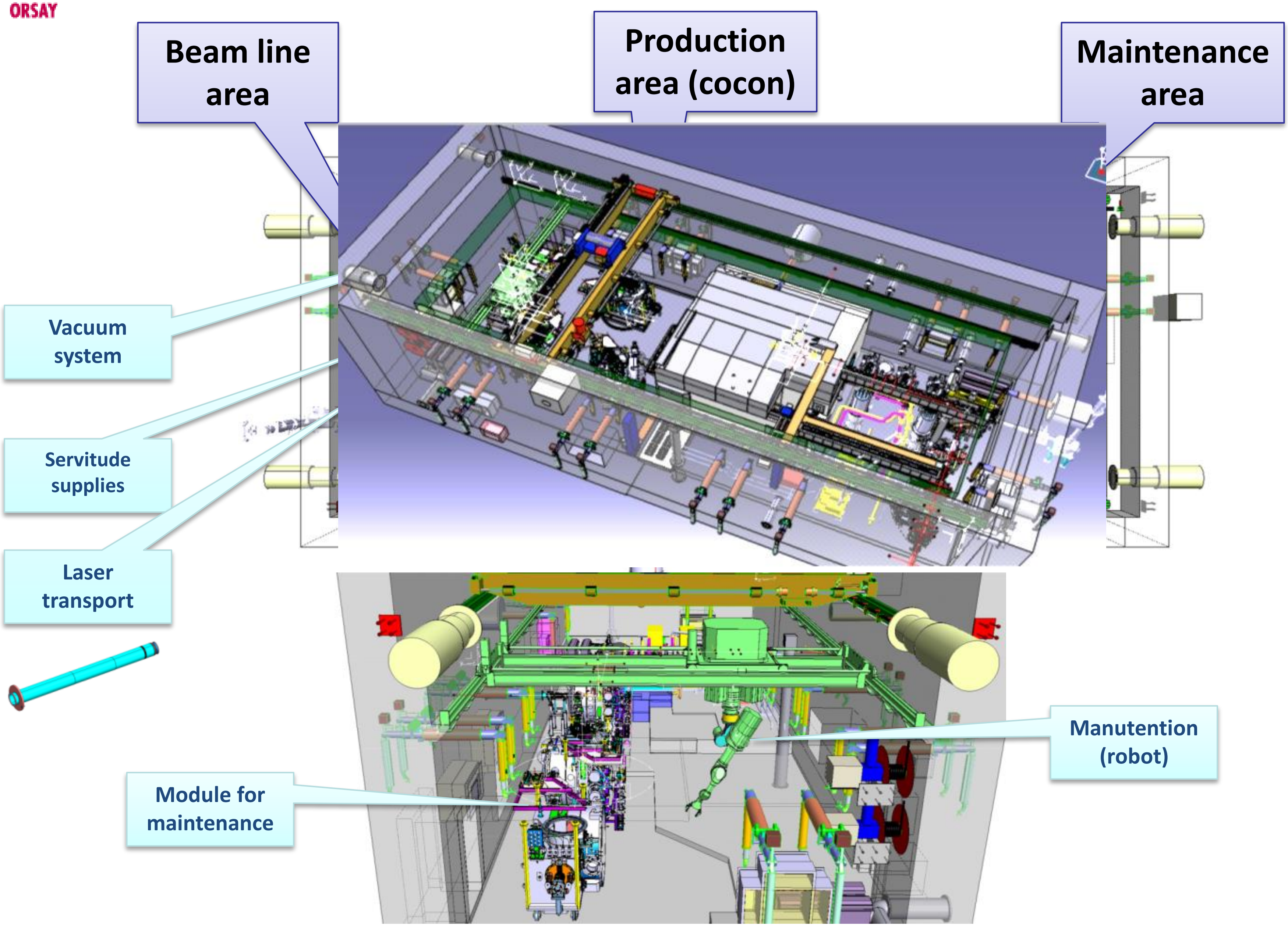


2 kV pulsed beam

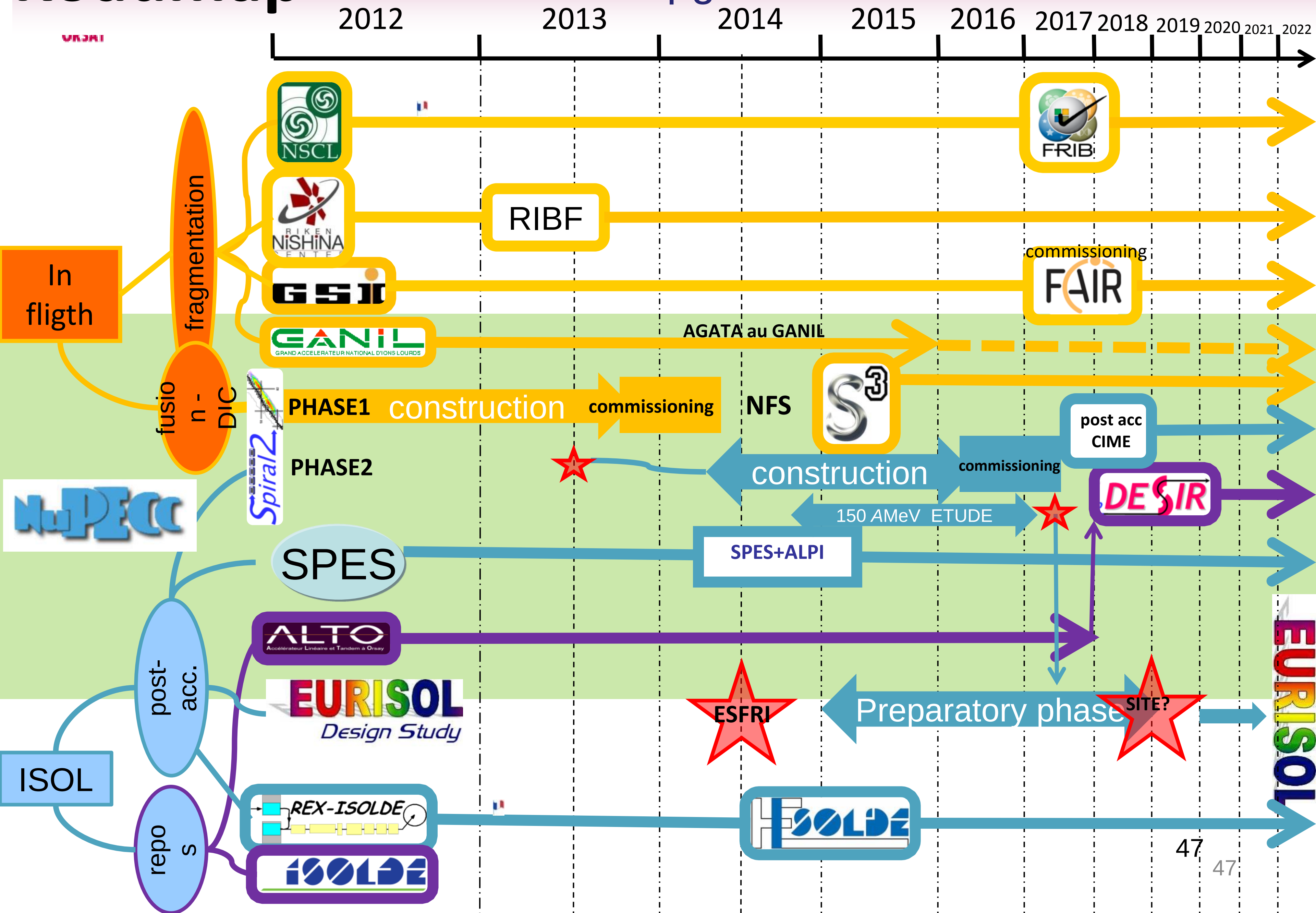
cryogenic linear ion trap

Traps (Isolde,Triumf, GSI,ANL,NSCL,JYVL,GANIL,..)
Manipulating ion - New high precision tools
Open new domains

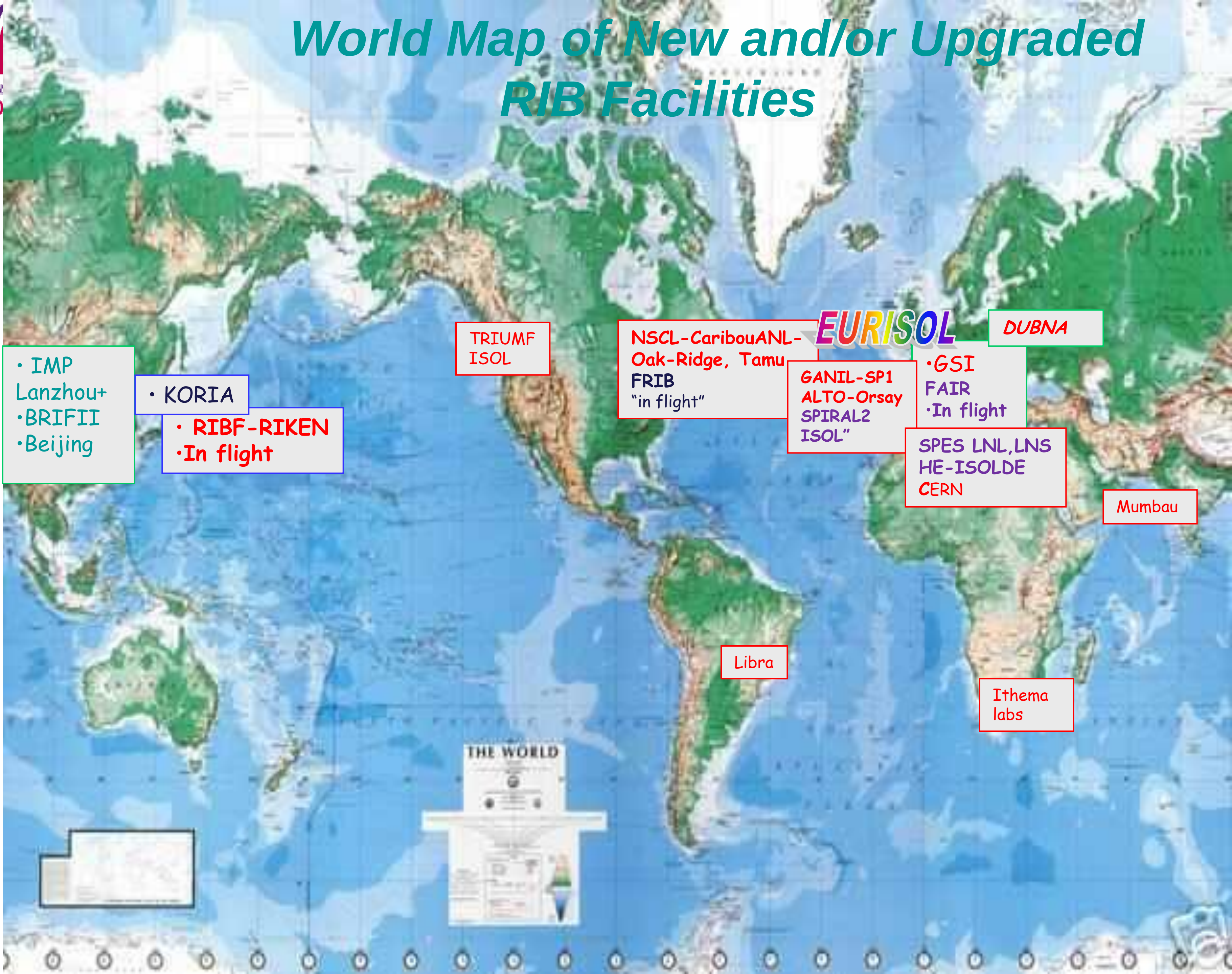
Production Module Cave



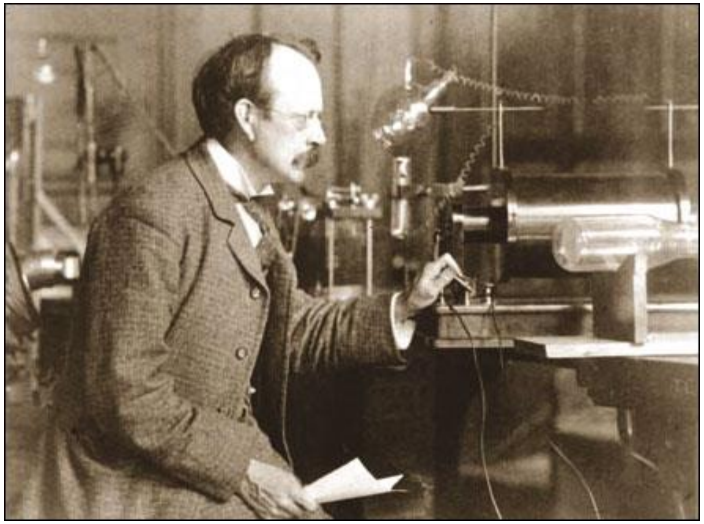
Roadmap Facilities new and upgrades 2010-2025

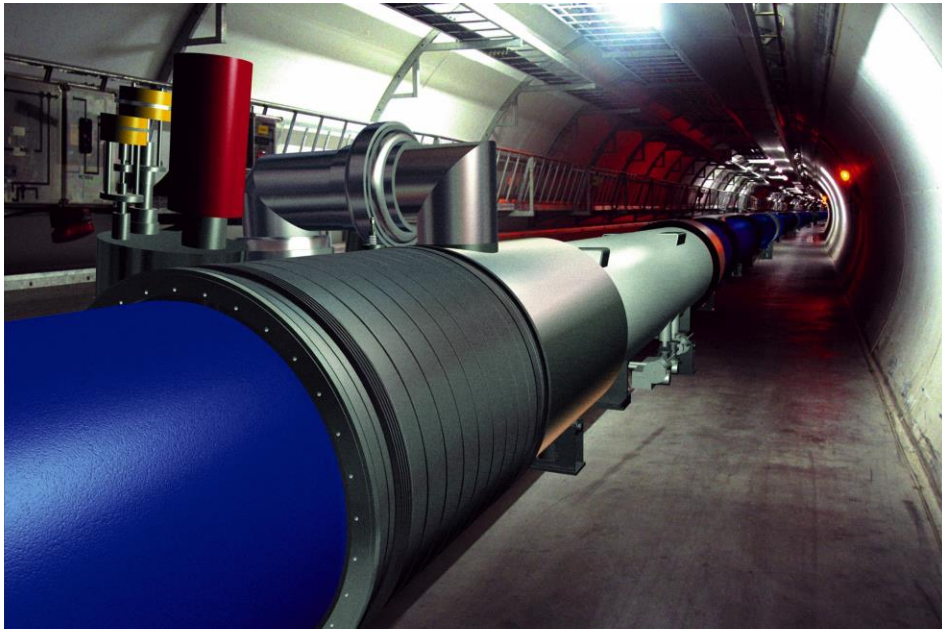


World Map of New and/or Upgraded RIB Facilities

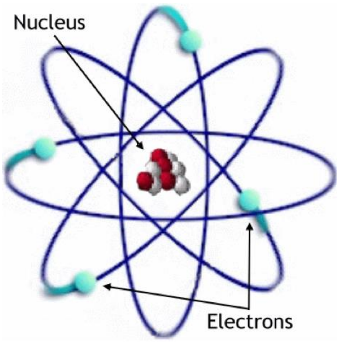


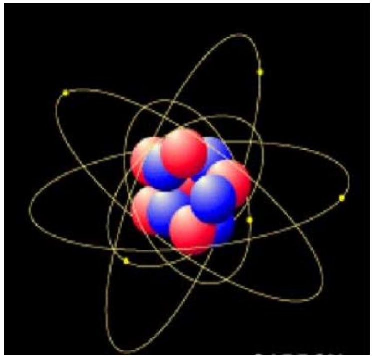
In the 20th century
Fundamental Research has been carried out and dominated by the Particle-based Paradigm:
namely accelerator for Massive and Charged particles

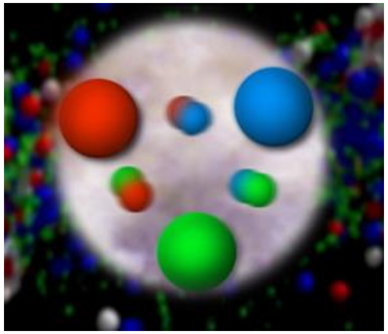




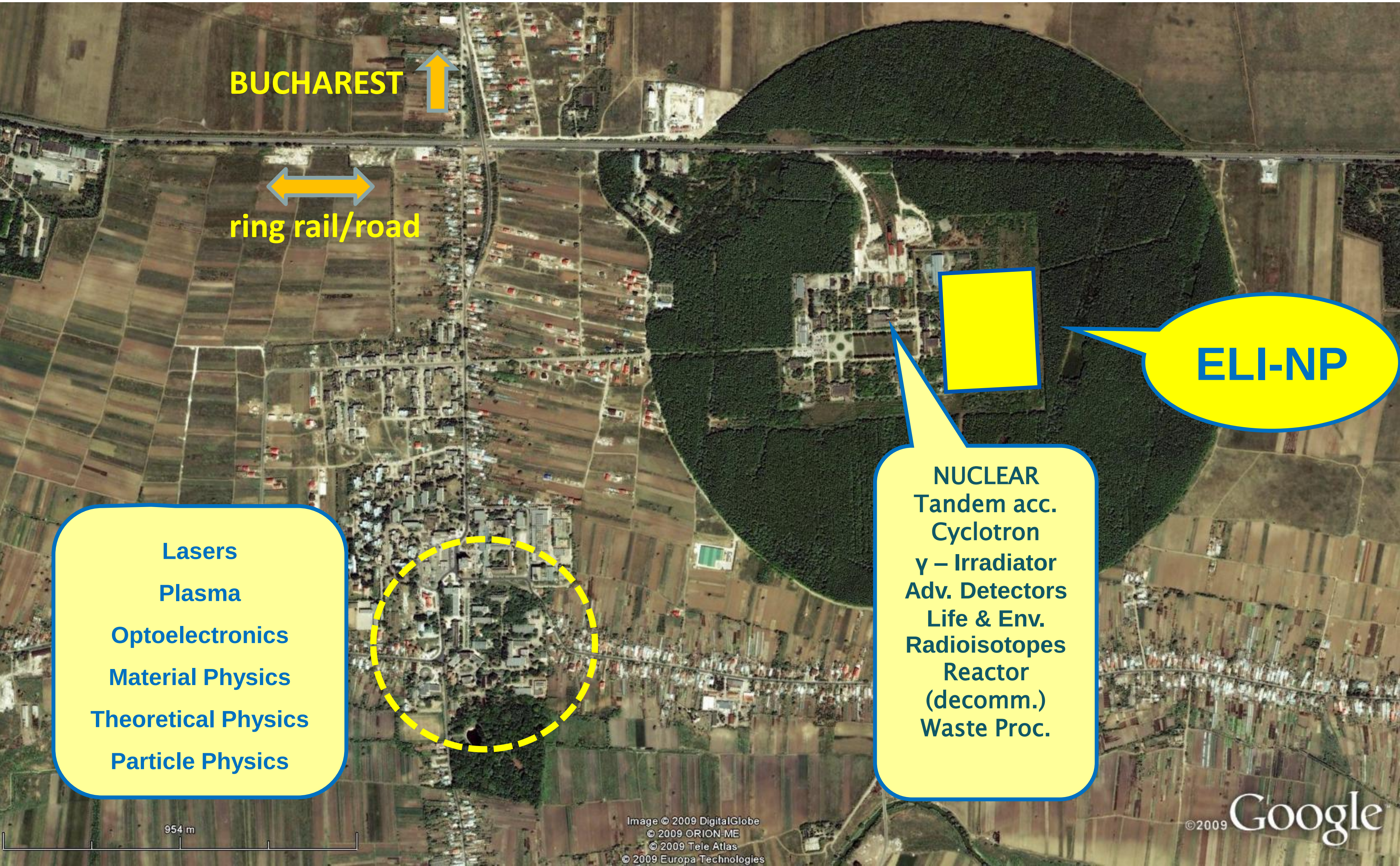
Mission:
Study matter from atom to vacuum
Fundamental Research &
Applications of Laser & Ion beams







Bucharest-Magurele Physics Campus
National Physics Institutes



IFIN-HH: International cooperation

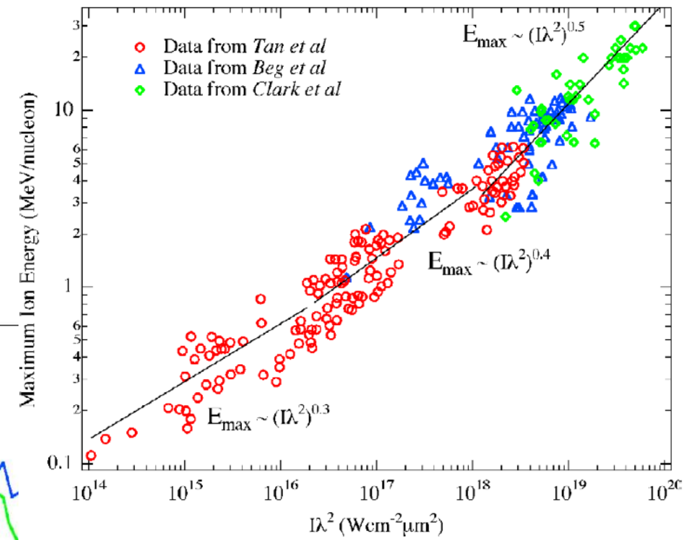
- **Member of: JINR Dubna, FAIR Darmstadt, CERN, ELI**
- European FP 7: 15 projects
- International Organizations: NuPECC, EPS-NPB, IUPAP, ECT.
- Agreements:

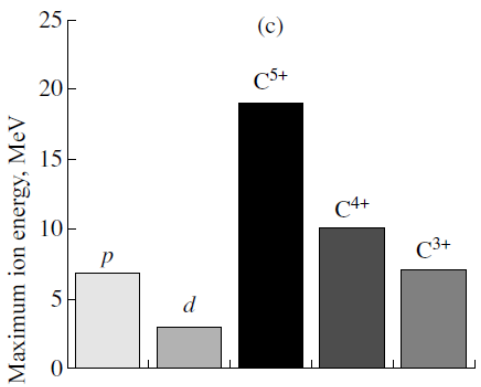
  IN2P3- France, CEA Saclay, ICTP-Trieste, INFN - Italy

  Universities & Research Centers: ~50.

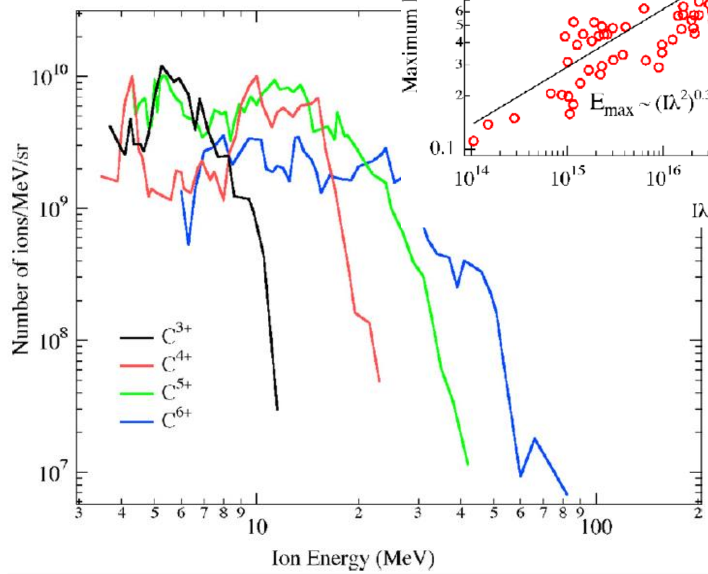
Ion beam acceleration

- Dependence of maximum energy function of the ion species
- Graphs show results for multi-TW-class lasers





Mylar target irradiated with a 10^{19}W/cm^2 laser pulse



Vulcan 50TW, Appleton Lab, $2x10^{19}$W/cm^2, thick lead target

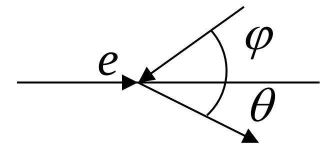
ELI-NP, the next step

- Proposed Gamma Beam Infrastructure
  - Very high intensity, narrow bandwidth
  - ~20keV resolution at E = 10MeV
  - A crystal monochromator may bring the BW down to 10^{-6}

Parameter	ELI-NP Laser, C.B.	S-DALINAC Bremsstrahlung	NEPTUNE Bremss + PT	AIST FEL, C.B.	HIGS FEL, C.B.	MEGA-ray Laser, C.B.
Energy range (MeV)	**0.1 – 20**	1 – 10	8 – 20	1 – 20	1 – 160	< 3.5 MeV
Relative bandwidth	**<0.3%**	-	>0.3%	1-8%	1-10%	0.1%
Time-average spectral density photons$(eV*s)^{-1}$	**$>10^4$**	$<10^3$	10	?	$<10^3$	10^5

ELI-NP Gamma beam production

$$E_\gamma = n \cdot 2\gamma_e^2 \cdot \frac{1+\cos\varphi}{1+(\gamma_e\theta)^2 + a_0^2 + \frac{4\gamma_e E_0}{mc^2}} \cdot E_0$$



$$n = \text{harmonic number}\,; \quad \frac{4\gamma_e E_0}{mc^2} = \text{recoil parameter}\,; \quad a_0 = \frac{eE}{m\omega_0}\,; \quad E_0 = \hbar\omega_0$$

Compton backscattering is the most efficient « frequency amplifier »

w_{diff}**$=4g_e^2$**w_{laser}

E_e=300 MeV and optical laser <=> g_e~ 600 => E_g > 3 MeV

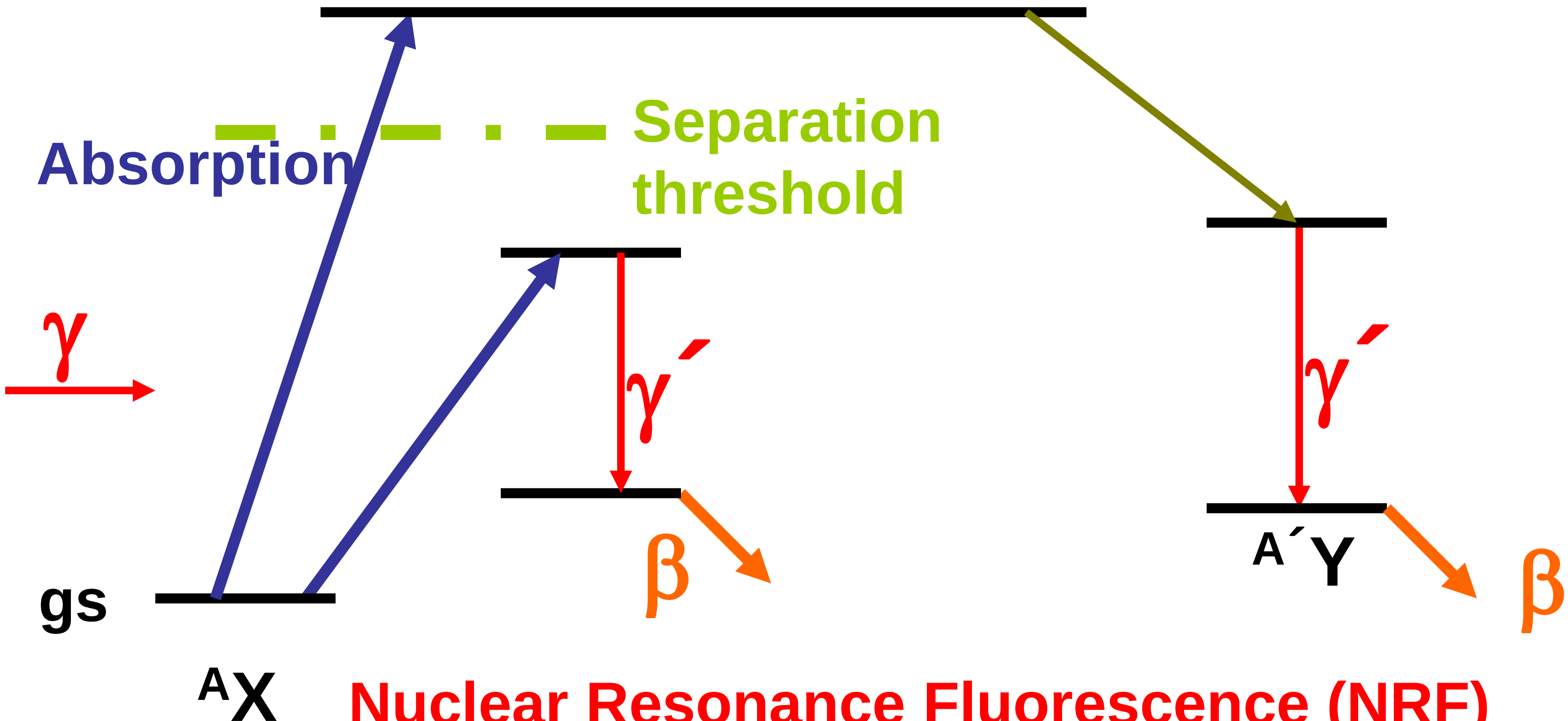
but very weak cross section: 6.6524 10^{-25} cm^2

Therefore for a powerful γ beam, one needs:

- high intensity electron beams
- very brilliant optical photon beams
- very small collision volume
- very high repetition frequency

Other 3rd generation MEGa-ray projects are now emerging to pursue nuclear science & applications

Photonuclear reactions



Nuclear Resonance Fluorescence (NRF)

Photoactivation

Photodisintegration (-activation)

ELI – NP Experiments (2)

Laser + γ /e− Beam

- Probing the Pair Creation from the Vacuum in the Focus of Strong Electrical Fields with a High Energy **γ** Beam
- The Real Part of the Index of Refraction of the Vacuum in High Fields: Vacuum Birefringence
- Cascades of e+e− Pairs and **γ** -Rays triggered by a Single Slow Electron in Strong Fields
- Compton Scattering and Radiation Reaction of a Single Electron at High Intensities
- Nuclear Lifetime Measurements by Streaking Conversion Electrons with a Laser Field.