Overview of perspectives in nuclear structure and Reactions at the european laboratories

OUTLINE

- **Exotic nuclei, nuclear excitations and nuclear matter properties and astrophysical implications**

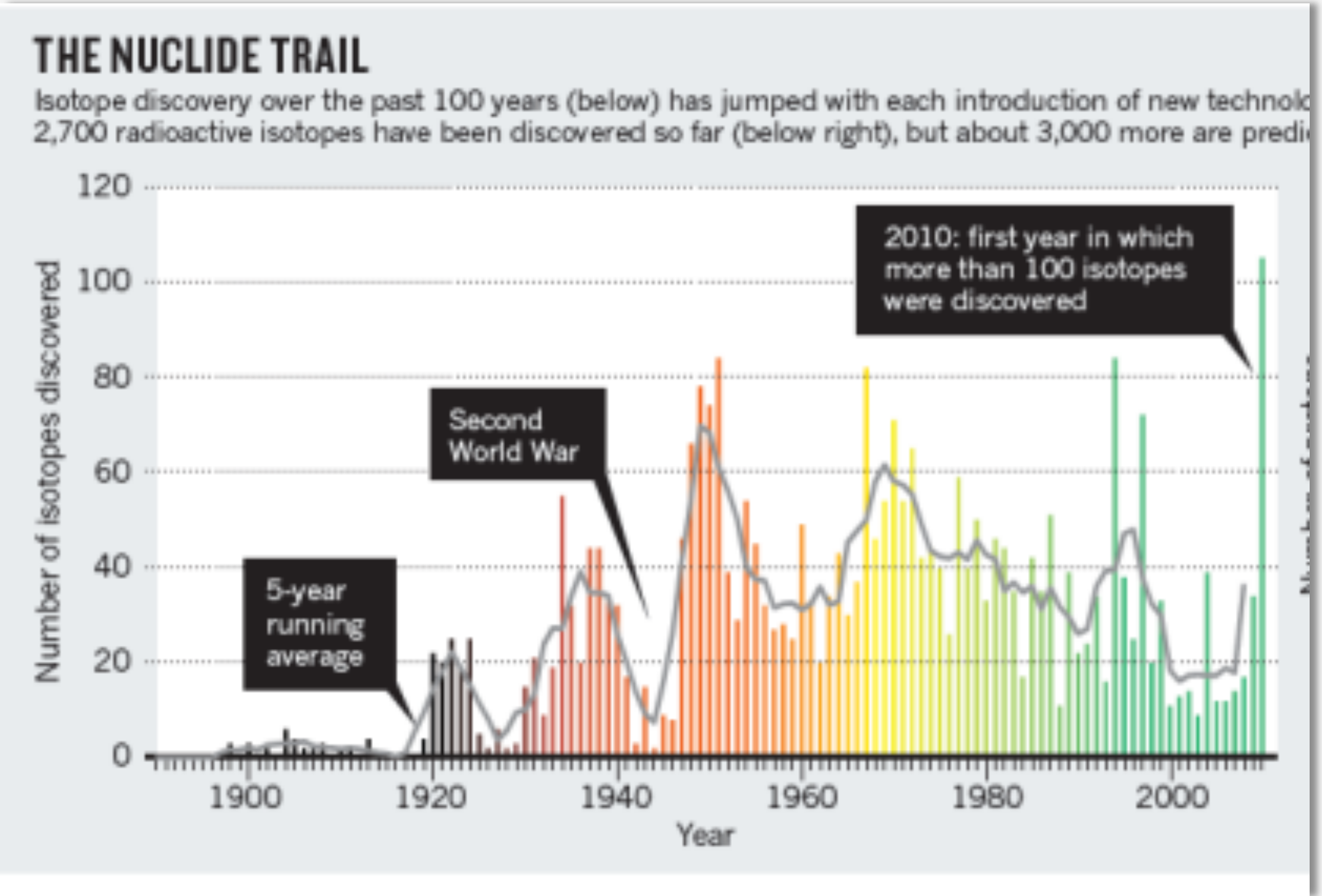
- **radioactive beam facilities :**

defining feature in the developments in this field over the last decade

Angela Bracco(Milano) - 20 Novembre 2011

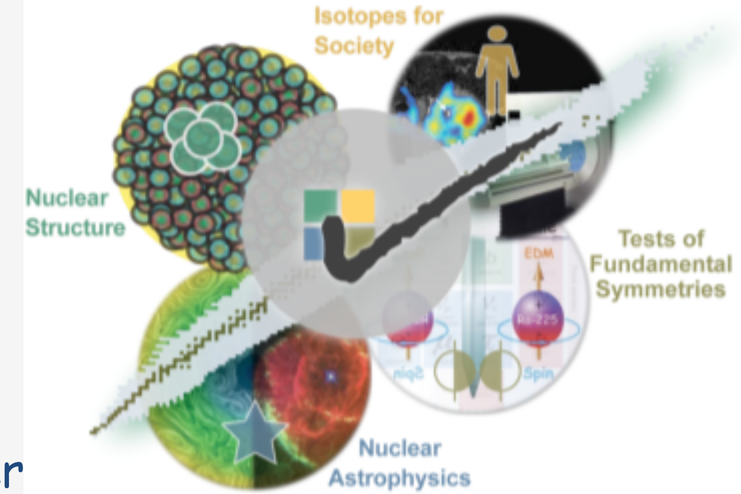
From isotopes to the stars

Creating more exotic isotopes will reveal the stellar formation of atoms



Nature. Vol 473, May2011 M. Thoennesen and B. Sherill

The Science of Rare Isotopes



Properties of nuclei (nuclear structure)

– Many-body quantum problem: intellectual over mesoscopic
science, quantum dots, atomic clusters, etc.

Nuclear processes in the universe

– Chemical history of the universe, (explosive) nucleo-synthesis
– Properties of neutron stars,
EOS of asymmetric nuclear matter

Tests of fundamental symmetries

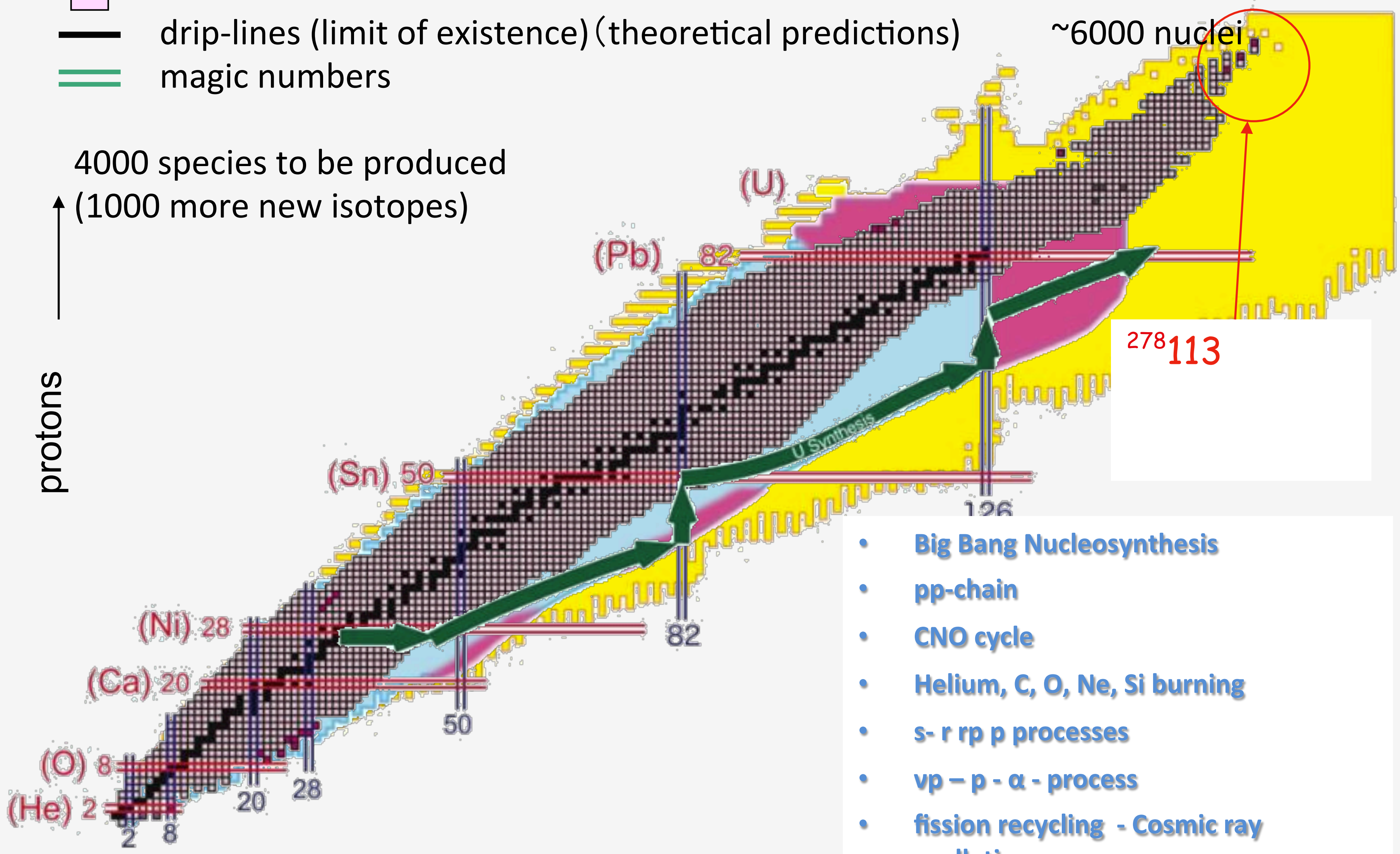
Societal applications and benefits

– Bio-medicine, energy, material sciences, national security

Exploration of the Limit of Existence

■	stable nuclei	~300 nuclei
□	unstable nuclei observed so far	~2700 nuclei
—	drip-lines (limit of existence)（theoretical predictions)	~6000 nuclei
=	magic numbers	

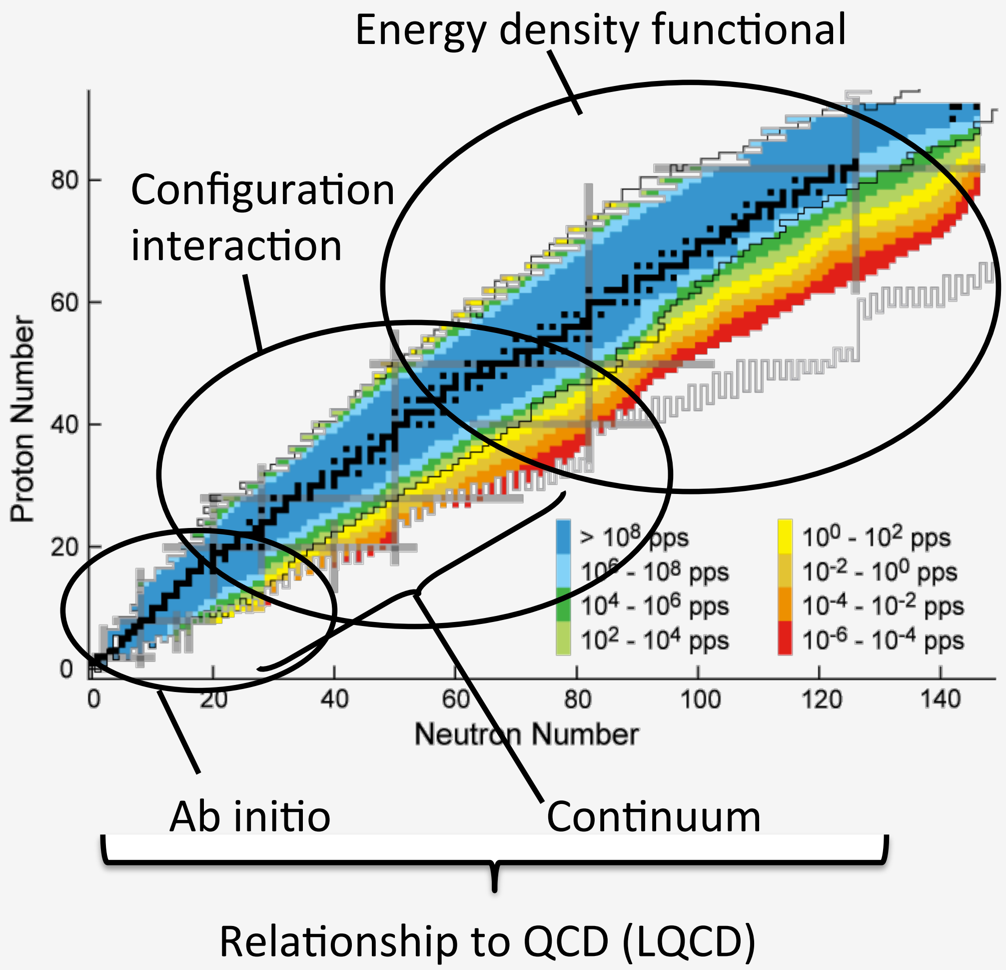
4000 species to be produced
(1000 more new isotopes)



- Big Bang Nucleosynthesis
- pp-chain
- CNO cycle
- Helium, C, O, Ne, Si burning
- s- r rp p processes
- νp – p - α - process
- fission recycling - Cosmic ray spallation
- + others

Theory Road Map: Comprehensive Model of Nuclear Structure and Reactions

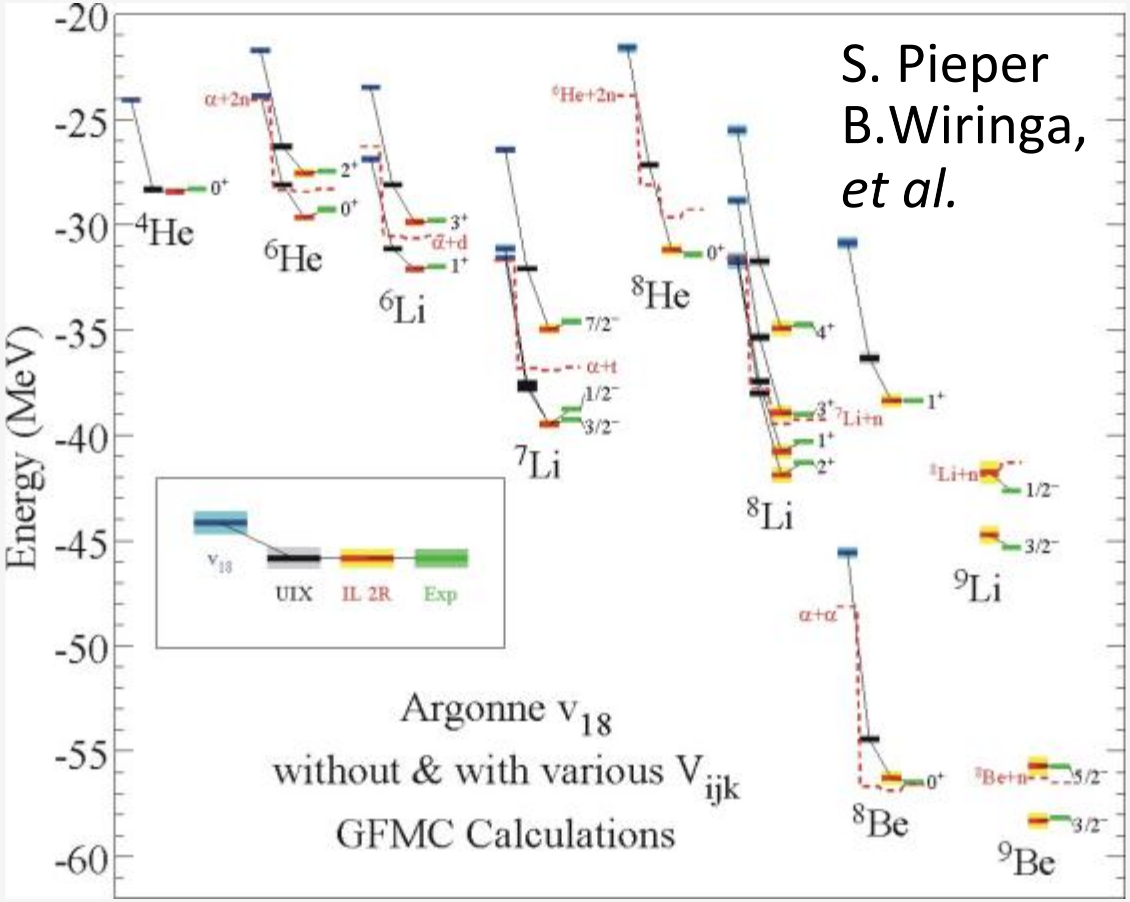
- **Ab initio models** – study of neutron-rich, light nuclei helps determine the force to use in models (measurement of sensitive properties for N=14, 16 nuclei)
- **Configuration-interaction theory**; study of shell and effective interactions (study of key nuclei such as ^{54}Ca, ^{60}Ca, ^{122}Zr)
- **The universal energy density functional** (DFT) – determine parameters (broad view of mass surface, BE(2)s, BE(4)s, fission barrier surface, etc.)
- **The role of the continuum and reactions and decays of nuclei** (halo studies up to A ~100)



- **IMPORTANT: Understand and select the most sensitive measurements**

Properties of exotic isotopes are essential in determining NN and NNN potentials

- Neutron rich nuclei were key in determining the isospin dependence of 3-body forces and the development of IL-2R from UIX
- New data on exotic nuclei continues to lead to refinements in the interactions
- EFT developments, LQCD and even computational power are providing insight for *ab initio* theories, but they need grounding in data

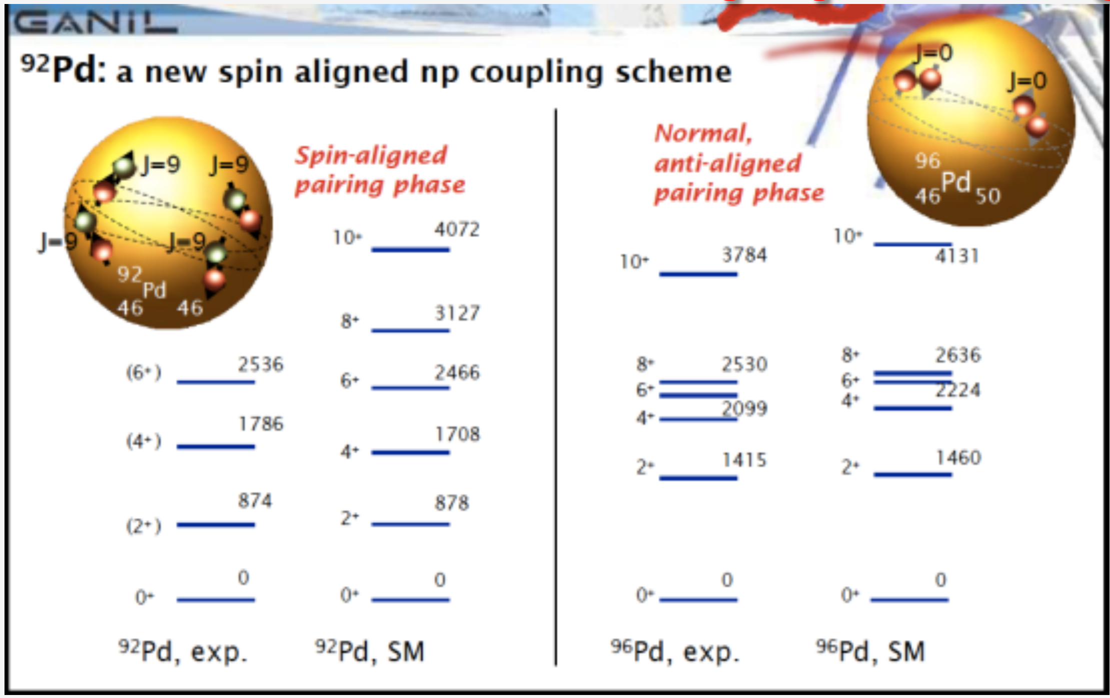


Interaction properties

proton rich nuclei

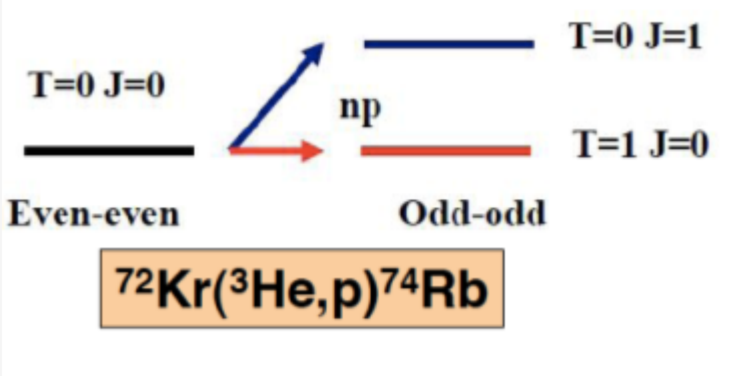
- **new form of pairing**
- **Isospin mixing**

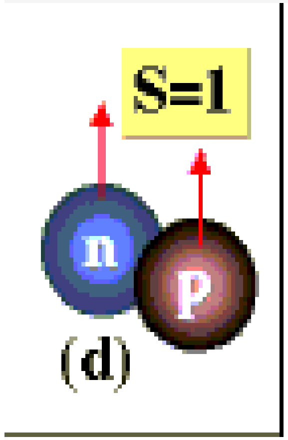
Forces : n-p pairing interaction

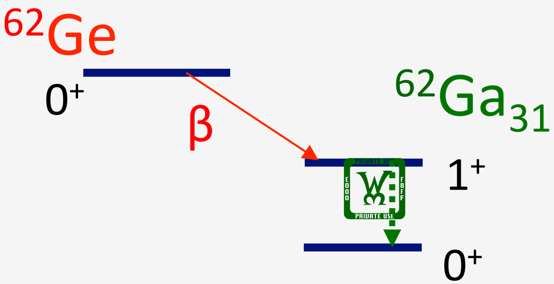


Fusion-evaporation reactions

+ np transfer reactions



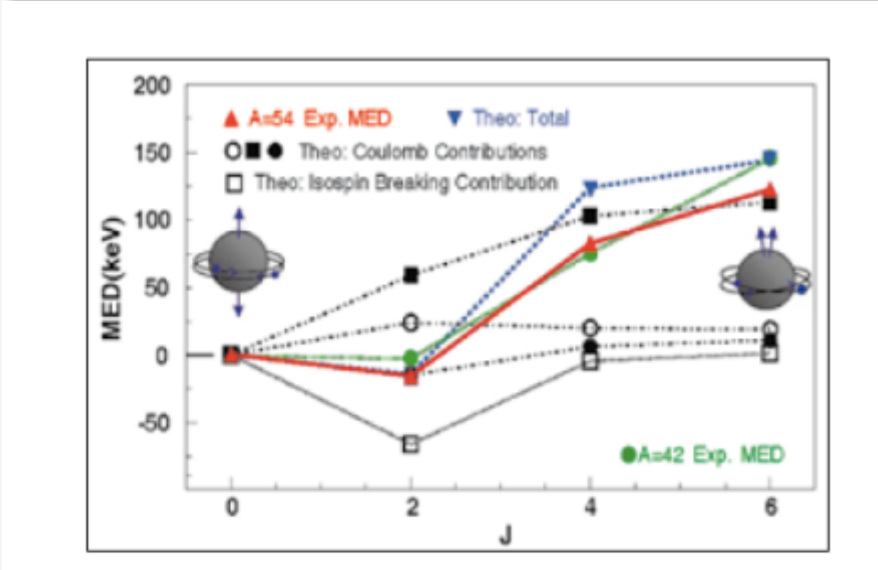


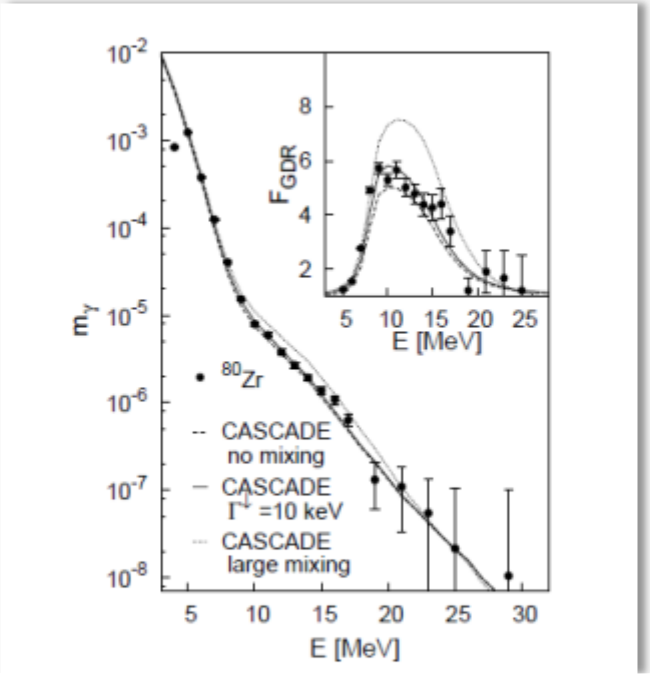


Favoured Gamow Teller decay at states 1^+ from odd-odd N=Z is expected

Symmetries – isospin mixing

Mirror nuclei -energy difference as a function of spin



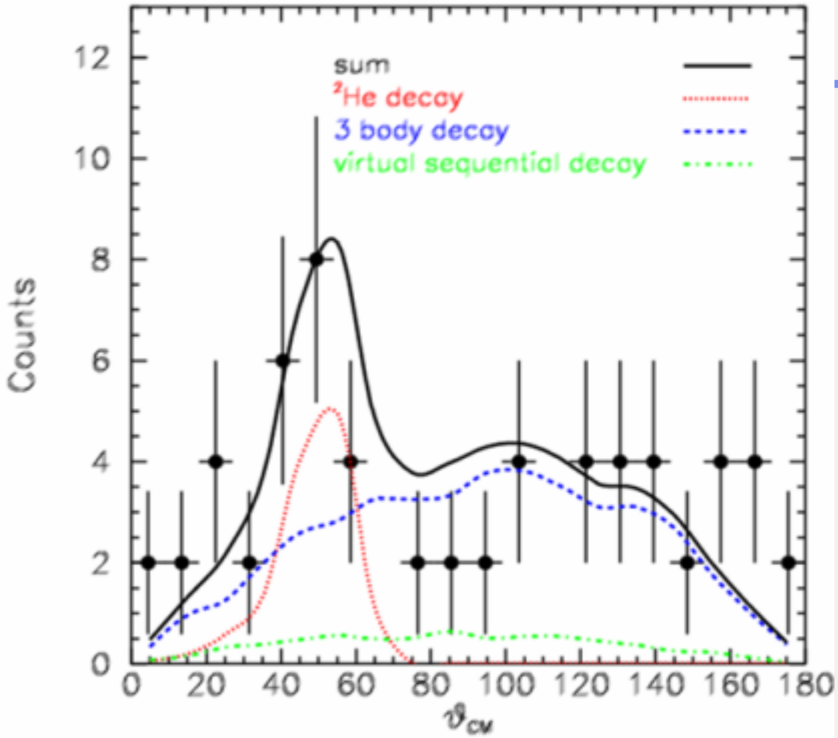


Isospin mixing at finite temperature

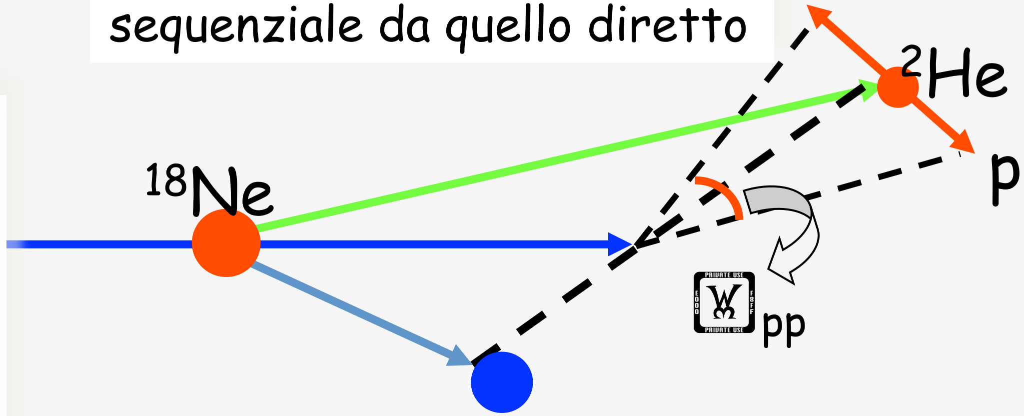
A. Corsi et al. PRC (2011)

2p decay del ^{18}Ne (prodotto per frammentazione)

FRIBS



La prima misura che separa il decadimento a tre corpi sequenziale da quello diretto



^{2}He (decay)=3± 7 %

3 body decay~6± 9 %

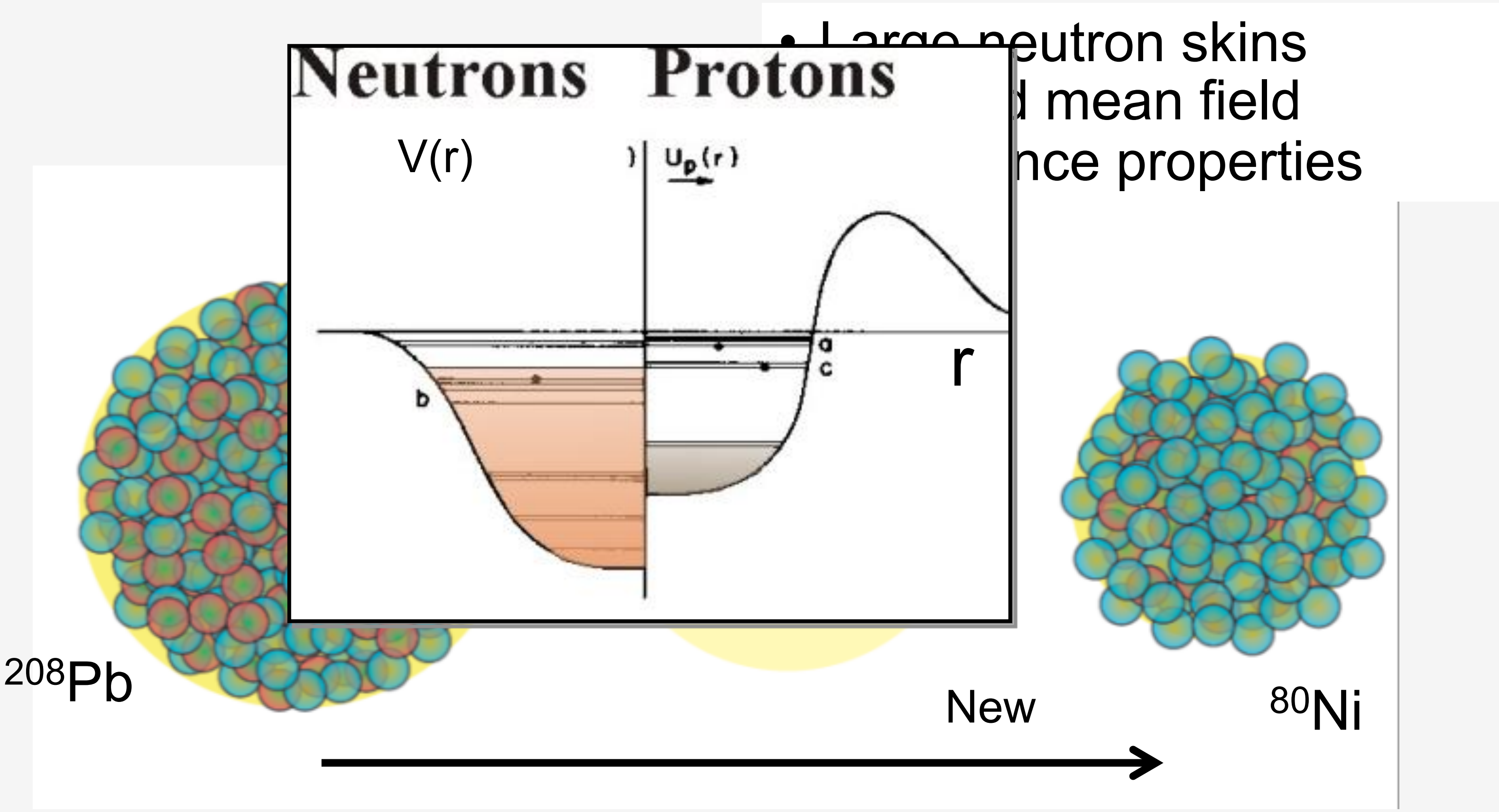
“Virtual” sequential decay=± 2%

Ruolo della forza di pairing in nuclei proton rich prossimi alla drip-line

PRL (2008)

Fasci dei Ciclotrone frammentati su Be e trasportati su bersaglio di Pb

new exotic isotopes n rich



Science: Pairing in low-density material, new tests of nuclear models, open quantum system, interaction with continuum states - Efimov States - Reactions

Challenge for r-process path and explosion in supernovae

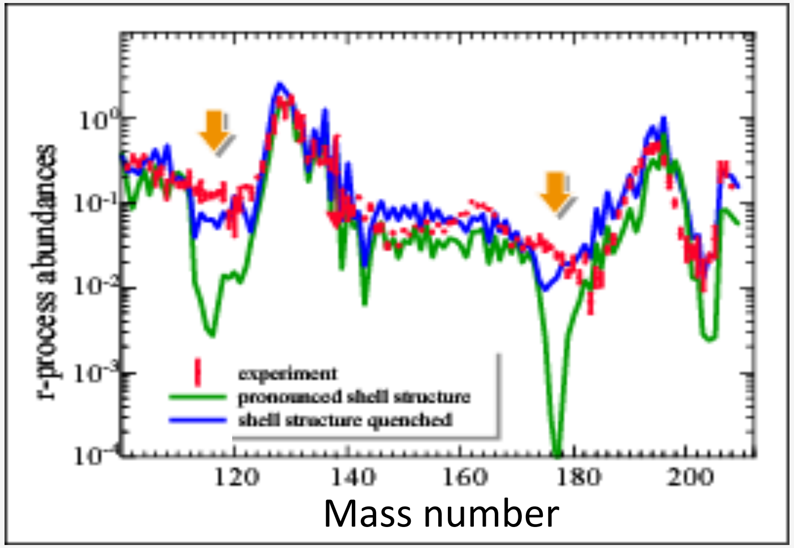
Synthesis up to U （r-process 50% of heavy elements）

unknown neutron-rich nuclei

theoretical predictions only

nuclear properties of heavy and neutron-rich nuclei

Mass, life-time, decay mode



Explosion mechanism of supernova

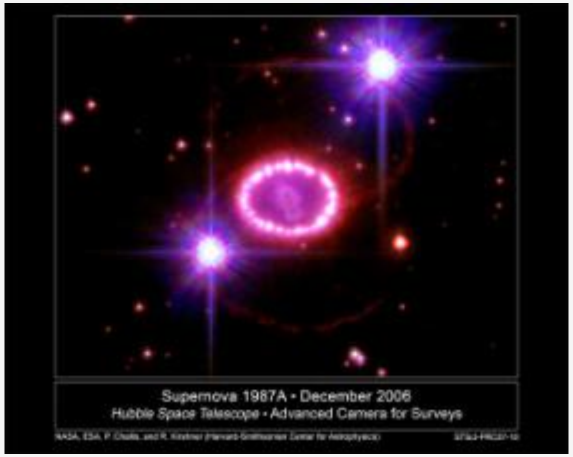
No explosion in theoretical works

Outer crust of neutron star

Equation-of-State in asymmetric matter

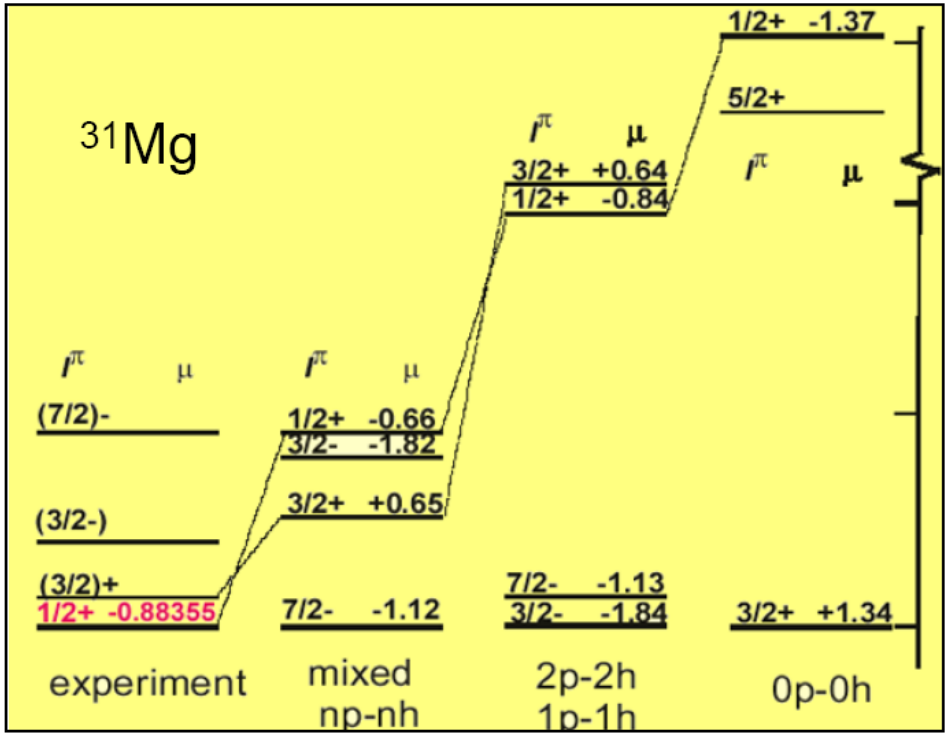
Higher density: 3NF (T=3/2)?

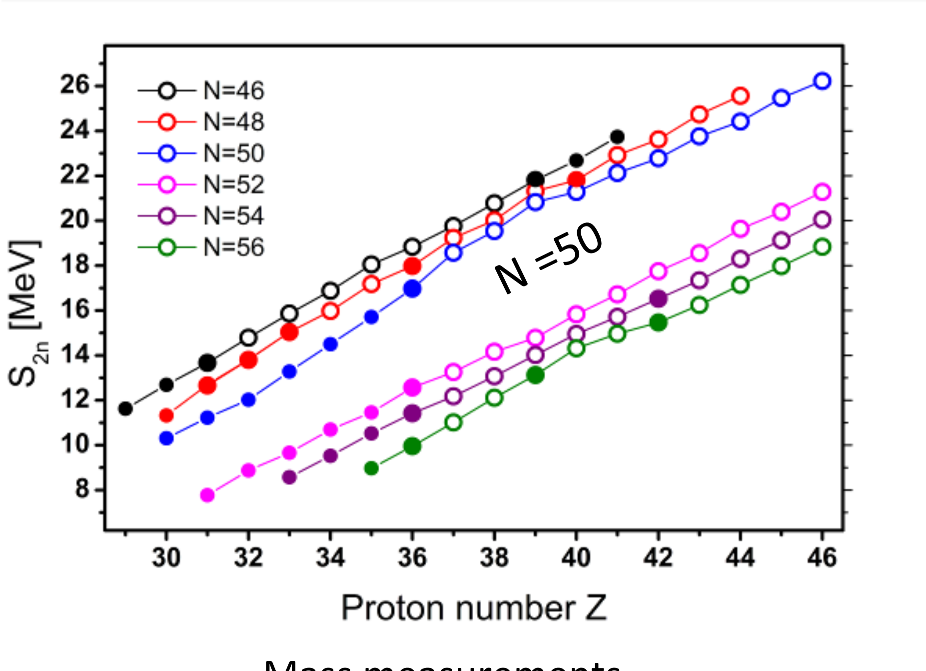
Dilute matter : BEC, cluster-formation?



1987A

Ground-state properties





Mass measurements
→ N = 50 gap survives

Hyperfine-structure and β -NMR measurement
→spin and magnetic moment
→the ground state of ^{31}Mg
is an 2p-2h deformed intruder state

Very large variety of instruments and ion-beam manipulation methods needed.. Extreme RIBs are welcome.

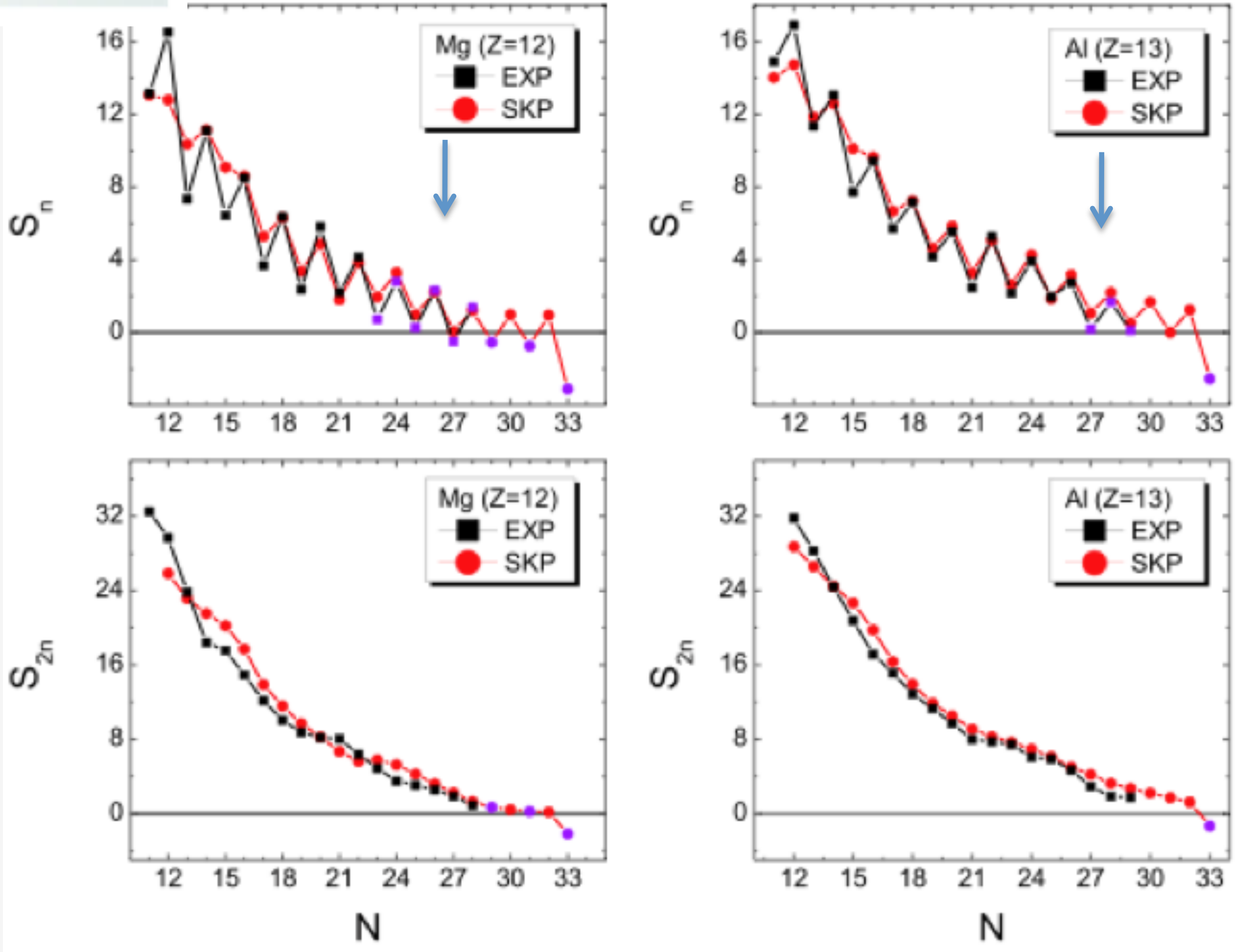
Density Functional Theory

UNEDF SciDAC Collaboration

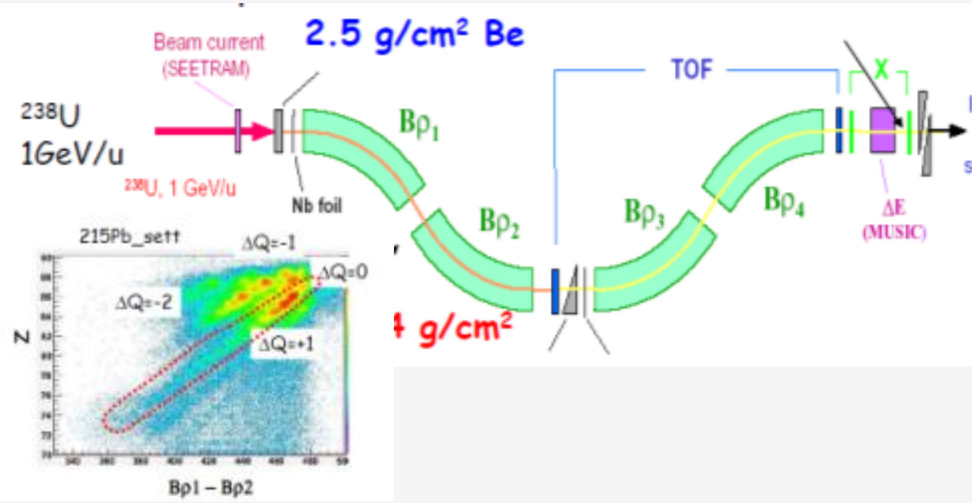
Universal Nuclear Energy Density Functional

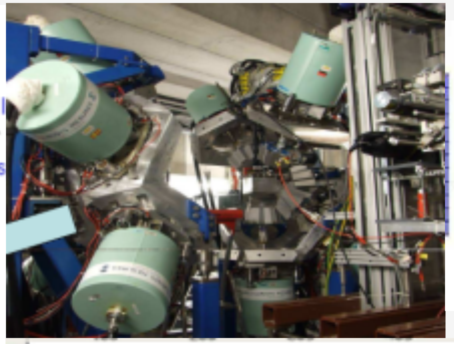
M. Stoitsov et al.

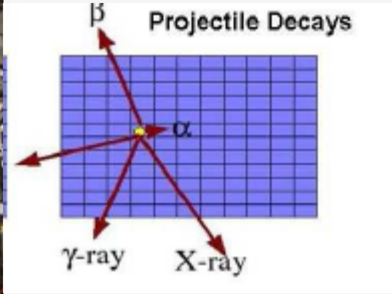
- EDF calculation of the binding energies of 9000 isotopes (M. Stoitsov et al.)
- Key tests of the theory come at the limits of binding (see figure)
- Remarkable success so far; Global DFT mass calculations from HFB Δm~700keV
- Goal is to achieve the kind of results obtained in quantum chemistry

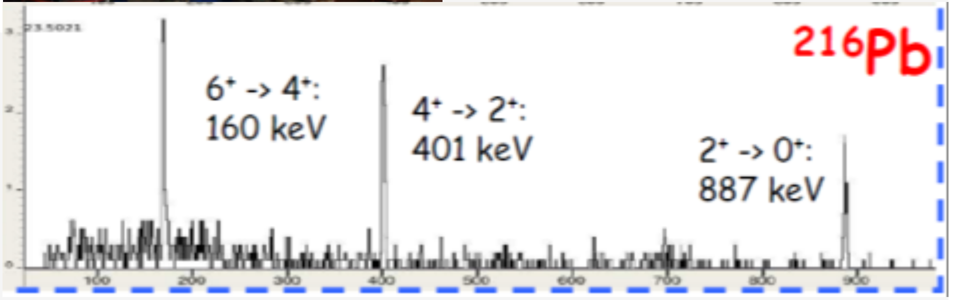


Beta decay of short lived n-rich nuclei

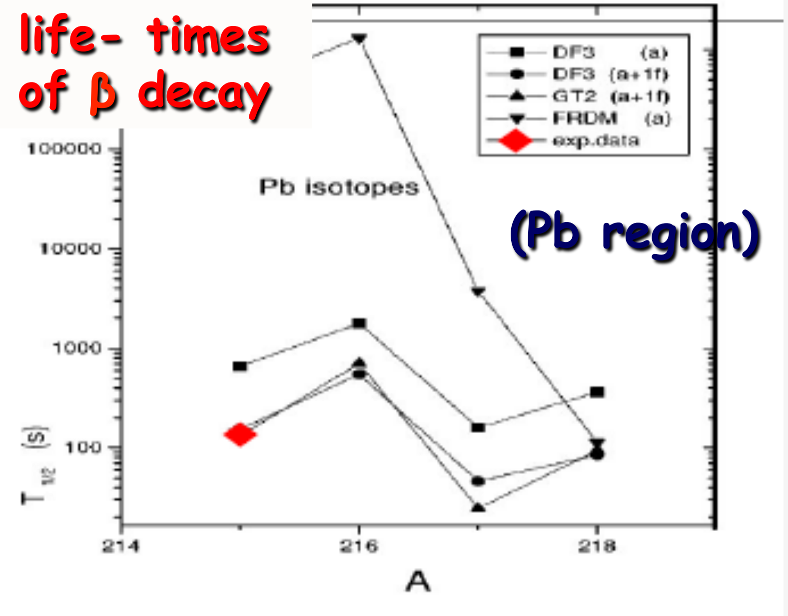








life- times of β decay

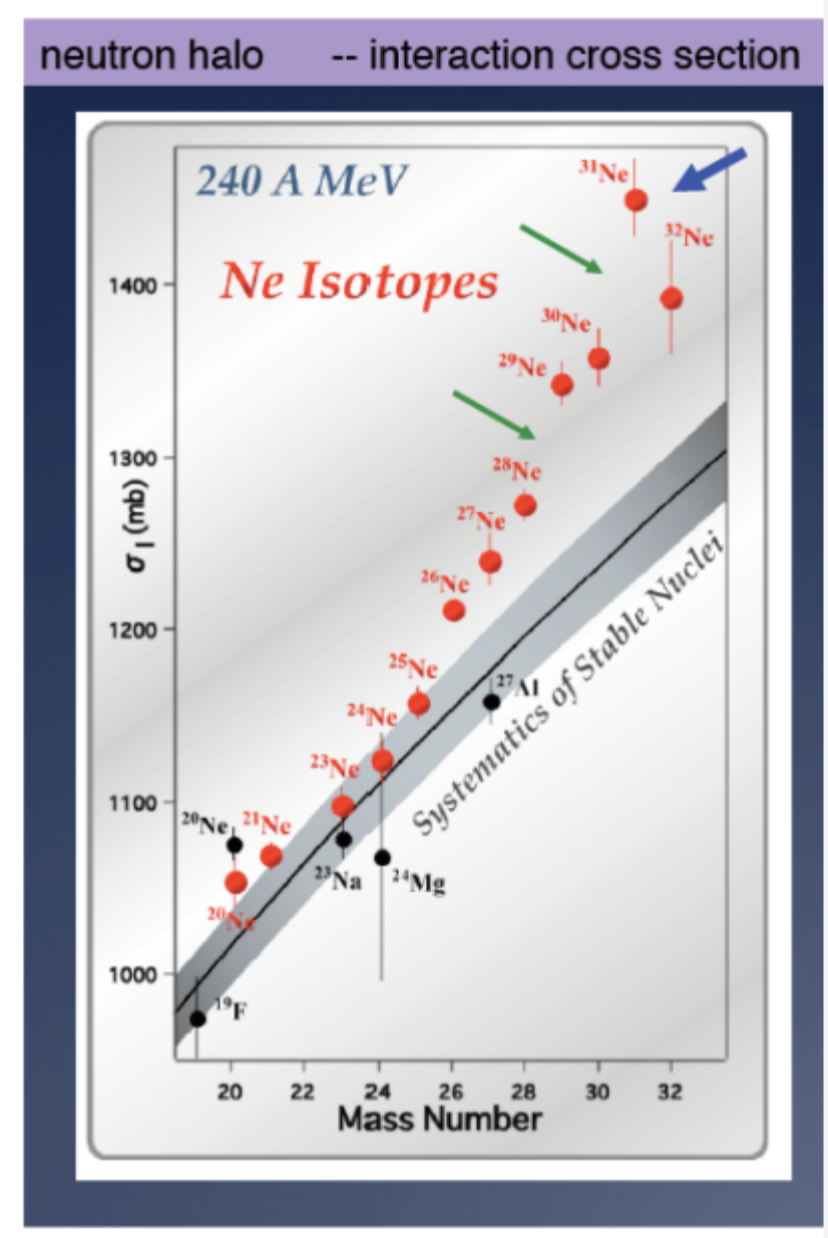


(Pb region)

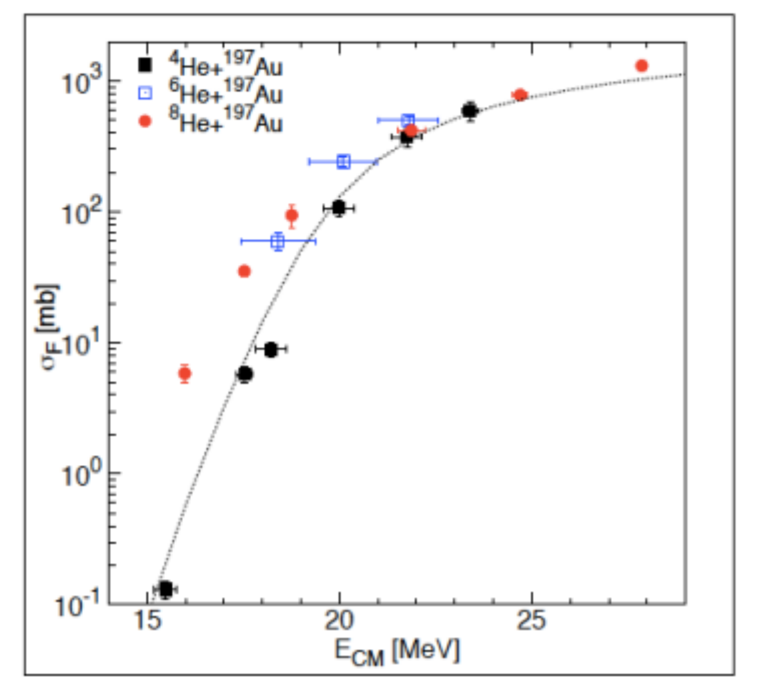
Gamma and beta decay

Stringent test to theory data are needed in different mass regions !

Halo and Nuclear radius



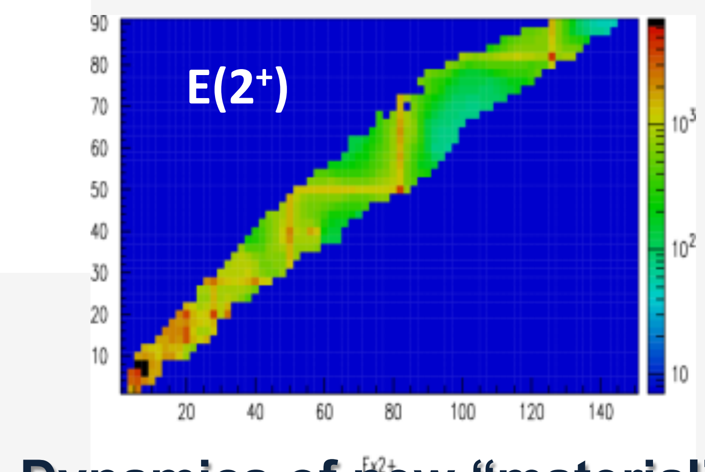
reaction measurements



Fusion reactions

Nuclei away from the Stable Region

Shell Evolution : magicity loss and new magicity

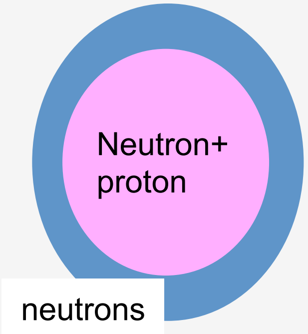


Shape ? shape coexistance?
Shell gap？
Single particle level？
Cluster formation?
Role of 3NF ?
Magicity loss ？
50、82、126、184

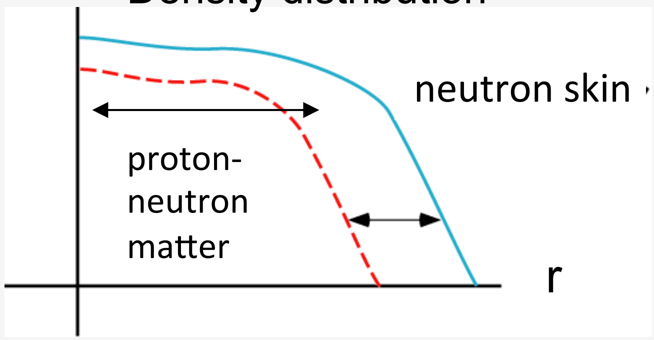
Deformed

Spherical

Dynamics of new "material" : Neutron-skin（halo）



Density distribution

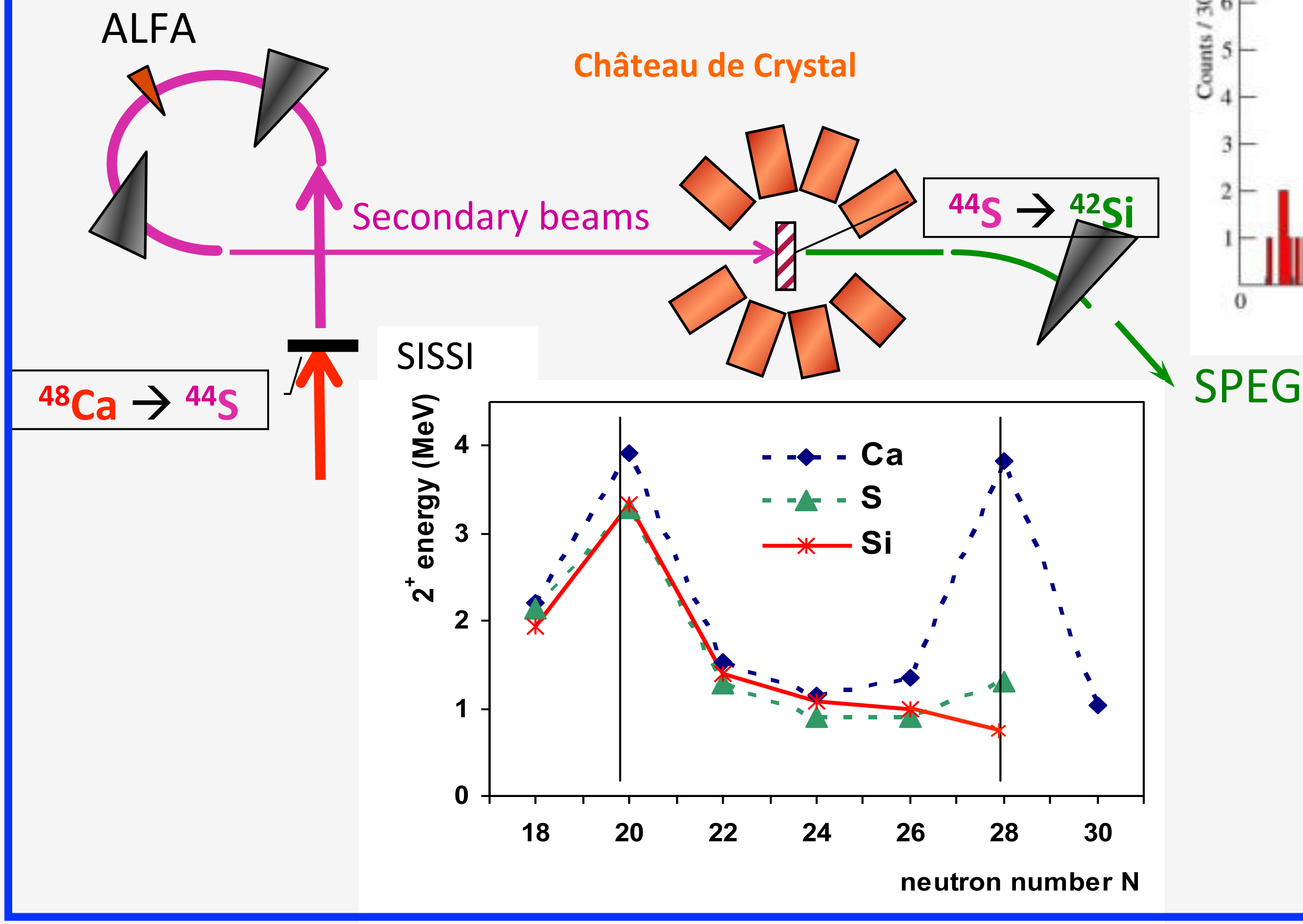


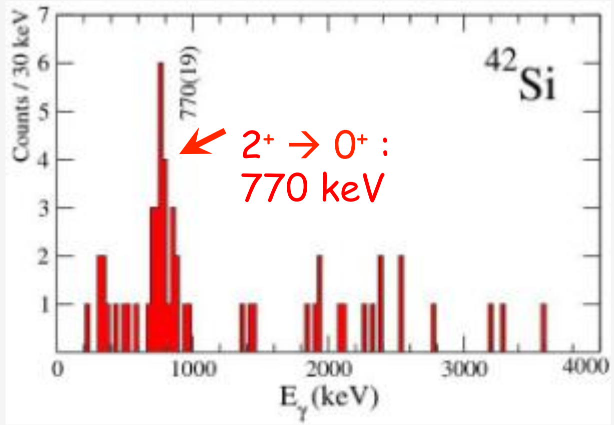
<u>Quantum-objects having two surfaces</u>
Skin thickness？Density distribution？
Role of skin in reactions？
Pairing in skin？ di-neutrons?
Exotic modes of skin？

Challenges in establishing new frame work of nuclear physics

Shell structure and isospin degree of freedom

Collaps of the N = 28 shell closure in $^{42}Si_{28}$





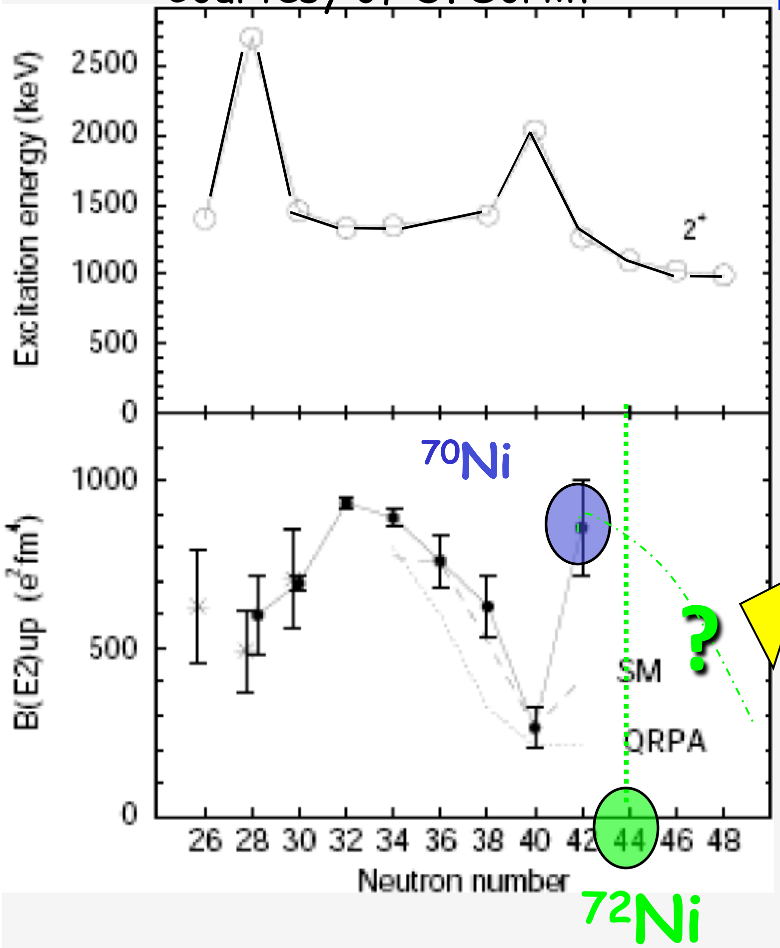
Wide range of intense RIBs, high-efficiency separators and gamma-ray arrays needed to probe new shell structures and isospin degree of freedom

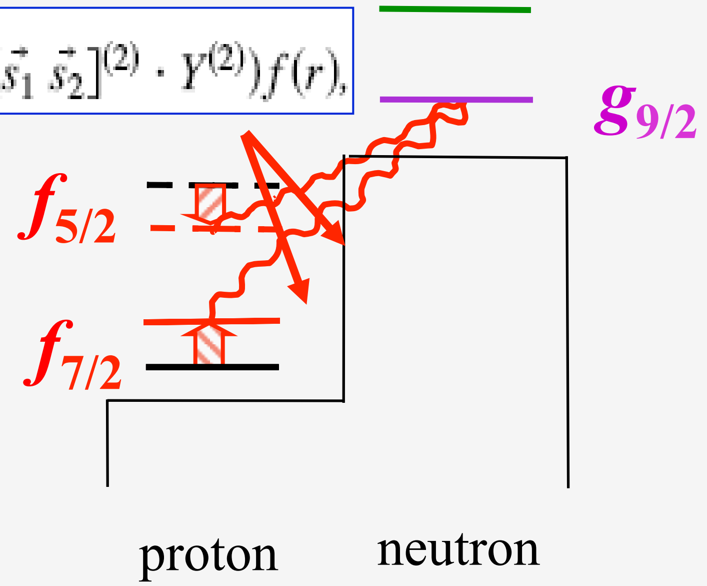
Tensor force in neutron rich nuclei

Variation of single proton particle energy due to the p-n tensor interaction p-n

$$V_T = (\vec{\tau}_1 \cdot \vec{\tau}_2)([\vec{s}_1\, \vec{s}_2]^{(2)} \cdot Y^{(2)}) f(r),$$

Courtesy of O. Sorlin





Region of stronger effect because there are more n in $g_{9/2}$ orbital

Gamma spectra + lifetimes

In ^{50}Ca PRL(2009)Valiente et al.

T. Otsuka et al. PRL 95, 232502 (2005)

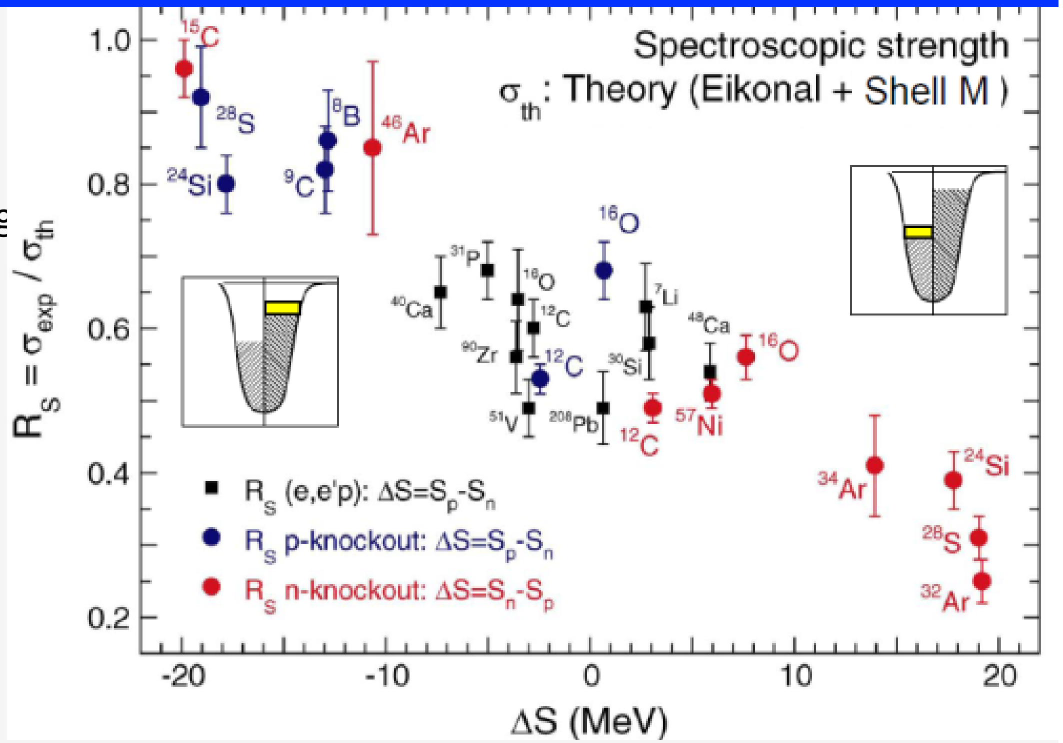
Reaction dynamics

Quasi-free scattering

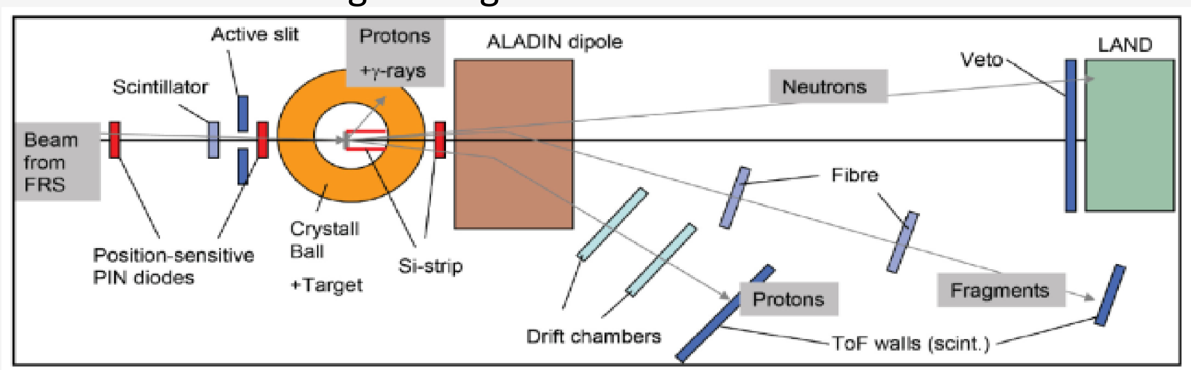
The striking observation of a strong quenching of the single-particle strength as a function of asymmetry of the neutron and proton separation energy

Origin : 3N forces

particle vibration couplings

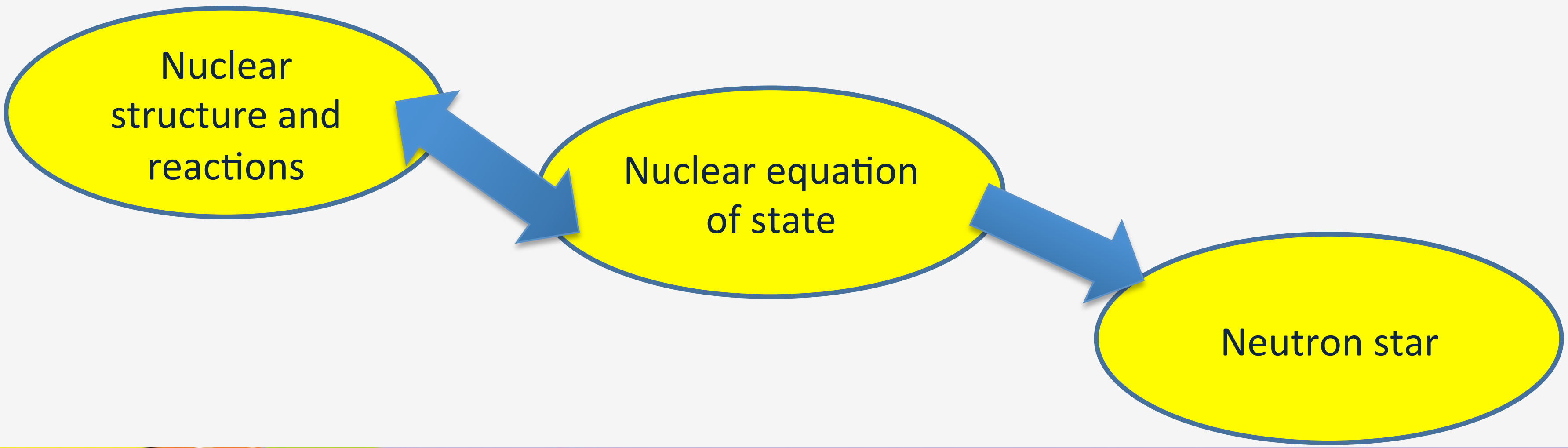


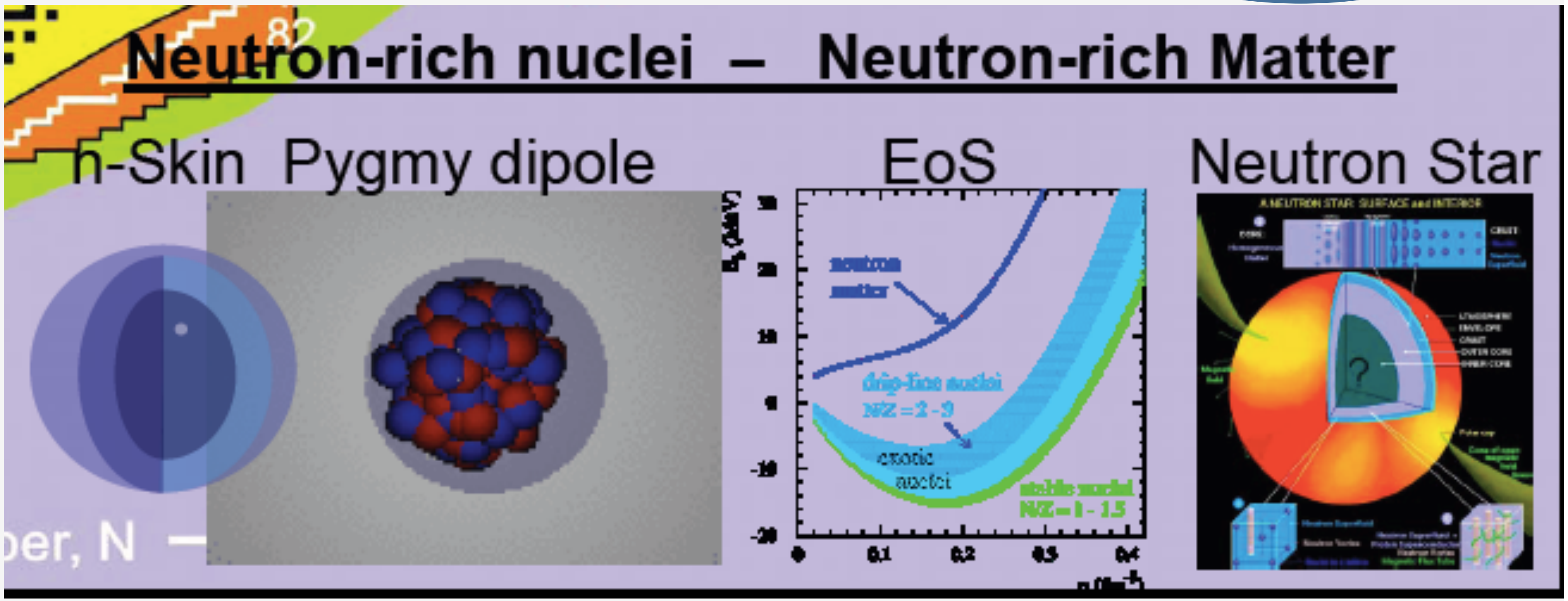
Knock-out reactions at high energies with RIB in inverse kinematics



Exotic RIBs up to high energies and innovative spectrometer systems for kinematically complete measurements are needed

Neutron – rich nuclei neutron-rich matter

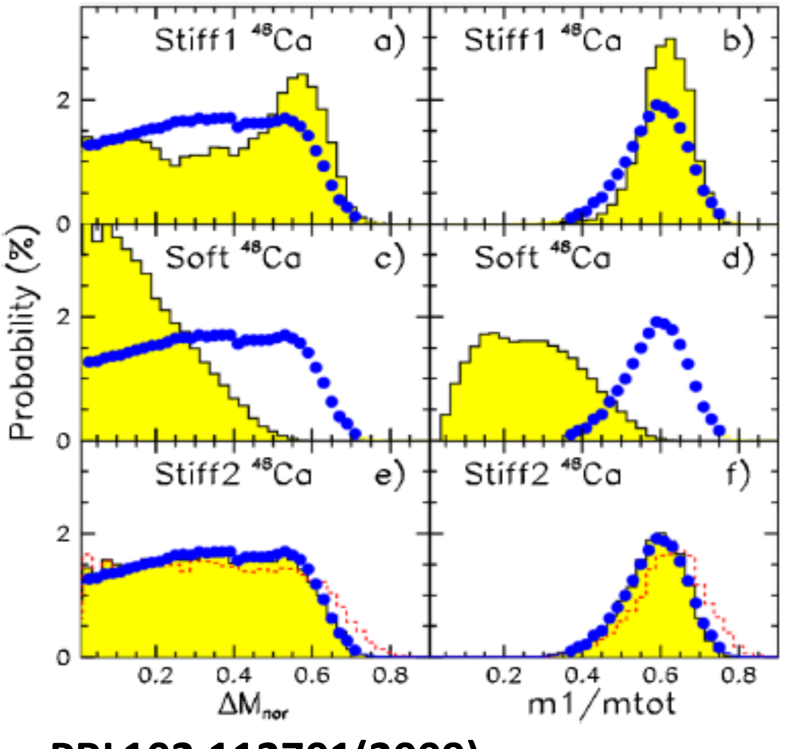




Isospin dependence of the equation of state : fragmentation reactions

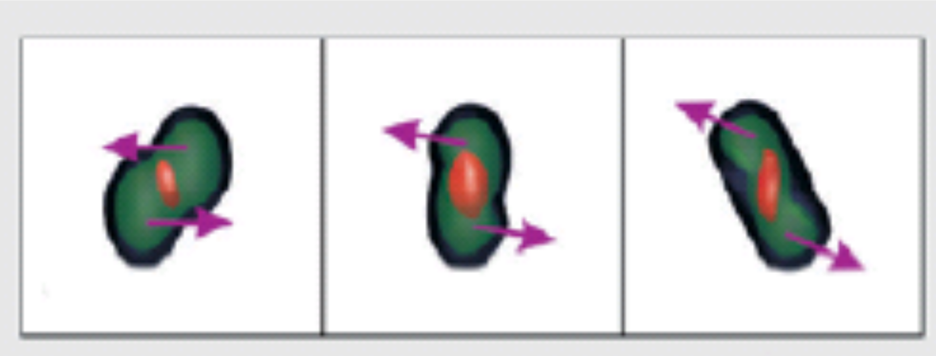
Competition among fusion-like and binary reactions

$^{40}Ca + ^{48}Ca$ a 25 MeV/u



PRL102,112701(2009)

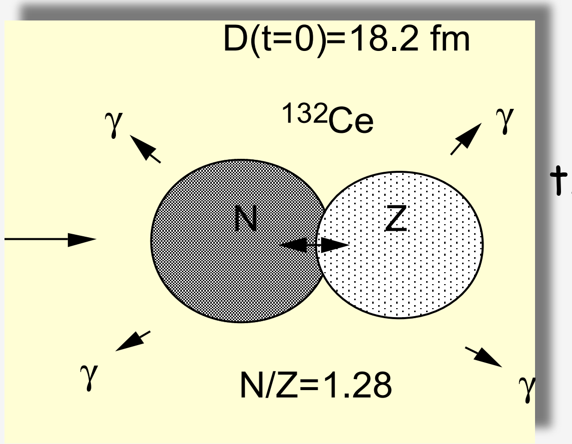
Calculation of molecular Dynamics with 2 different Parametrization of the symmetry term



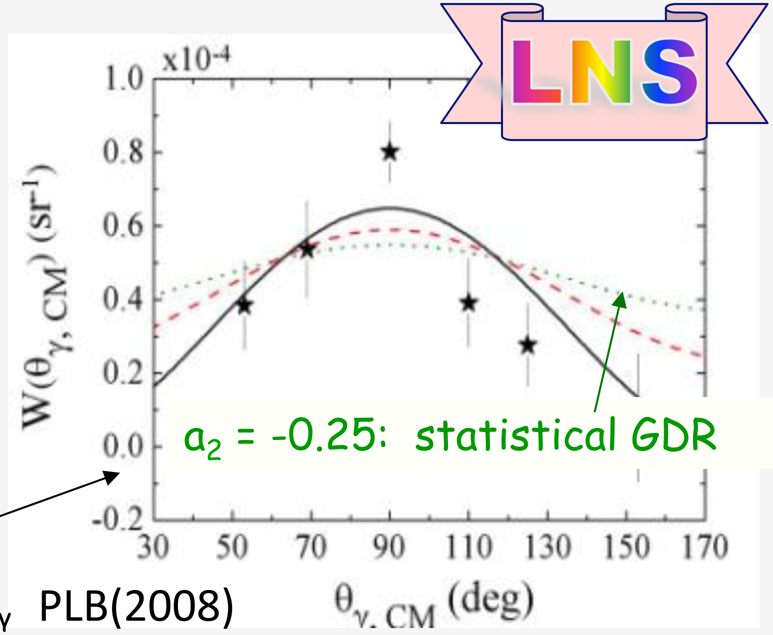
Dipole oscillation in asymmetric heavy ion reactions

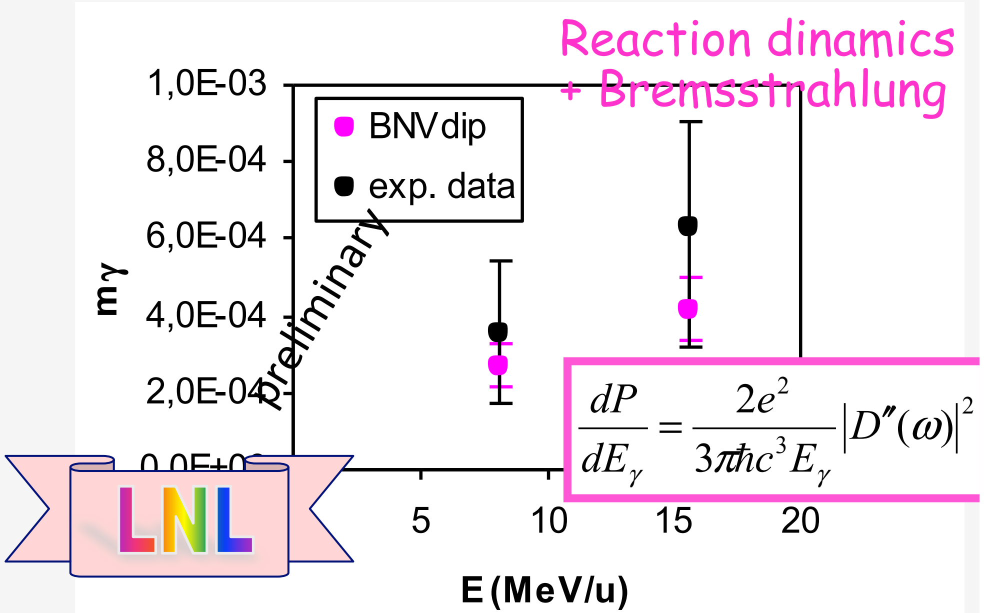
Charge equilibration

Symmetry energy



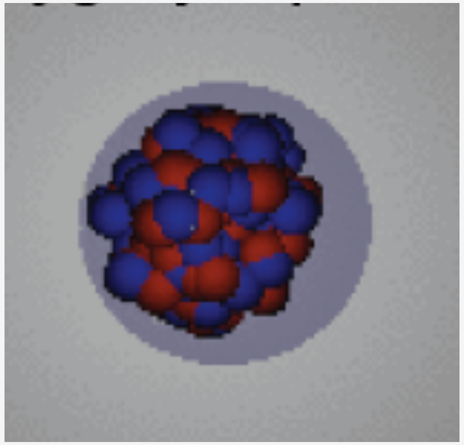
a_2 = -1 ⇒ Pure Dipole oscillation along the Beam Axis ⇒ ~ $\sin^2\theta_\gamma$ PLB(2008)





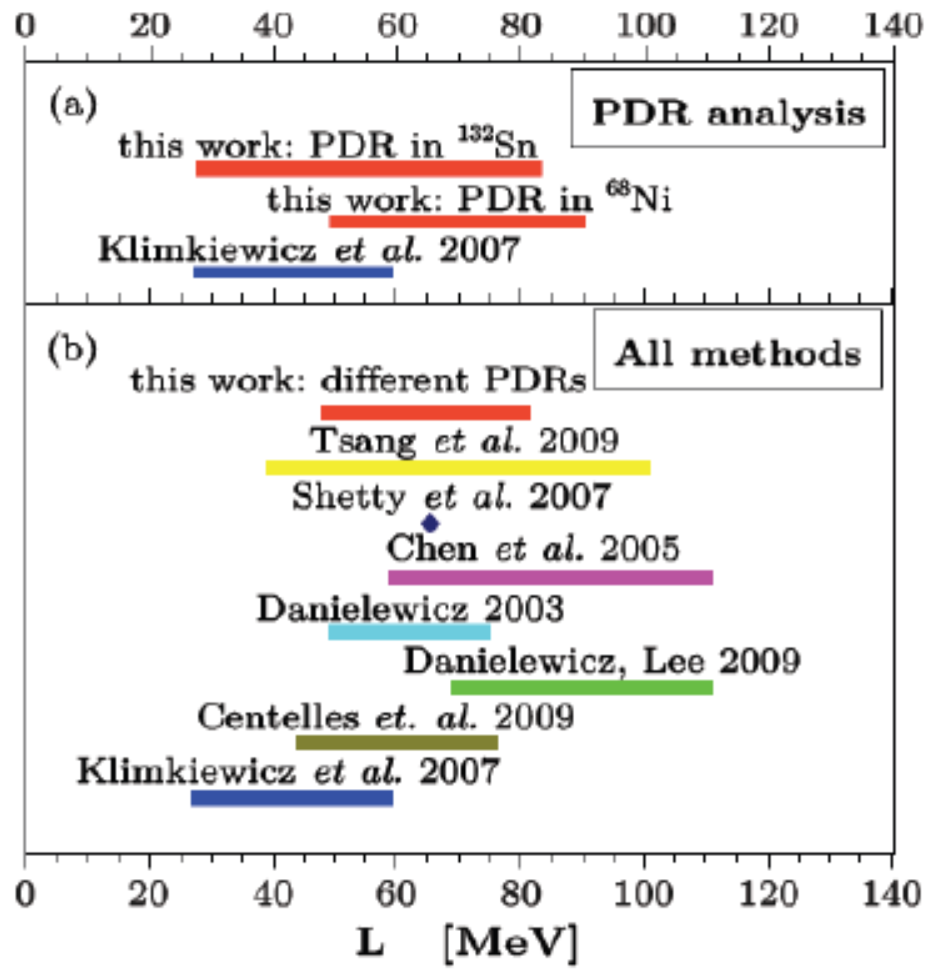
$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma} |D''(\omega)|^2$$

A LNS with MEDEA
A LNL with Garfield



Pygmy resonance –
low energy tail of the
nuclear electric dipole response

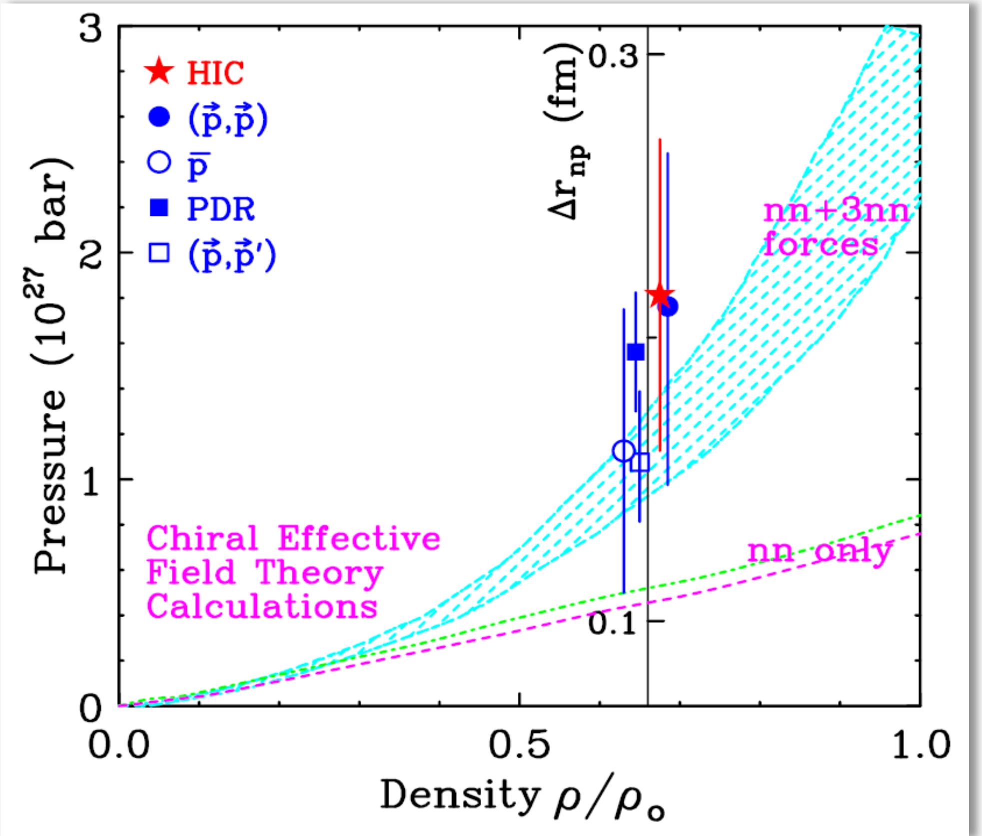
Constrain on the derivative of the symmetry energy parameter (L in MeV)



Neutron skin in ^{208}Pb
From several observables

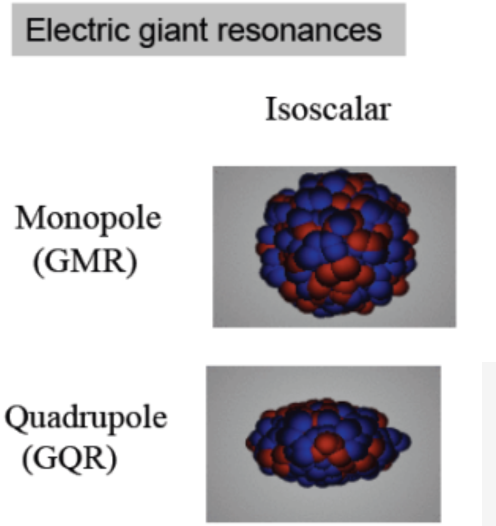
Deduced
Pressure value

Comparison
With theory



From Betty Tsang ….to be published
data from several references

Giant Quadrupole and monopole resonances in ^{56}Ni



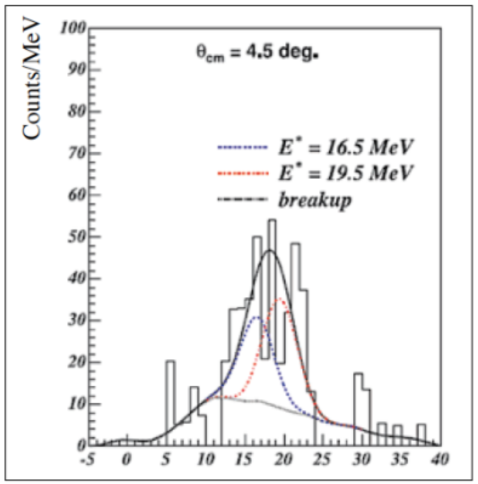


Figure 6. Giant quadrupole resonance (16.5 MeV) and giant monopole resonance (19.5 MeV) in ^{56}Ni induced by the ^{56}Ni(d,d') reaction at 50 MeV/u in the MAYA active target at GANIL .

Experiment with active target at GANIL

Gamow-Teller transition Strength in ^{56}Ni

Selected for a Viewpoint in *Physics*
PRL **107,** 202501 (2011) PHYSICAL REVIEW LETTERS week ending 11 NOVEMBER 2011

Gamow-Teller Transition Strengths from ^{56}Ni

M. Sasano,[1,2] G. Perdikakis,[1,2] R. G. T. Zegers,[1,2,3] Sam M. Austin,[1,2] D. Bazin,[1] B. A. Brown,[1,2,3] C. Caesar,[4] A. L. Cole,[5] J. M. Deaven,[1,2,3] N. Ferrante,[6] C. J. Guess,[7,2] G. W. Hitt,[8] R. Meharchand,[1,2,3] F. Montes,[1,2] J. Palardy,[6] A. Prinke,[1,2,3] L. A. Riley,[6] H. Sakai,[9] M. Scott,[1,2,3] A. Stolz,[1] L. Valdez,[1,2,3] and K. Yako[10]

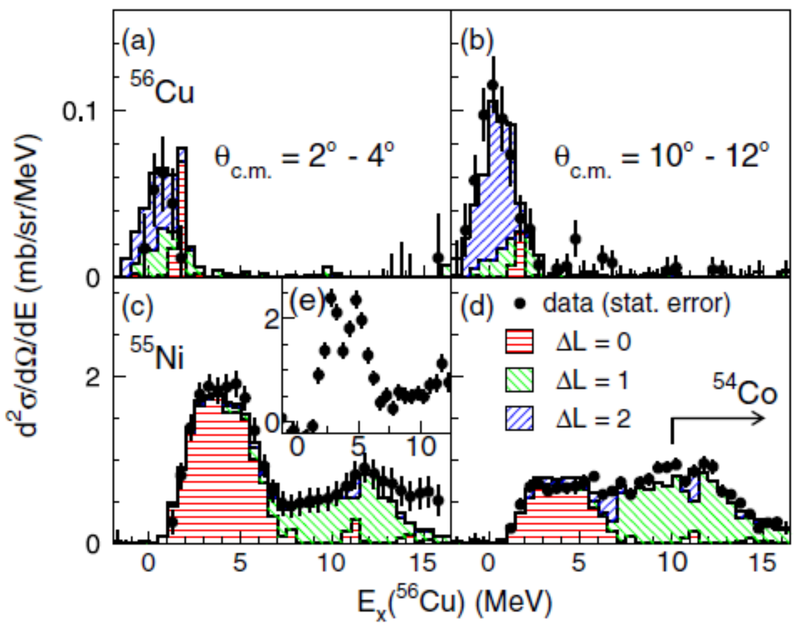
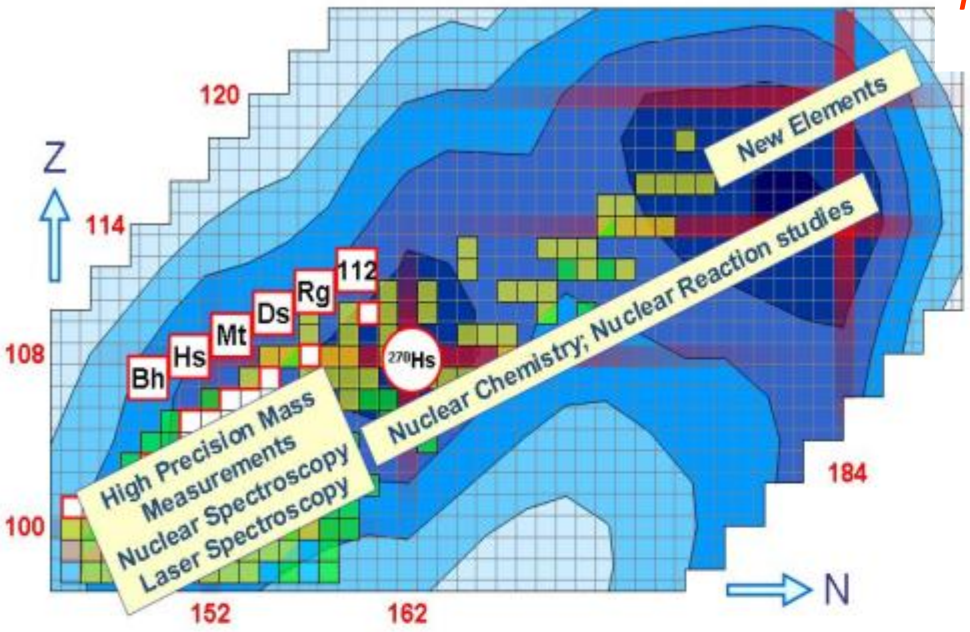


FIG. 2 (color online). Differential cross sections and the MDA of the ^{56}Ni$(p,n)^{56}$Cu* data. Results are presented for (a),

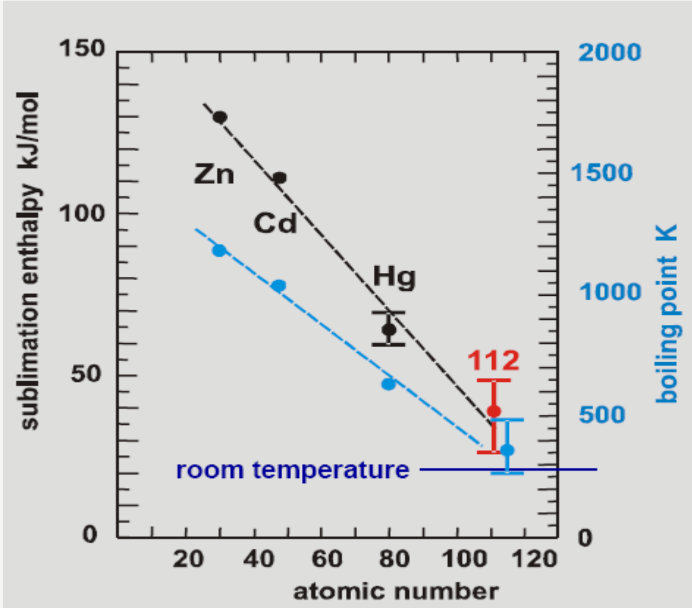
SUPER HEAVY ELEMENTS

Superheavy elements

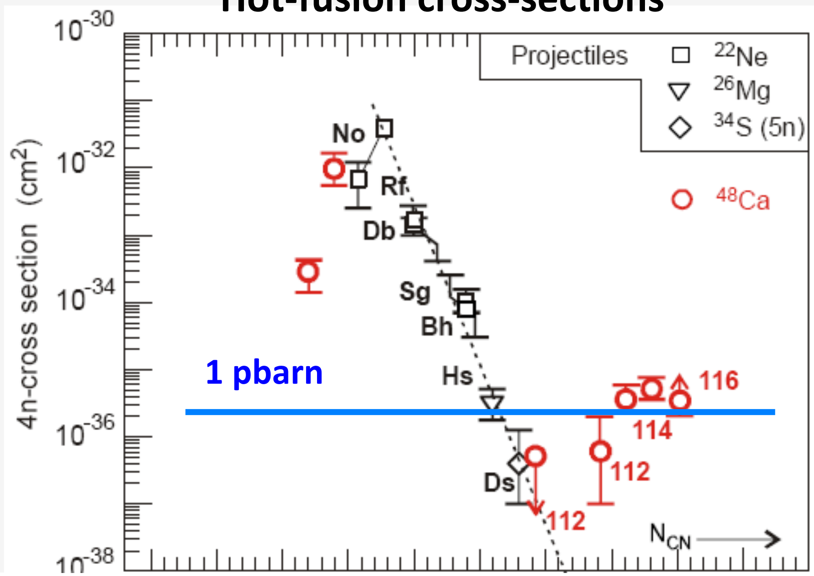


Taufe von Element 112, am 12. Juli 2010 um 10 Uhr

Copernicium is a noble metal



Hot-fusion cross-sections

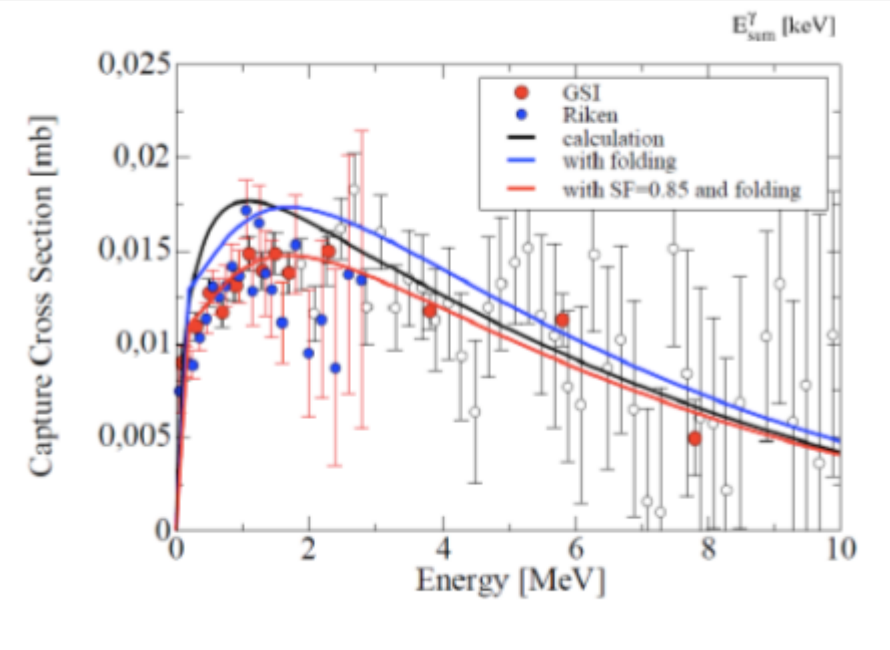


High-intensity stable-ion beams, target developments and high-efficiency detectors and separators are needed in the future SHE research

WG3

Reaction measurements for nuclear astrophysics

Neutron capture-



Comparison of direct neutron capture cross section on ^{14}C

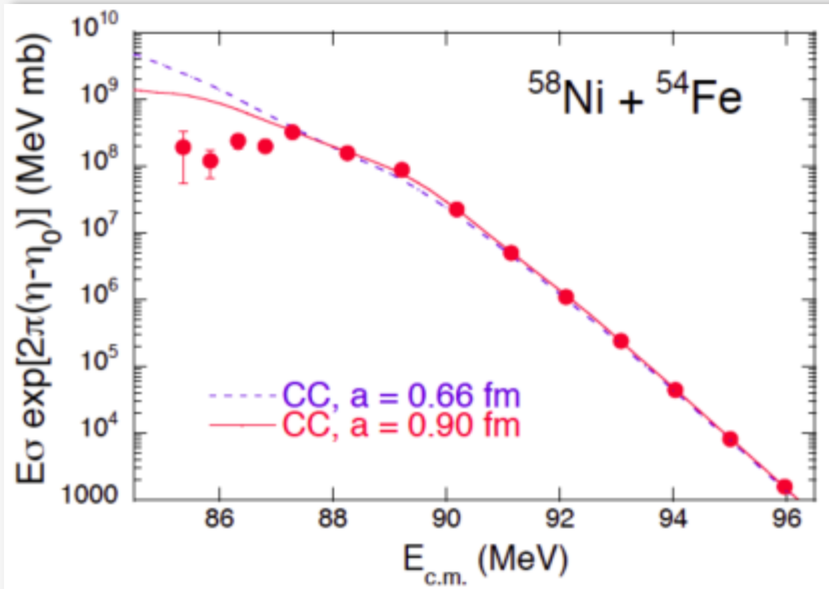
and

that obtained via Coulomb break up (GSI-RIKEN) of ^{15}C

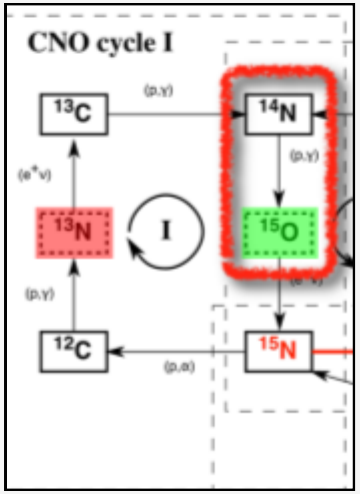
using detailed balance

sub barrier fusion

Astrophysical S factor



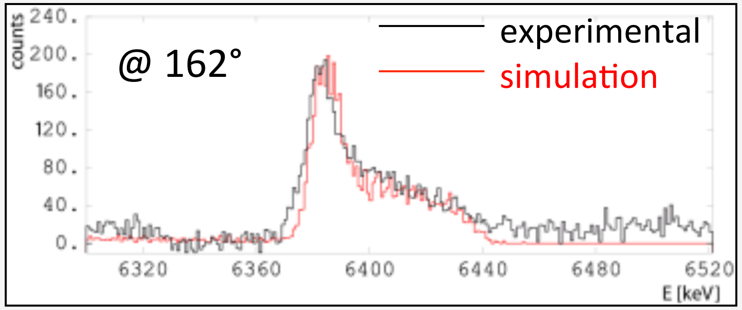
Stellar burning rates and $^{14}N(p,\gamma)^{15}O$ reaction



width of the resonance
⇕
lifetime of the excited nuclear level

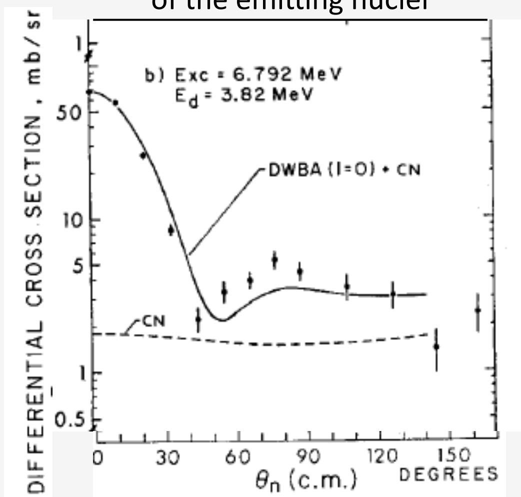
The sub-threshold resonance corresponding to the first excited 3/2+ state in ^{15}O is predicted to play a dominant role when extrapolating the cross-section to the Gamow peak region

Lifetime measurement of the 6.79 MeV state in ^{15}O with the AGATA Demonstrator



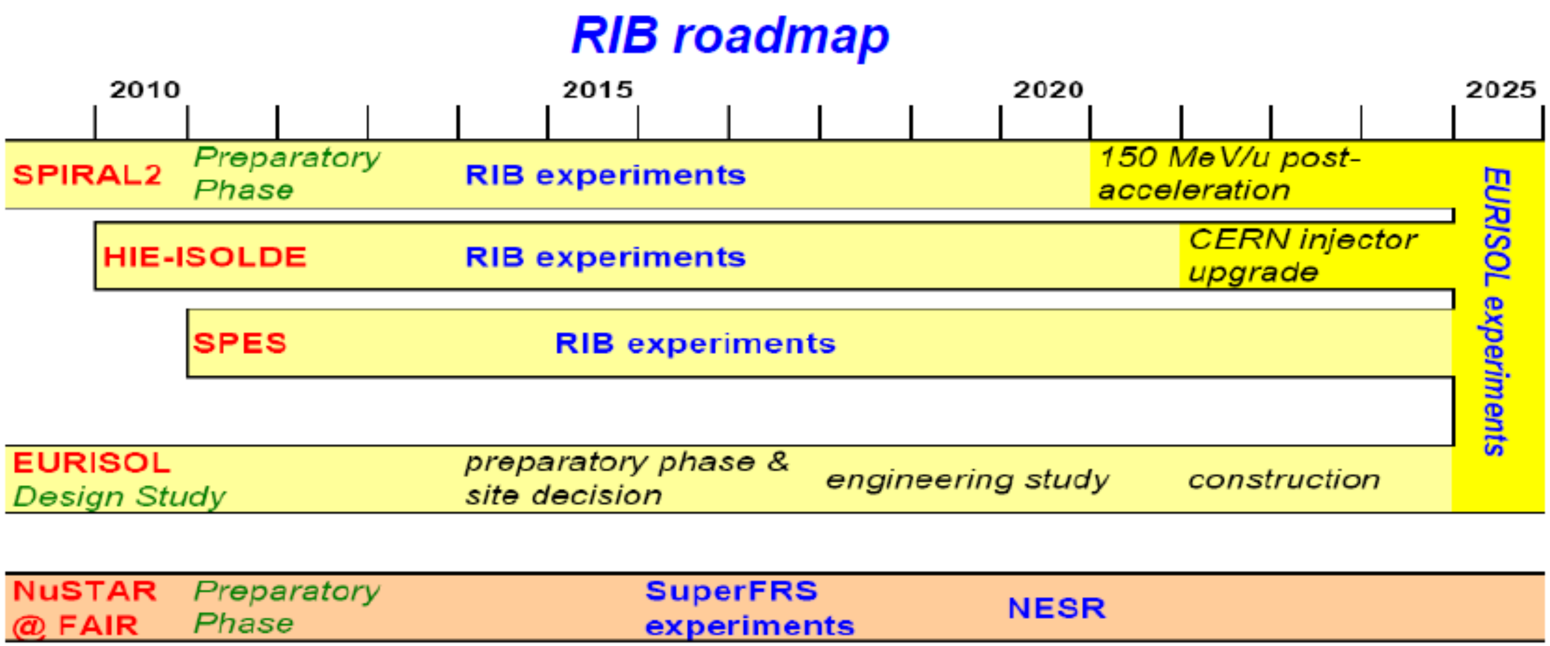
$^{14}N(^{2}H,n)^{15}O$ reaction @ 32 MeV (XTU LNL Tandem)
4 ATCs at backward angles (close to the beam-line)

CM angular distribution
of the emitting nuclei



R.C. Ritter *et al.*, NPA 140 (1970) 609

First application of the high gamma energy resolution and position sensitivity of AGATA to investigate ≈fs nuclear level lifetimes



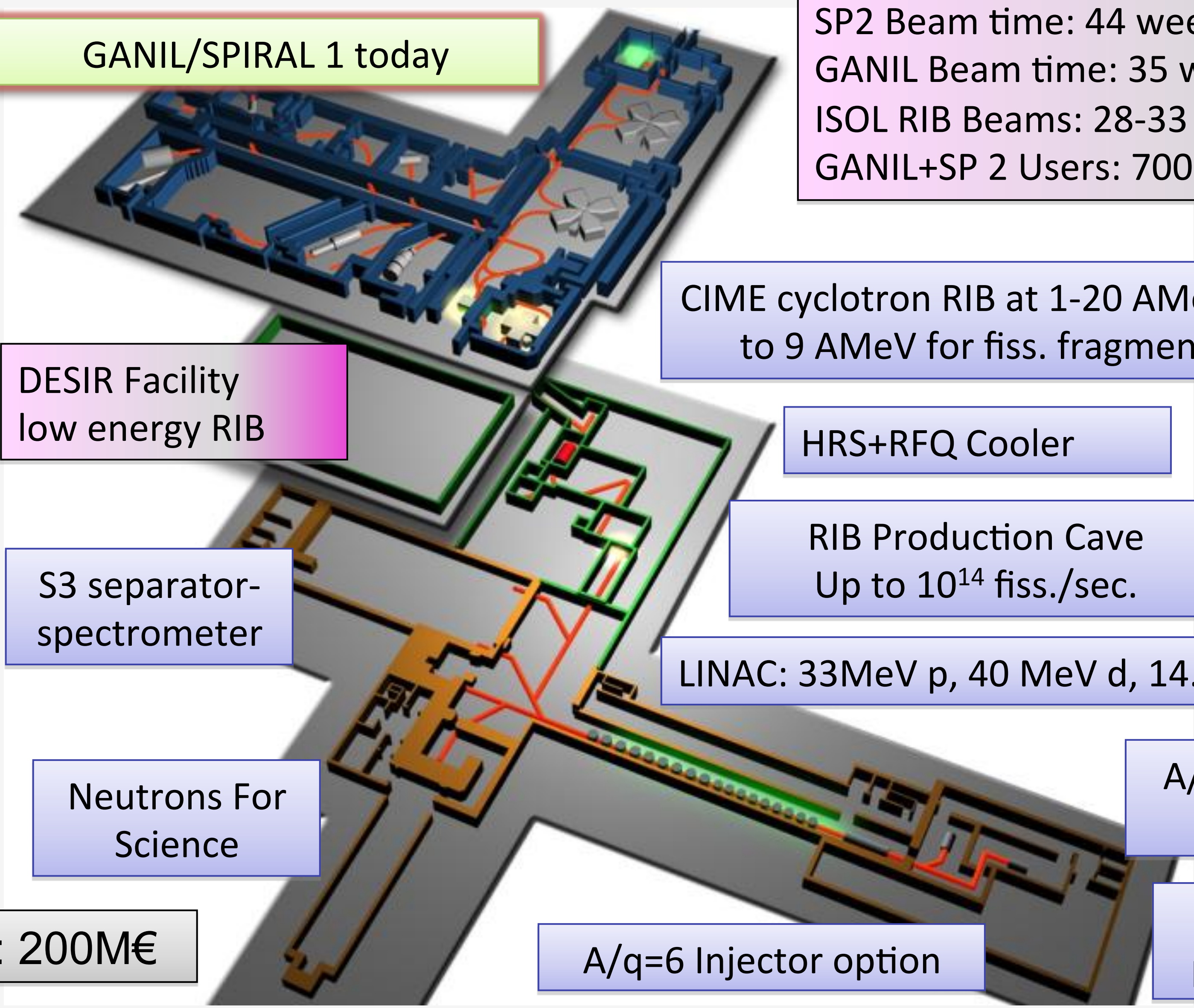
A new LINAC for reserach on superheavy elements

Exploitation of existing facilities : Trasnational access

LNL
LNS
ISOLDE
ALTO
GANIL
GSI

NuPECC recommendations

GANIL/SPIRAL1/SPIRAL2 facility



GANIL/SPIRAL 1 today

SP2 Beam time: 44 weeks/y
GANIL Beam time: 35 weeks/y
ISOL RIB Beams: 28-33 weeks/y
GANIL+SP 2 Users: 700-800/y

CIME cyclotron RIB at 1-20 AMeV (up to 9 AMeV for fiss. fragments)

DESIR Facility
low energy RIB

HRS+RFQ Cooler

RIB Production Cave
Up to 10^{14} fiss./sec.

S3 separator-spectrometer

LINAC: 33MeV p, 40 MeV d, 14.5 A MeV HI

A/q=3 HI source
Up to 1mA

Neutrons For Science

A/q=2 source
p, d, ^{3,4}He 5mA

Cost: 200M€

A/q=6 Injector option

SPIRAL2 is one of the ESFRI list projects (40 most important EU research infrastructure projects)

Day 1 experiments with S3

Proton Dripline & N=Z nuclei

LoI_Day1_6, LoI_Day1_8, LoI_Day1_9

LoI_Day1_11

- Tests of Shell Model
- Single-Particle structure
- Development of Collectivity
- Shape coexistence

LoI_Day1_3 & LoI_Day1_4

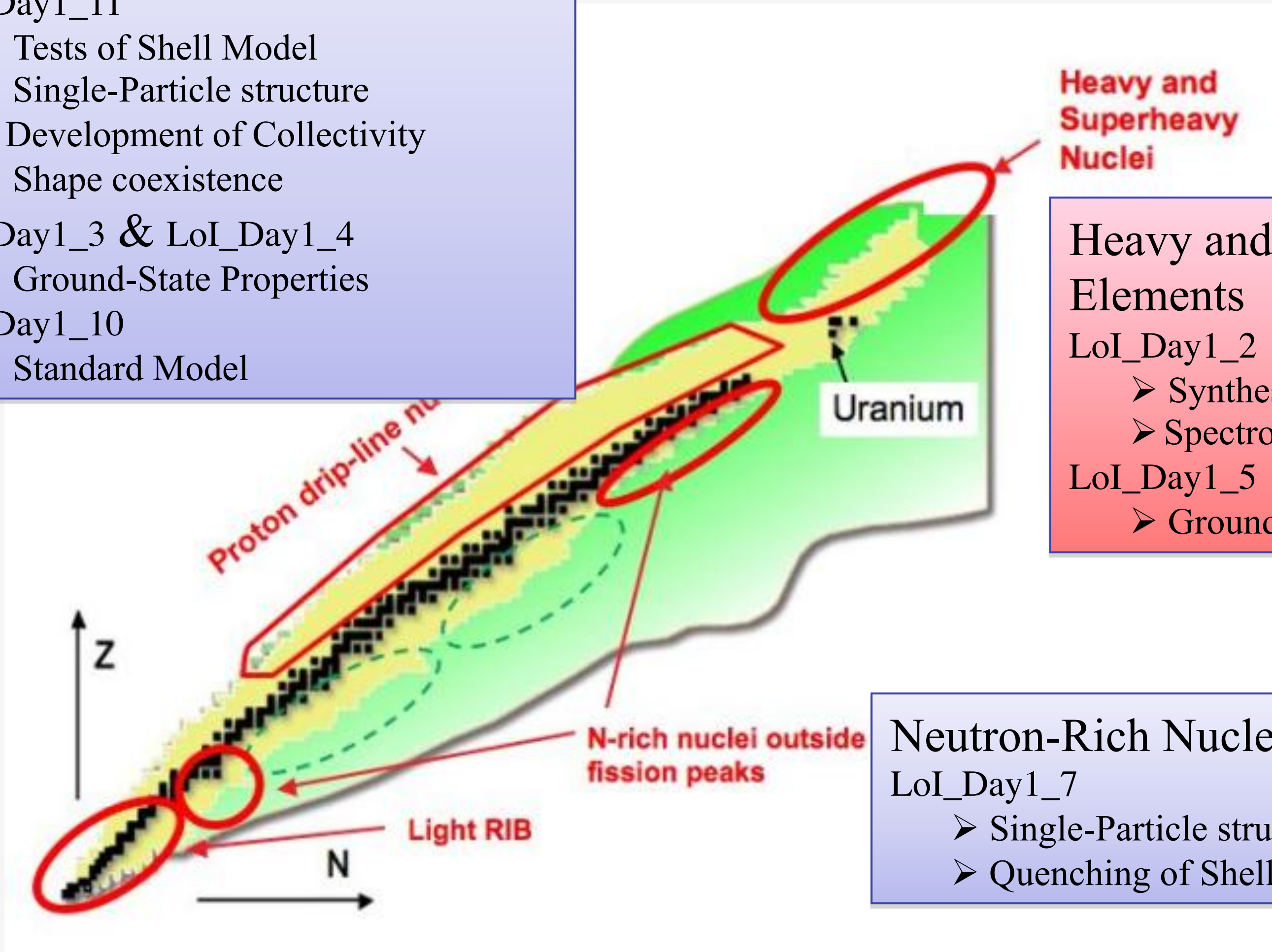
- Ground-State Properties

LoI_Day1_10

- Standard Model

FISIC project

LoI_Day1_1



Heavy and Superheavy Elements

LoI_Day1_2

- Synthesis
- Spectroscopy and Structure

LoI_Day1_5

- Ground-State Properties

Neutron-Rich Nuclei

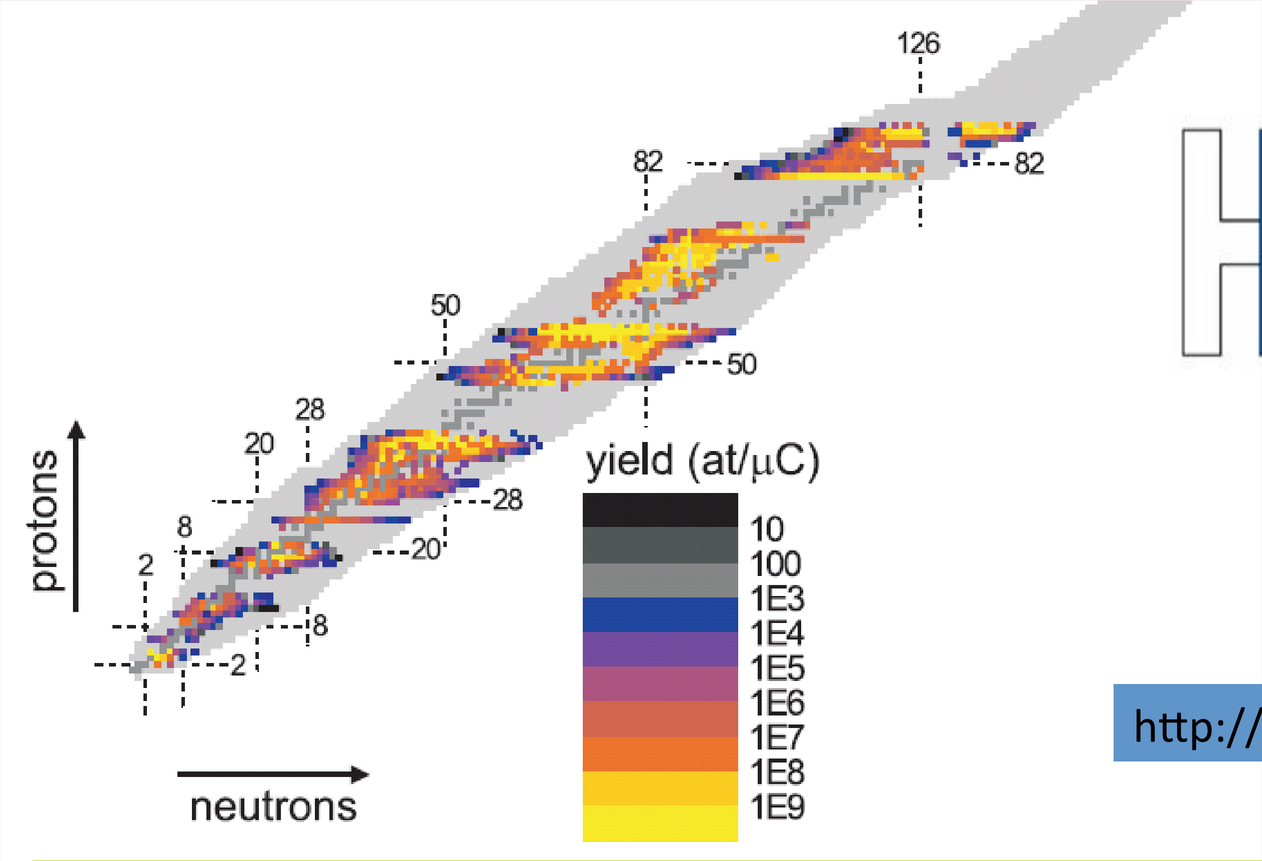
LoI_Day1_7

- Single-Particle structure
- Quenching of Shell Gaps

ISOLDE today offers the largest range of available isotopes of any ISOL facility worldwide.

HIE-ISOLDE aims at increasing the energy of these RIB up to 10A MeV and their intensity by a factor 10

HIE-ISOLDE will play an important role in the network of ISOL facilities preparing EURISOL (with SPIRAL2 and SPES)



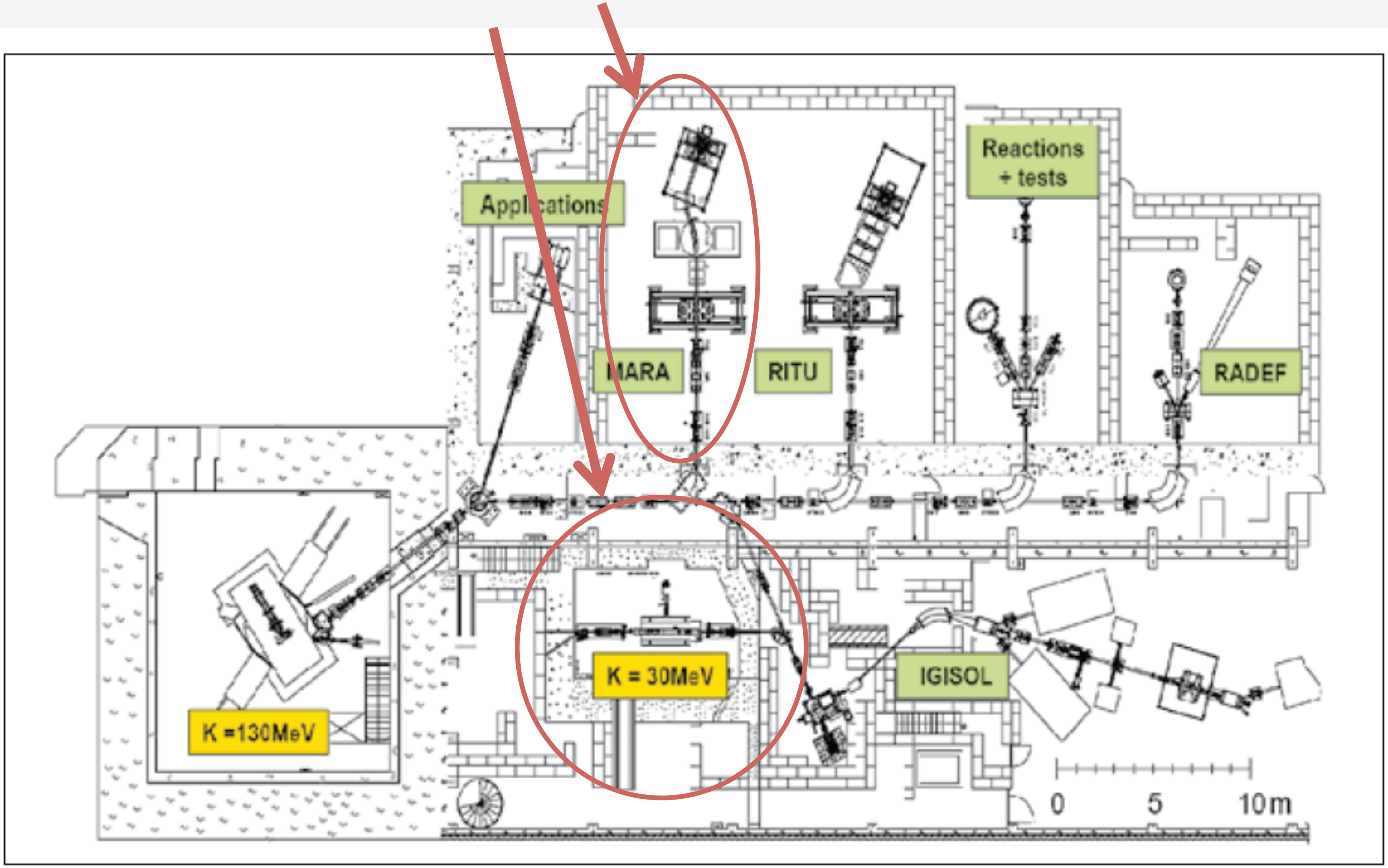
HIE ISOLDE

Stage 1 : 5.5 MeV/u
Stage 2: 8 MeV/u
Stage 3: 10 MeV/u

http://isolde.web.cern.ch/ISOLDE/

So far >600 radioactive isotopes of >60 elements

JYFL - upgrade of the laboratory



Plan for the upgrade of the JYFL Accelerator Laboratory.

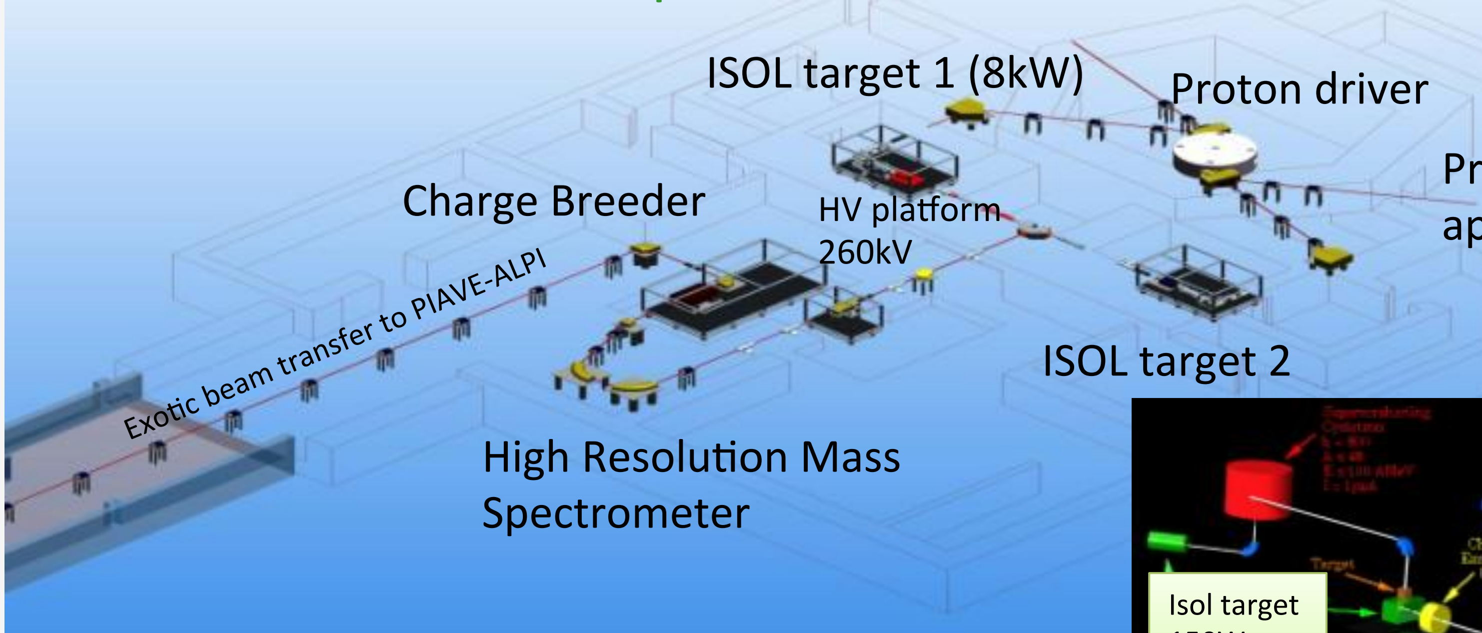
SPES ISOL facility at LNL

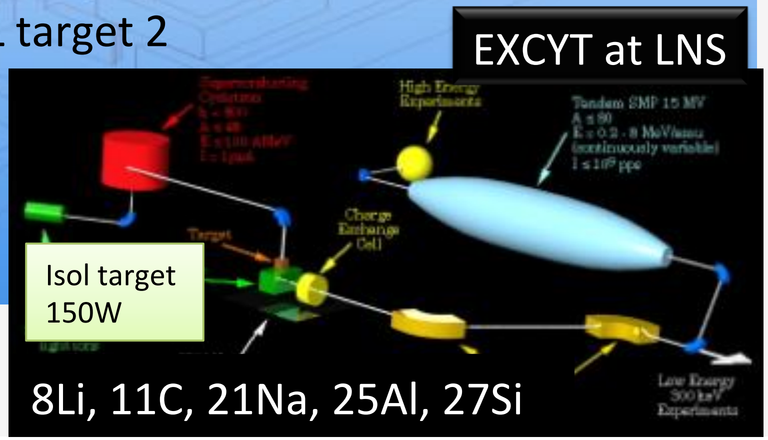
SPES ISOL facility
Proton induced fission on UCx
10^{13} fission/s

A second generation ISOL facility for neutron-rich ion beams and an interdisciplinary research center

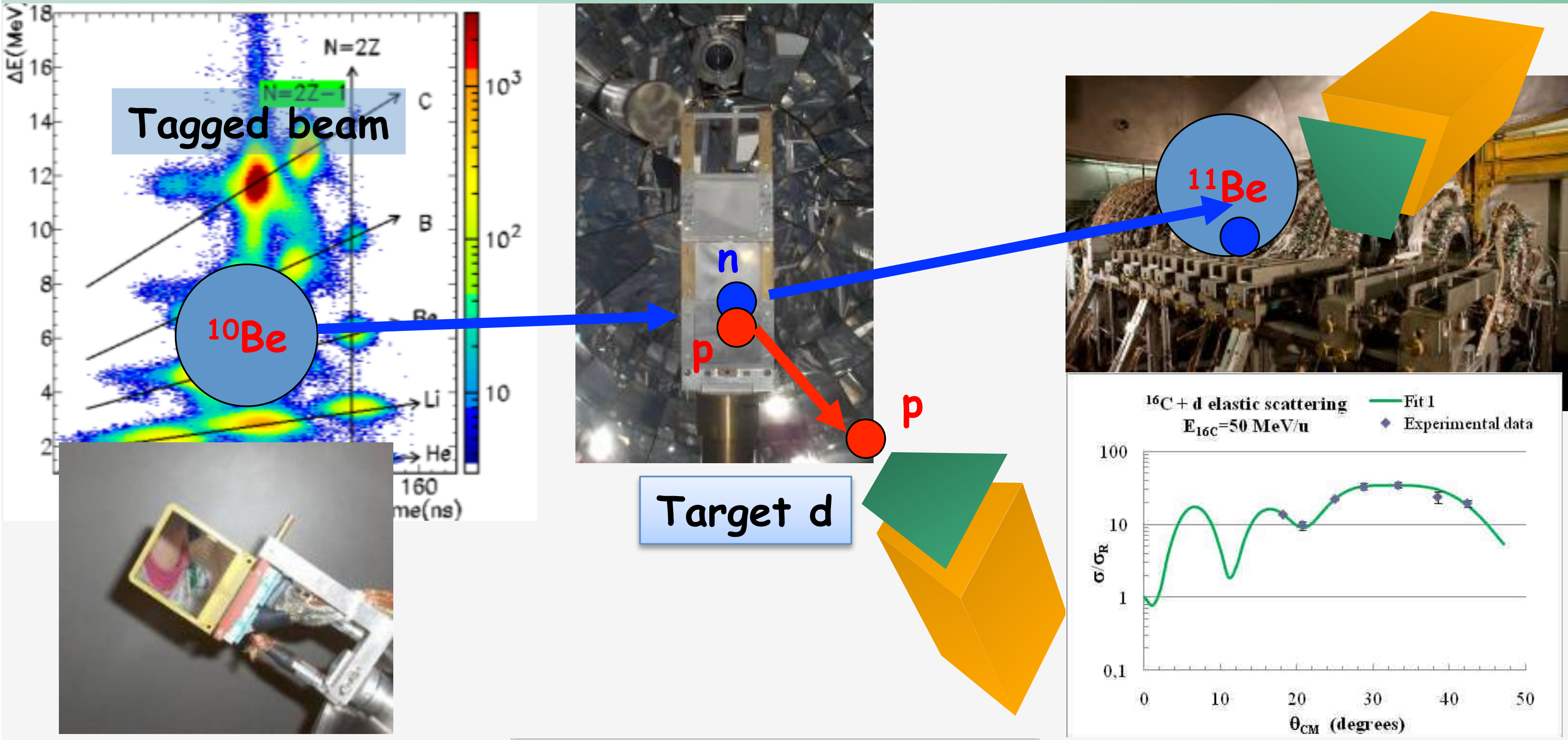
SPES exotic beams for science

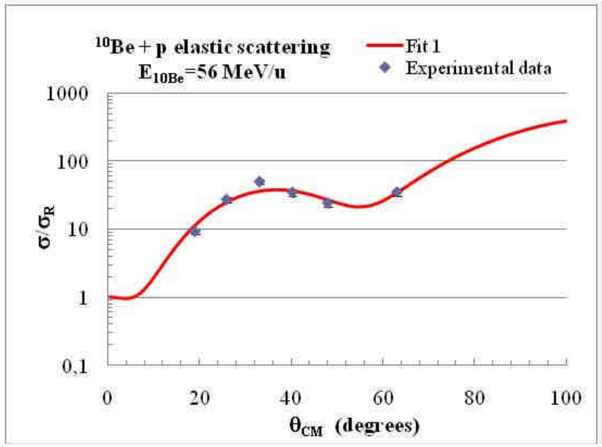
Selective Production of Exotic Species

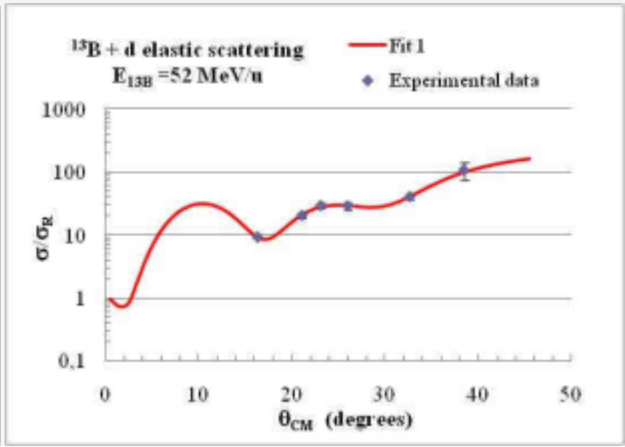


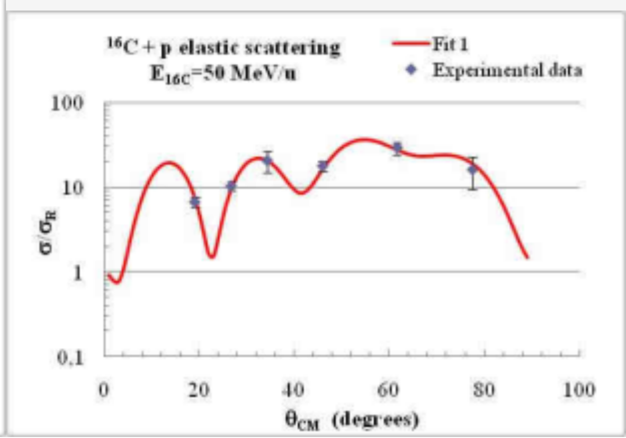


WITH FRIBS + EXCYT at LNS

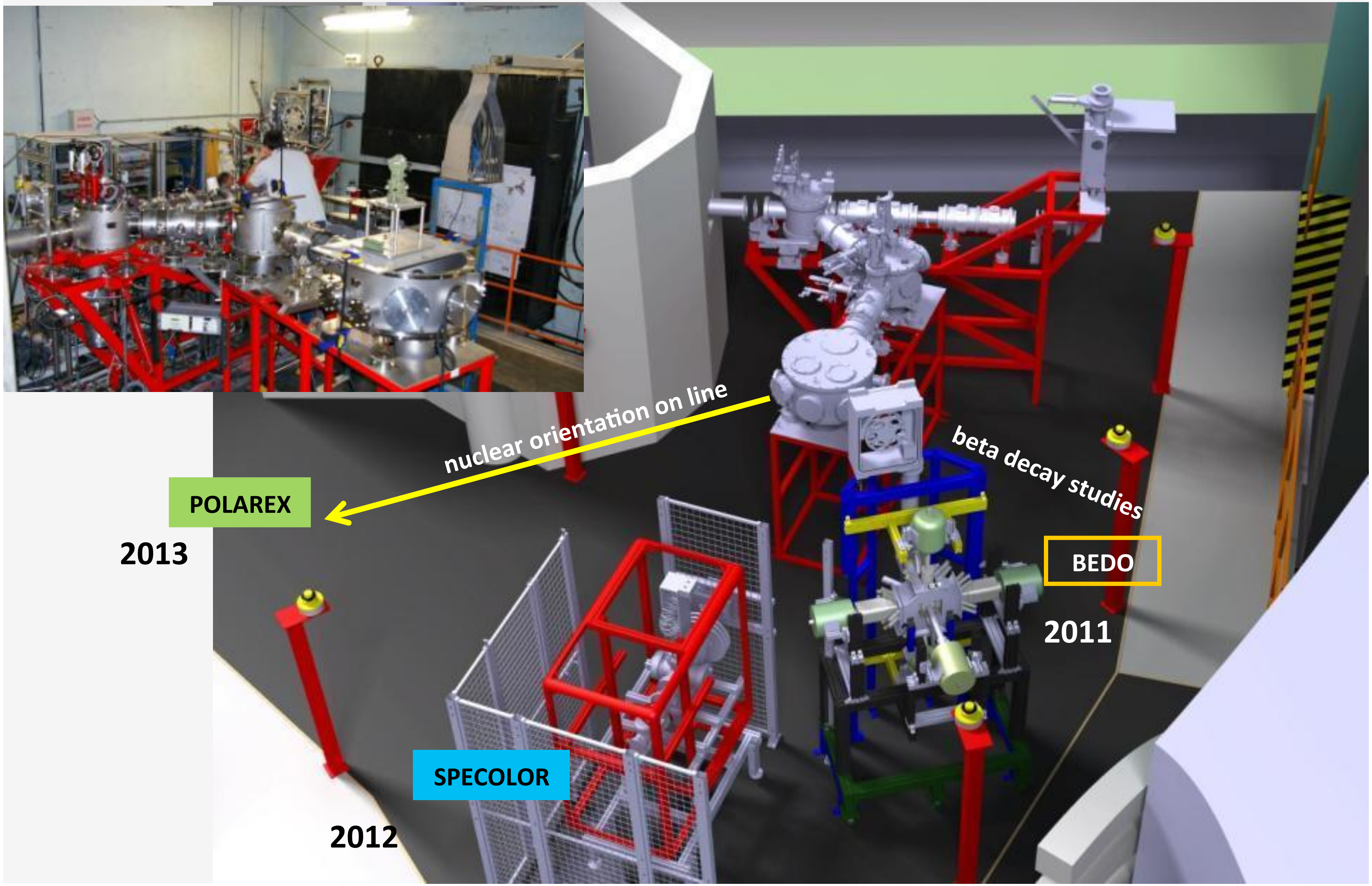






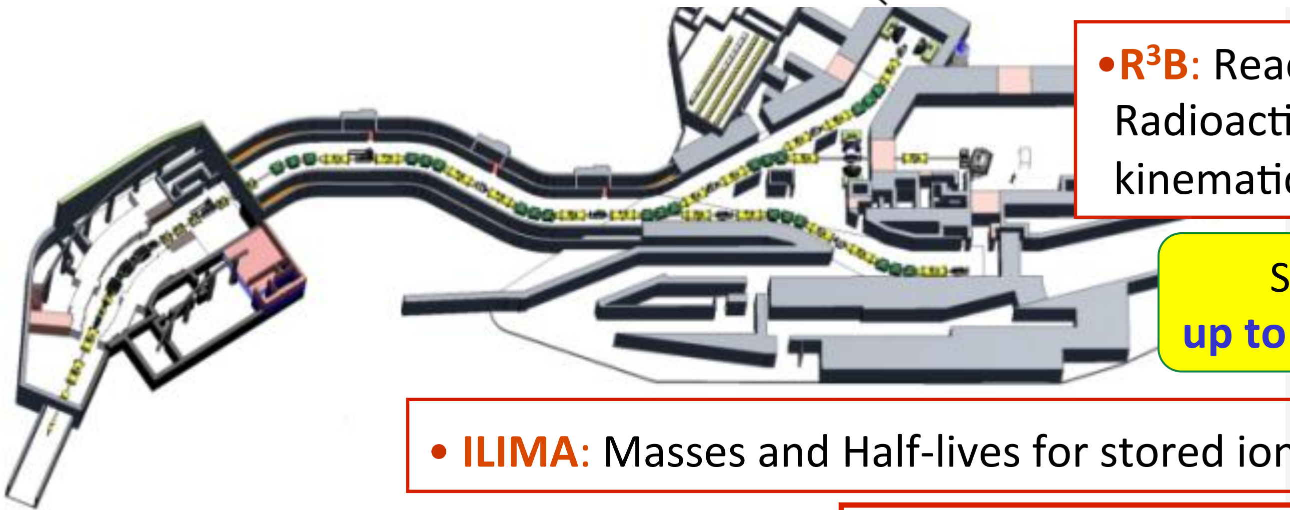


ALTO at ORSAY



Future NuSTAR facility (MSV Mod 2)

- **HISPEC:** In-Flight Spectroscopy
- **DESPEC:** Decay Spectroscopy
- **MATS:** Penning trap system (Masses)
- **LASPEC:** LASER Spectroscopy (Spins, Moments, isotope shifts)



- **R^3B:** Reactions with Relativistic Radioactive Beams in complete kinematics

Secondary Beams
up to factor 10.000 more

- **ILIMA:** Masses and Half-lives for stored ions, isomeric beams

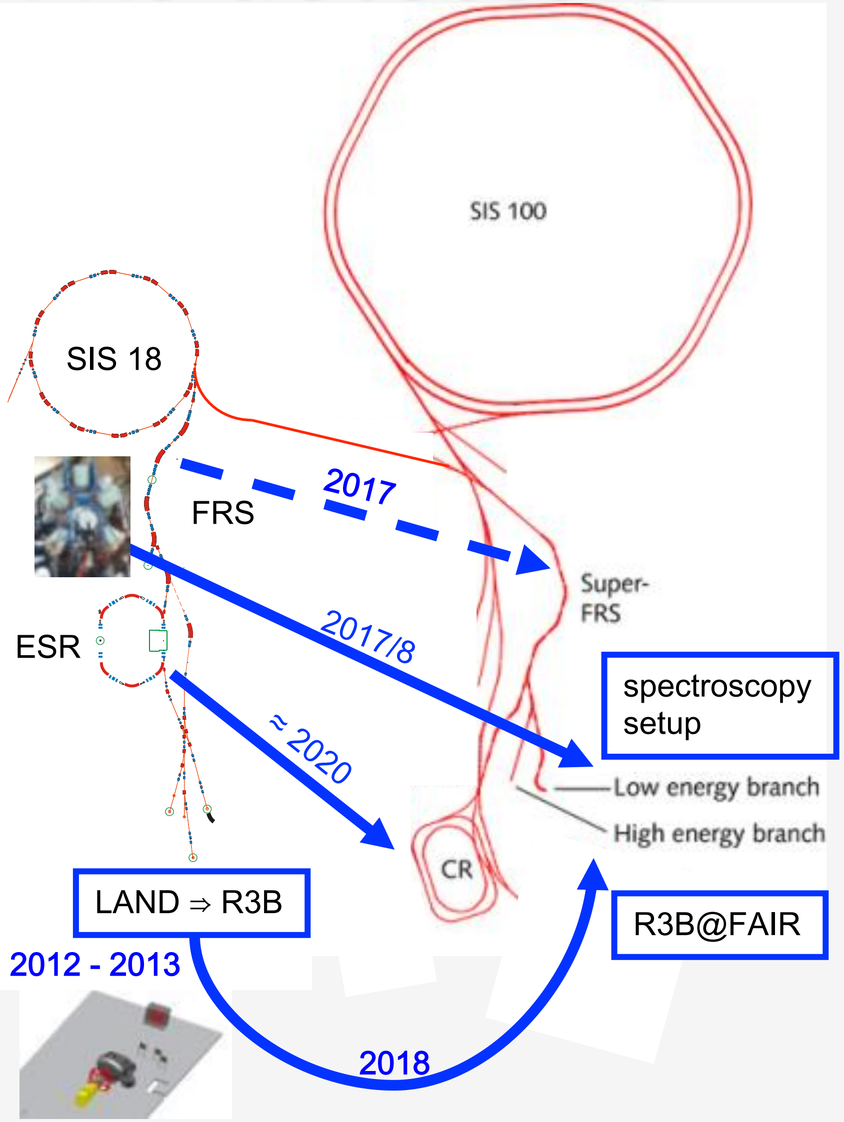
Primary Beams
Factor 100-1.000 more

Physics Highlights:

- r-process path up to high mass numbers
- shell structure in very neutron-rich nuclei
- neutron drip-line in medium-heavy nuclei
- dynamics of halos and neutron skins
- nuclear equation-of-state

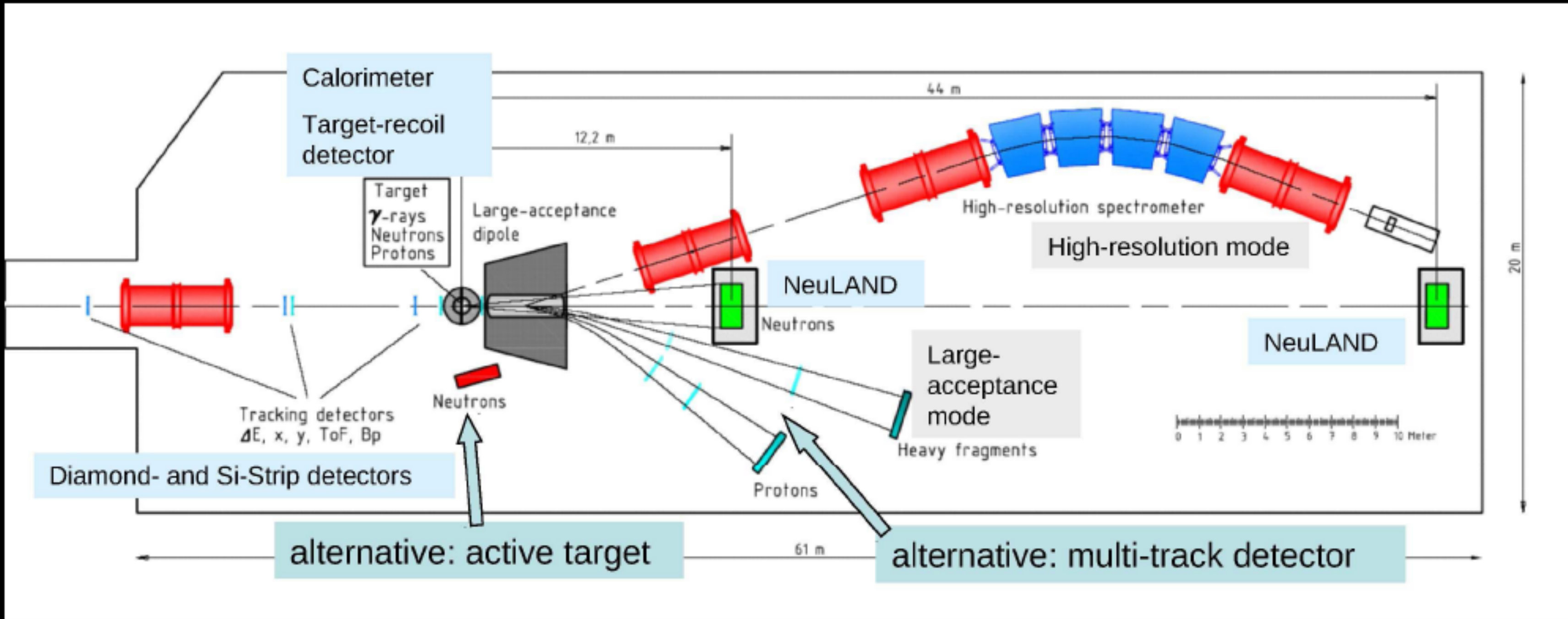
Itinerary of Super-FRS detectors

- Continue a concentraded programme until ~ 2015: „GSI-only“ experiments
- Collaboration obtains research results
- It is possible to start FAIR-experiments already at GSI, e.g. R3B
- Construction of Super-FRS starting ~ 2017
- Later (~2017/18): move experimental setups to Super-FRS



R^{3}B Overview

Reactions with **R**elativistic **R**adioactive **B**eams



Features:

- **kinematically complete** measurements of nuclear reactions
- high beam energies: $\sim$100–1000 MeV/u

Addresses:

- nuclear astrophysics
- structure of exotic nuclei
- neutron-rich matter

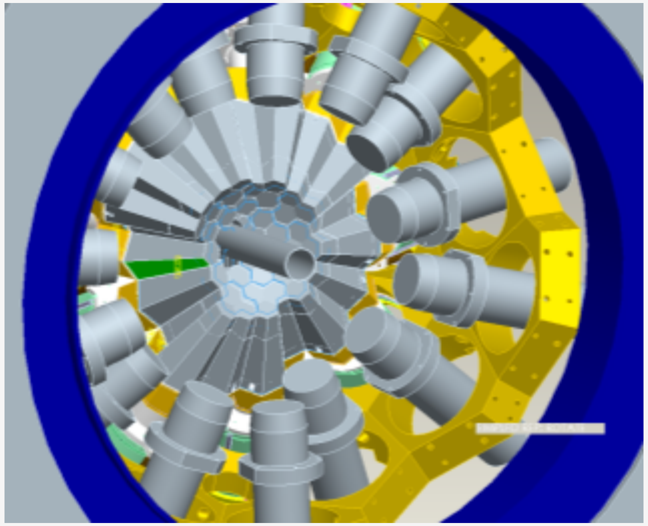
RISING – PRESPEC – HISPEC at LEB of Super-FRS

2007 2009 2011 2013 2015 2017

RISING
Stopped campaign

EUROBALL det.

PRESPEC - AGATA
In-Beam campaign

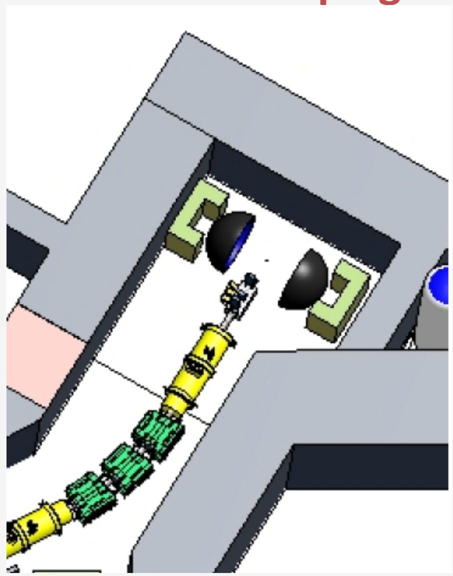


10 AGATA det.

beam tracking det. with digital electronics

Sensitivity gain: 10···100

HISPEC
In-Beam campaign



60 AGATA det.

faster beam tracking det.

at Super-FRS

Sensitivity gain: 10^3-10^4

ELI Nuclear Physics (ELI-NP)

"Extreme Light"

■ 10 PW lasers, output energy higher than 200 J,

20-30 fs, intensity higher than 10^{23}W/cm^2

■ the most brilliant γ beam, <19.5 MeV, BW:10^{-3}

produced by Compton scattering on a 600 MeV electron beam

- **Photonuclear reactions and astrophysical applications.**

- **Nuclear methods and techniques based on high intensity laser and γ beams**

Conclusion

- The physics program with the availability of RIBs is going to be very rich, interisting and vital.
Major advances for the understanding of properties of nuclear structure, interaction and nuclear matter are expected .

- Stringent tests to theory will be provided together with essential inputs to models of nucleosynthesis.

- Photon beams at ELI_NP will will be used to study specific nuclear structure and nuclear astrophysics and to study exotic beam production.

- The RIB program requires to be integrated by a number of very exclusive measurements with stable nuclei particularly in phase
The existing facilities with stable beams will be very useful in the transition period for reactions, decay measurements and detector developments.