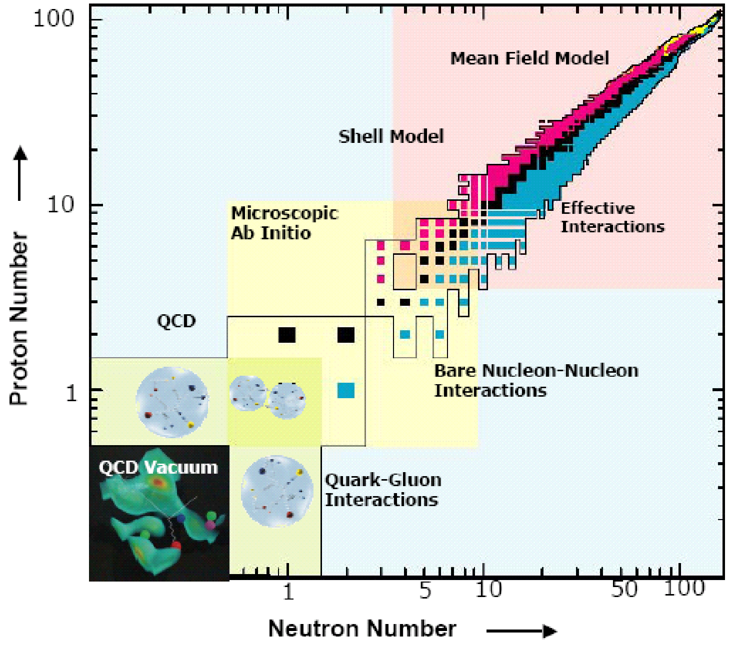
Physics with a Multi-MW Proton Source

Nuclear Physics Aspects

Muhsin N. Harakeh

NuPECC
&
KVI, Groningen, The Netherlands

NuPECC Long Range Plan 2004
“Perspective for Nuclear Physics Research in Europe in the Coming Decade and Beyond”



*Sponsored by CEC under Contract Nr. HPRI-CT-1999-40004

NuPECC is an Expert Committee of the European Science Foundation

LRP addressed six topics:

1. Quantum Chromo-Dynamics
2. Phases of Nuclear Matter
3. Nuclear Structure
4. Nuclei in the Universe
5. Fundamental Interactions
6. Applications of Nuclear Science

NuPECC $\Rightarrow$ Recommendations and priorities

NuPECC

Quantum Chromo-Dynamics

1. Hadron spectroscopy: glue balls; hybrid states; charm quark states;
   → PANDA at FAIR/GSI
2. Quark dynamics: gluon polarization; quark orbital angular momentum; nucleon transverse-spin distribution; ⇒ GPD
   → HERMES at DESY, COMPASS at CERN
3. Low-mass baryon spectrum, χpt, hyper-nuclei
   → MAMI-C at Mainz and DAΦNE at Frascati

NuPECC

Phases of Nuclear Matter

1. Very high densities and rather low temperatures

   → **Colour super-conductors (neutron stars; compressed nuclear matter in H.I. Collisions at several 10’s GeV/u at FAIR/GSI)**

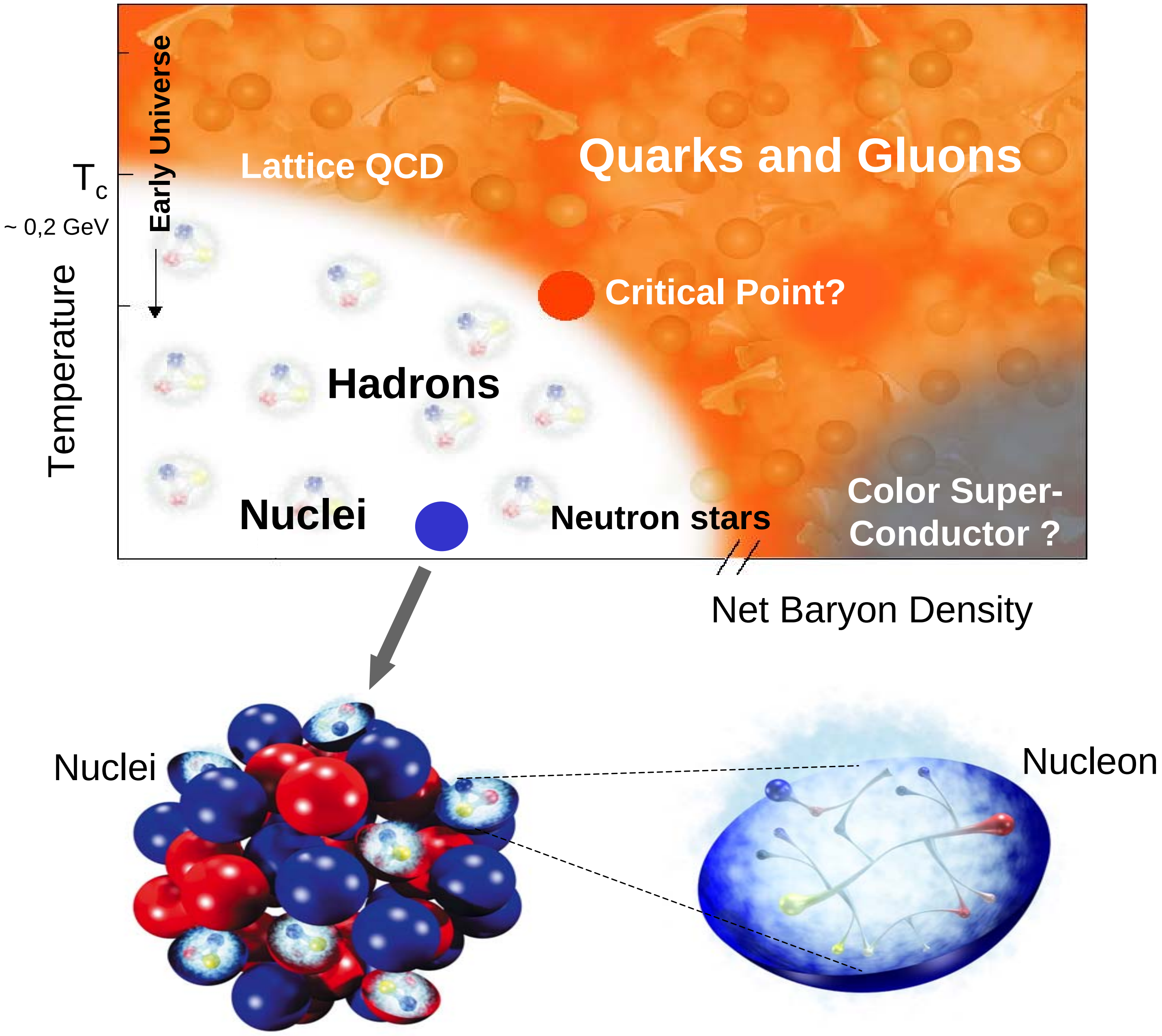
2. Very high temperatures (QGP; ALICE@CERN)

3. Liquid-gas phase transition (H.I. Collisions at Fermi energies at several 10’s MeV/u; 20-50 MeV/u)

   Equation of state (EOS) of (asymmetric) nuclear matter

   → **Radioactive Ion Beams (RIBs)**

NuPECC

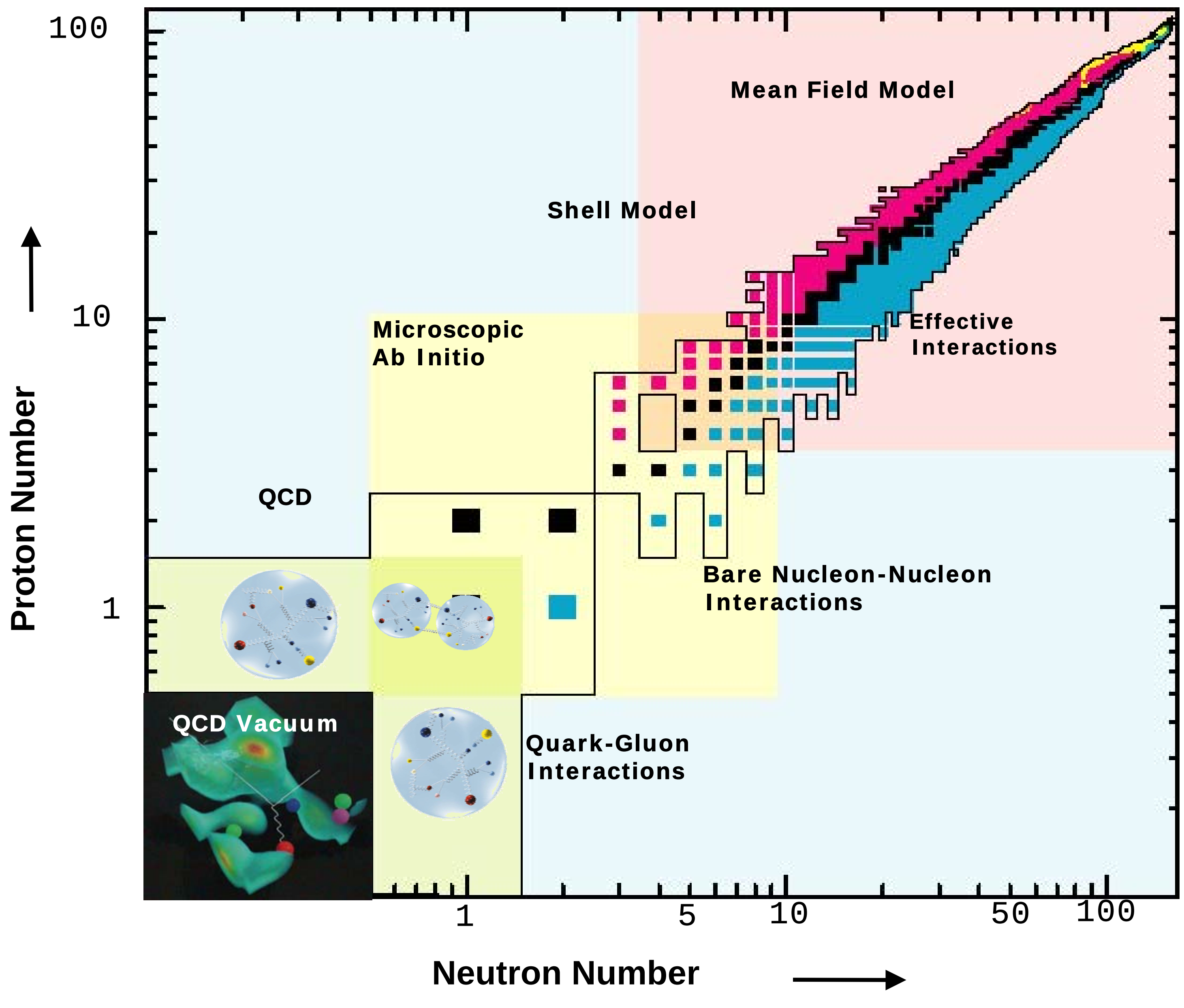

Temperature
T_c
~ 0,2 GeV
Early Universe
Lattice QCD
Quarks and Gluons
Critical Point?
Hadrons
Nuclei
Neutron stars
Color Super-
Conductor ?
Net Baryon Density
Nuclei
Nucleon

NuPECC

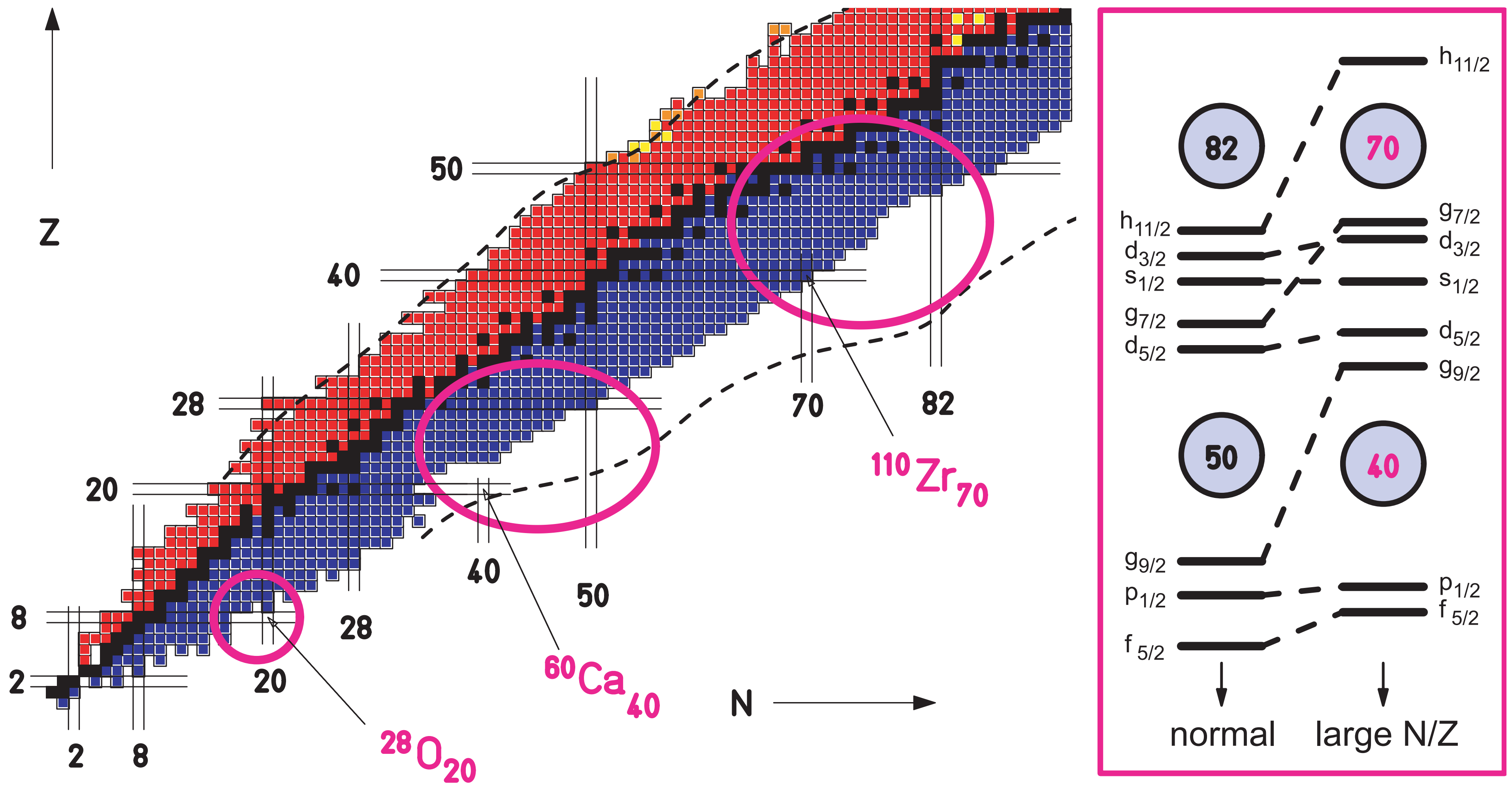
Nuclear Structure

1. Origin of nuclear binding (2- & 3-body forces)
2. Limits of nuclear stability (pairing, 2p radioactivity
3. New magic numbers for large N/Z (double-magic ^{78}Ni)
4. Exotic shapes (halos, triaxial and superdeformed shapes, clustering, molecular shape) & Symmetries; [dynamical SU(3),SU(5),O(6); Critical point E(5),X(5)]
5. Seach for super-heavy elements
6. Shape oscillations, collective excitations
7. Giant resonances in (hot & cold) n-rich nuclei asymmetry term EOS, n-skin thickness→n-star radius

→ **Radioactive Ion Beams (RIBs)**

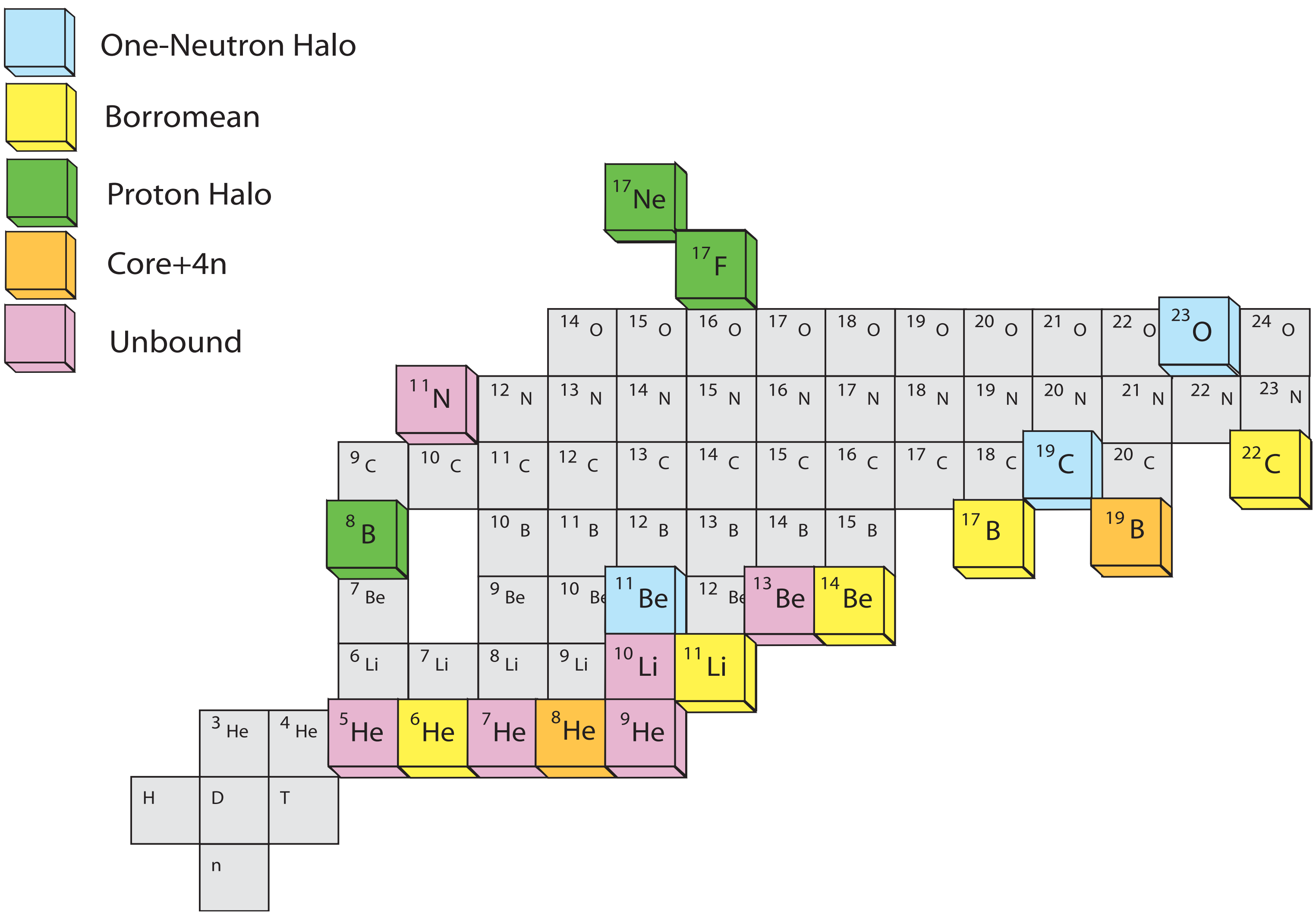


Mean Field Model
Shell Model
Microscopic
Ab Initio
Effective
Interactions
QCD
Bare Nucleon-Nucleon
Interactions
QCD Vacuum
Quark-Gluon
Interactions
Proton Number
Neutron Number
100
10
1
1
5
10
50
100

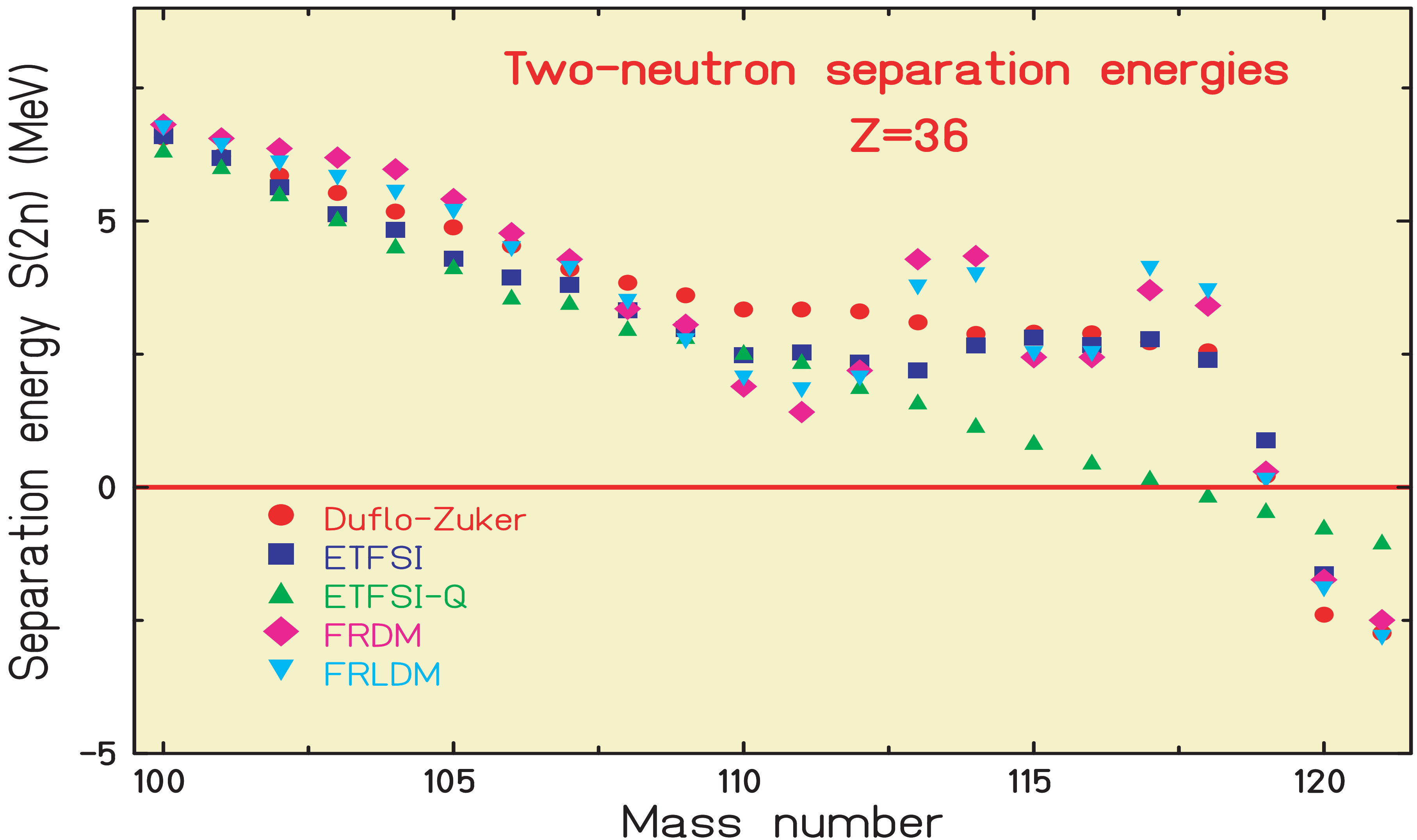


Regions where new magic numbers may occur as deduced from single particle energies for large N/Z

NuPECC

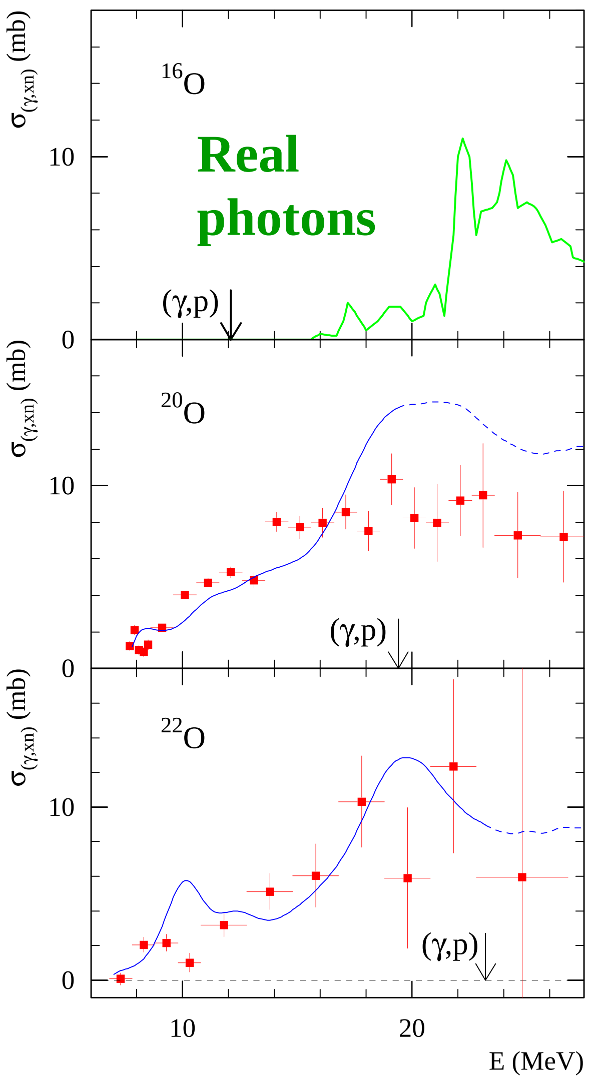


Known 1p, 1n and 2n (Borromean) halo nuclei



Two-neutron separation energies of Krypton sotopes as a function of mass number

Dipole Strength Distribution of n-Rich Nuclei



N-Z=0

N-Z=4

N-Z=6

^{A}O (~500 MeV/u) +Pb → $^{A-x}$O+γ+*xn*

⇒ Photo-neutron cross sections from virtual photons

⇒ Low-lying dipole strength

⇒ Fragmentation of GDR strength

? Collective soft mode ?

— Large-scale shell model calculation

H. Sagawa, T. Suzuki,

Phys. Rev. C 59 (1999) 3116

Data: LAND-FRS@GSI

A. Leistenschneider et al., Phys. Rev. Lett. 86 (2001) 5442

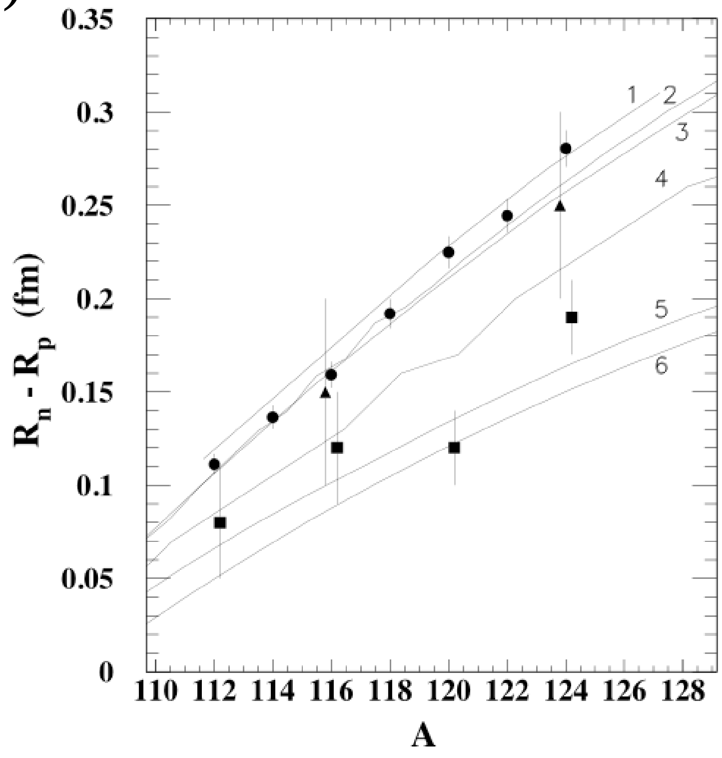
Giant Resonances

Bulk properties of **asymmetric** **(N/Z) nuclear matter:**

• nuclear compressibility (isoscalar monopole)

• symmetry energy (isovector excitations)

• neutron skin (spin dipole)



Astrophysics:

Gamow-Teller

threshold (γ,n) strength

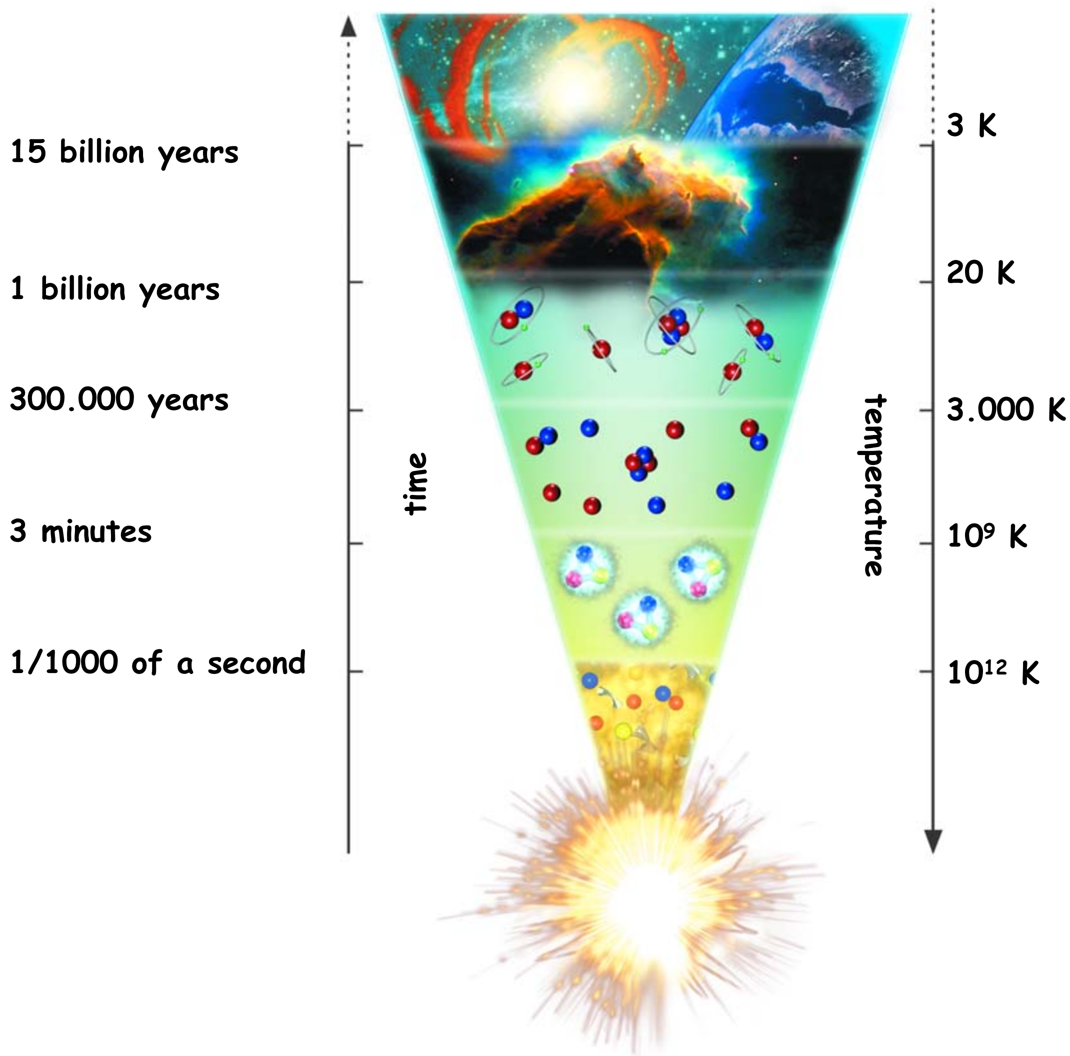
• …

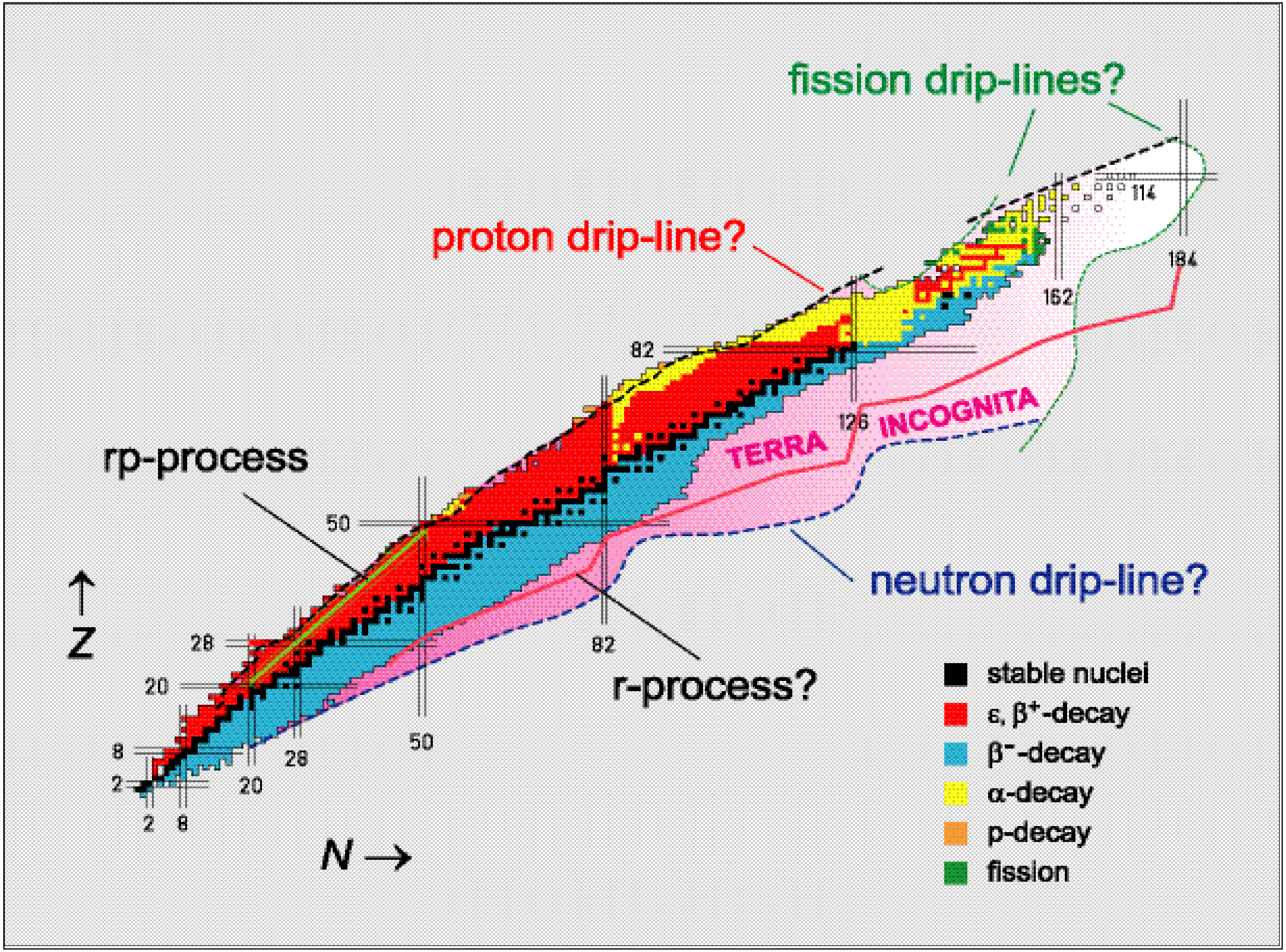
NuPECC

Nuclei in the Universe

1. Understanding processes in stars, e.g. leading to novae, X-ray bursters, supernovae, γ-ray bursts
2. Formation of elements in the universe (abundances)
   rapid neutron capture (r-process in type II supernova)
   rapid proton capture (rp-process in novae and X-ray bursters)
3. The p-process in type Ia supernova
4. υ-processes & propagation in supernova explosions
   GT & first-forbidden and M1 & spin-dipole transitions

$\rightarrow$ **Radioactive Ion Beams (RIBs)**


15 billion years
1 billion years
300.000 years
3 minutes
1/1000 of a second
time
3 K
20 K
3.000 K
temperature
10⁹ K
10¹² K



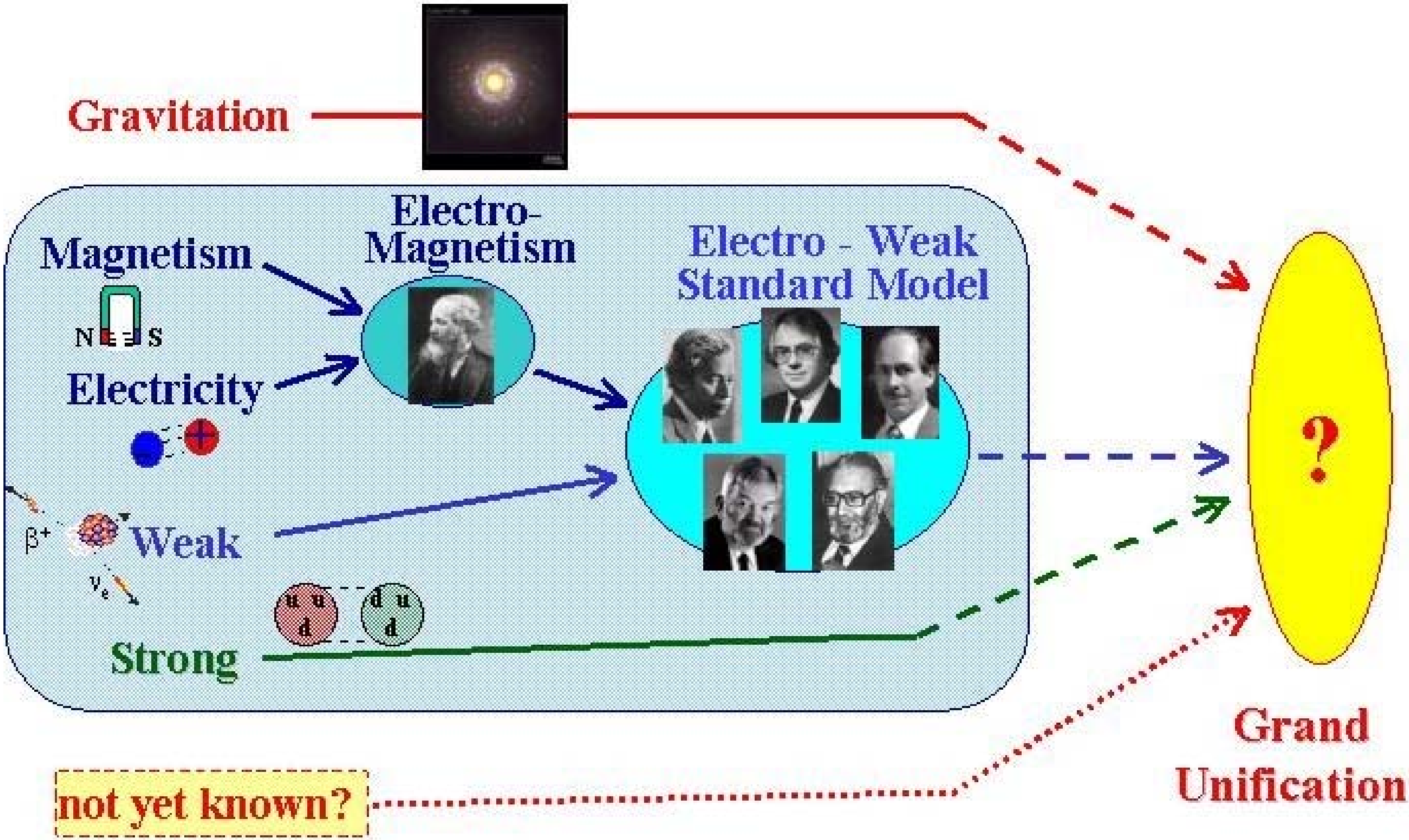
Nuclear Landscape

NuPECC

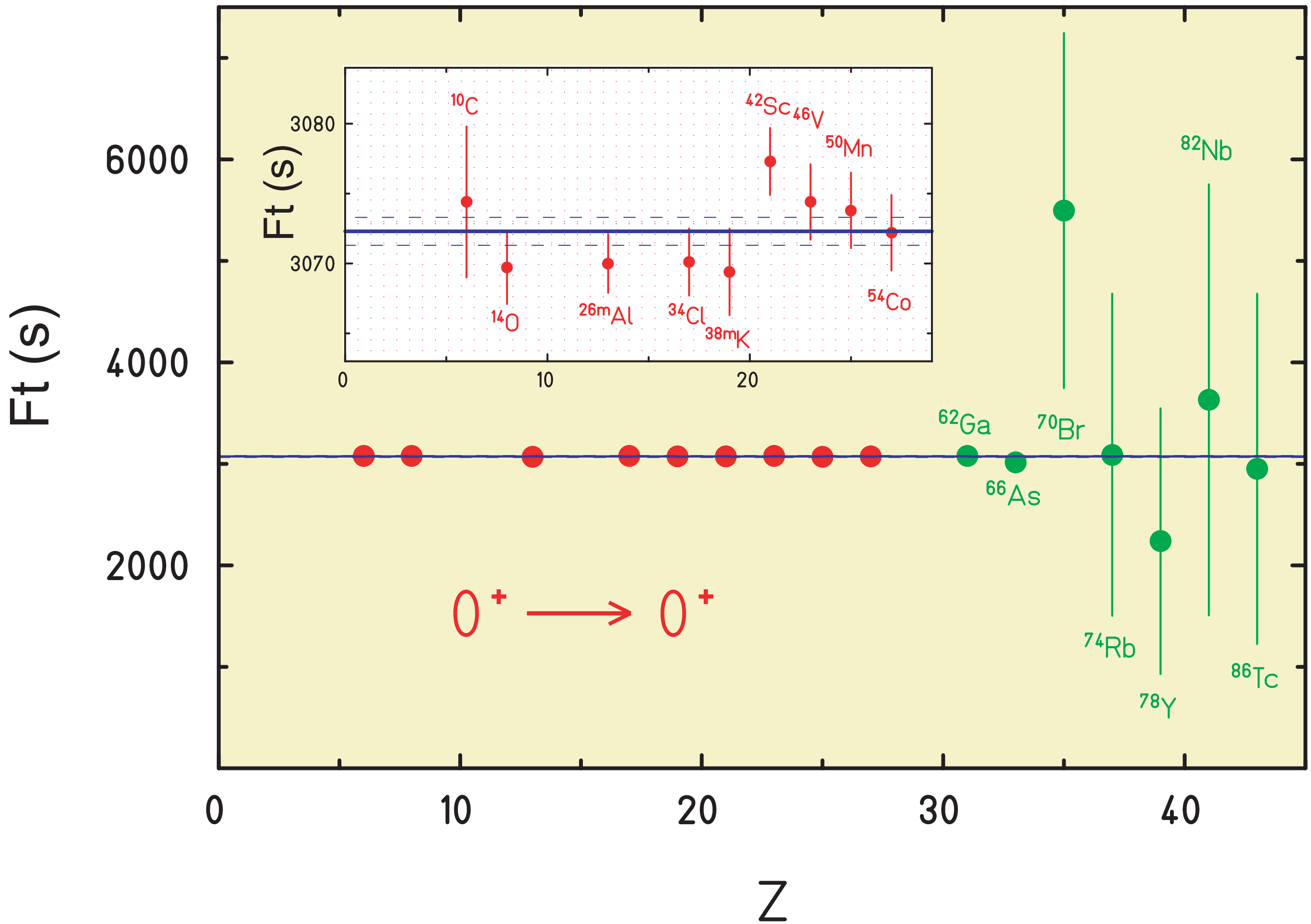
Fundamental Interactions & Symmetries

1. Super-allowed β-transitions (CKM quark-mixing matrix)
2. Properties of υ's (oscillations, mass, Dirac-Majorana 2β)
3. New TRI Scalar, Pseudoscalar and Tensor interactions
4. Time-reversal & CP violation (EDM, β-υ correlations)
   Matter-Anti-matter
5. Rare and forbidden decays (lepton and baryon number
   and lepton flavour violation)
6. Parity non-conservation in atoms (e.g. Cs, Fr, Ra)
7. Physics beyond the Standard Model

→ **Radioactive Ion Beams (RIBs)**



Gravitation
Electro-
Magnetism
Electro - Weak
Standard Model
Magnetism
N
S
Electricity
β+
Weak
Strong
u u
d
d u
d
?
Grand
Unification
not yet known?



Super-allowed $0^+ \rightarrow 0^+$ transitions text of CVC hypothesis ($V^2_{ud} = G_V/G_F$)

Applications of Nuclear Physics

1. Life Sciences and Medical applications (imaging techniques [PET, scans], hadron therapy)
2. Art-history, archaeology
3. Environmental sciences and industrial applications AMS, IBA (PIXE, PIGE)
4. Civil security (detection of explosives and mines)
5. Use of radioisotop in industry, other fields (Solid-state Physics, Atomic Physics)

→ **Radioactive Ion Beams (RIBs)**

NuPECC

European Network of Complementary Facilities

GSI
GANIL
LNL
ISOLDE
LNS
KVI
COSY
JYFL
CRC
MAX-Lab
MAMI
ECT*
TSL
HERMES
ALICE
COMPASS

NuPECC recommends the full exploitation of the existing and competititve lepton, proton, stable-isotope and radioactive-ion beam facilities and instrumentation

NuPECC strongly recommends the timely completion of the ALICE detector to allow early and full exploitation at the start of LHC

Figure 3.18: Schematic view of the ALICE detector.

NuPECC recommends that efforts should be undertaken to strengthen local theory groups in order to guarantee the theory development needed to address the challenging basic issues that exist or may arise from new experimantal observations

NuPECC recommends that efforts to increase literacy in nuclear science among the general public should be intensified

NuPECC recommends as the highest priority for a new construction project the building of the international "Facility for Antiproton and Ion Research (FAIR)" at the GSI Laboratory in Darmstadt

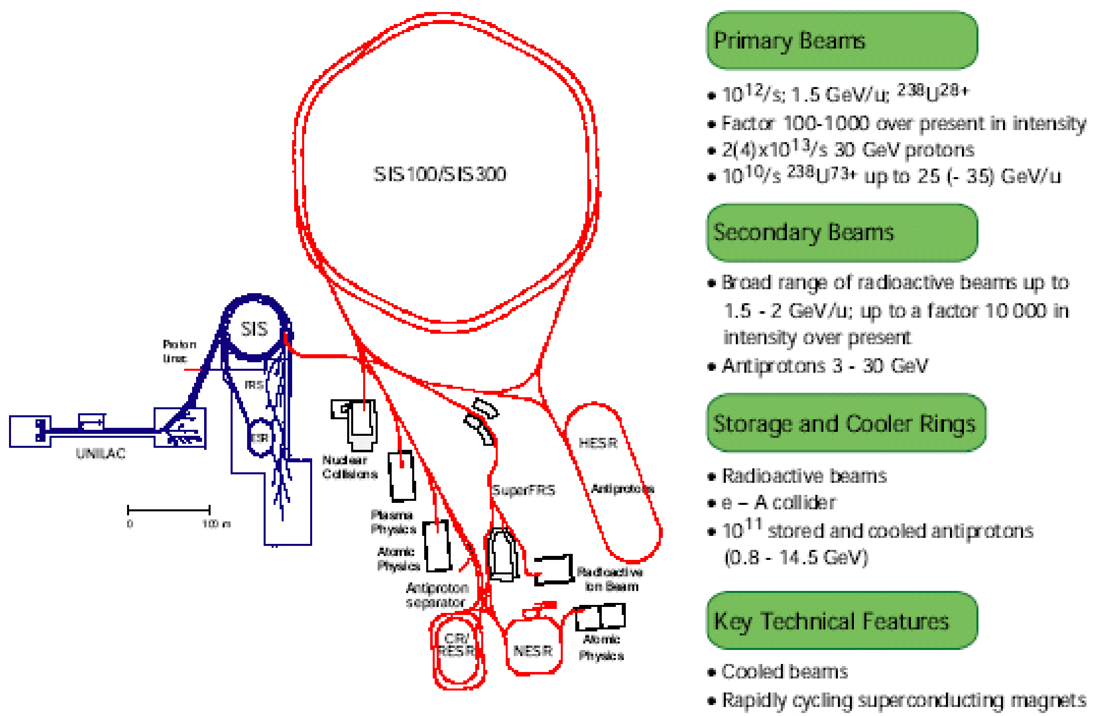
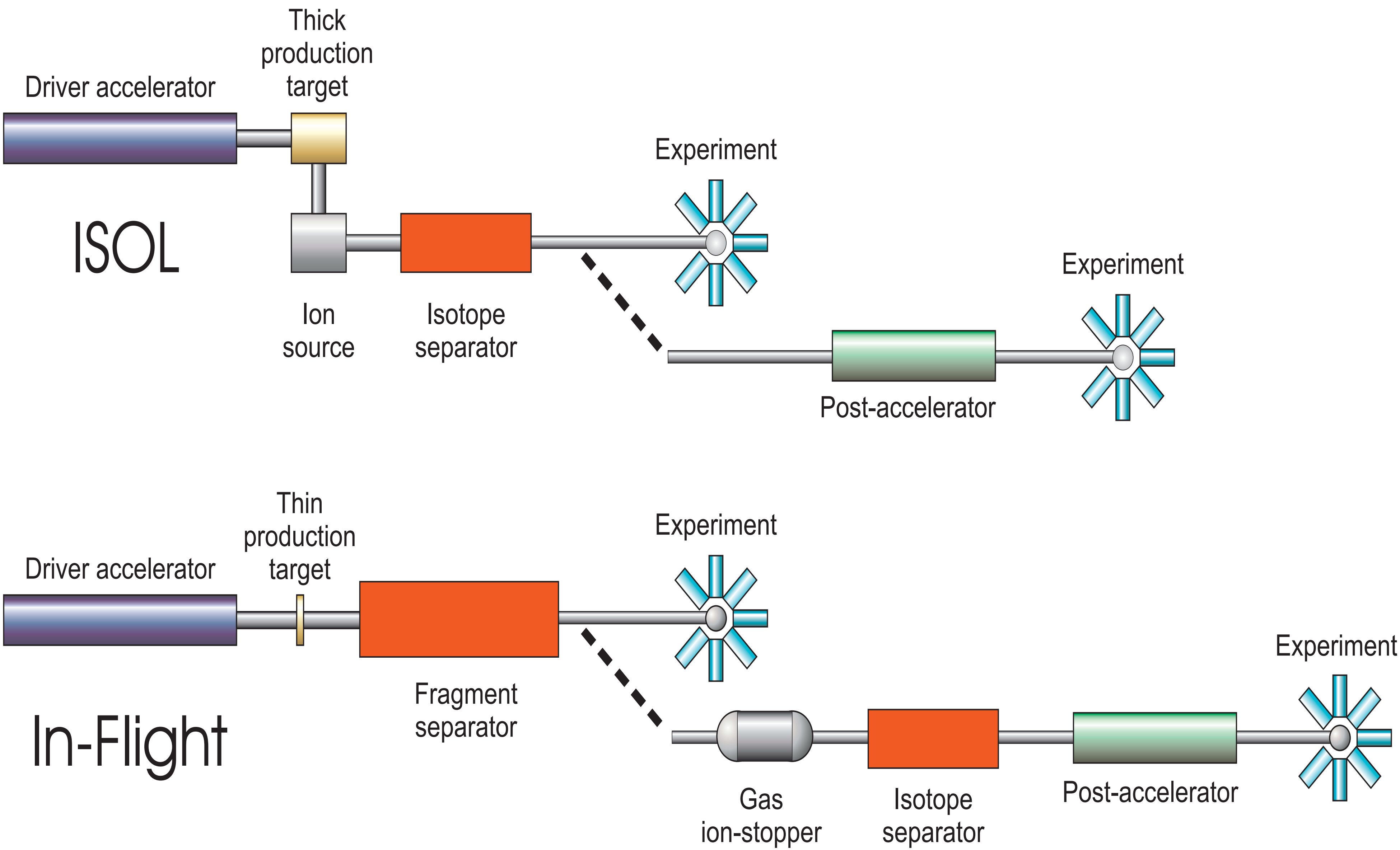


Figure 3.1: Layout of the existing GSI facility (blue) with the UNILAC accelerator, the heavy-ion synchrotron SIS18, the fragment separator FRS and the experimental storage ring ESR; and the planned new facilities (red): the Super-conducting Synchrotrons SIS100/300, the accumulator ring RESR and Collector Ring CR, the New Experimental Storage Ring NESR, the Super Fragment Separator Super-FRS, the Proton Linac and the High-Energy Storage Ring HESR. Also shown are the target areas for plasma physics, nucleus-nucleus collisions, radioactive ion beams, and atomic physics experiments.



Schematic comparison of ISOL and IN-Flight Methods for RIBs

NuPECC

After GSI, NuPECC recommends the highest priority for the construction of EURISOL

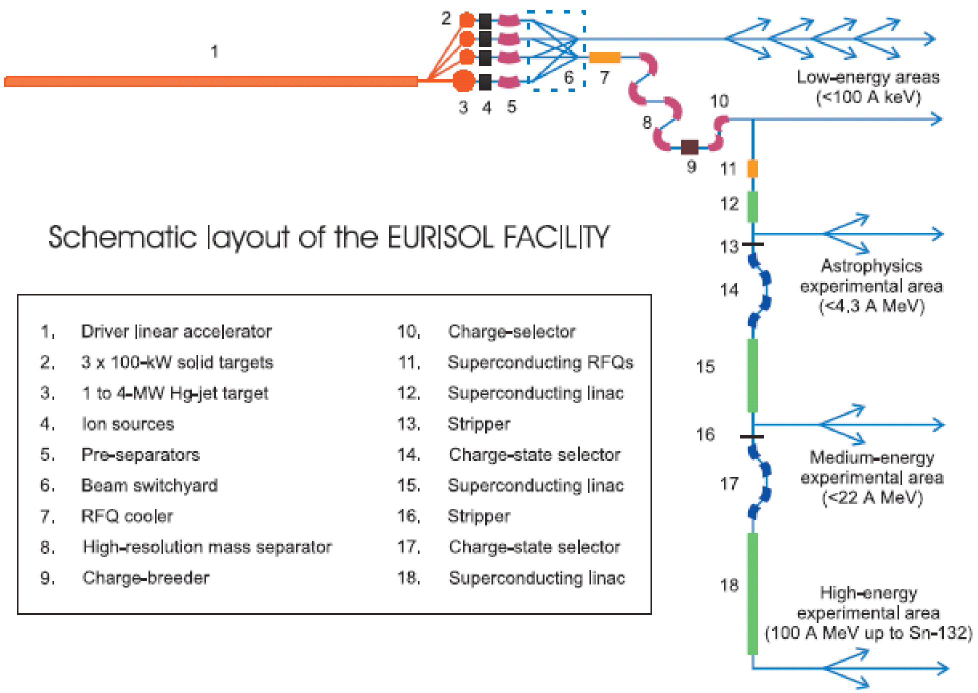


Fig. 4.1: Diagram showing a possible layout of the EURISOL facility. Details of the switchyard and other beamlines are represented very schematically.

NuPECC recommends joining efforts with other interested communities to do the RTD and design work necessary to realise the high-power p/d driver in the near future

NuPECC

The Road to EURISOL

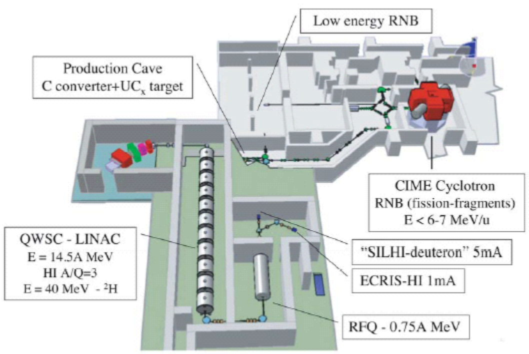


Figure 3.5: Layout of SPIRAL2.

SPIRAL-2

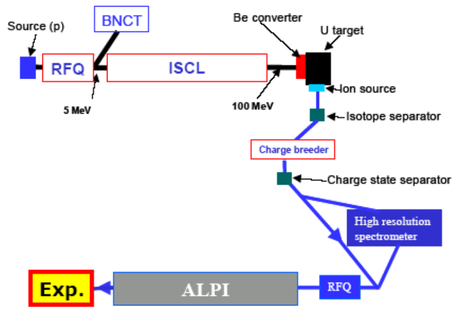


Fig. 2.1 - Block diagram of the facility: RFQ means Radio frequency Quadrupole, BNCT Boron Neutron Capture Therapy, ISCL Independently phased Superconducting Cavity Lina and ALPI Acceleratore Linac Per Ioni

SPES

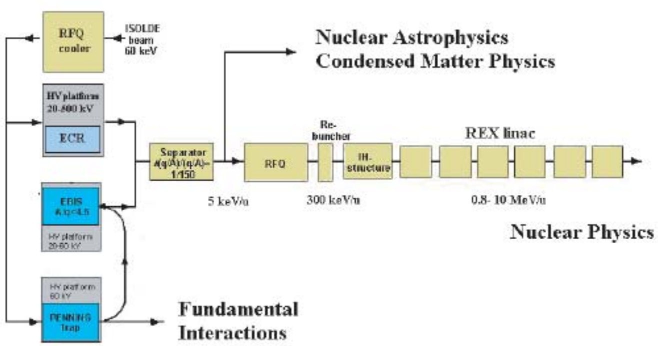
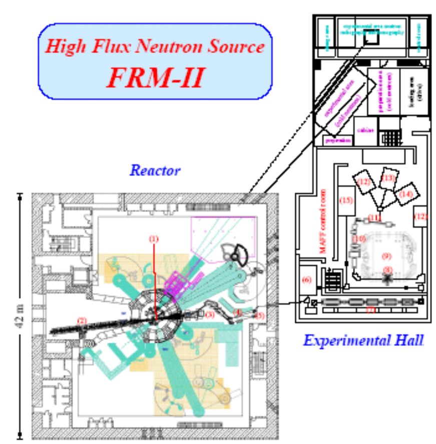


Figure 3.8: Scheme of HIE-ISOLDE.



HIE - ISOLDE

MAFF

NuPECC

NuPECC recommends with high priority the installation at the underground laboratory of Gran Sasso of a compact, high-current 5-MV accelerator for light ions equipped with a 4π-array of Ge-detectors

NuPECC encourages the community to pursue this research (i.e. at a high-luminosity multi-GeV lepton scattering facility) within an international perspective, incorporating it in existing or planned large-scale facilities worldwide

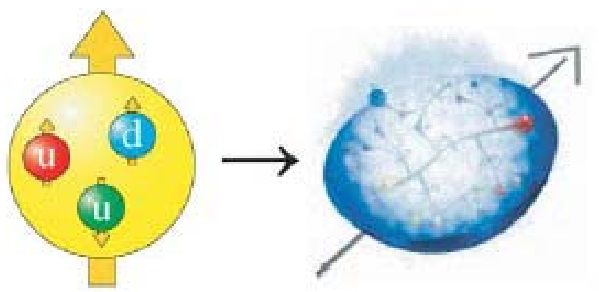
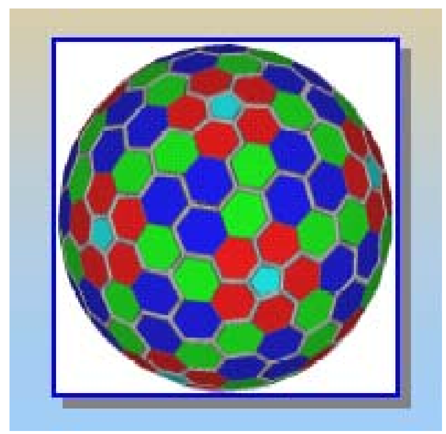


Figure 1.1: The evolution of the our understanding of the structure of the nucleon. In the naive model of the 80-ies (left picture), the nucleon was assumed to consist of two up-quarks and one down-quarks only. At present the nucleon is known to have a rich vacuum structure as well, containing a large number of virtual quark-antiquark pairs and gluons.

NuPECC gives full support for the construction of AGATA and recommends that the R&D phase be pursued with vigour

AGATA

- Advanced GAmma-ray Tracking Array -

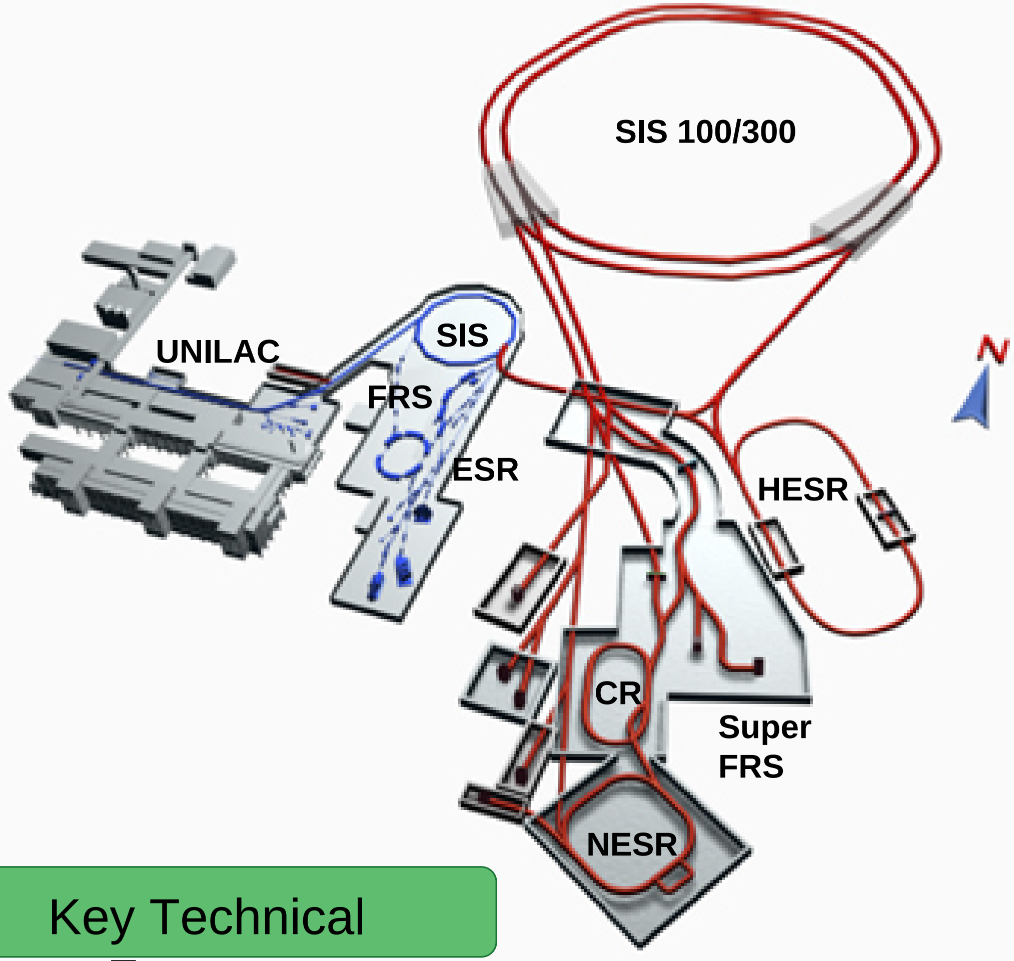


Spectroscopy of heavy and superheavy nuclei

Nuclei very far from stability

Exotic shapes of nuclei

FacilityCharacteristics



Primary Beams

•10^{12}/s; 1.5 – 2 GeV/u; $^{238}U^{28+}$
•Factor 100-1000 over present in intensity
•4x10^{13}/s 30 GeV protons
•10^{10}/s $^{238}U^{73+}$ up to 25 (- 35) GeV/u

Secondary Beams

•Broad range of radioactive beams up to 1.5 - 2 GeV/u; up to factor 10 000 in intensity over present
•Antiprotons 3(0) - 30 GeV

Storage and Cooler Rings

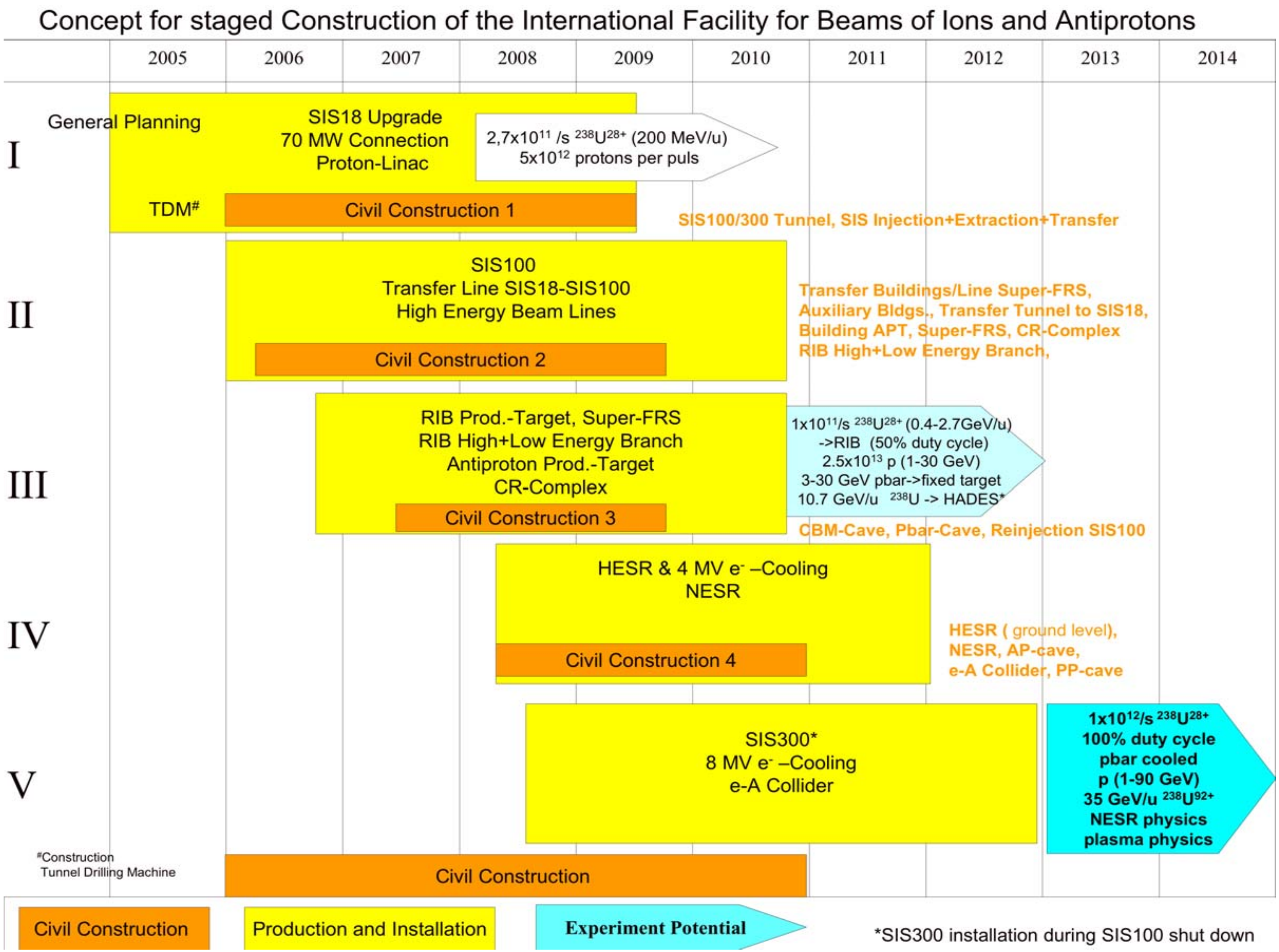
•Radioactive beams
•e – A collider
•10^{11} stored and cooled 3(0) - 15 GeV antiprotons

Key Technical Features

•Cooled beams
•Rapidly cycling superconducting magnets

NuPECC

CONCEPT FOR STAGED CONSTRUCTION OF FAIR



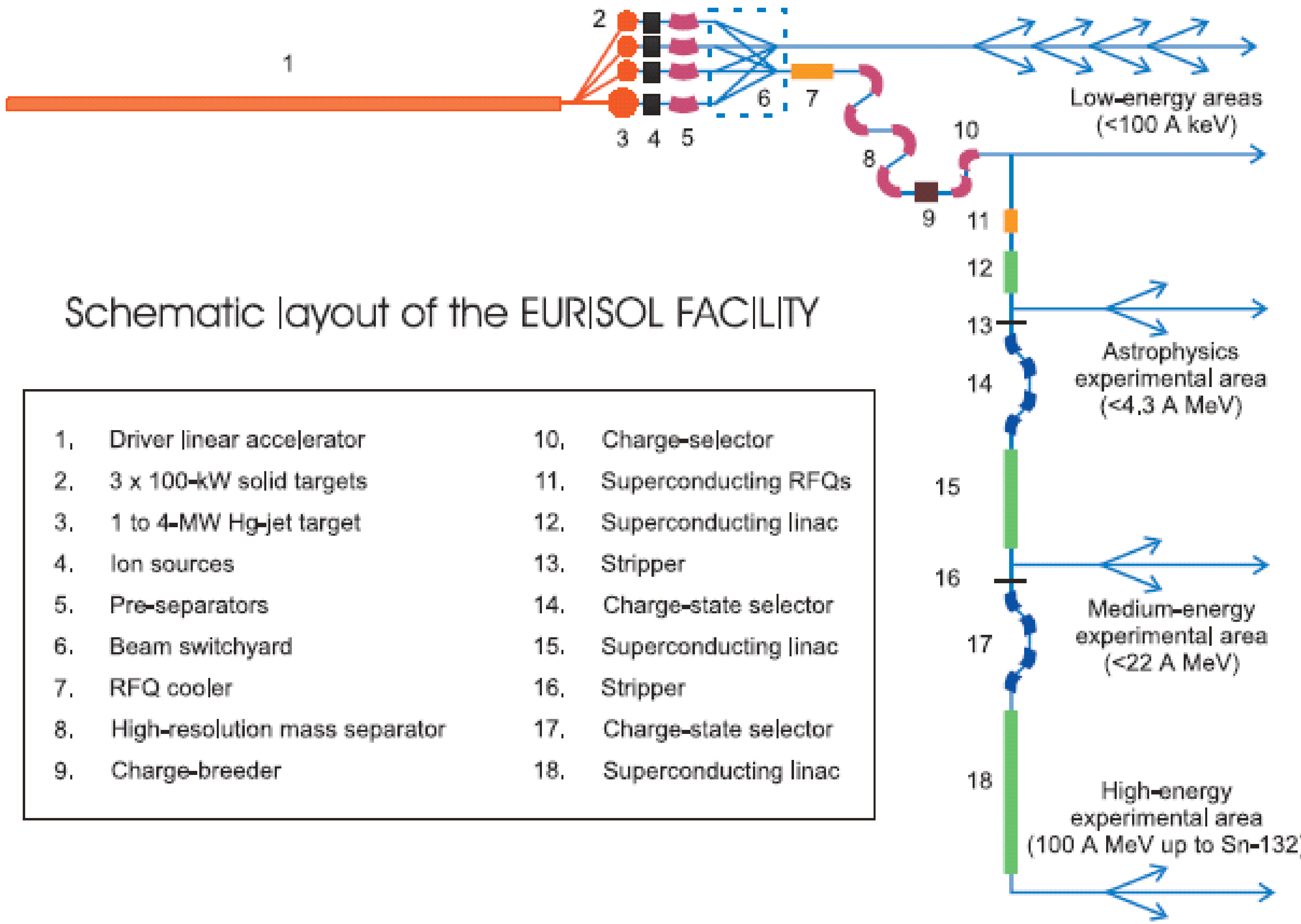
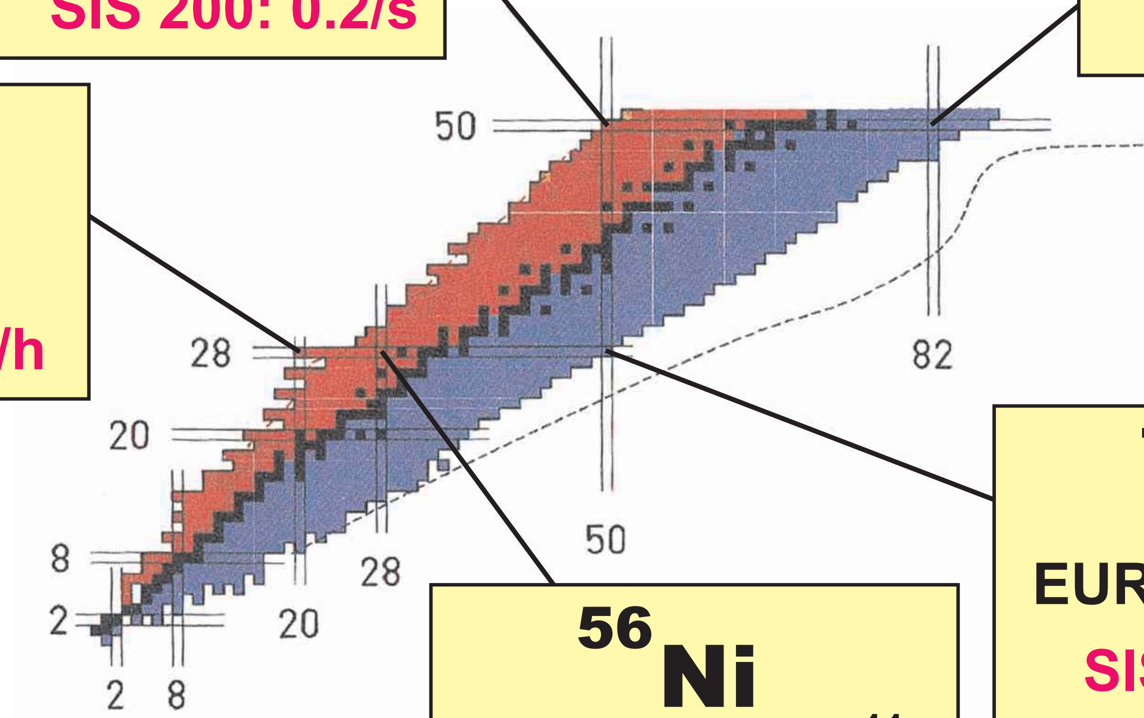


Fig. 4.1: Diagram showing a possible layout of the EURISOL facility. Details of the switchyard and other beamlines are represented very schematically.

NuPECC



^{100}Sn

EURISOL: 0.2/s

SIS 200: 0.2/s

^{132}Sn

EURISOL: 2×10^{13}/s

SIS 200: 1×10^{8}/s

^{48}Ni

EURISOL: ??

SIS 200: 65/h

^{78}Ni

EURISOL: 20/s

SIS 200: 8/s

^{56}Ni

EURISOL: 1×10^{11}/s

SIS 200: 1×10^{9}/s

neutron-rich fission

proton-rich spallation

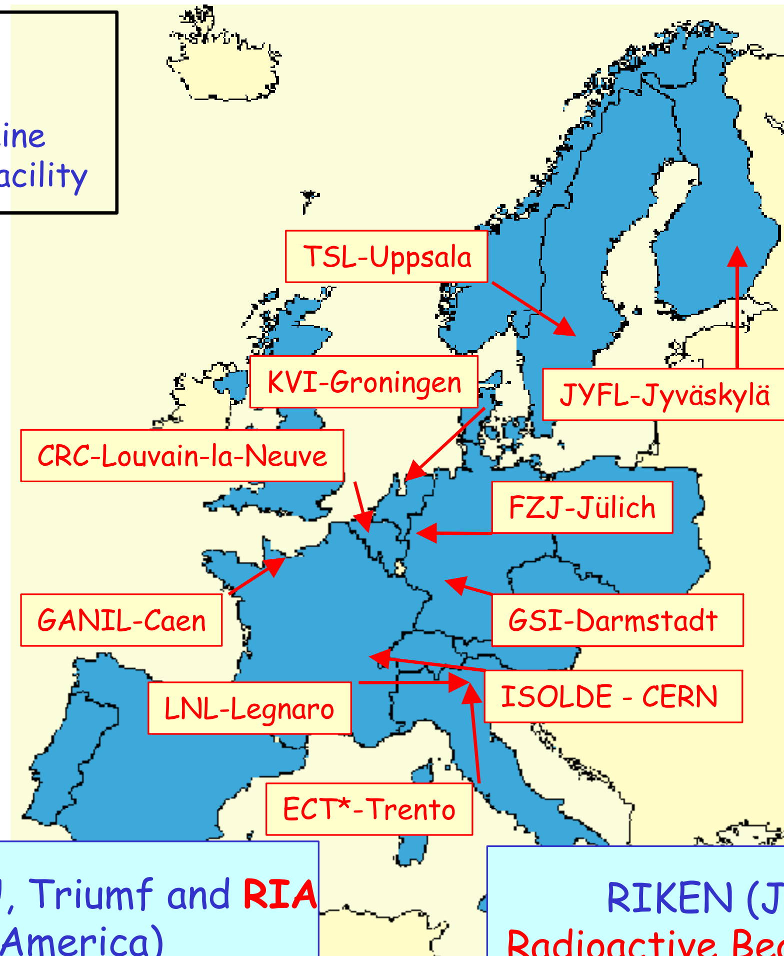
NuPECC

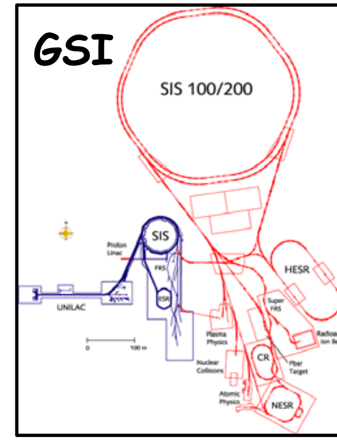
Instrumentation and facilities

EURISOL

European Separator On-Line
Radioactive Nuclear Beam Facility

ISOL





IF

Oak-Ridge, MSU, Triumf and **RIA**
(North-America)

RIKEN (Japan)
Radioactive Beam Factory

NuPECC

Possible related projects

Neutron Spallation Source (ESS)

Transmutation of Nuclear Waste (ADS)

ν and μ factories, K physics

Antiproton beams (?)

β beams

Synergies with ‘related’ field

Solid-state and Atomic Physics, etc.

Medical Applications

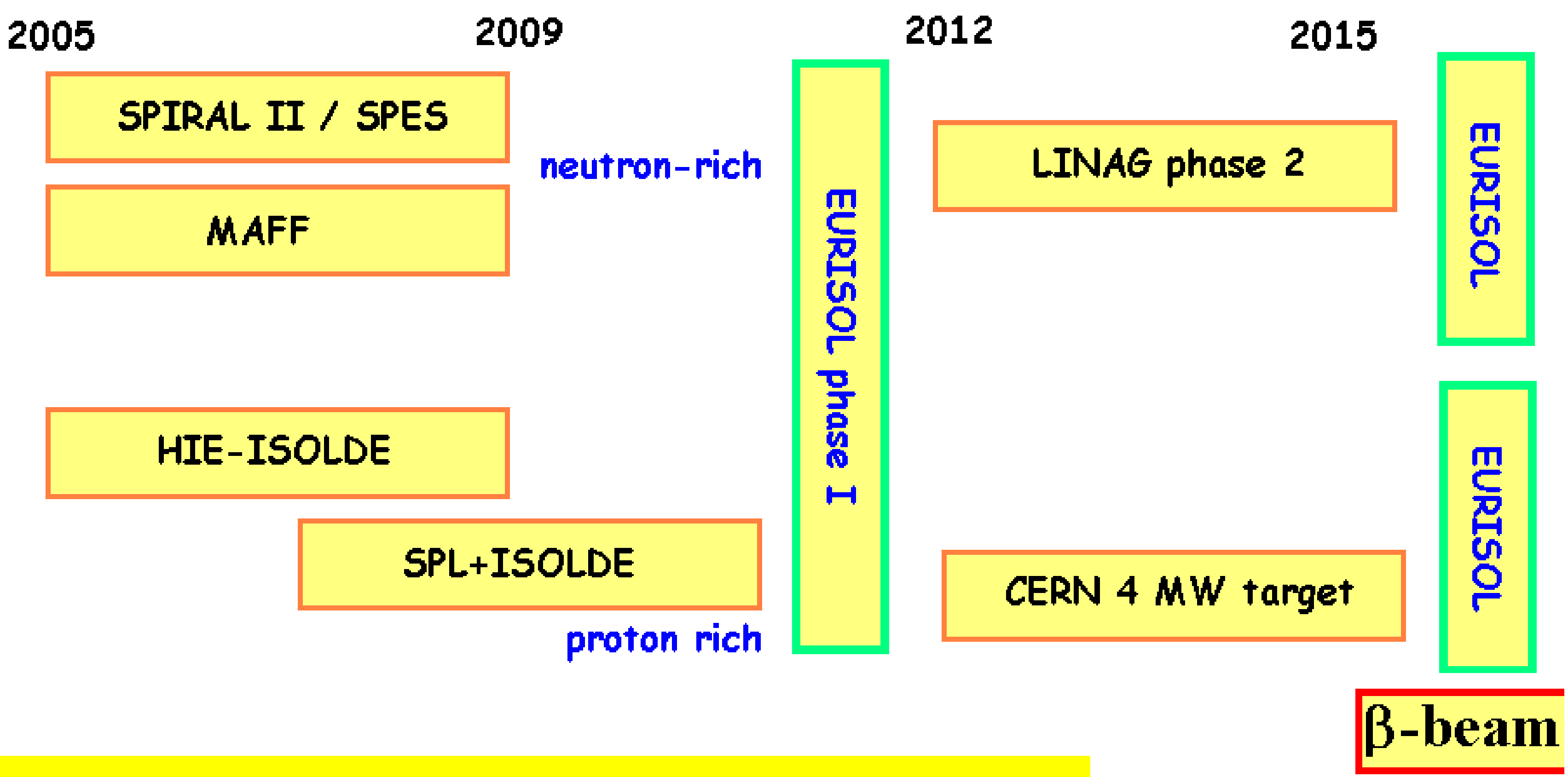
NuPECC

Table 8.10: Total capital costs for EURISOL

Capital items	Cost (M€)
Driver accelerator	120.0
Target stations and ion sources + labs	58.8
Post-accelerator & mass-separator	60.4
Instrumentation	85.2
SUB-TOTAL:	**324.4**
+ 20% contingency factor	64.9
SUB-TOTAL:	**389.3**
Buildings	224.1
GRAND TOTAL:	**613 M€**

NuPECC

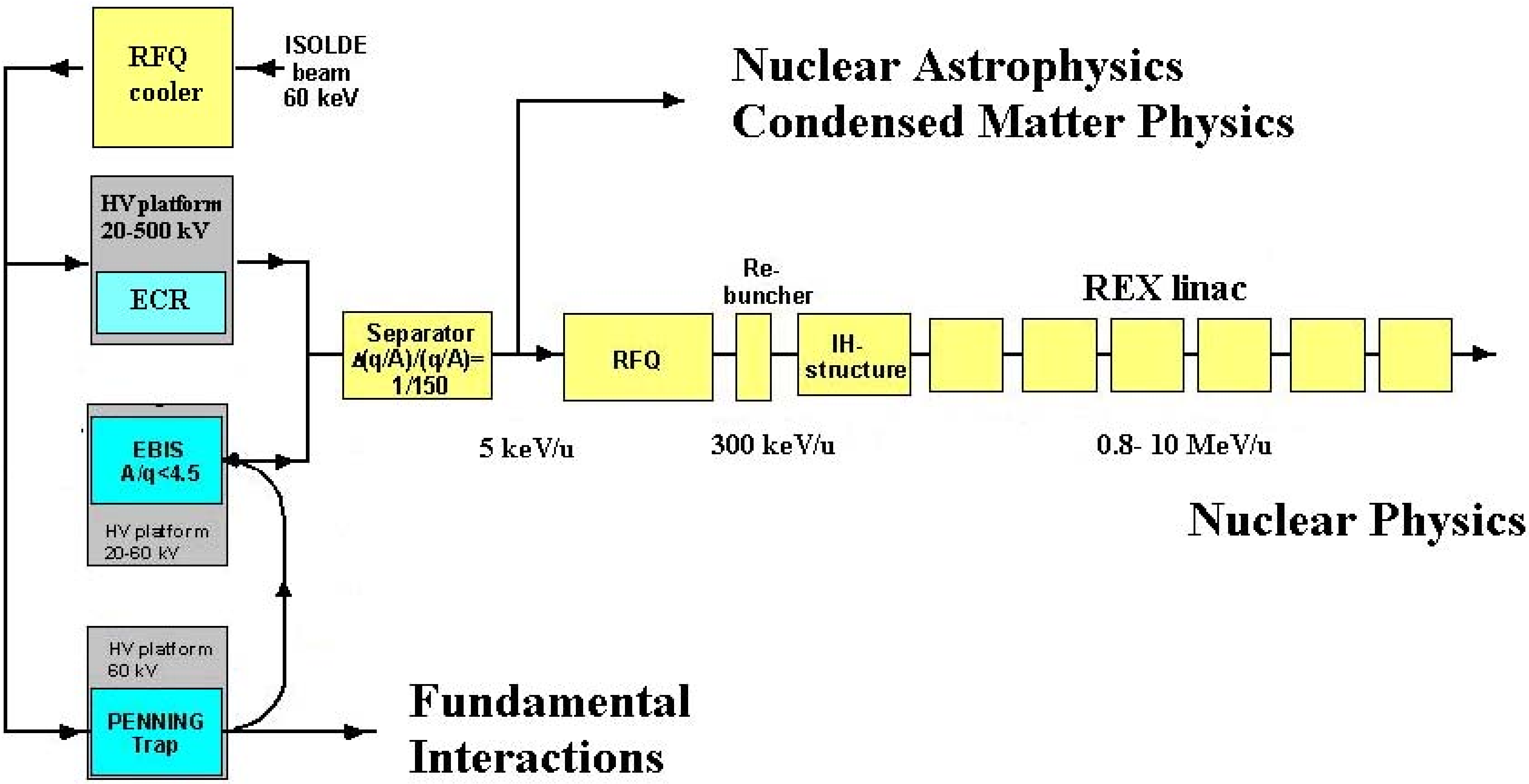
ISOL roadmap



RTD and initial design	2002 – 2007
detailed design, construction	2008 – 2011

NuPECC

HIE-ISOLDE



RFQ cooler
ISOLDE beam 60 keV
Nuclear Astrophysics
Condensed Matter Physics
HV platform 20-500 kV
ECR
Re-buncher
REX linac
Separator Δ(q/A)/(q/A)= 1/150
RFQ
IH-structure
5 keV/u
300 keV/u
0.8- 10 MeV/u
EBIS A/q<4.5
HV platform 20-60 kV
Nuclear Physics
HV platform 60 kV
PENNING Trap
Fundamental Interactions