Future of Nuclear Physics in Europe

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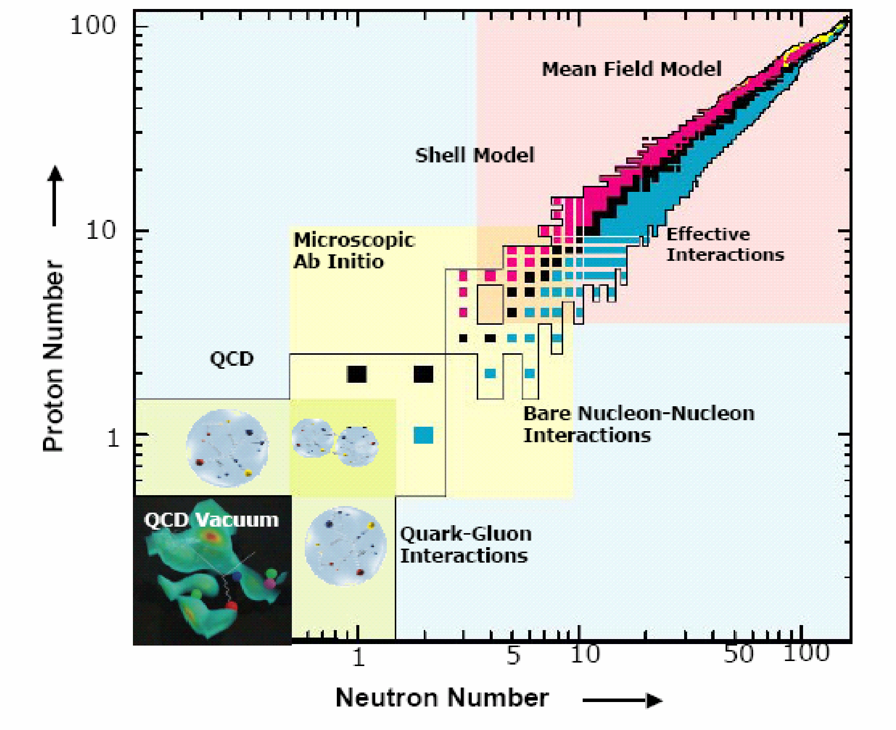
NuPECC Long Range Plan 2004
"Perspectives for Nuclear Physics Research in Europe in the Coming Decade and Beyond"



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

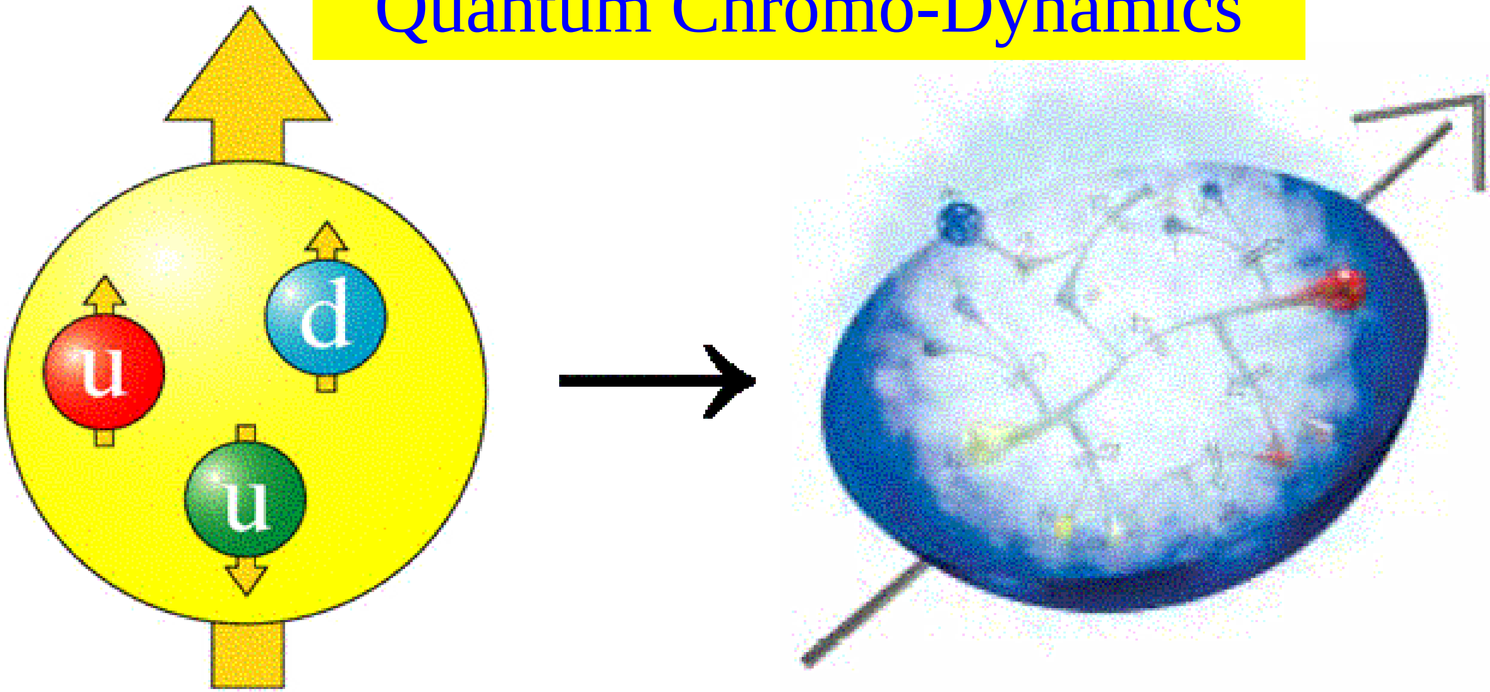
NuPECC is an Expert Committee of the European Science Foundation

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 ⇒ Recommendations and priorities

Quantum Chromo-Dynamics



Structure of the Nucleon

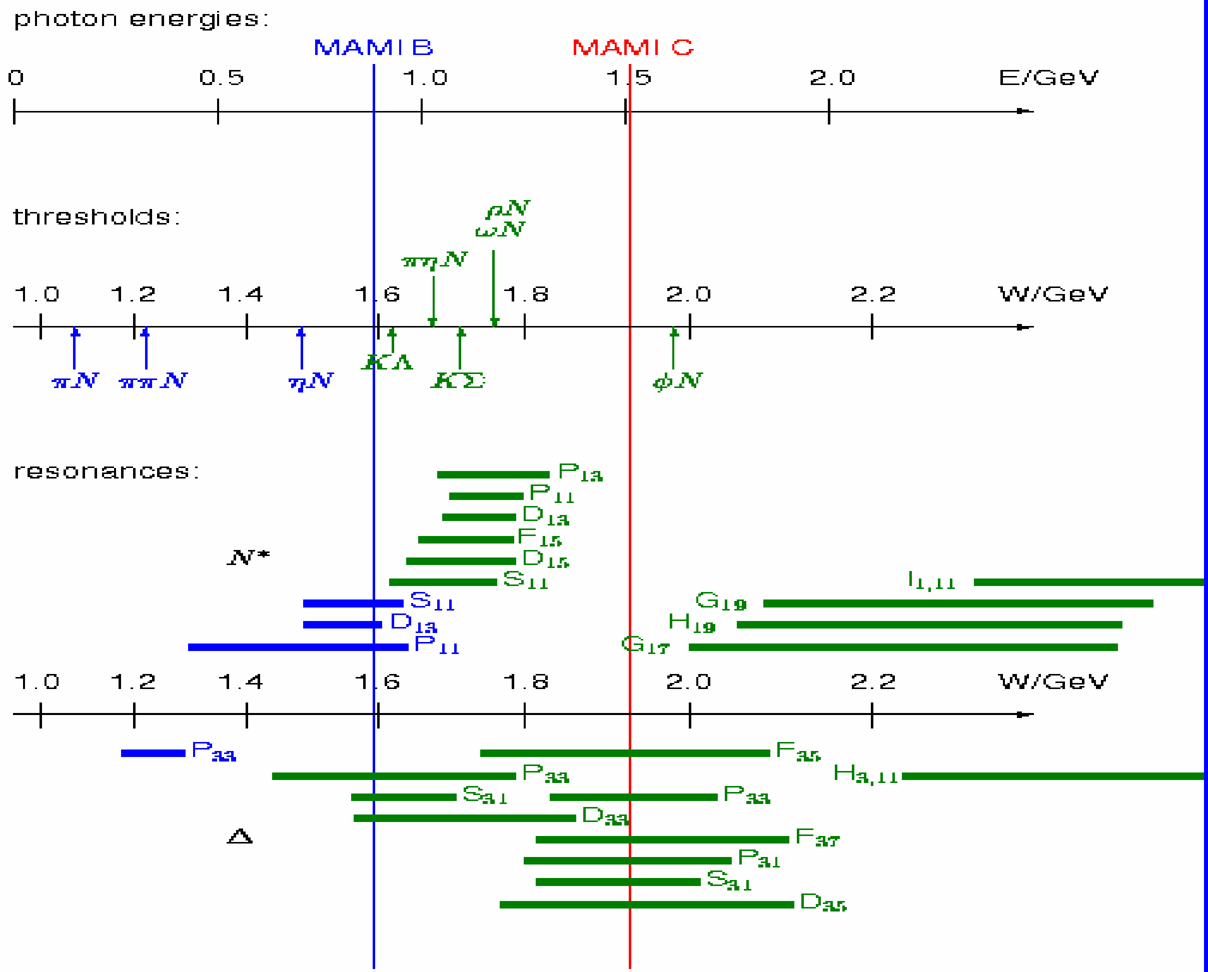
Naive quark model
Two up-quarks &
one down-quark
Colour neutral

Rich Vacuum Structure
Virtual quark-antiquark pairs
Gluons
Orbital angular momentum

Quantum Chromo-Dynamics

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

ranges of physics

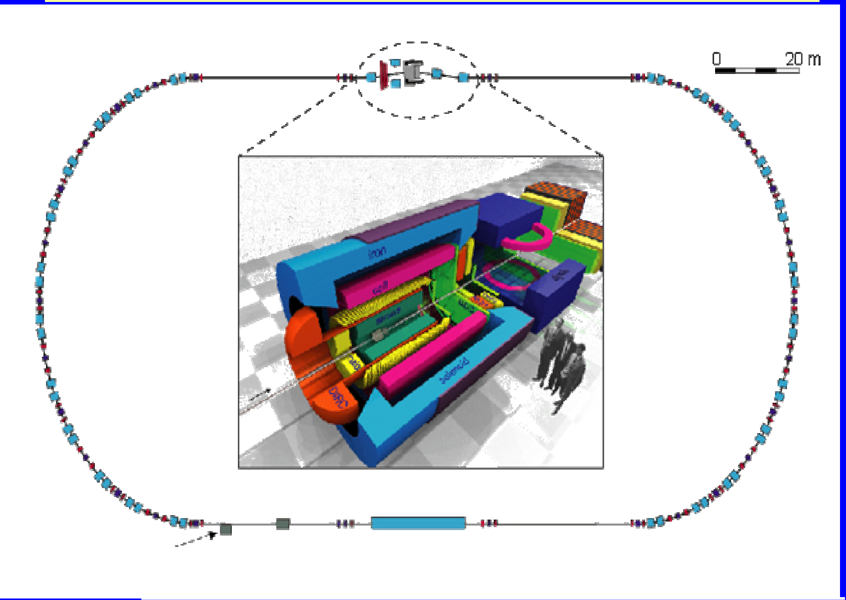


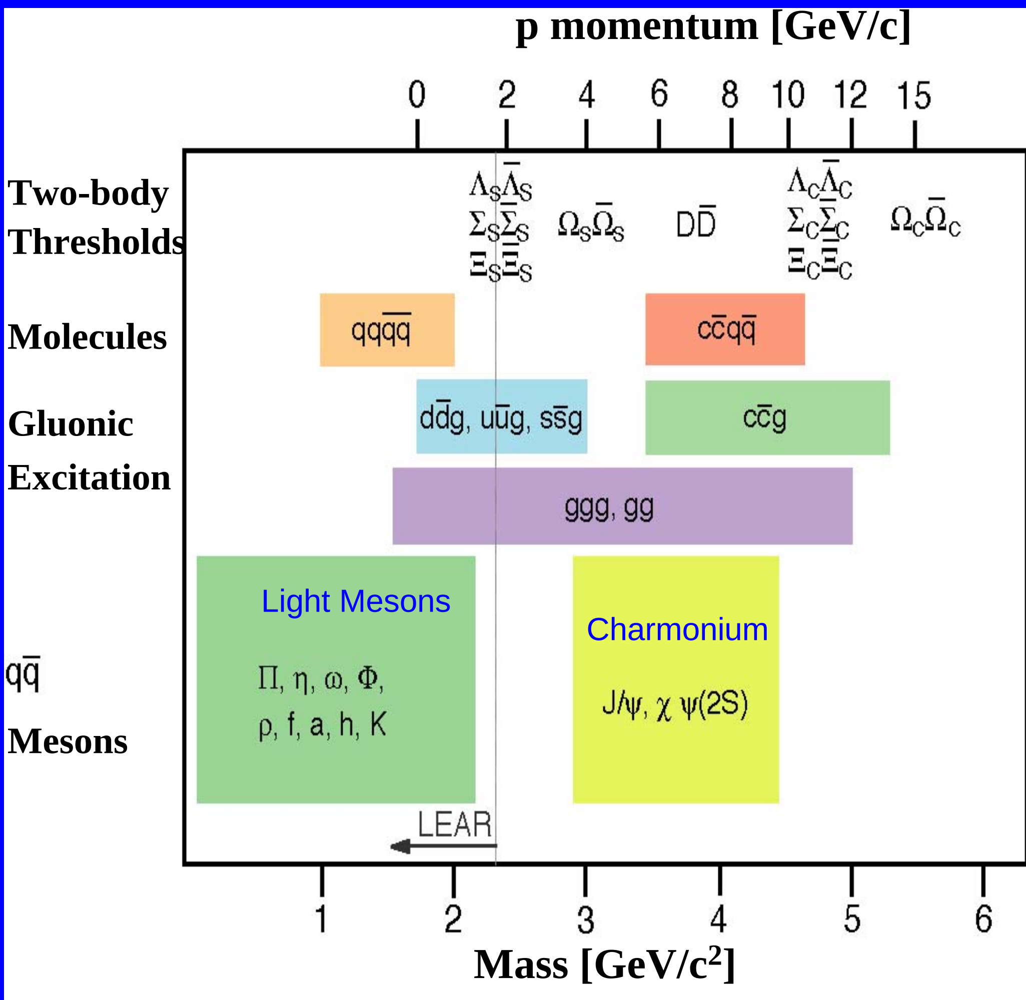
Physics Potential of the Antiproton Facility

Hadron Physics with Antiproton Beams

Quark gluon structure and dynamics of "strong" interacting particles;
Origin of the confinement and mass of hadrons

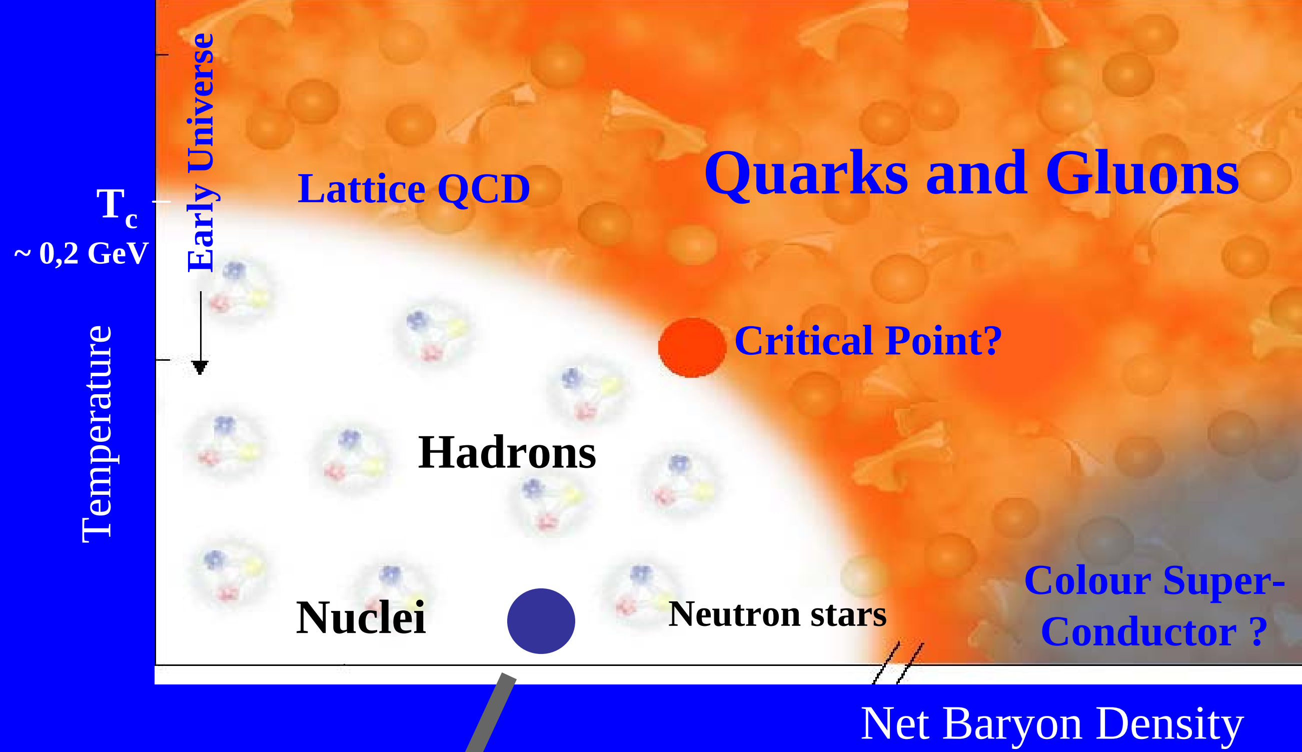
HESR: 3 – 30 GeV antiprotons
$L = 2 \times 10^{32}$ / cm^2 s
cooling: $\Delta p/p = 2 \times 10^{-5}$ / 2×10^{-4}



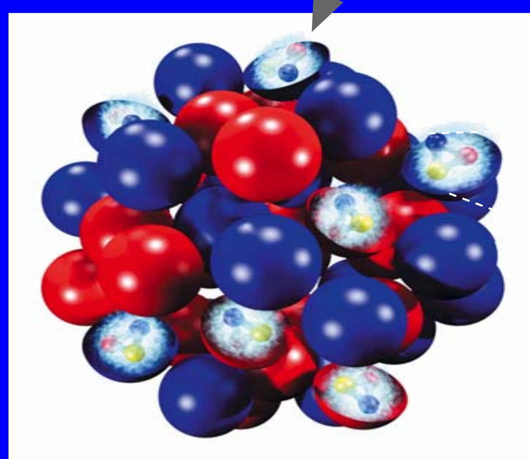


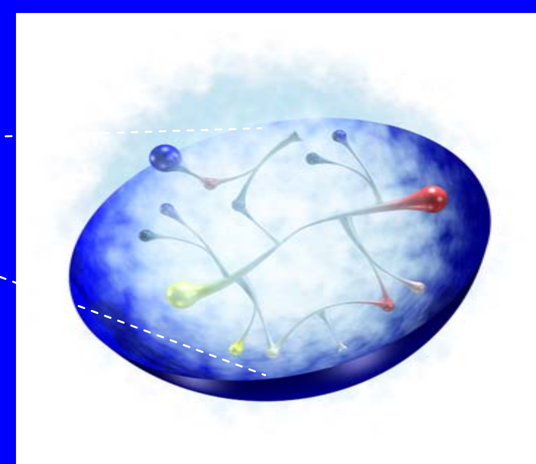
PANDA Collaboration

Phases of Nuclear Matter



Nuclei





Nucleon

Phases of Nuclear Matter

1. 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)**

2. Very high temperatures (QGP; ALICE@CERN)
3. 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)**

Schematic view of the ALICE Detector at CERN

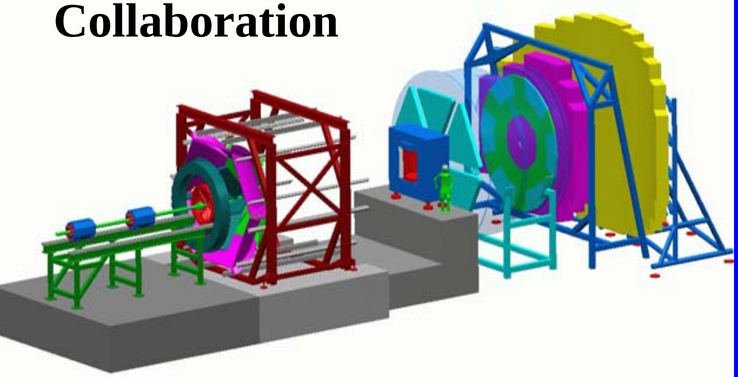
Physics Motivation for Nucleus-Nucleus Collisions

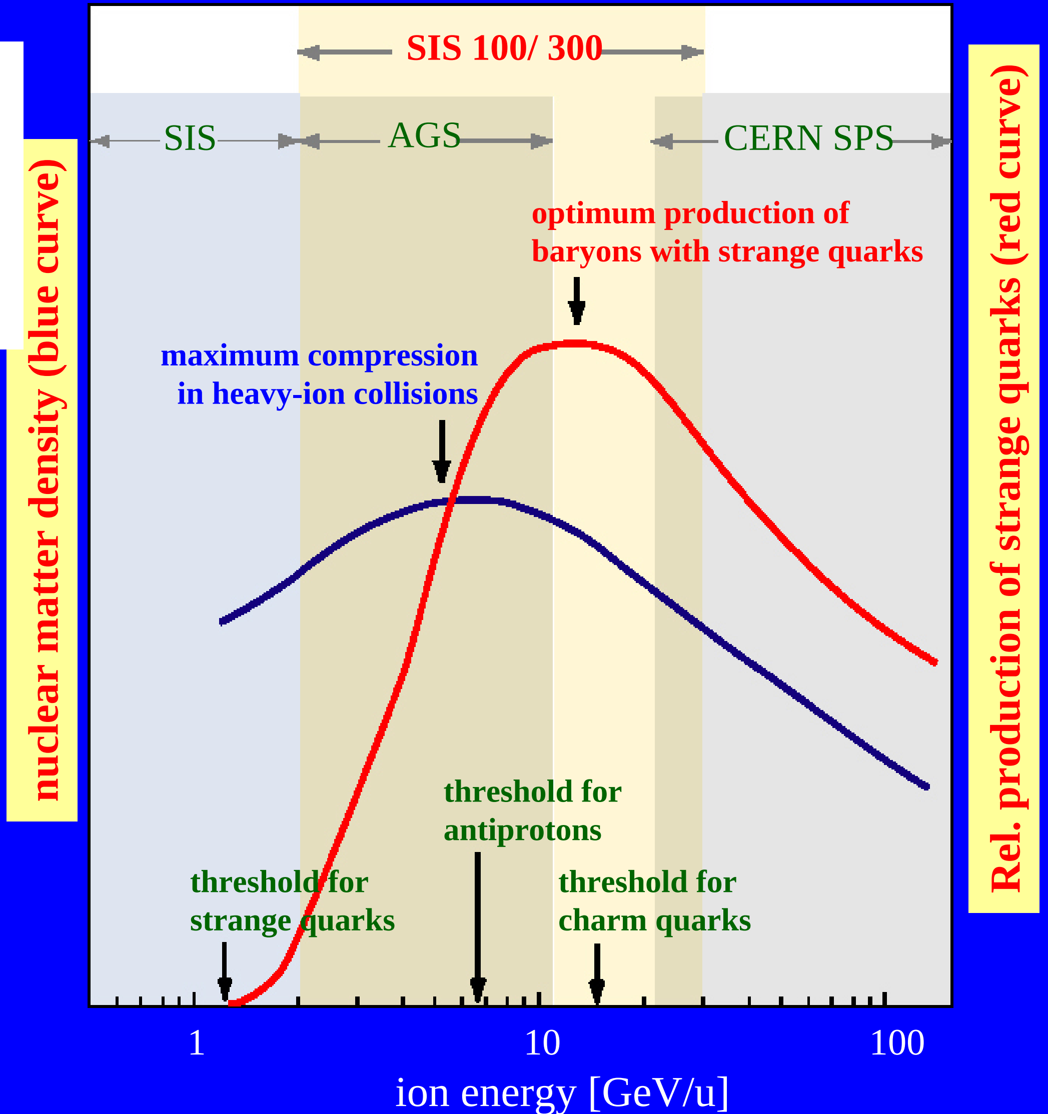
Physics of Nuclear Matter

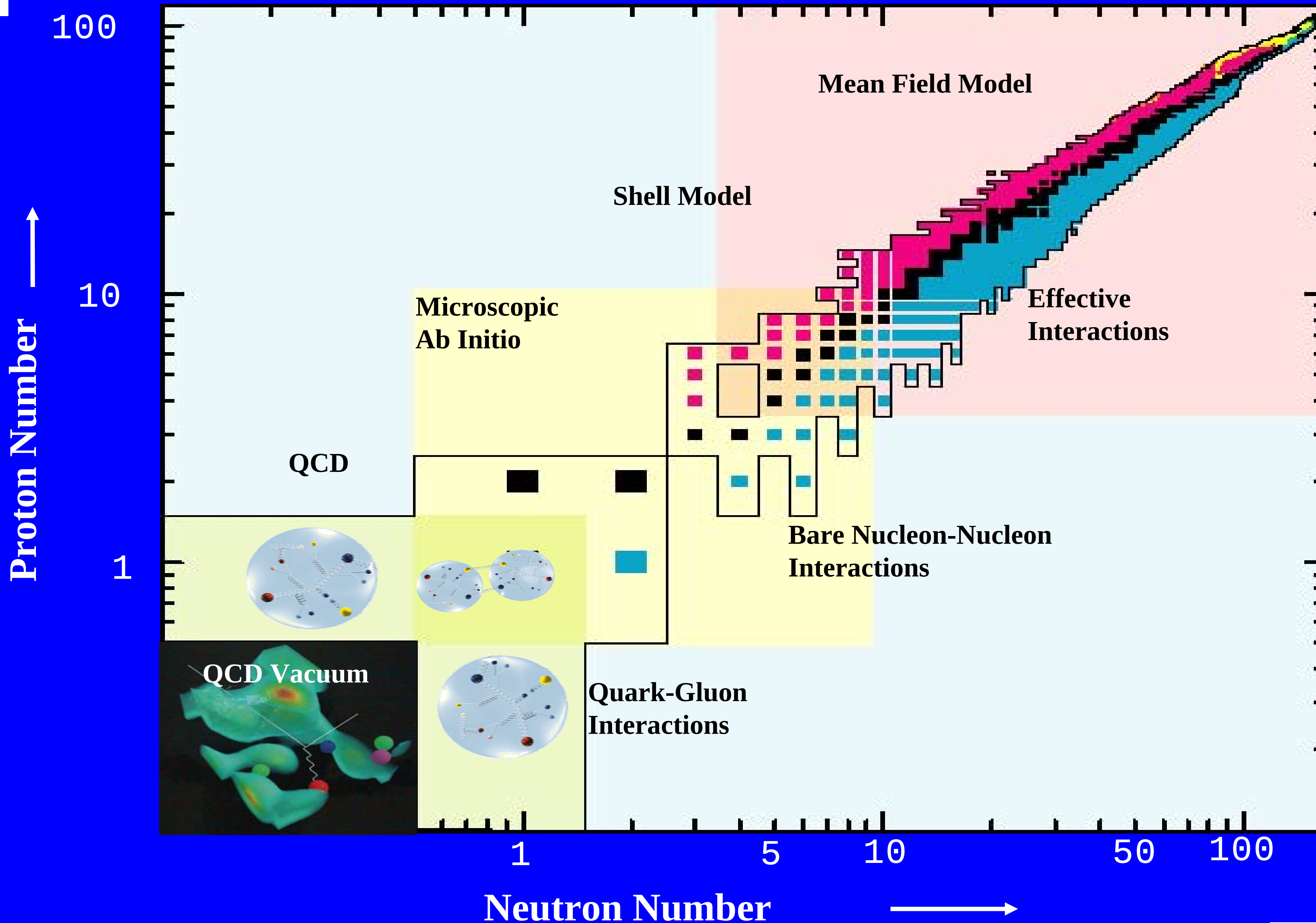
- Studies of hadronic matter at high densities;
- Phase transitions in quark matter;
- Properties of neutron stars

^{238}U: ~ 23 GeV/u ; 10^9 / s

CBM Collaboration



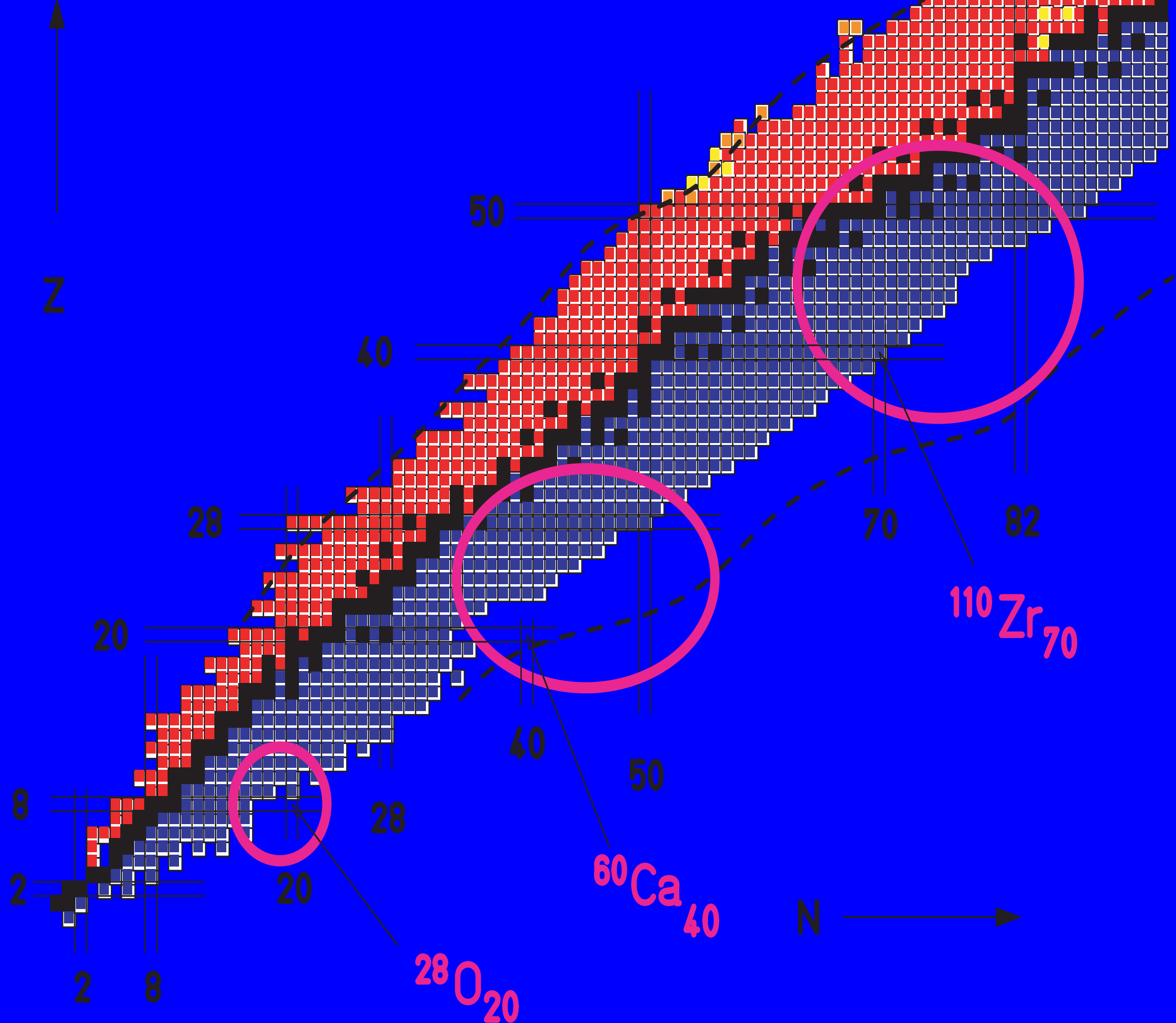


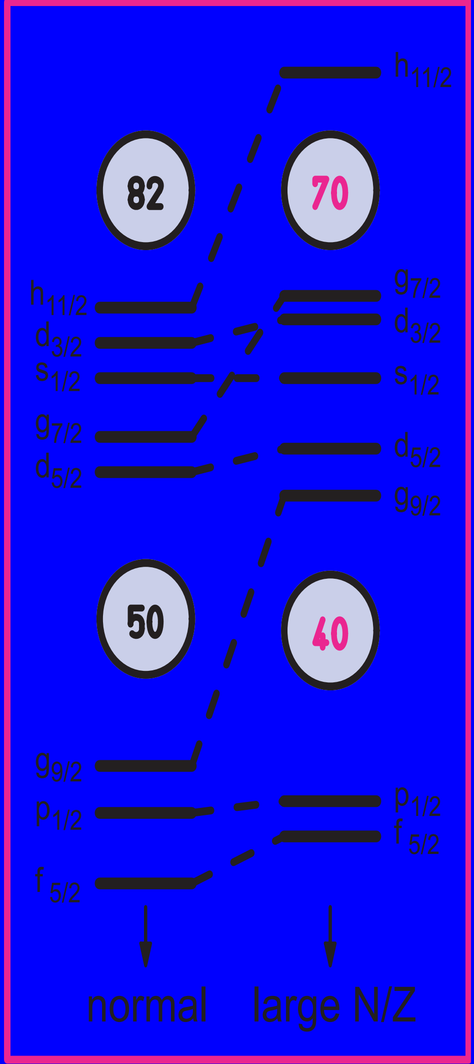

100
10
1
Proton Number
Mean Field Model
Shell Model
Microscopic
Ab Initio
Effective
Interactions
QCD
Bare Nucleon-Nucleon
Interactions
QCD Vacuum
Quark-Gluon
Interactions
1
5
10
50
100
Neutron Number

Nuclear Structure

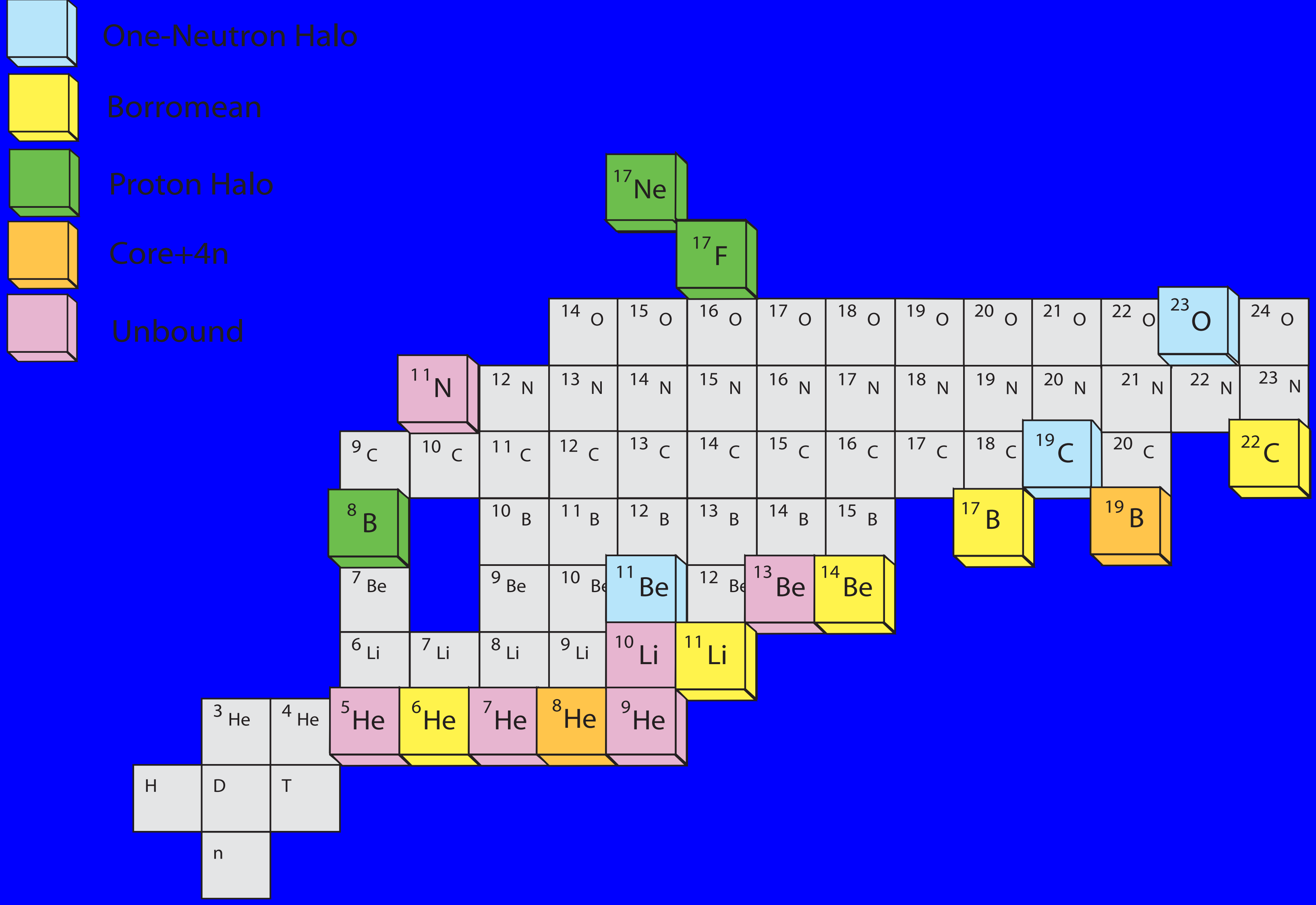
1. Origin of nuclear binding (2- & 3-body forces)
2. Dependence of effective nucleon-nucleon interaction on N & Z
3. Limits of nuclear stability (pairing, 2p radioactivity)
4. New magic numbers for large N/Z (double-magic ^{78}Ni)
5. Search for super-heavy elements (island of stability)
6. Exotic shapes (halos, triaxial and super- & hyperdeformed shapes, clustering, molecular shape) & Symmetries; [dynamical SU(3),SU(5),O(6); Critical point E(5),X(5)]
6. From single-particle excitations to 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)**

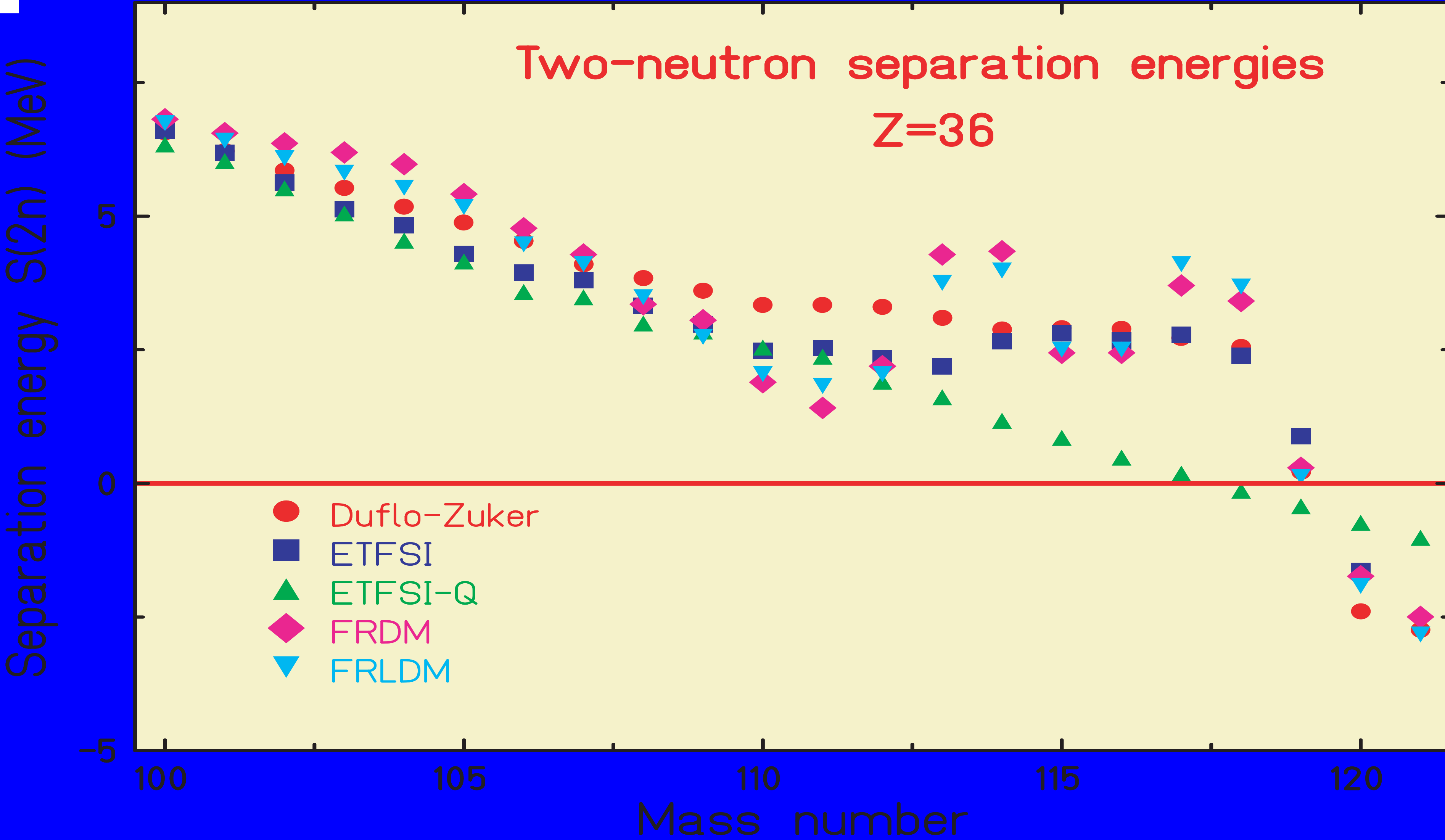




Regions where new magic numbers may occur as deduced from single-particle energies for large N/Z

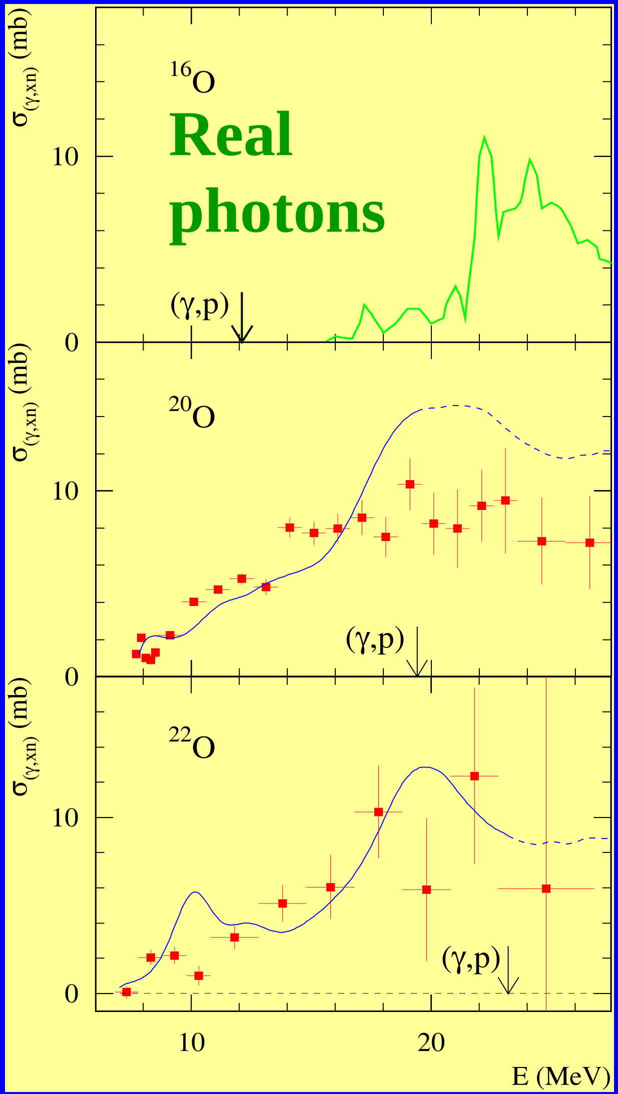


Known 1p, 1n and 2n (Borromean) halo nuclei



Two-neutron separation energies of krypton isotopes as a function of mass number

Dipole Strength Distribution of n-Rich Nuclei



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

N-Z=0

⇒ Photo-neutron cross sections from virtual photons

N-Z=4

N-Z=6

⇒ 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

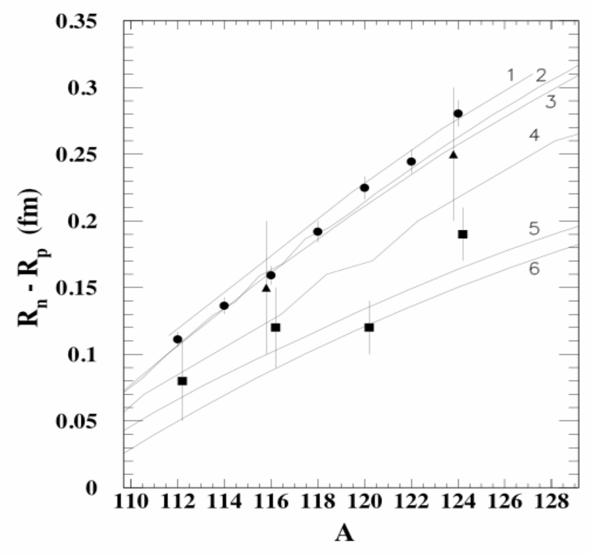
Giant Resonances

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

• nuclear compressibility (isoscalar monopole)

• symmetry energy (isovector excitations)

• neutron skin (spin dipole)

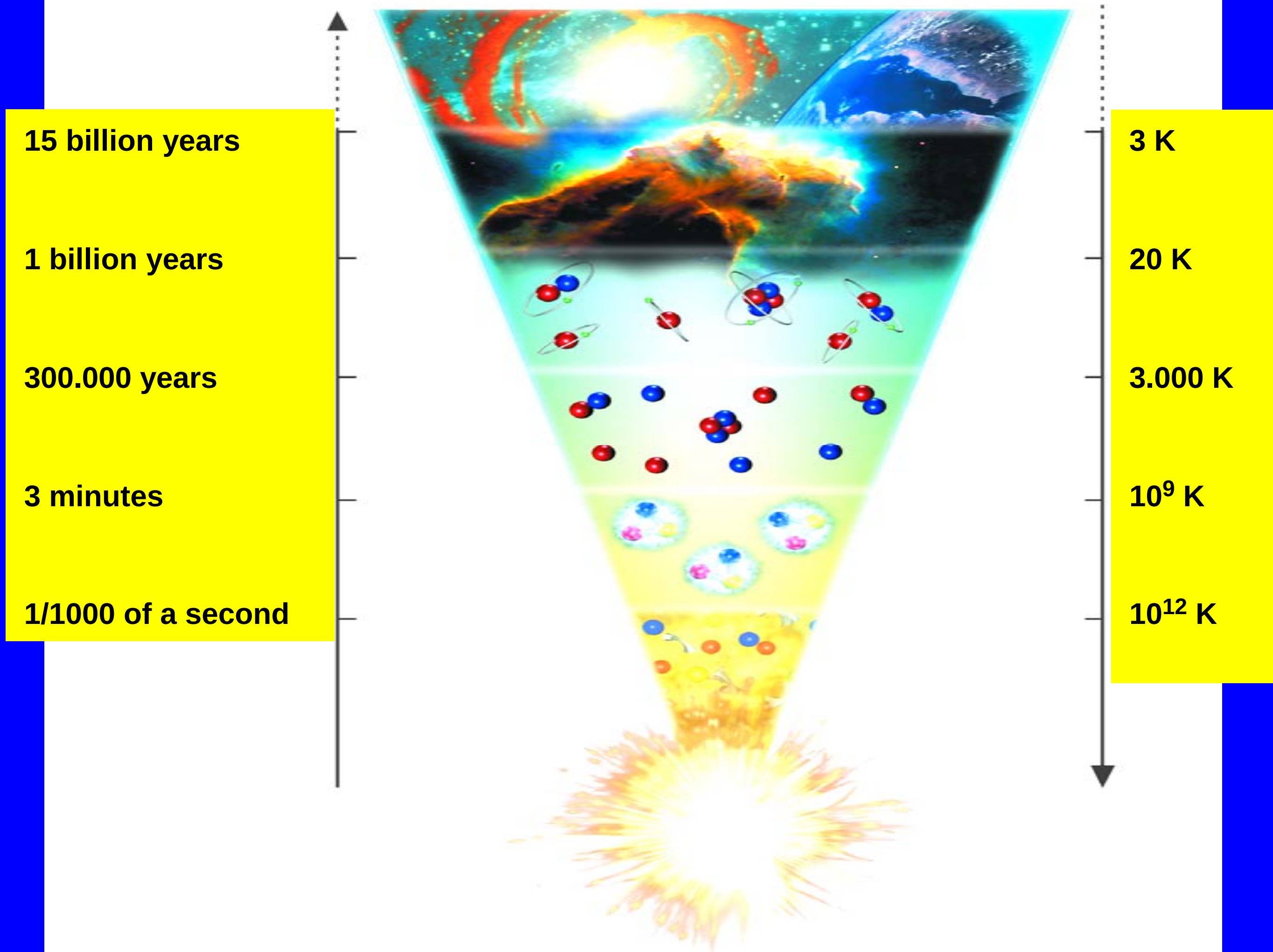


Astrophysics:

Gamow-Teller

threshold (γ,n) strength

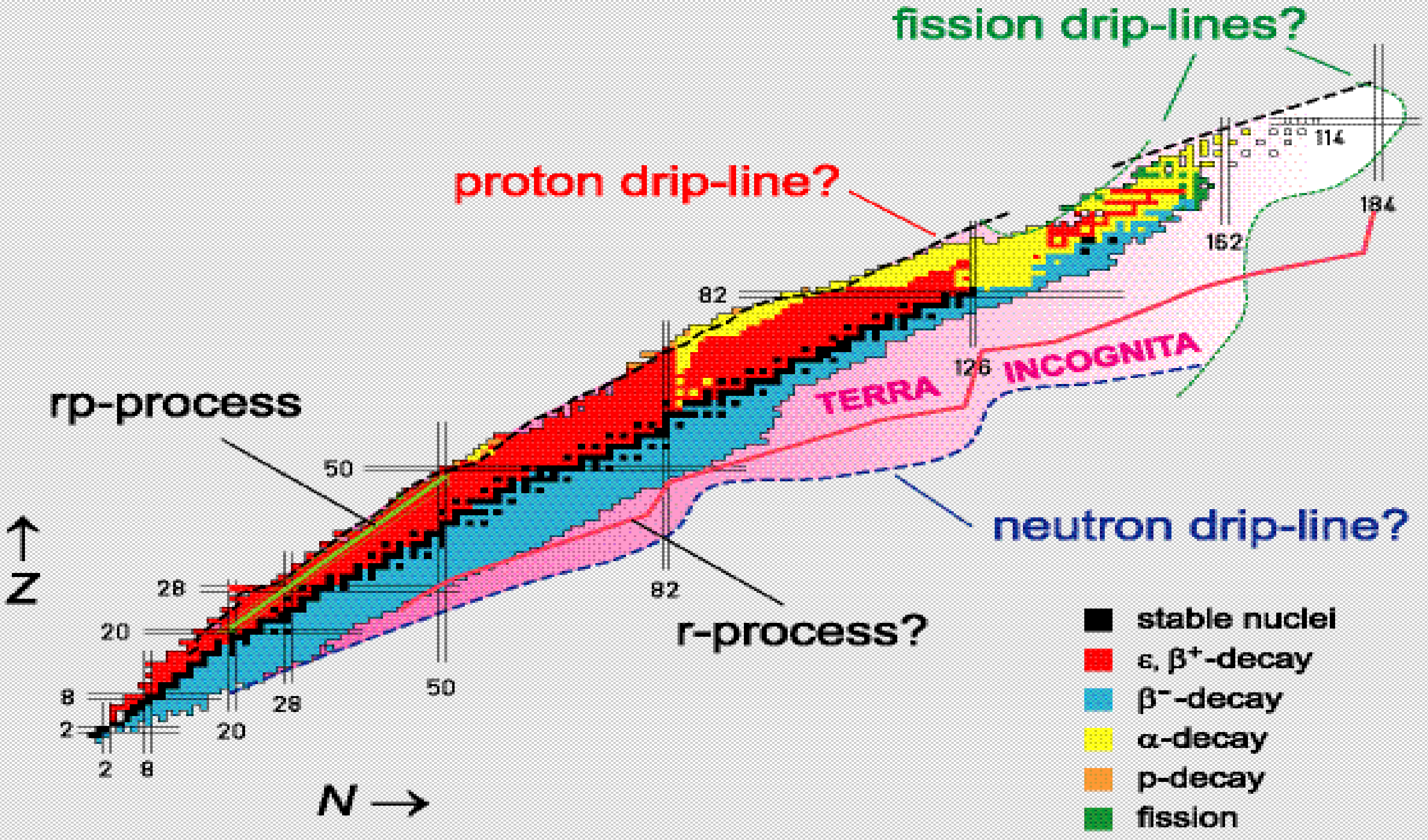
• …


15 billion years
1 billion years
300.000 years
3 minutes
1/1000 of a second
3 K
20 K
3.000 K
10^9 K
10^{12} K

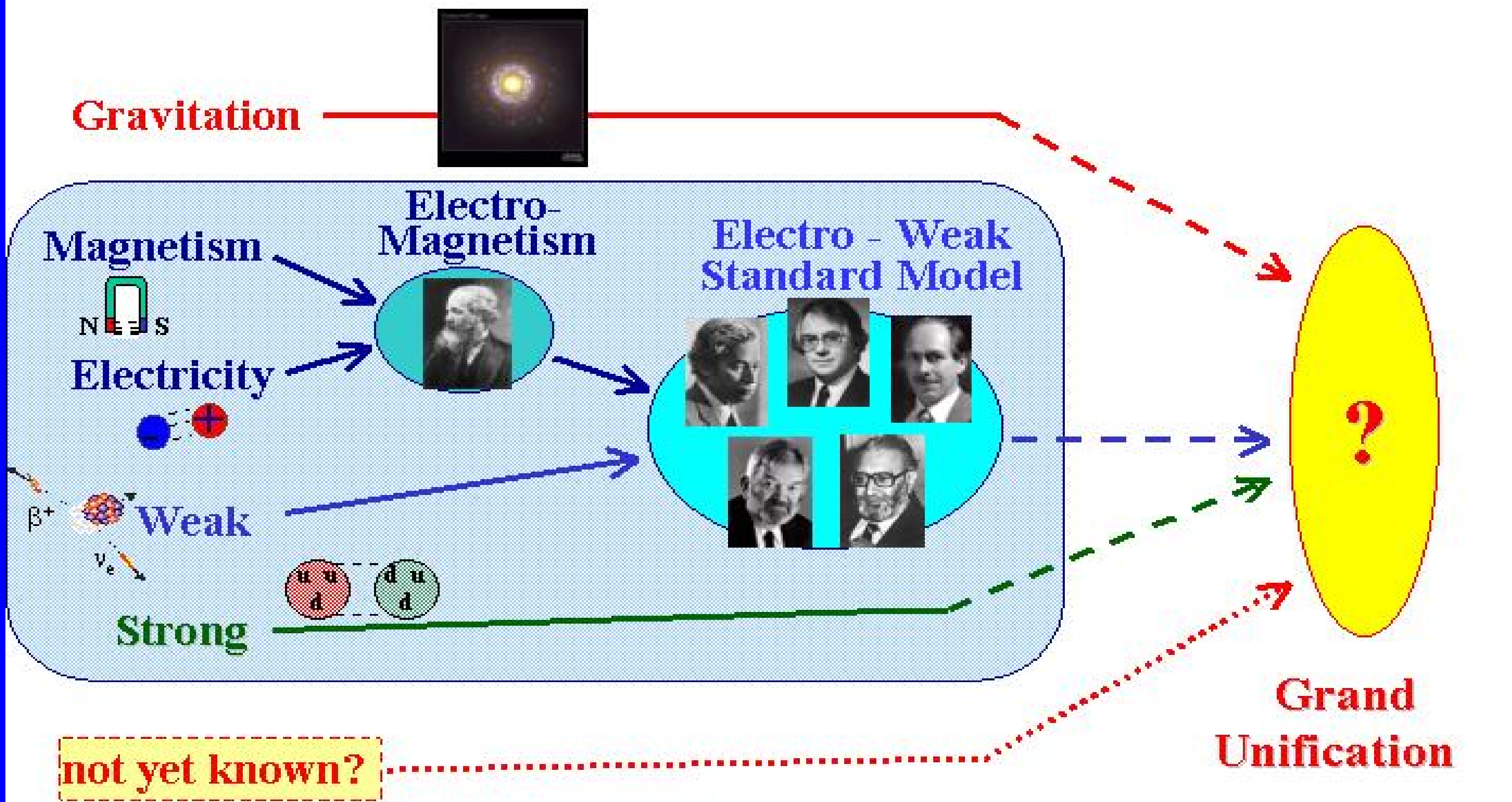
Nuclei in the Universe

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

→ **Radioactive Ion Beams (RIBs)**



Nuclear Landscape

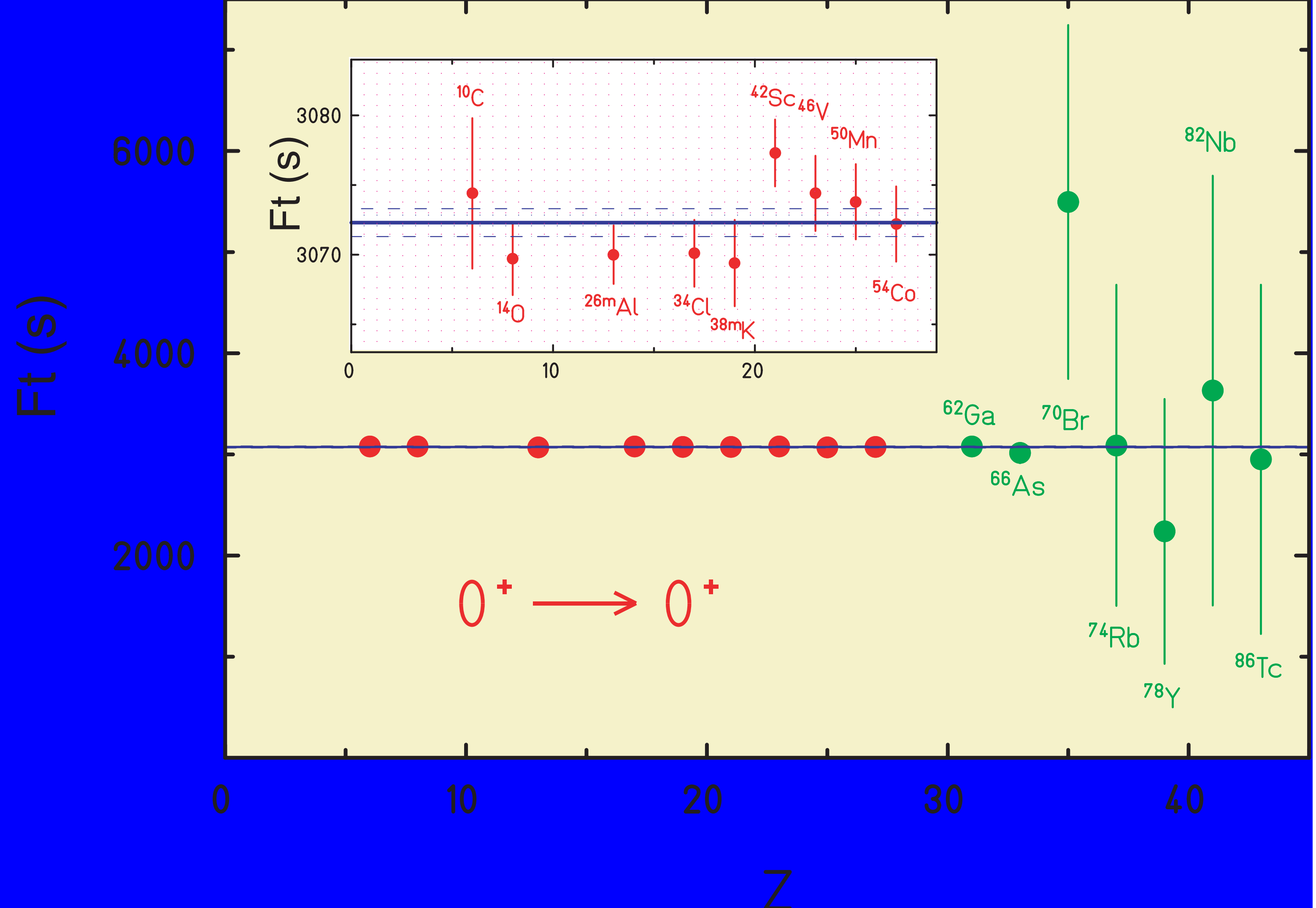


Fundamental Interactions

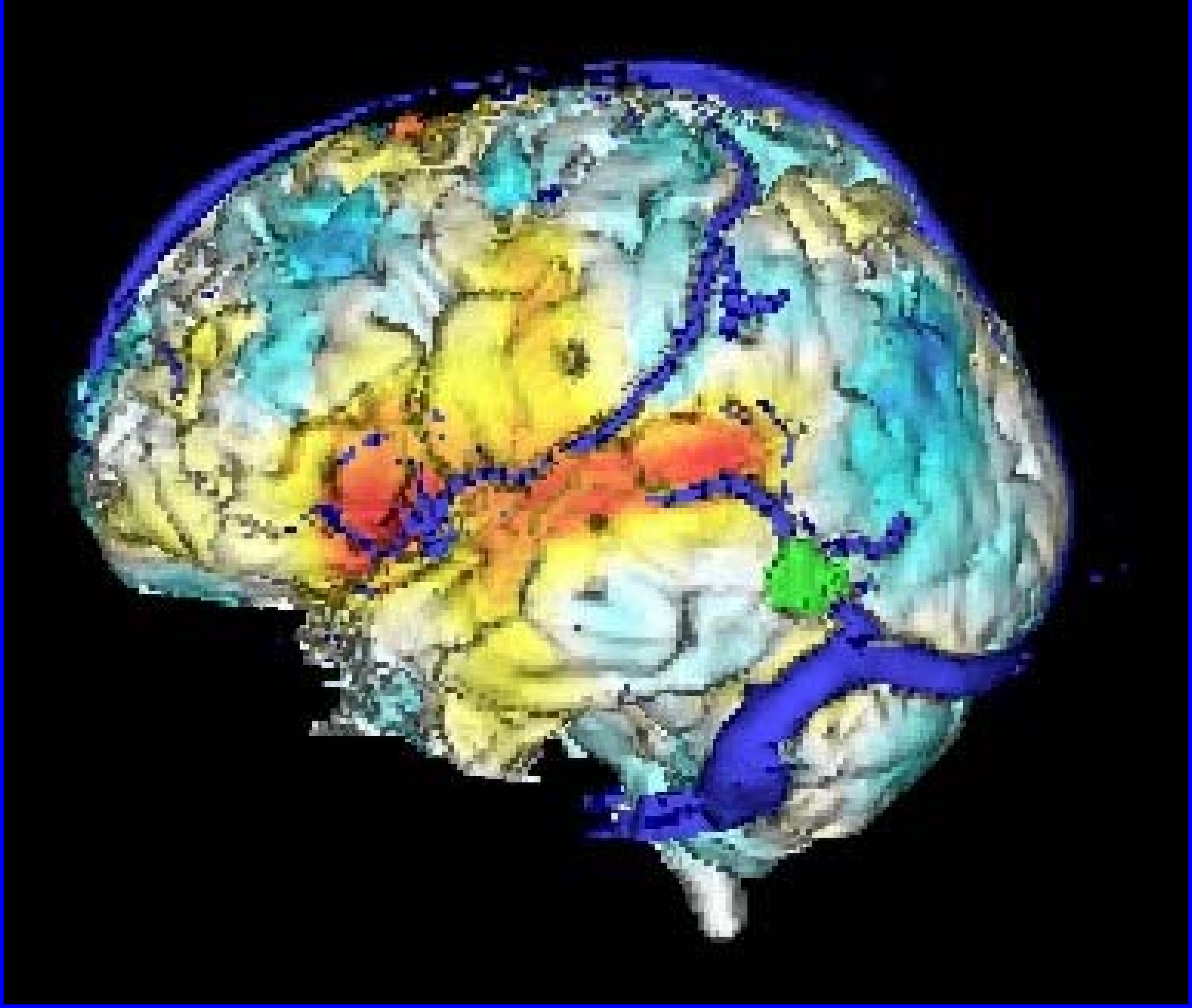
Fundamental Interactions & Symmetries

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)



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



PET image of an active brain

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 radioisotope in industry, other fields (Solid-state Physics, Atomic Physics)

→ **Radioactive Ion Beams (RIBs)**

European Network of Complementary Facilities

GSI, Darmstadt
GANIL, Caen
LNL, Legnaro
ISOLDE, Geneva
LNS, Catania
LNF, Frascati
KVI, Groningen
COSY, Jülich
JYFL, Jyväskylä
CRC, Louvain-la-Neuve
MAX-Lab, Lund
MAMI, Mainz
ECT*, Trento
TSL, Uppsala
HERMES, Hamburg
ALICE, Geneva
COMPASS, Geneva

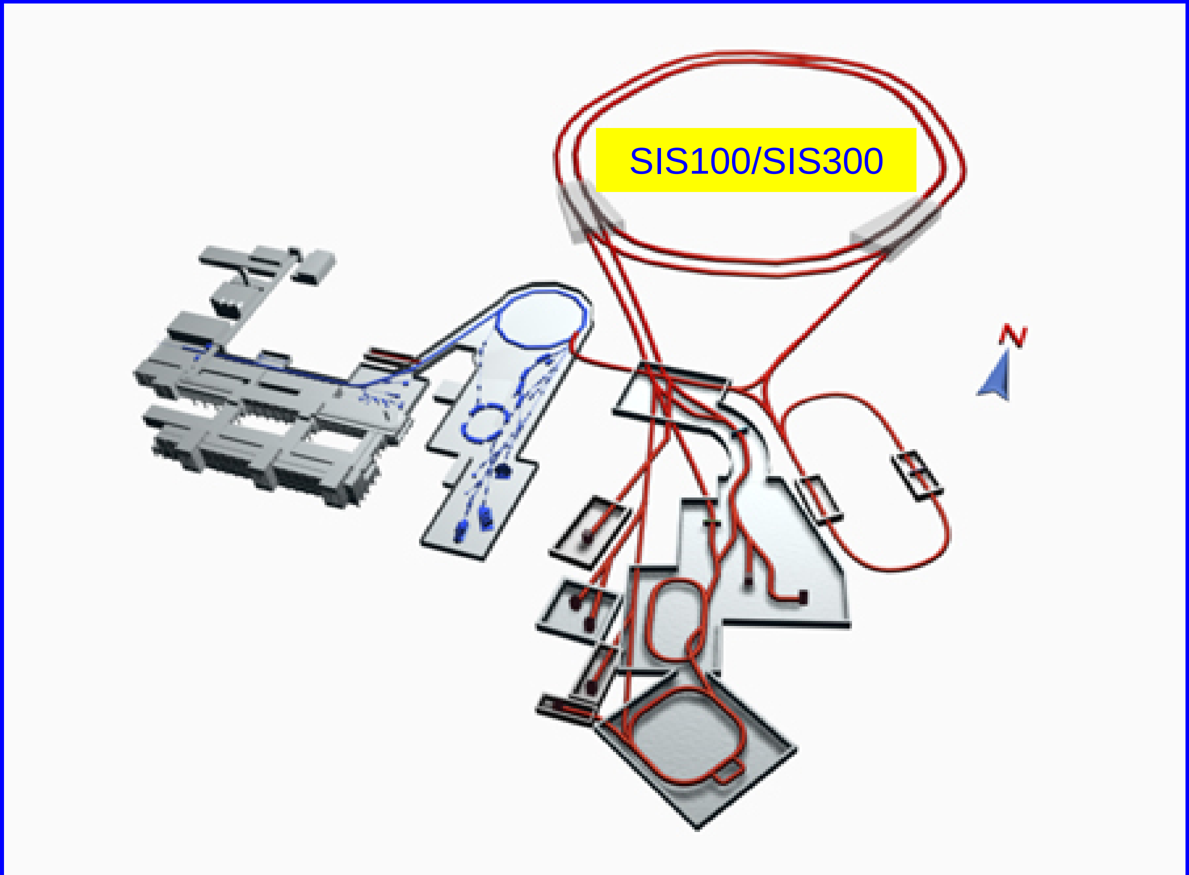
1. NuPECC recommends the full exploitation of the existing and competitive lepton, proton, stable-isotope and radioactive-ion beam facilities and instrumentation

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

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

4. 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, Darmstadt



Primary Beams

- 10^{12}/s 1.5-2 GeV/u $^{238}U^{28+}$
- factor 100-1000 over present in intensity
- $2.5 \cdot 10^{13}$/s 29 GeV protons
- 10^{9}/s $^{238}U^{92+}$ up to 34 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 - 30 GeV

Storage and Cooler Rings

- radioactive beams
- e - A collider
- 10^{11} stored and cooled 0.8 - 14.5 GeV antiprotons
- highly-charged ions and $\bar{p}$ at rest

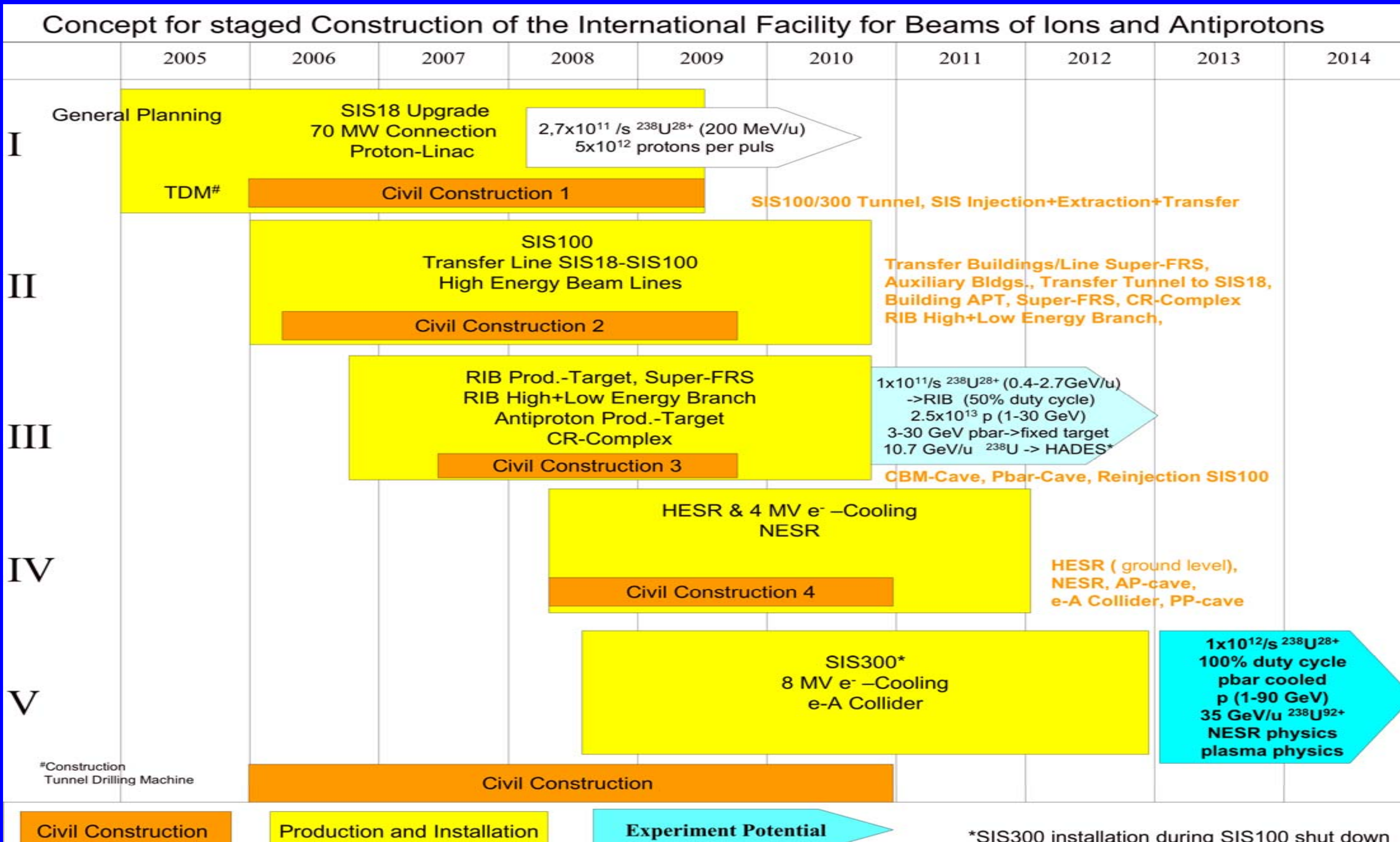
Key Technical Features

cooled and stored beams
rapidly cycling superconducting magnets
parallel operation

The Scientific Pillars

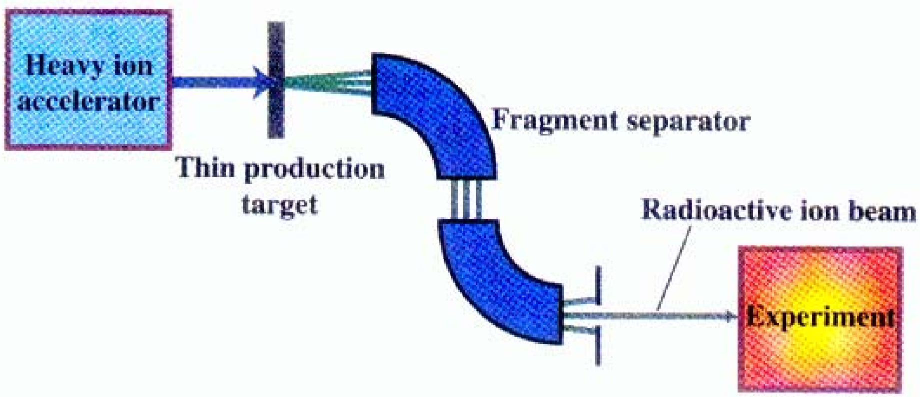
- **Nuclear Structure Physics and Nuclear Astrophysics with radioactive ion beams**
- **Hadron Physics with Antiproton Beams**
- **Physics of Hadronic Matter at high density**
- **Plasma Physics at very high p , ρ ,T**
- **Atomic Physics and Applied Science**

CONCEPT FOR STAGED CONSTRUCTION OF FAIR



Radioactive beam production
Two complementary methods

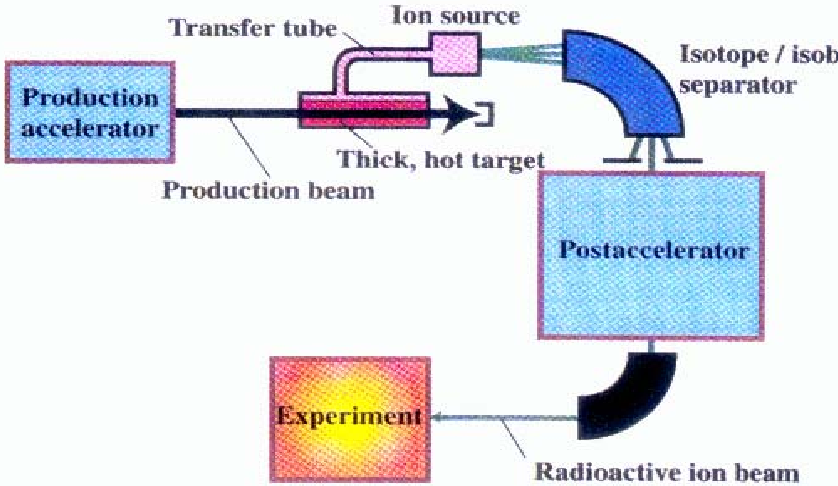
Projectile Fragmentation



SISSI/GANIL, GSI, RIKEN, NSCL/MSU

High energy, large variety of species, poor optical qualities

ISOL



SPIRAL/GANIL, REX/ISOLDE, ISAC/TRIUMF, CRC/LLN, Oak Ridge

Low energy, chemistry is difficult, good beam qualities

Complementarity of In-Flight and ISOL facilities

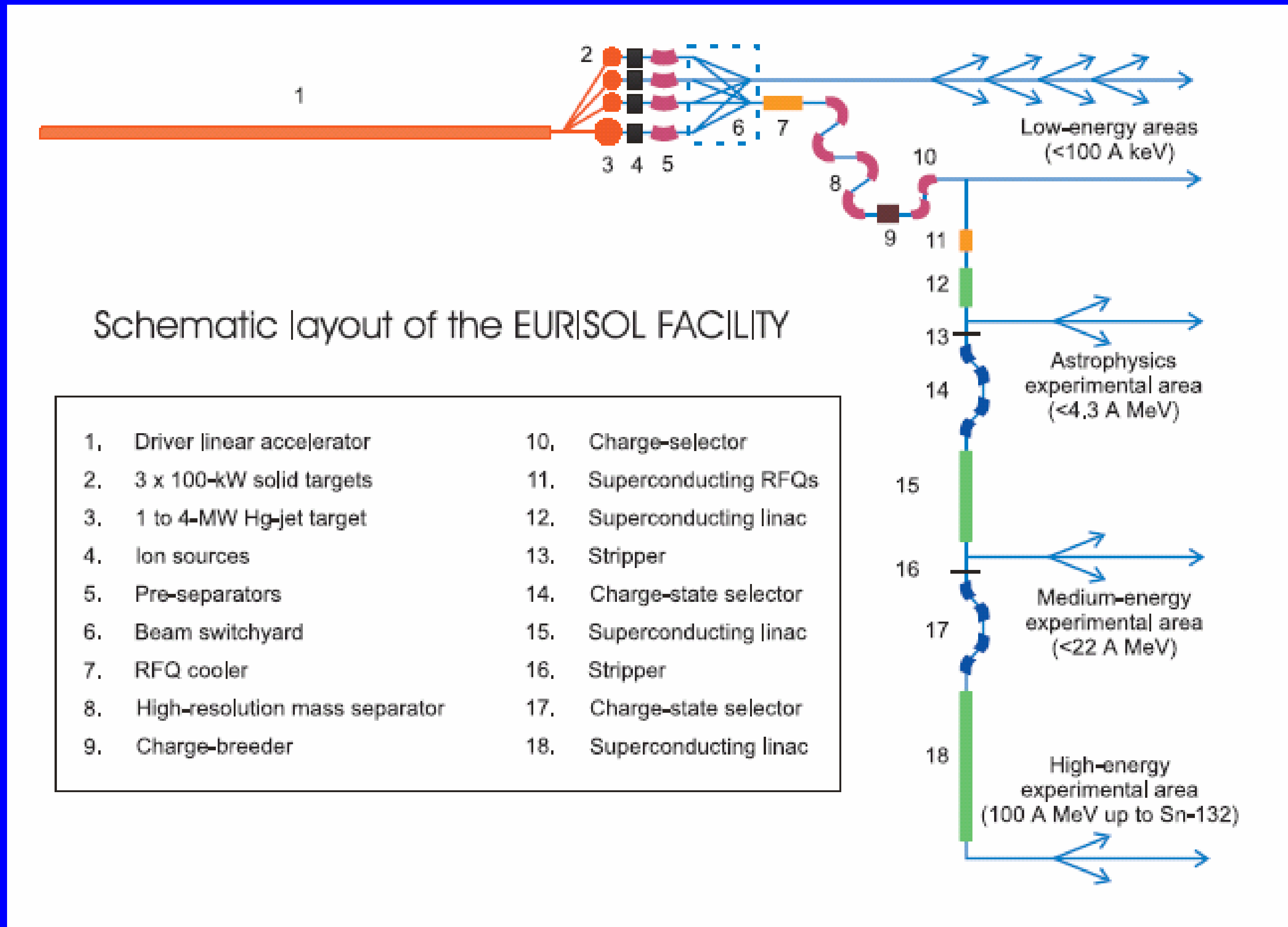
In-Flight

- High-energy (relativistic) beams
- Universal in Z
- Down to very short $T_{1/2}$
- Easily injected into and cooled in storage rings ⇒ colliding beam experiments

ISOL

- High-intensity beams
- Easy to manipulate beam energies from keV to 10s of MeV
- High quality beams with ion optics comparable to stable beams; ideally suited to produce pencil-like beams

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

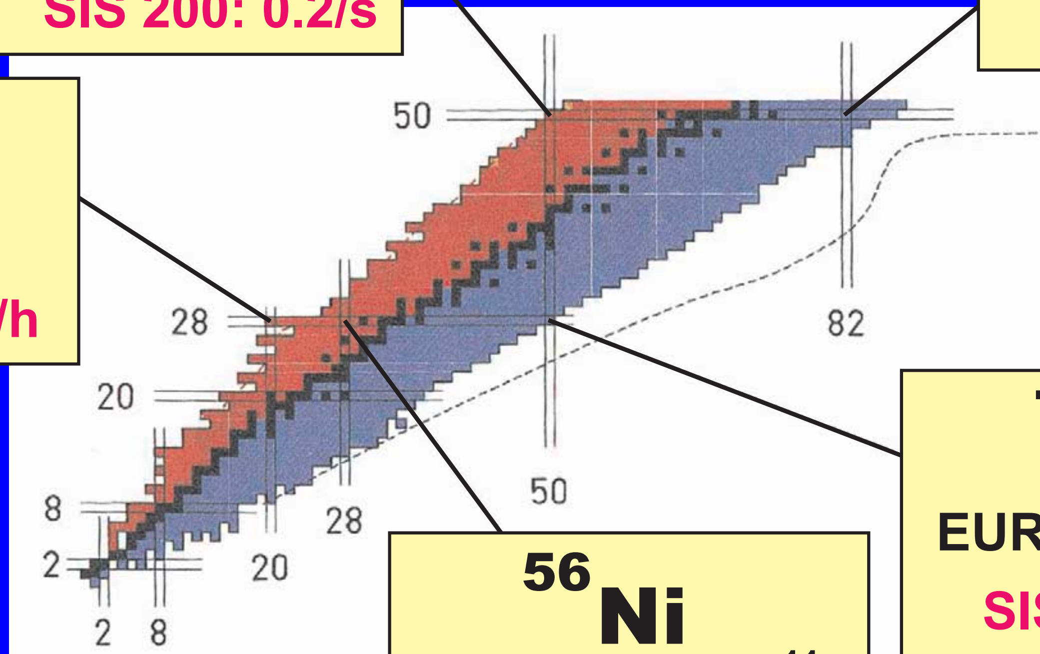


NuPECC recommends joining efforts with other interested communities to do the RTD and design work necessary to realise the high-power p/d driver in the near future

^{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

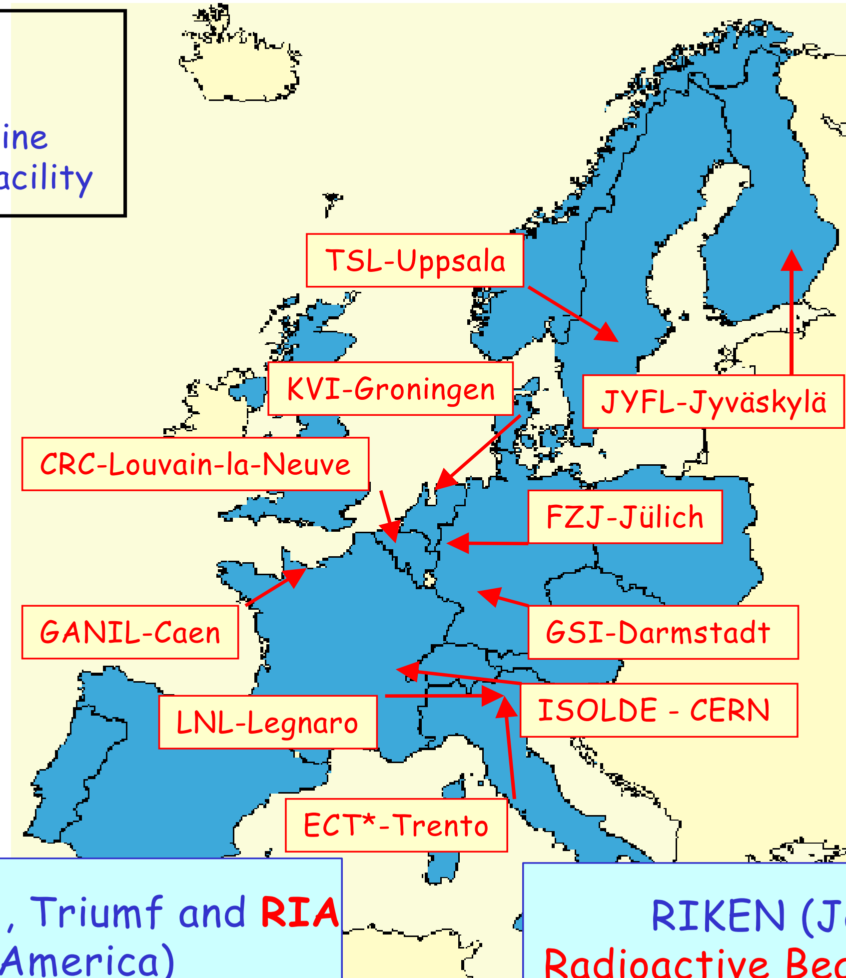
^{56}Ni
EURISOL: 1×10^{11}/s
SIS 200: 1×10^{9}/s

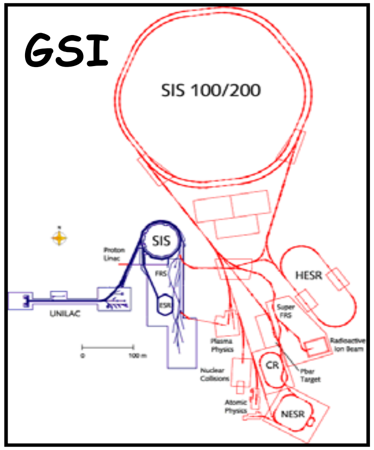
neutron-rich fission
proton-rich spallation

EURISOL

European Separator On-Line
Radioactive Nuclear Beam Facility

ISOL





IF

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

RIKEN (Japan)
Radioactive Beam Factory

Possible related projects

Neutron Spallation Source (ESS)

Transmutation of Nuclear Waste (ADS)

ν and μ factories, K physics

Antiproton beams (?)

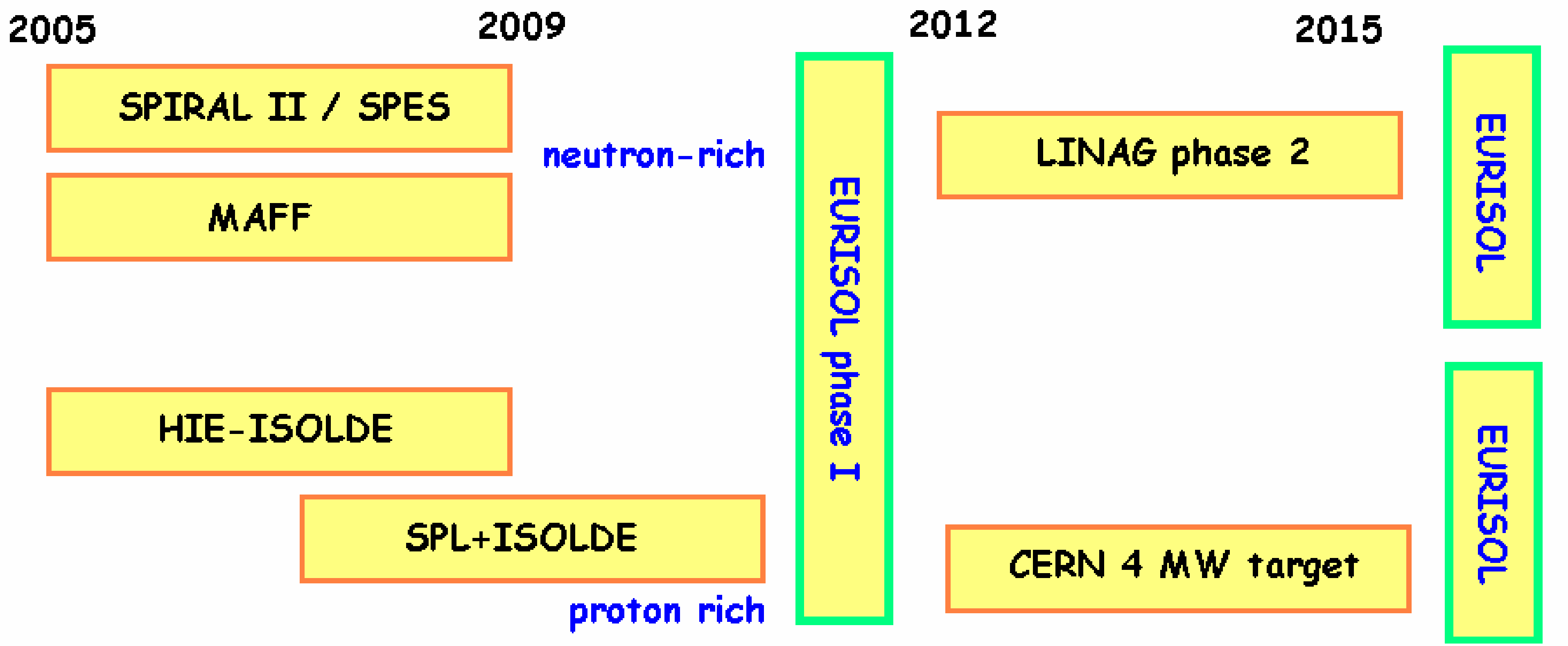
β beams

Synergies with ‘related’ field

Solid-state and Atomic Physics, etc.

Medical Applications

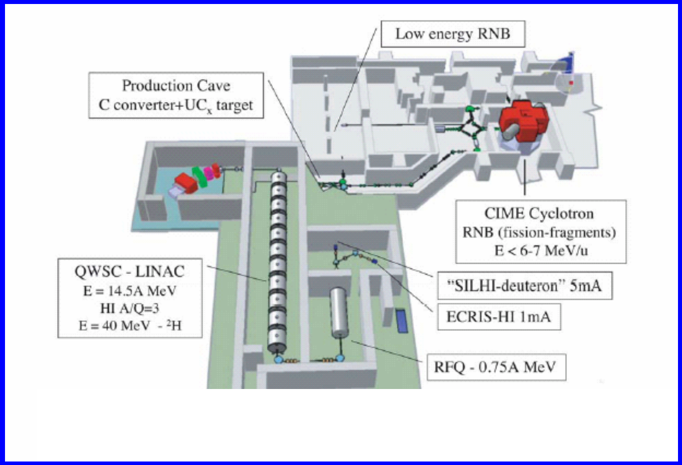
ISOL roadmap



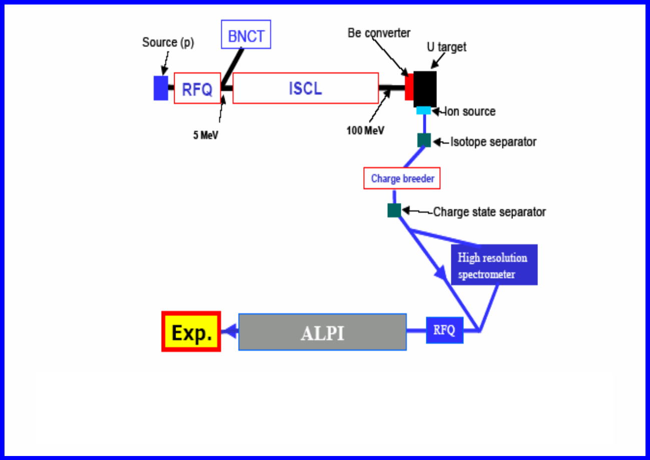
β-beam

RTD and initial design	2002 – 2007
detailed design, construction	2008 – 2015

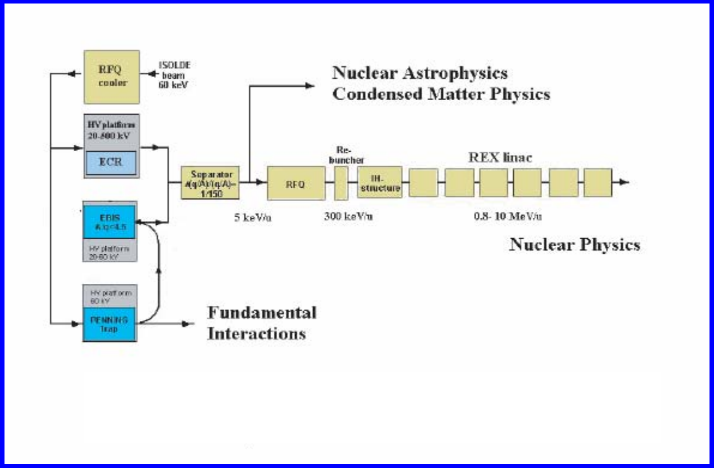
The Road to EURISOL



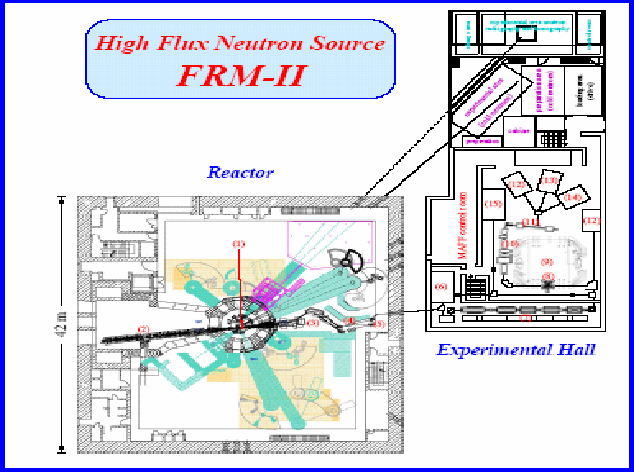
SPIRAL-2



SPES



HIE - ISOLDE



MAFF

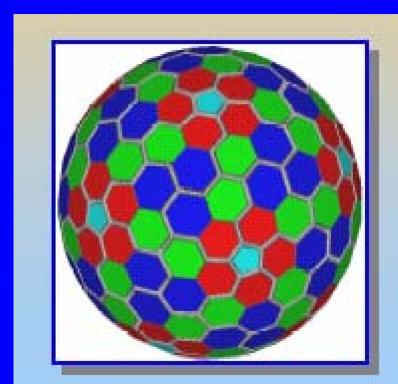
NuPECC recommends with high priority the installation at the underground laboratory of Gran Sasso of a compact, high-current 5-MV accelerator for light ions equipped with a 4p-array of Ge detectors

NuPECC encourages the community of hadronic structure and QCD to pursue research with a multi-GeV lepton scattering facility within an international perspective, incorporating it in existing or planned large-scale facilities worldwide

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 -



Research Infrastructures in FP7

Proposed Lines of Action (major role for RI)

- Continue and improve the current line of action on RI
- Reinforce RI action by adding new line for development of new ‘unique’ RI ⇒ Vision and Roadmap for RI in Europe in the next 10-20 years.

  The Roadmap can have periodic updates and revisions.

Criteria for priority projects in Roadmap

- Pan-European interest; potential impact on ERA; European partnership; size; maturity of project and timeliness; existence of multi-annual and long-term budgetary planning, quality of management.

To recount briefly: **For the roadmap of new large-scale nuclear physics research infrastructures, it is clear from the above that the nuclear physics community wants to have FAIR as the first priority for new construction project and EURISOL as the second priority. FAIR has a rather broad scope for scientific activities. As far as RIBs are concerned FAIR and EURISOL are complementary. FAIR in its phase one will deliver RIBS by the end of 2010. Because of the time-line of EURISOL NuPECC strongly recommends the building of intermediate-generation RIB facilities of the ISOL type. Of these SPIRAL2 meets the criteria of a European large research infrastructure in terms of scientific potential and size of investment and will deliver RIBs in 2009. Furthermore, timely completion of ALICE for the search for the quark-gluon plasma is mandatory.**

Preparations for FP7

- Nuclear Physics community should submit one I3, instead of I3HP and I3EURONS; but NuPECC is open for suggestions.
- A committee should be formed soon to look into the various issues and ‘new’ criteria connected with I3 applications in FP7.
- New design studies and new construction projects should be inventorised.

NuPECC/ECOS ⇒ Dedicated high-intensity stable beam facility? Other initiatives?

END