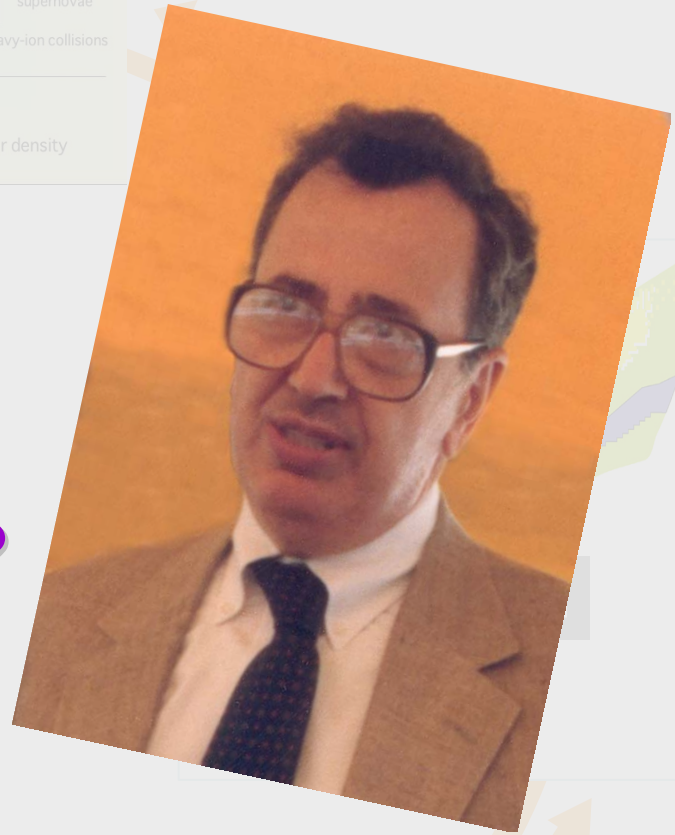
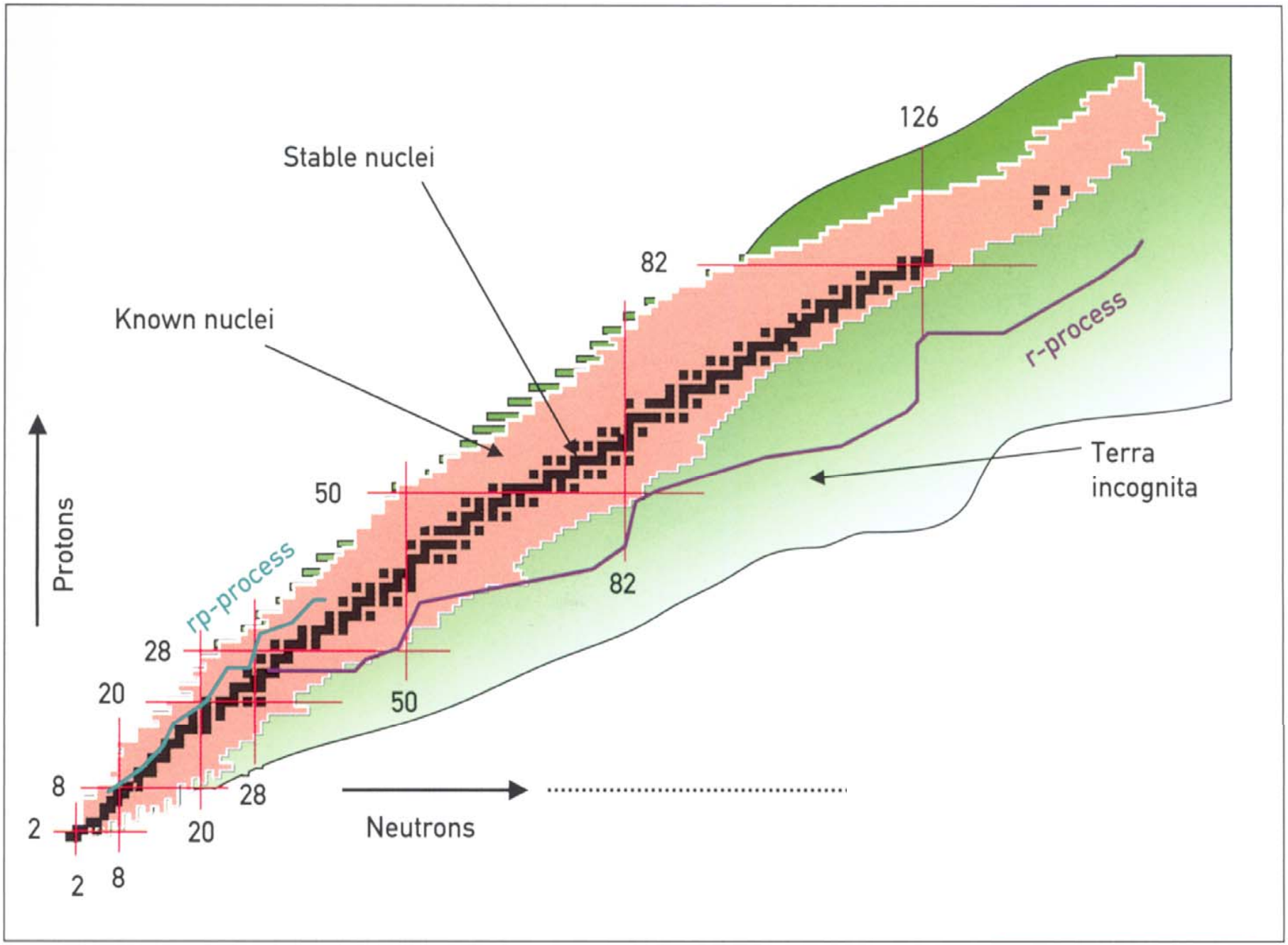
The Landscape of Nuclei –

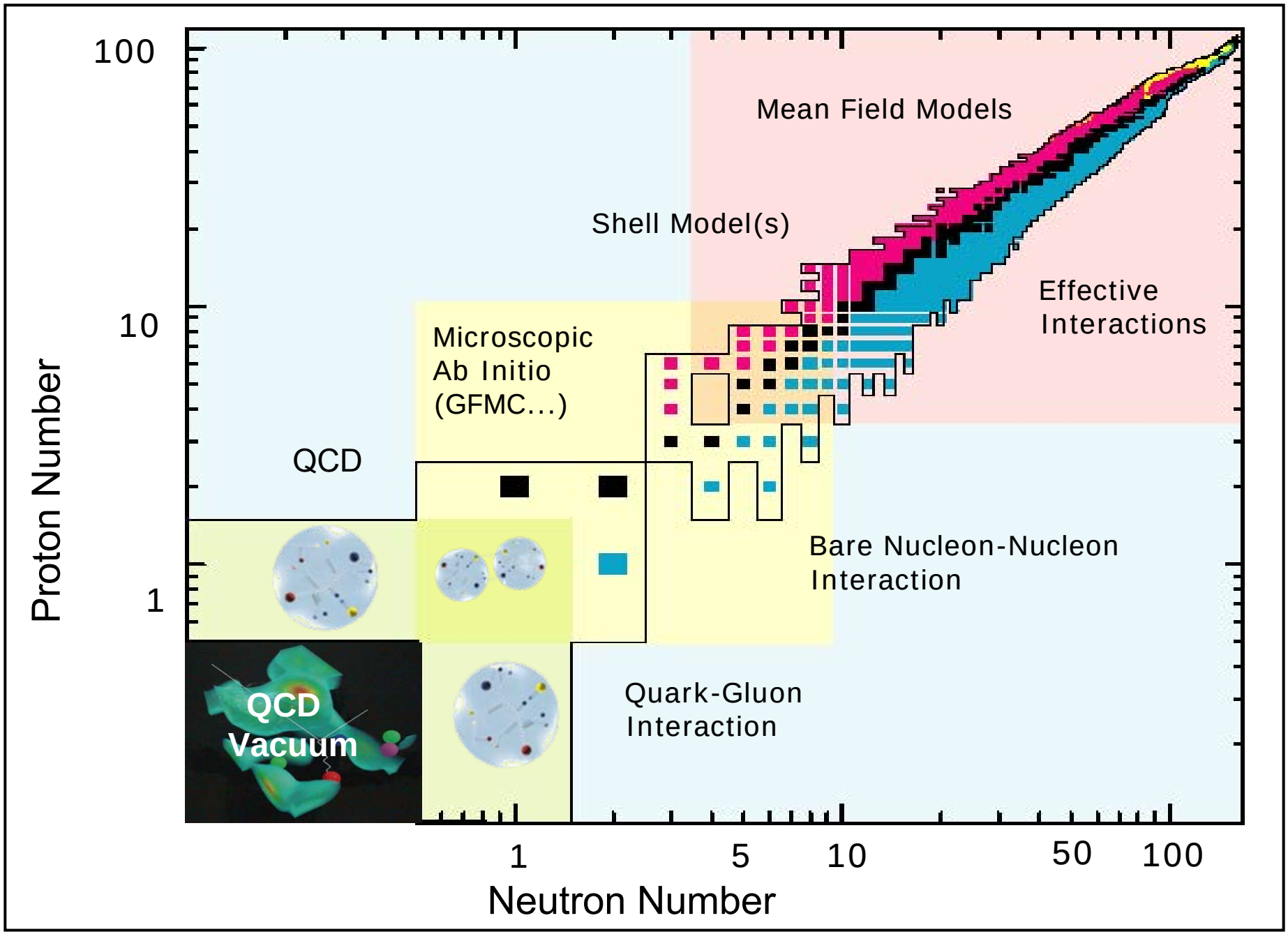
How far, how soon ?



Walter F. Henning – GSI Darmstadt & University of Frankfurt

NPSymposium at ANL, Sep 21 – Sep 22, 2006


Stable nuclei
Known nuclei
126
82
50
28
20
8
2
82
50
28
20
8
2
r-process
rp-process
Terra
incognita
Protons
Neutrons


100
10
1
Proton Number
Mean Field Models
Shell Model(s)
Effective
Interactions
Microscopic
Ab Initio
(GFMC...)
QCD
Bare Nucleon-Nucleon
Interaction
Quark-Gluon
Interaction
QCD
Vacuum
1
5
10
50
100
Neutron Number

neutron excess (N-Z)/A

1

0.6

0.3

0

-0.3

neutron halos & skins

? ?

neutron stars

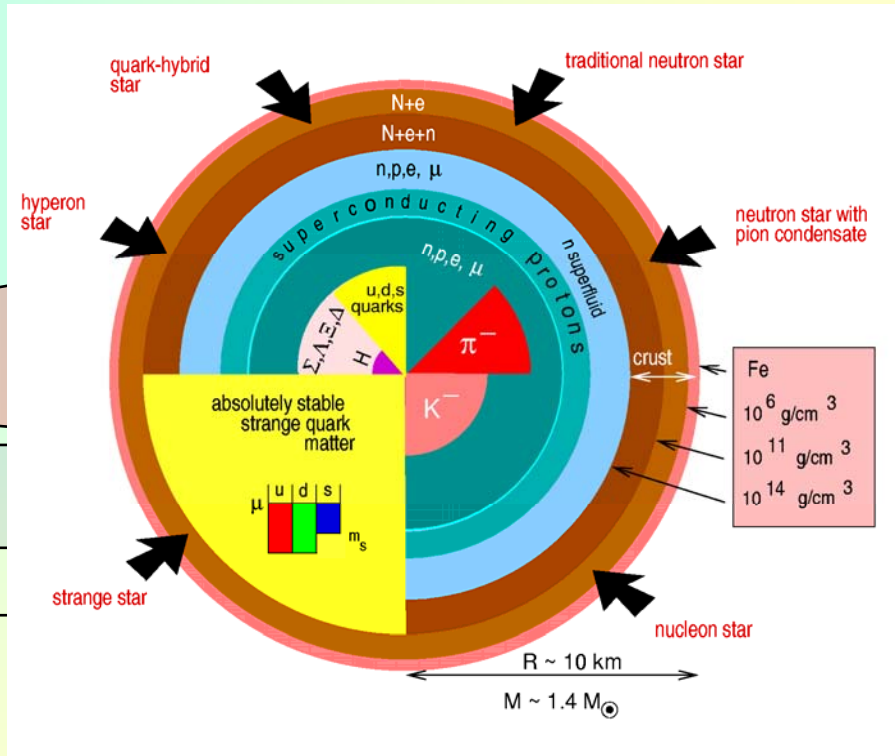
crust

finite nuclei

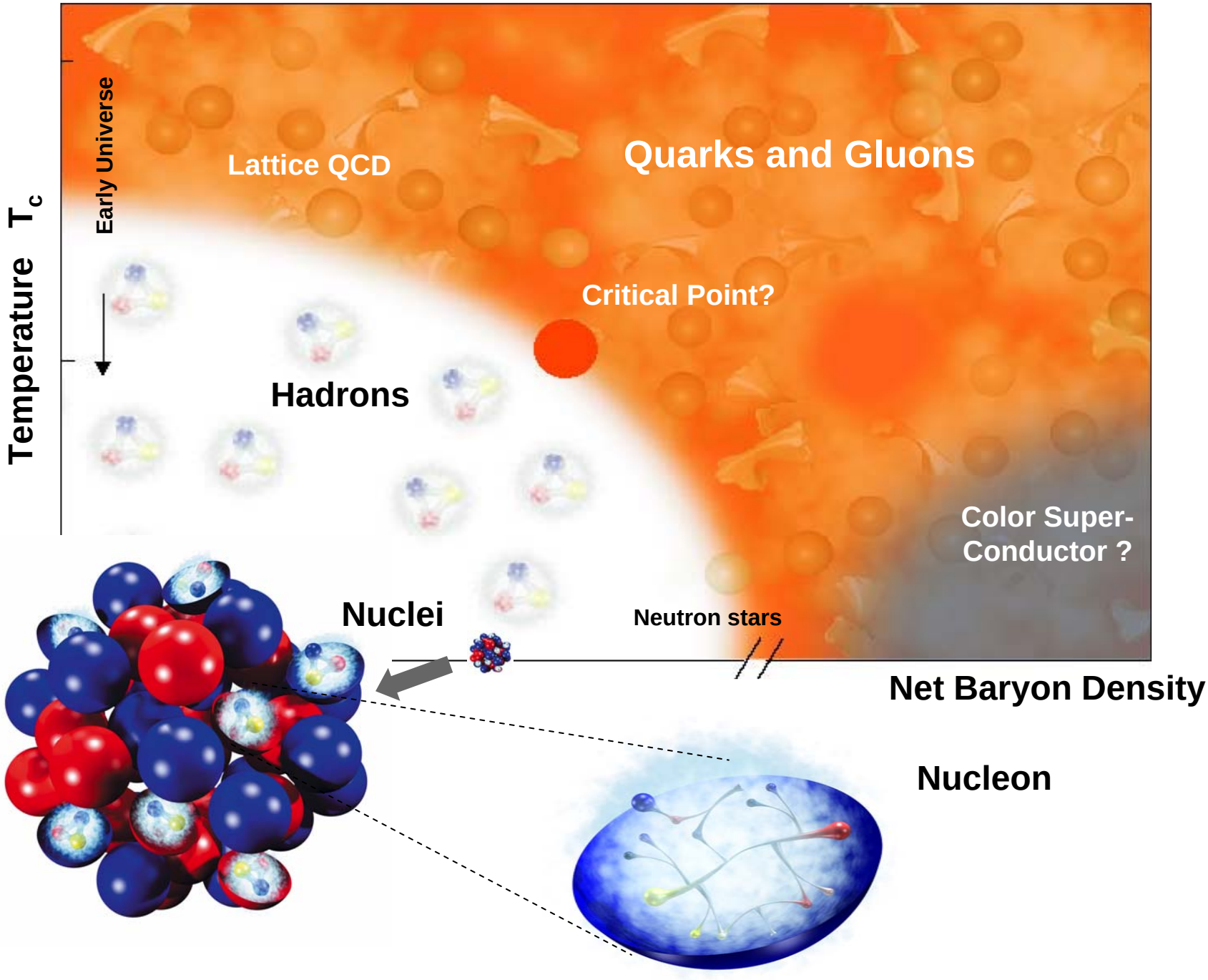
protron drip line

Local matter density

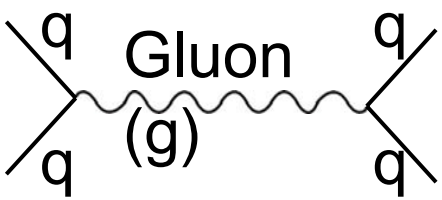
Properties of neutron stars

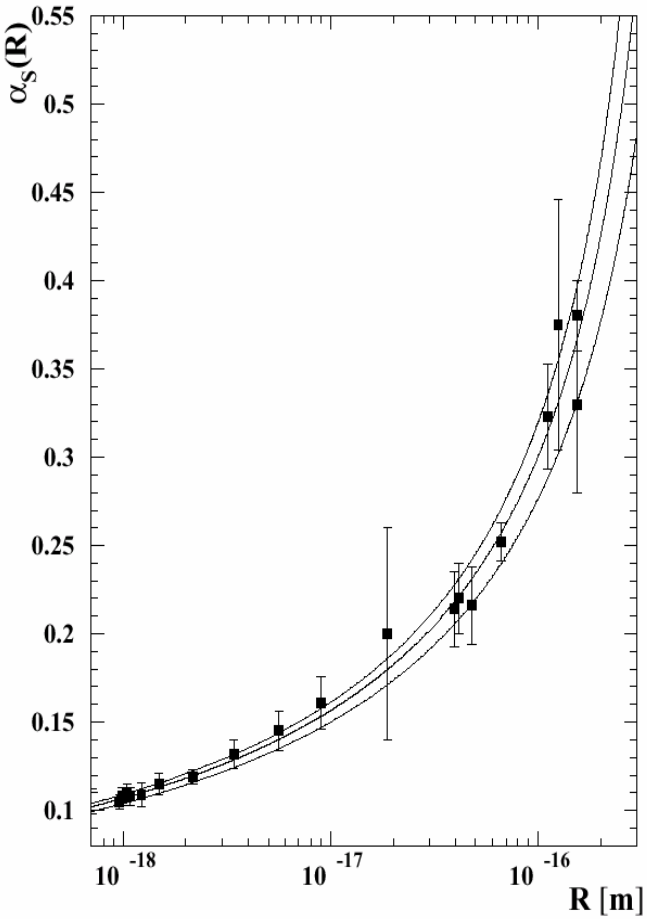


Pethik & Ravenhall (1996)

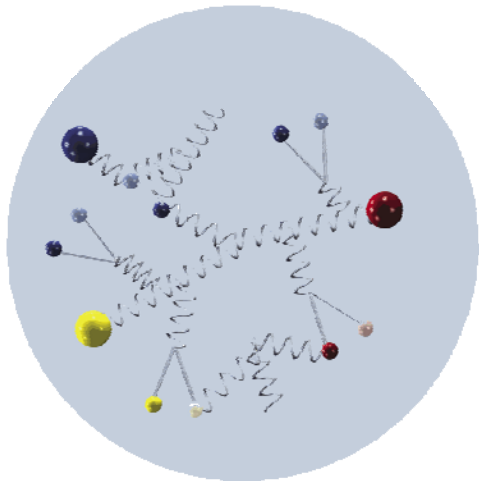

Temperature T_c
Early Universe
Lattice QCD
Quarks and Gluons
Critical Point?
Hadrons
Color Super-
Conductor ?
Nuclei
Neutron stars
Net Baryon Density
Nucleon

perturbative:
QCD: a_S <<1





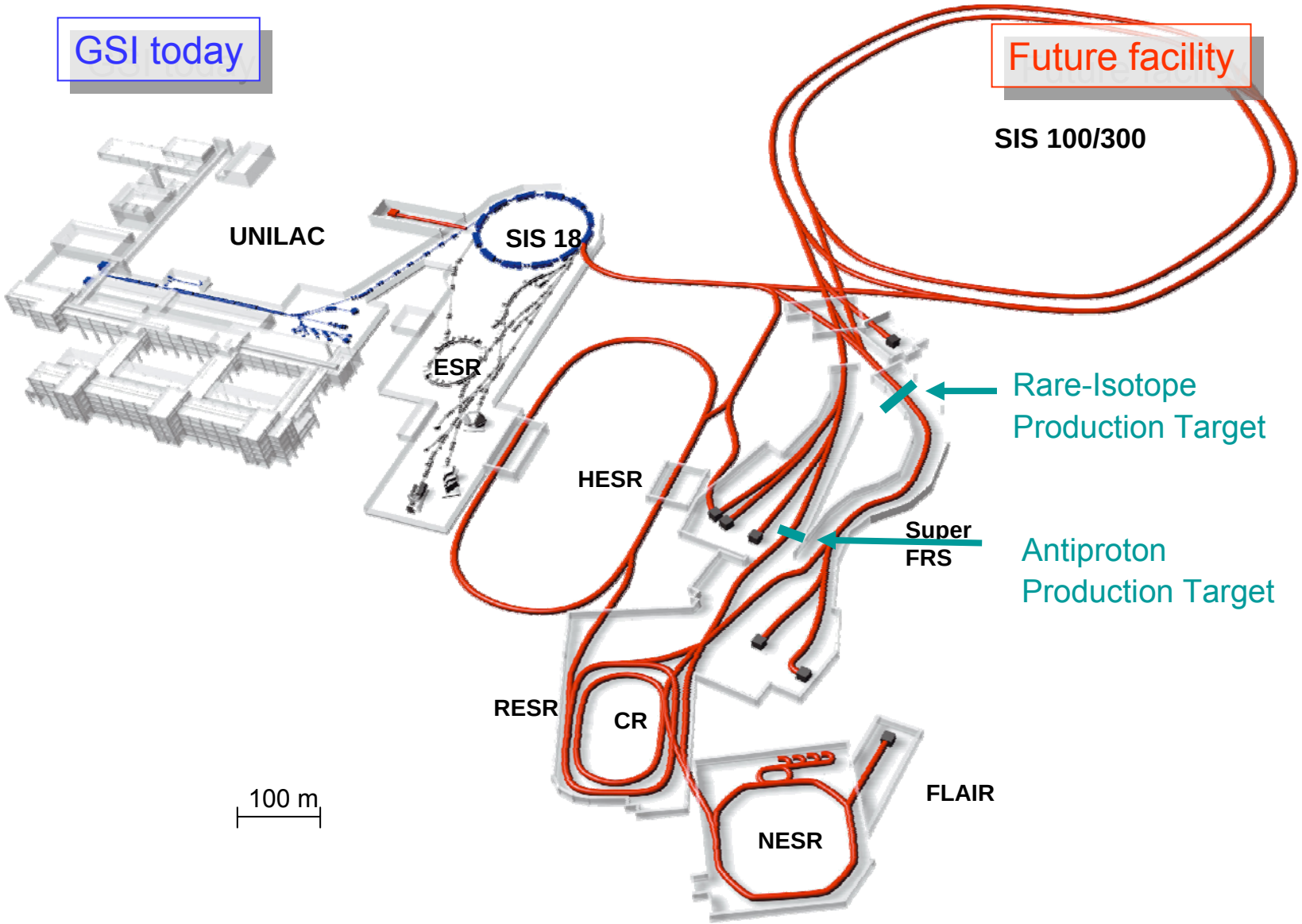
non-perturbative:
QCD: $a_S \leq 1$

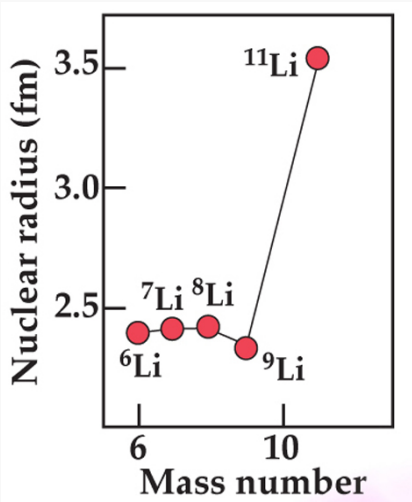


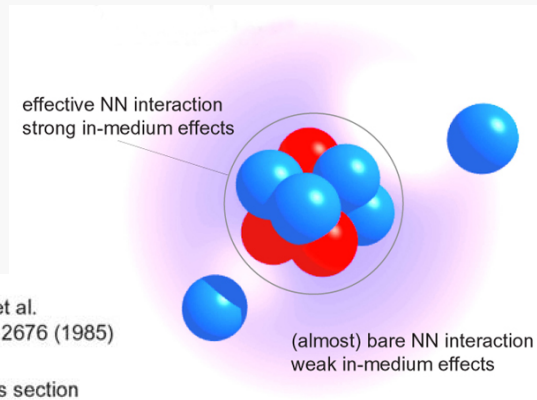
Quarks, Gluons
One-Gluon Exchange

Hadrons:
Baryons, Mesons
Models, Lattice QCD

FAIR - Facility for Antiproton and Ion Research

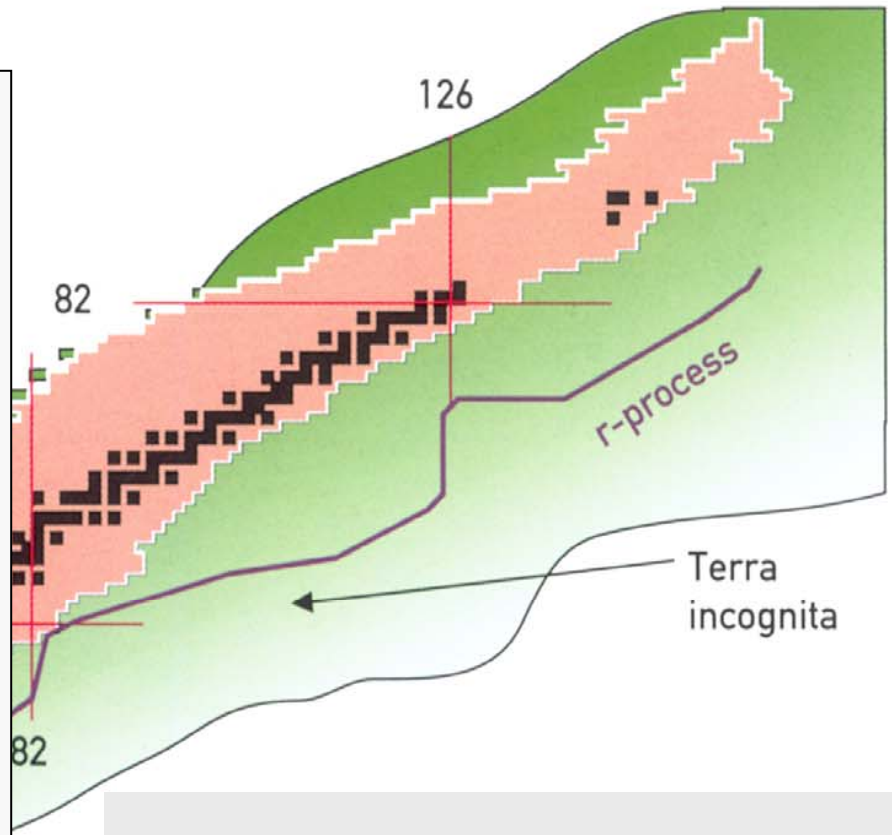






I. Tanihata et al.
Phys. Rev. Lett. 55, 2676 (1985)

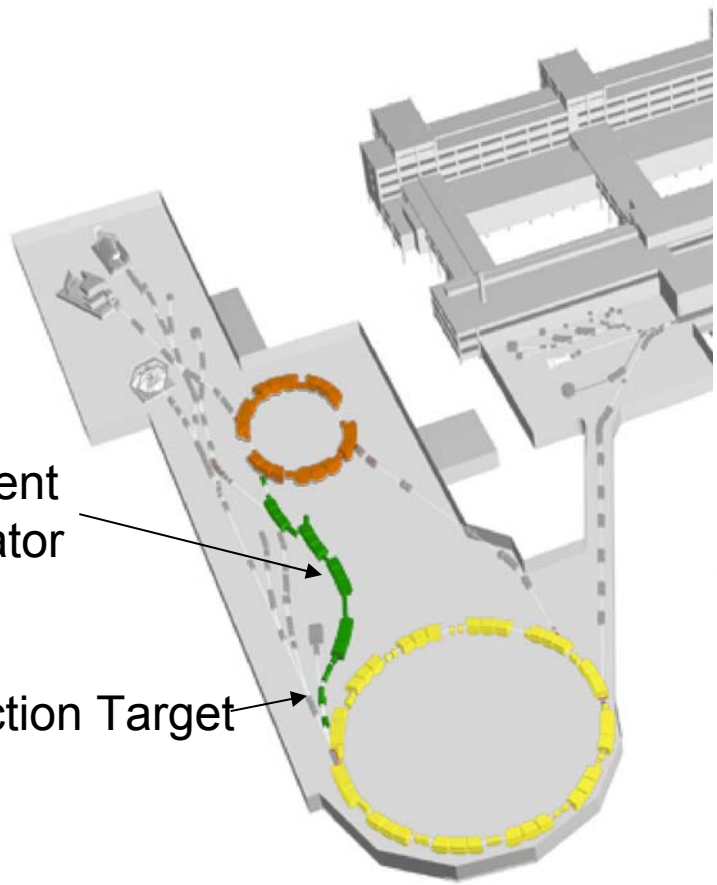
Interaction cross section measurements at Bevalac (790 MeV/u)

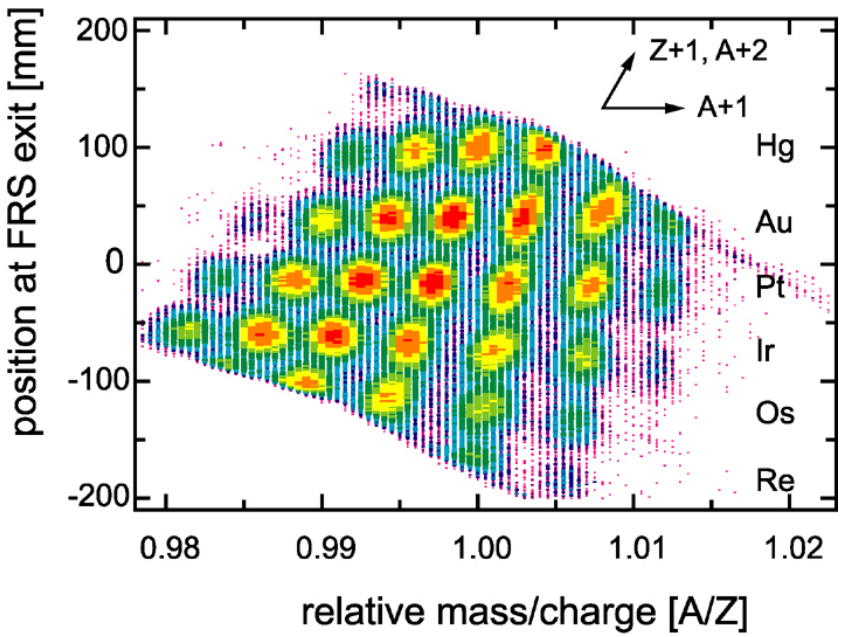


Much of what we know about nuclei comes from nuclear reactions

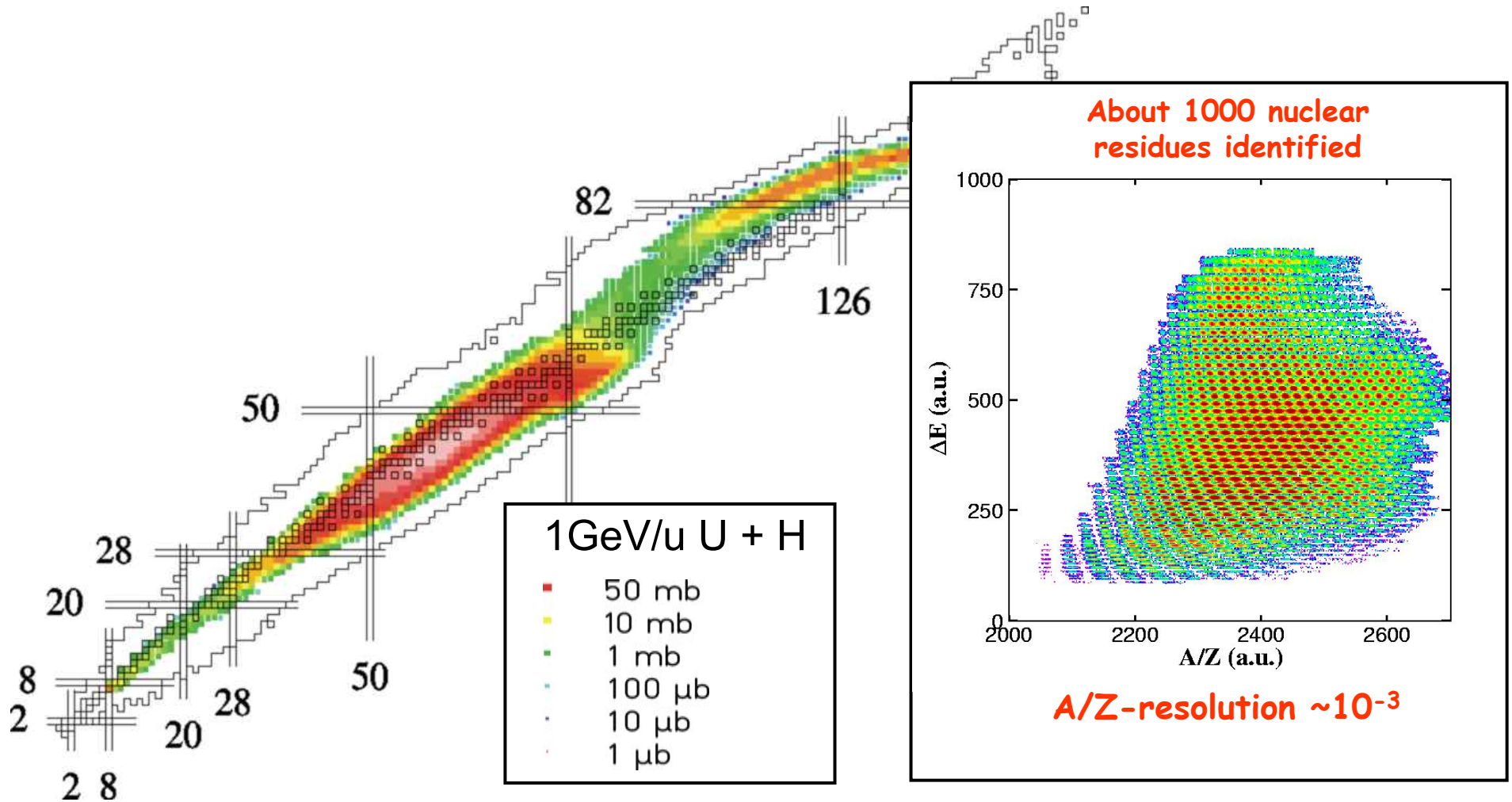
John Schiffer

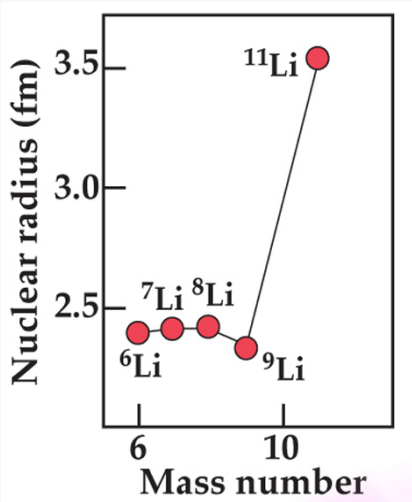
Secondary Beams of Short-Lived Nuclei

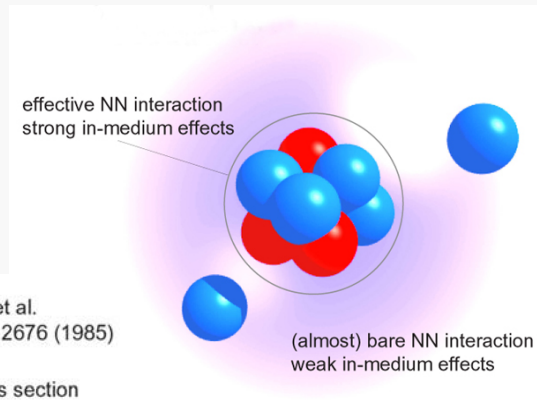




P. Armbruster et al.; Phys. Rev. Letters, Jan. 05







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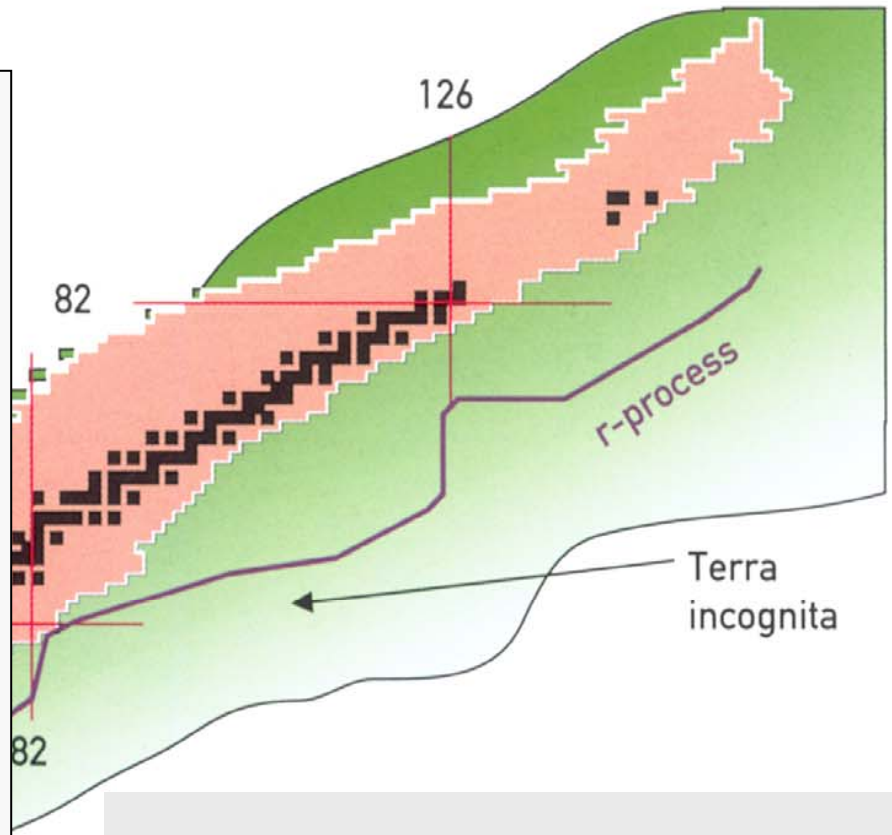
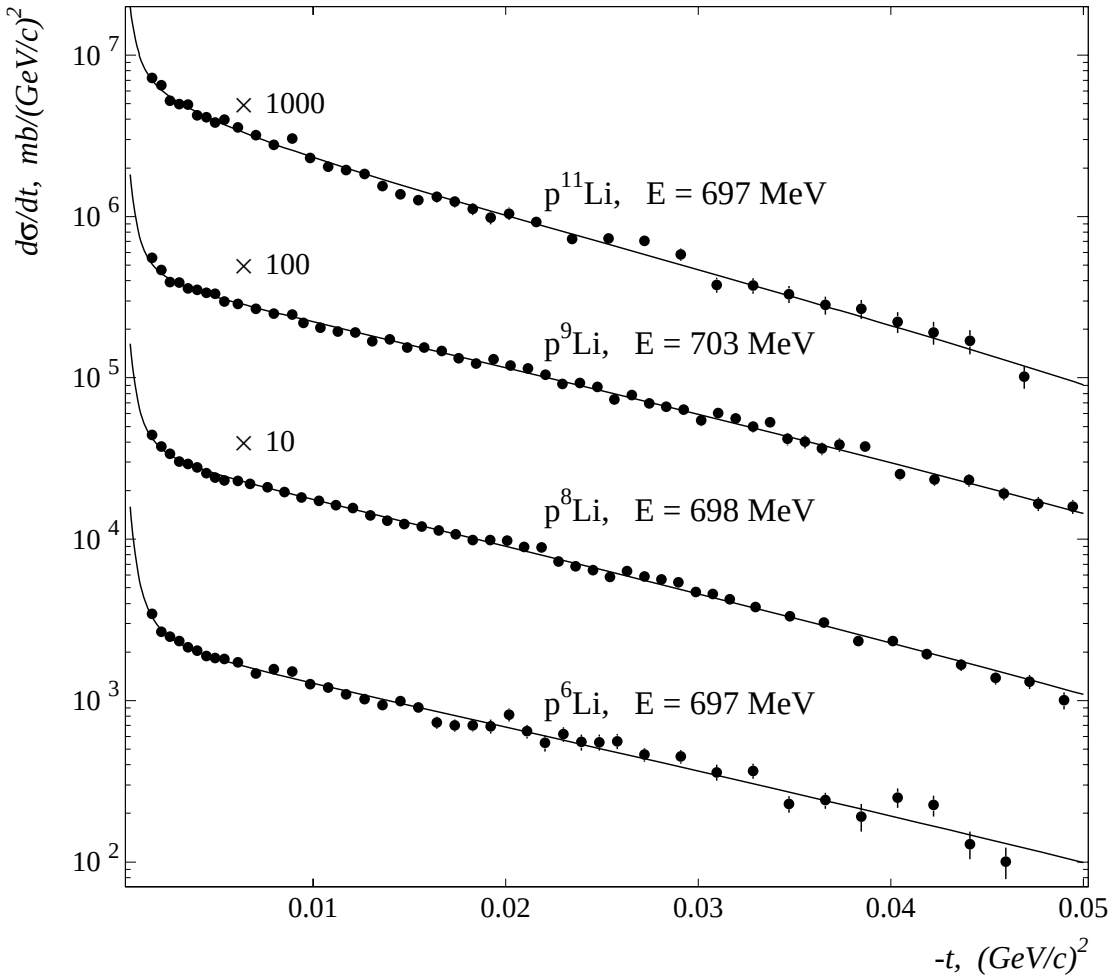


Much of what we know about nuclei comes from nuclear reactions

John Schiffer

Experimental Cross Sections for p Li Elastic Scattering



Concept of the Data Analysis

- Glauber multiple-scattering theory for calculation of cross sections:
  - use measured free pp, pn-cross sections as input (in medium effects negligible)
  - fold with nucleon density distribution
  - take into account multiple scattering (all terms!) (small for region of nuclear halo!)

- variation of the nucleon density distribution:

a) phenomenological parametrizations (point matter densities):

G: 1 Gaussian

SF: Symmetrized Fermi

GG: 2 Gaussians

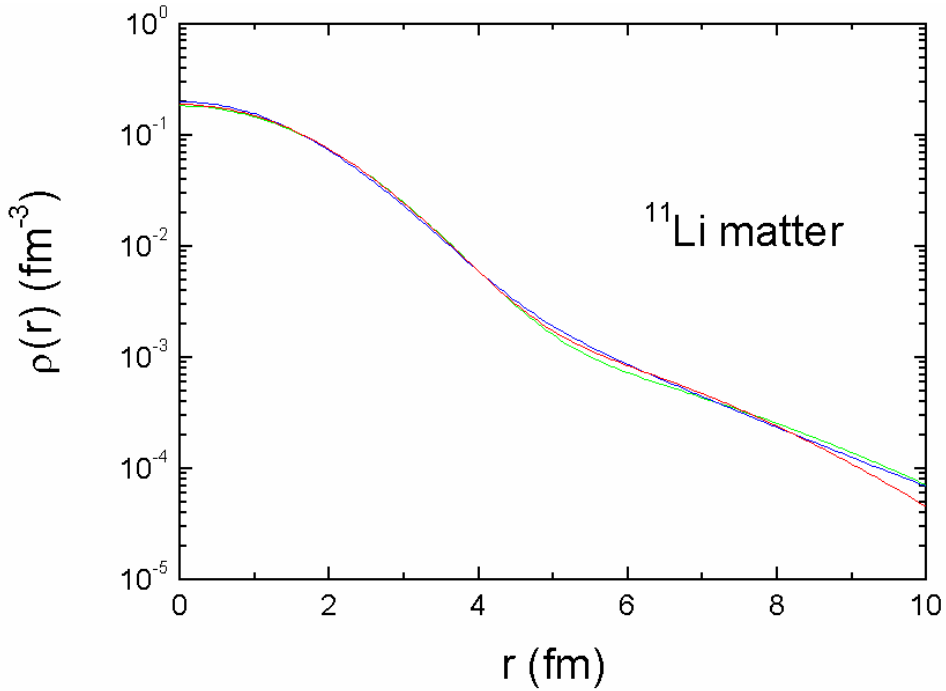
GO: Gaussian + Harmonic Oscillator

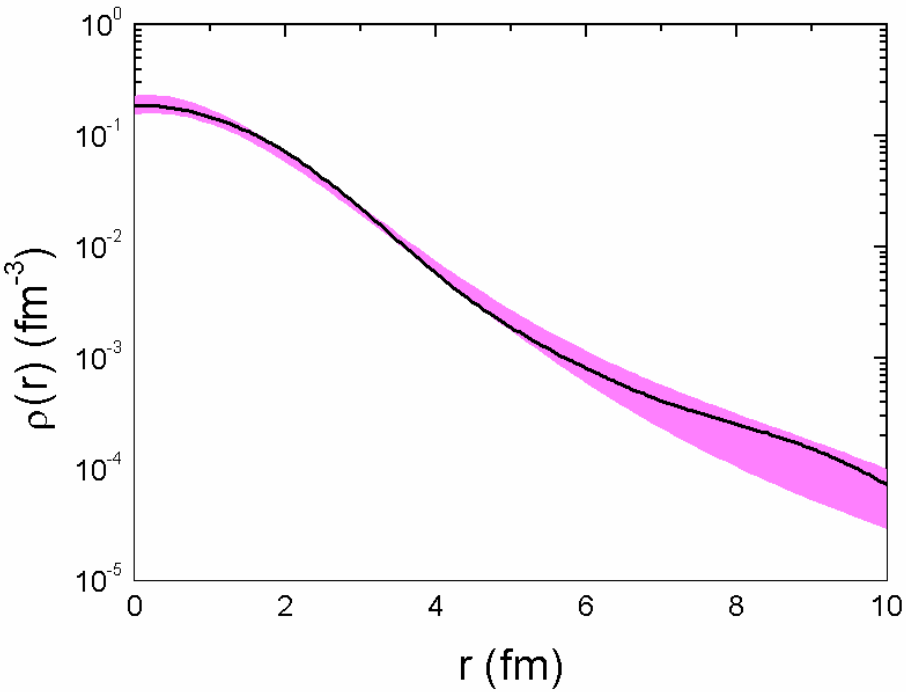
b) "model independent" analysis:

SOG: Sum Of Gaussians

(standard method for electron scattering data:
I. Sick, Nucl. Phys. A 218 (1974) 509)

Dependence of the Results on Constraints Implied in the Analysis





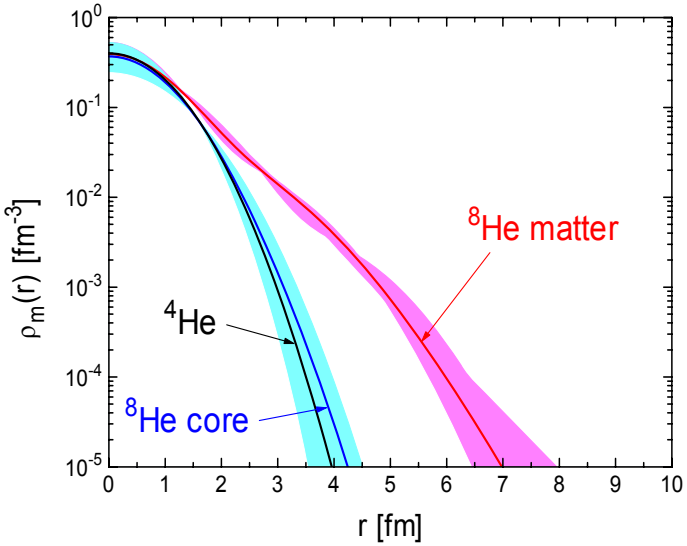
phenomenological parametrizations GG, GO without constraints — R_m = 3.62 (19) fm

phenomenological parametrization GG + Hankel-function for asymptotic behaviour for r > 6 fm — R_m = 3.72 (19) fm

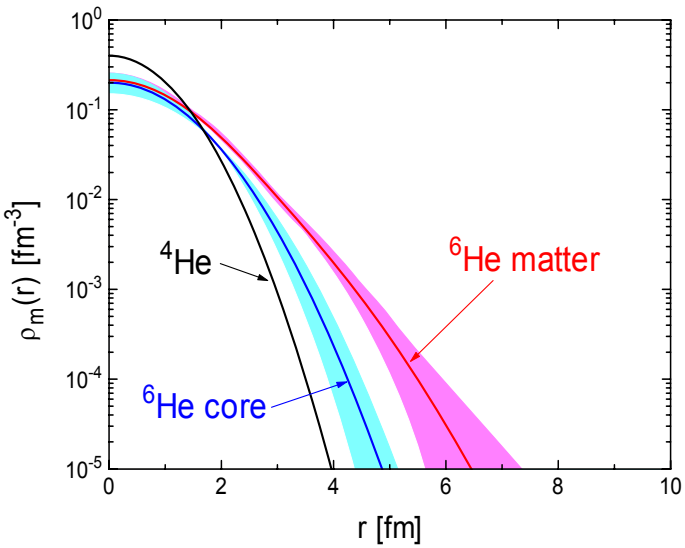
phenomenological parametrization GO with fixed $(1s_{1/2})^2 : (0p_{1/2})^2$ = 45 : 55% (from Land-Collaboration) — R_m = 3.53 (19) fm

- model independent SOG analysis — R_m = 3.67 (15) fm

Comparison of ^{11}Li and ^{6,8}He



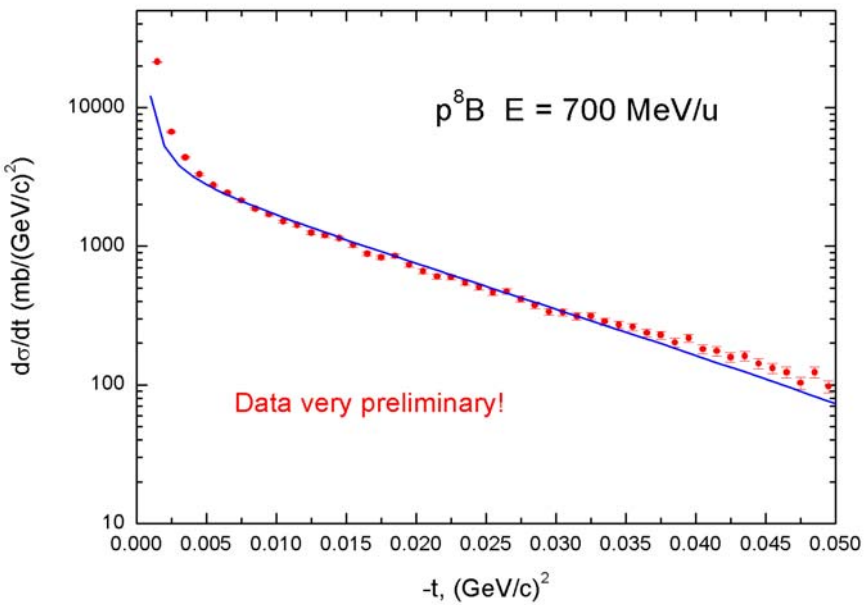
R_{halo} = 3.08 (10) fm



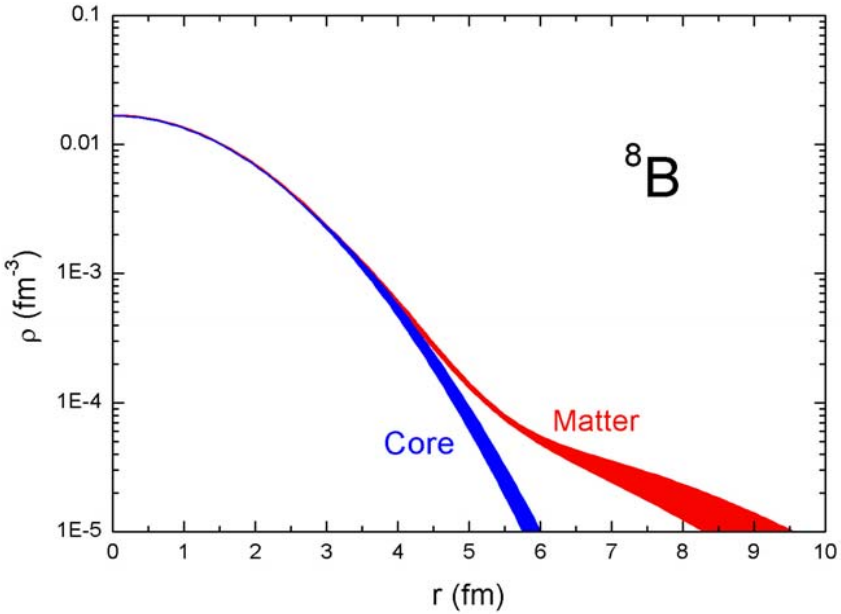
R_{halo} = 2.97 (26) fm

Most Recent Results on Elastic Proton Scattering from Exotic Nuclei

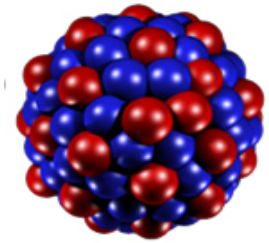
differential cross section:



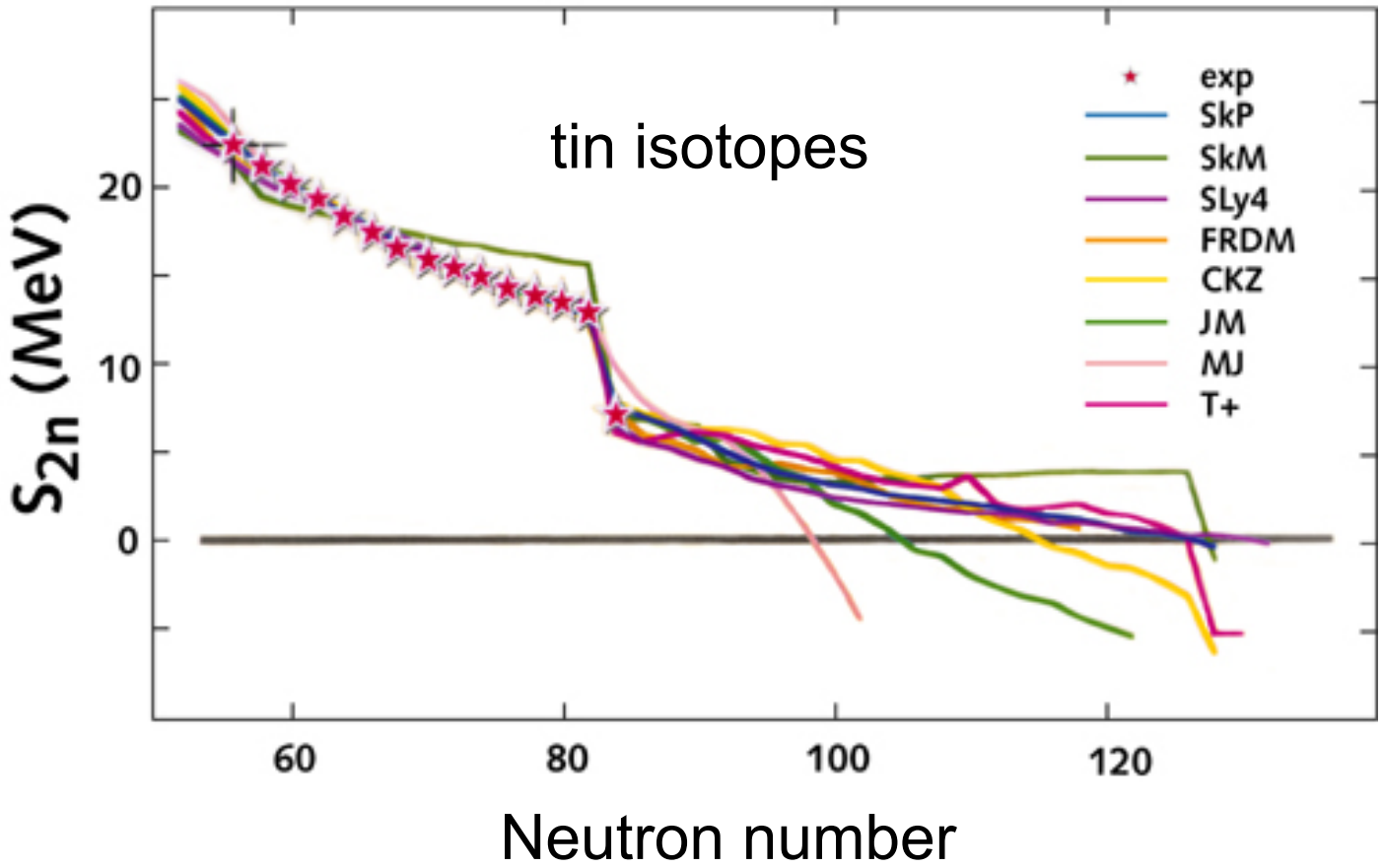
deduced nuclear matter distribution:



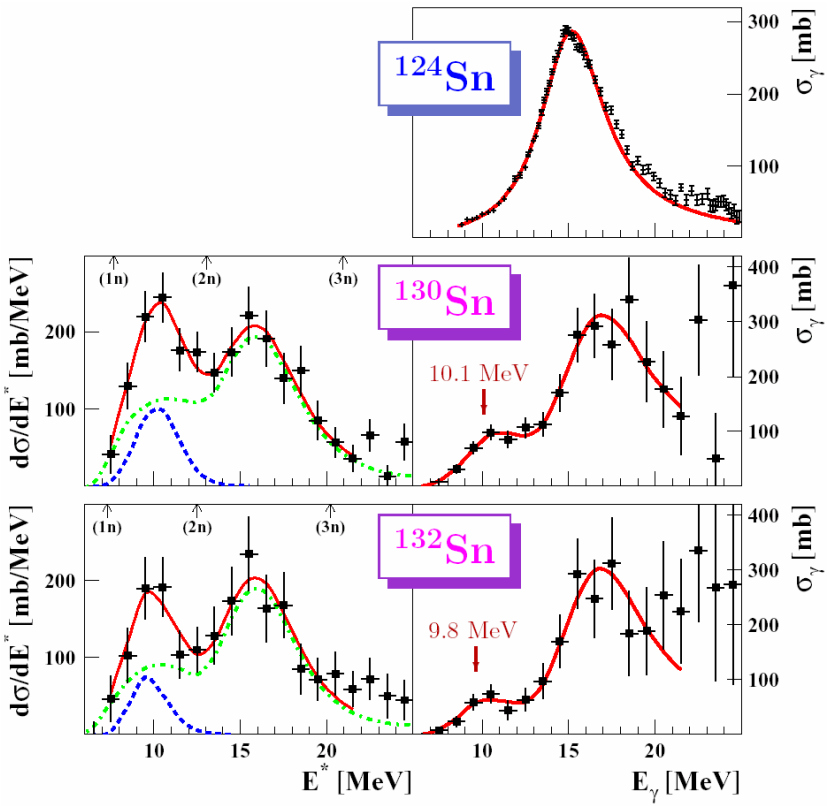
- for the first time a proton halo was investigated
- the halo structure of ^{8}B was confirmed
- the deduced shape of the matter distribution is in reasonable agreement with theoretical predictions
- the deduced matter radius R_m = 2.88 (10) fm is larger as compared to theoretical predictions (R_m = 2.60 fm)



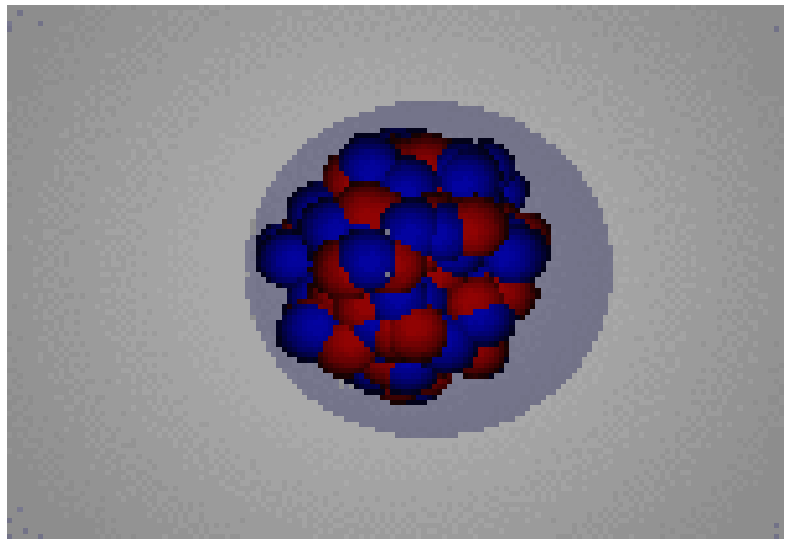
???


tin isotopes
exp
SkP
SkM
SLy4
FRDM
CKZ
JM
MJ
T+
S_{2n} (MeV)
20
10
0
60
80
100
120
Neutron number

Evidence for pygmy dipole in unstable neutron-rich Sn isotopes



P. Adrich et al., PRL 95 (2005) 132501
LAND Collaboration



at LAND - GSI:

Measurement ~ **10 days**

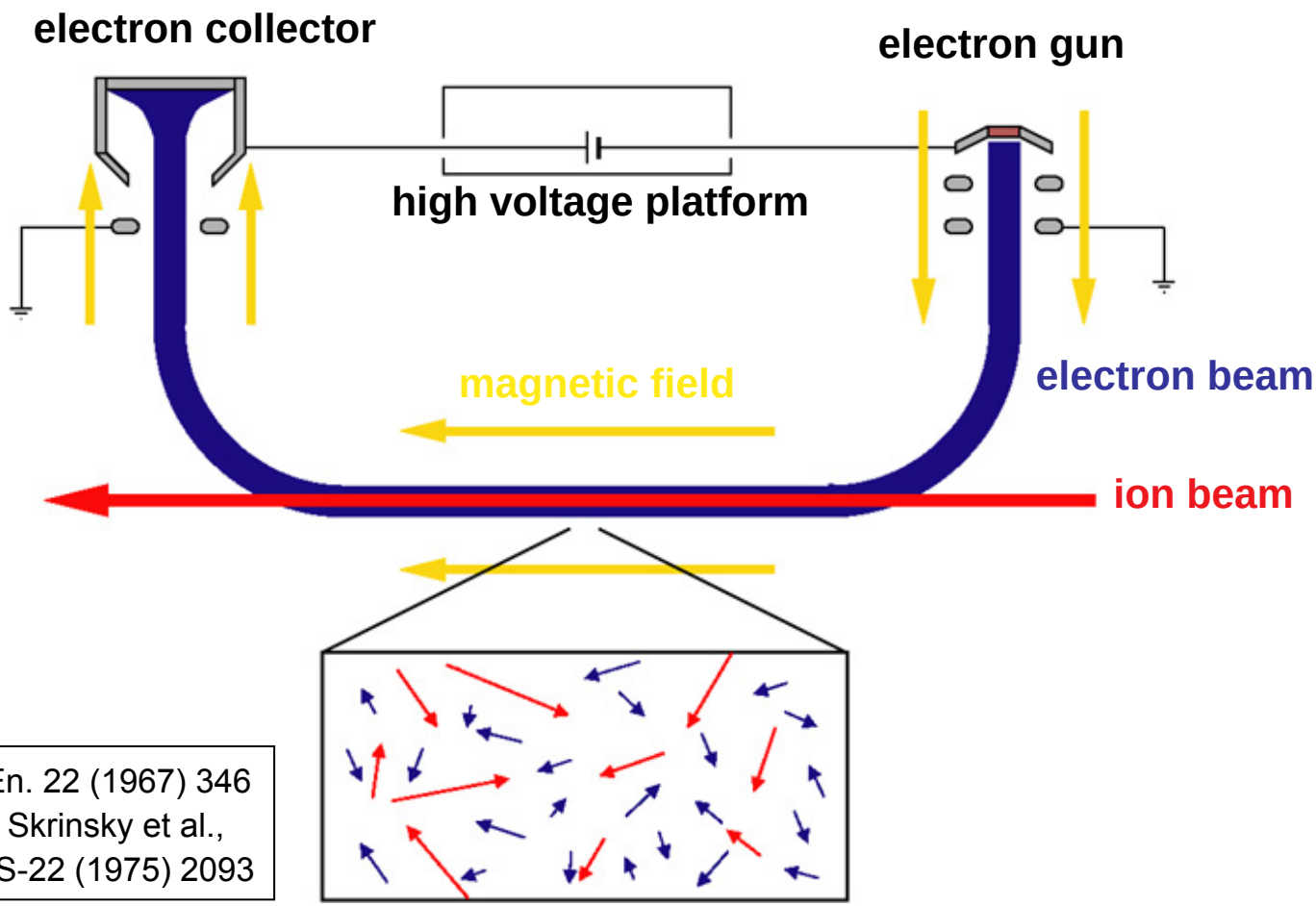
Resolution ~ 1 - 2 MeV

at R^3B - FAIR:

Measurement ~ **100 seconds**

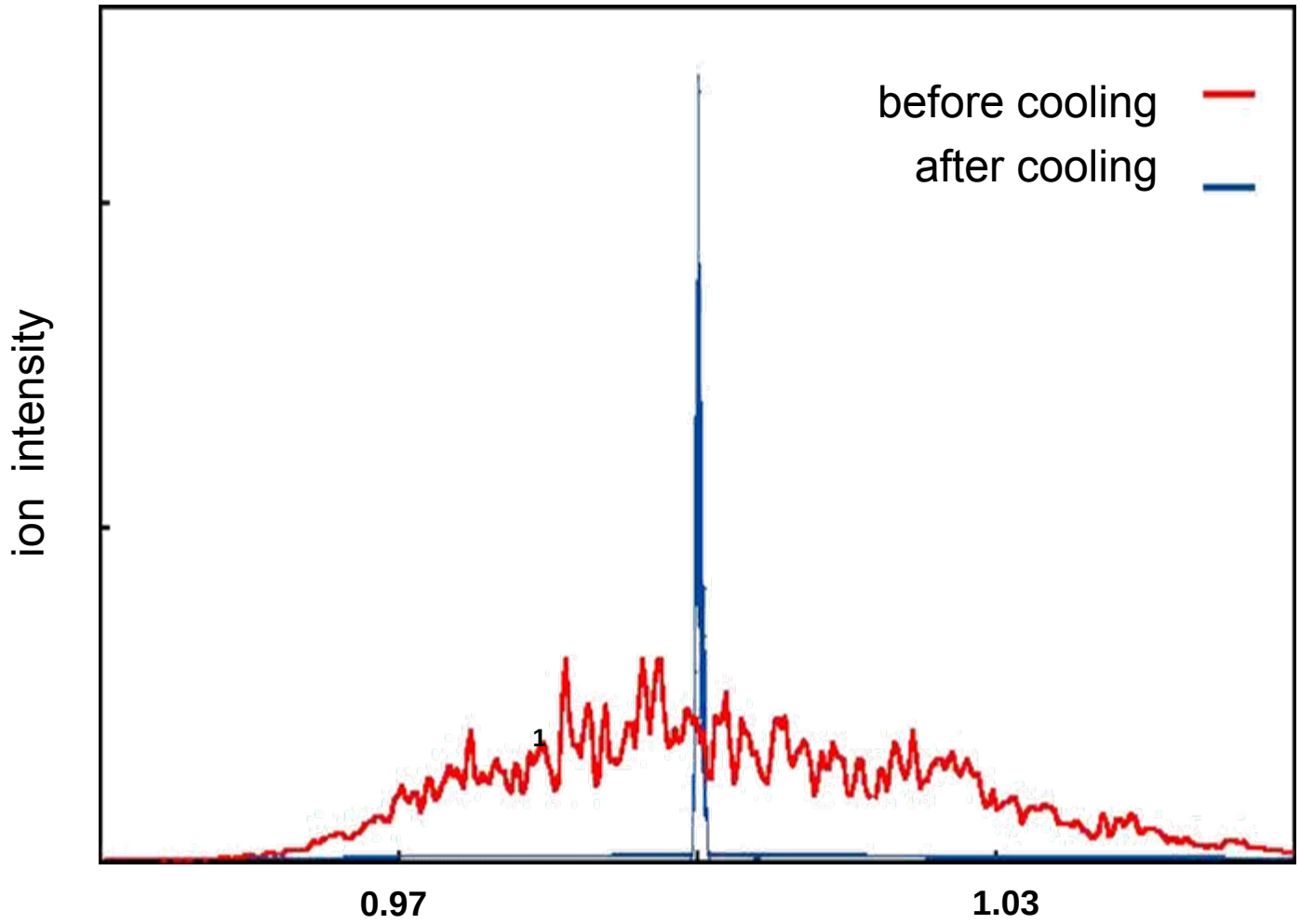
Resolution ~ order of 100 keV

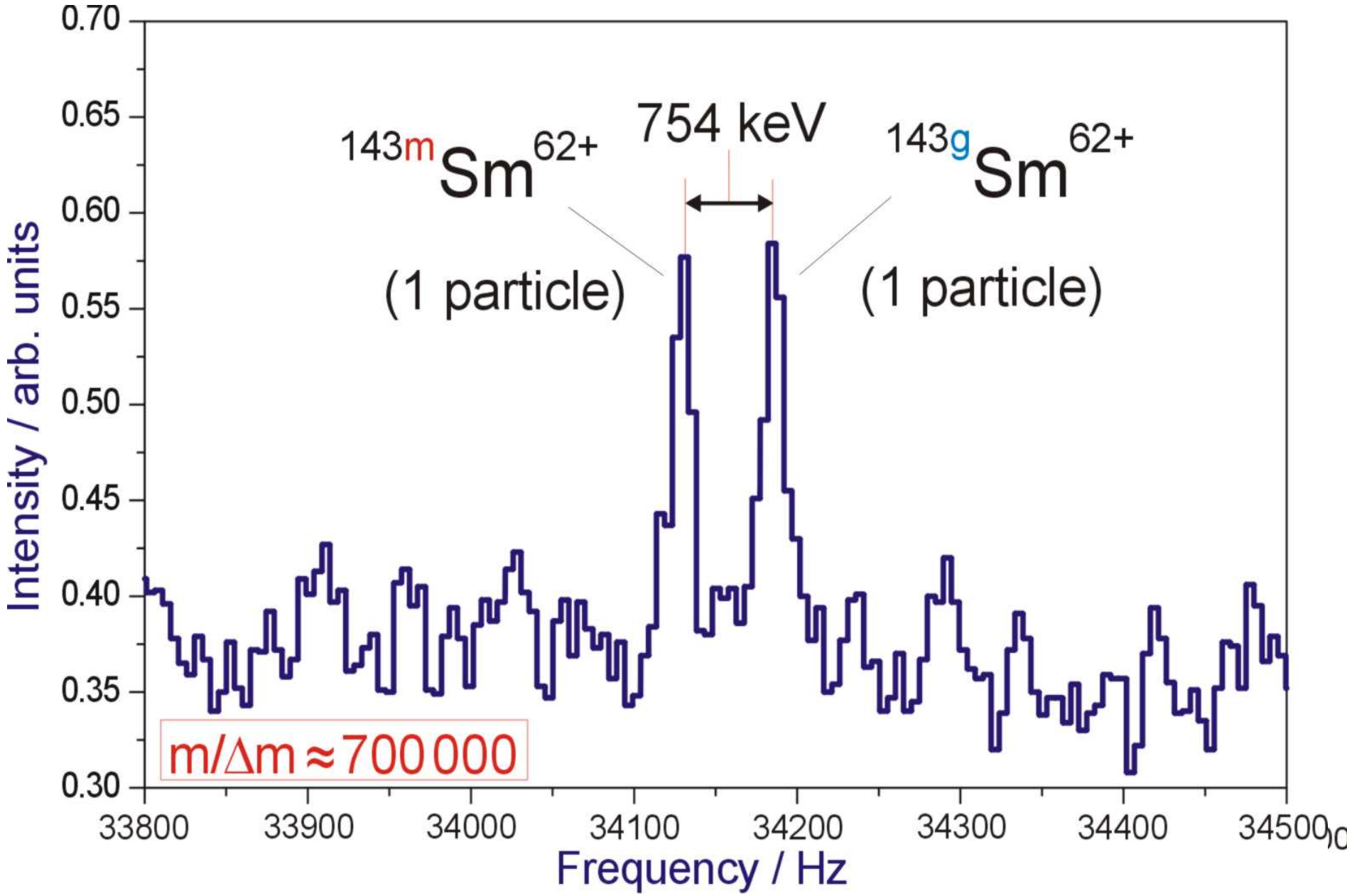
Electron-Beam Cooled Ion Beams

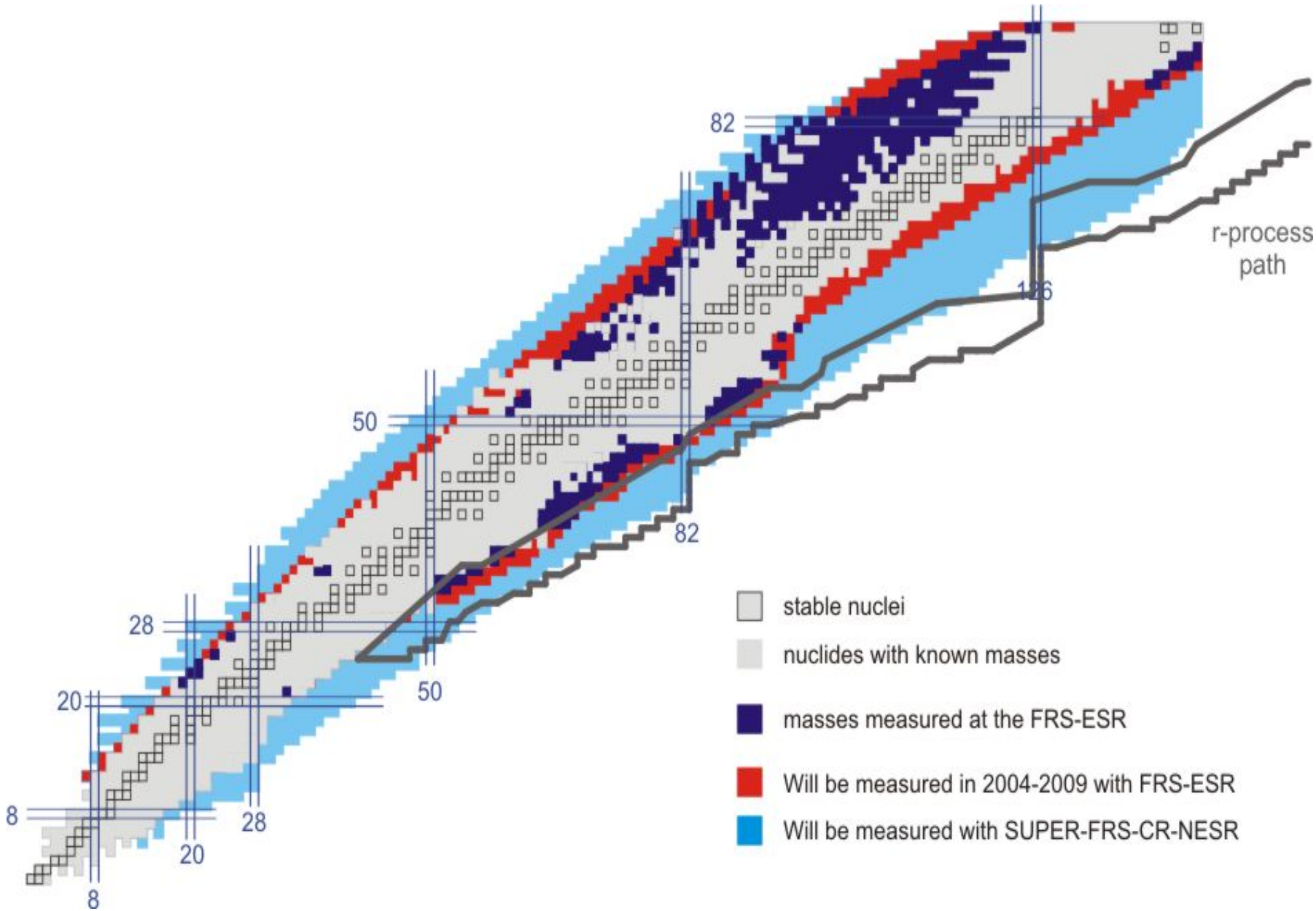


G.I. Budker, At. En. 22 (1967) 346
G.I. Budker, A.N. Skrinsky et al.,
IEEE NS-22 (1975) 2093

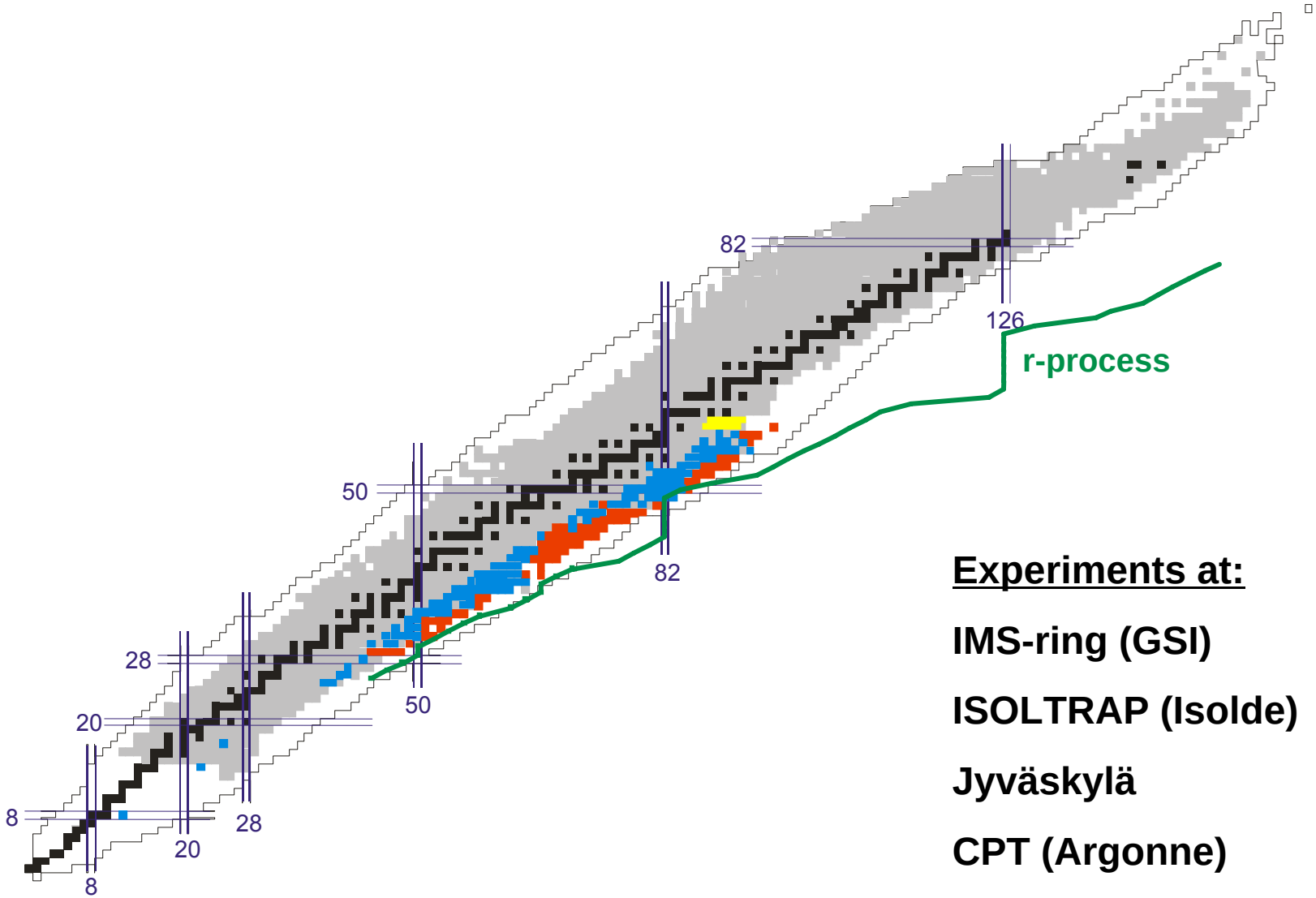
Ion Beam Cooling ...




0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
Intensity / arb. units
143m Sm 62+
754 keV
143g Sm 62+
(1 particle)
(1 particle)
m/Δm ≈ 700 000
33800
33900
34000
34100
34200
34300
34400
34500
Frequency / Hz


82
50
28
20
8
8
20
28
50
82
126
r-process
path
stable nuclei
nuclides with known masses
masses measured at the FRS-ESR
Will be measured in 2004-2009 with FRS-ESR
Will be measured with SUPER-FRS-CR-NESR

Mass measurements of neutron-rich nuclei



Experiments at:

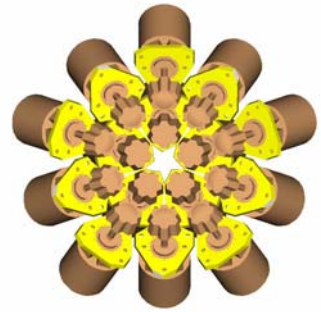
IMS-ring (GSI)

ISOLTRAP (Isolde)

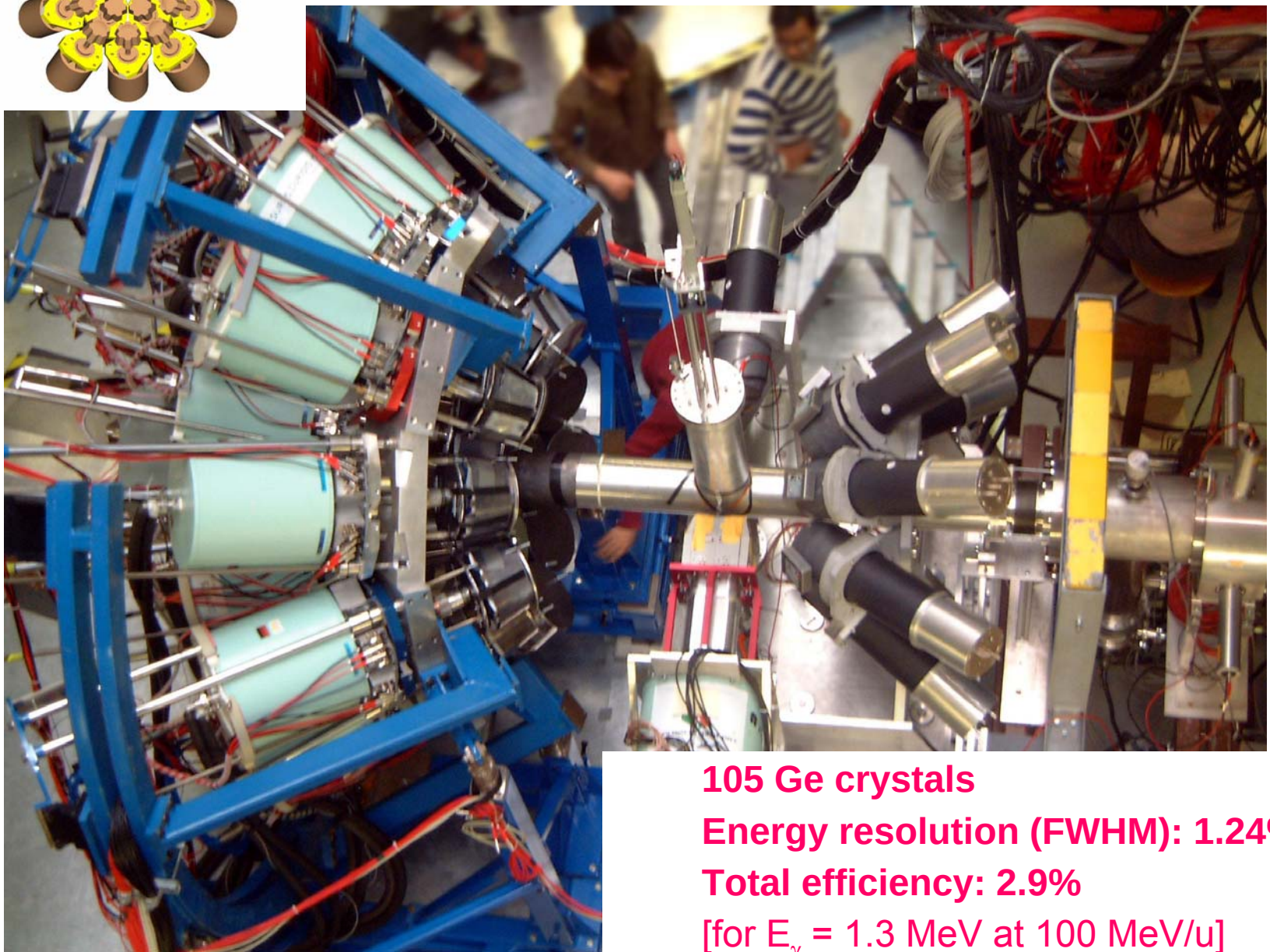
Jyväskylä

CPT (Argonne)

..



RISING In-flight set-up



105 Ge crystals

Energy resolution (FWHM): 1.24%

Total efficiency: 2.9%

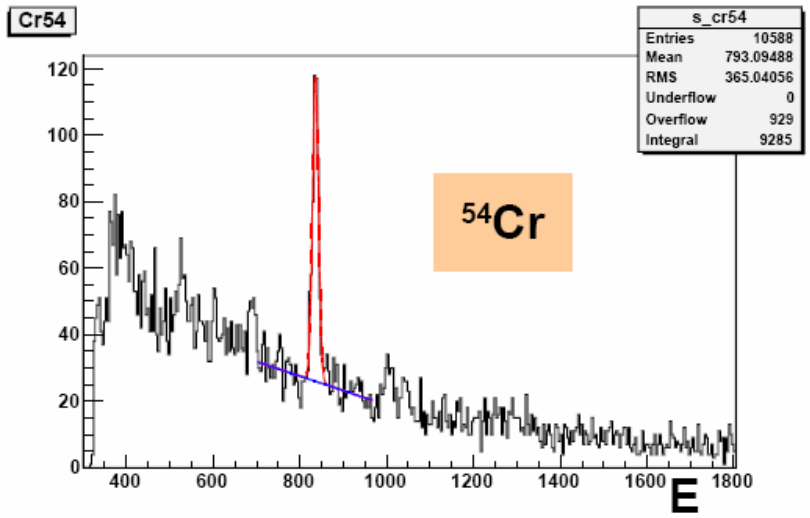
[for E_γ = 1.3 MeV at 100 MeV/u]

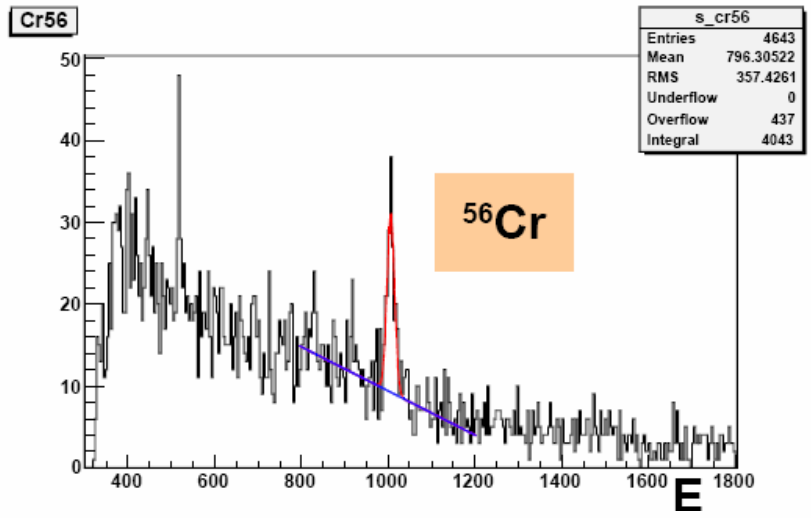
Coulomb Excitation of n-rich Cr Isotopes

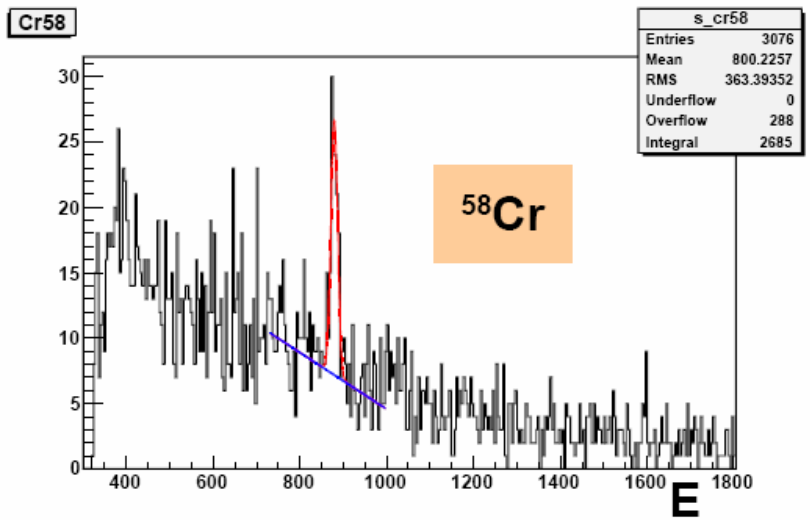
See talk by Takaharu Otsuka's

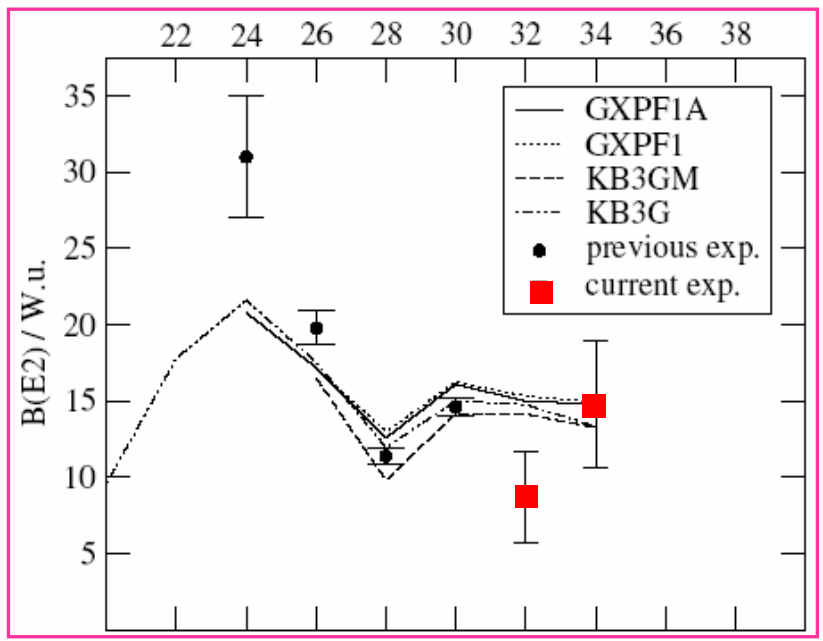
A. Bürger, Ph.D. thesis

Does a new sub-shell closure exist at N=32?







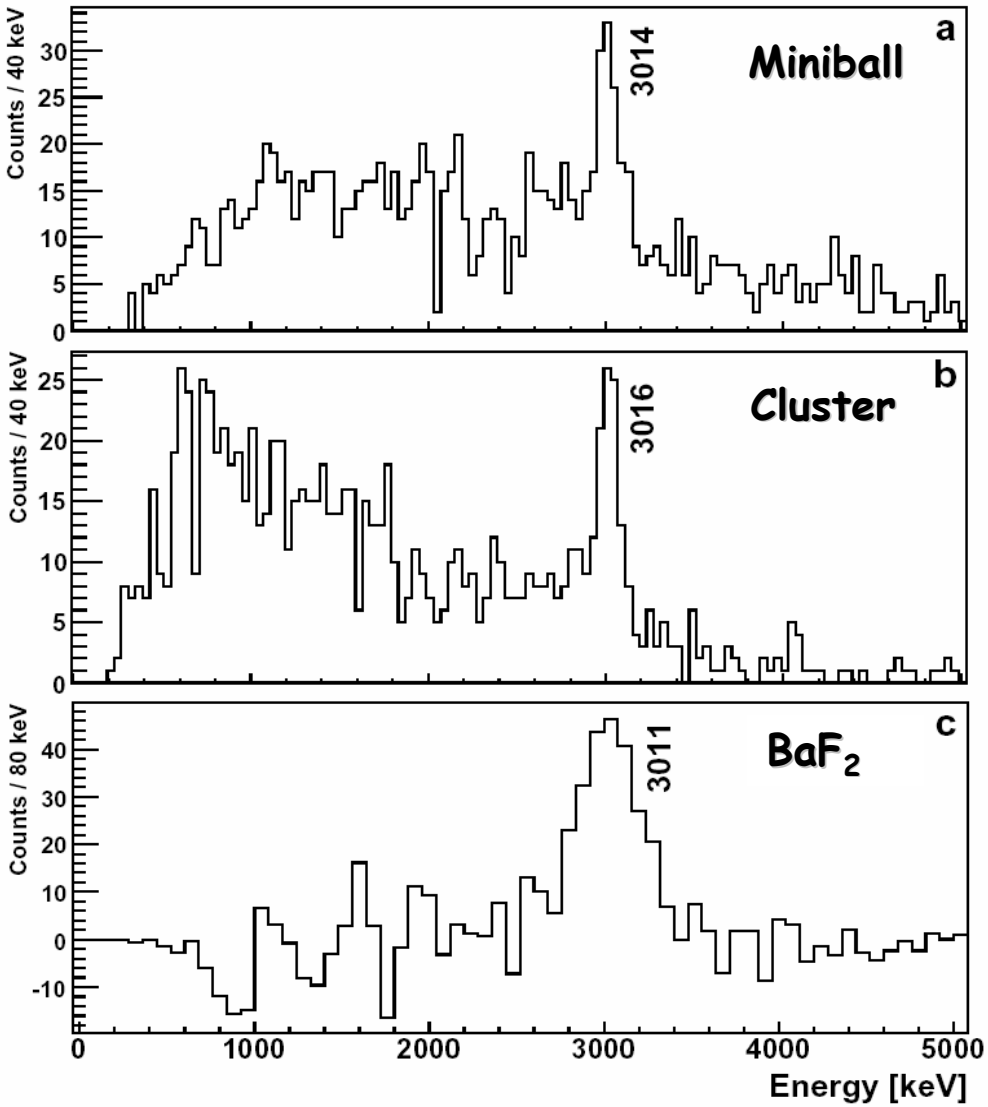


Evidence for reduced B(E2) value at N=32

^{36}Ca 1n knock-out reaction

P. Doornenbal, Ph.D. thesis

Is N,Z=14(16) shell stabilisation and N=20 shell quenching in $^{32}Mg_{20}$ symmetric in isospin projection T_z?



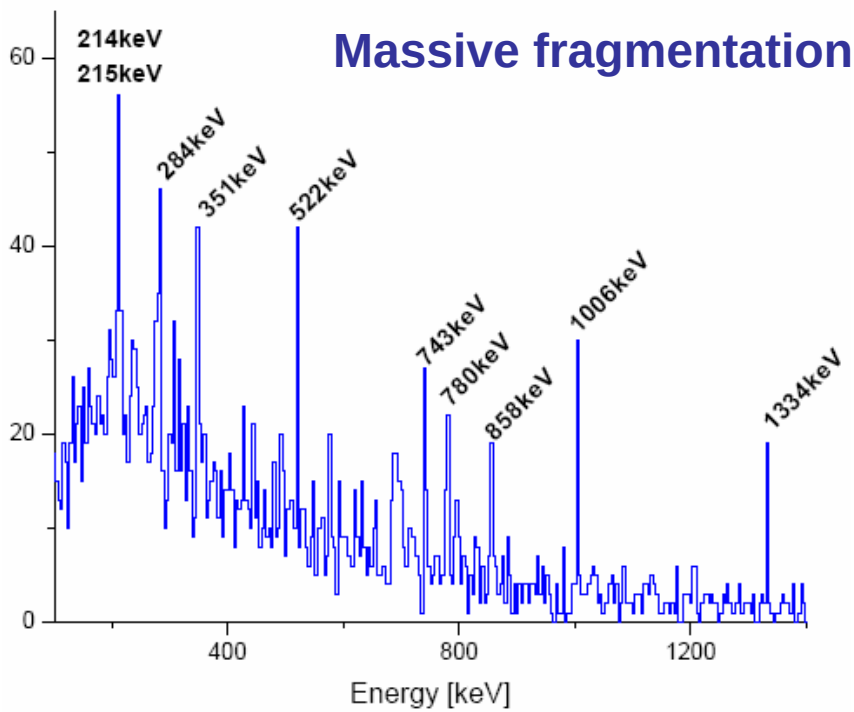
^{36}Ca E(2^+) = 3015(16) keV

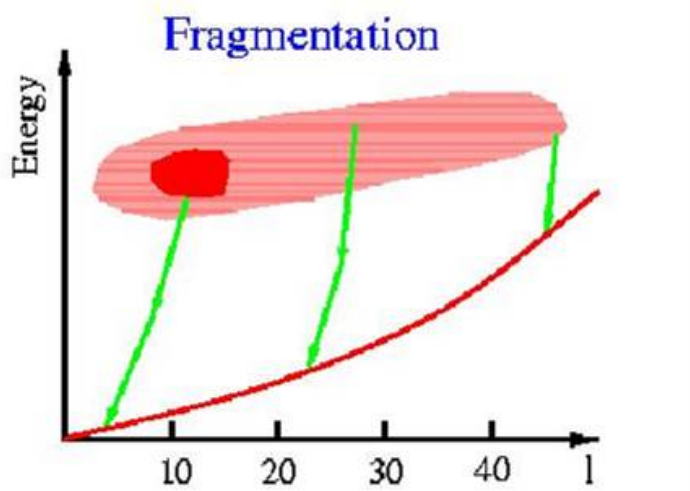
Ganil: 3023(30) keV

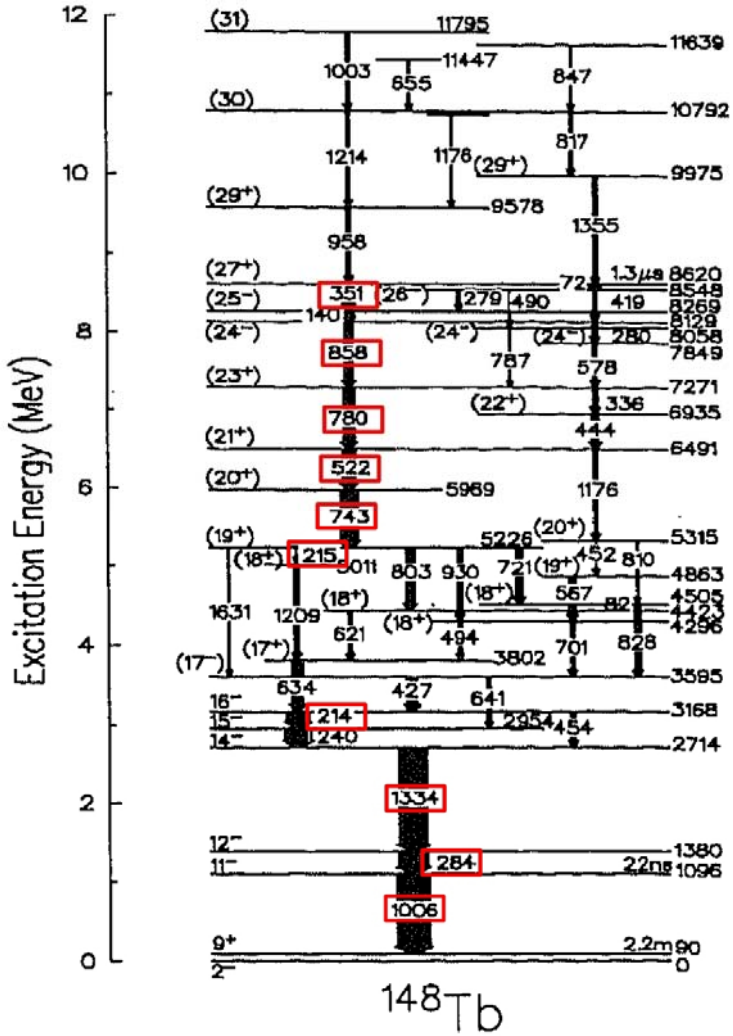
^{36}Ca E(2^+) - ^{36}S E(2^+) = -276 keV

Largest CED in sd shell nuclei

27^{+} state populated in ^{148}Tb



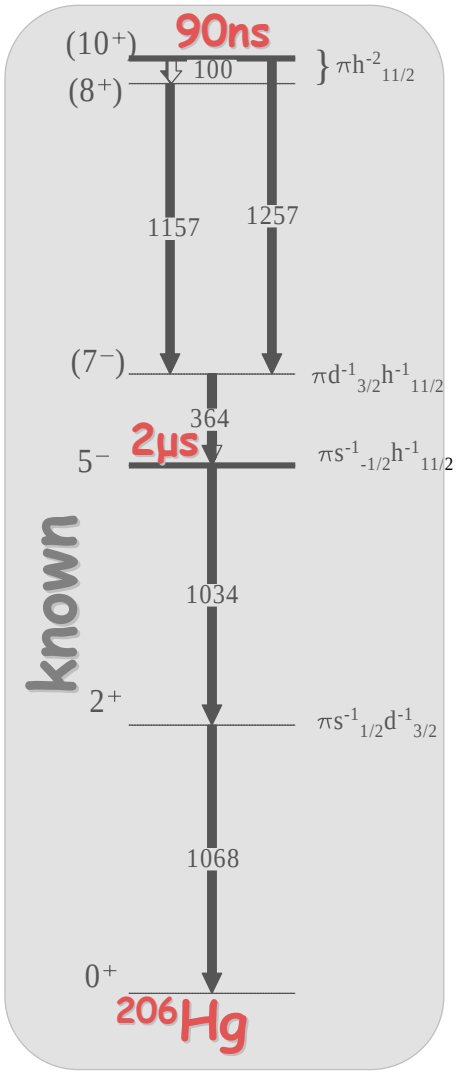


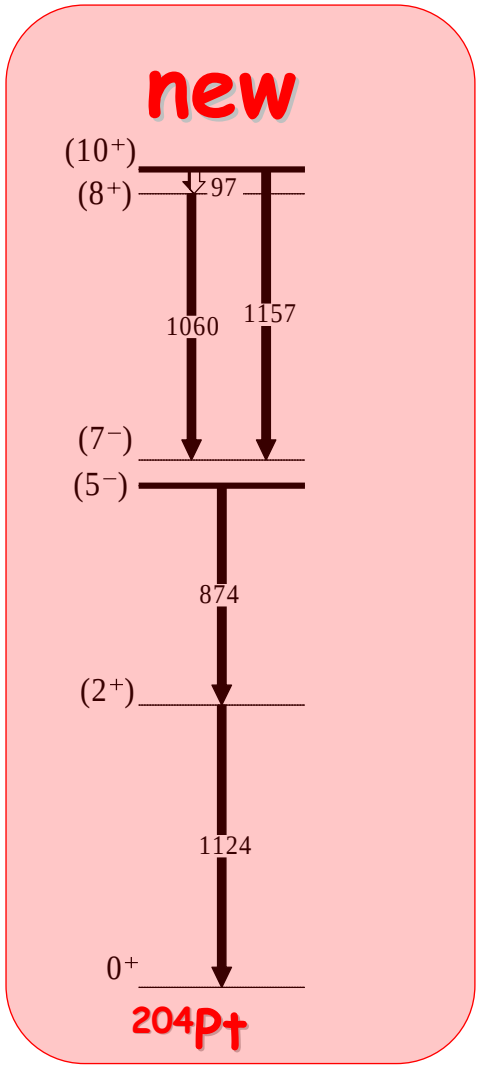


Fragmentation populates high spin states

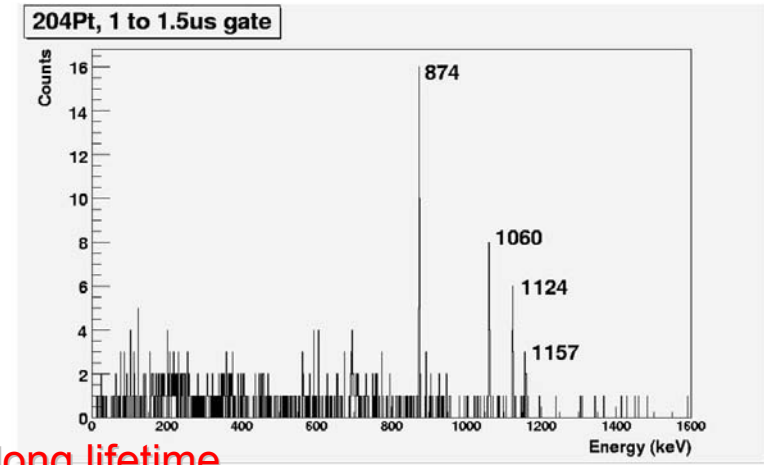
^{204}Pt: The lightest N=126 isotone

4 p holes in ^{208}Pb core

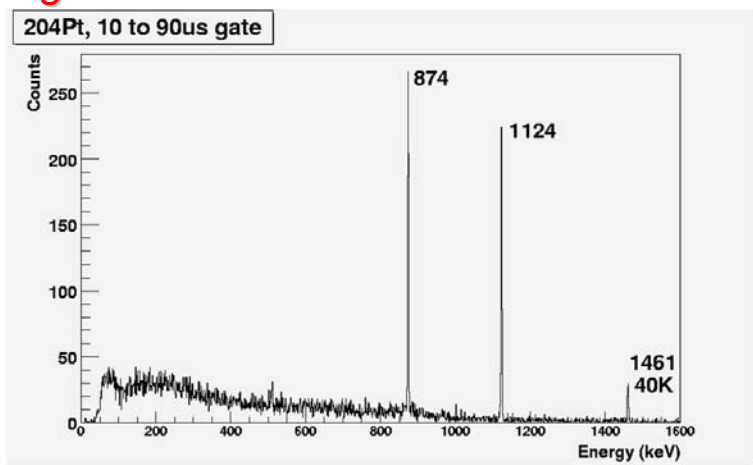




short lifetime



long lifetime

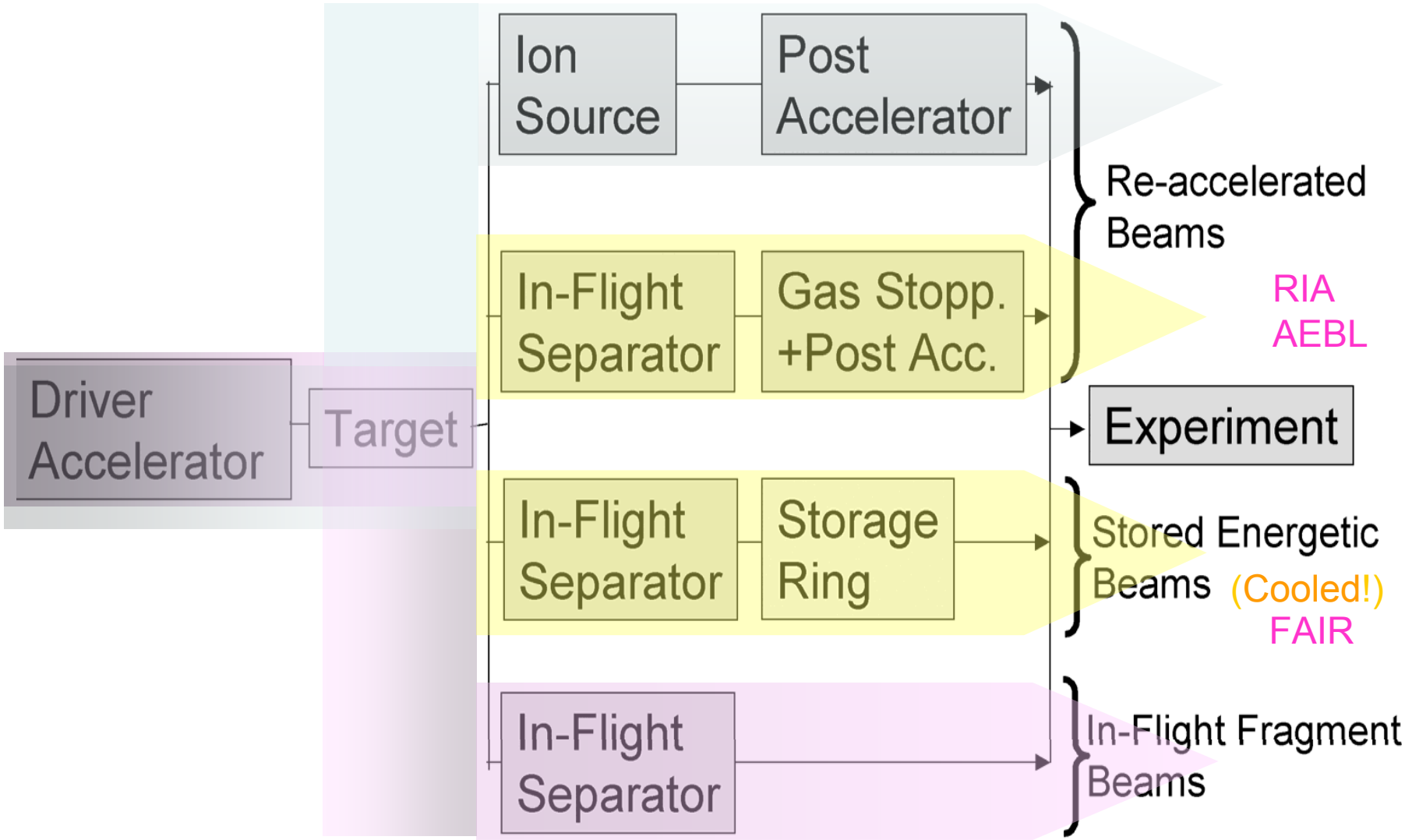


Zs. Podolyák, et al., Univ Surrey

Direct Reactions

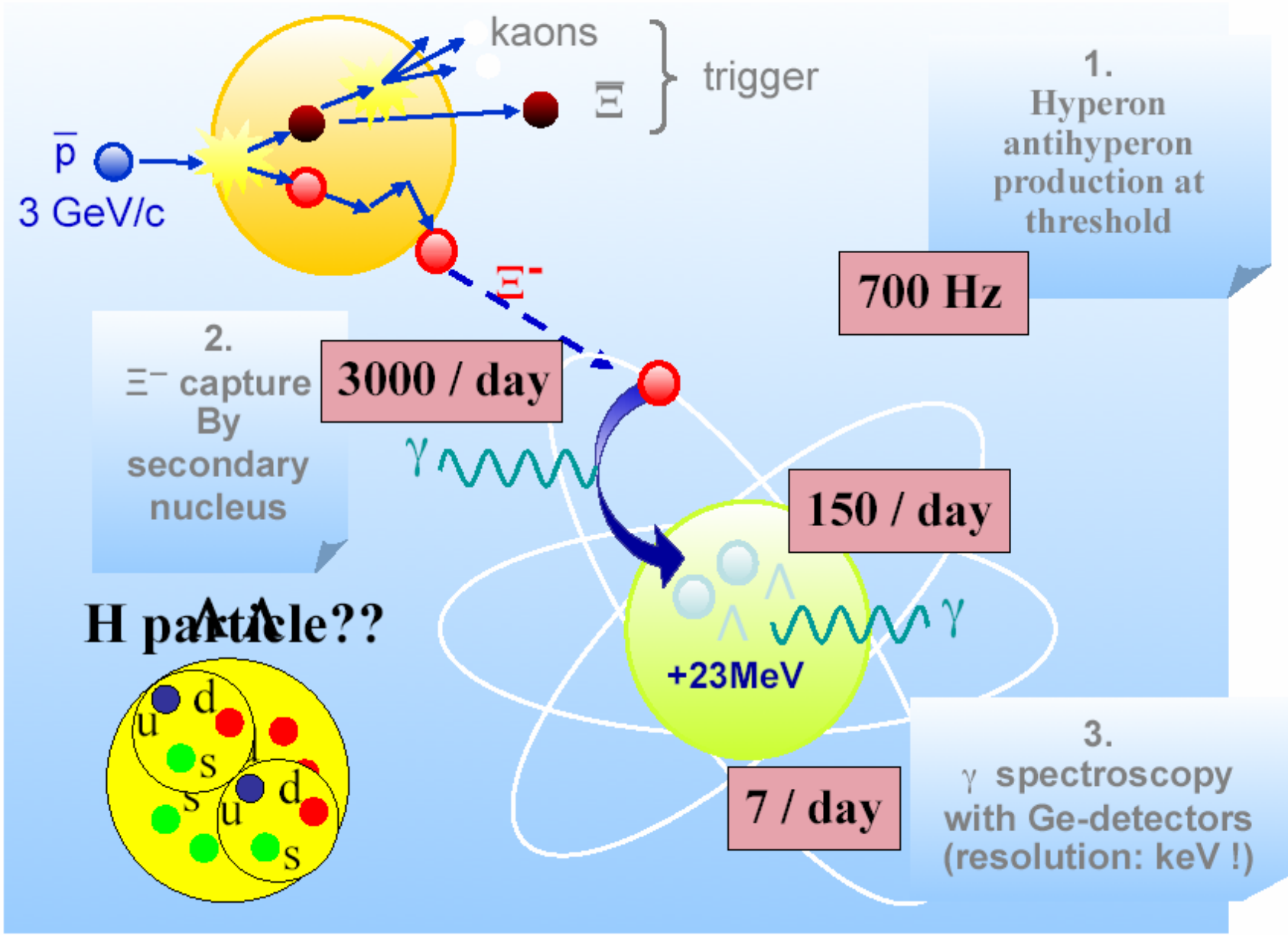
- elastic scattering (p,p), (α,α), …Coulomb excitation
  nuclear matter distribution ρ(r), skins, halo structures
- inelastic scattering (p,p'), (α,α'), …
  deformation parameters, B(E2) values, transition densities, giant resonances
- charge exchange reactions (p,n), (^{3}He,t), (d, ^{2}He), …
  Gamow-Teller strength
- transfer reactions (p,d), (p,t), (p, ^{3}He), (d,p), …
  single particle structure, spectroscopic factors
  spectroscopy beyond the driplines
  neutron pair correlations
  neutron (proton) capture cross sections
- knock-out reactions (p,2p), (p,pn), (p,p ^{4}He)…
  ground state configurations, nucleon momentum distributions, cluster correlations

'Classical' ISOL Method: ISOLDE; ORNL; TRIUMF; .....
SPIRAL-2; RIA; EURISOL

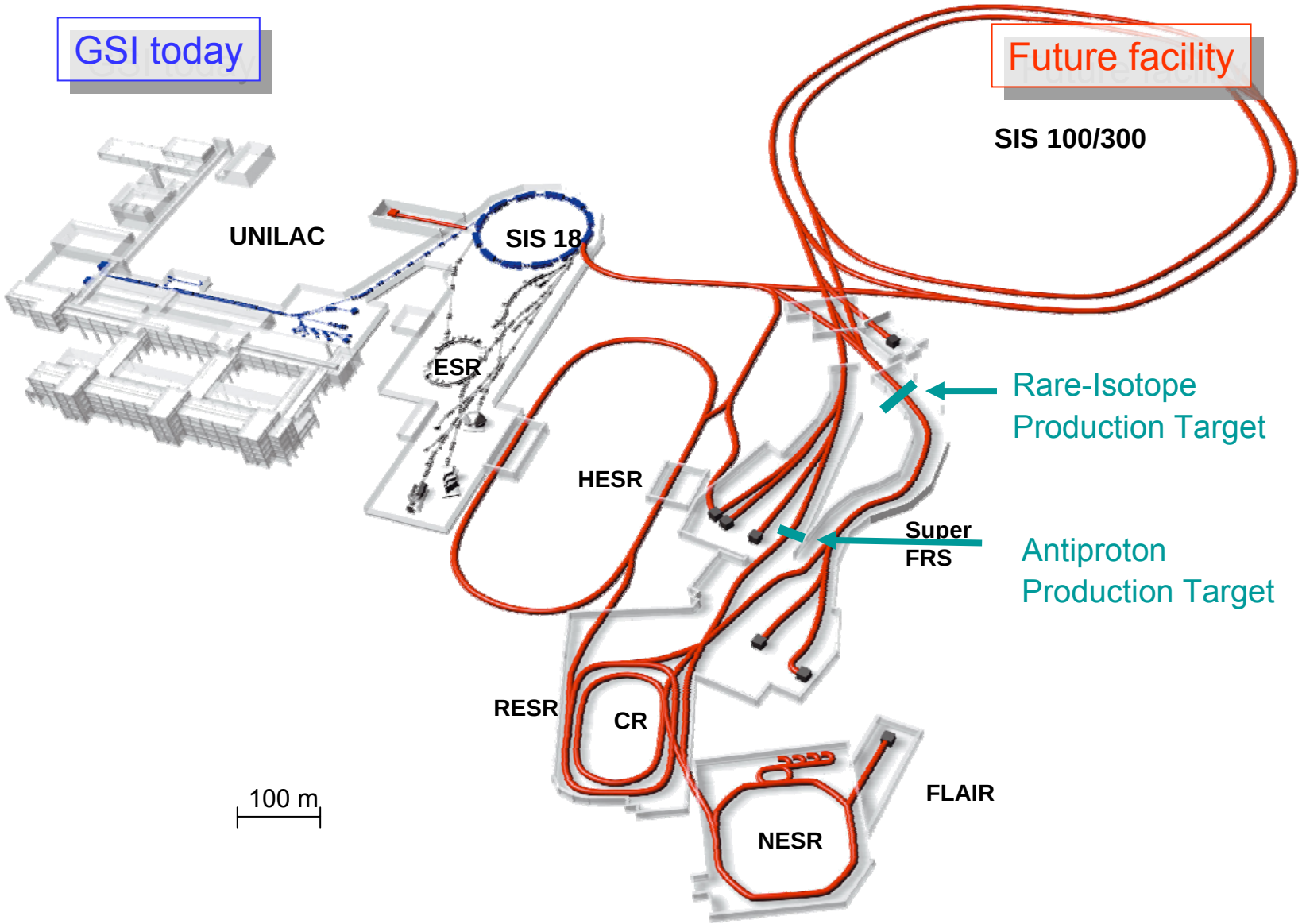


'Classical' In-Flight Method: GANIL; GSI; MSU; RIKEN; ...
RIKEN RIBF; FAIR; RIA

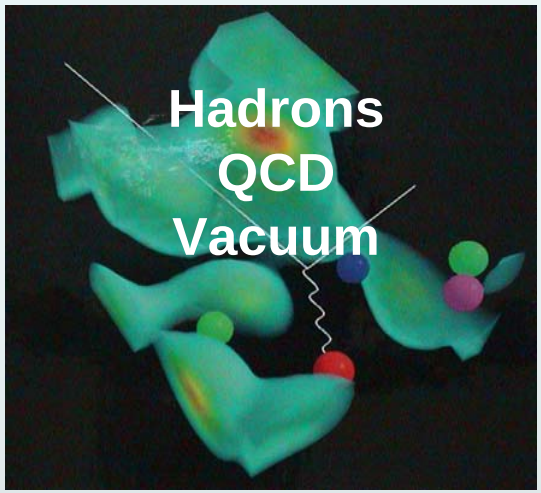
Production of double hypernuclei



FAIR - Facility for Antiproton and Ion Research

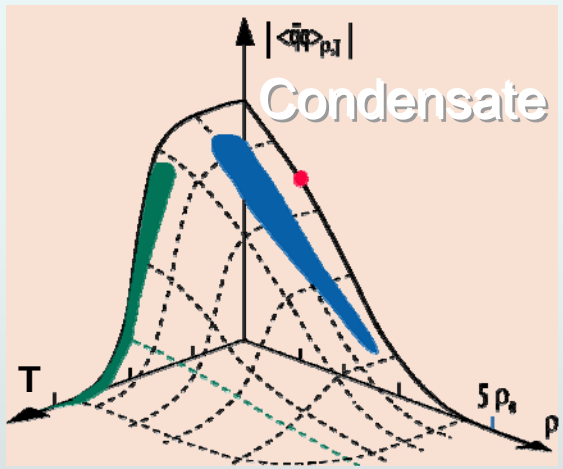


Non-perturbative QCD



QCD Bound Systems

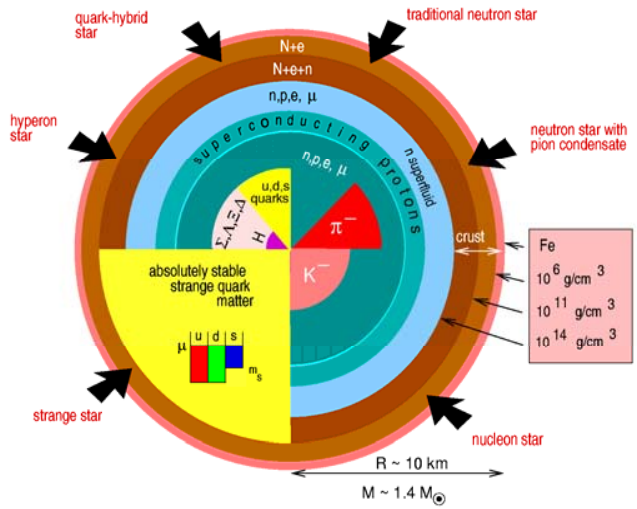
- hadron spectroscopy
- exotic systems: glue-balls, glue-lumps, hy-brids, molecules...
- spin observables
- van der Waals systems

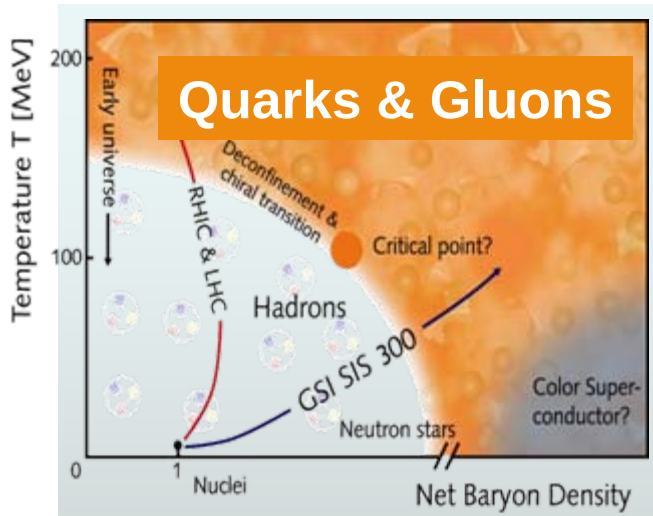


In-medium QCD

- shifts in hadron properties
- effective parameters
- symmetries: violations & restorations

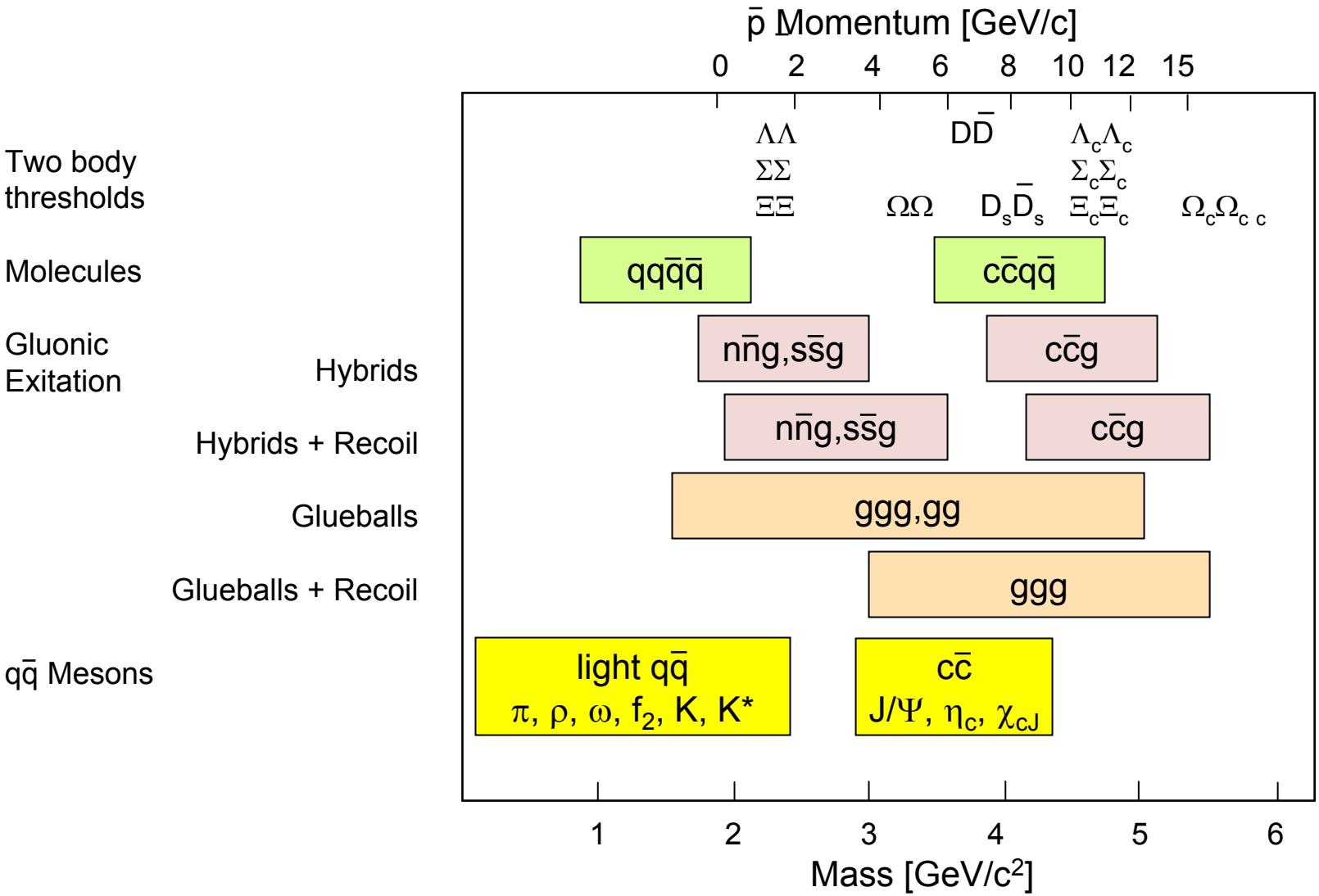
Properties of neutron stars





QCD Phase Diagram

- phase transition & critical point
- QGP properties
- Dense matter

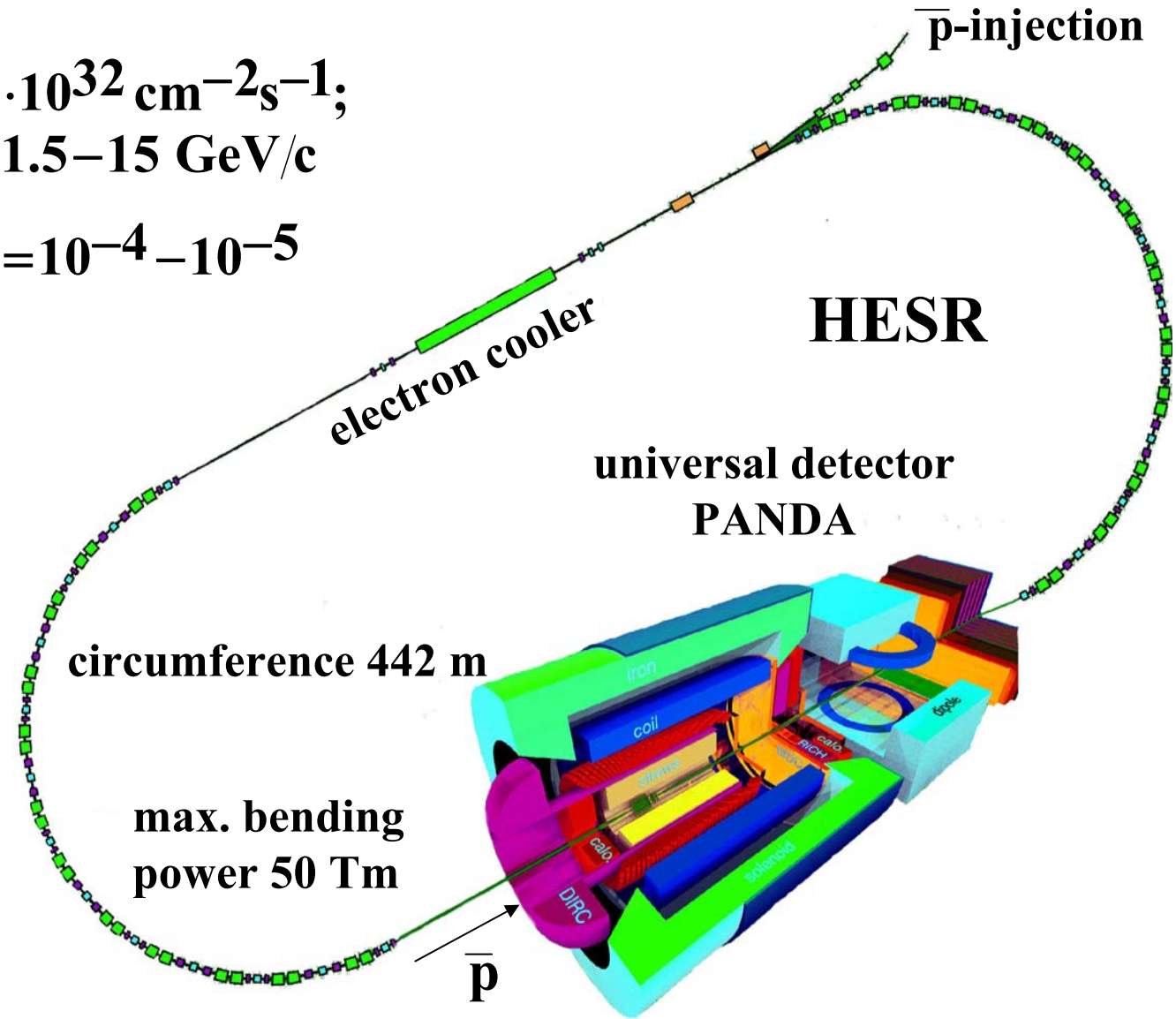

p̄ Momentum [GeV/c]
0
2
4
6
8
10
12
15
Two body thresholds
ΛΛ
ΣΣ
ΞΞ
ΩΩ
DD̄
DsD̄s
ΛcΛc
ΣcΣc
ΞcΞc
ΩcΩc c
Molecules
qqq̄q̄
cc̄qq̄
Gluonic Exitation
Hybrids
nn̄g,ss̄g
cc̄g
Hybrids + Recoil
nn̄g,ss̄g
cc̄g
Glueballs
ggg,gg
Glueballs + Recoil
ggg
qq̄ Mesons
light qq̄
π, ρ, ω, f2, K, K*
cc̄
J/Ψ, ηc, χcJ
1
2
3
4
5
6
Mass [GeV/c2]

High-Energy Storage & Cooler Ring (HESR) und Detector

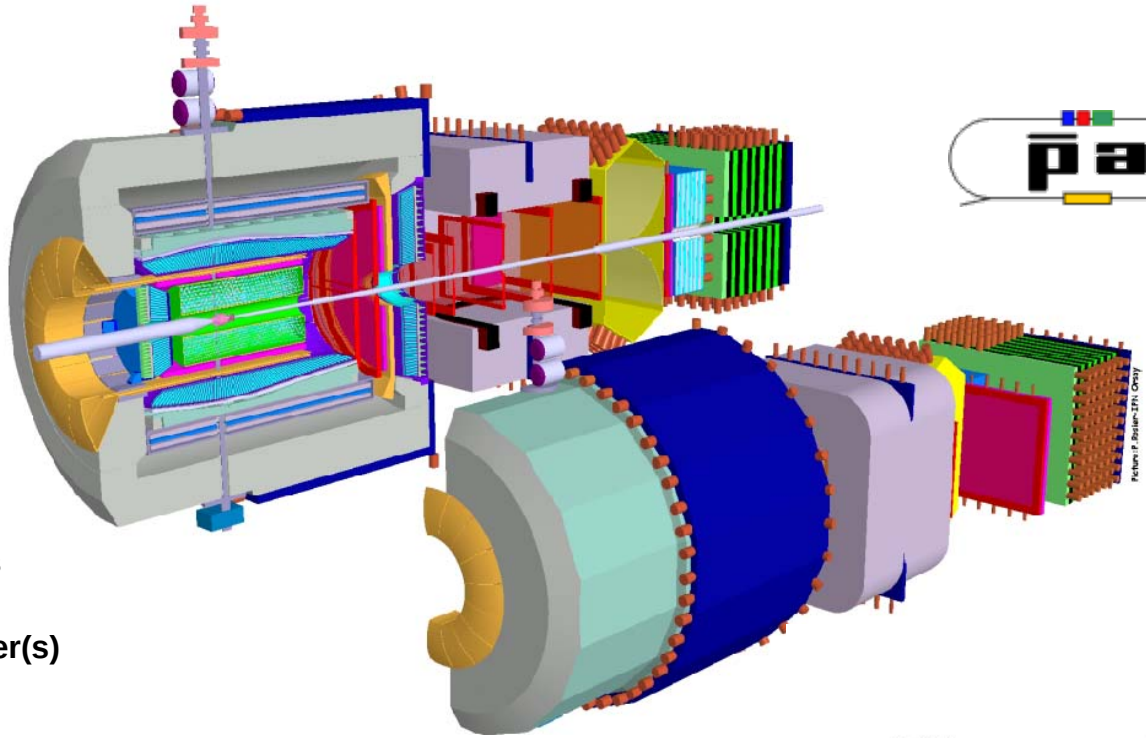
$L = 2 \cdot 10^{32}\,cm^{-2}s^{-1}$;

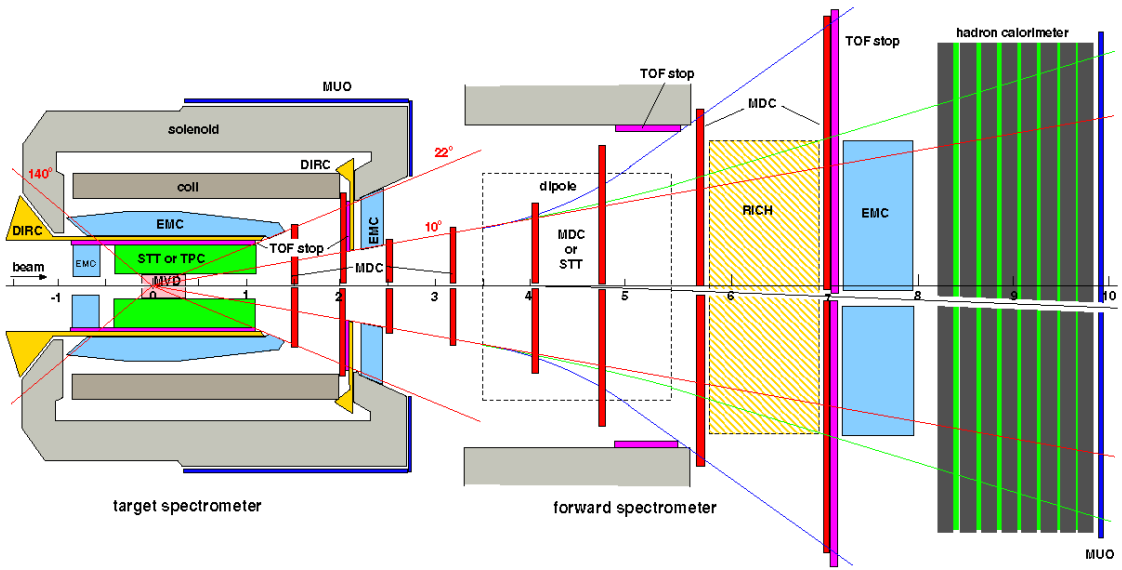
$p_{\bar{p}} = 1.5 - 15$ GeV/c

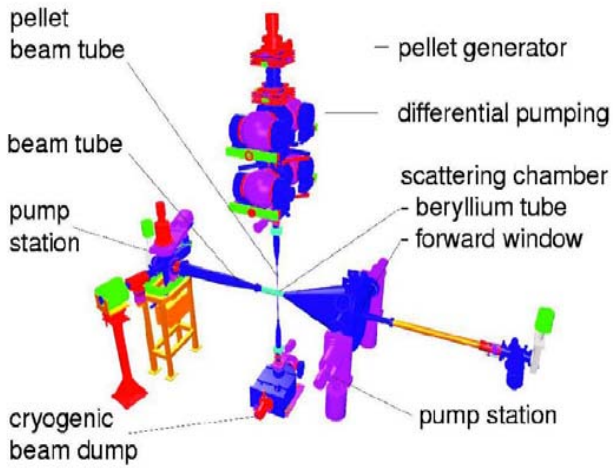
$\delta p/p = 10^{-4} - 10^{-5}$



- **High Rates**
  - Total σ ~ 55 mb
  - peak > 10^7 int/s
- **Vertexing**
  - (σ_p,K_S,Λ,…)
- **Charged particle ID**
  - ($e^{\pm}$,$\mu^{\pm}$,$\pi^{\pm}$,p,…)
- **Magnetic tracking**
- **El-mag. Calorimetry**
  - (γ,π^0,η)
- **Forward capabilities**
  - (leading particles)
- **Sophisticated Trigger(s)**







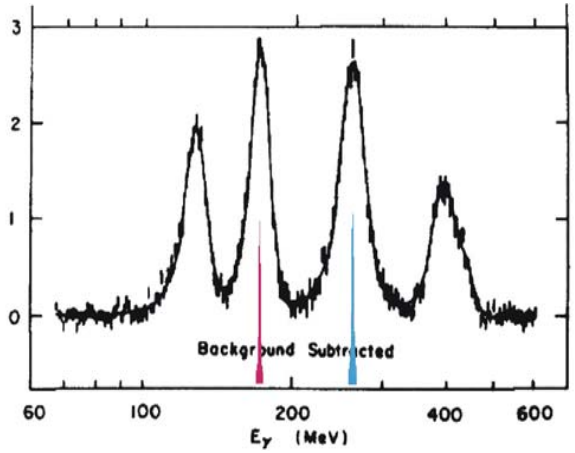
Comparison e^+e^- versus $p\bar{p}$

e^+e^- interactions:
only 1^{--} states formed
other states populated in secondary decays
(moderate mass resolution)

production of $\chi_{1,2}$

$$e^+e^- \rightarrow \psi'$$
$$\hookrightarrow \gamma\chi_{1,2}$$
$$\hookrightarrow \gamma\gamma\ J/\psi$$
$$\hookrightarrow \gamma\gamma e^+e^-$$

Crystal Ball

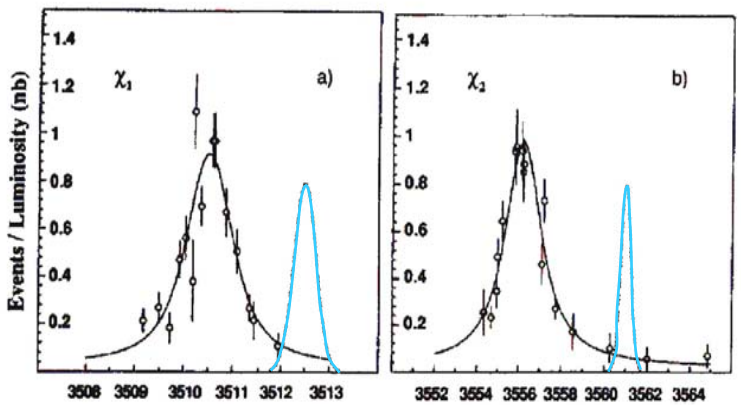


$p\bar{p}$ reactions:
all states directly formed
(very good mass resolution)

formation of $\chi_{1,2}$

$$\bar{p}p \rightarrow \chi_{1,2}$$
$$\hookrightarrow \gamma\ J/\psi$$
$$\hookrightarrow \gamma e^+e^-$$

E 760 (Fermilab)



σ_m (beam) = 0.5 MeV

Physics Program with Antiprotons

glueballs (ggg)
hybrids ($c\bar{c}g$)

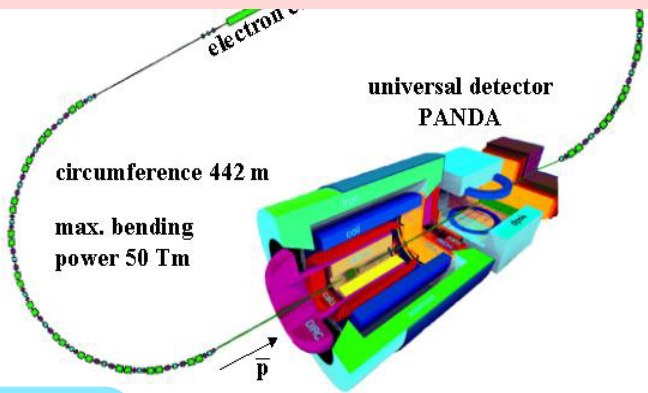
J/ψ spectroscopy
confinement

hidden and open
charm in nuclei

HESR Consortium
Jülich / Uppsala / Stockholm / GSI

fundamental
symmetries:
$\bar{p}$ in traps

strange and
charmed baryons
in nuclear field



FLAIR

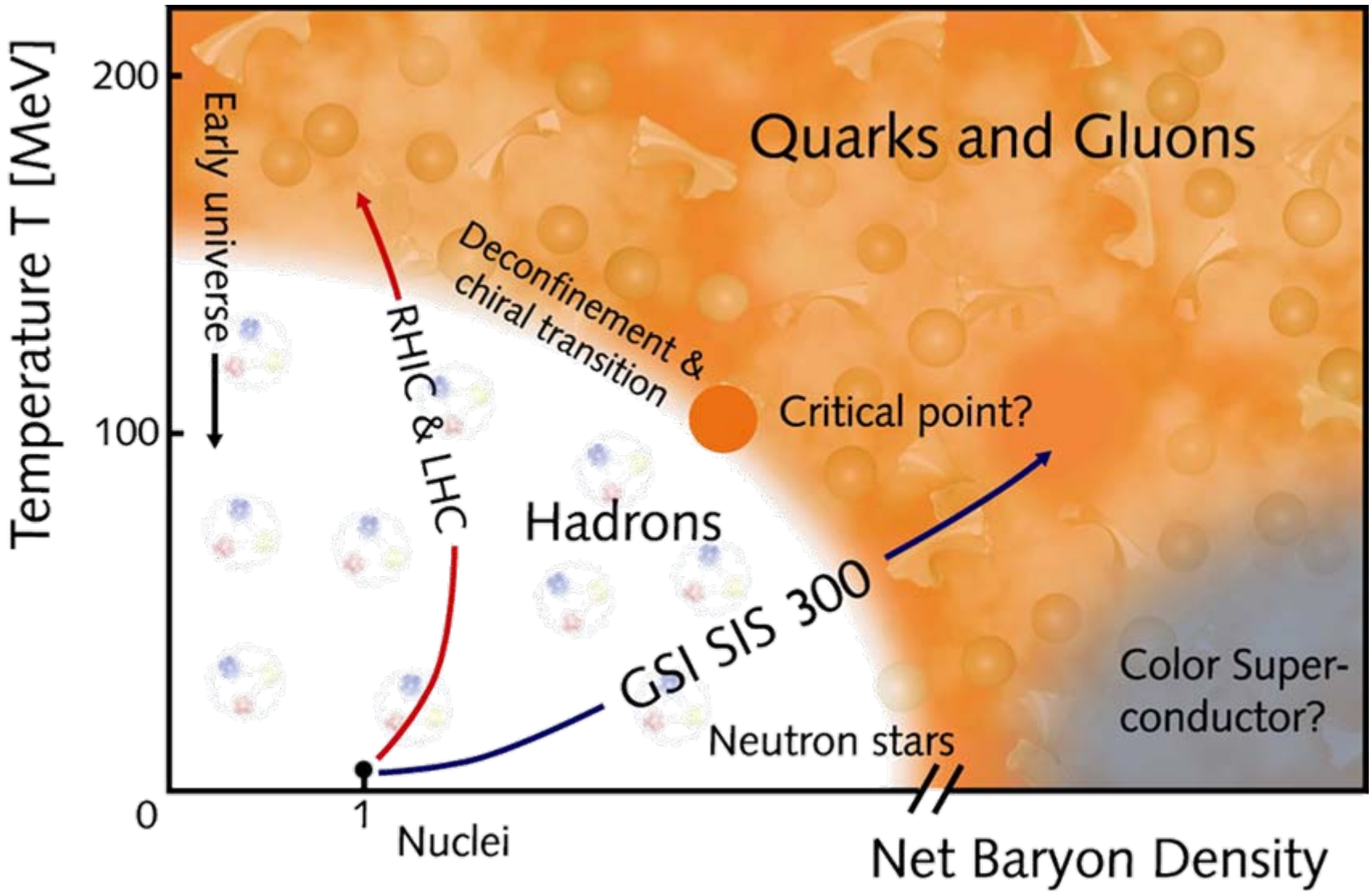
CP-violation
(D/Λ - sector)

inverted deeply virtual
Compton scattering

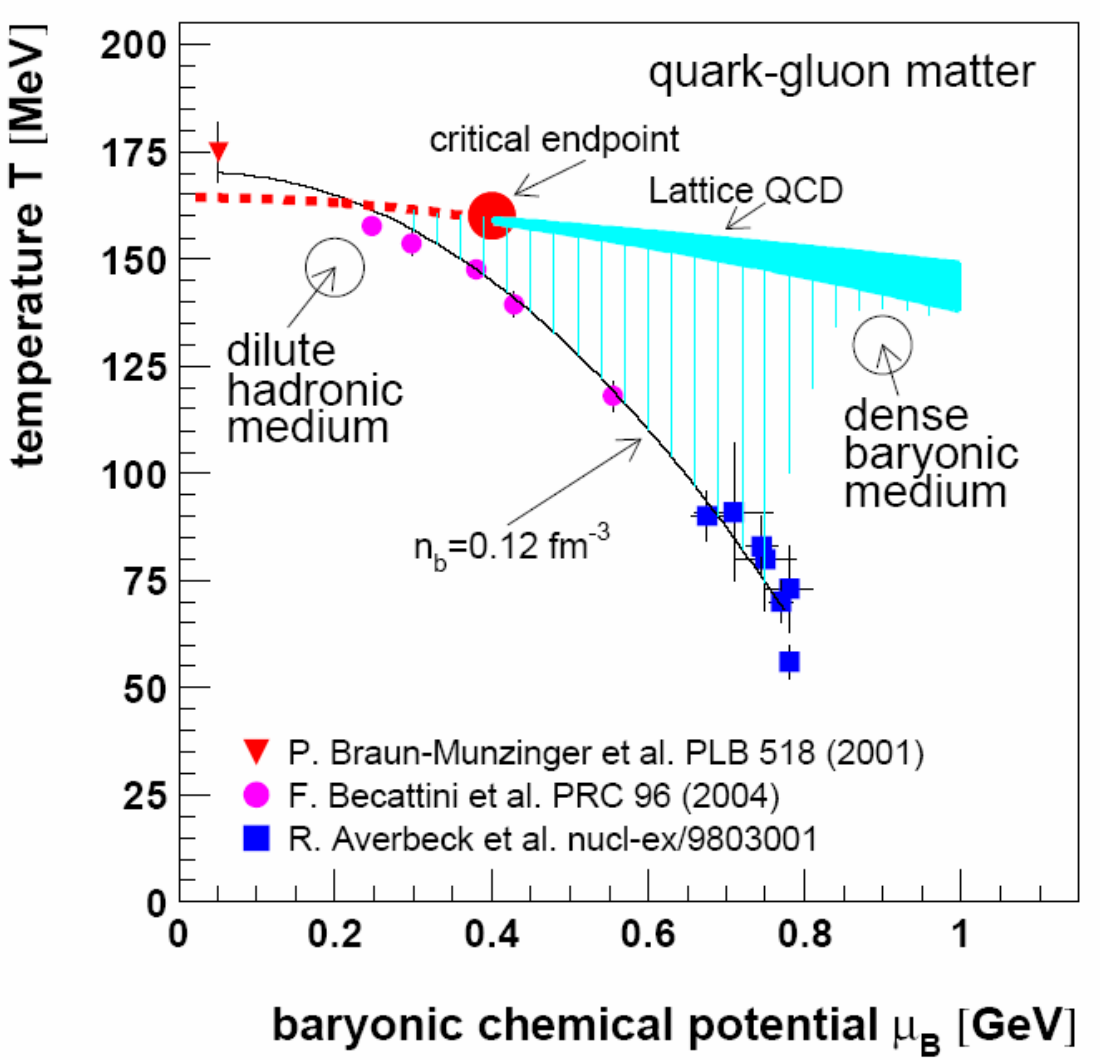
spin structure of the proton
with polarized antiprotons

PAX

The phase diagram of strongly interacting matter

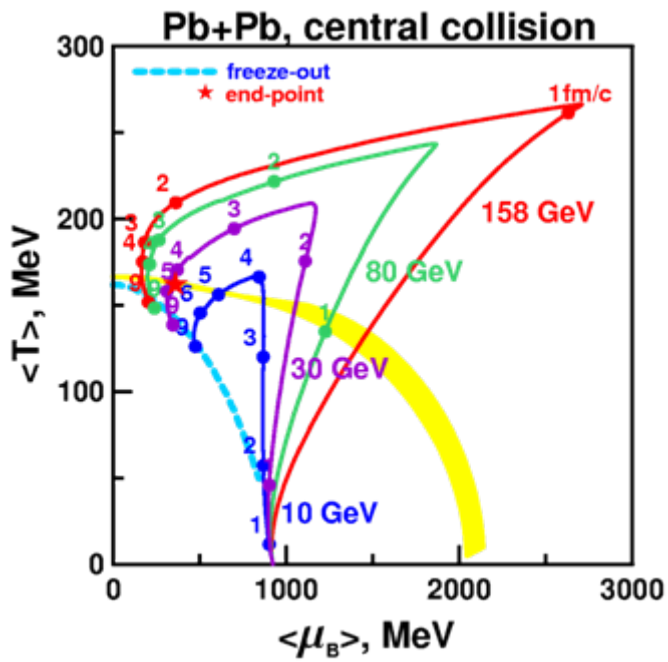


Mapping the QCD phase diagram

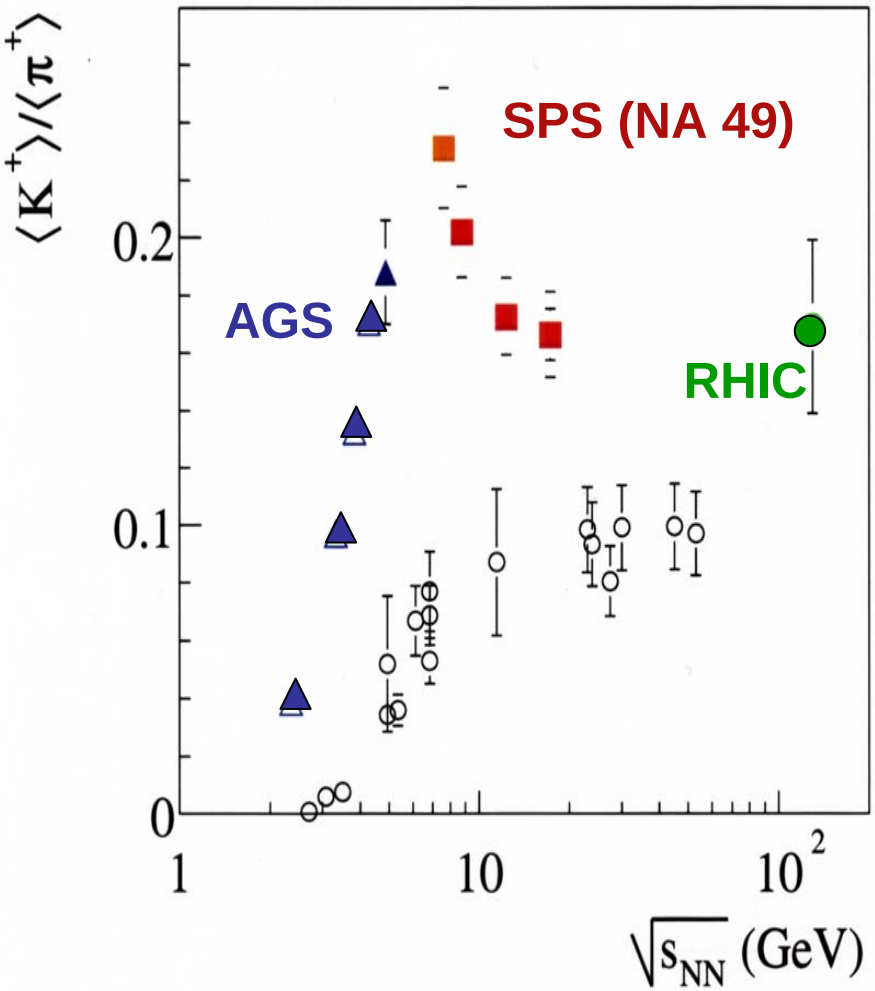


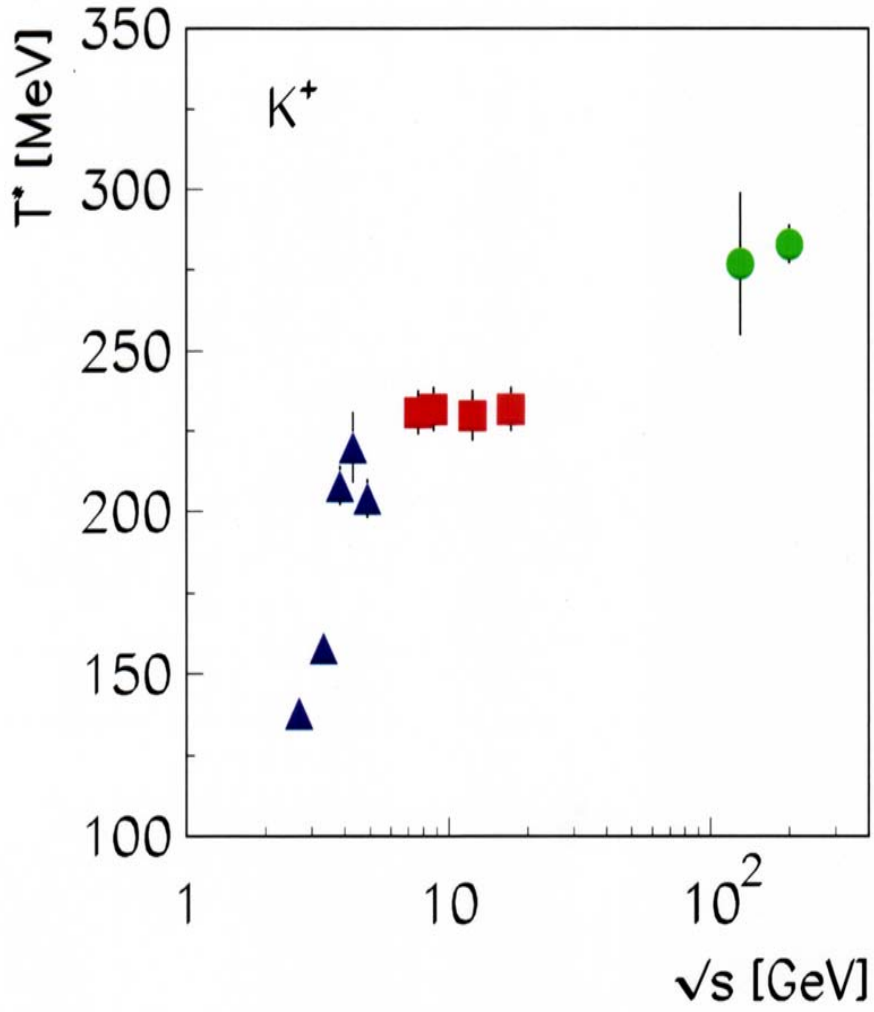
Critical endpoint:
Z. Fodor, S. Katz, hep-lat/0402006
S. Ejiri et al., hep-lat/0312006

Hadron gas EOS:
V.Toneev, Y. Ivanov et al.
nucl-th/0309008

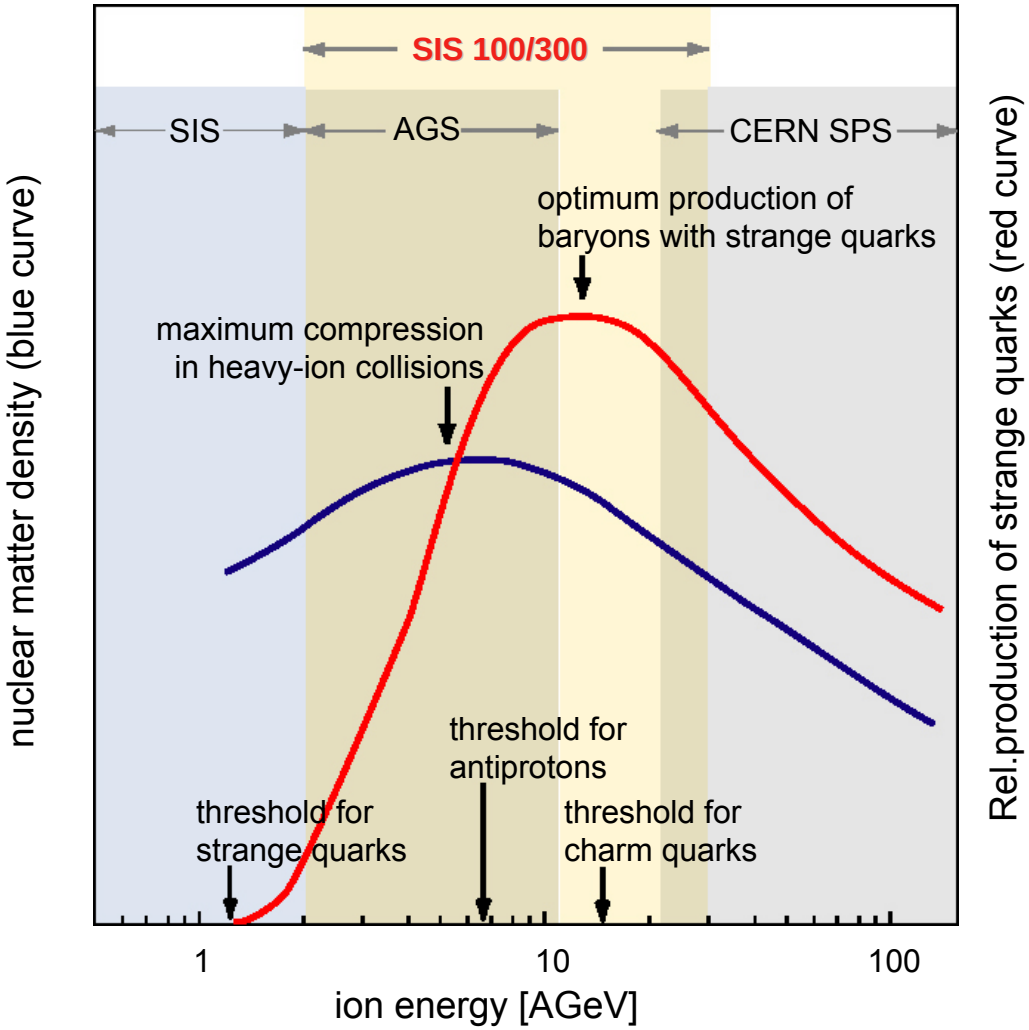


Strangeness Production in Au+Au / Pb+Pb

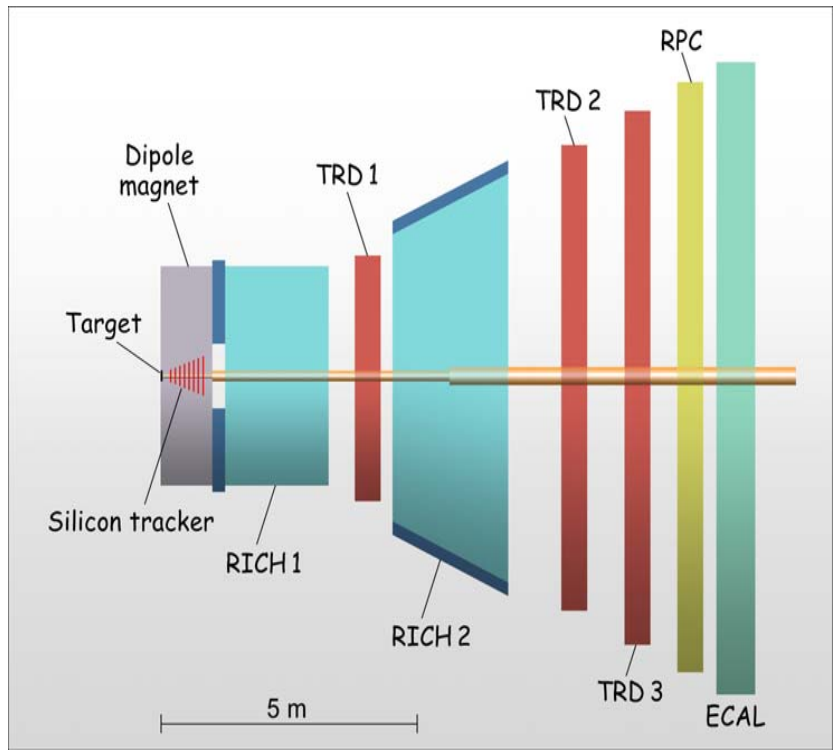




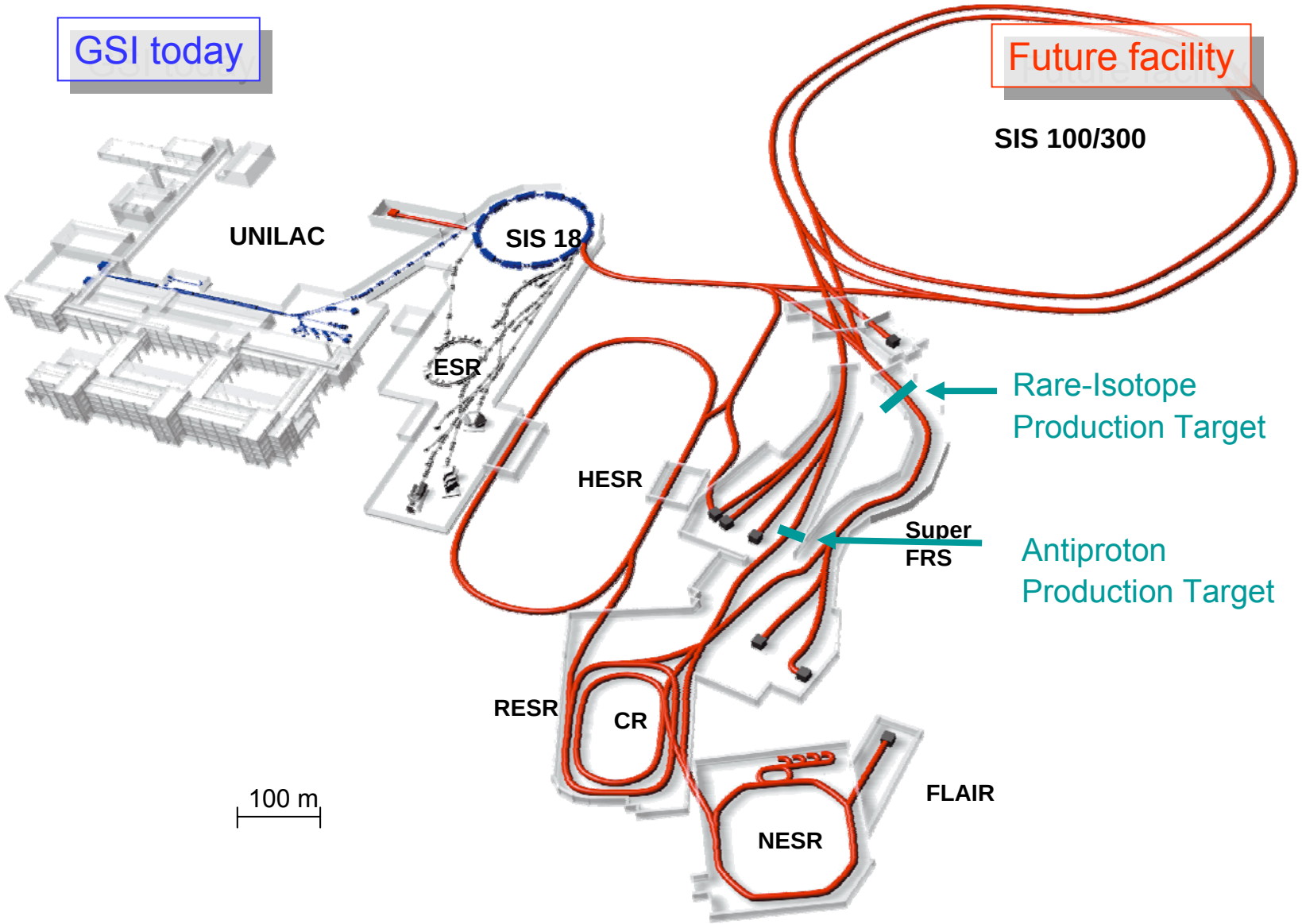
NN Collisions at 2-40 AGeV



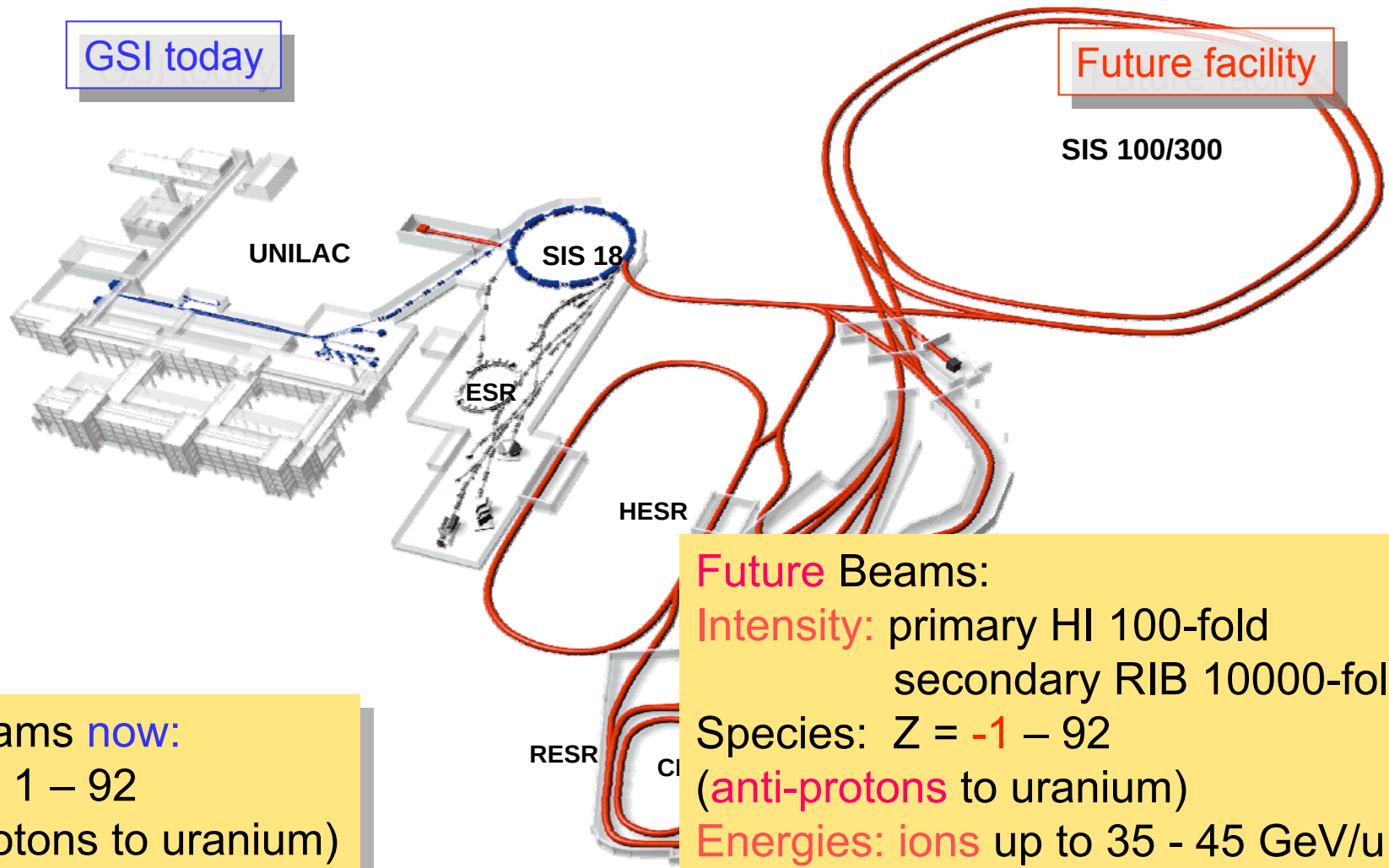
The CBM Experiment at FAIR



FAIR - Facility for Antiproton and Ion Research



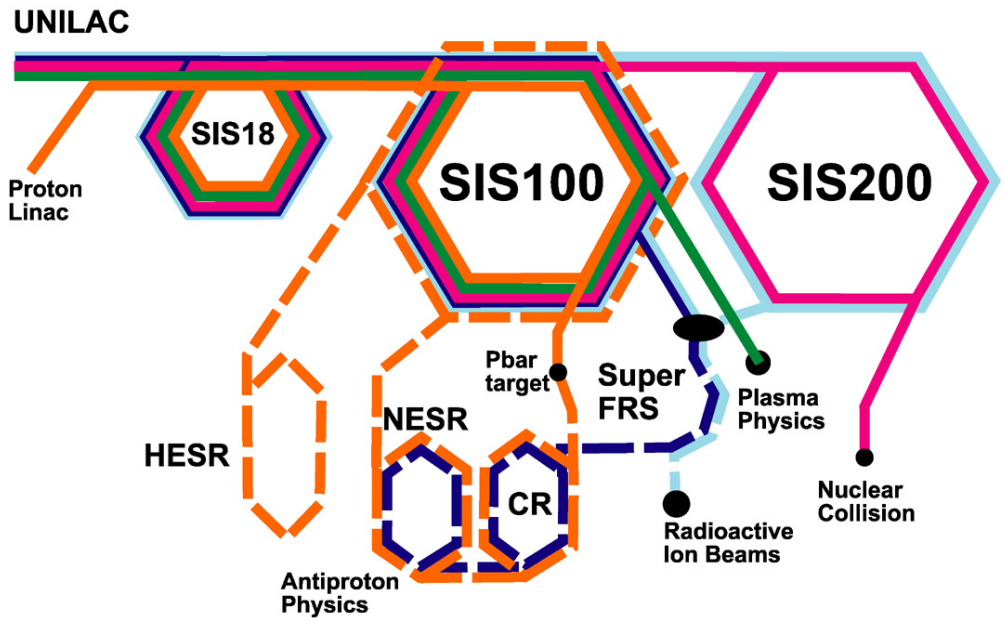
FAIR - Facility for Antiproton and Ion Research



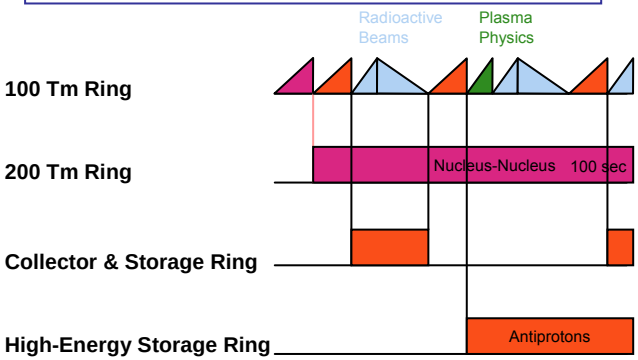
Beams now:
Z = 1 – 92
(protons to uranium)
up to 2 GeV/nucleon
Some beam cooling

Future Beams:
Intensity: primary HI 100-fold
secondary RIB 10000-fold
Species: Z = -1 – 92
(anti-protons to uranium)
Energies: ions up to 35 - 45 GeV/u
antiprotons 0 -15 GeV/c
Precision: full beam cooling

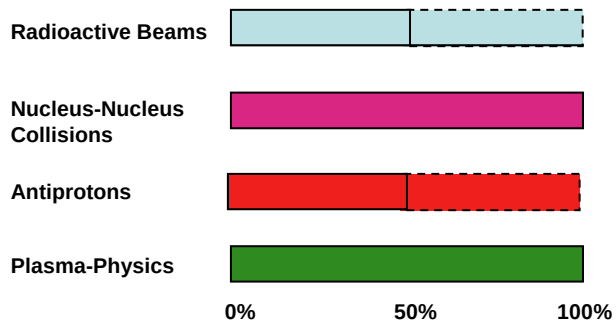
Parallel Operation



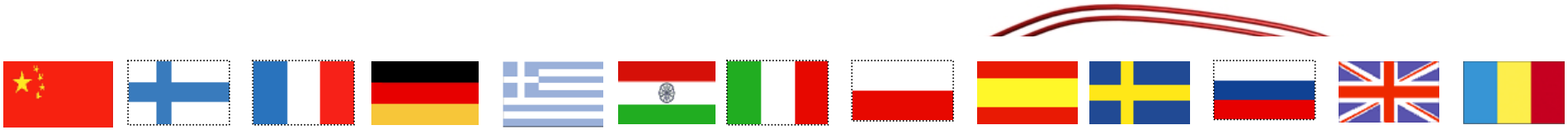
Duty-Cycles of the Accelerator Rings

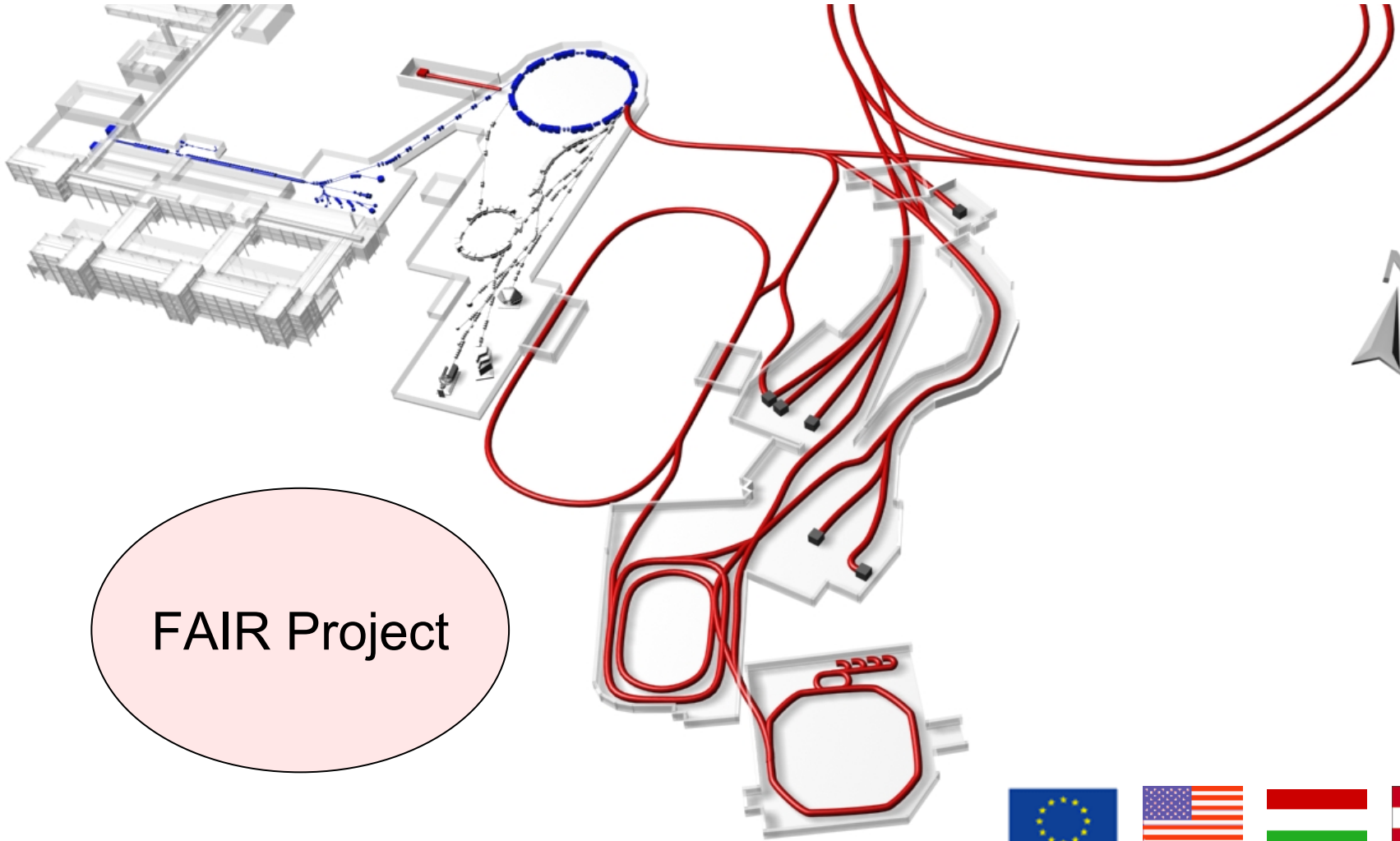


Duty-Cycles of the Physics Programs



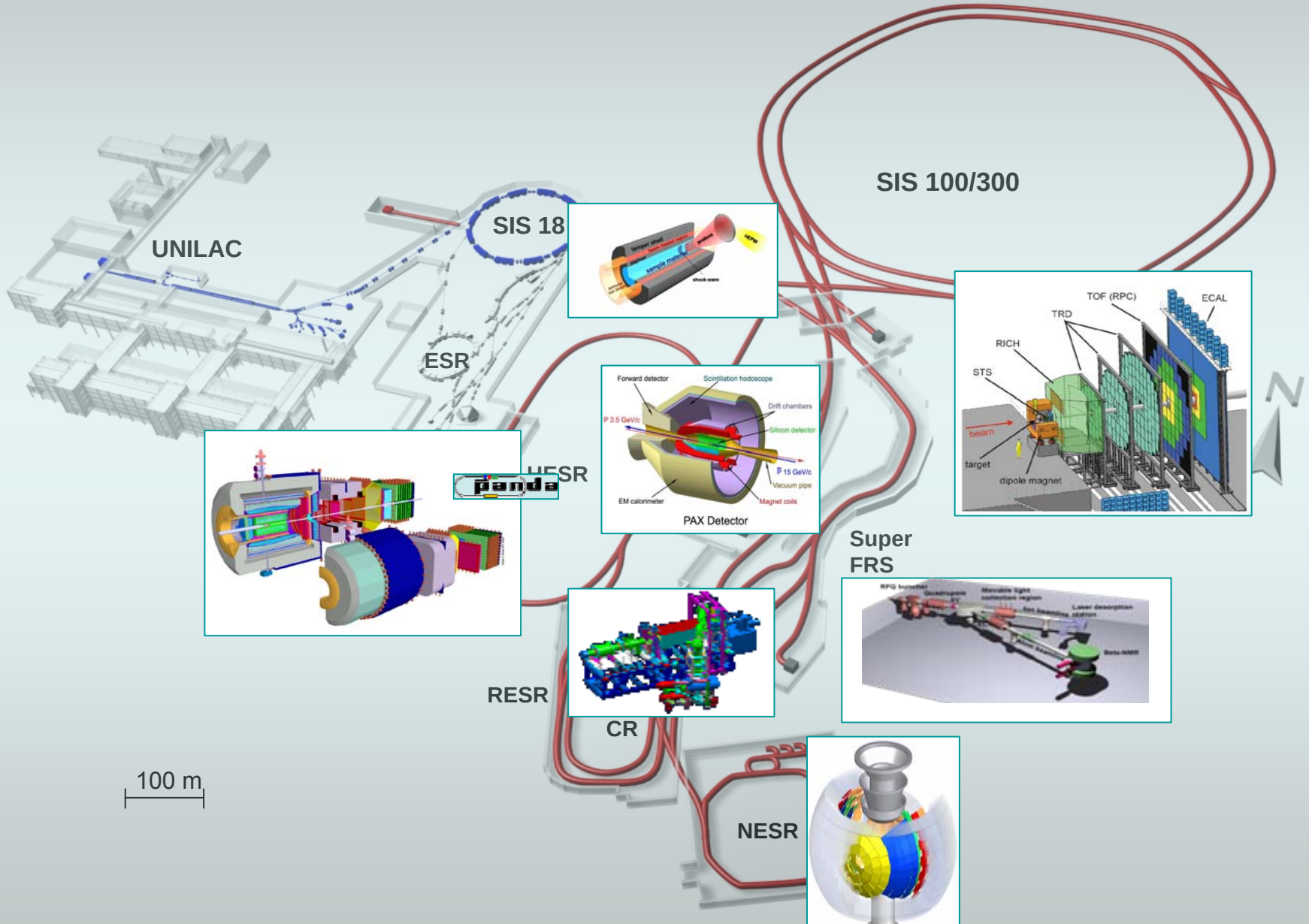
FAIR -- An International Facility for Europe





Observers

FAIR – Planned Experimental Facilities



FAIR Baseline Technical Report 2006

Volume 1: Executive Summary

Volume 2: Technical Report Acc **…structure**
ca. 700 pages

Volume 3: Techn. Experiment
ca. 450 pages

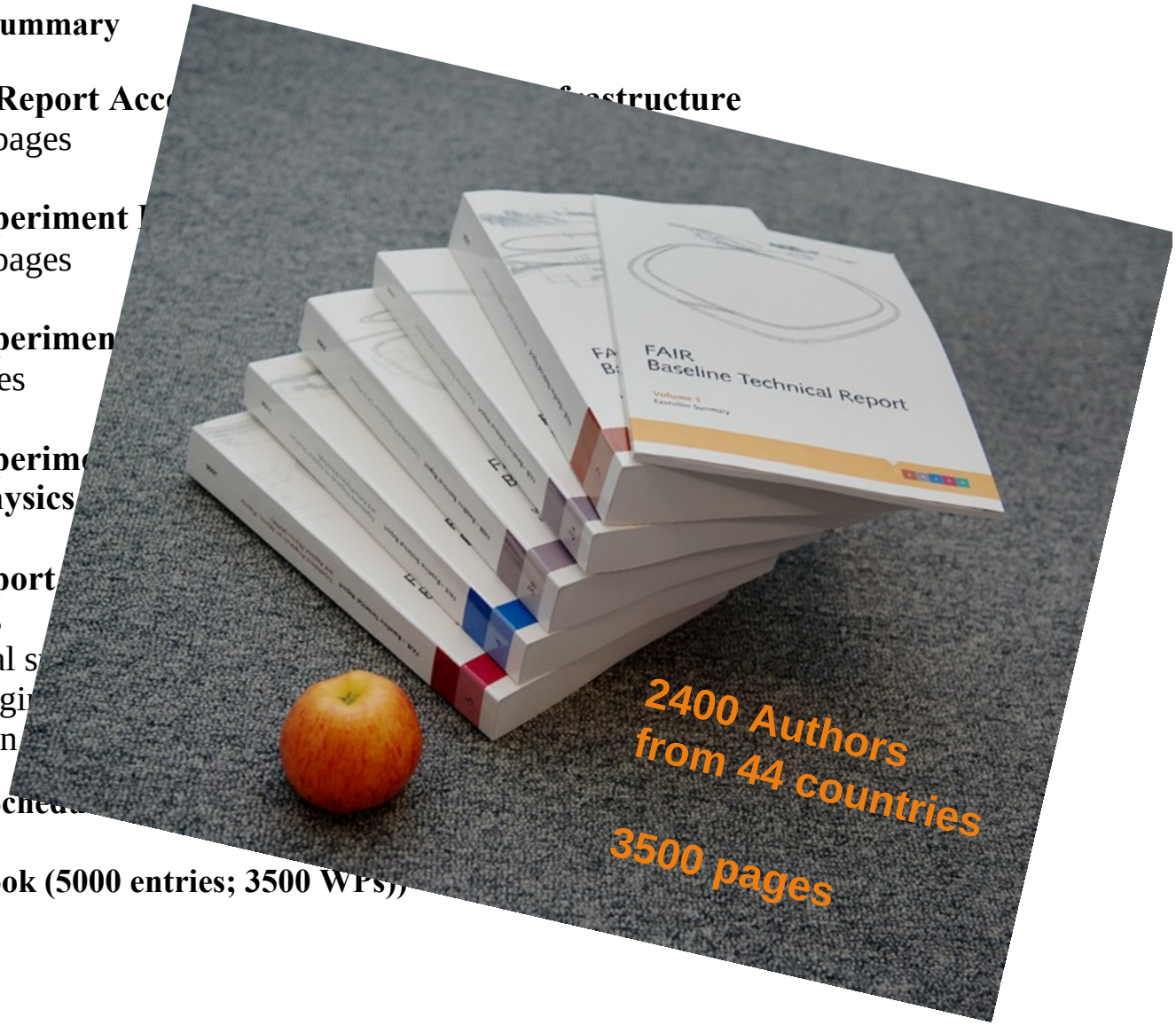
Volume 4: Techn. Experimen
ca. 700 pages

Volume 5: Techn. Experim
Applied Physics

Volume 6: Techn. Report
a. Supplies
b. Electrical s
c. Civil Engi
d. Radiation

Supplement 1: Cost, Sched

Supplement 2: Costbook (5000 entries; 3500 WPs))



Scientific, Technical and Legal Framework for FAIR

ISC
International Steering Committee
H. Schunck

STI Working Group
Scientific + Technical Issues
H. Wenninger

AFI Working Group
Administrative + Funding Issues
Ö. Skeppstedt

FAIR Project

- Baseline Technical Report
  - accelerator TR's
  - experiment proposals
  - civil construction plans

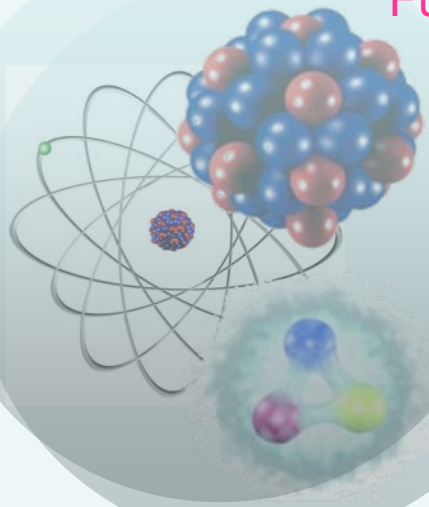
  (~ 3500 pages)
- PAC & TAC Review Reports
- Cost Book
- Cost Review Reports
  - accelerator & civil construction (CORE-A)
  - experiments (CORE-E)

MiniTACs
- Cryogenics
- Warm and Cold magnets
- Power Supplies
- Beam Instrumentation
- p-Linac

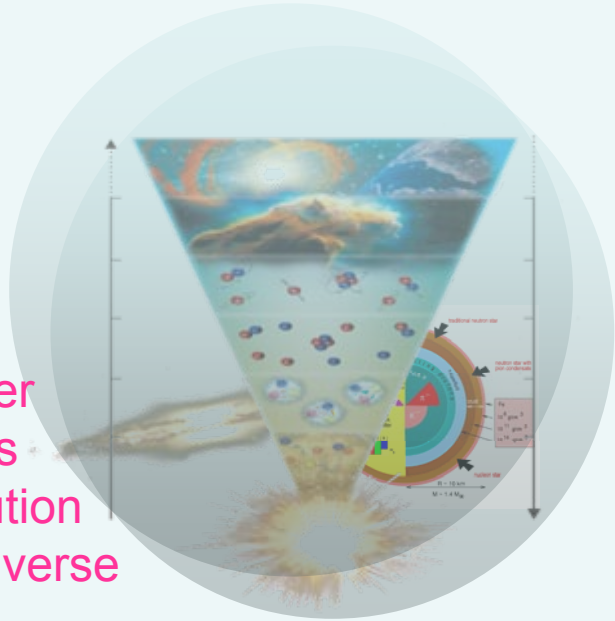
- Convention
- Articles of Association
- By-Laws
- Final Act Document
- Legal Framework Report (LFI)
- Full Cost Structure Report (FCI)

Observers:

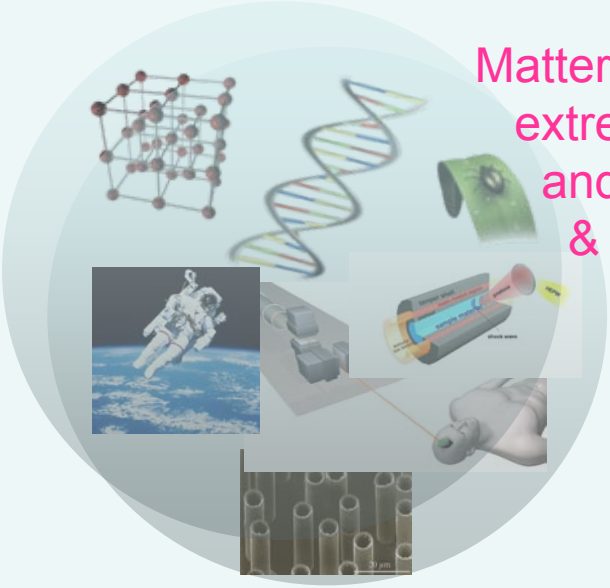
Highest Intensity Precision Beams of Energetic Ions



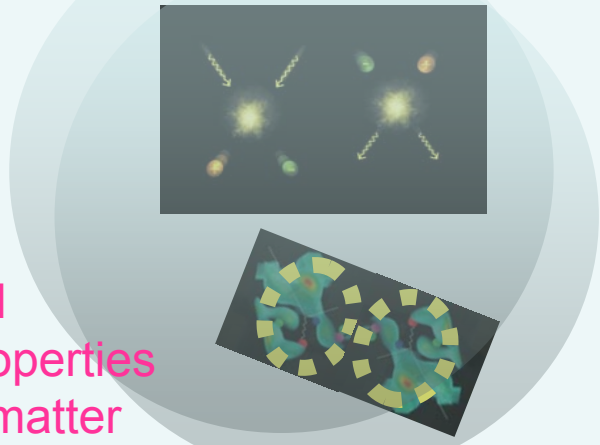
Fundamental Research
into the microscopic
structure of matter



Creation of matter
nucleosynthesis
and the evolution
of the Universe



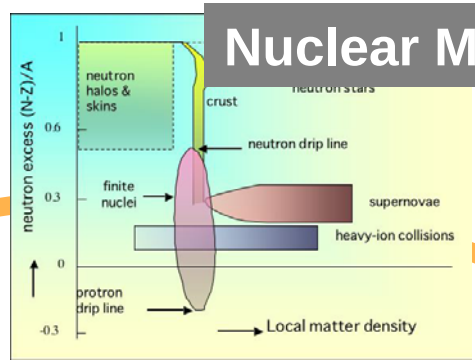
Matter in
extreme states
and material studies
& applications



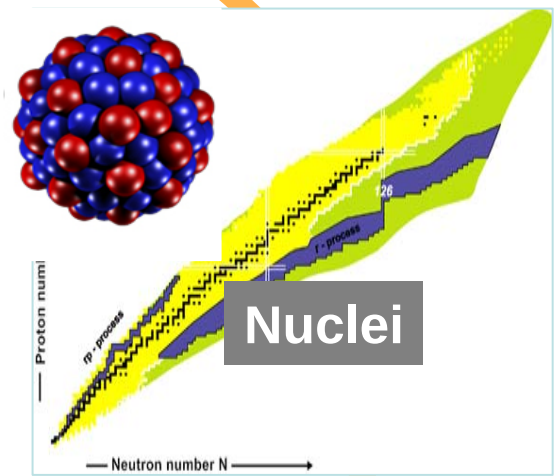
Structure and
fundamental properties
of anti-matter

Quark Matter

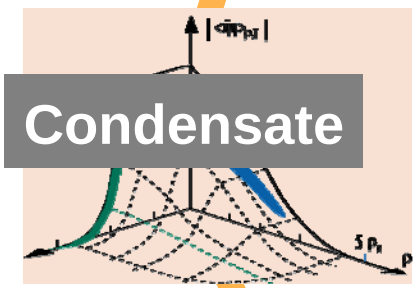
Nuclear Matter



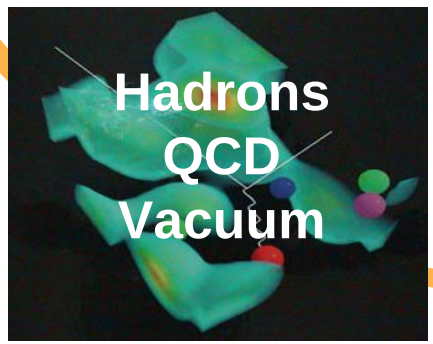
Nuclei



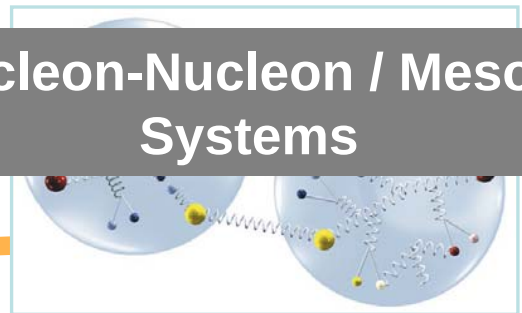
Condensate



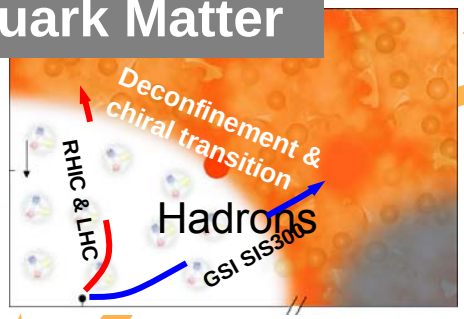
Hadrons
QCD
Vacuum



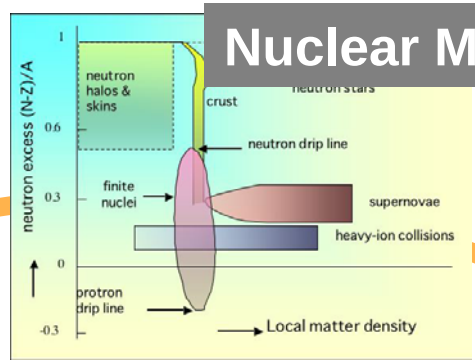
Nucleon-Nucleon / Meson Systems



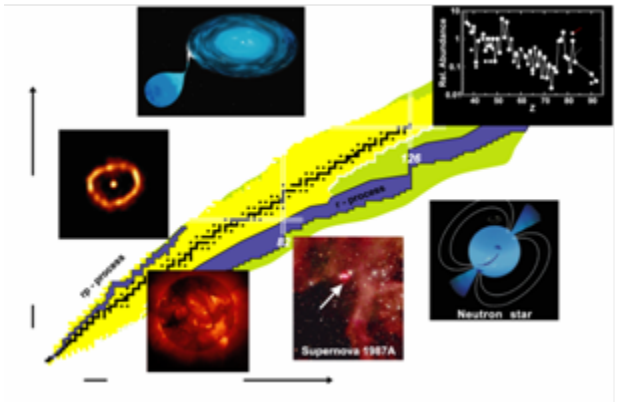
Quark Matter



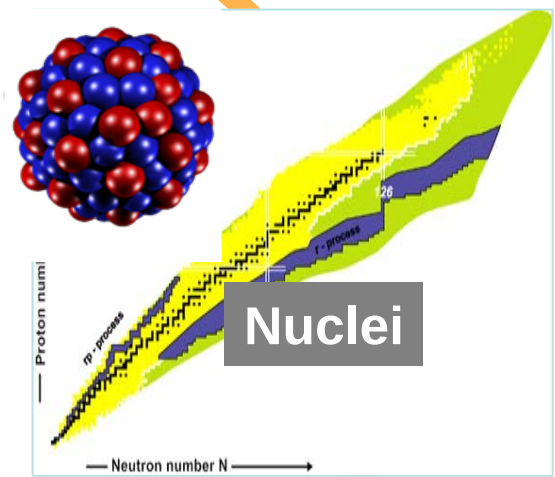
Nuclear Matter



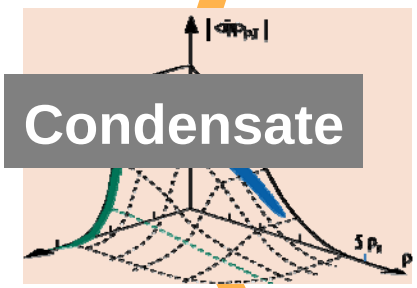
Nuclear Astrophysics



Nuclei

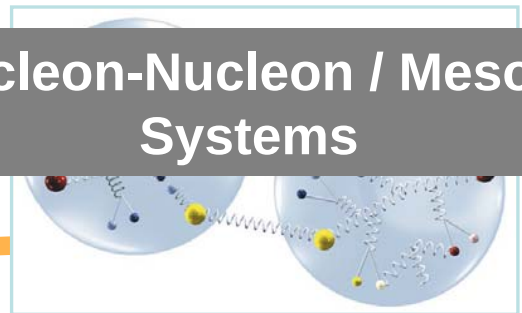


Condensate



Hadrons
QCD
Vacuum

Nucleon-Nucleon / Meson Systems



Nuclear Matter

Quark Matter

Symmetries

Nuclear Astrophysics

Condensate

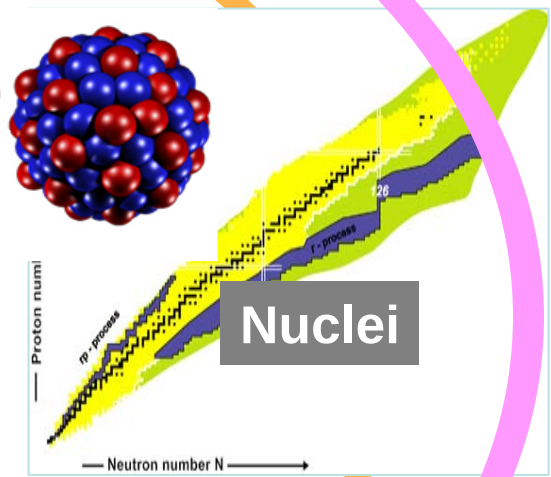
Nuclei

Hadrons
QCD
Vacuum

Nucleon-Nucleon / Meson Systems

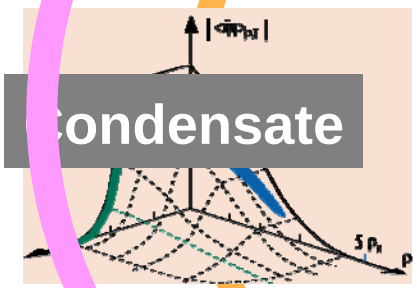
Nuclear Matter

Quark Matter



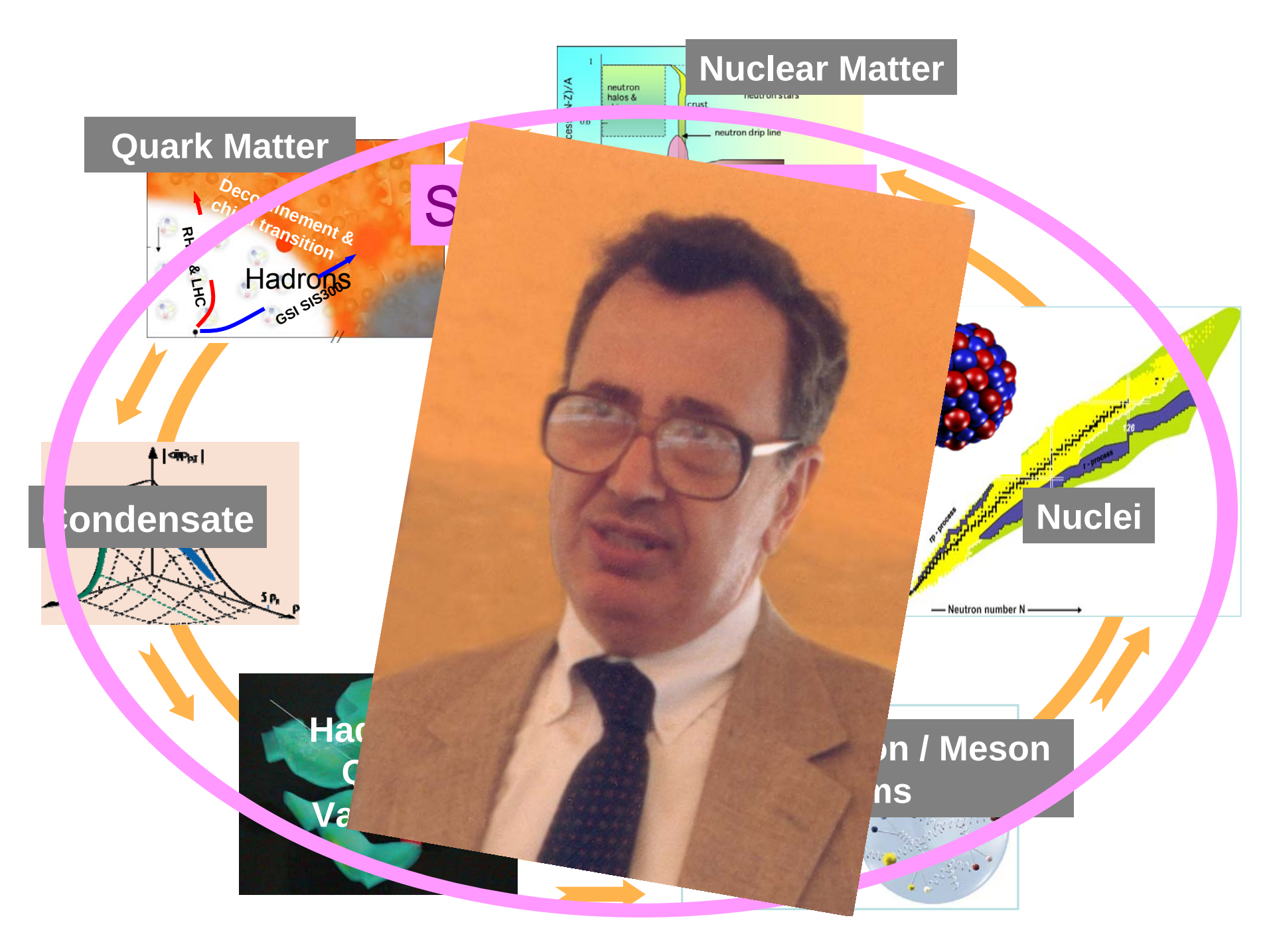
Nuclei

ondensate

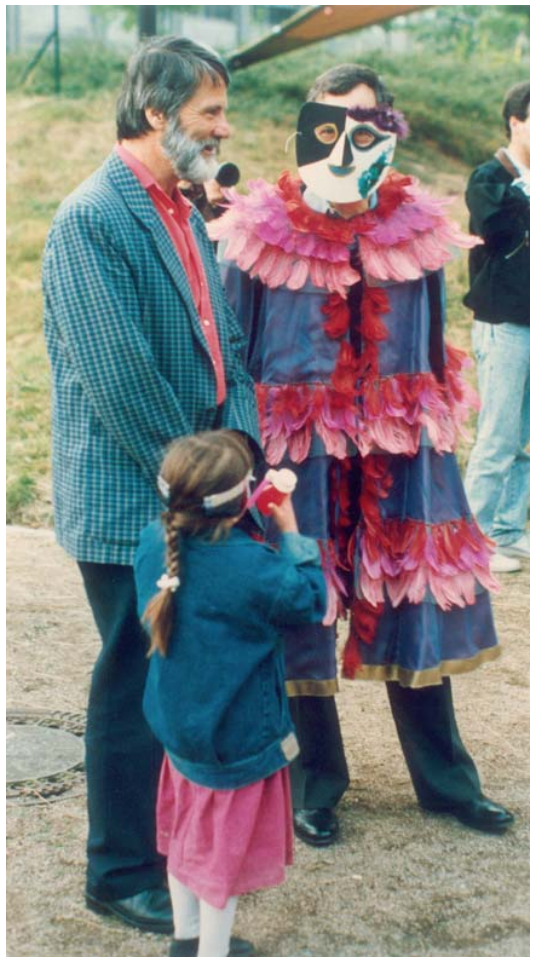


Hadron
QCD
Vacuun

on / Meson
ns


Nuclear Matter
neutron drip line
Quark Matter
Hadrons
GSI SIS300
Nuclei
Neutron number N
Condensate

Thank you
for your attention !!!




CHICAGO