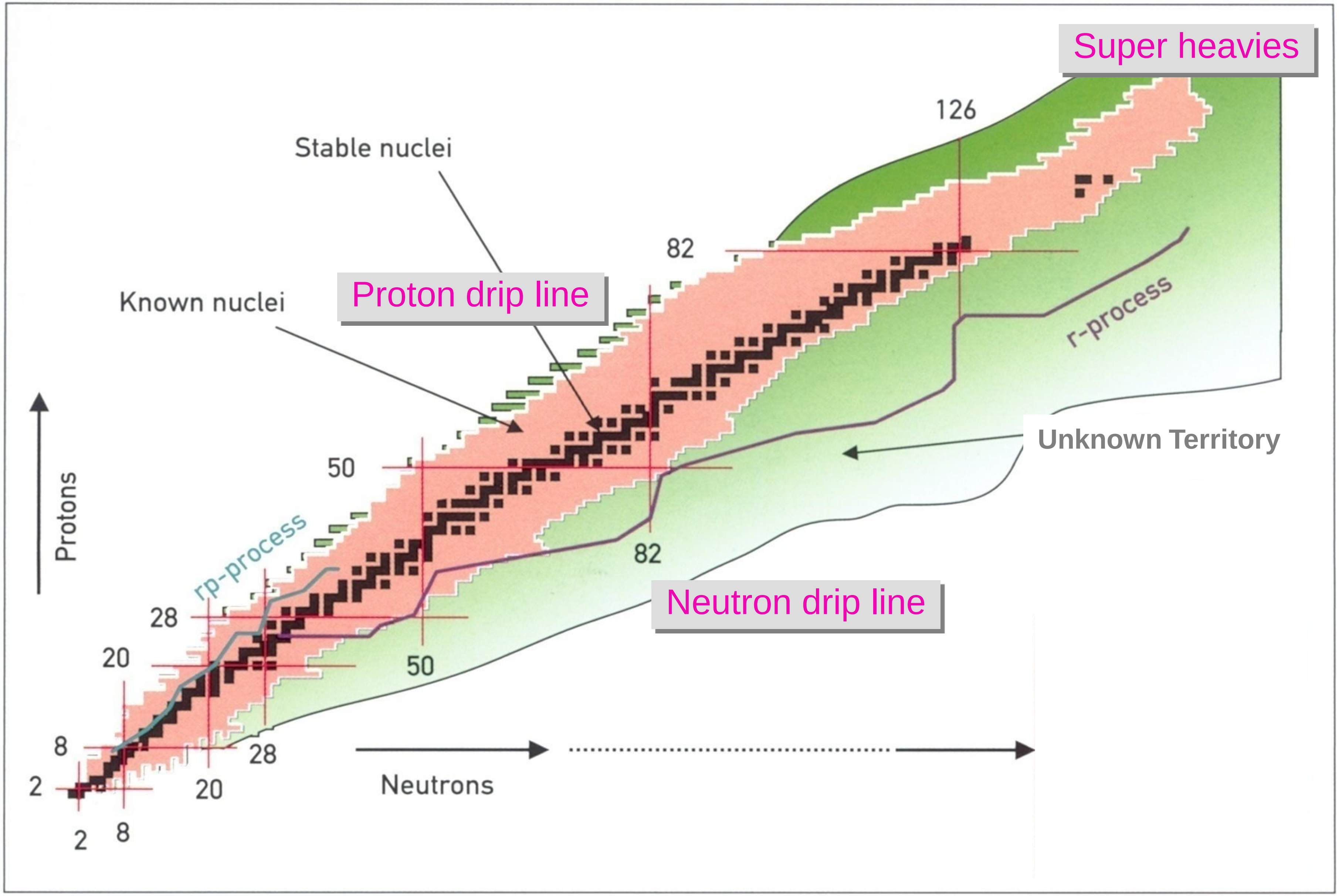
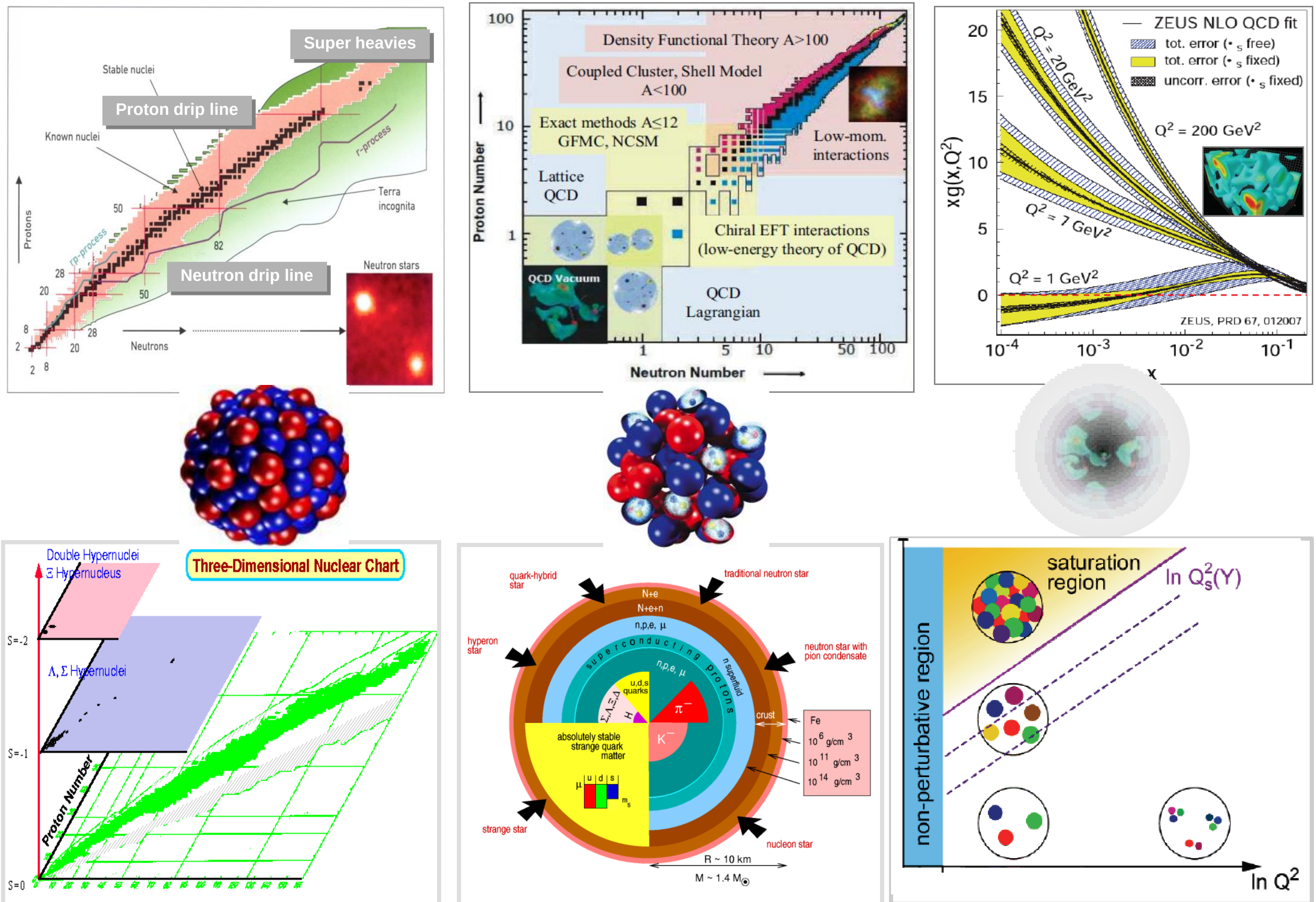
Towards the Extremes of the Nuclear Landscape

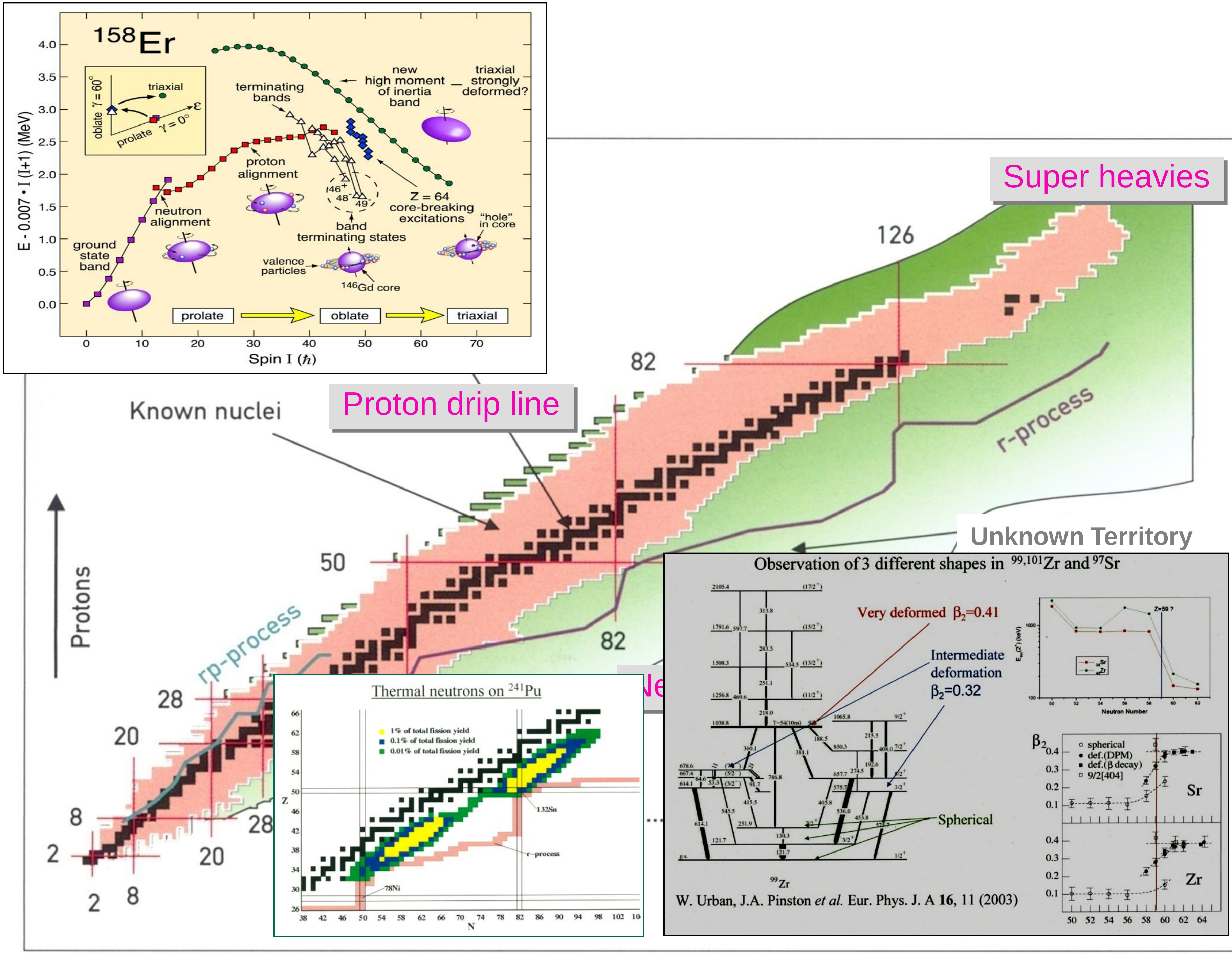
Walter F. Henning - RIKEN Nishina Center



Super heavies
126
Stable nuclei
82
Proton drip line
Known nuclei
r-process
Unknown Territory
50
82
Protons
rp-process
28
Neutron drip line
20
50
8
28
2
20
Neutrons
2
8



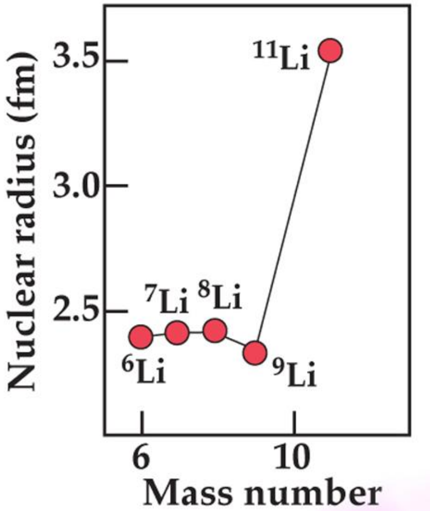
Super heavies
Stable nuclei
Proton drip line
Known nuclei
r-process
Terra incognita
rp-process
Neutron drip line
Neutron stars
Protons
Neutrons
Density Functional Theory A>100
Coupled Cluster, Shell Model A<100
Exact methods A≤12 GFMC, NCSM
Low-mom. interactions
Lattice QCD
Chiral EFT interactions (low-energy theory of QCD)
QCD Vacuum
QCD Lagrangian
Proton Number
Neutron Number
ZEUS NLO QCD fit
tot. error (α s free)
tot. error (α s fixed)
uncorr. error (α s fixed)
Q^2 = 20 GeV^2
Q^2 = 200 GeV^2
Q^2 = 7 GeV^2
Q^2 = 1 GeV^2
ZEUS, PRD 67, 012007
$xg(x,Q^2)$
x
Double Hypernuclei
Ξ Hypernucleus
Three-Dimensional Nuclear Chart
Λ, Σ Hypernuclei
S=-2
S=-1
S=0
Proton Number
quark-hybrid star
traditional neutron star
hyperon star
neutron star with pion condensate
N+e
N+e+n
n,p,e, μ
superconducting protons
n superfluid
n,p,e, μ
u,d,s quarks
crust
Fe
10^6 g/cm^3
10^{11} g/cm^3
10^{14} g/cm^3
absolutely stable strange quark matter
strange star
nucleon star
R ~ 10 km
M ~ 1.4 M$_\odot$
saturation region
ln $Q_s^2(Y)$
non-perturbative region
ln Q^2

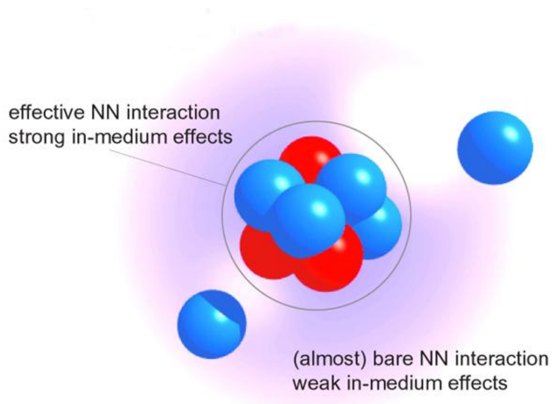


158Er
E - 0.007 • I (I+1) (MeV)
Spin I (ħ)
triaxial
oblate γ = 60°
prolate γ = 0°
ε
ground state band
neutron alignment
proton alignment
terminating bands
new high moment of inertia band
triaxial strongly deformed?
Z = 64 core-breaking excitations
band terminating states
"hole" in core
valence particles
146Gd core
prolate
oblate
triaxial
Super heavies
Proton drip line
Known nuclei
Unknown Territory
Protons
rp-process
r-process
126
82
50
28
20
8
2
Thermal neutrons on 241Pu
1% of total fission yield
0.1% of total fission yield
0.01% of total fission yield
Z
N
132Sn
78Ni
r-process
Observation of 3 different shapes in 99,101Zr and 97Sr
Very deformed β2=0.41
Intermediate deformation β2=0.32
Spherical
99Zr
Neutron Number
spherical
def.(DPM)
def.(β decay)
9/2[404]
Sr
Zr
W. Urban, J.A. Pinston et al. Eur. Phys. J. A 16, 11 (2003)

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

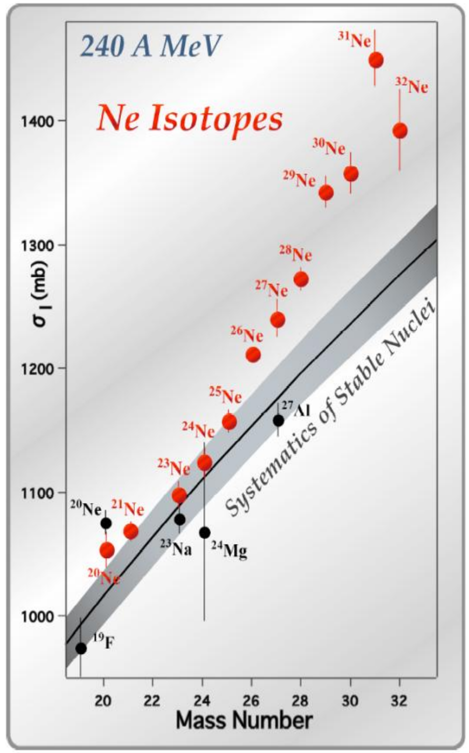
Transmission & Interaction Cross Section Measurement



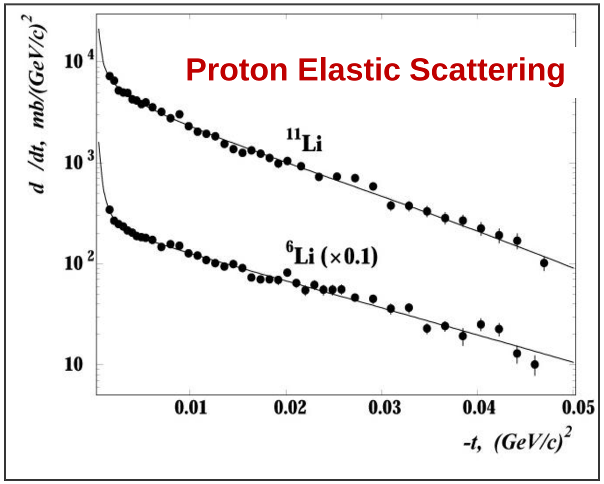


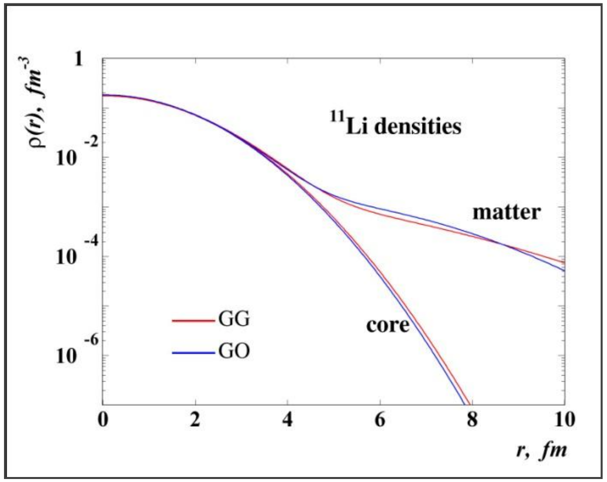
M. Takechi et al., Nucl. Phys. A 834 (2010) 412
(RIKEN RIBF)

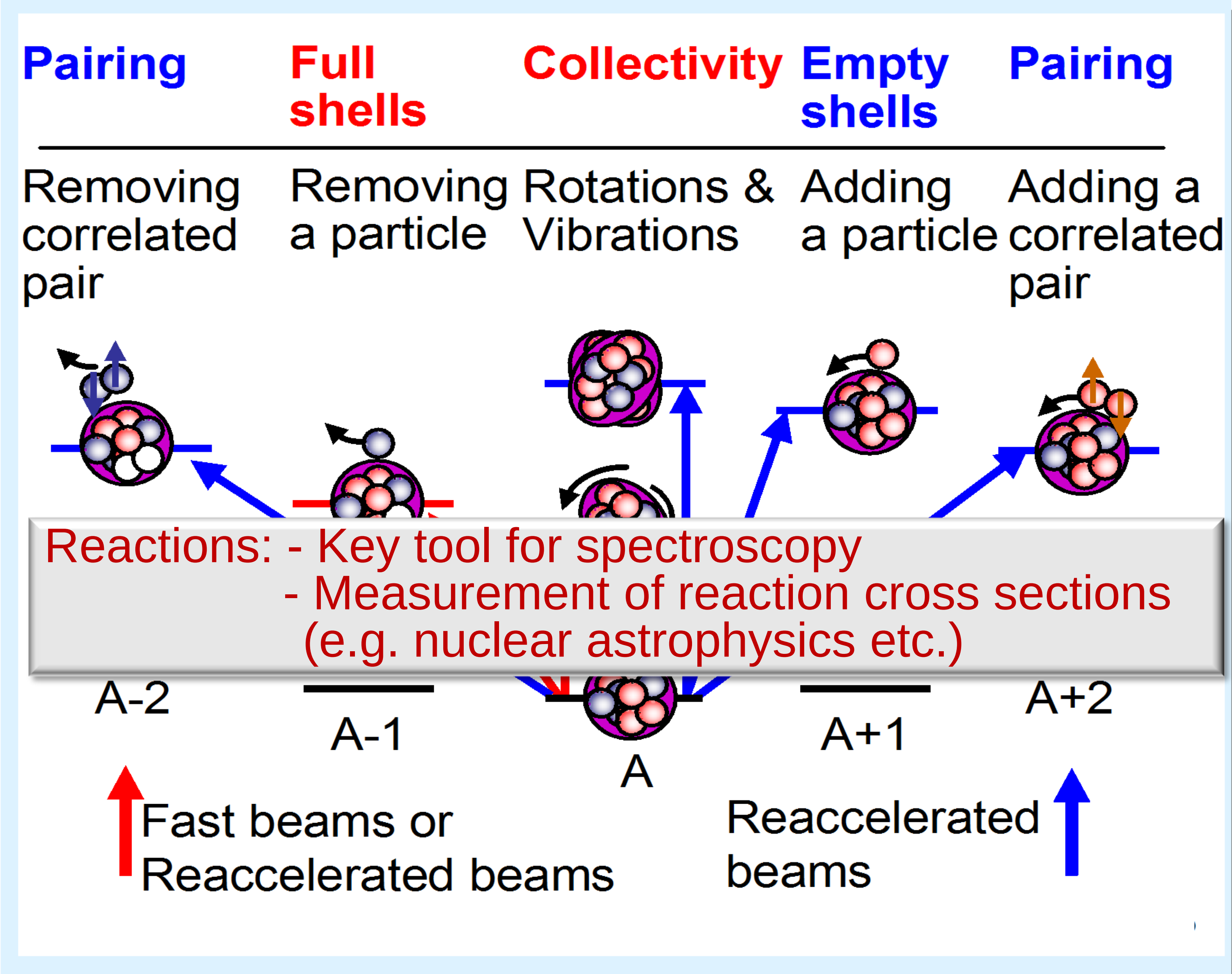
Transmission & Interaction Cross Section Measurement



IKAR Collaboration (GSI SIS18):
G.D. Alkhazov et al., Nucl. Phys. A 712 (2002) 269
P. Egelhof et al., Eur. Phys. J. A 15 (2002) 27
A. Dobrovolsky et a., Nucl. Phys. A 766 (2006) 1

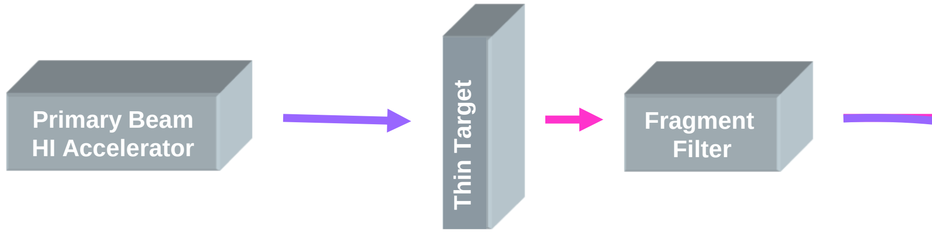


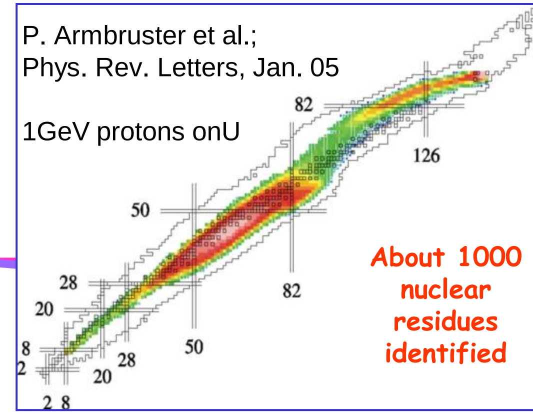



Pairing
Full shells
Collectivity
Empty shells
Pairing
Removing correlated pair
Removing a particle
Rotations & Vibrations
Adding a particle
Adding a correlated pair
Reactions: - Key tool for spectroscopy
- Measurement of reaction cross sections
(e.g. nuclear astrophysics etc.)
A-2
A-1
A
A+1
A+2
Fast beams or
Reaccelerated beams
Reaccelerated
beams

Production Methods for Radioactive Beams

In-Flight Reactions

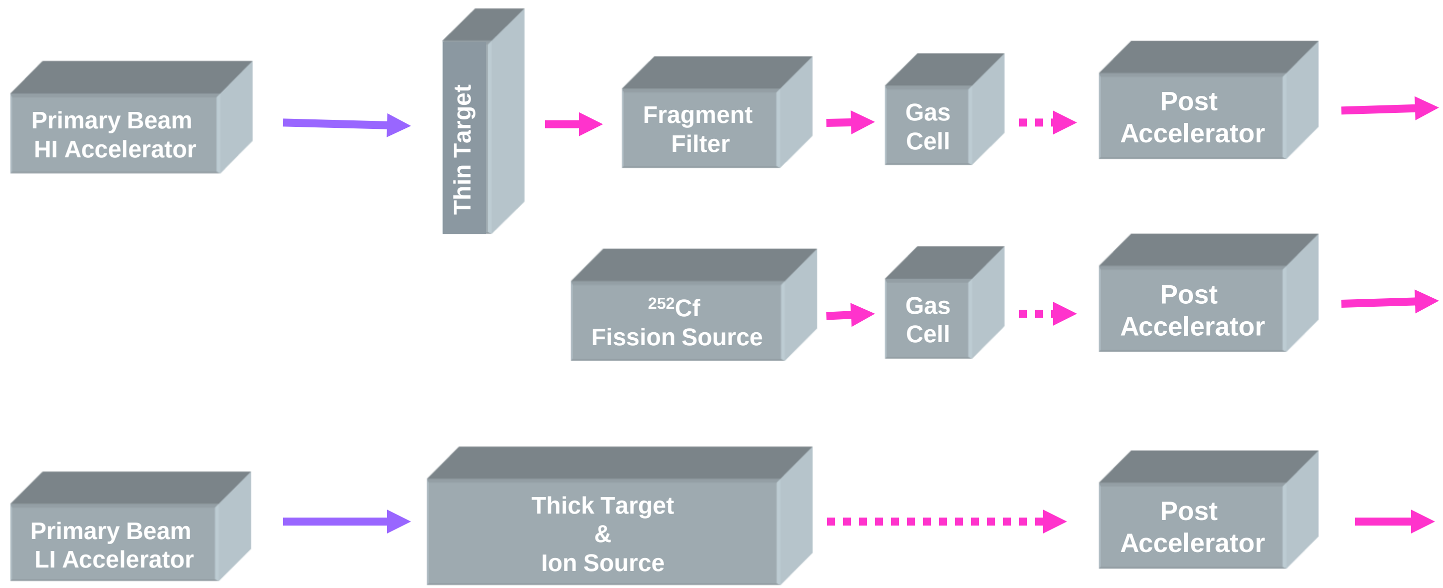




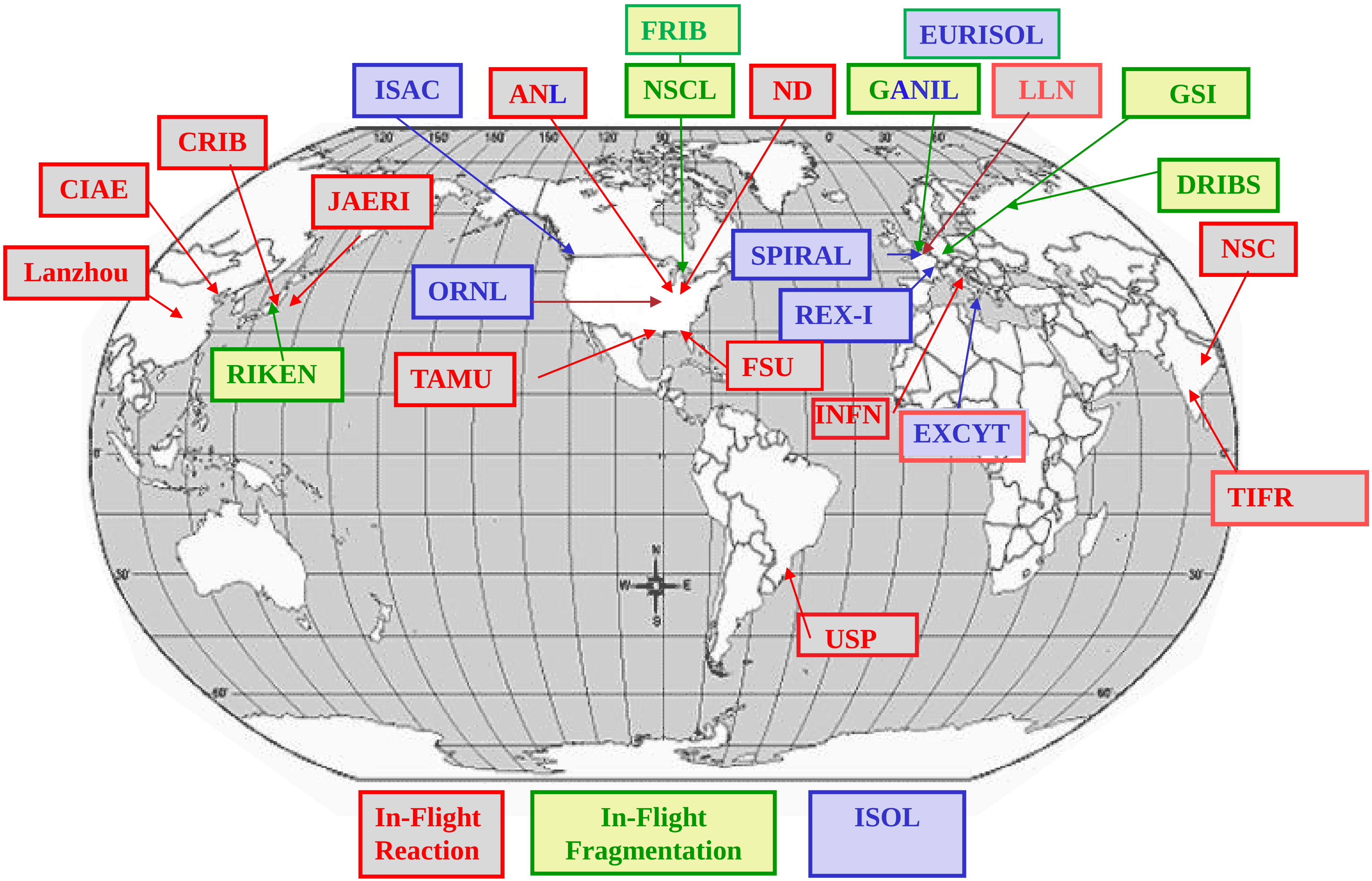
- High-energy fragmentation
- Low-energy reactions

Cross section	Target	Yield curve	Reaction channels	Phase space reduction
large (b)	thick (g)	saturates	many (1000)	passive
medium (~ few mb)	thin (mg)	linear	few (~5-10)	active

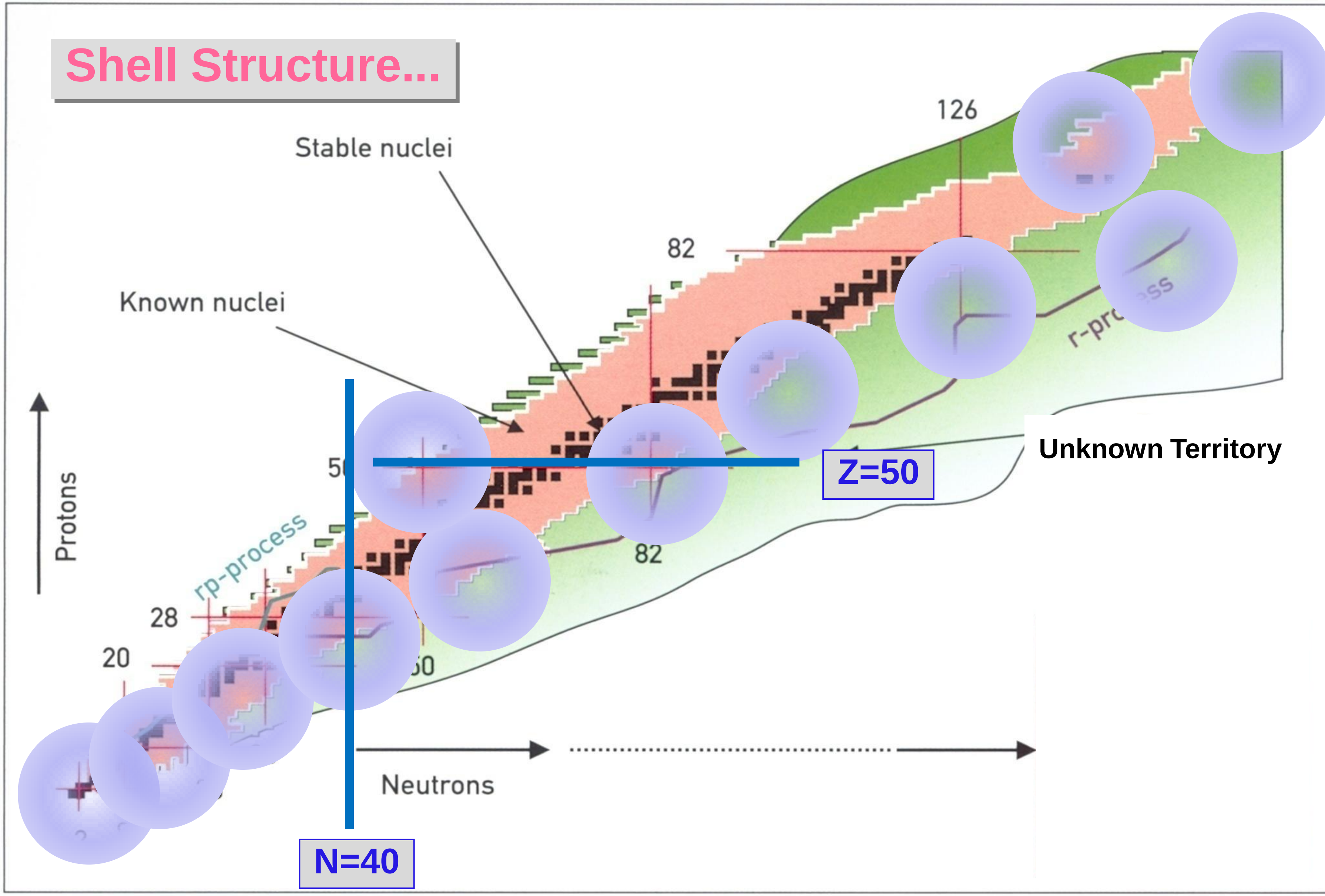
Stopping & Re-acceleration (ISOL)



RNB Production Facilities



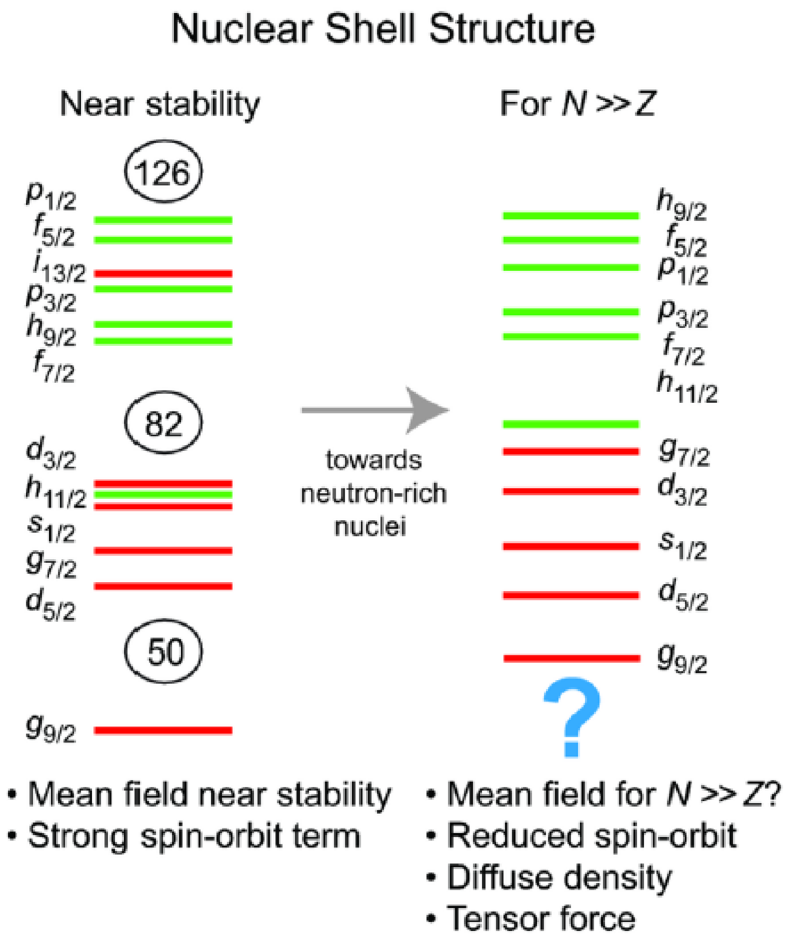
Shell Structure...



5 next slides:

A. Gade INPC2010

Driving forces for shell evolution in neutron-rich nuclei



- Spin-isospin parts of the NN interaction

  T. Otsuka et al., PRL 87, 082502 (2001)

  - Particularly the monopole parts of the tensor force

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

Also

- Central part
- 3N force

play important roles

T. Otsuka et al., PRL 104, 012501 (2010)
T. Otsuka, et al., PRL, in press arXiv:0908.2607

Weak binding:

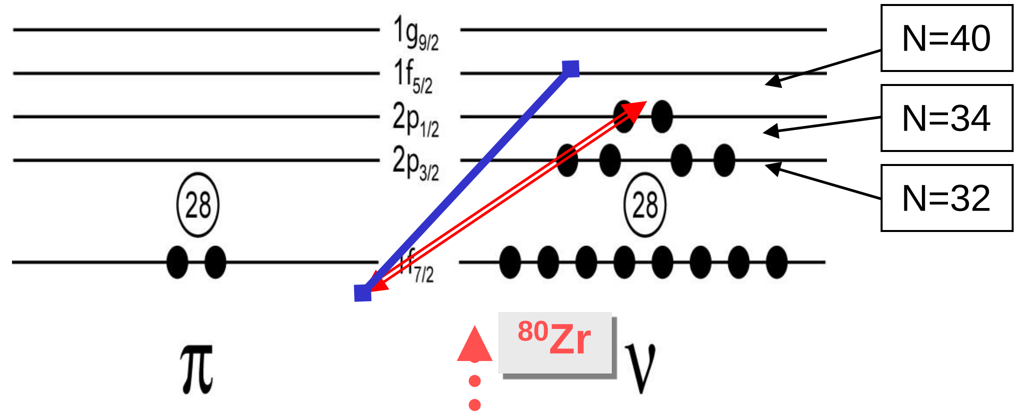
- Density dependent spin-orbit force
- Coupling to the continuum

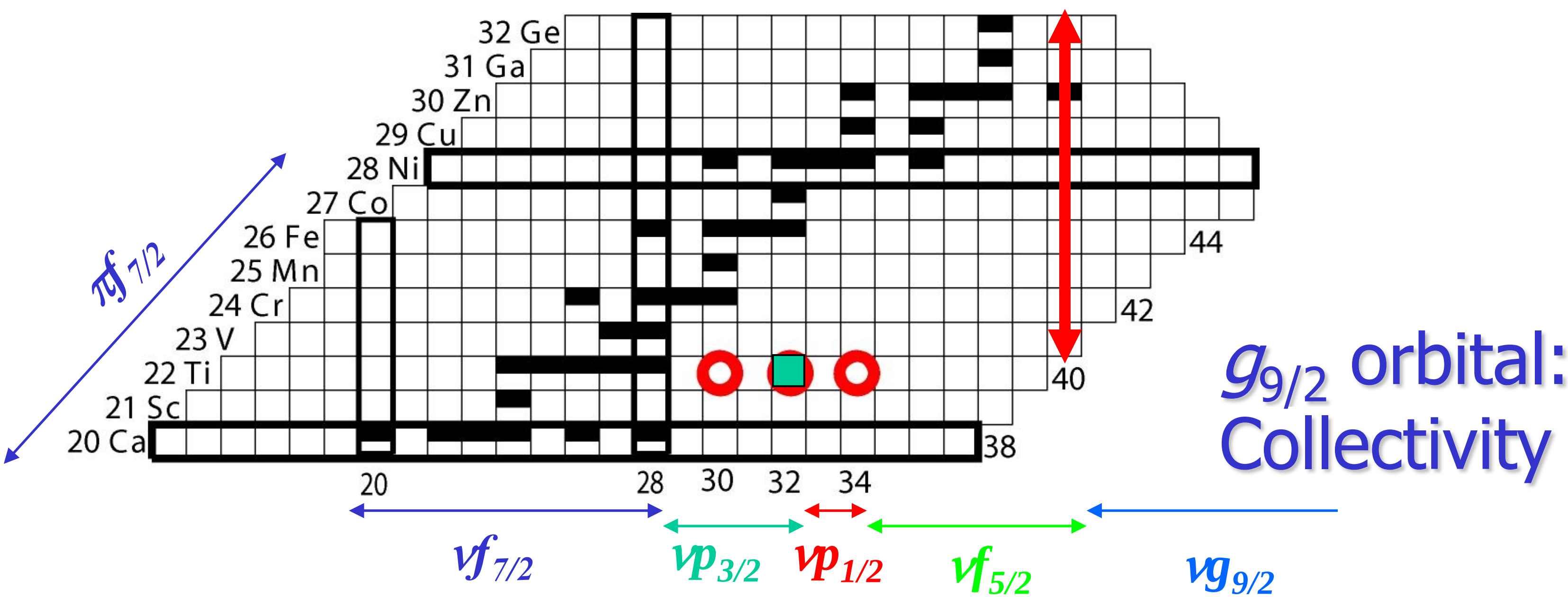
J. Dobaczewski et al., PPNP 59, 432 (2007)

Impacts of tensor force

As protons are removed from the $\pi f_{7/2}$ shell, the monopole pairing interaction weakens:

- $\pi f_{7/2} - \nu f_{5/2}$: attractive, $\nu f_{5/2}$ pushes up in energy
- $\pi f_{7/2} - \nu g_{9/2}$: repulsive, $\nu g_{9/2}$ comes down in energy

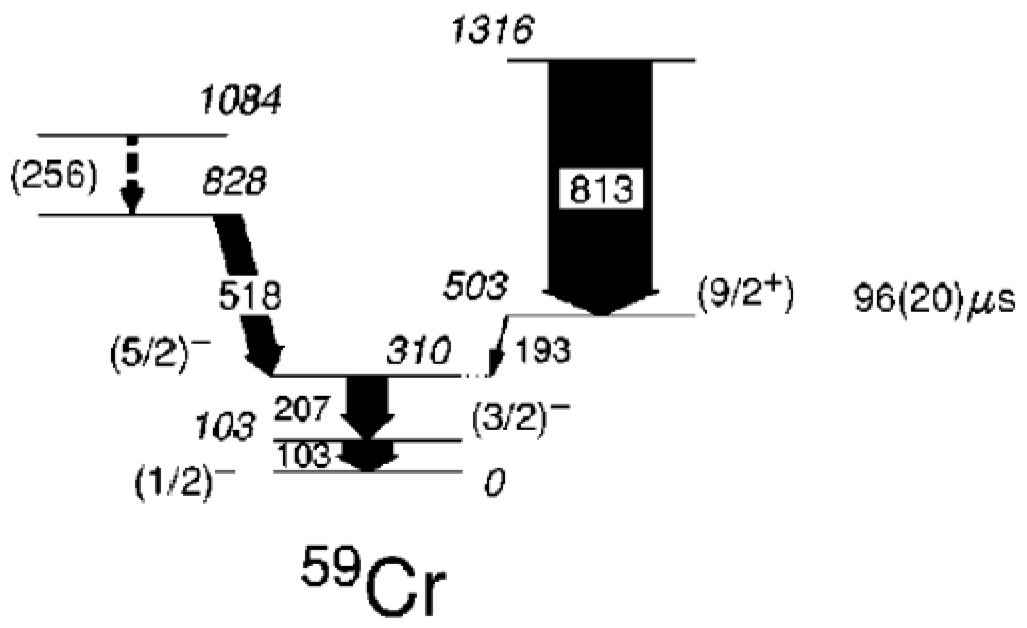




1) T. Otsuka *et al.*, Phys. Rev. Lett. 87 (2001),
2) T. Otsuka *et al.*, Phys. Rev. Lett. 104 (2010), 012501.

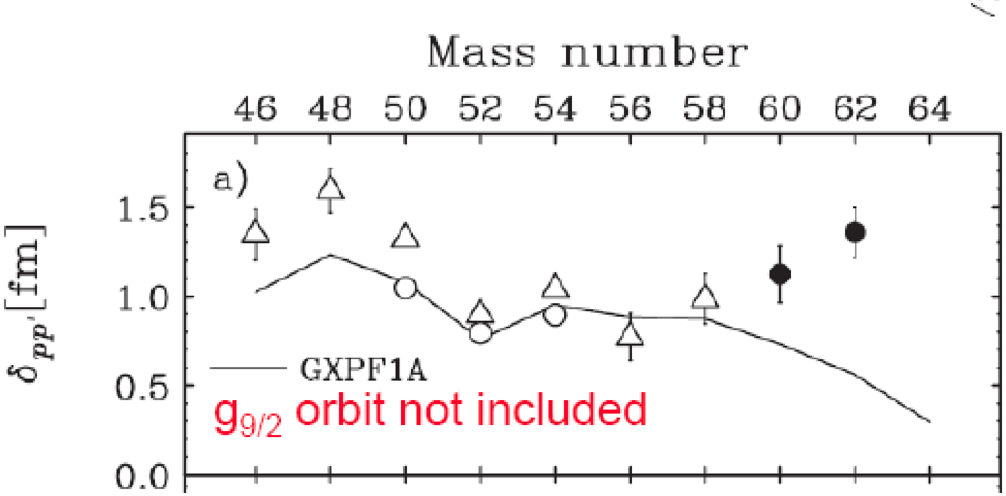
Neutron-rich *N=40*

- Beta decay to ^{64,66}Fe at CERN/ISOLDE [M. Hannawald *et al.*, PRL 82, 1391 (1999)]
- Beta decay to $^{60-63}$Cr (GANIL) [O. Sorlin *et al.*, EPJ A 16, 55 (2003)]
- Rotational band built on $9/2^+$ in ^{55,57}Cr (ANL) [A. Deacon *et al.*, PLB 622, 151 (2005)]
- Low-lying $9/2^+$ isomer in ^{59}Cr (ANL) at 503 keV with possibly oblate deformation [S. J. Freeman *et al.*, PRC 69, 064301 (2005)]
- Large deformation of ^{62}Cr (RIKEN) [N. Aoi *et al.*, J. Phys.: Conf. Ser. 49, 190 (2006), PRL 102, 012502 (2009)]

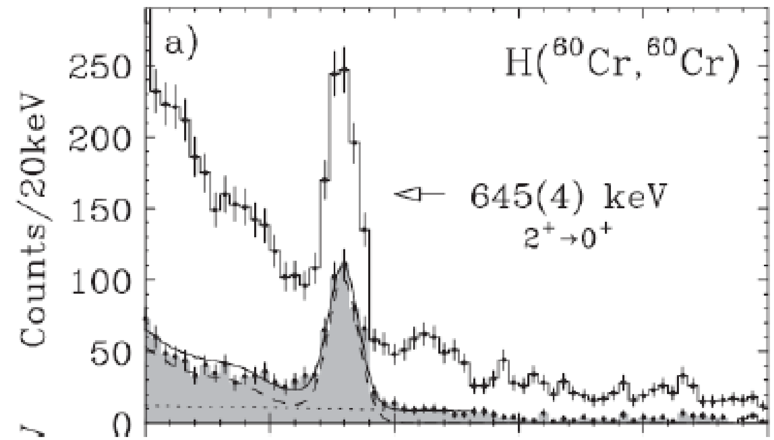


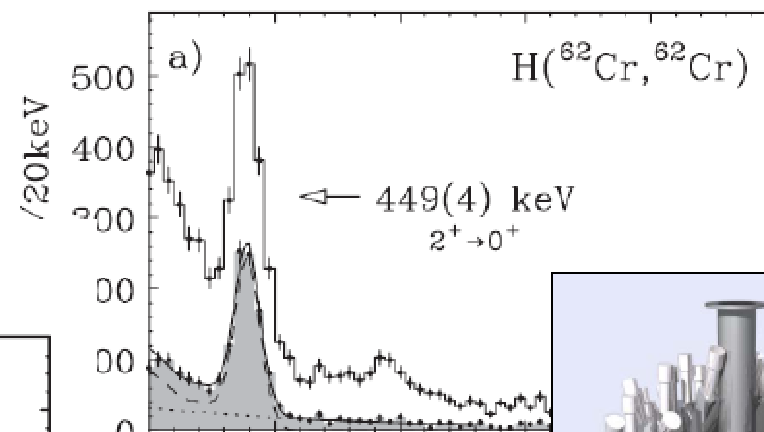
Collectivity in neutron-rich Cr

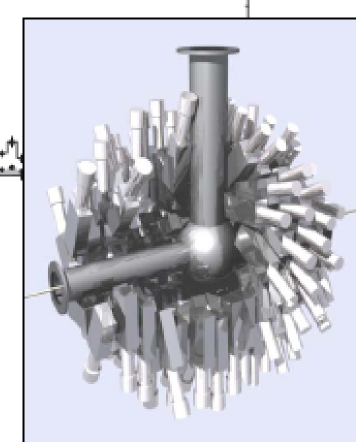
- ^{60,62}Cr produced by fragmentation of stable ^{70}Zn beam at 63 MeV/u
- Inelastic proton scattering induced by a LH_2 target, γ-ray detected in NaI array DALI2 and scattered Cr in a TOF spectrometer (TOMBEE)
- Deformation length deduced from angle-integrated cross sections, σ(2⁺), in comparison to CC calculations
- Data not described by models without neutron $g_{9/2}$ orbit



N. Aoi et al., PRL 102, 012502 (2009) - **RIKEN**

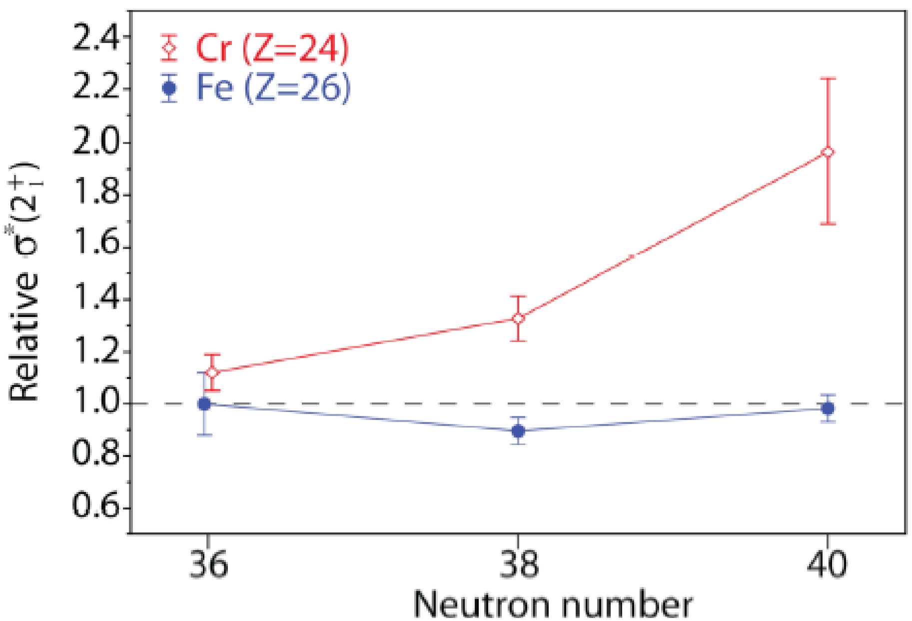




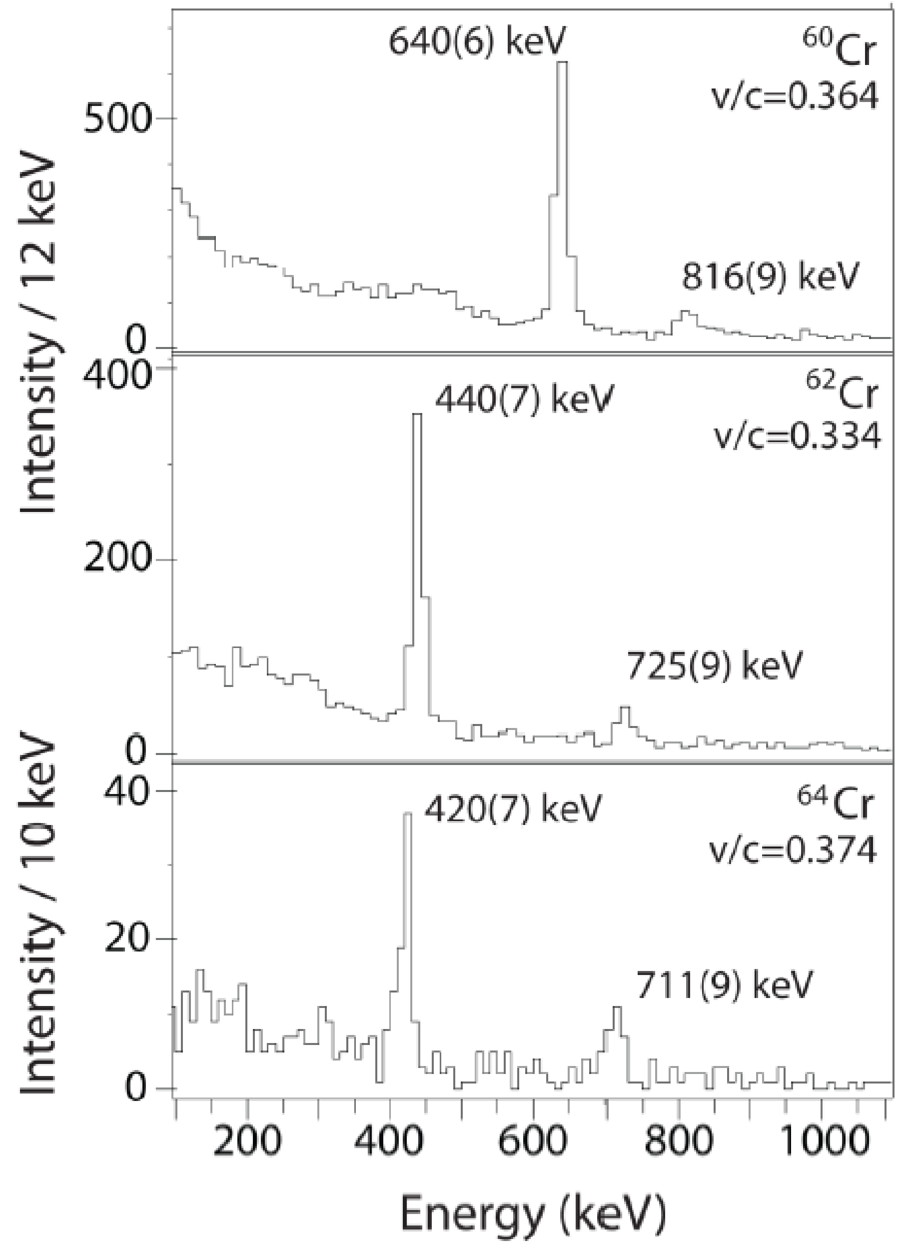


Inelastic scattering of ^{62,64,66}Fe and ^{60,62,64}Cr at NSCL

- Gamma-ray spectroscopy of excited states populated in ^{60,62,64}Cr and ^{62,64,66}Fe via inelastic scattering off ^{9}Be
- Relative cross section for the population of the 2^+ state – including observed and unobserved feeding – confirms change in structure between Fe and Cr

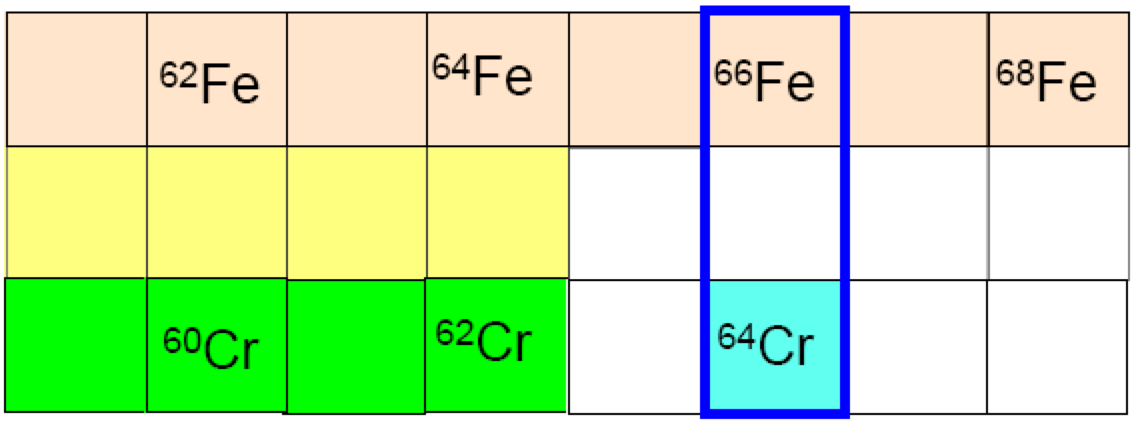


A. Gade *et al.*, PRC 81, 051304(R) (2010)



Deformation in Co and Ni approaching N=40:
D. Pauwels *et al.*, PRC 78, 041307(R) (2008); PRC 79, 044309 (2009)

N=40



Neutron-rich Cr up to ^{62}Cr:

N. Aoi *et al.*, PRL 102, 012502 (2009)
S. Zhu *et al.*, PRC 74, 064315 (2006)

Structure of iron up to ^{68}Fe:

J. Ljungvall *et al.*, PRC 81, 061301(R) (2010)

P. Adrich *et al.*, PRC 77, 054306 (2008)

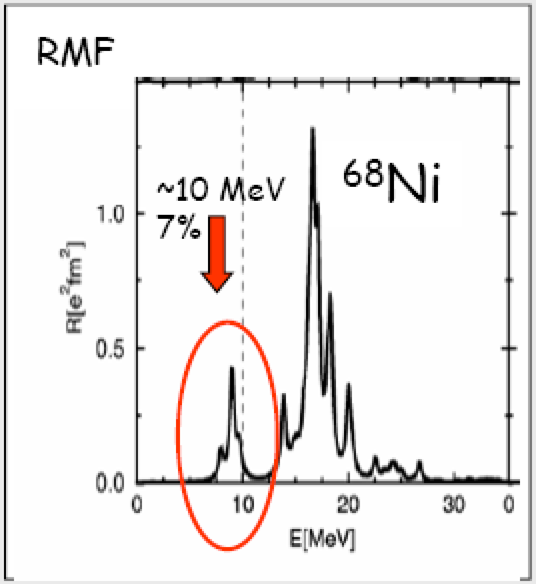
S. Lunardi *et al.*, PRC 76, 034303 (2007)

Structure of Mn up to ^{63}Mn:

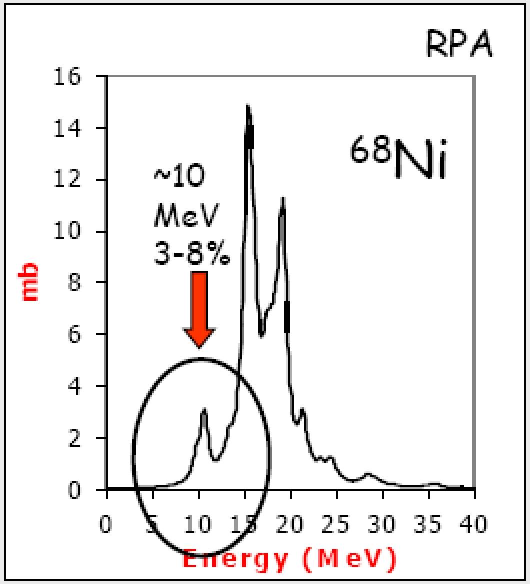
D. Steppenbeck, *et al.*, PRC 81, 014305 (2010)

H. L. Crawford, *et al.*, PRC 79, 054320 (2009)

J. J. Valiente-Dobón *et al.*, PRC 78, 024302 (2008)

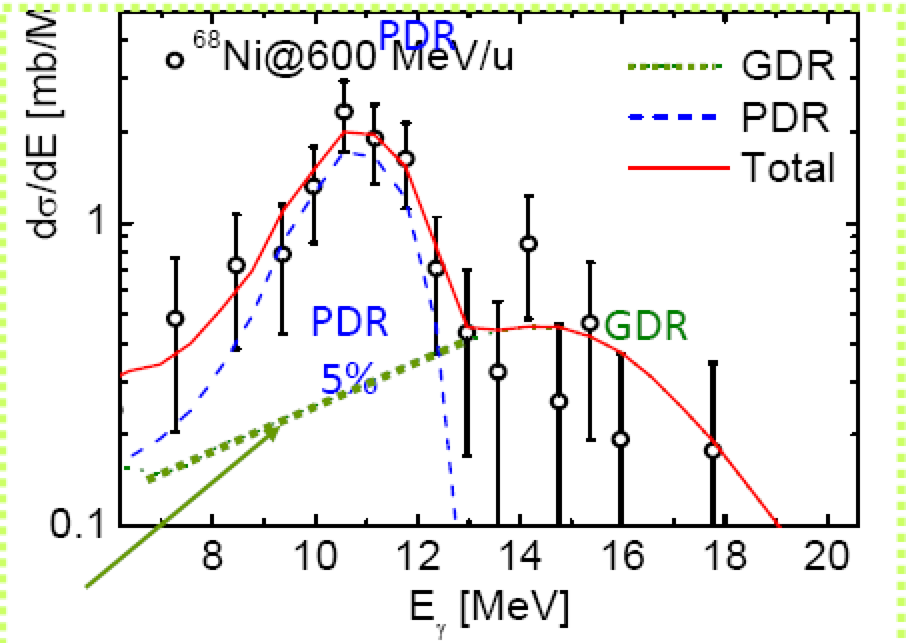


D. Vretnar et al. NPA 692(2001)496



G. Colo private communications

+ J. Liang et al., PRC75(2007)
fRPA: 7-8%:



O. Wieland et al., PRL102(2009)092502

Pygmy in ^{68}Ni at 11 MeV

Width ≈ 2 MeV mainly due to Doppler Broadening

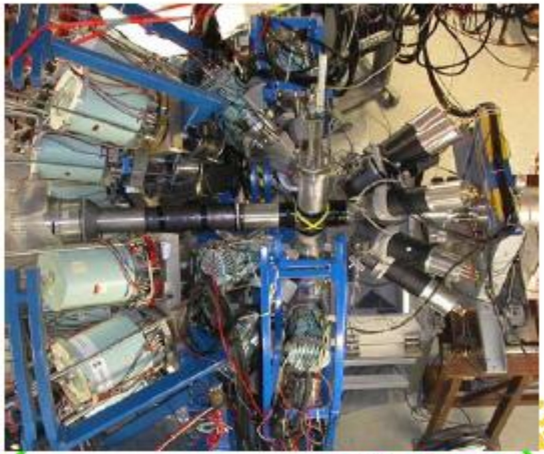
5 (p/m 1.5) % of the EWSR

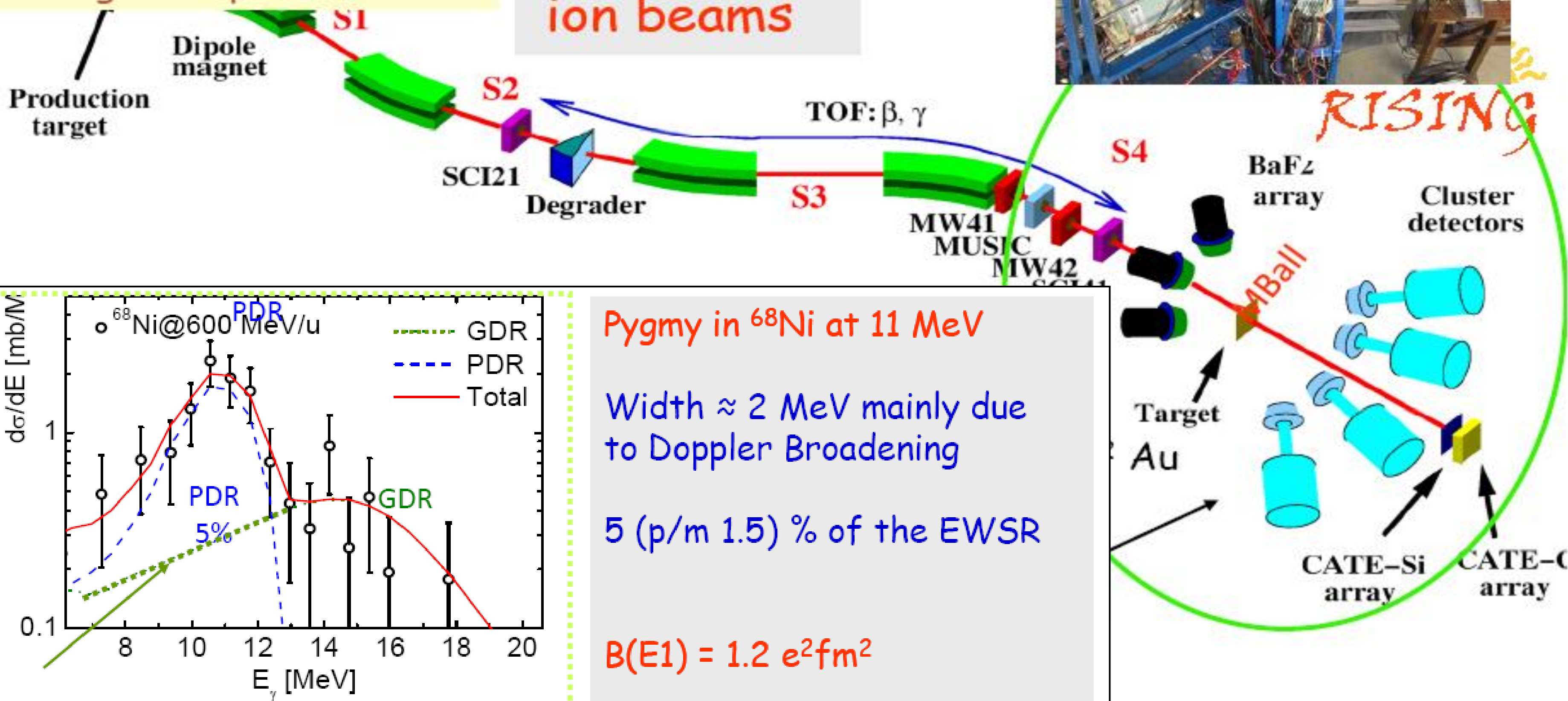
B(E1) = 1.2 e^2fm^2

High resolution γ-spectroscopy at the FRS of GSI

- ^{68}Ni beam by fragmentation of ^{86}Kr @ 900 MeV/u on Be target (4g/cm^2):
- 10^{10} ppspill ^{86}Kr, Spill length 6s,period 10 s

FRS provides secondary radioactive ion beams





O. Wieland et al., PRL102(2009)092502

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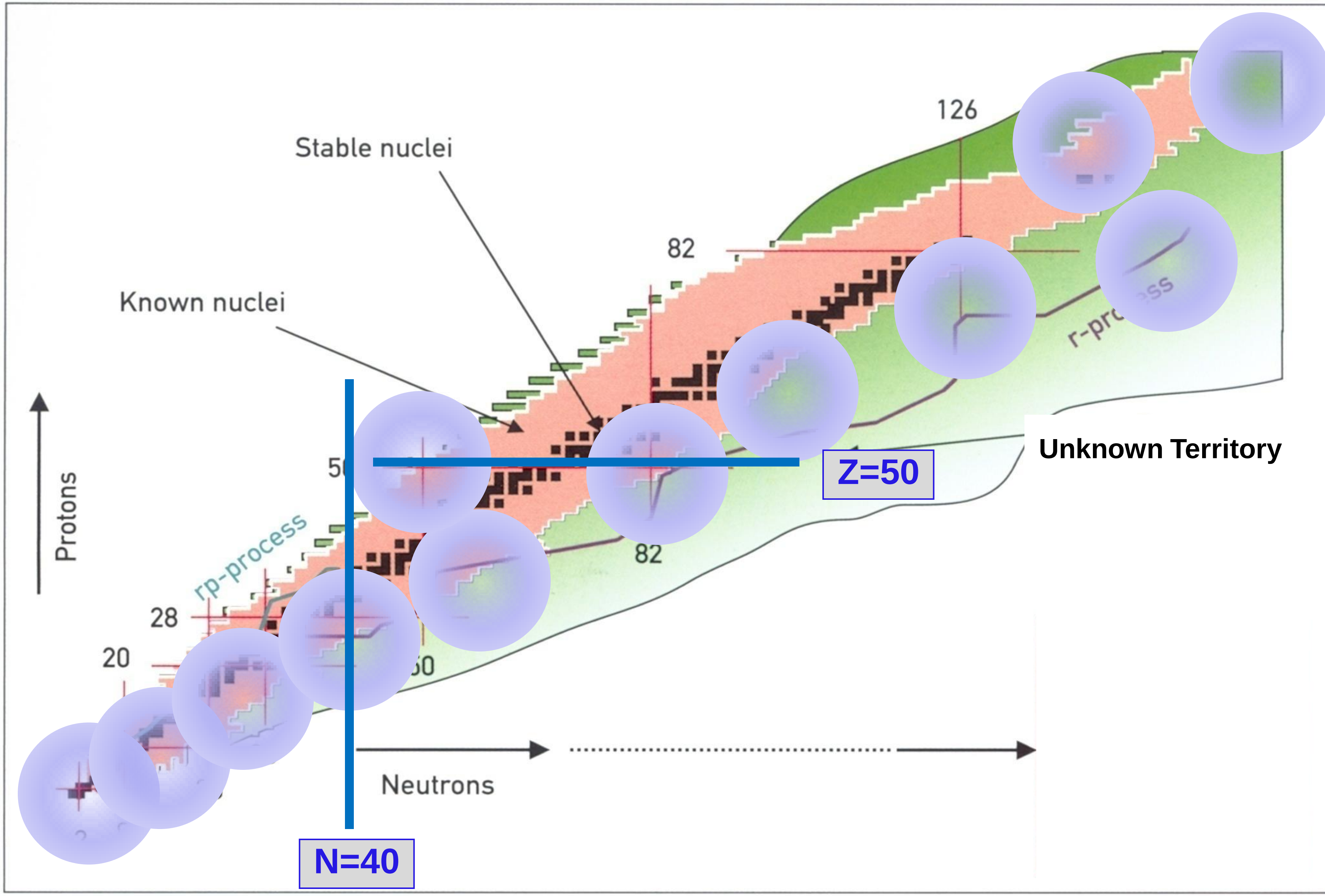
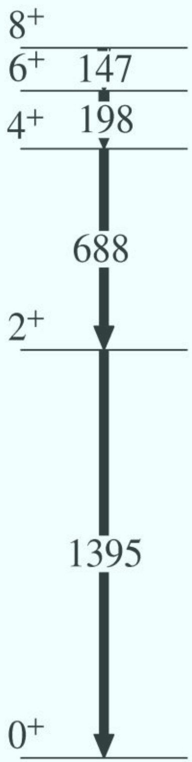


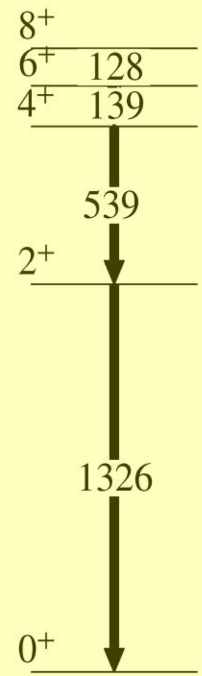
Stable nuclei
Known nuclei
126
82
82
50
28
20
rp-process
r-process
Protons
Neutrons
Unknown Territory
Z=50
N=40



$T_{1/2}$ ~ 200ns

$^{98}_{48}Cd_{50}$

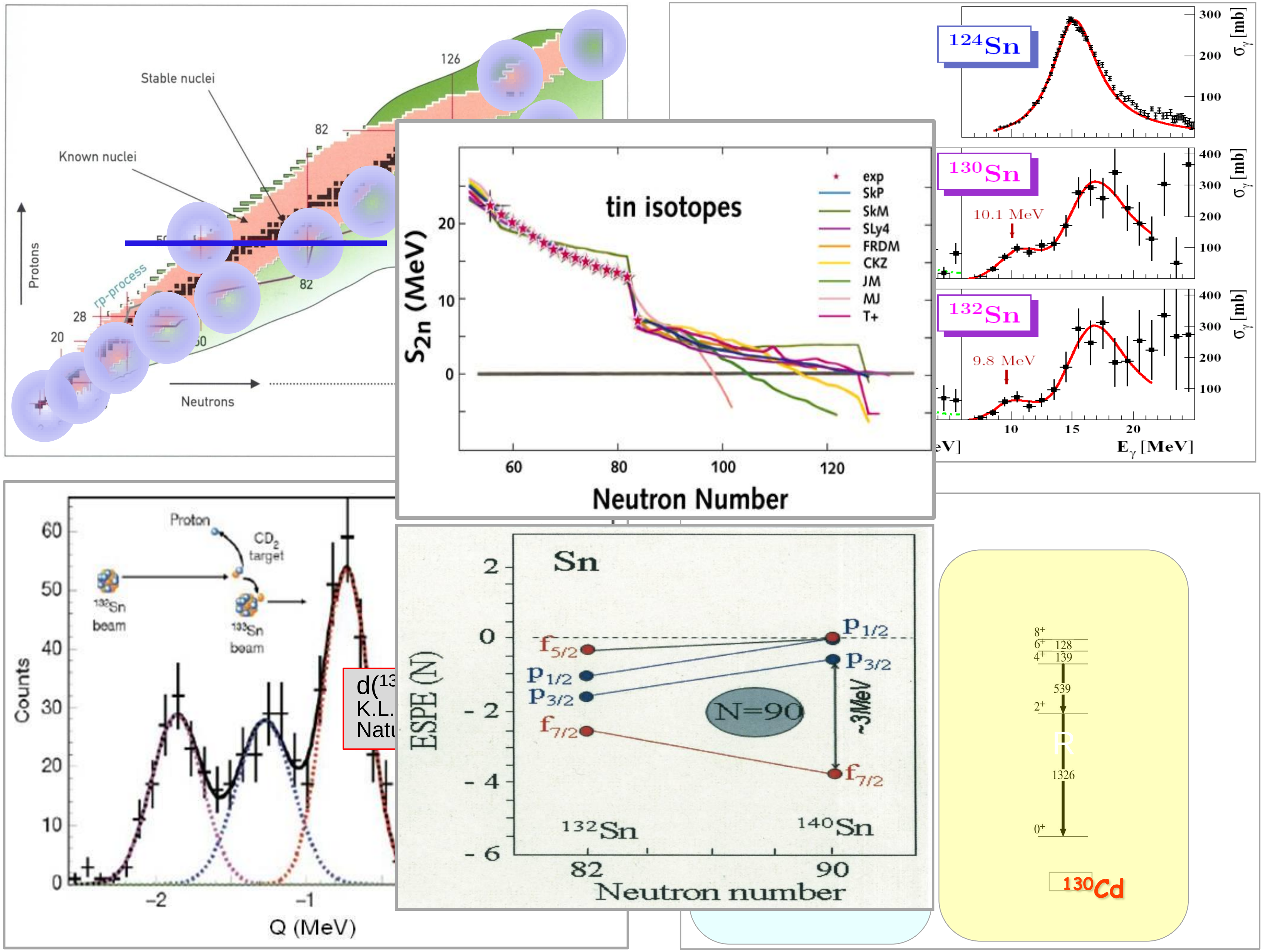
M.Górska et al., PRL 79 (1997) 2415



$T_{1/2}$ ~ 200ns

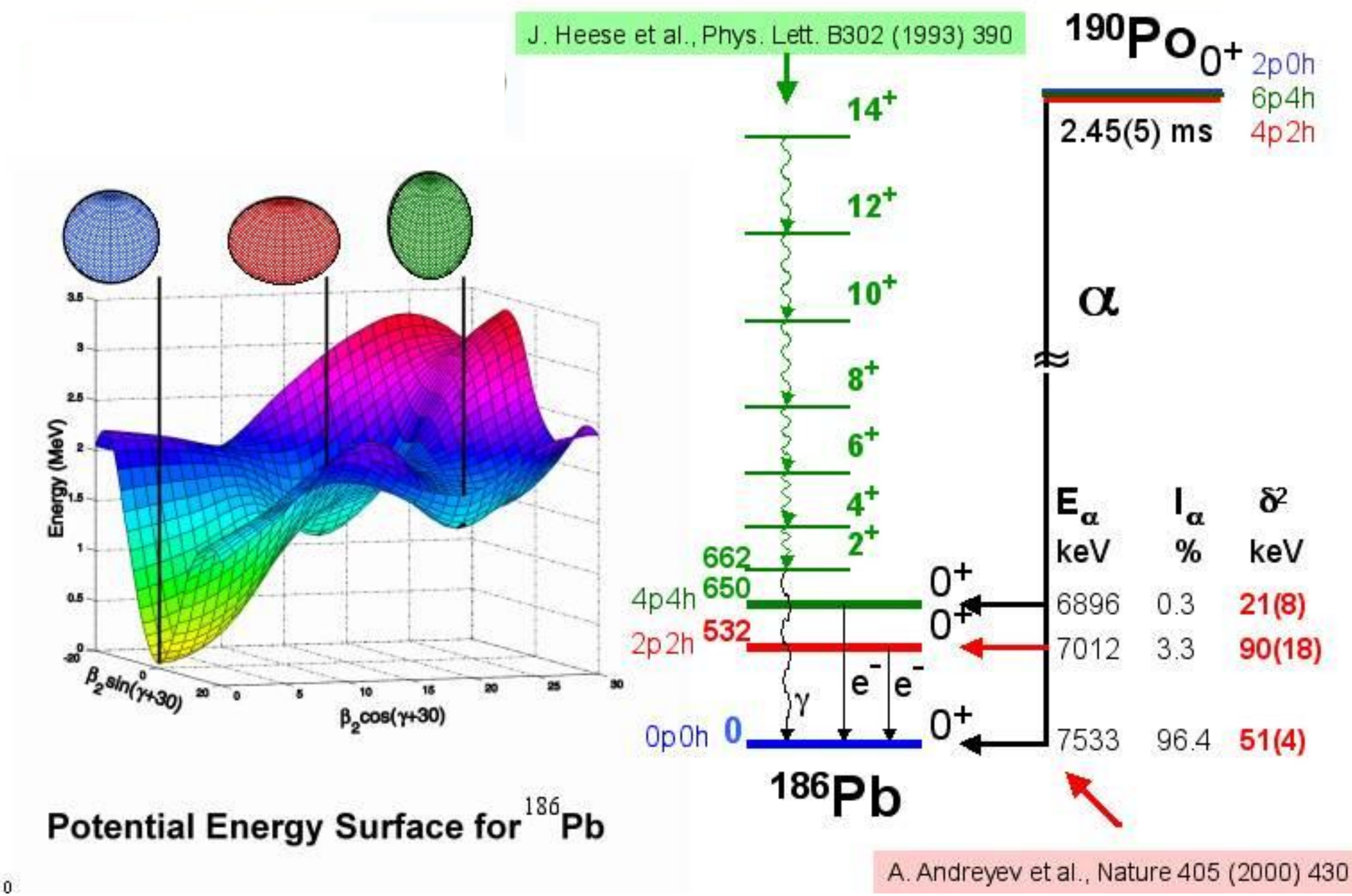
$^{130}_{48}Cd_{82}$

A. Jungclaus et al., PRL 99 (2007) 132501



Stable nuclei
Known nuclei
126
82
28
20
rp-process
Protons
Neutrons
tin isotopes
S_{2n} (MeV)
Neutron Number
exp
SkP
SkM
SLy4
FRDM
CKZ
JM
MJ
T+
^{124}Sn
^{130}Sn
^{132}Sn
10.1 MeV
9.8 MeV
σ_γ [mb]
E_γ [MeV]
Counts
Q (MeV)
Proton
CD_2 target
^{132}Sn beam
^{133}Sn beam
Sn
ESPE (N)
$f_{5/2}$
$p_{1/2}$
$p_{3/2}$
$f_{7/2}$
N=90
~3MeV
^{132}Sn
^{140}Sn
Neutron number
8^+
6^+ 128
4^+ 139
539
2^+
1326
0^+
^{130}Cd

Shape Co-existence and Quantum Phase Transitions



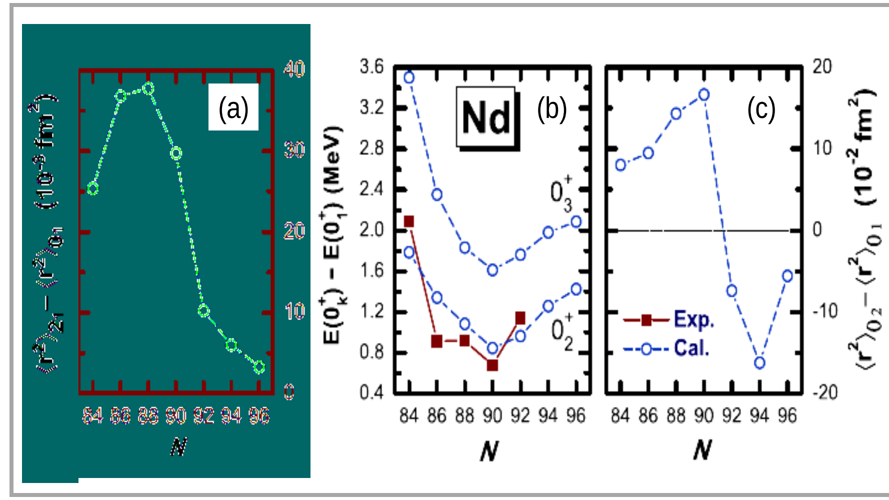
Quantum Phase Transitions QPT)

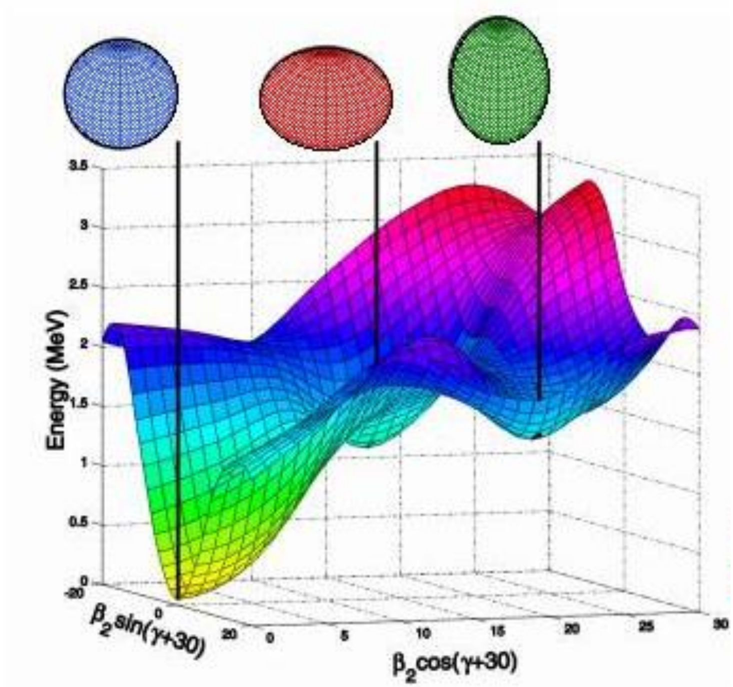
QPT defined for N → ∞

Iachello and Zamfir (PRL 92 (2004) 212501) show that main features persist down to N ~ 10

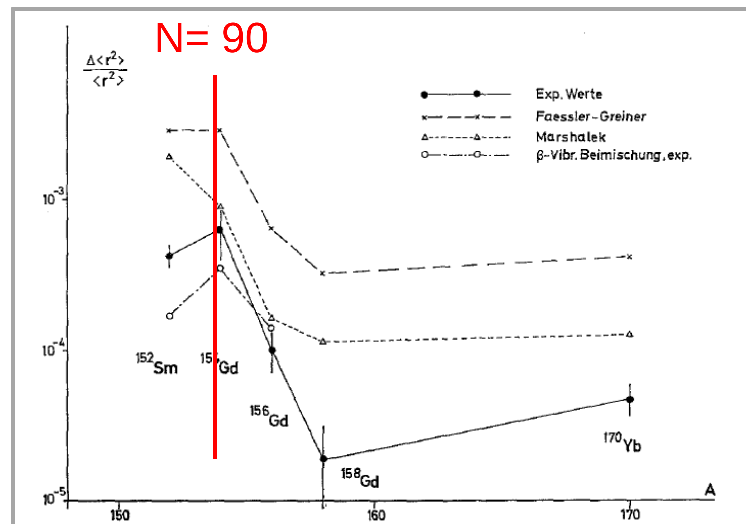
Z.P. Li et al. PRC 80 (2009) 061301 present calculations on observables →

ISOLDE: QPT in masses of n-rich Kr isotopes

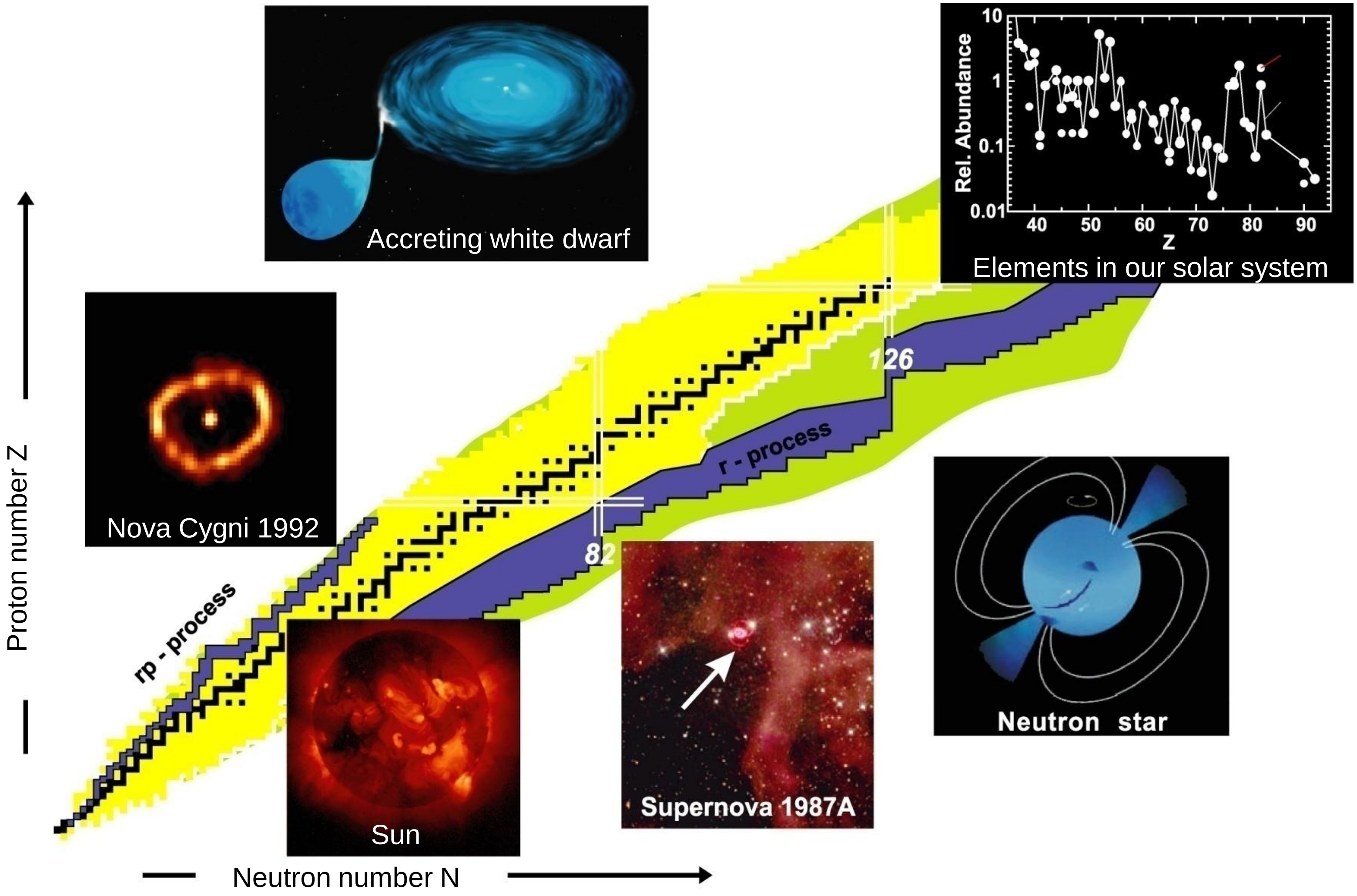




Potential Energy Surface for ^{186}Pb

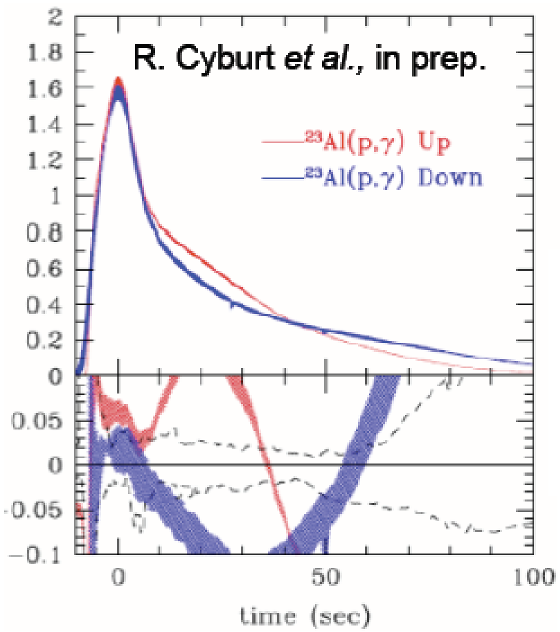


Nuclear astrophysics with RI Beams:

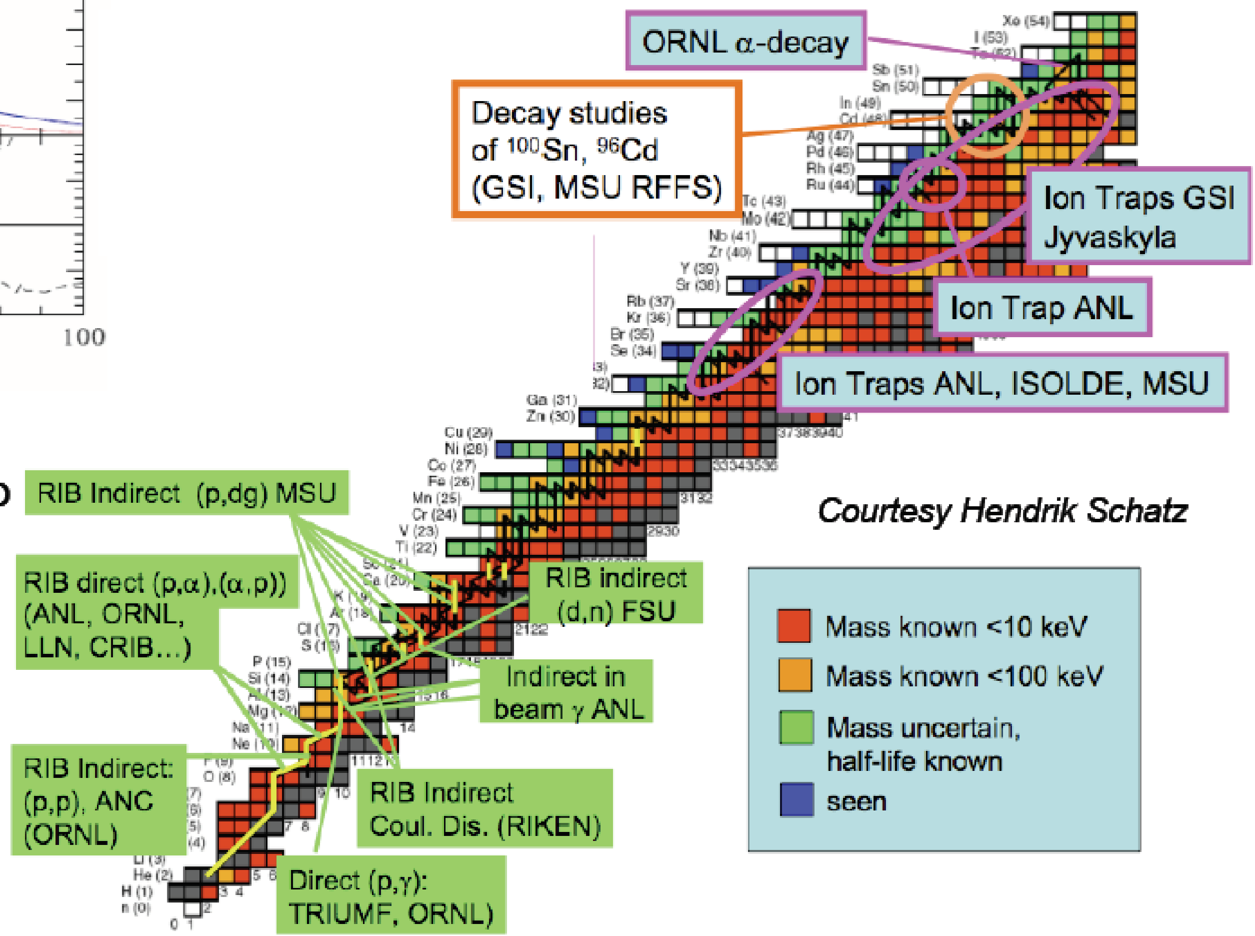


X-ray bursts

Calculated X-ray light curve



- Reaction rates are important, but few direct measurements have been possible so far



Courtesy Hendrik Schatz

- Sensitivity studies allow experiments to be focused on most important rates
- Must improve data for statistical rates

$$\langle \sigma v \rangle \propto e^{-Q/kT}$$

➔*Masses*

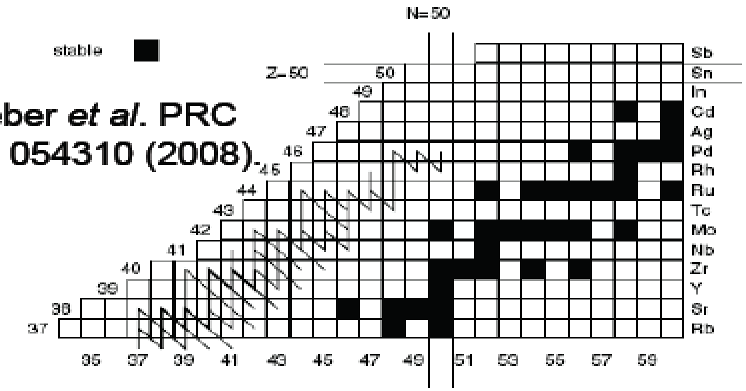
- Decay properties

νp process

Fröhlich *et al.*, PRL **96**, 142502 (2006).

- The intense neutrino/antineutrino flux in a supernova can strongly influence the formation of elements
- Nuclei that form in the “alpha-rich freezeout” are expected to experience a high anti-neutrino flux
- $\bar{\nu} + p \rightarrow n + e^{+}$ reactions produce neutrons that bypass the decay of long-lived nuclei
- Reaction sequence starting on iron-group nuclei that is similar to the rp process

Weber *et al.* PRC **78**, 054310 (2008).

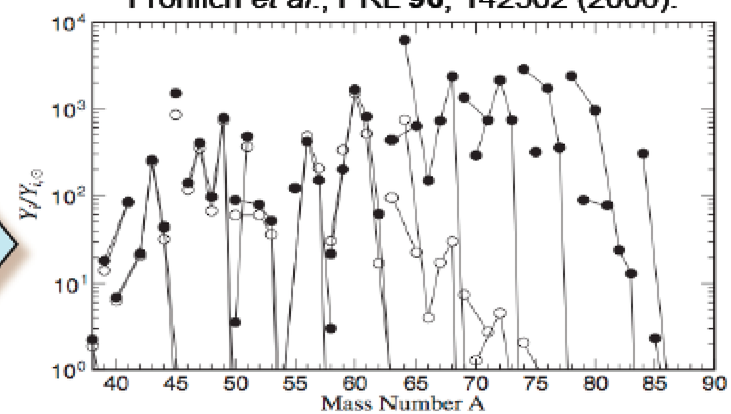


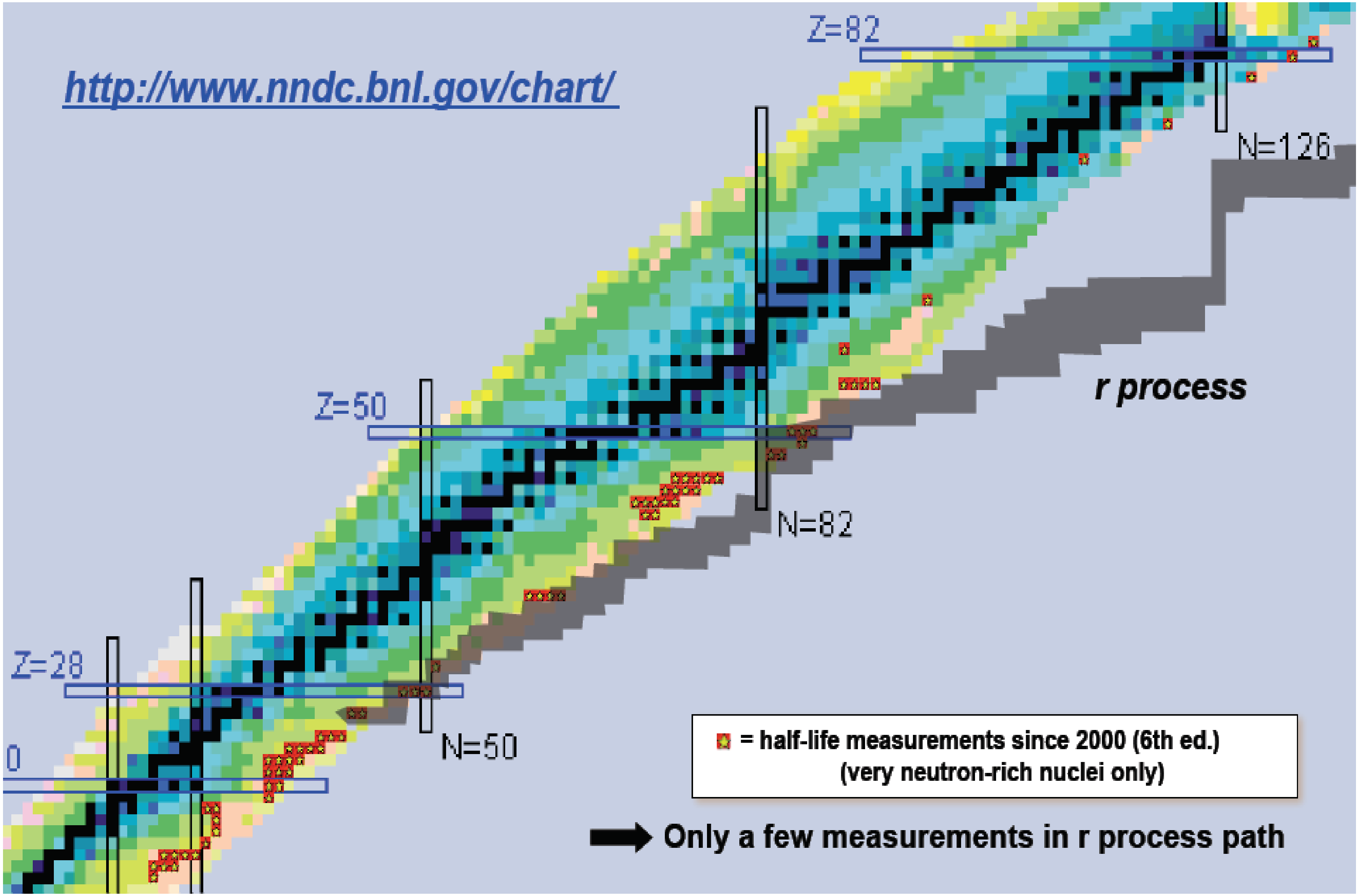
See Suzuki
5:00pm Thur

Abundaces relative to solar

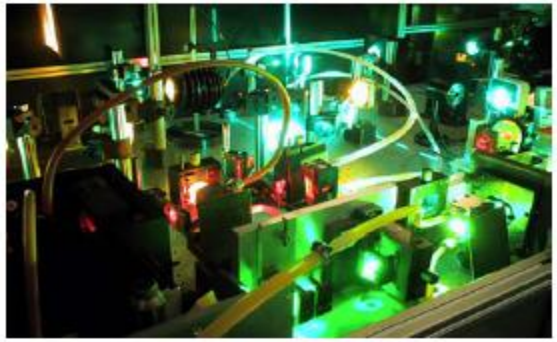
- ● with ν reactions
- ○ without ν reactions

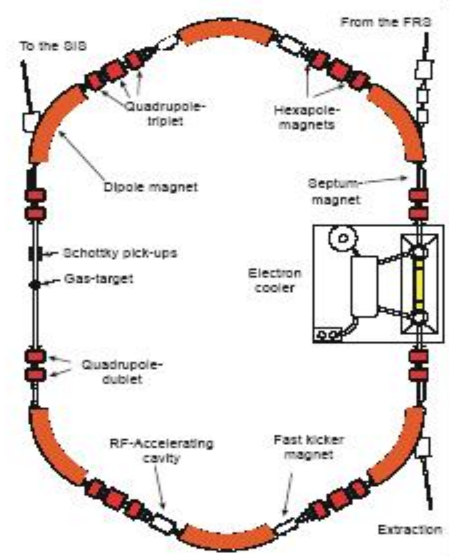
Fröhlich *et al.*, PRL **96**, 142502 (2006).




http://www.nndc.bnl.gov/chart/
Z=82
Z=50
Z=28
N=126
N=82
N=50
r process
= half-life measurements since 2000 (6th ed.)
(very neutron-rich nuclei only)
Only a few measurements in r process path

Groundstate Properties of Nuclei: Lasers, Traps, and Storage Rings

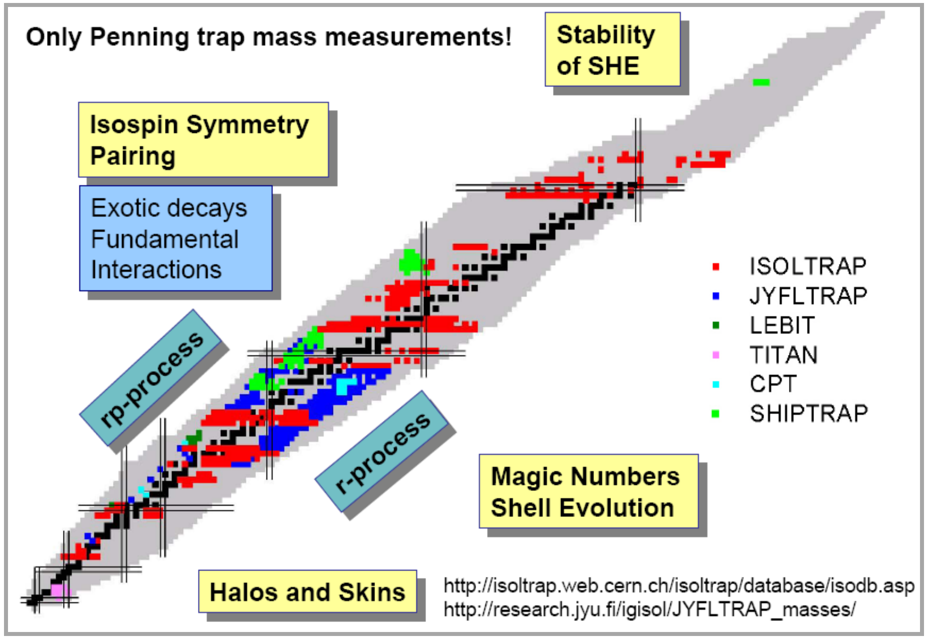


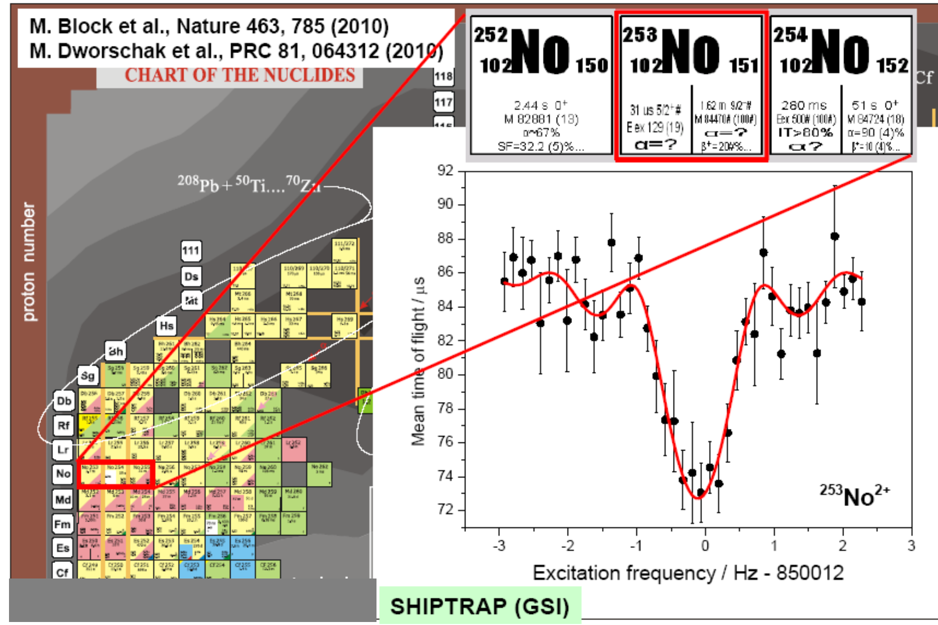


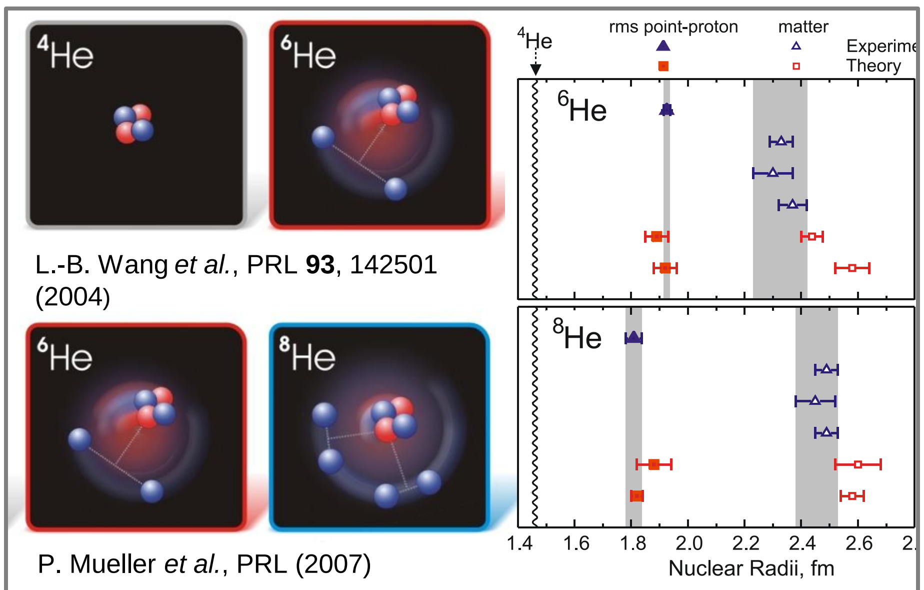
What do we learn?

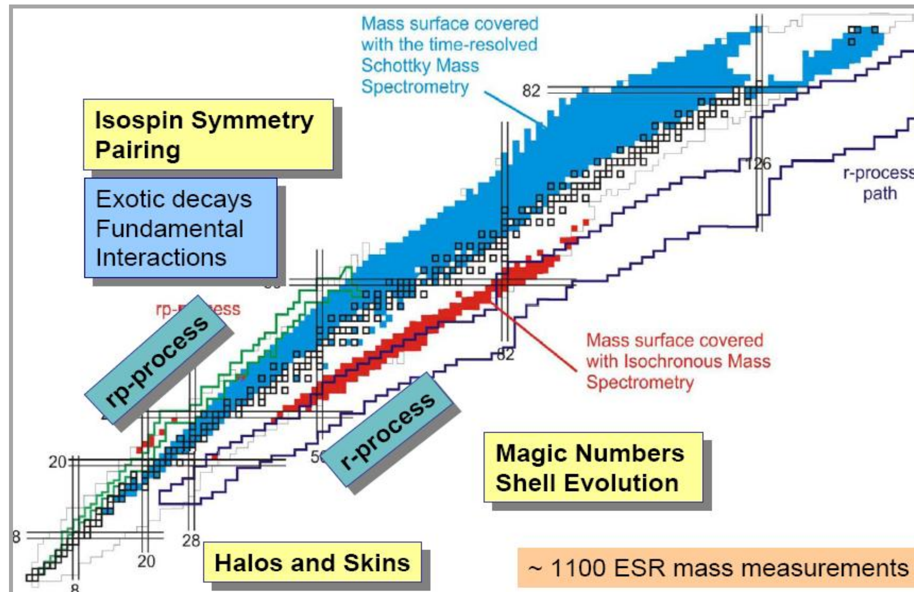
Charge Radii	<u>nuclear structure</u>: nuclear charge distribution, deformation
Spins, Moments	<u>microscopic nuclear structure</u>: wave functions, coupling of nucleons, configuration mixing, shell structure <u>macroscopic nuclear structure</u>: deformation
Masses	nuclear binding energy basic test of nuclear models <u>nuclear structure:</u> shell closures, pairing, onset of deformation, drip lines, halos

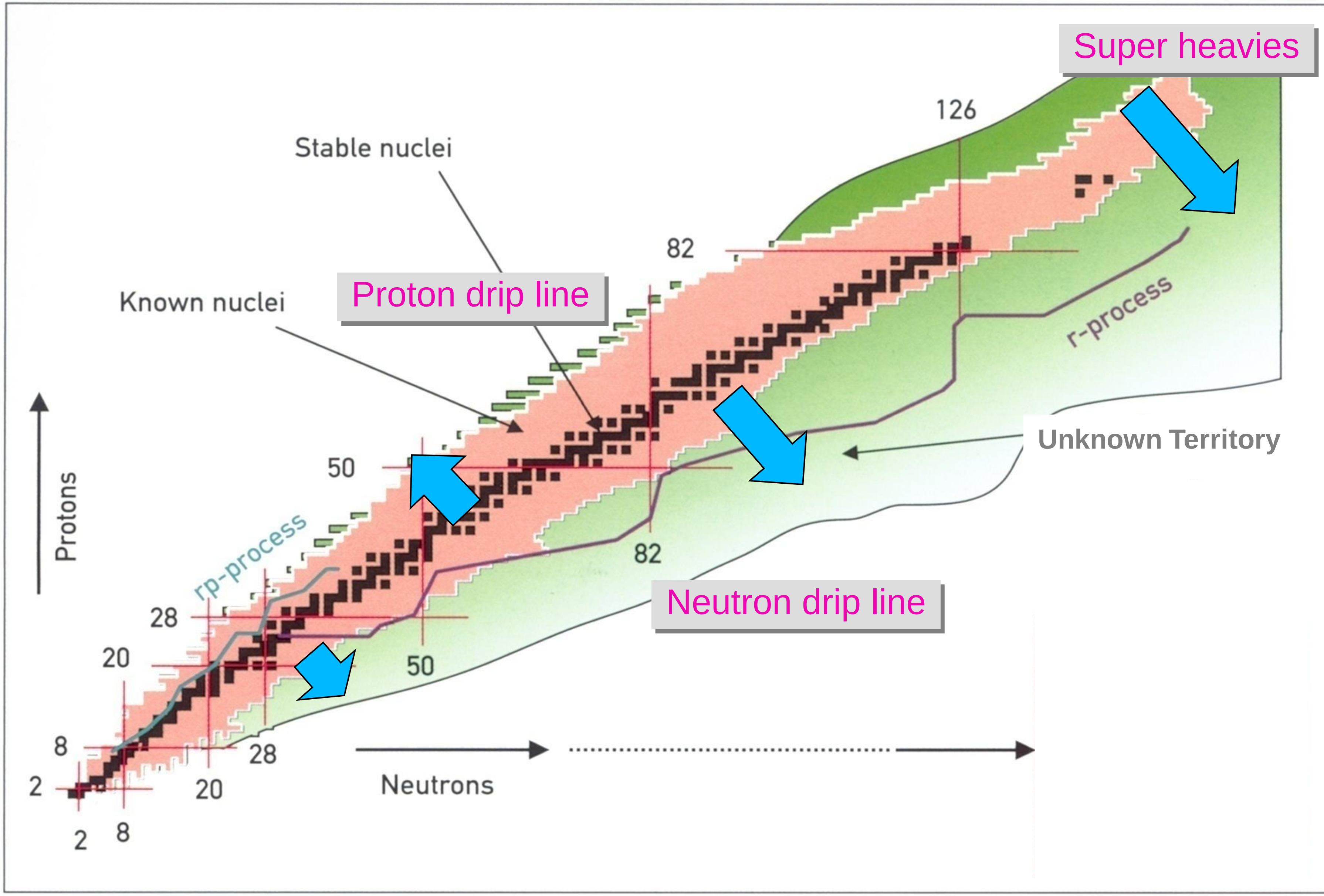
Mass measurements





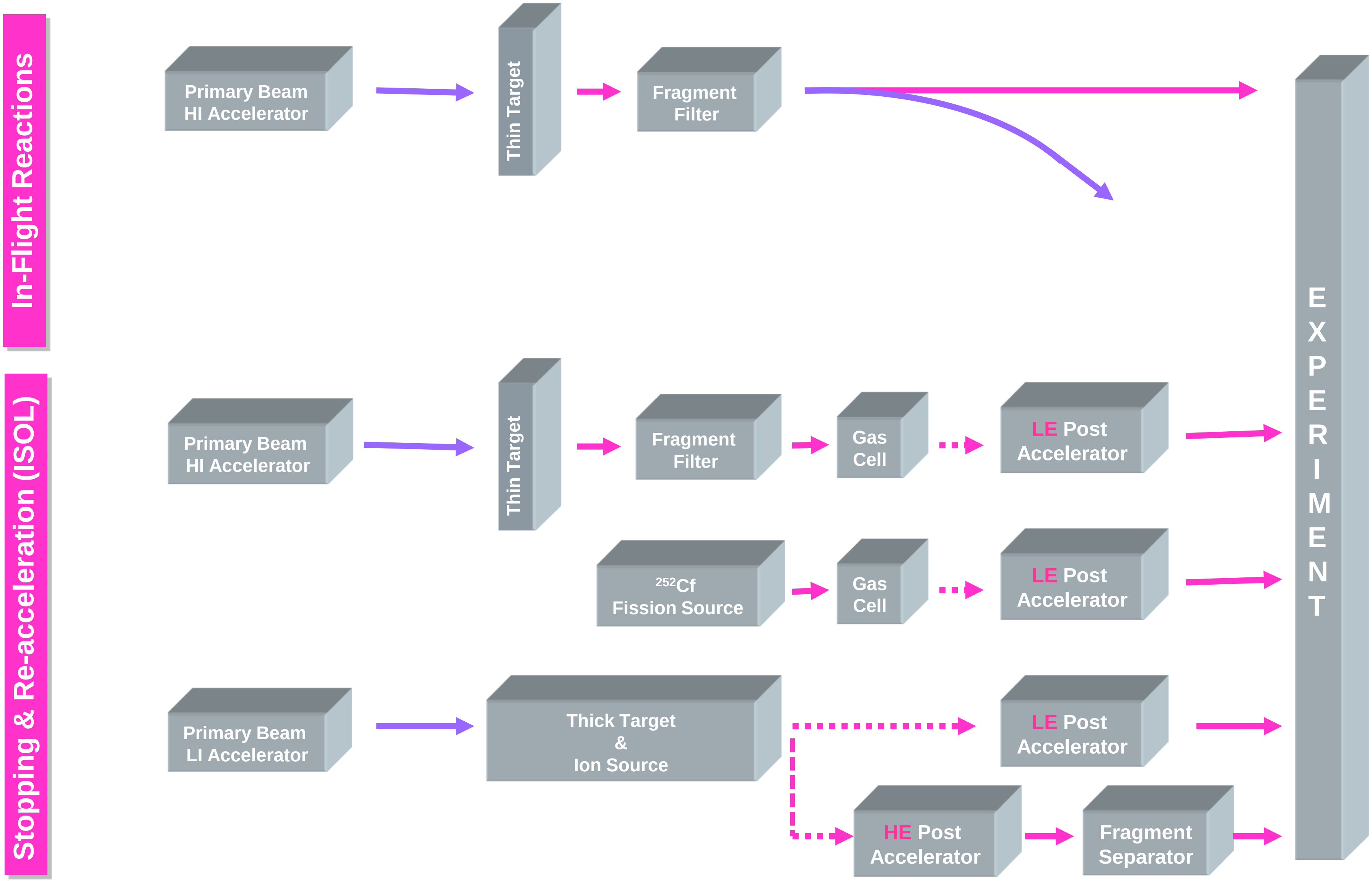




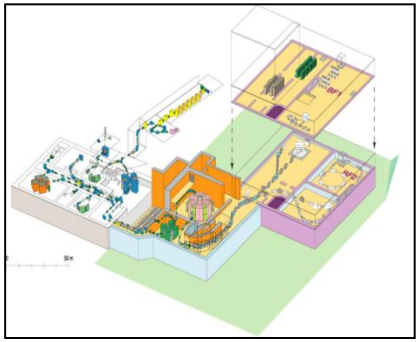


Super heavies
126
Stable nuclei
82
Known nuclei
Proton drip line
50
Protons
rp-process
28
20
8
2
2
8
20
28
50
82
r-process
Unknown Territory
Neutron drip line
Neutrons

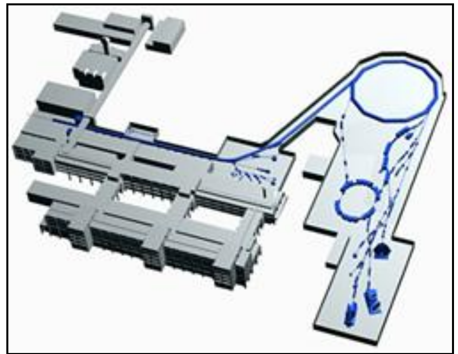
Production Methods for Radioactive Beams



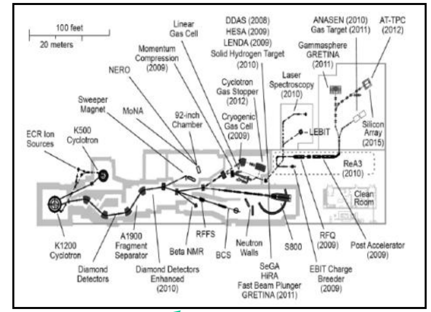
RIKEN-RIBF



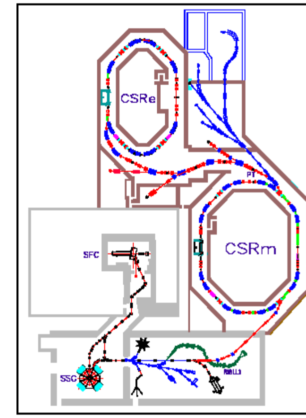
GSI-FRS/SIS18



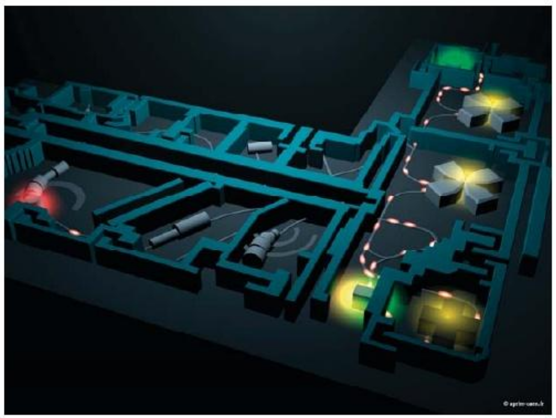
MSU-NSCL



CSR-Lanzhou



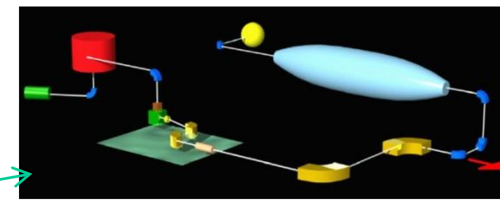
GANIL



In-Flight

OPERATING

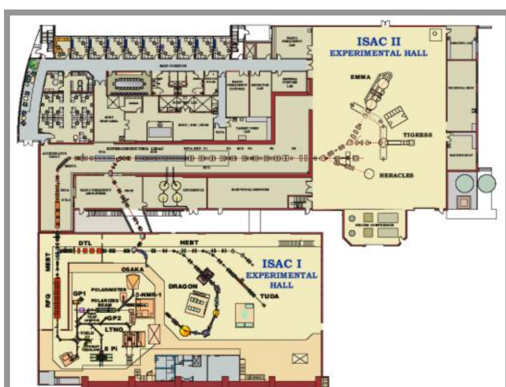
ISOL



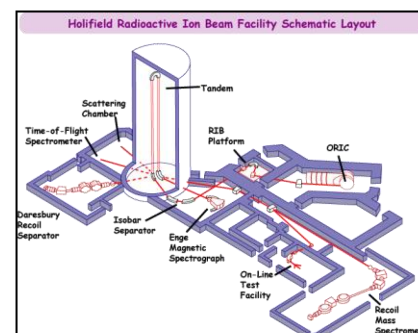
EXCYT-Catania

SPIRAL

TRIUMF
ISAC-2

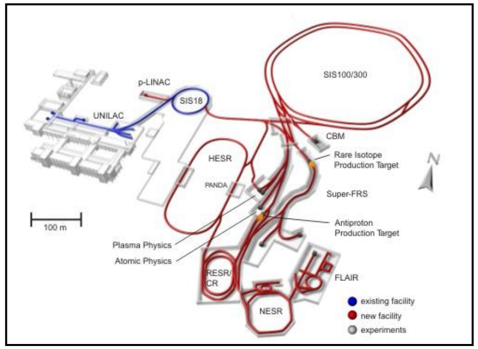


CERN-ISOLDE

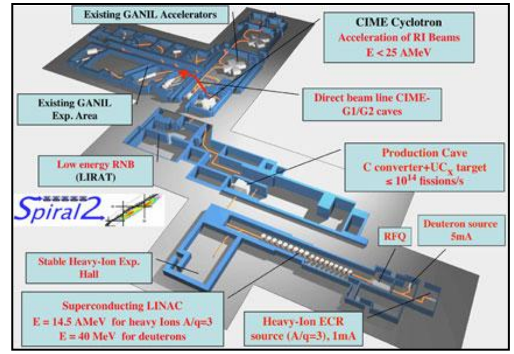


ORNL-HIRF

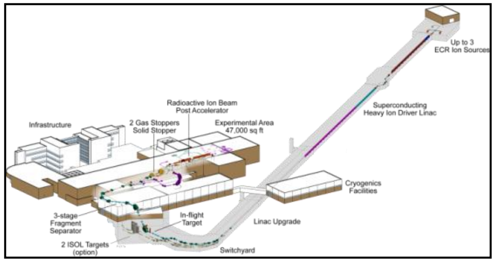
FAIR-GSI



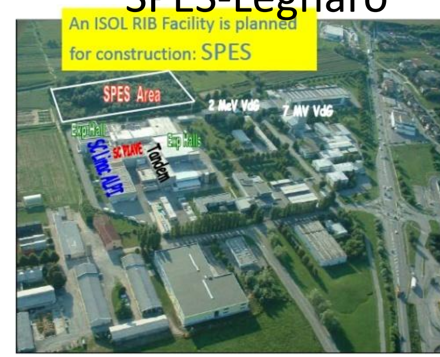
SPIRAL2-GANIL



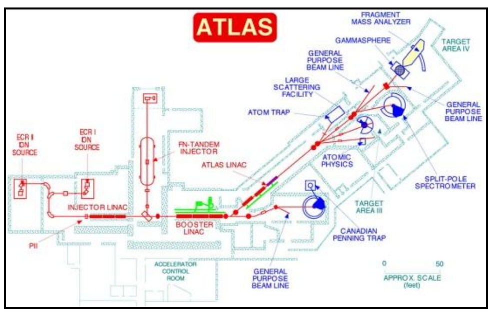
FRIB-MSU



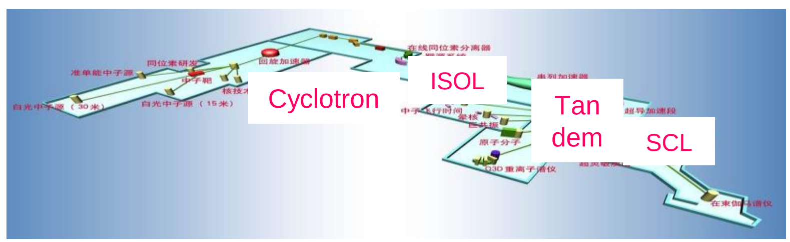
SPES-Legnaro



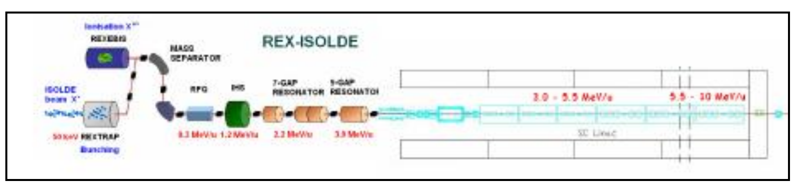
UNDER CONSTRUCTION
or
Funding Approved



CARIBU (Argonne)

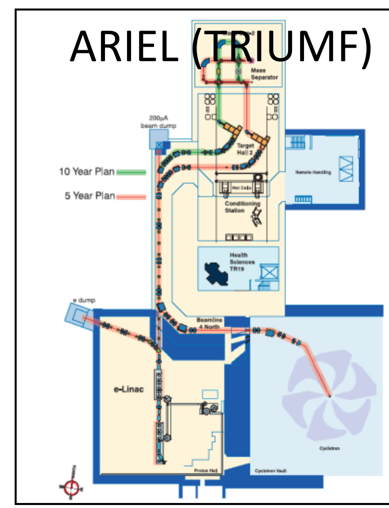


BRIF – Beijing)



HIE-ISOLDE (CERN)

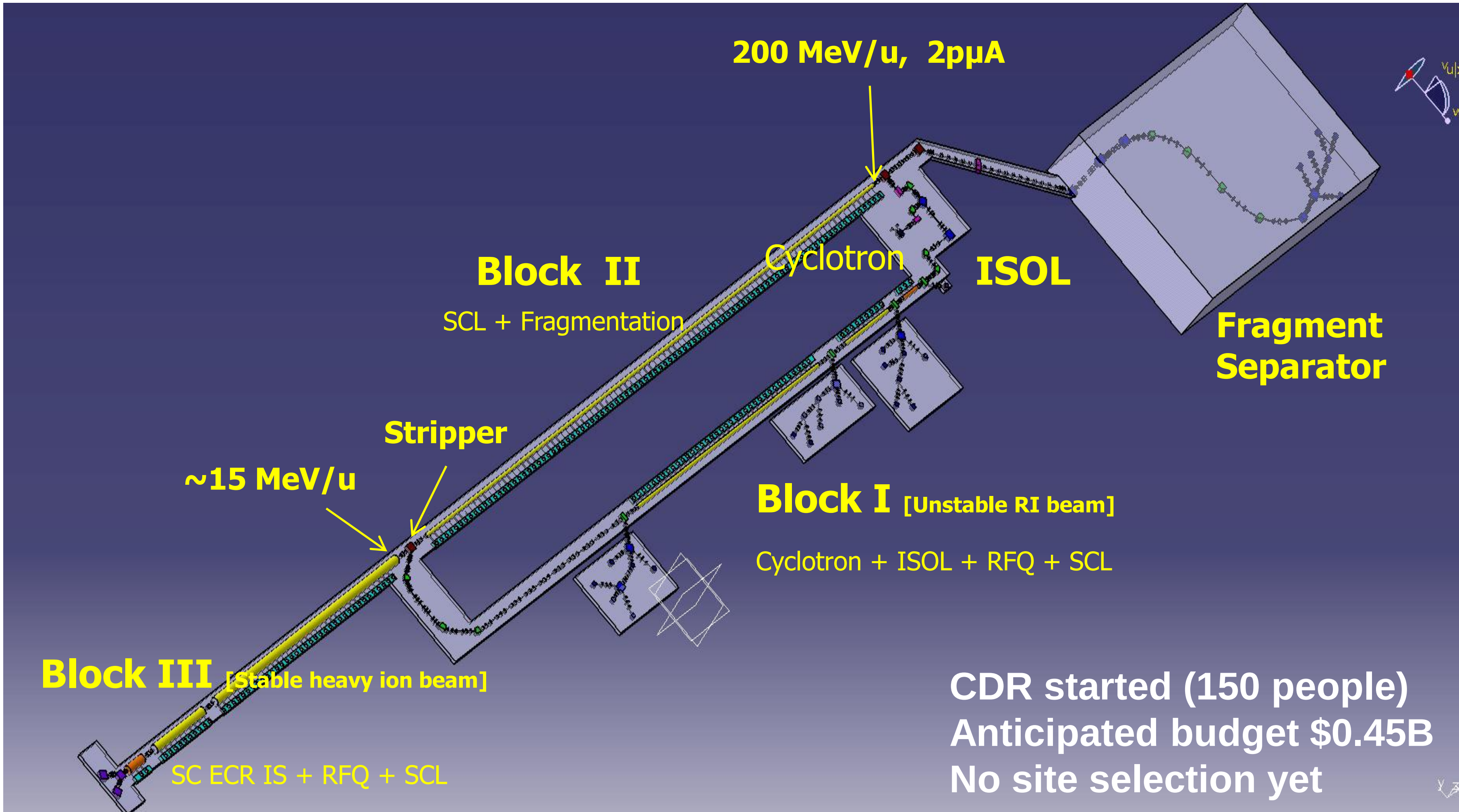
ARIEL (TRIUMF)

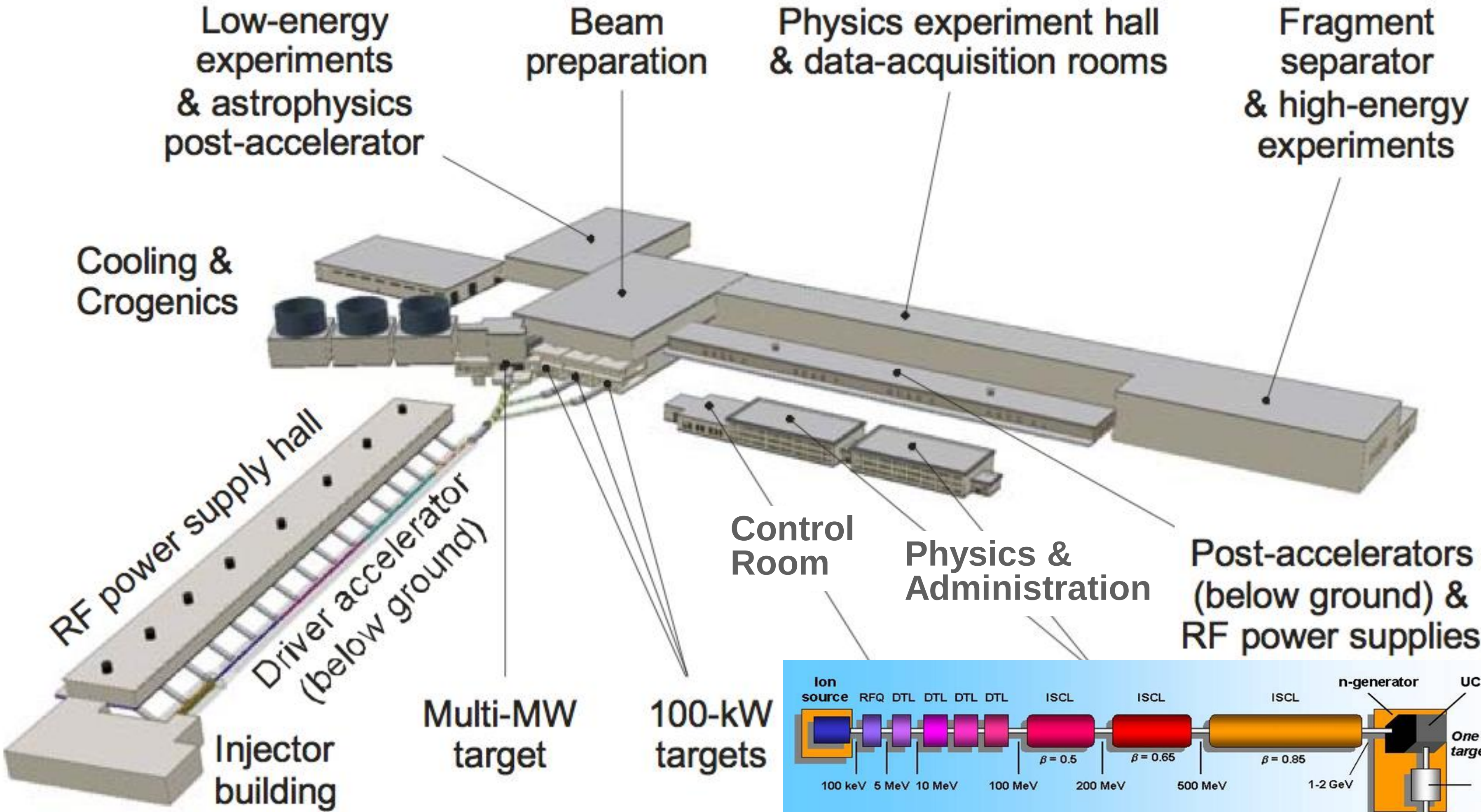


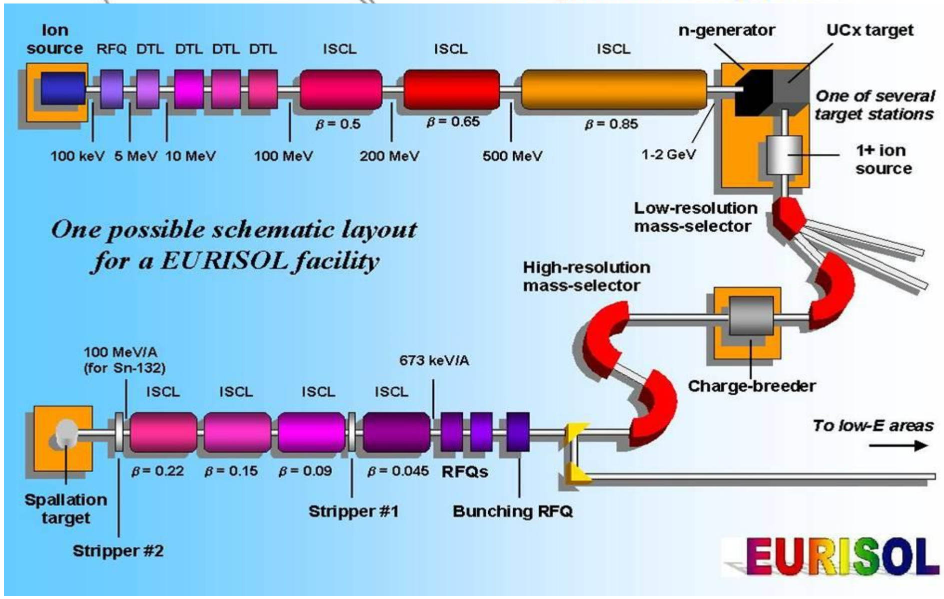
KoRIA (Korean Rare Isotope Accelerator)

Driver cyclotron (H 70MeV 1mA and D 35MeV 0.1mA)

Phase 1 (ISOL to 15MeV/u) / **Phase 2** (Linac to 200MeV/u for fragmentation beams)







Enormous amount of work done in
EU funded Design Study (Euro 30M)
http://www.eurisol.org
Cost estimate €1.3B.
Possible first beam 2015?

The CARIF Concept

China Advanced Rare Ion-beam Facility

I. Tanihata, NIM B266 (2008) 4067

CARR 反应堆 — n_{th} → ISOL 同位素分离器 → LINAC 直线加速器 → FRS 次级束流线 → Halo, r process, Magic

LINAC 直线加速器 → SHE Reaction Structure

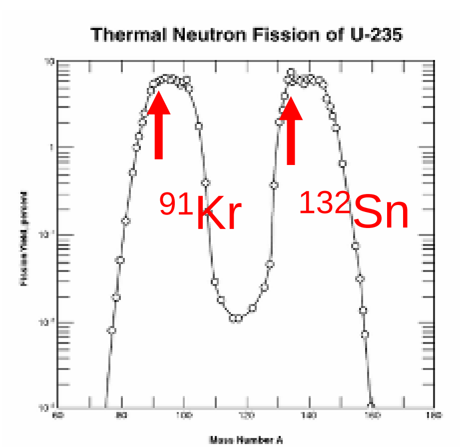
CARR: 8×10^{14} $cm^2 s^{-1}$

ISOL → LINAC: ^{132}Sn, ^{91}Kr, ^{142}Xe; $10^{8\text{-}9}$ pps; 300 keV

LINAC → FRS: ^{132}Sn, ^{91}Kr, ^{142}Xe; $10^{7\text{-}8}$ pps; 150 MeV/u

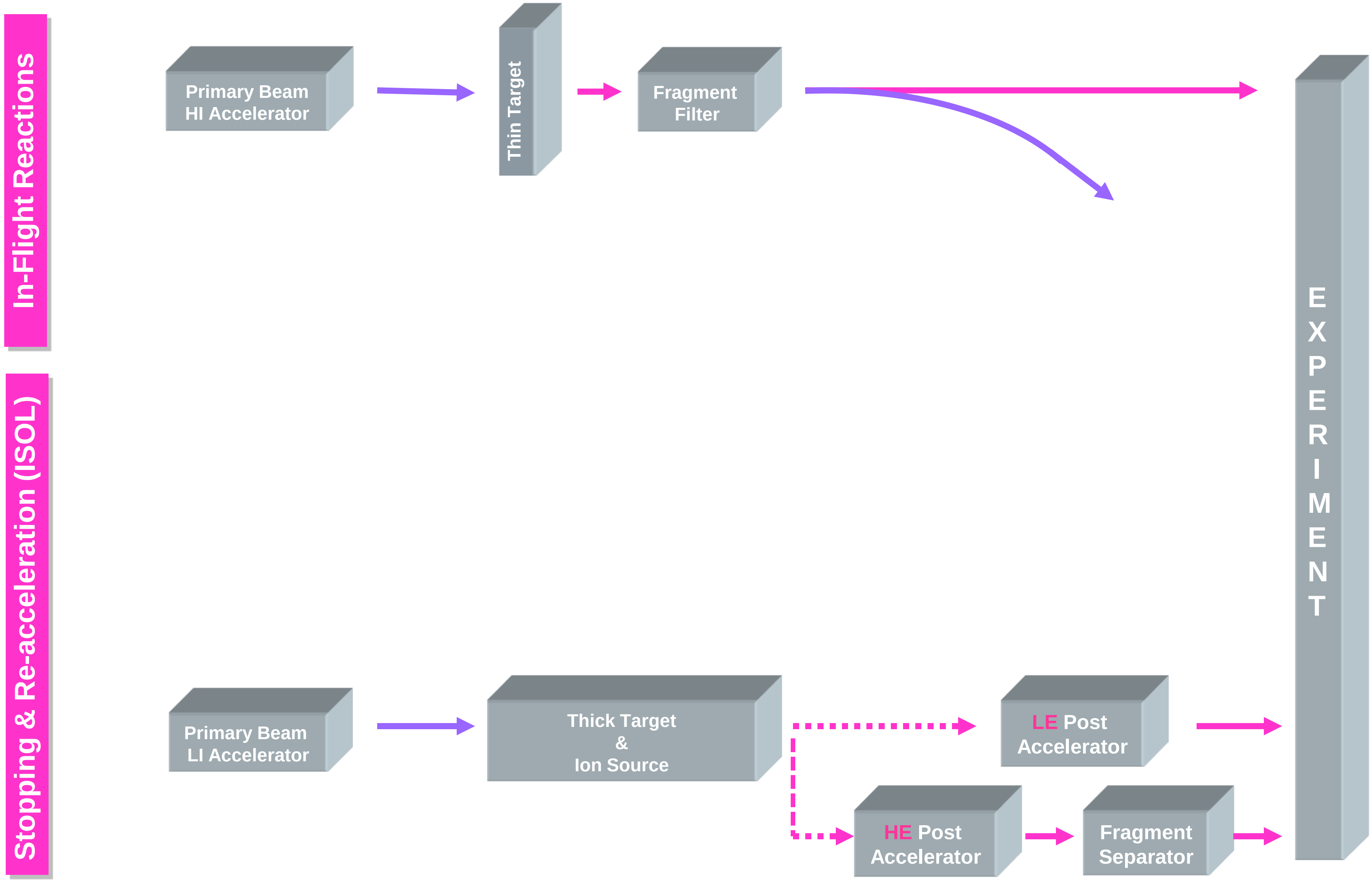
FRS → Halo / r process / Magic: ^{130}Cd, ^{78}Ni, ^{138}Sn; $10^{2\text{-}3}$ pps; 50 MeV/u

SHE Reaction Structure: ^{132}Sn, ^{91}Kr, ^{142}Xe; 10 MeV/u



Expectation: Fragmentation of fission products can result in highly n-rich beams

Production Methods for Radioactive Beams



Some comments on 2-step RIB Production

ISOL
1GeV p + ^{238}U
1 MW

Production →

$^{124}Pd: 10^{8}$

$^{132}Sn: 10^{12}$

Extraction → 1^{+}

$^{124}Pd: 10^{7}$

$^{132}Sn: 10^{11}$

^{132}Sn
("2-step")
Fragmentation

$^{124}Pd: 2x10^{4}$ at 100MeV/u

$1x10^{5}$ a 400MeV/u

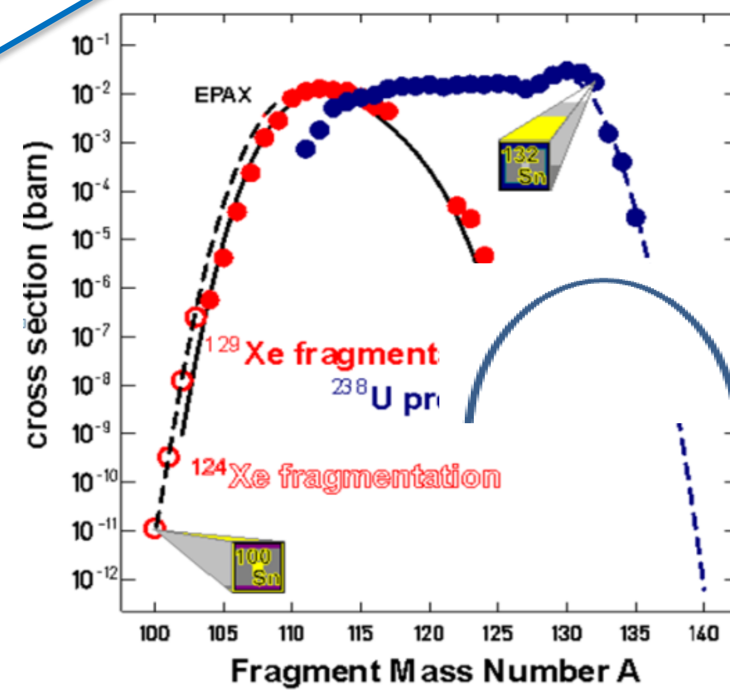
K. Helariutta et al, Eur. Phys. J. A, **17** (2003) 193

In-flight Fragmentation
345MeV/u ^{238}U
10^{12} sec^{-1}

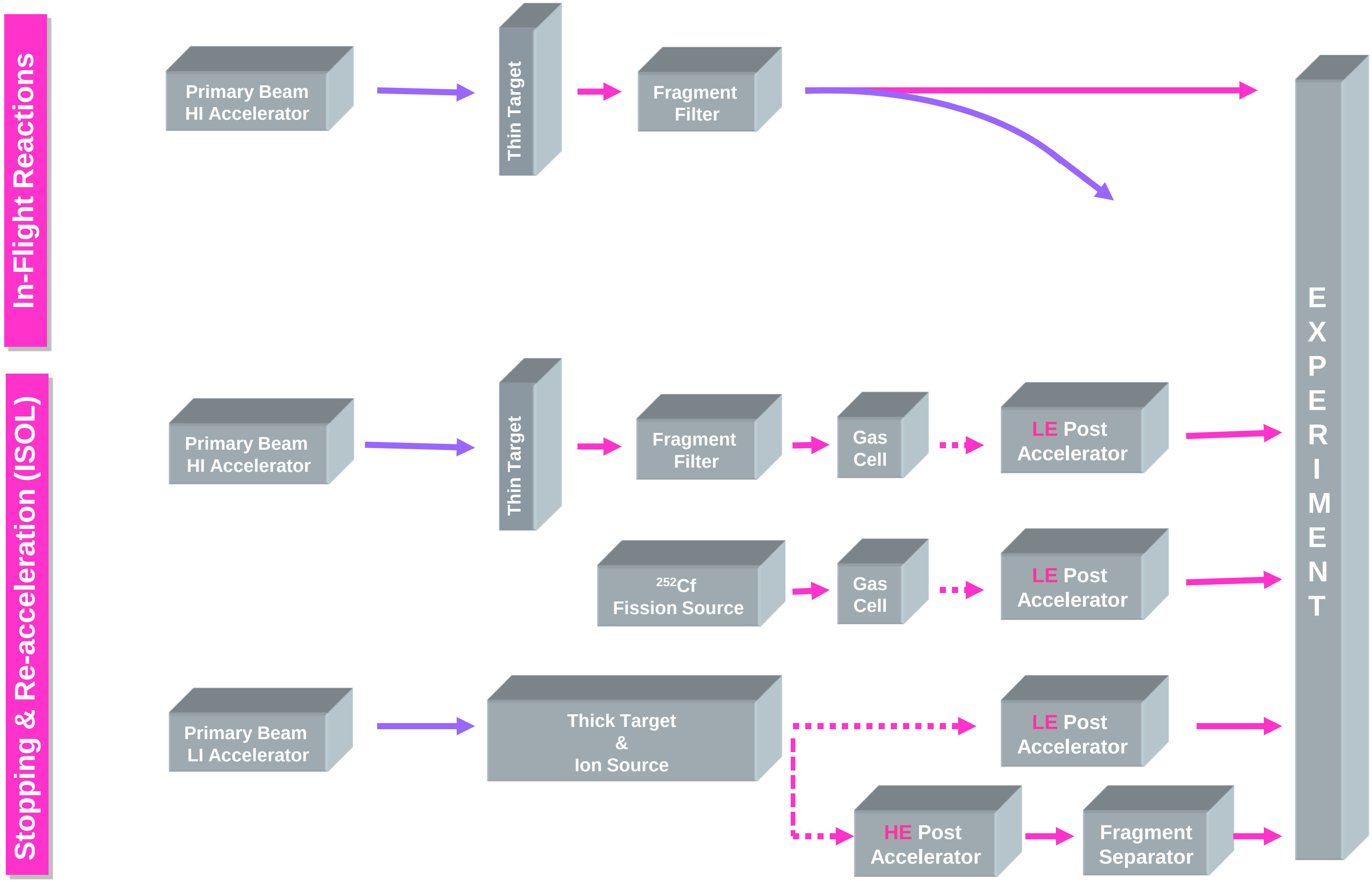
→

$^{124}Pd: 10^{4}$

$^{132}Sn: 10^{8}$

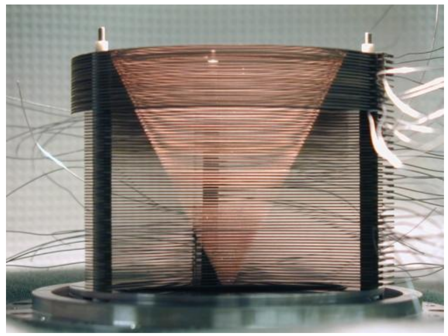


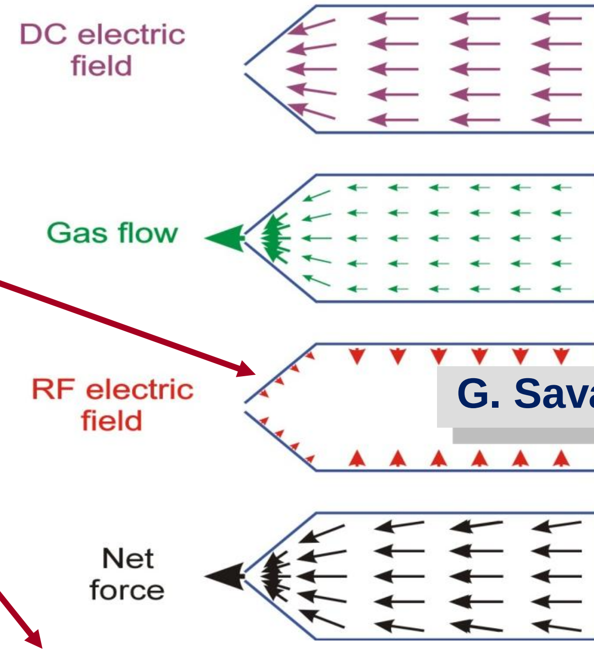
Production Methods for Radioactive Beams



Gas catcher at the ATLAS Canadian Penning Trap

• 20 cm long gas cell with second generation RF cone





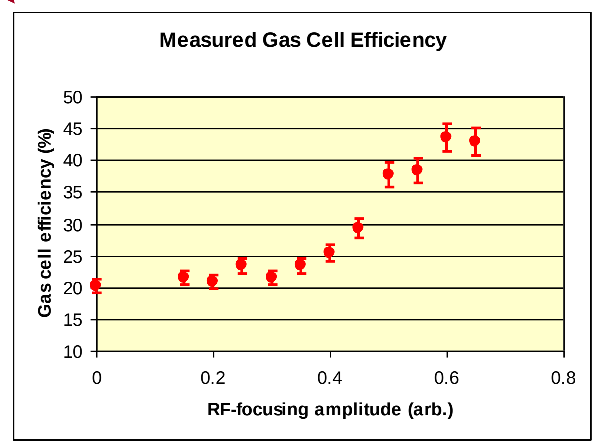
G. Savard 1997

• ε ~ 45%

• mean delay time below 10 ms

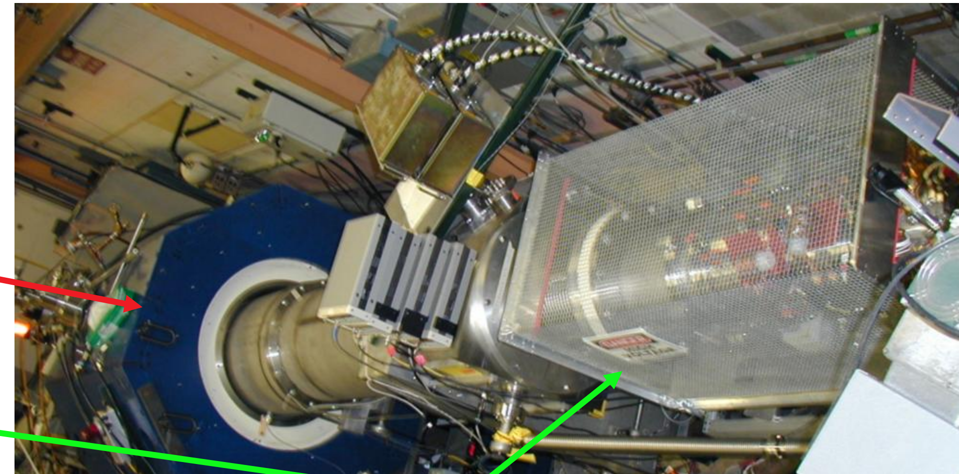
• demonstrated off-line with fission products and on-line with fusion–evaporation reactions

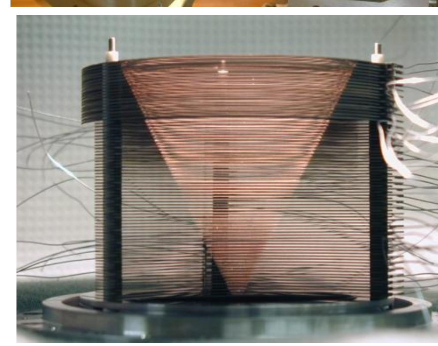
• several years of operating experience



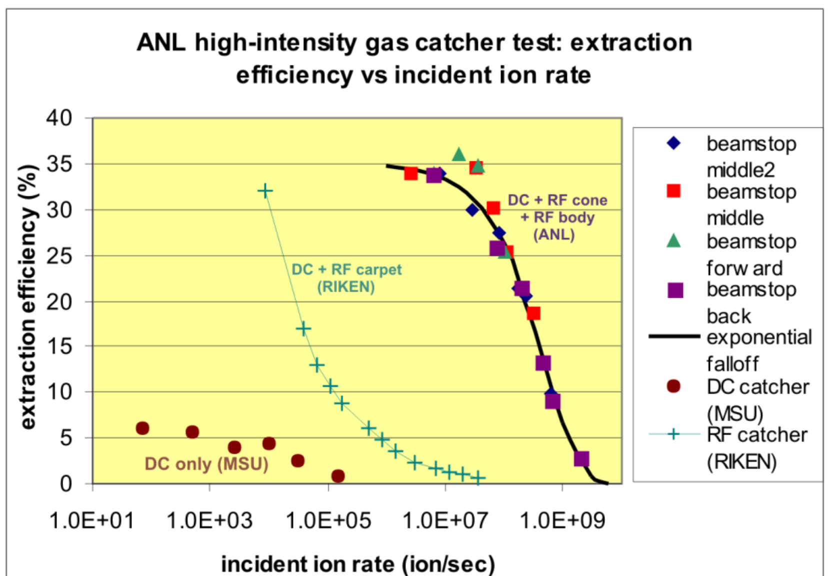
Gas catcher operation at FRIB intensities

- High intensity beamline built at ANL to reproduce ion distribution expected behind RIA/AEBL fragment separator
- Focusing by 68 cm bore superconducting solenoid
- Large gas catcher using large RF cone developed for high energy test at GSI, combined with full body RF focusing





- First tests at high intensity beamline in Sept and Oct 06
- High efficiency obtained at up to 10^9 incoming particles per second



What species have been extracted so far

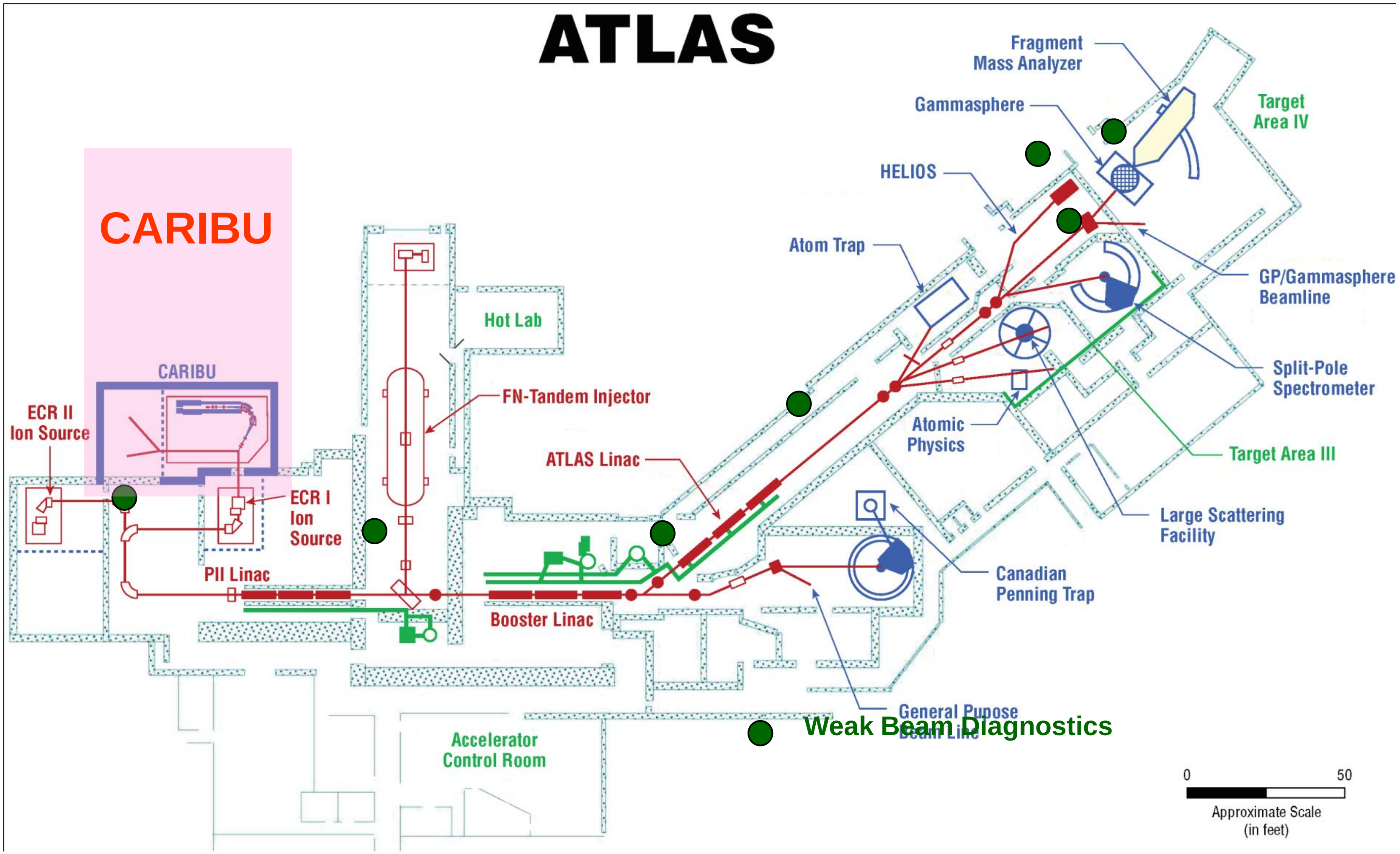
Gas catcher should be a “universal” approach … how diverse are the species that have been extracted so far:

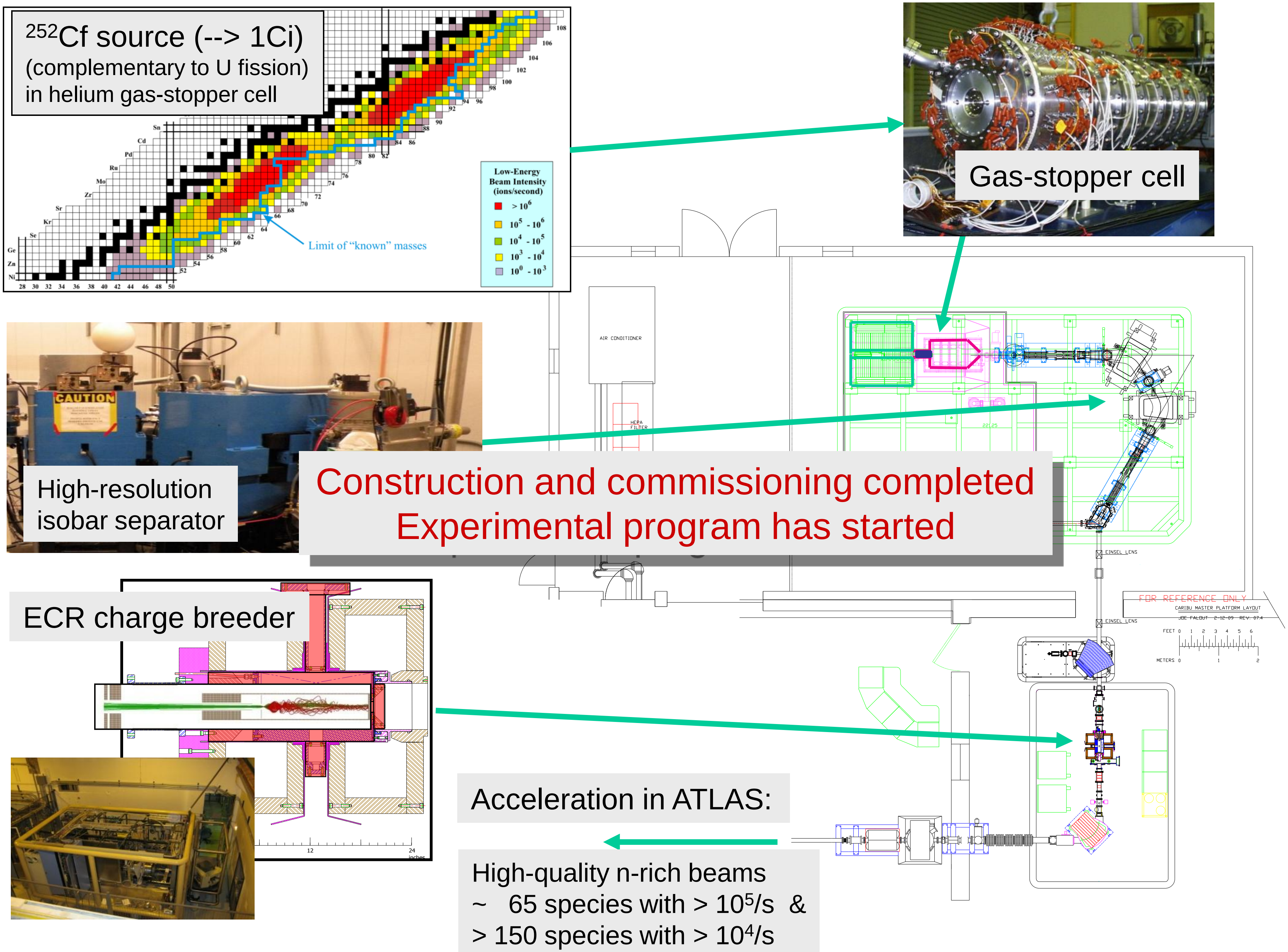
- **Neutron-deficient isotopes**
  - **Cs, Xe, Te, Sb, Sn, In, Rh, Ru, Tc, Mo, Se, As, Ge, Ga, As, Zn, Co, Fe, V, Ti, Al, Mg, Na, O, C**
- **Neutron-rich isotopes**
  - **Nd, Ce, Pr, La, Ba, Rh, Ru, Te, Tc, Mo, Sr**
- **Stable isotopes**
  - **Xe, Kr, Ar, Ne**

Essentially all attempted species, from the “easy” (alcali atoms and noble gases) up to the very refractory cases (Mo, Tc, Co, etc …) , have been extracted as singly or doubly charged ions.

All with good efficiency.

Layout for ^{252}Cf fission source system at ATLAS

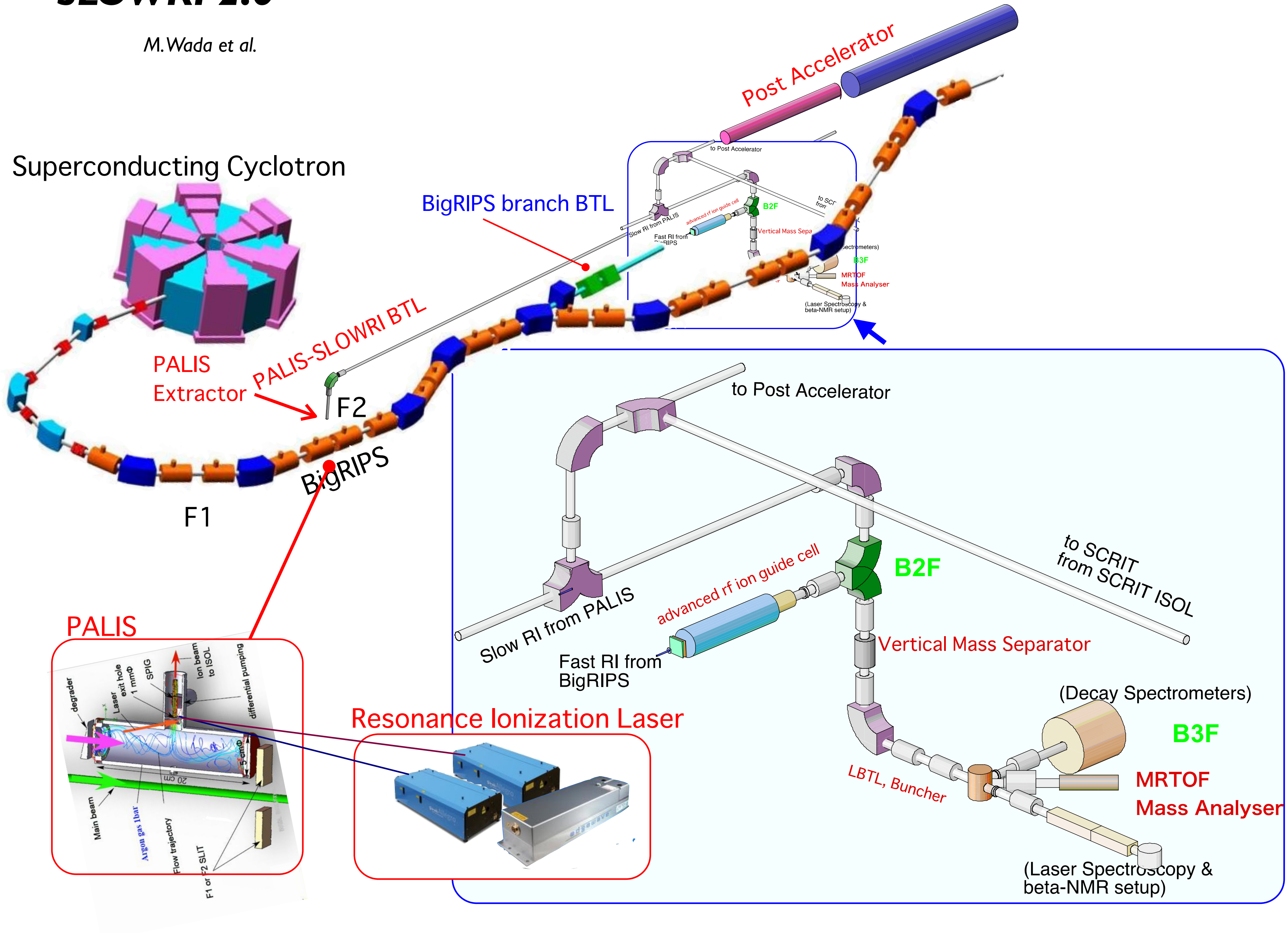


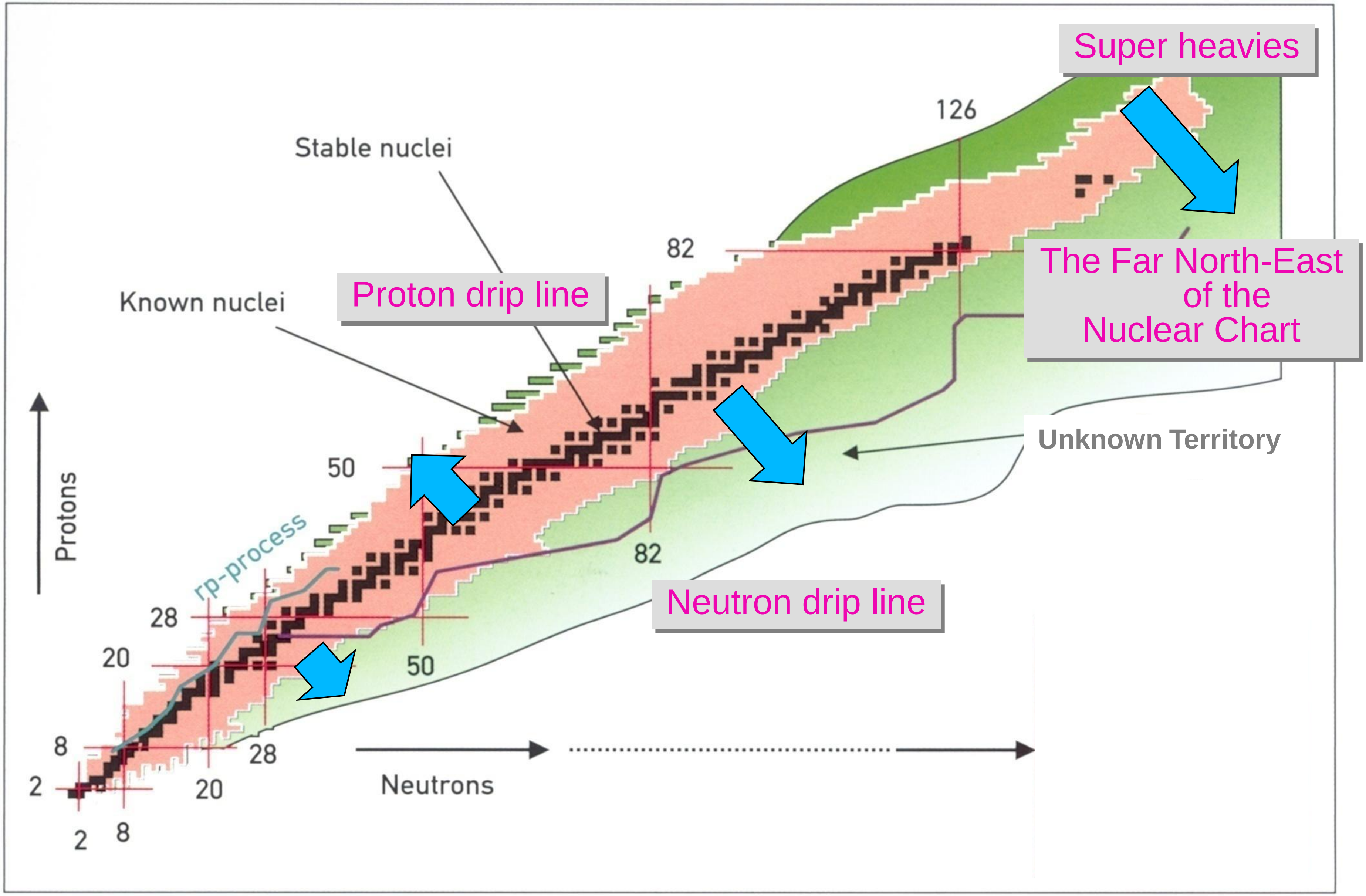


^{252}Cf source (--> 1Ci)
(complementary to U fission)
in helium gas-stopper cell
Low-Energy Beam Intensity (ions/second)
> 10^6
10^5 - 10^6
10^4 - 10^5
10^3 - 10^4
10^0 - 10^3
Limit of "known" masses
Gas-stopper cell
High-resolution isobar separator
CAUTION
Construction and commissioning completed
Experimental program has started
ECR charge breeder
AIR CONDITIONER
HEPA FILTER
EINSEL LENS
FOR REFERENCE ONLY
CARIBU MASTER PLATFORM LAYOUT
FEET
METERS
Acceleration in ATLAS:
High-quality n-rich beams
~ 65 species with > 10^5/s &
> 150 species with > 10^4/s

SLOWRI 2.0

M.Wada et al.




Super heavies
126
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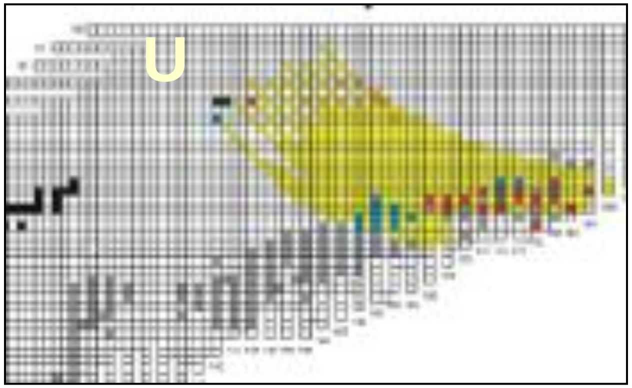
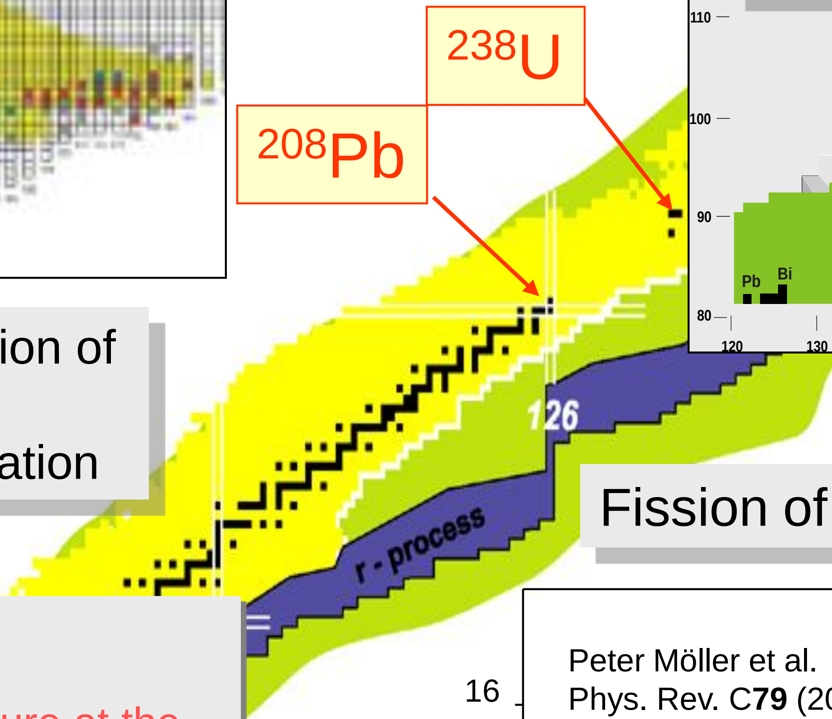
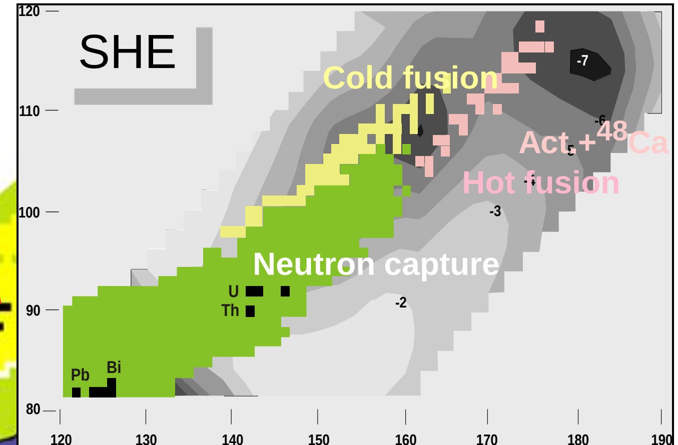


r-Process production of ^{232}Th and ^{238}U -- and fission termination

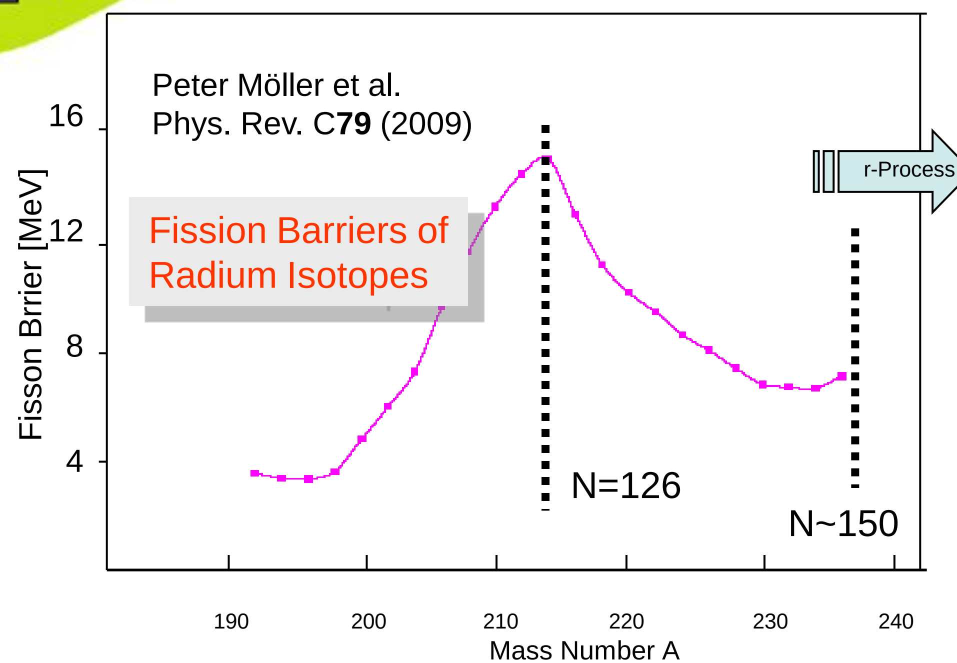


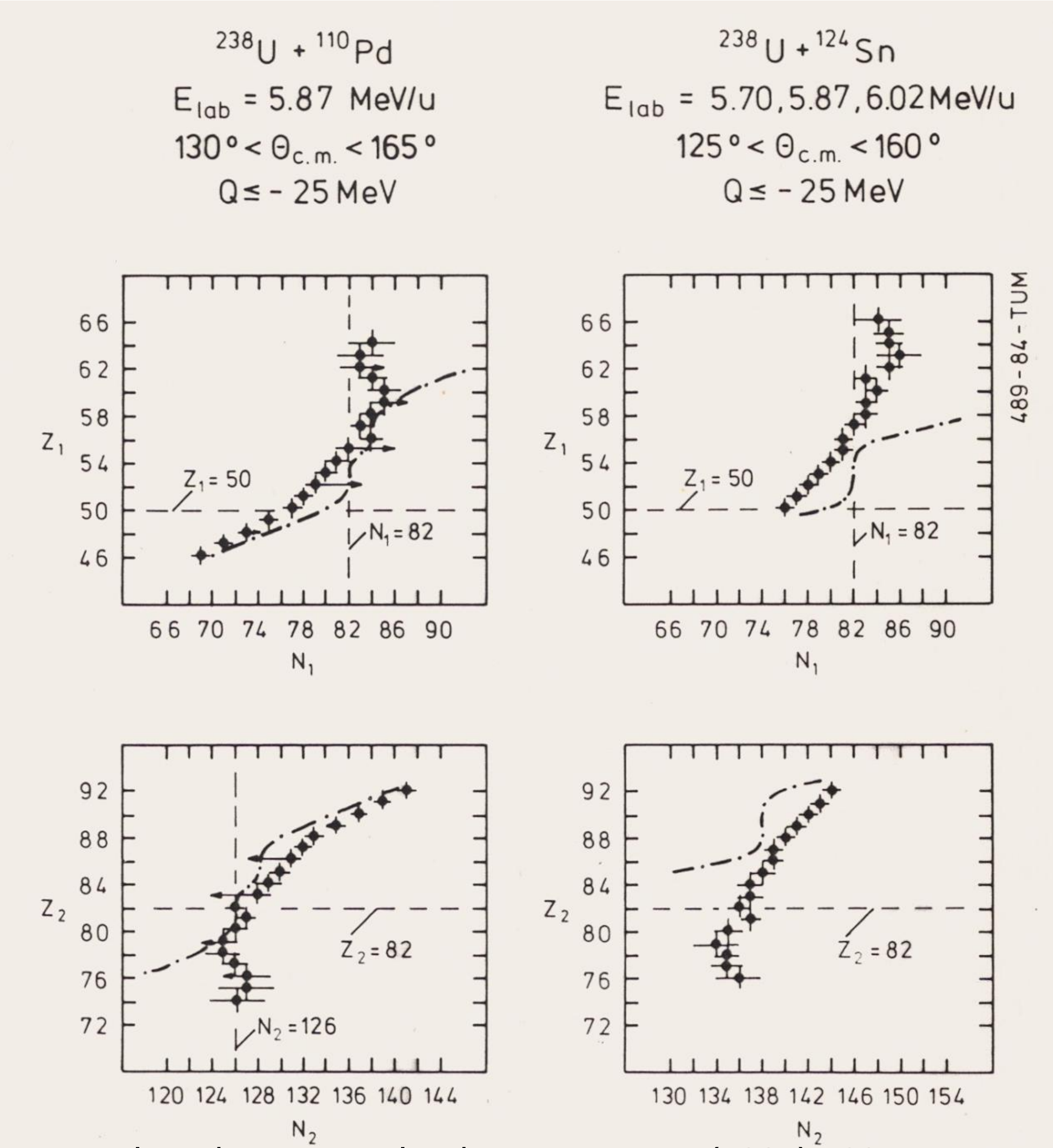


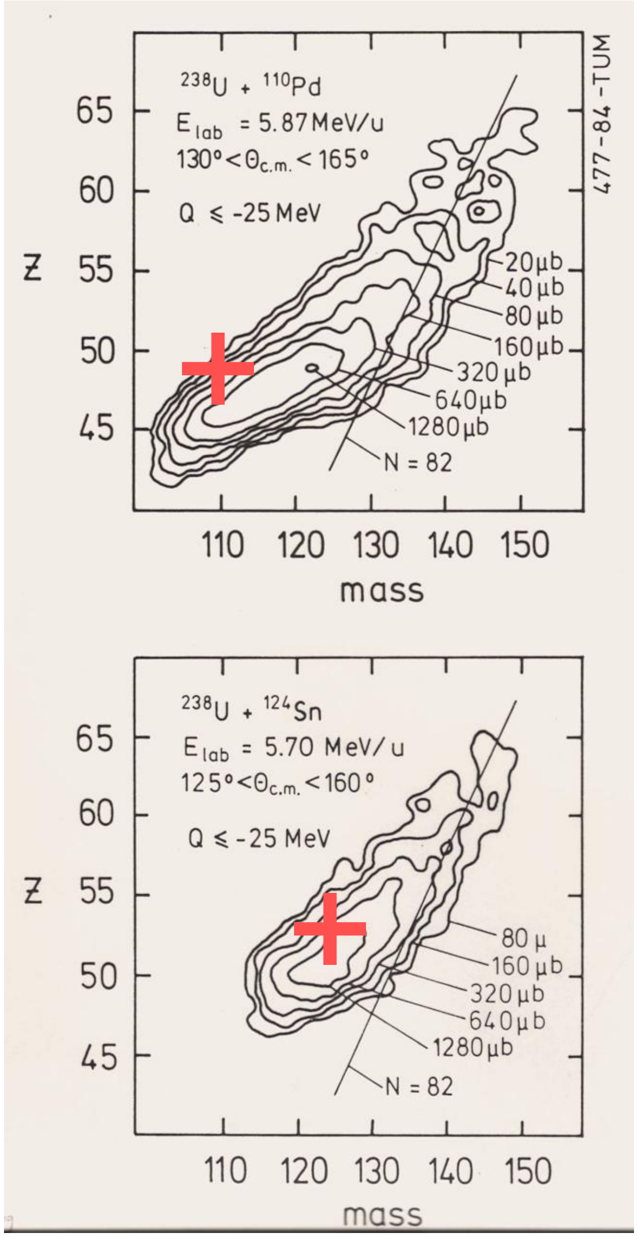
Fission of Neutron-Rich Nuclei

The Science:

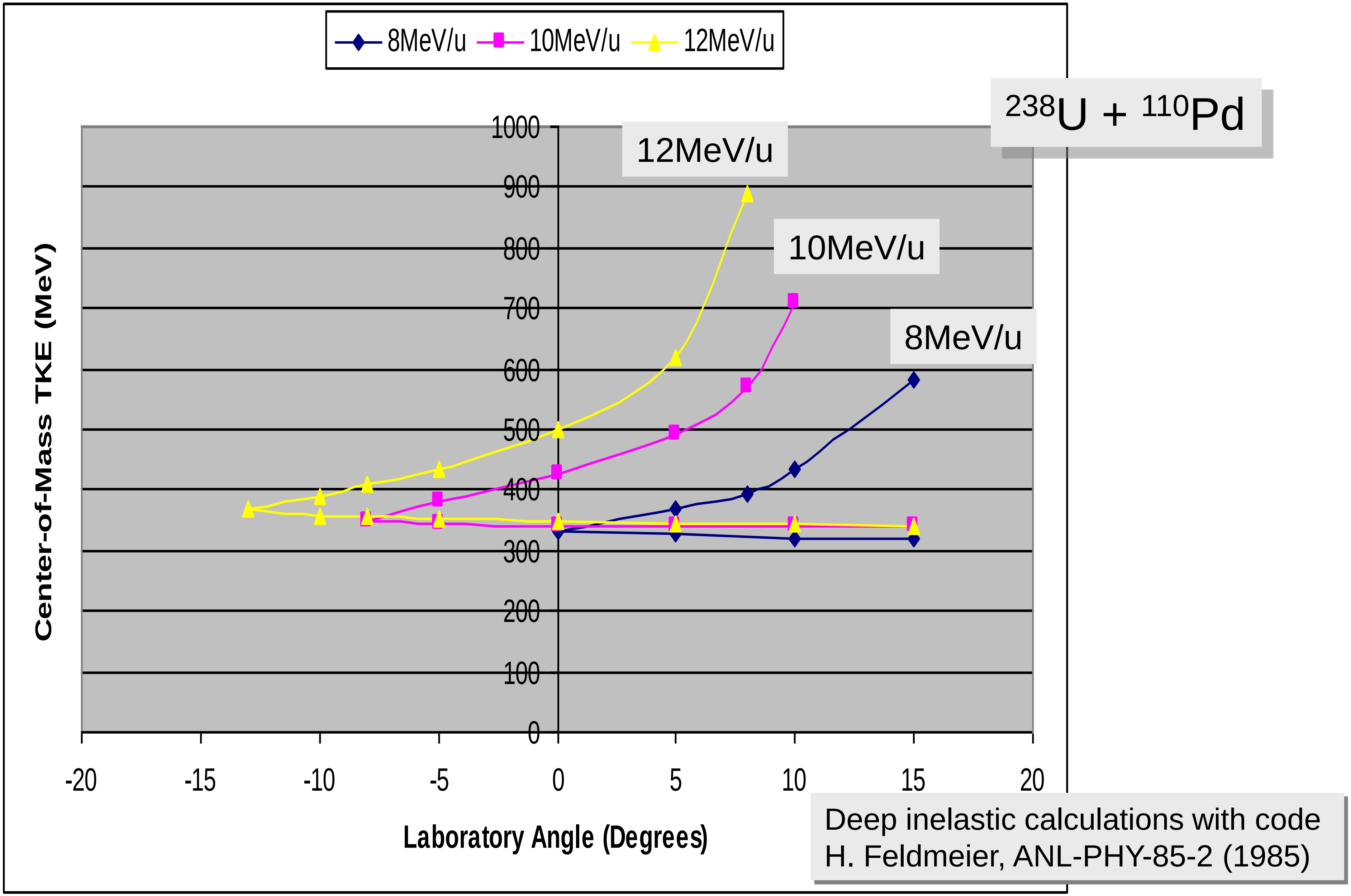
- nuclear shell structure at the extremes
- r-process: fission recycling and termination
- fission barriers of neutron-rich nuclei and symmetry energy
- connection of hot-fusion SHE island and mainland
- Unusual GT vs 1st forbidden decay ratios







Waltraud Mayer et al., Phys. Lett. **B115** (1985) 162



8MeV/u
10MeV/u
12MeV/u
$^{238}U + ^{110}Pd$
12MeV/u
10MeV/u
8MeV/u
1000
900
800
700
600
500
400
300
200
100
0
-20
-15
-10
-5
0
5
10
15
20
Center-of-Mass TKE (MeV)
Laboratory Angle (Degrees)
Deep inelastic calculations with code
H. Feldmeier, ANL-PHY-85-2 (1985)

Extremes of the (nuclear) landscape...

Exploring the unknown...

Many facets of new physics...

RIBF is well positioned for the future...

Thank you for your attention!