Plan for Korea Rare Isotope Accelerator (KoRIA*)

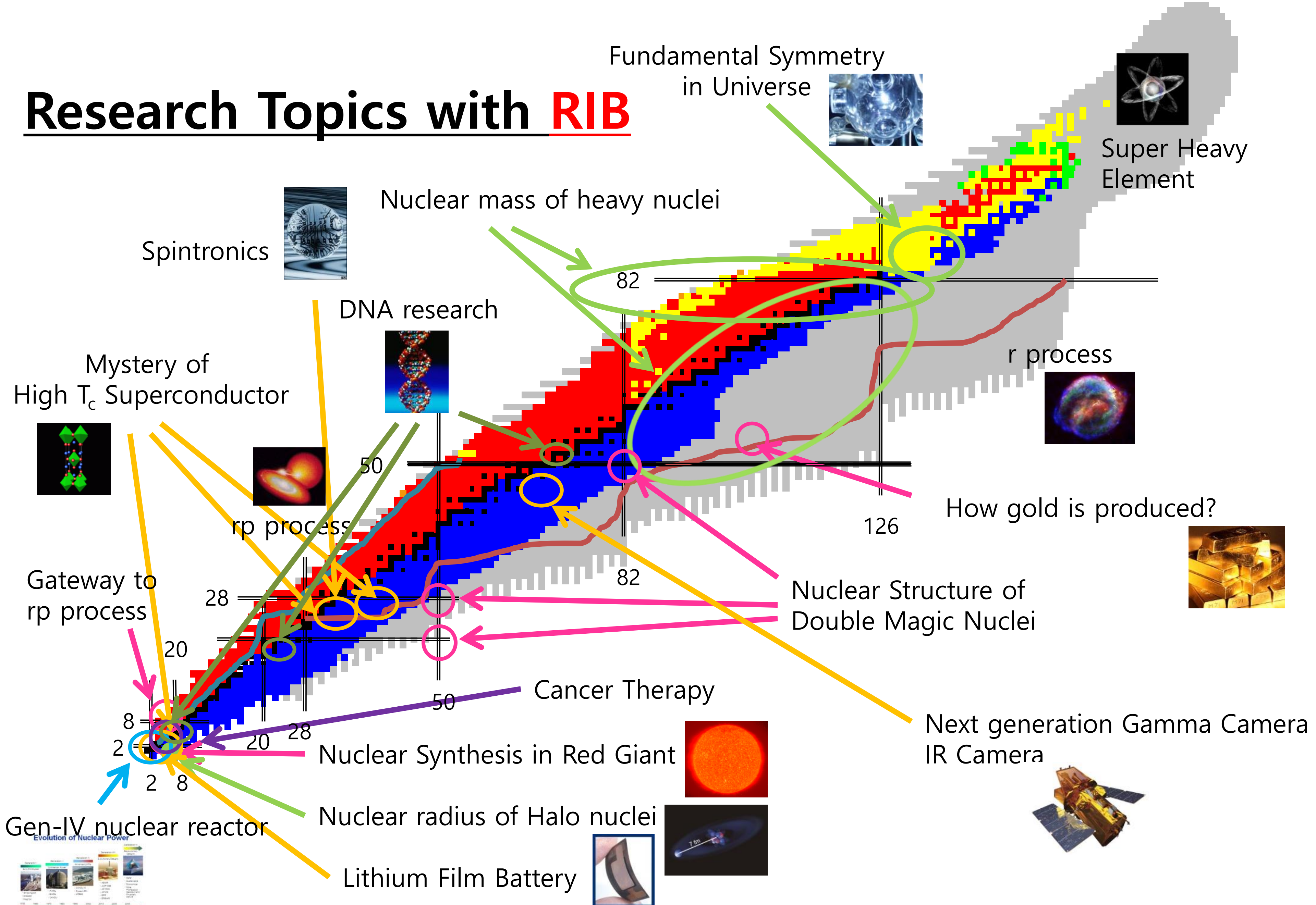
* Tentative

Byungsik Hong (Korea University)

<u>Outline</u>

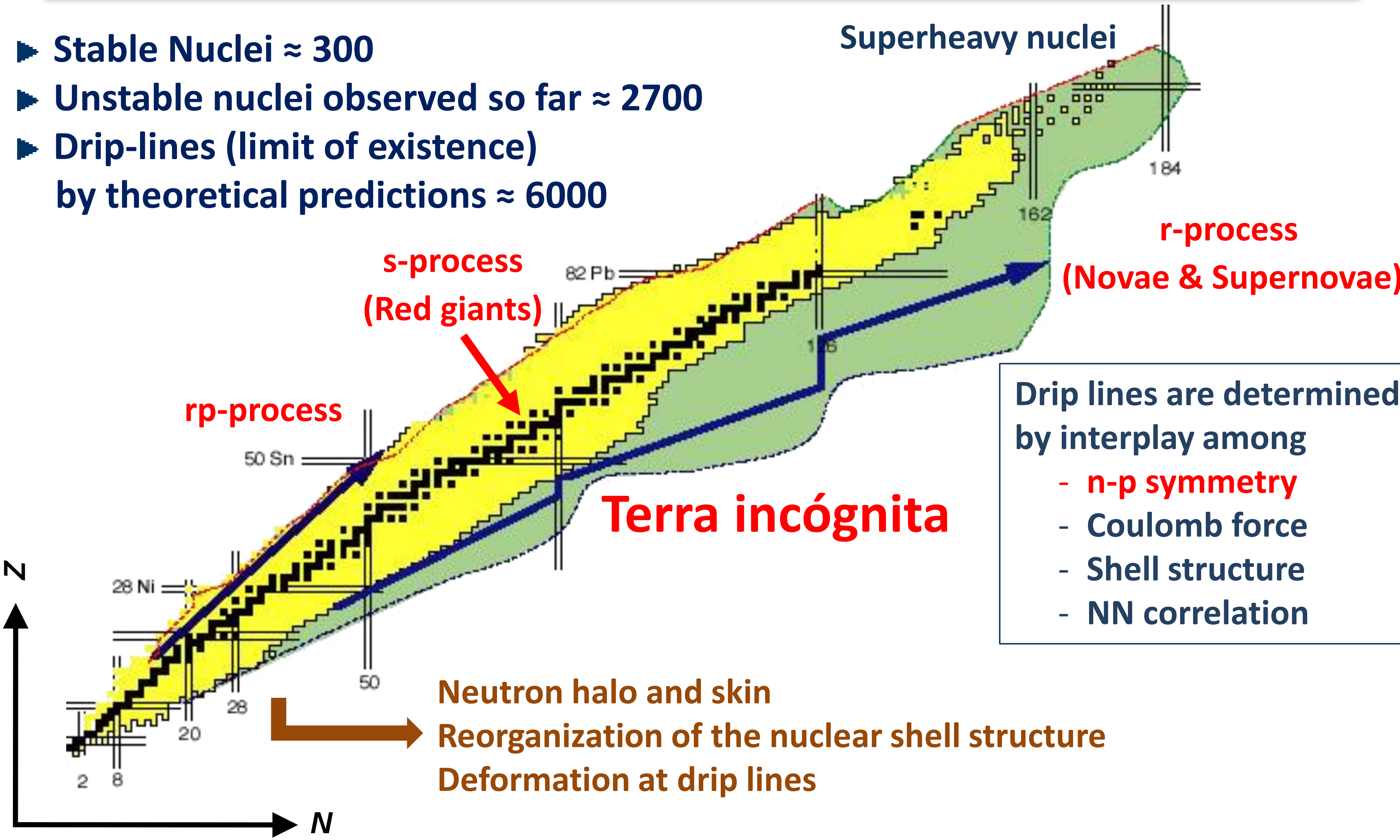
- Introduction
- Physics topics
- Experimental observables
- Summary

Research Topics with RIB



Nuclear Chart for Nuclear Physics

- Stable Nuclei ≈ 300
- Unstable nuclei observed so far ≈ 2700
- Drip-lines (limit of existence)
  by theoretical predictions ≈ 6000

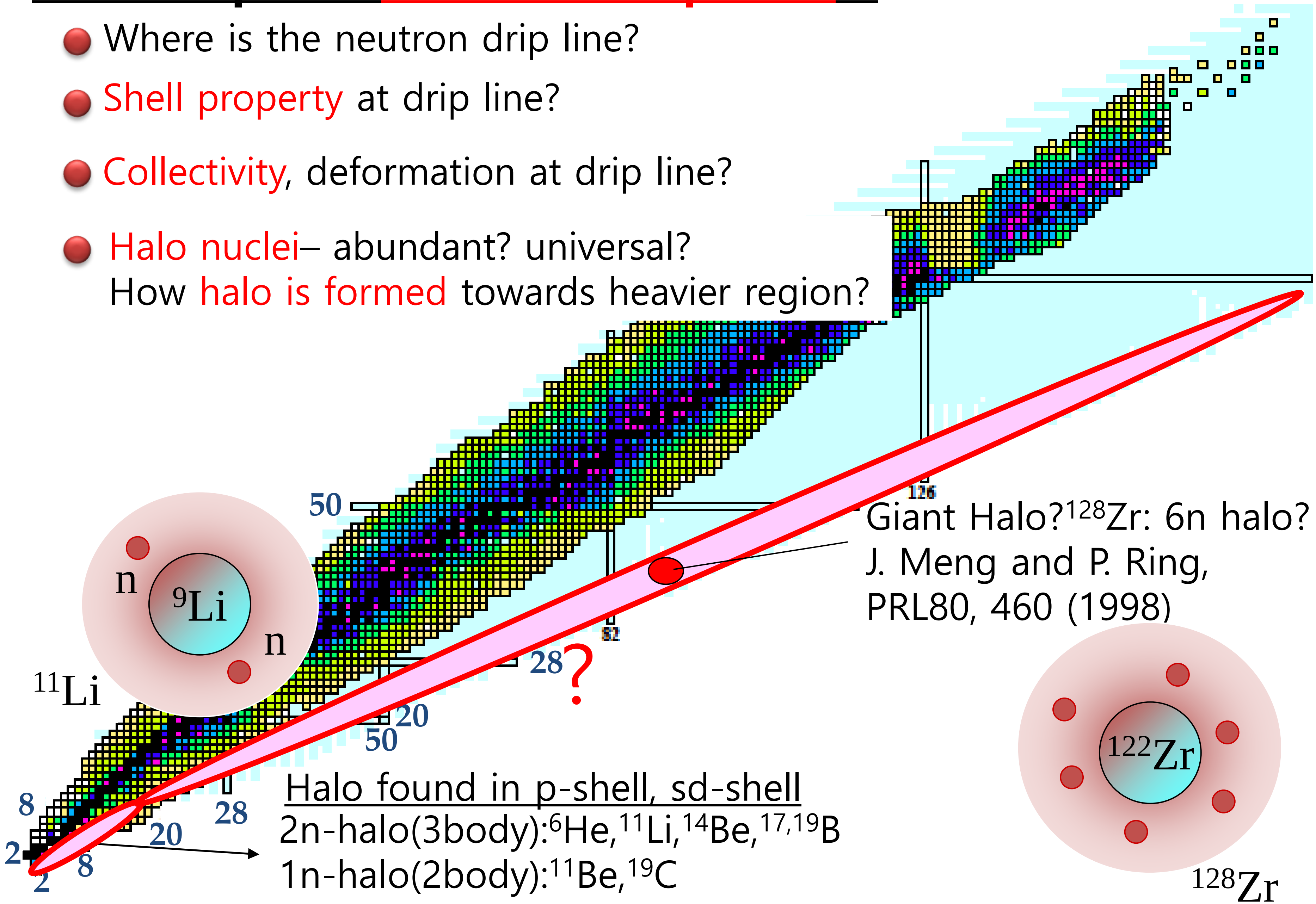


Drip lines are determined by interplay among
- n-p symmetry
- Coulomb force
- Shell structure
- NN correlation

Landscape of Neutron Drip Line?

From T. Nakamura

- Where is the neutron drip line?
- Shell property at drip line?
- Collectivity, deformation at drip line?
- Halo nuclei– abundant? universal?
  How halo is formed towards heavier region?



Giant Halo? ^{128}Zr: 6n halo?
J. Meng and P. Ring, PRL80, 460 (1998)

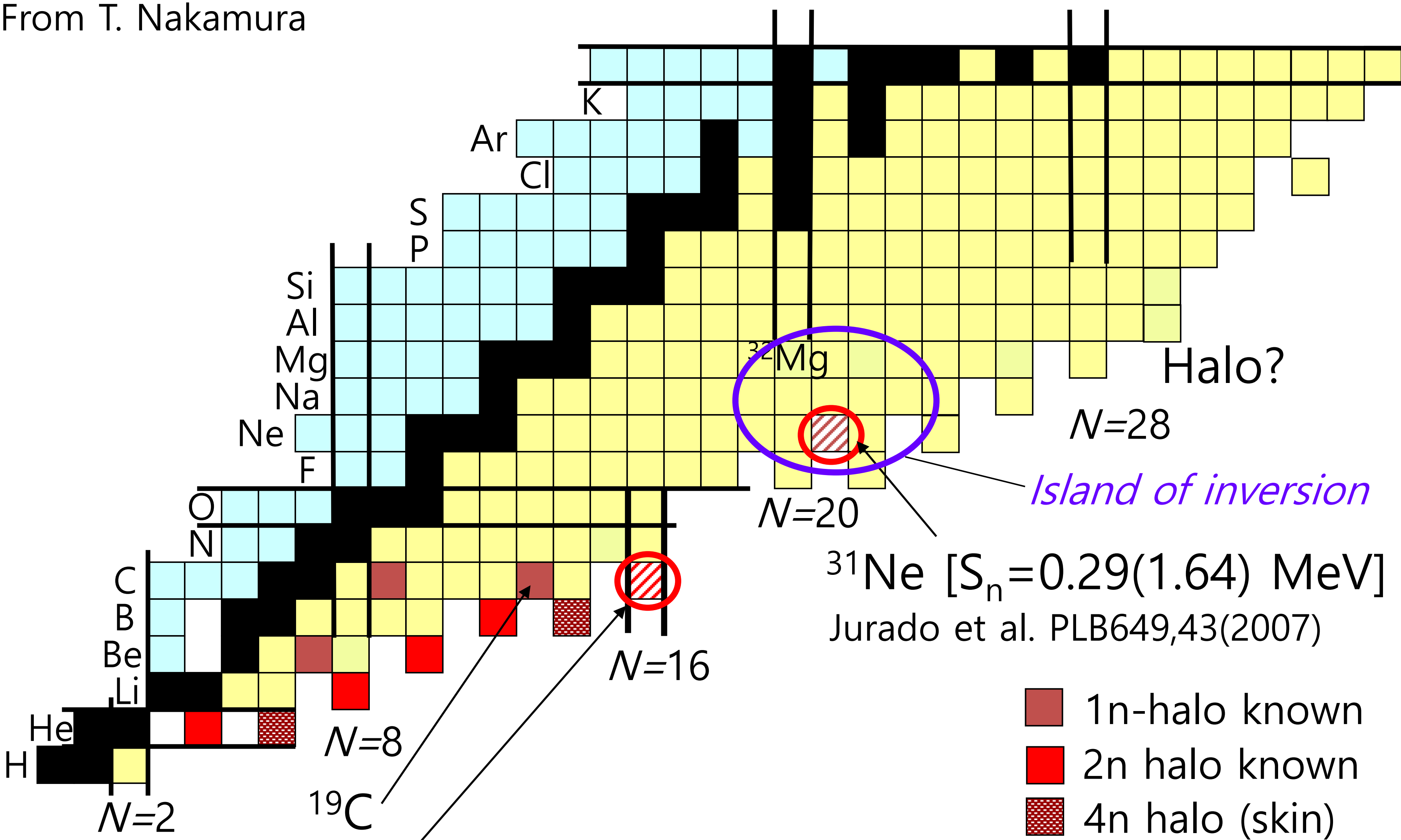
Halo found in p-shell, sd-shell

2n-halo(3body): ^{6}He, ^{11}Li, ^{14}Be, ^{17,19}B

1n-halo(2body): ^{11}Be, ^{19}C

More neutron halo's along the drip line?

From T. Nakamura

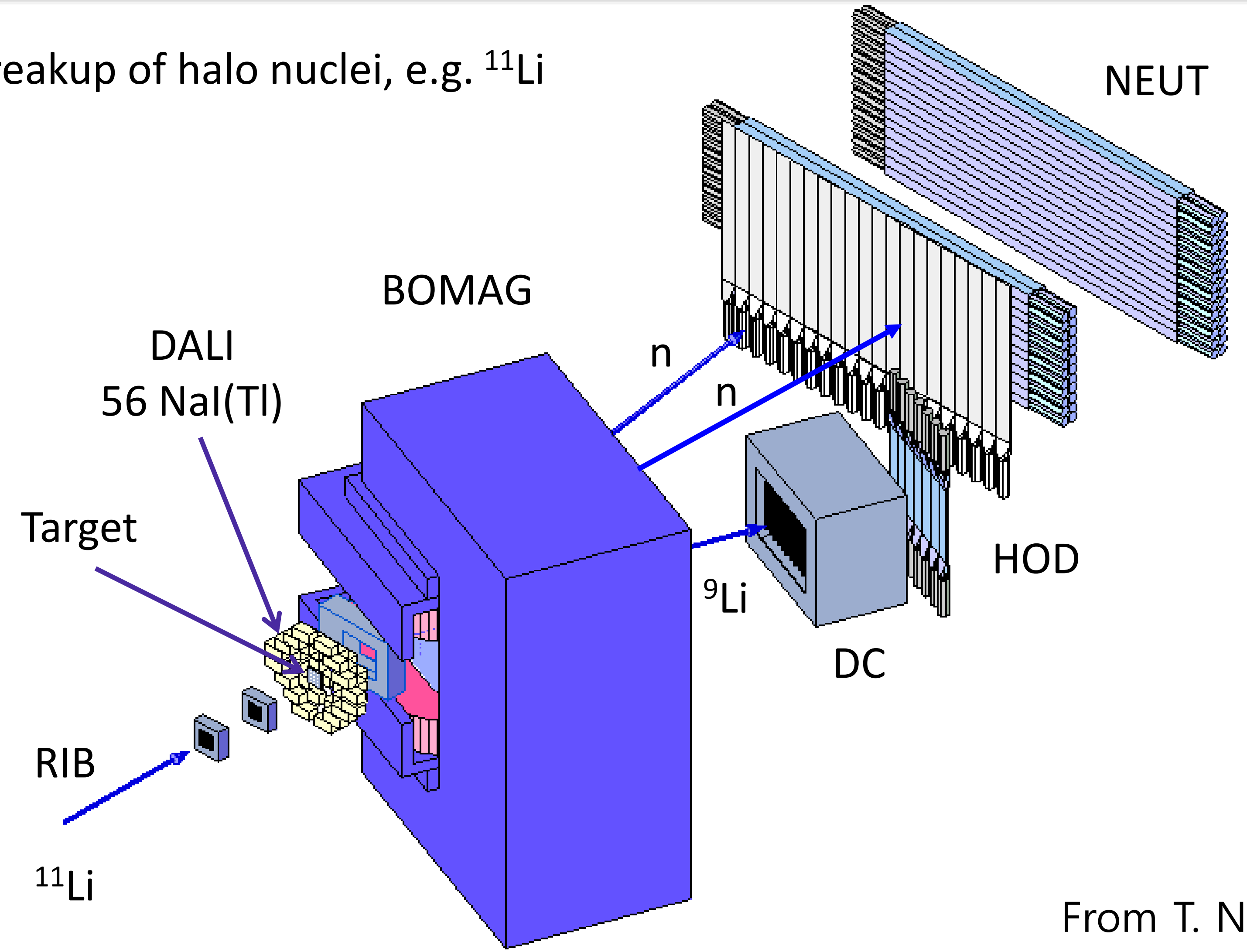


^{22}C [S_{2n^*}=0.42(94) MeV]

* Estimated value by Audi & Wapstra

RIPS @ RIKEN

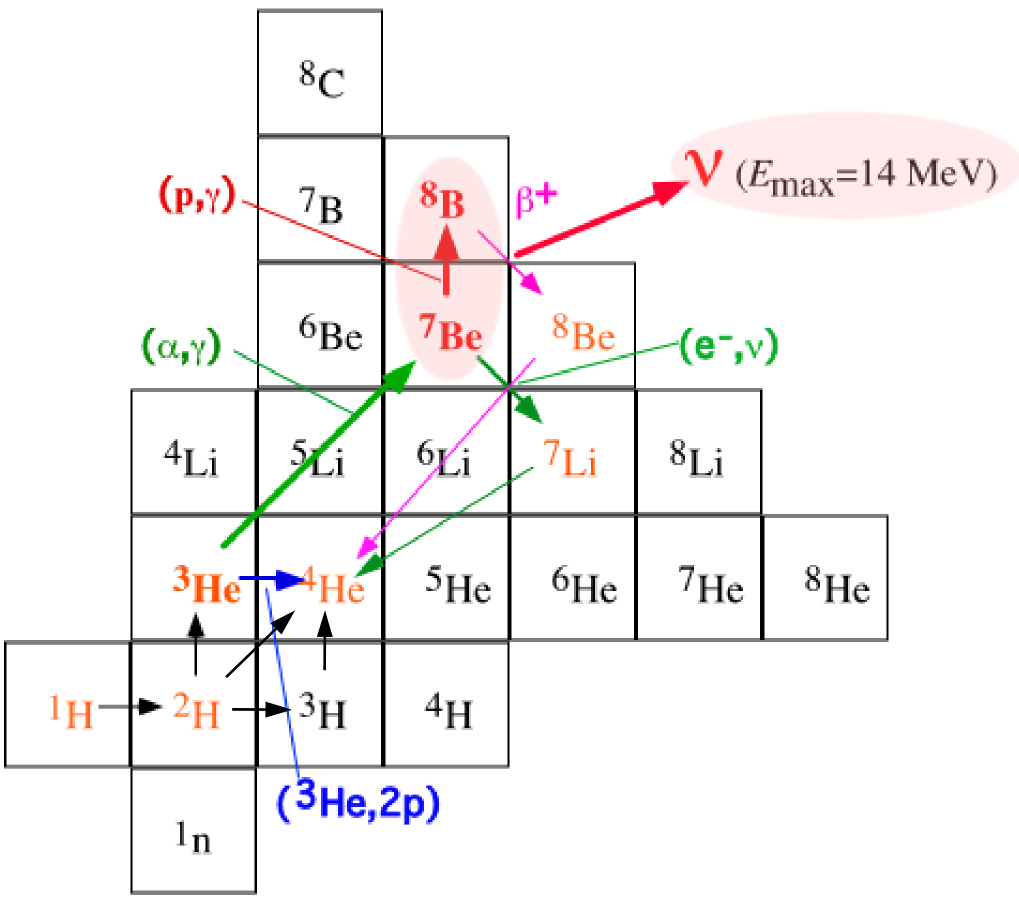
2n breakup of halo nuclei, e.g. ^{11}Li



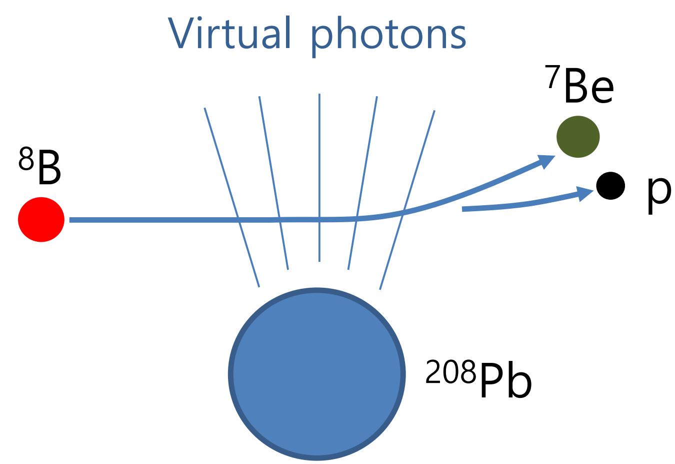
From T. Nakamura

Nuclear Astrophysics

p-p chain in the sun $^{7}Be(p,\gamma)^{8}B$ From T. Motobayashi

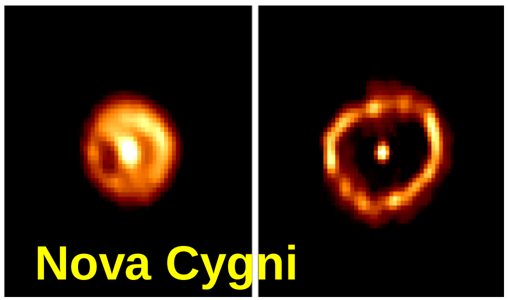


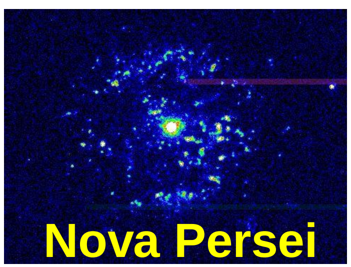
We can measure ^{8}B Coulomb dissociation with RIB

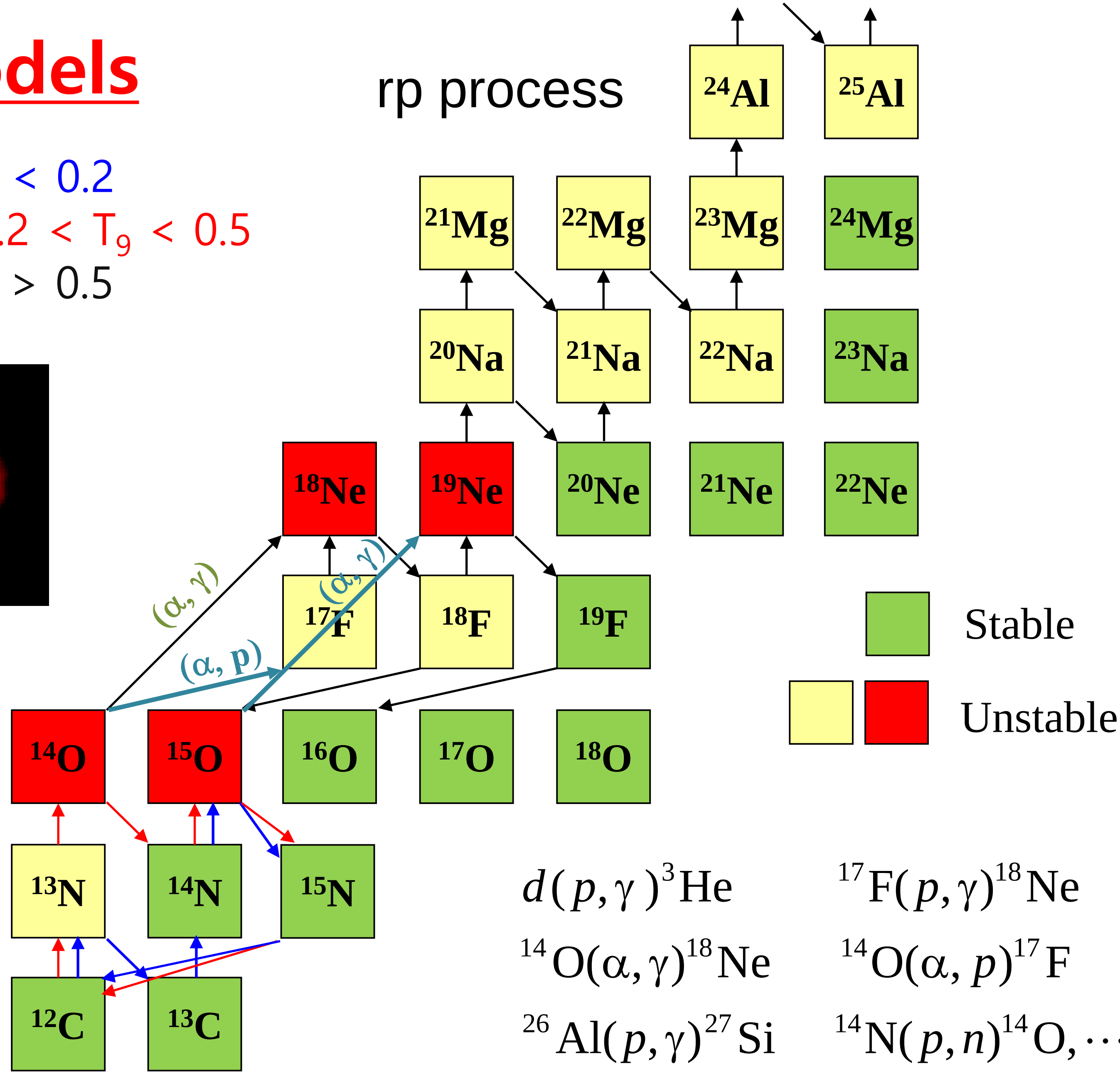


Nova Models

CNO cycle : $T_9 < 0.2$
HCNO cycle: $0.2 < T_9 < 0.5$
rp process : $T_9 > 0.5$







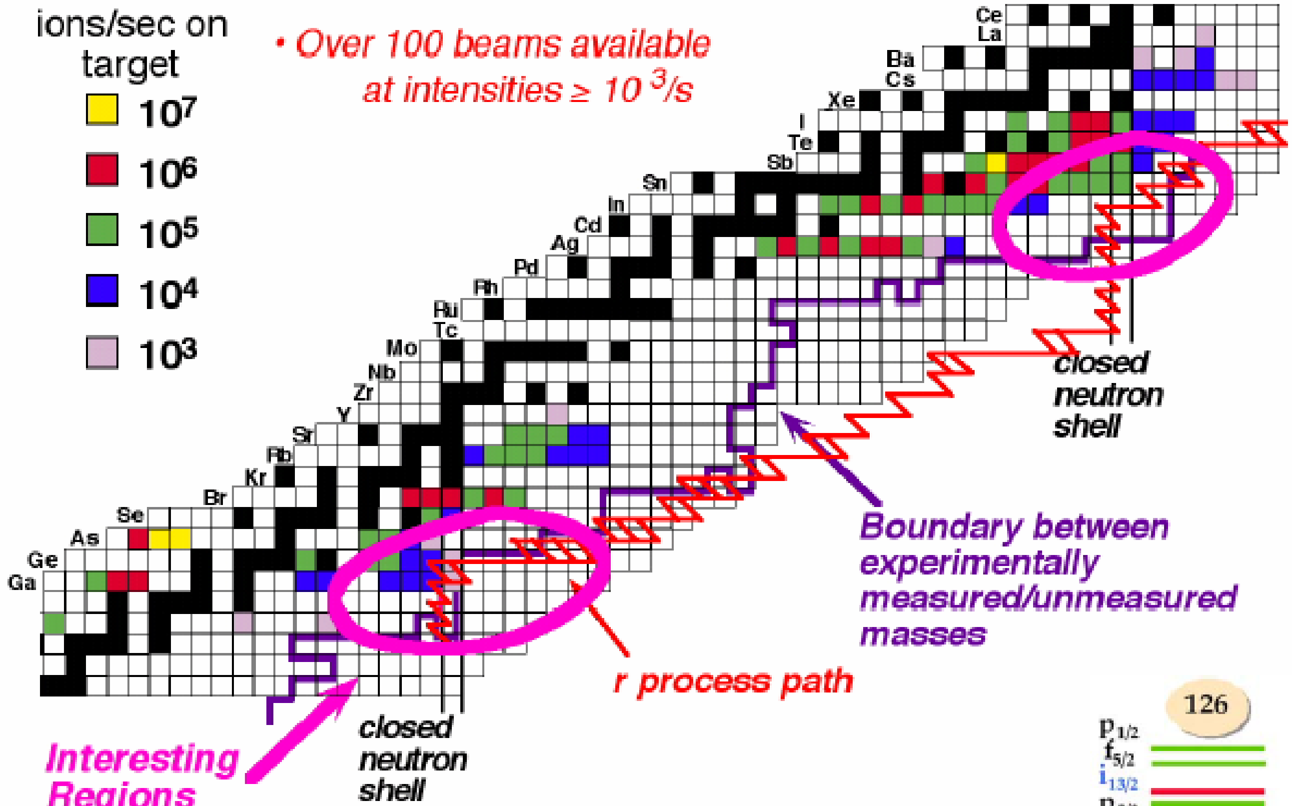
CNO cycle
HCNO cycle

$d(p,\gamma)^3\mathrm{He}$ $\quad {}^{17}\mathrm{F}(p,\gamma)^{18}\mathrm{Ne}$

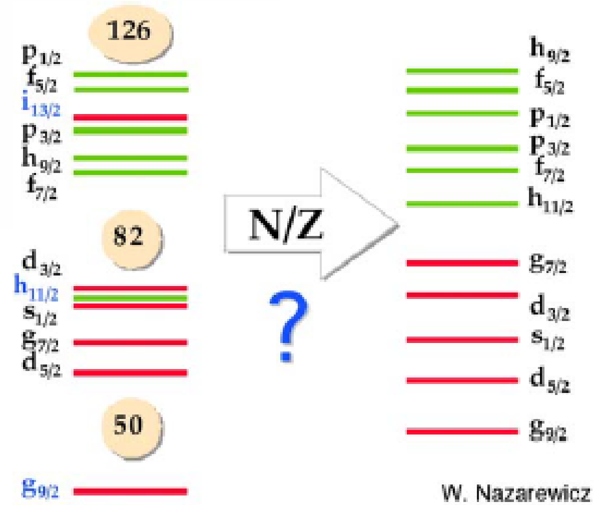
${}^{14}\mathrm{O}(\alpha,\gamma)^{18}\mathrm{Ne}$ $\quad {}^{14}\mathrm{O}(\alpha,p)^{17}\mathrm{F}$

${}^{26}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$ $\quad {}^{14}\mathrm{N}(p,n)^{14}\mathrm{O},\cdots$

Nuclear Structure Studies at Large Neutron Excess

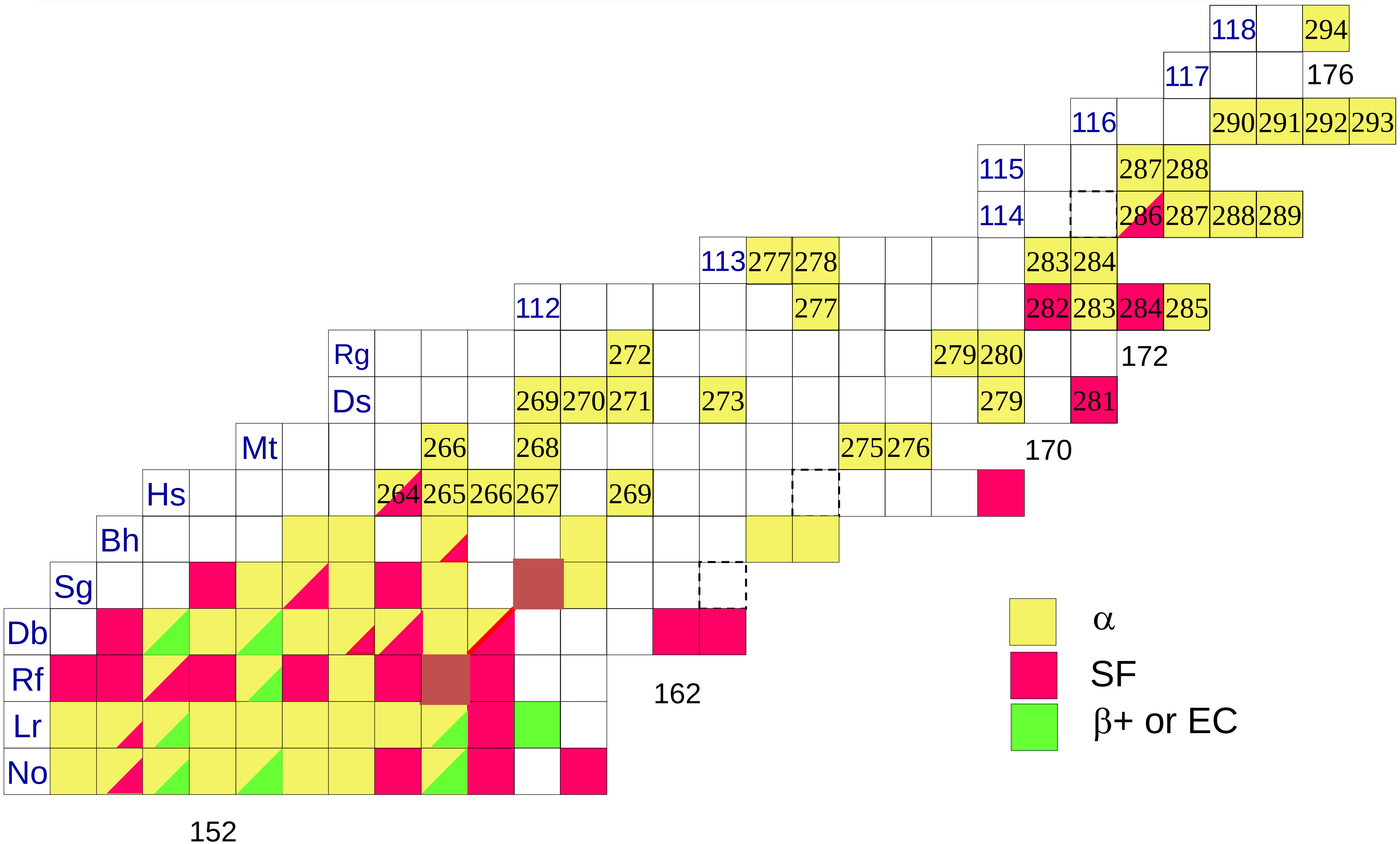


- Nuclear Structure in & near the r-process path



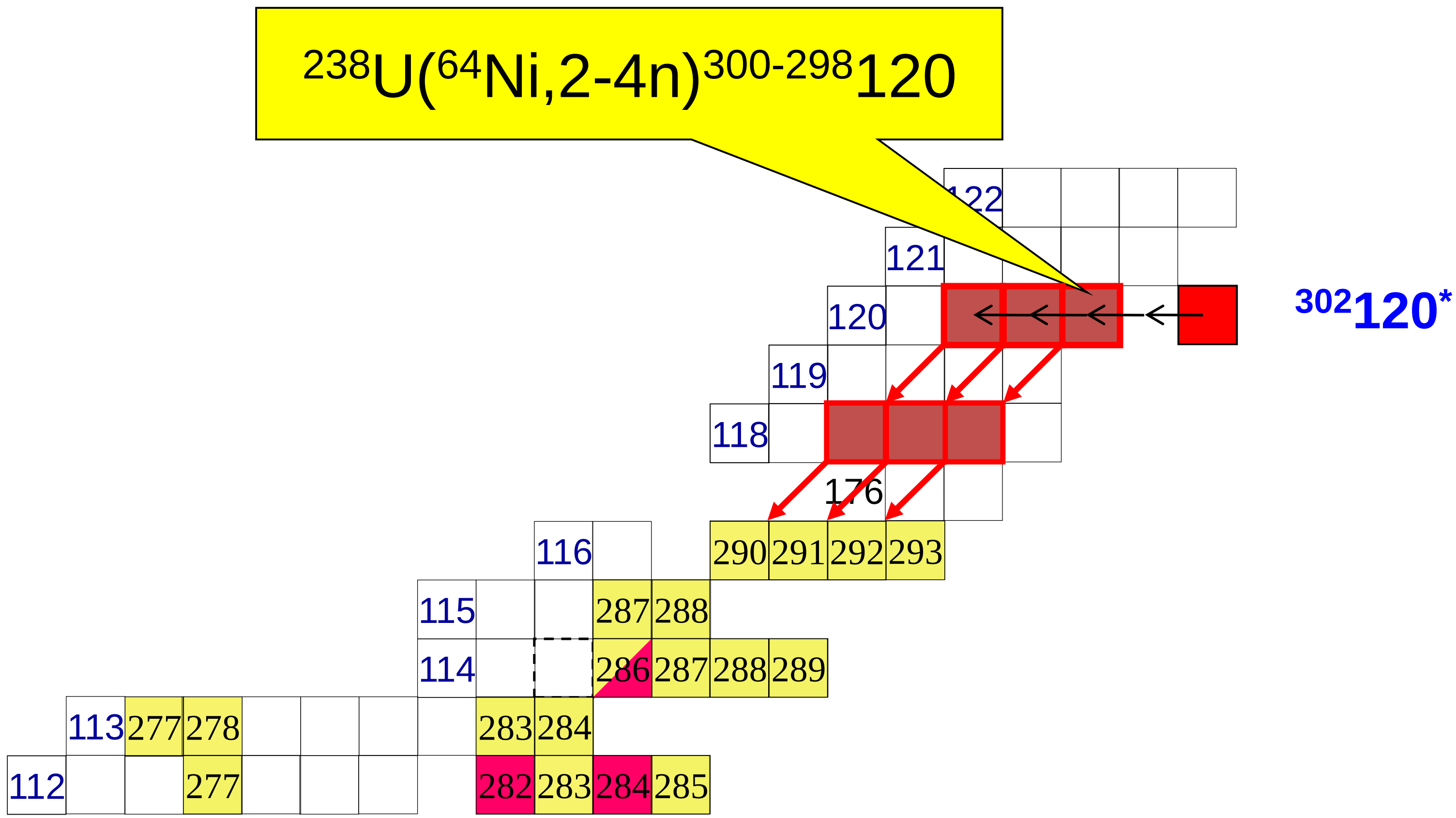
hribf

Superheavy Nuclei: Current Status

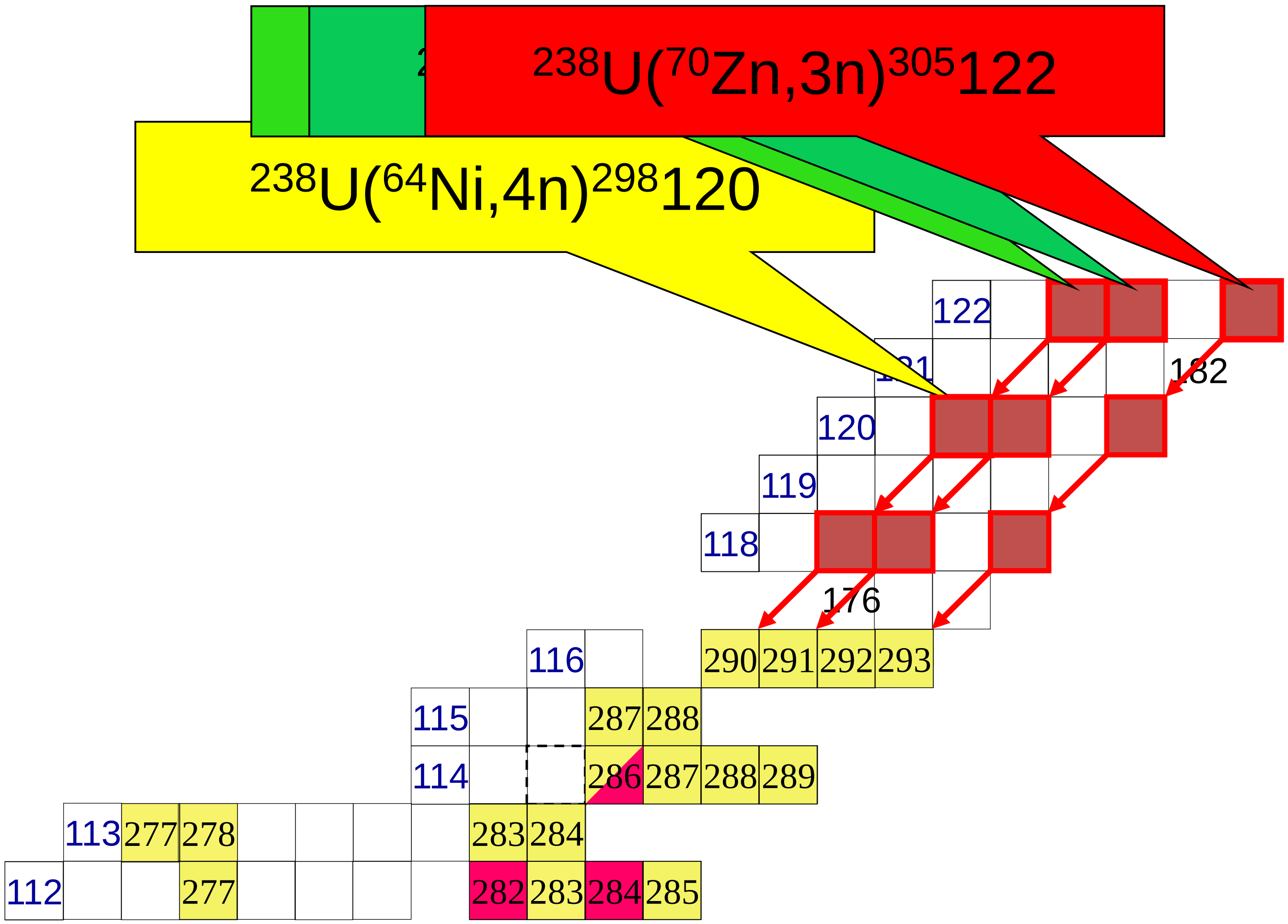


Reactions Tried at GSI in 2007-2008

$^{64}Ni + ^{238}U \rightarrow ^{302}120^{*}$

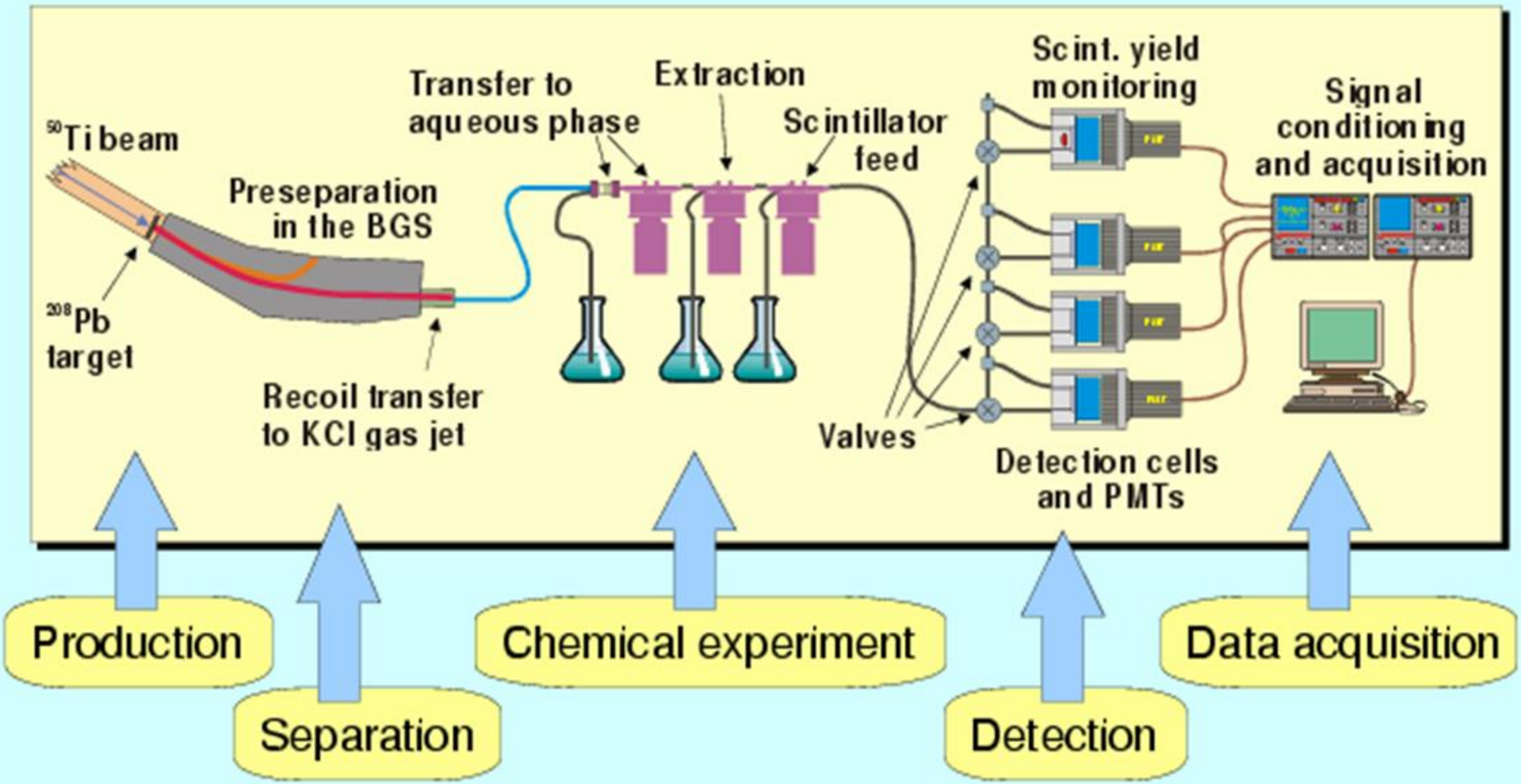


Reactions Could be Studied



From Y.H. Chung, Hallym Univ.

Overview



50Ti beam
208Pb target
Preseparation in the BGS
Recoil transfer to KCl gas jet
Transfer to aqueous phase
Extraction
Scintillator feed
Scint. yield monitoring
Valves
Detection cells and PMTs
Signal conditioning and acquisition
Production
Separation
Chemical experiment
Detection
Data acquisition

Spin Structure of Unstable Nuclei

From W.Y. Kim, Kyungbook Nat. Univ.

1. Spin-dependent interactions
   - Origin of fundamental properties of nuclei
   - Modification in neutron rich nuclei
2. Spin-orbit couplings and potentials
   - Localized at the nuclear surface

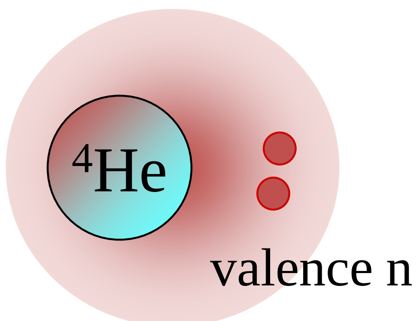
$$V_{LS} \sim \frac{1}{r}\frac{d\rho(r)}{dr}$$

   - Will be modified in neutron rich nuclei
   - Should be composed of two parts localized at different positions if p and n have different $\rho(r)$
   - Would have extended shape if n has an extended distribution in skin or halo nuclei
3. Need polarized p, d, and ^{3}He targets

Present Status at RIKEN

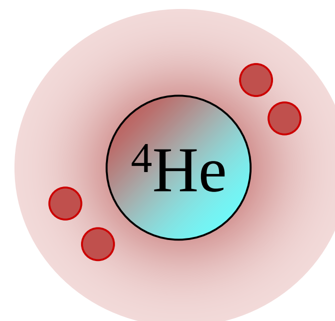
S.Sakaguchi Ph.D. Thesis, University of Tokyo (2008)

^{6}He



1. Di-neutron structure
   → Large recoil motion of α-core
   → Large charge radius (2.068 fm)
2. Two valence neutrons
   → Small matter radius (2.45 fm)

^{8}He

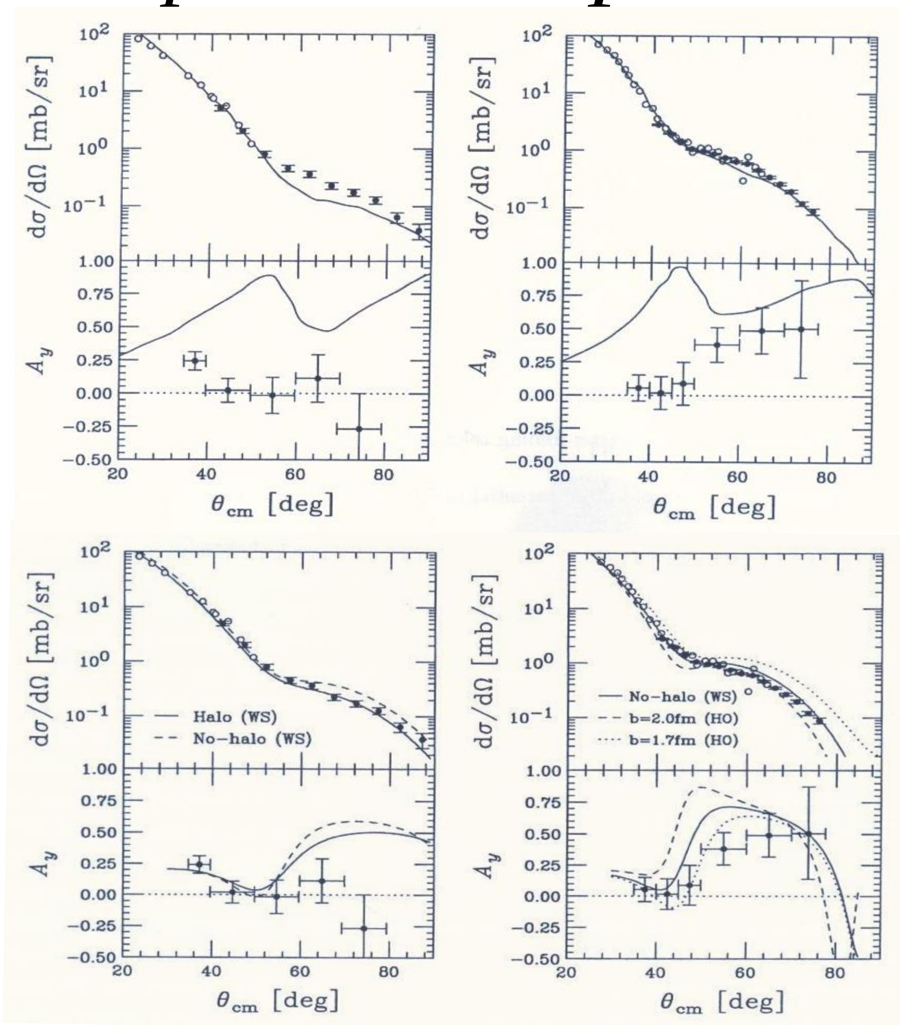


1. Isotropically distributed neutrons
   → Small recoil motion of α-core
   → Small charge radius (1.929 fm)
2. Four valence neutrons
   → Large matter radius (2.53 fm)

Present Status at RIKEN

$\vec{p}-{}^{6}\mathrm{He}$ $\vec{p}-{}^{8}\mathrm{He}$

S.Sakaguchi (2008)



t-matrix folding calculation

Non-local g-matrix folding calculation

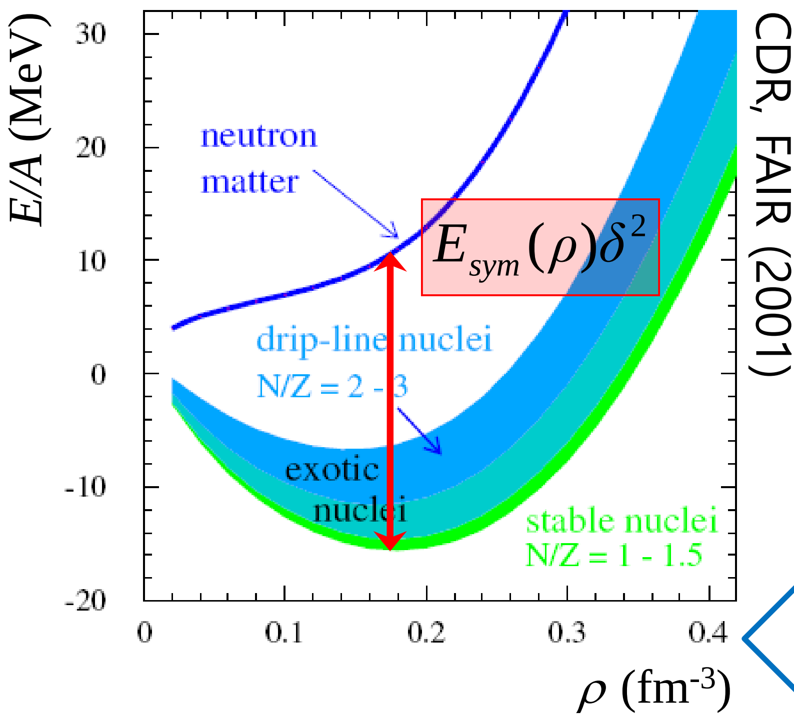
Nuclear Equation of State

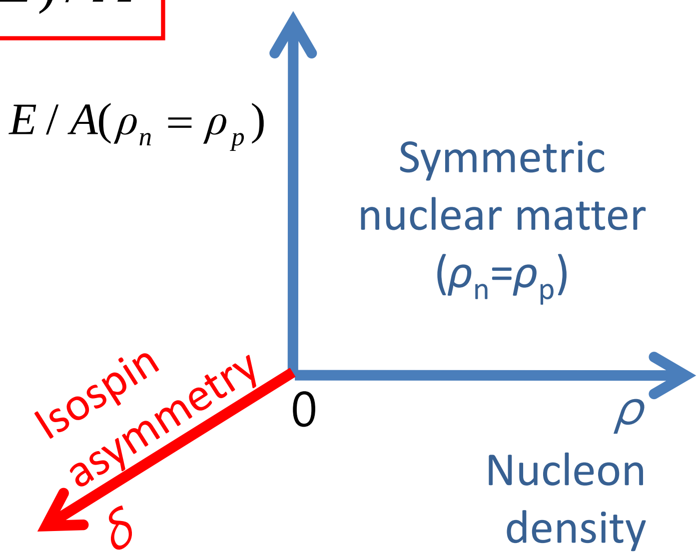
$$E(\rho_n, \rho_p) = E(\rho_n = \rho_p) + E_{sym}(\rho)\delta^2 + O(\delta^4)$$

$$E_{sym}(\rho) = \frac{1}{2}\frac{\partial^2 E}{\partial \delta^2} \approx E(\rho)_{\substack{\text{pure}\\ \text{neutron matter}}} - E(\rho)_{\substack{\text{symmetric}\\ \text{nuclear matter}}}$$

with $\rho = \rho_n + \rho_p,\ \delta = (\rho_n - \rho_p)/\rho = (N-Z)/A$

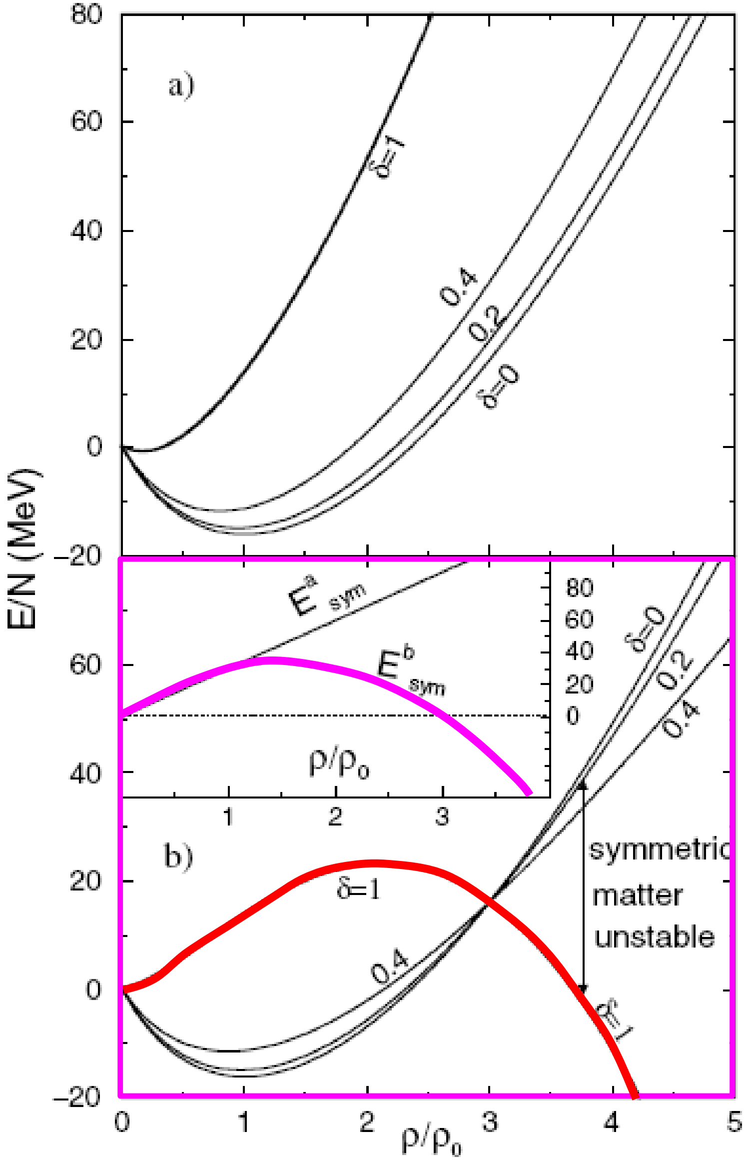
B.-A. Li, L.-W. Chen & C.M. Ko
Physics Report, **464,** 113 (2008)



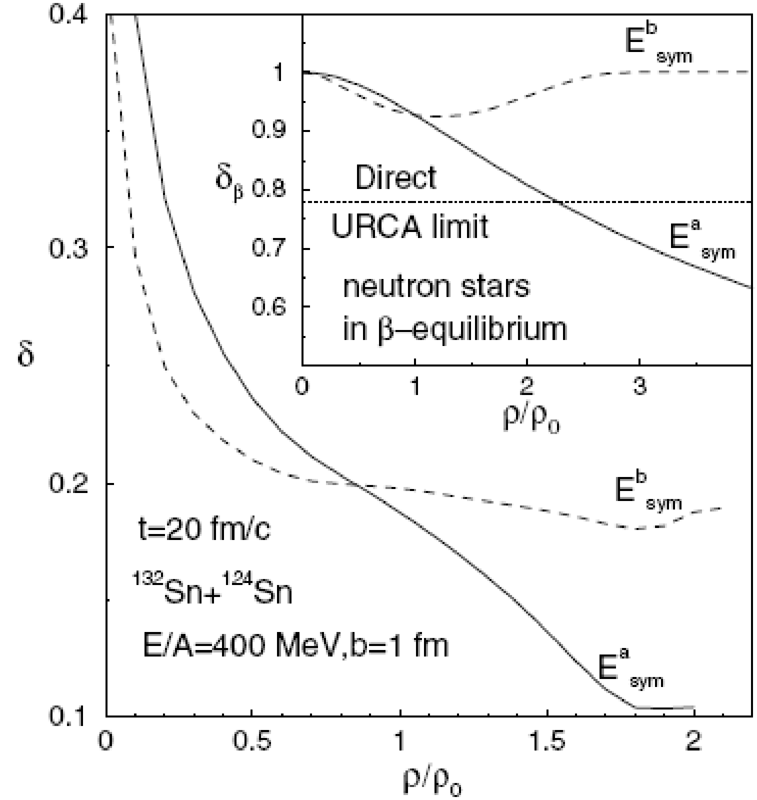


F. de Jong & H. Lenske, RPC 57, 3099 (1998)
F. Hofman, C.M. Keil & H. Lenske, PRC 64, 034314 (2001)

Nuclear Equation of State

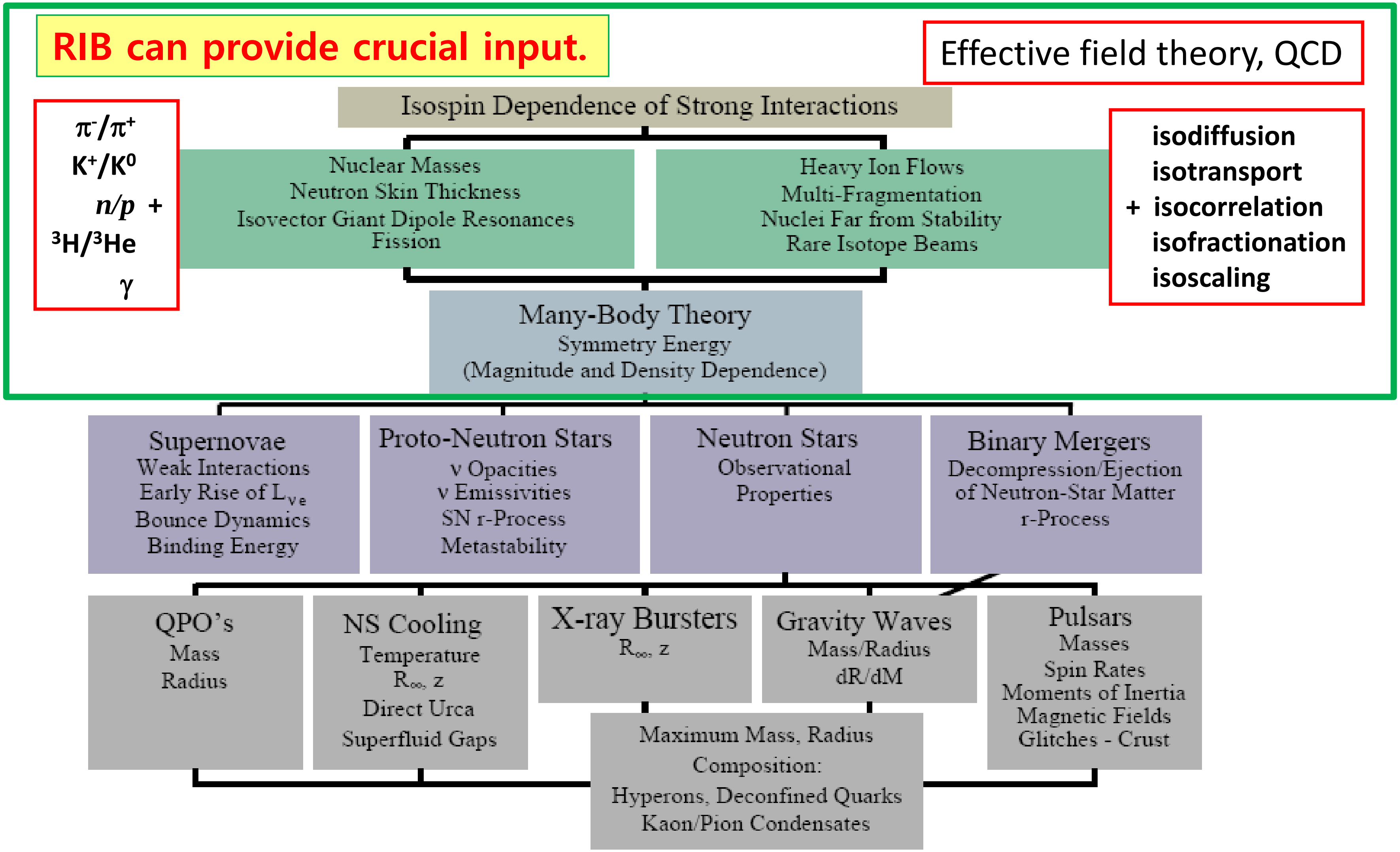


Bao-An Li, PRL 88, 192701 (2002)



High **(Low)** density matter is more neutron rich with **soft** **(stiff)** symmetry energy

Importance of Symmetry Energy



- A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, Physics Report 411, 325 (2005)
- Red boxes: added by B.-A. Li

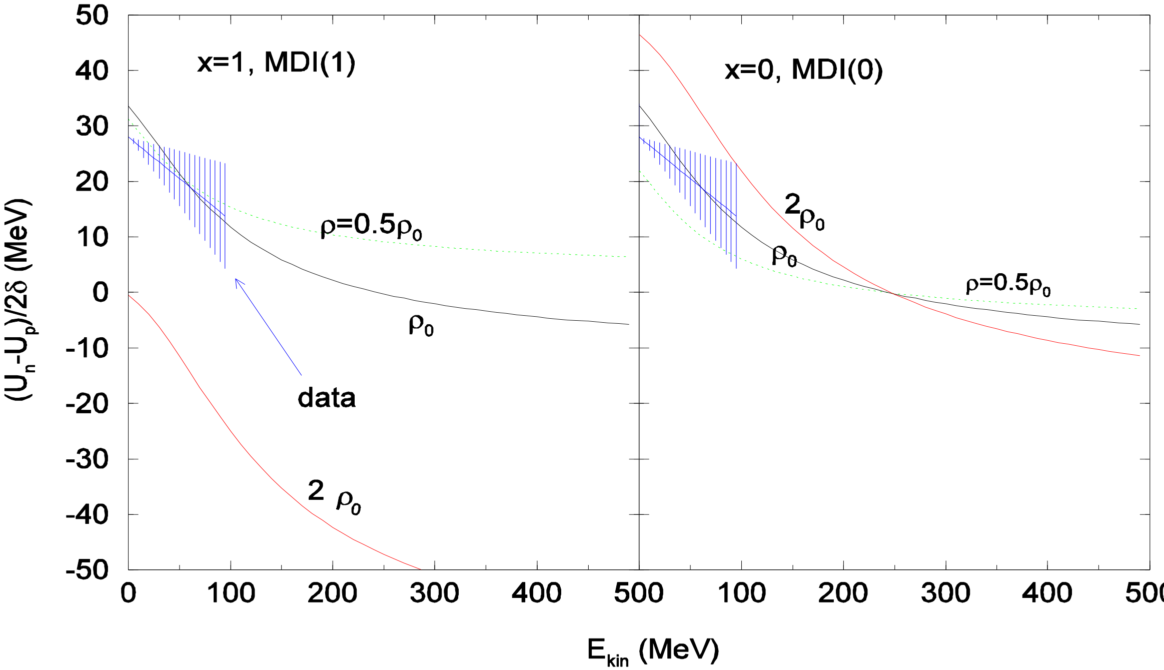
Uncertainty in E_{sym} at high ρ

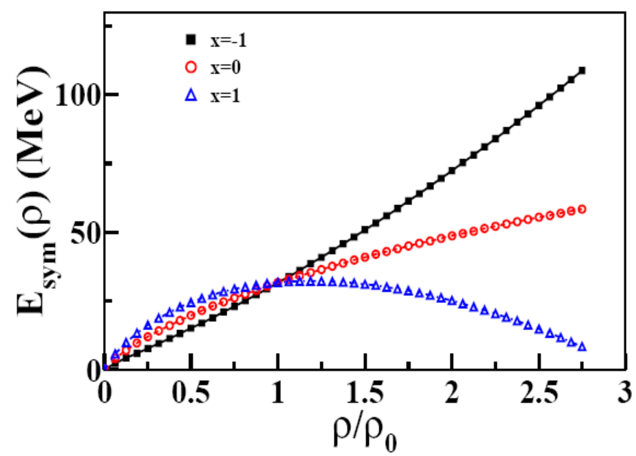
$$E_{sym} = E_{sym}^{kin} + E_{sym}^{pot1} + E_{sym}^{pot2} = \frac{1}{3} t(k_F) + \frac{1}{6} \frac{\partial U_0(k)}{\partial k}\bigg|_{k_F} k_F + \frac{3}{2k_F^3} \int_0^{2^{1/3} k_F} U_{sym}(k) k^2 dk$$

Kinetic **Isoscalar** **Isovector**

$$U_0 = \frac{1}{2}\left(U_n + U_p\right) = \frac{1}{4}\left(3u_{T1} + u_{T0}\right): \text{ Isoscalar particle potential}$$

$$U_{sym} = \frac{1}{2\delta}\left(U_n - U_p\right) = \frac{1}{4}\left(u_{T1} - u_{T0}\right) \begin{cases} \text{Isovector potential: Isospin dep. SI in medium} \\ \text{We know very little about this term at high } \rho! \end{cases}$$



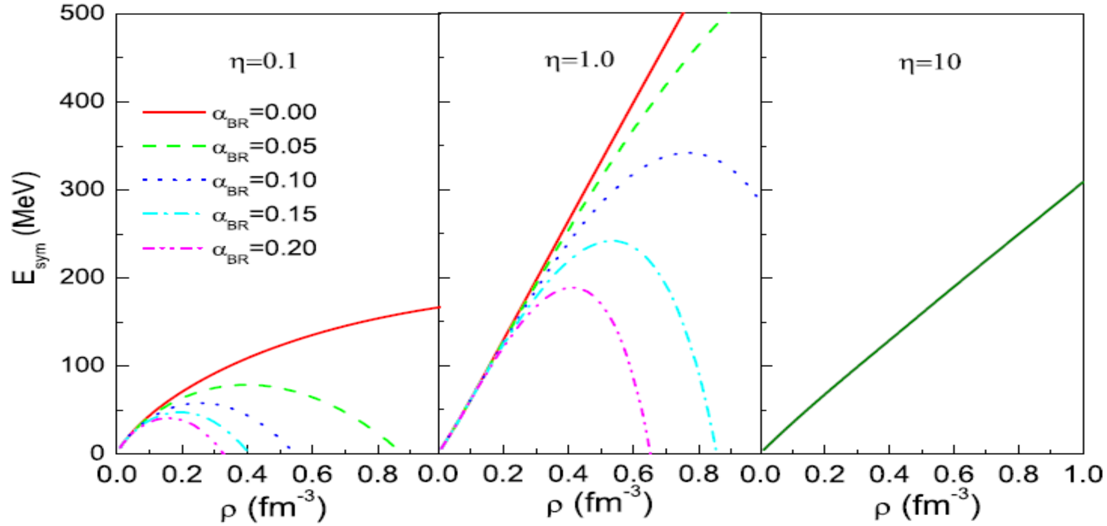


Possible Effects on E_{sym}

Brown-Rho Scaling

$$\frac{m_\rho^*}{m_\rho} = 1 - \alpha_{BR}\frac{\rho}{\rho_0}$$

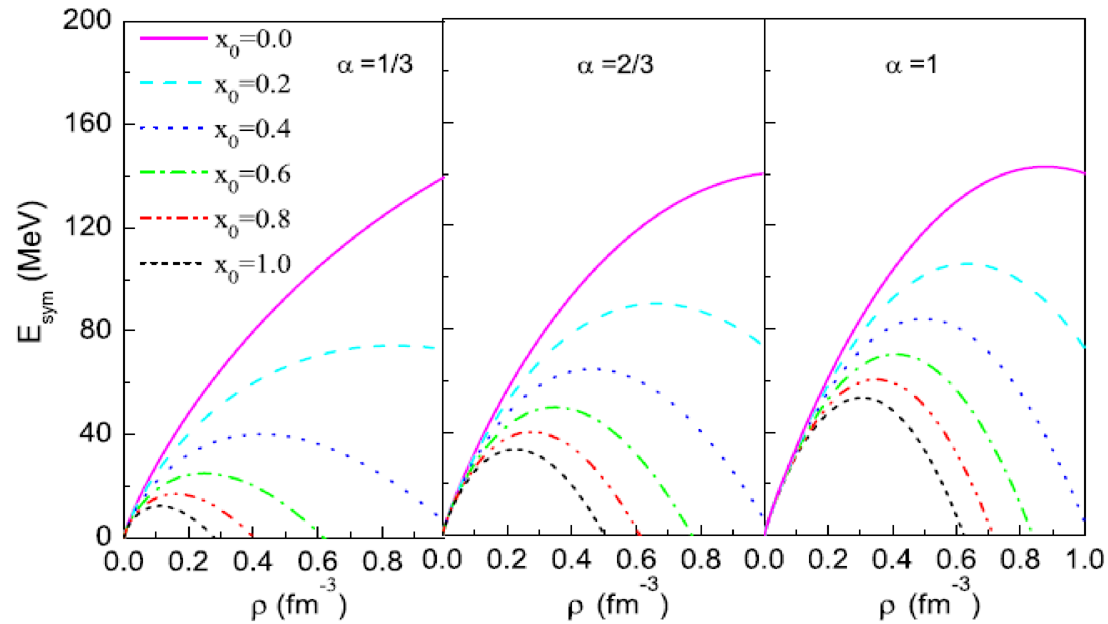
G.E. Brown and M. Rho,
PRL 66, 2720 (1991);
Phys. Rep. 396, 1 (2004)



3-Body Force

$$E_{sym}^{pot2} = -F(\rho)$$

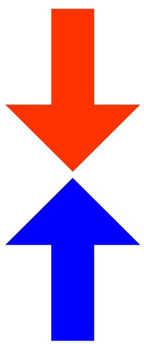
$$-(1+2x_0)\frac{t_0}{8}\rho^{\alpha+1}$$



Is NS Stable with a Super Soft E_{sym}?

If the symmetry energy is too soft, then a mechanical instability will occur when $dP/d\rho<0$, neutron stars will, then, collapse while they exist in nature.

Gravity



Nuclear pressure

$$\frac{dP}{dr} = -(\varepsilon + P)\frac{m_g + 4\pi r^3 P}{r(r-2m_g)}$$

TOV equation: a condition at hydrodynamical equilibrium

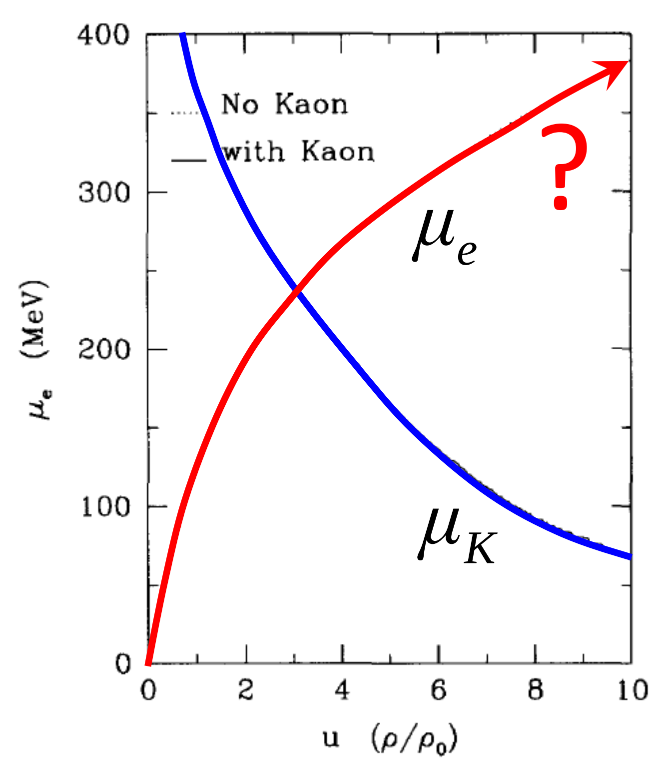
$\mu_e(\rho)$ is critical for kaon condensation

For *npe* matter,

$$P(\rho,\delta) = P_0(\rho) + P_{asy}(\rho,\delta) = \rho^2\left(\frac{\partial E}{\partial \rho}\right)_\delta + \frac{1}{4}\rho_e \mu_e$$

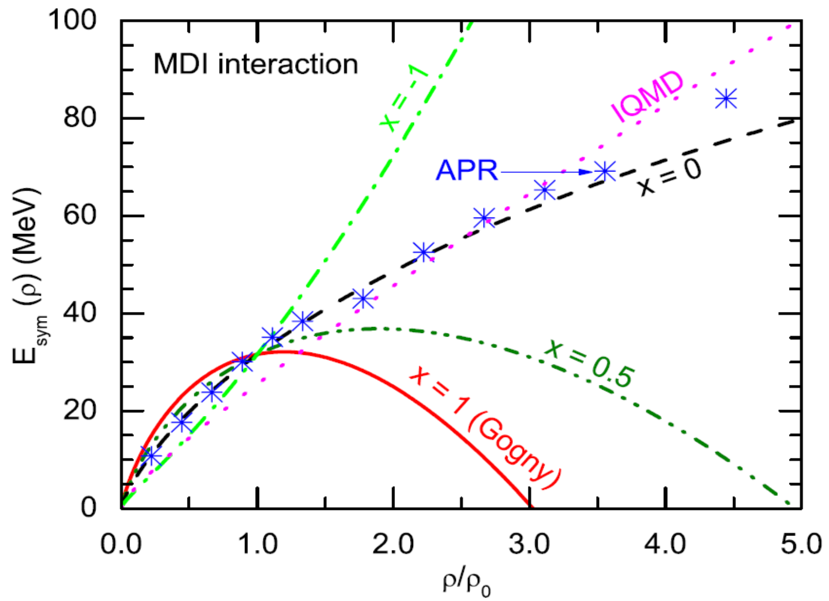
$$= \rho^2\left[E'(\rho,\delta=0) + E'_{sym}(\rho)\delta^2\right] + \frac{1}{2}\delta(1-\delta)\rho E_{sym}(\rho)$$

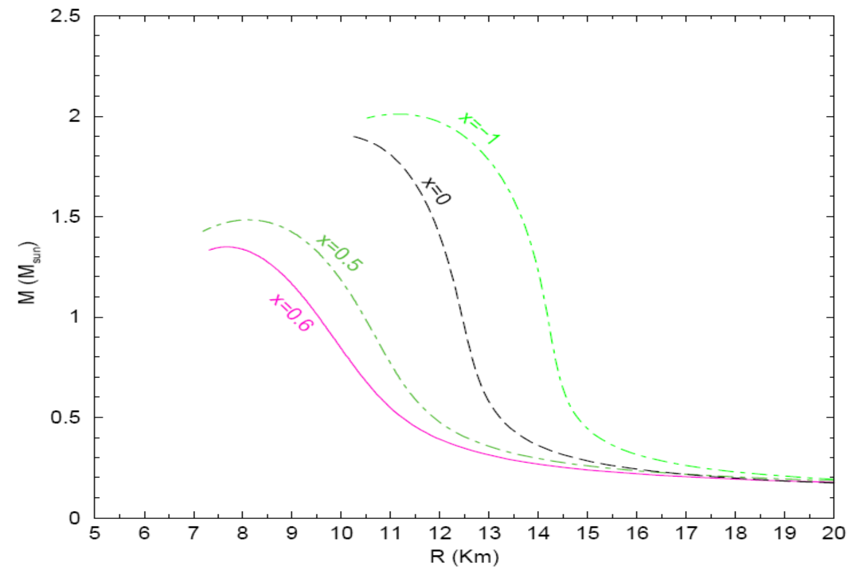
$dP/d\rho<0$, if E'_{sym} is big and negative (super-soft)



G.Q. Li, C.-H. Lee & G.E. Brown
Nucl. Phys. A 625, 372 (1997)

Astrophysical Implication



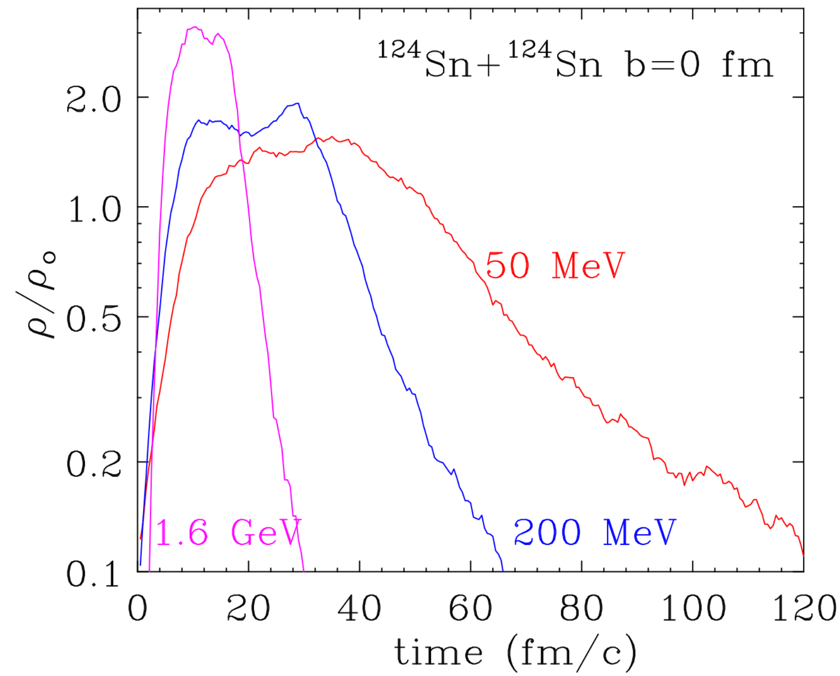


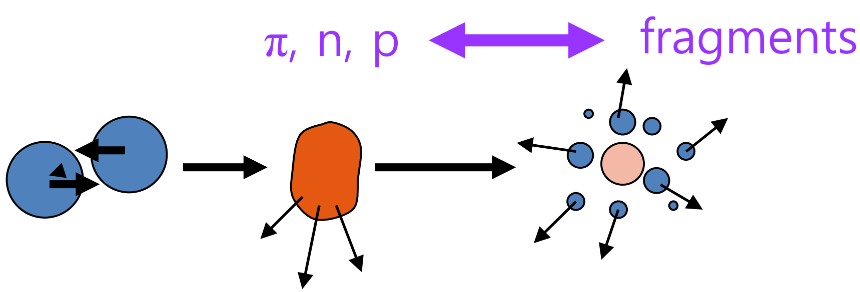
K_0=211 MeV is used for this calculation; higher incompressibility for symmetric matter will lead to higher masses, systematically.

The softest symmetry energy that the TOV is still stable is x = 0.93, giving M_{max} = 0.11 $M_\odot$ and $R \geq 28$ km.

Experimental Principles

- Range of density in HIC by
  - incident energy
  - impact parameter
- Types of particles formed
  - emission time & density
  - n & p are emitted throughout
  - Fragments (Z=3-20) at sub-saturation densities
- Change N/Z of nuclei
  - larger N/Z ratio is preferable

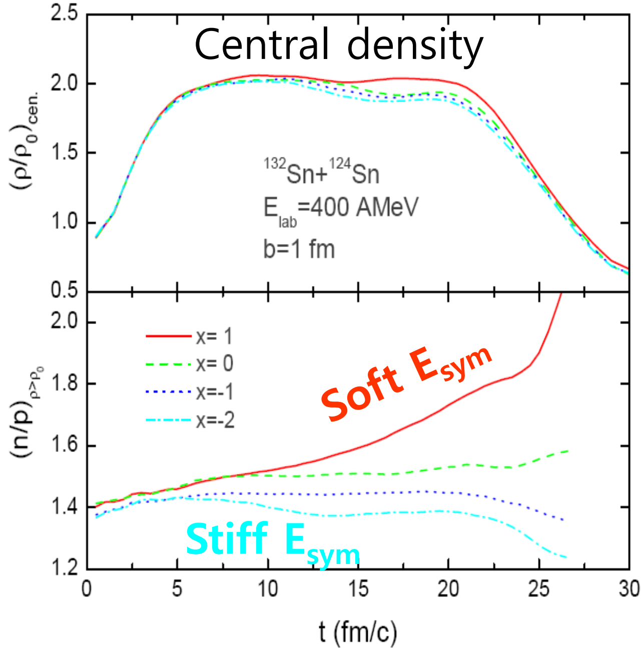




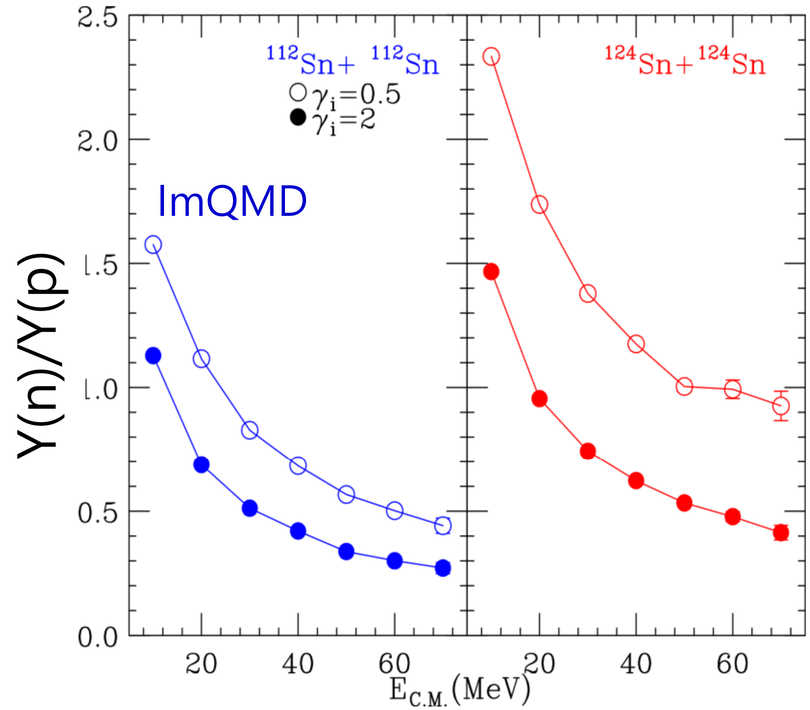
Experimental Observables

- Signals at sub-saturation densities
  1) Sizes of n-skins for unstable nuclei
  2) n/p ratio of fast, pre-equilibrium nucleons
  3) $^3H/^3He$ ratio
  4) Isospin fractionation and isoscaling in nuclear multufragmentation
  5) Isospin diffusion (transport)
  6) Differential collective flows (v_1 & v_2) of n and p
  7) Correlation function of n and p
- Signals at supra-saturation densities
  1) π^-/π^+ ratio
  2) K^+/K^0 ratio
  3) Differential collective flows (v_1 & v_2) of n and p
  4) Azimuthal angle dependence of n/p ratio with respect to the R.P.
- Correlation of various observables
- Simultaneous measurement of neutrons and charged particles

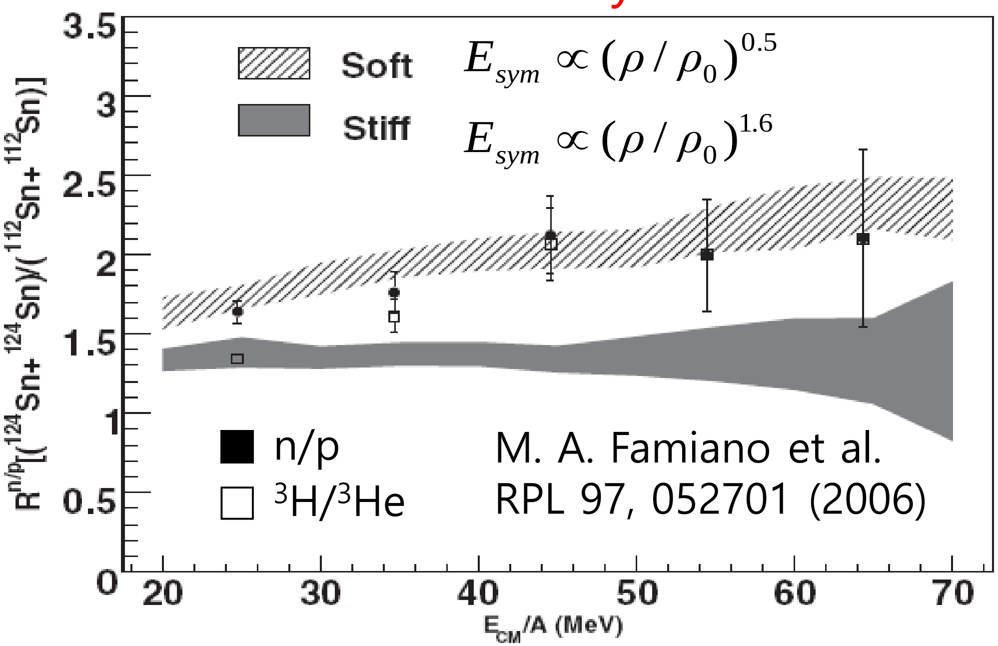
Yield Ratio



$E_{sym}(\rho)=12.7(\rho/\rho_0)^{2/3}+17.6(\rho/\rho_0)^{\gamma i}$



Double ratio: min. systematic error

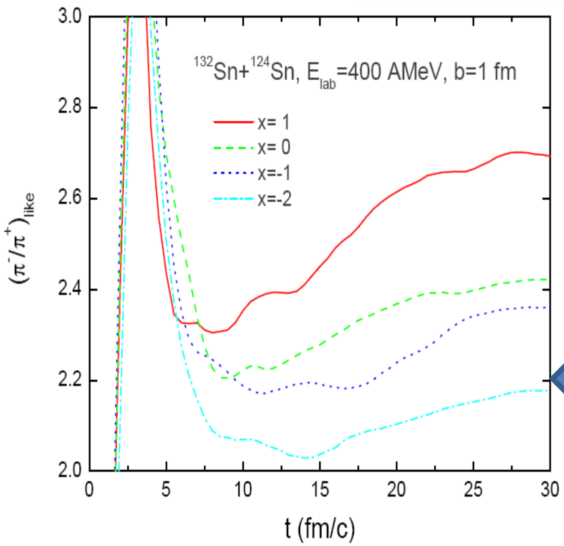


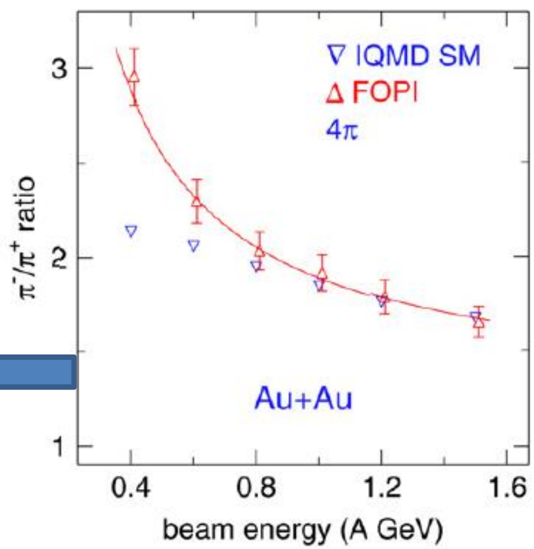
More neutrons are emitted from the n-rich system and softer symmetry energies.

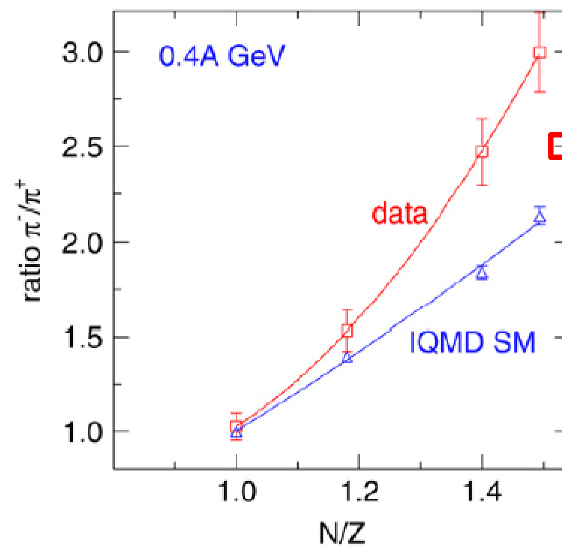
Yield Ratio (π^-/π^+)

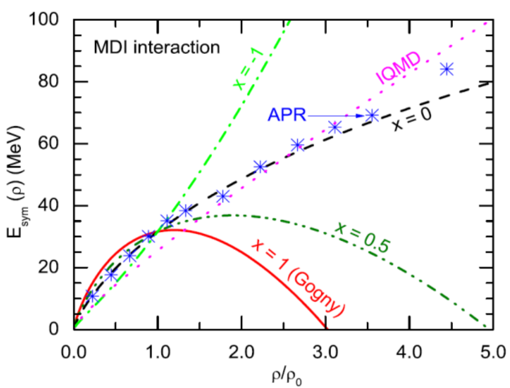
Data: FOPI Collaboration, Nucl. Phys. A 781, 459 (2007)
IQMD: Eur. Phys. J. A 1, 151 (1998)

corresponding to $E_{sym}(\rho) = \frac{100}{8}\frac{\rho}{\rho_0} + (2^{2/3}-1)\frac{3}{5}E_F^0(\frac{\rho}{\rho_0})^{2/3}$



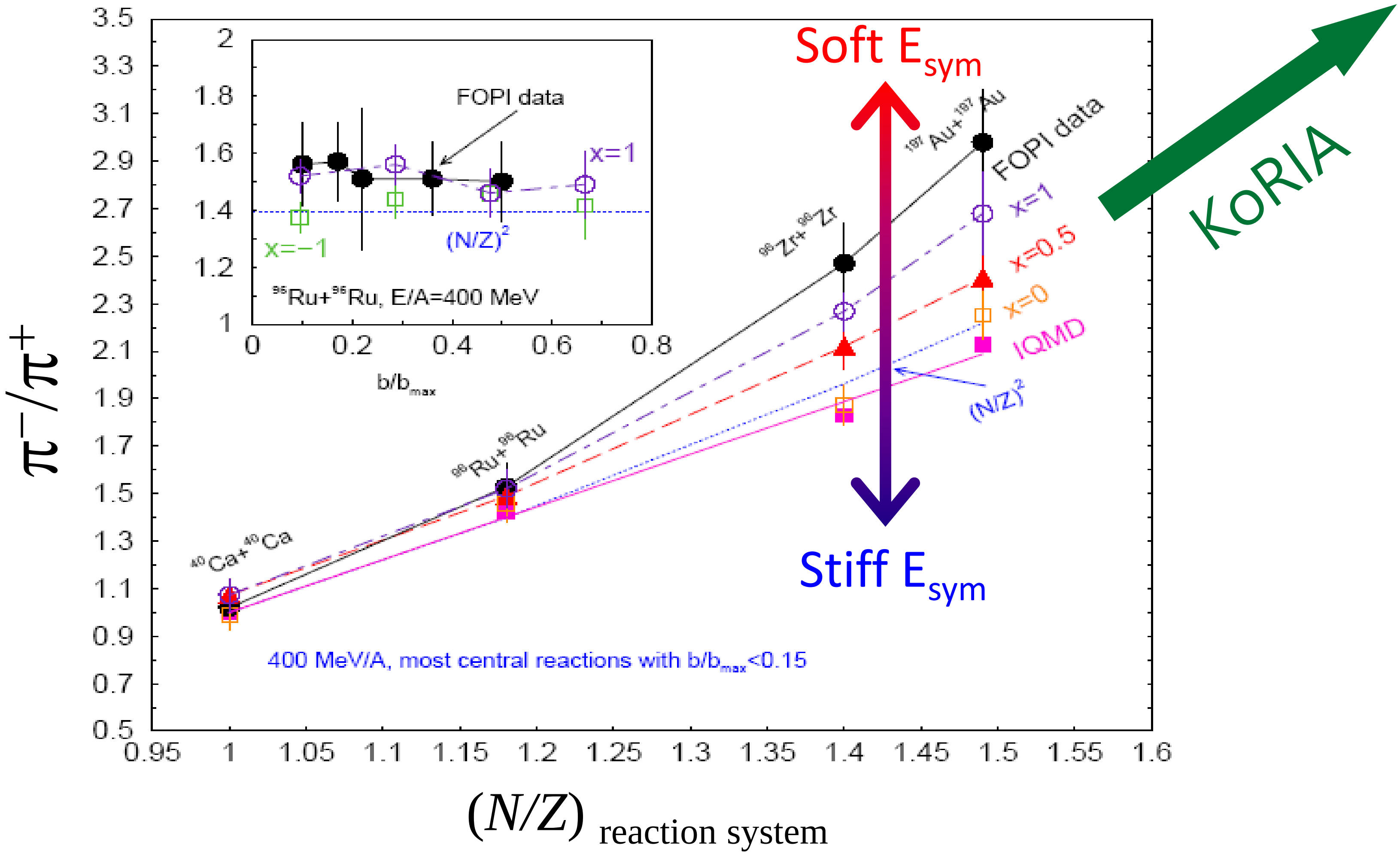






Need a symmetry energy softer than the above to make the pion production region more neutron-rich!

π^-/π^+ Ratio



Soft E_{sym}
Stiff E_{sym}
KoRIA
FOPI data
x=1
x=0.5
x=0
IQMD
$(N/Z)^2$
^{40}Ca+^{40}Ca
^{96}Ru+^{96}Ru
^{96}Zr+^{96}Zr
^{197}Au+^{197}Au
400 MeV/A, most central reactions with b/b_{max}<0.15
x=−1
^{96}Ru+^{96}Ru, E/A=400 MeV
b/b_{max}
π^-/π^+
(N/Z) reaction system

Isospin Diffusion Parameter

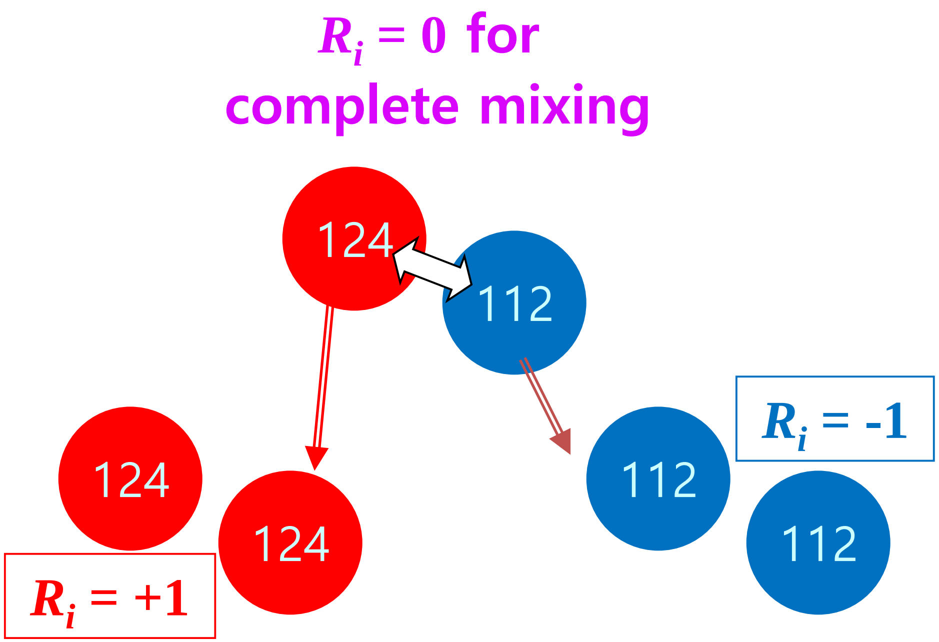
Isospin diffusion occurs only in asymmetric systems A+B

No isospin diffusion between symmetric systems

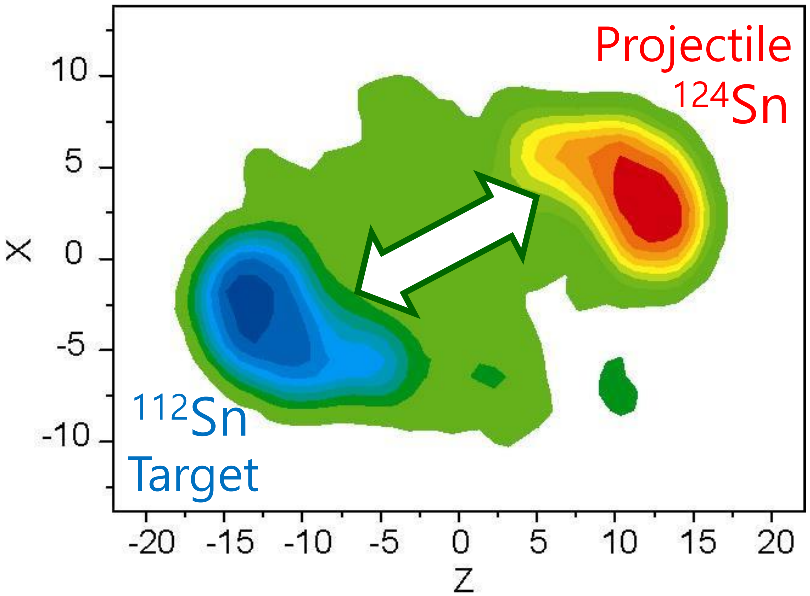
Non-isospin diffusion effects are the same for A in A+B & A+A and also for B in B+A & B+B

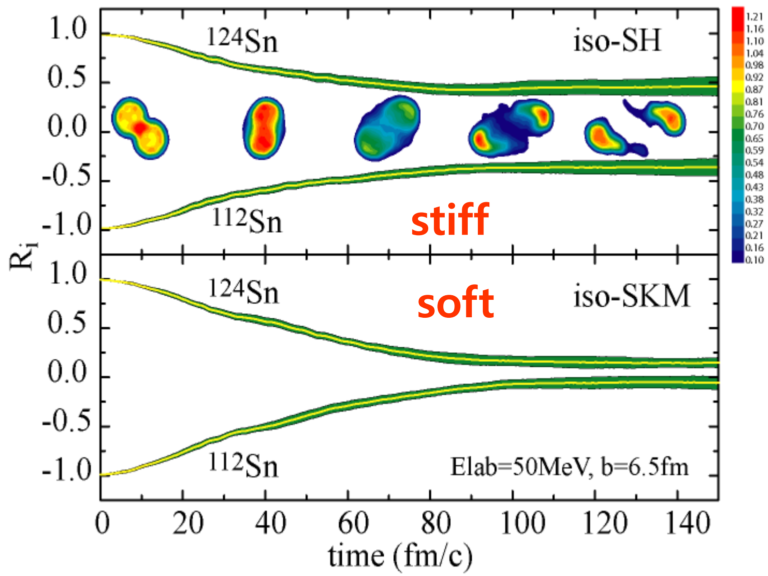
$$R_i = 2\frac{x_{AB} - (x_{AA} + x_{BB})/2}{x_{AA} - x_{BB}}$$

F. Rami et al., FOPI, PRL 84, 1120 (2000)
B. Hong et al., FOPI, PRC 66, 034901 (2002)
Y.-J. Kim & B. Hong, in preparation



Isospin Diffusion Parameter





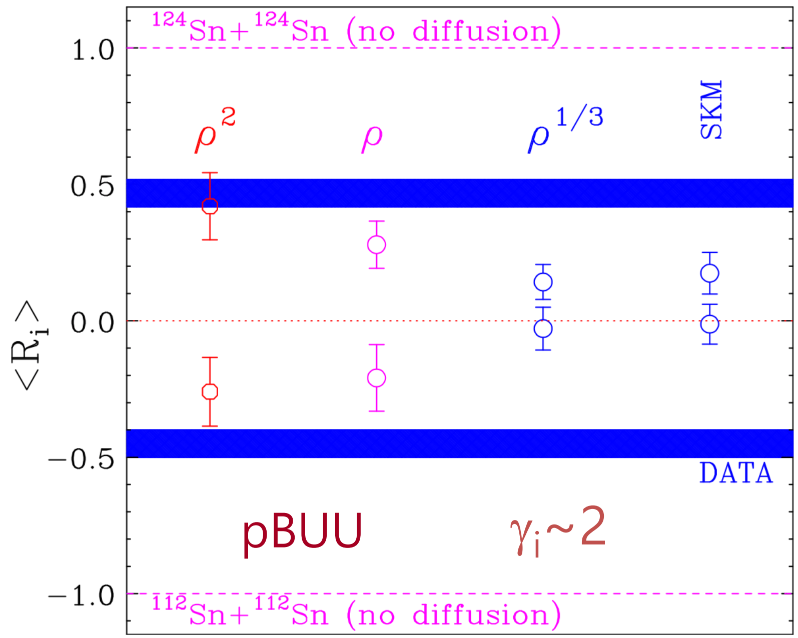
- Symmetry energy drives system towards equilibrium
  - stiff EOS : small diffusion ($|R_i| \gg 0$)
  - soft EOS : large diffusion & fast equilibrium ($R_i \rightarrow 0$)

M.B. Tsang et al., PRL 92, 062701 (2004)

Isospin Diffusion Parameter

M.B. Tsang et al., PRL 92, 062701 (2004)

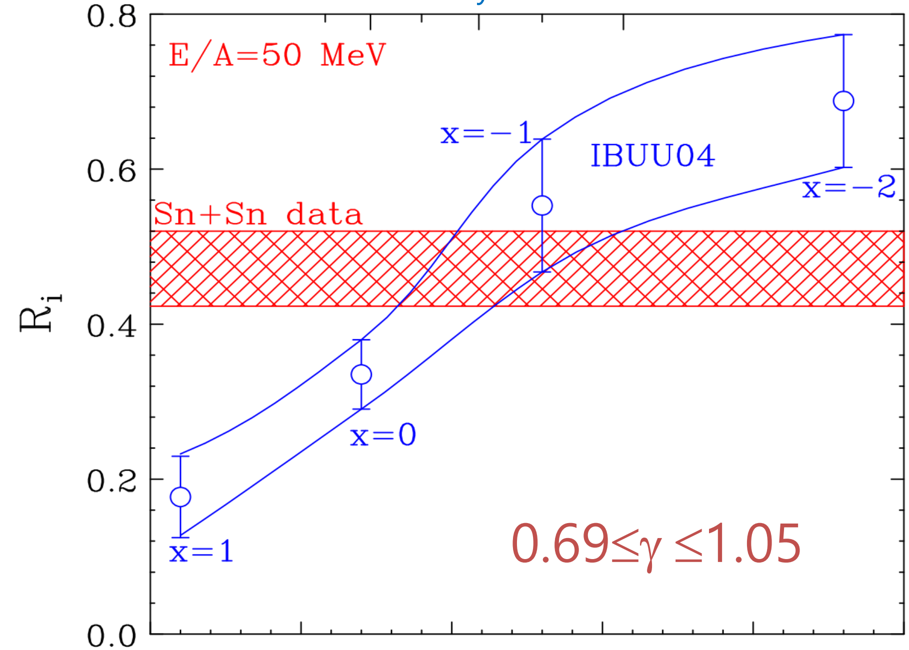
$E_{sym}(\rho)=12.7(\rho/\rho_o)^{2/3}+12.5(\rho/\rho_o)^{\gamma i}$



stiff ⟷ soft

L.W. Chen et al., PRL 94, 032701 (2005)

IBUU04: $E_{sym}(\rho)\sim 31.6(\rho/\rho_o)^{\gamma}$



stiff ⟷ soft

Observable in HIC is sensitive to the ρ dependence of E_{sym} and should provide constraints to the symmetry energy.

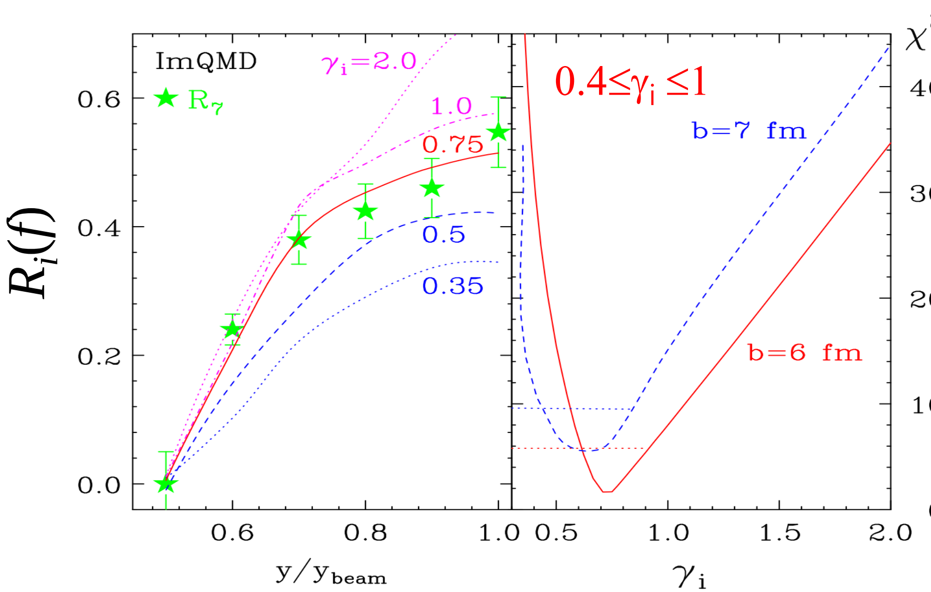
Isospin Diffusion Parameter

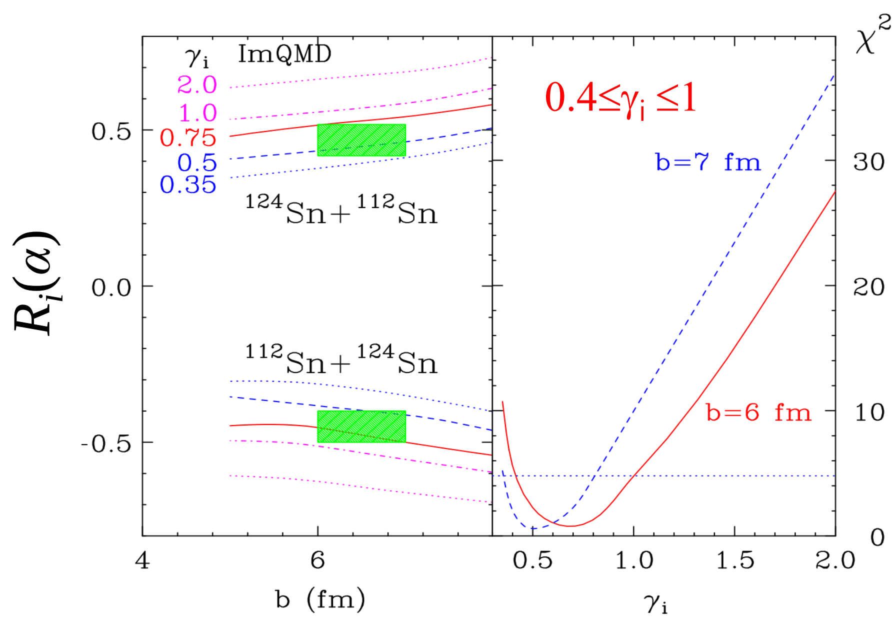
NSCL/MSU Data at Low Energy

$E_{sym}(\rho) = 12.5(\rho/\rho_0)^{2/3} + 17.6\,(\rho/\rho_0)^{\gamma i}$

$$f = \frac{Y_{124}(^7\mathrm{Li}) / Y_{124}(^7\mathrm{Be})}{Y_{112}(^7\mathrm{Li}) / Y_{112}(^7\mathrm{Be})}$$

$$f = \frac{Y_{124+124}(Z = 3 \sim 8)}{Y_{112+112}(Z = 3 \sim 8)} \propto \exp(\alpha N)$$





Collective Flow

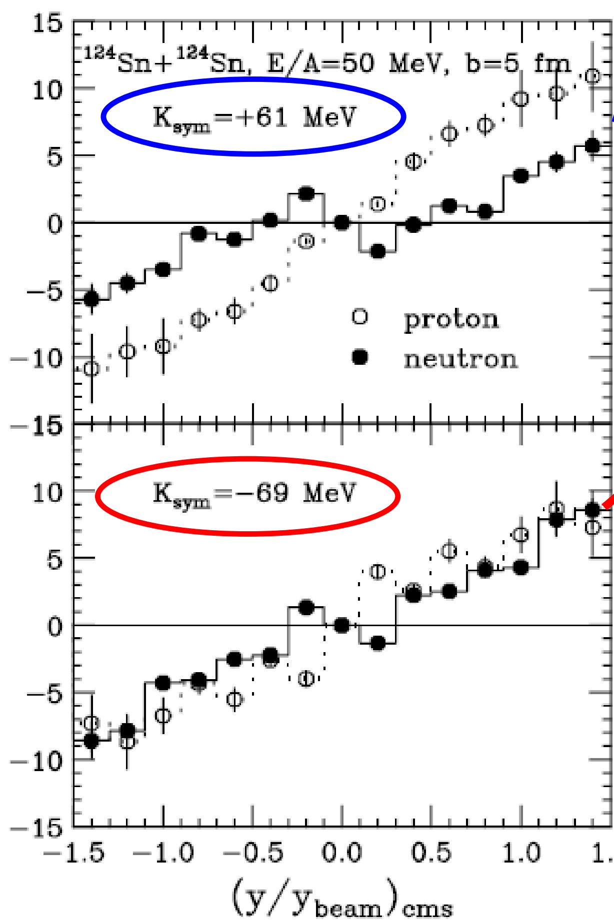
B.-A. Li, PRL 85, 4221 (2000)

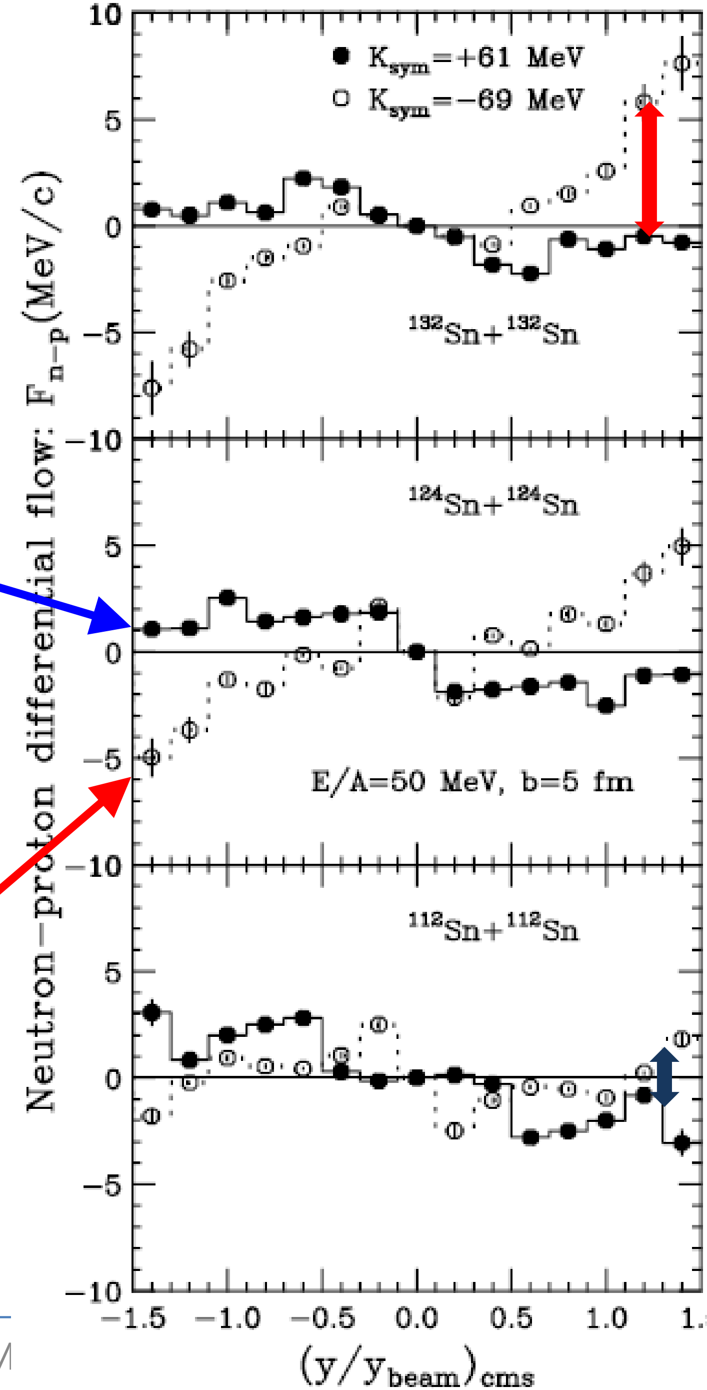
$$K_{sym} \equiv 9\rho_0^2 \left. \frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2} \right|_{\rho=\rho_0}$$

Stiff

Also known as v_1

Super Soft

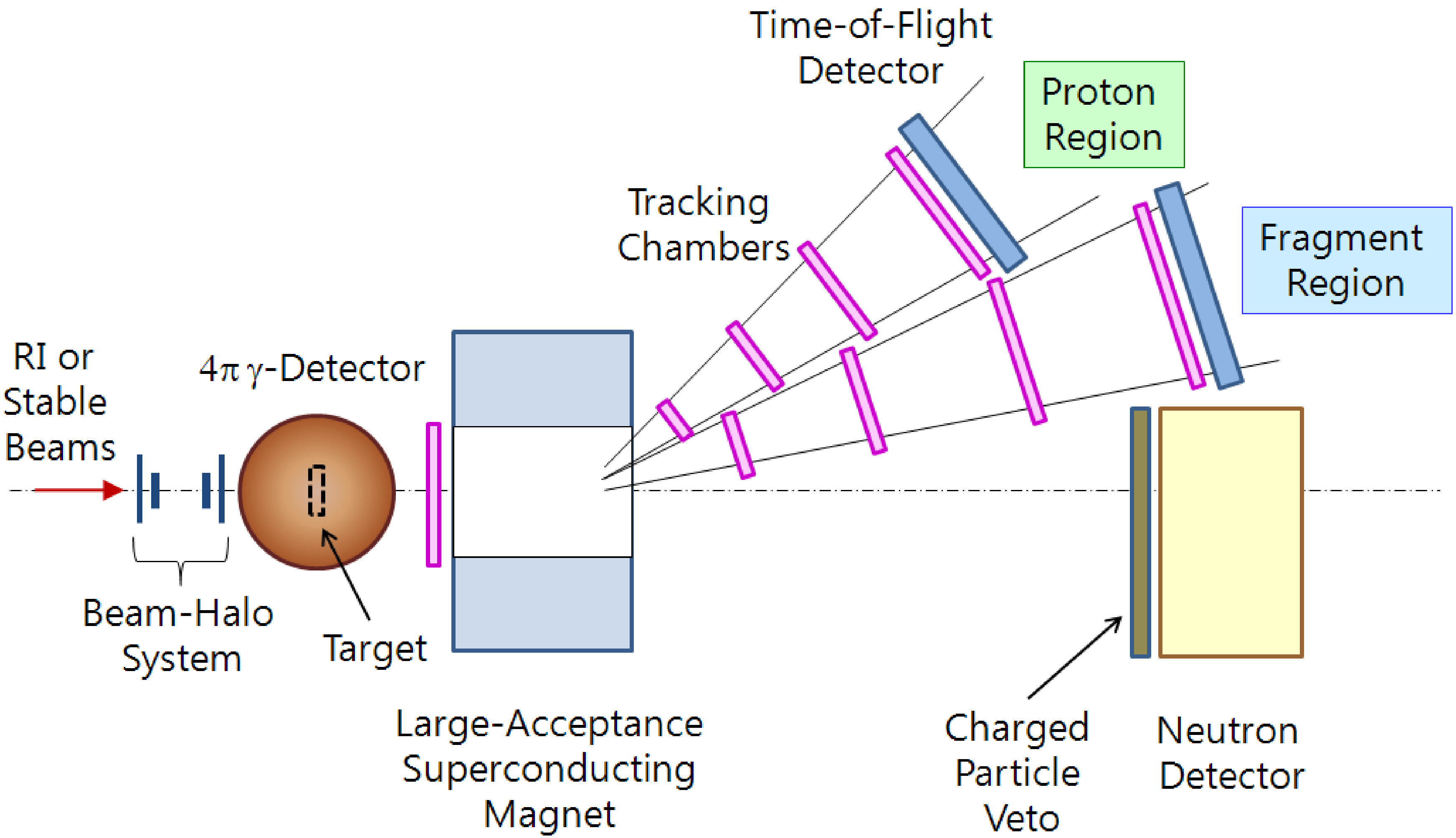


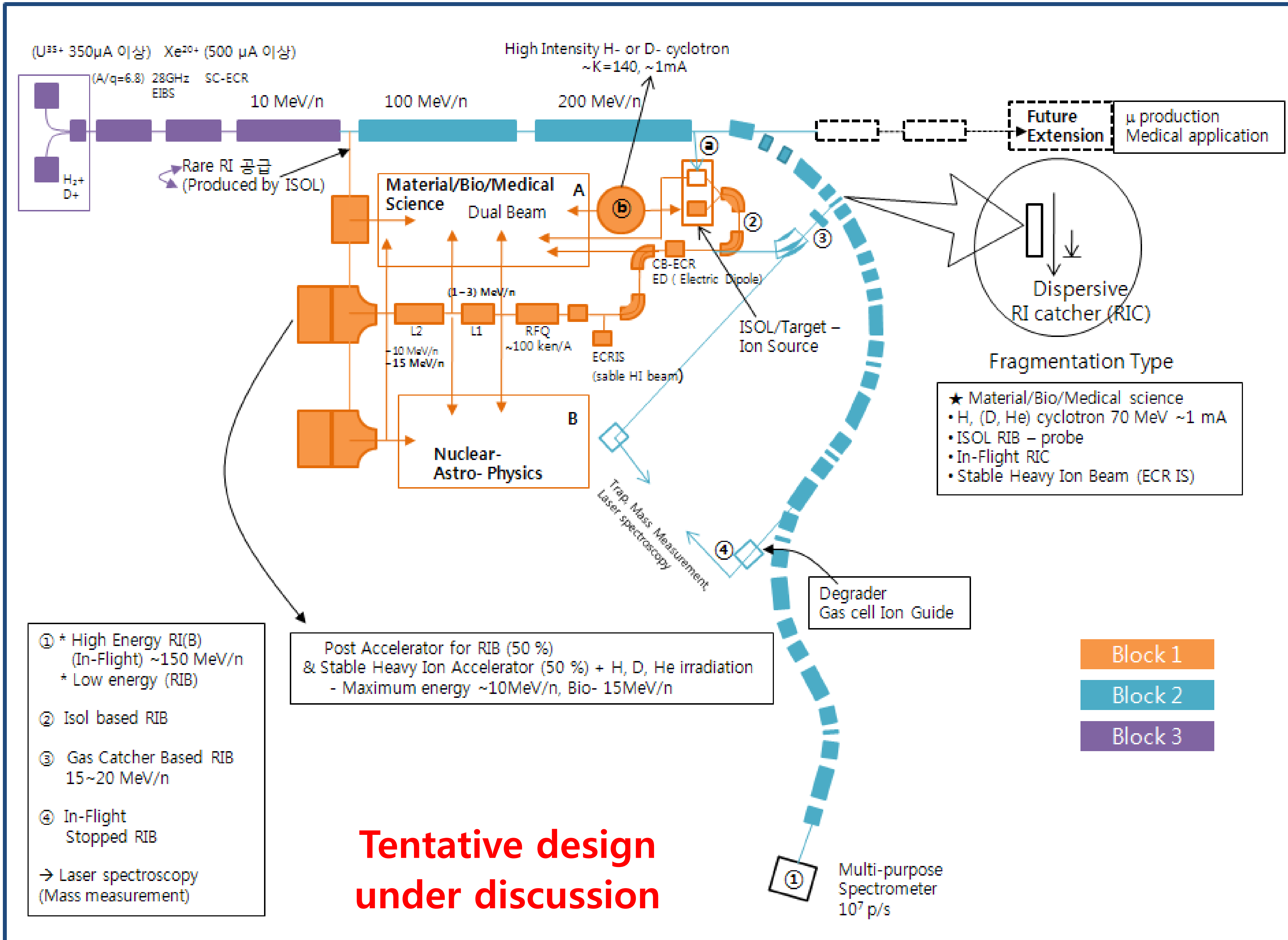


Large N/Z

Small N/Z

Multi-Purpose Detector




(U33+ 350μA 이상) Xe20+ (500 μA 이상)
(A/q=6.8) 28GHz SC-ECR
EIBS
H2+
D+
10 MeV/n
100 MeV/n
200 MeV/n
High Intensity H- or D- cyclotron
~K=140, ~1mA
Future Extension
μ production
Medical application
Rare RI 공급
(Produced by ISOL)
Material/Bio/Medical Science
A
Dual Beam
ⓐ
ⓑ
②
③
CB-ECR
ED (Electric Dipole)
(1~3) MeV/n
L2
L1
RFQ
~100 keV/A
10 MeV/n
15 MeV/n
ECRIS
(sable HI beam)
ISOL/Target – Ion Source
Dispersive
RI catcher (RIC)
Fragmentation Type
★ Material/Bio/Medical science
• H, (D, He) cyclotron 70 MeV ~1 mA
• ISOL RIB – probe
• In-Flight RIC
• Stable Heavy Ion Beam (ECR IS)
B
Nuclear-
Astro- Physics
Trap Mass Measurement
Laser spectroscopy
④
Degrader
Gas cell Ion Guide
① * High Energy RI(B)
(In-Flight) ~150 MeV/n
* Low energy (RIB)
② Isol based RIB
③ Gas Catcher Based RIB
15~20 MeV/n
④ In-Flight
Stopped RIB
→ Laser spectroscopy
(Mass measurement)
Post Accelerator for RIB (50 %)
& Stable Heavy Ion Accelerator (50 %) + H, D, He irradiation
- Maximum energy ~10MeV/n, Bio- 15MeV/n
Block 1
Block 2
Block 3
Tentative design
under discussion
①
Multi-purpose
Spectrometer
10^7 p/s

Summary

1. Rich physics with RI beams
   - Neutron & proton drip lines
   - Neutron halo & skin structures
   - Nuclear Astrophysics
   - Super-heavy elements
   - Fundamental symmetries
   - Nuclear symmetry energy
     - Long-standing problem in nuclear physics
     - Crucial to understand the neutron matter
     - Crucial to understand the astrophysical objects
2. KoRIA
   - First large scale accelerator for basic science in Korea
   - We need your help & participation!