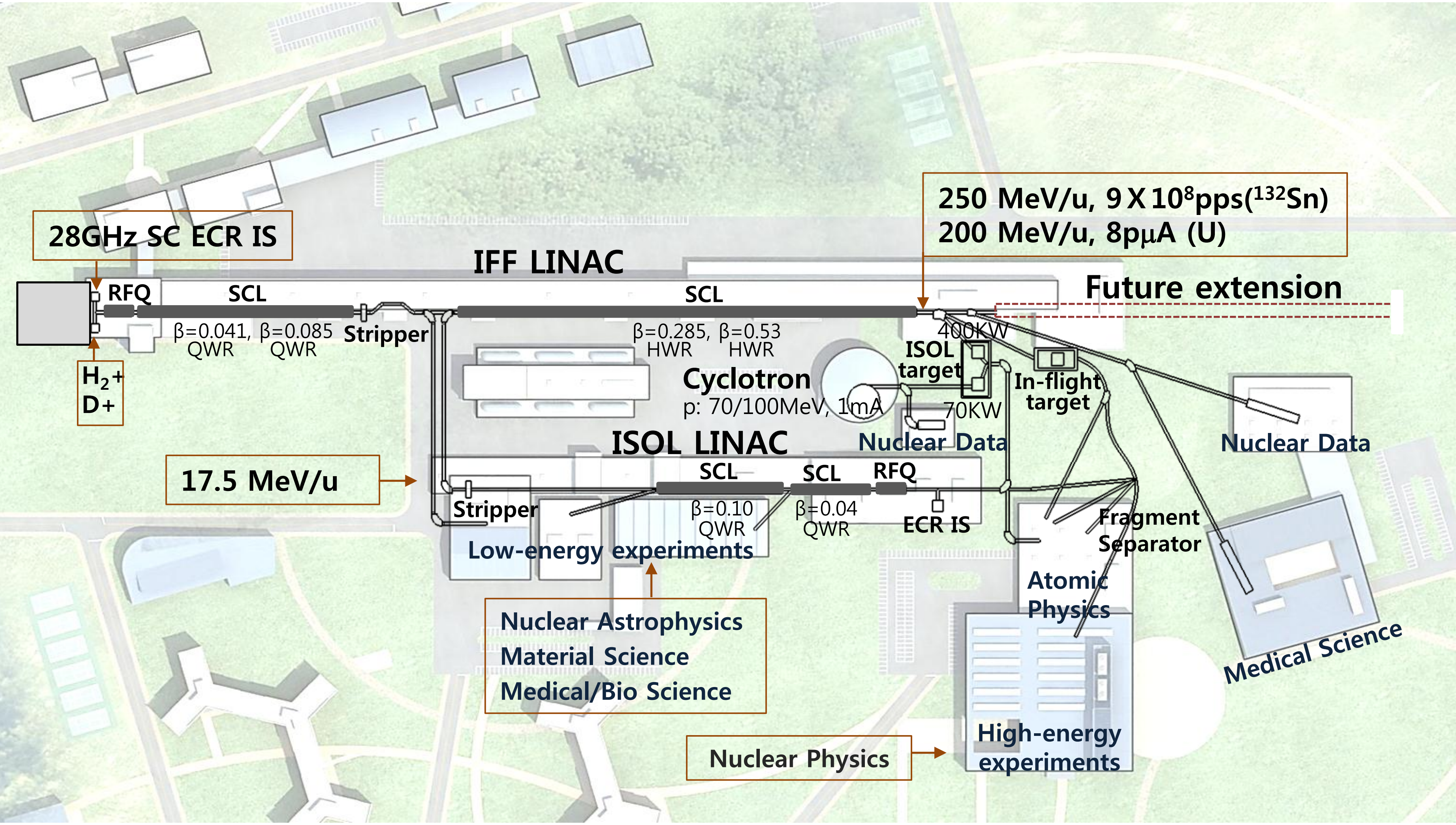
Plan for LAMPS at KoRIA

Byungsik Hong (Korea University)

Outline

- **Brief introduction to KoRIA**
- **Physics of Symmetry Energy for Dense Matter**
- **Design of LAMPS detector system**
- **Summary**

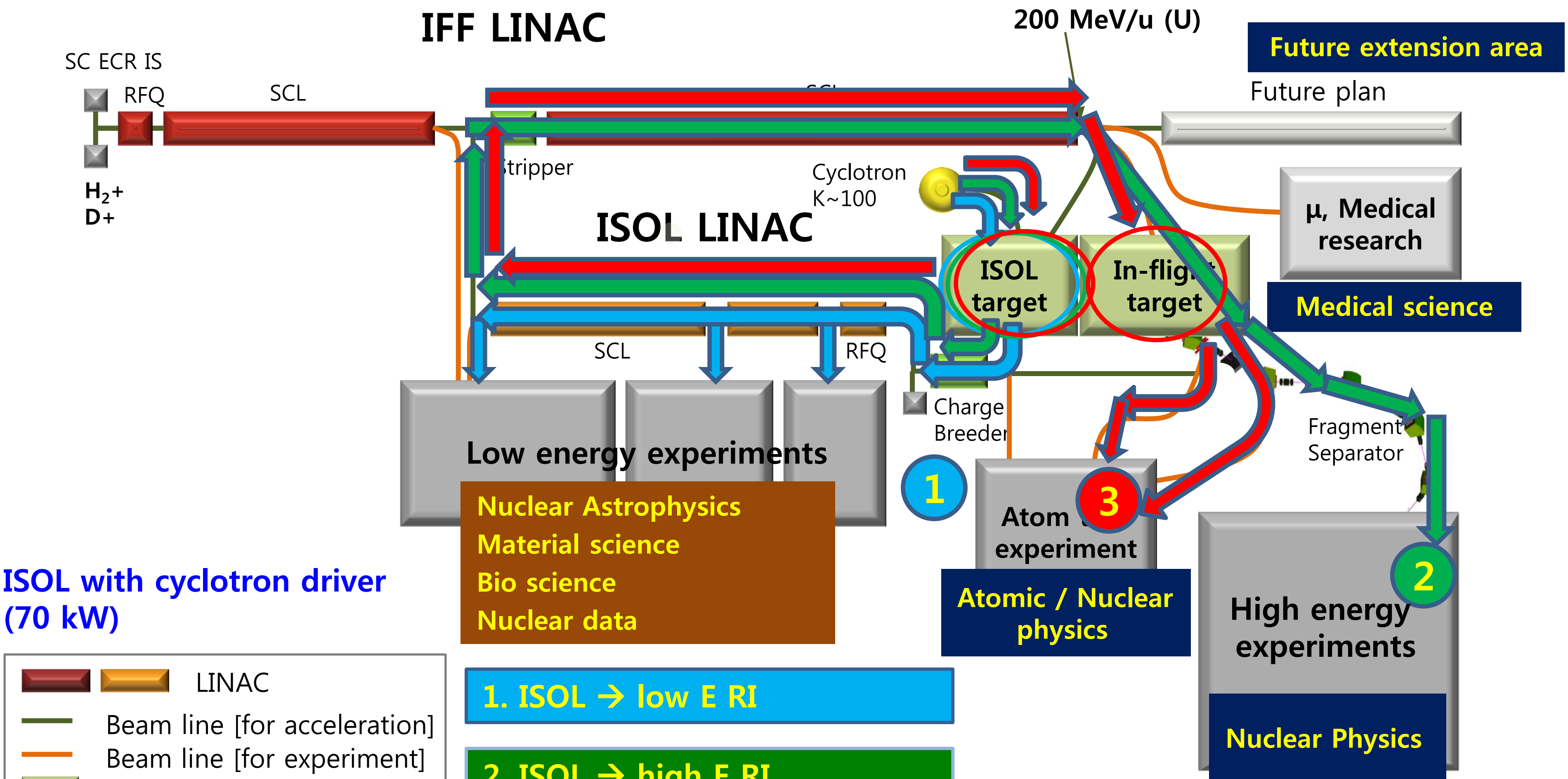
KoRIA: Korea Rare Isotope Accelerator



Aim of Technical Specification

1. High-intensity RI beams by ISOL & IFF
   - 70 kW ISOL from direct fission of ^{238}U induced by 70 MeV protons with the current of 1 mA
   - 400 kW IFF by 200 MeV/u ^{238}U with the current of 8pμA
2. High-energy, high-intensity neutron-rich RI beams
   - E.g., ^{132}Sn at ~250 MeV/u up to 9×10^8 pps
3. More exotic RI beams by using multi-step RI production processes (the combination of ISOL & IFF)
4. Design the facility for the simultaneous operation mode for maximal use
5. We want to keep the diversity.

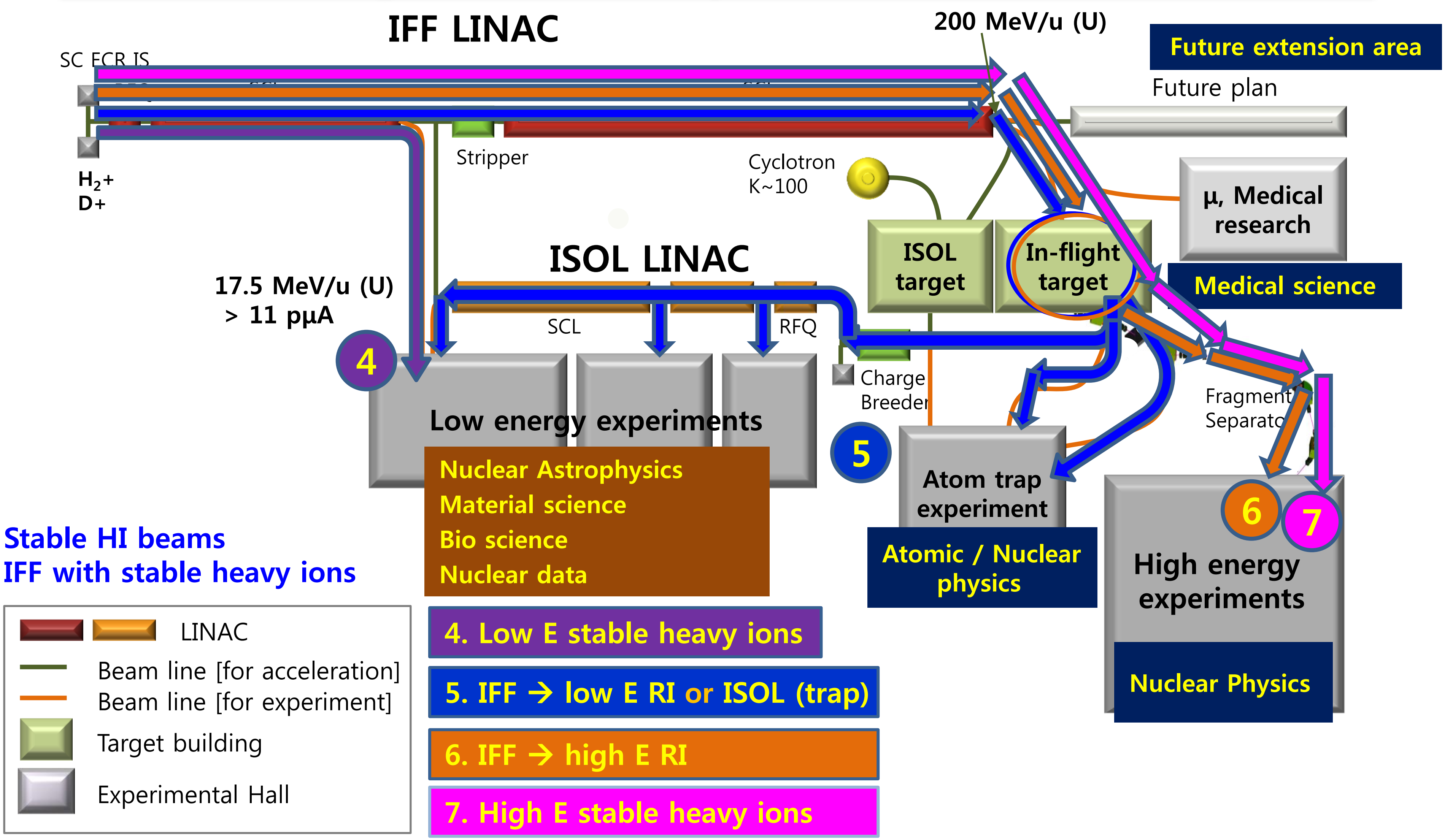
RI from ISOL by Cyclotron



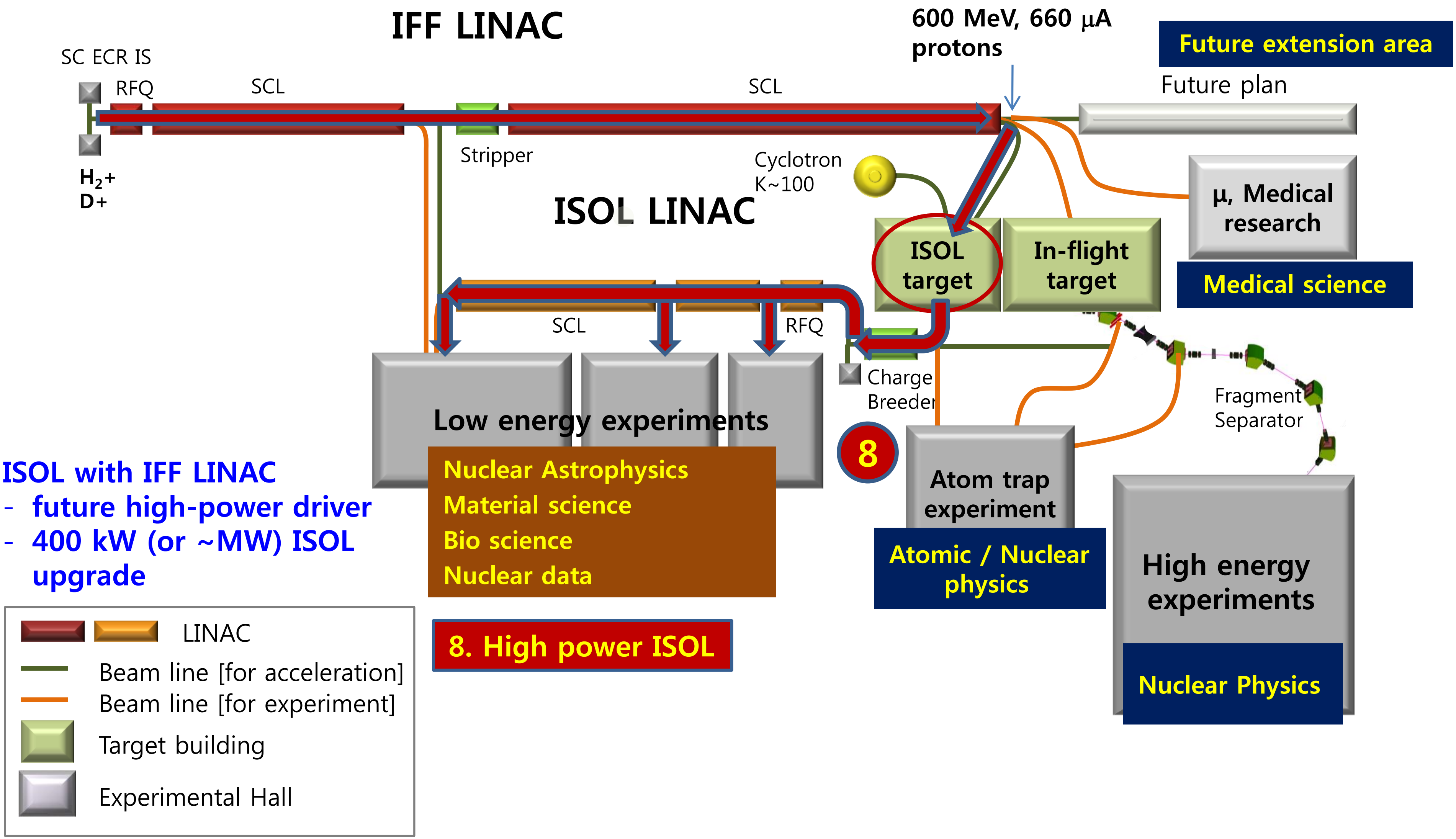
LINAC
Beam line [for acceleration]
Beam line [for experiment]
Target building
Experimental Hall

1. ISOL → low E RI
2. ISOL → high E RI
3. ISOL → IFF → ISOL (trap)

RI from IFF by High-Power SC LINAC and High-Intensity Stable HI beams

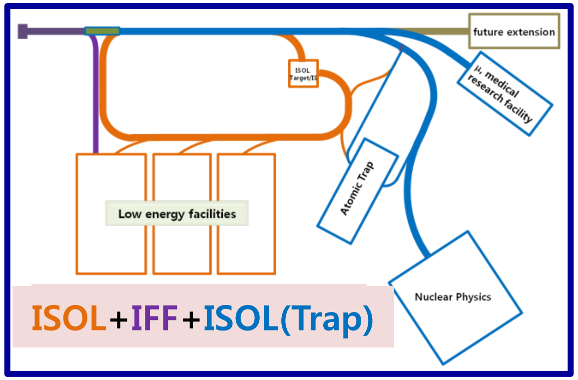


RI from ISOL by High-Power SC LINAC (Long term future upgrade option)



ISOL with IFF LINAC
- future high-power driver
- 400 kW (or ~MW) ISOL upgrade

Research Goals



- **Nuclear Physics**
  - Exotic nuclei near the neutron drip line
  - Super-Heavy Elements (SHE)
  - Equation-of-state (EoS) of nuclear matter
- **Nuclear Astrophysics**
  - Origin of nuclei
  - Paths of nucleosynthesis
  - Neutron stars and supernovae
- **Atomic physics**
  - Limits of nuclear existence
  - Fundamental conservation law
- **Nuclear data using fast neutrons**
  - Basic data for future nuclear energy
  - Radioactive waste transmutation
- **Material science**
  - Production & Characterization of new materials
  - Dynamic image in nm scale
- **Medical and Bio sciences**
  - Advanced therapy technology
  - Mutation of DNA

In this talk, I am going to focus on the isospin dependent EoS.
(*Large aid by B.-A. Li in the WCU program*)

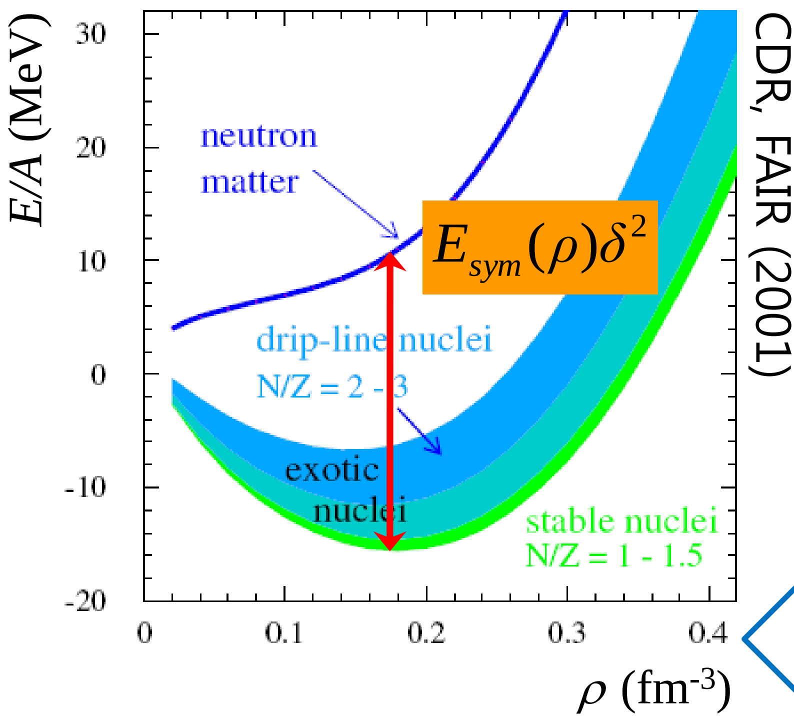
Nuclear Equation of State

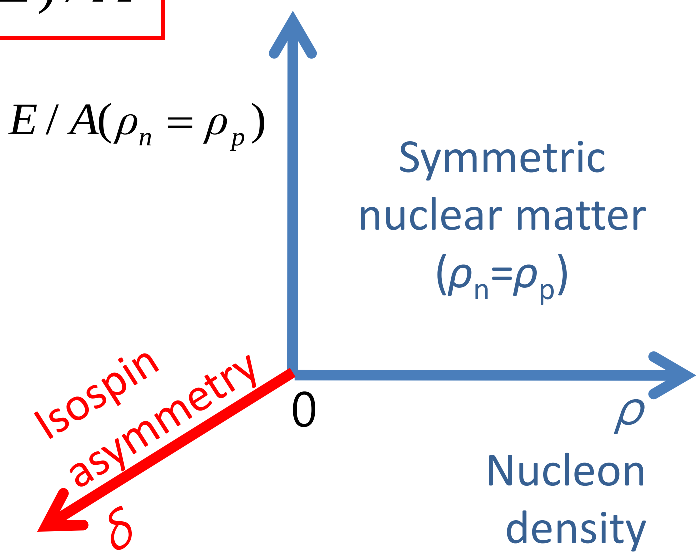
$$E(\rho_n,\rho_p) = E(\rho_n=\rho_p) + E_{sym}(\rho)\delta^2 + O(\delta^4)$$

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

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

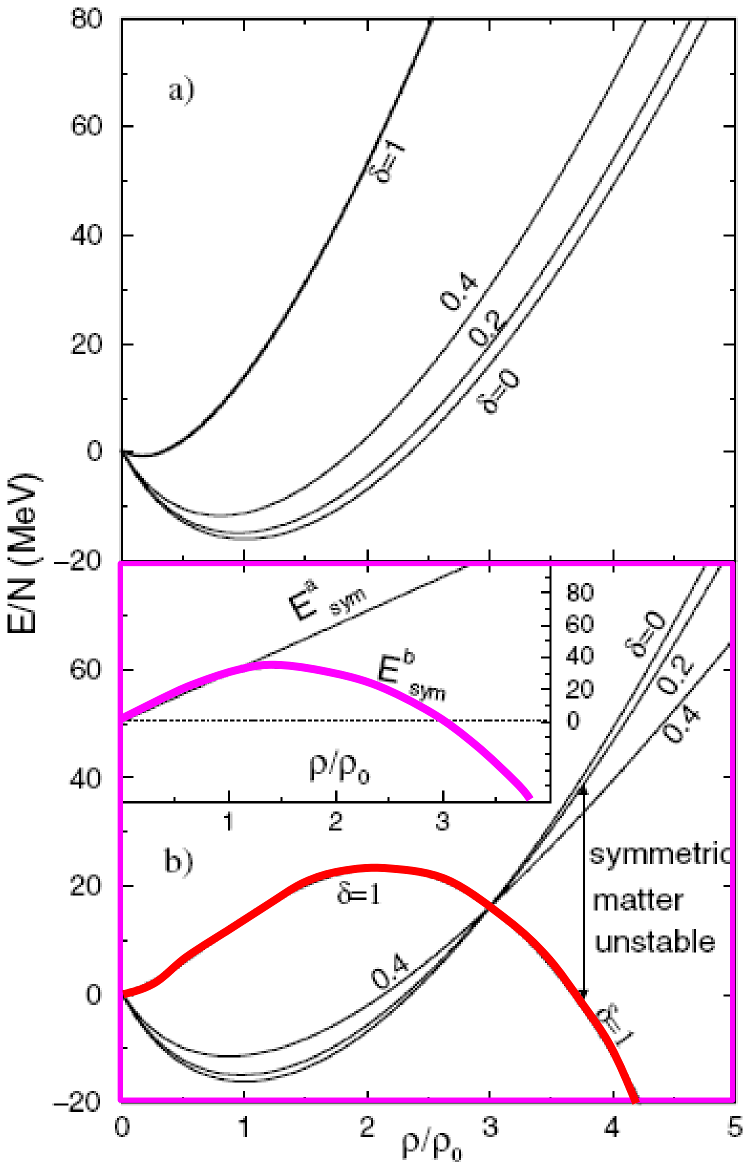
B.-A. Li, L.-W. Chen & C.M. Ko
Physics Report, **464,** 113 (2008)



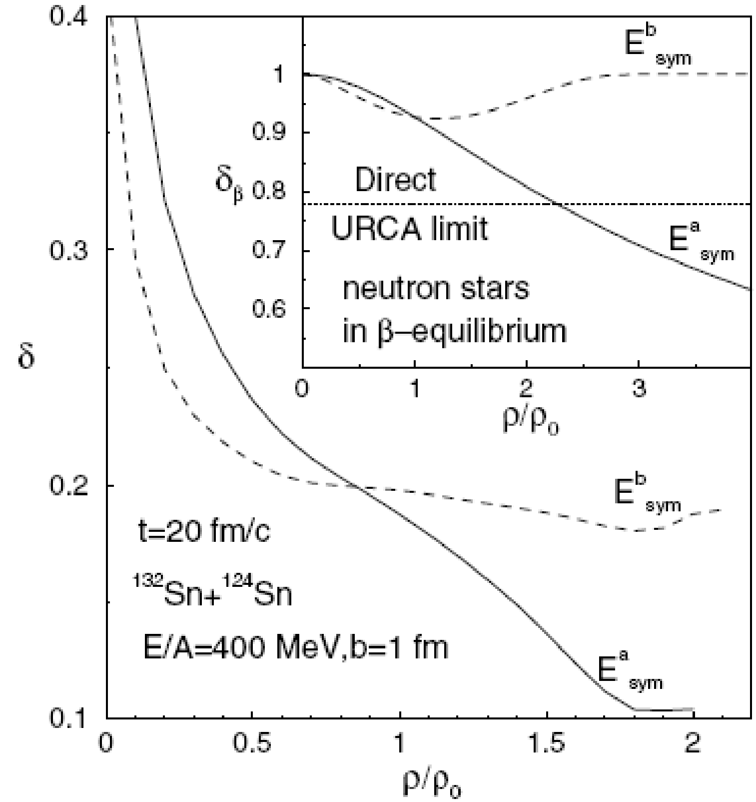


F. de Jong & H. Lenske, RPC 57, 3099 (1998)
F. Hofman, C.M. Keil & H. Lenske, PRC 64, 034314 (2001)

Nuclear Equation of State

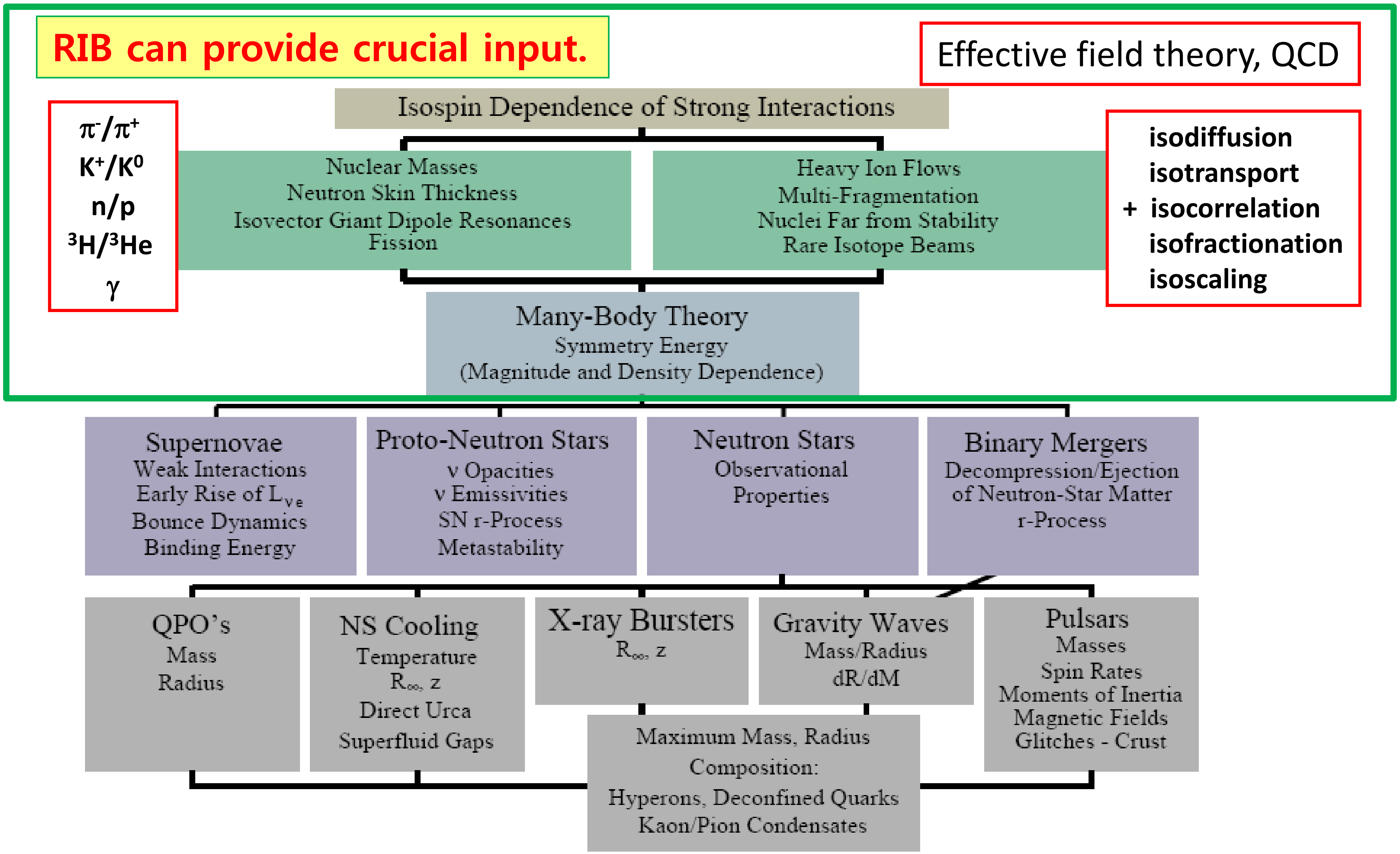


Bao-An Li, PRL 88, 192701 (2002)



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

Importance of Symmetry Energy

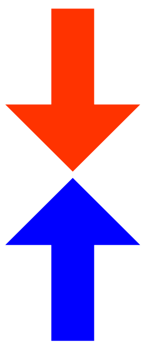


- A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, Physics Report 411, 325 (2005)
- Red boxes: added by B.-A. Li

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

If the symmetry energy is too soft, then a mechanical instability will occur when *dP/dρ*<0, neutron stars will, then, collapse.

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

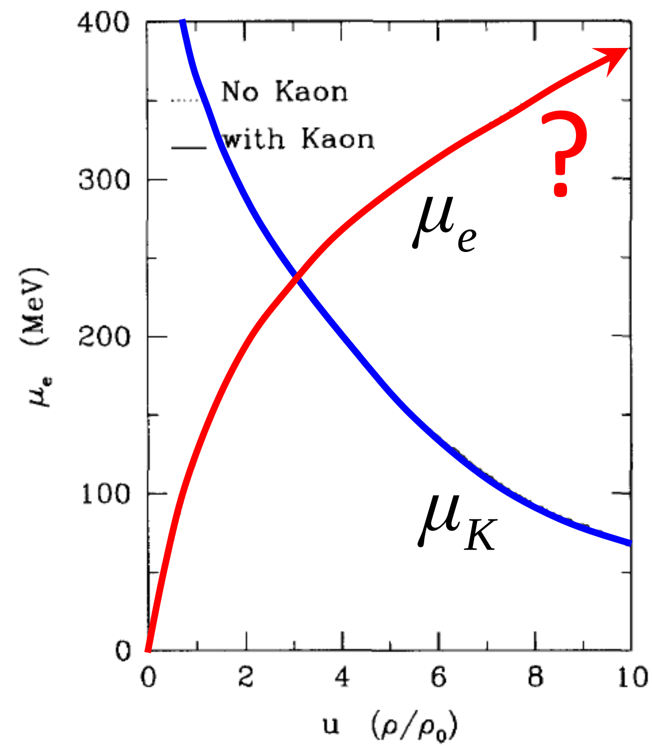
$\mu_e(\rho)$ is critical for kaon condensation

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/dρ<0, if E'_{sym} is big and negative (super-soft)

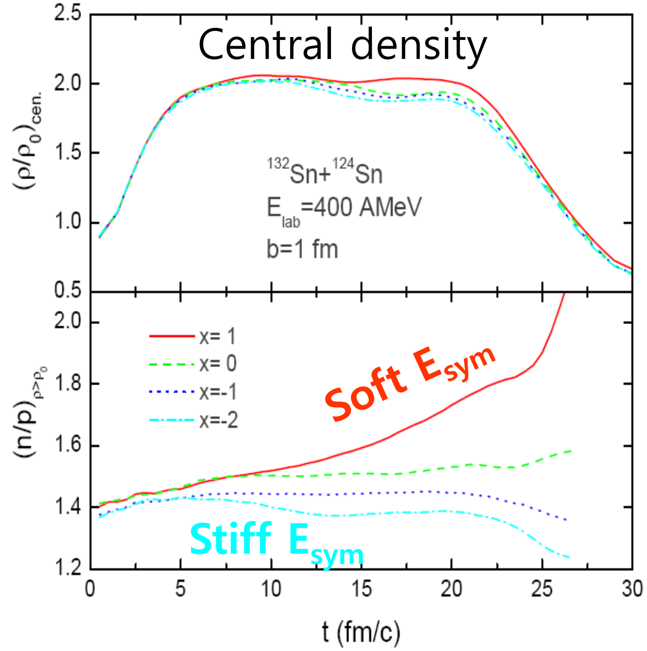


G.Q. Li, C.-H. Lee & G.E. Brown Nucl. Phys. A 625, 372 (1997)

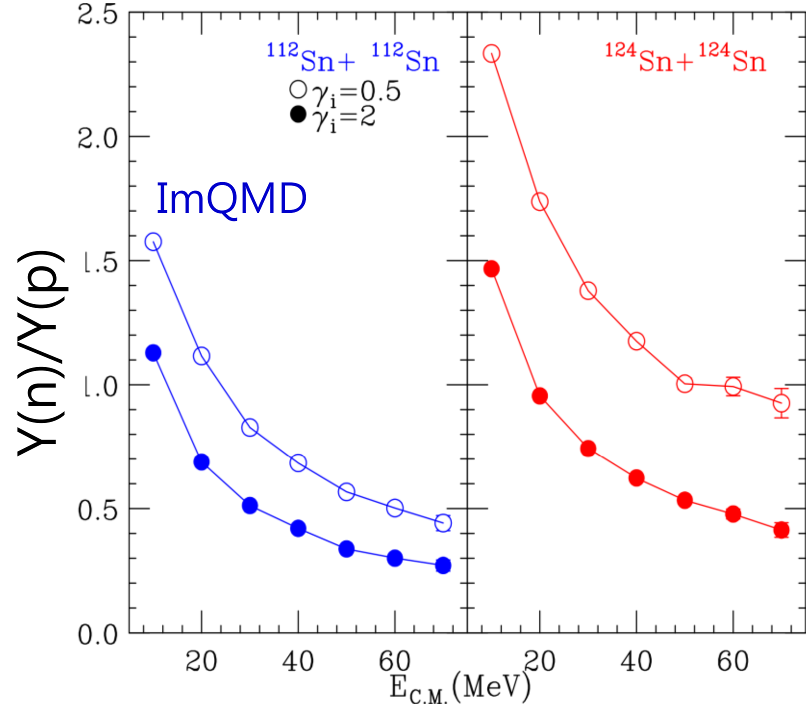
Experimental Observables

- Signals at sub-saturation densities
  1) Sizes of n-skins for unstable nuclei
  2) n/p ratio of fast, pre-equilibrium nucleons
  3) Isospin fractionation and isoscaling in nuclear multifragmentation
  4) Isospin diffusion (transport)
  5) Differential collective flows (v_1 & v_2) of n and p
  6) Correlation function of n and p
  7) $^3H/^3He$ ratio, etc.
- Signals at supra-saturation densities
  1) π^-/π^+ ratio
  2) K^+/K^0 ratio (irrelevant to KoRIA energies)
  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

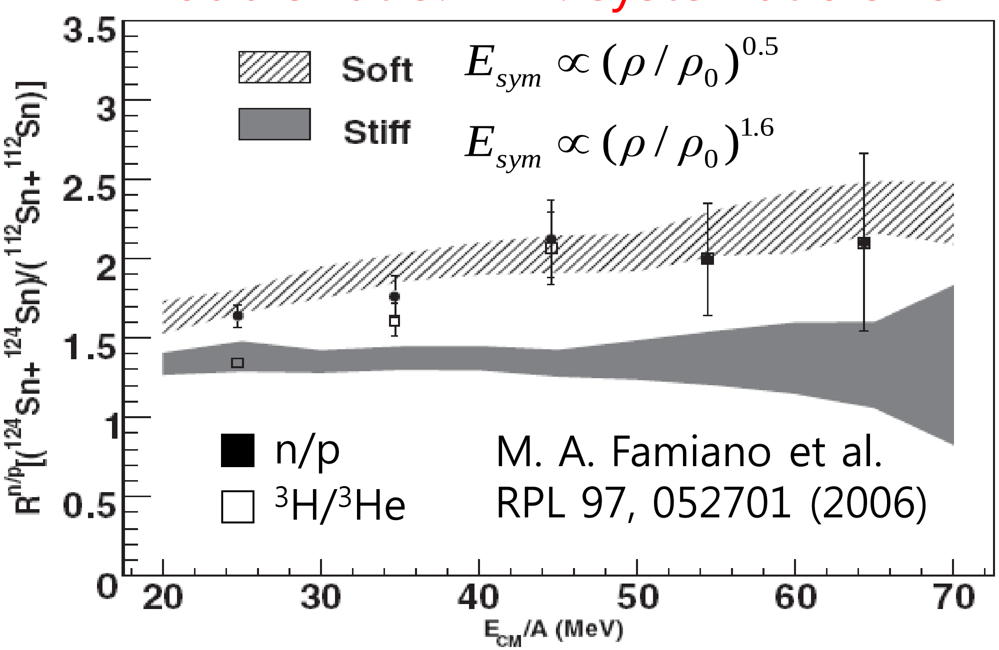
Yield Ratio



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



Double ratio: min. systematic error

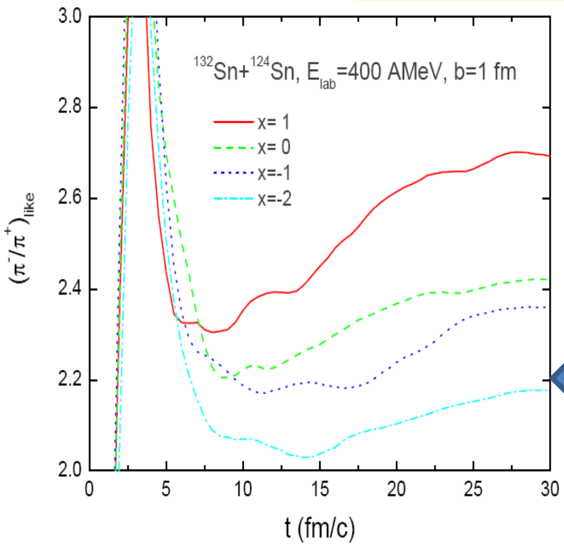


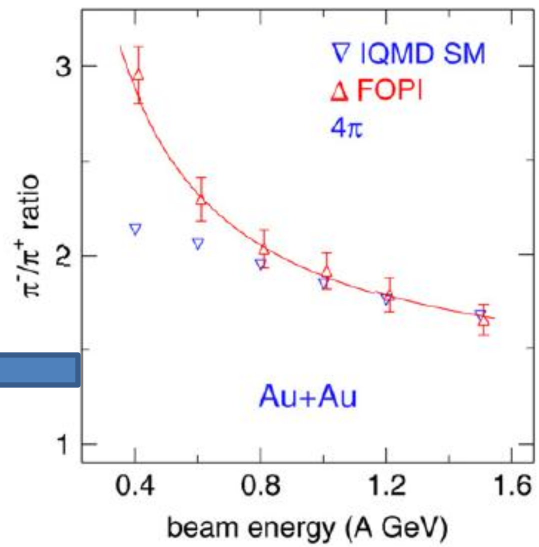
More neutrons are emitted from the n-rich system and softer symmetry energies.

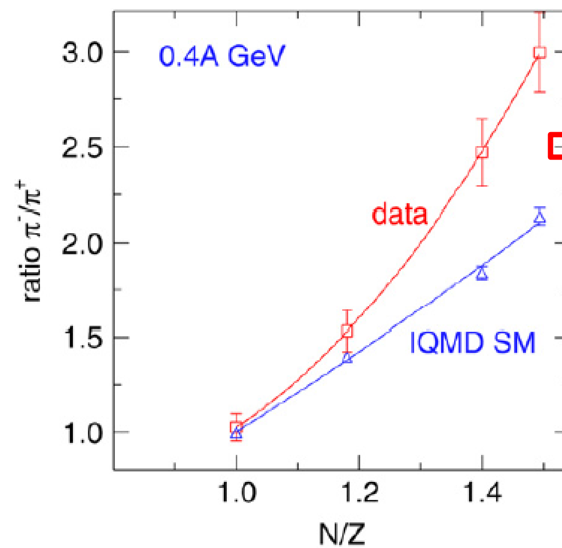
Yield Ratio (π^-/π^+)

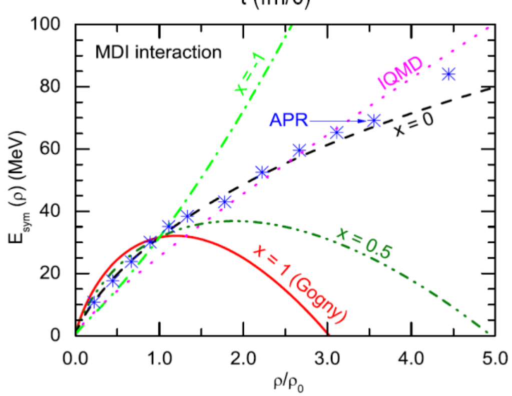
Data: FOPI Collaboration, Nucl. Phys. A 781, 459 (2007)
IQMD: Eur. Phys. J. A 1, 151 (1998)

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



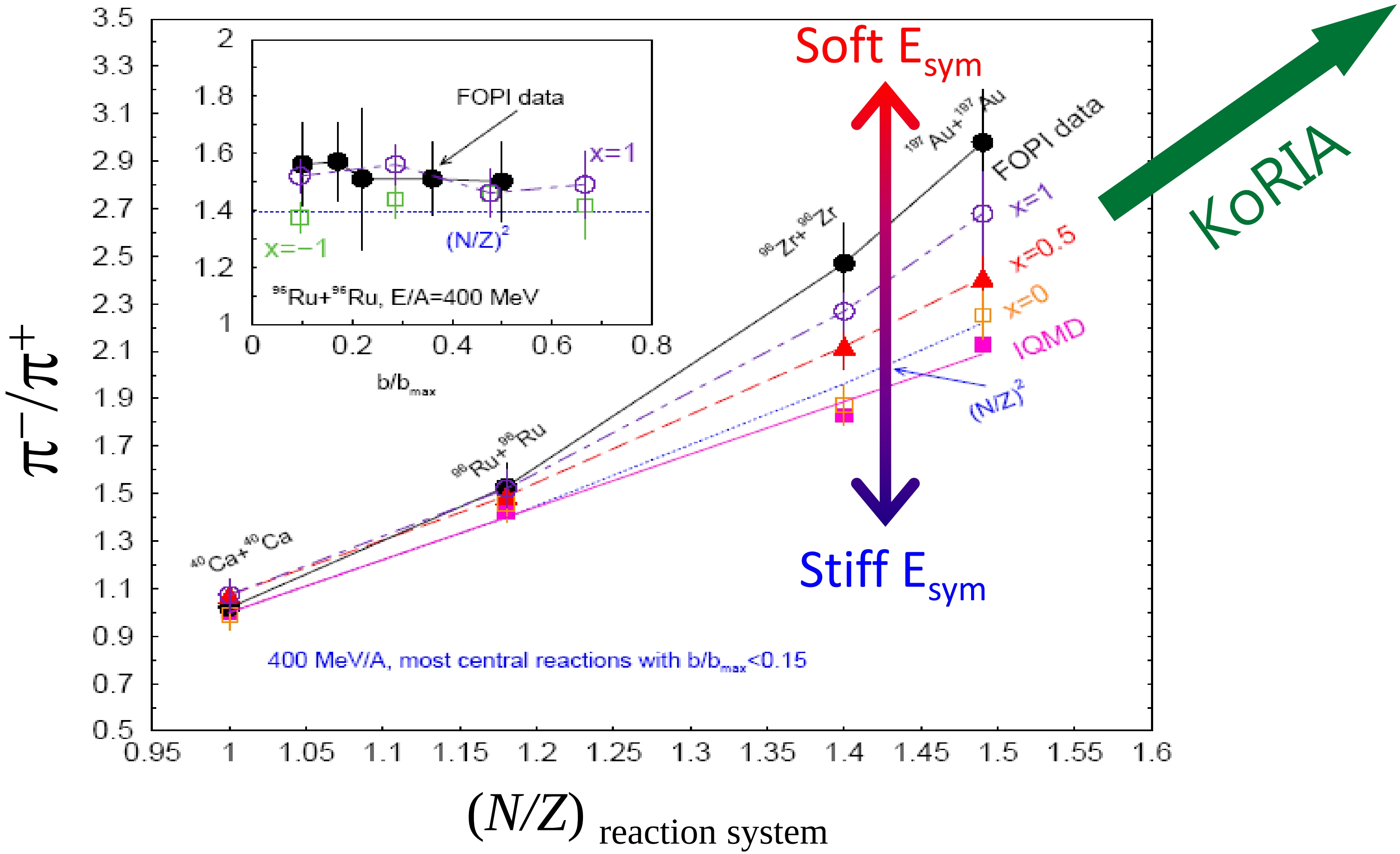






Need a symmetry energy softer than the above to make the pion production region more neutron-rich!

π^-/π^+ Ratio



Soft E_{sym}
Stiff E_{sym}
KoRIA
FOPI data
x=1
x=0.5
x=0
IQMD
$(N/Z)^2$
^{197}Au+^{197}Au
^{96}Zr+^{96}Zr
^{96}Ru+^{96}Ru
^{40}Ca+^{40}Ca
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

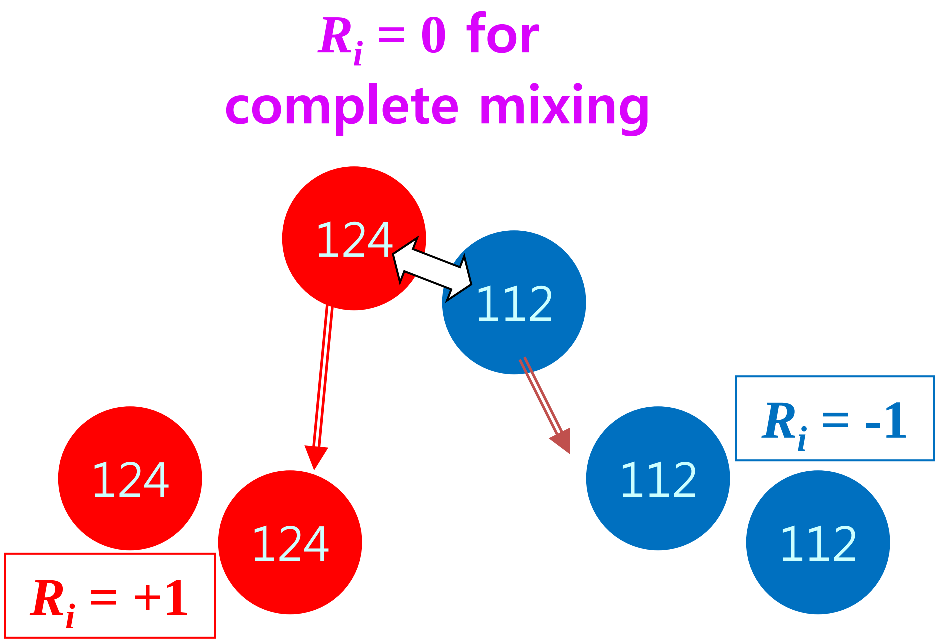
Isospin Diffusion Parameter

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

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

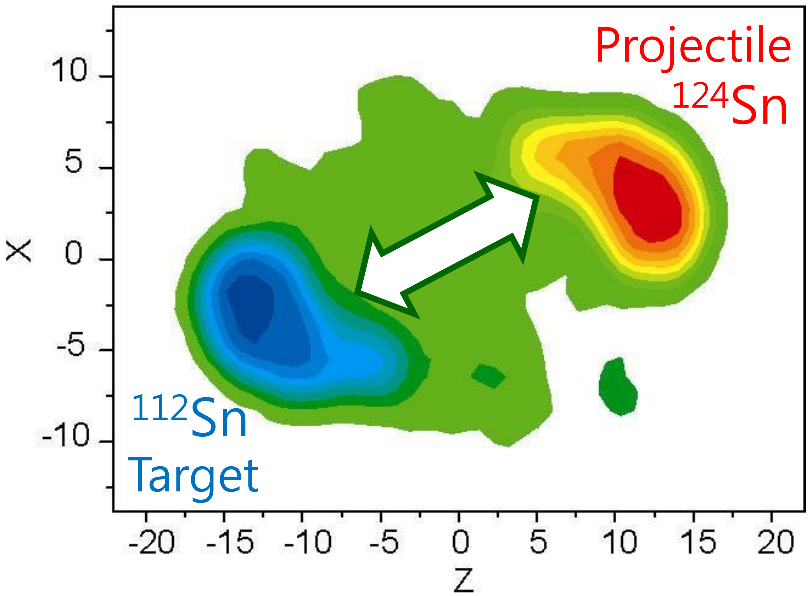


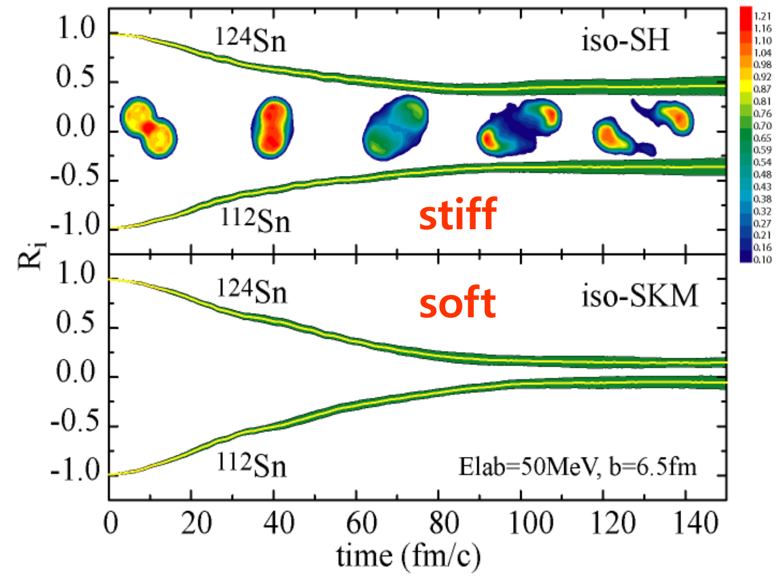
F. Rami et al., FOPI, PRL 84, 1120 (2000)

B. Hong et al., FOPI, PRC 66, 034901 (2002)

Y.-J. Kim & B. Hong, To be published.

Isospin Diffusion Parameter





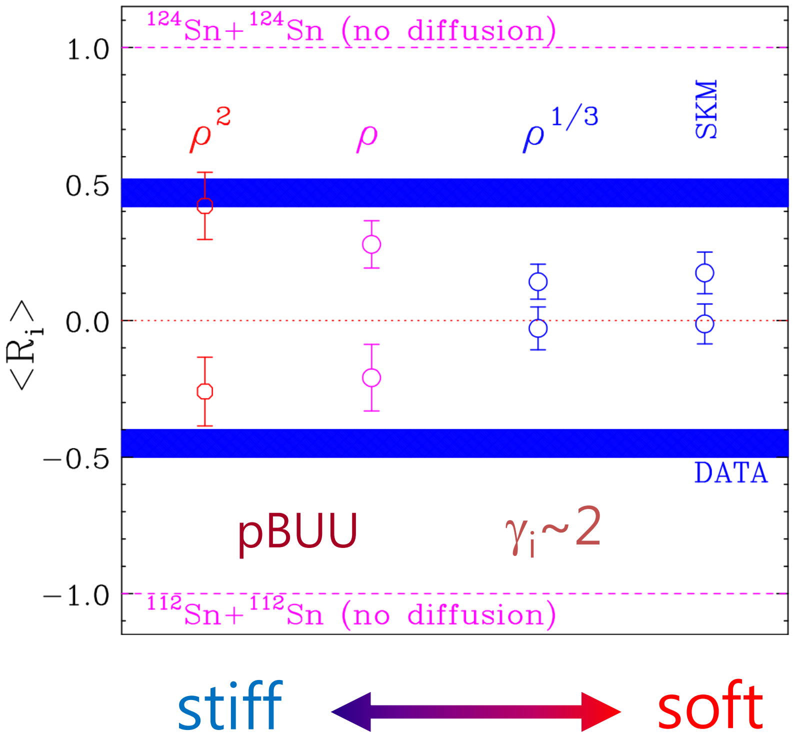
- Symmetry energy drives system towards equilibrium
  - stiff EOS : small diffusion ($|R_i| \gg 0$)
  - soft EOS : large diffusion & fast equilibrium ($R_i \rightarrow 0$)

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

Isospin Diffusion Parameter

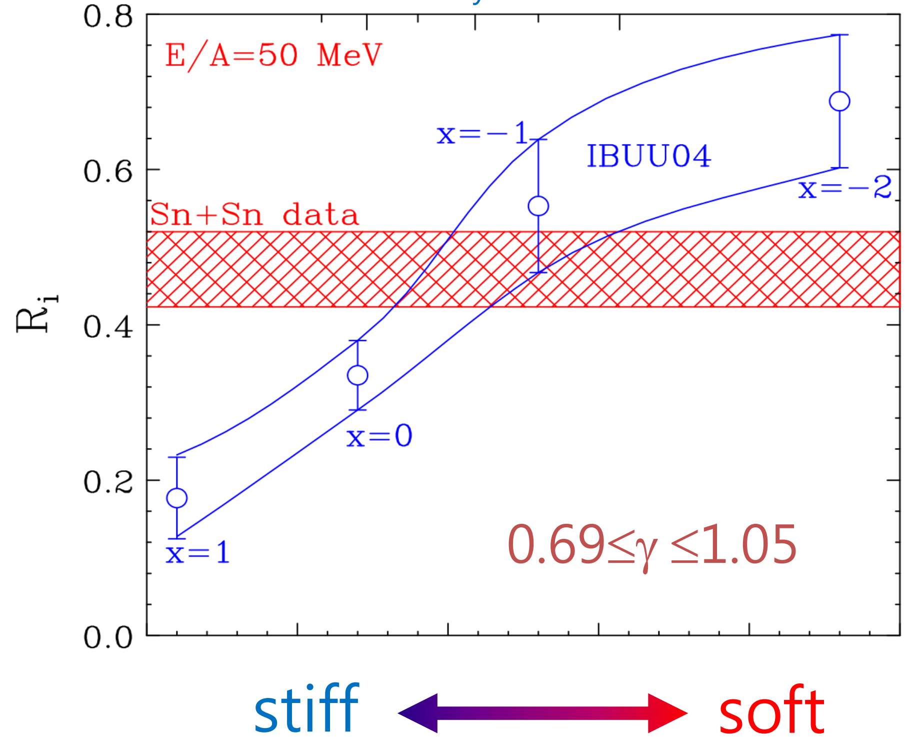
M.B. Tsang et al., PRL 92, 062701 (2004)

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



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

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



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

Collective Flow

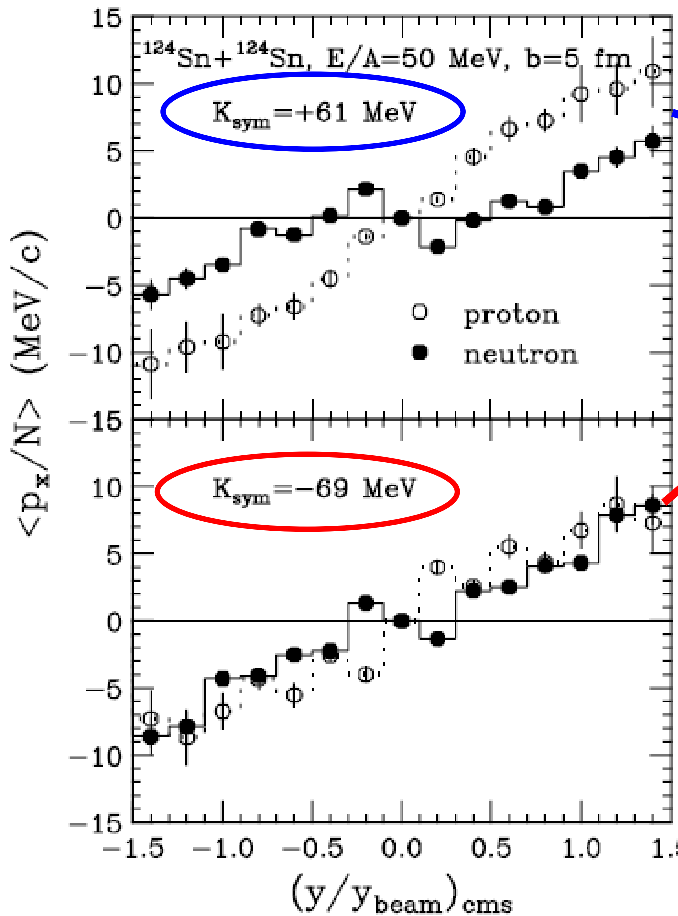
B.-A. Li,
PRL 85, 4221
(2000)

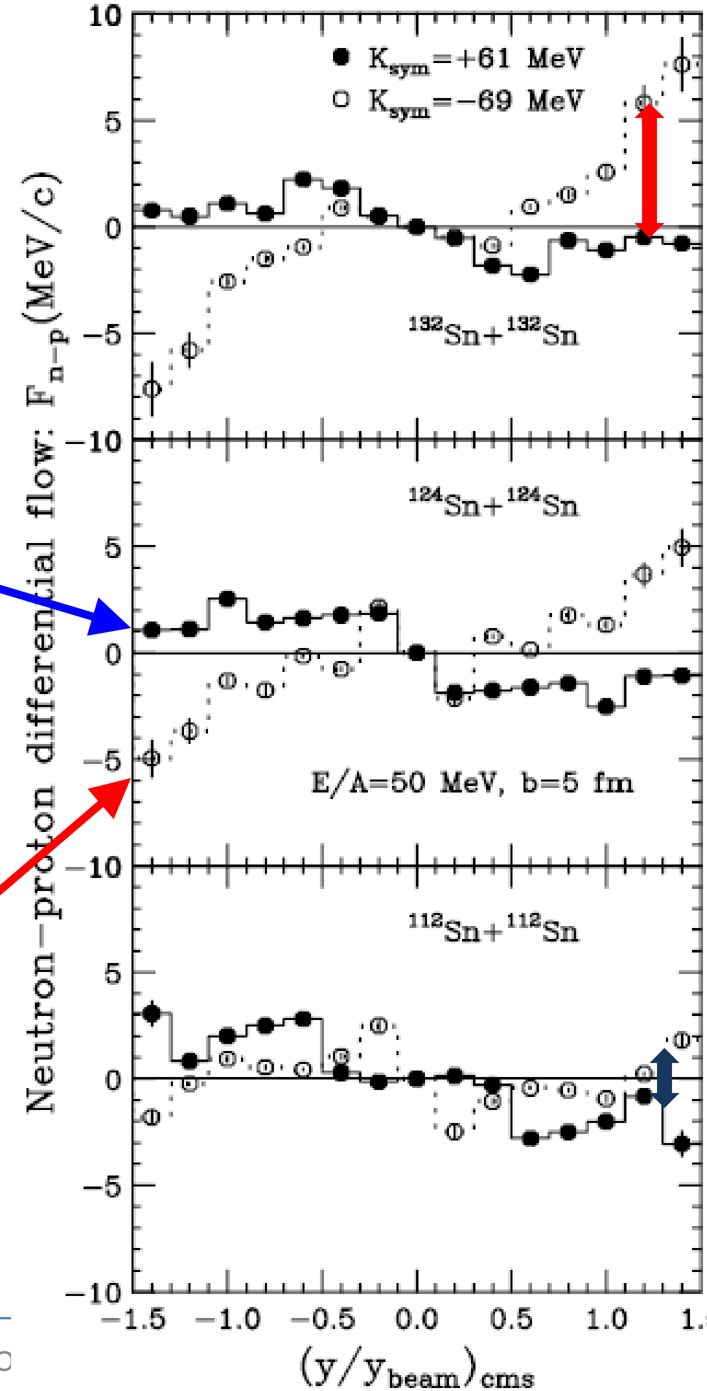
$$K_{sym} \equiv 9\rho_0^2 \frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}\bigg|_{\rho=\rho_0}$$

Stiff

Super
Soft

Also known as v_1





Large
N/Z

Small
N/Z

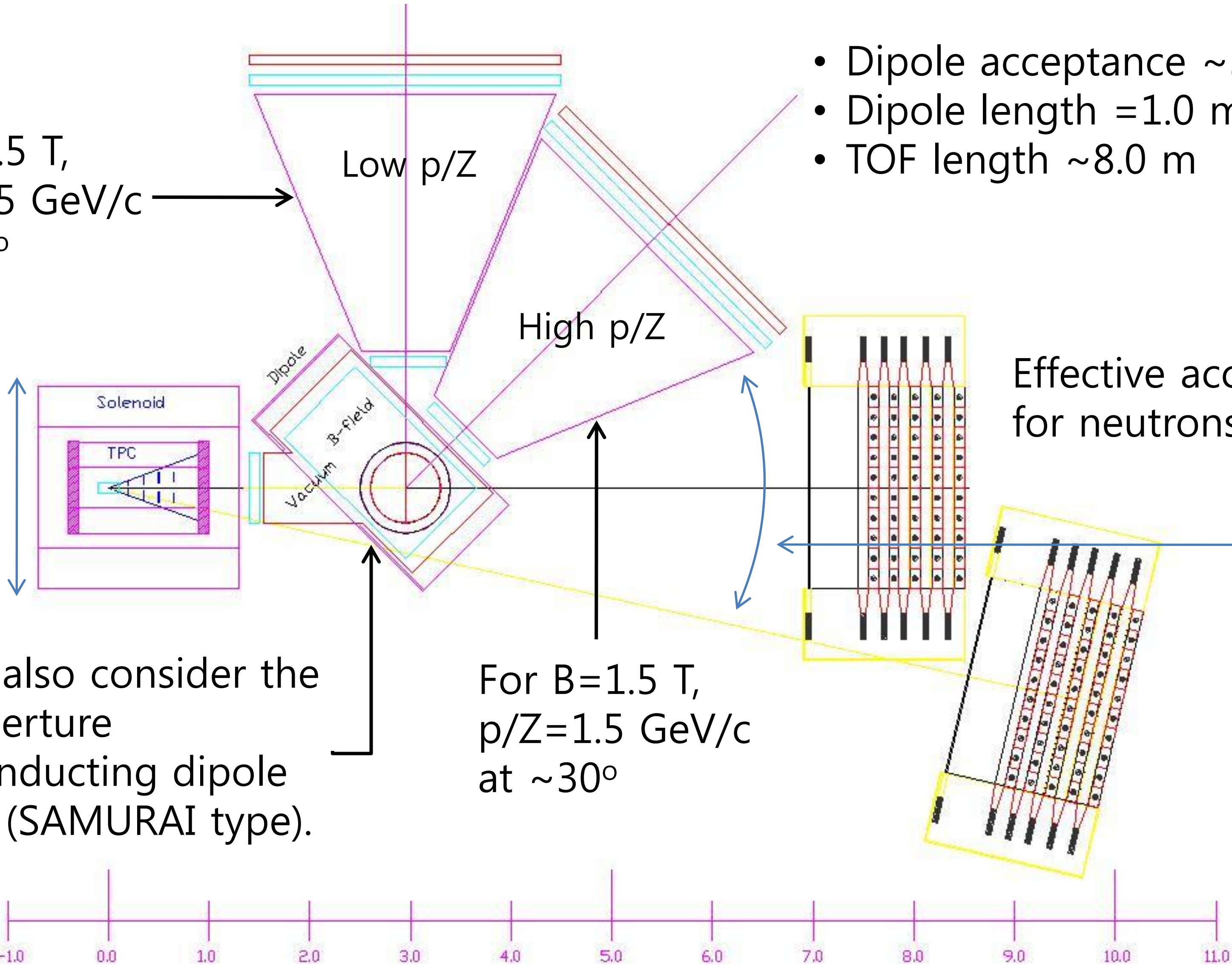
Design of Detector System

1. We need to accommodate
   - Large acceptance
   - Precision measurement of momentum or energy for variety of particle species including $\pi^{+/-}$ and neutrons with high efficiency
   - Keep flexibility for other physics topics in the future
2. This leads to the design of **LAMPS**
   - Large-Acceptance Multipurpose Spectrometer
3. Unique features of LAMPS
   - Combination of solenoid and dipole spectrometers
   - Movable arms
   - Large acceptance of neutron detector with precision energy measurement

Conceptual Design of LAMPS

- Dipole acceptance ~30mSr
- Dipole length =1.0 m
- TOF length ~8.0 m

For B=1.5 T,
p/Z=0.35 GeV/c
at ~110°



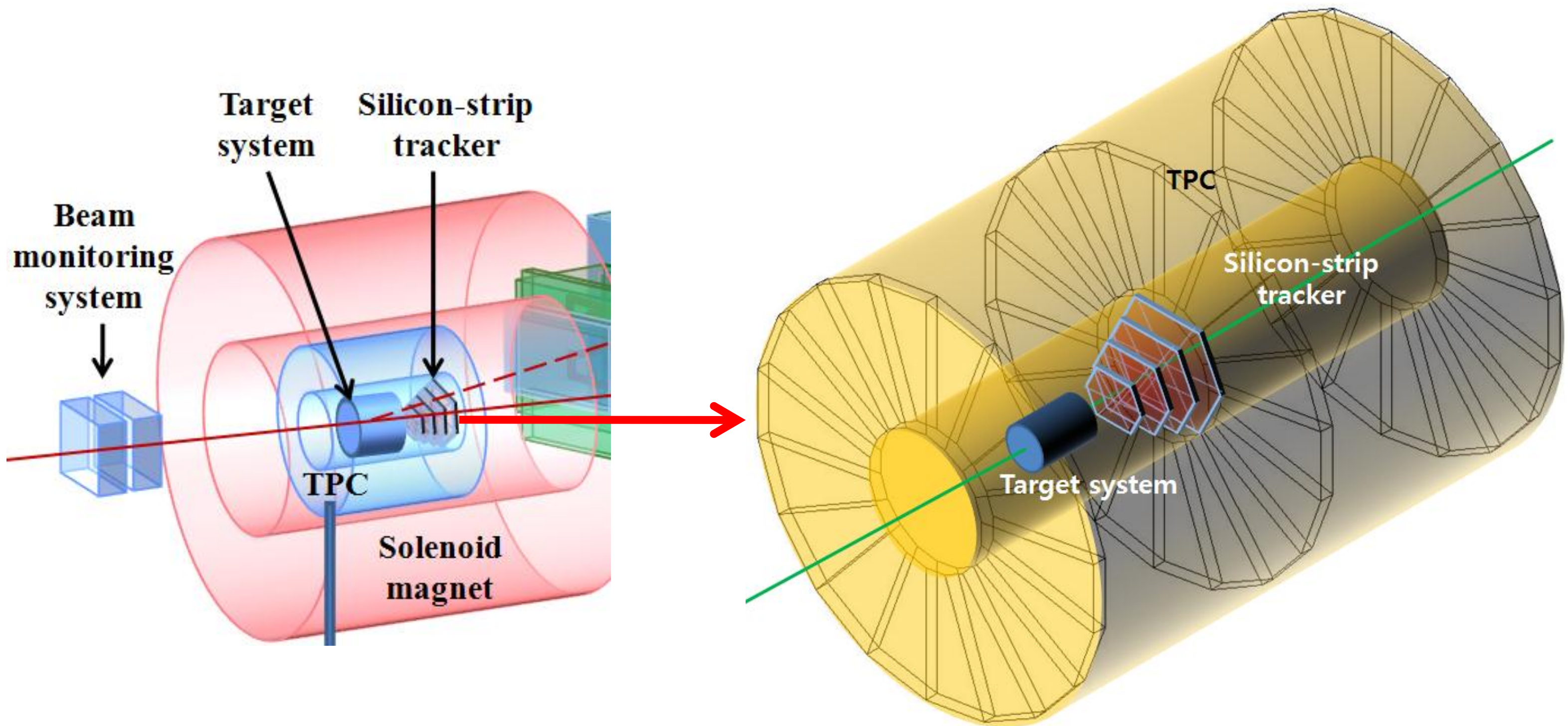
Effective acceptance
for neutrons ~100mSr

For B=1.5 T,
p/Z=1.5 GeV/c
at ~30°

We can also consider the large aperture superconducting dipole magnet (SAMURAI type).

Characteristics of LAMPS

1. Solenoid spectrometer
   - TPC: large acceptance (~3π Sr) for $\pi^{+/-}$ and light fragments
   - Silicon strip detector: 3~4 layers for nuclear fragments
   - Useful for event characterization



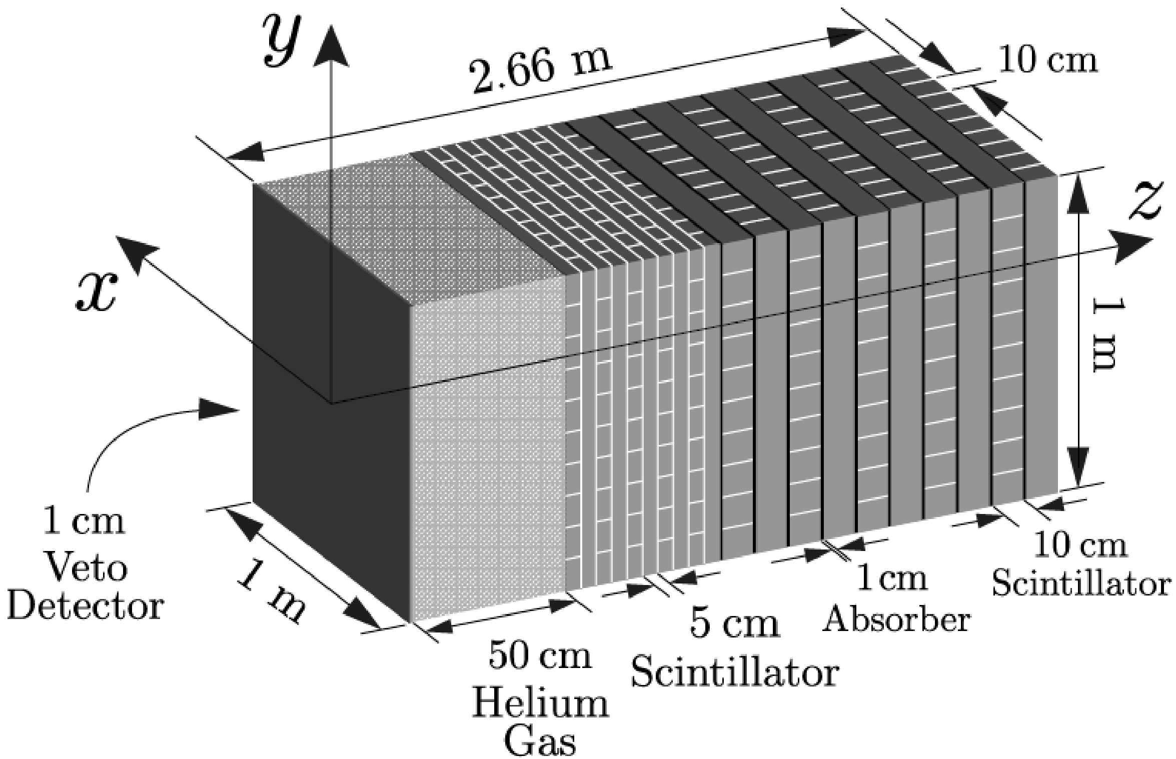
Characteristics of LAMPS

2. Dipole spectrometer
   - Acceptance: > 50 mSr
   - Multiparticle tracking of p, d, t, and He isotopes, etc.
   - Tracking chambers: ≥ 3 stations of drift chambers (+pad readout possible)
   - ToF: Conventional scintillation plastic detector or RPC technology

     [σ_t < 100 ps, essential for $\Delta p/p < 10^{-3}$ @ β=0.5]

Characteristics of LAMPS

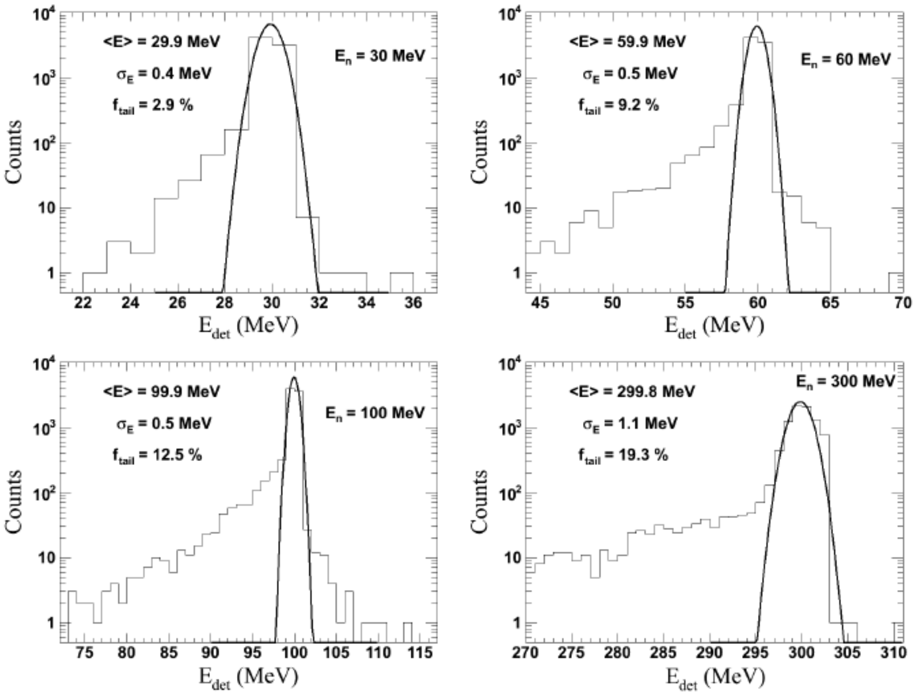
3. Neutron detection system
   - Hybrid system of the upstream homogeneous and the downstream sampling components



B. Hong, G. Jhang et al., J. Korean Phys. Soc. 58, 211 (2011)

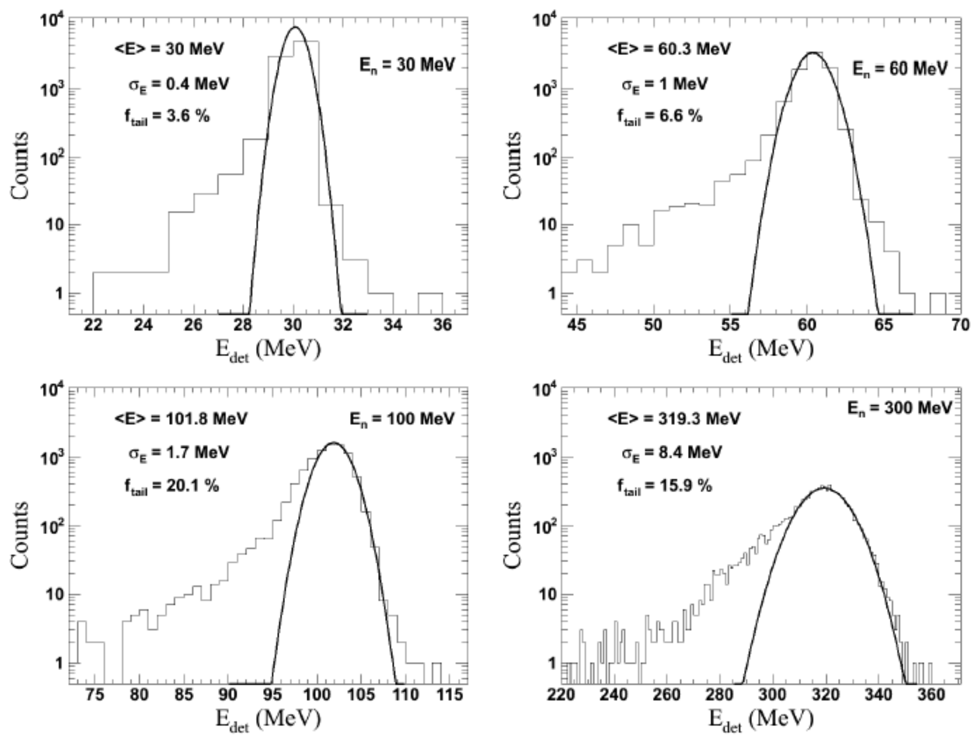
Simulation of Neutron Detector

Assuming Perfect Time Resolution



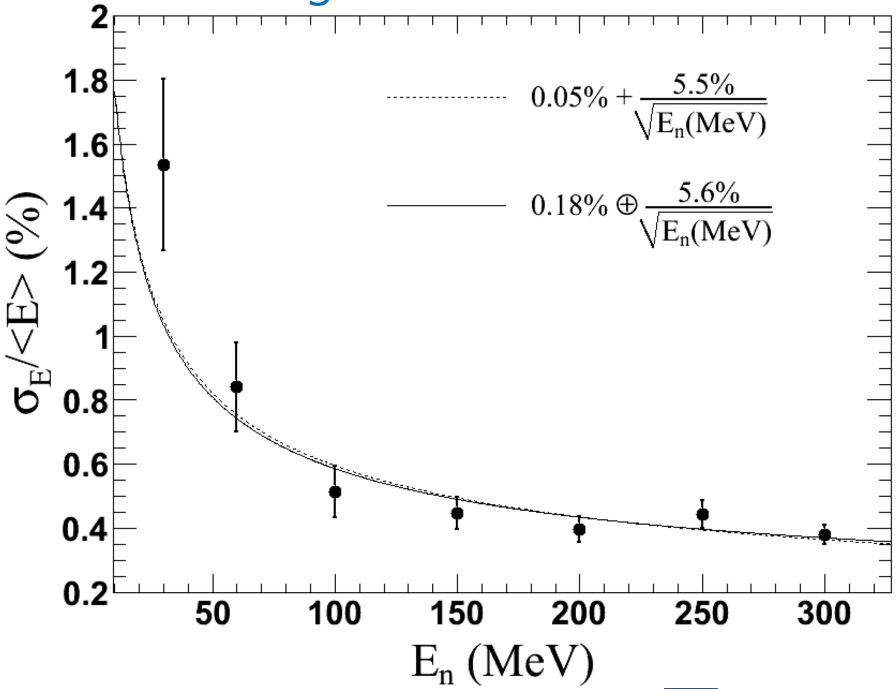
E_{det} estimated by ToF

Assuming σ_t = 1 ns

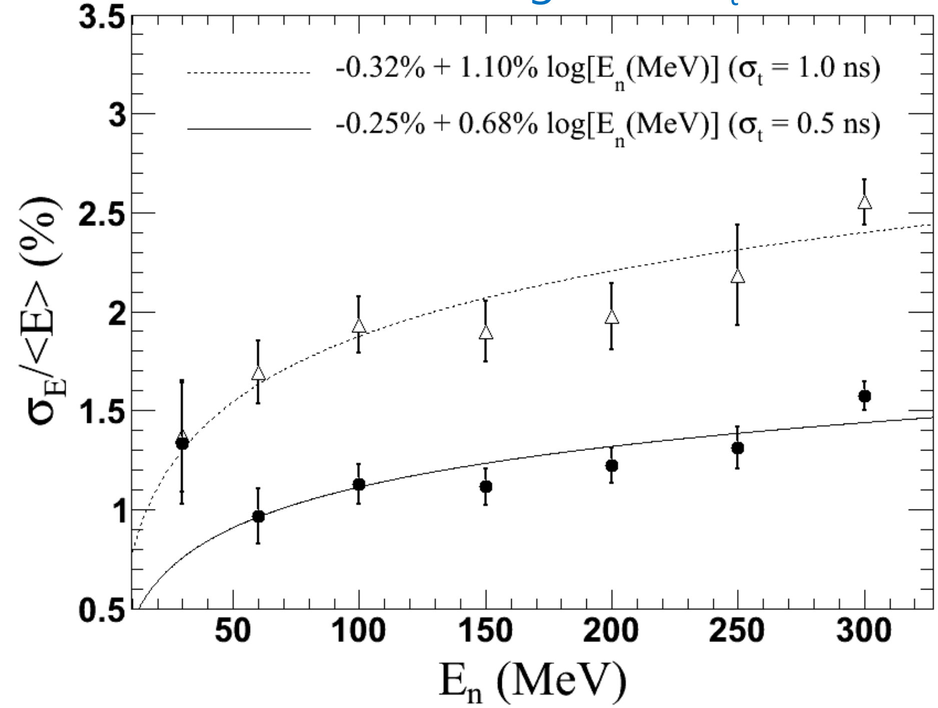


Simulation of Neutron Detector

Assuming Perfect Time Resolution

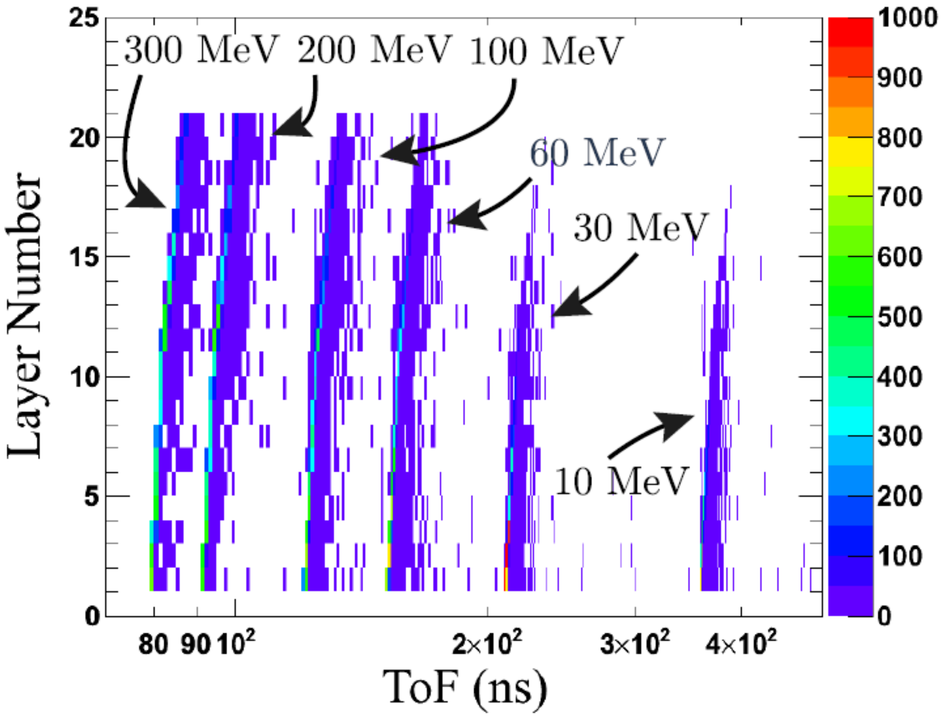


Assuming finite σ_t

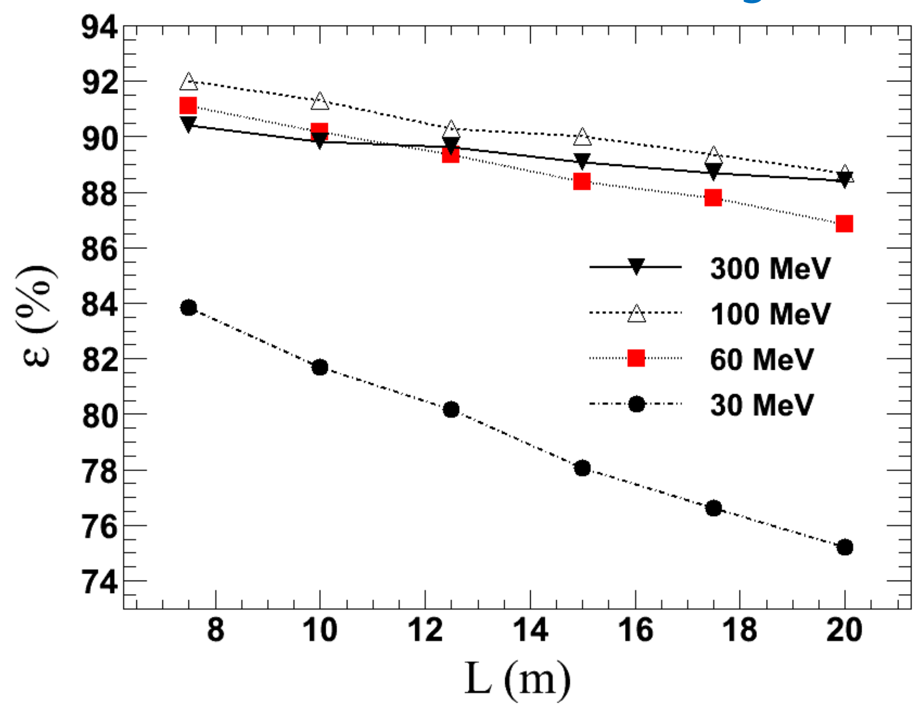


Simulation of Neutron Detector

Layer Number vs. ToF

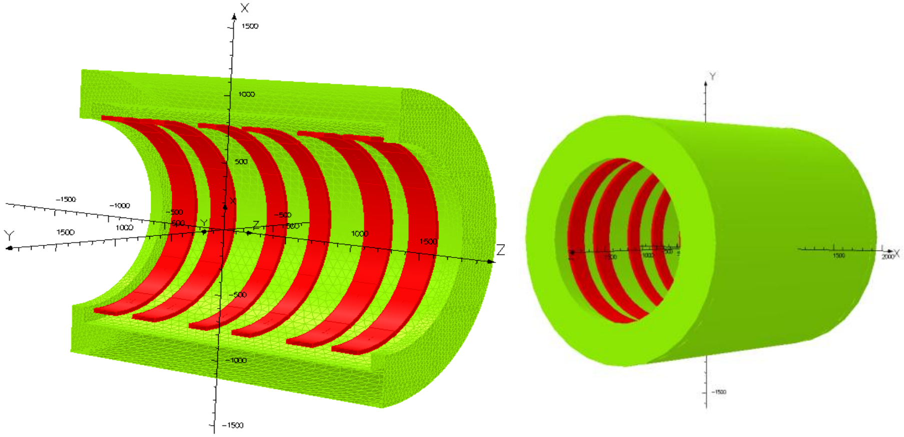


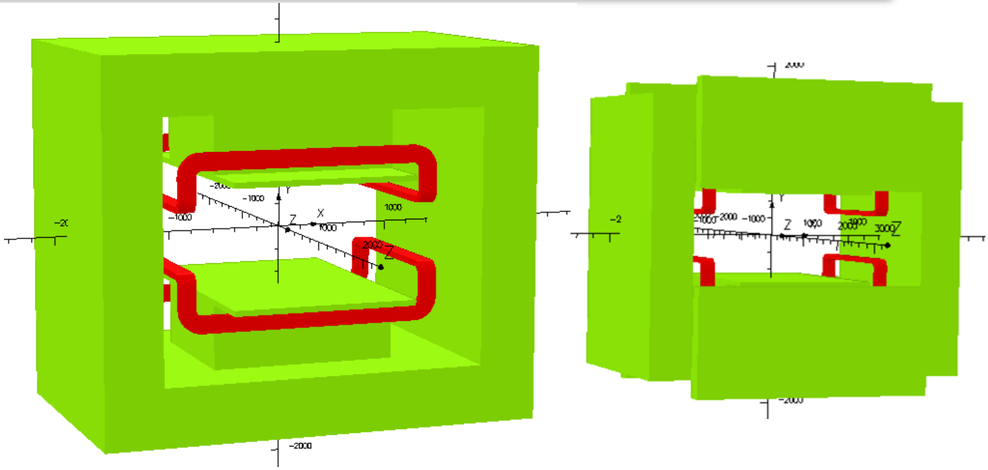
Efficiency as a function of the distance from the target



Magnets

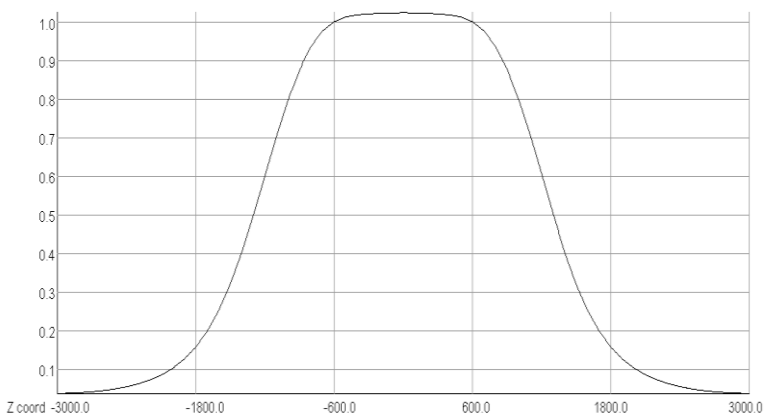
Simulation by S. Hwang & J. K. Ahn

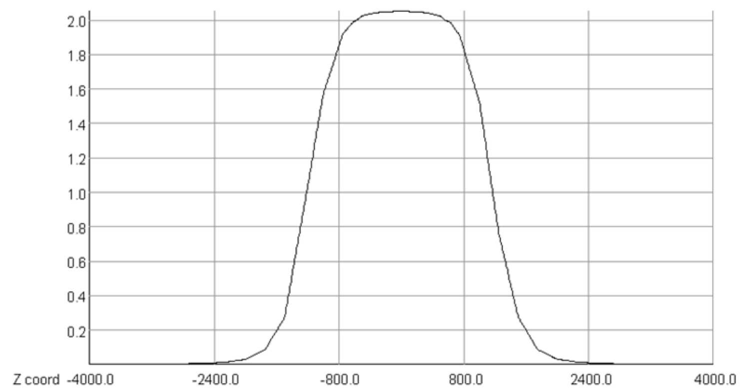




Solenoid
Size (r, z) : (50 cm, 200 cm)
Maximum B_z: about 1.0 T

H-type dipole
Pole size: (x, z)=(150 cm, 100 cm)
Maximum B_y: ~1.5 T (~4 T for SC option)
Gradient: 1.0 T·m < $\int B_y \cdot dz$ < 2.0 T·m





Summary

1. Korea Rare Isotope Accelerator (KoRIA)
   - Plan to deliver more exotic RI beams using multi-step production and acceleration processes
   - Keep the philosophy of diversity
2. Large-Acceptance Multipurpose Spectrometer (LAMPS)
   - Large acceptance
   - Combination of solenoid and dipole spectrometers
   - Movable arms
   - Keep flexibility for other physics topics in the future
3. Symmetry Energy in EoS
   - Long-standing problem in nuclear physics
   - Crucial to understand the neutron matter & several astrophysical objects

Backup

IFF Linac Beam Specification

Ion Species	Z/ A	Ion source output		SC linac output			
		Charge	Current (pμA)	Charge	Current (pμA)	Energy (MeV/u)	Power (kW)
Proton	1/ 1	1	660	1	660	610	400
Ar	18/ 40	8	42.1	18	33.7	300	400
Kr	36/ 86	14	22.1	34-36	17.5	265	400
Xe	54/ 136	18	18.6	47-51	12.5	235	400
U	92/ 238	33-34	11.7	77-81	8.4	200	400

Estimated RIBs based on ISOL

Isotope	Half-life	Yield at target (pps)	Overall eff. (%)	Expected Intensity (pps)
^{78}Zn	1.5 s	2.75×10^{10}	0.0384	1.1×10^{7}
^{94}Kr	0.2 s	7.44×10^{11}	0.512	3.8×10^{9}
^{97}Rb	170 ms	7.00×10^{11}	0.88	6.2×10^{9}
^{124}Cd	1.24 s	1.40×10^{12}	0.02	2.8×10^{8}
^{132}Sn	40 s	4.68×10^{11}	0.192	9.0×10^{8}
^{133}In	180 ms	1.15×10^{10}	0.184	2.1×10^{7}
^{142}Xe	1.22 s	5.11×10^{11}	2.08	1.1×10^{10}

KoRIA RI Beam intensities compared for ISOL & IFF

RIB species	ISOL (pps)	In-Flight Fragmentation (pps)	comment
^{15}O	$5x10^8$ * $^{19}F(p,\alpha n)$, LiF pressed powder	To be estimated	Nuclear astropysics
^{94}Kr	$4x10^9$	$4x10^2$	Nuclear structure
^{109}Y	$2x10^5$	$<10^2$	New discovery at RIKEN
^{117}Mo	Not available due to low vapor pressure	$<10^3$	New discovery at RIKEN
^{132}Sn	$9x10^8$	$2x10^5$	Double magic
^{142}Xe	$1x10^{10}$	$1x10^4$	Symmetry energy
^{144}Cs	$7x10^8$	$3x10^4$	Nuclear astrophysics