1st RAON Users' Workshop
IBS, Korea, April 3-5, 2019

Some thoughts on possible measurements with LAMPS

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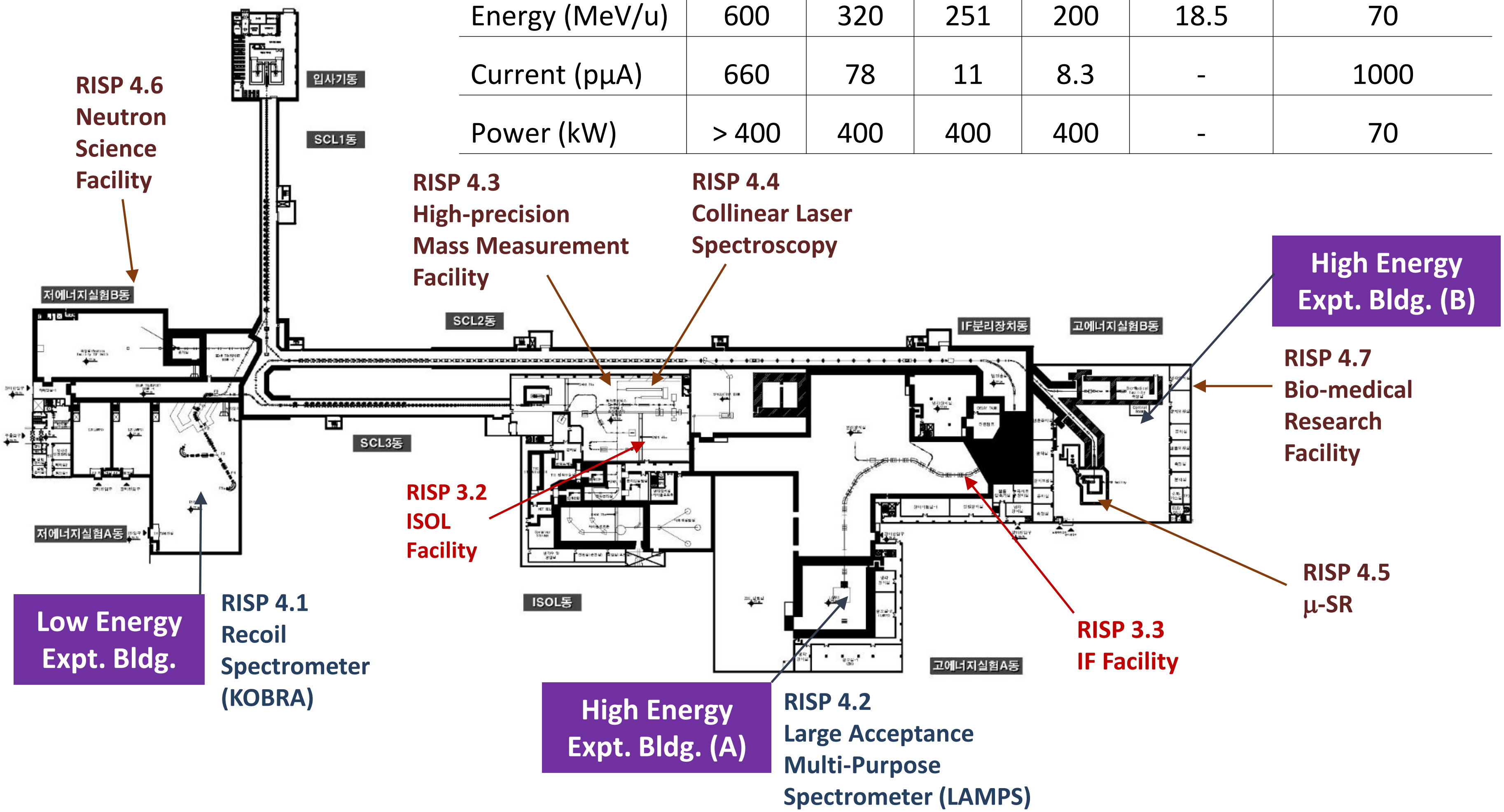
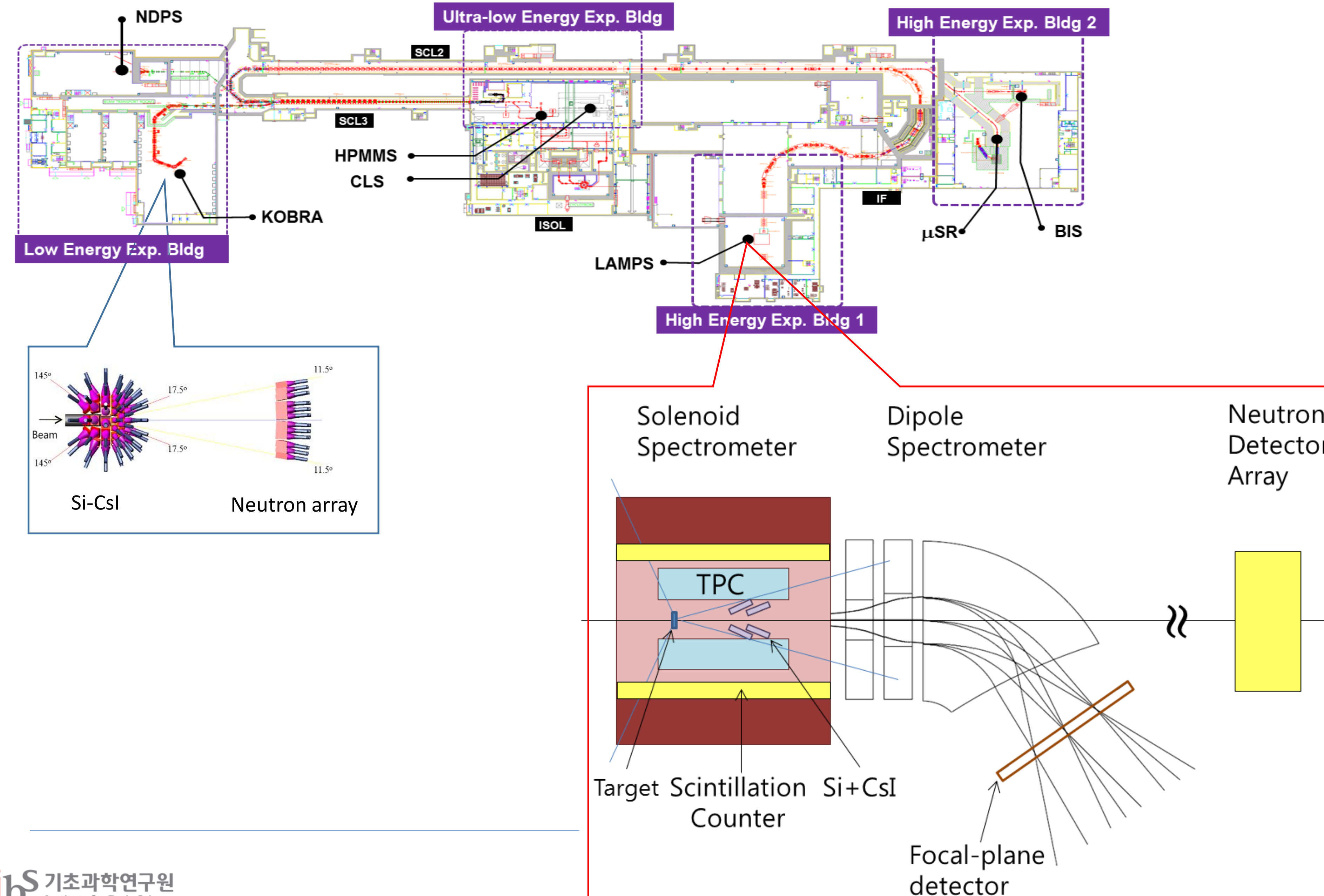
CENuM
Center for Extreme Nuclear Matters

Layout of RAON

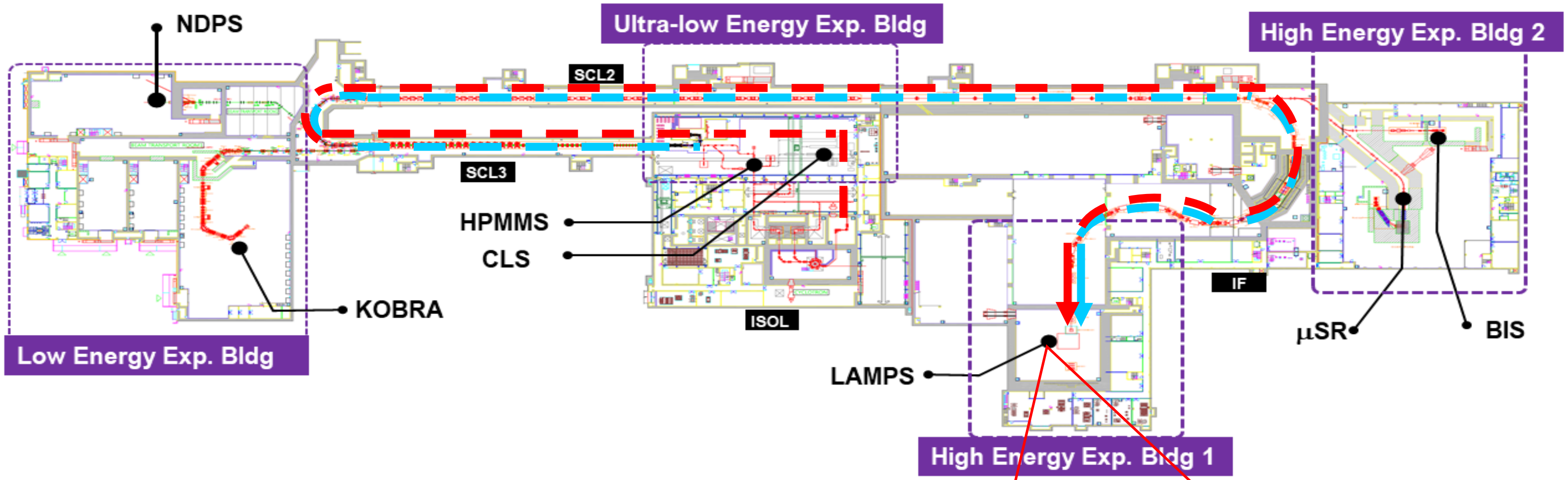
	Driver Linac				Post Acc.	Cyclotron
Particle	H^{+}	O^{+8}	Xe^{+54}	U^{+79}	RI beam	proton
Energy (MeV/u)	600	320	251	200	18.5	70
Current (pμA)	660	78	11	8.3	-	1000
Power (kW)	> 400	400	400	400	-	70



Brief History

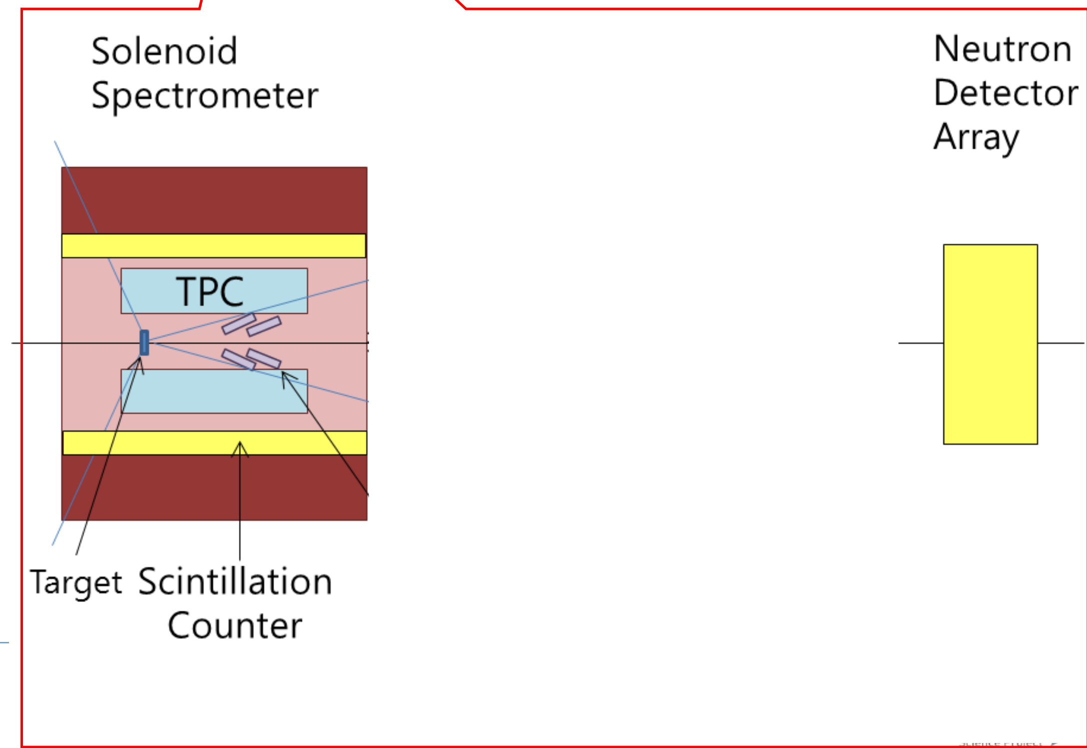


Brief History



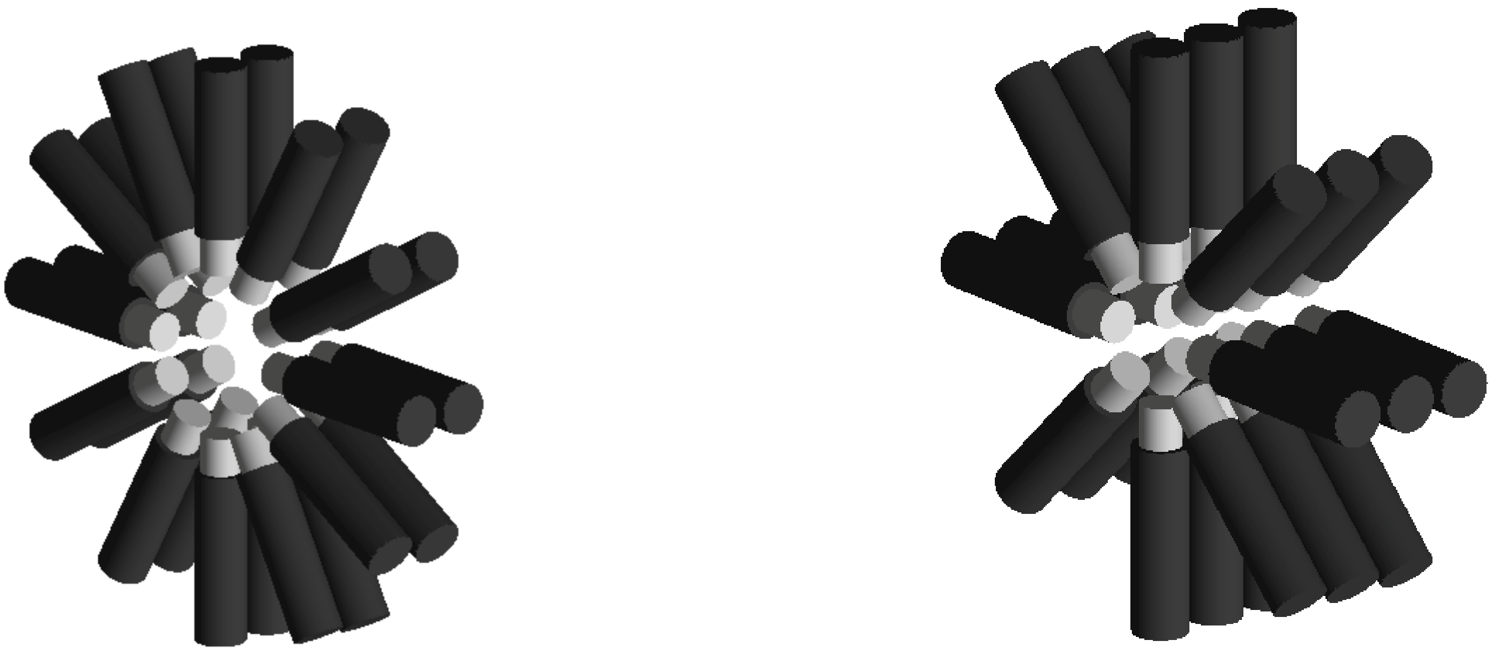
Stable ion beams to IF target
via SCL3+SCL2

RIB to IF target
via ISOL+SCL3+SCL2



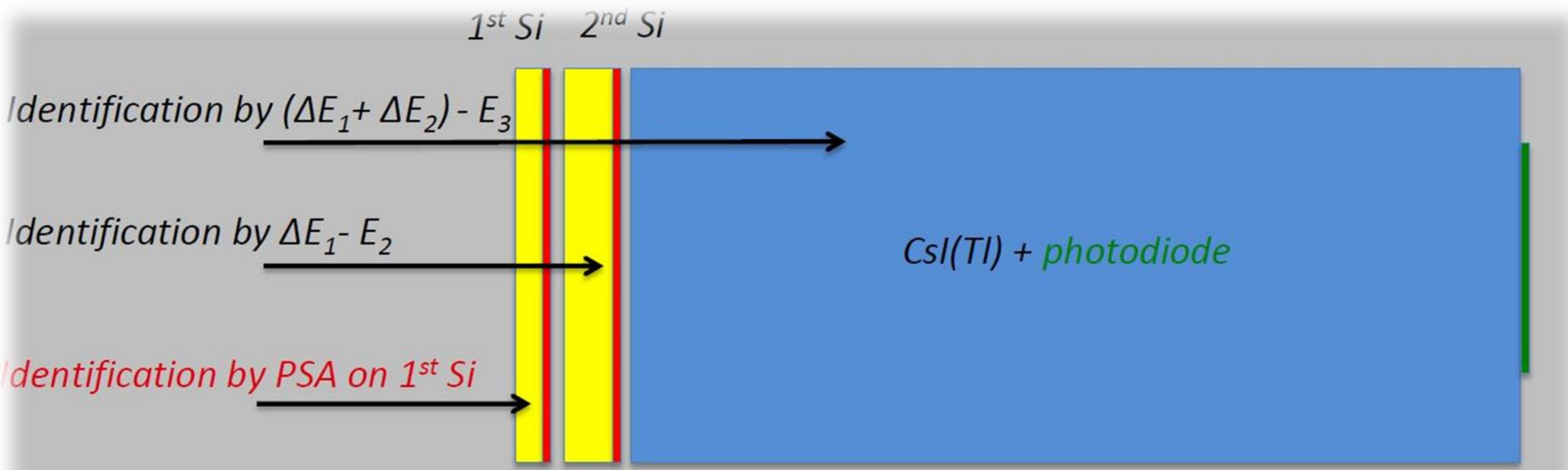
New idea about LAMPS detectors at low-energy experimental hall

- $LaBr_3$(Ce) gamma detector system
  - Total 24 modules with fast timing PMTs (R_t< 200 ps, R_E< 3.5%, ε~6.8% at 664 keV)
  - Plan to build 12 modules by 2020



New idea about LAMPS detectors at low-energy experimental hall

- FAZIA type Si+CsI detector (configuration)



1^{st} element: reverse mount 300 µm thick, nTD Silicon of doping uniformity apt to PSA

2^{nd} element: reverse mount 500 µm thick, nTD Silicon for redundant PSA

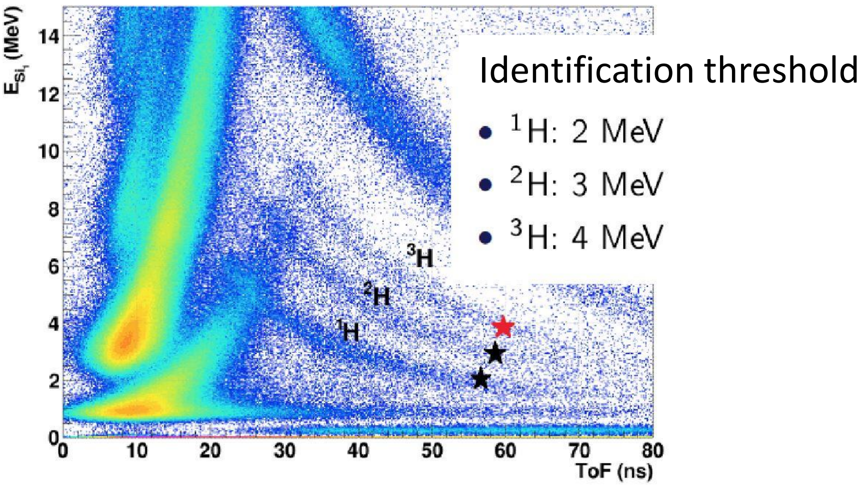
3^{rd} element: 10 cm long CsI(Tl) crystal, coupled to Si-photodiode

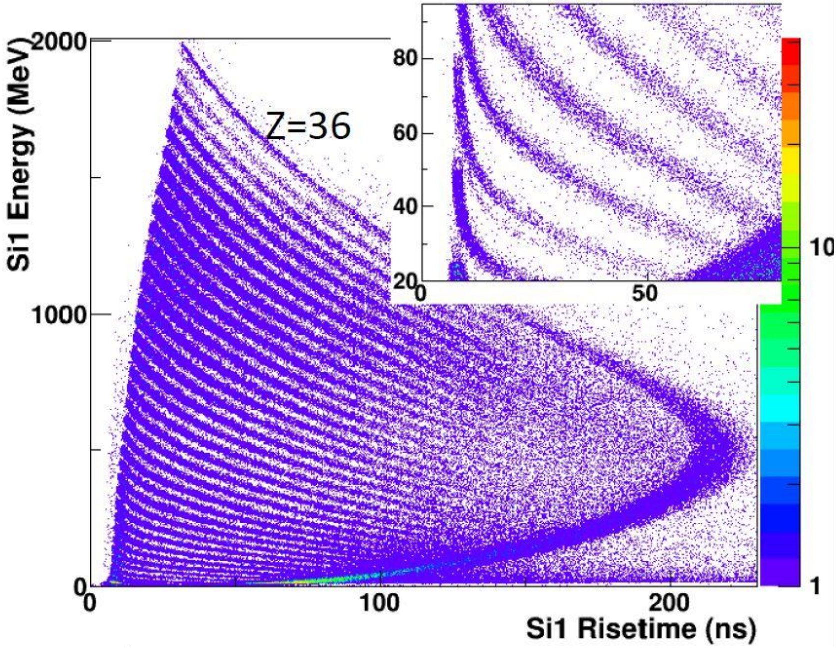
First and second Silicon detectors are cut out of a <100> crystal along a properly selected direction in order to avoid channelling.

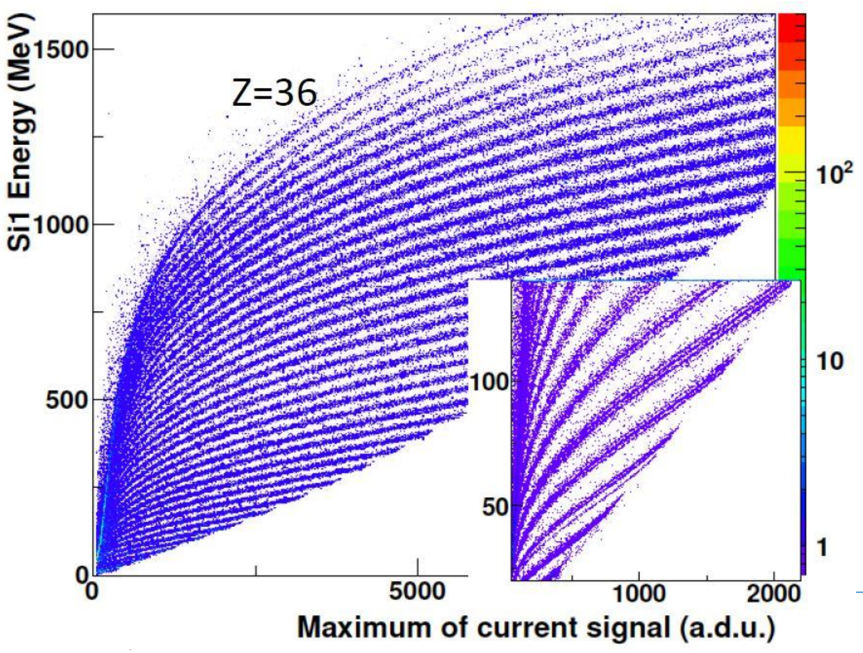
Total thickness variation of both Silicon detectors over the active area ≈ 2-3 µm

New idea about LAMPS detectors at low-energy experimental hall

- FAZIA type Si+CsI detector
  (PID capability)

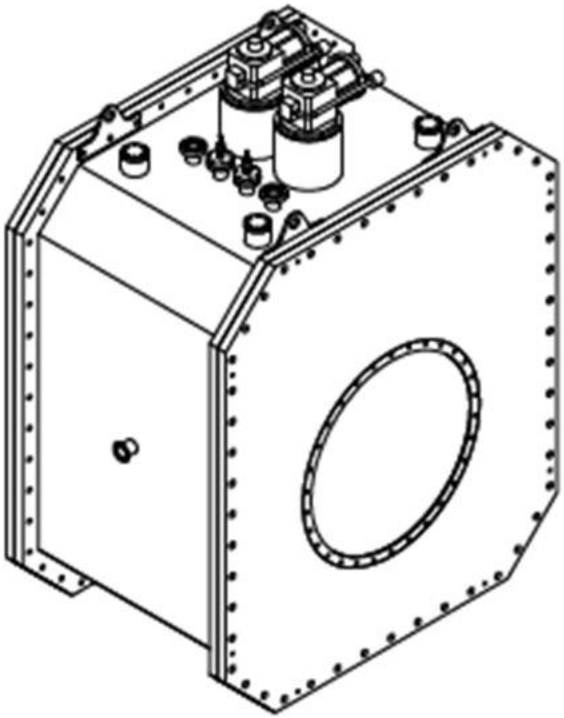




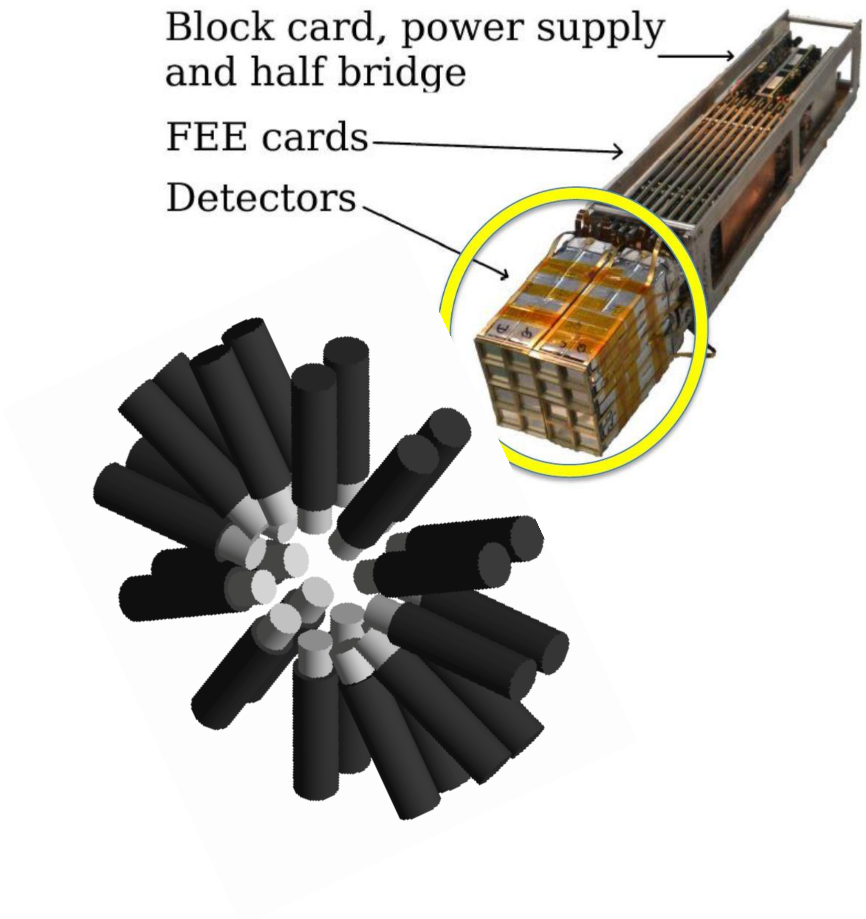


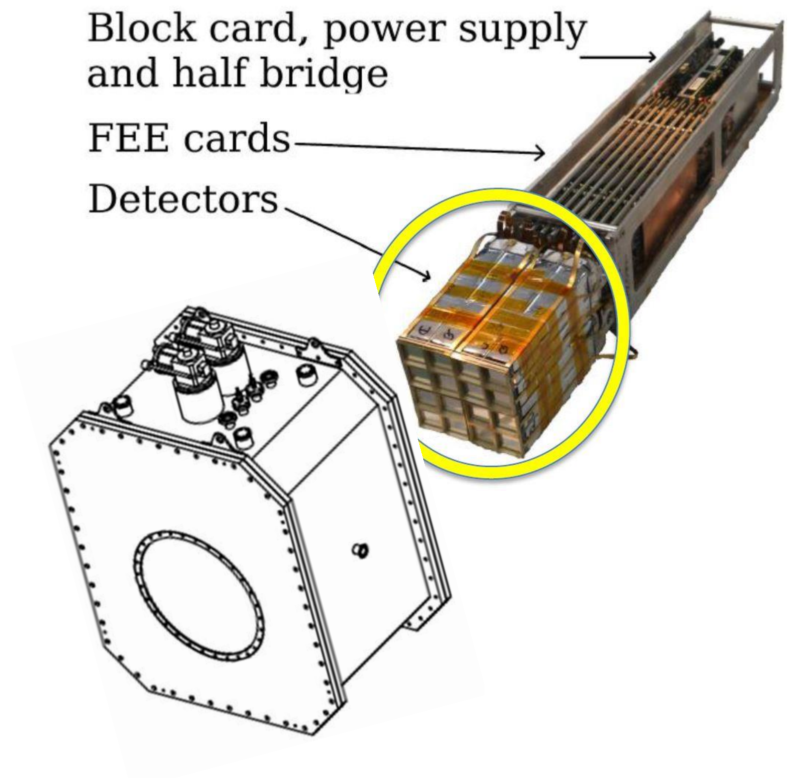
New idea about LAMPS detectors at low-energy experimental hall

- AT-TPC
  - Amplification: GEM or μPIC
  - Superconducting solenoid magnet: 1.5 T, inner radius & length = 60 cm each
  - Magnet construction in 2019
  - AT-TPC construction in 2020



New idea about LAMPS detectors at low-energy experimental hall





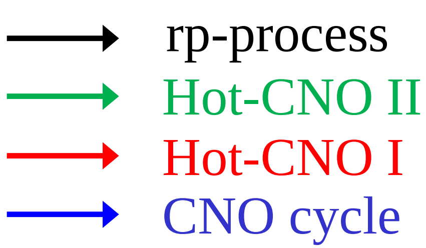
Nuclear astrophysics

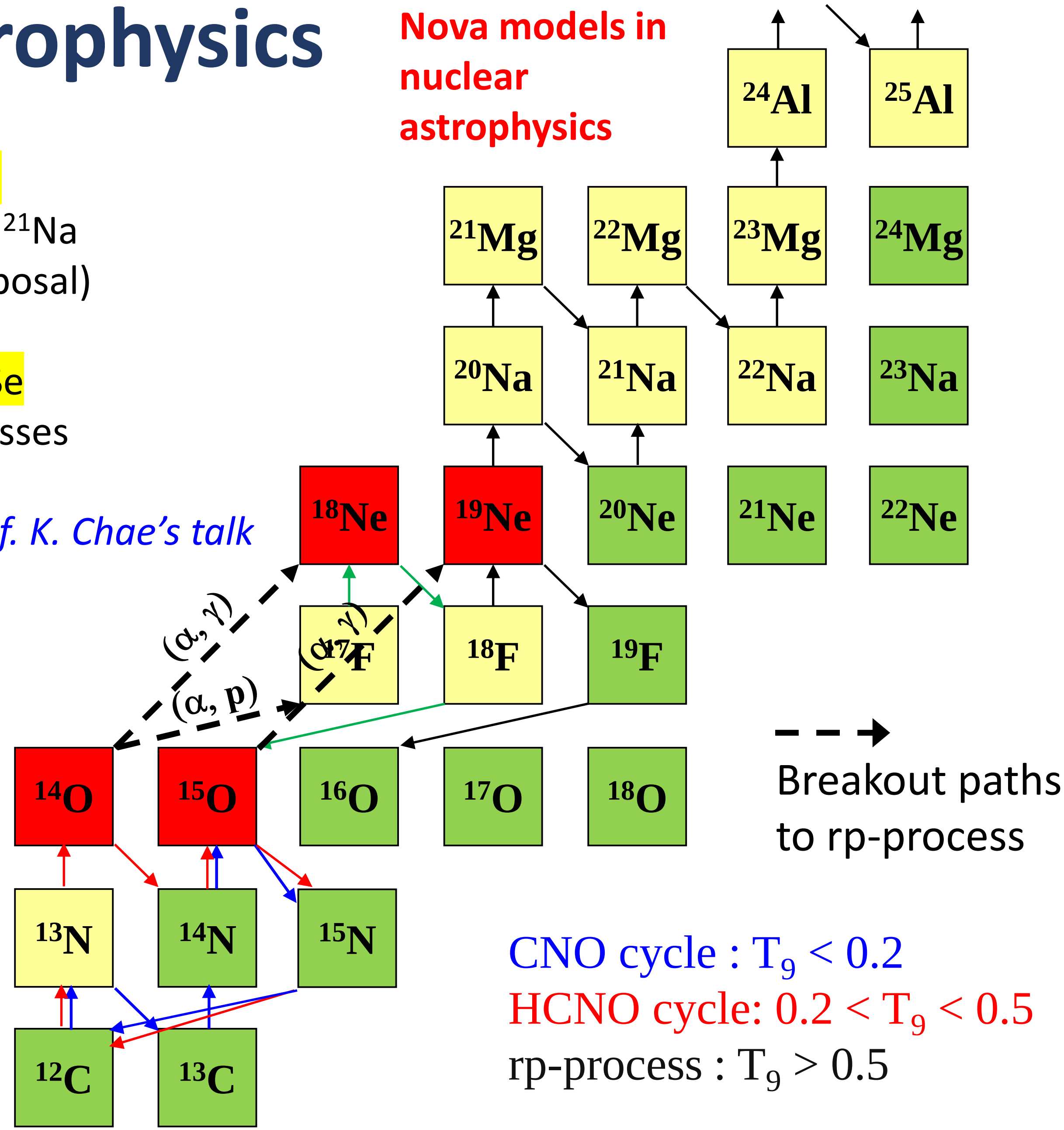
Nova models in nuclear astrophysics

- $^{14}O(\alpha,\gamma)^{18}Ne$, $^{14}O(\alpha,p)^{17}F$
- $^{15}O(\alpha,\gamma)^{19}Ne$, $^{15}O(\alpha,p)^{18}F$
- $^{18}Ne(\alpha,\gamma)^{22}Mg$, $^{18}Ne(\alpha,p)^{21}Na$
- $^{22}Mg(\alpha,p)^{25}Al$ (NSCL proposal)
- $^{26}Al(\alpha,p)^{24}Si$
- $^{18}F(p,\gamma)^{19}Ne$, $^{65}As(p,\gamma)^{66}Se$
- More (n,γ) & (p, γ) processes
- $^{16}O(\alpha,pn)^{18}F$, $^{29}P(d,\alpha)^{30}P$

Yellow: Confirmed by Prof. K. Chae's talk

- $^{83}Nb(p,\alpha)^{80}Zr$, $^{84}Mo(\gamma,\alpha)^{80}Zr$ (Yuhu Zhang)
- $^{4}He(^{3}He,\gamma)^{7}Be$, $^{7}Be(n,p)^{7}Li$, $^{4}He(\alpha n,\gamma)^{9}Be$ etc. (Taka Kajino)





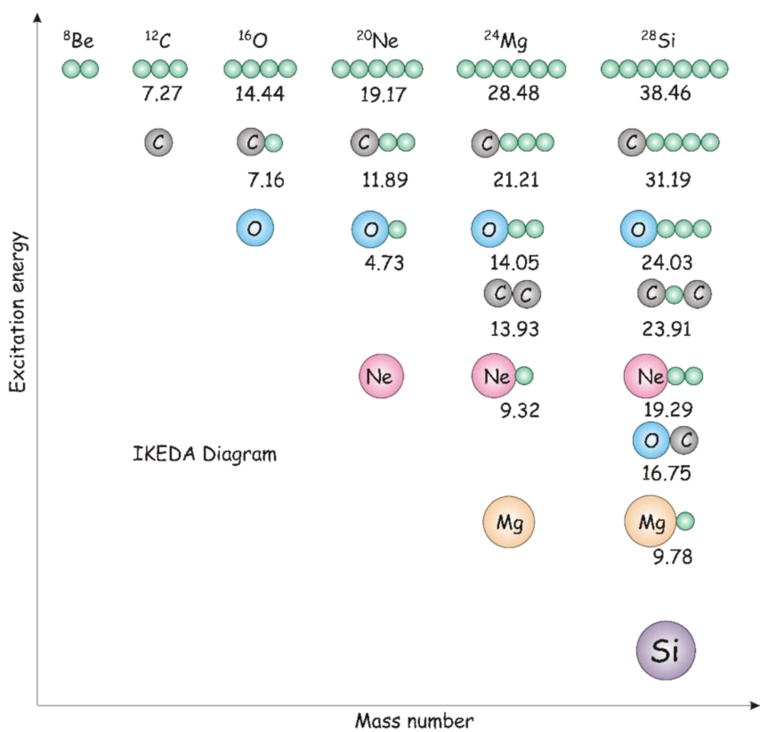
CNO cycle : $T_9 < 0.2$

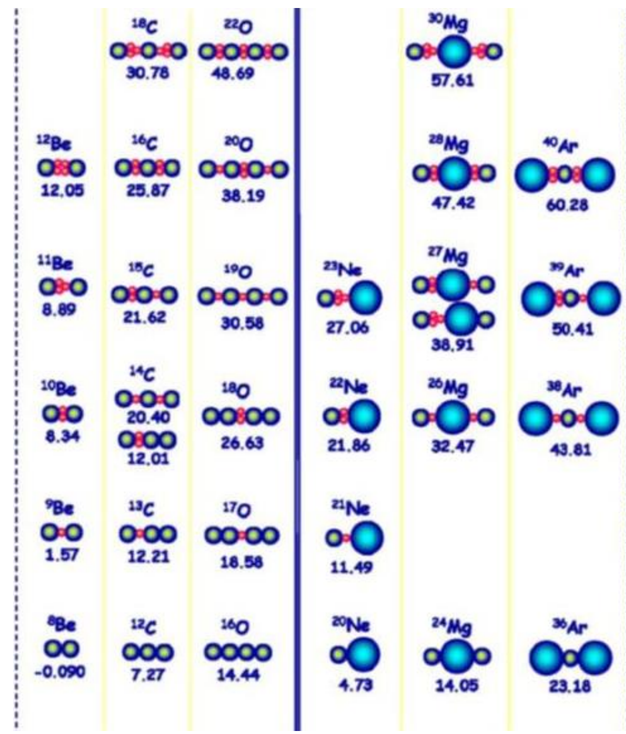
HCNO cycle: $0.2 < T_9 < 0.5$

rp-process : $T_9 > 0.5$

Nuclear structure

- Cluster linear chain of ^{14}C: Ikeda diagram [PRC 432, 43 (2006)]
  - ^{10}Be+α → ^{10}Be+α, ^{6}He+2α
  - Angular correlation θ_{Lab}^{Be10} vs. θ_{Lab}^{α} and E_X distribution give J^{π} information.





Nuclear structure

- Cluster state of ^{12}Be: ^{8}He+α @ 17 MeV at TRIUMF
  - Elastic reaction: $^{8}\text{He}(\alpha,\alpha')^{8}\text{He}$
  - Transfer reactions: ^{7}He+^{5}He, ^{6}He+^{6}He, (Search for resonant states)
  - Range vs. angle, angular correlation
- Neutron-rich C isotopes: Cluster vs. molecular states
  - ^{X}C(α,α’) with X=14, 16, 18, 20, etc. (exotic α condensates)
- Resonance scattering of ^{46}Ar on p (isobutane)
  - Proton energy vs. scattering angle
  - ReA3 proposal
- np pairing in N=Z nuclei using (^{3}He,p) reactions

- Very nice presentations by Gregory Rogachev and Leonid Grigorenko in the plenary session in April 3

Symmetry pressure and radii

- The density profile can be approximated by a Fermi function:

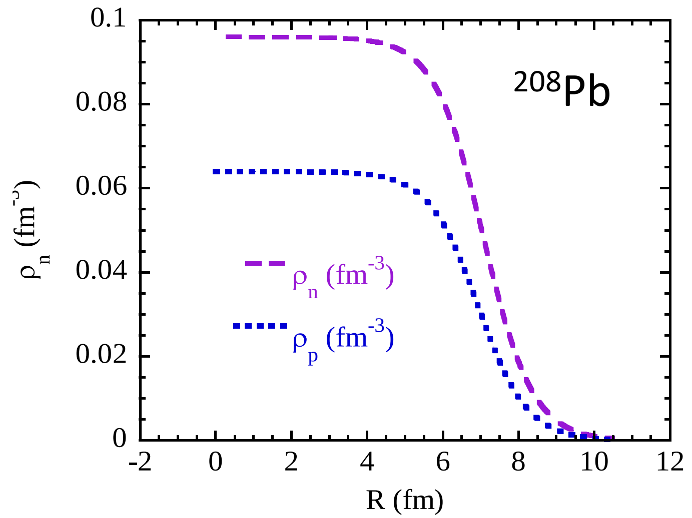
$$\rho(r) = \frac{\rho_0}{1 + \exp[(r - R)/a]}$$

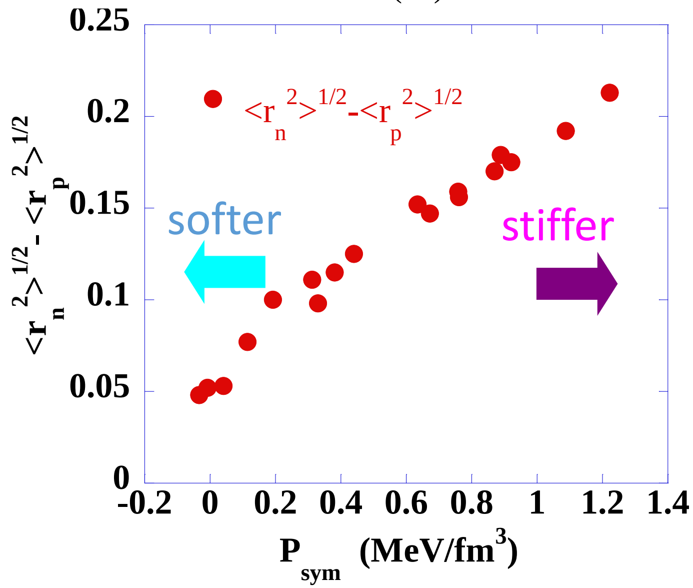
- R_n vs. E_{sym}
  - P_{sym} is larger if $E_{sym}(\rho)$ is strongly density dependent:

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

$$P_{n-matter} = P_{symmetric-matter} + P_{sym}$$

  - The symmetry pressure repels neutrons and attracts protons.
  - A stiff symmetry energy results in a larger neutron skin.





Measurement of radii

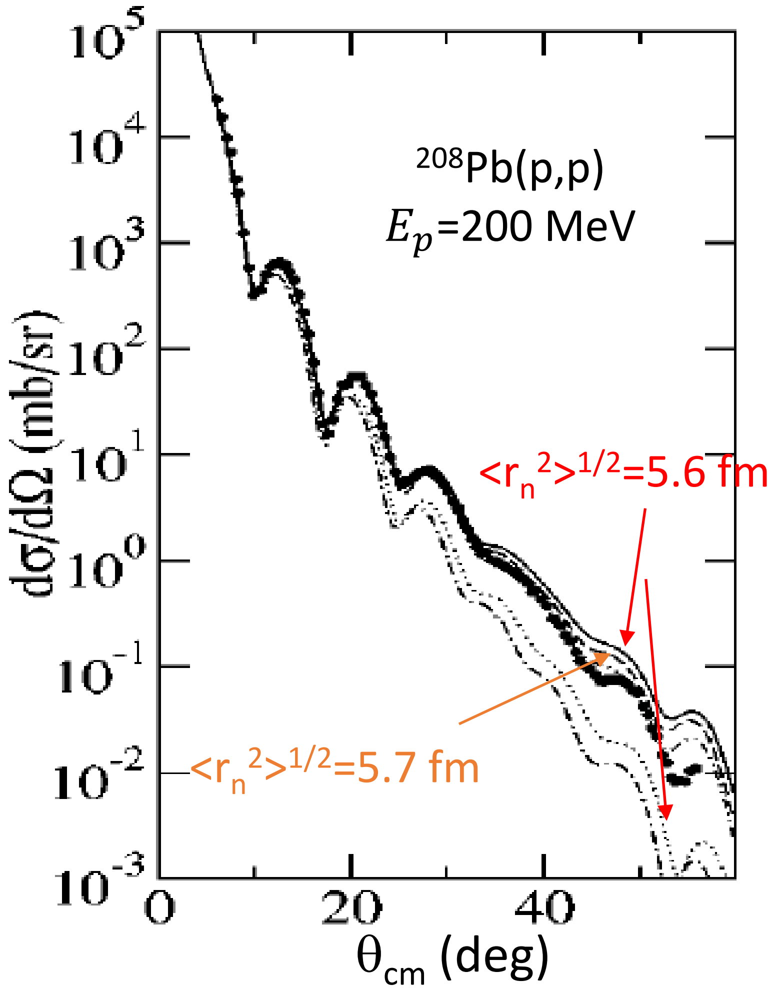
- Electron scattering may provide strong constraints on $\langle r_n^2\rangle^{1/2} - \langle r_p^2\rangle^{1/2}$ and subsequently $E_{sym}(\rho)$ for $\rho < \rho_0$
  - Expected uncertainties of order 0.06 fm by Horowitz et al., PRC 63, 025501 (2001)
  - Cf., $\langle r_p^2\rangle^{1/2}$ for stable nuclei measured by electron scattering to accuracy of ~0.02 fm
- Strong interaction shifts in the $4f \rightarrow 3d$ transition in pionic ^{208}Pb
  - Also sensitive to the rms radius of neutrons by Garcia-Recio, NPA 547, 473 (1992)

$$\langle r_n^2\rangle^{1/2} = 5.74 \pm .07_{ran} \pm .03_{sys}\ \text{fm}$$

$$\langle r_n^2\rangle^{1/2} - \langle r_p^2\rangle^{\frac{1}{2}} = 0.22 \pm .07_{ran} \pm .03_{sys}\ \text{fm}$$

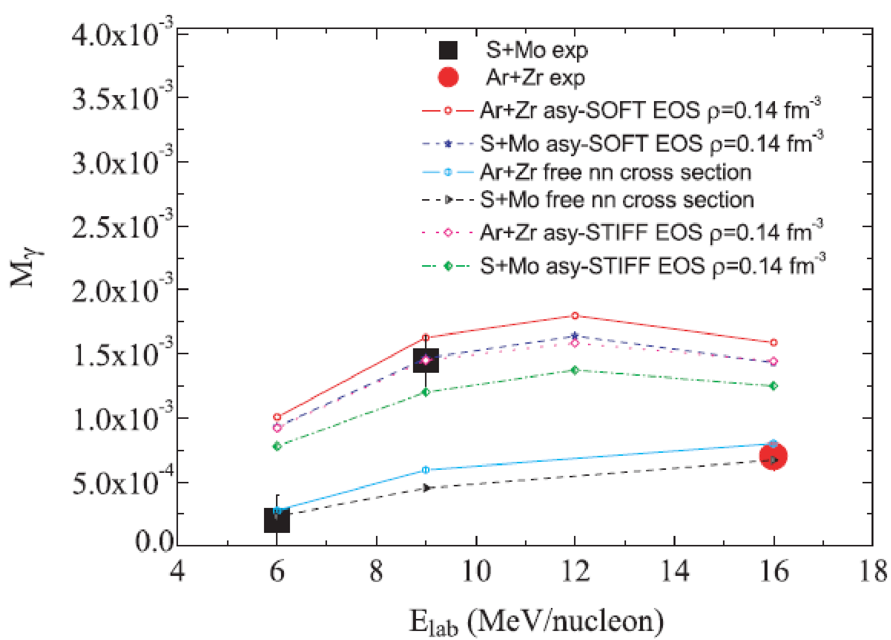
- Various neutron rich isotope target을 이용하여 중성자 반지름을 도출
- Very nice presentation by Atsushi Tamii in the plenary session in April 3.

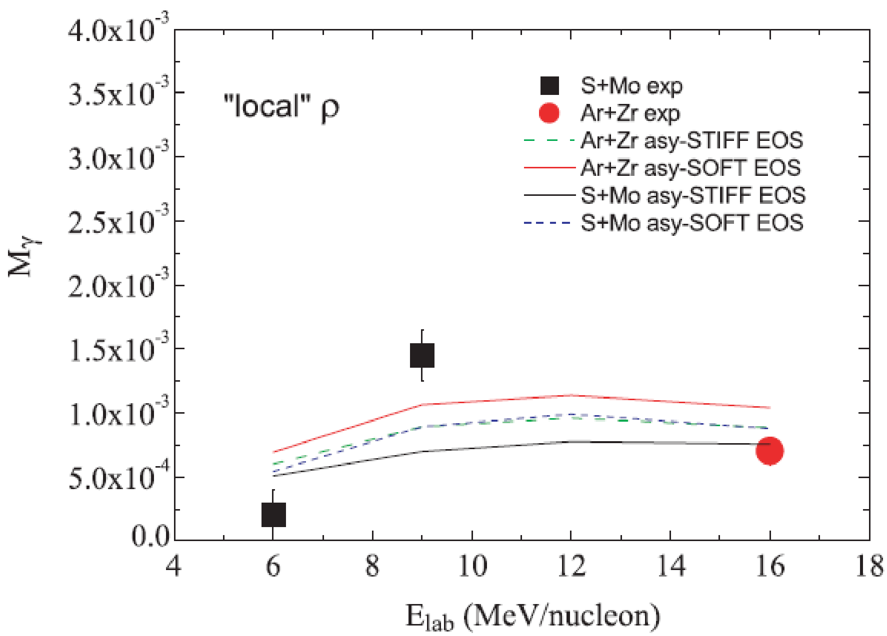
Karataglidis et al., PRC 65, 044306 (2002)



Dipole emission in fusion

- $LaBr_3$(Ce)(+FAZIA) experiments at LE
- Neck, PDR, GDR, and more
- Light beams
  - $^{X}Ar+^{96}Zr$ with X=36 (reference) and > 40
  - $^{X}S+^{100}Mo$ with X=32 (reference) and > 40
  - Comparison with LNS data [D. Pierroutsakou et al., PRC 80, 024612 (2009)]
  - Solid symbols: Charge asymmetric $^{36}Ar+^{96}Zr$ and $^{32}S+^{100}Mo$





Dipole emission

- Systematic study using heavier beams
  - n-poor system vs. n-rich system
  - ^{X}Ca beams with X=50, 54, 60, …
  - ^{X}Ni beams with X=68, 70, 72, …
  - ^{X}Sn beams with X=112, 124, 130, 132, …
- Repeat similar experiments at high energies

  Oscillation in $\mathcal{O}(10\ \mathrm{MeV})$

  → Diffusion in $\mathcal{O}(50\ \mathrm{MeV})$

  → Nuclear structure of neutron skin, PDR, and GDR in $\mathcal{O}(\sim 200\ \mathrm{MeV})$

  → Isospin equilibration in nuclear stopping power in $\mathcal{O}(> 200\ \mathrm{MeV})$
- Talk by Carlos Bertulani in April 4

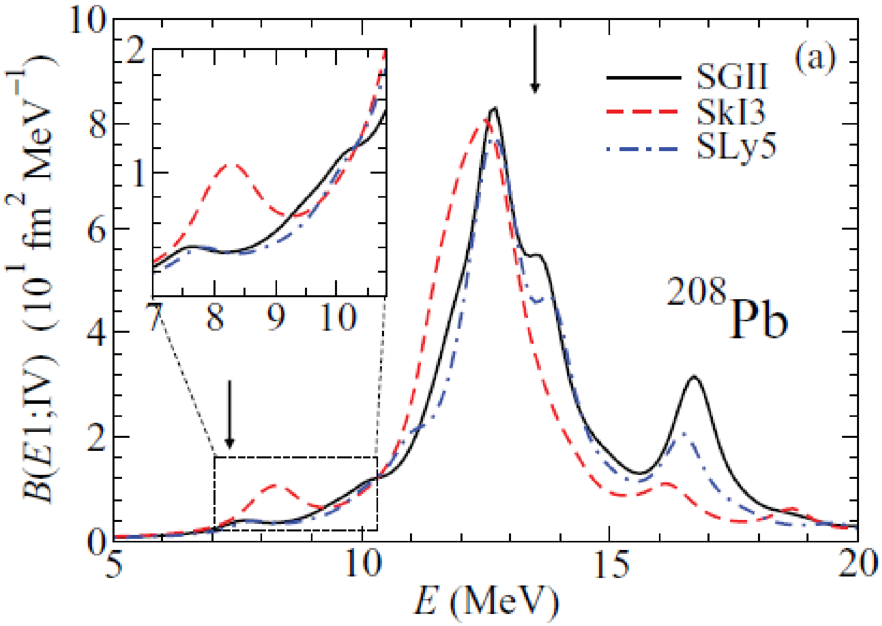
Dipole emission in n-rich nuclei

X. Roca-Maza et al., PRC 85, 024601 (2012)

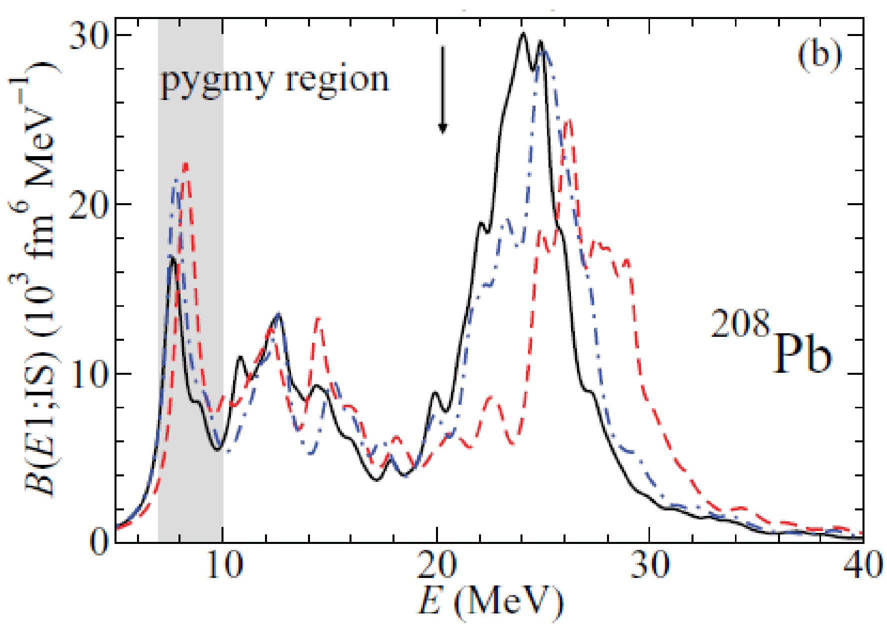
HF+RPA with various Skyrme potentials

L = SGII (38 MeV) < SLy5 (48 MeV) < SkI3 (100 MeV)

Isovector dipole response



Isoscalar dipole response

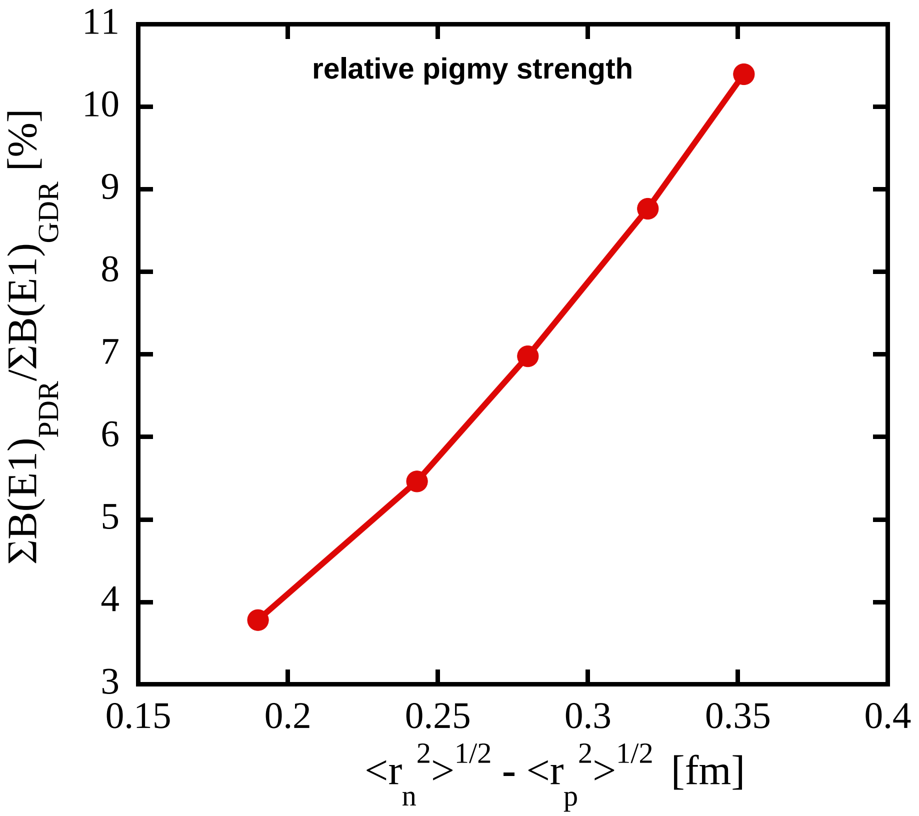


- PDR is sensitive to Asy-EOS: A larger L gives a larger strength

Dipole emission of n-rich nuclei

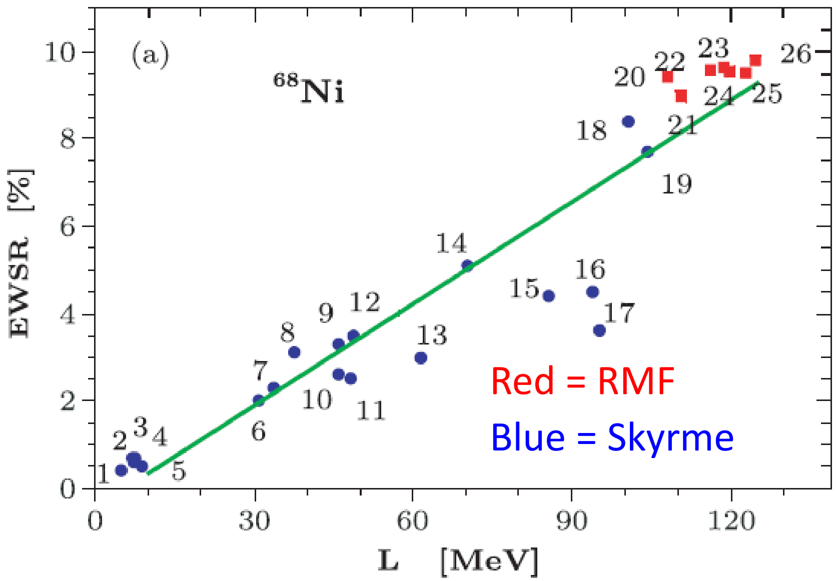
A. Klimkiewicz, et al., PRC76, 051603(R) (2007)

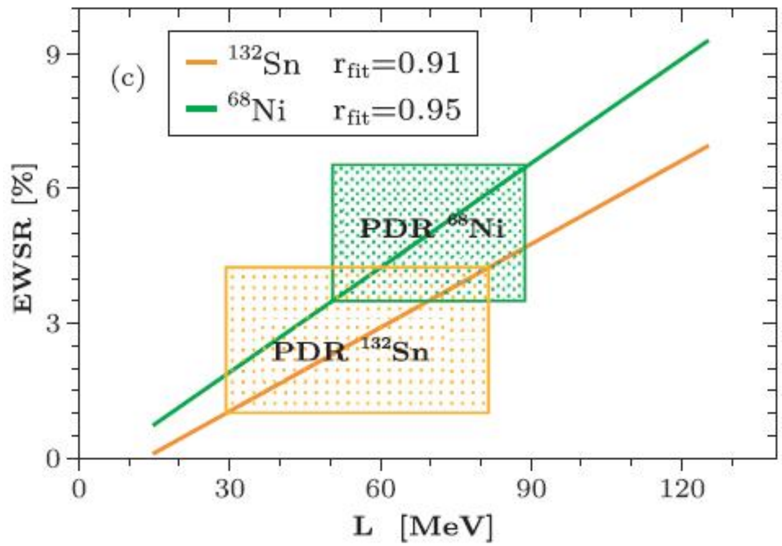
- RPA calculations show a strong correlation between the n-p radius difference and the fractional strength in the PDR.



Dipole emission of n-rich nuclei

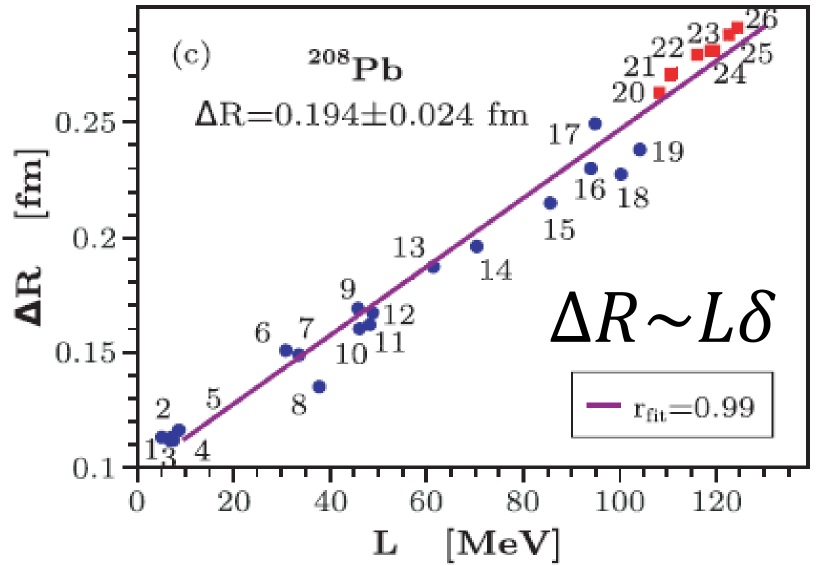
A. Carbone et al., PRC 81, 041313 (2010)





RPA calculations show a strong correlation between the fractional strength and the symmetry pressure or parameter L.

$$L = 64.8 \pm 15.7 \text{ MeV}$$



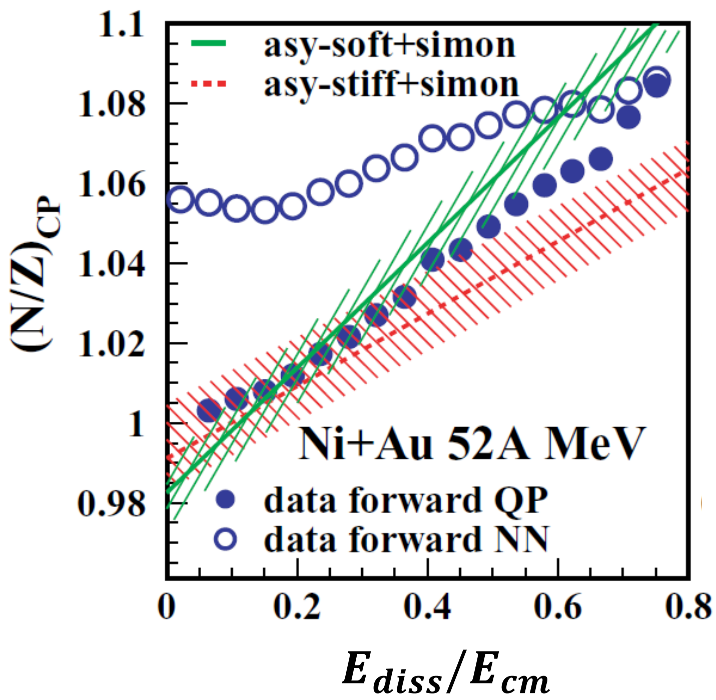
$\Delta R \sim L\delta$

Isospin mixing

- Charge equilibration
  - In fusion, dipole oscillation is important
  - In deep inelastic coll., dipole oscillation is overdamped: Diffusion of charges

$$D(t) = D(0)\exp\left(-t/\tau_d\right) \qquad \left(\tau_d \rightarrow E_{sym}\right)$$

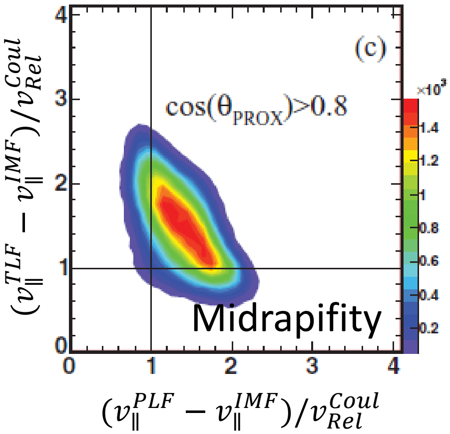
- Degree of equilibration governed by contact time and symmetry energy
- Observable: N/Z of light charged particles emitted by PLF as a function of dissipated energy: $(N/Z)_{CP}$ vs. $E_{diss} \equiv E_{cm} - E_{kin}(PLF + TLF)$



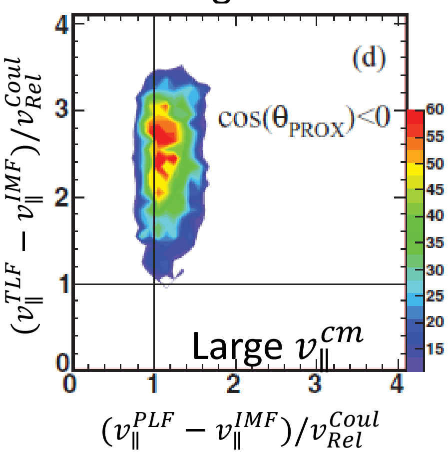
E. Galichet et al., PRC 79, 064615 (2009)

Isospin mixing (neck)

Dynamically emitted IMFs (Z=3~18) from neck in early stage

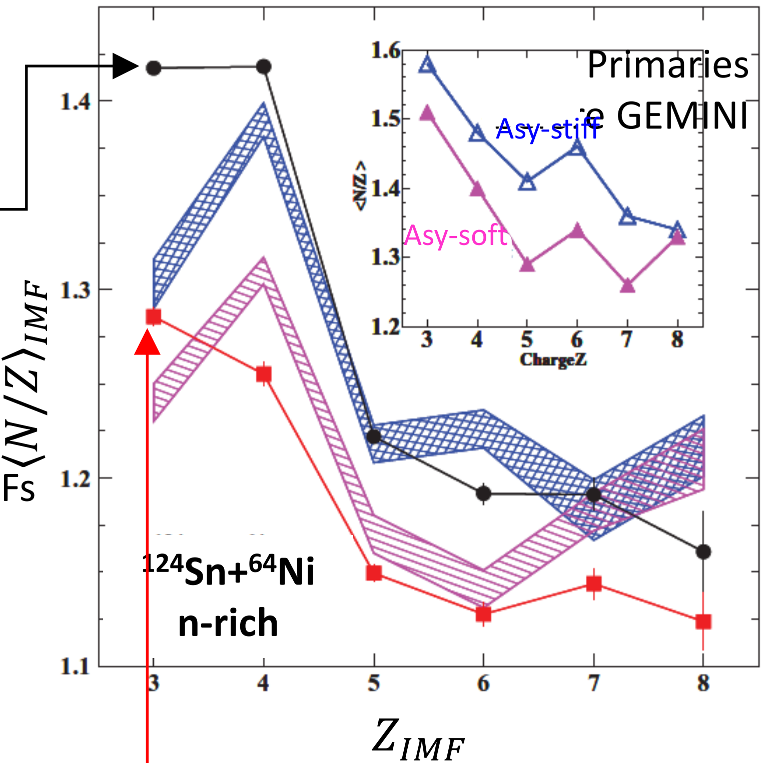


Statistically emitted IMFs (Z=3~18) from PLF in later stage



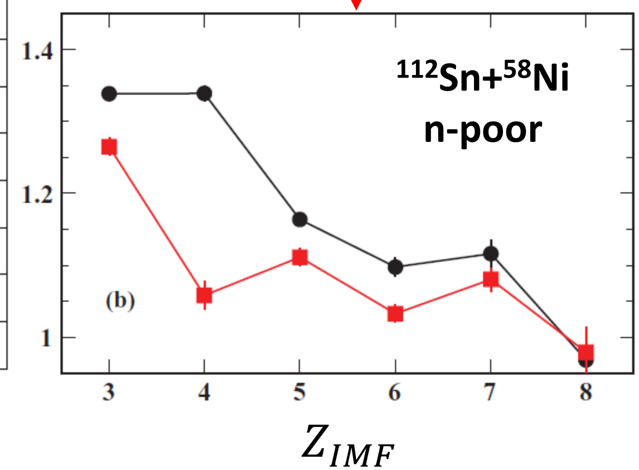
E. De Filippo et al., PRC 86, 014610 (2012)

Sn+Ni @ 35A MeV (SMF+GEMINI)



CHIMERA

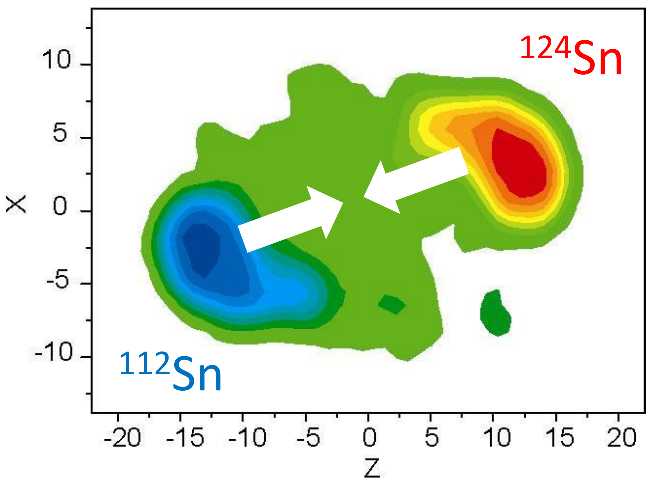
The even-odd effect weaker in n-rich system.



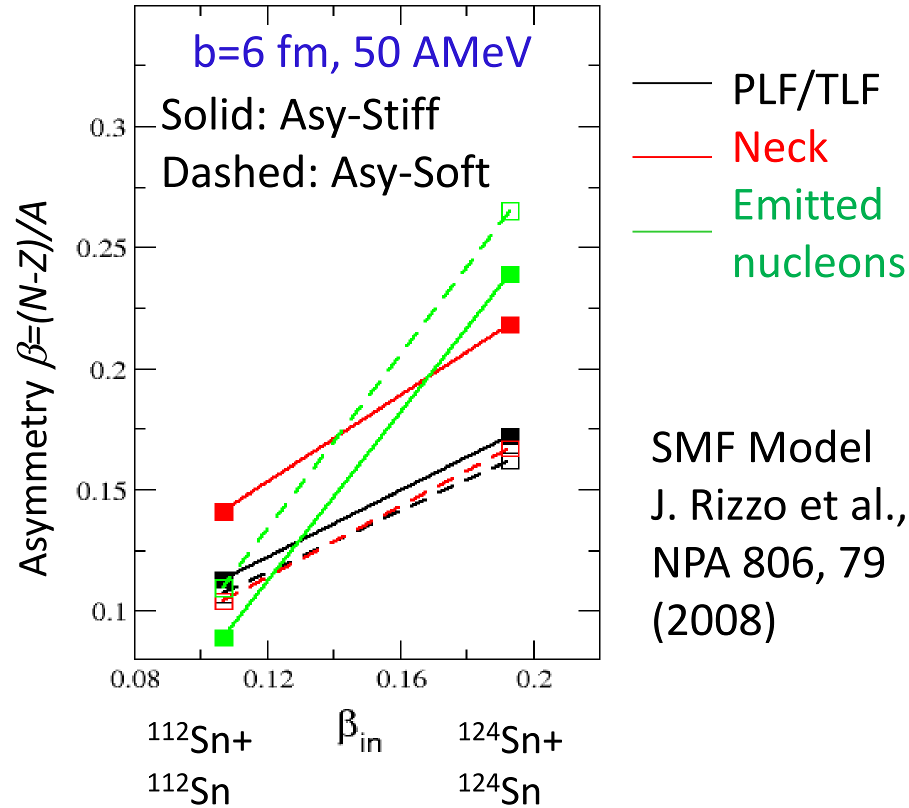
- Isospin diffusion and isospin drift can compete to characterize the midrapidity and projectile residue emission.

Isospin mixing (neck)

- Isospin asymmetry of PLF and TLF ⟹ Low-density neck



$$\rho_{IMF} < \rho_{PLF(TLF)}$$



SMF Model
J. Rizzo et al., NPA 806, 79 (2008)

- Effect related to the symmetry pressure, L
- Stiff E_{sym}: Larger isospin migration effect

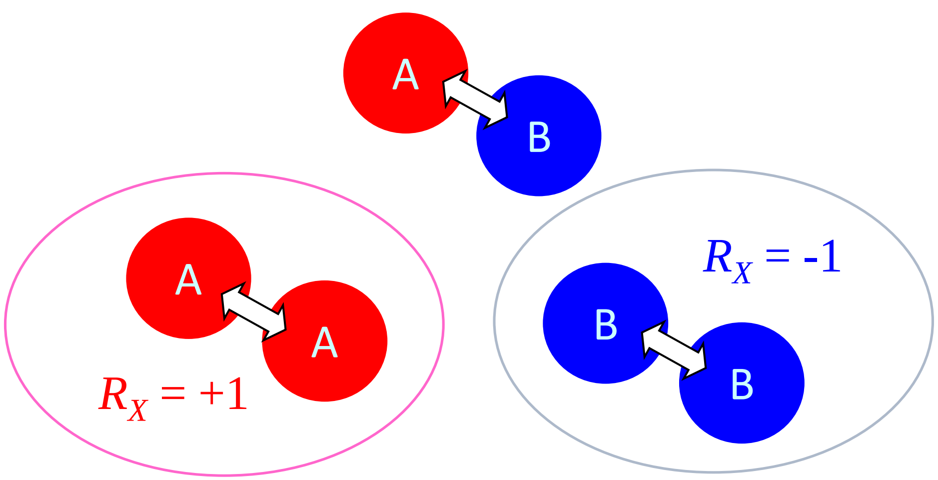
The asymmetry of the neck is larger than the asymmetry of PLF (TLF) in the Asy-stiff case.

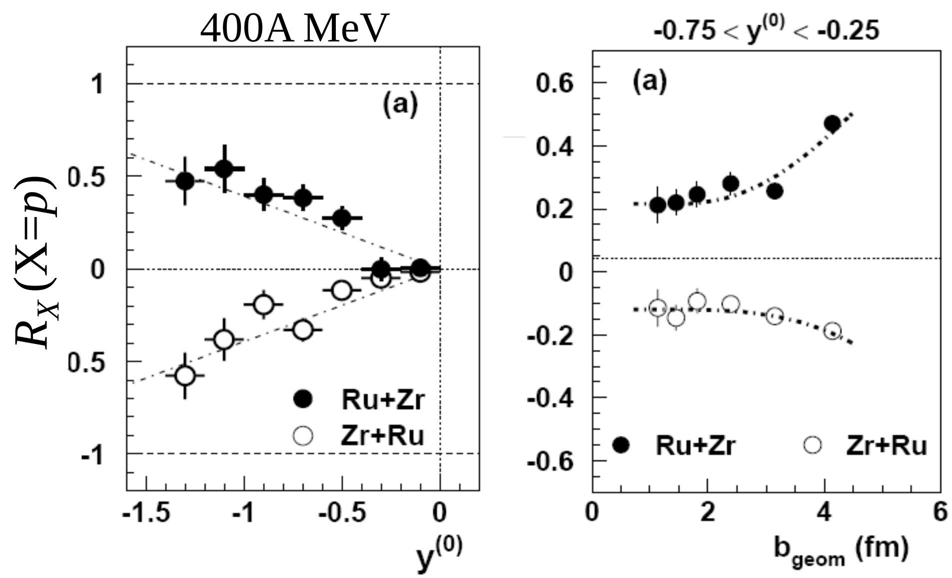
Isospin mixing (diffusion)

No isospin mixing between symmetric systems

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

$R_X = 0$ for complete mixing





High-energy applications:

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

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

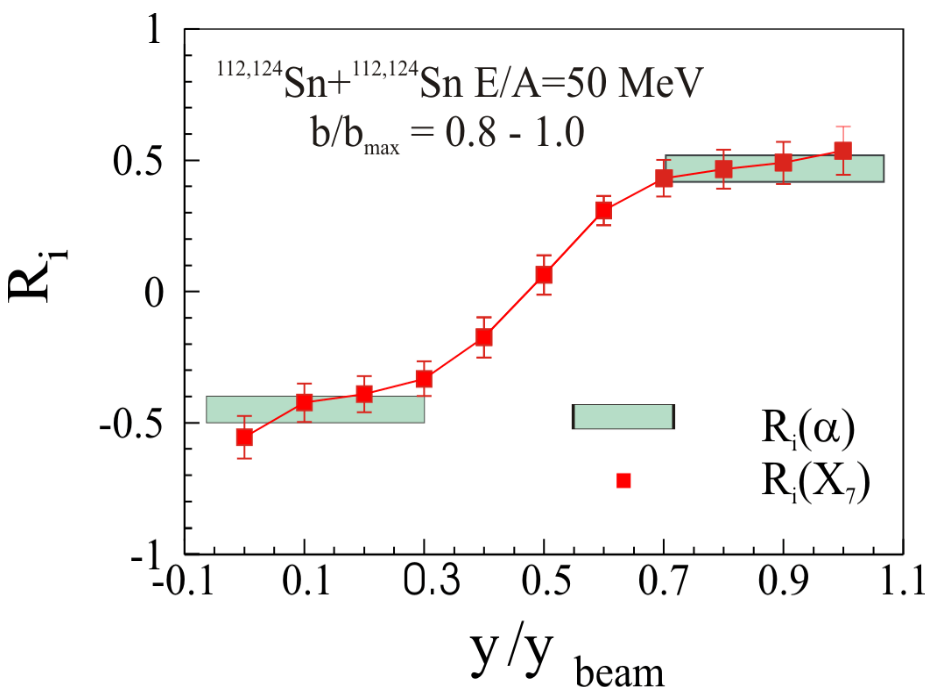
Try any observable X related to N/Z of PLF (or TLF) for isospin migration to neck at LE

Isospin mixing (diffusion)

$$R_i(\delta) = 2\frac{\delta - (\delta_{n-rich} + \delta_{p-rich})/2}{\delta_{n-rich} - \delta_{p-rich}}$$

- Reactions
  - ^{124}Sn+^{112}Sn: diffusion
  - ^{112}Sn+^{124}Sn: diffusion
  - ^{124}Sn+^{124}Sn: n-rich limit
  - ^{112}Sn+^{112}Sn: p-rich limit
- Exchanging the target & projectile
  - Allowed full rapidity dependence to be measured.
- $R_i(\alpha)$ near beam rapidity
  - $R_i(\alpha)$≈0.47±0.05 (^{124}Sn+^{112}Sn)
  - $R_i(\alpha)$≈-0.44 ±0.05 (^{112}Sn+^{124}Sn)
- $R_i[\ln\{Y(^7\mathrm{Li})/Y(^7\mathrm{Be})\}]$
  - Exploration of the rapidity dependence

Liu et al., PRC 76, 034603 (2007)

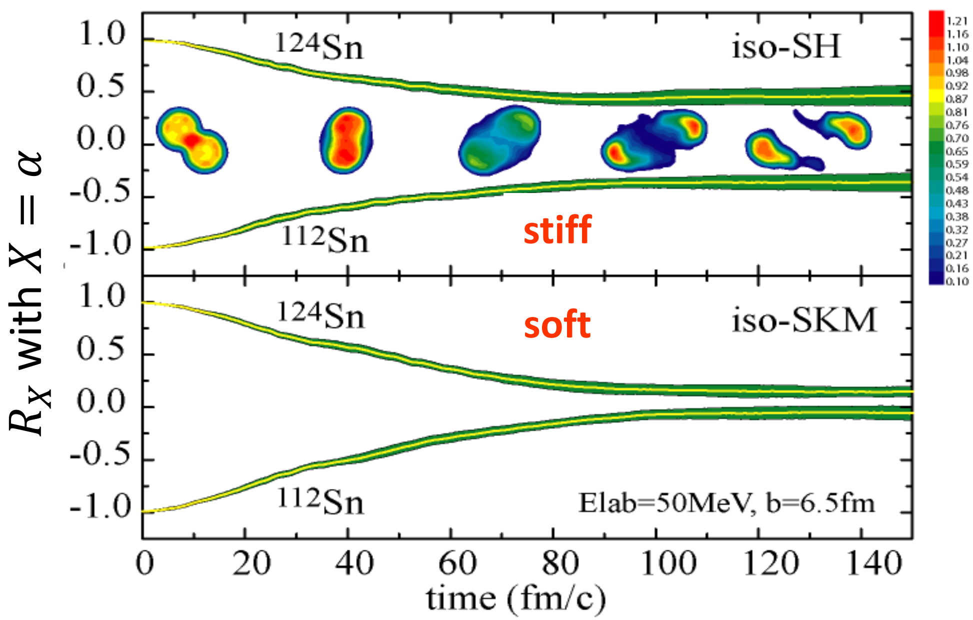


Isospin mixing (diffusion)

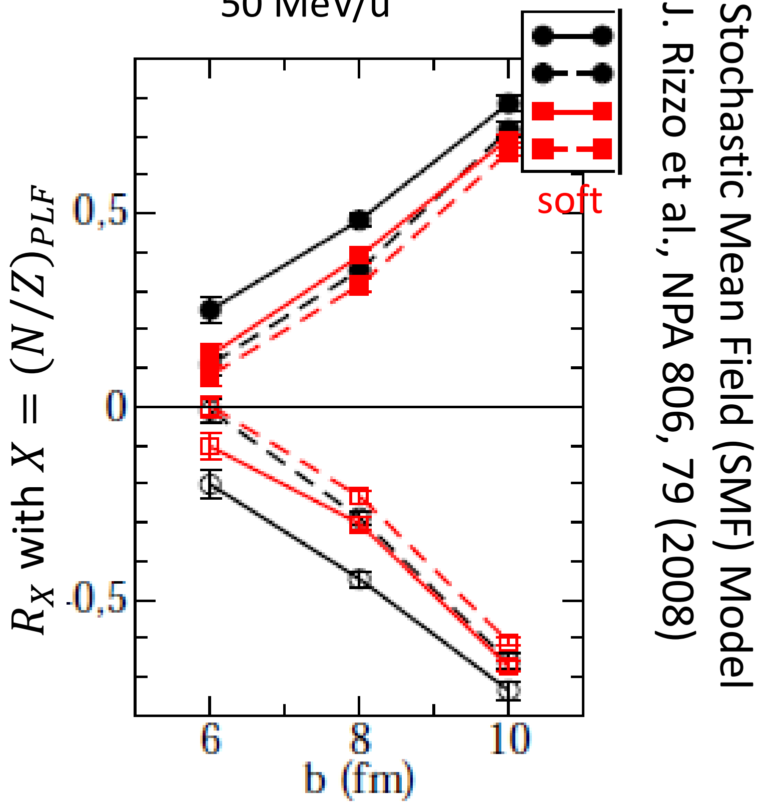
M.B. Tsang et al., PRL 92, 062701 (2004)

α = neutron-isoscaling parameter

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



$^{124}Sn+^{112}Sn$ @ 50 MeV/u



- Softer symmetry energy towards equilibrium ($R_X \rightarrow 0$)
- Good sensitivity to Asy-EOS

Directed flow

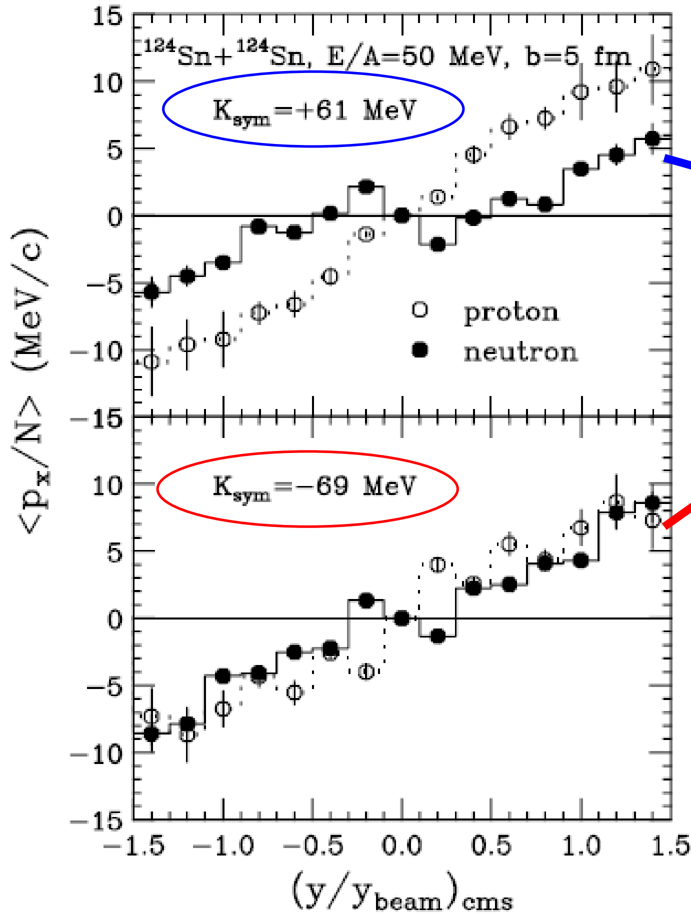
B.-A. Li,
PRL 85, 4221
(2000)

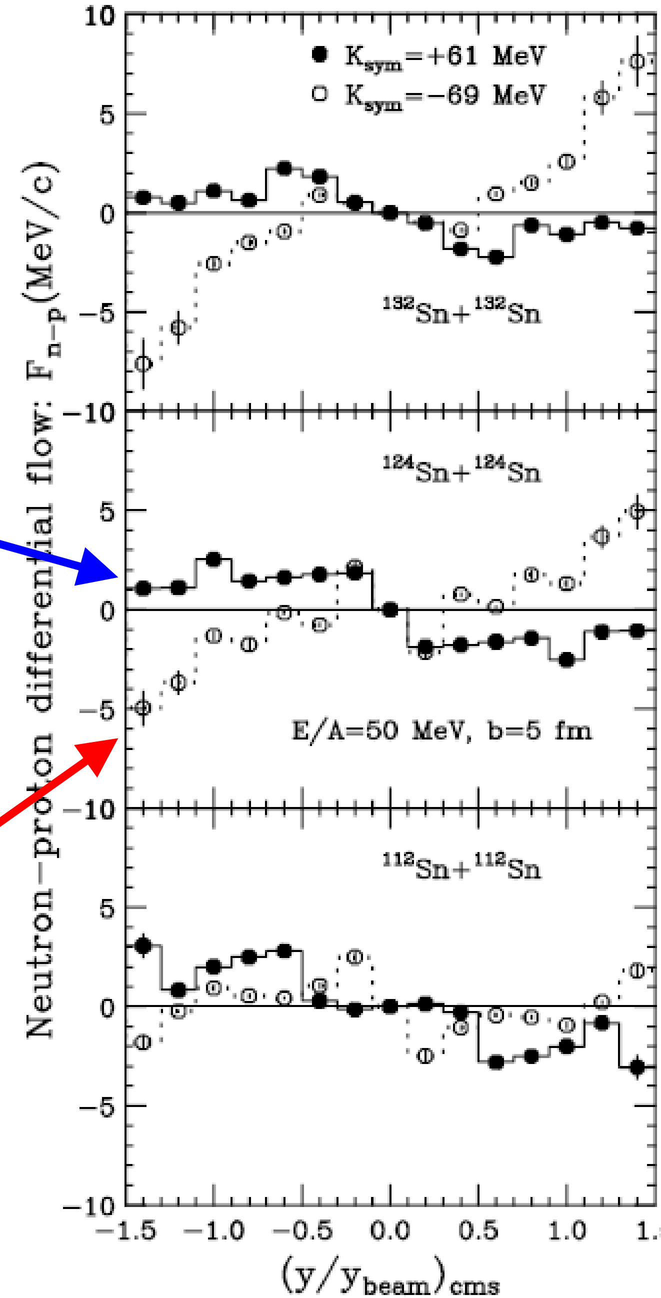
$$K_{sym} \equiv 9\rho_0^2 \frac{\partial^2 E_{sym}(\rho)}{\partial \rho^2}\Bigg|_{\rho=\rho_0}$$

Asy-stiff

Also known as v_1

Asy-soft





Large

N/Z

Small

N/Z

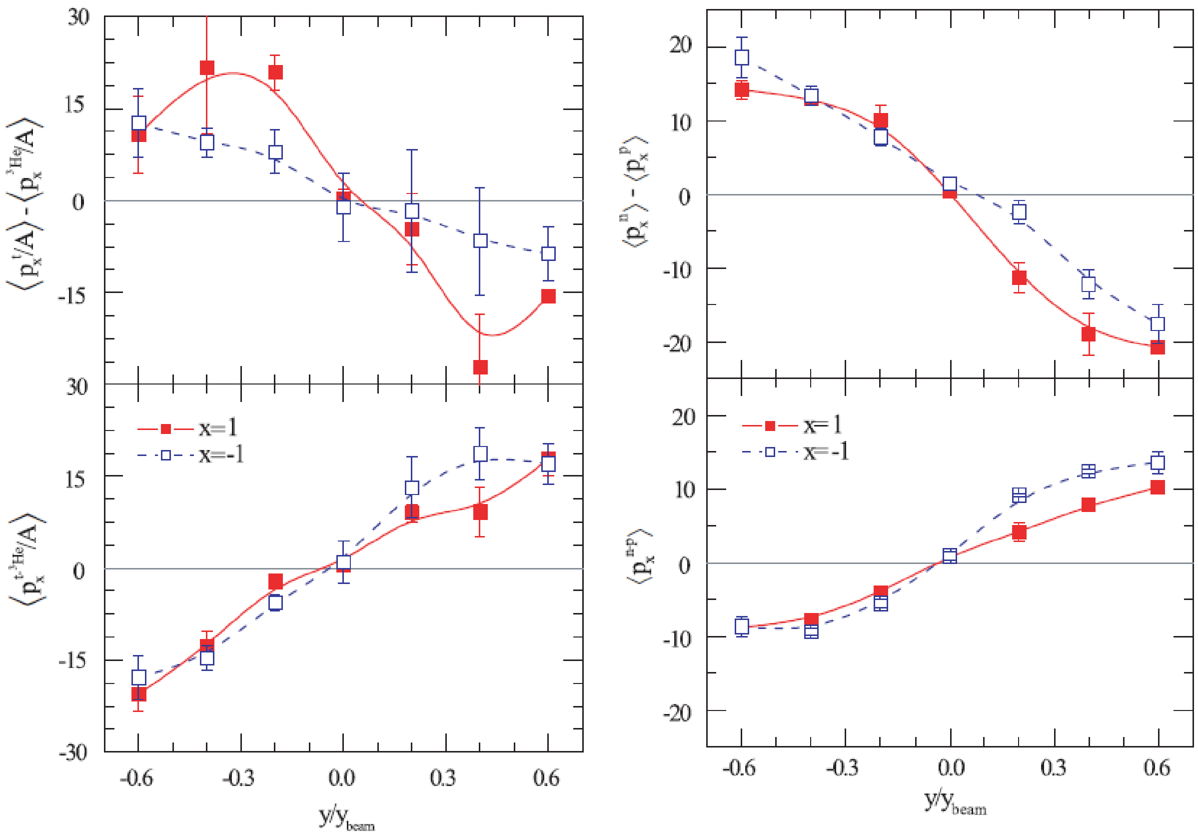
Directed flow

Relative flow:

$$\langle p_x^t/A\rangle - \langle p_x^{^3\mathrm{He}}/A\rangle = \frac{1}{N_t}\sum_{i=1}^{N_t} p_x^i/A - \frac{1}{N_{^3\mathrm{He}}}\sum_{i=1}^{N_{^3\mathrm{He}}} p_x^i/A$$

t-^{3}He differential flow:

$$\langle p_x^{t\text{-}^3\mathrm{He}}/A\rangle = \frac{1}{N_t + N_{^3\mathrm{He}}}\left(\sum_{i=1}^{N_t} p_x^i/A - \sum_{i=1}^{N_{^3\mathrm{He}}} p_x^i/A\right)$$



^{132}Sn+^{124}Sn @ 400A MeV

$x = 1$: Asy-Supersoft

$x = -1$: Asy-Stiff

Larger A ⇒ larger sensitivity to Asy-EOS

G.-C. Yong et al., PRC 80, 044608 (2009)

Tentative Schedule if beams are available

	1단계 (~2025)	2단계 (2026~2030)	3단계 (2031-2040)
극한 핵물질 상태	**Low-energy reactions** ▪ Cluster linear chain of ^{14}C ($^{10}Be+\alpha$, $^{6}He+2\alpha$) ▪ Cluster state of ^{12}Be ($^{8}He+\alpha$) ▪ Some nuclear astrophysics reactions in rp- and r-processes ($^{14}O(\alpha,\gamma)^{18}Ne$, $^{14}O(\alpha,p)^{17}F$, $^{15}O(\alpha,\gamma)^{19}Ne$, $^{22}Mg(\alpha,p)^{25}Al$) **High-energy reactions** ▪ Isospin mixing ($^{X}Ca+Pb$ with X=50, 54, 60, $^{X}Ni+Pb$ with X=68, 70, 72, $^{X}Sn+Pb$ with X=106, 112, 124, 130, 132 at ~50A MeV)	**Low-energy reactions** ▪ Neutron-rich C isotopes: Cluster vs. Molecular states ($^{X}C(\alpha,\alpha')$ with X=14, 16, 18, 20, more even numbers) ▪ Dipole emission ($^{36}Ar+^{96}Zr$ and $^{32}S+^{100}Mo$ for comparison) **High-energy reactions** ▪ Charge radii of neutron-rich nuclei ($^{208}Pb(p,p')$) ▪ Isospin mixing ($^{124}Sn+^{112}Sn$ $^{112}Sn+^{124}Sn$ $^{124}Sn+^{124}Sn$, $^{112}Sn+^{112}Sn$)	**Low-energy reactions** ▪ Dipole emission ($^{X}Sn+^{Y}Sn$ with X=106, 112, 124, 130, 132 and Y=112, 118, 124) **High-energy reactions** ▪ Dipole emission ($^{X}Sn+^{Y}Sn$ with X=106, 112, 124, 130, 132 and Y=112, 118, 124) ▪ Isospin dependence of directed and elliptic flow ($^{124}Sn+^{112}Sn$ $^{112}Sn+^{124}Sn$ $^{124}Sn+^{124}Sn$, $^{112}Sn+^{112}Sn$)

Summary

- Detector
  - RISP and LAMPS are in close collaboration for developing and constructing the detector components for high-energy LAMPS.
  - SRC is adding additional fuel to the development of several elements like AT-TPC, $LaBr_3$(Ce), FAZIA, Si for low-energy LAMPS.
- Physics
  - Nuclear astrophysics, nuclear structure, nuclear symmetry energy are the major research topics for low-energy LAMPS.
  - Nuclear symmetry energy is the prime goal for high-energy LAMPS, but nuclear structure can be also studies.
  - Very good opportunity to study the energy dependence of various variables, e.g., the isospin mixing parameter and dipole emission.
- We need to seriously think about the following items:
  - More idea on physics, of course
  - List of beam species to request (priority)
  - Realistic timeline for the detector development and construction
  - Detailed plan to perform specific experiment and analysis
  - Collaboration issue (how to get there?)