LAMPS kick-off meeting, IBS, July 31, 2018

Overview of Large Acceptance Multi-purpose Spectrometer (LAMPS)

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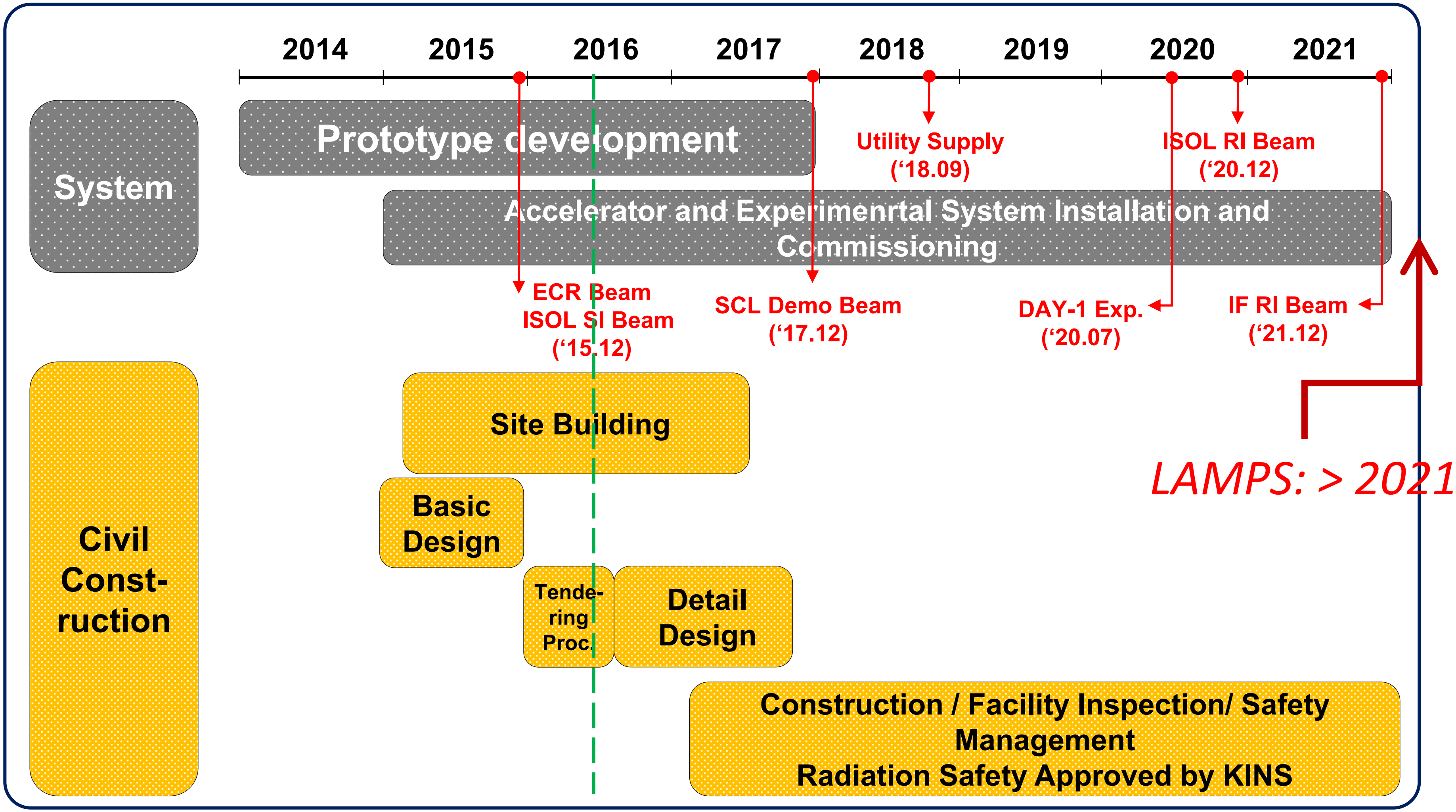
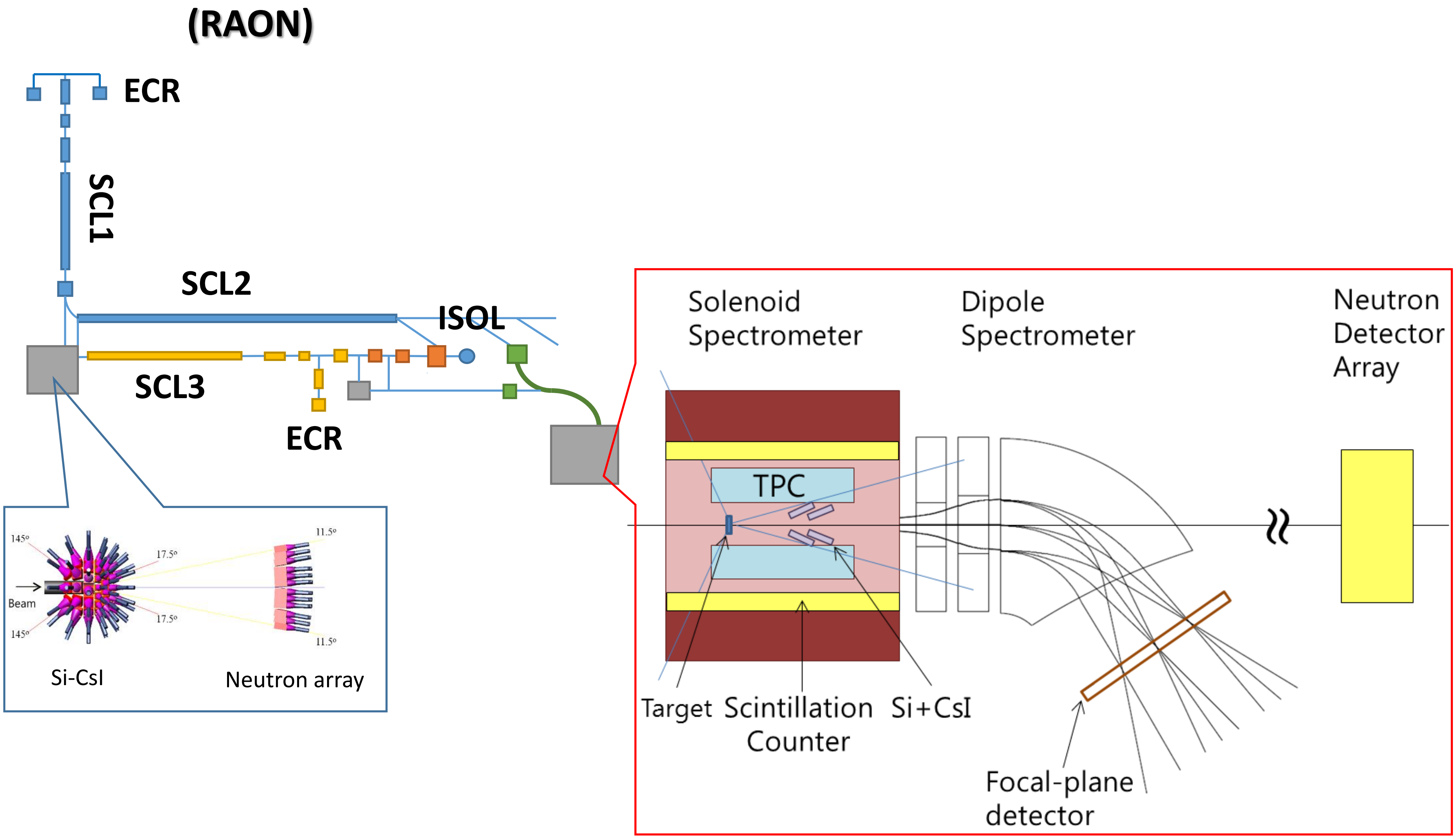
(Korea University)

Schedule

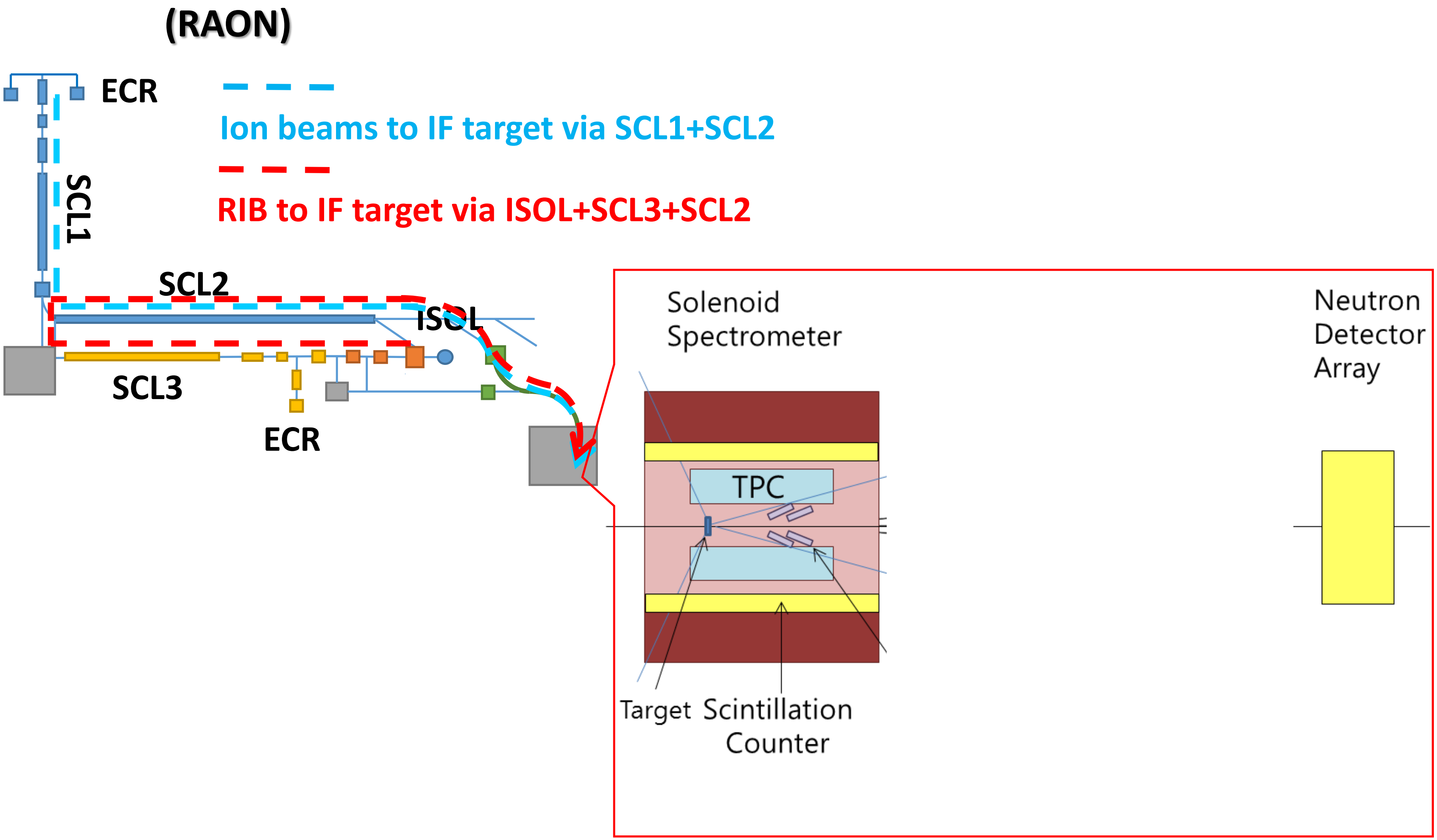


2014
2015
2016
2017
2018
2019
2020
2021
System
Prototype development
Utility Supply
('18.09)
ISOL RI Beam
('20.12)
Accelerator and Experimenrtal System Installation and Commissioning
ECR Beam
ISOL SI Beam
('15.12)
SCL Demo Beam
('17.12)
DAY-1 Exp.
('20.07)
IF RI Beam
('21.12)
Civil Const-ruction
Site Building
Basic Design
Tende-ring Proc.
Detail Design
Construction / Facility Inspection/ Safety Management
Radiation Safety Approved by KINS
LAMPS: > 2021

Status of LAMPS



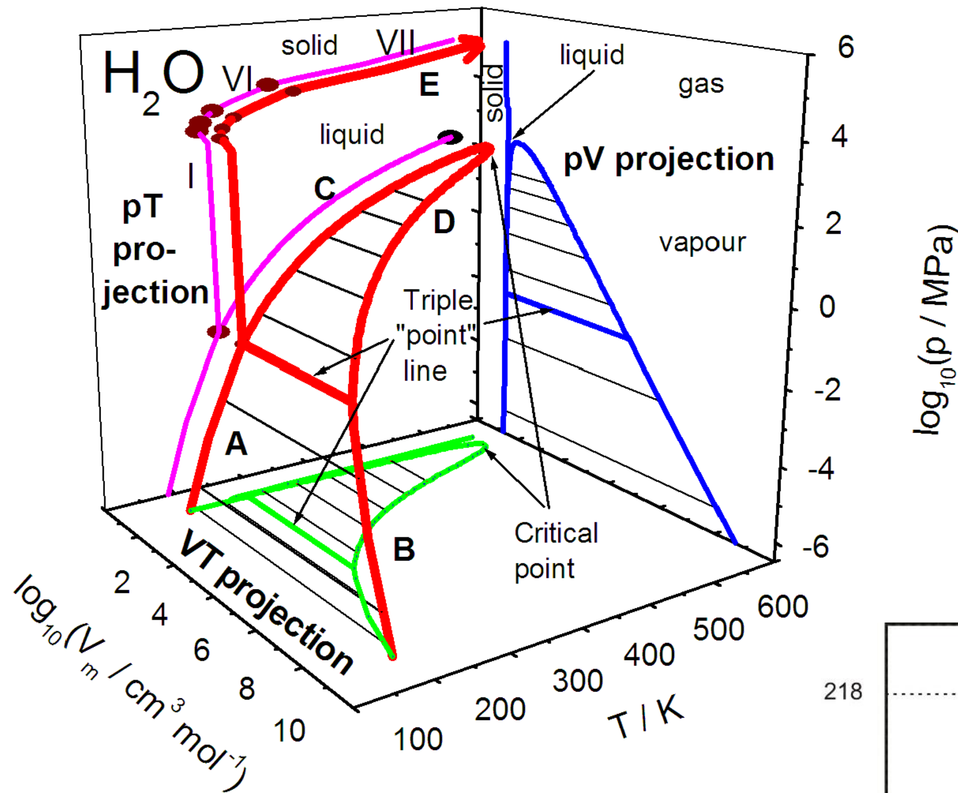
Status of LAMPS



Status of LAMPS (Site as of April)

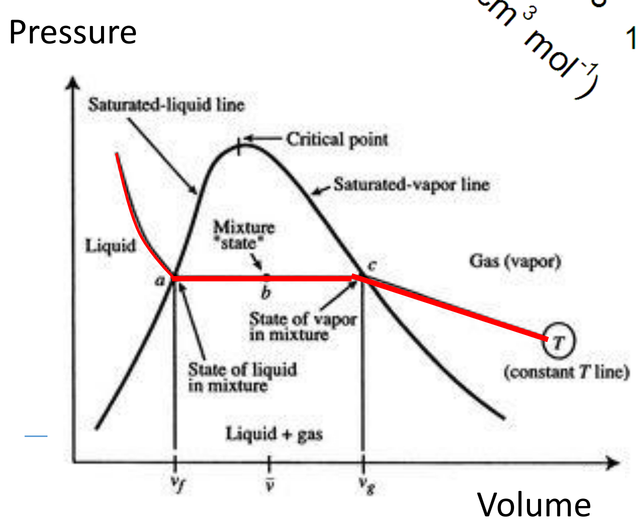
Phase Diagram of Matter

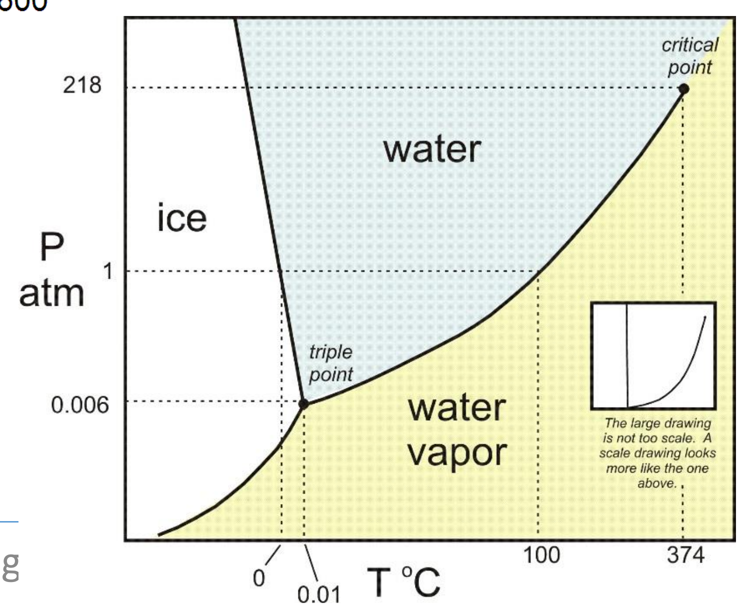
Phase diagram of H_2O



States/Phases:

- Solid (ice)
- Liquid (water)
- Gas (vapor)





Equation of State

- Practical approach:
  To calculate the average energy per nucleon

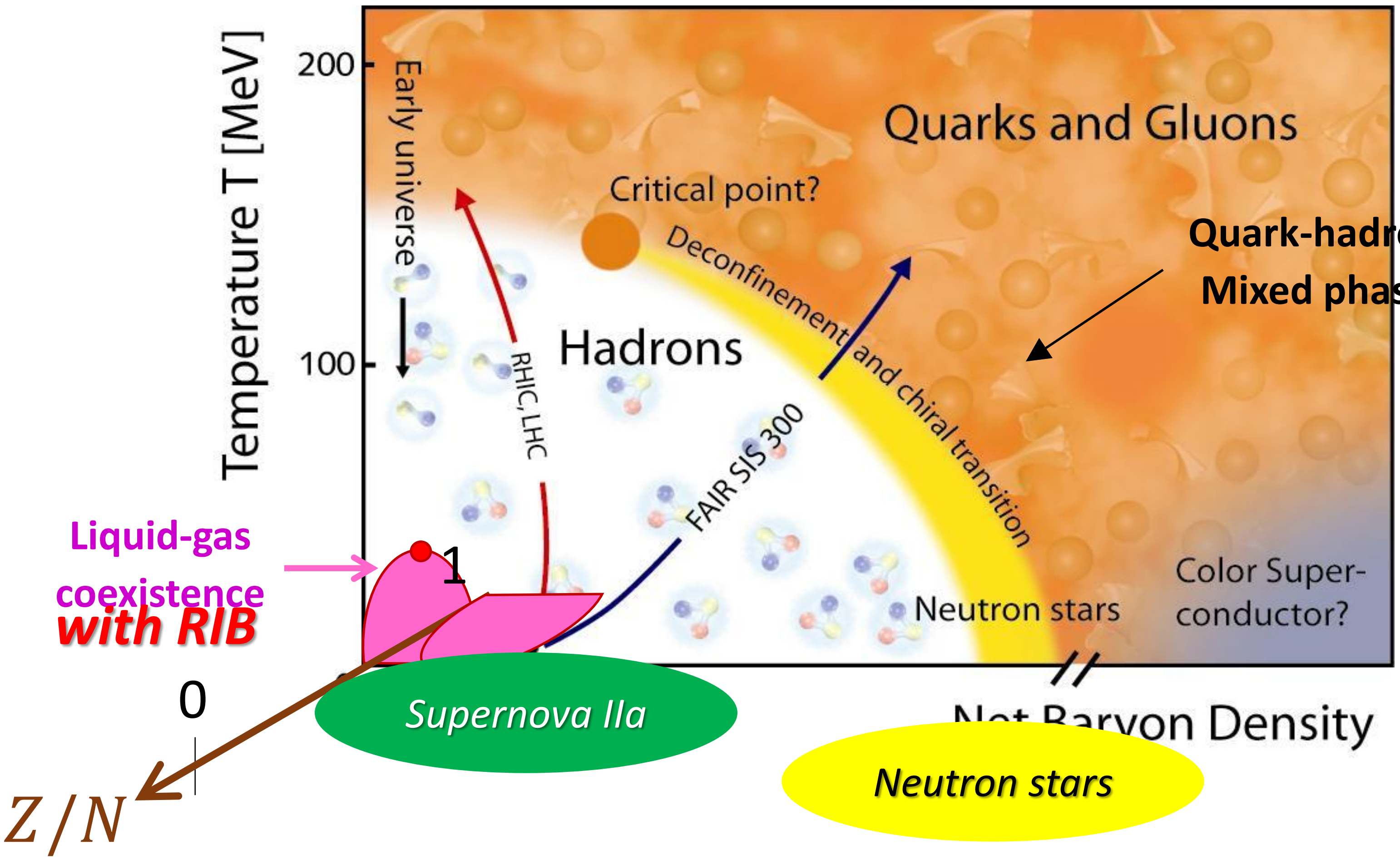
  $\varepsilon(\rho, \tau, \delta) \equiv U(\rho, \tau, \delta)/A$

  as functions of baryon density ρ and isospin asymmetry δ

- Theoretical approach:
  Estimate $\varepsilon(\rho, \tau, \delta)$ by some density functional forms
  (e.g., Hartree-Fock) and variational calculations

- Experimental approach:
  Constrain EOS by using controlled laboratory experiments at specific densities
  (Some examples will be given later in this talk.)

Nuclear Phase Diagram



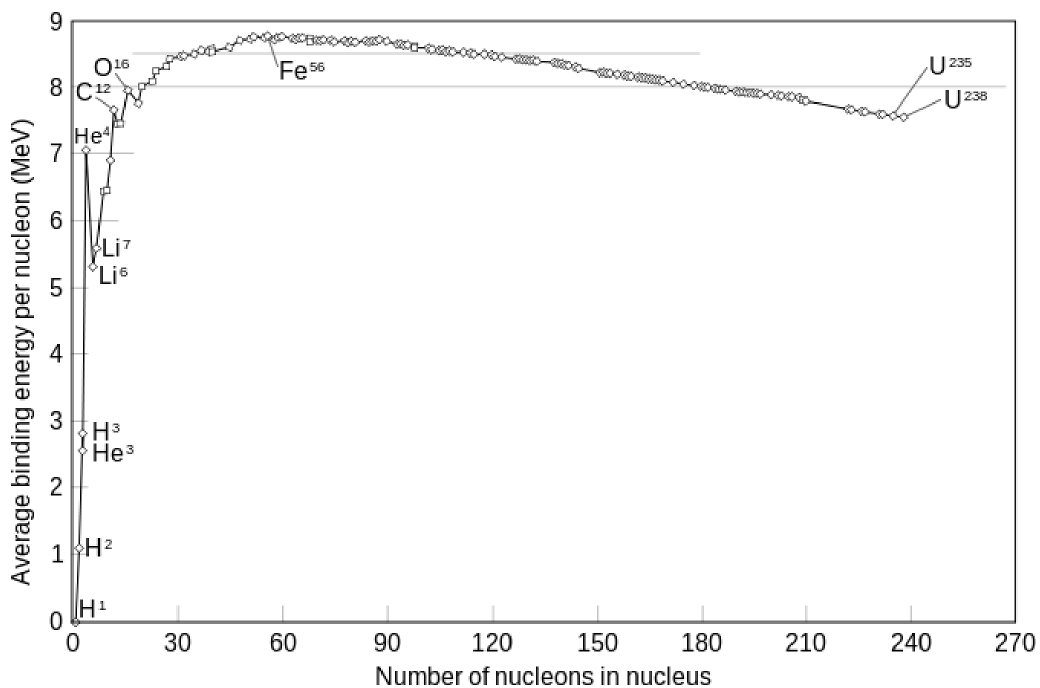
EOS of Nuclei & Nuclear Matter

- Bethe-Weizsäcker formula from the liquid drop model

$$B(A,Z) = a_{vol}A - a_{sur}A^{2/3} - a_{Coul}\frac{Z(Z-1)}{A^{1/3}} - a_{sym}\frac{(N-Z)^2}{A} \pm \delta_{pair}$$

[Ref.] C. F. von Weizsäcker, Z. Physik 96, 431 (1935)
N. Bohr, Nature 137, 344 (1936)

Already ~80 years long problem!



EOS & Symmetry Energy

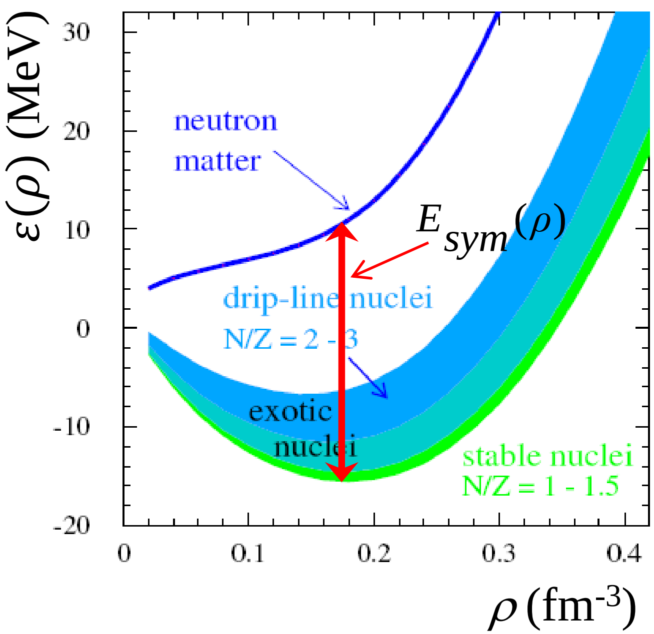
- Energy of nuclei and nuclear matter

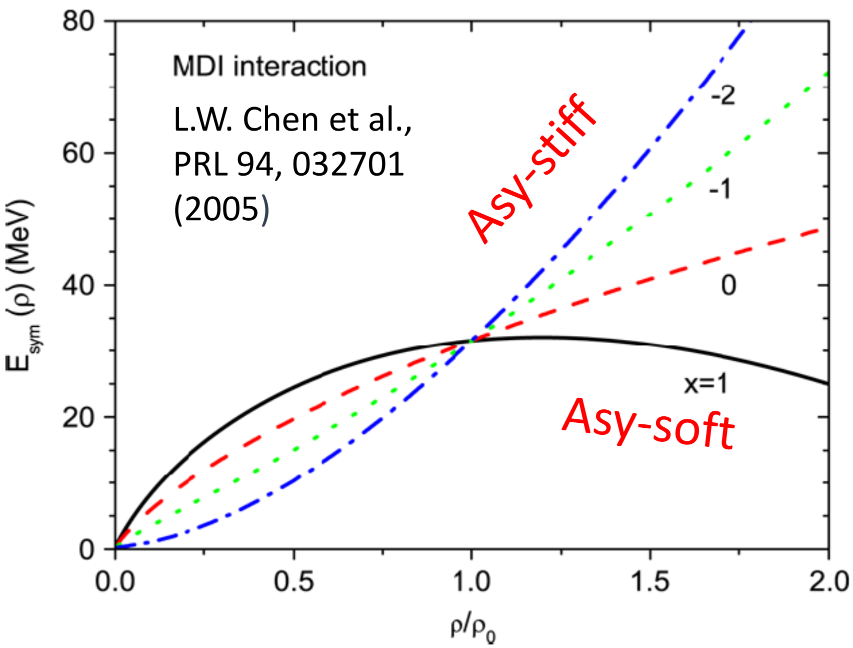
$$\varepsilon(\rho,\delta)A = Zm_p + Nm_n - B(A,Z)$$

$$\varepsilon(\rho,\delta) = \varepsilon(\rho,\delta=0) + E_{sym}(\rho)\delta^2 + \mathcal{O}(\delta^4) + \cdots$$

where $a_{sym} \approx E_{sym}(0.6\rho_0)$

- **Symmetry energy**: Energy difference between the neutron matter and isospin symmetric matter





Nuclear Symmetry Energy

- Two components of the symmetry energy:

$$E_{sym}(\rho) = S(\rho) = \frac{1}{3} E_F \, (\rho \,/\rho_0)^{2/3} + E_{sym}^{pot}(\rho)$$

where $E_{sym}^{pot}(\rho)$ is often parameterized as $C(\rho \,/\rho_0)^{\gamma}$.

- A useful empirical expansion of $E_{sym}(\rho)$ around ρ_0:

$$E_{sym}(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2$$

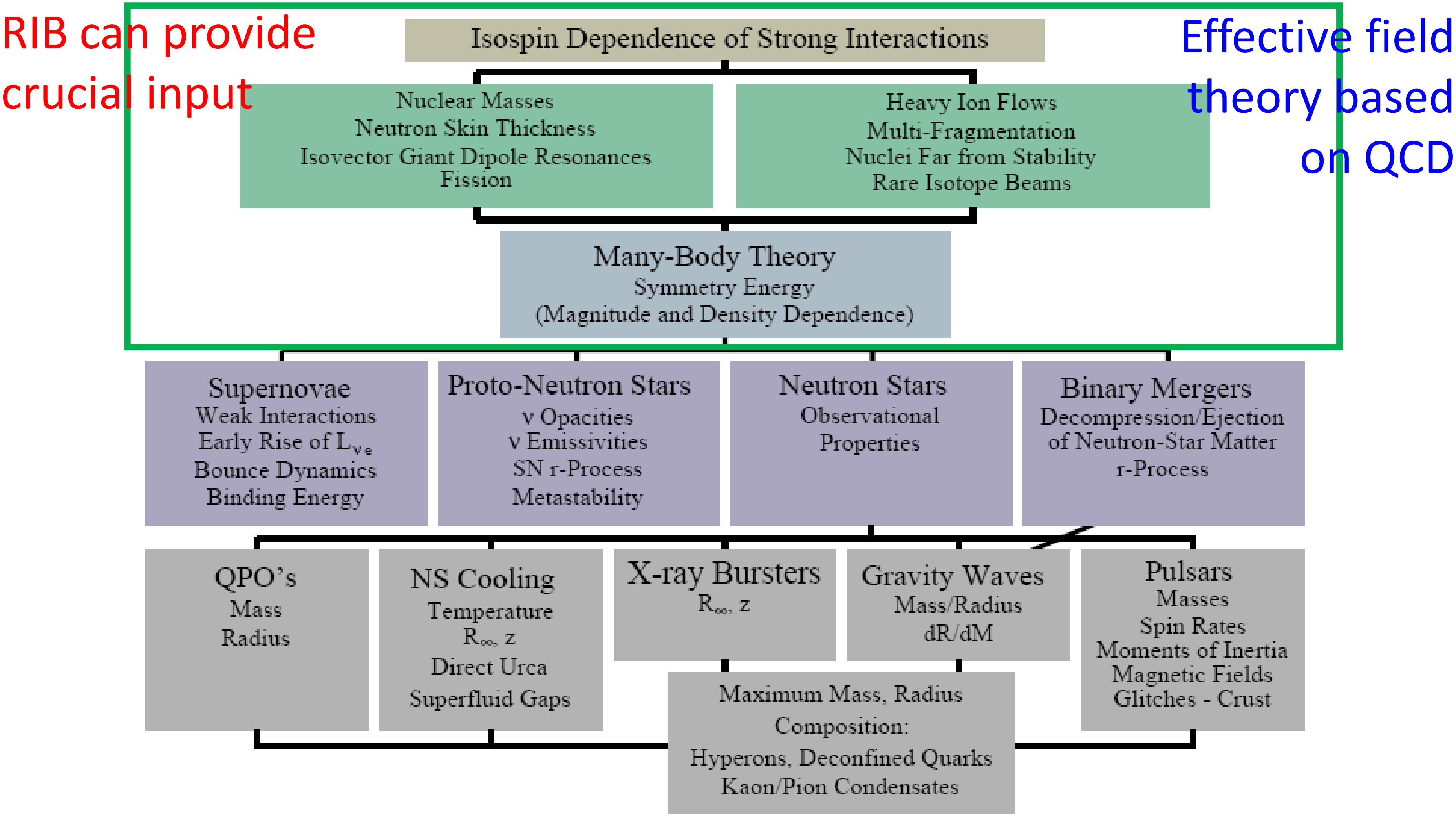
where

$$L = \frac{3}{\rho_0} P_{sym} = 3\rho_0 \left.\frac{\partial E_{sym}(\rho)}{\partial \rho}\right|_{\rho=\rho_0} \qquad \text{(slope)}$$

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

- Also important constraint on nuclear effective interactions

Nucear Symmetry Energy



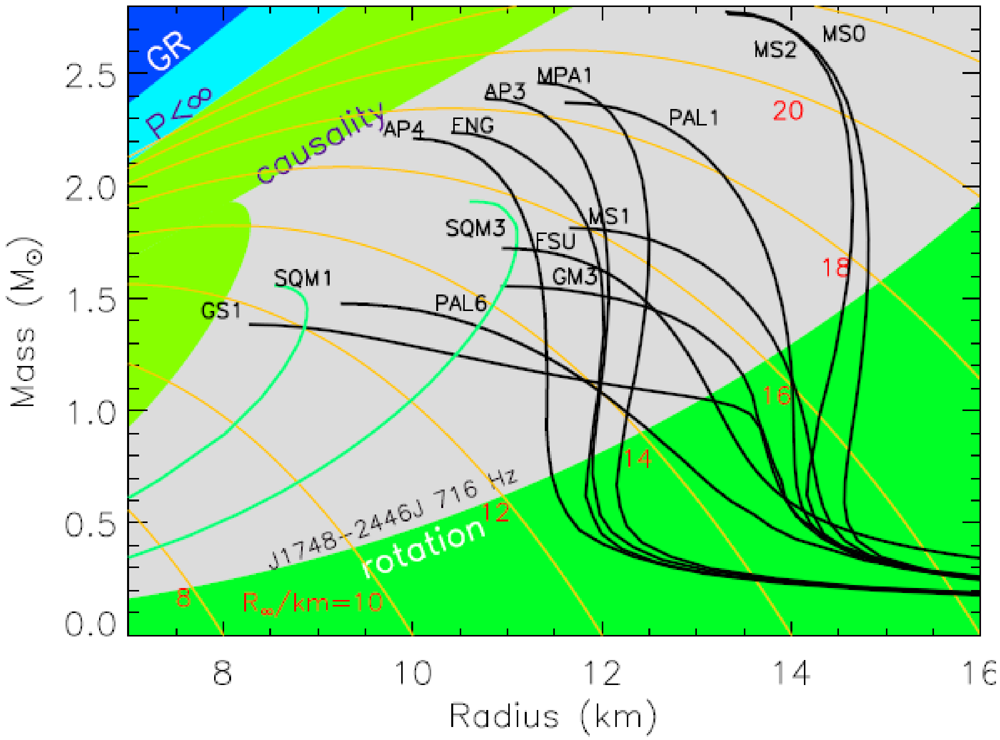
- A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, Physics Report 411, 325 (2005)

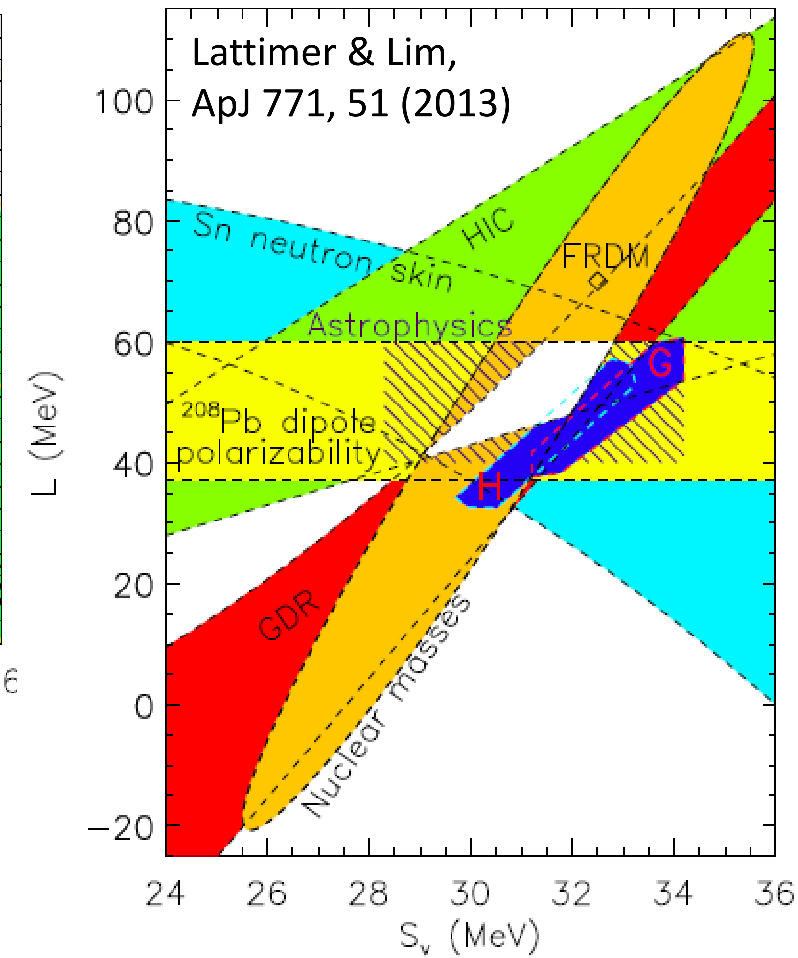
Symmetry Energy & Neutron Stars

- Neutron stars for their stability against gravitational collapse
- Determines stellar density profile and internal structure
- Observational consequences
  - Cooling rates of proto-neutron stars
  - Stellar masses, radii & moment of inertia from temperatures & luminosities of X-ray bursters
- M vs. R relationship
  - Uncertainty of softness of EOS
  - Critical relation to Asy-EOS
- For deeper understanding, we need to provide *systematic constraints from the controlled laboratory experiments* at specific densities.

Symmetry Energy & Neutron Stars

J.M. Lattimer, Ann. Rev. Nucl. Part. Sci. 62, 485 (2012)





- Black line: Hadronic EOS
- Green line: SQM EOS
- GR: Excluded by general relativity
- P<∞: Excluded by requiring finite pressure
- Causality: Excluded by causality
- Rotation: Bounded by realistic mass-shedding limit for the highest known pulsar frequency

Observables

- Charge equilibration: isospin mixing
- Particle ratios: n/p, $^{3}H/^{3}He$, etc.
- Pion ratio
- Collective flow
- Electric dipole emission

Backups

Equation of State

- Equation of state (EOS):
  Equation for the relation among pressure (p), temperature ($\tau = k_B T$), and volume (V) to describe the states of matter

- Examples:
  - Vapor pressure equation (or Clausius-Clapeyron equation)
    $dp/d\tau = L/\tau\Delta v$ (L: latent heat, Δv: the volume change when one molecule is transferred from liquid to gas)
    $\longrightarrow p(T) = p_0 \exp(-L/N_0\tau)$ for $v_g \gg v_l$ and $pV_g = N_g\tau$
  - Van der Waals equation of state
    Simplest model of a liquid-gas phase transition
    $(p + N^2a/V^2)(V - Nb) = N\tau$
    where
    a: long-range attraction between two molecules
    b: short-range repulsion between two molecules

[Ref.] E.g., Chap. 10 of Thermal Physics by C. Kittel & H. Kroemer

Equation of State

- EOS of nuclear matter can be reconstructed by using the differential thermodynamic identity like

$$p(\rho,\tau,\delta) = -\left[\frac{\partial F}{\partial V}\right]_{\tau,\delta};\, F(\rho,T,\delta) = U(\rho,T,\delta) - \tau\cdot\sigma(\rho,T,\delta)$$

where
F is the Helmholtz free energy,
U is the average energy of the state,
σ is the entropy,
$\rho = \rho_n + \rho_p$ is the total baryon density,
$\delta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$ is the isospin asymmetry.

- Using the baryon density $\rho = A/V$ and $\partial V = -A\partial\rho/\rho^2$,

$$p(\rho,\tau,\delta) = -\left[\frac{\partial U}{\partial V}\right]_{\tau,\delta} = \left[\rho^2 \frac{\partial(U(\rho,\tau,\delta)/A)}{\partial\rho}\right]_{\tau,\delta} - \left[\tau\rho^2 \frac{\partial(\sigma/A)}{\partial\rho}\right]_{\tau,\delta}$$

- At low temperatures, the second term becomes negligible.

Charge Equilibration

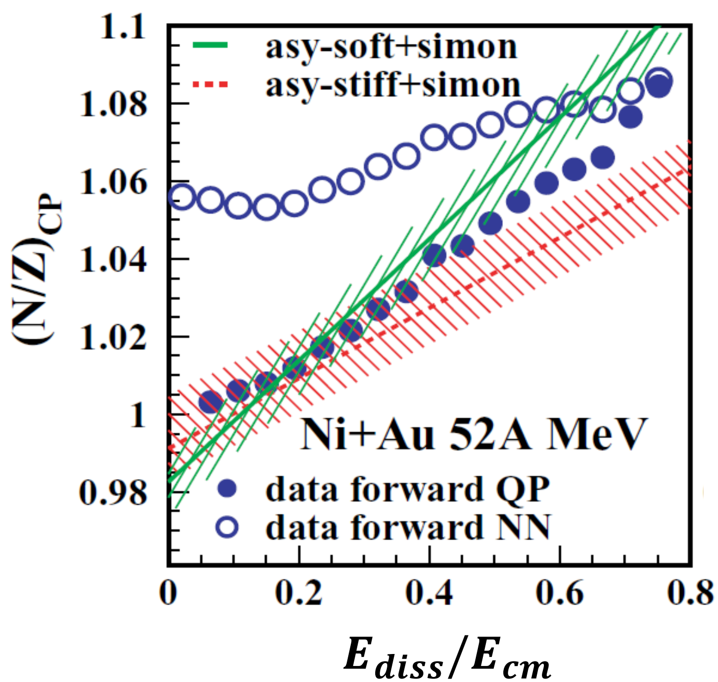
- Charge equilibration
  - In fusion, dipole oscillation is important.
  - In deep inelastic coll., dipole oscillation is overdamped: Diffusion of charges

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

- Degree of equilibration governed by contact time and symmetry energy
- Observable
  - N/Z of particles emitted by PLF as a function of dissipated energy:

$(N/Z)_{CP}$ vs. E_{diss}

$E_{diss} \equiv E_{cm} - E_{kin}(PLF + TLF)$



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

Isospin Mixing/Diffusion

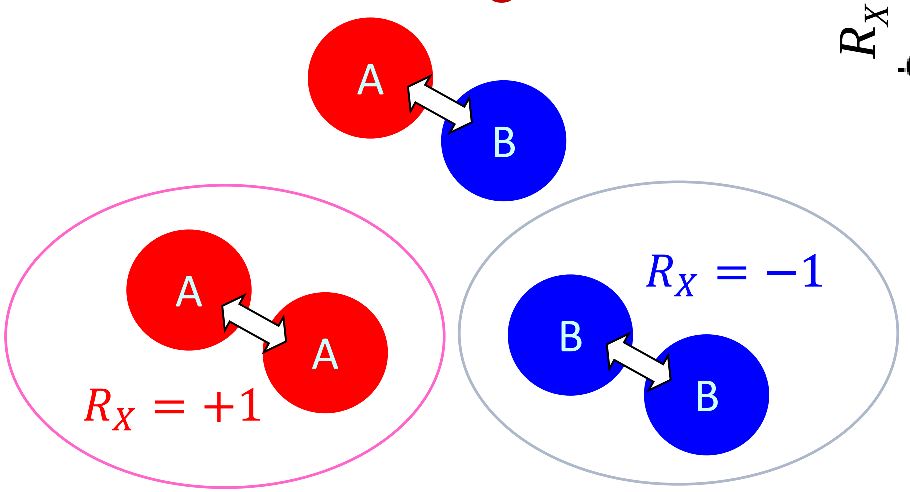
F. Rami et al., PRL 84, 1120 (2000)

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

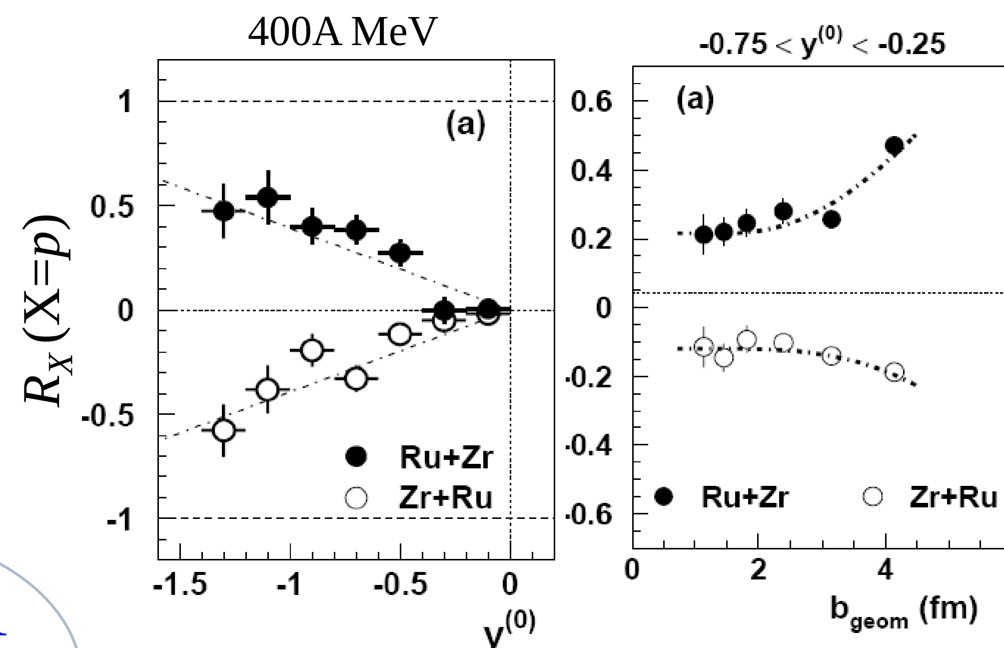
B. Hong et al., NPA 721, 317c (2003)

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

$R_X = 0$ for complete isospin mixing



^{96}Ru(Zr)+^{96}Zr(Ru)

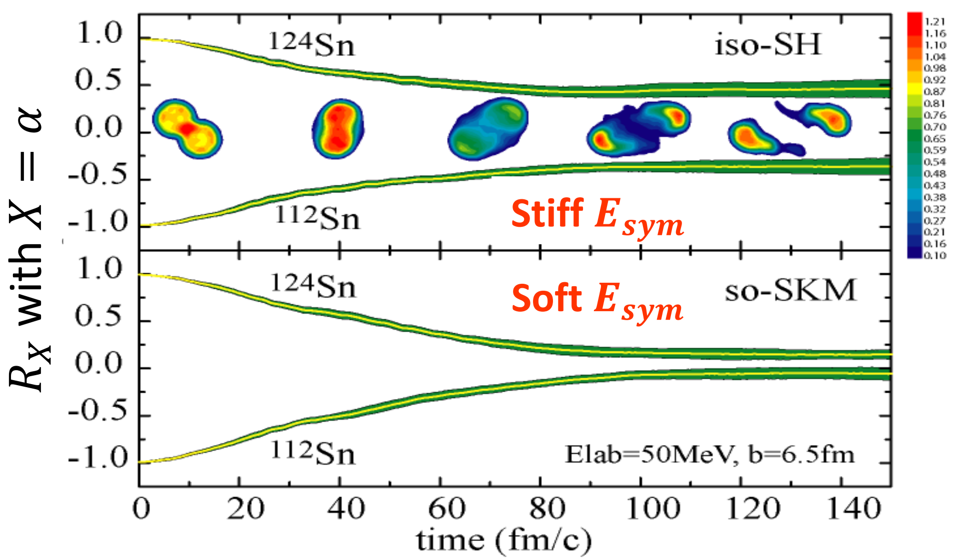


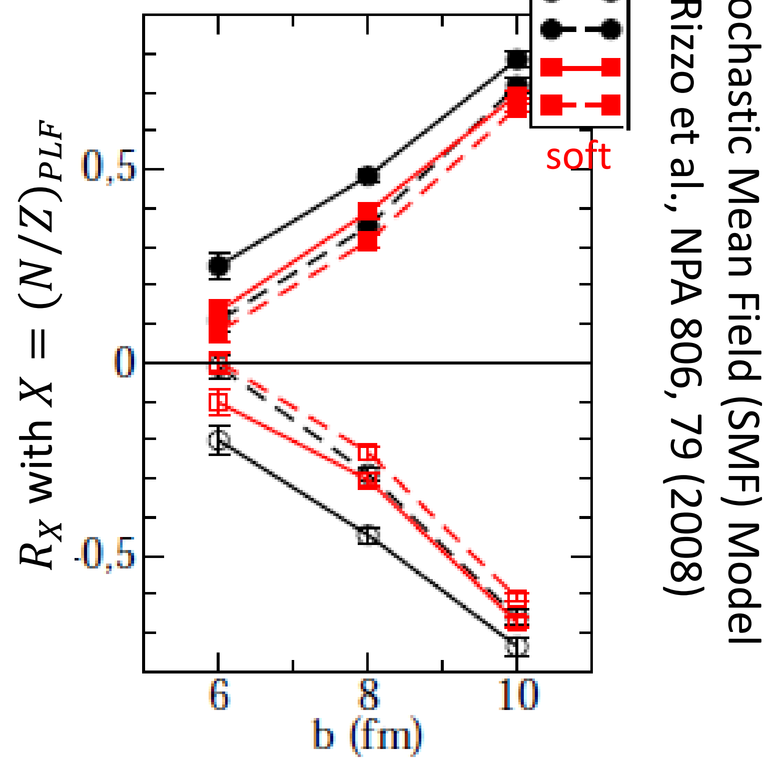
Isospin Mixing/Diffusion

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

α=Neutron-isoscaling parameter

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





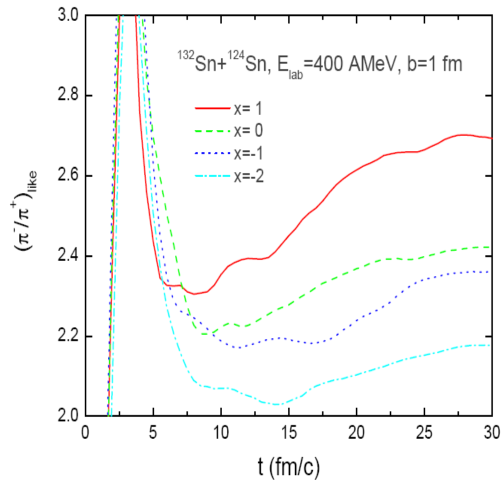
- Softer symmetry energy towards equilibrium ($R_X \rightarrow 0$)
- Good sensitivity to Asy-EOS

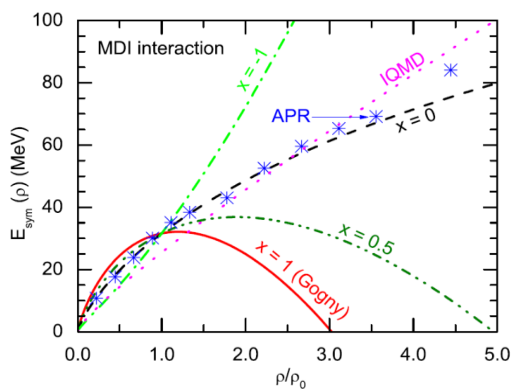
π^-/π^+ Ratio

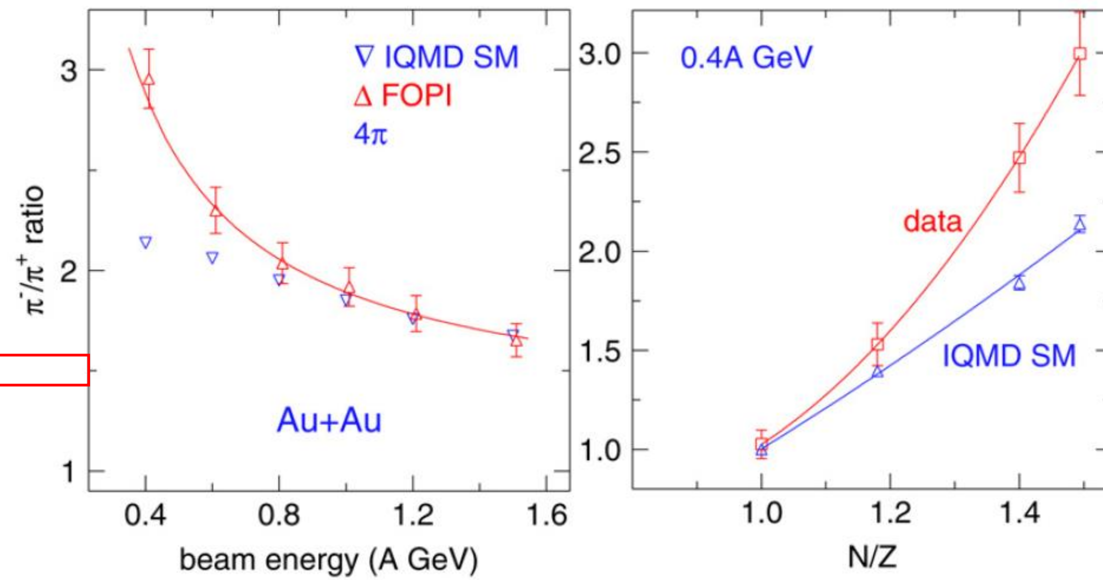
Data: FOPI, NPA 781, 459 (2007)

IQMD: EPJA 1, 151 (1998)

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

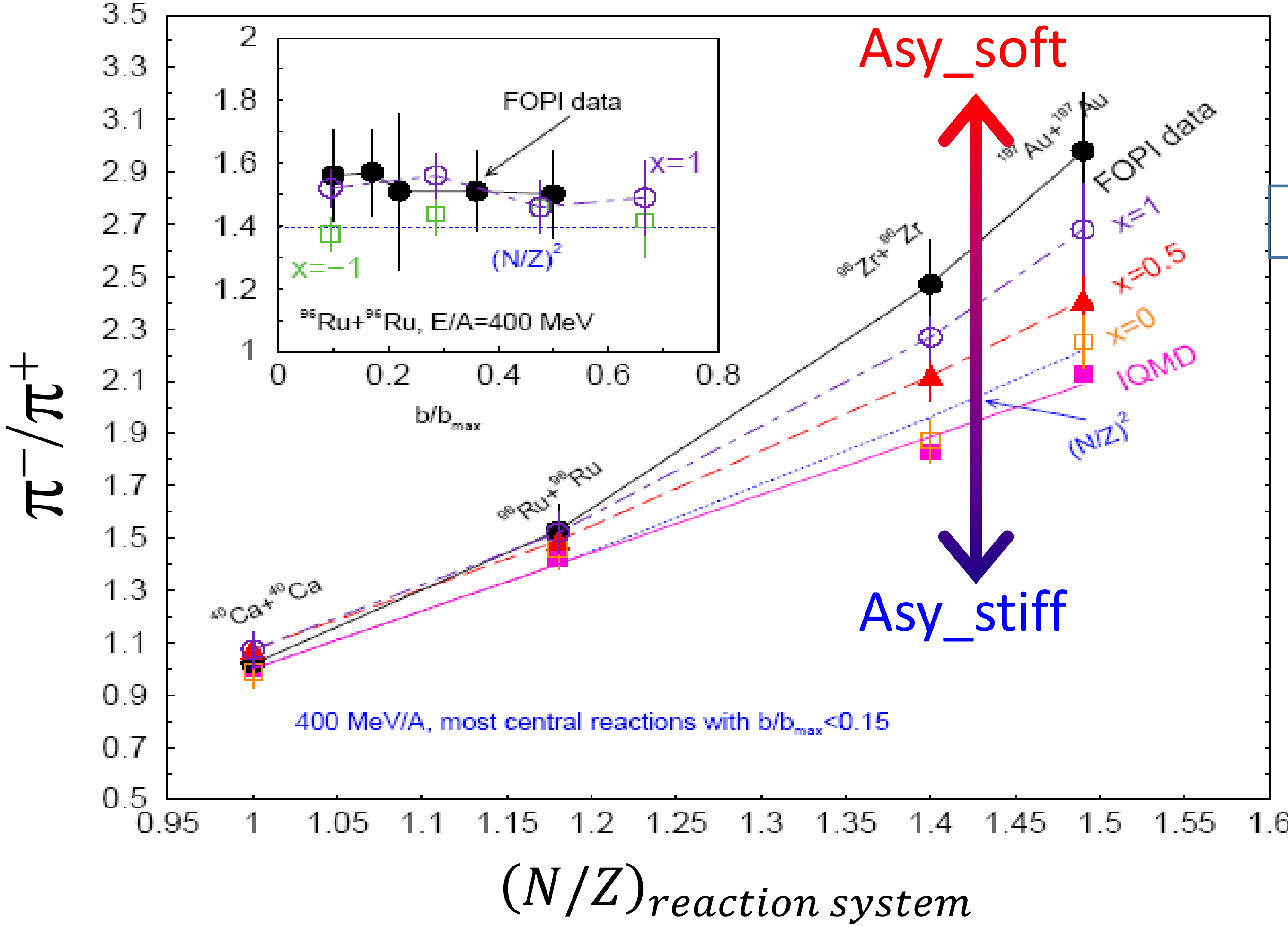






Symmetry energy softer than the present IQMD makes the pion production region more neutron-rich!

π^-/π^+ Ratio



Future RI beam expts. at, e.g., RAON, RIBF, FRIB, etc.

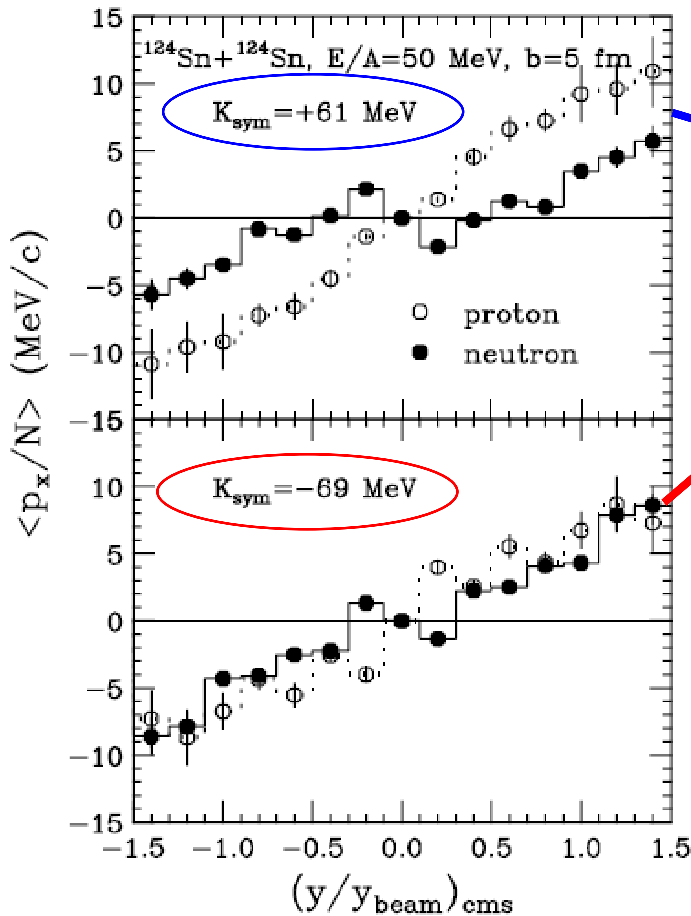
Directed Flow for K_{sym}

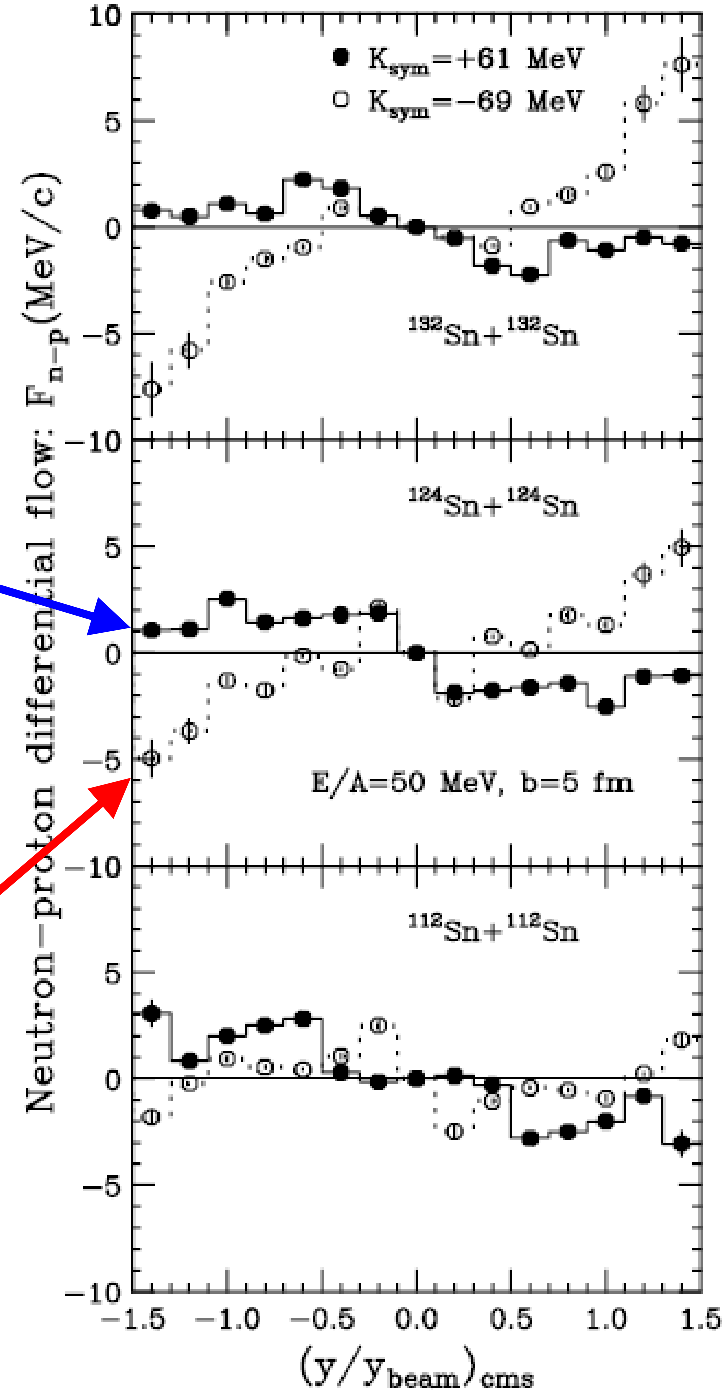
B.-A. Li, PRL 85, 4221 (2000)

Asy-stiff

Also known as v_1

Asy-soft





Large N/Z

Small N/Z