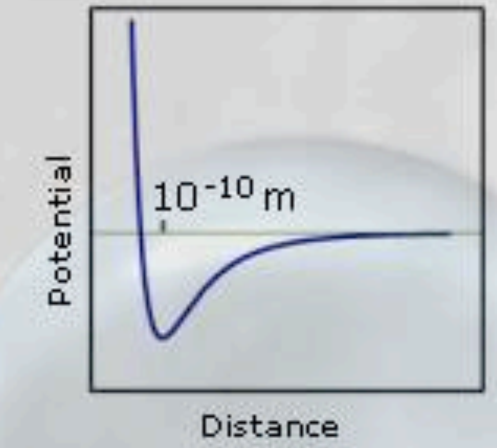
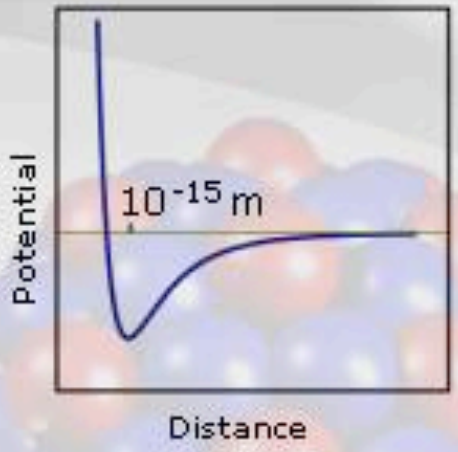
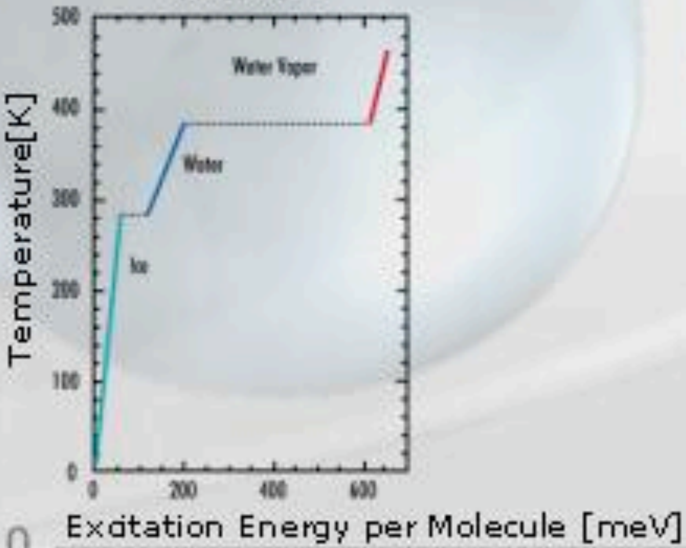
The nucleus as a liquid drop

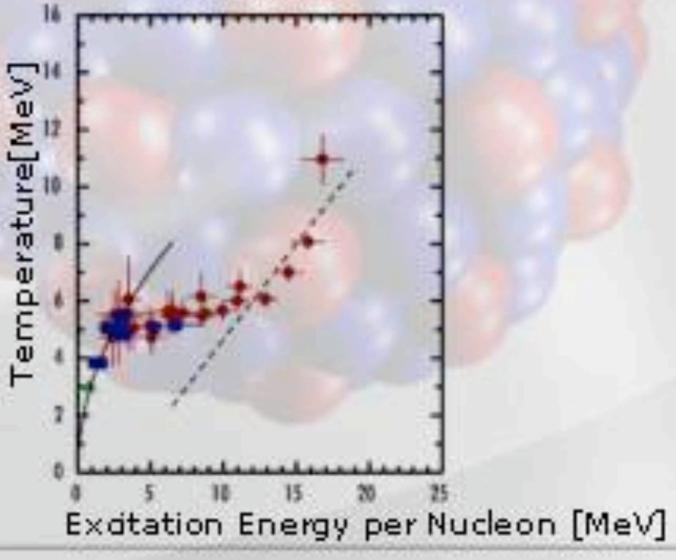
$$BE = a_{Vol}A - a_{Sur}A^{2/3} - a_{Coul}\frac{Z^2}{A^{1/3}} - a_{Asym}\frac{(N-Z)^2}{A} + \Delta$$

The Phases of Nuclear Matter









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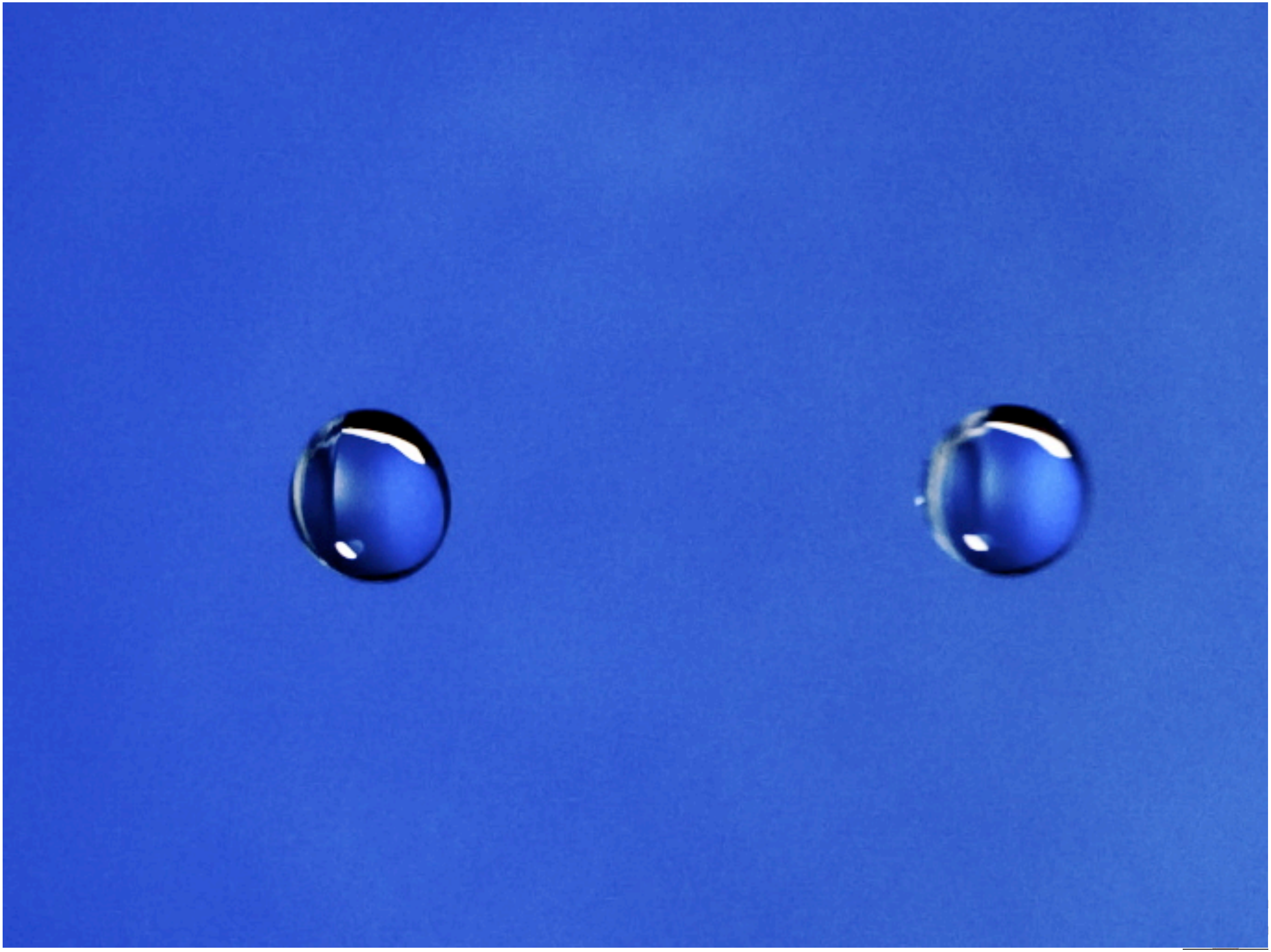

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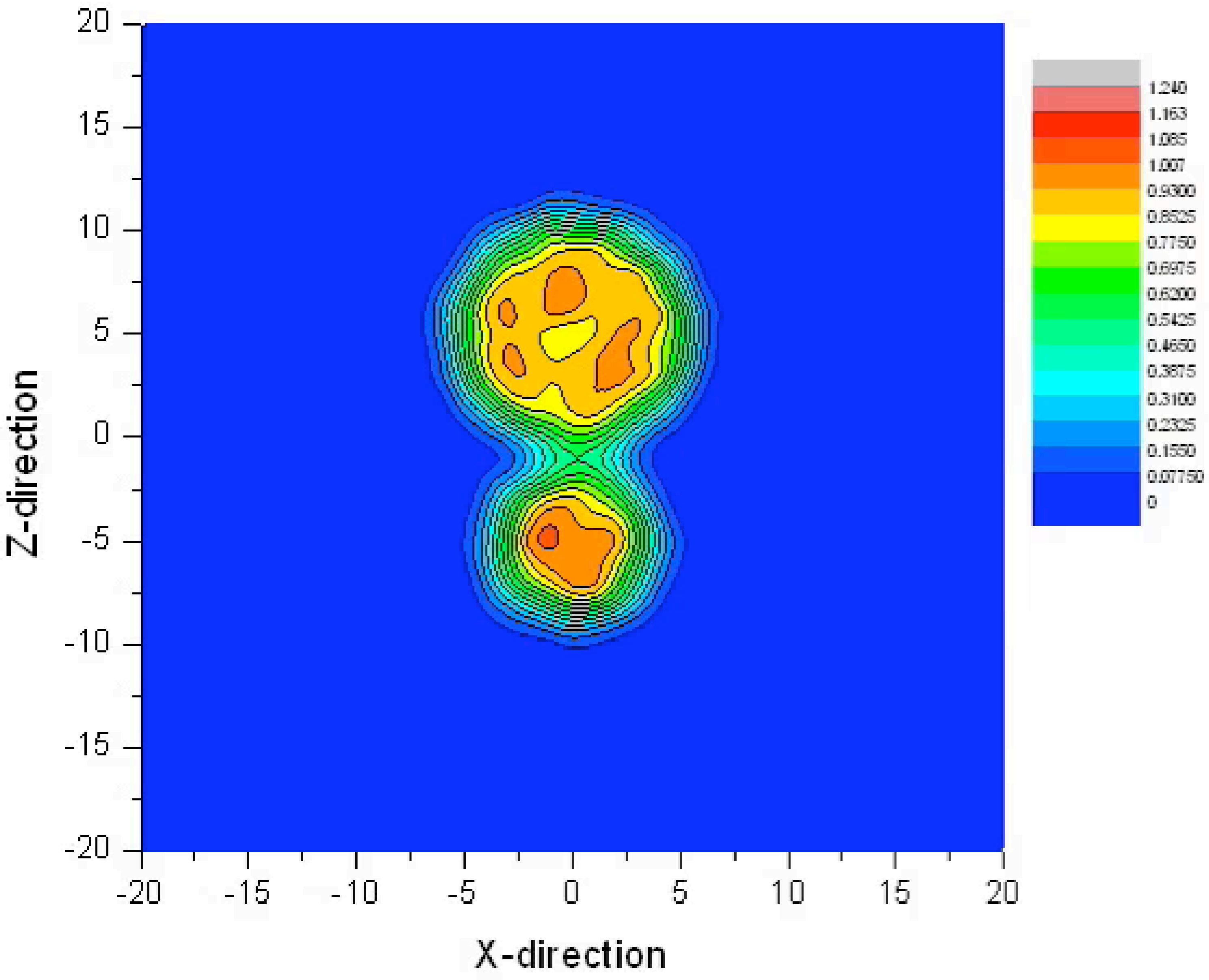
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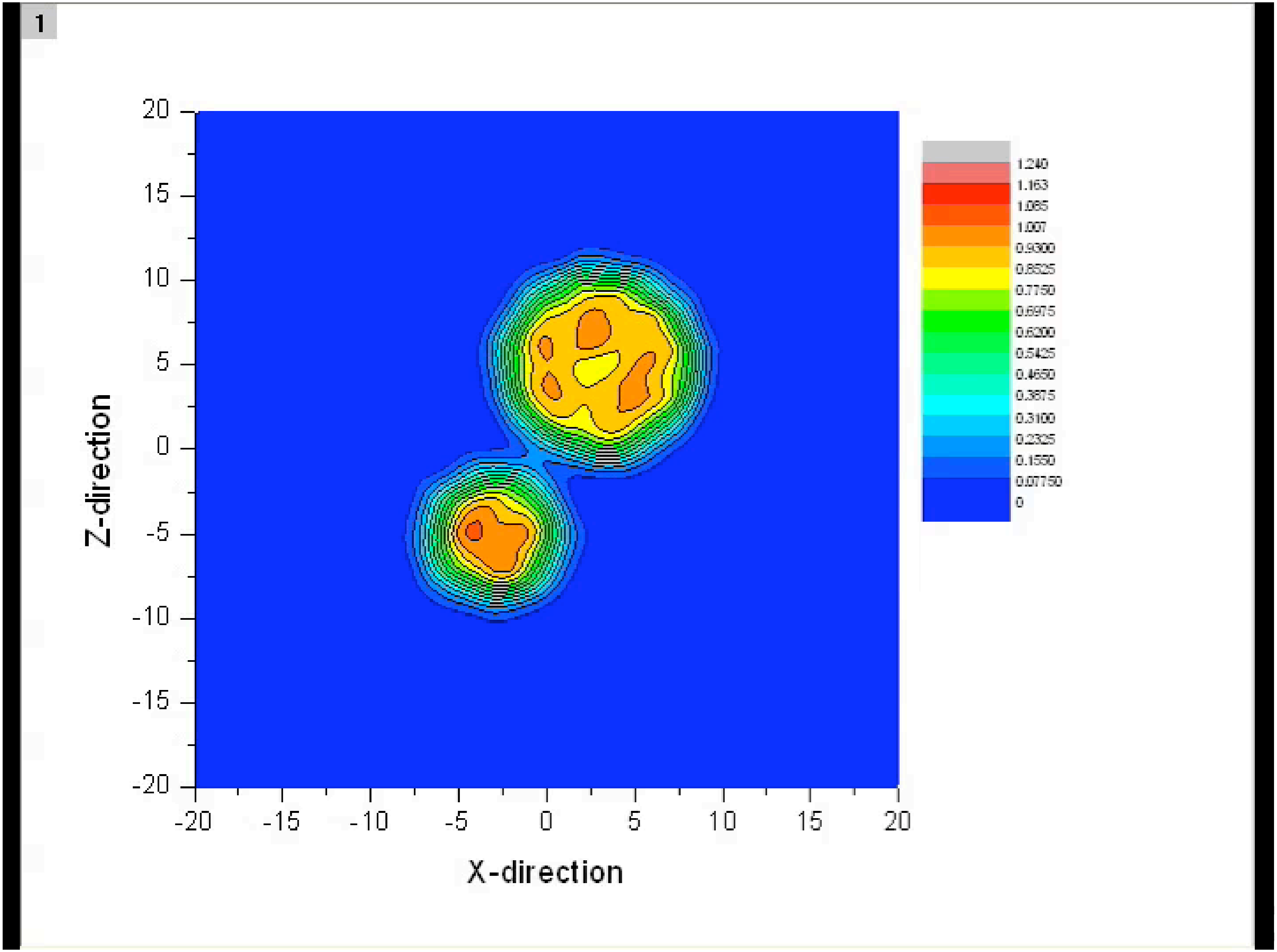
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0.8525
0.7750
0.6975
0.6200
0.5425
0.4650
0.3875
0.3100
0.2325
0.1550
0.07750
0

Nuclear Reactions

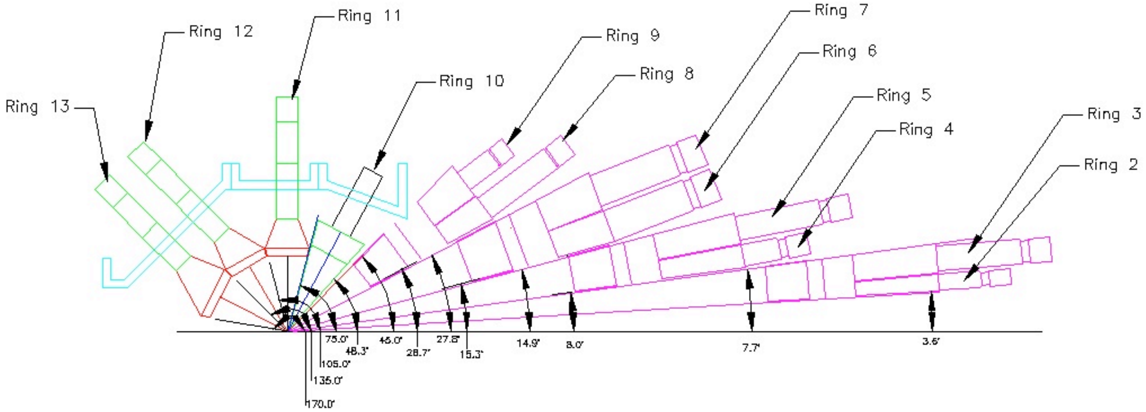
- What can we learn from heavy-ion (and light-ion) reactions?
- How do we do these experiments?
- Connections to nuclear astrophysics

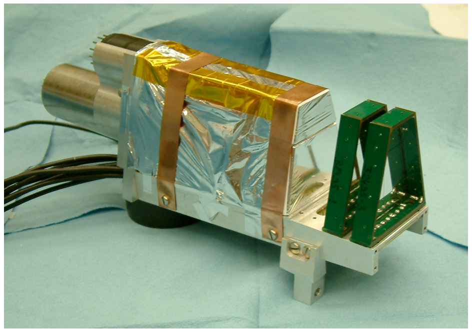
What can we learn from heavy-ion (and light-ion) reactions?

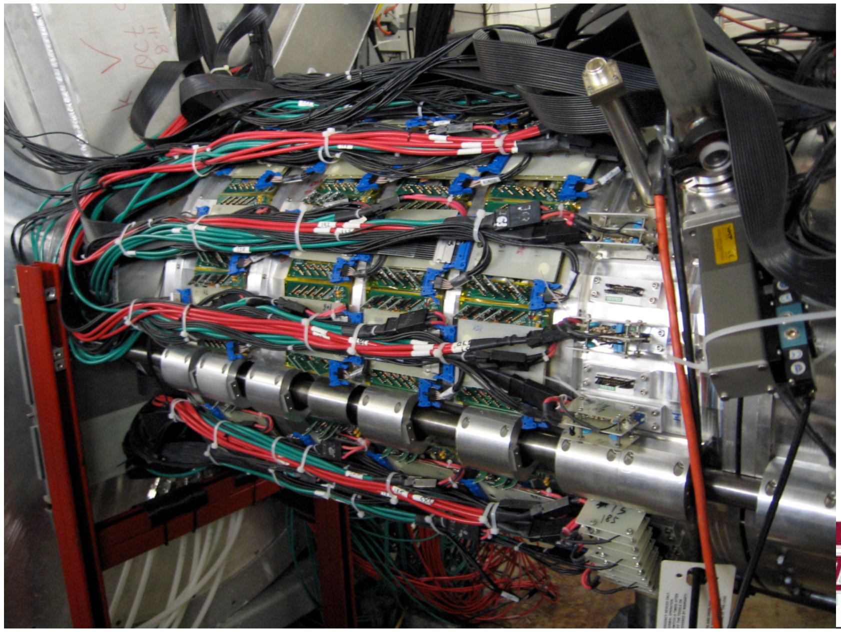
- Nuclear liquid – gas phase transition
- Equation of state of nuclear matter
- Symmetry energy

NIMROD - ISiS

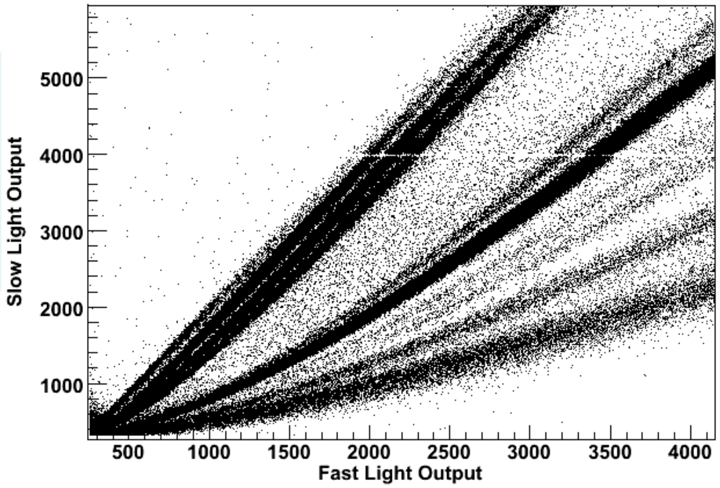
- 228 modules
  - Si/CsI
  - Some Si/Si/CsI
  - Ion Chambers
- 14 rings
- 3.6^{o}-167^{o}
- Neutron Ball

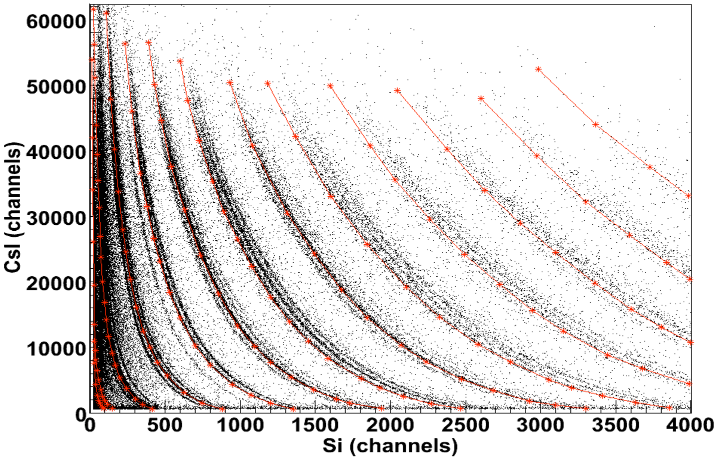


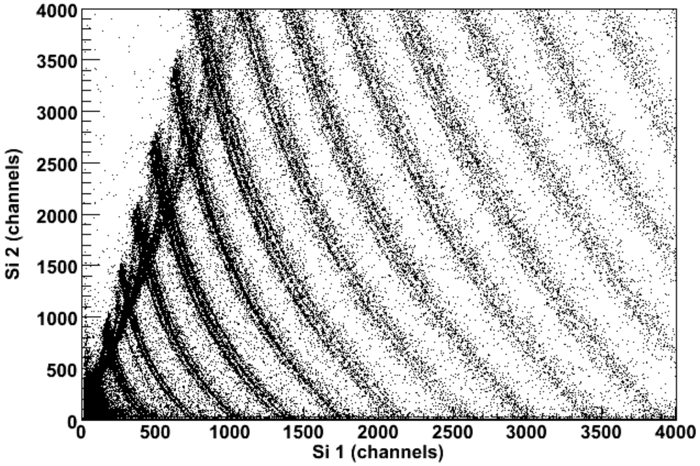




S. Wuenschel et al. NIMA doi:10.1016/j.nima.2009.03.187







Particle ID

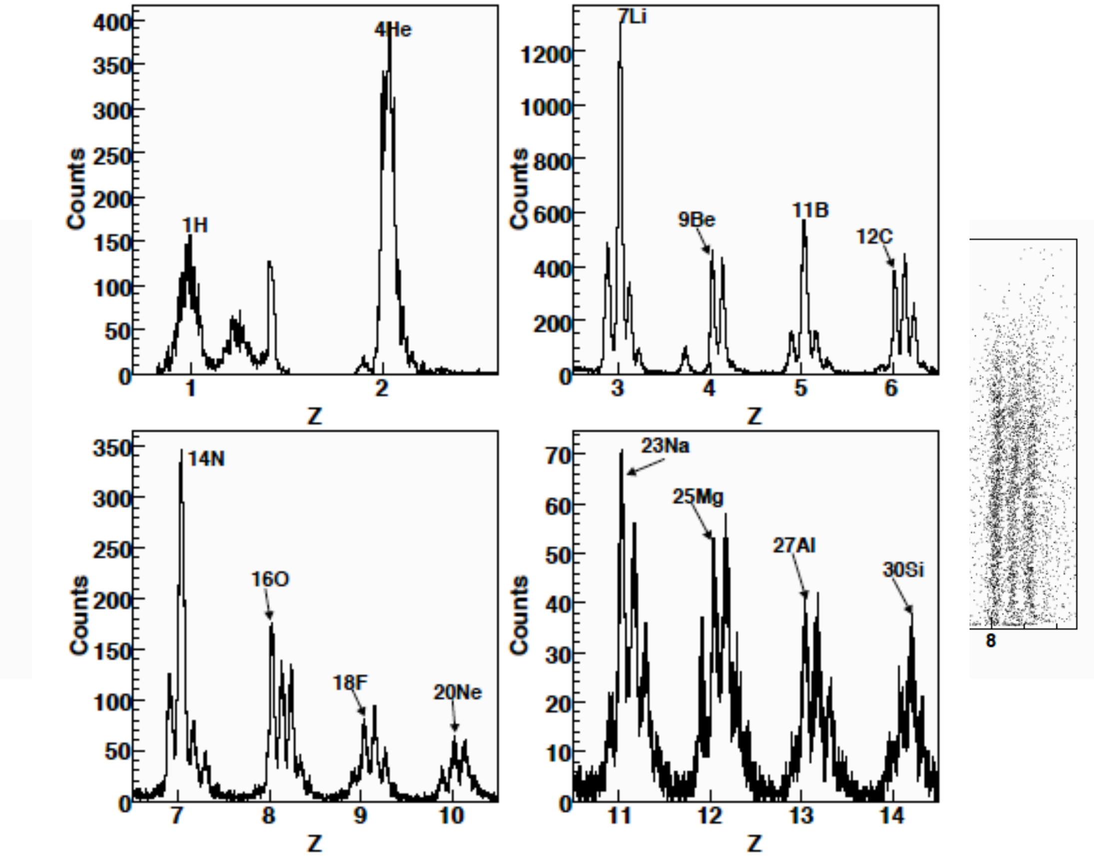
- Three sources of fragment identities
  - – CsI (Fast v. Slow)
  - – Si-CsI (dE v. E)
  - – Si-Si (dE v. E)

$$\frac{\delta E}{\delta x} \propto \frac{AZ^2}{E}$$

- Linearization
  - Note: lines on Si-CsI plot

Particle Identification

- Linearization
  - Place lines
    - Si-CsI
    - Si-Si
    - CsI
  - Calculate distance
  - Project



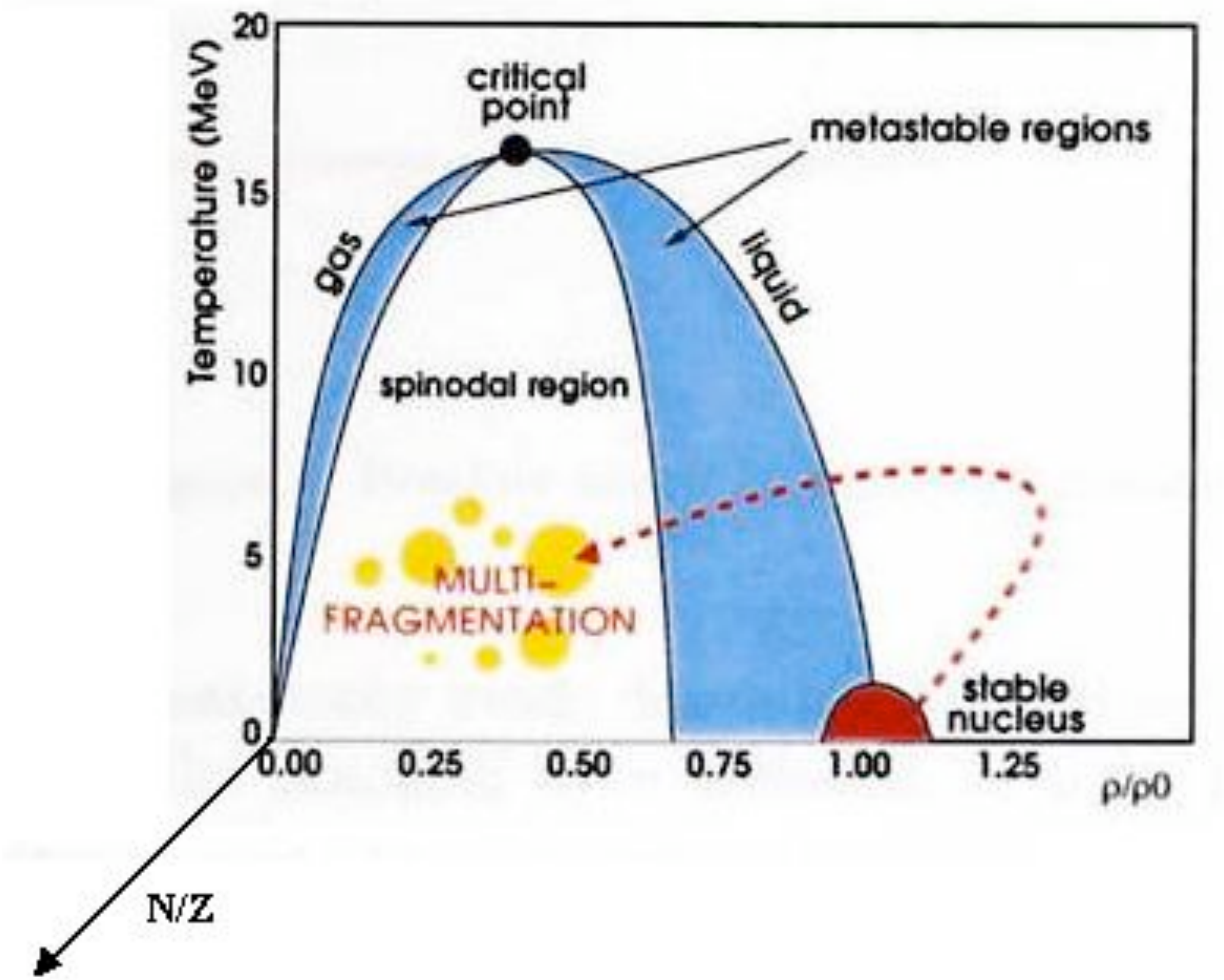
$$P_A = \frac{G_A(L_X)}{\sum_i G_i(L_X)}$$

Common observables

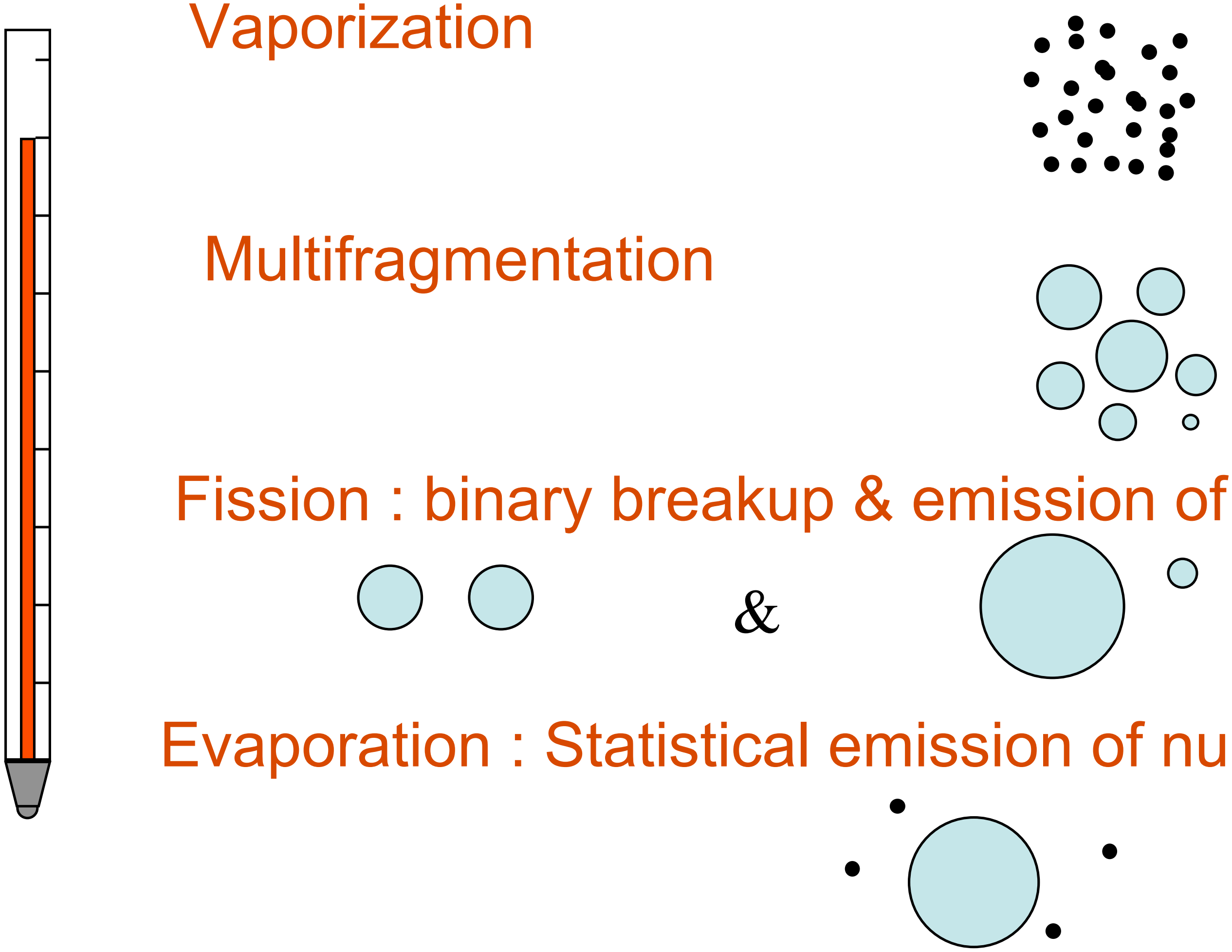
- Particle Information
  - Charged particles
    - Identity (Z,A), energy, direction
  - Neutrons
    - Multiplicity / energy
  - Angular Distributions
  - Charge Distributions
  - Spectral shapes

- Event information
  - Multiplicity Distributions (cp, lcp, n….)
  - Excitation energy
  - Event shape
  - Temperature
  - Breakup Density
  - Timescale
  - Distributions of neutron/proton content
  - Flow

Exploring phase transitions in excited nuclear material



Reactions between nuclei at various energies allow us to probe nuclear behavior at different "temperatures"



Vaporization

Multifragmentation

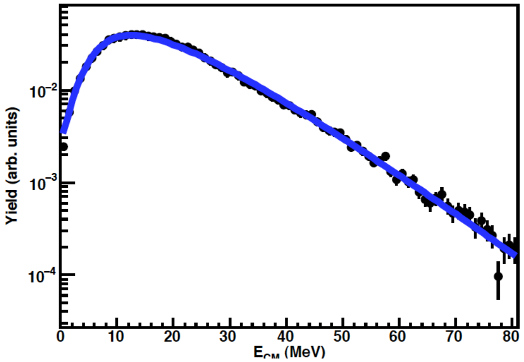
Fission : binary breakup & emission of small clusters

Evaporation : Statistical emission of nucleons

Temperature

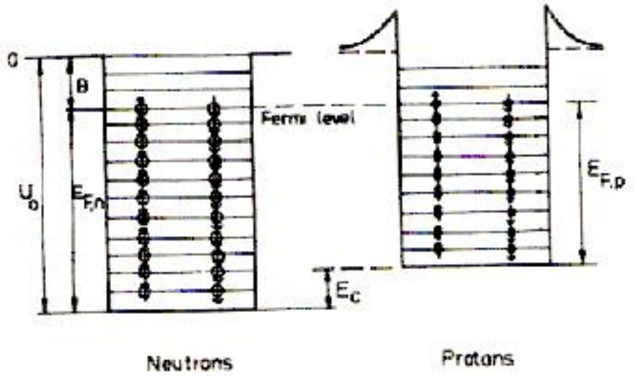
- Common thermometers:
  - Slope

$$Yield \propto \exp^{-E/kT}$$



  - Excited State

$$\frac{P_1}{P_2} = \frac{2s_1+1}{2s_2+1} exp\left[\frac{-(E_1-E_2)}{T}\right]$$



  - Double Isotope Ratio

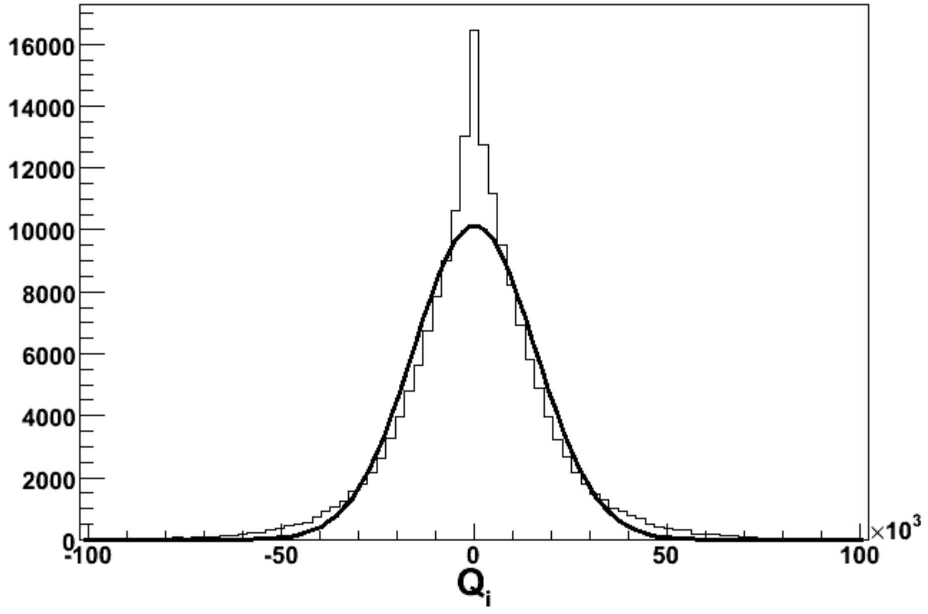
$$T_{app} = B/ln(aR_{app})$$

$$R_{app} = \frac{[Y(A_i,Z_i)/Y(A_i+1,Z_i)]}{[Y(A_j,Z_j)/Y(A_j+1,Z_j)]}$$

Fluctuation Thermometer

$$Q_i = 2 * P_Z^2 - P_T^2$$

- For each particle in an event in the reference frame of the source event
- If T>0 Q does not have to equal zero
  - Fluctuations $\langle Q_i \rangle = 0$
- Fluctuations provide a variance
  - Changes with E*
  - Can be linked to T



Phase transitions

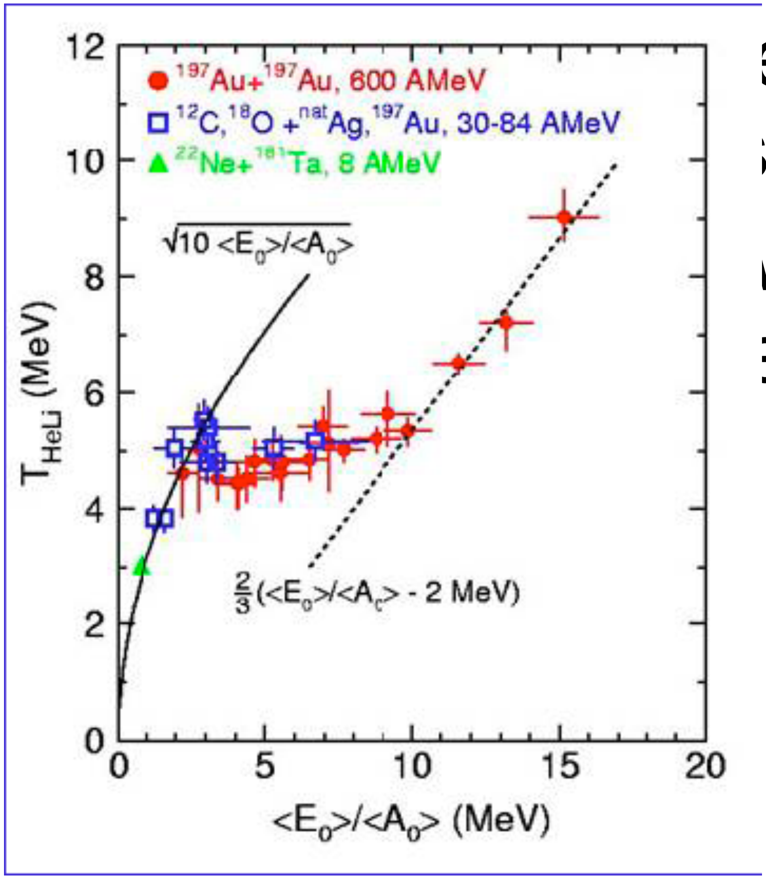
- Transition from surface evaporation to bulk boiling happens when you hit the phase boundary

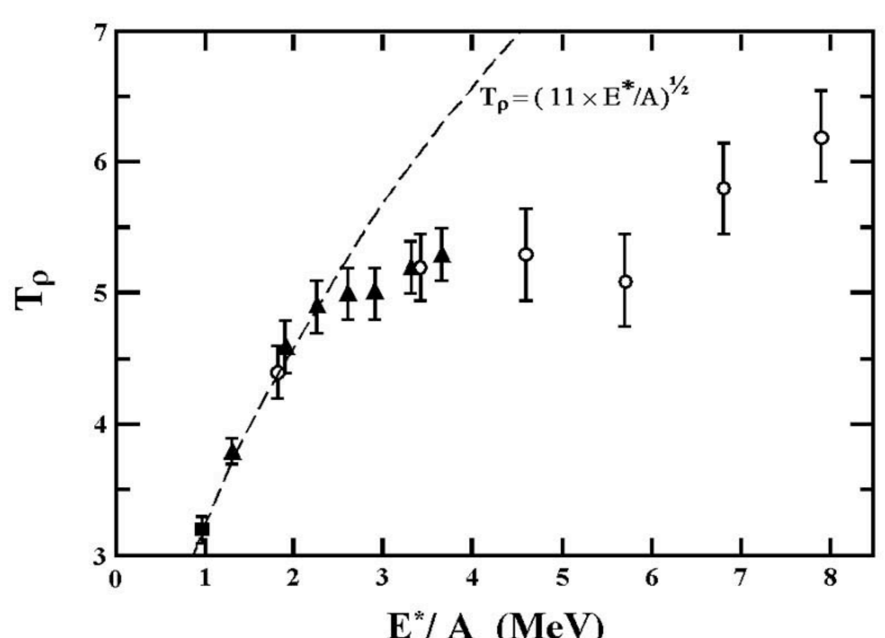
- Transition from fragments emitted at the surface to bulk multifragmentation

Signatures of phase transition

- Caloric curve
- Bulk multifragmentation
  - Fragment size distributions
  - Timescales

Caloric Curve





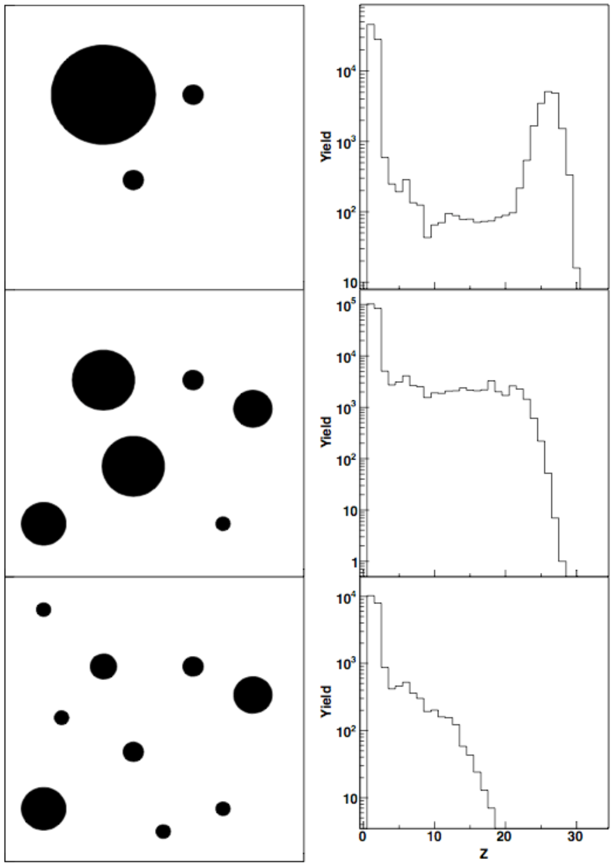
$$T = [K_0(\rho/\rho_0)^{2/3}(E^*/A)]^{1/2}$$

PRL **93**, 132701/1-4 (2004)

Phys. Rev. C 65 (2002) 034618

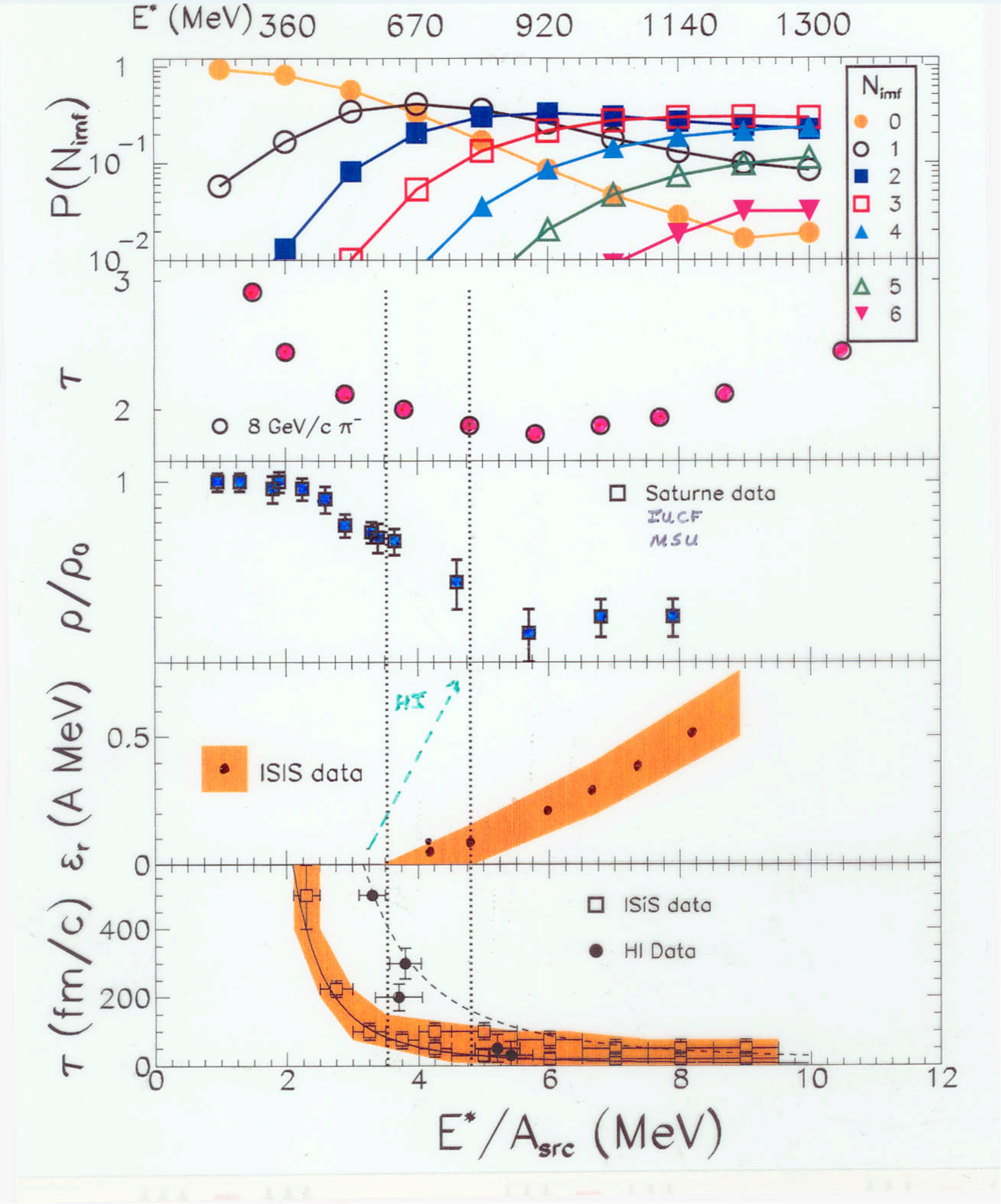
Phys. Rev. Lett. 75 (1995)

Bulk Multifragmantation



- Fragment multiplicity
- Charge distributions
- Breakup density
- Timescale

Many indications of phase transition

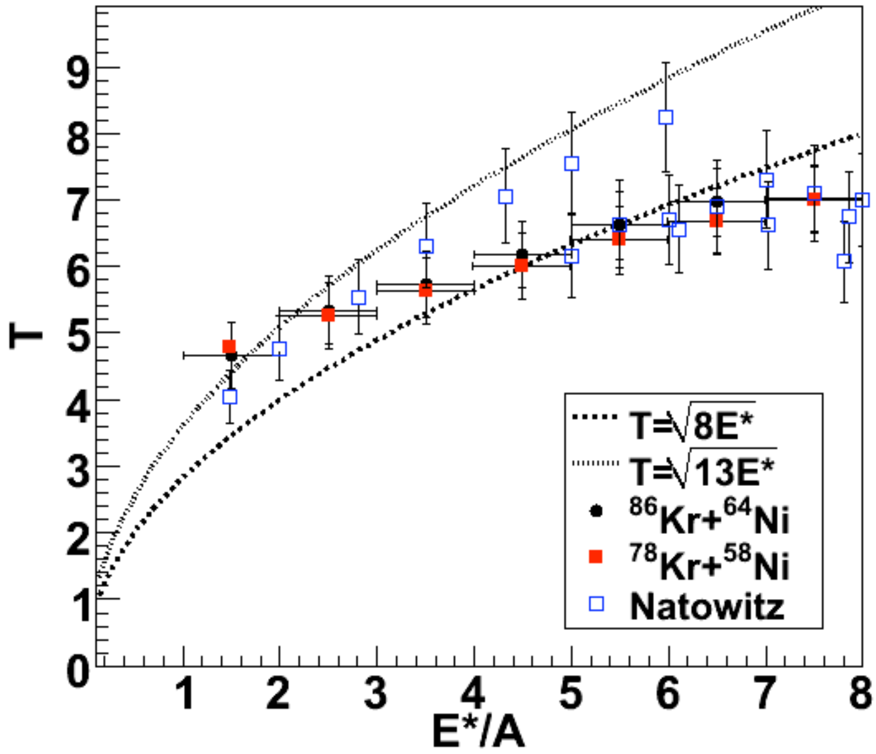


Predictions for the liquid-gas phase transition in asymmetric (N/Z > 1) nuclear matter

(H. Muller & B. Serot, Phys. Rev. C 52, 2072 (1995))

- *Critical temperature decreases with increasing isospin asymmetry*
- *Isospin fractionation (two phase separation in the co-existence region)*

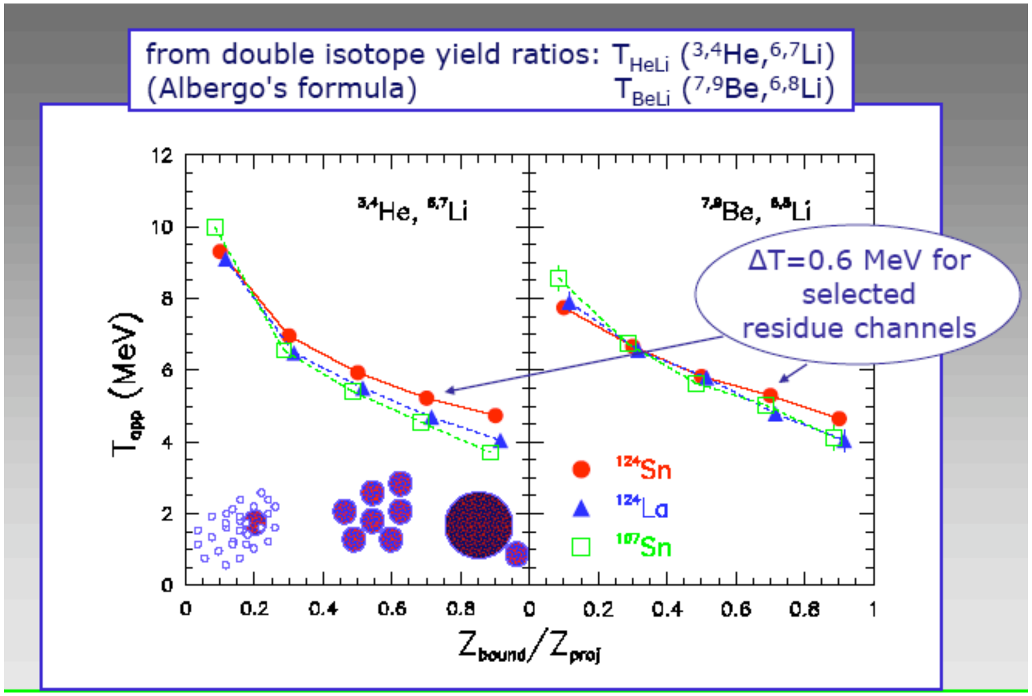
Temperature(N/Z) ?



Quadrapole Fluctuation - Protons

- ^{86}Kr+^{64}Ni, ^{78}Kr+^{58}Ni

S. Wuenschel, thesis



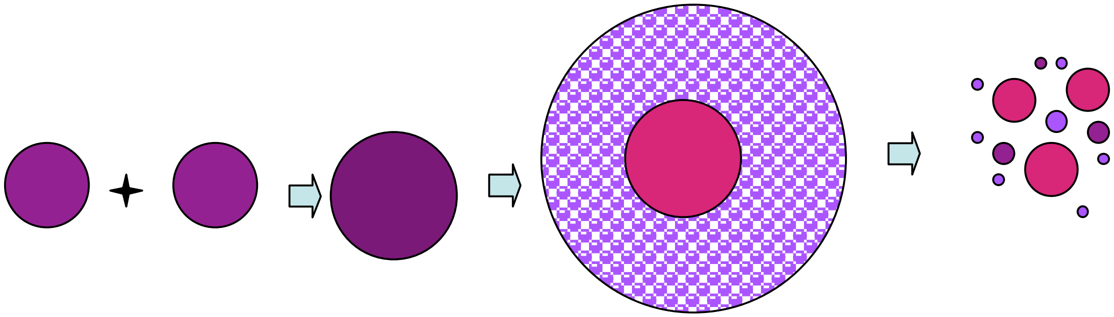
from double isotope yield ratios: T_{HeLi} (^{3,4}He,^{6,7}Li)
(Albergo's formula) T_{BeLi} (^{7,9}Be,^{6,8}Li)

ΔT=0.6 MeV for selected residue channels

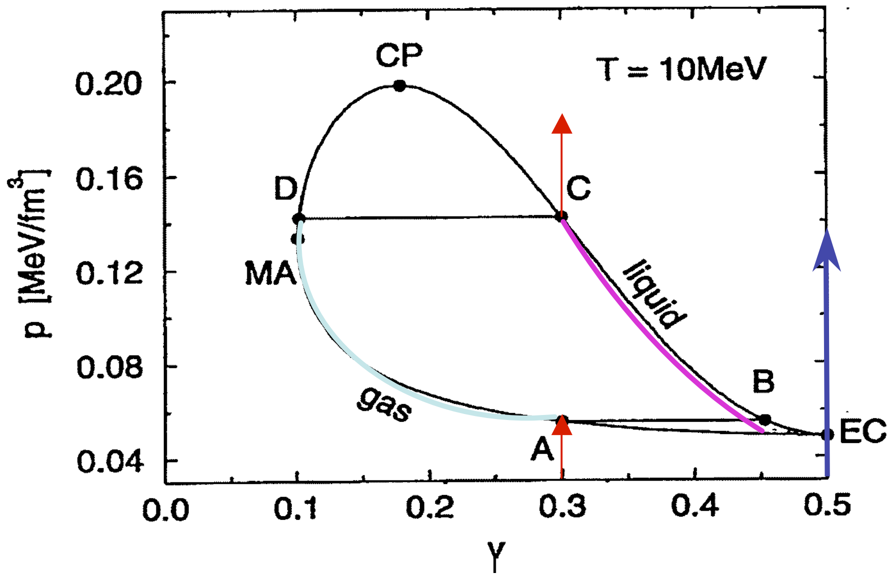
Sfienti, Phys. Rev. Lett. 102, 152701 (2009)

Isospin distillation in asymmetric (N/Z > 1) nuclear matter

(H. Muller & B. Serot. Phys. Rev. C 52, 2072 (1995))



An inhomogeneous distribution of the neutrons and protons within the system is predicted, resulting in a dilute neutron rich (N/Z > 1) gas (light clusters) and a dense and symmetric (N/Z ~ 1) liquid (heavy fragments)



Mueller & Serot PRC1995

Is there Nuclear Distillation?

(a non homogeneous distribution if isospin)

Relative neutron and proton density from isotopic yields

$$Y(N,Z) \propto \rho_n^N \rho_p^Z P_{N,Z}(T) F_{N,Z}(T) e^{B(N,Z)/T}$$

$$R_{21} = \frac{Y_2(N,Z)}{Y_1(N,Z)} = C\left(\frac{\rho_{n,2}}{\rho_{n,1}}\right)^N \left(\frac{\rho_{p,2}}{\rho_{p,1}}\right)^Z$$

free neutron & proton densities

$$\frac{Y_2(N+k,Z)/Y_1(N+k,Z)}{Y_2(N,Z)/Y_1(N,Z)} = \left(\frac{\rho_{n,2}}{\rho_{n,1}}\right)^N$$

Relative n density

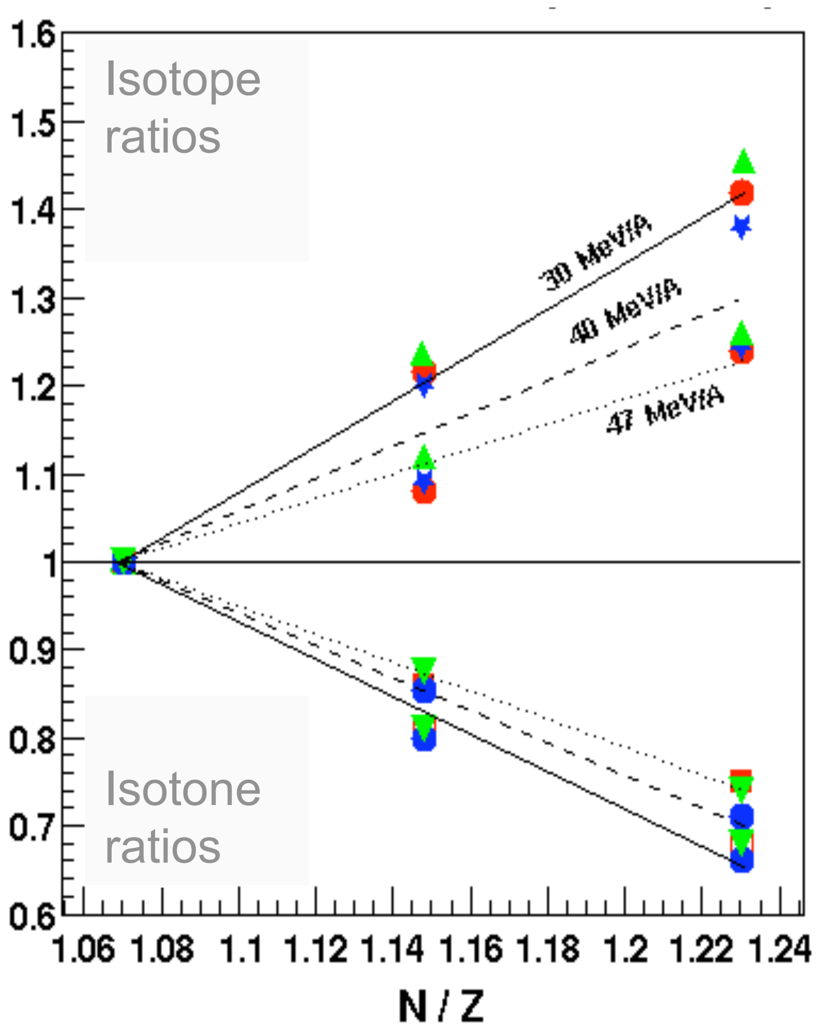
$$\frac{Y_2(N,Z+k)/Y_1(N,Z+k)}{Y_2(N,Z)/Y_1(N,Z)} = \left(\frac{\rho_{p,2}}{\rho_{p,1}}\right)^Z$$

Relative p density

Relative neutron, proton densities
^{58}Fe,^{58}Ni + ^{58}Fe,^{58}Ni; 30,40,47MeV/nucleon

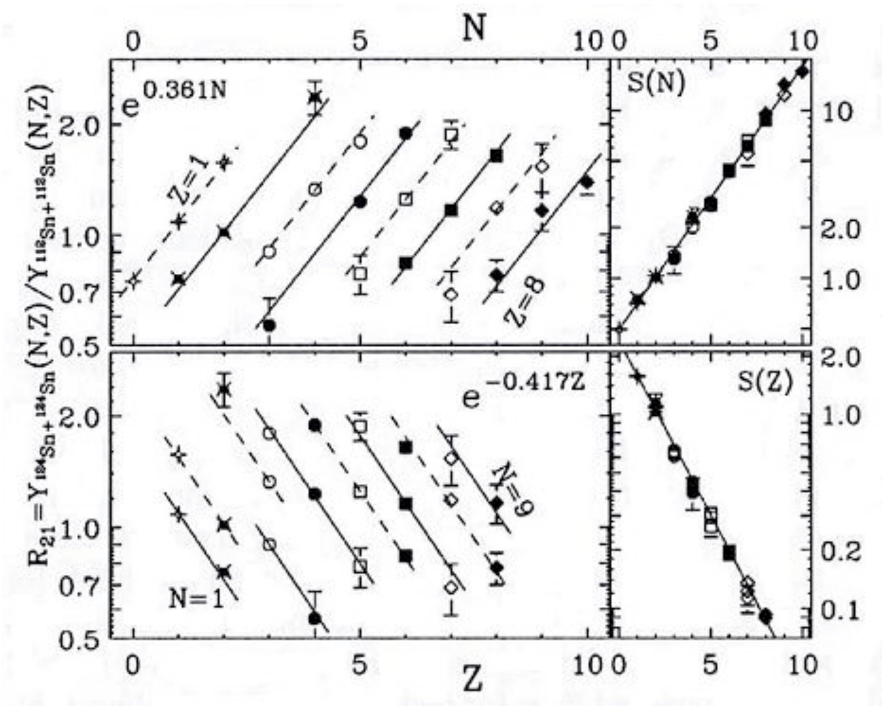
ρ_n / ρ_n^{Ni+Ni}

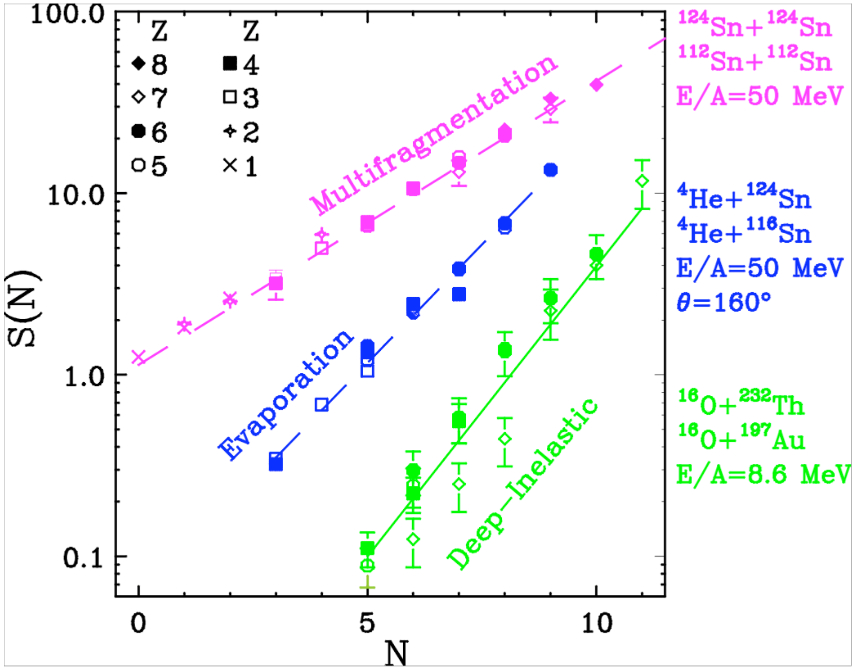
ρ_p / ρ_p^{Ni+Ni}



Isoscaling

$$R_{21}(N,Z)=Y_2(N,Z)/Y_1(N,Z)=C\exp(N\alpha+Z\beta), \qquad \alpha=\frac{4C_{sym}}{T}\left(\frac{Z_1^2}{A_1^2}-\frac{Z_2^2}{A_2^2}\right)$$





M.B. Tsang et al, Phys. Rev. Lett 68 (2001) 5023

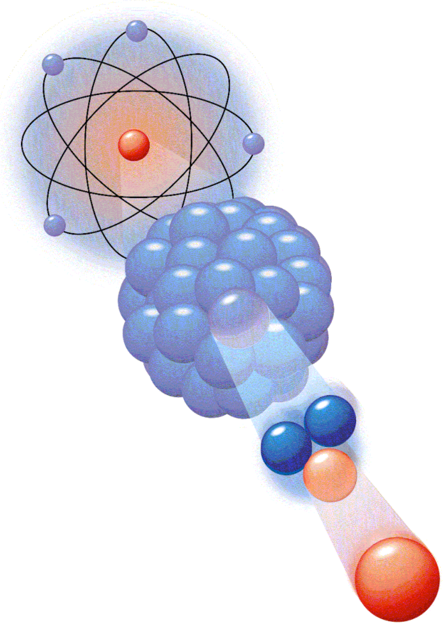
M.B. Tsang et al, Phys. Rev. C 64 (2001) 041603(R)

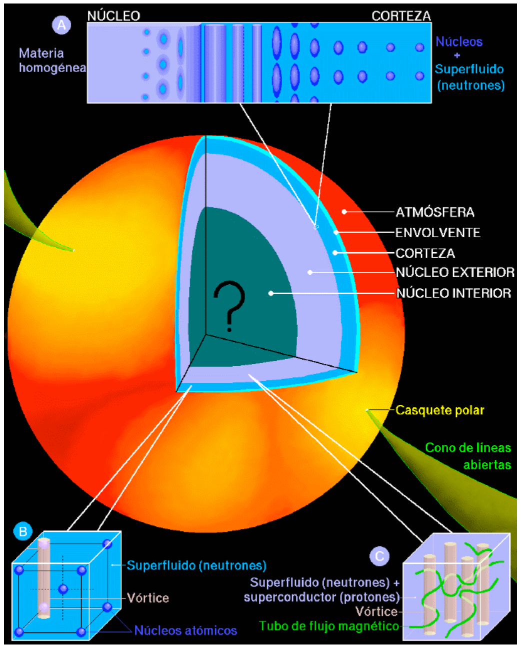
M.B. Tsang et al, Phys. Rev. C 64 (2002) 054615

Atomic nuclei & Neutron star

(two vastly different systems)

A heavy nucleus (like ^{208}Pb) is 18 orders of magnitude smaller and 55 orders of magnitude lighter than a neutron star !





Yet bounded by a common entity, the nuclear Equation Of State (EOS) !

Studying Nuclear Equation of State (EOS) Using Heavy Ions

- Direct excess to supernova core or neutron star impossible

- High temperature & density can be achieved in intermediate energy heavy ion collision.

  (At relativistic energies : T ~ 150 - 200 MeV, $\rho \sim (10 – 20)\ \rho_o$)

- Coupled with the possibility of neutron rich beams, very asymmetric nuclear matter (N/Z > 1) can be probed.

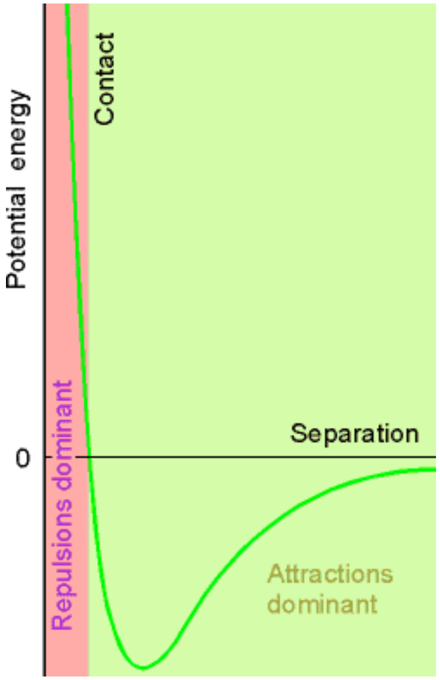
- The largely unconstrained density dependence of the asymmetry term in the EOS is sensitive to many observables in heavy ion collisions

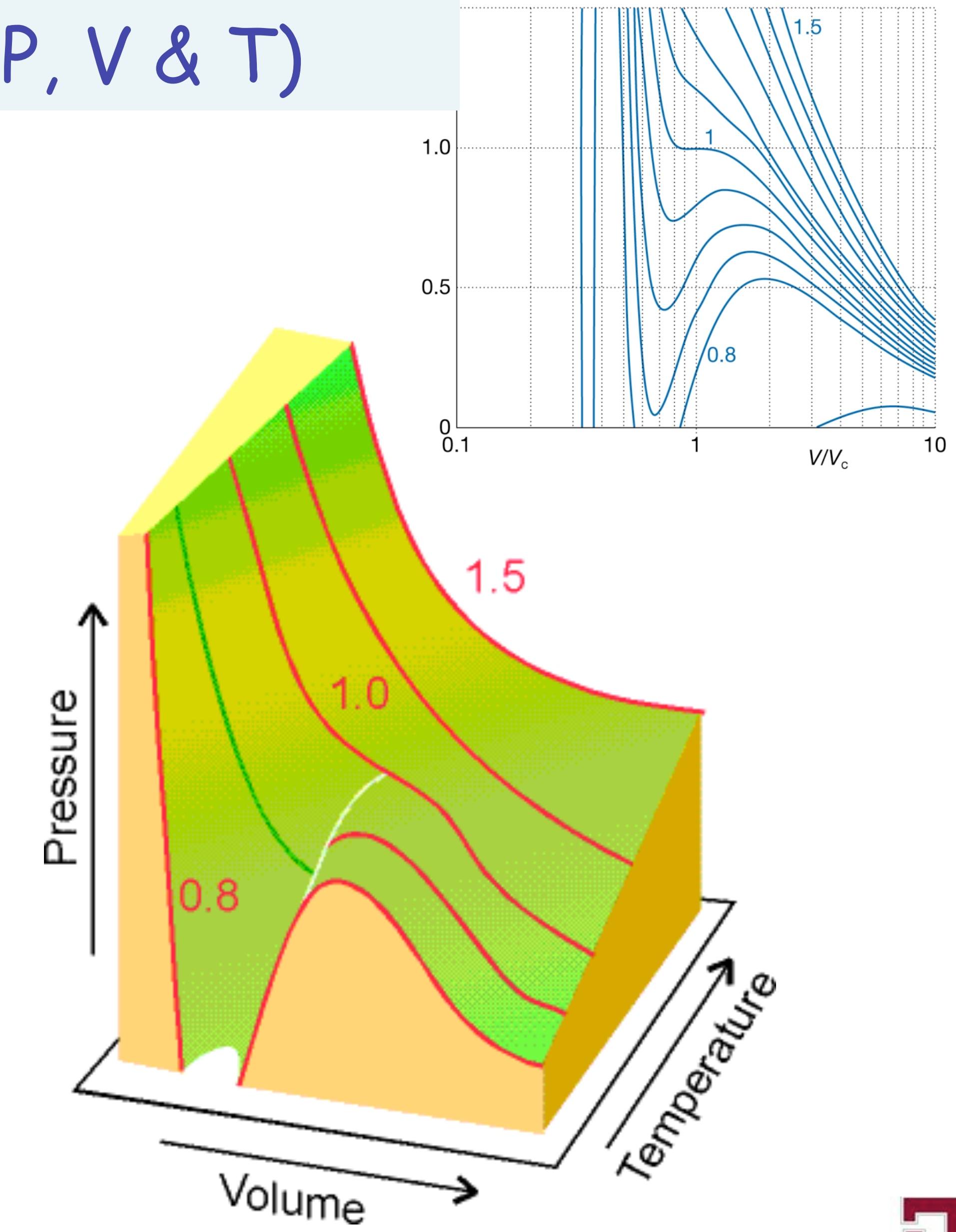
Equation of State (EOS) of a real gas (A relation between P, V & T)

$$p = \frac{nRT}{V - nb} - a\left(\frac{n}{V}\right)^2$$

Inter-molecular force of attraction

(Van der Waal force)





Constructing Equation of State (EOS) for a real gas

The key ingredient for constructing the equation of state of a system is the knowledge of interacting force (potential) between the internal constituents of the system

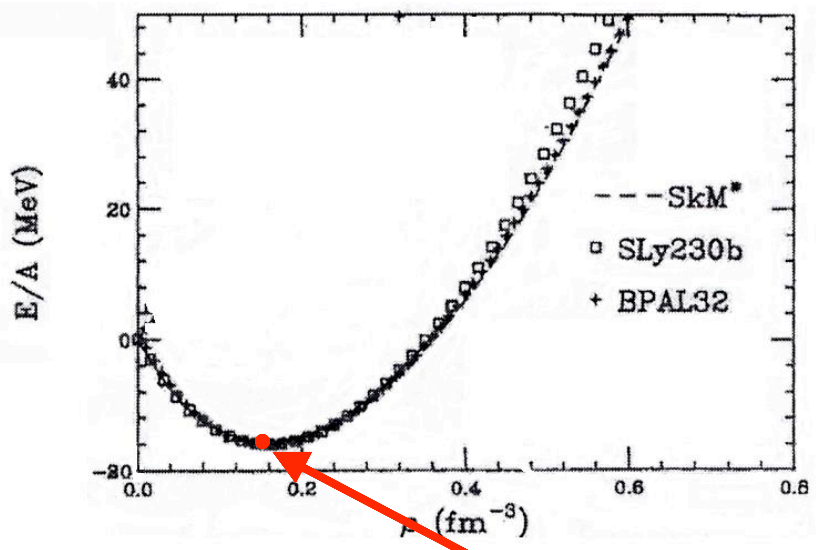
Equation of State (EOS) for nuclear matter

Theoretically, it is difficult to construct the nuclear EOS from an elementary nucleon-nucleon interaction for 2 reasons :

Existence of many body effects beyond two-body ones

In-medium effects on the elementary nn interaction

Equation of state for symmetric (N = Z) nuclear matter



Symmetric (N = Z)matter EOS

Saturation point : a single (equilibrium) point in the EOS of nuclear matter at T = 0

ρ_o ~ 0.17 fm^{-3} ; E/A ~ -16 MeV ;

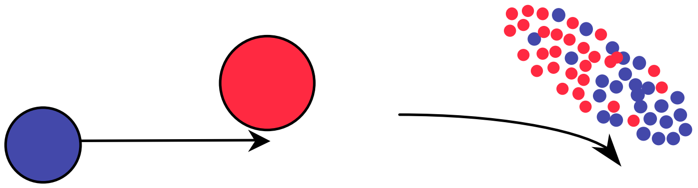
K ~ 220 MeV (compressibility from giant monopole resonance studies)

Transverse Collective Flow

Low beam energy

negative scattering
dominated by the attractive
mean field

High beam energy



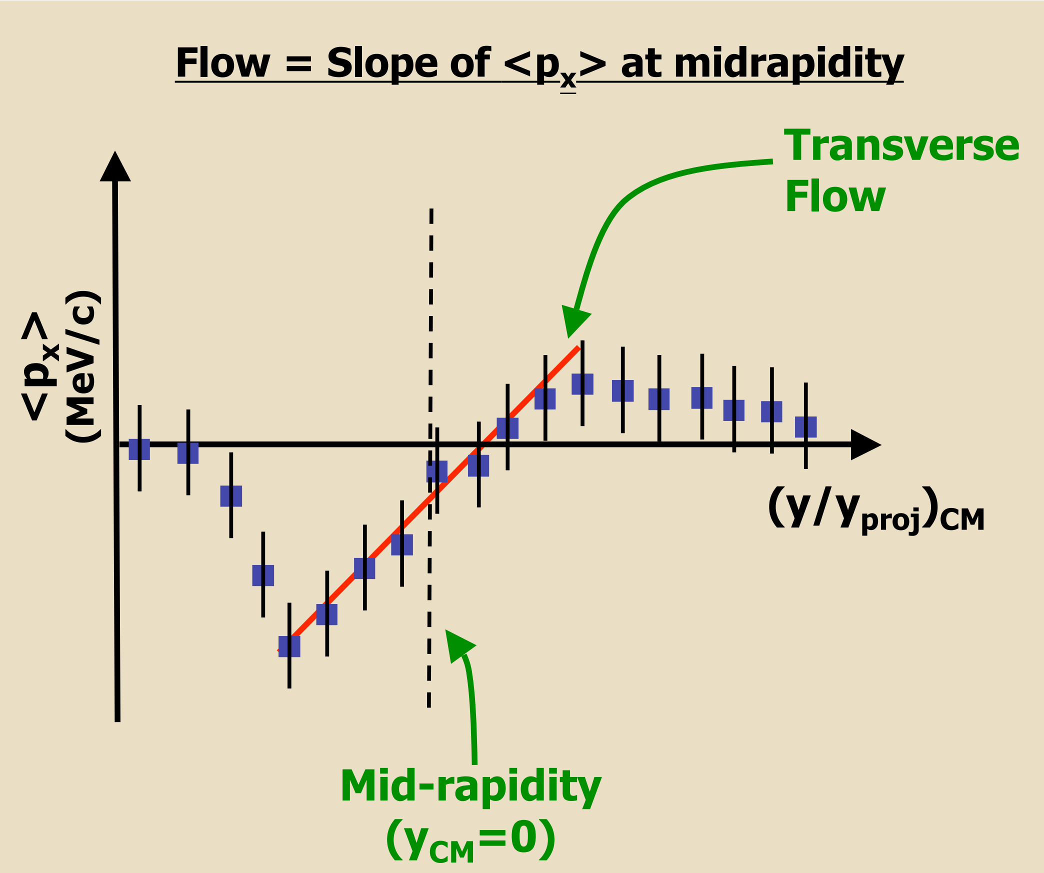
positive scattering
dominated by repulsive
nucleon-nucleon collisions

Balance energy :

Beam energy where flow is observed to be zero

Flow

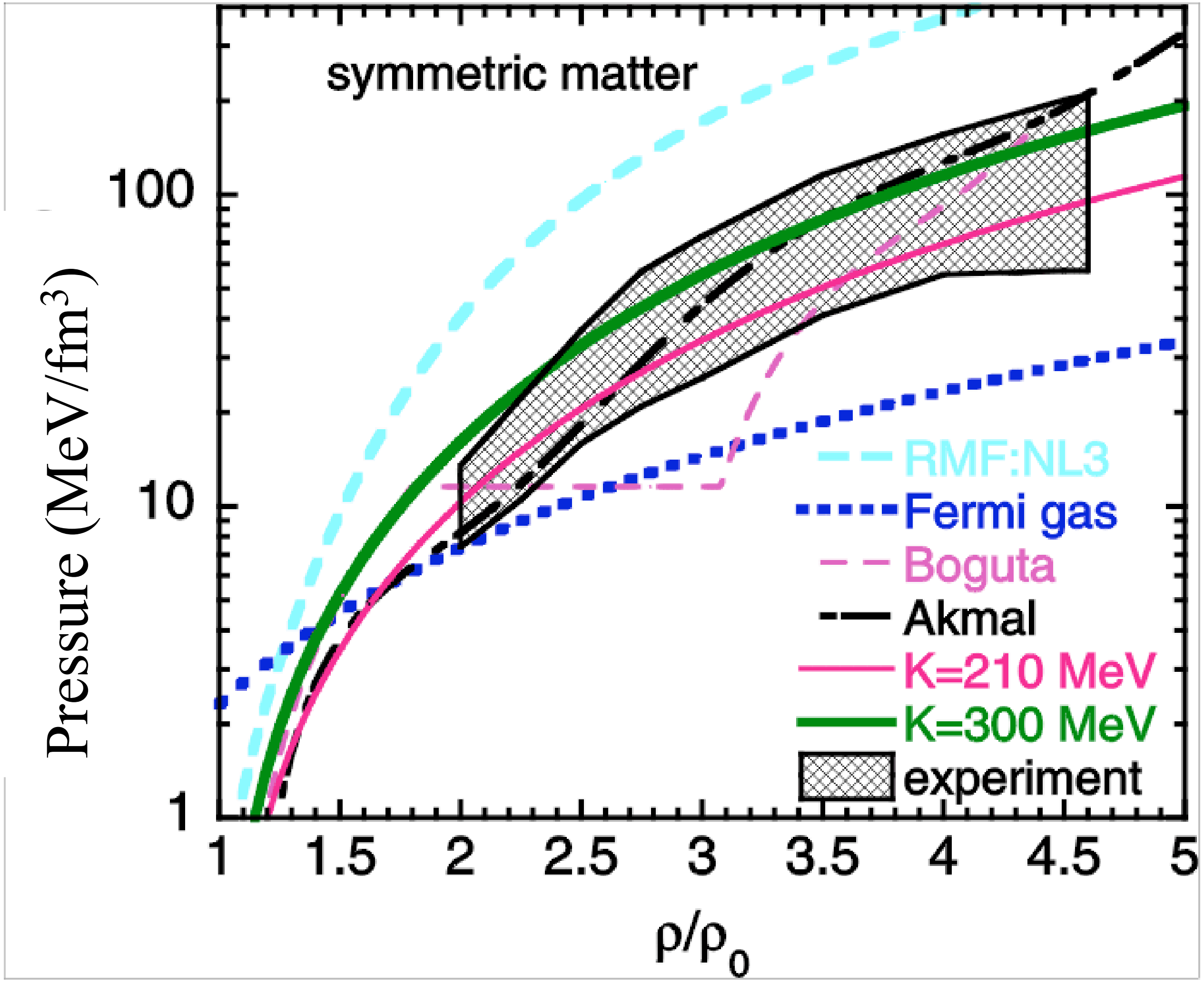
- Directed transverse flow
  - Determine reaction plane
  - Project on reaction plane
  - Calculate $\langle p_x \rangle$ as a function of y_{cm}
  - Flow is slope of $\langle p_x \rangle$ vs y_{cm} at $y_{cm} = 0$



Constraining EOS from the flow measurements (Probing the high density dependence)

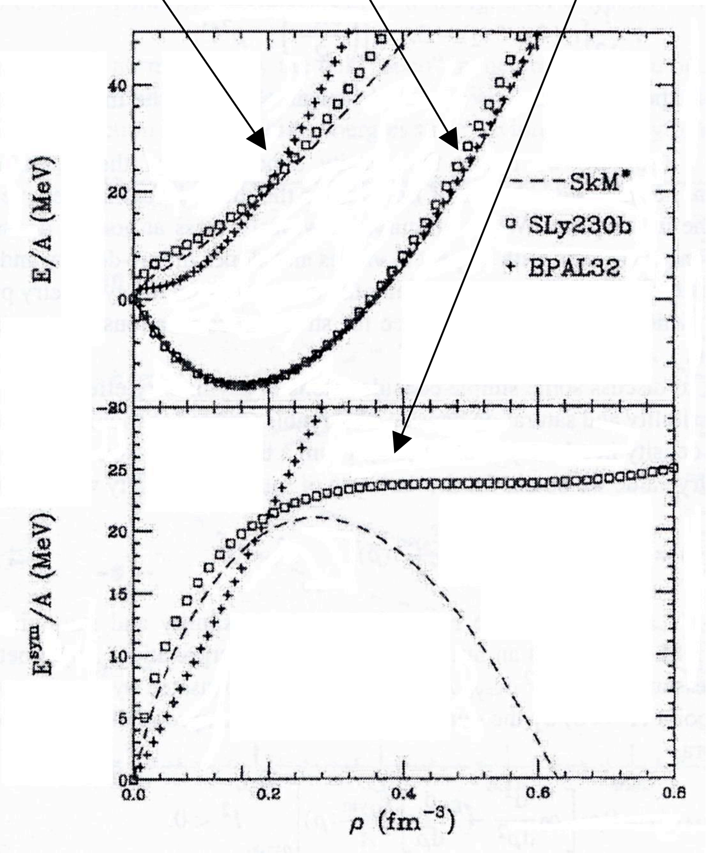
Au+Au flow (E/A~1-8 GeV)

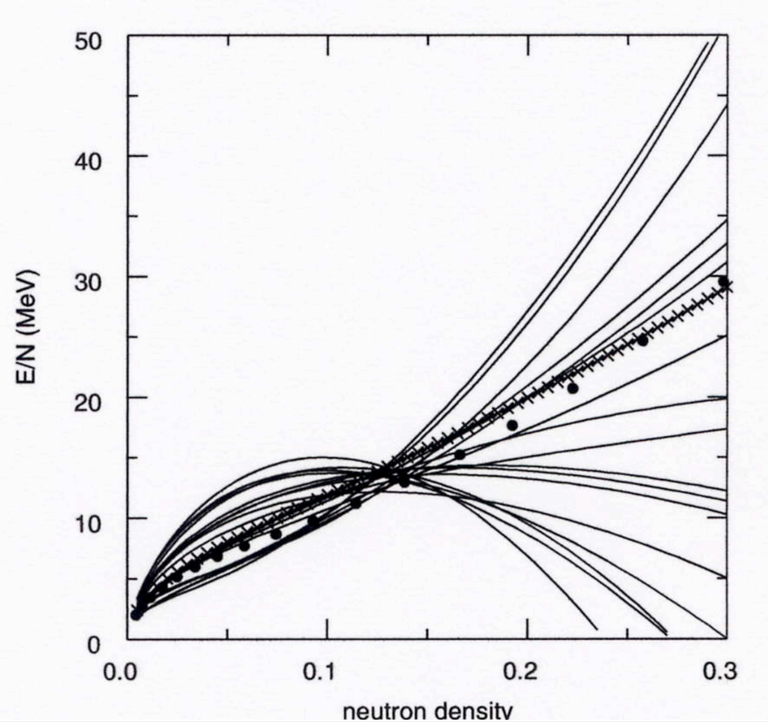
Danielewicz, Lacy, Lynch, Science 298,1592 (2002)



Equation of State of Asymmetric (N/Z > 1) Nuclear Matter

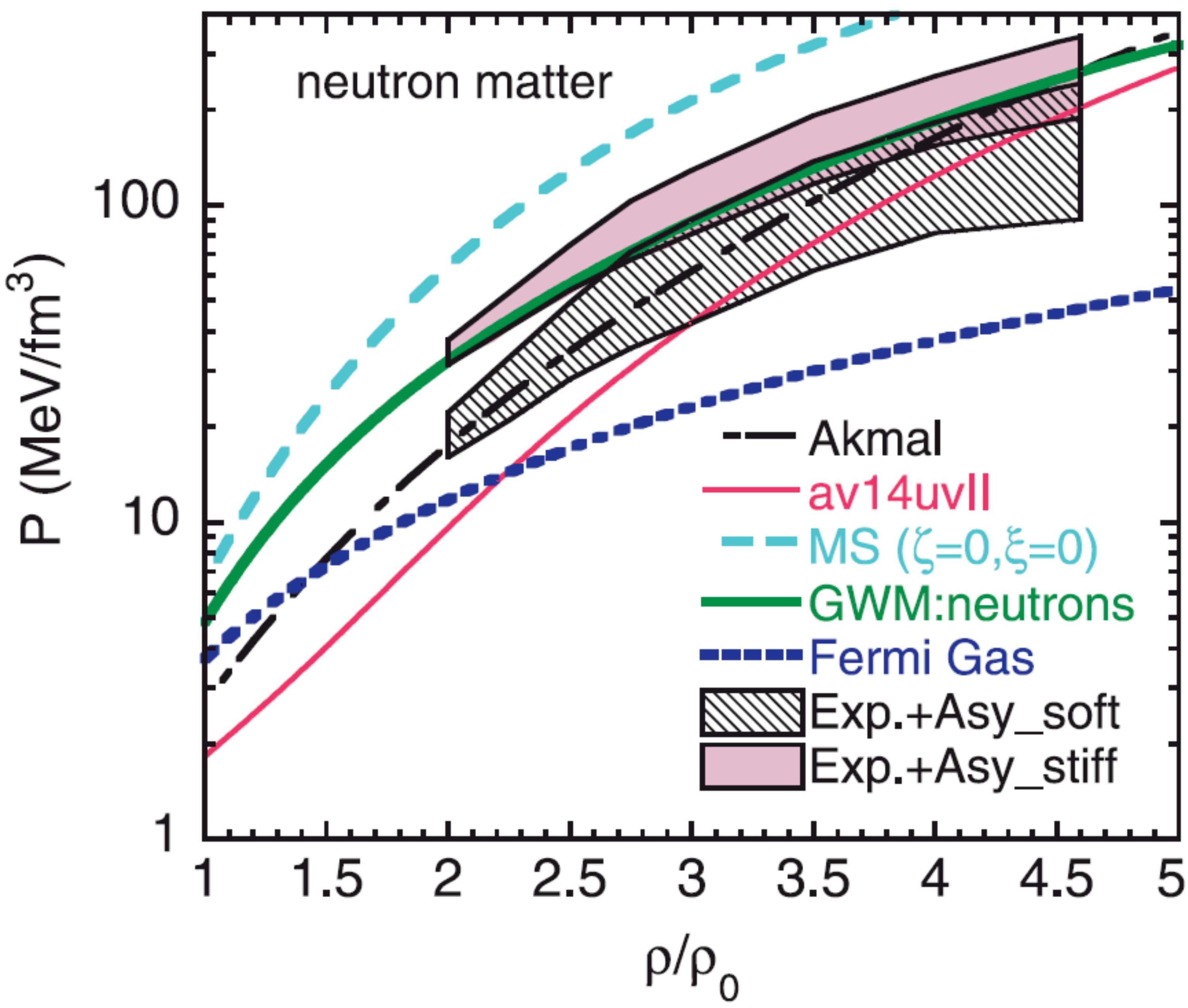
$$E(\rho,\delta) \approx E(\rho,\delta=0)+E_{\mathrm{sym}}(\rho)\delta^2, \quad \delta=\frac{\rho_n-\rho_p}{\rho_n+\rho_p}$$





Largely unconstrained below and above saturation density

B.A. Brown, Phys. Rev. Lett. 85 (2000) 5296


neutron matter
P (MeV/fm^3)
100
10
1
1
1.5
2
2.5
3
3.5
4
4.5
5
ρ/ρ_0
Akmal
av14uvII
MS (ζ=0,ξ=0)
GWM:neutrons
Fermi Gas
Exp.+Asy_soft
Exp.+Asy_stiff

Observables sensitive to the asymmetry term in the EOS ?

Moderate density ($\rho < 1.5\ \rho_o$) :

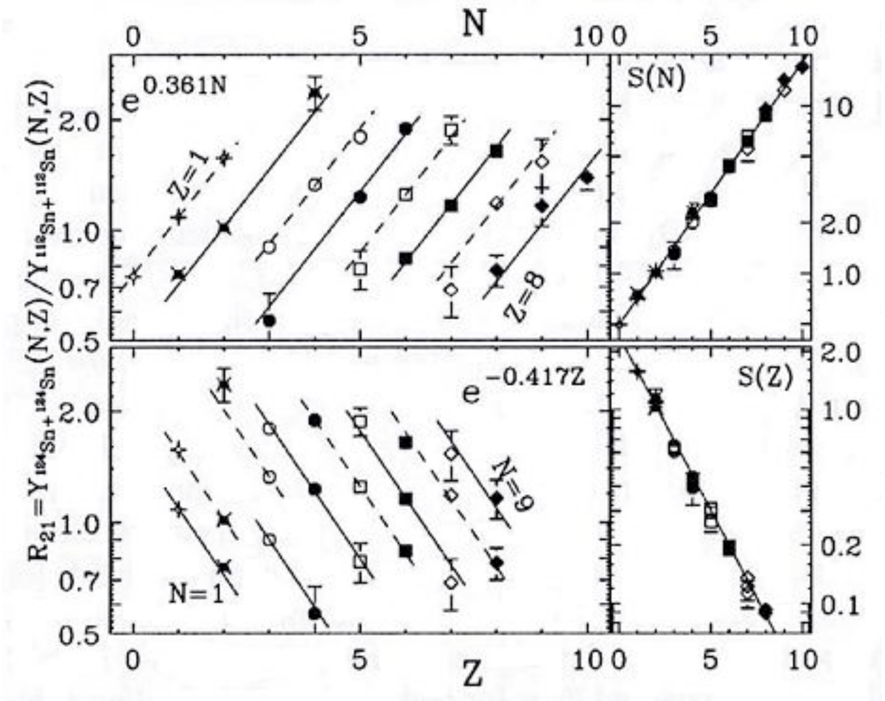
Fragment isotope distribution, isotopic & isobaric yield ratios
Isospin distillation/fractionation, relative n & p densities
Isospin diffusion
Nuclear stopping & N/Z equilibration
Pre-equilibrium emission
Particle - particle correlation
Light cluster production

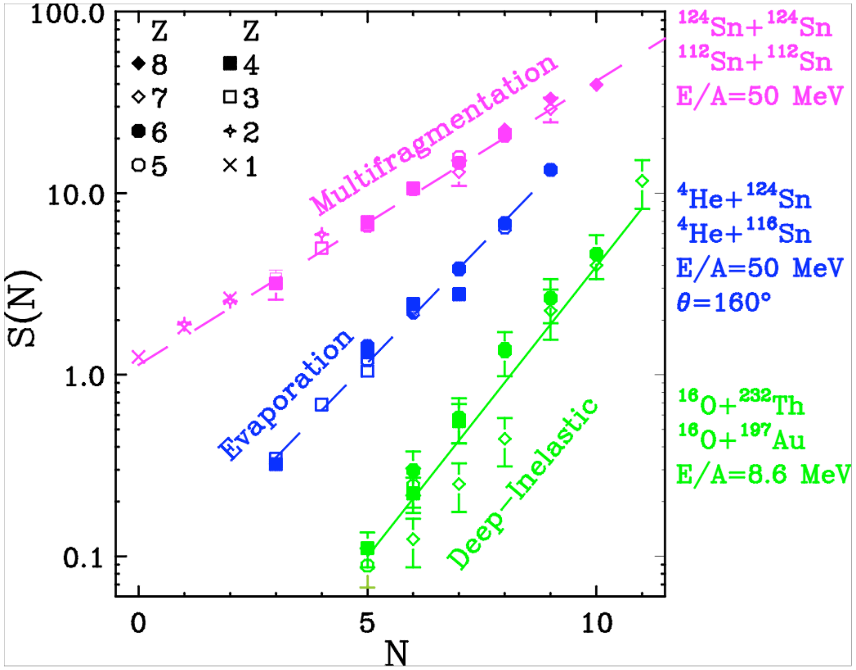
High density ($\rho > 1.5\ \rho_o$) :

Collective flow
Subthreshold particle production

Isoscaling

$$R_{21}(N,Z) = Y_2(N,Z)/Y_1(N,Z) = C\exp(N\alpha + Z\beta), \qquad \alpha = \frac{4C_{sym}}{T}\left(\frac{Z_1^2}{A_1^2} - \frac{Z_2^2}{A_2^2}\right)$$



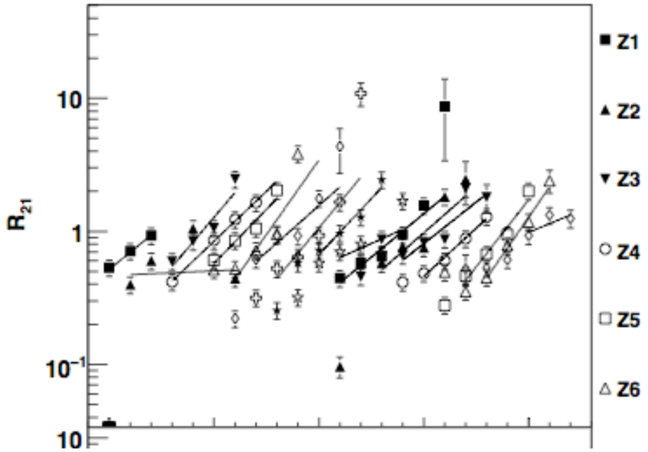


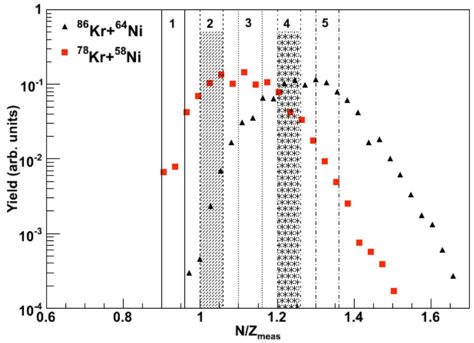
M.B. Tsang et al, Phys. Rev. Lett 68 (2001) 5023

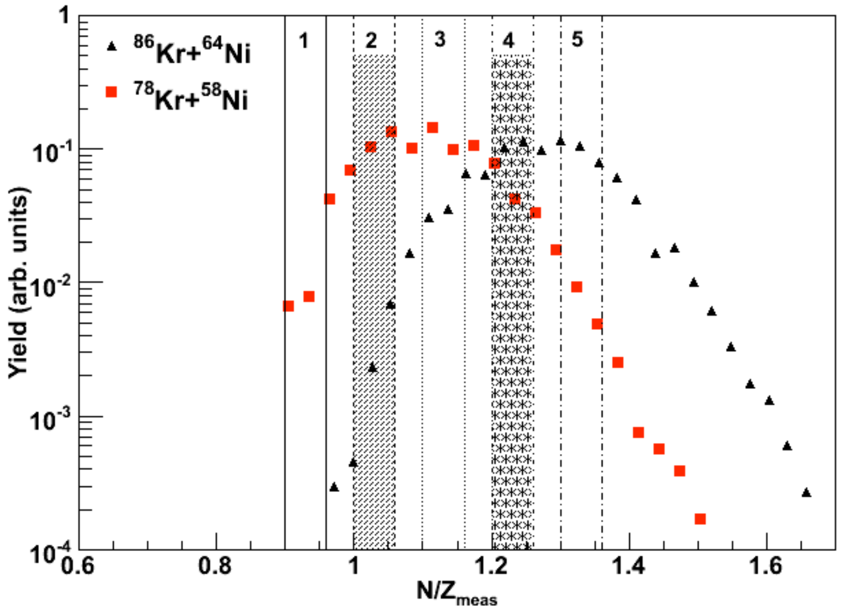
M.B. Tsang et al, Phys. Rev. C 64 (2001) 041603(R)

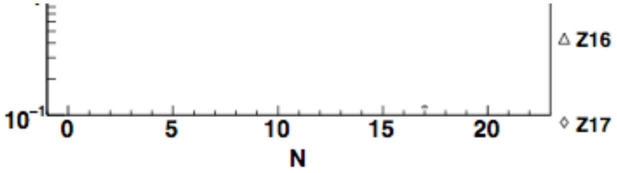
M.B. Tsang et al, Phys. Rev. C 64 (2002) 054615

Isoscaling





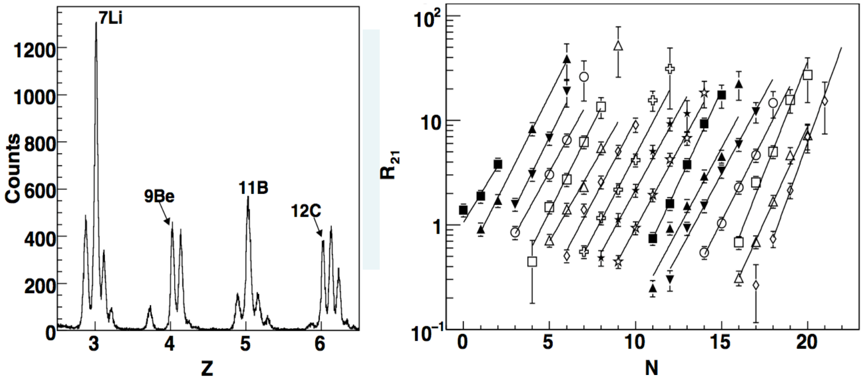




- Relates the relative yields of isotopes from two sources to the symmetry energy coefficient[1]
- System to system
  - ^{86}Kr+^{64}Ni, ^{78}Kr+^{58}Ni
- N/Z_{bound} defined
- N/Z_{meas} defined

$$R_{21}(N,Z) = Y_2(N,Z)/Y_1(N,Z) = Cexp(N\alpha + Z\beta)$$

S. Wuenschel, Thesis 2009



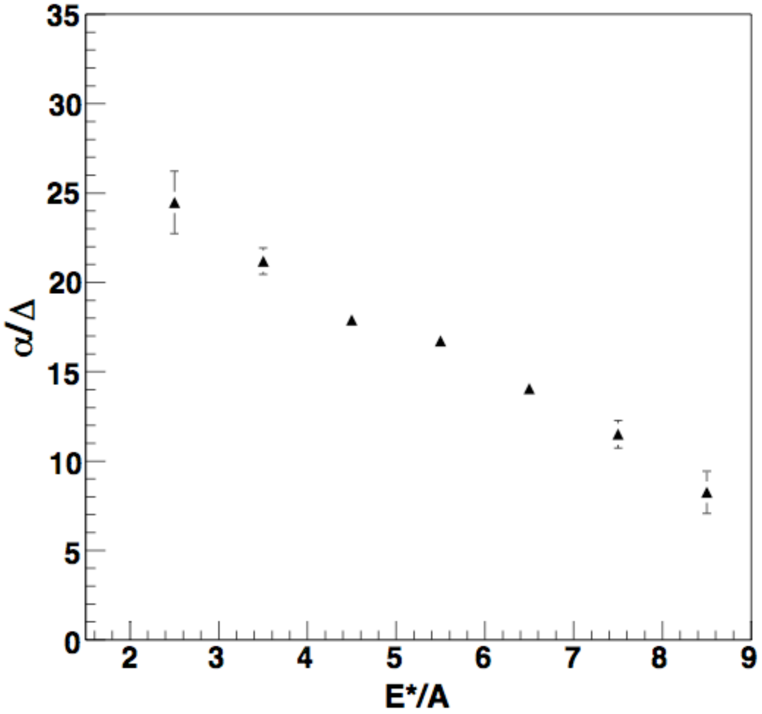
α/Δ

- α obtained from isoscaling

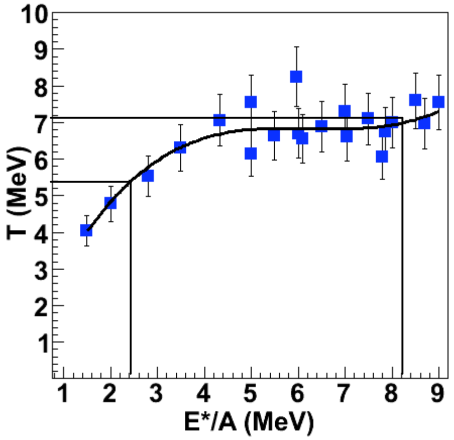
- Relates to C_{sym}

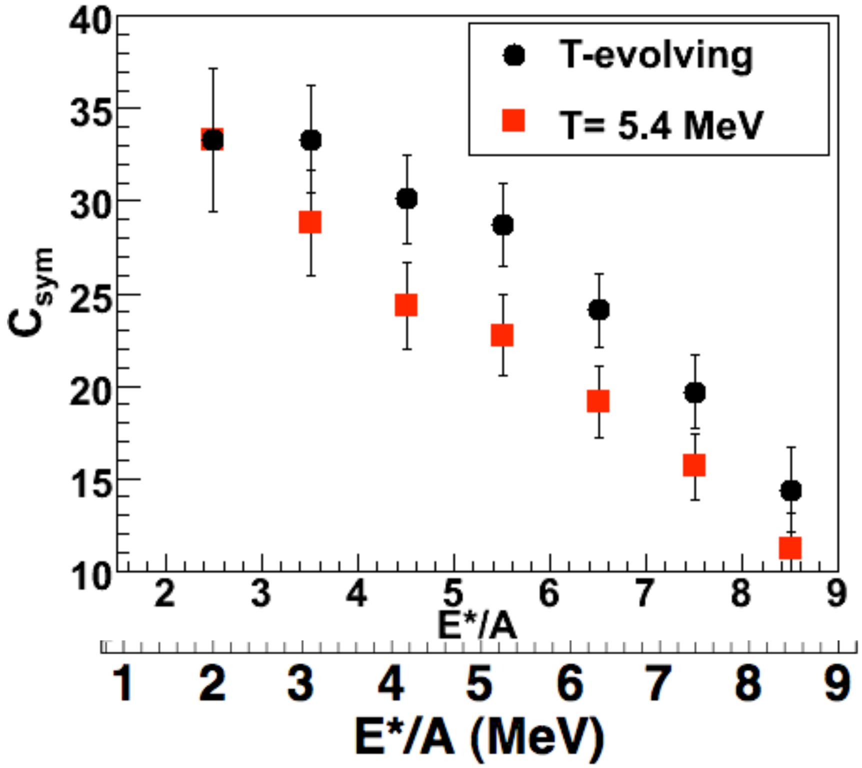
$$\frac{\alpha}{\Delta} = \frac{4C_{sym}}{T}$$

$$\Delta = \left(\frac{Z}{A}\right)_1^2 - \left(\frac{Z}{A}\right)_2^2$$



C_{sym}

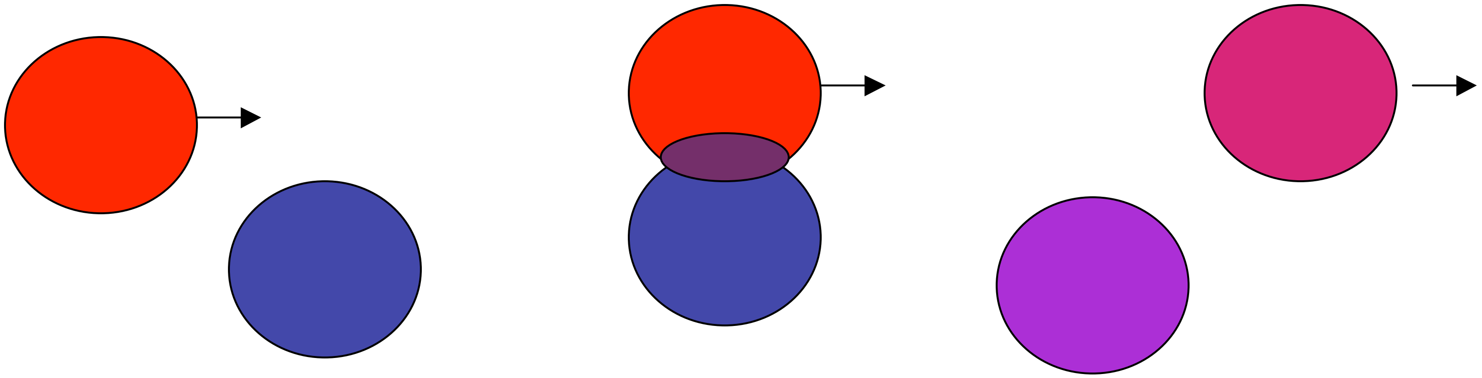


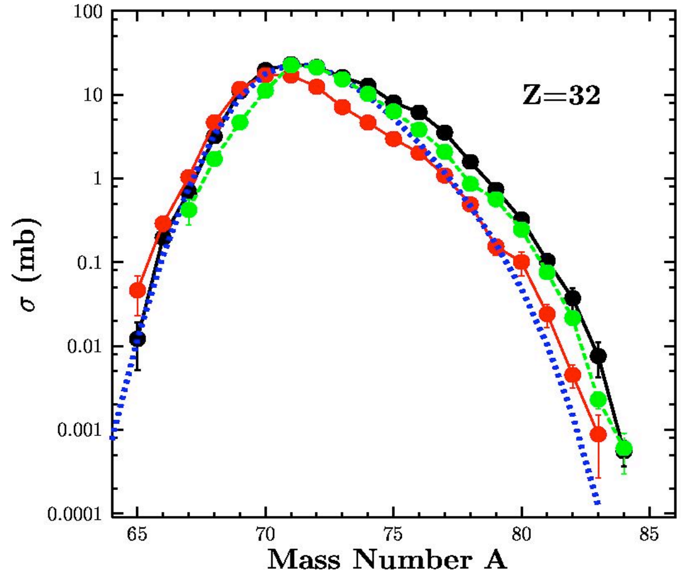


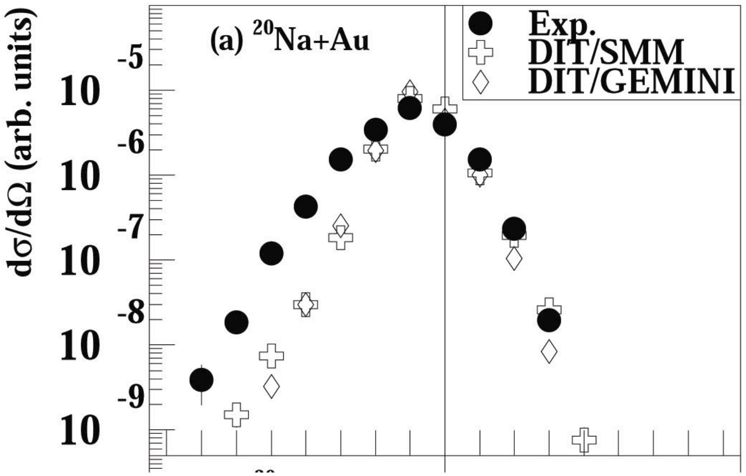
- Must have T to obtain Csym
  - Natowitz compilation

J.B. Natowitz et al. Phys. Rev. C 65, 034618 (2002).

Equilibration from Deep Inelastic Transfer mechanism - heavy residue isoscaling



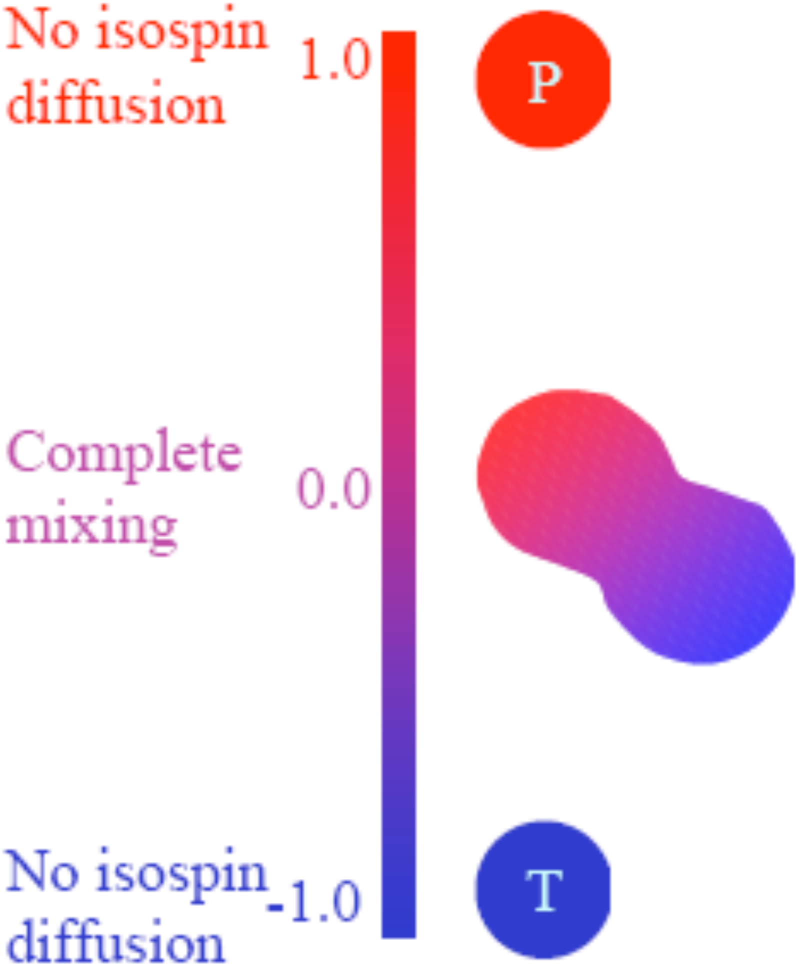




Isospin Diffusion

$$R_i = \frac{2\delta - \delta_{PP} - \delta_{TT}}{\delta_{PP} - \delta_{TT}}$$

- *symmetry energy will act as a driving force to transport the n or p between projectile to target*



No isospin diffusion

1.0

P

Complete mixing

0.0

No isospin diffusion

-1.0

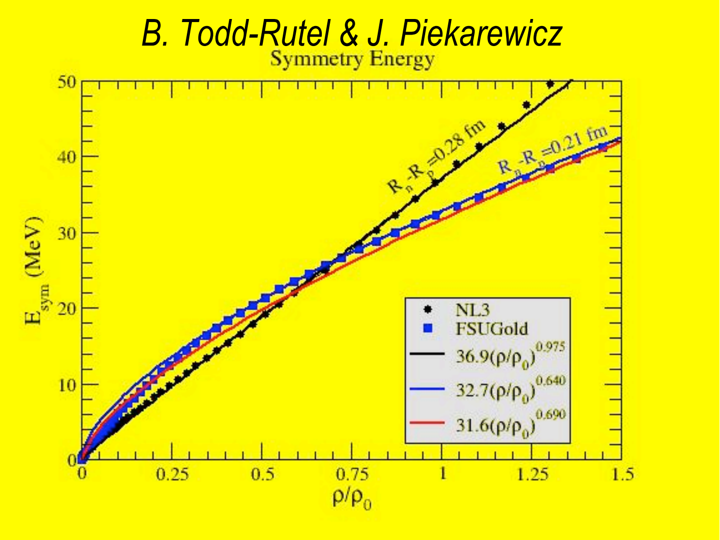
T

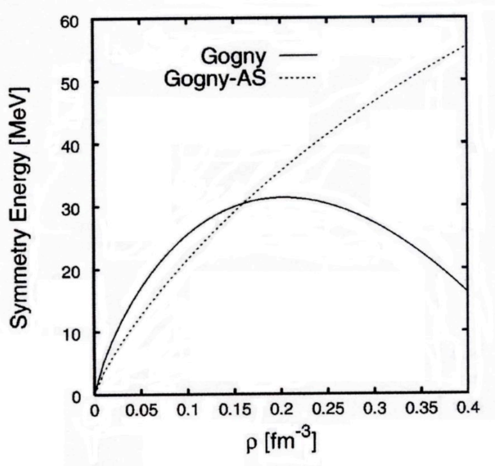
Difference between projectile and target spectator asymmetry, *δ=(N-Z)/(N+Z)*, measures the isospin diffusion which can be used to extract information about symmetry energy.

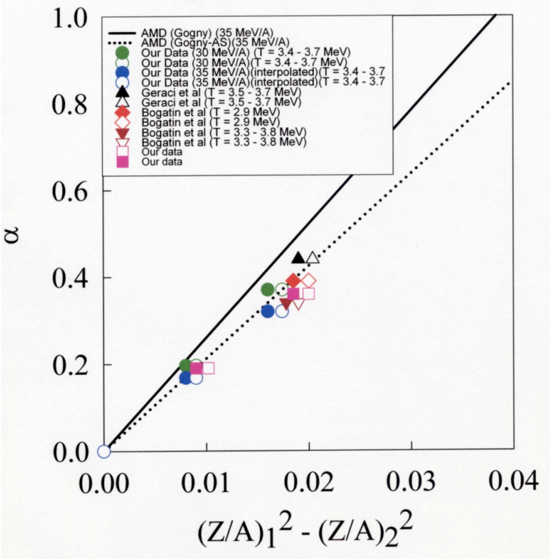
^{112,124}Sn, 50 MeV/nucleon

Tsang et al PLB 2004 and others

Current best estimate of $E_{sym}(\rho)$


B. Todd-Rutel & J. Piekarewicz



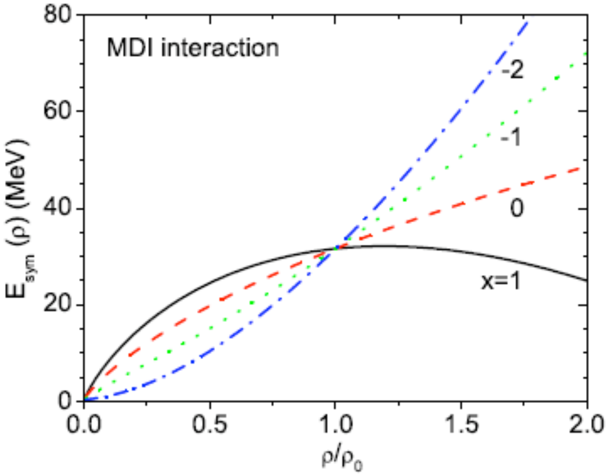


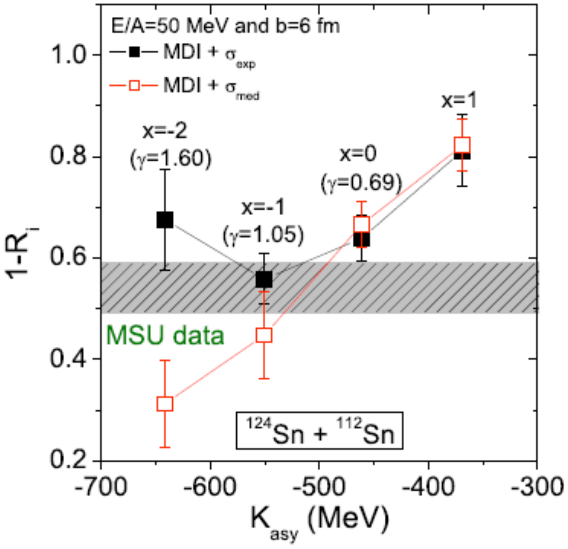
D. V. Shetty et al, PRC 70 (2004) 011601(R)

Experiments favors :

$$E_{sym}(\rho) = 32\,(\rho/\rho_o)^{\gamma}$$

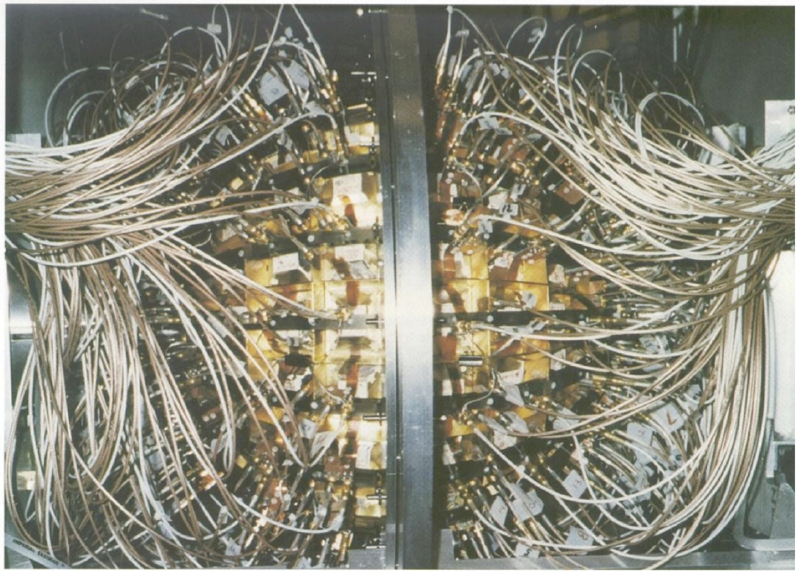
$$\gamma = 0.69 - 1.05$$





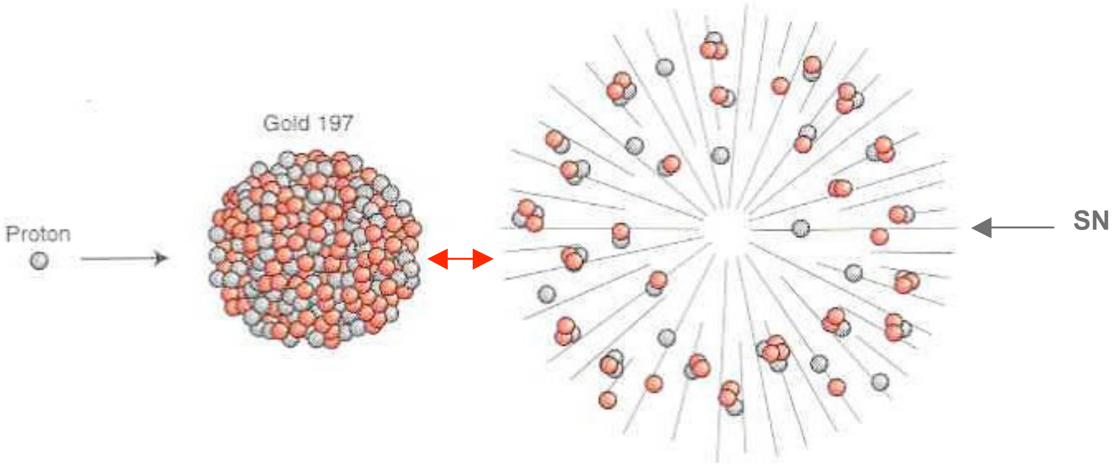
B.A. Li and L.W. Chen, PRC (2005)

Connections between nuclear reactions and astrophysics



?

Multifragmentation

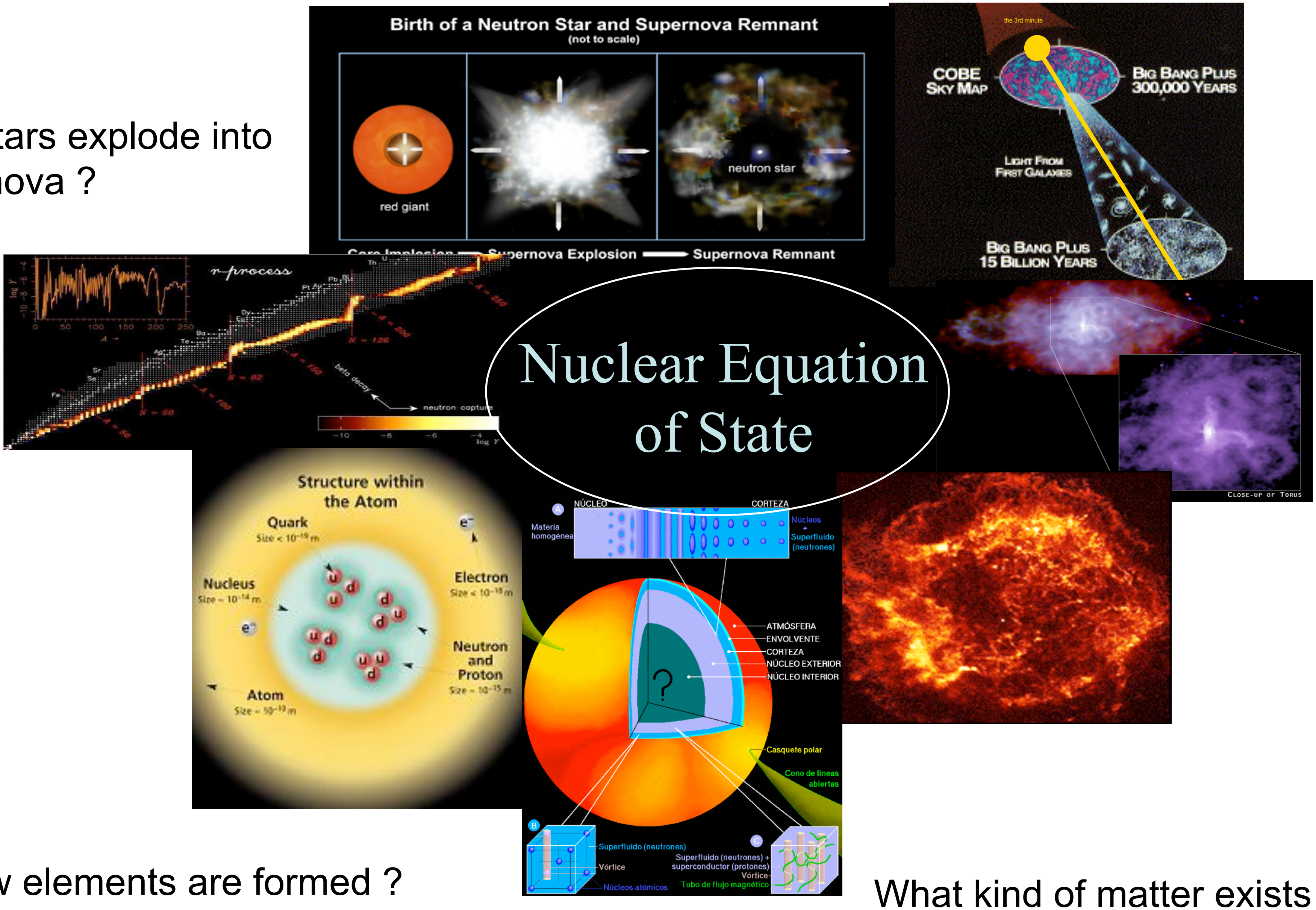


Supernova

?

Nuclear Equation of State

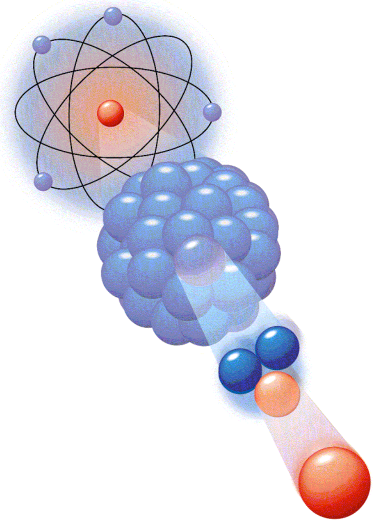
How stars explode into supernova ?

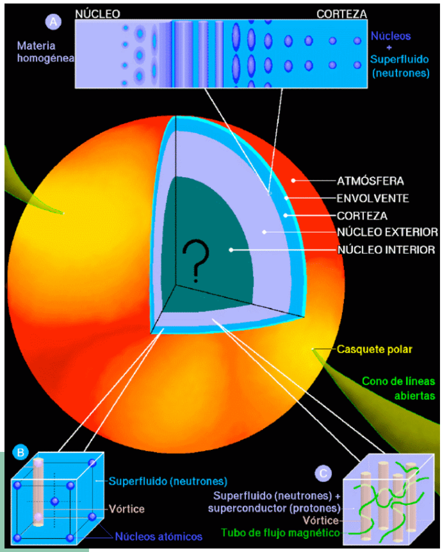


How elements are formed ?

What kind of matter exists inside a neutron star ?

Nuclear Equation of State
(from atomic nuclei to neutron stars)





Isospin Dependence of Strong Interactions

Nuclear Masses
Neutron Skin Thickness
Isovector Giant Dipole Resonances
Fission

Heavy Ion Flows
Multi-Fragmentation
Nuclei Far from Stability
Rare Isotope Beams

Many-Body Theory
Symmetry Energy
(Magnitude and Density Dependence)

Supernovae
Weak Interactions
Early Rise of L_{ν_e}
Bounce Dynamics
Binding Energy

Proto-Neutron Stars
ν Opacities
ν Emissivities
SN r-Process
Metastability

Neutron Stars
Observational
Properties

Binary Mergers
Decompression/Ejection
of Neutron-Star Matter
r-Process

QPO's
Mass
Radius

NS Cooling
Temperature
R_∞, z
Direct Urca
Superfluid Gaps

X-ray Bursters
R_∞, z

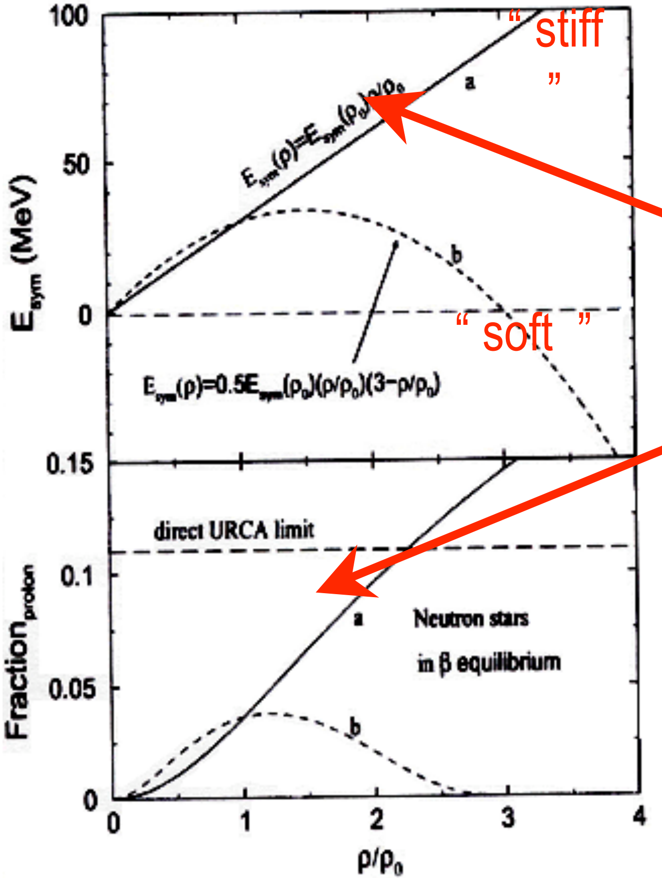
Gravity Waves
Mass/Radius
dR/dM

Pulsars
Masses
Spin Rates
Moments of Inertia
Magnetic Fields
Glitches - Crust

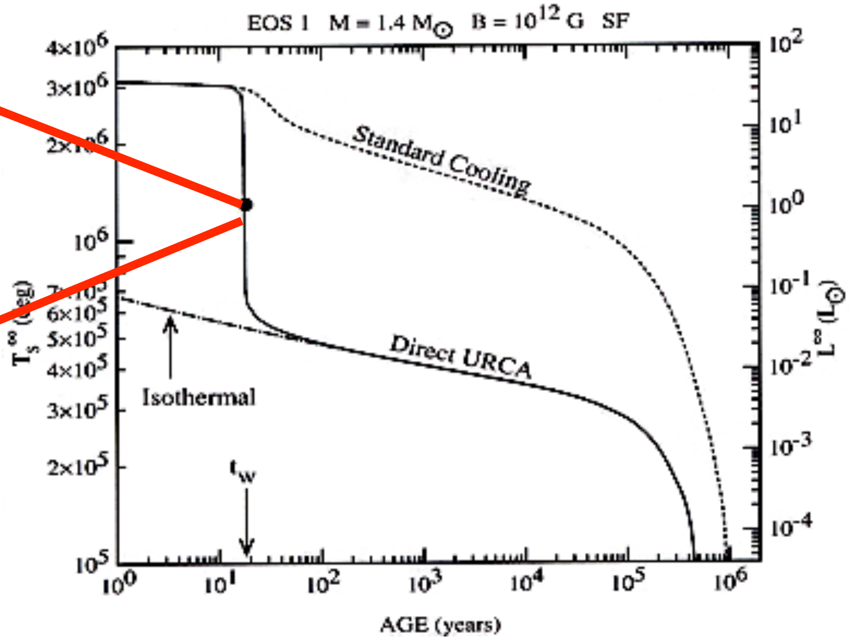
Maximum Mass, Radius
Composition:
Hyperons, Deconfined Quarks
Kaon/Pion Condensates

A. Steiner et al, Phys. Rept. 411 (2005) 325

Neutron Star cooling is sensitive to $E_{sym}(\rho)$



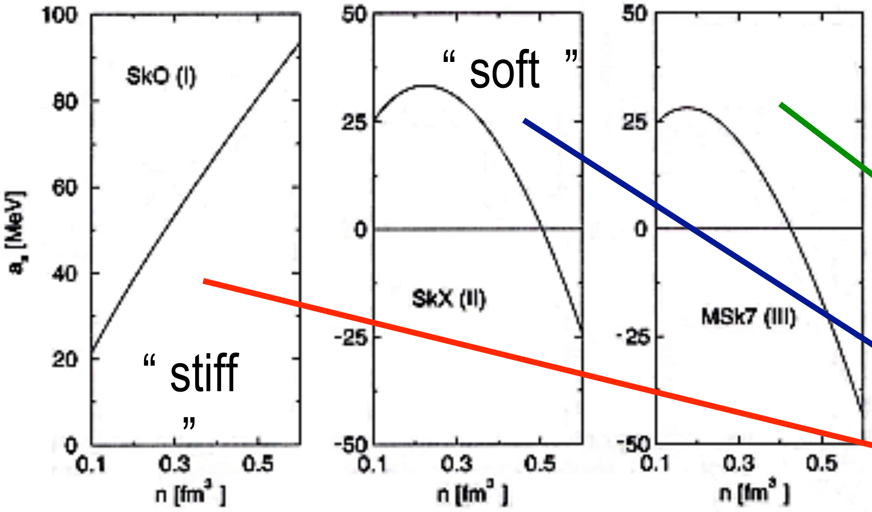
Lattimer et al, Ap. J. 425 (1994) 802



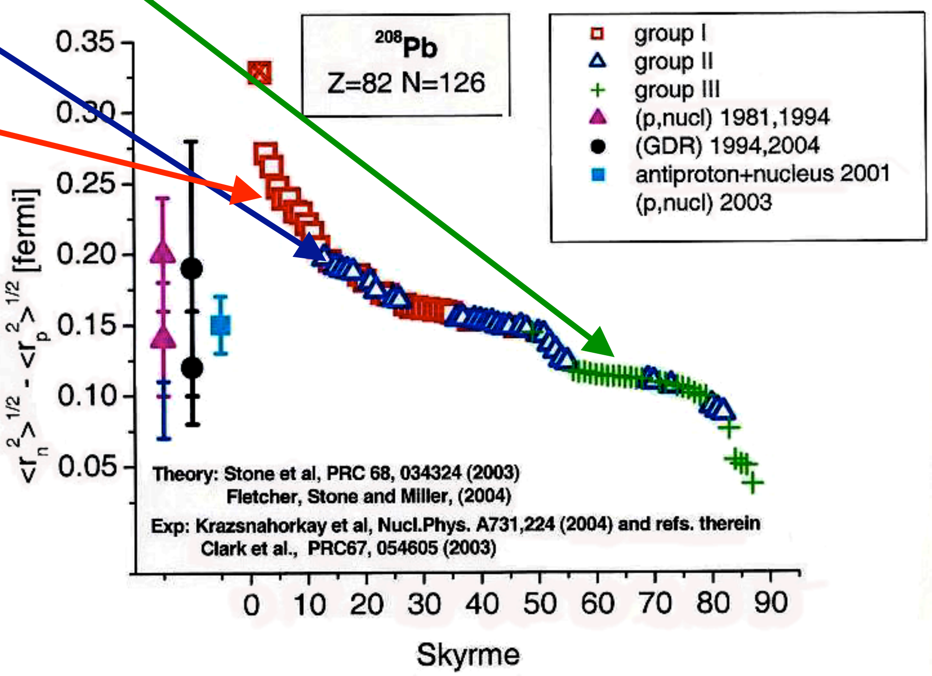
direct URCA process $p + e^- \rightarrow n + \nu$

Stronger is the density dependence of E_{sym}, greater is the proton fraction, & neutron star cools rapidly through the direct URCA process

Neutron skin thickness is sensitive to $E_{sym}(\rho)$



Stiffer the density dependence of E_{sym}, larger is the neutron skin thickness

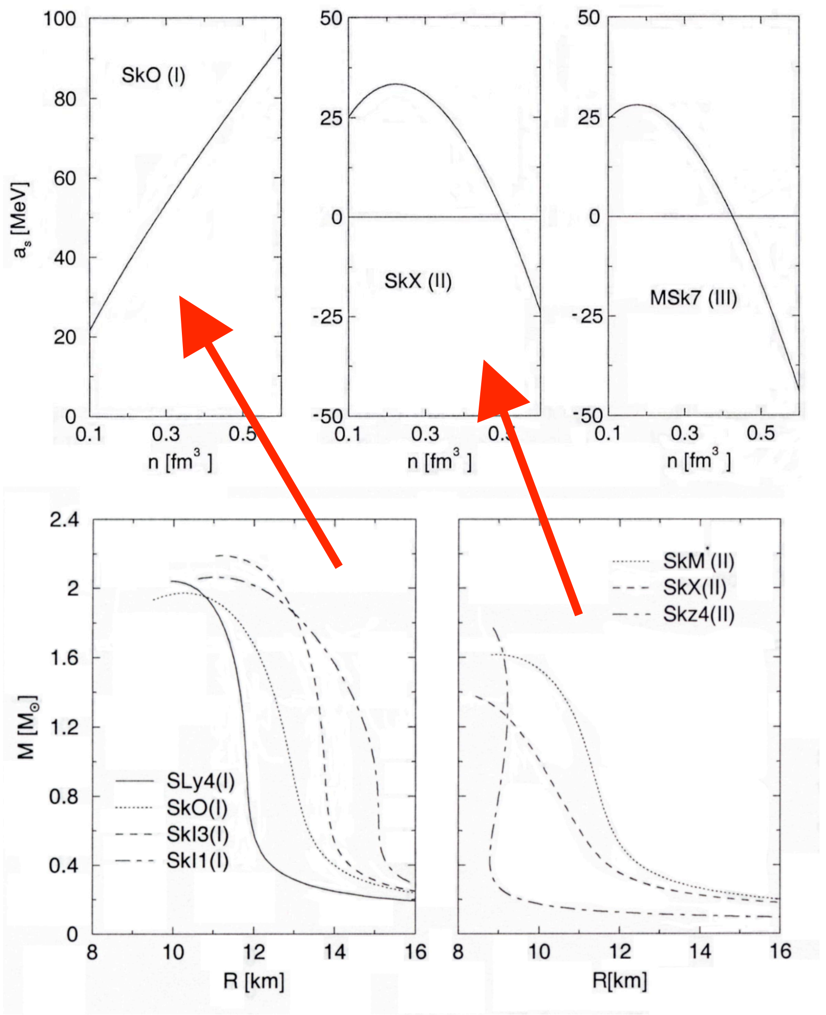


Theory: Stone et al, PRC 68, 034324 (2003)
Fletcher, Stone and Miller, (2004)

Exp: Krazsnahorkay et al, Nucl.Phys. A731,224 (2004) and refs. therein
Clark et al., PRC67, 054605 (2003)

The density dependence of the symmetry energy dictates the difference between proton and neutron matter radii in heavy nuclei away from the valley of stability

maximum neutron star masses and radii are sensitive to $E_{sym}(\rho)$



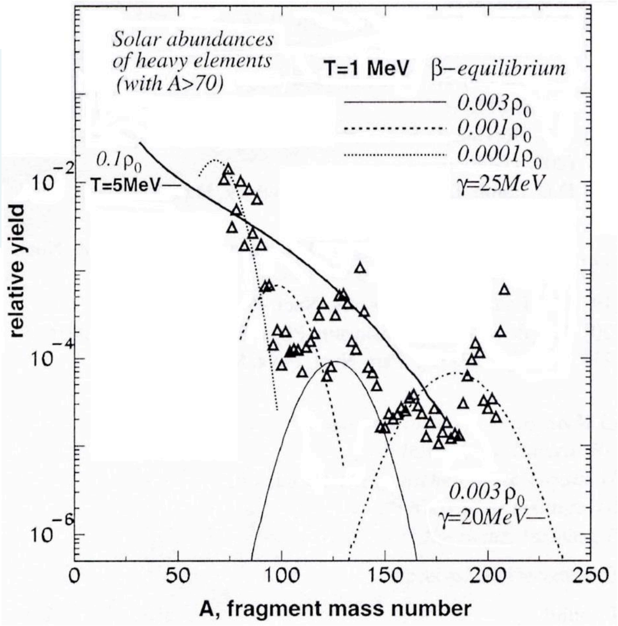
J. Stone et al, Phys. Rev. C 68 (2003) 034324

Stronger is the density dependence of E_{sym}, greater is the neutron star mass and radii

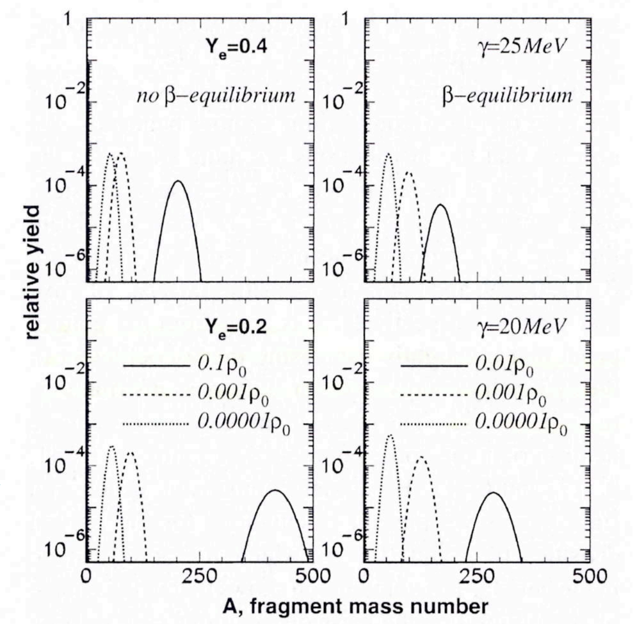
Determining the exact form of the $E_{sym}(\rho)$ is important in astrophysical studies, such as the structure of neutron star and the dynamics of supernova collapse

Formation of hot neutron rich nuclei in supernova explosion

During supernova II type explosion the thermodynamical conditions of stellar matter between the protoneutron star & the shock front correspond to nuclear liquid-gas coexistence region. Neutron rich hot nuclei can be produced in this region which can influence the dynamics of the explosion contribute to the synthesis of heavy elements



A slight decrease in the symmetry energy co-efficient can shift the mass distribution to higher masses



A. Botvina et al, Phys. Lett. B 584 (2004) 233

Summary

- Liquid gas phase transition in nuclei
  - Many observables --> transition about 4MeV
  - $T_{obs} < T_{crit}$ - Coulomb
- Equation of State
  - Accessible through HI collisions
- Symmetry energy
  - Current best estimates for density dependence seem to rule out the most soft and most stiff.
  - Need experiments to probe above saturation density
- Important for nuclear astrophysics