# *Physics of Hadronic Matter Probed by High Energy Nuclear Collisions*

Akira Ohnishi Hokkaido U.

Hierarchies in Nuclear Physics
  and Physics of Hadronic Matter
Theoretical Preparation:
  Microscopic Transport Model and Statistical Models
Fragment Formation and Liquid-Gas Phase Transition
Roles of Strangeness in Dense Matter
High Energy Heavy-Ion Collision
  and Hot/Dense Hadronic Matter
Summary

## *Hierarchies in Nuclear Physics*

**Quarks and Gluons (QCD)**
**Nucleons and Hadrons (NN Interaction, Effective Lagrangian, ...)**
**Finite Nuclei (Effective NN Interaction, Model Space, ...)**
**Nuclear/Hadronic Matter**

***Nuclear Physics = Physics of Four (or Three) Hierarchies***

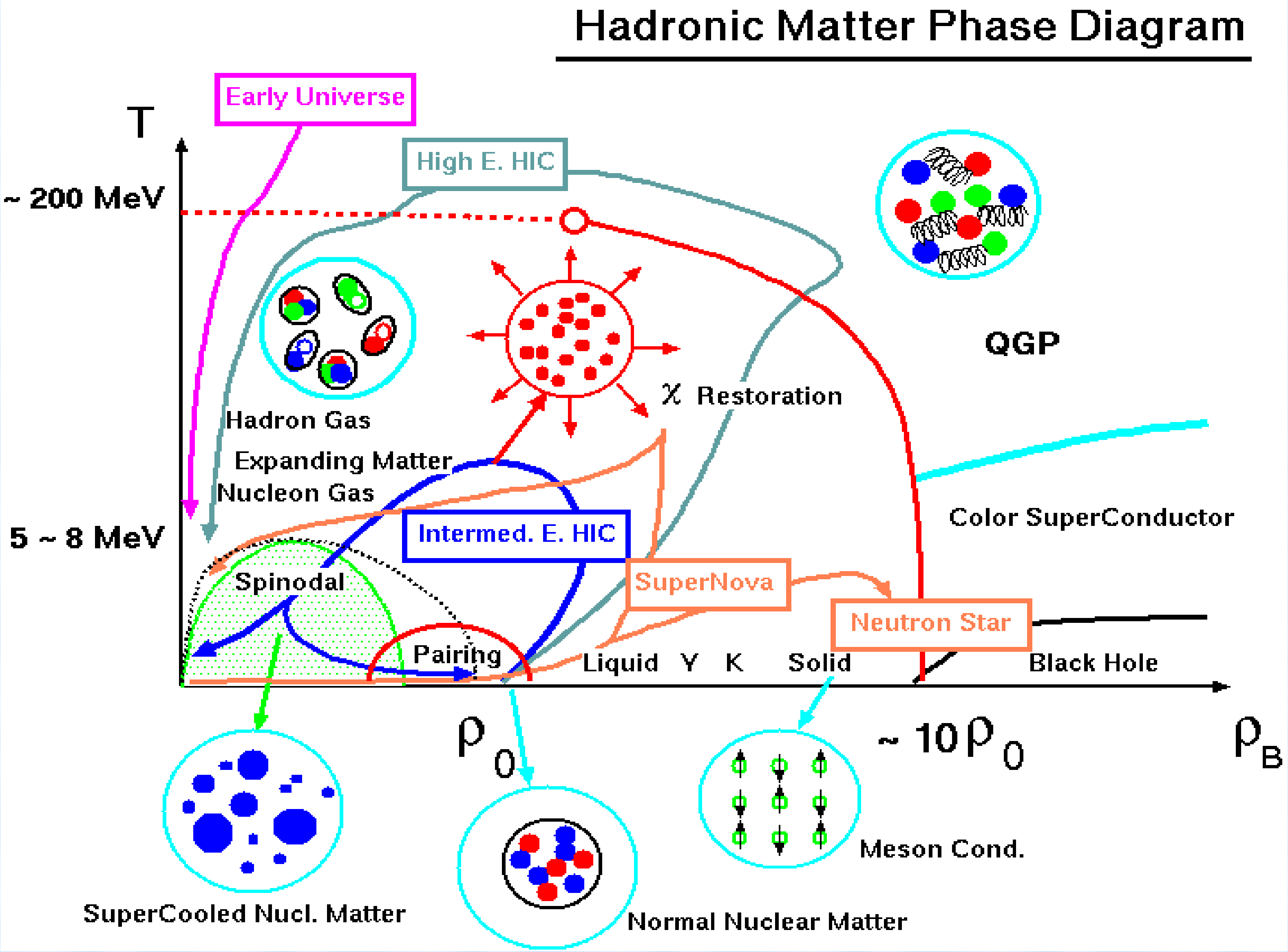
## *Physics of Nuclear/Hadronic Matter*

*** Two-Fold Structure:**
**Quark & Gluon ↔ Nucleon/Hadron ↔ Nucleus**

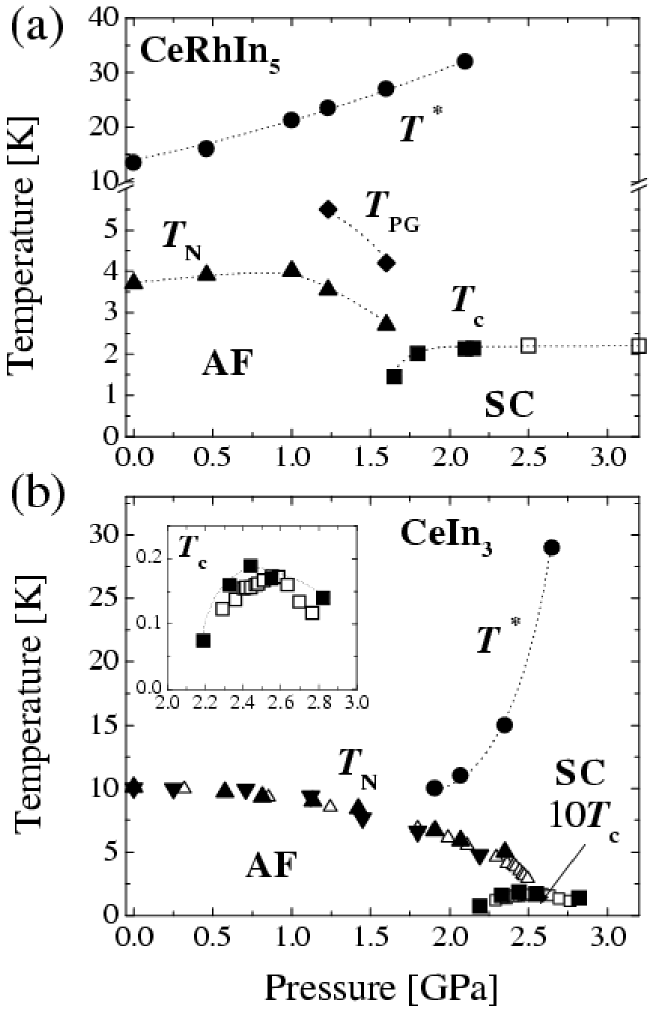
*** Relation to Astrophysical Objects/Phenomena:**
**Early Universe, Compact Objects**

*** Similarities to Superconductor in Solid State**

# *Hadronic Matter Phase Diagram*



# Phase Diagram of Superconductor CeRhIn5 and CeIn3

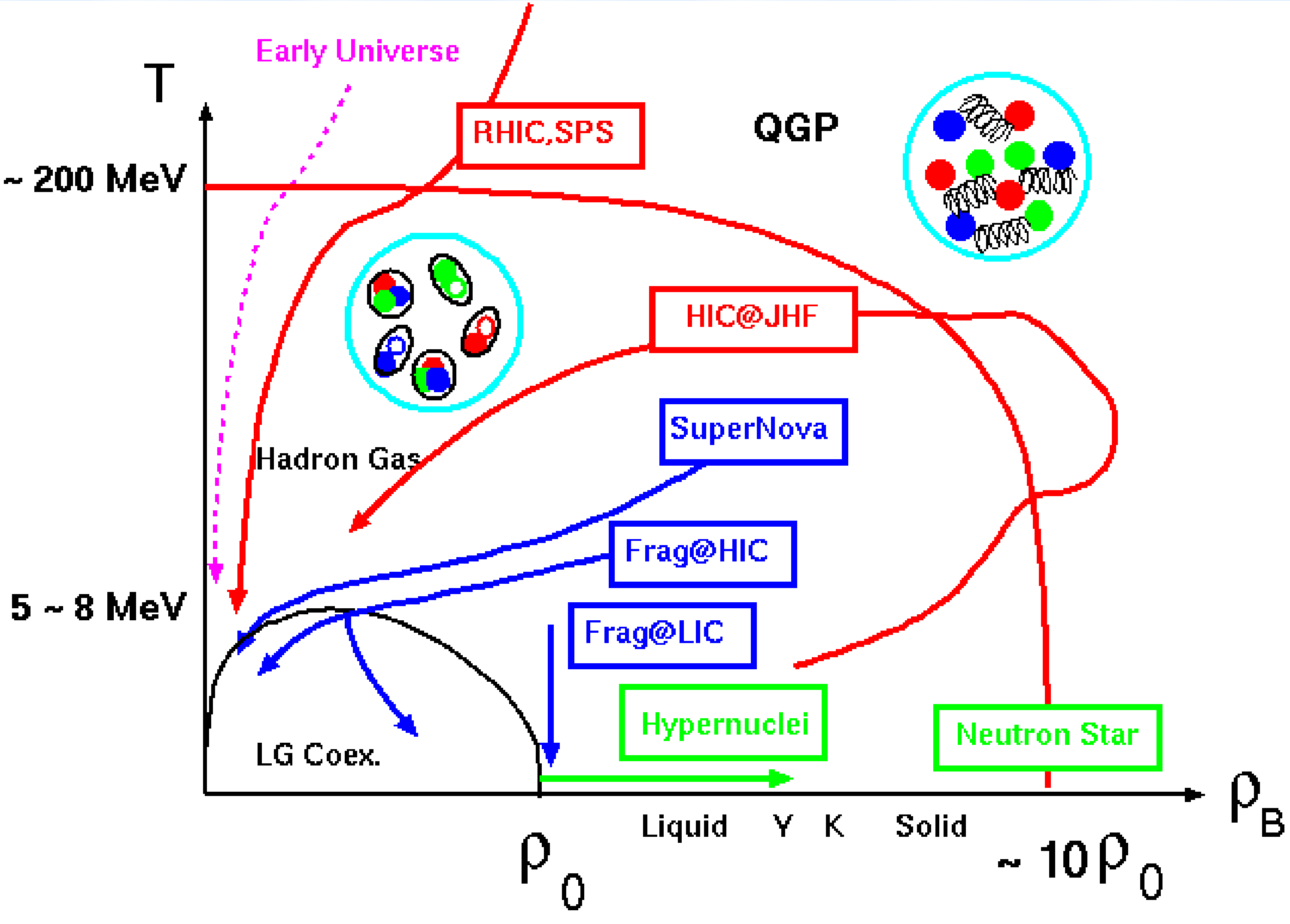


**(Kawasaki et al., cond -mat/0110620.)**

# *Approaches for Hadronic Matter Study*

**Constructive Way: Quarks and Gluons → Hadrons → Matter**

**My Individual Problems: Phenomenology of Each Region**



# Theoretical Preparation

*Mean Field Evolution*

*TDHF – Vlasov – BUU,  AMD*

*Collision Term*

*Resonance, String and Jet*

*Statistical Model*

*Statistical Model of Hadrons and Fragments*

# *TDHF and Wigner Transformation*

**Mean Field Theory (e.g., TDHF)**

$$i\hbar\frac{\partial\phi}{\partial t}=h\phi,\quad \rho(r,r')=\sum_i^{Occ}\phi_i(r)\phi_i^*(r'),\quad i\hbar\frac{\partial\rho}{\partial t}=[h,\rho]$$

**Wigner Transformation and Wigner-Kirkwood Expansion**

**(Ref.: Ring-Schuck)**

$$O_W(r,p)\equiv\int d^3s\exp(-ip\cdot s)<r+s/2|O|r-s/2>$$

$$(AB)_W=A_W\exp(i\hbar\Lambda)B_W$$

$$\Lambda\equiv\nabla'_r\cdot\nabla_p-\nabla'_p\cdot\nabla_r\qquad(\nabla'\ \textit{acts on the left})$$

$$[A,B]_W=2iA_W\sin(\hbar\Lambda/2)B_W=i\hbar\{A_W,B_W\}_{P.B.}+O(\hbar^3)$$

# *Vlasov Equation and Test Particle Method*

**Wigner Transform of TDHF**

$$\left. \left( i\hbar \frac{\partial \rho}{\partial t} = [h, \rho] \right) \right|_W \rightarrow \frac{\partial f}{\partial t} = \{ h_W, f \}_{P.B.} + O\left(\hbar^2\right)$$

**Winger Function: *f(r,p)* ... Phase Space Density**

**Classical Hamiltonian:** $h_W(r, p) = \frac{p^2}{2m} + U(r, p)$

**Vlasov Equation**

$$\frac{\partial f}{\partial t} + v \cdot \nabla_r f - \nabla U \cdot \nabla_p f = 0$$

**Test Particle Method (C. Y. Wong, 1982)**

$$f(r, p) = \sum_i^{AN_0} \delta(r - r_i)\, \delta(p - p_i) \rightarrow \frac{dr_i}{dt} = \nabla_p h, \quad \frac{dp_i}{dt} = -\nabla_r h,$$

**Mean Field Evolution can be simulated by Classical Test Particles**

# BUU (Boltzmann-Uehling-Uhlenbeck) Equation

(Bertsch and Das Gupta, Phys. Rept.  160( 88), 190)

$$\frac{\partial f}{\partial t} + v \cdot \nabla_r f - \nabla U \cdot \nabla_p f = I_{coll}[f]$$

$$\begin{aligned} I_{coll}[f] &= -\frac{1}{2} \int \frac{d^3 p_2 \, d\Omega}{(2\pi\hbar)^3} v_{12} \frac{d\sigma}{d\Omega} \\ &\times \left[ f f_2 (1-f_3)(1-f_4) - f_3 f_4 (1-f)(1-f_2) \right] \end{aligned}$$

**Incorporated Physics in BUU**

**Mean Field Evolution**
**(Incoherent) Two-Body Collisions**
**Pauli Blocking in Two-Body Collisions**

O **One-Body Observables (Particle Spectra, Collective Flow, ..)**
X **Event-by-Event Fluctuation (Fragment, Intermittency, ...)**

# AMD (Antisymmetrized Molecular Dynamics)

**Wave Function**

$$|\Psi> = A\prod |\psi_i> \quad , \quad \psi_i = \phi(r;Z_i)\,\chi(\sigma,\tau) \quad ,$$

$$\phi(r;Z) = \left(\frac{2\nu}{\pi}\right)^{3/4} \exp\left(-\nu\left(r - Z/\sqrt{\nu}\right)^2 + Z^2/2\right)$$

$$\propto \exp\left(-\nu(r-D)^2 + i\,K\cdot(r-D)/\hbar\right) \quad \left(Z = \sqrt{\nu}\,D + \frac{i}{2\hbar\sqrt{\nu}}K\right)$$

**Equation of Motion**

$$L = \frac{\langle\Psi|i\hbar\partial/\partial t - H|\Psi\rangle}{\langle\Psi|\Psi\rangle} \quad , \quad \frac{d}{dt}\frac{\partial L}{\partial\left(d\bar{Z}_i/dt\right)} - \frac{\partial L}{\partial \bar{Z}_i} = 0$$

$$\rightarrow \quad i\hbar\,C_{i\alpha,j\beta}\frac{dZ_i}{dt} = \frac{\partial H}{\partial \bar{Z}_i}$$

**No Antisymmetrization** $C=\delta \rightarrow \dfrac{dD_i}{dt} = \dfrac{\partial H}{\partial K_i} \quad , \quad \dfrac{dK_i}{dt} = -\dfrac{\partial H}{\partial D_i}$

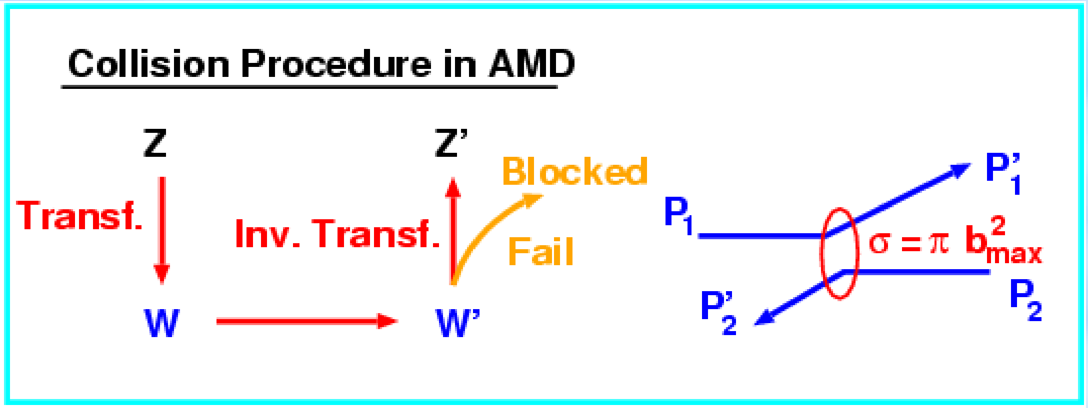
# Collision Term in AMD

## Approximate Canonical Variables

$$W_i = \sqrt{Q}_{ij} Z_j = \sqrt{\nu}\, R_i + \frac{i}{\sqrt{\nu}\,\hbar} P_i \quad , \quad Q_{ij} \equiv B_{ij} \ \ B_{ij}^{-1} \quad , \quad B_{ij} = \langle \psi_i | \psi_j \rangle$$

*Example*

$$\langle \boldsymbol{L} \rangle = \sum_{ij} B_{ji}^{-1} B_{ij} \frac{1}{i} \overline{Z}_i \times Z_j = \sum_i \overline{W}_i \times W_i$$



**Collision Term = "Canonical" Variable + Classical Analogy**

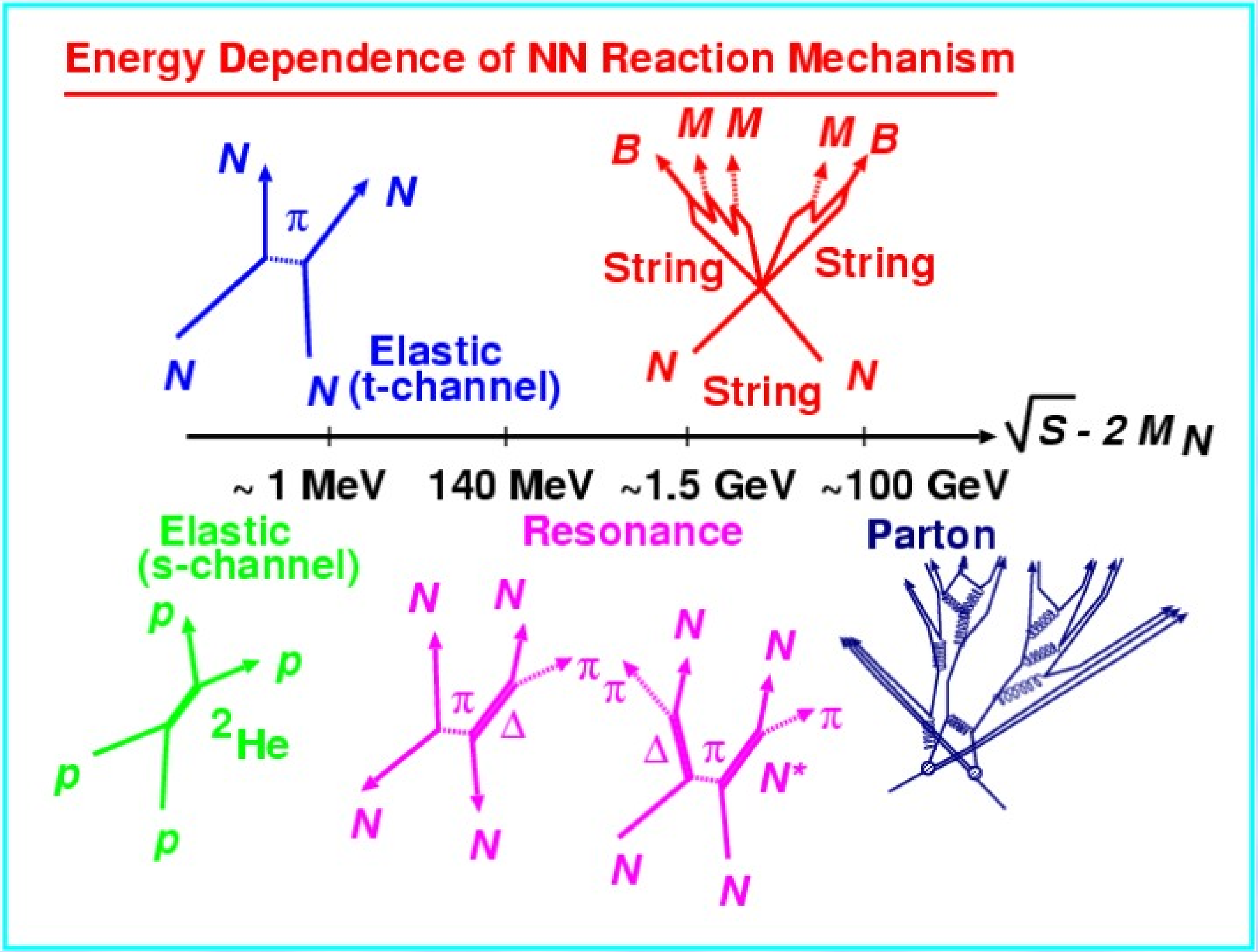
# *Physics included in AMD*

**Time Evolution of Anti-Symmetrized Wave Function**
**Two-Body Collisions with Pauli Blocking**
**Event-by-Event Fluctuation**

## Points to be Improved in AMD

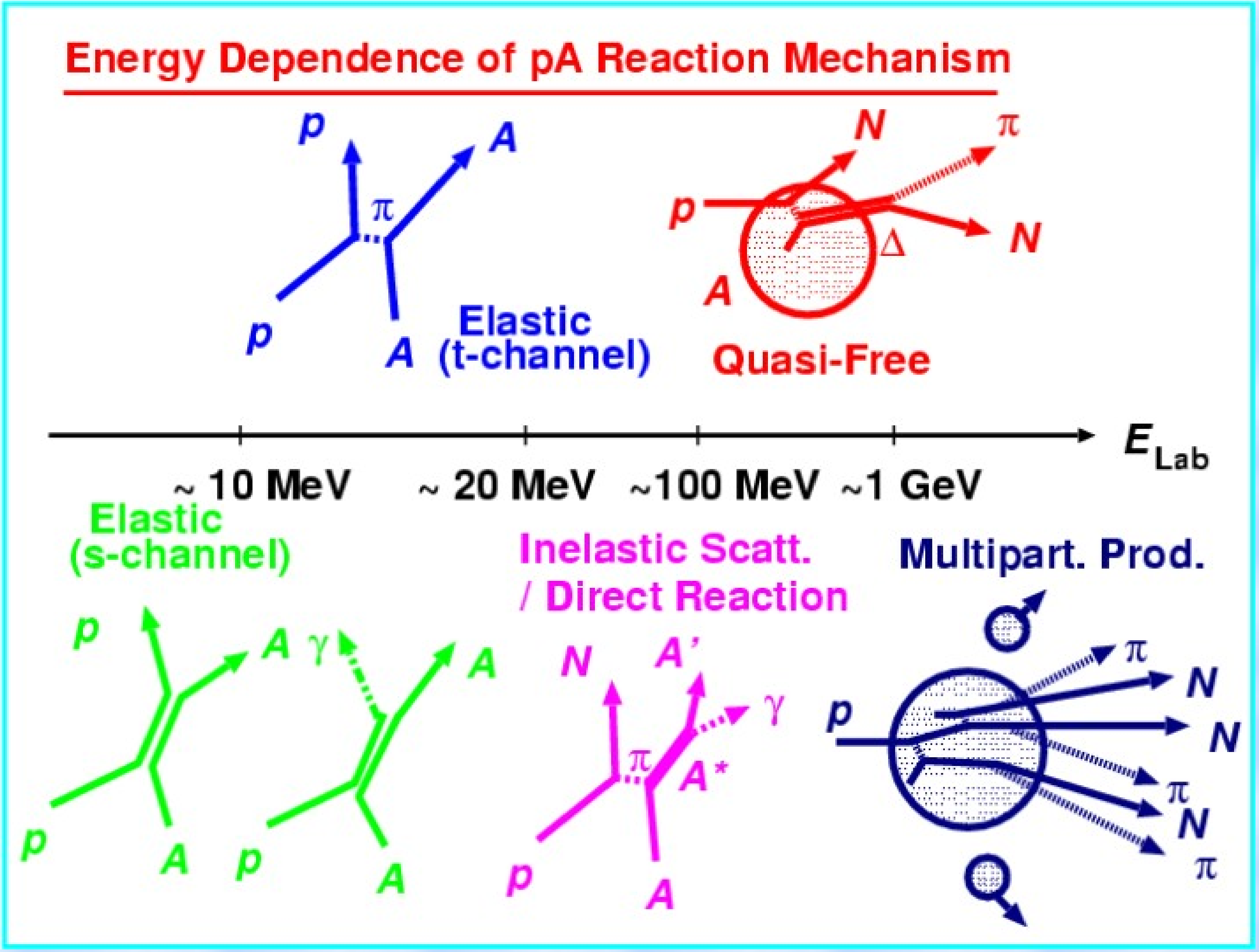
**Wave Packet Dynamics → Not an Eigen State of Energy, Jπ**
**Initial and Final Fragment State → Not Quantized**
**Two Body Collisions → Classical Analogue (Not Derived)**

# Rough Reaction Mechanism of NN Collisions



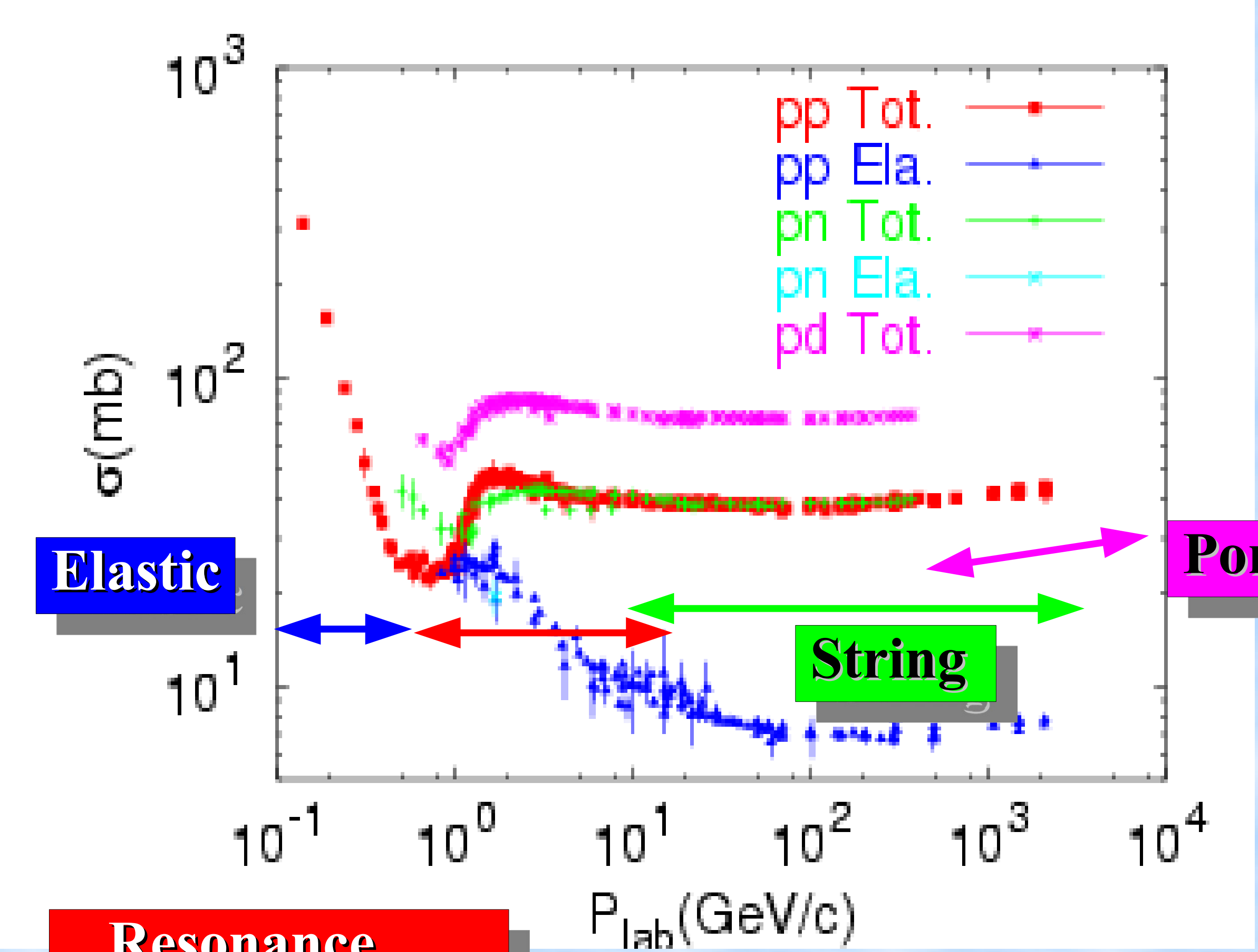
**Elastic ➔ Resonance ➔ String ➔ Jet**

# *Rough Reaction Mechanism of NA Collisions*



# *NN Cross Sections*

**From Particle Data Group**



**Elastic**

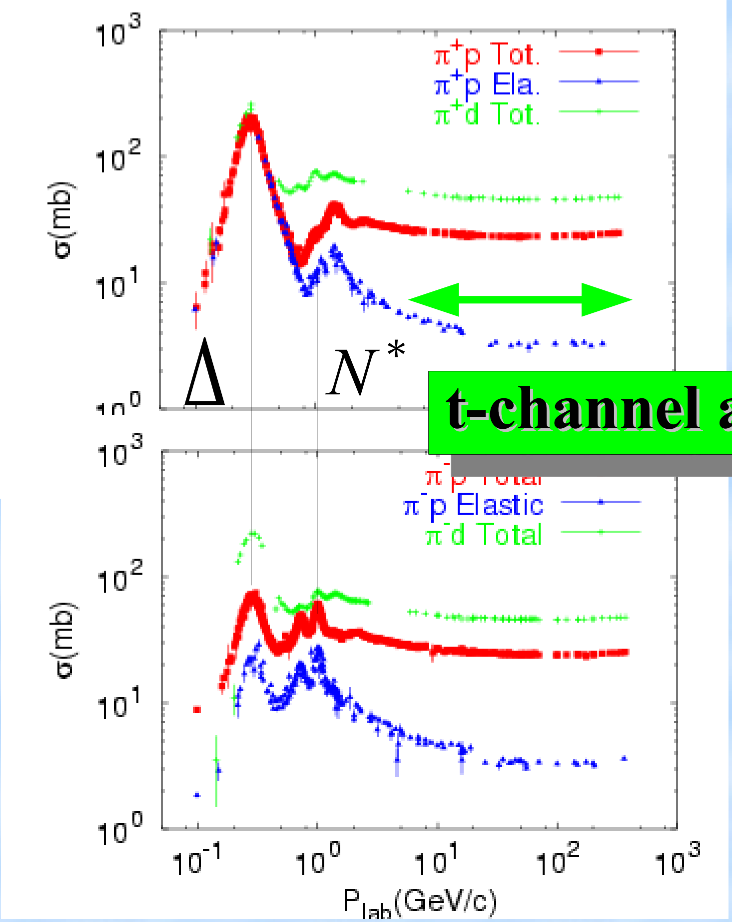
**Resonance (Threshold Enh.)**

**String**

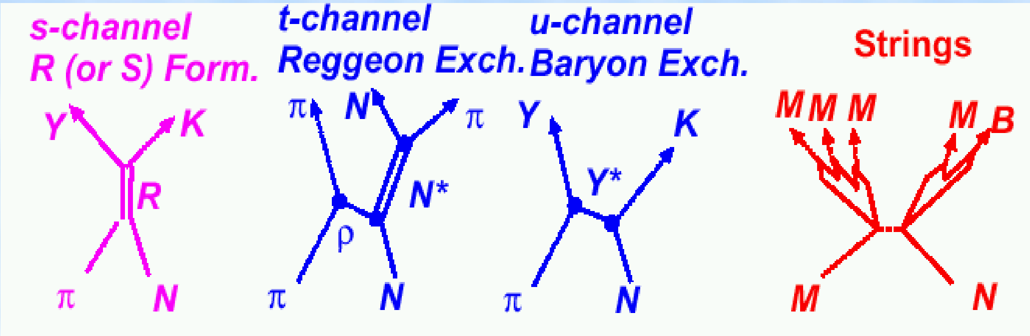
**Pomeron**

# *Meson-Baryon Cross Section*

**Resonance (s-channel)**



**t-channel and String**



*Strong Resonance Formation at Low Energy*

*→ Smooth Behavior at High Energy*

# *Statistical Model of Hadrons and Fragments*

## Grand Canonical Statistical Ensemble of Constituents

$$
\begin{aligned}
N_i &= \int \mathrm{d}\Gamma_i f_i(E_i - \mu_i, T) \ , \\
d\Gamma_i &\equiv \frac{g_i \mathrm{d}^3 r_i \mathrm{d}^3 p_i}{(2\pi)^3} \ , \\
f_i &\equiv \frac{1}{\exp\left[(E_i - \mu_i)/T\right] \mp 1},
\end{aligned}
$$

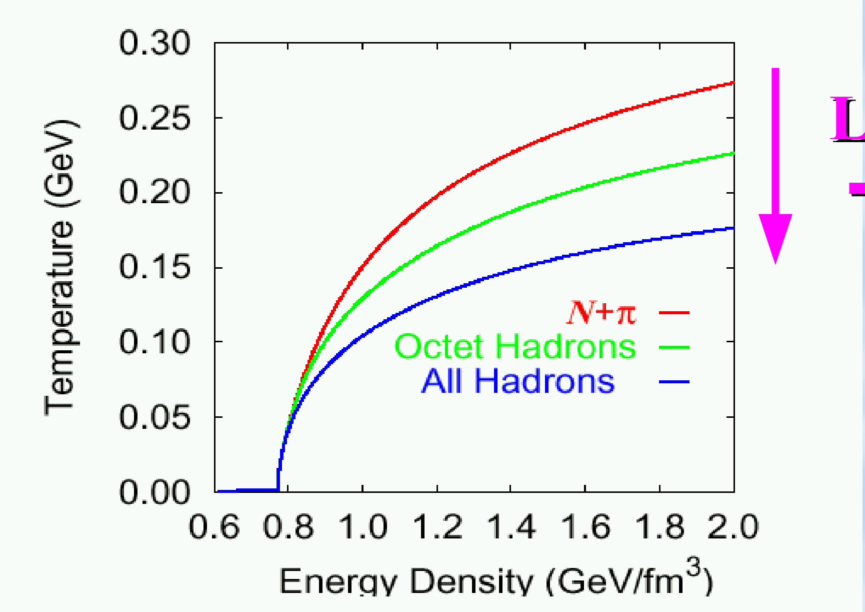
## Thermodynamical Functions

$$
\begin{aligned}
\Omega &= -\sum_i \int d\Gamma_i \, f_i \, \frac{p_i^2}{3E_i} = -PV \ , \\
S &= \frac{1}{T} \sum_i \int d\Gamma_i \, f_i \left( E_i - \mu_i + \frac{p_i^2}{3E_i} \right) \ , \\
P &= -\Omega / V \\
N_i &= \int d\Gamma_i f_i \ , \\
E &= \sum_i d\Gamma_i \, f_i \, E_i \ .
\end{aligned}
$$

**Constituents can either be Hadrons (high-T) or Fragments (low-T)**

# *Hadronic Caloric Curve and Hagedorn Gas Behavior*

## Hadronic Caloric Curve (Otuka, Thesis)



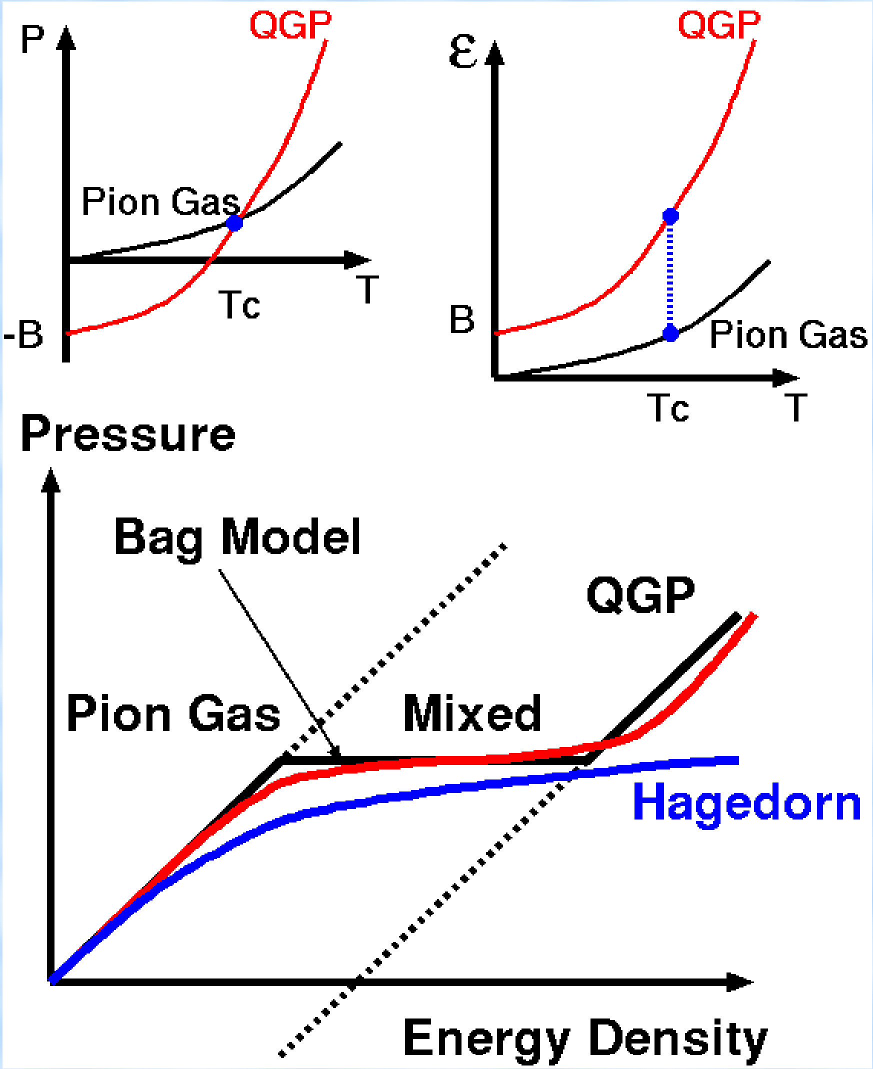
**Larger DOF**
**→ Lower *T***

**Hagedorn Gas Behavior:**
**Exponentially Growing Level Density → Limiting Temperature**

$$\rho(m) \to a m^{-\frac{5}{2}} \exp\left(\frac{m}{T_0}\right) (\mathrm{GeV}^{-1}).$$

$$\begin{aligned}
Z(V,T) &= \sum_{(k)} \exp\left(\frac{1}{T}\sum_i \sum_\tau \epsilon_{i,\tau}\nu_{i,\tau}\right) - 1 \\
&= \exp\left[\frac{VT}{2\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\int_0^\infty \mathrm{d}m \rho(m,n) m^2 K_2\left(\frac{nm}{T}\right)\right] - 1 \\
&\equiv \frac{VT^3}{(2\pi)^{\frac{3}{2}}}\int_0^\infty \mathrm{d}m \; m^{\frac{3}{2}} \rho(m) Q\left(\frac{m}{T}\right),
\end{aligned}$$

# Simple Model of QCD Phase Transition



**Massless Particles at Zero Chem. Pot.**

$$\Omega = -\frac{\pi^2 V}{90}\left(\sum_B g_B + \frac{7}{8}\sum_F g_F\right) T^4,$$

**Massless (Free) Pion Gas**

$$P_\pi = \frac{\pi^2}{30} T^4 \quad , \qquad \epsilon_\pi = \frac{\pi^2}{10} T^4$$

**QGP with Finite Bag Constant**

$$P_{QGP} = \frac{37\pi^2}{90} T^4 - B$$

$$\epsilon_{QGP} = \frac{37\pi^2}{30} T^4 + B$$

$$DOF = 2(spin) \times 2(q, \bar{q}) \times 3(color) \times 2(flavor) \times 7/8(Fermion) + 2(spin) \times 8(color)$$

# *Statistical Model of Nuclear Fragments*

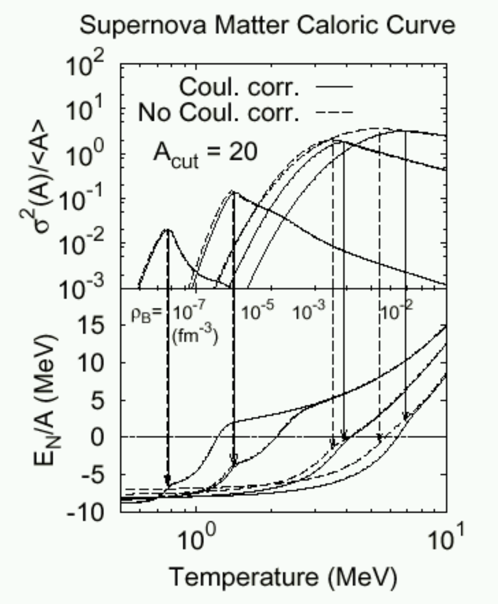
## Nuclear Level Density (taken from Randrup & Fai)

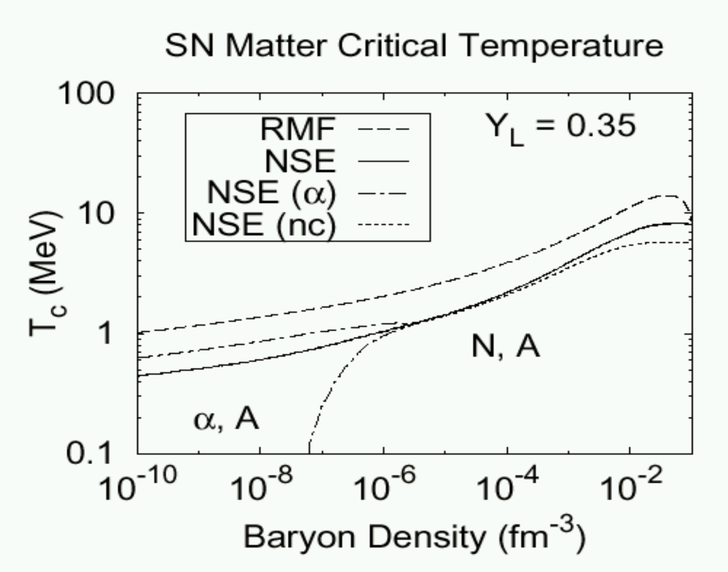
$$\zeta_f(T) = \sum_i g_f^{(i)} \exp\left(-E_f^{*(i)}/T\right)$$

$$\simeq g_f^{(g.s.)} + \frac{c_1}{A_f^{5/3}} \int_0^\infty dE^* e^{-E^*/T} \exp(2\sqrt{a_f E^*}) \,,$$

$$a_f = \frac{A_f}{8}\left(1 - c_2 A_f^{-1/3}\right) \ (\mathrm{MeV}^{-1}) \,, \quad c_1 = 0.2 \ (\mathrm{MeV}^{-1}) \,, \quad c_2 = 0.8$$

$$\zeta \propto \exp\left(2\sqrt{a E^*}\right) \quad \rightarrow \quad E^* = a T^2$$

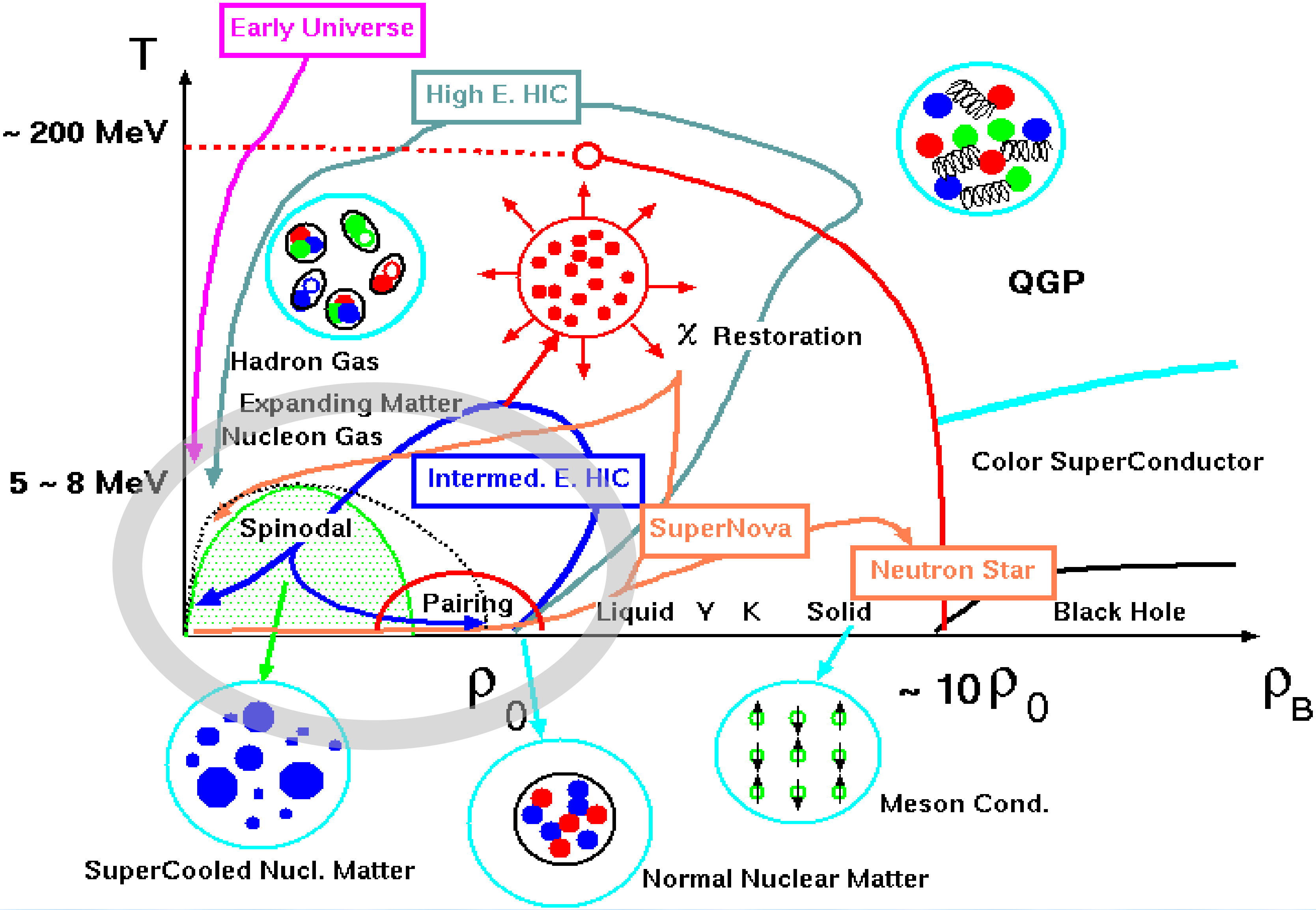




**Ishizuka,AO,Sumiyoshi (nucl-th/0208020)**

# Part I:
# Fragment Formation and Nuclear Liquid Gas Phase Transition

# Hadronic Matter Phase Diagram

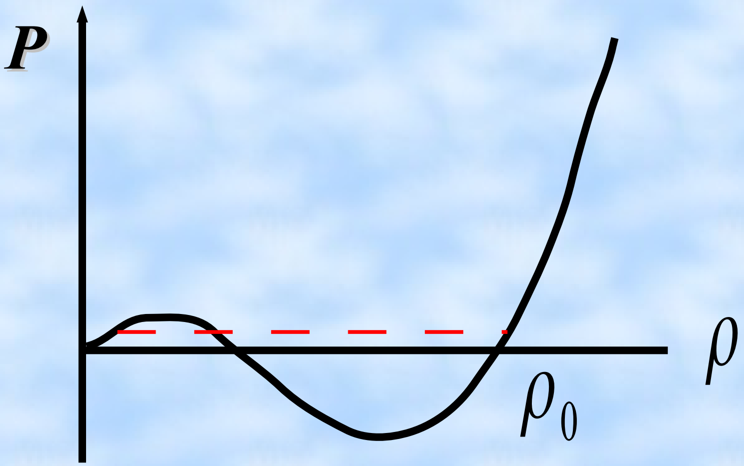


# *Contents*

Introduction — Liquid-Gas Phase Transition
Sideward Peak of IMF Emission in High Energy pA Reaction
Phase Transition of Supernova Matter

Nuclear Int.  Van der Waals Int.

➜ LG Phase Transition is expected.



RMF

**Recent Experimental Progress**

Two indep. exp. on two indep. Observables show the Existence of First Order L.-G. Phase Transition.

# *Nuclear Caloric Curve*

**J. Pochadzalla et al.**
**Phys. Rev. Lett. 75 (1995) 1040.**
**(GSI-ALLADIN collab.)**

***Boiling Temperature is Clearly Seen***

**Fragment Yields are assumed to follow Equilibrium Statistics**

$$Y_f \propto g_f \exp\left(\left(B_f + Z\mu_p + N\mu_n\right)/T\right)$$

$$\rightarrow \frac{Y\left({}^4He\right)/Y\left({}^3He\right)}{Y\left({}^7Li\right)/Y\left({}^6Li\right)} \propto \exp\left(\Delta B/T\right)$$

# *Negative Heat Capacity*

*Negative Heat Capacity*
➡ *First Order*

***T*** **and $E^*$ are determined from** ***Fragment Multiplicity*** **and** ***Kinetic Energy*** **based on Theoretical Model**

**M. D Agostino et al.**
**(MSU Exp./INFN-IN2P3 Collab.)**
**PLB 473 (2000) 219.**

**For theoretical understanding, we need models,**

**Which describes both of Reactions and Statistics**

**T in Exp. Fragment Yield in H.I. Collisions + Equil. Assumption**

**With Quantum Statistical nature**

$E \propto T^2$ **in nuclei at low T.**

***Molecular Dynamics with Quantum Fluctuation***

**AO & Randrup,**

**Nucl. Phys. A565(1993), 474; Phys. Rev. Lett. 75(1995), 596;**
**Ann. Phys. 253 (1997), 279; Phys. Lett. B394(1997), 260;**
**Phys. Rev. A55(1997), 3315R)**

**Hirata, Nara, AO, Harada, Randrup,**

**Prog. Theor. Phys. 102 (1999), 89.**

**Ono-Horiuchi (AMD-V, Phys. Rev. C53 (1996), 2958)**
**Sugawa-Horiuchi-Ono (AMD-MF, Phys. Rev. C60 (1999) 064607)**

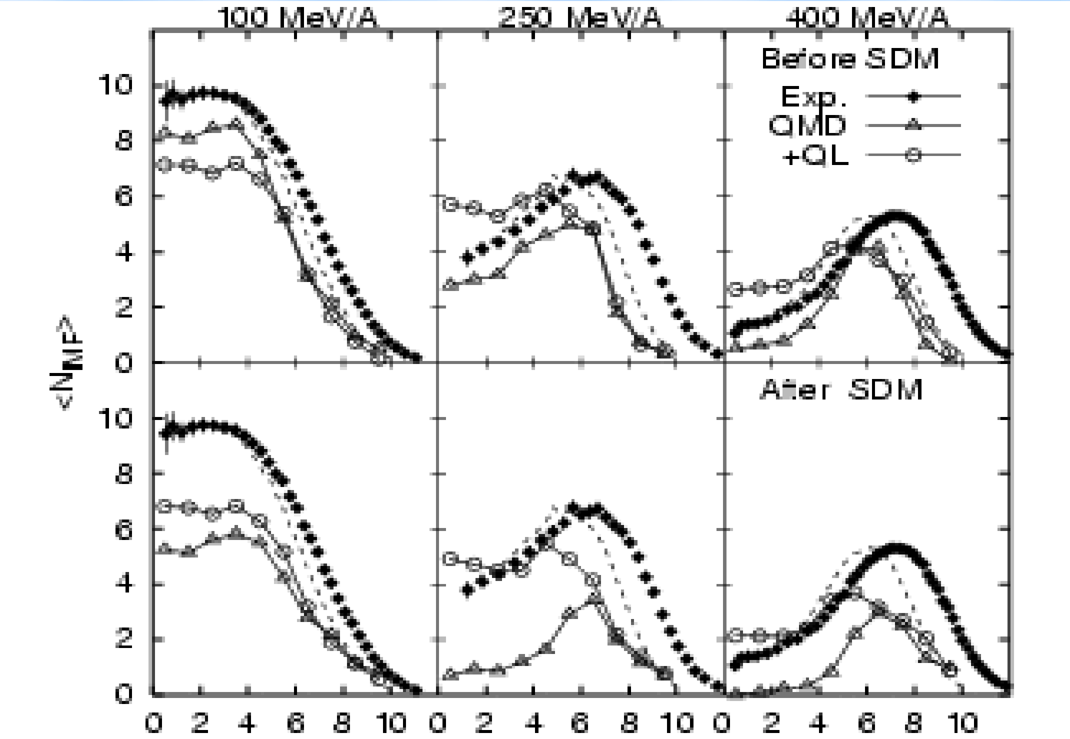
# *Wave Packet Statistics*

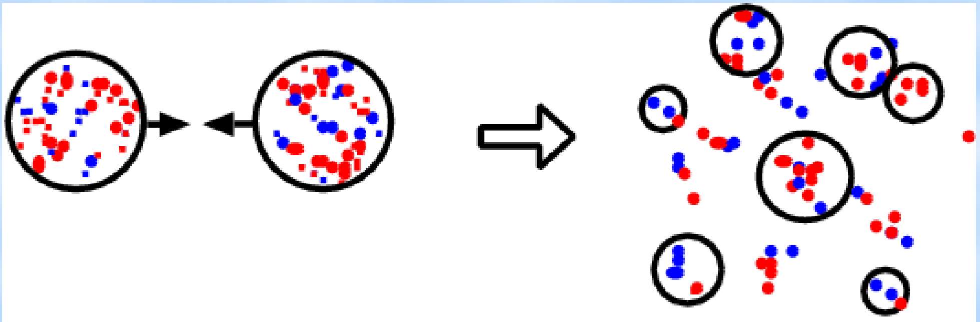
**Mass Distribution**

**Caloric Curve**

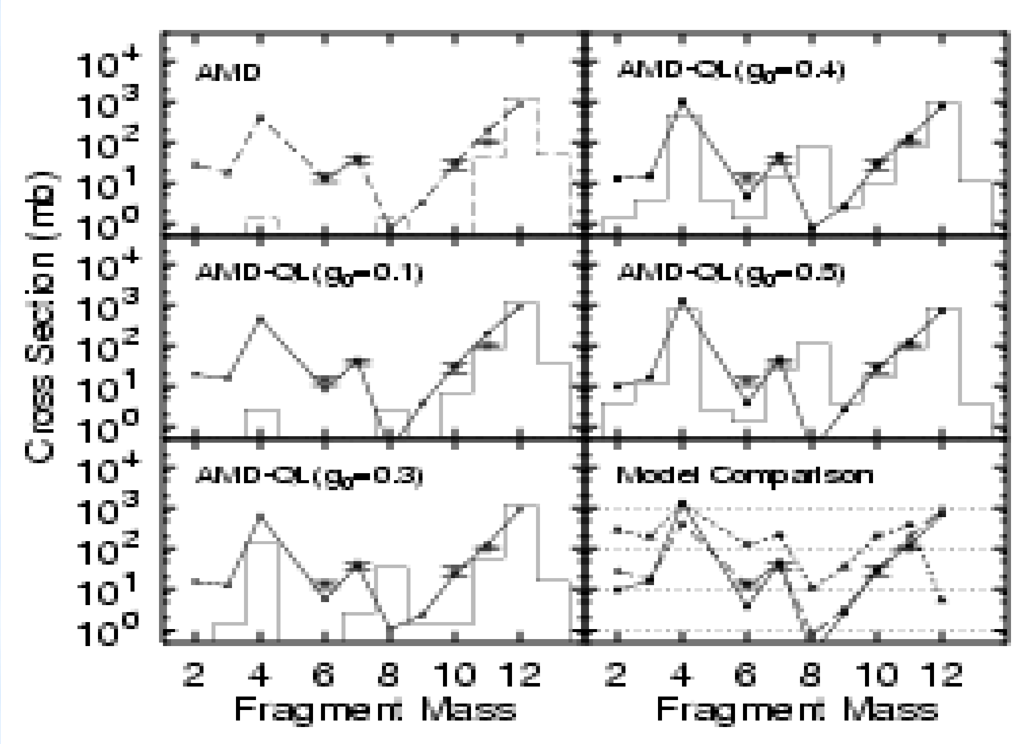
# *Wave Packet Dynamics*

## Au + Au Collisions





## p + 12 C Collisions



**(Hirata et al. PTP102(99),89)**

## *What is Understood ?*

**LG Phase Transition is of First Order (Exp.).**

**It can be understood in Microscopic MD qualitatively, e.g. Fragment Yield.**

## *What is NOT Understood ?*

**Direct Relation between Fragment Formation and the Properties of Nuclear Matter**

***Are Fragments Produced through LG Phase Transition ?***

**“Initial” Condition of Fragmenation**

***At Which $T$ and $\rho$ Fragments are Formed ?***

**Is Equilibrium Reached in Heavy-Ion Collisions ?**

***Simpler Cases: pA Reaction & Supernova Explosion !***

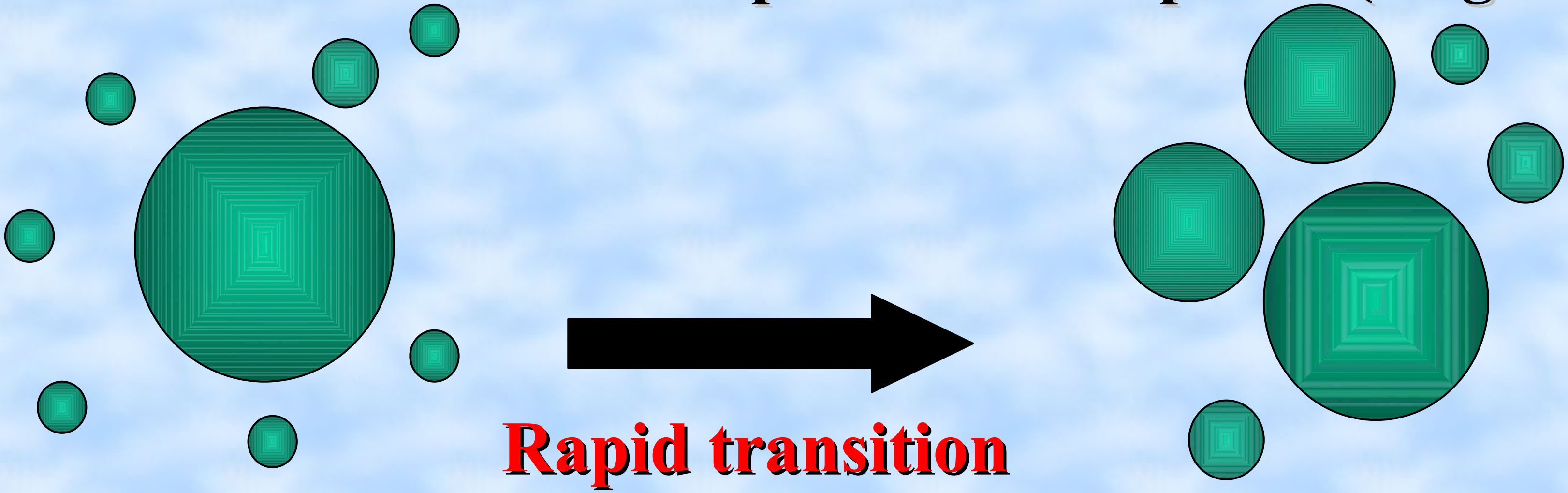
# *Shape effects on high-energy proton induced nuclear fragmentation*

Shuji Yamguchi        Hokkaido Univ.
Akira Ohnishi

# 1.Introduction

## Nuclear fragmentation

Excited nucleus breaks up into several pieces (fragments).



**Rapid transition**

Evaporation
$E^*$ low

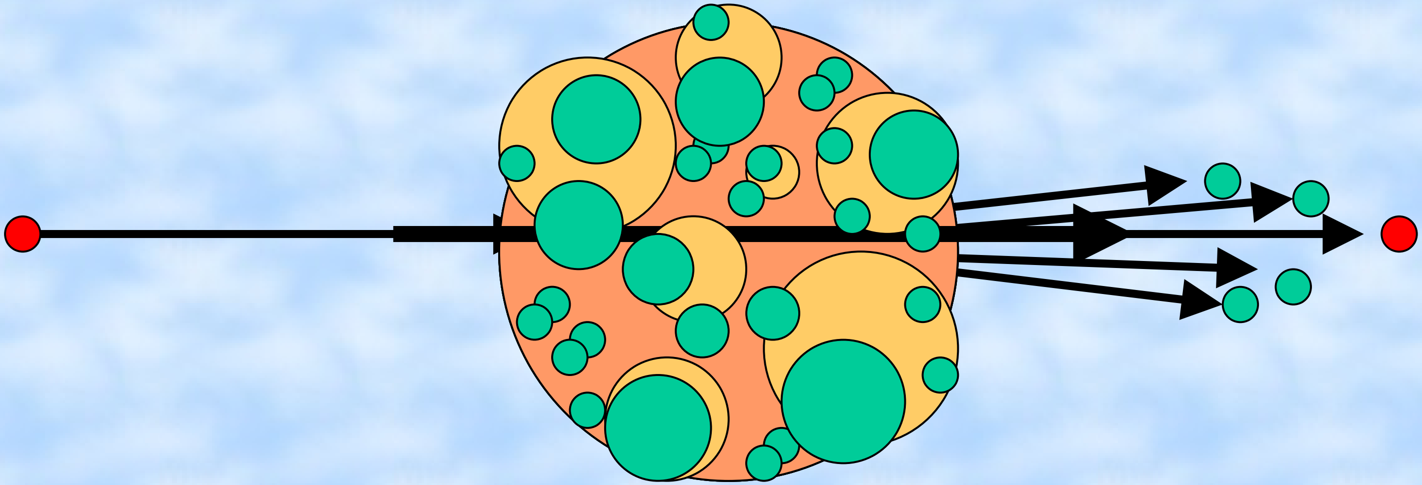
Multifragmentation
$E^*$ high

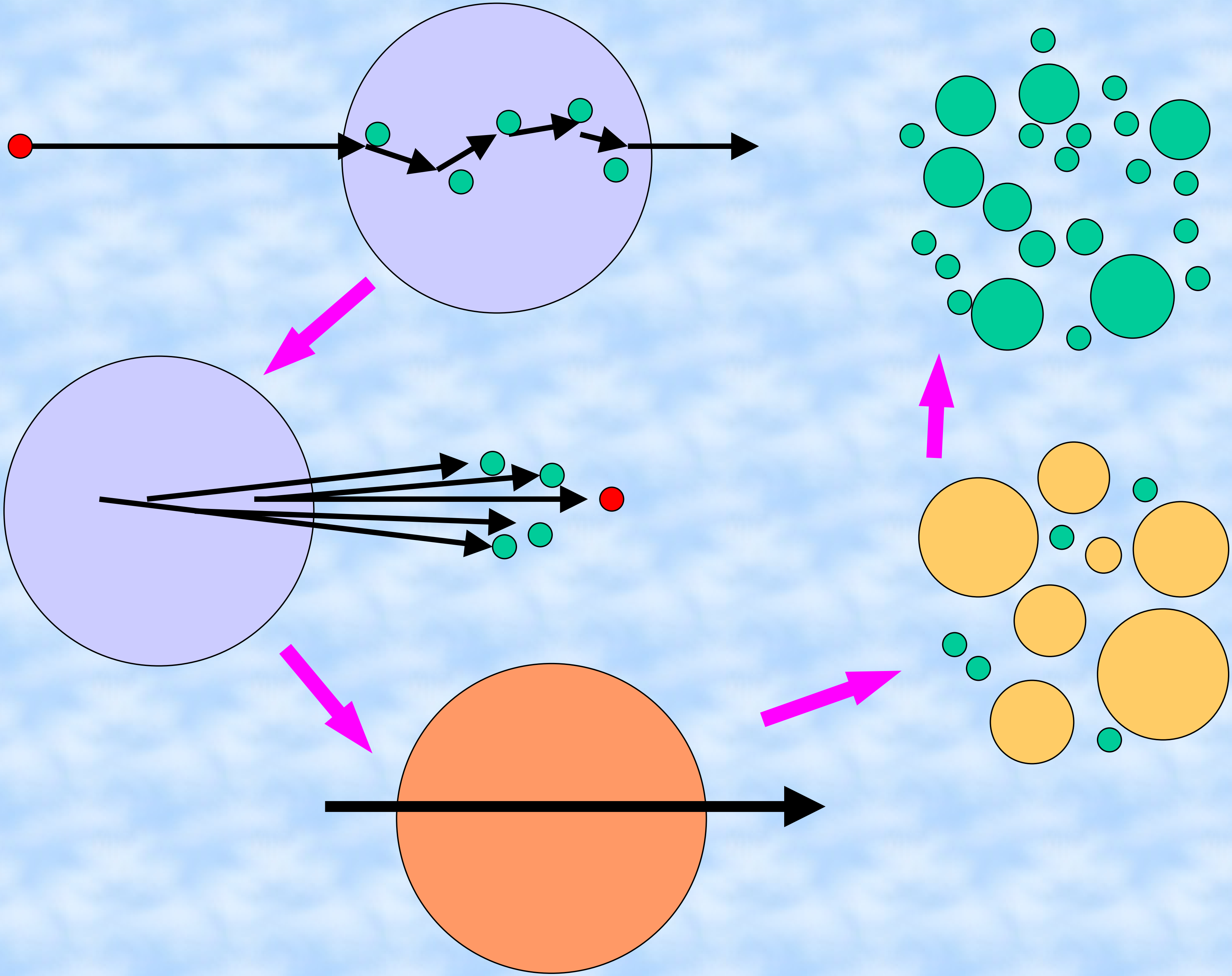
This evolution has been discussed in relation to the phase transition of nuclear matter [1].
Especially in **Equilibrium Percolation Model** [2].

[1] M.K.Berkenbusch P.R.L. 88 (2002) 022701 [2] W.Bauer P.R.C. 38 3 (1988) 1297

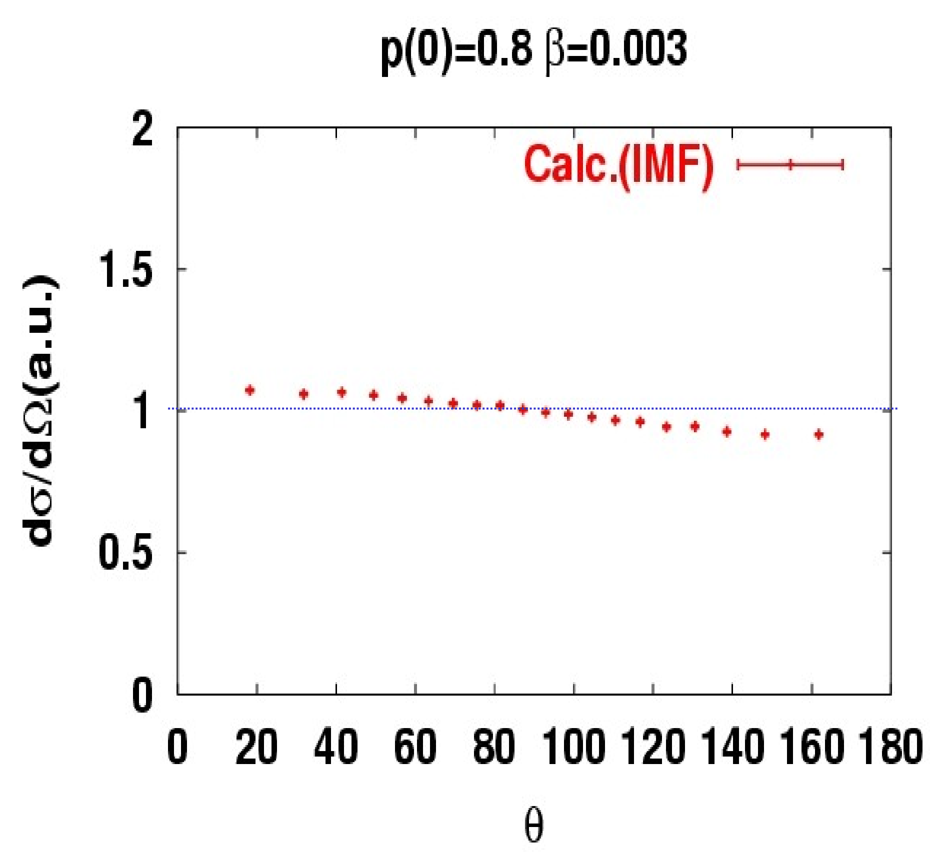
# *Standard Picture of proton induced Nuclear Fragmentation*

The incident proton passes through the target nucleus.
Residual excited nucleus reaches equilibrium,moving in forward.
The excited nucleus breaks up into fragments.
These fragments evaporate nucleons and alphas or make fission.





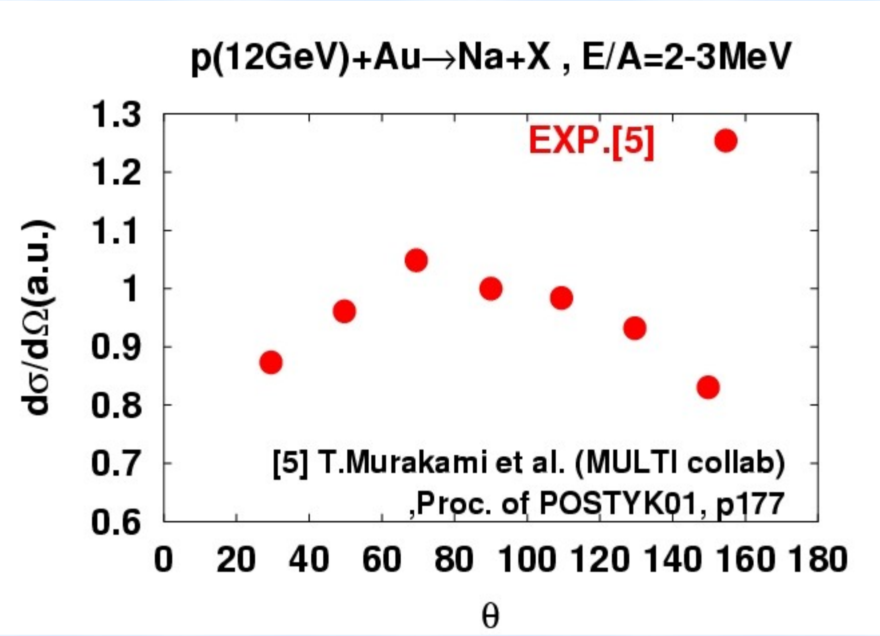
**The fragment angular distribution is peaked in forward.**



# *Long-standing problems*

## 1. p(10GeV~)+A

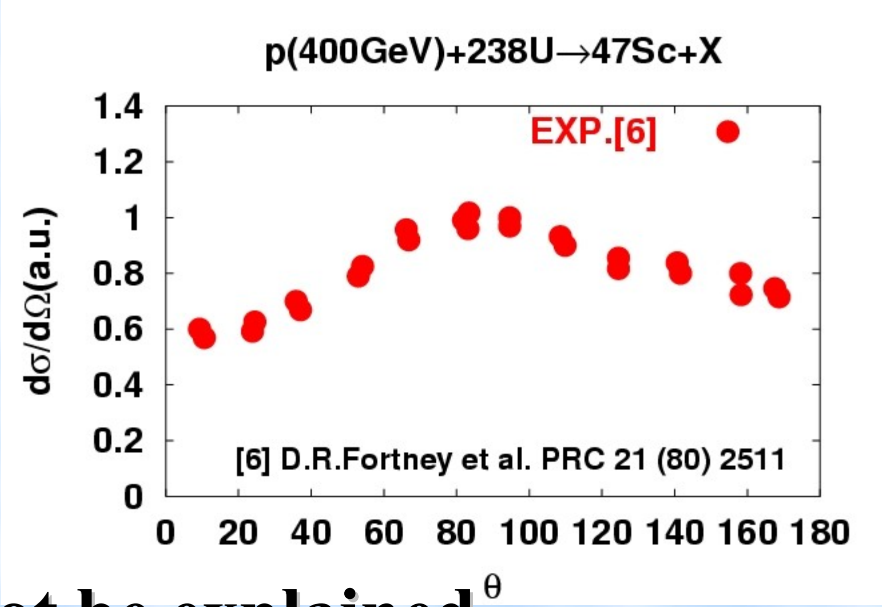
**Sideward peak** of
IMF angular distribution


p(12GeV)+Au→Na+X , E/A=2-3MeV

[5] T.Murakami et al. (MULTI collab) ,Proc. of POSTYK01, p177

## 2. p(100GeV~)+A

**backward enhancement** of
IMF angular distribution


p(400GeV)+238U→47Sc+X

[6] D.R.Fortney et al. PRC 21 (80) 2511

**These phenomena can not be explained**

**(IMF:Intermediate Mass Fragment , A=10~50)**

# *Standard picture need to be modified!*

**Purpose** The sideward peak and the backward enhancement

We study
the non-equilibrium shape effects of nuclear fragmentation,
within Bond Percolation Model.

Fragmentation should occur BEFORE equilibrium.

→ Temperature distribution may NOT BE UNIFORM.

Thus, we consider two models.

Cylinder model and Cone model

# 2. *Equilibrium Percolation Model [2]*

**Show a power low**
**Position information**

**Nucleons □ Sites on a simple cubic lattice in 3D**

**Bond breaking probability P(b)**

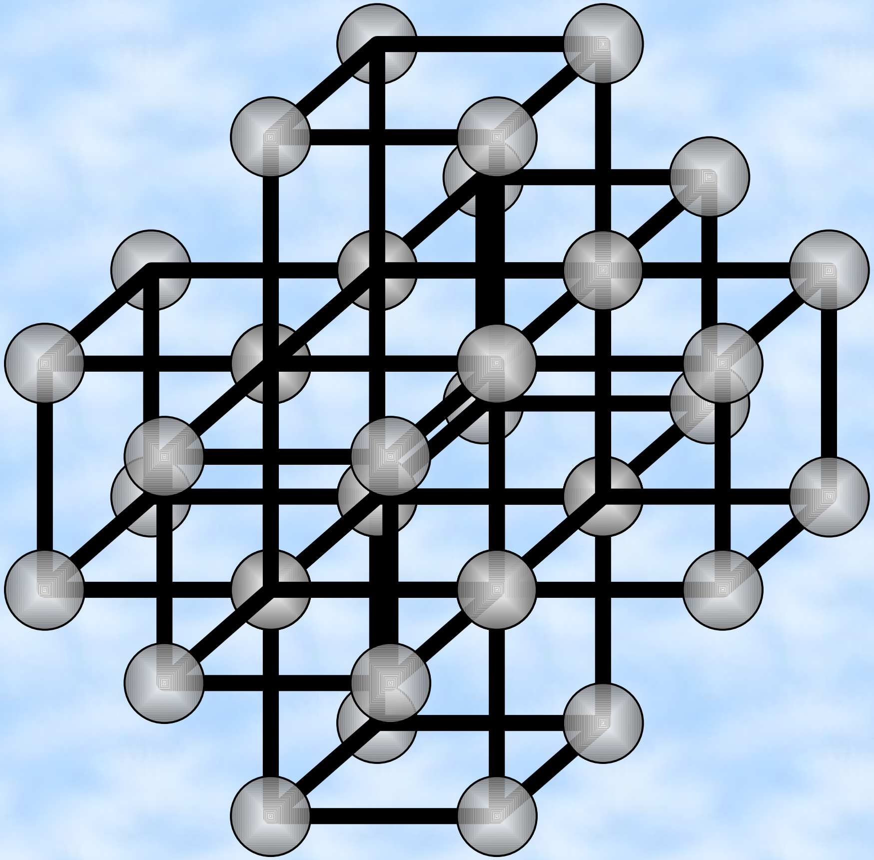
$$P(b)=P(0)\frac{\int \rho(x=b,0,z)\,dz}{\int \rho(0,0,z)\,dz}$$

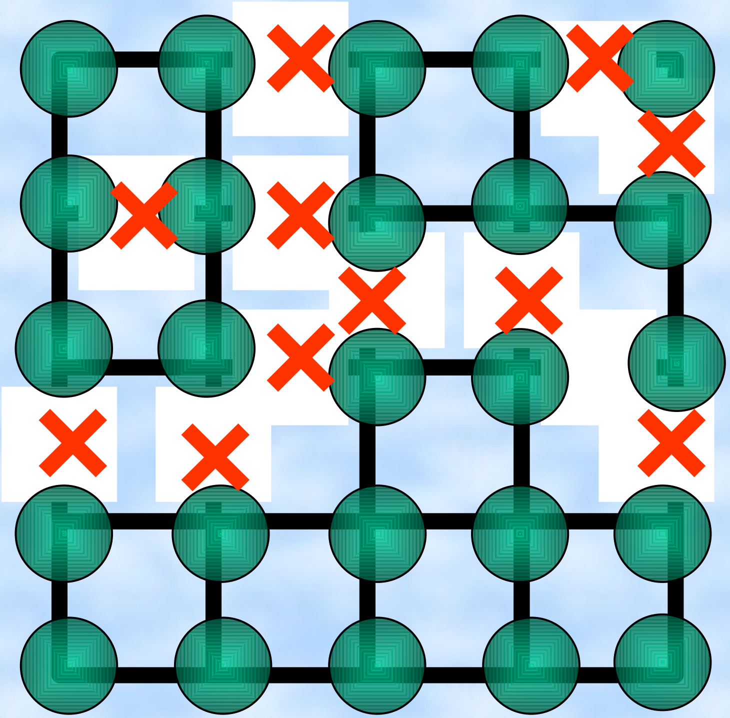
**(Eikonal)**

**Connected sites □ Fragment**

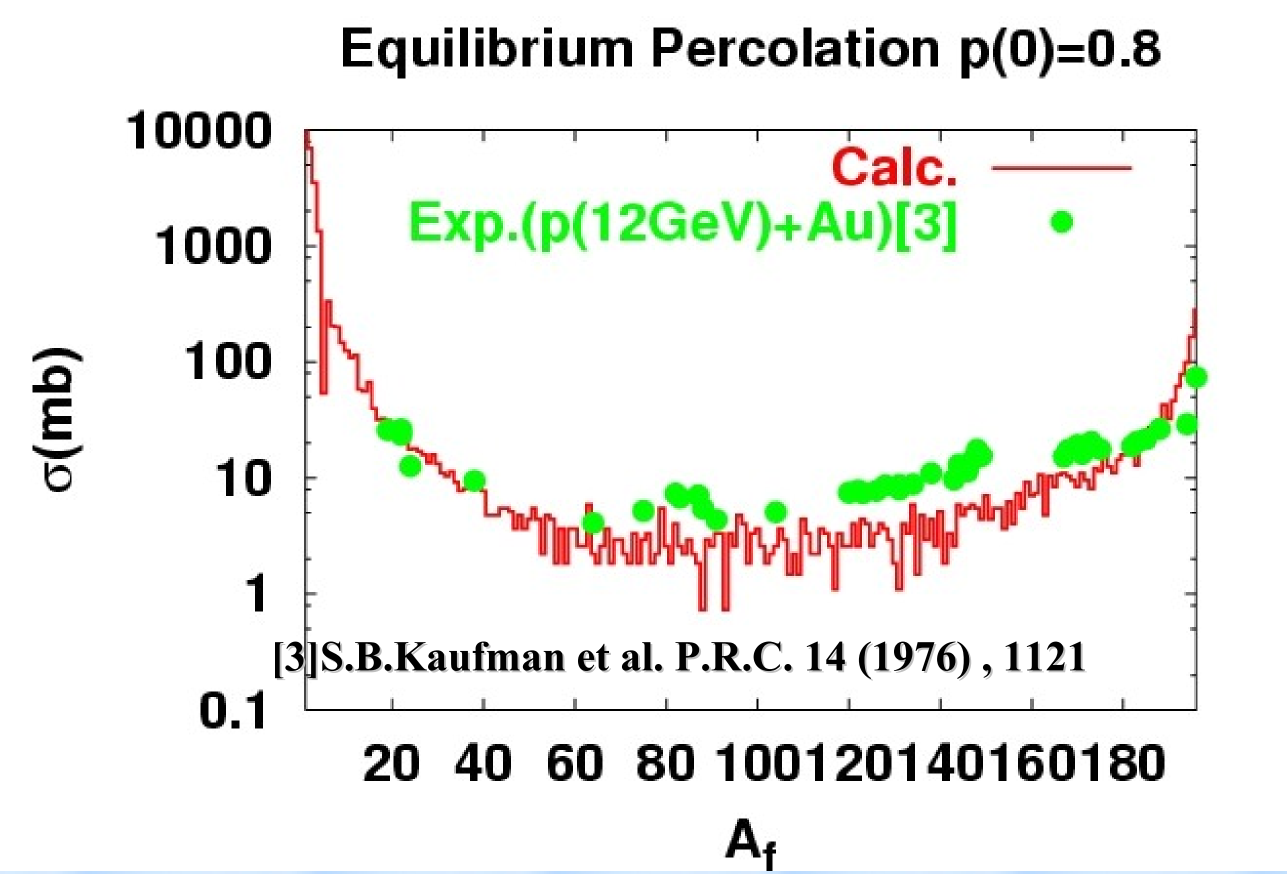
$$\sigma(A_f)=2\pi\int_0^{b(max)} b\,db\,\frac{N(A_f,b)}{N_{run}(b)}$$

# Examples





# *Fragment Mass Distribution in Equilibrium Percolation Model*



[3]S.B.Kaufman et al. P.R.C. 14 (1976) , 1121

**Features**

U-Shape
A power low

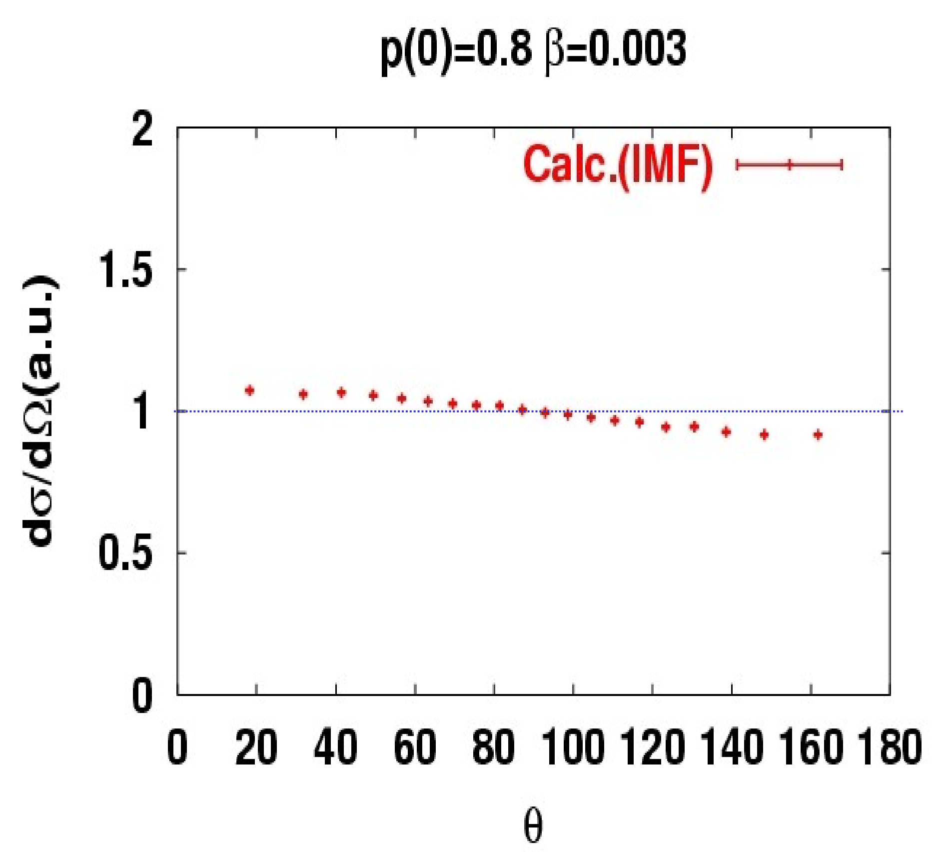
**Using SDM(Statistical Decay Model)[4]**
**to consider evaporation and fission of fragments**

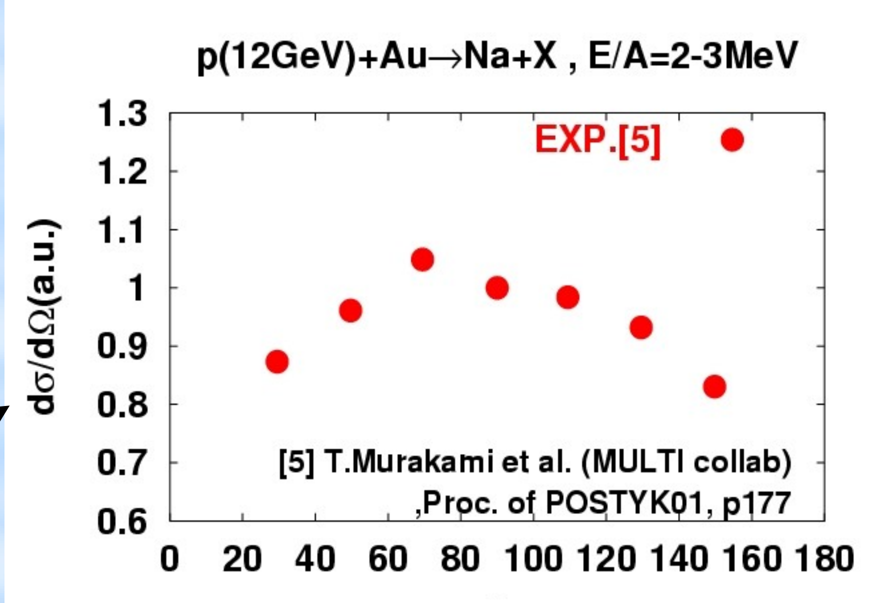
**Excitation energy in SDM**

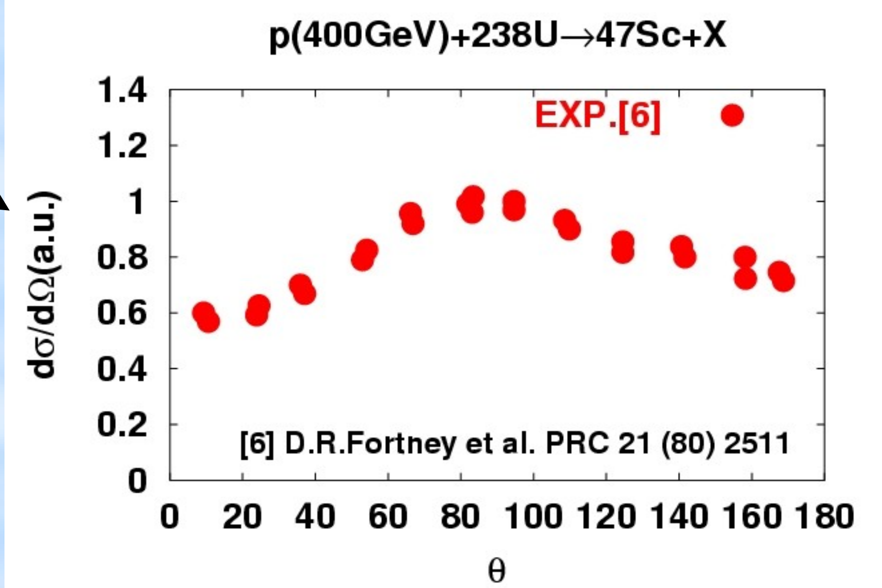
$$E^* = 5.25 \times p(b) \times (All\ Bonds) - 5.25 \times (Broken\ Bonds)$$

[4]K.Niita et al. PRC 52 (95) 2620

**However,the observed fragment angular distribution cannot be explained in Equilibrium Percolation Model.**







**Equilibrium Percolation Model**

# 3. Non Equilibrium Percolation Model

Sideward peak : Cylinder Model

Cylindrical hot region[7]

Backward enhancement : Cone Model

Conic hot region

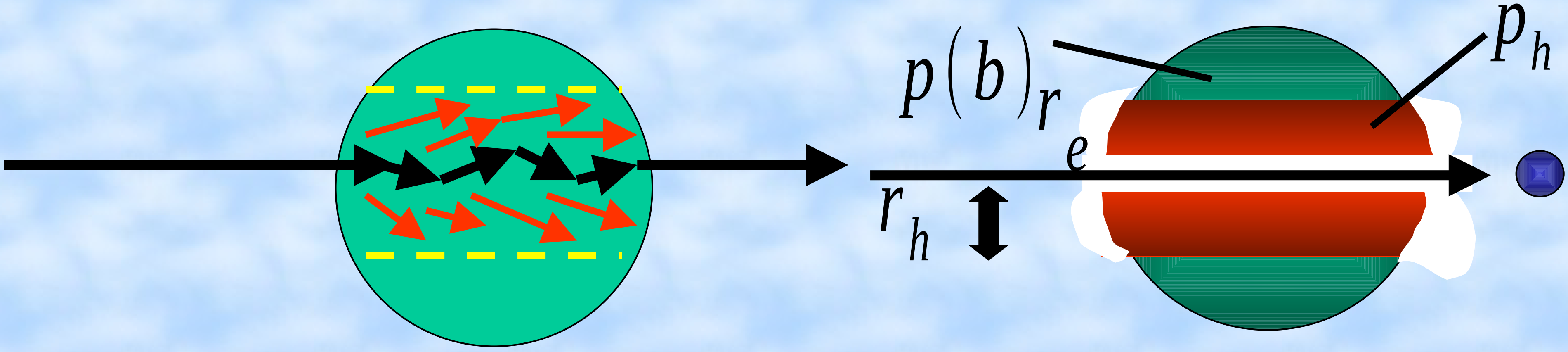
Previous works[8,9] :low $\rho$ ↔ Present work : high T

[7] Y.Hirata et al.N.P.A707 (2002) 193
[8] T.Maruyama et al.PTP 97 4 (1997) 579
[9] J.Hufner Phys.rep.125(85)129

# 3.1. Cylinder Model + SDM

## Processes

When nucleus breaks up ,high temperature zone remains.
Isotropic Fermi momentum is distributed to each nucleon.
Coulomb expansion.
Residual nucleus moves in forward direction with a velocity □.

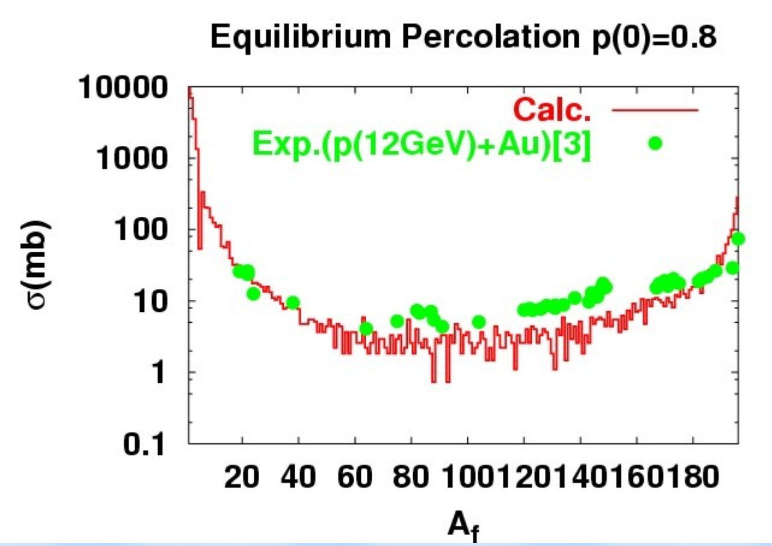


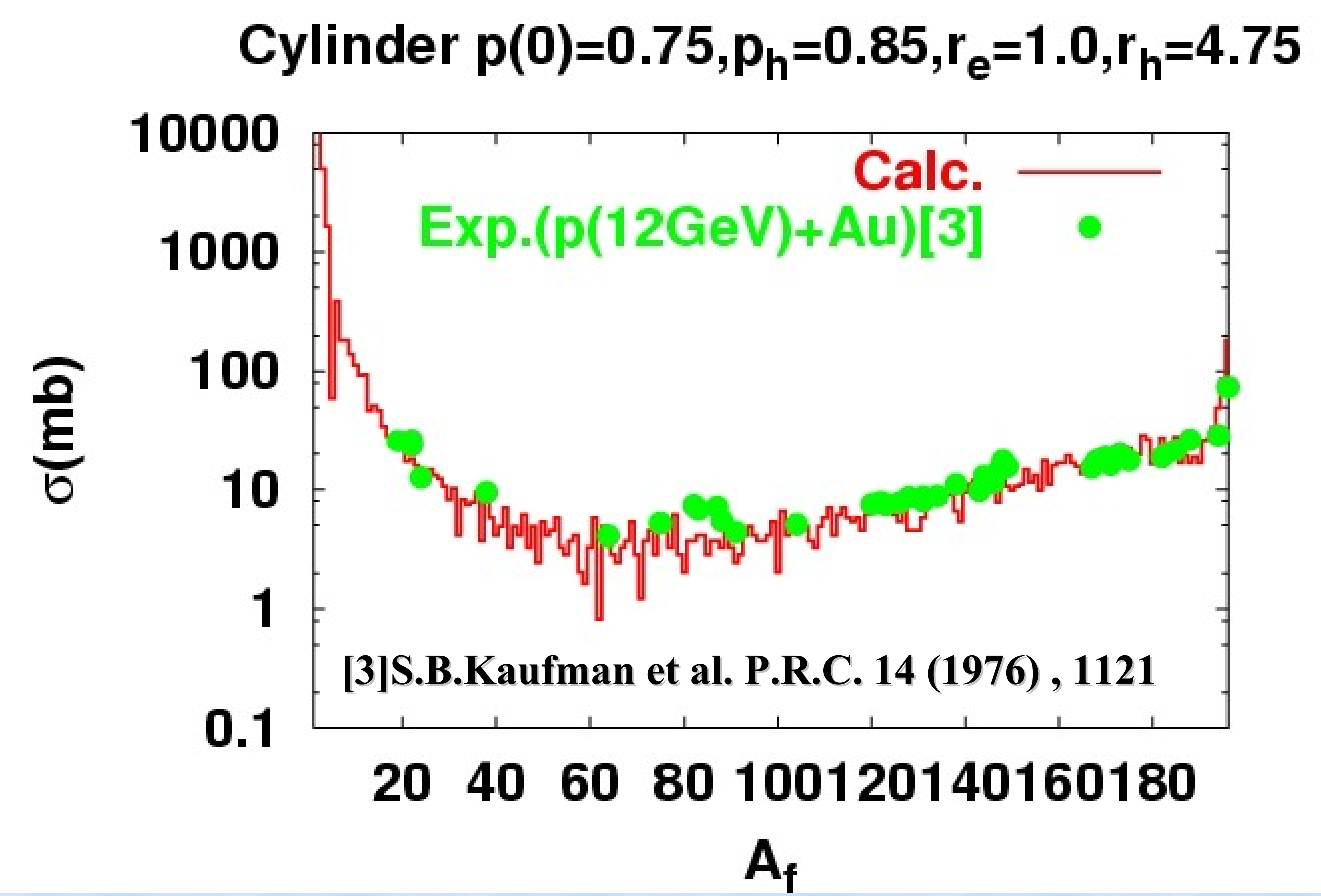
$$\beta = \frac{P_Z(Res)}{M_N A(Res)}$$

$M_N$ : mass of nucleon
$A$ : mass number of target
$P_Z$ : momentum of z-axis

# Cylinder Model

## *$A_f$ Distribution*

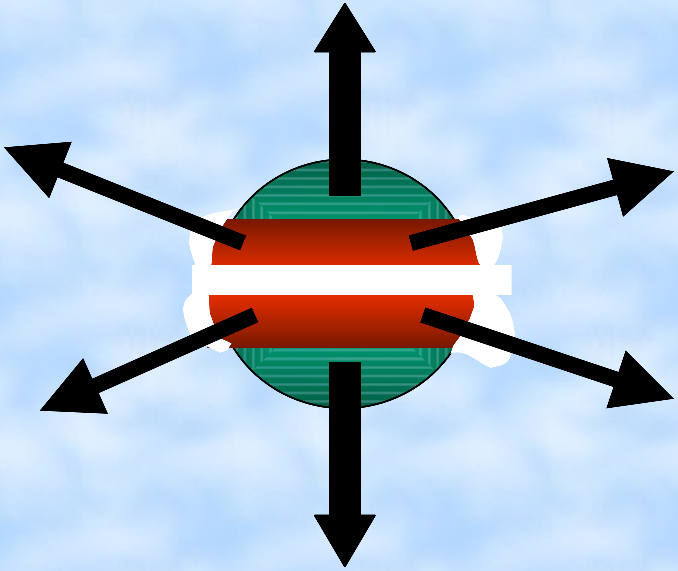


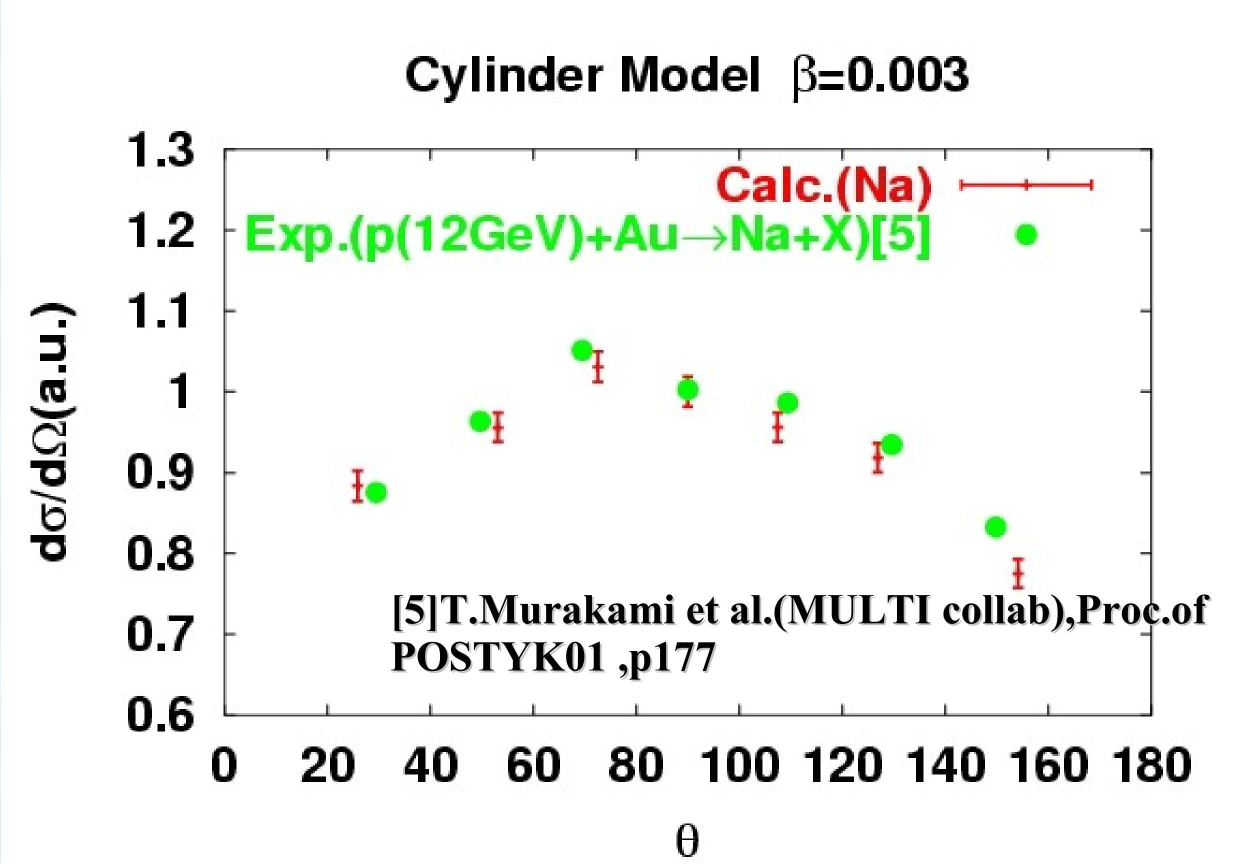


[3]S.B.Kaufman et al. P.R.C. 14 (1976) , 1121

**Better description**

# □$_f$ Distribution





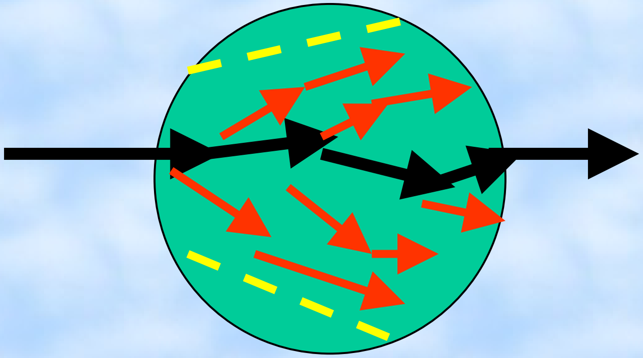
[5]T.Murakami et al.(MULTI collab),Proc.of POSTYK01 ,p177

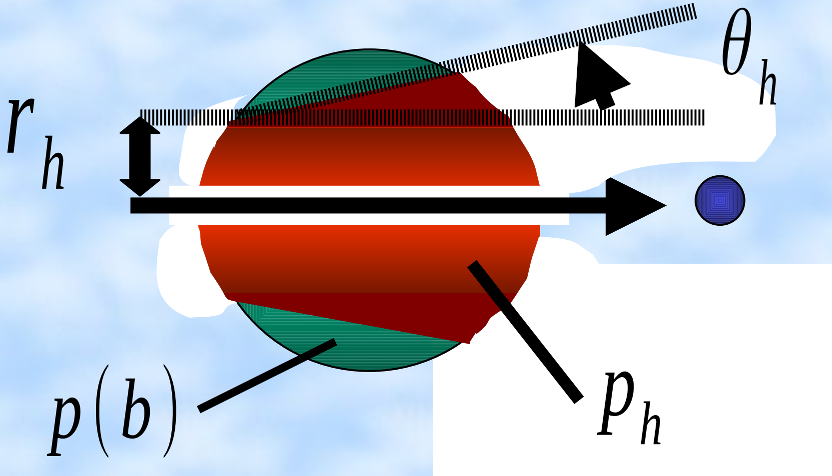
**Sideward peak**

**However backward enhancement cannot be explained in this Model.**

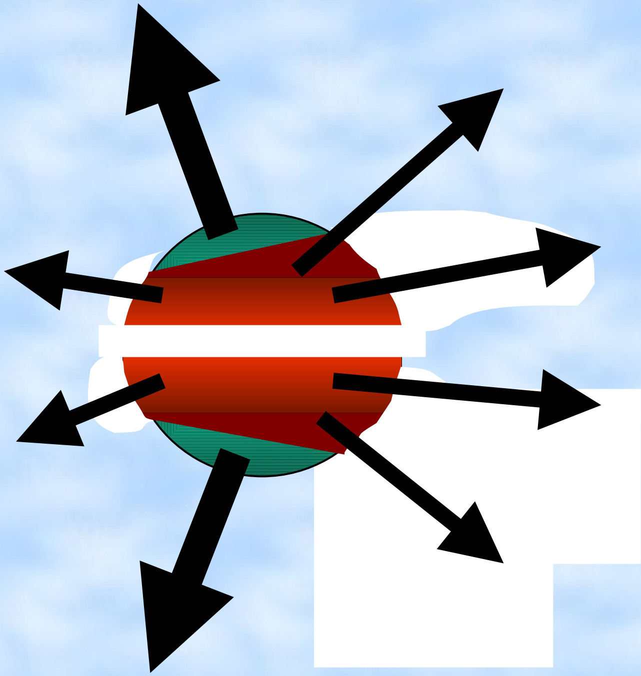
# *2.2. Cone Model + SDM*

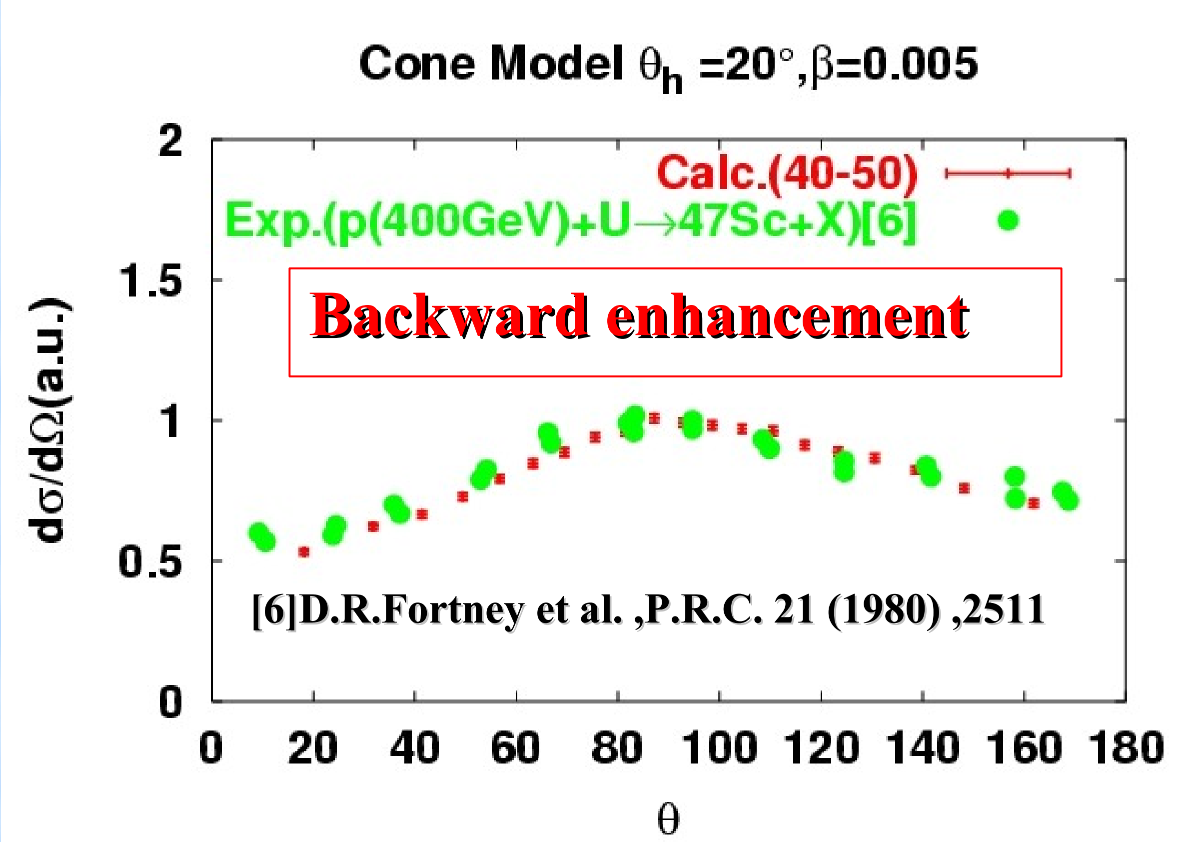
## High T conic region





## $\theta_f$ Distribution





**Backward enhancement**

[6]D.R.Fortney et al. ,P.R.C. 21 (1980) ,2511

# 3. *Summary*

**We investigate high-energy proton induced nuclear fragmentation by using the Percolation Model with non-equilibrium shape effects.**

**For Fragment Mass Distribution**

**We can reproduce fragment mass distribution well.**

**For Angular Distribution**

**The sideward peak and backward enhancement can be explained quantitatively.**

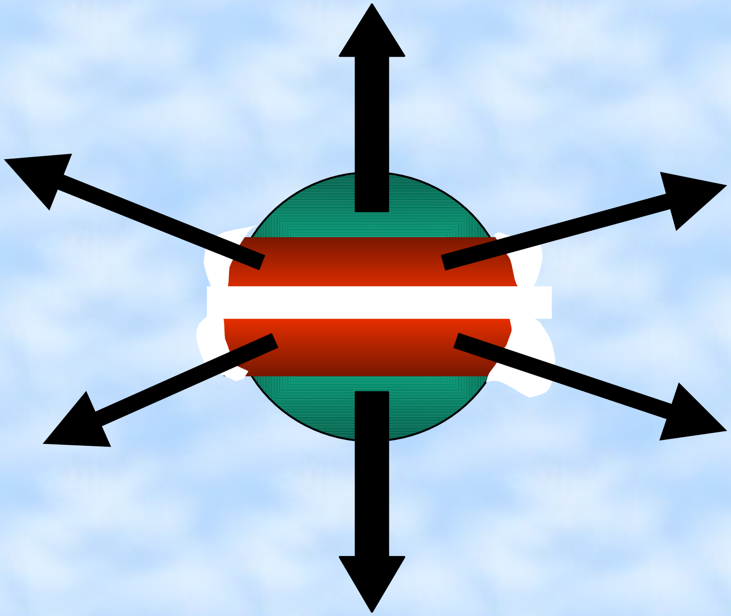
□ ***Coulomb repulsion from light fragments***

***This work implies the necessity to modify the step(2) in the standard picture of high-energy proton induced nuclear fragmentation.***

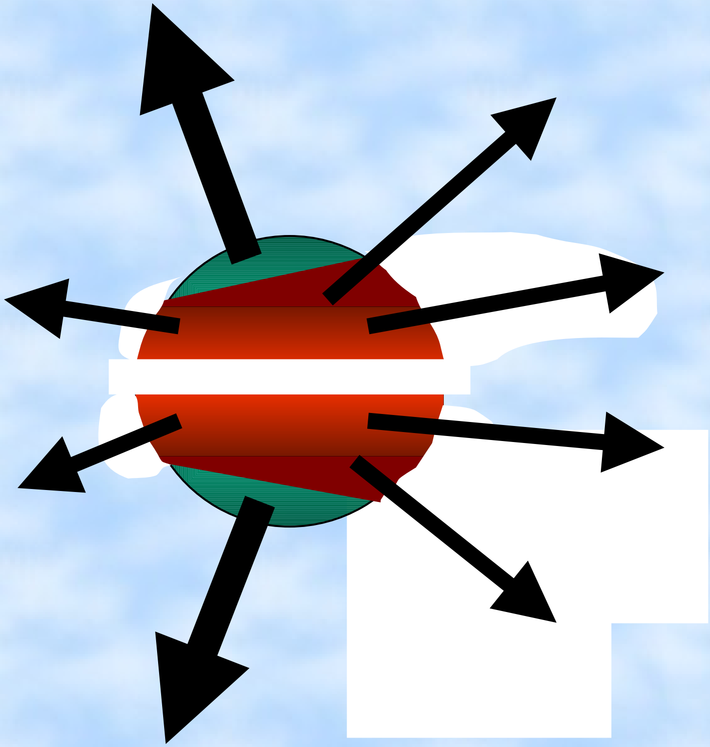
**(2)Residual excited nucleus reaches equilibrium.**

**→ (2)' The excited nucleus breaks up into fragments**
**from non-spherical shaped region**
**before reaching equilibrium.**

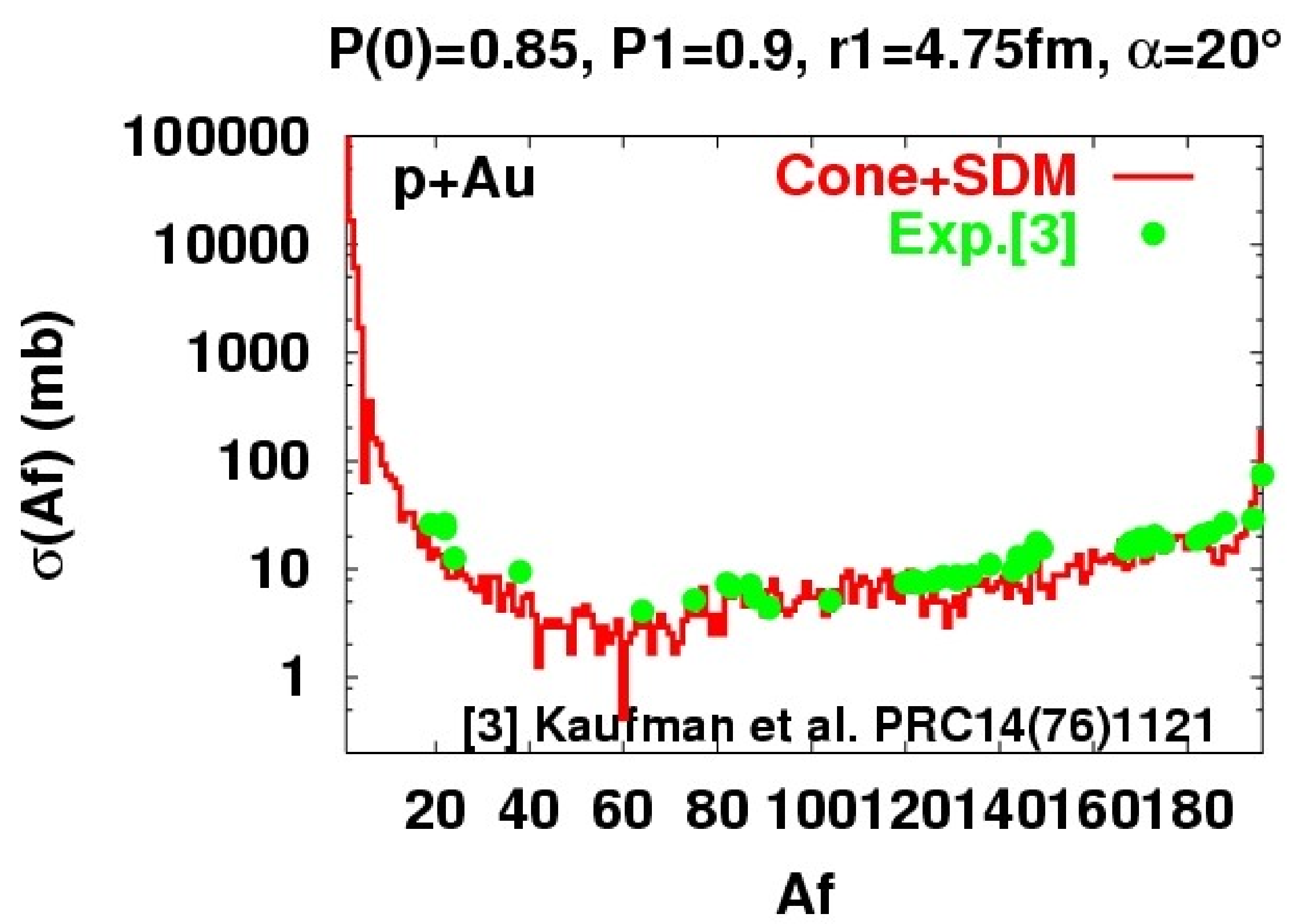
## Cylinder model



## Cone model

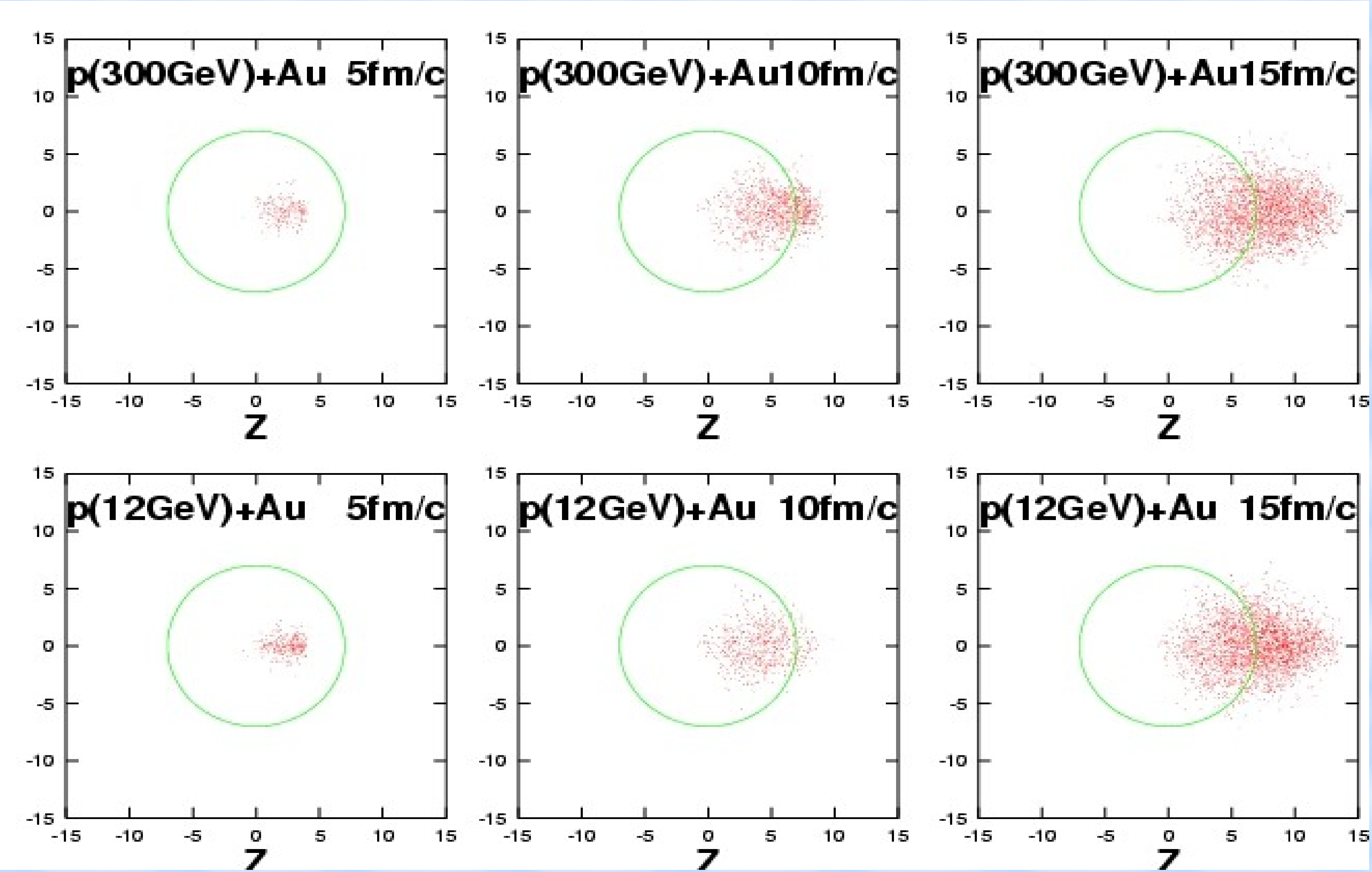


# Fragment Mass Distribution of Cone Model



# *JAM Calculation*

time



$$\xi \le 1 - \exp\left(-T\left(b\right)\right)$$

➡ **High temperature region is created.**

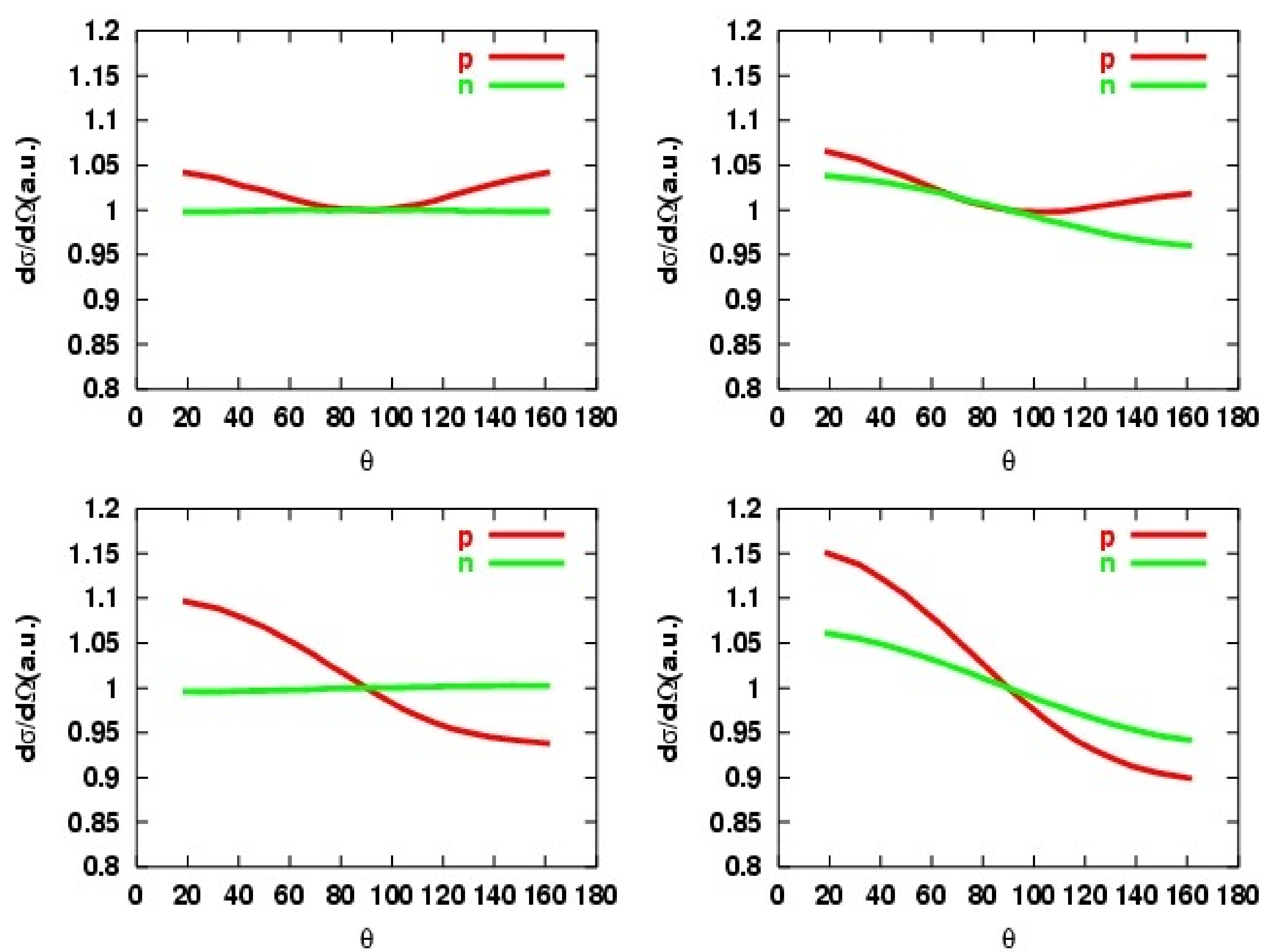
$$\xi \ge 1 - \exp\left(-T\left(b\right)\right)$$

➡ **High temperature region is not created.**

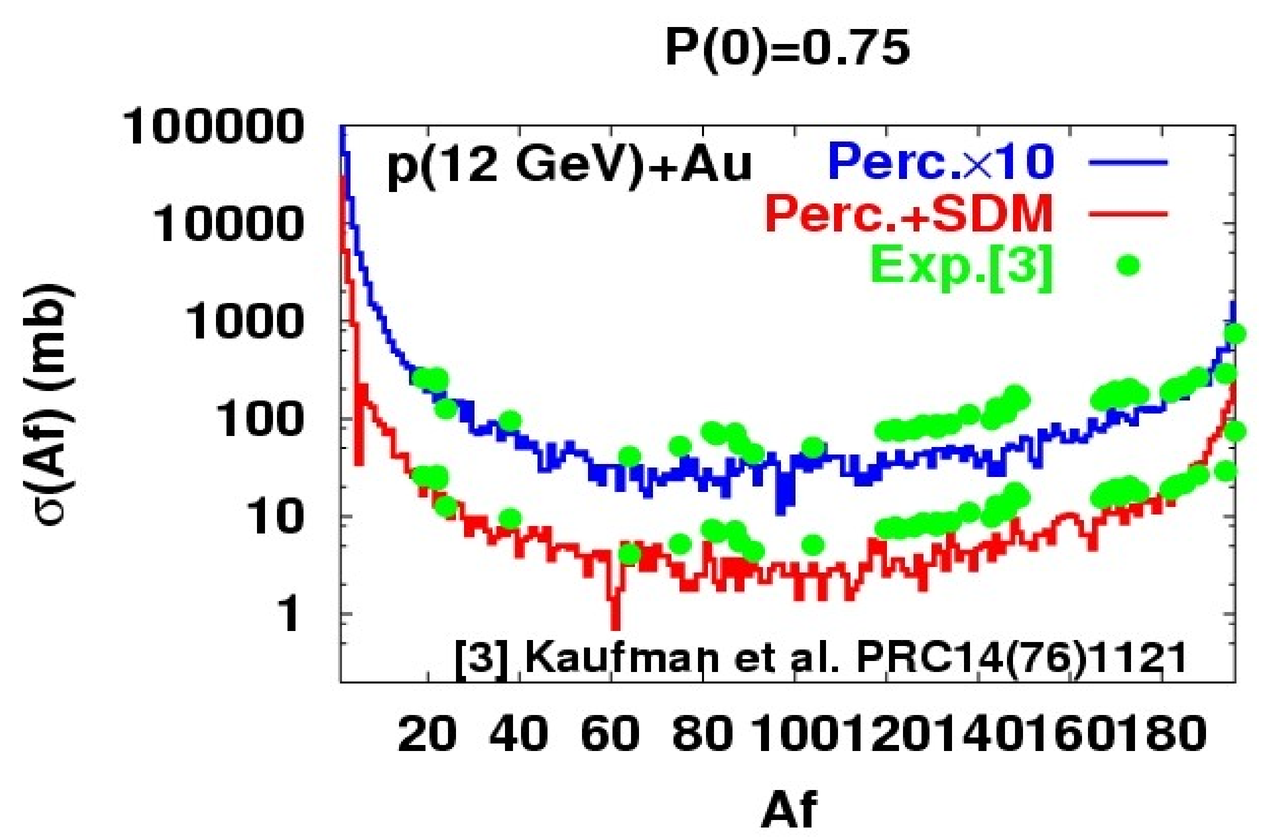
**C.M. system** **Lab. system**

**Cylinder**

**Cone**

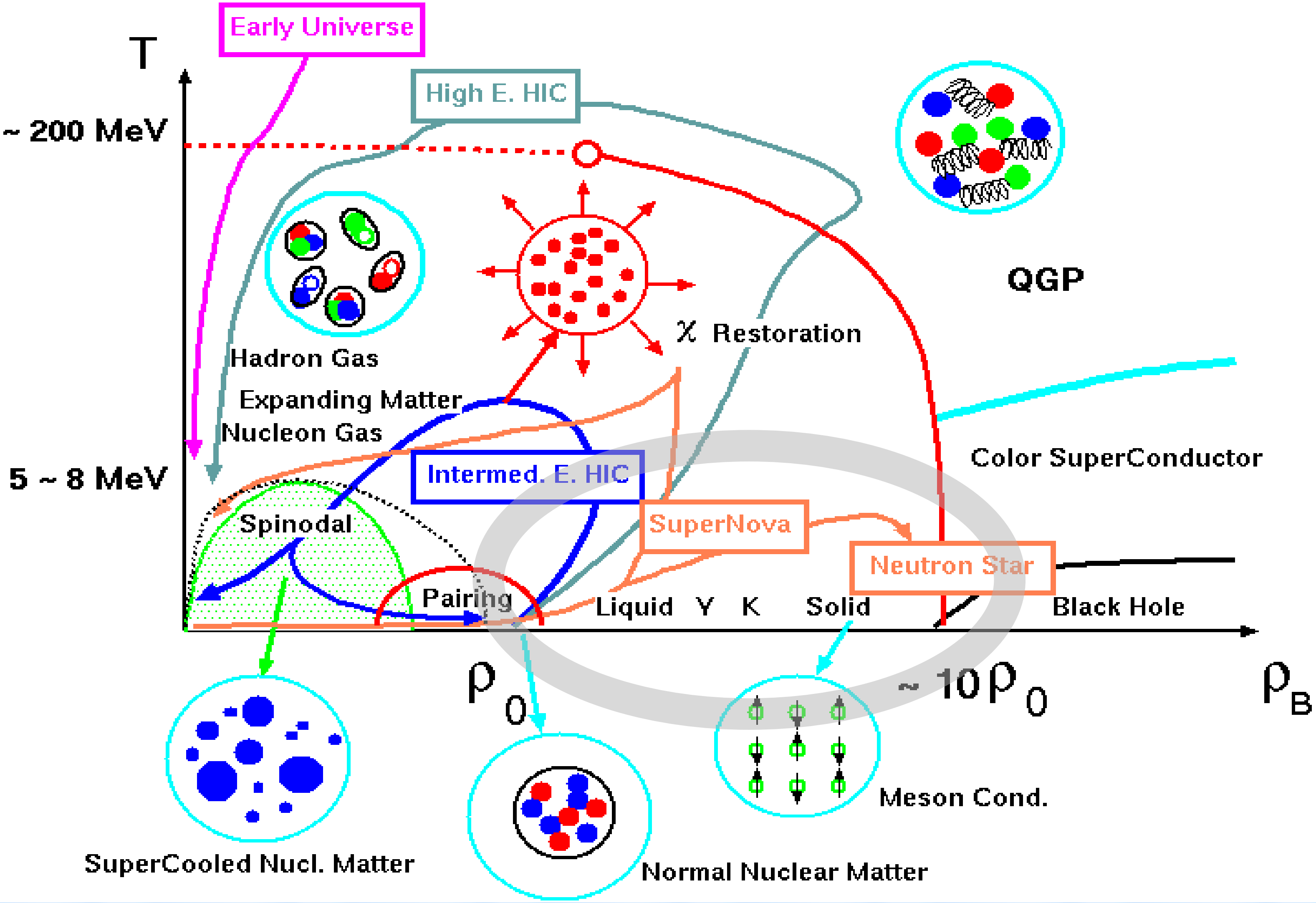


# *Perc. in comparison with Perc. + SDM*



# Part II:
# Roles of Strangeness in Dense Matter

# Hadronic Matter Phase Diagram



# *Contents*

Introduction — Roles of Hyperons in Dense Matter
What is Known, and What is Unknown ?
Several Recent Topics Related to Hyperons in Dense Matter
Summary

# What is Expected in the Neutron Star Core ?

**Nucleon Superfluid** $\left({}^1S_0, {}^3P_2\right)$

**Pion Condensation**

**Hyperon Matter ← Strangeness**

**Tsuruta-Cameron (66), Langer-Rosen (70), Pand-haripande (71), Itoh(75), Glendenning, Weber-Weigel, Sugahara-Toki, Schaffner-Mishustin, Balberg-Gal, Baldo et al., Vidana et al., Nishizaki-Yamamoto-Takatsuka, Kohno-Fujiwara et al., ...**

**Kaon Condensation ← Strangeness**

**Kaplan-Nelson(88), Forkel-Rho et al.(SUNY), Davidson-Miller, Claymans et al., Politzer-Wise, Miller et al., Muto-Tatsumi, Brown-Thorsson-Lee-Rho-Min, Fujii et al., Yabu et al, Maruyama et al., Ellis-Knorren-Prakashi (with Y ), Li-Ning, Li-Brown, Tiwari-Prasad-Singh, Glendenning-Schaffner, ....**

**Quark-Gluon Plasma**

**We cannot understand Highly Dense Hadronic Matter without the Knowledges of Strangeness Nuclear Physics**

# *Why is Strangeness important in Dense Matter ?*

**Constituents:**

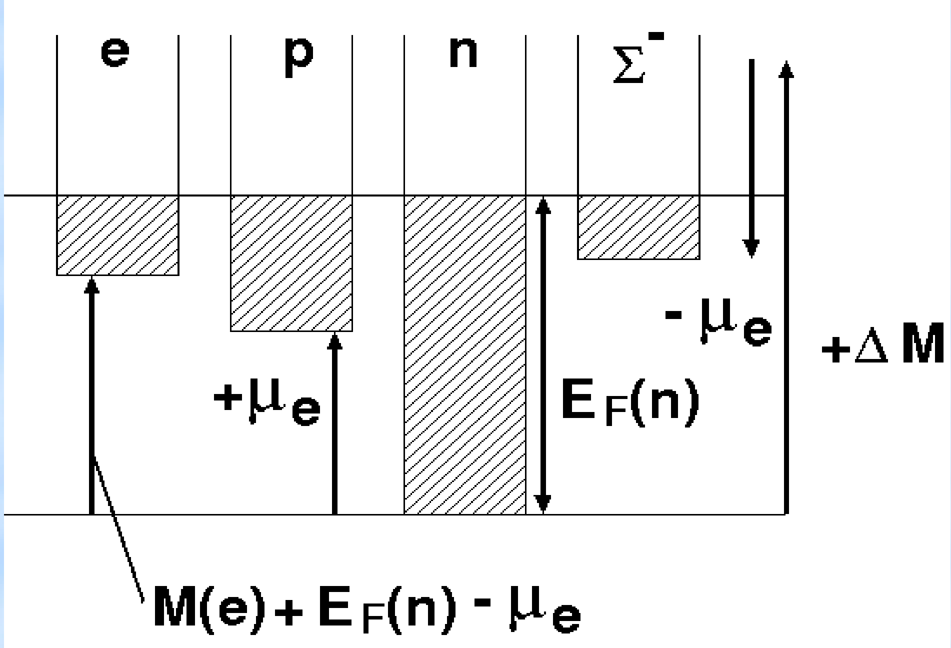
$$p\,,n\,,e^{\pm}\,,\mu^{\pm}\,,\Lambda\,,\Sigma^{\pm\,,0}\,,\ldots$$

**Chemical Equilibrium:**

× **Strangeness (Weak)**

× **Lepton (ν Emission)**

$$\mu_i = B_i\,\mu_B + Q_i\,\mu_Q$$

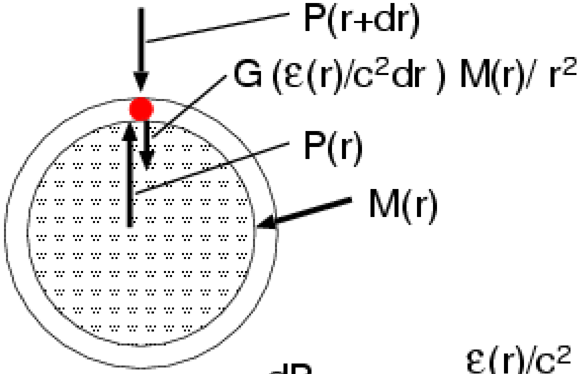


**Negatively Chaged or Neutral Baryons are Favored**

$$E_F^*(n)+U(n)+\mu_e = M^*(\Sigma^-)+U(\Sigma^-) \qquad \textstyle\sum \textbf{ appears}$$

$$E_F^*(n)+U(n) \qquad = M^*(\Lambda)+U(\Lambda) \qquad \Lambda \textbf{ appears}$$

# *TOV Equation: Balance of Pressure and Gravitation*



Non-Rela. $\frac{dP}{dr} = - G \frac{\varepsilon(r)/c^2 \;\; M(r)}{r^2}$

$$\frac{dP}{dr} = -G\frac{(\varepsilon/c^2 + P/c^2)(M + 4\pi r^3 P/c^2)}{r^2(1 - 2GM/rc^2)}$$

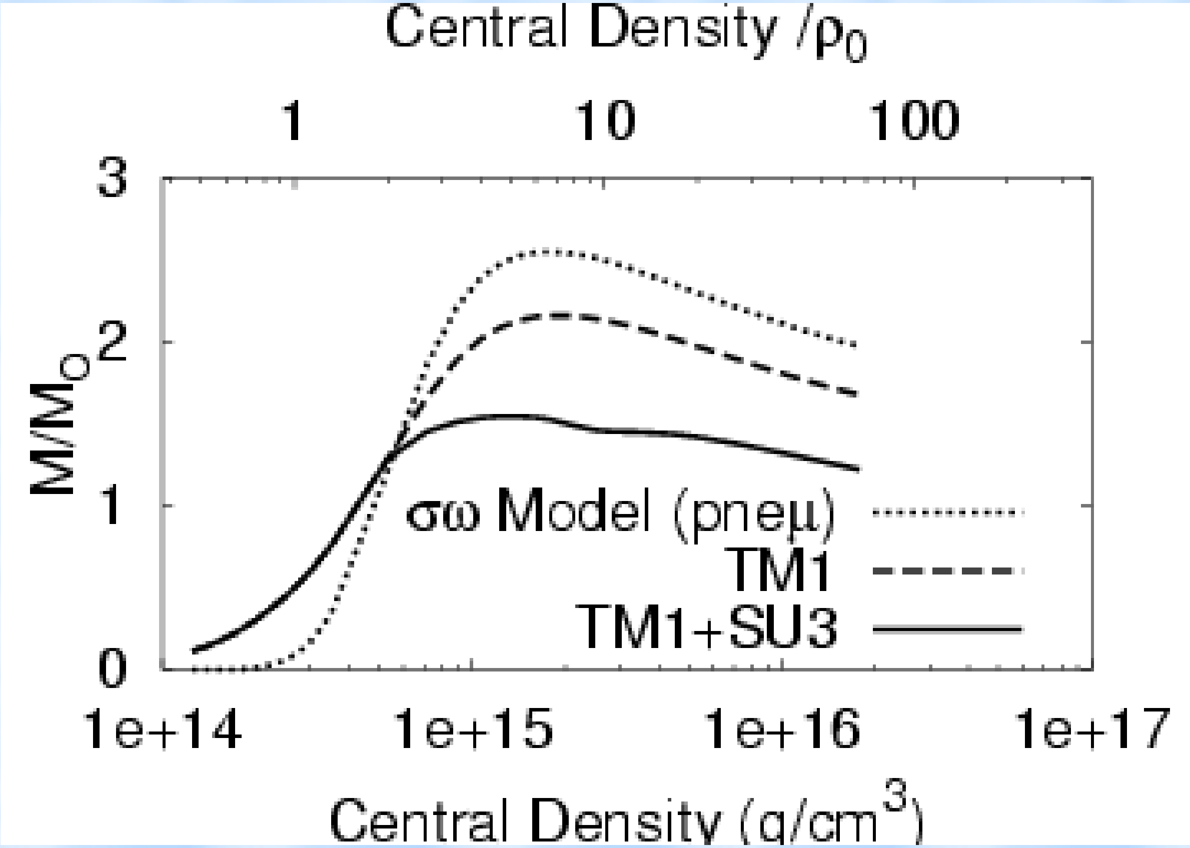
$$\frac{dM}{dr} = 4\pi r^2 \varepsilon/c^2 \; , \quad \frac{dP}{dr} = \frac{dP}{d\varepsilon}\frac{d\varepsilon}{dr}$$

$$P = P(\varepsilon) \; , \quad \frac{dP}{d\varepsilon} = \frac{dP}{d\varepsilon}(\varepsilon) \quad \text{(EOS)}$$

**Neutron Star Mass = M(R), where P(R) = 0**

***When You Make a New EOS, Please Check Neutron Star Mass !***

# Neutron Star Max. Mass



**A. Isshiki, AO, JPS @ Akita; Serot-Walecka (σω);**
**Sugahara-Toki (TM1); Schaffner-Mishustin (TM1+SU3); Glendenning, ...**

**Maximum Mass Reduction ~ 0.5-1.0** $M_{sun}$

# *$\Sigma$ Potential Effects on Neutron Star Matter*

**Potential for $\Lambda$; Relatively Well Known**

$U(\Lambda) \sim -30\,MeV$ **(Many Single Hypernuclei)**

**Potential for $\Xi$; Recently Suggested from** $(K^-, K^+)$ **Experiments**

$U(\Xi) \sim -(14-16)\,MeV$

**(KEK-E224, BNL-E885, BNL-E906)**

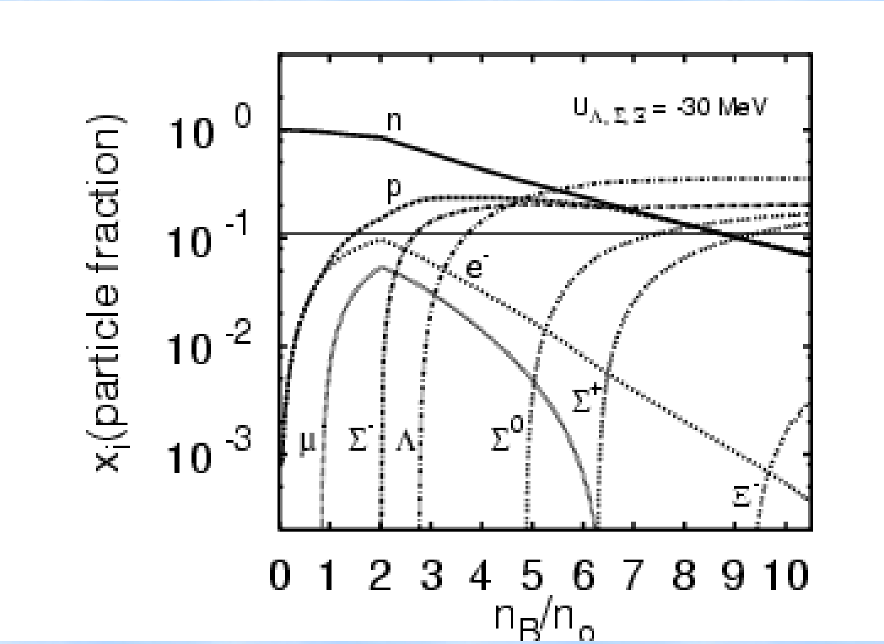
→ ***Potential Depth $\propto$ Number of ud Quarks ?***

**Potential for $\Sigma$: Contradicting Conjectures**

$U(\Sigma) \sim -(24-30)\,MeV$ **(Old Conjectures)**

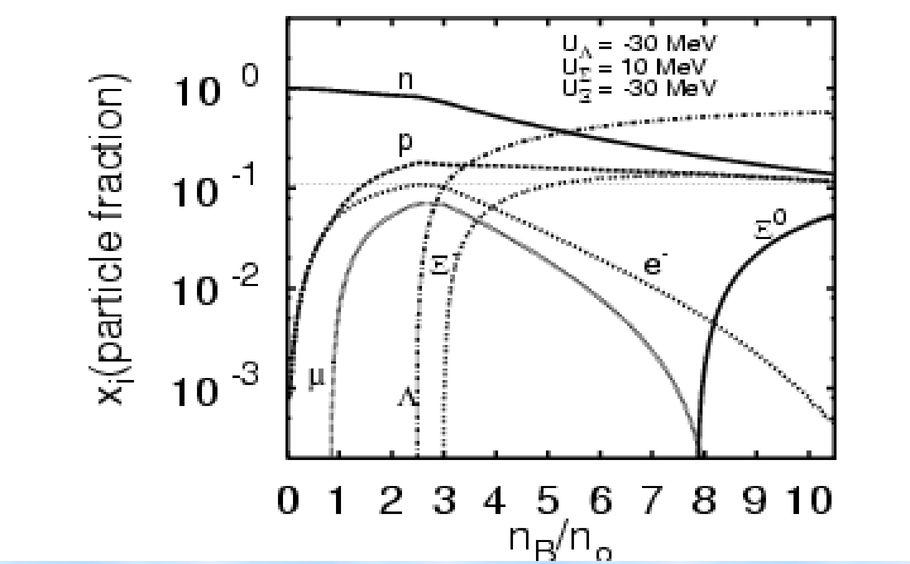
$U(\Sigma) > 0$

**(Dabrowski, Yamamoto et al., Kohno-Fujiwara et al.)**



**Attractive Potential for ∑**
**➜ ∑ appears at around**

$$\rho \approx 2\,\rho_0$$



**Repulsive Potential for ∑**
**➜ ∑ does not appear**

**(RMF: Sahu, Ohnishi Nucl. Phys. A691 (2001), 439.)**

# *What is Already Known ?*

**Light Single Λ Hypernuclear Shell/Cluster Structure**
**Bare Λ N Interaction**
  **Germanium γ -ray Detector(Tamura et al.)**
 **+Precise Few-Body Calculation (Hiyama et al., Nemura et al.)**
**Structure of $^{4}_{\Lambda}$He :**
  **Coherent ΛΣ Coupling**
   **(Harada-Akaishi-Shinmura-Myint, Hiyama et al.)**
**ΛΛ Interaction in Nuclei = Weakly Attractive**
  **Recent Experiment KEK-E373 (Nagara Event)**

# *What is Still Unknown ?*

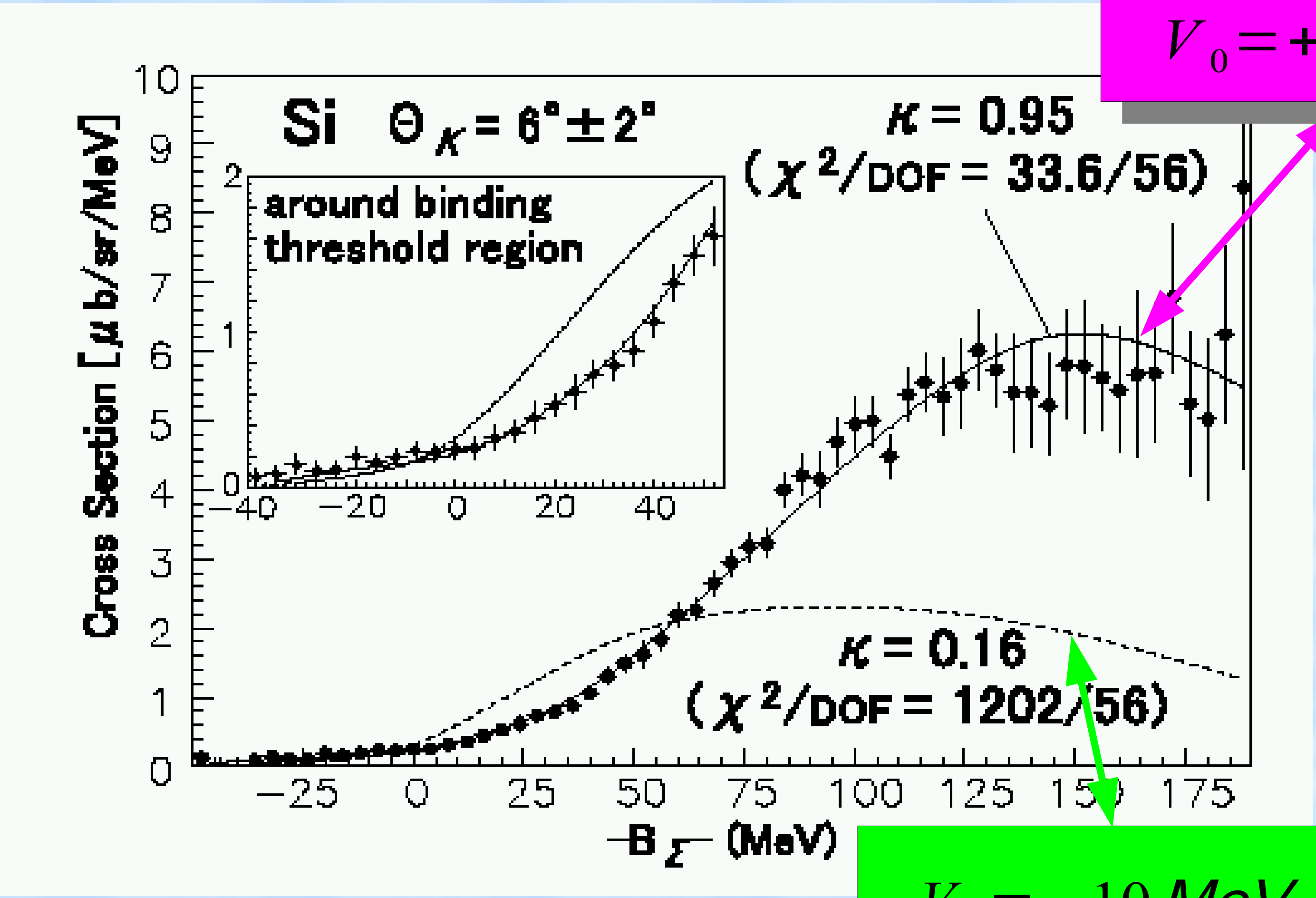
- Properties of Hyperons (All) at Higher Densities.
- $\Sigma$ Potential at $\rho_0$ and Higher Densities
- $\Lambda\Lambda$ Interaction in “Free” Space

➡ Very Recent Experiments !

Direct Quasi-Free Production of $\Sigma$ (Noumi et al.)
Strangeness Enhancement in HIC at SPS (NA49)

# Does $\Sigma$ Feel +150 MeV (Repulsive) in Nuclei ?

**Noumi et al., Phys. Rev. Lett. 89 (2002) , 072301.**



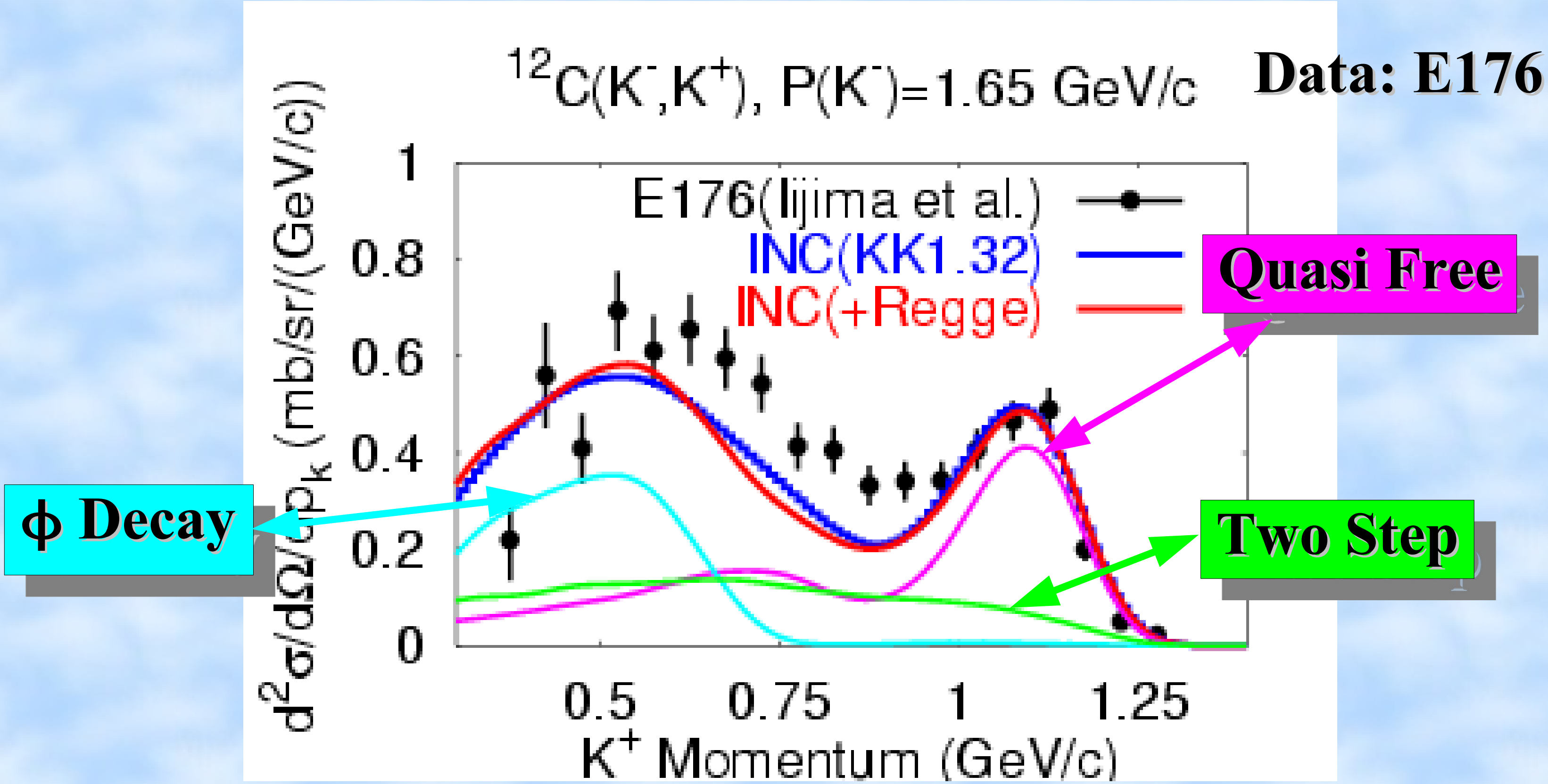
$V_0 = +150\ MeV$

$V_0 = -10\ MeV$

**No Theoretical Model Support** $V_0 = +150\ MeV$ **! ➡ Big Puzzle !!**

# *Multi-Step Effects ?*

**In the case of $\left(K^{-}, K^{+}\right)$ Reaction,**
**Multi-Step Effects was Important to Understand**
***Highly Excited Region.***

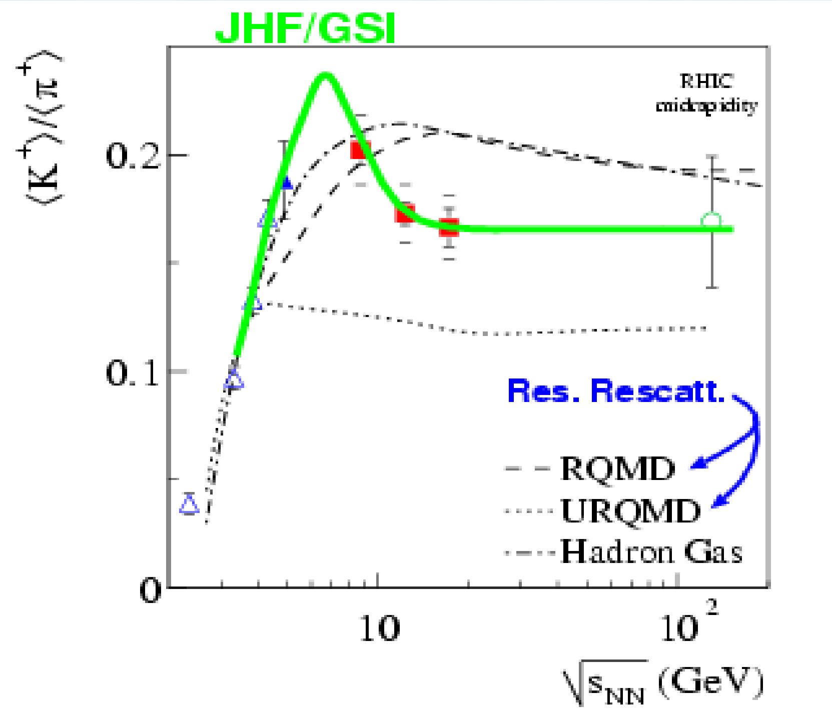


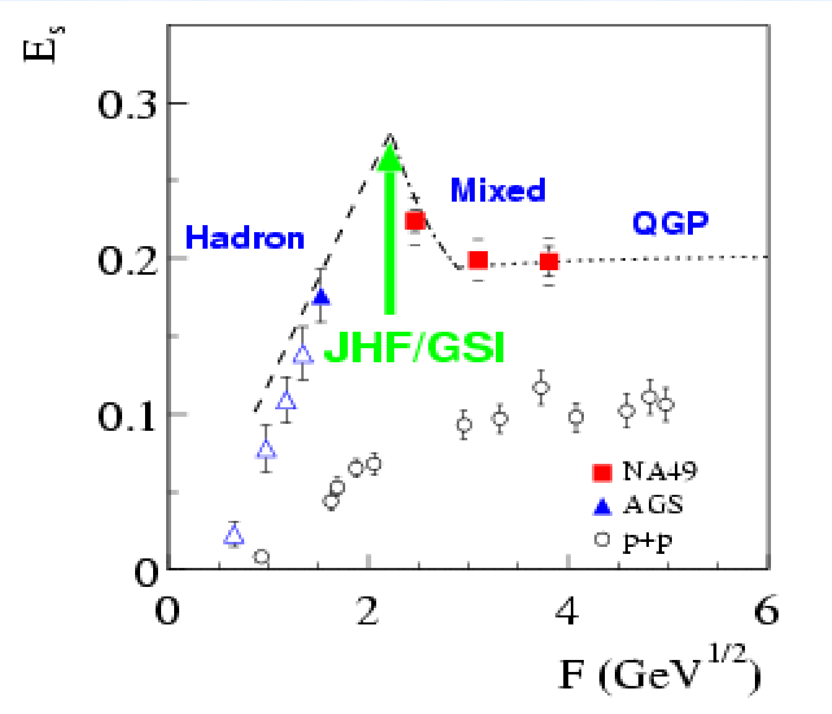
***Is it also Important in $\left(\pi^{-}, K^{+}\right)$ Reactions ?***

# *Strangeness Enhancement: Rescattering, Potential, or Phase Transition ?*

**Strangeness is Enhanced Sharply at Einc = 10 □ 40 GeV/A !**

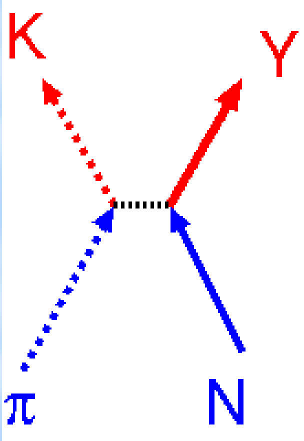
**NA49 (nucl-ex/0205002)**



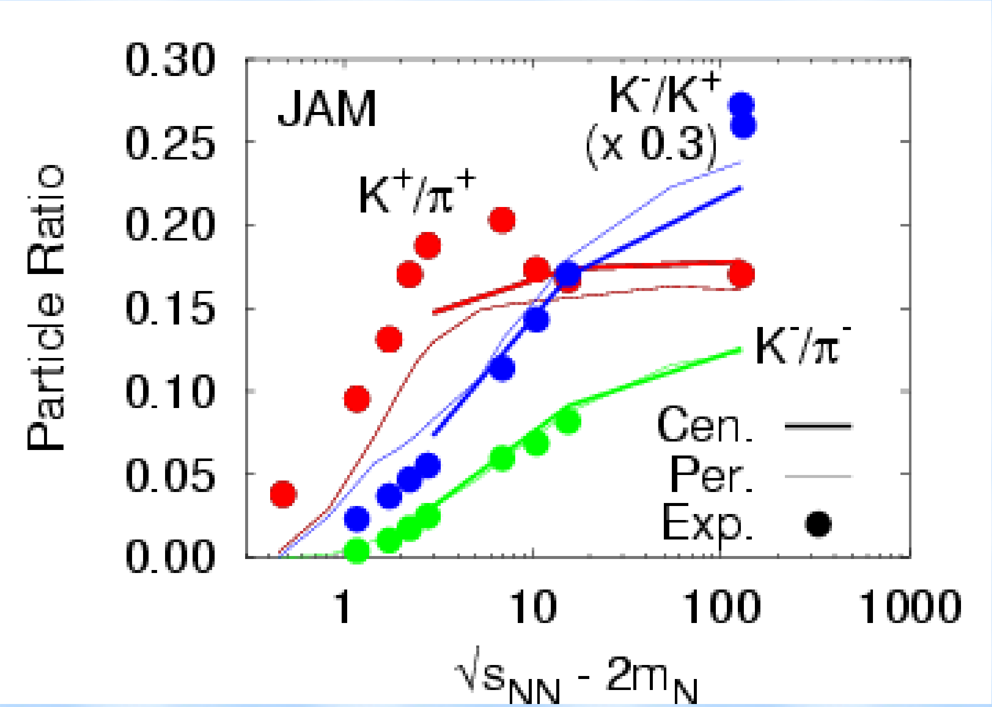


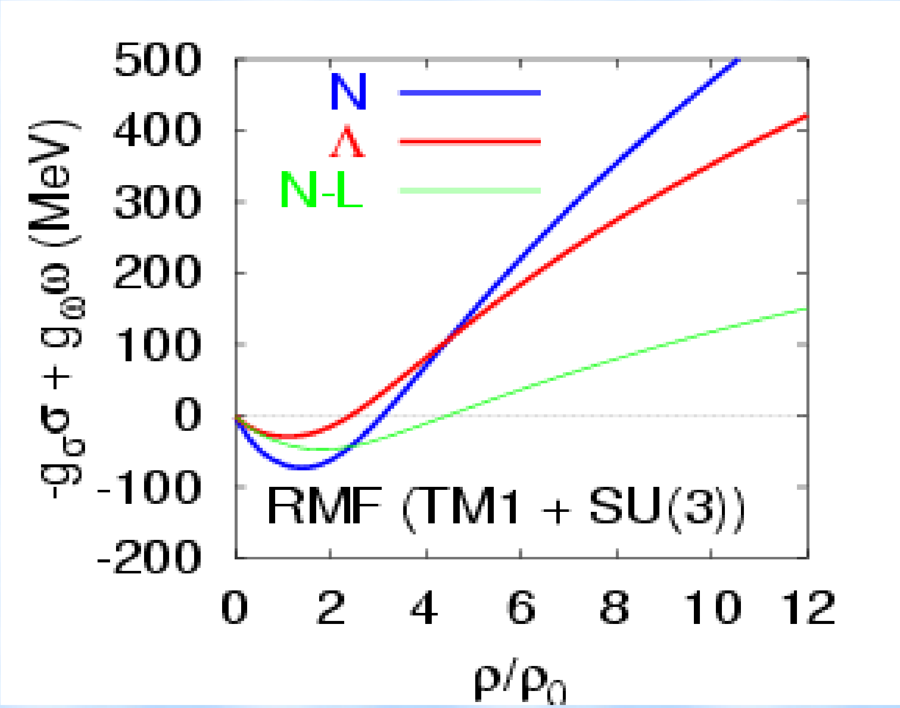
**JHF Energy: ~ Maximum K/π ratio**

# *Does Hyperon Potential Help It ?*



**Rescattering of Resonances/Strings (RQMD)**
**Baryon Rich QGP Formation**
**High Baryon Density Effect (Associated Prod. of Y**





**At $\rho > 5\rho_0$ Hyperon Feels More Attractive Potential than N**

# *Is Lambda-Lambda Interaction Really Weak ?*

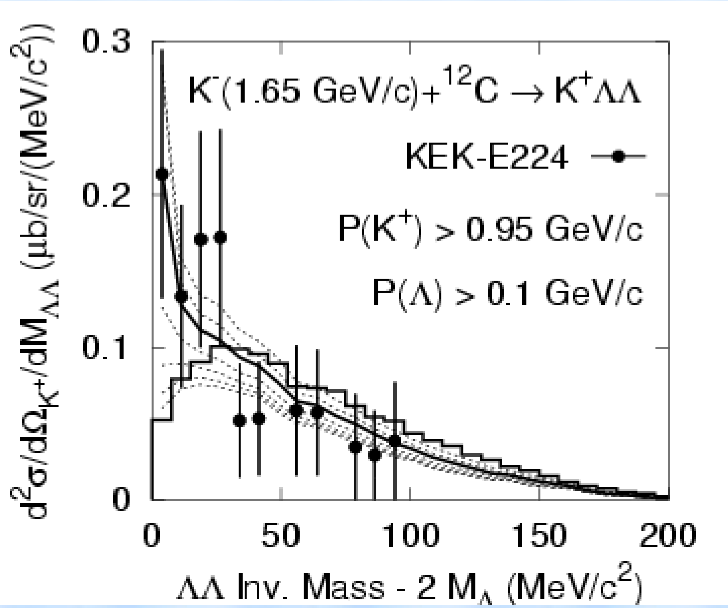
**Khin Swe Myint, Shinmura, Akaishi, Euro. Phys. J. A16 (2003) 21.**

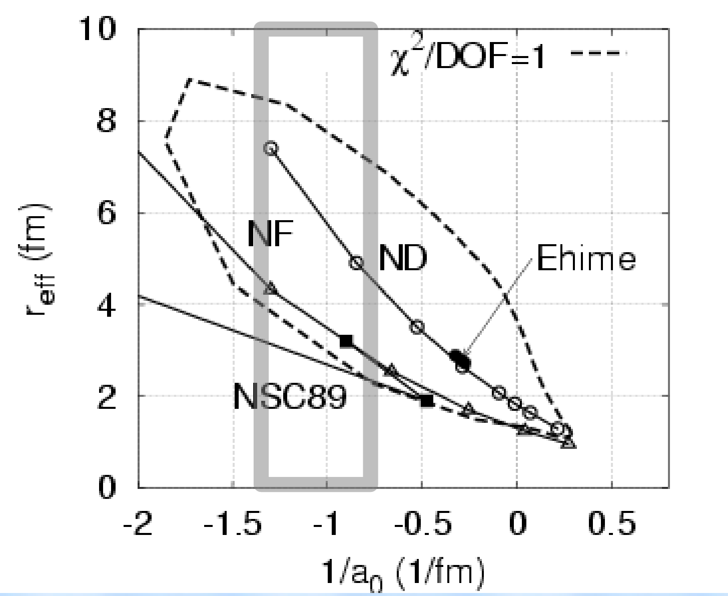
**From Nagara Event,**

$a_{\Lambda\Lambda}=0.7$ *fm (Weak* $\Lambda\Lambda-\Xi N$ *Coupling)*

$\sim 1.3$ *fm (Strong Coupling, Pauli Suppressed in Nuclei)*

## Momentum Correlation of ΛΛ





***We have the range of overlap !***

# *Summary*

1. **Strangeness is important in dense matter such as in neutron star core.**

   *Strangeness changes the max. mass of neutron star,*
   *modifies the order of QCD phase transition,*
   *probes deeply inside the nucleus,*
   *mixes elementary particles in nuclei.*

2. **Hypernuclear spectroscopy have developed a lot in these years, but we need more data for the understanding of dense matter.**

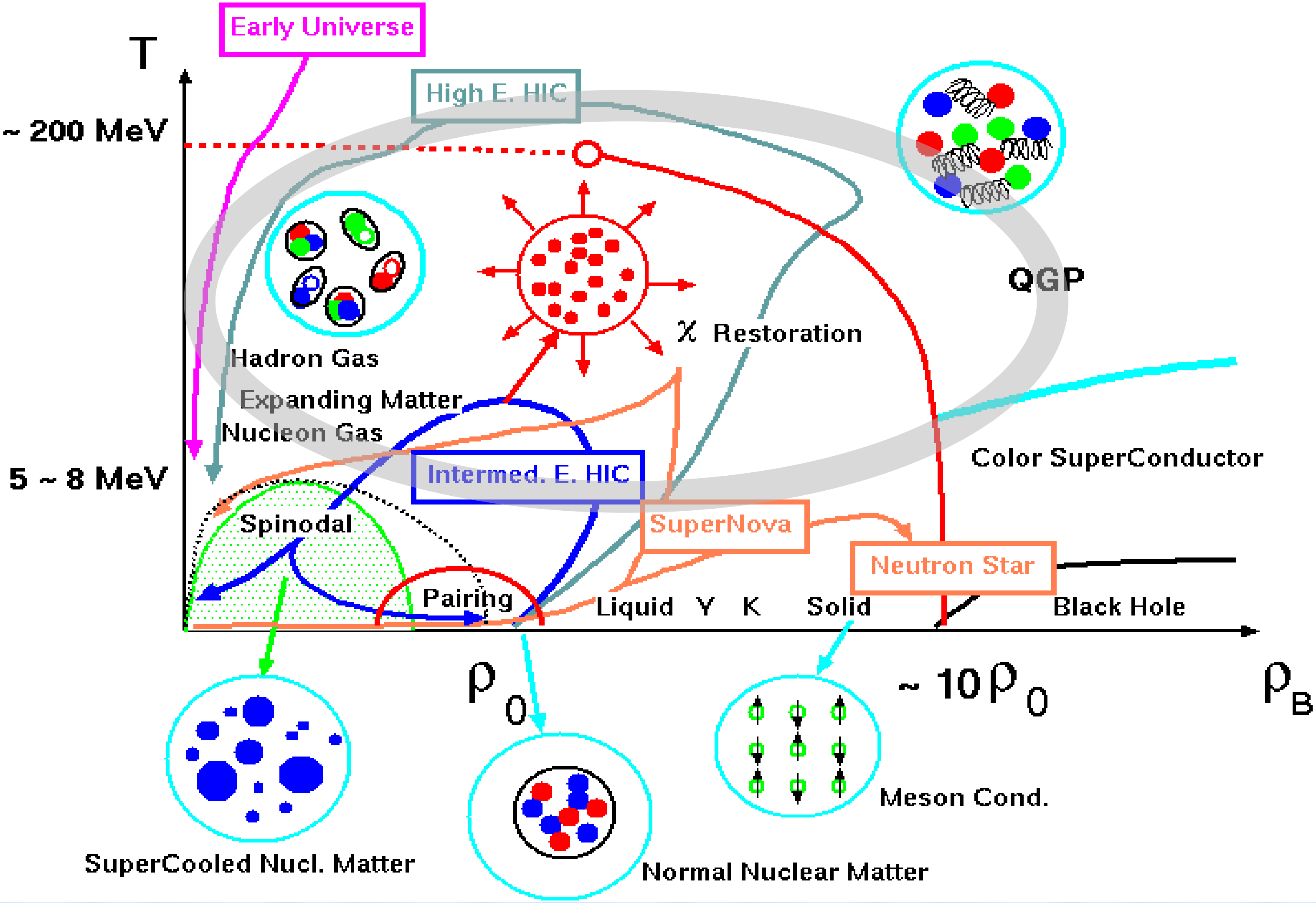
   *∑ Potential, ΛΛ Interaction, ΛN-∑N and ΛΛ-ΞN Coupling,*
   *Hyperon Potential in Dense Matter, ....*

3. **Recent Data would be Helpful to Understand Hyperons in Dense Matter based on *Real Data***

   *Quasi Free ∑ Production, Kaon Enhancement, ΛΛ Nuclei,*
   *ΛΛ Correlation, ....*

# Part III:
# High Energy Heavy-Ion Collisions, and Equation of State of Hot / Dense Matter

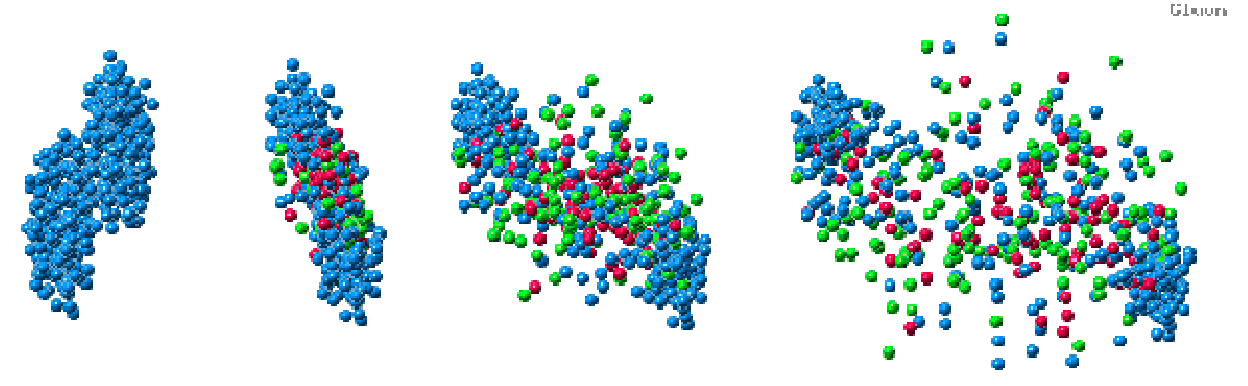
# Hadronic Matter Phase Diagram



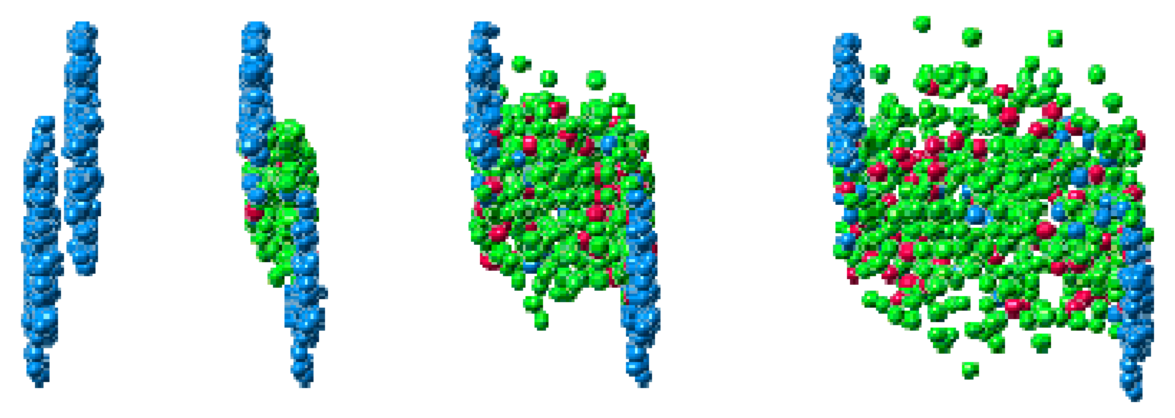
# JAMming on the Web

http://nova.sci.hokudai.ac.jp/~ohtsuka/

## AGS

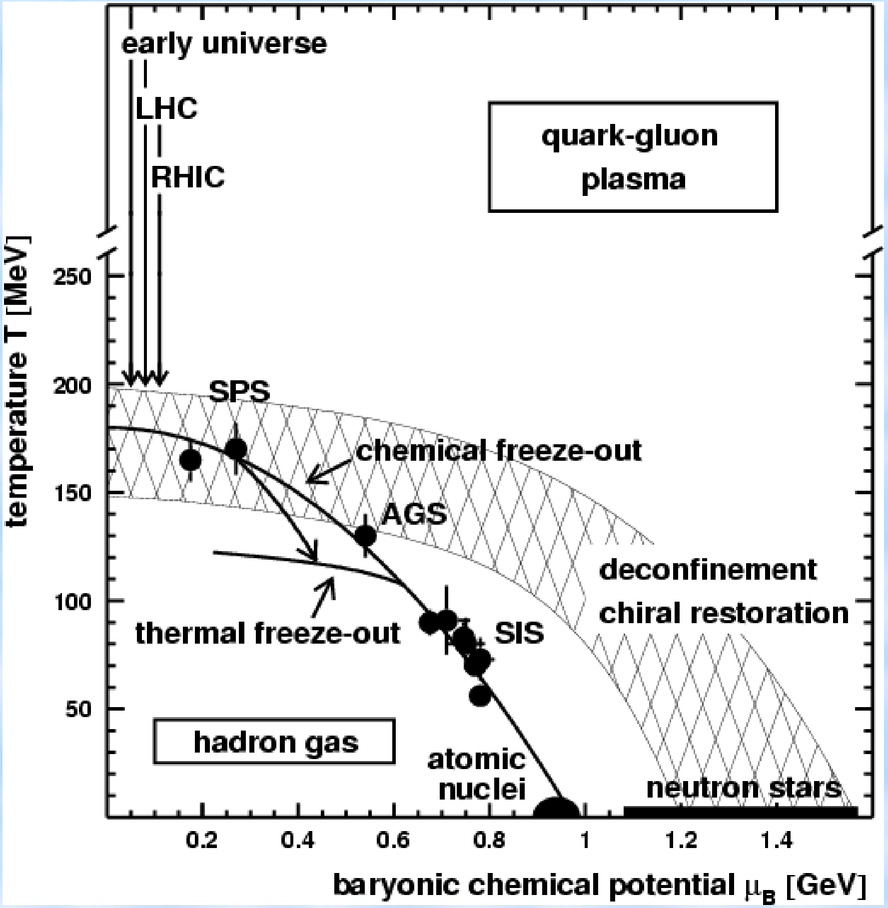


## SPS

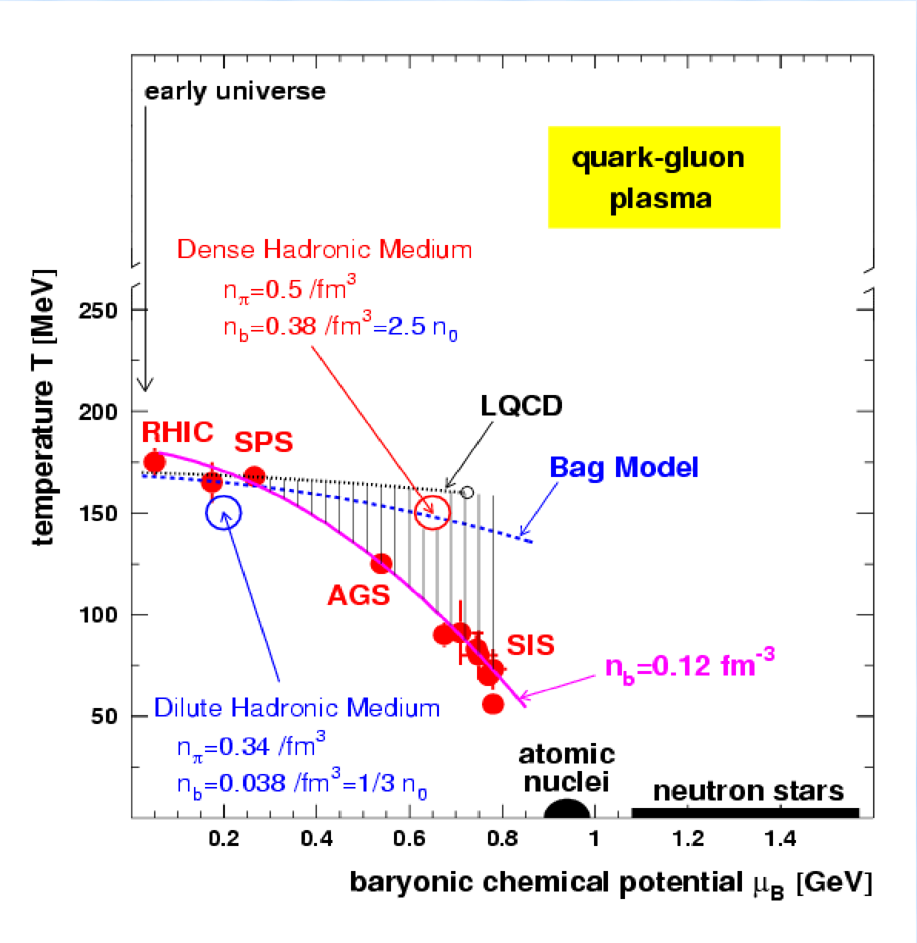


# *Experimentally Estimated Phase Diagram*

## Chemical Freeze-Out Points in High-Energy Heavy-Ion Collisions



1998 (J. Stachel et al.)

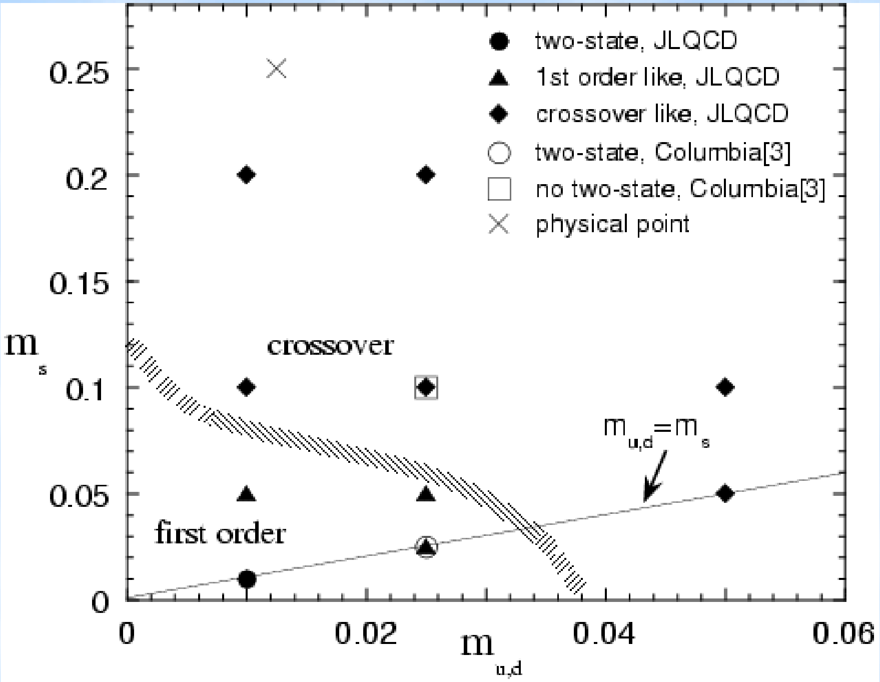


2002 (Braun-Munzinger et al.
J. Phys. G28 (2002) 1971.)

**Chem. Freeze-Out Points are very Close to Expected QCD Phase Transition Boundary**

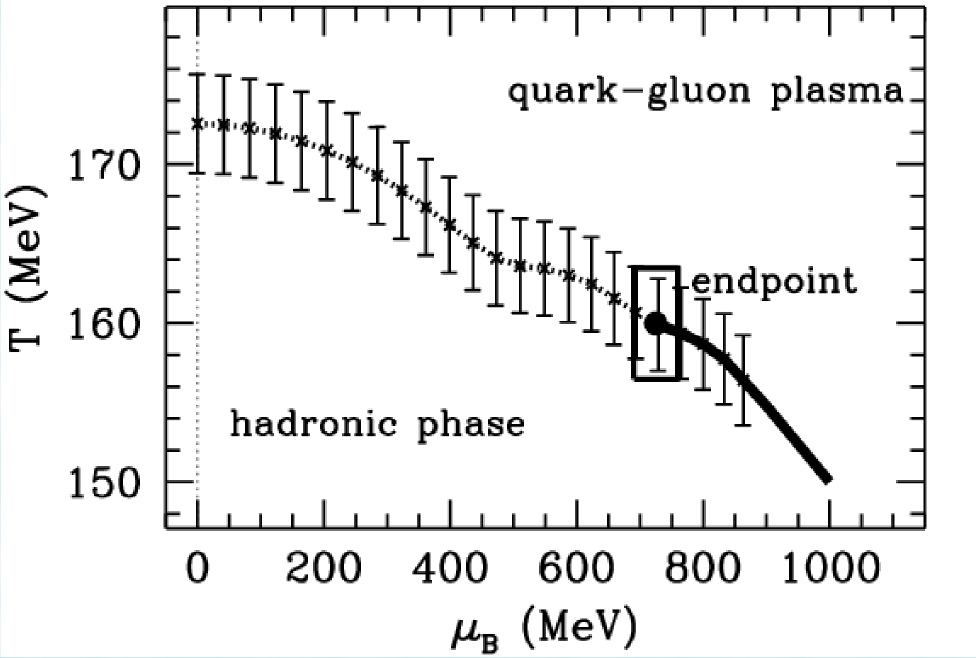
# *Theoretically Expected QCD Phase Diagram*

**Zero Chem. Pot.**



JLQCD Collab. (S. Aoki et al.),
Nucl. Phys. Proc. Suppl. 73 (1999) 459.

**Finite Chem. Pot.**



Finite □: Fodor & Katz,
JHEP 0203 (2002), 014.

Zero Chem. Pot. : *Cross Over*
Finite Chem. Pot.: *Critical End Point*

# *Is QGP Formed at AGS, SPS and/or RHIC ?*

**Proposed and/or Measured Signals**

**Collective Flow (AGS, SPS, RHIC)**
*EOS modification / Thermalization Degree*
**Low-Mass Lepton Pair (Yes @ SPS, Not Yet @ RHIC)**
*Partial Restoration at High Temperature/Density*
**High-Mass Lepton Pair (Yes @ SPS, Preliminary @ RHIC)**
*J/Ψ Suppresion at High Temperature*
**Jet Energy Loss ( @ RHIC)**
*Parton Dynamics at High (Freed) Gluon Density*
**Strangeness Enhancement (Yes @ AGS, Lower E. SPS, No @ RHIC)**
*Rescattering or Potential at High Density or QGP*

**Later on, I mainly Discuss *Collective Flows***

# *What is Collective Flow ?*

**(Directed) Flow ($dP_X/dY$)**

Stiffness (Low E)
+ Time Scale (High E)

**Elliptic Flow ($V_2$)**

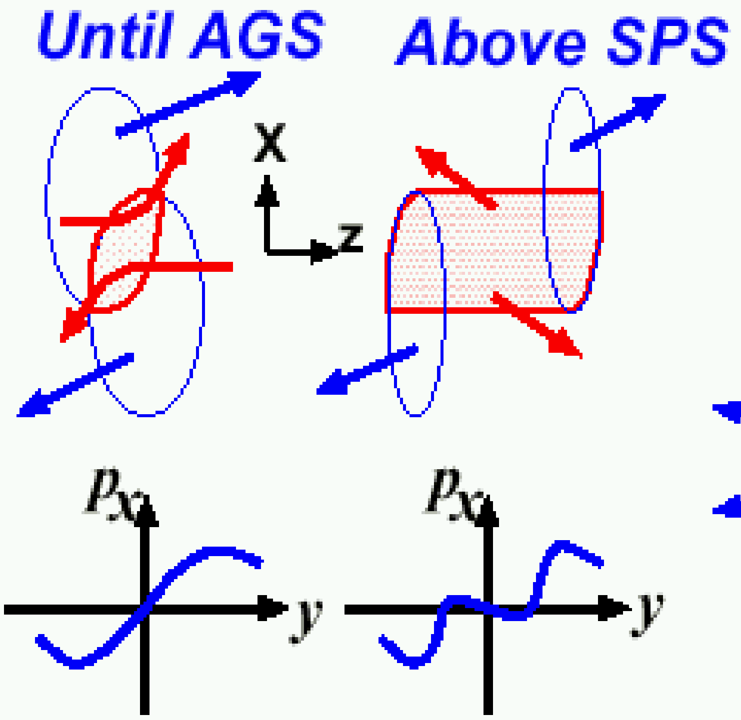
Thermalization
& Pressure Gradient

**Radial Flow ($\beta_T$)**

Pressure History

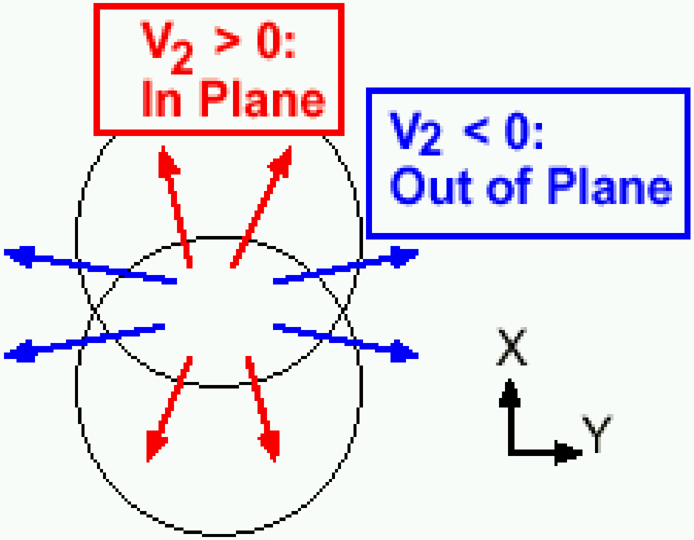
$$\epsilon \frac{DV}{Dt} = -\nabla P$$

$$\rightarrow V = \int_{path} \frac{-\nabla P dt}{\epsilon}$$



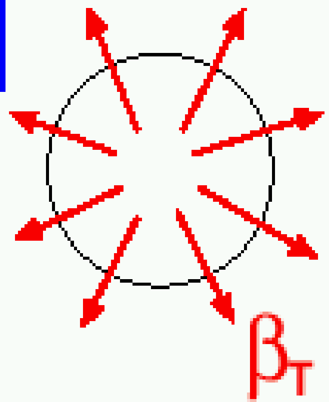
**Until AGS**

**Above SPS**



**$V_2 > 0$:**
**In Plane**

**$V_2 < 0$:**
**Out of Plane**



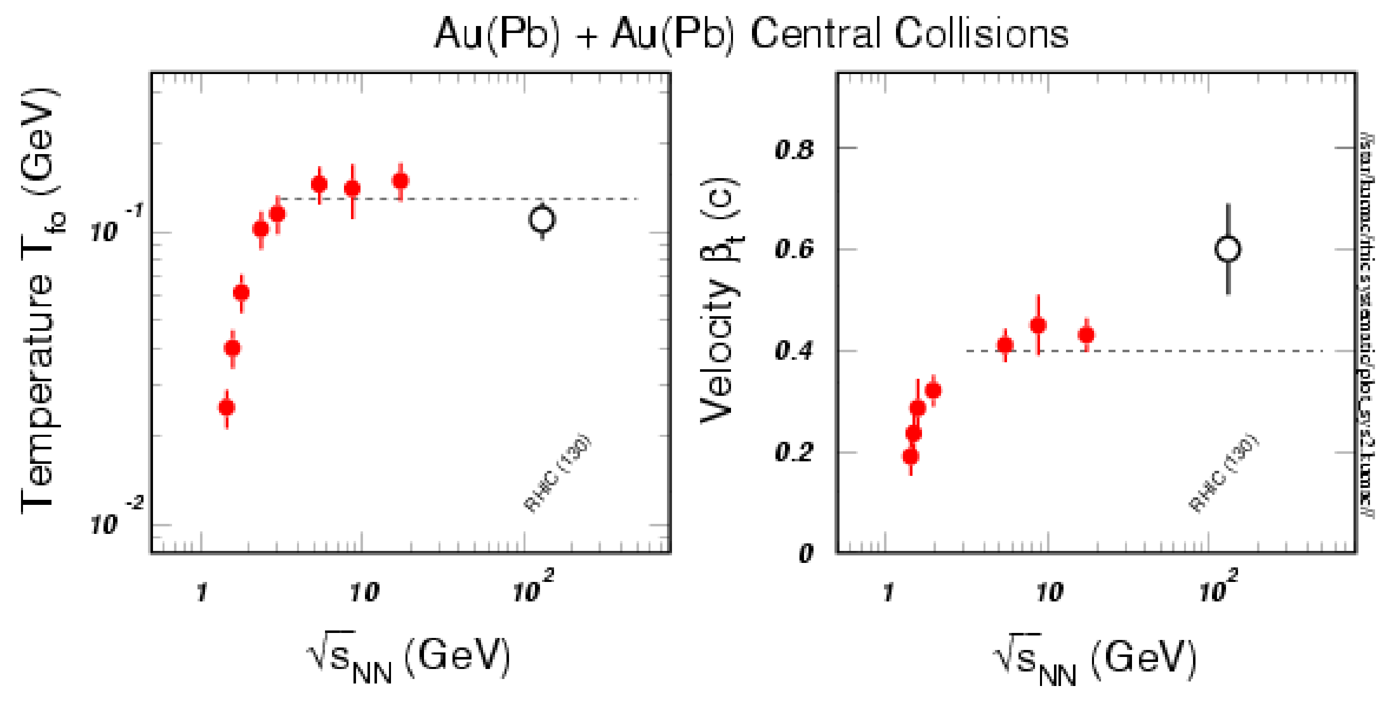
**Complex Observables, but Closely Related to EOS**

# *Can we see ANOMALIES in Collective Flows at RHIC ?*

## *Answer = Yes !*

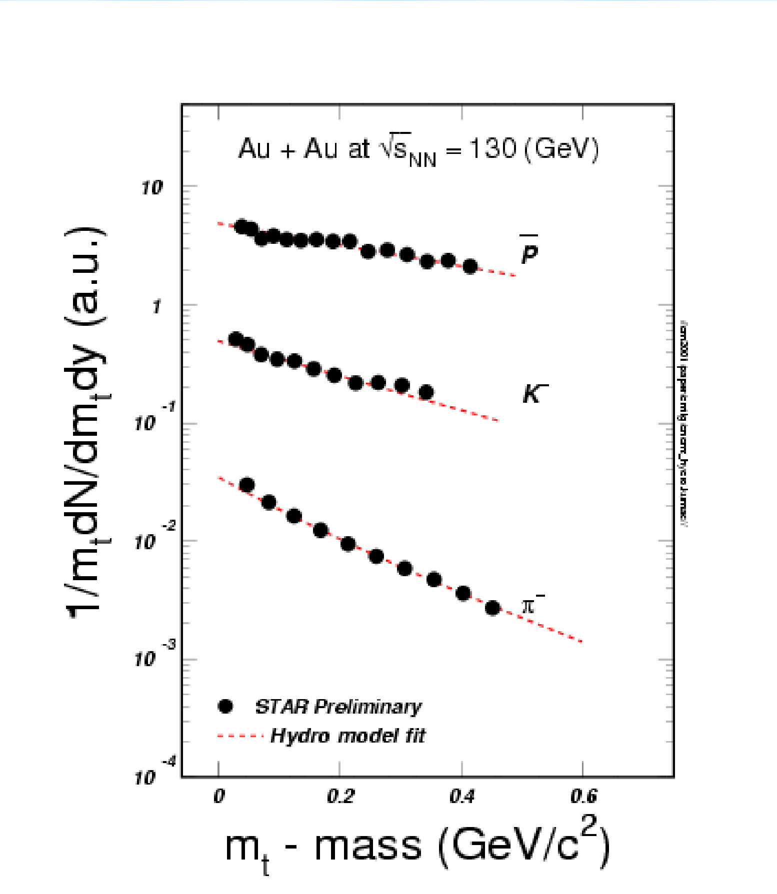
## *Radial Flow*

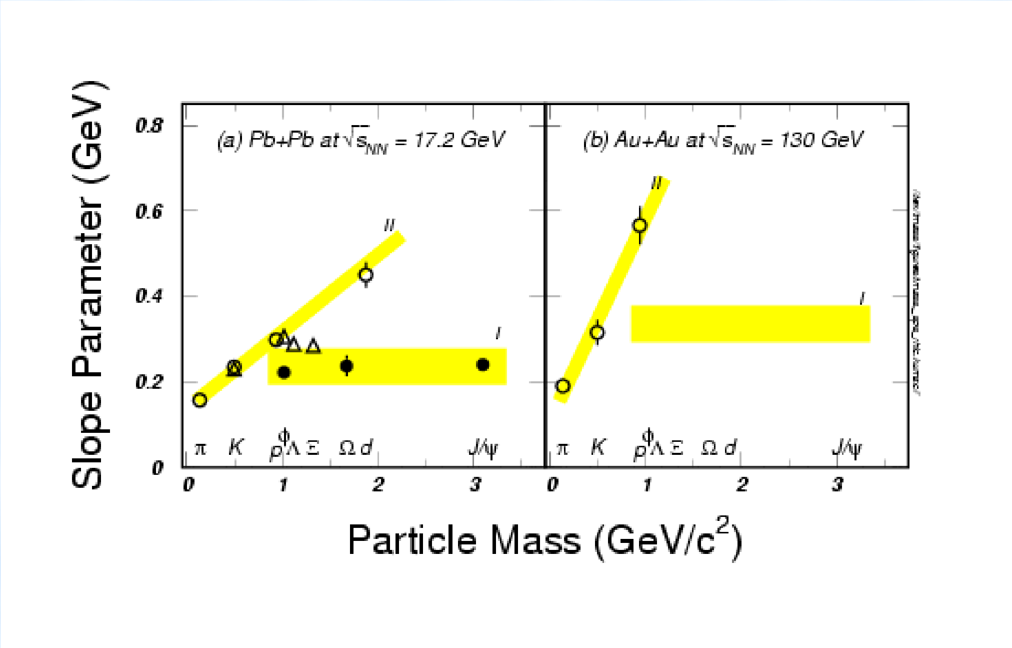
**Nu Xu and M. Kaneta (STAR)**



**Formed matter seems to become STIFF Quickly at RHIC**

# *How can we estimate Collective Radial Flow ?*
# *…. Mt Spectra of Several Particles*





$$\frac{d^2N}{M_t dM_t dY d\phi} \propto \exp(-M_t/T'), \quad T'(M) = T + \frac{1}{2} M\,\beta^2$$

# Simple Model of QCD Phase Transition

**Massless Particles at Zero Chem. Pot.**

$$\Omega = -\frac{\pi^2 V}{90}\left(\sum_B g_B + \frac{7}{8}\sum_F g_F\right) T^4,$$

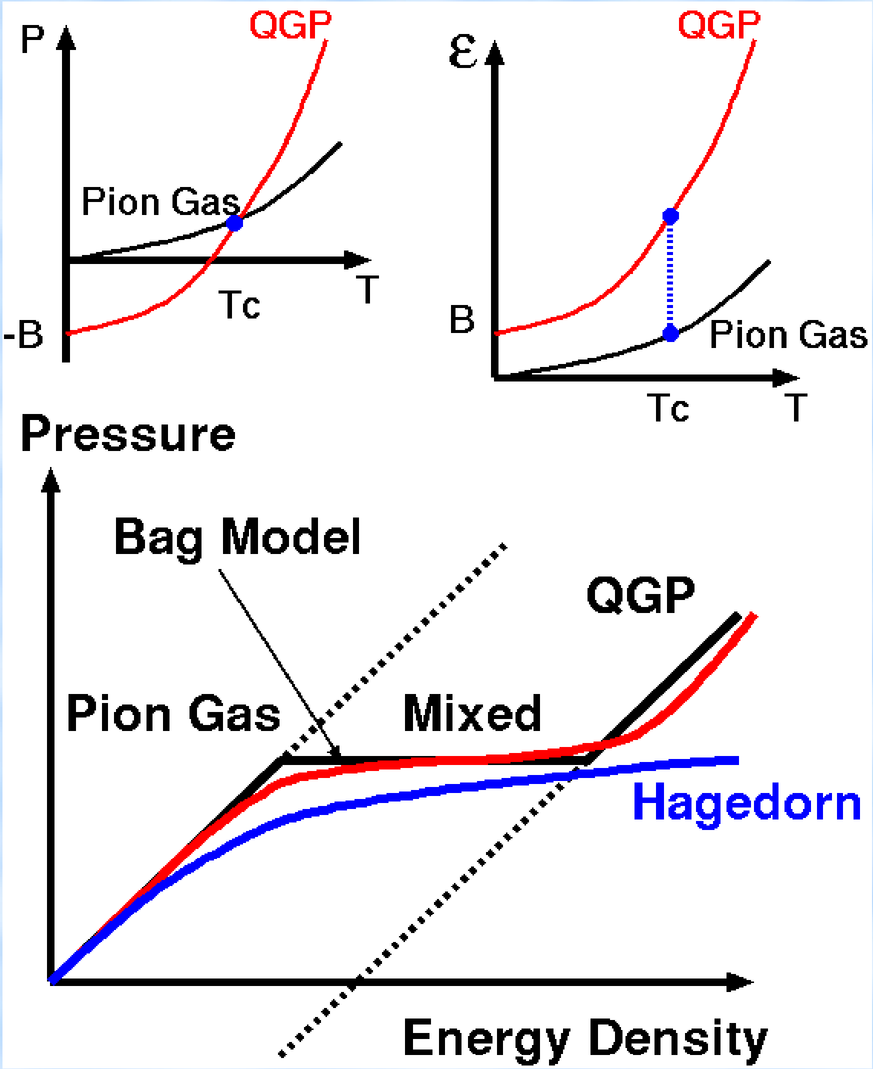
**Massless (Free) Pion Gas**

$$P_\pi = \frac{\pi^2}{30} T^4 \quad , \qquad \epsilon_\pi = \frac{\pi^2}{10} T^4$$

**QGP with Finite Bag Constant**

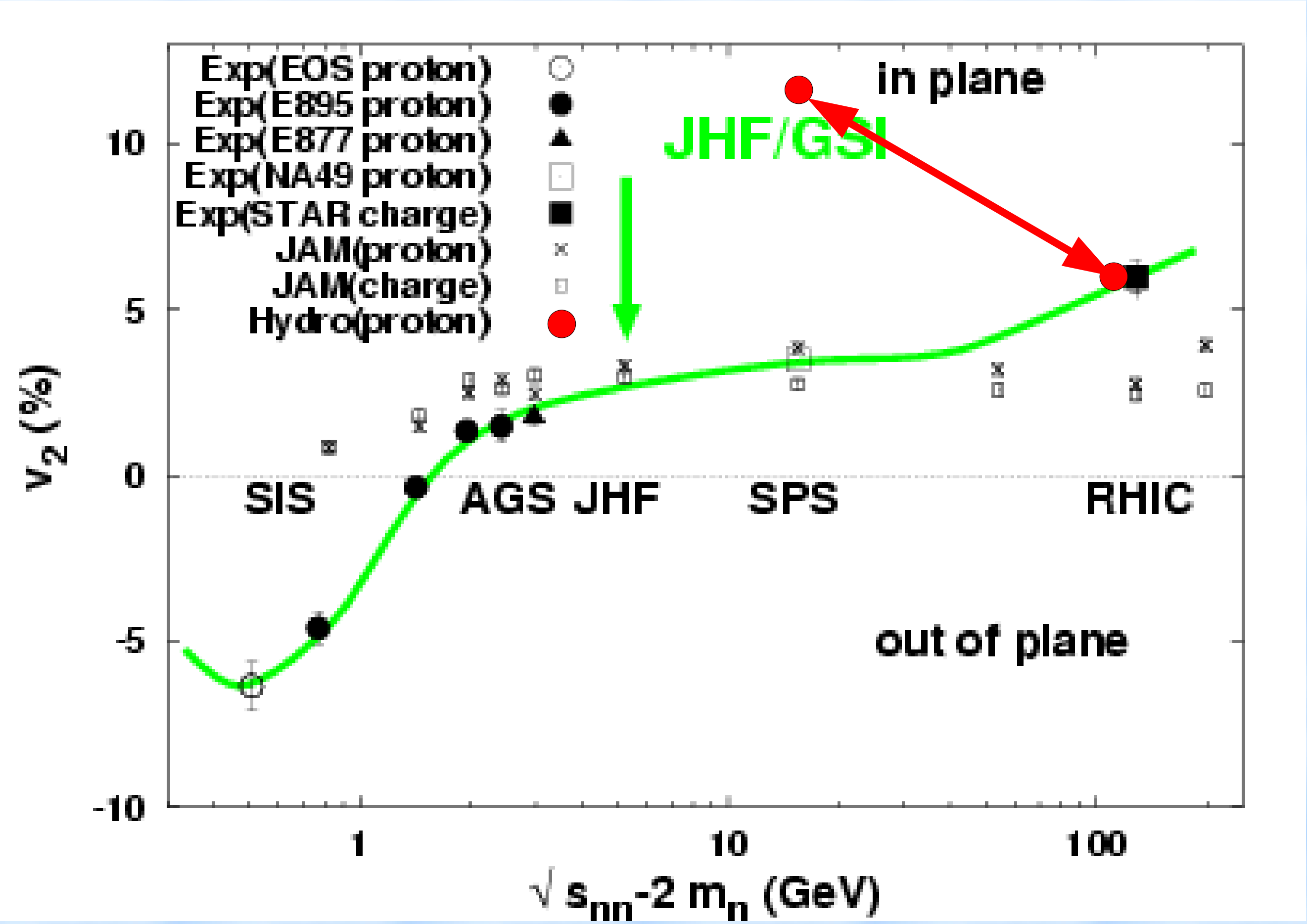
$$P_{QGP} = \frac{37\pi^2}{90} T^4 - B$$

$$\epsilon_{QGP} = \frac{37\pi^2}{30} T^4 + B$$



$$DOF = 2(spin)\times 2(q,\bar{q})\times 3(color)\times 2(flavor)\times 7/8(Fermion) + 2(spin)\times 8(color)$$

# *Elliptic Flow*

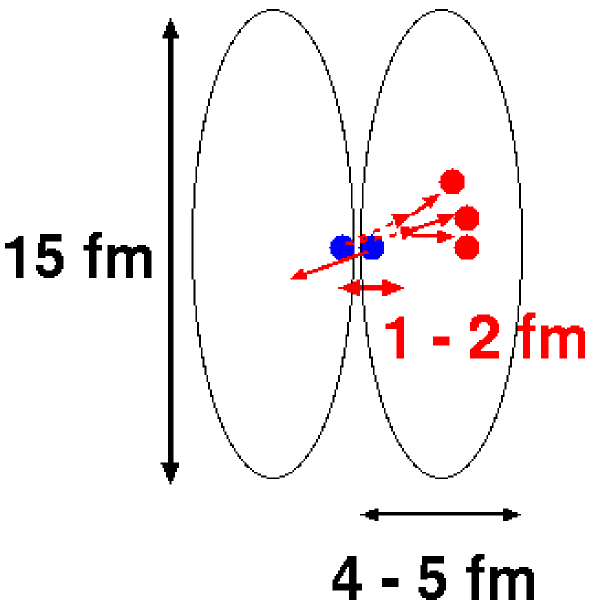


**Anisotropic Pressure is close to Hydrodynamical Values @ RHIC**
**→ Particles are interacting before Almond Shape is obscured.**

# *Hadron Formation Time*

## JHF Energies

$\gamma_{cm} \simeq 3.5, \quad \tau \simeq 0.5 - 1$ fm/c

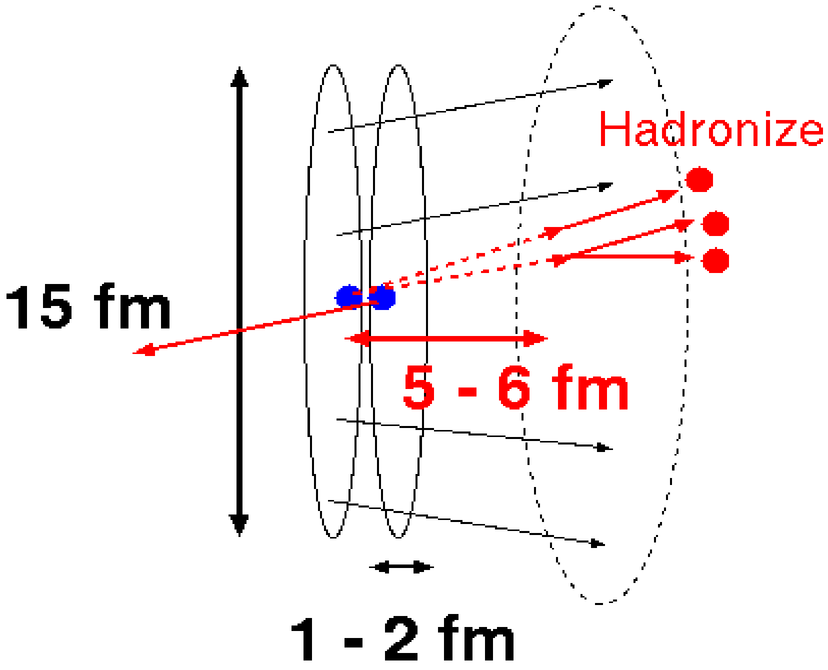


Multiple Hadron-Hadron Collisions

☞ (Approx.) Thermalized Hadron Gas

## SPS Energies

$\gamma_{cm} \simeq 10, \quad \tau \simeq 0.5 - 1$ fm/c



String-String, String-Hadron Int.
+ Int. within Co-Movers

**It takes □ 1 fm for hadrons to be formed (and thus to interact)**
**→ *Pre-Hadronic* Interactions are necessary at SPS & RHIC**

# *What is Suggested from Collective Flows*

**Radial Flow**
**→ Re-Hardening Behavior**
**Elliptic Flow**
**→ Pre-Hadronic Interaction**
**Jet Observation (□ Correlation, Energy Loss)**
**→ Partons are Propagating**

***Do these really require QGP formation ?***
***→ Verification by Hadron-String Cascade Model is Necessary***

# *JAM (Jet AA Microscopic transport model)*

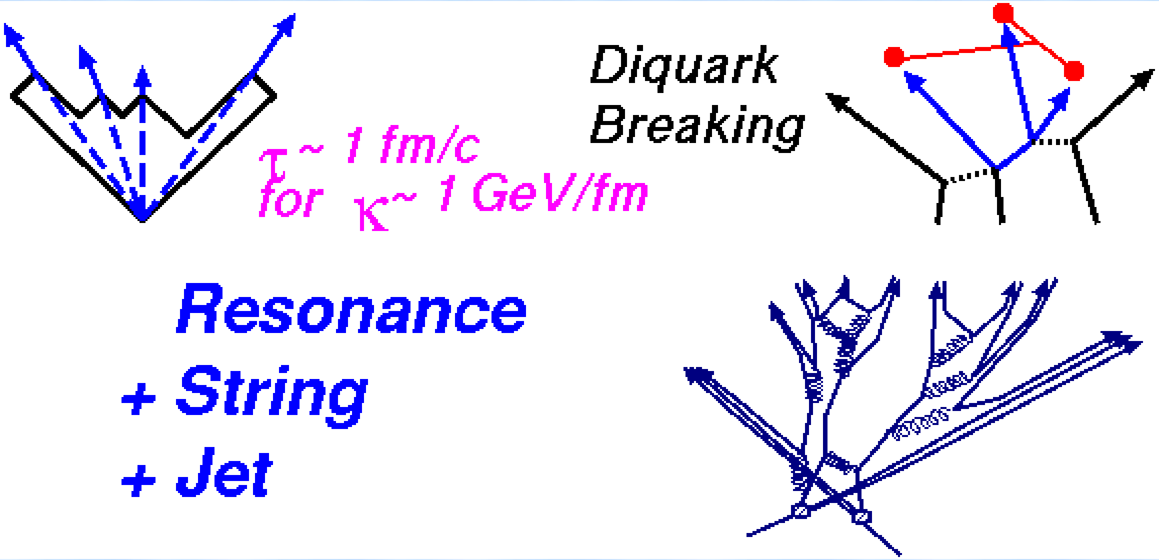
**Y. Nara et al., Phys. Rev. C61 (2000), 024901.**

***DOF***

**Hadrons (h, m < 2 GeV) + Strings (s) + Partons (in Jet)**

**Cross Sections**

**Hadronic (hh □ hh, hh □ h, h □ hh)**
**+ Soft (hh □ s, hh □ ss, s □ hh, hh □ hs [1] ,**
**sh □ s'h, ....[2])**
**+ Hard (Jet Production)**

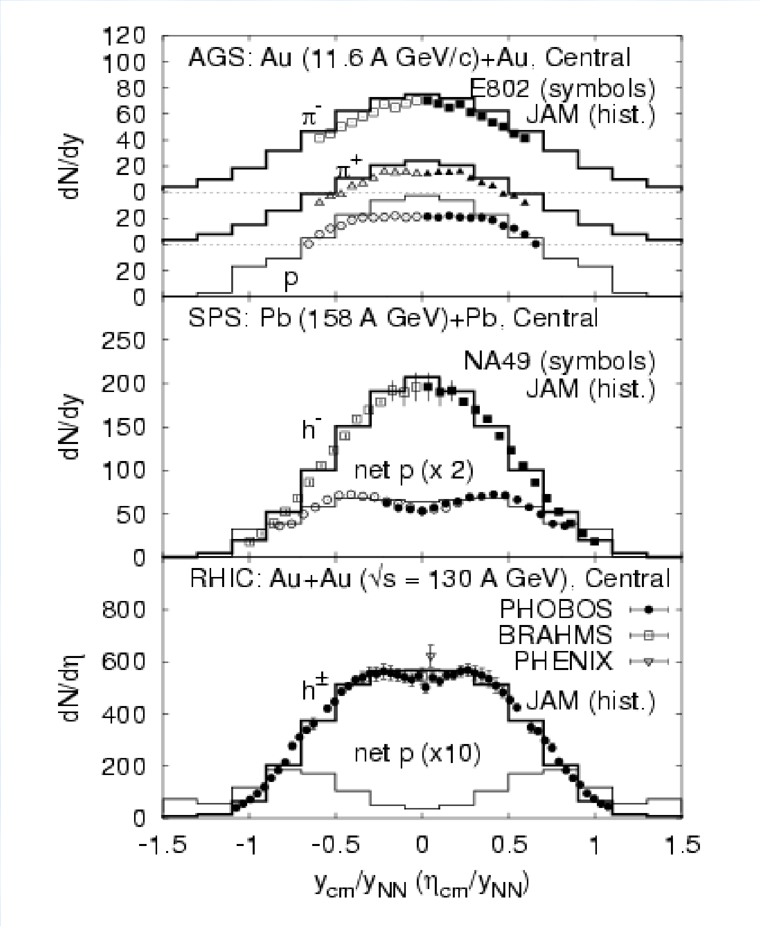


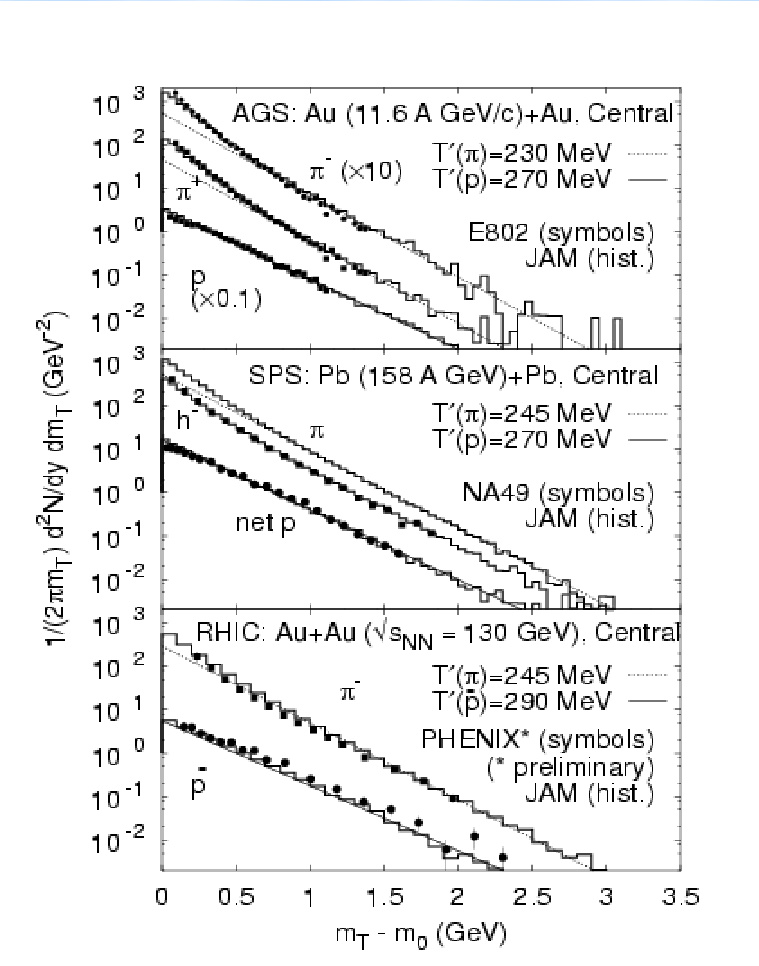
[1] "DPM + Lund" (□ HIJING) + Phase Space
[2] Consituent Rescattering (□ RQMD)

# *Followings are NOT included in JAM*

**Mean Field (in progress)**
**Medium Modification**
***Secondary Interaction of Partons***
***with Other Hadrons, String and Partons from Other Jets***

# *Hadron Spectra at AGS-SPS-RHIC*

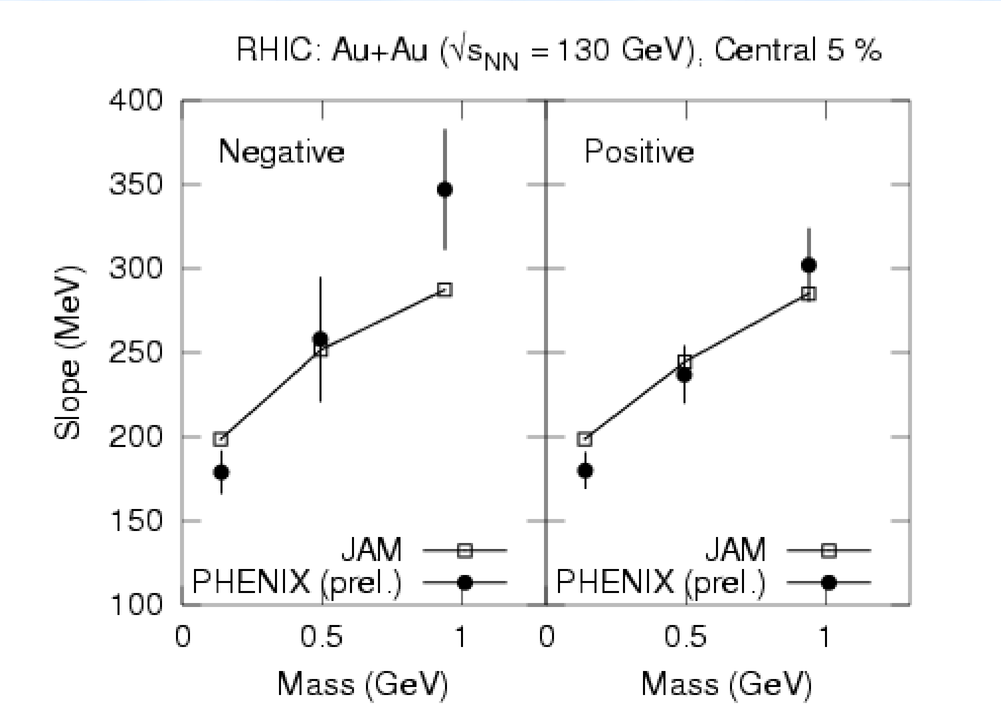


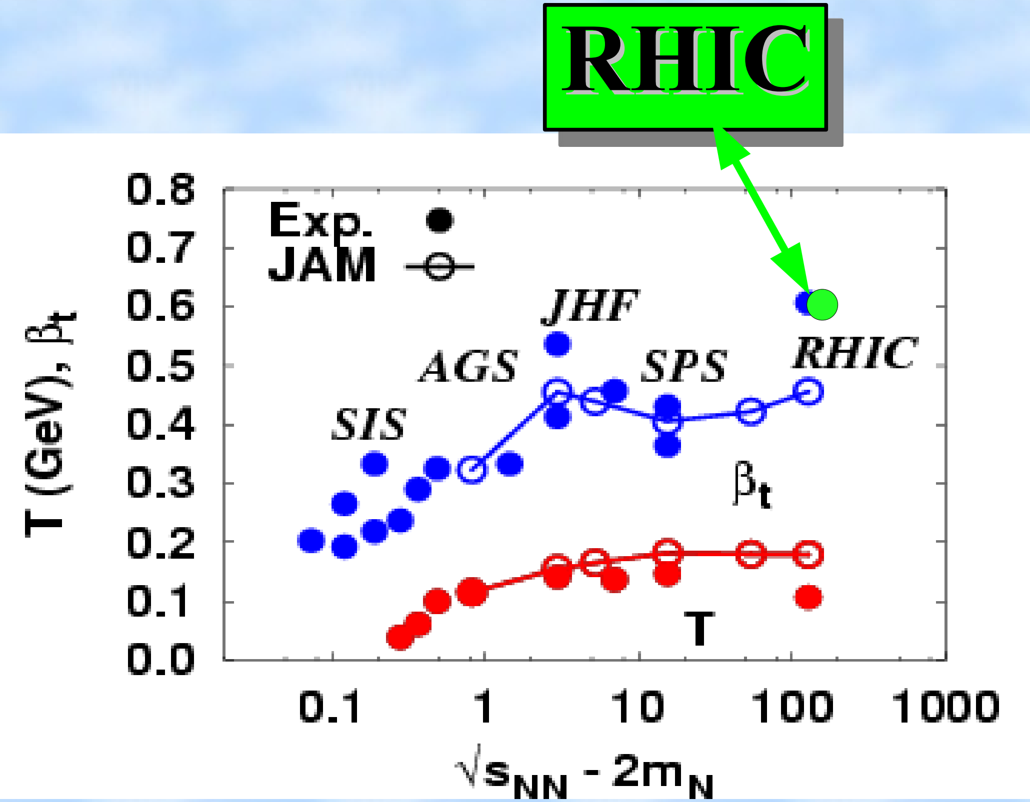


**Hadron Spectra @ RHIC is too soft in JAM.**

** Mean Field Effects are included for AGS and SPS energies*

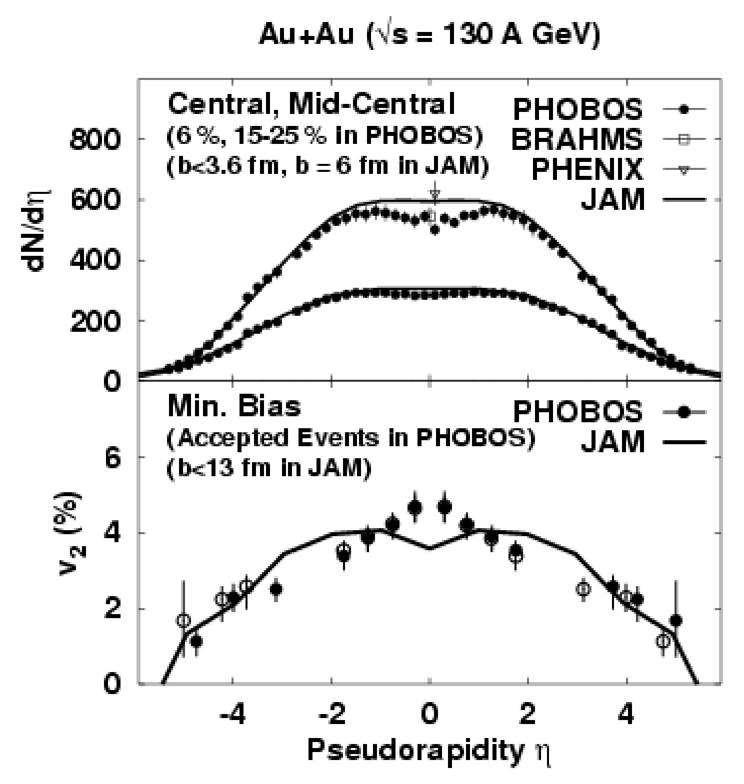
# *Radial Flow and Temperature in JAM*



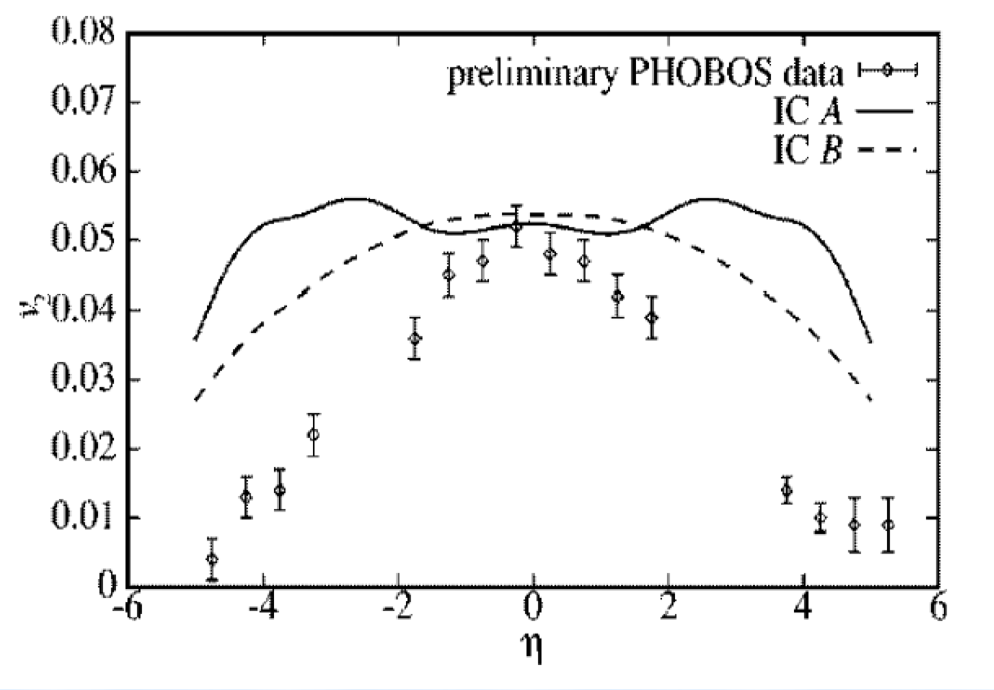


**Re-Hardening Behavior Cannot Be Explained !**

# *Pseudo Rapidity Dep. of Elliptic Flow*

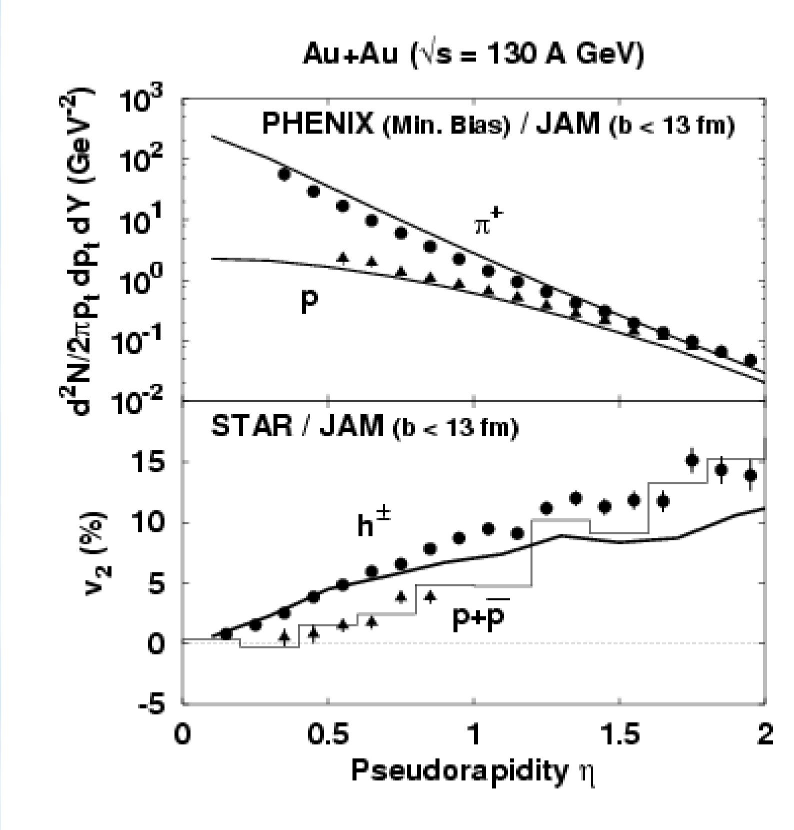


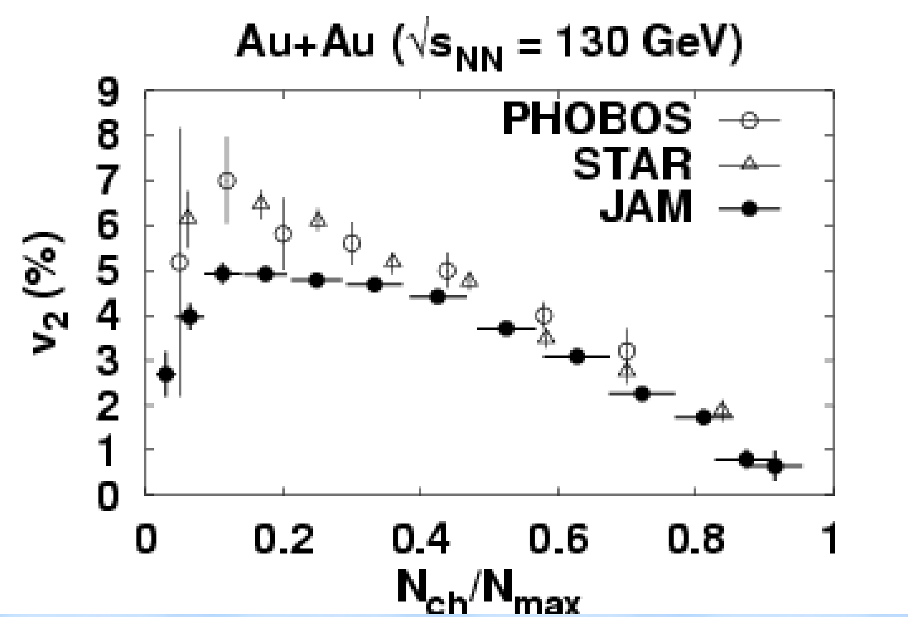
**Hydro Results (Hirano, 2001)**



Mid-Rapidity : Underestimate of V2 (QGP ?)
Large Rapidities : JAM Explains the Data (Hadronic ?)

# *Pt and Impact Par. Dep. of Elliptic Flow*
# *Where Do We Underestimate ?*

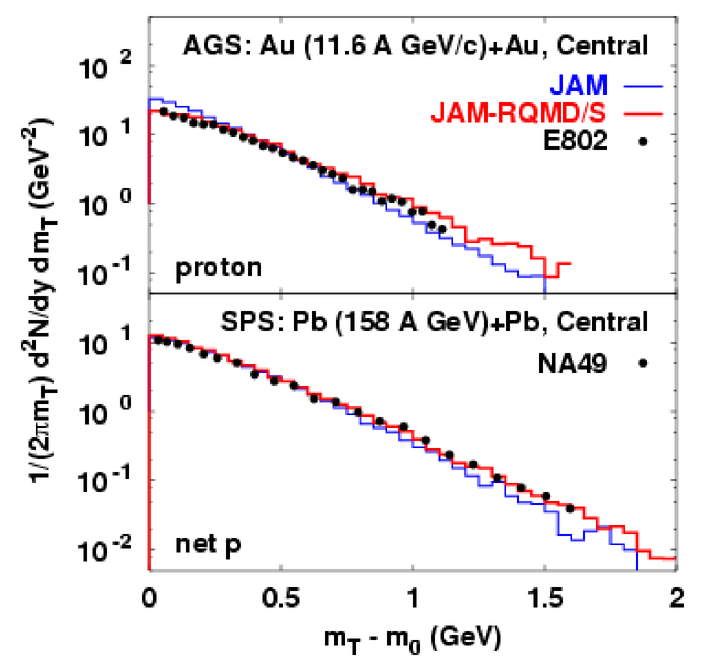


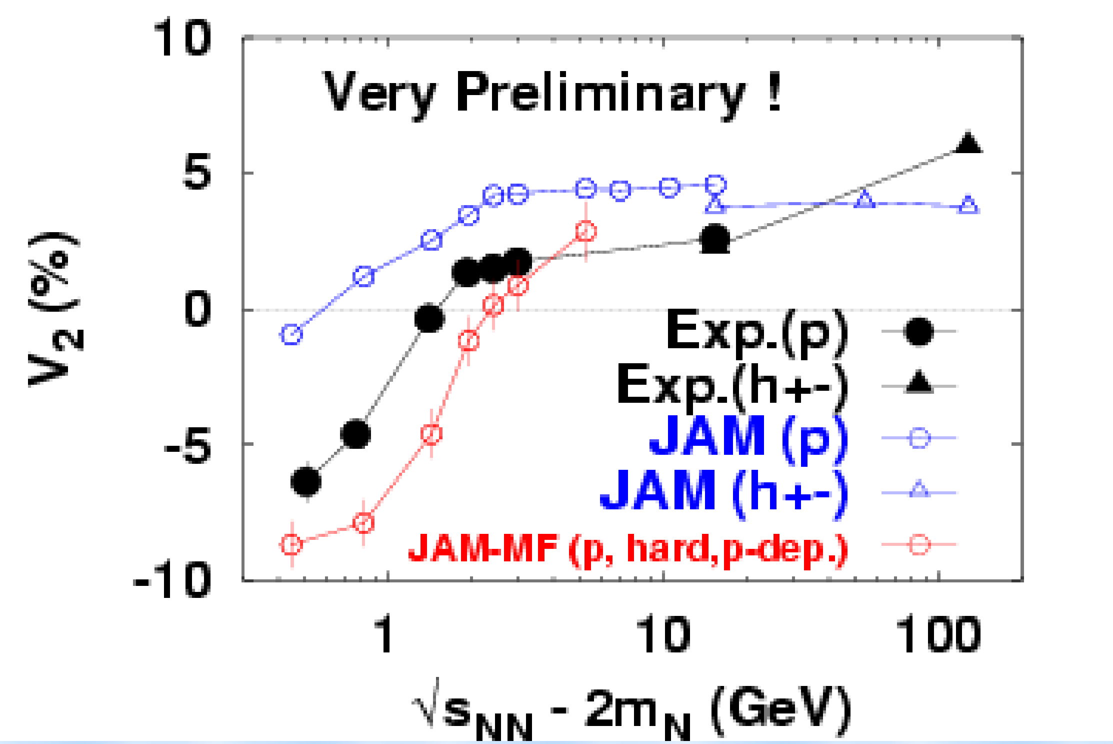


***Answer = High Pt Regions !***

# *Incident Energy Deps. of V2*

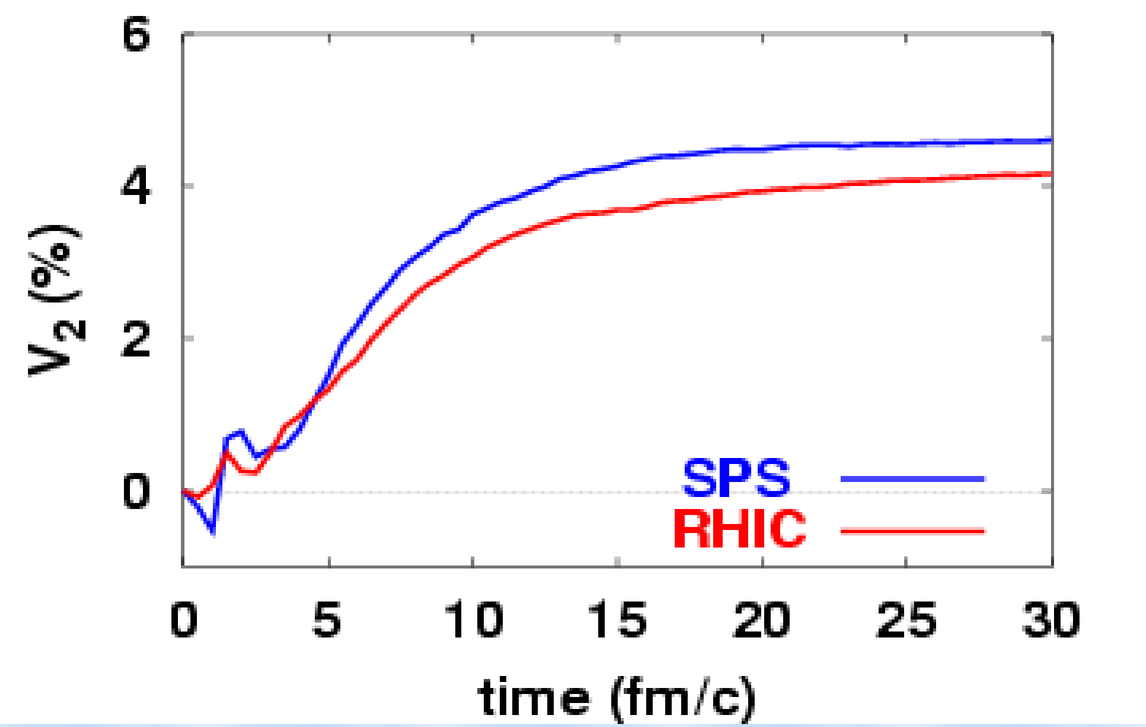
## Mean Fields Effects (JAM-RQMD/S)





**Mean Field Effects → Downward Shift in V2**

# *When are Collective Flows Generated ?*
# *Why Do We Underestimate ?*



(b = 6 fm)

**V2 is Generated at a long time scale in Hadron-String Cascade.**
**→ Almond Shape is already obscured.**

# *Summary*

**Collective Flow Data at RHIC seems to suggest QGP formation.**

***Large V2 at Mid-Rapidity : Early Thermalization***
***Strong Radial Flow : Re-Hardening***
***Jet Quenching : Partonic Interaction***

**JAM (Hadron-String Cascade with Jet Prod.) cannot explain RHIC Data, Especially in High Pt Region at Mid Rapidity.**

***Slow Growth of Elliptic Flow***
***No Secondary Partonic Interaction***
***Mean Field Does NOT Help much at RHIC***

**There are many things to do, especially at RHIC and LHC.**

*Elementary Cross Sections*
*Coherence & Incoherence in Collision*
*Side and Out Radii Puzzle*
*Parton-Hadron, Parton-String, Parton-Parton Interactions*
*Modification of the "Vacuum"*