夏の学校 2003

核反応によるハドロン物質相の探索

北海道大学　大西　明

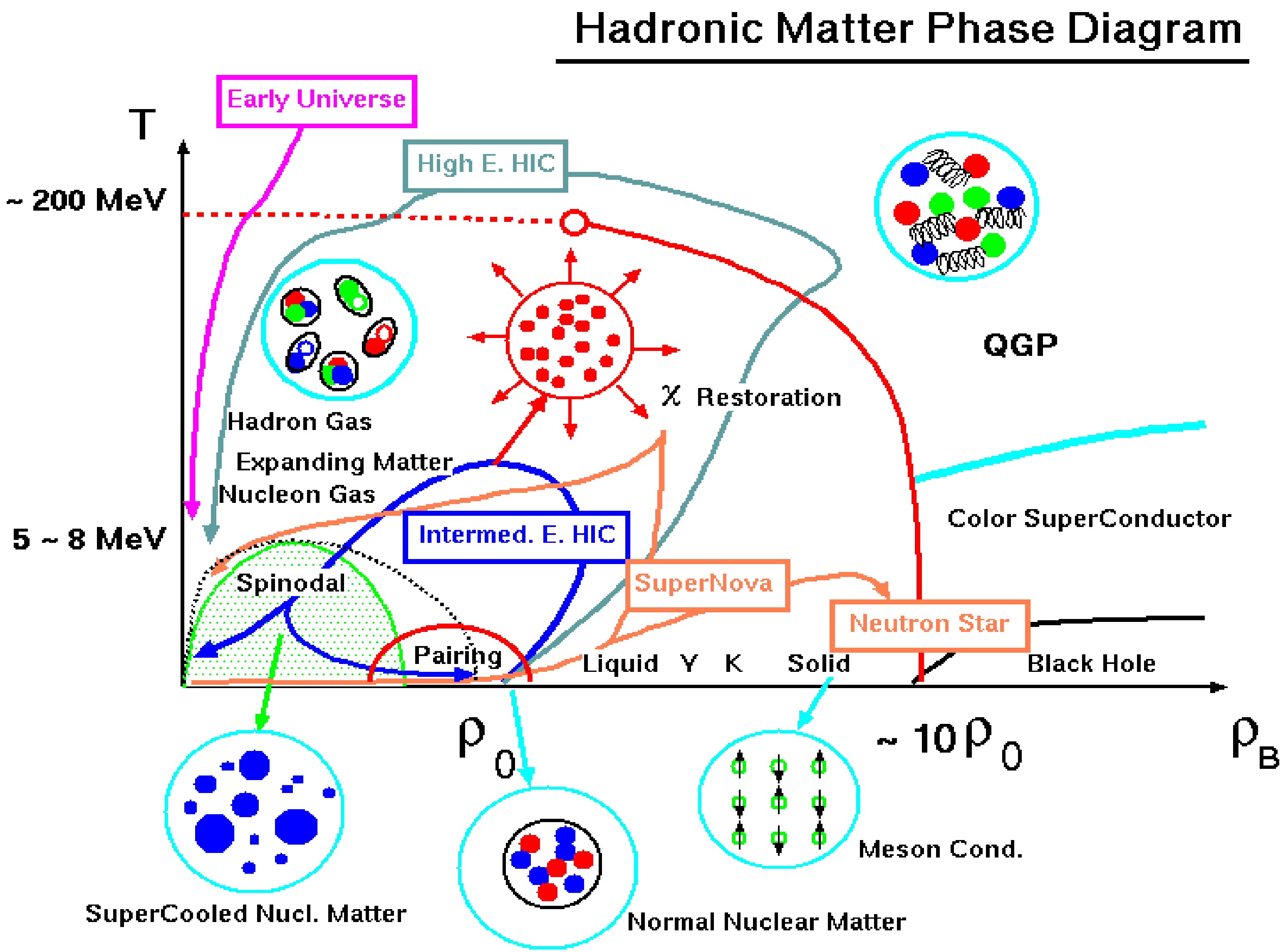
高エネルギーの核反応等で生成される標準核物質から遠く離れた核・ハドロン物質の性質について講義する。また、このために必要となる理論的枠組みと様々な核反応についての基本的な理解についての解説を行う。

１．核・ハドロン物質の相図の概要
　低密度核物質：液相・気相相転移
　低温高密度物質：ストレンジネス物質、
　高温/高密度核物質：励起ハドロン物質とQCD相転移
２．理論的枠組み
　平均場と状態方程式、相共存条件、統計模型、半古典的輸送模型、
　相対論的分子動力学、ハドロン素過程反応断面積、パートン力学
３．低温・高密度物質とストレンジネス
４．高温 / 高密度物質と高エネルギー重イオン反応
5. まとめ

1. 核・ハドロン物質の相図の概要

- 核物質の相図
- 低密度核物質：液相・気相相転移
- 低温高密度物質：ストレンジネス物質
- 高温/高密度核物質：励起ハドロン物質とQCD相転移

Hadronic Matter Phase Diagram



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:**

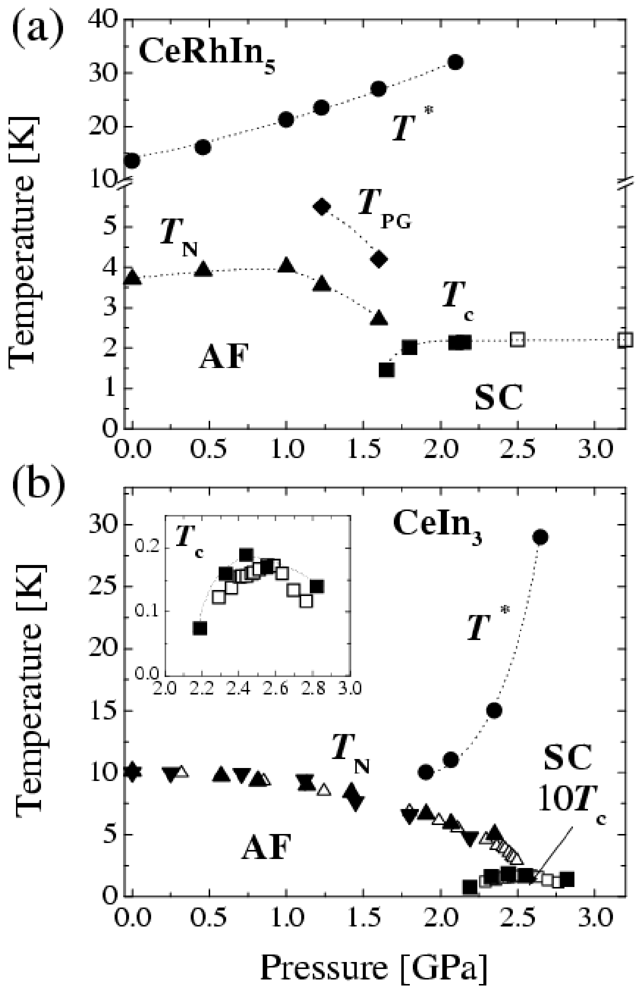
Quark & Gluon ↔ Nucleon/Hadron ↔ Nucleus

*** Relation to Astrophysical Objects/Phenomena:**

Early Universe, Compact Objects

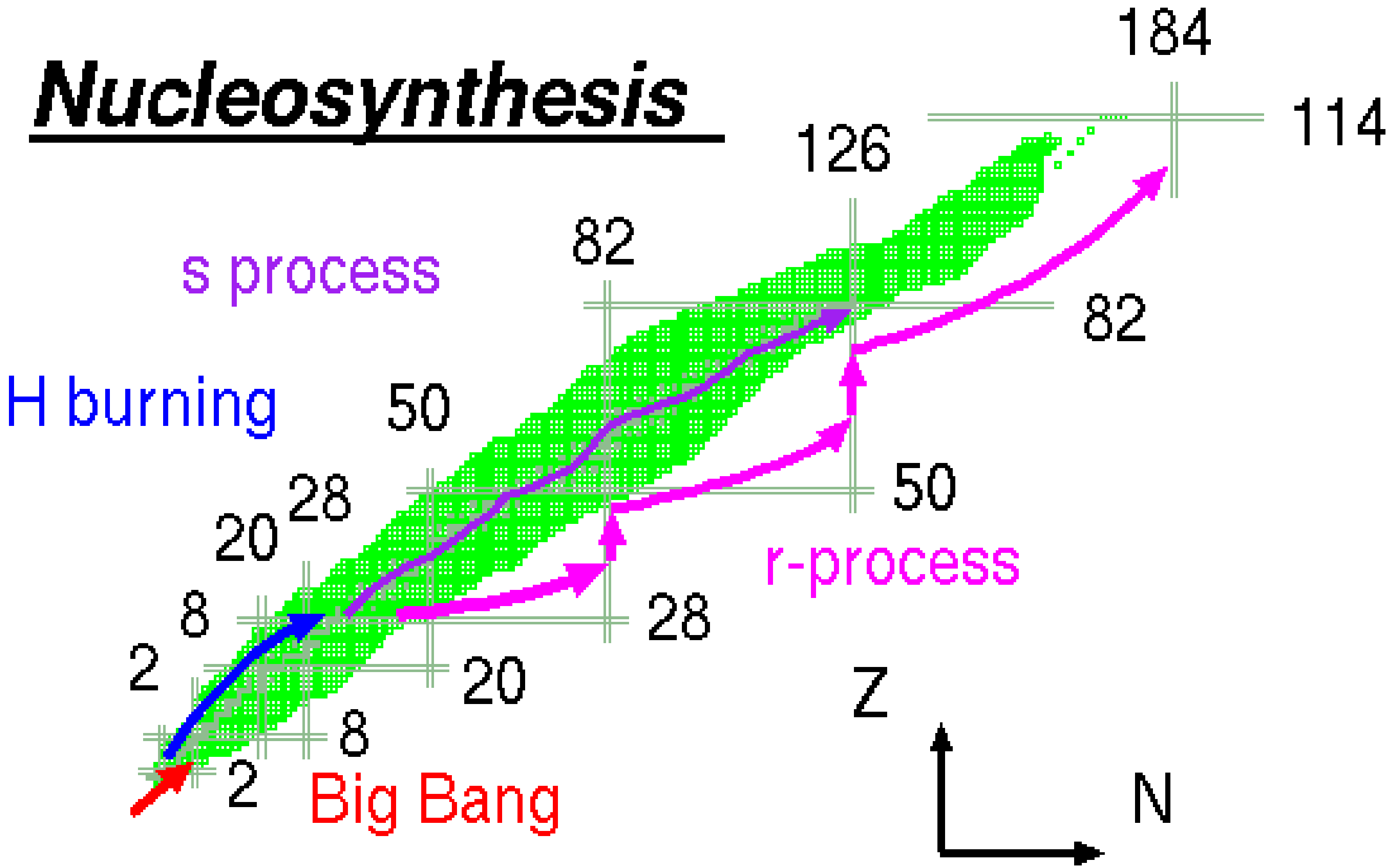
*** Similarities to Superconductor in Solid State**

Phase Diagram of Superconductor $CeRhIn_5$ and $CeIn_3$



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

Nucleosynthesis



Nuclear Physics in Supernova

- **Nuclear Reaction Rate**
- **Mass, Life-time, Excited Levels of Unstable (esp. n-rich) Nuclei**

  r-process path and element abundance

Physics of Nuclear/Hadronic Matter

- **Nuclear Matter Equation of State → Hydrodynamical Evolution**

  $\rho_B = (10^{-9} - 5)\rho_0 \qquad (10^5 - 10^{15}\,\text{g/cc})$

  $T = (0.1 - 30)\,\text{MeV} \qquad (10^9 - 3\times 10^{11}\,\text{K})$

- **Particle/Fragment Composition → Various Reaction Rates**

  $Y_p,\ \ Y_L,\ \ Y_\alpha,\ \ Y_S,\ \ Y(^{56}\text{Fe}),\ldots.$

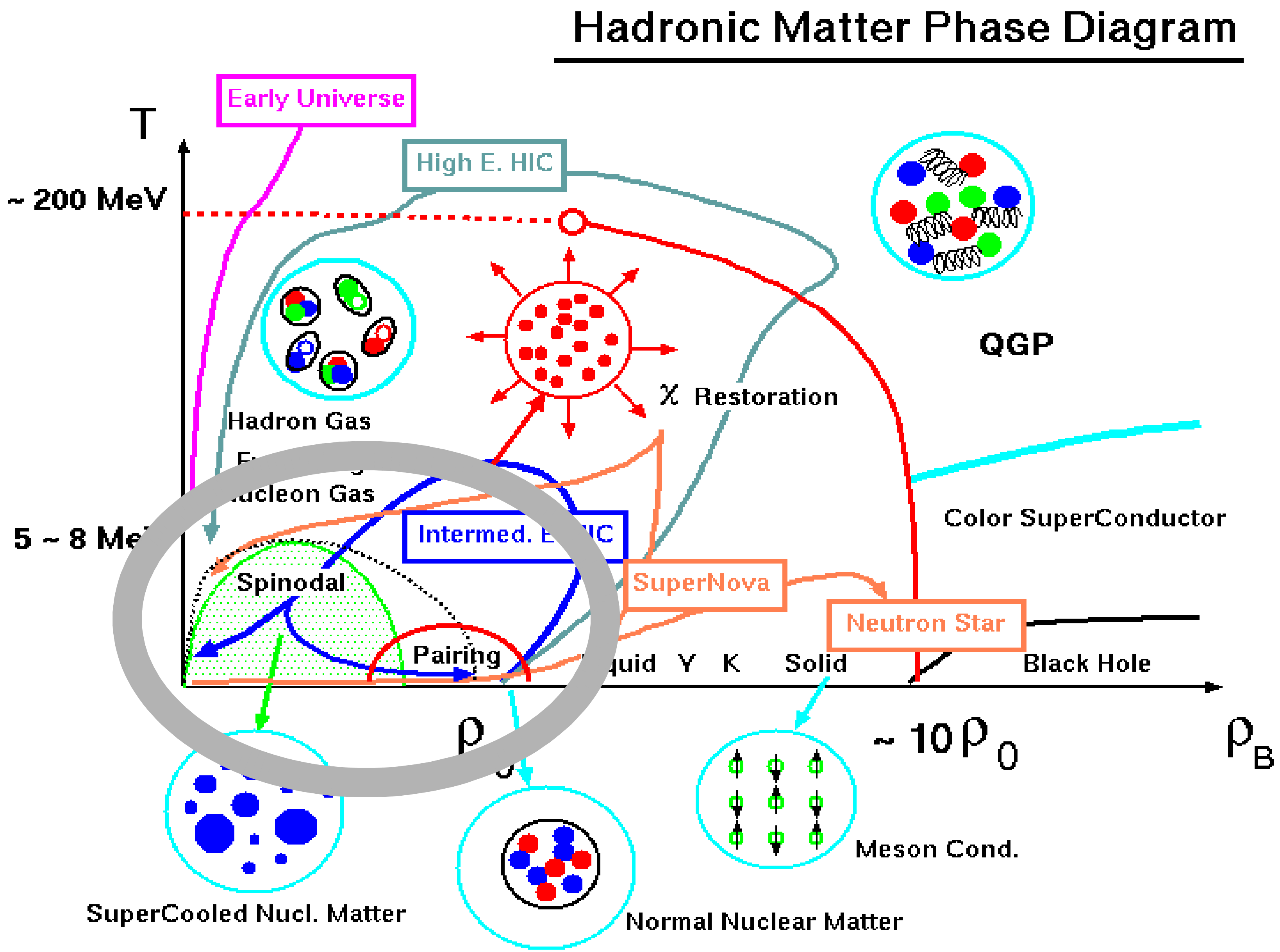
- **Neutrino Interaction on Nucleon and Nuclei**

  → Initial Electron Density and Later Opacity

  $e + A \rightarrow \nu + B,\ \ \nu + A \rightarrow e + B,\ \ \nu + A \rightarrow \nu' + N + B,\ \ \ldots$

  (Physics at K2K Near Detector !)

低温·低密度核物質

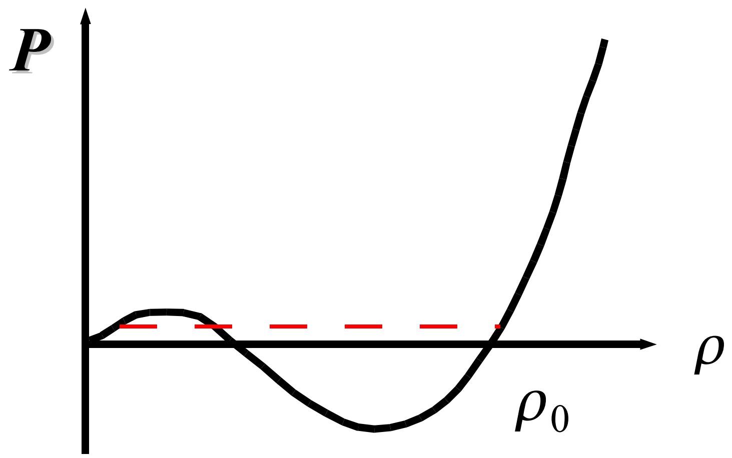


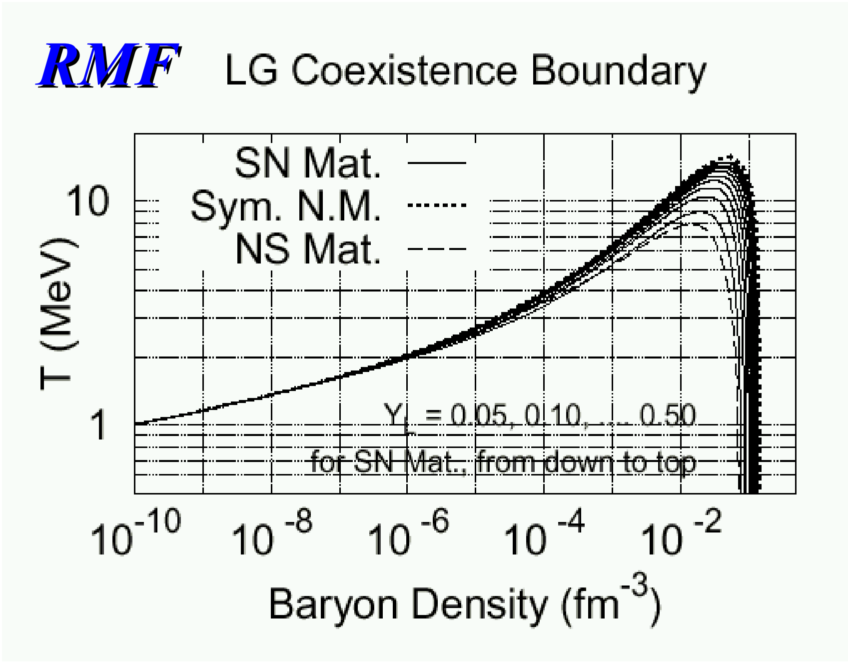
Hadronic Matter Phase Diagram
Early Universe
T
High E. HIC
~ 200 MeV
QGP
Hadron Gas
χ Restoration
ucleon Gas
5 ~ 8 Me
Intermed. E HIC
Color SuperConductor
Spinodal
SuperNova
Neutron Star
Pairing
quid Y K Solid
Black Hole
ρ
~ 10 ρ0
ρB
Meson Cond.
SuperCooled Nucl. Matter
Normal Nuclear Matter

Nuclear Liquid-Gas Phase Transition

Nuclear Int. Van der Waals Int.

→ LG Phase Transition is expected.



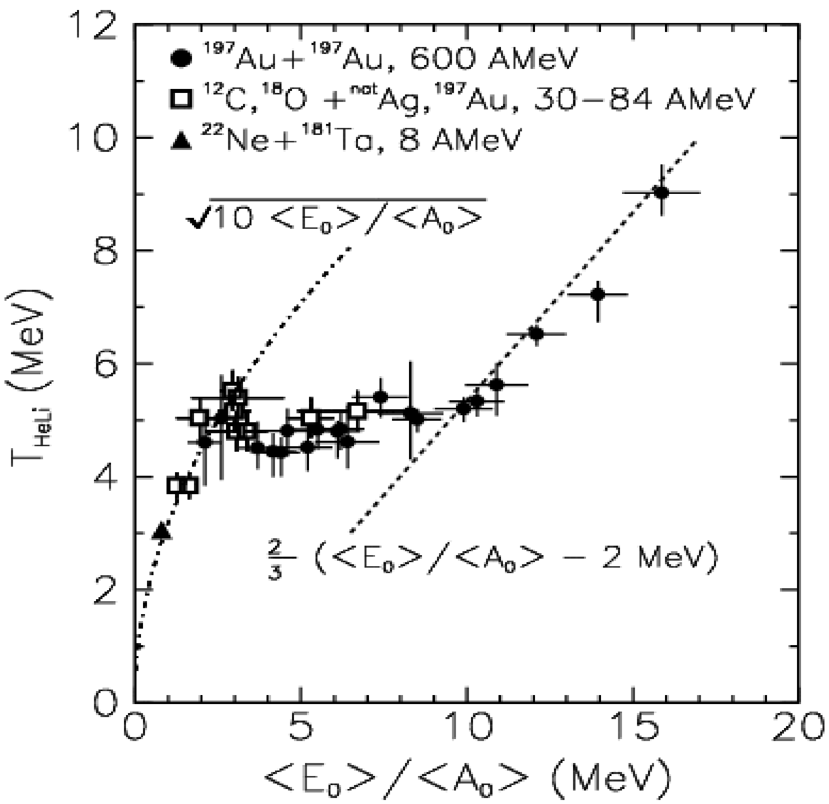


Recent Experimental Progress

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

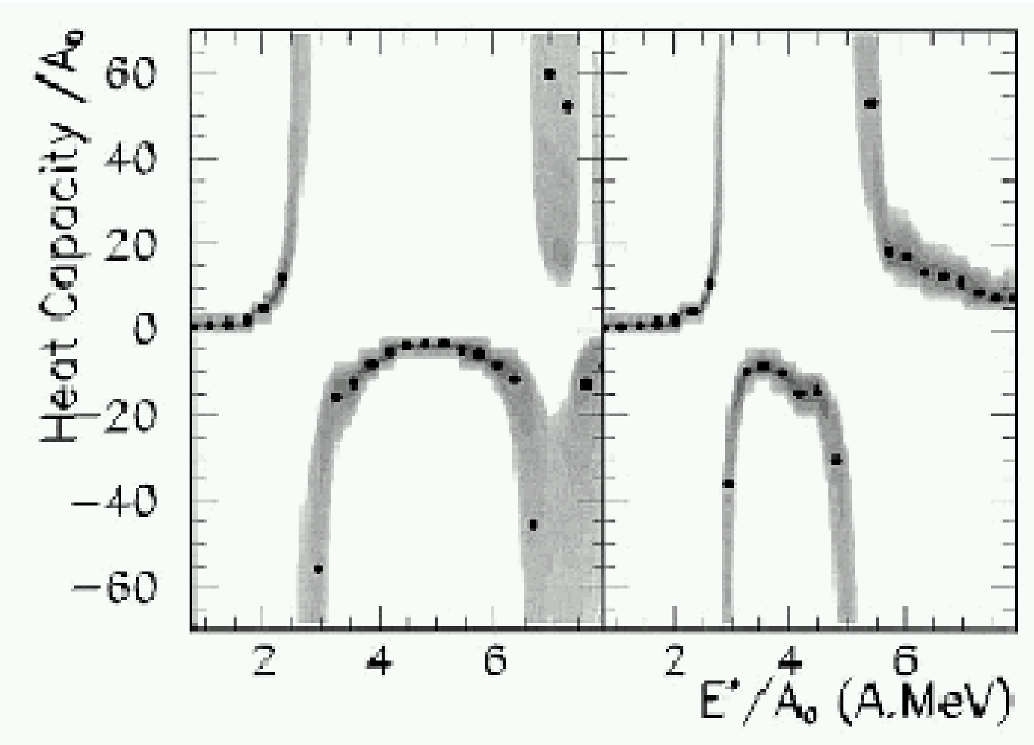
Fragment Yields are assumed to follow Equilibrium Statistics

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

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

Negative Heat Capacity

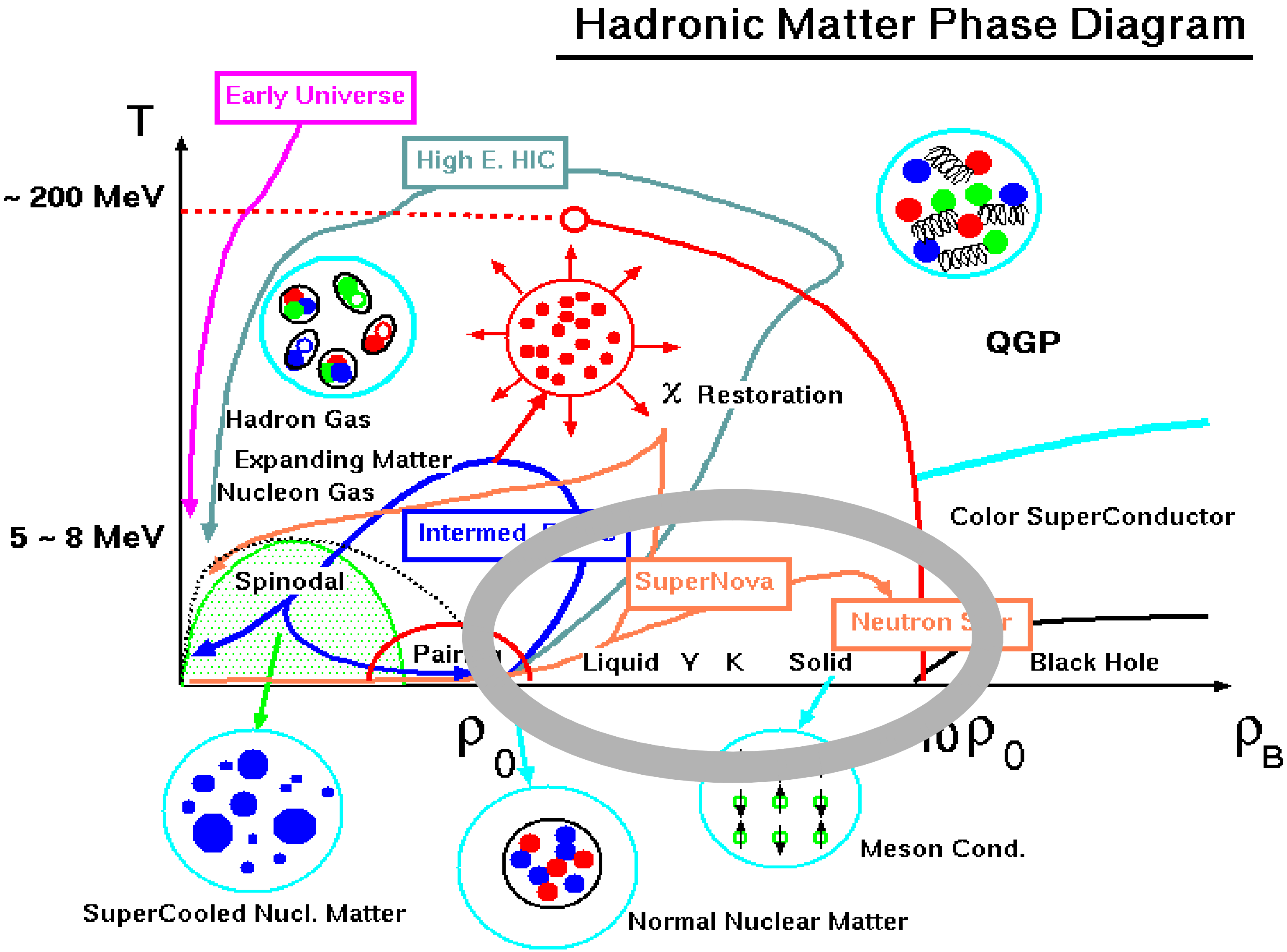
M. D Agostino et al., PLB 473 (2000) 219.
(MSU Exp./INFN-IN2P3 Collab.)



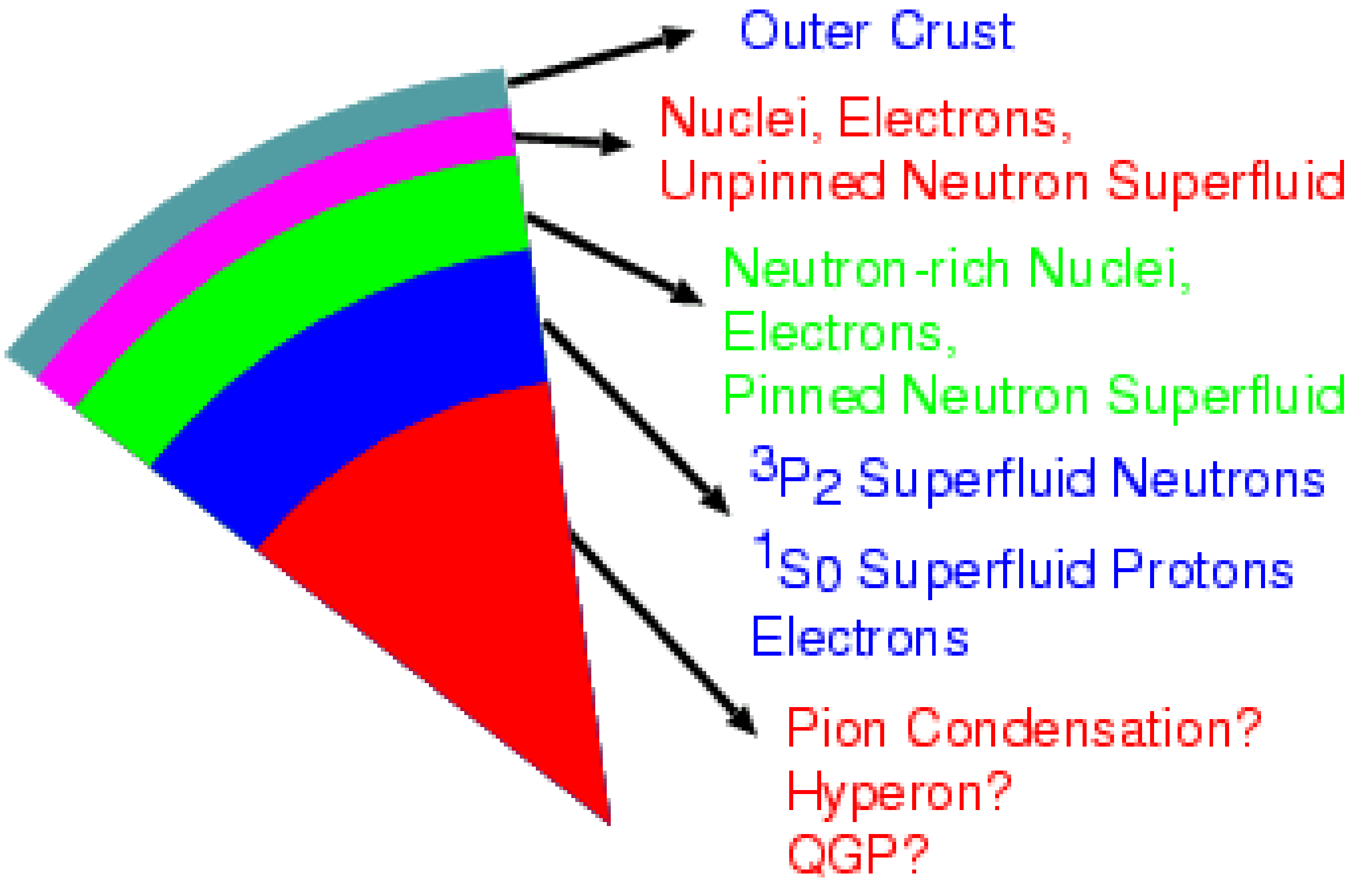
Negative Heat Capacity
➡ *First Order*

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

低温・高密度核物質


Hadronic Matter Phase Diagram
Early Universe
T
High E. HIC
~ 200 MeV
QGP
Hadron Gas
χ Restoration
Expanding Matter
Nucleon Gas
Color SuperConductor
5 ~ 8 MeV
Intermed
SuperNova
Spinodal
Neutron S
Pair
Liquid Y K Solid
Black Hole
ρ0
ρB
Meson Cond.
SuperCooled Nucl. Matter
Normal Nuclear Matter

Deep Inside the Neutron Star



Various Hadronic (and QGP) Phases appear as the Density Increases

What is Expected in the Neutron Star Core ?

Nucleon Superfluid $({}^1S_0, {}^3P_2)$

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

Low T and High ρ Matter: Importance of Strangeness Degrees of Freedom

Constituents:

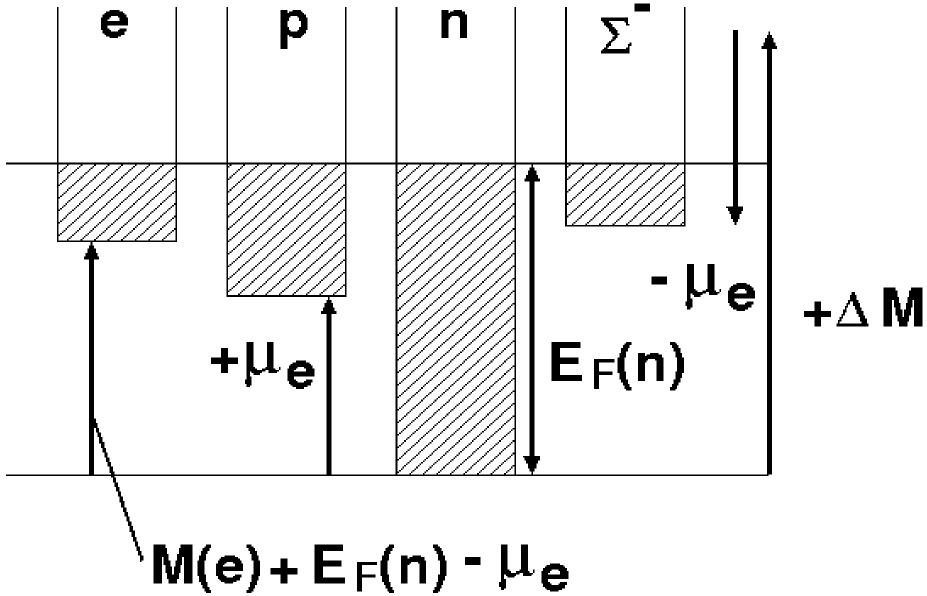
$$p\,,n\,,e^{\pm}\,,\mu^{\pm}\,,\Lambda\,,\Sigma^{\pm\,,\,0}\,,\ldots$$

Chemical Equilibrium:

◊ **Strangeness (Weak)**

◊ **Lepton (ν Emission)**

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

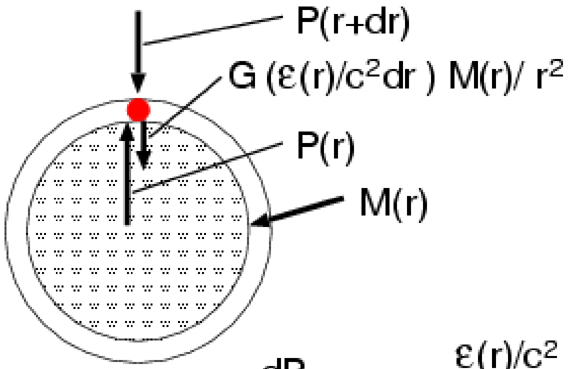


Negatively Chaged or Neutral Baryons are Favored

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

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

TOV Equation: Balance of Pressure and Gravitation



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

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

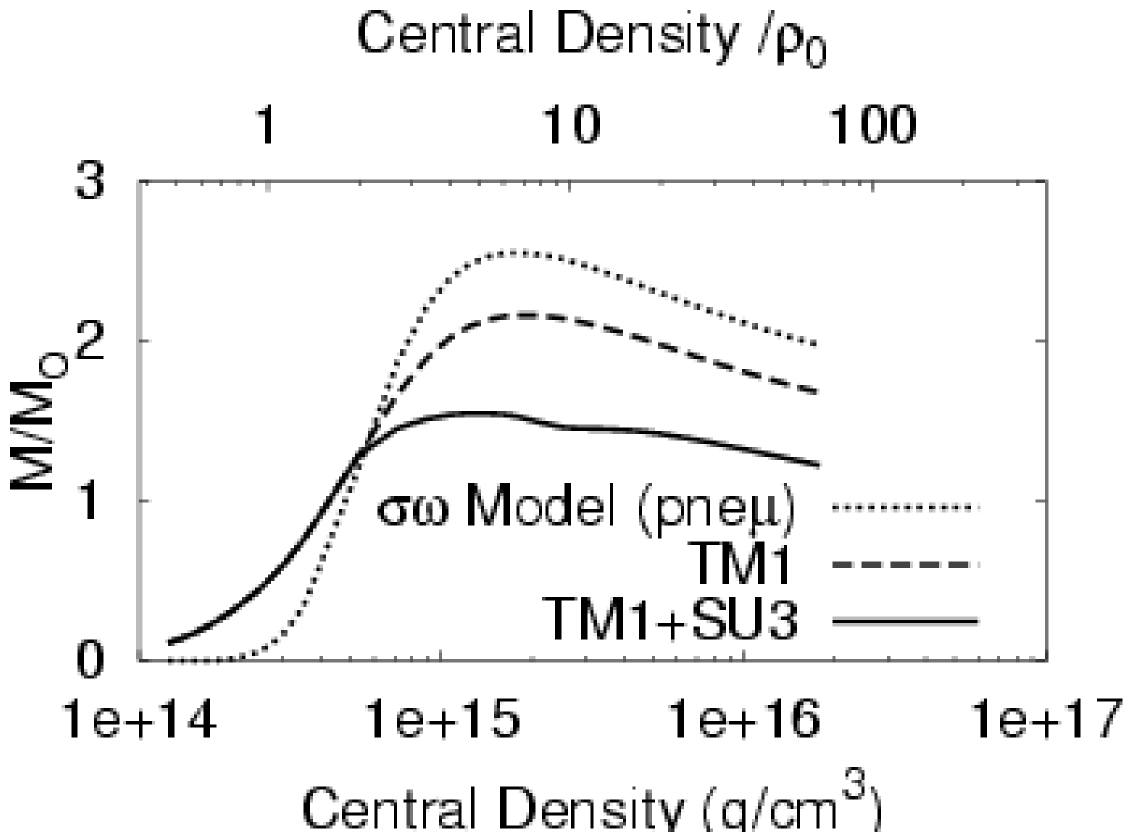
$$\frac{dM}{dr} = 4\pi r^2 \varepsilon/c^2 \;, \quad \frac{dP}{dr} = \frac{dP}{d\varepsilon}\frac{d\varepsilon}{dr}$$

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

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

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

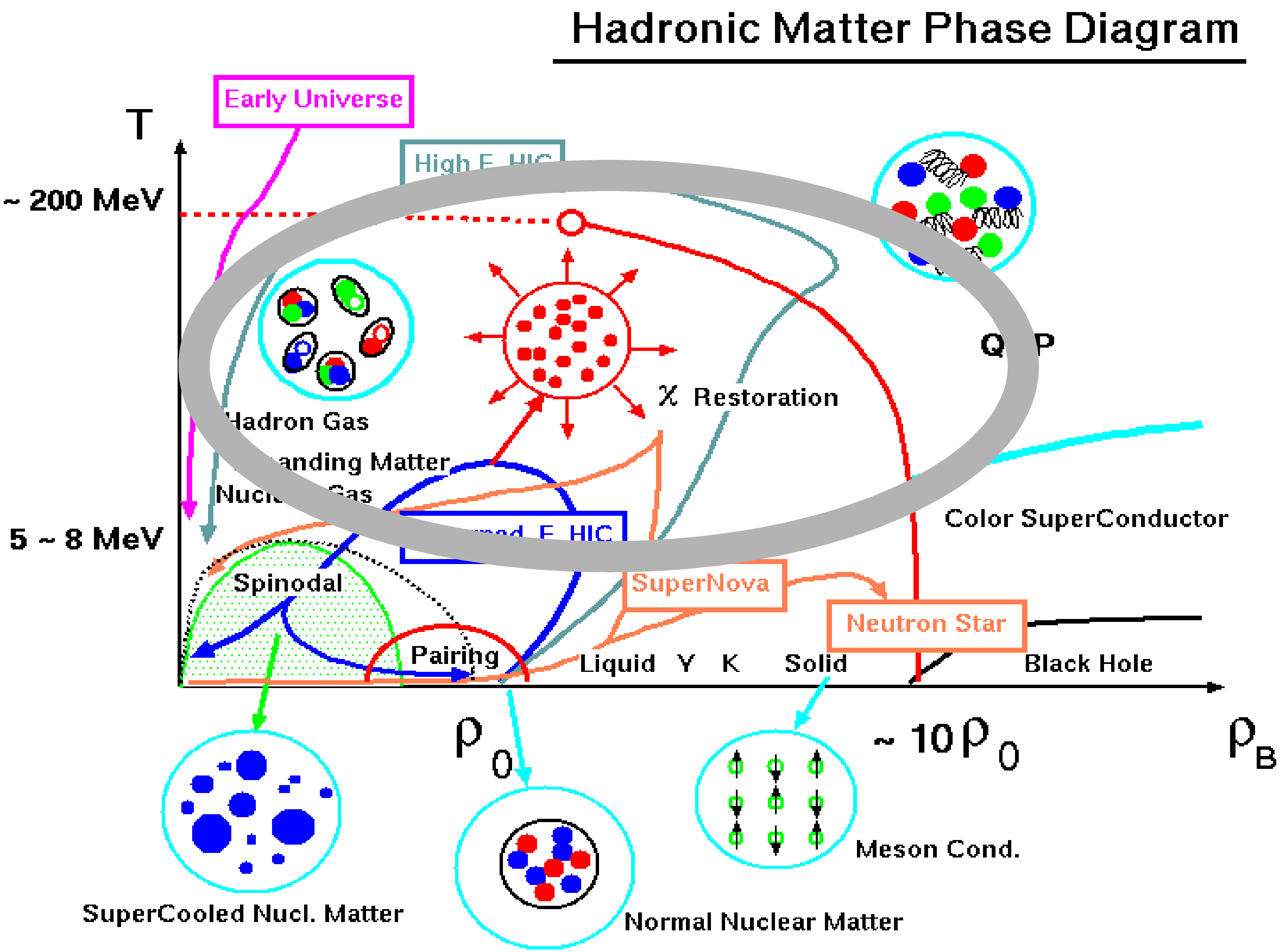
Neutron Star Max. Mass



A. Isshiki, AO, JPS @ Akita; Serot-Walecka ($\sigma\omega$); Sugahara-Toki (TM1); Schaffner-Mishustin (TM1+SU3); Glendenning, ...

Maximum Mass Reduction ~ 0.5-1.0 M_{sun}

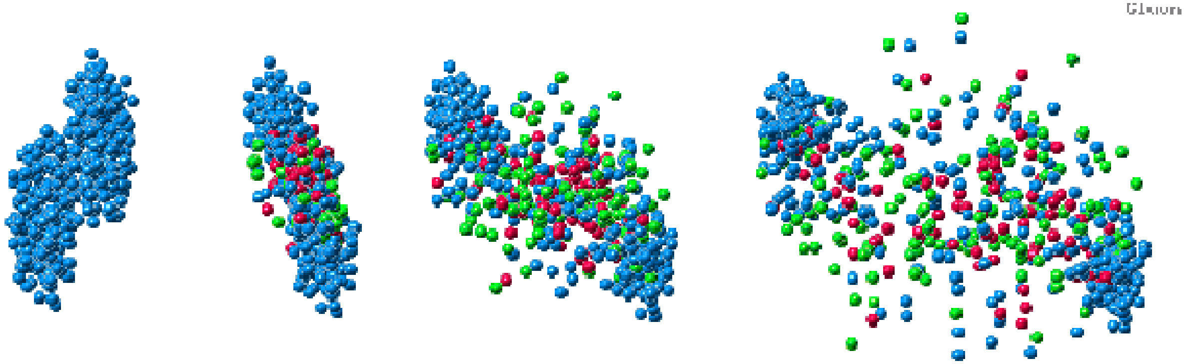
高温 and/or 高密度核物質


Hadronic Matter Phase Diagram
Early Universe
T
~ 200 MeV
5 ~ 8 MeV
High E HIC
Q P
χ Restoration
Hadron Gas
anding Matter
Nucl Gas
Color SuperConductor
Spinodal
SuperNova
Neutron Star
Pairing
Liquid Y K Solid
Black Hole
ρ0
~ 10 ρ0
ρB
SuperCooled Nucl. Matter
Normal Nuclear Matter
Meson Cond.

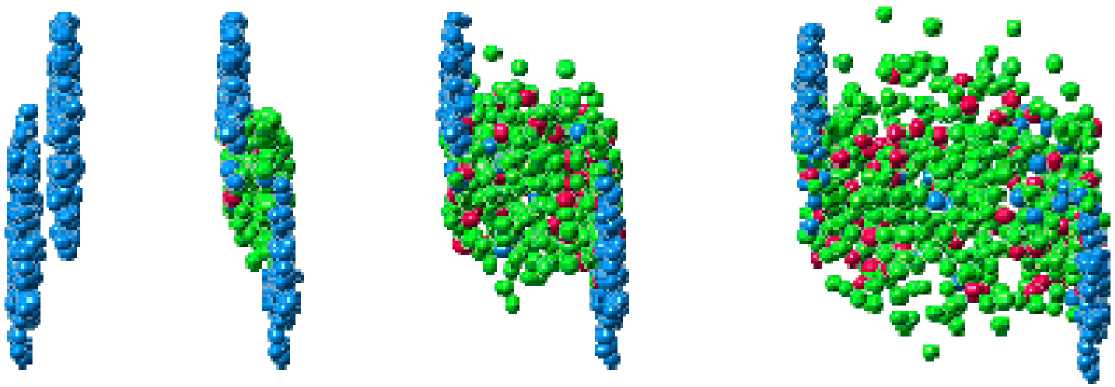
High T and/or High ρ Matter:
Hadronic Resonance Matter and QCD Phase Transition

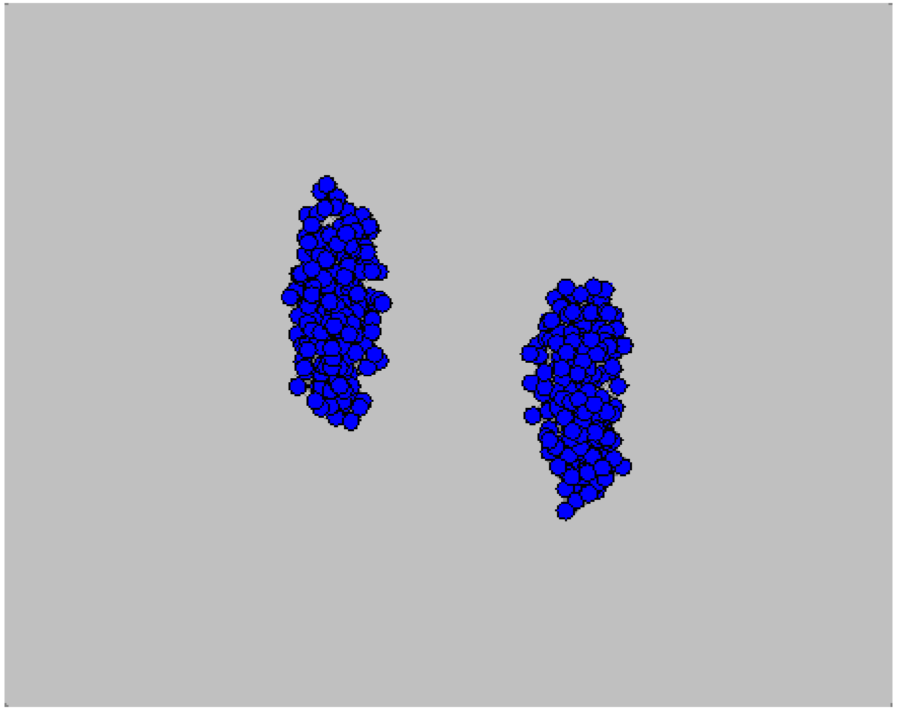
JAMming on the Web http://nova.sci.hokudai.ac.jp/~ohtsuka/

AGS



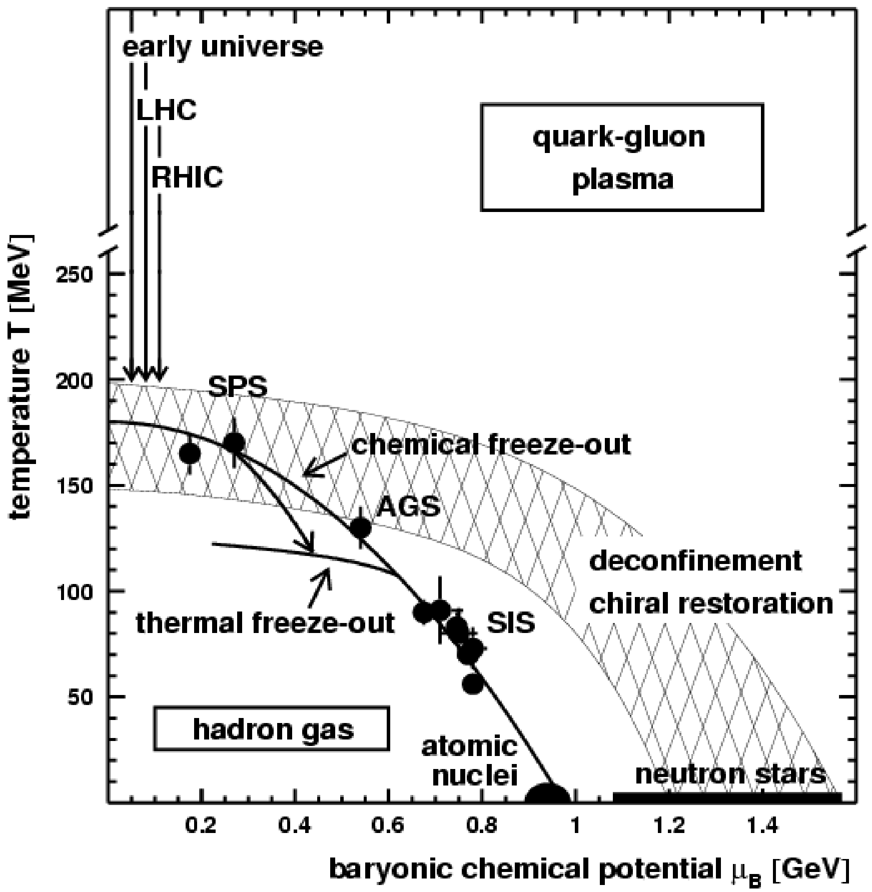
SPS



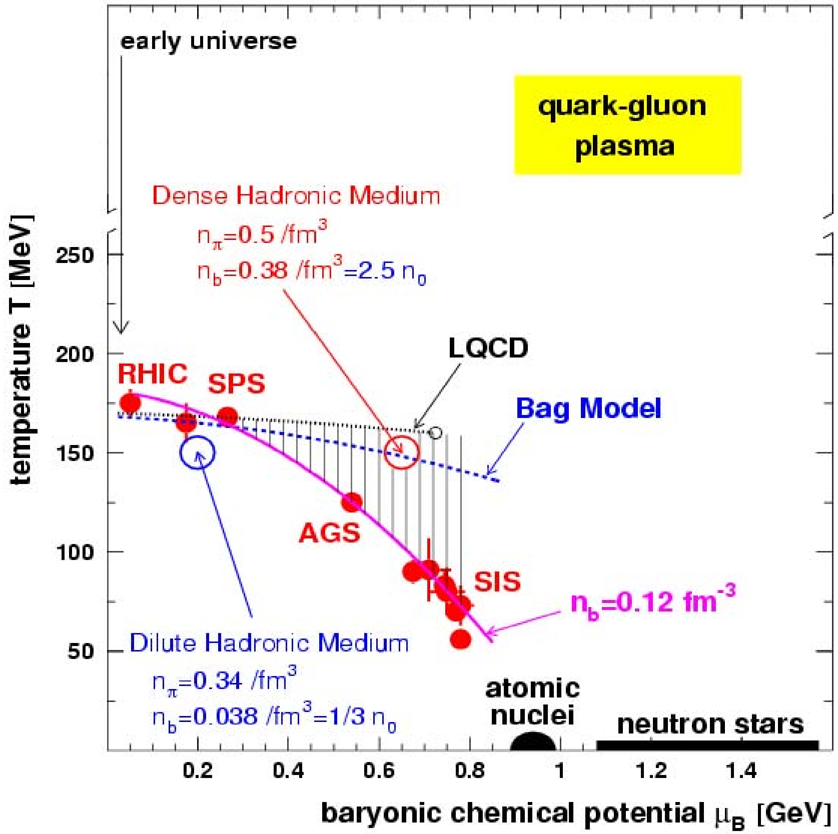


Experimentally Estimated Phase Diagram

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



1998 (J. Stachel et al.)

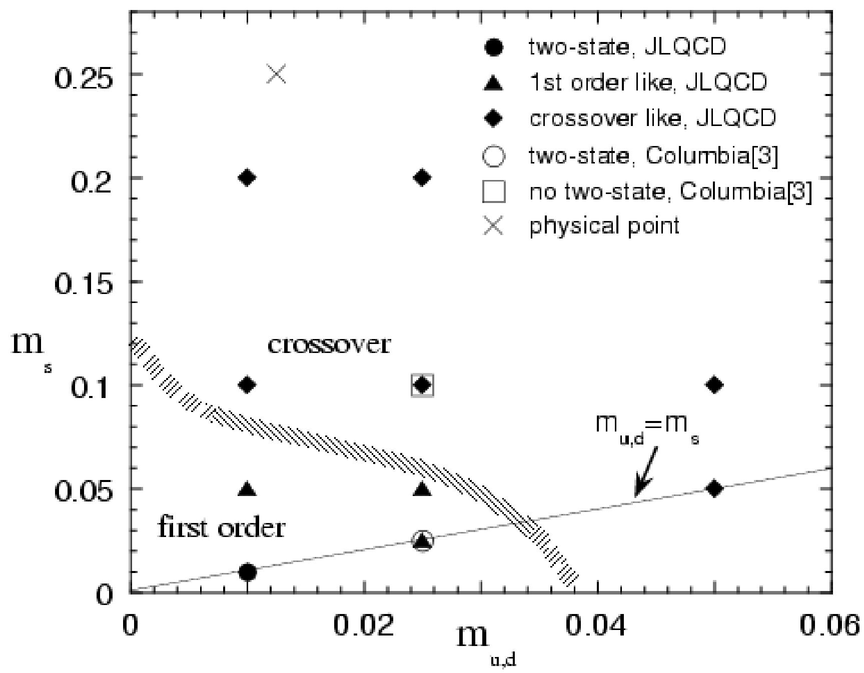


2002 (Braun-Munzinger et al.
J. Phys. G28 (2002) 1971.)

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

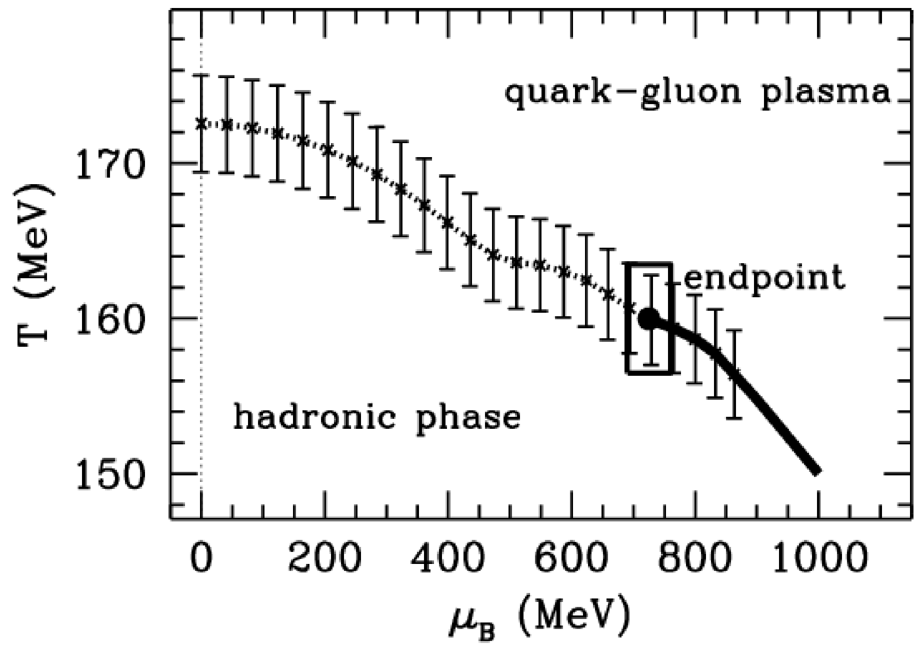
Theoretically Expected QCD Phase Diagram

Zero Chem. Pot.



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

Finite Chem. Pot.



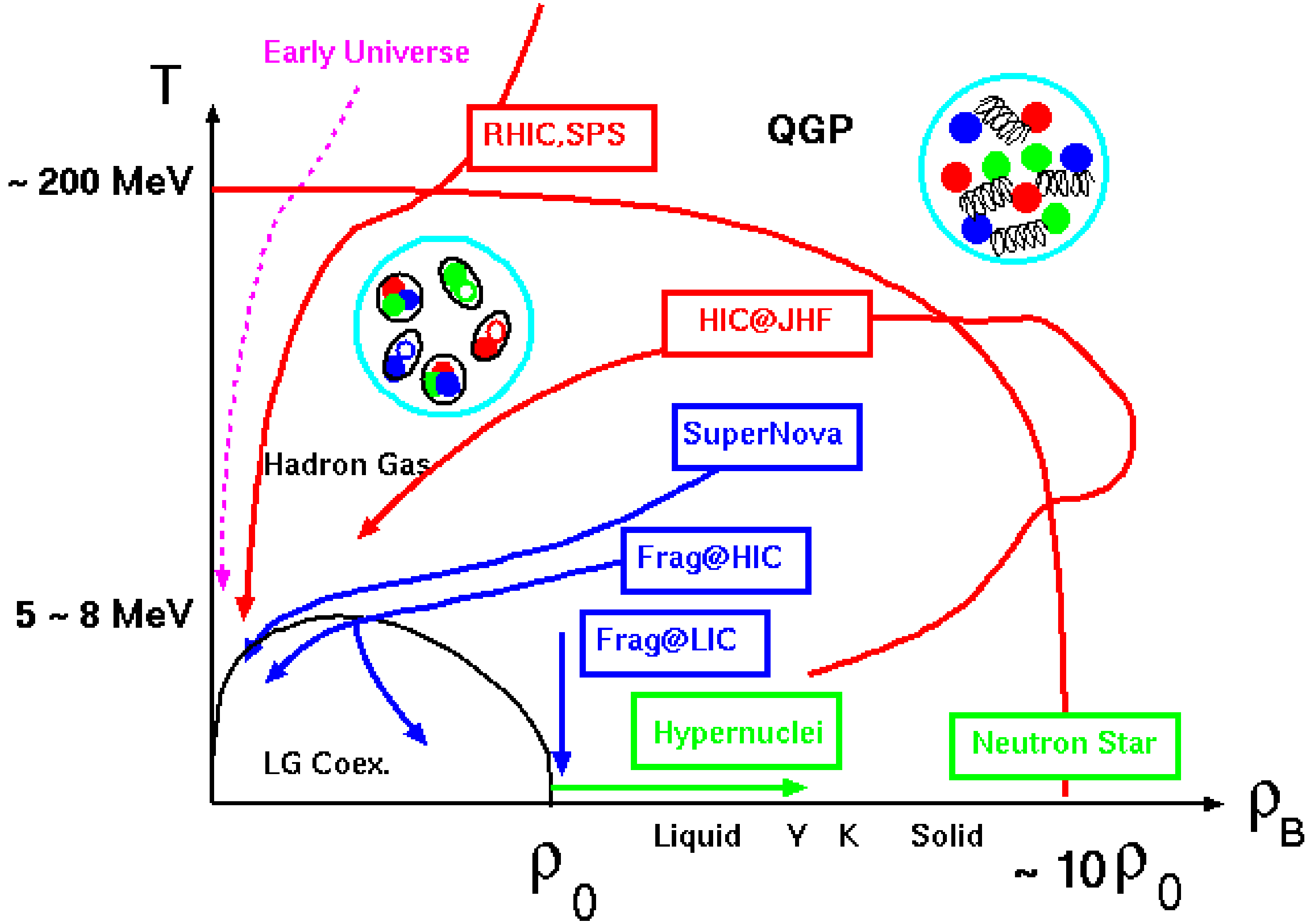
Finite μ: Fodor & Katz,
JHEP 0203 (2002), 014.

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

Approaches for Hadronic Matter Study

- Constructive Way: Quarks and Gluons → Hadrons → Matter

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



ハドロン物質の議論に必要な要素

平均場:
　粒子間の平均的な相互作用
　c.f. 少数系におけるスピン・アイソスピンに敏感な相互作用
粒子自由度:
　どのような「粒子」が現れるか？
　　c.f. クォーク・グルーオン、ストリング、
（励起）ハドロン、フラグメント
統計性:
　「平均的」配位からのずれが圧力などに
　　どのような影響を与えるか？

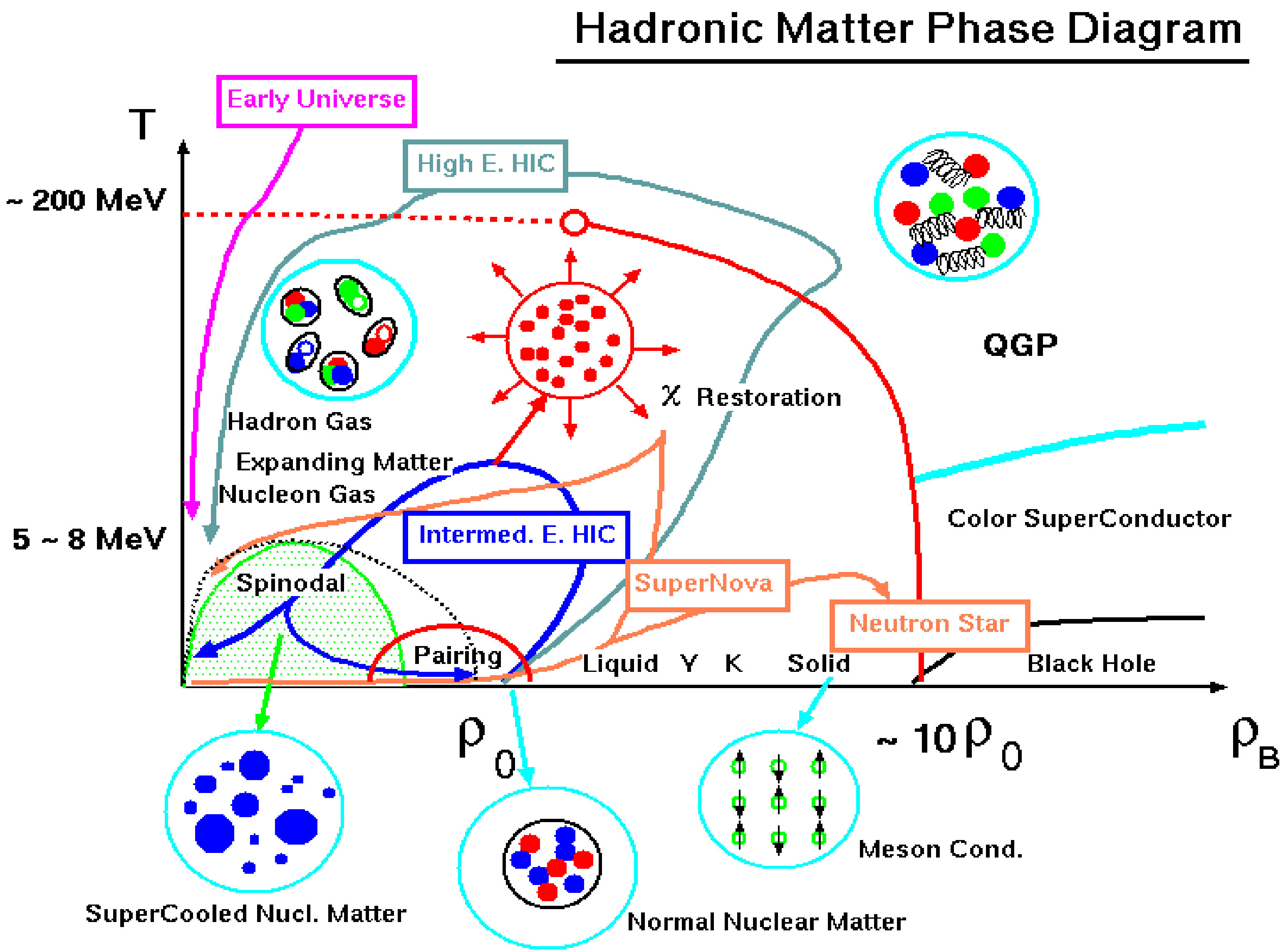
さらに核反応と結び付けて議論するためには、

相互作用の時間スケール:
　反応断面積、ハドロン「生成」時間、....
反応のダイナミクス

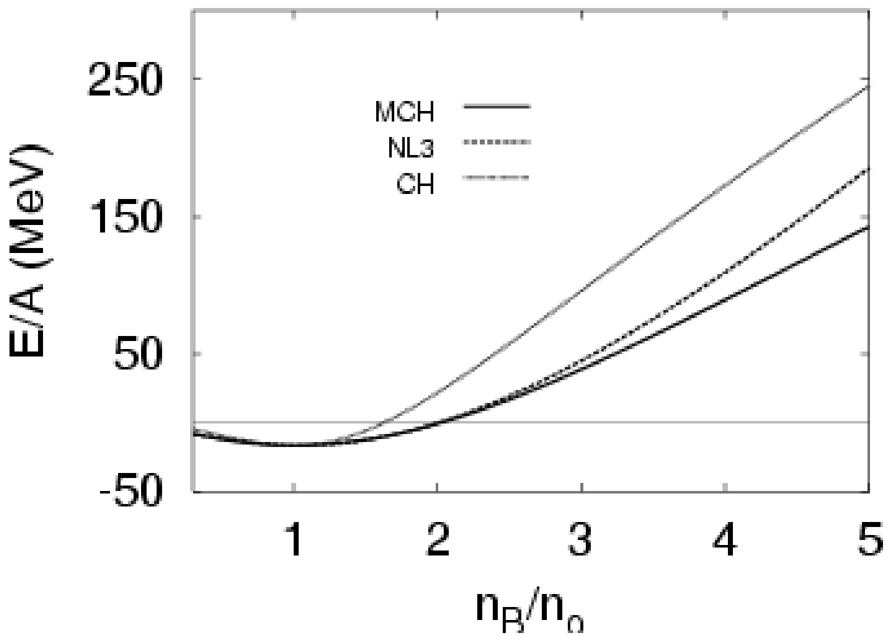
2. 理論的枠組み

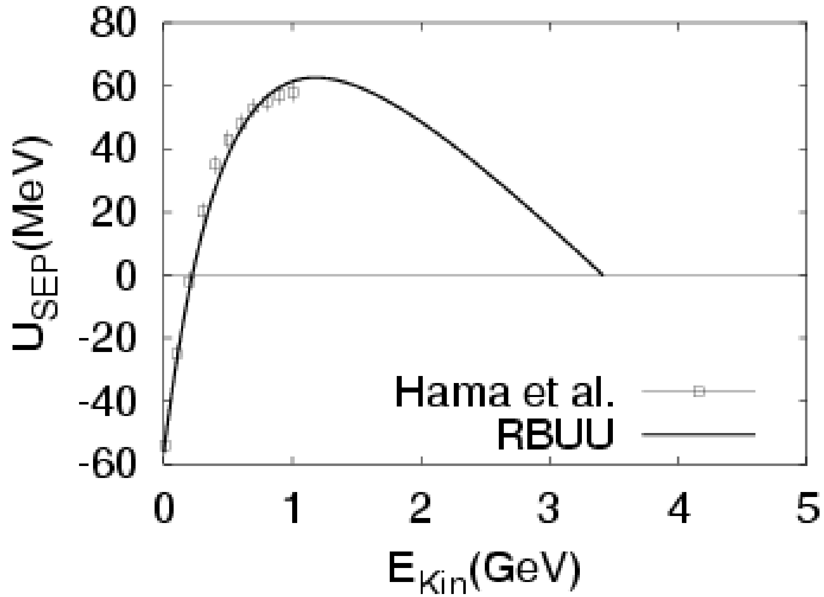
- 平均場と状態方程式
- 相共存条件
- 統計模型
- 半古典的輸送模型
- 相対論的分子動力学
- ハドロン素過程反応断面積

Hadronic Matter Phase Diagram



平均場と状態方程式





Saturation: ρ_0 = (0.14-0.17) fm^{-3}, E/A = -16 MeV

E-dep.: U(E=0) ~ -50 MeV, U(E=1GeV)~ +60 MeV

平均場と状態方程式

基本的相互作用からの構築

Lattice QCD:　有限密度では困難
核力＋ G行列: 核物質の飽和性が説明できていない。
現状では現象論的な力を加えることが必要
(UMOA などの方法に期待！)
DBHF:　　飽和性をほぼ説明。
高エネルギー粒子のポテンシャルには？

現象論的な方法

Skyrme HF:
飽和性 + 有効質量を取り入れたゼロレンジ力
デルタ型3体斥力は中性子物質では消える。
RMF:
飽和性 + 強い LS力 + エネルギー依存性を簡単に説明
高エネルギーで強すぎる斥力、高密度への外挿

Skyrme Hartree-Fock

(See Ring-Schuck for details)

Zero-Range Two- and Three-Body Interaction

$$v_{ij} = t_0 \delta(r_i - r_j) + \frac{1}{2}\left[\delta(r_i - r_j) k^2 + k^2 \delta(r_i - r_j)\right]$$

$$+ t_2 k \delta(r_i - r_j) k + i W_0 [\sigma_i + \sigma_j] \times \delta(r_i - r_j) k$$

$$k = \frac{1}{2i}(\nabla_i - \nabla_j)$$

$$v_{ijk} = t_3 \delta(r_i - r_j) \delta(r_j - r_k)$$

Energy Density (Even-Even, N=Z)

$$H(r) = \frac{\hbar^2}{2m^*(\rho)} \tau + \frac{3}{8} t_0 \rho^2 + \frac{1}{16} t_3 \rho^3 + \text{Derivative Terms}$$

$$\tau = \sum_i |\nabla \phi_i|^2$$

$$\frac{\hbar^2}{2m^*(\rho)} = \frac{\hbar^2}{2m} + \frac{1}{16}(3 t_1 + 5 t_2) \rho$$

Nuclear Matter in Skyrme HF

Energy per Nucleon

$$E/A = \frac{3}{5}\ \frac{\hbar^2 k_F^2}{2m^*(\rho)} + \frac{3}{8} t_0 \rho + \frac{1}{16} t_3 \rho^2$$

Problems in Skyrme HF (in Dense Nuclear Matter)

Repulsive Zero-Range 3-body Int.:
→ Ferromagnetism in Dense Matter
Kinetic Energy Dependence = Linear (m* term)
→ Too Repulsive for High Energy Particles

Relativistic Mean Field

TM1 parameter set (Sugahara and Toki, Nucl. Phys. A579 (1994), 557.)

- **Fit B.E. of Stable as well as Unstable (n-rich) Nuclei**
- **Has been successfully applied to Supernova Explosion**
- **Three Mesons (σ, ω, ρ) are included**
- **Meson Self-Energy Term (σ, ω)**

Lagrangian

$$
\begin{aligned}
\mathcal{L} =& \bar{\psi}_N \left(i\partial\!\!\!/ - M - g_\sigma \sigma - g_\omega \omega\!\!\!/ - g_\rho \tau^a \rho\!\!\!/^a \right) \psi_N \\
&+ \frac{1}{2}\partial^\mu \sigma \partial_\mu \sigma - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{1}{3} g_2 \sigma^3 - \frac{1}{4} g_3 \sigma^4 \\
&- \frac{1}{4} W^{\mu\nu} W_{\mu\nu} + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu - \frac{1}{4} R^{a\mu\nu} R^a_{\mu\nu} + \frac{1}{2} m_\rho^2 \rho^{a\mu} \rho^a_\mu + \frac{1}{4} c_3 \left(\omega_\mu \omega^\mu \right)^2 \\
&+ \bar{\psi}_e \left(i\partial\!\!\!/ - m_e \right) \psi_e + \bar{\psi}_\nu i\partial\!\!\!/ \psi_\nu - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \ , \\
W_{\mu\nu} =& \partial_\mu \omega_\nu - \partial_\nu \omega_\mu \ , \\
R^a_{\mu\nu} =& \partial_\mu \rho^a_\nu - \partial_\nu \rho^a_\mu + g_\rho \epsilon^{abc} \rho^{b\mu} \rho^{c\nu} \ , \\
F_{\mu\nu} =& \partial_\mu A_\nu - \partial_\nu A_\mu \ . \qquad (2)
\end{aligned}
$$

Relativistic Mean Field

Schroedinger Equivalent Potential

$$U_{sep} \sim U_S + \frac{E}{m} U_V = -g_\sigma \sigma + \frac{E}{m} g_\omega \omega$$

$$= -\frac{g_\sigma^2}{m_\sigma^2} \rho_s + \frac{E}{m} \frac{g_\omega^2}{m_\omega^2} \rho_B$$

Saturating Scalar Density + Baryon Density : Saturation
Linear Energy Dependence: Good at Low Energies,
Bad at High Energies

TDHF and Wigner Transformation

Time-Dependent Mean Field Theory (e.g., TDHF)

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

Wigner Transformation and Wigner-Kirkwood Expansion

(Ref.: Ring-Schuck)

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

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

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

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

Vlasov Equation and Test Particle Method

Wigner Transform of TDHF

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

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

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

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)

$$f(r, p) = \frac{1}{N_0} \sum_i^{A N_0} \delta(r - r_i)\, \delta(p - p_i) \quad \rightarrow \quad \frac{dr_i}{dt} = \nabla_p h, \quad \frac{dp_i}{dt} = -\nabla_r h,$$

Mean Field Evolution can be simulated by Classical Test Particles

BUU (Boltzmann-Uehling-Uhlenbeck) Equation

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

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

$$I_{coll}[f] = -\frac{1}{2}\int \frac{d^3 p_2 d\Omega}{(2\pi\hbar)^3} v_{12} \frac{d\sigma}{d\Omega}$$
$$\times \quad [f f_2 (1 - f_3)(1 - f_4) - f_3 f_4 (1 - f)(1 - f_2)]$$

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

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

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

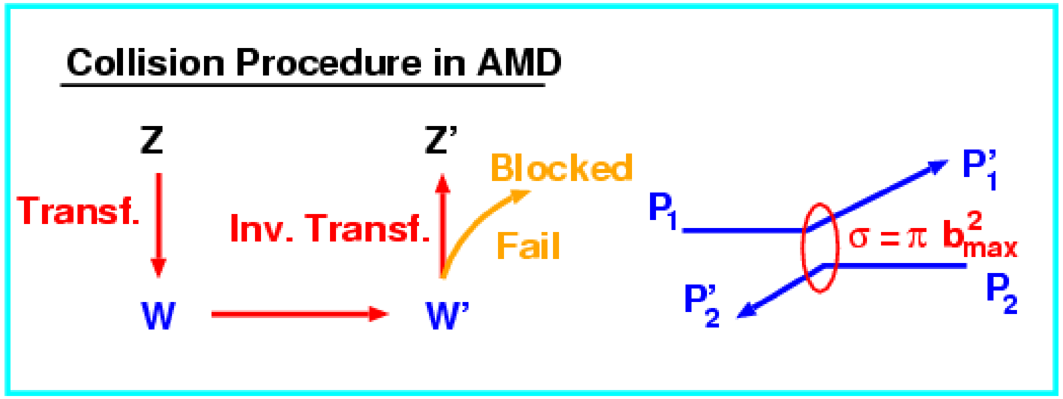
No Antisymmetrization $\quad C = \delta \rightarrow \dfrac{dD_i}{dt} = \dfrac{\partial H}{\partial K_i} \quad , \quad \dfrac{dK_i}{dt} = -\dfrac{\partial H}{\partial D_i}$

Collision Term in AMD

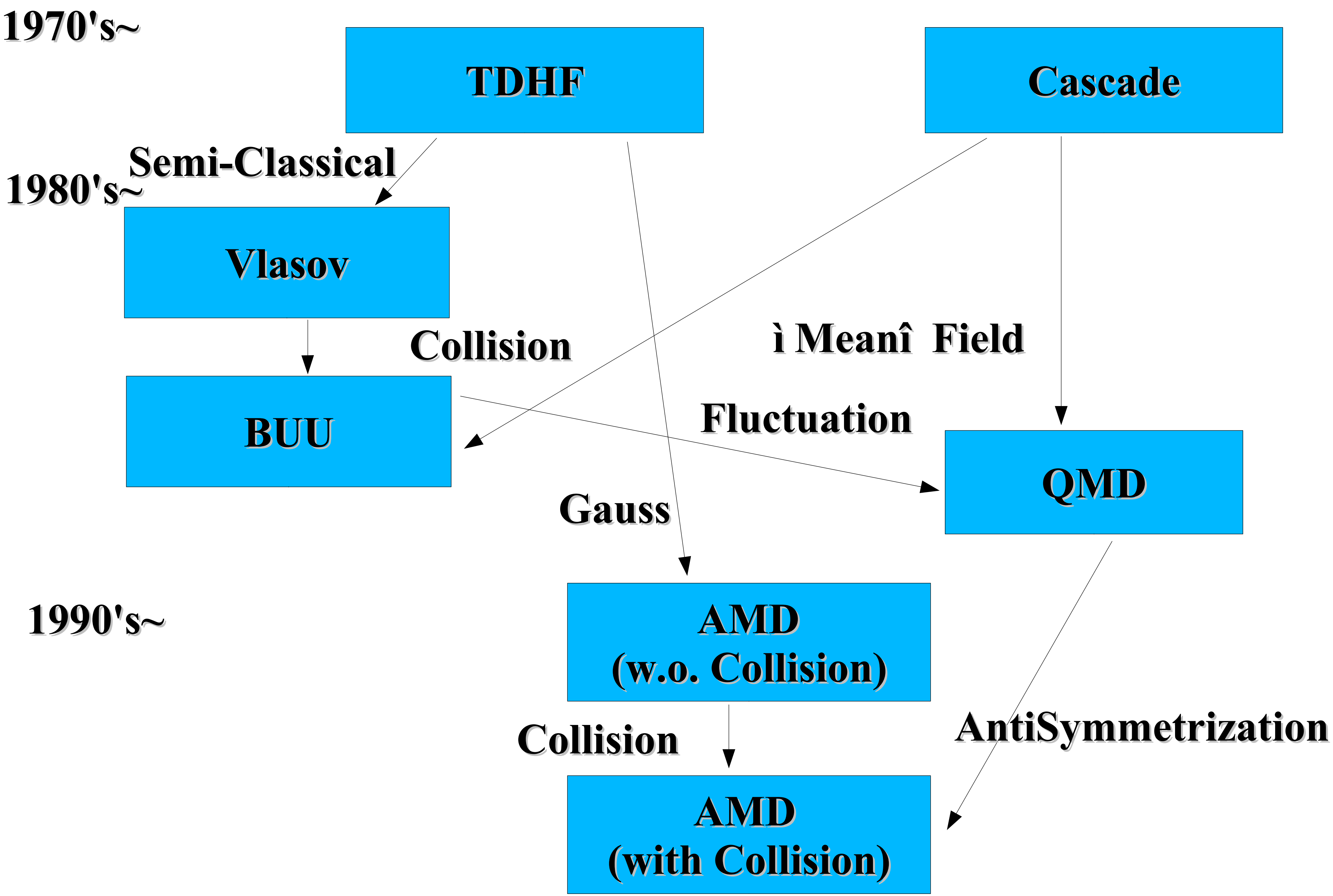
Approximate Canonical Variables

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

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 = ì Canonical" Variable + Classical Analogy


1970's~
TDHF
Cascade
Semi-Classical
1980's~
Vlasov
Collision
ì Meanî Field
BUU
Fluctuation
QMD
Gauss
1990's~
AMD
(w.o. Collision)
Collision
AntiSymmetrization
AMD
(with Collision)

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

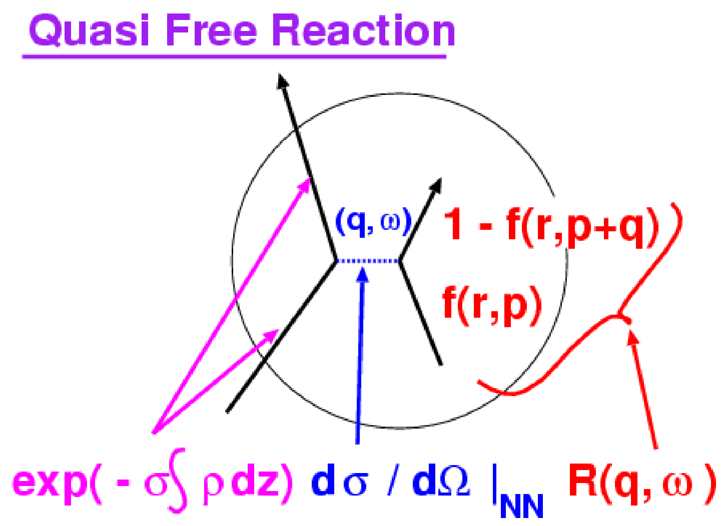
- ✓ Wave Packet Dynamics → Not an Eigen State of Energy, Jπ
- ✓ Initial and Final Fragment State → Not Quantized
- ✓ Two Body Collisions → Classical Analogue (Not Derived)
- ✓ Non-Relativistic → Not Applicable to Very High Energy

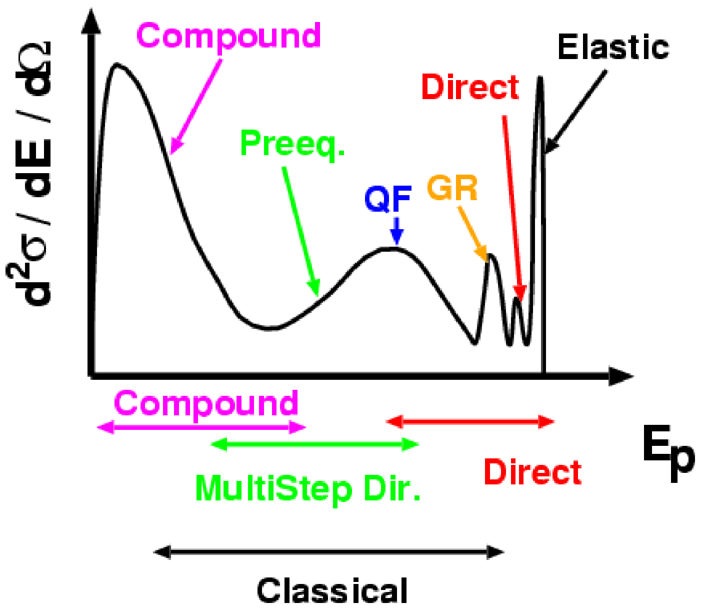
Direct Reactions

One Step Direct Reaction

- Elementary Cross Section
- Absorption of Projectile
  and Emitted Particle.
  → Effective Number
- **Response Function**
  (Spectroscopic Info.)

In order to extract spectroscopic info., we need elementary cross section





Direct Reactions

Distorted Wave Impulse Approximation (DWIA)

$$\frac{d^2\sigma}{d\omega d\Omega} \simeq A_{eff} \left.\frac{d\sigma}{d\Omega}\right|_{NN} R(\vec{q},\omega)$$

$$R(\vec{q},\omega) = -\frac{1}{\pi A}\mathrm{Im}\left\langle\Phi_0\right| \delta\hat{O}^\dagger(\vec{q})\; G(\omega)\; \delta\hat{O}(\vec{q})\; \left|\Phi_0\right\rangle$$

$$\simeq \frac{1}{A}\int \frac{d\vec{r}\,d\vec{p}}{(2\pi\hbar)^3}\; f(\vec{r},\vec{p})\; (1 - f(\vec{r},\vec{p}+\vec{q}))$$

$$\times\, \delta(\omega + h(\vec{r},\vec{p}) - h(\vec{r},\vec{p}+\vec{q}))$$

One-Step INC

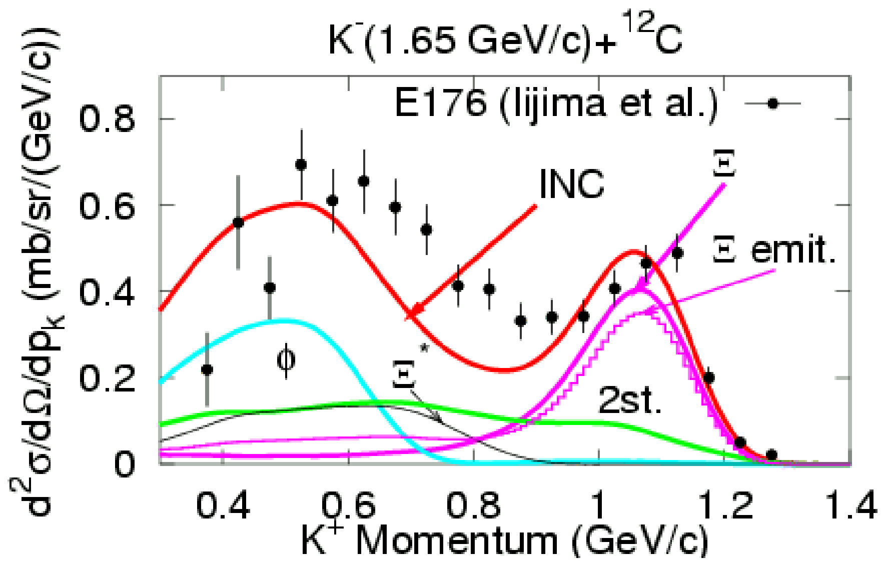
$$\hat{O}(\vec{q}) = \sum_i \exp(i\vec{q}\cdot\vec{r}_i)\,\hat{O}_{S,T,Y,..}$$

Quantum Mechanical Treatment

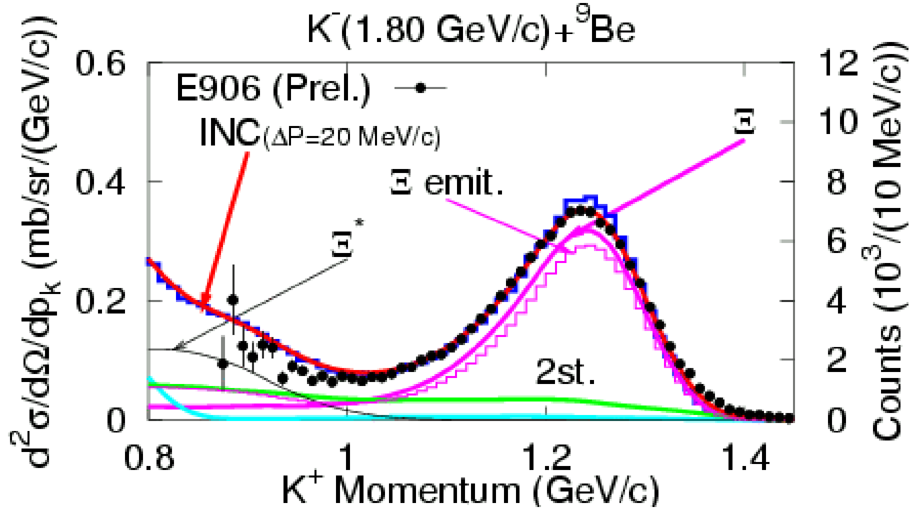
$$G(\omega) = \frac{1}{\omega - H - i\epsilon}$$

Examples: (K^-,K^+) Reaction

- KEK-E176 data (Iijima et al.)



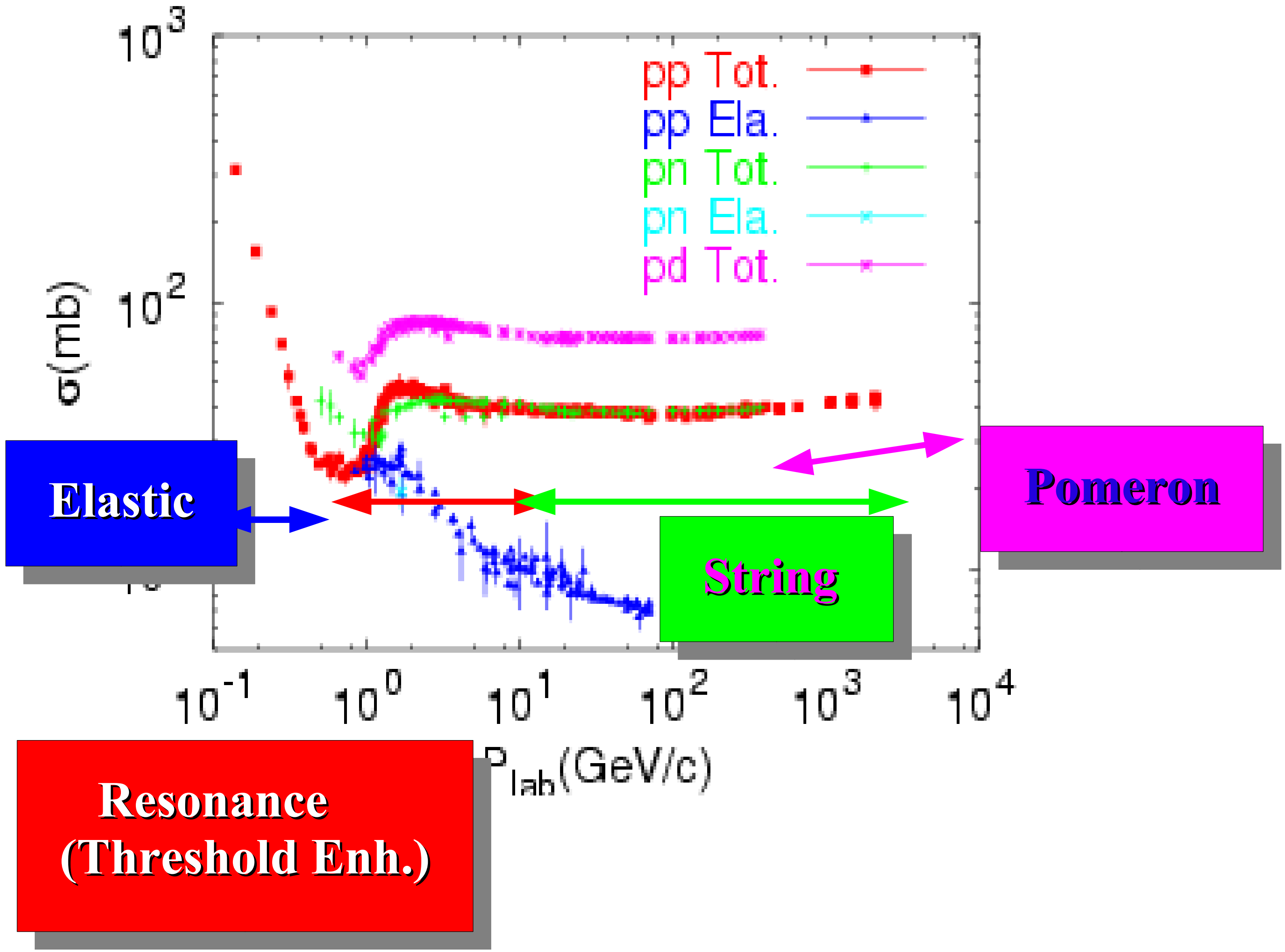
- BNL-E906 data (Tamagawa et al.)



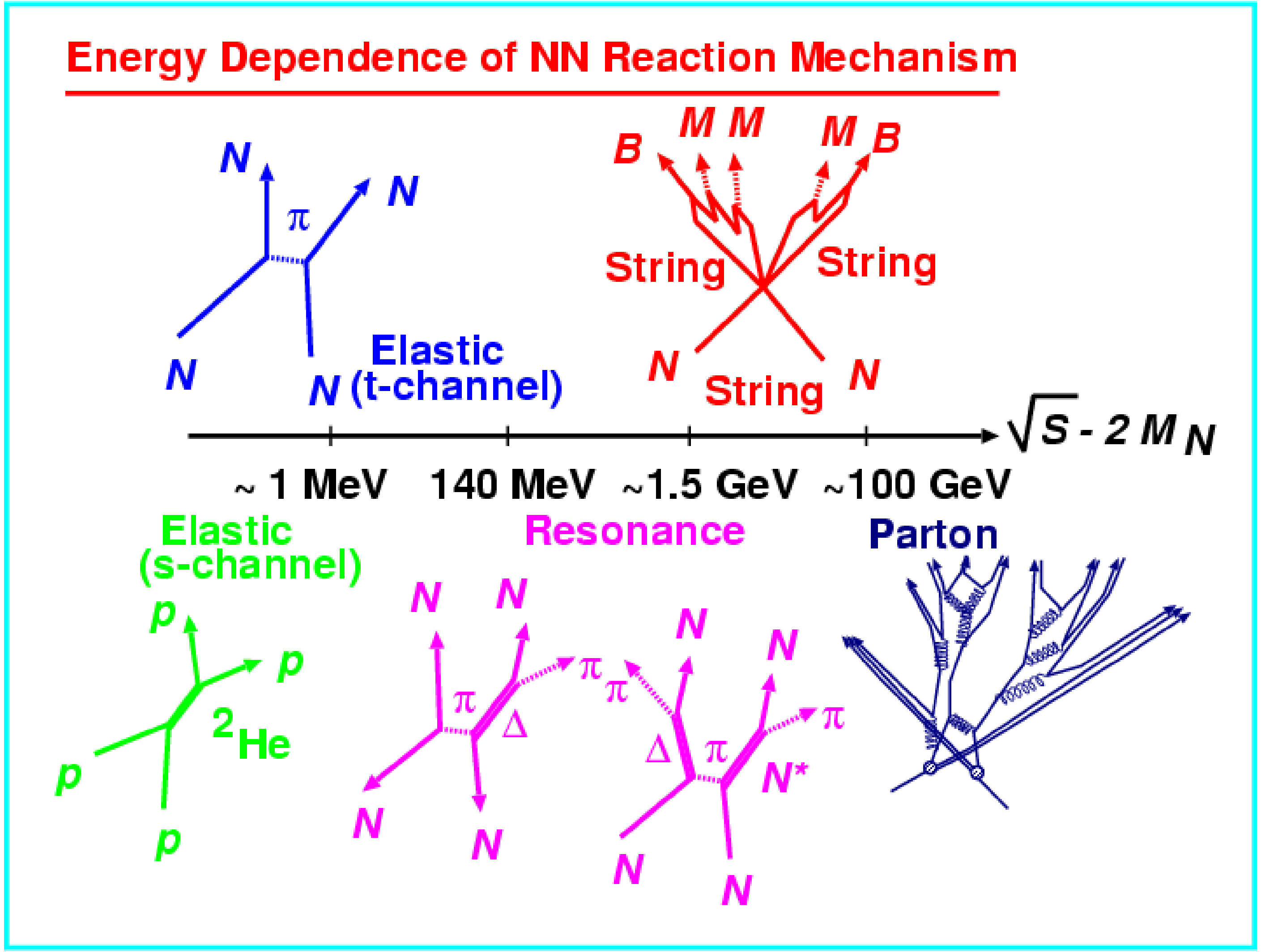
Continuum: Semi-Classical Treatment Works Well
Bound and Resonance: Quantum Mechanical Treatment is Required

NN Cross Sections

From Particle Data Group

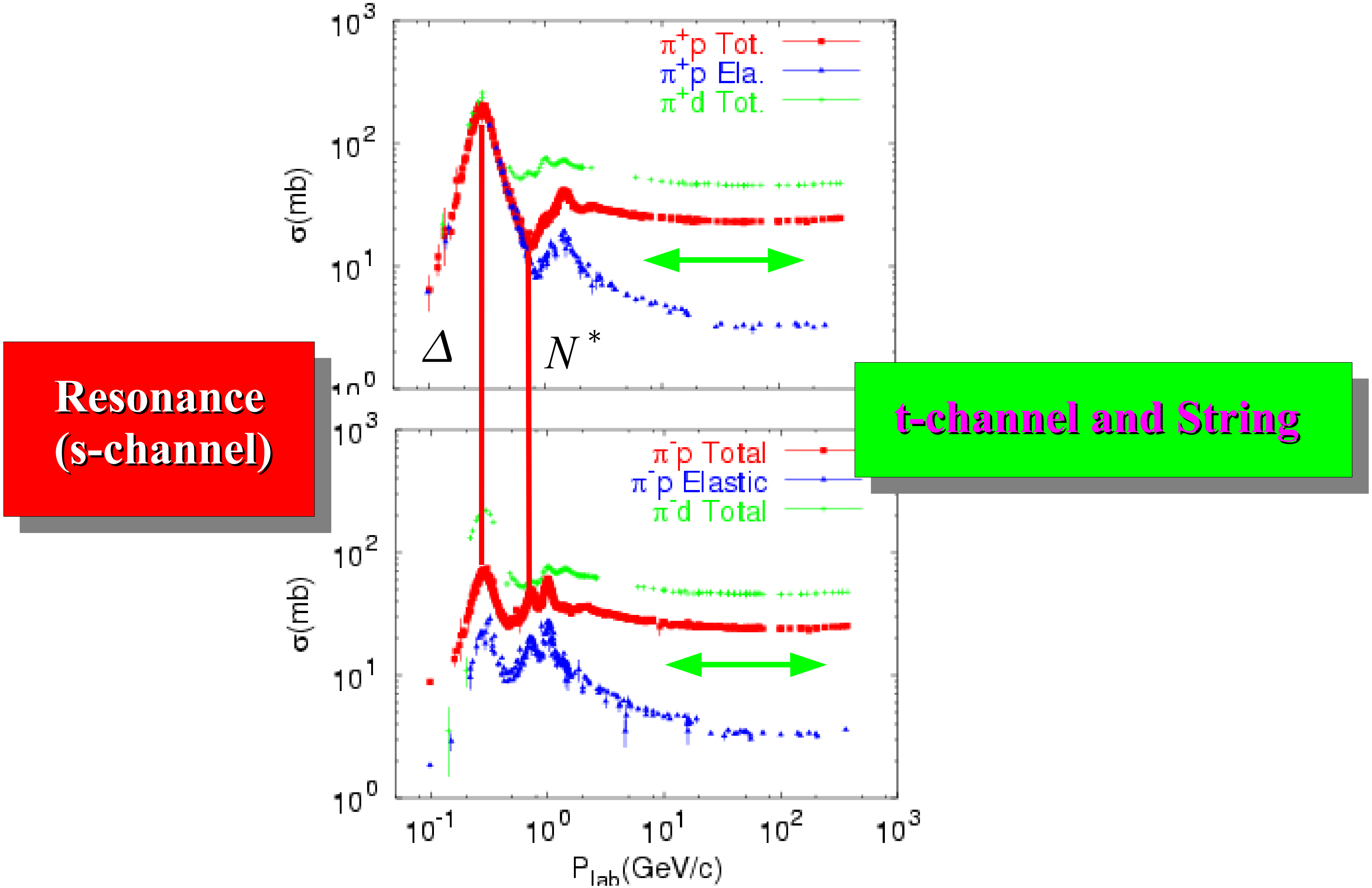


Rough Reaction Mechanism of NN Collisions

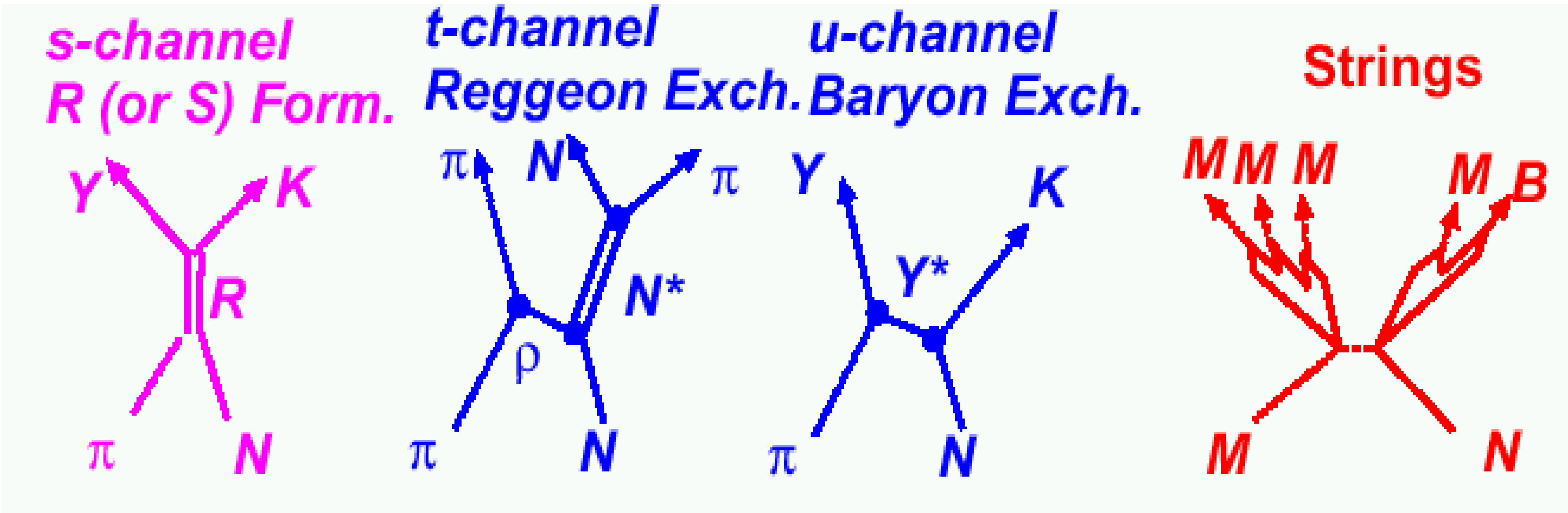


Elastic → Resonance → String → Jet

Meson-Baryon Cross Section



Meson-Baryon Cross Section



Strong Resonance Formation at Low Energy

→ Smooth Behavior at High Energy

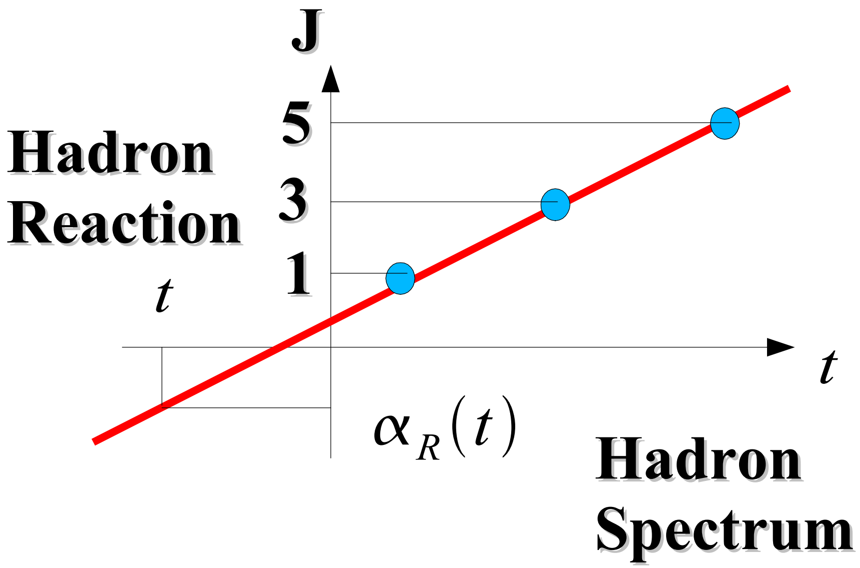
Reggeon Exchange Model

(Barger and Cline (Benjamin, 1969), H. Sorge, PRC (1995), RQMD2.1)

Regge Trajectory

$$J = \alpha_R(t) \sim \alpha_R(0) + \alpha'_R(0)\, t$$

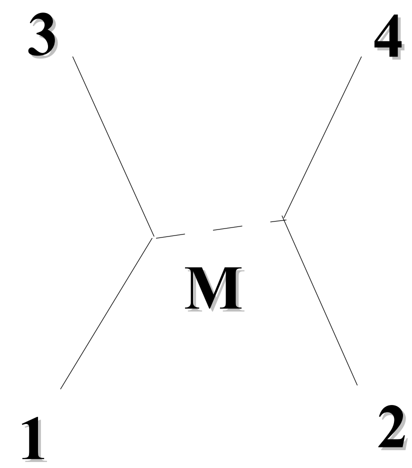
(Hadron String Model)



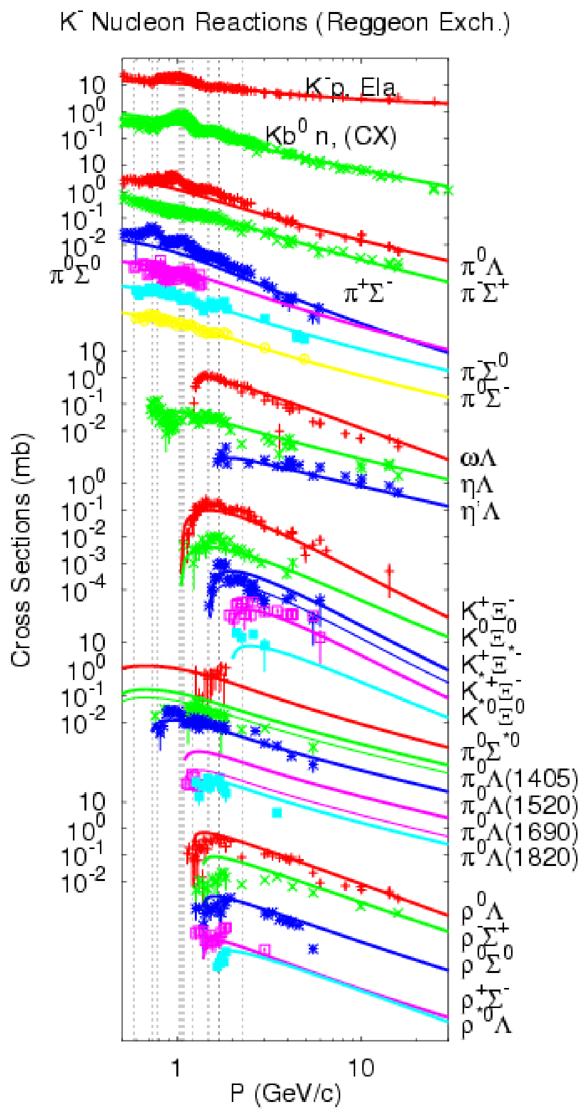
2 to 2 Cross Section

$$\frac{d\sigma}{d\Omega} = \frac{p_f}{64\pi s\, p_i} |M(s,t)|^2$$

$$M(s,t) \sim \sum_R \frac{(p_i p_f)^J}{t - M_R} \sim F(t) \left(\frac{s}{s_0} \right)^{\alpha_R(t)}$$



Reggeon Exchange Cross Sections



JAM (Jet AA Microscopic transport model)

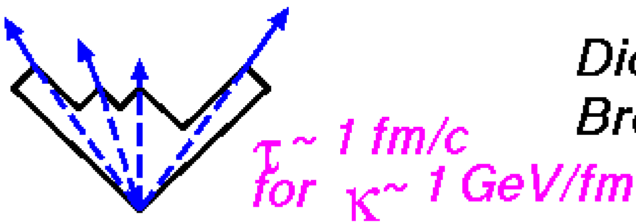
Y. Nara et al., Phys. Rev. C61 (2000), 024901.

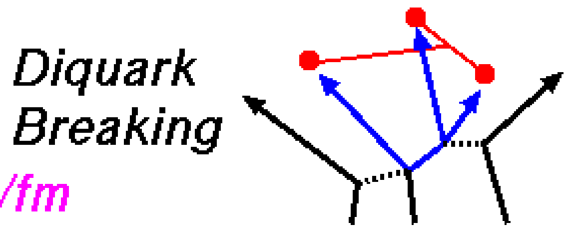
DOF

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

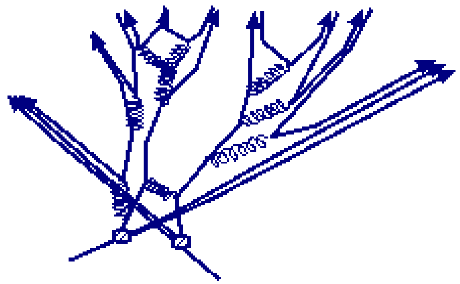
Cross Sections

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





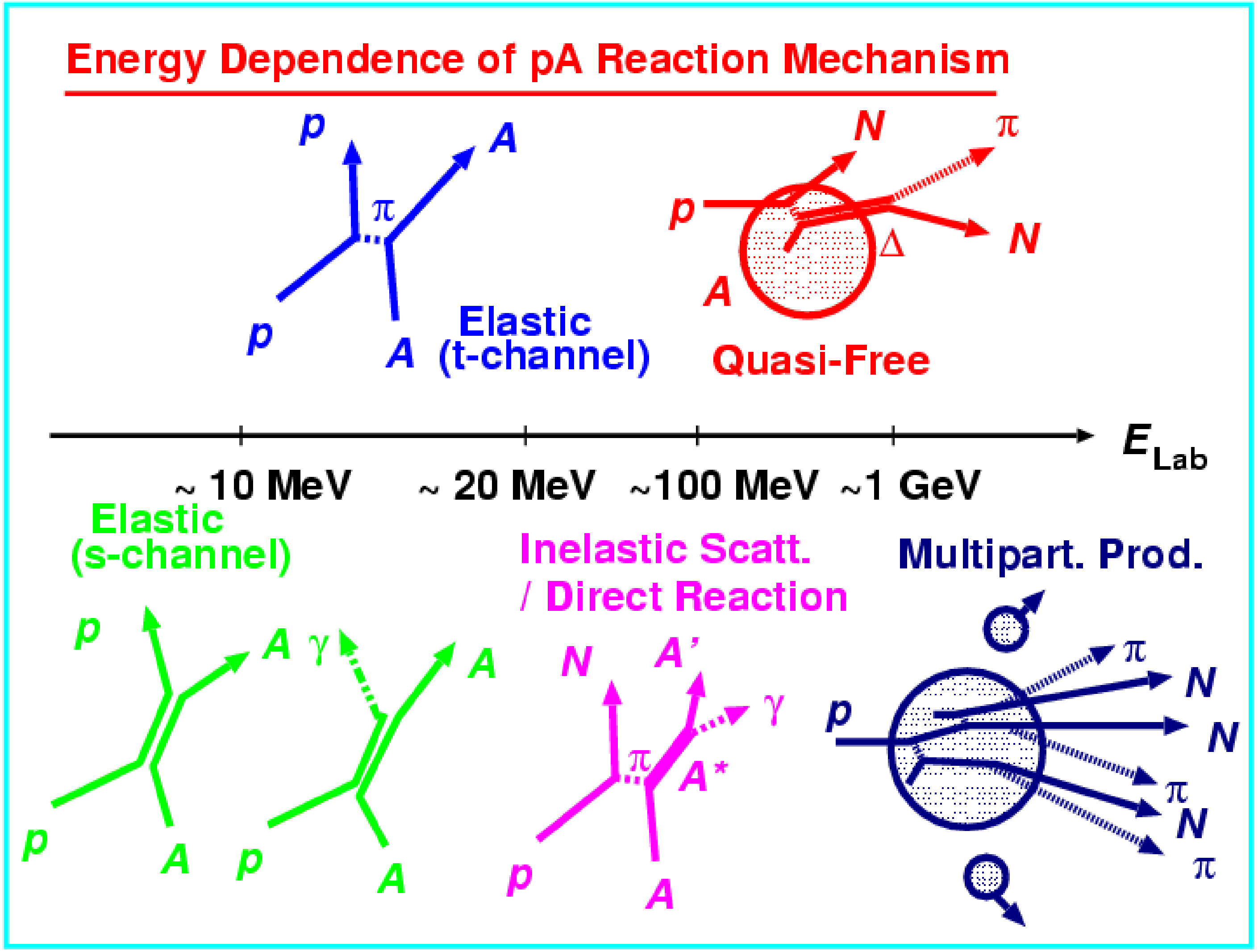
Resonance
+ String
+ Jet



[1] îDPM+ Lundî (~ HIJING) + Phase Space

[2] Consituent Rescattering (~ RQMD)

Rough Reaction Mechanism of NA Collisions



Statistical Model of Hadrons and Fragments

Grand Canonical Statistical Ensemble of Constituents

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

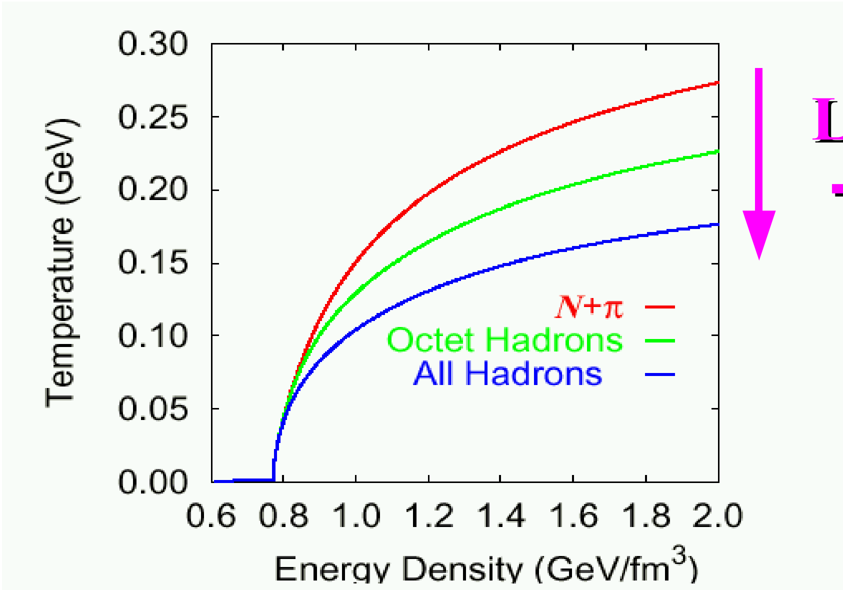
Thermodynamical Functions

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

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

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

$$Z(V,T) = \sum_{(k)} \exp\left(\frac{1}{T}\sum_i \sum_\tau \epsilon_{i,\tau}\nu_{i,\tau}\right) - 1$$

$$= \exp\left[\frac{VT}{2\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\int_0^\infty \mathrm{d}m\rho(m,n)m^2 K_2\left(\frac{nm}{T}\right)\right] - 1$$

$$\equiv \frac{VT^3}{(2\pi)^{\frac{3}{2}}}\int_0^\infty \mathrm{d}m \ m^{\frac{3}{2}}\rho(m)Q\left(\frac{m}{T}\right),$$

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

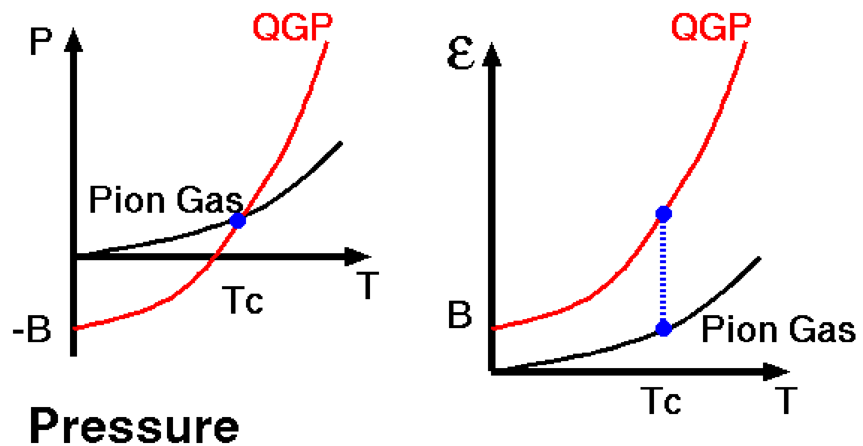
$$P_\pi = \frac{\pi^2}{30} T^4 \quad , \quad \epsilon_\pi = \frac{\pi^2}{10} T^4$$

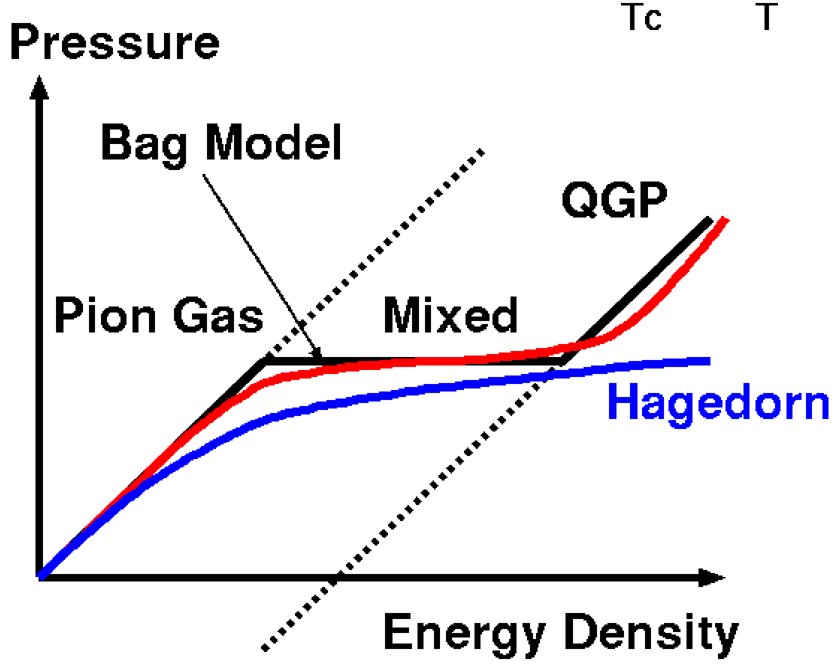
QGP with Finite Bag Constant

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

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

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



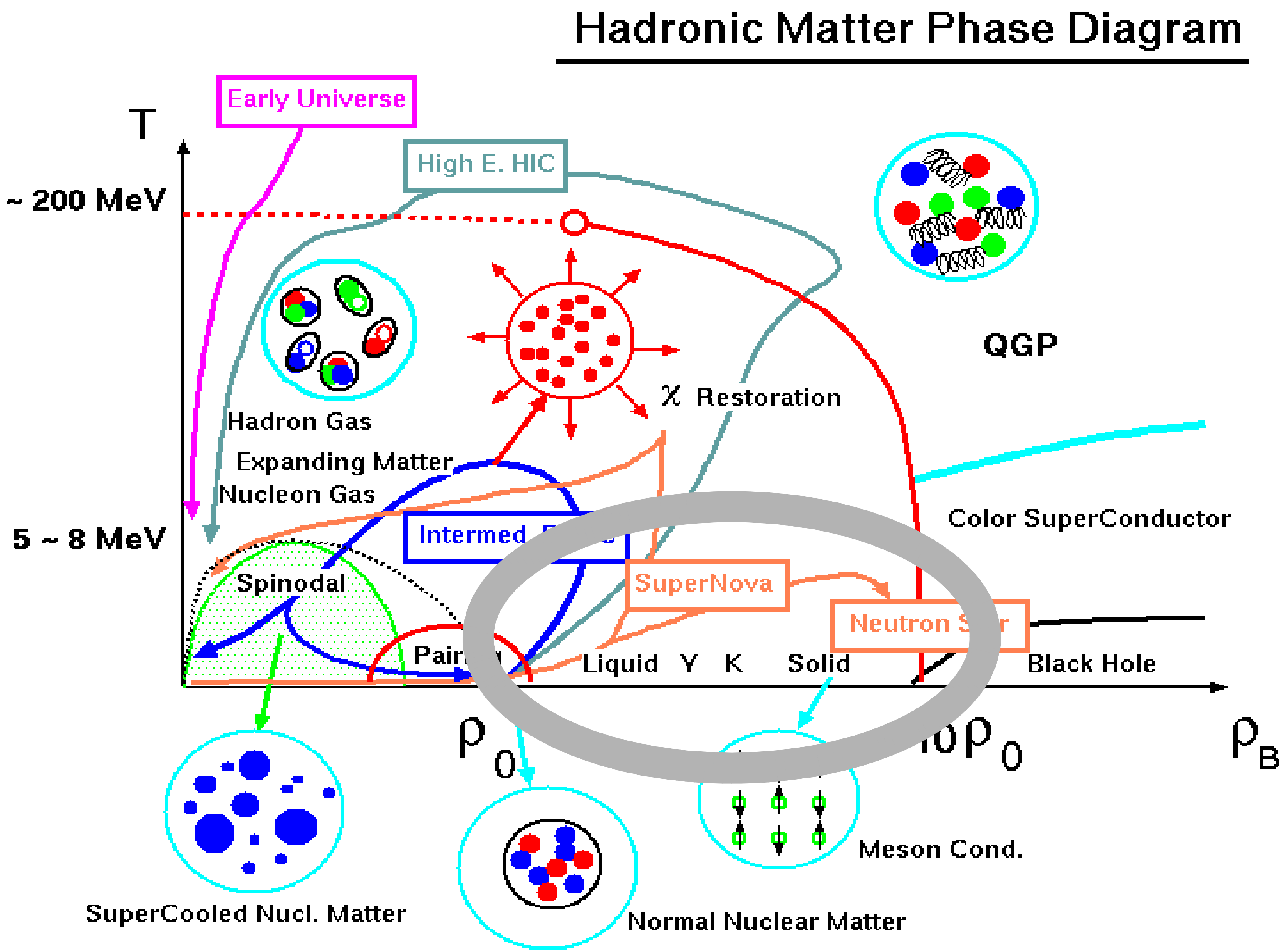


Summary

- 様々な核反応から「相図」までを記述できる ***Super Model*** は
存在するか？
  → No！(Not Yet)
  → 「入射エネルギー」、「観測量」ごとに
  適した模型を使って理解する。

- 低～中間エネルギーでの集団運動、平均的粒子移行など:
TDHF (TDLA), Vlasov Eq., BUU Eq.
.... One-body Mean Field Dyn.
- 低～中間エネルギー領域でのフラグメント生成:
QMD, AMD (AMD-V, AMD-QL), ... + 統計崩壊
- 中間～高エネルギー領域での粒子スペクトル
直接反応 (SCDW)、カスケード、QMD、...
- 高エネルギー領域でのフラグメント生成:
Cascade 模型 + Percolation 等 + 統計崩壊

3. 低温・高密度物質とストレンジネス


Hadronic Matter Phase Diagram
Early Universe
High E. HIC
T
~ 200 MeV
5 ~ 8 MeV
Hadron Gas
χ Restoration
QGP
Expanding Matter
Nucleon Gas
Intermed
Spinodal
SuperNova
Neutron S
r
Color SuperConductor
Pair
Liquid Y K Solid
Black Hole
ρ 0
ρ B
SuperCooled Nucl. Matter
Normal Nuclear Matter
Meson Cond.

Contents

Flavor SU(3) Symmetry

Flavor SU(3) Symmetry (I)

SU(3) Symmetry in QCD

$$\mathcal{L} = \bar{q}\,(i\,\not\partial - g\,\not G)\,q - \frac{1}{4}\mathrm{Tr}\left(G^a_{\mu\nu}G^{a\mu\nu}\right) - \bar{q}mq$$

$$m = \mathrm{diag}(m_u, m_d, m_s)$$

If we can ignore mass difference,
the Lagrangian is invariant under *flavor rotation*.

$$q \longrightarrow q' = Uq\ , \quad U \in \mathrm{SU}(3)$$

Flavor SU(3) Symmetry (II)

Meson State

$$M = q\bar{q} = \begin{pmatrix} u\bar{u} & u\bar{d} & u\bar{s} \\ d\bar{u} & d\bar{d} & d\bar{s} \\ s\bar{u} & s\bar{d} & s\bar{s} \end{pmatrix}$$

$$M = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & -\frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \bar{K}^0 & -2\eta/\sqrt{6} \end{pmatrix}$$

$$M \rightarrow M' = UMU^\dagger$$

Baryon State

$$B_{ij} = q_i \epsilon_{jkl} q_k q_l = \begin{pmatrix} u[ds] & u[su] & u[ud] \\ d[ds] & d[su] & d[ud] \\ s[ds] & s[su] & s[ud] \end{pmatrix}$$

$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -2\Lambda/\sqrt{6} \end{pmatrix}$$

$$B \rightarrow B' = UBU^\dagger$$

Flavor SU(3) Symmetry (III)

SU(3) Invariant Meson-Baryon Coupling

$$\mathrm{Tr}\left(\bar{B}MB\right)\;,\quad \mathrm{Tr}\left(\bar{B}BM\right)$$

$$\rightarrow \text{D Coupling}\;:\;\mathrm{Tr}\left(\bar{B}\left(MB+BM\right)\right)$$

$$\text{F Coupling}\;:\;\mathrm{Tr}\left(\bar{B}\left(MB-BM\right)\right)$$

SU(3) Symmetry

Approximate Symmetry in QCD

Basic Symmetry in Constructing BB Interaction

Recent Developments in Hypernuclear Physics

Recent Developments in Hypernuclear Spectroscopy

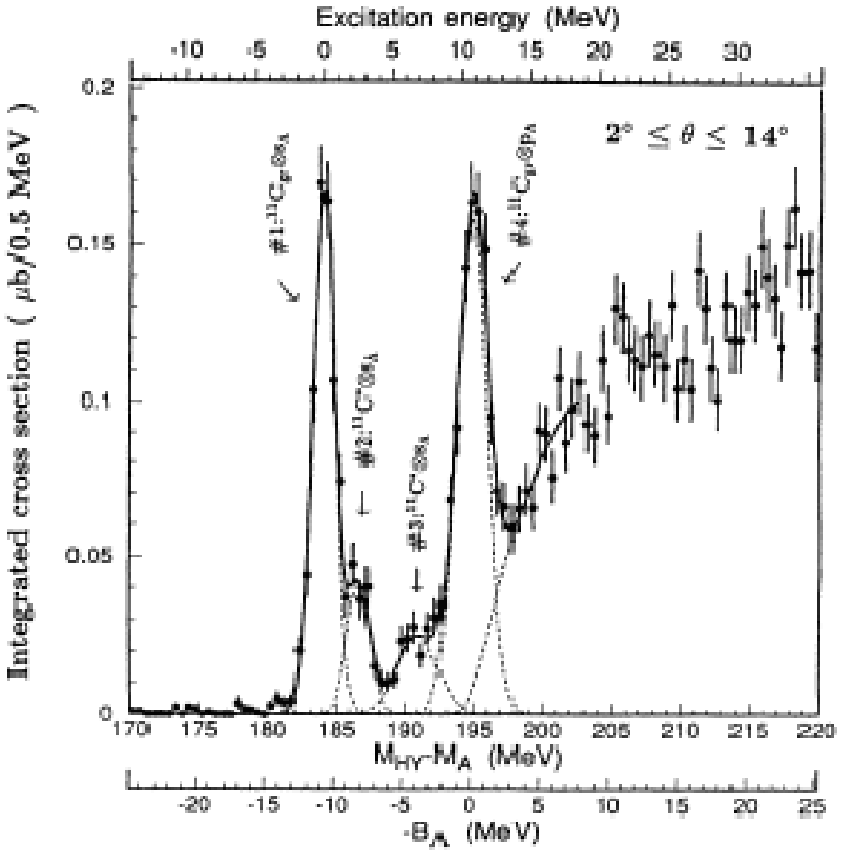


FIG. 2. Excitation spectrum of $^{12}_{\Lambda}C$ observed in the (π^+, K^+) reaction at $p_\pi = 1.06$ GeV/c using the SKS spectrometer. The vertical scale gives a cross section integrated from 2 to 14 deg after correcting the angular dependence of the spectrometer acceptance. The energy resolution is better than 2.0 MeV.

T.Hasegawa et al.,
Phys. Rev. Lett. 74, 224 (1995)

High Resolution Experiments

(π^+, K^+) Reaction $\Delta E < 2$ MeV

γ ray with Ge array $\Delta E \gg$ keV

→ Fine Structures, Core Exc.

Good YN Int & Precise Calc.

Nijmegen vs Quark Model

G-matrix

Three-Body Corr.

In OPEN shell core

Three-, Four-Body Calc.

Very Small LS int for YN → Paradigm Change in BB interaction !

Old:

BB interaction is well described by Meson Theory,
EXCEPT for the Repulsive Core

New:

Quarks also play important roles in longer range BB interaction
such as the LS force.

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 $^{4}_{\Sigma}He$:

  Coherent ΛΣ Coupling

  (Harada-Akaishi-Shinmura-Myint, Hiyama et al.)
- ΛΛ Interaction in Nuclei = Weakly Attractive

  Recent Experiment KEK-E373 (Nagara Event)

Σ Potential Effects on Neutron Star Matter

- **Potential for Λ; Relatively Well Known**

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

- **Potential for Ξ; 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 Σ: Contradicting Conjectures**

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

  $U(\Sigma) > 0$

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

Why is Strangeness important in Dense Matter ?

Constituents:

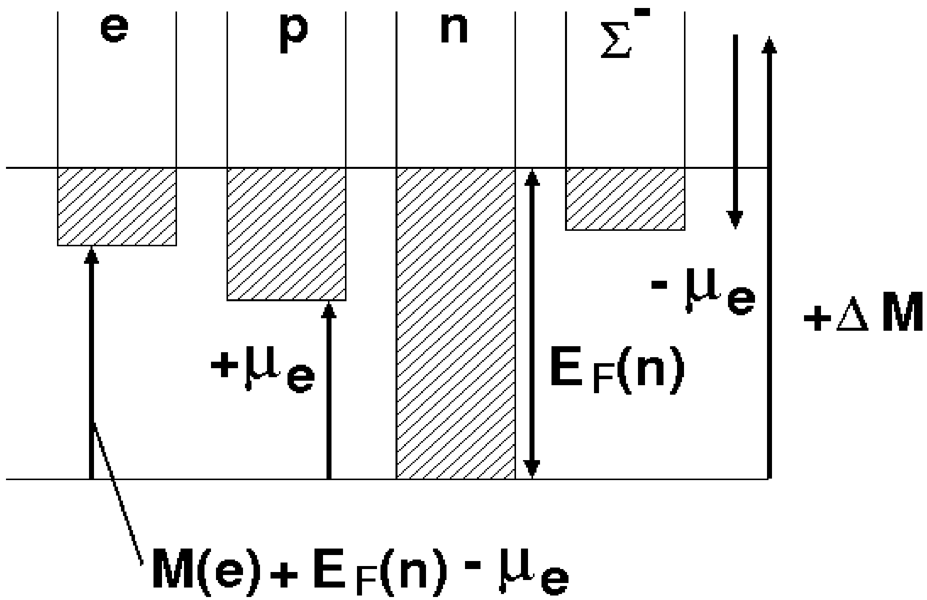
$$p, n, e^{\pm}, \mu^{\pm}, \Lambda, \Sigma^{\pm,0}, \ldots$$

Chemical Equilibrium:

◊ **Strangeness (Weak)**

◊ **Lepton (ν Emission)**

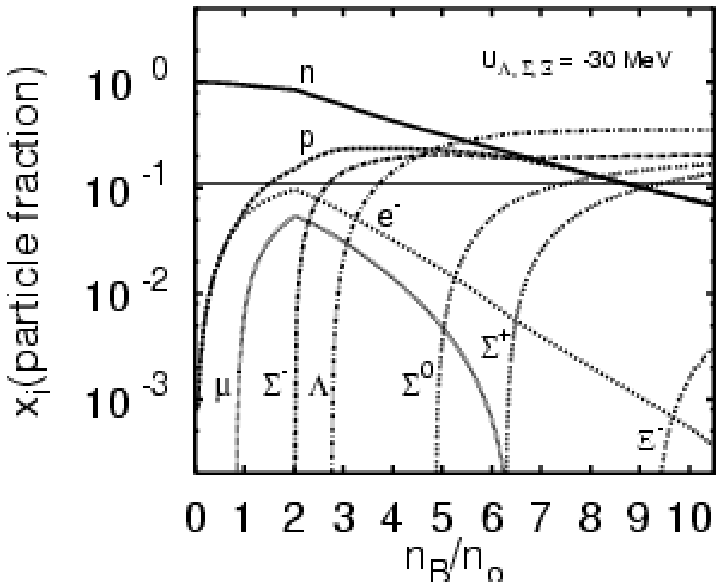
$$\mu_i = B_i \mu_B + Q_i \mu_Q$$



Negatively Chaged or Neutral Baryons are Favored

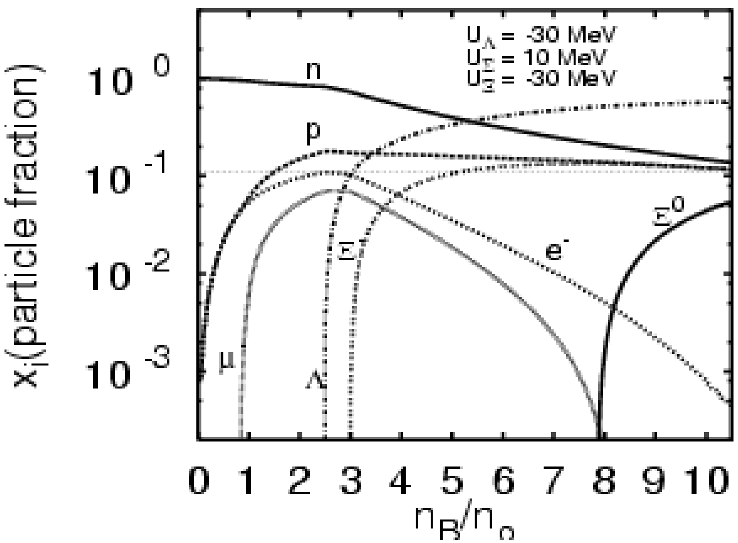
$$E_F^*(n) + U(n) + \mu_e = M^*(\Sigma^-) + U(\Sigma^-) \qquad \text{N appears}$$

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



Attractive Potential for ∑
➔ N appears at around

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



Repulsive Potential for N
➔ N does not appear

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

What is Still Unknown ?

- Properties of Hyperons (All) at Higher Densities.
- Σ Potential at ρ_0 and Higher Densities
- $\Lambda\Lambda$ Interaction in ì Freeî Space

→ Very Recent Experiments !

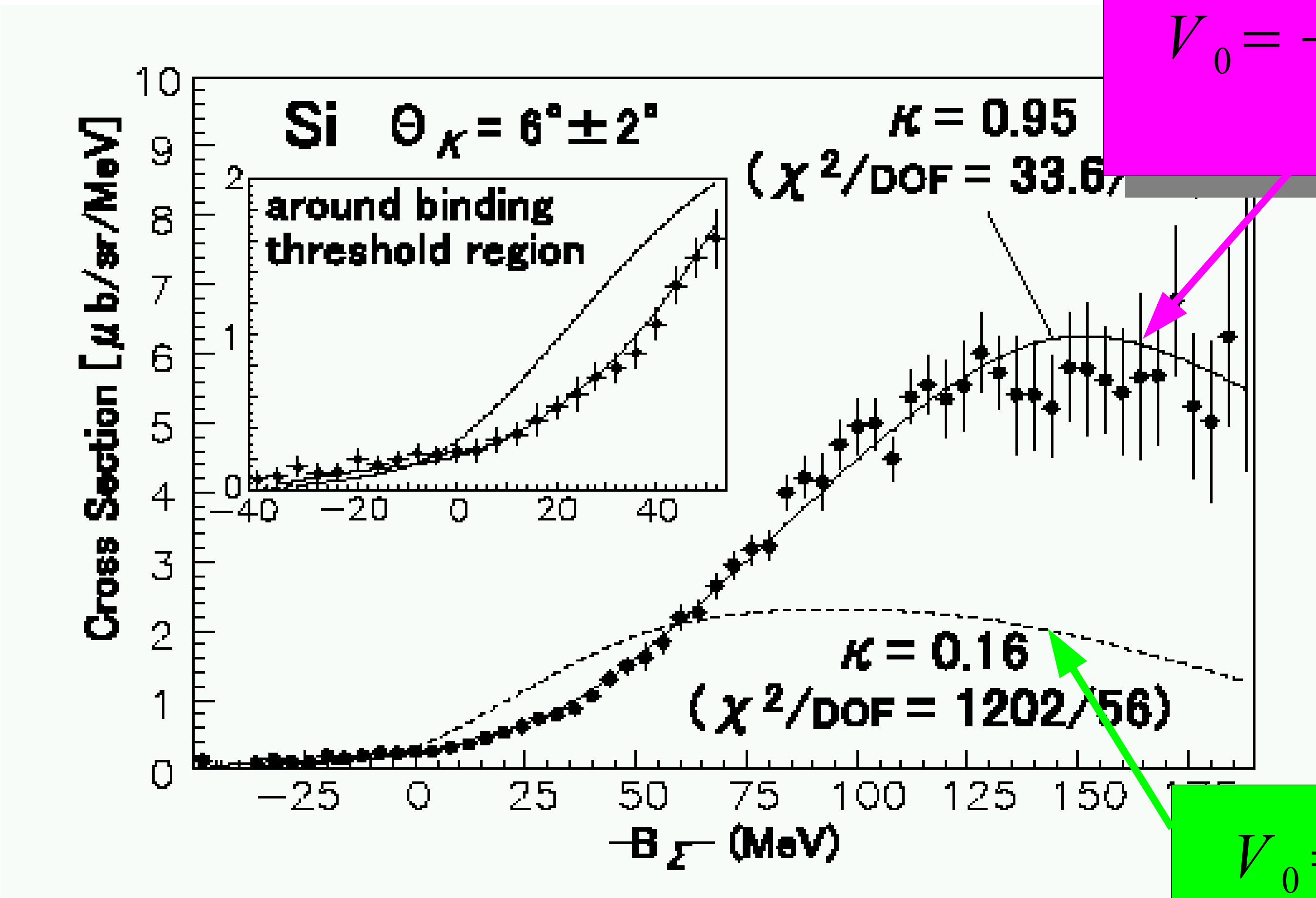
- Direct Quasi-Free Production of Σ (Noumi et al.)
- Strangeness Enhancement in HIC at SPS (NA49)

Several Recent Topics Related to Hyperons in Dense Matter

- **Direct Quasi-Free Production of Σ (Noumi et al.)**
- **Strangeness Enhancement in HIC at SPS (NA49)**

Does N Feel +150 MeV (Repulsive) in Nuclei ?

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



$V_0 = +150\,\text{MeV}$

$V_0 = -10\,\text{MeV}$

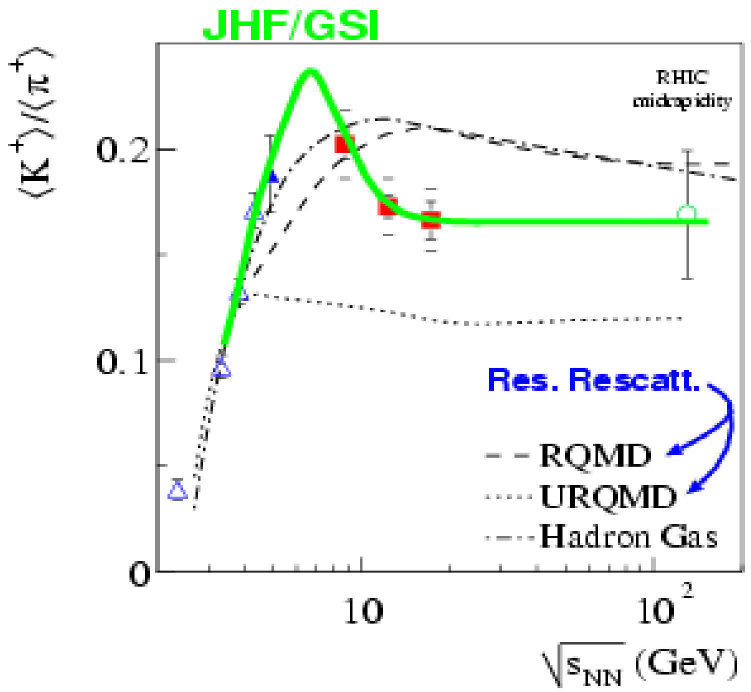
No Theoretical Model Support $V_0 = +150\,\text{MeV}$ **! ➡ Big Puzzle !!**

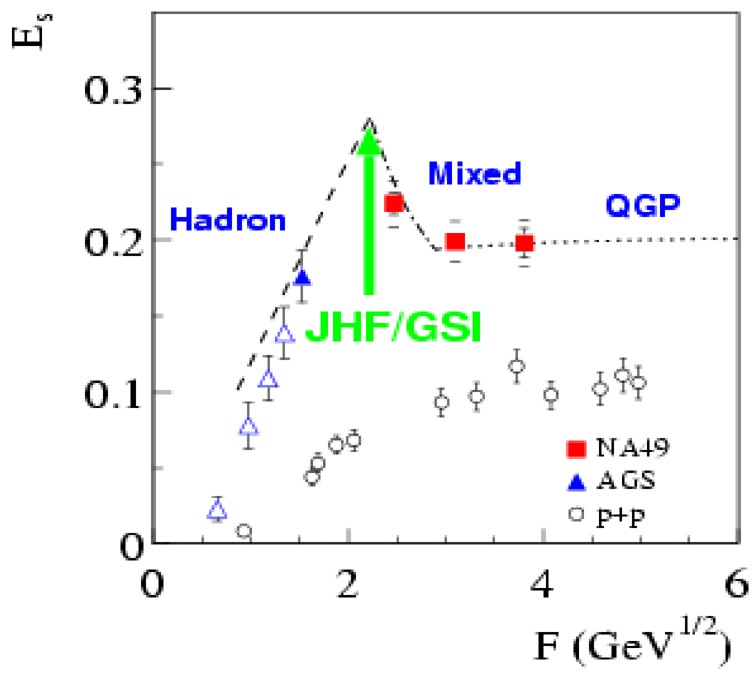
c.f. Kohno et al. (last JPS Meeting)

Strangeness Enhancement: Rescattering, Potential, or Phase Transition ?

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

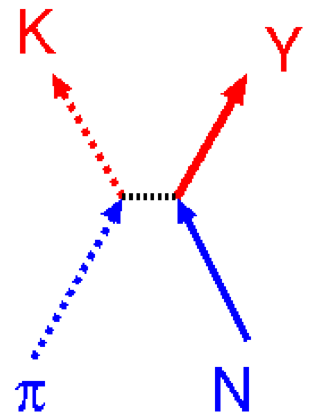
NA49 (nucl-ex/0205002)



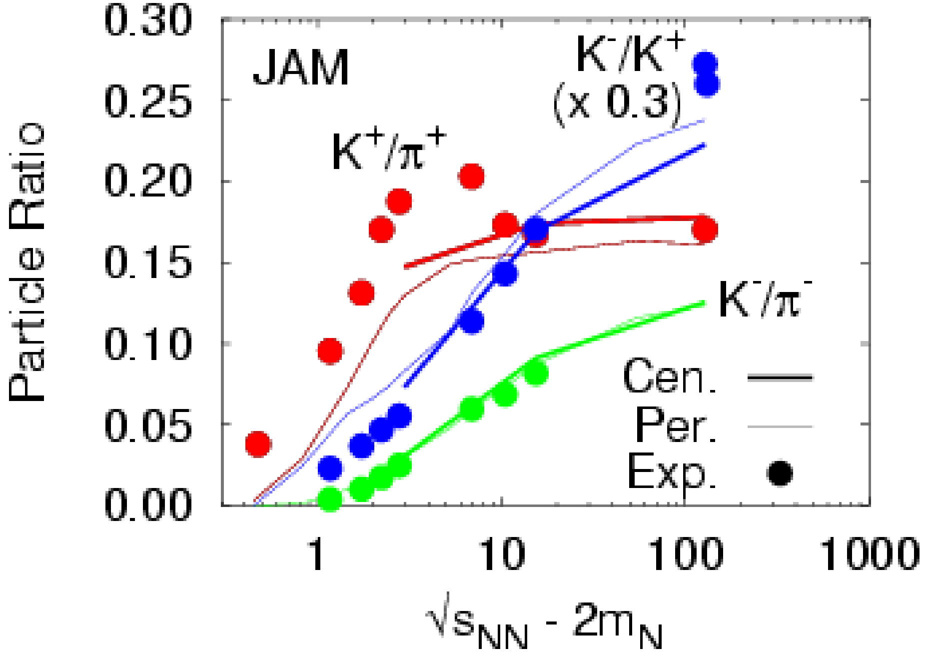


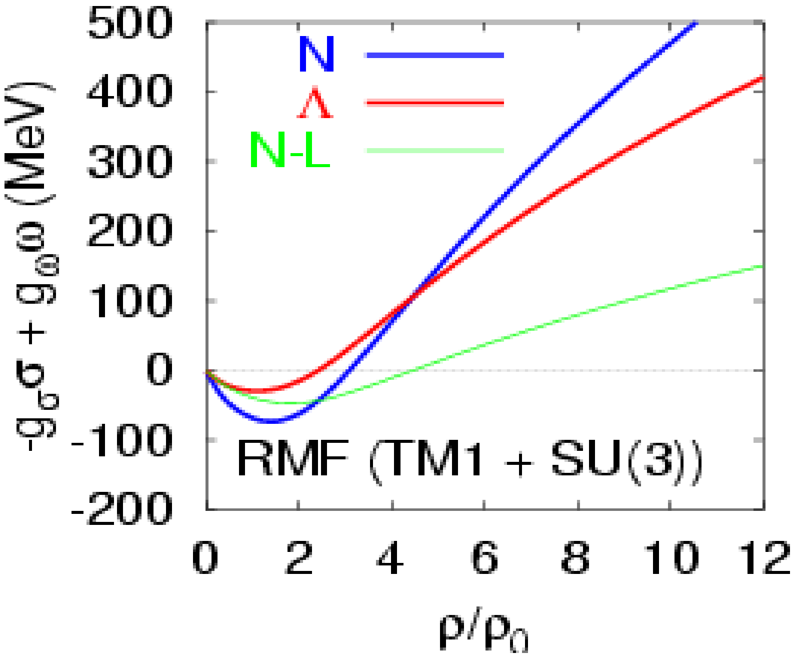
JHF Energy: ~ Maximum K/π ratio

Does Hyperon Potential Help It ?



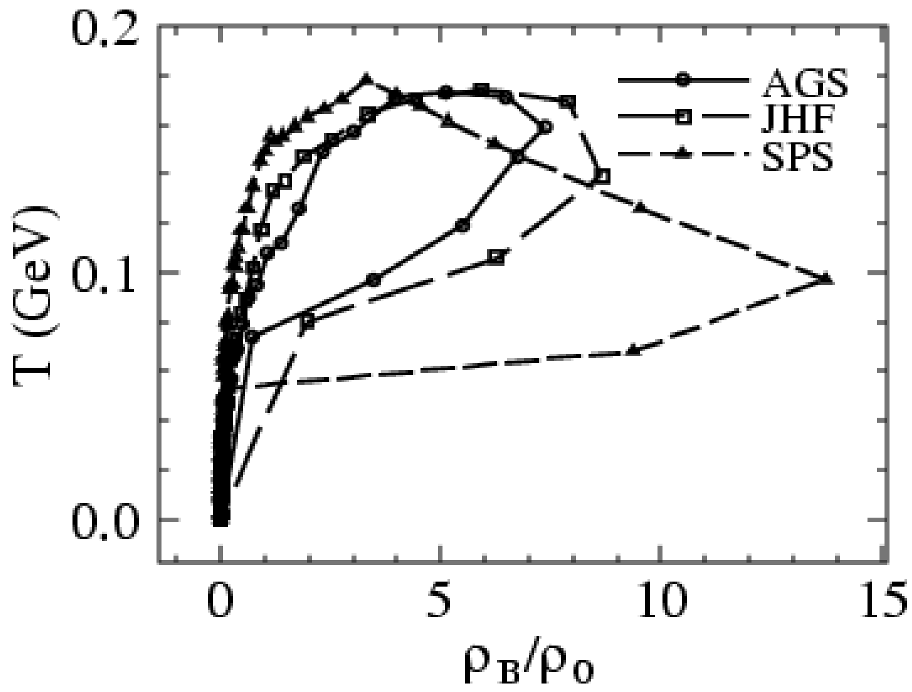
- **Rescattering of Resonances/Strings (RQMD)**
- **Baryon Rich QGP Formation**
- **High Baryon Density Effect (Associated Prod. of Y**





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

Thermal Evolution from AGS to SPS Energies



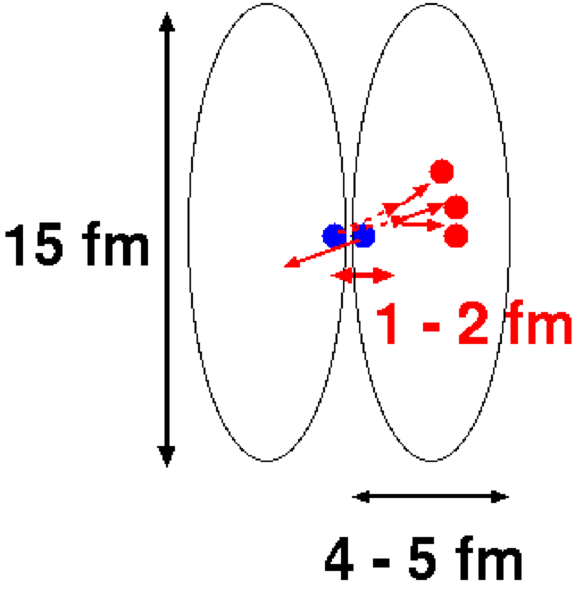
- **AGS (11 A GeV), JHF (25 A GeV)**
  - **Smooth Evolution in (ρ, T)**
  - $\rho_{max} > 2\gamma\rho_0$
- **SPS (200 A GeV), RHIC**
  - **Sudden Jump in (ρ, T)**
  - $\rho_{max} < 2\gamma\rho_0$

(JAM Calc., Y. Nara, FRONP99, 8/2-4, 1999 at JAERI)

Hadron Formation Time

JHF Energies

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

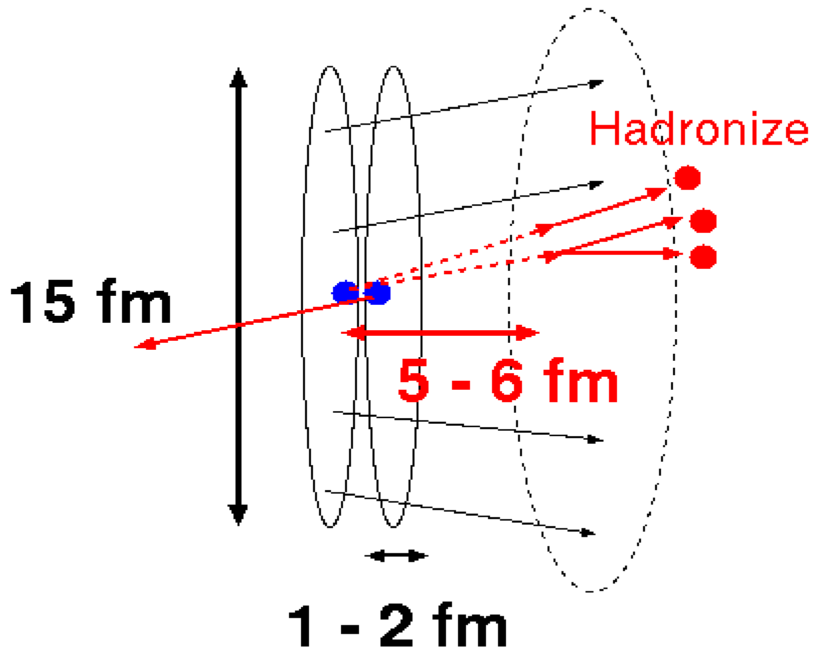


Multiple Hadron-Hadron Collisions

☞ (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 τ □ 1 fm for hadrons to be formed (and thus to interact)
→ *Pre-Hadronic* Interactions are necessary at SPS & RHIC
→ *Hot & Dense Hadronic* Matter would be formed at AGS & JHF

Summary

1. **Flavor SU(3) Symmetry is an approximate but fundamental symmetry in QCD, as well as in YN interaction Models.**
2. **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.

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

   Σ Potential, $\Lambda\Lambda$ Interaction, ΛN-NN and $\Lambda\Lambda$-ΞN Coupling, Hyperon Potential in Dense Matter, ...

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

   Quasi Free Σ Production, Kaon Enhancement, $\Lambda\Lambda$ Nuclei, $\Lambda\Lambda$ Correlation, ...

Elliptic Flow at RHIC
ó Is the QGP formed ? ó

Akira Ohnishi (Hokkaido Univ.)

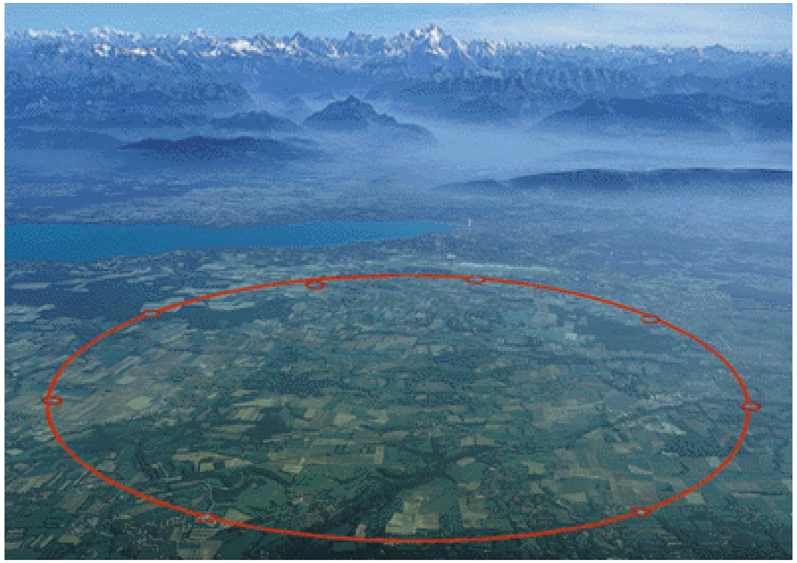
1. Introduction:
Hadronic Matter Phase Diagram, and Search for QGP
2. Recent Data from RHIC: Jet Quenching
3. Elliptic Flow at RHIC: Hadronic Cascade Model Study
4. Summary

In Collaboration with M. Isse, N. Otuka, P.K. Sahu, C. Phatak, N. Nara

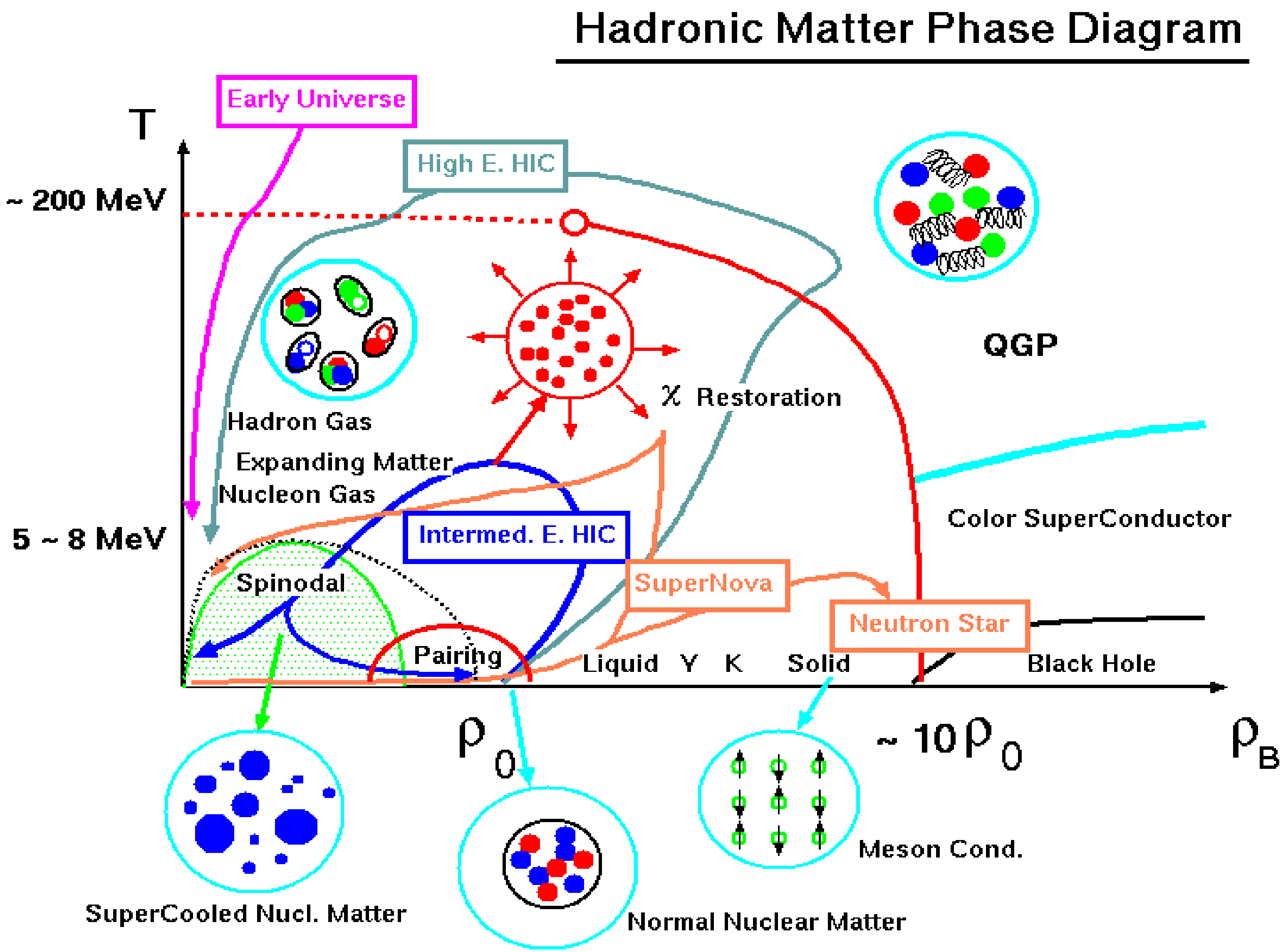
Introduction

High Energy Heavy-Ion Collision Experiments

Heavy-ion physisists wanted to create QGP for a long time ...

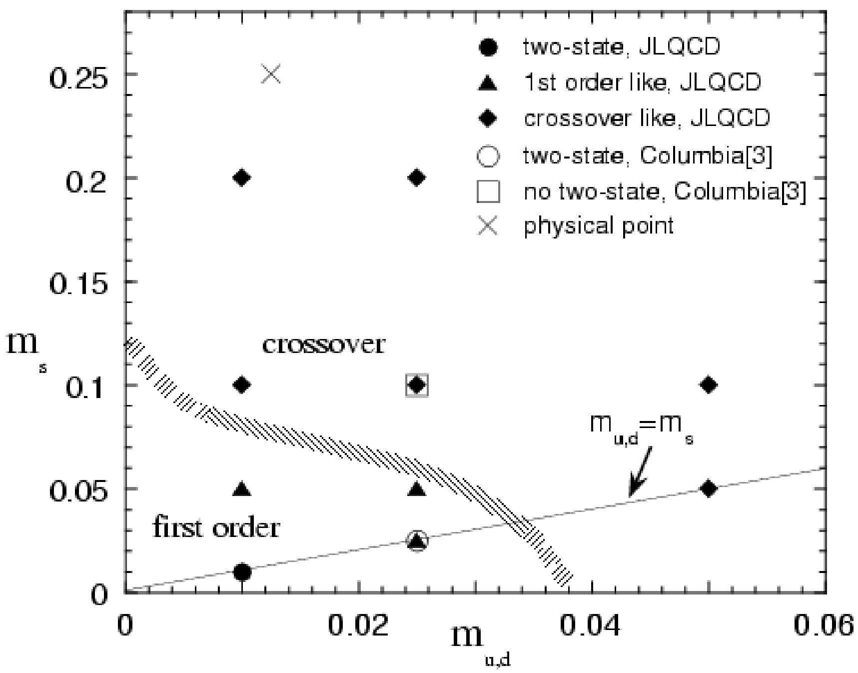


LBL-Bevalac (Bevatron + HILAC) : 800 A MeV
GSI-SIS: 1-2 A GeV
BNL-AGS (1987-): 10 A GeV
CERN-SPS (1987-): 160 A GeV
BNL-RHIC (2000-): 100+100 A GeV
CERN-LHC (2004(?)-): 3 + 3 A TeV


Hadronic Matter Phase Diagram
Early Universe
T
High E. HIC
~ 200 MeV
QGP
Hadron Gas
χ Restoration
Expanding Matter
Nucleon Gas
Color SuperConductor
5 ~ 8 MeV
Intermed. E. HIC
Spinodal
SuperNova
Neutron Star
Pairing
Liquid Y K Solid
Black Hole
ρ0
~ 10 ρ0
ρB
Meson Cond.
SuperCooled Nucl. Matter
Normal Nuclear Matter

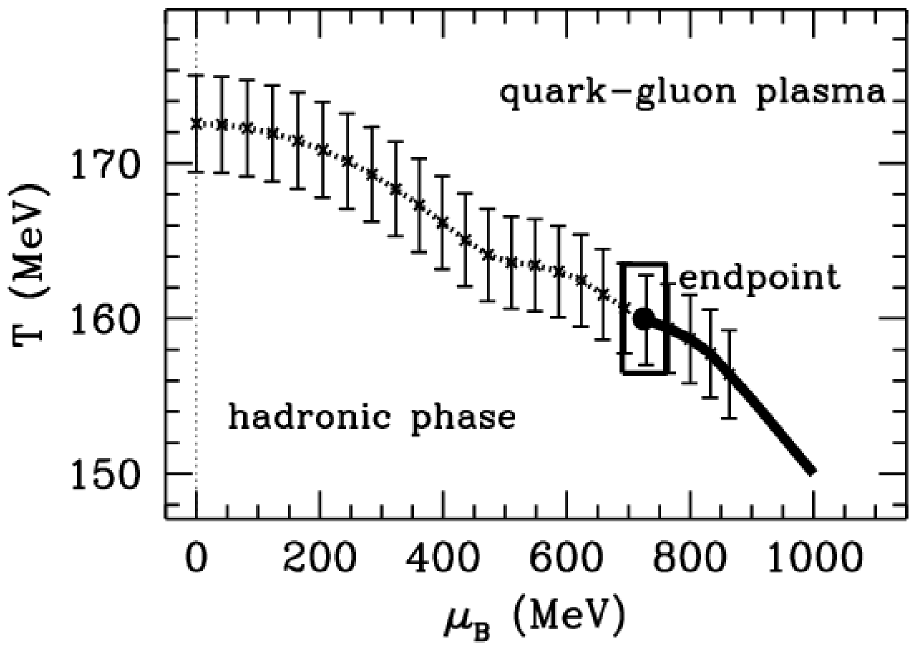
Theoretically Expected QCD Phase Diagram

Zero Chem. Pot.



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

Finite Chem. Pot.



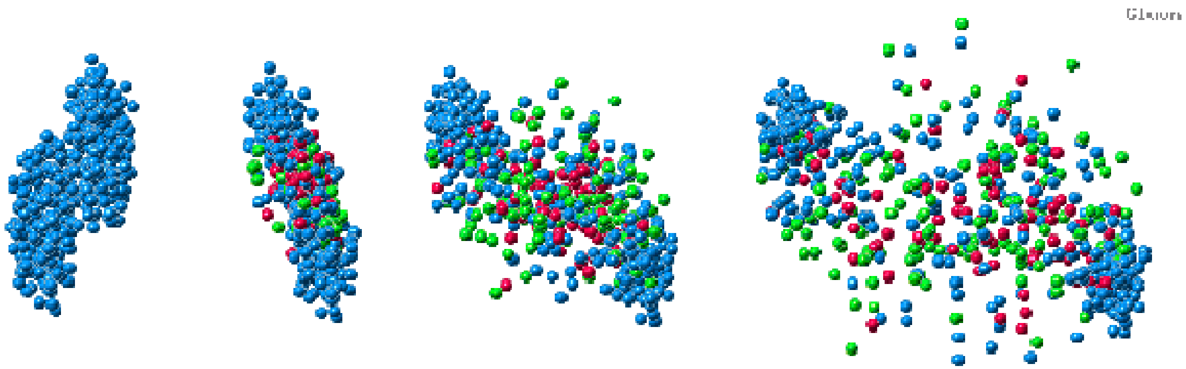
Finite μ: Fodor & Katz,
JHEP 0203 (2002), 014.

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

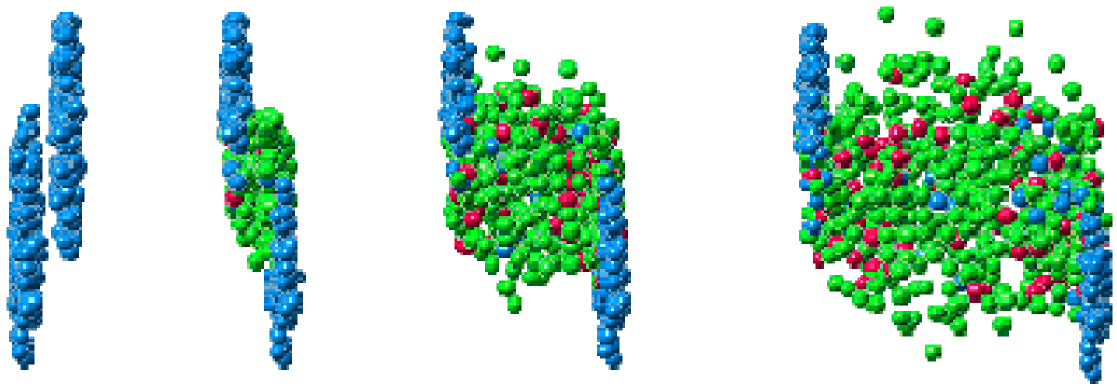
JAMming on the Web

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

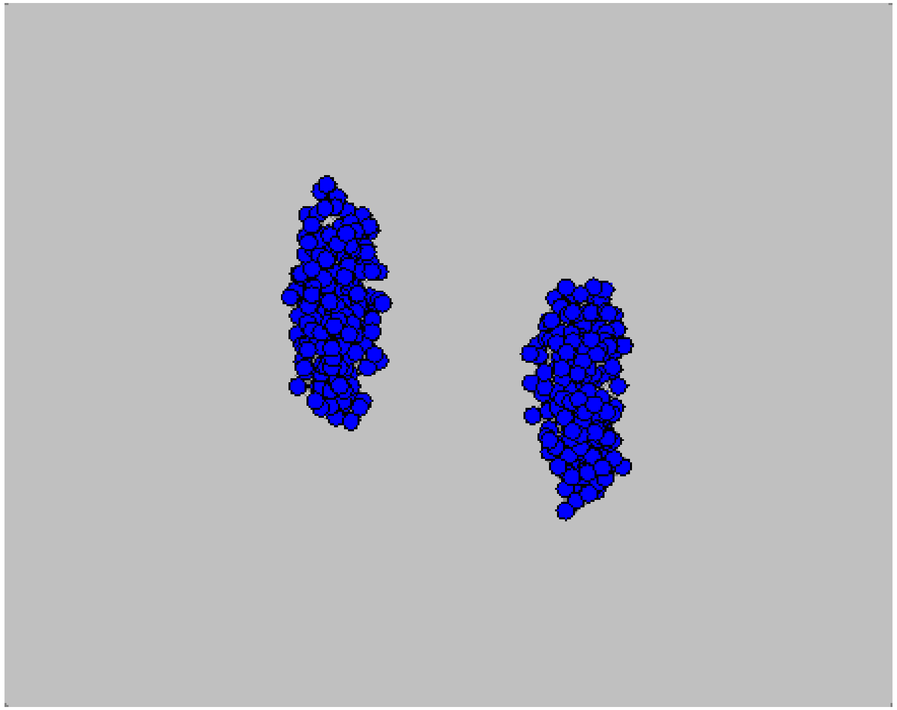
AGS



SPS

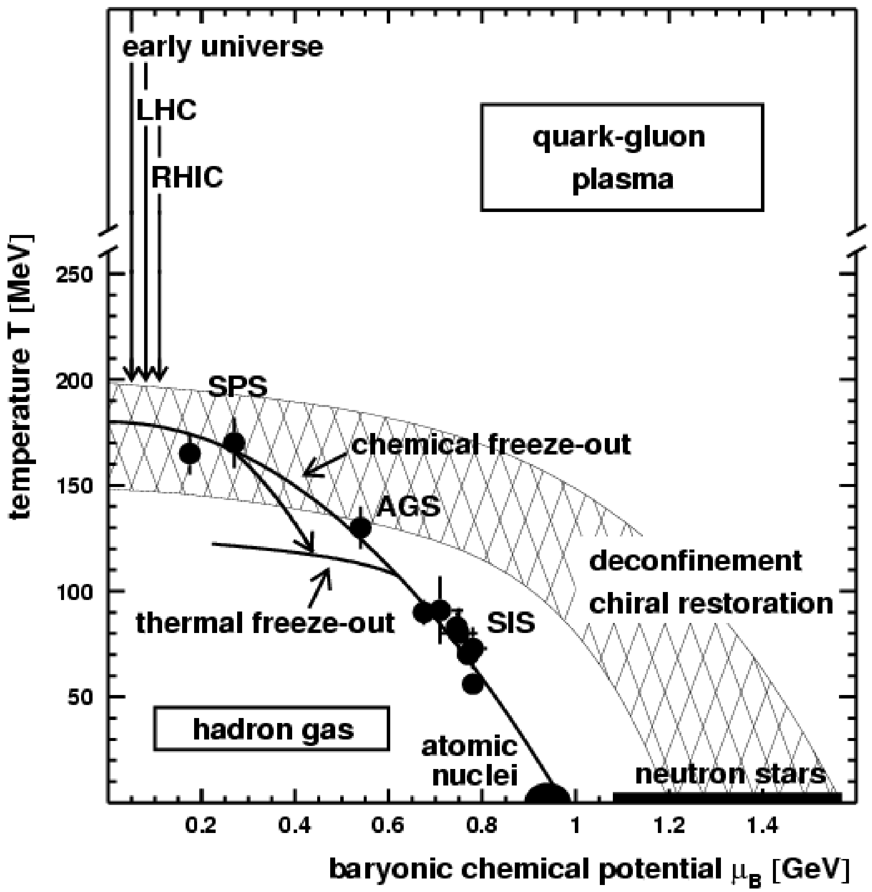


Collision Example

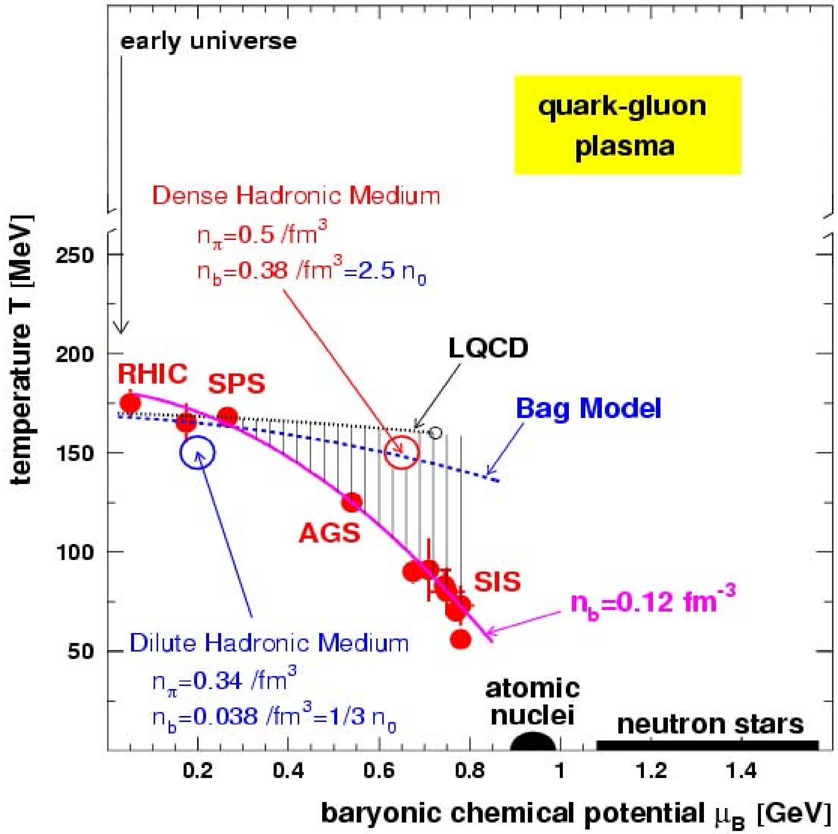


Experimentally Estimated Phase Diagram

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

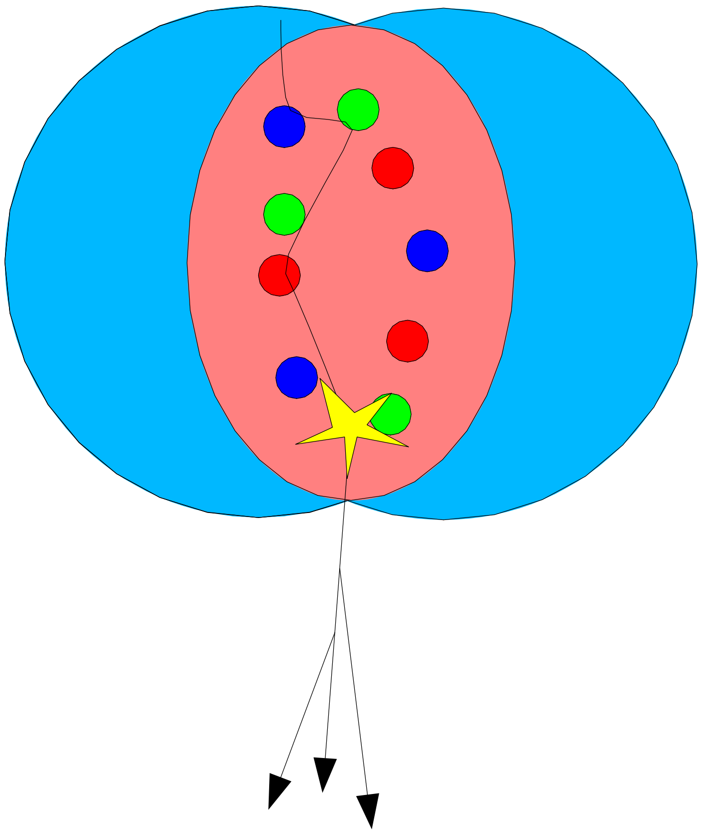
Is QGP Formed at AGS, SPS and/or RHIC ?

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***

Signature of QGP formation
ó Jet Energy Loss ó
(from Recent RHIC Data)

Jet Energy Loss at RHIC (I)



6/18 Press Release

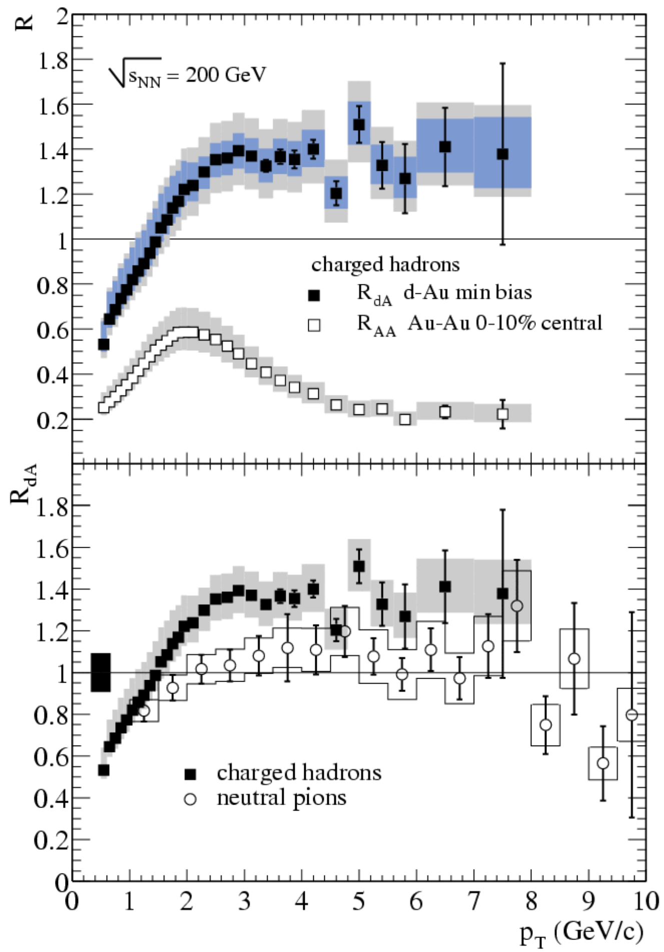
Colored partons will lose energy
in colored gas environment (=QGP)

Since High Energy Particles are expected
to come from Jet Fragmentation,
they are suppressed if QGP is formed.

Jet Energy Loss at RHIC (II)

Do we really see suppression of high energy particles at RHIC ?
→ YES for Au+Au Collisions, and NO for d+Au Collisions !

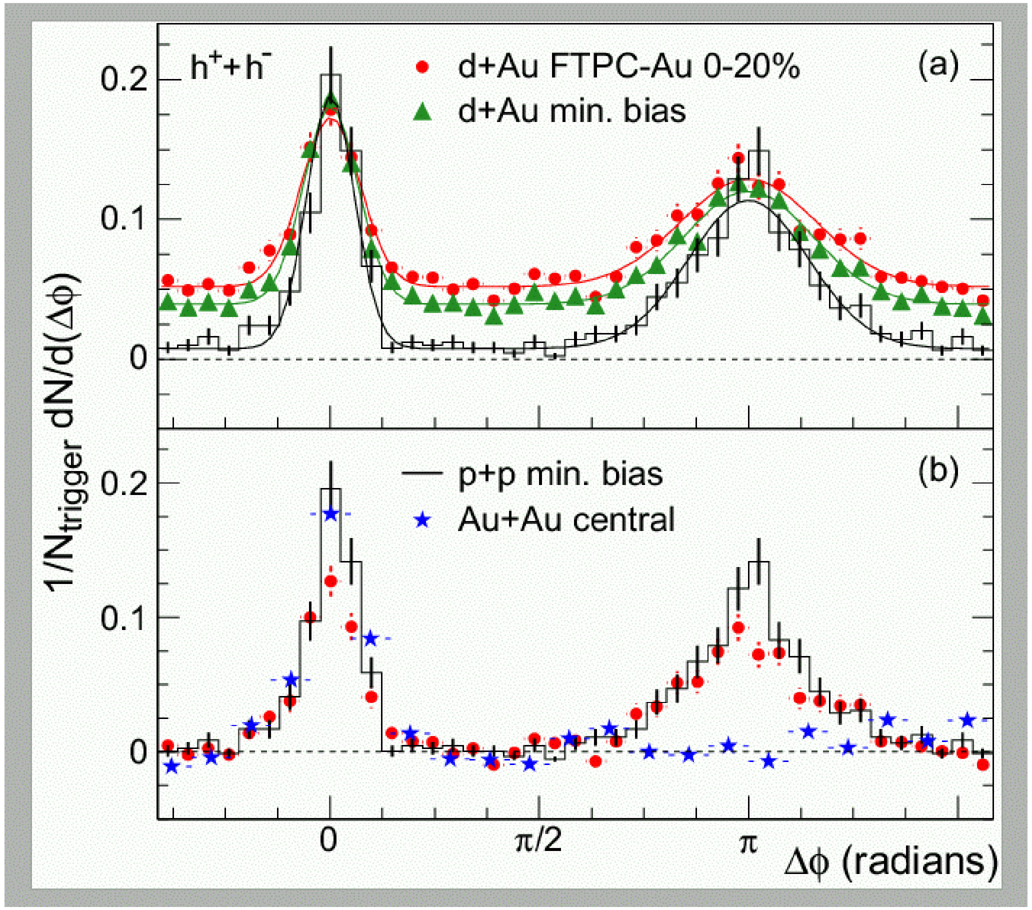
$$R_{AB}(p_T) = \frac{d^2N/dp_T d\eta}{T_{AB}\, d^2\sigma^{pp}/dp_T d\eta}$$

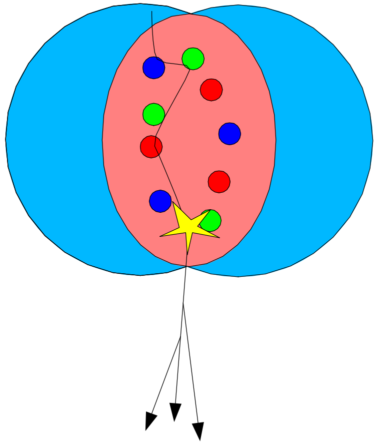


High Energy Particles are suppressed in Au + Au Collisions but NOT suppressed in d + Au Collisions at RHIC compared to p+p collisions !

(PHENIX: nucl-ex/0306021)

Jet Energy Loss at RHIC (III)





STAR (nucl-ex/0306024)

Jet Energy Loss also lead
to reduction of back-to-back correlation

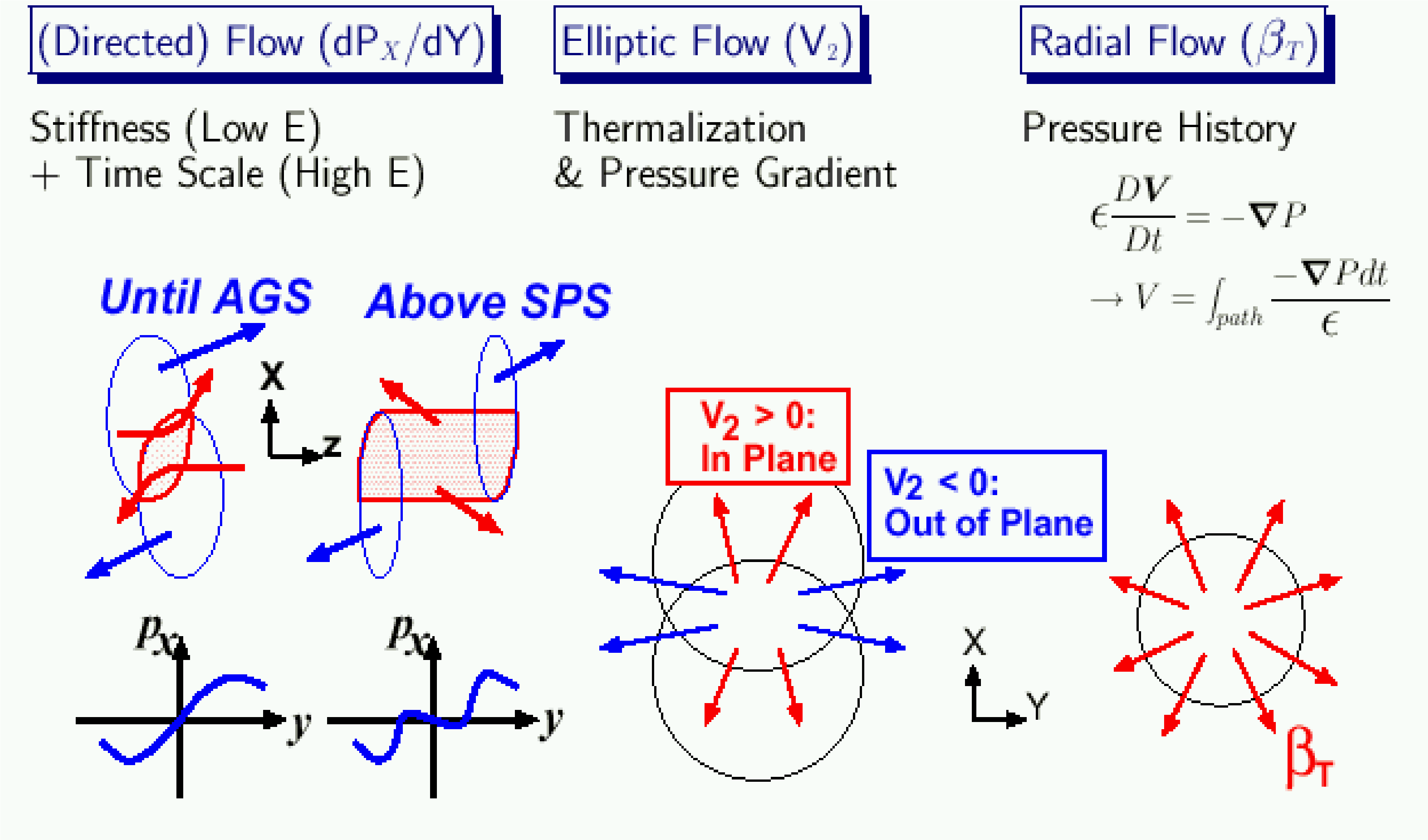
Jet Energy Loss at RHIC (IV)

1. High energy particles are suppressed compared to pp collisions at RHIC. Note that it has not been seen at lower energies, e.g. SPS.
2. This high energy particle suppression is not found in d+A collision, where QGP formation is not expected. Thus it is considered to be the final state effect rather than the initial state effect such as the color glass condensate.
3. Back-to-back correlation is also suppressed in Au+Au collisions at RHIC. This is consistent with the Jet Energy Loss scenario of high energy particle suppression.
4. The ratio R_{AA} is calculated by using Glauber model, in which small momentum transfer is assumed.

It is very likely that QGP is formed in Au+Au collisions at RHIC. Further confirmation may be necessary.

Elliptic Flow at RHIC Energy

What is Collective Flow ?



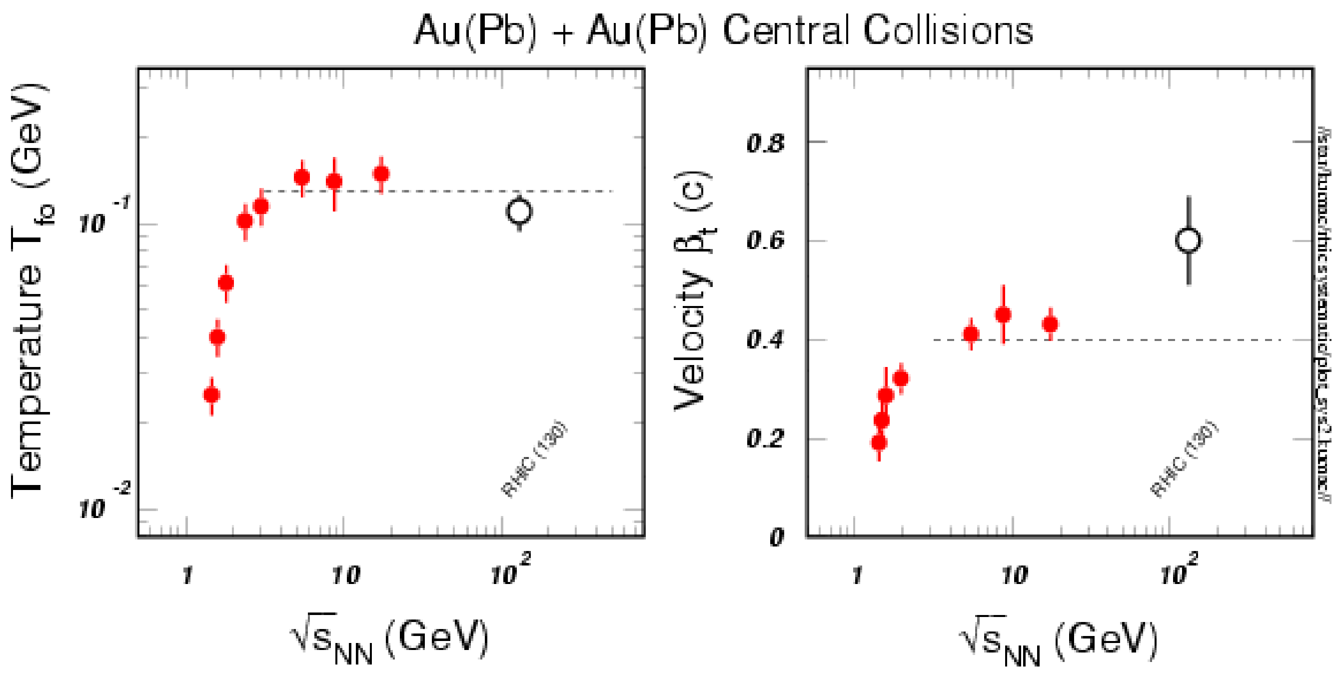
Complex Observables, but Closely Related to EOS

Can we see ANOMALIES in Collective Flows at RHIC ?

Answer = Yes !

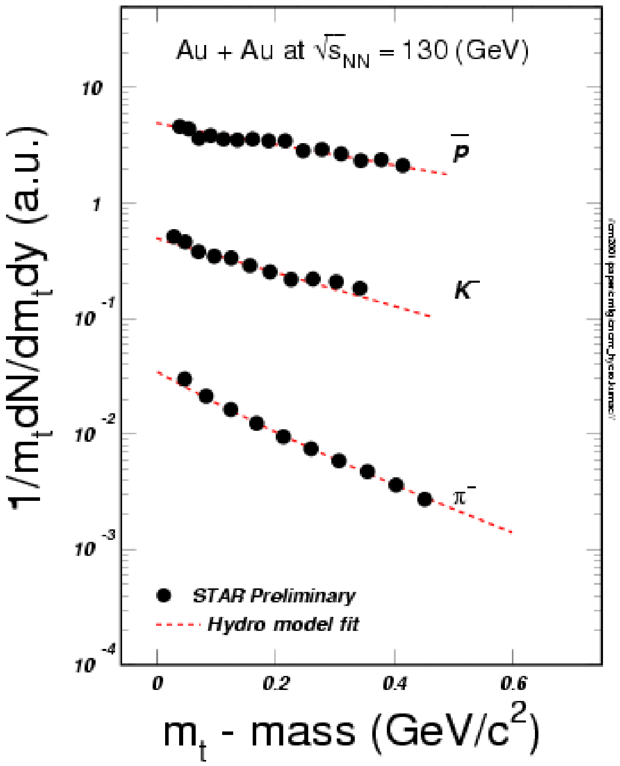
Radial Flow

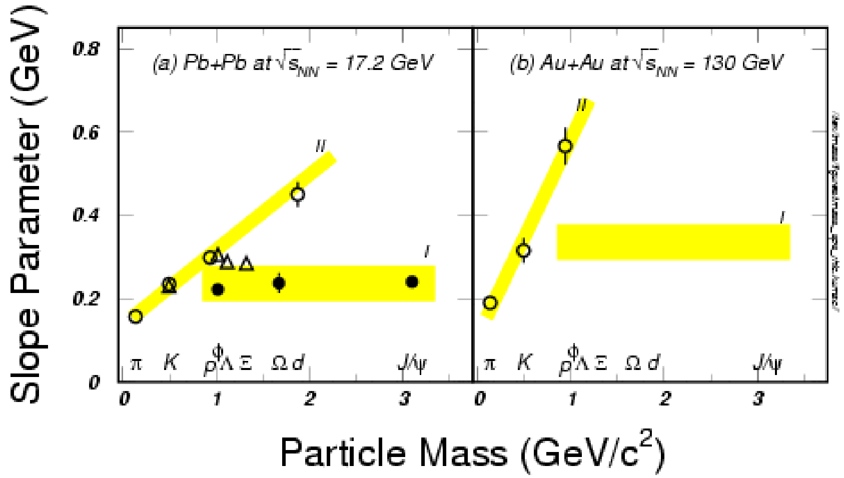
Nu Xu and M. Kaneta (STAR)



Formed matter seems to become STIFF Quickly at RHIC

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



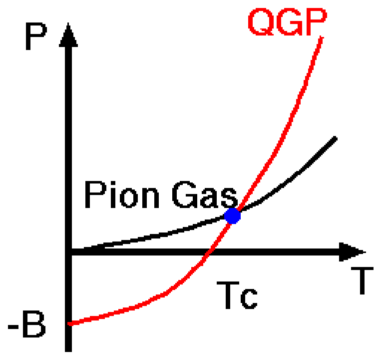


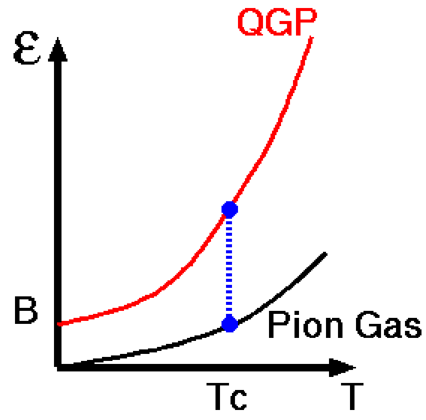
$$\frac{d^2N}{M_t dM_t dY d\phi} \propto \exp(-M_t/T'), \qquad T'(M) = T + \frac{1}{2} M \beta^2$$

Simple Model of QCD Phase Transition

Massless Particles at Zero Chem. Pot.

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





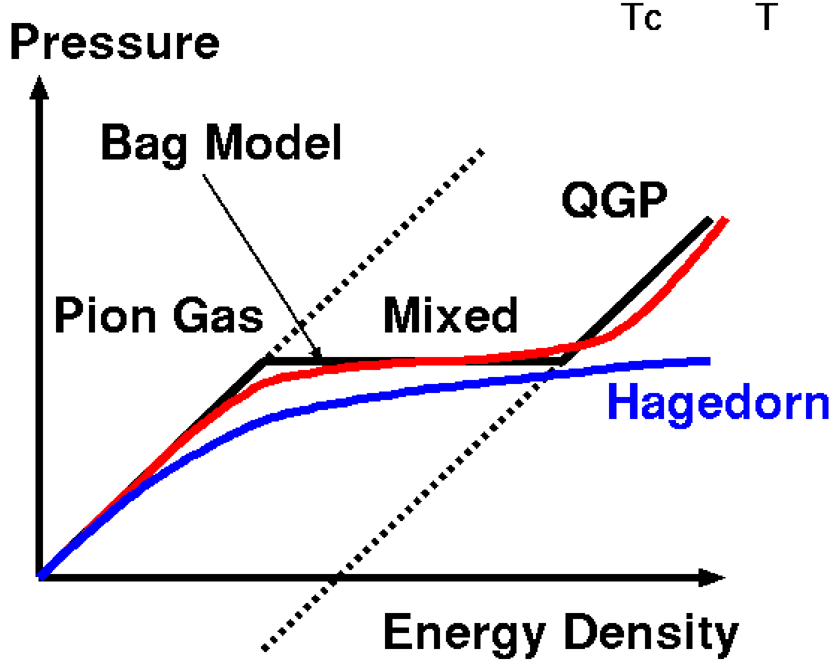
Massless (Free) Pion Gas

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

QGP with Finite Bag Constant

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

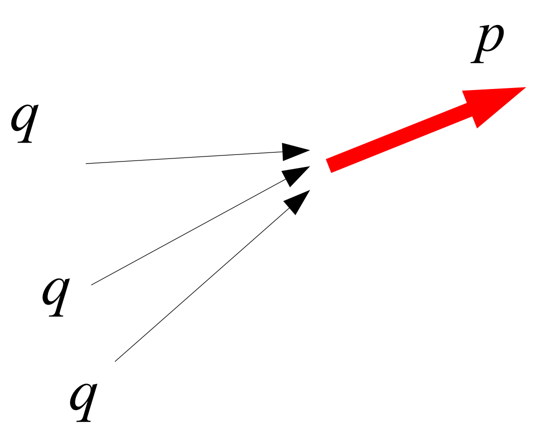
$$\epsilon_{QGP} = \frac{37\pi^2}{30} T^4 + B$$

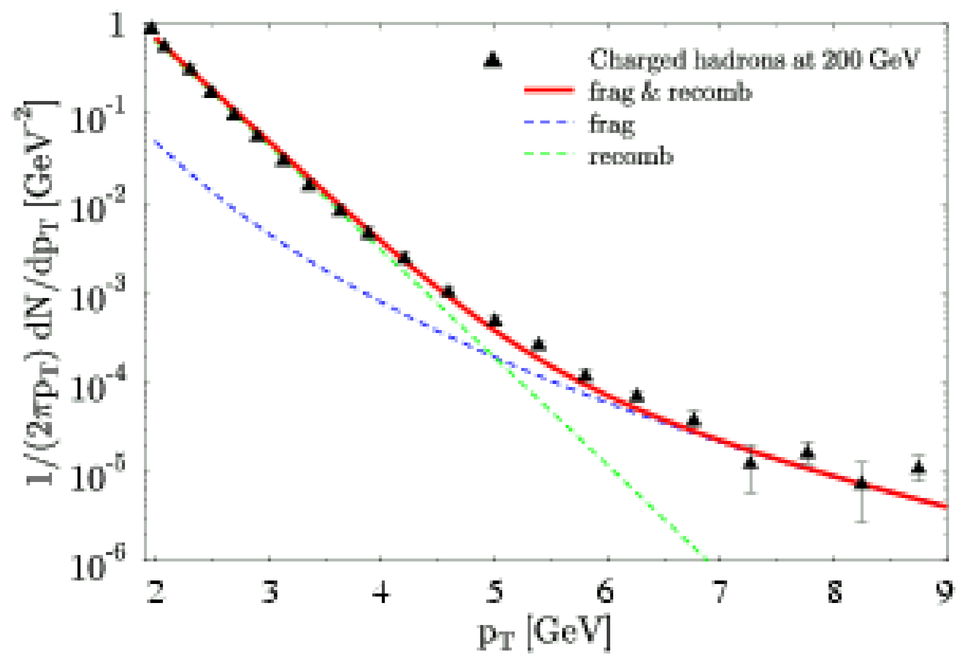


$$DOF = 2(\text{spin})\times 2(q,\bar{q})\times 3(\text{color})\times 2(\text{flavor})\times 7/8(\text{Fermion}) + 2(\text{spin})\times 8(\textit{color})$$

Another Interpretation of Proton Enhancement: Quark Recombination

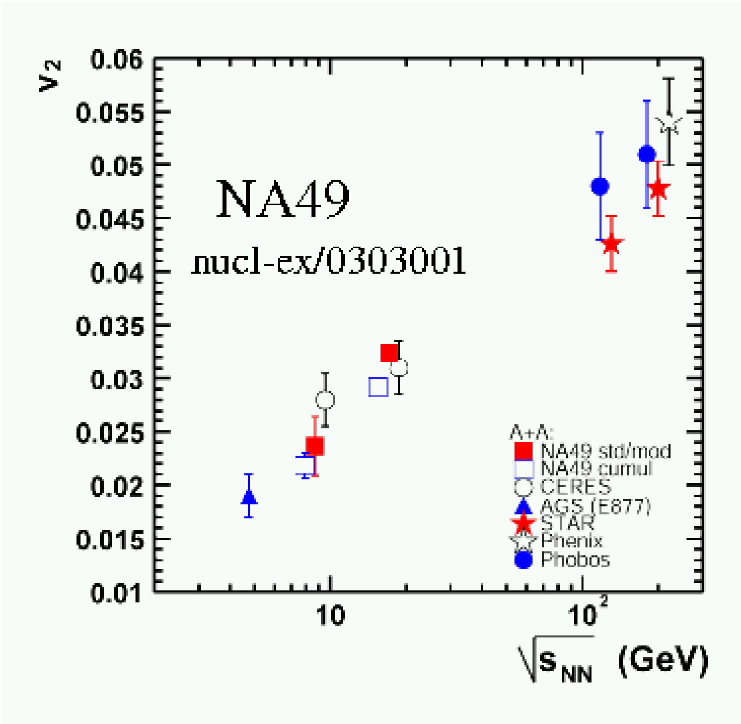
(Fries, Bass, Mueller, Nonaka, nucl-th/0301087; PRC(2003))

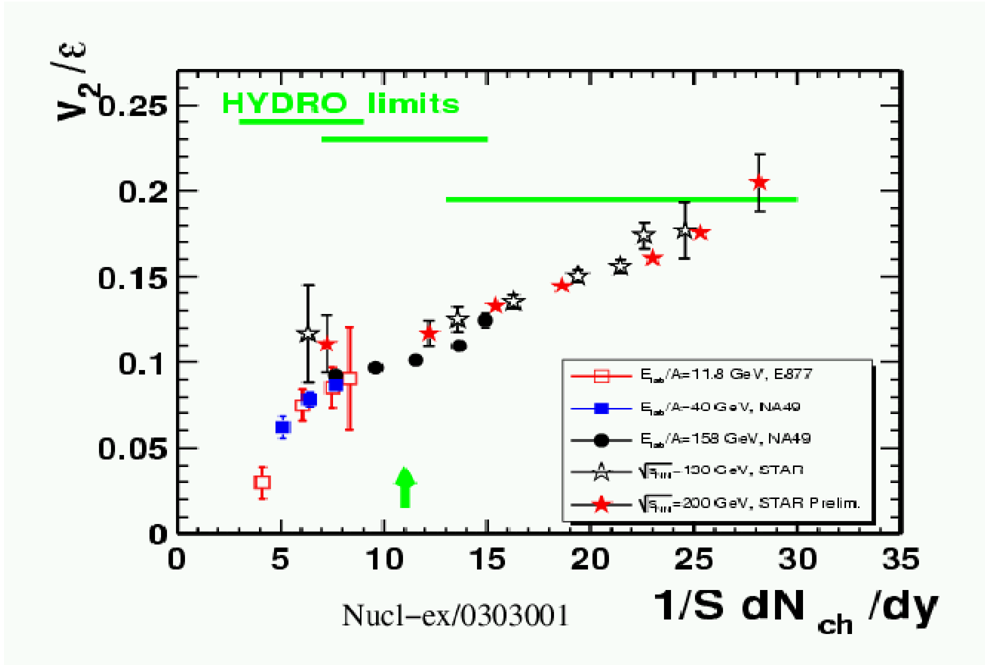




Quark Recombination model also requires that quarks move freely.

Elliptic Flow





○ **Anisotropic Pressure is close to Hydrodynamical Values @ RHIC**

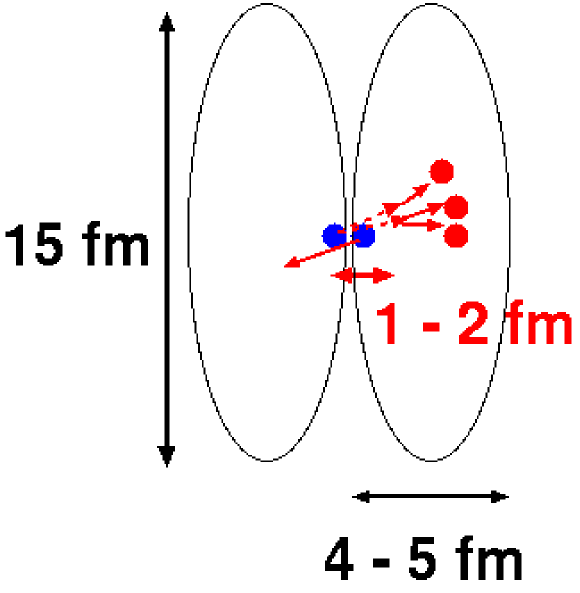
→ **Particles should interact before Almond Shape is obscured.**

? **Incident Energy Dependence is Smooth. Why ?**

Hadron Formation Time

JHF Energies

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

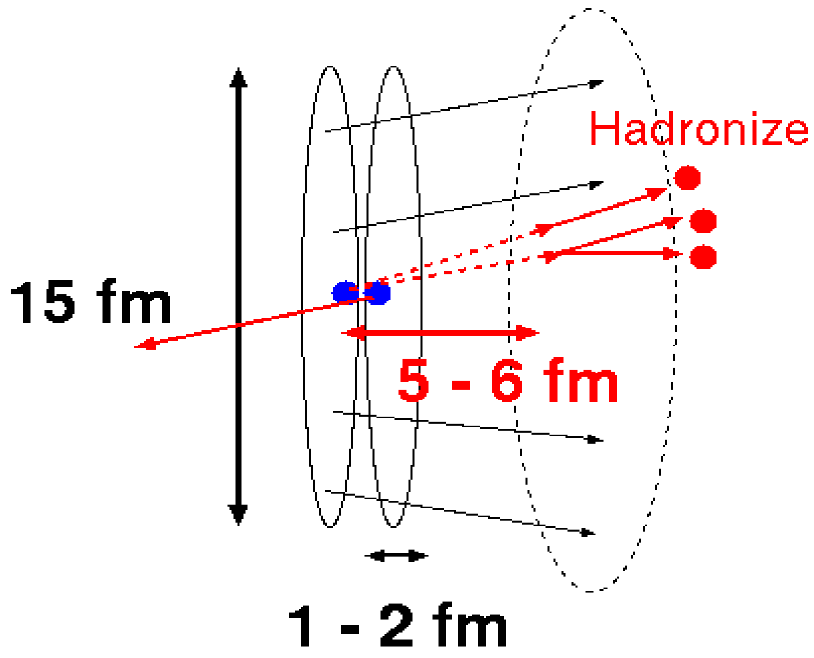


Multiple Hadron-Hadron Collisions

☞ (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 (ϕ 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

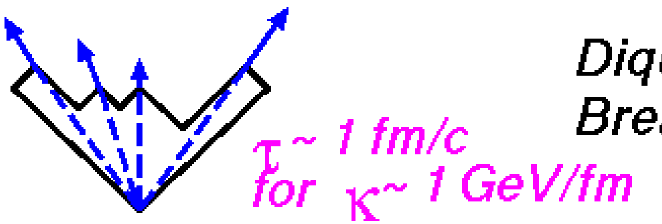
Hadrons (h, m < 2 GeV) + Strings (s) + Partons (in Jet)

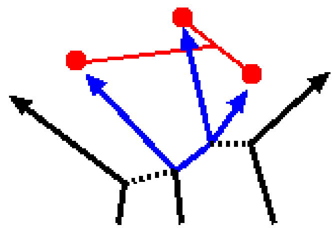
Cross Sections

Hadronic (hh $\rightarrow$ hh, hh $\rightarrow$ h, h $\rightarrow$ hh)

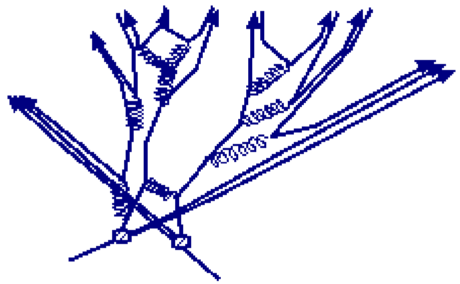
+ Soft (hh $\rightarrow$ s, hh $\rightarrow$ ss, s $\rightarrow$ hh, hh $\rightarrow$ hs [1] ,
sh $\rightarrow$ s'h, ...[2])

+ Hard (Jet Production)





Resonance
+ String
+ Jet



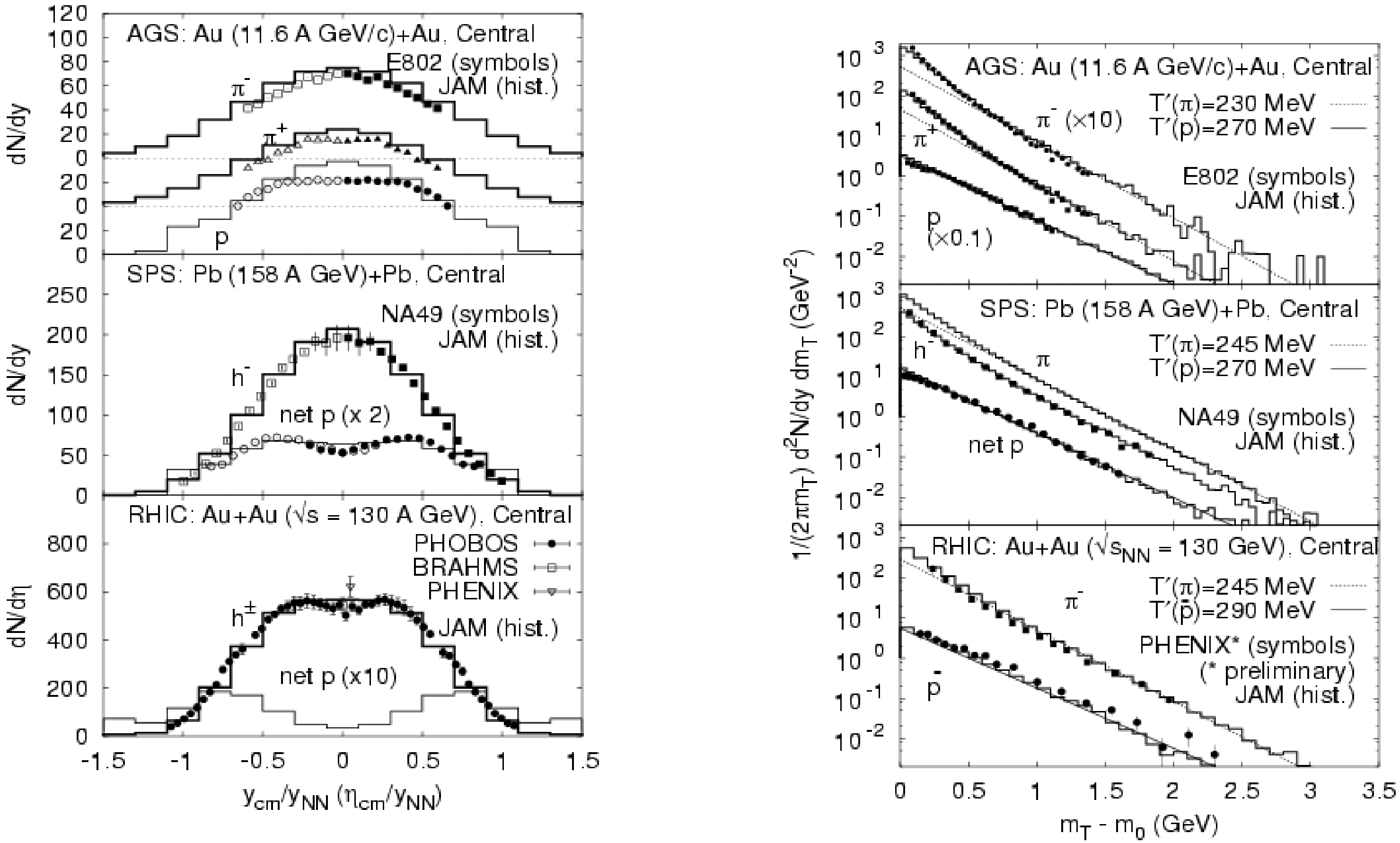
[1] îDPM+ Lundî (~ HIJING) + Phase Space

[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

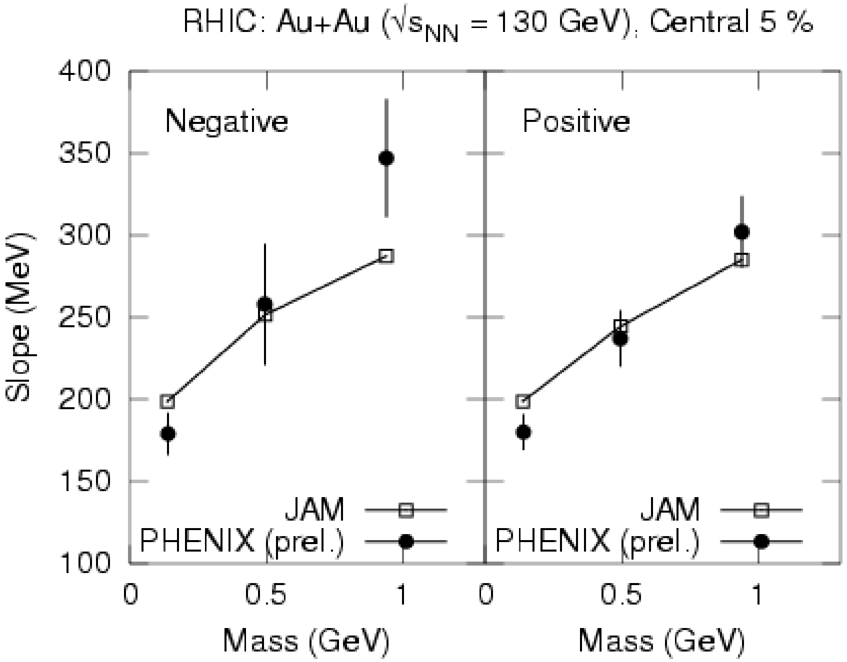
Hadron Spectra at AGS-SPS-RHIC

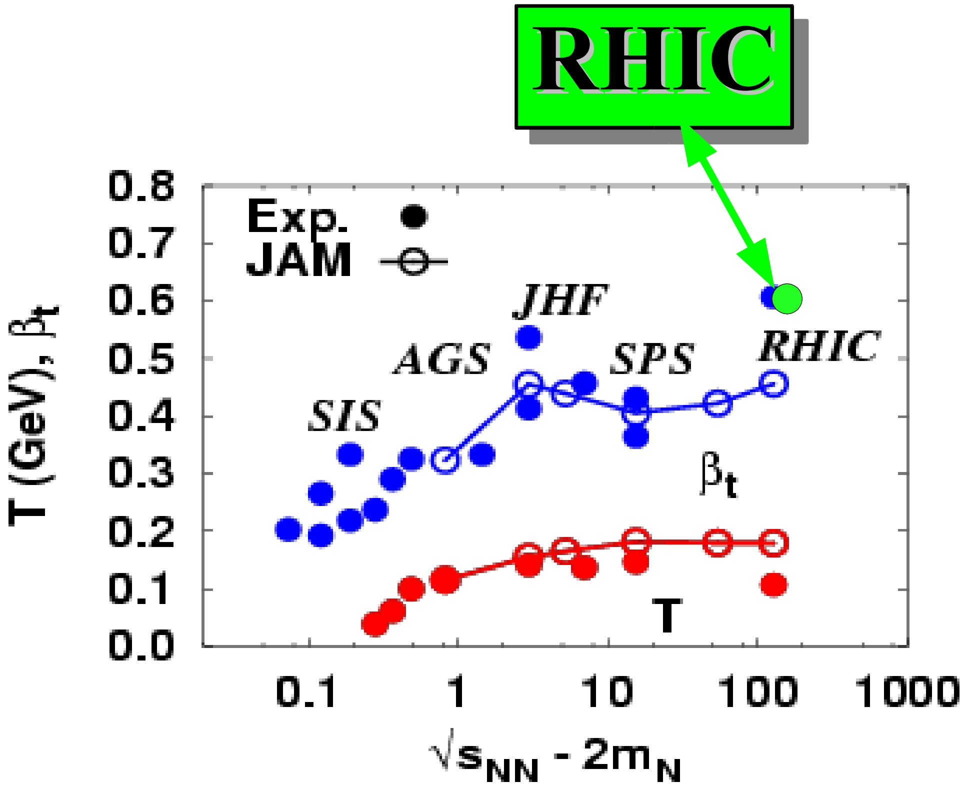


Hadron Spectra @ RHIC is too soft in JAM.

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

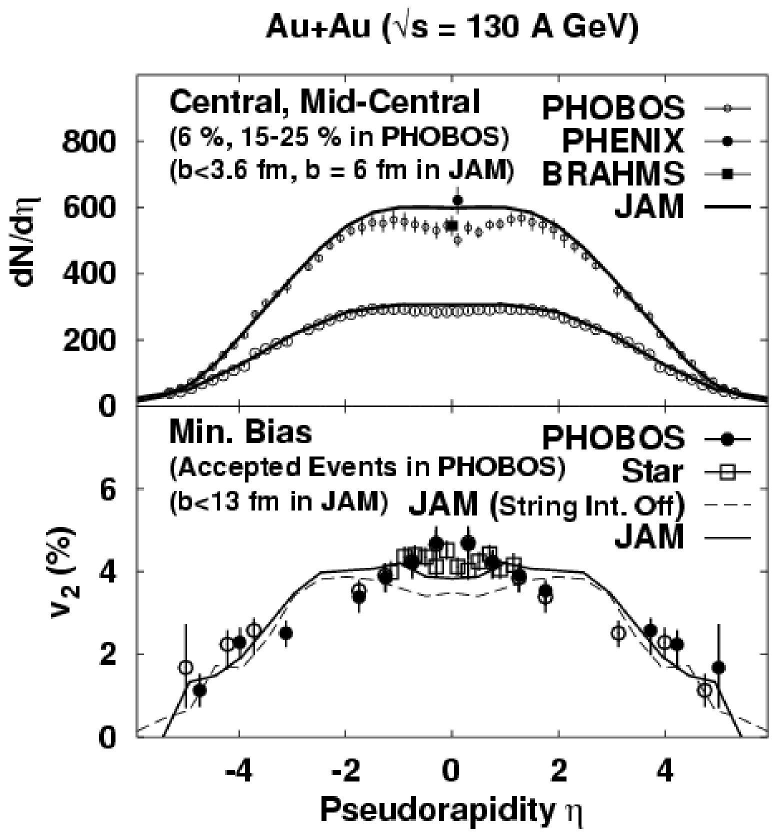
Radial Flow and Temperature in JAM



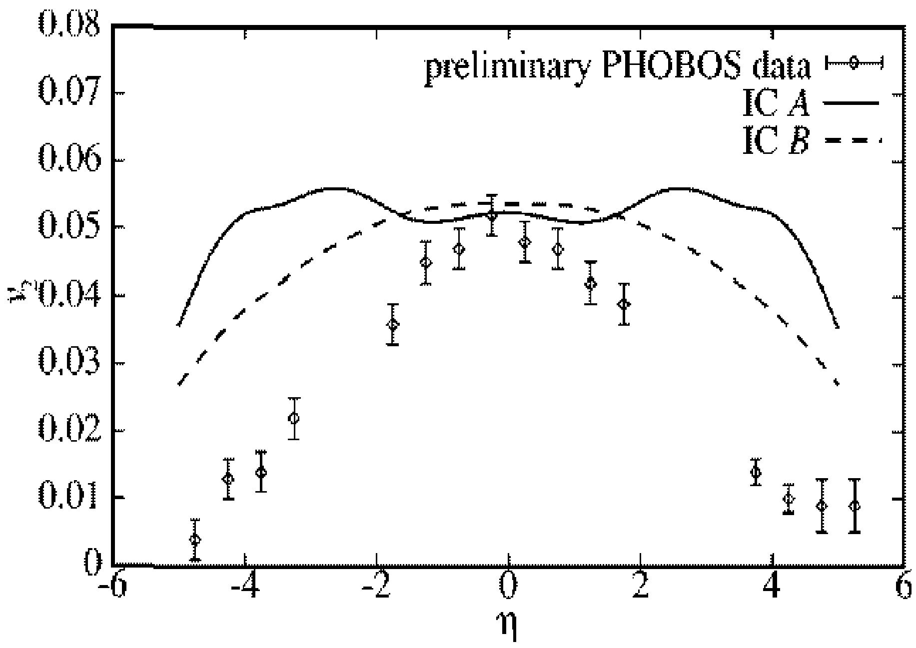


Re-Hardening Behavior Cannot Be Explained in Hadron-String Cascade.

Pseudo Rapidity Dep. of Elliptic Flow

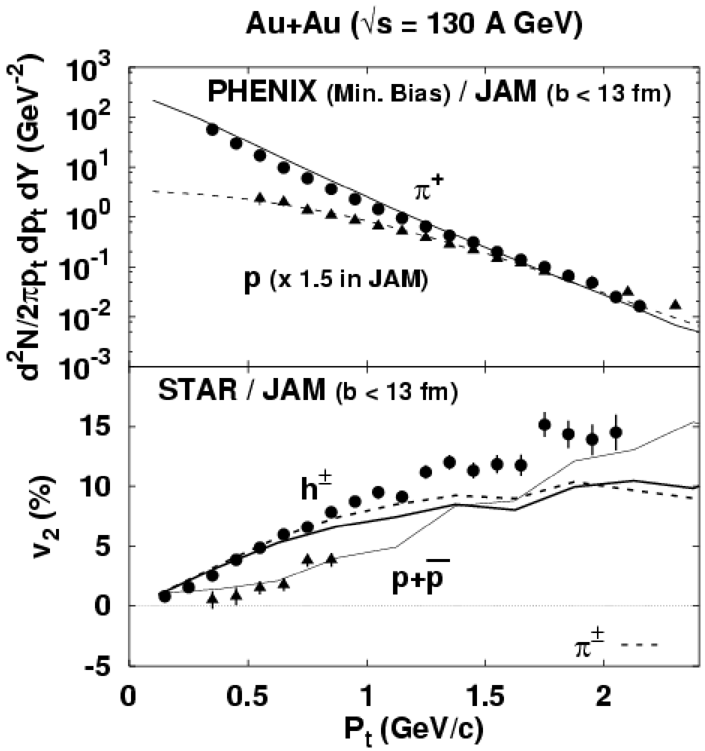


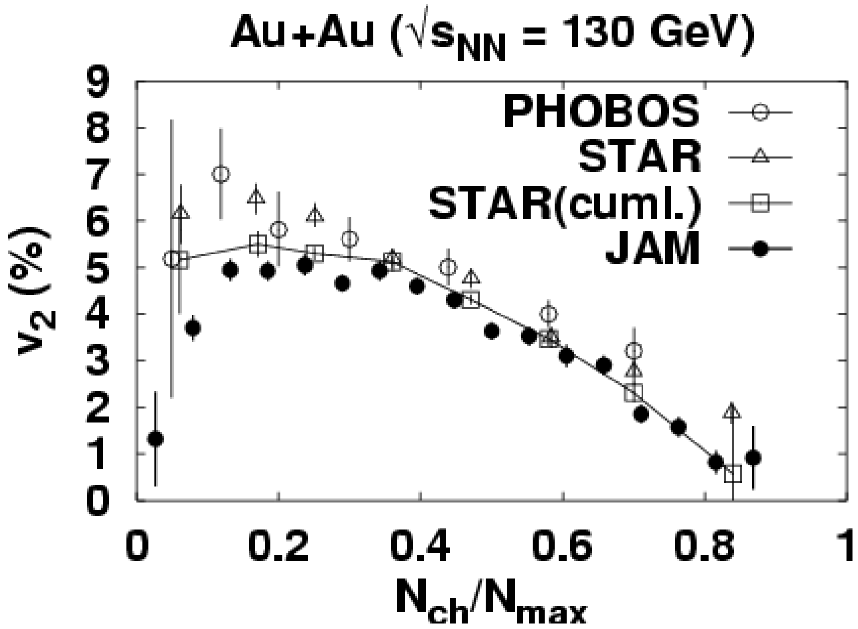
Hydro Results (Hirano, 2001)



Flat v_2 in JAM as well as in Hydrodynamical model.
→ What is the origin of v_2 enhancement at Mid-Rapidity ?

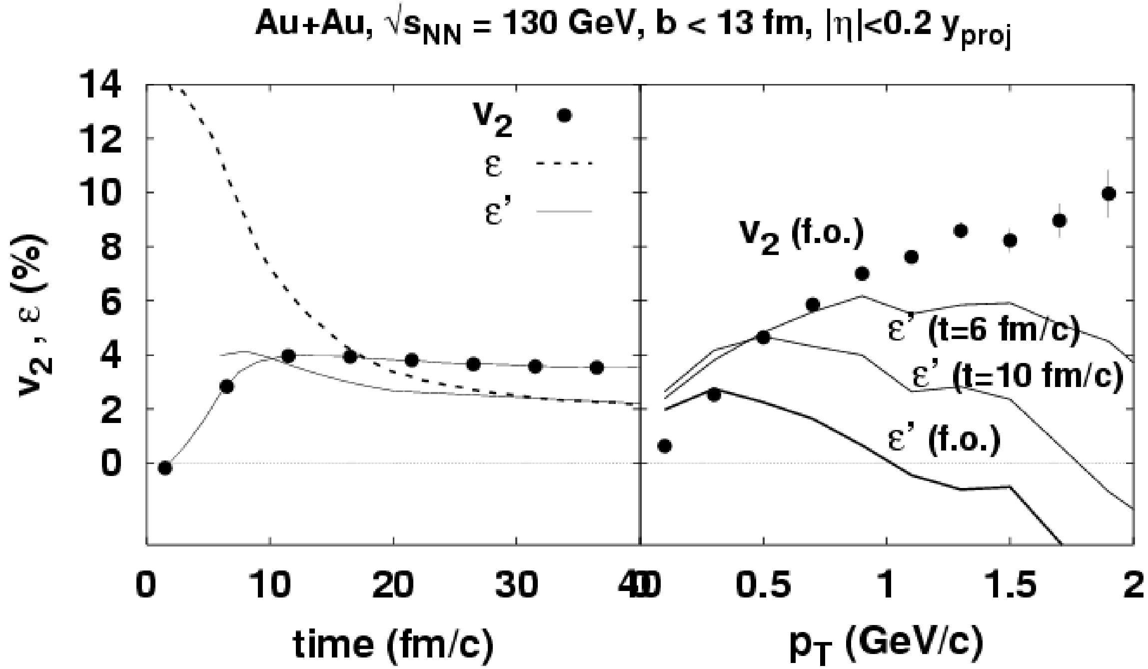
Pt and Impact Par. Dep. of Elliptic Flow
Where Do We Underestimate ?





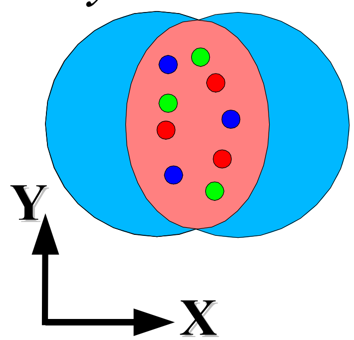
Answer = High Pt Regions !

When are Collective Flows Generated ?
Why Do We Underestimate ?



For v2 to grow, spatial eccentricity is necessary.

$$\epsilon = \langle \frac{y^2 - x^2}{y^2 + x^2} \rangle$$



V2 is Generated at a long time scale in Hadron-String Cascade.
After formation time, Almond shape is still kept
Due to forward emission of strings.

Summary

Collective Flow Data at RHIC seems to suggest QGP formation.

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

JAM (Hadron-String Cascade with Jet Prod.) cannot explain RHIC v2 Data in High Pt Region.

- ***Very Early Growth of Elliptic Flow is necessary for high Pt***
- ***No Secondary Partonic Interaction in JAM***
- ***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 ì Vacuumî***