核子・ハドロン物質のダイナミクス

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1. Introduction
   --- 核子・ハドロン物質の相図
2. Selected Topics of Recent Developments
   --- Penta Quark
   --- Hypernuclear Physics
   --- Mean Field from Pions
   --- RHIC Physics
3. Summary

Introduction
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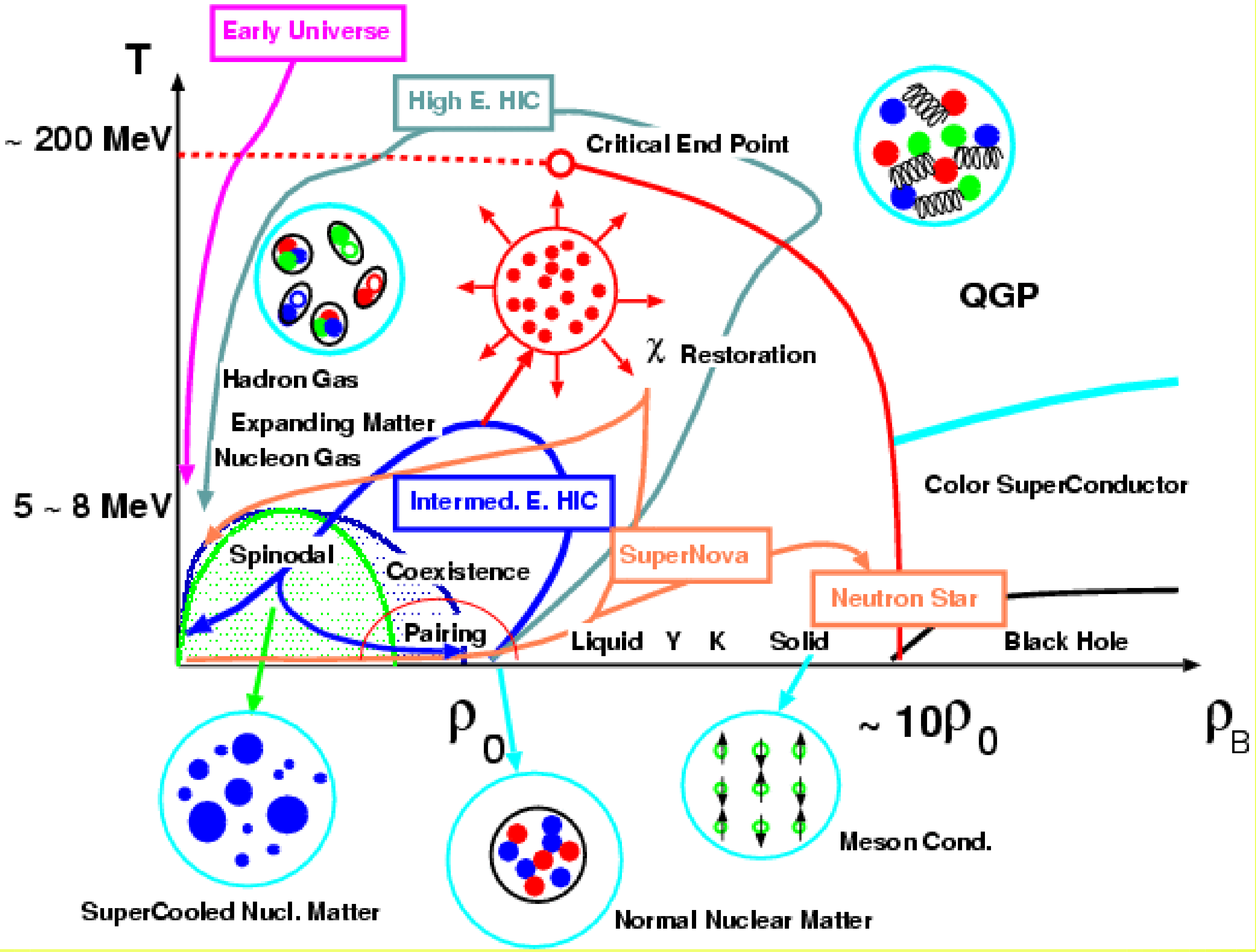
Hadronic Matter Phase Diagram



Various State of Matter and Relation to Various Field of Physics

Hierarchies in Nuclear Physics

- ***Quarks and Gluons***

  ↓ QCD (Perturbative, Lattice), Chiral Quark Model (NJL etc), …

- ***Hadrons***

  ↓ Chiral Perturbation, Hadron Lagrangian,
  BB Interaction, Effective Interaction, Model Space, …

- ***Finite Nuclei***

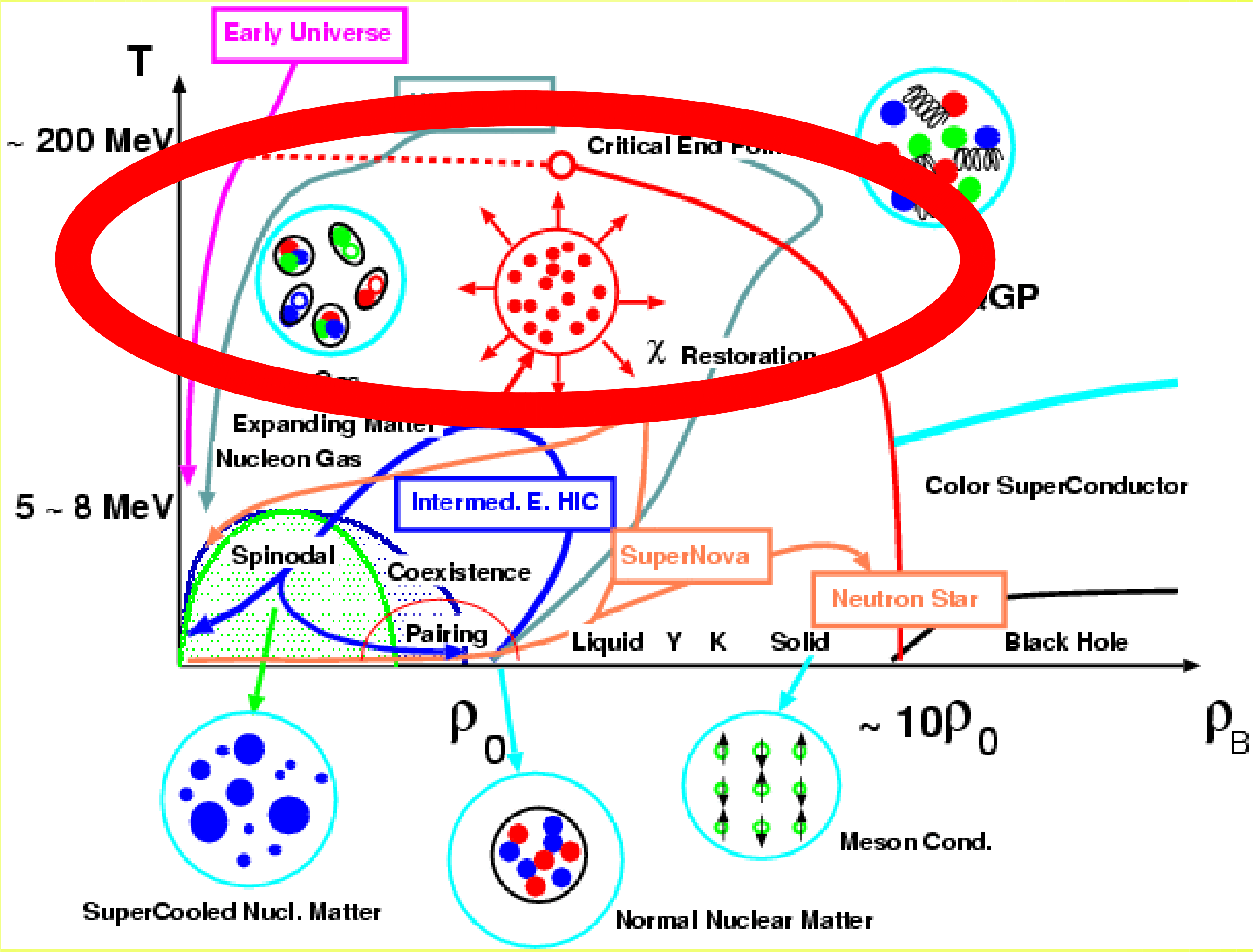
  ↓ Equation of State, Statistical Model, ….

- ***Nuclear/Hadronic/Quark Matter***

  → Compact Astrophysical Objects, Early Universe, …

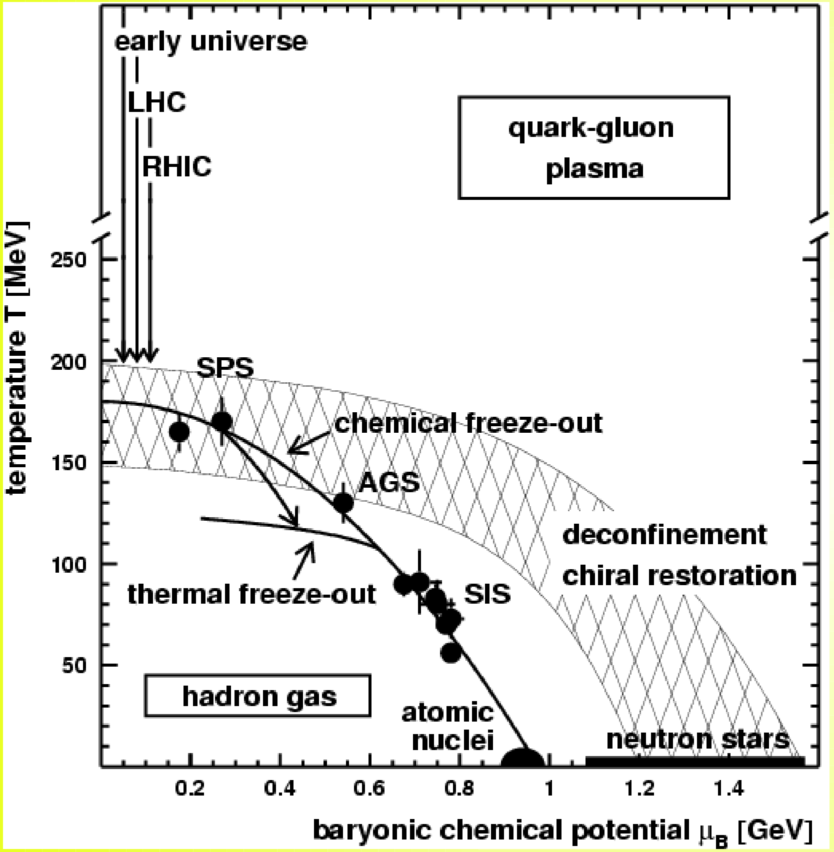
Nuclear Physics = Physics of Four (or Three)Hierarchies

High T and/or High ρ Matter

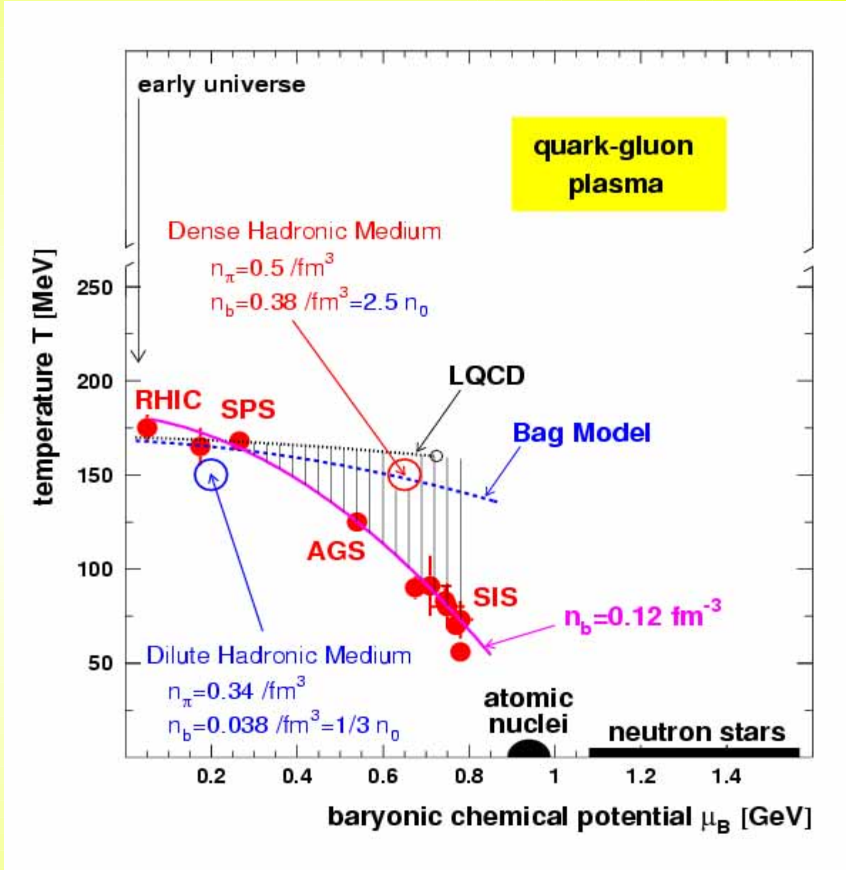


QCD Phase Transition

Experimentally Estimated Phase Diagram



1998 (J. Stachel et al.)

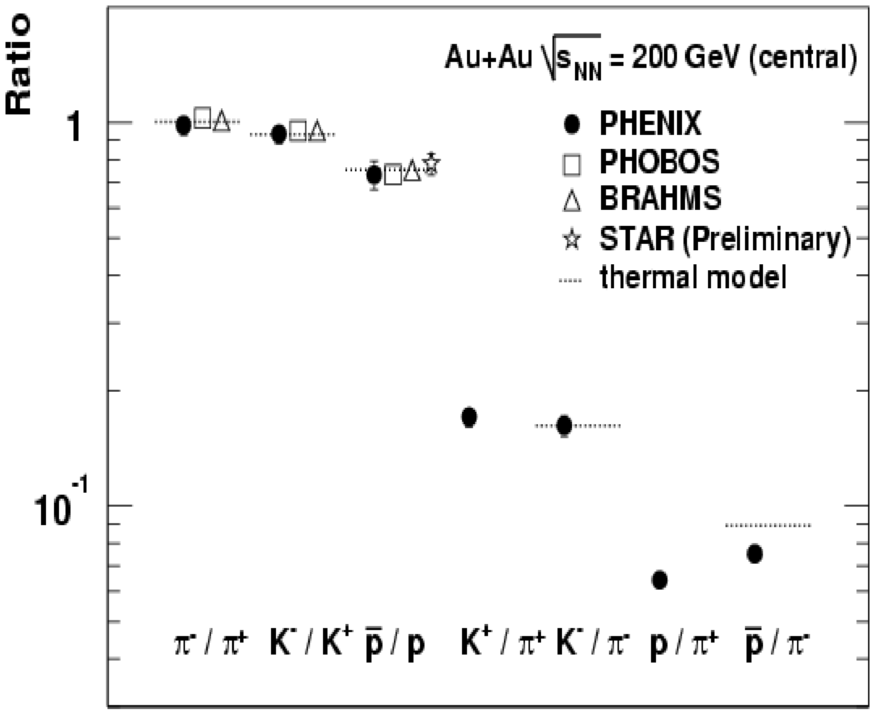


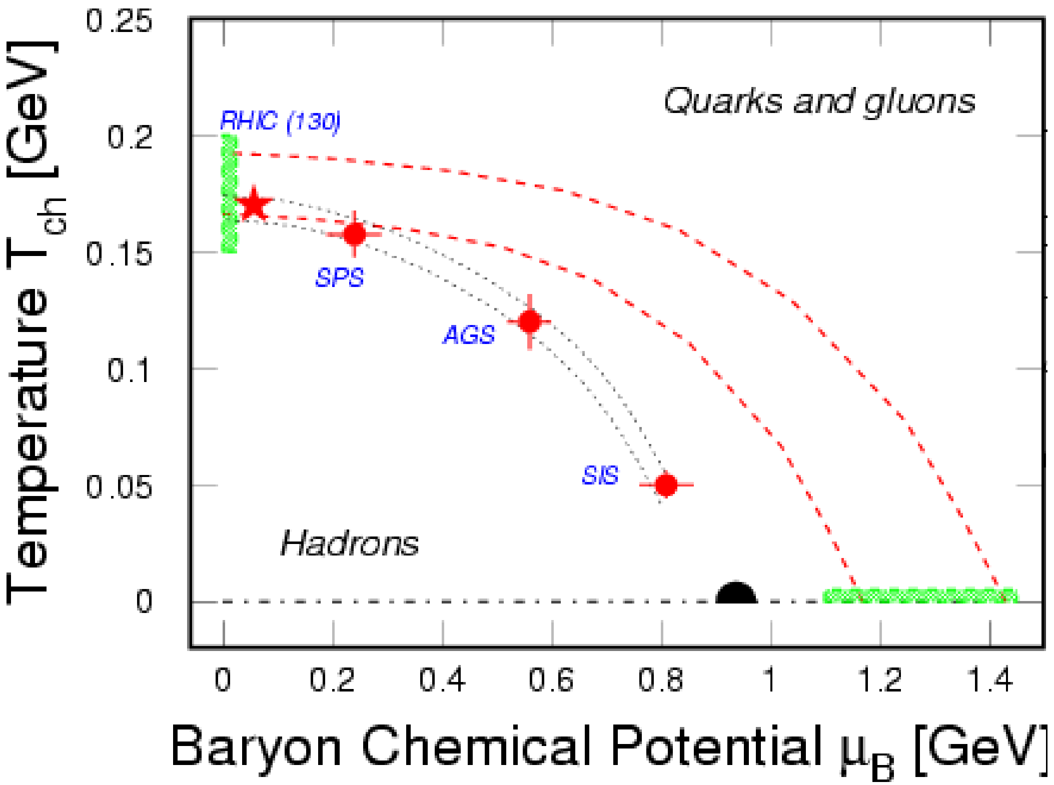
2002 (Braun-Munzinger et al.
J. Phys. G28 (2002) 1971.)

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

by Esumi, Matter03

Thermal freeze-out parameters from the particle ratios





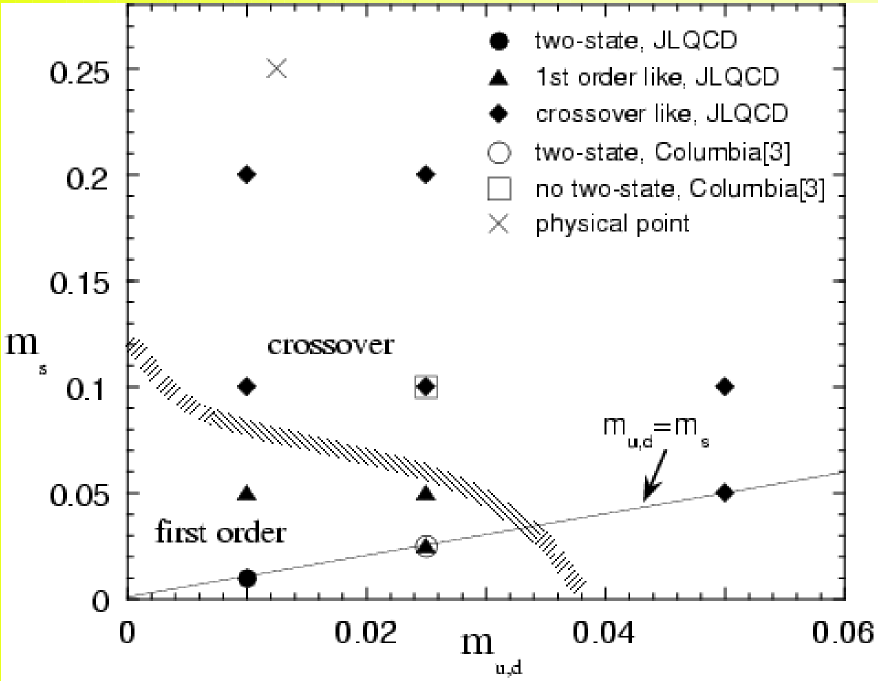
- **Almost complete reconstruction of particle ratios by the statistical thermal model.**
- **Thermal model prediction in AuAu 200 GeV central.**

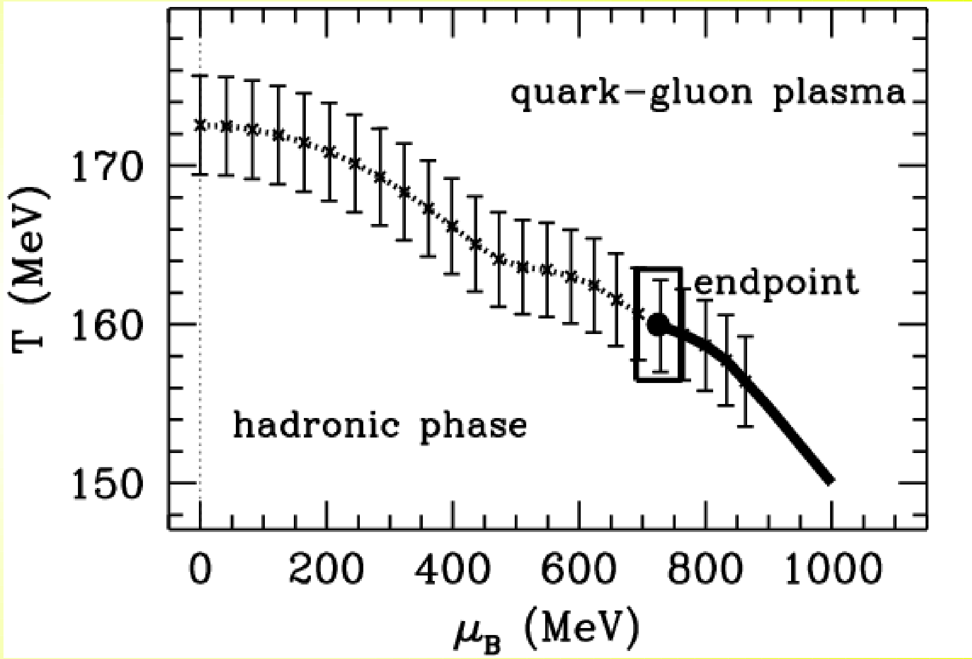
T_{ch} = 177 MeV, m_B = 29 MeV

Theoretically Expected QCD Phase Diagram

Zero Chem. Pot.

Finite Chem. Pot.





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

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

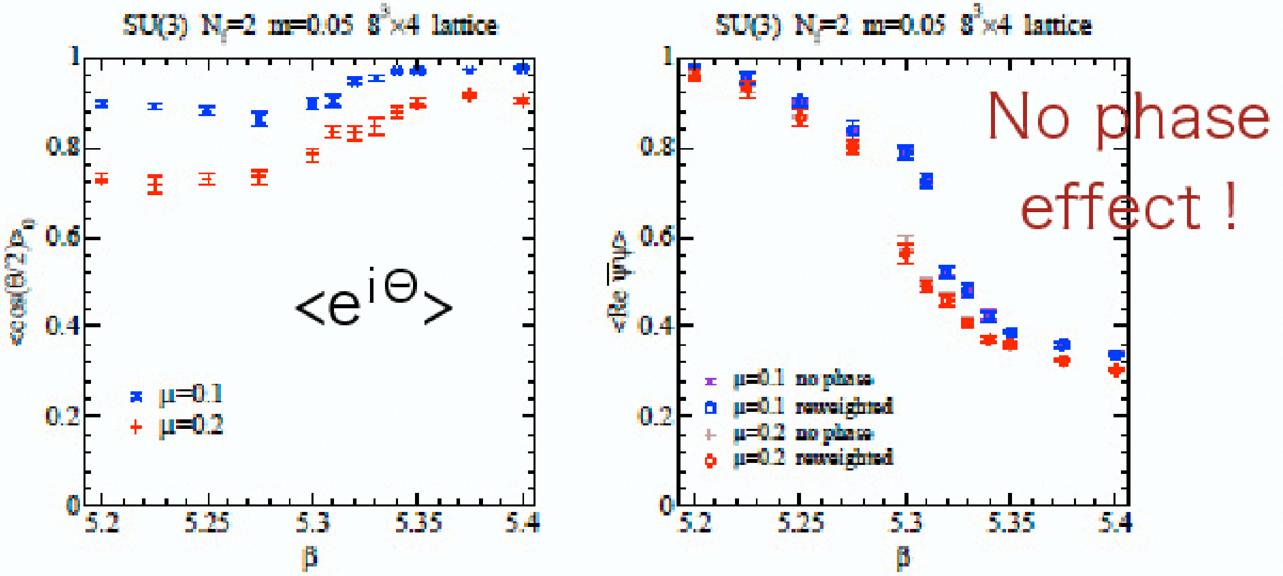
Zero Chem. Pot. : Cross Over
Finite Chem. Pot.: Critical End Point

Very Recent Progress (A. Nakamura)

Phase of Determinant

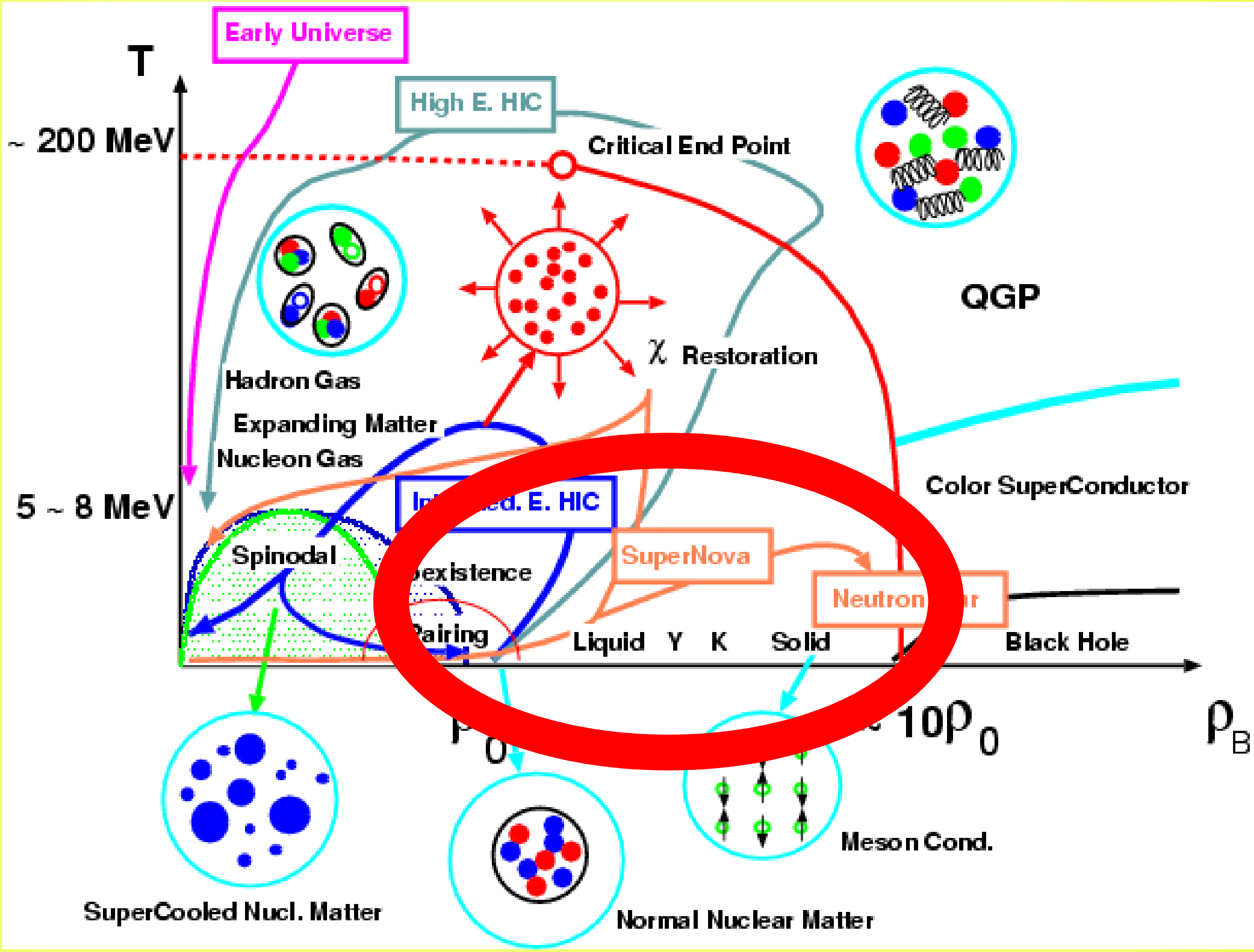
- The phase of the fermion determinant really fluctuate ?

$$< O >= \frac{< Oe^{i\theta} >_{|\det|}}{< e^{i\theta} >_{|\det|}} \approx \frac{0}{0} \quad ??$$



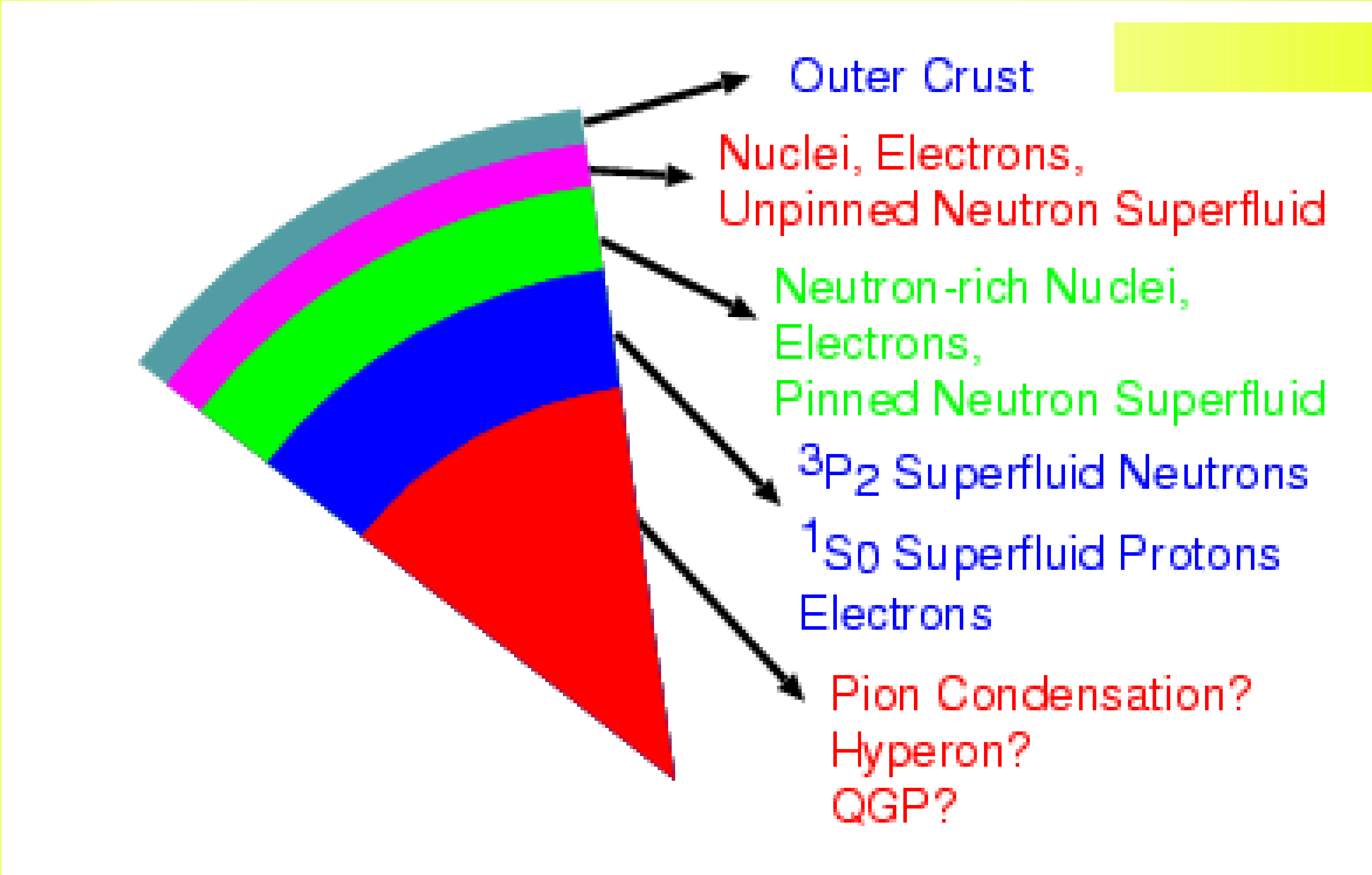
A. Nakamura, Oral Presentation at Matter03, Dec. 1-3, YITP

Low T and High ρ Matter



Hyperon, Kaon, Baryon Rich QGP, Color Superconductor, …

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

Strangeness

Hyperon Matter

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

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

Importance of Strangeness Degrees of Freedom

Constituents:

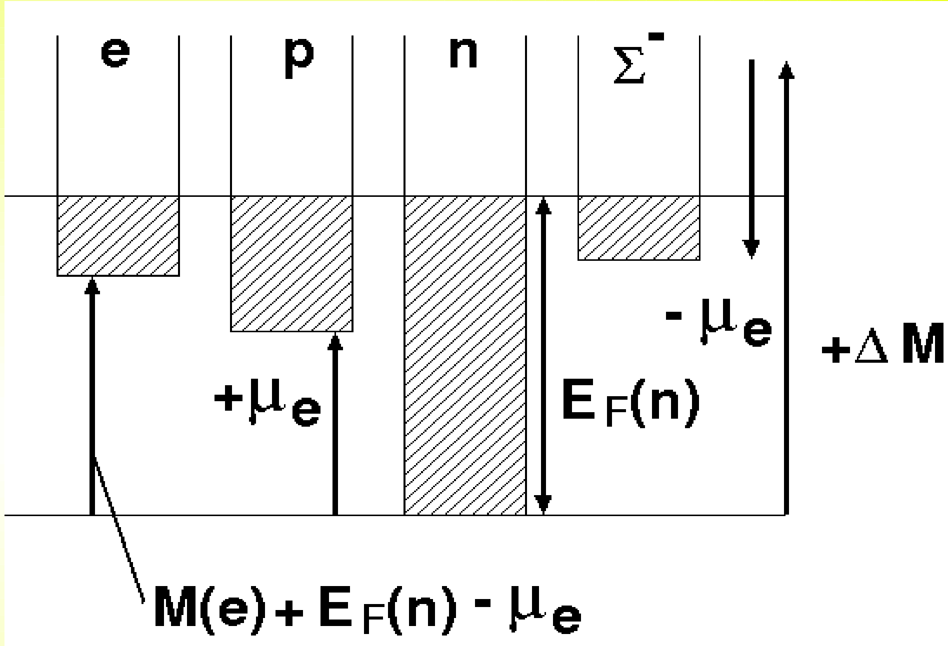
$$p, n, e^{\pm}, \mu^{\pm}, \Lambda, \Sigma^{\pm,0}, \ldots$$

Chemical Equilibrium:

× Strangeness (Weak)

× Lepton (ν **Emission)**

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

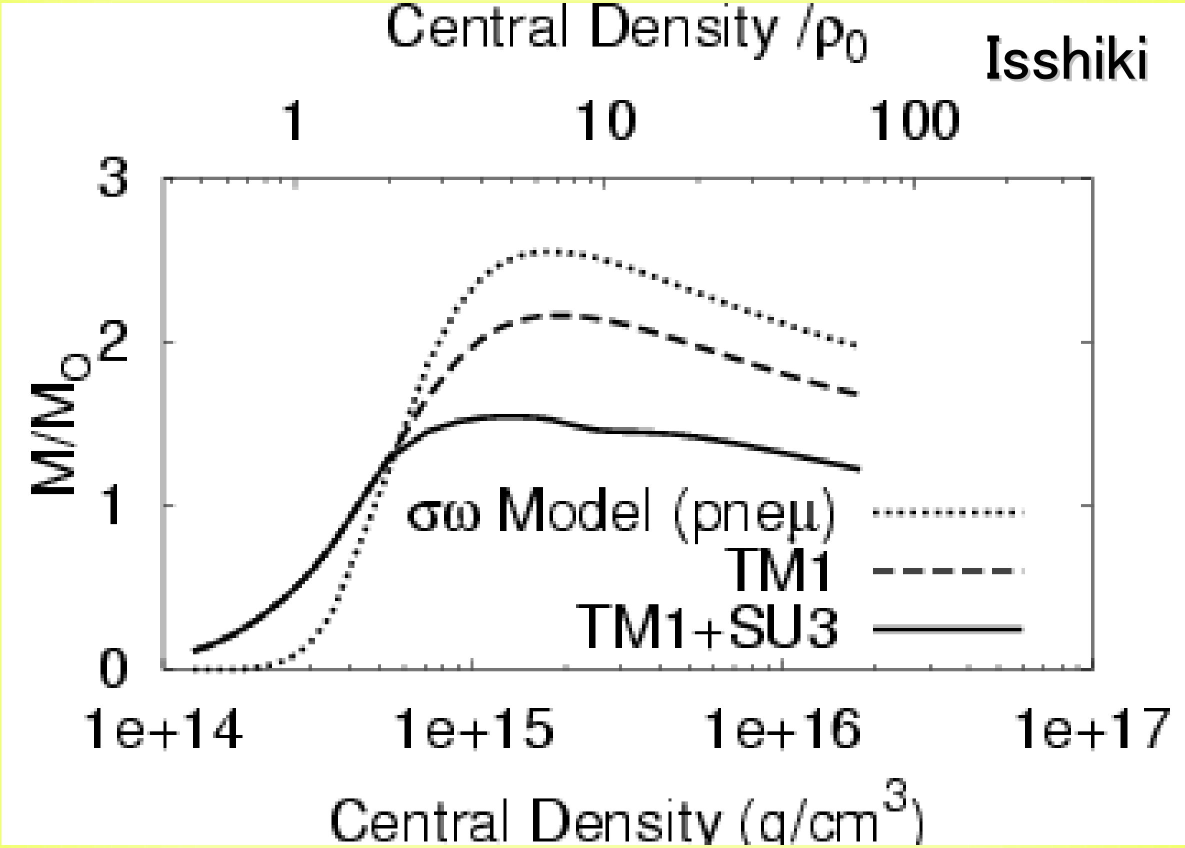


Negatively Chaged or Neutral Baryons are Favored

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

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

Example: Neutron Star Max. Mass

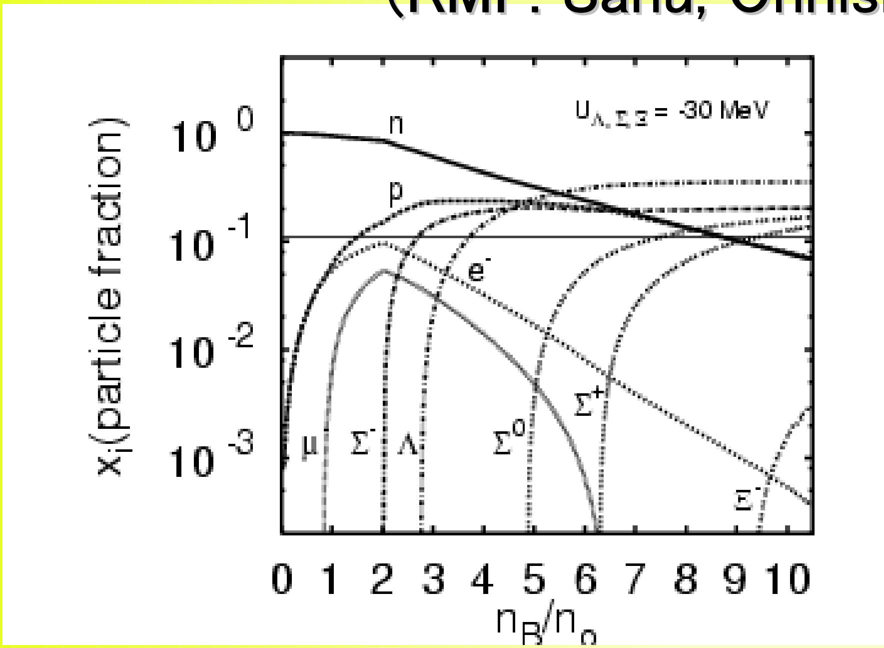


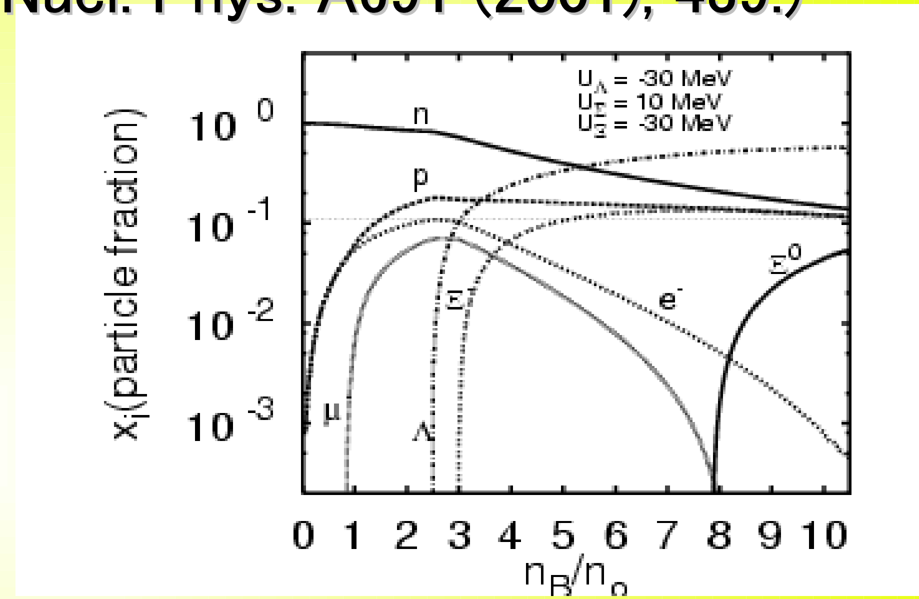
Serot–Walecka ($\sigma\omega$); Sugahara–Toki (TM1);
Glendenning; Schaffner–Mishustin (TM1+SU3); ...

Maximum Mass Reduction ~ 0.5–1.0 M_{sun}

Σ Potential Effects in Neutron Star

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





Attractive Potential for ∑
→ ∑ **appears at around** $\rho \approx 2\rho_0$

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

Max. Mass and Compositions are SENSITIVE to Interaction !!

E.g. Nishizaki-Takatsuka-Yamamoto, PTP 108 (02) 703.

G-matrix Approach

Nishizaki-Takatsuka-Yamamoto,
PTP 108 (2002),703.
G-matrix for NN and YN, YY
+ Three Baryon Int.(phen.)

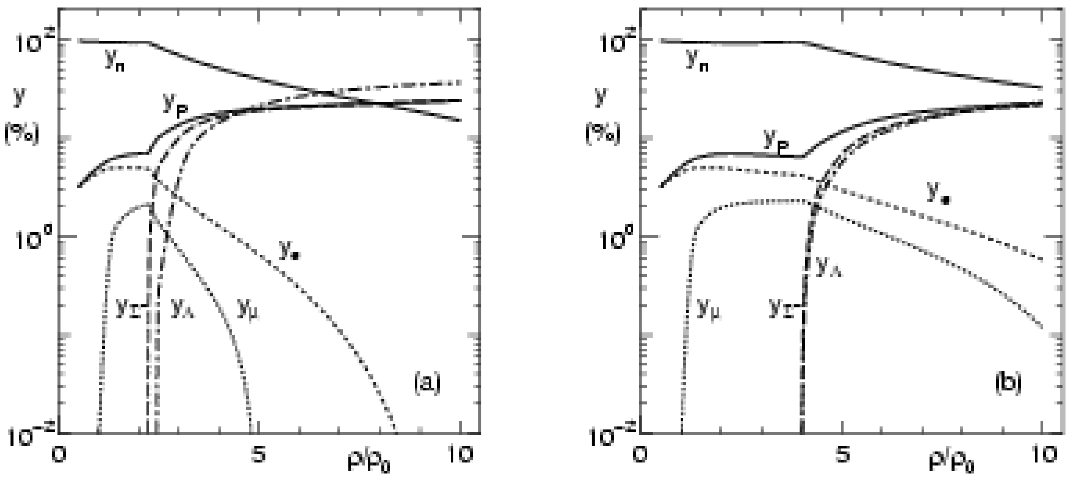


Fig. 4. The fractions of constituent particles as functions of the baryon density. (a) TNI3 only for the NN part (TNI3), (b) TNR3 for the YN and YY parts and for the NN part (TNI3u).

Hyperon Composition

Max. Mass

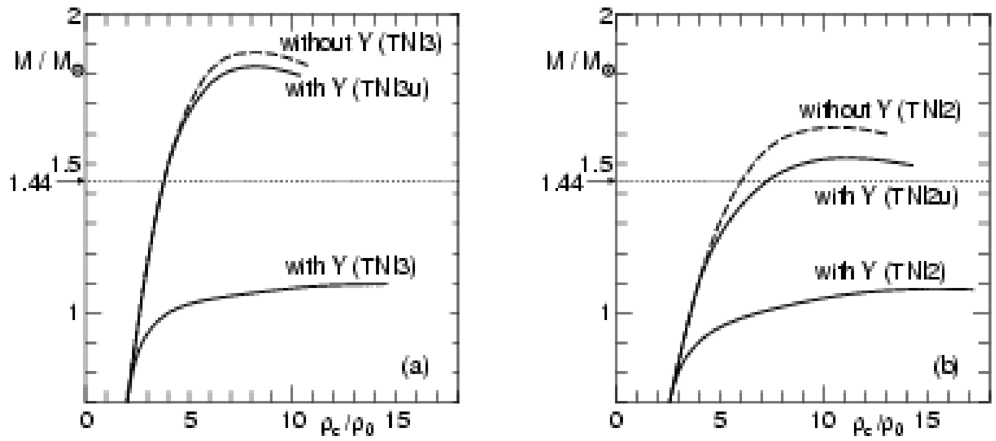


Fig. 9. The mass of a neutron star in units of the solar mass $M_\odot$ as functions of the central baryon density ρ_c with use of (a) TNI3 and (b) TNI2. The notation here is the same as in Fig. 8.

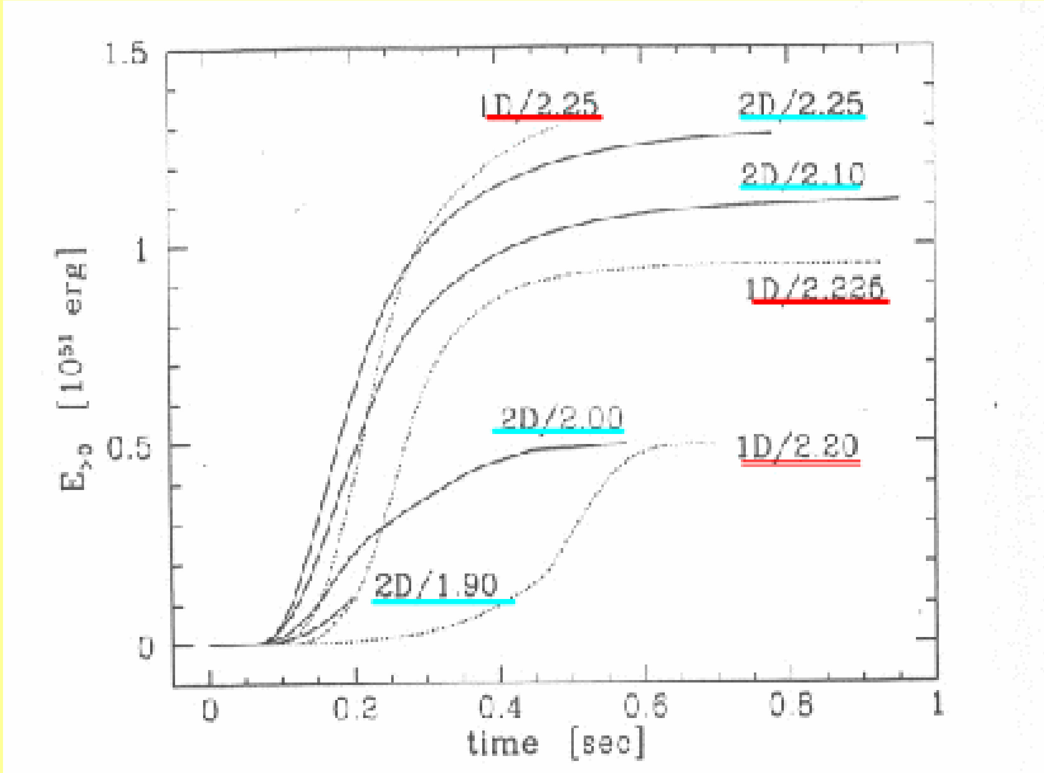
by S. Yamada

Crucial Role of Neutrinos

There is a critical luminosity!

- confirmed by analytic models
  - — Burrows & Ghoshy 93
  - — Janka 01

Accurate treatment of neutrino transport is mandatory !

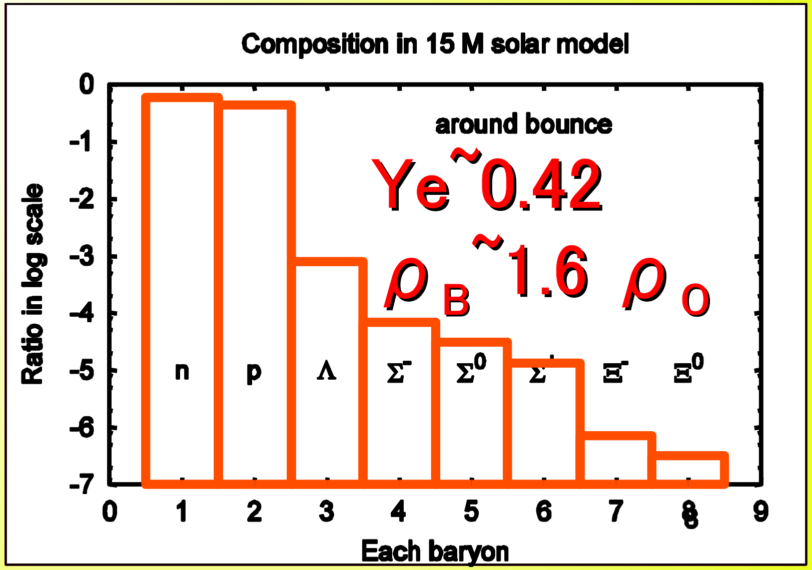


Janka & Mueller 95

Hyperons in Supernova Explosion

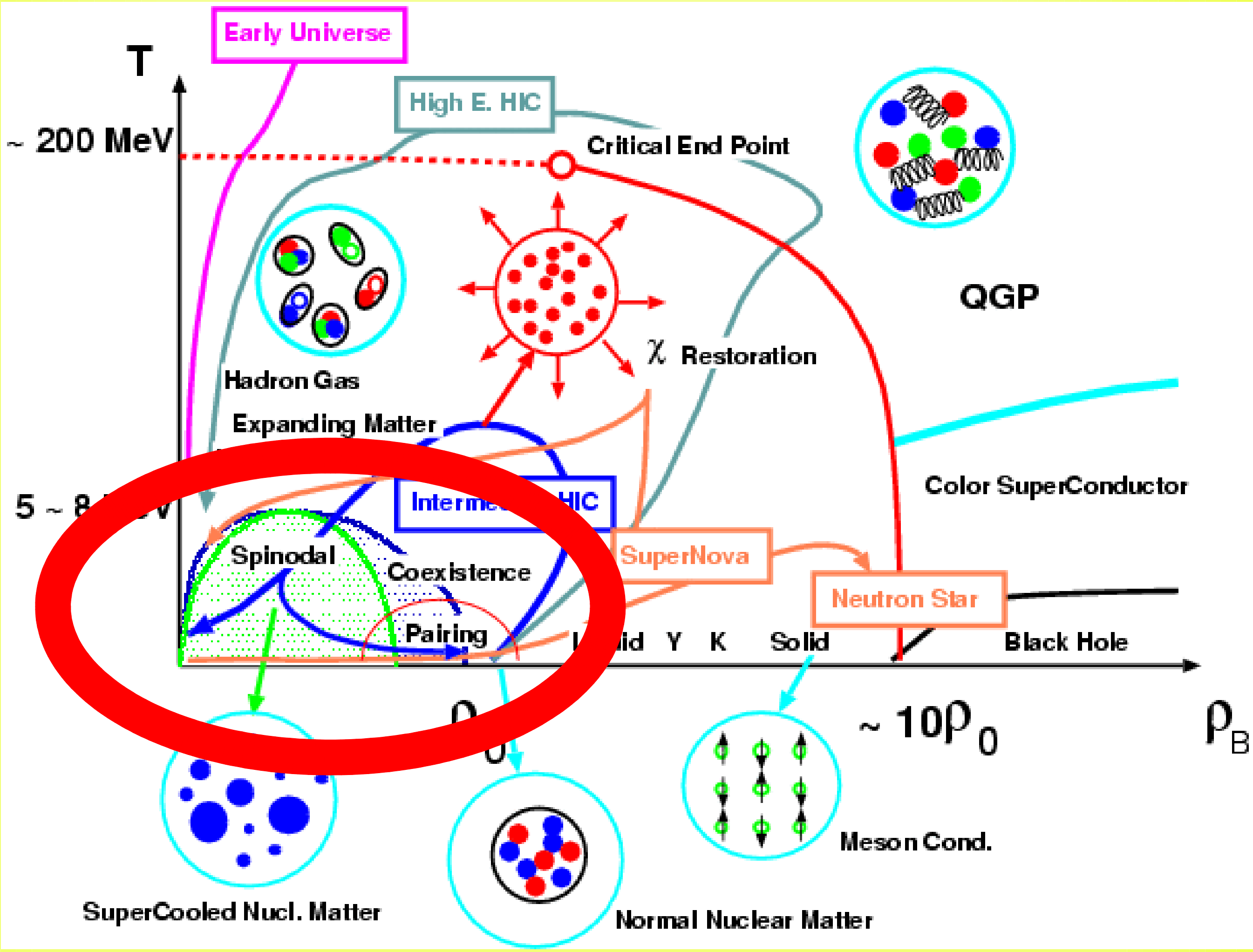
- Supernova explode in pure 1D hydro with Rel. EOS.
- With ν transport shock tends to stall.
- 3 % increase of ν flux leads to hydrodynamical explosion (Janka and Mueller 1995)
- Hyperons increase explosion energy by around 4 % (TM1 + SU(3), Ishizuka, AO, Sumiyoshi, Yamada, in preparation)

Ishizuka



Hyperons may play crutial roles in dense matter, such as in neutron stars and supernova explosion.

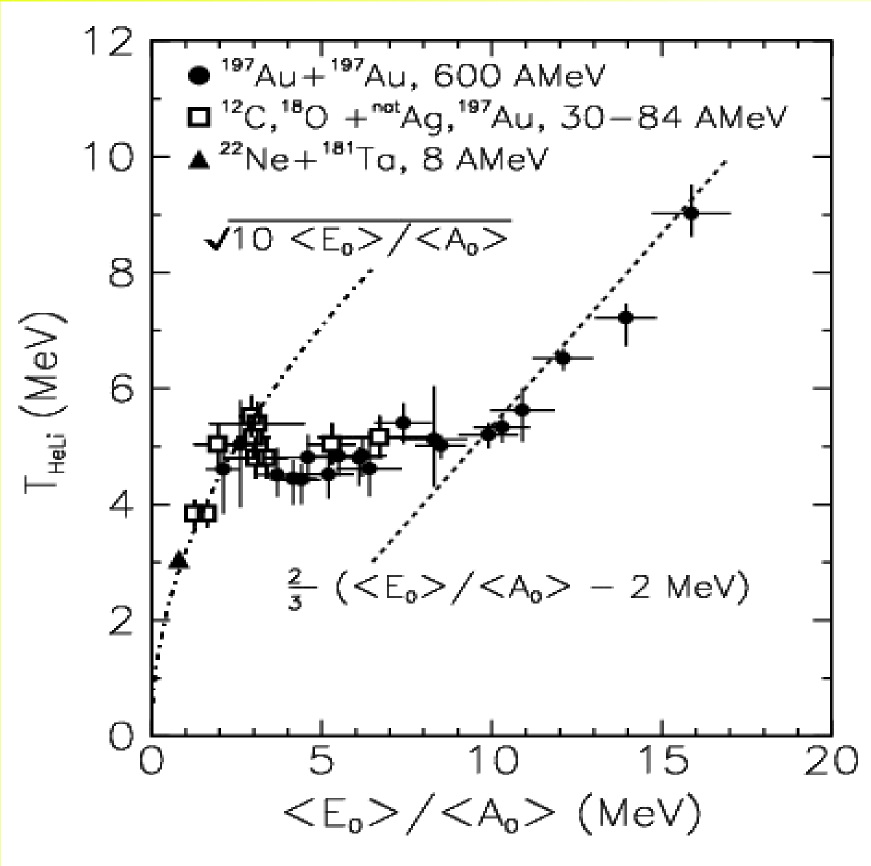
Low T and Low ρ Matter



Normal/Unstable Nuclei, Fragment Formation, …

Nuclear Caloric Curve

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



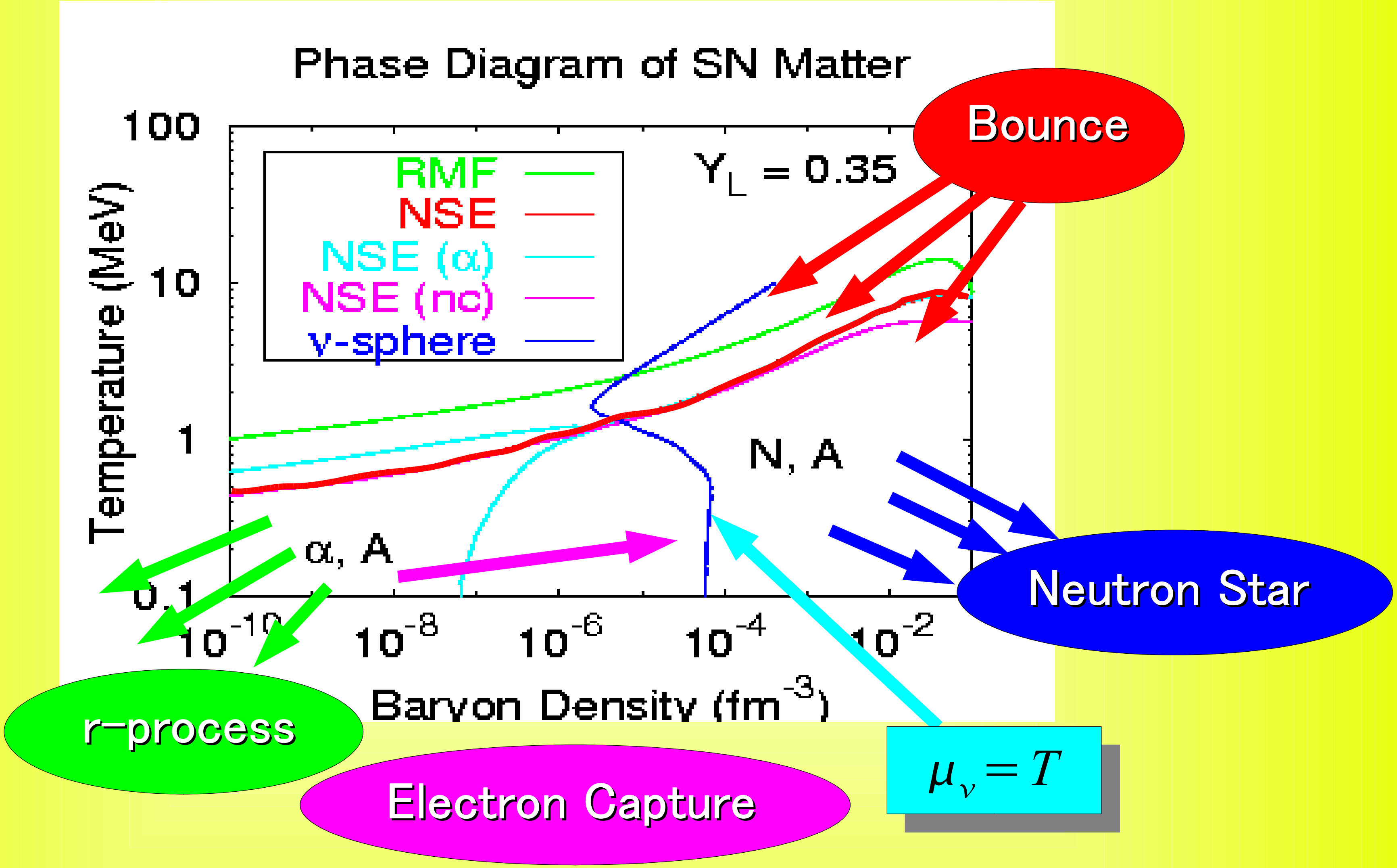
Boiling Temperature is Clearly Seen

Fragment Yields are assumed
to follow Equilibrium Statistics

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

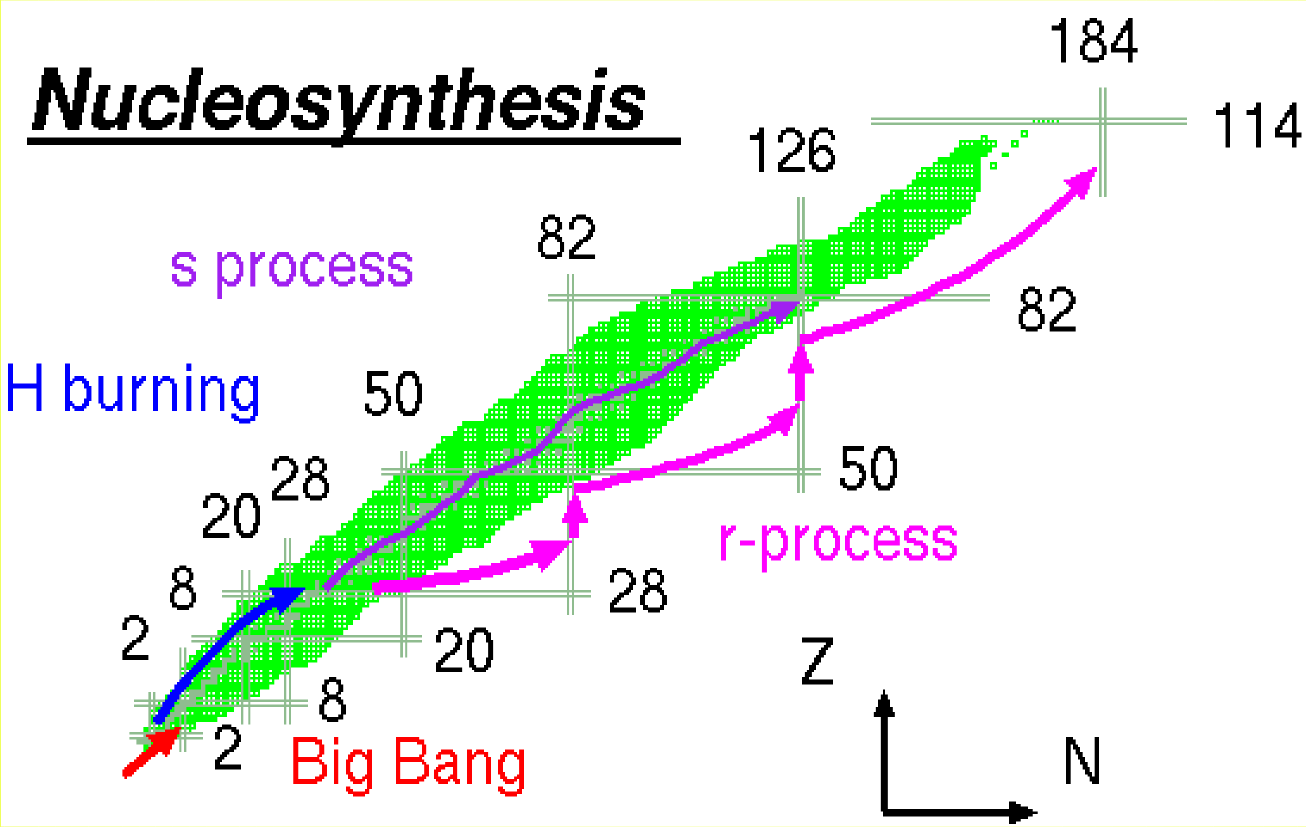
$$\to \frac{Y(^4He)/Y(^3He)}{Y(^7Li)/Y(^6Li)} \propto \exp(\Delta B/T)$$

Phase Diagram in RMF and NSE



Effect of Finite Nuclei: Reduction of ,T Existence of αA region

Nucleosynthesis



Supernova Nucleosynthesis is affected by
Nuclear EOS at High and Low Density, Low-E Nuclear Reactions,
Neutrino-Nuclear (and Hyperon) Reactions, ...

What should be done ?

- Ingredients of Nuclear/Hadronic Matter Study
  - Composition
    - Quark/Gluon, Hyperon, Meson
  - Interaction
    - Hyperon Int.
    - Density Deps. of Symmetic Energy
  - Statistics
    - Thermalization Deg. in Nuclear Reaction
- We Need ....
  - More Data and Expeirmental Evidences
  - Theoretial Developments
  - Exchange of Knowledgd with Other Field of Physics

Selected Topics of Developments in the 21 st Century

Selected Topics of Recent Developments

- **Quarks and Gluons**

  Discovery of a New Constituent --- Penta Quark

- **Hadrons**

  Change of Paradigm --- YN Interaction

- **Finite Nuclei**

  Discovery of New Finite Systems --- Kaonic Nucleus

  Determining New Interaction --- Double Hypernuclei

  Development in Understanding --- New Roles of Pions

- **Nuclear/Hadronic/Quark Matter**

  New State of Matter --- Quark Gluon Plasma

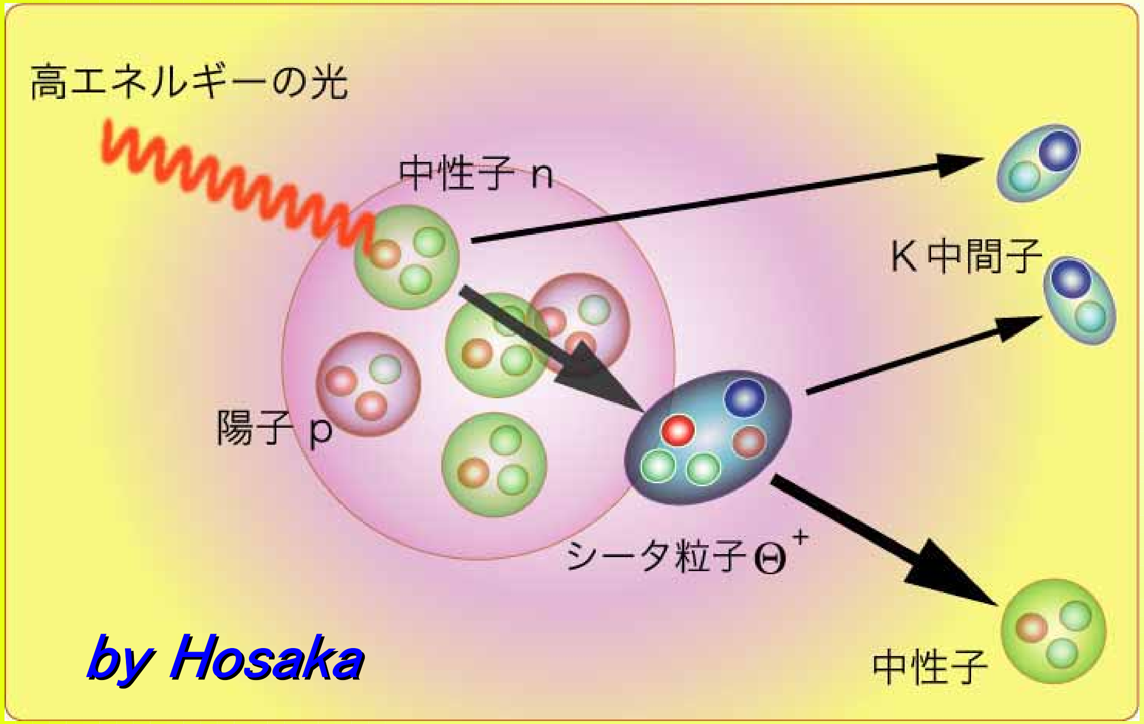
New Constituents (Hadrons)
--- Penta Quark ---

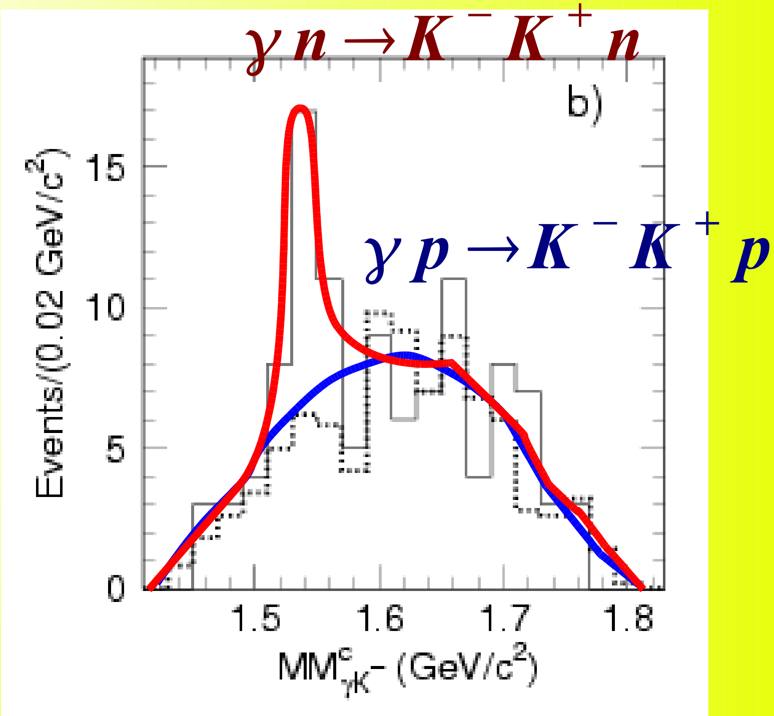
Discovery of Penta Quark State

LEPS @ Spring8

$$\gamma + n \to K^- + \Theta^+, \quad \Theta^+ \to K^+ + n, \quad \Theta^+ = uudd\bar{s}$$

M = 1540±10 MeV, Γ < 25 MeV, Gaussian significance 4.6 σ





T. Nakano et al. (LEPS Collaboration)
Phys.Rev.Lett.91 (2003) 012002 ; hep-ex/0301020

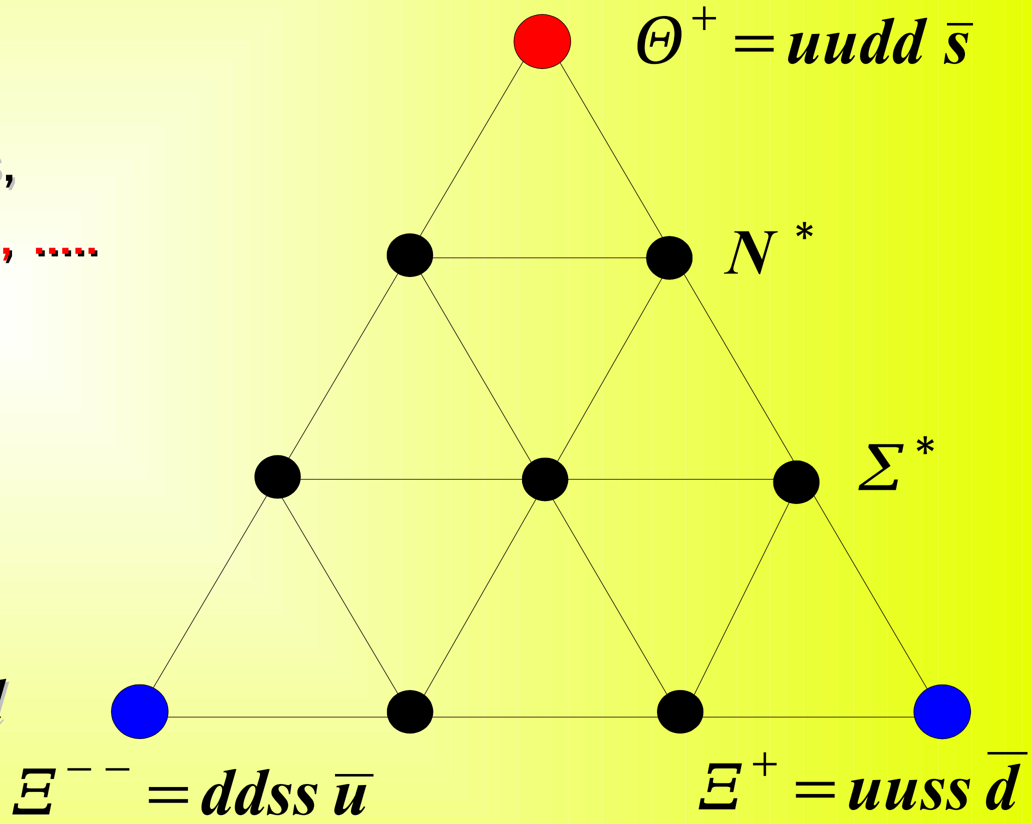
Impact of Penta Quark Discovery

First Manifestly Exotic Hadron

Elementary Particles

Gauge Bosons, Leptons, Quarks,
Mesons, Baryons, Penta Quarks, ...

Low Mass (threshold + 100 MeV)
→ Quark-Quark Interaction
Narrow Width < 25 MeV
→ Wave Function
Member of Anti-Decouplet
→ Other Members to be discovered



Renaissance of Hadron Spectroscopy !
Birth of Exotic Hadron Spectroscopy !
(K. Imai, Hyp03)

Experimental Confirmations

- ITEP (DIANA Collab.), hep-ex/0304040 (Phys.Atom.Nucl.66(03)1715, Yad.Fiz.66(03)1763

$$K^+ + \mathrm{Xe} \to \Theta^+ \to K_s^0 + p\,, M = 1539 \pm 2\,\mathrm{MeV}, \Gamma < 9\,\mathrm{MeV}$$

- JLab (CLAS Collab.), hep-ex/0307018

$$\gamma + \mathrm{d} \to K^- p\, \Theta^+, \Theta^+ \to K^+ n\,, M = 1542 \pm 5\,\mathrm{MeV}, \Gamma < 21\,\mathrm{MeV}$$

- ELSA (SAPHIR Collab.), hep-ex/0307083 (PLB 572(03)127)

$$\gamma + \mathrm{p} \to \overline{K}_s^0 \Theta^+, \Theta^+ \to K^+ \mathrm{n}, M = 1540 \pm 4 \pm 2\,\mathrm{MeV}, \Gamma < 25\,\mathrm{MeV}$$

- SPS (NA49 Collab.), hep-ex/0310014 (PRL accepted)

$$\mathrm{p} + \mathrm{p} \to \Xi^{--}, \Xi^{--} \to \Xi^- \pi^-, M = 1862 \pm 2\,\mathrm{MeV}, \Gamma < 18\,\mathrm{MeV}$$

- Bubble chamber (WA21, WA25, WA59, E180, E632),hep-ex/0309042

$$\nu + \mathrm{Ne(d)} \to \Theta^+, \Theta^+ \to K_s^0 \mathrm{p}, M = 1533 \pm 5\,\mathrm{MeV}, \Gamma < 20\,\mathrm{MeV}$$

Particle identification

by C. Hoehne, 18-th Nishinomiya-Yukawa

recent highlight from p+p analysis (158 GeV):

first evidence for an exotic S = -2, Q = -2 baryon resonance

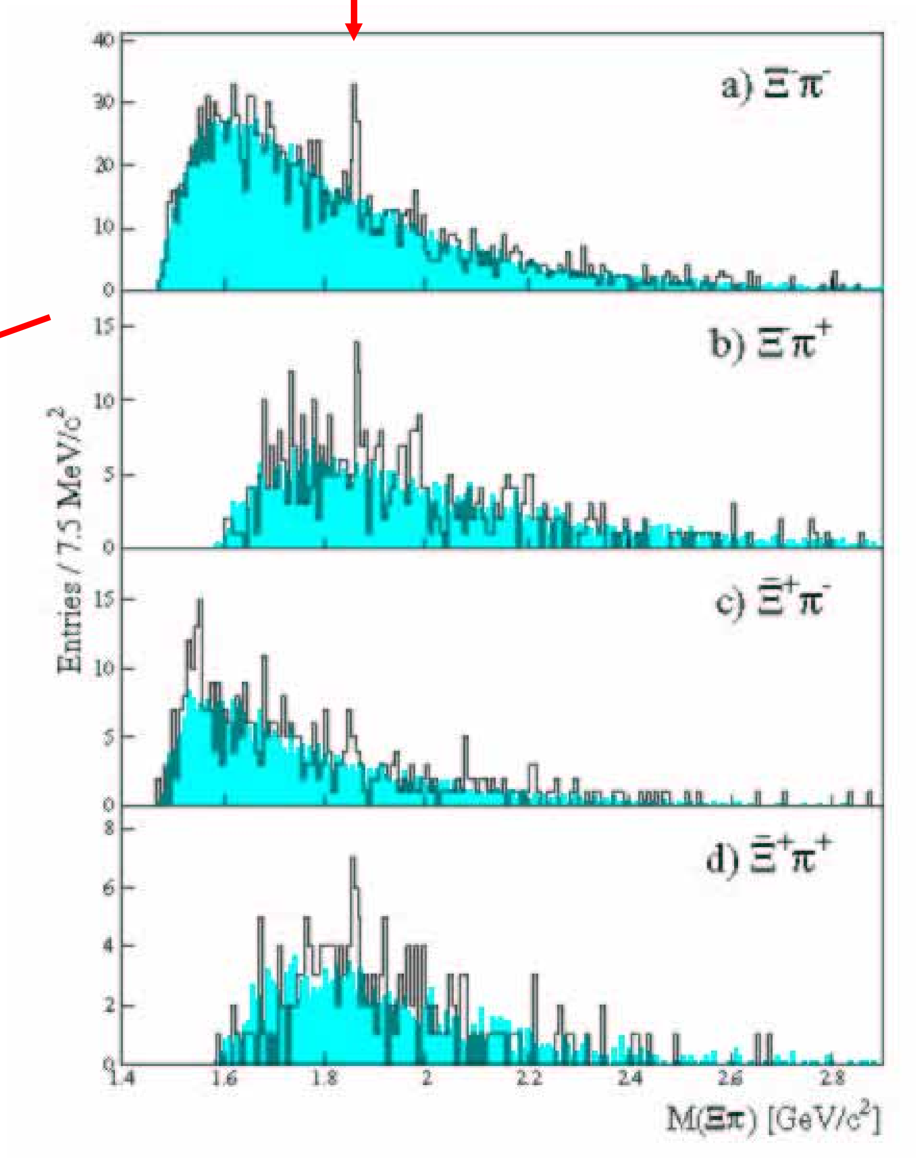
significance > 4.2 σ

mass = 1.862 $\pm$ 0.002 GeV/c^2

width below detector resolution of 0.018 GeV/c^2

state is candidate for the exotic $\Xi^{--}_{3/2}$ with a quark content of (dsds$\bar{u}$)

indication for $\Xi^{0}_{3/2}$ (dsus$\bar{d}$) and corresponding antibaryons



hep-ex/0310014, accepted by PRL

Theoretical Works

- Prediction :
  D. Diakonov, V. Petrov, and M. Polyakov, ZPA359(97),305.
  Chiral soliton model (Skyrmion)
  N(1710) is assumed to be a member of Anti-Decouplet
  Small mass and narrow width

$$M = 1890 - 180\,Y = 1530\,\mathrm{MeV},\ \Gamma < 15\,\mathrm{MeV},\ J^{\pi} = 1/2^{+}$$

- After Discovery, Flood of Papers are coming out....
  Jaffe-Wilczek (di-quark, hep-ph/0307341)
  Karliner-Lipkin (di-quark+tri-quark, hep-ph/0307243)
  Hosaka (chiral bag, PLB571(03)55)
  Capstick-Page-Roberts (I=2 pentaquark, hep-ph/0307019)
  Llanes-Estrada-Oset-Mateu ($K\pi N$ bound state, nucl-th/0311020)
  Zhu (QSR, hep-ph/0307345)
  Matheus et al. (QSR, hep-ph/030900)
  Sugiyama-Doi-Oka (QSR, hep-ph/0309271)
  Csikor, Fodor, Katz, Kovacs (hep-lat/0309090)
  Sasaki (hep-lat/0310014)
  Lee-Liu (Hyp03)
  ....

A Lot of Mysteries...

by Oka, 18-th Nishinomiya-Yukawa Symp.

Questions

- QCD predicts a negative-parity ($1/2^-$) pentaquark.
  - Problem: The predictions are very close to the KN threshold.
- Various models suggest positive parity ($1/2^+$) pentaquarks.
  - No serious microscopic calculations so far.
- Mass 1540 MeV
  - The quark model prefers $1/2^-$. It may be too light for $1/2^+$.
- Width < 10 MeV ?

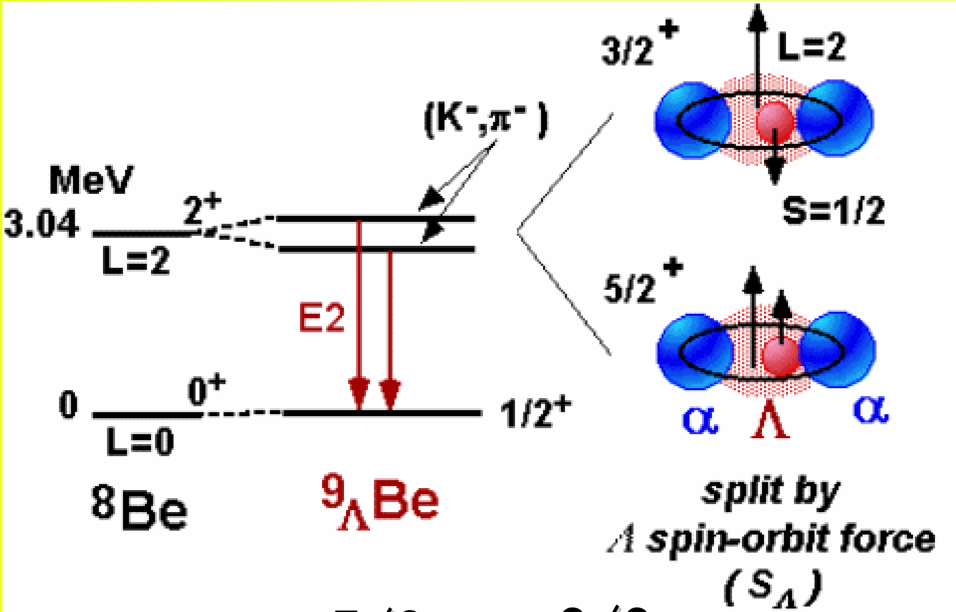
  Arndt et al. nucl-th/0308012

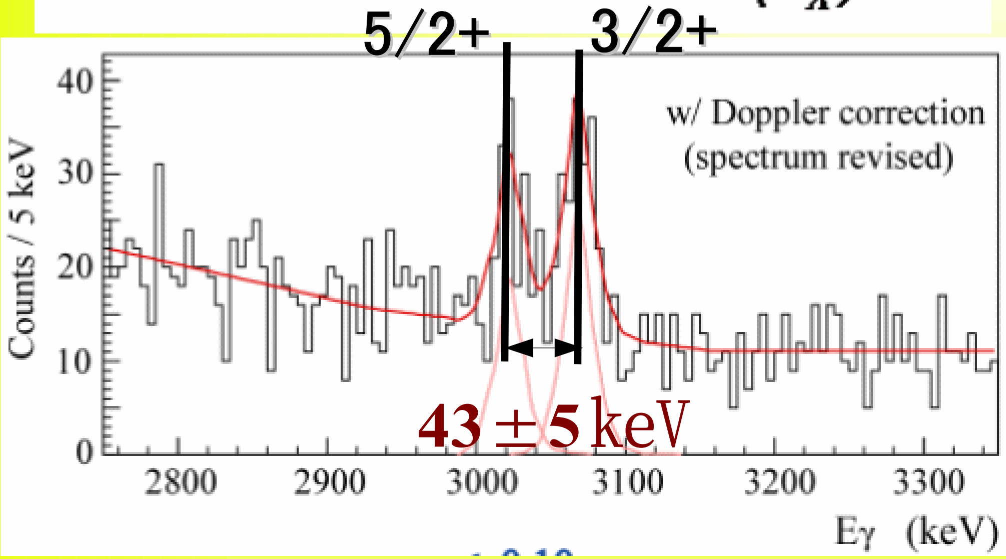
  Γ < 1 MeV to be consistent with KN PSA
- *We need more data* ***and*** *new (revolutionary) theoretical ideas!*

Recent Developments in Hypernuclear Physics

- Gamma Ray Spectroscopy of Hypernuclei
- Deeply Bound Kaonic Nuclei
- Double Hypernuclei

Gamma Ray Spectroscopy of Hypernuclei





Experiment: BNL-E930-1

Akikawa et al., PRL 88 (2002)082501;
Tamura et al., Hyp03

$$^{9}\mathrm{Be}(K^-,\pi^-\gamma)^{9}_{\Lambda}\mathrm{Be}$$

LS splitting $43 \pm 5\,\mathrm{keV}$

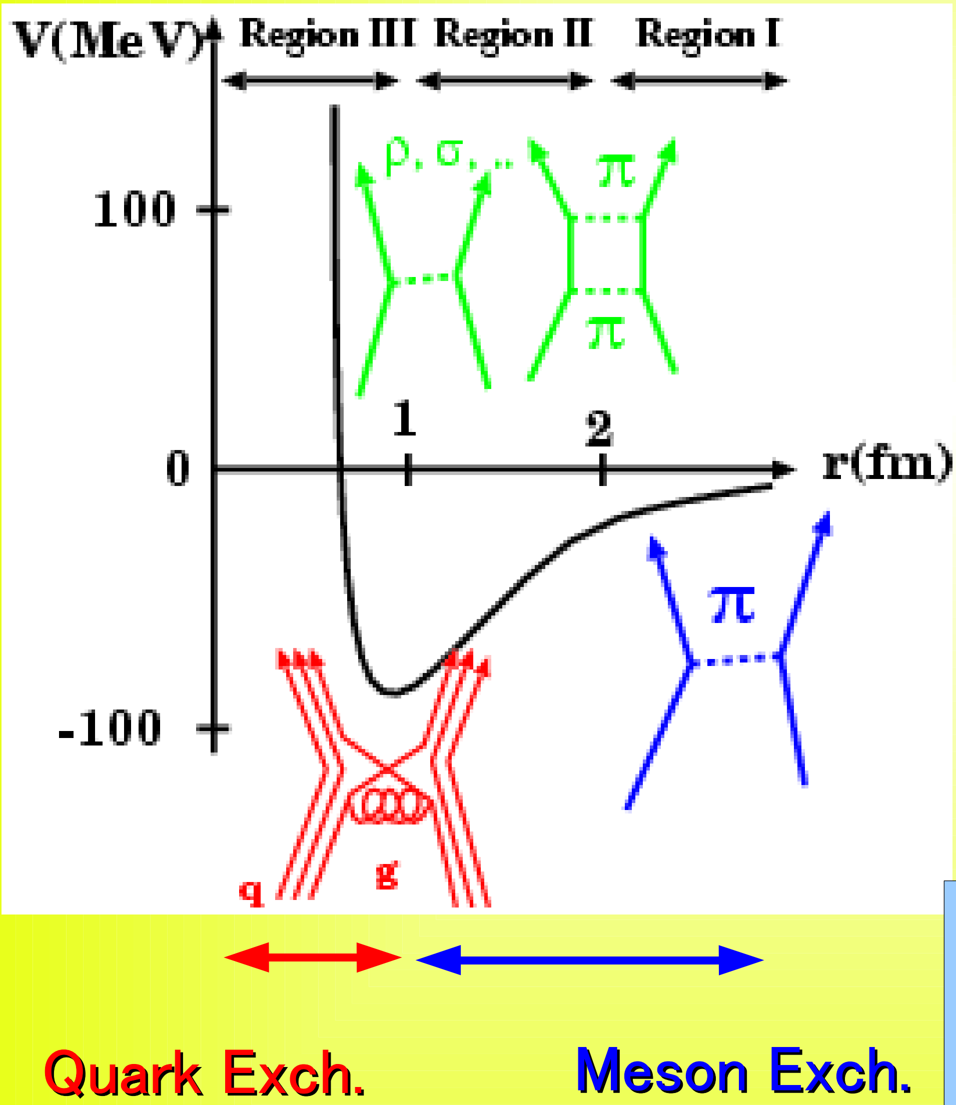
Theory:

Hiyama et al, PRL85(2000), 270.

Meson Exch. 80-200 keV
Quark Model 30-40 keV

Inconsistent with
Meson Exchange Potential

Paradigm Change of BB Potential



Before Hypernuclear
Gamma-Ray Spectroscopy

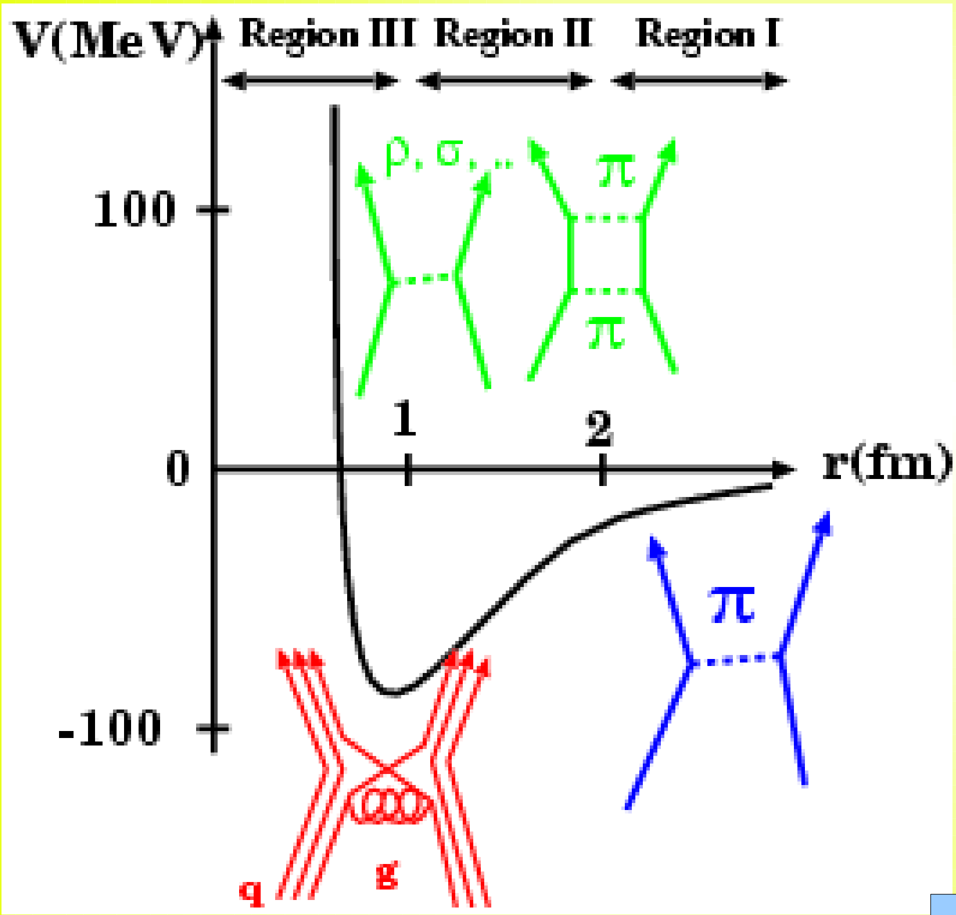
Region I:
OPEP

Region II:
Two Pion Exch.,
One Boson Exch.

Region III:
Pauli blocking and OGE
between Quarks

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

Paradigm Change of BB Potential



Quark Exch.

Meson Exch.

After Hypernuclear Gamma-Ray Spectroscopy

Region I:
OPEP

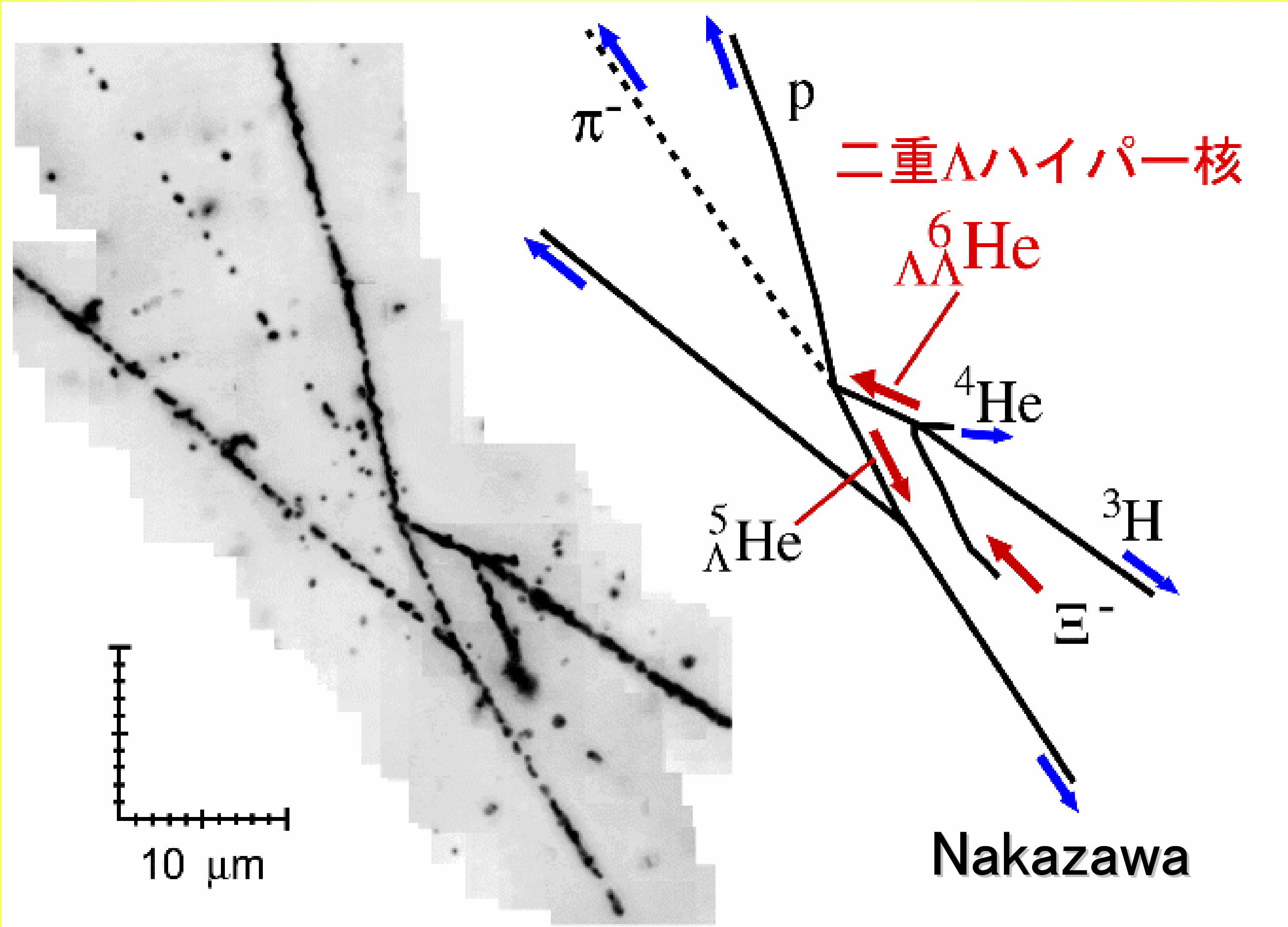
Region II:
Two Pion Exch.,
One Boson Exch.

Region III:
Color Magnetic (OGE)
Pauli blocking and OGE
between Quarks

Quarks may play roles also in Region II at least for LS int. for YN

Double Λ Hypernuclei

Nagara Event --- the Best Event

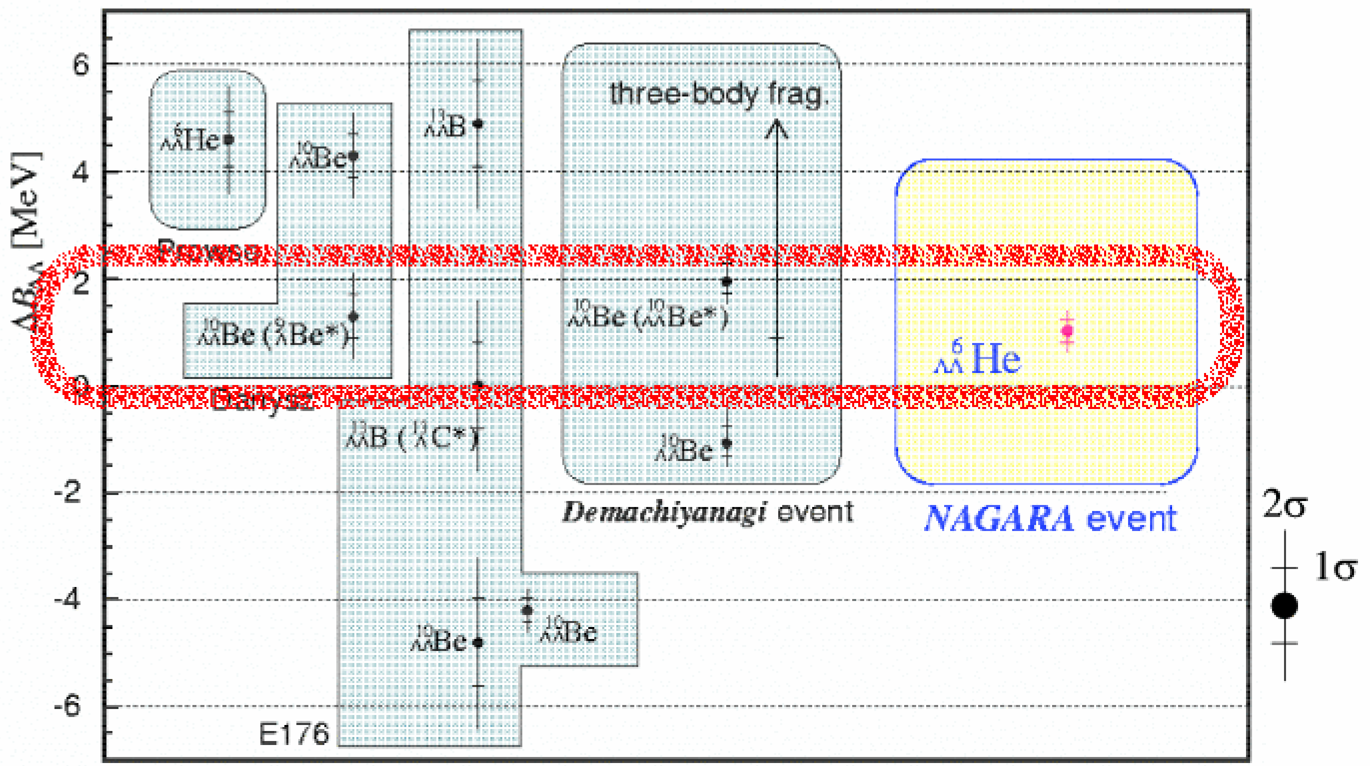


Takahashi et al, PRL 87 (2001), 212502.

HYP2003
at J-Lab
Oct.14-18,

Comparison with past results

ΛΛ interaction is attractive but weak

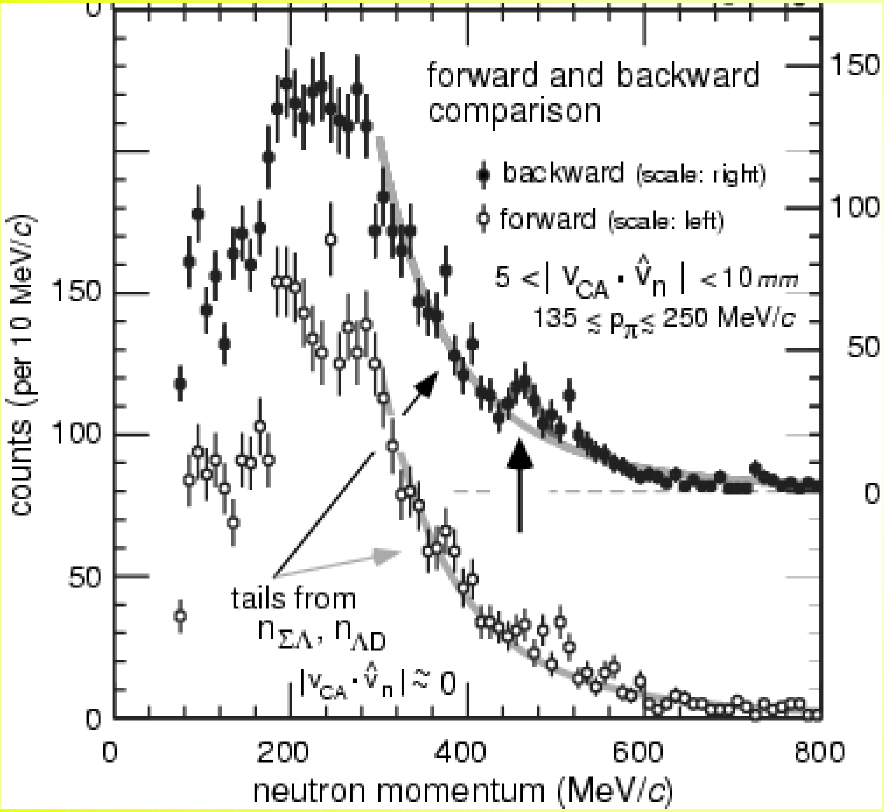


All experiments are consistent except for that of Prowse.

Impact of Narara Event

- H particle : Even if bound, B.E. is very small.
- Lampha: Triple Magic Nuclei
- Z and A: Unambiguously Determined
- Binding Energy: $\Delta B_{\Lambda\Lambda} = 1.01 \pm 0.20^{+0.18}_{-0.11}\,\mathrm{MeV}$
  - ΛΛ: Attraction is Weak
    - BB interaction Model: Nijmegen, Funabashi-Gifu, Ehime, Kyoto-Niigata, Tokyo-Tuebingen, ...
    - Superfluidity in Hyperons may not realized (Takatsuka)
- Another Double hyper Nucleus (4-H-LL) is also found (BNL-E906).

Discovery of Deeply Bound Kaonic Nucleus



Stopped K on He

$$^4\mathrm{He}(K^-_{Stopped}, n)^3_K\mathrm{H}$$

T. Suzuki et al.(KEK-PS-E471), Hyp03, nucl-ex/0310018.

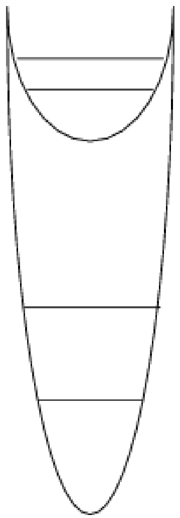
B.E. = **165.1 ± 3.6** MeV (Stat. Only)

Γ = **14.1** MeV (Stat. Err. < **25.1** MeV)

Very Deeply Bound (B.E. ~ 165 MeV)
Size May be Very Small (T.Suzuki, Large $\hbar\omega$ (prel.))

Discovery of Deeply Bound Kaonic Nucleus

Shell Spacing



$$\hbar\omega_K \sim \hbar\omega_N \sqrt{V_K / V_N}\sqrt{m_N / m_K}$$

$$\hbar\omega_N \sim 15 MeV$$

$$\sqrt{V_K / V_N} \sim \sqrt{190/50}$$

$$\sqrt{m_N / m_K} \sim \sqrt{0.94/0.5}$$

$$\hbar\omega_K \sim 40 MeV$$

U~190 MeV

Neutron Knock-out by Kaon

$$^{16}\mathrm{O}(K^-, n)^{15}_{K}\mathrm{N}$$

BNL-E930 parasite

T. Kishimoto et al.
PTP Suppl. 149(2003),264.

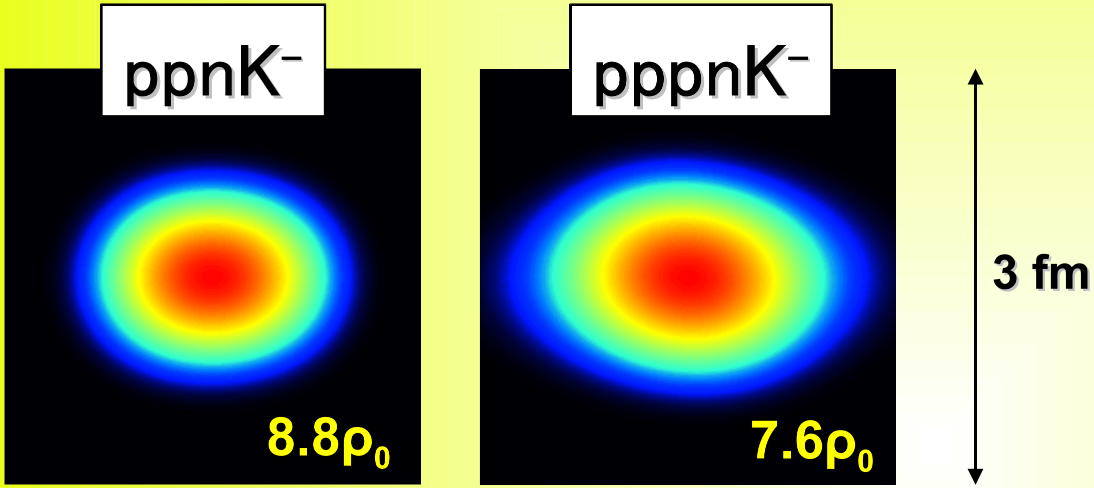
Kishimoto, Hyp03

U can be as deep as 190 MeV.
Excited States are observed.

by Dote, Matter03

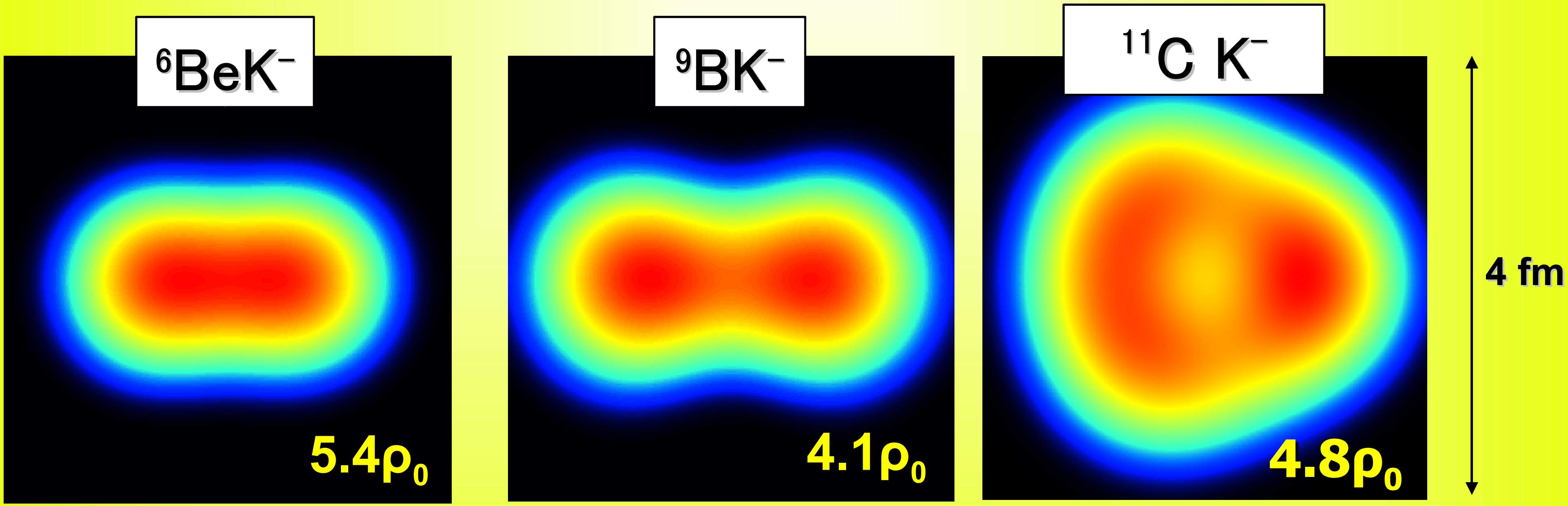
YITP 50-th Anniversary, 12/8-9, 2003, YITP

Dense Matter in Finite Nuclei ?

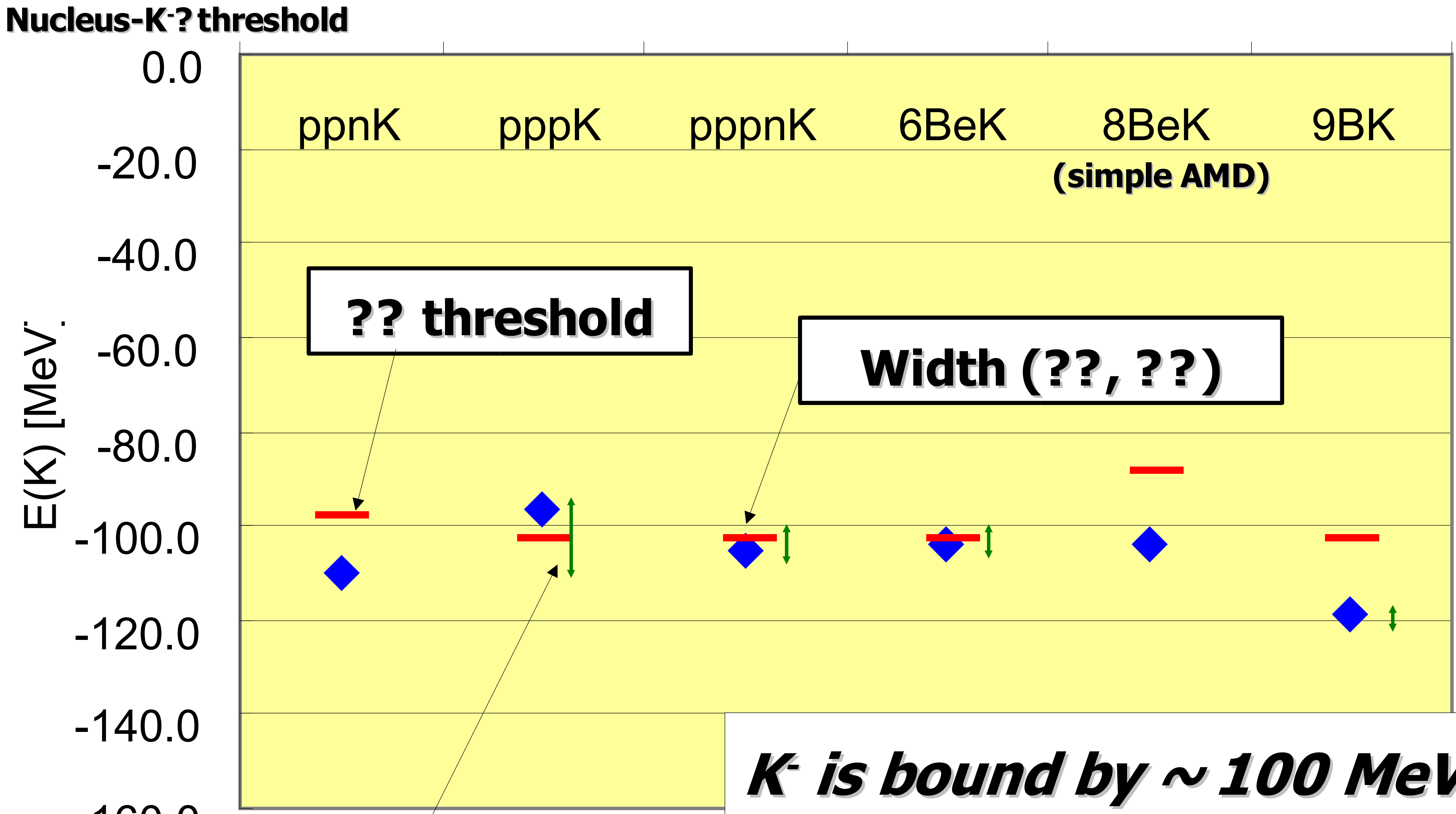


AMD
\+ Yamazaki-Akaishi
Kbar N Interaction

Dote, Akaishi, Yamazaki
nucl-th/0309062



Binding energy of K- and Decay-width



K- is bound by ~ 100 MeV in these nuclei.

Uncertainty due to the inconsistency between the obtained results and the G-matrix used in the calculation

by Dote, Matter03

Impact of Deeply Bound Kaonic Nuclei

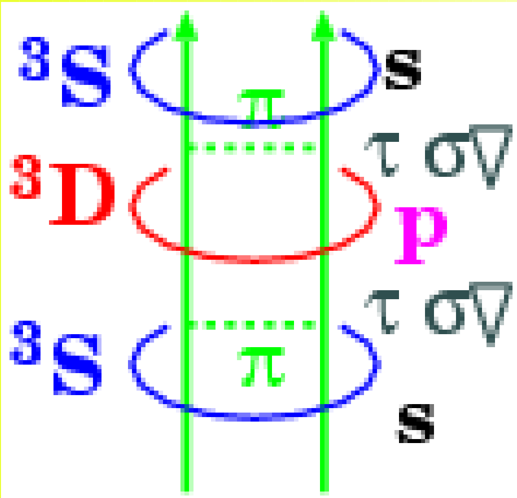
Puzzle in Kbar N Interaction
- Attractive
  - Chiral pert. --> **Kaon cond. (Kaplan & Nelson)**
- **Repulsive**
  - **Scatt. ampl. at threshold (Martin)**
  - **Kaonic hydrogen X-ray shift (Iwasaki et al.)**

Solution:Λ(1405) = Kbar N bound state
- **Orthogonality of Scatt. State to Bound State**
  - **Looks repulsive at threshold, Strongly Attractive in Dense Matter**

Problem of Kaon Condensation
- **EOS of dense matter would be too soft !**
- **Self-bound "Strange" (Kaon) Star ? (Muto)**

Mean Field Generated by Pions

Mean Field / Shell Model Picture of Nuclei



Mean Field / Shell Model
= Standard Picture of Nuclei.

- Nucleons are filled in the Mean Field potential consisting with central and LS part.
- Nucleon single particle w.f. is specified by nlj (radial, orbital angular momentum, and total angular momentum).
- Bare tensor interactions are included in the Effective Central (and LS) interaction.

Where are the Pions in Nuclei ?

- Standard Picture
  - Pion Effects can be represented by Effective Central and LS int.

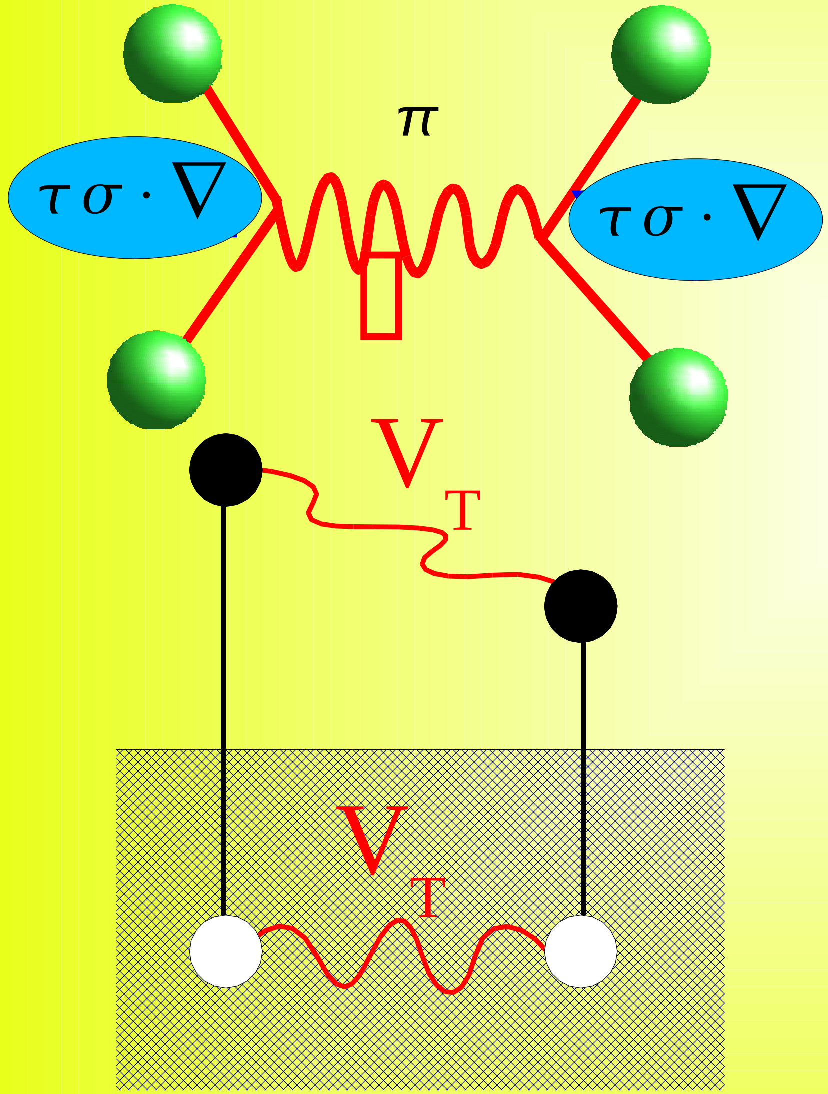
Objection !

- Pion Condensation in Nuclei and in Dense Matter
  - Migdal, Tamagaki school, Toki-Weise, ...
  - Pion Cond. will not be realized if $g'_{N\Delta} > 0.6$.
- Revival : GT strength Sum > 90 % (Sakai et al., RCNP Exp't.)
  - Considered to be Quenched because of the Delta excitation due to large $g'_{N\Delta}$.
  - GT Strength Sum → $g'_{N\Delta} < 0.25$ (T. Suzuki (Fukui) et al.)
  - **Quenching is due to residual interaction.**
- **Large Tensor and OPEP contribution in Realistic Few-Body Calc. with Realistic NN interaction. (Wiringa et al.)**

Let's See Pions in Nuclei AGAIN !

Toki, Sugimoto, Ikeda, PTP 108 (2002), 903; Ikeda/Akaishi/Toki, Cluster8

Mean Field generated by Pions



Mean Field from Pion

$$U_\pi = \frac{f_{\pi N}}{m_\pi} \tau\sigma\cdot\nabla\phi$$

☆τ: Couples
Proton and Neutron States
☆ $\sigma\cdot\nabla\phi$: Couples
Even and Odd Parity States

→ Charge Parity Projected HF

1) Fill the Nucleus with
Charge and Parity Mixed Single Particle States
2) Project w.f. to
Charge and Parity Eigen State
3) Make Variation

Schematic example (^{4}He;A=4,Z=2)

$(\pi 0s)^2(\nu 0s)^2$ $\left(\alpha(\pi 0s)+\beta(\nu 0s)+\gamma(\pi 0p)+\delta(\nu 0p)\right)^4$ **mixed wave function**

simple (0s)^4

$$= \underbrace{6\alpha^2\beta^2(\pi 0s)^2(\nu 0s)^2}_{\text{0p-0h}}$$

$$+\underbrace{6\alpha^2\delta^2(\pi 0s)^2(\nu 0p)^2+6\beta^2\gamma^2(\nu 0s)^2(\pi 0p)^2+24\alpha\beta\gamma\delta(\pi 0s)(\nu 0s)(\pi 0p)(\nu 0p)}_{\text{2p-2h}}$$

$$+\underbrace{6\gamma^2\delta^2(\pi 0p)^2(\nu 0p)^2}_{\text{4p-4h}}$$

^{4}He, 0$^+$

$$+\underbrace{12\alpha^2\beta\delta(\pi 0s)^2(\nu 0s)(\nu 0p)+12\alpha\beta^2\gamma(\pi 0s)(\nu 0s)^2(\pi 0p)}_{\text{1p-1h}}$$

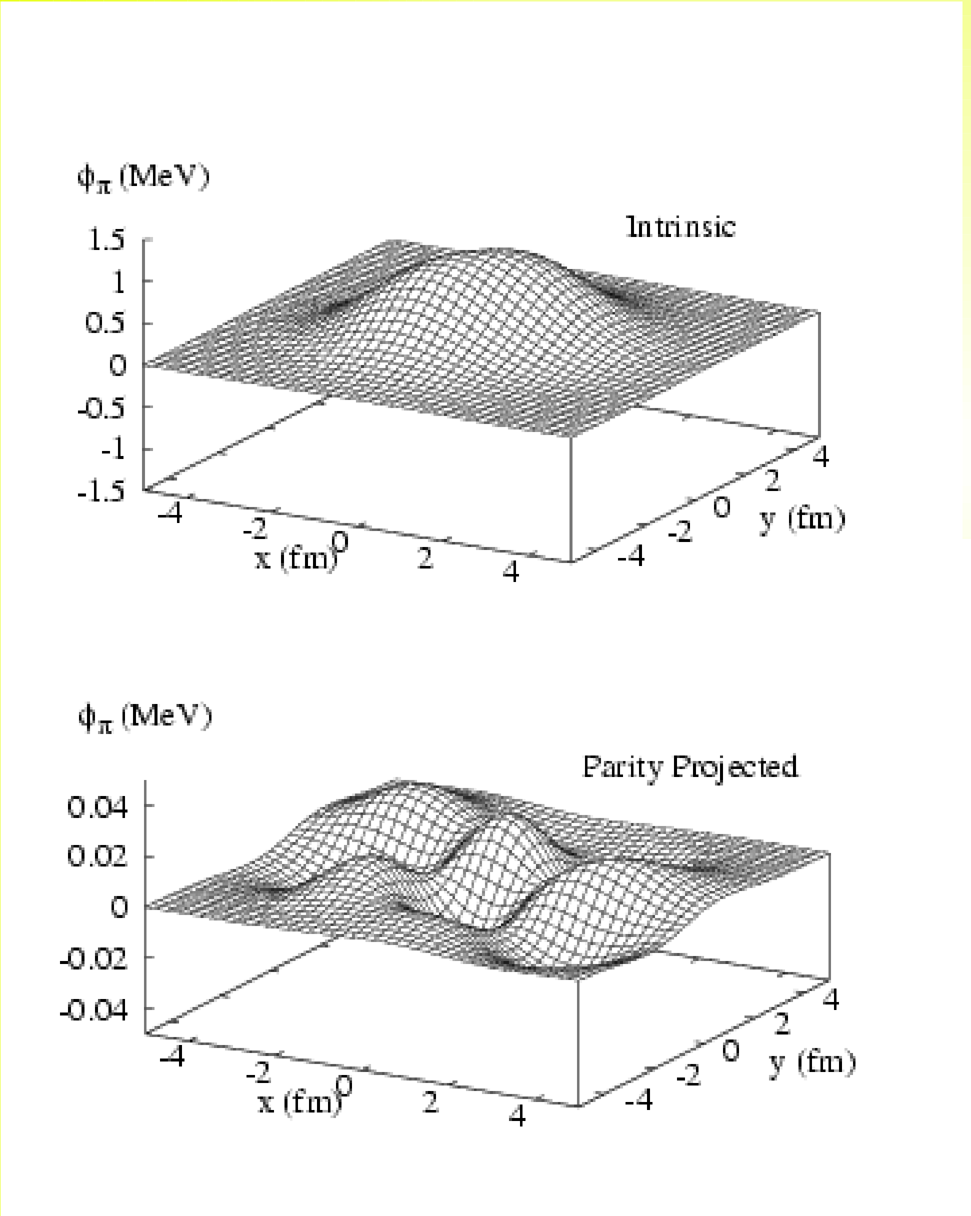
$$+\underbrace{12\beta\gamma^2\delta(\nu 0s)(\pi 0p)(\nu 0p)+12\alpha\gamma\delta^2(\pi 0s)(\pi 0p)(\nu 0p)^2}_{\text{3p-3h}}$$

^{4}He, 0$^-$

+(other 160 terms (4n, ^{4}H, ^{4}Li, ^{4}Be))

By combining <u>the charge and the parity mixings and projections</u>, we can obtain a wave function which includes <u>the correlations induced by the tensor force.</u>

Pionic Amplitude (Example)



AMD with Coherent Neutral Pions

(Isshiki, Naito, AO, Cluster8)

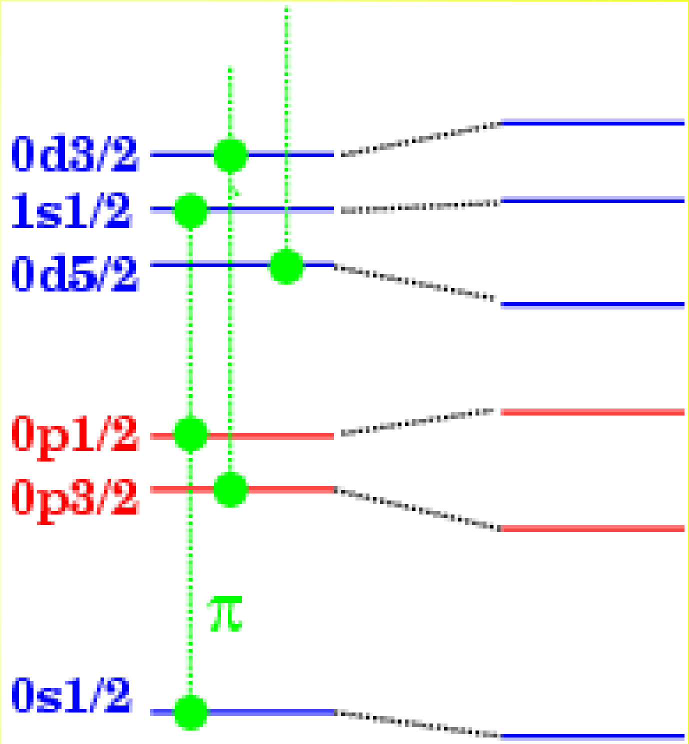
Pionic amplitude can be as large as MeV in Nuclei !

LS-like Effects of Pions

Ogawa et al. (2003)

- ✯ Pion mixes different parity (but same j) states.
- ✯ Lower state gains energy, while higher state goes up.

  → **LS like !**



New Type of Mean Field Model just started.
Let's see what happens !

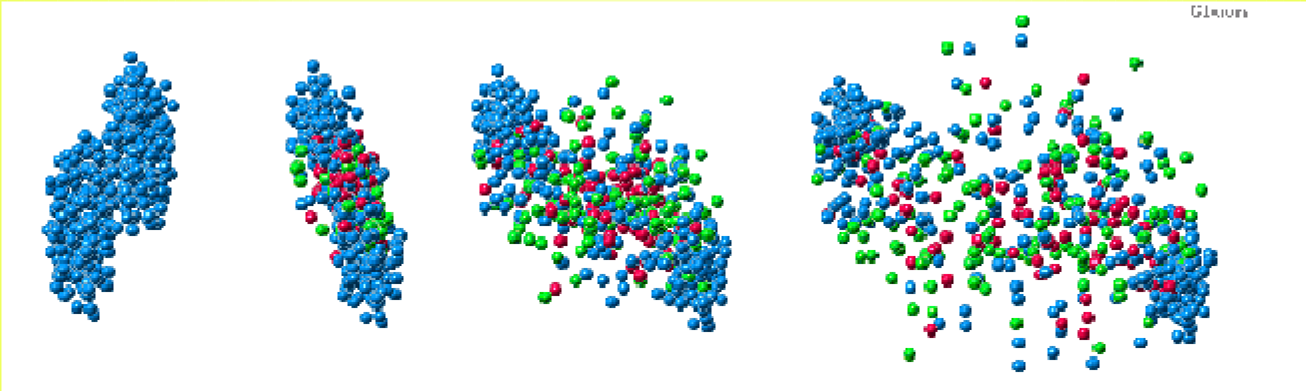
New State of Matter
--- Quark-Gluon Plasma ---

- Jet Quenching
- Elliptic Flow

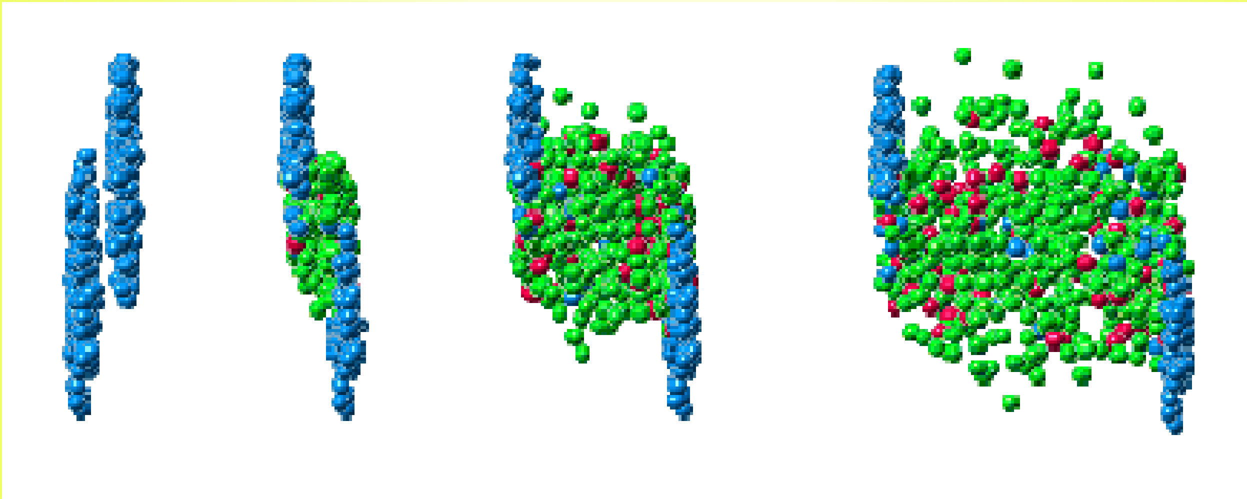
High T and/or High ρ Matter: Hadronic Resonance Matter and QCD Phase Transition

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

AGS



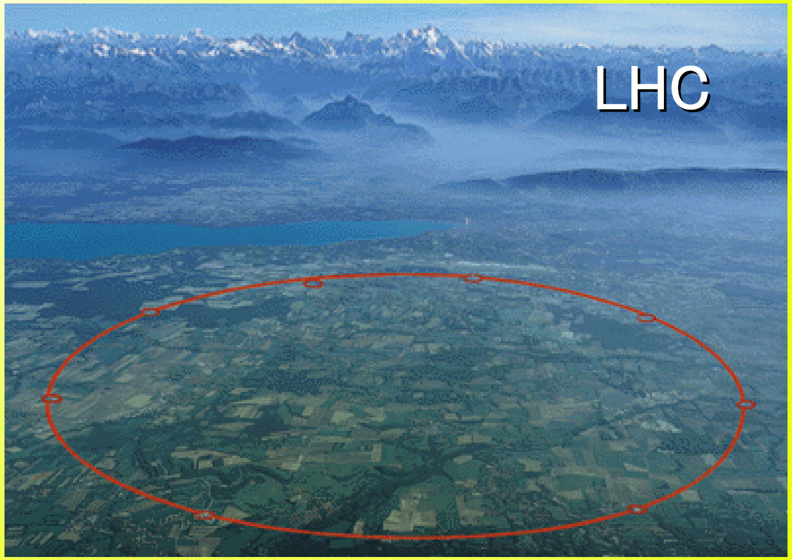
SPS



High Energy Heavy-Ion Collision Experiments

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

LBL-Bevalac: 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



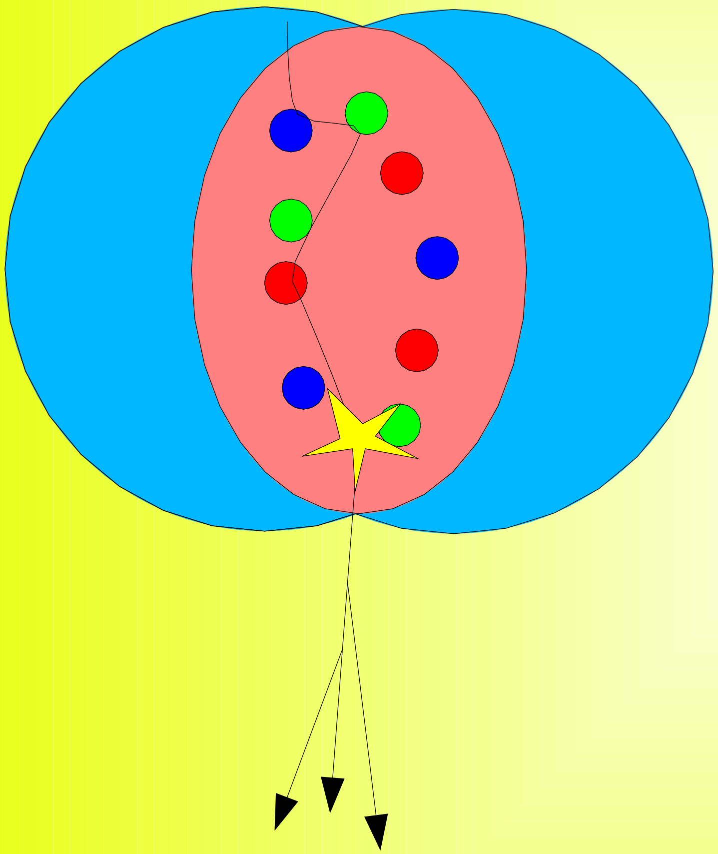
Is QGP Formed at AGS, SPS and/or RHIC ?

Proposed and/or Measured Signals

This Talk

- 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*

Jet Quenching at RHIC (I)

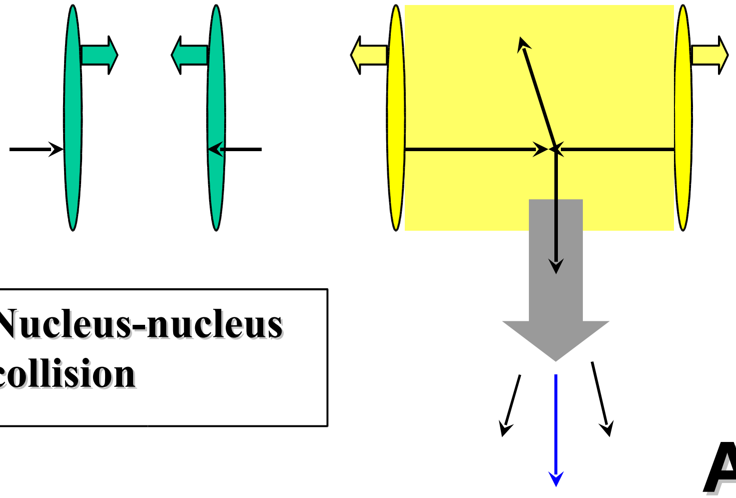


6/18 Press Release

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

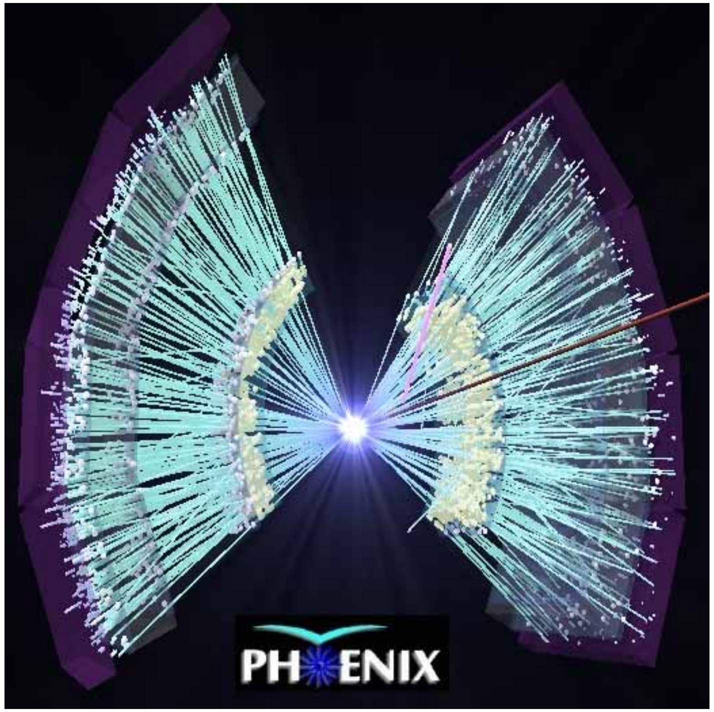
Since High Energy Particles are expected
to come from Jet Fragmentation,
they are suppressed if QGP is formed.

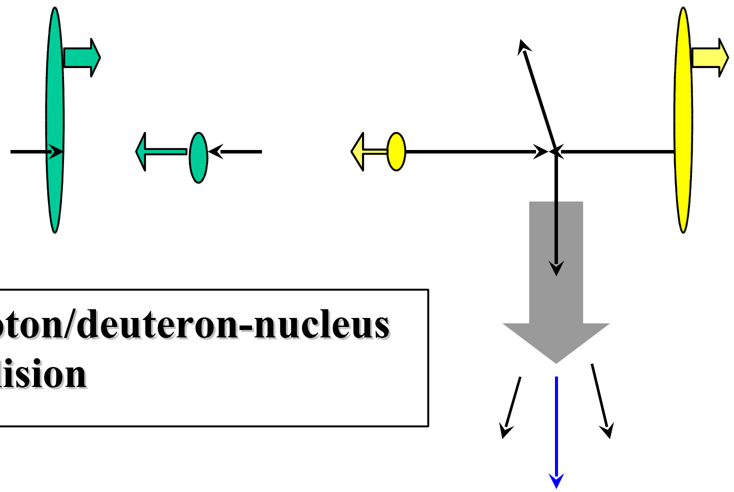
by Esumi, Matter03



Nucleus-nucleus collision

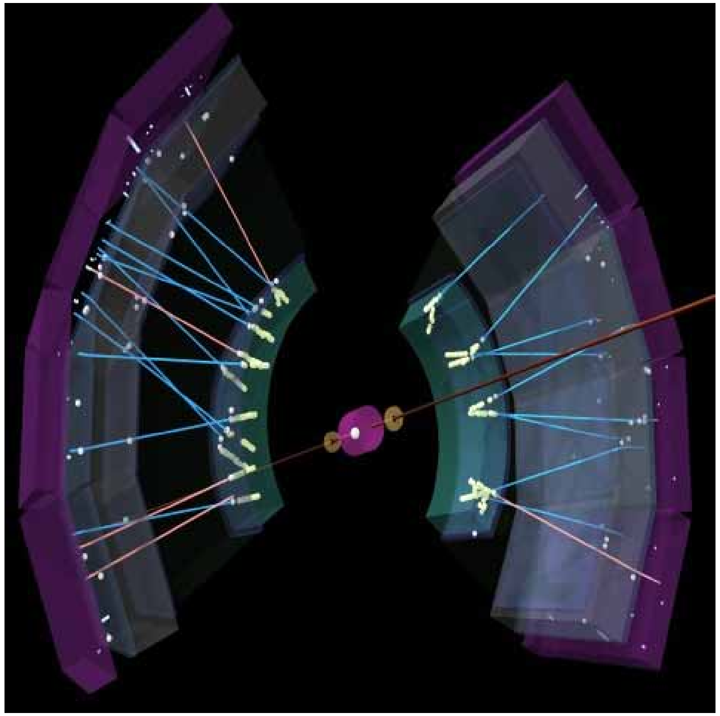
Au + Au





Proton/deuteron-nucleus collision

d + Au

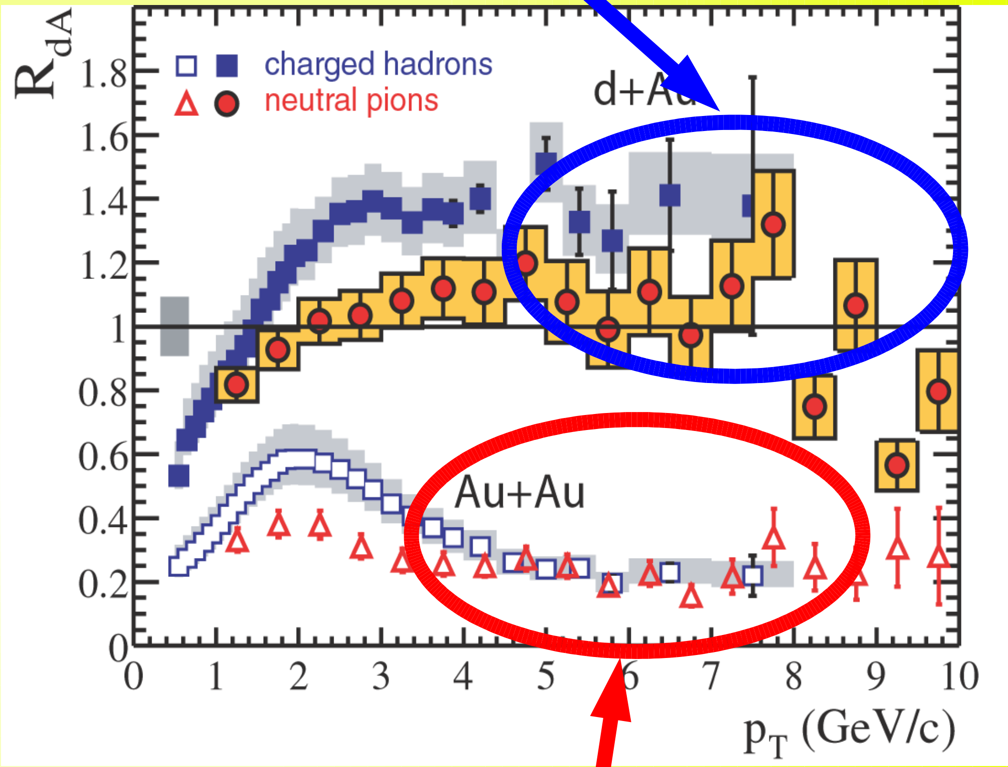


Jet Quenching at RHIC (II)

d + Au: Initial State Effects

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

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

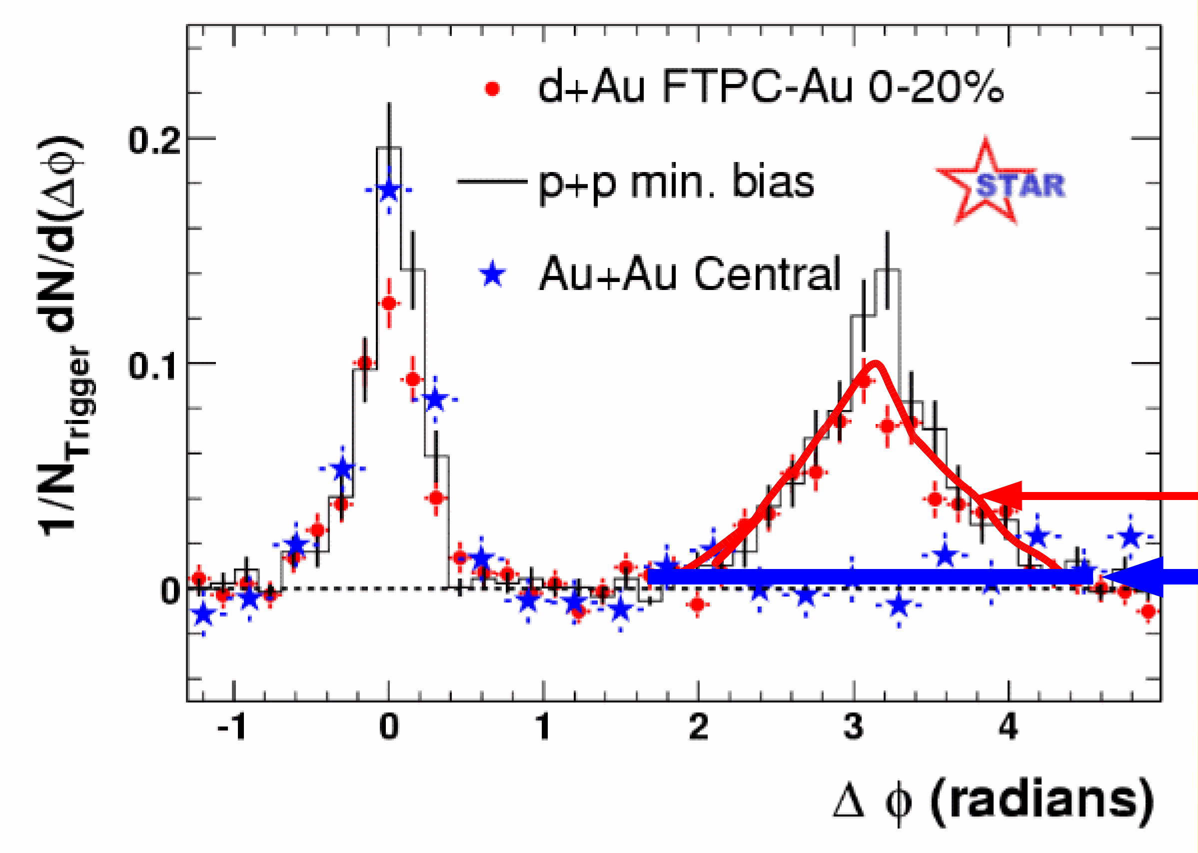


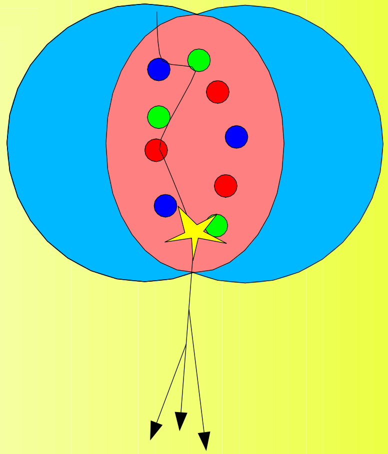
Au + Au:
Initial State
+ Final State Effects

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

by Esumi, Matter03

Jet Quenching at RHIC (III)





d + Au: Backward Peak

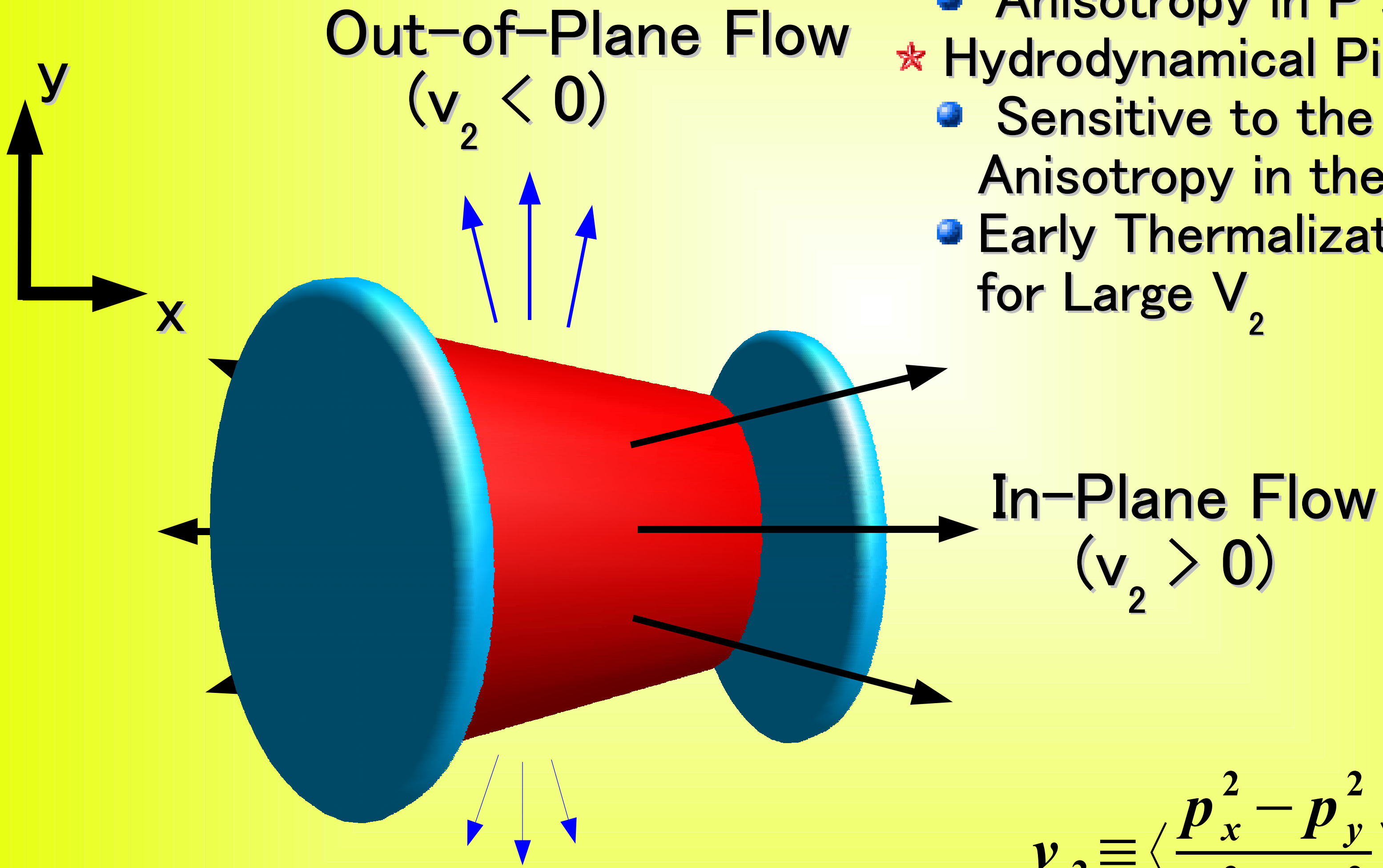
Au + Au: No Backward Peak

STAR (nucl-ex/0306024)

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

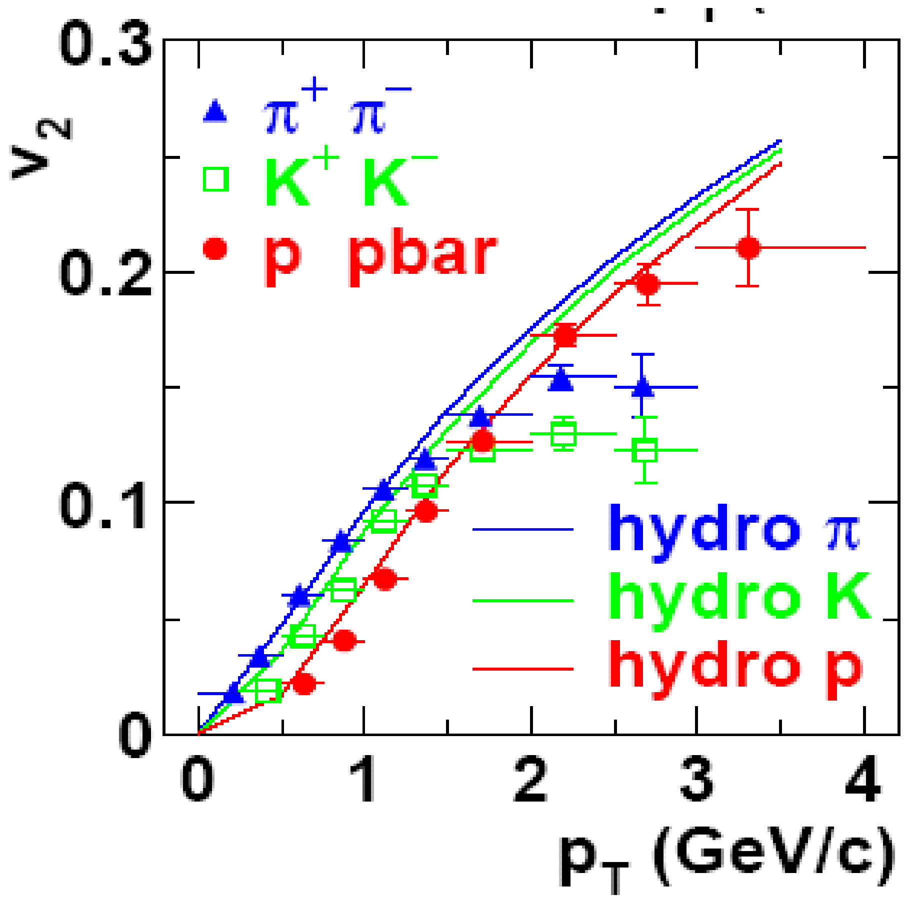
Elliptic Flow (I)

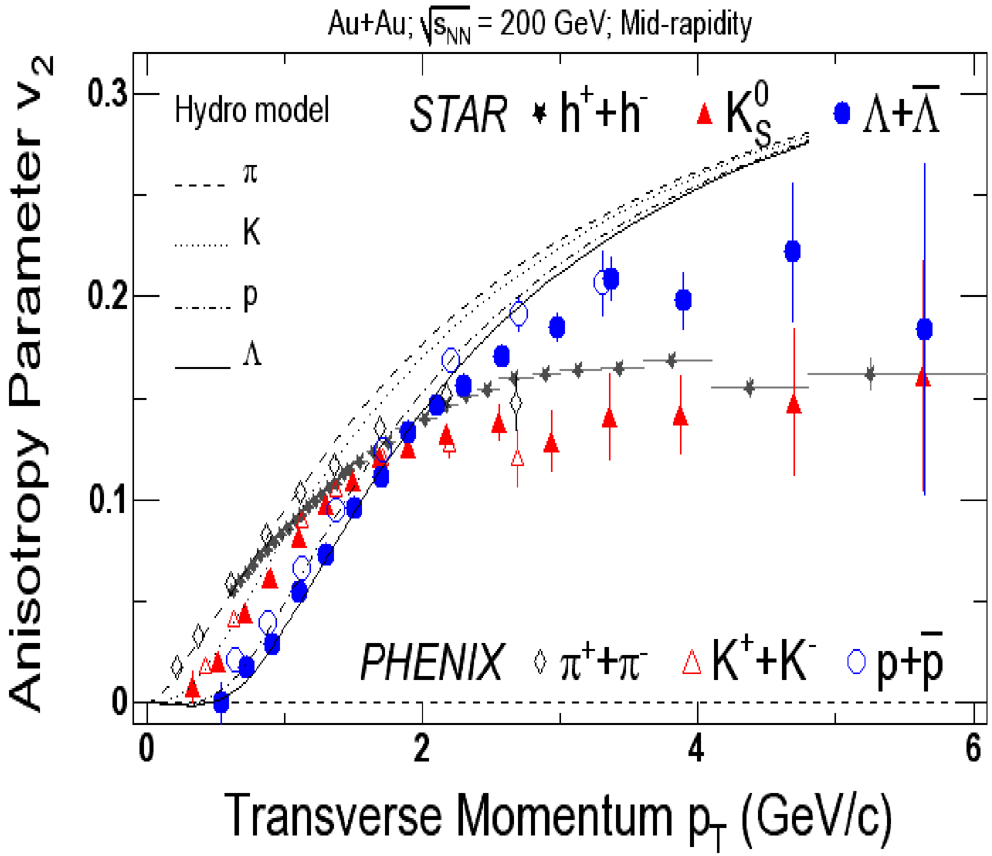
- What is Elliptic Flow ?
  - Anisotropy in P space
- Hydrodynamical Picture
  - Sensitive to the Pressure Anisotropy in the Early Stage
  - Early Thermalization is Required for Large V_2



$$v_2 \equiv \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle = \langle \cos 2\phi \rangle$$

by Esumi, Matter03





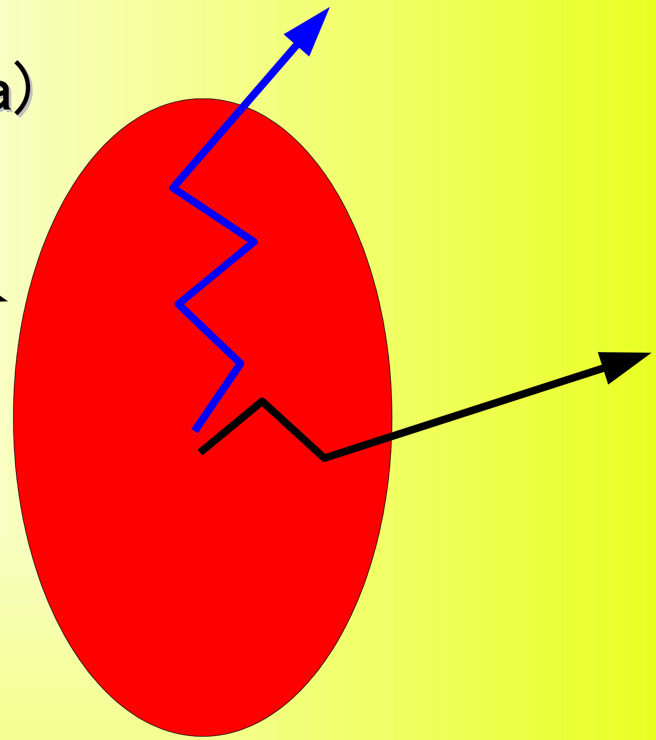
Low Momentum : Hydrodynamical calc. with Early Thermalization
High Momentum : Reduction from Hydro. calc.

Elliptic Flow (II)

- What is the Origin of Elliptic Flow ?
  - Hydrodynamics
  - Jet Energy Loss
  - Coalescence

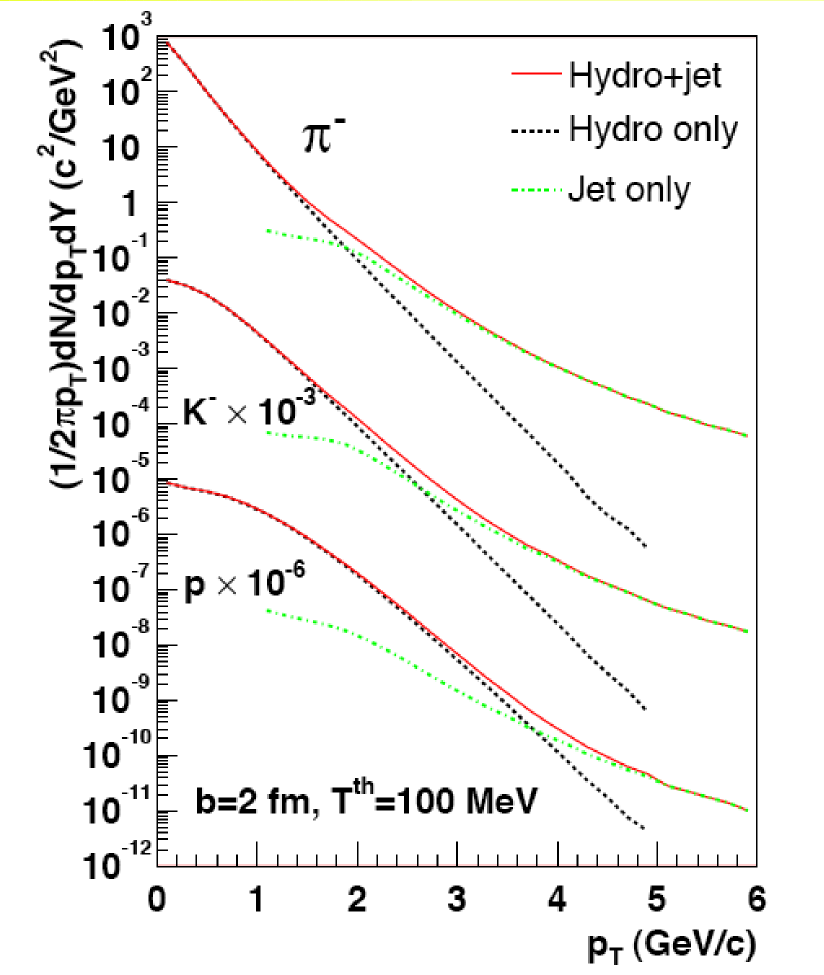
Jet + Hydro
(Hirano and Nara)

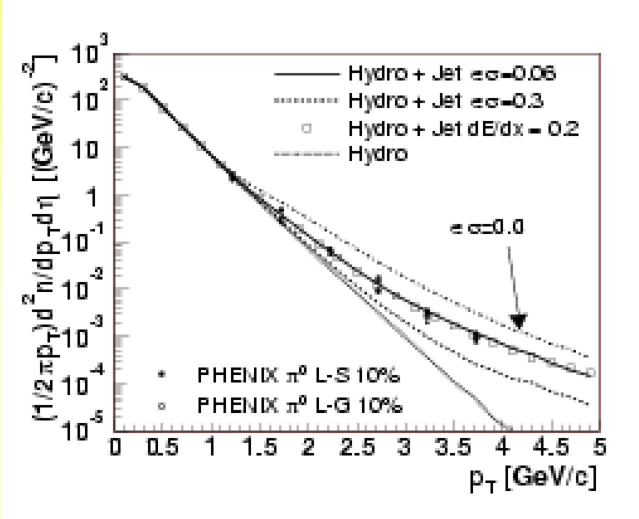
Fragmentation & Recombination
Fries, Nonaka, …



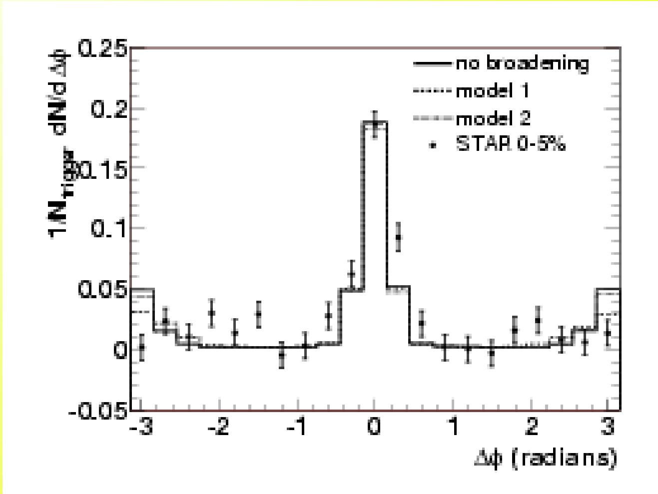
$$f(\phi) \simeq f_1(\phi) f(\phi)$$
$$\propto (1+2v_2\cos\phi)\times(1+2v_2\cos\phi)$$
$$= 1+2\times 2v_2\cos\phi$$

Hydro + Jet Model (Hirano and Nara)





PRC66 (2002) 041901.

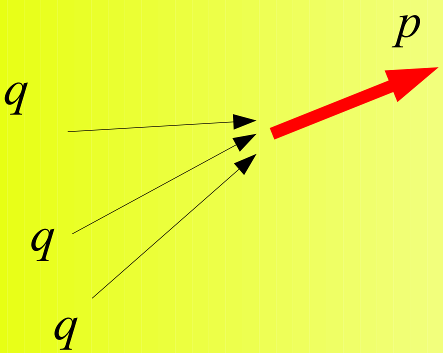


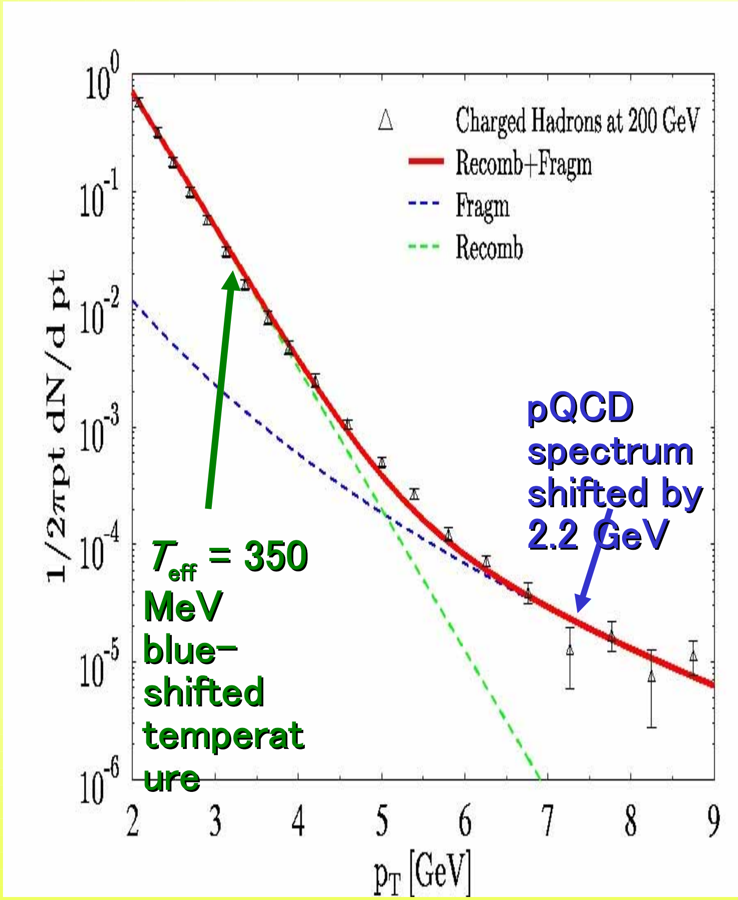
PRL 91 (2003) 082301.

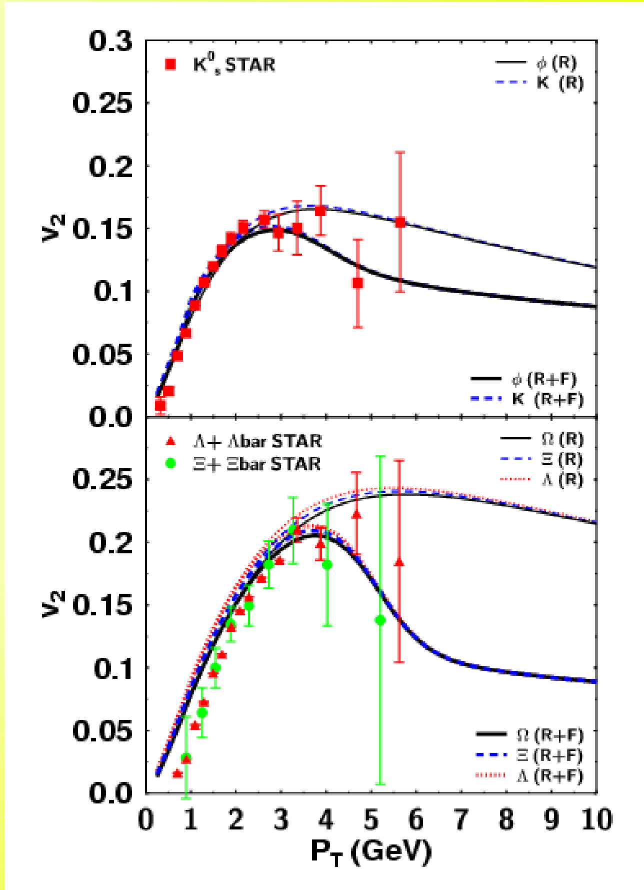
Heavy-Particles are affected by Hydro. Flow until Larger P_T

Fragmentation and Recombination (Duke U. Group)

Recombination Enhances Intermed. P_T Hadrons and Baryon V_2.

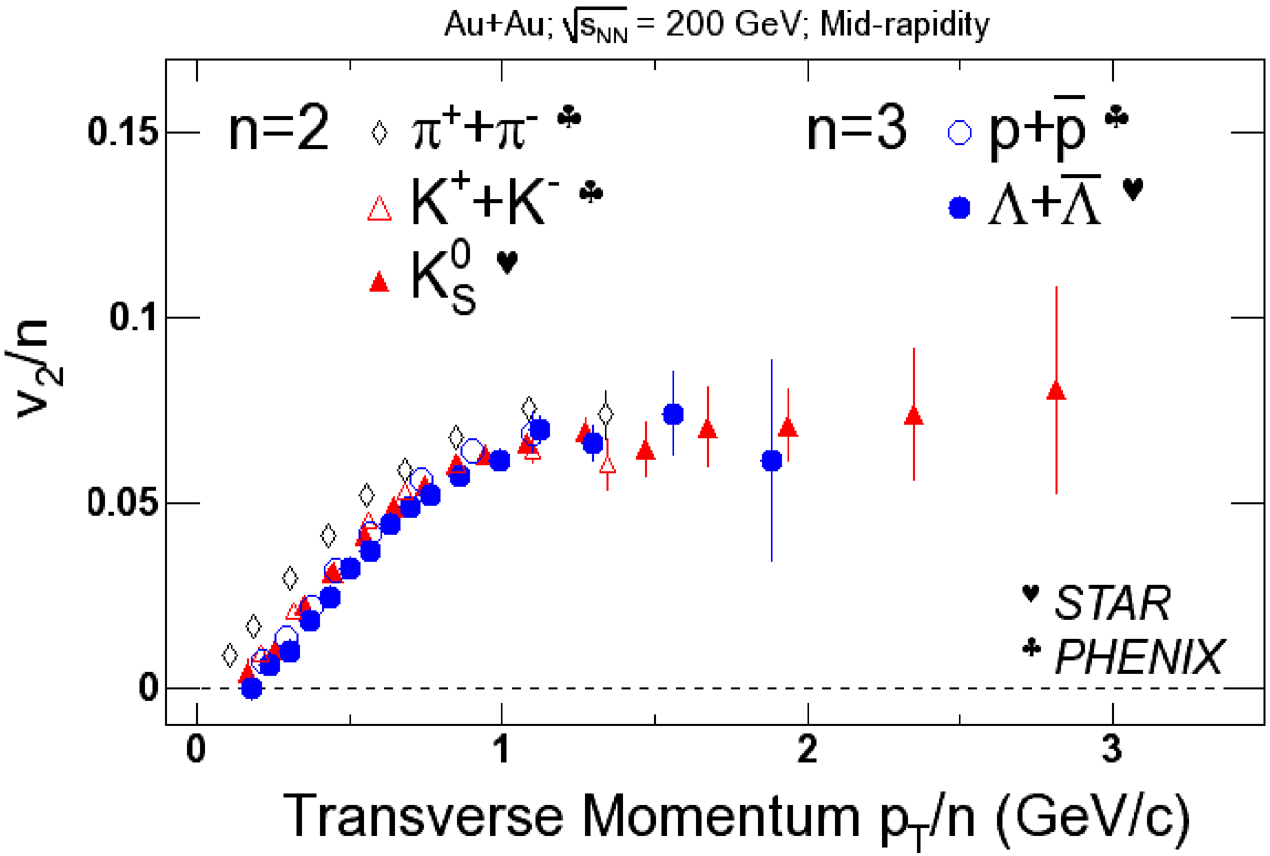






Fries et al. PRL 90 (2003), 202303, Nonaka et al., nucl-th/0308051

by Esumi, Matter03

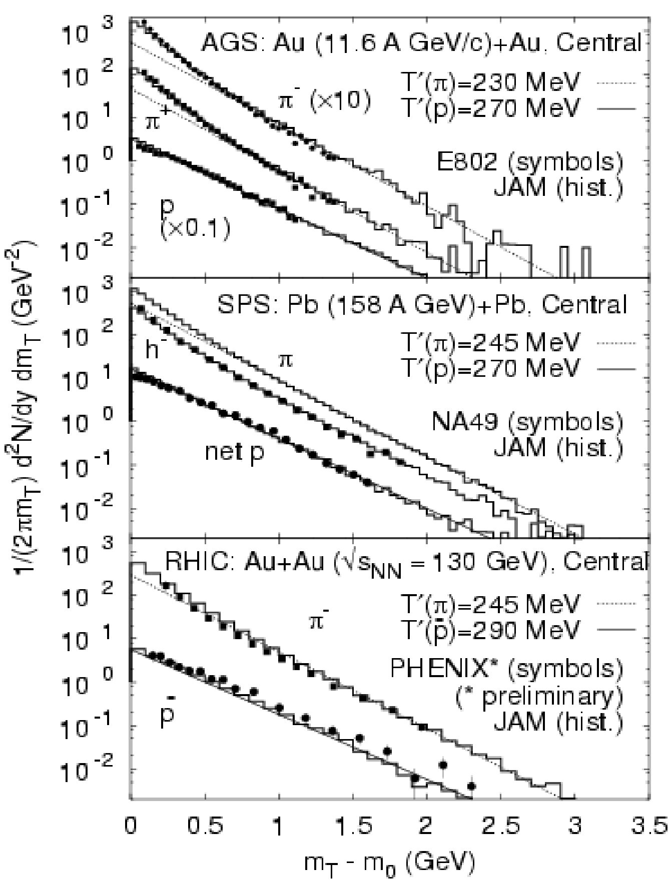


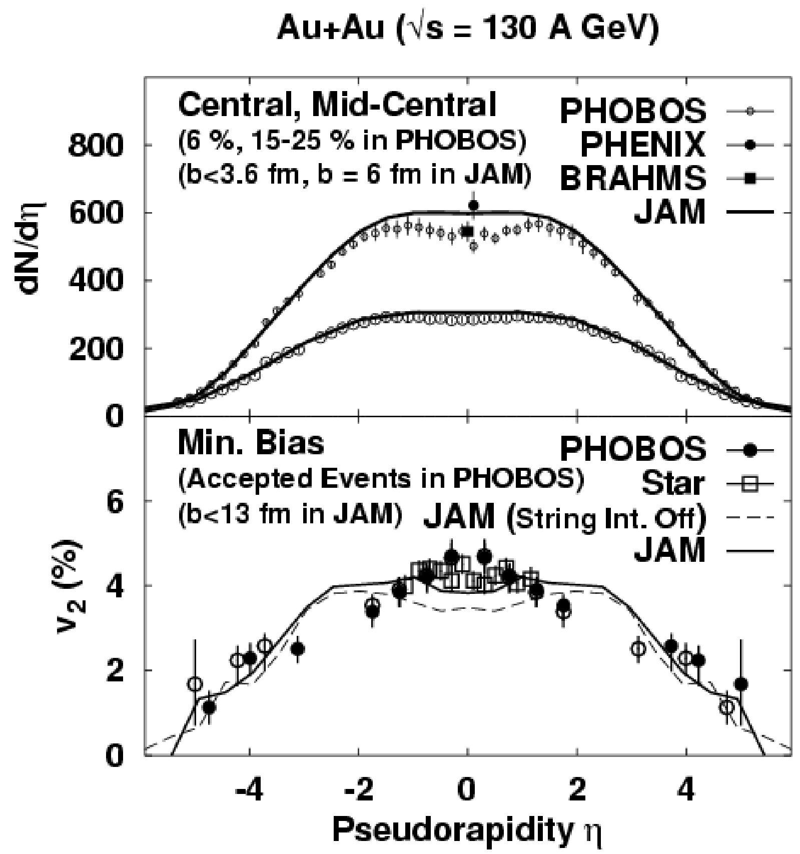
Coalescence (Recombination) Picture

$$v_2^{Hadron}(P_T/n) = n\, v_2^{Parton}(P_T/n)$$

Recombination Picture seems to work well
... Parton Elliptic Flow

Hadron Cascade Study (I) : Global Observables

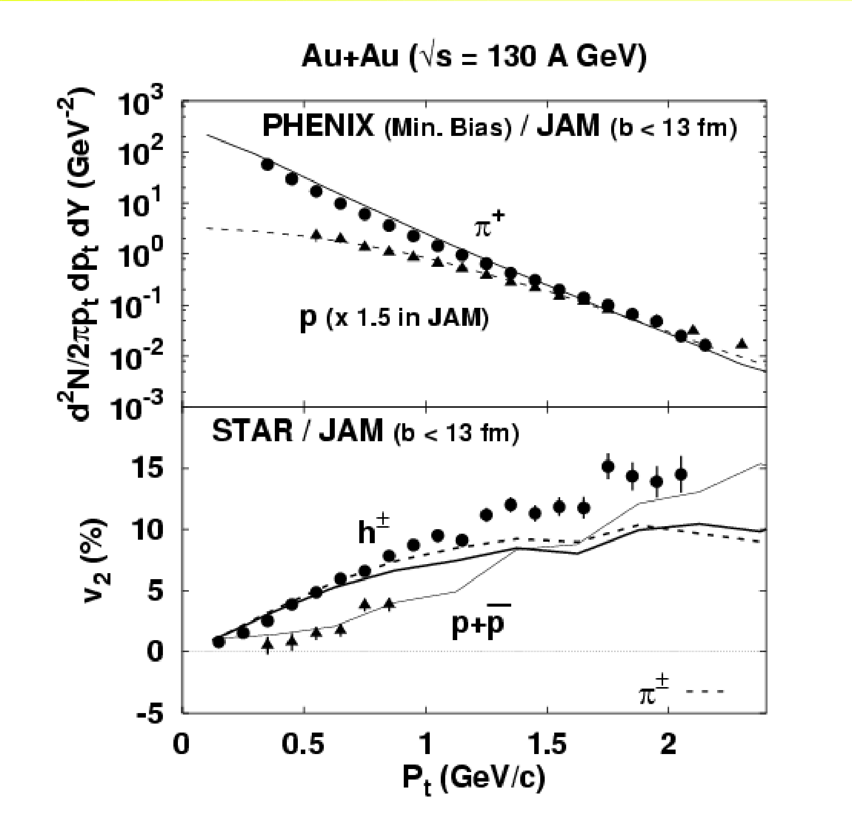




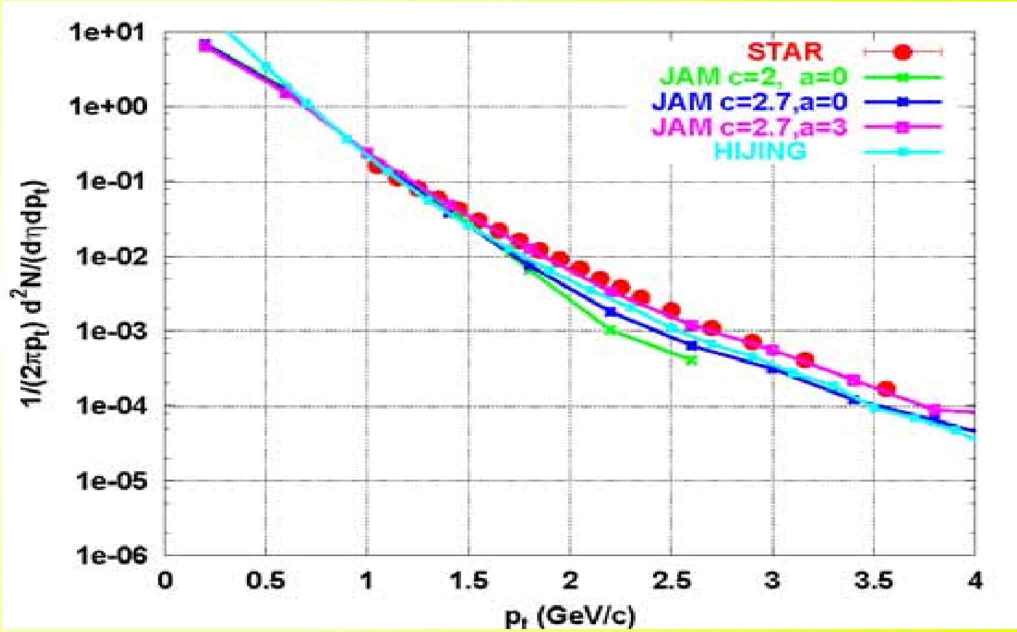
Proton Spectra @ RHIC is too soft in JAM (Proton Puzzle).

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

Hadron Cascade Results (II) : High PT Elliptic Flow



Isse



We can fit P_T spectra
by changing the "Thickness" of Nuclei,
but we cannot Reproduce High P_T Elliptic Flow

Summary (I)

- 原子核物理学 = 異なる階層が詰まった領域
  - Quark/Gluon Hadron Nuclei Matter
- 大きな最近の発展
  - Penta Quark :*Renaissance of Hadron Spectroscopy*
  - Gamma-Ray Hypernuclear Spectroscopy : *Third Paradigm Change of BB Potential*
  - Deeply Bound Kaonic Nucleus : *EOS of Dense Matter*
  - Double Hypernuclei : *Solved the Puzzle for 40 Years*
  - Mean Field Model with Pions : *Explicit Role of NG Bosons*
  - RHIC Physics : *QGP formation is PROBABLE*

Summary (II)

触れられなかった最近の発展 Many

magic number change, α condensate, n-rich cluster, exotic atom, hypernuclear shrinkage, partial chiral sym. restoration, strange enhancement at SPS energies, developments in chiral models, Color Superconductor, Color Glass Condensate, Chiral and quark model analyses of lattice QCD “Data”, ...

これからの発展の可能性

New (and active) Accelerators (RIBF, J-PARC, Jlab, LHC, SPring8, ...) are closely related to new areas of nuclear/hadronic matter

Hadronic Matter Phase Diagram

RHIC/LHC

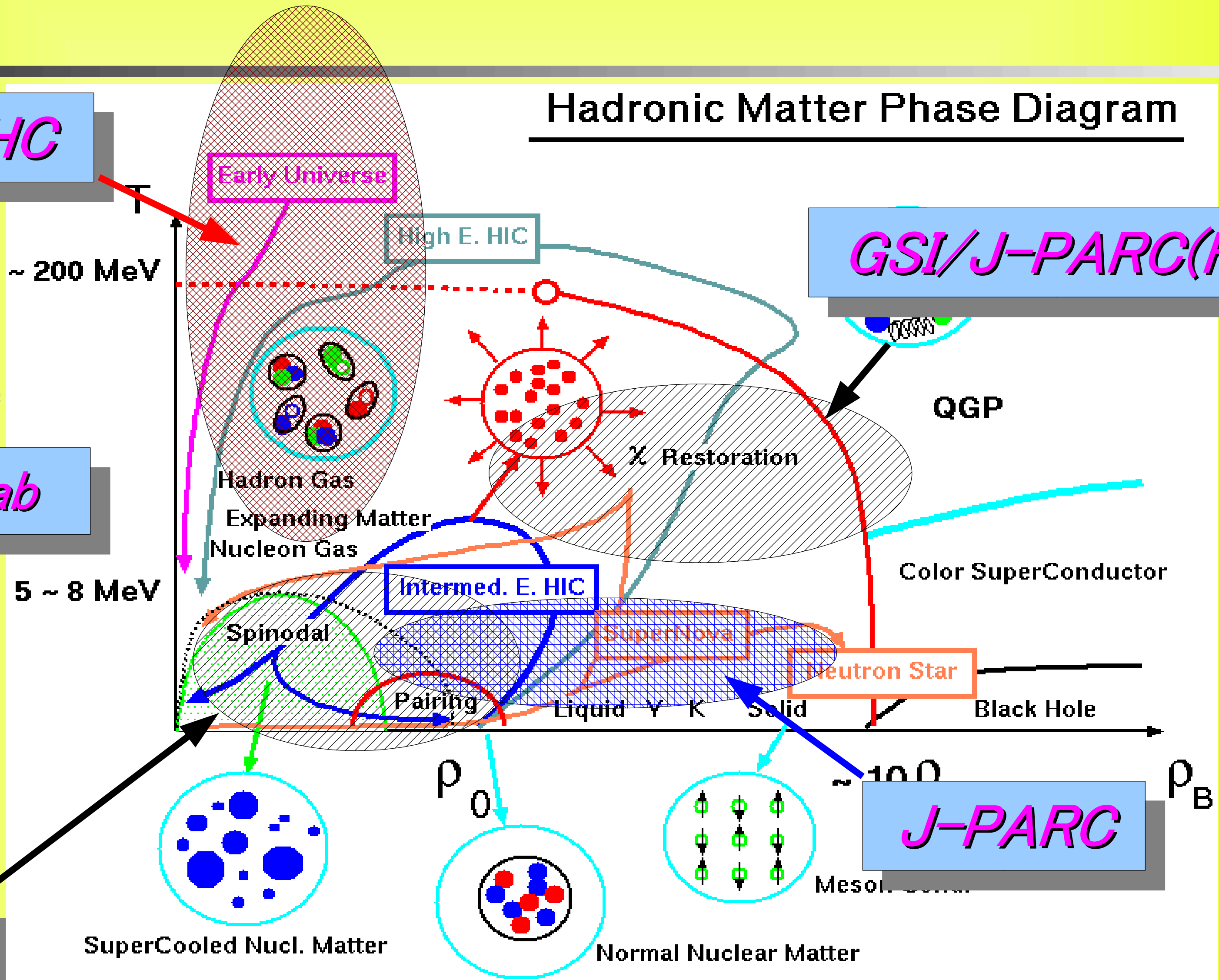
Small Distance

SPring8, JLab

RIBF

GSI/J-PARC(HI)

J-PARC



新たな加速器 = 探索領域の大幅な拡張

Thank you

I would like to thank my collaborators

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and

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