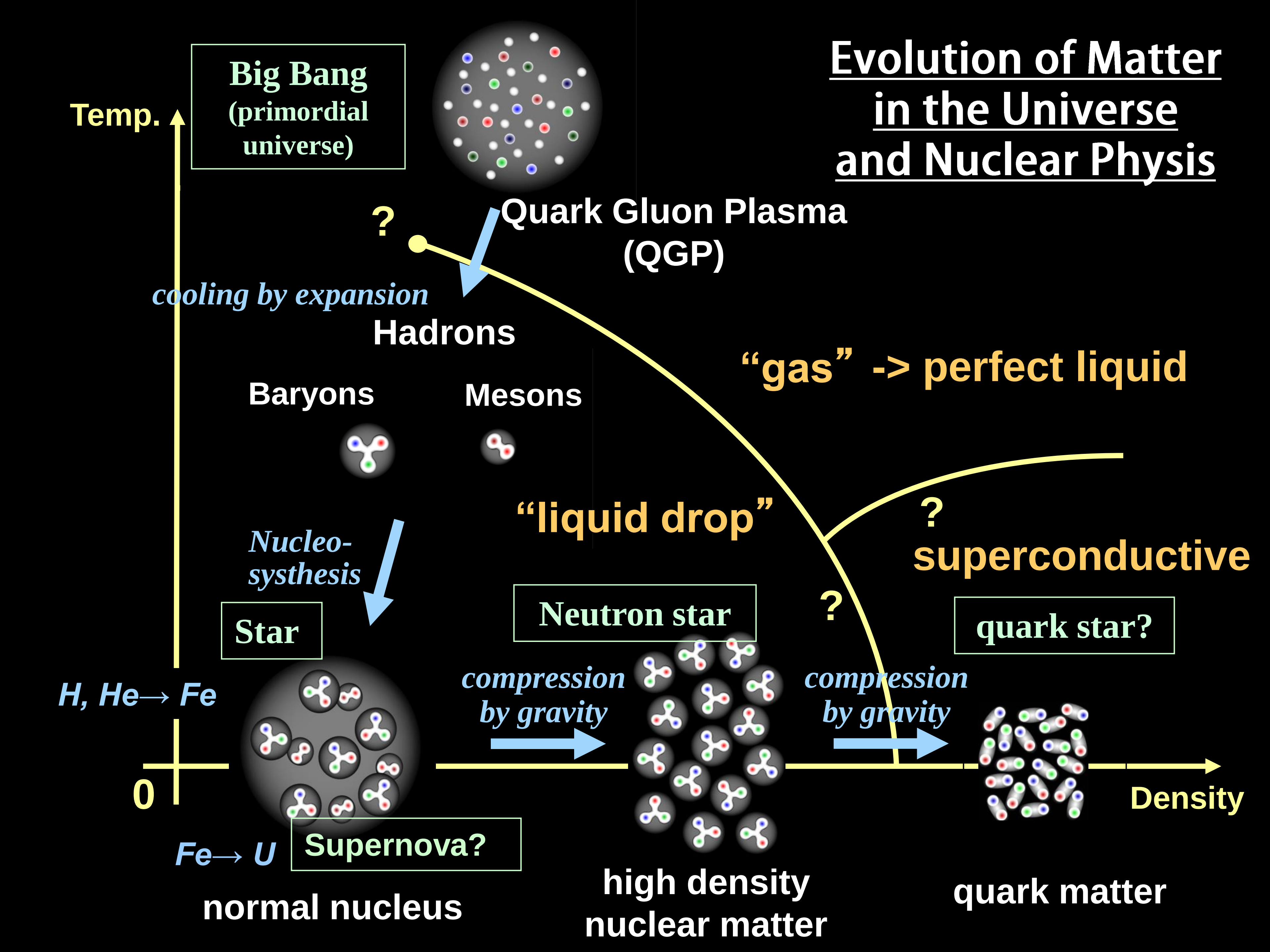
Prospect of
Experimental Nuclear Physics
(in Japan)
--Personal View--

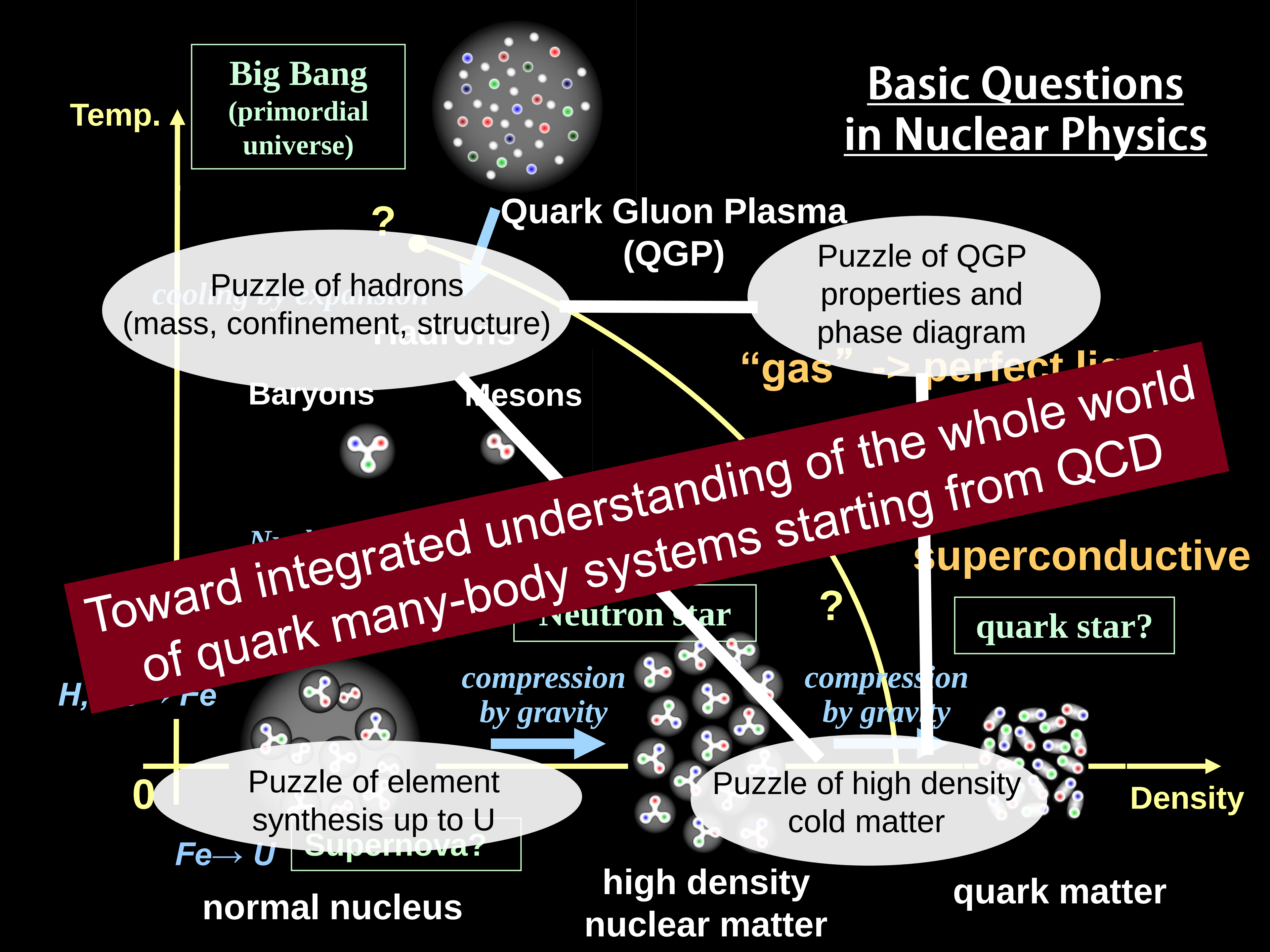
Tohoku University
H. Tamura

Contents

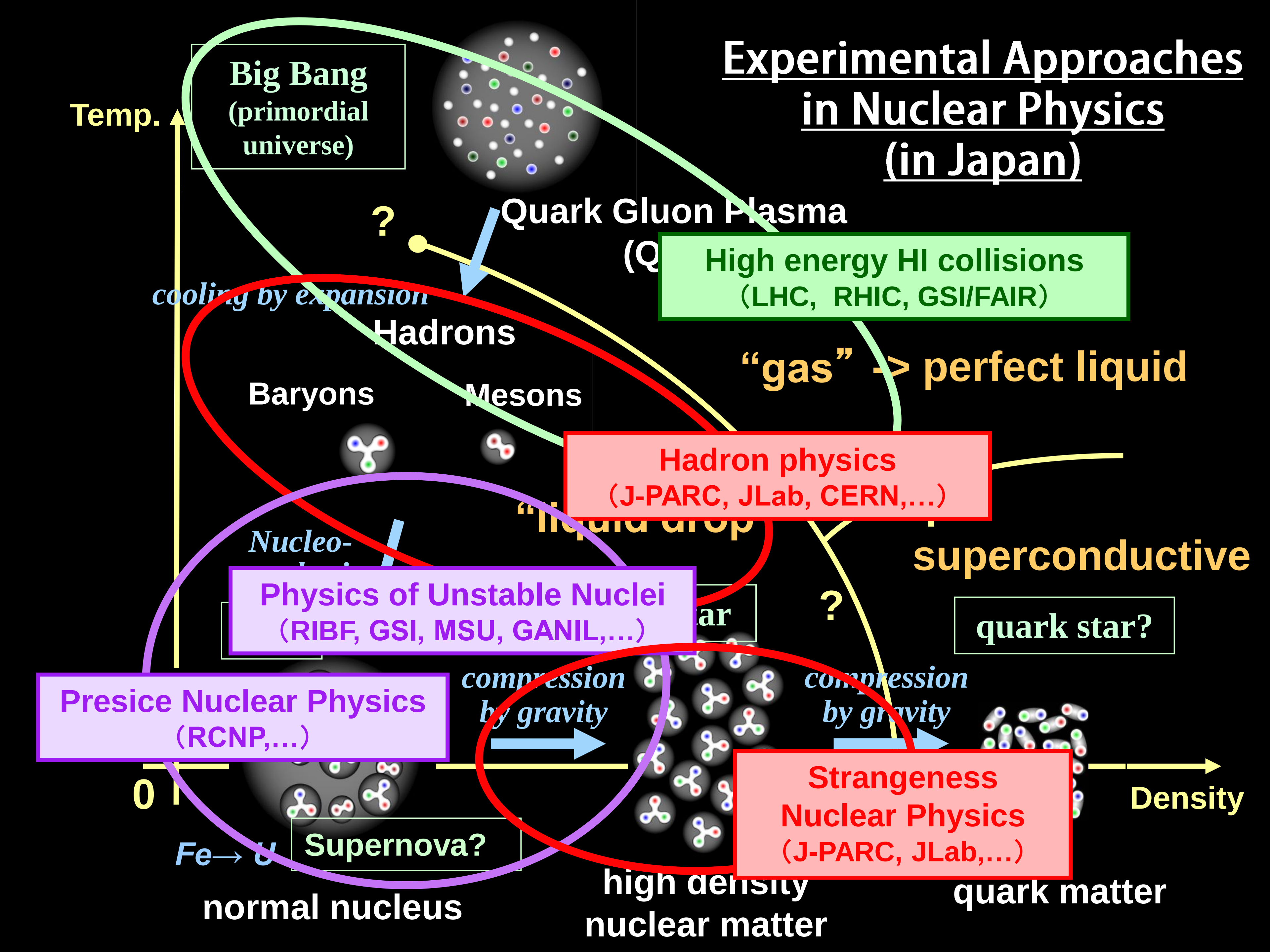
1. Basic questions and present activities in nuclear physics



Evolution of Matter
in the Universe
and Nuclear Physis
Big Bang
(primordial
universe)
Temp.
Quark Gluon Plasma
(QGP)
?
cooling by expansion
Hadrons
"gas" -> perfect liquid
Baryons
Mesons
"liquid drop"
?
superconductive
Nucleo-
systhesis
?
Star
Neutron star
quark star?
H, He→ Fe
compression
by gravity
compression
by gravity
0
Density
Fe→ U
Supernova?
normal nucleus
high density
nuclear matter
quark matter



Basic Questions in Nuclear Physics
Temp.
Big Bang (primordial universe)
Quark Gluon Plasma (QGP)
?
Puzzle of hadrons (mass, confinement, structure)
cooling by expansion
Puzzle of QGP properties and phase diagram
“gas”
Baryons
Mesons
Toward integrated understanding of the whole world of quark many-body systems starting from QCD
superconductive
?
Neutron star
quark star?
compression by gravity
compression by gravity
0
Puzzle of element synthesis up to U
Fe→ U
Supernova?
Puzzle of high density cold matter
Density
normal nucleus
high density nuclear matter
quark matter



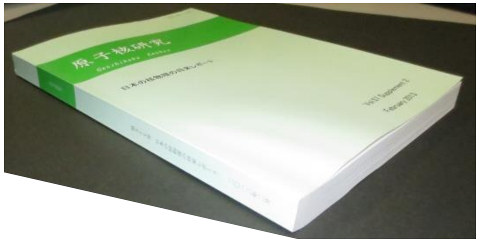
Experimental Approaches
in Nuclear Physics
(in Japan)
Big Bang
(primordial
universe)
Temp.
?
Quark Gluon Plasma
High energy HI collisions
（LHC, RHIC, GSI/FAIR）
cooling by expansion
Hadrons
"gas" -> perfect liquid
Baryons
Mesons
Hadron physics
（J-PARC, JLab, CERN,…）
"liquid drop"
superconductive
Nucleo-
Physics of Unstable Nuclei
（RIBF, GSI, MSU, GANIL,…）
?
quark star?
Presice Nuclear Physics
（RCNP,…）
compression
by gravity
compression
by gravity
0
Density
Strangeness
Nuclear Physics
（J-PARC, JLab,…）
Fe→ U
Supernova?
normal nucleus
high density
nuclear matter
quark matter

“Prospects of Nuclear Physics in Japan”

Feb. 2013

Nuclear Physics Executive Committee of Japan

(312 pages, in Japanese)



1. **Physics of Unstable Nuclei** (RIBF,…)
2. **Precise Nuclear Physics** (RCNP,…)
3. **Hypernuclei and Strangeness Nuclear Physics** (J-PARC, JLab)
4. **Hadron Physics** (J-PARC, ELPH, RCNP-LEPS, CERN, JLab,…)
5. **Physics of High Energy Heavy Ion Collisions** (RHIC, LHC)
6. **Nucleon Structure** (RHIC, CERN, Femilab, J-PARC,…)
7. **Fundamental Physics using Nuclear Techniques** (J-PARC, RCNP, CERN, …)
8. **Computational Nuclear Physics** (Kei,…)

2. High Density Cold Matter

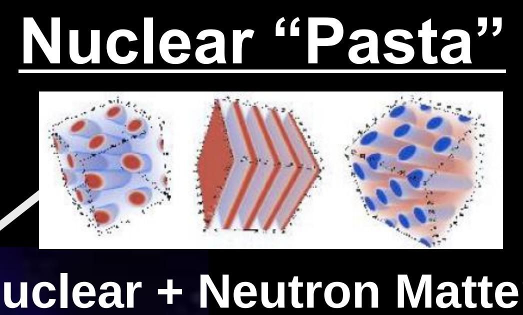
Mistery of neutron star matter

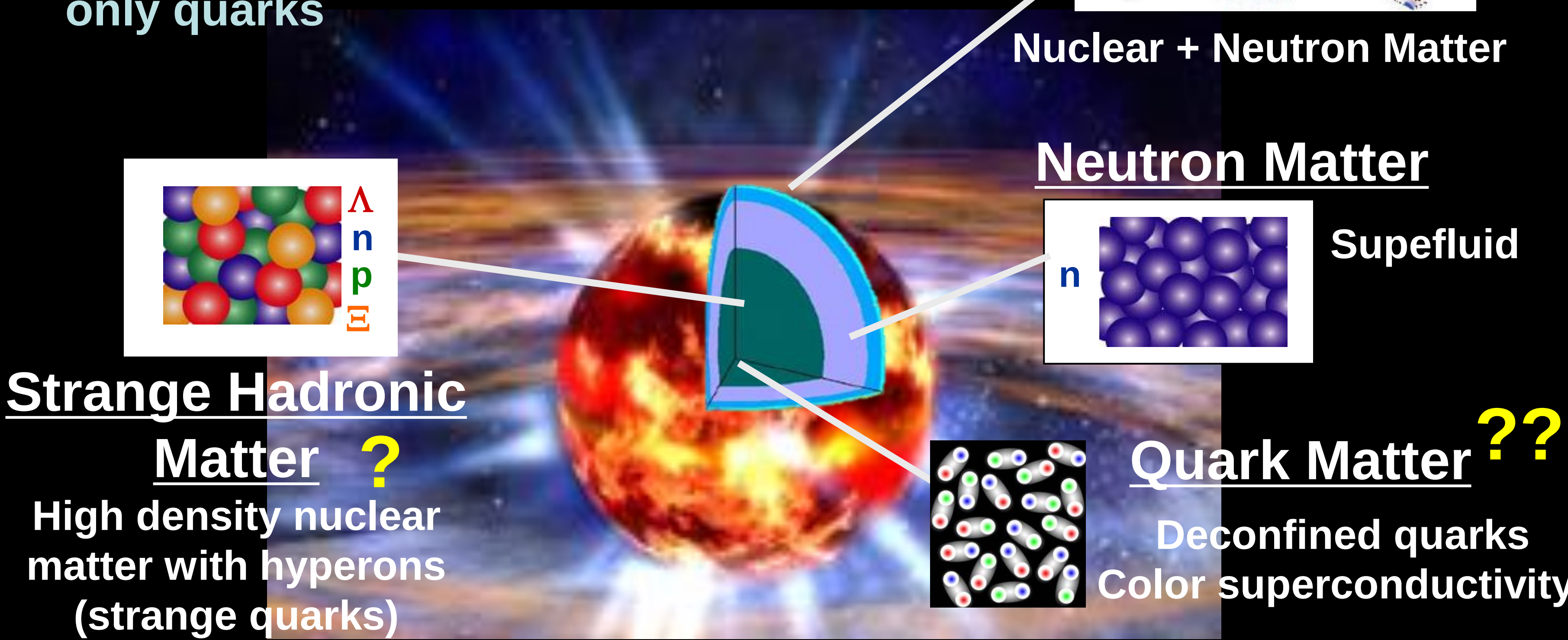
- Highest density matter in the universe

  M = 1~2 $M_\odot$, R ~ 10~20 km

  => Density of the core = 3~10ρ_0 (1～3 Btons/cm^3)

- Various forms of matter made of almost only quarks





EOS (Equation Of State) for Nuclear Matter at T~0

■ **Outer core ($\rho < 2\rho_0$)**

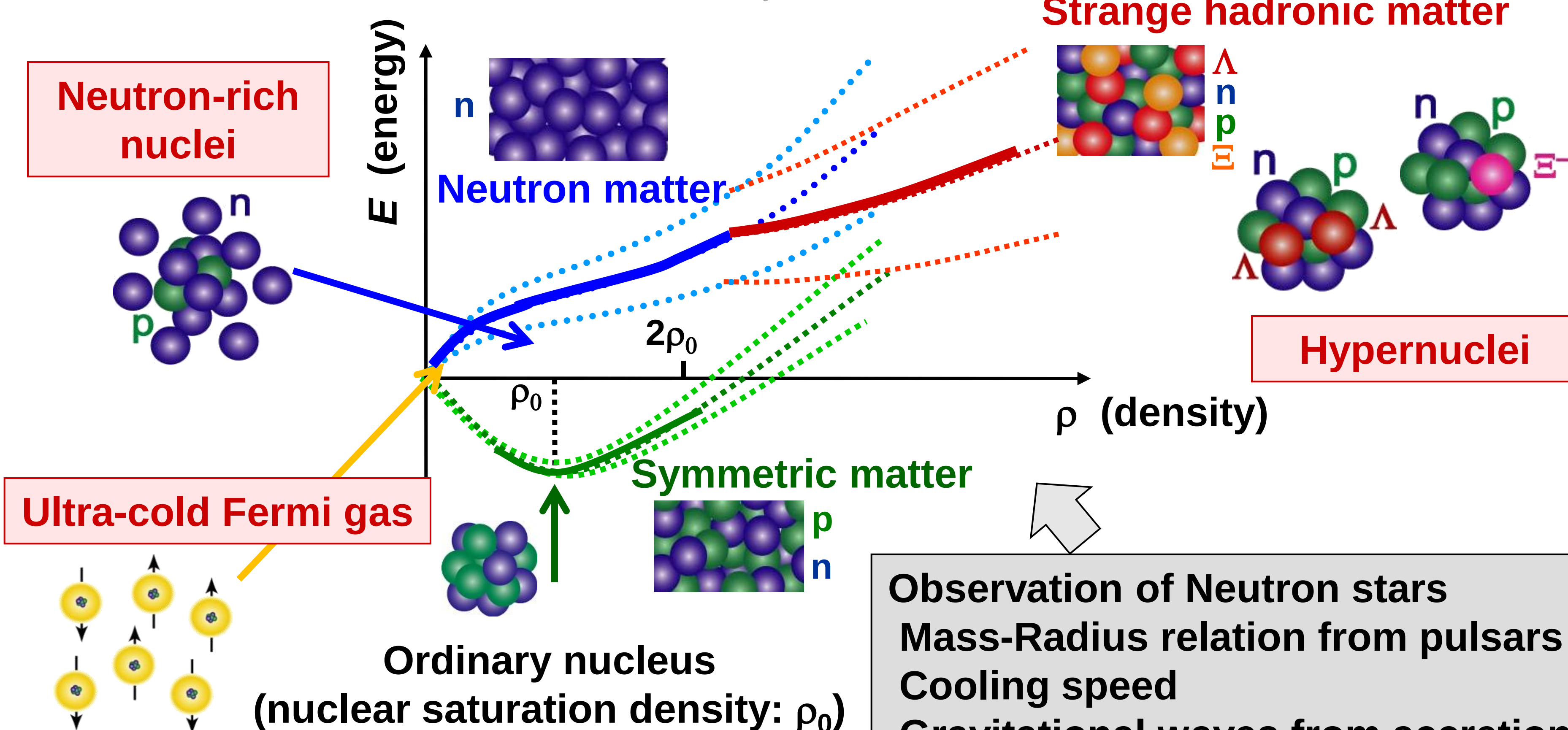
How EOS changes in n-rich matter?

■ **Inner core ($\rho > 2\rho_0$)**

Hyperon really appear? Which and how much?

Density Fraction

$$E = F(\,\rho,\,(n_n, n_p, n_Y, \ldots)\,)$$

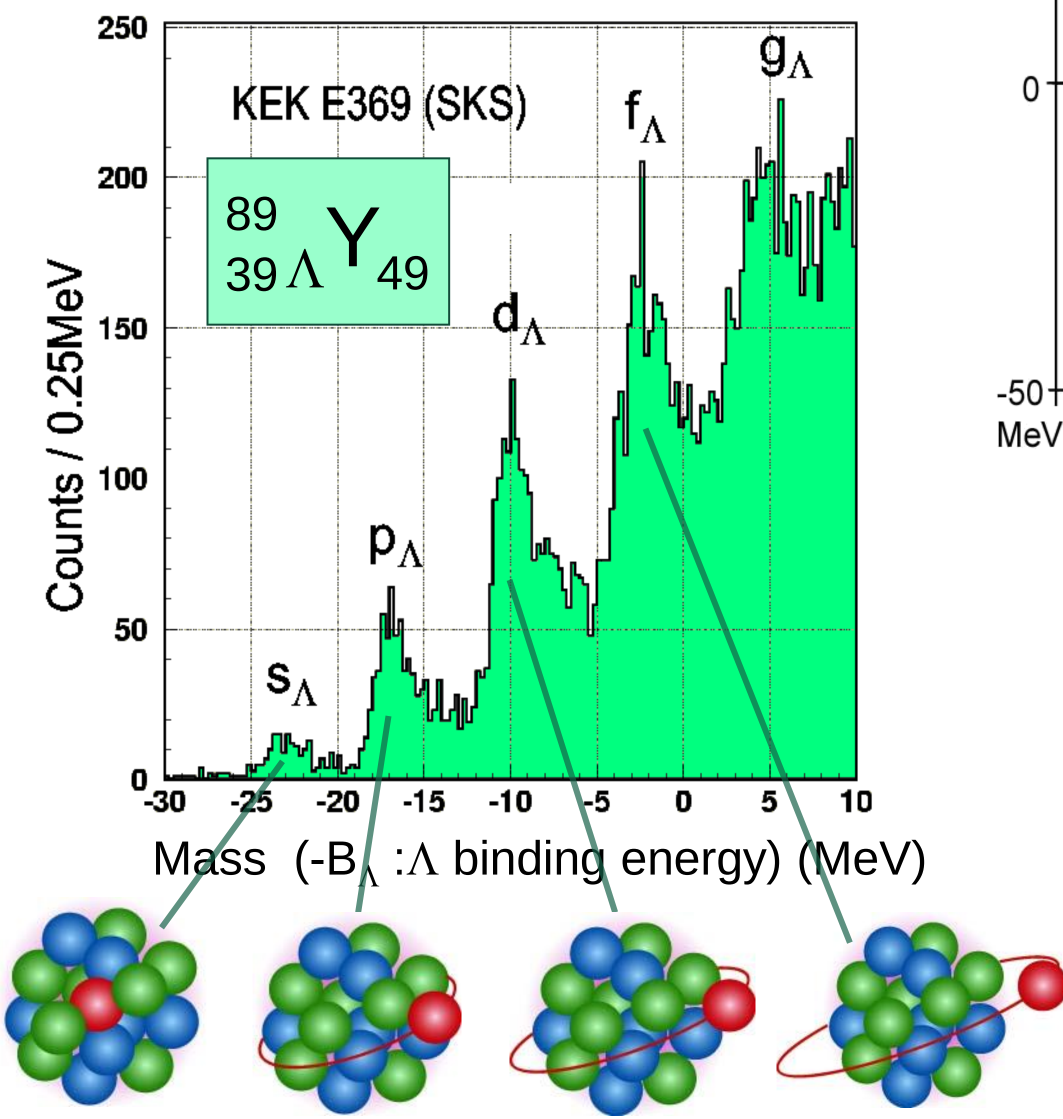


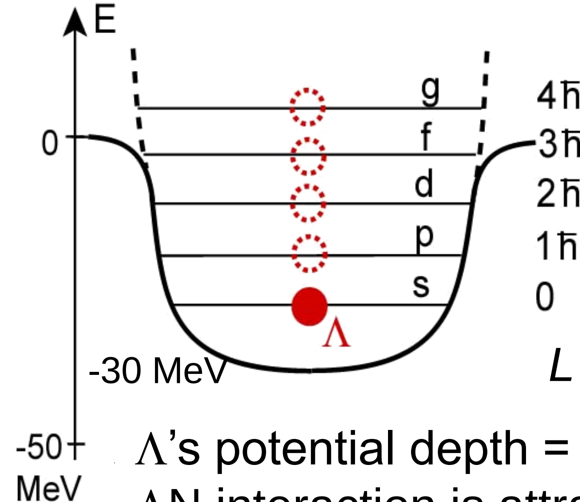
Observation of Neutron stars

- Mass-Radius relation from pulsars
- Cooling speed
- Gravitational waves from accretion

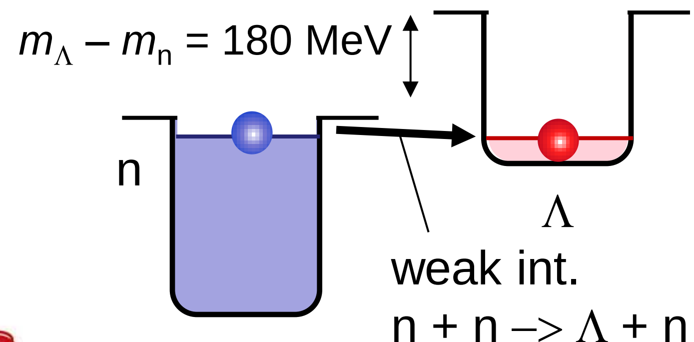
Attractive ΛN interaction well established

$^{89}Y\ (\pi^+, K^+)\ ^{89}{}_{\Lambda}Y$



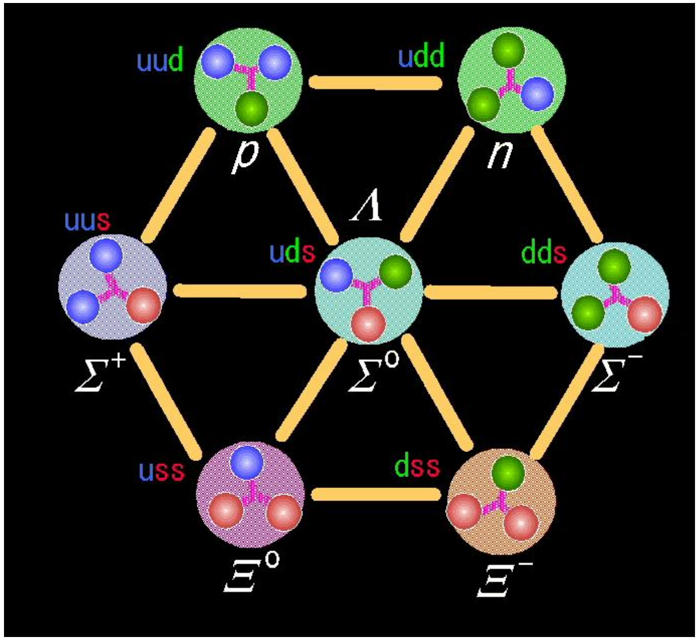


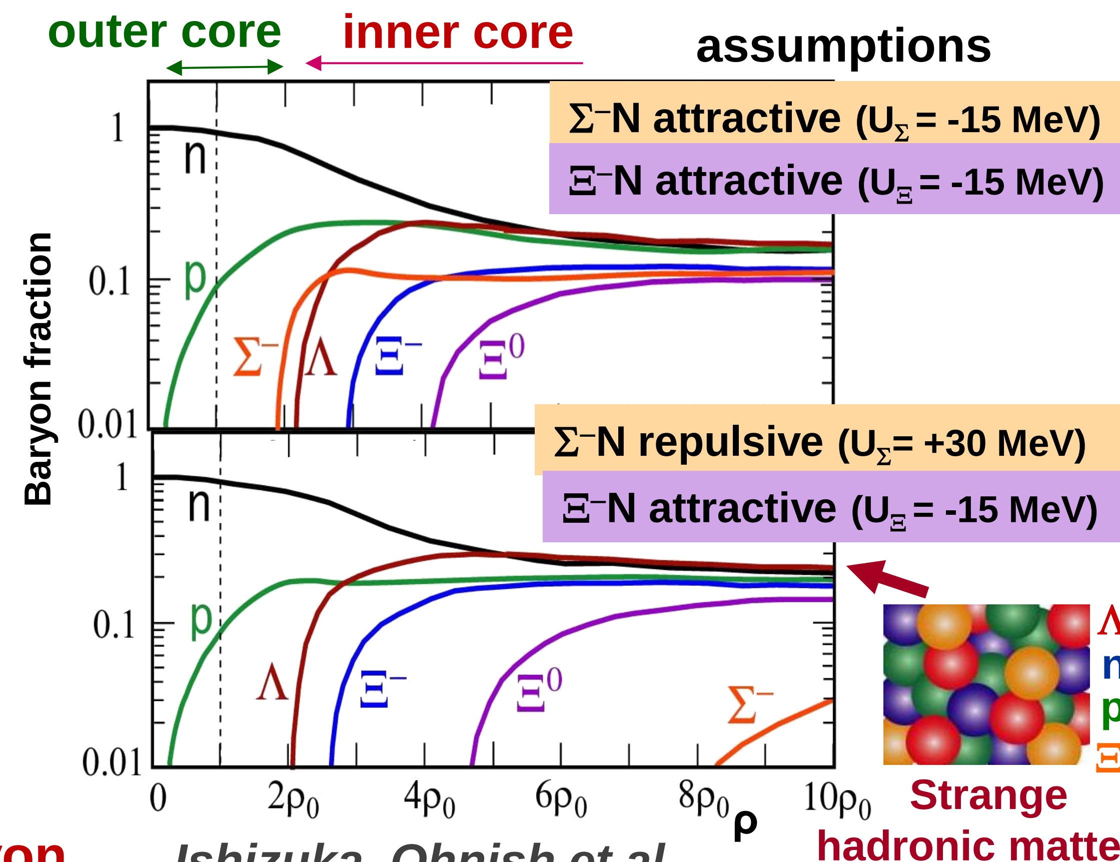
Λ's potential depth = 30 MeV
ΛN interaction is attractive
(~2/3 of NN interaction)



Λ's must appear at $\rho = 2\sim3\ \rho_0$

Hyperons mixing in the inner core



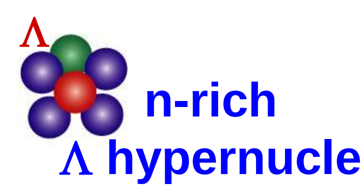


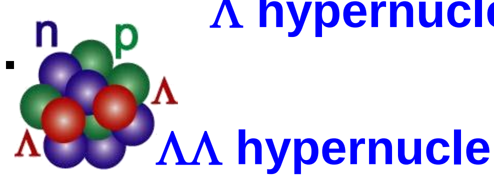
Ishizuka, Ohnish et al.

All the YN, YY interactions necessary

-> Understand Baryon-Baryon Interactions in a unified way

- **ΛN int. in neutron matter? (effect by ΛN-ΣN force?)**
- **ΛΛ int. looks weakly attractive. To be established.**
- **ΞN int. unknown (attractive??)**





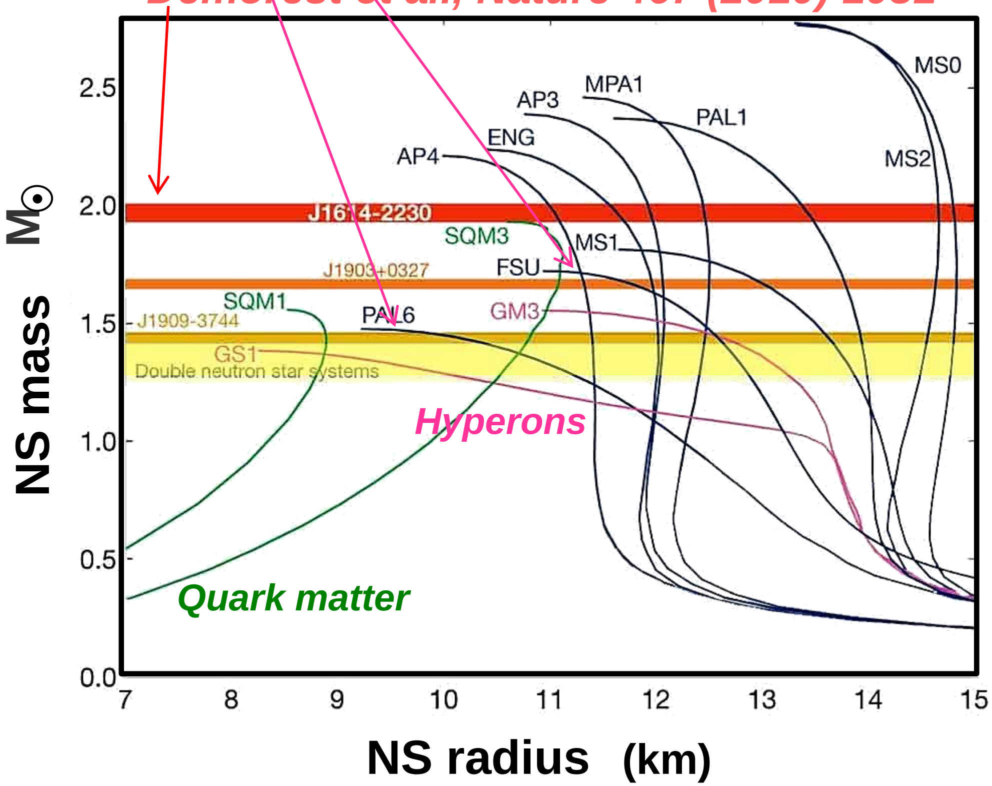
Mystery in EOS

- Hyperons must appear at $\rho = 2\sim3\ \rho_0$
- EOS with hyperons (or kaons) too soft -> too high density
  -> easily form a BH and cannot support $1.97\pm0.042\ M_{sun}$ NS

A big mistery in nuclear physics

Framework should be reconsidered

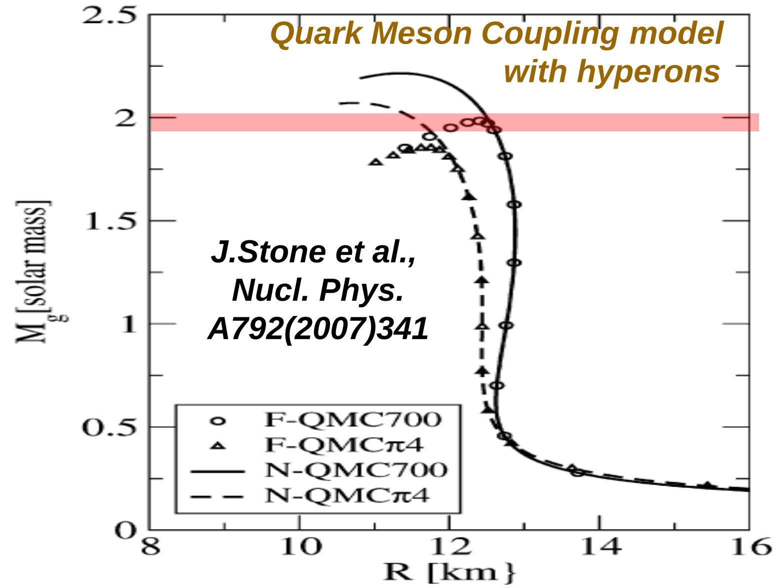
Demorest et al., Nature 467 (2010) 1081



No direct measurement

Unknown repulsion at high ρ

- Strong repulsion in three-body force (NNN, YNN, YYN, YYY)
- Change of meson-baryon coupling constants or baryon structure
- Phase transition to quark matter (quark star or hybrid star)



An important direction: “Hadrons in Nuclei”

- Properties of mesons in nuclei
  - Vector meson mass in a nucleus (pA collision)
  - K^- nucleus, π nucleus, η' nucleus bound states
- Properties of hyperons in nuclei
  - μ_Λ in hypernuclei
  - Single particle energies and weak decay properties of Λ in hypernuclei
- NN Short Range Correlations
  - Role of tensor force in nuclear structure
  - DIS and the EMC effect

=> Clues to understand high density cold matter

3.1 Hadrons in Nuclei

-- Vector meson mass in nuclei

Origin of hadron mass

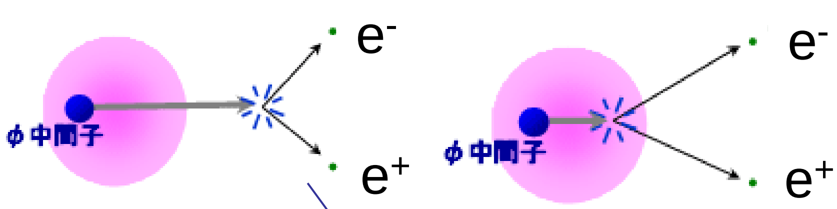
Experimental evidence of hadron mass generation by chiral symmetry breaking?

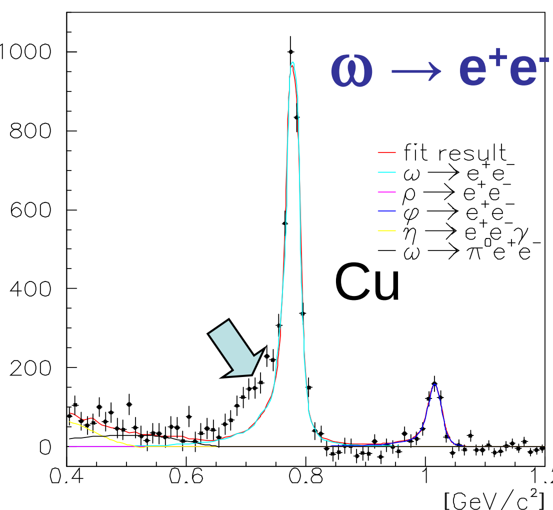
-- Effective (u,d) quark mass should be partially restored in nuclear matter density

To be observed as hadron mass change in nuclei.

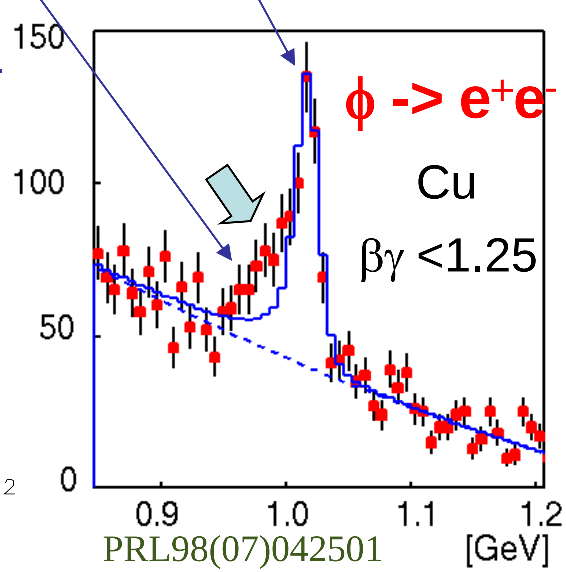
Implications from e^+e^- invariant mass spectra in HI collisions

Mass shift of $\phi \to e^+e^-$ in pA reaction (KEK E325)

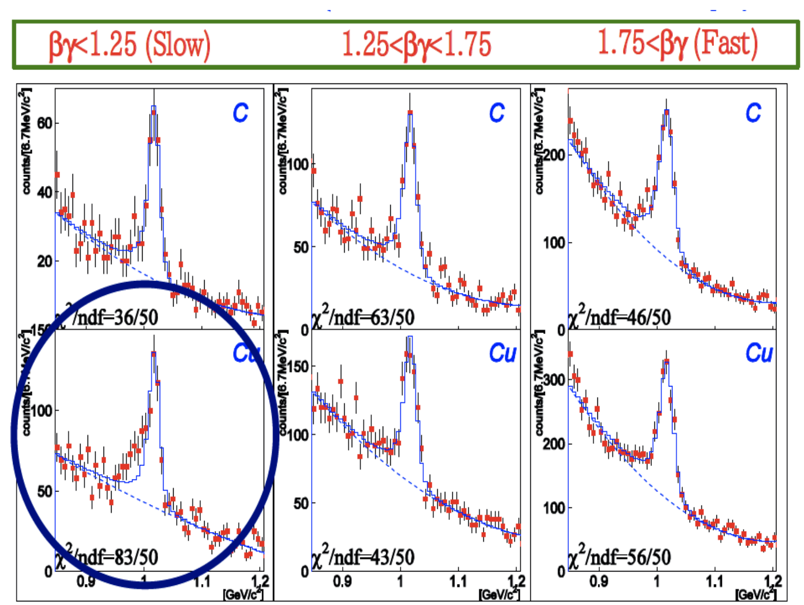




PRL96(06)092301



PRL98(07)042501



Mass of vector mesons in nucleus

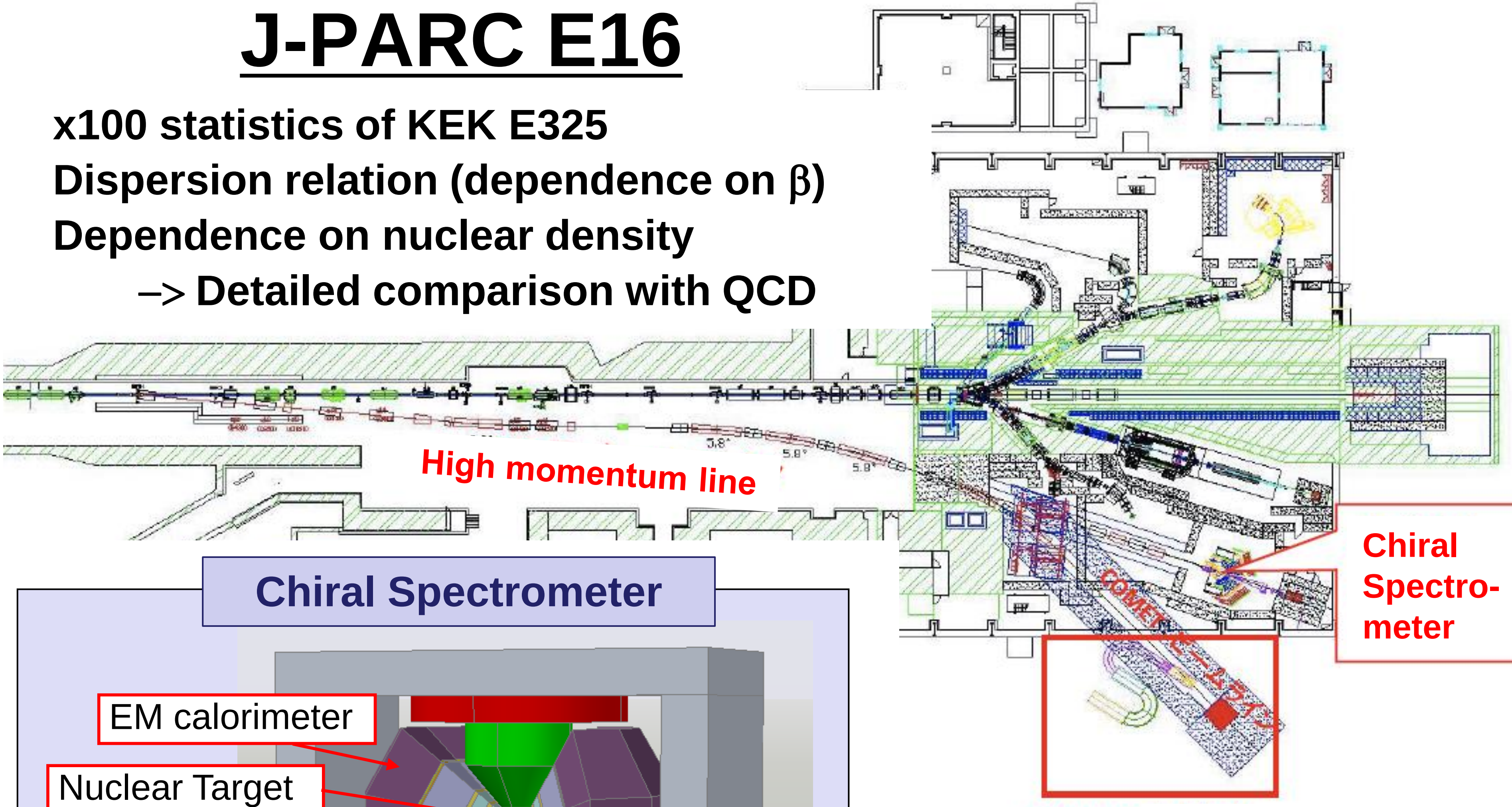
J-PARC E16

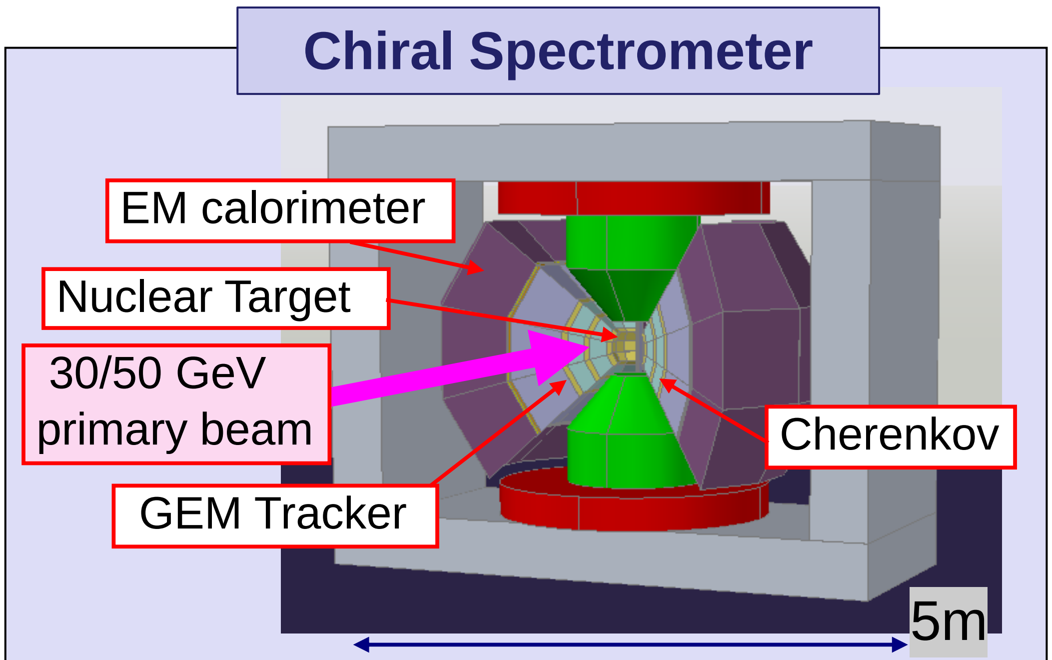
x100 statistics of KEK E325

Dispersion relation (dependence on β)

Dependence on nuclear density

–> Detailed comparison with QCD





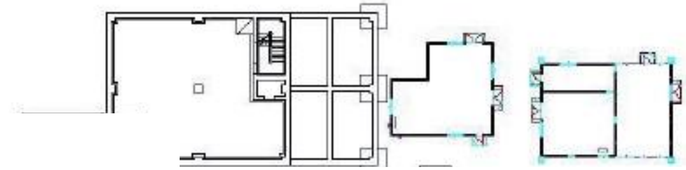
J-PARC E16

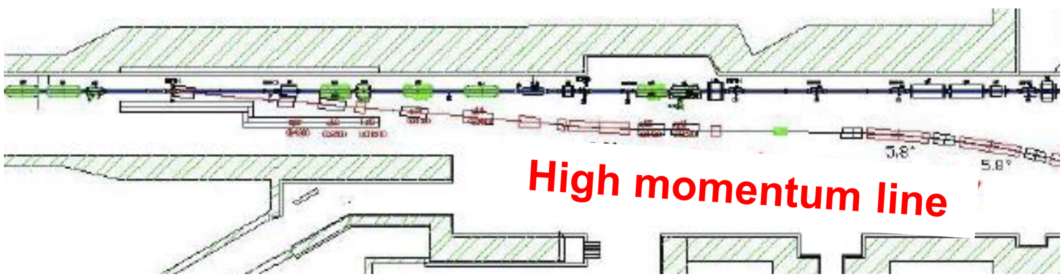
x100 statistics of KEK E325

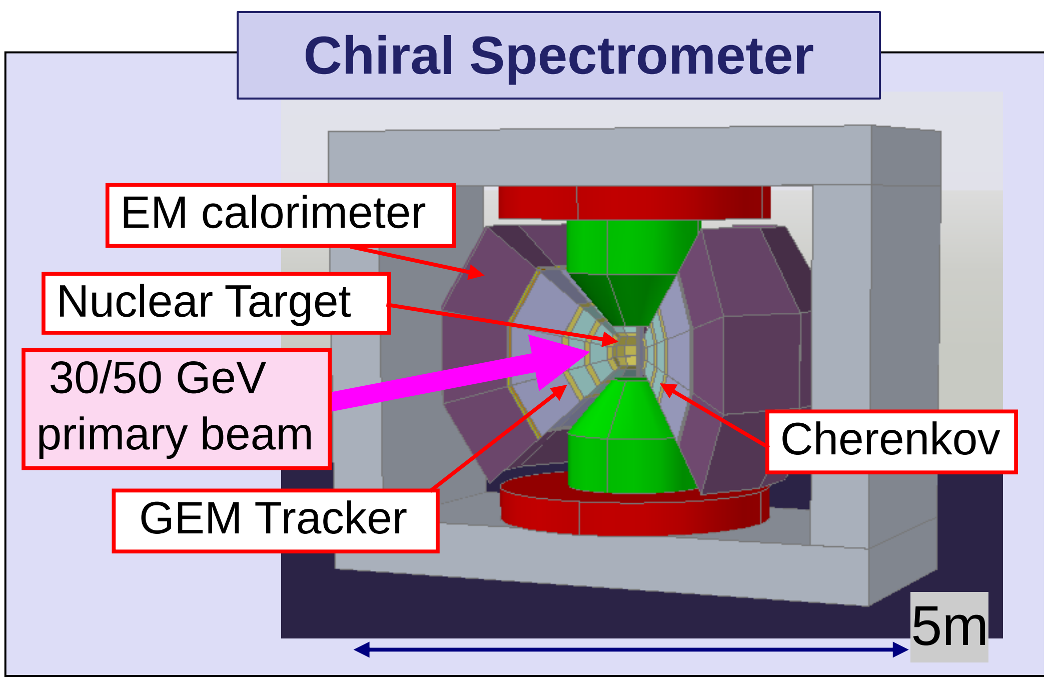
Dispersion relation (dependence on β)

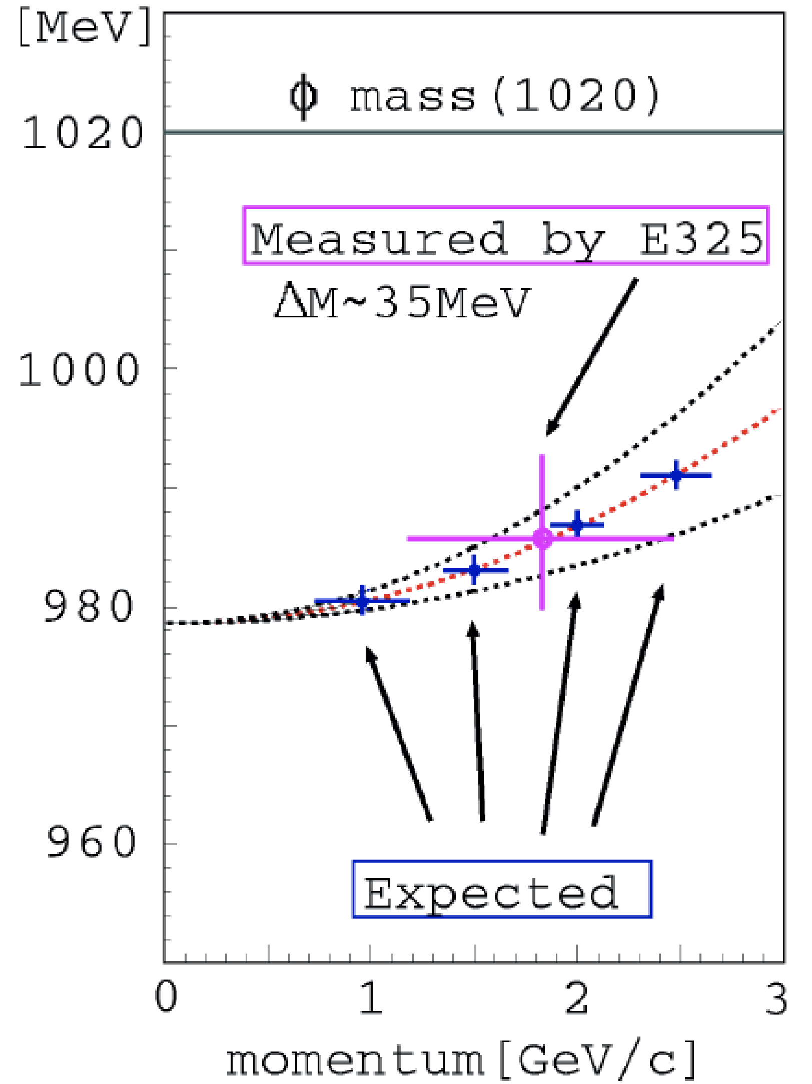
Dependence on nuclear density

–> Detailed comparison with QCD









3.2 Hadrons in Nuclei

-- K^- bound states

Very dense matter? K$^-$-nucleus bound states

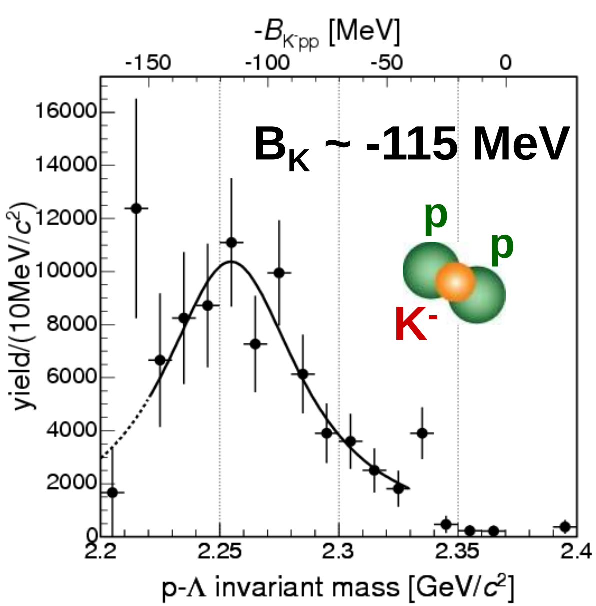
- Strong K$^-$p attraction from K$^-$ p atomic/scattering data
- Under a big debate by theorists: Deep (150~200 MeV, phem. models) or shallow (~50 MeV chiral model)?
- Experimental hints of K$^-$ nuclei *But still controversial*
- K$^-$ can make a nucleus extremely dense.

–> The only experimental method to produce cold and dense matter.

- K$^-$ may condensate in n-star at high ρ

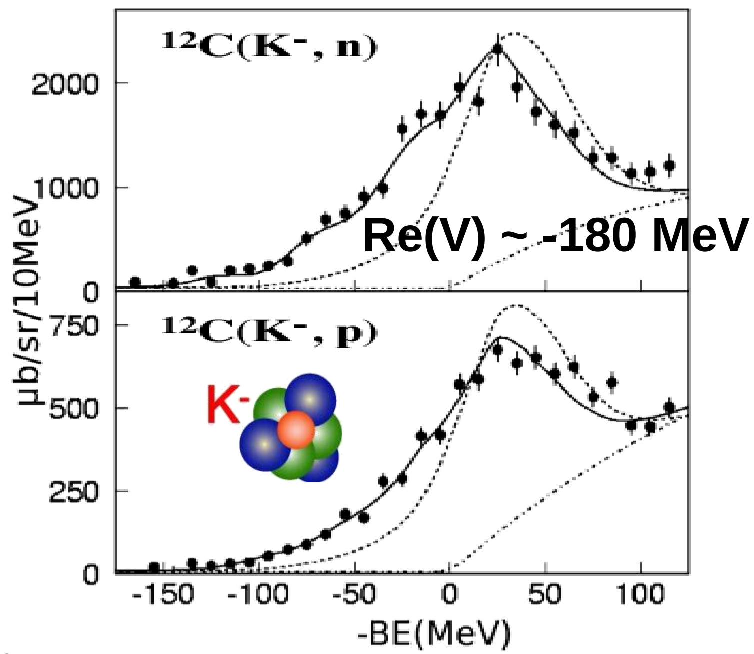
Invariant Mass of K$^-$pp

Back-to-back Λ-p pair

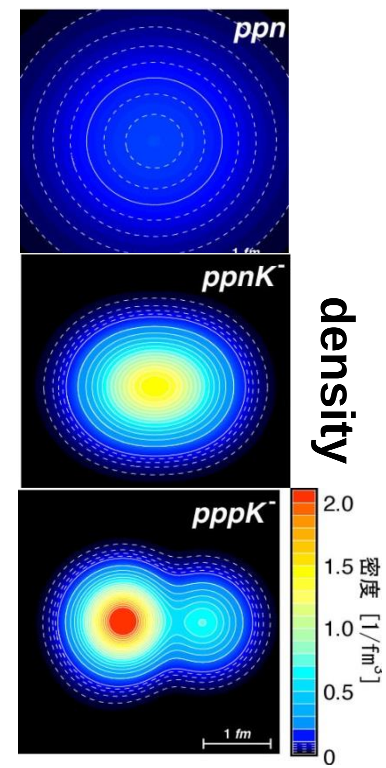


M. Agnello et al., PRL 94 (2005) 212303.

Missing Mass of K$^-$ ^{11}C



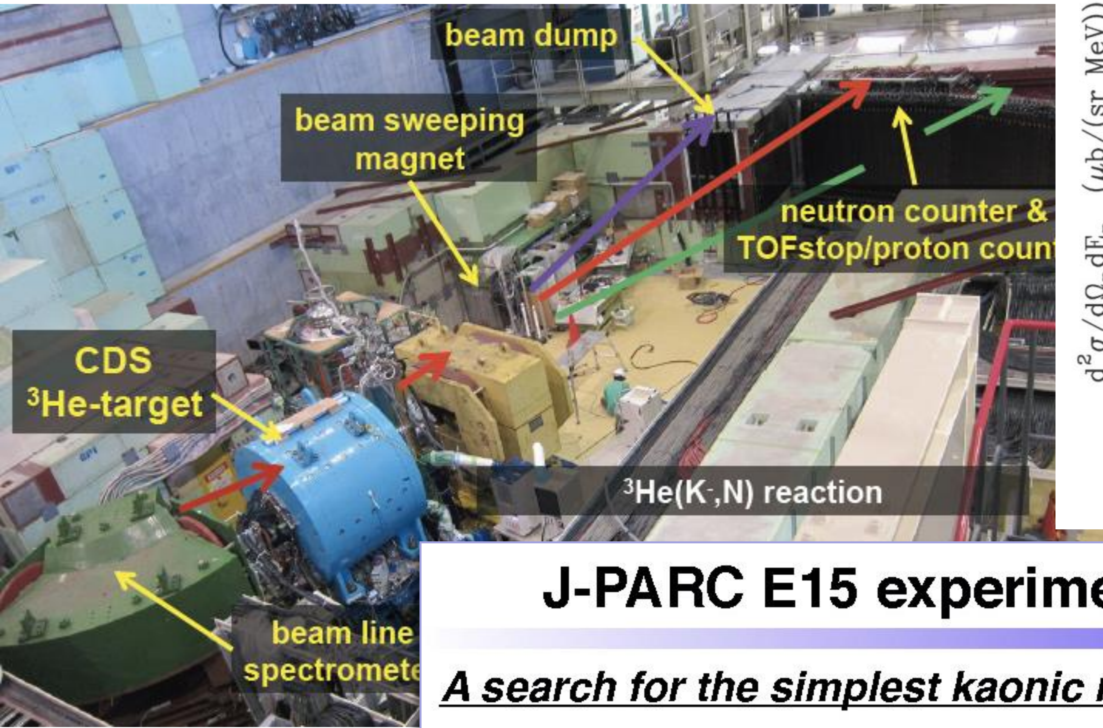
T. Kishimoto et al., PTP 118 (2007) 181

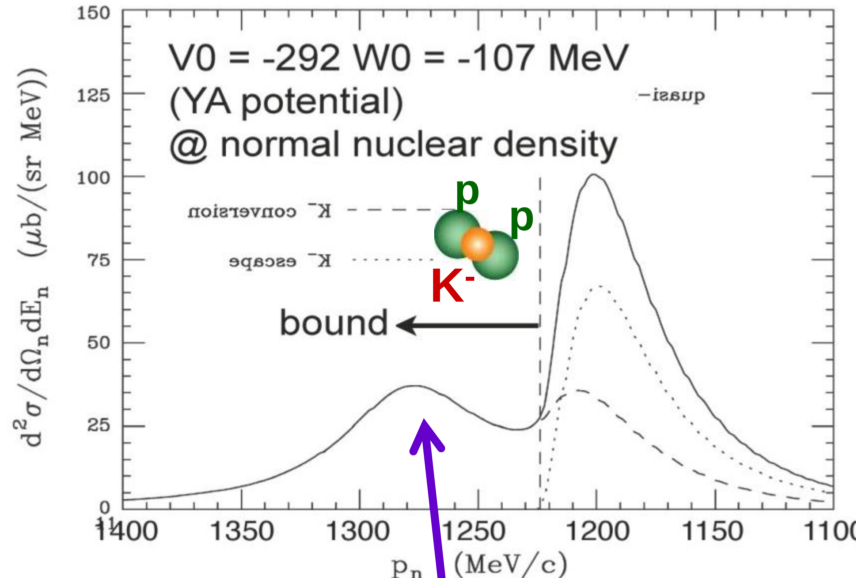


Dote et al. PLB590 (2004) 51

J-PARC E15 for "K⁻pp"

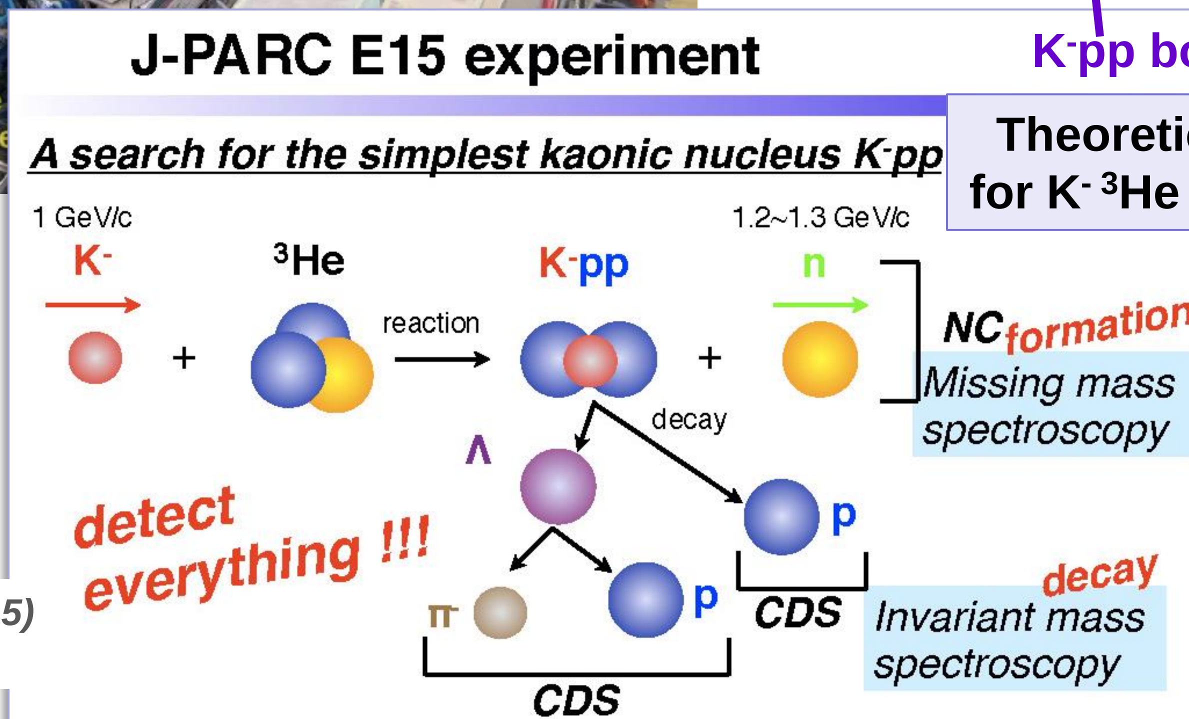
Slide from J-PARC E15





K⁻pp bound state

Theoretical estimate for K⁻ ³He -> "K⁻pp" + n



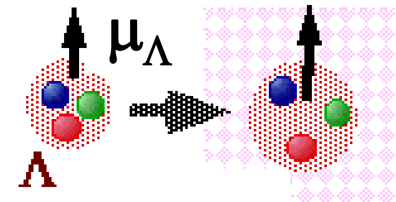
T. Hashimoto (E15) INPC2013

3.3 Hadrons in Nuclei

-- Λ's magnetic moment in a nucleus

Magnetic moment of Λ in a nucleus

Constituent quark model works well for baryon μ.
Partial restoration of chiral symmetry affects baryon μ ?



$$\mu_q = \frac{e\hbar}{2m_q c}$$

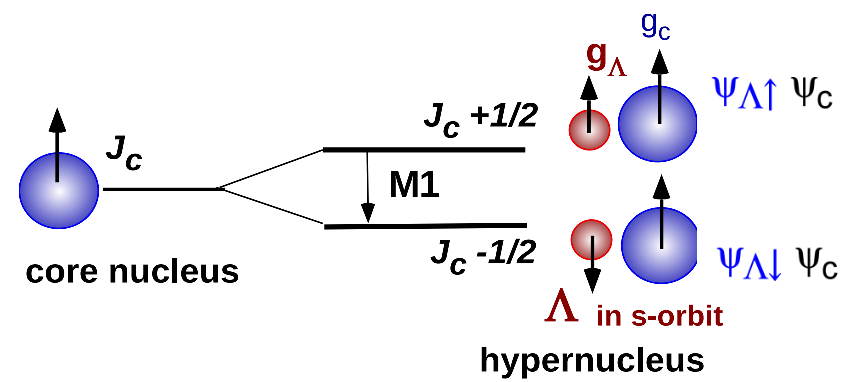
m_q : Const. quark mass

m_q decreases in a nucleus -> μ increases?

-> What is a constituent quark ? What is the origin of the baryon spin?

Λ in 0s orbit is the best probe

B(M1) of Λ-spin-flip M1 transition



$$B(M1) = (2J_{up}+1)^{-1} \left|\langle \Psi_{low} \| \mu \| \Psi_{up} \rangle\right|^2$$

$$= (2J_{up}+1)^{-1} \left|\langle \psi_{\Lambda\downarrow}\psi_c \| \mu \| \psi_{\Lambda\uparrow}\psi_c \rangle\right|^2$$

$$\mu = g_c \boldsymbol{J}_c + g_\Lambda \boldsymbol{J}_\Lambda = g_c \boldsymbol{J} + (g_\Lambda - g_c)\boldsymbol{J}_\Lambda$$

$$= \frac{3}{8\pi}\frac{2J_{low}+1}{2J_c+1}(g_\Lambda - g_c)^2 \quad [\mu_N^2]$$

Doppler Shift Attenuation Method

~100%

$$\Gamma = BR / \cancel{\tau} = \frac{16\pi}{9} E_\gamma^3 \, B(M1)$$

g_c is assumed to be unchanged by a Λ

← Λ-spin-dependent ΛN interaction is small

ΛN spin-spin force ~ 1/10 of NN spin-isospin force

ΛN spin-orbit force ~ 1/40 of NN spin-orbit force

Volume 160B, number 4,5 PHYSICS LETTERS 10 October 1985

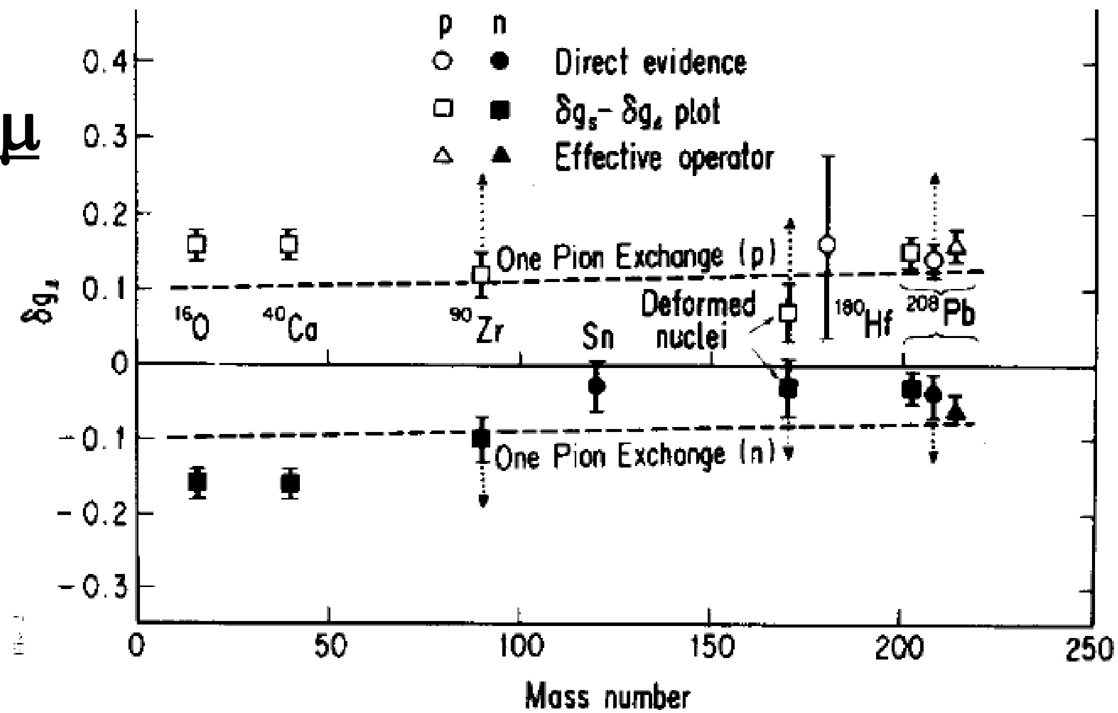
EVIDENCE FOR AN ENHANCED NUCLEAR MAGNETON IN NUCLEI FROM δg_l ANOMALIES; A MODIFICATION OF THE NUCLEON'S PROPERTIES IN NUCLEI

Toshimitsu YAMAZAKI
Physik Department, Technische Universität München, D-8046 Garching, Fed. Rep. Germany and Department of Physics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113, Japan

The effective nuclear magneton in nuclei has been found to be (8 ± 3)% larger than the free value from a careful analysis of the proton–neutron asymmetric effect of the observed δg_l factors in the $A = 208$ region. This suggests a modification of the nucleon's properties in nuclei.

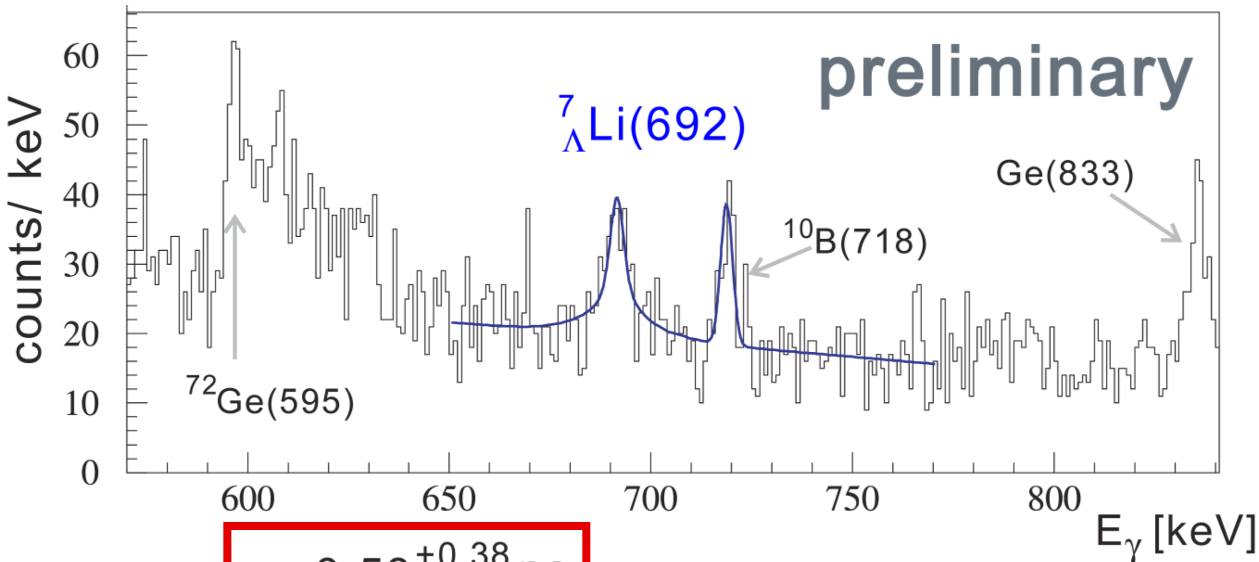
Change of nucleon μ in a nucleus?

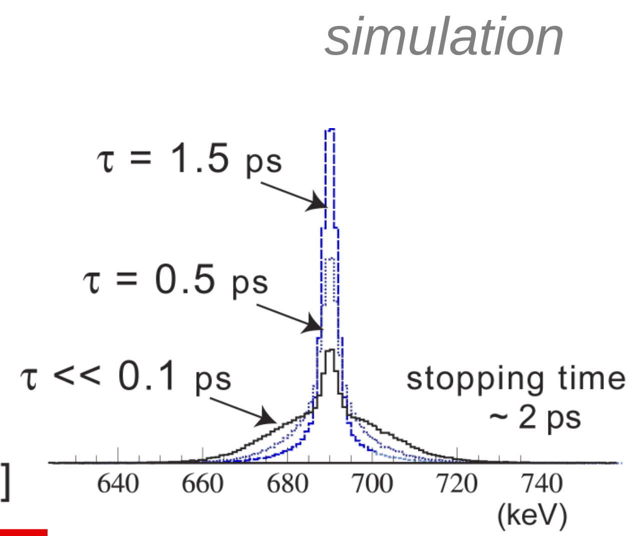
μ_N 8±3% enhanced after removing the effect of meson exchange current.



Preliminary data on g_Λ in ${}^{7}_{\Lambda}$Li (BNL E930)

${}^{10}B\ (K^-, \pi^-)\ {}^{10}_{\Lambda}B^*$, ${}^{10}_{\Lambda}B^*(3^+) \rightarrow {}^{7}_{\Lambda}Li^*(3/2^+) + {}^{3}He$ indirect population

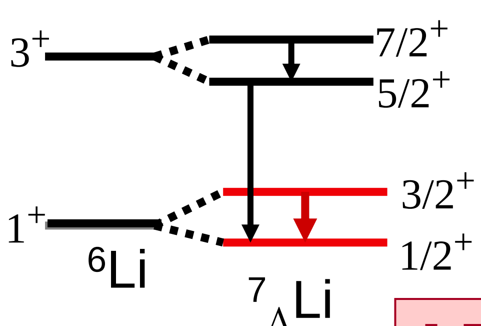




$\tau = 0.58^{+0.38}_{-0.20}$ ps

BR(M1)=100%

$\Rightarrow$ $B(M1) = 0.30^{+0.12}_{-0.16}\ [\mu_N^2]$



$\Rightarrow$ $-\ g_\Lambda = 1.1^{+0.4}_{-0.6}\ \mu_N$

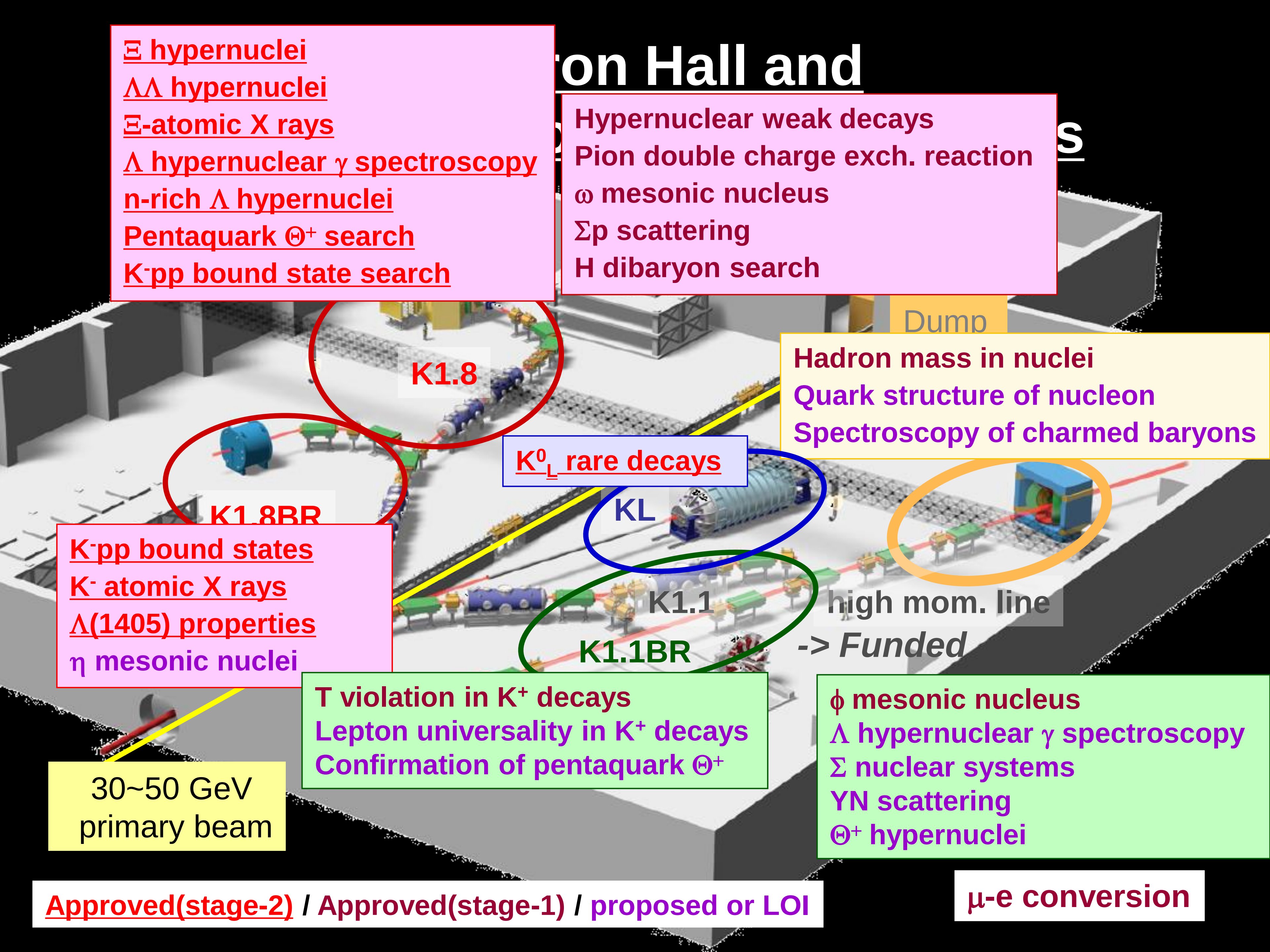
preliminary
(statistical error only)

First data of g_Λ in nucleus

$\Leftrightarrow$ $-\ g_\Lambda(\text{free}) = 1.226\ \mu_N$

J-PARC E13

Precise(~3%) measurement of $|g_\Lambda - g_c|$ for ${}^{7}_{\Lambda}$Li

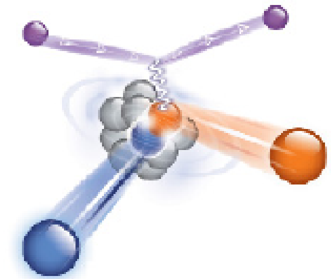

ron Hall and
s
Ξ hypernuclei
ΛΛ hypernuclei
Ξ-atomic X rays
Λ hypernuclear γ spectroscopy
n-rich Λ hypernuclei
Pentaquark Θ^+ search
K^-pp bound state search
Hypernuclear weak decays
Pion double charge exch. reaction
ω mesonic nucleus
Σp scattering
H dibaryon search
Dump
K1.8
Hadron mass in nuclei
Quark structure of nucleon
Spectroscopy of charmed baryons
K^0_L rare decays
K1.8BR
KL
K^-pp bound states
K^- atomic X rays
Λ(1405) properties
η mesonic nuclei
K1.1
high mom. line
-> *Funded*
K1.1BR
T violation in K^+ decays
Lepton universality in K^+ decays
Confirmation of pentaquark Θ^+
φ mesonic nucleus
Λ hypernuclear γ spectroscopy
Σ nuclear systems
YN scattering
Θ^+ hypernuclei
30~50 GeV
primary beam
Approved(stage-2) / Approved(stage-1) / proposed or LOI
μ-e conversion

3.4 Hadrons in Nuclei

-- NN Short Range Correlations

and the EMC effect

DIS for NN and NNN in Short Range Correlation



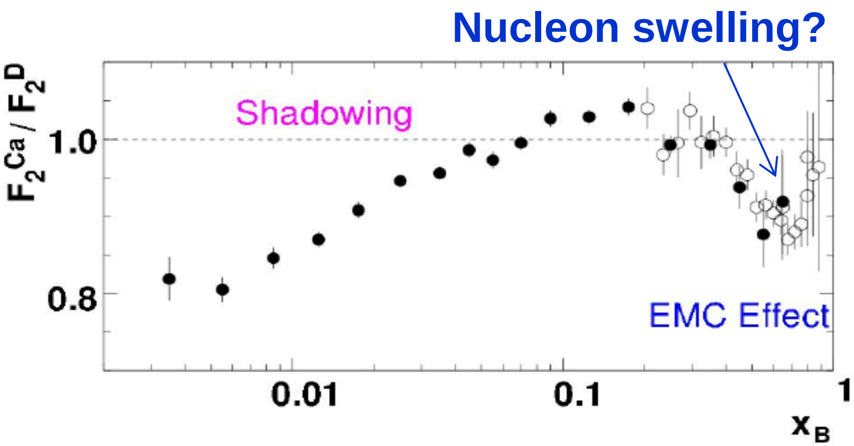
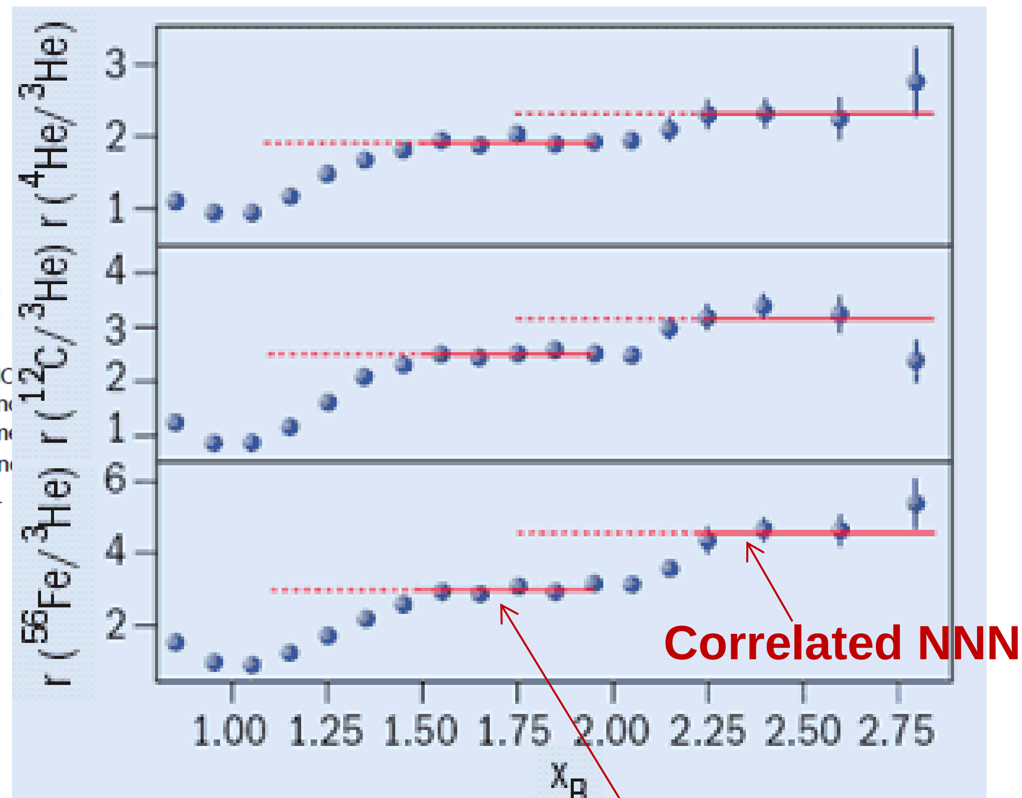


Fig. 2: The image shows the ratio of deep-inelastic cross sections of Ca to D from NMC (solid circles) and SLAC (open circles). The downward slope from 0.3 < x < 0.7 and subsequent rise from x_B > 0.7 is a universal characteristic of EMC data and has became known as the EMC effect. The reduction of the ratio at lower values of x_B, where valen quarks should no longer be playing a significant role, is known as the shadowing region.

$^{12}C(e,e'pn), (e,e'pp), (e,e'nn)$



CLAS collaboration, PRL 96, 082501 (2006)

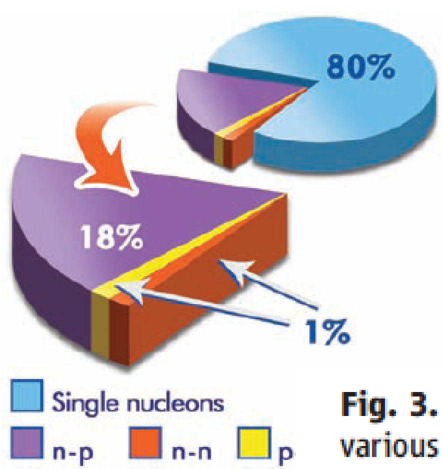


Fig. 3. The average fraction of nucleons in the various initial-state configurations of ^{12}C.

Relation between EMC effect and SRC

L. B. Weinstein et al., PRL 106 (2011) 052301
CERN Courier, May 2013

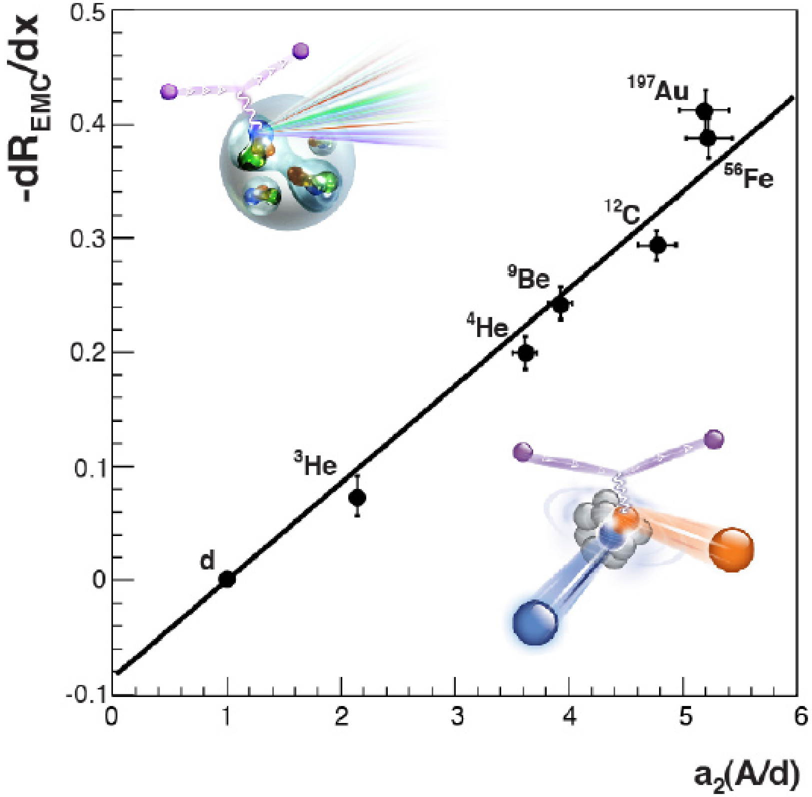
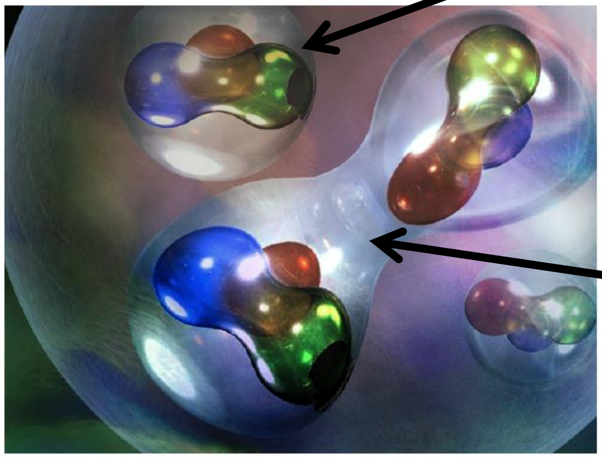


Fig. 4: The slope of the EMC effect, dR/dx for $0.3 < x < 0.7$ with $R = F^2_A/F^2_D$, is plotted versus the magnitude of the observed $x > 1$ plateaus, denoted as a_2, for various nuclei. For data that were taken by completely different groups, the linearity is striking and has caused renewed interest in understanding the cause of both effects. The inset cartoons illustrate the kinematic difference of deep inelastic EMC effect scatterings and the scattering from a correlated pair in $x > 1$ kinematics.

80%



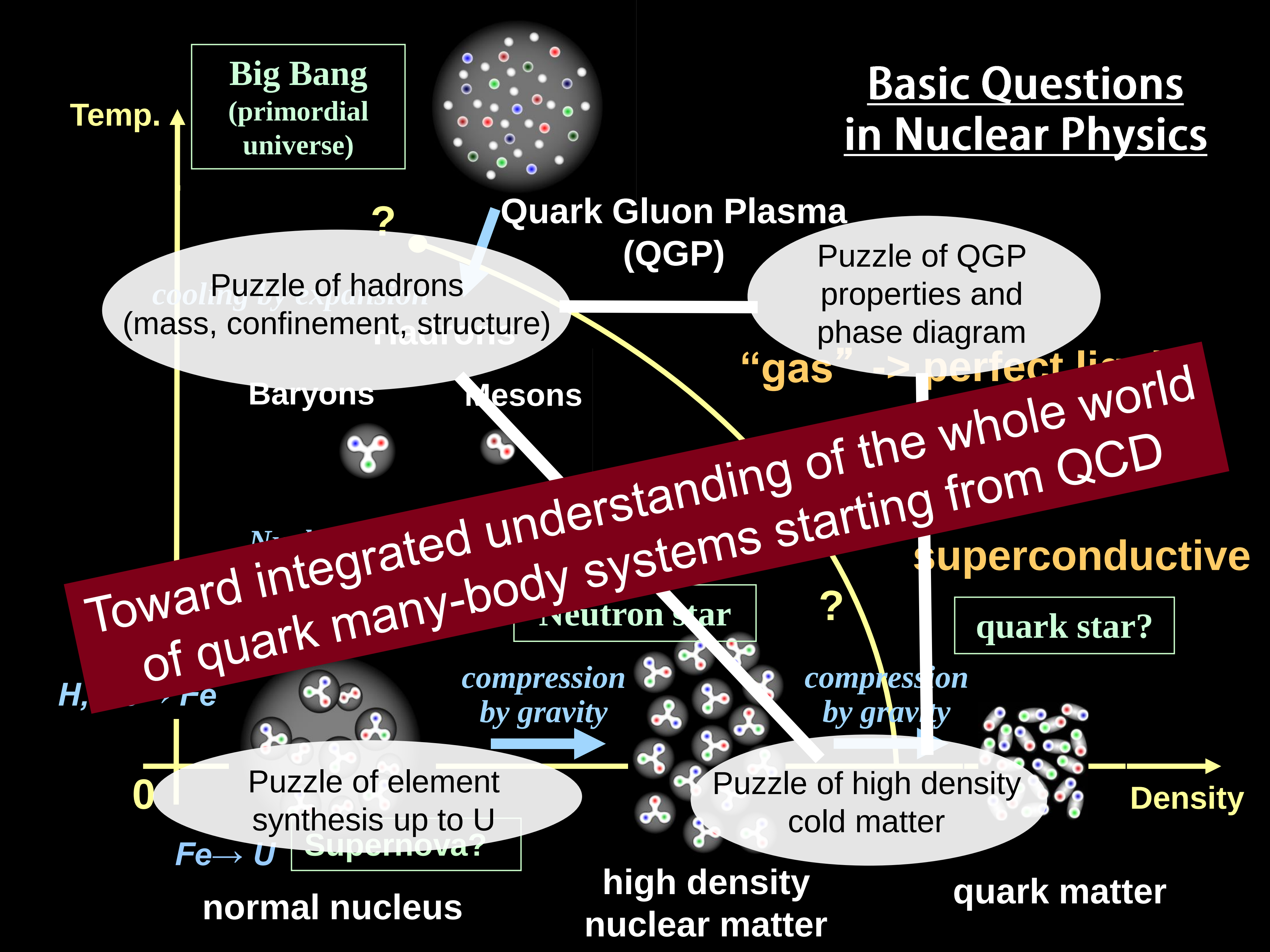
20%

"Cover-Art": An artist's depiction of nucleons being distorted in the nuclear medium as they come close together.

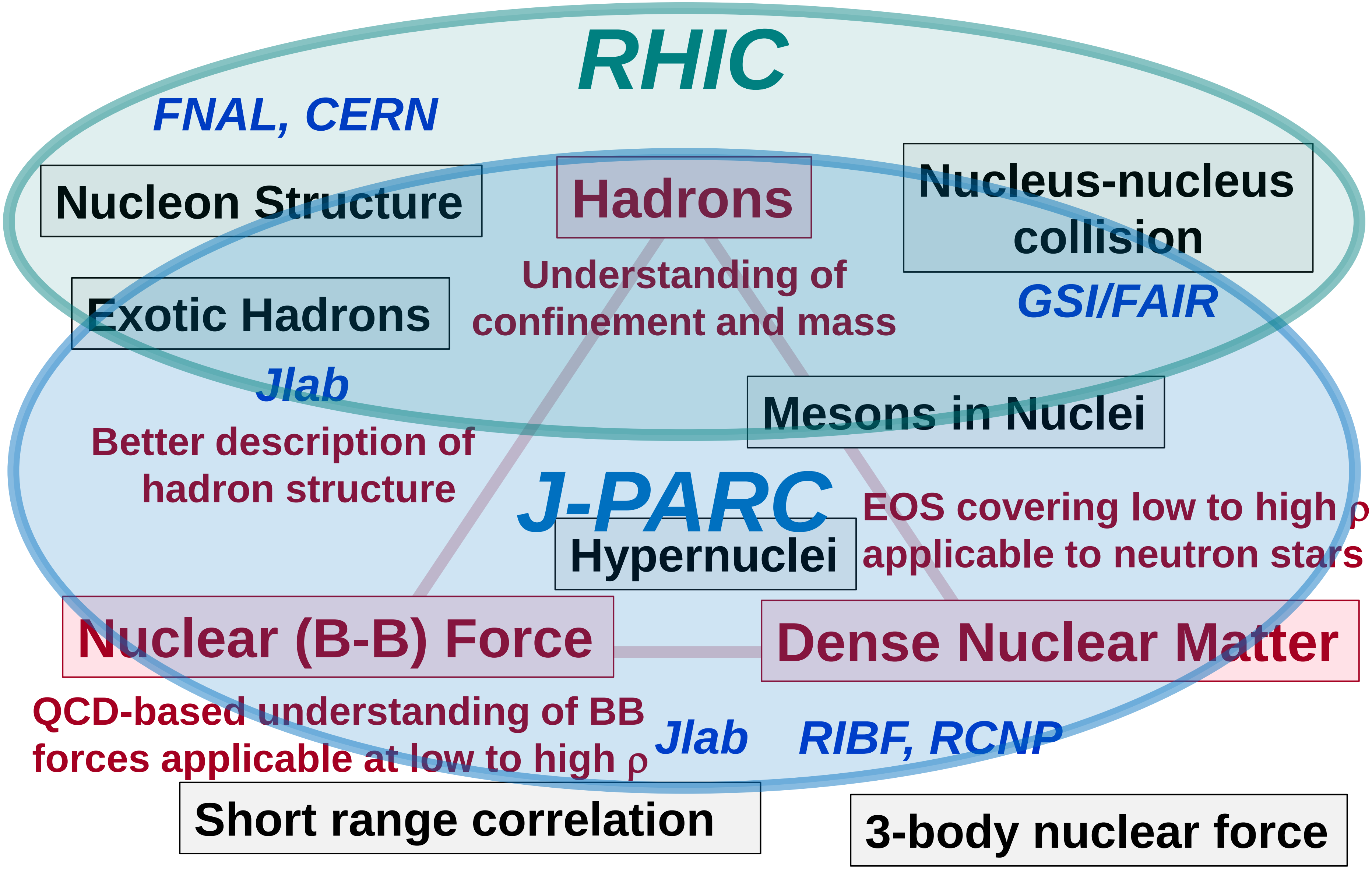
Previously, EMC effect (at large x) was interpreted as nucleon swelling (partial deconfinement), but

- Nucleons look "modified" <u>only when</u> they are interacting at a close distance?
- EMC effect seems nothing to do with partial deconfinement or partial restoration of chiral symmetry, but is it true?
- <u>SRC and EMC effect provide information on what's happening in high-density cold matter</u>.

4. Concluding Remarks


Basic Questions
in Nuclear Physics
Temp.
Big Bang
(primordial
universe)
Quark Gluon Plasma
(QGP)
?
Puzzle of hadrons
(mass, confinement, structure)
Puzzle of QGP
properties and
phase diagram
"gas" -> perfect li
Baryons
Mesons
superconductive
Toward integrated understanding of the whole world
of quark many-body systems starting from QCD
Neutron star
?
quark star?
compression
by gravity
compression
by gravity
H,
Fe
0
Puzzle of element
synthesis up to U
Fe→ U
Supernova?
Puzzle of high density
cold matter
Density
normal nucleus
high density
nuclear matter
quark matter

Bridging between
low energy and high energy nuclear physics



Message to the PHENIX people

High energy / small x phenomena:

Essential and quite unique. We support you.
Please go ahead!

Lower energy / larger x phenomena:

Low energy scan, e+e- spectra, exotic hadrons,
Large x DIS / Drell-Yan, …. -> also FAIR, J-PARC

Also consider connections to low-energy QCD problems and to J-PARC experiments, toward our dream to understand hadrons, BB forces, nuclei, and dense nuclear matter in the integrated framework based on QCD.

RHIC + J-PARC will solve the whole problem.