QCD fossils in nuclei?
a model study

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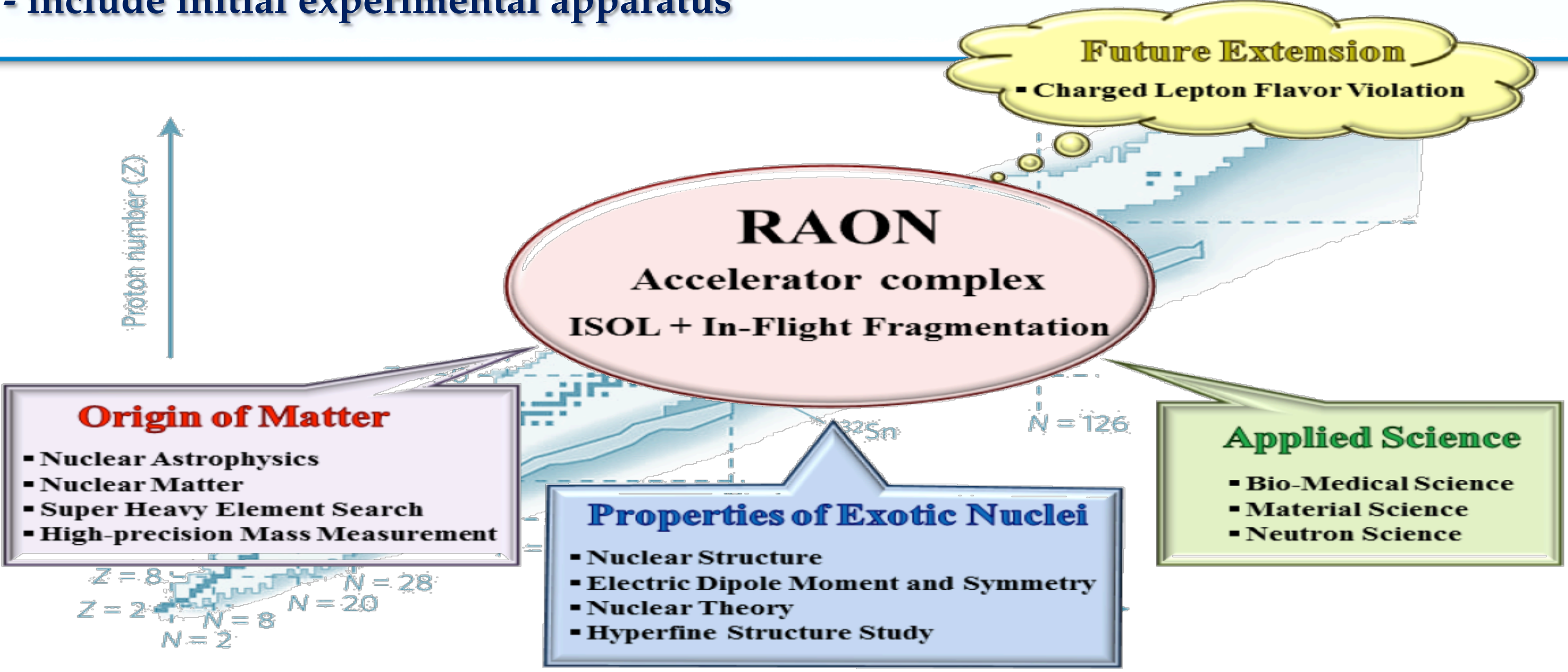
Rare Isotope Science Project (RISP)

RISP

- ○ Goal : To build a heavy ion accelerator complex RAON for rare isotope science researches in Korea
- ○ Project period : 2011.12 - 2021.12
- ○ Total Budget : ~$ 1.43 billion

(Facilities ~ $ 0.46 bill., Bldgs & Utilities ~ $ 0.97 bill.)

- include initial experimental apparatus



Future Extension

- Charged Lepton Flavor Violation

RAON

Accelerator complex

ISOL + In-Flight Fragmentation

Origin of Matter

- Nuclear Astrophysics
- Nuclear Matter
- Super Heavy Element Search
- High-precision Mass Measurement

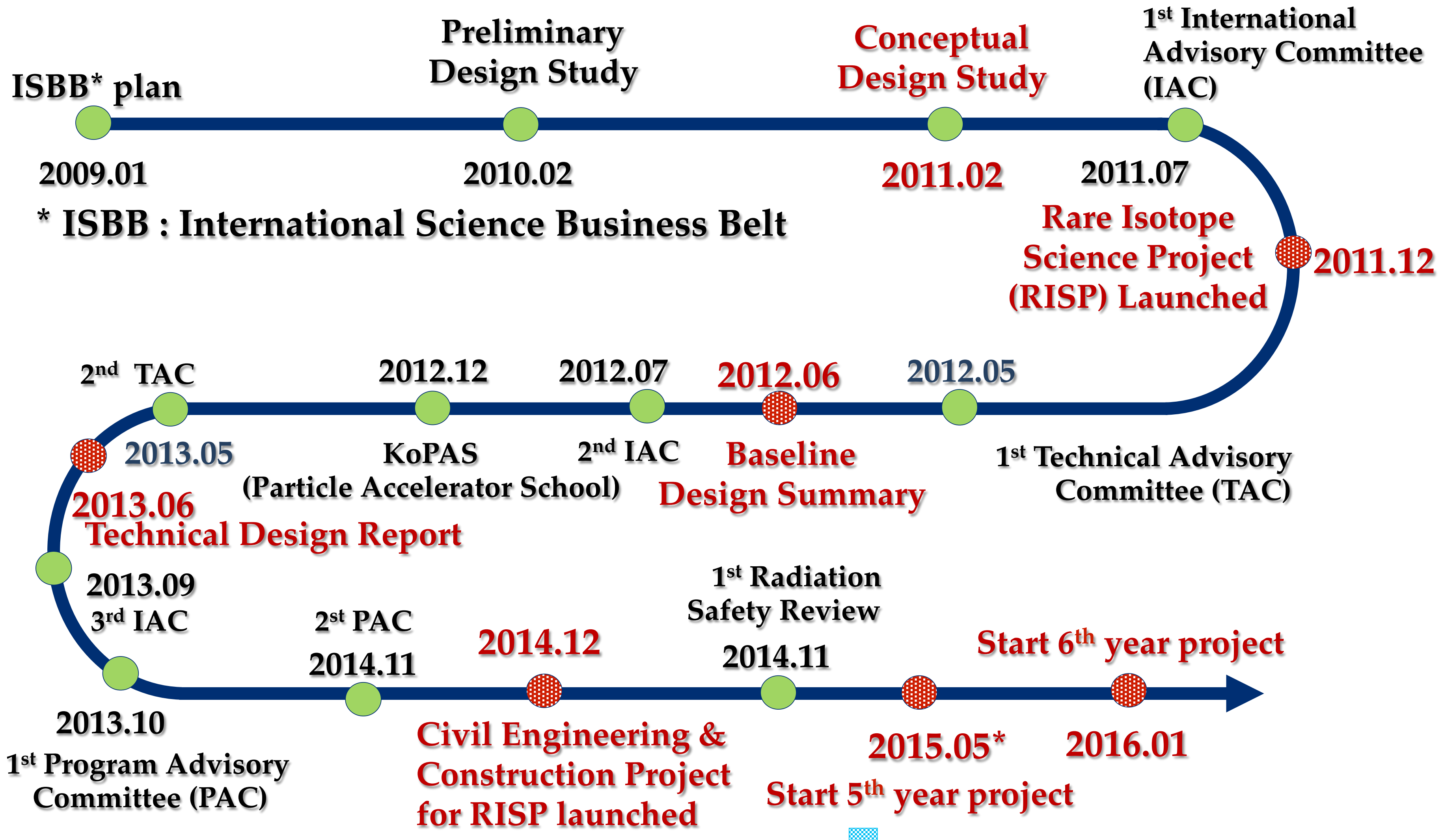
Properties of Exotic Nuclei

- Nuclear Structure
- Electric Dipole Moment and Symmetry
- Nuclear Theory
- Hyperfine Structure Study

Applied Science

- Bio-Medical Science
- Material Science
- Neutron Science

History of the RISP



ISBB* plan
2009.01

Preliminary Design Study
2010.02

Conceptual Design Study
2011.02

1st International Advisory Committee (IAC)
2011.07

* ISBB : International Science Business Belt

2011.12
Rare Isotope Science Project (RISP) Launched

2012.05
1st Technical Advisory Committee (TAC)

2012.06
Baseline Design Summary

2012.07
2nd IAC

2012.12
KoPAS (Particle Accelerator School)

2nd TAC
2013.05

2013.06
Technical Design Report

2013.09
3rd IAC

2013.10
1st Program Advisory Committee (PAC)

2st PAC
2014.11

2014.12
Civil Engineering & Construction Project for RISP launched

1st Radiation Safety Review
2014.11

2015.05*
Start 5th year project

2016.01
Start 6th year project

RISP Baseline Schedule(the 3rd) changed to complete RAON by 2021 and schedule & cost for facility construction released

RAON Concept

❑ High intensity RI beams by ISOL & IF

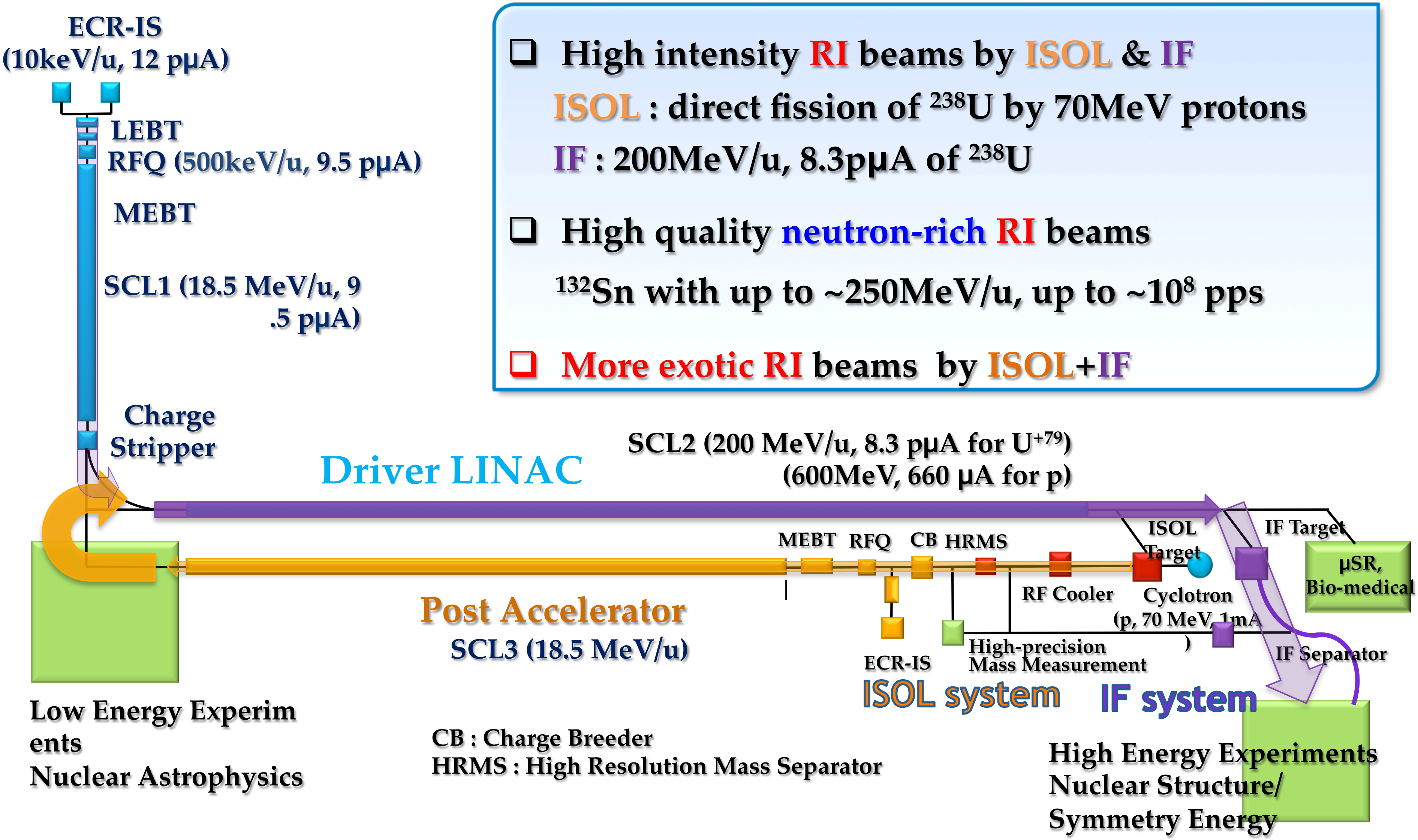
ISOL : direct fission of ^{238}U by 70MeV protons

IF : 200MeV/u, 8.3pμA of ^{238}U

❑ High quality neutron-rich RI beams

^{132}Sn with up to ~250MeV/u, up to ~10^{8} pps

❑ More exotic RI beams by ISOL+IF



ECR-IS
(10keV/u, 12 pμA)

LEBT

RFQ (500keV/u, 9.5 pμA)

MEBT

SCL1 (18.5 MeV/u, 9.5 pμA)

Charge Stripper

Driver LINAC

SCL2 (200 MeV/u, 8.3 pμA for U^{+79})
(600MeV, 660 μA for p)

MEBT RFQ CB HRMS

ISOL Target

IF Target

μSR, Bio-medical

RF Cooler

Cyclotron
(p, 70 MeV, 1mA)

Post Accelerator

SCL3 (18.5 MeV/u)

ECR-IS

High-precision Mass Measurement

IF Separator

ISOL system

IF system

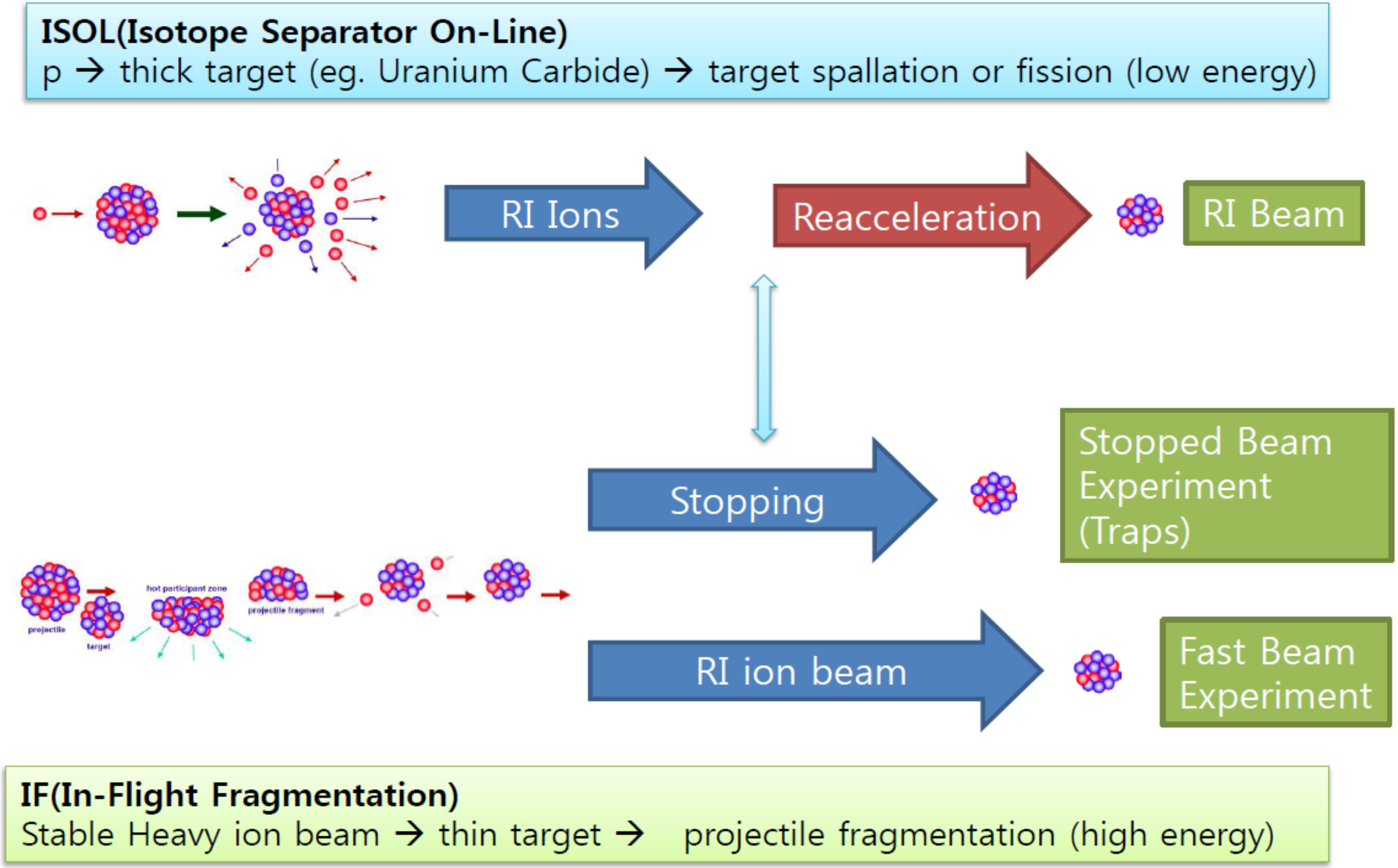
Low Energy Experiments
Nuclear Astrophysics

CB : Charge Breeder
HRMS : High Resolution Mass Separator

High Energy Experiments
Nuclear Structure/
Symmetry Energy

- ISOL-type facilities: radioactive ions are produced at rest in a thick target either by direct bombardment with particles from a driver accelerator or via fission induced both by fast and thermal secondary neutrons.

- In-flight (IF) facilities: a high energy ion beam is fragmented in a suitable thin target and the reaction products are and then transported to the secondary target.



ISOL(Isotope Separator On-Line)
p → thick target (eg. Uranium Carbide) → target spallation or fission (low energy)

RI Ions

Reacceleration

RI Beam

Stopping

Stopped Beam Experiment (Traps)

RI ion beam

Fast Beam Experiment

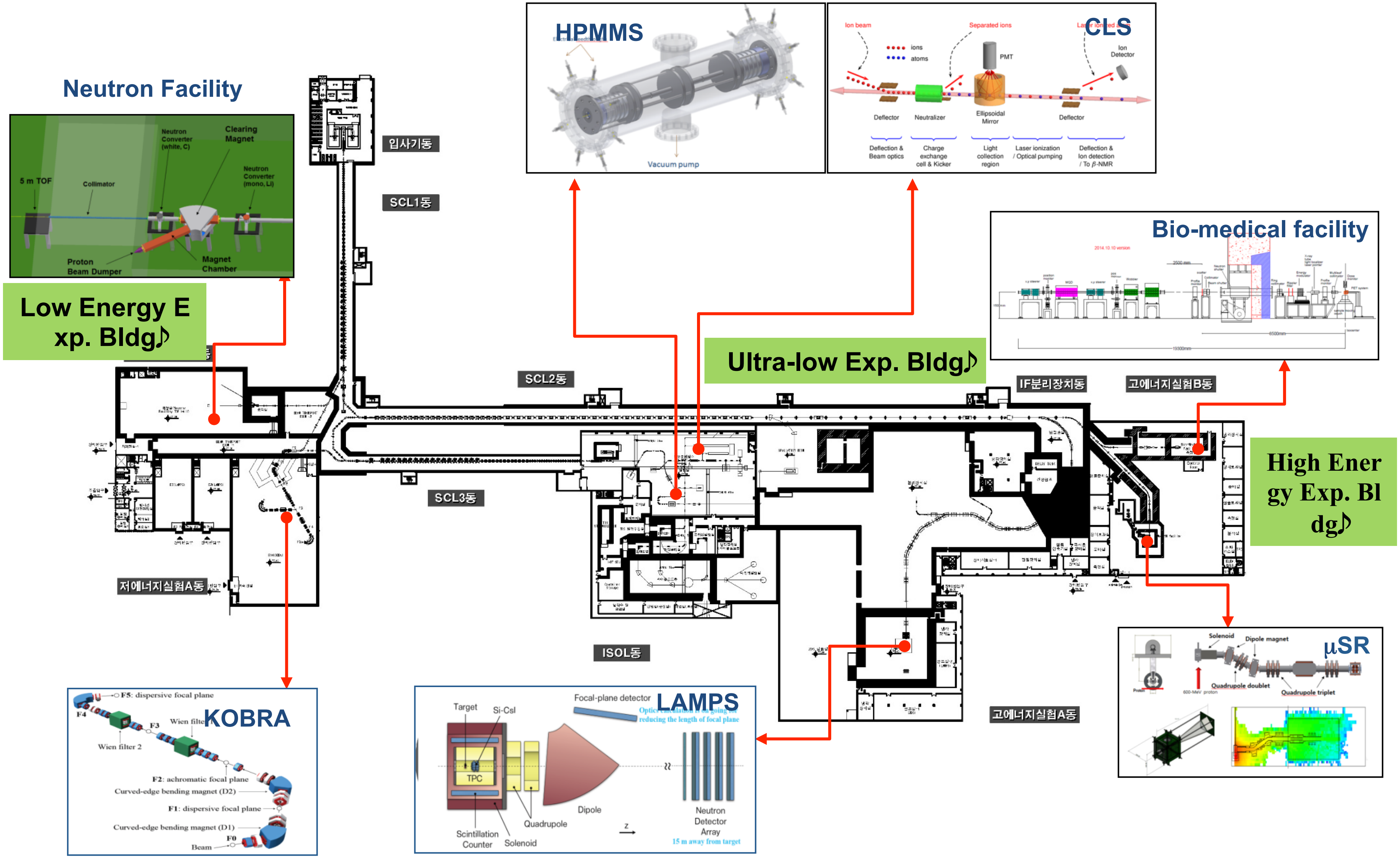
IF(In-Flight Fragmentation)
Stable Heavy ion beam → thin target → projectile fragmentation (high energy)

RAON Site : Sindong in Daejeong

Basic design was finished Dec. 2015

A construction company will be selected in Sept. 2016.

RAON Layout: Experimental system



Neutron Facility

Low Energy Exp. Bldg♪

Ultra-low Exp. Bldg♪

Bio-medical facility

High Energy Exp. Bldg♪

HPMMS

CLS

KOBRA

LAMPS

μSR

RAON System Dev. Performance

Total Performance

Prototype : 92.0 %
Production : 14.8 %

1 Injector

이온빔 생성 및 주입 장치
ECR-IS[1]/LEBT[2]/RFQ[3]/MEBT[4]로 구성

[1] Superconducting Electron Cyclotron Resonance Ion Source
[2] Low Energy Beam Transport
[3] Radio Frequency Quadrupole accelerator
[4] Medium Energy Beam Transport

Prototype	94.6%	Production	29.5 %

2 SCL1

초전도 이온원에서 인출된 안정된 중이온 빔을18.5MeV/u 까지 가속하는 초전도 선형 가속기(QWR[5], HWR[6] 초전도 가속관으로 구성)

[5] Quarter Wave Resonator
[6] Half Wave Resonator

Prototype	98.2%	Production	6.0%

3 SCL2

초전도선형가속기1 또는 초전도선형가속기3에서 가속된 빔을 200MeV/u 까지 가속하는 초전도선형가속기(SSR[7] 초전도가속관으로구성)

[7] Single Spoke Resonator

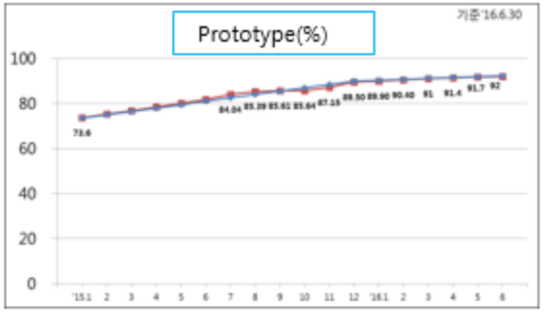
Prototype	94.2%	Production	4.3%

4 SCL3

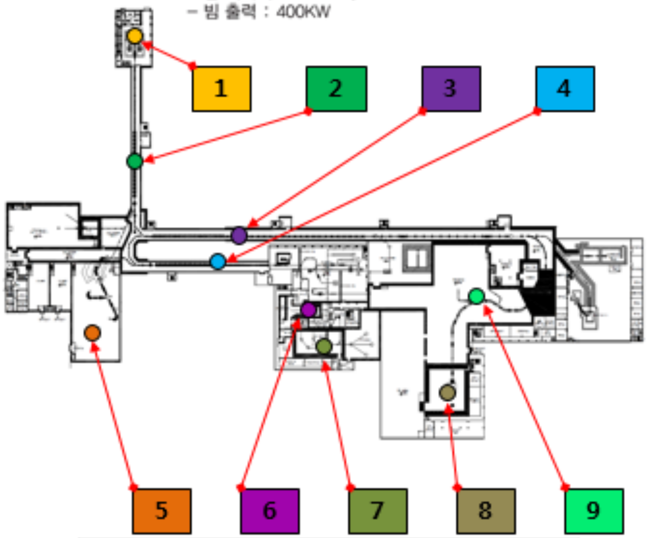
ISOL 시스템으로부터 분리된 동위원소 빔을 18.5MeV/u 까지 가속하는 초전도선형가속기(QWR[5], HWR[6] 가속관으로 구성)

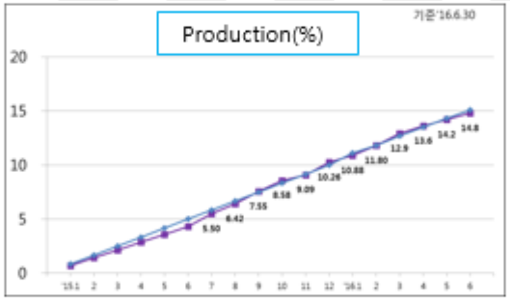
[5] Quarter Wave Resonator
[6] Half Wave Resonator

Prototype	98.2%	Production	17.7%

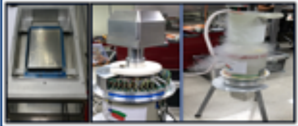


- 장치사양
  - 빔 에너지 : 200MeV/u
  - 빔 출력 : 400KW





5 Low Energy Hall A : KOBRA



18.5MeV/u 에너지 빔을 이용하는 저에너지 실험 시설(KOBRA[8] 등)

[8] KOrea Broad Acceptance Recoil Spectrometer and Apparatus

Prototype	100%	Production	41.3%

6 ISOL[9] System

저에너지 희귀동위원소 빔을 생성하고 분리·공급하는 장치

[9] Isotope Separate On Line (온라인 분리 장치)

Prototype	95.8%	Production	32.0%

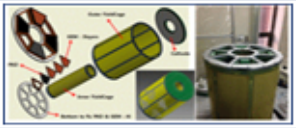
7 Cyclotron[10]

ISOL 시스템에 70MeV 양성자 빔을 공급하는 원형 가속기

[10] Cyclotron

Prototype	도입	Production	20.5%

8 High Energy Hall A: LAMPS



200MeV/u 빔 또는 IF 시스템에서 분리된 빔을 이용하는 고에너지 실험시설(LAMPS[11] 등)

[11] Large Acceptance Multi Purpose Spectrometer

Prototype	98.2%	Production	8.5%

9 IF[12] System

고에너지 희귀동위원소 빔을 생성하고 분리·공급하는 장치

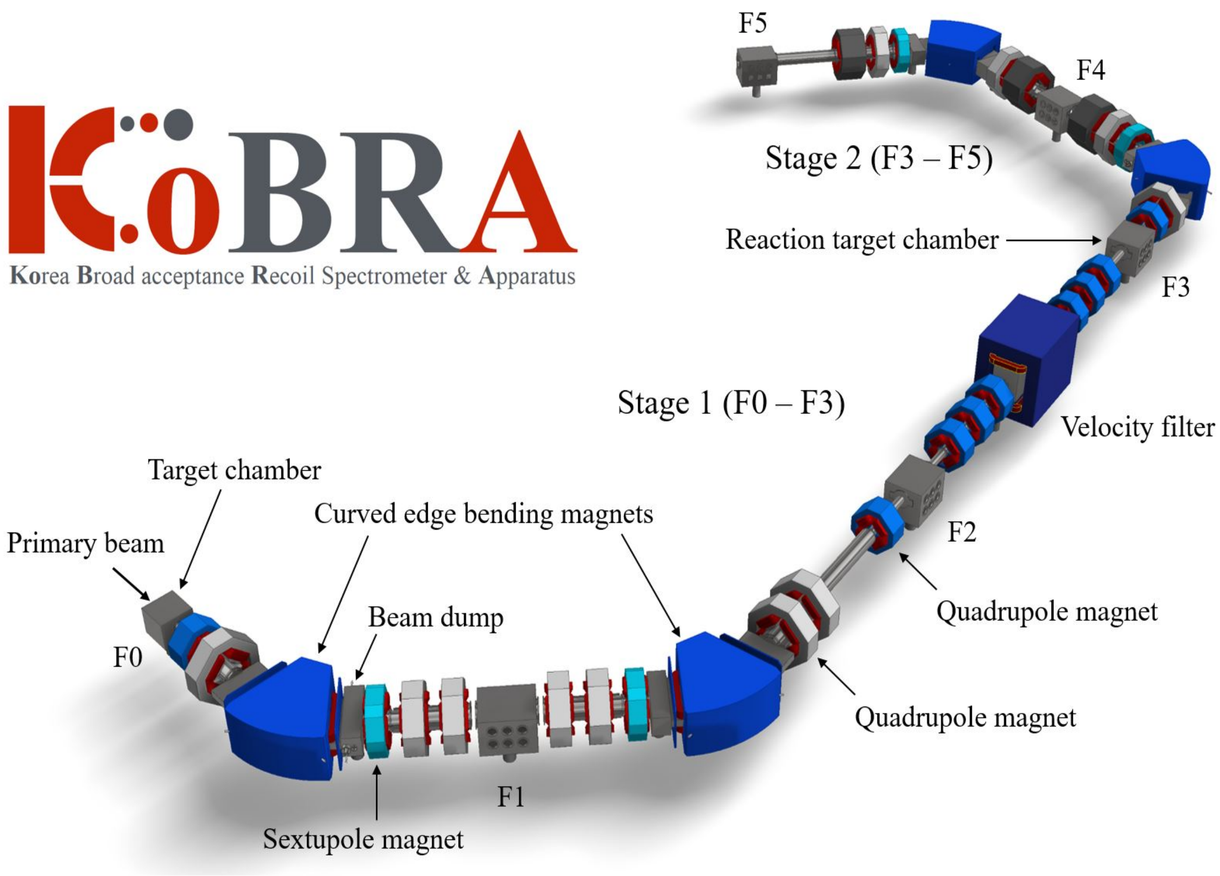
[12] In flight Fragmentation (비행파쇄 분리 장치)

Prototype	72.2%	Production	7.1%

Main facility for nuclear structure and nuclear astrophysics studies with low-energy stable and rare isotope beams

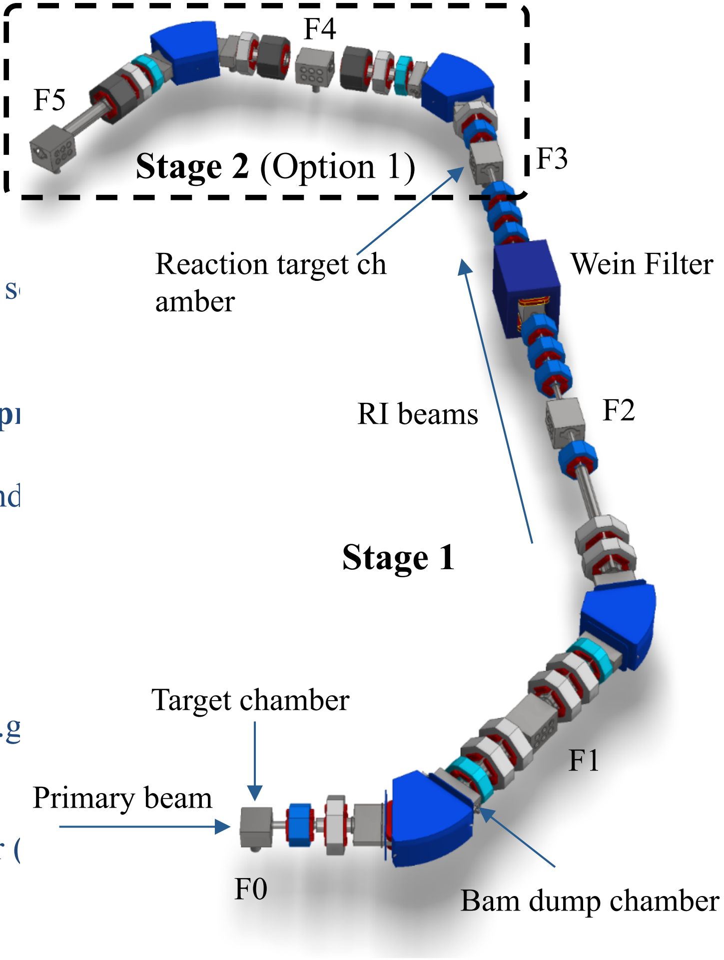
KoBRA

Korea **B**road acceptance **R**ecoil Spectrometer & **A**pparatus



- Nuclear Structure
  - **Study of shell evolution in proton- and neutron-rich nuclei:**
    Measurements of excitation energy and angular distribution
    Determination of nucleon occupancy in single particle orbit
    (inelastic scattering, (d,p) reaction, nucleon removal reaction, and s
    n)
  - **Study of soft dipole and Pygmy dipole resonances using nuclear p be, e.g., α, Ca and Pb:**
    Measurements of excitation energy and angular distribution (Bound ate: Υ ray spectroscopy, unbound state: missing mass method)

- Nuclear Astrophysics
  - **Direct measurement of charged-particle capture cross section**, e.g., for ^{65}As(p, Υ) and ^{15}O(α, Υ) reactions at < ~1 MeV/nucleon
  - **Indirect measurement of radiative capture cross section**, e.g., for (d,p) reaction at a few MeV/nucleon



slide from K.H. Tshoo (RISP, IBS)

V.Z.Goldberg et al., PLB692(2010)307.
^{13}O(p,p)^{13}O

F.Wamers et al., PRL112(2014)132502.
C(^{17}Ne,^{16,15}Ne)

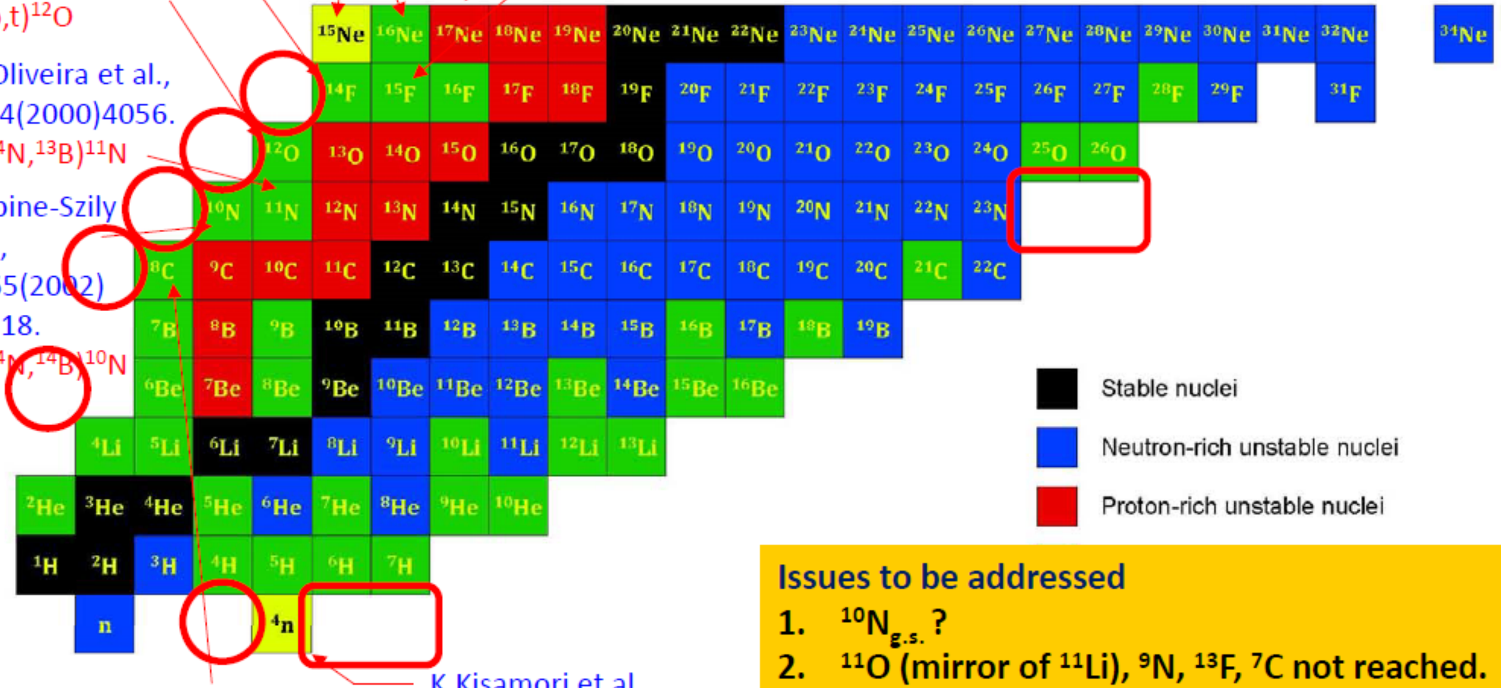
J.Marganiec et al., PLB759(2016)200.
C(^{17}Ne,^{17}Ne)

F.De Grancey et al., PLB758(2016)26.
^{14}O(p,p)^{14}O

D.Suzuki et al., PRL103(2009)152503.
^{14}O(p,t)^{12}O

J.M.Oliveira et al., PRL84(2000)4056.
^{10}B(^{14}N,^{13}B)^{11}N

A.Lepine-Szily et al., PRC65(2002) 054318.
^{10}B(^{14}N,^{14}B)^{10}N



⬛ Stable nuclei

🟦 Neutron-rich unstable nuclei

🟥 Proton-rich unstable nuclei

R.E.Tribble et al., PRC13(1976)50.
^{12}C(α,^{8}He)^{8}C
R.G.Robertson et al., PRC17(1978)1929.
^{14}N(^{3}He,^{9}Li)^{8}C

K.Kisamori et al., PRL116(2016)052501.
^{4}He(^{8}He,^{8}Be)4n

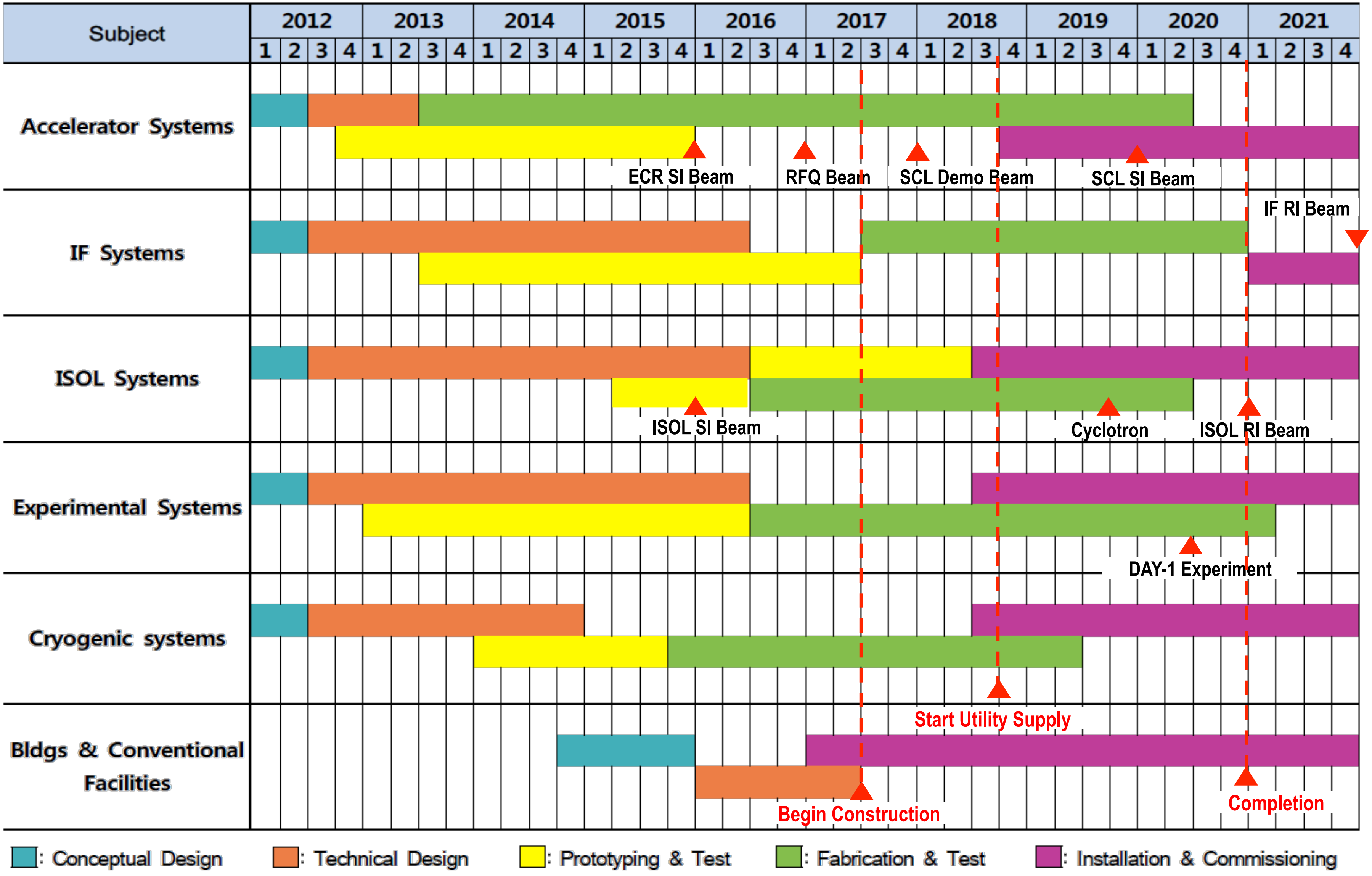
Issues to be addressed

1. ^{10}N$_{g.s.}$?
2. ^{11}O (mirror of ^{11}Li), ^{9}N, ^{13}F, ^{7}C not reached.
3. Further characterizations of 4n.
4. 3n, 5n, 6n, ^{5,7}H, 4p ?
5. Nuclei away from the drip line.
6. Unbound excited states (^{8}C, …)?

:

T. Sato (RISP, IBS)

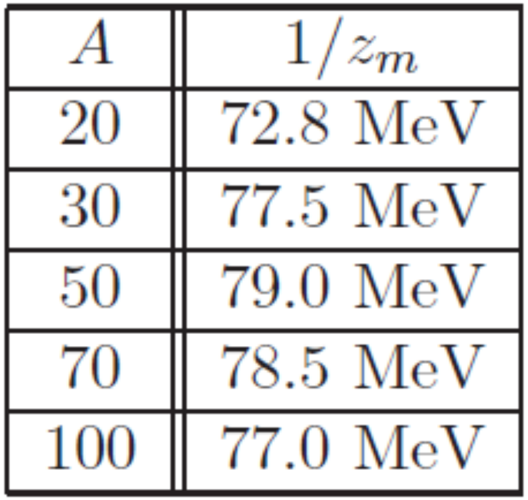
RISP Milestones and Schedule



Though I said “Nuclear physics” is to be ‘New Clear physics” thanks to RIB facilities (to come) and supercomputers, …

Motivation I

A simple holographic QCD model study has claimed that (a naive) typical scale of QCD changes in nuclei.



A	$1/z_m$
20	72.8 MeV
30	77.5 MeV
50	79.0 MeV
70	78.5 MeV
100	77.0 MeV

$$1/z_m \sim 320 \ \mathrm{MeV}$$

K. K. Kim, YK, Y. Ko, JHEP 1010 (2010) 039

Motivation II

Origin of nucleon mass? due to smallness of current quark mass

Can Nuclei do anything for this?

Nucleon mass (in the chiral limit) in the linear sigma model

$$\delta\mathcal{L} = -g_\pi \left[\left(i\bar{\psi}\gamma_5\vec{\tau}\psi \right) \vec{\pi} + \left(\bar{\psi}\psi \right) \sigma \right]$$

$$\begin{aligned} <\sigma> &= \sigma_0 = f_\pi \\ <\pi> &= 0 \\ M_N &= g_\pi\sigma_0 = g_\pi f_\pi \end{aligned}$$

How about QCD trace anomaly in effective models?

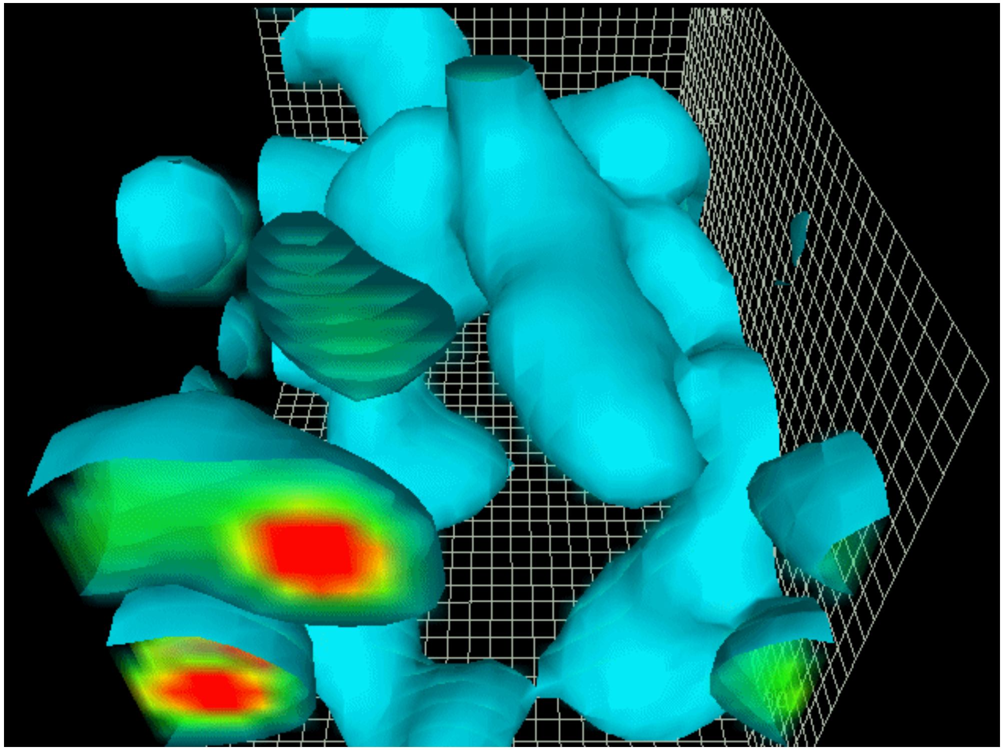
The effective chiral quark Lagrangian supplemented with the QCD conformal anomaly

$$\begin{aligned} L &= \bar{\psi} i(\not{D} + \not{V})\psi + g_A \bar{\psi} \not{A} \gamma_5 \psi - \sqrt{\kappa}\frac{m}{f_\pi}\bar{\psi}\psi\chi + \frac{1}{4}\kappa tr(\partial_\mu U \partial^\mu U^\dagger)\chi^2 \\ &+ \frac{1}{2}\partial_\mu \chi \partial^\mu \chi - \frac{1}{2} tr(G_{\mu\nu}G^{\mu\nu}) - V(\chi) + \ldots \end{aligned}$$

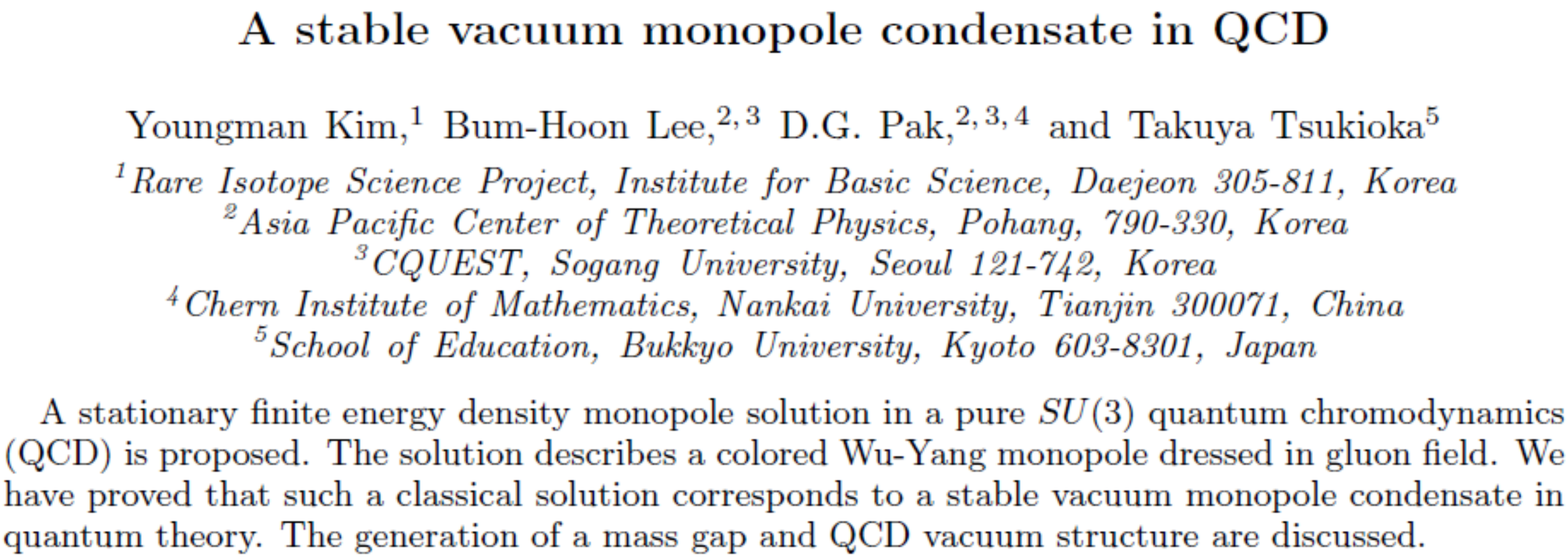
where $D_\mu = \partial_\mu + igG_\mu$, $V_\mu = \frac{1}{2}i(\xi^\dagger \partial_\mu \xi + \xi \partial_\mu \xi^\dagger)$ and $A_\mu = \frac{1}{2}i(\xi^\dagger \partial_\mu \xi - \xi \partial_\mu \xi^\dagger)$ with $\xi^2 = U = \exp(\frac{i2\pi_i T_i}{f_\pi})$. The scale anomaly of QCD appearing at quantum level is contained in the potential V written as

$$V(\chi) = -\frac{\kappa m_\chi^2}{8{f_\pi}^2}[\frac{1}{2}\chi^4 - \chi^4 \ln(\frac{\kappa \chi^2}{f_\pi^2})]$$

Motivation III



http://www.physics.adelaide.edu.au/theory/staff/leinweber/VisualQCD/QCDvacuum/su3b600s24t36cool30actionEnd.gif



A stable vacuum monopole condensate in QCD

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[2] *Asia Pacific Center of Theoretical Physics, Pohang, 790-330, Korea*
[3] *CQUEST, Sogang University, Seoul 121-742, Korea*
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A stationary finite energy density monopole solution in a pure $SU(3)$ quantum chromodynamics (QCD) is proposed. The solution describes a colored Wu-Yang monopole dressed in gluon field. We have proved that such a classical solution corresponds to a stable vacuum monopole condensate in quantum theory. The generation of a mass gap and QCD vacuum structure are discussed.

Nontrivial QCD vacuum does nothing to nuclei?
Confinement wash it out?
All encrypted in LECs except chiral symmetry?

Here, the focus will be on a nucleon mass and a possible role of nuclear structure in clarifying the origin of the nucleon mass.

Nucleon mass in the chiral limit: two different pictures

$$m_\pm = \frac{1}{2}\left(\sqrt{(g_1+g_2)^2\sigma_0^2 + 4m_0^2} \pm (g_1-g_2)\sigma_0\right)$$

in parity doublet model

$$\begin{aligned} <\sigma> &= \sigma_0 = f_\pi \\ <\pi> &= 0 \\ M_N &= g_\pi\sigma_0 = g_\pi f_\pi \end{aligned}$$

in linear sigma model

Extended Parity doublet model

Introduce two nucleon fields that transform in a mirror way under chiral transformations:

$$\mathrm{SU}_L(2) \times \mathrm{SU}(2)_R$$

$$\psi_{1R} \to R\psi_{1R}, \quad \psi_{1L} \to L\psi_{1L},$$
$$\psi_{2R} \to L\psi_{2R}, \quad \psi_{2L} \to R\psi_{2L}.$$

$$m_0(\bar{\psi}_2\gamma_5\psi_1 - \bar{\psi}_1\gamma_5\psi_2)$$
$$= m_0(\bar{\psi}_{2L}\psi_{1R} - \bar{\psi}_{2R}\psi_{1L} - \bar{\psi}_{1L}\psi_{2R} + \bar{\psi}_{1R}\psi_{2L})$$

the decay width $\Gamma_{N\pi}$ for $N^*(1535) \to N + \pi$, $\quad m_0 = 270$ MeV

“Linear sigma model with parity doubling,” C. E. DeTar and T. Kunihiro, Phys. Rev. D **39**, 2805 (1989)

$$
\begin{aligned}
\mathcal{L} = {} & \bar{\psi}_1 i \not\partial \psi_1 + \bar{\psi}_2 i \not\partial \psi_2 + m_0 (\bar{\psi}_2 \gamma_5 \psi_1 - \bar{\psi}_1 \gamma_5 \psi_2) \\
& + a \bar{\psi}_1 (\sigma + i \gamma_5 \vec{\tau} \cdot \vec{\pi}) \psi_1 + b \bar{\psi}_2 (\sigma - i \gamma_5 \vec{\tau} \cdot \vec{\pi}) \psi_2
\end{aligned}
$$

$$
m_{N\pm} = \frac{1}{2} \left(\sqrt{(a+b)^2 \sigma^2 + 4 m_0^2} \mp (a-b) \sigma \right)
$$

The state N+ is the nucleon N(938). while N- is its parity partner conventionally identified with N(1500).

Cf. $$\delta \mathcal{L} = -g_\pi \left[(i \bar{\psi} \gamma_5 \vec{\tau} \psi) \vec{\pi} + (\bar{\psi} \psi) \sigma \right]$$

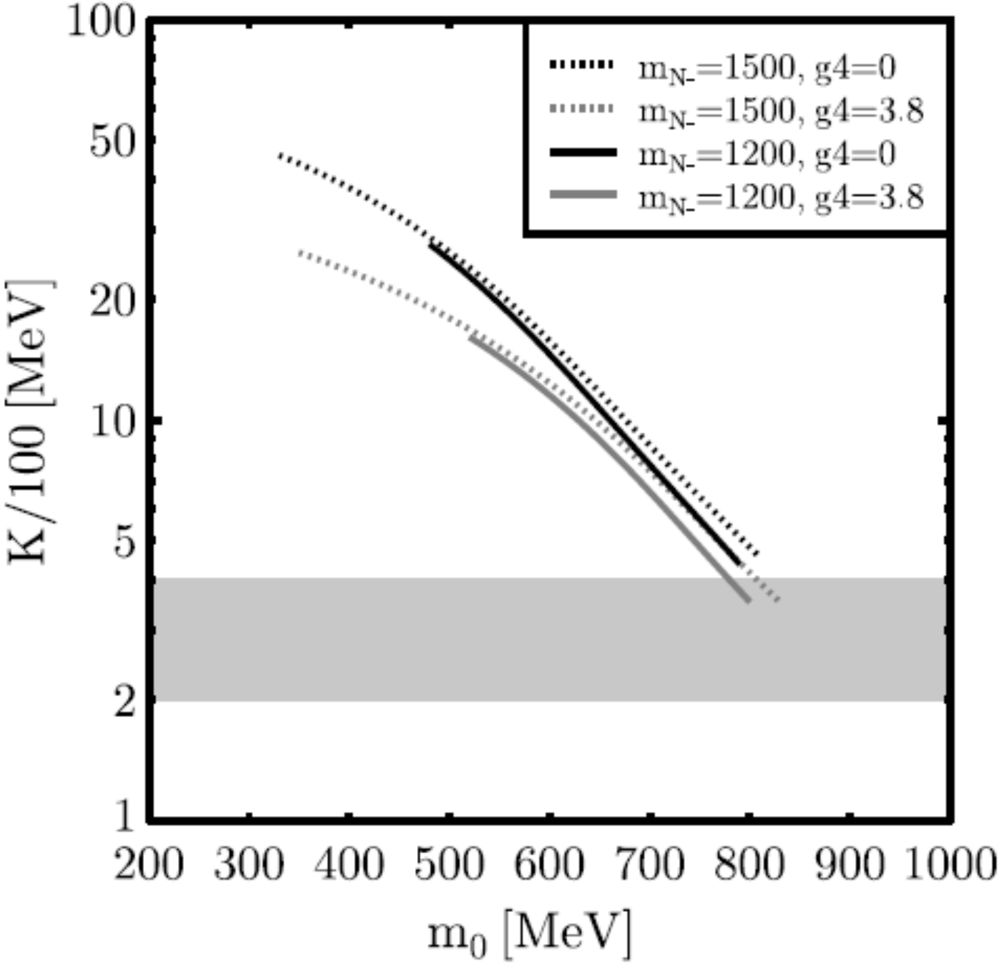
$$
\begin{aligned}
< \sigma > & = \sigma_0 = f_\pi \\
< \pi > & = 0 \\
M_N & = g_\pi \sigma_0 = g_\pi f_\pi
\end{aligned}
$$

Cold, dense nuclear matter in a SU(2) parity doublet model

$$\begin{aligned}
\mathcal{L} = {} & \bar{\psi}_1 i \not\partial \psi_1 + \bar{\psi}_2 i \not\partial \psi_2 + m_0 (\bar{\psi}_2 \gamma_5 \psi_1 - \bar{\psi}_1 \gamma_5 \psi_2) \\
& + a \bar{\psi}_1 (\sigma + i \gamma_5 \vec{\tau} \cdot \vec{\pi}) \psi_1 + b \bar{\psi}_2 (\sigma - i \gamma_5 \vec{\tau} \cdot \vec{\pi}) \psi_2 \\
& - g_\omega \bar{\psi}_1 \gamma_\mu \omega^\mu \psi_1 - g_\omega \bar{\psi}_2 \gamma_\mu \omega^\mu \psi_2 + \mathcal{L}_M ,
\end{aligned}$$

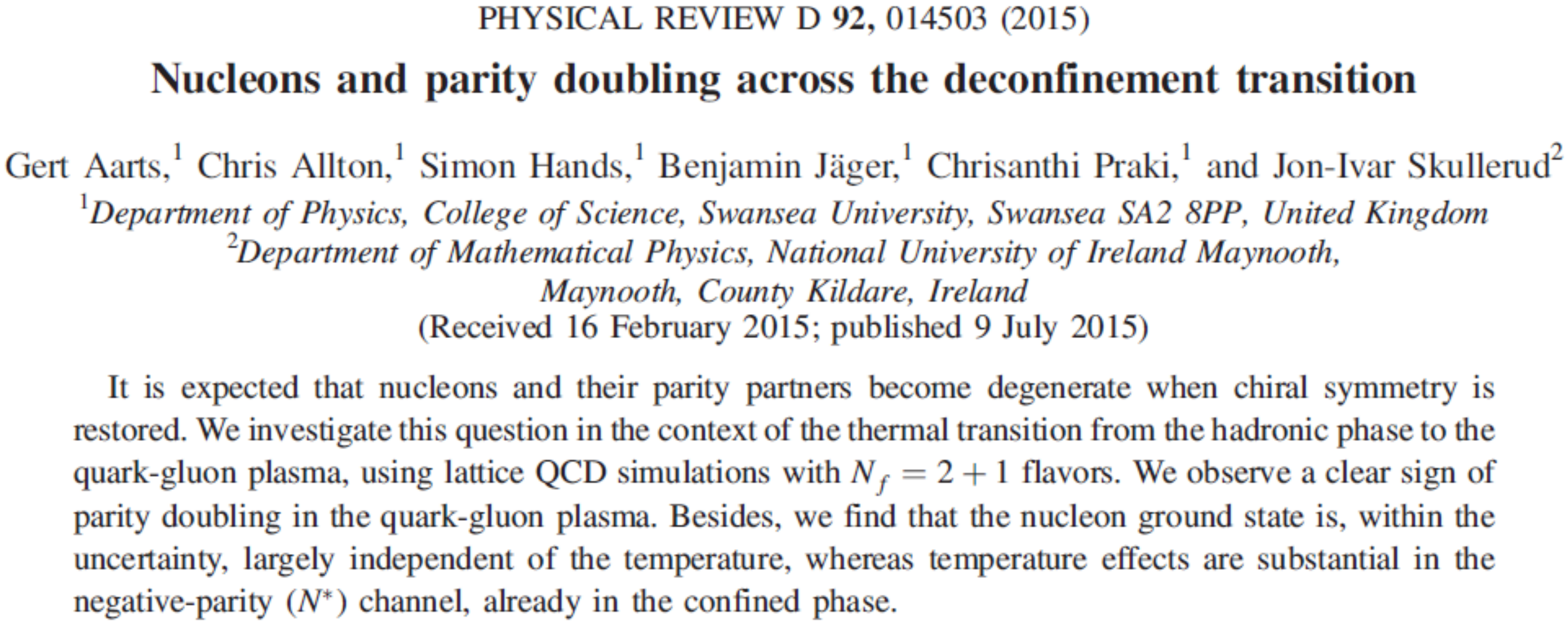
$$\begin{aligned}
\mathcal{L}_M = {} & \frac{1}{2} \partial_\mu \sigma^\mu \partial^\mu \sigma_\mu + \frac{1}{2} \partial_\mu \vec{\pi}^\mu \partial^\mu \vec{\pi}_\mu - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \\
& + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu + g_4^4 (\omega_\mu \omega^\mu)^2 \\
& + \frac{1}{2} \bar{\mu}^2 (\sigma^2 + \vec{\pi}^2) - \frac{\lambda}{4} (\sigma^2 + \vec{\pi}^2)^2 + \epsilon \sigma ,
\end{aligned}$$

D. Zschiesche, L. Tolos, Jurgen Schaffner-Bielich, Robert D. Pisarski, Phys. Rev. C75 (2007) 055202



If the N' is identified as the $N'(1535)$, the parity doublet model shows a first order phase transition to a chirally restored phase at large densities, $\rho \approx 10\rho_0$, defining the transition by the degeneracy of the masses of the nucleon and the N'. If the mass of the N' is chosen to be 1.2 GeV, then the critical density of the chiral phase transition is lowered to three times normal nuclear matter density,

D. Zschiesche, L. Tolos, Jurgen Schaffner-Bielich, Robert D. Pisarski, Phys .Rev. C75 (2007) 055202



PHYSICAL REVIEW D **92,** 014503 (2015)

Nucleons and parity doubling across the deconfinement transition

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It is expected that nucleons and their parity partners become degenerate when chiral symmetry is restored. We investigate this question in the context of the thermal transition from the hadronic phase to the quark-gluon plasma, using lattice QCD simulations with $N_f = 2 + 1$ flavors. We observe a clear sign of parity doubling in the quark-gluon plasma. Besides, we find that the nucleon ground state is, within the uncertainty, largely independent of the temperature, whereas temperature effects are substantial in the negative-parity (N^*) channel, already in the confined phase.

may imply m_0~m_N ? Or, m_0 increases as T goes up?

Parity doublet model with HLS

Motivation:

- Lower m_0 ?
- Non-zero isospin density (chemical potential)
- Lower T_c for (chiral) transitions?
- Any sensitive observables to m_0 from nuclear structure or HIC?

Hidden Local Symmetry

A way to introduce vector mesons in chiral Lagrangian

Non–linear sigma model

$$\mathrm{SU}(N_f)_\mathrm{L} \times \mathrm{SU}(N_f)_\mathrm{R} / \mathrm{SU}(N_f)_\mathrm{V}$$

$$U = \mathrm{e}^{2\mathrm{i}\pi/F_\pi}, \quad \pi = \pi_a T_a$$

$$U \to g_\mathrm{L}\, U\, g_\mathrm{R}^\dagger \ .$$

HLS

$$G_\mathrm{global} \times H_\mathrm{local} \quad H = \mathrm{SU}(N_f)_\mathrm{V}$$

$$U = \xi_\mathrm{L}^\dagger \xi_\mathrm{R} \quad \xi_\mathrm{L,R} = \mathrm{e}^{\mathrm{i}\sigma/F_\sigma} \mathrm{e}^{\mp i\pi/F_\pi}$$

$$\xi_\mathrm{L,R}(x) \to \xi'_\mathrm{L,R}(x) = h(x) \cdot \xi_\mathrm{L,R}(x) \cdot g^\dagger_\mathrm{L,R}$$

$$h(x) \in H_\mathrm{local}, \quad g_\mathrm{L,R} \in G_\mathrm{global}$$

gauge equivalent to the non-linear sigma model corresponding to the coset space G/H

(HLS has to assume that the kinetic term of the HLS gauge boson is to be generated dynamically)

M. Harada and K. Yamawaki, Physics Reports 381 (2003) 1

Parity doublet model with HLS

$$\begin{aligned}\mathcal{L}_N = {} & \bar{\psi}_{1r} i\gamma^\mu D_\mu \psi_{1r} + \bar{\psi}_{1l} i\gamma^\mu D_\mu \psi_{1l} \\ & + \bar{\psi}_{2r} i\gamma^\mu D_\mu \psi_{2r} + \bar{\psi}_{2l} i\gamma^\mu D_\mu \psi_{2l} \\ & - m_0[\bar{\psi}_{1l}\psi_{2r} - \bar{\psi}_{1r}\psi_{2l} - \bar{\psi}_{2l}\psi_{1r} + \bar{\psi}_{2r}\psi_{1l}] \\ & - g_1[\bar{\psi}_{1r} M^\dagger \psi_{1l} + \bar{\psi}_{1l} M \psi_{1r}] \\ & - g_2[\bar{\psi}_{2r} M \psi_{2l} + \bar{\psi}_{2l} M^\dagger \psi_{2r}],\end{aligned}$$

$$M = \sigma + i\vec{\pi}\cdot\vec{\tau}, \quad M \to g_L M g_R^\dagger$$

HLS

$$M = \xi_L \sigma \xi_R = \sigma \xi_L^\dagger \xi_R = \sigma U, \quad \xi_{L,R} \to h_\omega h_\rho \xi_{L,R} g_{L,R}^\dagger,$$

$$\omega_\mu \to h_\omega \omega_\mu h_\omega^\dagger + \frac{i}{g_\omega} \partial_\mu h_\omega h_\omega^\dagger,$$
$$\rho_\mu \to h_\rho \rho_\mu h_\rho^\dagger + \frac{i}{g_\rho} \partial_\mu h_\rho h_\rho^\dagger,$$

$$\begin{aligned}\mathcal{L}_M =&\frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma + \sigma^2 \mathrm{tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_\perp^\mu\right] - V_\sigma - V_{SB} \\ &+ \frac{m_\rho^2}{g_\rho^2}\mathrm{tr}\left[\hat{\alpha}_{\parallel\mu}\hat{\alpha}_\parallel^\mu\right] + \left(\frac{m_\omega^2}{2g_\omega^2} - \frac{m_\rho^2}{2g_\rho^2}\right)\mathrm{tr}\left[\hat{\alpha}_{\parallel\mu}\right]\mathrm{tr}\left[\hat{\alpha}_\parallel^\mu\right] \\ &- \frac{1}{2g_\rho^2}\mathrm{tr}\left[\rho_{\mu\nu}\rho^{\mu\nu}\right] - \left(\frac{1}{2g_\omega^2} - \frac{1}{2g_\rho^2}\right)\mathrm{tr}\left[\omega_{\mu\nu}\right]\mathrm{tr}\left[\omega^{\mu\nu}\right]\end{aligned}$$

$$\begin{aligned}\hat{\alpha}_\perp^\mu &\equiv \frac{1}{2i}\left[D^\mu\xi_R\cdot\xi_R^\dagger - D^\mu\xi_L\cdot\xi_L^\dagger\right] \\ \hat{\alpha}_\parallel^\mu &\equiv \frac{1}{2i}\left[D^\mu\xi_R\cdot\xi_R^\dagger + D^\mu\xi_L\cdot\xi_L^\dagger\right]\end{aligned}$$

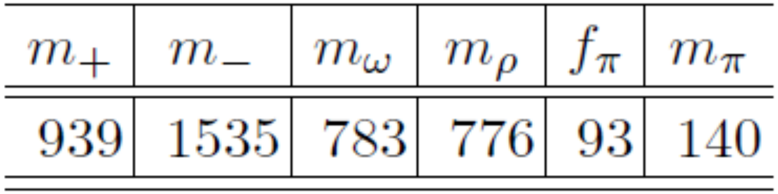
$$\begin{aligned}D^\mu\xi_L &= \partial^\mu\xi_L + ig_\rho\rho^\mu\xi_L + ig_\omega\omega^\mu\xi_L + i\xi_L\mathcal{L}^\mu \\ D^\mu\xi_R &= \partial^\mu\xi_R + ig_\rho\rho^\mu\xi_R + ig_\omega\omega^\mu\xi_R + i\xi_R\mathcal{R}^\mu\end{aligned}$$

Y. Motohiro, YK, M. Harada, PRC 92, 025201 (2015)

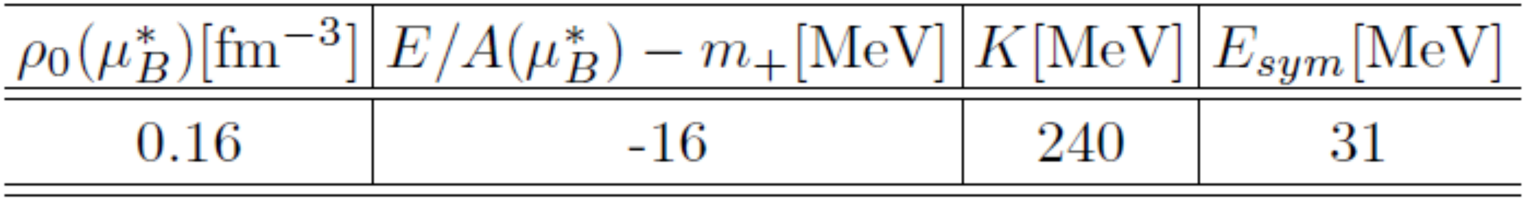
$$V_\sigma = -\tfrac{1}{2}\bar{\mu}^2\sigma^2 + \tfrac{1}{4}\lambda\sigma^4 - \tfrac{1}{6}\lambda_6\sigma^6,$$

$$V_{\mathrm{SB}} = -\tfrac{1}{4}\bar{m}\epsilon\sigma\,\mathrm{tr}[U + U^\dagger].$$

Inputs to fix the model parameters



m_+	m_-	m_ω	m_ρ	f_π	m_π
939	1535	783	776	93	140



$\rho_0(\mu_B^*)[\mathrm{fm}^{-3}]$	$E/A(\mu_B^*) - m_+[\mathrm{MeV}]$	$K[\mathrm{MeV}]$	$E_{sym}[\mathrm{MeV}]$
0.16	-16	240	31

Symmetry energy

$$\mathcal{E}(\rho,\alpha)=\mathcal{E}(\rho,\alpha=0)+S(\rho)\alpha^2+\cdots \qquad \alpha = (N-Z)/A$$

$$S(\rho)\equiv\frac{1}{2}\left(\frac{\partial^2\mathcal{E}(\rho,\alpha)}{\partial\alpha^2}\right)_{\alpha=0}\approx\mathcal{E}(\rho,\alpha=1)-\mathcal{E}(\rho,\alpha=0)$$

$$S(\rho)=J+Lx+\tfrac{1}{2}K_{\mathrm{sym}}x^2+\cdots \qquad x=(\rho-\rho_0)/3\rho_0 \qquad L\equiv 3\rho_0\left(\frac{\partial S}{\partial\rho}\right)\Bigg|_{\rho_0}$$

Favors N=Z, one may say it is energy cost to convert all the protons in (symmetric) nuclear matter to neutrons at a fixed density

$$m = Zm_p + Nm_n - \frac{E_B}{c^2}$$

Liquid-drop model

$$E_{\mathrm{B}} = a_{\mathrm{v}}A - a_a(N-Z)^2/A - a_cZ^2/A^{1/3} - a_sA^{2/3} \pm a_\delta/A^{3/4}$$

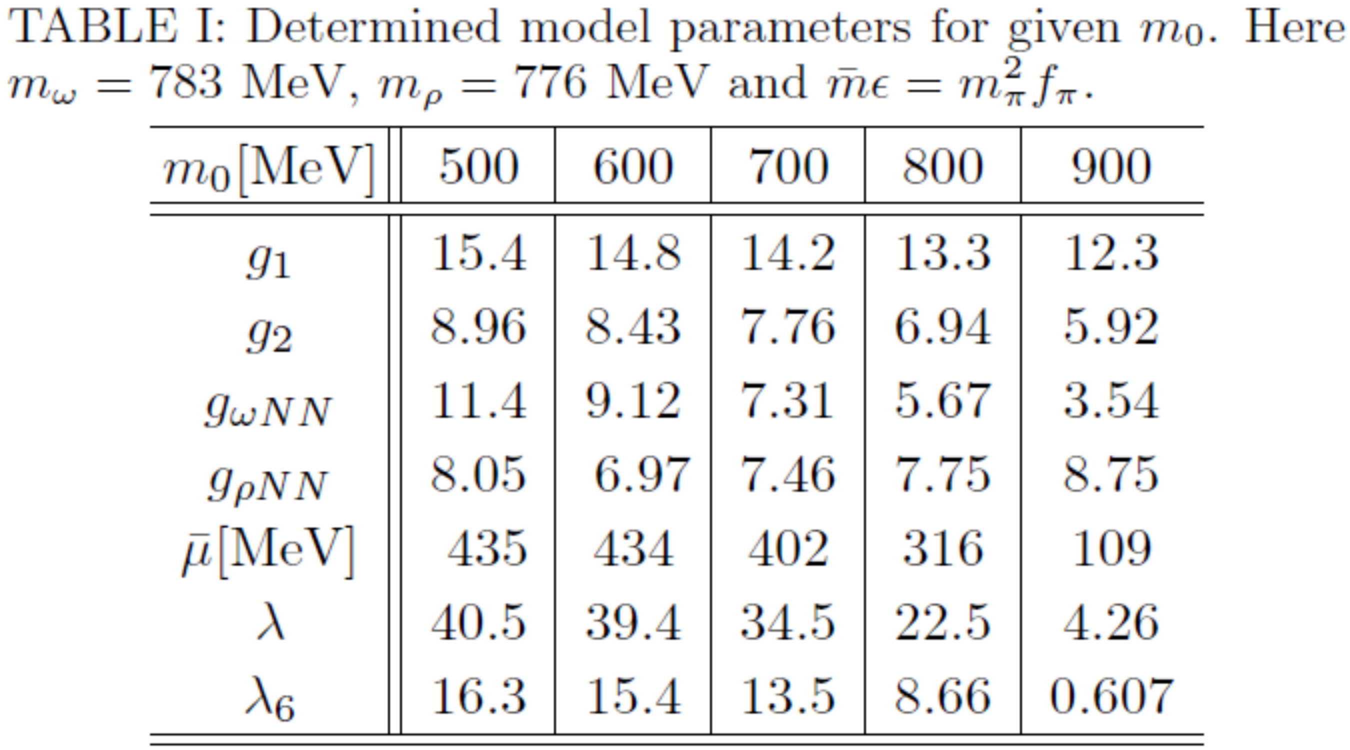
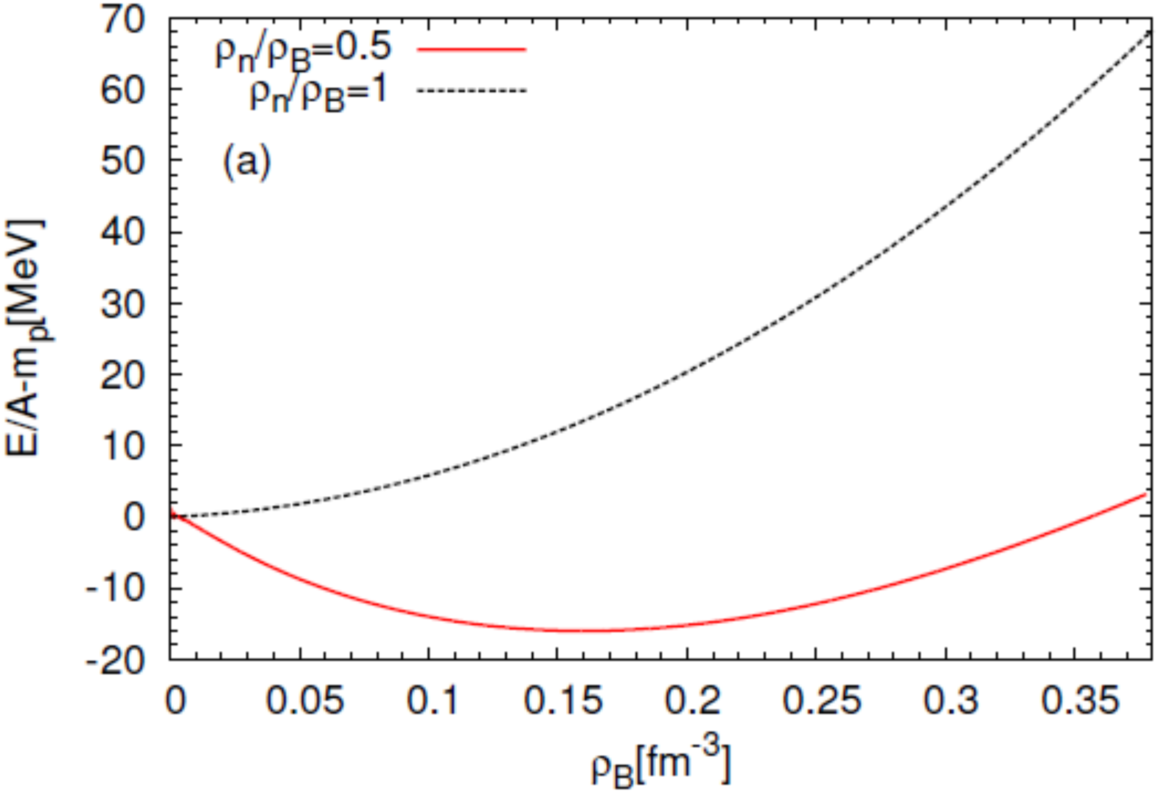


TABLE I: Determined model parameters for given m_0. Here $m_\omega = 783$ MeV, $m_\rho = 776$ MeV and $\bar{m}\epsilon = m_\pi^2 f_\pi$.

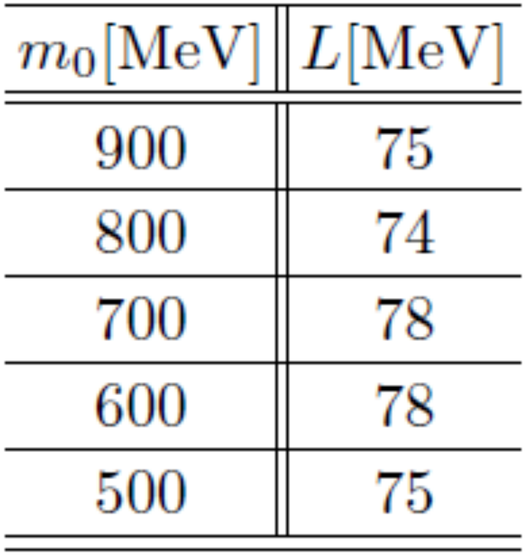
m_0[MeV]	500	600	700	800	900
g_1	15.4	14.8	14.2	13.3	12.3
g_2	8.96	8.43	7.76	6.94	5.92
$g_{\omega NN}$	11.4	9.12	7.31	5.67	3.54
$g_{\rho NN}$	8.05	6.97	7.46	7.75	8.75
$\bar{\mu}$[MeV]	435	434	402	316	109
λ	40.5	39.4	34.5	22.5	4.26
λ_6	16.3	15.4	13.5	8.66	0.607

Note that in free space m_0=(270-500) MeV



Density dependence of the binding energy

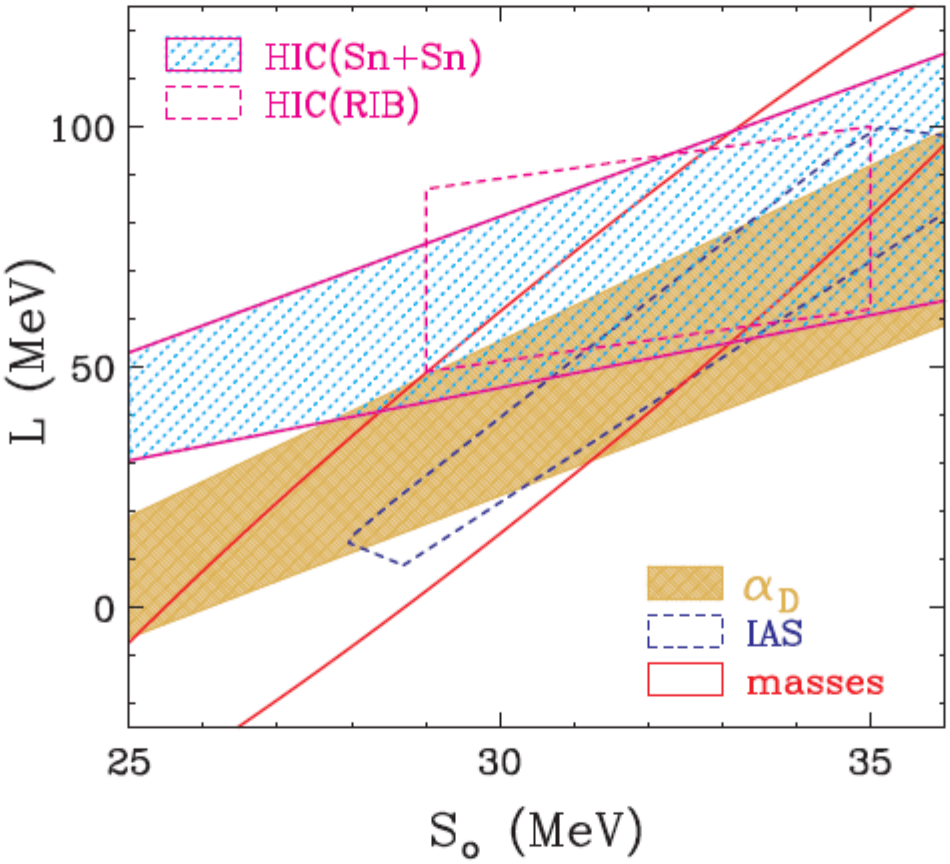
slope parameter



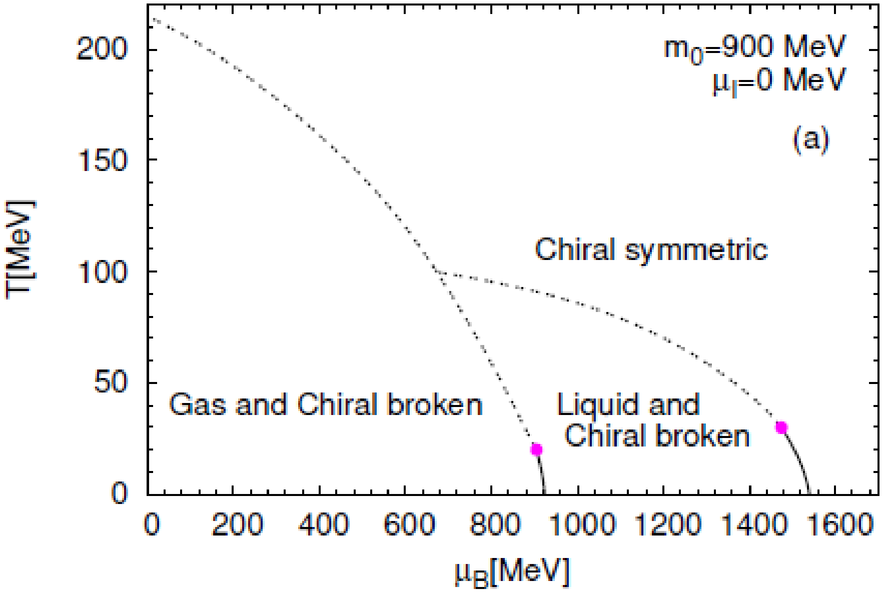
m_0[MeV]	L[MeV]
900	75
800	74
700	78
600	78
500	75

S_0=31 MeV

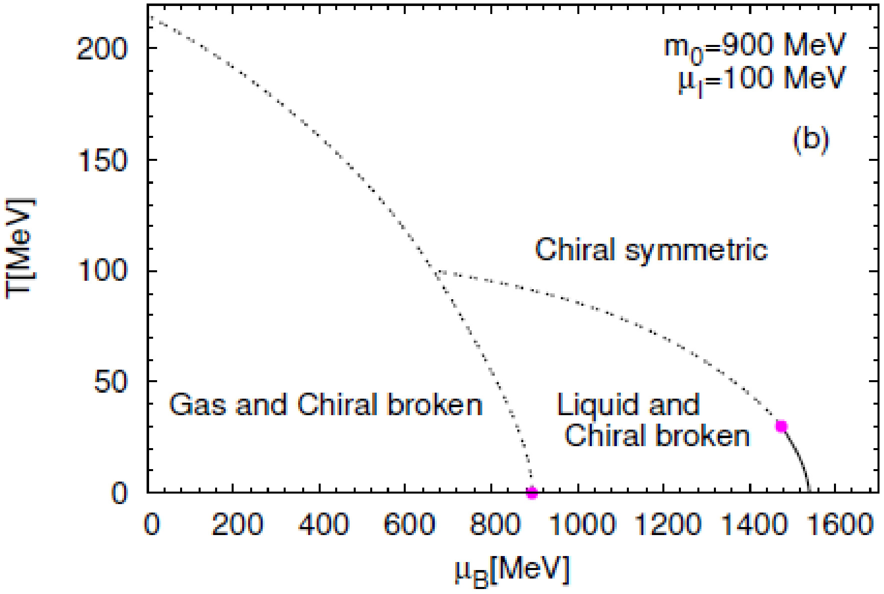
J. Phys. G: Nucl. Part. Phys. **41** (2014) 093001



Phase diagrams for m_0 = 900 MeV

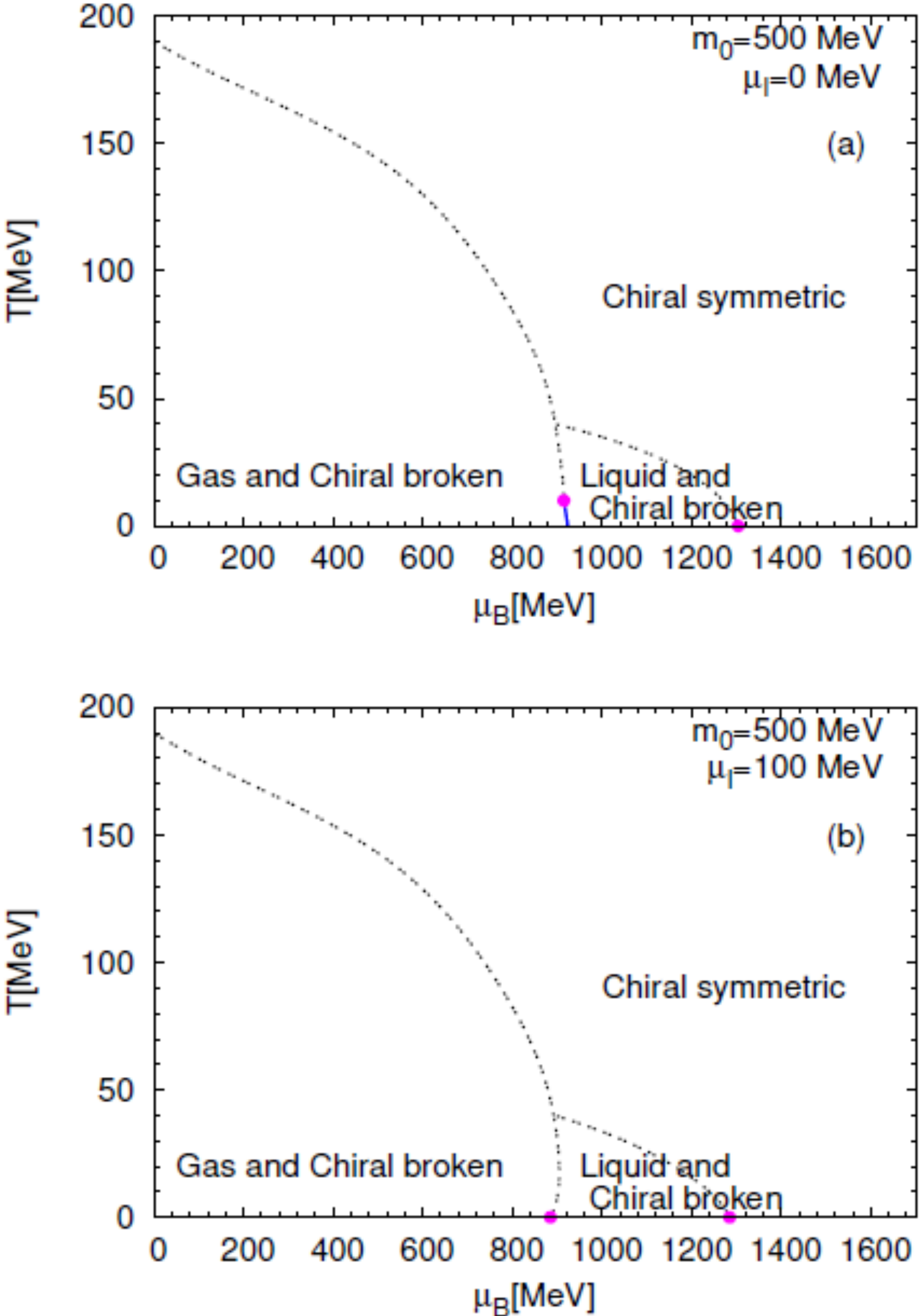


solid: first-order,
dashed: crossover
point: critical point (second order)



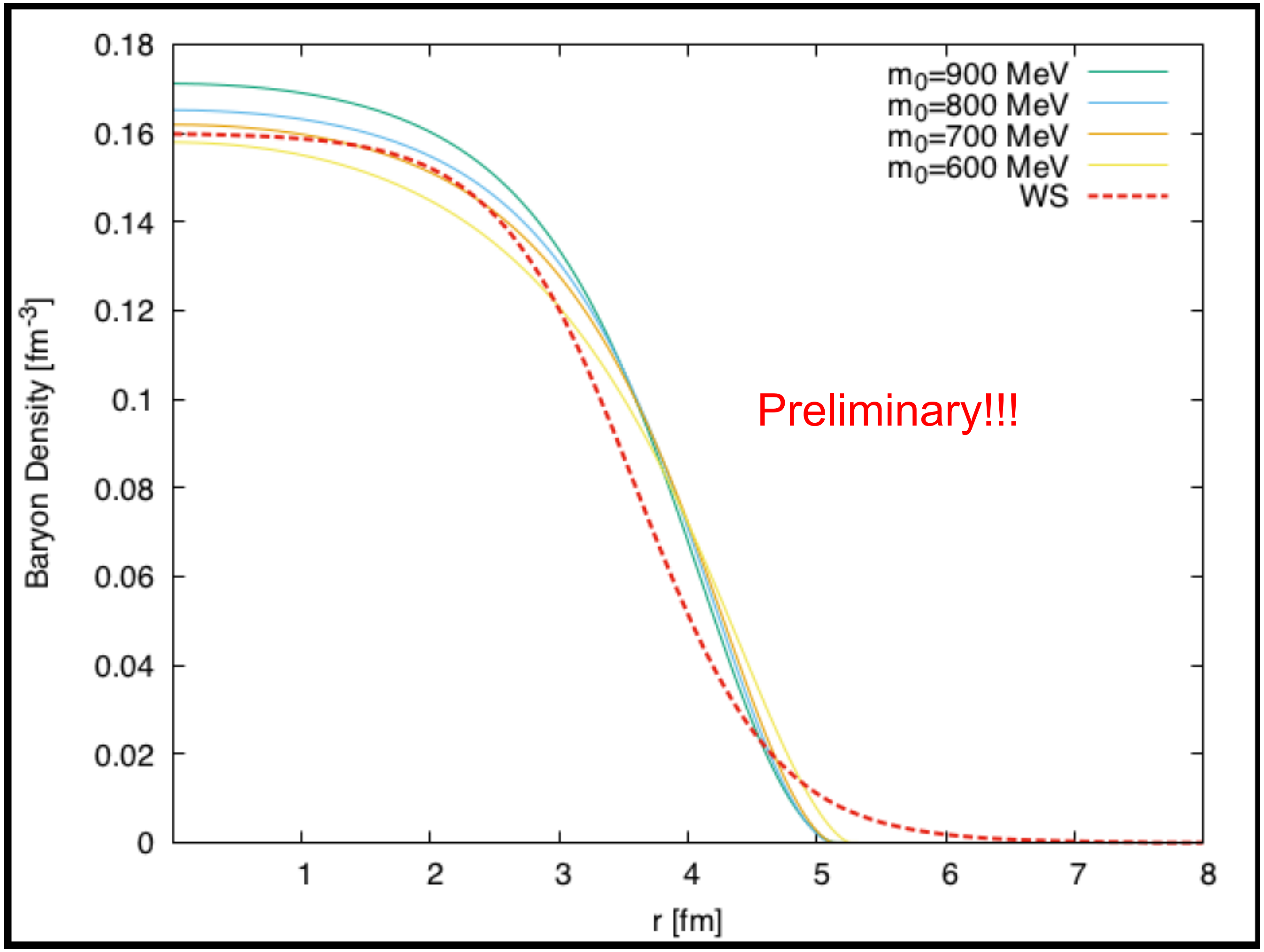
LGT: 1st→ 2nd
Critical chemical potential
drops a bit

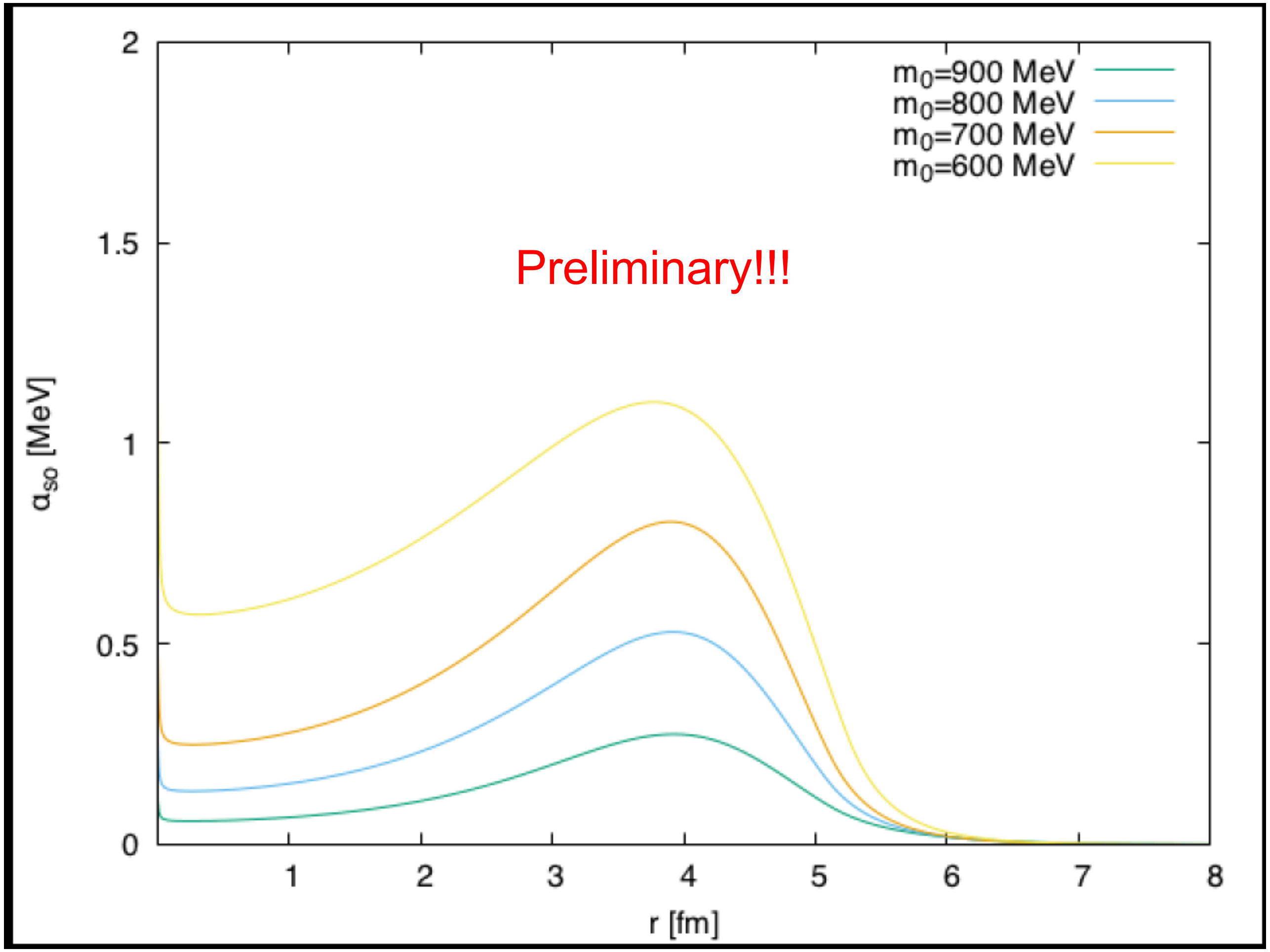
Phase diagrams for m_0 = 500 MeV



smaller m_0 favors
smaller critical density for
chiral phase transition
both in symmetric and asymmetric
dense matter

Nuclei in RTF





$$V_{\rm so}(r) = \frac{1}{2m_+^2 r}\left(g_\omega \frac{d\omega_0}{dr} - \frac{dm_+}{dr}\right)\boldsymbol{s}\cdot\boldsymbol{L} \equiv -\alpha(r)\boldsymbol{s}\cdot\boldsymbol{L}$$

Summary

- RAON will be available from 2020
- Parity doublet model might be a framework to say somet hing about the remnants of QCD in nuclei
- Eventually, we need to have model-independent method for new clear physics!

Remarks:

Nuclei in a chiral SU(3) model, P. Papazoglou, et al, Phys. Rev. C59 (1999)

Finite nuclei in relativistic models with a light chiral scalar meson,
R.J. Furnstahl, et al. Phys. Rev. C47 (1993) 2338

Relativistic chiral mean field model for finite nuclei,
H. Toki, et al, PPNP 59 (2007) 209