Compact stars from holographic QCD

Chang-Hwan Lee @ PUSAN NATIONAL UNIVERSITY

We didn't have any nuclear accelerator

but, in 2011, government approved
Korean Rare Isotope Accelerator

KoRIA(nick name) → RAON(official name)

RAON

"라온"

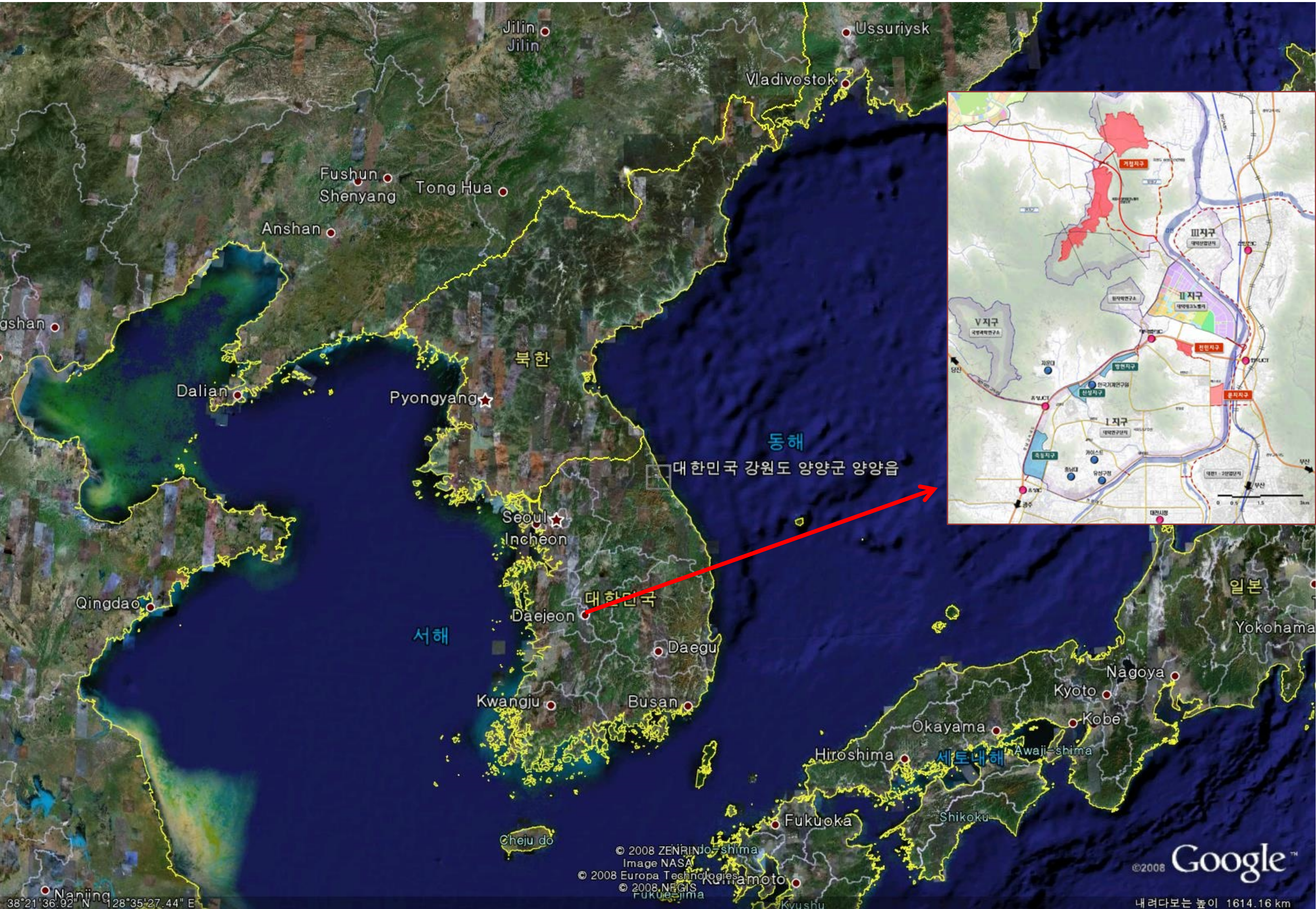
a pure Korean word
meaning Delightful, Joyful, Happy,…

"with a wish that this accelerator would be a delightful gift for scientists all over the world and for the bright future of mankind."

Brief History

- International Science Business Belt(ISBB) plan (2009.1)
- Preliminary Design Study (2009.3-2010.2)
- Conceptual Design study (2010.3-2011.2)
- International Advisory Committee(2011.7)
- **Institute for Basic Science(IBS)** established(2011.11)
- **Rare Isotope Science Project(RISP)** launched(2011.12)
  - ***Rare isotope accelerator complex is the representative facility of IBS***
- Technical Advisory Committee(2012.5)
- Baseline Design Summary (2012.6)
- International Advisory Committee(2012.7)
- Technical Design (present – 2013.6)

Location


Jilin
Jilin
Ussuriysk
Vladivostok
Fushun
Shenyang
Tong Hua
Anshan
gshan
Dalian
Pyongyang
북한
동해
대한민국 강원도 양양군 양양읍
Seoul
Incheon
Qingdao
Daejeon
대한민국
서해
Daegu
Kwangju
Busan
일본
Yokohama
Nagoya
Kyoto
Kobe
Okayama
Hiroshima
세토내해
Awaji-shima
Shikoku
Fukuoka
Cheju do
Nanjing
© 2008 ZENRIN
Image NASA
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© 2008 NFGIS
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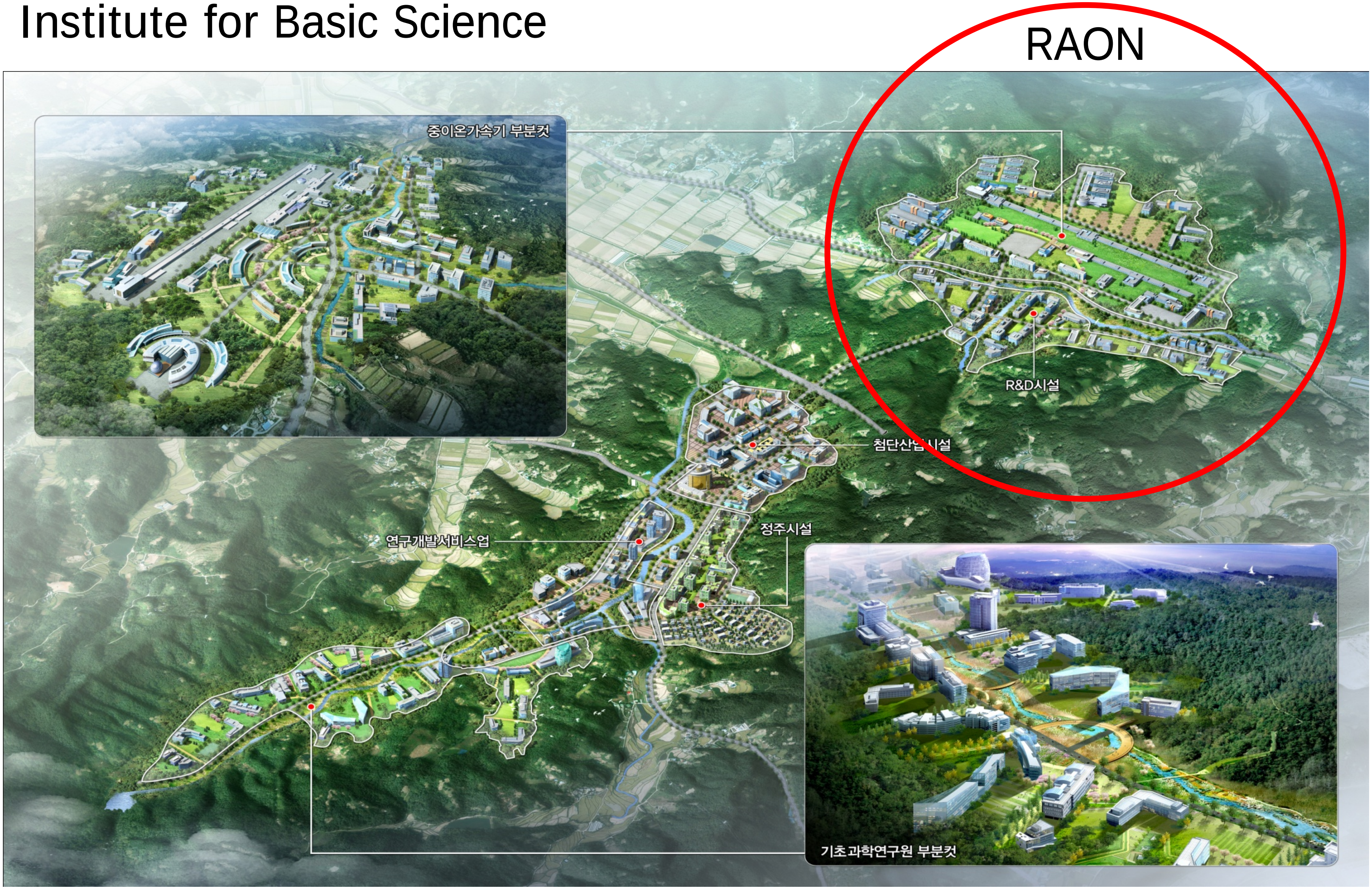
38°21'36.92" N 128°35'27.44" E
내려다보는 높이 1614.16 km
I 지구
II 지구
III지구
V 지구

Institute for Basic Science



Accelerator : RAON

High intensity rare isotope beam with ISOL and IF methods

- 70MeV, 1mA proton beam, ^{238}U target - 70kW ISOL system
- 200MeV/u, 8.3pμA, ^{238}U beam and other stable isotope beam - 400kW IF system

- **High current high purity neutron-rich RI beam**

  For example, ^{132}Sn : ~250MeV/u, ~ 10^8 pps

  - ISOL + acceleration

- **Production of exotic beams combining ISOL and IF methods**
- **Simultaneous operation of IF and ISOL systems**

Design Consideration for the future

- Wide variety of isotope beams
- Upgradable to higher energy and higher intensity
- World leading RI beam facility for longer term

Research area with rare isotopes

RISP

Pure Science

Nuclear Physics

- Nuclei with excessive neutrons
- New elements
- Equation of state of nucleus

Nuclear astrophysic

- Origin of elements
- Nucleosythesis
- Evolution of stars, neutron stars, supernovae

Atomic/Particle Physics

- Atomic trap
- Fundamental Symmetries

Application for the society

Nuclear Data - Energy

- Basic data for next generation nuclear reactor
- Transmutation of nuclear waste

Material Science

- New material development
- New method of characterization

  β-NMR / μSR

Bio & medical application

- New medical theraphy
- Genetic modification
- New isotopes for medical imaging

Science topics

RISP

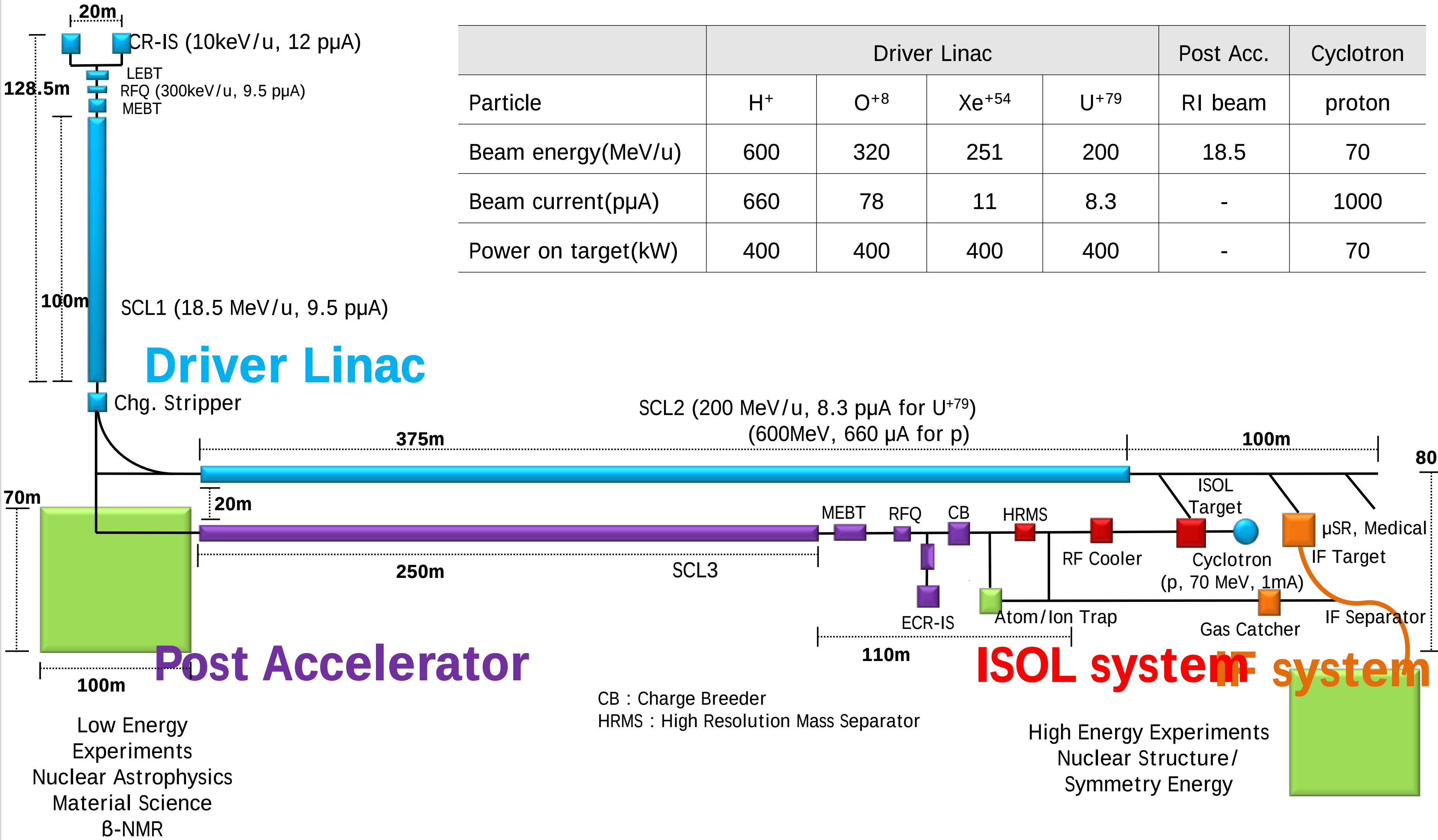
Research Field	Theme	Topics	Example reactions Apparatus	Beam	Production
Nuclear Science	Origin of elements/ Stellar Evolution	r-process waiting point	· ^{123}Nb, ^{124}Mo, ^{125}Tc, ^{126}Ru · Decay Station	· primary beam(PB) : ^{238}U - E: 200 AMeV - Intensity: > 1 pμA	· IF
		Contribution of isomer interaction to nucleosynthesis	· $^{26m}Al+p \rightarrow {}^{27}Si+\gamma$ · Recoil Spectrometer	· PB : ^{28}Si · SB : ^{26m}Al - E: < 5 AMeV - Intensy: > 10^7 pps	· IF
		Escape process to rp-proces	· $^{15}O+\alpha \rightarrow {}^{19}Ne+\gamma$ · Recoil Spectrometer	· PB : p(ISOL), ^{16}O(IF) · SB : ^{15}O - E: < 10 AMeV - Intensity: > 10^{10} pps	· ISOL · IF
		Superheavy elements	· $^{64}Ni + {}^{238}U \rightarrow {}^{299}120 + 3n$ · SHE spectrometer	· PB: ^{64}Ni - E: < few AMeV - Intensity: > few pμA	· Stable Ion Beam
	Nuclear structure and Nuclear force	Nuclear structure of rare isotopes with neutron magic number near 126	· $^{144}Xe + {}^{208}Pb \rightarrow {}^{196}Yb + X$ · Decay Station	· SB: ^{144}Xe - E: > 100 AMeV - Intensity: > 10^6 pps	· ISOL
		Symmetry energy	· $^{132}Sn+{}^{119}Sn \rightarrow X+Y$ · Large Acceptance Spectrometer	· PB:p(ISOL), ^{238}U(IF) · SB: ^{132}Sn - E: 10~250 AMeV - Intensity: > 10^7 pps	· ISOL (Low E) · IF (High E)
	Nuclear data	Neutron capture cross section	· p + Be, Li, C · neutron irradiation facility	· PB: p - 70 MeV (p) - 1 kHz ~10 MHz pulse beam	· Cyclotron

Science topics

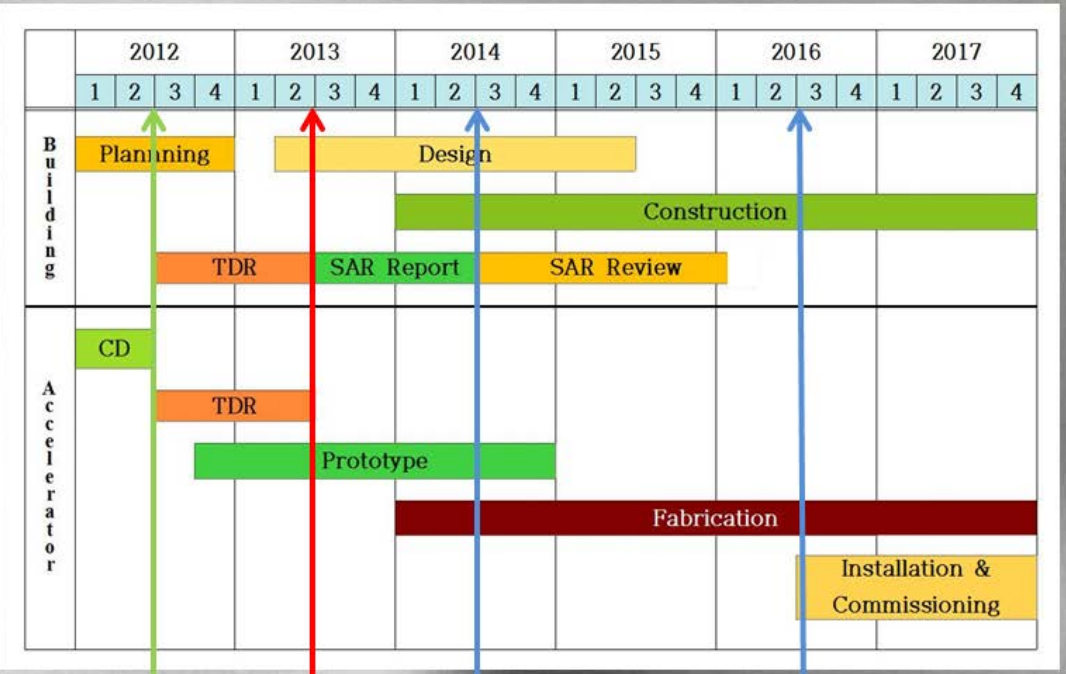
Research Field	Theme	Topics	Example reactions Apparatus	Beam	Production
Atomic and Molecular Physic	Mass and spectroscopy of rare isotopes	Study of rare isotopes near neutron Dripline	· medium mass n-rich beam · Atomic trap facility	· PB: p(ISOL), ^{238}U(IF) · SB : ^{132}Sn toward neutron drip line - E: < 60 keV - Intensity: > 1 pps	· ISOL · IF
Material Science	Characterization of new material	Local Electromagneic structure of material	· Low Mass RI beam · β-NMR, β-NQR · μSR spectroscopy	· PB : ^{8}Li, ^{11}Be, ^{15}O, ^{17}Ne, muon - E: < ~10 keV - Intensit: > 10^{8} pps	· ISOL · IF
Bio and Medical Science	Understanding	Biological optimization of heavy ion therapy and on-line imaging of dose of nuclear therapy	· Low Mass RI beam · RI irradiation facility	· SB : ^{8}B, ^{9}C, ^{11}C - E: 200~400 AMeV - Intensity: > 10^{7} pps	· ISOL · IF

Concept of RAON

	Driver Linac				Post Acc.	Cyclotron
Particle	H^{+}	O^{+8}	Xe^{+54}	U^{+79}	RI beam	proton
Beam energy(MeV/u)	600	320	251	200	18.5	70
Beam current(pμA)	660	78	11	8.3	-	1000
Power on target(kW)	400	400	400	400	-	70



Schedule and Major Milestone



Baseline Design Summary (June 2012)

Technical Design Report (by June 2013)

First SCL Module

Start Installation

- Ground breaking : 2014
- SAR clear : early 2016

For the success of RAON

We need your help

My interests & collaborators

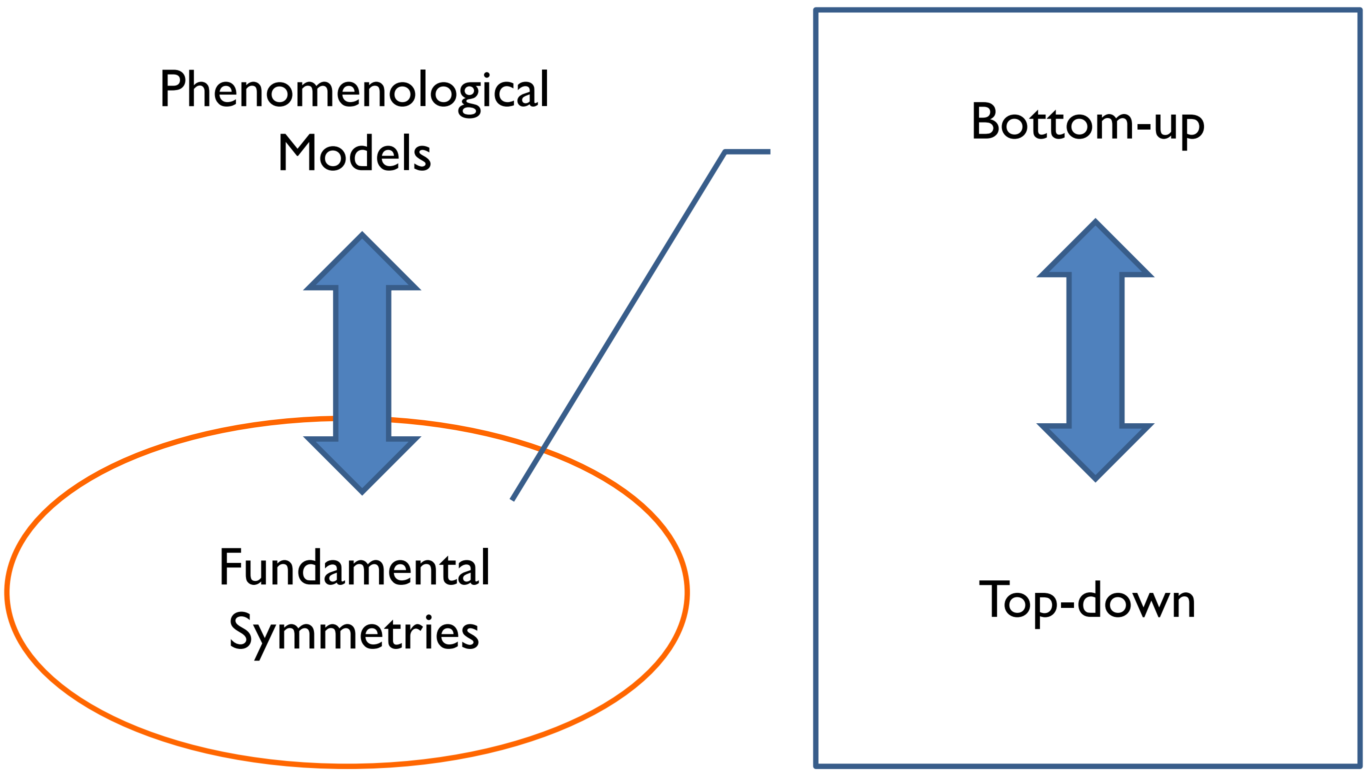
Something related to Neutron Stars

- NS equation of states : kaon condensation
  - M. Rho, G.E. Brown, et al.
- NS binary evolution, gamma-ray bursts, …
  - G.E. Brown, R.A.M.J. Wijers, et al.
- Gravitational-wave radiation from NS binary coalescence
  - with 2 Ph.D. students (Hee-Suk Cho, Young-Min Kim)
  - as a member of KGWG(Korean Gravitational Wave Group) & LSC (LIGO Scientific Collaboration)
- Compact Stars in hQCD
  (Y. Kim et al.)

1[st] visit to Hirschegg

2nd visit to Hirschegg

As a theorist : which way to go ?



This talk

Contents

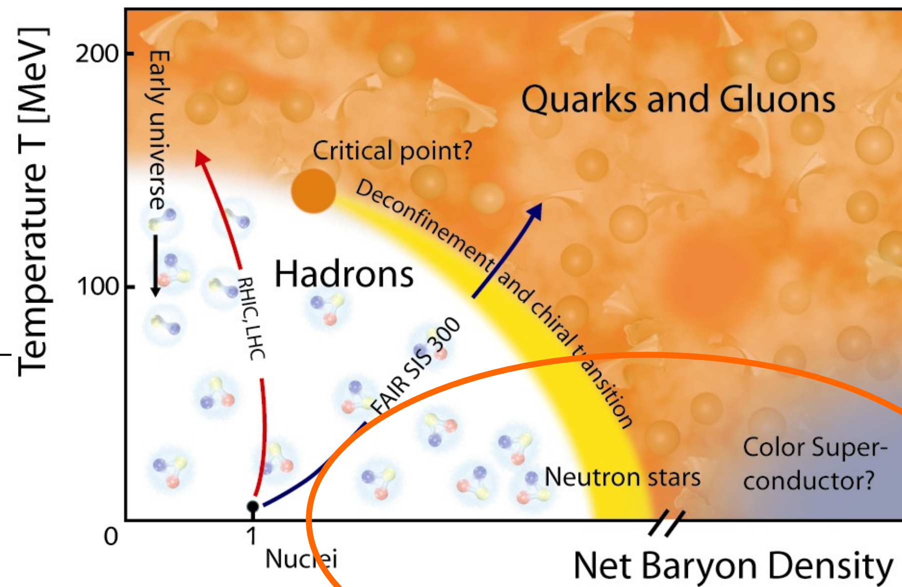
- Why neutron stars?
- Fundamental symmetries for dense matter
- Dense matter in hQCD
- Prospects

- The purpose of this talk is not to sell specific hQCD models
- but, to review my own perspectives on the connection between dense matter physics & hQCD

Why Neutron Stars ?

Ultimate Testing place for physics of dense matter

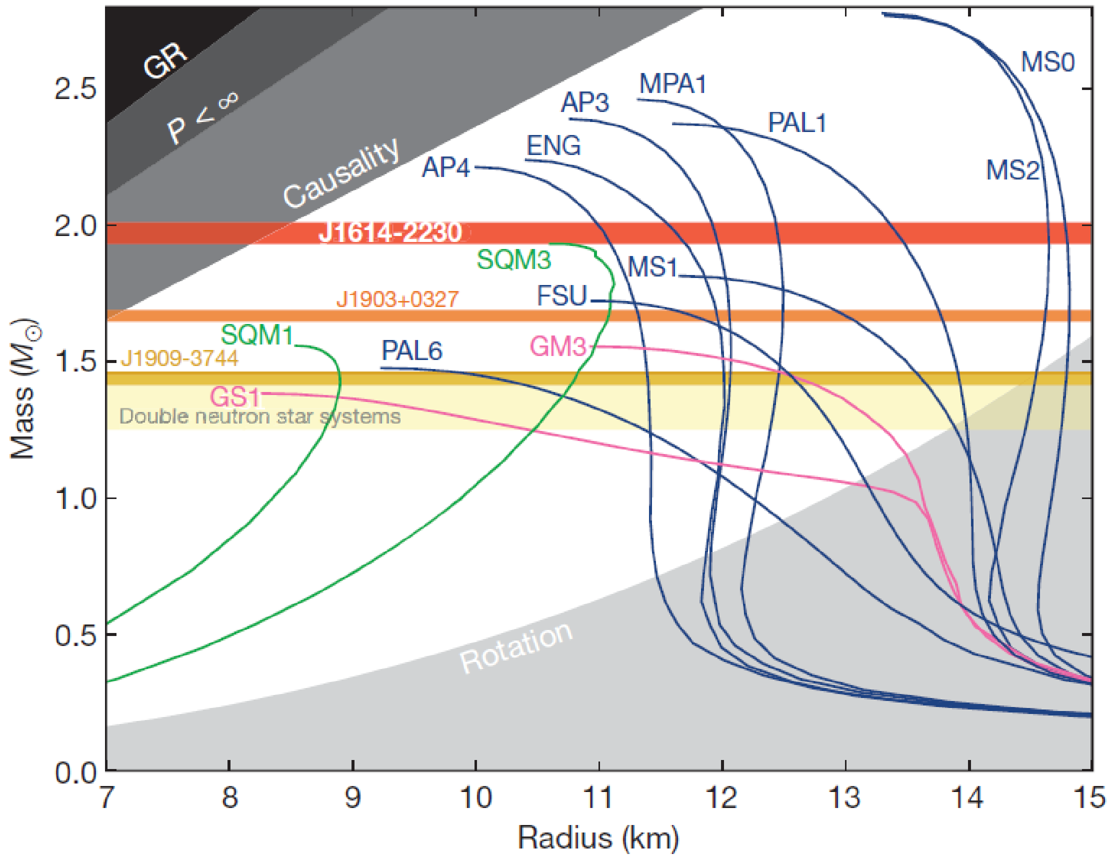
- ✓ Chiral symmetry restoration
- ✓ Color superconductivity
- ✓ Color-flavor locking
- ✓ Quark-Gluon-Plasma ?
- ✓ AdS/QCD?



Neutron Stars
M = 1.5 solar mass
R < 15km
A = 10^57 nucleons
composed of p, n, e, hyperons, quarks, …

Open Question:

Given the theoretical uncertainties,
which one is right ?



Nature 467, 1081

Contents

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How to obtain EOS (equation of state) ?

- Construct Lagrangian based on symmetries
- Mean field approximation (locally uniform matter)
  + alpha
- Obtain pressure/energy-density vs density: p(r),e(r)

Two different approaches for dense matter physics

- ✓ Conventional approach :
  - start from zero density where symmetry is broken
- ✓ Top-down approaches :
  - start from high density where symmetry believed to be restored

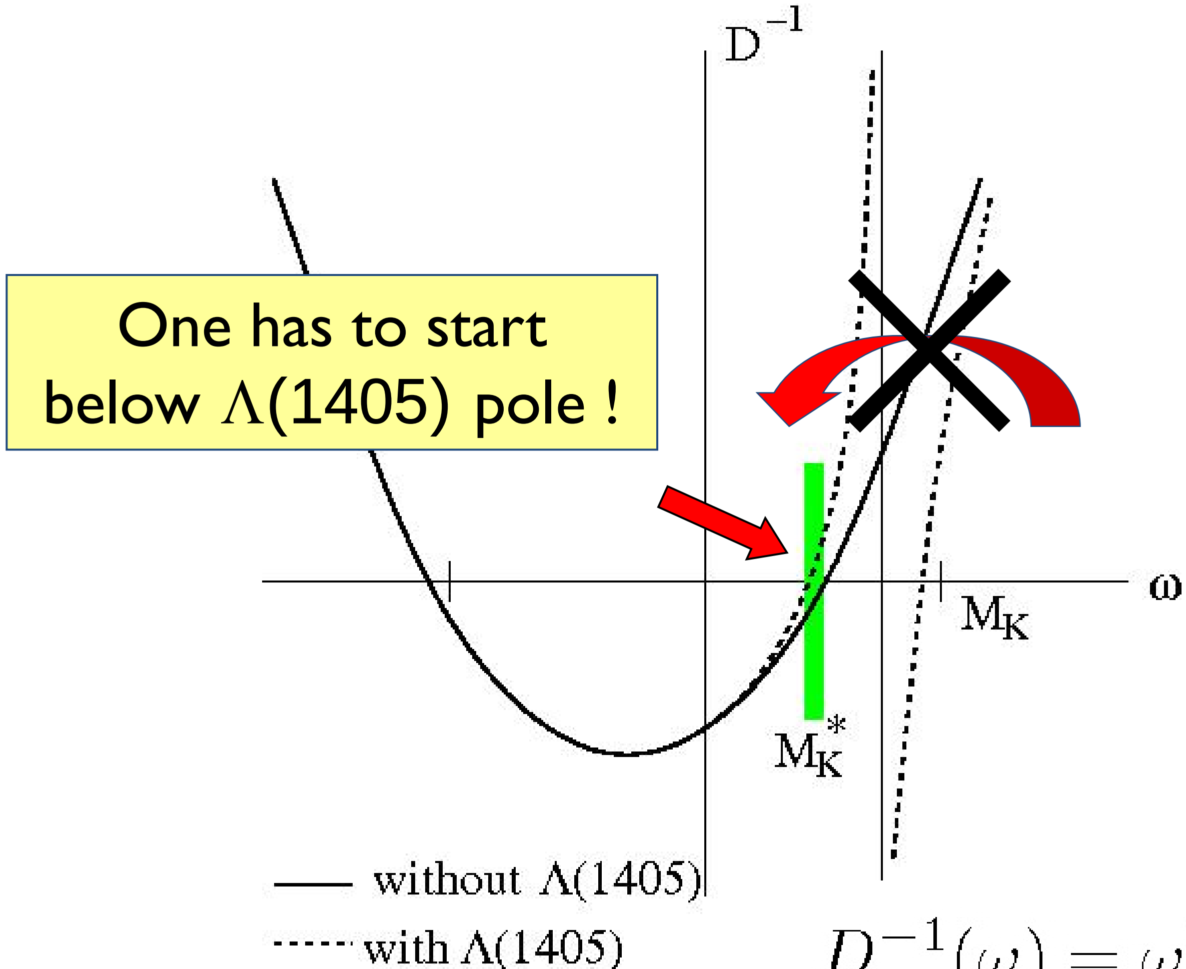
Example) problems in conventional approaches

- ✓ Problem in $K^{-}p$ Scattering amplitude:
  experiment : - 0.65 + i 0.81 fm (repulsive)
  chiral symmetry : + (attractive !)

- ✓ Problem of $\Lambda(1405)$
  pole position of $\Lambda(1405)$
  → only 30 MeV below KN threshold

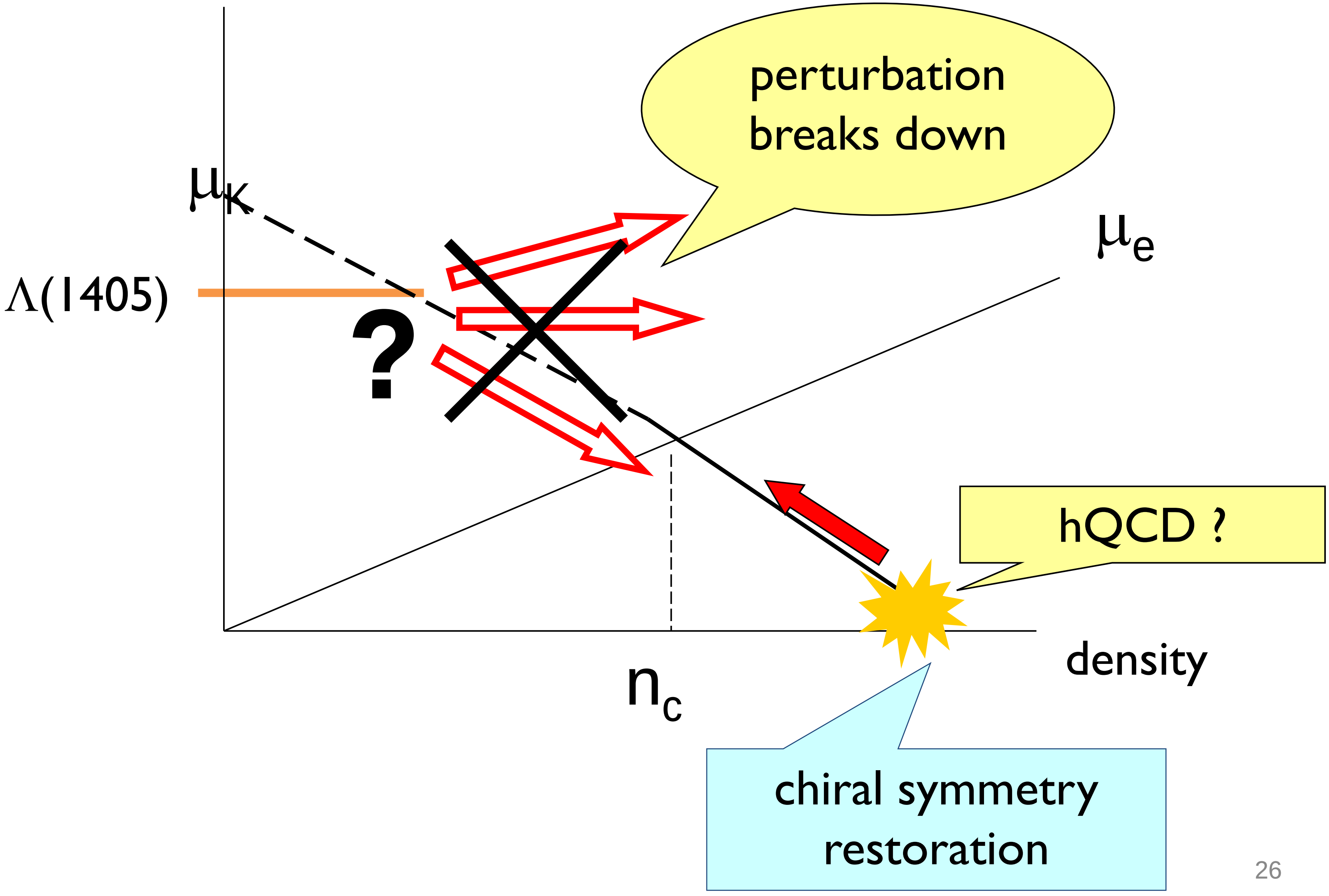
Perturbation breaks down in conventional approach !

Far below $\Lambda(1405)$ pole, $\Lambda(1405)$ is irrelevant !



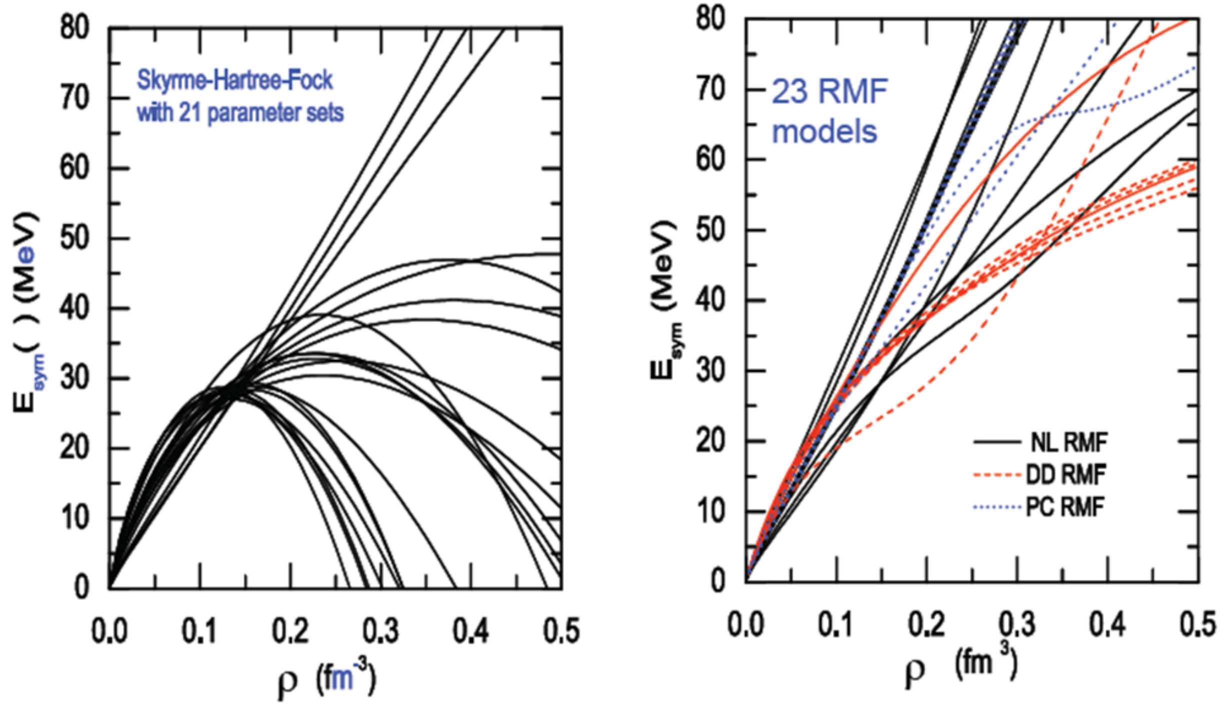
$$D^{-1}(\omega) = \omega^2 - M_K^2 - \Pi(\omega)$$

Can hQCD give a guideline ?



Another example : which one is correct ? C.M.Ko (A&M)

Symmetry energy from phenomenological models



$$E(\rho,\delta) \approx E(\rho,\delta=0) + E_{sym}(\rho)\delta^2, \quad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

Fundamental symmetries for dense matter physics

In order to understand dense matter physics, we need some guidelines which are based on fundamental symmetries

Contents

- Why neutron stars?
- Fundamental symmetries for dense matter
- Dense matter in hQCD
- Prospects

Motivation for holographic QCD

- Strong interaction in QCD
  - perturbation is impossible

- Holographic QCD
  - strong interaction in QCD might be the result of non-trivial geometry of 5-dim space time

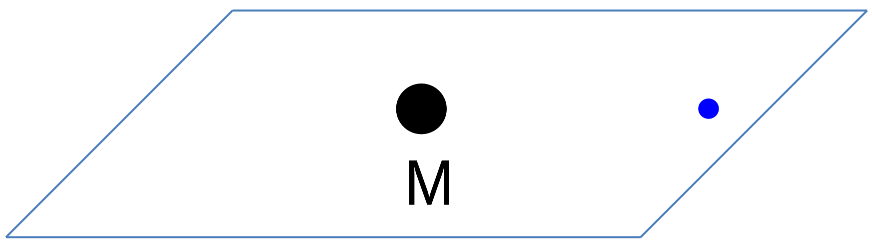
  → find proper geometry which is equivalent to QCD

  → with weak coupling : perturbation is possible

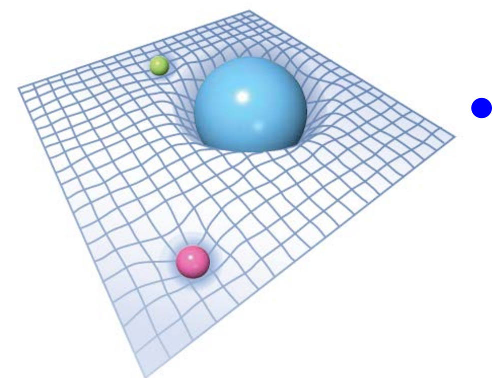
Motivation for holographic QCD

- What is main advantage?
  - less parameters due to symmetries in higher dimension
- How to test?
  - asymptotic freedom at high mementum
  - meson/baryon spectrums in vacuum
  - ….

Q) Are extra dimensions physical ?



2-dim gravity



3-dim geometry

Energy($E=mc^2$) ? new dimension

space(3)+time(1)+extra(1,energy) = 5 dim space

Holographic QCD

- Bottom-up approach :
  start from QCD and attempt to guess
  its 5d holographic dual, AdS/CFT dictionaries
  → hard-wall model, soft-wall model, …

- Top-down approach :
  start from string theory, set brane configuration with DBI action, reproduce QCD-like theory
  → D3/D7, D4/D6, Sakai-Sugimoto …

Top-down in hQCD

JHEP

Published for SISSA by Springer

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Accepted: *October 17, 2011*
Published: *October 24, 2011*

Holographic equations of state and astrophysical compact objects

Youngman Kim,[a,b] Chang-Hwan Lee,[c] Ik Jae Shin[a] and Mew-Bing Wan[a]

No strangeness, yet : JHEP 10 (2011) 111

- String
  - * one-dimensional object

$$X^\mu(\tau,\sigma) = X^\mu(\sigma^0,\sigma^1)$$

  - * Nambu-Goto action

$$S_{\rm NG} = -T\int d\mathcal{A} = -T\int d\tau d\sigma\sqrt{(\dot{X}\cdot X')^2 - \dot{X}^2 X'^2}$$

using an induced metric γ_{ab} on the world-sheet

$$\gamma_{ab} = \eta_{\mu\nu}\frac{\partial X^\mu}{\partial\sigma^a}\frac{\partial X^\nu}{\partial\sigma^b}$$

in the reparametrization invariant form

$$S_{\rm NG} = -T\int d^2\sigma\sqrt{-\gamma} \qquad \text{where} \quad \gamma = \det(\gamma_{ab})$$

- Dp-brane
  - * multi-dimensional object

$$X^\mu(\sigma^0,\sigma^1) \quad \to \quad X^\mu(\sigma^0,\sigma^1,\cdots,\sigma^p)$$

  - * DBI action

$$S_{\mathrm{D}_p} = -T_p \int d^{p+1}\sigma \sqrt{-\det P[g]}$$

using a pull-back metric $P[g]_{ab}$ on the world-volume

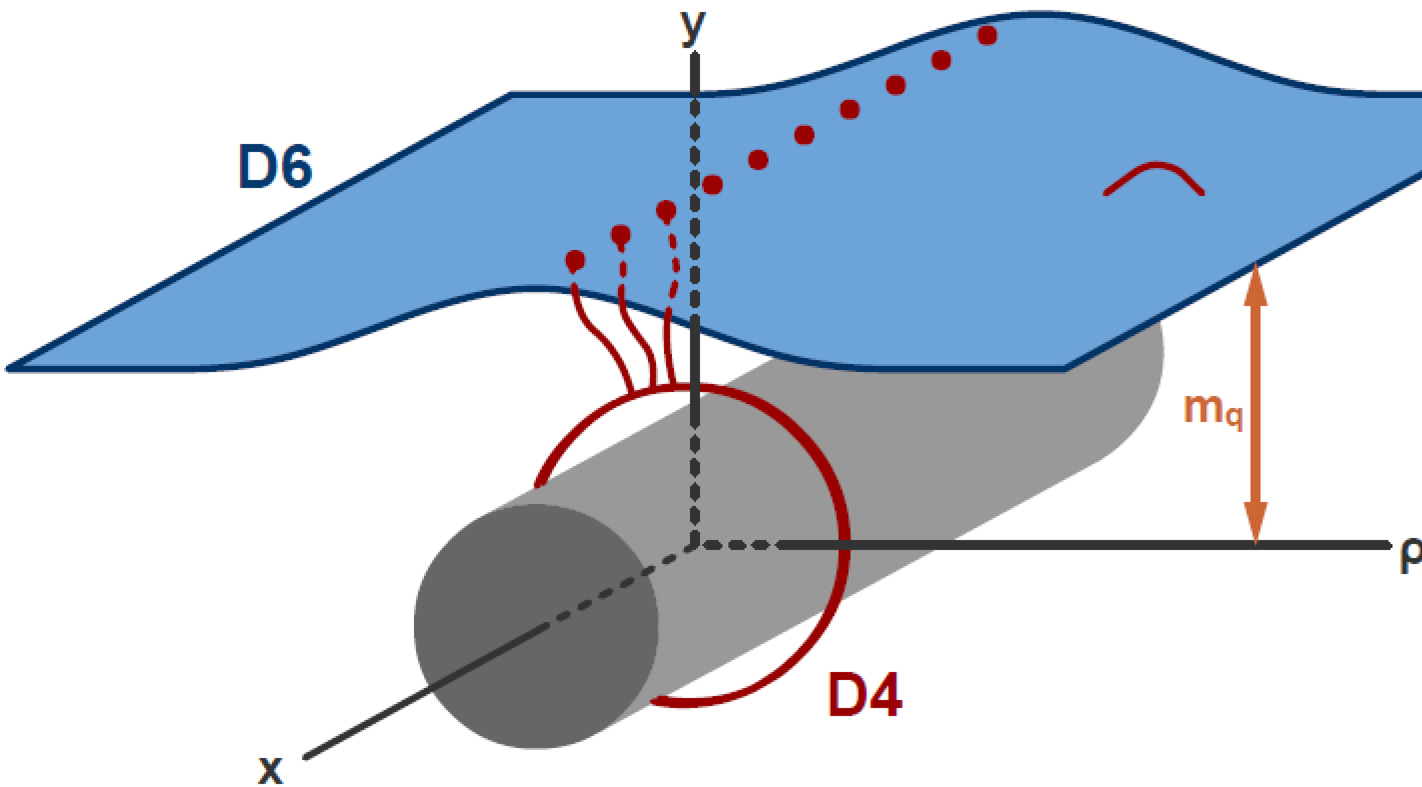
$$P[g]_{ab} = g_{\mu\nu} \frac{\partial X^\mu}{\partial \sigma^a} \frac{\partial X^\nu}{\partial \sigma^b}$$

including a gauge field A_a on the world-volume

$$S_{\mathrm{DBI}} = -T_p \int d^{p+1}\sigma \sqrt{-\det\left(P[g] + 2\pi\alpha' F\right)}$$

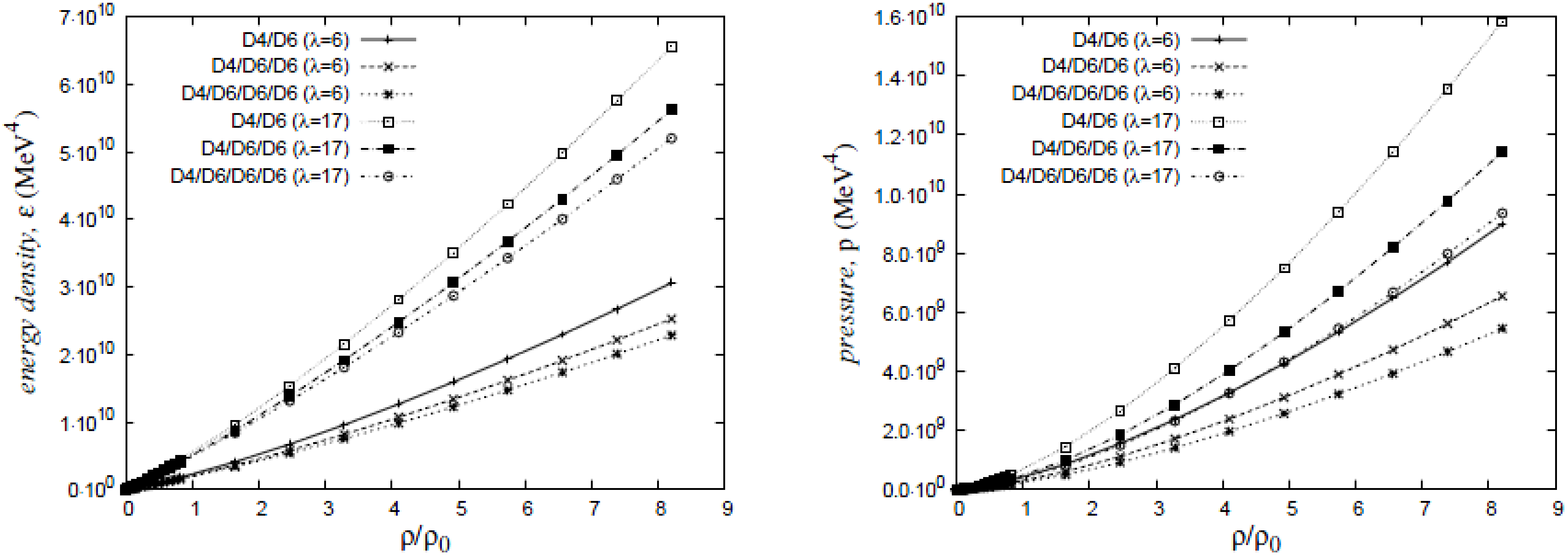
figure by D. Yi

- add compact D4 branes ⇒ Baryon



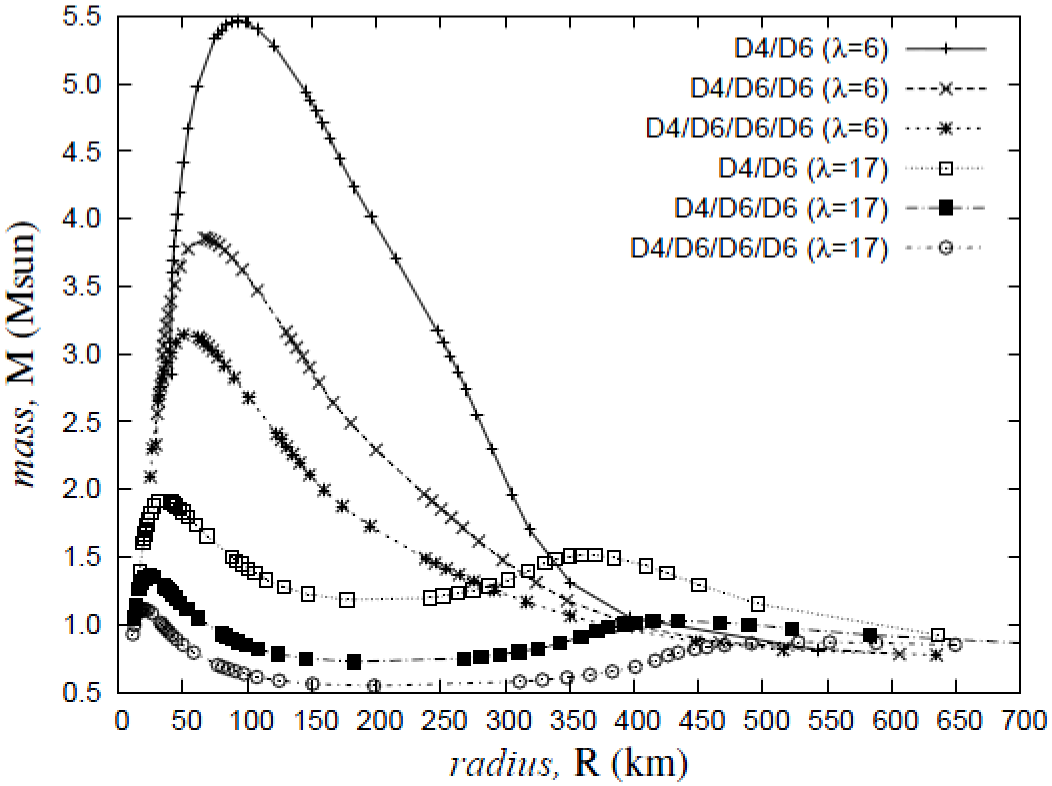
$$\lim_{\rho\to\infty} A_t(\rho) \sim \mu - \frac{Q}{\rho} + \cdots$$

Equation of states



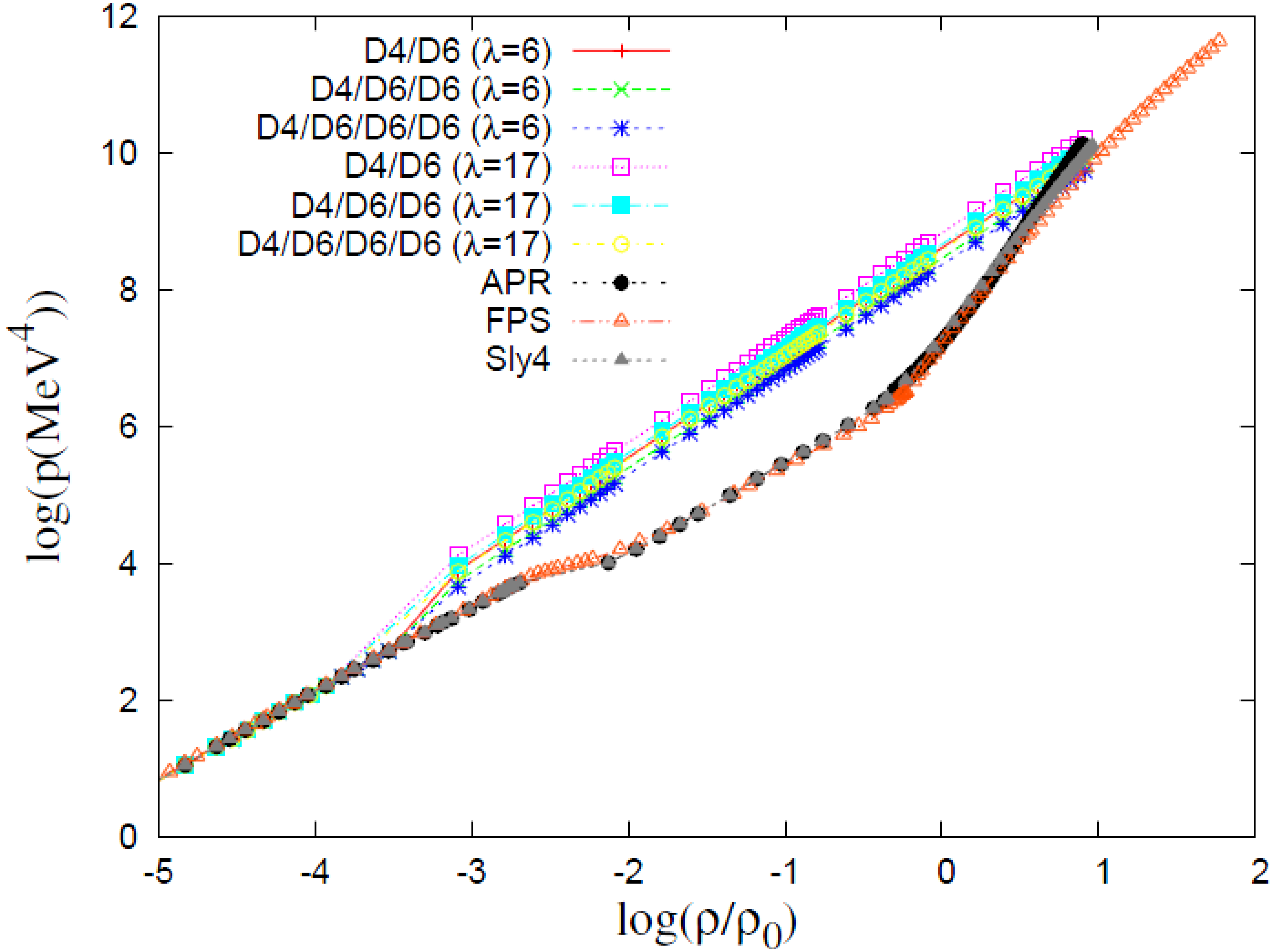
energy density $\epsilon(\rho)$ and pressure $p(\rho)$

Mass-radius relation



Far from realistic : what is the problem ?

Comparison of pressure



Open problems in hQCD

- ✓ Proper attraction is missing
  in large Nc limit & large t'Hooft coupling limit
- ✓ Mass of scalar field is bigger than that of vector field
- ✓ No unique way of putting baryons
- ✓ How to introduce strangeness

Prospects

- ✓ hQCD has been partly successful in explaining meson/baryon mass spectrum in vacuum.
- ✓ however, hQCD is not so successful in explaining compact stars, yet.
- ✓ in the future, hQCD may be able to contribute to the real physics by providing more guidelines to QCD effective models.

Many Thanks