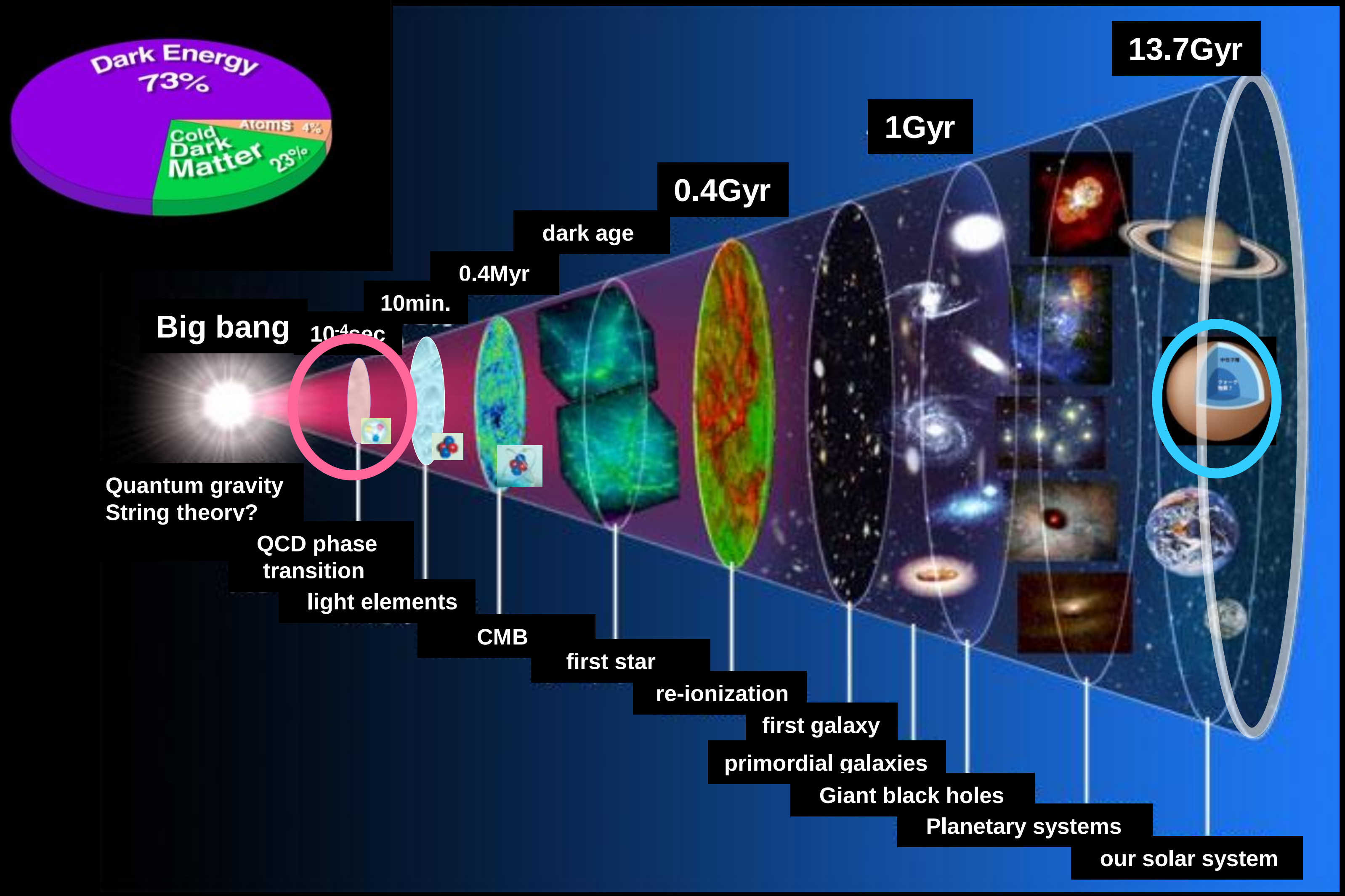
From Quarks to Cosmos



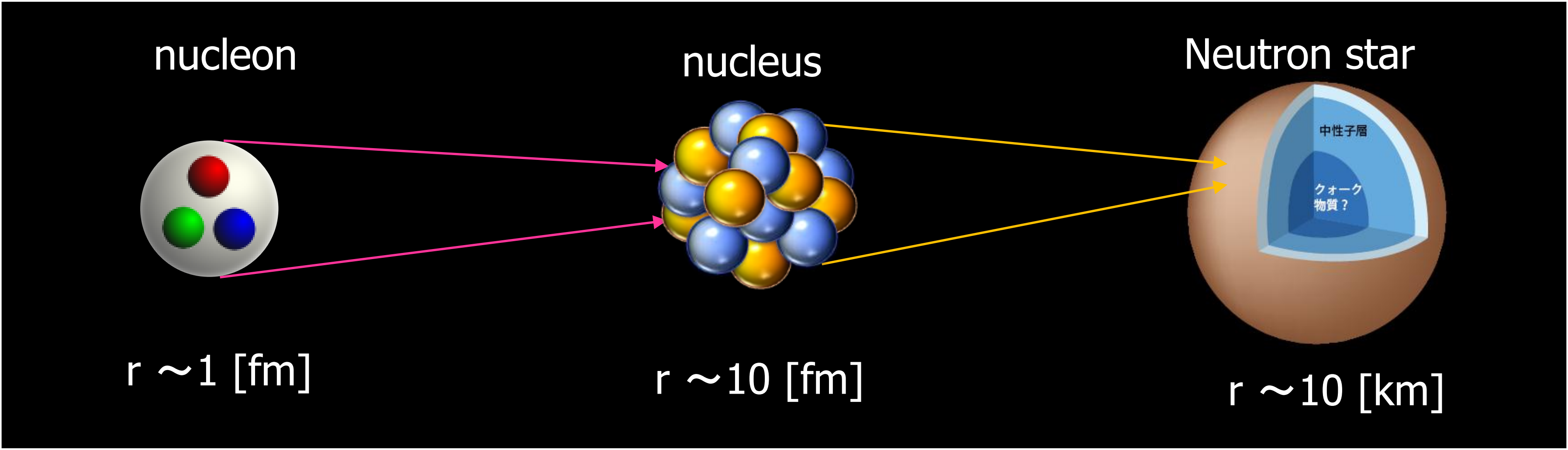
Tetsuo Hatsuda (Nishina Center, RIKEN)

「実験と観測で解き明かす中性子星の核物質」

キックオフシンポジウム(RIKEN, Oct.26, 2012)

RIKEN NiSHiNA CENTER

Building blocks of Matter



nucleon

nucleus

Neutron star

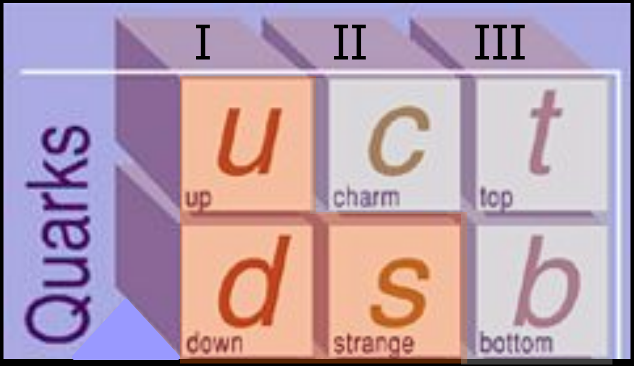
r ∼1 [fm]

r ∼10 [fm]

r ∼10 [km]

Light quarks

$m_u \sim\ 2$ MeV
$m_d \sim\ 5$ MeV
$m_s \sim\ 90$ MeV



Heavy quarks

$m_c \sim 1.3$ GeV
$m_b \sim 4.2$ GeV
$m_t \sim 171$ GeV

Fundamental theory of strong int. ＝ Quantum Chromo Dynamics (QCD)

Characteristic strong int. scale ~ $(1\text{fm})^{-1}$ ~ 200 MeV

Quantum Chromo Dynamics

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}\gamma^\mu (i\partial_\mu - g t^a A^a_\mu) q - m\bar{q}q$$

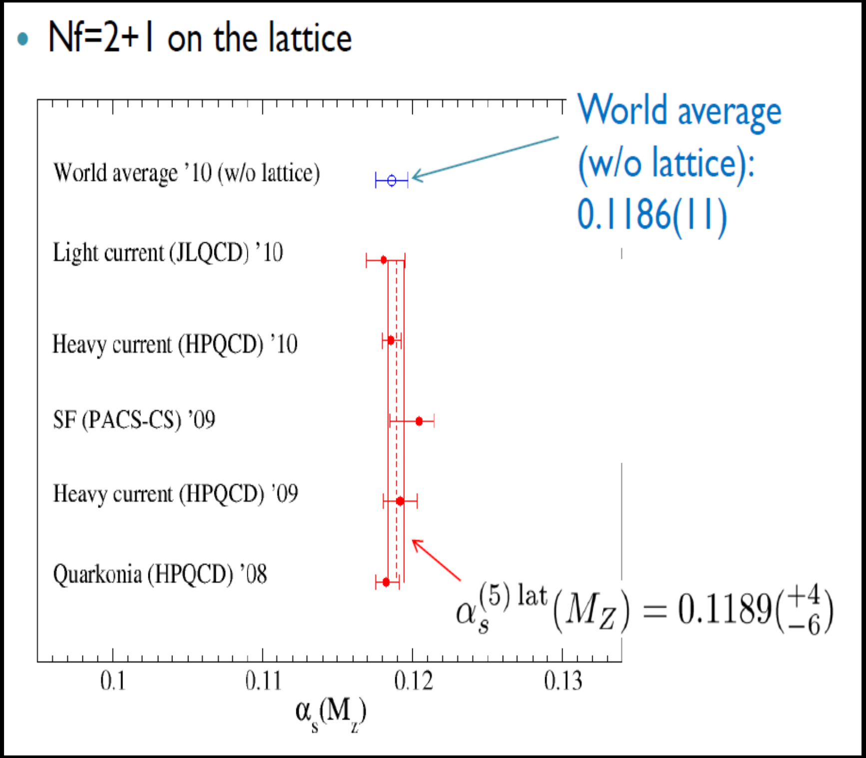
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f_{abc} A^b_\mu A^c_\nu$$

Running masses: $m_q(Q)$

quark masses **(from lattice QCD)**	**[MeV]** **(MS-bar @ 2GeV)**
m_u	2.19(15)
m_d	4.67(20)
m_s	94(3)

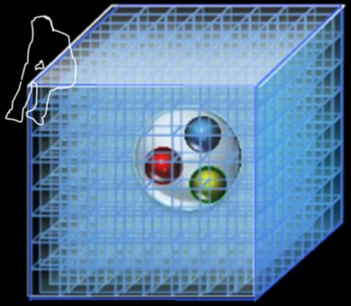
FLAG working group,
arXiv:1011.4408 [hep-lat]

Running coupling: $\alpha_s(Q)=g^2/4\pi$



Shintani, PoSLAT2011

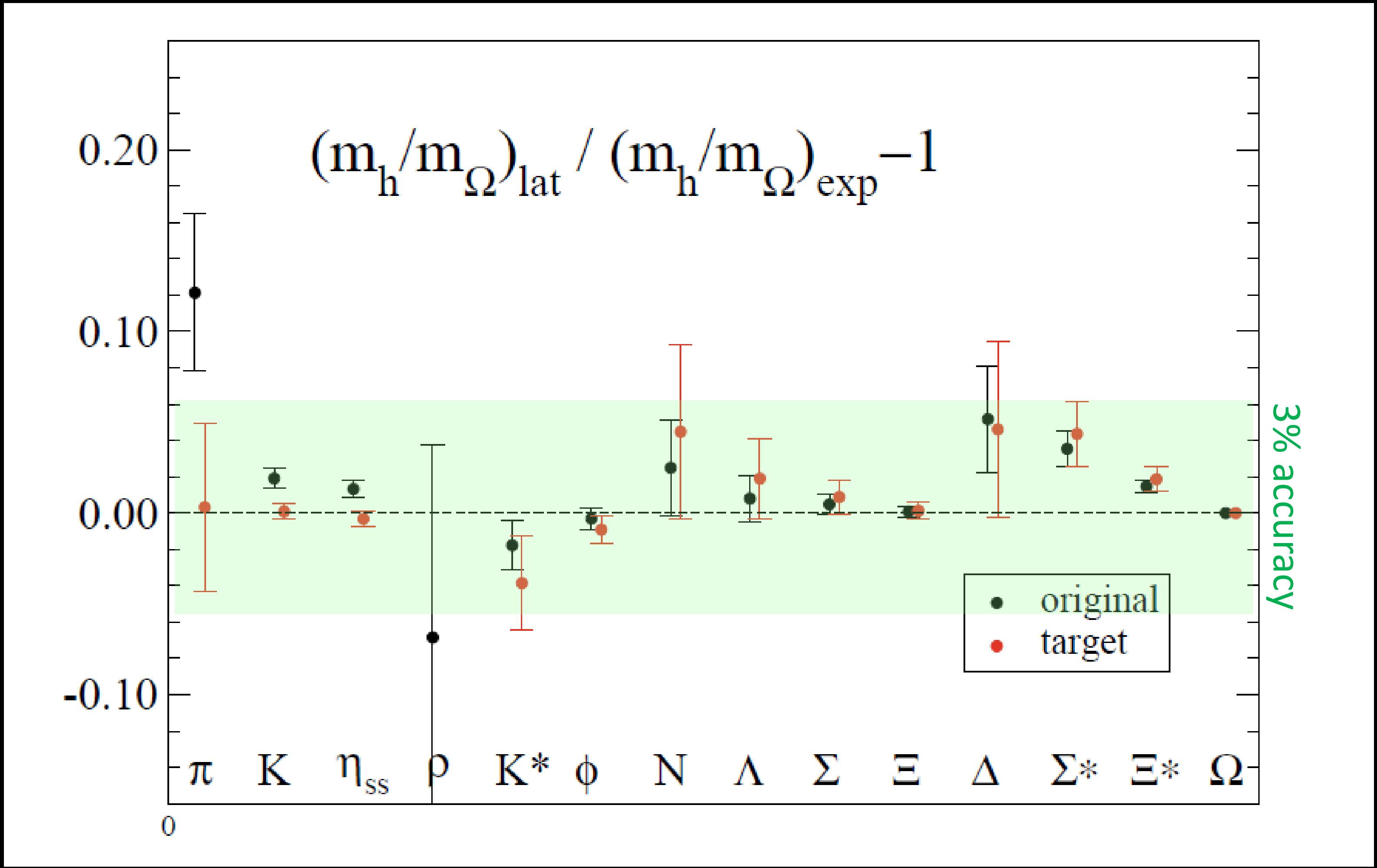
Physical point simulation in (2+1)-flavor QCD @ 2010



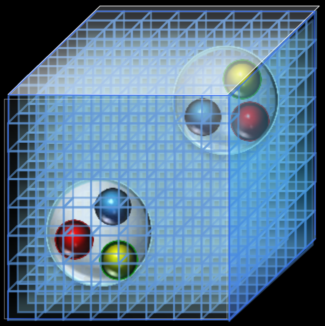
Improved Wilson + Iwasaki gauge action

$a = 0.09$ fm, $L=2.9$ fm, $m_\pi=135$ MeV

PACS-CS Coll., Phys. Rev. D 81, 074503 (2010)

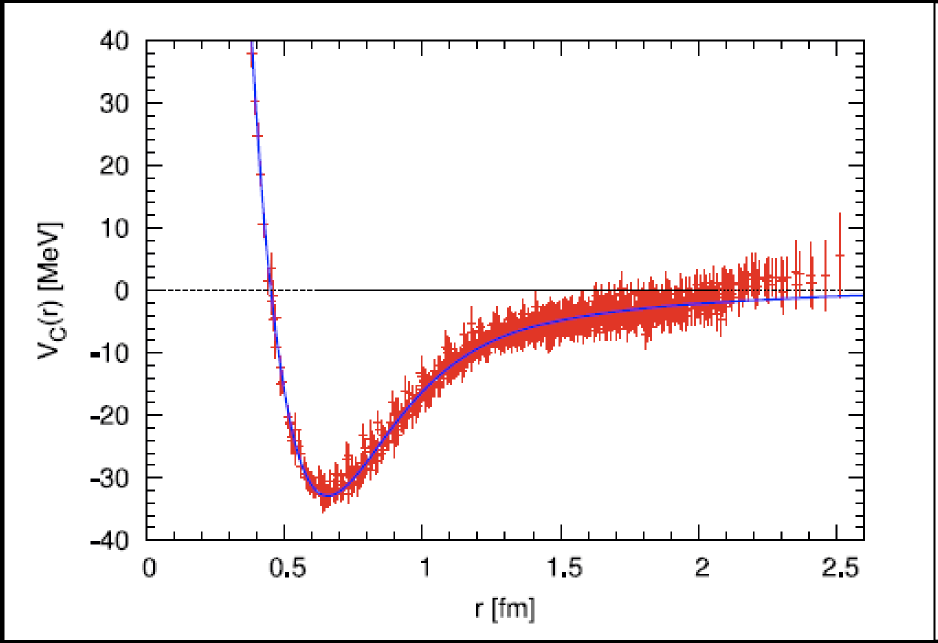


Nuclear Force from LQCD

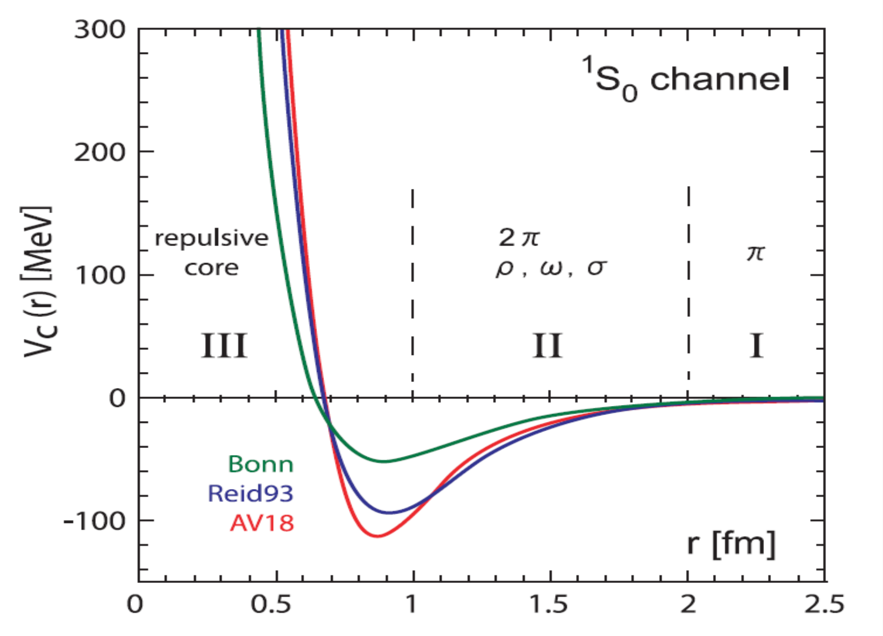


Ishii, Aoki & Hatsuda, Phys. Rev. Lett. 92 (2007) 022001
Ishii et al., [HAL QCD Coll.], Phys. Lett. 712 (2012) 437

$^1S_0$ NN potential（Lattice QCD）

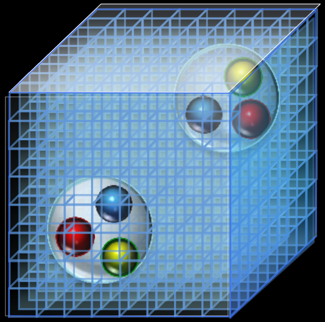


$^1S_0$ NN potential（Phenomenological）



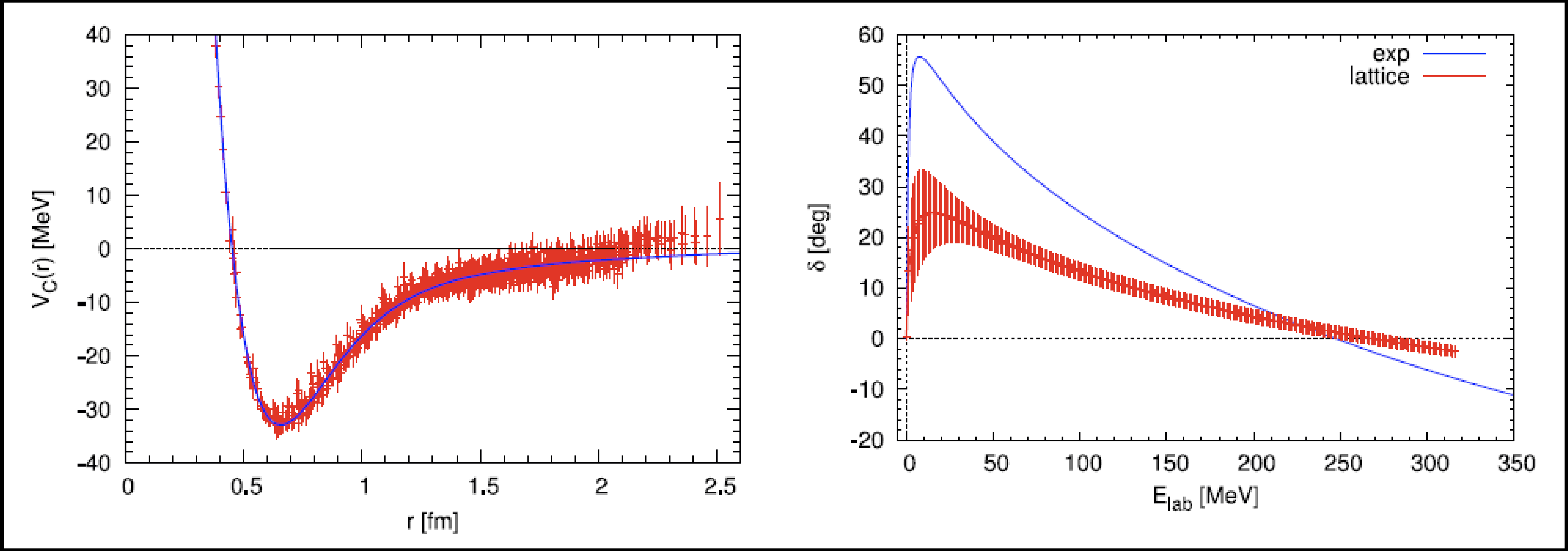
$M_\pi \sim 3\, M_\pi$(phys.) ➔ $M_\pi = M_\pi$(phys.) , NN, NNN
by KEI Computer

Nuclear Force from LQCD



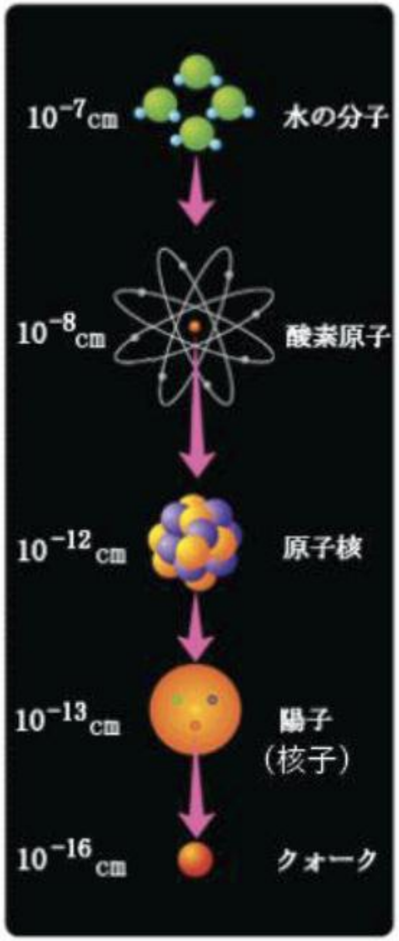
Ishii, Aoki & Hatsuda, Phys. Rev. Lett. 92 (2007) 022001
Ishii et al., [HAL QCD Coll.], Phys. Lett. 712 (2012) 437

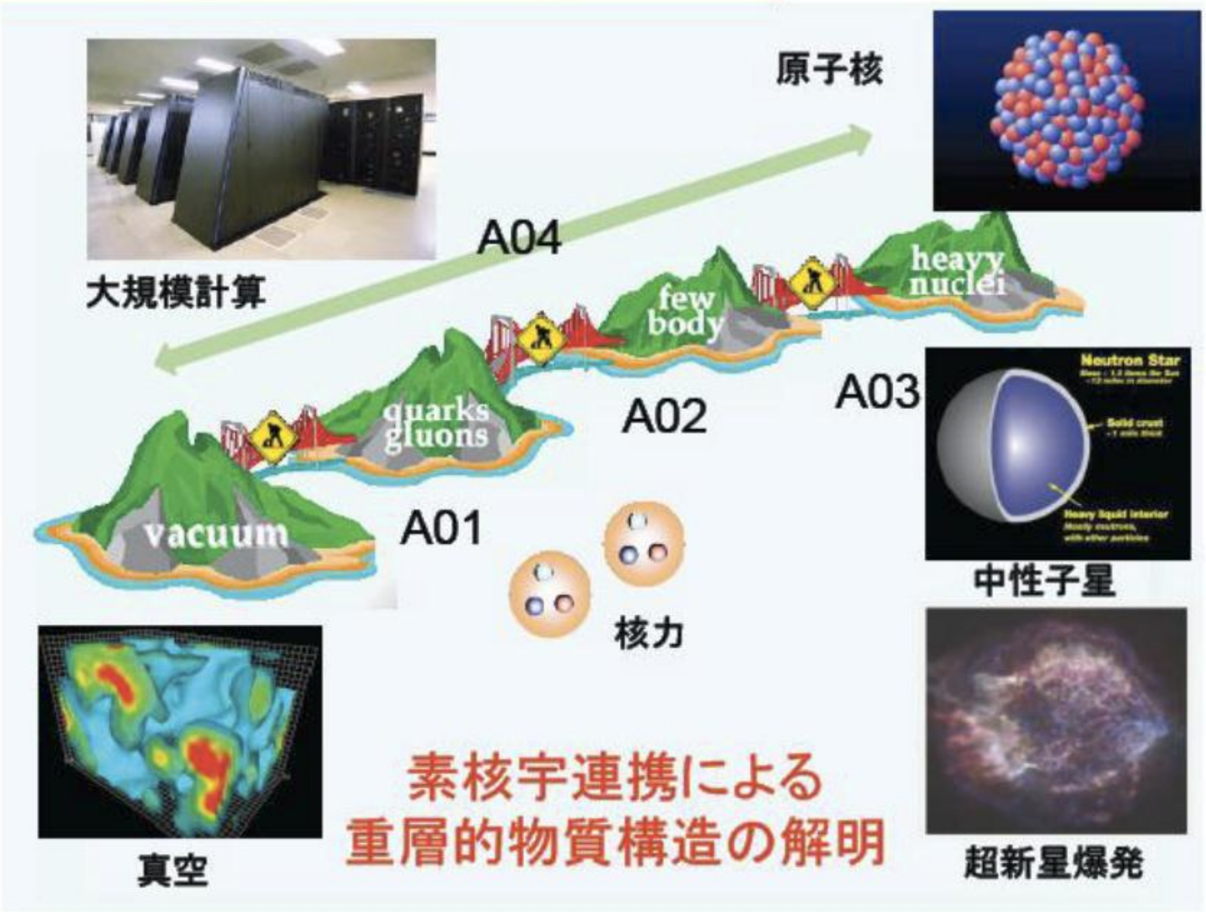
$^1S_0$ NN potential（Lattice QCD）



$M_\pi \sim 3\ M_\pi$(phys.) ➔ $M_\pi = M_\pi$(phys.) , NN, NNN
by KEI Computer

新学術領域「素核宇融合」(2008-2012)





素核宇連携による
重層的物質構造の解明

「様々な階層での物質の性質・構造・起源を、クォークから元素合成までという流れの中で、異なった専門分野の研究者が計算科学という新しい手法を基盤に、共同で解明して行く」、という新しい研究領域を構築することがこの提案の目的である。

http://www.aics.riken.jp/en/

Five “strategic” programs (FY 2010-2015)

1. Life and Medicine
2. New Materials
3. Environment
4. Engineering
5. Particle, Nuclear and Astrophysics

Project 1: Baryon-Baryon interaction from lattice QCD simulations at physical point
Project 2: Large scale quantum many-body calculation of nuclei and its applications
Project 3: Realistic simulation of supernova explosion and black-hole formation
Project 4: Large scale simulation of first generation of stars and galaxies

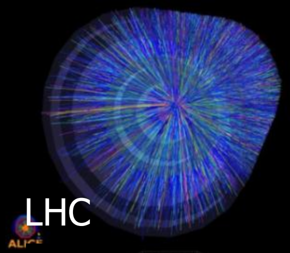
Physical point simulation started : 96^4 lattice, $a=0.1$fm, $L=9.6$fm, $m_\pi=135$MeV http://www.aics.riken.jp/en/

HPCI戦略プログラム分野5
「物質と宇宙の起源と構造」(2010-2015)

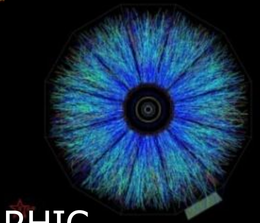
Project 1: Baryon-Baryon interaction from lattice QCD simulations at physical point
Project 2: Large scale quantum many-body calculation of nuclei and its applications
Project 3: Realistic simulation of supernova explosion and black-hole formation
Project 4: Large scale simulation of first generation of stars and galaxies

Physical point simulation started : 96^4 lattice, $a=0.1\mathrm{fm}$, $L=9.6\mathrm{fm}$, $m_\pi=135\mathrm{MeV}$

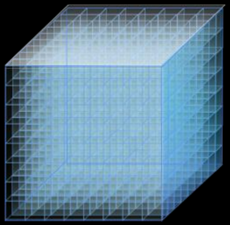
QCD Phase Diagram @ 2011



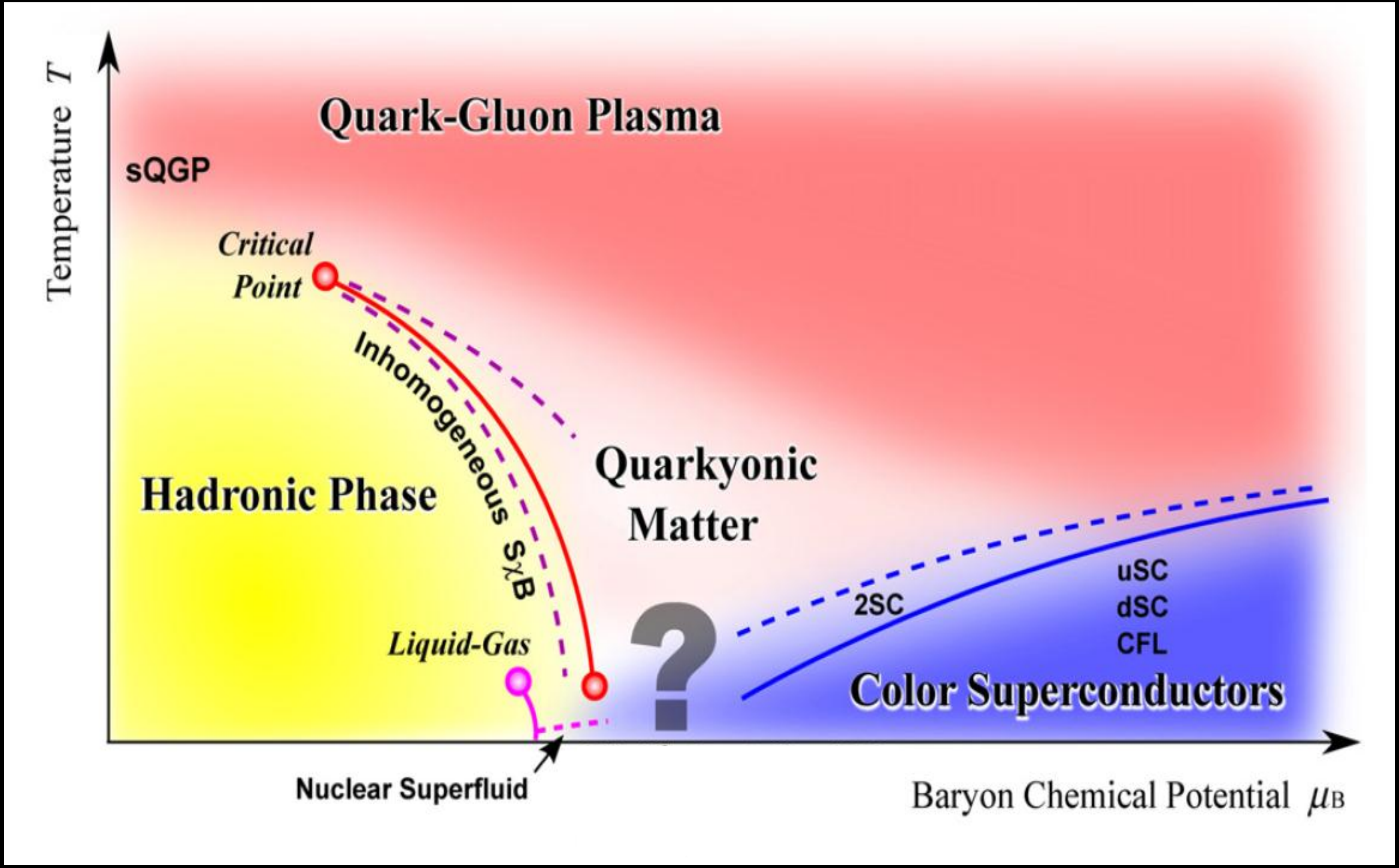
LHC

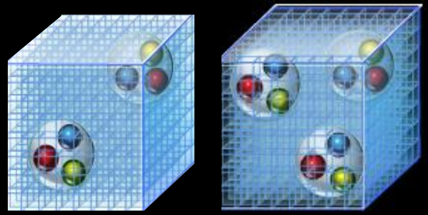


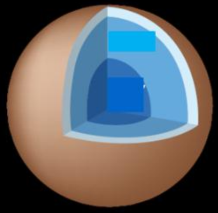
RHIC



Lattice QCD



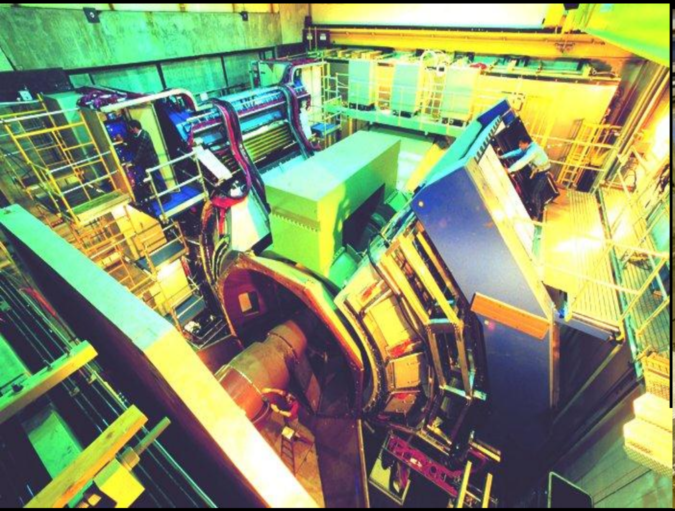




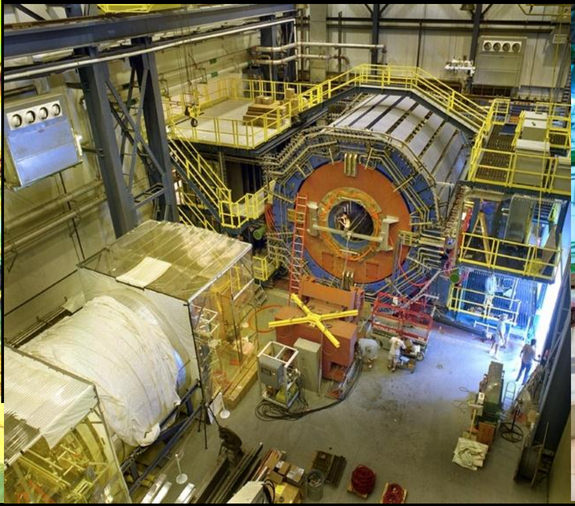
K. Fukushima and T. Hatsuda,
“The Phase Diagram of Dense QCD”
Rep. Prog. Phys. 74 (2011) 014001

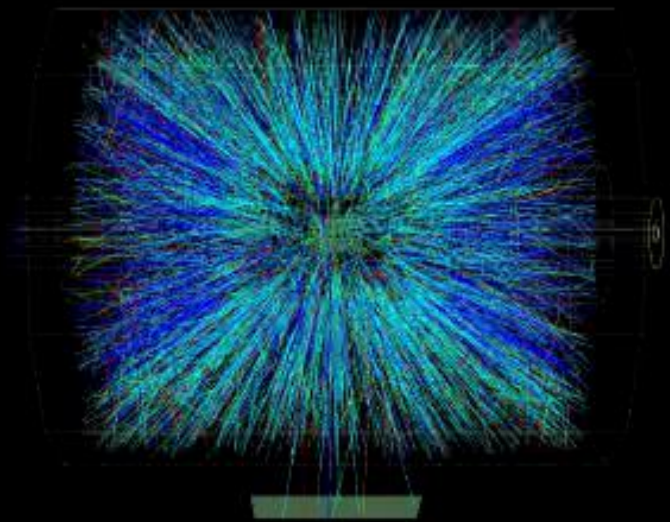
RHIC & LHC

PHENIX@RHIC

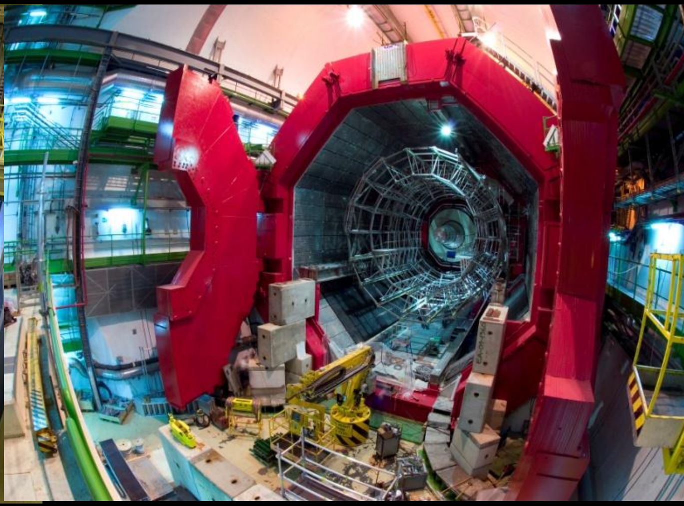


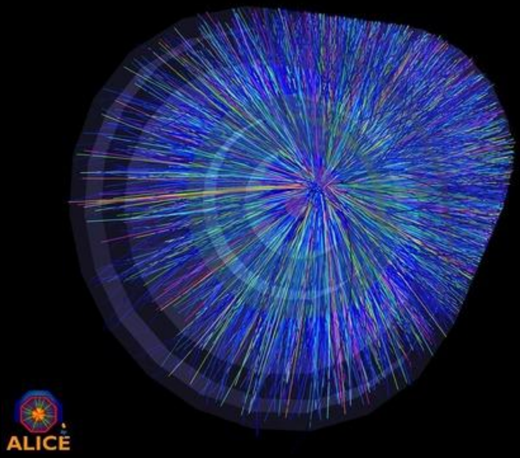
STAR@RHIC



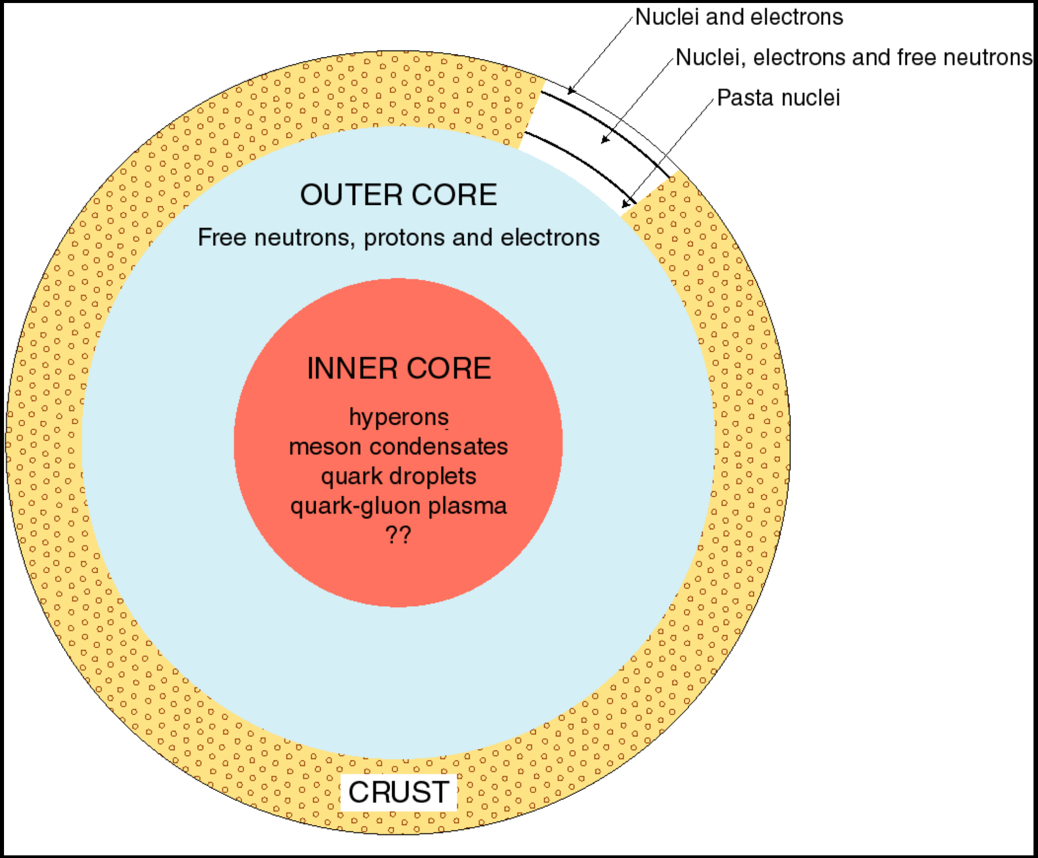


ALICE@LHC





Neutron Star



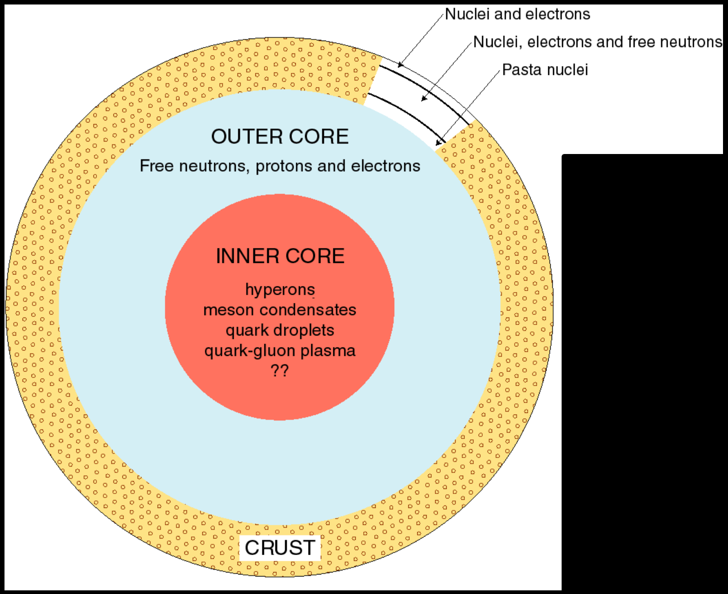
- $M \sim (1\text{-}2) M_\odot$
- $R \sim 10\text{km}$
- $0 < \rho < 10\,\rho_0$

composition

- nuclei
- neutrons & protons
- mesons (π, K)
- hyperons (Λ, Σ^-, Ξ^-)
- quarks (u,d,s)

+ leptons (e, μ)

Possible phases inside neutron stars



- Nuclei
  nuclear pasta
- Neutrons & Protons
  superfluidity, superconductivity
- mesons (π, K)
  Bose-Einstein condensate
- Hyperons
  superfluidity
- Quarks (u,d,s)
  color superconductivity

- Theoretically sound
- Quantitative predictions still difficult

Recent developments

1. Ab initio calculations : QMD, Lattice QCD etc
2. New observations : M, R, T, B, P, …
3. New experiments : RIBF, J−PARC etc
4. Proposals to relate theories and observations

examples

$M=(1.97\pm0.04)M_\odot$ ⇔ cold EOS

X-ray burst ⇔ cold EOS

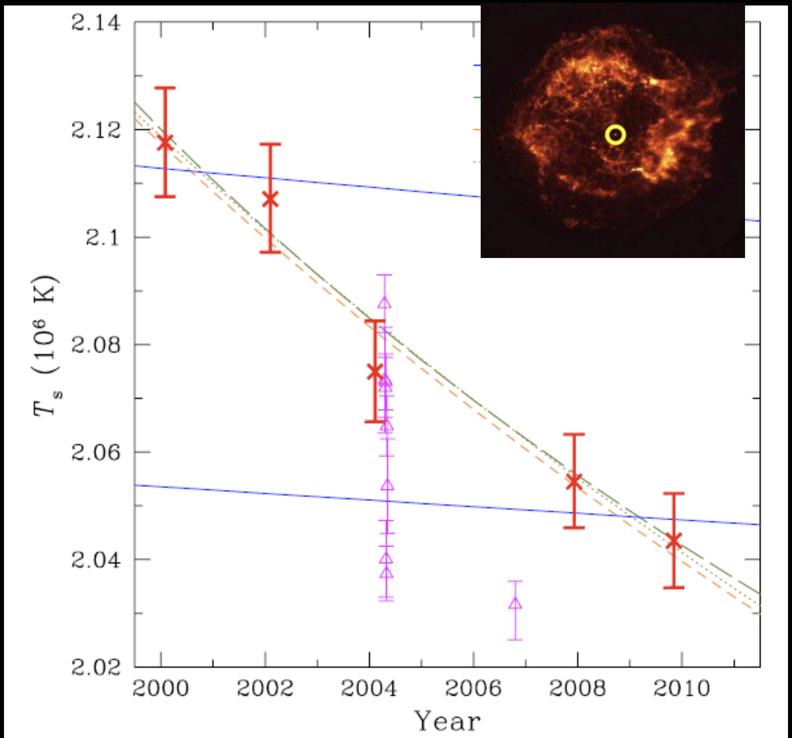
GW from $N_{\star}$ merger ⇔ hot EOS

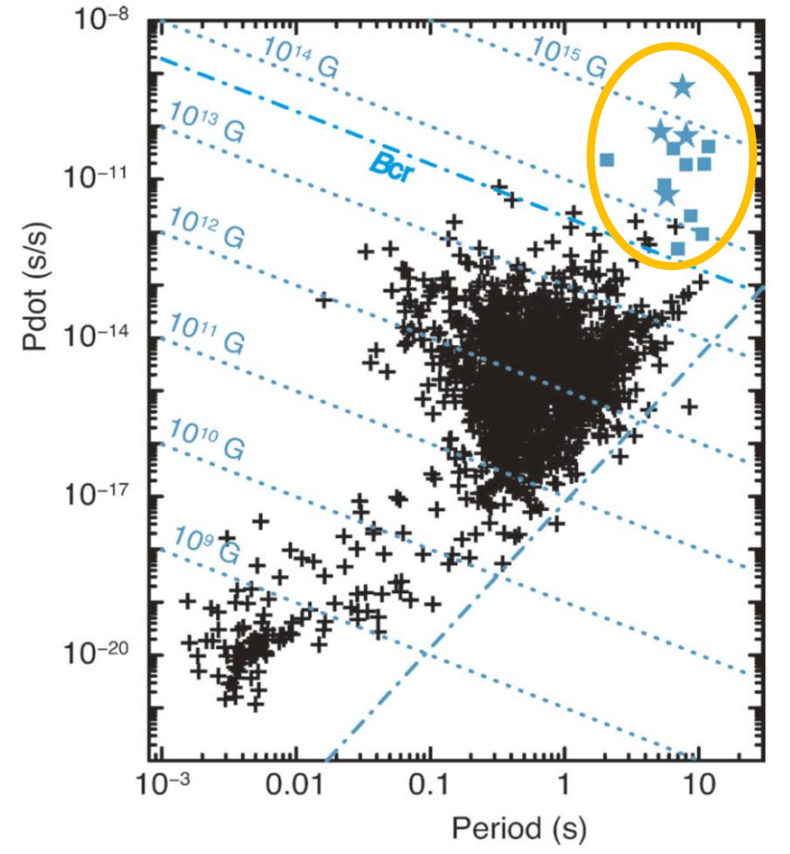
Seismology ⇔ crust structure

Cooling of CAS-A ⇔ $^3P_2$ superfluid

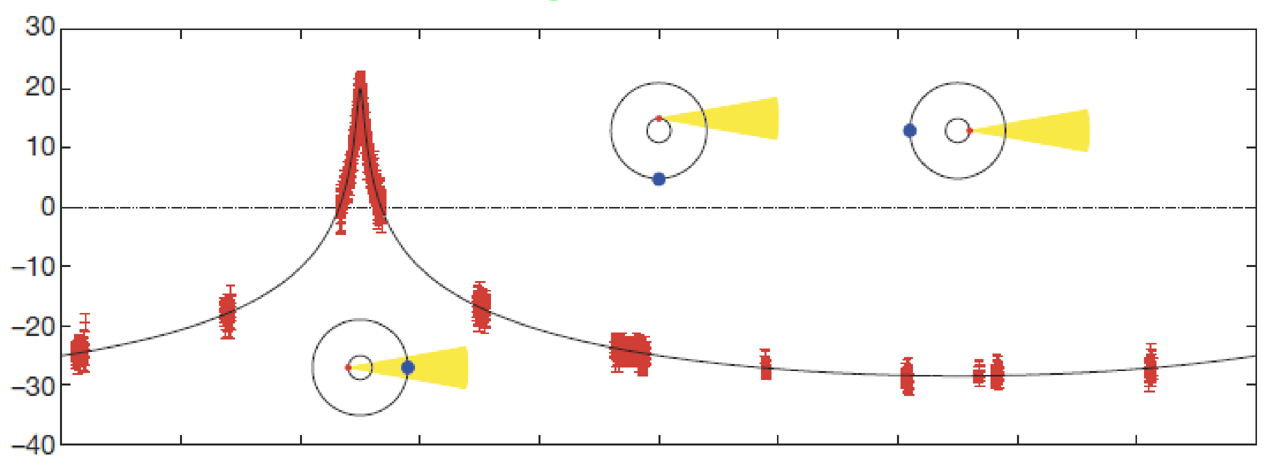
Magnetars ⇔ ferromagnetic core

Cassiopeia A Cooling, 4% decrease in 9 years
(Heinke & Ho, ApJ 2010)





PSR J1614-2230 , 1.97(4) $M_\odot$, (Demorest et al., Nature 2010)



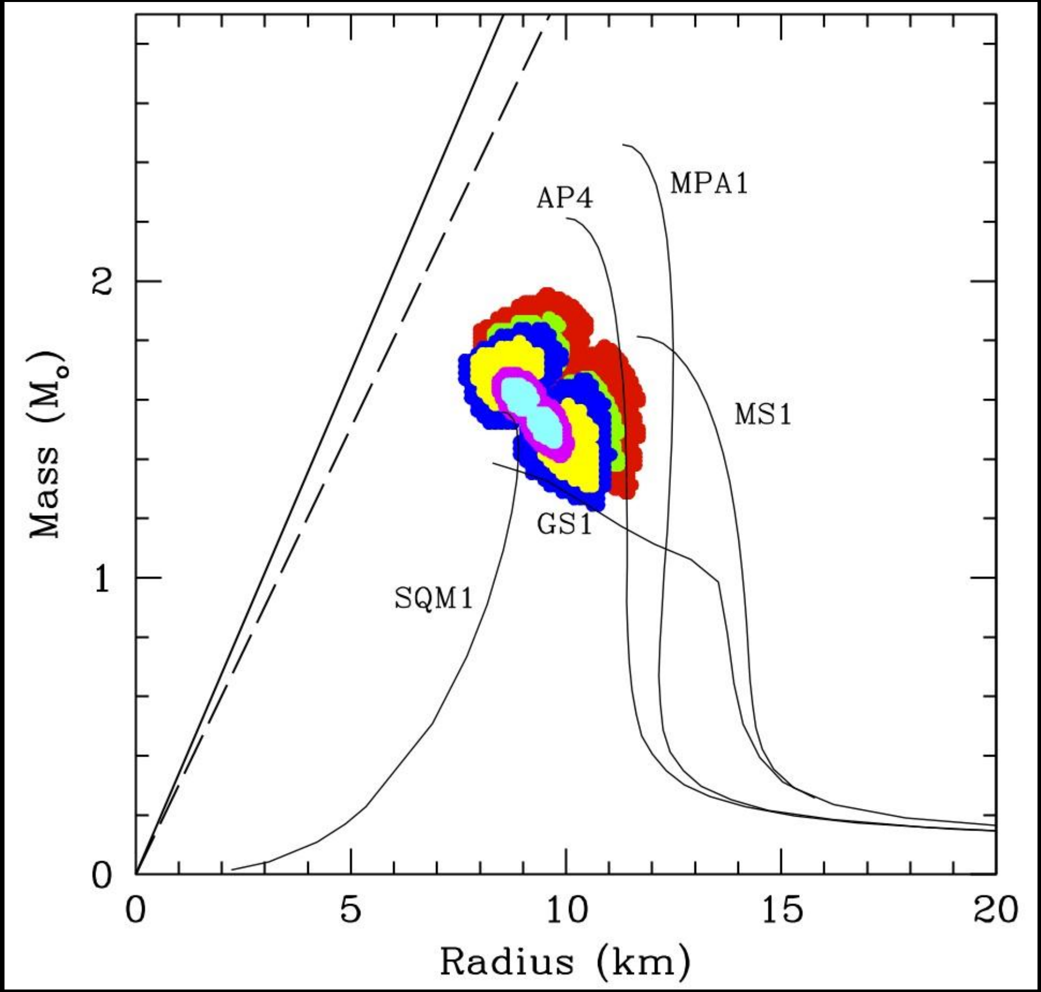
Magnetars
(from Enoto, 2012)
Bs=3.2x$10^{19}\sqrt{}$(PPdot) [G]

T, B, M

M-R

Thermonuclear Burst in X-ray Binaries

4U 1608-248 EXO 1745-248 4U 1820-30



(i) Surface emmision

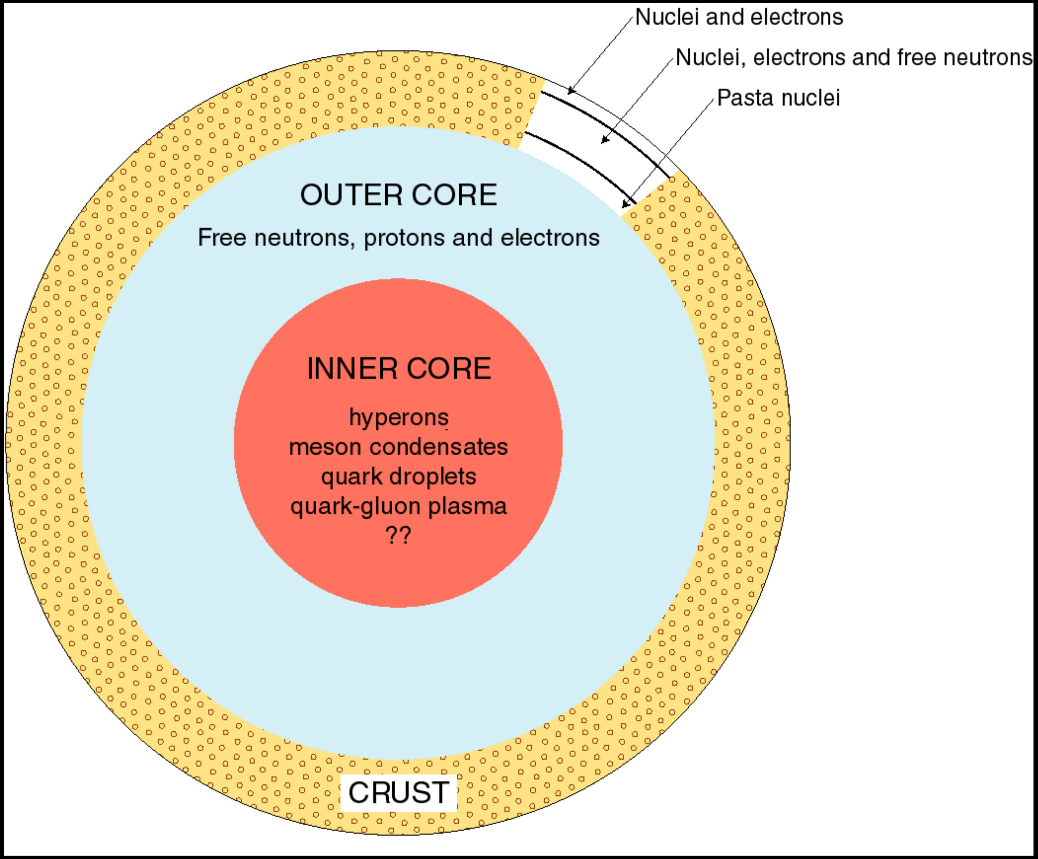
$$R^2 = \frac{F\,D^2}{\sigma\,T^4}\left(1 - \frac{2M}{R}\right)^{-1}$$

(ii) Eddington limit

$$L_{Edd} = \frac{4\,\pi\,G\,M}{\sigma(1+X)}\left(1 - \frac{2M}{R}\right)^{1/2}$$

Ozel, Baym & Guver, PRD 82 (2010) 101301
Steiner, Luttimer & Brown, ApJ 722 (2010)

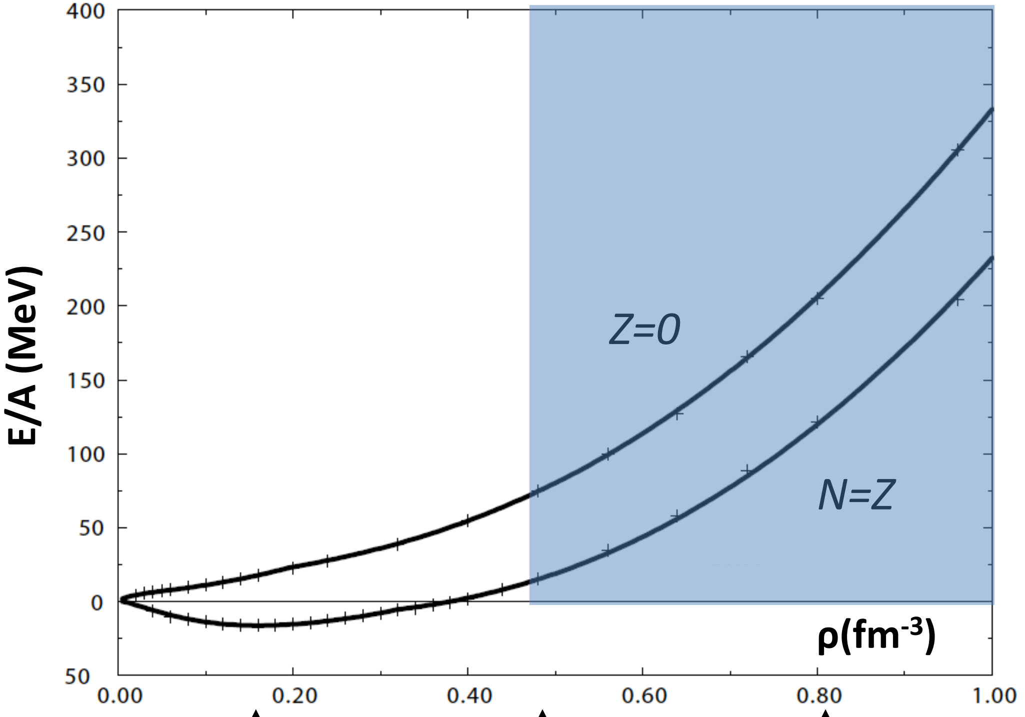
EOS of Dense Matter



- $M \sim (1\text{-}2) M_\odot$
- $R \sim 10\text{km}$
- $0 < \rho < 10\ \rho_0$

Nuclear Force and dense EOS（case for nucleons only）

Akmal, Pandharipande & Ravenhall, PRC58 ('98)

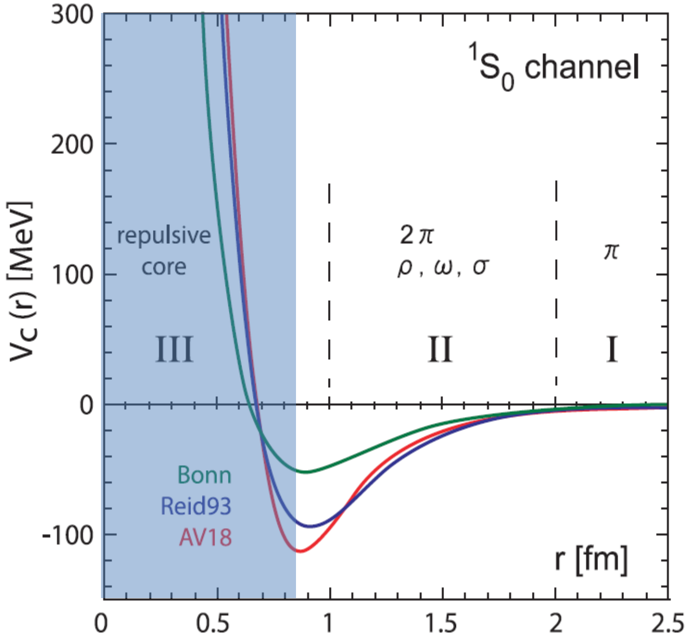


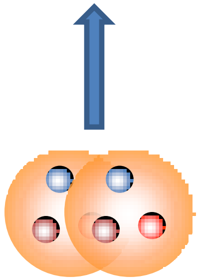
ρ_0
$= 0.16\ \mathrm{fm}^{-3}$

$3\rho_0$

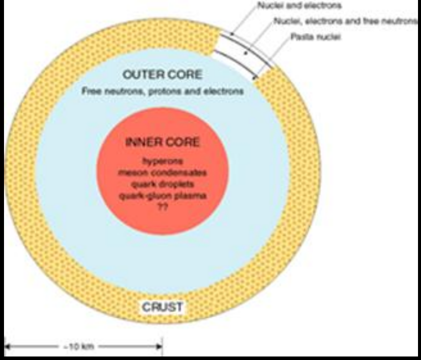
$5\rho_0$

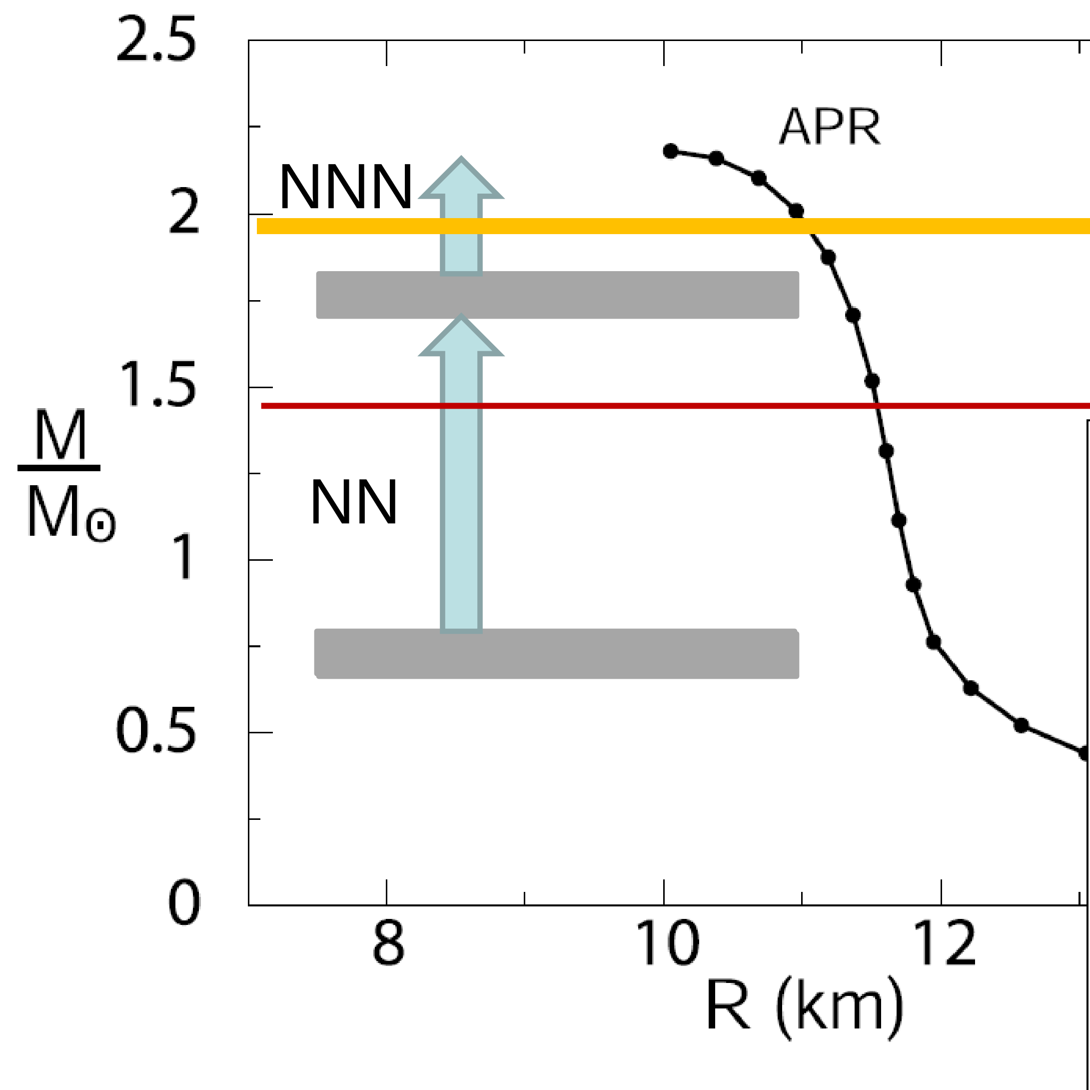
Phenomenological nuclear force



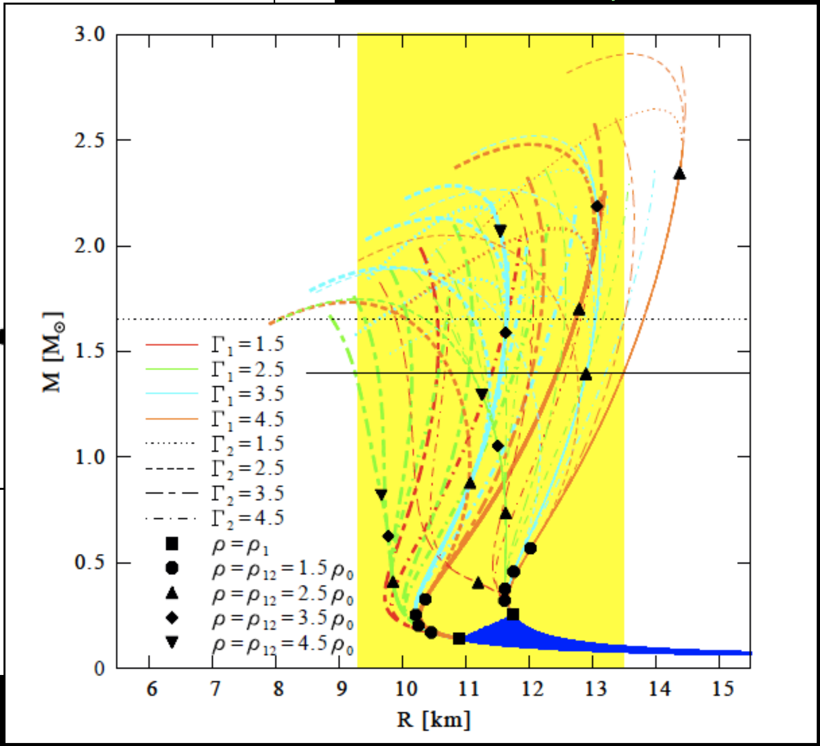


Nuclear Force and dense EOS（case for nucleons only）





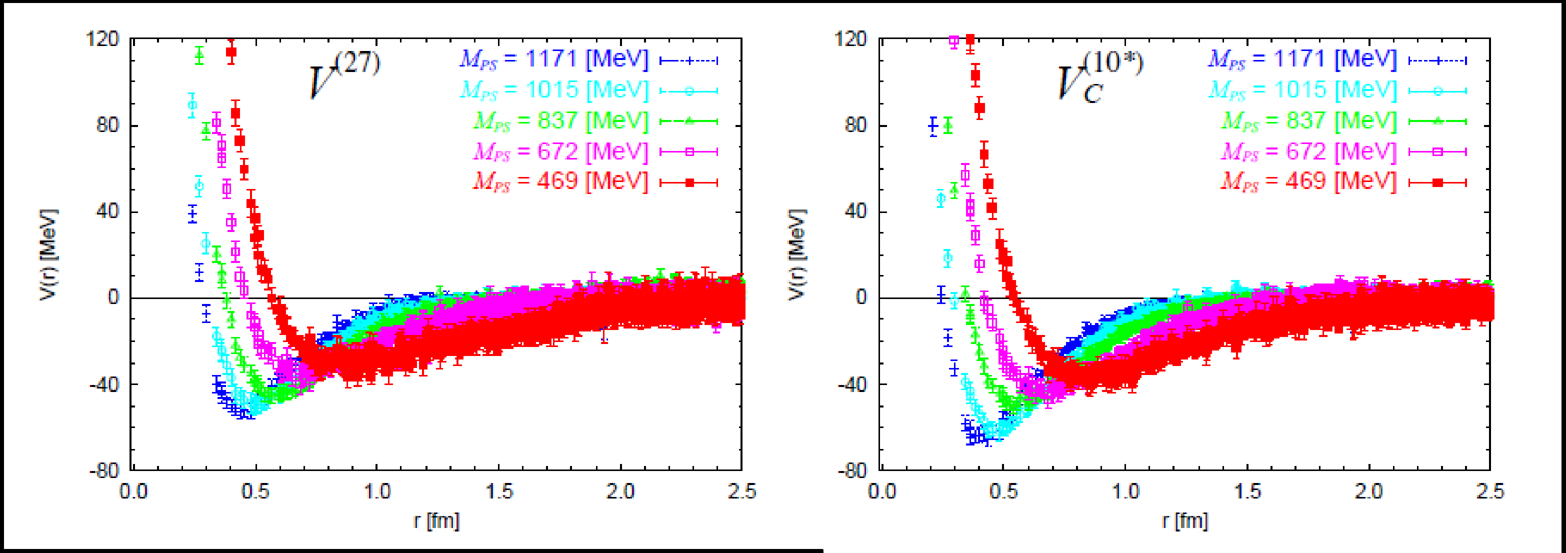
Hebeler et al., PRL 2010



BB potentials (flavor SU(3) limit)

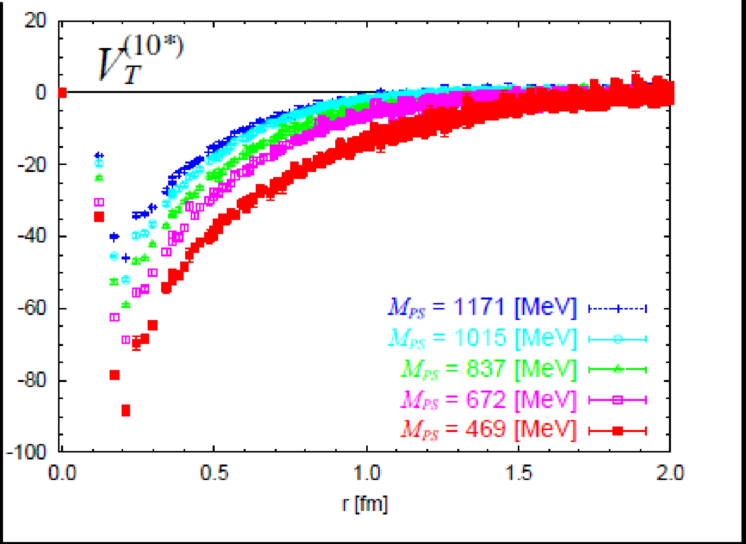
IHAL QCD Coll.
Phys. Rev. Lett. 106 (2011) 162002
Nucl. Phys. A881 (2012) 28

Repulsive core in NN channel



$^1S_0$ channel

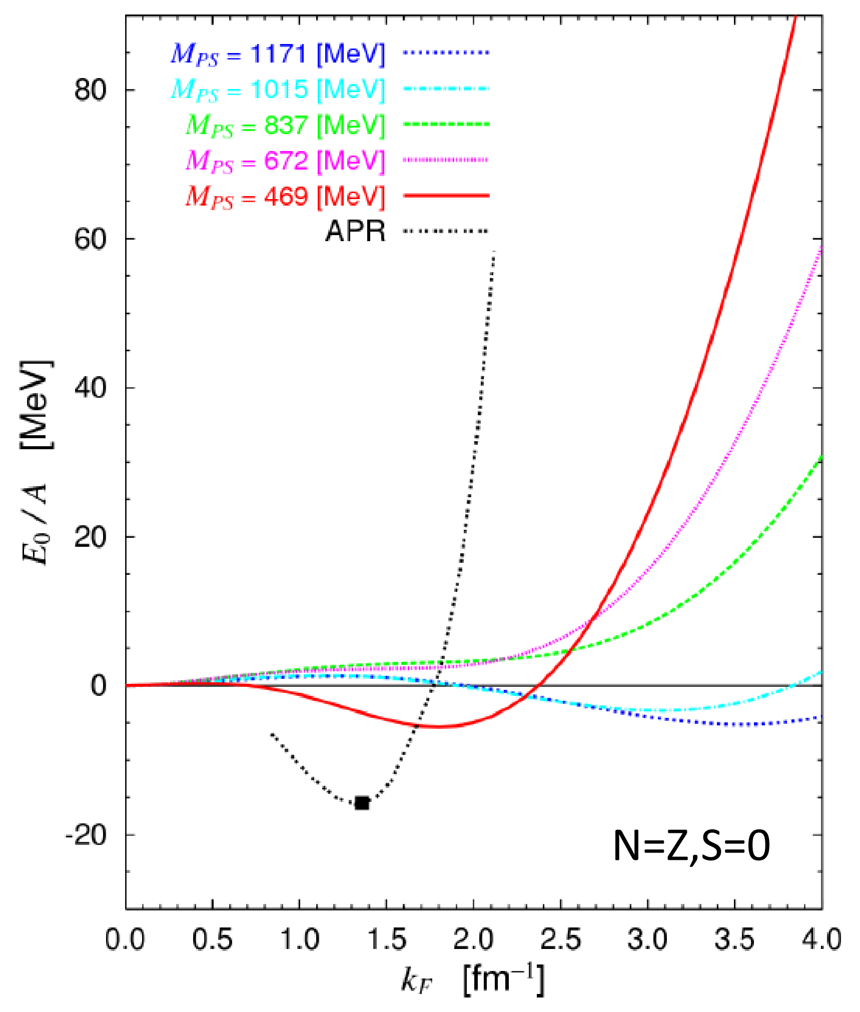
$^3S_1 - {}^3D_1$ channel

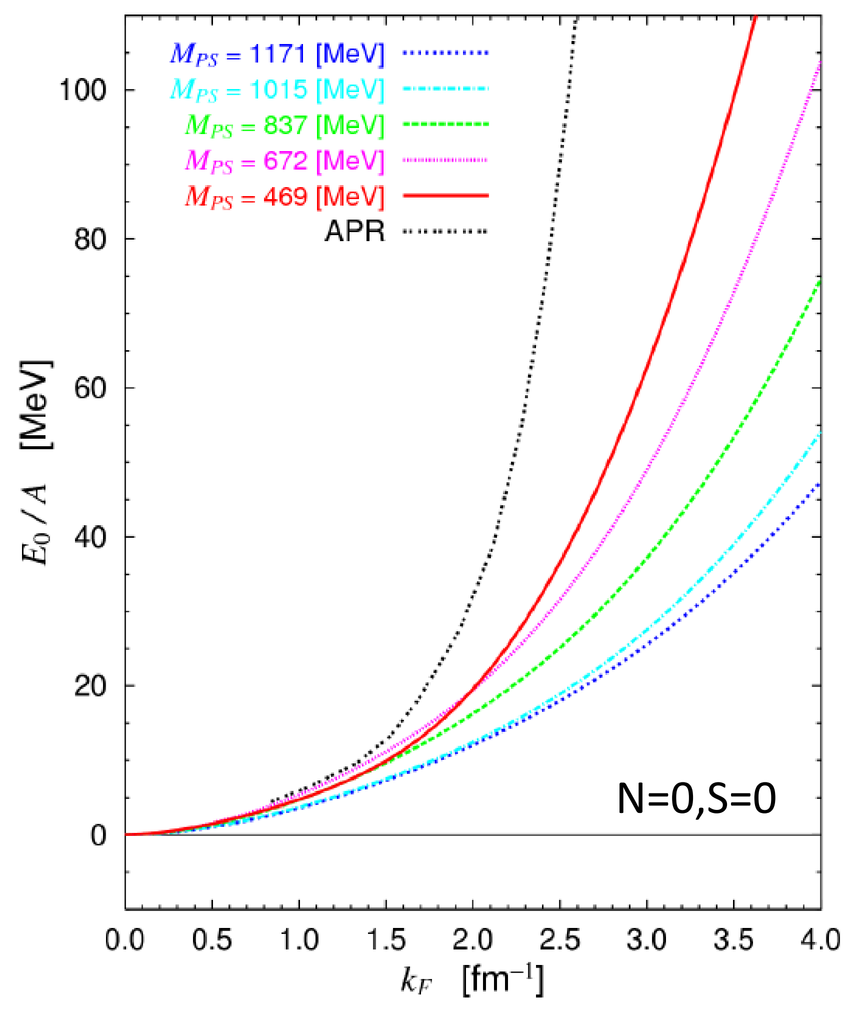


Growing NN tensor force

Just for fun: Neutron star from NN potential in flavor SU(3) limit

EOS with Lattice NN force by BHF calculation → M-R relation by TOV equation

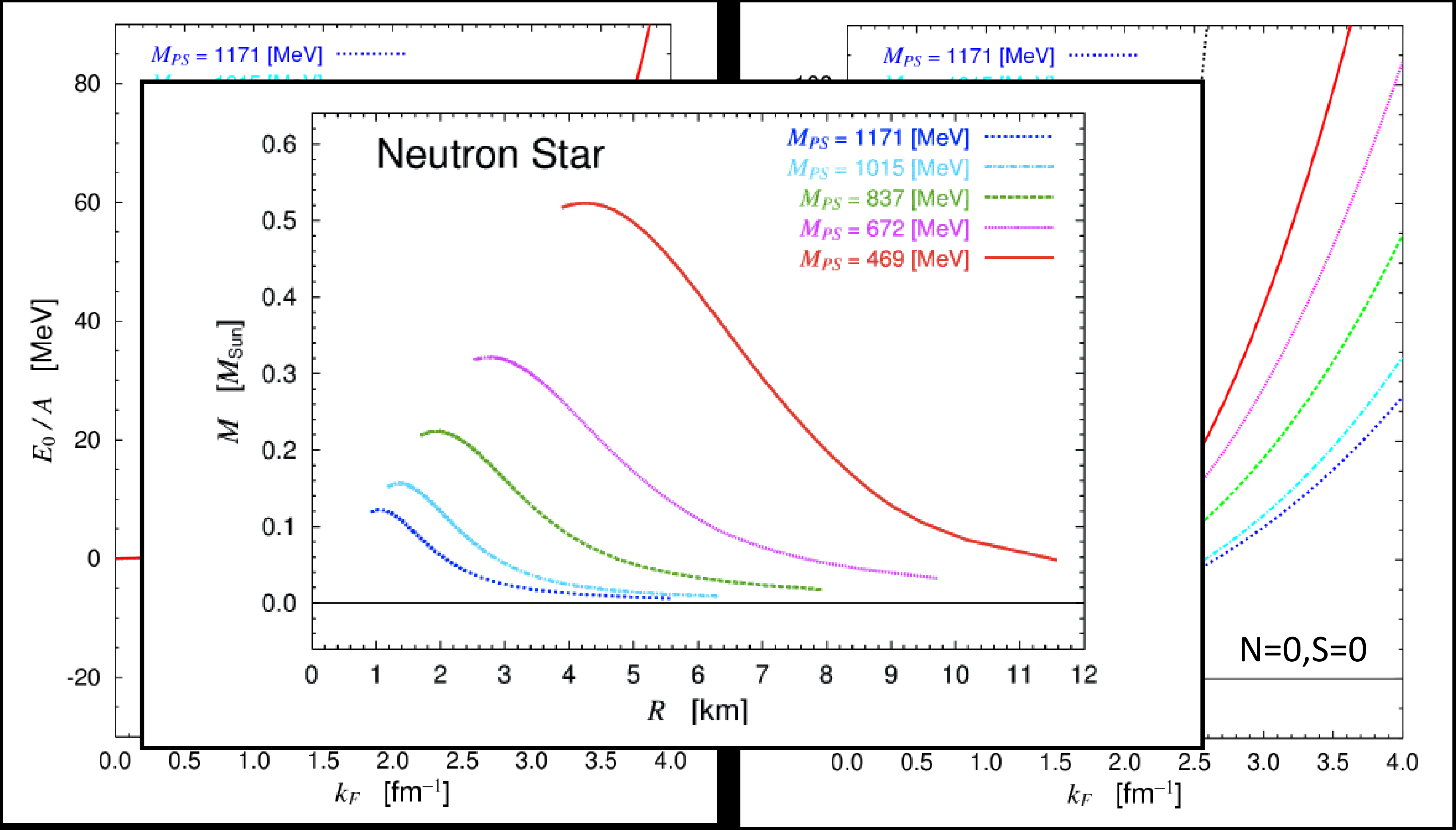




Inoue et al. [HAL QCD Coll.] (2012)

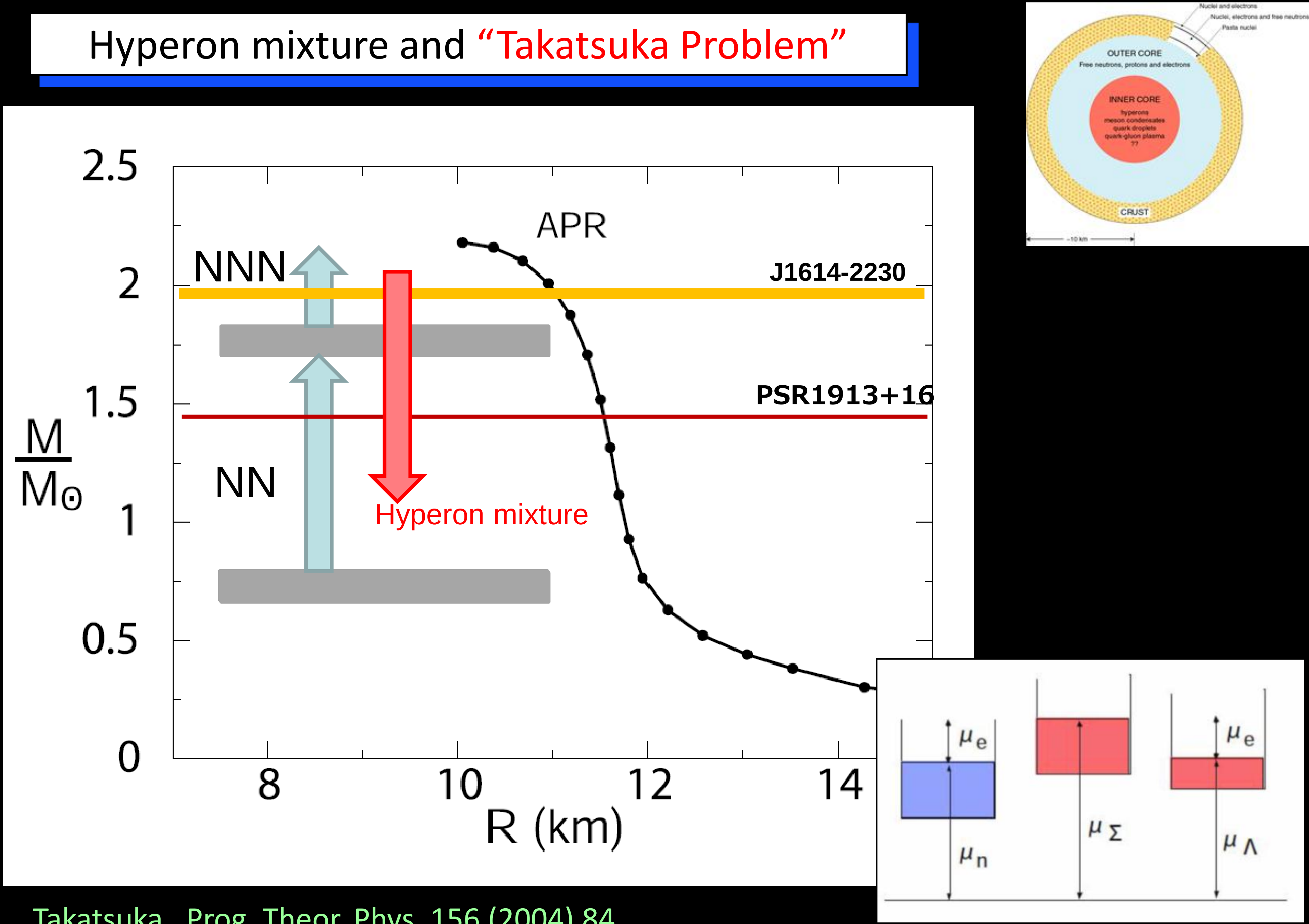
Just for fun: Neutron star from NN potential in flavor SU(3) limit

EOS with Lattice NN force by BHF calculation → M-R relation by TOV equation



Inoue et al. [HAL QCD Coll.] (2012)

Hyperon mixture and “Takatsuka Problem”

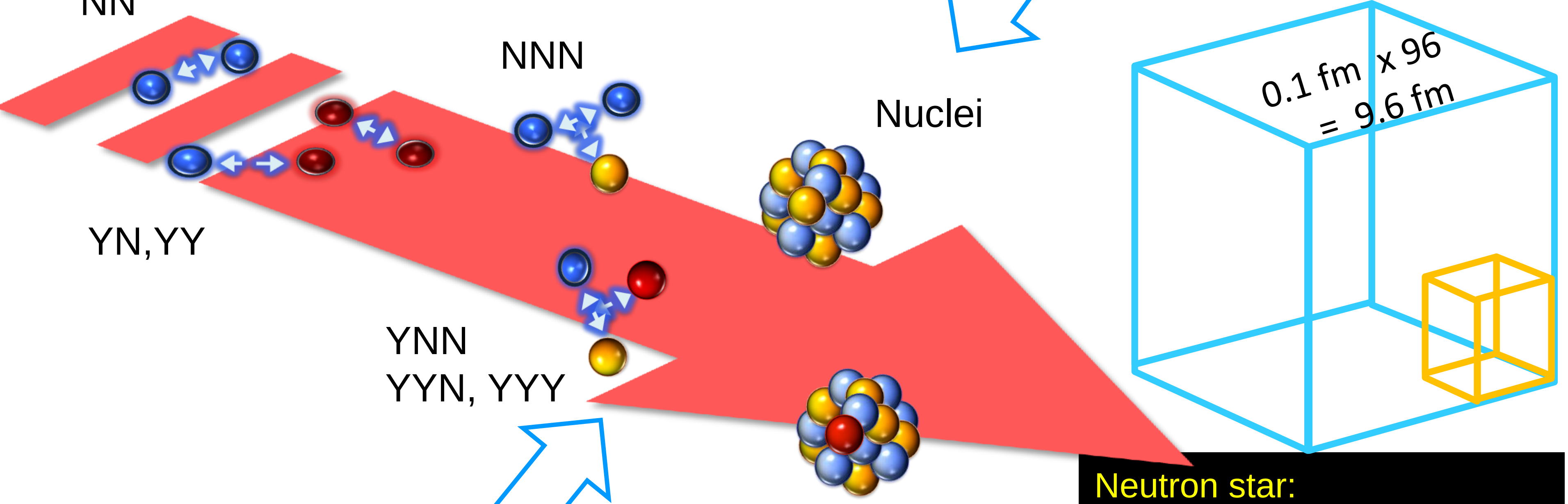


Takatsuka, Prog. Theor. Phys. 156 (2004) 84

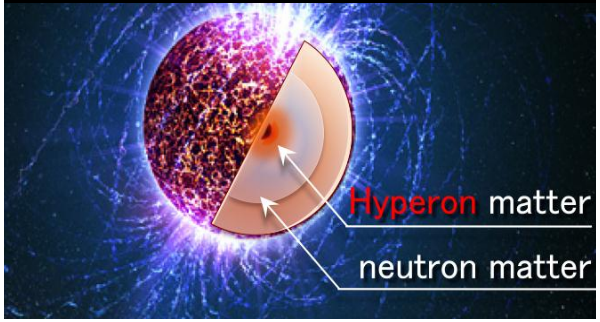
From Quarks to Cosmos

BG/L -> PACS-CS -> T2K -> BG/Q -> KEI
(10TF -> 100TF -> 1PF -> 10PF)

KEI Computer @ AICS (RIKEN)
(10PFlops)



Neutron star:
max mass, cooling etc



J-PARC (KEK/JAEA)

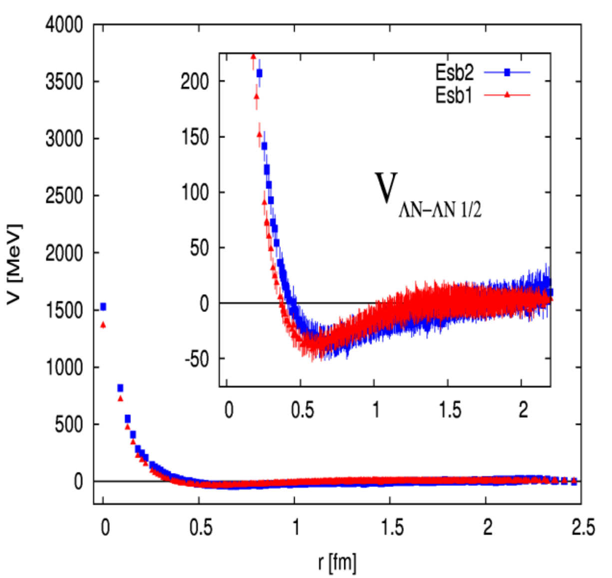
SU(3) breaking: coupled channel LQCD

Sasaki et al.
[HAL QCD Coll.] (2012)

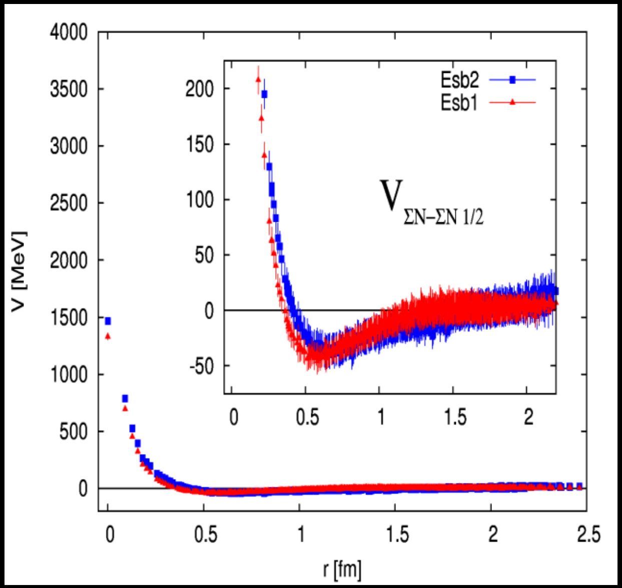
$$(k_n^2+\nabla^2)\,\phi_n^{\alpha}(\vec{r},t)=\int U(\vec{r},\vec{r}')^{\alpha\beta}\phi_n^{\beta}(\vec{r}',t)d^3r'$$

Example: S=-1, $^3S_1$, I=1/2 (m_π/m_K=0.89, 0.8)

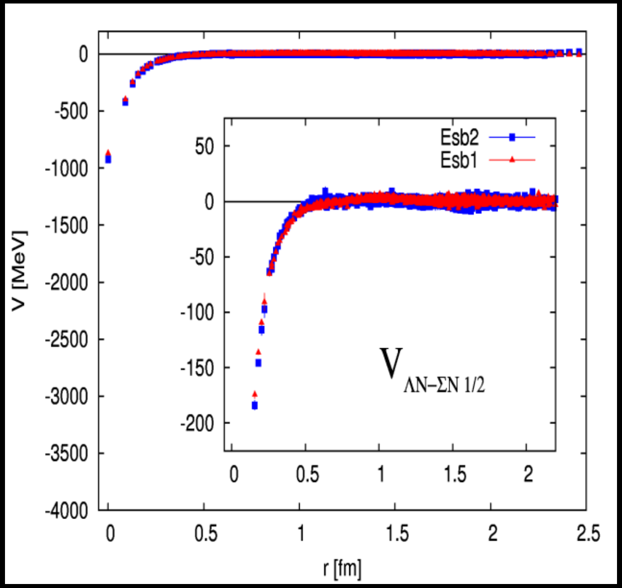
ΛN-ΛN



ΣN-ΣN

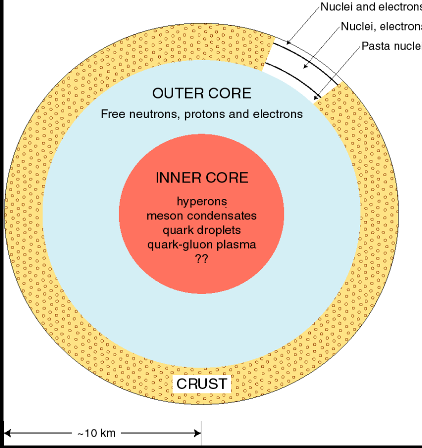


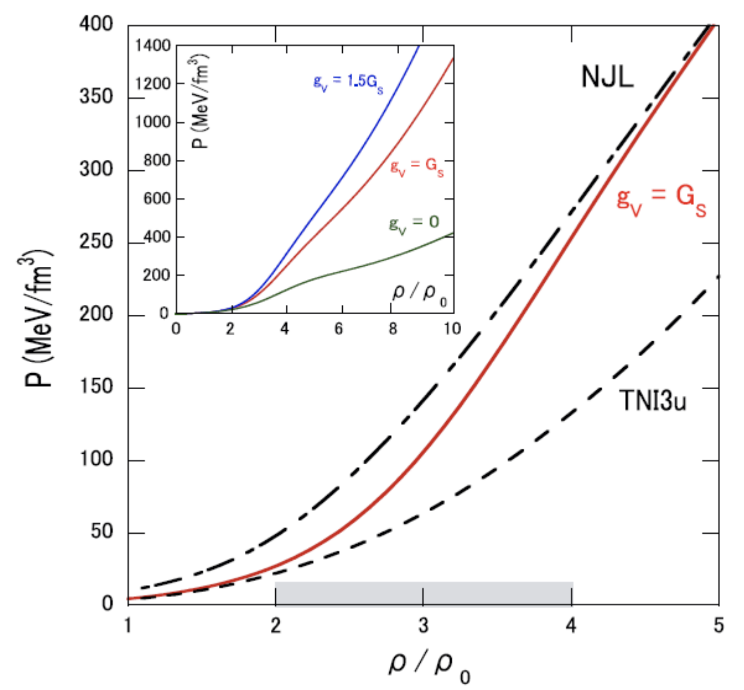
ΛN-ΣN

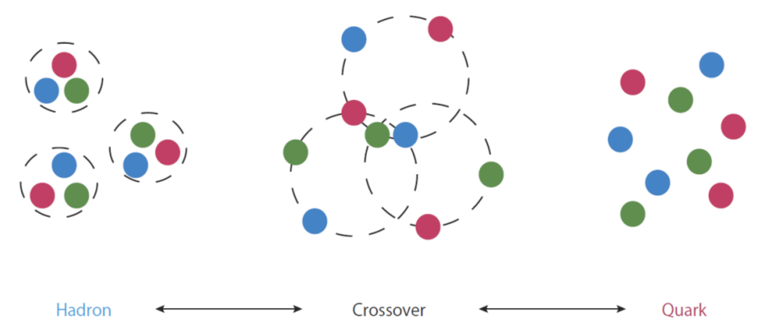


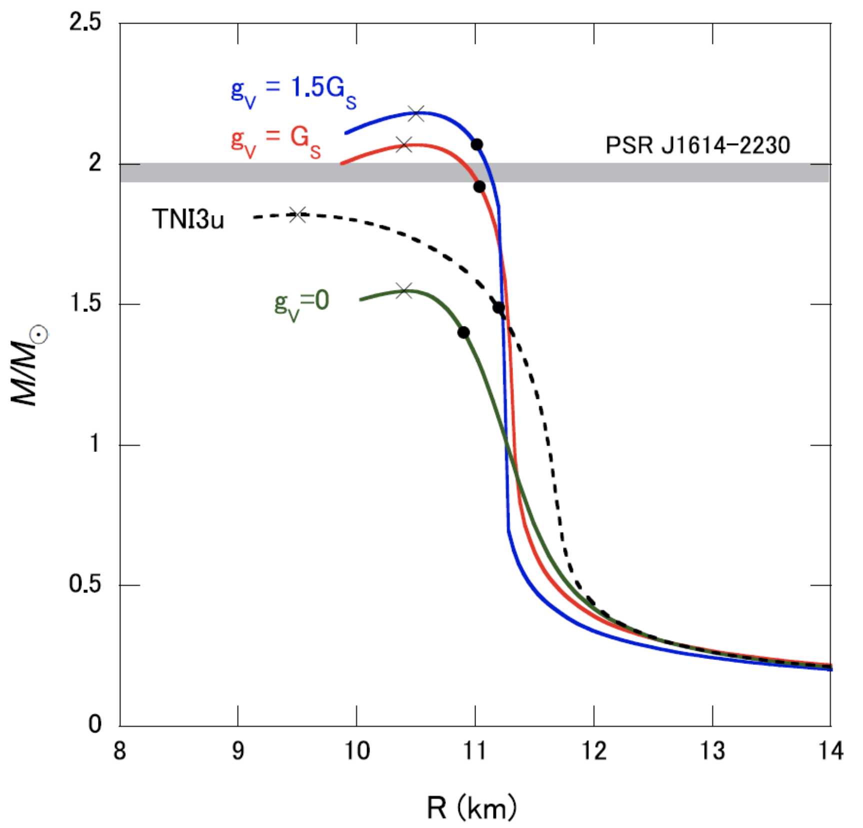
PACS-CS (2+1)-flavor config.
L=2.9 fm

Hadron-quark crossover and strongly interacting quark matter in inner core ?





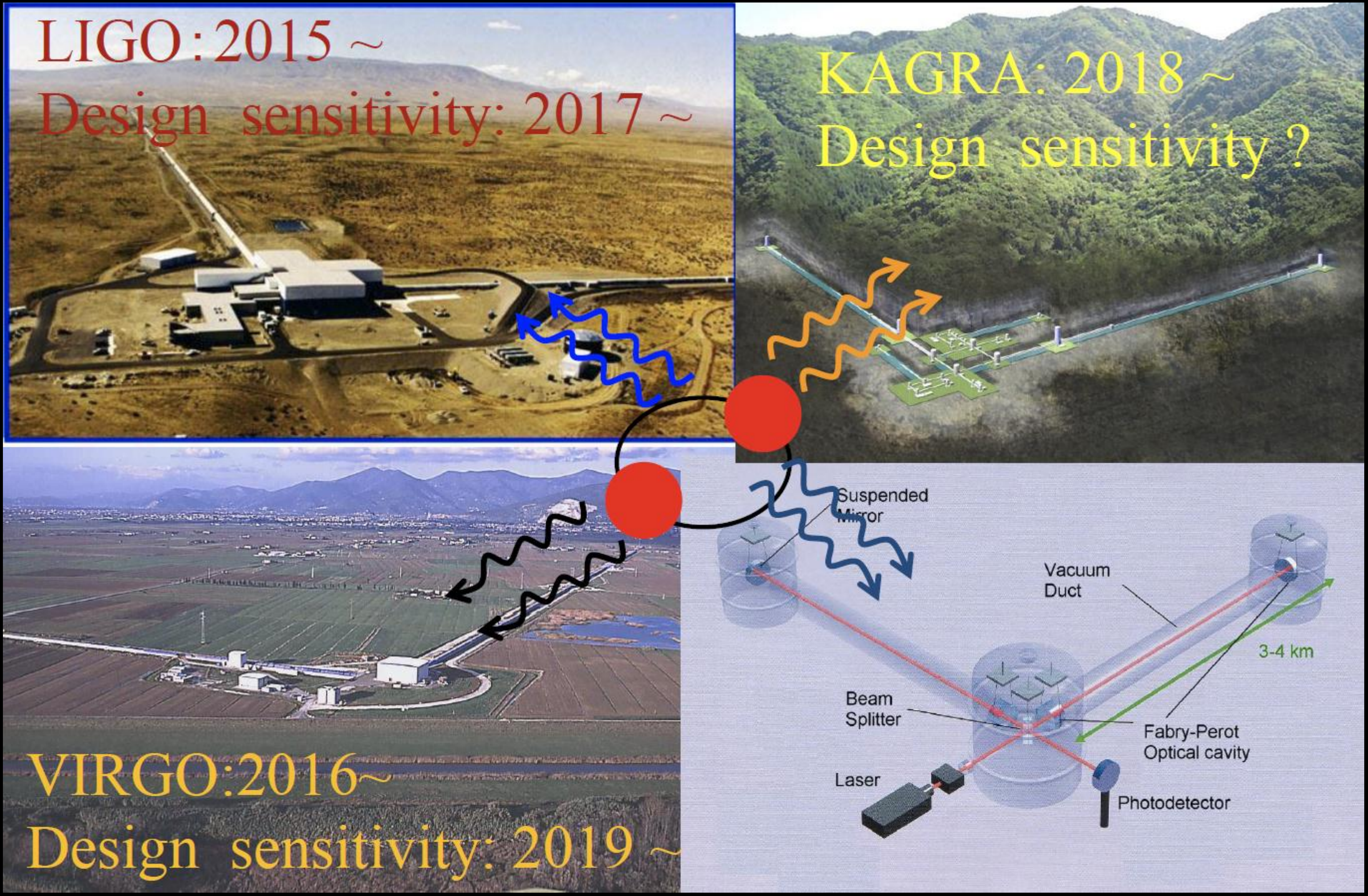




Hatsuda,Tachibana, Yamamoto & Baym,
Phys. Rev. Lett.97 (2006) 122001

Masuda, Takatsuka & Hatsuda,
arXiv: 1205.3621 [nucl-th]

Gravitational waves

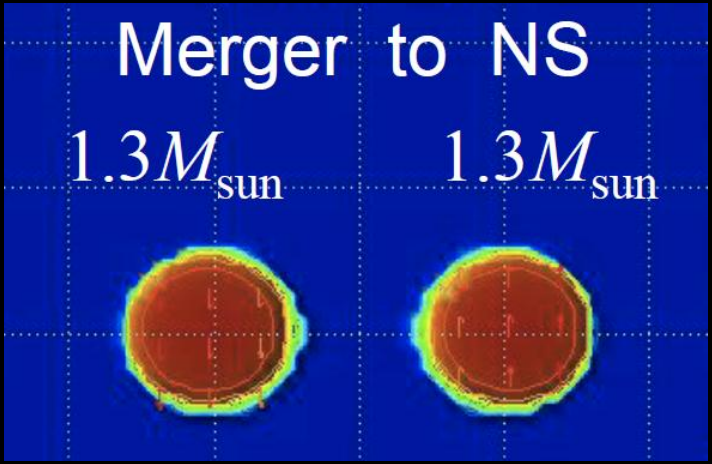


LIGO: 2015 ~
Design sensitivity: 2017 ~

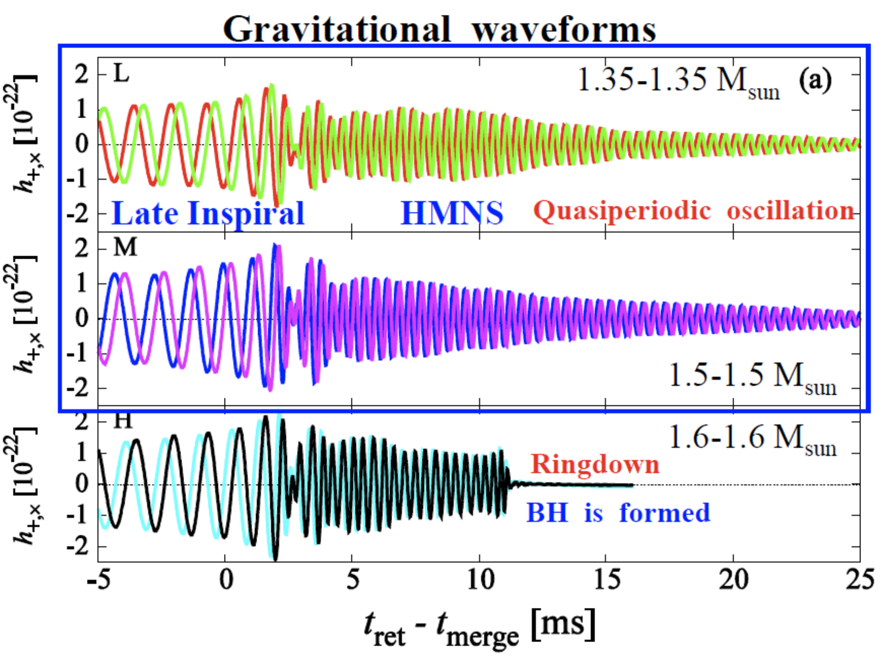
KAGRA: 2018 ~
Design sensitivity ?

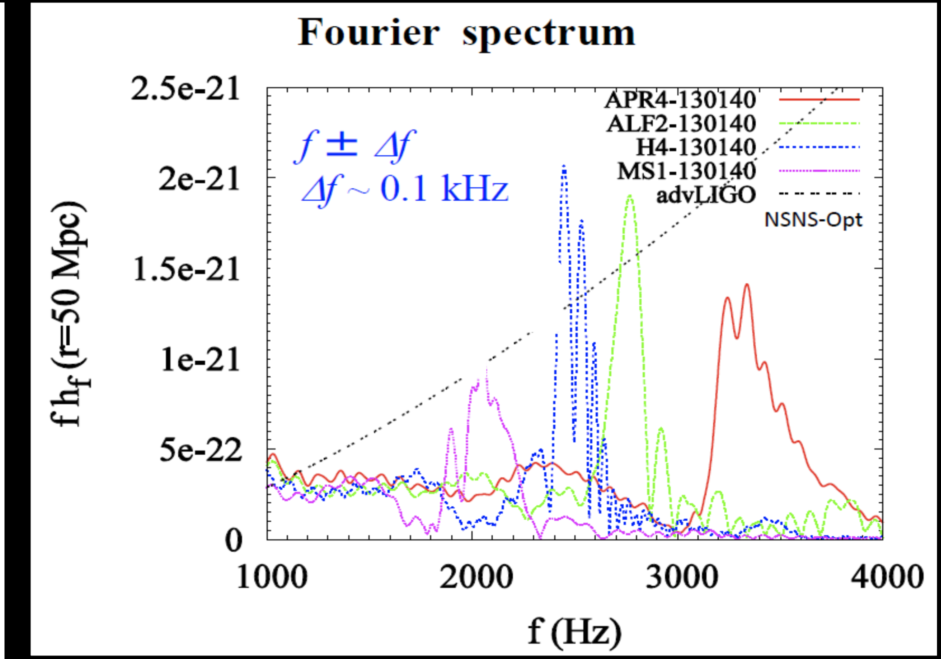
VIRGO:2016~
Design sensitivity: 2019 ~

EOS from Gravitational wave from $N_{\star}$ merger

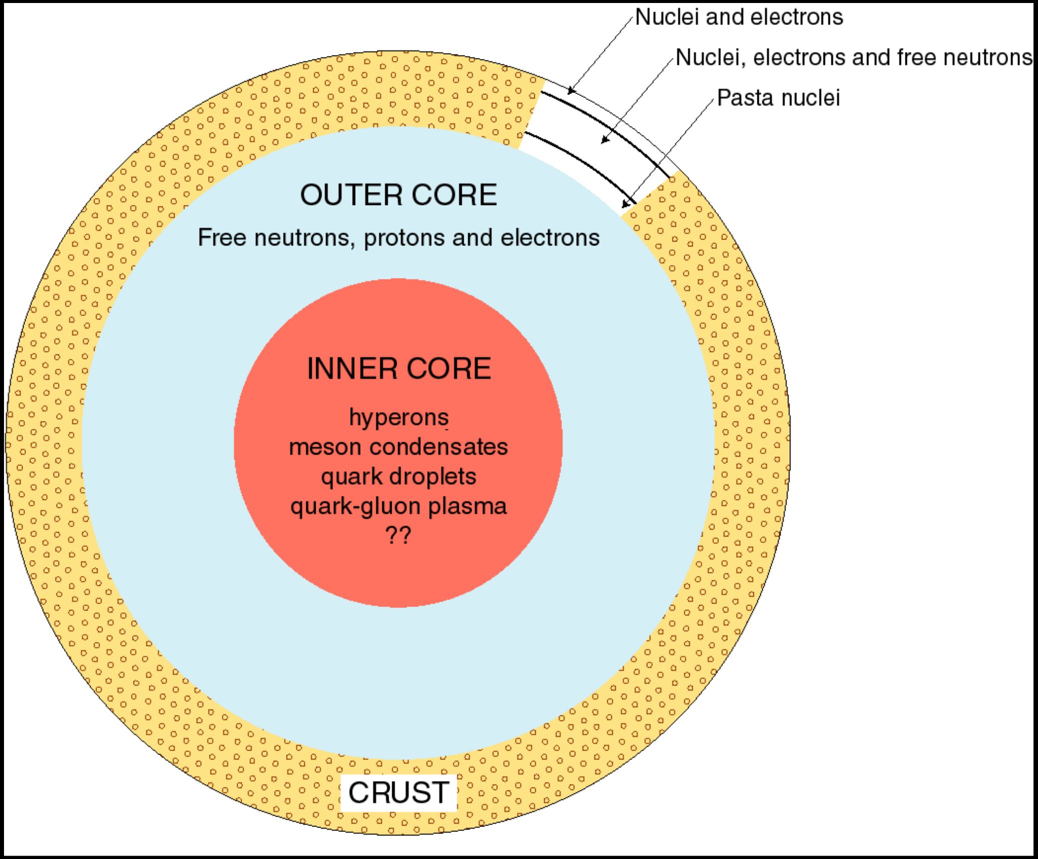


Sekiguchi, Kiuchi, Kyutoku & Shiata, PRL (2011)



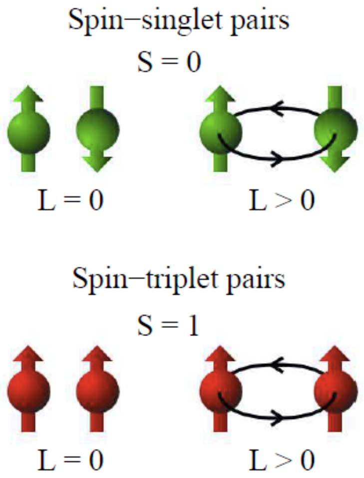


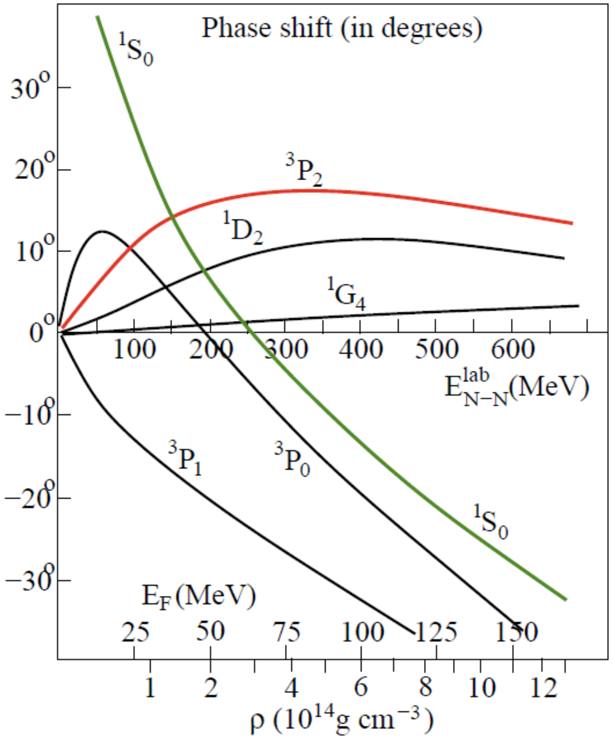
Superfluidity



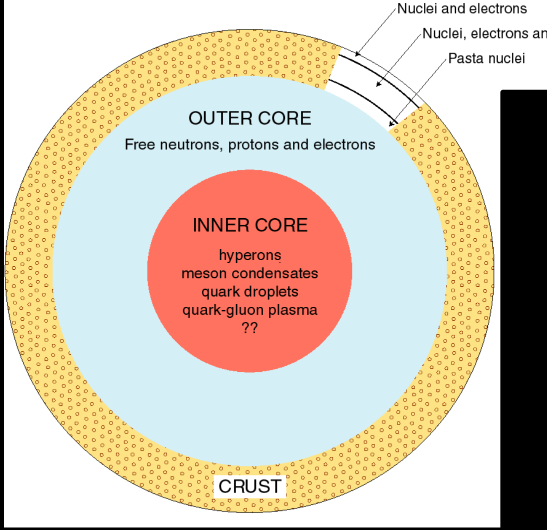
- $M \sim (1\text{-}2) M_\odot$
- $R \sim 10\text{km}$
- $0 < \rho < 10\, \rho_0$

Nuclear superfluidity

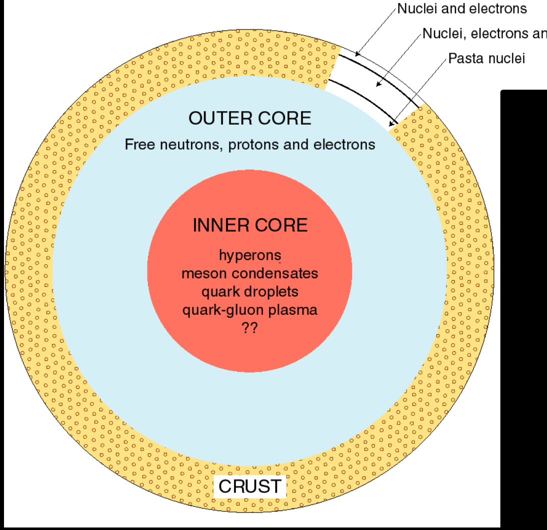


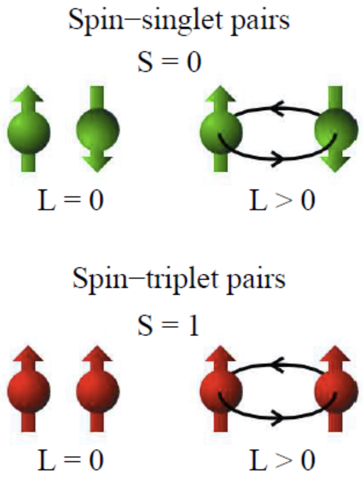


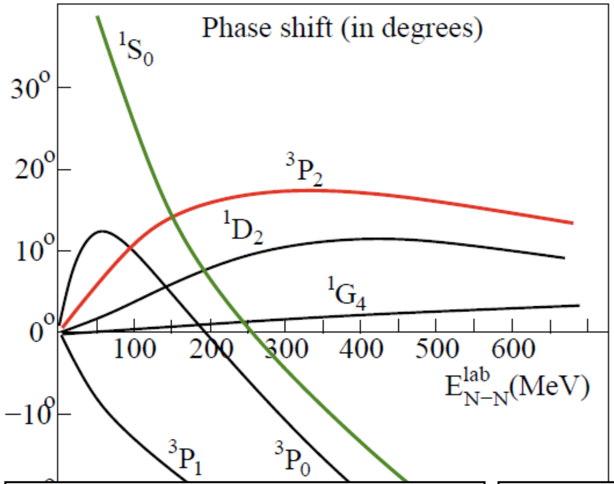
Tamagaki (1970)
Takatsuka (1972)



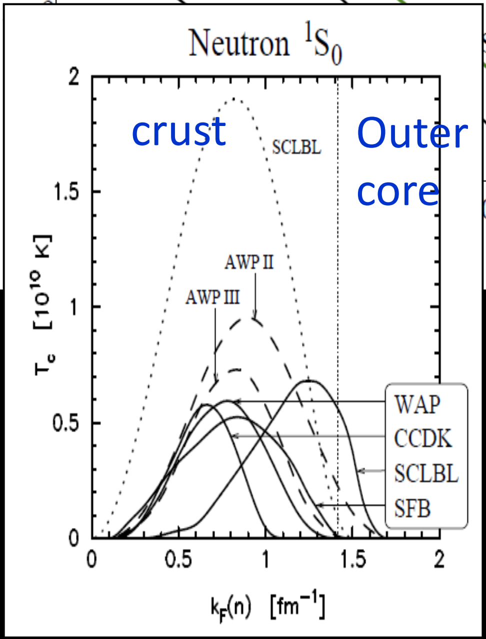
Nuclear superfluidity

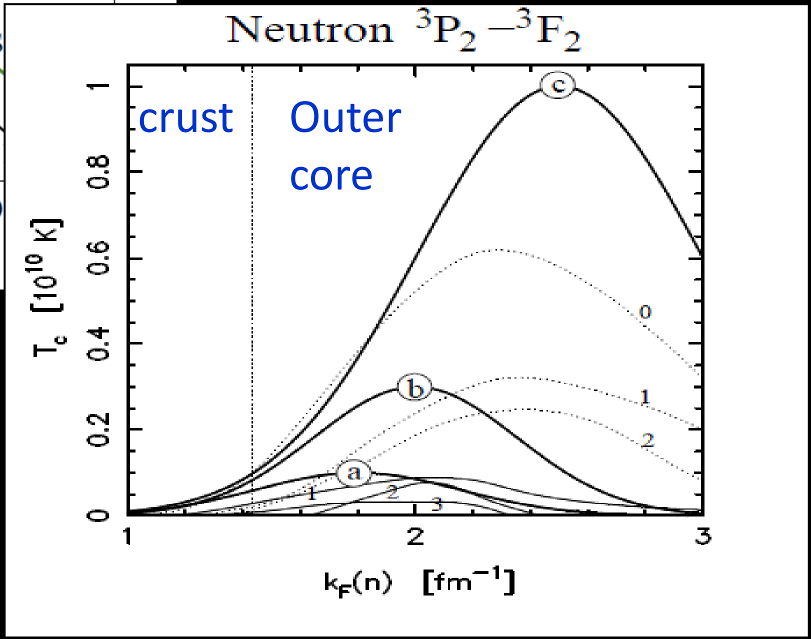






Tamagaki (1970)
Takatsuka (1972)





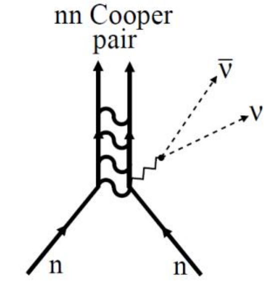
Cassiopeia A cooling (9 years CHANDRA data)

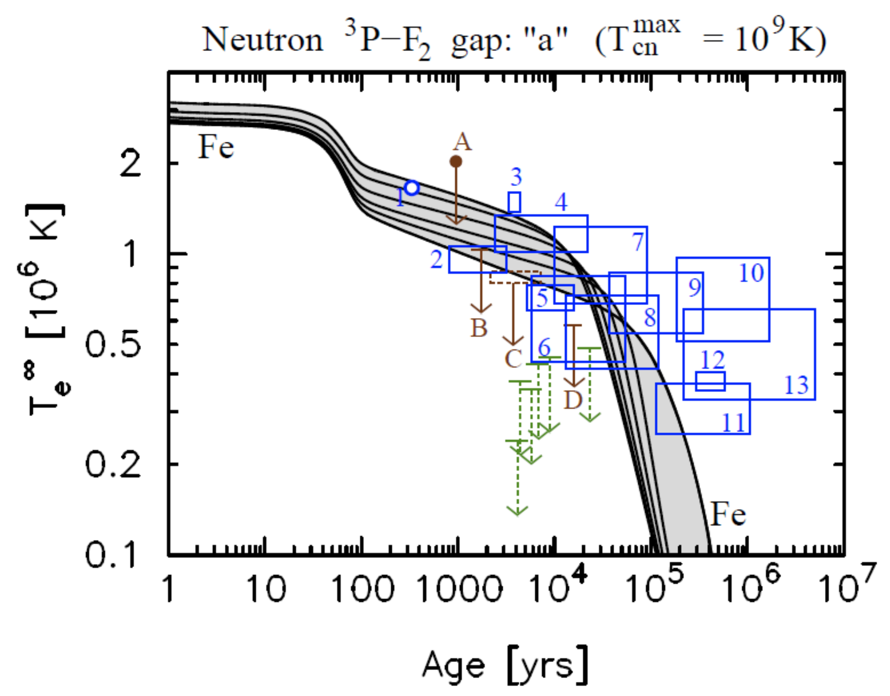
Onset of $^3P_2$ superfluidity ?

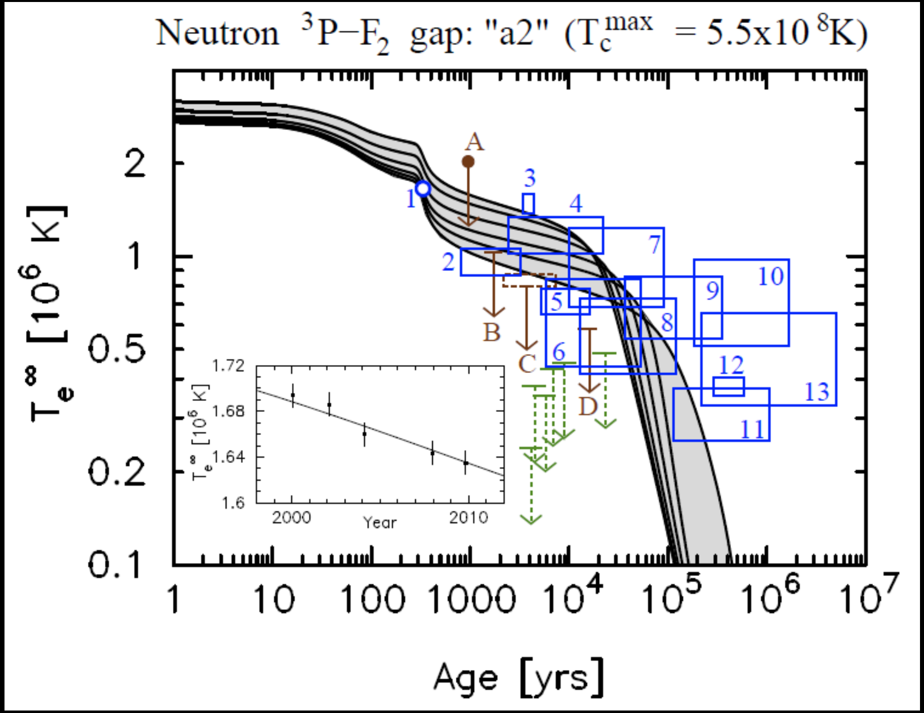
Heike & Ho, ApJ Lett. 719 (2010) L167
Shternin et al., Mon. Not. Astr. Soc. (2010)
Page et al., PRL (2011)

Siimple thermal relaxation ?

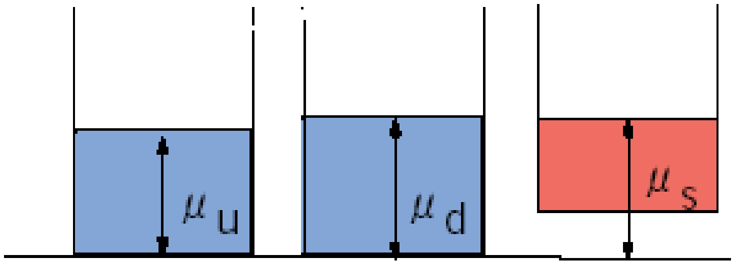
Heike & Ho, ApJ Lett. 719 (2010) L167
Tsuruta et al (2012)

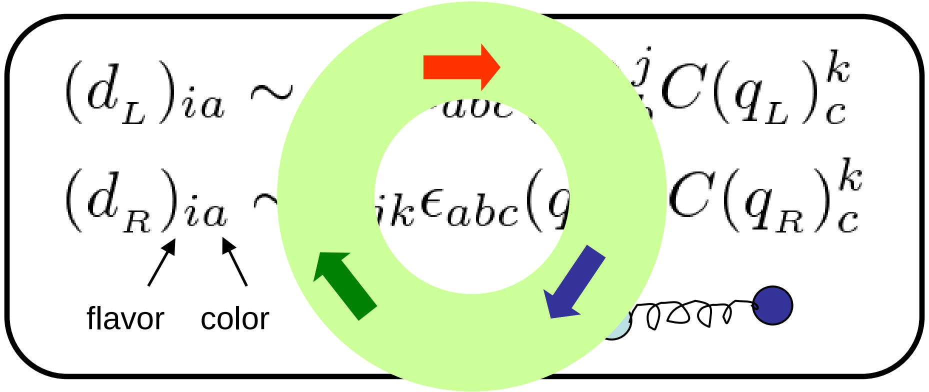






Color superconductivity





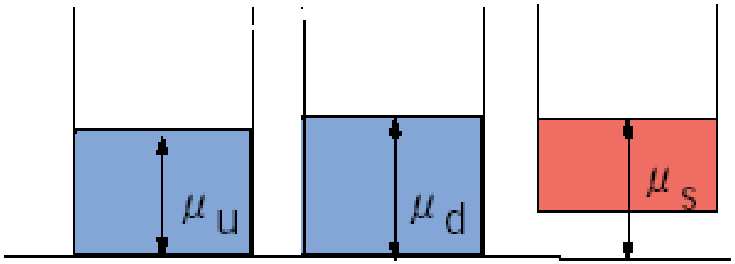
major differences from the standard BCS superconductor

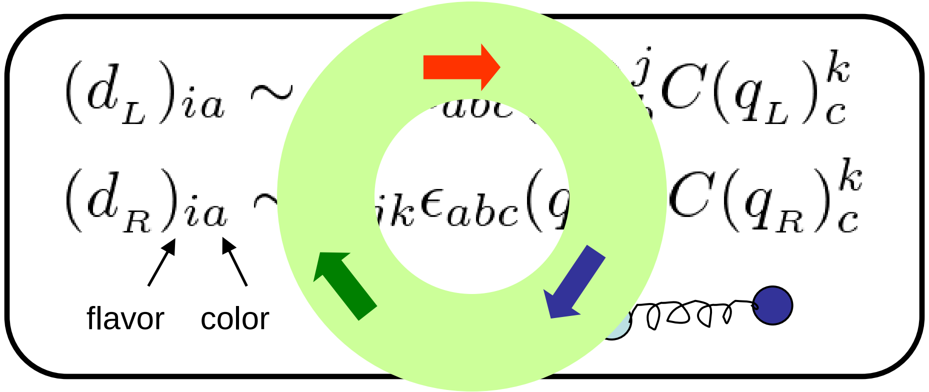
1. Relativistic fermi system
   color-magnetic int. dominant ⇒ $|d| \sim \varepsilon_F \; e^{-c/\sqrt{\alpha_s}}$

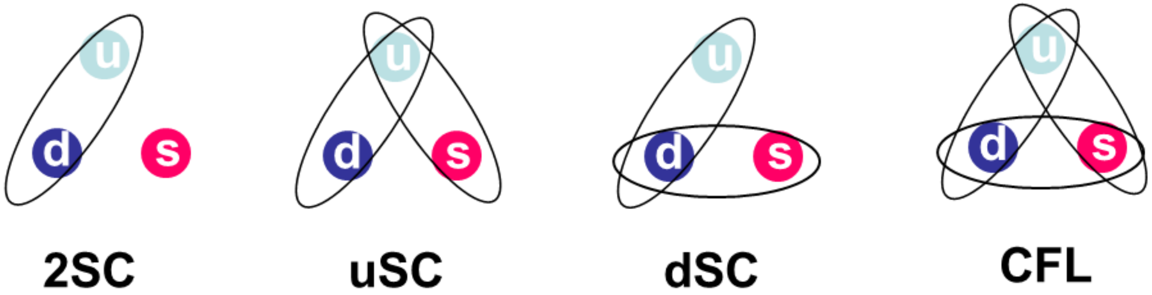
   High T_c : $T_c/\varepsilon_F \sim 0.1$
   Compact pair : r~ 1-10 fm

2. Color-flavor entanglement d_{ia} ⇒ Various phases (c.f. Ice, ^{3}He)
   2SC, uSC, dSC, CFL etc

Color superconductivity







2. Color-flavor entanglement

$$d_{ia}$$

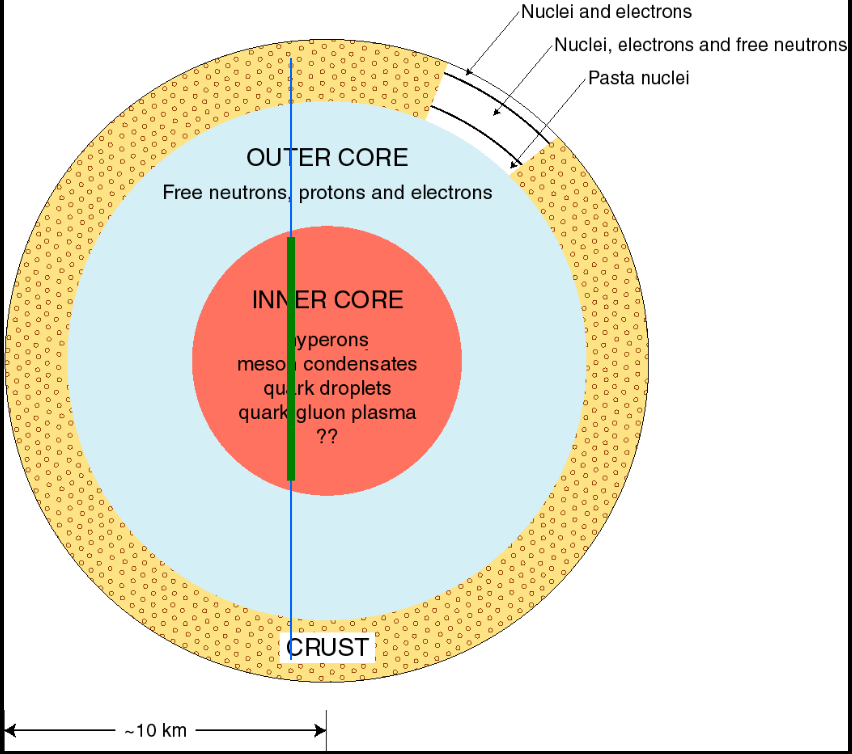
➡ Various phases (c.f. Ice, ^{3}He)

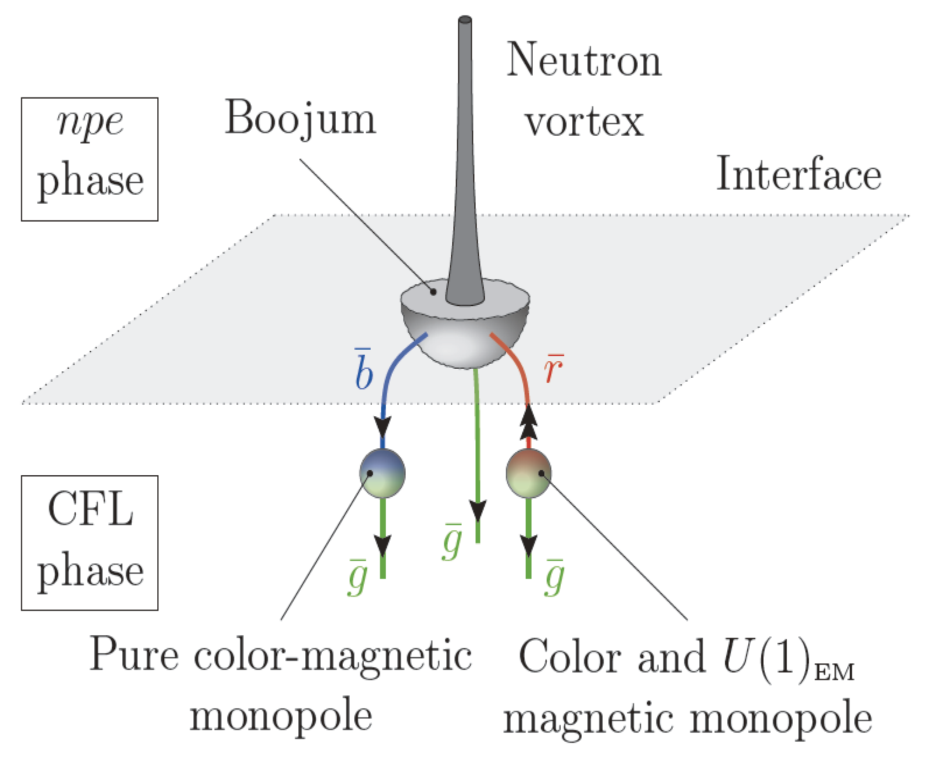
2SC, uSC, dSC, CFL etc

Quantum vortices in outer & inner cores

vortex size $\sim$ 10 fm

vortex distance $\sim$ $0.01P(s)^{1/2}$cm





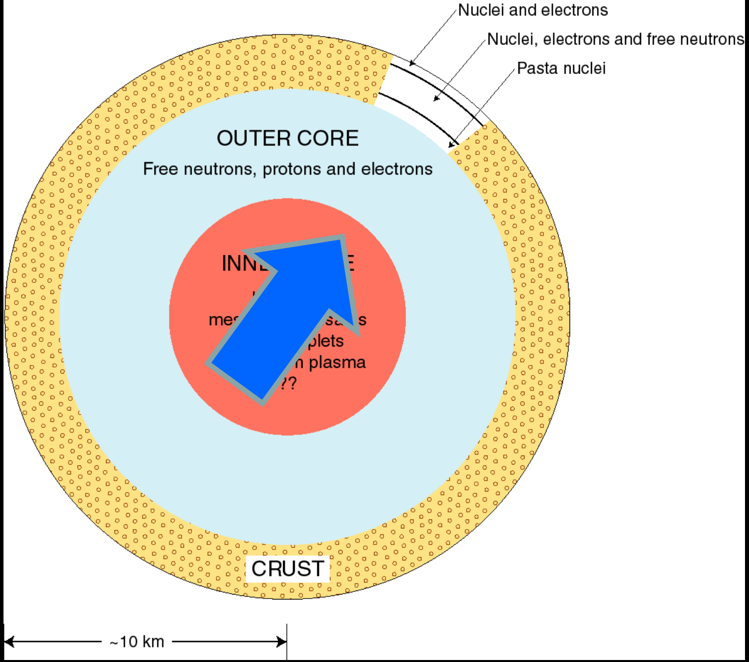
Cipriani,Vinci & Nitta, arXiv:1208.5704

Magnetars

$$10^{15}\,\mathrm{G} \simeq (10\ \mathrm{MeV})^2$$

$$10^{19}\,\mathrm{G} \simeq (1000\ \mathrm{MeV})^2$$

due to strong interaction ？



- ferromagnetism in neutron matter
  Brownell & Callaway (1969), Rice (1969), Silverstein (1969), Makishima (1999)
  negative in modern many-body theories : e. g. Bordar & Bigdeli, PRC77 (2008)

- ferromagnetism in quark core
  Tatsumi, Phys. Lett. B489 (2000); arXiv:1107.0807 [hep-ph]].

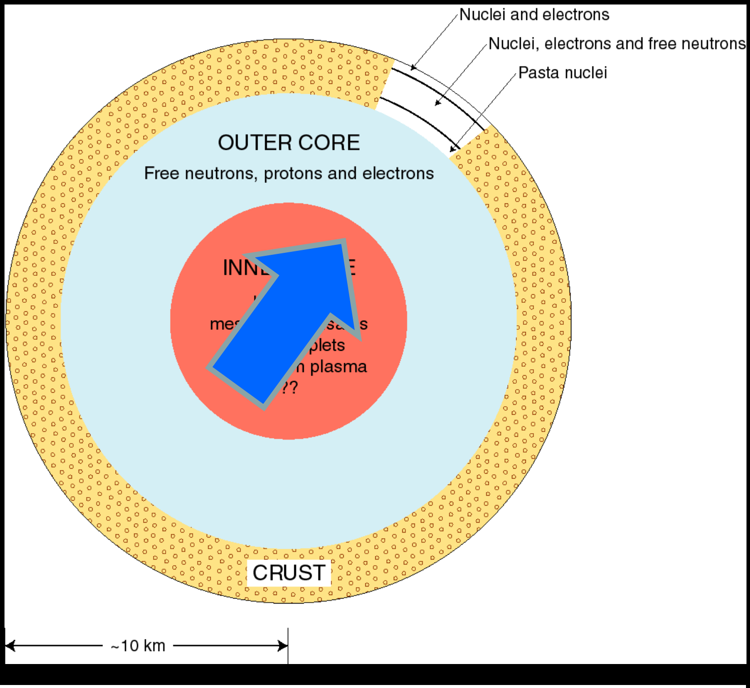
- ferromagnetism due to pion domain wall
  Hatsuda (1986), Son-Stephanov (2008)
  Eto, Hashimoto & Hatsuda (2012) arXiv:1209.4814 [hep-ph]

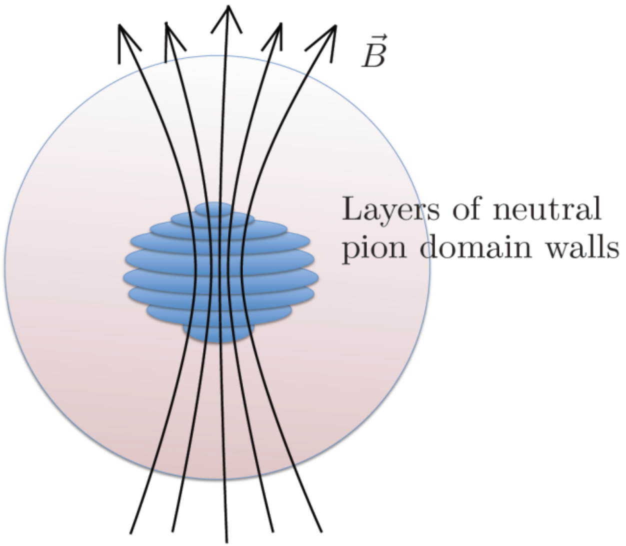
Magnetars

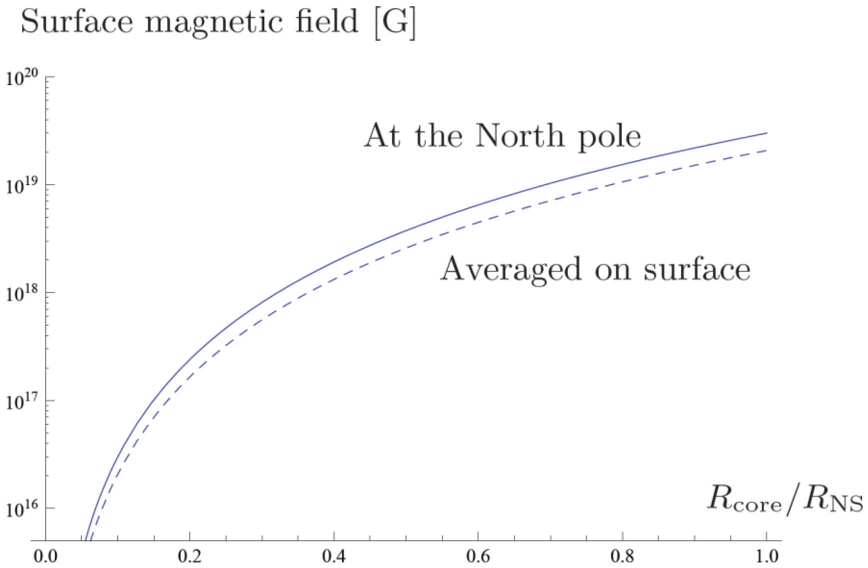
$10^{15}\,\mathrm{G} \simeq (10\ \mathrm{MeV})^2$

$10^{19}\,\mathrm{G} \simeq (1000\ \mathrm{MeV})^2$

due to strong interaction ？

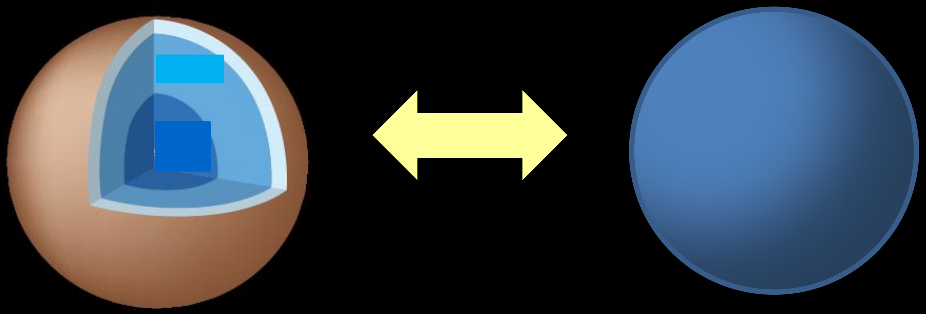






Eto, Hashimoto & Hatsuda (2012) arXiv:1209.4814 [hep-ph]

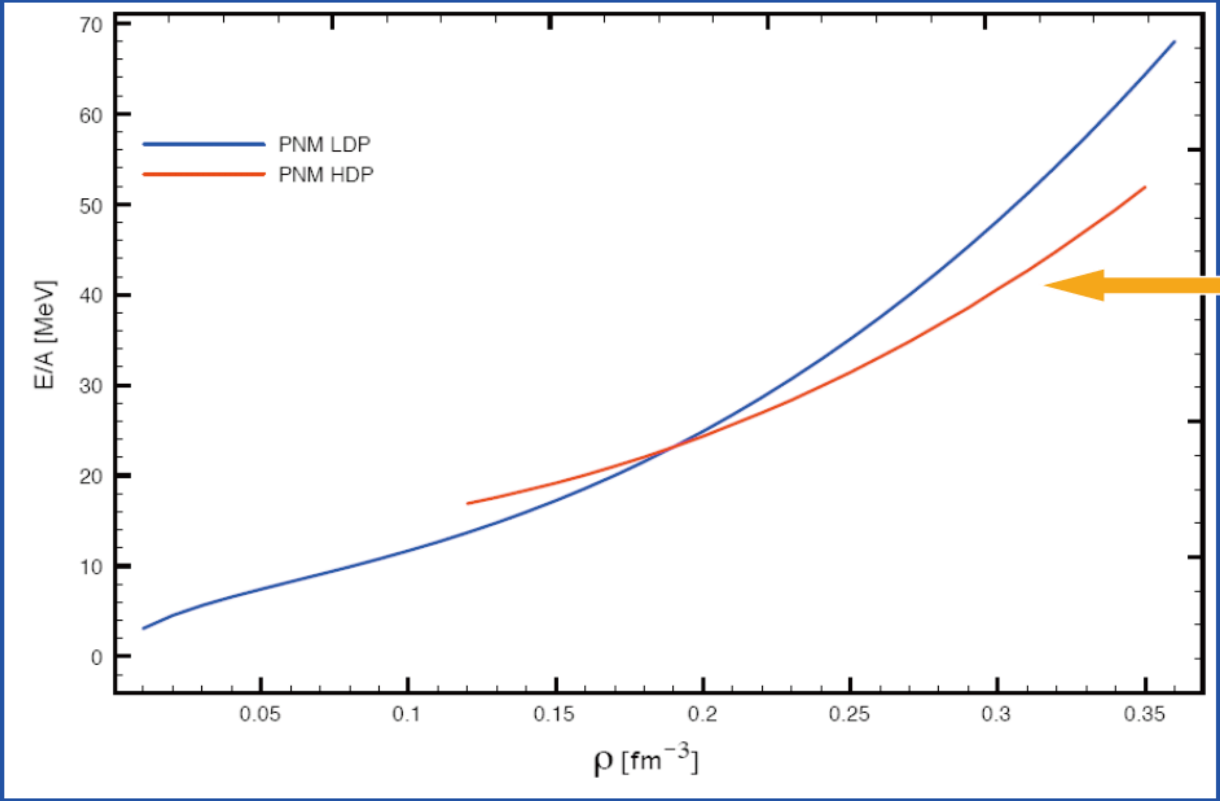
Neutron Star Structure
by Tabletop Expt.?



- Hadron-quark crossover ⇔ Bose-Fermi mixture
  Maeda, Baym & Hatsuda, PRL 103 (2009) 085301
- Meson condensation ⇔ Dipolar atoms
  Meada, Baym & Hatsuda, arXiv: 1205.1086 [cond-mat]

Energy per nucleon in pure neutron matter

Morales, (Pandharipande) & Ravenhall, in progress

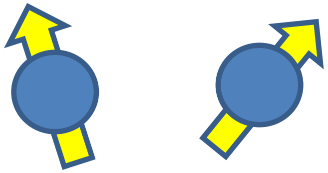


π^0 condensate

AV-18 + UIV 3-body (IL 3-body too attractive) Improved FHNC algorithms. Two minima!

E/A slightly higher than *Akmal, Pandharipande and Ravenhall, Phys. Rev. C58 (1998) 1804*

Dipolar fermi systems



$$U = \frac{\mu^2}{r^3}\{\vec{\sigma}_1\cdot\vec{\sigma}_2 - 3(\vec{\sigma}_1\cdot\hat{r})(\vec{\sigma}_2\cdot\hat{r})\} + g\,\delta(\vec{r})$$

Neutron matter
（neutron+meson）

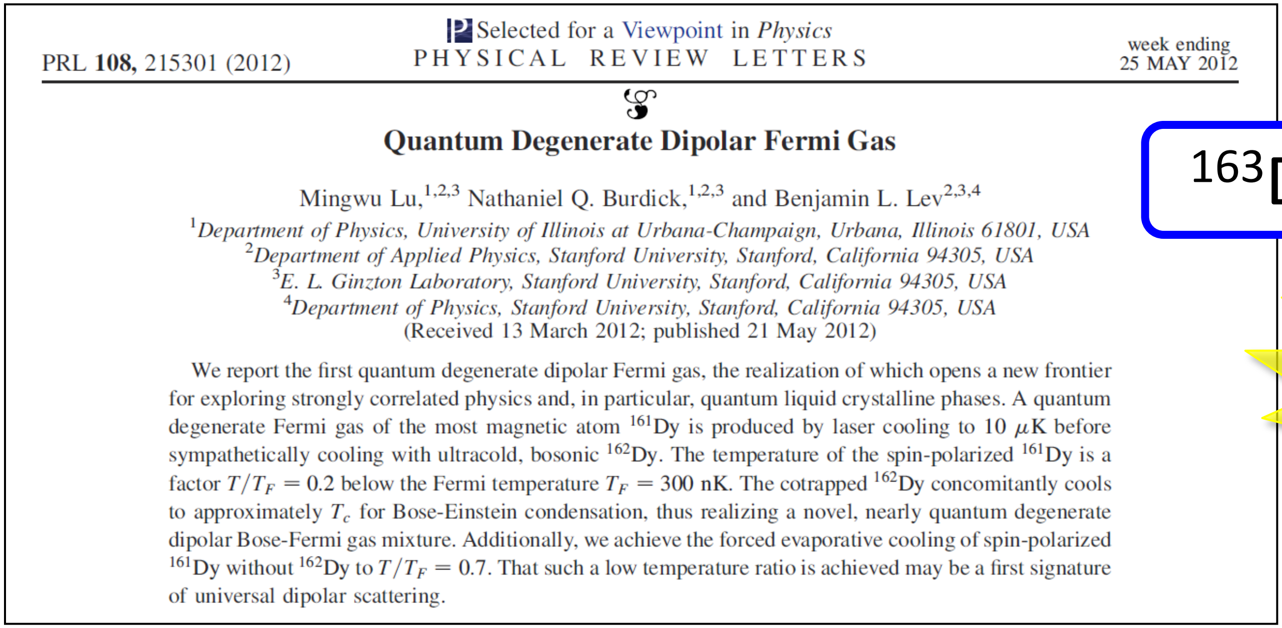
↔

Cold atoms with
large magnetic moment

↓

^{163}Dy, ^{167}Dy fermions

expt. data
（2012~）



Selected for a Viewpoint in *Physics*
PRL **108,** 215301 (2012) PHYSICAL REVIEW LETTERS week ending 25 MAY 2012

Quantum Degenerate Dipolar Fermi Gas

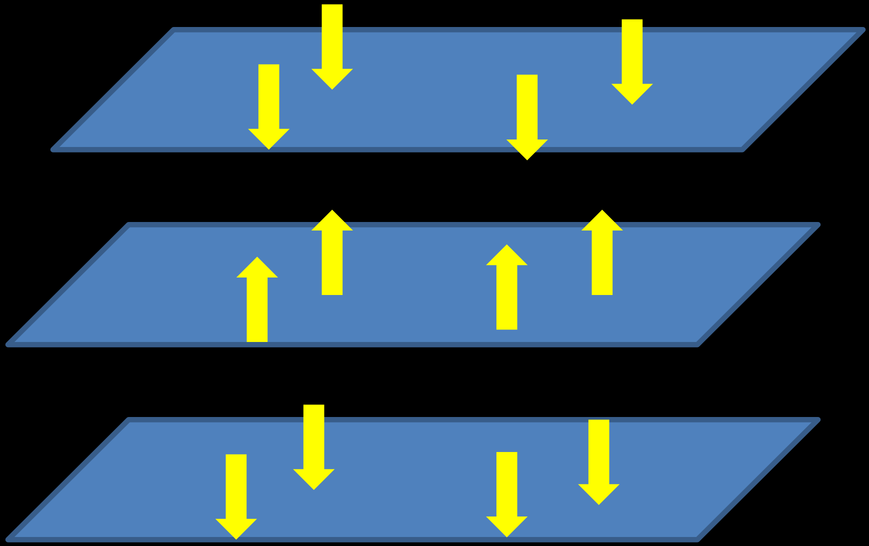
Mingwu Lu,[1,2,3] Nathaniel Q. Burdick,[1,2,3] and Benjamin L. Lev[2,3,4]
[1]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[2]*Department of Applied Physics, Stanford University, Stanford, California 94305, USA*
[3]*E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*
[4]*Department of Physics, Stanford University, Stanford, California 94305, USA*

(Received 13 March 2012; published 21 May 2012)

We report the first quantum degenerate dipolar Fermi gas, the realization of which opens a new frontier for exploring strongly correlated physics and, in particular, quantum liquid crystalline phases. A quantum degenerate Fermi gas of the most magnetic atom ^{161}Dy is produced by laser cooling to 10 μK before sympathetically cooling with ultracold, bosonic ^{162}Dy. The temperature of the spin-polarized ^{161}Dy is a factor $T/T_F = 0.2$ below the Fermi temperature $T_F = 300$ nK. The cotrapped ^{162}Dy concomitantly cools to approximately T_c for Bose-Einstein condensation, thus realizing a novel, nearly quantum degenerate dipolar Bose-Fermi gas mixture. Additionally, we achieve the forced evaporative cooling of spin-polarized ^{161}Dy without ^{162}Dy to $T/T_F = 0.7$. That such a low temperature ratio is achieved may be a first signature of universal dipolar scattering.

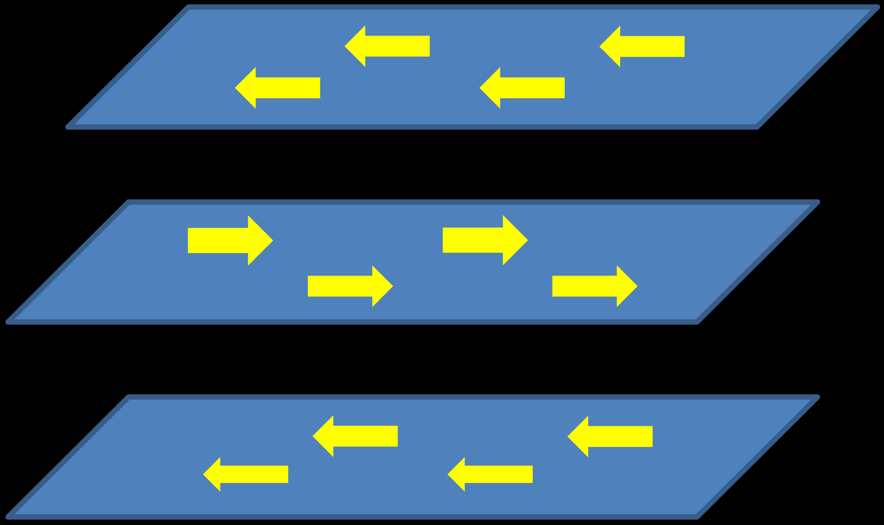
π^0 and ρ^0 condensations in neutron matter

E and B condensations in dipolar atoms/molecules



$$(-\nabla^2+m_\pi^2)\varphi_c(\boldsymbol{r}) = (f/m_\pi)\boldsymbol{\nabla}\cdot\langle\psi^\dagger\boldsymbol{\sigma}\psi\rangle$$

A. B. Migdal, NPA (1972)
Takatsuka, Tamagaki & Tatsumi,
Prog. Theor. Phys. Suppl. 112 ('93) 67

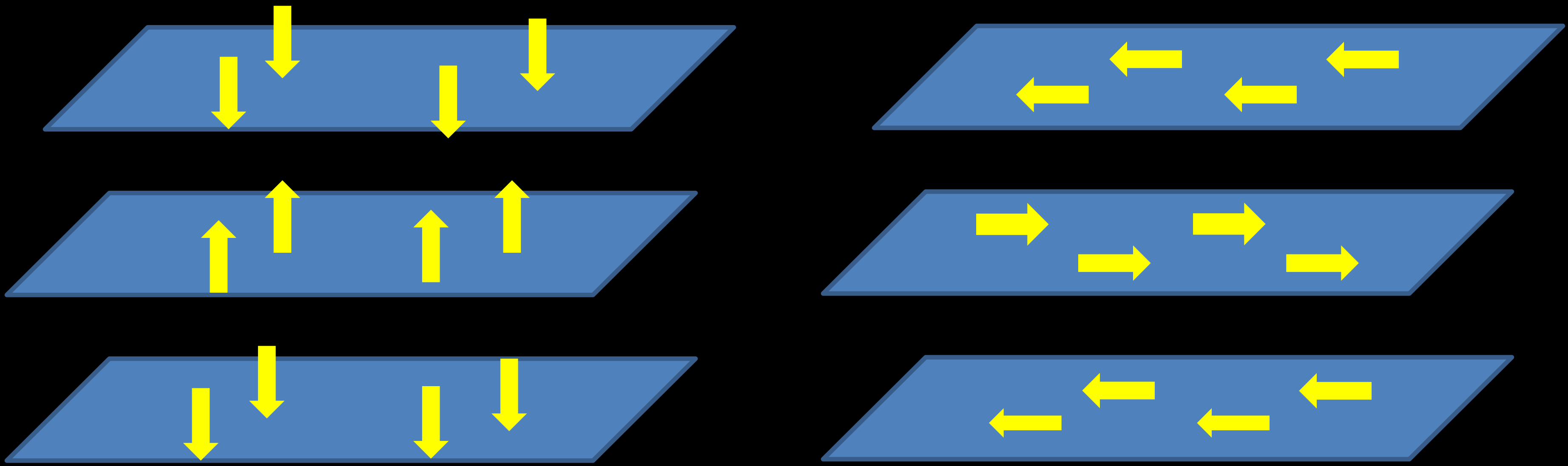


$$(-\nabla^2+m_\rho^2)\boldsymbol{\rho}_c(\boldsymbol{r}) = (f_\rho/m_\rho)\boldsymbol{\nabla}\times\langle\psi^\dagger\boldsymbol{\sigma}\psi\rangle$$

Kunihiro, Prog. Theor. Phys. 60 ('78) 1229

π^0 and ρ^0 condensations in neutron matter

E and B condensations in dipolar atoms/molecules



$$(-\nabla^2 + m_\pi^2)\,\varphi_c(\boldsymbol{r}) = (f/m_\pi)\,\boldsymbol{\nabla}\cdot\langle\psi^\dagger\boldsymbol{\sigma}\psi\rangle$$

$$(-\nabla^2 + m_\rho^2)\,\boldsymbol{\rho}_c(\boldsymbol{r}) = (f_\rho/m_\rho)\,\boldsymbol{\nabla}\times\langle\psi^\dagger\boldsymbol{\sigma}\psi\rangle$$

$\varphi \Leftrightarrow A_0$

$-\nabla\varphi \Leftrightarrow \boldsymbol{E}$

$\boldsymbol{S} \Leftrightarrow \boldsymbol{d}$

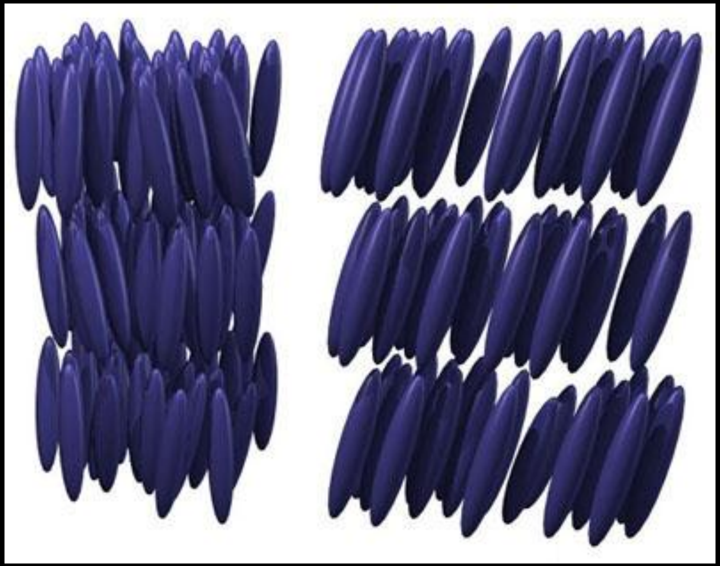
$\boldsymbol{\rho} \Leftrightarrow \boldsymbol{A}$

$\nabla \times \boldsymbol{\rho} \Leftrightarrow \boldsymbol{B}$

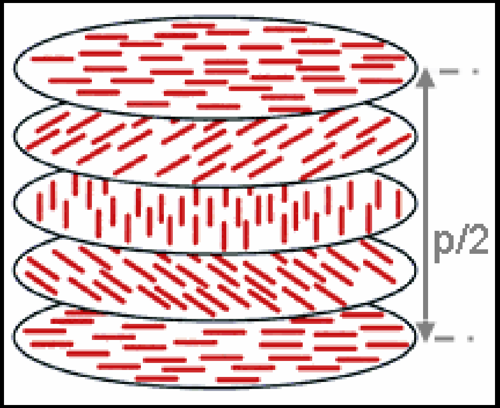
$\boldsymbol{S} \Leftrightarrow \boldsymbol{\mu}$

Liquid crystals

Nematic



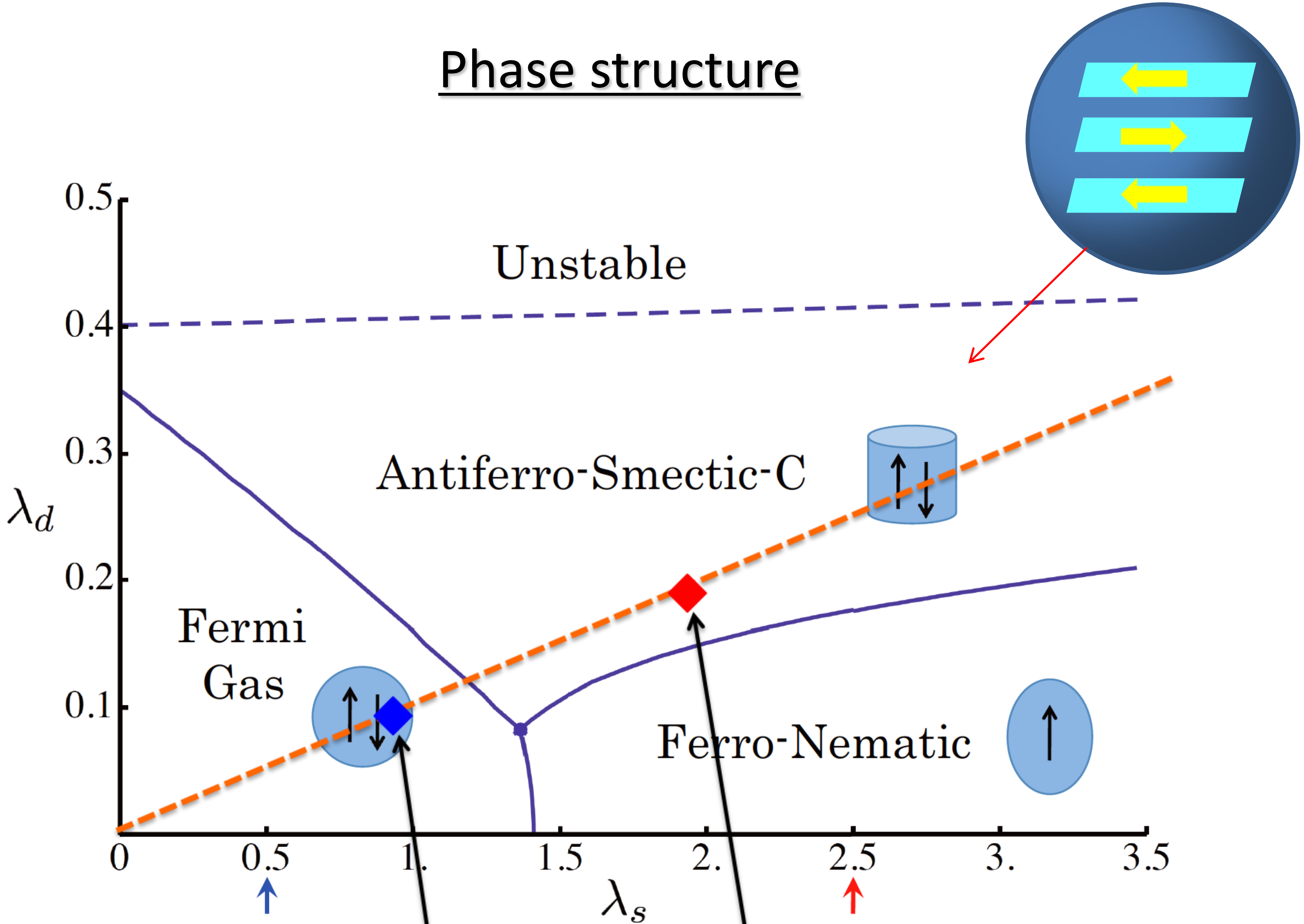
Smectic A Smectic C



Chiral Nematic (=cholesteric)

http://en.wikipedia.org/wiki/Liquid_crystal

Phase structure



$7.5*10^{16}$ /cm^3

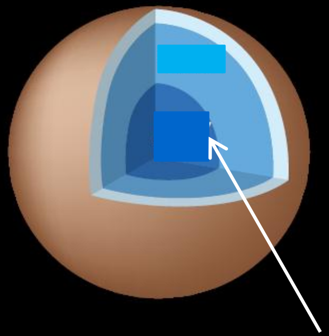
$6.0*10^{17}$ /cm^3

Dy atom

$5\mu_B$, a=10nm

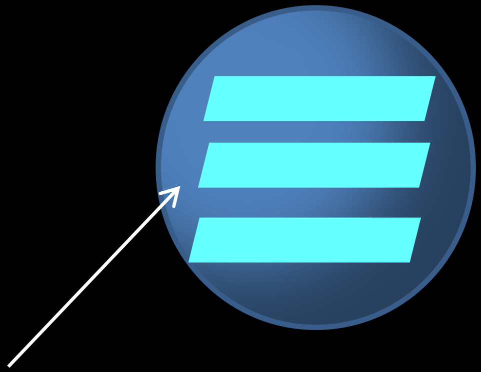
Neutrons confined by gravity ⇔ cold atoms confined by MOT

Neutron star



Meson condensation
By tensor force

cold atoms/molecules



Photon condensation
by dipolar interaction

- Same hamiltonian in both systems

ρ^0 cond. ⇔ magnetic dipolars (smectic C phase)
ρ^c cond. ⇔ magnetic dipolars (chiral nematic phase)
π^0 cond. ⇔ electric dipolars (smectic A phase)
π^c cond. ⇔ electric dipolars (chiral nematic phase)

Dense QCD Summary

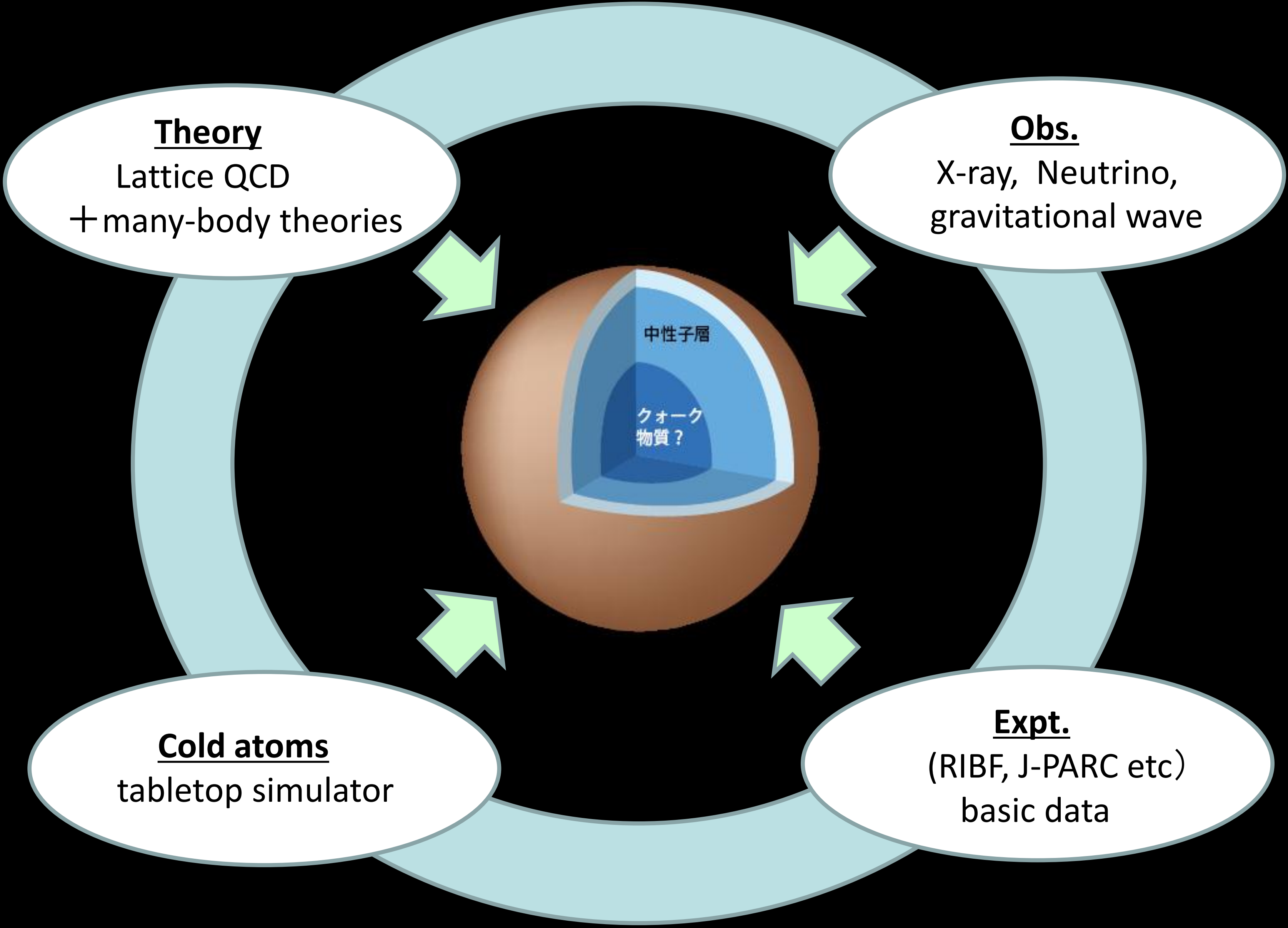
1. LQCD calculation of dense EOS
    - Best approach if it is possible
    - Still difficult for $\mu/T > 1$ due to sign problem

2. LQCD calculation of nuclear force + nuclear many-body echniques
    - Second best approach, possible to carry out BB, BBB at KEI computer
    - What about 4B, 5B etc? What about transition to sQM?

3. Low-energy heavy-ions
    - Possible to come to a few times ρ_0
    - Temperature not negligible.

4. Neutron star observations
    - great progress in a past few years and more to come
      M, R, T, B, …., gravitational wave

5. Tabletop neutron star
    - low density neutron matter ⇔ 2-component fermionic atoms
    - meson condensation ⇔ dipolar atoms and molecules
    - hadron-quark transition ⇔ 3-component fermioic atoms, Bose-Fermi mixture



Theory
Lattice QCD
＋many-body theories

Obs.
X-ray, Neutrino,
gravitational wave

Cold atoms
tabletop simulator

Expt.
(RIBF, J-PARC etc）
basic data