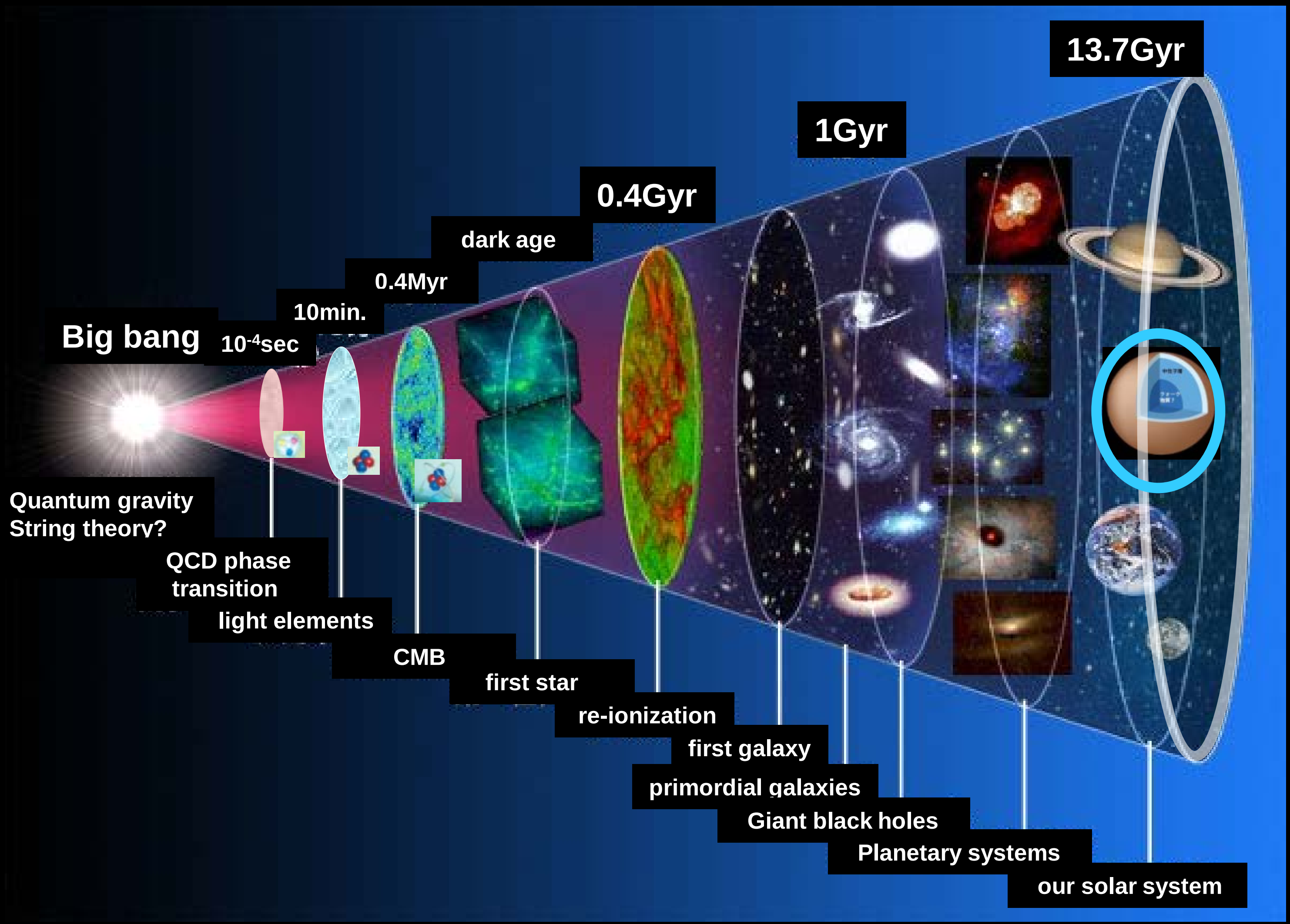
中間子のボース･アインシュタイン凝縮と冷却原子気体

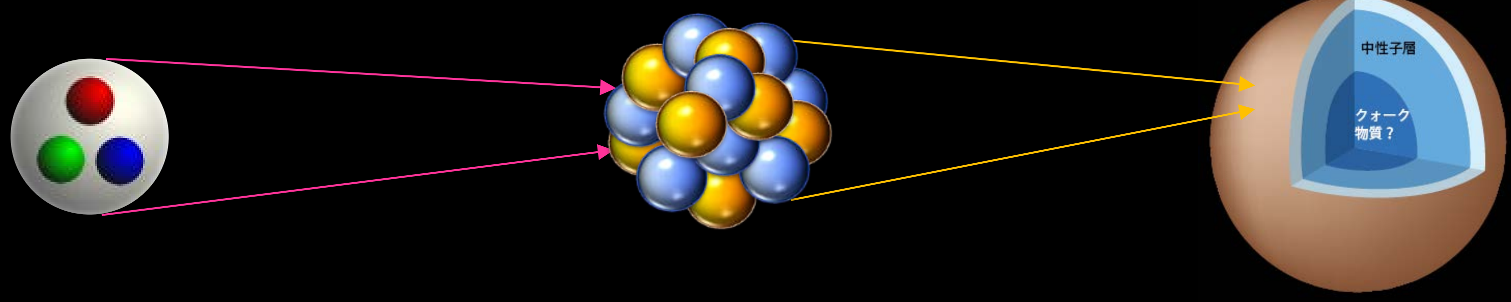


千葉工大(2013.5.11)

初田哲男 (仁科センター、理論研究部門)

Building blocks of Matter

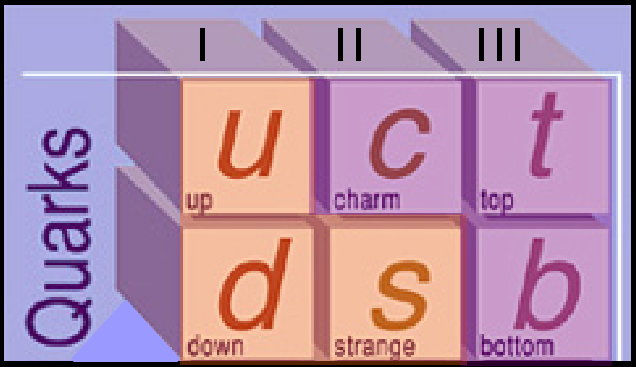
nucleon | nucleus | Neutron star



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



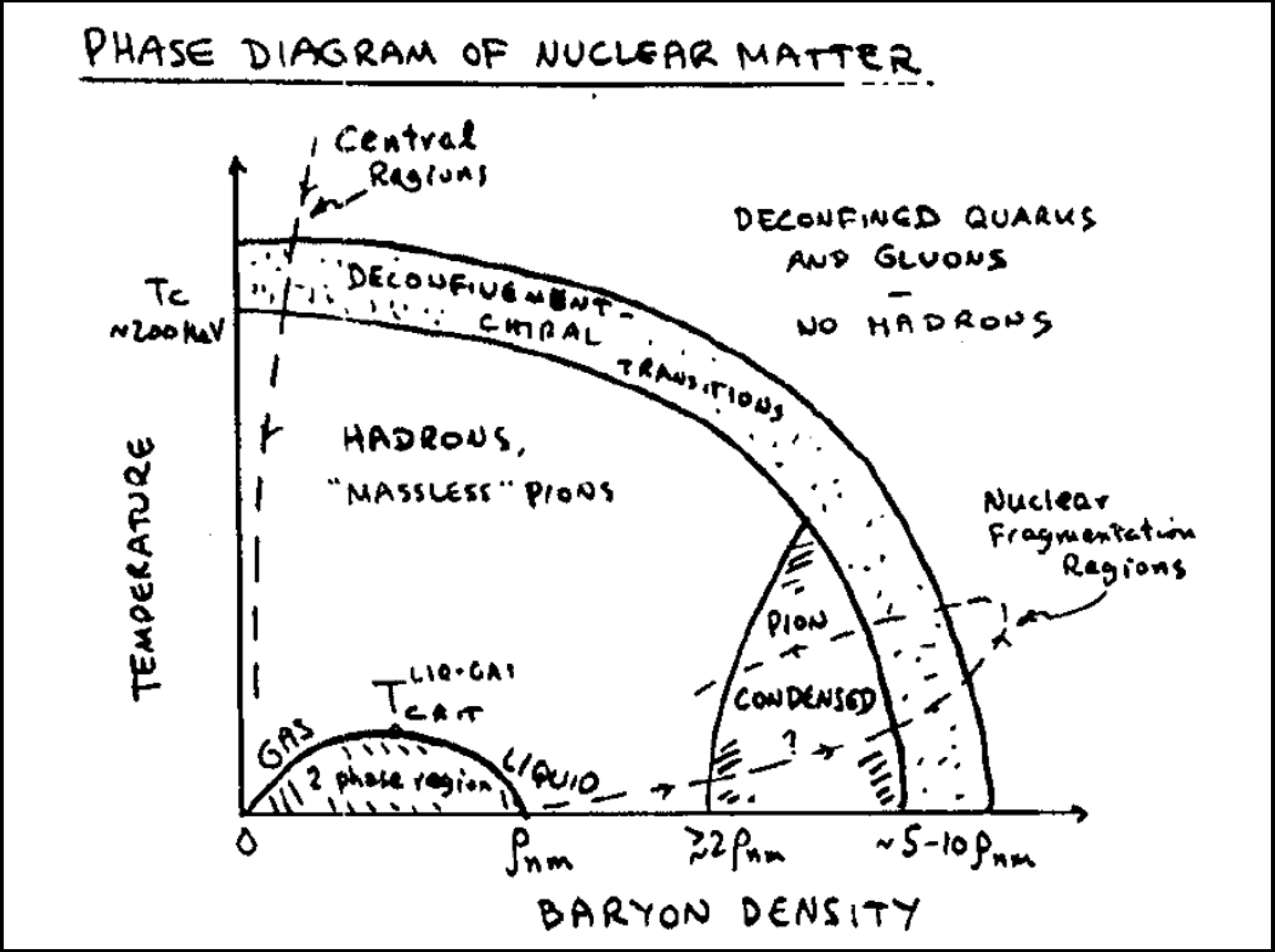
Heavy quarks

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

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

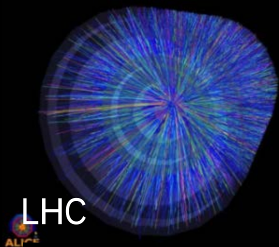
Characteristic strong int. scale ~ $(1\mathrm{fm})^{-1}$ ~ 200 MeV

Phase Diagram @ 1980

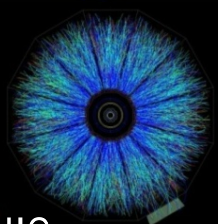


G. Baym (1980)

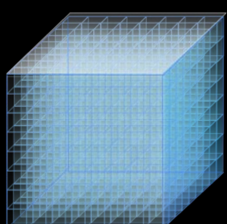
Phase Diagram @ 2011



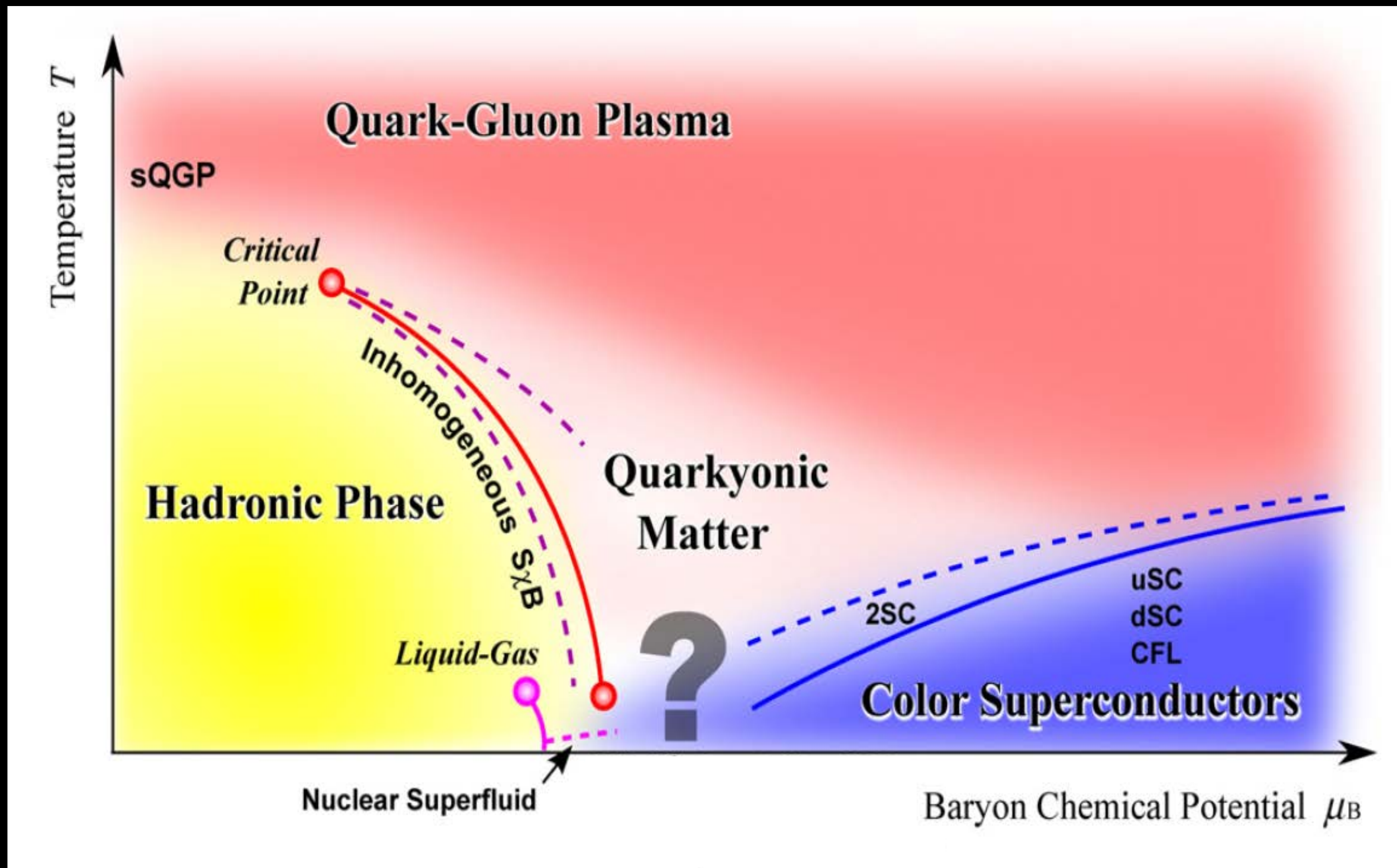
LHC

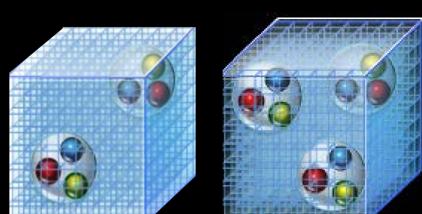


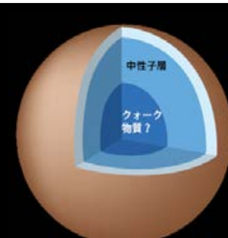
RHIC



Lattice QCD

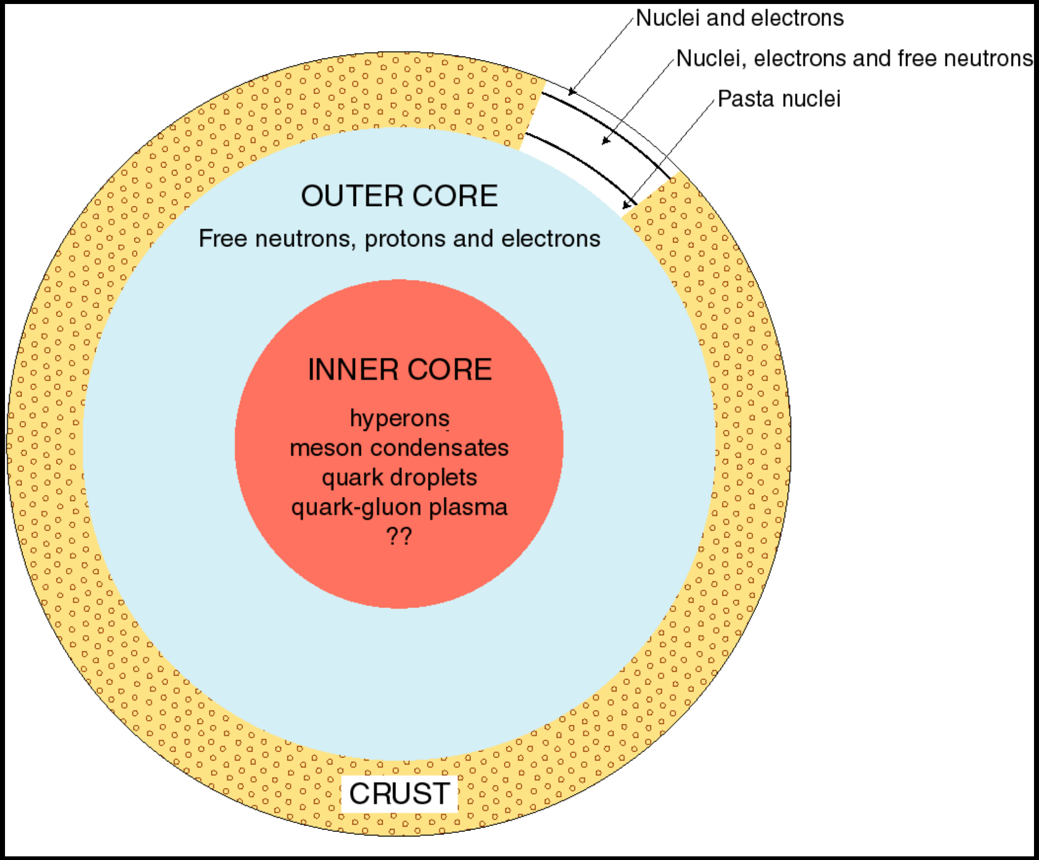






K. Fukushima and T. Hatsuda,
“The Phase Diagram of Dense QCD”
Rep. Prog. Phys. 74 (2011) 014001

Neutron Star

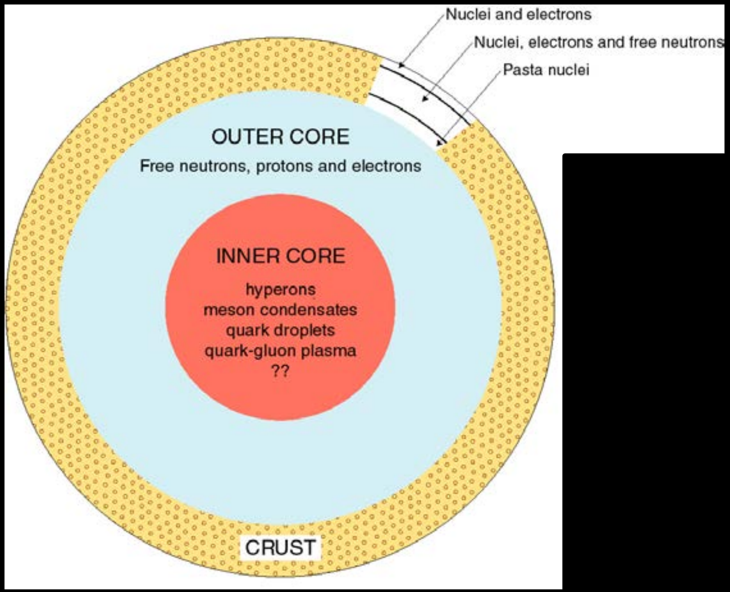


- $M \sim (1\text{-}2) M_{\odot}$
- $R \sim 10\text{km}$
- $0 < \rho < 10\ \rho_0$

- 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

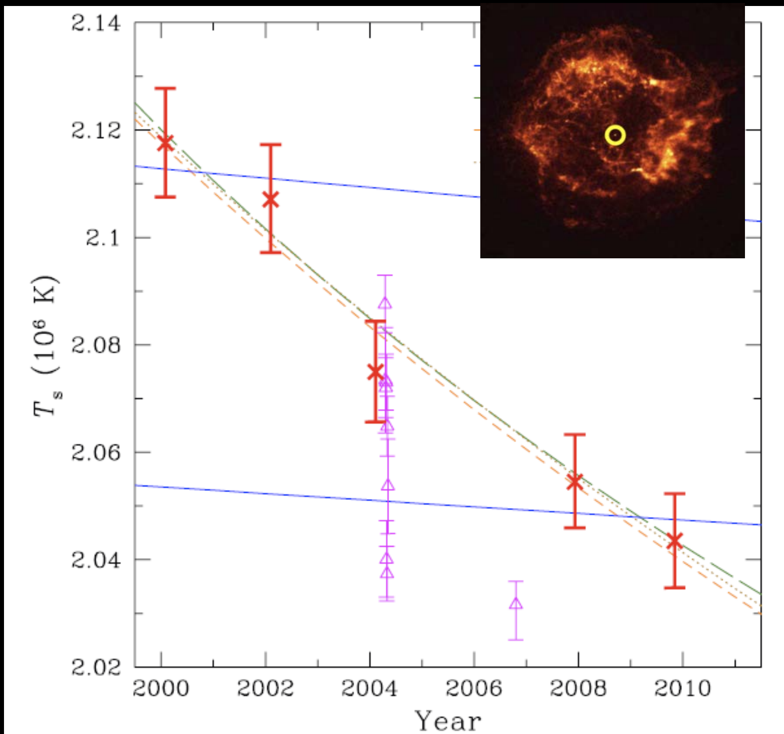
Recent developments

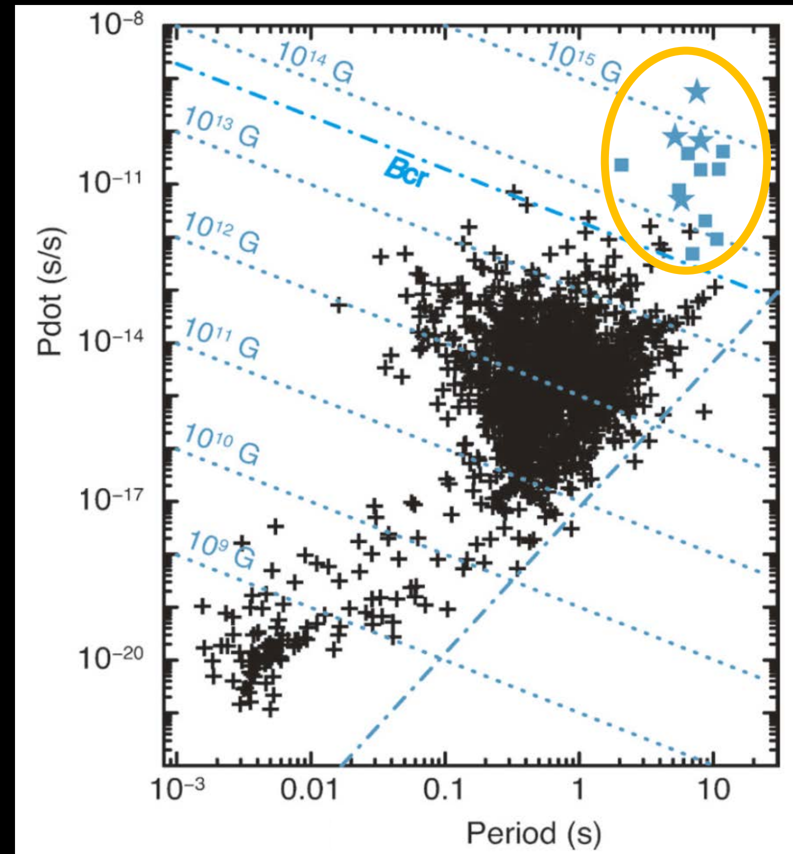
1. Ab initio calculations ： QMD, Lattice QCD etc
2. New observations ： M, R, T, B, P, …
3. New experiments ： RIBF, J－PARC etc
4. Proposals to relate theories and observations

examples

$M=(1.97\pm 0.04)M_{\odot}$	⇔	cold EOS
X-ray burst	⇔	cold EOS
GW from $N_{☆}$ merger	⇔	hot EOS
Seismology	⇔	crust structure
Cooling of CAS-A	⇔	$^3P_2$ superfluid
Magnetars	⇔	ferromagnetic core

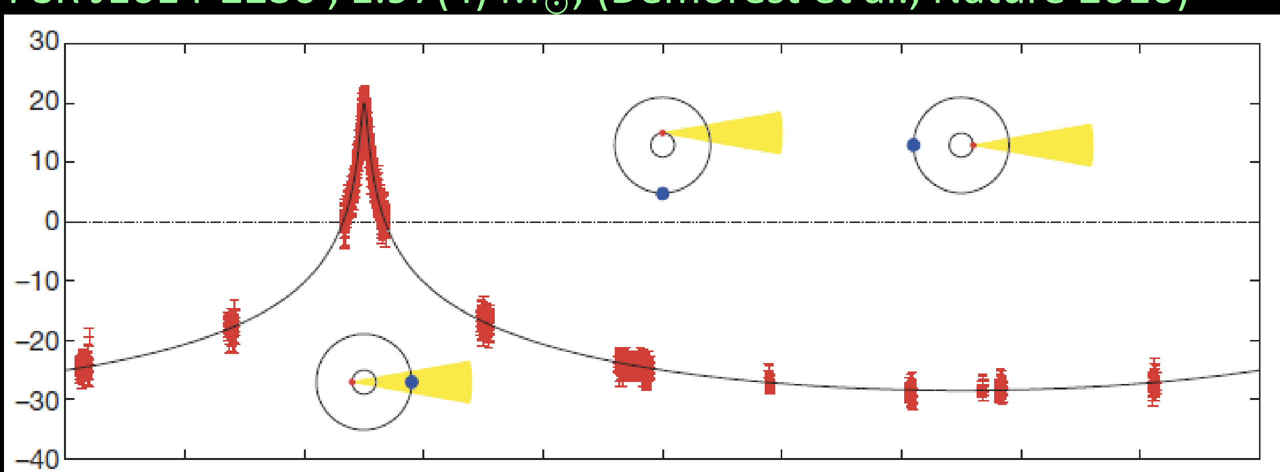
Cassiopeia A Cooling, 4% decrease in 9 years
(Heinke & Ho, ApJ 2010)





Magnetars
(from Enoto, 2012)
Bs=3.2x10^{19}√(PPdot) [G]

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



T, B, M

Another massive Neutron Star !

PSR J0348+0432 : M= 2.01(4) $M_\odot$

RESEARCH ARTICLE

A Massive Pulsar in a Compact Relativistic Binary

John Antoniadis[1,*], Paulo C. C. Freire[1], Norbert Wex[1], Thomas M. Tauris[2,1], Ryan S. Lynch[3], Marten H. van Kerkwijk[4], Michael Kramer[1,5], Cees Bassa[5], Vik S. Dhillon[6], Thomas Driebe[7], Jason W. T. Hessels[8,9], Victoria M. Kaspi[3], Vladislav I. Kondratiev[8,10], Norbert Langer[2], Thomas R. Marsh[11], Maura A. McLaughlin[12], Timothy T. Pennucci[13], Scott M. Ransom[14], Ingrid H. Stairs[15], Joeri van Leeuwen[8,9], Joris P. W. Verbiest[1], David G. Whelan[13]

± Author Affiliations

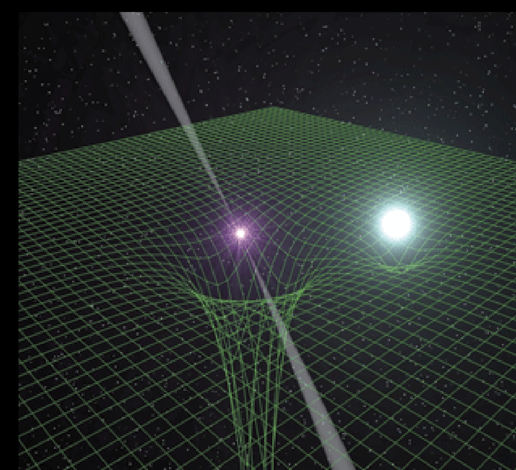
*Corresponding author. E-mail: jantoniadis@mpifr-bonn.mpg.de

ABSTRACT | STRUCTURED ABSTRACT | EDITOR'S SUMMARY

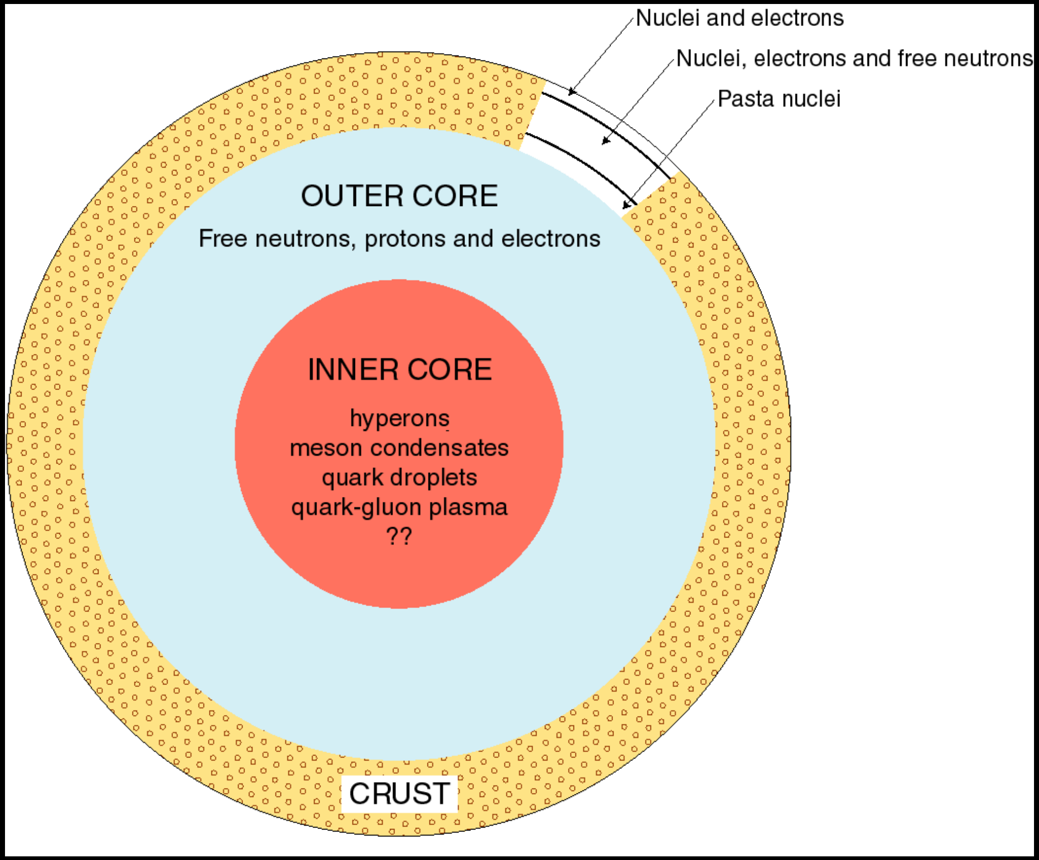
Many physically motivated extensions to general relativity (GR) predict substantial deviations in the properties of spacetime surrounding massive neutron stars. We report the measurement of a 2.01 ± 0.04 solar mass ($M_\odot$) pulsar in a 2.46-hour orbit with a 0.172 ± 0.003 $M_\odot$ white dwarf. The high pulsar mass and the compact orbit make this system a sensitive laboratory of a previously untested strong-field gravity regime. Thus far, the observed orbital decay agrees with GR, supporting its validity even for the extreme conditions present in the system. The resulting constraints on deviations support the use of GR-based templates for ground-based gravitational wave detectors. Additionally, the system strengthens recent constraints on the properties of dense matter and provides insight to binary stellar astrophysics and pulsar recycling.

Science

Science 26 April 2013:
Vol. 340 no. 6131
DOI: 10.1126/science.1233232



Neutron Star



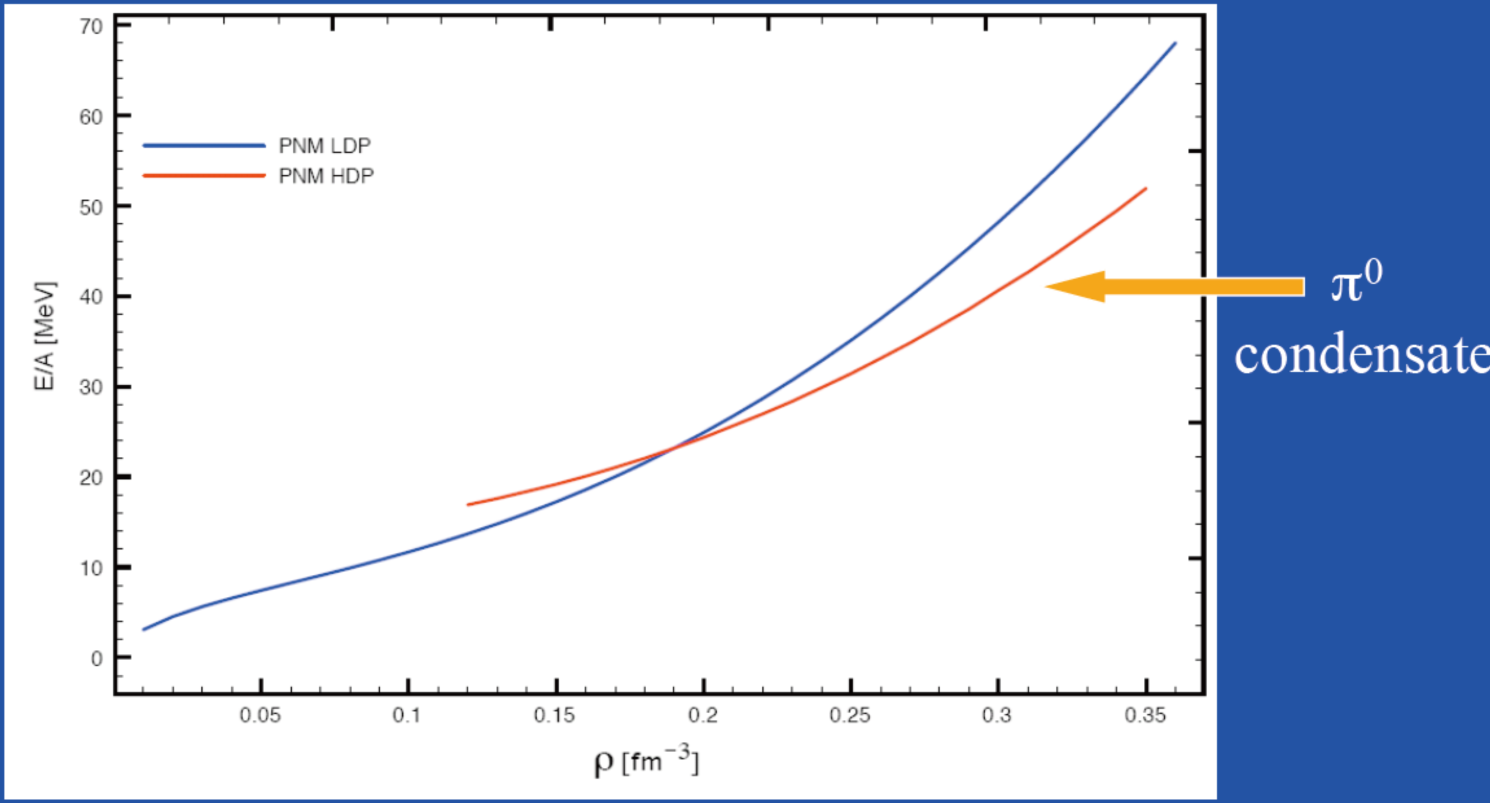
- $M \sim (1\text{-}2)M_\odot$
- $R \sim 10\text{km}$
- $0 < \rho < 10\ \rho_0$

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

+ leptons (e, μ)

Energy per nucleon in pure neutron matter

Morales, (Pandharipande) & Ravenhall, in progress



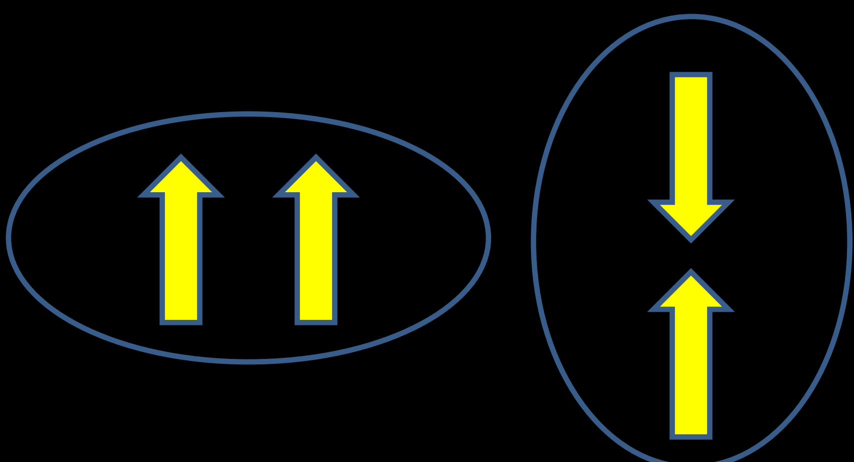
AV-18 + UIV 3-body (IL 3-body too attractive) Improved FHNC algorithms. Two minima!

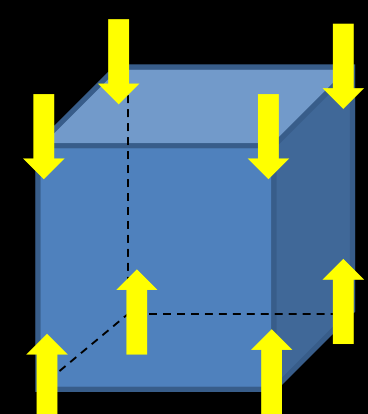
E/A slightly higher than *Akmal, Pandharipande and Ravenhall, Phys. Rev. C58 (1998) 1804*

Attractive configuration for neutrons (pion-exchange)

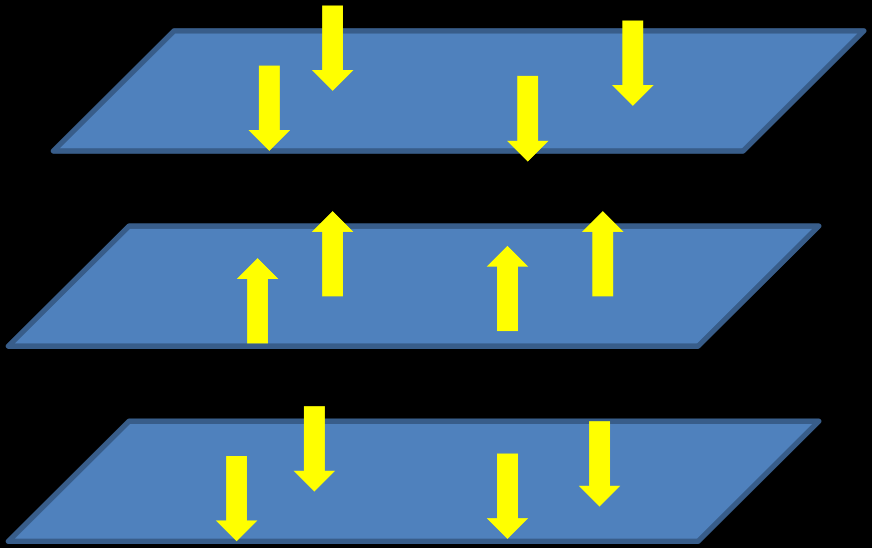
$$
\begin{aligned}
V_{\mathrm{OPEP}}(r)
&= \frac{f_{\pi N}^2}{4\pi}(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)(\boldsymbol{\sigma}_1 \cdot \nabla_1)(\boldsymbol{\sigma}_2 \cdot \nabla_2)\frac{e^{-m_\pi r}}{r} \\
&= \frac{g_{\pi N}^2}{4\pi}\left(\frac{m_\pi}{2M_N}\right)^2 \frac{(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)}{3}\left[(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2) + S_{12}\left(1 + \frac{3}{m_\pi r} + \frac{3}{m_\pi^2 r^2}\right)\right]\frac{e^{-m_\pi r}}{r}, \\
&\xrightarrow[\text{chiral limit}]{} \frac{g_A^2}{16\pi F_\pi^2}(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)\frac{S_{12}}{r^3}
\end{aligned}
$$

$$
S_{12} = 3(\boldsymbol{\sigma}_1 \cdot \hat{\boldsymbol{r}})(\boldsymbol{\sigma}_2 \cdot \hat{\boldsymbol{r}}) - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2,
$$





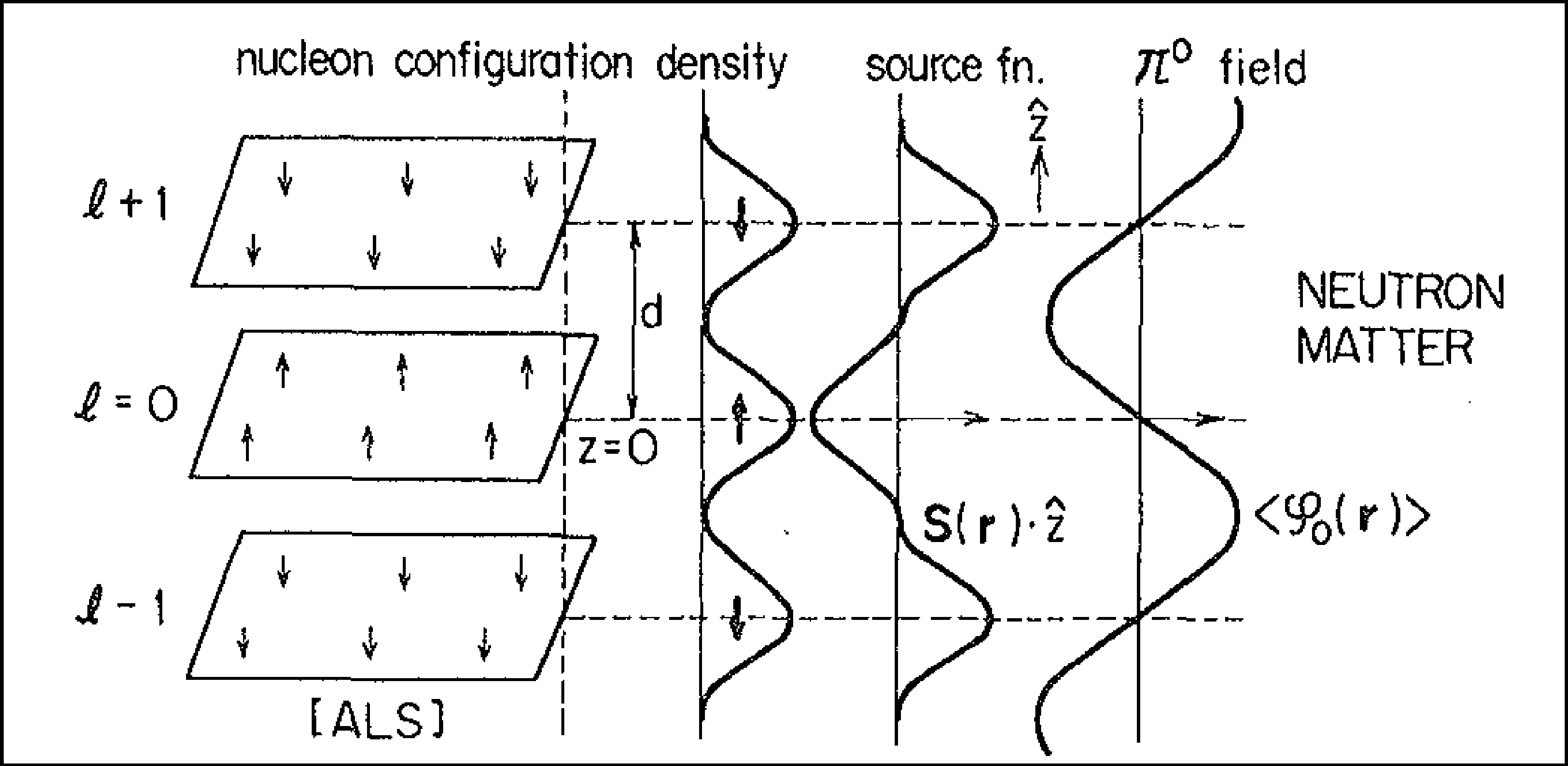
π^0 condensation in neutron matter



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

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

π^0 condensation = SDW



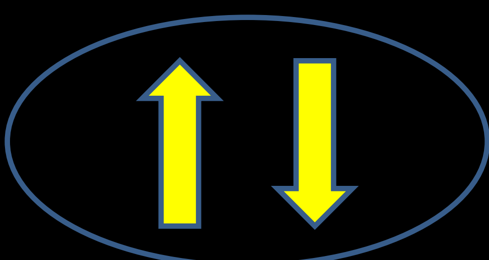
$$(-\nabla^2+m_\pi{}^2)\varphi_c(\boldsymbol{r})=(f/m_\pi)\boldsymbol{\nabla}\cdot\langle\psi^\dagger\boldsymbol{\sigma}\psi\rangle$$

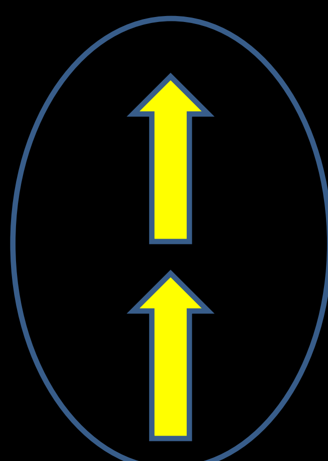
Fig. from Takatsuka, Tamagaki & Tatsumi,
, Prog. Theor. Phys. Suppl. 112 ('83) 67

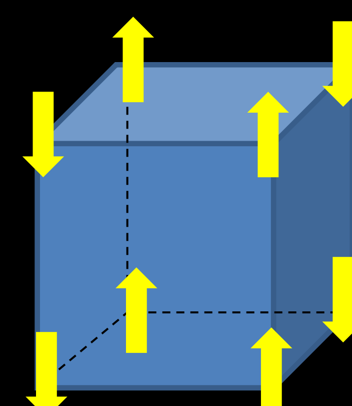
Attractive configuration for neutrons (rho-exchange)

$$
\begin{aligned}
&V_{\text{OREP}}(r) \\
&= \frac{f_{\rho N}}{4\pi}(\tau_1 \cdot \tau_2)(\sigma_1 \times \nabla_1)(\sigma_2 \times \nabla_2)\frac{e^{-m_\rho r}}{r} \\
&= \frac{g_{\rho N}^2}{4\pi}\left(\frac{m_\rho}{2M_N}\right)^2 \frac{\tau_1 \cdot \tau_2}{3}\left[2(\sigma_1 \cdot \sigma_2) - S_{12}\left(1 + \frac{3}{m_\rho r} + \frac{3}{m_\rho^2 r^2}\right)\right]\frac{e^{-m_\rho r}}{r} \\
&\to -\frac{g_{\rho N}^2}{16\pi M_N^2}(\tau_1 \cdot \tau_2)\frac{S_{12}}{r^3}
\end{aligned}
$$

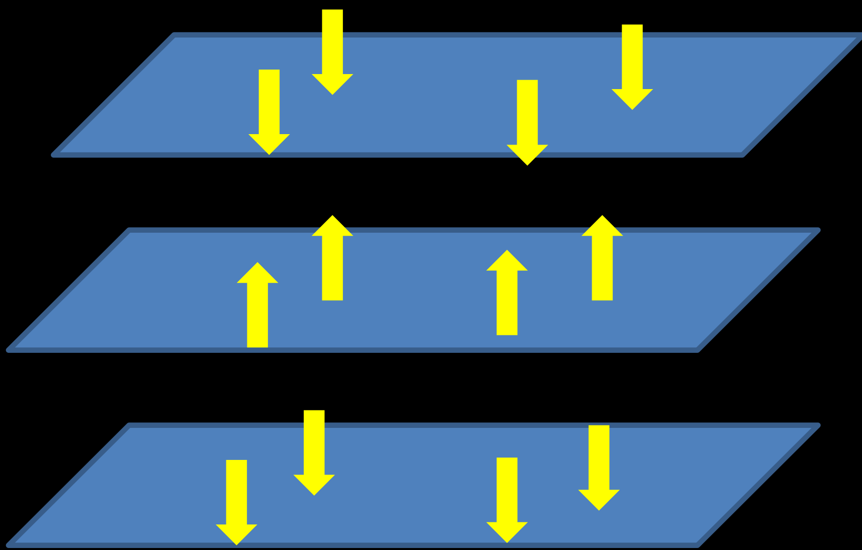
$$S_{12} = 3(\boldsymbol{\sigma}_1 \cdot \hat{\boldsymbol{r}})(\boldsymbol{\sigma}_2 \cdot \hat{\boldsymbol{r}}) - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2,$$



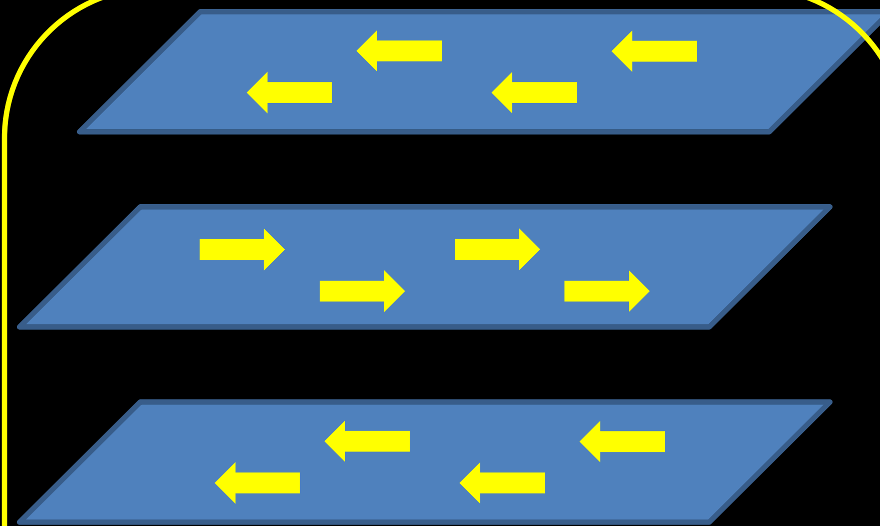




B condensations in dipolar atoms ?



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



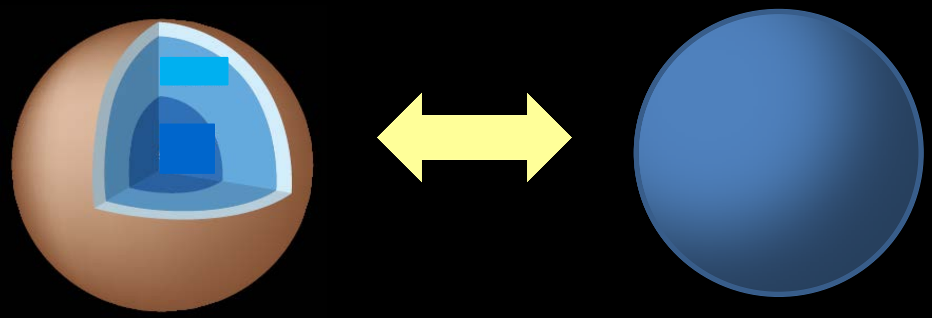
$$(-\nabla^2 + m_\rho^2)\,\boldsymbol{\rho}_c(\boldsymbol{r}) = (f_\rho/m_\rho)\,\boldsymbol{\nabla}\times\langle\psi^\dagger\boldsymbol{\sigma}\psi\rangle$$

$\rho \Leftrightarrow A$

$\nabla x\rho \Leftrightarrow B$

$S \Leftrightarrow \mu$

Neutron Star Structure by Tabletop Expt.?



- Hadron-quark crossover ⇔ Bose-Fermi mixture
  Maeda, Baym & Hatsuda, Phys. Rev. Lett. 103 (2009) 085301

- Meson condensation ⇔ Dipolar atoms
  Meada, Baym & Hatsuda, Phys. Rev. A 87 (2013) 021604(R)

Ultra-cold atomic Gasses

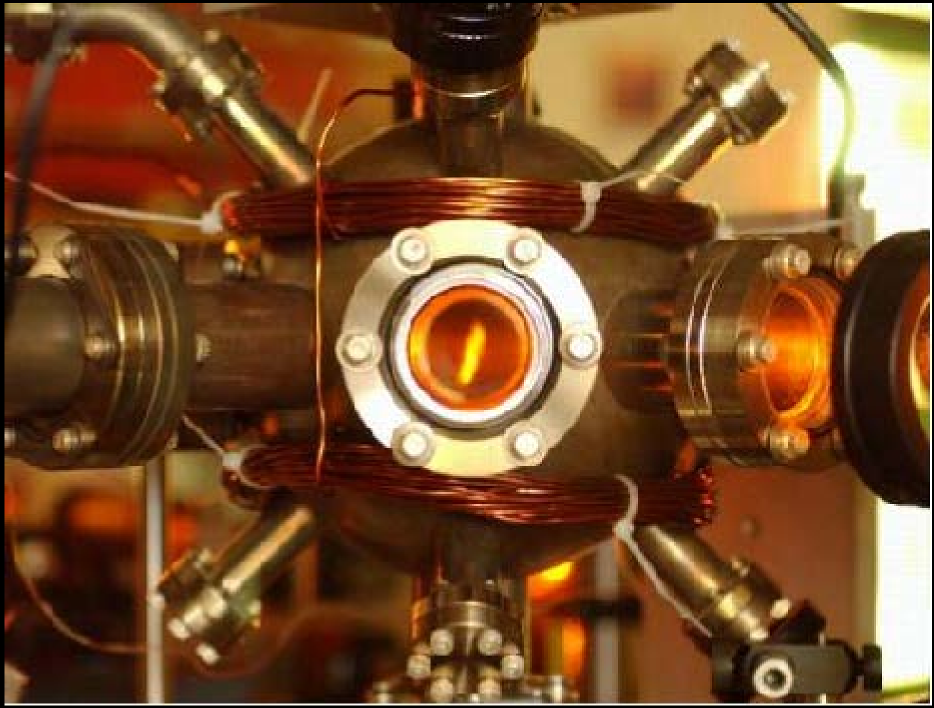
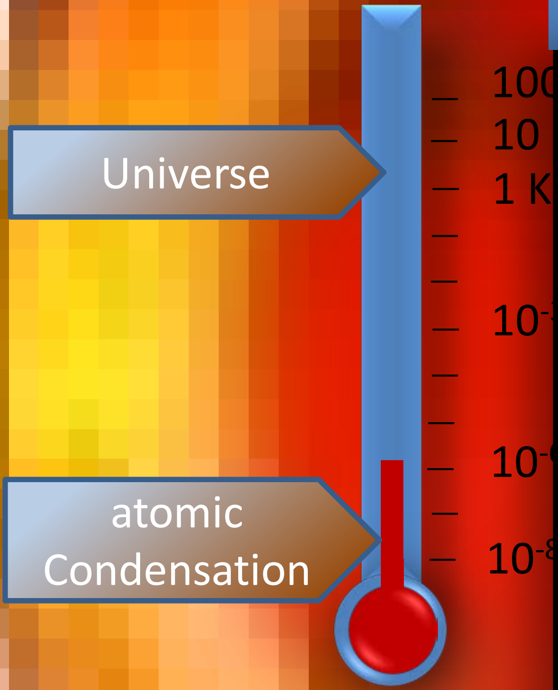
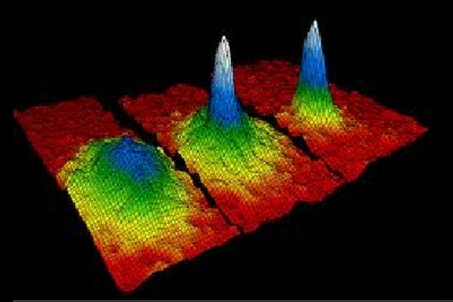


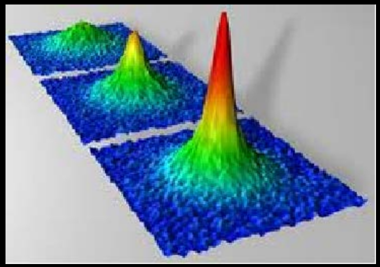
Figure from Pascal Naidon (RIKEN)



Bose-Einstein Condensate 1995



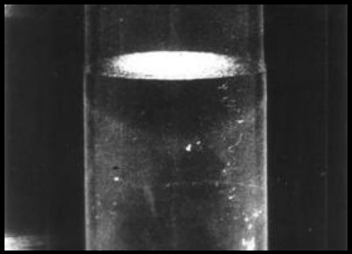
Fermi superfluid 2003



10^{-7} K

QUANTUM FLUIDS (SUPERFLUIDS)

Superfluid helium



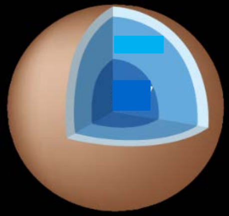
10^{-1} K
1 K

Superconducting electrons

10 K

Superfluid nucleons

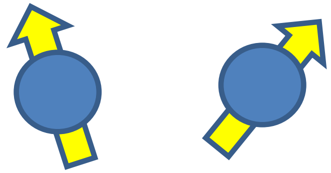
Superconducting quarks



10^{9} K

10^{10}K

Dipolar fermi systems

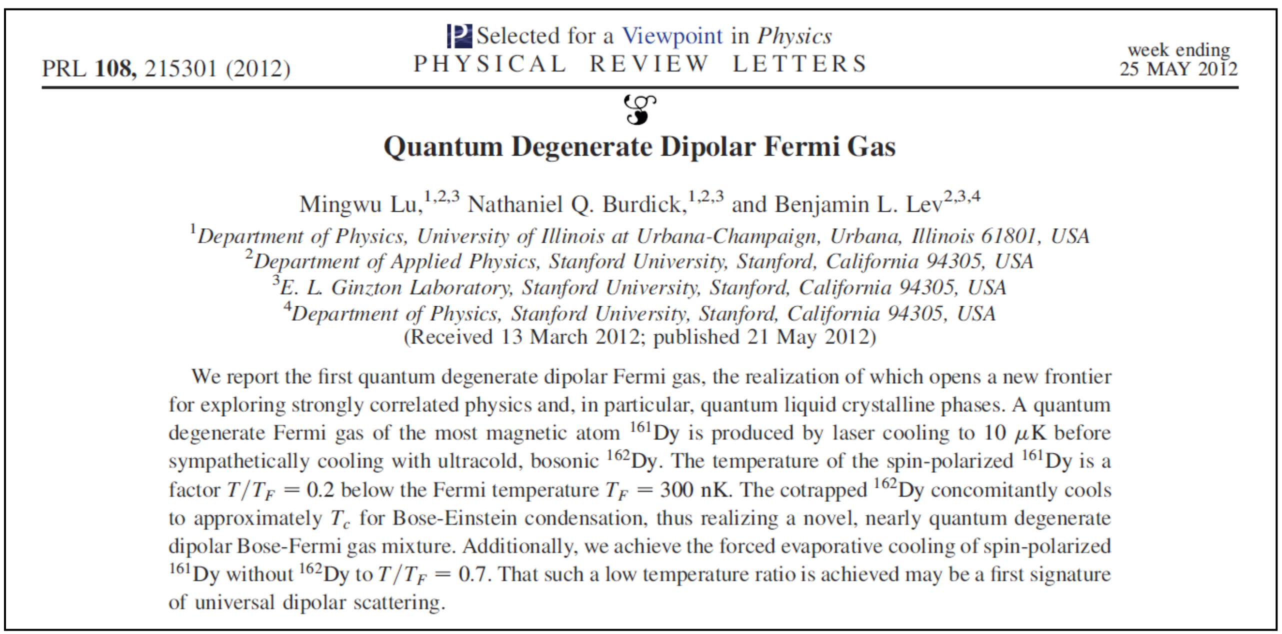


$$U = \frac{\mu^2}{r^3}\{\vec{\sigma}_1\cdot\vec{\sigma}_2 - 3(\vec{\sigma}_1\cdot\hat{r})(\vec{\sigma}_2\cdot\hat{r})\} + g\,\delta(\vec{r})$$

Cold atoms with
large magnetic moment

^{161}Dy fermions

$|21/2, -21/2\rangle$, $\mu = 10\mu_B$



PRL **108**, 215301 (2012) Selected for a Viewpoint in *Physics* 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]

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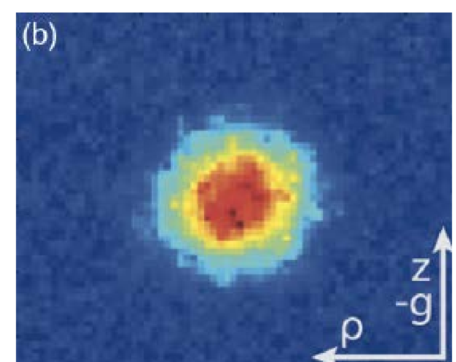
[2]*Department of Applied Physics, Stanford University, Stanford, California 94305, USA*
[3]*E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA*
[4]*Department of Physics, Stanford University, Stanford, California 94305, USA*
(Received 13 March 2012; published 21 May 2012)

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.

v_F=5.6 mm/s
T/T_F=0.2, T_F=306nK

R=20 nm, N~6000
n_{max}= 4x10^{13} /cm^3



Two-level toy model

$$H = \frac{1}{2m}\int d\vec{r}\,\nabla\Psi^\dagger(\vec{r})\cdot\nabla\Psi(\vec{r}) + \frac{1}{8\pi}\int d\vec{r}\,\vec{\mathcal{H}}(\vec{r})^2$$
$$-\mu\int d\vec{r}\,\Psi^\dagger\vec{\sigma}\,\Psi\cdot\vec{\mathcal{H}}(\vec{r}) + g'\int d\vec{r}\,\psi_1^\dagger\psi_2^\dagger\psi_2\psi_1$$

- $\Psi \equiv (\psi_1, \psi_2)^T$: two-component fermions
- $\vec{H}(\vec{r})$: local magnetic field produced by the dipolars
- $\vec{\sigma}$: Pauli matrices

$$\vec{H} = \nabla \times \vec{A}$$

Physical parameters

m : mass , μ : magnetic moment , n : density of atoms

$$n(\vec{r}) = \langle\Psi^\dagger\Psi\rangle, \quad \vec{M}(\vec{r}) = \langle\Psi^\dagger\vec{\sigma}\Psi\rangle,$$

冷却原子・分子気体に相応しい現象論的ポテンシャル：

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

長距離：双極子–双極子ポテンシャル
短距離：接触型斥力ポテンシャル

物理パラメータ（無次元量）

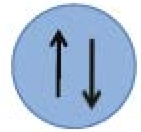
双極子–双極子相互作用の強さ： $\lambda_d = n\mu^2/\epsilon_F$

接触型斥力の強さ： $\lambda_s = gn/\epsilon_F$

λ_s - λ_d 平面上の相構造を明らかにする。

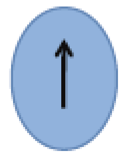
基底状態の候補

1. フェルミ気体状態



$$|\Phi_{\mathrm{FG}}\rangle \quad := \quad \prod_{\alpha=\uparrow,\downarrow}\left(\prod_{p\le p_{\mathrm{F}}} a^{\dagger}_{\alpha,\vec{p}}\right)|0\rangle$$

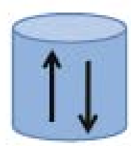
2. 偏極フェロネマティック状態



$$|\Phi_{\mathrm{FN}}\rangle \quad = \prod_{\gamma^{-1}(p_x^2+p_y^2)+\gamma^2 p_z^2\le p_{\mathrm{F},\uparrow}^2} a^{\dagger}_{\uparrow,\vec{p}}\,|0\rangle$$

B.M. Fregoso, E. Fradkin, PRL **103**, 205301 (2009)

3. AFSC状態



$$|\Phi_{\mathrm{AFSC}}\rangle \quad = \prod_{\ell,\vec{q}_\perp}^{(\mathrm{occ.})} c^{\dagger}_{(\ell,\vec{q}_\perp)}\,|0\rangle$$

Maeda, Hatsuda, Baym, Phys. Rev. A 87 (2013) 021604(R)

運動エネルギー	近距離斥力	双極子相互作用
控え目	あり	なし
多い	なし	あり
非常に多い	僅かにあり	あり

エネルギー密度--- FG状態

以下、エネルギー密度の期待値を
二成分自由フェルミ気体のエネルギー密度で無次元化して表記。

1. フェルミ気体状態

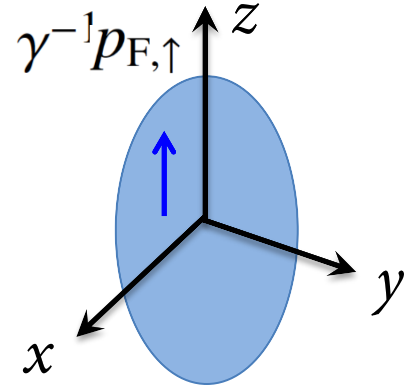
$$\tilde{\mathcal{E}}_{\mathrm{FG}} = 1 + \frac{5}{12}\lambda_{\mathrm{s}}$$

二成分フェルミエネルギー ＋ 短距離斥力

双極子ポテンシャルの寄与はゼロ

エネルギー密度--- FN状態

$$p_{\mathrm{F},\uparrow} = (6\pi^2 n)^{1/3}$$



$$\tilde{\mathcal{E}}_{\mathrm{FN}} = \frac{2^{2/3}}{3}\left(2\gamma + \frac{1}{\gamma^2}\right) - \frac{5\pi}{9}\lambda_d I(\gamma)$$

二成分フェルミエネルギー
(回転楕円体型変形)

双極子ポテンシャル

短距離斥力の寄与はゼロ

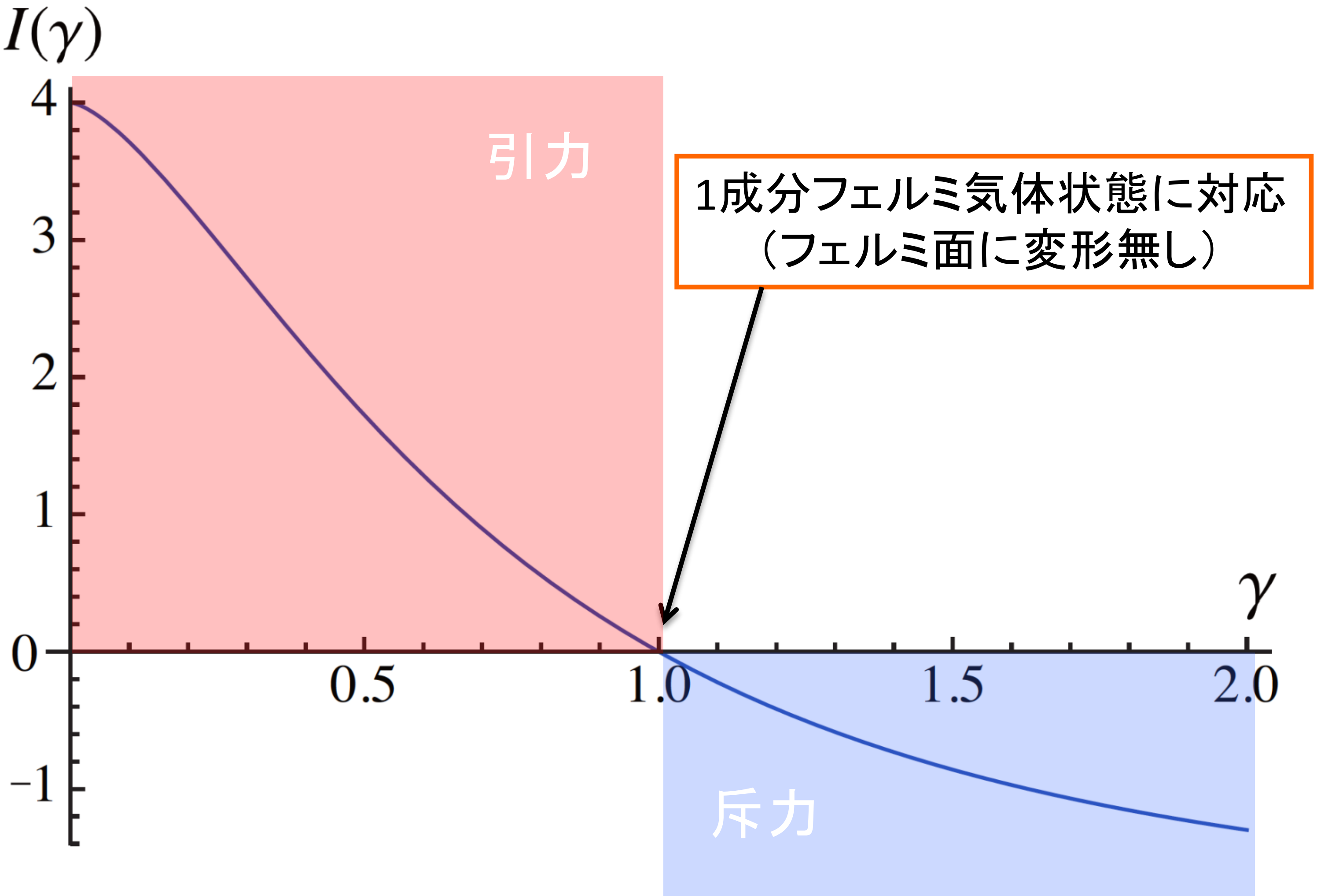
変形関数

$$I(\gamma) = -2 - \frac{6}{\gamma^3 - 1} - \frac{6 \arccos \gamma^{3/2}}{(\gamma^{-1} - \gamma^2)^{3/2}}$$

B.M. Fregoso, E. Fradkin, PRL **103**, 205301 (2009)

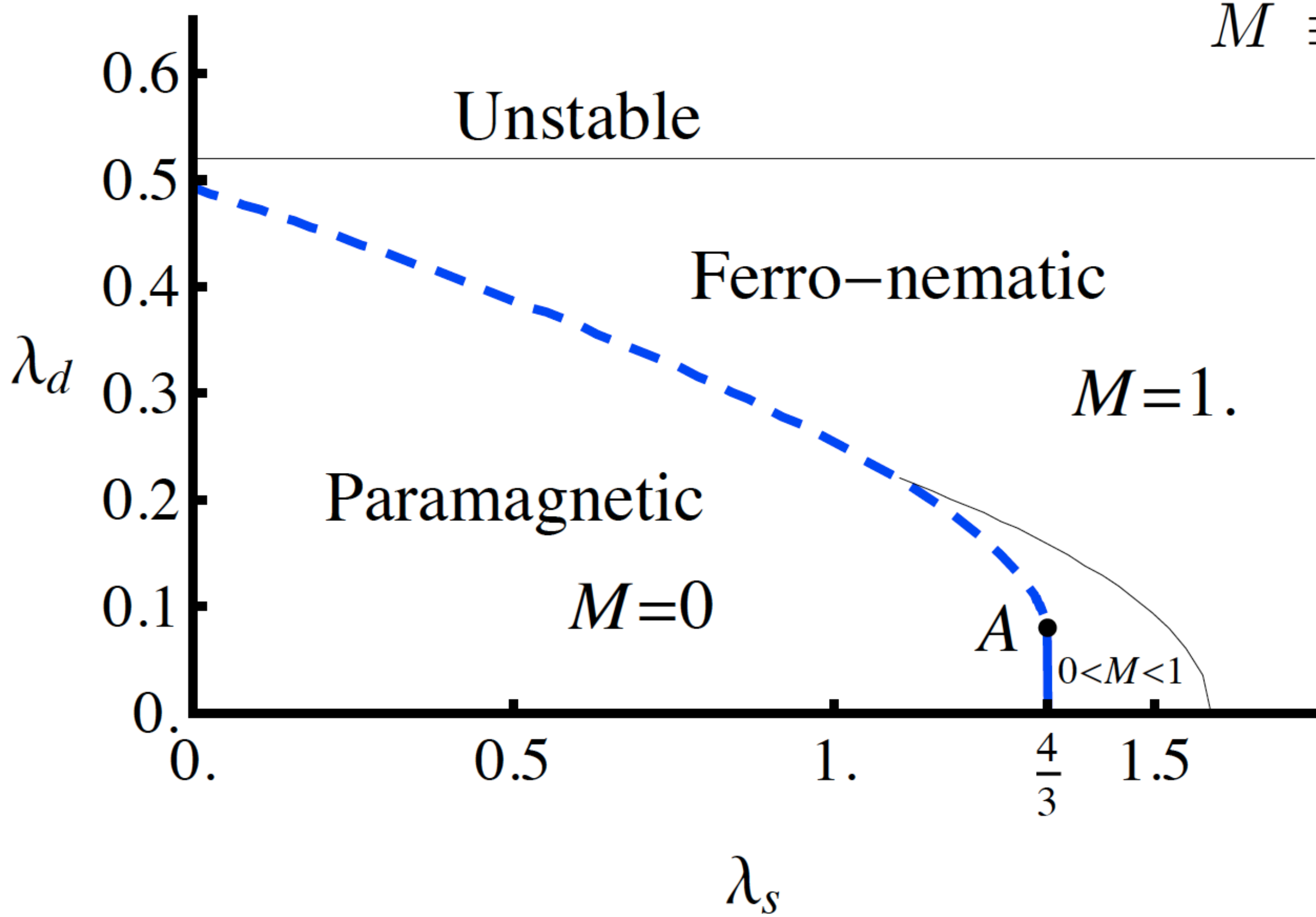
変形関数 --- FN状態

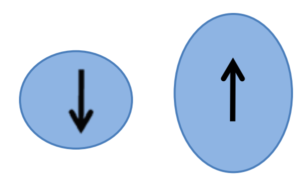
$$\tilde{\mathcal{E}}_{\mathrm{FN}} = \frac{2^{2/3}}{3}\left(2\gamma + \frac{1}{\gamma^2}\right) - \frac{5\pi}{9}\lambda_d I(\gamma)$$



FG状態 v.s. FN状態

$$M \equiv (n_1 - n_2)/n$$

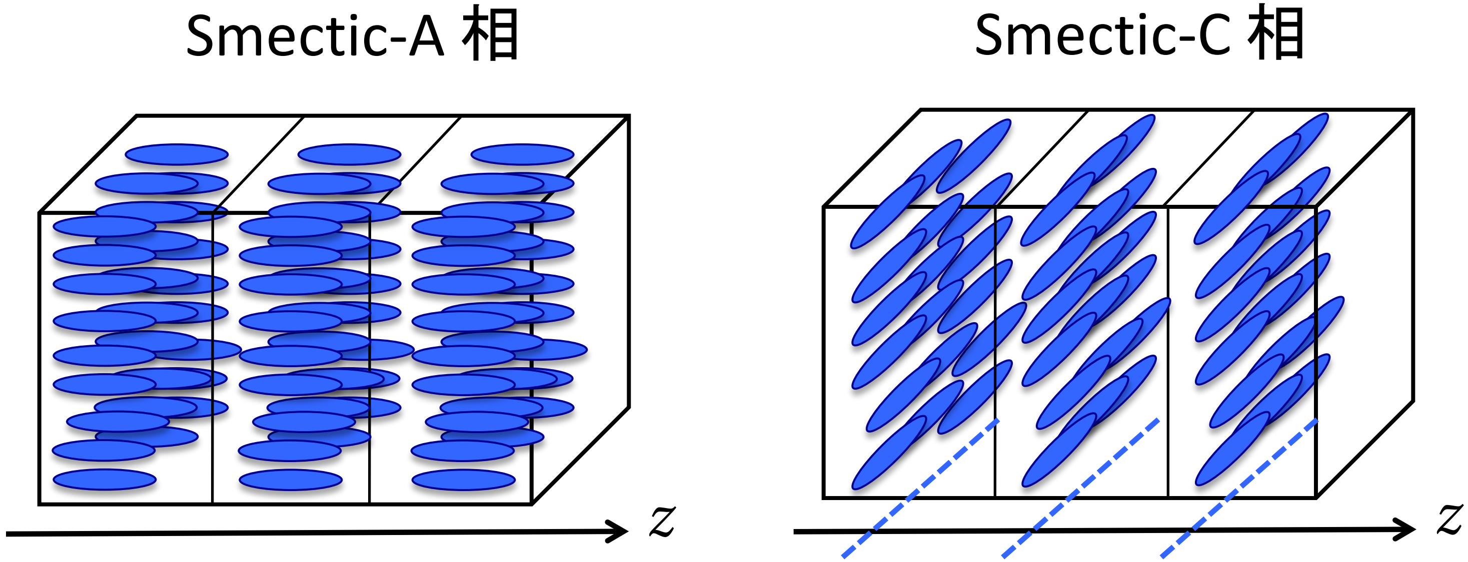


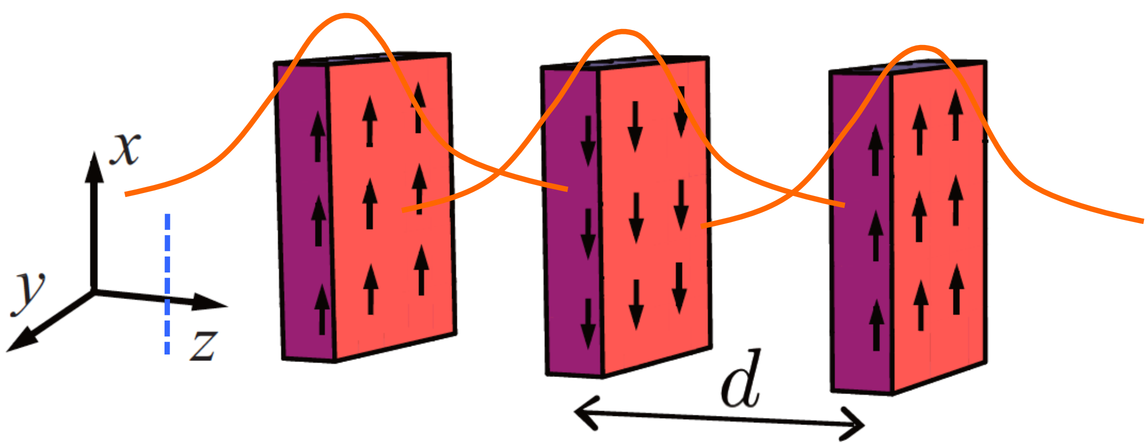


"Ferronematic Ground State of the Dilute Dipolar Fermi Gas"
B.M. Fregoso, E. Fradkin, PRL **103**, 205301 (2009)

AFSC状態 --- 液晶とのアナロジー

液晶

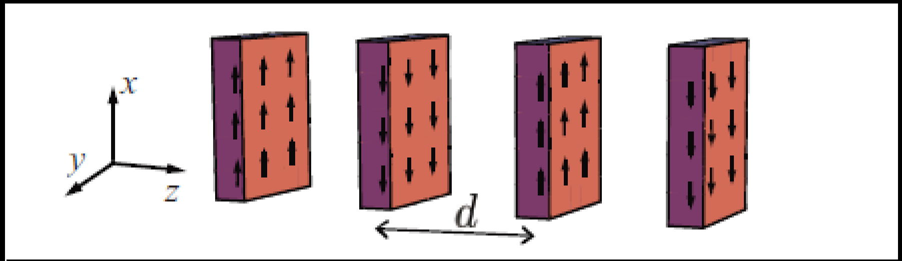




Anti-**F**erro
Smectic-**C** **(AFSC)** state

Maeda, Hatsuda, Baym, Phys. Rev. A 87 (2013) 021604(R)

Antiferrosmectic –C (AFSC)



- Variational wave function

$$\phi_{\ell,\vec{q}_\perp}(x,y,z) \;=\; \frac{e^{-(z-d\ell)^2/2b^2}}{(\pi b^2)^{1/4}} \frac{e^{i\vec{q}_\perp\cdot\vec{r}_\perp}}{\sqrt{V_\perp}}\chi_\ell$$

$$\chi_\ell = (1,(-1)^{\ell+1})/\sqrt{2}$$

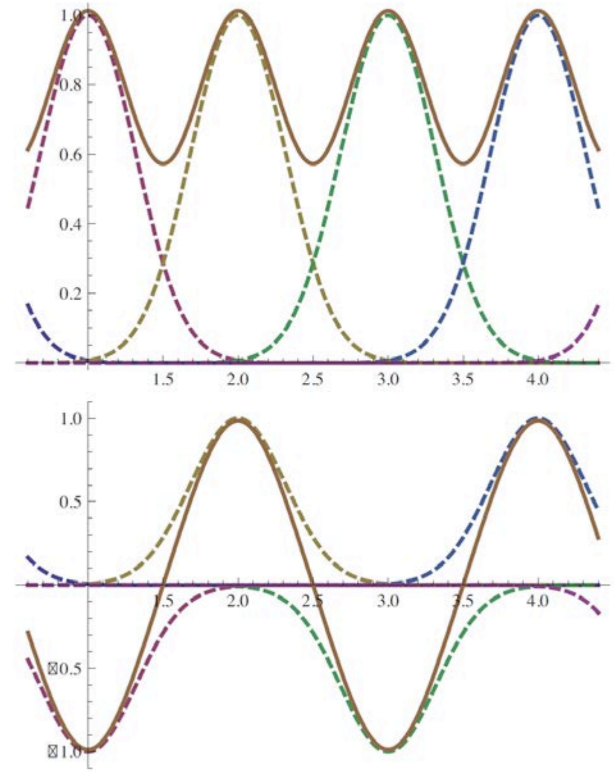
We assume that the fermions are well localized in the z-direction, with $d \gtrsim \sqrt{2}b$, and in the AFSC ground state fill these states with all ℓ, and $q_\perp$ up to the transverse Fermi momentum, $q_{F\perp} = \sqrt{4\pi n d}$, where n is the average density.

AFSC状態での物理量

フェルミオンの数密度

$$n(\vec{r}) = \langle \Psi^\dagger \Psi \rangle \;=\; \frac{nd}{b\sqrt{\pi}} \sum_{\ell=-\infty}^{\infty} e^{-(z-d\ell)^2/b^2}$$

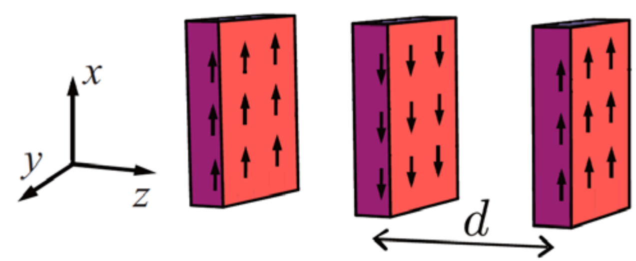
$$= \; n + 2n \sum_{j=1}^{\infty} e^{-j^2\pi^2/\Gamma} \cos\left(2j\pi z/d\right)$$



局所磁化

$$\langle M_x(\vec{r}) \rangle \;=\; -\frac{\mu nd}{b\sqrt{\pi}} \sum_{\ell=-\infty}^{\infty} (-1)^\ell e^{-(z-d\ell)^2/b^2}$$

$$= -2\mu n \sum_{j=1}^{\infty} e^{-(2j-1)^2\pi^2/4\Gamma} \cos\left\{(2j-1)\pi z/d\right\}$$



エネルギー密度
AFSC状態

変分パラメータ(無次元量)

$$\Gamma = (d/b)^2 \qquad \alpha = 1/(2q_F^2 b^2)$$

$$\begin{aligned}
&\tilde{\mathcal{E}}_{\mathrm{AFSC}} \\
&= \frac{10}{3(3\pi)^{2/3}}\Gamma^{1/3}\alpha^{2/3} + \frac{5}{3(3\pi)^{2/3}}\Gamma^{1/3}\alpha^{-1/3} \\
&\quad -\frac{20\pi}{3}\lambda_d \sum_{j=1}^{\infty} e^{-(2j-1)^2\pi^2/2\Gamma}\left\{\underbrace{\frac{1}{3}}_{\text{Hartree}} - \underbrace{F(\alpha)}_{\text{Fock}}\right\} \\
&\quad +\frac{5}{6}\lambda_s \underbrace{\left\{\frac{1}{2} - \sum_{j=1}^{\infty}\left[e^{-(2j-1)^2\pi^2/2\Gamma} - e^{-2j^2\pi^2/\Gamma}\right]\right\}}_{Q(\Gamma)}
\end{aligned}$$

運動エネルギー

z方向の零点振動

xy方向の2次元F.E.

競合

双極子ポテンシャル

競合

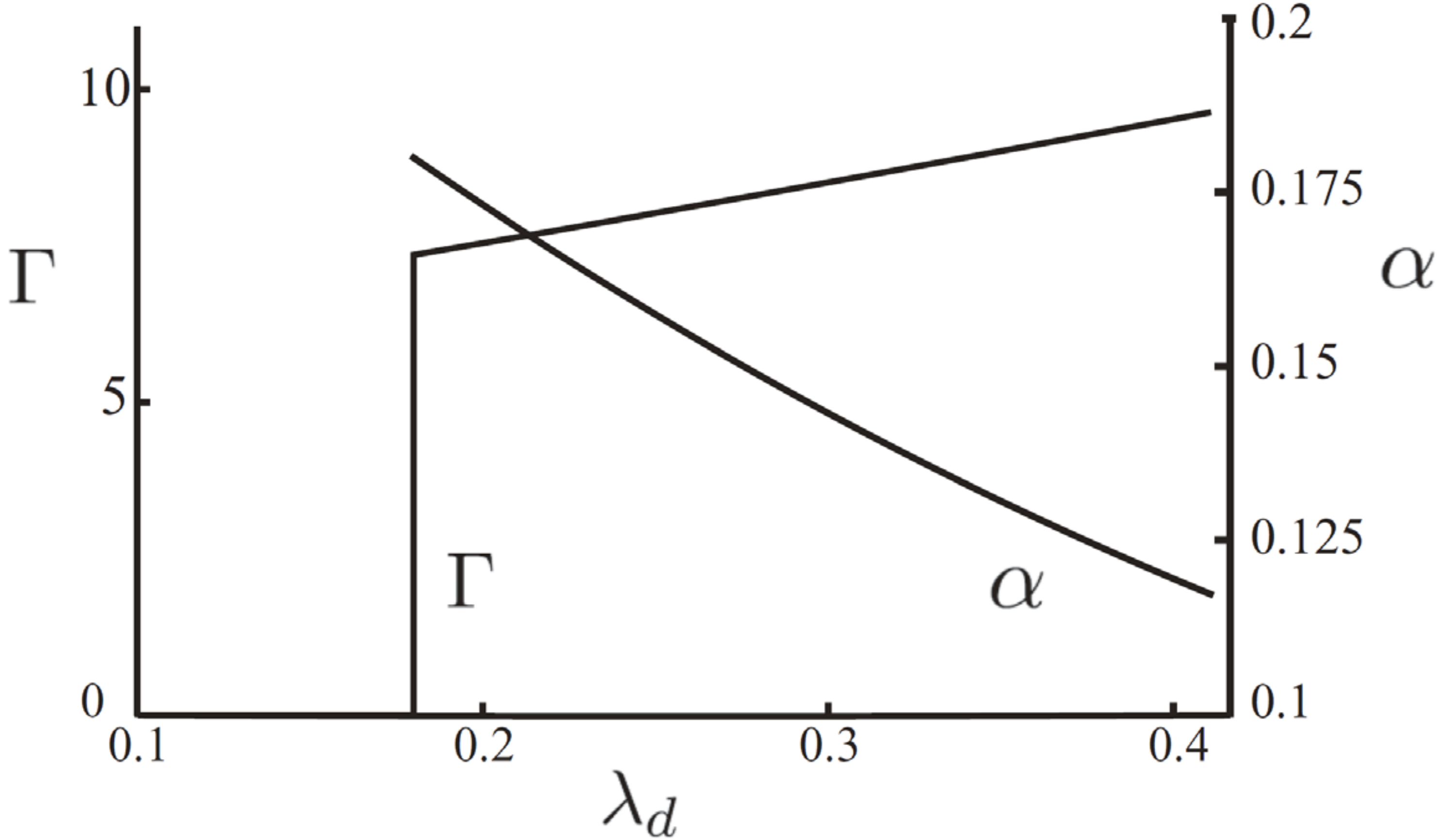
短距離斥力

$Q(\Gamma)$ 僅かな寄与(パウリの排他律による)

$$F(\alpha) = \alpha \int_0^{\infty} \mathrm{d}s\, J_1\left(\sqrt{2s/\alpha}\right)^2 \mathrm{e}^s \left\{(2 + s^{-1})K_0(s) - 2K_1(s)\right\}$$

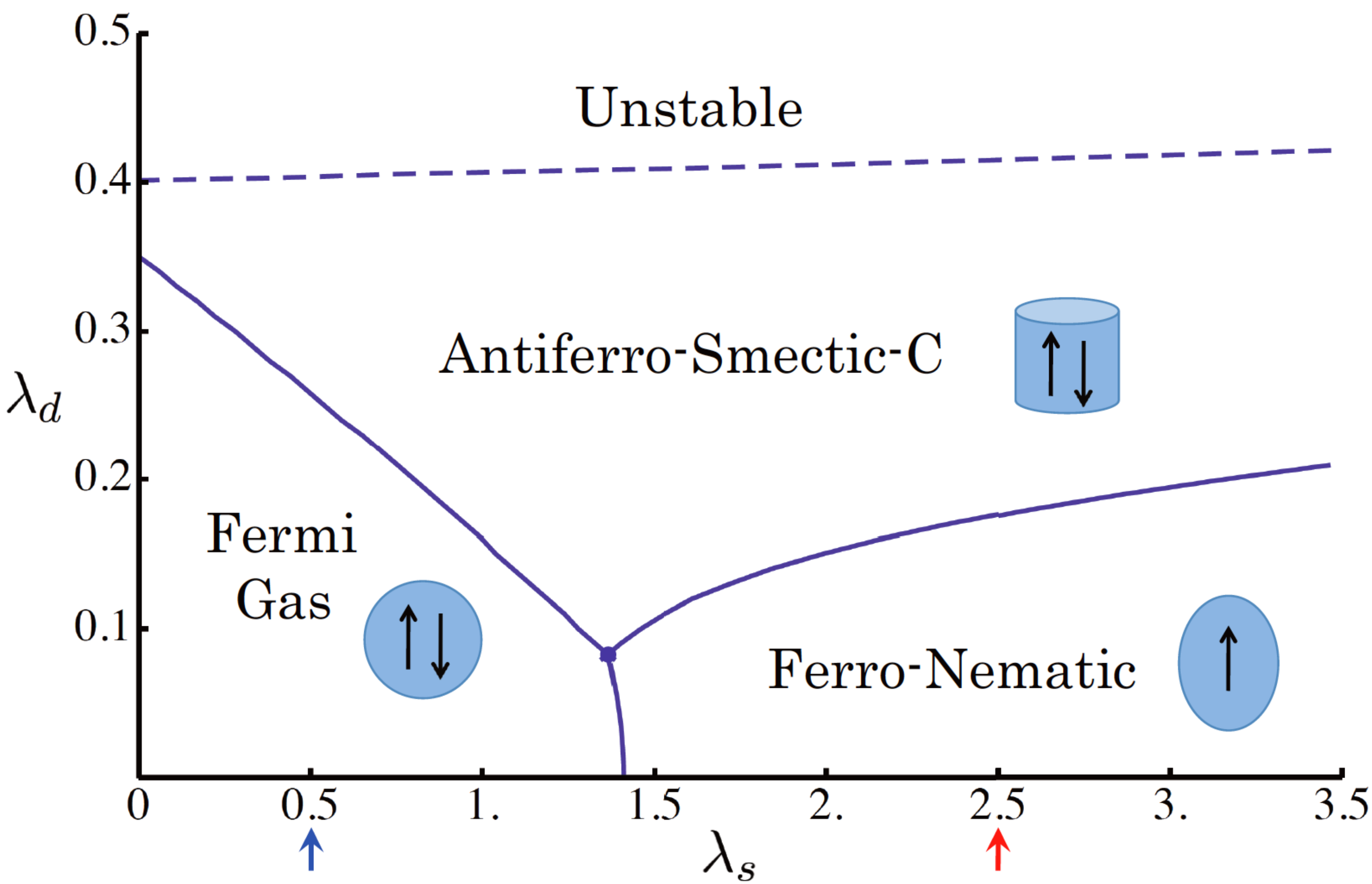
変分パラメータ（無次元量）

$\Gamma = (d/b)^2 \qquad \alpha = 1/(2q_F^2 b^2)$



λs=2.5

変分法による相図



Unstable
Antiferro-Smectic-C
Fermi Gas
Ferro-Nematic
λ_d
0.5
0.4
0.3
0.2
0.1
0
0.5
1.
1.5
2.
2.5
3.
3.5
λ_s

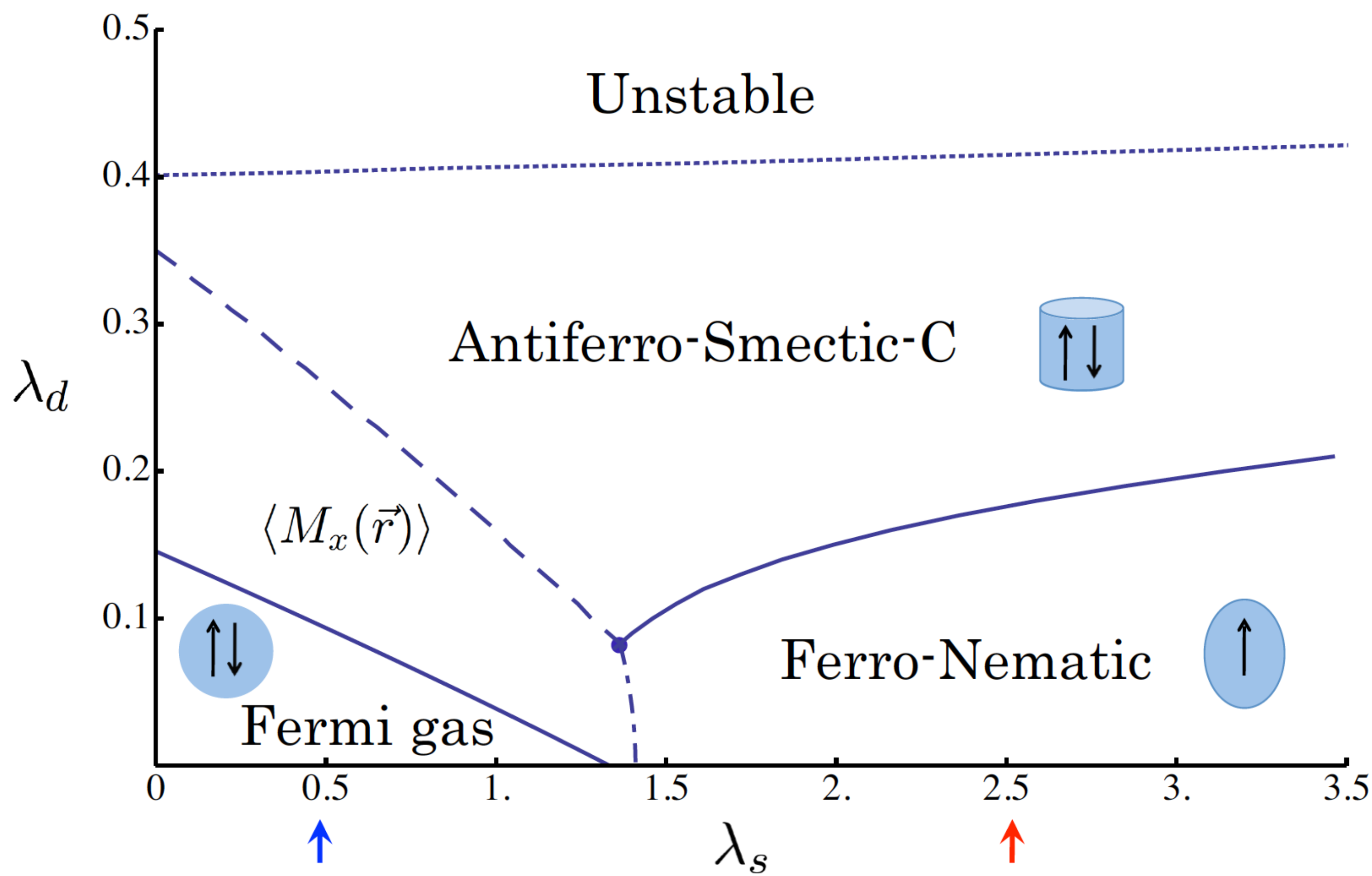
○　結合チャンネル<u>RPA解析</u>(L=0とL=2の結合)

フェルミ気体状態は
『空間変調する磁化の発現』に対して不安定である:

$$\left(1-\frac{3}{4}\lambda_s-2\pi\lambda_d\right)\left(1+\frac{\pi}{2}\right)-\frac{\pi^2}{2}\lambda_d^2 \quad = \quad 0$$

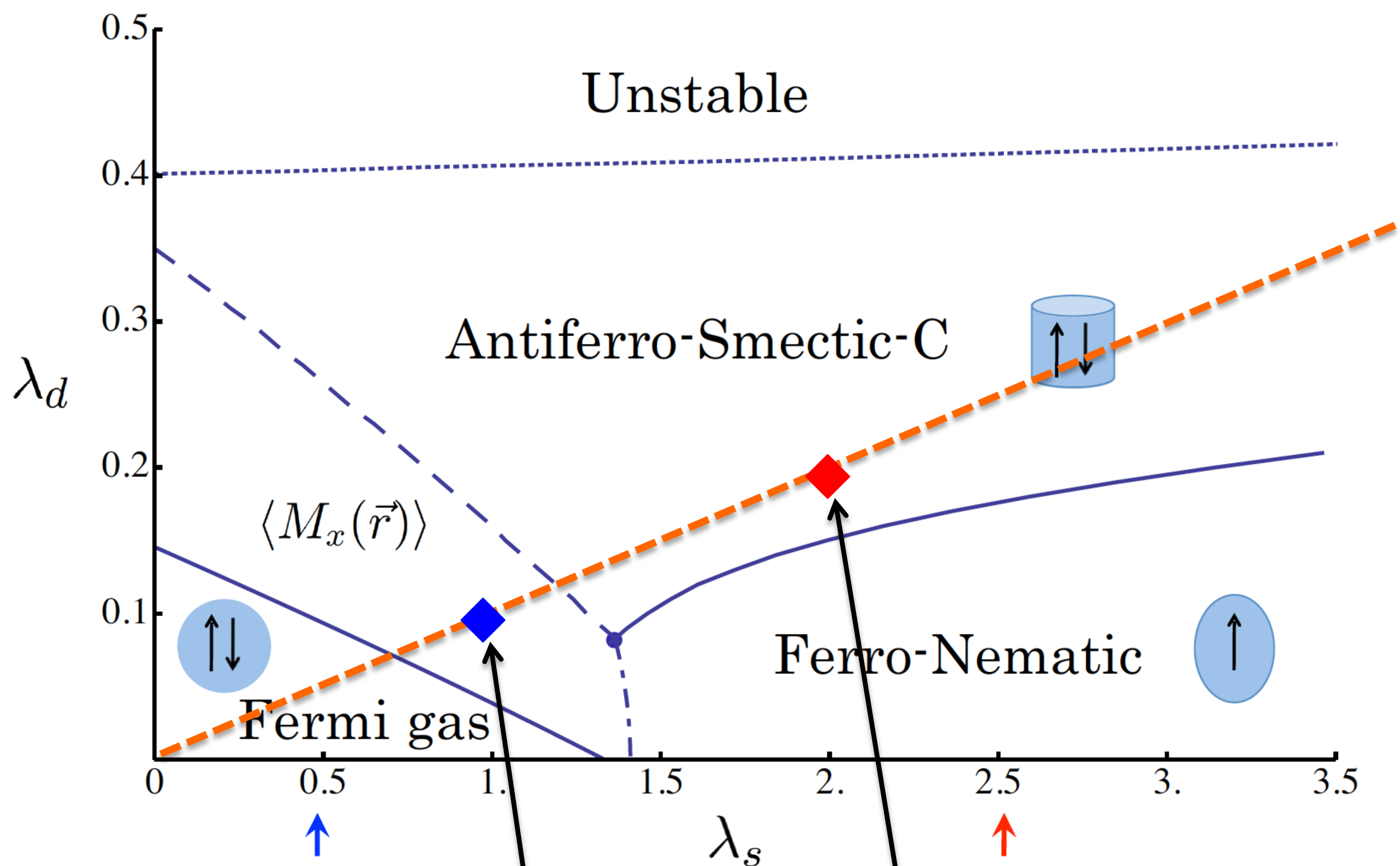
T. Sogo, M. Urban, P. Shuck, T. Miyakawa ,
PRA **85**, 031601(R) (2012)

RPA解析も考慮した相図



実験との関連

Dy原子、5μB、散乱長10nm



数密度

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

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

トイモデルの問題点とその克服可能性

1. ^{161}Dyのスピンは 21/2

   2-hyperfine stateをとる。厳密にはPauli-spinで書けない。

   → mult-level model への拡張必要。

2. ^{161}Dyでも、AFSCにはMagnetic moment がまだ小さい。

$$\lambda_d = n\mu^2/\epsilon_F = \boxed{0.3} \times 10^{-2}\, m_{100} n_{12}^{1/3} \mu_{10}^2$$

ターゲット

→ Electric dipolar molecules の可能性: μ_{10}^2 ~1(^{161}Dy), 310(CH_3F)

Simulating quantum magnets with symmetric top molecules

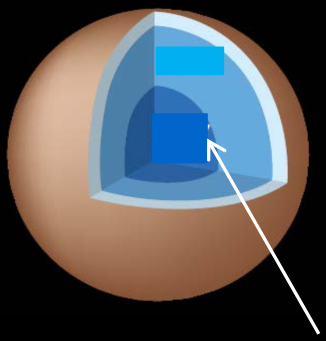
Michael L Wall*, Kenji Maeda, and Lincoln D Carr**

Department of Physics, Colorado School of Mines, Golden, Colorado 80401, USA

arXiv:1305.1236v1 [cond-mat.quant-gas] 6 May 2013

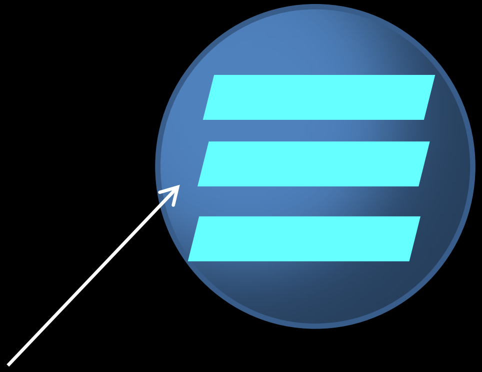
Summary

Neutron star



Meson condensation
By tensor force

cold atoms



Photon condensation
by dipolar interaction

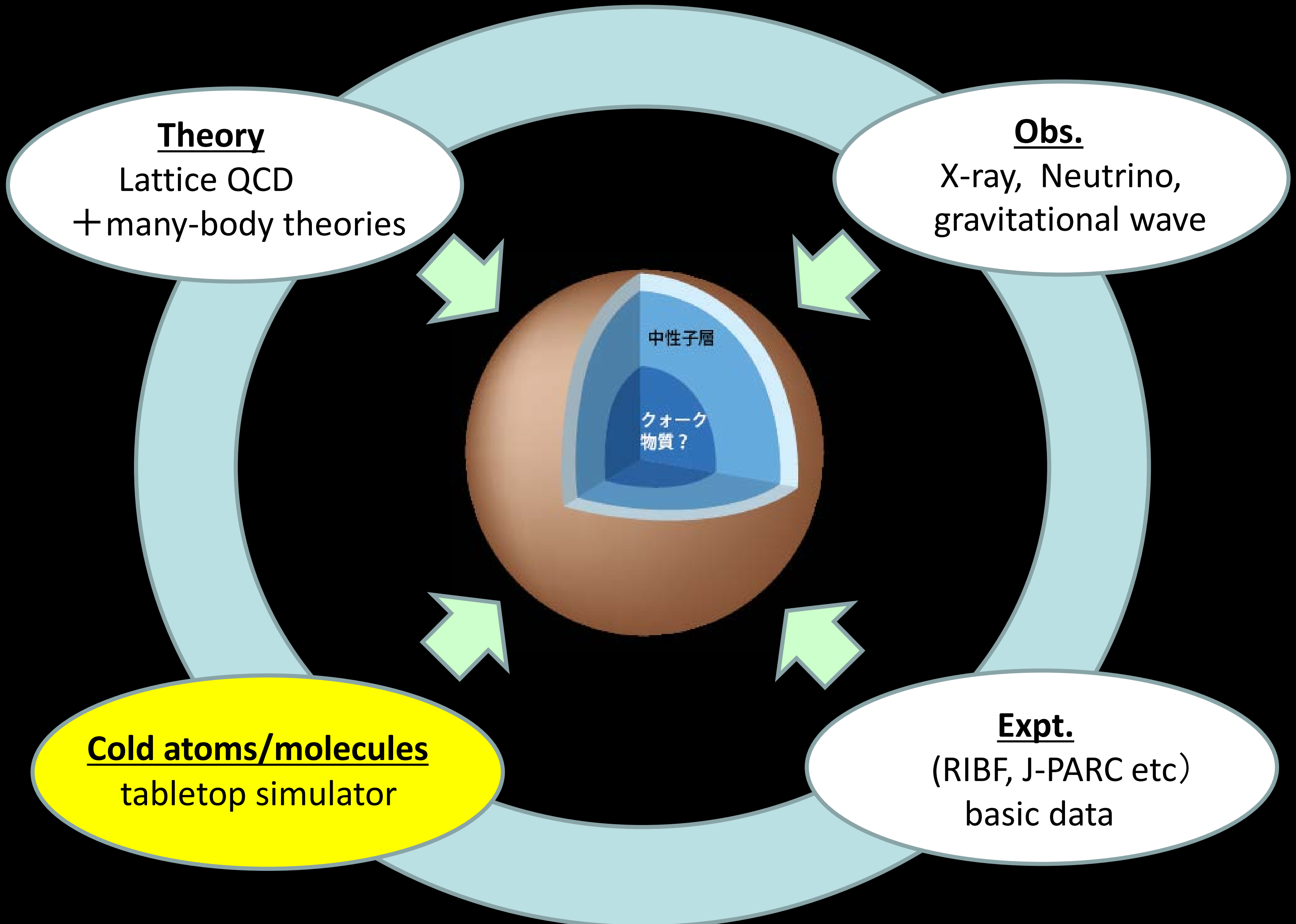
- Almost the same hamiltonian in both systems

  ρ^0 cond. $\Leftrightarrow$ magnetic dipolars (smectic C phase)

  ρ^c cond. $\Leftrightarrow$ magnetic dipolars (chiral nematic phase) ?

- $\mu \sim 10\mu_B$ of magnetic dipolar atoms too small….

  $\Rightarrow$ electric dipolar molecules ($d \sim 1000\mu_B$) e.g. CH_3F


Theory
Lattice QCD
＋many-body theories
Obs.
X-ray, Neutrino,
gravitational wave
中性子層
クォーク
物質？
Cold atoms/molecules
tabletop simulator
Expt.
(RIBF, J-PARC etc）
basic data