Nuclear Matter in Neutron Stars by Experiments and Astronomical Observations

Takashi Nakamura
Tokyo Institute of Technology

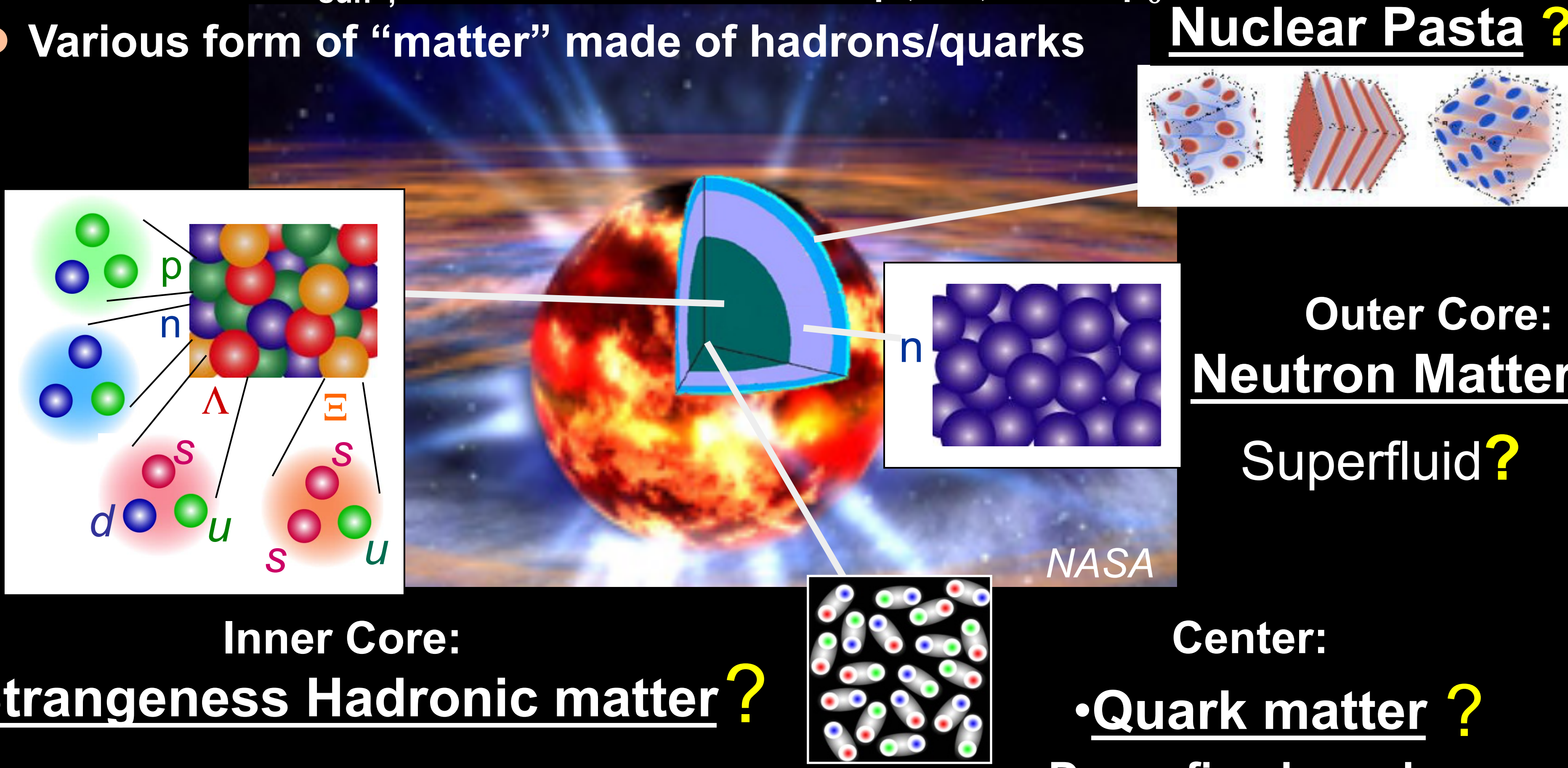
Hadrons and Hadron Interactions in QCD 2015, @YITP, Kyoto Univ. Mar. 2015

Mysteries of Neutron Star

- Final form of "matter" evolution in the universe
- Highest dense "matter" in the universe (Gigantic Nuclei)

  Mass: 1~2 M_{sun} , Radius：~10-15 km , $\rho(r=0)$ =3~10ρ_0
- Various form of "matter" made of hadrons/quarks

Crust:
Nuclear Pasta ?



Outer Core:
Neutron Matter
Superfluid?

Inner Core:
Strangeness Hadronic matter?

High dense nuclear matter
with Hyperons

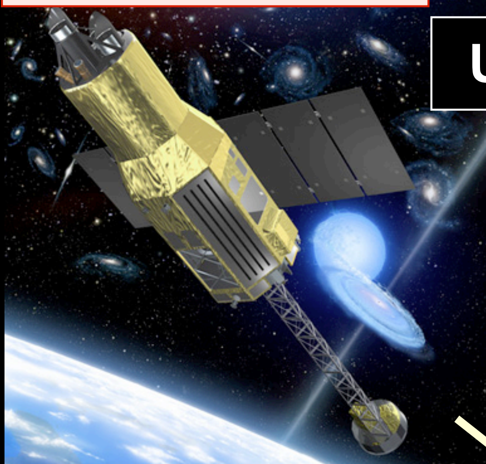
Center:
•**Quark matter ?**
Deconfined quarks
Color superconductivity

2012-2016 新学術領域
「実験と観測で解き明かす中性子星の核物質」

Grant-in-aid for innovative area:
“ Nuclear Matter in neutron Stars investigated by experiments and astronomical observations”

H. Tamura (Tohoku U.)
T.Takahashi (KEK), T.Murakami(Kyoto U.),
T.Nakamura(Tokyo Tech), S.Horikoshi(U.Tokyo),
T. Takahashi(JAXA),A.Onishi(YITP)

Joint project among Experiments, Observations, Theories



X-ray observatory
ASTRO-H

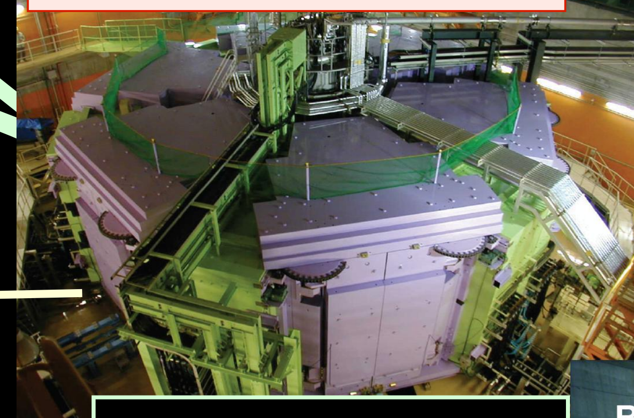
"Science of Matter based on quarks"

Understand structure of n-star

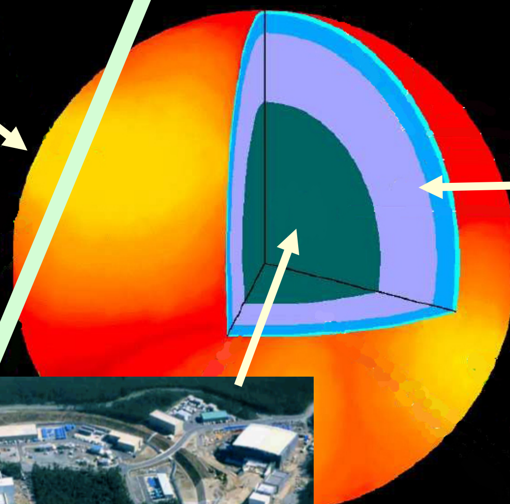
Theories

World-leading two accelerators and X-ray satellite

RIKEN RI Beam Factory
RIBF



Nuclear matter EOS



X-ray astronomy

⇒ n-star radius

n-rich nuclei

High Int. Proton Acc. ***J-PARC***

Cold atoms

⇒ properties of neutron matter

Strangeness nuclear physics

⇒ Interaction of hyperons

Contents

- Introduction –**Nuclear matter in Neutron Stars**
- EOS of Neutron-rich matter probed by RI-Beam Experiments (My expertise)
- EOS for Low-density Neutron-rich Nuclear Matter Studied by Cold Atoms
- Hadronic Matter with Strangeness in Neutron Stars Explored by Experiments
- New development of Research on Neutron Stars by X- and Gamma-Rays Observatory
- Theoretical studies of neutron star and nuclear matter
- Summary and Outlook

EOS

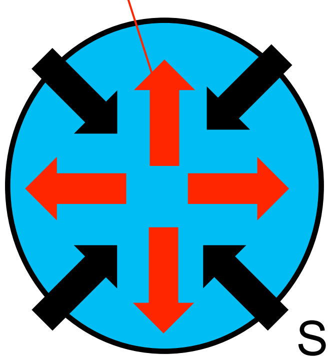
Equation of State of Nuclear Matter E=E(ρ) ⇨ $P = \rho^2 \dfrac{\partial E}{\partial \rho}$

Energy/Baryon

Hydrostatic Equilibrium (General Relativity: T.O.V. Eq.) + **EOS**

→ Radius, Maximum Mass, Mass-Radius Relation of N Star

Pressure (Nuclear/Hadronic Interactions, + Fermi motion)

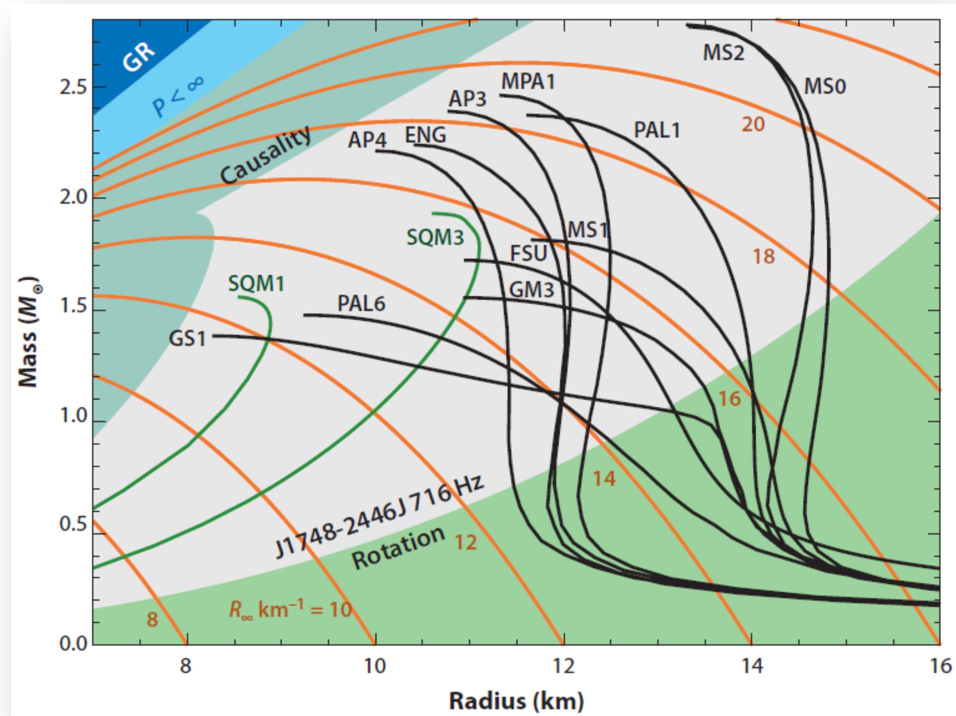


Stiffer(Softer) EOS

→ Pressure is high(low)

→ Larger(Smaller) mass is sustainable

Self-Gravity(Attractive)



- **Composition of N Star**
- **Cooling Mechanism (URCA)**
- **Glitch (Sudden jump in Rotation)**

J.M. Lattimer, Annu. Rev. Nucl. Part. Sci. 62, 485 (2012).

Experiments to explore EOS

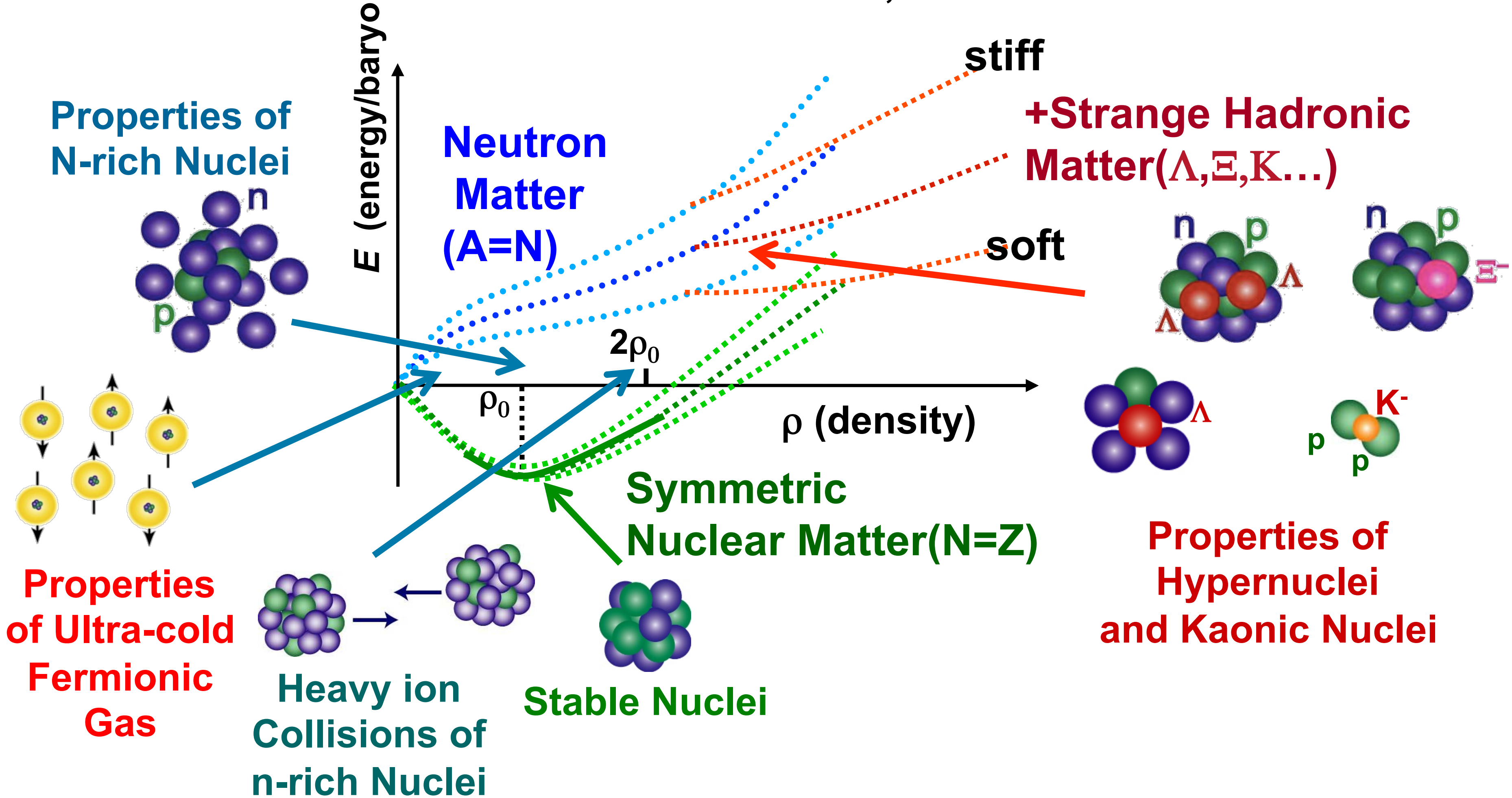
■ Outer Core ($\rho < 2\rho_0$)

How EOS changes with N/Z ratio?

■ Inner Core ($\rho > 2\rho_0$)

Hyperons Exist in N-Star?

If so, How?

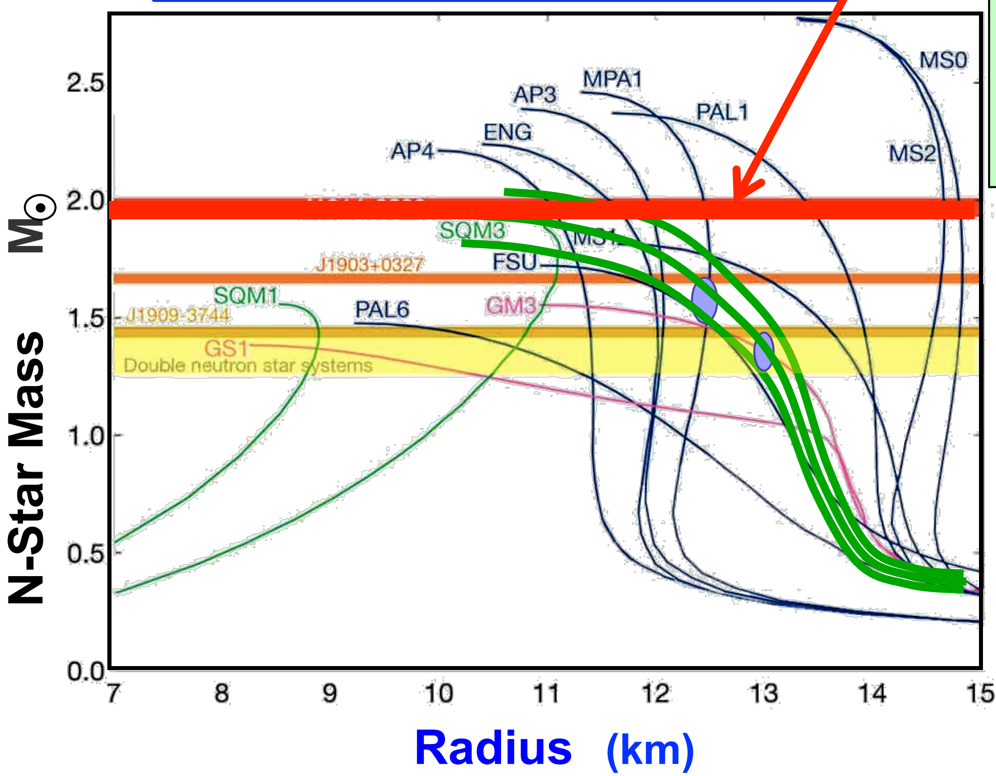


Collaboration among Experiments /Astrophysical Observations/ Theories

EOS of Nuclear Matter

Uniquely Determined

Mass-Radius Curve



(Not yet determidirectly by observations)

EOS Puzzle !

Demorest et al., Nature 467, 1081 (2010)

1.97(4) $M_\odot$ (Shapiro Delay)

Experiments at RIBF/J-PARC /Ultra-cold Fermions +Theories → **Determine EOS**

+

Observations of Radius of N-Star → **Confirm EOS**

The EOS

Constrain on Hadronic/Nuclear Theories, Existence of Quark Star

EOS of neutron-rich matter probed by RI-Beam Experiments

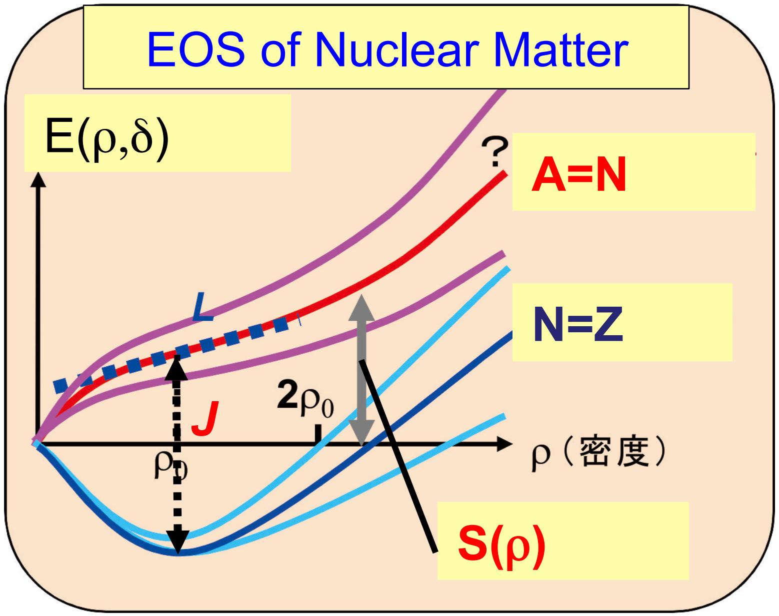
Properties of Medium and Low-density Neutron-rich Nuclear Matter ($\rho \sim \rho_0$, $\rho < \rho_0$)

T.Nakamura(Tokyo Tech), S.Shimoura(CNS,U-Tokyo), Y.Togano(Tokyo Tech), Y.Kondo(Tokyo Tech), T.Teranishi(Kyushu)

EOS for High-Density Neutron-rich Nuclear Matter ($\rho \sim 2\rho_0$)

T. Murakami(Kyoto), K. Ieki(Rikkyo), T. Isobe(RIKEN), A.Taketani(RIKEN), K.Kurita(Rikkyo), H.Baba(RIKEN)

EOS (Nucleonic Degree of Freedom)



Difference of n and p densities

$$E(\rho,\delta) = E(\rho,0) + S(\rho)\delta^2 + \dots \qquad \delta = \frac{\rho_n - \rho_p}{\rho_0} \approx \frac{N-Z}{A}$$

$$S(\rho) = J + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \dots$$

Symmetry Energy: S(ρ)

EOS of nuclear matter within nucleonic D.O.F

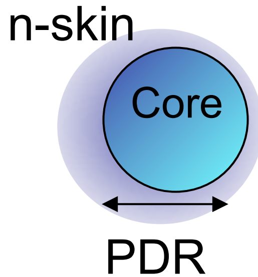
- Provide Basis of EOS with non-nucleonic D.O.F
  → Maximum density→ Composition→ Maximum Mass/Radii of N-Star
- Direct determination of EOS (within nucleonic D.O.F)
  can be possible using a variety of observables
- Most important but unknown term: **Symmetry Energy S(ρ)**

Neutron-rich Nuclei →Microscopic Laboratory for Neutron-Star Physics

How to determine the EOS?

□ S(ρ) : *J*, *L*(*pressure*), K_{sym}(*Incompressibility*)

← Collective Motion of Neutron-rich Nuclei

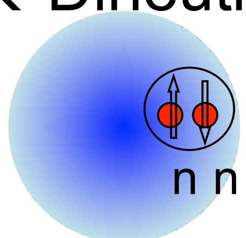


Pygmy Dipole Resonance (E1)

Breathing Mode (E0)

Y.Togano, M. Shikata, CATANA→ PDR of ^{52}Ca,

□ Superfluidity ←Dineutron correlation in low-dense matter



Coulomb Breakup of 2n Halo ^{22}C and ^{19}B

***Deformed Driven Halos**:* ^{31}*Ne*,^{37}*Mg*

TN et al., PRL112,142501(2014).

N.Kobayashi, TN et al.,PRL112, 242501(2014).

□ S(ρ)←Nuclear force

(density dependence, isospin dependence, 3N/4N force)

← tetra neutron, exotic nucleonic system

4n  26, 28O

S.Shimoura 4n exp at SHARAQ Done, Next-generation N-array

Kondo: ^{26}O, Done at SAMURAI, 2012, ^{28}O Approved experiment (Grade-S)

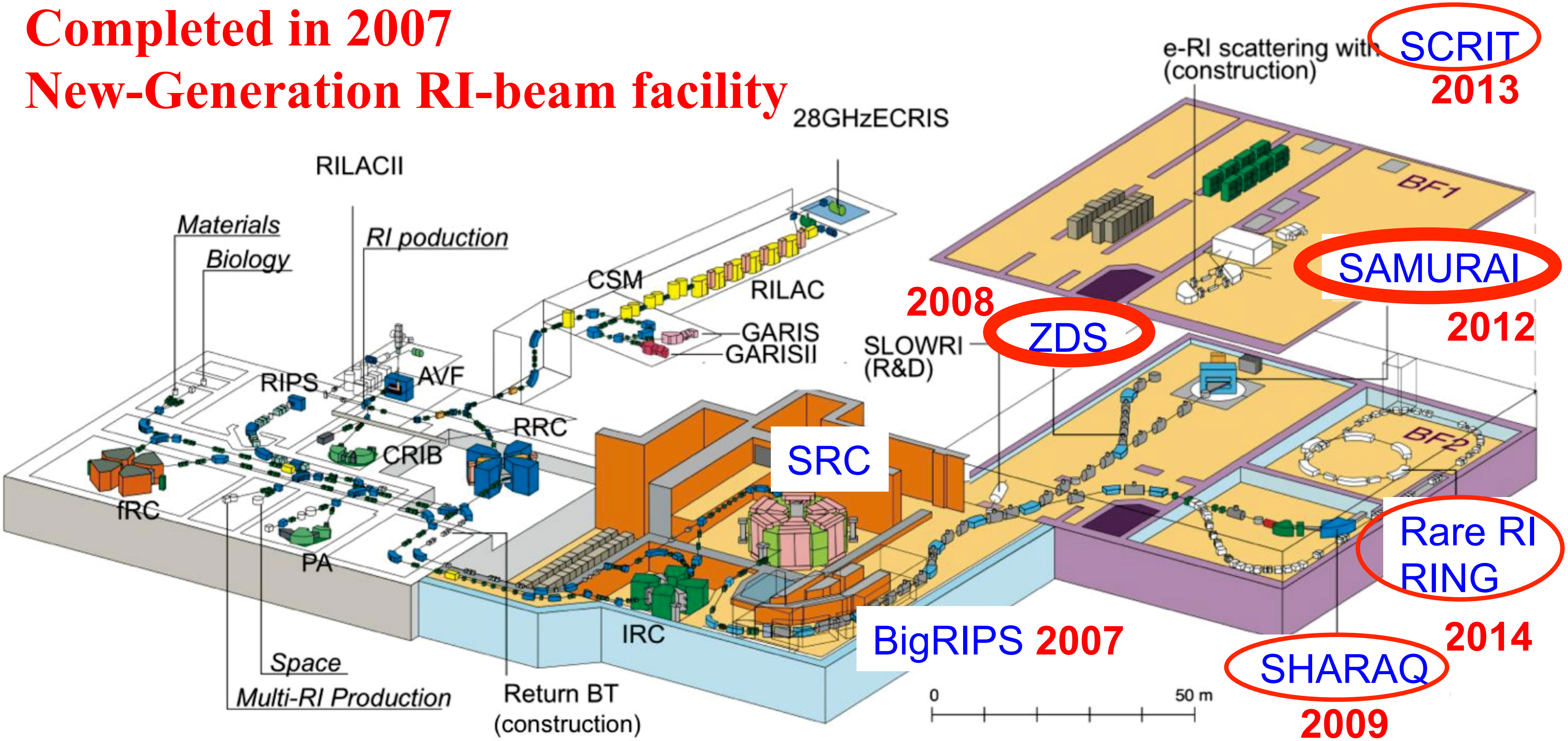
Sekiguchi 3N force

□ S(ρ)←Bulk Property

← neutron skin thickness(**Tamii,Togano**),masses (**Yamaguchi**)

RIKEN RI Beam Factory (RIBF)

Completed in 2007
New-Generation RI-beam facility

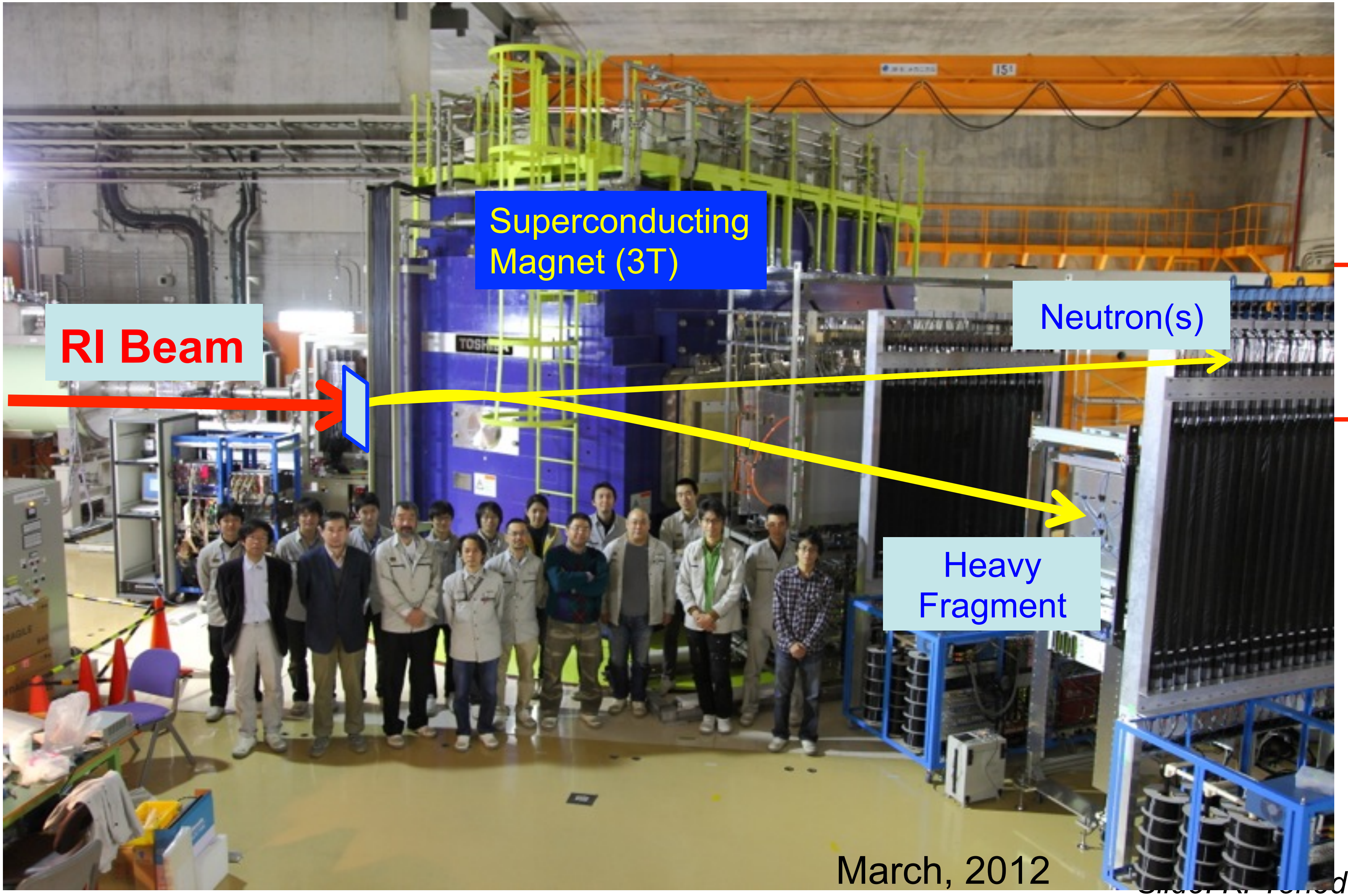


SRC: World Largest Cyclotron (K=2500 MeV)
Heavy Ion Beams up to ^{238}U at 345MeV/u (Light Ions up to 440MeV/u)
BigRIPS: Large Acceptance Fragment Separator (80mradx100mrad, dP/P:6%)

- ✓ **3-5 Orders Gain in the Yield of Neutron-rich Nuclei**
- ✓ **>1000 New Species in neutron-rich nuclei**

SAMURAI

--Large Acceptance Spectrometer in RIBF --



Approach to EOS of Neutron matter/Neutron-rich Matter

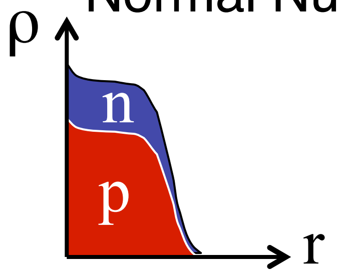
⇒ Neutron Skin Nuclei

N-rich → Larger neutron Fermi energy

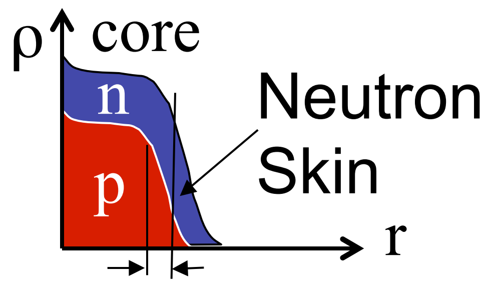
$$\varepsilon_F^{(n)} = \frac{\hbar^2}{2m_n}(3\pi^2\rho_n)^{2/3} = \left(\frac{2N}{A}\right)^{2/3}\varepsilon_F^{(0)}$$

for N=2Z → $1.2\varepsilon_F^{(0)}$ (without n-skin)

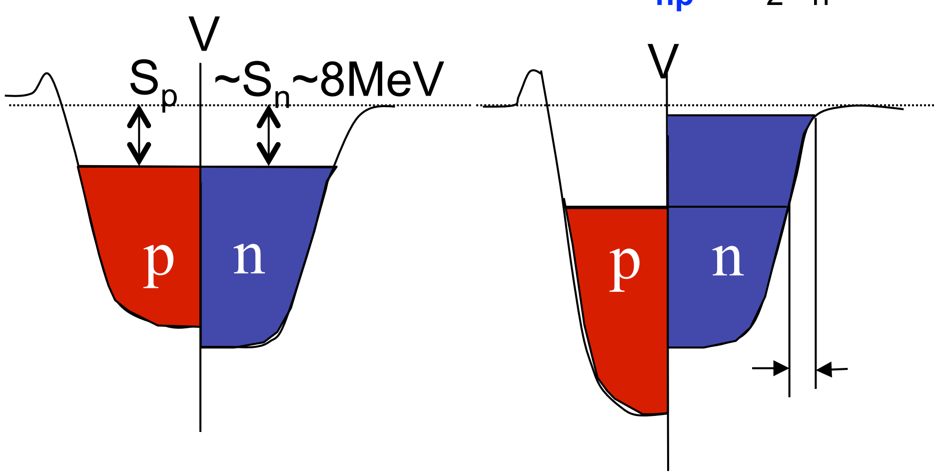
Normal Nuclei

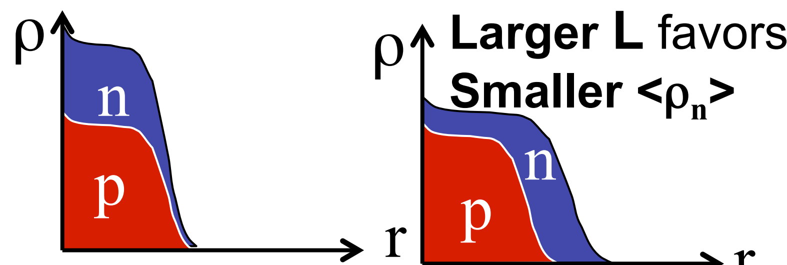


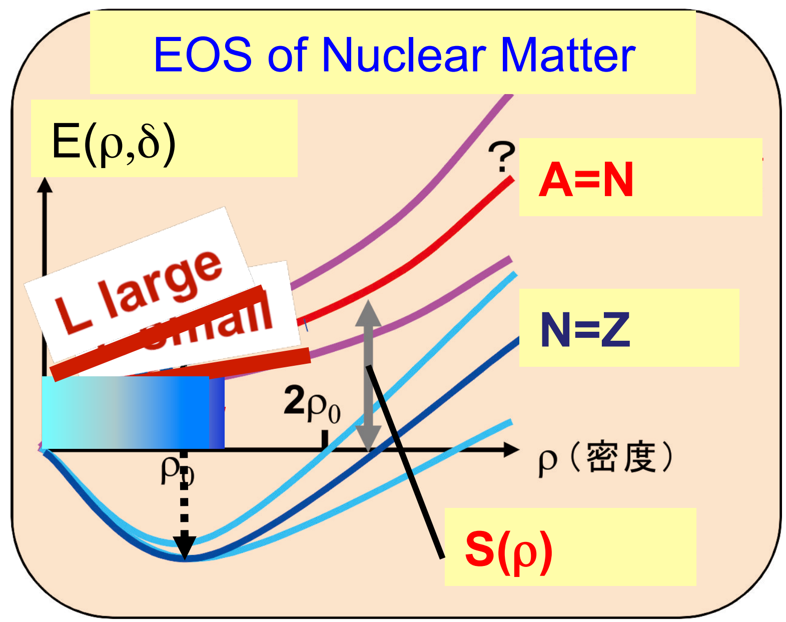
Neutron-Skin Nuclei (Neutron-rich Nuclei)



$\delta R_{np} = \langle r_2 \rangle_n^{1/2} - \langle r_2 \rangle_p^{1/2}$





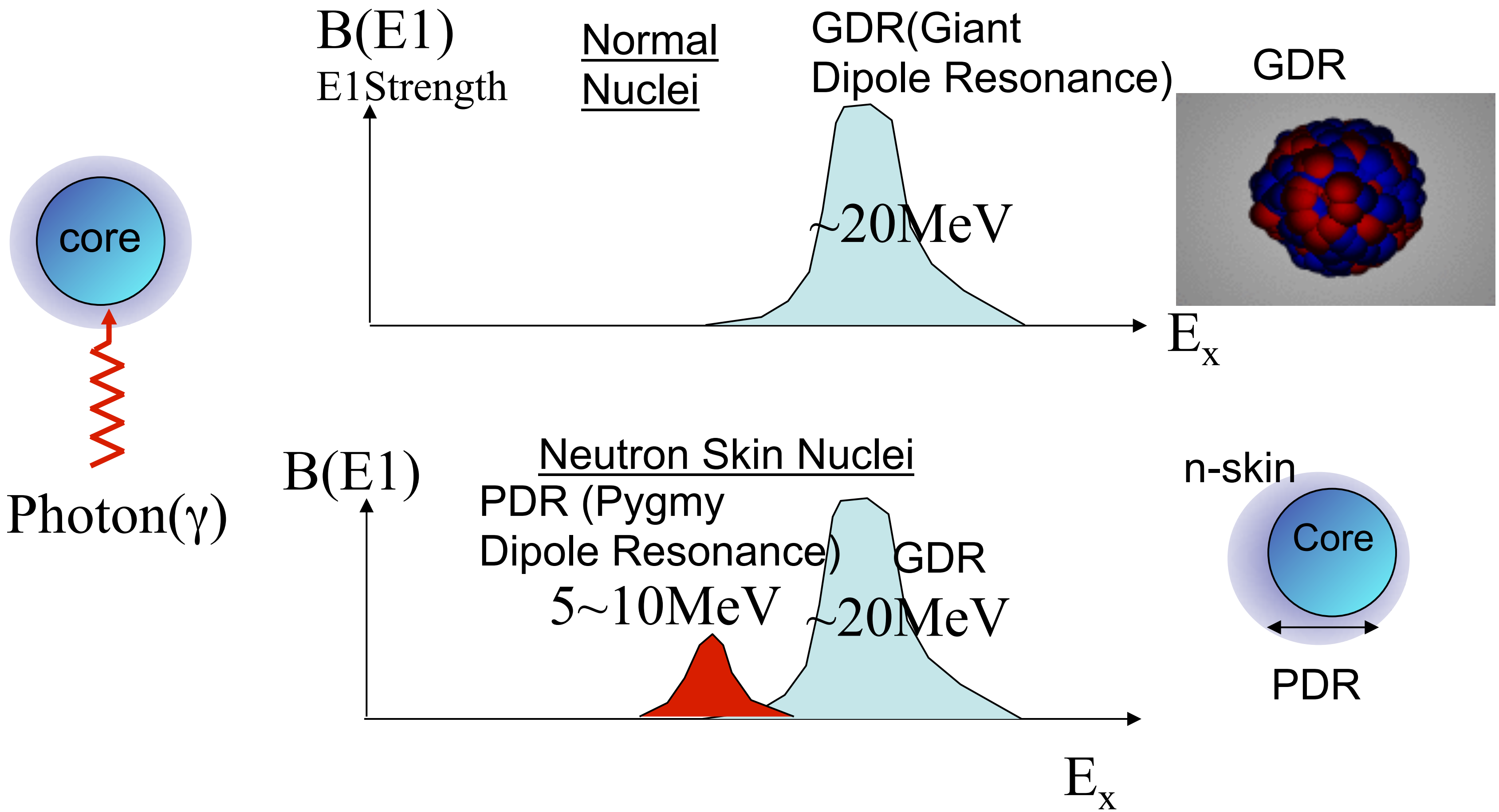


Neutron Skin : Formed due to S(ρ)

δR_{np}(or R_n)-- Depends on EOS

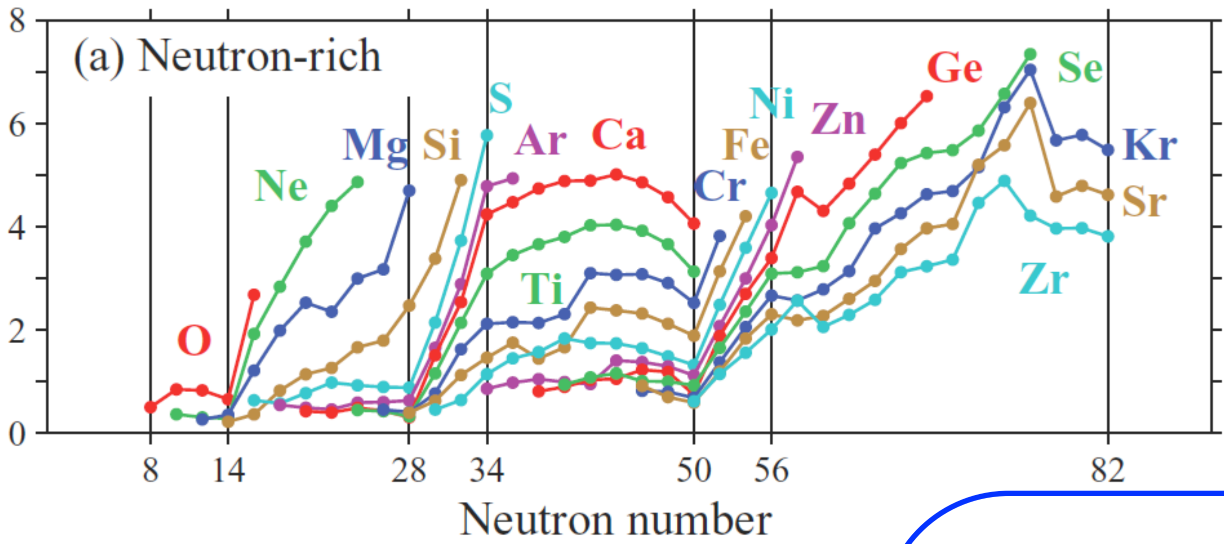
as in NS radius $\quad R_{NS} \propto P_0^{1/4} \propto L^{1/4}$

Pygmy Dipole Resonance of Neutron Skin Nuclei --- Also Sensitive to EOS



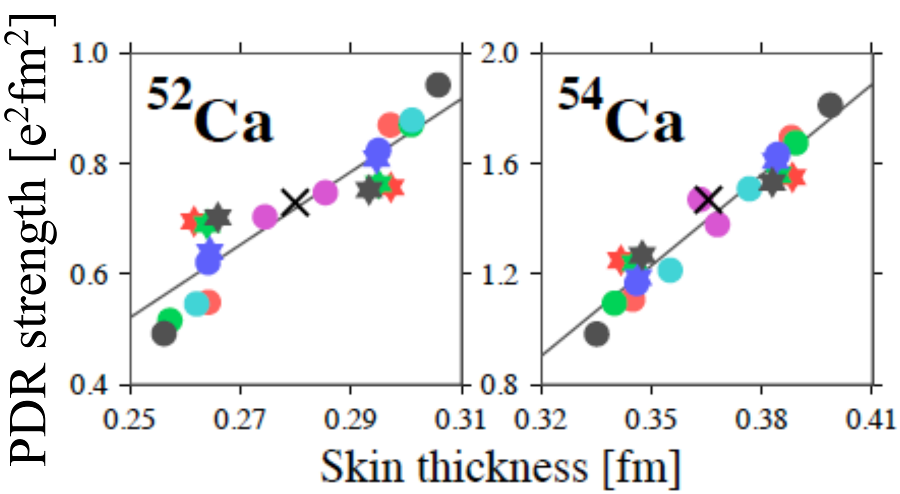
Stiff EOS→Thicker Neutron Skin → Larger Pygmy Mode

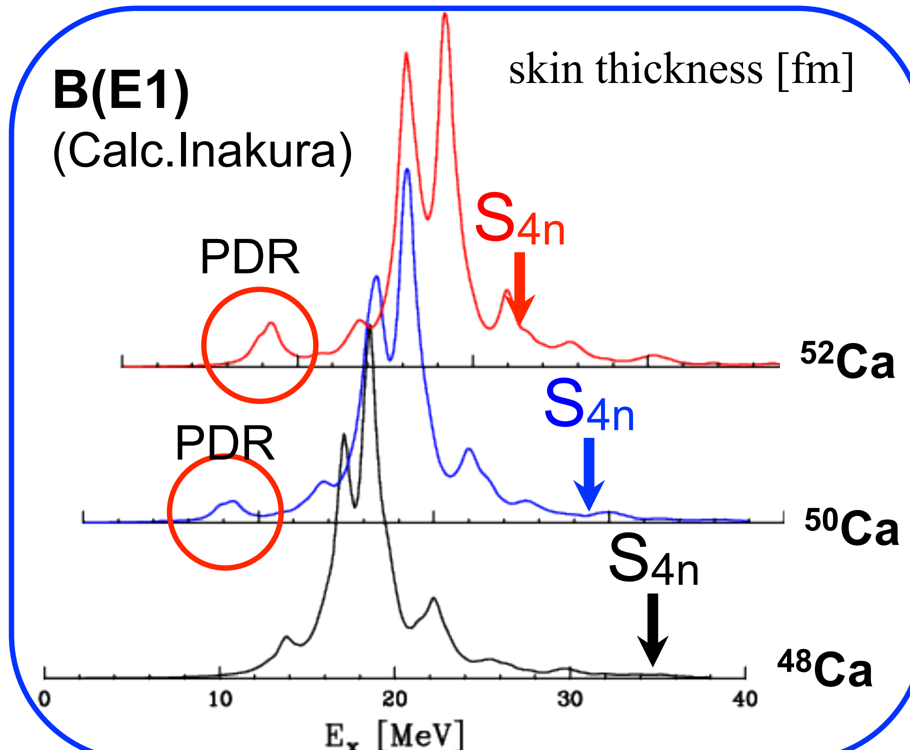
PDR and skin thickness



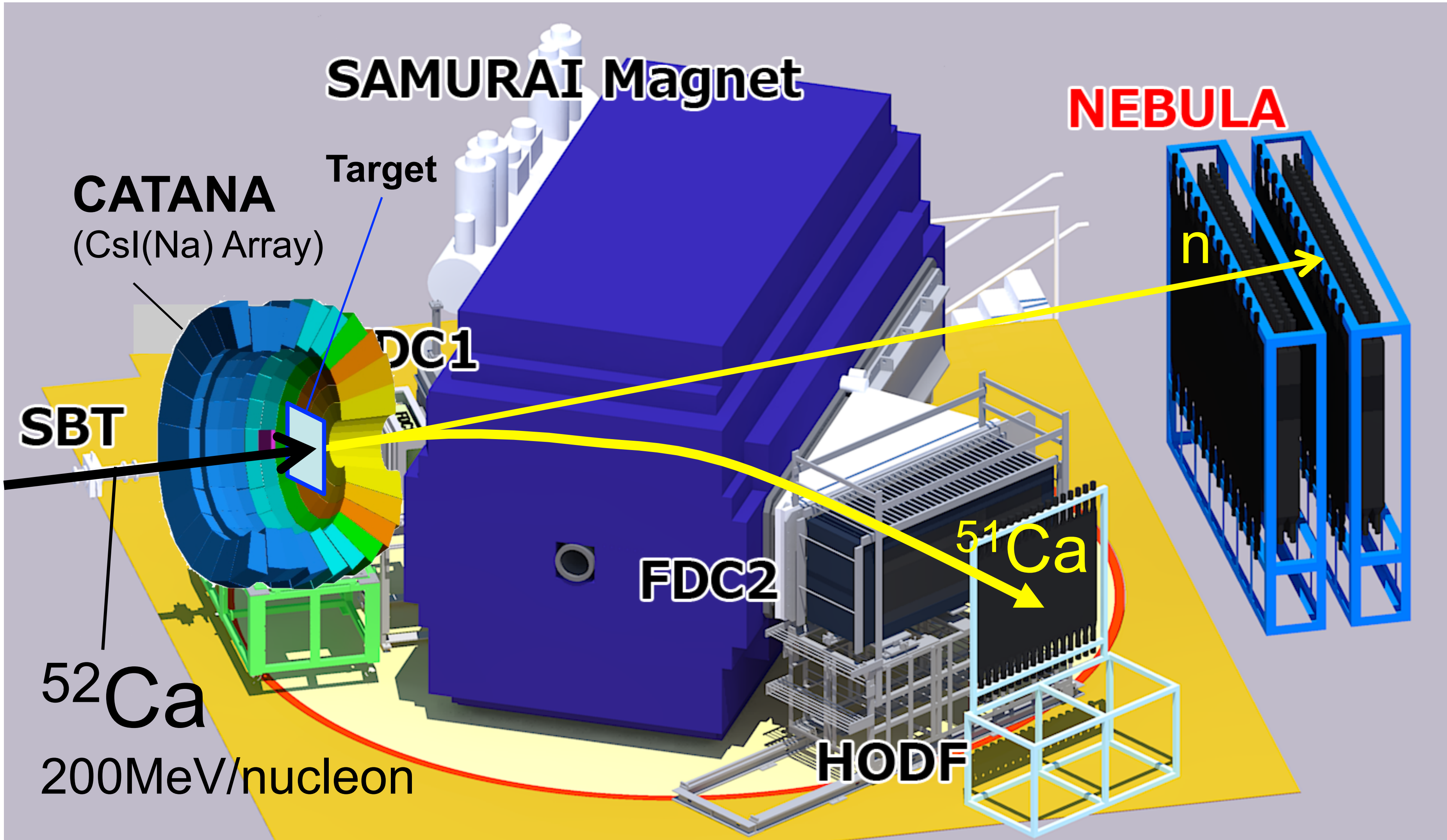
T. Inakura et al., PRC84, 021302 (2011)

T. Inakura et al., arXiv:1306.3089



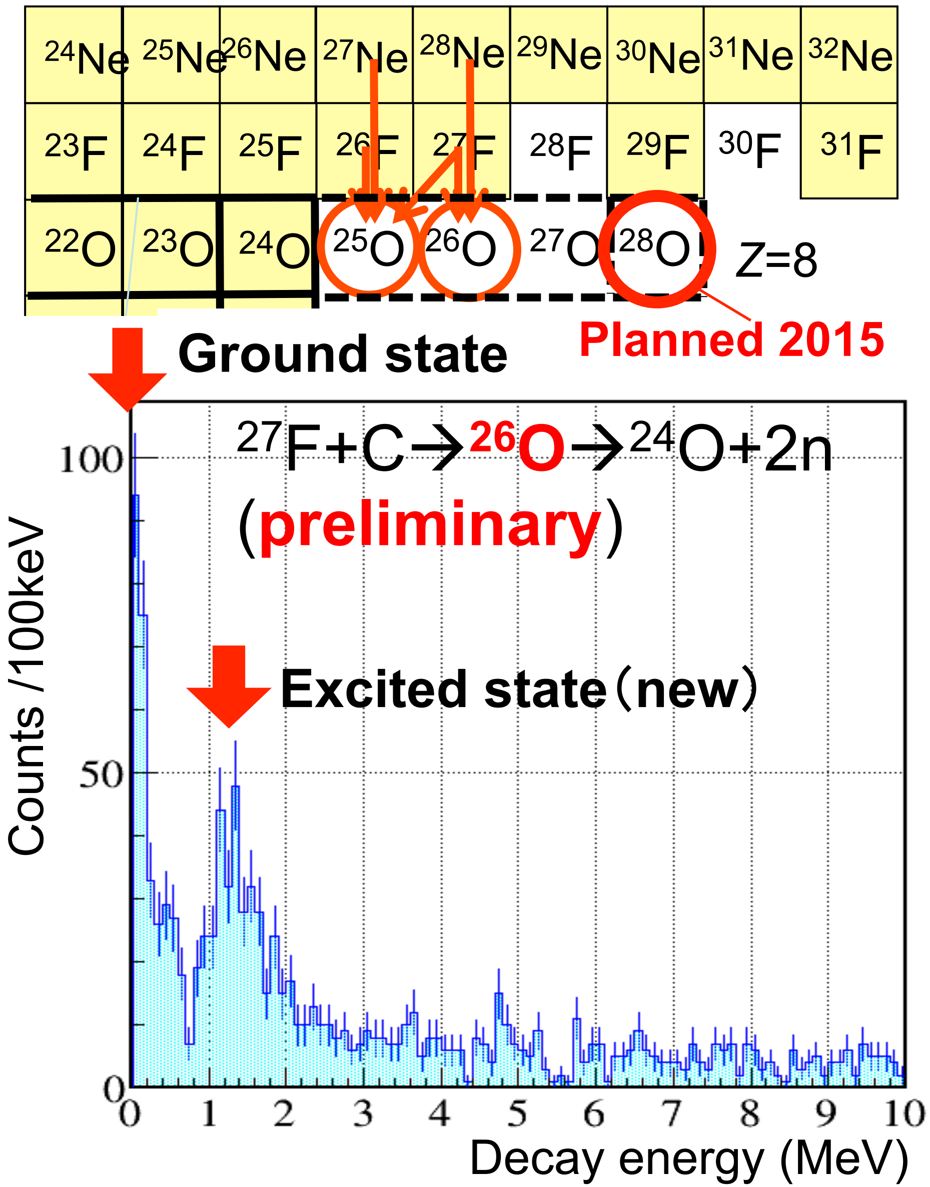


PDR of neutron-skin nuclei



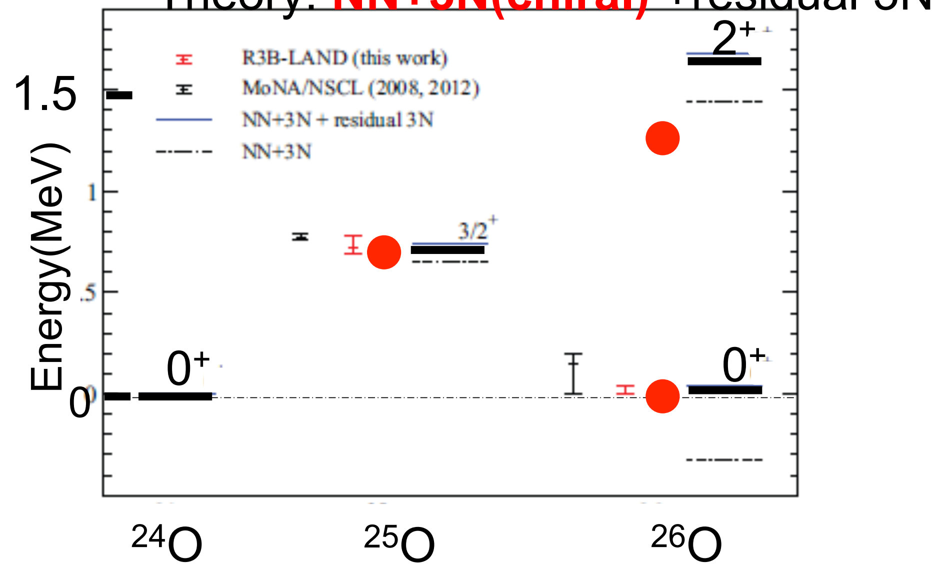
Y. Togano: Approved experiment at RIBF
Planned in 2016

Production of Unbound ^{26}O States: Y.Kondo et al.

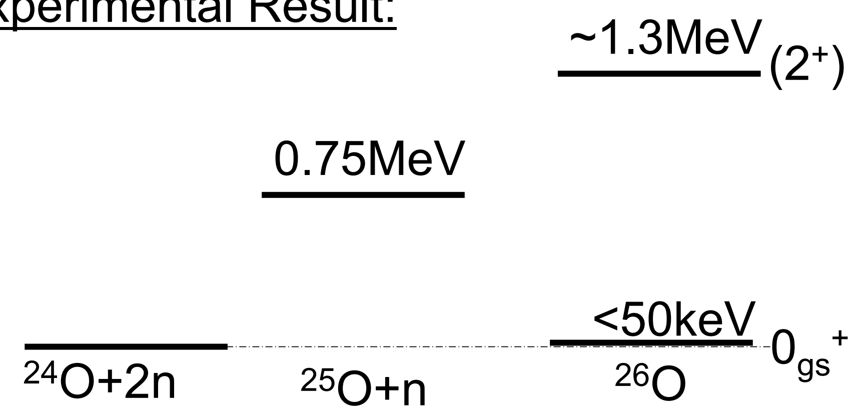


C.Caesar et al.(GSI,Data), A.Schwenk (Theory)PRC88,034313 (2013)

Theory: **NN+3N(chiral)** +residual 3N

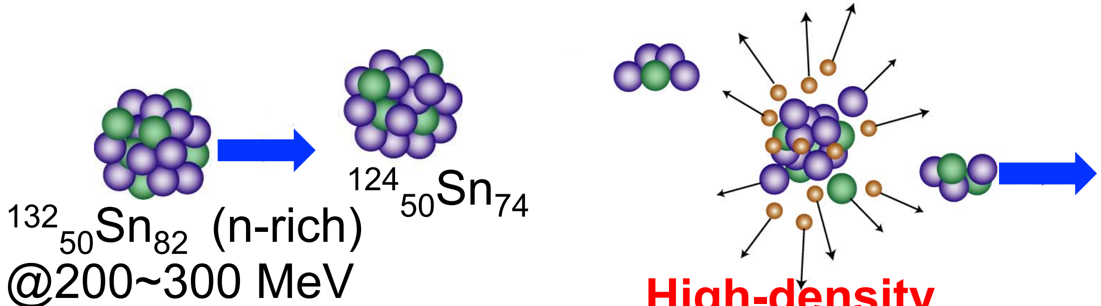


Experimental Result:



π^-/π^+ ratio in Heavy ion collisions

T.Murakami, T. Isobe et al.

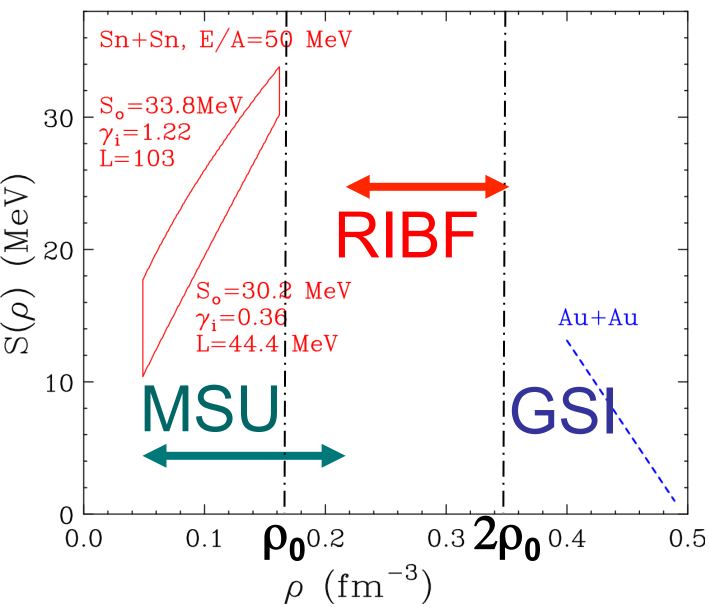


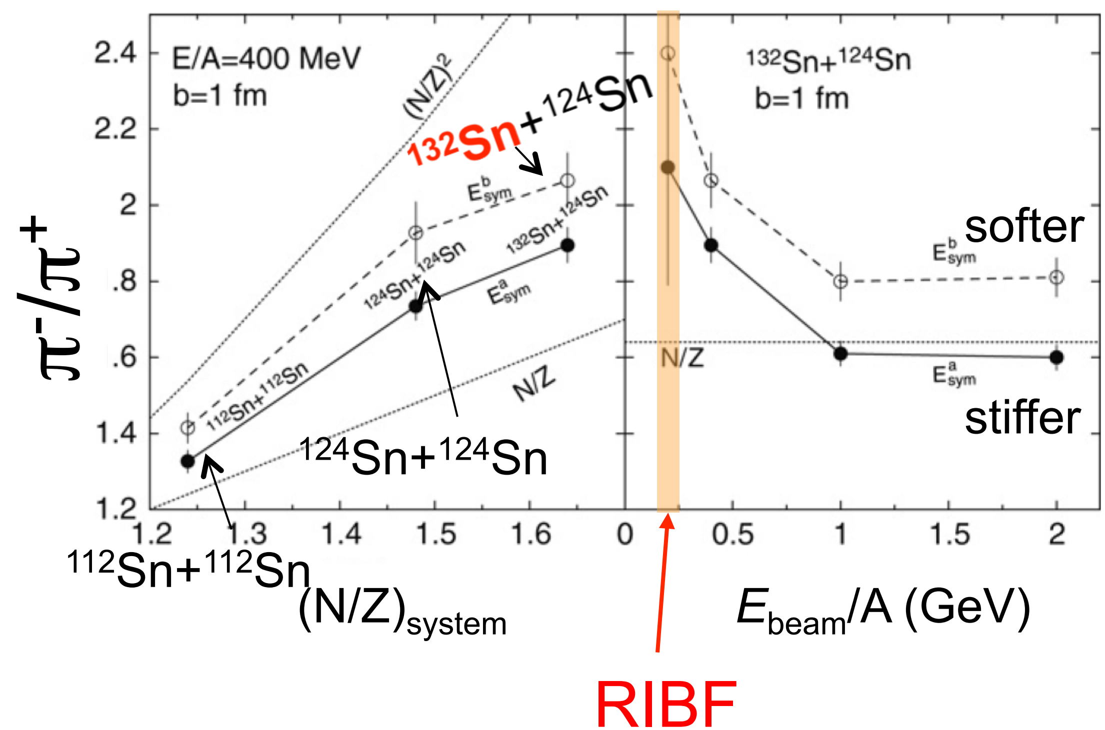
High-density (participant region)

$(\pi^-/\pi^+) \sim (N/Z)^2$ of participant region of heavy ion collisions (Δ resonance model)

-- sensitive to $S(\rho)$

Bao-An Li et al.,
Phys. Rep. 464, 113 (2008).



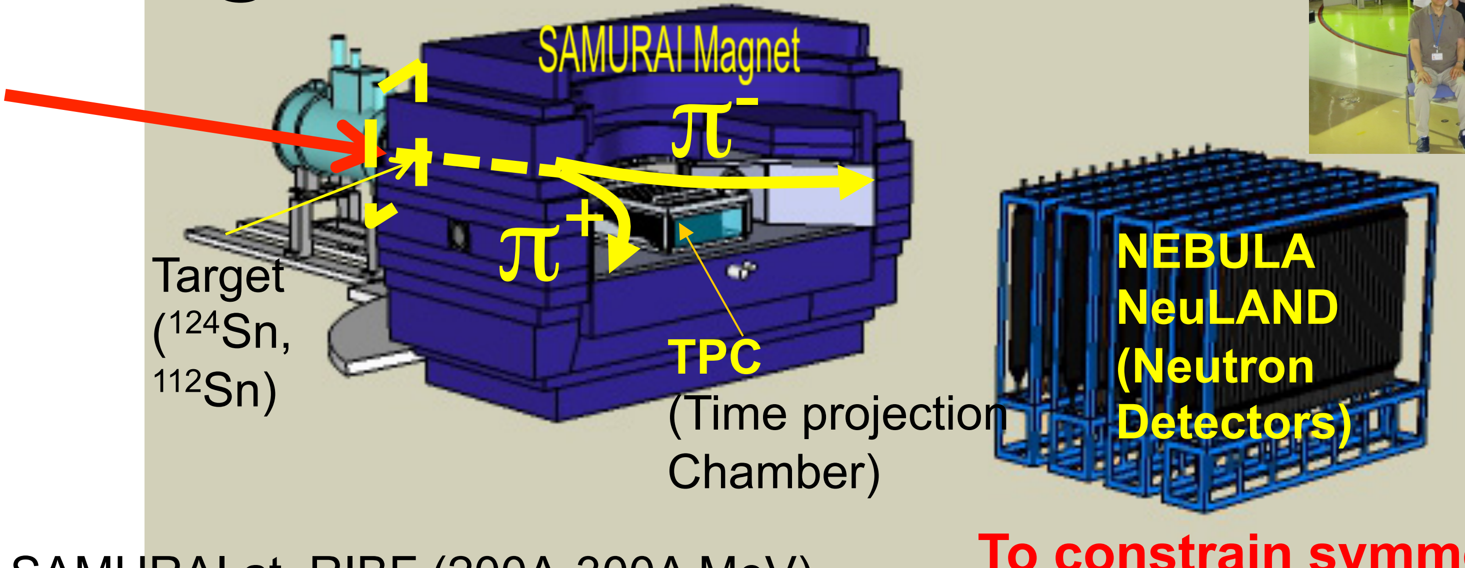


SπRIT Collaboration

SAMURAI Pion Reconstruction and Ion-Tracker

^{132}Sn @ 200 A MeV

^{108}Sn @ 300 A MeV



SAMURAI at RIBF (200A-300A MeV)

$^{132}_{50}Sn_{82} + ^{124}_{50}Sn_{74} \rightarrow \pi^+/\pi^- + X$

$^{124}_{50}Sn_{74} + ^{112}_{50}Sn_{62} \rightarrow \pi^+/\pi^- + X$

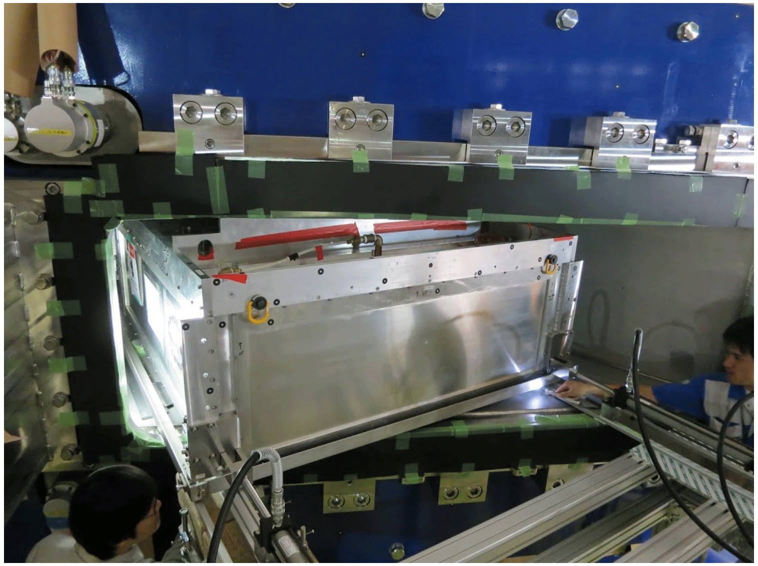
$^{112}_{50}Sn_{62} + ^{124}_{50}Sn_{74} \rightarrow \pi^+/\pi^- + X$

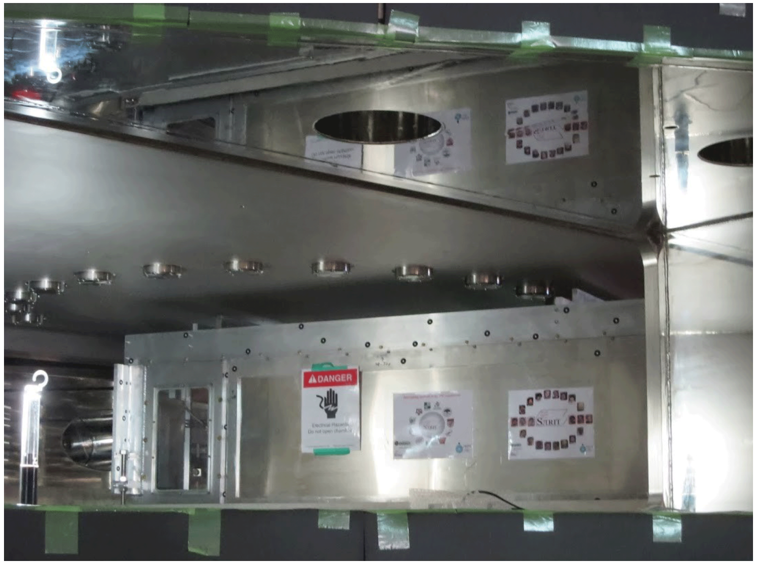
$^{108}_{50}Sn_{58} + ^{112}_{50}Sn_{74} \rightarrow \pi^+/\pi^- + X$

$\delta = (\rho_n - \rho_p)/\rho_0$: 0.09--0.22

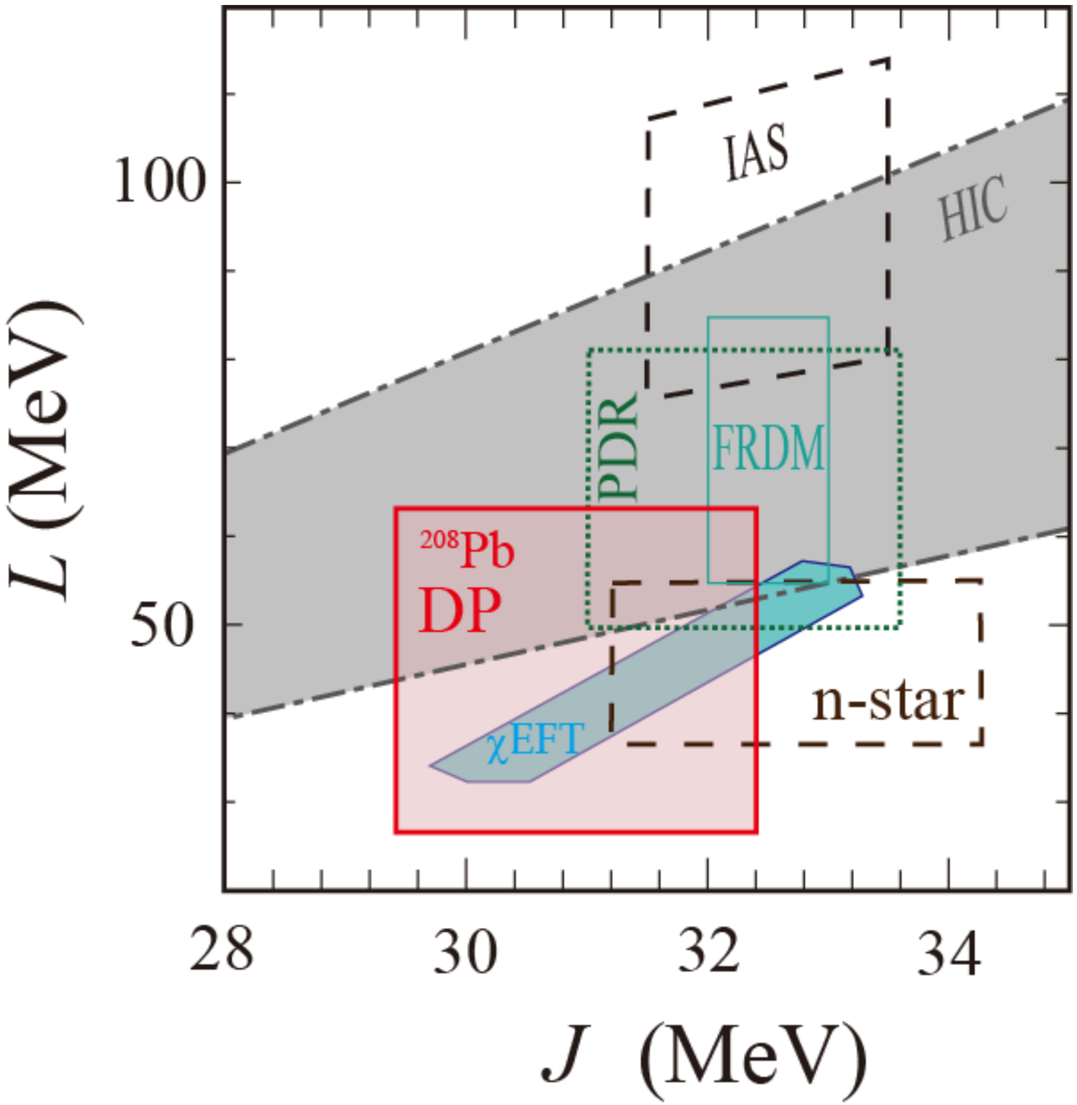
To constrain symmetry energy
Y(n)/Y(p), $Y(\pi^-)/Y(\pi^+)$ etc.

Installation Test of TPC into SAMURAI in July 2014





Symmetry Energy ($\rho \sim \rho_0$) ---*Current Status*



M.B. Tsang *et al.*, PRC**86**, 015803 (2012).
I. Tews et al., PRL**110**,032504 (2013).

DP: Dipole Polarizability

(A. Tamii PRL107, 062502 (2011)).
HIC: Heavy Ion Collision
PDR: Pygmy Dipole Resonance
IAS: Isobaric Analogue State
FRDM: Finite Range Droplet Model (nuclear mass analysis)
n-star: Neutron Star Observation
χEFT: Chiral Effective Field Theory

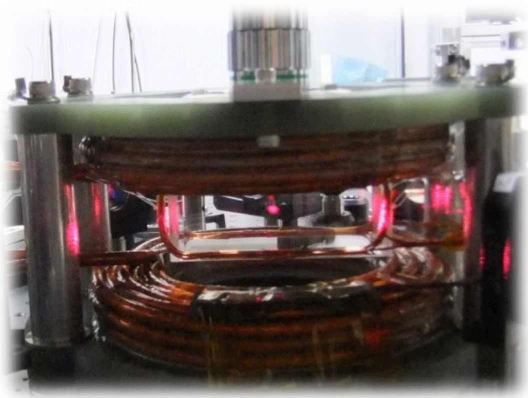
DP: L=45±18 MeV
J=30.9±1.5 MeV

$$S(\rho) = J + \frac{L}{3\rho_0}(\rho - \rho_0) + \frac{K_{sym}}{18\rho_0^2}(\rho - \rho_0)^2 + \dots$$

EOS for Low-density Neutron-rich Nuclear Matter Studied by Cold Atoms

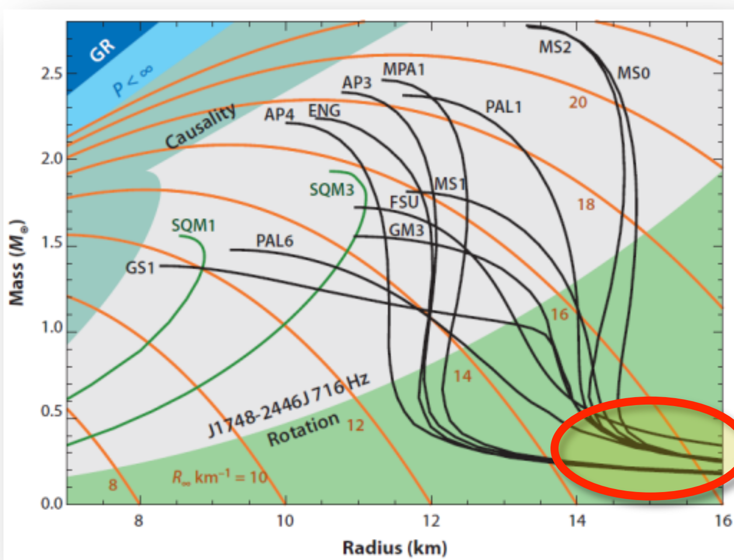
M. Horikoshi (U.Tokyo), T. Mukaiyama (UEC),
T.Nakatsukasa(Tsukuba U), K. Mizushima (Okayama U.)

From ultracold atom to the neutron star M-R curve

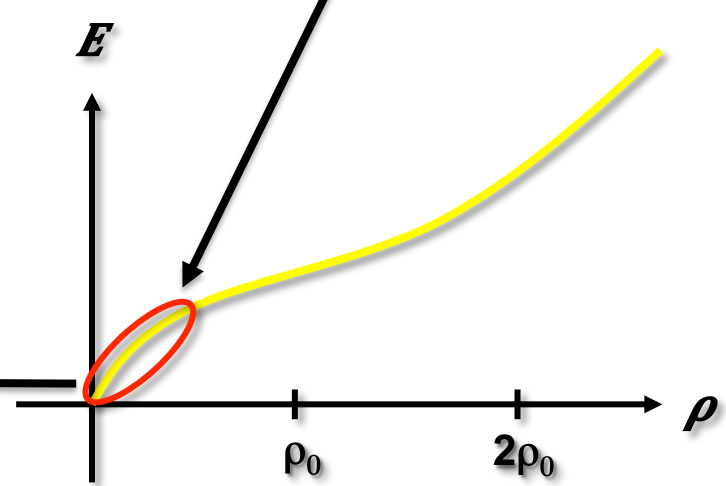


Cold Fermi atoms
E=f(ρ)

Neutron Star
$E(\rho, \delta = 1)$

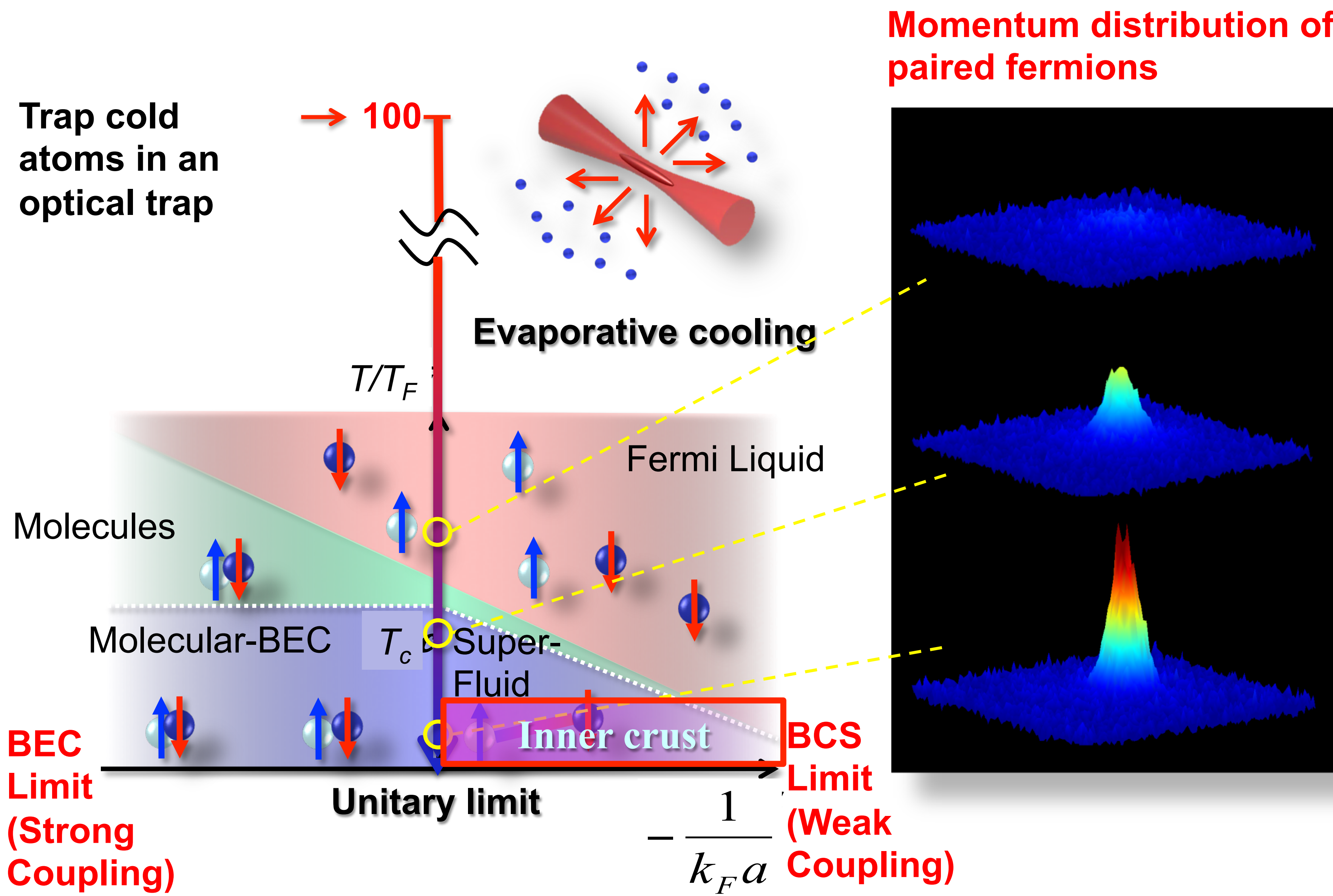


TOV



Constrain in these regions

Superfluid transition at the unitarity



M.Horikoshi et al.

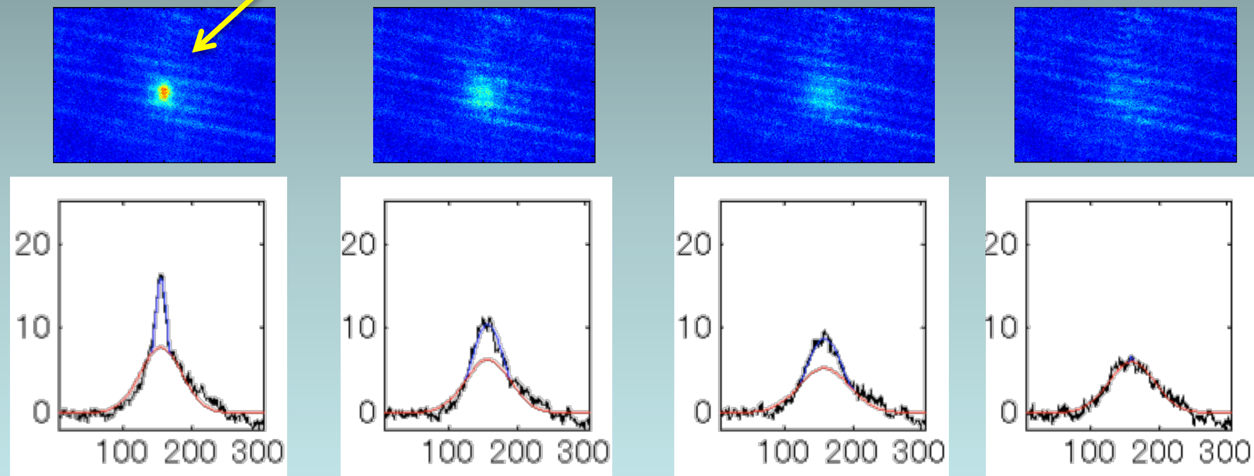
Hot topic : Bose-Fermi superfluid mixture *!!*

Strongly correlated Fermion Pairs

Fermi Superfluid

^{6}Li (Fermi)

Momentum distribution of paired Fermions

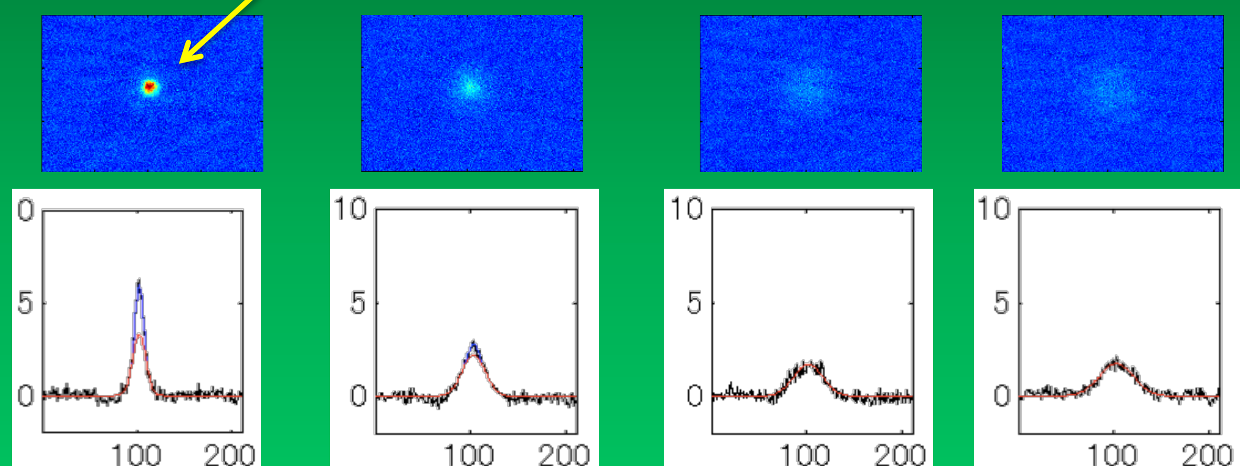


Possible Thermometer for ^{6}Li gas

BEC

^{7}Li (Bose)

Momentum distribution of Bosons



Strangeness Matter in Neutron Stars Explored by Experiments at J-PARC

Baryon-baryon Interaction with Multi-Strangeness

T.Takahashi(KEK), K.Nakazawa(Gifu U.), S.Sato (JAEA), H.Takahashi(KEK), M.Naruki(Kyoto U.), K.Imai(JAEA), H.Sako(JAEA), S.Hasegawa(JAEA), M.Sumihama (Gifu U.)

Strangeness in the Neutron-rich Nuclear Matter

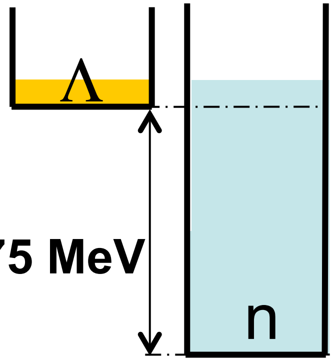
H. Tamura(Tohoku U.), A. Sakaguchi(Osaka U.), H. Outa(RIKEN), K. Miwa (Tohoku U.), T. Koike (Tohoku U.), S.Ajimura(RCNP), T. Fukuda(OECU), T.Suzuki (U.Tokyo), S.Nakamura (Tohoku U.)

Hyperon Matter should appear at Higher Density

($\rho > \sim 2\rho_0$)

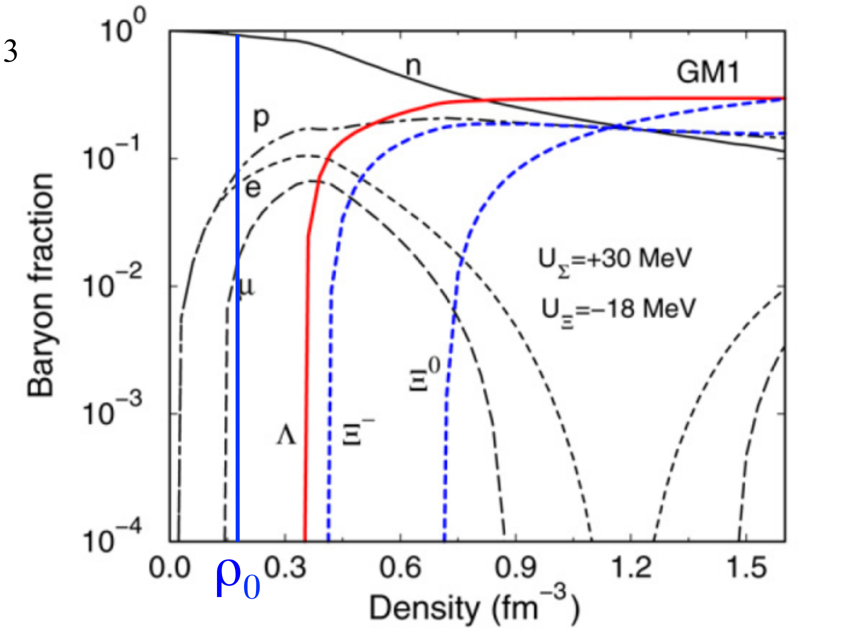
Fermi energy: $\varepsilon_F = \frac{\hbar^2}{2m_B}\left(3\pi^2\rho\right)^{2/3}$

$$\mu_Y = m_Y + \varepsilon_F^{(Y)} \qquad \mu_n = m_n + \varepsilon_F^{(n)}$$



m_Λ-m_n=175 MeV

$$\Rightarrow \rho_{\mathrm{th}}(\Lambda) \approx 2\rho_0$$



J.Schaffner-Bielich, NPA804(2008)309

In reality:

$$\mu_n = m_n + \varepsilon_F^{(n)} + U_n(k_F^{(n)})$$
$$\mu_Y = m_Y + \varepsilon_F^{(Y)} + U_Y(k_F^{(Y)})$$

← Should be determined.

YY, YN, YNN Interactions (in high density neutron matter) Essential!

N.B. For two(or more) kinds of Fermions ρ → $\rho = \rho_n + \rho_\Lambda + \ldots$ → **Lower <E>** Kinetic energy

Hyperons in NS→ **Softening of EOS**

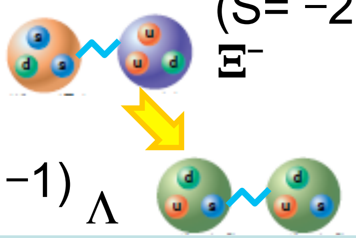
→How to solve 2M⊙ puzzle?→3-Body force (YNN, YYY) ?

Baryon-baryon interaction with multi-strangeness

T.Takahashi (KEK)
Nakazawa(Gifu U.) et al.

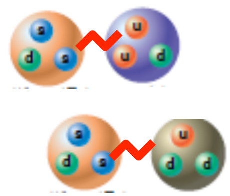
ΞN→ΛΛ Conversion

(S= −2)

p  Ξ^-

(S= −1) Λ

ΞN interaction



Ξ^0

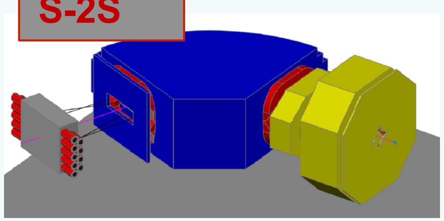
ΛΛ interaction

Λ

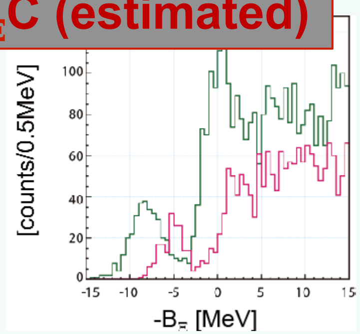
EOS at high−density region

Spectroscopy of Ξ hypernuclei

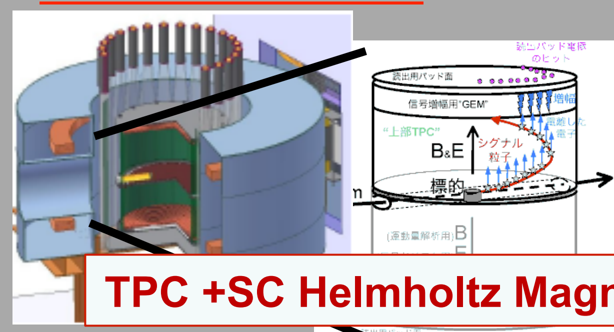
S-2S



$^{12}_{\Xi}$C (estimated)

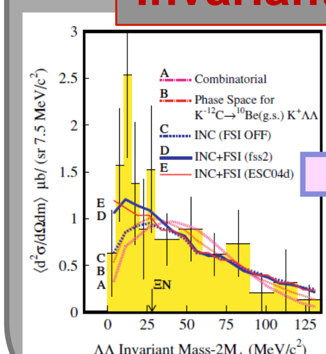


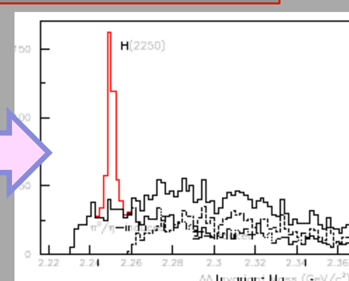
Search for H and Study of ΛΛ correlation



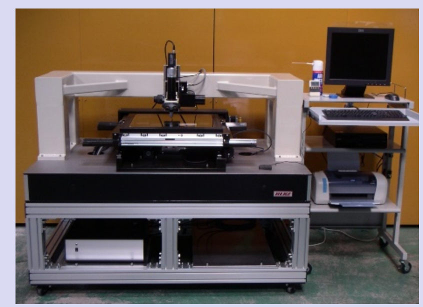
TPC +SC Helmholtz Magnet

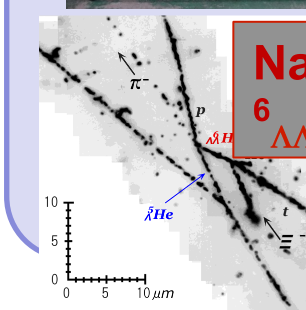
Invariant mass of ΛΛ





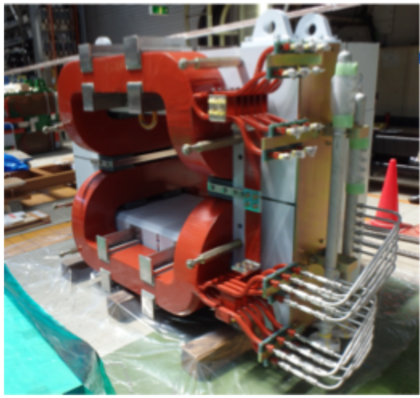
Emulsion experiments & Automatic scanning





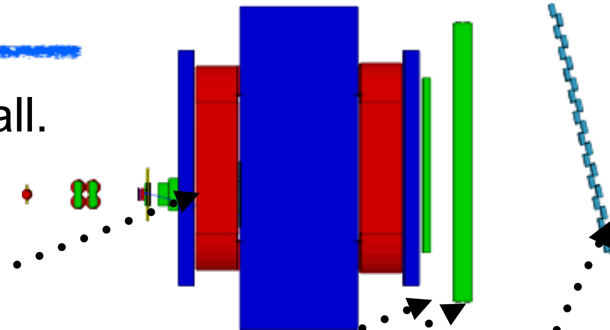
Nagara Event
$^{6}_{\Lambda\Lambda}$He

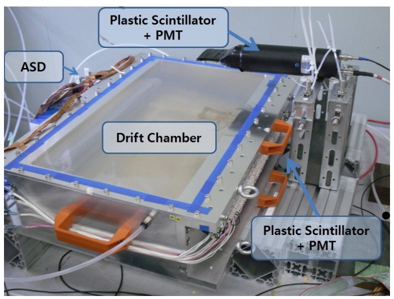
KURAMA spectrometer as a tagger of the (K^-,K^+) reaction for emulsion and H search exp.



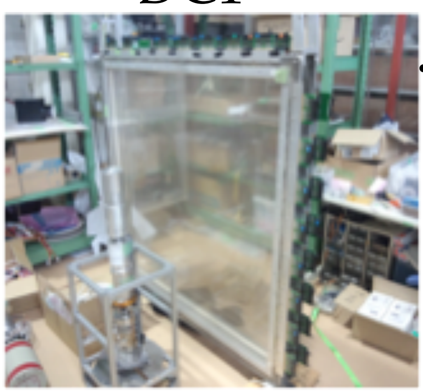
KURAMA magnet

Most of the detectors are ready to install.
(waiting for beam time allocation)





DC1



KL chamber

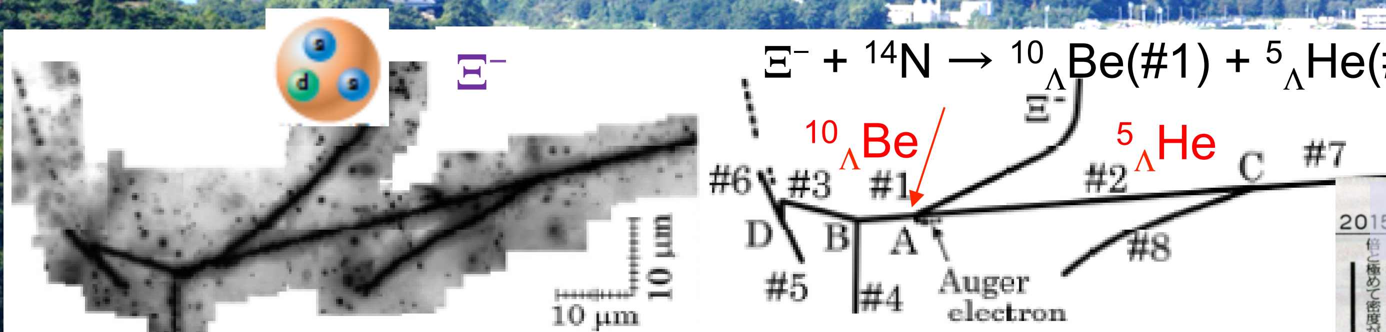
AIDA chamber

TOF wall

Discovery of Ξ-nucleus for the first time
– KISO Event – K.Nakazawa et al.(PTEP in Press)

In the test application of Overall Scanning Method, to the emulsion sample irradiated before, we found the event in which Ξ^- is deeply bound in ^{14}N. →This is the first evidence of Ξ-nucleus

ΞN interaction is attractive



$$\Xi^- + {}^{14}N \rightarrow {}^{10}_{\Lambda}Be(\#1) + {}^{5}_{\Lambda}He(\#2)$$

<u>Binding energy of Ξ^-</u>

> 1.11±0.25 MeV c.f. 0.17 MeV（atomic orbit）

4.38±0.25MeV if $^{10}_{\Lambda}$Be is in ground state.

E07 will be carried out in 2016 to find ~100 double-strangeness events by both Hybrid method and overall scanning method.

Newpaper（2015/1/19）

岐大、宇宙創生の謎に一歩

中性子星に「グザイ」存在

岐阜大の仲沢和馬教授（実験物理学）と日本原子力研究開発機構（茨城県）などのグループは、恒星の最終形態である中性子星に含まれていると推定されている素粒子「グザイ」の性質を解明した。中性子星にグザイが存在することをほぼ確定する成果で、宇宙創生の秘密に迫る一歩として注目される。（松野穂波）

仲沢和馬教授

結果は、日本物理学会などがインターネットで発表する学術論文誌に近く掲載される。

中性子星は、寿命が尽きた恒星が爆発した後に残る星。大きさは太陽の百万分の一程度だが、質量は約二倍と極めて密度が高い。このため、素粒子のうち陽子や中性子より重い「ラムダ」「シグマ」「グザイ」のいずれかが存在すると考えられた。

仲沢教授は二〇〇一年、通常は陽子と中性子でできている原子核に、ラムダを結合した超原子核を作製。陽子、中性子とラムダが結び付くことが分かり、中性子星に存在する可能性が高まった。シグマは原子核と反発する関係と判明し、残るグザイの性質を解き明かすことが、中性子星を知る最後の鍵と位置付けられていた。グザイは、中性子星より低密度の地球では百億分の一秒で崩壊してしまうため、地球上に存在しないとみられる。このため、仲沢教授らは高エネルギー加速器研究機構（茨城県）で、K中間子という粒子の放射線をダイヤモンドに照射することで、人工的にグザイ粒子を生成。特殊な写真乾板に当てて顕微鏡で撮影した。約八百万枚の画像を分析した結果、窒素の原子核にグザイが吸収された超原子核を発見した。

超原子核内の引力を測定すると、原子核とグザイが互いの電磁力の三十倍の強さで引き合っていた。グザ

中性子星

大きさは太陽の100万分の1だが重さは2個分

重い素粒子が存在?

太陽 太陽

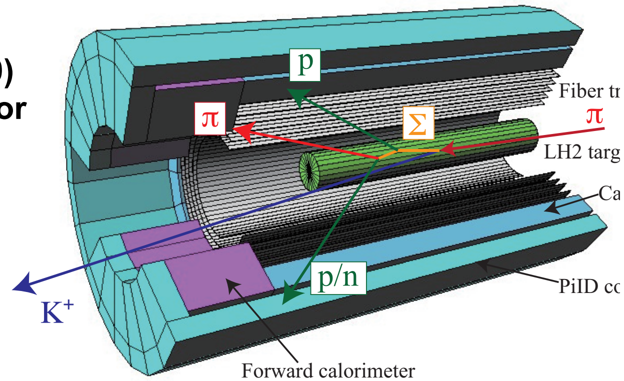
○=陽子 △=中性子 ●=グザイ、ラムダなどの重い素粒子

Strangeness in n-rich matter

H.Tamura,Miwa,Koike(Tohoku U.)
Sakaguchi(Osaka U.), Outa (RIKEN)
et al.

Determine hyperon mixing in ρ=2~3ρ_0 region where hyperons begin to appear

Ultra-fast (x100) Tracking detector Using MPPC

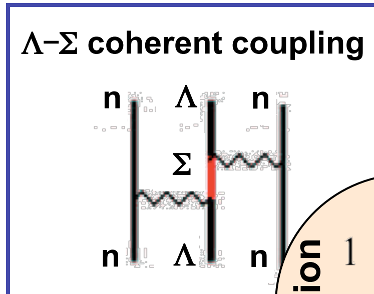


(1) Σ^+p scattering (unique) **Miwa, Tamura**

E40

-> Σ^-n (= Σ^+p) int.

=> Σ^- exists in n-star or not



(2a) γ spectroscopy of Λ hypernuclei **E13**

(Unique method) **Koike, Tamura**

-> Details of ΛN, ΛNN int.

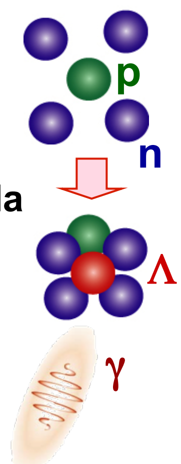
(2b) n-rich hypernuclei **E10**

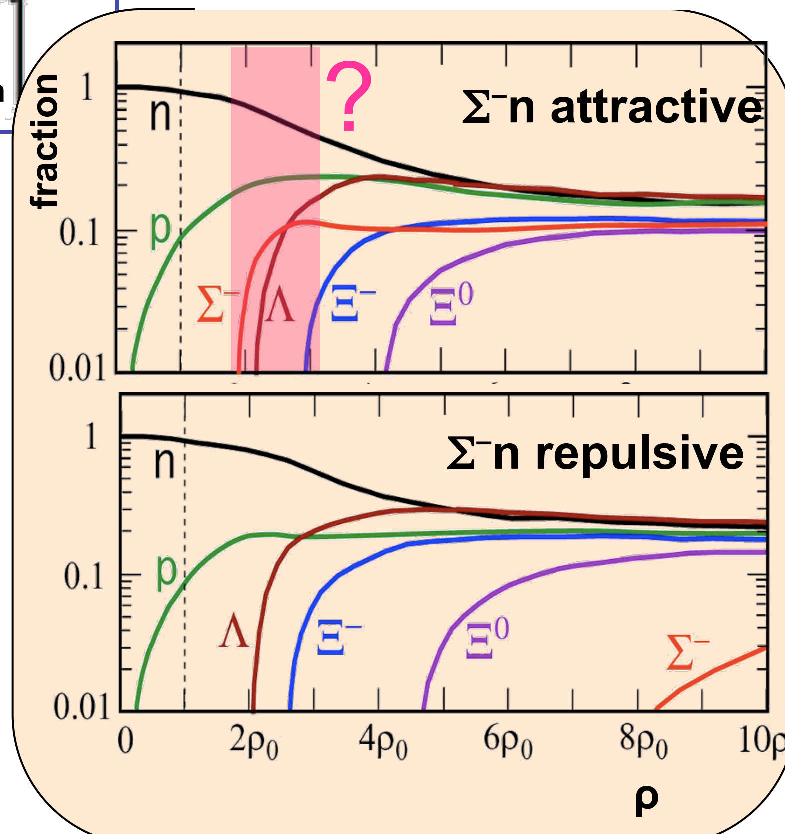
(Unique method) **Sakaguchi, Ajimura, Fukuda**

-> Λnn int. in n-rich environment

=> Fraction of Λ in n-star

Search for $^6_\Lambda$H: Not observed in (π^-,K^+)
Sugimura et al. PLB729 (2014) 39.



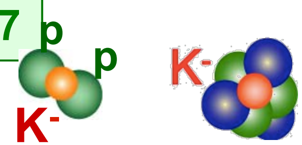


(3) K⁻ nuclear bound states **Outa, Suzuki**

E15, E27

-> K^{bar}N int. in matter

=> K condensation in n star?

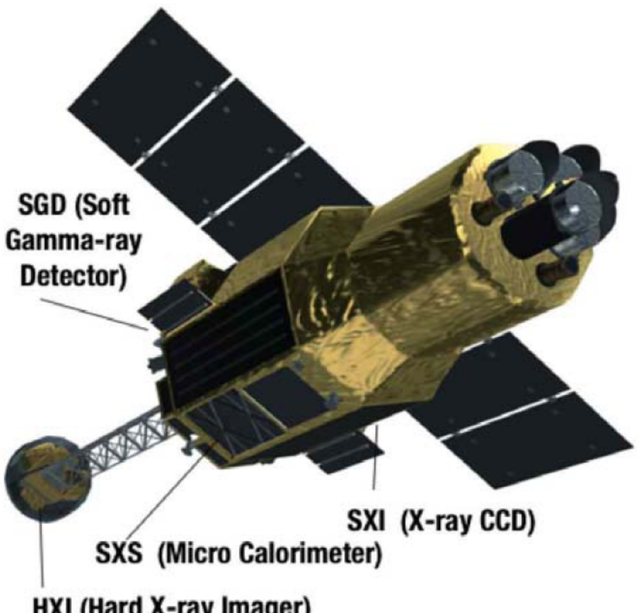


New development of Research on Neutron Stars by X- and Gamma-Rays Observatory

T. Takahashi(JAXA), T. Tamagawa (RIKEN),
T. Dotani(JAXA), M.Tsujimoto(JAXA), S. Miyazaki (NAO)

Direct observation of Radius of N-Star by ASTRO-H (2015)

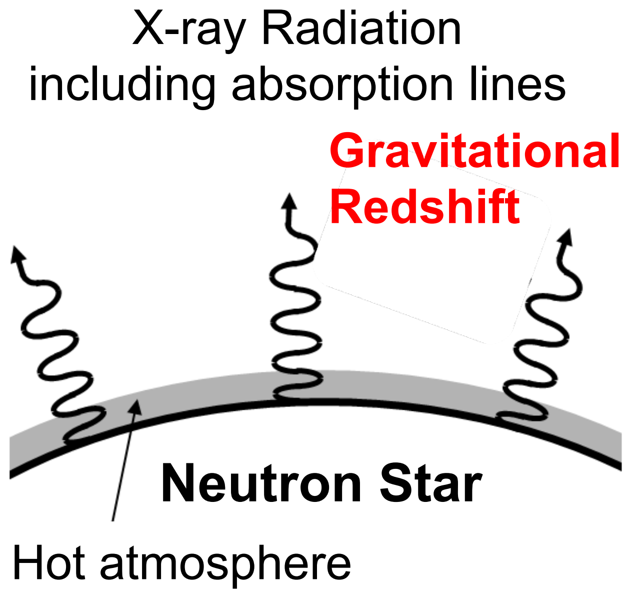
→Gravitational Redshift of narrow absorption lines of heavy elements in the X-ray burst --- Sensitive to R/M of Neutron Star (NS)

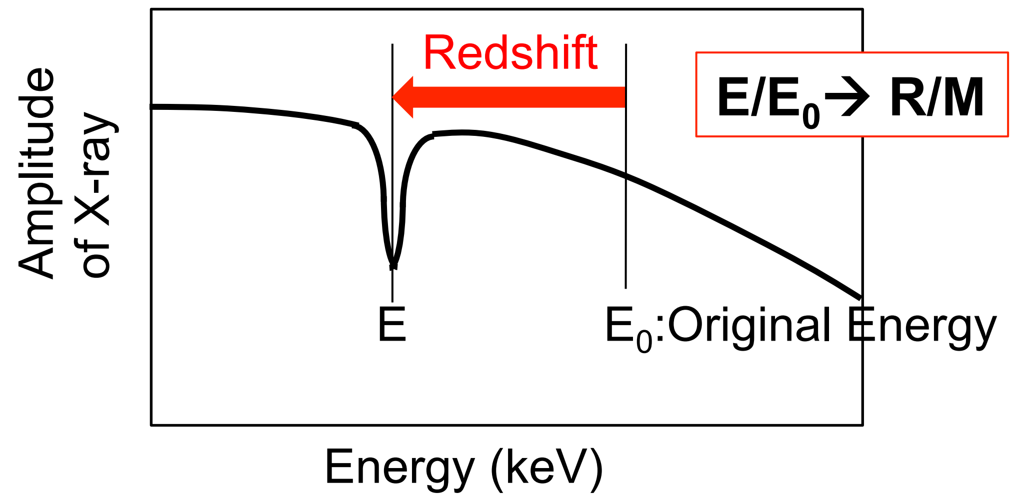


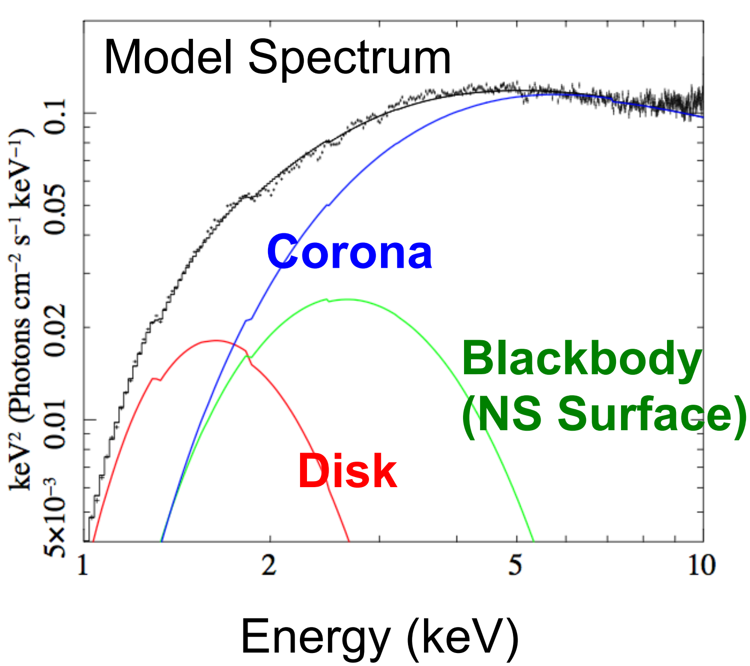
Soft X-ray Spectrometer (SXS)
-- Micro Calorimeter Spectrometer

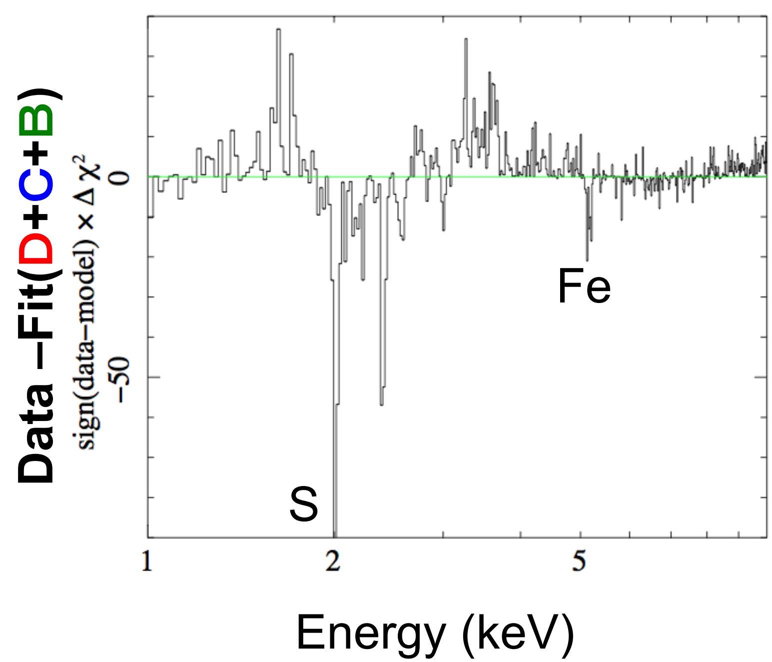
T. Takahashi et al., Proc. SPIE Int. Soc. Opt. Eng. 8443 (2012) 1Z

Expected Redshift Spectrum



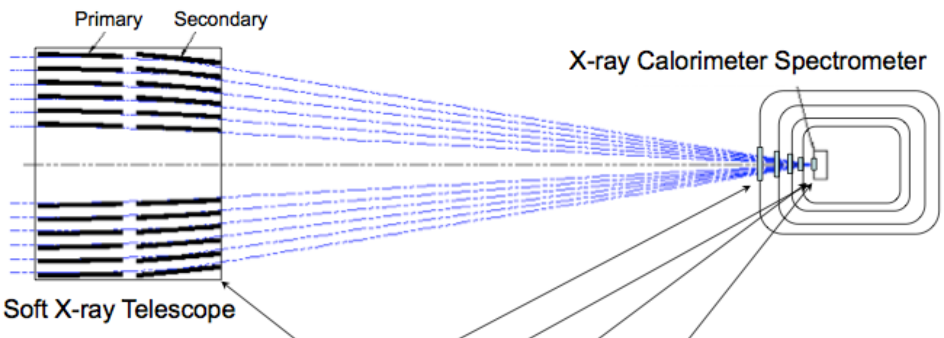






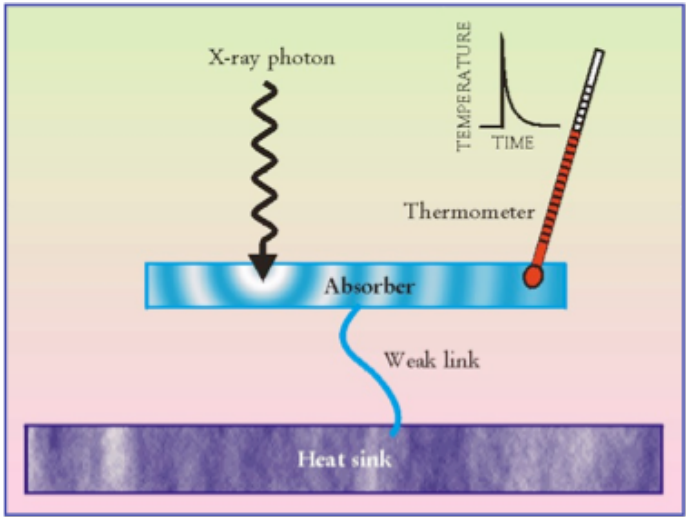
Micro-calorimeter and Dewar

Slide by
T.Takahashi(JAXA)

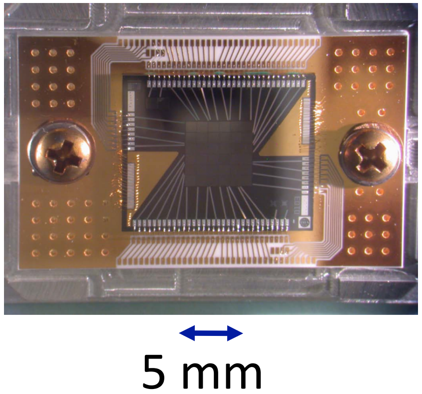


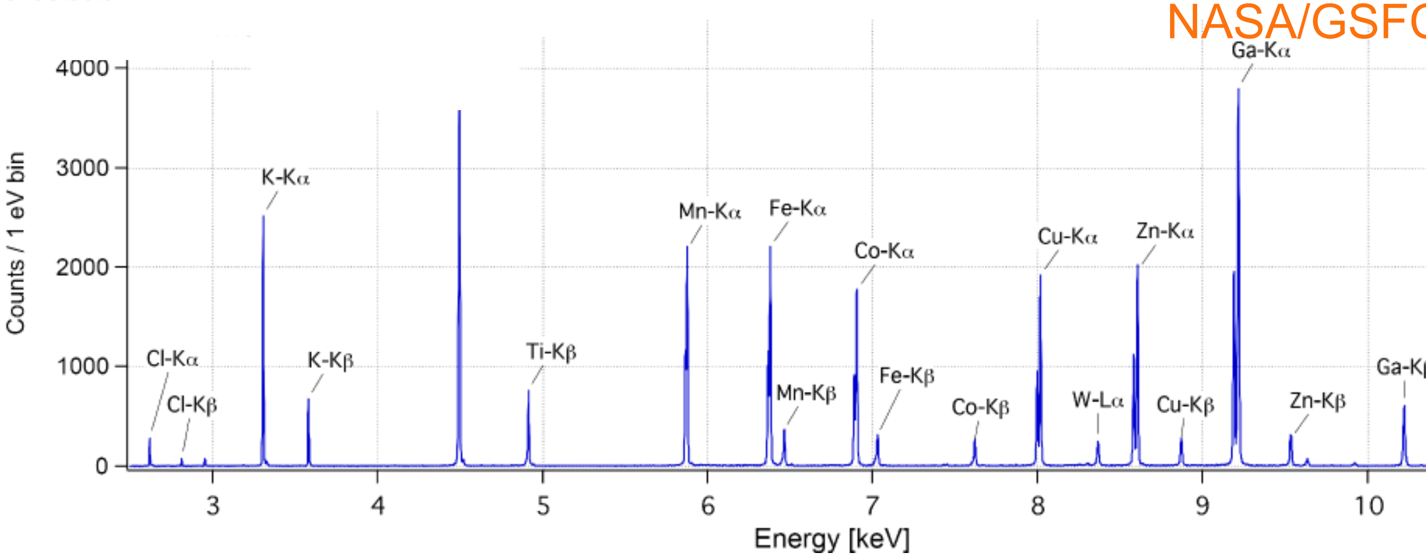
$$A_{eff}(E) = A_{XRT}(E) * t(E) * psf * f_{array} * a(E)$$

t = transmission of blocking filters
psf = x-ray image point spread function
f_{array} = geometric filling factor of array
a = absorption efficiency of detector



NASA/GSFC

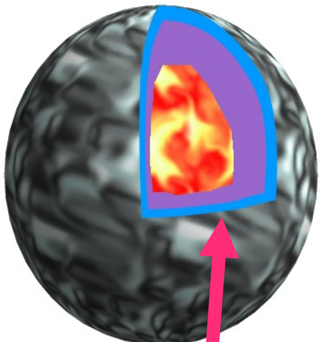


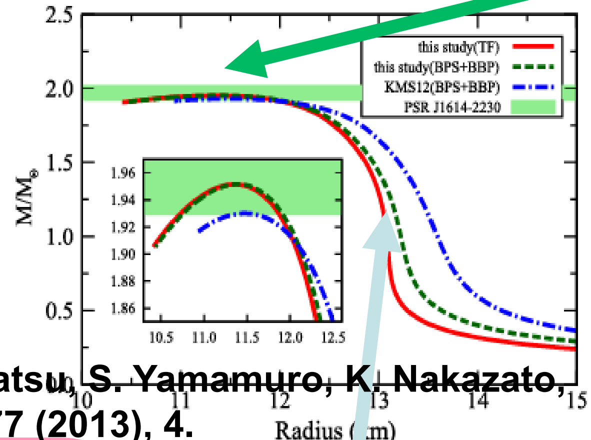


(Takahashi et al., 2012, SPIE, 8443, 1)

Theoretical studies of neutron star and nuclear matter (A.Ohnishi, K. Morita et al.)

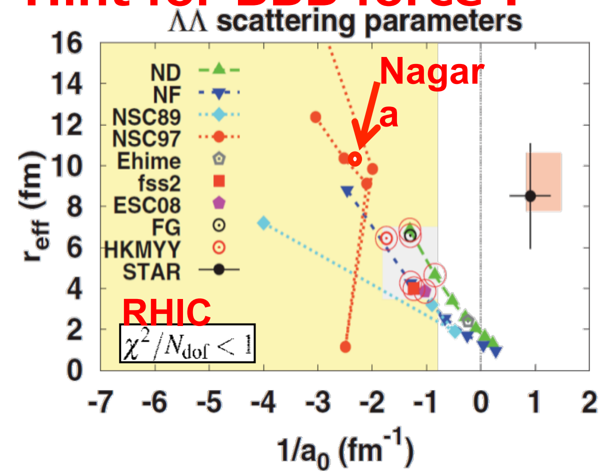
- Construction of NS matter EOS
  Understanding NS phenomena



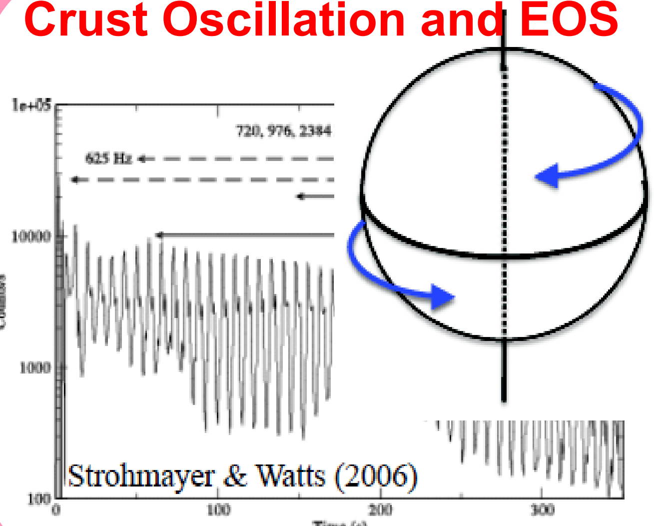


T. Miyatsu, S. Yamamuro, K. Nakazato, ApJ 777 (2013), 4.

Hint for BBB force ?

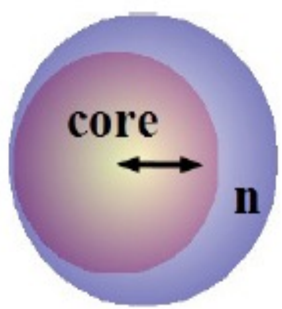


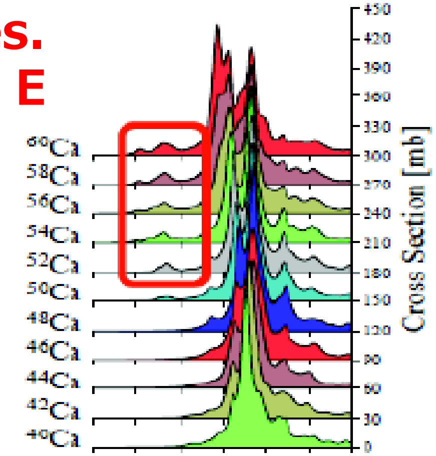
Crust Oscillation and EOS



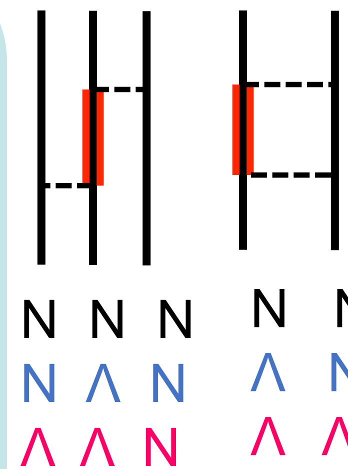
H. Sotani, K.Nakazato, K. Iida, K. Oyamatsu, Mon. Not. Roy. Astron. Soc. 434 (2013), 2060

Pygmy res. and Sym. E





T. Inakura, T. Nakatsukasa, K. Yabana, PRC84 (2011) 021302



K. Morita, T. Furumoto, A. Ohnishi PRC91 (2015), 024916.

→ Talk by K.Morita (Mar.4)

Summary

Neutron-rich Nuclei

- Neutron Skin Thickness
- Pygmy Dipole Resonance
- Giant Monopole Resonance
- Many-Body correlation

(superfluidity, 3N)

- Nuclear Force
- Nuclear Masses
- Heavy Ion Collisions
- Mean Field Theory

Cold Fermi Gas
EOS at very low dense limit

Hypernuclei/Hyperons

Λ (S= −1)
$\Sigma^+, \Sigma^-, \Sigma^0$ (S= −1)
Ξ^+, Ξ^-, Ξ^0 (S= −2)

- Structure of Hypernuclei
- Scattering of Hyperons
- Interactions of Hyperons

EOS of Asymmetric Nuclear Matter/ Hyperons

Neutron Star

Bulk Property (Radius, Mass)
Superfluidity, Glitch
Composition, Quark/Strangeness Phase
Gravitational Wave

Neutron Star Matter

Theories

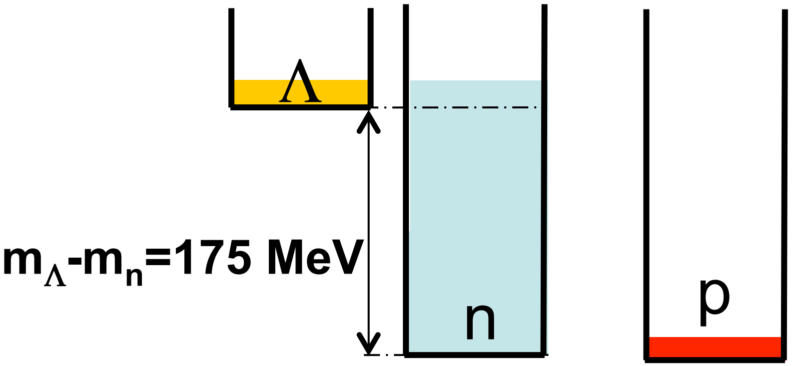
Special Thanks to Colleagues in

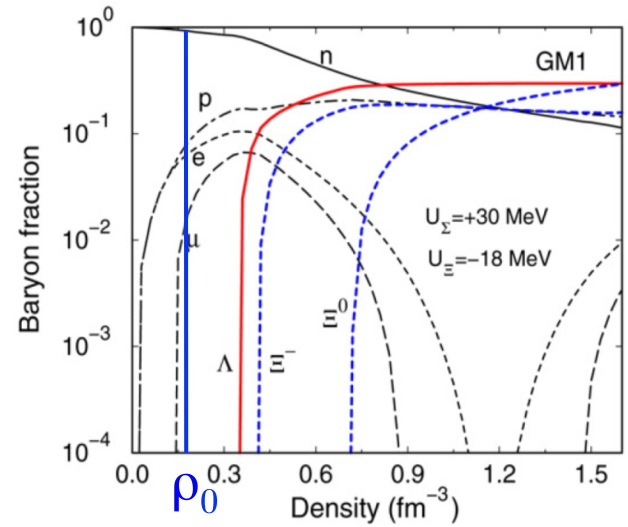
Grant-in-aid for innovative area:
" Nuclear Matter in neutron Stars investigated by experiments and astronomical observations"

H. Tamura (Tohoku U.)
T.Takahashi (KEK), T.Murakami(Kyoto U.),
T. Nakamura(Tokyo Tech), S.Horikoshi(Tokyo.U),
T. Takahashi(JAXA),A.Ohnishi(YITP)

Some Remarks

$$\varepsilon_F = \left(3\pi^2\rho\right)^{2/3}$$



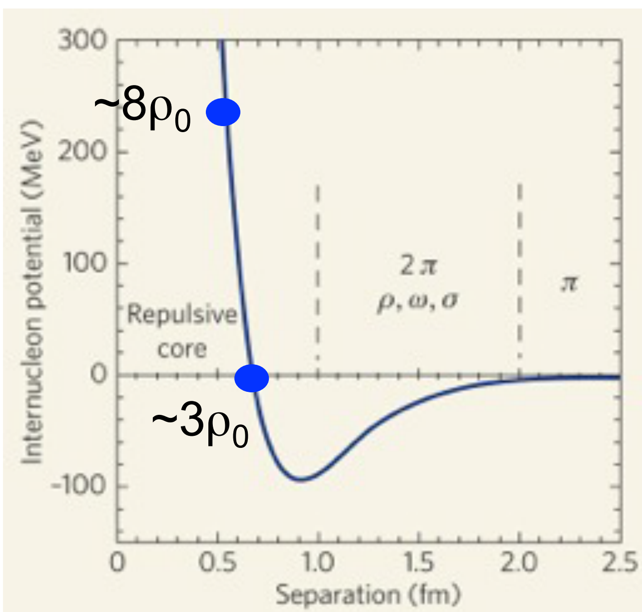


High-momentum **n** ⟺ **Interaction?** ⟺ **Low**-momentum **p, Λ …**

$$d \propto 1/\rho^{1/3}$$

separation

$3\rho_0 \rightarrow 0.7d_0$
$8\rho_0 \rightarrow 0.5d_0$



How such interactions with large asymmetry in momenta are understood?

3-Body Forces?
NNN,YNN,YYY in dense N matter?

QCD has an answer?