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”

-- Aim of the project—

Tohoku Univ.
H. Tamura

Mistery of neutron star matter

- **Final form of matter evolution in the universe**

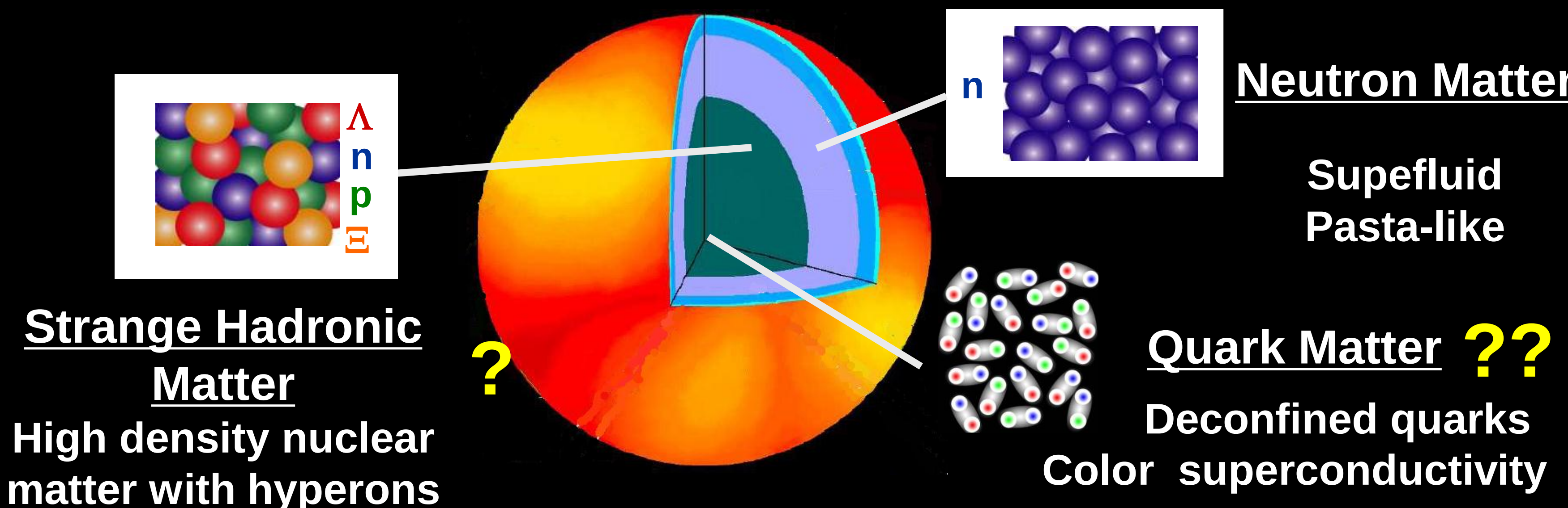
  Produced by supernova explosion, Observed as X-ray pulsars

- **Highest density matter in the universe**

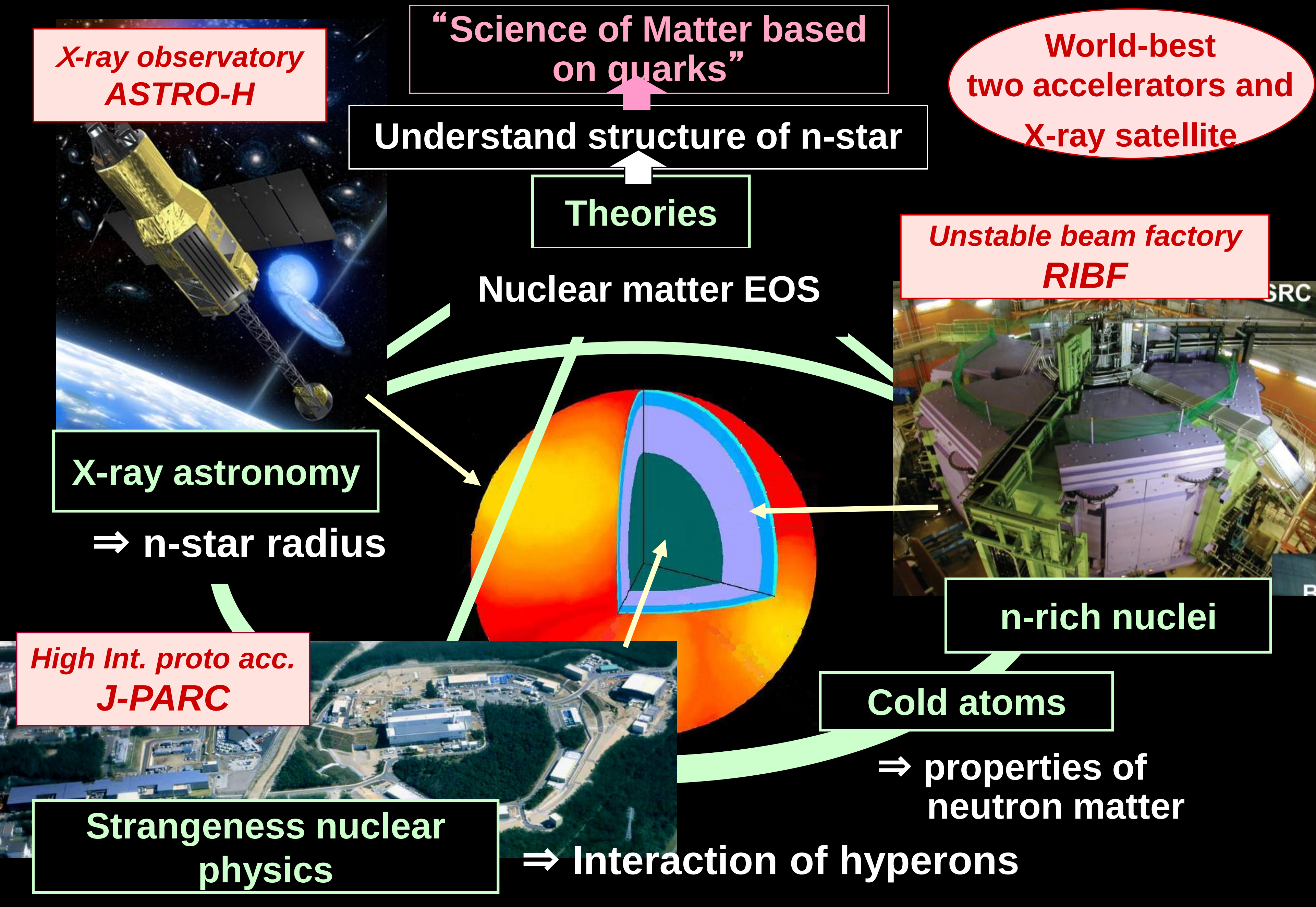
  M = 1~2 $M_{\odot}$, R ~ around 10 km?

  => Density of the core = $3\sim10\rho_0$ (1〜3 Btons/cm^3)

- **Various forms of matter made of quarks only**



Joint project between experiments, observations, theories



Joint project between experiments, observations, theories

"Science of Matter based on quarks"

Understand structure of n-star

Theories

World-best two accelerators and X-ray satellite

X-ray observatory
ASTRO-H

X-ray astronomy

⇒ n-star radius

Nuclear matter EOS

No collaboration before

Unstable beam factory
RIBF

n-rich nuclei

Cold atoms

⇒ properties of neutron matter

High Int. proto acc.
J-PARC

Strangeness nuclear physics

⇒ Interaction of hyperons

"Science of Matter made of only Quarks

Matter made of electrons and quarks(nuclei)

Atomic matter

Matter on the Earth

- "Atomic/molecular physic"
- "Condensed matter physics"
- "Chemistry"

Plasma

Matter in the Stars

"Plasma physics"

Electron (+ Nuclei) and Electromagnetic Interaction

Matter made of only quarks

Matter in neutron stars

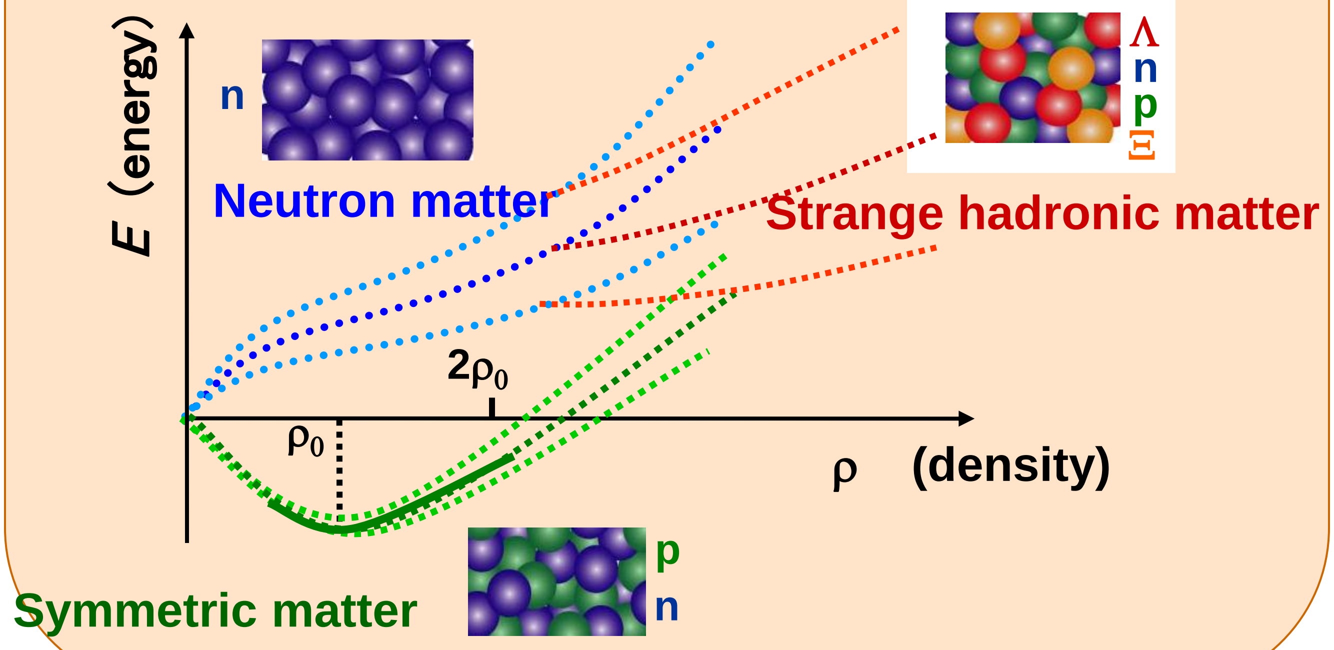
"Nuclear physics" → "Physic of quark's matter"

Quarks (Hadrons) and Strong Interaction

Nuclear Matter Equation Of State

Density Fraction

$E = F(\rho, (n_n, n_p, n_Y))$



EOS ➡ inner structure of n-stars

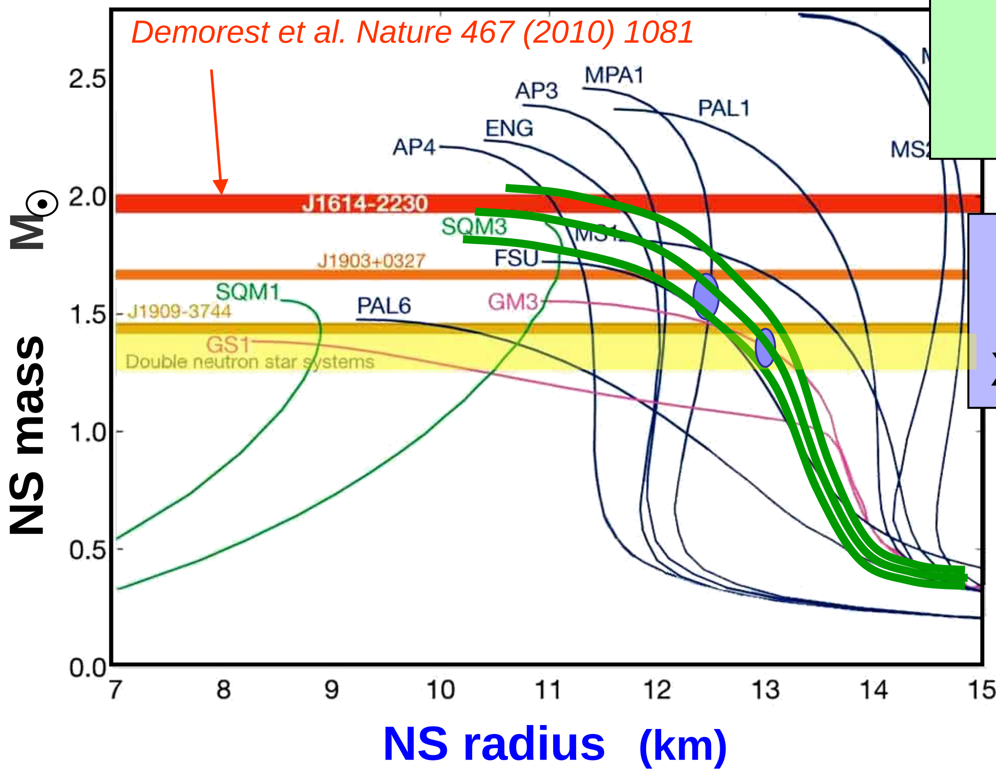
Why do we combine experiments on earth and observation in space?

Nuclear Matter EOS

$E = F(\rho, (n_n, n_p, n_Y))$

Uniquely (gravity-pressure balance)

Mass-Radius relation



No direct measurement

Info. on nuclear matter from experiments on the earth + theories → **Selection of EOS**

+

Measurement of radius by X-ray observatory → **Confirmation of EOS**

Determination of EOS

+ Confirmation of theoretical framework
+ Existence of quark matter

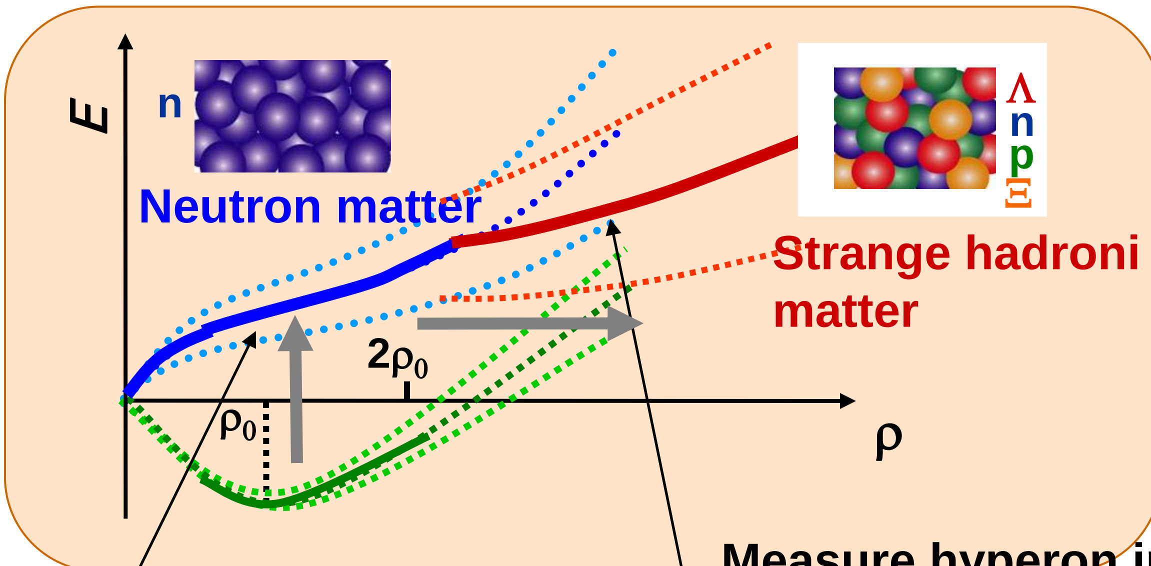
Selection of EOS from experiments on the earth

■ **Outer core ($\rho < 2\rho_0$)**

How EOS changes in n-rich matter?

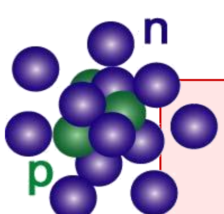
■ **Inner core ($\rho > 2\rho_0$)**

Hyperon really appear? Which and how much?



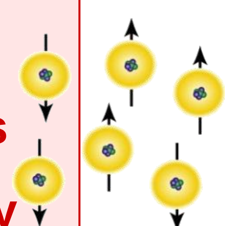
Directly determine neutron matter EOS

Measure hyperon interaction for input of EOS



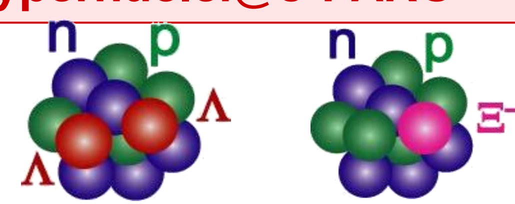
Group B

n-rich nuclei@RIBF
+
Ultra-cold Fermi gas
Study experimentally

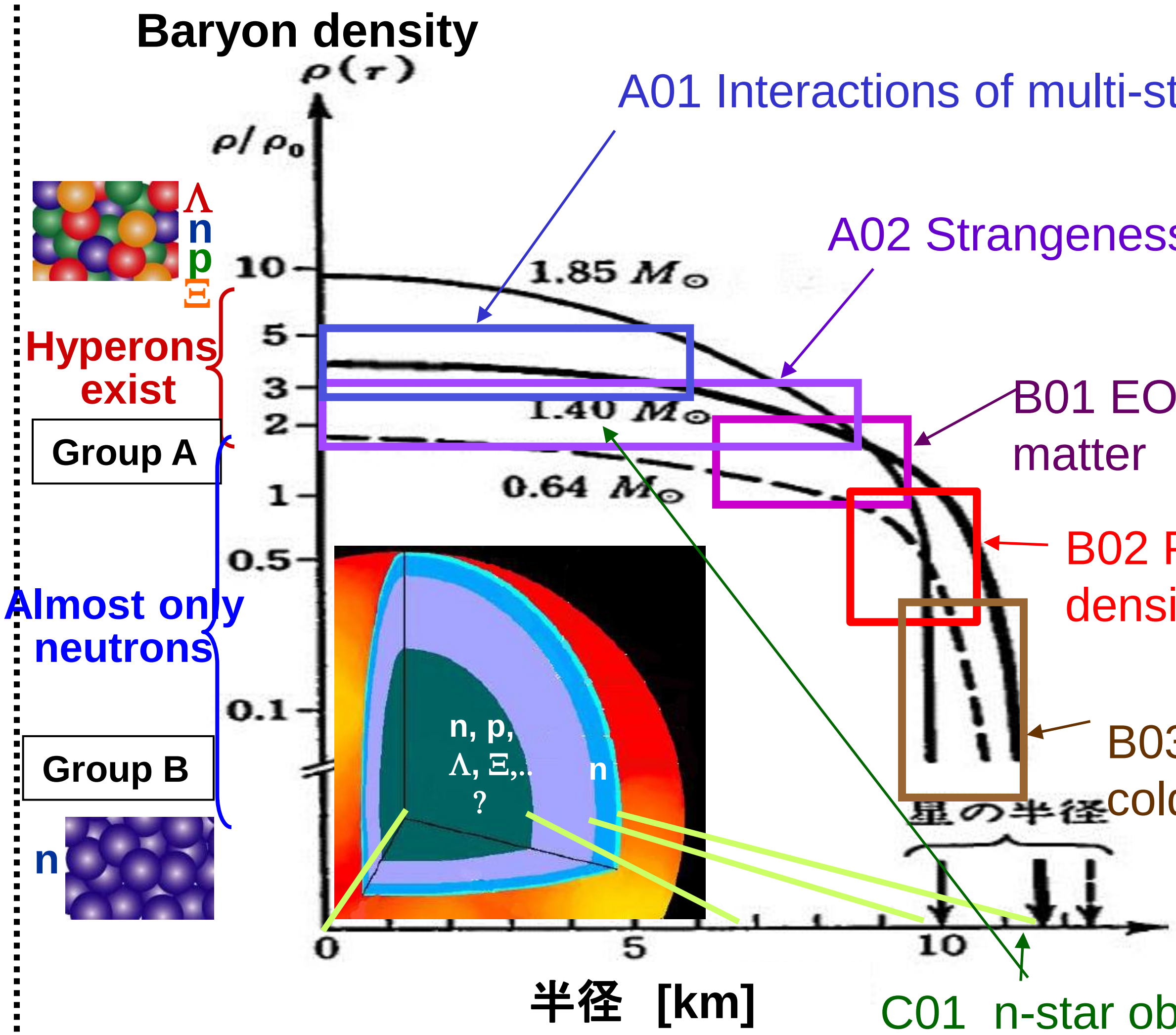


Experimentally study from hypernuclei@J-PARC

Group A



Groups and research subjects



A01 Interactions of multi-strangeness systems

T.Takahashi (KEK)

A02 Strangeness in n-rich matter

H.Tamura(Tohoku)

Group A

B01 EOS of high density n-rich matter

T.Murakami (Kyoto)

B02 Properties of medium/low density n-rich matter

T.Nakamura (TIT)

B03 EOS of thin n-matter from cold atoms

S.Horikoshi (U.Tokyo)

Group B

C01 n-star observation using X–rays and γ-rays

T.Takahashi(JAXA)

Group C

D01 Theoretical studies on n-star matter

A.Onishi (Kyoto)

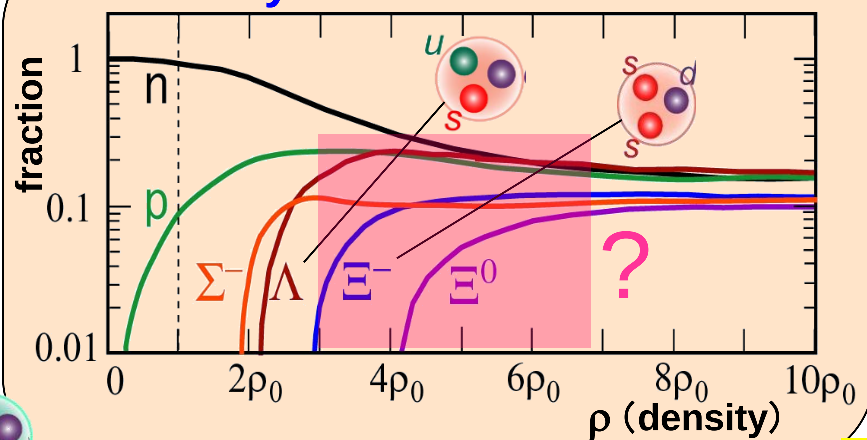
Group D

A01: Interactions of multi-strangeness systems

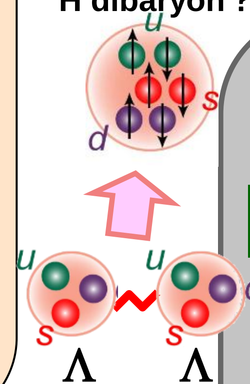
Determine hyperon mixing in the inner core (ρ > 3ρ$_0$)

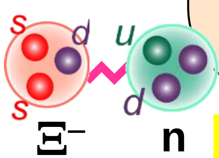
→ EOS of high density matter

Baryon fraction



H dibaryon？





ΞN int.

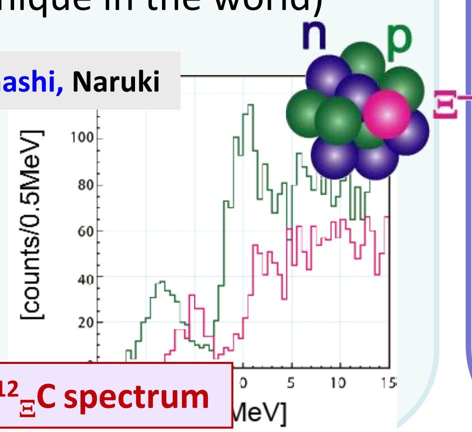
ΞN→ΛΛ int.

ΛΛ int.

Ξ hypernuclear spetrocopy

E05 (Unique in the world)

Takahashi, Naruki

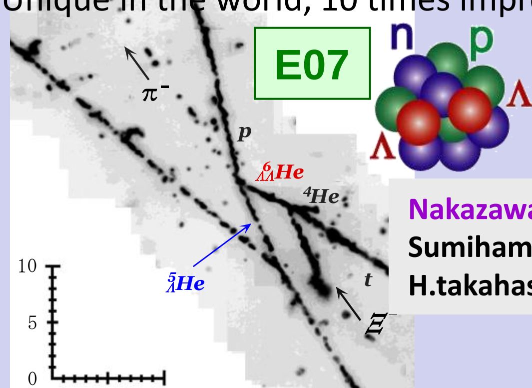


Expected $^{12}{}_{\Xi}$C spectrum

ΛΛ nuclei from emulsion

(Unique in the world, 10 times improved)

E07



Nakazawa、Sumihama H.takahashi

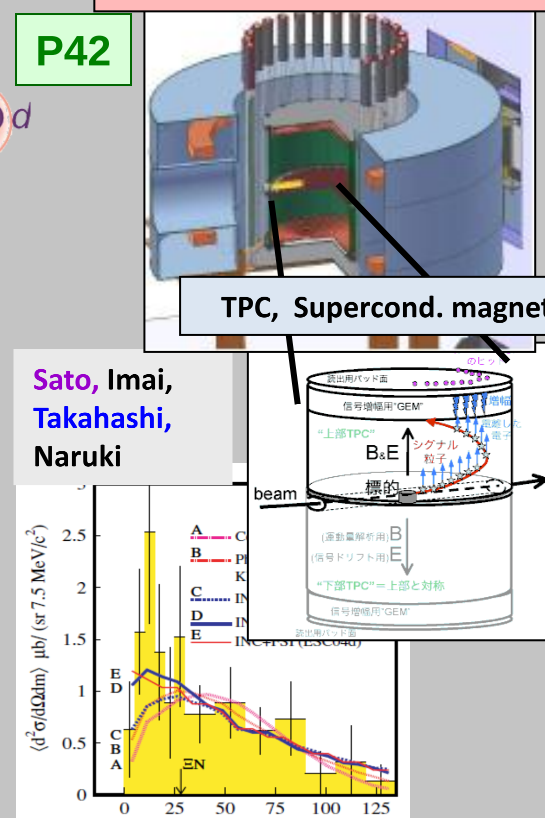
$^{6}{}_{\Lambda\Lambda}$He hypernucleus

ΛΛ correlation

(Unique in te world)

Hyperon decay spectrometer

P42



Sato, Imai, Takahashi, Naruki

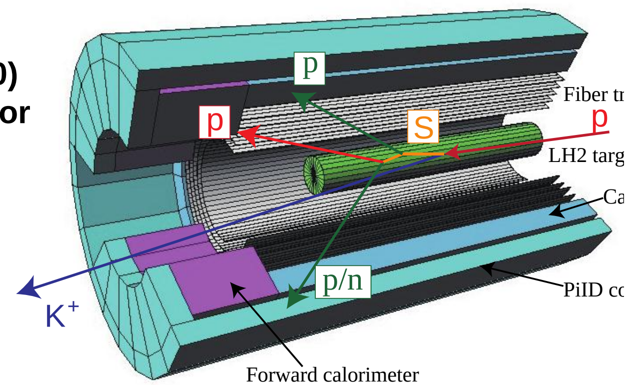
Peak in ΛΛ invariant mass

A02: Strangeness in n-rich matter

Sattered proton detector

Determine hyperon mixing in $\rho=2\sim3\rho_0$ region whre hyperons begin to appear

Ultra-fast (x100) Tracking detector Using MPPC

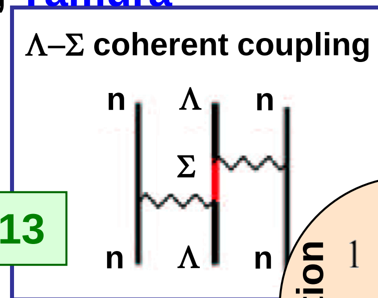


(1) Σ^+p scattering (unique) Miwa, Tamura

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.

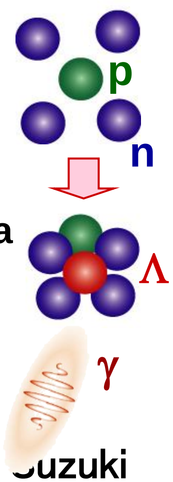
E10

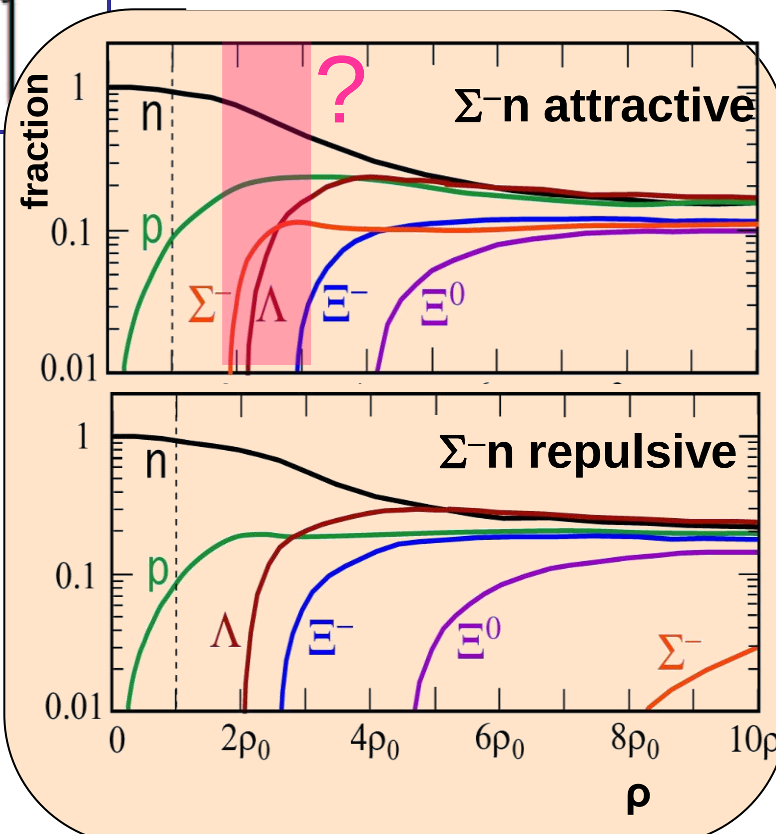
(2b) n-rich hypernuclei

(Unique method) Sakaguchi, Ajimura, Fukuda

-> Λnn int. in n-rich environment

=> Fraction of Λ in n-star



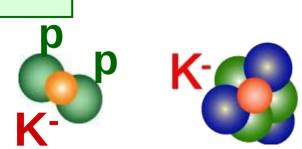


(3) K^- nuclear bound states Outa,, Suzuki

E15, E27

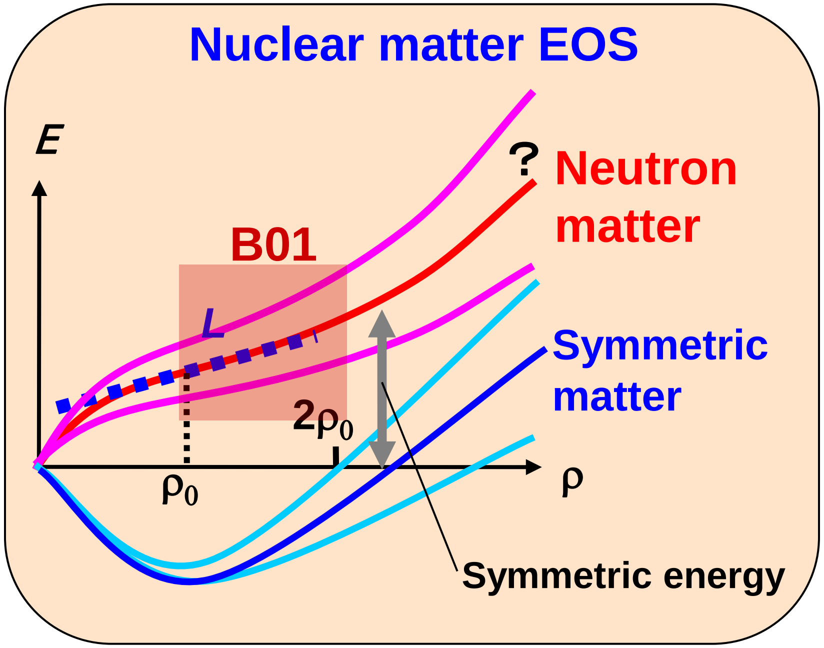
-> $K^{bar}N$ int. in matter

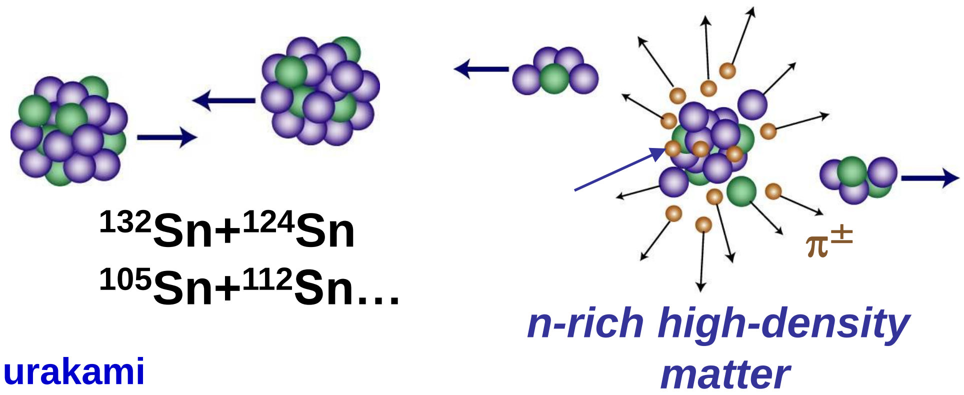
=> K condensation in n star?



B01: EOS of high-density n-rich matter

Density dependence of symmetric energy in $\rho \sim 2\rho_0$ region

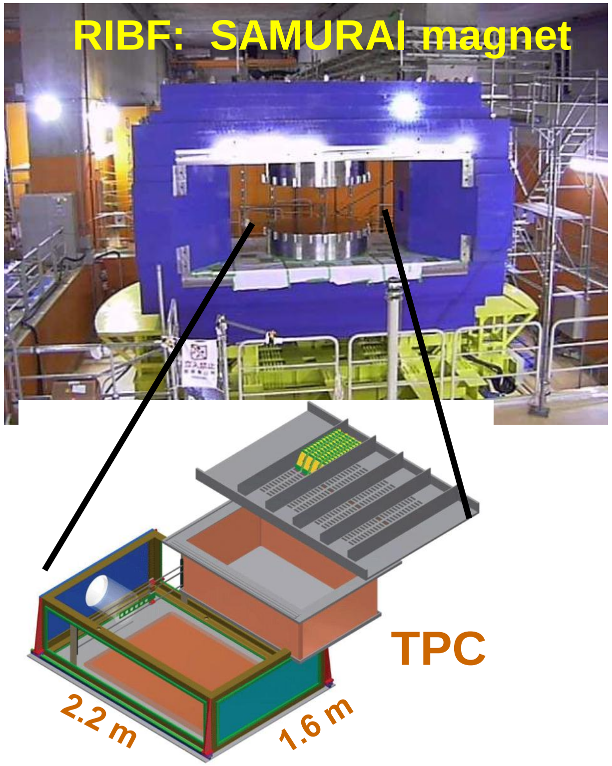




Murakami

Kawabata, Isobe, Ieki

Taketani, Mizoi, Kurita, Baba



Develop new detectors

TPC and readout systems
Forward calorimeter
Silicon multiplicity detector

⇩

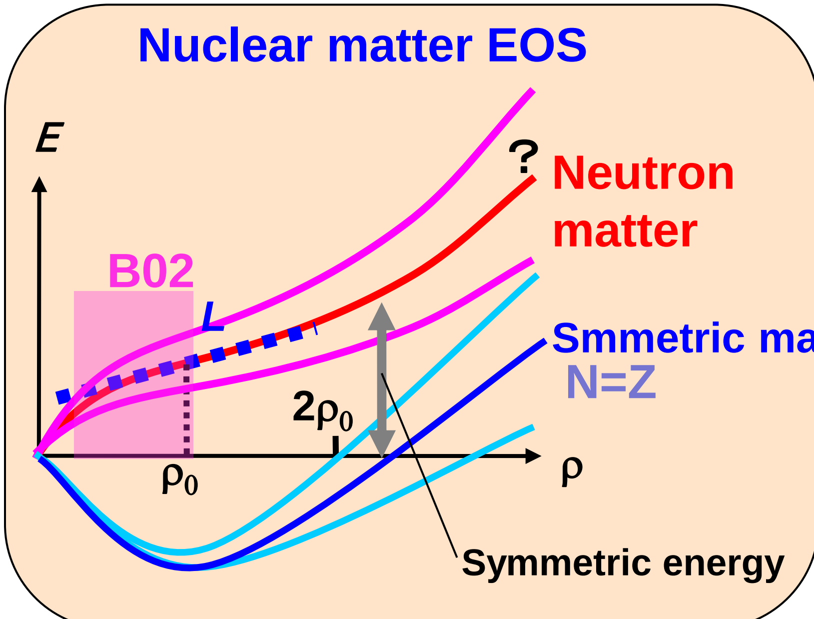
Measure π^+/π^- yields from A-A collisions of various nuclei with various proton/neutron ratios

⇩

Information on symmetric energy for $\rho \sim 2\rho_0$ region

B02: Properties of low/medium density n-rich matter

Determined EOS in $\rho < \rho_0$ region

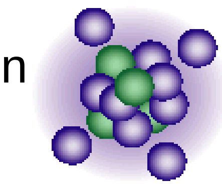


Reaction of n-rich nuclei with RI beams

Nakamura, Shimoura, Kondo, Teranishi

① response of n-skin nuclei

n-skin

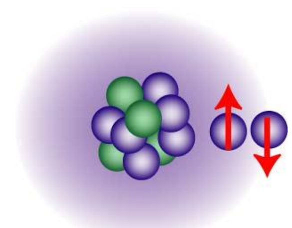


Pigmy dipole resonance
Density oscillation (E0)

Pressure, incompressibility of EOS for n-rich matter

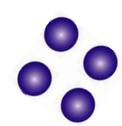
γ calorimeter

② Di-neutron correlation in thin neutron matter



Superfluid in n-star

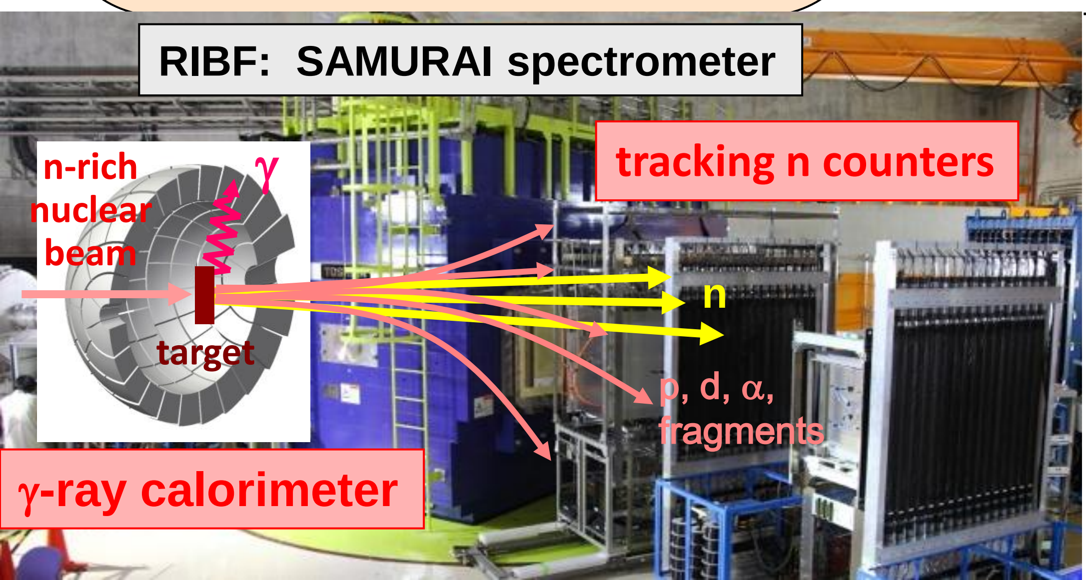
③ n-rich multi-nucleon systems



4n

Nuclear force for n-rich Systems (isospin dep.)

Neutron tracking detector

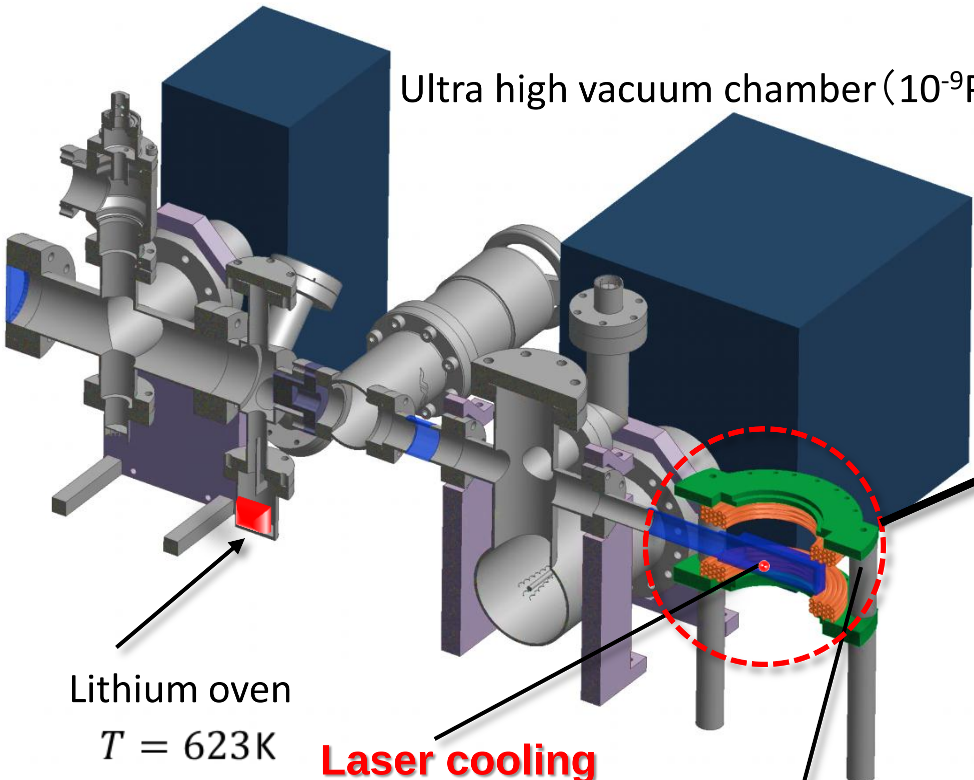


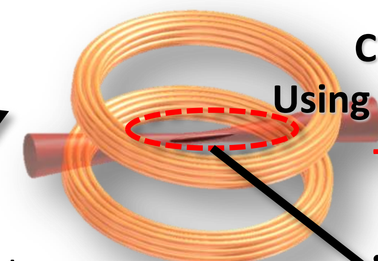
B03: EOS of thin n-matter from cold atoms

Universal func. $h(\tau,\xi)$ as a function of $\tau = T/T_F$ $\xi = 1/(k_F a)$

Horikoshi, Mukaiyama,
Mizushima, Nakatsukasa

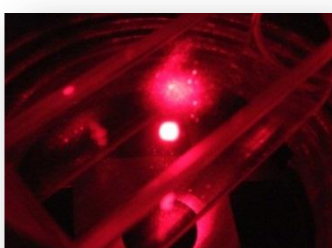
inner crust region：
~$0.5\rho_0$， a=－18.5 fm
=> ξ=－0.04～－0.280





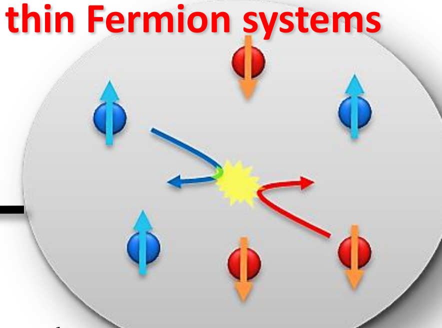
Experimental simulation of
Strongly interacting (with a short int. range) thin Fermion systems

**Laser-cooled
Ultra-cold
Fermi gas (^{6}Li)**



$N = 10^8, T \sim 1\mu\text{K}$

EOS
Gap energy



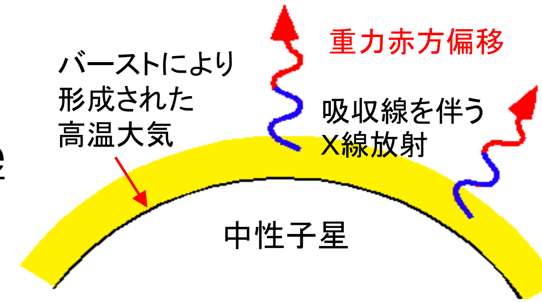
Control interaction strength

- ***BCS-BEC crossover***
- ***Finite density effect***
- ***P-wave interactions***

C01: Innovative X-ray astronomy

Takahashi, Tamagawa, Dotani, Tsujimoto, Miyazaki

Precise measurement of n-star radius using new-generation X-ray telescopes



(1) Red shift of absorption lines of in X-ray burst

(2) Quasi-Periodic Oscillation (QPO) from n-star surface

(3) Polarized X-ray pulse from n-star

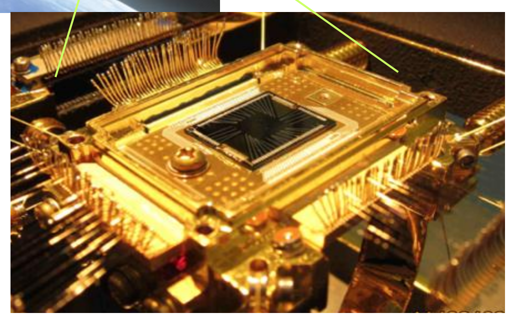
ASTRO-H (JAXA, 2014~)

+

X-ray calorimeter

Resolution improved by 2 order

GEMS (NASA, 2014~) pol. X-ray det.



(4) R&D for new-generation X–ray detectors

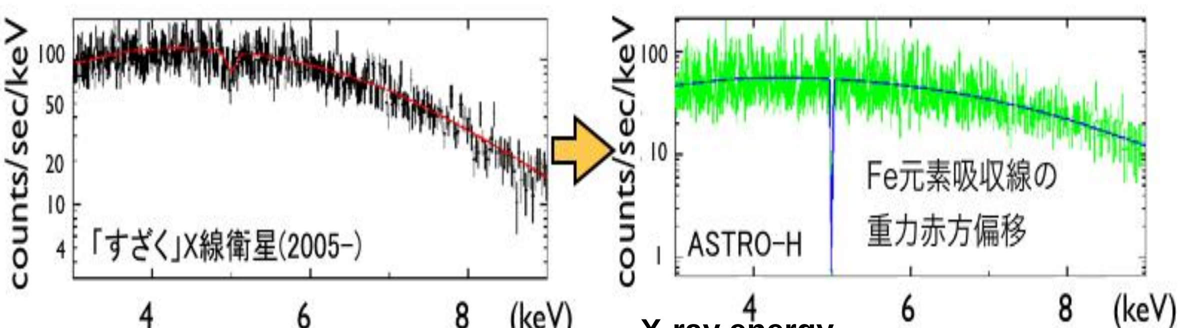
High rate, high resolution, polarization

→ First precise measurement of bursts

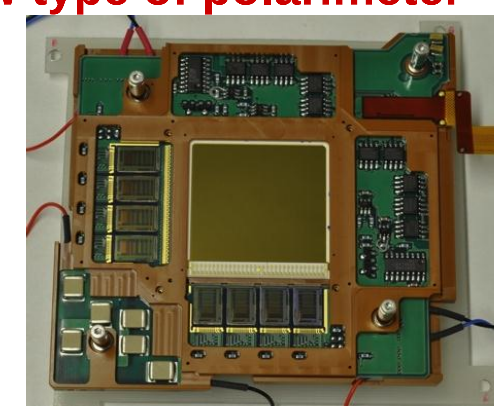
=> CMOS X-ray image sensor

γ-ray camera (CdTe,Ge strip）

New type of polarimeter



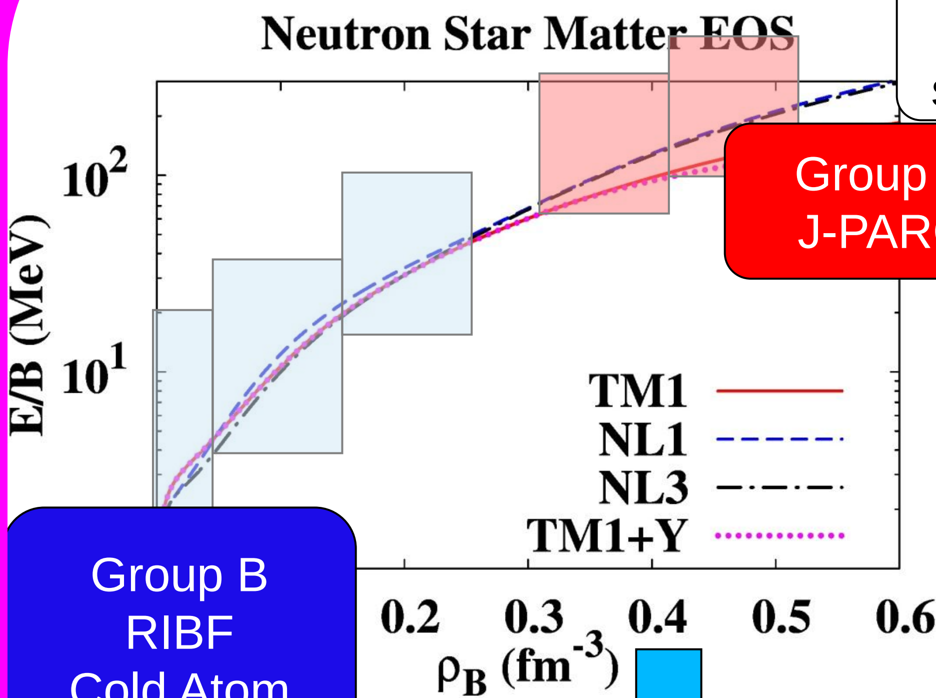
X-ray energy



D01: Theoretical studies of n-star matter

Group D

Onishi, Harada, Nakada, Iida, Matsuo, Tatsumi, Ono, Dote, Kimura, Nakazato
Kunihiro, Nishizaki, Oyamatsu, Maruyama, Abuki, Ohashi, Shibazaki



RHIC・GSI data,
BB, 3-body forces from lattice QCD,
Stiffening of EOS, Quark matter EOS,…

Kei computer

Group A
J-PARC

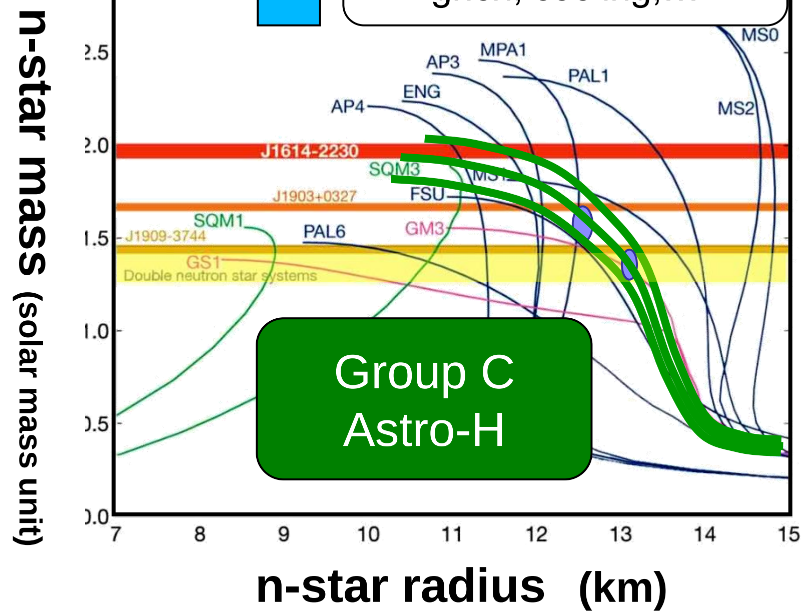
confirmation

Mass, Radius, QPO.
grich, cooling,…

Group B
RIBF
Cold Atom

Symmetric energy,
Pair correlation, Pasta phase,
Quasi-unitary gas,…

Pressure balance



Group C
Astro-H

Theories combine

physics fields on hypernuclei, n-rich nuclei, cold atoms, stellar objects

and determine "*The* EOS" confirmed by experiments and observations

Remarks

Academic Value

- Elucidate a new forms of matter existing in the universe
- Extend our understanding of "matter"
- Construct "Physics of quark's matter"

Features

- The subject can be elucidated only by combining different physics fields.
- Association of the world-top group in each field.
- The project should be carried out now in Japan when the world-best three facilities are to be launched.

本日は、ご参加ありがとうございます。

他分野、他グループとの相互理解を深めるため、活発な質疑、コメントをお願いします。