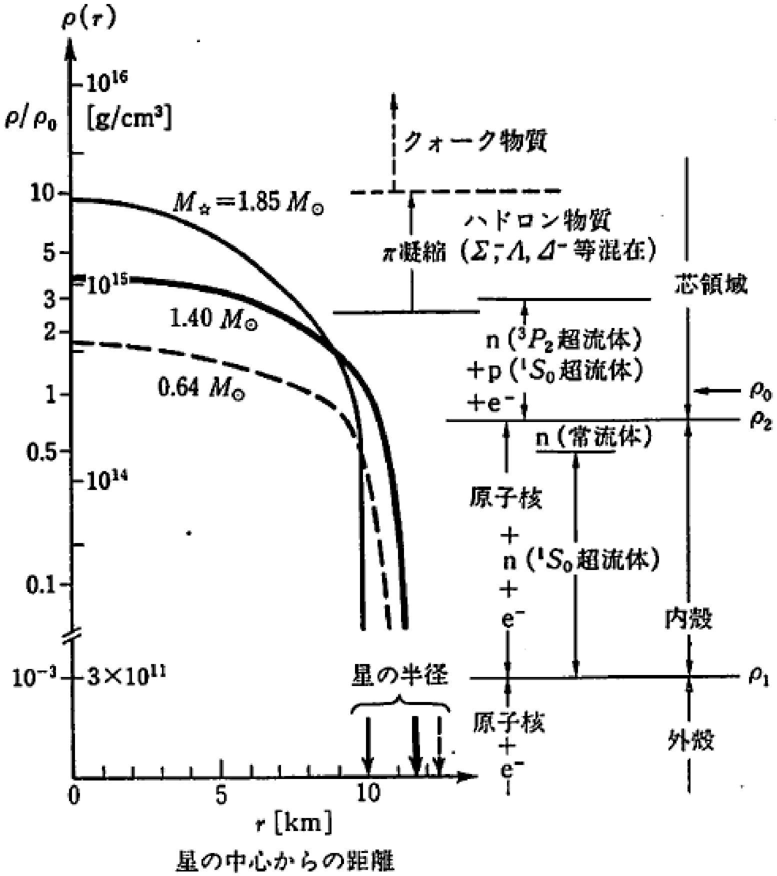
中性子過剰な中低密度核物質の物性

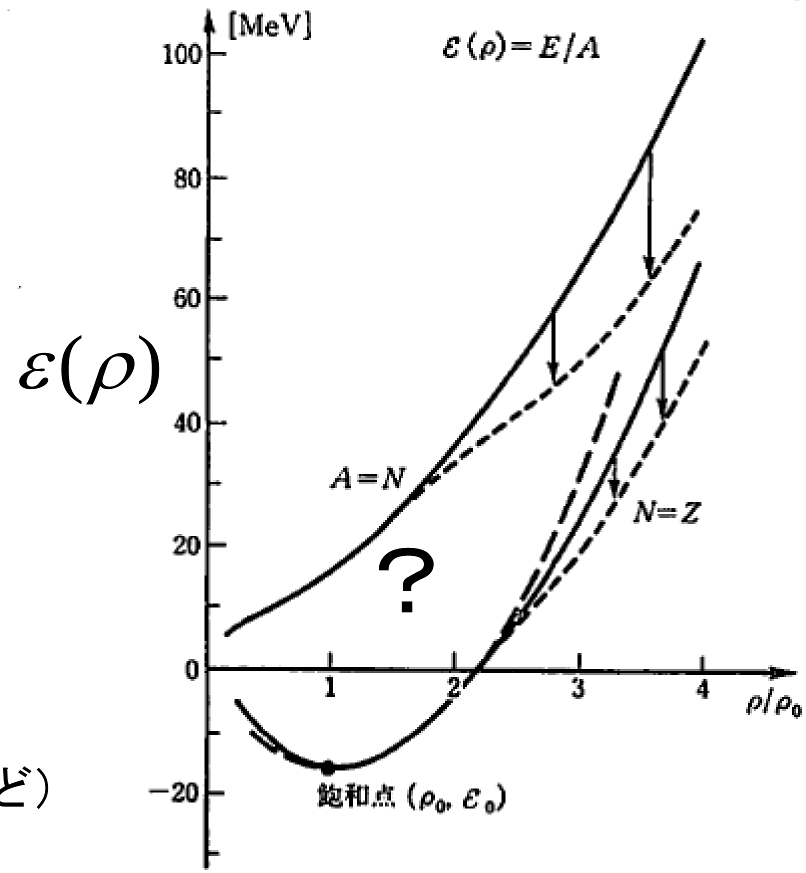
--不安定核ビーム実験による
中性子星・ＥＯＳ物理
へのアプローチ

中村隆司
東京工業大学　理工学研究科
基礎物理学専攻

中性子星Ｍｉｎｉ　Ｗｏｒｋｓｈｏｐ＠ＲＩＫＥＮ
2011.9.13

中性子星とEOS





Stiff
P(傾き）大

Soft
P小

EOS(N>>Z)が決まれば、
中性子星の巨視的性質が決まる（半径など）
核子対による超流動も重要

玉垣良三　高密度核物質（共立出版）

EOS and Symmetry Energy

EOS N~Z

$$E(\rho) = E(\rho_0) + \frac{1}{2}\frac{K}{9}\frac{(\rho - \rho_0)^2}{\rho_0{}^2}\ldots$$

K: Incompressibility 非圧縮率

一般化 Symmetry Energy (E_{sym})を導入

$$E(\rho,\alpha) = E(\rho,0) + E_{sym}\alpha^2 + \ldots$$

$$\alpha = \frac{\rho_n - \rho_p}{\rho} = \frac{N - Z}{A}$$

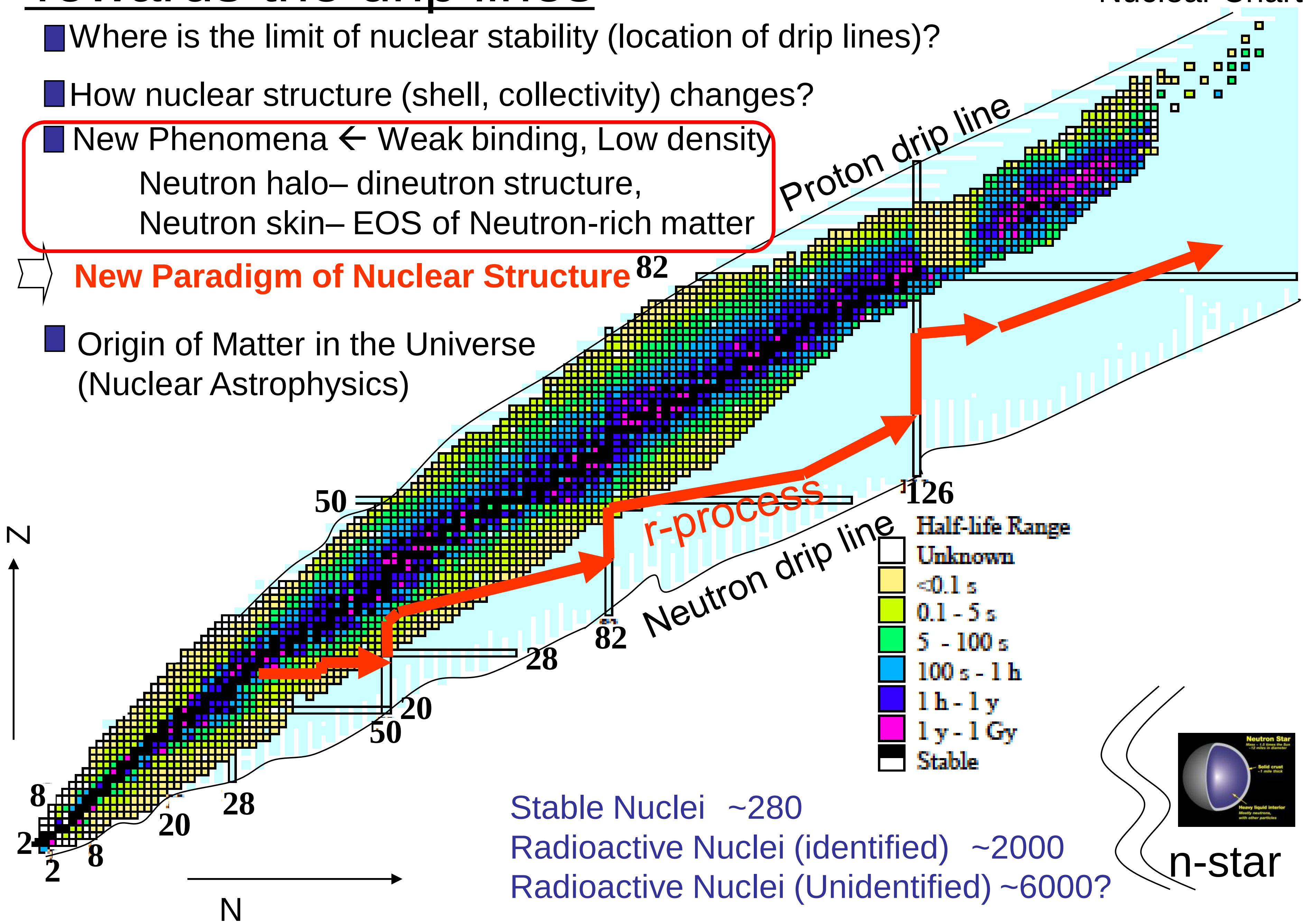
$$E_{sym} = \frac{1}{2}\frac{\partial^2 E}{\partial \alpha^2}\bigg|_{\alpha=0} = a_4 + \frac{p_0}{\rho_0{}^2}(\rho - \rho_0) + \frac{\Delta K_0}{18\rho_0{}^2}(\rho - \rho_0)^2 + \ldots$$

Towards the drip lines

- Where is the limit of nuclear stability (location of drip lines)?
- How nuclear structure (shell, collectivity) changes?
- New Phenomena ← Weak binding, Low density
  - Neutron halo– dineutron structure,
  - Neutron skin– EOS of Neutron-rich matter

⇨ **New Paradigm of Nuclear Structure**

- Origin of Matter in the Universe (Nuclear Astrophysics)

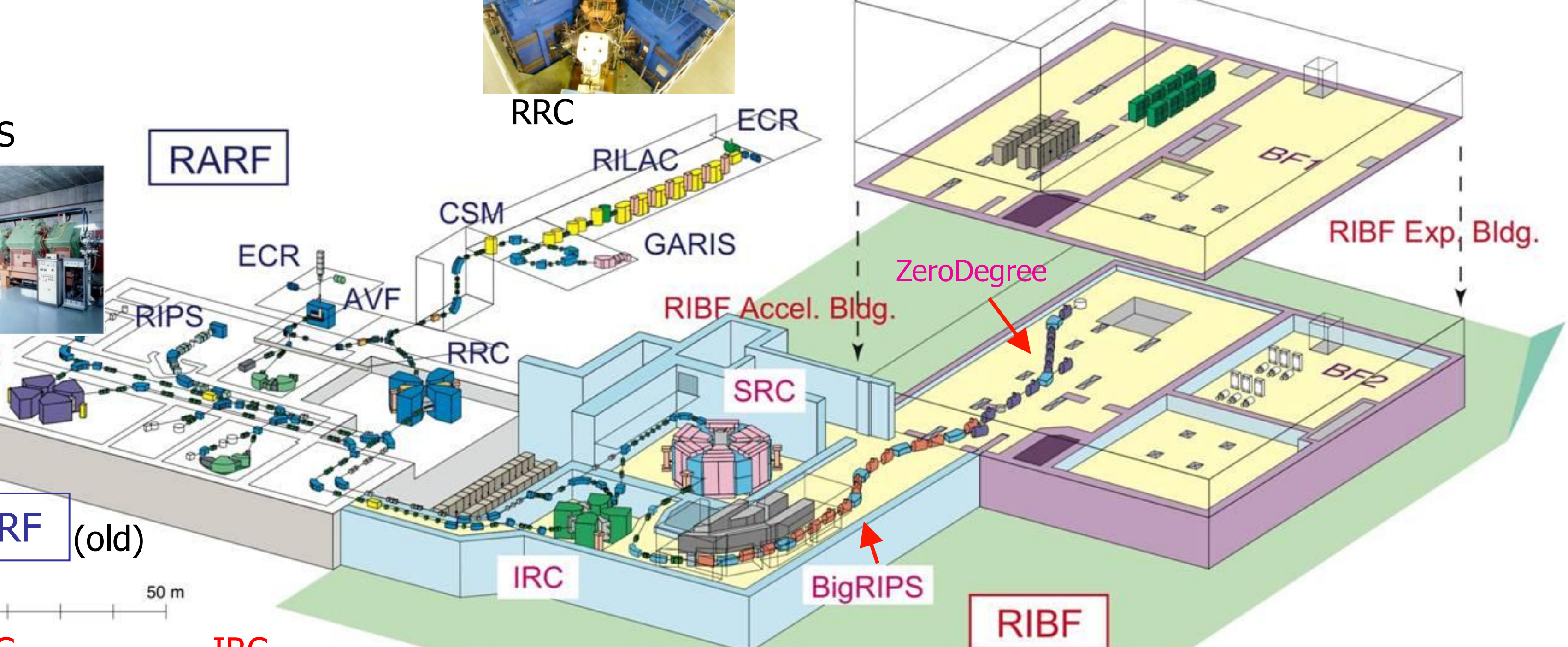


Stable Nuclei ~280
Radioactive Nuclei (identified) ~2000
Radioactive Nuclei (Unidentified) ~6000?

RIビームファクトリー鳥瞰図(2007-)

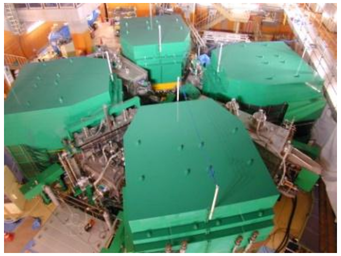
RRC

RIPS



fRC

IRC



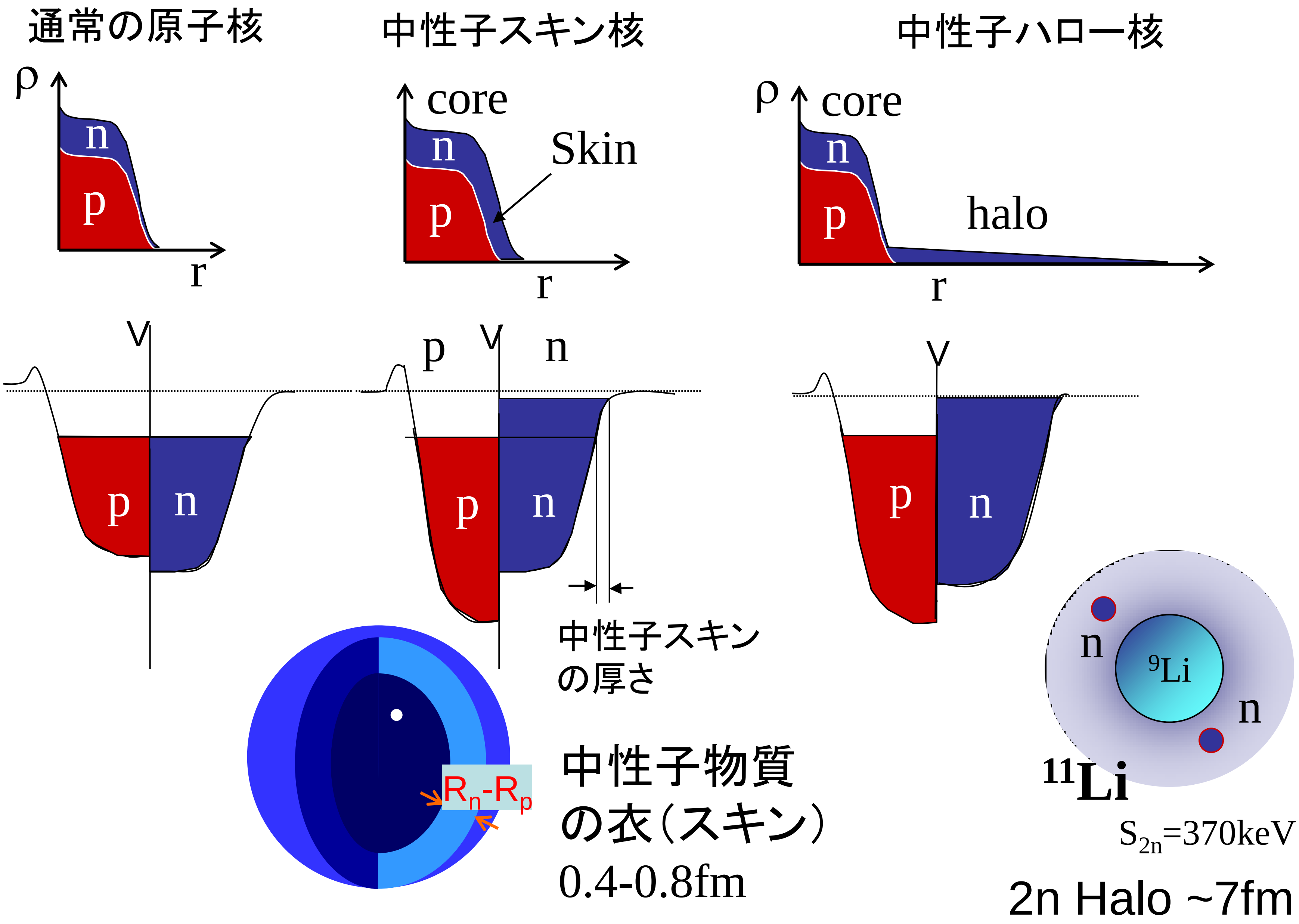
SRC

世界最大の重イオン加速器施設
第3世代不安定核ビーム施設として、
世界の先陣を切る
Accelerate Heavy ions (up to U)
@345MeV/nucleon
(c.f. GSI Fair, MSU FRIB 5-10年後)

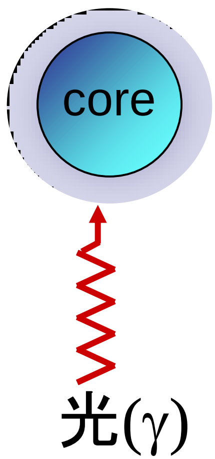
Project-1

Systematic Study of
Pygmy Dipole Resonance
→ Symmetry Energy of EOS

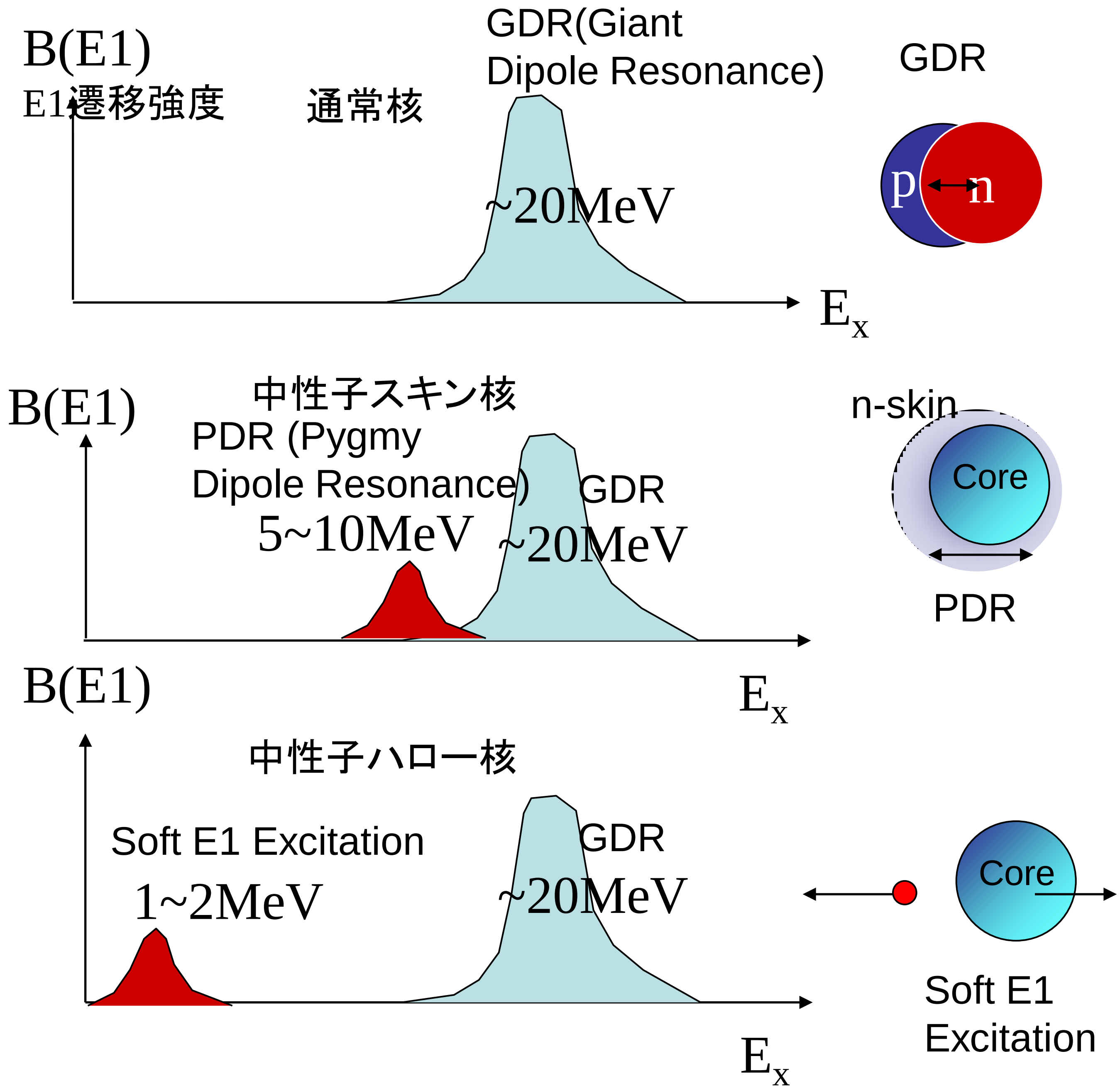
中性子スキン核 ハロー核



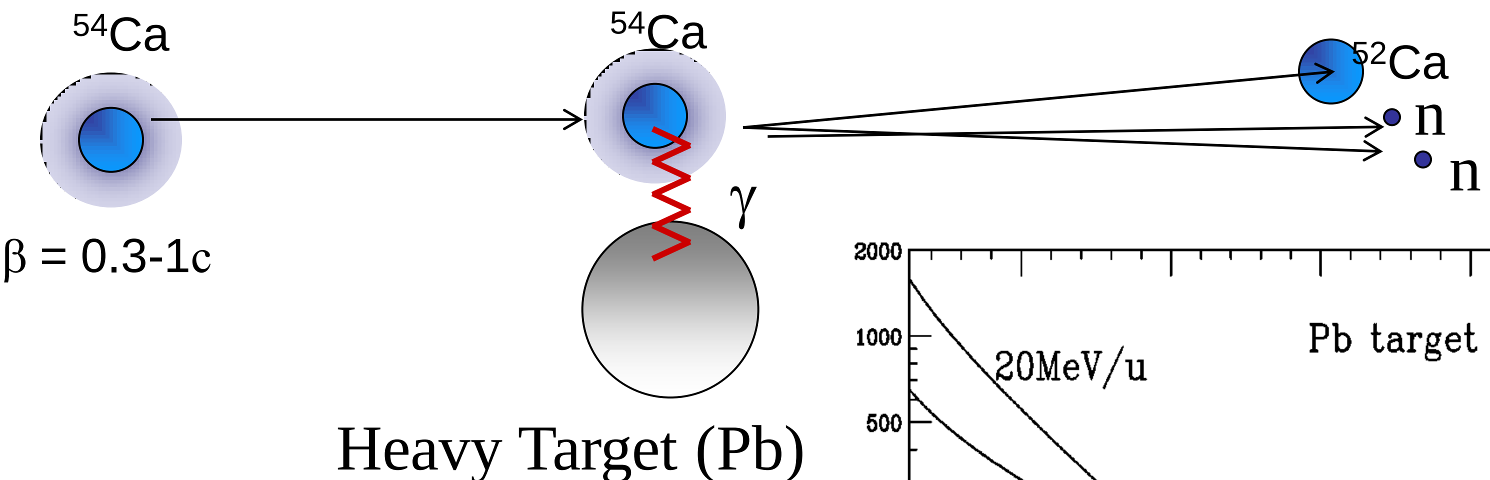
E1 Response of Nuclei

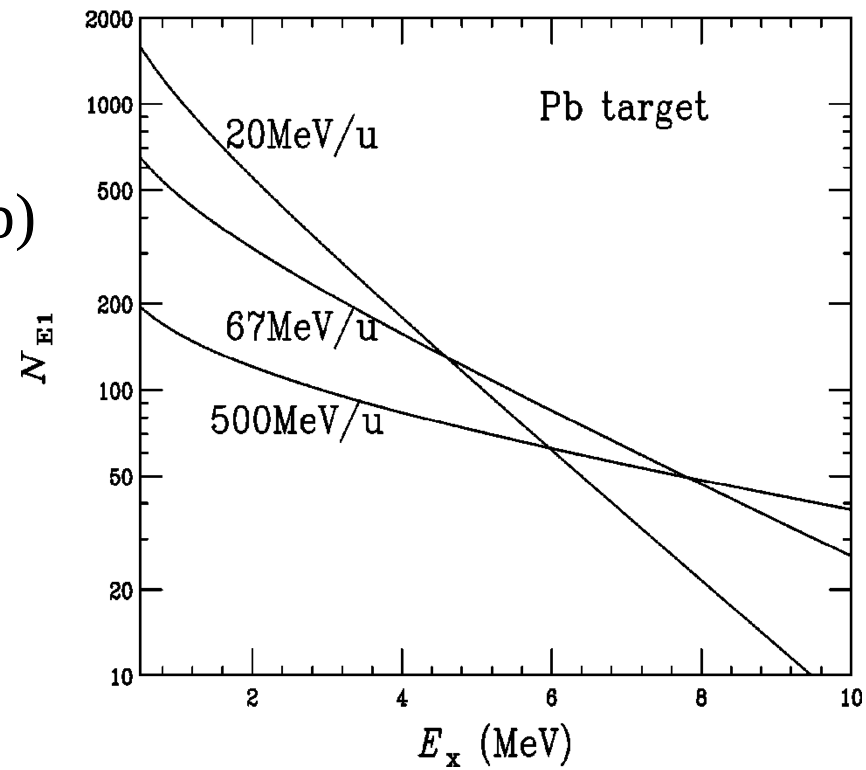


どういう応答？



Coulomb Breakup





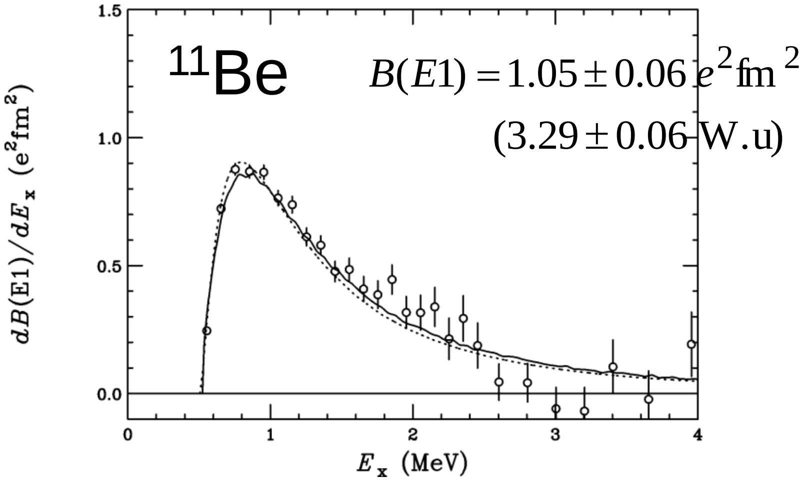
Excitation by a Virtual Photon

$$\frac{d\sigma_{CB}}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x) \frac{dB(E1)}{dE_x}$$

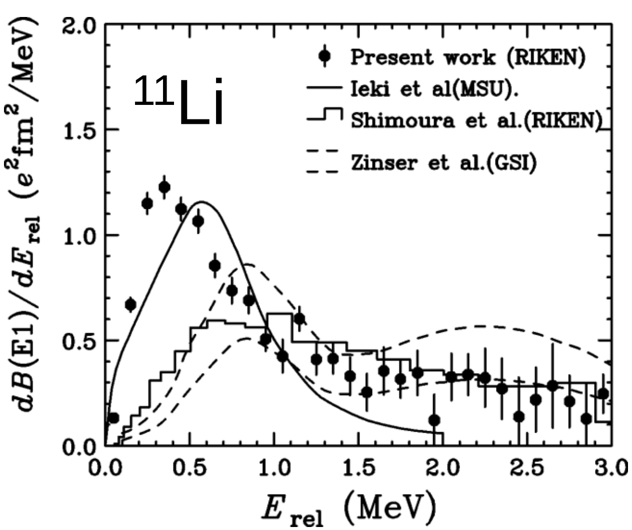
Cross Section = (Photon Number) x(Transition Probability)

Excitation Energy
(=Photon Energy)

Soft E1 Excitation for Halo Nuclei



N.Fukuda, TN et al., PRC70, 054606 (2004)

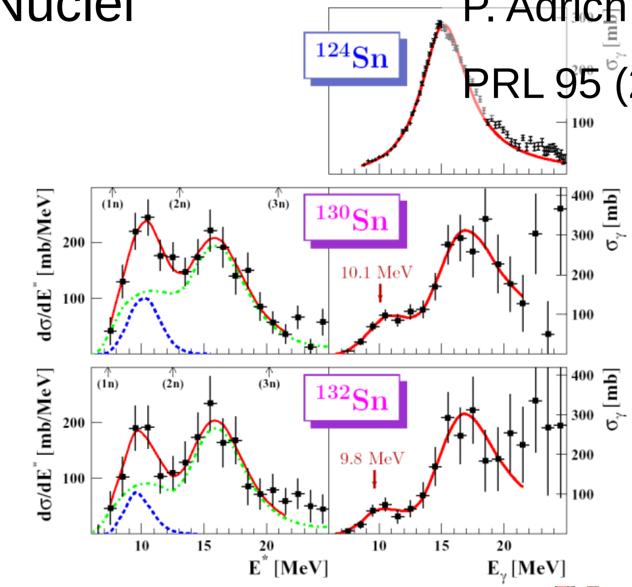


T.Nakamura et al. PRL96,252502(2006).

Pygmy Dipole Resonance for n-Skin Nuclei

P. Adrich et al.,

PRL 95 (2005) 132501



2

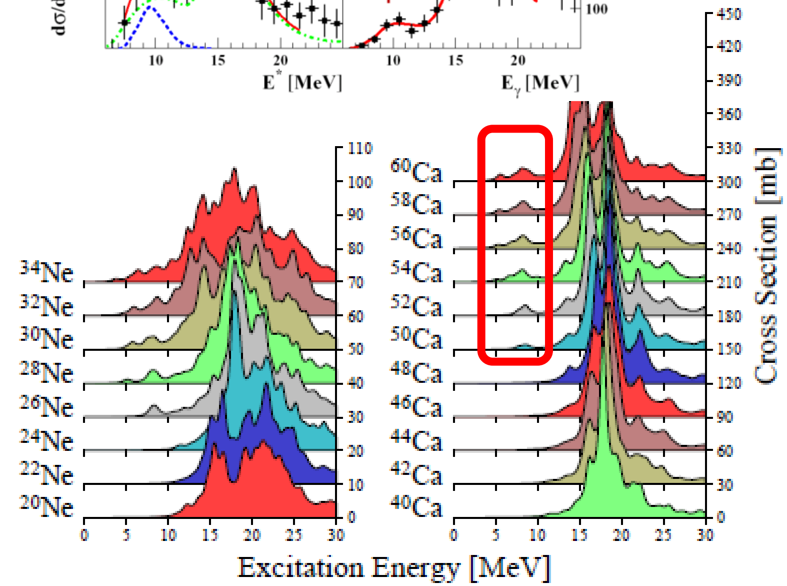
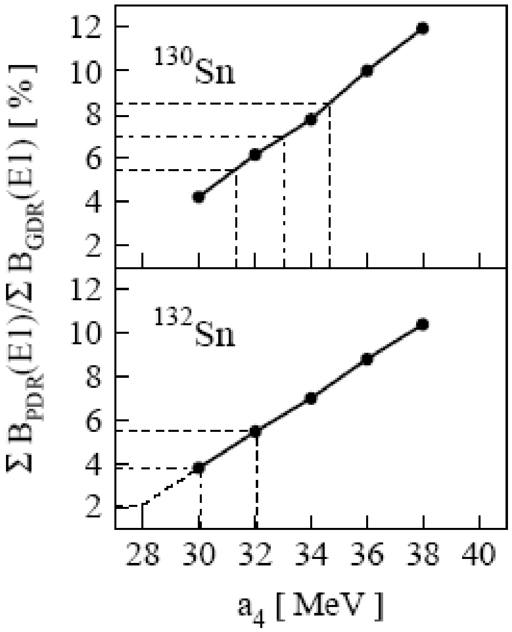


FIG. 1: (Color online) Calculated photoabsorption cross sections in Ne and Ca isotopes.

Inakura, Nakatsukasa, Yabana
(平均場理論)

Pygmy Dipole Resonance
←→ Neutron Skin Thickness
←→ Equation of State of Nuclear Matter



RQRPA – DD-ME

N. Paar et al.

Result (*averaged* ^{130,132}*Sn) :*

a_4 = 32.0 ± 1.8 MeV

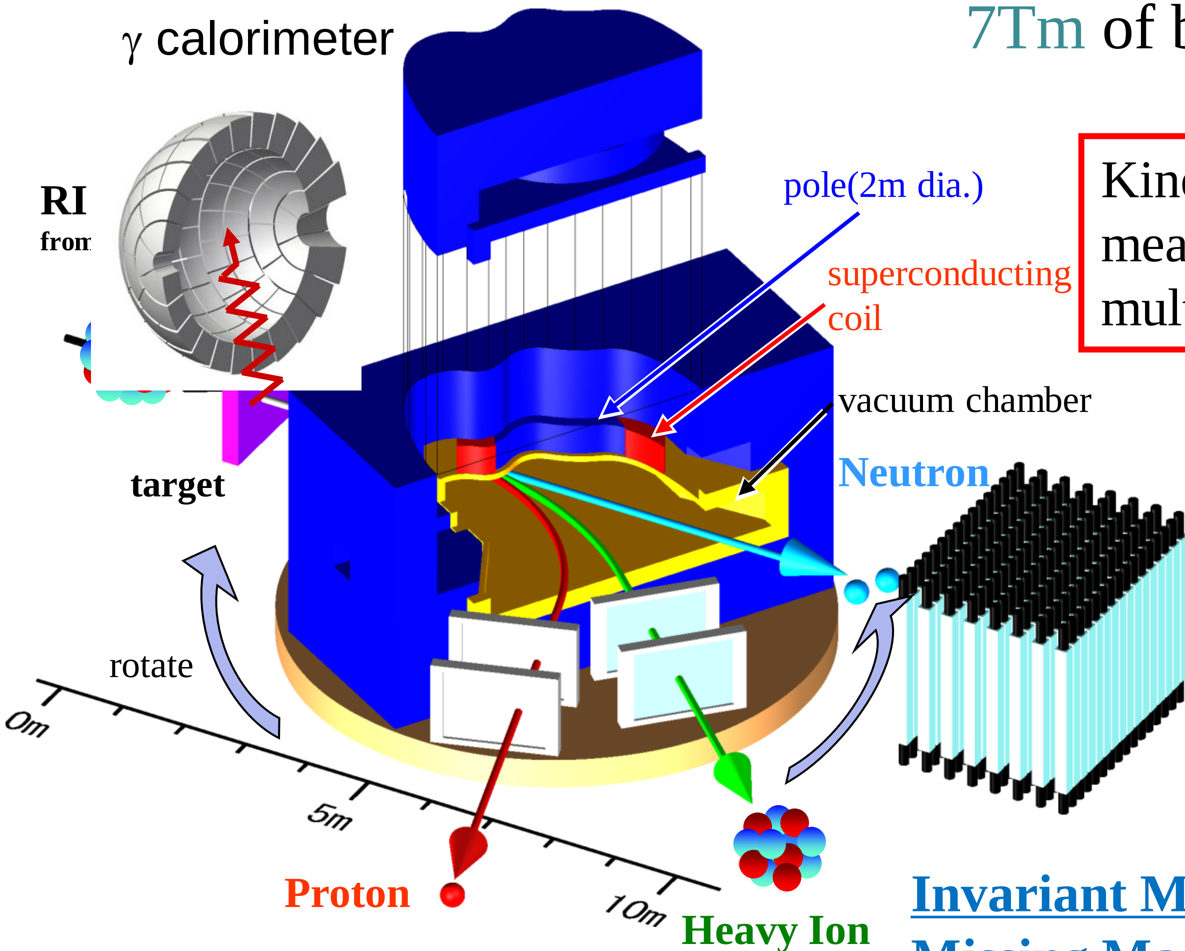
S(ρ) : moderate stiffness

SAMURAI

-- new spectrometer in RIBF --

Superconducting **A**nalyzer for **MU**lti-particle from **RA**dio **I**sotope Beam with 7Tm of bending power

Kinematically complete measurements by detecting multiple particles in coincidence

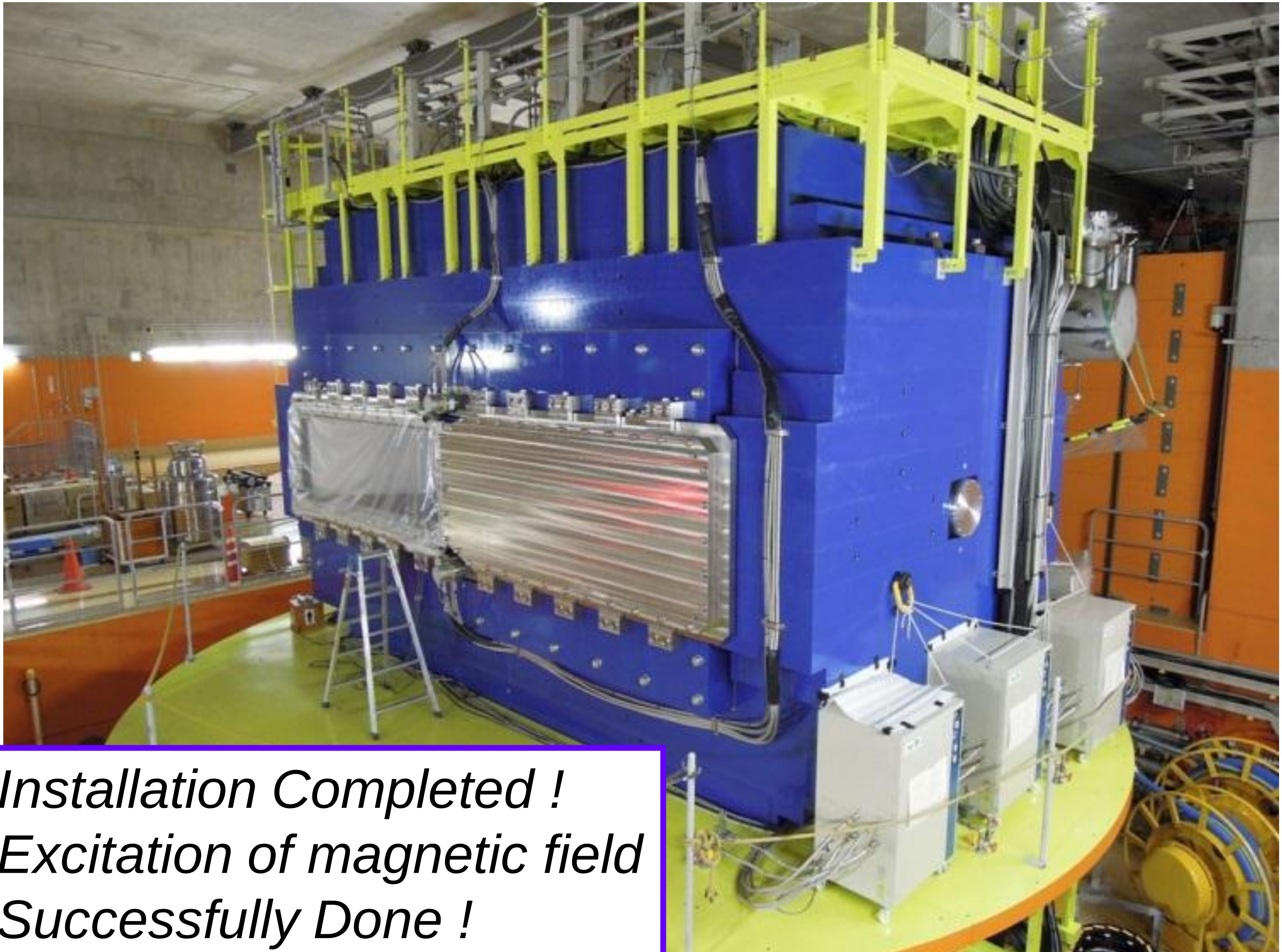


- Superconducting Magnet
  - 3T with 2m dia. pole
  - (designed resolution 1/700)
  - 80cm gap (vertical)
- Heavy Ion Detectors
- Proton Detectors
- Neutron Detectors
- Large Vacuum Chamber
- Rotational Stage

Invariant Mass Measurement

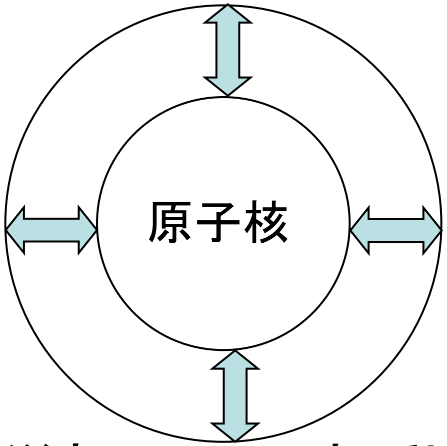
Missing Mass Measurement

Slide: K. Yoneda

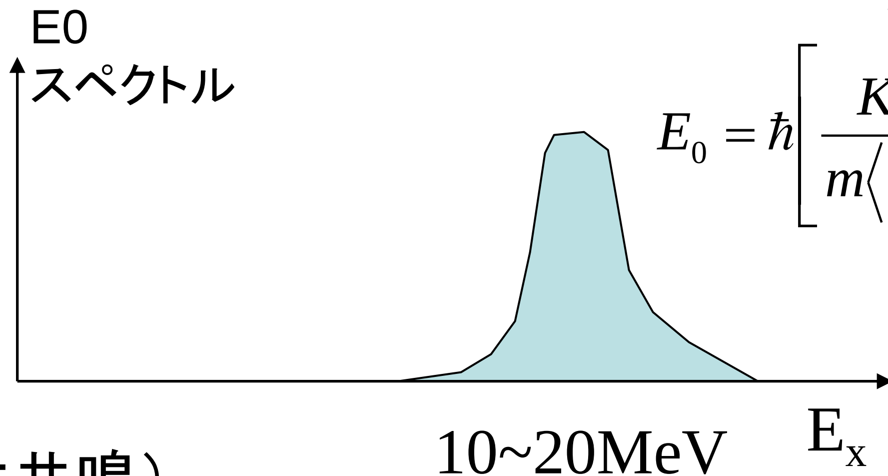


Installation Completed !
Excitation of magnetic field
Successfully Done !

非圧縮率と単極子(E0)巨大共鳴



単極子(E0)振動(巨大共鳴)
Breathing Mode

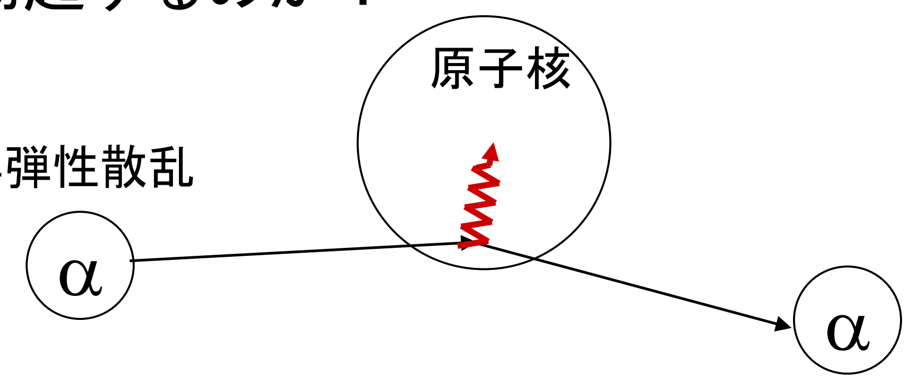


非圧縮率

$$E_0 = \hbar \left[\frac{K_A}{m \langle r^2 \rangle} \right]^{1/2}$$

どうやってE0を励起するのか？

アルファ粒子の非弾性散乱



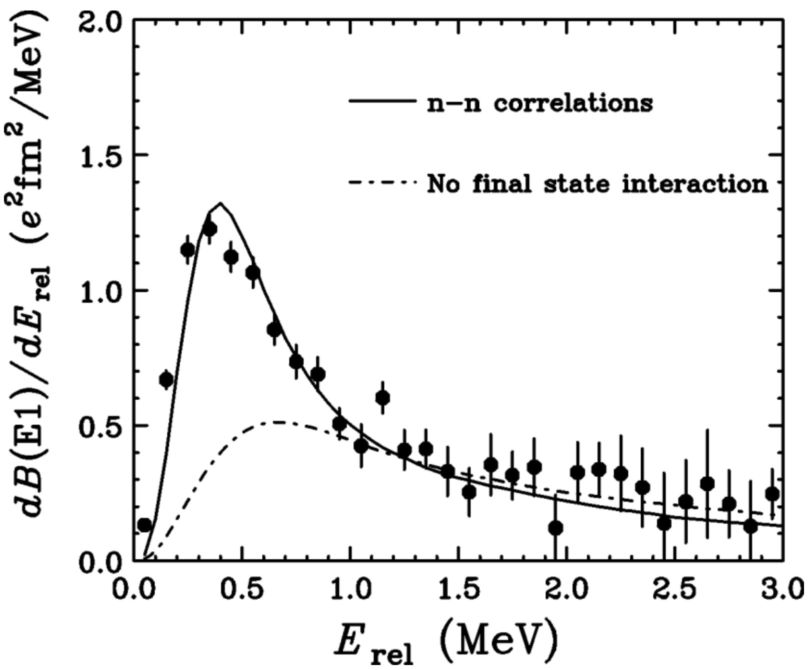
不安定核では逆運動学

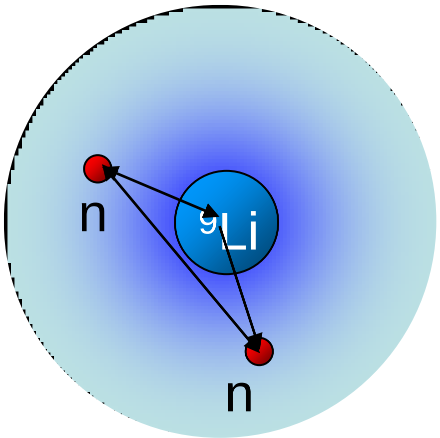
Project-2

Dineutron correlation
in low-dense neutron matter

n-n correlations in halo nulcei by Coulomb breakup

T.Nakamura PRL96,252502(2006)





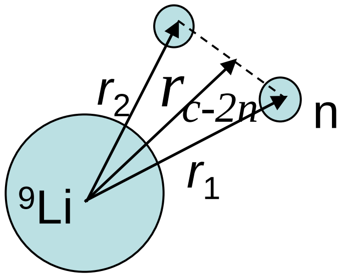
$$B(E1) = 1.42 \pm 0.18\, e^2\, fm^2$$

$$E_{rel} \le 3\,\mathrm{MeV}$$

$$B(E1) = \int_0^\infty \frac{dB(E1)}{dE_x} dE_x = \frac{3}{4\pi}\left(\frac{Ze}{A}\right)^2 \left\langle r_1^{\ 2} + r_2^{\ 2} + 2(\vec{r}_1 \cdot \vec{r}_2)\right\rangle$$

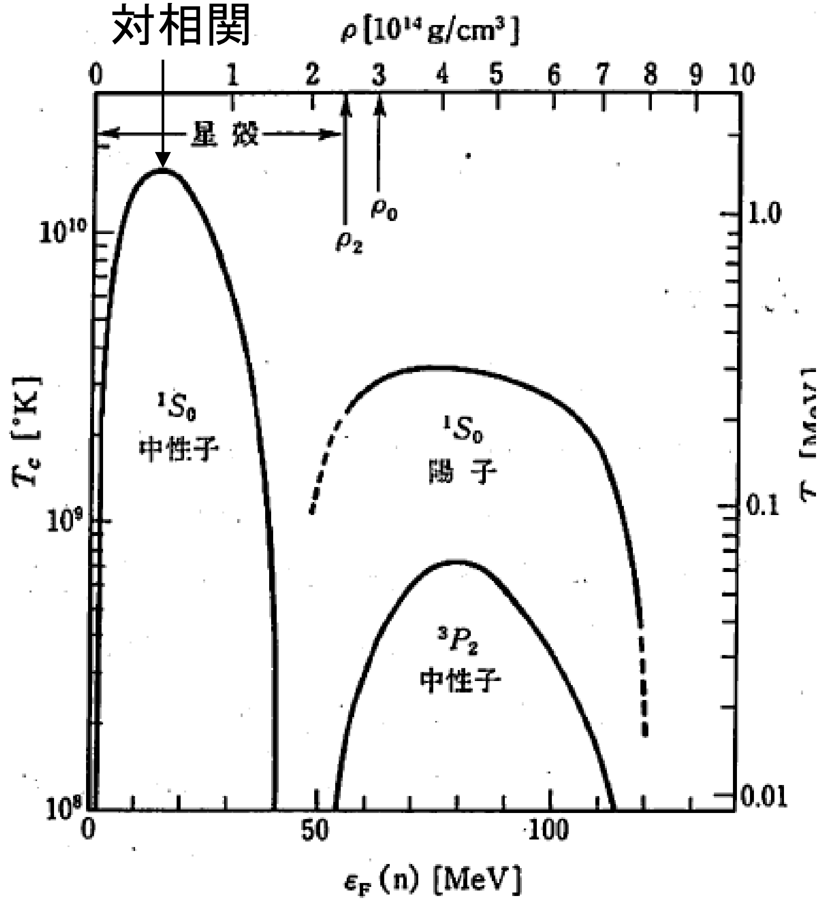
$$= \frac{3}{\pi}\left(\frac{Ze}{A}\right)^2 \left\langle r_{c-2n}^{\ \ 2}\right\rangle$$

$$\sqrt{\left\langle r_{c-2n}\right\rangle^2} = 5.01 \pm 0.32\ \mathrm{fm}$$



中性子星ー超流動状態

強いnn
対相関



線：超流体の発現する密度
をエネルギーギャップが消える
エネルギーで示したもの。
（Tcが高いほどΔが大きい）

$$kT_c(^1S_0) \approx 0.57\Delta(^1S_0)$$

$$kT_c(^3P_2) \approx 0.12\Delta(^3P_2)$$

理論的予想

$\rho_0/8<\rho<\rho_0/2$ $^1S_0(S=L=J=0)$ nn超流体

$(2/3)\rho_0<\rho<3\rho_0$ $^3P_2(S=1,L=1,J=2)$ nn超流体

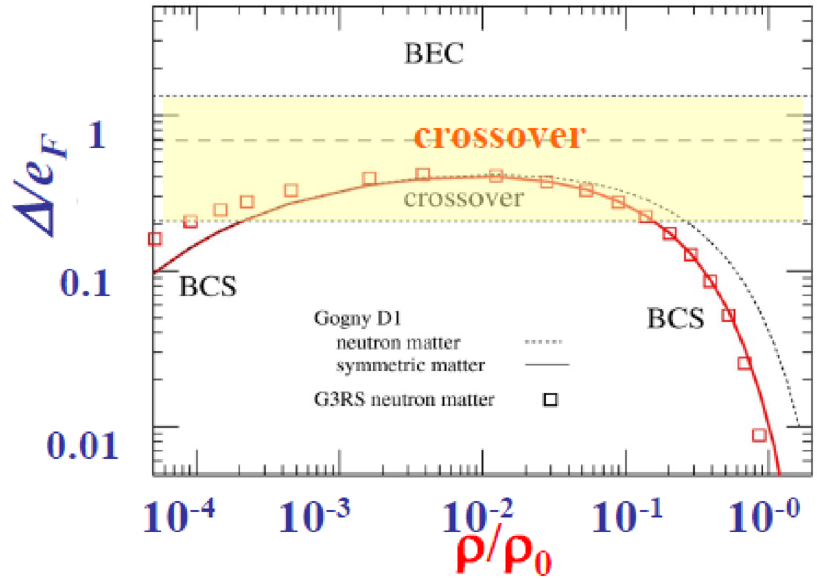
N.B. ２核子状態：$^{2S+1}L_J$

低密度下で中性子中性子相関が強まる？

nn-correlation (density dependence)

Mean-field calculation (BCS approx.)

$\rho/\rho_0 = 10^{-4} \sim 2\mathrm{x}10^{-1}$



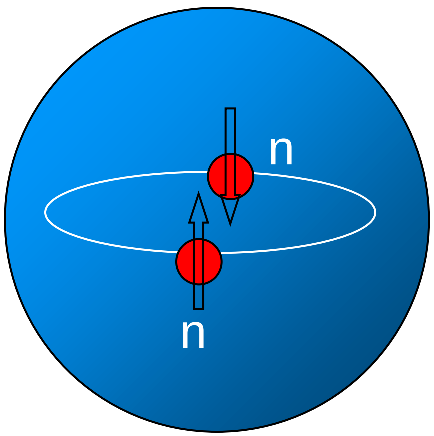
MM, PRC73,044309(2006)

Gap Energy Δ の Density Dependenceは重要！

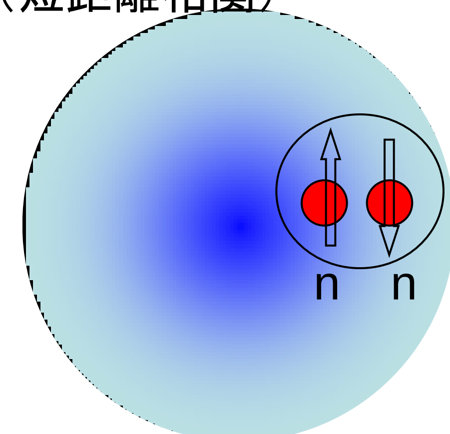
Dineutron 相関？

Migdal Sov.J.Nucl.Phys. 16,238 (1973)
2n Threshold ,核表面：2nが強く相関？

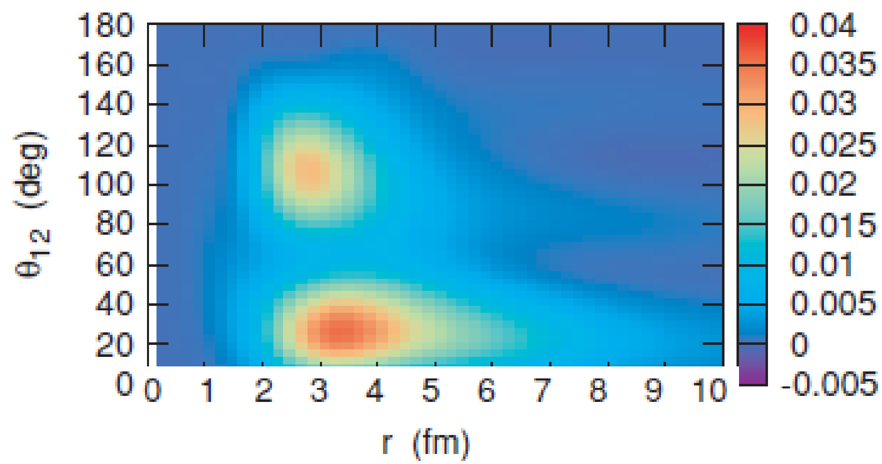
通常のBCS的対相関
（長距離相関）



dineutron的対相関(BEC like)
（短距離相関）

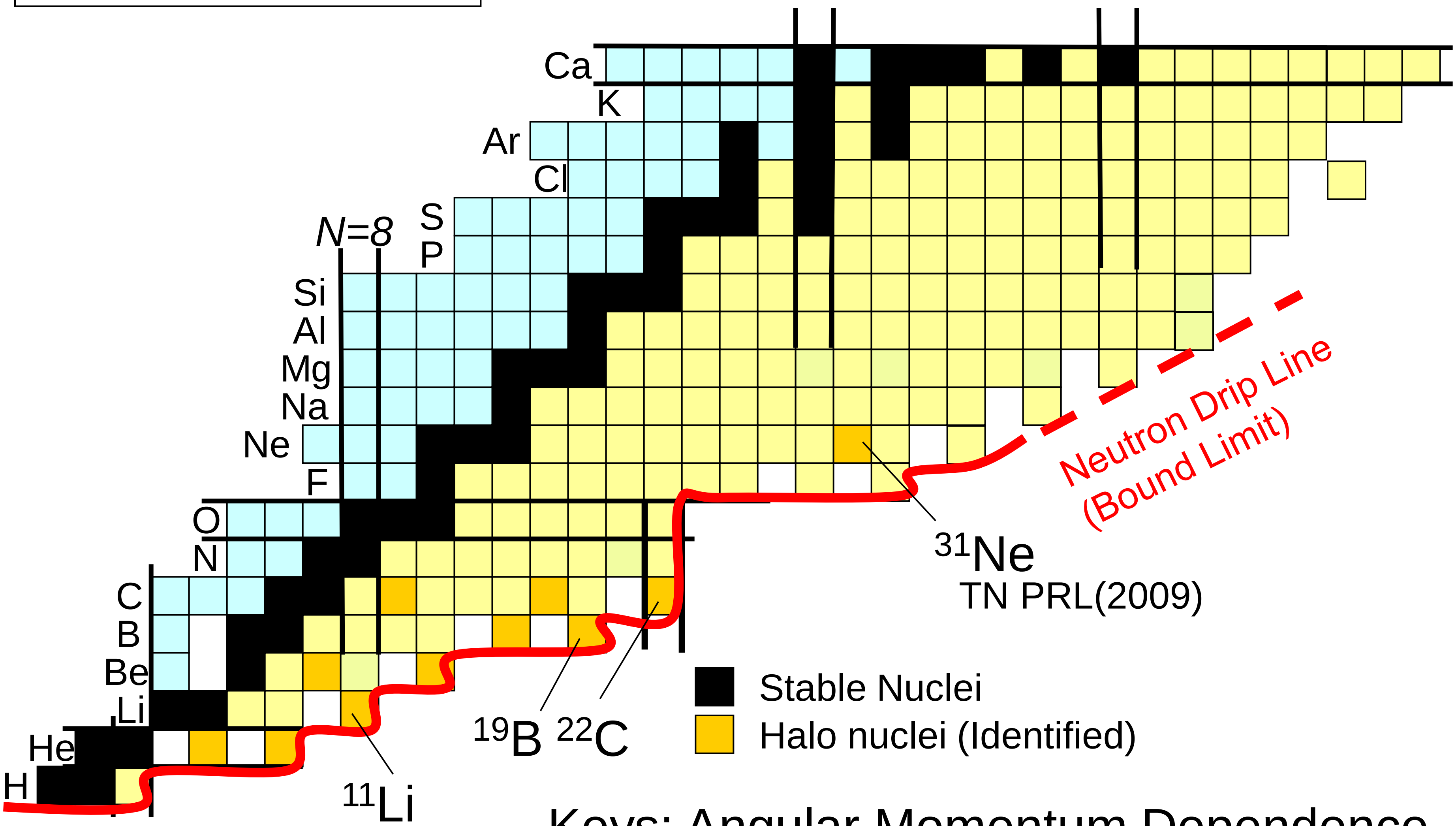


M.Matsuo et al.
PRC73,044309(2006).
Dineutron的相関
低密度下でおこる
$\rho/\rho_0 \sim 10^{-4\sim-5}$



K.Hagino, H.Sagawa, J.Carbonell, P.Schuck
PRL99,022506 (2007).

Nuclear Landscape
(from H to Ca)



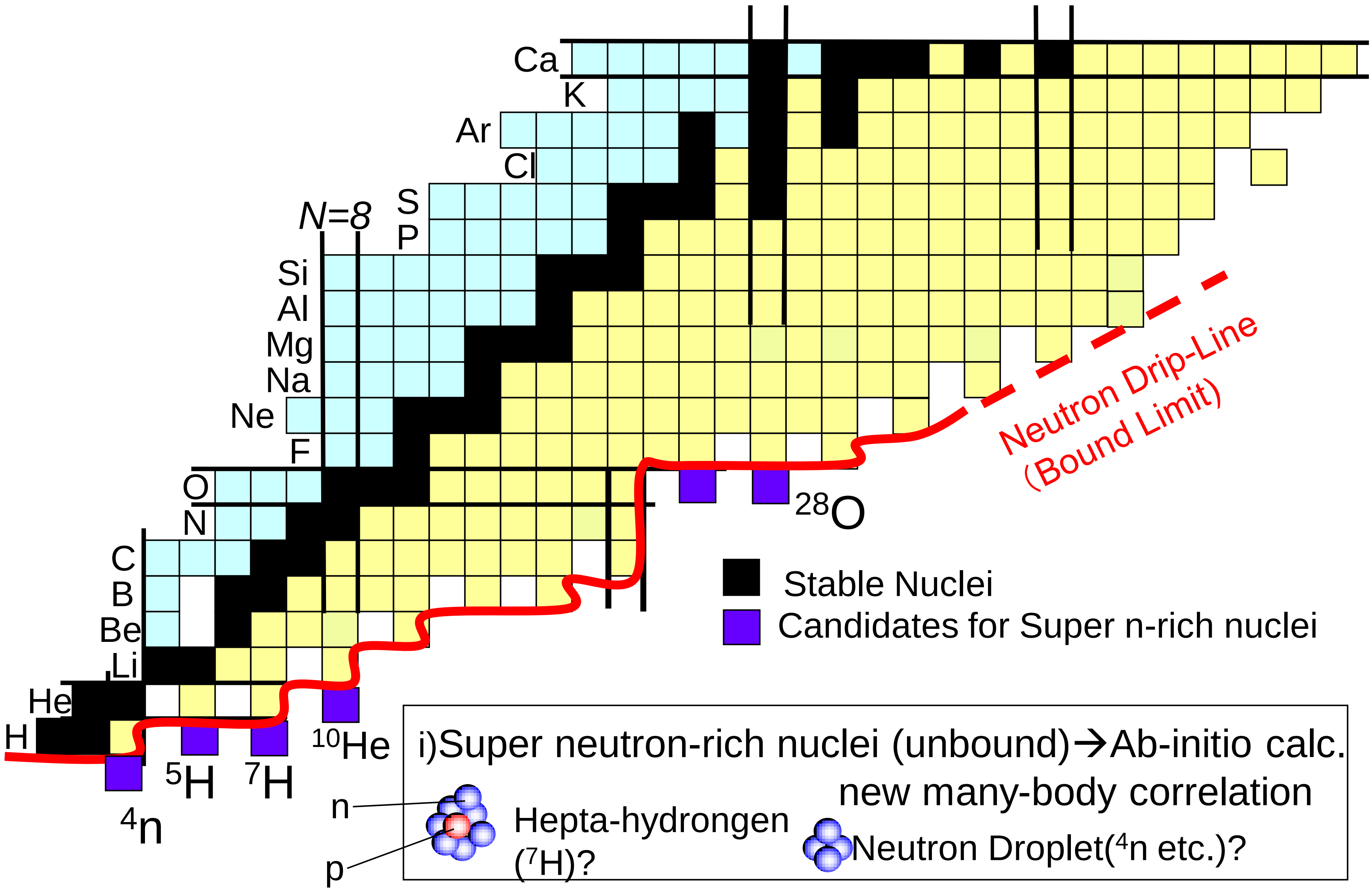
Keys: Angular Momentum Dependence

Density Dependence

Project-3

Search for neutron-droplet

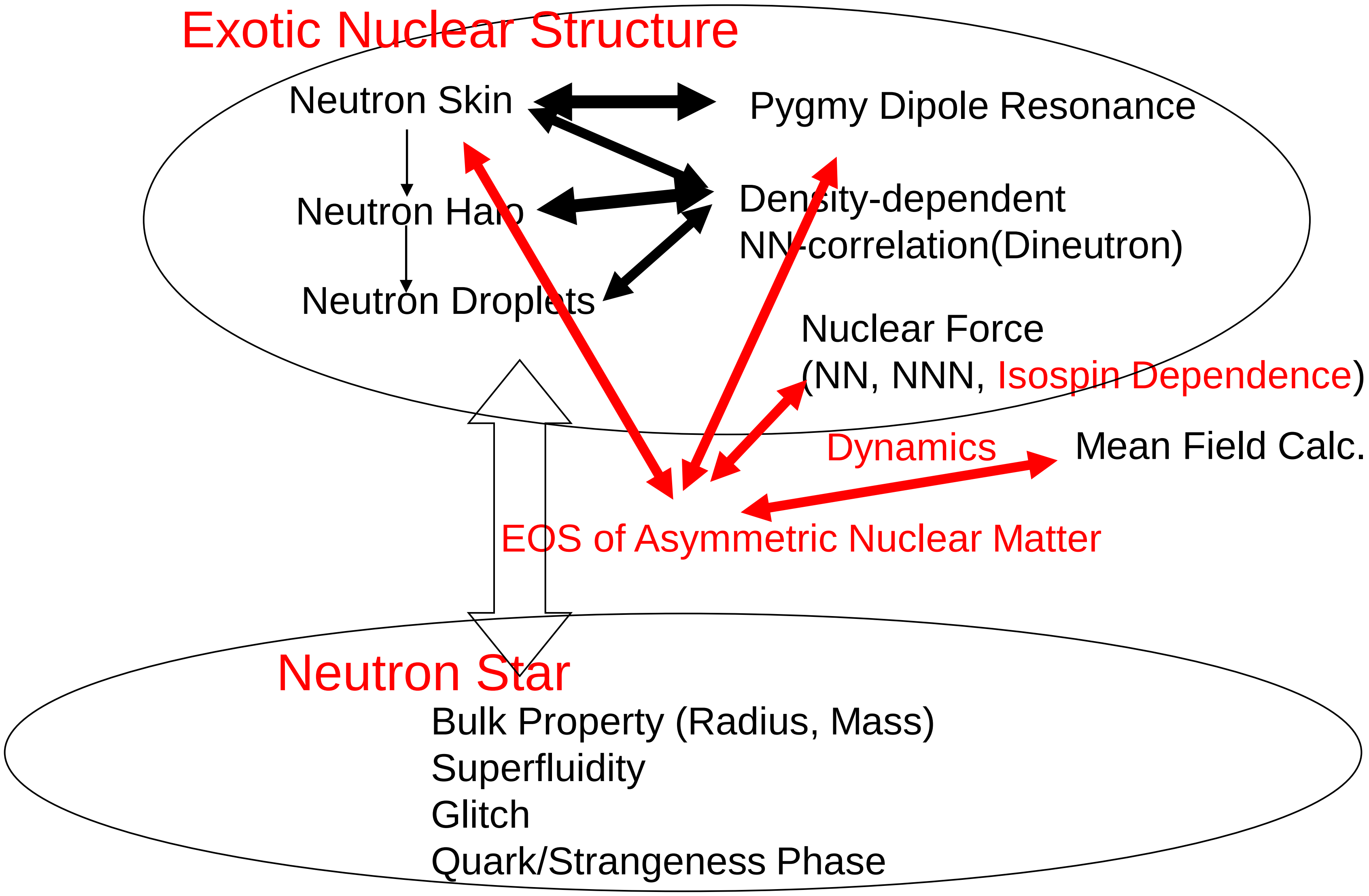
(or neutron-droplet like structure)



Ca
K
Ar
Cl
S
P
N=8
Si
Al
Mg
Na
Ne
F
O
N
C
B
Be
Li
He
H
Neutron Drip-Line
(Bound Limit)
28O
Stable Nuclei
Candidates for Super n-rich nuclei
10He
4n
5H
7H
i)Super neutron-rich nuclei (unbound)→Ab-initio calc.
new many-body correlation
n
p
Hepta-hydrongen
(7H)?
Neutron Droplet(4n etc.)?

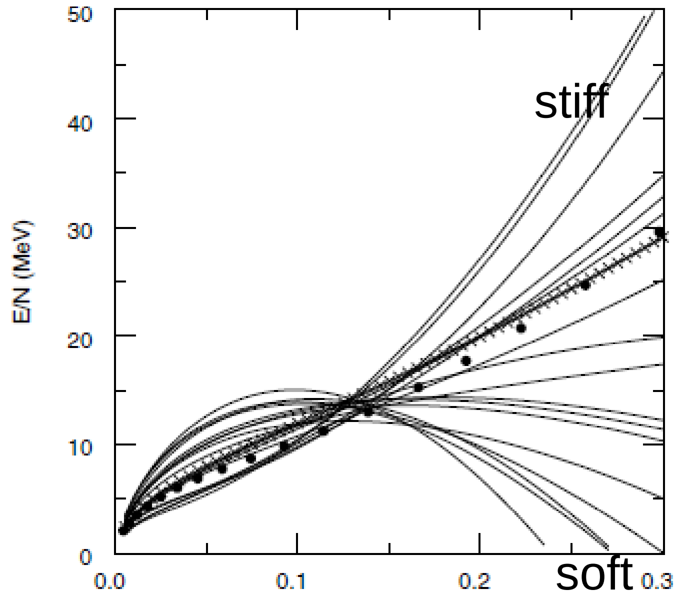
Summary

Nuclear Structure using RI Beams



Backup

E_{sym} and neutron-skin thickness



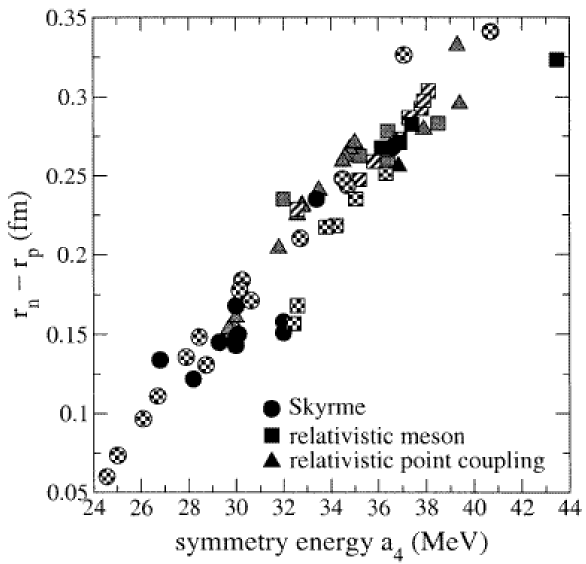
Alex Brown, PRL85, 5296 (2000).

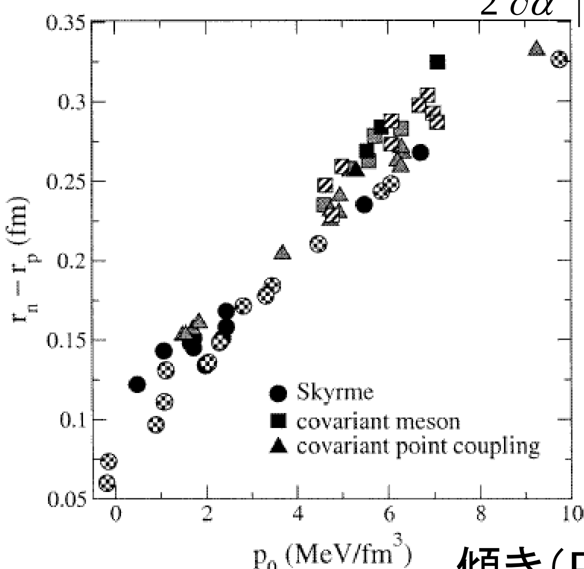
Skyrme Hartree Fock
(18 different parameter sets,
Filled circle: Friedman-Pandharipande
Crosses: SKX)

$$E(\rho,\alpha) = E(\rho,0) + E_{sym}\alpha^2 + \ldots$$

$$\alpha = \frac{\rho_n - \rho_p}{\rho} \approx \frac{N-Z}{A}$$

$$E_{sym} = \frac{1}{2}\frac{\partial^2 E}{\partial \alpha^2}\bigg|_{\alpha=0} = a_4 + \frac{p_0}{\rho_0^2}(\rho-\rho_0) + \frac{\Delta K_0}{18\rho_0^2}(\rho-\rho_0)^2 + \ldots$$





R.J.Furnstahl
Nucl. Phys. A 706, 85 (2002).

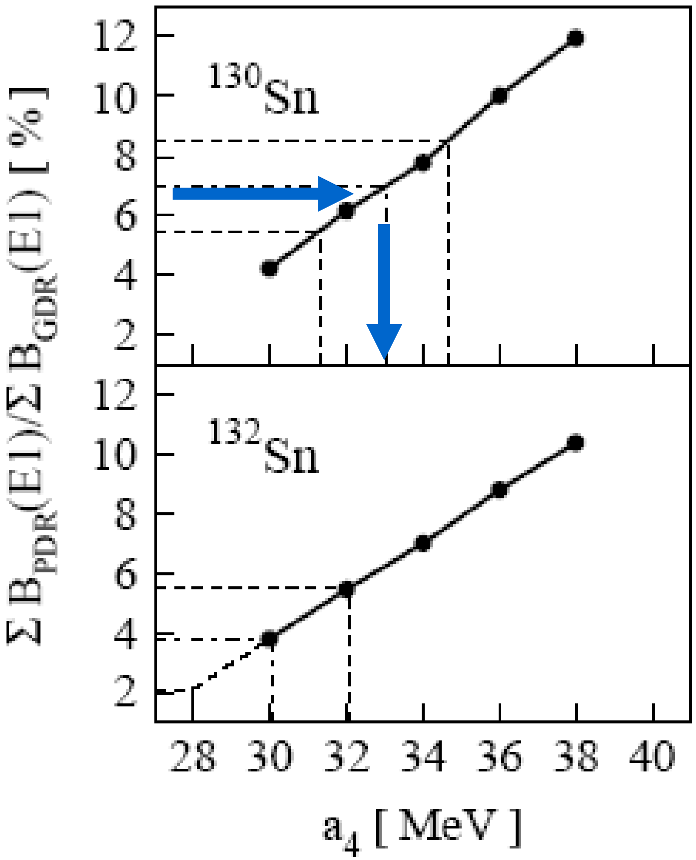
a_4, p_0(Slope)
Linear correlation with
Neutron skin thickness

傾き（Pressure)

PDR strength versus a_4, p_o

PDR GSI
における先行研究

P. Adrich et al., PRL 95 (2005) 132501

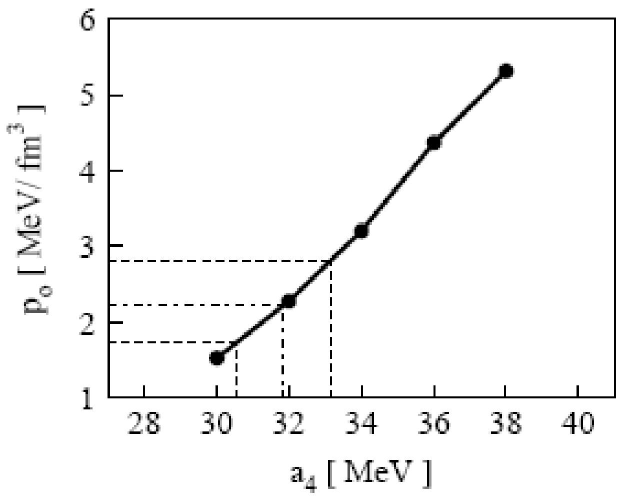


RQRPA – DD-ME

N. Paar et al.

Result (*averaged ^{130,132}Sn) :*

a_4 = 32.0 ± 1.8 MeV

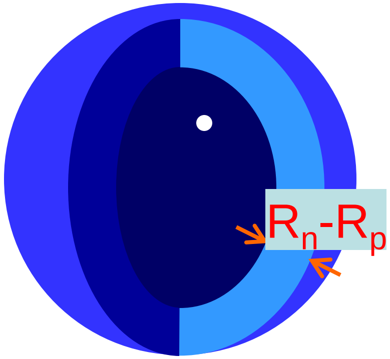


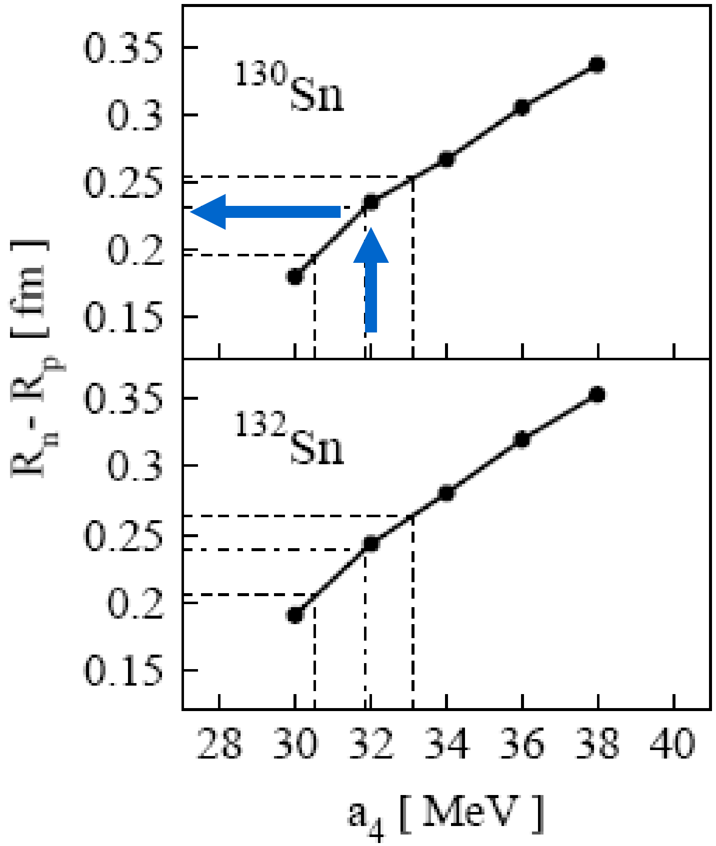
p_o = 2.3 ± 0.8 MeV/fm^3

S(ρ) : moderate stiffness

Slide:T.Aumann

Neutron skin thickness

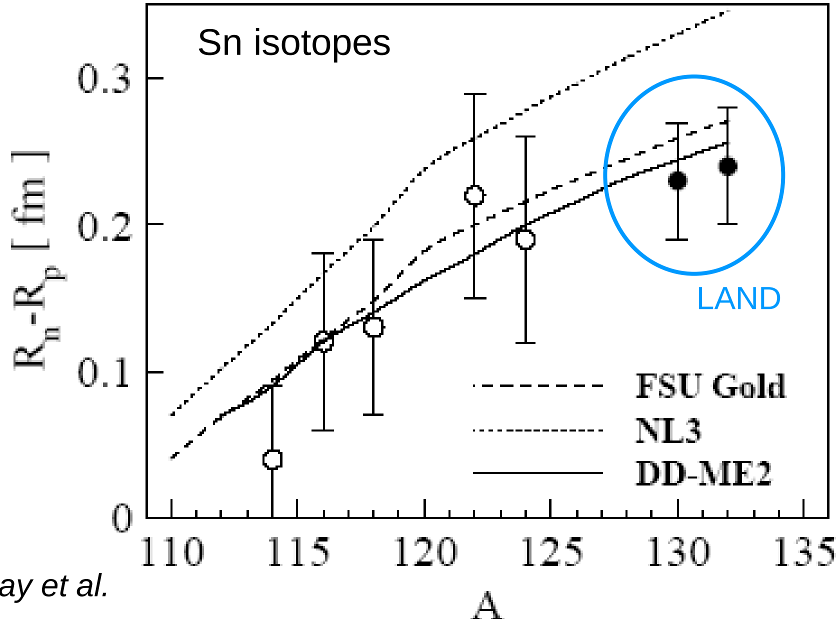




R_n – R_p :

^{130}Sn: 0.23 ± 0.04 fm

^{132}Sn: 0.24 ± 0.04 fm



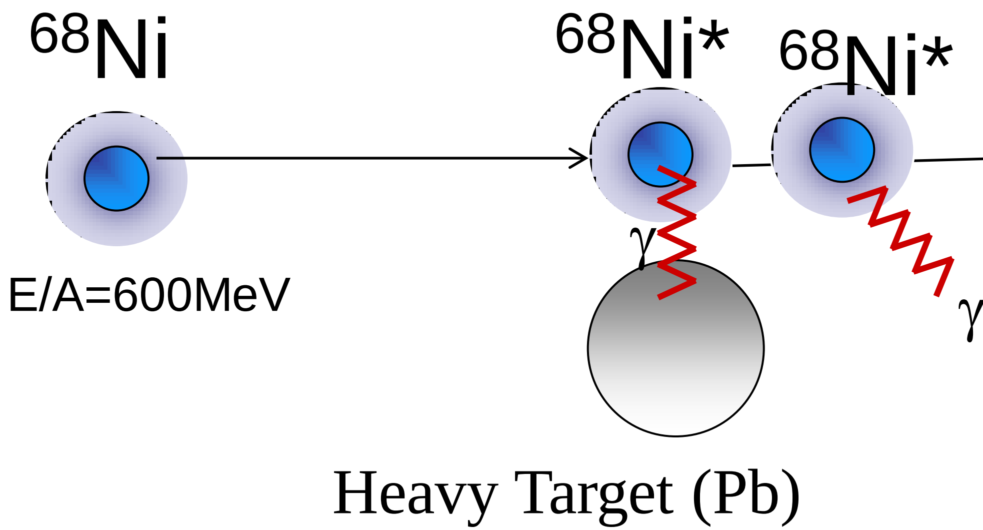
A. Klimkiewicz, N. Paar, et al,

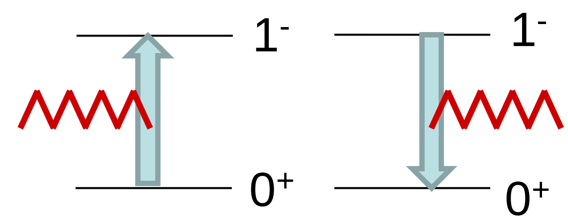
submitted to PRL

A.Krasznahorkay et al.
PRL 82(1999)3216

Slide:T.Aumann

$^{68}Ni(\gamma,\gamma')$　仮想光子の散乱実験

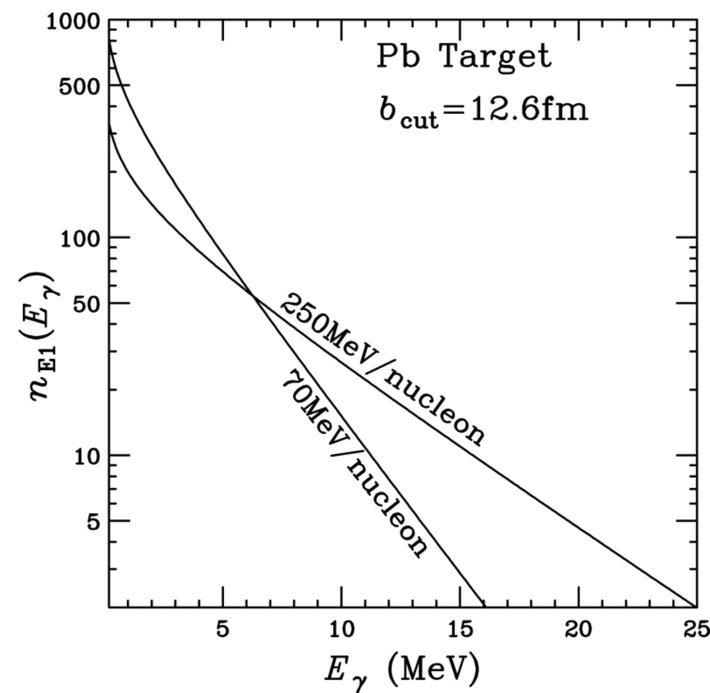




Equivalent Photon Method

$$\frac{d\sigma_{E1}}{dE_x} = \frac{16\pi^3}{9\hbar c} N_{E1}(E_x)\frac{dB(E1)}{dE_x}$$

Cross section = (Photon Number)x(Transition Probability)



E_γ spectrum by BaF_2

PRL 102, 092502 (2009).
O. Wieland et al.,

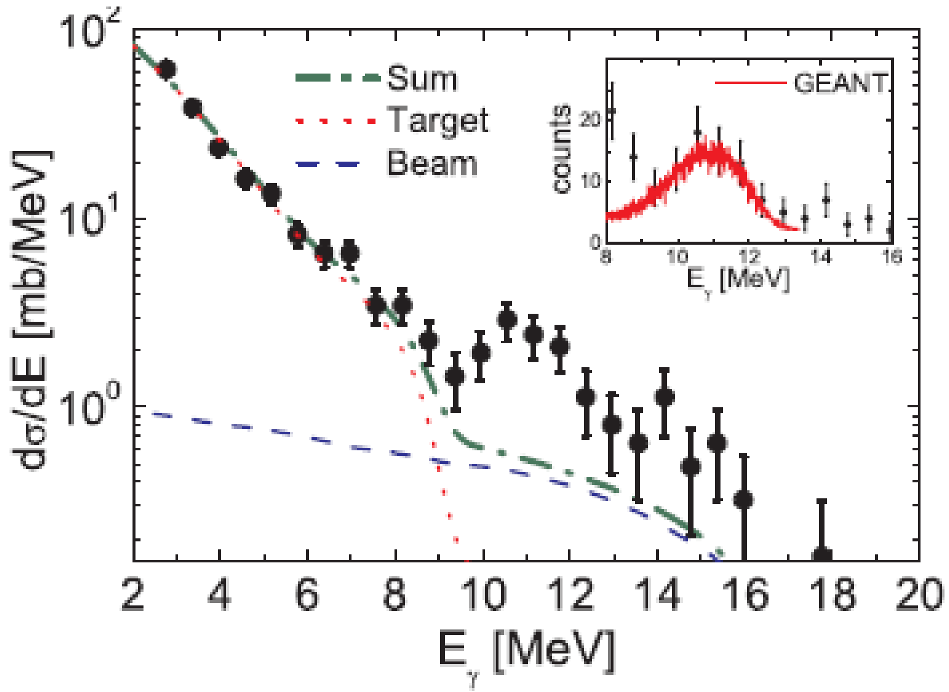
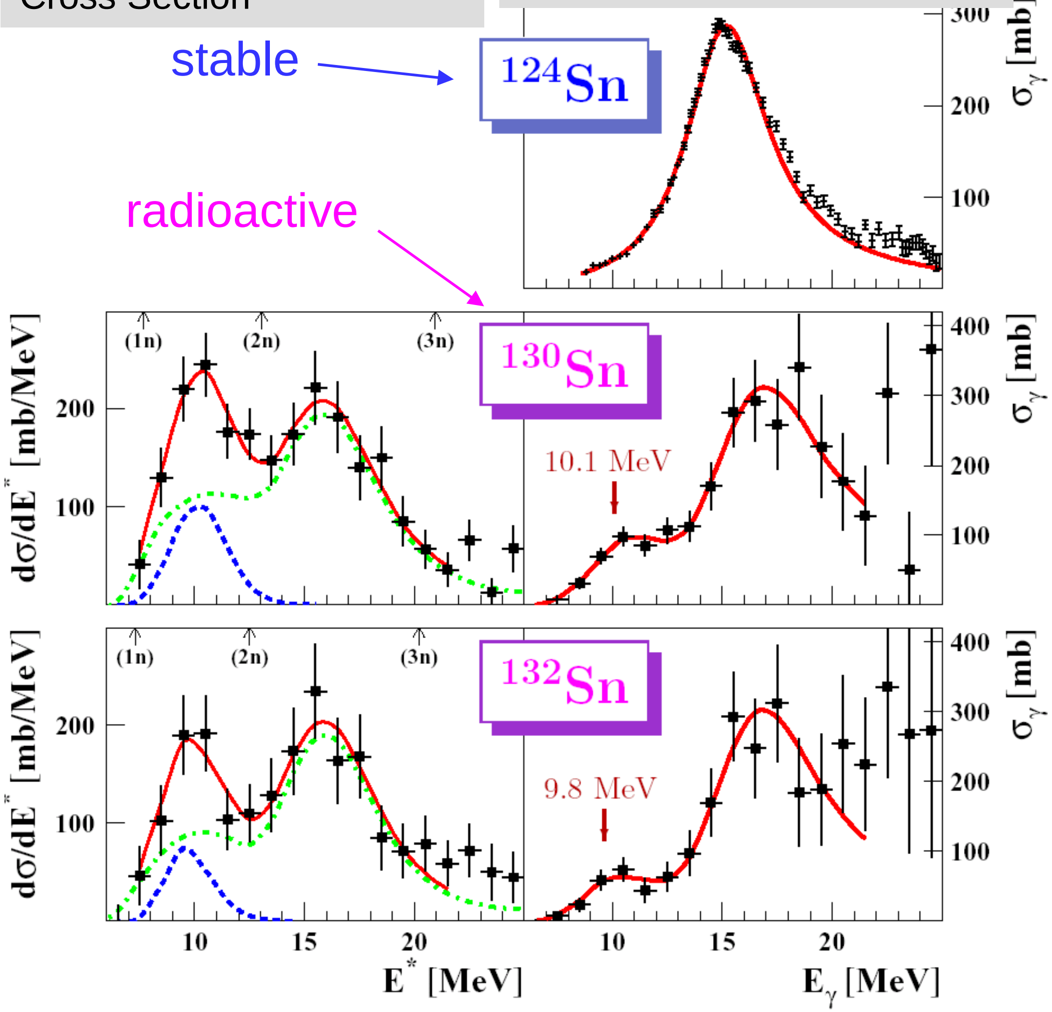


FIG. 2 (color online). The high-energy γ-ray spectrum measured with BaF_2 detectors and Doppler corrected with the velocity of the projectile. The lines are the statistical model calculations for the target (dotted line) and for the beam (dashed line) nuclei. In the inset the continuous line superimposed to the measured data is the result of a GEANT simulation for a γ-transition at 11 MeV.

Dipole-strength distributions in neutron-rich Sn isotopes

Coulomb Breakup Cross Section

Photo absorption cross section



A	PDR		GDR		
	E_{centr} [MeV]	sum rule fraction [%]	E_{centr} [MeV]	Γ [MeV]	sum rule fraction [%]
^{124}Sn	-	-	15.3	4.8	116
^{130}Sn	10.1 (0.7)	7.0 (3.0)	15.9 (0.5)	4.8 (1.8)	145 (19)
^{132}Sn	9.8 (0.7)	4.0 (3.1)	16.1 (0.8)	4.7 (2.2)	125 (32)

PDR

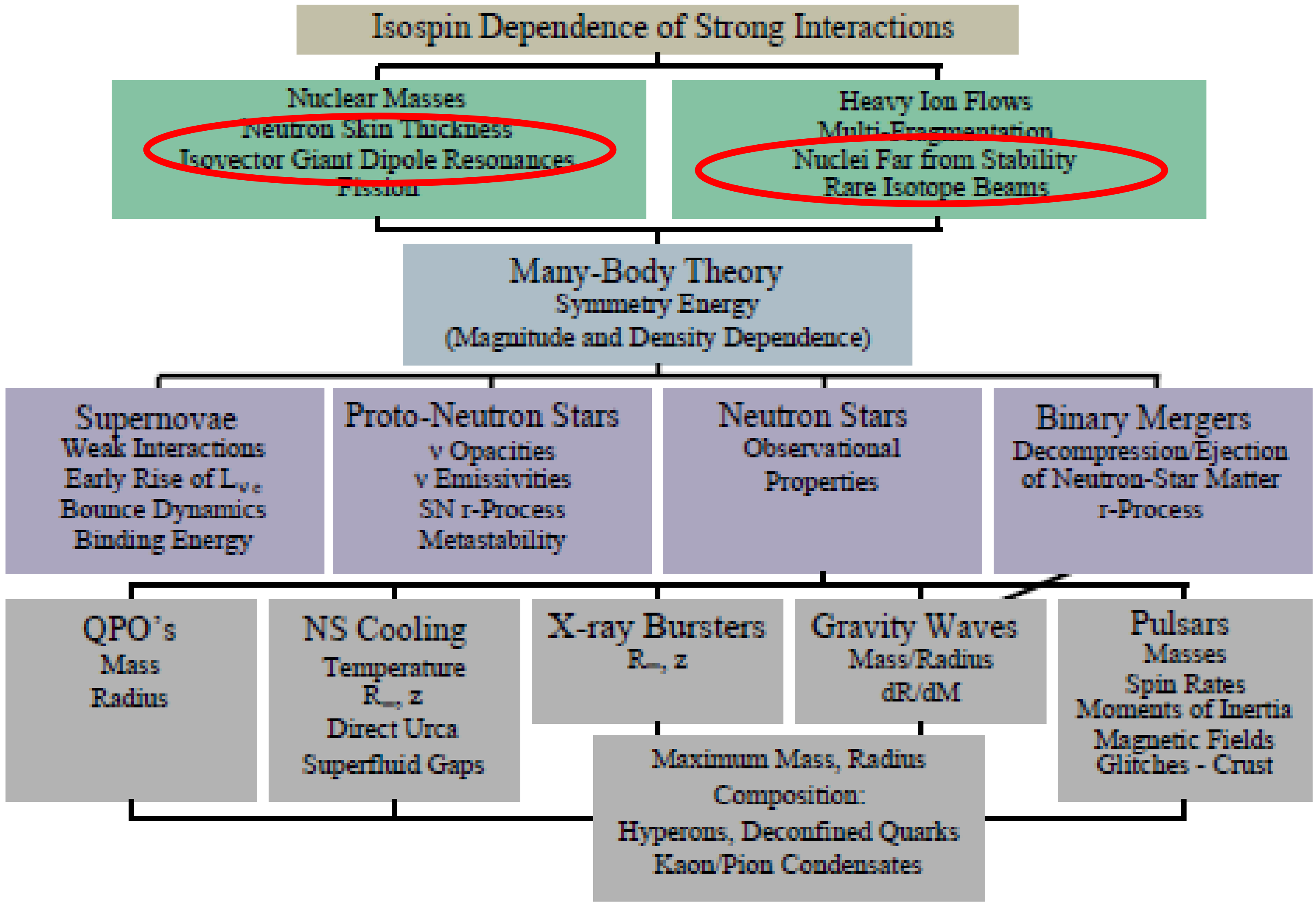
- located at 10 MeV
- exhausts a few % TRK sum rule
- in agreement with theory

GDR

- no deviation from systematics

P. Adrich et al., PRL 95 (2005) 132501

Slide:T.Aumann



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