HADRON 2023

# Chiral symmetry restoration in nuclear medium observed in pionic atoms


## RIKEN Nishina Center
## Kenta Itahashi
### for piAF collaboration


**published 2023/3/23**


nature physics

**T. Nishi, K.I. et al., Nat. Phys. (2023)**

Article https://doi.org/10.1038/s41567-023-02001-x


**Chiral symmetry restoration at high matter density observed in pionic atoms**

- Nature Physics (2023/3/23)
  **Article** DOI: 10.1038/s41567-023-02001-x
- Nature Physics (2023/3/23)
  **News and Views** "Modified in Medium"

# Chiral symmetry restoration in nuclear medium observed in pionic atoms

- **Dominant symmetry of the vacuum in low-energy QCD.**
- **Spontaneous breakdown due to the non-perturbative nature of the strong interaction.**
- **Non-trivial structure of the QCD vacuum.**

**published 2023/3/23**

nature physics

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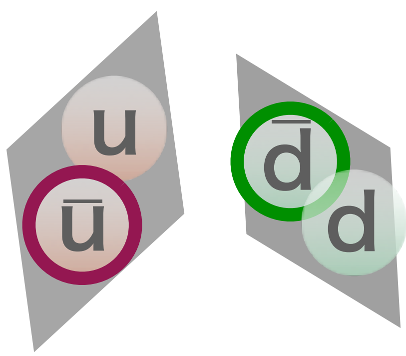
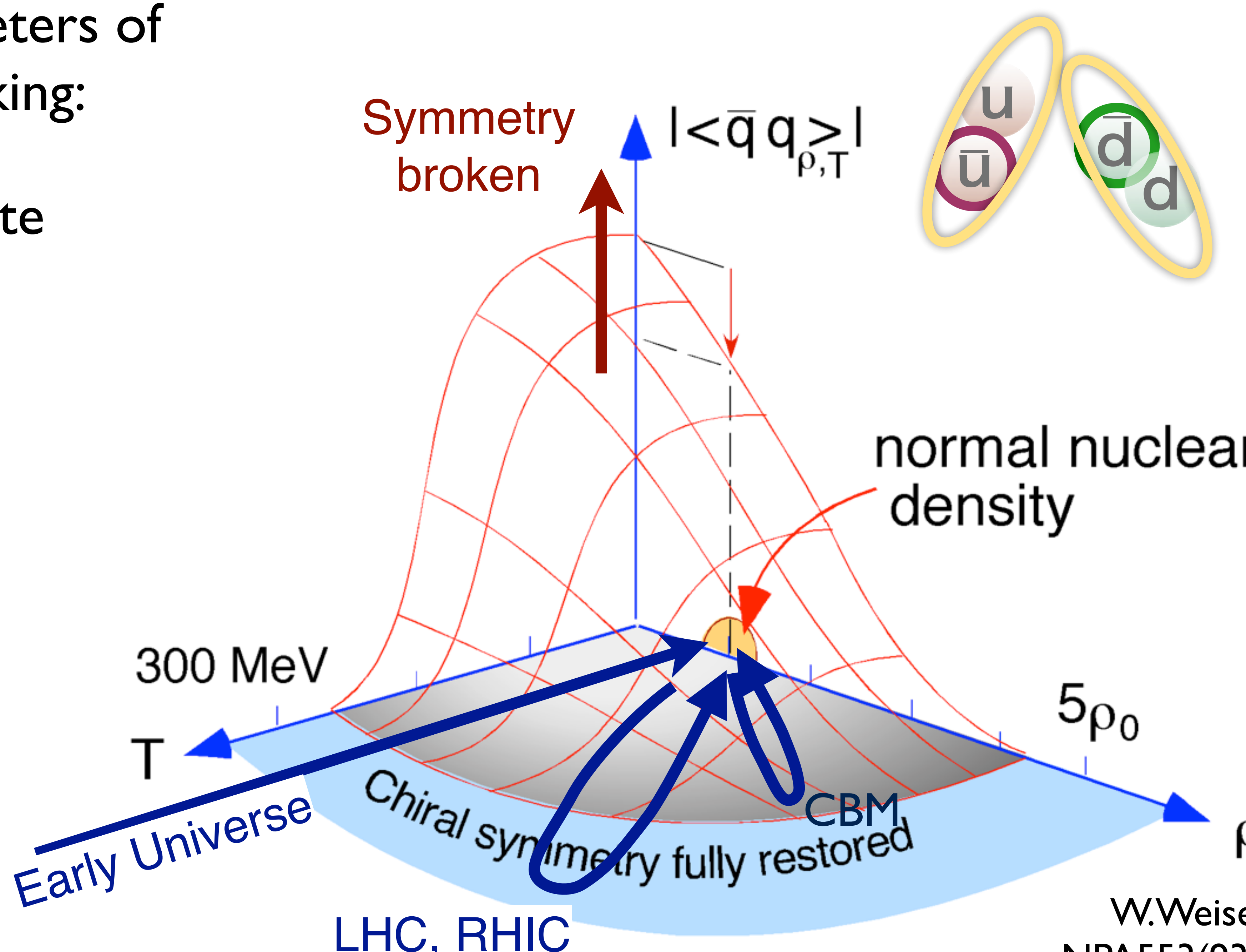
# Chiral condensate, order parameter of chiral symmetry

One of order parameters of
χ-symmetry breaking:

Chiral condensate

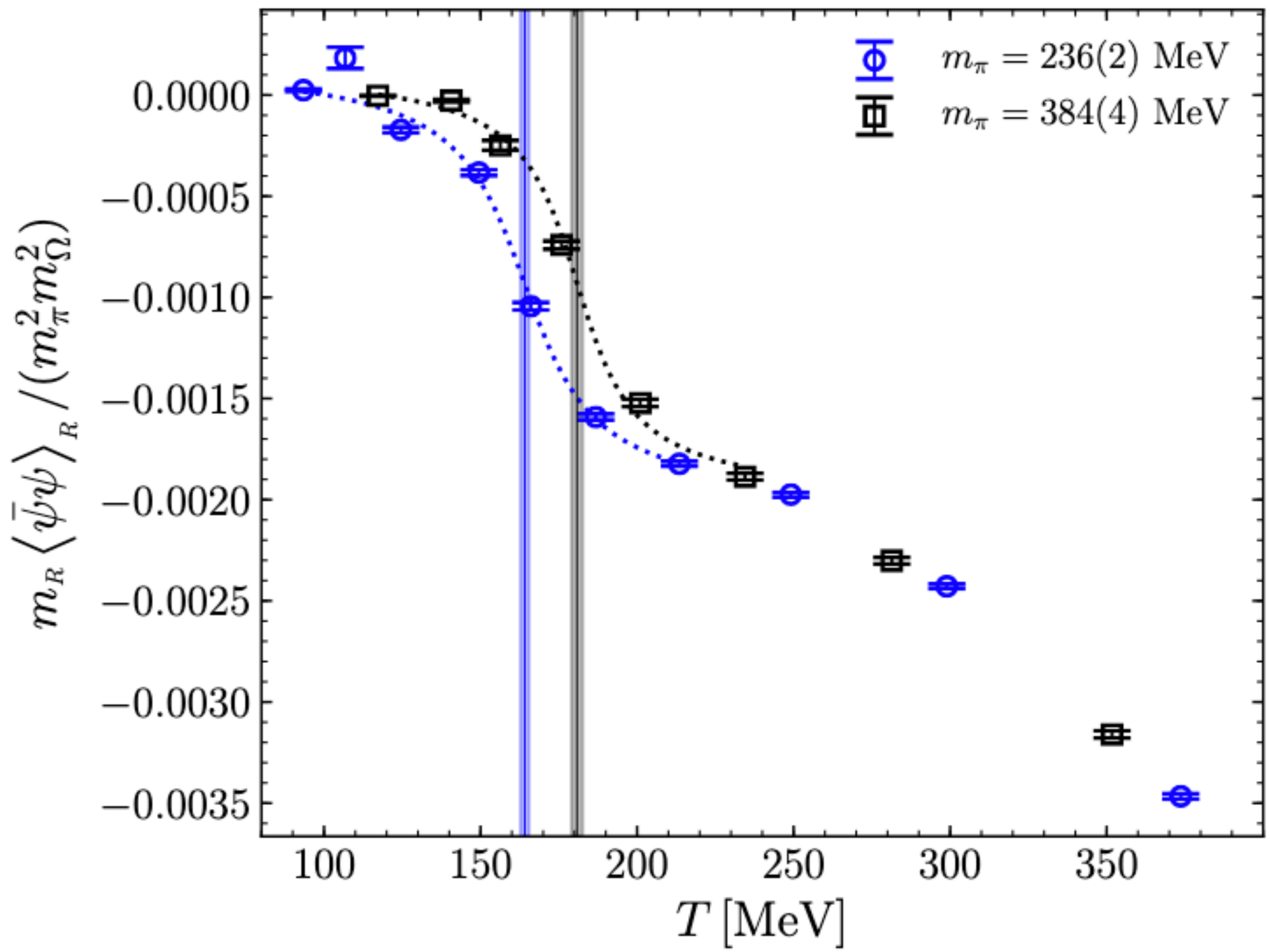



W.Weise, NPA553(93)59.

Analysis of material properties
of QCD vacuum

# Lattice QCD calculated T dependence of chiral condensate



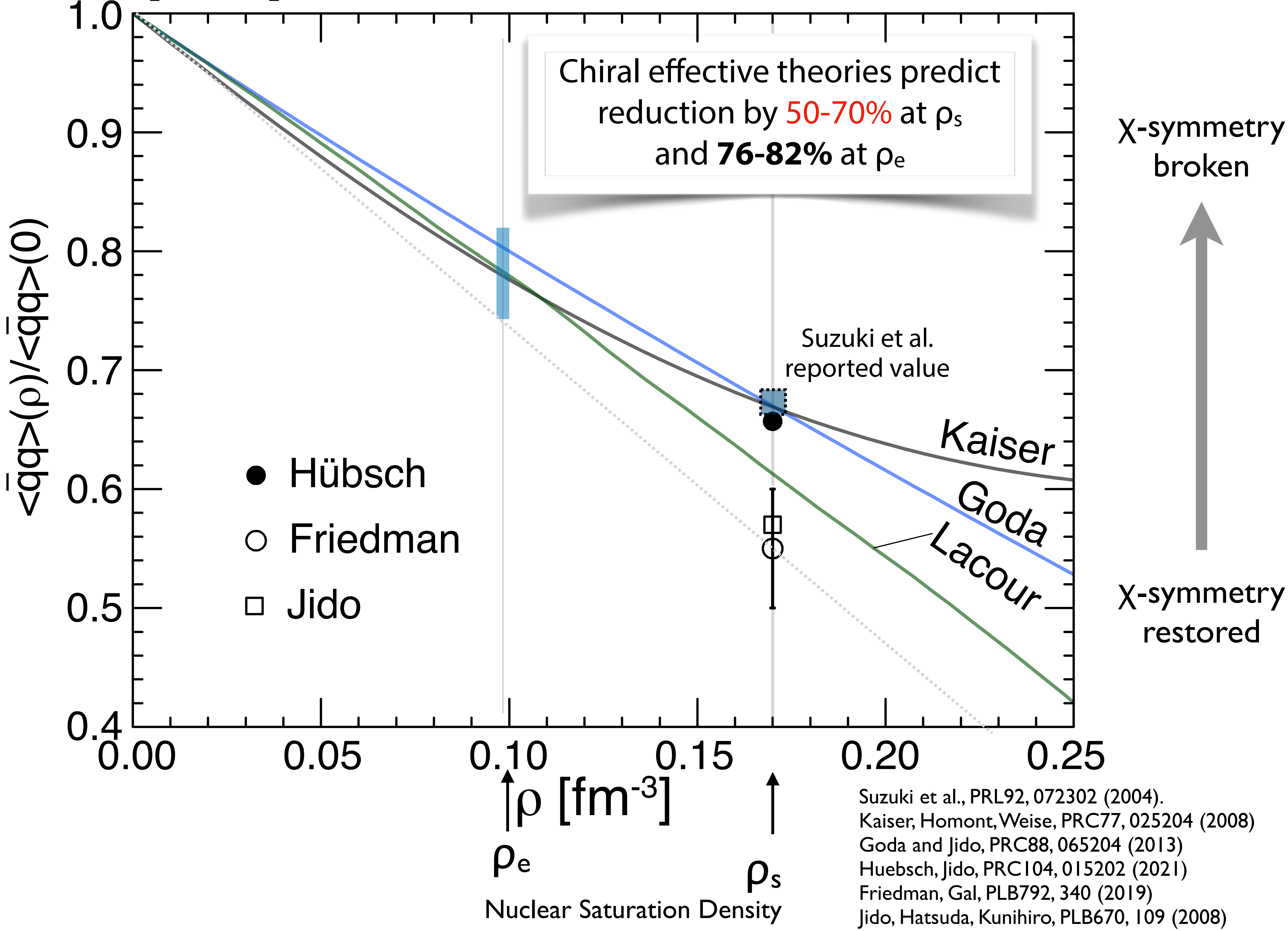

χ-symmetry broken

χ-symmetry restored

Remark: sign problem makes it difficult for lattice to approach non-zero ρ region

Jon-Ivar Skullerud
PRD105(2022)034504

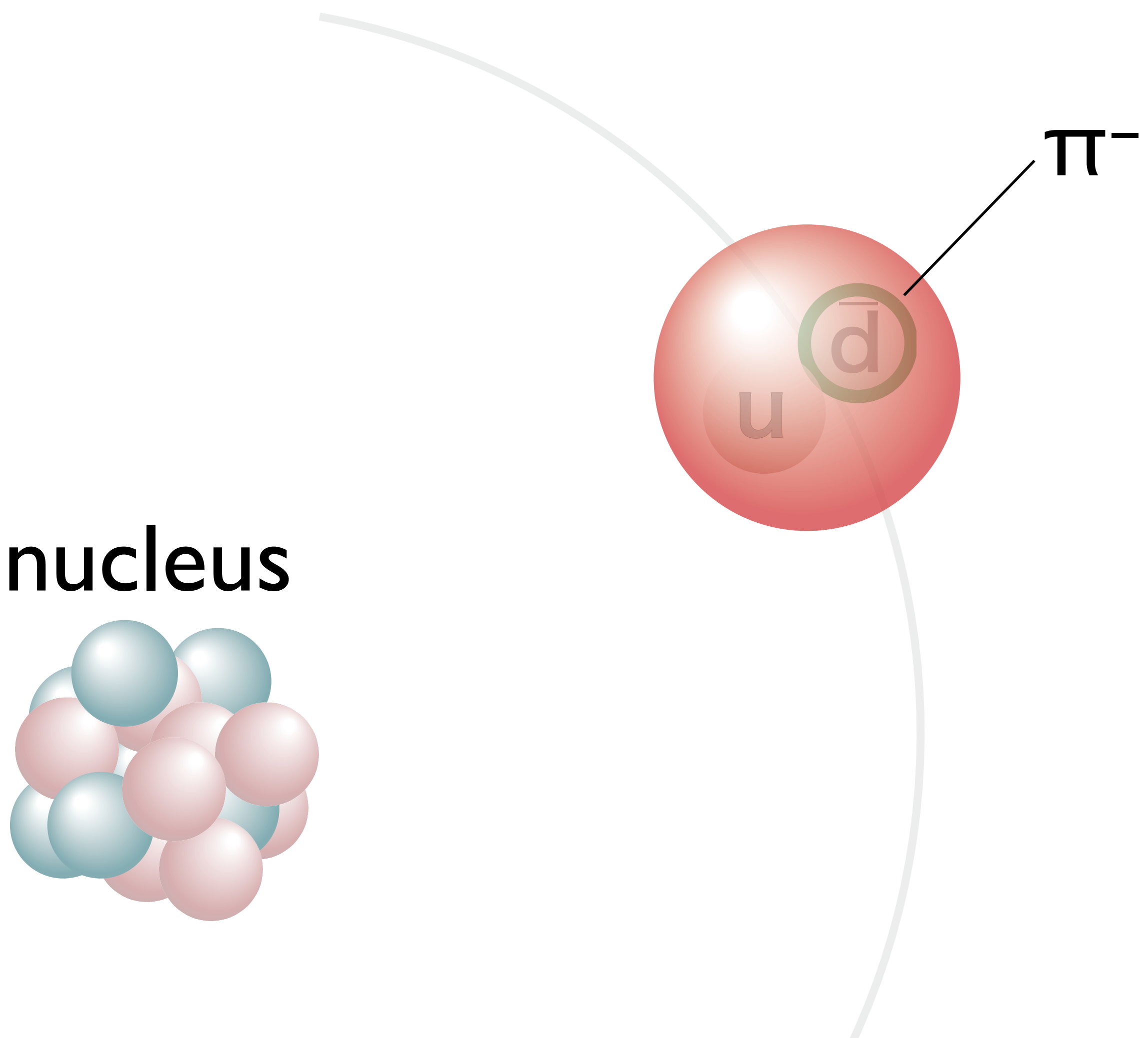
# ρ dependence of chiral condensate





Suzuki et al., PRL92, 072302 (2004).
Kaiser, Homont, Weise, PRC77, 025204 (2008)
Goda and Jido, PRC88, 065204 (2013)
Huebsch, Jido, PRC104, 015202 (2021)
Friedman, Gal, PLB792, 340 (2019)
Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)
Lacour, Oller, Meissner, J. Phys. G. 37, 125002 (2010)

# Pionic atoms



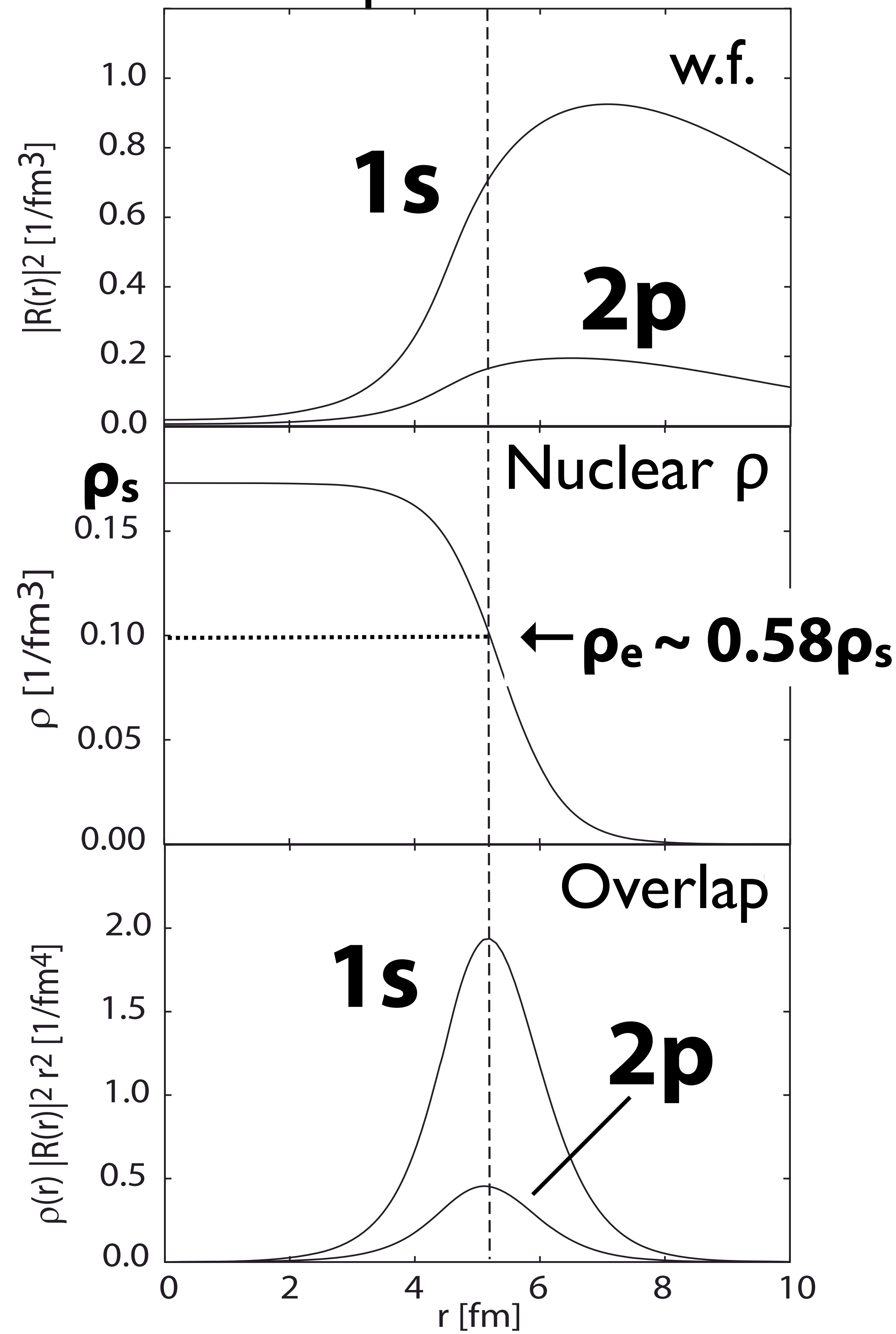

Ericson-Ericson potential

$$U_{\rm opt}(r) = U_s(r) + U_p(r),$$

$$U_s(r) = b_0\, \rho + \mathbf{b_1}\, (\rho_n - \rho_p) + B_0\, \rho^2$$

$$U_p(r) = \frac{2\pi}{\mu} \vec{\nabla} \cdot [c(r) + \varepsilon_2^{-1} C_0 \rho^2(r)] L(r) \vec{\nabla}$$

pionic Sn




Ikeno et al., PTP126 (2011) 483

# Pion-nucleus interaction

Overlap between
pion w.f. and nucleus
→ π works as a probe
at $\rho_e \sim 0.58\rho_s$

π-nucleus interaction is changed
for wavefunction renormalization
of medium effect

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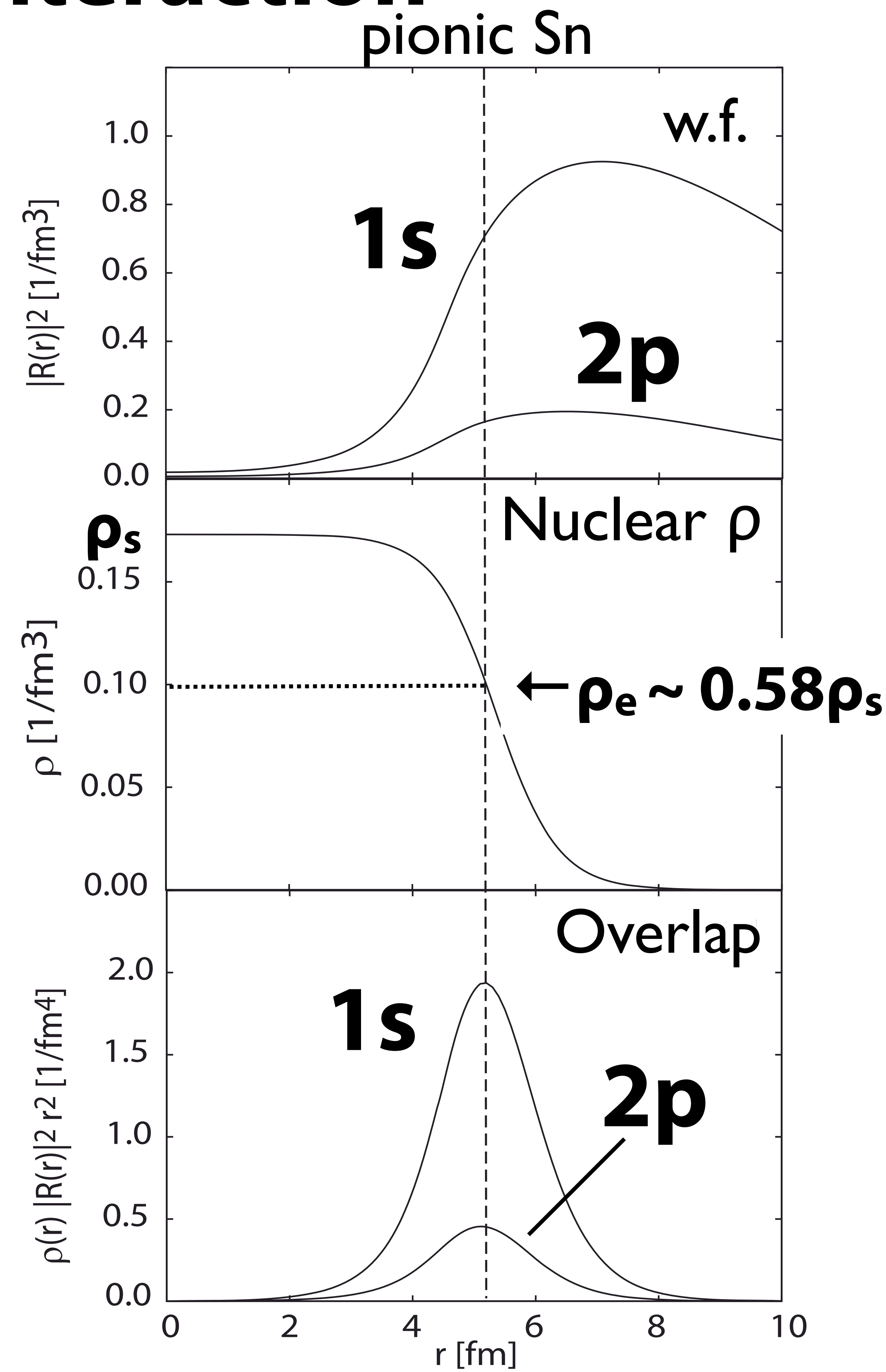


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# Pion-nucleus interaction and chiral condensate

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**In-medium Glashow-Weinberg relation**

$$\frac{\langle\bar{q}q\rangle^*}{\langle\bar{q}q\rangle} \simeq \left(\frac{b_1^{\mathbf{v}}}{b_1}\right)^{1/2}\left(1-\gamma\frac{\rho}{\rho_0}\right)$$

$\gamma = 0.184 \pm 0.003$

Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)

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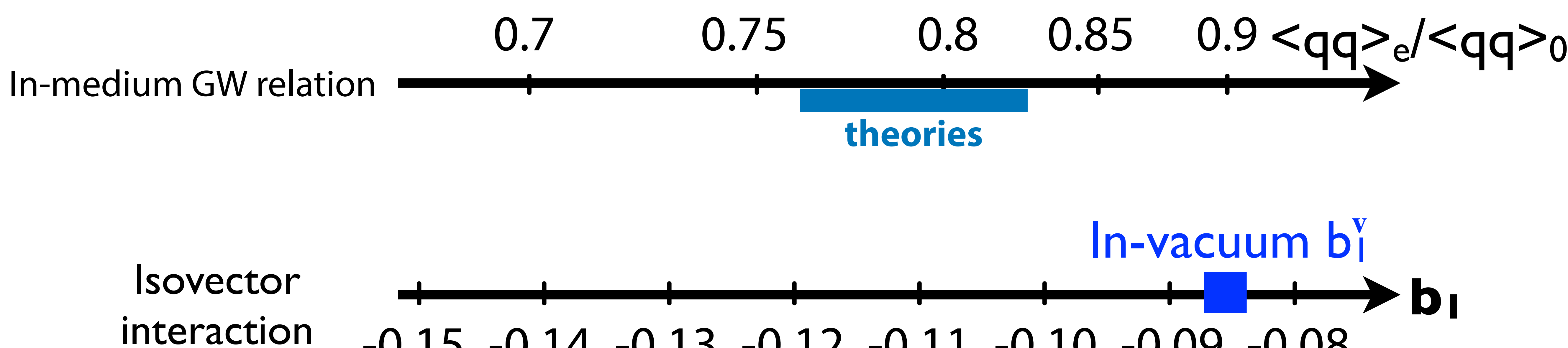
Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)

**Pionic hydrogen and deuterium**

$b_1^{\mathrm{v}} = 0.0866 \pm 0.0010$

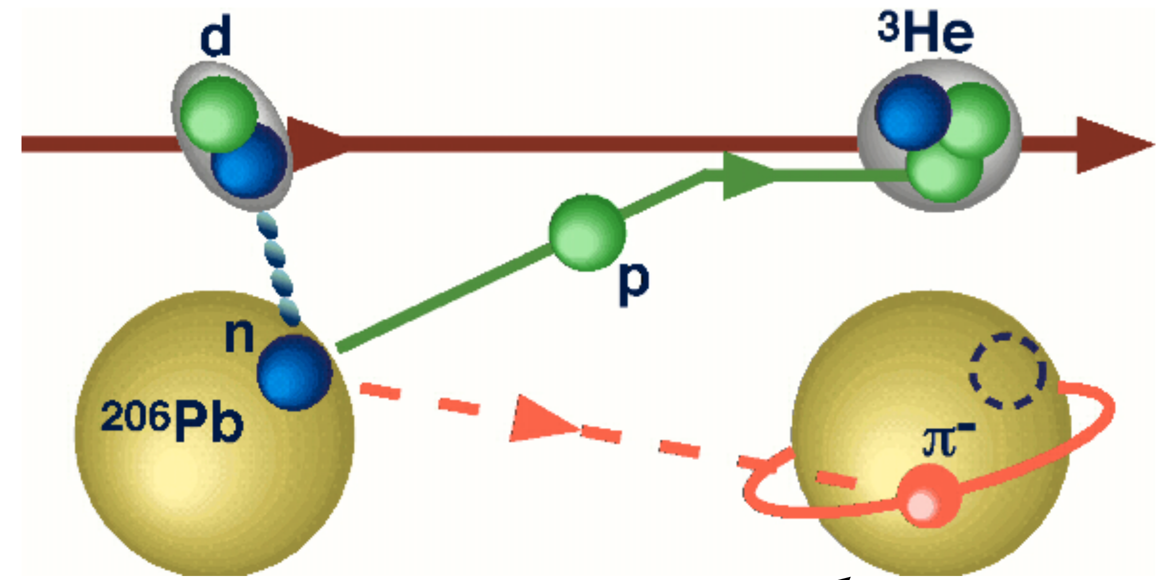
Hirtl et al., EPJA57, 70 (2021)



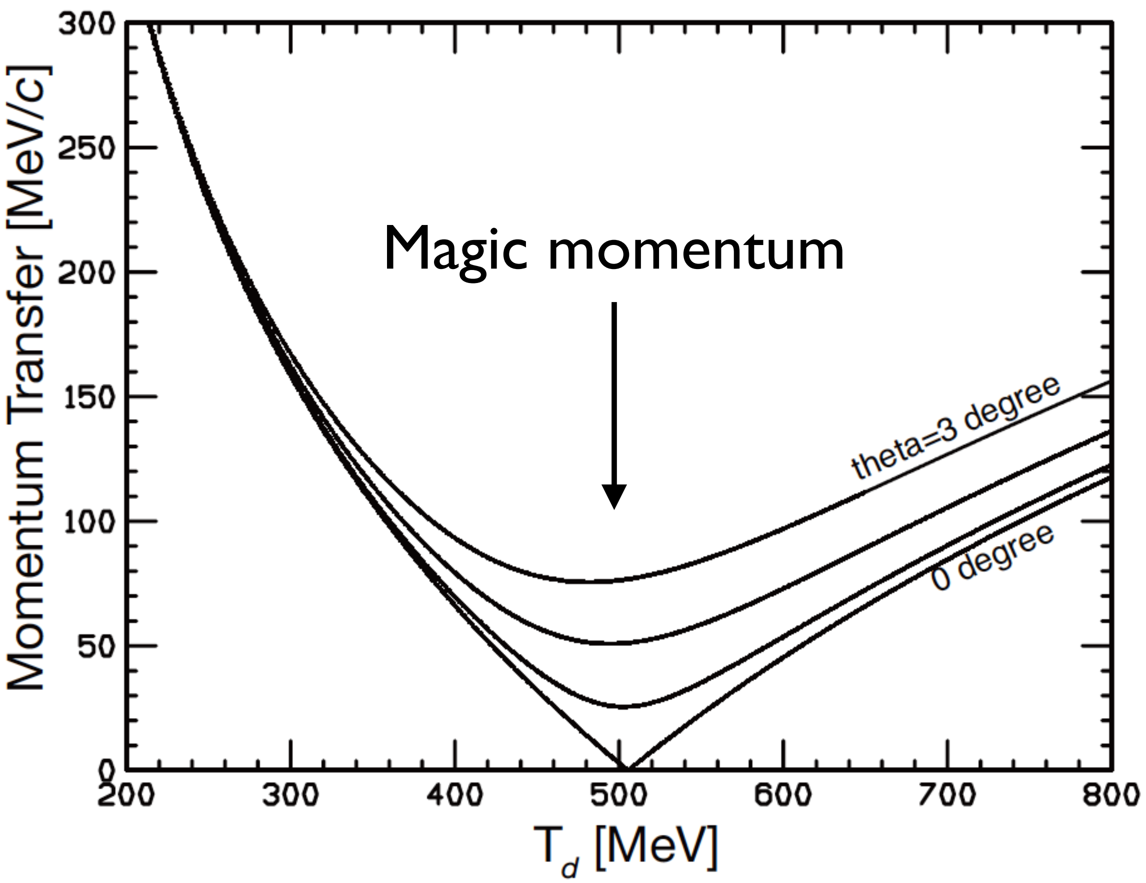
# Spectroscopy of pionic atoms in ($d$,$^3$He) reactions

Missing mass spectroscopy to measure excitation spectrum of pionic atoms

Direct production of pionic atoms

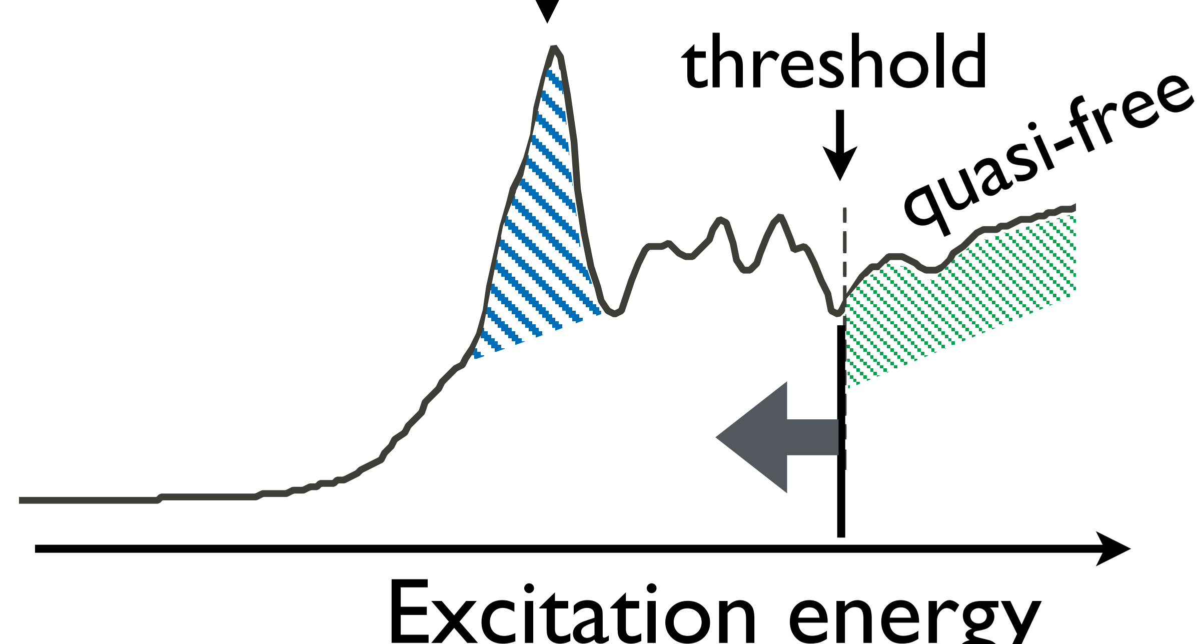



Momentum transfer

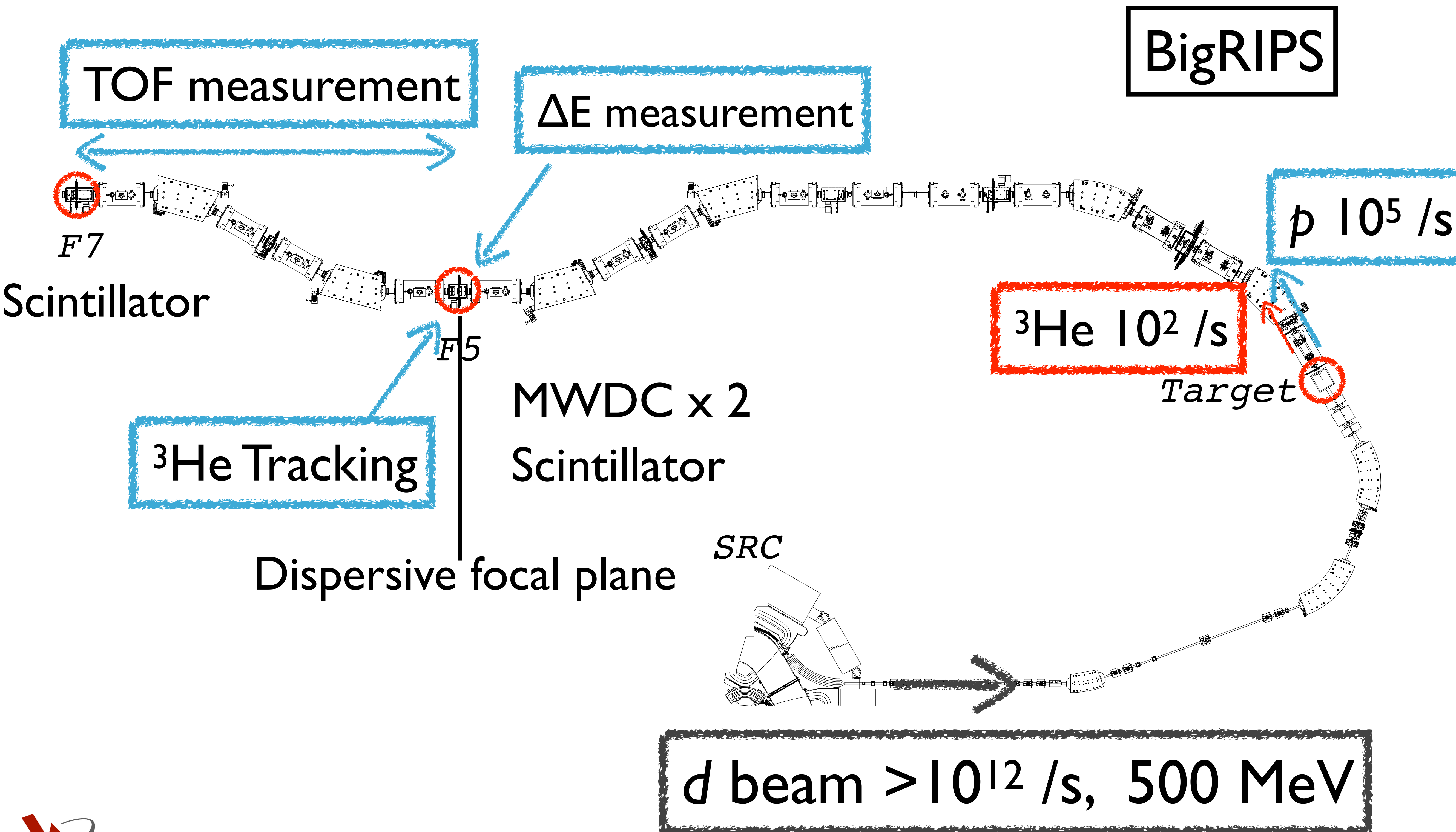



Pion bound state

(coupled with *n* hole)



# (d,³He) Reaction Spectroscopy in RIBF




Kenta Itahashi, RIKEN

# Pionic $^{121}$Sn atom

Pilot run

15 hours DAQ in 2010

**First simultaneous 1s and 2p observation**

$$B_{1s} = 3.828 \pm 0.013(\mathrm{stat})^{+0.036}_{-0.033}(\mathrm{syst})\ \mathrm{MeV}$$
$$\Gamma_{1s} = 0.252 \pm 0.054(\mathrm{stat})^{+0.053}_{-0.070}(\mathrm{syst})\ \mathrm{MeV}$$
$$B_{2p} = 2.238 \pm 0.015(\mathrm{stat})^{+0.046}_{-0.043}(\mathrm{syst})\ \mathrm{MeV}$$

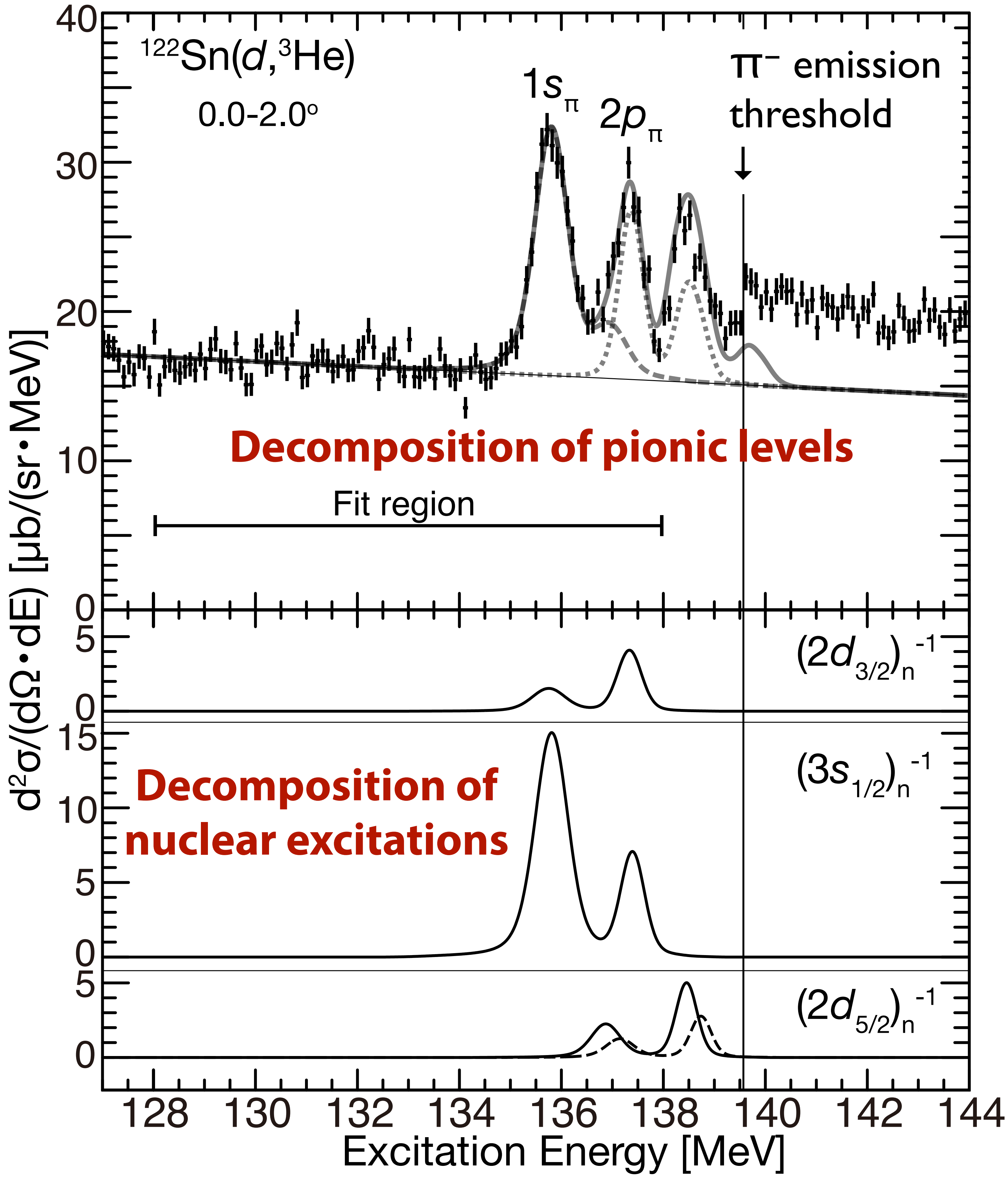
Resolution 394 keV (FWHM)

Theories

$B_{1s}$= 3.787–3.850 MeV

$\Gamma_{1s}$= 0.306–0.324 MeV

$B_{2p}$= 2.257–2.276 MeV




T. Nishi KI et al., PRL120, 152505 (2018)

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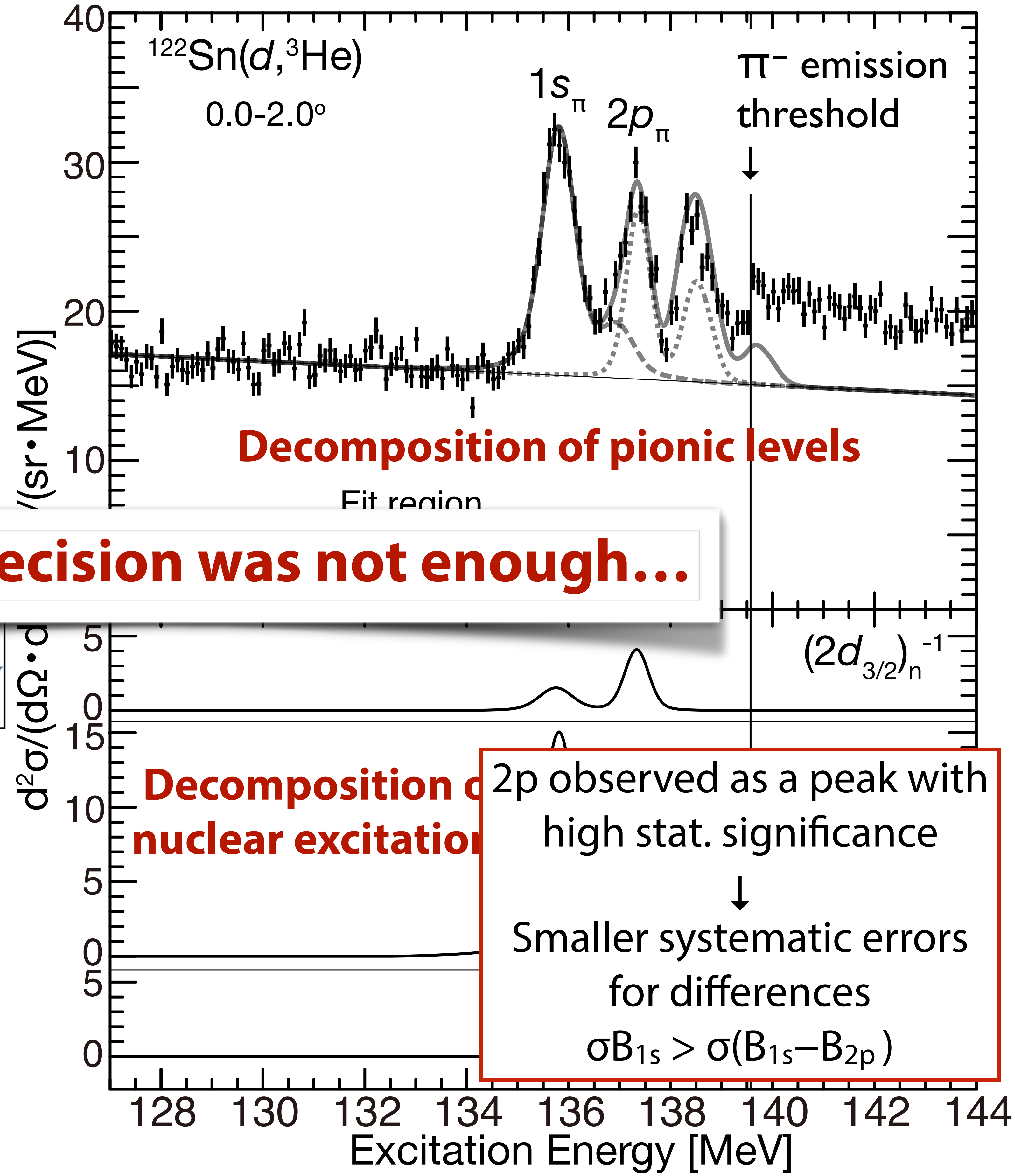


**However, precision was not enough…**

2p observed as a peak with high stat. significance

↓

Smaller systematic errors for differences

$\sigma B_{1s} > \sigma(B_{1s} - B_{2p})$

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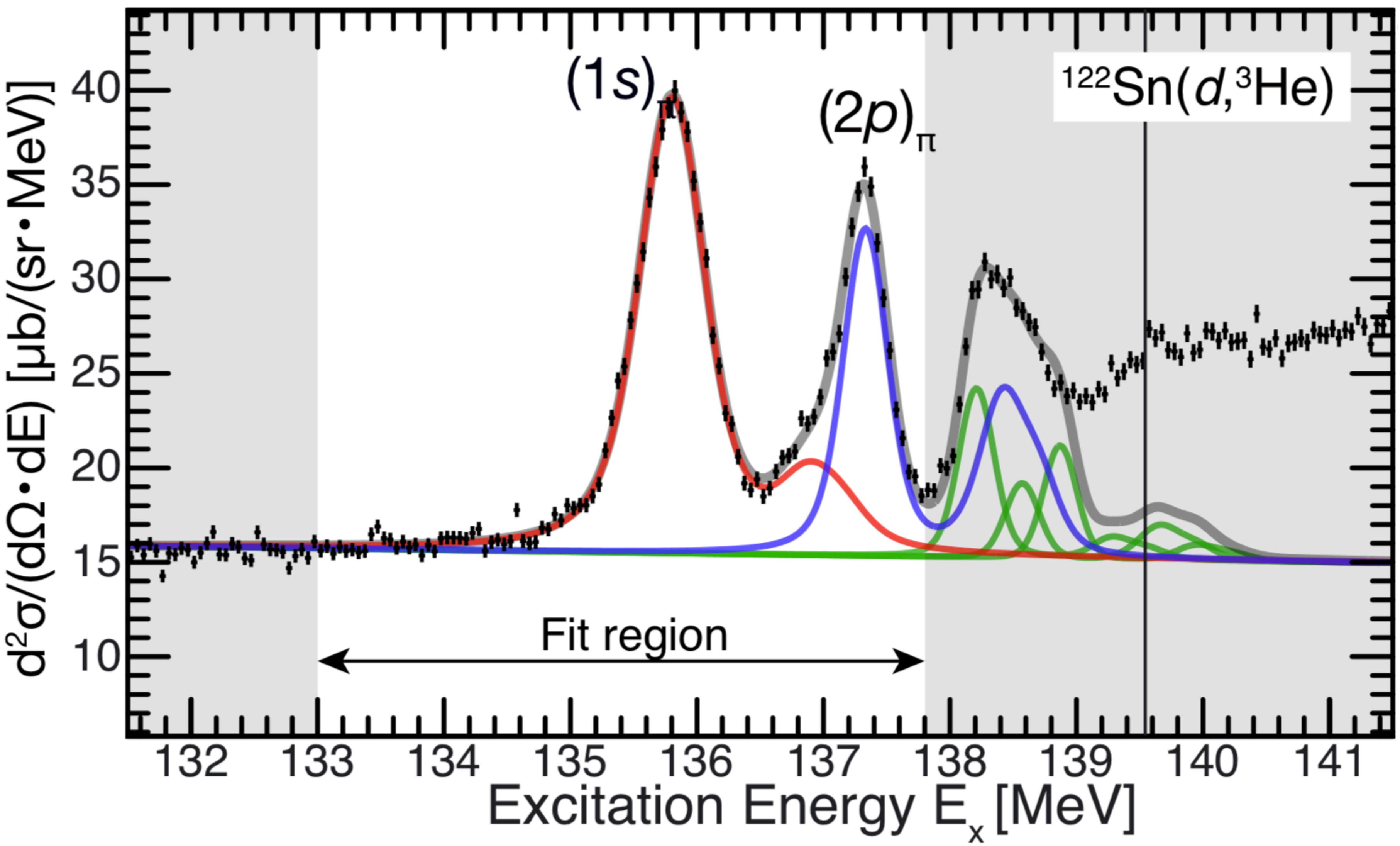
T. Nishi KI et al., PRL120, 152505 (2018)

# High Precision Spectrum of $^{122}Sn(d,^3He)$ in 2014 run

**Pionic atom unveils hidden structure of QCD vacuum**

Takahiro Nishi[1], Kenta Itahashi[1,*] DeukSoon Ahn[1,2], Georg P.A. Berg[3], Masanori Dozono[1], Daijiro Etoh[4], Hiroyuki Fujioka[5], Naoki Fukuda[1], Nobuhisa Fukunishi[1], Hans Geissel[6], Emma Haettner[6], Tadashi Hashimoto[1], Ryugo S. Hayano[7], Satoru Hirenzaki[8], Hiroshi Horii[7], Natsumi Ikeno[9], Naoto Inabe[1], Masahiko Iwasaki[1], Daisuke Kameda[1], Keichi Kisamori[10], Yu Kiyokawa[10], Toshiyuki Kubo[1], Kensuke Kusaka[1], Masafumi Matsushita[10], Shin'ichiro Michimasa[10], Go Mishima[7], Hiroyuki Miya[1], Daichi Murai[1], Hideko Nagahiro[8], Megumi Niikura[7], Naoko Nose-Togawa[11], Shinsuke Ota[10], Naruhiko Sakamoto[1], Kimiko Sekiguchi[4], Yuta Shiokawa[4], Hiroshi Suzuki[1], Ken Suzuki[12], Motonobu Takaki[10], Hiroyuki Takeda[1], Yoshiki K. Tanaka[1], Tomohiro Uesaka[1], Yasumori Wada[4], Atomu Watanabe[4], Yuni N. Watanabe[7], Helmut Weick[6], Hiroki Yamakami[5], Yoshiyuki Yanagisawa[1], and Koichi Yoshida[1]




2p observed as a peak with high stat. significance

↓

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$\sigma B_{1s} > \sigma(B_{1s} - B_{2p})$

Nishi, KI et al., Nat. Phys. (2023)

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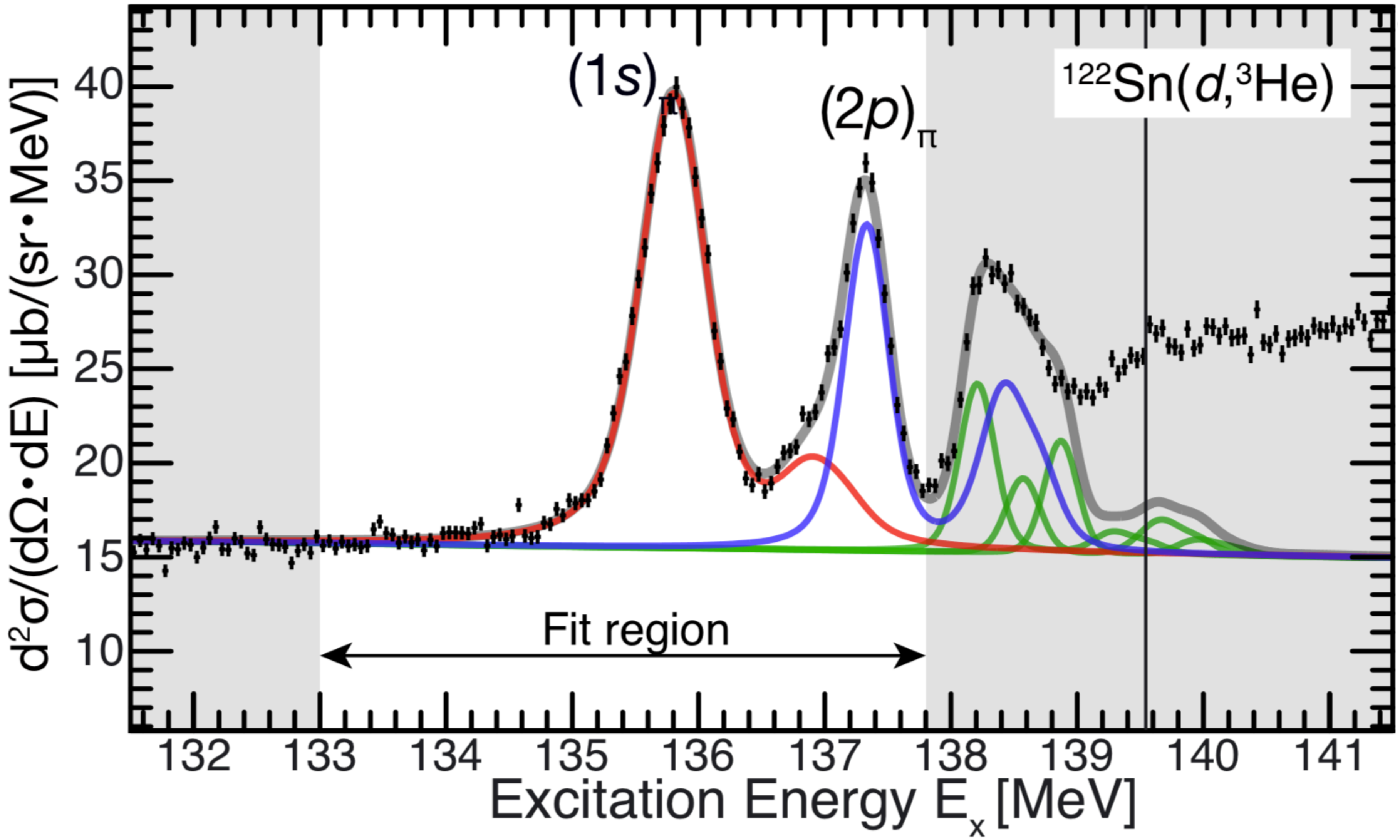



| | [keV] | Statistical | Systematic |
|---|---|---|---|
| $B_\pi(1s)$ | 3831 | $\pm 3$ | $+78 - 76$ |
| $B_\pi(2p)$ | 2276 | $\pm 3$ | $+84 - 83$ |
| $B_\pi(1s) - B_\pi(2p)$ | 1555 | $\pm 4$ | $\pm 12$ |
| $\Gamma_\pi(1s)$ | 316 | $\pm 12$ | $+36 - 39$ |
| $\Gamma_\pi(2p)$ | 164 | $\pm 17$ | $+41 - 32$ |
| $\Gamma_\pi(1s) - \Gamma_\pi(2p)$ | 152 | $\pm 20$ | $+28 - 36$ |

2p observed as a peak with high stat. significance

↓

Smaller systematic errors for differences

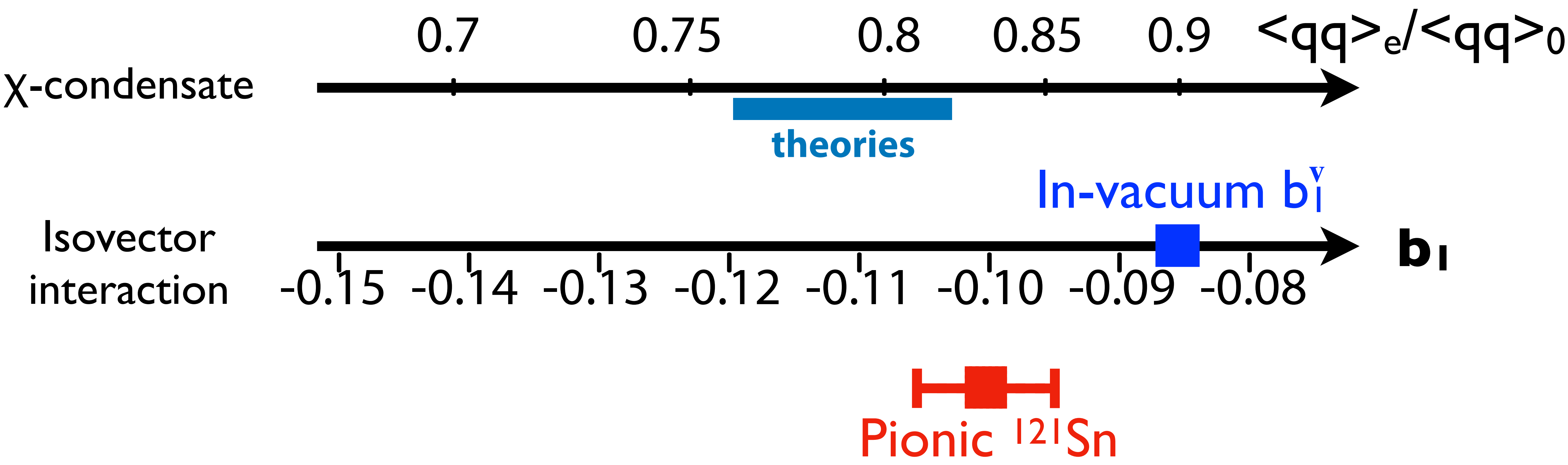
$\sigma B_{1s} > \sigma(B_{1s} - B_{2p})$

Best resolution 287 keV (FWHM)



Nishi, KI et al., Nat. Phys. (2023)

# Deduced $b_1$ from pionic Sn spectrum




**$b_1$ = -0.1005 is deduced**

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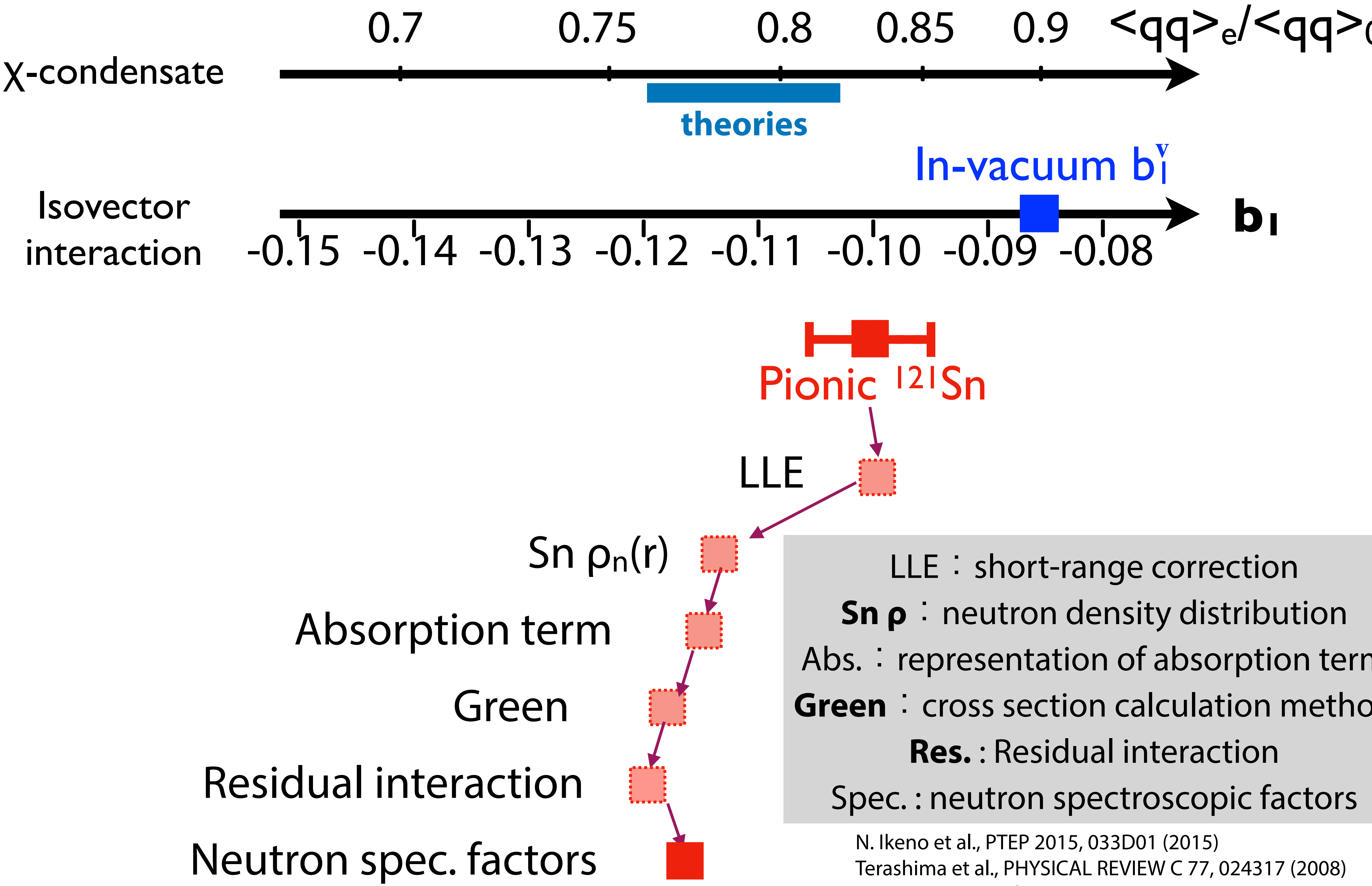
Nishi, KI et al., Nat. Phys. (2023)

# Deduced $b_1$ with corrections




LLE : short-range correction

**Sn ρ** : neutron density distribution

Abs. : representation of absorption term

**Green** : cross section calculation method

**Res.** : Residual interaction

Spec. : neutron spectroscopic factors

N. Ikeno et al., PTEP 2015, 033D01 (2015)
Terashima et al., PHYSICAL REVIEW C 77, 024317 (2008)
Nose-Togawa et al., PRC71, 061601(R) (2005)
Szwec et al., PRC104,054308

Nishi, KI et al., Nat. Phys. (2023)



17

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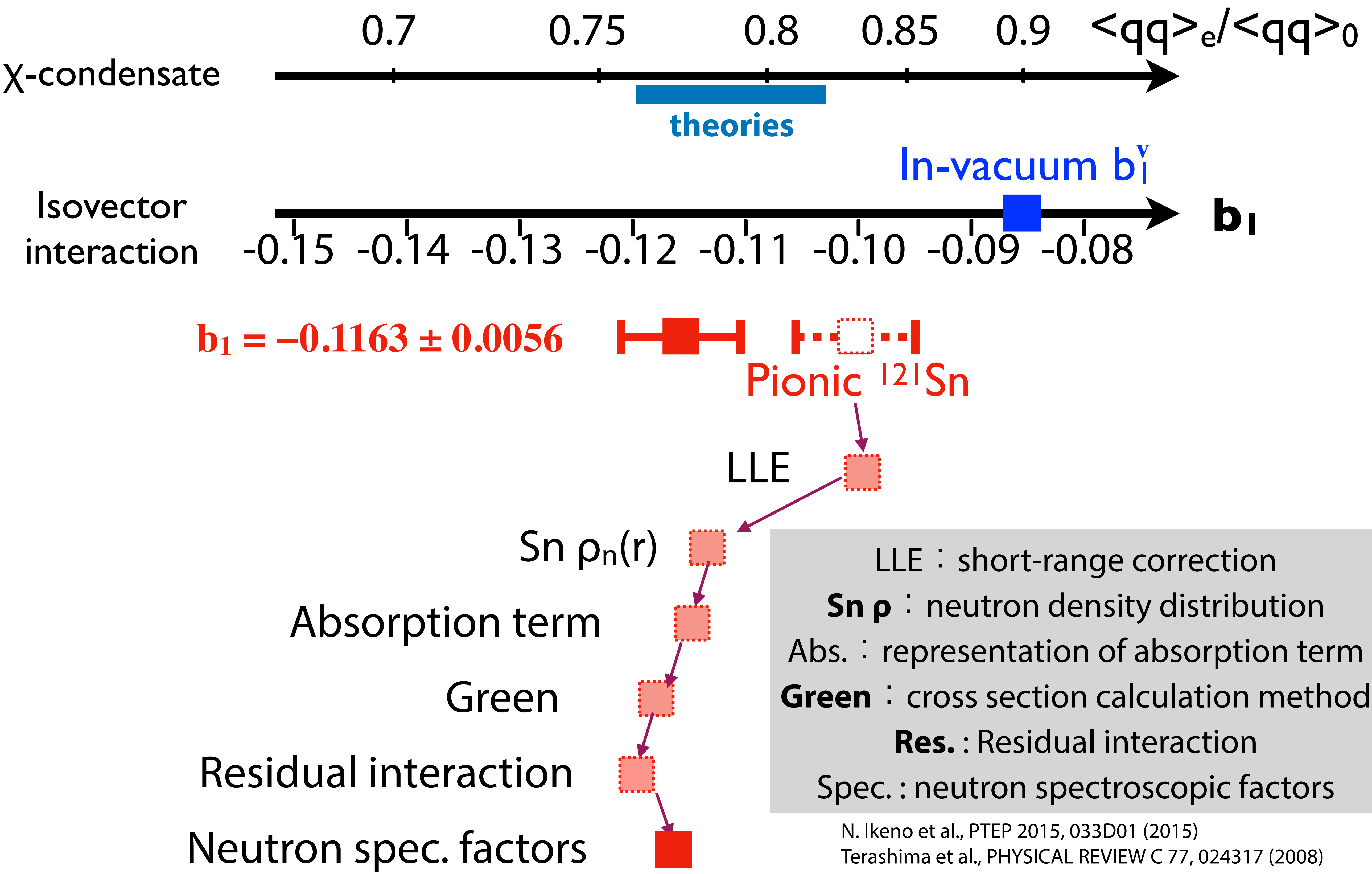



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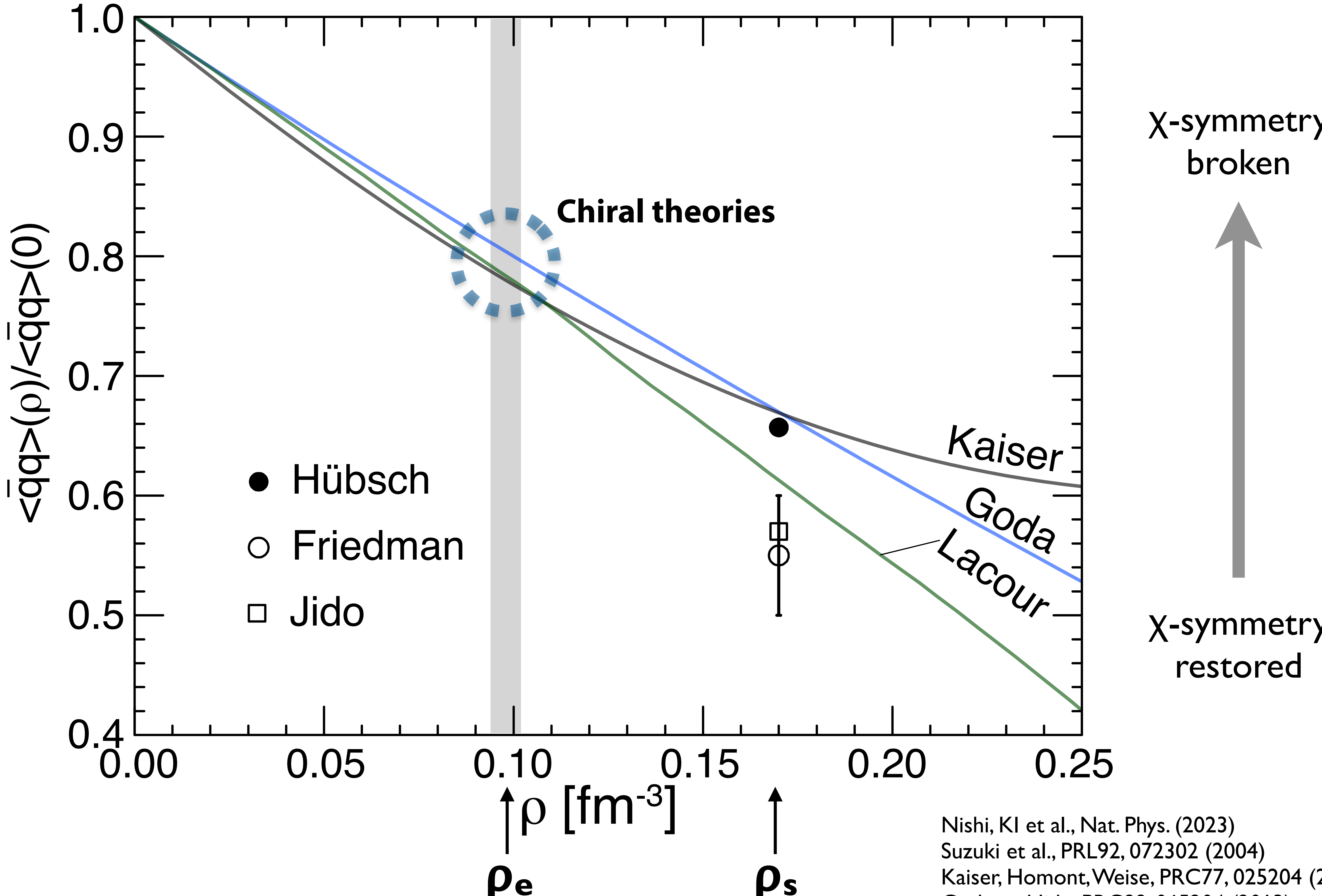
Nishi, KI et al., Nat. Phys. (2023)

# Result: deduced chiral condensate





Nishi, KI et al., Nat. Phys. (2023)
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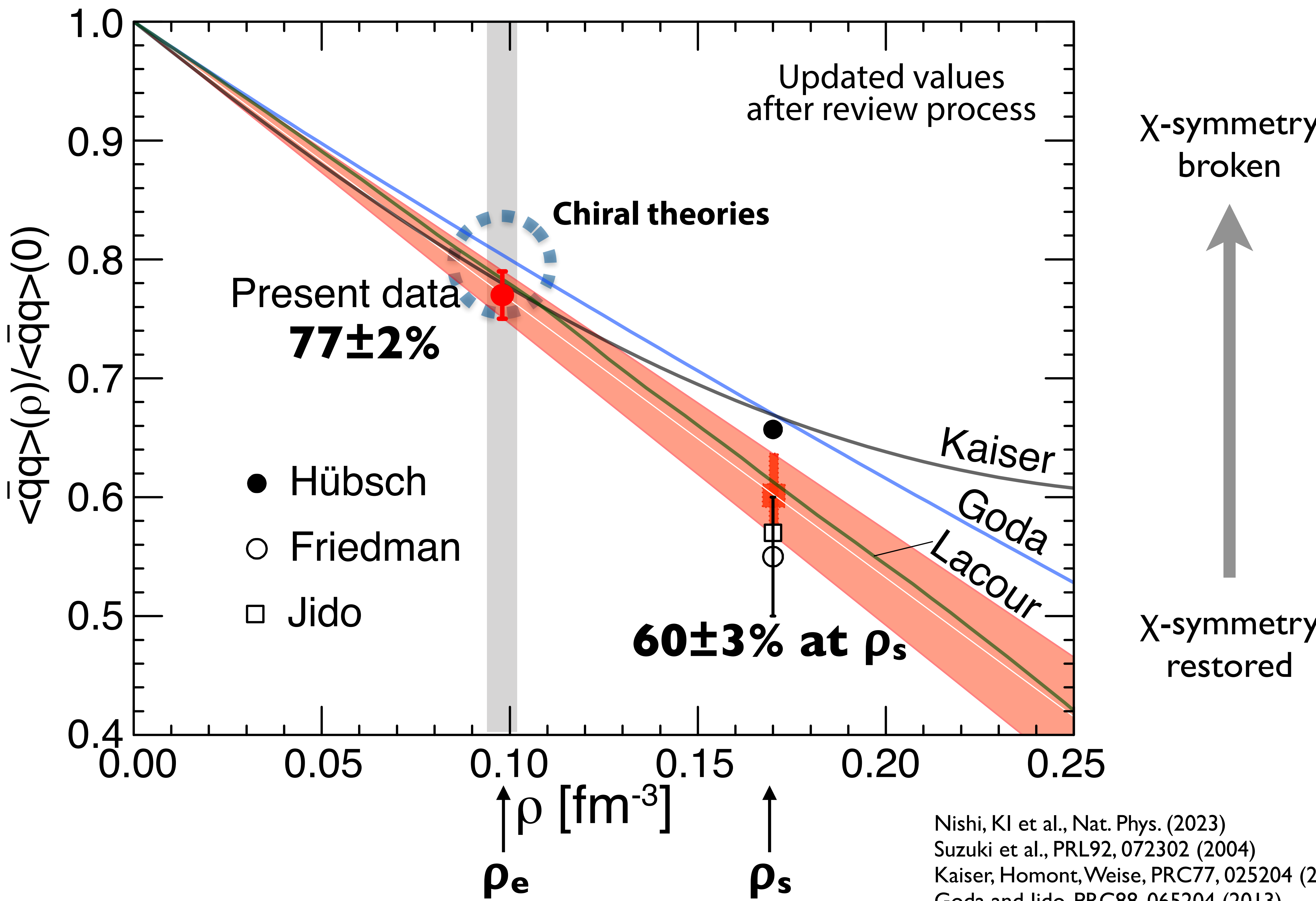


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Lacour, Oller, Meissner, J. Phys. G. 37, 125002 (201

# Summary

- Chiral condensate at $\rho_e$ is evaluated to be reduced by 77±2%, which is linearly extrapolated to 60±3% at the nuclear saturation density.
- The binding energies and widths of the pionic 1*s* and 2*p* states in Sn121 were determined with very high precision. Difference between the 1*s* and 2*p* values drastically reduces the systematic errors.
- Recent theoretical progress was adopted to the <qbar q> deduction, which directly relates the chiral condensate and the pion-nucleus interaction.
- We calculated various corrections for the first time and applied them. The corrections made substantial effects. After the corrections, the chiral condensate ratio was deduced with much higher reliability.
- For future, we are analyzing data of systematic study of pionic Sn isotopes to deduce ρ dependence of chiral condensate. We also plan measurement with “inverse kinematics” reactions for pionic xenon, which leads to future experiments for pionic unstable nuclei.