QNP 2024

Precision spectroscopy of pionic atoms for deduction of chiral symmetry in nuclear matter

RIKEN Nishina Center
Kenta Itahashi

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

- T.Nishi, KI et al., N. Phys. **19**, 788 (2023)
  Article DOI: 10.1038/s41567-023-02001-x
- Nature Physics (2023/3/23)
  News and Views "Modified in Medium"

QNP 2024

Precision spectroscopy of pionic atoms for deduction of **chiral symmetry** in nuclear matter

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

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

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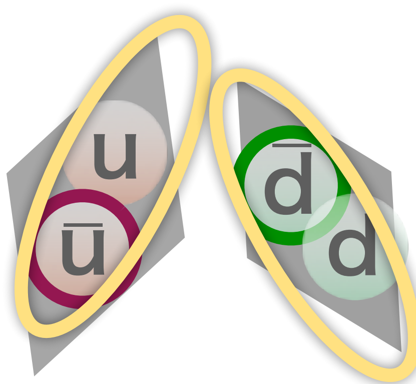
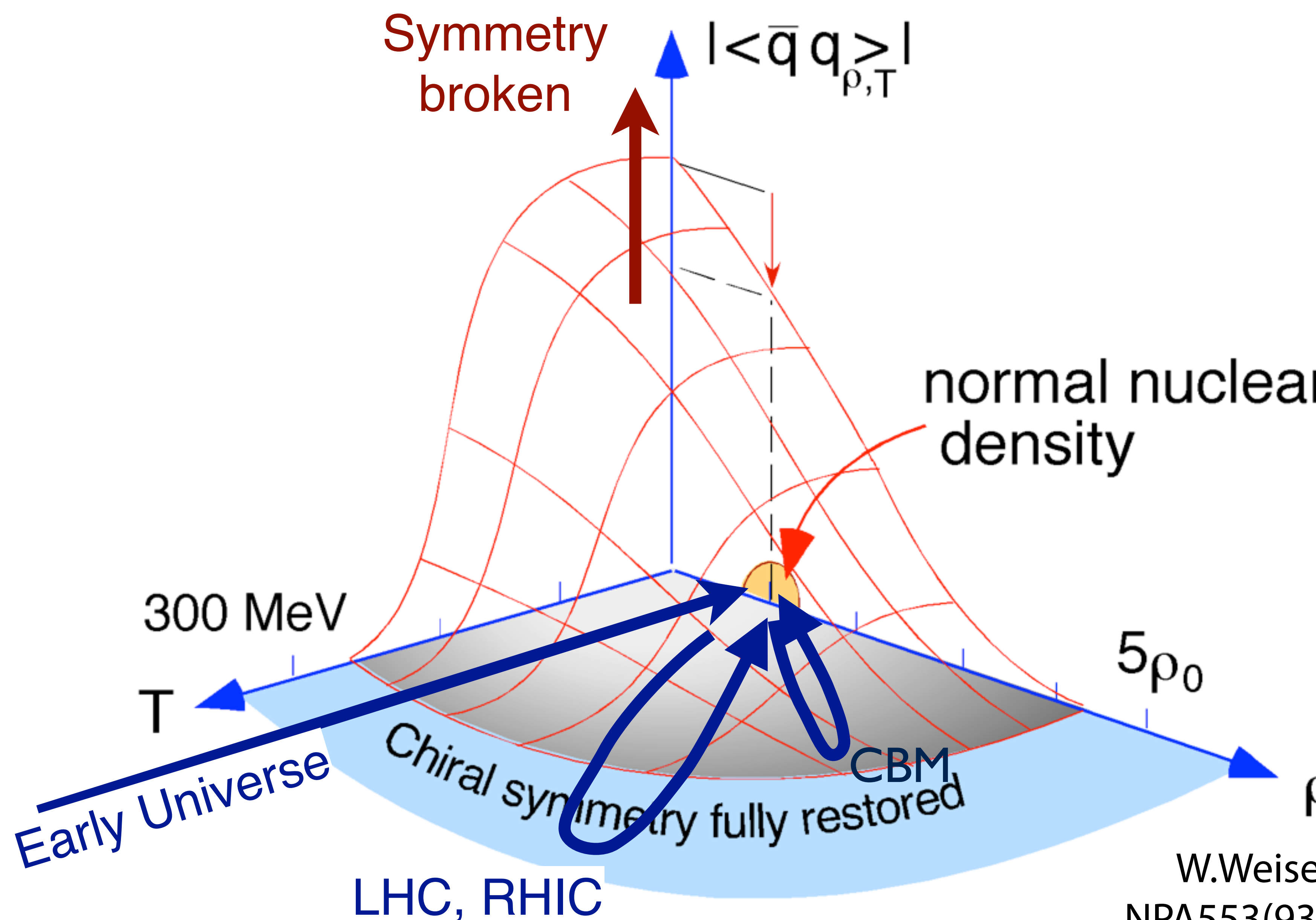
Chiral condensate $\bar{q}q$ on Tρ plane

An order parameters of
χ-symmetry

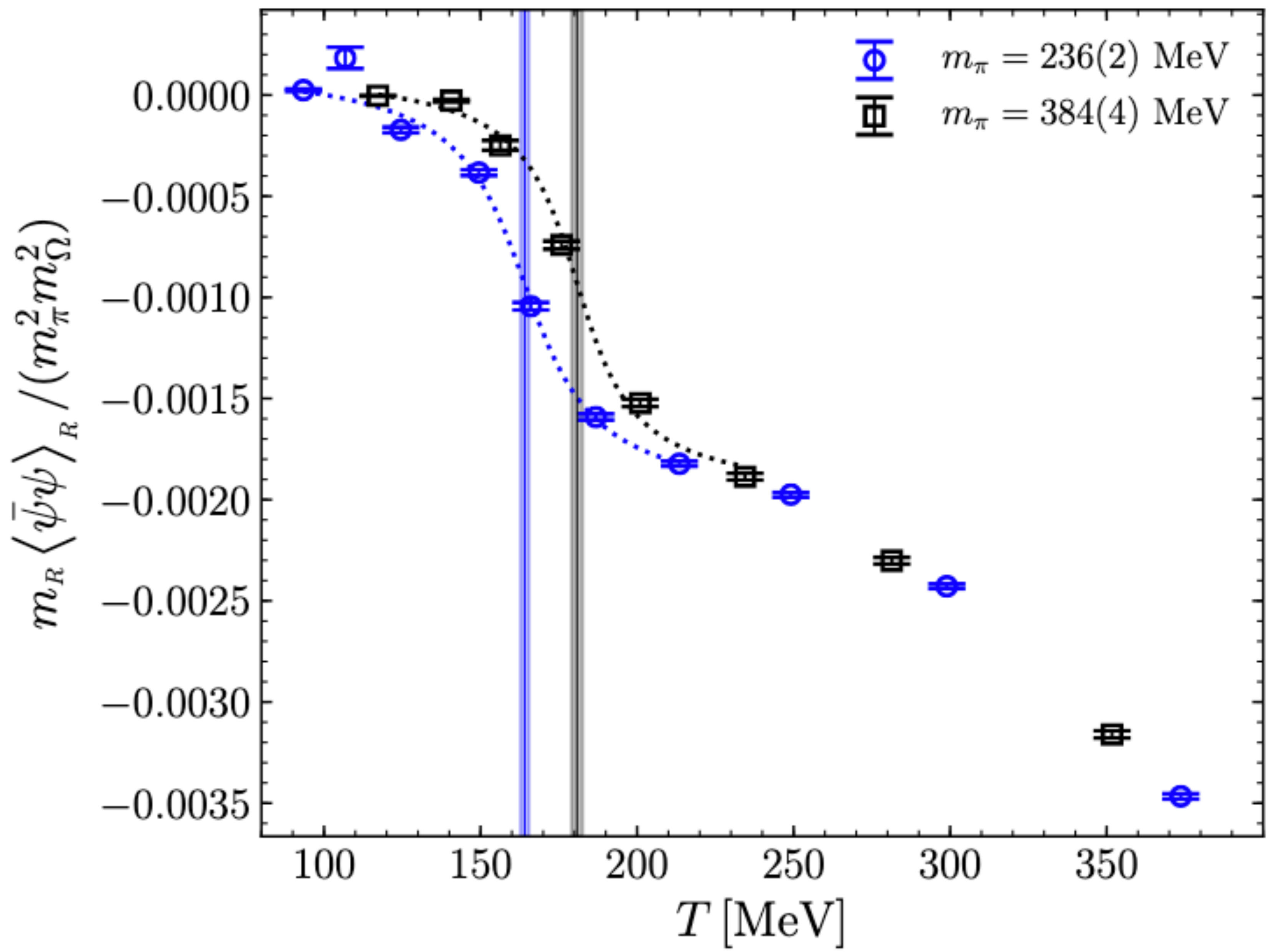




W.Weise,
NPA553(93)59.

Material properties
of QCD vacuum

Lattice QCD calculated T dependence of <q̄q>



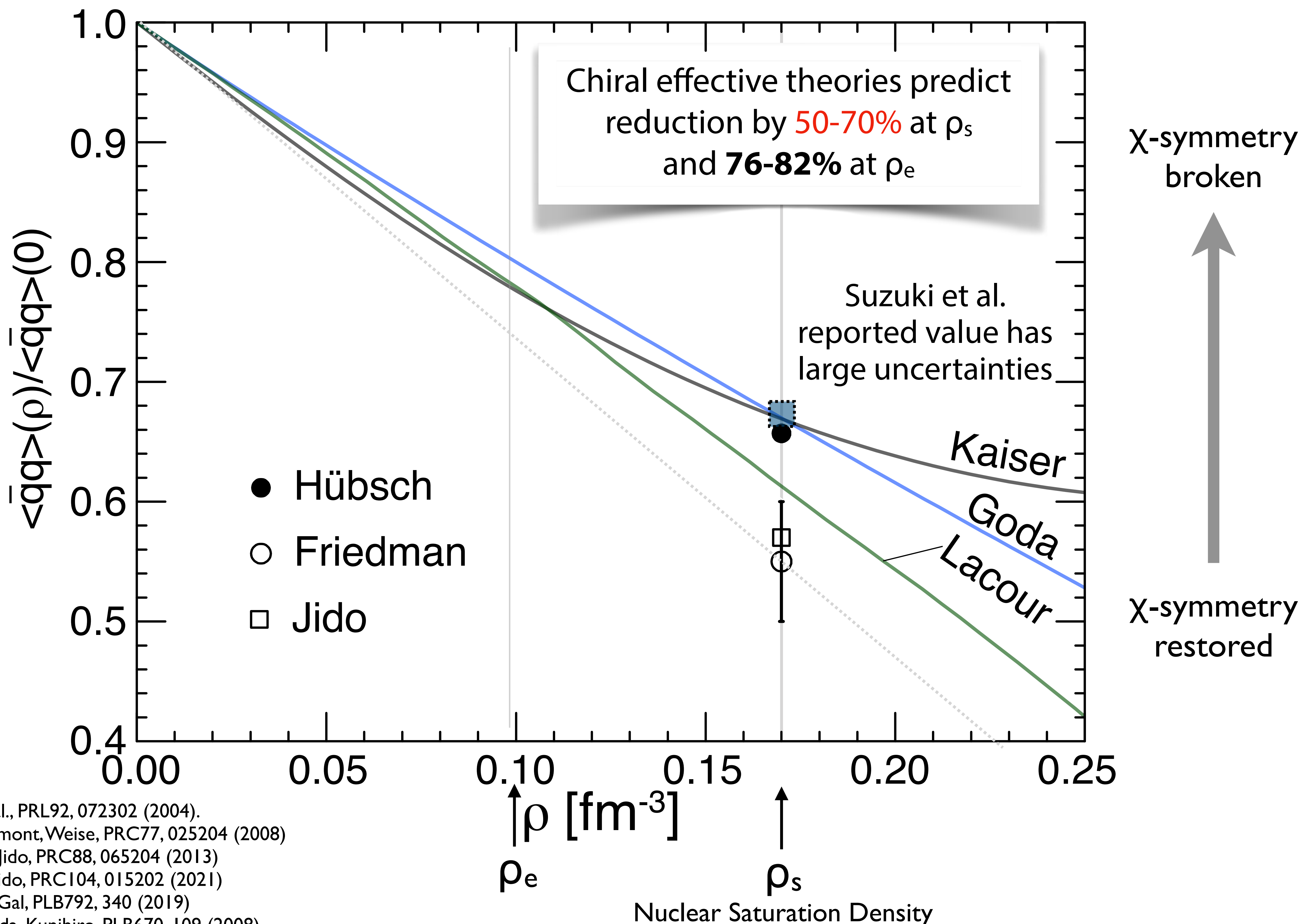
χ-symmetry broken

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 <q̄q> known so far



Suzuki et al., PRL92, 072302 (2004).
Kaiser, Homont, Weise, PRC77, 025204 (2008)
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Friedman, Gal, PLB792, 340 (2019)
Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)
Lacour, Oller, Meissner, J. Phys. G. 37, 125002 (2010)

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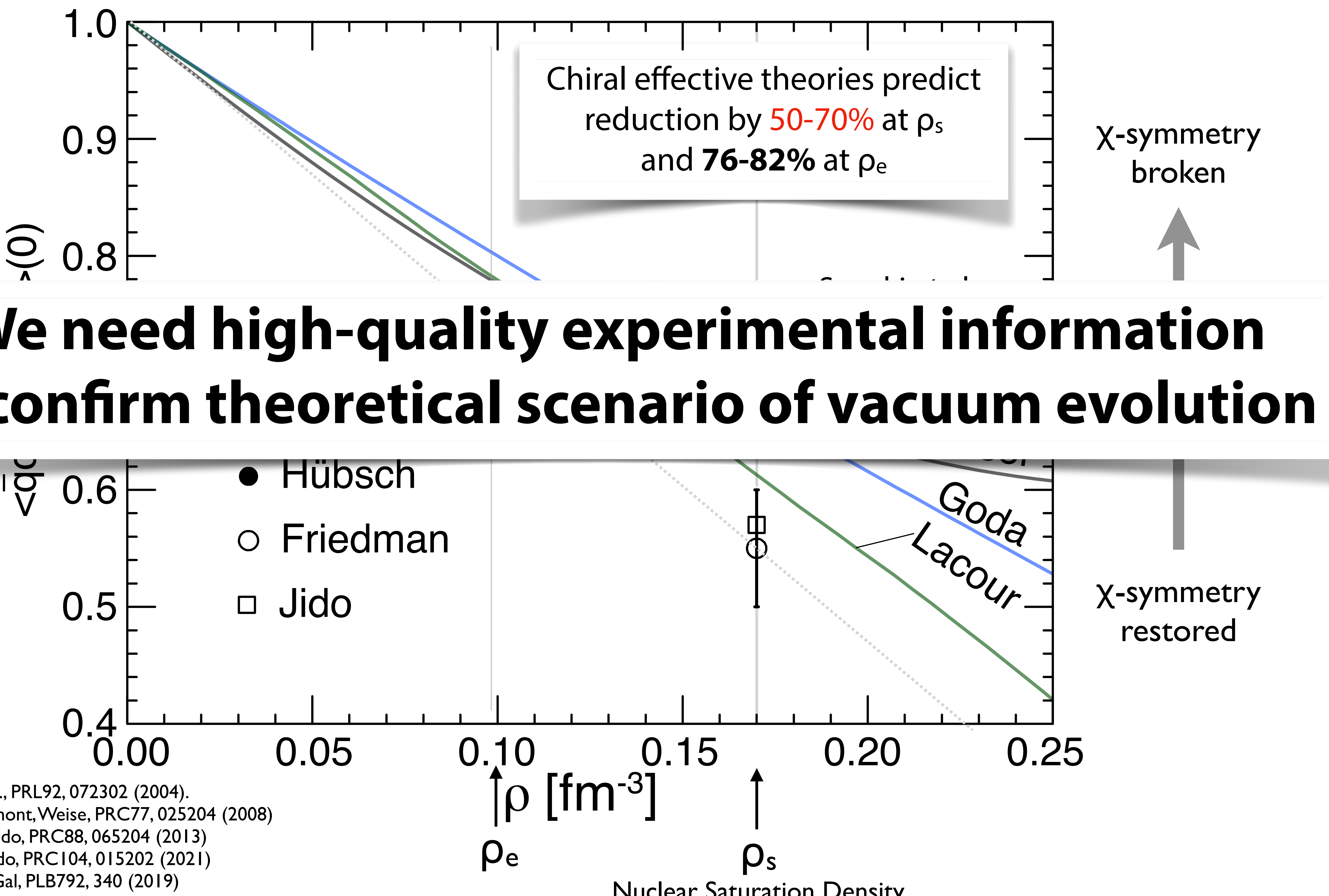

We need high-quality experimental information to confirm theoretical scenario of vacuum evolution

Suzuki et al., PRL92, 072302 (2004).
Kaiser, Homont, Weise, PRC77, 025204 (2008)
Goda and Jido, PRC88, 065204 (2013)
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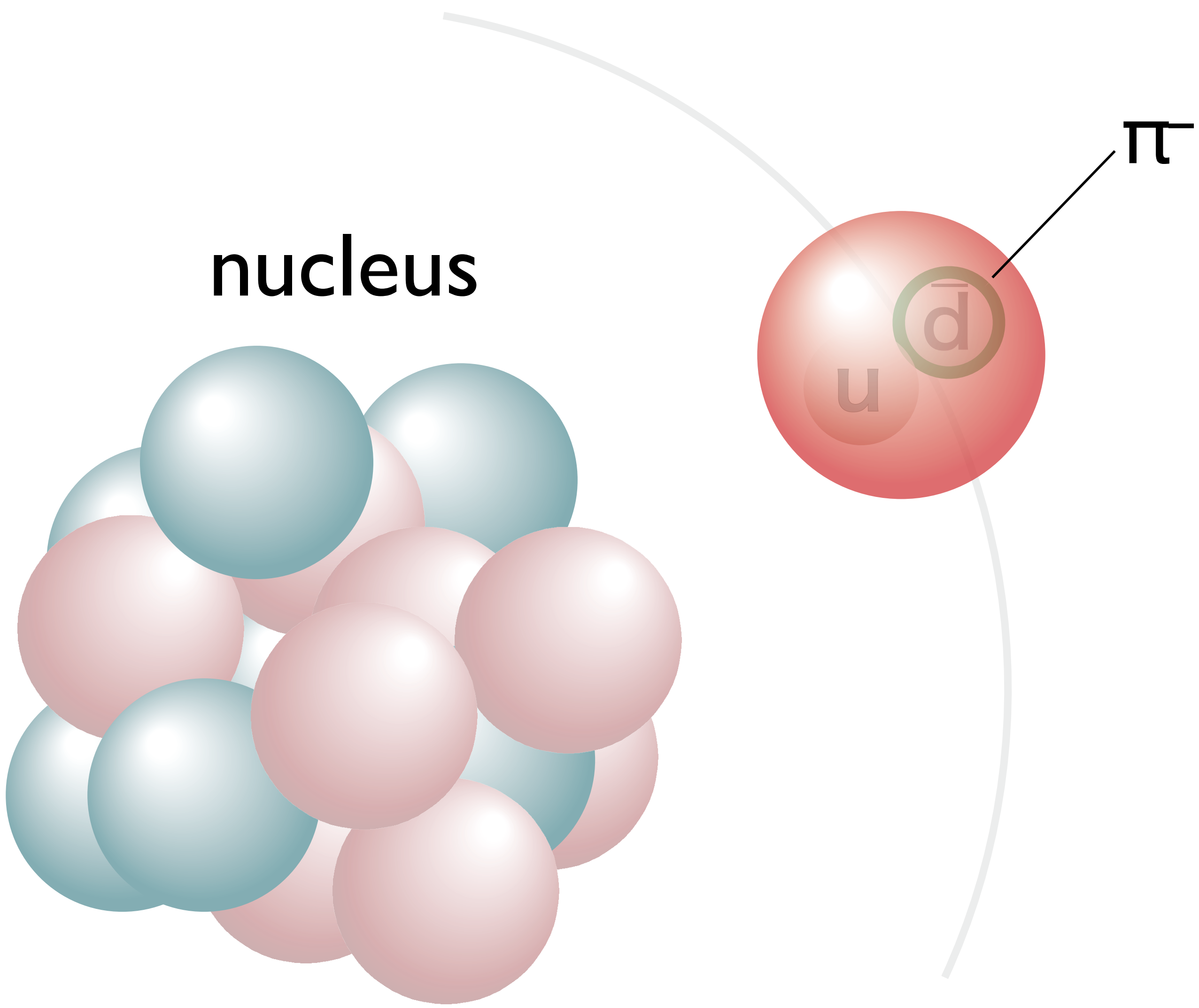
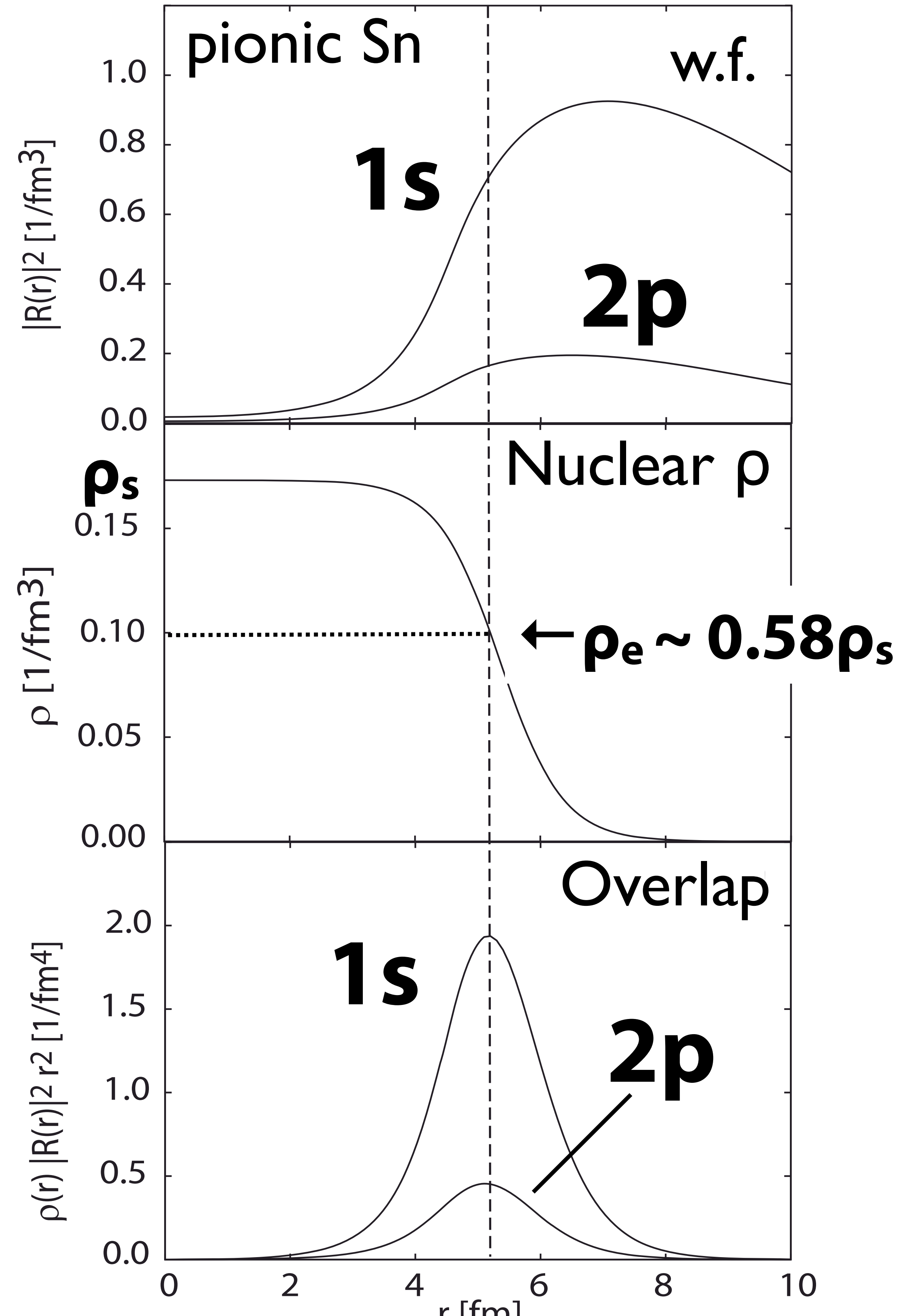
Precision Spectroscopy of Pionic Atoms





Ericson-Ericson potential

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

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

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

Ikeno et al., PTP126 (2011) 483

Pion-nucleus strong 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** in nuclear medium for wavefunction renormalization effect

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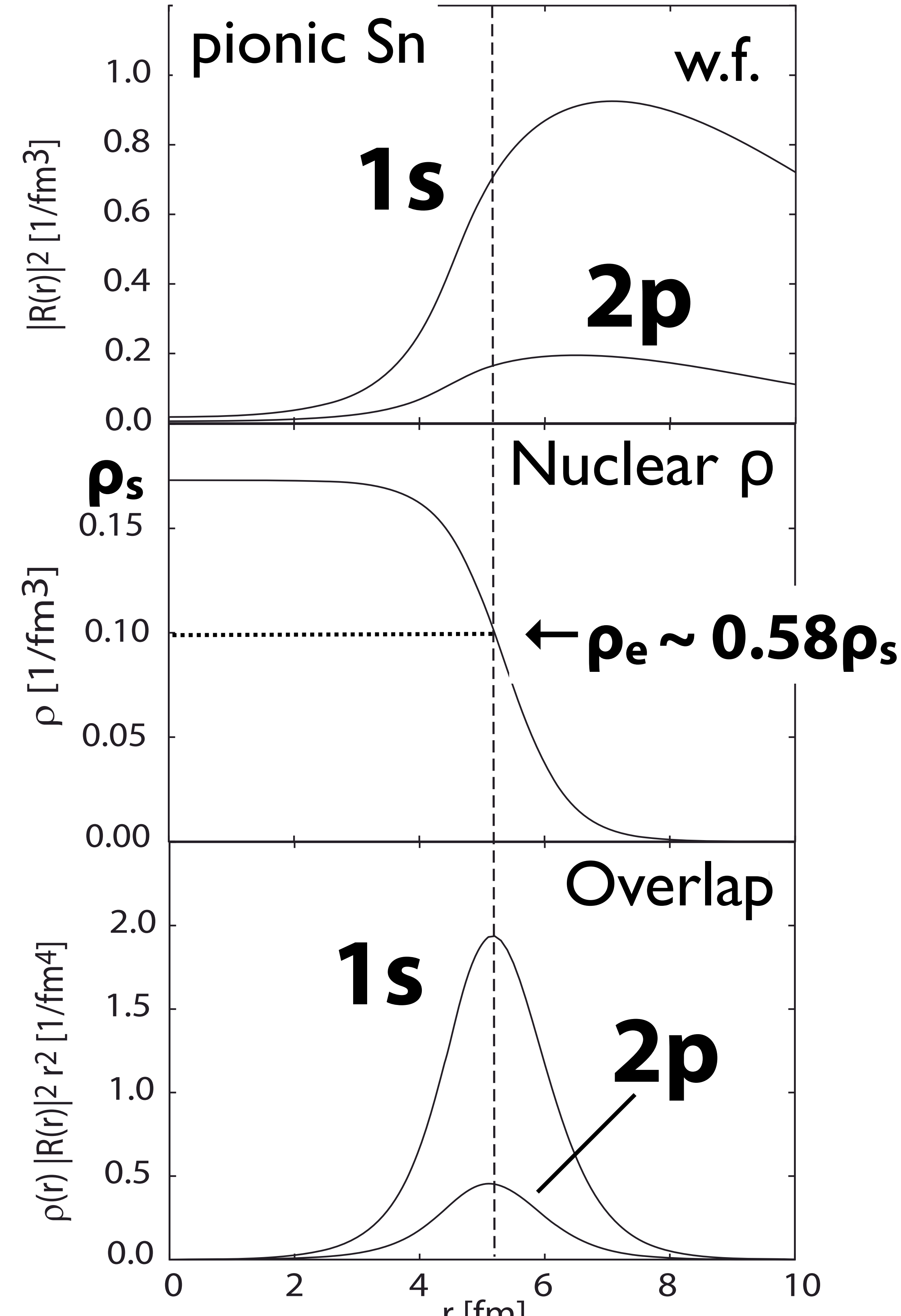

Ikeno et al., PTP126 (2011) 483

Strong interaction and chiral condensate

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In-medium Glashow-Weinberg relation

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

$\gamma = 0.184 \pm 0.003$

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

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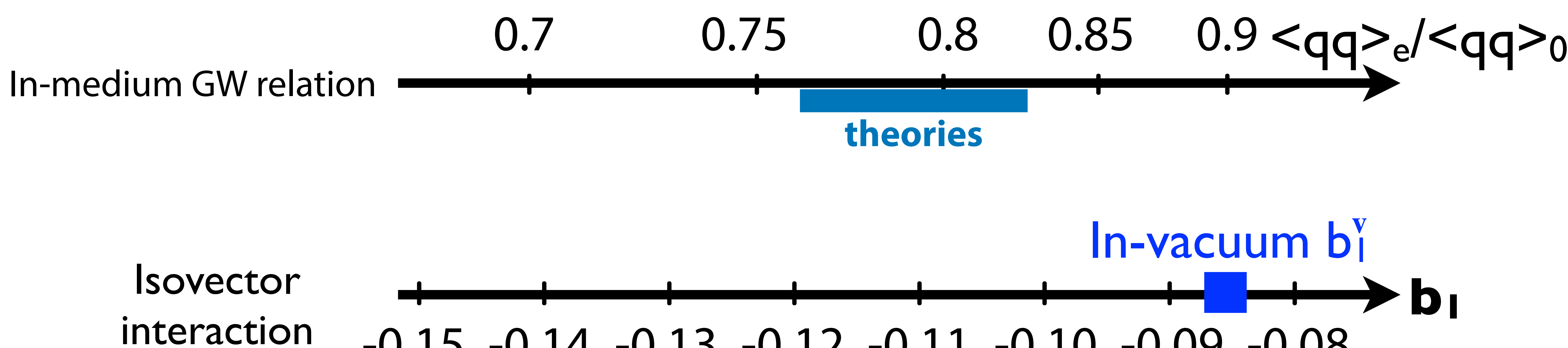
Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)

Pionic hydrogen and deuterium

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

Hirtl et al., EPJA57, 70 (2021)



Deduction of pion-nucleus interaction in medium by

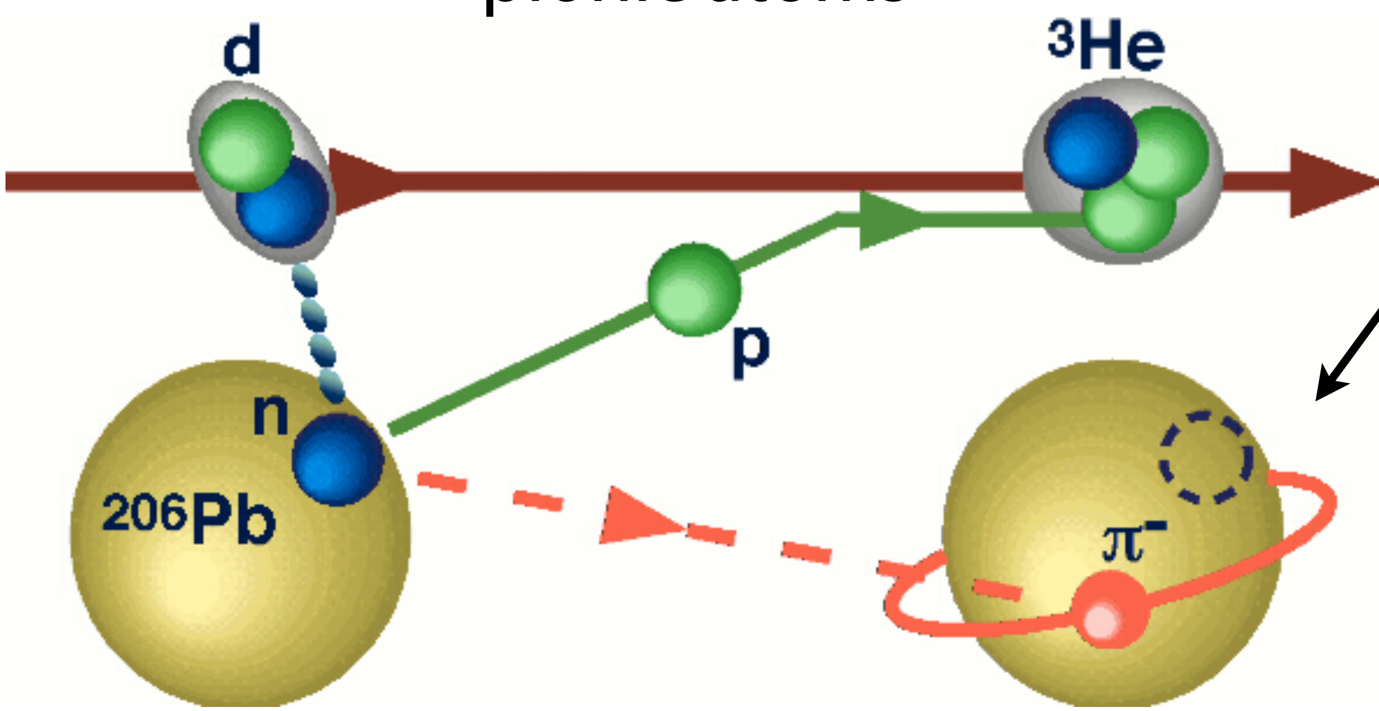
Spectroscopy of pionic atoms in (*d*,^{3}He) reactions

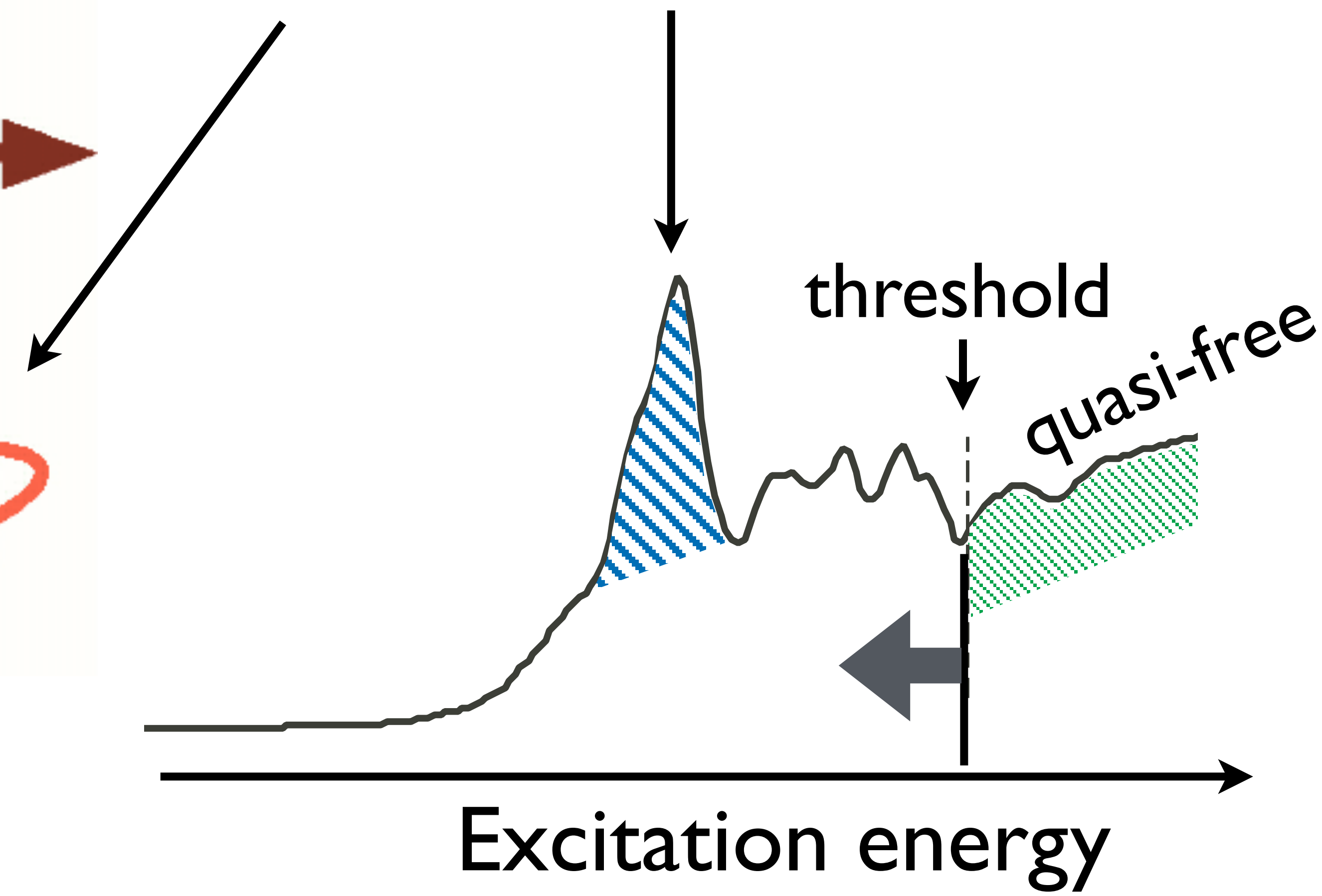
Based on energy-momentum conservation law:

$$\text{Excitation energy} \sim T_d - T_{3He}$$

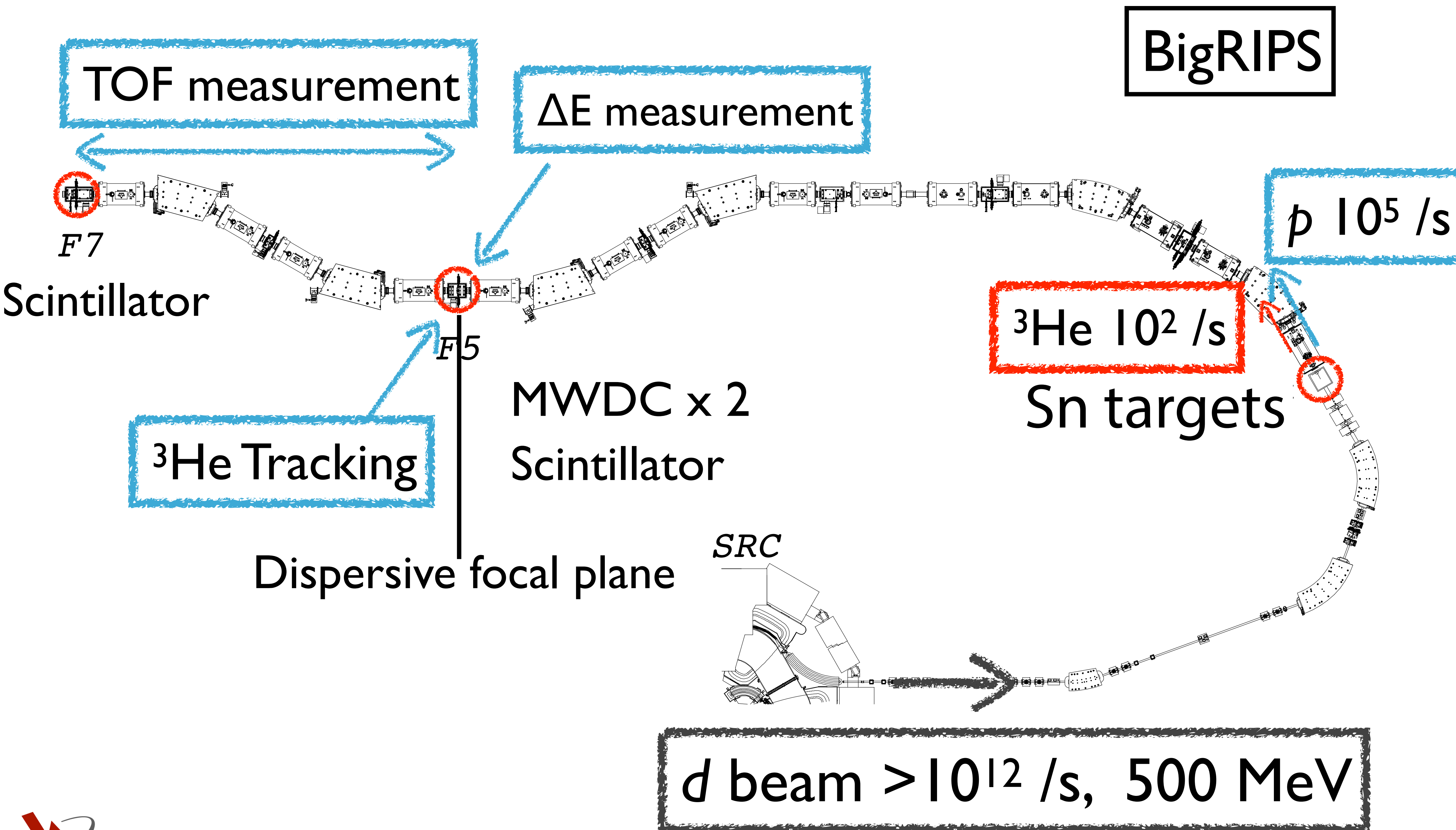
Direct excitation of pionic atoms

Pionic atoms coupled with *n* hole





(d,³He) Reaction Spectroscopy in RIBF



Kenta Itahashi, RIKEN

First pionic atom in RIBF (2010)

Pionic ^{121}Sn atom

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)

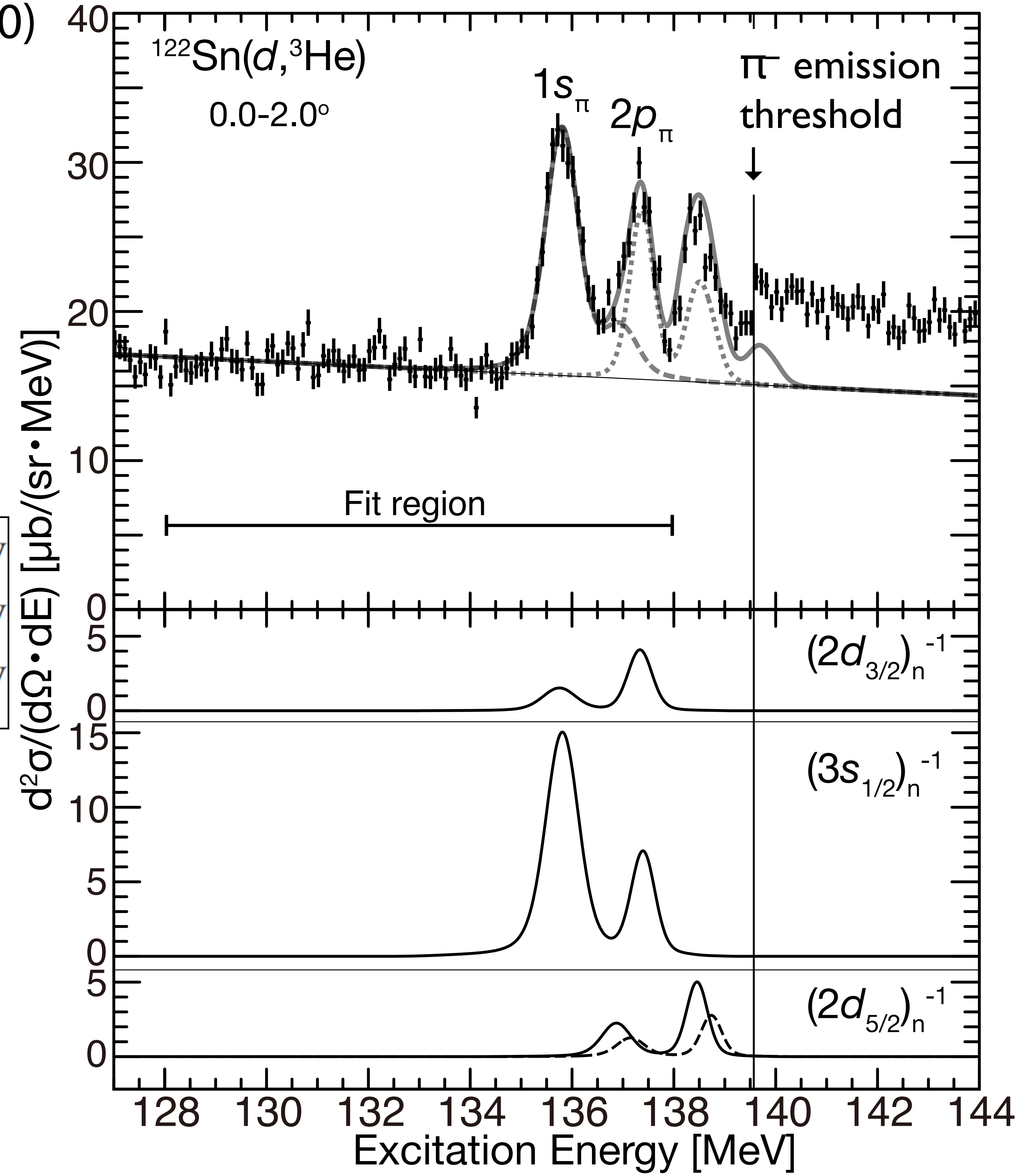
Theories

B_{1s}= 3.787–3.850 MeV

Γ_{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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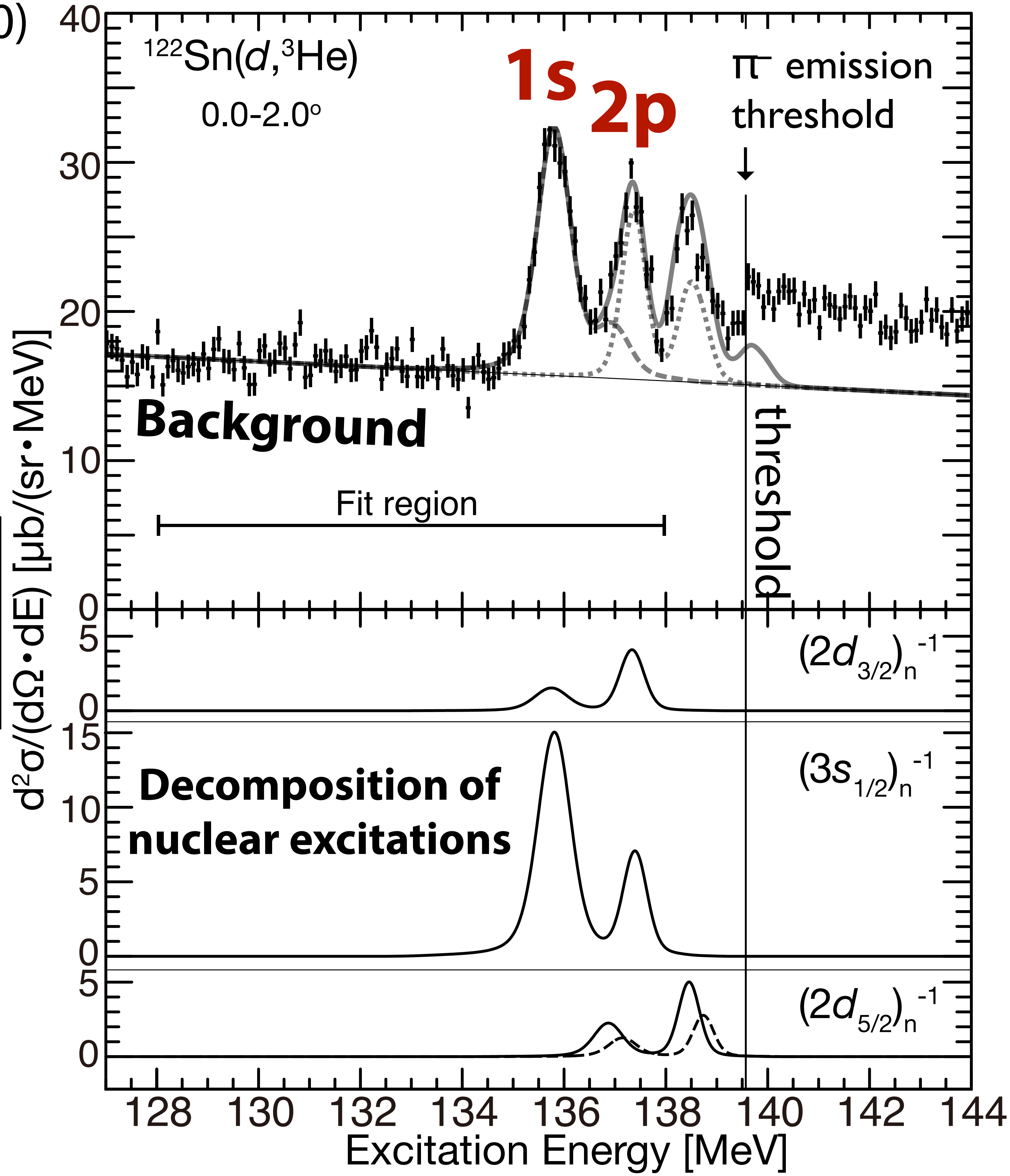

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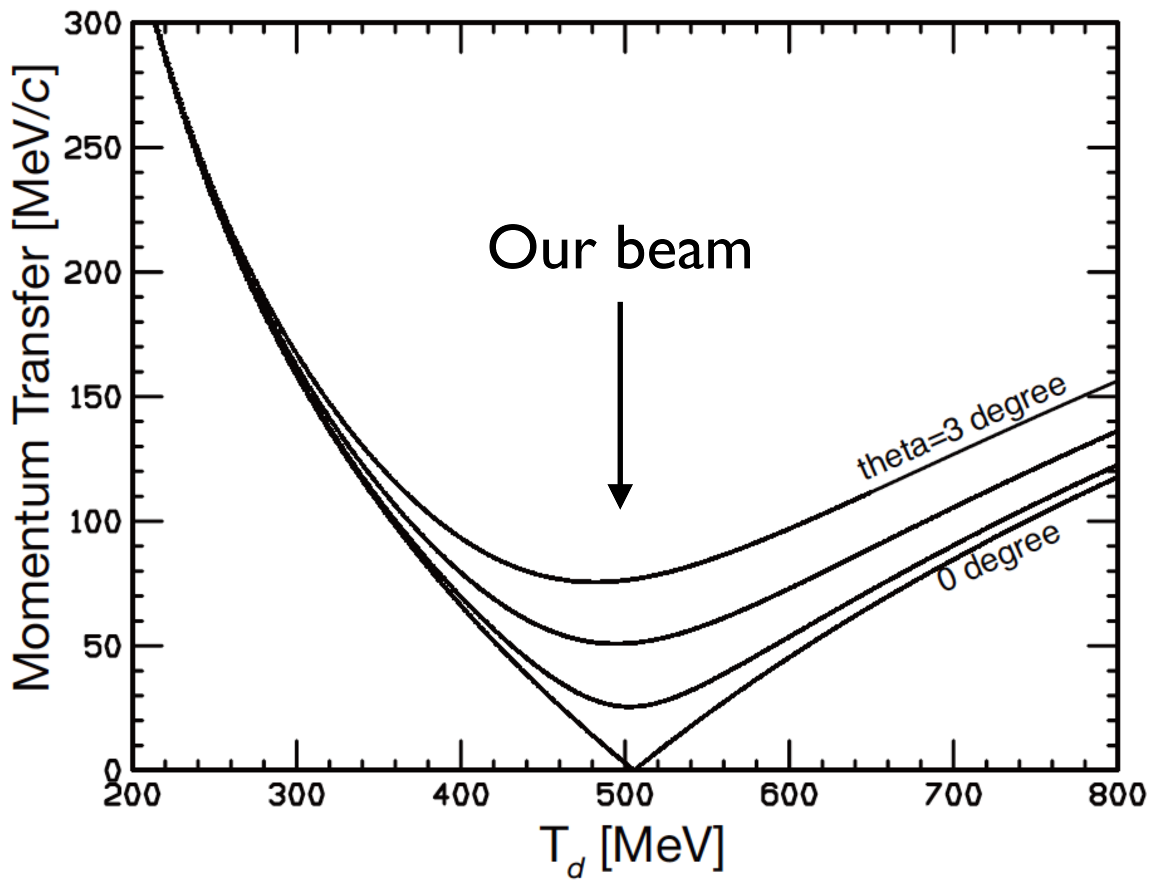
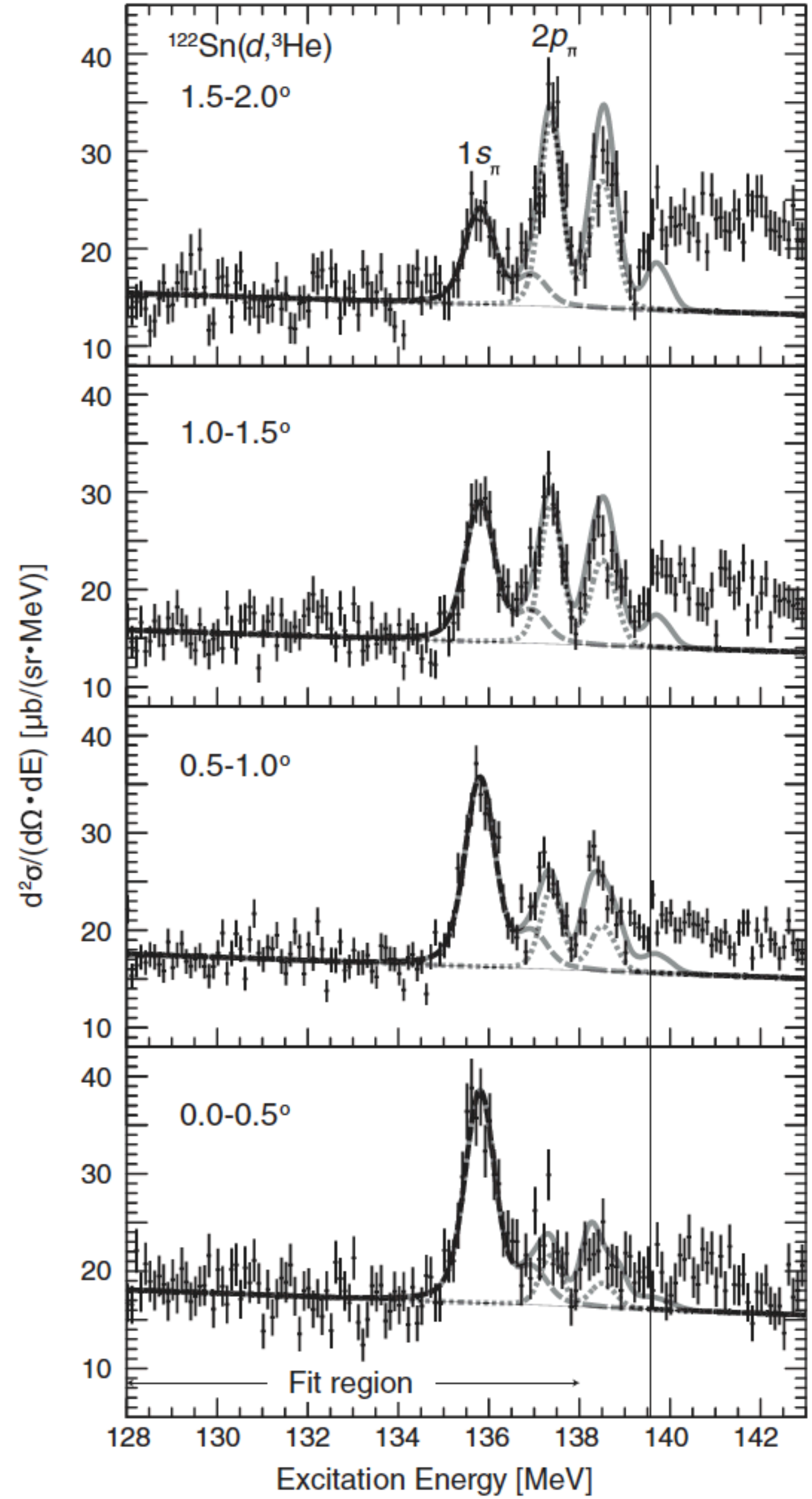
Pionic ^{121}Sn atom

First observation of θ dependence of π atom cross section

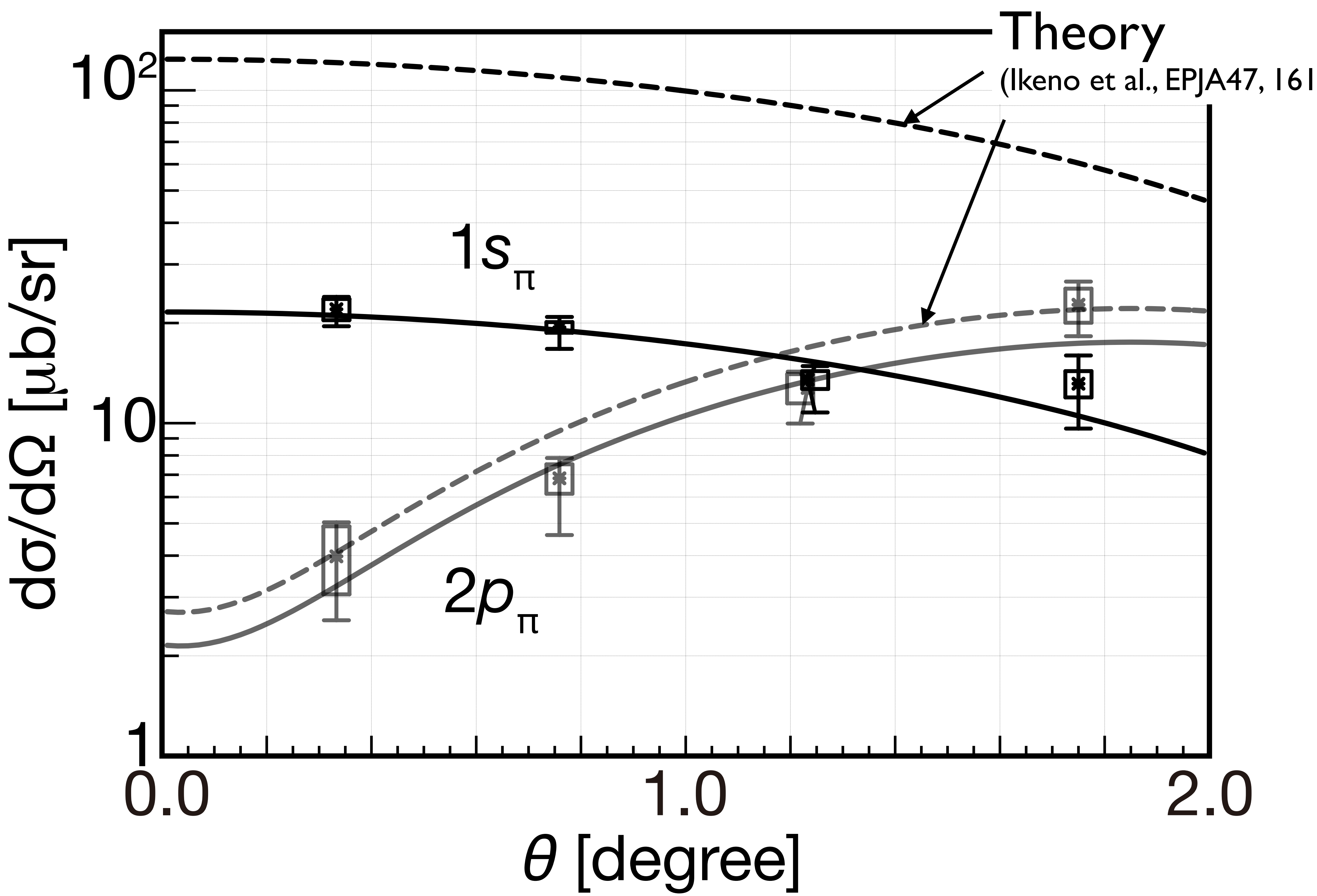
$\Delta L \sim R \times q$



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



1s and 2p pionic atom cross sections in (d,^{3}He)



θ dependence is well reproduced.
Theory calculates 5x larger cross section for 1s

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

First pionic atom in RIBF (2010)

Pionic ^{121}Sn atom

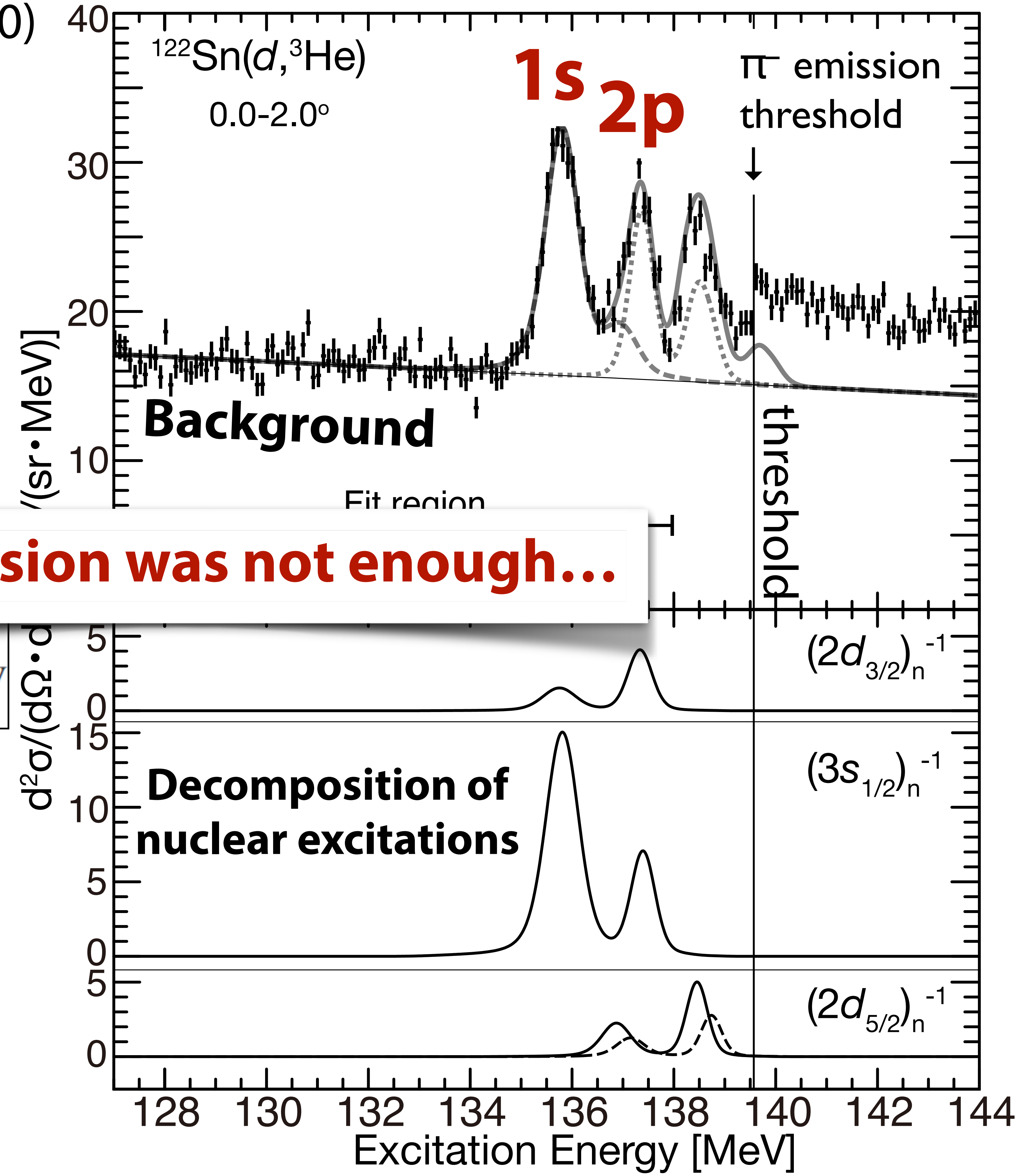
First simultaneous 1s and 2p observation

$B_{1s} = 3.828 \pm 0.013$(st...

$\Gamma_{1s} = 0.252 \pm 0.054$(st... $_{-0.070}$ ...

$B_{2p} = 2.238 \pm 0.015(\mathrm{stat})^{+0.046}_{-0.043}(\mathrm{syst})$ MeV

The precision was not enough…



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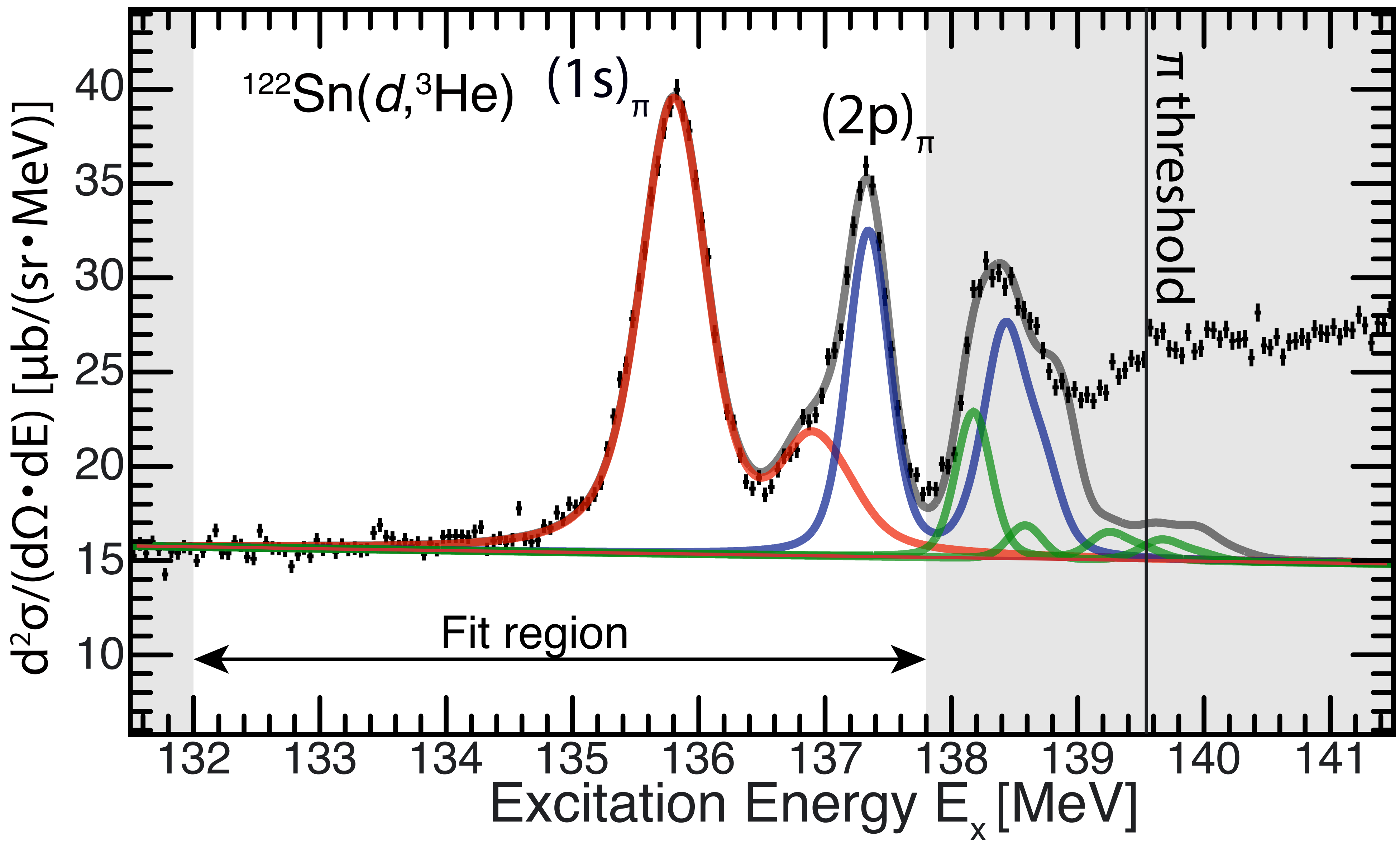
T. Nishi KI et al., PRL120, 152505 (2018)

High Precision Spectrum of $^{122}Sn(d,^{3}He)$ in RIBF-54



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

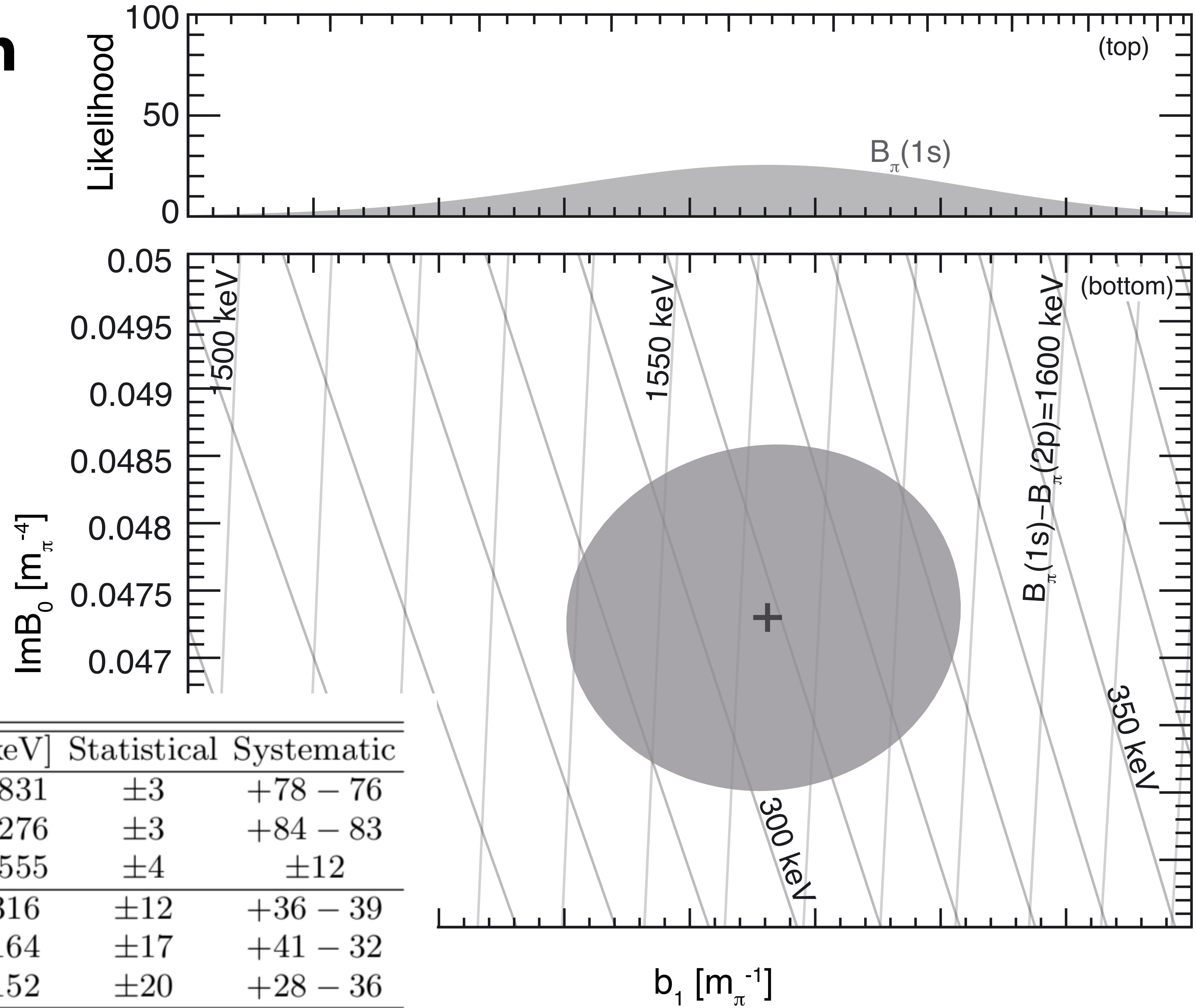
Resolution 287 keV (FWHM)

2p observed as a peak with high stat. significance
↓
Smaller systematic errors for differences
$\sigma B_{1s} > \sigma(B_{1s} - B_{2p})$

Nishi, KI et al., Nat. Phys. **19**, 788(2023)

b_1 parameter Deduction

based on pionic C, N, O, and Sn atoms



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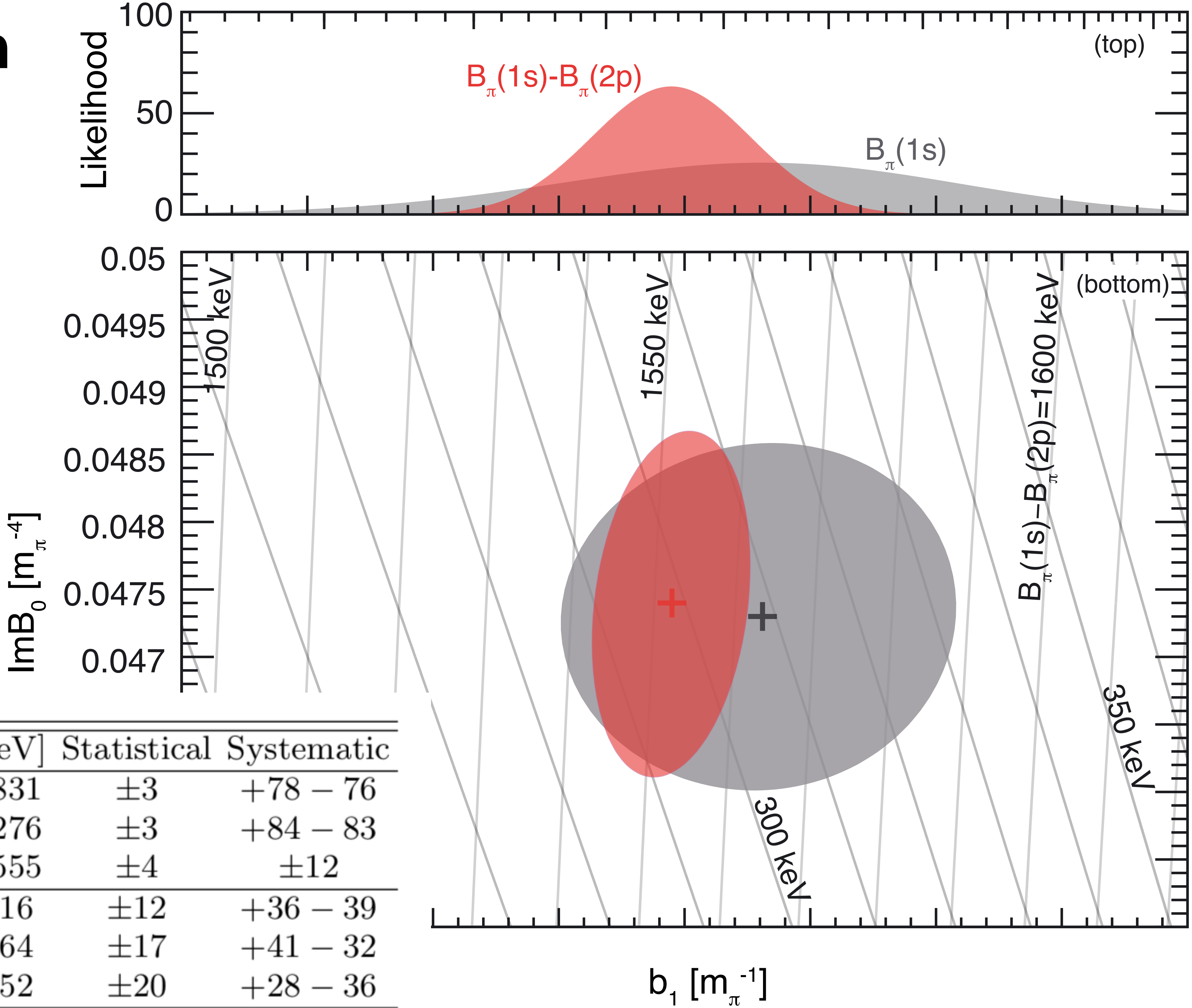

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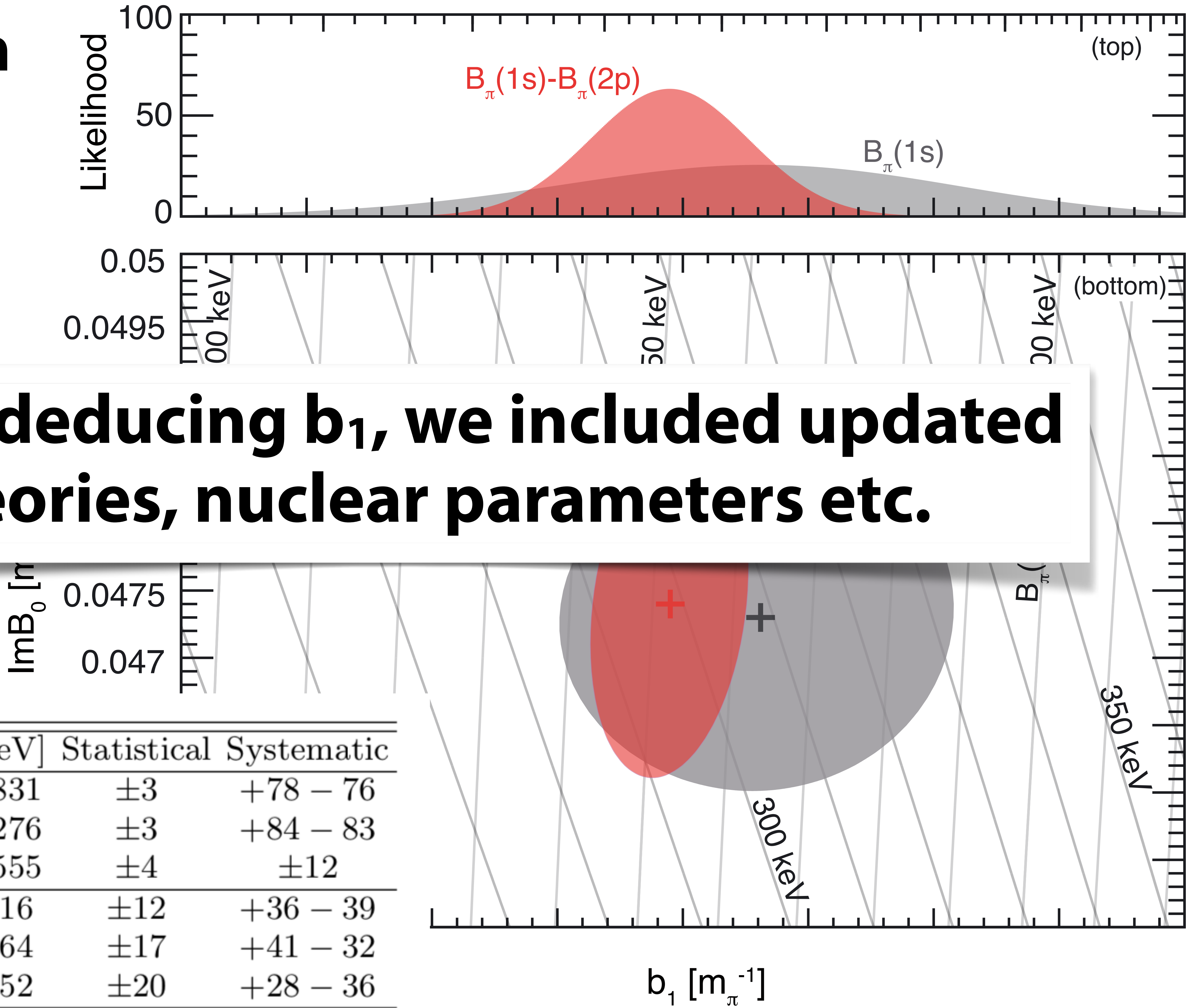

Before deducing b_1, we included updated theories, nuclear parameters etc.

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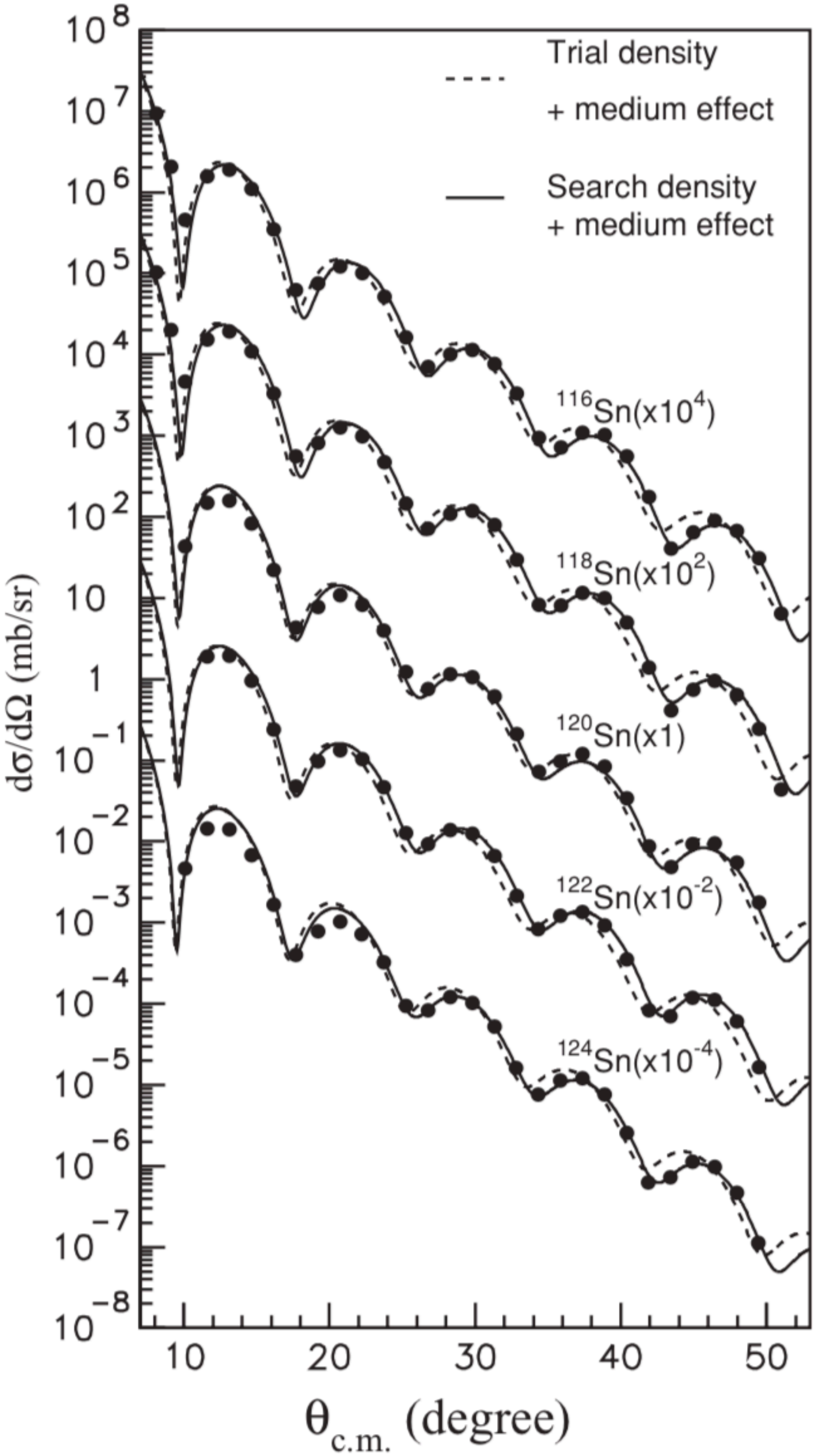
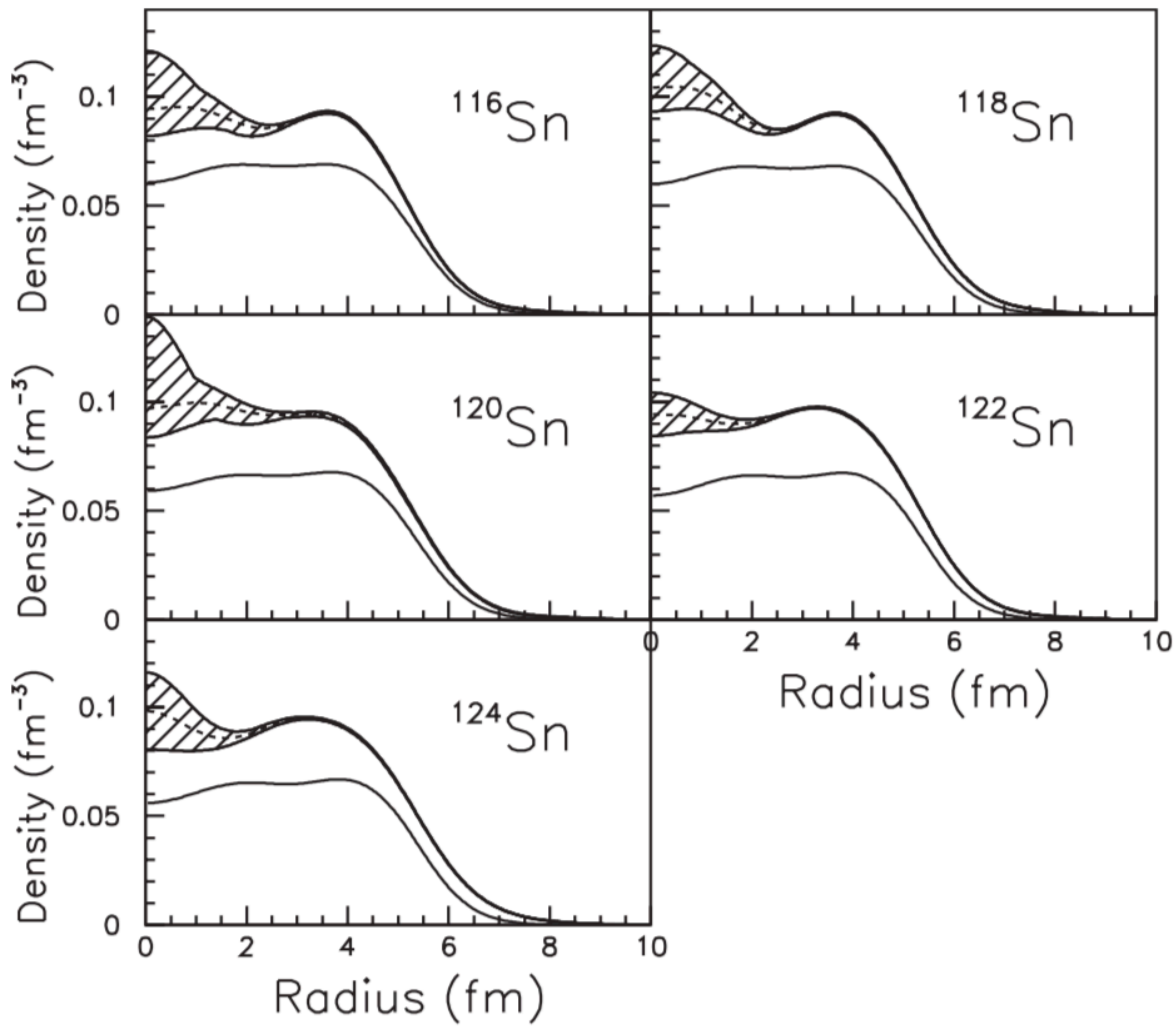
Nuclear ρ distribution measured in Sn(p,p')

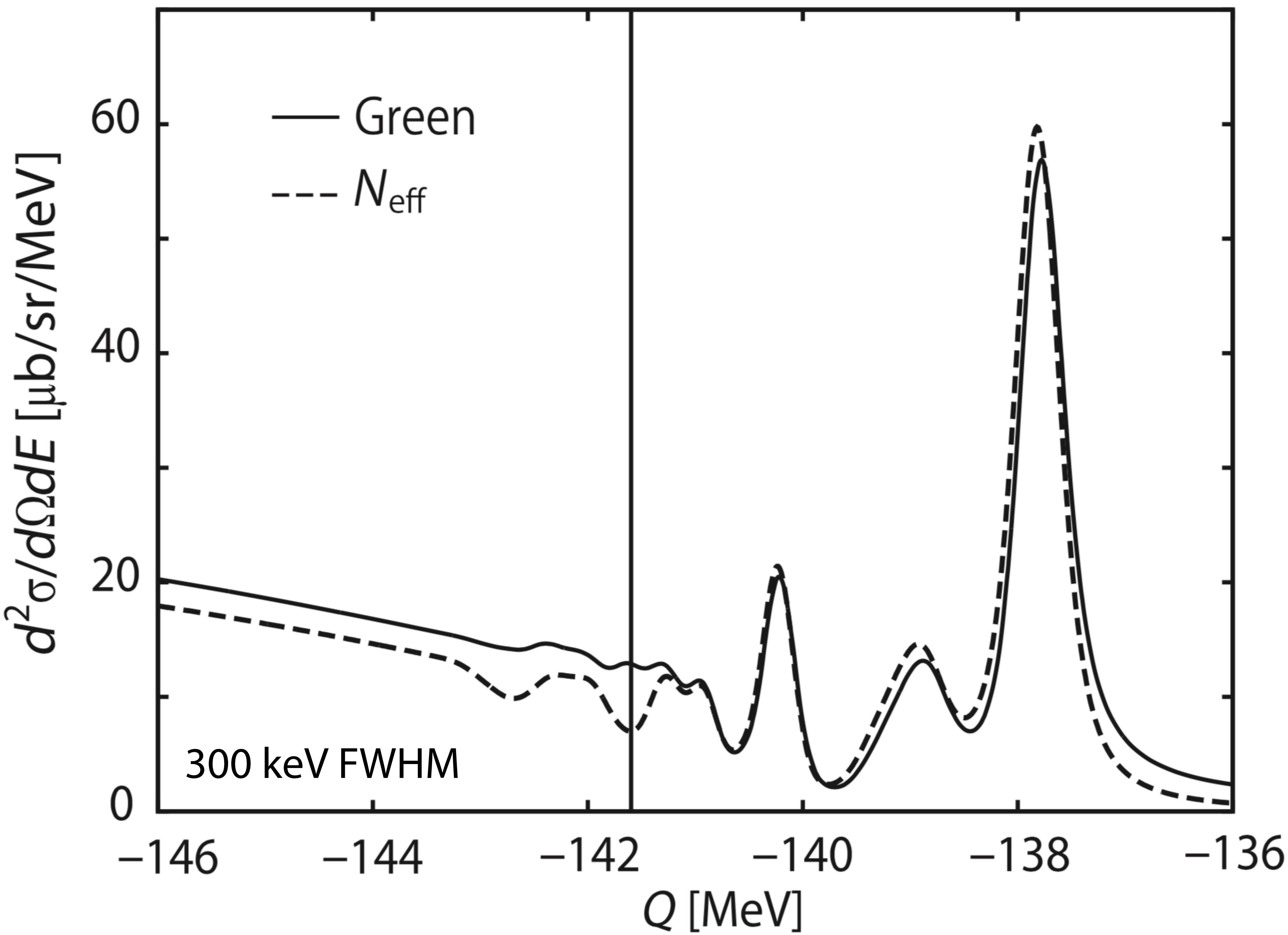
at RCNP, Osaka





Terashima et al., PHYSICAL REVIEW C **77**, 024317 (2008)

Theoretical spectra calculated with **Effective number and Green's function methods**



N. Ikeno et al., PTEP 2015, 033D01 (2015)

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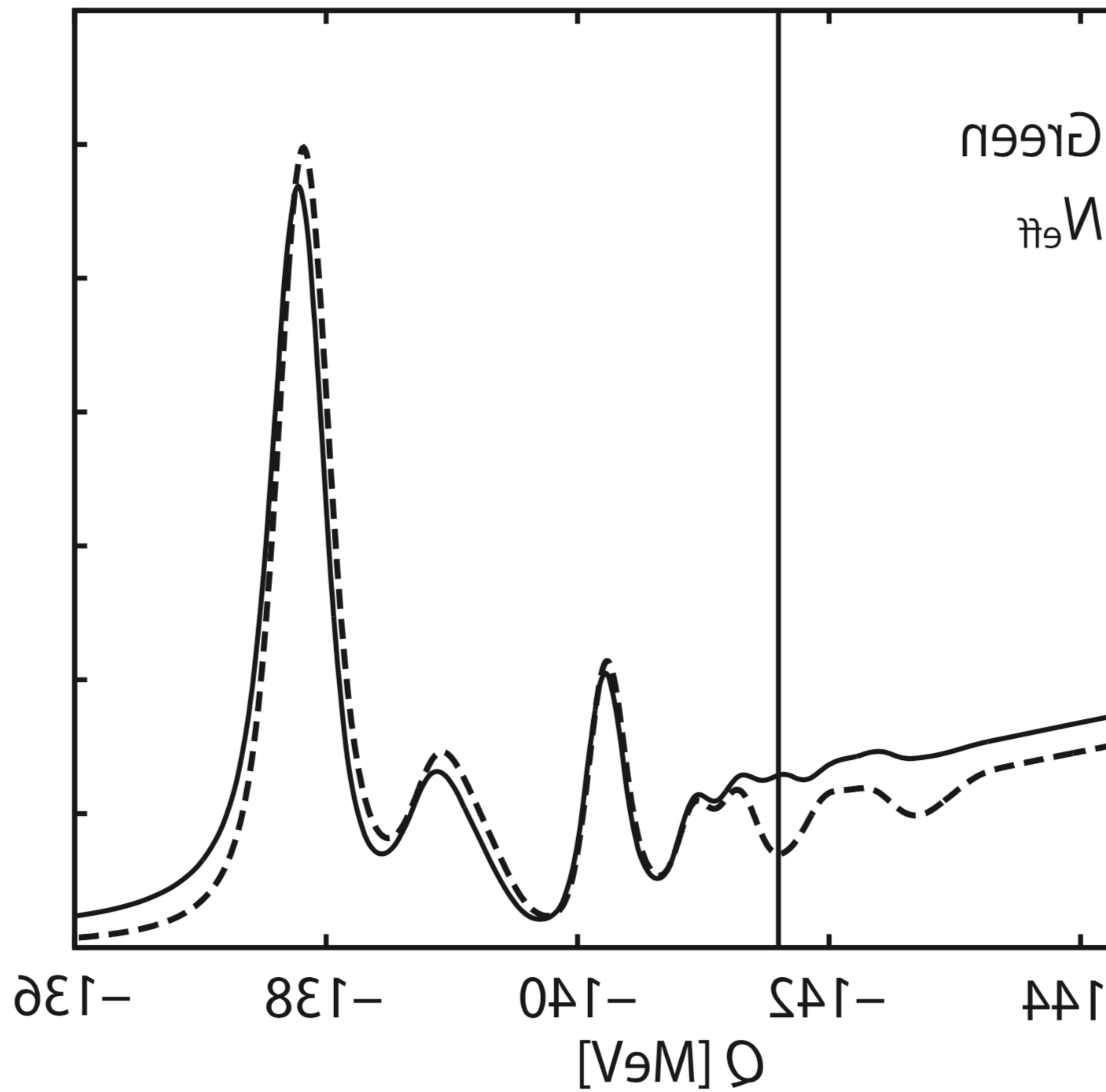
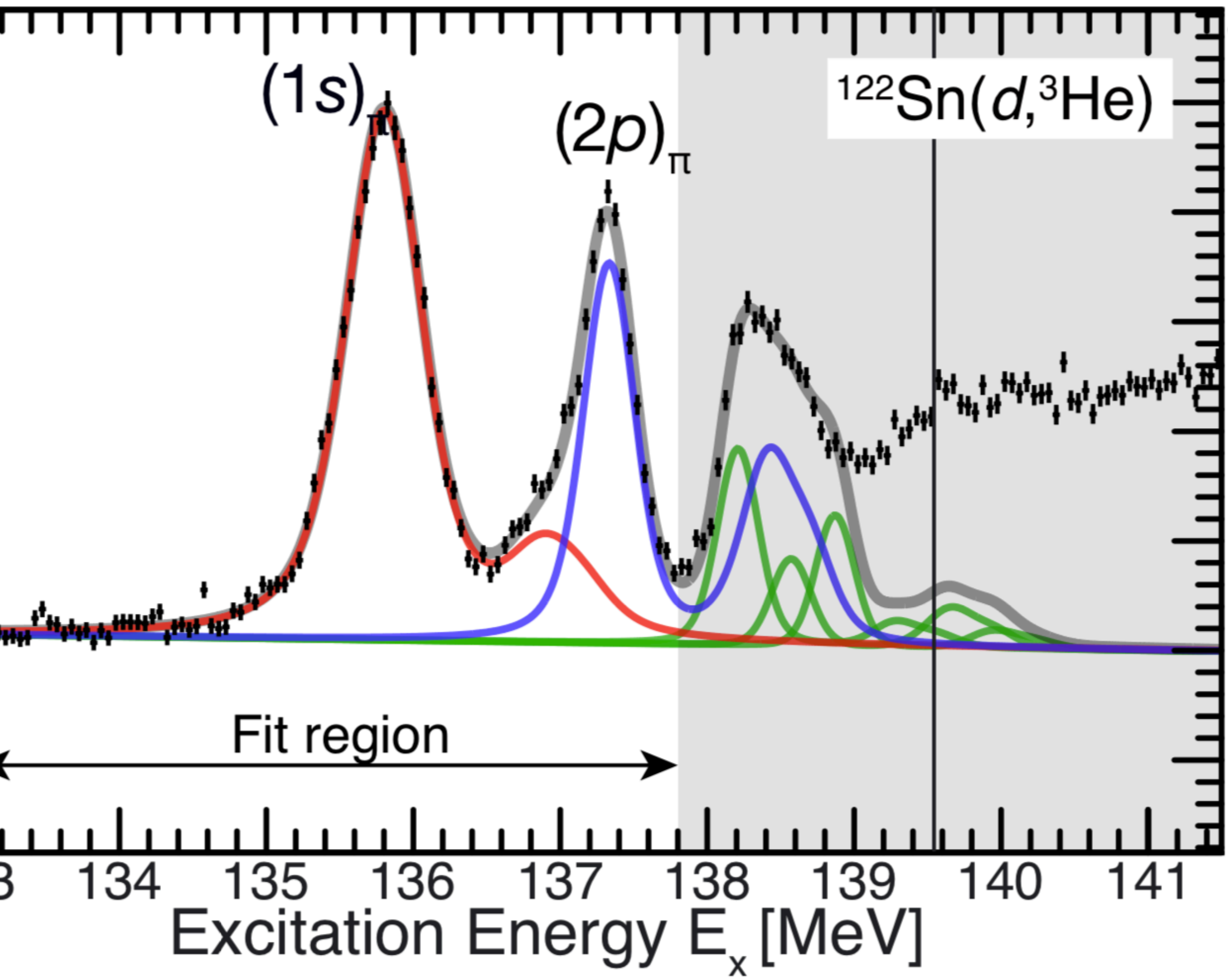
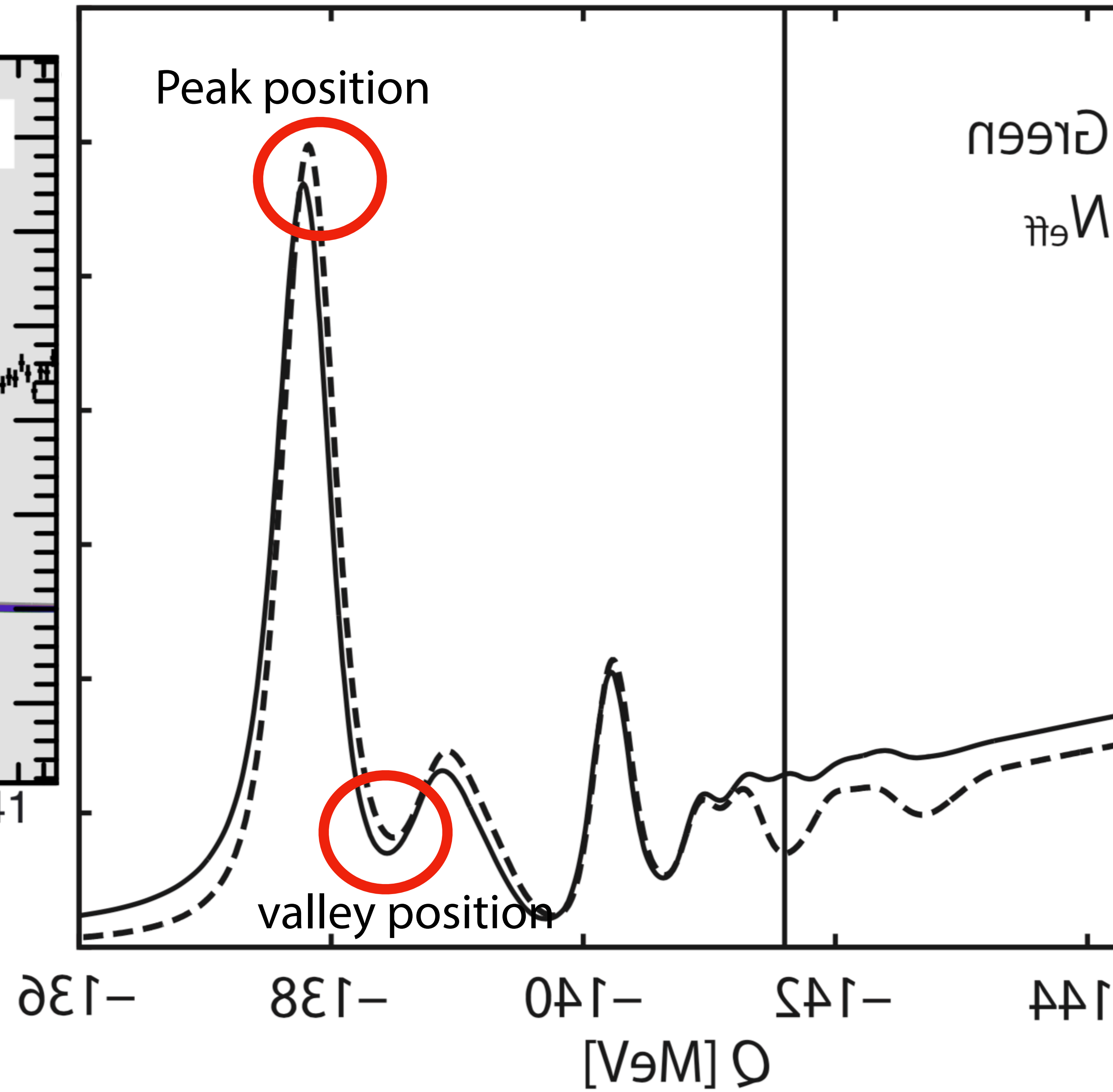


N. Ikeno et al., PTEP 2015, 033D01 (2015)

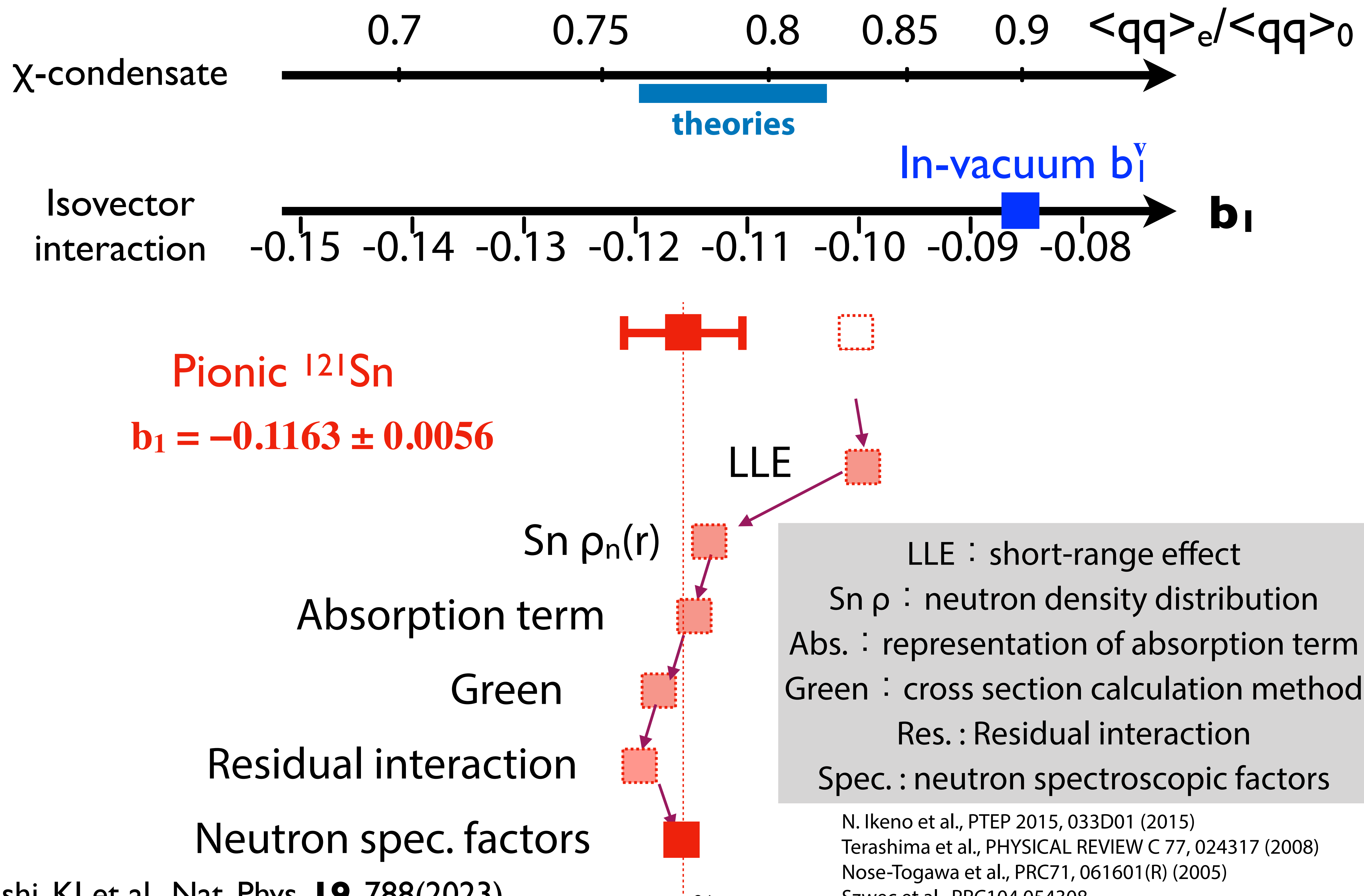
Theoretical spectra calculated with **Effective number and Green's function methods** have small but non-negligible differences





N. Ikeno et al., PTEP 2015, 033D01 (2015)

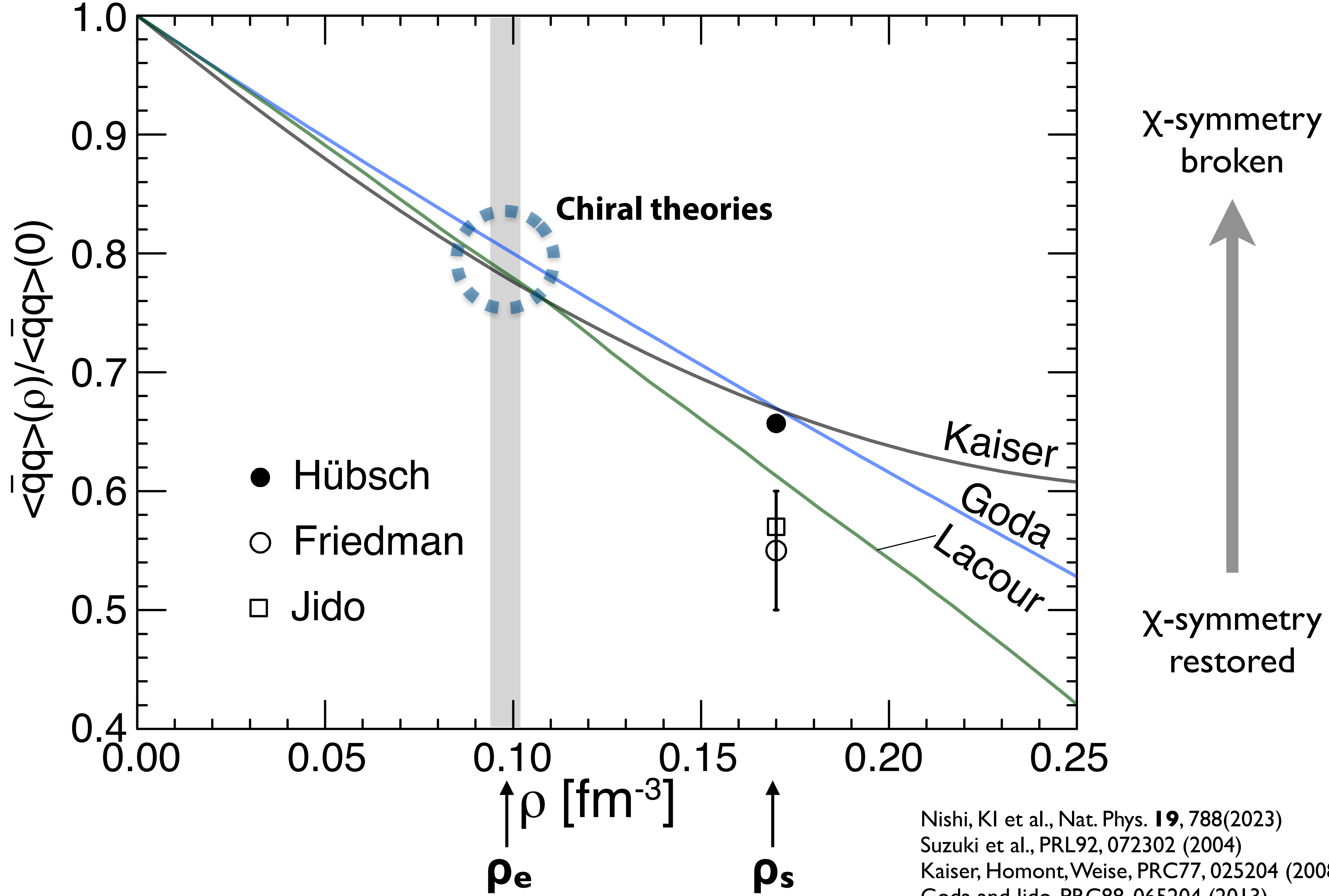
Deduced b_1 with updated parameters



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. **19**, 788(2023)

Result: deduced chiral condensate



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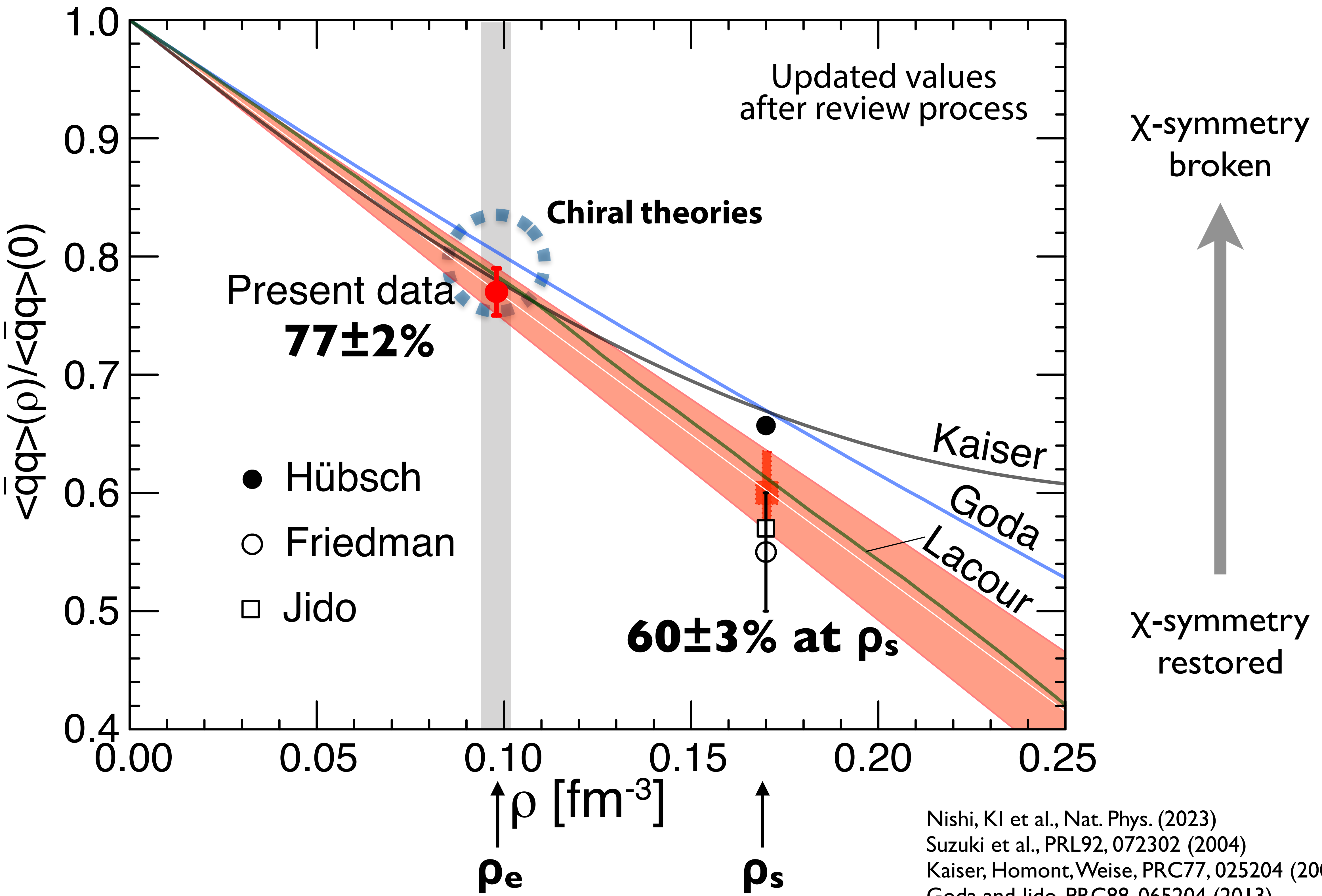

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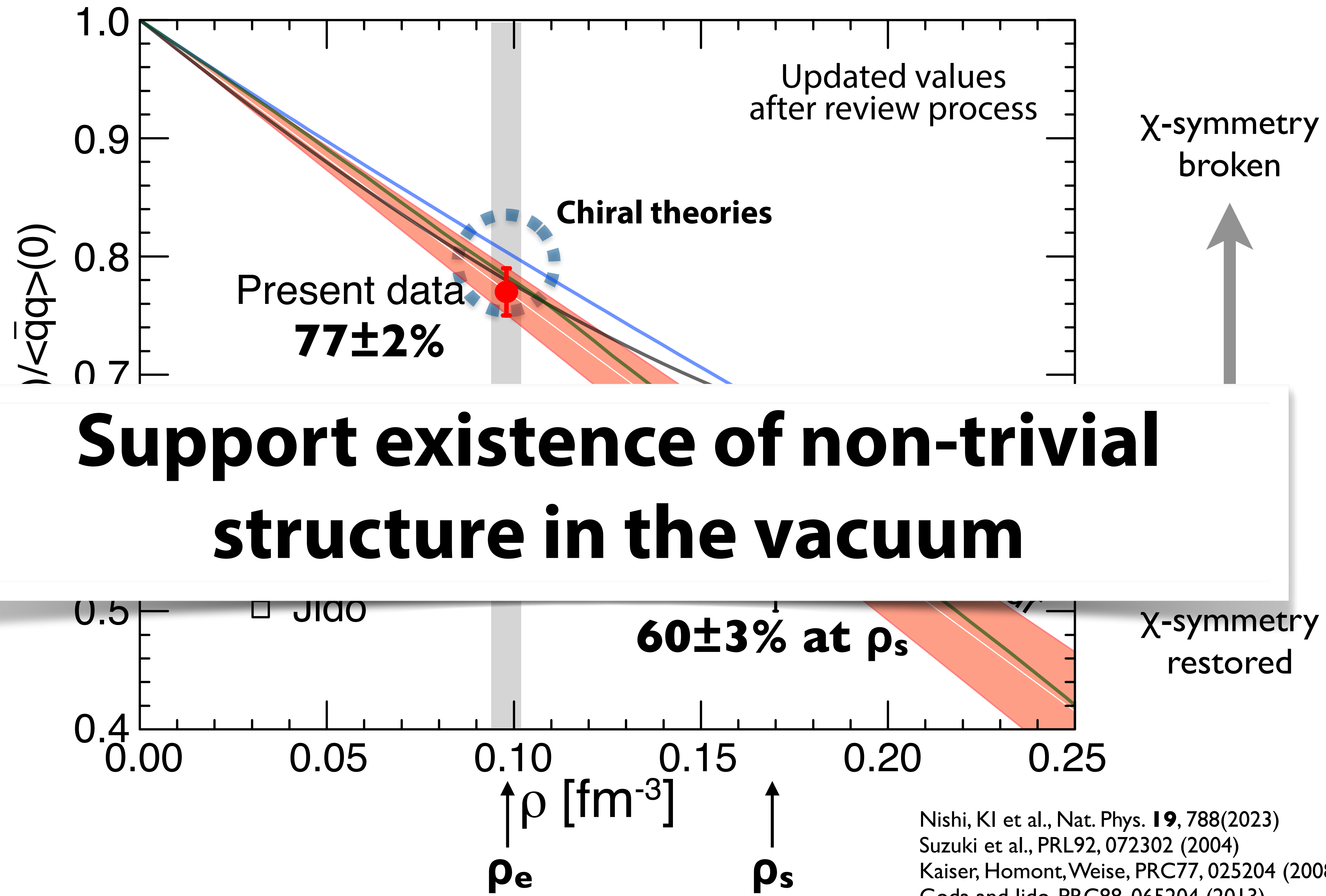

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Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)
Lacour, Oller, Meissner, J. Phys. G. 37, 125002 (2010)

To step further forward,
RIBF-135 for systematic study of Sn isotopes

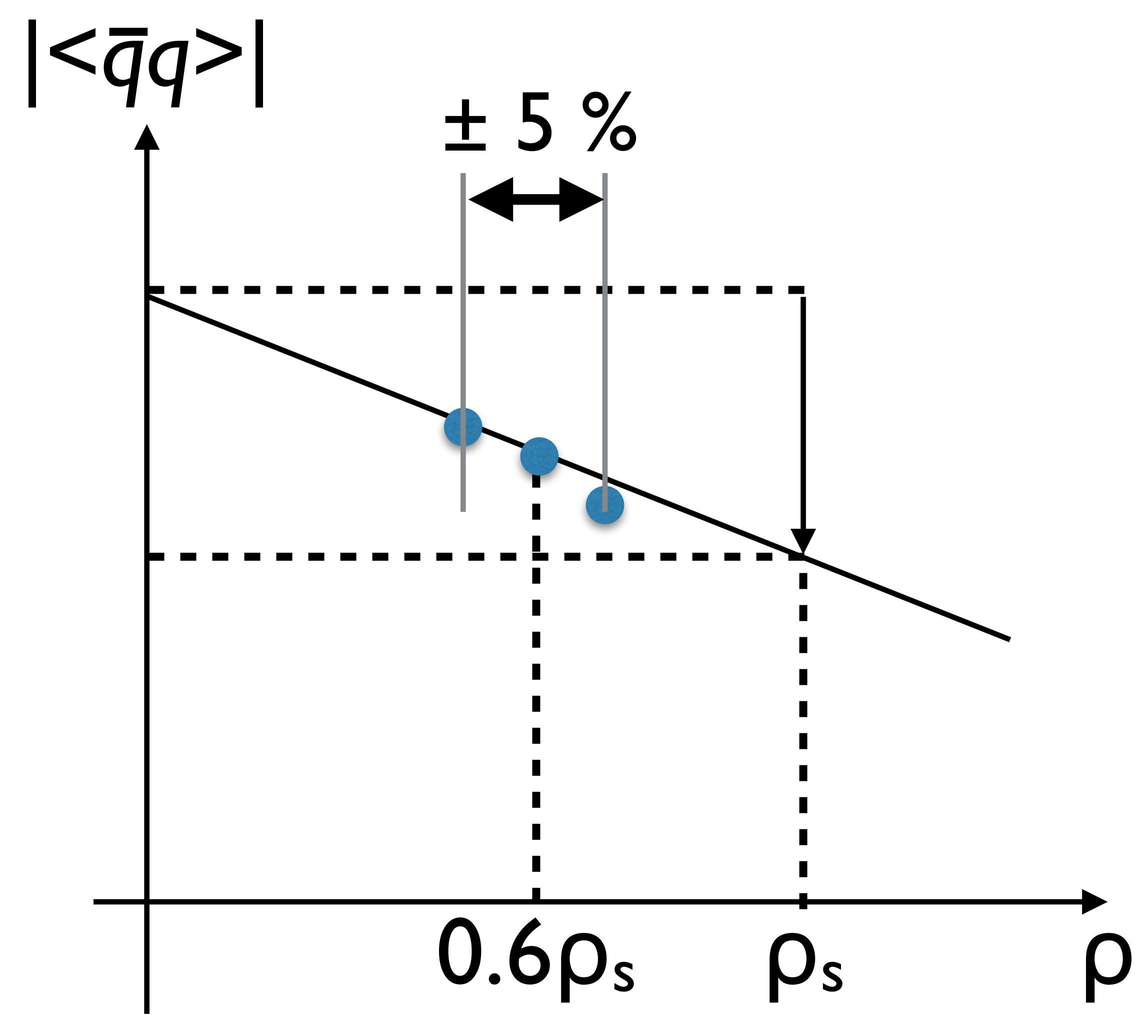
Density Dependence of Chiral Condensate

Q. what can be achieved by measuring isotopes? why not single isotope? How far can we discuss?

Ans.: **density dependence of chiral condensate** can be studied based on deeply bound pionic atoms

Densities probed by pionic Sn with wide range of A

Important for $\sigma_{\pi N}$ for investigation of origin of matter mass



Pionic atoms are known to probe $\sim 0.6\rho_s$

Systematic spectroscopy of pionic Sn isotopes
RIBF-135

113 I	114 I	115 I	116 I	117 I	118 I	119 I	120 I	121 I	122 I	123 I	124 I	125 I	126 I	127 I	128 I
112 Te	113 Te	114 Te	115 Te	116 Te	117 Te	118 Te	119 Te	120 Te	121 Te	122 Te	123 Te	124 Te	125 Te	126 Te	127 Te
111 Sb	112 Sb	113 Sb	114 Sb	115 Sb	116 Sb	117 Sb	118 Sb	119 Sb	120 Sb	121 Sb	122 Sb	123 Sb	124 Sb	125 Sb	126 Sb
110 Sn	111 Sn	112 Sn	113 Sn	114 Sn	115 Sn	116 Sn	117 Sn	118 Sn	119 Sn	120 Sn	121 Sn	122 Sn	123 Sn	124 Sn	125 Sn
109 In	110 In	111 In	112 In	113 In	114 In	115 In	116 In	117 In	118 In	119 In	120 In	121 In	122 In	123 In	124 In
108 Cd	109 Cd	110 Cd	111 Cd	112 Cd	113 Cd	114 Cd	115 Cd	116 Cd	117 Cd	118 Cd	119 Cd	120 Cd	121 Cd	122 Cd	123 Cd
107 Ag	108 Ag	109 Ag	110 Ag	111 Ag	112 Ag	113 Ag	114 Ag	115 Ag	116 Ag	117 Ag	118 Ag	119 Ag	120 Ag	121 Ag	122 Ag

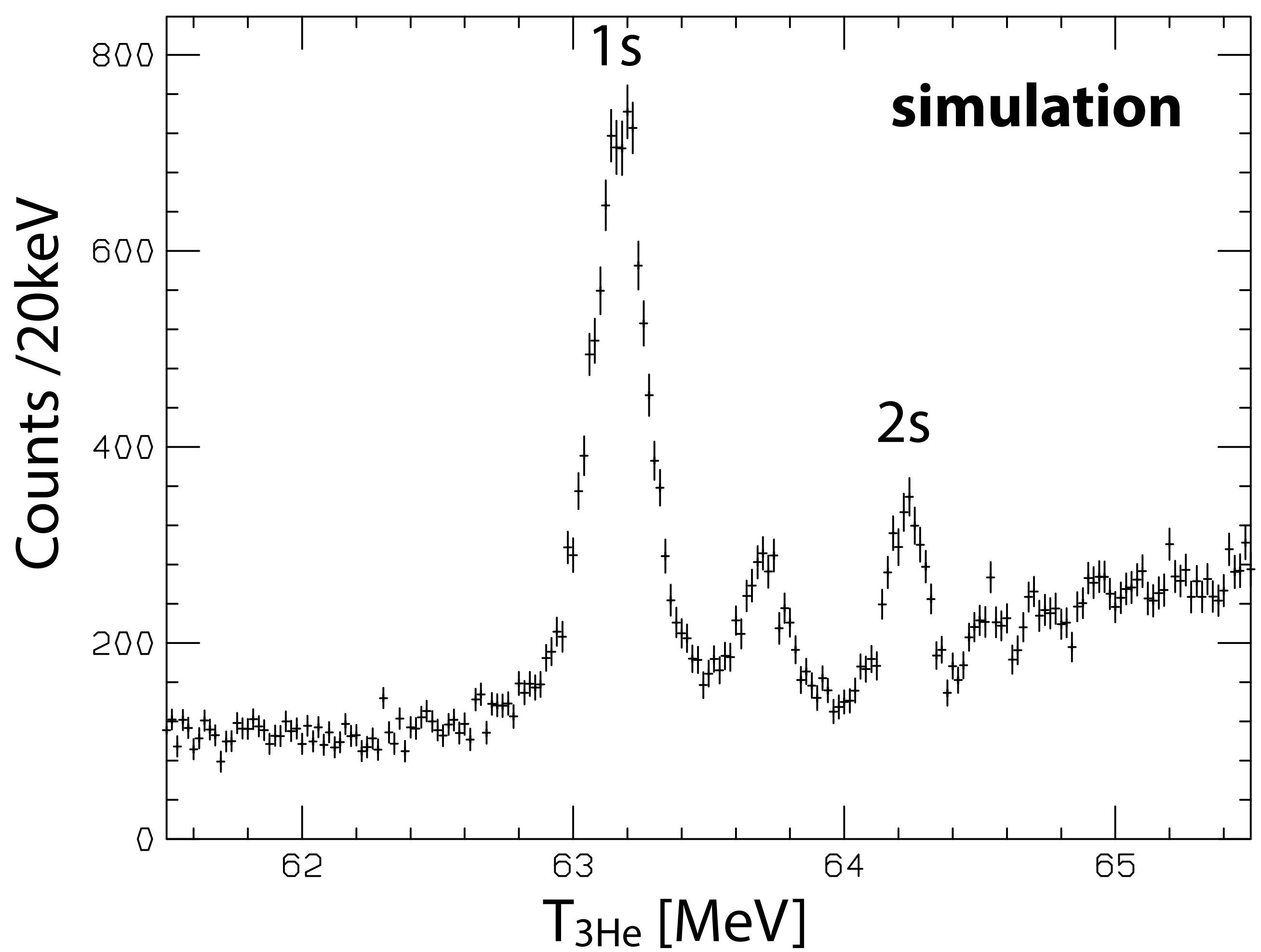
We are preparing for

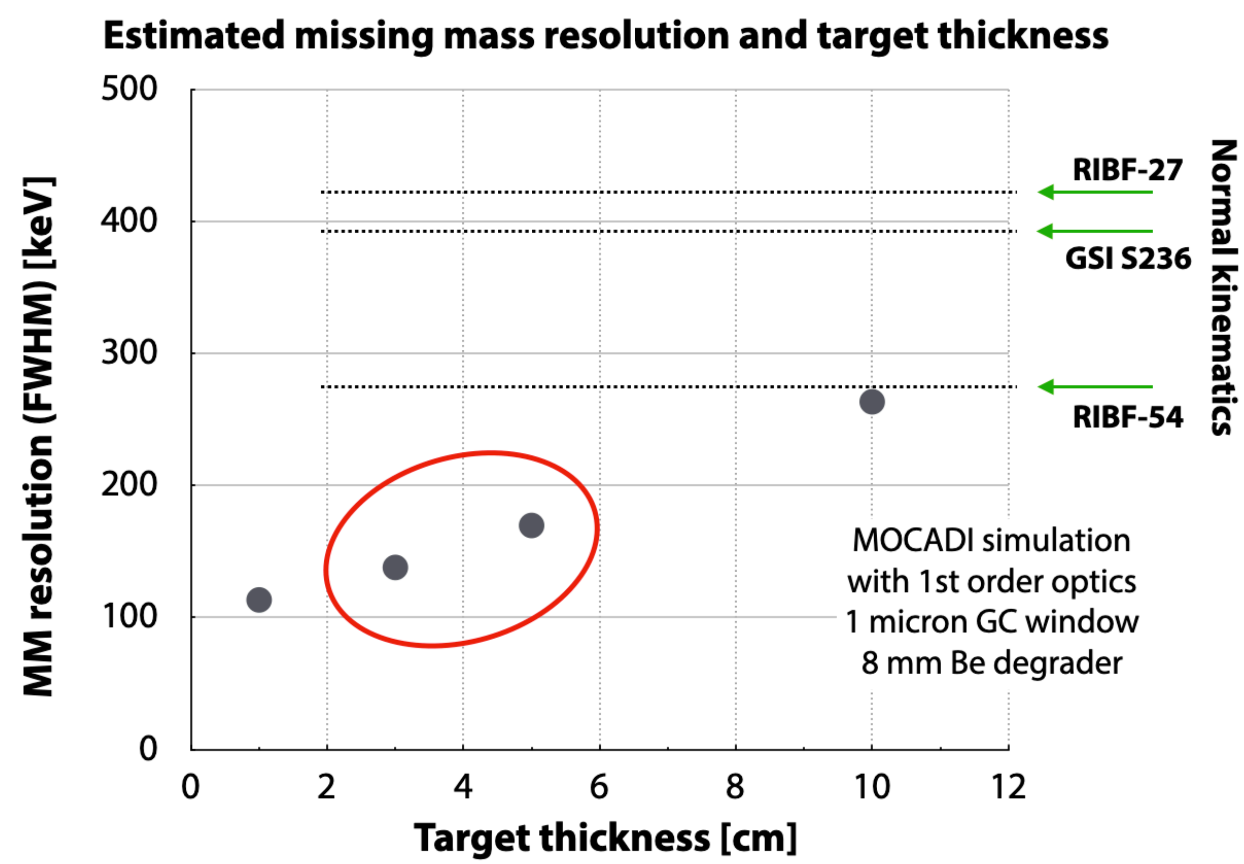
Inverse kinematics (RIBF-214)

For kinematical reasons, ambiguities in the incident beam energy do not affect the results.
The resolution will be even improved.

Proposing D(^{136}Xe,^{3}He) reaction at T = 250 MeV/u at RIBF

72 hours with 10^{10}/s ^{136}Xe beam



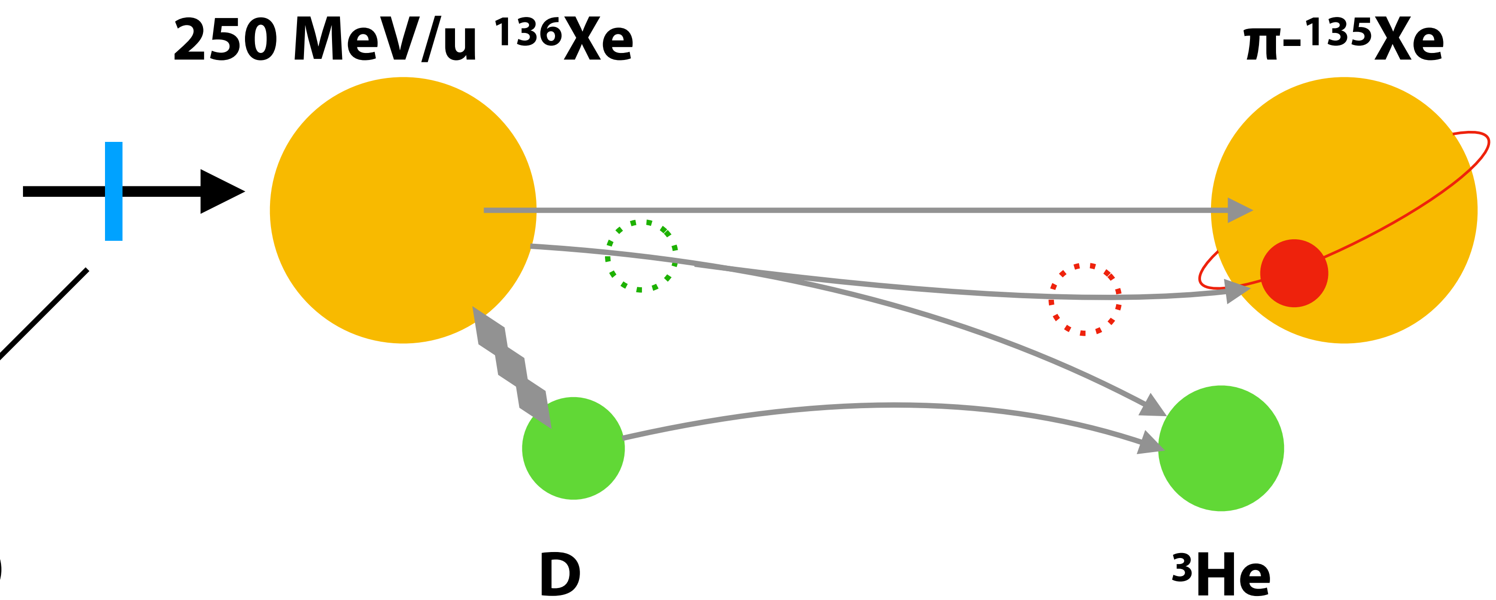


Experimental setup

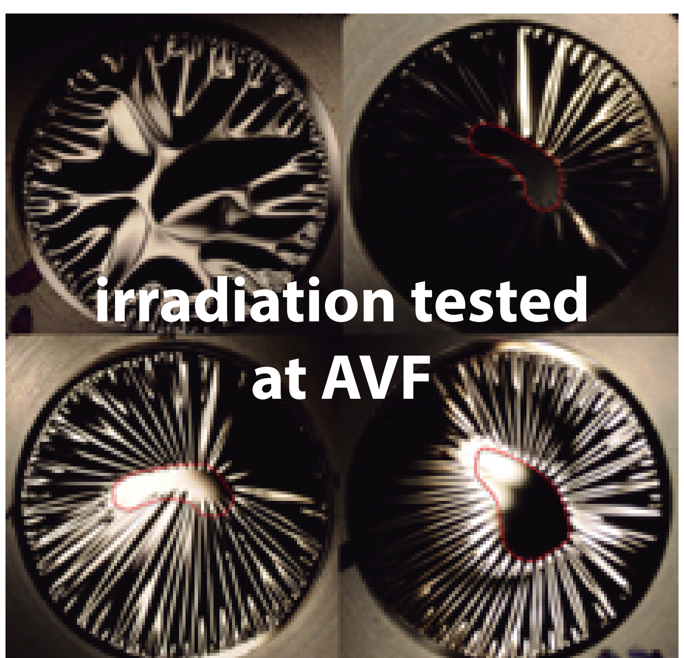
NP2212-RIBF214

345 MeV/u ^{136}Xe beam
(RRC-fRC-IRC-SRC)

Be degrader 8.14 mm
Energy straggling = 0.2 MeV/u (σ)
Angular straggling = 1.15 mrad (σ)
Charge state stays by 92.5%

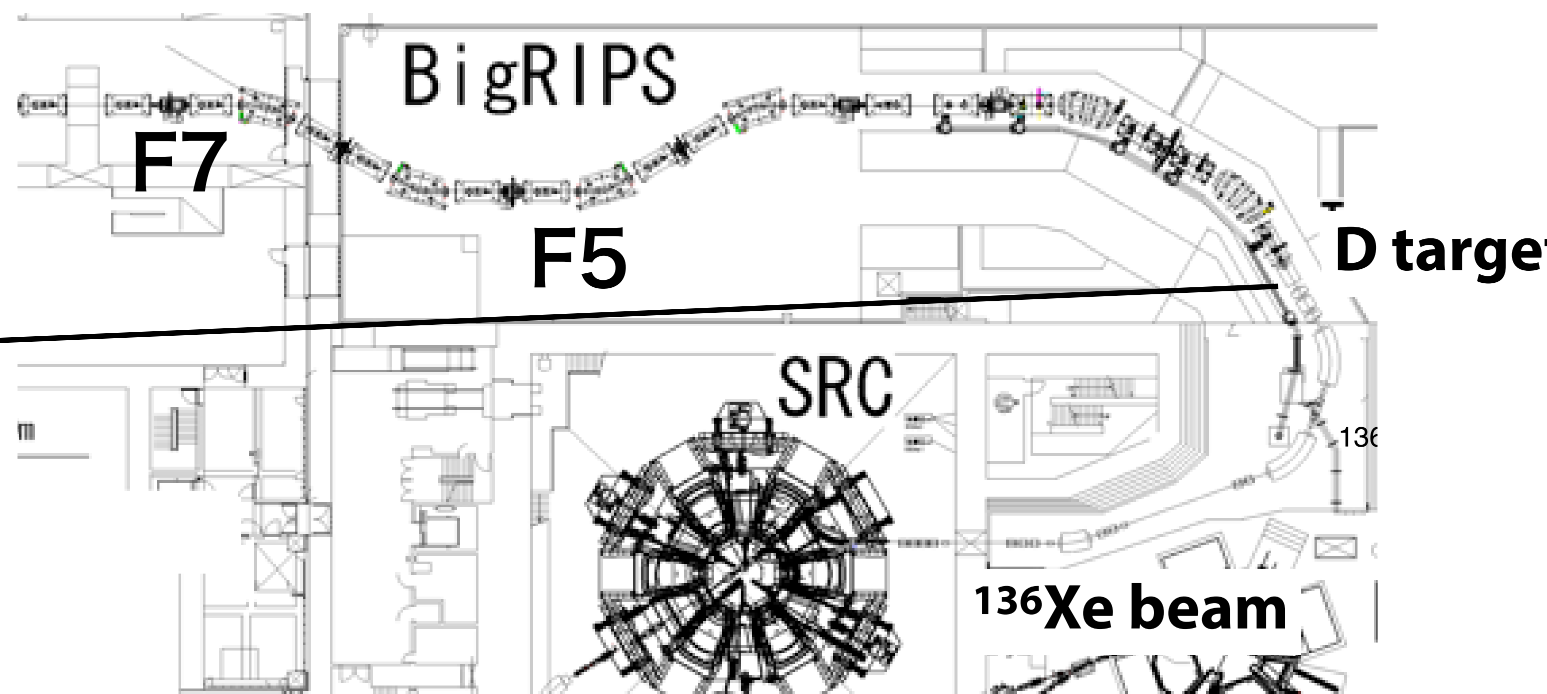


1-atm deuterium gas target at F0
with **graphenic carbon** windows



S. Purushothaman et al., APR **53**, 134 (2019)

BigRIPS as spectrometer to measure
~1 Tm ^{3}He momentum



Summary

- Chiral condensate at ρ_e is evaluated to be reduced by 77±2%, which is linearly extrapolated to 60±3% at the nuclear saturation density [N. Phys. 19 (2023) 788].

- The binding energies and widths of the pionic 1*s* and 2*p* states in Sn121 are 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 included various updates for the first time. The updated parameters made substantial effects leading to 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.

Hadron 2025 (Osaka, Mar. 27-31)
Hadron in Nucleus 2025 (Kyoto, Apr. 2-4)