XVth Quark Confinement and the Hadron Spectrum Conference
2022 - University of Stavanger

What can pionic atoms tell us about the chiral symmetry of the vacuum

Meson Science Laboratory, RIKEN
Kenta Itahashi

Nishi, KI et al., arXiv: 2204.05568

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]

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What can pionic atoms tell us about the chiral symmetry

- **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.**

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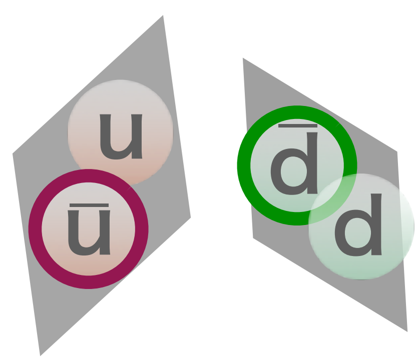
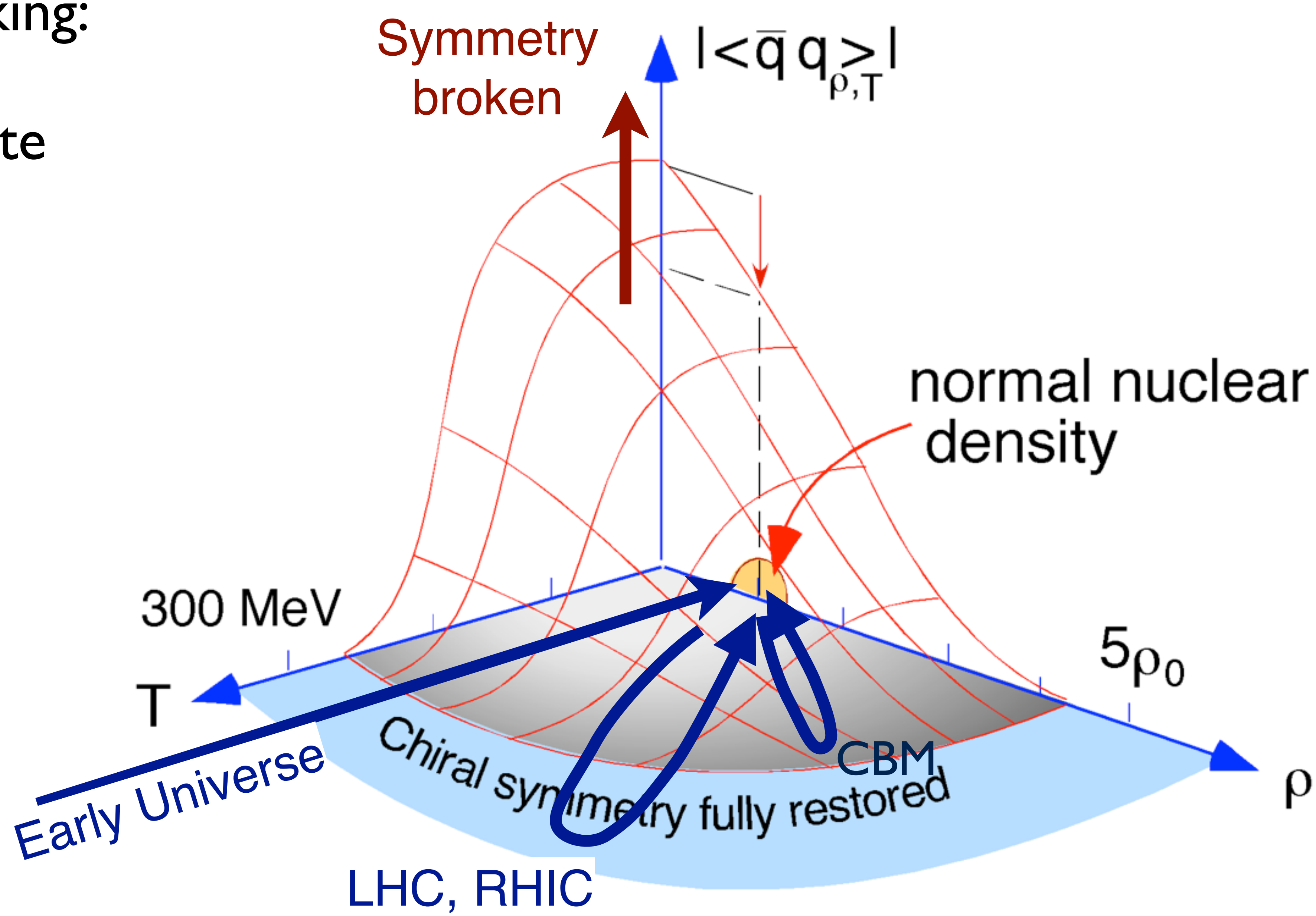
Chiral condensate, order parameter of chiral symmetry

One of order parameters of
χ-symmetry breaking:

Chiral condensate

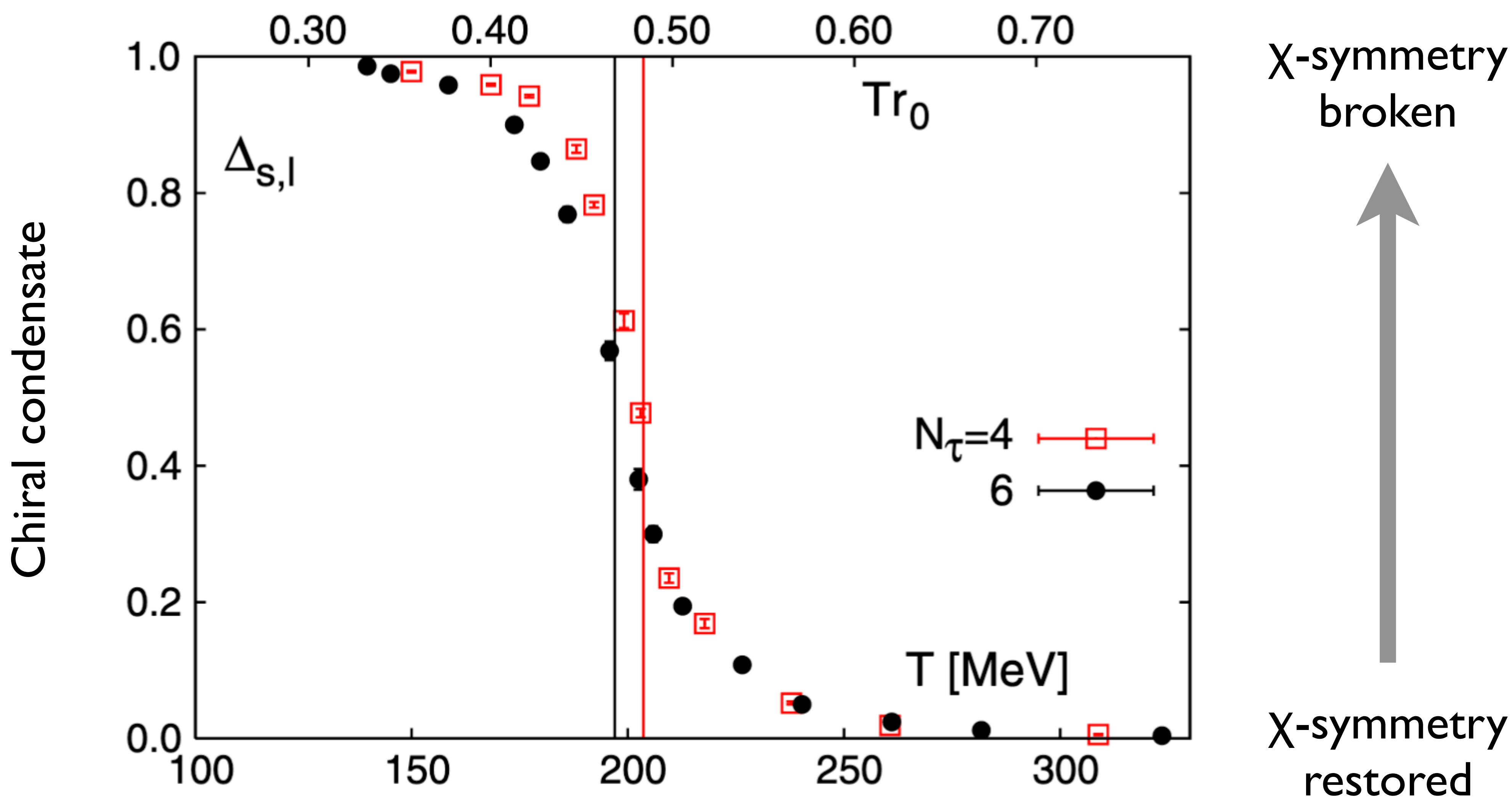




Analysis of material properties
of QCD vacuum

W.Weise,
NPA553(93)59.

Lattice QCD calculated T dependence of chiral condensate

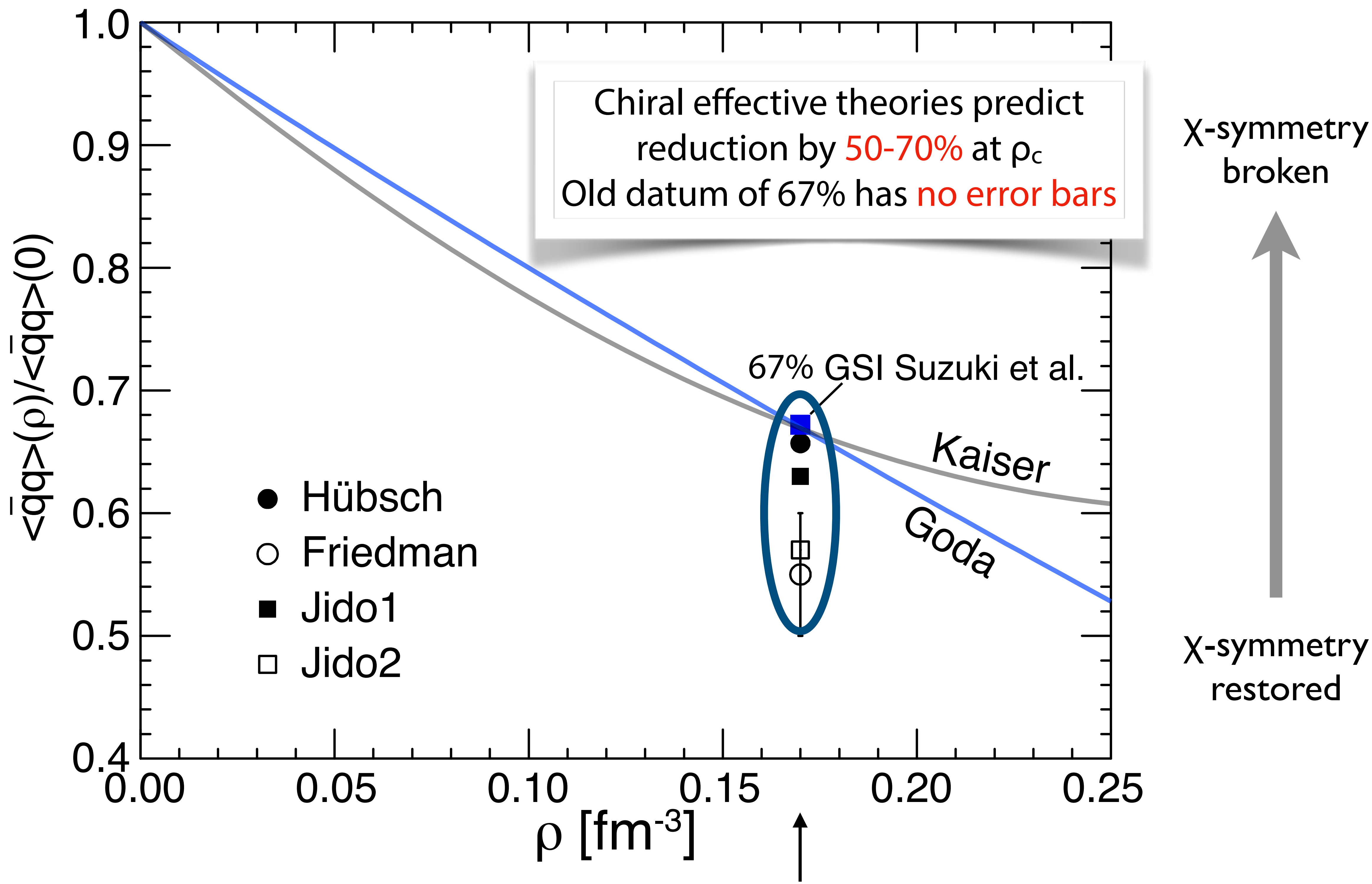


Temperature dependence of the chiral condensate from lattice QCD with 2 + 1 quark flavours and almost physical quark masses

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

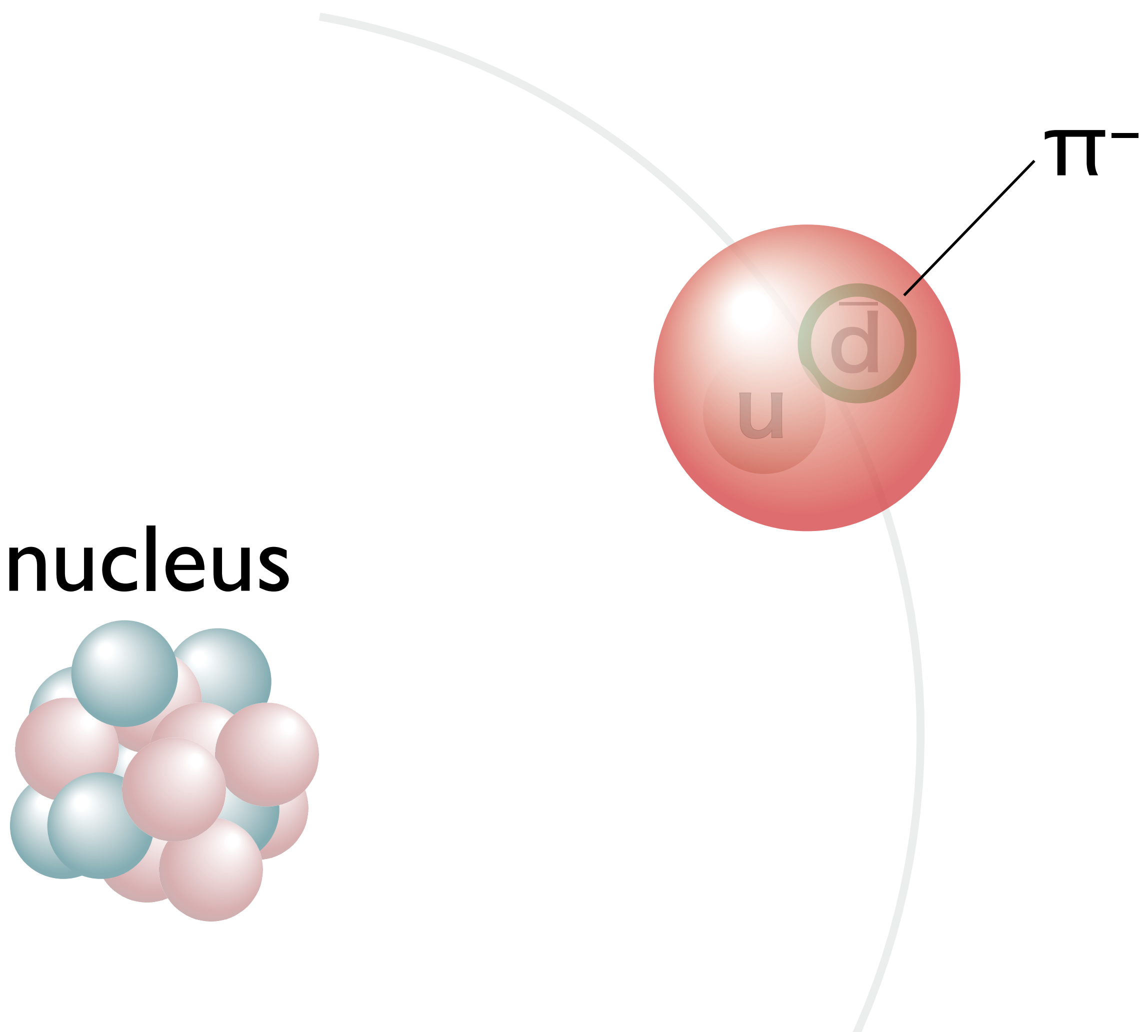
M. Cheng et al., Phys. Rev. D77(2008), 014511.

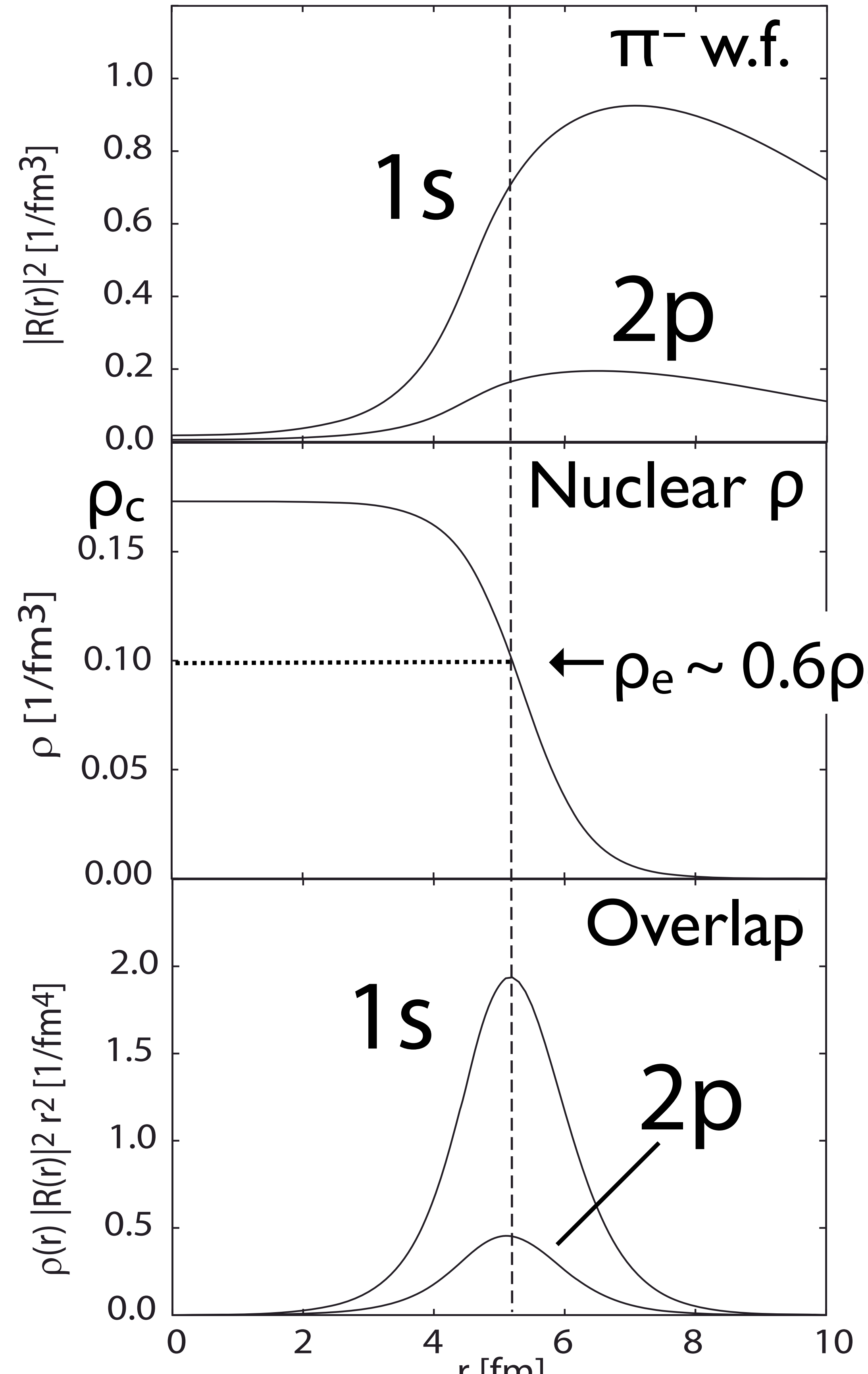
ρ dependence of chiral condensate



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)

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 interaction

Overlap between
pion w.f. and nucleus
→ π works as a probe
at $\rho_e \sim 0.6\rho_c$

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

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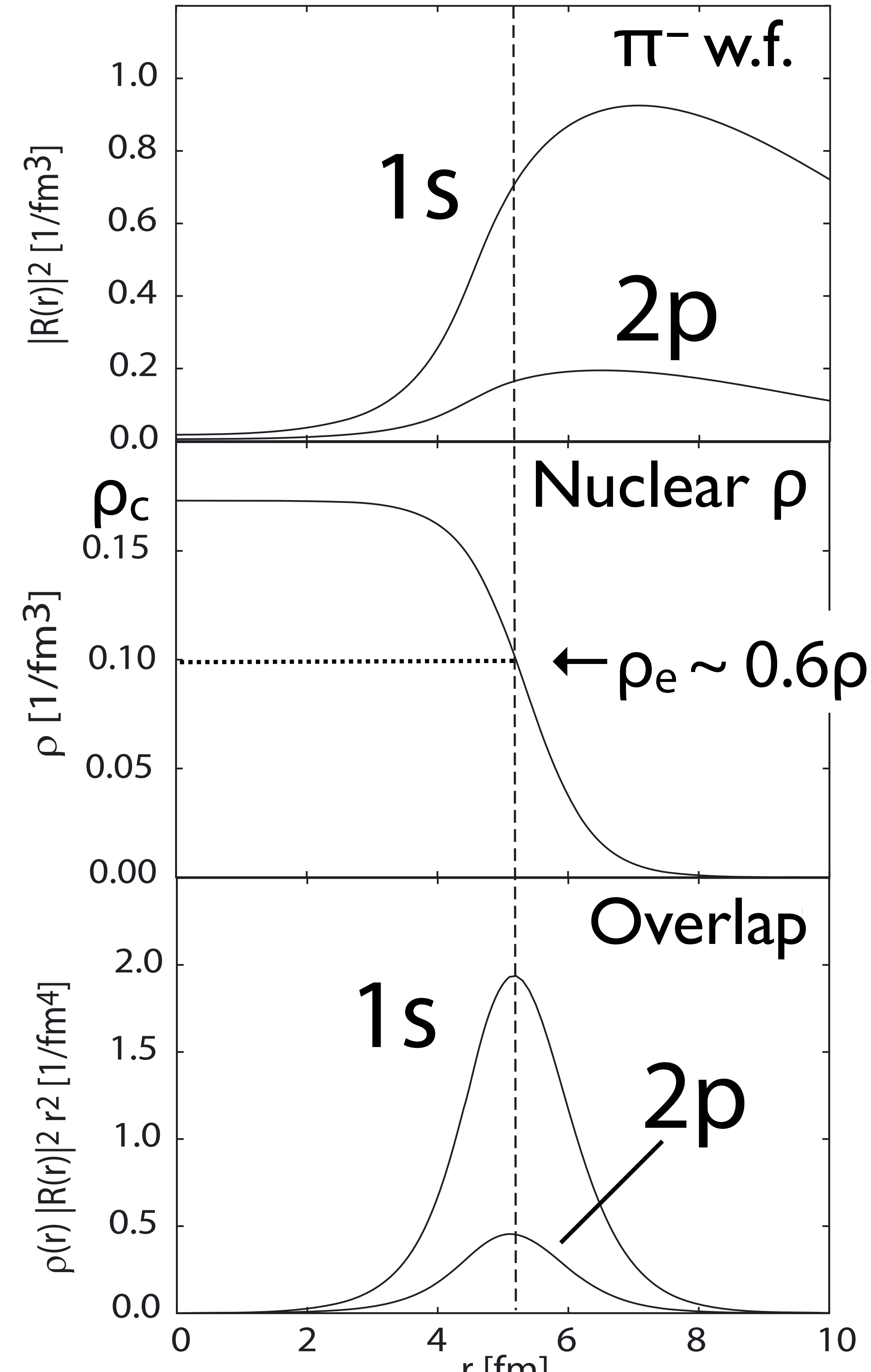

Ikeno et al., PTP126 (2011) 483

Pion-nucleus interaction and chiral condensate

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In-medium Glashow-Weinberg relation

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

$\gamma = 0.184 \pm 0.003$

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

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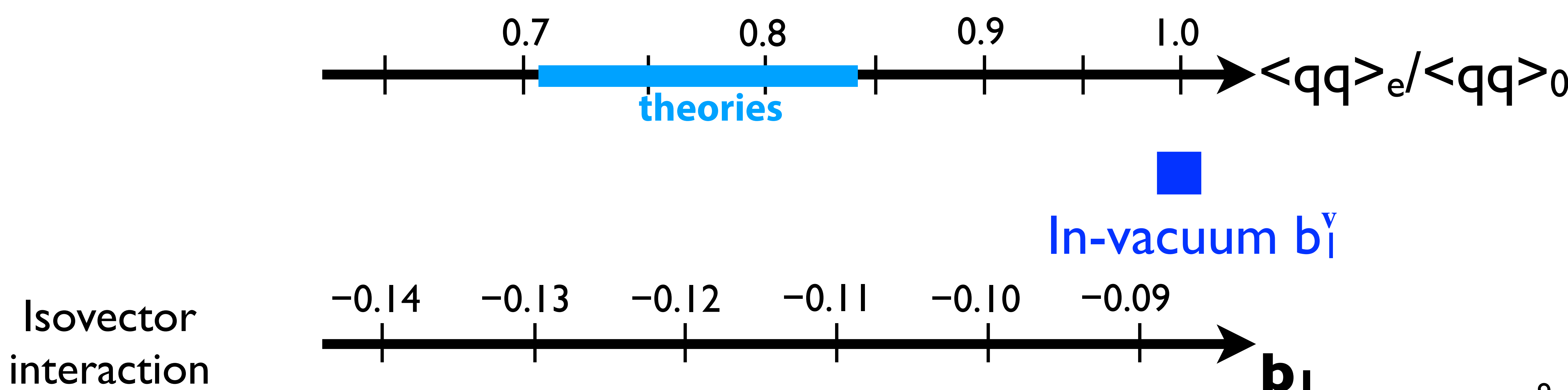
Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)

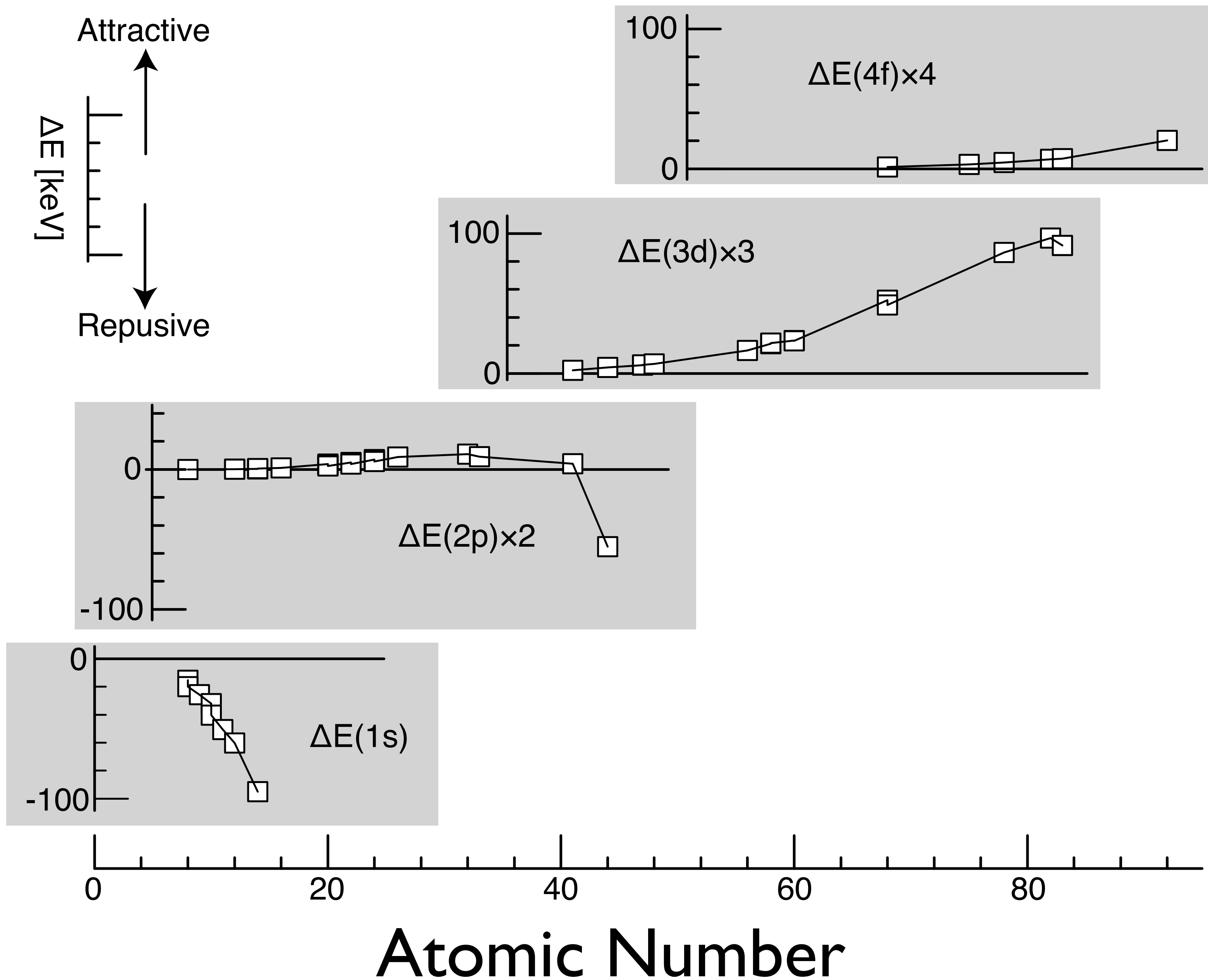
Pionic hydrogen and deuterium

$b_1^{v} = 0.0882 \pm 0.0014 \pm 0.0006$

Hirtl et al., EPJA57, 70 (2021)



Level shifts in pionic X-ray measurements



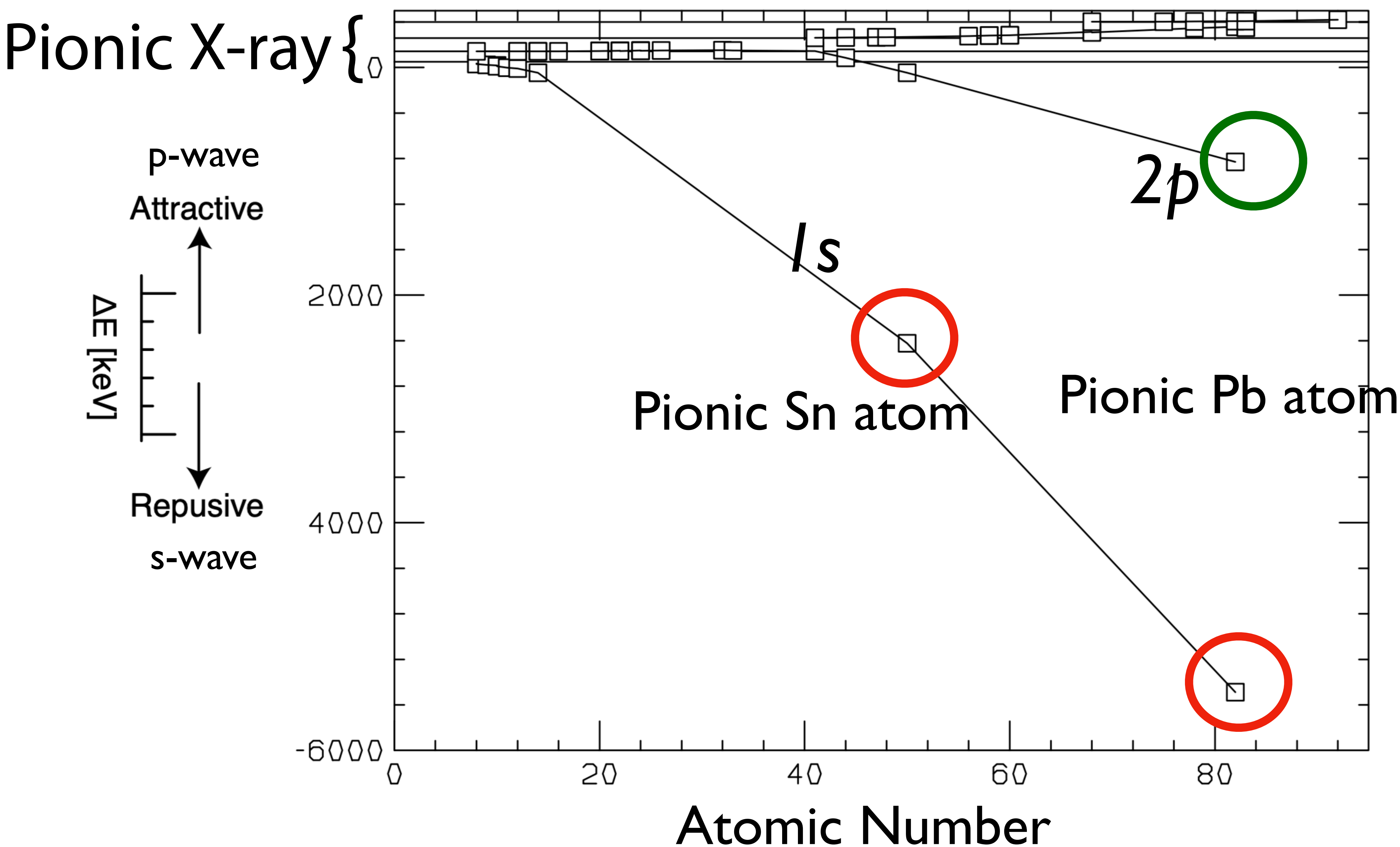
Ericson-Ericson potential

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

$$U_s(r) = b_0\,\rho + \mathbf{b_1}\,(\rho_n - \rho_p) + B_0\,\rho^2 \longrightarrow$$ s-wave = repulsive = negative shift

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

Deeply bound pionic atoms
Level shifts

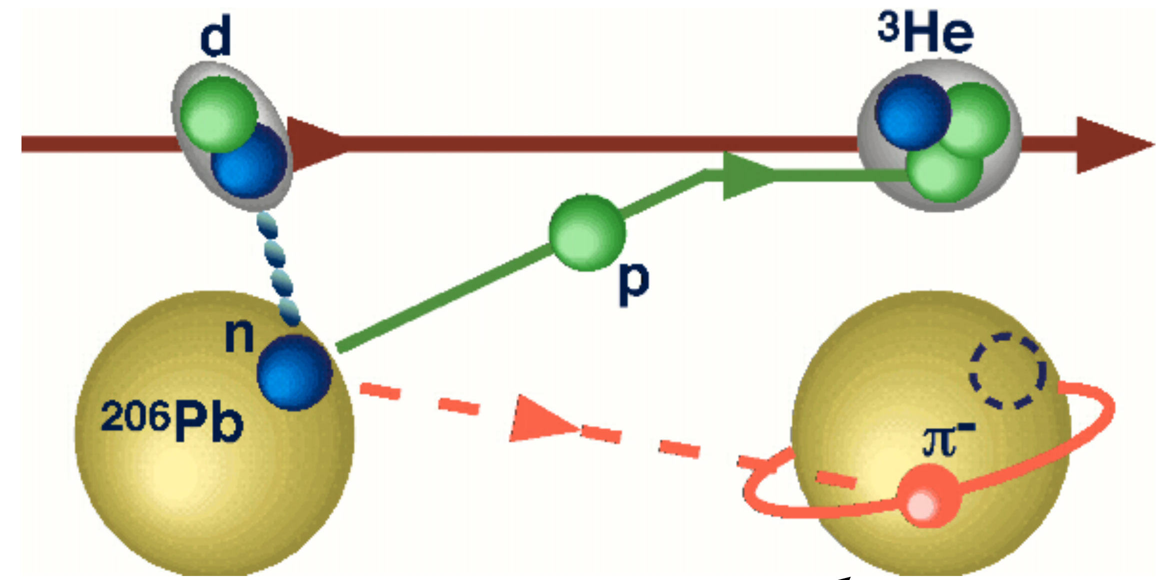


Deeply bound atoms have "super" repulsive shifts and provide *s*-wave information

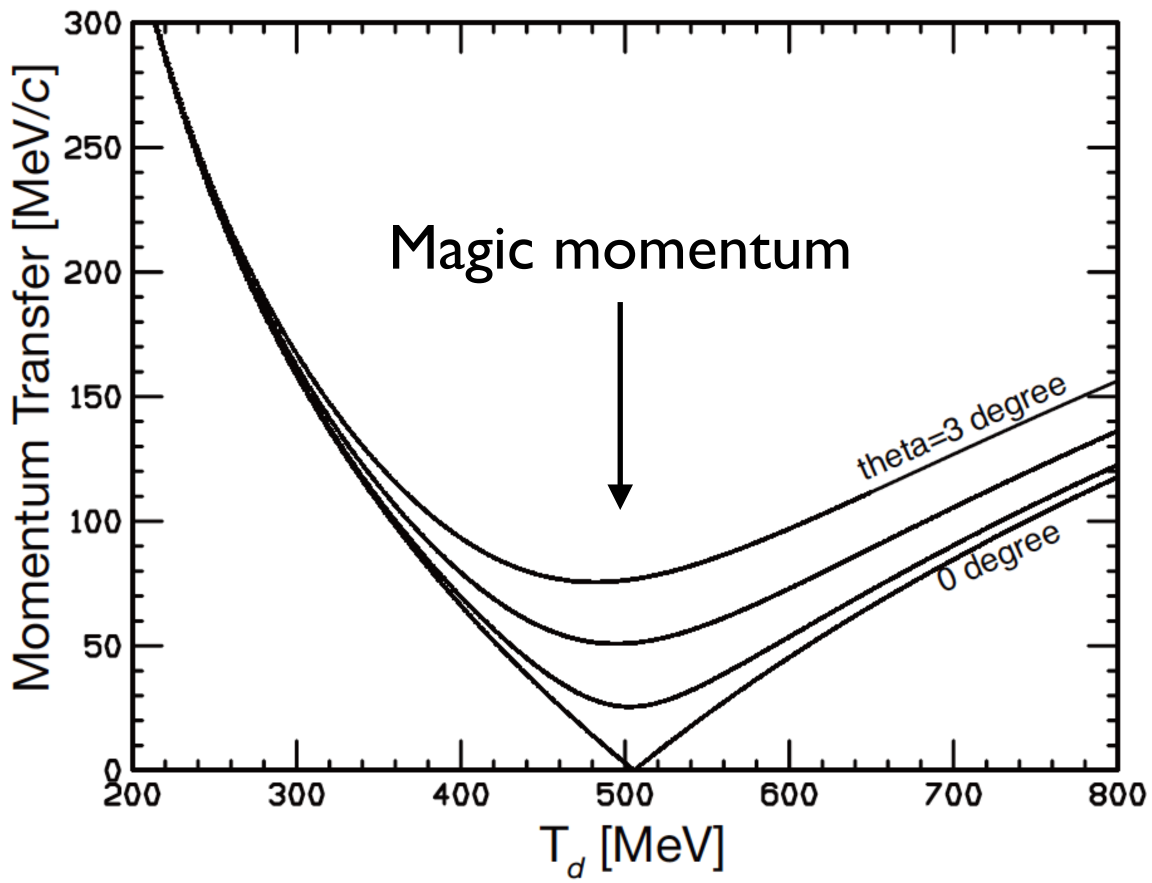
Spectroscopy of pionic atoms in (*d*,^{3}He) reactions

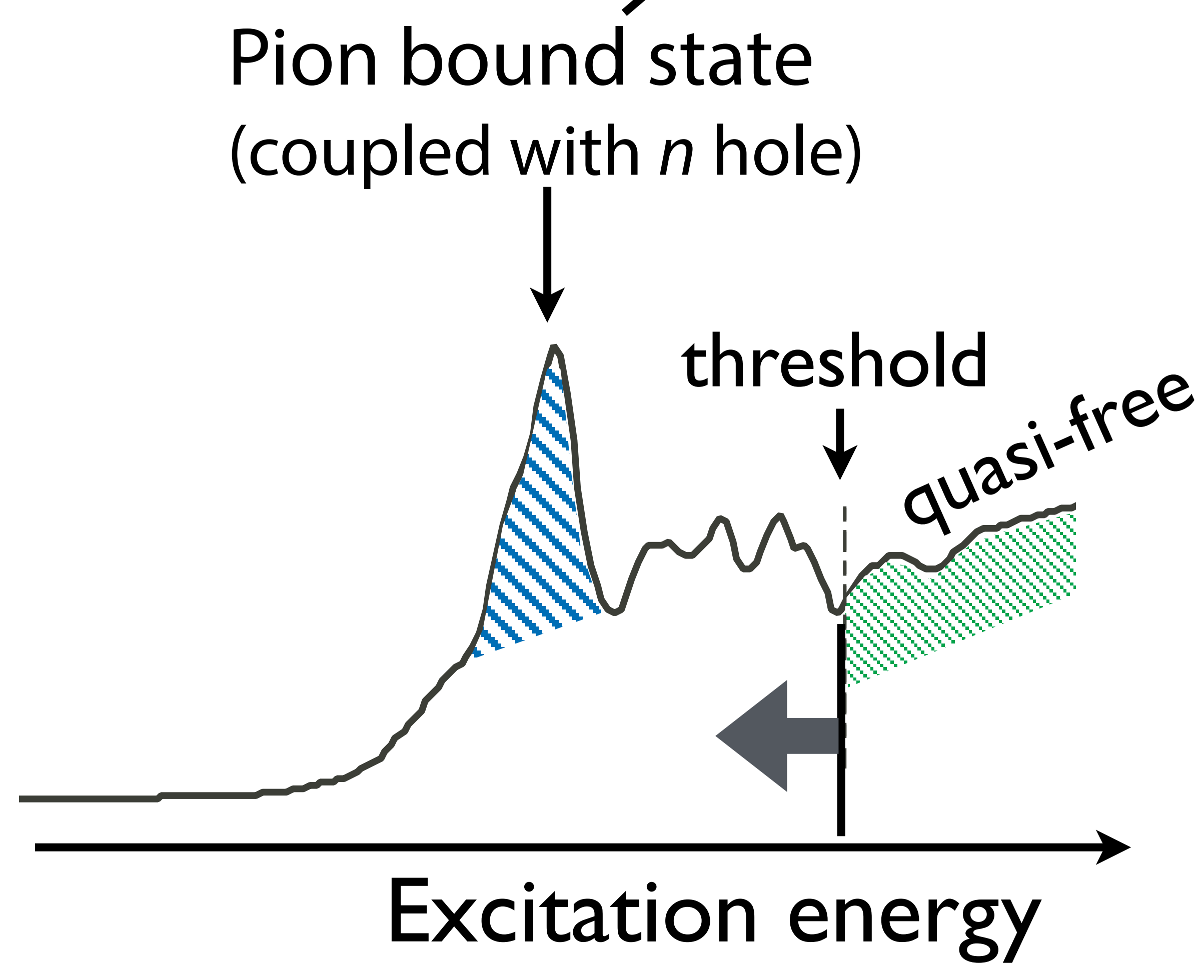
Missing mass spectroscopy to measure excitation spectrum of pionic atoms

Direct production of pionic atoms



Momentum transfer





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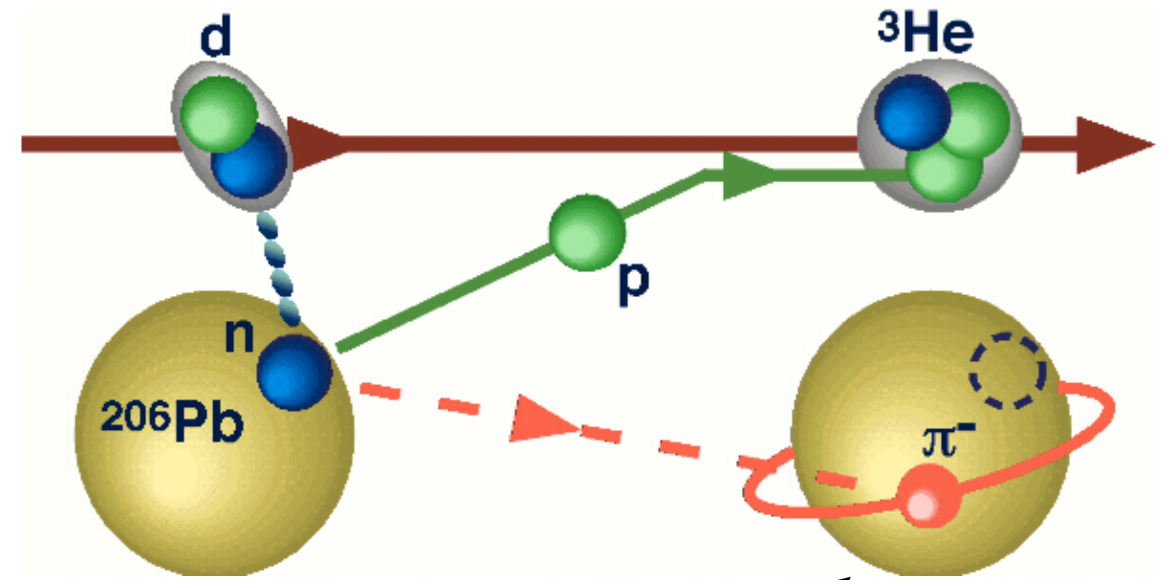

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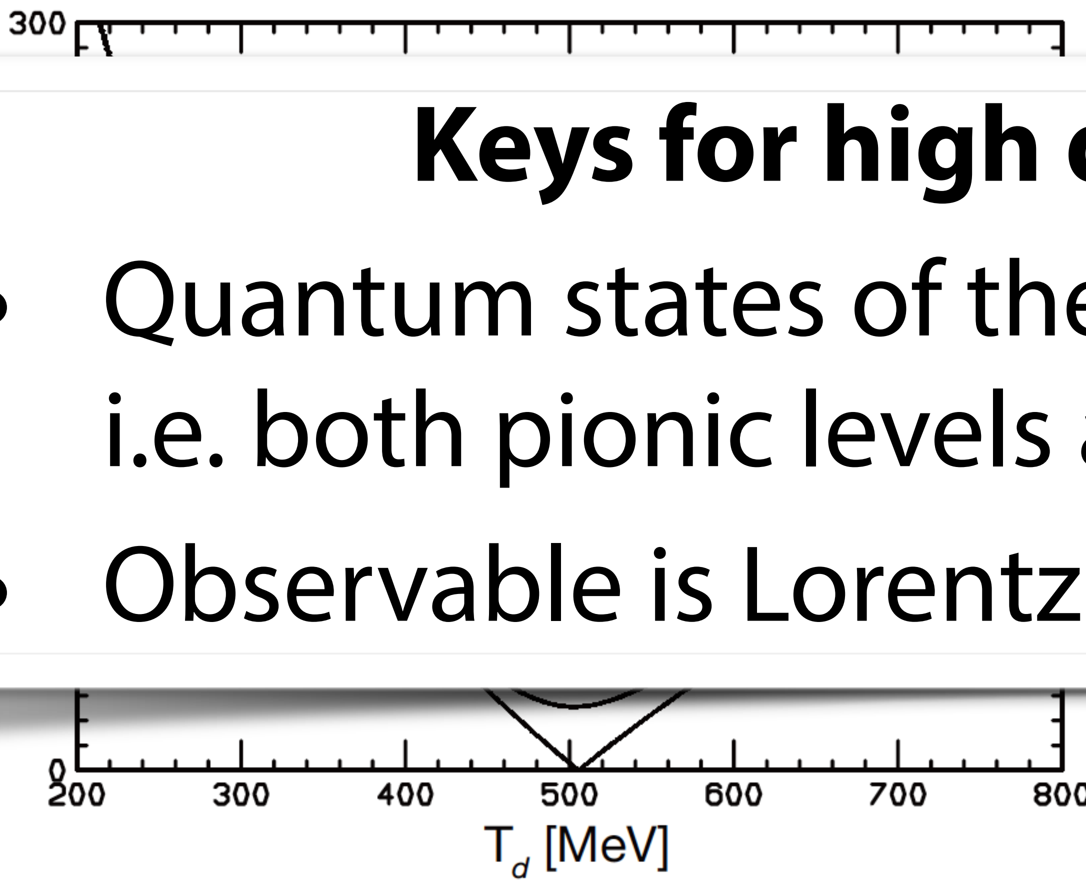
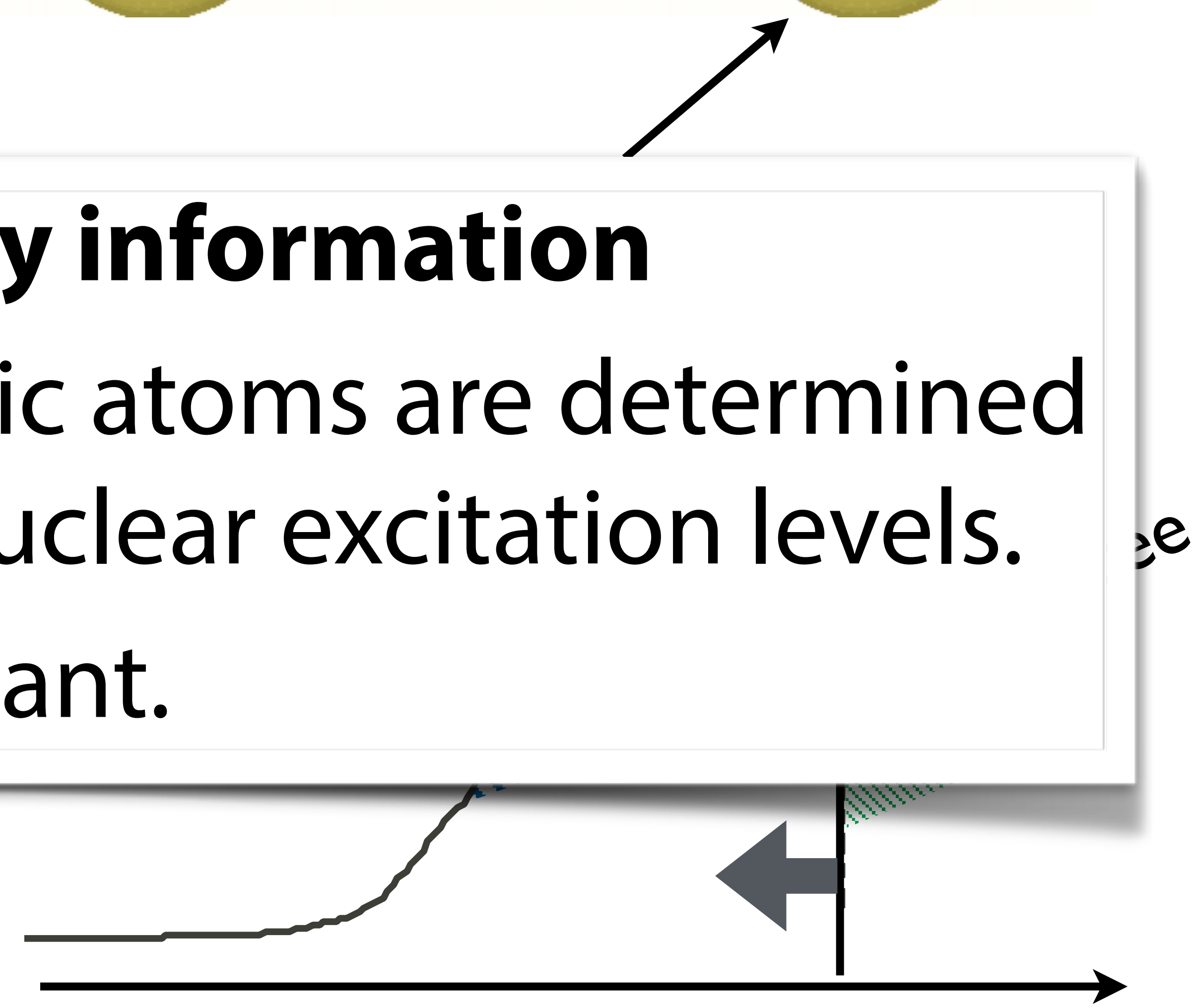
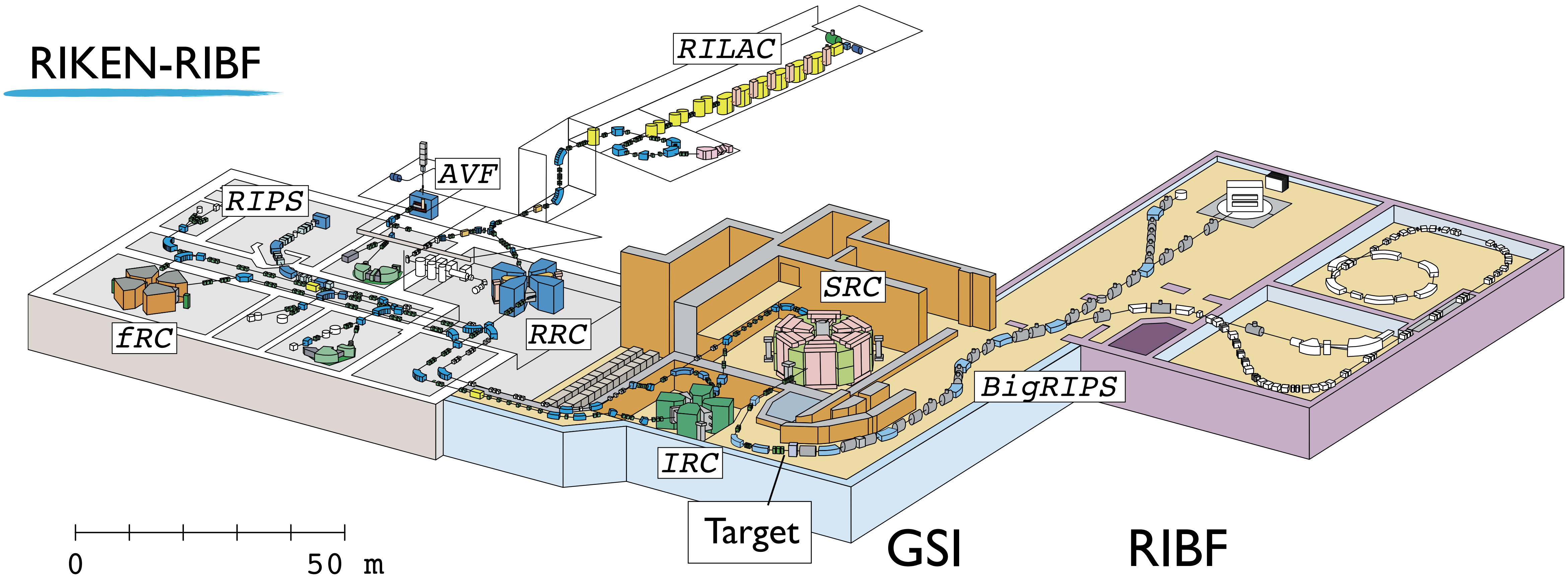


Keys for high quality information

- Quantum states of the pionic atoms are determined i.e. both pionic levels and nuclear excitation levels.
- Observable is Lorentz invariant.



RI Beam Factory

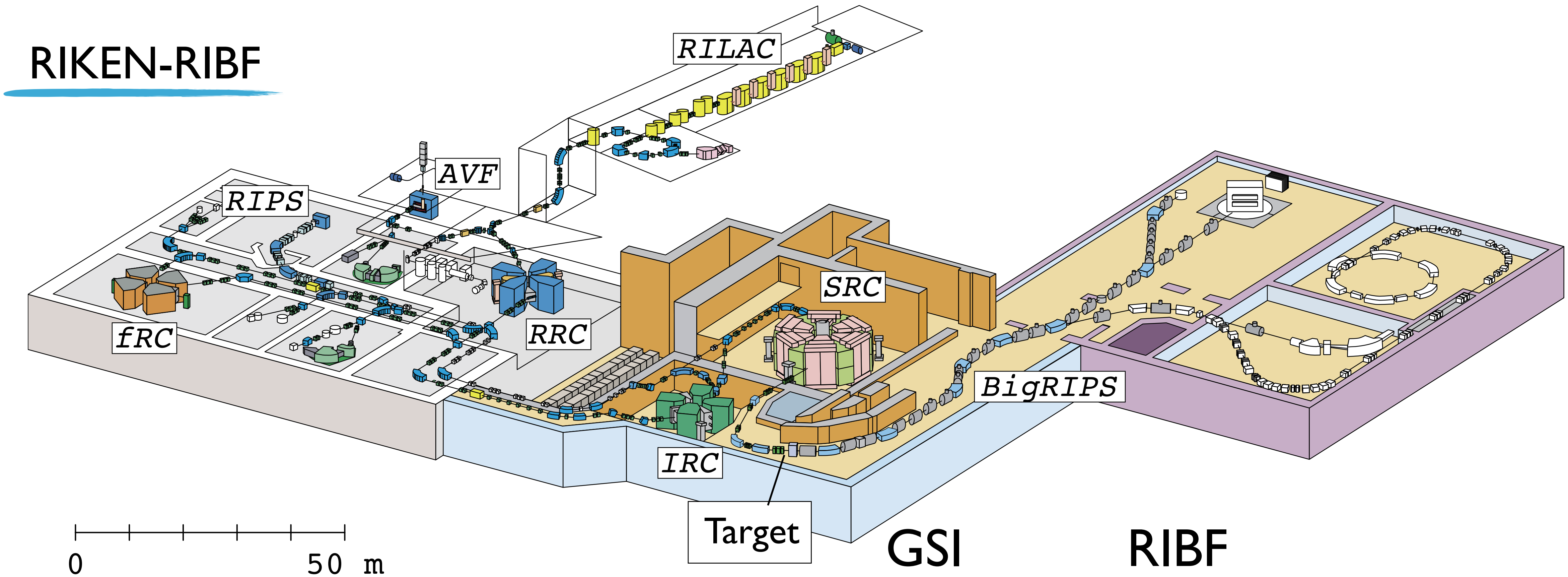


	GSI	RIBF
d beam Intensity	10^{11}/spill	>10^{12}/s
Target	20 mg/cm^2	10 mg/cm^2
$\Delta p_d/p_d$ (FWHM)	0.02%	0.06%
Resolution (FWHM)	400 keV	~1000 keV
Acceptance (mrad)	15H, 10V	40H, 60V

RIKEN NiSHiNA CENTER

Kenta Itahashi, RIKEN

RI Beam Factory

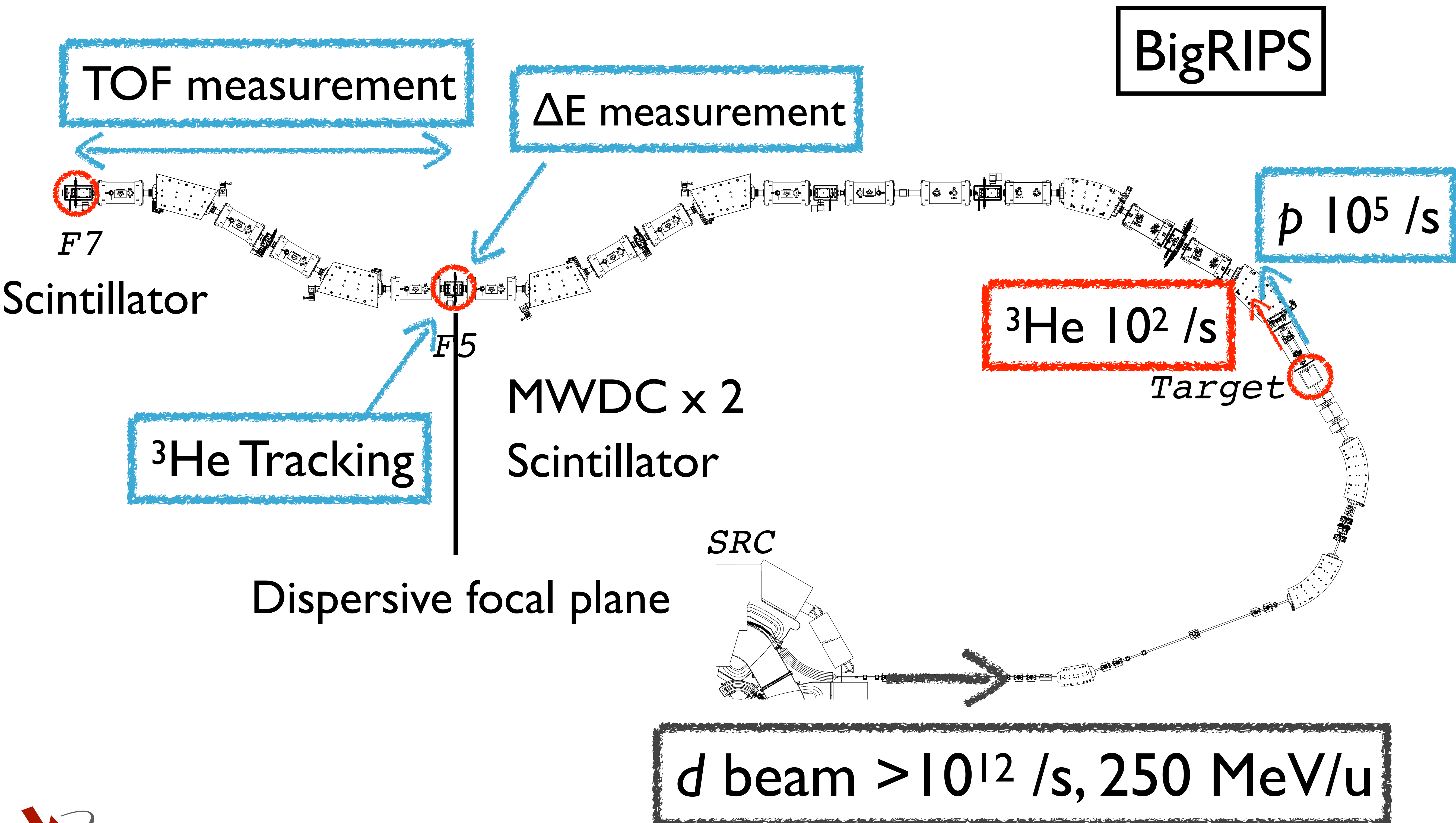


	GSI	RIBF
d beam Intensity	10^{11}/spill	$>10^{12}$/s
Target	20 mg/cm^2	10 mg/cm^2
$\Delta p_d/p_d$ (FWHM)	0.02%	0.06%
Resolution (FWHM)	400 keV	< 300 keV
Acceptance (mrad)	15H, 10V	40H, 60V

Dispersion matching

Kenta Itahashi, RIKEN

(d,^{3}He) Reaction Spectroscopy in RIBF



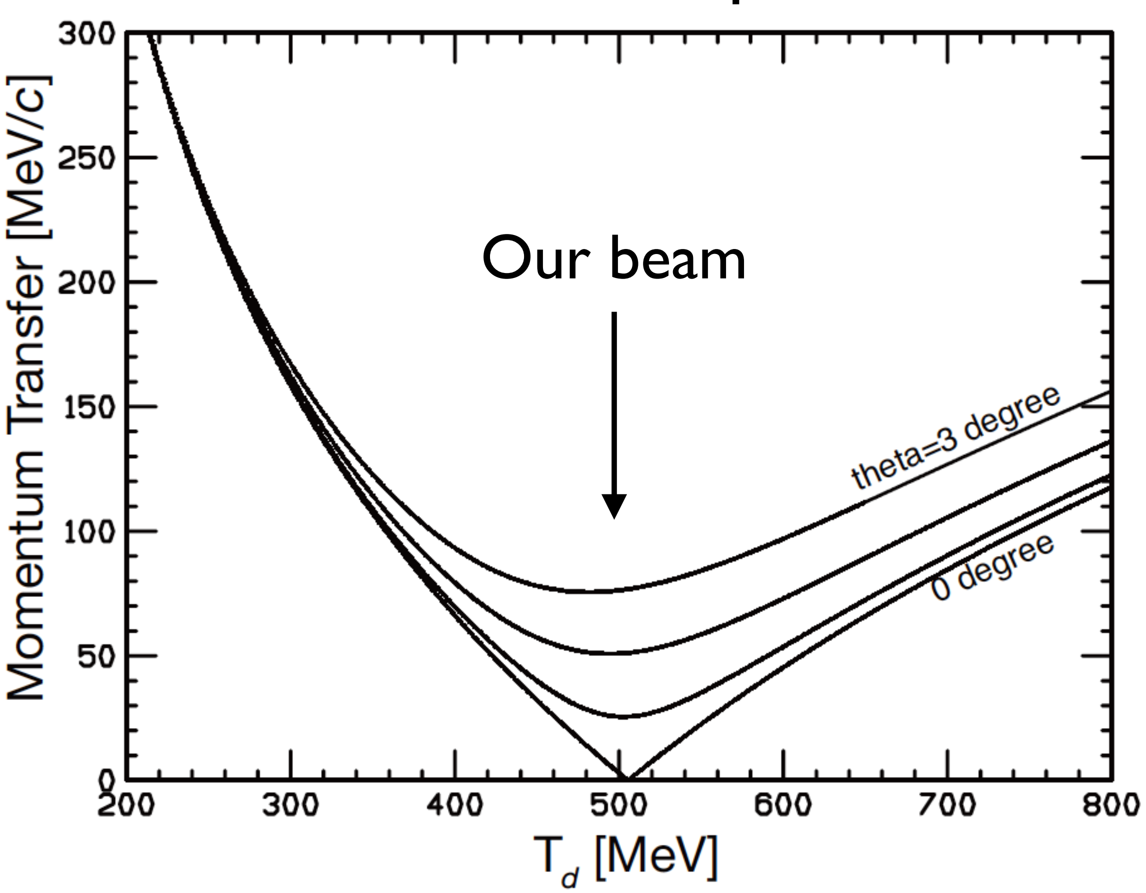
Pionic ^{121}Sn atom

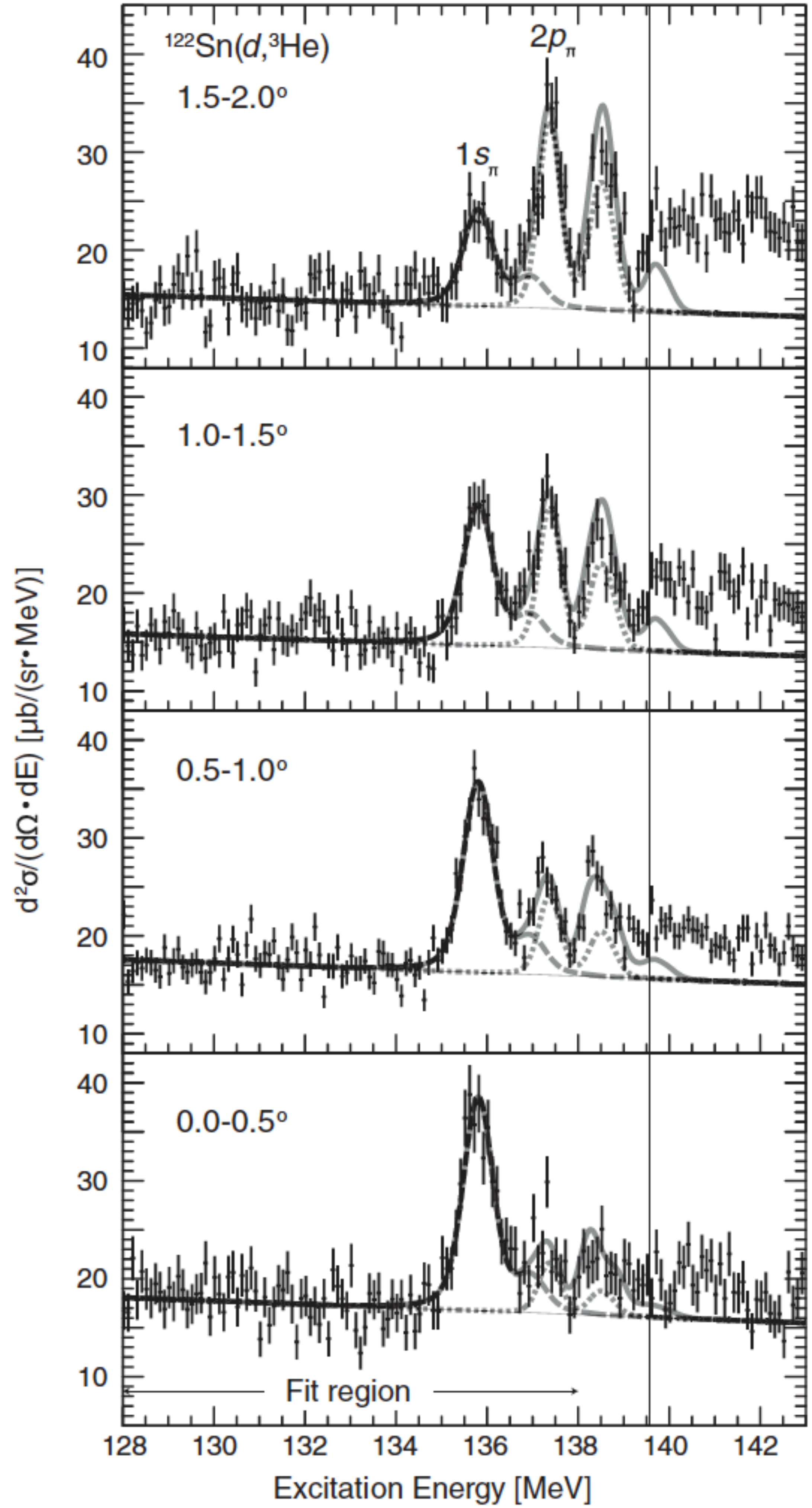
Pilot run

15 hours DAQ in 2010

First observation of θ dependence of π atom cross section

$\Delta L \sim R \times q$





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

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)

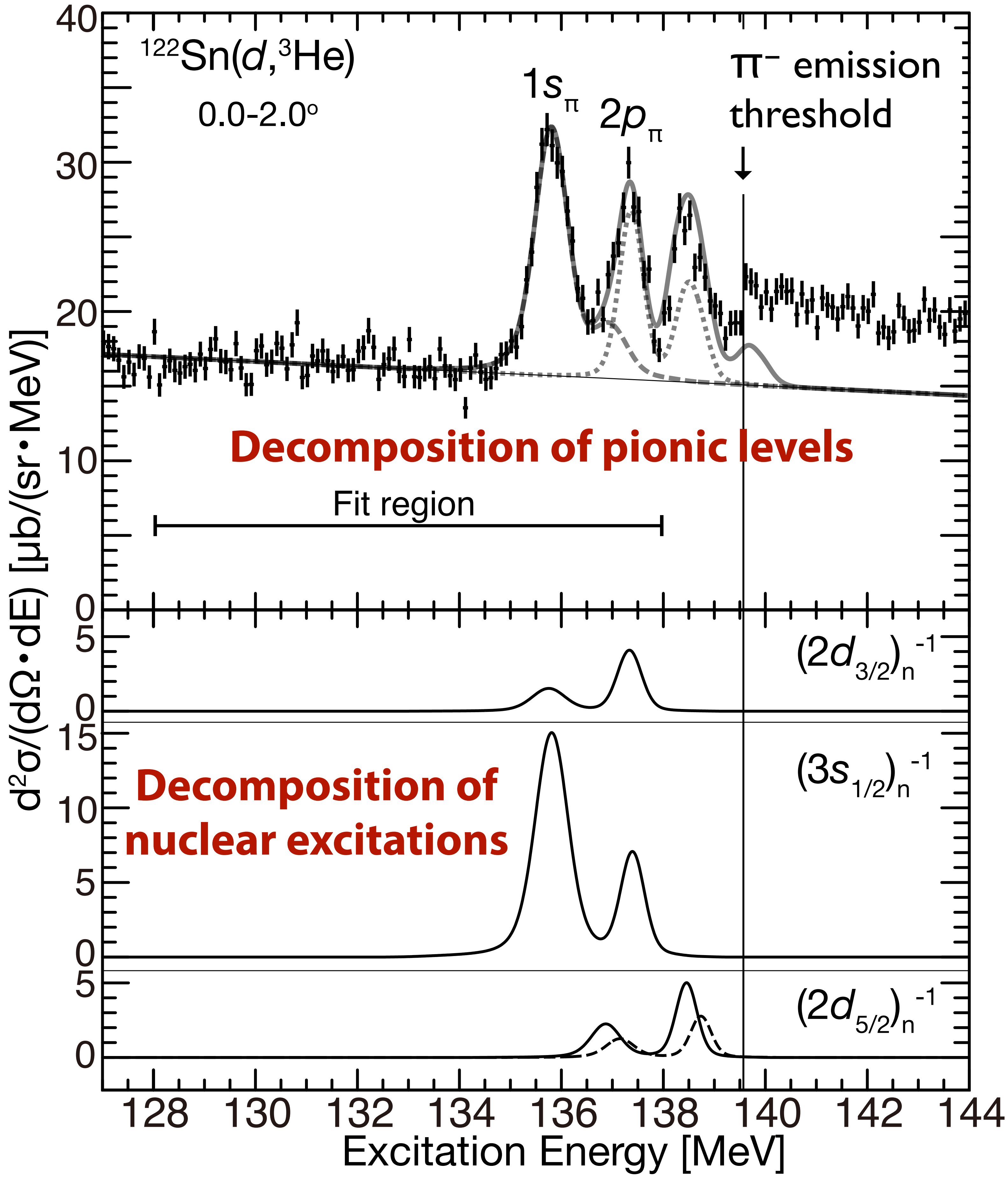
Theories

B_{1s}= 3.787–3.850 MeV

Γ_{1s}= 0.306–0.324 MeV

B_{2p}= 2.257–2.276 MeV

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



Pionic ^{121}Sn atom

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$B_{1s} = 3.828 \pm 0.0$

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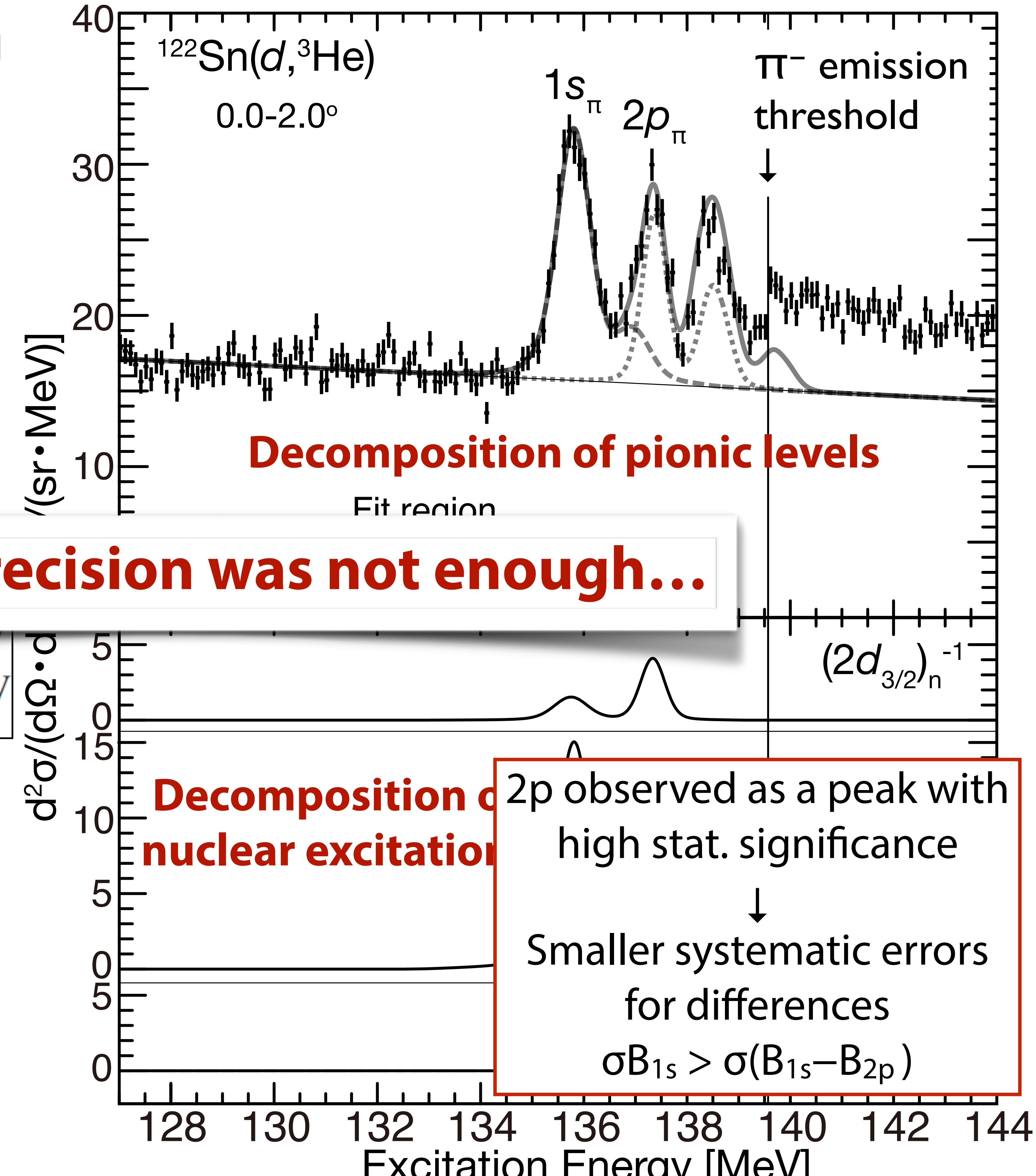

However, precision was not enough…

2p observed as a peak with high stat. significance

↓

Smaller systematic errors for differences

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

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

Pionic atom unveils hidden structure of QCD vacuum

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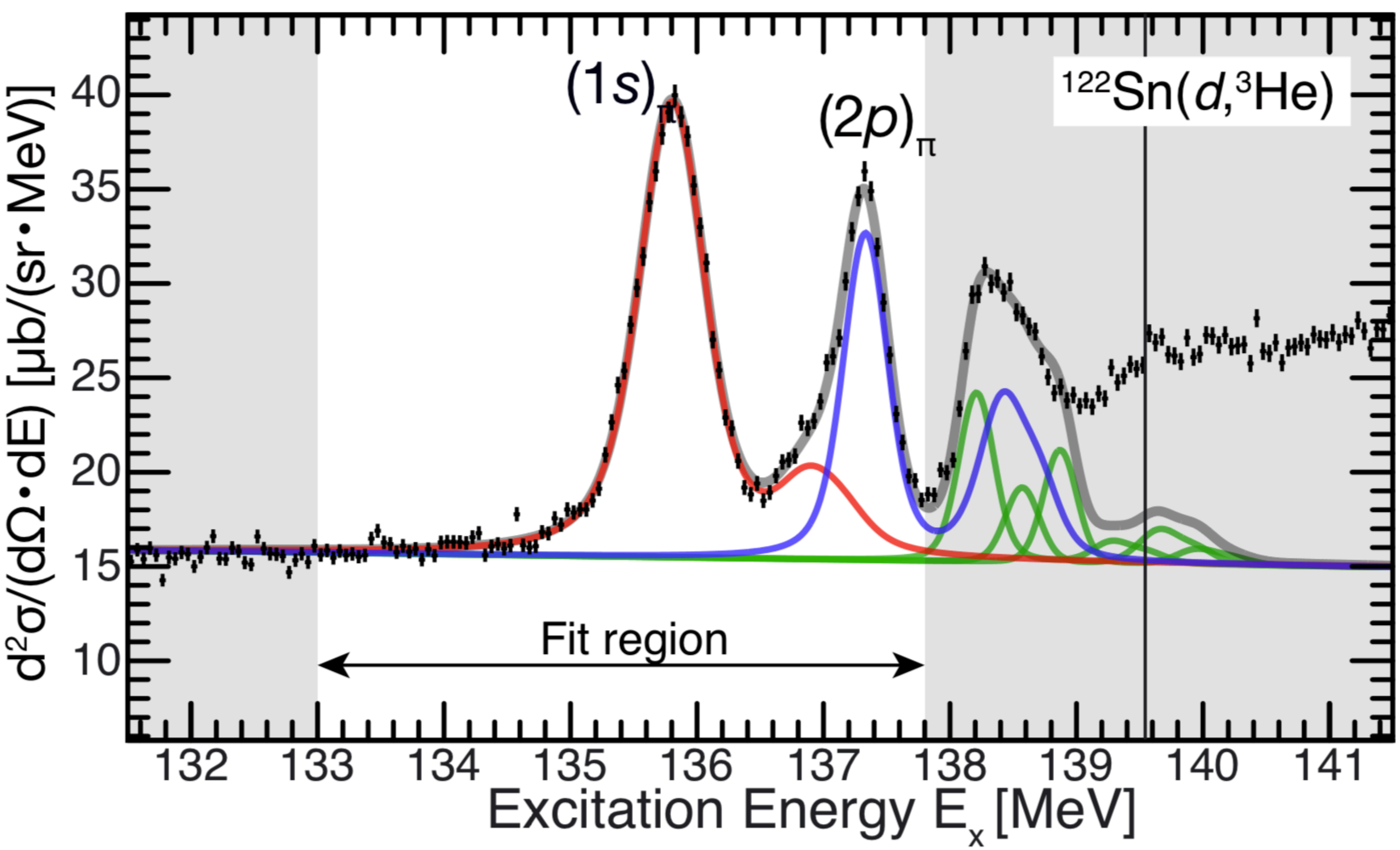

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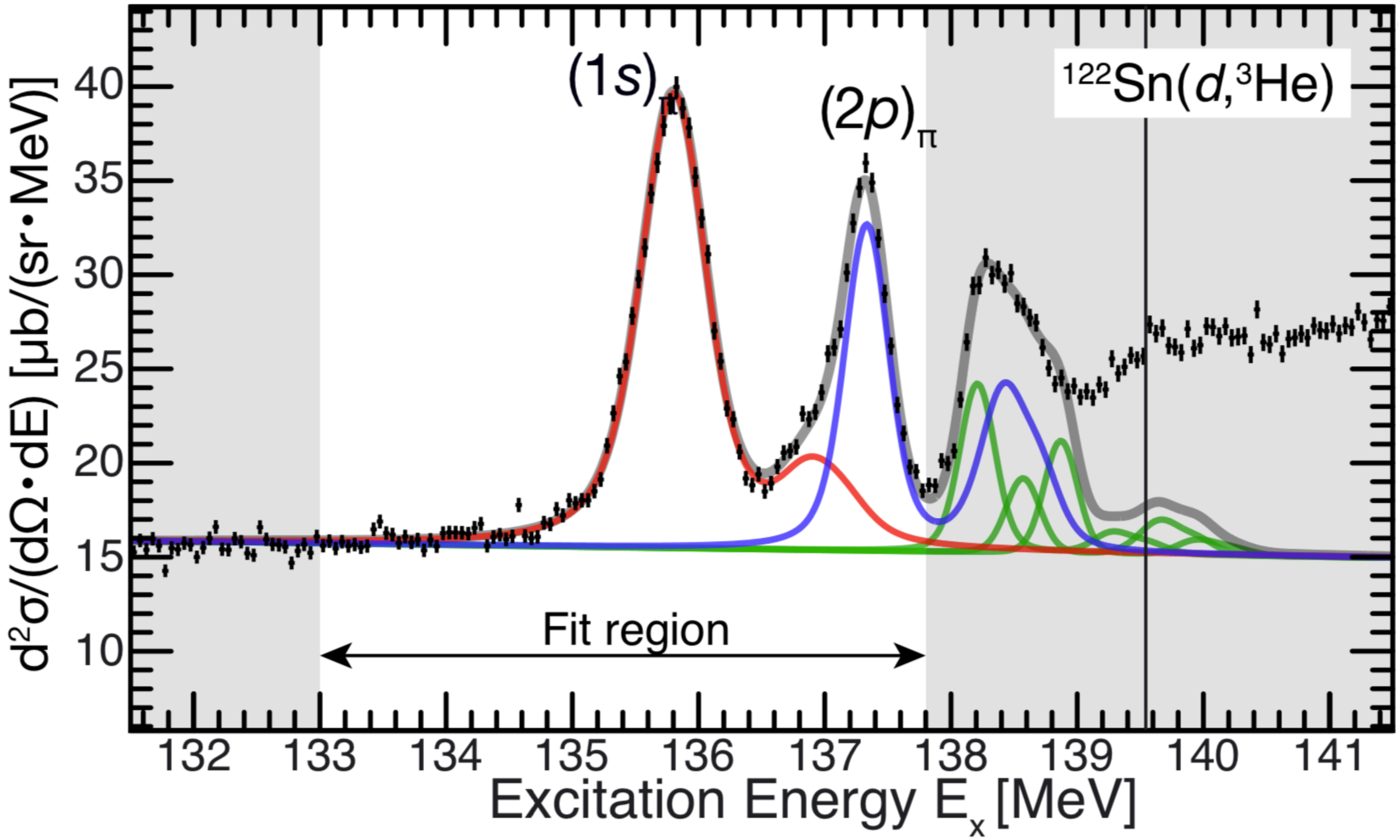
Under review

arXiv: 2204.05568

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



	[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	$+28-36$

Best resolution 287 keV (FWHM)

2p observed as a peak with high stat. significance

↓

Smaller systematic errors for differences

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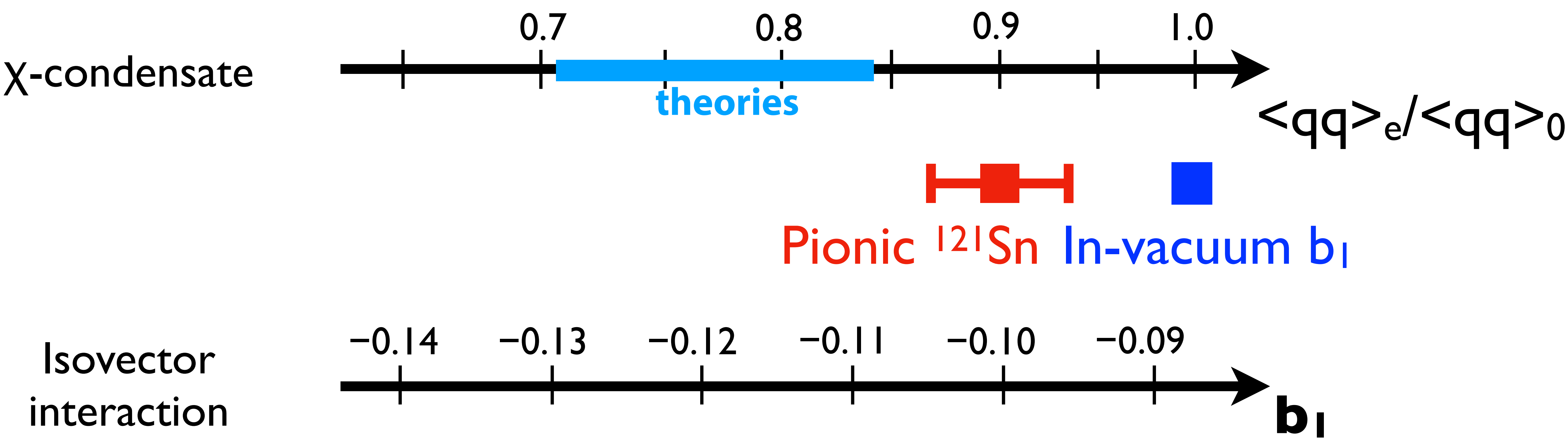
Under review
arXiv: 2204.05568

Deduced b_1 and chiral condensate at ρ_c



Before corrections: b_1 = -0.1005

ξ	$\rho_n(r)$	Abs.	C.S.	Res.	$b_1\,[m_\pi^{-1}]$	$\mathrm{Im}B_0\,[m_\pi^{-4}]$
0	2pF	ρ^2	Neff	–	−0.1005	0.0469
1	2pF	ρ^2	Neff	–	−0.0997	0.0473
1	Osaka	ρ^2	Neff	–	−0.1148	0.0473
1	Osaka	$pp+2np$	Neff	–	−0.1162	0.0474
1	Osaka	$pp+2np$	Green	–	−0.1194	0.0474
1	Osaka	$pp+2np$	Green	✓	−0.1210	0.0474

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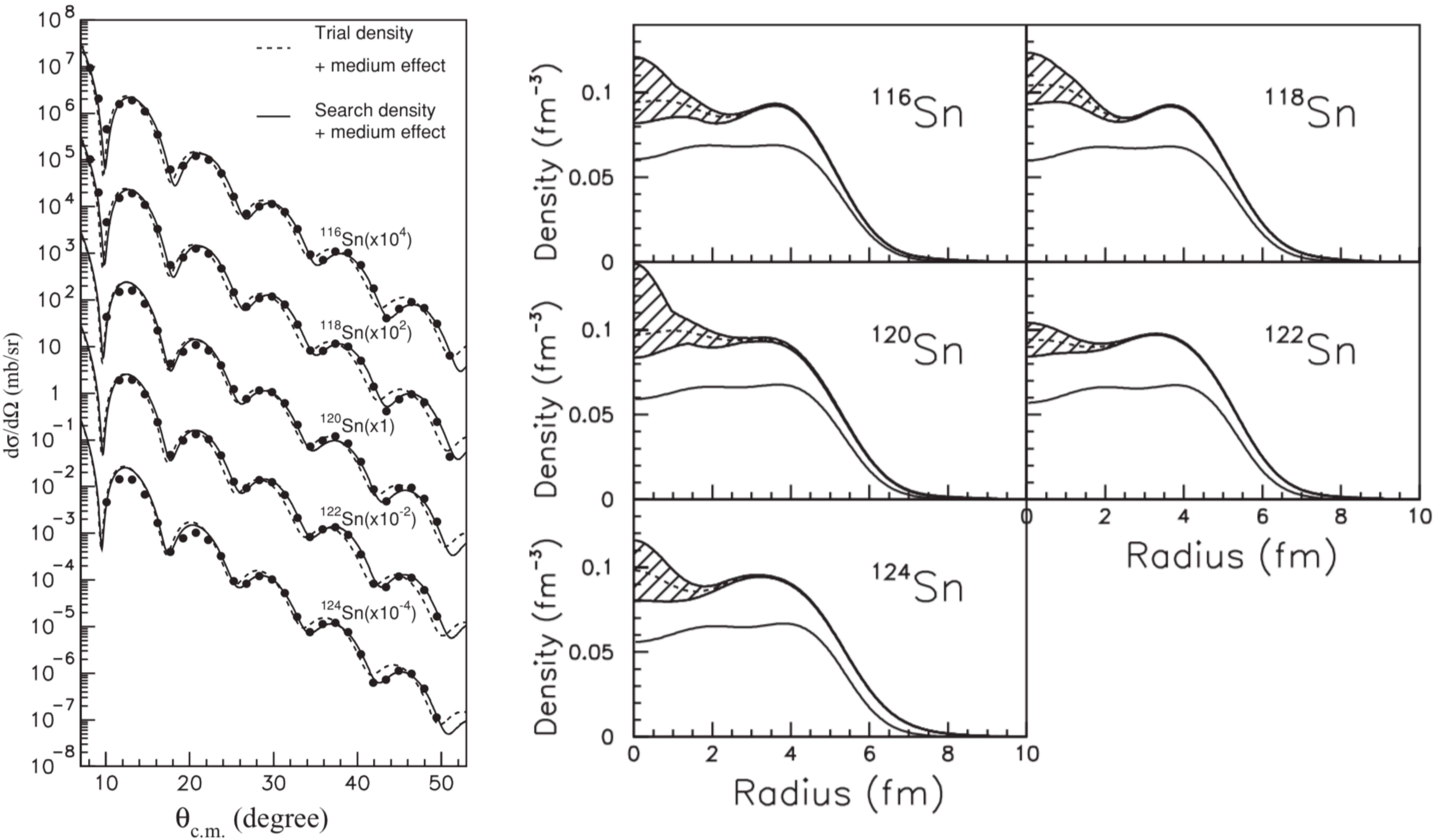
ξ：short-range correction, LLE
ρ：neutron density distribution
Abs.：absorption term formulation
C.S.：cross section calculation method
Res.: residual interaction

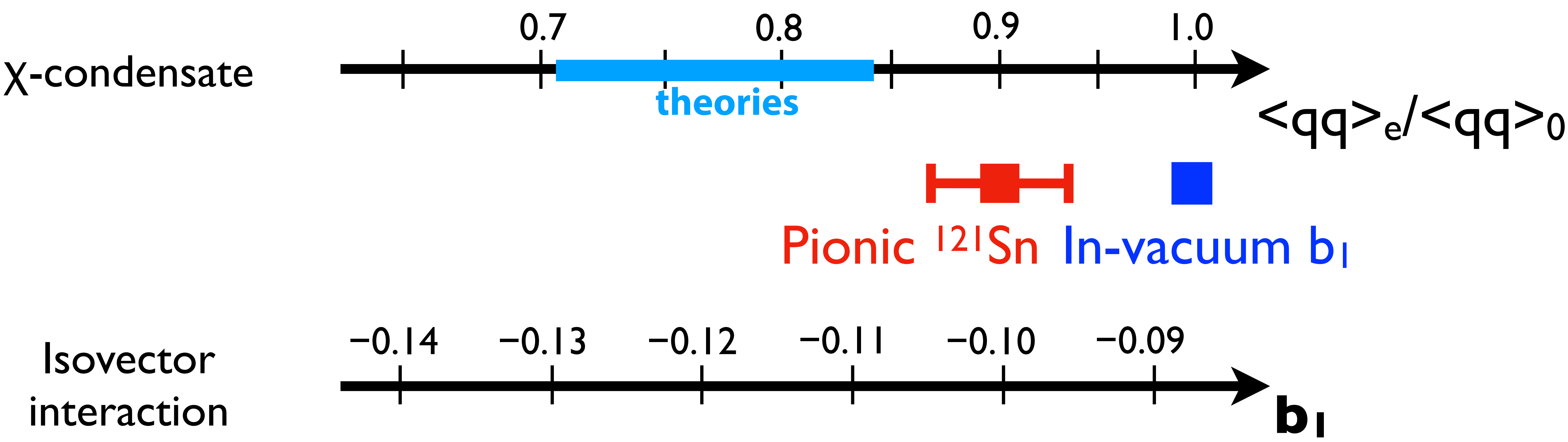
Measured nuclear density distribution of Sn isotopes

Sn(p,p') reaction at RCNP, Osaka



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

Deduced b_1 and chiral condensate at ρ_e



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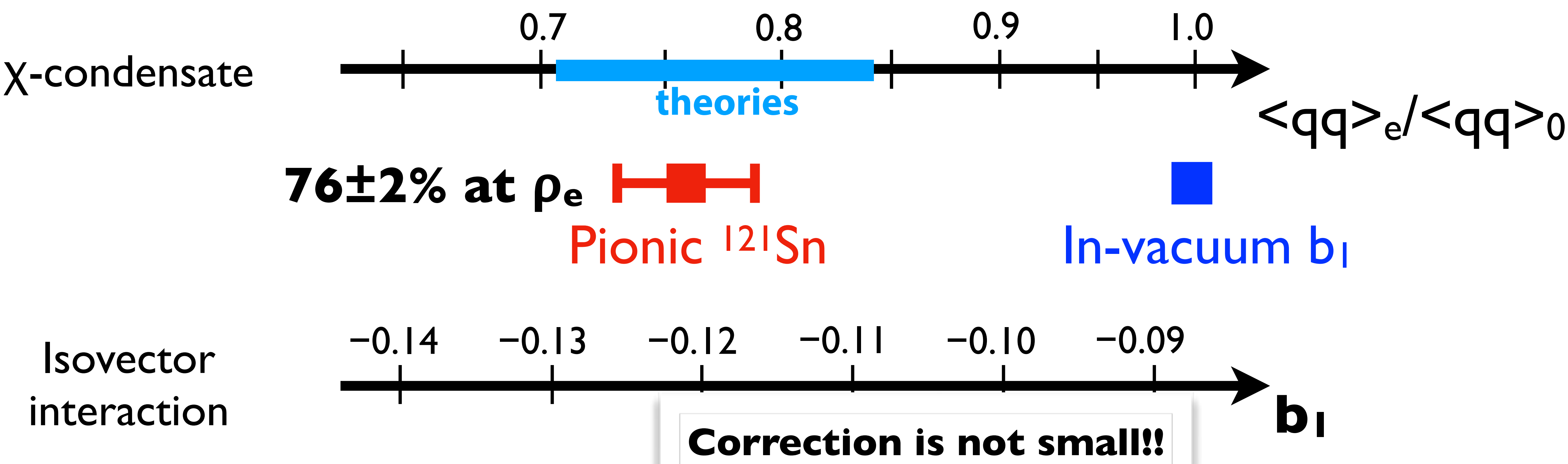

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ξ	$\rho_n(r)$	Abs.	C.S.	Res.	$b_1\,[m_\pi^{-1}]$	$\mathrm{Im}B_0\,[m_\pi^{-4}]$
0	2pF	ρ^2	Neff	–	−0.1005	0.0469
1	2pF	ρ^2	Neff	–	−0.0997	0.0473
1	Osaka	ρ^2	Neff	–	−0.1148	0.0473
1	Osaka	$pp + 2np$	Neff	–	−0.1162	0.0474
1	Osaka	$pp + 2np$	Green	–	−0.1194	0.0474
1	Osaka	$pp + 2np$	Green	✓	−0.1210	0.0474

	[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	$+28-36$

After including corrections

b_1 = -0.1210±0.0063

ξ : short-range correction, LLE

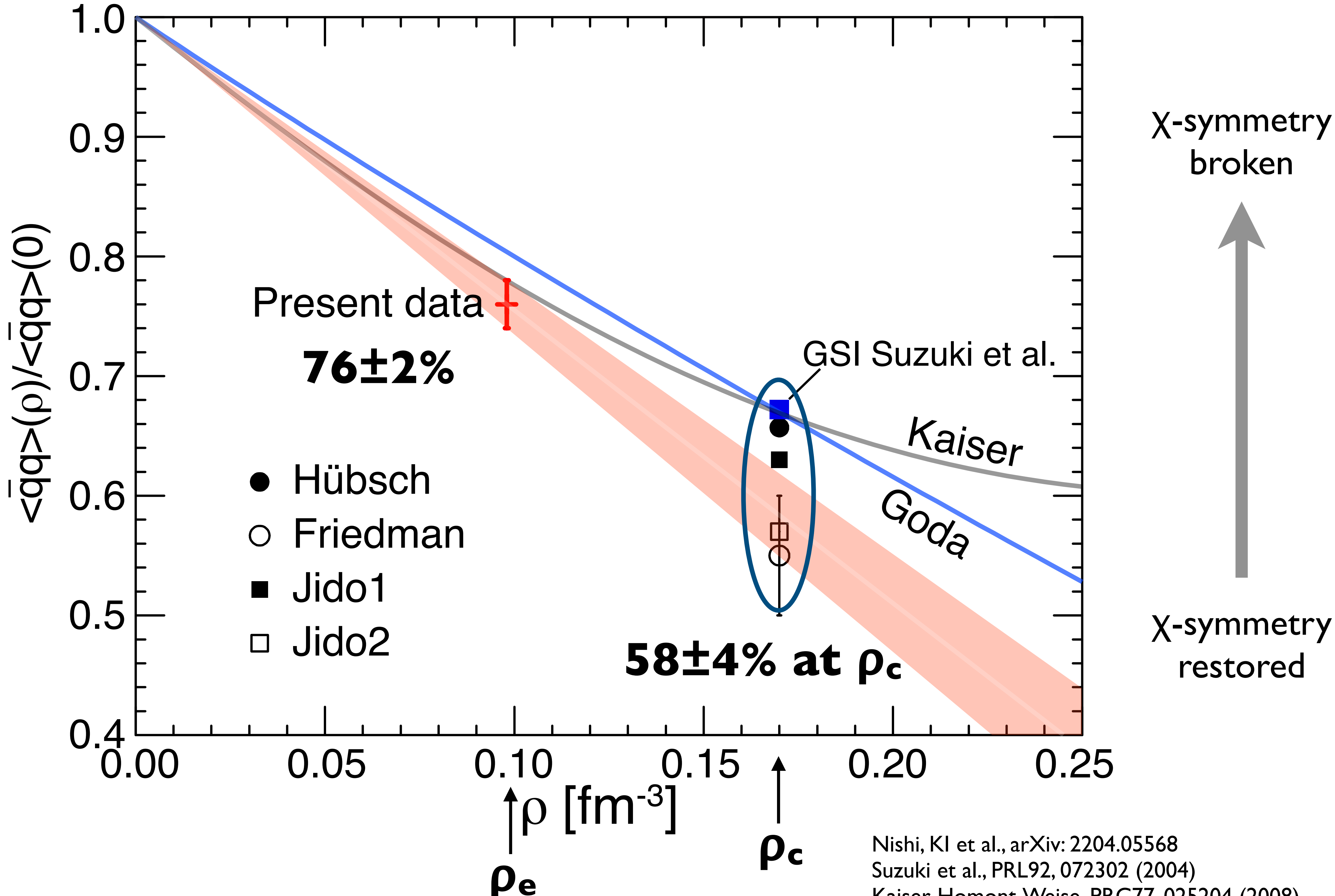
ρ : neutron density distribution

Abs. : absorption term formulation

C.S. : cross section calculation method

Res.: residual interaction

ρ dependence of chiral condensate



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Summary

- Chiral condensate at the normal nuclear density is evaluated to be reduced by 58±4%. We evaluated chiral condensate with errors at the well-defined density for the first time by pionic atom spectroscopy.
- The binding energies and widths of the 1*s* and 2*p* states in Sn121 were determined with unprecedented precision. Difference between the 1*s* and 2*p* values reduces the systematic errors drastically.
- Recent theoretical progress was adopted for the evaluation, which directly relates the chiral condensate and the pion-nucleus interaction.
- We calculated various corrections for the first time and applied them. The application made a huge jump of the deduced chiral condensate. After the "blind-analysis" of the correction, the chiral condensate ratio was deduced to be 58±4% with much higher reliability.
- We plan measurement of ρ dependence of chiral condensate in systematic study.