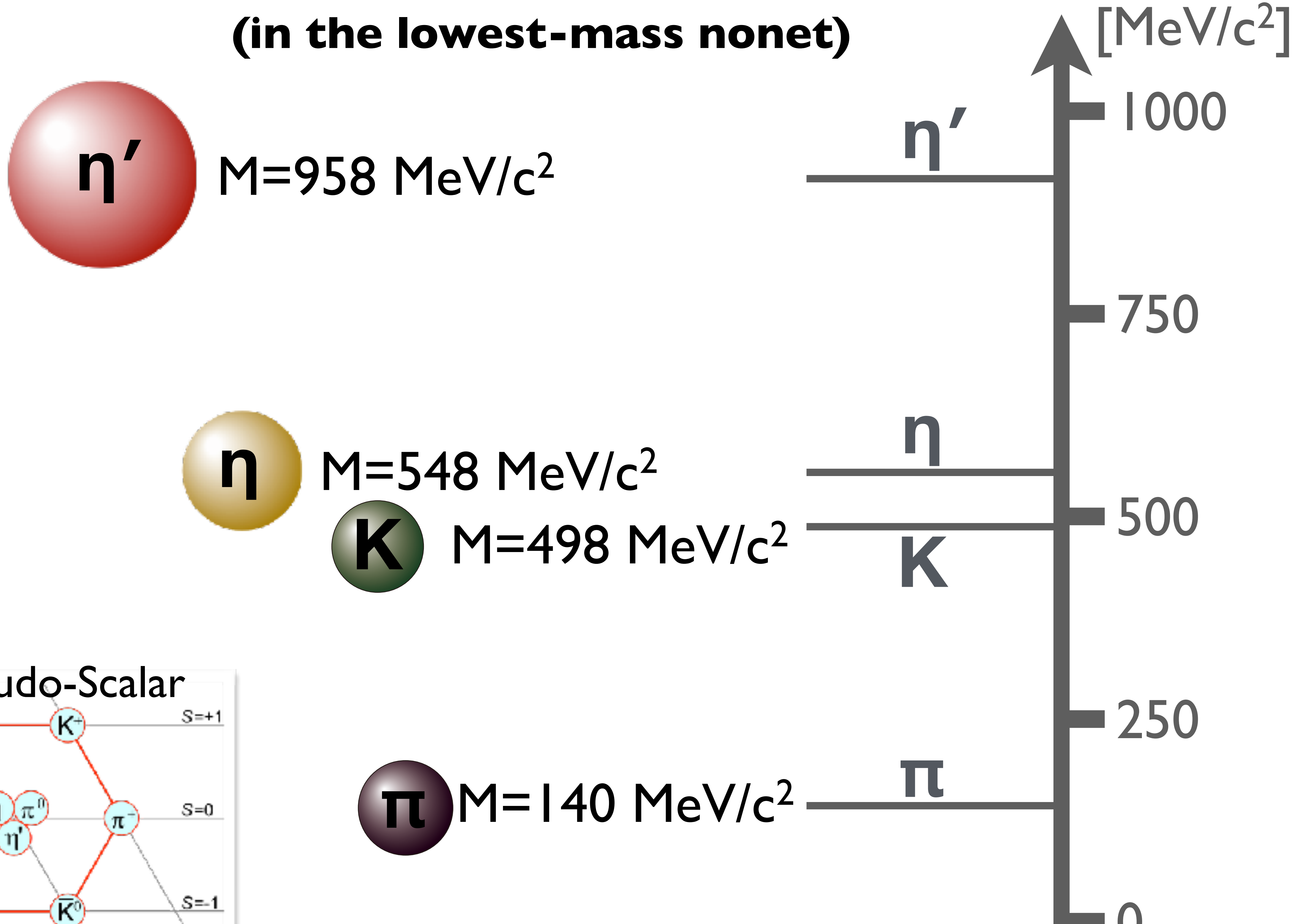
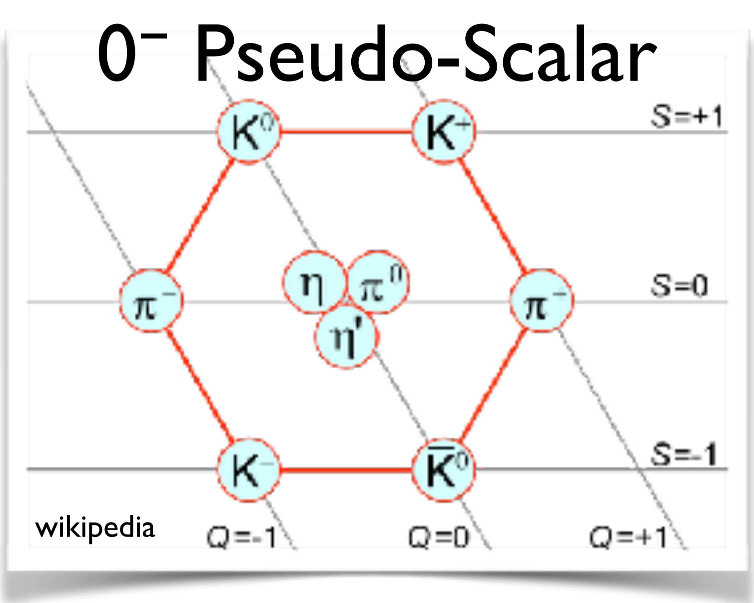
Status and plans of pionic atom spectroscopy at RIBF

ITAHASHI, Kenta
RIKEN Nishina Center

Pseudo-scalar mesons

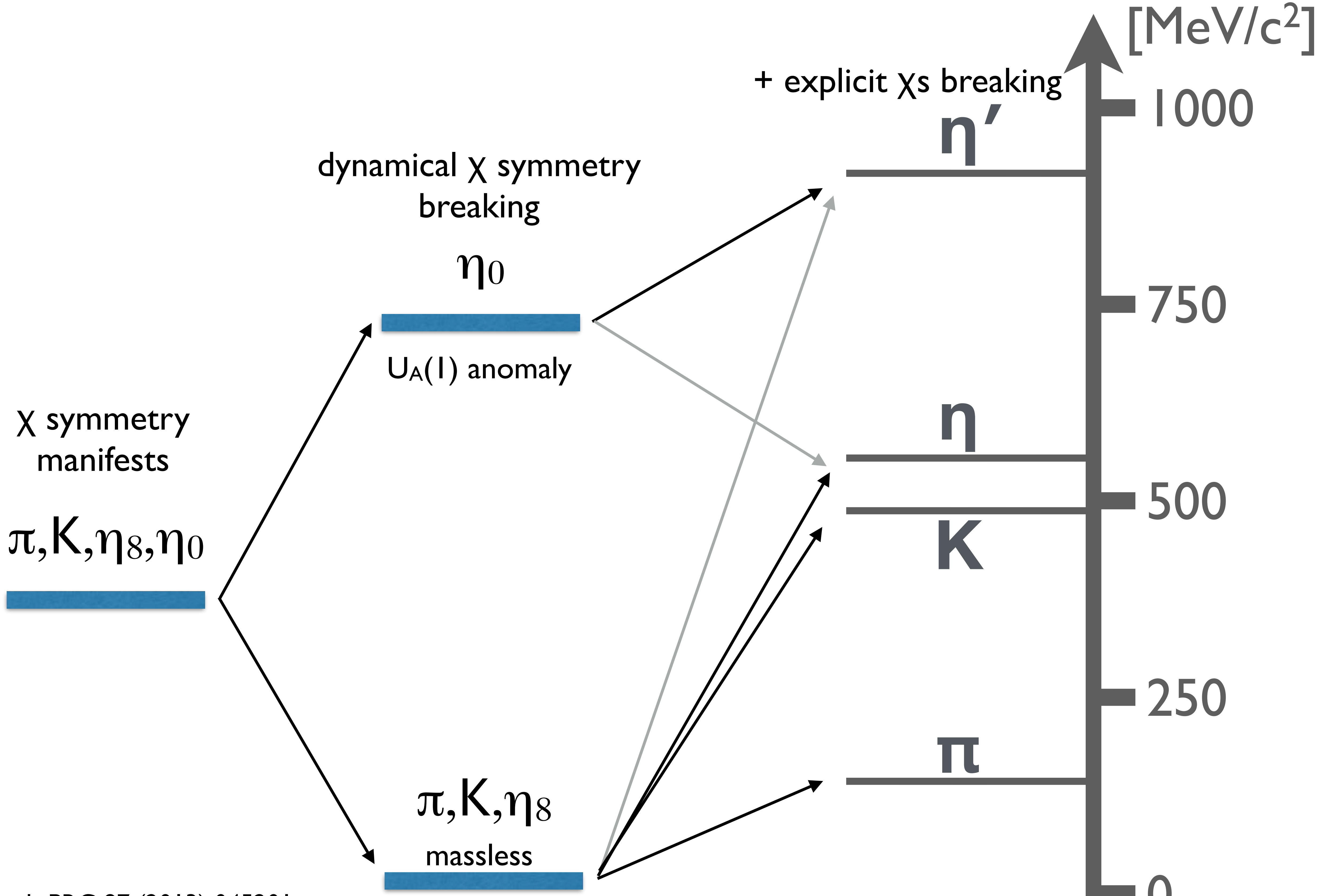
(in the lowest-mass nonet)





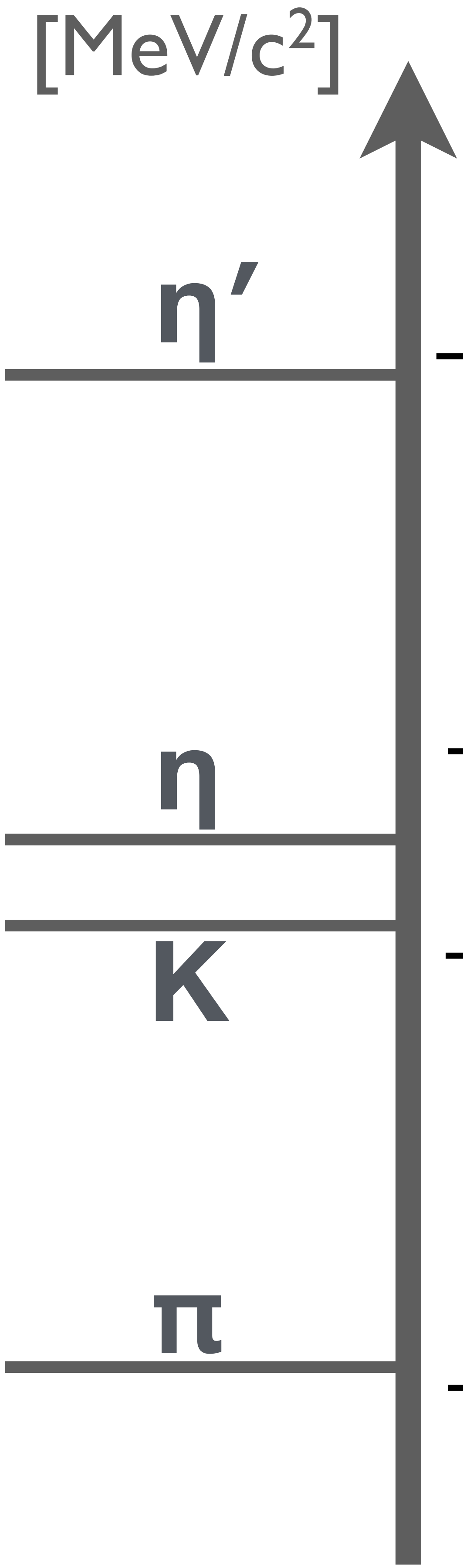
Masses of Pseudo-Scalar Mesons

with various symmetry breaking patterns



Nagahiro et al., PRC 87 (2013) 045201
Jido et al., NPA 914 (2013) 354

Motivations in mesic atoms/nuclei



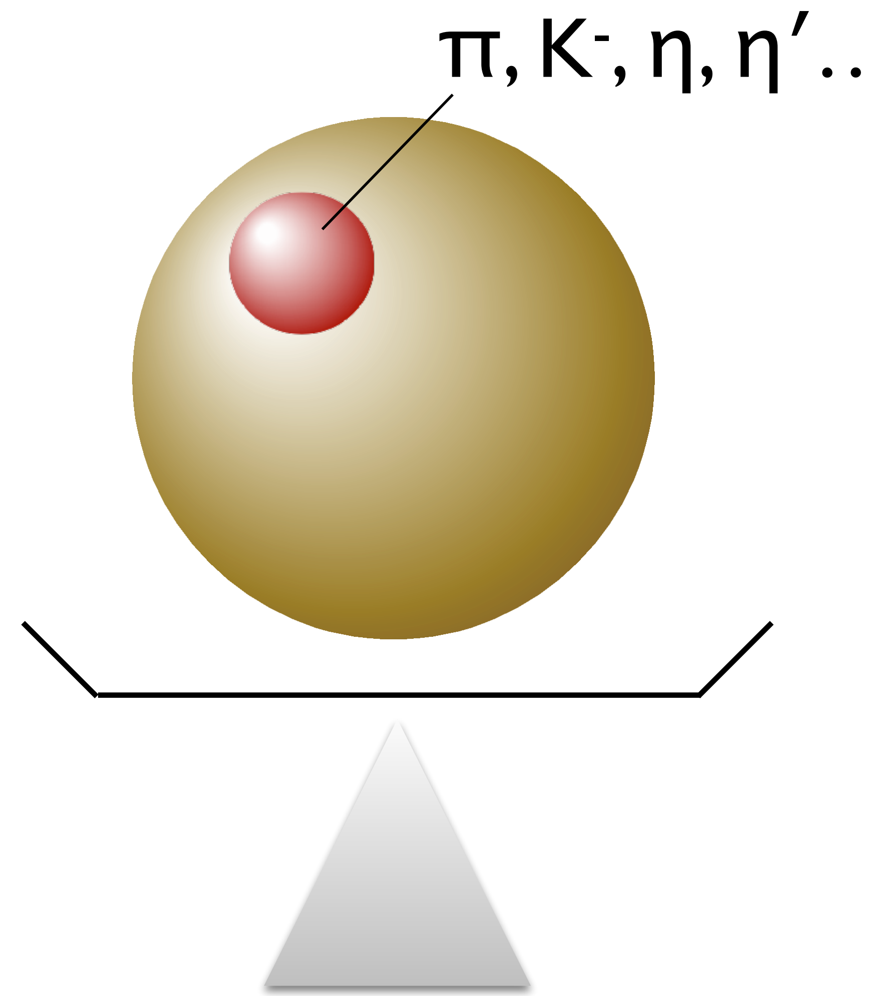
→ $U_A(1)$ anomaly
Gluon dynamics

Strong coupling to $N^*(1535)$
→ χ-symmetry in baryon sector

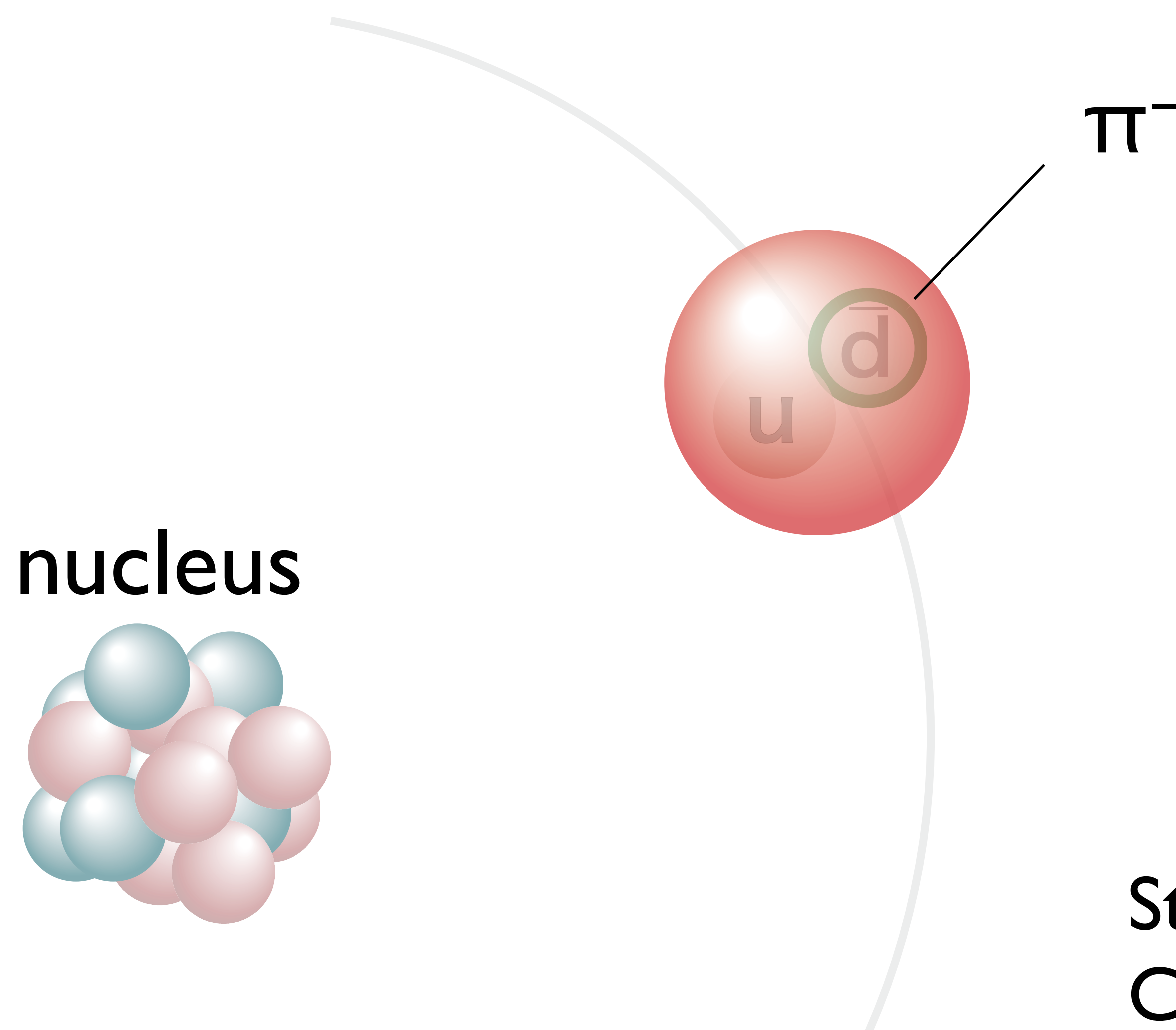
→ $\rho > \rho_0$
Λ(1405)
Explicit χ-symmetry breaking

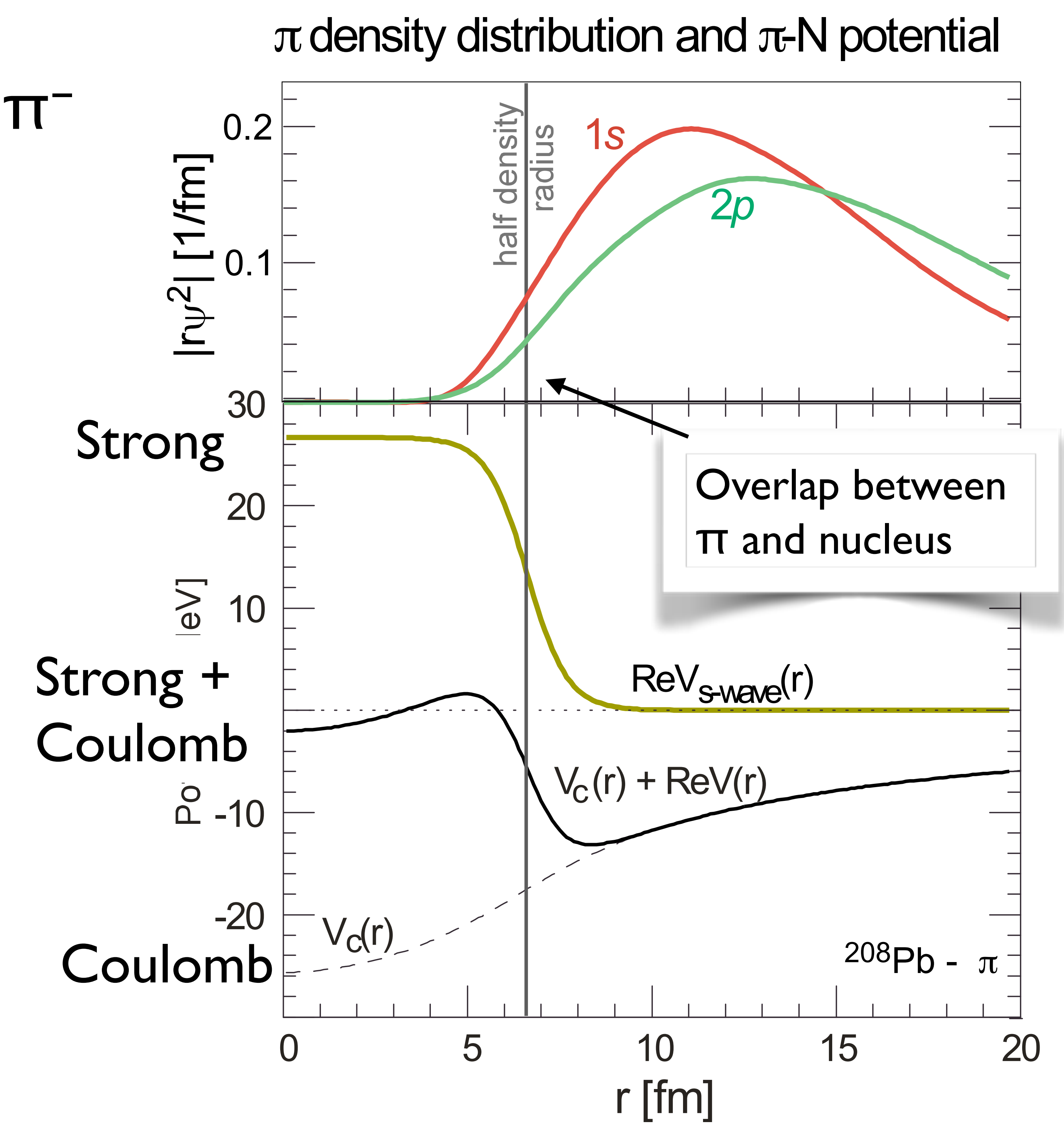
→ Quantitative est. of **quark condensate**

Hadrons as probes



Deeply bound pionic states





Ericson-Ericson potential

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

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

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

KI et al., PRC62,025202(2000)

Deeply bound pionic states

Overlap between
pion w.f. and nucleus
→ chance to study local
s-wave interaction $U_s(r)$

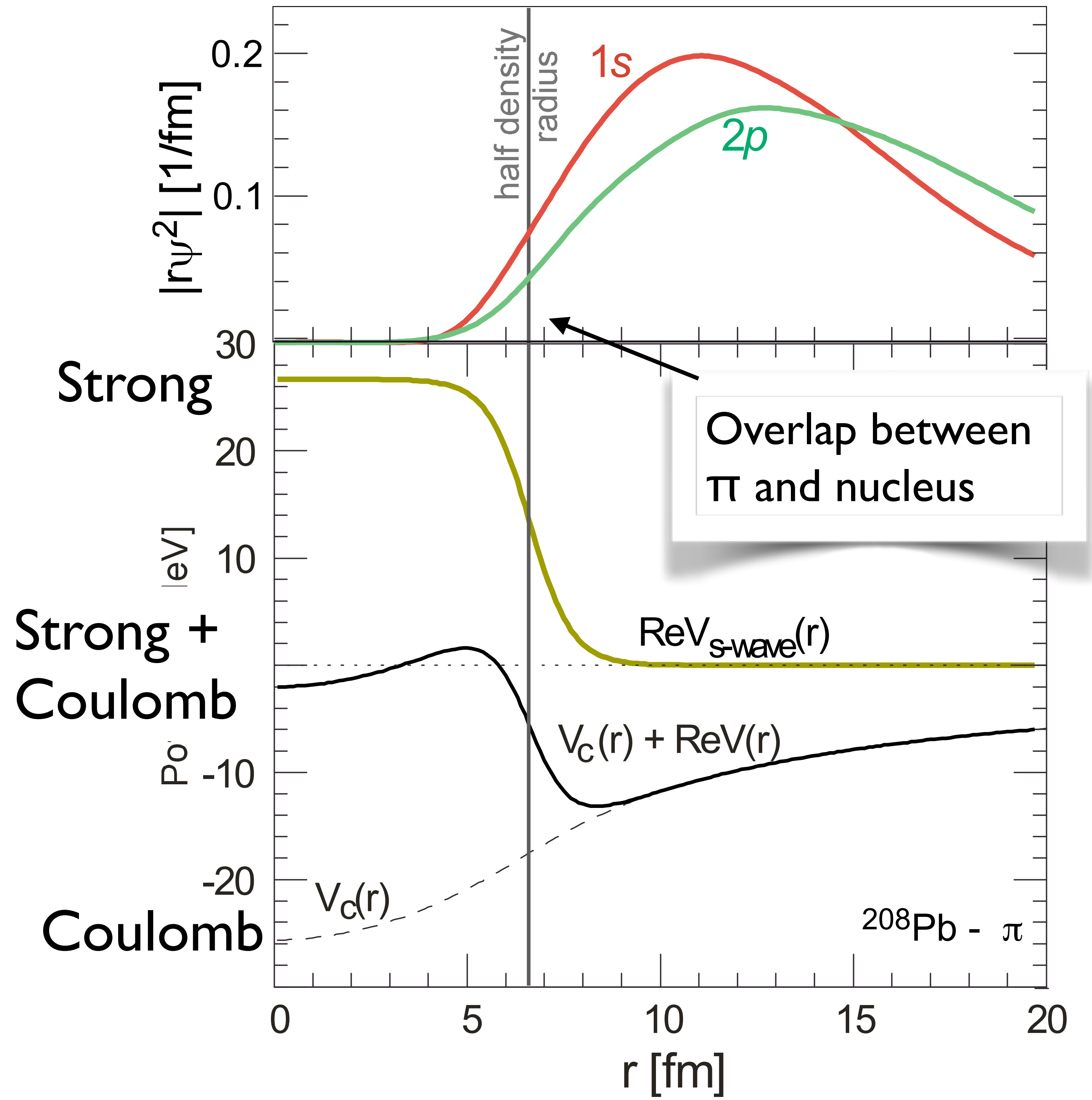
Ericson-Ericson potential

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

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

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

π density distribution and π-N potential



KI et al., PRC62,025202(2000)

Pionic-nucleus interaction and chiral symmetry

Overlap between
pion w.f. and nucleus
→ chance to study local
s-wave interaction $U_s(r)$

Ericson-Ericson potential

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

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

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

M. Gell-Mann *et al.*, PR175(1968)2195.

Gell-Mann-Oakes-Renner relation

$$f_\pi^2 m_\pi^2 = -2m_q\langle\bar{q}q\rangle$$

f_π : pion decay constant

Y. Tomozawa, NuovoCimA46(1966)707.
S. Weinberg, PRL17(1966)616.

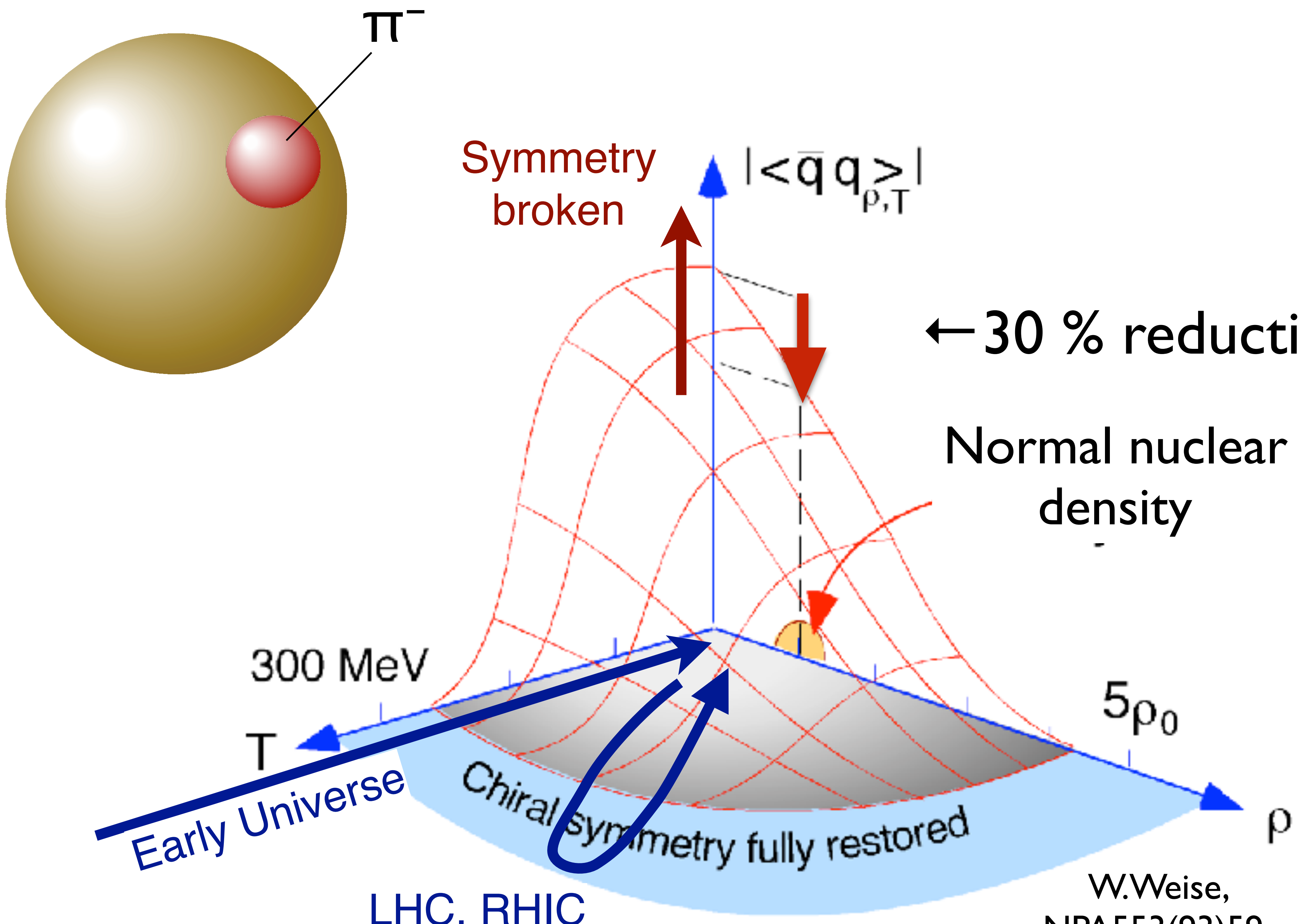
Tomozawa-Weinberg relation

$$b_1 = -\frac{m_\pi}{8\pi f_\pi^2}$$

$$\frac{\langle\bar{q}q\rangle_\rho}{\langle\bar{q}q\rangle_0} \approx \frac{b_1^{\text{free}}}{b_1(\rho)}$$

Jido, Hatsuda, Kunihiro, Phys.Lett.B670:109-113,2008.
Kolomeitsev, Kaiser, Weise, Phys. Rev. Lett. 90(2003)092501

Order parameter at nuclear density



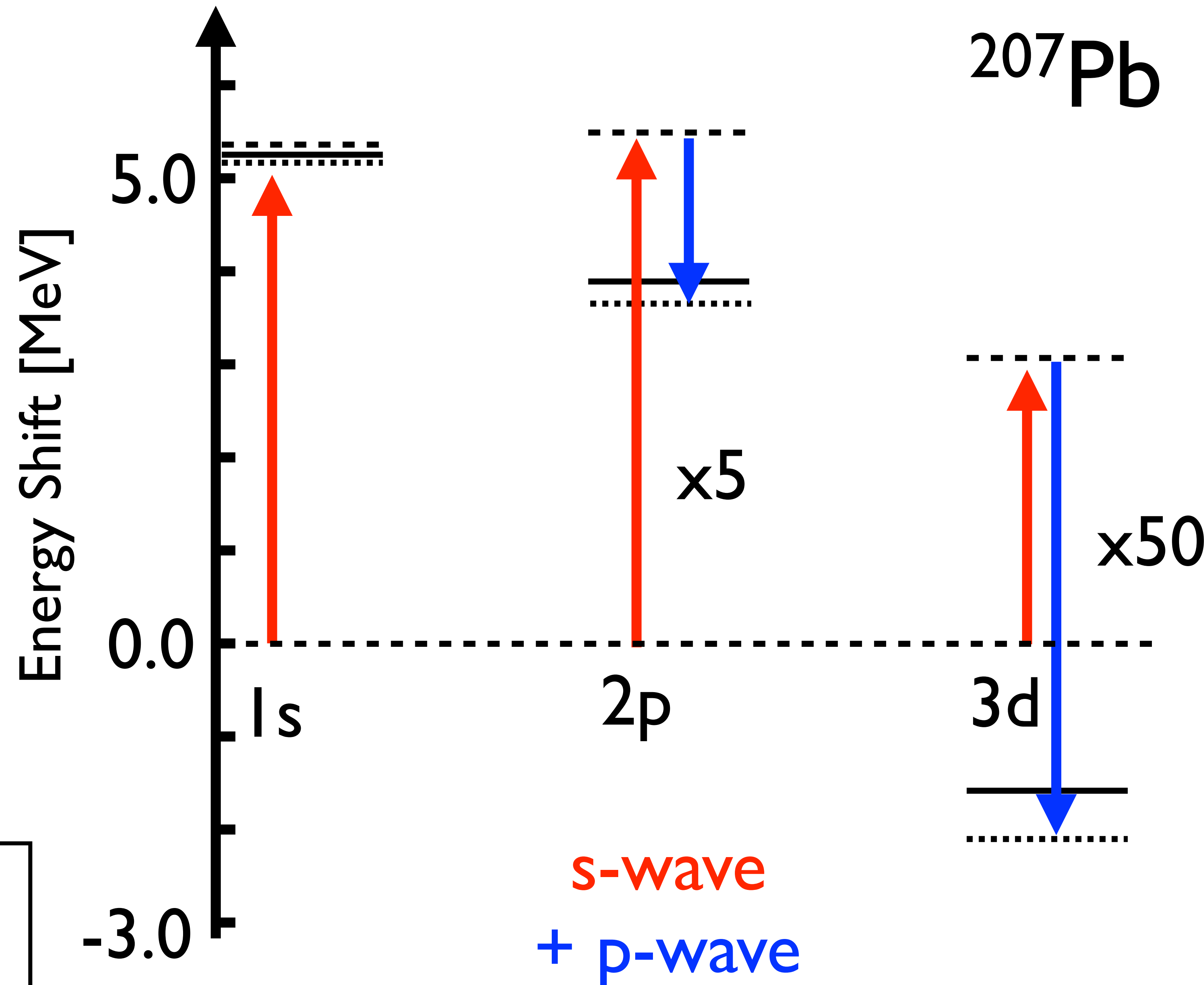
W.Weise, NPA553(93)59.

χ-condensate decreases by 30 % at ρ_0

Strong interaction and pionic level shifts

s-wave interaction is dominating in **1s shift**, whereas p-wave is larger in 3d

Deeply bound states are sensitive to $U_s(r)$



Ericson-Ericson potential

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

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

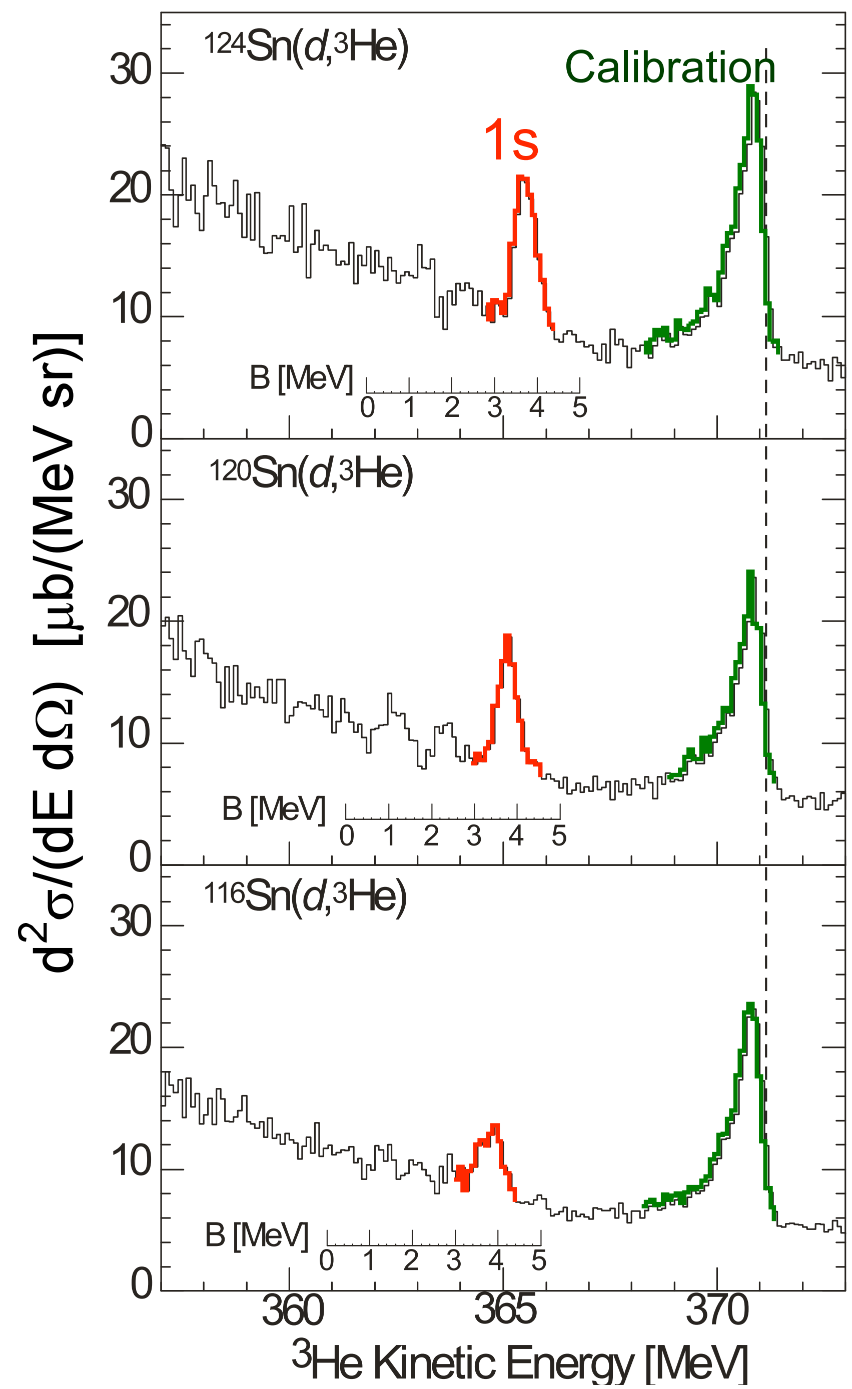
$$U_p(r) = \frac{2\pi}{\mu}\vec{\nabla}\cdot[c(r) + \varepsilon_2^{-1}C_0\rho^2(r)]L(r)\vec{\nabla}$$

PHYSICAL REVIEW C, VOLUME 62, 024606

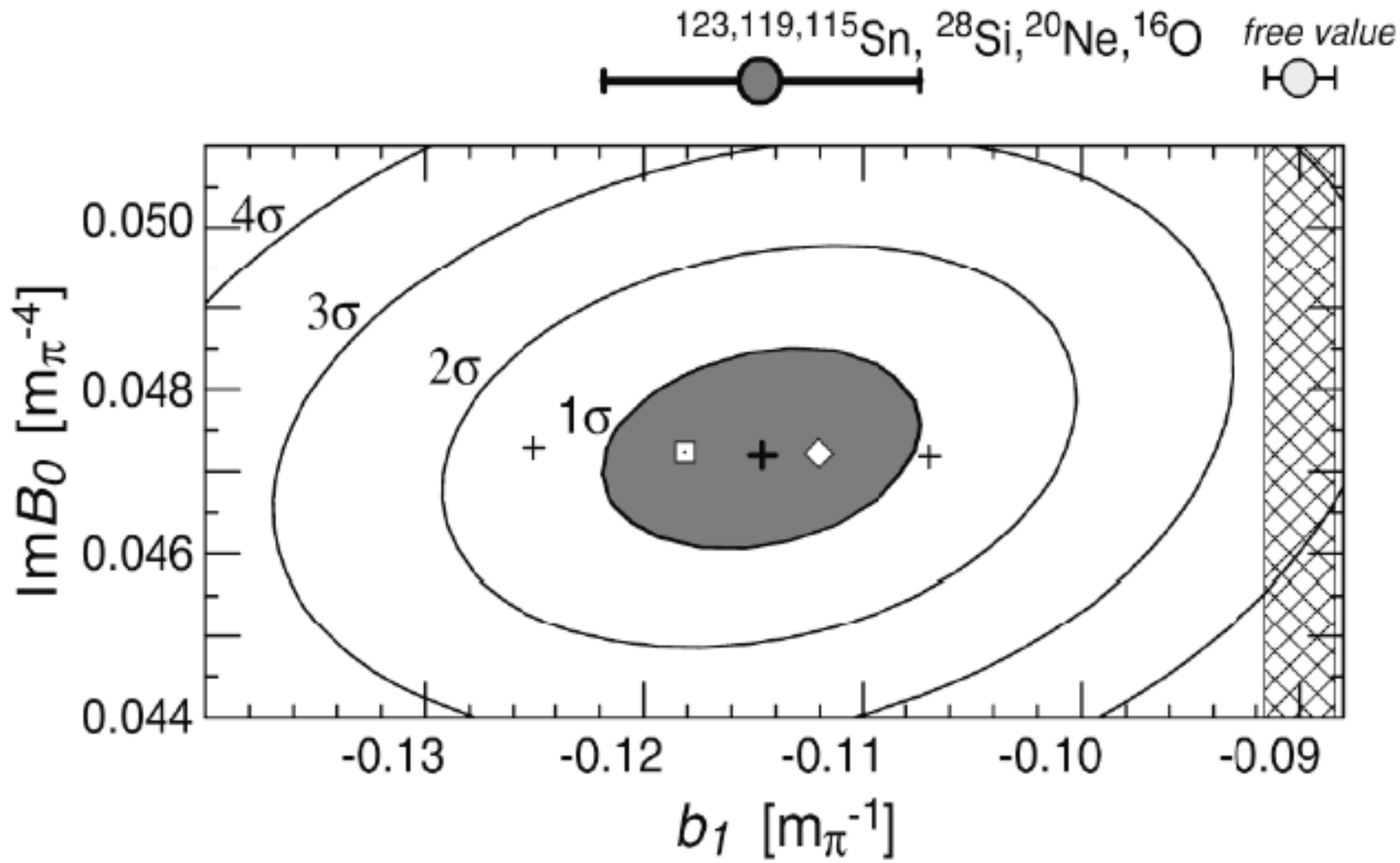
Isotope dependence of deeply bound pionic states in Sn and Pb

Y. Umemoto,[1] S. Hirenzaki,[1] K. Kume,[1] and H. Toki[2]

Present b_1 precision



K. Suzuki et al.,
PRL92(04)072302.

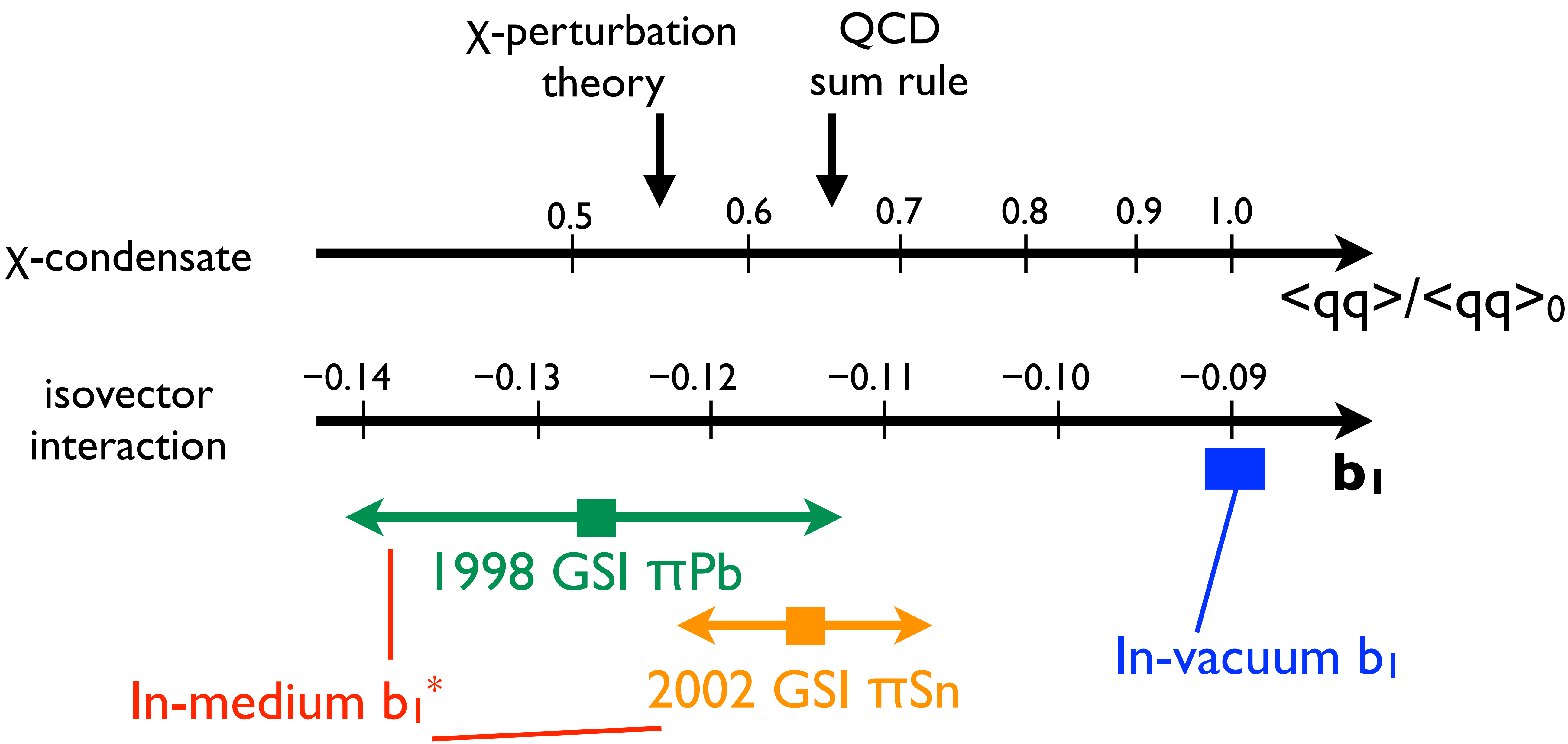


$$V_{s\text{-wave}} = b_0\,\rho + \mathbf{b_1}\,(\rho_n - \rho_p) + B_0\,\rho^2$$

$$\rho_e = 0.6\,\rho_0$$

In-medium b_1 is calculated based on deeply bound pionic states data combined with light spherical pionic atom data.

π-nucleus interaction and χ-symmetry



We intended to improve the precision.

Precision measurement of deeply bound pionic Sn atoms in RIBF

Kenta Itahashi

Advanced Meson Science Laboratory, RIKEN
for piAF collaboration

DeukSoon Ahn, Georg P. A. Berg, Masanori Dozono, Hiroyuki Fujioka, Naoki Fukuda, Nobuhisa Fukunishi, Hans Geissel, Emma Haettner, Ryugo S. Hayano, Satoru Hirenzaki, Hiroshi Horii, Natsumi Ikeno, Naoto Inabe, Kenta Itahashi*, Masahiko Iwasaki, Daisuke Kameda, Nobuyuki Kobayashi, Toshiyuki Kubo, Hiroaki Matsubara, Shin'ichiro Michimasa, Kenjiro Miki, Go Mishima, Daichi Murai, Hiroyuki Miya, Hideko Nagahiro, Megumi Niikura, Takahiro Nishi**, Shumpei Noji, Shinsuke Ota, Haruhiko Outa, Naruhiko Sakamoto, Hiroshi Suzuki, Ken Suzuki, Motonobu Takaki, Hiroyuki Takeda, Yoshiki K. Tanaka, Tomohiro Uesaka, Yuni N. Watanabe, Helmut Weick, Hiroki Yamakami, Koichi Yoshida.

* spokesperson, ** co-spokesperson

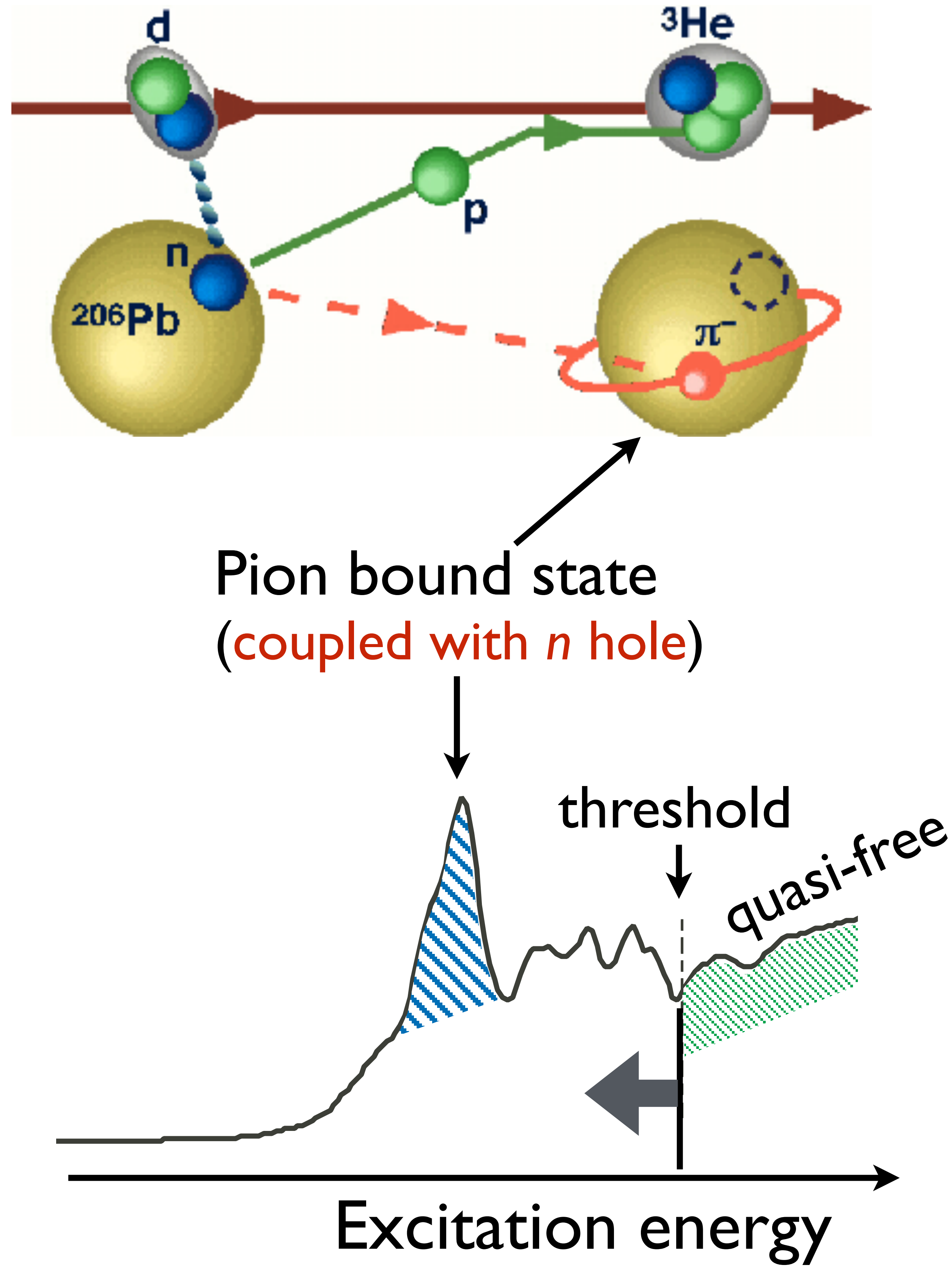
RIKEN Nishina Center, RIKEN
Department of Physics, University of Notre Dame
Department of Physics, Kyoto University
GSI Helmholtzzentrum fuer Schwerionenforschung GmbH
Department of Physics, The University of Tokyo
Department of Physics, Nara Women's University
National Institute of Radiological Sciences
Center of Nuclear Study, The University of Tokyo
Research Center for Nuclear Physics, Osaka University
National Superconducting Cyclotron Laboratory, Michigan State University
Stefan-Meyer-Institut für subatomare Physik, Österreichische Akademie der Wissenschaften

T. Nishi

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

Direct production
in (d,^{3}He) nuclear reaction

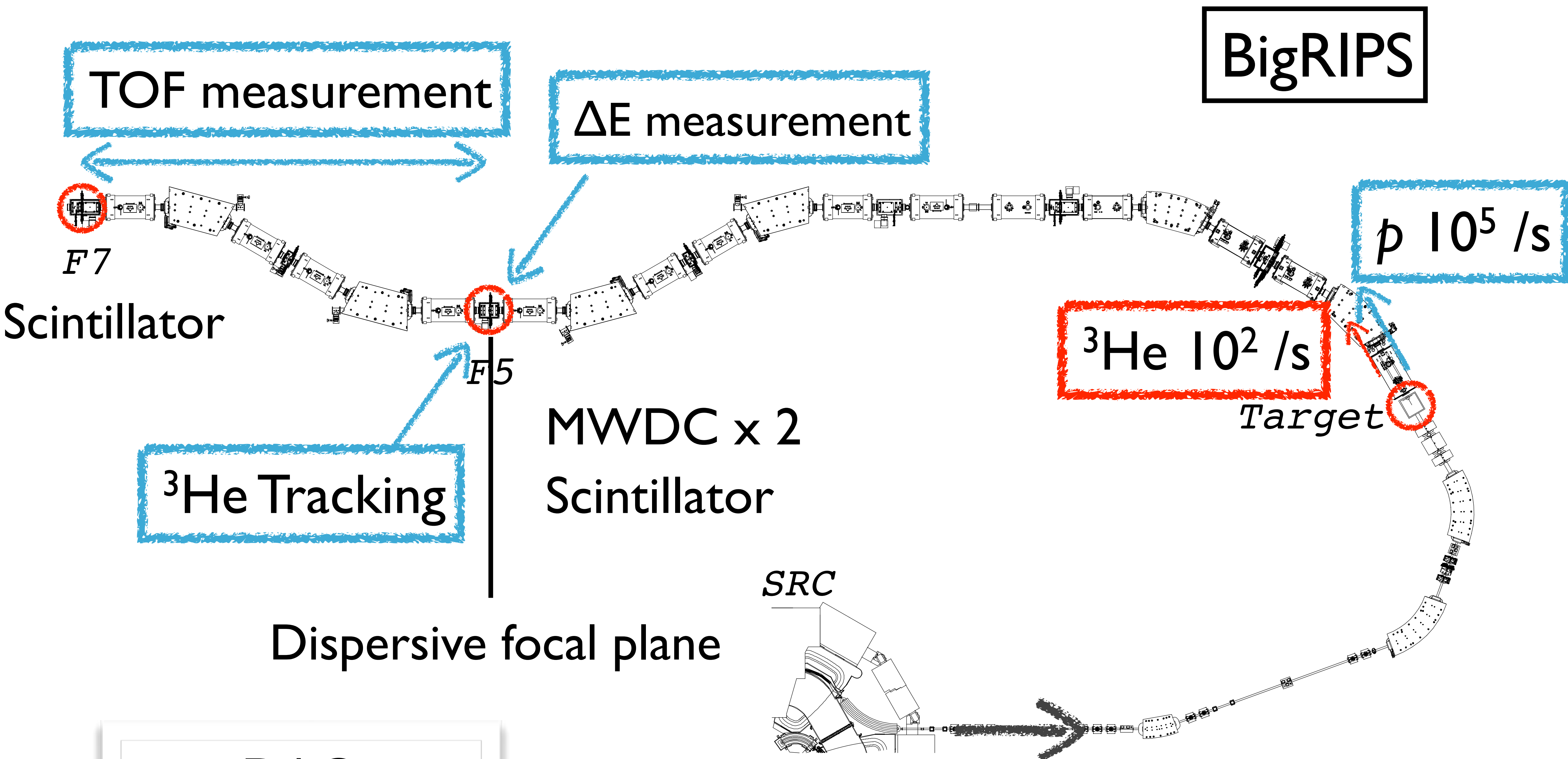
Missing mass spectroscopy
to measure excitation spectrum
in Q-value measurement



A pion bound state is produced coupling with a neutron hole state.

A peak structure is expected below the threshold if the pion bound state is produced.

Reaction Spectroscopy in RIBF



d beam >10^{12} /s, 250 MeV/u

DAQ
2010 15 hours
2014 ~3 days

Kenta Itahashi, RIKEN

2010 Pilot run
15 hours DAQ

Recently **finalized**
to be submitted
within < 1 month

Pionic ^{121}Sn atom

2010 Pilot run
15 hours DAQ

^{122}Sn(d,^{3}He)
0-2°

π^- emission
threshold

$(2p)_\pi(3s_{1/2\ldots})_n$

$(1s)_\pi(3s_{1/2})_n$

2s,3s…

Fitting region

Recently **finalized**
to be submitted
within < 1 month

T. Nishi

Pionic ^{121}Sn atom

First observation of
θ dependence of
π atom cross section

Excitation Energy [MeV]

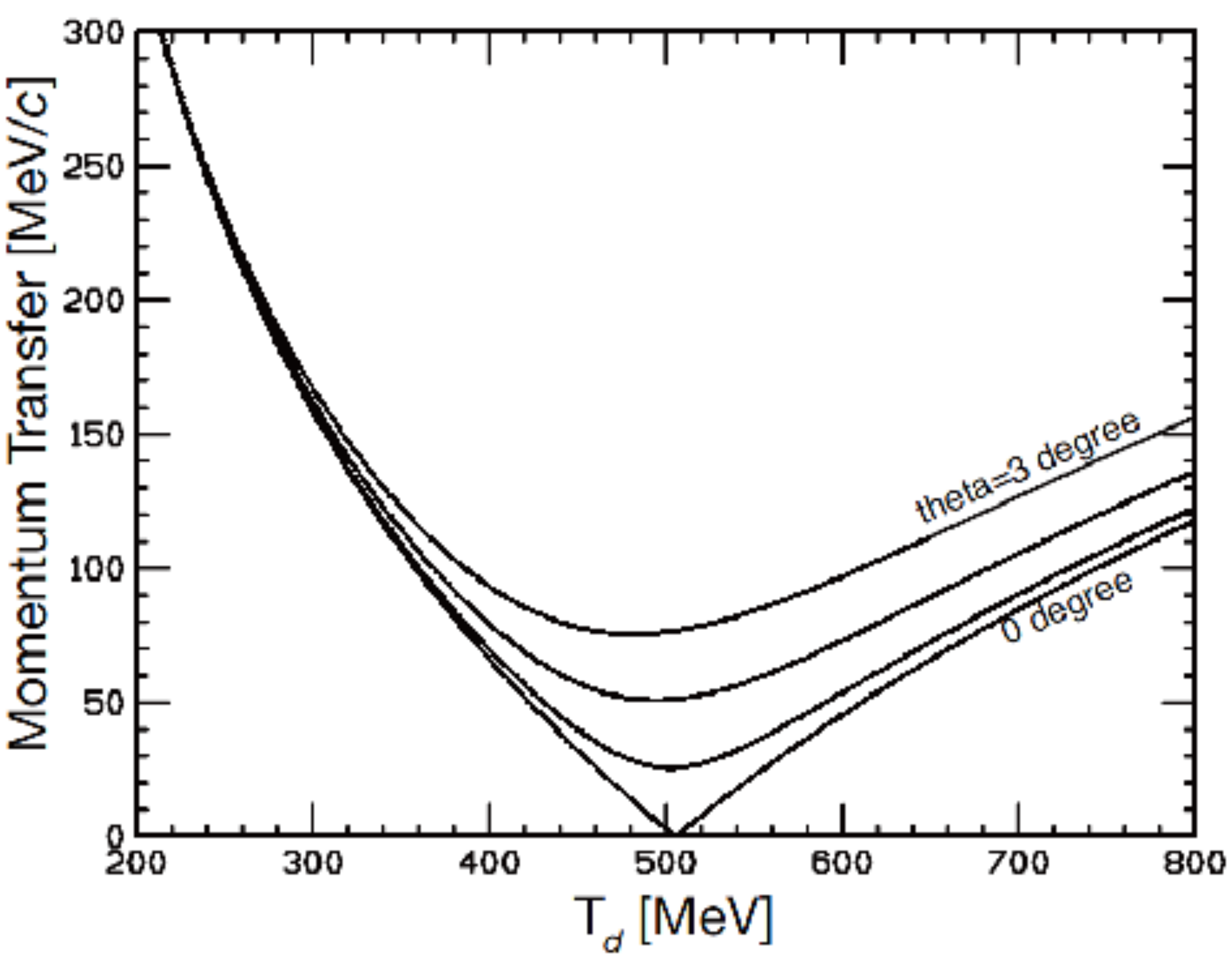
θ dependence of π atom cross section

reaction angle

∝

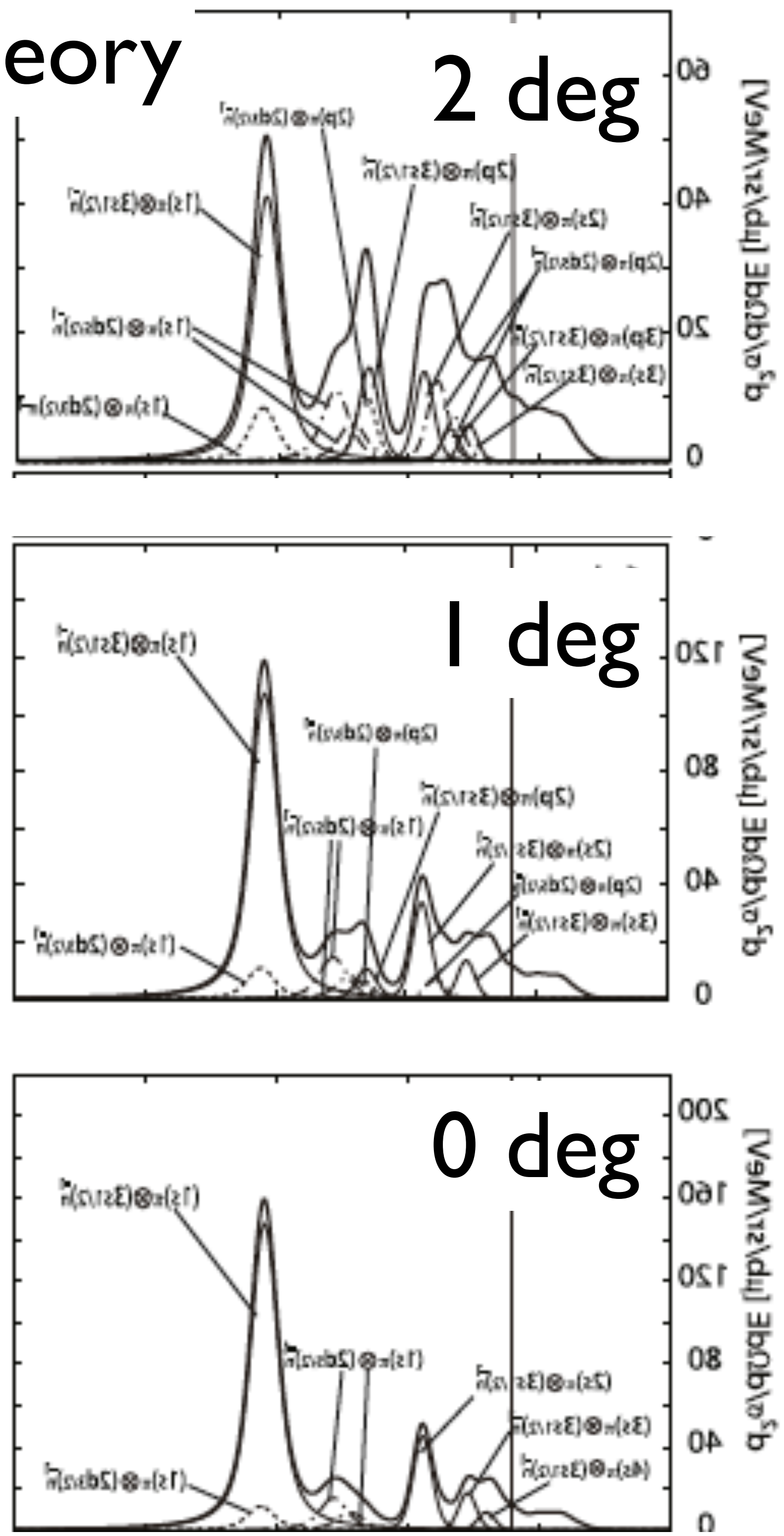
momentum transfer

$\Delta L = q \times r$



θ dependence of π atom cross section

Theory



Ikeno et al., Eur. Phys. J. A (2011) 47,161

1s and 2p pionic atom formation cross sections

2p/1s cross section ratio has least systematic uncertainties

T. Nishi et al., *to be submitted*

1s and 2p pionic atom formation cross sections

Preliminary

Theory
(Ikeno et al.)

Theory × factor

Angular dependence
is quite well reproduced.
1s cross section shows discrepancies.
2p/1s ratio also.

T. Nishi et al., *to be submitted*

Comparison with preceding results

Ericson-Ericson potential

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

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

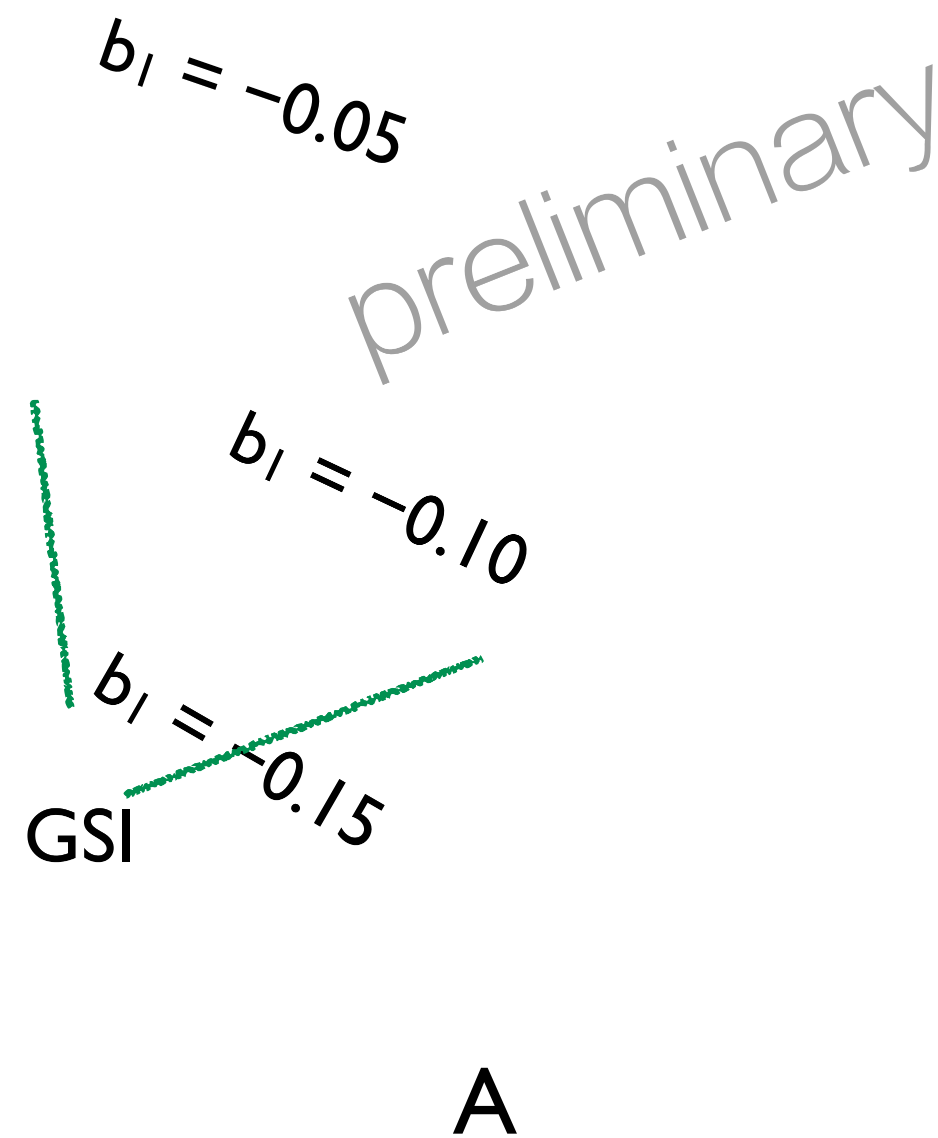
$$U_p(r) = \frac{2\pi}{\mu}\vec{\nabla}\cdot[c(r) + \varepsilon_2^{-1}C_0\rho^2(r)]L(r)\vec{\nabla}$$

2010 pilot run
15 hours
analysis finalized

T. Nishi et al., *to be submitted*

Binding energies and widths and potential parameters

Calculated B_{1s} w. different b_1



Binding energies
for pionic tin isotopes
with b_1 contours

Analysis of pilot run (2010)
shows consistent result.

2010 pilot run
15 hours
analysis finalized

Preliminary spectrum from 2014

π-

Fitting region

2014 main run
~3 days
analysis ongoing

For your eyes only

2014 data analysis ongoing

Ericson-Ericson potential

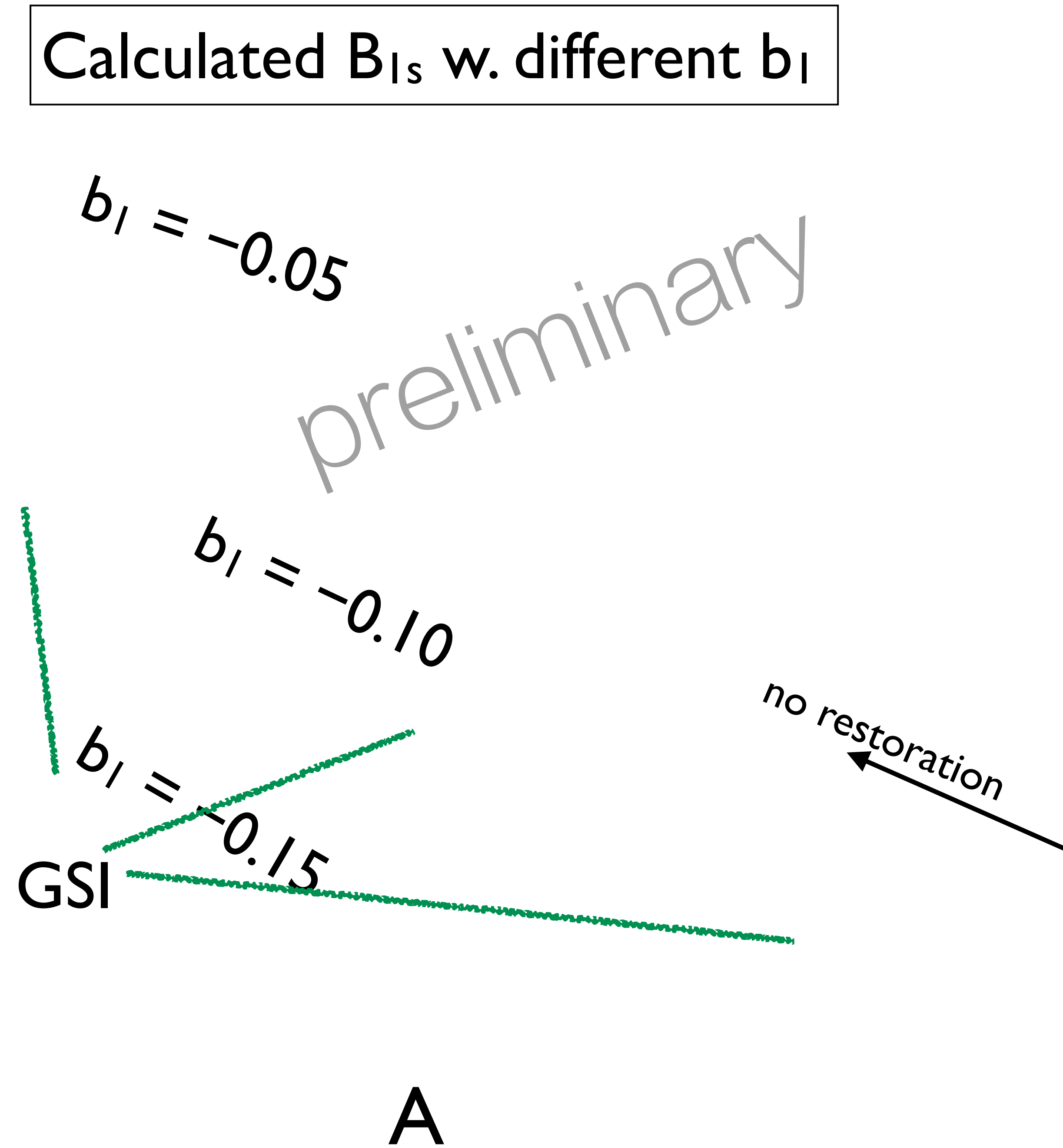
$$U_{\mathrm{opt}}(r) = U_s(r) + U_p(r),$$

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

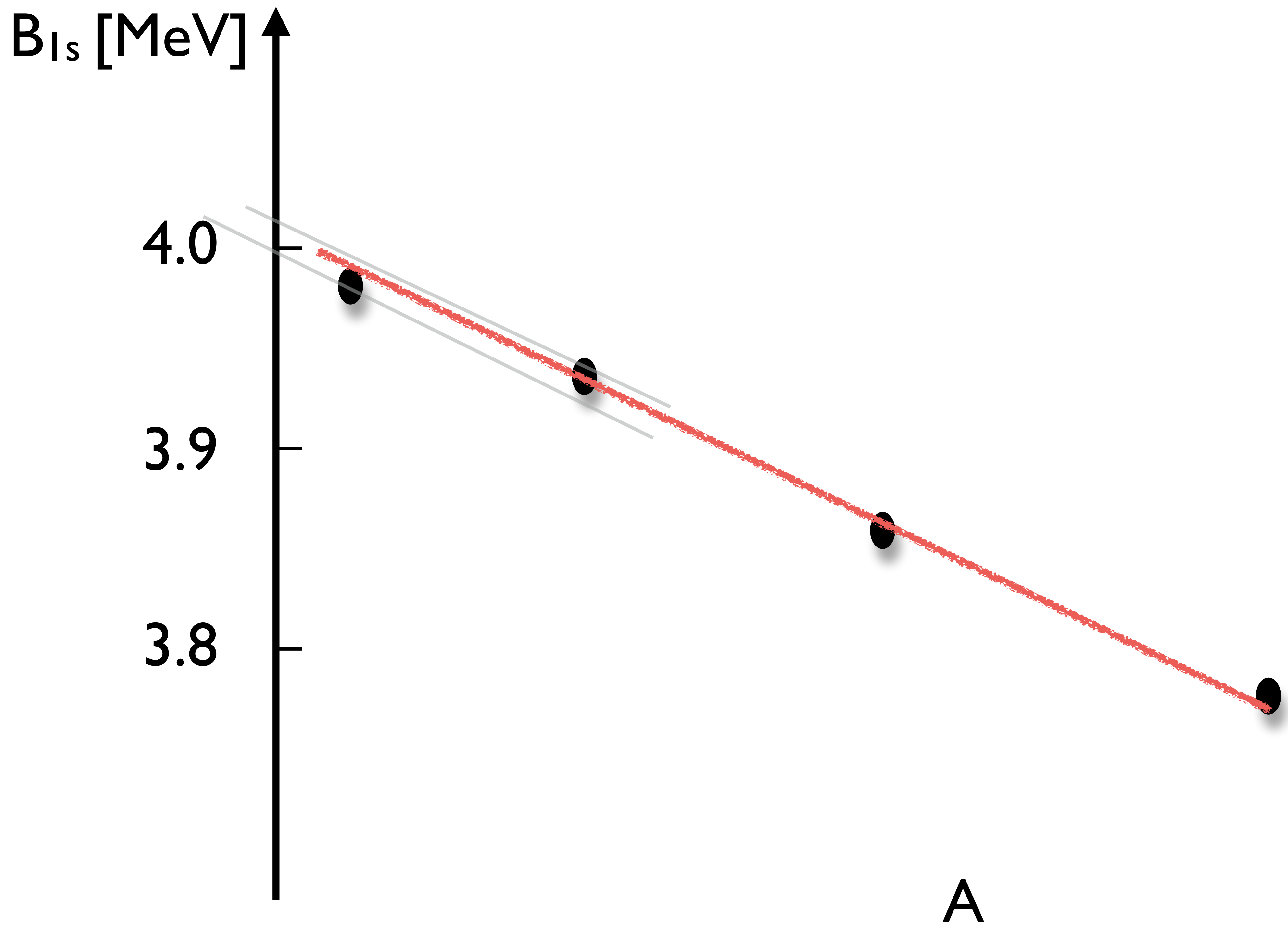
$$U_p(r) = \frac{2\pi}{\mu}\,\vec{\nabla}\cdot[c(r) + \varepsilon_2^{-1} C_0 \rho^2(r)]L(r)\vec{\nabla}$$

Binding energies and widths and potential parameters

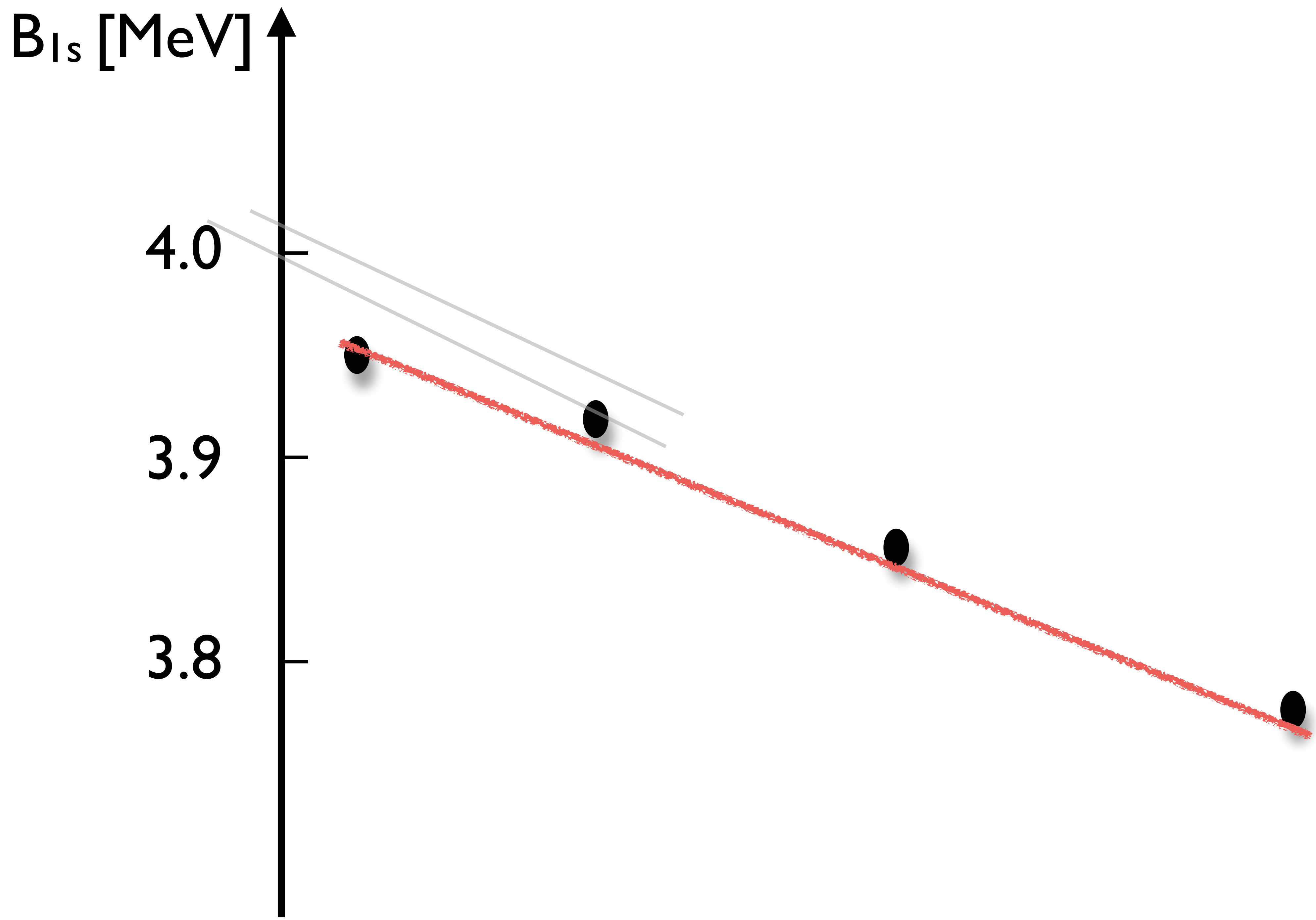
Binding energies
for pionic tin isotopes
with b_1 contours



Future perspectives
Density dependence of potential parameters



Future perspectives
Density dependence of potential parameters

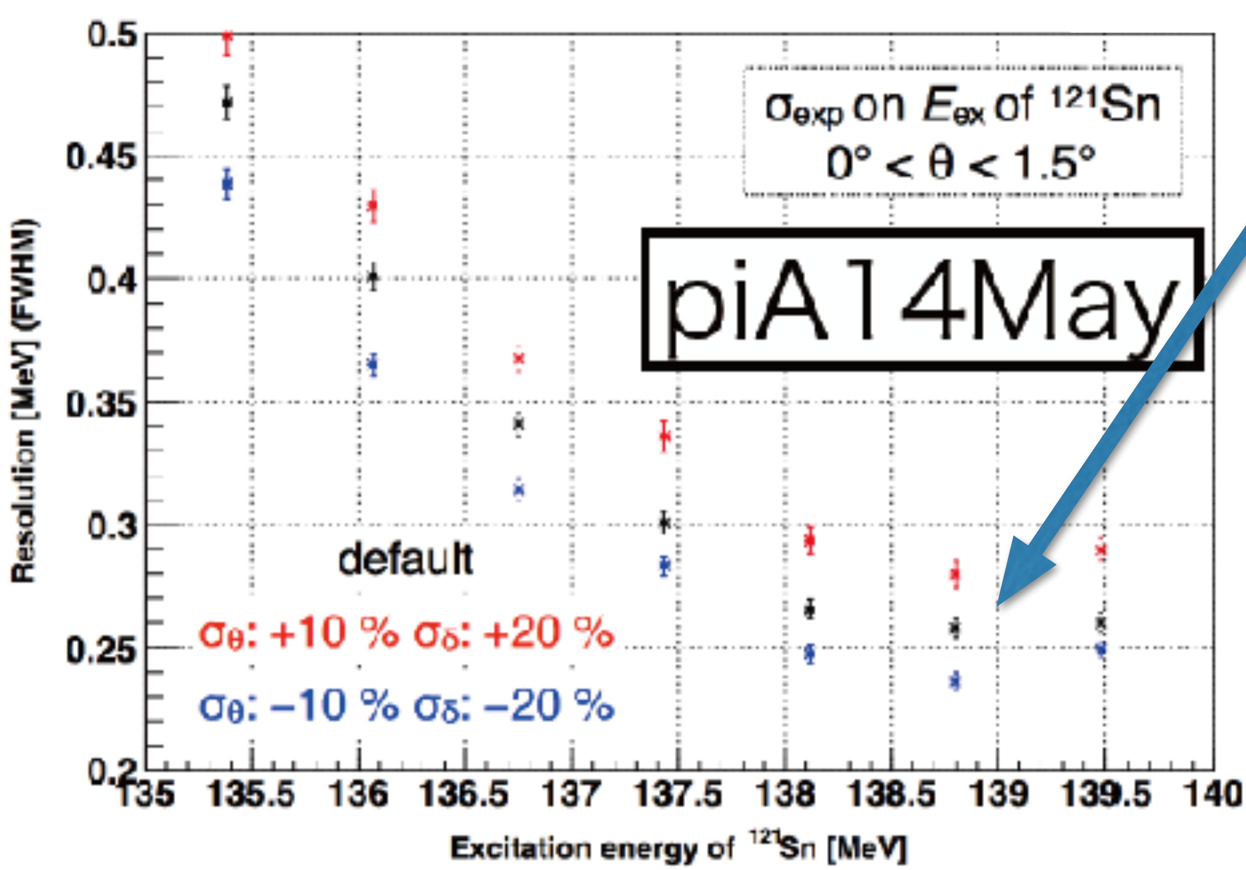


→Challenge toward higher precision aiming at study of ρ dependence of χ

Resolution Improvement Program for Primary Beam w. Disp. Matching

Resolution vs. Position

Present best resolution ~ 280 keV (FWHM)

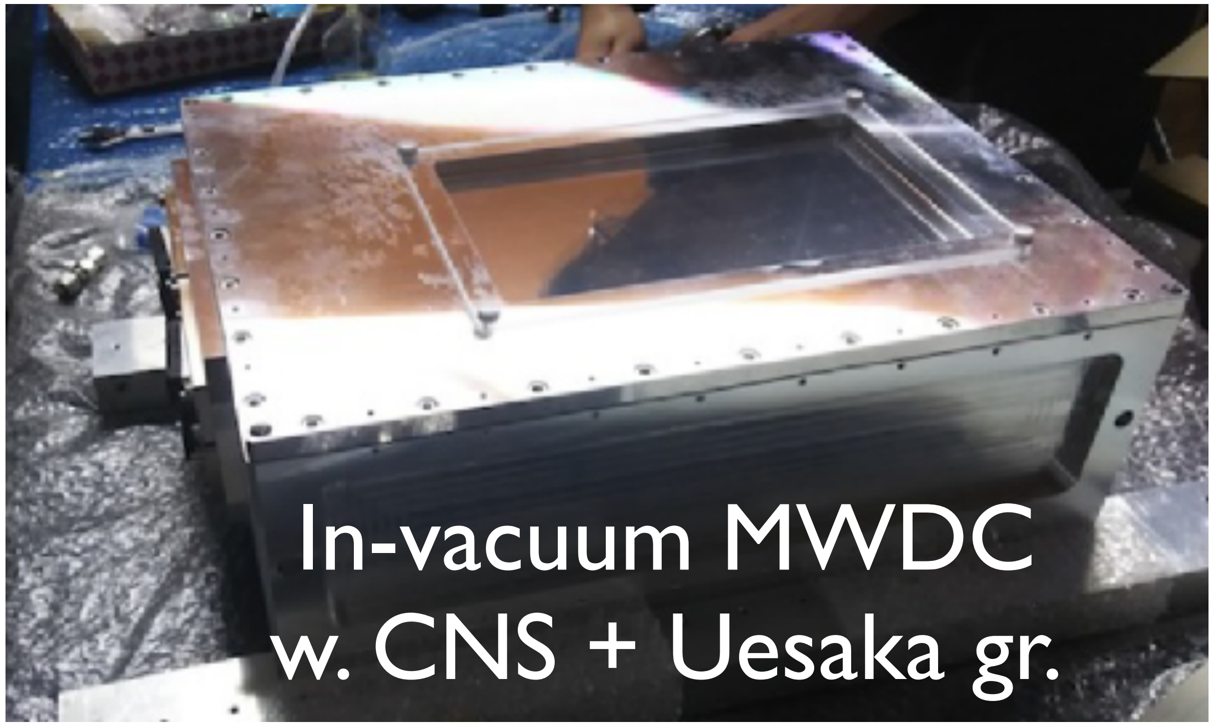


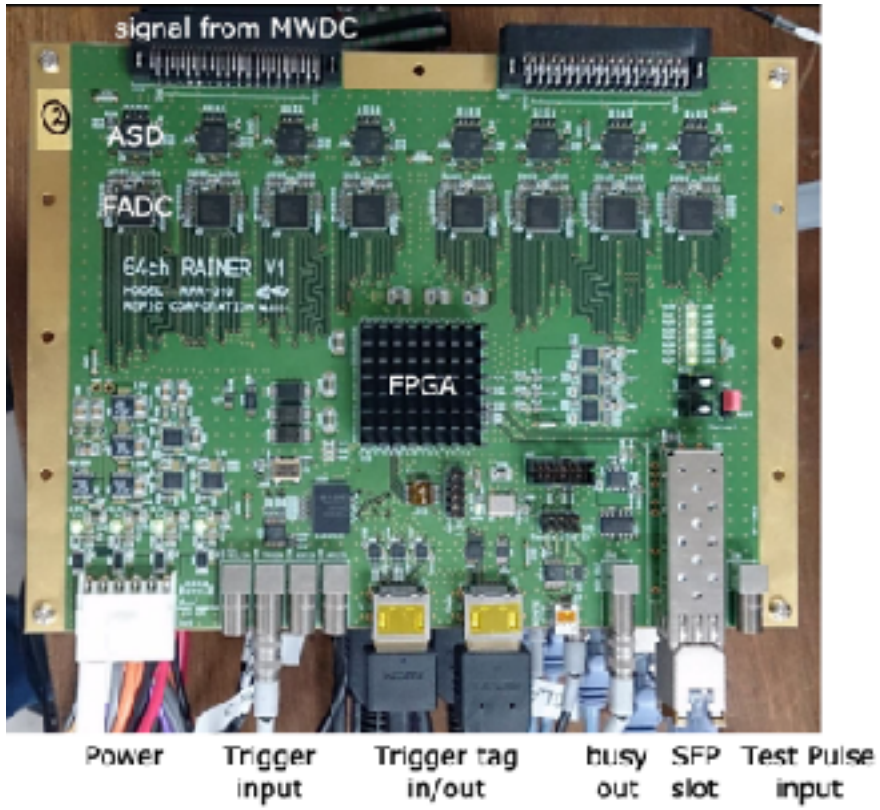
- Beam transfer line
  Ion optical tuning
- BigRIPS + detectors
  In-vacuum MWDC

We aim at

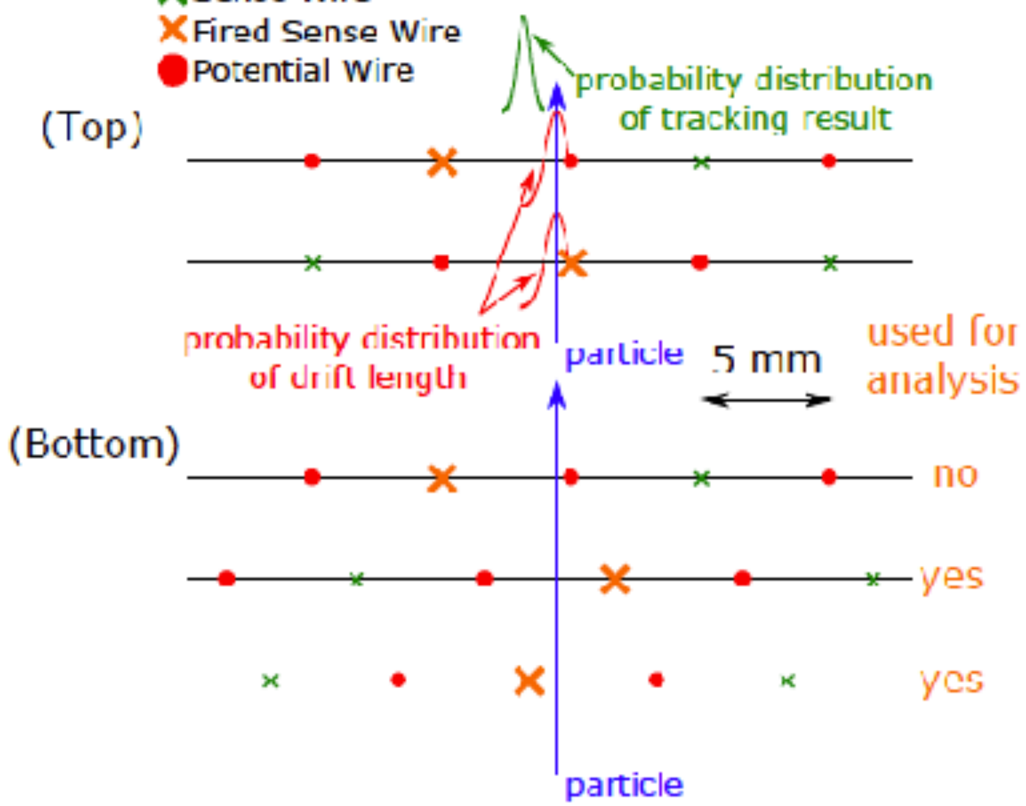
<u>Resolution < 150 keV</u>

Resolution Improvement Program for Primary Beam w. Disp. Matching





S. Matsumoto

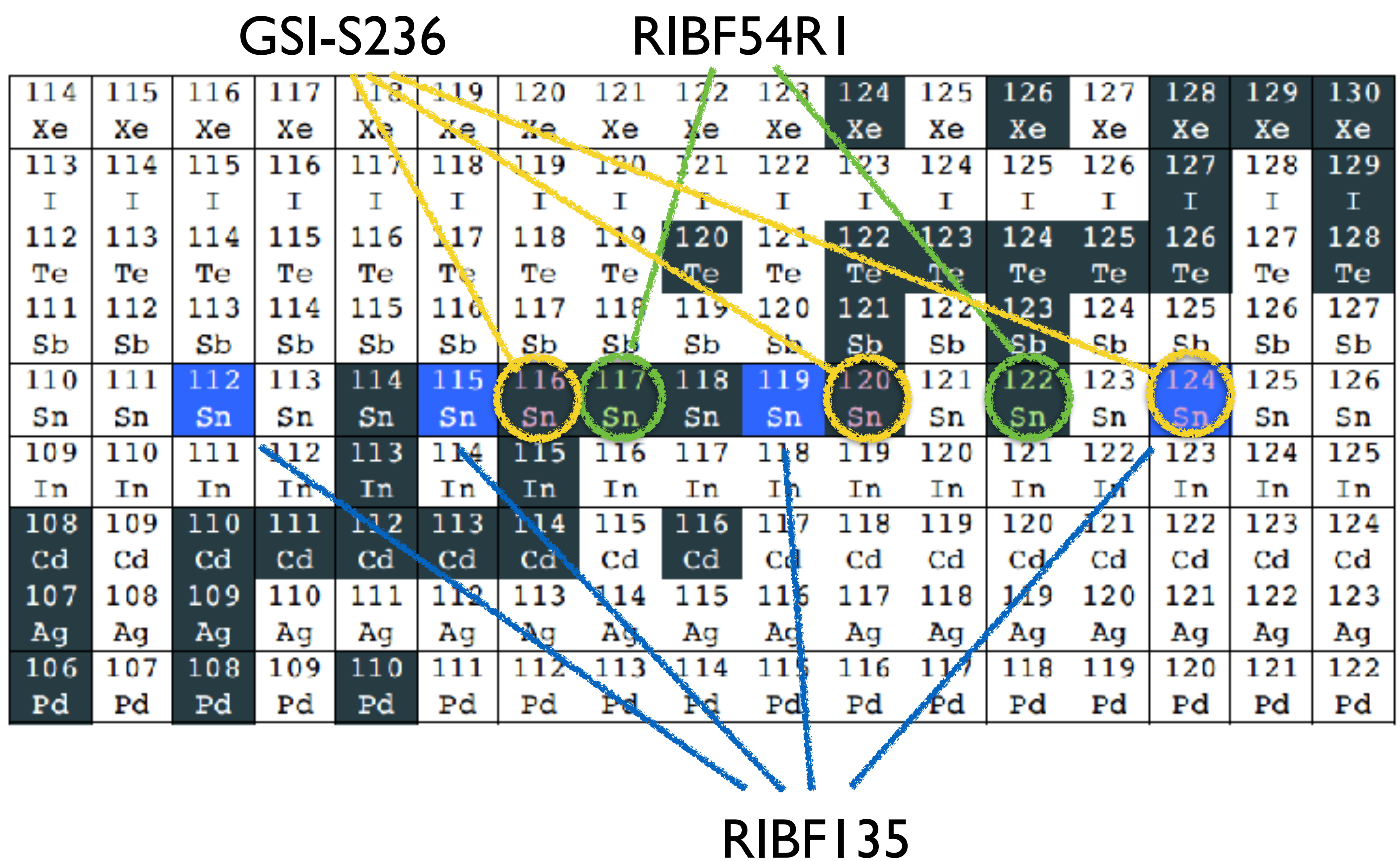


newly invented
1/3-cell staggered
MWDC

Y.N. Watanabe, *to be submitted*

Present status and near-future plans

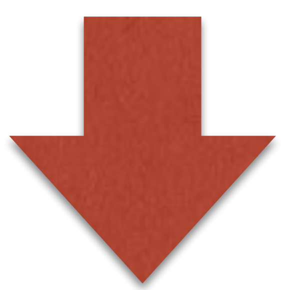
Measurement of pionic atoms over the long chain of tin isotopes
with a similar statistical precision level of ~ 3 keV
to deduce isovector part of pi-nucleus interaction



Summary of the proposal

Beam time approval of 7 days

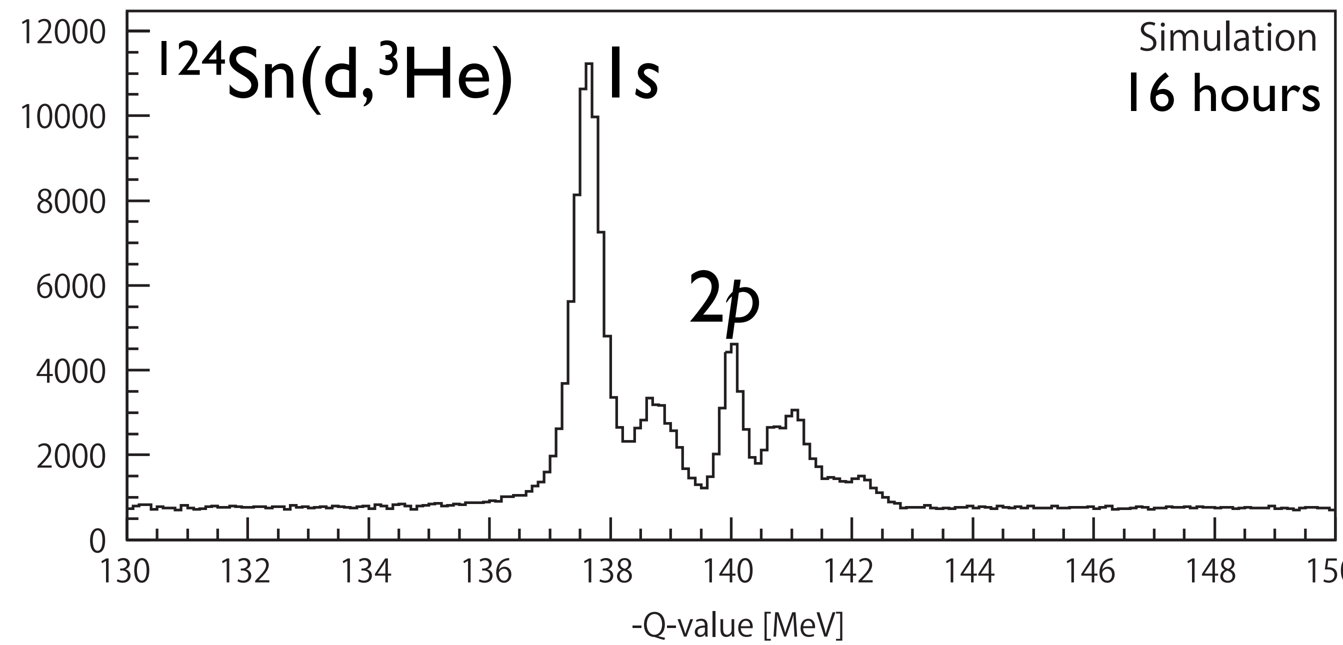
Systematic spectroscopy of pionic tin isotopes
Tin 112, 115, 119, and 124

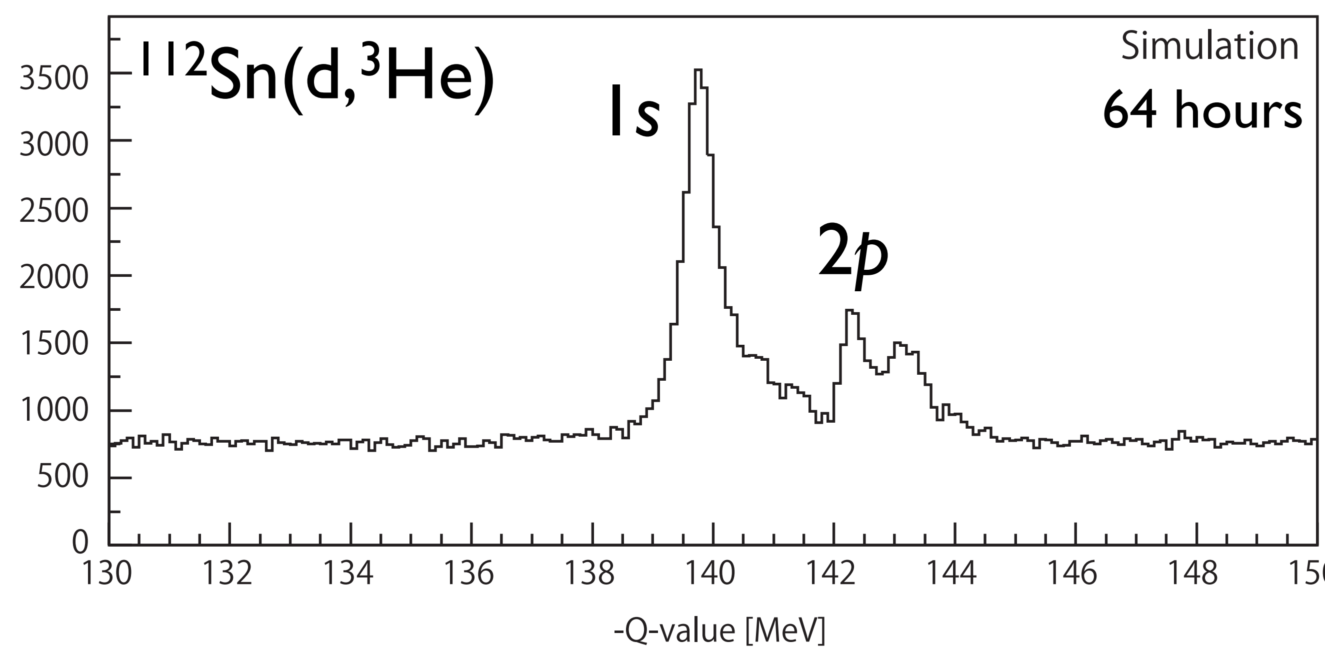


pion-nucleus interaction

Simultaneous observation of multiple states
→ small systematic errors

Expected spectra at 0 degree with 300 keV (FWHM)



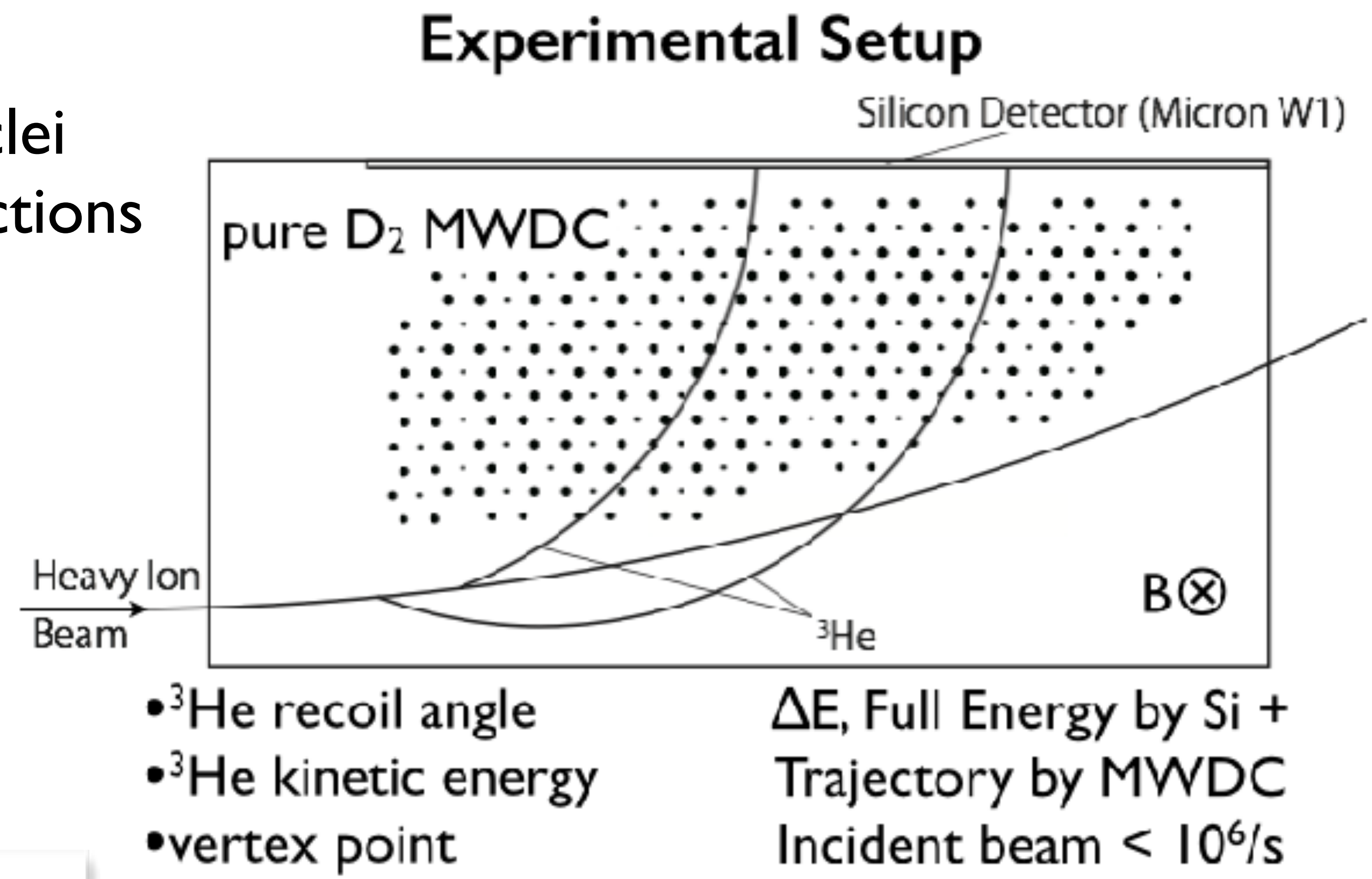


10 mg/cm^2 target

Density dependence of chiral condensate and Pionic atoms with unstable nuclei

Pionic atoms with unstable nuclei using **inverse kinematics** reactions

Neutron skin thickness can be measured



Some new experimental setups have been considered by Y.K. Tanaka

Summary

- Study of meson properties in nuclear medium provides information at high density, low-temperature region of QCD.
- Spectroscopy of mesic atoms and mesic nuclei provide information with less uncertainties because the observed states are in well-defined quantum states with Lorentz invariance.
- A large overlap between pion w.f. and nucleus is essential in deduction of the pion properties in nuclear medium leading to the understanding of the QCD and non-trivial structure of vacuum.
- Binding energies, widths, formation cross sections are determined. χ-condensate at ρ^0 is deduced from pionic atom data to be 30% reduced from that in vacuum.
- Angular dependence of the cross section is determined and compared with theories. 2p agrees but 1s does not agree.
- New experiments with better precision is in preparation to study density dependence of χ-condensate as well as pionic atoms with unstable nuclei.