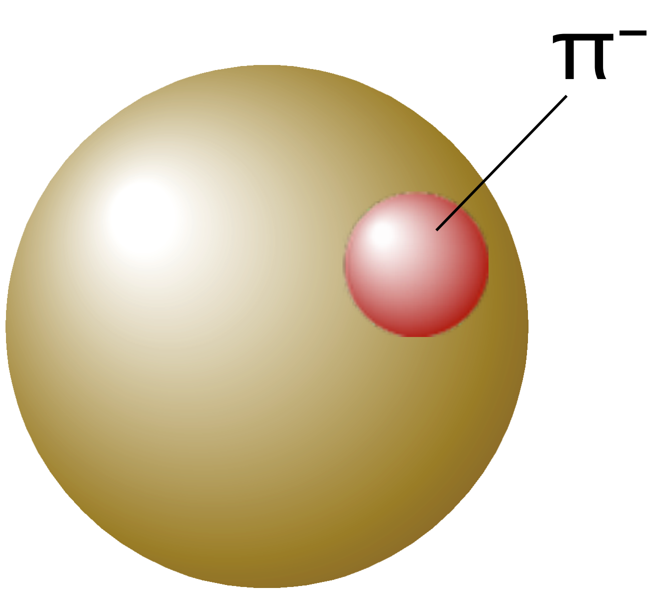
Precision spectroscopy of pionic atoms and chiral symmetry in nuclei

RIKEN Nishina Center
Kenta Itahashi
for piAF collaboration



cf. Bastian Kubis on πH and πD on Friday

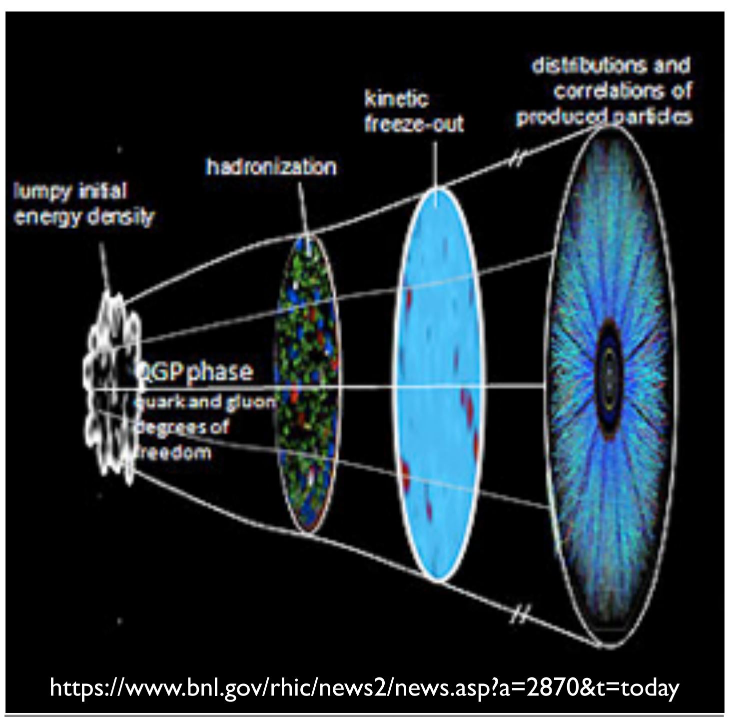
Strong interaction in low energy region

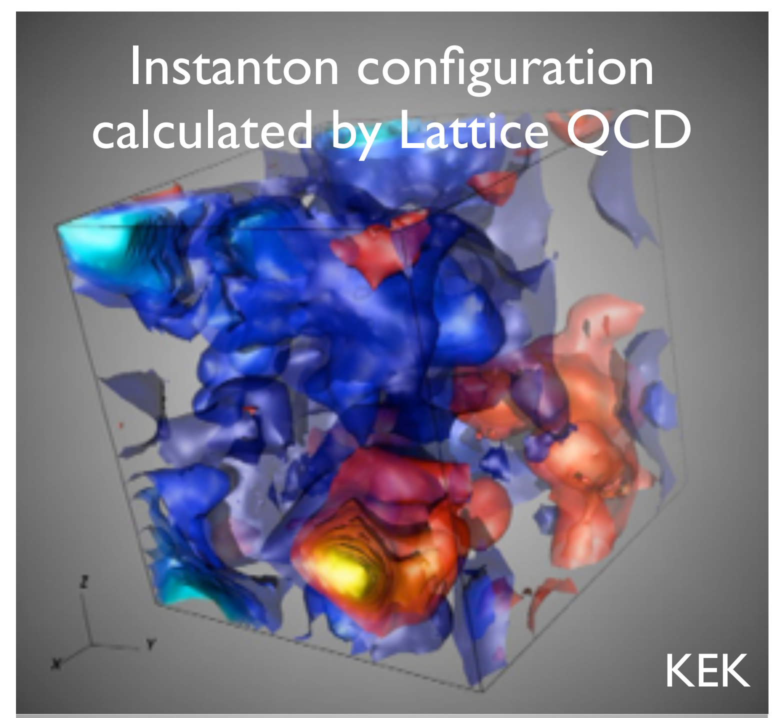
Quark confinement

↔ evolution of matter

Spontaneous breakdown of chiral symmetry

↔ non-trivial structure of vacuum





Strong interaction in low energy region

Quark confinement

↔ evolution of matter

Spontaneous breakdown of chiral symmetry

↔ non-trivial structure of vacuum

Low energy region is interesting

Non-perturbative aspects when energy < Λ_{QCD}

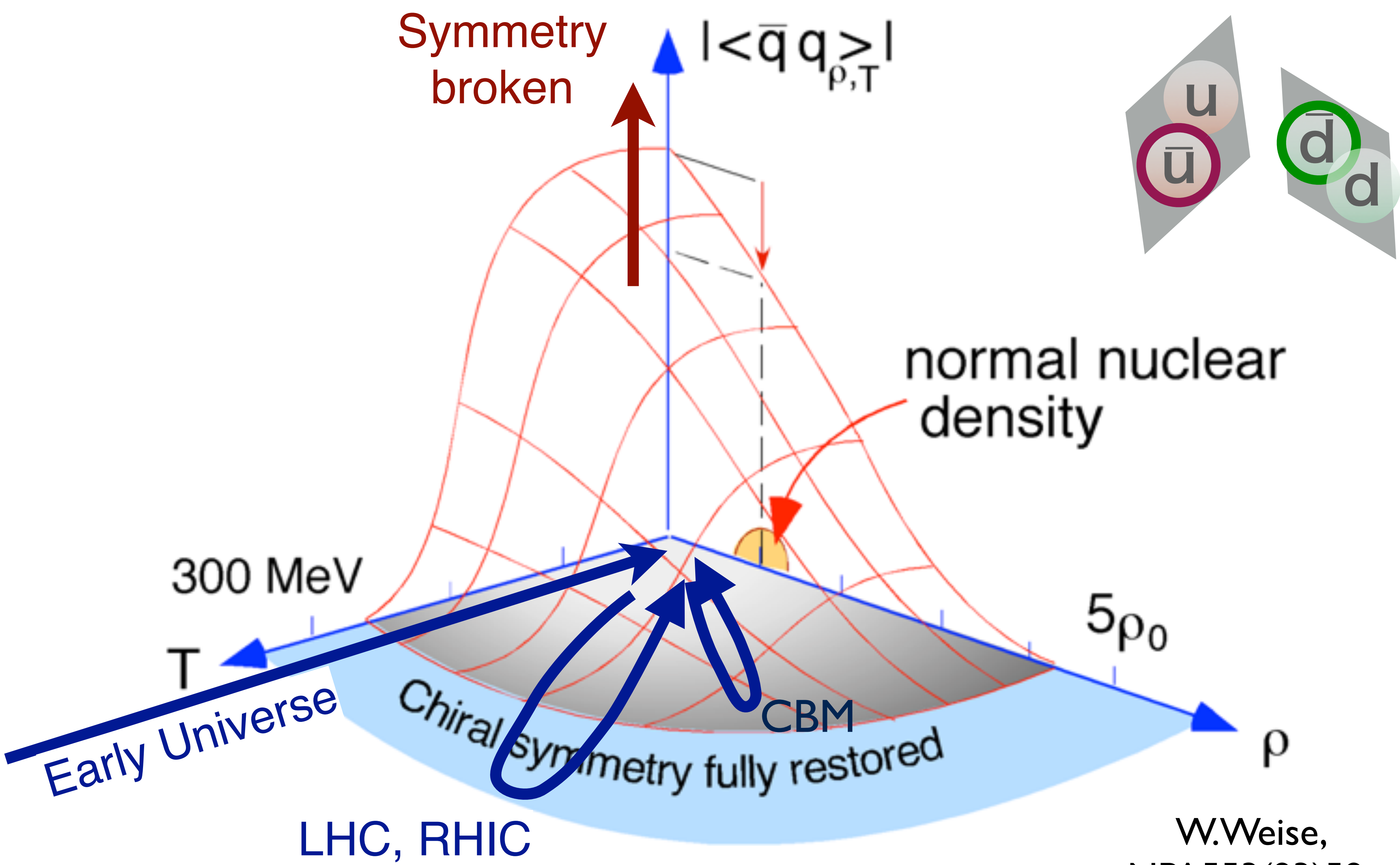
Finite density → sign problem makes Lattice QCD approach difficult

Low T, high ρ experimental inputs are important

Structure of vacuum

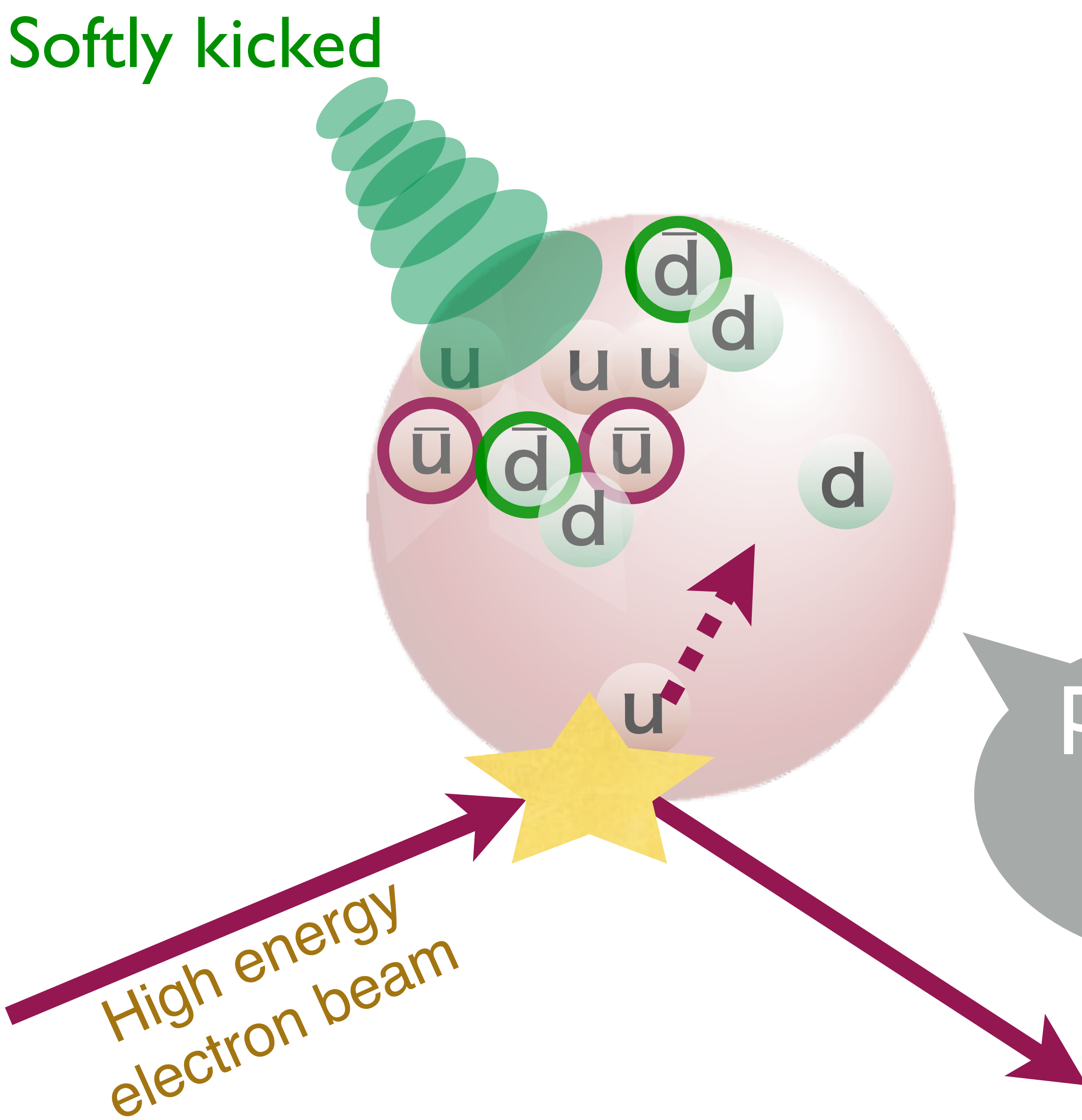
chiral symmetry and order parameter

Chiral condensate $\langle\bar{q}q\rangle$

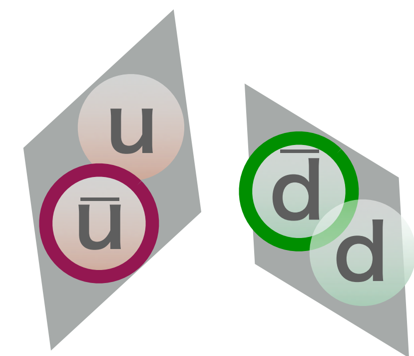


W.Weise, NPA553(93)59.

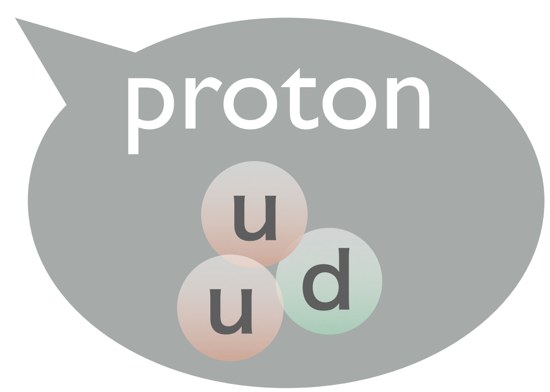
Hadron masses and chiral symmetry



Chiral condensate $\langle\bar{q}q\rangle$

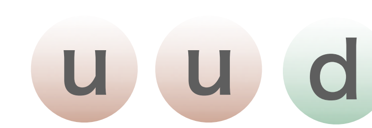


proton mass ≠sum of qqq mass



940 ≠ 10

[MeV/c^2]



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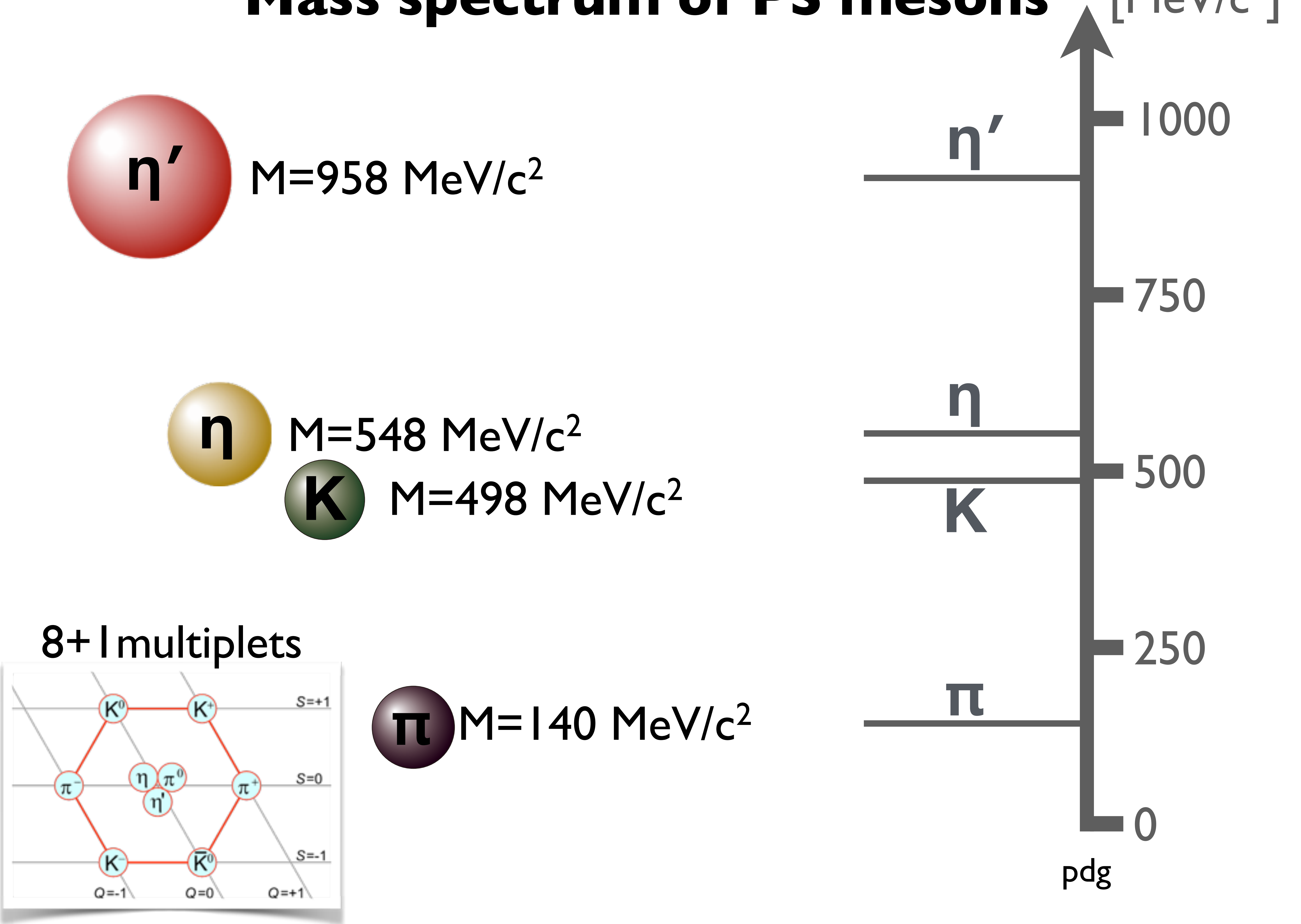
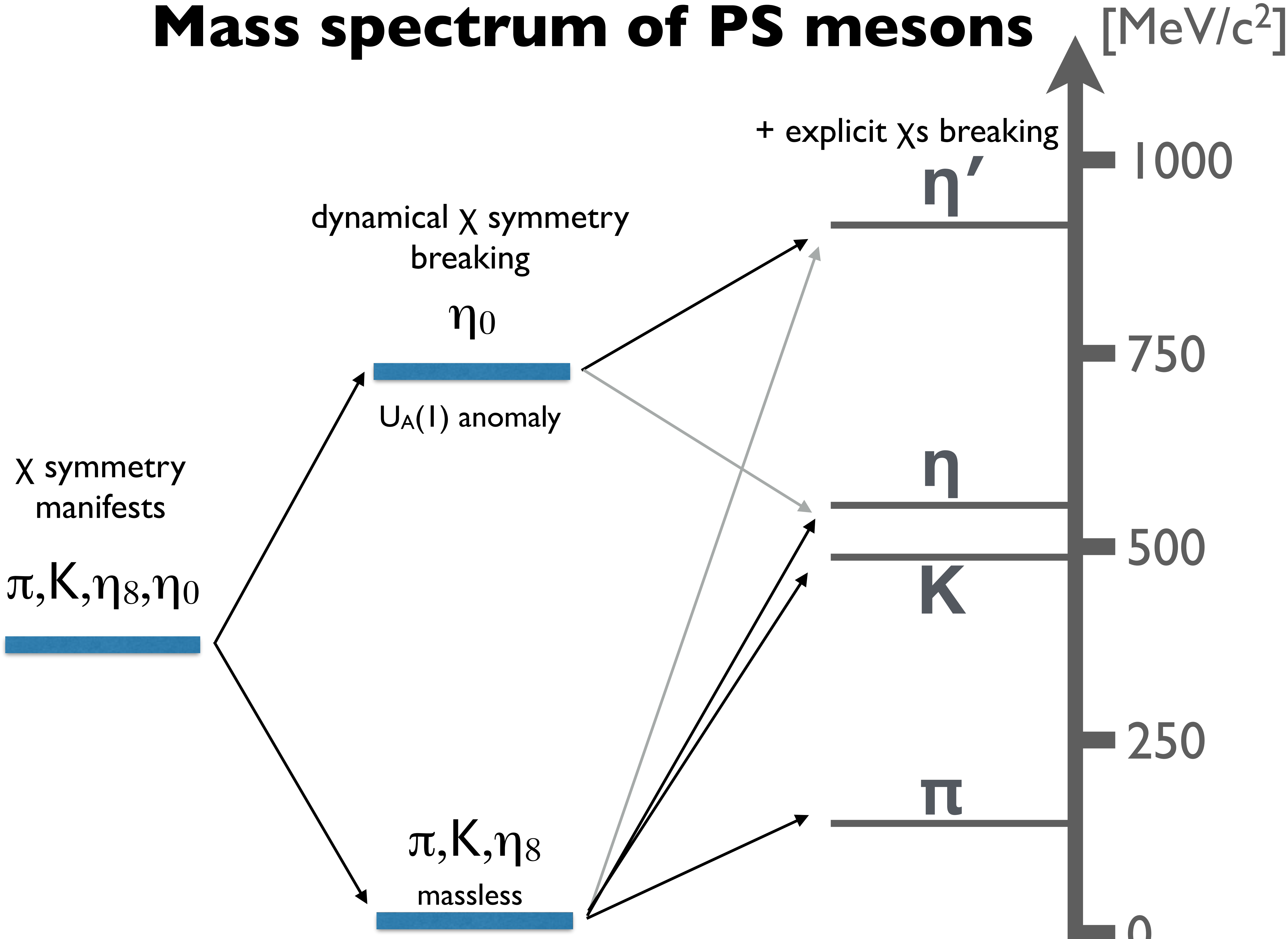
Mass spectrum of PS mesons



Mass spectrum of PS mesons



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

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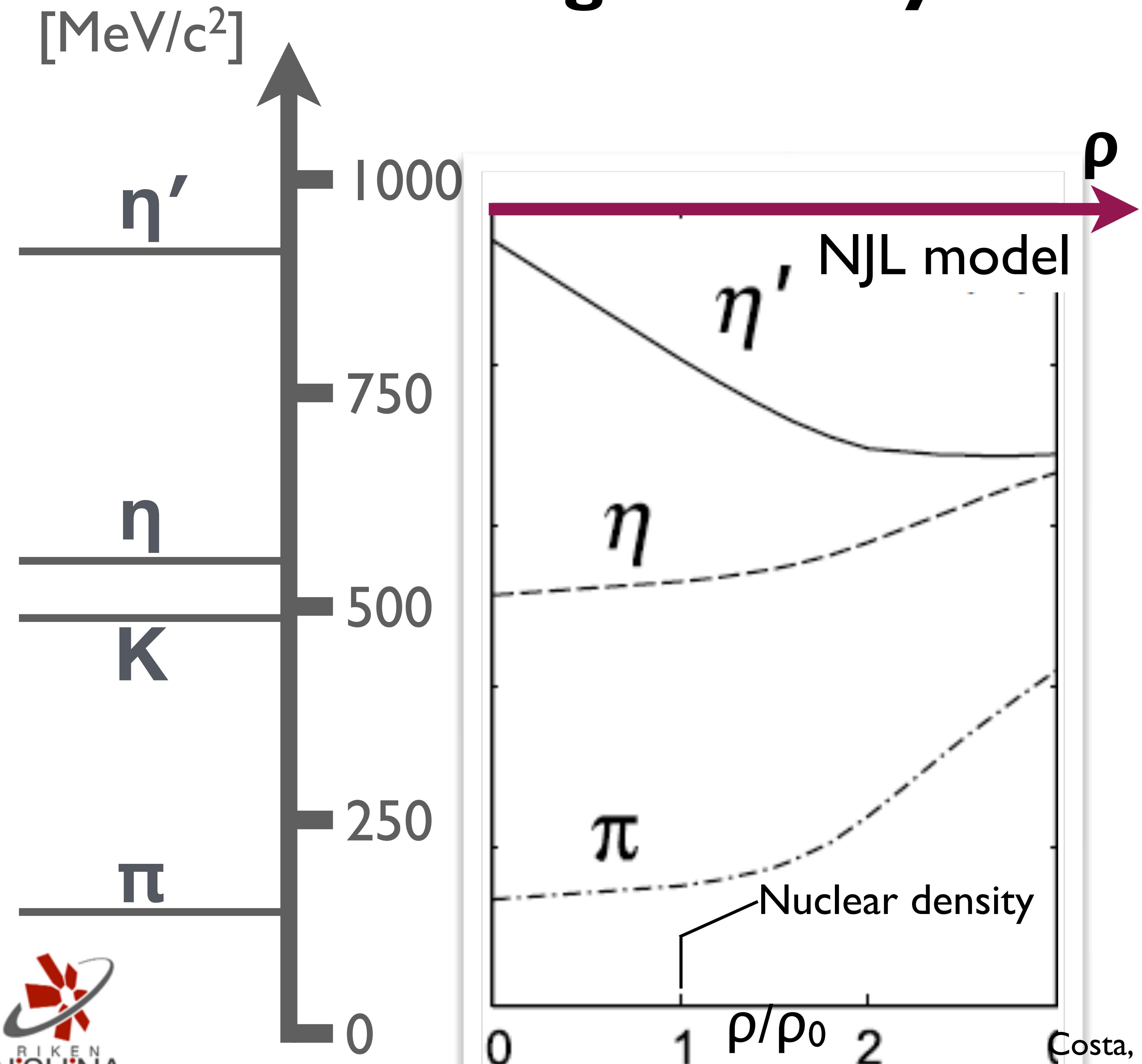
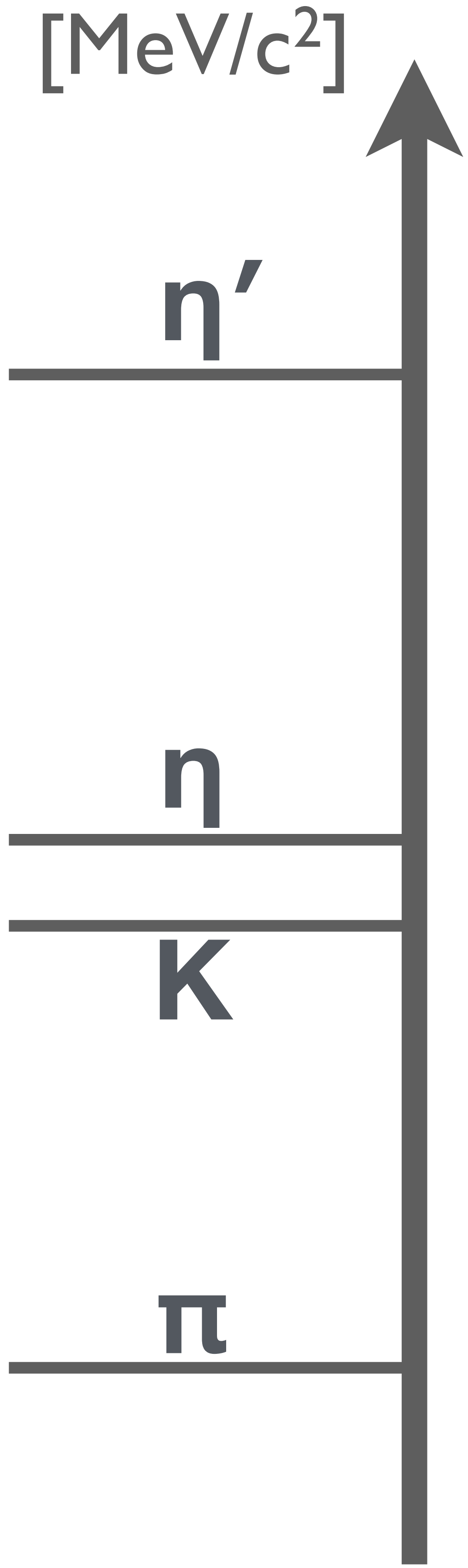
PS in high density medium



At high ρ, chiral symmetry partially restores.

Costa, PLB560
Nagahiro *et al*, PRC 74, 045203 (2006)

Motivations in mesic atoms/nuclei

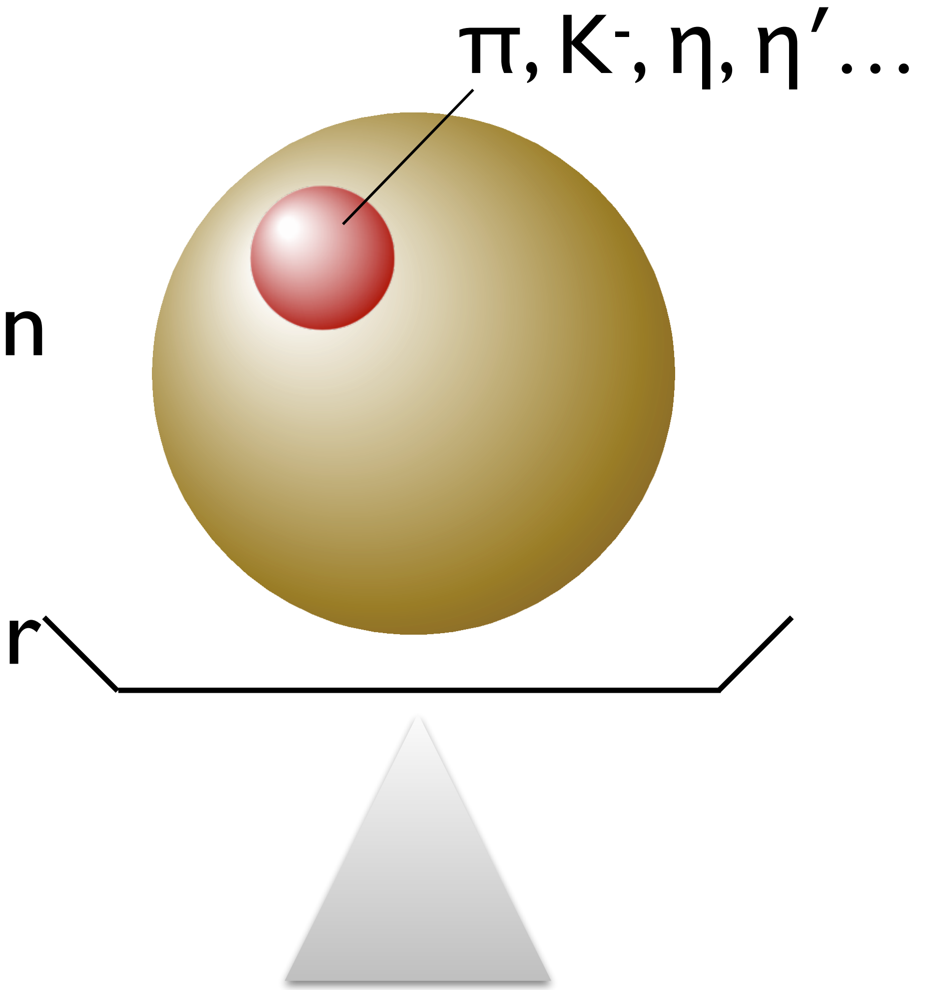


→ $U_A(1)$ anomaly
gluon dynamics
instanton-induced interaction

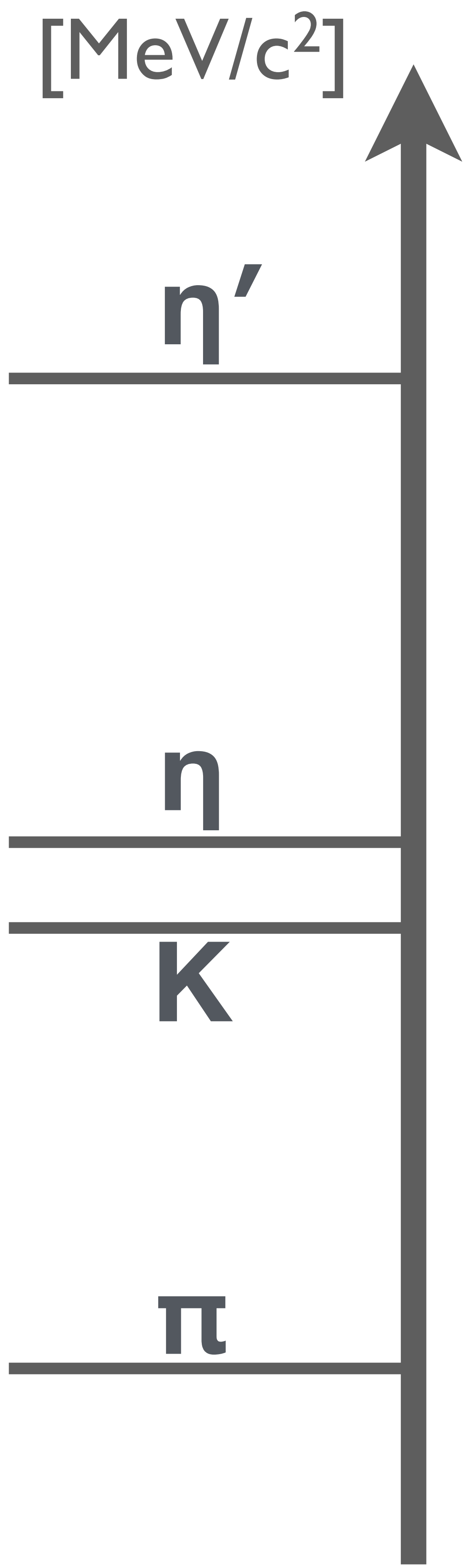
Strong coupling to $N^*(1535)$
→ χ-symmetry in baryon sector
→ $\rho > \rho_0$
Relation to neutron stars

→ quantitative est. of chiral condensate
sensitivity to nuclear structure (neutron skins)

Hadrons as probes



Motivations in mesic atoms/nuclei



Hadrons as probes

π, K^-, η, η'...

→ $U_A(1)$ anomaly
gluon dynamics
instanton-induced interaction

Strong coupling to $N^*(1535)$
→ χ-symmetry in baryon sector
→ $\rho > \rho_0$
Relation to neutron stars

REMARK 1

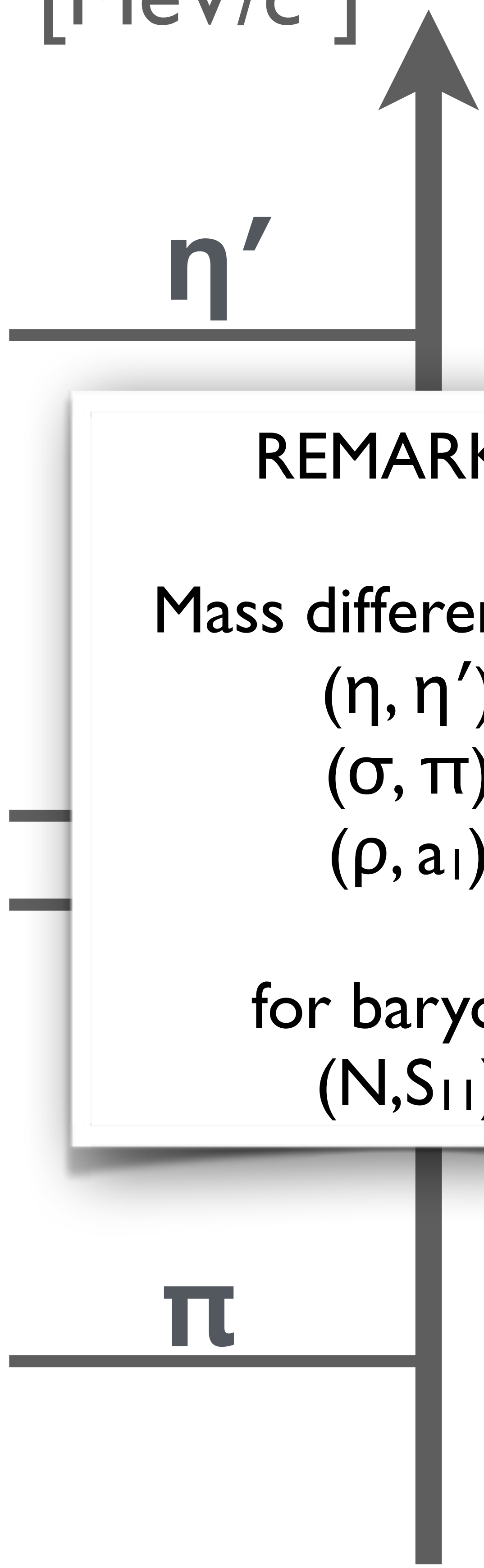
Mass differences in
(η, η')
(σ, π)
(ρ, a_1)

for baryons
(N, S_{11})

→ quantitative est. of chiral condensate
sensitivity to nuclear structure (neutron skins)

Motivations in mesic atoms/nuclei

[MeV/c^2]



→ $U_A(1)$ anomaly
n dynamics
nton-induced interaction
ng c 5)
mm tor
ρ_0
tion to neutron stars

REMARK I

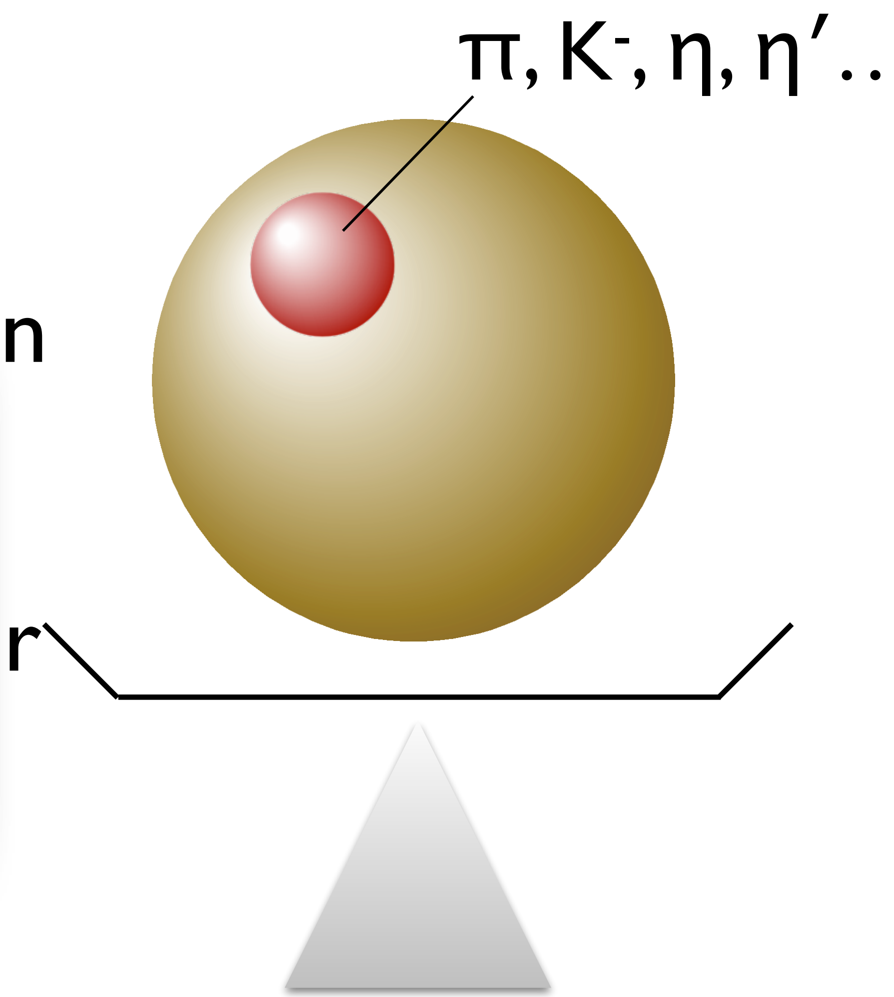
Mass differences in
(η, η')
(σ, π)
(ρ, a_1)

for baryons
(N, S_{11})

REMARK II

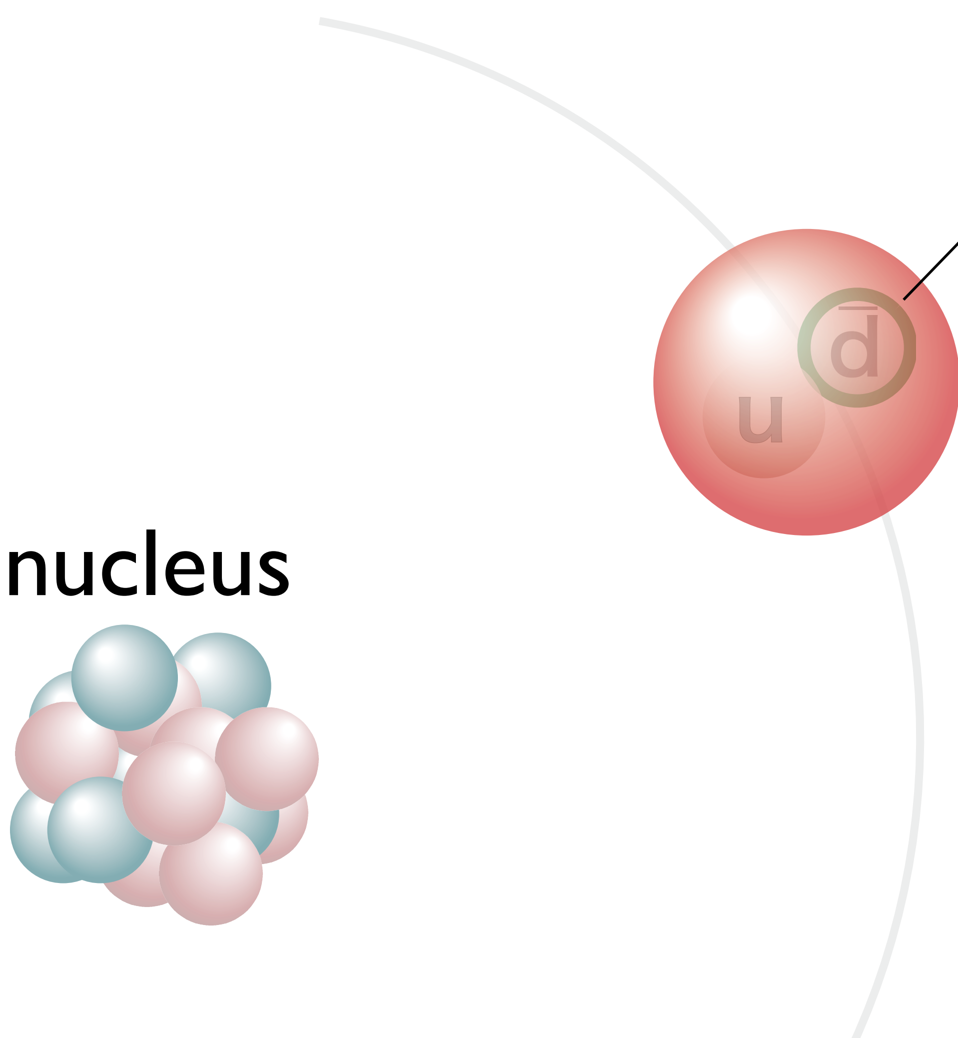
Quantum mechanically
well-defined objects

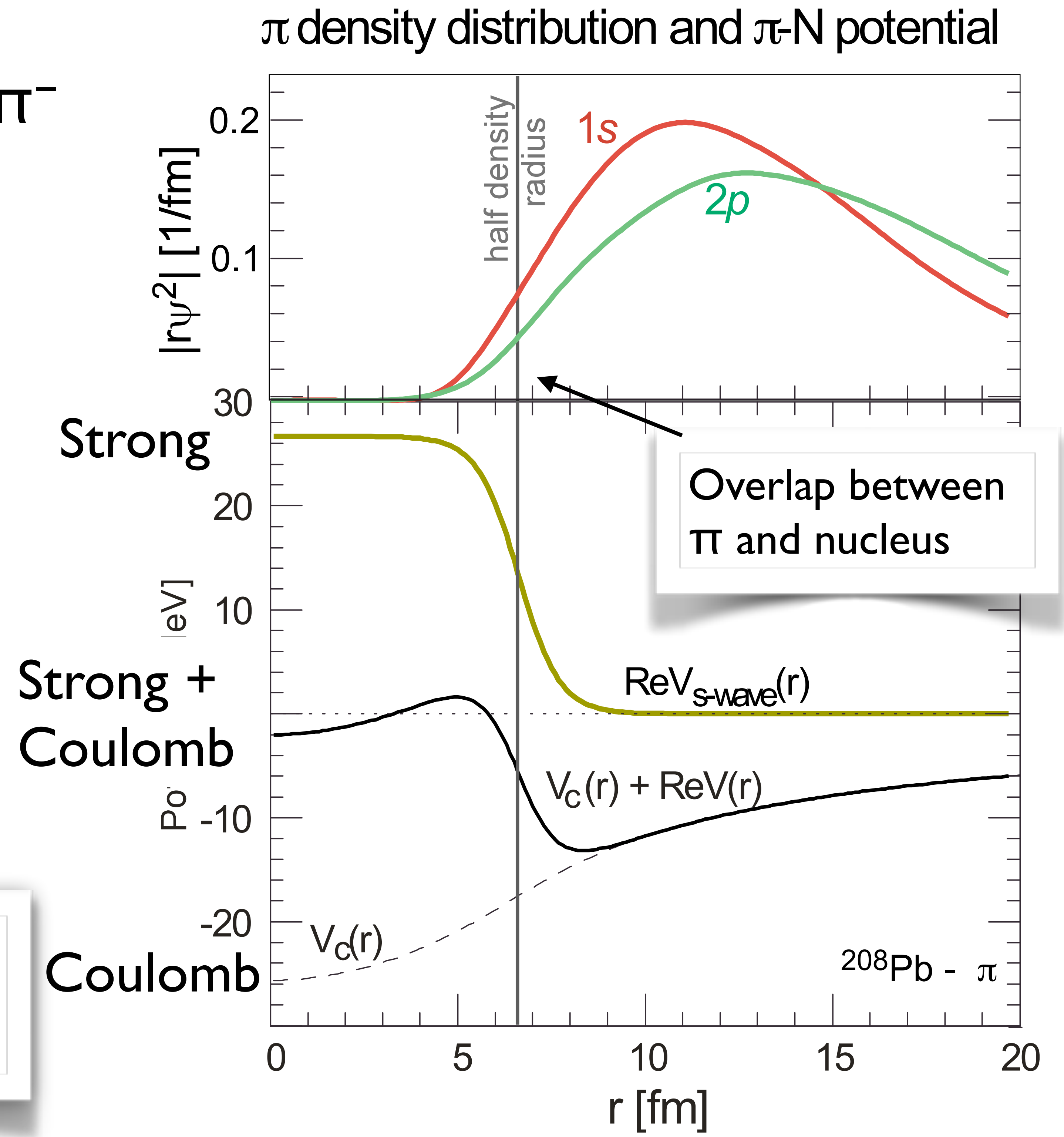
Hadrons as probes



→ quantitative est. of chiral condensate
sensitivity to nuclear structure (neutron skins)

Pionic Atoms

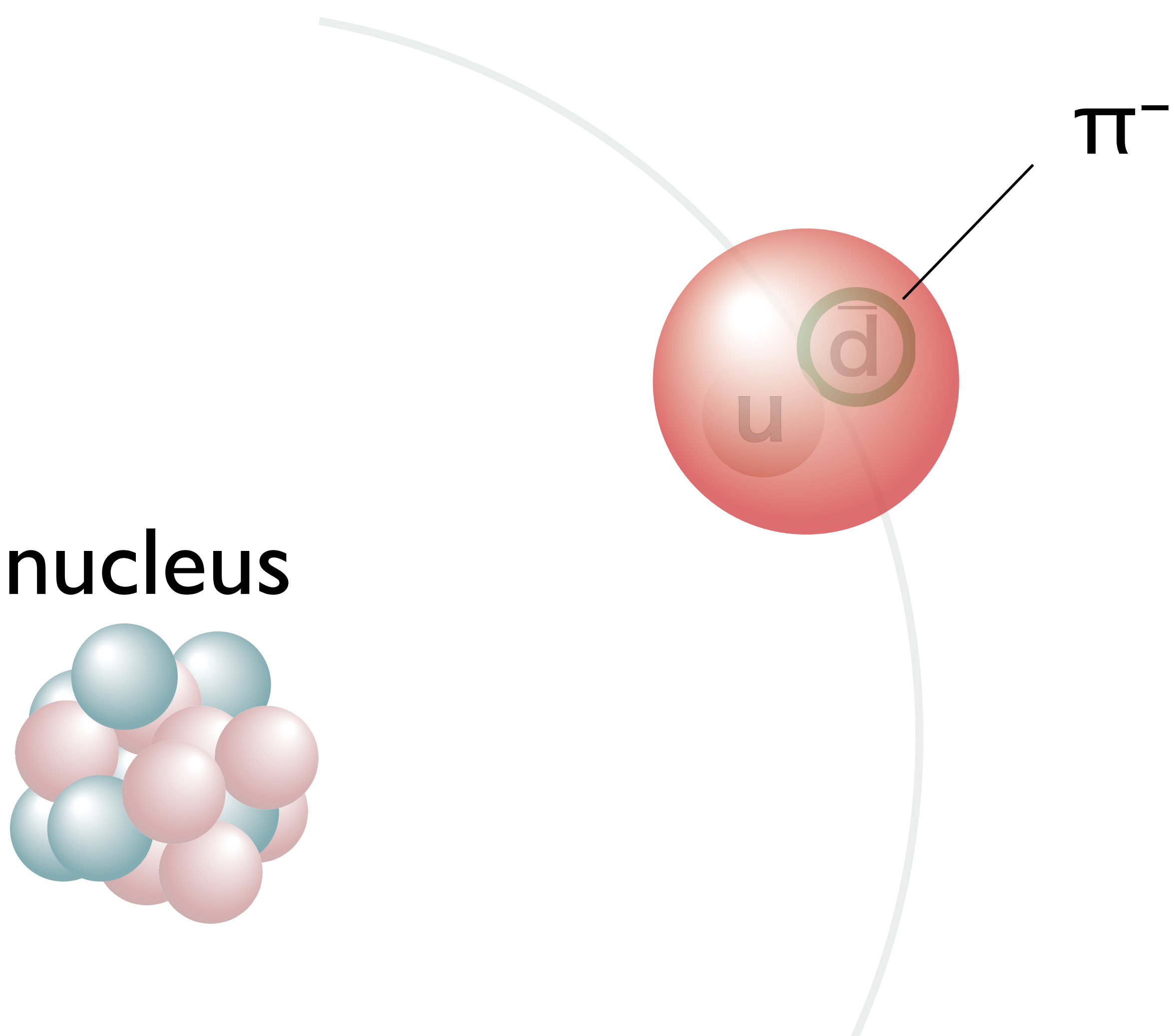




Strong interaction:

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

Pionic Atoms



Strong interaction:

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

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

Gell-Mann-Oakes-Renner relation

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

f_π : pion decay constant

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

Tomozawa-Weinberg relation

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

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

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

b_I acting as an order parameter of χ-symmetry

Order parameter of
Chiral symmetry breaking

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

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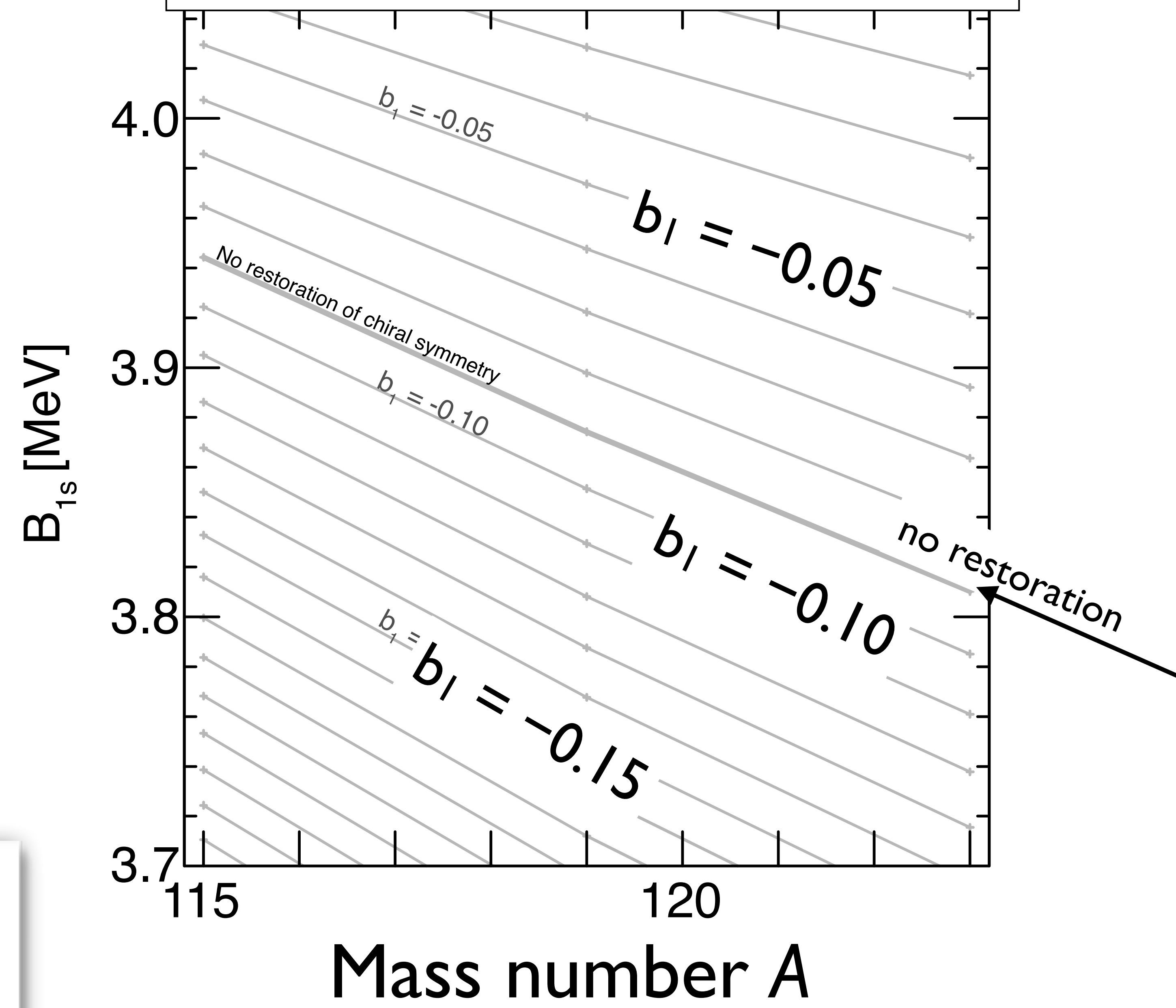
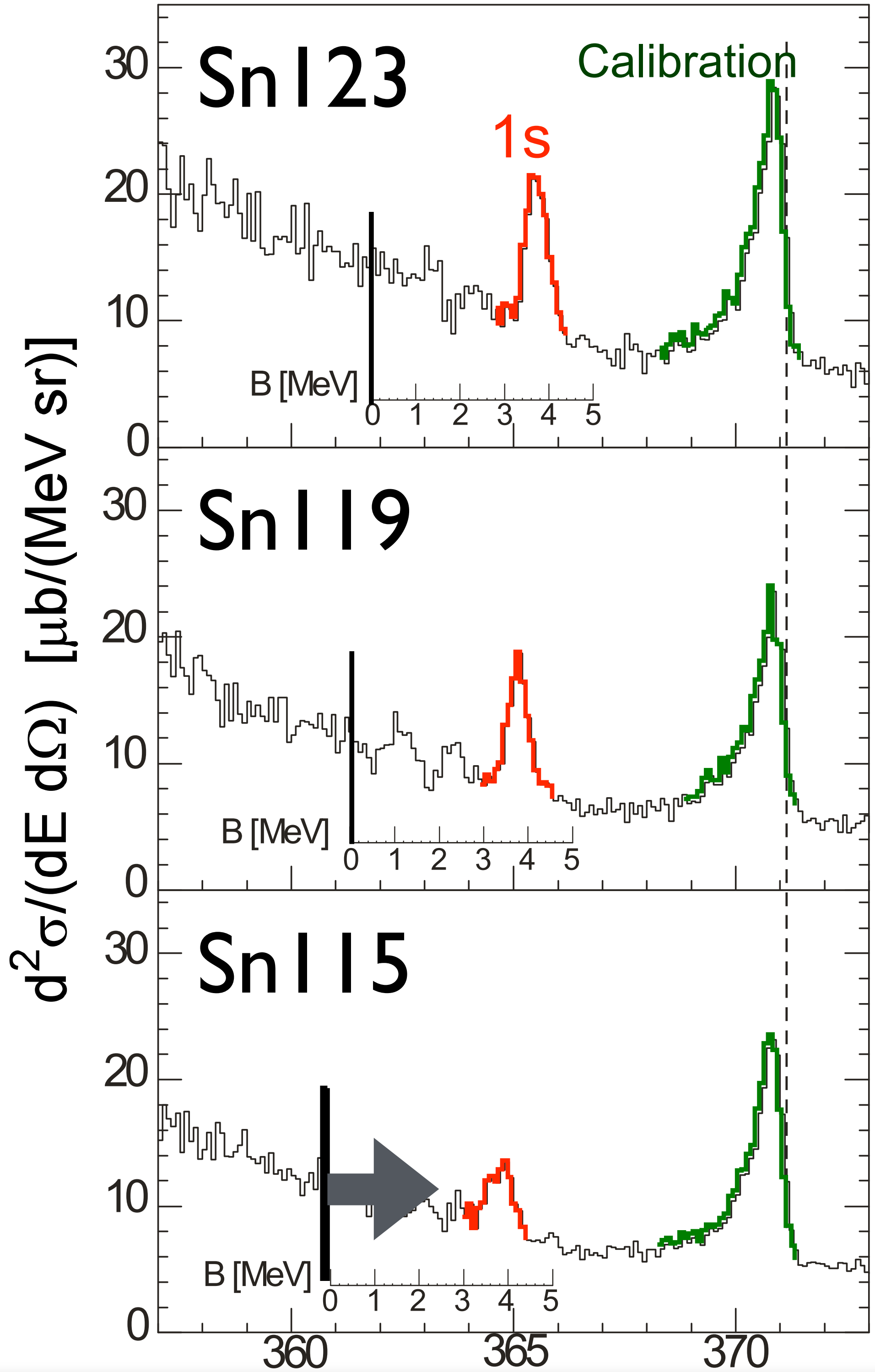
Jido, Hatsuda, Kunihiro, Phys.Lett.B670:109-113,2008.
Kolomeitsev, Kaiser, Weise, Phys. Rev. Lett. 90(2003)092501

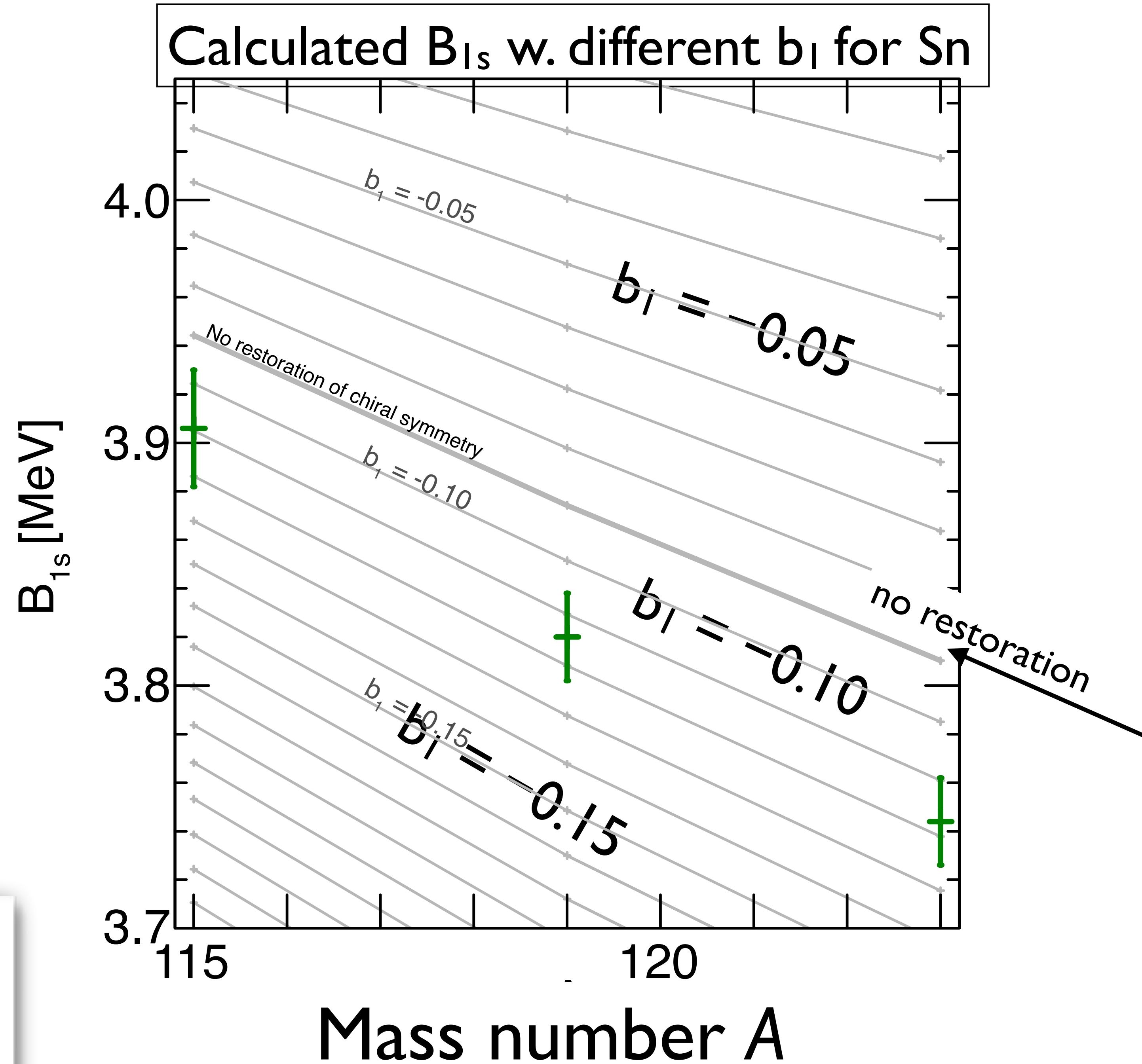
Calculated B_{1s} w. different b_I for Sn



aft. combination with light pi-A data

Pionic Sn isotopes at GSI





Strong interaction:

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

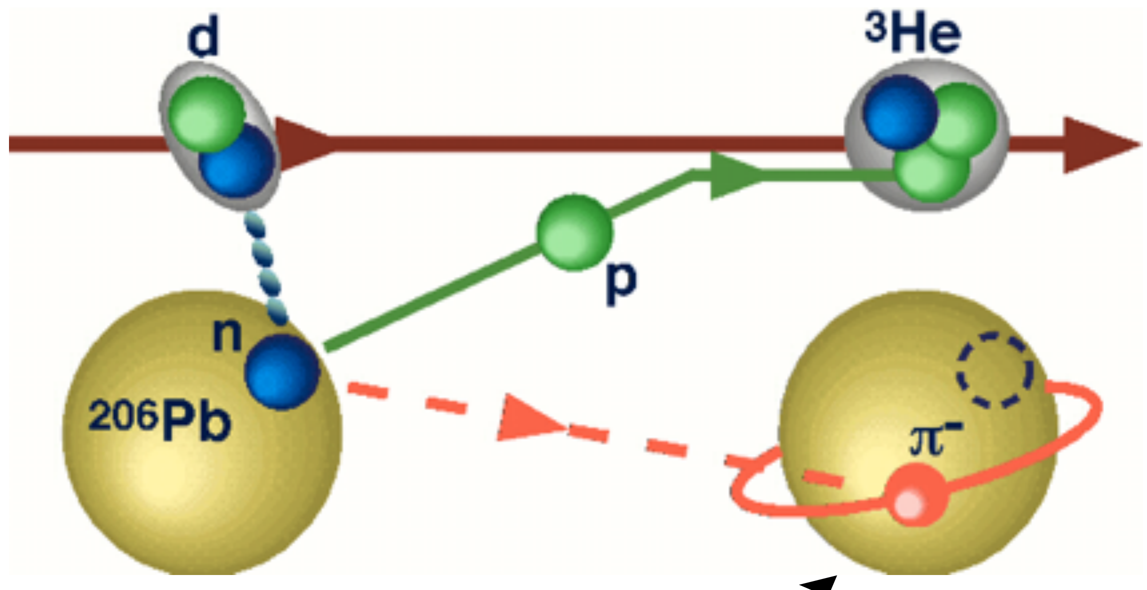
aft. combination with light pi-A data

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

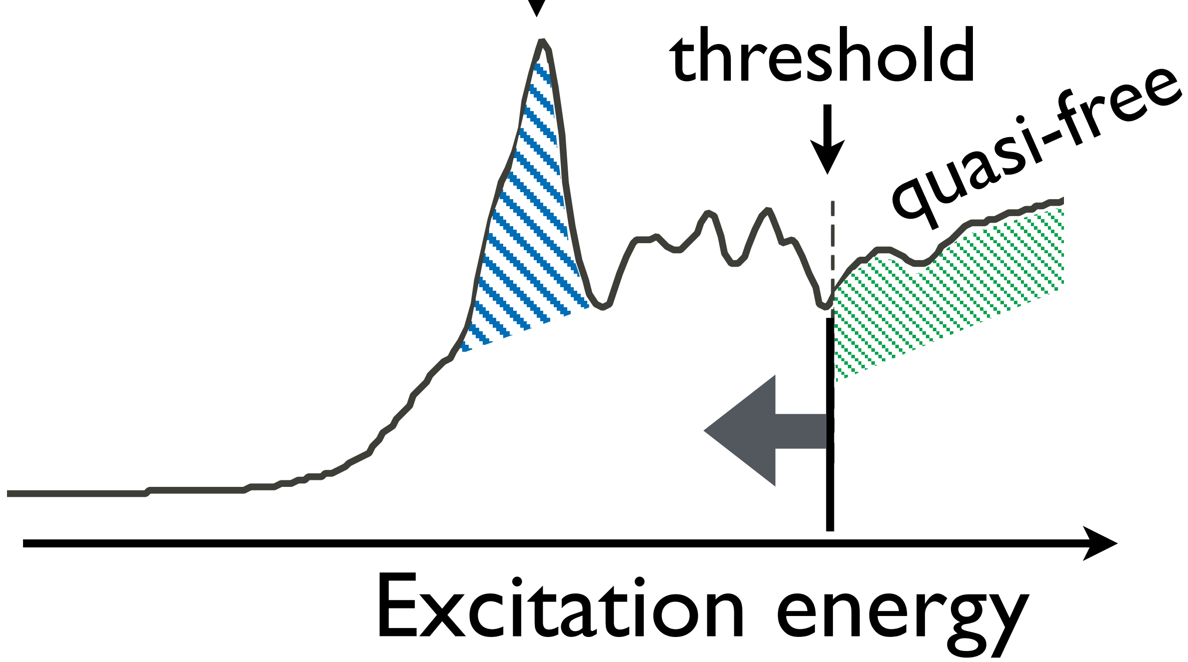
Spectroscopy of pionic atoms

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

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



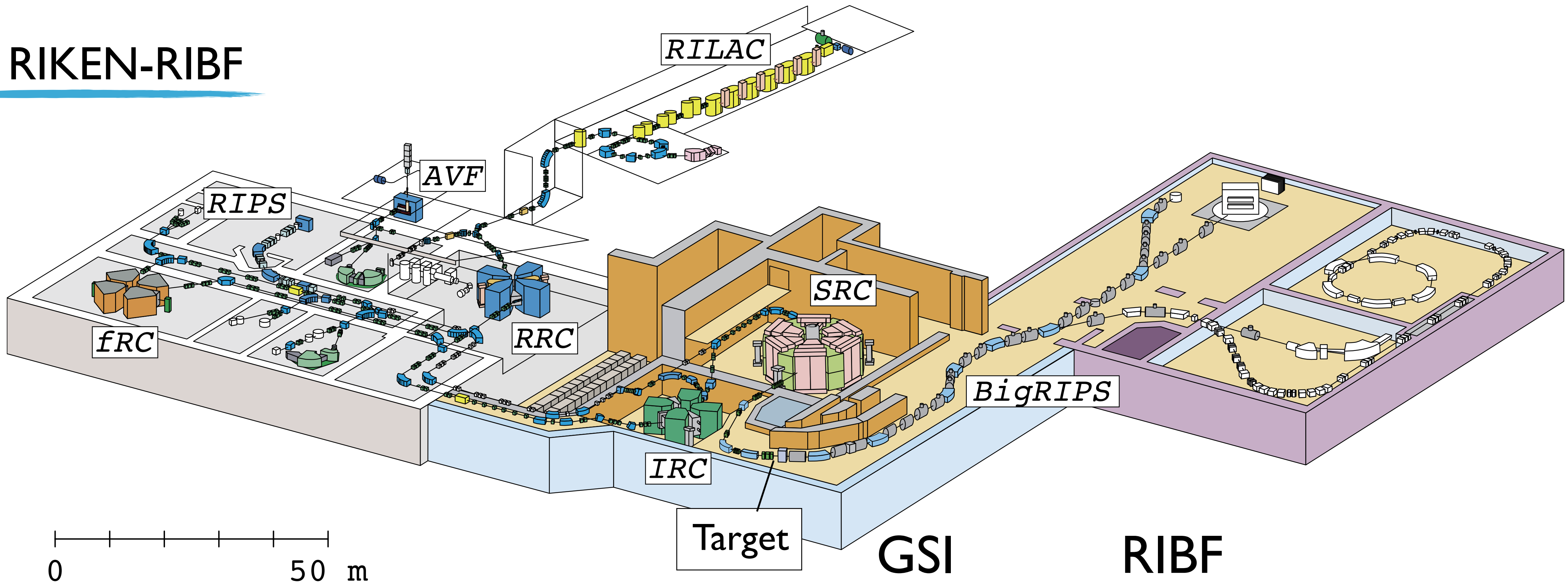
Pion bound state
(coupled with *n* hole)



We are aiming at
300 keV (FWHM) resolution.
(prev. 400 keV)

Precision spectroscopy at RI Beam Factory

RIKEN-RIBF



	GSI	RIBF
d beam Intensity	10	>10
Target	20 mg/cm	10 mg/cm
Δ	0.03%	0.06%
Resolution (FWHM)	400 keV	1000 keV
Acceptance (mrad)	15H, 10V	40H, 60V

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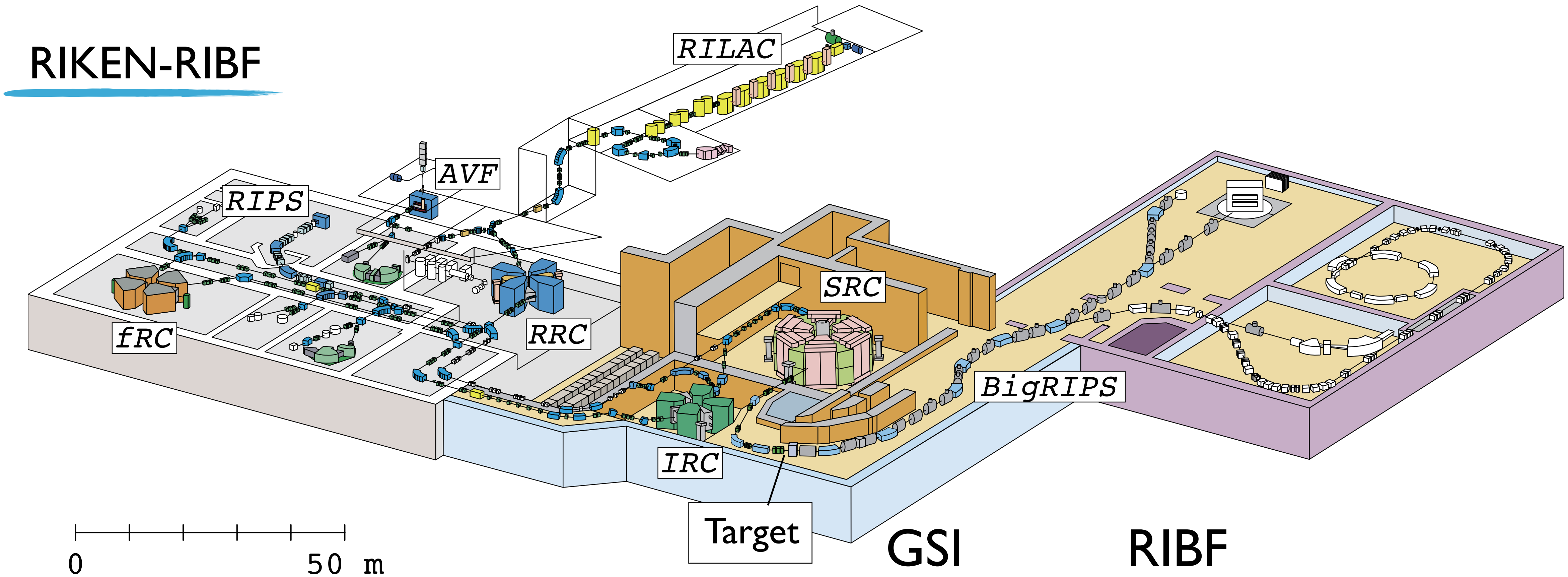
Precision spectroscopy at RI Beam Factory



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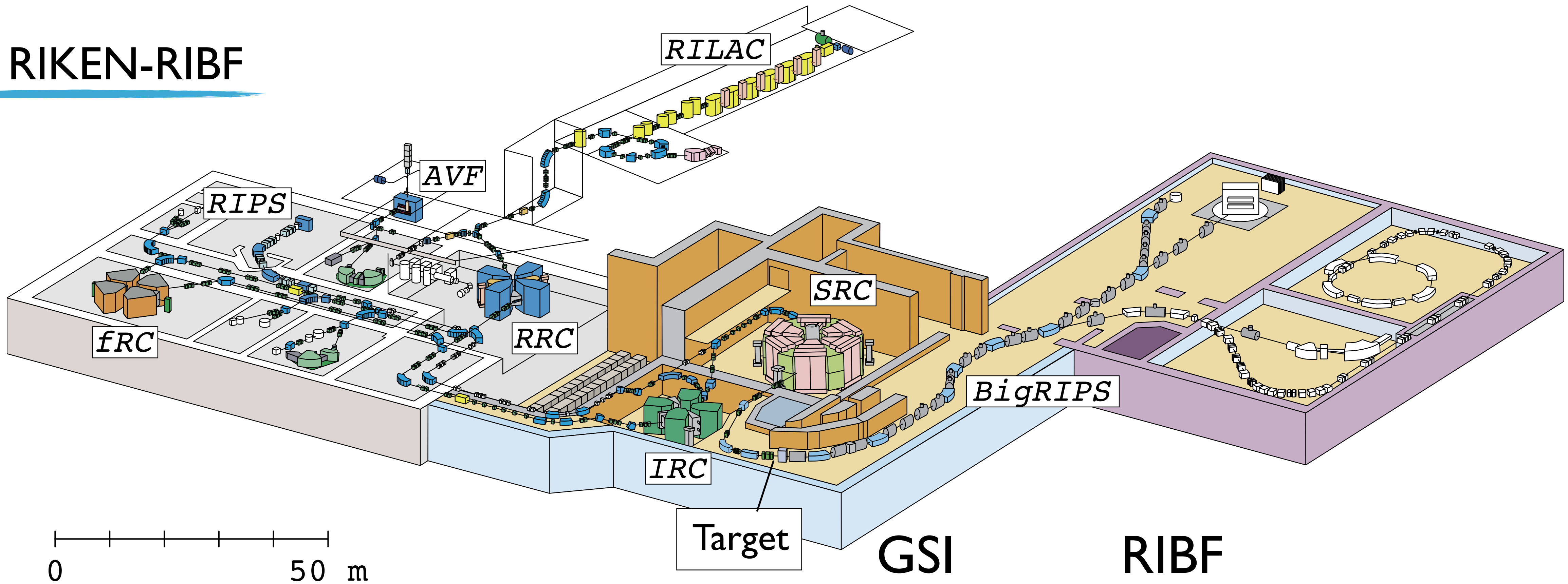
Precision spectroscopy at RI Beam Factory

RIKEN-RIBF



	GSI	RIBF
d beam Intensity	10	>10
Target	20 mg/cm	10 mg/cm
Δ	0.03%	0.06%
Resolution (FWHM)	400 keV	< 300 keV
Acceptance (mrad)	15H, 10V	40H, 60V

Resol. Matching

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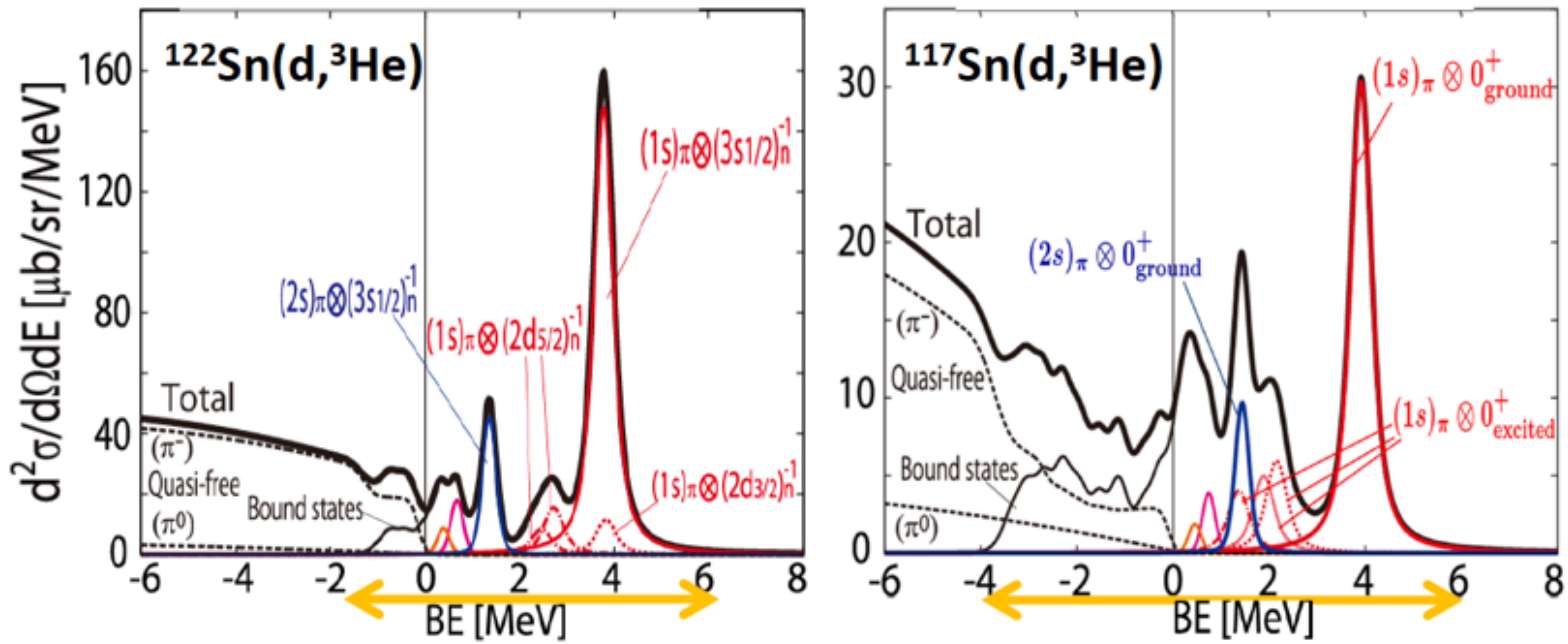
Theoretical predictions

Numerical Results: Even vs. Odd target

0 degrees

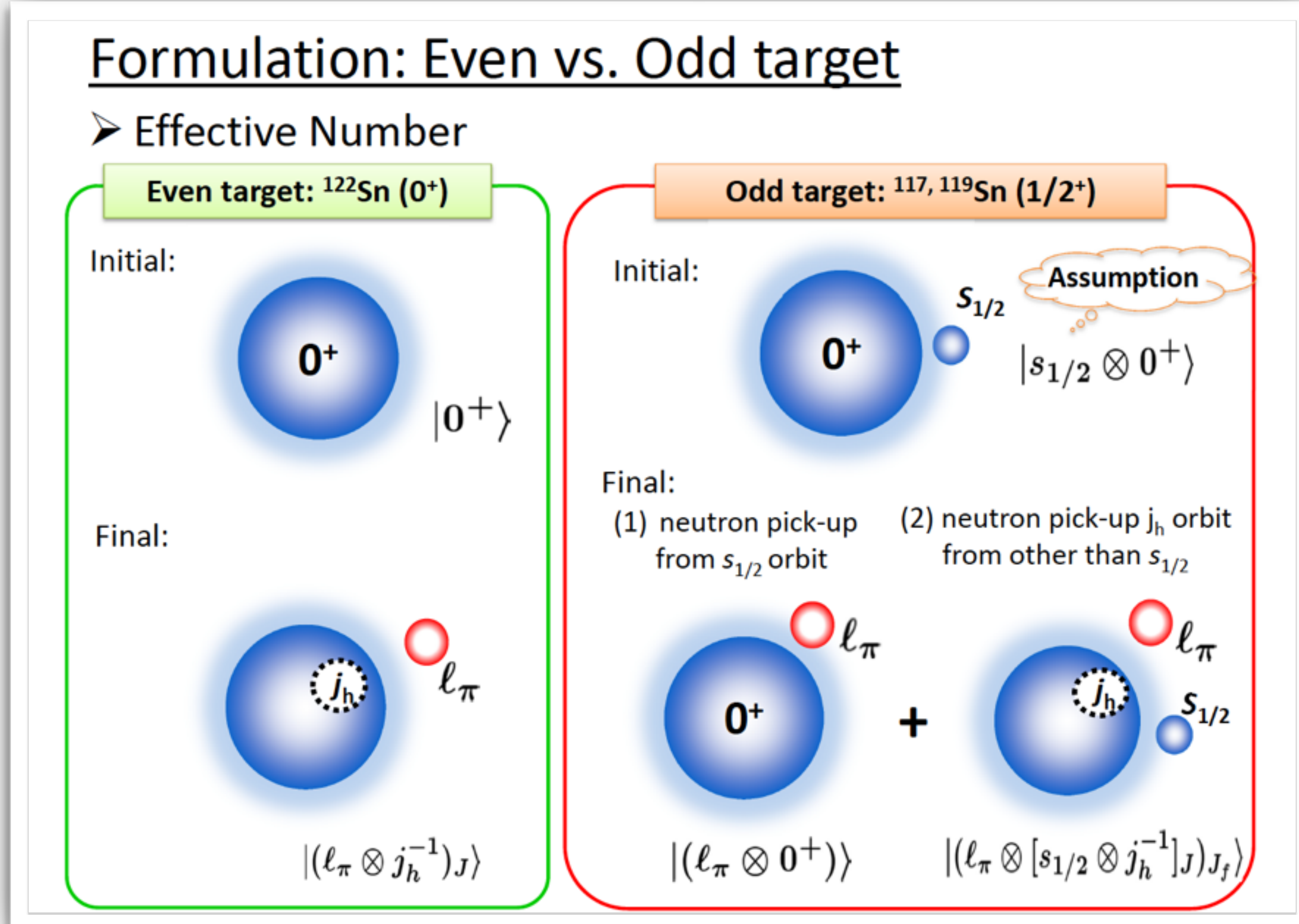
Even target: ^{122}Sn (0^+) | **Odd target: ^{117}Sn ($1/2^+$)**



- Pionic 1s state formation with neutron s-hole state is large in both spectra.
- Bound pionic state formation spectra in ^{117}Sn(d,^{3}He) are spread over wider energy range.
- Absolute value of cross section in ^{117}Sn(d,^{3}He) is smaller.

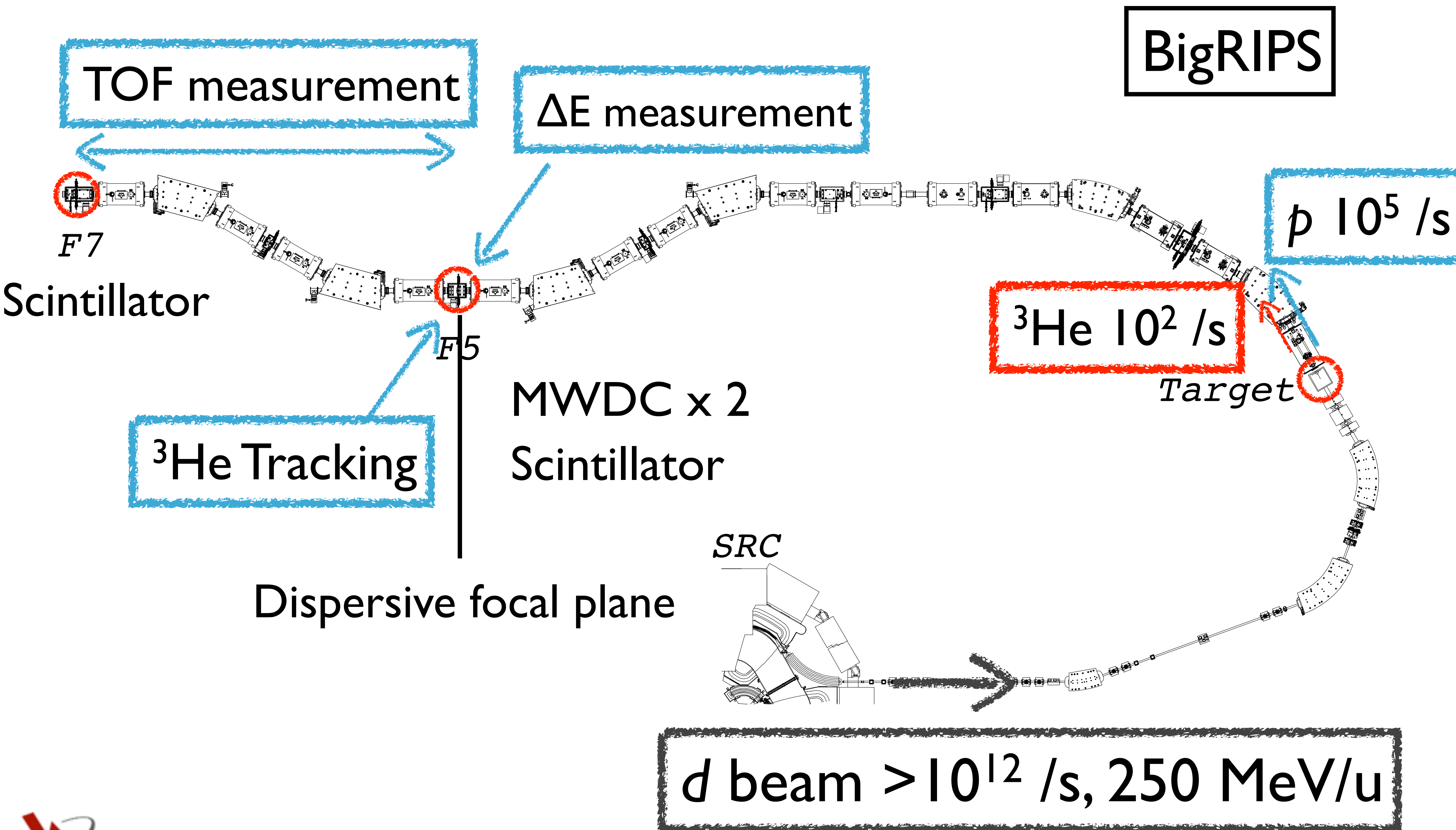
Ikeno@Hadron 2013

Theoretical predictions



Ikeno@Hadron 2013

Experimental setup



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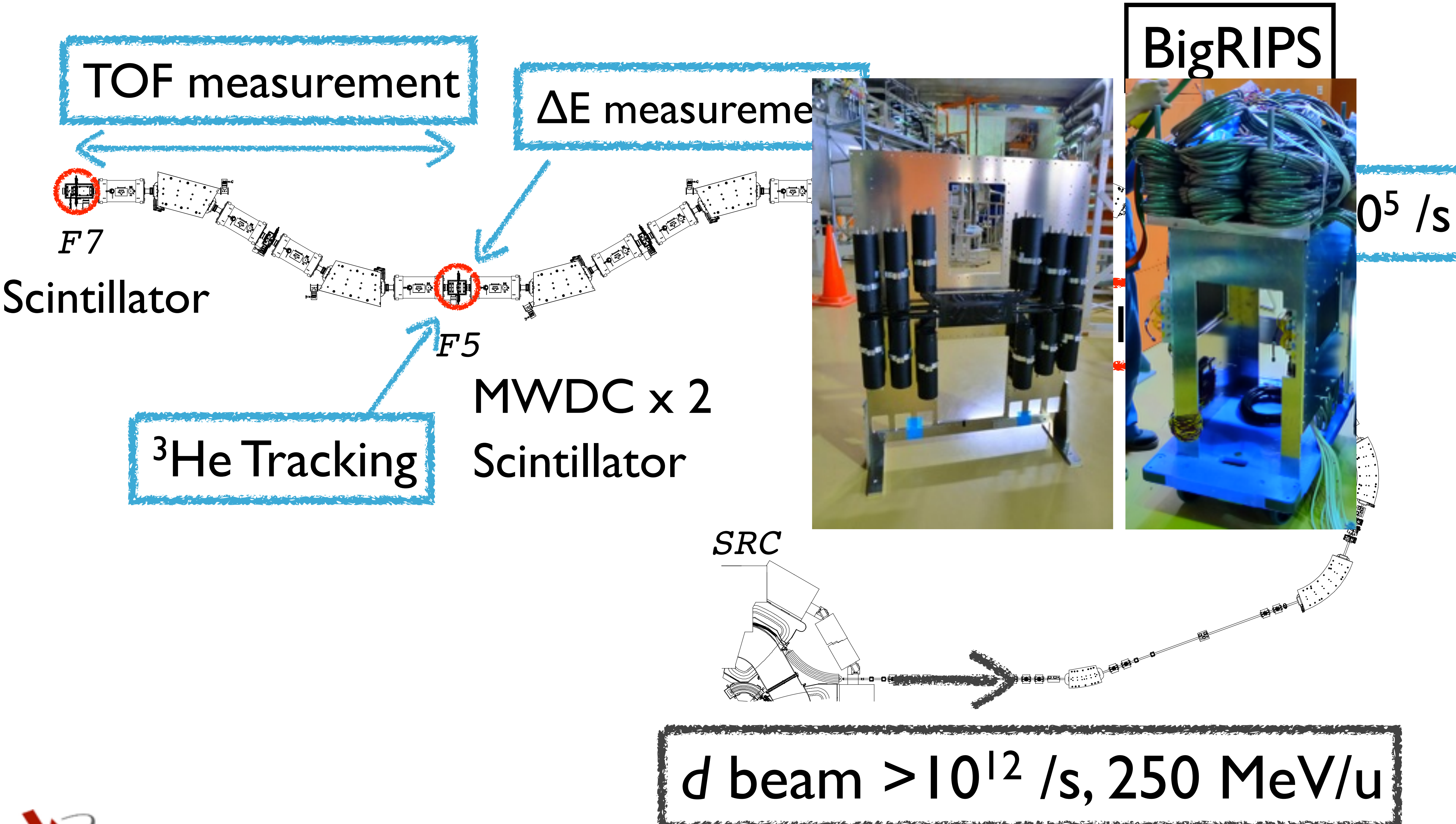
Experimental setup



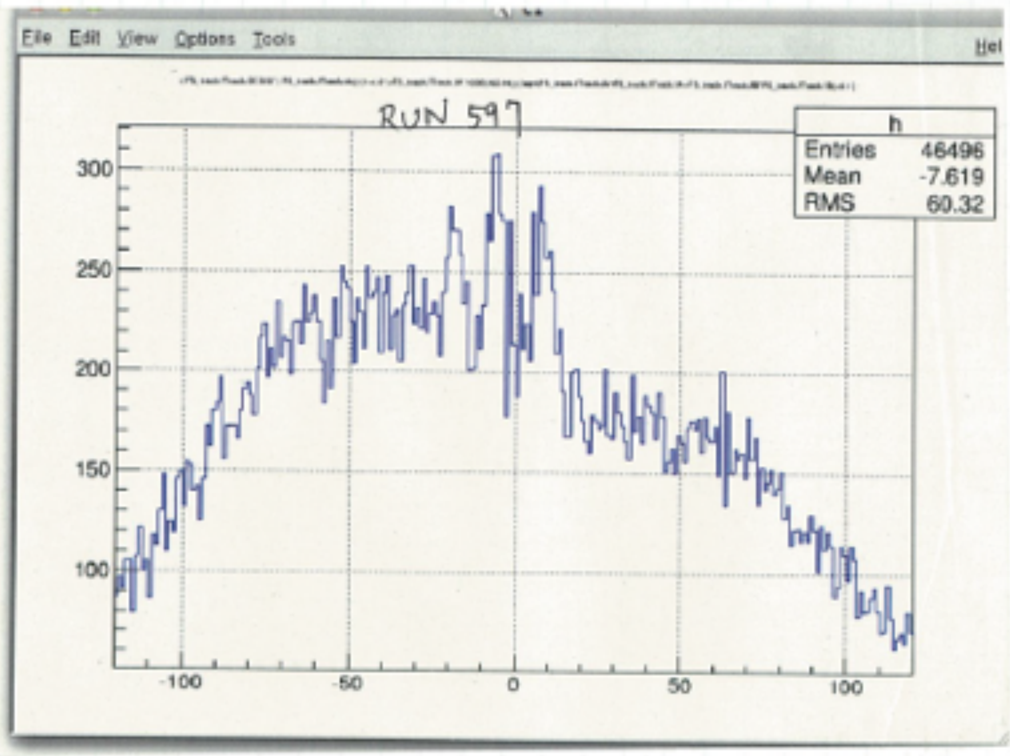
Group photo of working team in main experiment 2014

Horii, Yamakami, Watanabe, Suzuki, Geissel, Itahashi, Nishi, Tanaka, Weick, Haettner, Fujioka, Berg
phD candidate

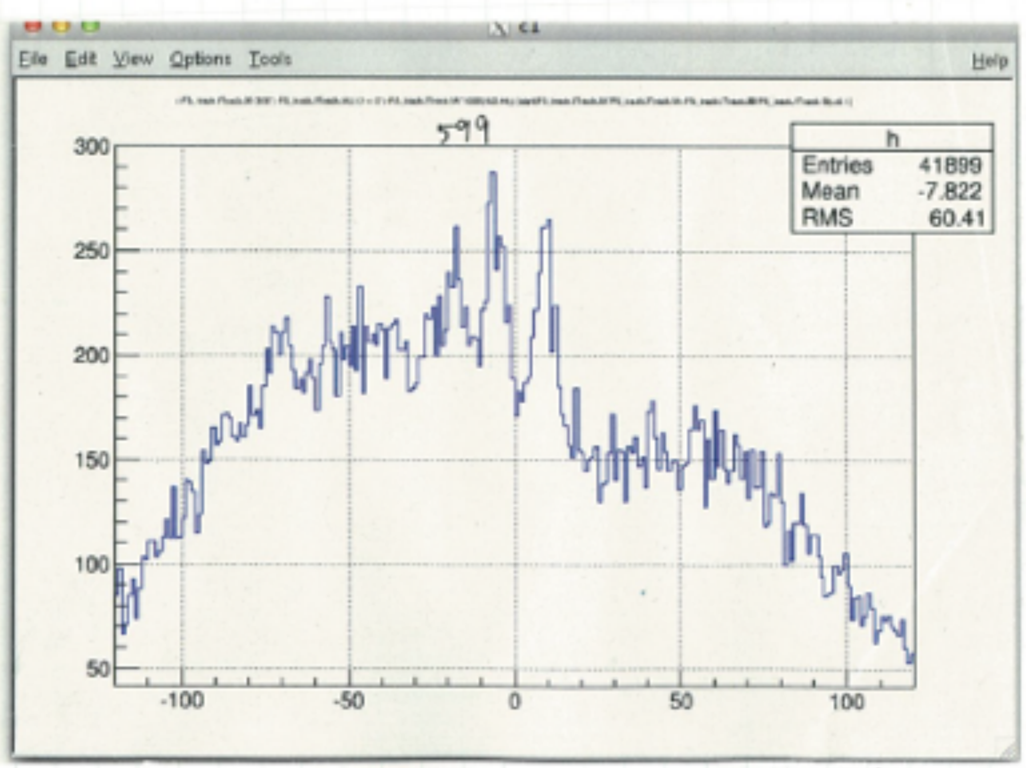
Status of analysis

solely by T. Nishi

Toward higher resolution (2014)



RUN597 resolution worse?

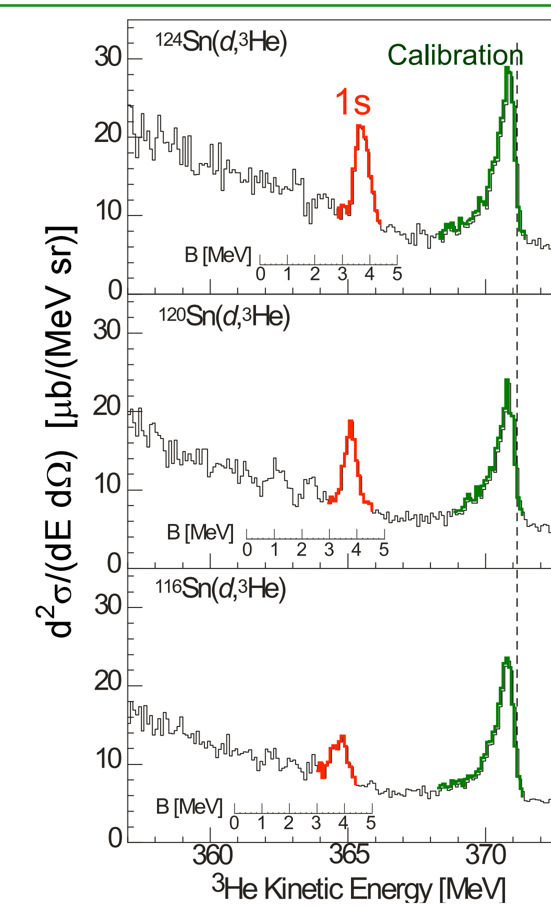


RUN 599 resolution restored?
after accelerator tune.

Online spectra

10 mg/cm^2 ^{122}Sn
10^{12}/s 30 minutes.

cf. 2 weeks for each target



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Achieved high quality spectra

RIBF54R1 (preliminary)

^{122}Sn(d,^{3}He)

2p

1s

RIBF54R1 measured
binding energies and widths

preliminary

^{117}Sn(d,^{3}He)

2p

1s

Binding energies and widths are determined with very high precision of 3 keV (stat.)

Ikeno, Hirenzaki, priv. comm.

Achieved high quality spectra

RIBF54R1 (preliminary)

^{122}Sn(d,^{3}He)

??

??

RIBF54R1 measured binding energies and widths

preliminary

^{117}Sn(d,^{3}He)

??

??

Binding energies and widths are determined with very high precision of 3 keV (stat.)

Ikeno, Hirenzaki, priv. comm.

First observation of θ dependence of π atom cross section

1.5-2°

1-1.5°

0.5-1°

0-0.5°

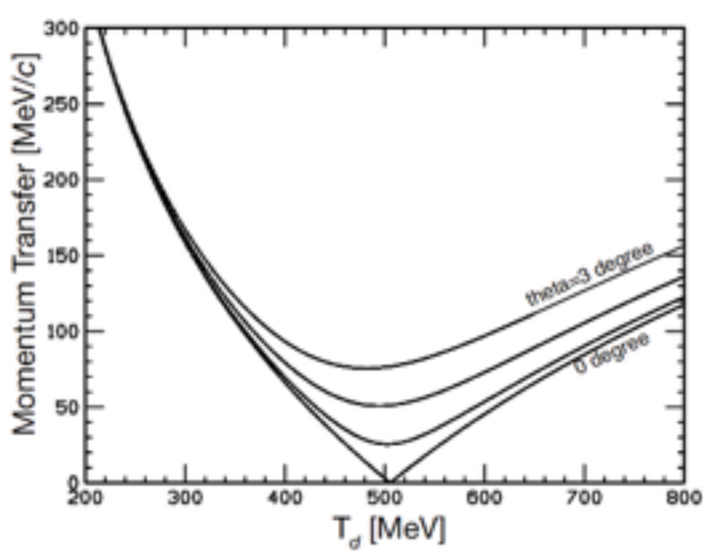
reaction angle

$\propto$

momentum transfer

$\Delta L = q \times r$

momentum transfer

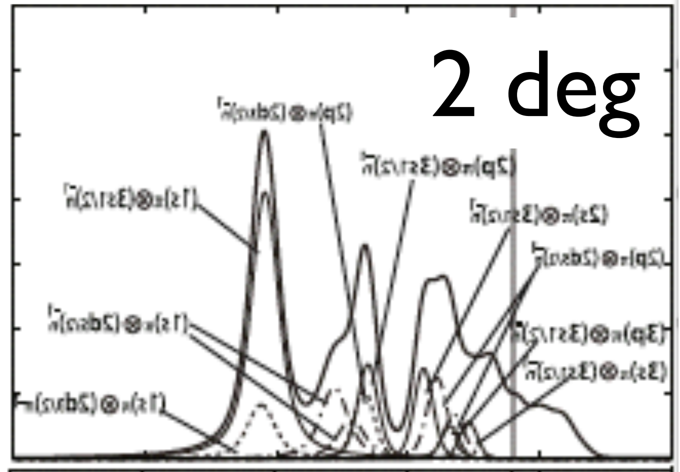


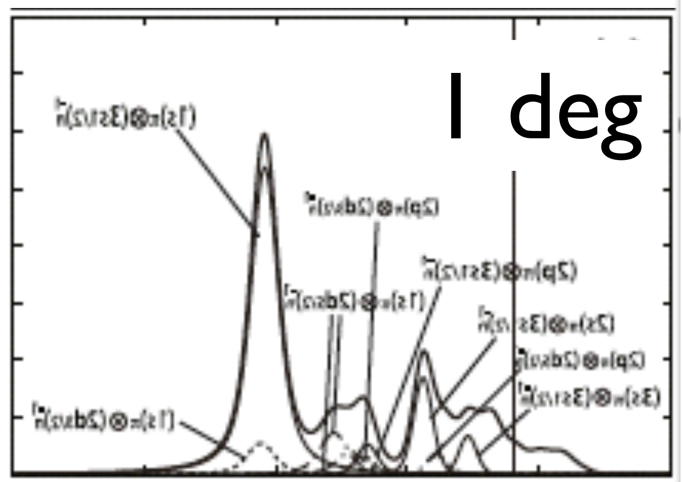
2010
16 hour measurement

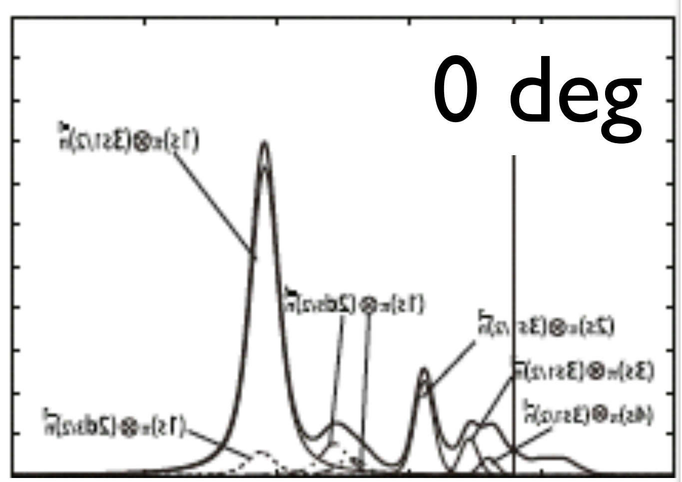
T. Nishi et al., *to be submitted*

Theory vs Experiment

Theory







Ikeno, Hirenzaki

1.5-2°

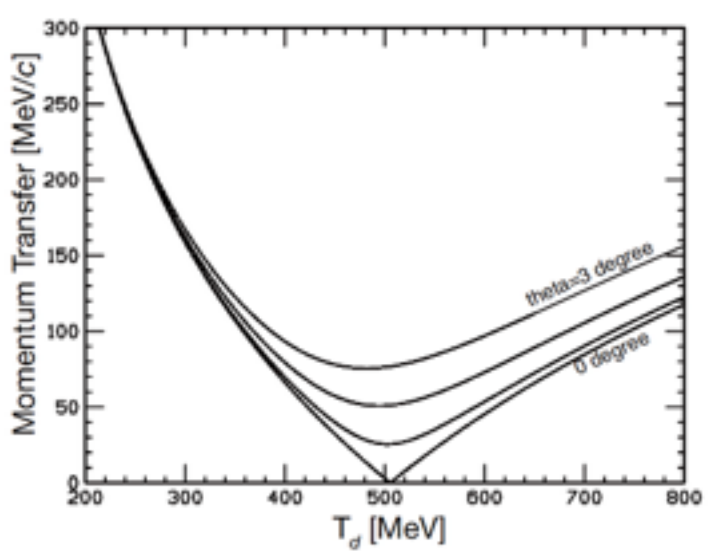
1-1.5°

0.5-1°

0-0.5°

Angular dependent Xsec is explained fairly well by theory based on *q* dependence

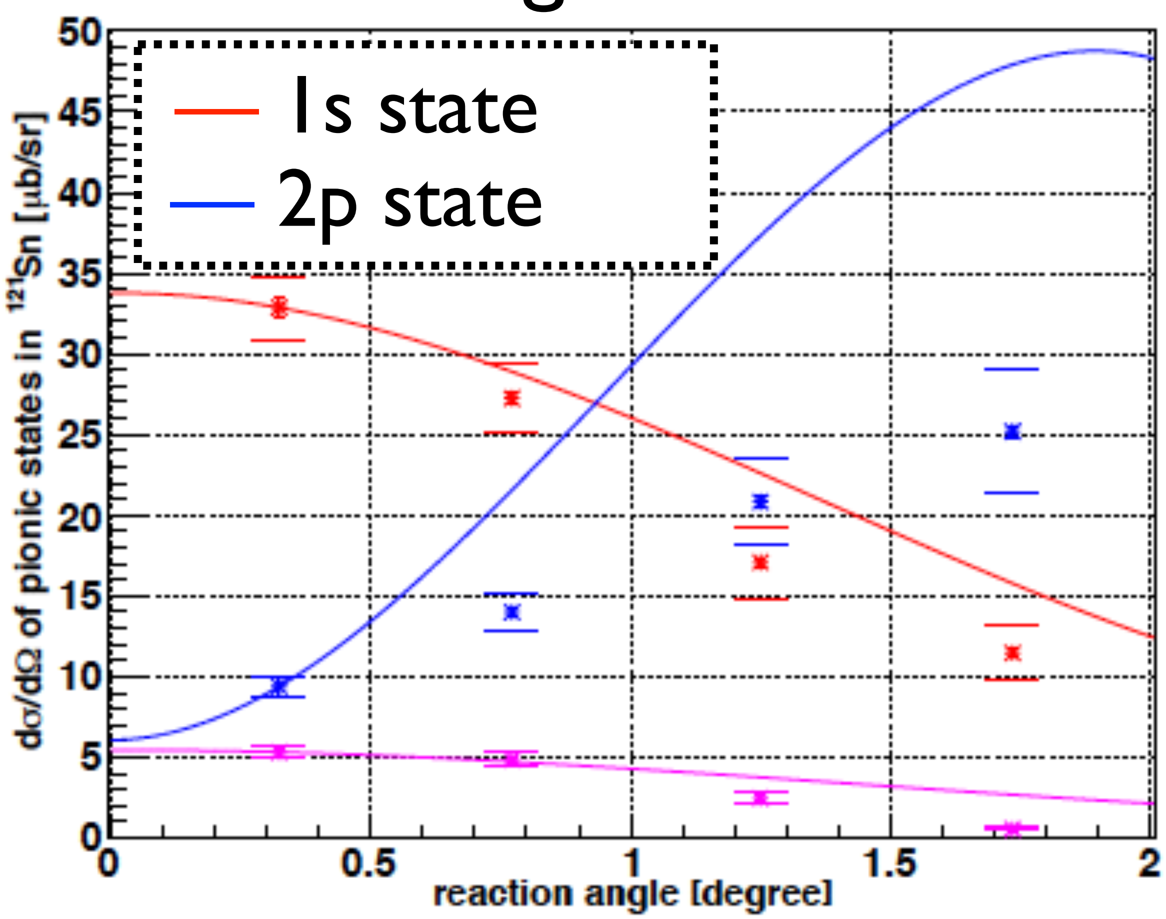
momentum transfer



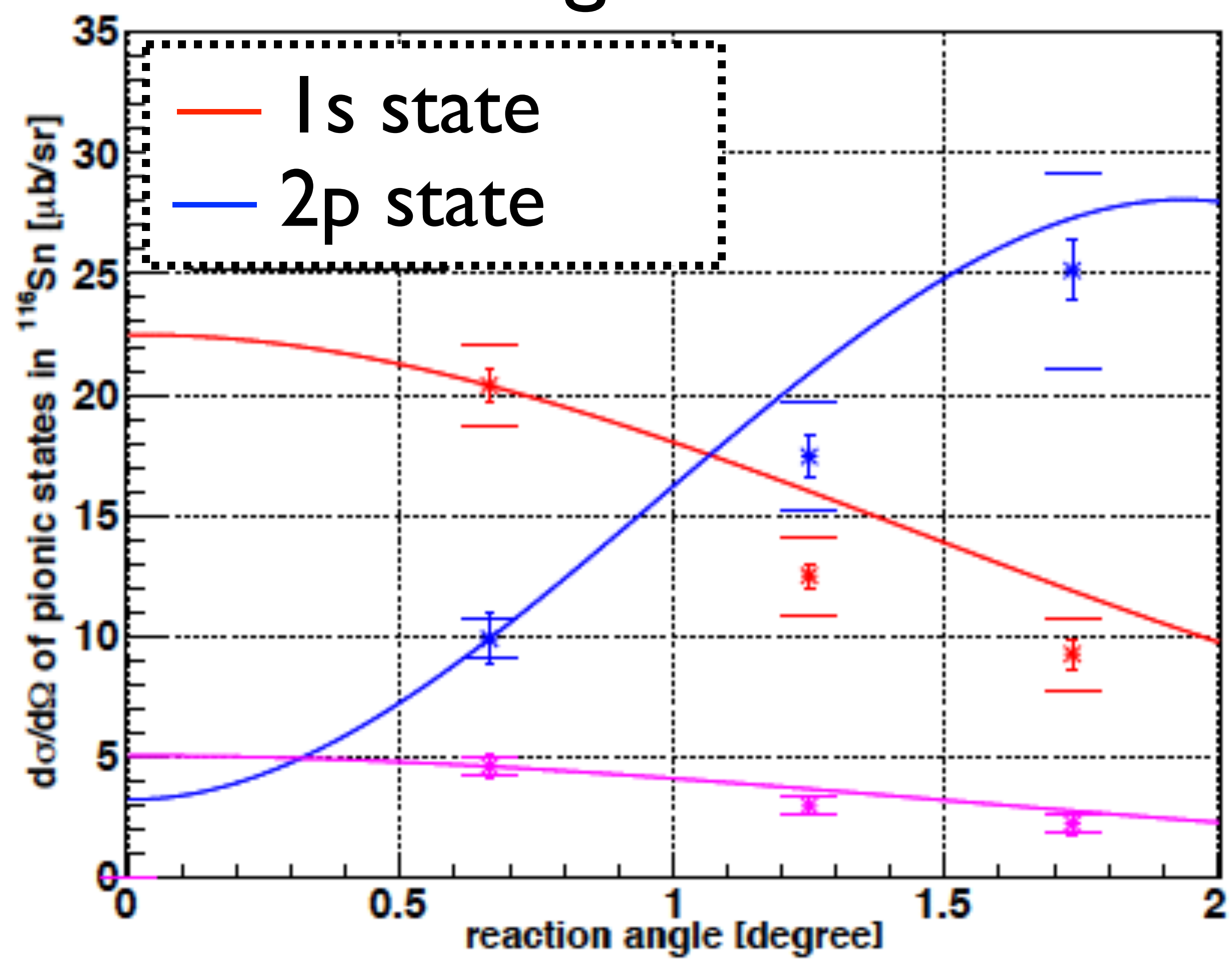
Angular dependence

- Angular dependence of the formation cross section are discovered for the first time by the experiment at RIKEN.
- The dependences are qualitatively consistent with the theoretical predictions.

target: ^{122}Sn



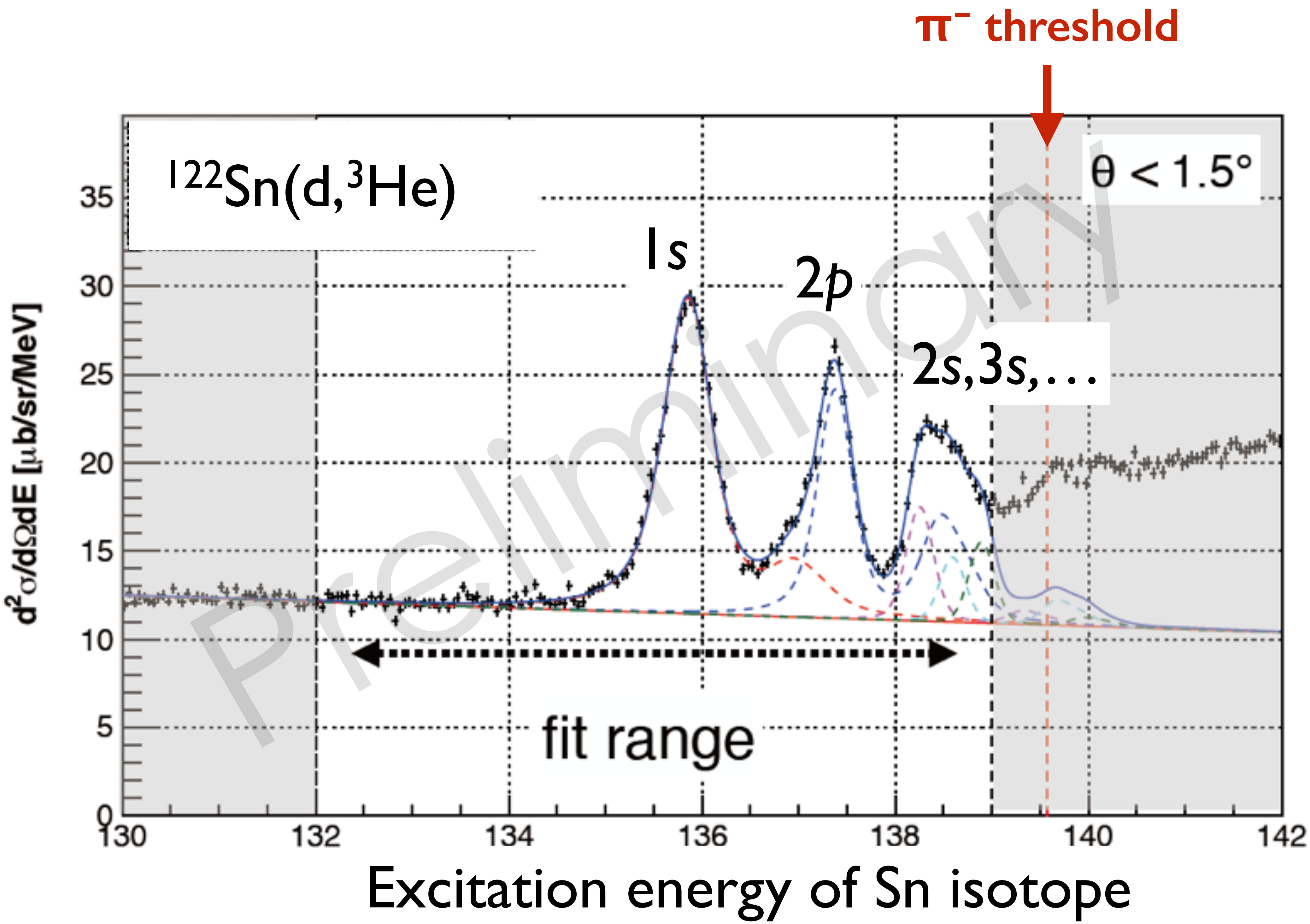
target: ^{117}Sn



Ikeno, Hirenzaki, priv. comm.

Looking into observed spectrum

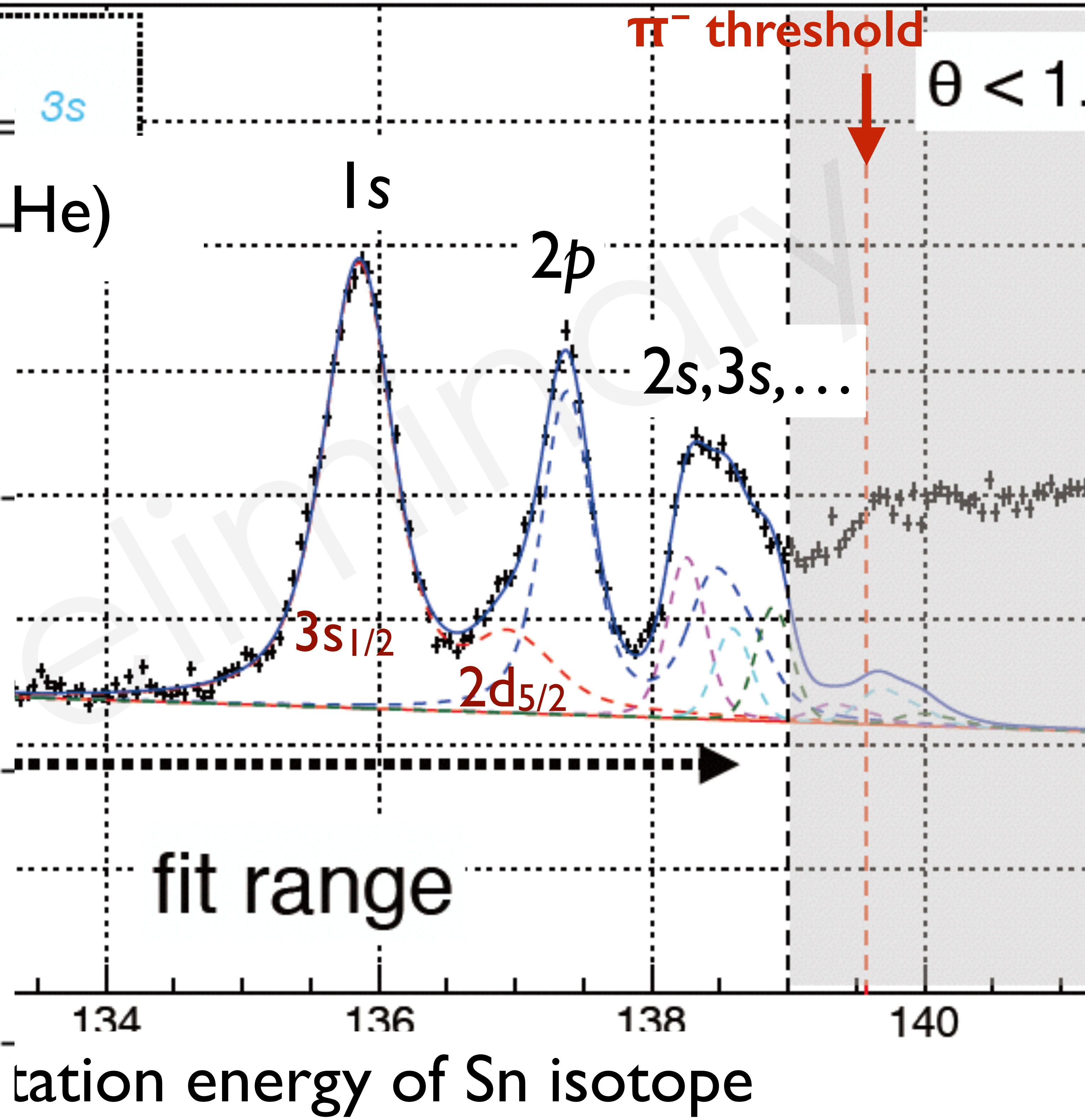
configuration $(nl)_\pi \otimes (j_n)_n^{-1}$	$N_{\rm eff}$ $0^\circ < \theta < 1.5^\circ$	$\Delta S^n_{j_n}$ [MeV]
$(1s)_\pi \otimes (3s_{1/2})_n^{-1}$	4.99×10^{-2}	0.060
$(1s)_\pi \otimes (2d_{3/2})_n^{-1}$	4.03×10^{-3}	0.000
$(1s)_\pi \otimes (2d_{5/2})_n^{-1}$	5.36×10^{-3}	1.121
$(1s)_\pi \otimes (2d_{5/2})_n^{-1}$	2.92×10^{-3}	1.403
$(1s)_\pi \otimes (1g_{7/2})_n^{-1}$	8.84×10^{-5}	0.926
$(1s)_\pi \otimes (1h_{11/2})_n^{-1}$	2.03×10^{-5}	0.006
$(2p)_\pi \otimes (3s_{1/2})_n^{-1}$	8.78×10^{-4}	0.060
$(2p)_\pi \otimes (2d_{3/2})_n^{-1}$	5.09×10^{-4}	0.000
$(2p)_\pi \otimes (2d_{5/2})_n^{-1}$	4.83×10^{-4}	1.121
$(2p)_\pi \otimes (2d_{5/2})_n^{-1}$	2.53×10^{-4}	1.403
$(2p)_\pi \otimes (1g_{7/2})_n^{-1}$	6.87×10^{-5}	0.926
$(2p)_\pi \otimes (1h_{11/2})_n^{-1}$	8.87×10^{-5}	0.006
$(2s)_\pi \otimes (3s_{1/2})_n^{-1}$	9.05×10^{-3}	0.060
$(2s)_\pi \otimes (2d_{3/2})_n^{-1}$	7.47×10^{-4}	0.000
$(2s)_\pi \otimes (2d_{5/2})_n^{-1}$	1.02×10^{-3}	1.121
$(2s)_\pi \otimes (2d_{5/2})_n^{-1}$	5.54×10^{-4}	1.403
$(2s)_\pi \otimes (1g_{7/2})_n^{-1}$	1.77×10^{-5}	0.926
$(2s)_\pi \otimes (1h_{11/2})_n^{-1}$	2.82×10^{-6}	0.006
$(3p)_\pi \otimes (3s_{1/2})_n^{-1}$	1.91×10^{-4}	0.060
$(3p)_\pi \otimes (2d_{3/2})_n^{-1}$	1.13×10^{-4}	0.000
$(3p)_\pi \otimes (2d_{5/2})_n^{-1}$	1.14×10^{-4}	1.121
$(3p)_\pi \otimes (2d_{5/2})_n^{-1}$	6.03×10^{-5}	1.403
$(3p)_\pi \otimes (1g_{7/2})_n^{-1}$	1.72×10^{-5}	0.926
$(3p)_\pi \otimes (1h_{11/2})_n^{-1}$	2.69×10^{-5}	0.006
$(3s)_\pi \otimes (3s_{1/2})_n^{-1}$	3.15×10^{-3}	0.060
$(3s)_\pi \otimes (2d_{3/2})_n^{-1}$	2.63×10^{-4}	0.000
$(3s)_\pi \otimes (2d_{5/2})_n^{-1}$	3.60×10^{-4}	1.121
$(3s)_\pi \otimes (2d_{5/2})_n^{-1}$	1.96×10^{-4}	1.403
$(3s)_\pi \otimes (1g_{7/2})_n^{-1}$	6.48×10^{-6}	0.926
$(3s)_\pi \otimes (1h_{11/2})_n^{-1}$	9.31×10^{-7}	0.006



Kenta Itahashi, RIKEN

A close look into observed spectrum

configuration $(nl)_\pi \otimes (j_n)_n^{-1}$	$N_{\rm eff}$ $0^\circ < \theta < 1.5^\circ$	$\Delta S^n_{j_n}$ [MeV]
$(1s)_\pi \otimes (3s_{1/2})_n^{-1}$	4.99×10^{-2}	0.060
$(1s)_\pi \otimes (2d_{3/2})_n^{-1}$	4.03×10^{-3}	0.000
$(1s)_\pi \otimes (2d_{5/2})_n^{-1}$	5.36×10^{-3}	1.121
$(1s)_\pi \otimes (2d_{5/2})_n^{-1}$	2.92×10^{-3}	1.403
$(1s)_\pi \otimes (1g_{7/2})_n^{-1}$	8.84×10^{-5}	0.926
$(1s)_\pi \otimes (1h_{11/2})_n^{-1}$	2.03×10^{-5}	0.006
$(2p)_\pi \otimes (3s_{1/2})_n^{-1}$	8.78×10^{-4}	0.060
$(2p)_\pi \otimes (2d_{3/2})_n^{-1}$	5.09×10^{-4}	0.000
$(2p)_\pi \otimes (2d_{5/2})_n^{-1}$	4.83×10^{-4}	1.121
$(2p)_\pi \otimes (2d_{5/2})_n^{-1}$	2.53×10^{-4}	1.403
$(2p)_\pi \otimes (1g_{7/2})_n^{-1}$	6.87×10^{-5}	0.926
$(2p)_\pi \otimes (1h_{11/2})_n^{-1}$	8.87×10^{-5}	0.006
$(2s)_\pi \otimes (3s_{1/2})_n^{-1}$	9.05×10^{-3}	0.060
$(2s)_\pi \otimes (2d_{3/2})_n^{-1}$	7.47×10^{-4}	0.000
$(2s)_\pi \otimes (2d_{5/2})_n^{-1}$	1.02×10^{-3}	1.121
$(2s)_\pi \otimes (2d_{5/2})_n^{-1}$	5.54×10^{-4}	1.403
$(2s)_\pi \otimes (1g_{7/2})_n^{-1}$	1.77×10^{-5}	0.926
$(2s)_\pi \otimes (1h_{11/2})_n^{-1}$	2.82×10^{-6}	0.006
$(3p)_\pi \otimes (3s_{1/2})_n^{-1}$	1.91×10^{-4}	0.060
$(3p)_\pi \otimes (2d_{3/2})_n^{-1}$	1.13×10^{-4}	0.000
$(3p)_\pi \otimes (2d_{5/2})_n^{-1}$	1.14×10^{-4}	1.121
$(3p)_\pi \otimes (2d_{5/2})_n^{-1}$	6.03×10^{-5}	1.403



tahashi, RIKEN

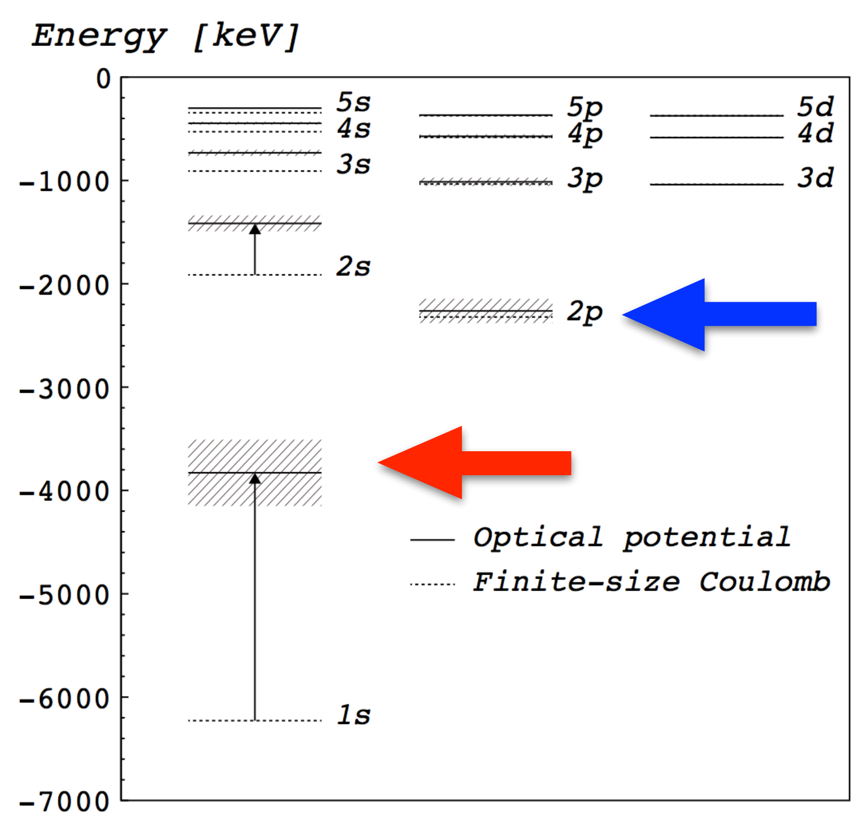
Calibration methods

(i) calibration by two body reaction of the $p(d,{}^3\mathrm{He})\pi^0$ reaction on polyethylene target

(ii) deduction of B_{1s} - B_{2p} in addition

Use pionic $2p$ state as a reference.

Shift of B_{2p} by strong interaction is much smaller than that of B_{1s} (~ 1/50)



Excitation spectrum of ^{121}Sn (exp. in 2014)

Theoretically calculated B_{1s} and B_{2p} in ^{121}Sn※

※ N. Ikeno et al., Prog. Theor. Phys. 126 (2011) 483., S. Itoh, Doctoral Dissertation, Univ. of Tokyo (2011)

Achieved high quality spectra

RIBF54R1 (preliminary)

^{122}Sn(d,^{3}He)

2p

1s

^{117}Sn(d,^{3}He)

2p

1s

aft. combination with light pi-A data

→we are ready to start high precision study of b_1

Result of recent experiment

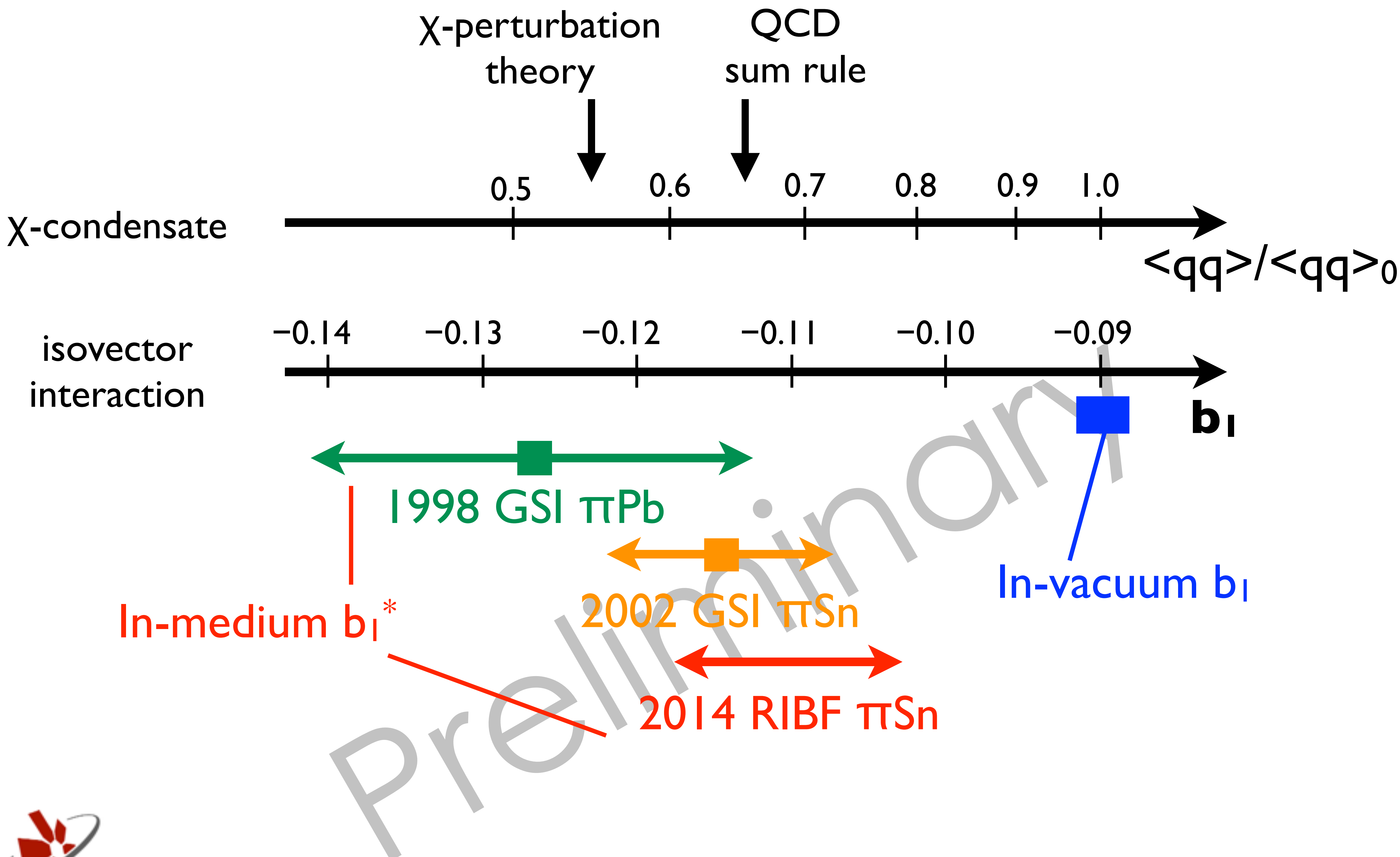
Preliminary

aft. combination with light pi-A data

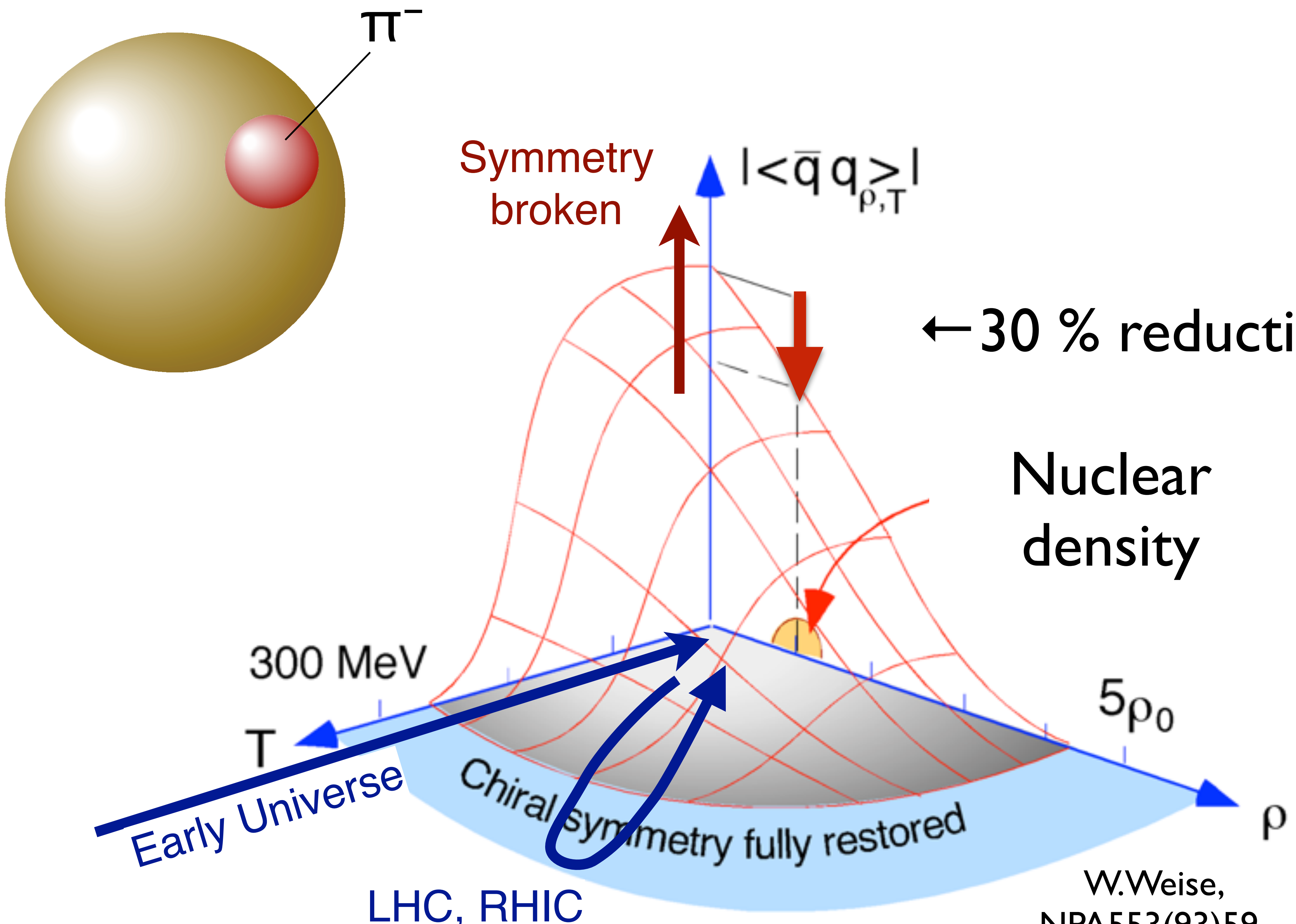
b_1 can be deduced from measurement of each pionic isotope

$$V_{s\text{-wave}} = b_0\ \rho + \color{red}{b_1}\ (\rho_n - \rho_p) + B_0\ \rho^2 \qquad \rho_e = 0.6\ \rho_0$$

π-nucleus interaction and χ-symmetry



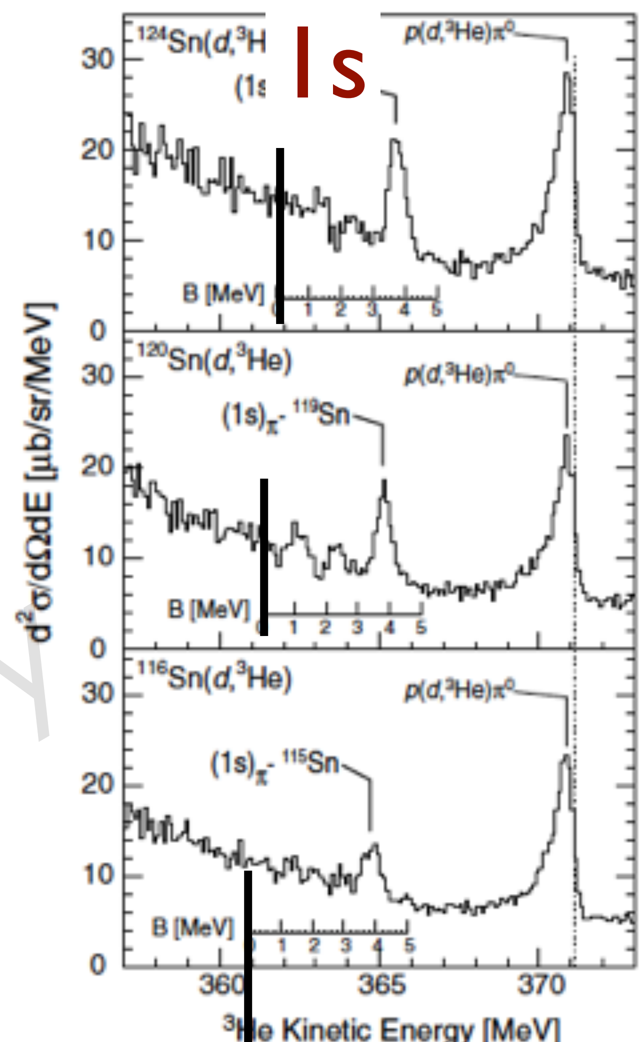
Order parameter at nuclear density



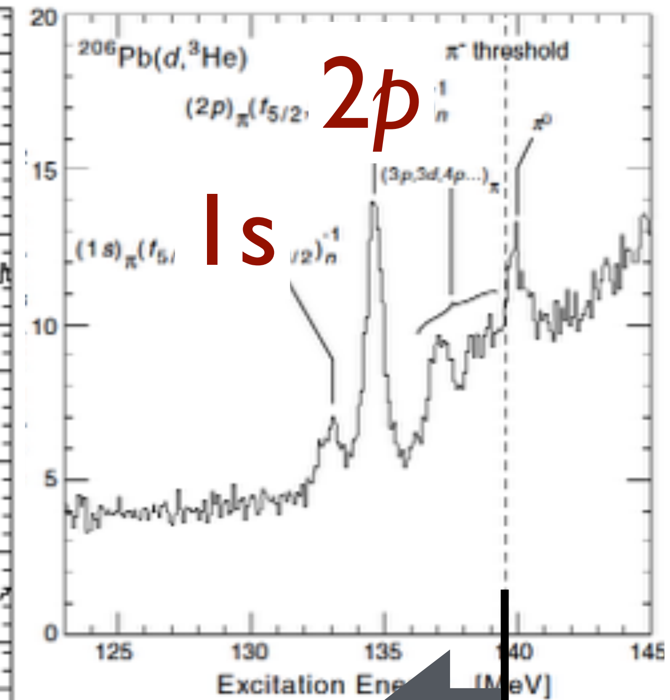
χ-condensate decreases by 30 % at ρ_0

Development of pionic atom spectroscopy

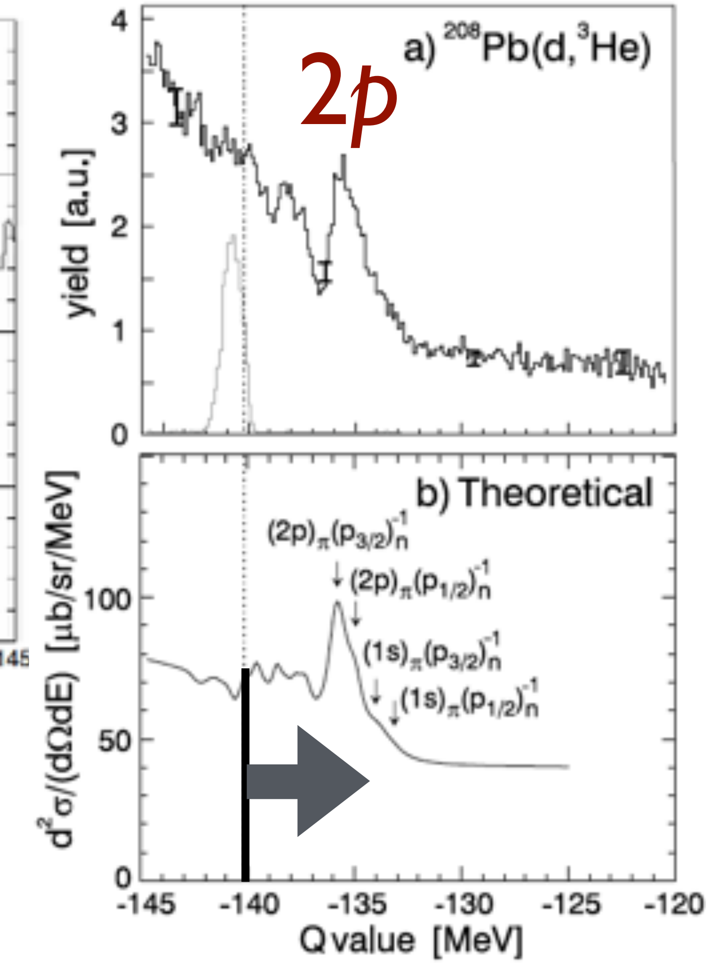
High precision | Systematic | 1*s* observation | Discovery



2002 GSI



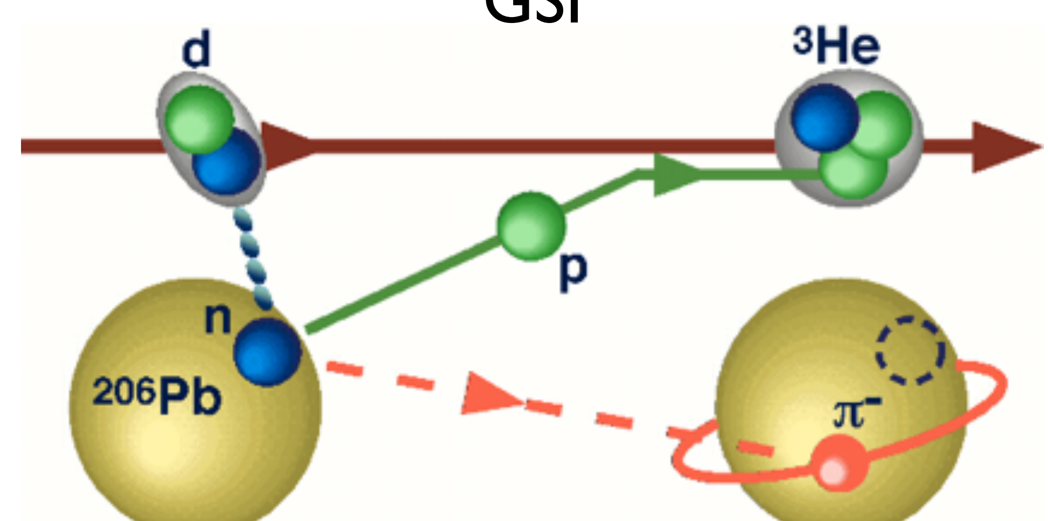
1998 GSI



1996 (d,^{3}He)
GSI

bound | 2010 RIBF
threshold

Yamazaki et al., Z. Phys A355
Geissel et al., PRL 88
Suzuki et al., PRL 92
T. Nishi et al., *to be submitted*



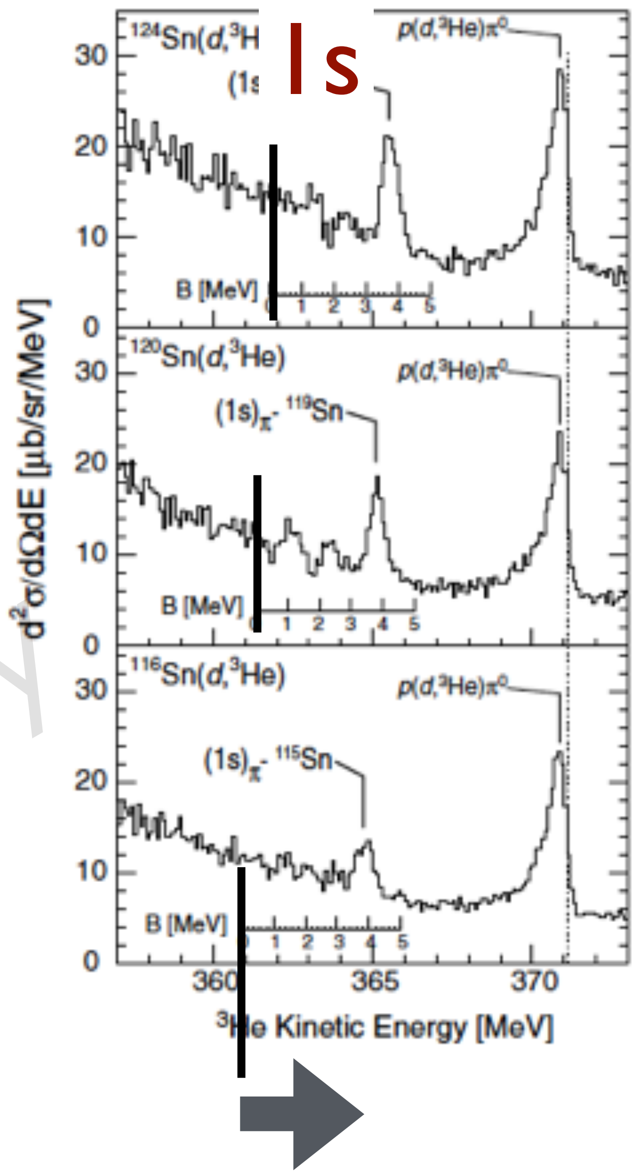
Development of pionic atom spectroscopy

High precision

Preliminary

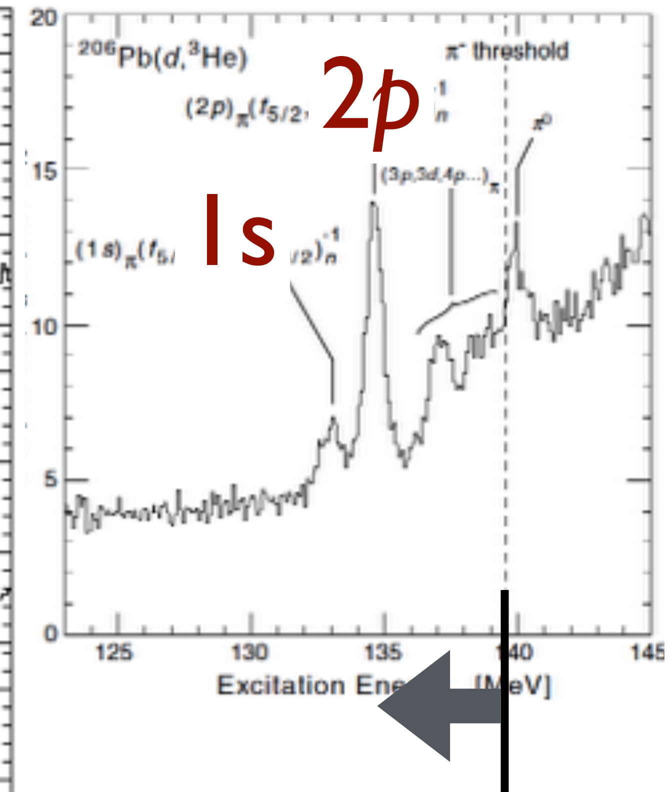
Preliminary

Systematic



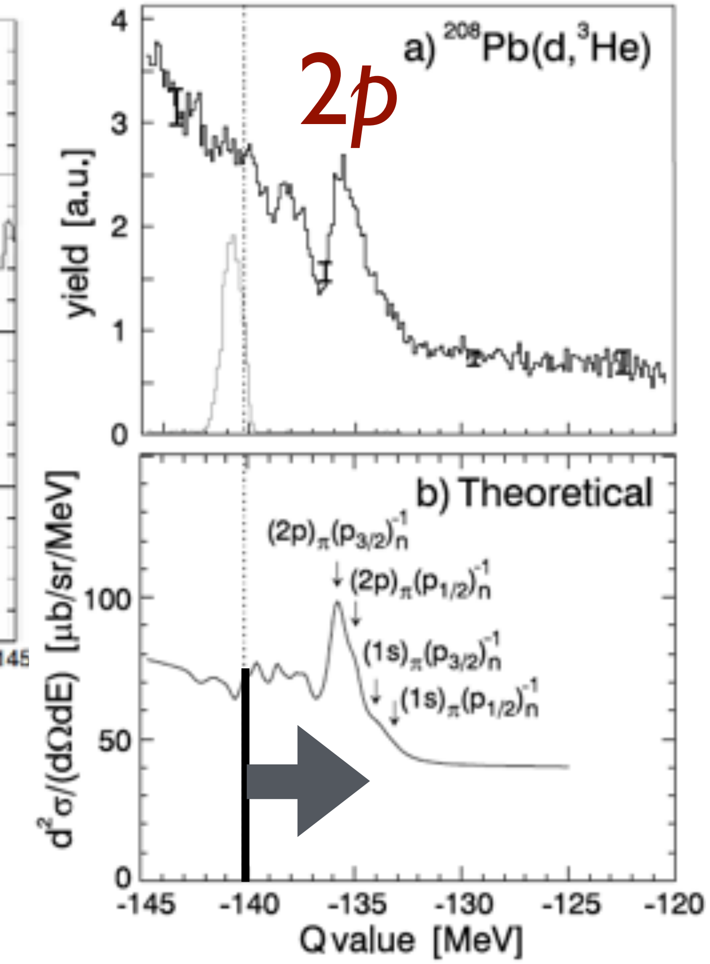
2002 GSI

1s observation



1998 GSI

Discovery



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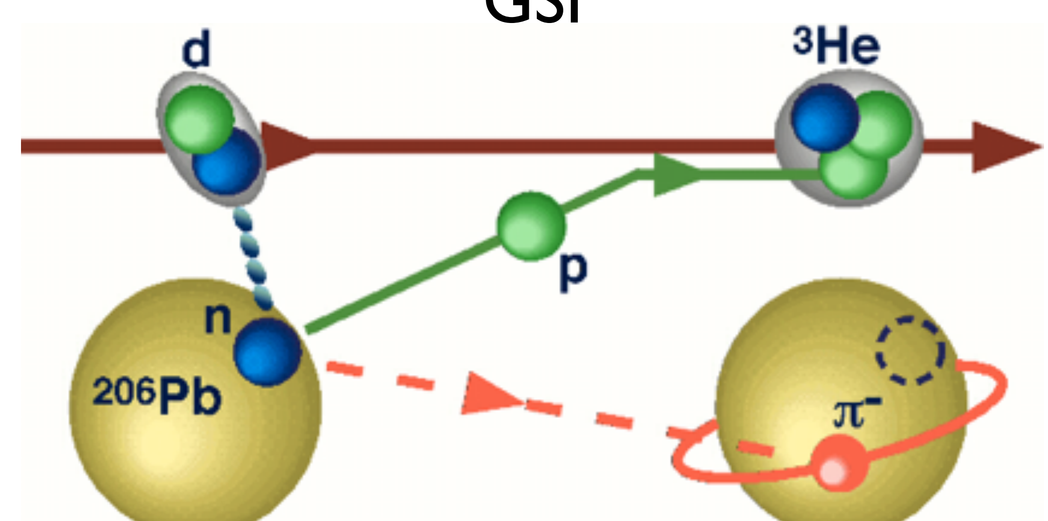


Future perspectives

Pionic atoms with long chain of tin isotopes

We propose to perform measurement of pionic atoms over the long chain of tin isotopes with a similar statistical precision level of ~ 3 keV

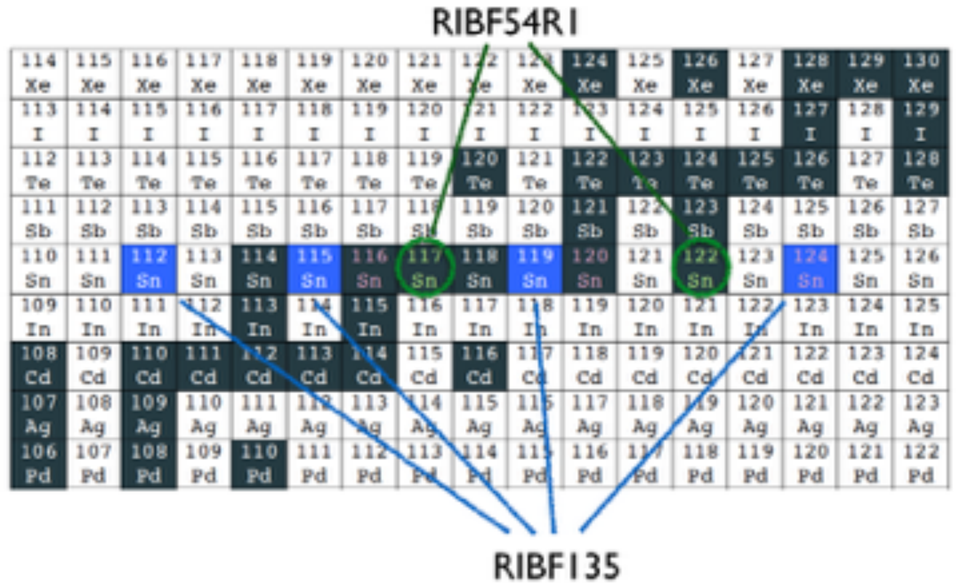
RIBF54R1

114 Xe	115 Xe	116 Xe	117 Xe	118 Xe	119 Xe	120 Xe	121 Xe	122 Xe	123 Xe	124 Xe	125 Xe	126 Xe	127 Xe	128 Xe	129 Xe	130 Xe
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	129 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	128 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	127 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	126 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	125 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	124 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	123 Ag
106 Pd	107 Pd	108 Pd	109 Pd	110 Pd	111 Pd	112 Pd	113 Pd	114 Pd	115 Pd	116 Pd	117 Pd	118 Pd	119 Pd	120 Pd	121 Pd	122 Pd

RIBF135

Future perspectives

RIBF135

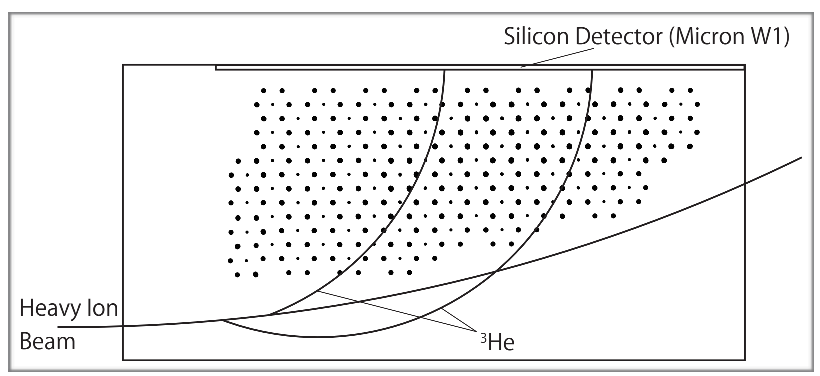


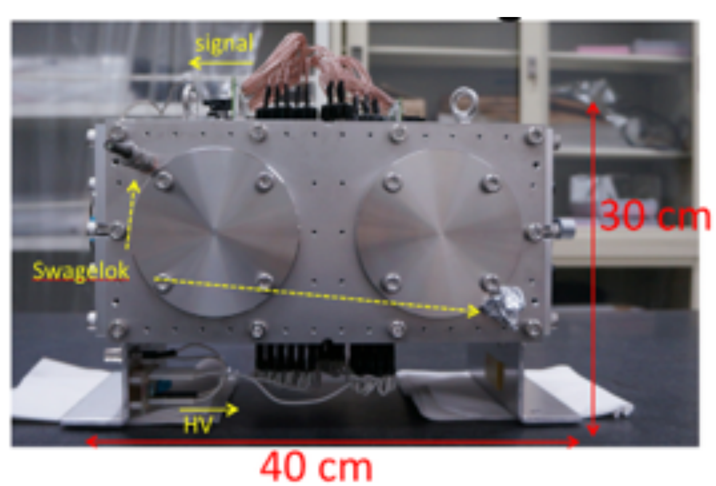
Systematic
high precision

RIBF54

2016

Pionic atoms
with unstable
nuclei





Large impacts on

- Density dependence of χ-condensate
- Nuclear structure including EOS (neutron stars)

Perturbative effects on
the nuclear structure
induced by pionic atoms

Conclusion

- Deeply bound pionic atoms provides b_1^* information
  → chiral condensate at nuclear medium
- World highest precision in RIBF
- Extremely good statistics for ^{121}Sn-pi
- First data for pionic even *N* atom
- First measurement of angular dependent X-sec
- Analysis is ongoing to finalization
- New experiment is proposed and approved for systematic spectroscopy
- We are also working on piA with unstable nuclei.